UCLouvain
Institut de recherche en mathématique et physique
Centre de Cosmologie, Physique des Particules et Phénoménologie

Electroweak and Higgs phenomenology including EFT

Celine Degrande

Plan

- Electroweak interaction
  - Beta decay and Fermi theory
  - Parity violation
  - Weak algebra and neutral currents
  - Electroweak theory
- Spontaneous symmetry breaking
  - U(1)
  - SM
  - Fermions masses
- Effective field theory
  - Introduction
  - Operators and interactions
  - Interference

Exercices in purple by hand and in MadGraph

Connection to pheno along the way

Questions

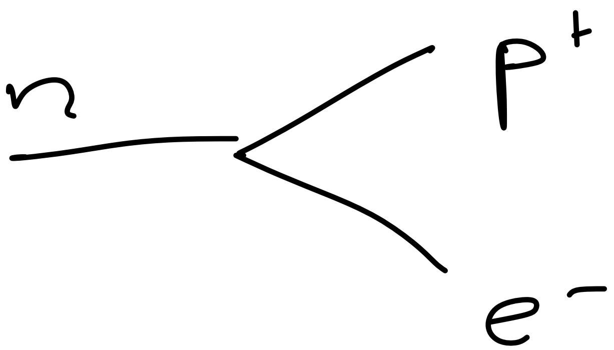
- Does the weak interaction explain why they are rocky planets?
- Is the proportionality of the Higgs to fermion couplings to their masses due to
  - Parity
  - Gauge invariance
  - Spontaneous symmetry breaking
- Why are they so many muons produced by CR in the atmosphere?

Questions

- Why is the proton stable and not the neutron?
- Can I predict the W and z masses from low energy data?

Electroweak interaction

Beta decay

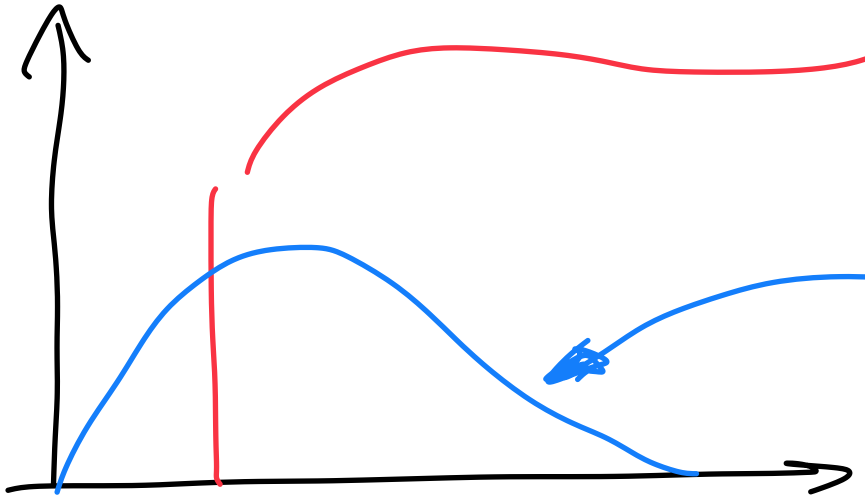


$1 \longrightarrow 2$

Ex: $p_n = p_p + p_e$

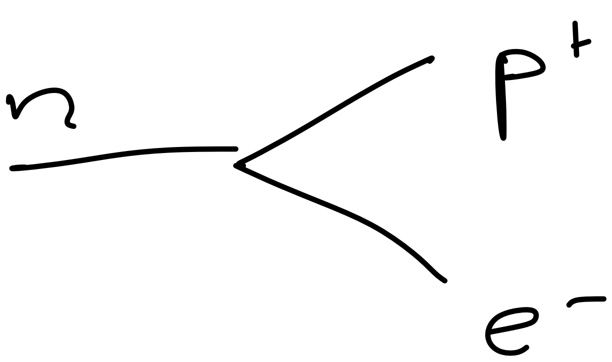
$$E_e^2 = \frac{(m_n^2 - m_p^2 + m_e)^2}{2 m_n} \longrightarrow m_e^2$$

$m_n \to m_p + m_e$



Pauli (1930) : + neutrino

Beta decay



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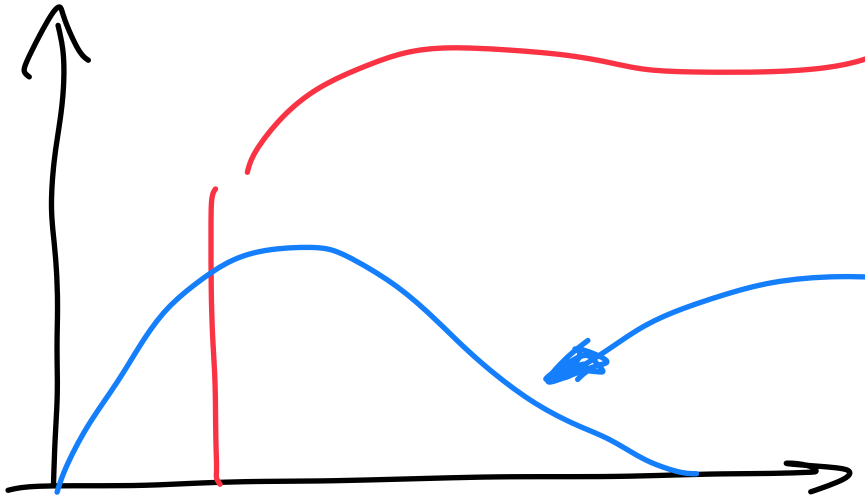
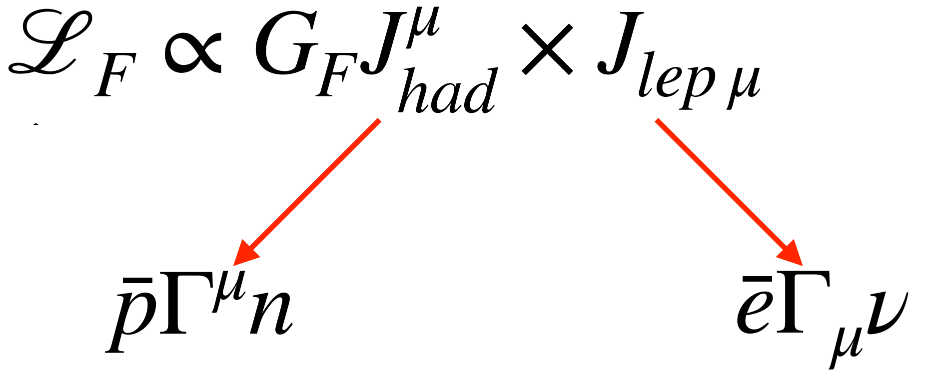


E and Spin conservation

Pauli (1930) : + neutrino

Fermi theory (1933)

Current x current

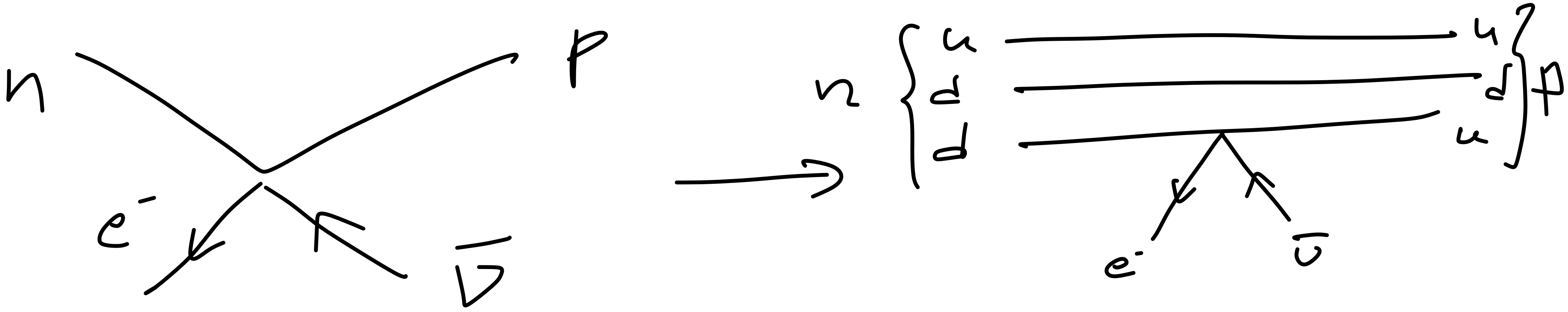


$$\mathscr{L}_F \propto G_F J^{\mu}_{had} \times J_{lep\,\mu}$$

$$\bar{p}\Gamma^{\mu} n \qquad \bar{e}\Gamma_{\mu}\nu$$

$$\Gamma_{\mu} = ?\gamma_{\mu}$$

n destroyed and p, e, ν created



$$\mathscr{L}_F \propto G_F(\bar{u}\gamma^{\mu}d) \times (\bar{e}\gamma_{\mu}\nu)$$

Refused by Nature

Fermi and dimension

$$c = \hbar = 1$$

$$S = \int d^4x\, \mathscr{L}$$

Dimensionless

$$[\quad] = mass^{-4}$$

$$[\quad] = mass^{4}$$

$$\mathscr{L}_{Dirac} \ni \bar{\psi}\gamma_\mu\partial^\mu\psi,\, m\bar{\psi}\psi$$

$$[\quad] = mass^{3/2}$$

$$\left[\bar{\psi}\gamma^\mu\psi\bar{\psi}\gamma_\mu\psi\right] = mass^6 \rightarrow [G_F] = mass^{-2}$$

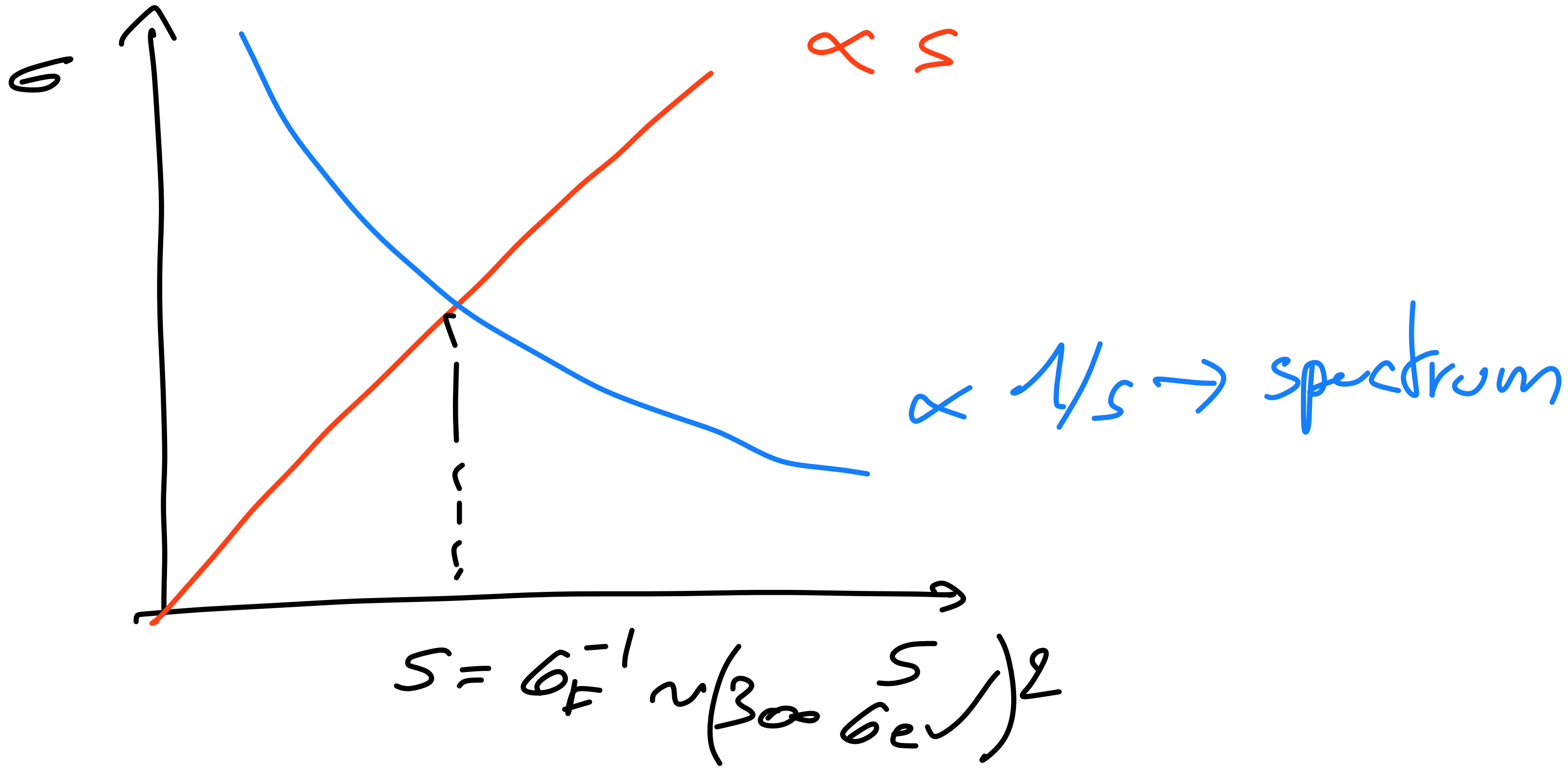
Unitarity violation

$$\sigma_{Fermi} \propto G_F^2 \times s$$

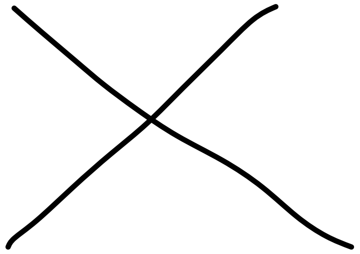
$$[\quad] = mass^{-2}$$

Proba > 1

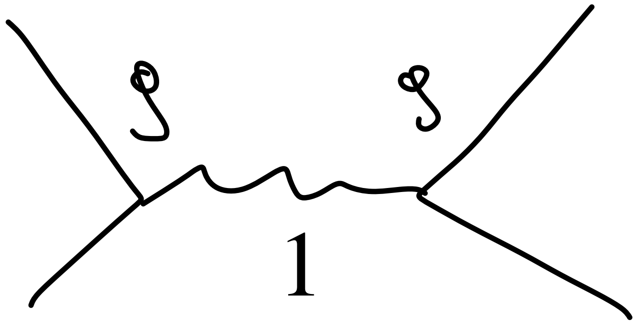
When?



Unitarity violation



4F but in QED

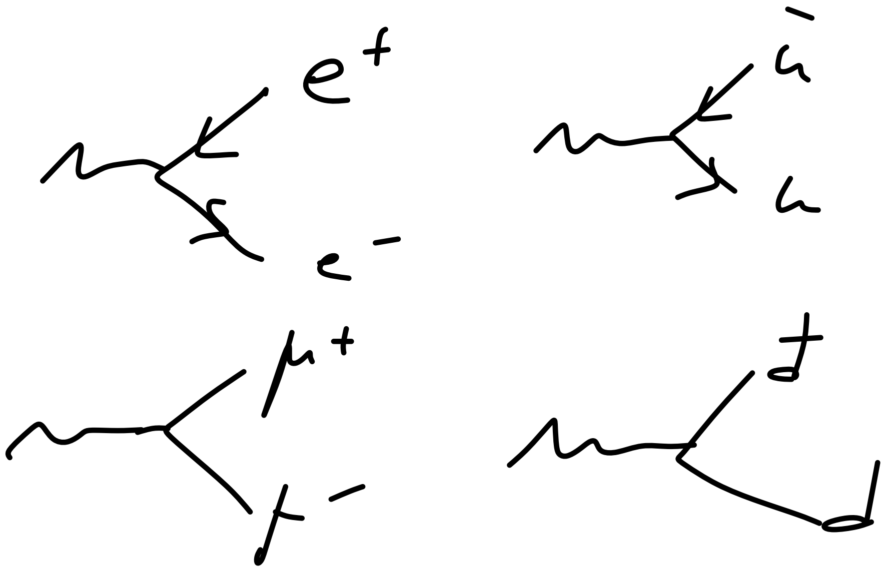


$$\frac{-g^2}{m^2} \sim G_F \xleftarrow[p^2 < < m^2]{} \frac{1}{p^2 - m^2}$$

But in QED

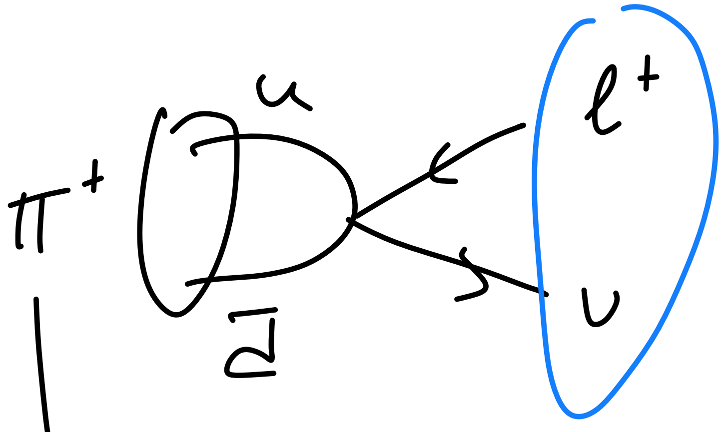
- Always the same fermion
- Massless gauge boson

$$\bar{\psi}\gamma^\mu \underset{\substack{\downarrow \\ \partial_\mu - iqA_\mu}}{D_\mu}\psi$$



$$\left[\begin{array}{l} \text{no } \nu \\ G_\nu = 0 \end{array}\right]$$

Pion decay



$J_{lep\,\mu} \ni \bar{\nu}\gamma^\mu \ell$

↓

$J^\mu_{had} \ni \pi^\pm$

↓

$V \implies J^{had}_\mu \sim f_\pi \, \partial_\mu \pi$

$[f_\pi] = \text{mass}$.

$\mathcal{L}_{KG} \ni m^2 \phi^\dagger \phi, \partial_\mu\phi\partial^\mu\phi$

$[\phi] = \text{mass}$

$$\mathcal{L}_{FERMI} \ni G_F \, f_\pi \, \partial_\mu \pi^+ \, \bar{\nu}\gamma^\mu \ell = G_F \, f_\pi \, \pi^+ \left(\bar{\nu}\underbrace{\not{\partial}\ell}_{m_\ell \ell} + \underbrace{(\partial_\mu \bar{\nu})\gamma^\mu \ell}_{0.\bar{\nu}}\right)$$

by part

↓

Dirac

$M \propto G_F \, f_\pi \, m_e$

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Pion decay

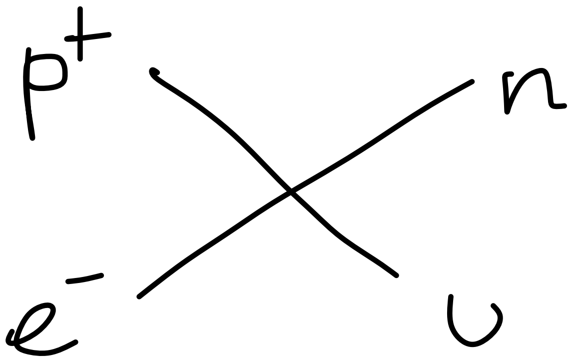
$$\underset{\substack{\downarrow\\ [\ ]=\text{mass}}}{\Gamma} \propto G_F^2\, f_\pi^2\, m_e^2\, m_\pi \underbrace{\left(1-\frac{m_e^2}{m_\pi^2}\right)^2}_{\hookrightarrow\, 0 \text{ if } m_e \to m_\pi}$$

$$\frac{\text{Br}(\pi \to e\nu)}{\text{Br}(\pi \to \mu\nu)} \simeq \frac{m_e^2}{m_\mu^2\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2} \simeq 1.23\, 10^{-4}$$

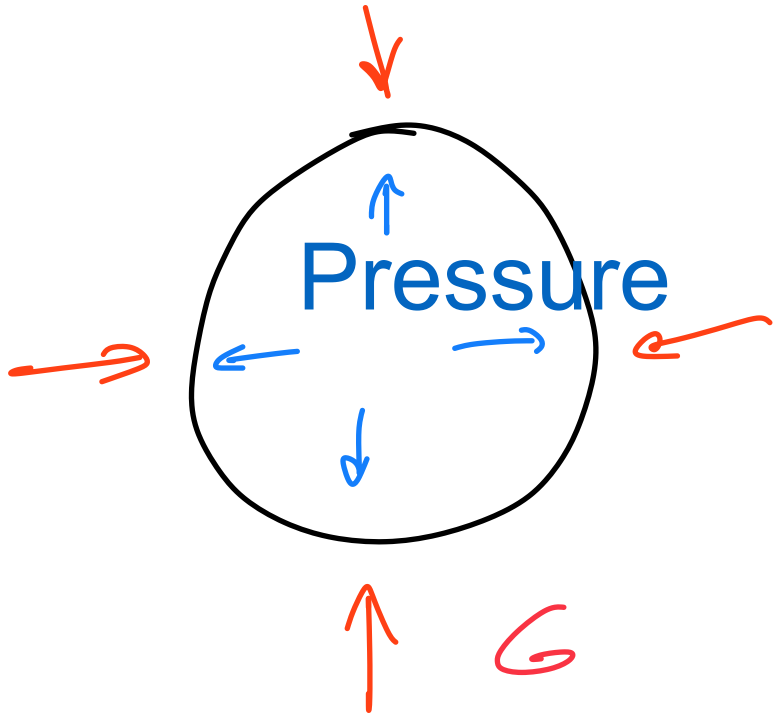
https://pdg.lbl.gov/

Because V interaction

Inverse beta decay



→ star collapse



neutron star (fermi pressure)

produce neutrinos

Ex: momentum in CM

$$\Delta m = m_n - m_p$$

$$|\vec{p}_i| = \frac{m_n^2 - m_p^2}{2 m_n} \simeq \Delta m \simeq 1.3 \text{ MeV}$$

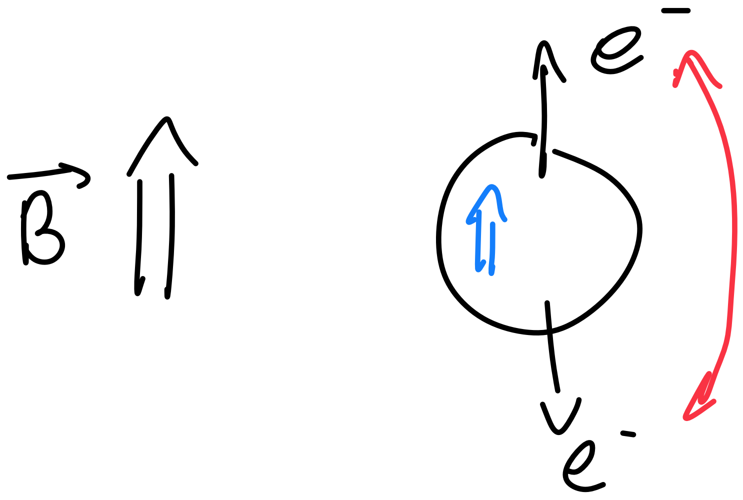
$$1 \text{ eV} \simeq 10^4 \text{ K} \implies 1.3 \text{ MeV} \sim 10^{10} \text{ K}$$

Parity violation

$\Gamma^\mu = \gamma^\mu$?

1956 Lee-Yang

Exp 1957 Wu



or

$$\begin{tikzcd} {}^{60}_{27}\mathrm{Co} \arrow[r] & {}^{60}_{28}\mathrm{Ni} \arrow[d] + e^- + \bar{\nu}_e \\ & 2\gamma \end{tikzcd}$$

$$\langle \vec{p}_e \cdot \vec{B} \rangle \neq 0 \implies \cancel{P}$$

Averaged value over the events

Parity

$\vec{x} \longrightarrow -\vec{x}$ $\qquad t \longrightarrow t$

m,q are scalars

$$\dot{\vec{x}} = \frac{\partial \vec{x}}{\partial t} \longrightarrow -\dot{\vec{x}} \quad \Rightarrow \quad \vec{p} \longrightarrow -\vec{p}$$

$\vec{E} \longrightarrow -\vec{E}$

Vector

$\vec{B} \longrightarrow +\vec{B}$

Axial vector or pseudo vector

$$\mathcal{L}_{QED} \propto A_\mu \bar{\psi} \gamma^\mu \psi$$

$$\hookrightarrow (\phi, \vec{A})$$

P-conserving

$$A^\mu \longrightarrow A_\mu$$

$$\underset{\overset{\shortparallel}{J^\mu}}{\bar{\psi} \gamma^\mu \psi} \longrightarrow \bar{\psi} \gamma_\mu \psi$$

Parity

Axial vector spin ~ $\vec{L} = \vec{r} \times \vec{p}$

Spin projector $s_\mu \gamma^\mu \gamma^5$

$s^2 = -1$

$s \cdot p = 0$

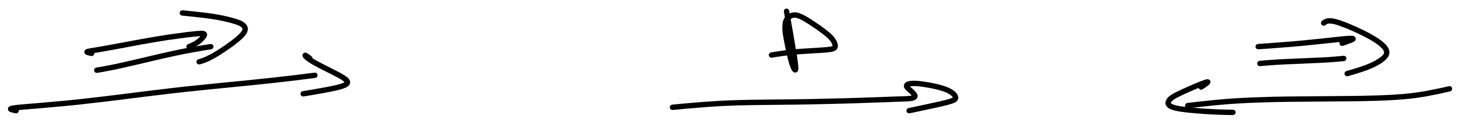
$\Downarrow$

$s = \frac{1}{m}\left(|\vec{p}|, \frac{E}{|\vec{p}|}\vec{p}\right)$

Helicity projector

$$P_\pm = \frac{1 \pm \not{s}\gamma^5}{2}$$

$m \to 0$ $\quad \gamma_{R/L} \; \frac{1 \pm \gamma_5}{2} \longrightarrow$ Chirality projector



$\psi_L = \gamma_L \psi \longrightarrow \psi_R$

$\psi_R = \gamma_R \psi \longrightarrow \psi_L$

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Parity

$$J^\mu = \bar\Psi \gamma^\mu \psi = \bar\Psi \gamma^\mu (\gamma_L + \gamma_R) \psi$$

$$= \bar\Psi_L \gamma^\mu \psi_L + \bar\Psi_R \gamma^\mu \psi_R \xrightarrow{P} J_\mu$$

$$A^\mu = \bar\Psi \gamma^\mu \gamma^5 \psi = \bar\Psi \gamma^\mu (\gamma_R - \gamma_L) \psi$$

$$= \bar\Psi_R \gamma^\mu \psi_R - \bar\Psi_L \gamma^\mu \psi_L \xrightarrow{P} -A_\mu$$

Maximal violating interaction (1958)

Feynman Gell-Mann Marshak Sudarshan

Weak interaction with the left only

$V_\mu \curvearrowright M_V$ $\quad M_V \xrightarrow{P} M_V$

$A_\mu \curvearrowright M_A$ $\quad M_A \xrightarrow{P} -M_A$ $\quad |M_A|^2 \xrightarrow{P} |M_A|^2$

Max if $M_A = \pm M_V$

$$|M_V + M_A|^2 = |M_V|^2 + |M_A|^2 + 2\,\mathrm{Re}(M_V M_A^*)$$

$$\xrightarrow{P} |M_V|^2 + |M_A|^2 - 2\,\mathrm{Re}(M_V M_A^*)$$

Fermi summary

$$\mathcal{L}_F \propto G_F \, \bar{u}_L \gamma^\mu d_L \, \bar{\nu}_L \gamma_\mu \ell_L$$

Requests: pure left

massive Vector boson

changing particle flavour

$\hookrightarrow e \leftrightarrow \nu \; , \; u \leftrightarrow d$

All the generations but only the leptons for now

Ex : $\sigma(e^- \mu^+ \to \nu_e \bar{\nu}_\mu)$ in Fermi and SM

at $s = 1, 5, 50, 500$

Weak group

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F \left(\bar{\nu}_{\mu L}\, \gamma^\alpha\, \mu_L\right)\left(\bar{e}_L\, \gamma_\alpha\, \nu_{eL}\right) + \text{other flavours}$$

solution : $L_e = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$, $L_\mu = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F\, \bar{L}_\mu \gamma^\alpha T^- L_\mu \quad \bar{L}_e \gamma_\alpha T^+ L_e$$

$$T^- = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \qquad T^+ = \left(T^-\right)^\dagger = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$J_L^\mu = \sum_\ell \bar{L}_\ell \gamma^\alpha T^- L_\ell$$

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F\, J_L^\mu \quad J^\dagger_{\mu L}$$

Weak group

In QED

$$\psi \rightarrow e^{iq\theta(x)}\,\psi$$

$$\partial_\mu \longrightarrow D_\mu = \partial_\mu - i\underset{\downarrow}{q}\,A_\mu$$

Local gauge symmetry

charge replaced by $T^\pm$

Do not commute: non abelian

symmetry group close under commutation

$$[T^+, T^-] = -2T^3 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} = -2\begin{pmatrix} 1/2 & 0 \\ 0 & -1/2 \end{pmatrix}$$

$$\underbrace{\begin{aligned} T^1 &= \frac{T^+ + T^-}{2} = 1/2\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\ T^2 &= i\frac{(T^+ - T^-)}{2} = 1/2\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \end{aligned}}$$

$$\overset{\Updownarrow}{[T^i, T^j]} = i\varepsilon^{ijk}\,T^k$$

$$\left.\begin{aligned} SU(2) &: U = e^{i\vec{\alpha}\cdot\vec{T}} \\ \det U &= \underline{1} \end{aligned}\right\}$$

$$\Updownarrow$$

$$\mathrm{Tr}(T^i) = 0$$

Neutral currents and right leptons

$$L \sim 2_{SU(2)}$$

changed currents and group $\Longrightarrow$ neutral currents

$$J_3^\alpha = J_{NC}^\alpha = \bar{L}_\ell \gamma^\alpha T^3 L_\ell = \underbrace{\bar{\nu}_{\ell L} \gamma^\alpha \nu_{\ell L}}_{\text{Not EM}} - \bar{\ell}_L \gamma^\alpha \ell_L$$

$Q(\nu) = 0$

No charged currents with the right fermions

$$\nu_R \, , \; \ell_R \sim 1_{SU(2)} \qquad \mathrm{Tr}(1 \times 1) = 0$$

$= 0$

⚠ $m\bar{\psi}\psi = m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

Not invariant under SU(2)

Electroweak group

$+ U(1)_Y \neq EM \longrightarrow [Q, T^a]$

All particles in an SU(2) multiplet have the same charge

$$\Psi \longrightarrow e^{i g_2 \vec{\alpha}(x)\cdot\vec{T} + i g_1 Y \theta(x)} \psi$$

$$D_\alpha = \partial_\alpha - i g_2 \vec{W}_\alpha \cdot \vec{T} - i g_1 Y B_\alpha$$

$$B_\mu \longrightarrow B_\mu + \partial_\mu \theta(x)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$\vec{W}_\mu \longrightarrow \vec{W}_\mu + \partial_\mu \vec{\alpha}(x) + g_2 \underbrace{(\vec{W}_\mu \times \vec{\alpha})}_{\varepsilon^{ijk} W_\mu^j \alpha^k}$$

$$\downarrow$$

$$[\,,\,]$$

Invariant

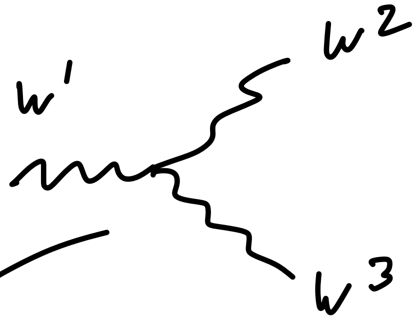
$\bar{\Psi} \not{D} \psi$

Non Abelian

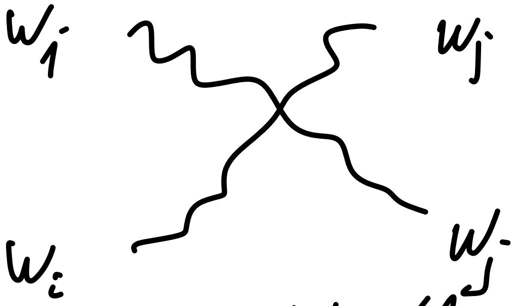
$$T^i W^i_{\mu\nu} = \partial_\mu W^i_\nu T^i - \partial_\nu W^i_\mu T^i - i g_2 [W^j_\mu T^j, W^k_\nu T^k]$$

Pheno of non abelian gauge theory

$W^i_{\mu\nu} W^{\mu\nu}_i \ni$



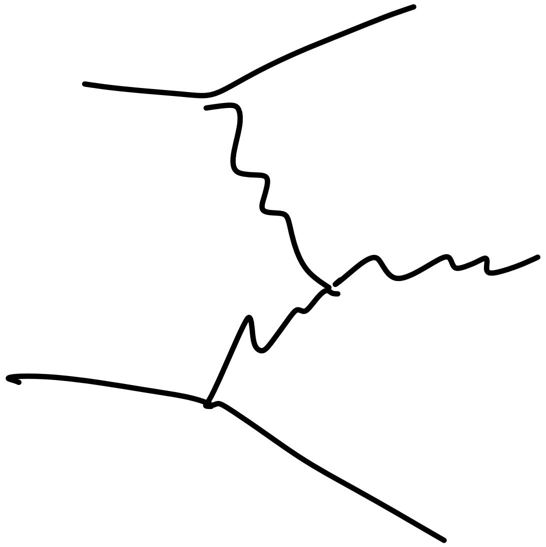
$\propto p^\mu \eta^{\alpha\beta}, g_2$



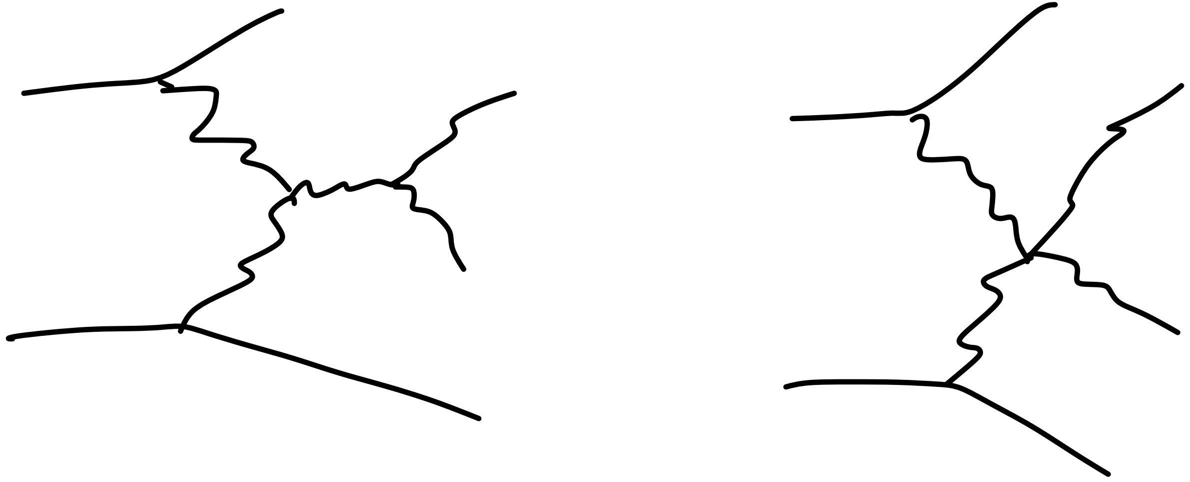
$\propto \eta^{\mu\nu} \eta^{\alpha\beta}, g_2^2$

$W^+ W^- \gamma$ since $Q(W^\pm) = 1$

DIBOSON



VBF



VBS

Z-A mixing

$$\mathcal{L} \ni \bar{L} \not{D} L + \bar{\nu}_R \not{D} \nu_R + l_R \not{D} l_R$$

$$= \bar{L} \not{\partial} L + \bar{\nu}_R \not{\partial} \nu_R + l_R \not{\partial} l_R - i\sqrt{2}\, g_2 \bar{L} \not{W}^+ T^- L$$

$$- i\sqrt{2}\, g_2 \bar{L} \not{W}^- T^+ L$$

$$\boxed{- i\, g_2 \bar{L} \not{W}_3 T^3 L - i g_1 \bar{L} Y_L \not{B} L - i g_1 Y_{\nu_R} \bar{\nu}_R \not{B} \nu_R - i\, g_1 Y_{l_R} \bar{l}_R \not{B} l_R}$$

$\mathcal{L}_{NC}$ ''

$$W^+ = \frac{W_1 - iW_2}{\sqrt{2}} \qquad W^- = \frac{W_1 + iW_2}{\sqrt{2}}$$

$$\begin{pmatrix} W_3 \\ B \end{pmatrix} = \begin{pmatrix} c_W & s_W \\ -s_W & c_W \end{pmatrix} \begin{pmatrix} Z \\ A \end{pmatrix} \xrightarrow[s.t.]{c_W,\, s_W} \mathcal{L}_{NC} \ni i e\, Q_F A_\mu \underline{\bar{F} \gamma^\mu F}$$

VECTOR

$$\left.\begin{aligned} Q(\nu) &= 0 \\ Q(e) &= -1 \end{aligned}\right\} \Rightarrow \begin{aligned} e &= g_2 s_W = g_1 c_W \\ Y_L &= -1/2 \end{aligned}$$

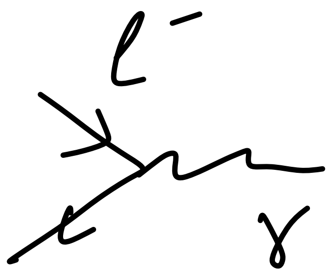
$$Q = T^3 + Y$$

FFV

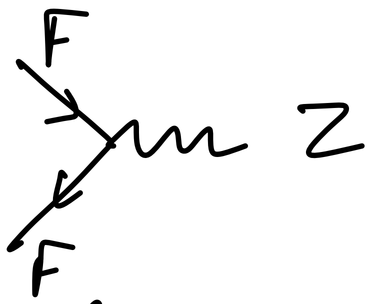
$\Longrightarrow \quad Y_{\nu_R} = 0 \longrightarrow$ Not interacting, not in the SM

$Y_{e_R} = -1$

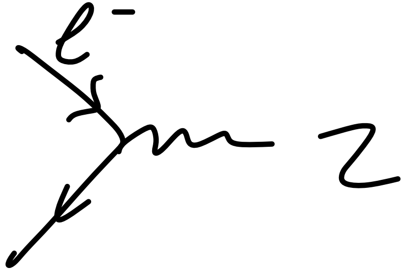
$$\mathcal{L}_{NC} = \sum_{F=\nu_R, e_R, L} \left\{ -ie\, Q_F A_\mu \bar{F} \gamma^\mu F - i \frac{e}{s_w c_w} Z_\mu \left(T^3 - s_w^2 Q\right) \right\}$$



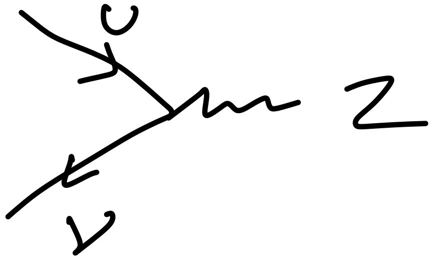
$i q_\ell \gamma^\mu$



$$\frac{ie}{s_w c_w} \left(T^3 - s_w^2\, Q\right) \gamma^\mu$$

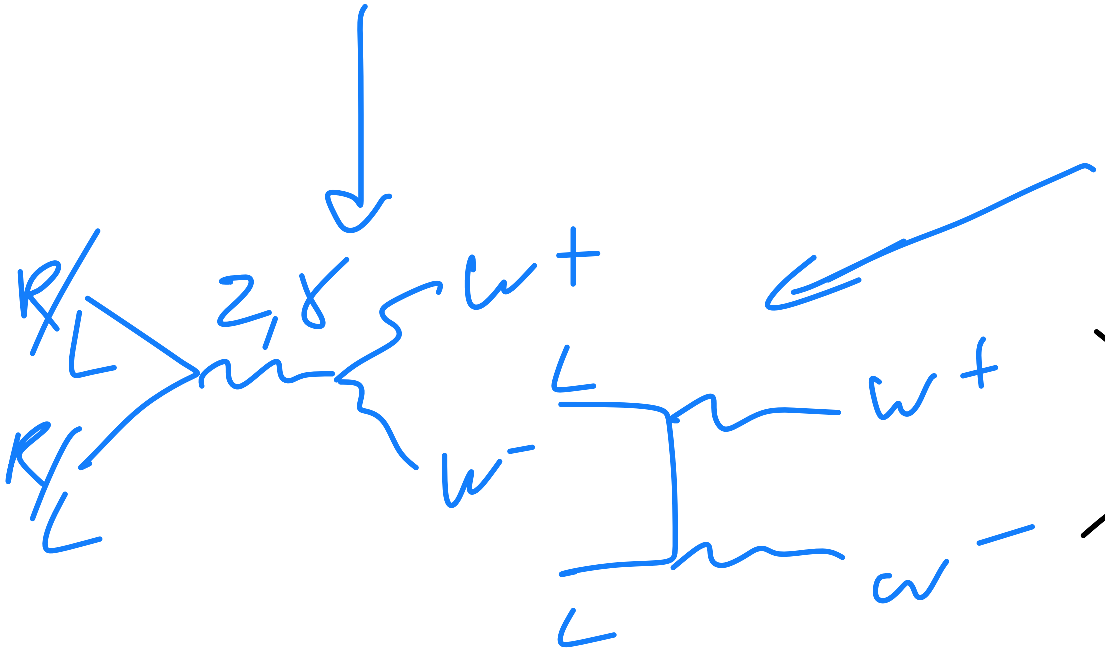


$$\frac{ie}{s_w c_w} \left[\left(-1/2 - s_w^2\right) \gamma^\mu \gamma_L + \left(-s_w^2\right) \gamma^\mu \gamma_R \right]$$

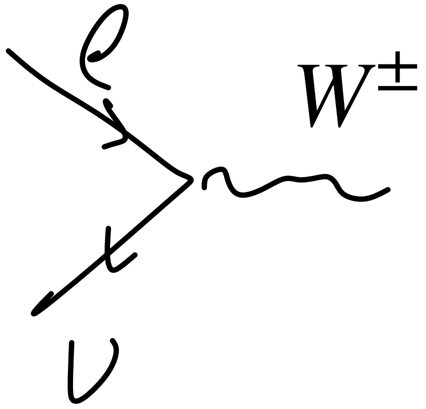


$$\frac{ie}{s_w c_w} \quad \frac{1}{2} \gamma^\mu \gamma_L$$

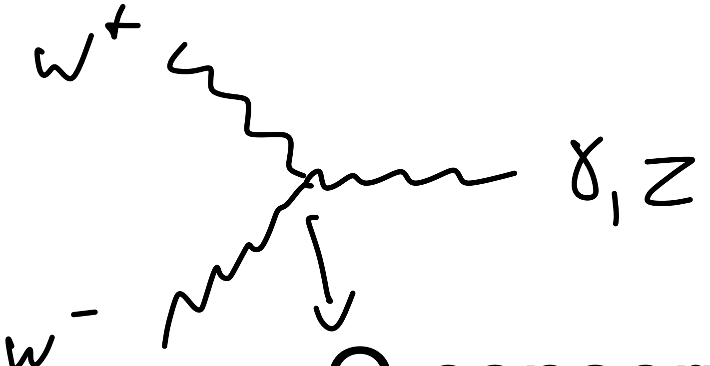
no γ_R!



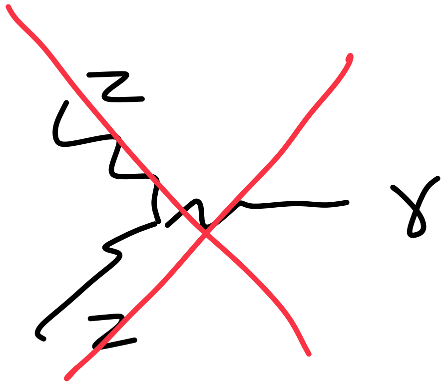
More electroweak interactions



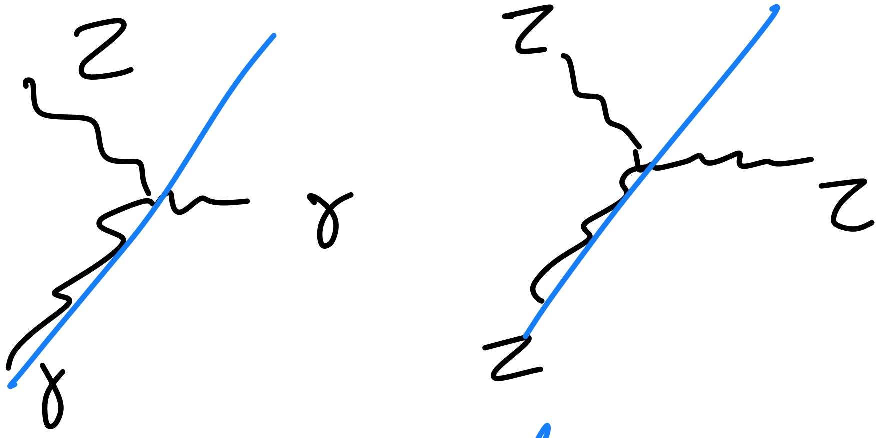
$\frac{ie}{s_W}\gamma_\mu \gamma_L$



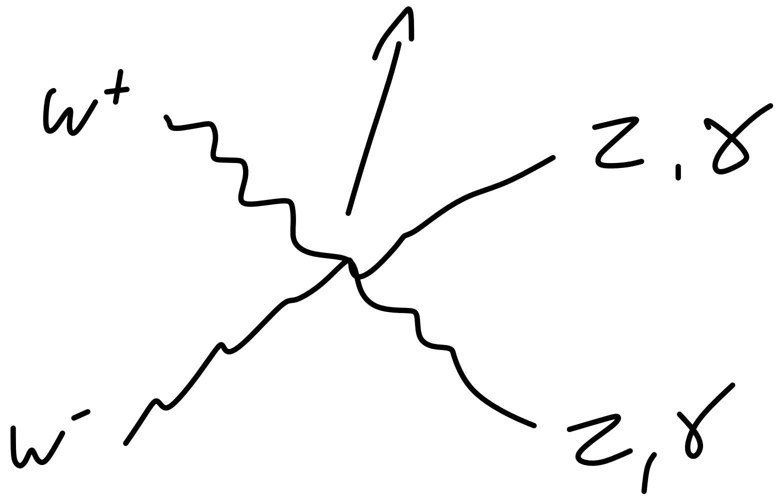
Q conserved

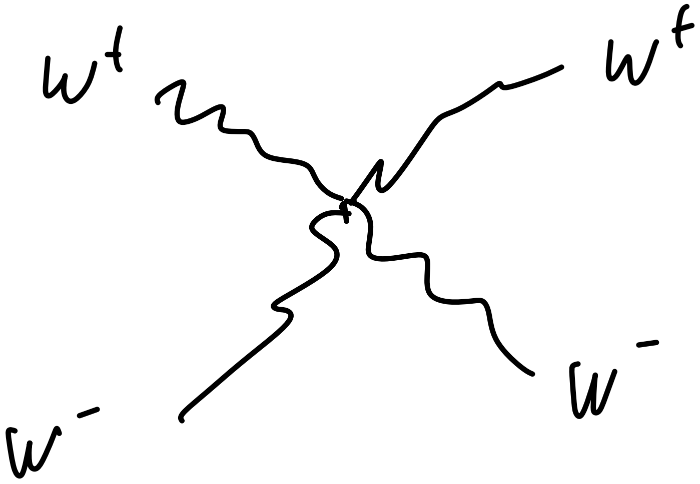


$Q_Z = 0$



Z-γ is abelian





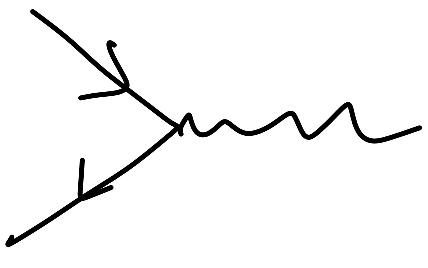
no Z-γ only
in the SM!

Z production

e^- q

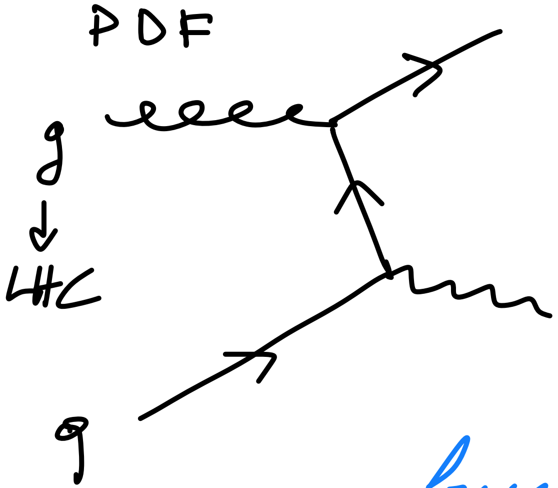
e^+ $\bar{q}$

LEP LHC TEVATRON



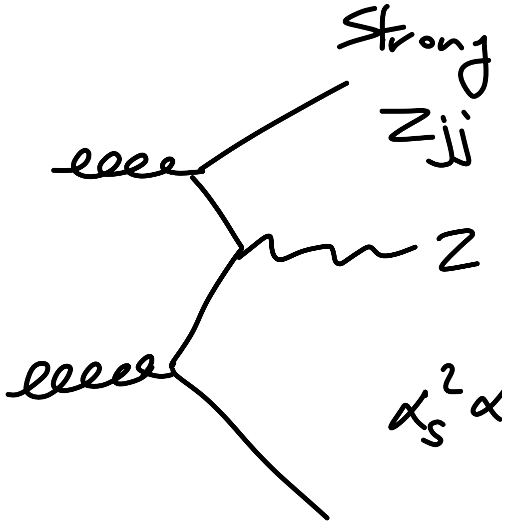
PDF

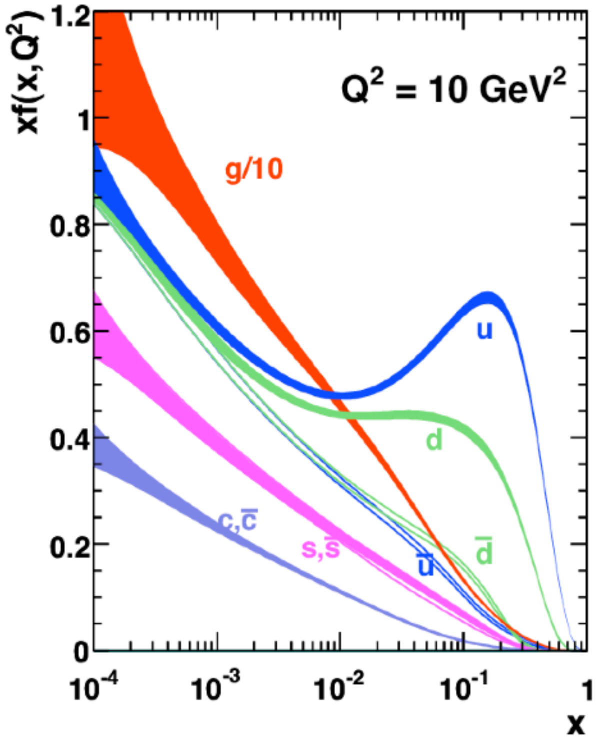
g ↓ LHC



Z+j

large bkg





- $\frac{\sigma(Zj)}{\sigma(Z)}(p_T^{j})$ ⚠ IR

rapidity gap, large m_{jj}, ...

- $\frac{\sigma^{EW}(Zjj)}{\sigma^{QCD}(Zjj)}$ → find cut to improve

NLO : ? Mixed EW / QCD

- $\sigma(pp\to Z\to \ell\ell)/\sigma(pp\to\ell\ell)$ + ≠ in distributions

WW scattering

Gauge invariance implies massless boson

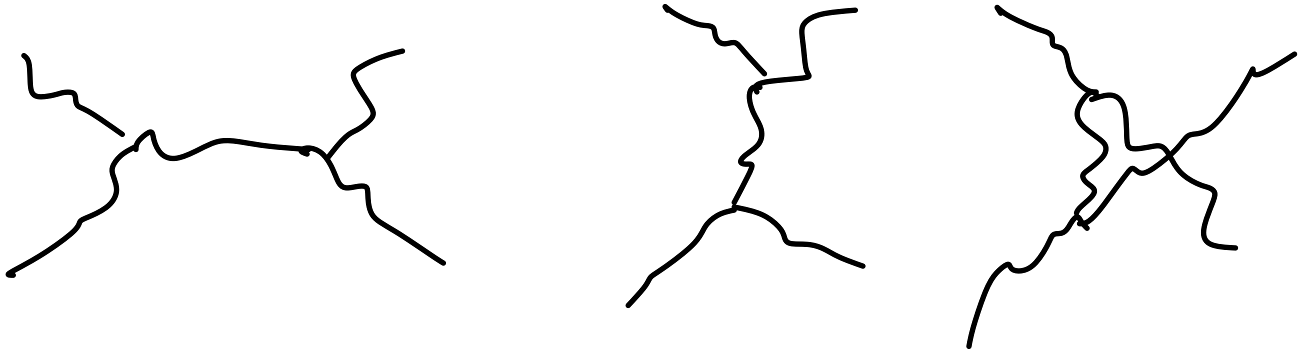
$$p^\mu = (E, 0, 0, p) \qquad \epsilon_\pm = \frac{(0, 1, \pm i, 0)}{\sqrt{2}}$$

$$\epsilon_L = \frac{1}{m}(p, 0, 0, E)$$

$$W_L \, W_L \to W_L \, W_L$$

↳ longitudinal, only if massive
otherwise transverse only

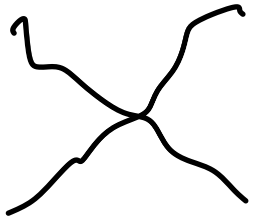
3 pt only



$$|M_1 + M_2|^2 \propto \frac{(s^2 + 4ts + t^2)}{m_w^4}$$

$$\Rightarrow \sigma \sim s \qquad \left(\sigma \sim \frac{|M|^2}{s}\right)$$

3 pt and 4 pt



$$|M_1 + M_2 + M_3|^2 \propto \frac{(-s-t)}{m_w^2}$$

$$\sigma \sim \text{const}$$

Electroweak symmetry breaking

The U(1) case

$$A_\mu \longrightarrow A_\mu + \partial_\mu \alpha(x)$$

$$D_\mu \longrightarrow \partial_\mu - ieA_\mu$$

$$\phi \longrightarrow e^{ie\alpha(x)}\phi$$

complex field or not charged

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + D_\mu \phi^\dagger D^\mu \phi - V(\phi)$$

scalar potential

Renormalisable $\Rightarrow d \leq 4$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \qquad \lambda > 0$$

$$\mu^2 > 0 \longrightarrow \langle \phi \rangle = 0$$

$$\mu^2 < 0 \longrightarrow \langle \phi \rangle = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{V}{2}$$

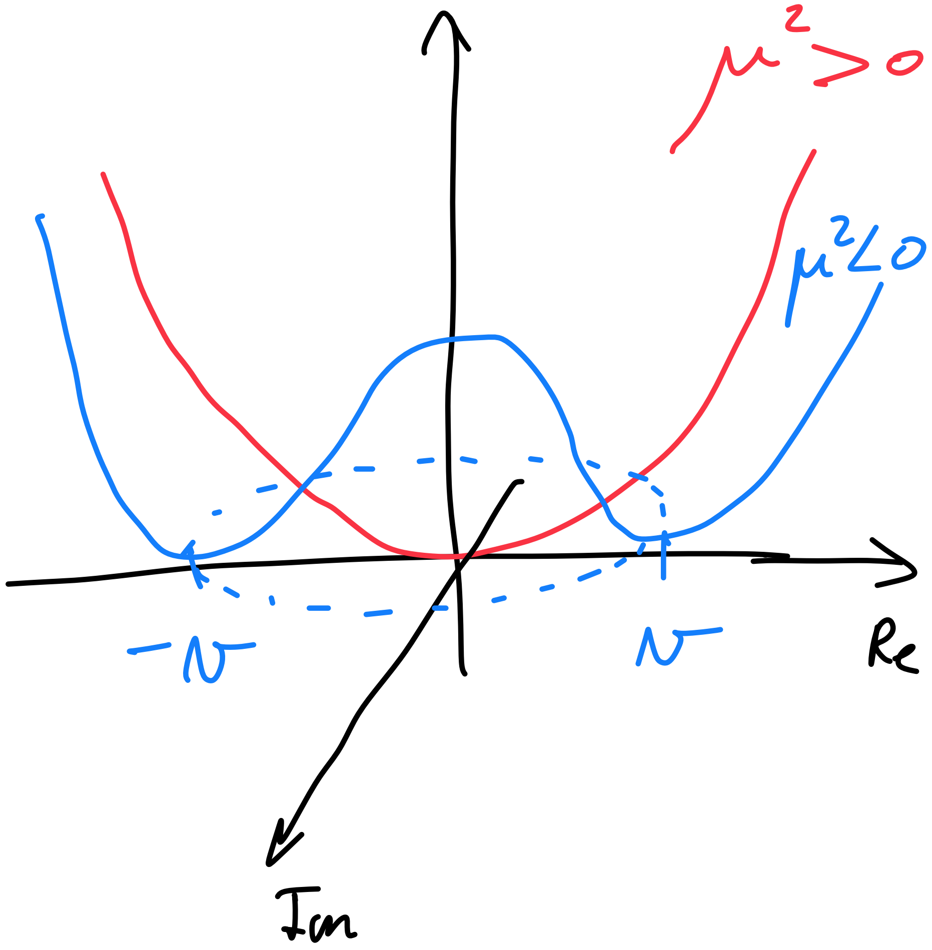
Chosen real by gauge inv.

Minimum of the potential

$\langle \phi \rangle$ min of V

$$\frac{\partial V}{\partial v} = \frac{\partial}{\partial v}\left(\mu^2 \frac{v^2}{2} + \frac{\lambda v^4}{4}\right) = \underbrace{(\mu^2 + \lambda v^2)\, v}$$

$v = 0$ $\qquad$ $v^2 = -\frac{\mu^2}{\lambda}$



Spontaneous Sym Breaking

$$\phi \equiv \frac{1}{\sqrt{2}}\, e^{i\chi/v}\,(v + h)$$

↳ $[\ ]$ = mass like h, χ

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - e v A_\mu \partial^\mu \chi + \frac{e^2 v^2}{2} A_\mu A^\mu$$
$$+ \frac{1}{2}\left(\partial_\mu h\, \partial^\mu h + 2\mu^2 h^2\right) + \frac{1}{2} \partial_\mu \chi\, \partial^\mu \chi$$

Massive gauge boson

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - e v A_\mu \partial^\mu \chi + \frac{e^2 v^2}{2} A_\mu A^\mu$$
$$+ \frac{1}{2} \left(\partial_\mu h \partial^\mu h + 2\mu^2 h^2 \right) + \frac{1}{2} \partial_\mu \chi \partial^\mu \chi$$

1 gauge boson of mass

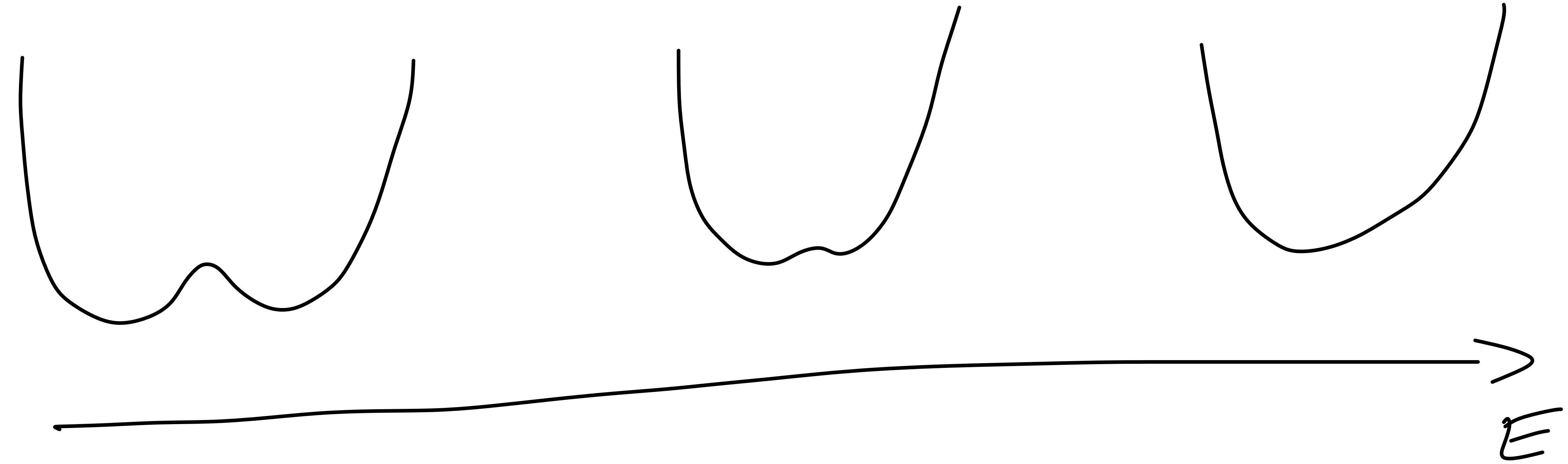
1 real scalar field h of mass^2 $= -2\mu^2 > 0$

1 massless scalar field χ mixed with A

↳ Unphysical: removed by gauge transformation
Only derivative interactions: Goldstone boson(massless)
transforms linearly with the gauge $\chi \to \chi + \alpha e v$

Massive vector = 3 d.o.f.=1 scalar + 1 massless vector

At high energy



symmetry is restored

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Electroweak symmetry breaking

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$$

$\downarrow$

Broken $\Longrightarrow$ $\phi \sim \boxed{2}, 3, 4, \ldots$ of $SU(2)_L$ not 1

$Q = T^3 + Y$ $\longrightarrow$ 1 neutral component a break EM

$$Y = \pm 1/2$$

$$\phi = \begin{pmatrix} \phi^+ \\ \frac{h + i\sigma + v}{\sqrt{2}} \end{pmatrix} \Longrightarrow \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$\hookrightarrow$ chosen by gauge

Same potential

$$V(\phi) = -\mu^2 \phi^+ \phi + \lambda (\phi^+ \phi)^2 \qquad v^2 = \frac{\mu^2}{\lambda}$$

Vector bosons masses

$$\mathcal{L}_S = D_\mu \phi^\dagger D^\mu \phi - V(\phi)$$

$$D^\mu \hookrightarrow \partial_\mu - i g_2 T^a W^{a\mu} - i g_1 B_\mu Y$$

$$\ni \frac{1}{8}\begin{pmatrix} 0 & v \end{pmatrix}\left(g_2\begin{pmatrix} W_3^\mu & \sqrt{2}W^{+\mu} \\ \sqrt{2}W^{-\mu} & -W_3^\mu \end{pmatrix} + g_1\begin{pmatrix} B_\mu & 0 \\ 0 & B_\mu \end{pmatrix}\right)^2\begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$= \frac{v^2}{8}\left(2 g_2^2 W_\mu^+ W^{\mu -} + (g_1 B_\mu - g_2 W_3^\mu)^2\right)$$

$$= m_W^2 W_\mu^+ W^{\mu -} + \frac{m_Z^2}{2} Z_\mu Z^\mu$$

$$\Longrightarrow m_W^2 = \frac{g^2 v^2}{4} = \left(\frac{ev}{2 s_W}\right)^2$$

$$s_W = g_1 / \sqrt{g_1^2 + g_2^2}$$

$$Z_\mu = \frac{(-g_1 B_\mu + g_2 W_{3\mu})}{\sqrt{g_1^2 + g_2^2}} = -s_W B_\mu + c_W W_\mu^3$$

$$c_W = g_2 / \sqrt{g_1^2 + g_2^2}$$

$\rightsquigarrow$ Normalization

Vector bosons masses

$$M_Z^2 = \frac{1}{4}\left(g_1^2 + g_2^2\right) v^2 = \left(\frac{ev}{2 s_W c_W}\right)^2$$

$$\rho = \frac{m_W^2}{m_Z^2 \, c_W^2} = 1 \quad \text{in the SM}$$

if $\xi \sim 3_{SU(2)}$ with $\langle \xi \rangle \longrightarrow \rho = 1 - \frac{2\langle \xi^0 \rangle^2}{\langle \phi^0 \rangle^2}$

Protected by custodial symmetry, only broken by gauge and Yukawa interactions

Fermi $\quad \frac{g_2^2}{m_W^2} \propto \frac{1}{v^2} \Rightarrow G_F = \frac{1}{\sqrt{2}\, v^2}$

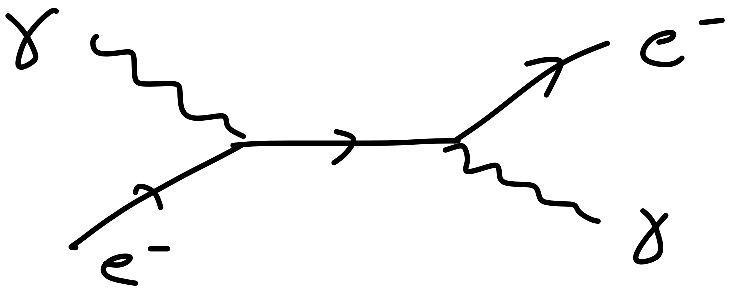
$v \simeq 246$ GeV

$s_W^2 \simeq 0.23$

$\alpha_{EM}(m_e) \simeq \frac{1}{137}$

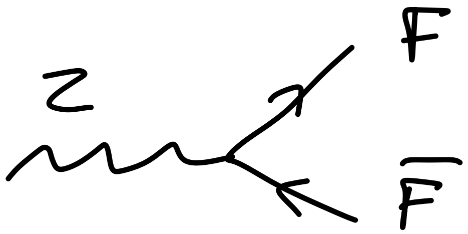
Masses predictions

$\alpha_{EM}(m_e)$

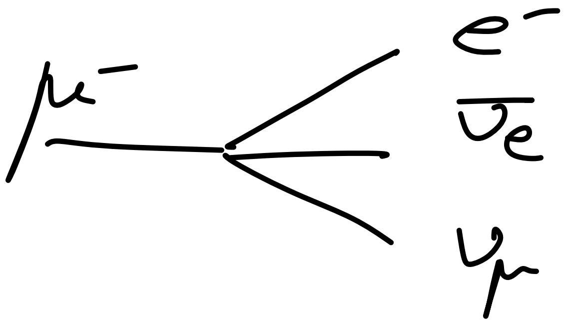


Very soft Compton scattering

s_W^2



G_F



(G_μ)

$m_W \simeq 80$ GeV

$m_Z \simeq 91$ GeV

More about EWSB

3 Goldstone bosons $\sigma\,,\ \phi^+\,,\ \phi^-$

$$\Updownarrow$$

3 broken generators

$$SU(2)_L \otimes U(1)_Y \to U(1)_{EM}$$

$$3 + 1 \longrightarrow 1$$

3 massive gauge vector bosons eat 3 d.o.f.

Unitary gauge: $\sigma = 0 = \phi^\pm$

At high energy: $V_L \sim$ G. B.

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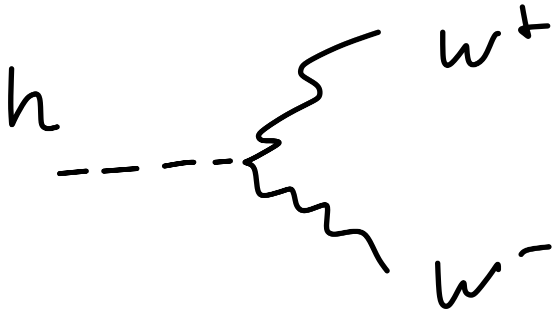
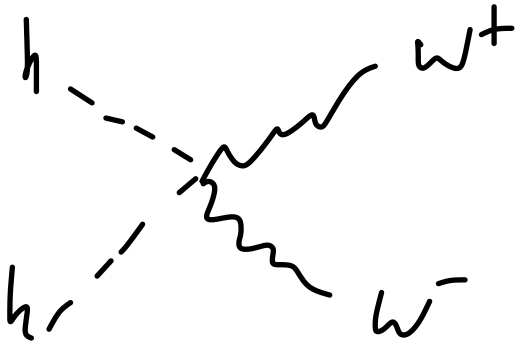
Higgs gauge interactions

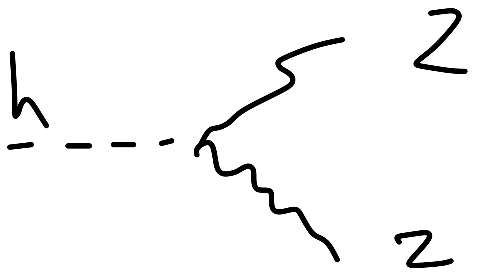
$$D_\mu \phi^\dagger D^\mu \phi \ni \frac{(v+h)^2}{v^2}\left(m_W^2 W^\mu W_\mu + \frac{m_Z^2}{2} Z_\mu Z^\mu\right)$$



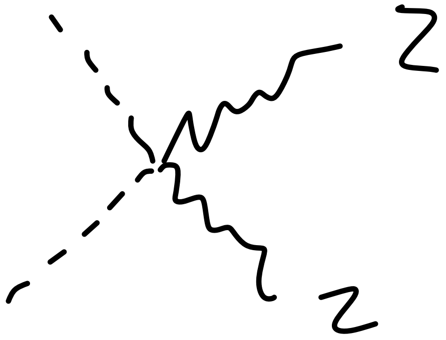
$$\propto \frac{m_W^2}{v}\eta^{\mu\nu}$$



$$\propto \frac{m_W^2}{v^2}\eta^{\mu\nu}$$

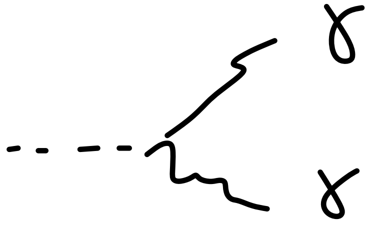


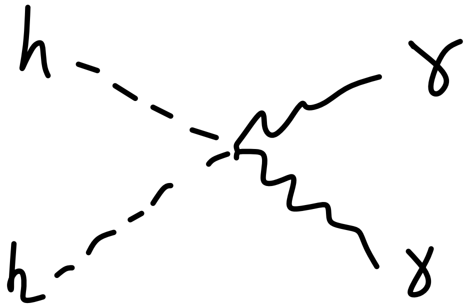
$$\propto \frac{m_Z^2}{v}\eta^{\mu\nu}$$



$$\propto \frac{m_Z^2}{v^2}\eta^{\mu\nu}$$

Again no





$$Q(h)=0$$

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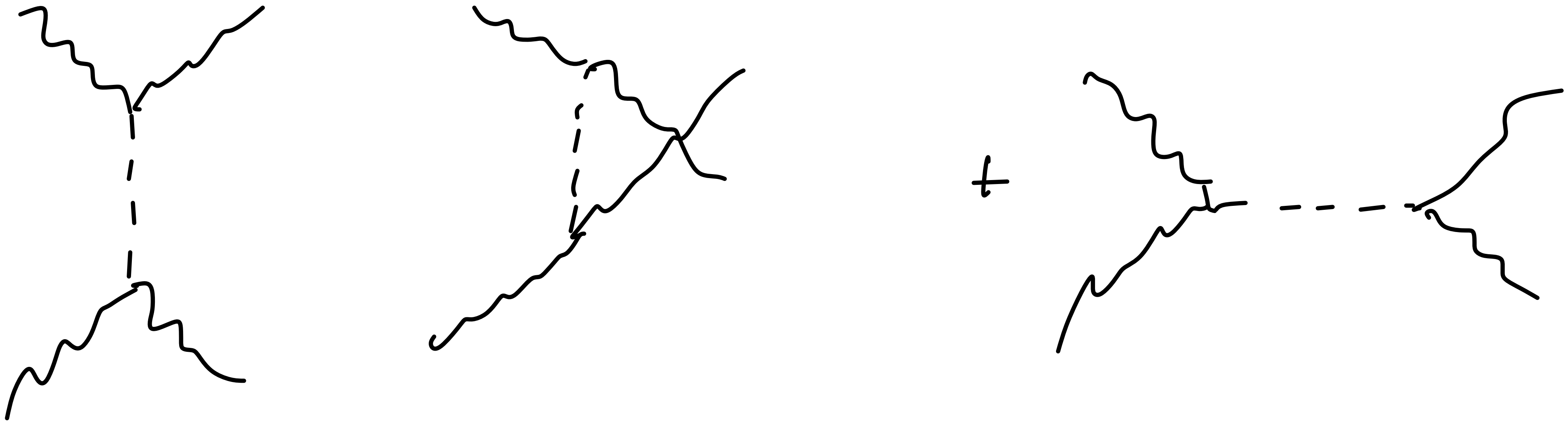
WW scattering



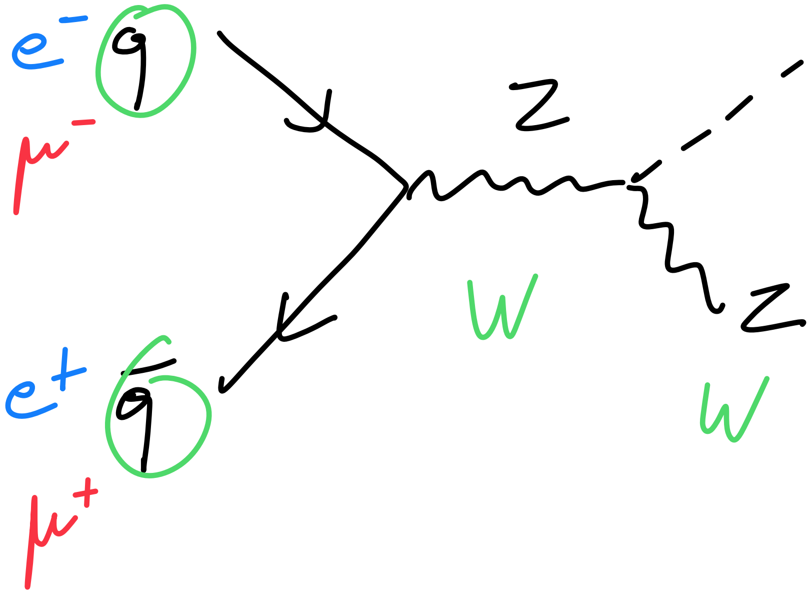
$$|M_4 + M_5|^2 \sim -\frac{g_2^2}{m_W^2}\left\{\frac{s^2}{s-m_h^2} + \frac{t^2}{t-m_h^2}\right\}$$

if $m_h << s, t \longrightarrow \sigma_{1+2+3+4+5} \sim \frac{1}{s}$

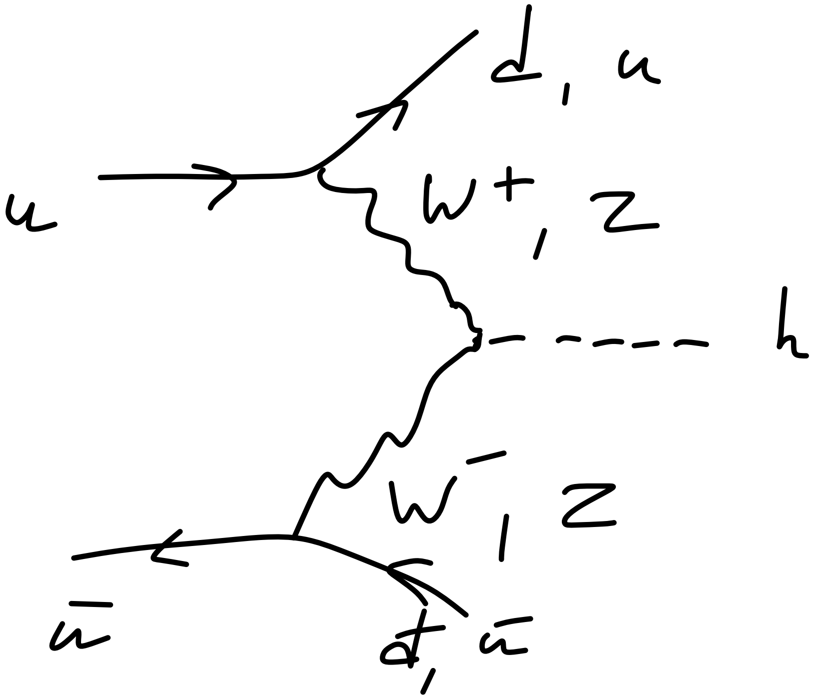
Test in MG
with & without
Higgs

No unitarity violation at high energy

Some H production



Associated production

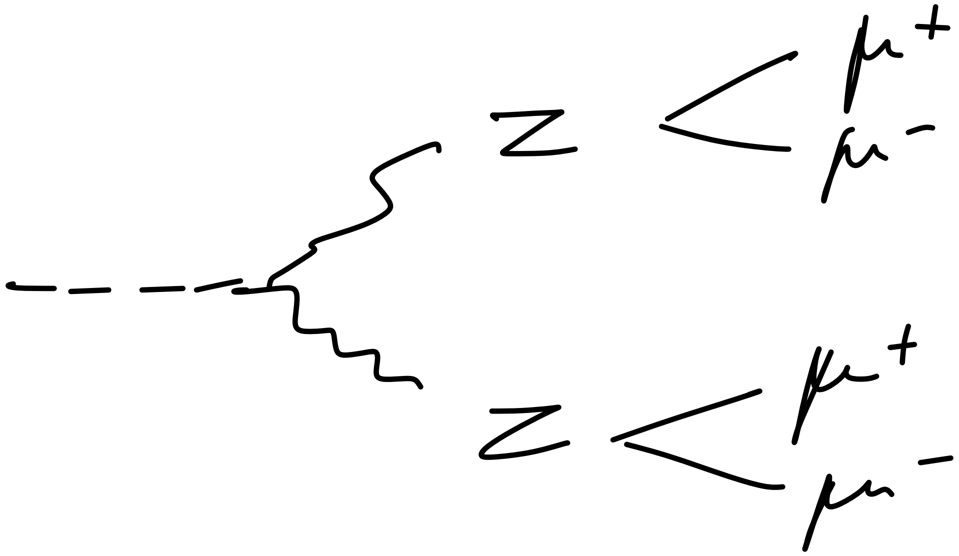


Vector boson fusion

Some H decay

Depends on the Higgs mass

one off-shell



Golden channel

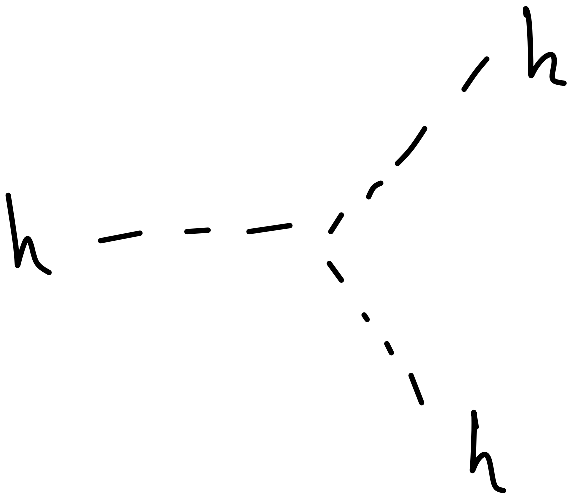
CMS

$2\lambda v = m_h^2$

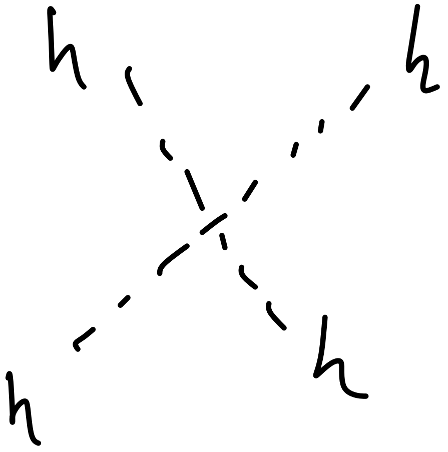
Free

Last free parameter

m_h or λ



$i\lambda v$

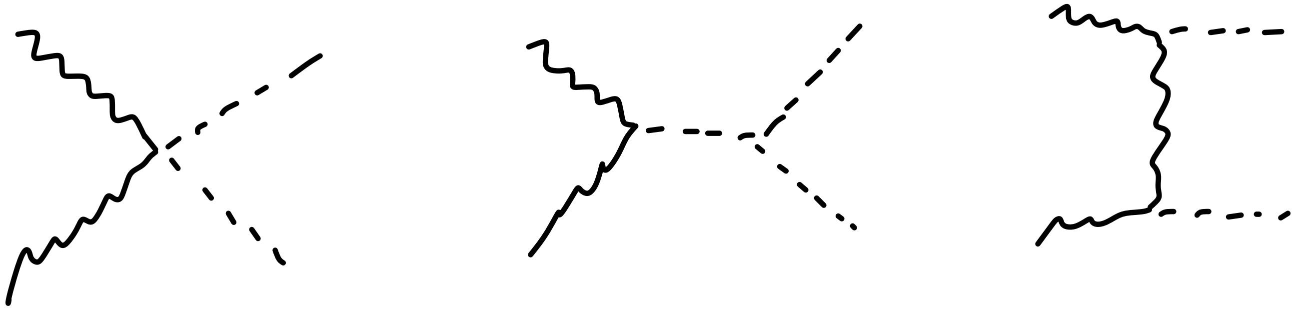


$i\lambda$

check the potential

consistency check

Double or more Higgs production but other diagrams



Fermion masses

$$m\bar\Psi\Psi = m(\underbrace{\bar\Psi_L \Psi_R}_{\boxed{\bar L \ell_R}} + \bar\Psi_R \Psi_L)$$

$$\boxed{\bar L \ell_R} \longrightarrow 2_{SU(2)_L} \quad , Y = 1/2 - 1 = -1/2$$

$\bar L$: $2_{SU(2)_L}$ $\quad$ ℓ_R: $1_{SU(2)_L}$

Same as ϕ

One field solve 2 problems!

not mass eigenstate

$$\mathcal{L}_{Leptons} = -y_e^{ij}\,\bar L'^i \phi\, \ell_R'^j + h.c. + i\bar L'^i \not D L'^i + i\bar\ell_R'^i D \ell_R'^i$$

$$U_R \ell_R = \ell_R' \qquad U_L L = L' \qquad U_L^\dagger y_l U_R = diag(y_e, y_\mu, y_\tau)$$

$$\mathcal{L}_{Leptons} = \underbrace{i\bar L \not D L + i\bar\ell_R \not D \ell_R}_{\swarrow} - \underbrace{\bar L \begin{pmatrix} y_e & & \\ & y_\mu & \\ & & y_\tau \end{pmatrix} \phi\, \ell_R}_{\bar\ell_L^i \frac{(v+h)}{\sqrt{2}} y_i \ell_R^i} + h.c.$$

U_L, U_R disappear

$$U_L U_L^\dagger = U_L^\dagger U_L = U_R U_R^\dagger = U_R^\dagger U_R = 1$$

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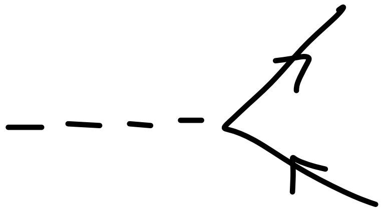
More about lepton masses



$\frac{i m_\ell}{v}$

y^{ij} $\ni$ 18 parameters but only 3 are physical

Fermions $\propto$ m_F

Gauge bosons $\propto$ m_V^2

Quark masses

$$\mathcal{L}_{quarks} = i \bar{Q}' \not{D} Q' + i \bar{u}_R' \not{D} u_R' + i \bar{d}_R' \not{D} d_R'$$

$$- y_u^{ij} \bar{Q}' \tilde{\phi} u_R' - y_d^{ij} \bar{Q}' \phi d_R' + h.c.$$

$$U_R^u u_R = u_R' \qquad U_R^d d_R = d_R'$$

$$U_L^u u_L = u_L' \qquad U_L^d d_L = d_L'$$

No one for the left-handed but 2

$$\bar{u}_L' W^+ d_L' \longrightarrow \bar{u}_L V_{CKM} W^+ d_L$$

$$V_{CKM} = U_L^{u\dagger} U_L^d$$

Unitary

$$d^j_{L/R} \longrightarrow e^{i\varphi^d_j} d^j_{L/R} \, , \quad u^j_{L/R} \longrightarrow e^{i\varphi^u_j} u^i_{L/R}$$

$V_{CKM} \ni$ 3 angles and one phase

Parameter counting

5 $g_1 \quad g_2 \quad g_3 \quad v \quad \lambda \quad \longleftrightarrow \quad \alpha_{EM} \quad G_F \quad M_Z \quad \alpha_s \quad m_h$

3 $y_e, \ y_\mu, \ y_\tau \quad \longleftrightarrow \quad m_e, \ m_\mu, \ m_\tau$

3 $y_d, \ y_s, \ y_b \quad \longleftrightarrow \quad m_d, \ m_s, \ m_b$

3 $y_u, \ y_c, \ y_t \quad \longleftrightarrow \quad m_u, \ m_c, \ m_t$

4 $V_{CKM} : \alpha, \beta, \gamma, \varphi \longrightarrow \cancel{CP}$

18

Mostly from the Yukawa matrices!

3 generations

Higgs production through top

$y_t \sim 1$ $\quad$ $y_b \sim y_\tau \sim y_c \sim 10^{-2}$

$y_s \sim y_\mu \sim 10^{-3}$

$y_e \sim y_u \sim y_d \sim 10^{-5} \to$ No e^+e^-, $u\bar{u}$, $d\bar{d} \to h$

too small

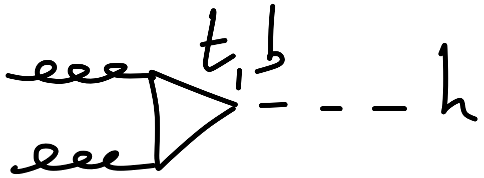
$m_p > m_n$

$\Uparrow$

$y_u < y_d$

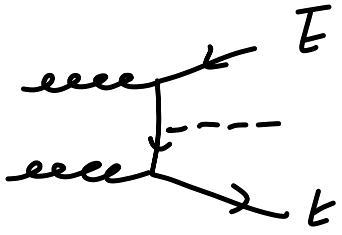
inverted!

$\Rightarrow$



↓

- loop induced but strong coupling and PDF
- top – bottom loop interference ~ 5%



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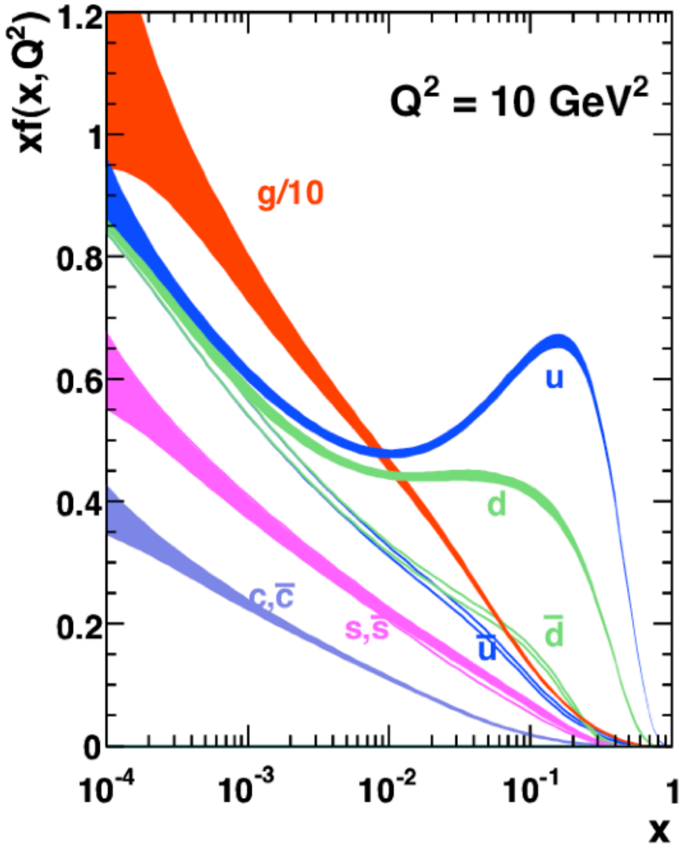
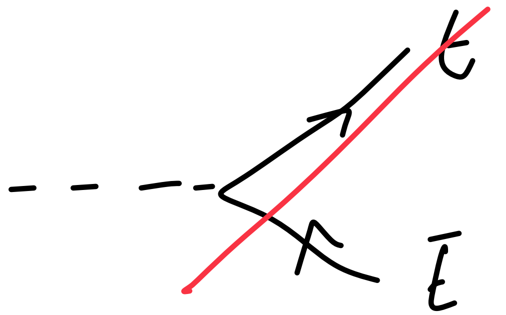
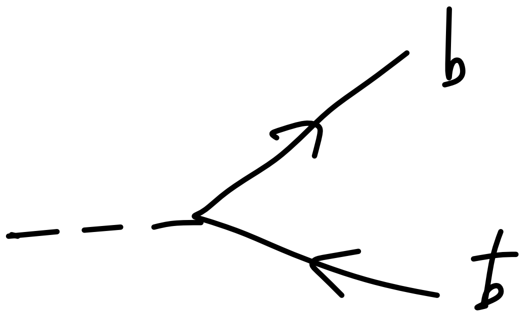


Higgs with fermions



too heavy



Largest but QCD background

$h \to \tau \bar{\tau}$, $h \to c\bar{c}$

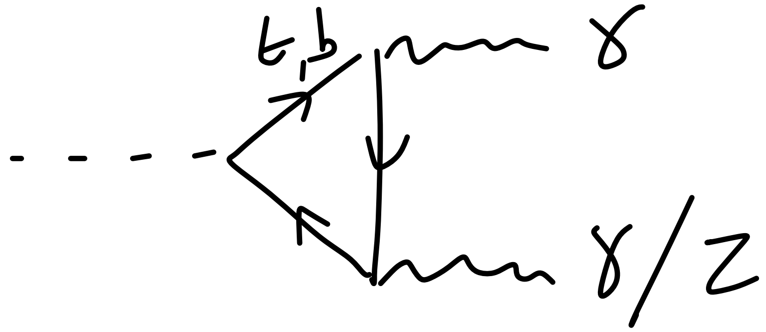
$\downarrow$

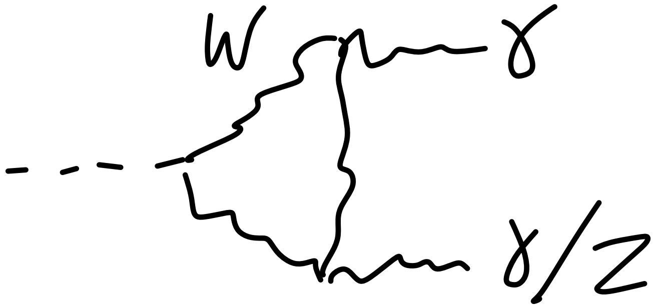
τ decay

charm tagging ?

$h \to \mu\mu$ 2500 smaller than

Loop induced





Higgs exercises

$\sigma_{LHC}(pp \to h)$ with top, bottom & interference

$\sigma_{LHC}(pp \to Zh)$

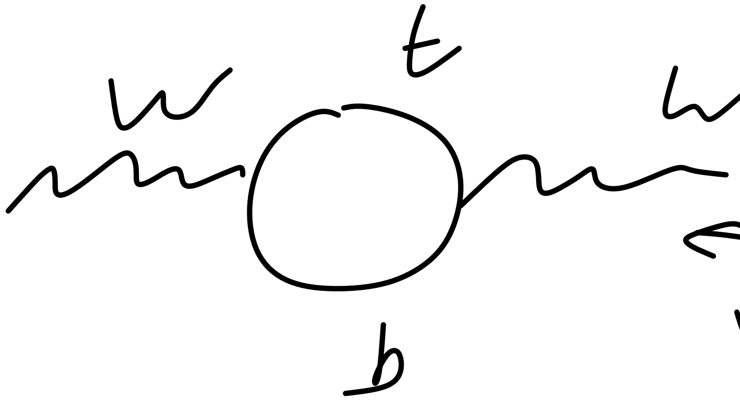
$\sigma_{LHC}(pp \to W^{\pm}h)$

$\sigma_{LHC}(pp \to hjj)$

$\sigma_{LHC}(pp \to ht\bar{t})$

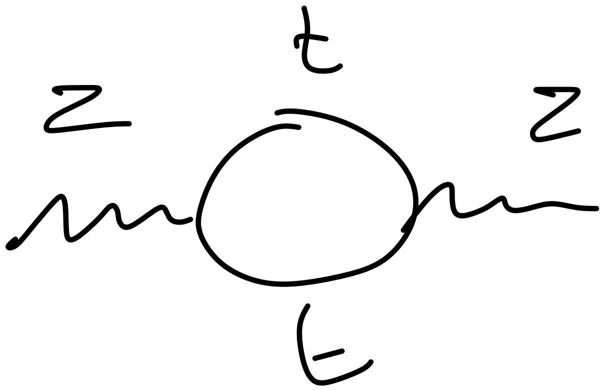
$\Gamma(h \to \gamma\gamma)$ with top, W & interference

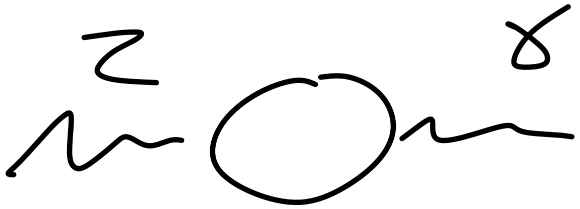
Electroweak precision tests



↔ mass relation

ρ



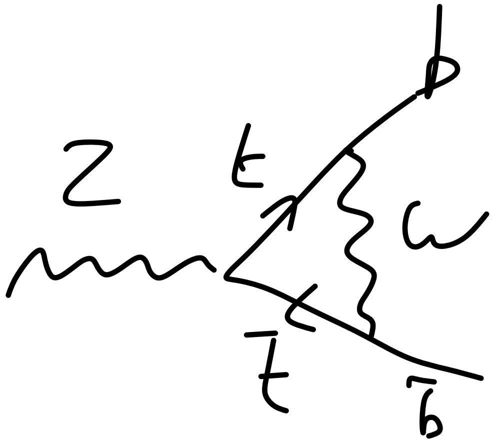


↓

change mixing

m_T from LEP!

corr $\propto m_t^2$

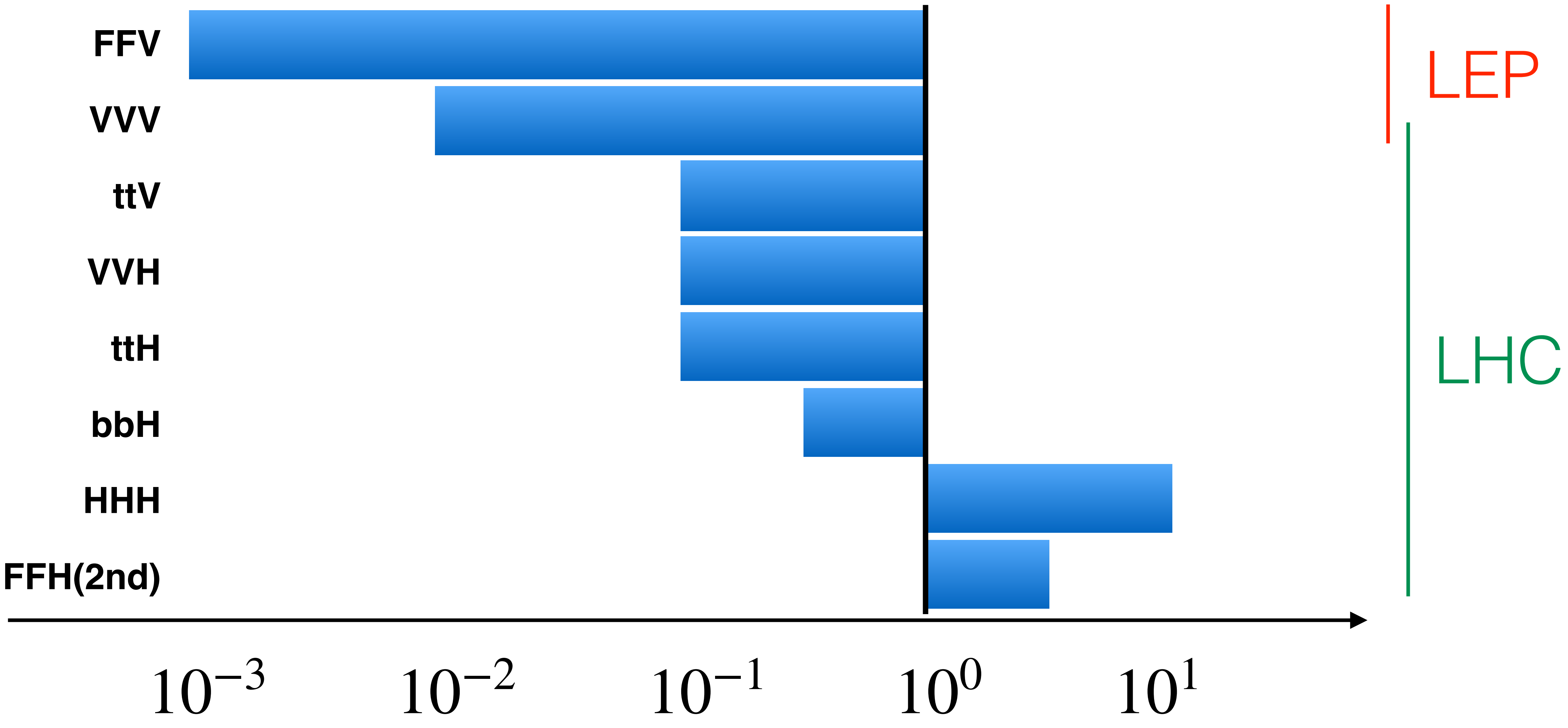


$\longrightarrow$ 1‰ + $N_\nu \simeq 3$

Effective field theory

Precision: LEP vs LHC

How well do we know the SM?



LHC<LEP: QCD perturbative (α_S) and non-pert. (PDF,hadronisation), backgrounds, …

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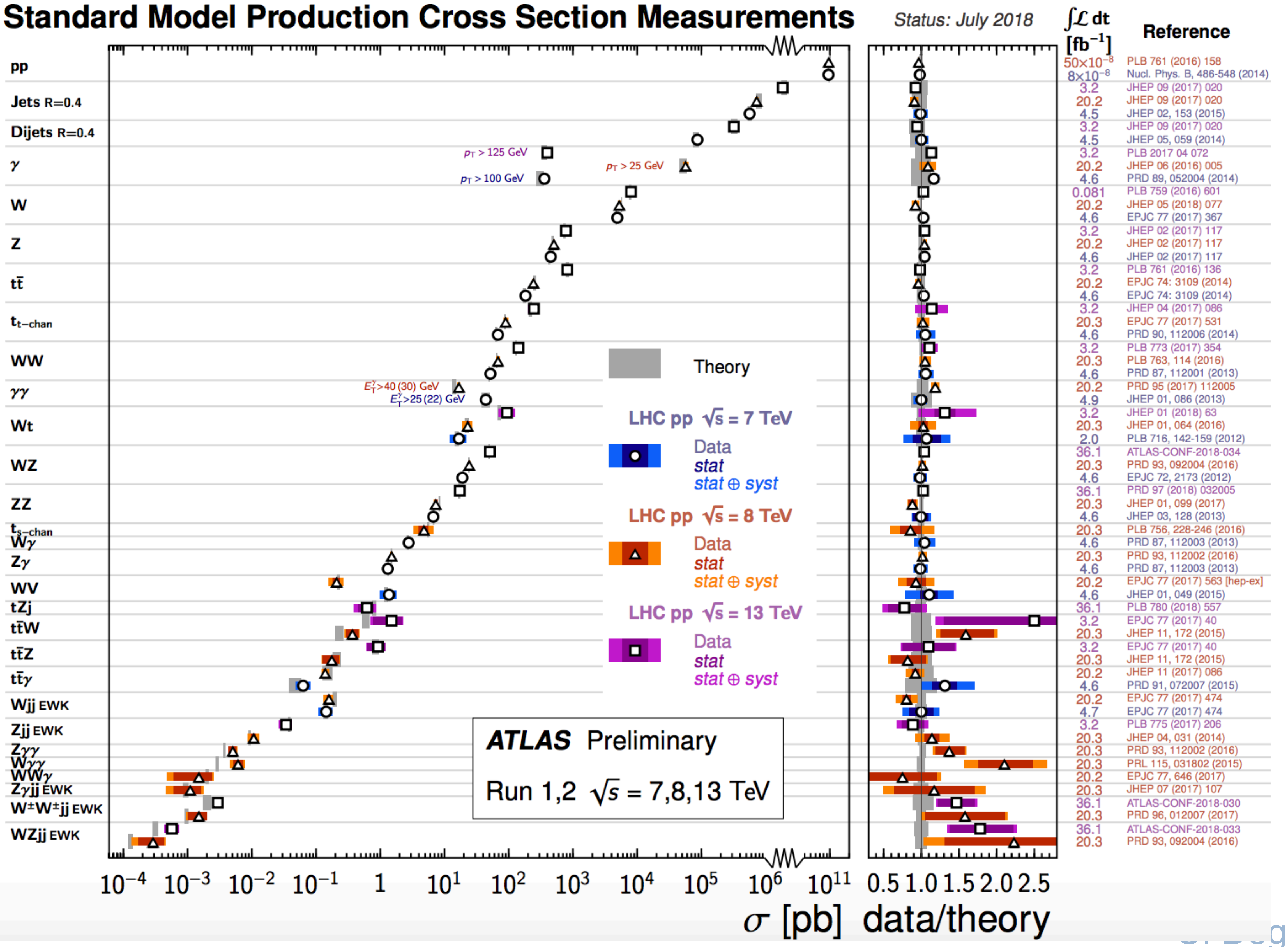
Precision era at the LHC

Multiplicity, power of α_{EW}, masses



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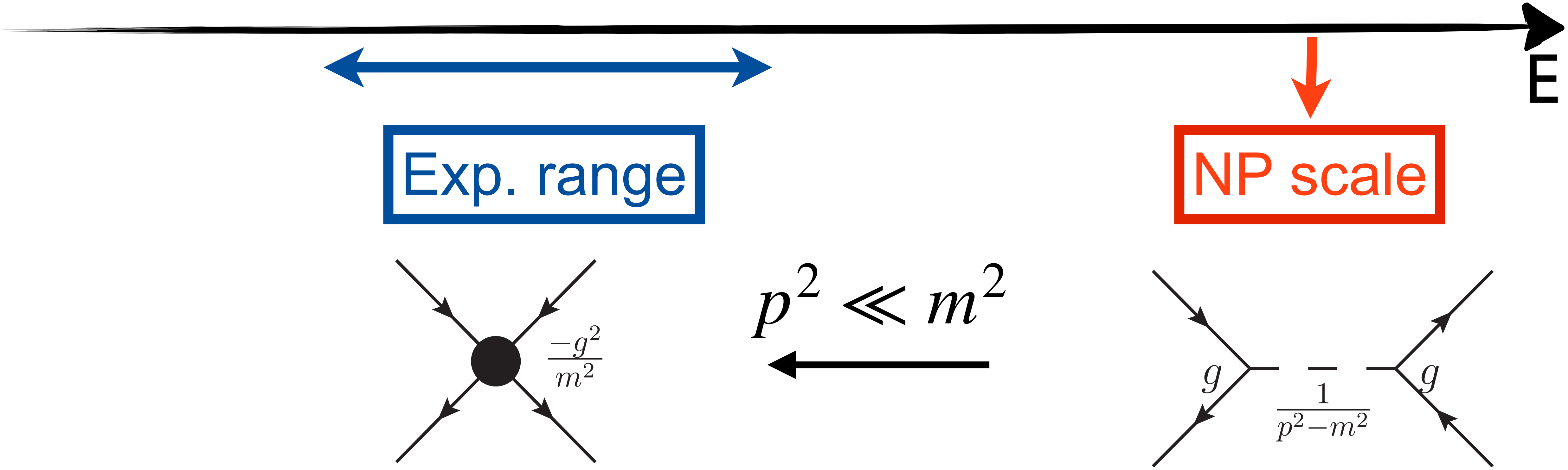
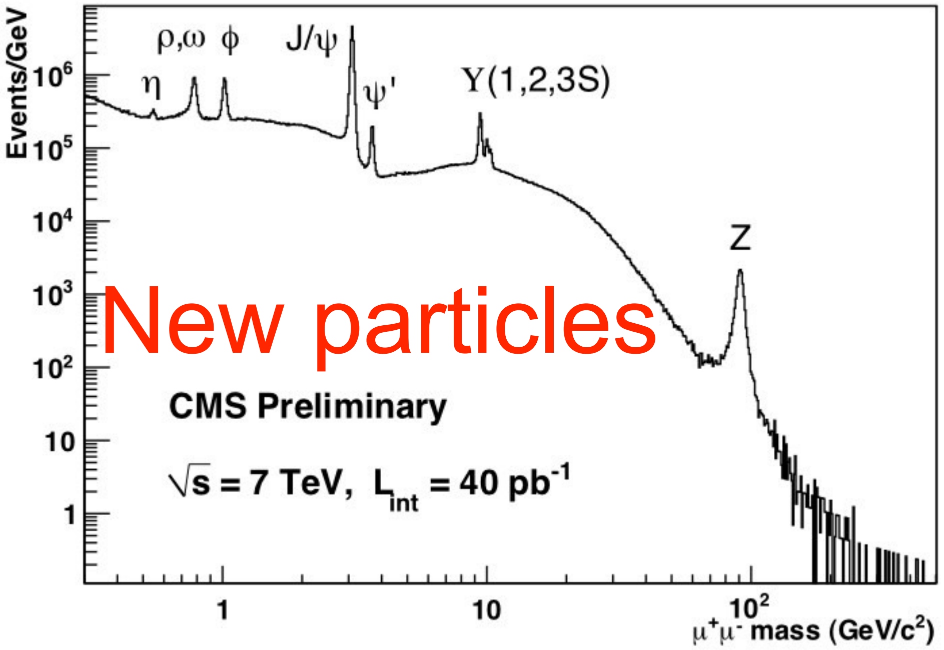
Indirect detection of NP

- Assumption : NP scale >> energies probed in experiments



One assumption : $p^2 \ll m^2$

New/modified interactions between SM particles



New particles

C. Degrande

EFT

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

← SM fields & sym.

C. Degrande

EFT

Parametrize any NP but an ∞ number of coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

SM fields & sym.

- Assumption : $E_{exp} << \Lambda$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i} \frac{C_i}{\Lambda^2} \mathcal{O}_i^6$$

a finite number of coefficients
=>Predictive!

- Model independent (i.e. parametrize a large class of models) : any HEAVY NP
- SM is the leading term : EFT for precision physics
- higher the exp. precision => smaller EFT error

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EFT

Parametrize any NP but an ∞ number of coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

SM fields & sym.

- Assumption : $E_{exp} << \Lambda$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i} \frac{C_i}{\Lambda^2} \mathcal{O}_i^6$$

measure only C_i/Λ^2

a finite number of coefficients =>Predictive!

- Model independent (i.e. parametrize a large class of models) : any HEAVY NP
- SM is the leading term : EFT for precision physics
- higher the exp. precision => smaller EFT error

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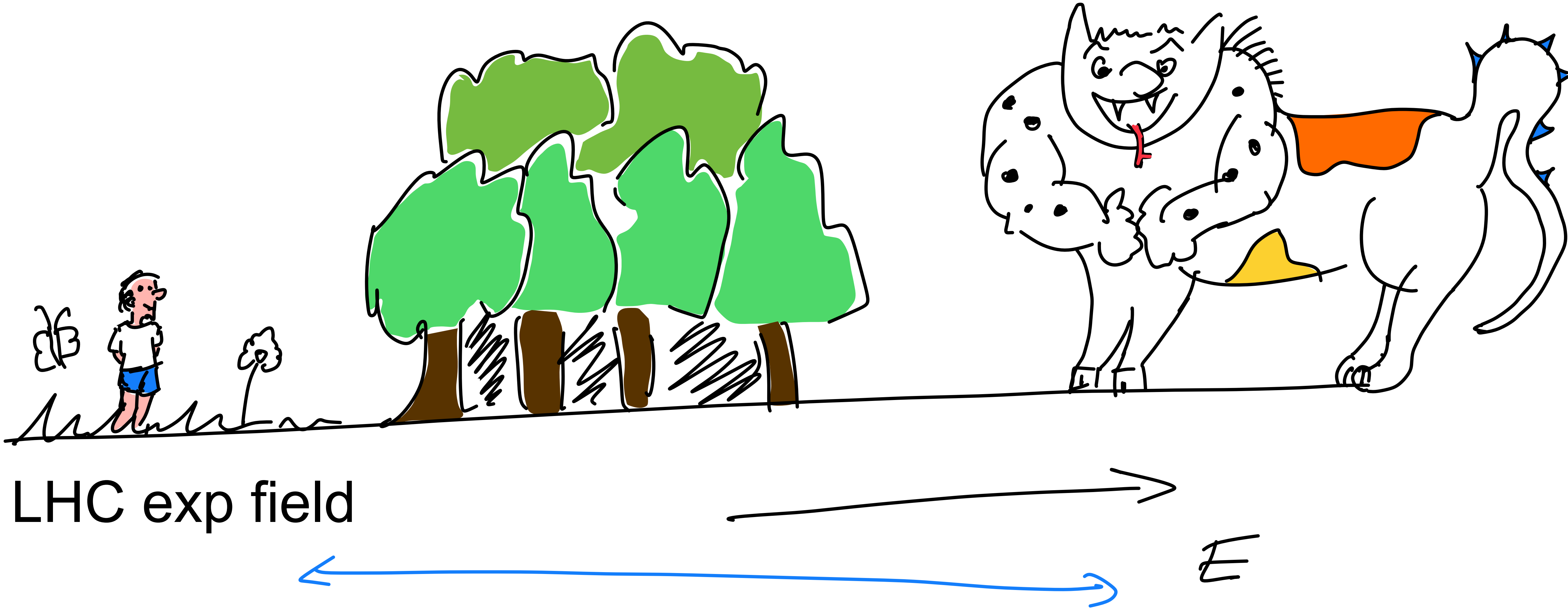
One hypothesis



LHC exp field

Validity: How far?

C. Degrande

0/2F operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

New interactions + param/field redefinitions

C. Degrande

4F operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

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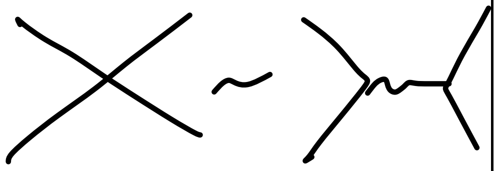
4F

$(\bar L L)(\bar L L)$		$(\bar R R)(\bar R R)$		$(\bar L L)(\bar R R)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
	FERMI	$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
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$(\bar L R)(\bar R L)$ and $(\bar L R)(\bar L R)$		B-violating	
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$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
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$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

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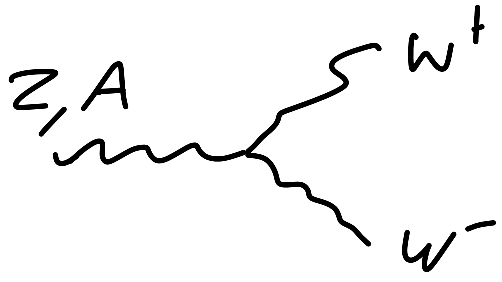
Pure gauge

$$Q_W \quad \Big| \quad \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

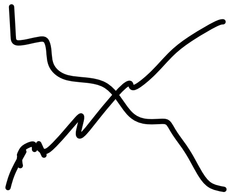


$\propto p^3$

TGC

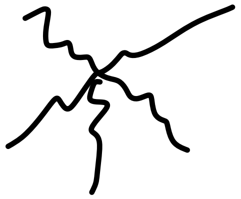
GGC

Together by gauge inv

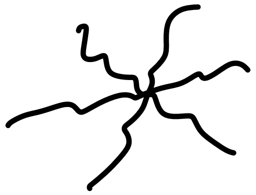


WWWW, WWZZ, WWZA, WWAA

$\propto p^2$



$\propto p$



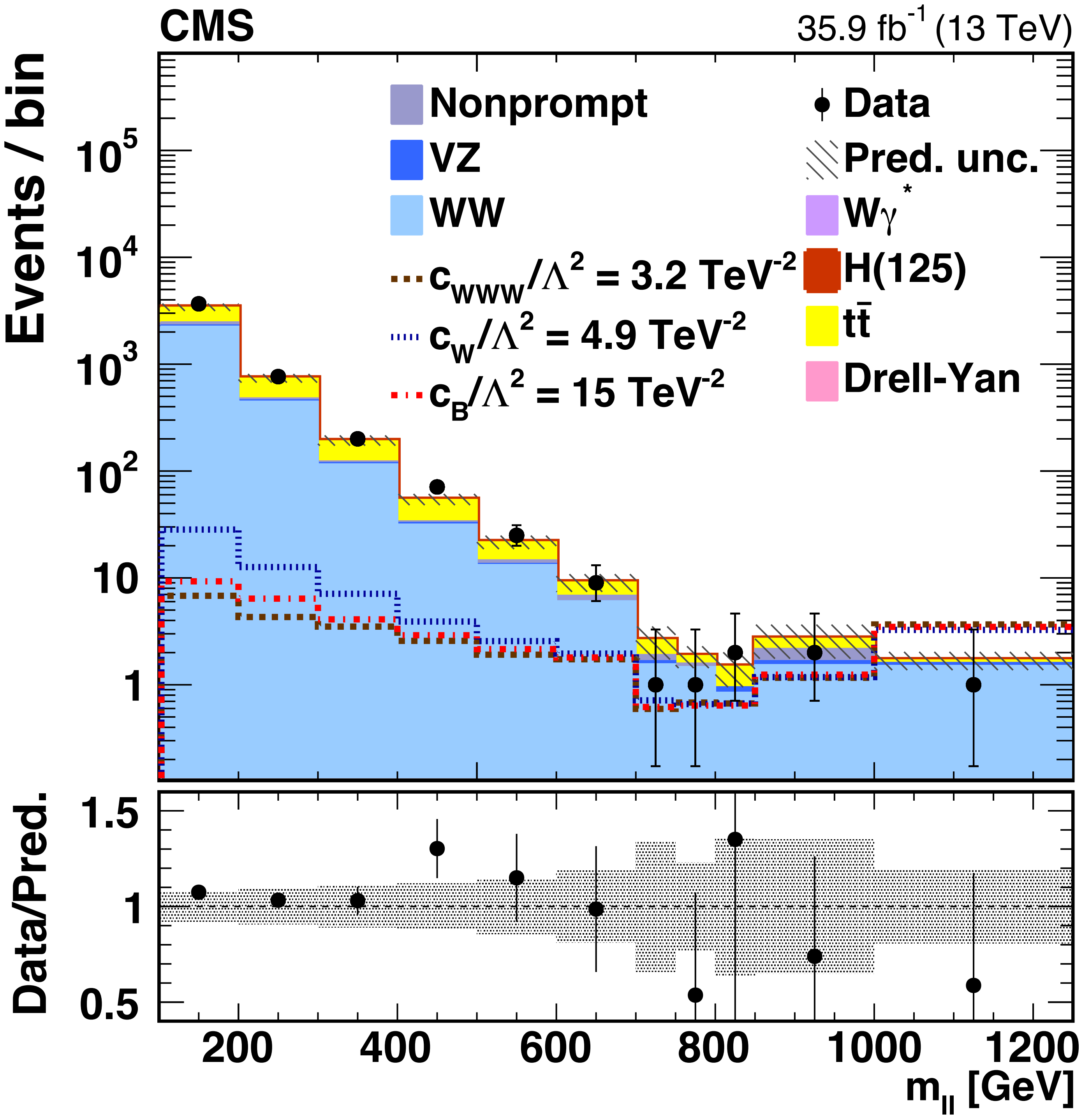
$\propto p^0$

similar for Gluon

and $\cancel{CP}$

No neutral TGC (ZZA, ZAA)

High energy tails



2009.00119

Cross-sections and precision plummet at high energy

EFT/SM is larger at H.E. but so are the EFT errors

Higgs operators

Potential/self-coupling modification

$$\frac{c_\varphi}{\Lambda^2}\left(\frac{h+v}{\sqrt{2}}\right)^6 + \mu^2\left(\frac{h+v}{\sqrt{2}}\right)^2 - \lambda\left(\frac{h+v}{\sqrt{2}}\right)^4$$

$$\hookrightarrow hv\left(\mu^2 - \lambda v^2 + \frac{3}{2}\frac{c_\varphi}{\Lambda^2} v^4\right) + h^2 \ldots$$

$$+ h^3 \ldots \quad + h^4 \ldots$$

---X modification of $v - \mu^2 - \lambda$ relation

Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$

or $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \longrightarrow$ only

≠ SM but only one free parameter

Field redefinition

$$\ni h\Box h \overset{\text{by part}}{=} \partial_\mu h\, \partial^\mu h \qquad h \to h\left(1 + \frac{c_{\varphi\Box} v^2}{\Lambda^2}\right)$$

change all the SM Higgs coupling

$$FFh \longrightarrow y_F\left(1 + \frac{c_{\varphi D} v^2}{\Lambda^2}\right), \ldots$$ by the same amount

Mass redefinition

$$+ \frac{c_{\varphi D}}{\Lambda^2}\frac{v^4}{16}\left(-g_2 W_3^\mu + g_1 B^\mu\right)^2$$

External parameter dependent

C. Degrande

Higgs-Fermion

$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

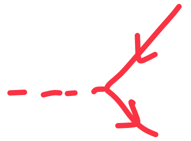
break the mass-coupling relation

$$\longrightarrow \ni \left(v^3\, \bar{u}_L u_R + \underset{\xi}{3}\, h v^2 \bar{u}_L u_R + \dots\right) \rightarrow m_u = y_u v + \frac{c_{u\varphi}}{\Lambda^2} v^3$$

mass & coupling have ≠ contributions

OR
$$\underbrace{\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)}_{\left(hv + \frac{h^2}{2}\right)} \underbrace{\left(\bar{q}\; u\; \tilde{\varphi}\right)}_{\left(\bar{u}_L u_R \left(\frac{h+v}{\sqrt{2}}\right)\right)}$$

$\downarrow$

only change  , no mass redefinition

! one operator for each fermion unless FLAVOUR assumption

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More Higgs and gauge

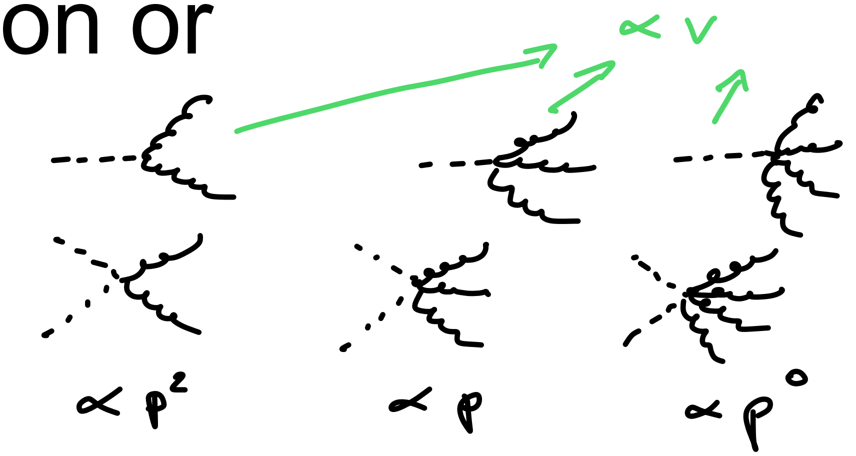
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$

$\longrightarrow \quad \ni \frac{v^2}{2} G^A_{\mu\nu} G^{\mu\nu}_A$

Modification of the kinetic term

Field redefinition or

$(\varphi^+\varphi - v^2/2) \to$ only



Not allowed: A-Z mixing

$\frac{c_{\varphi WB}}{\Lambda^2}\frac{v^2}{4}\, W^3_{\mu\nu}\, B^{\mu\nu} \longrightarrow$ kinetic mixing

$\downarrow$

mass mixing

depend on which external parameters are chosen

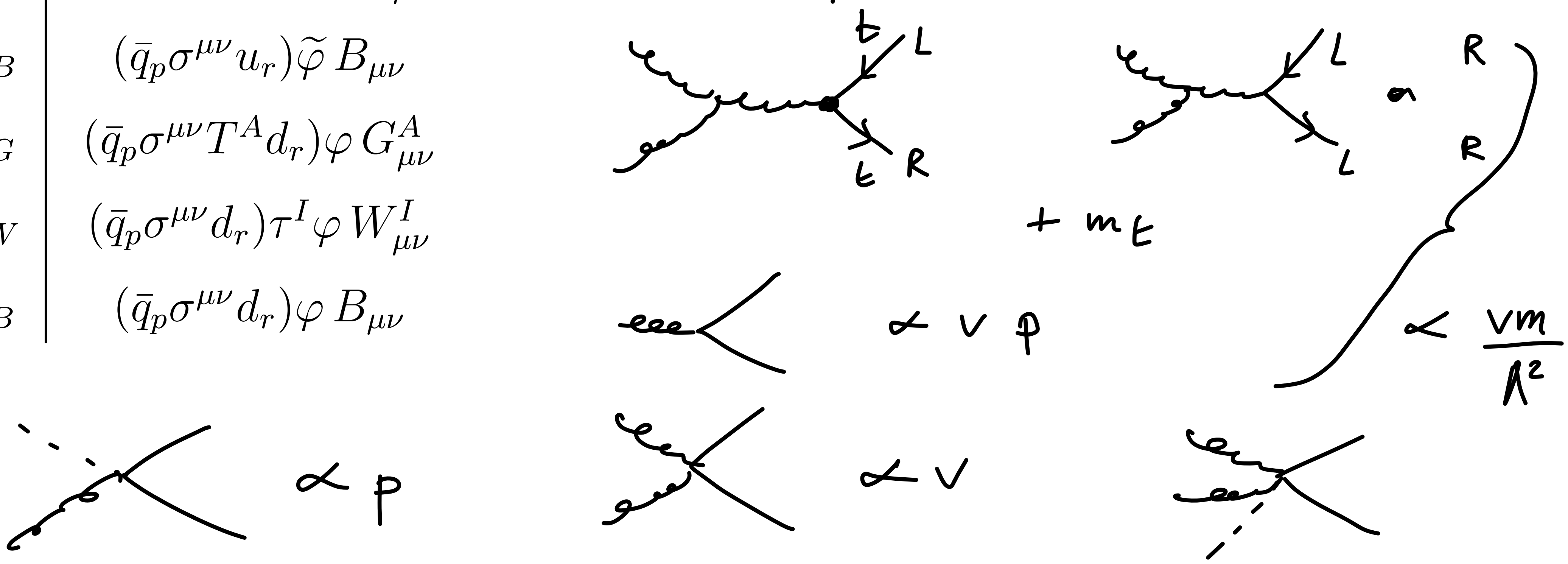
Dipoles

Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$

like EDM or MDM

$$\text{EDM} \downarrow \cancel{CP} \qquad \text{MDM} \downarrow CP$$

L-R operators

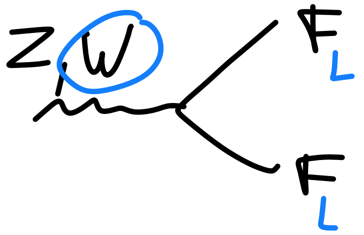


same for other gauge bosons (W, Z, γ)

Higgs, gauge and fermion

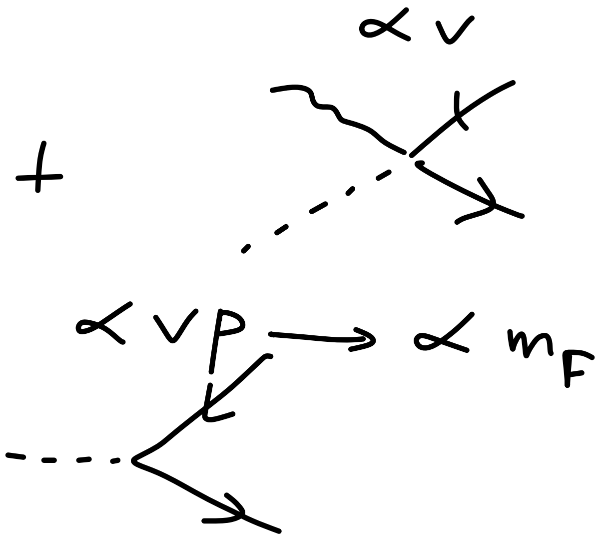
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

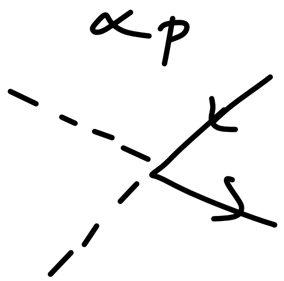
$Q_{\varphi e}, Q_{\varphi u}, Q_{\varphi d} \rightarrow Z\,F_R\,F_R$

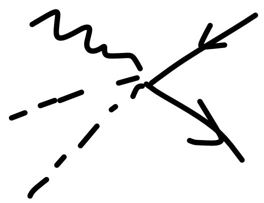


like SM (γ^μ)

No γFF
with γ^μ
because of $U(1)_{EM}$







SMEFT and interference

Errors : higher power of $1/\Lambda$

$$|M(x)|^2 = \boxed{\underset{\Lambda^0}{|M_{SM}(x)|^2}} + \boxed{\underset{\Lambda^{-2}}{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}} + \boxed{\underset{\mathcal{O}\left(\Lambda^{-4}\right)}{|M_{d6}(x)|^2 + \ldots}}$$

- Contains :
  - 1 dim6 insertion squared
  - interference with 2 dim6 insertions
  - interference with 1 dim8 insertion
  - … at $1/\Lambda^{-6}$
- Error (estimate)

usually not included

Dimension 8 basis: Li et al., 2005.00008

Errors : higher power of $1/\Lambda$

$$|M(x)|^2 = \boxed{\begin{array}{c}|M_{SM}(x)|^2\\ \Lambda^0\end{array}} + \boxed{\begin{array}{c}2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)\\ \Lambda^{-2}\end{array}} + \boxed{\begin{array}{c}|M_{d6}(x)|^2 + \dots\\ \mathcal{O}\left(\Lambda^{-4}\right)\end{array}}$$

$\mathcal{O}(1)$	$\mathcal{O}(0.1)$	↔ 10%	$\mathcal{O}(0.01)$
$\mathcal{O}(1)$	$\mathcal{O}(0.5)$	↔ 50%	$\mathcal{O}(0.25)$

- Contains :
    - 1 dim6 insertion squared
    - interference with 2 dim6 insertions
    - interference with 1 dim8 insertion
    - … at $1/\Lambda^{-6}$
- Error (estimate)

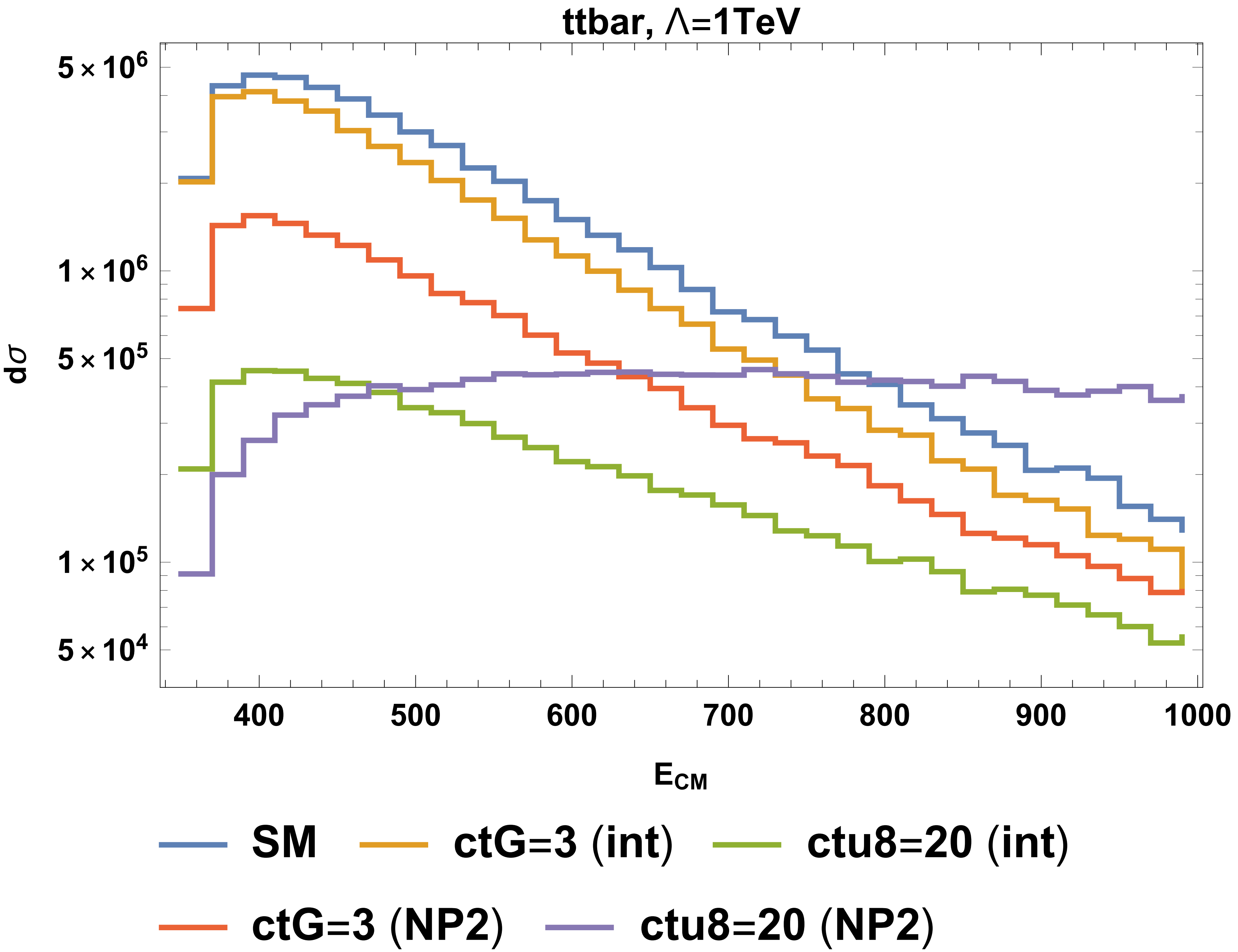
usually not included

Dimension 8 basis: Li et al., 2005.00008

C. Degrande

top pair production

4F interfere only with qq



$\sim \frac{s^2}{\Lambda^4}$

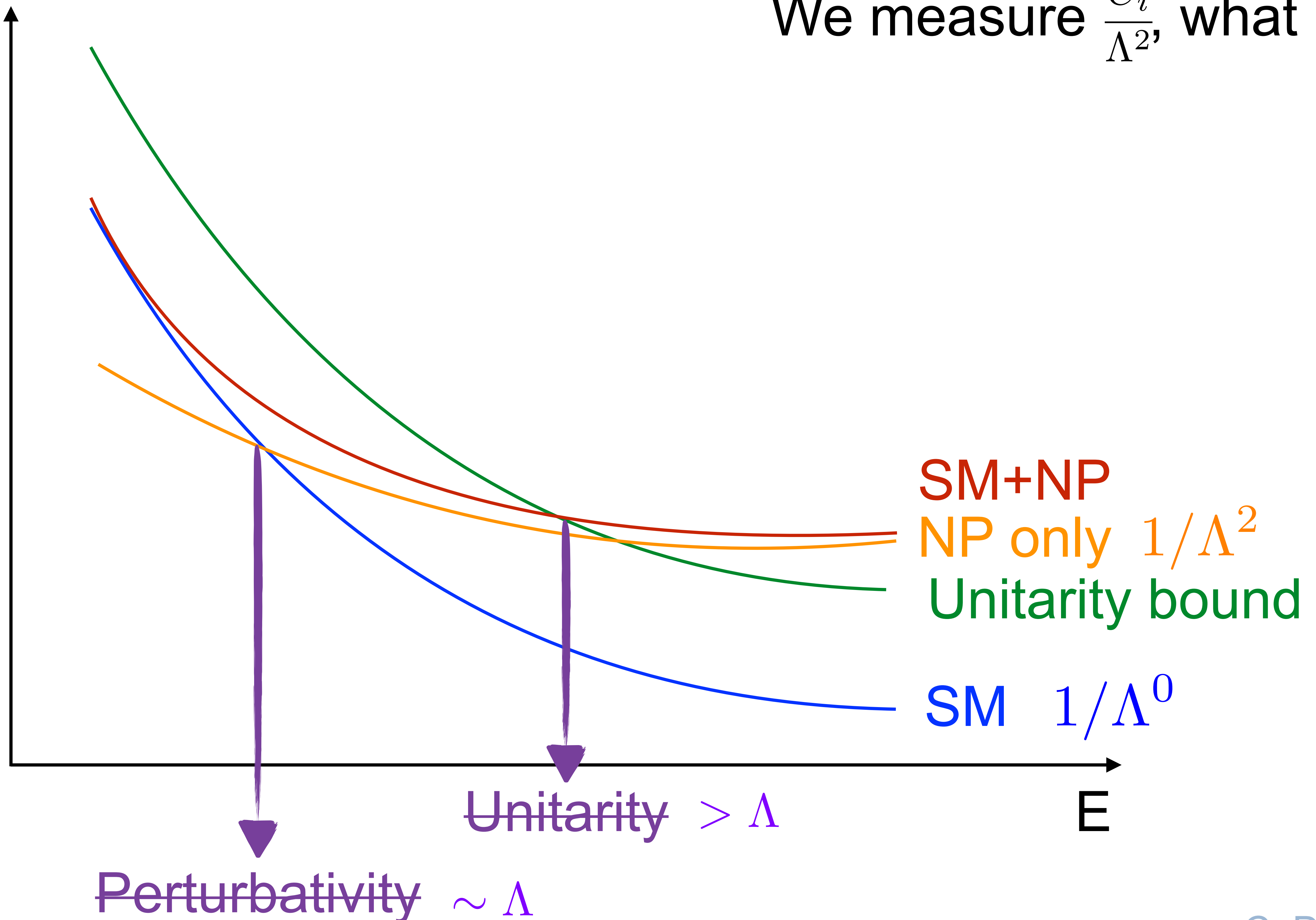
$\sim \frac{v^2 s}{\Lambda^4} \sim \frac{m_t v}{\Lambda^2}$

$\sim \frac{s}{\Lambda^2}$

C. Degrande

EFT & scales

We measure $\frac{C_i}{\Lambda^2}$, what is Λ?

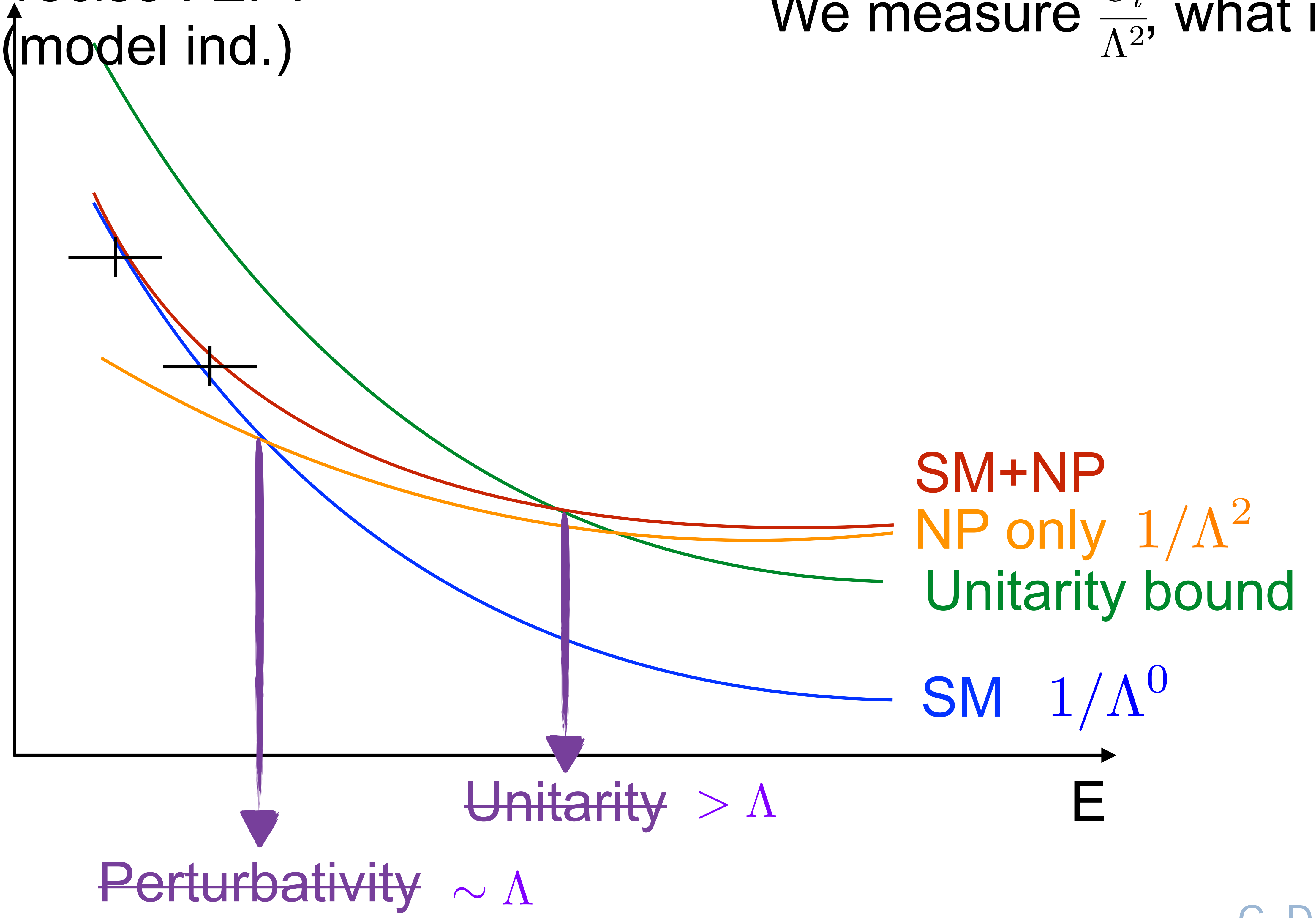


C. Degrande

EFT & scales

Precise : EFT
(model ind.)

We measure $\frac{C_i}{\Lambda^2}$, what is Λ?



SM+NP

NP only $1/\Lambda^2$

Unitarity bound

SM $1/\Lambda^0$

E

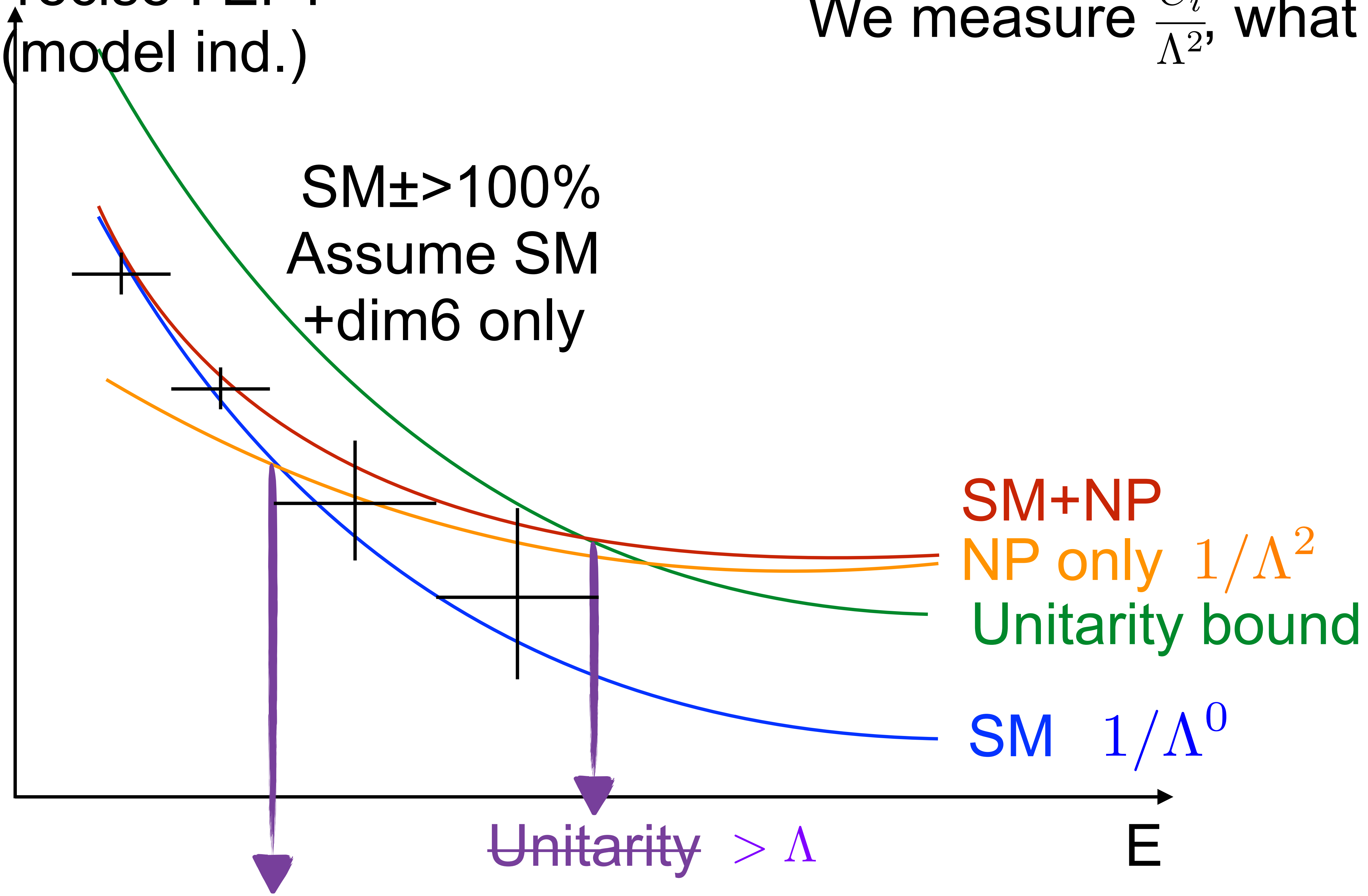
~~Unitarity~~ $> \Lambda$

~~Perturbativity~~ $\sim \Lambda$

C. Degrande

EFT & scales

We measure $\frac{C_i}{\Lambda^2}$, what is Λ?



Precise : EFT
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SM±>100%
Assume SM
+dim6 only

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C. Degrande

EFT & scales

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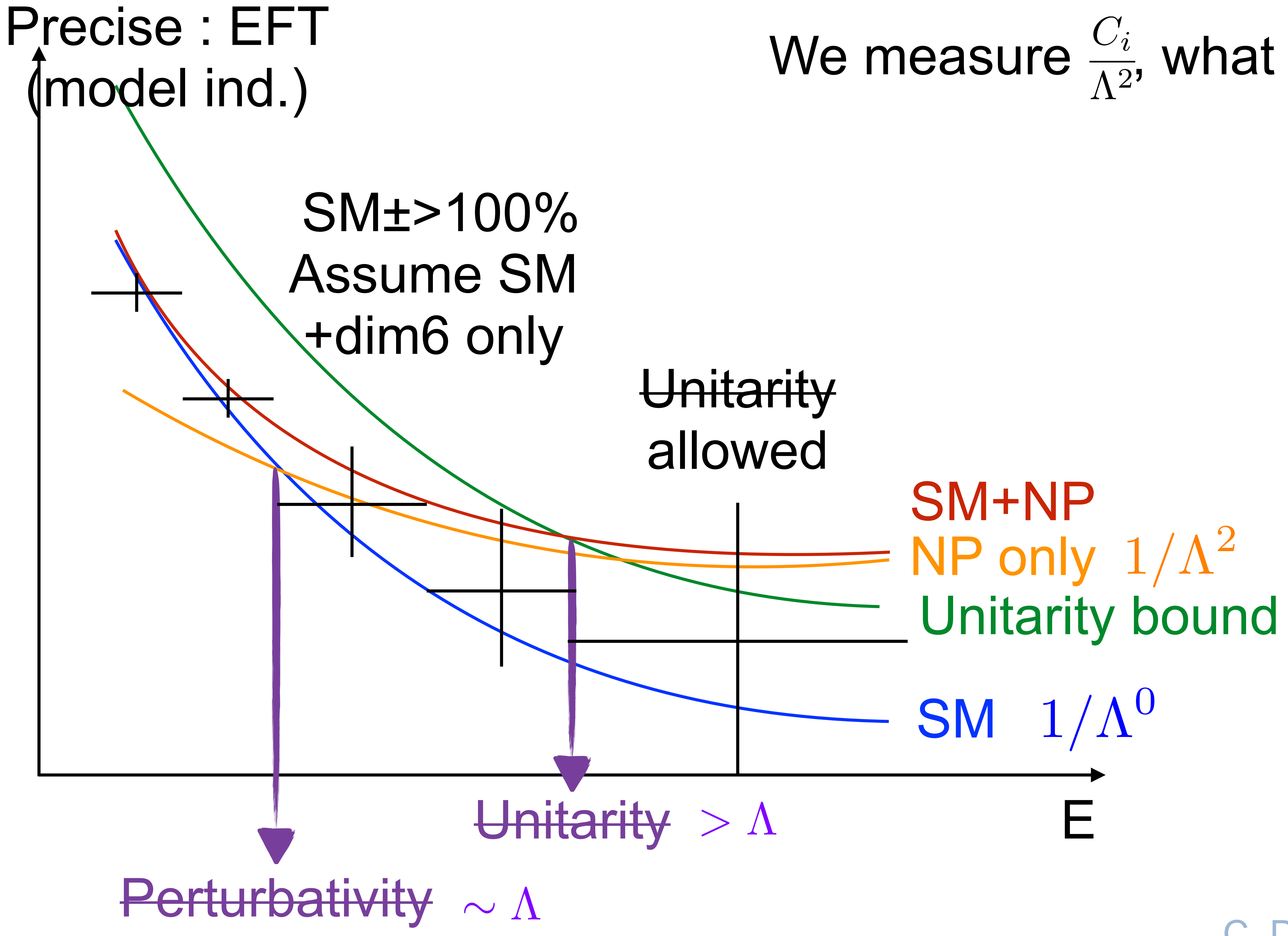

Precise : EFT (model ind.)

SM±>100%
Assume SM
+dim6 only

~~Unitarity~~
allowed

SM+NP

NP only $1/\Lambda^2$

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~~Unitarity~~ $> \Lambda$

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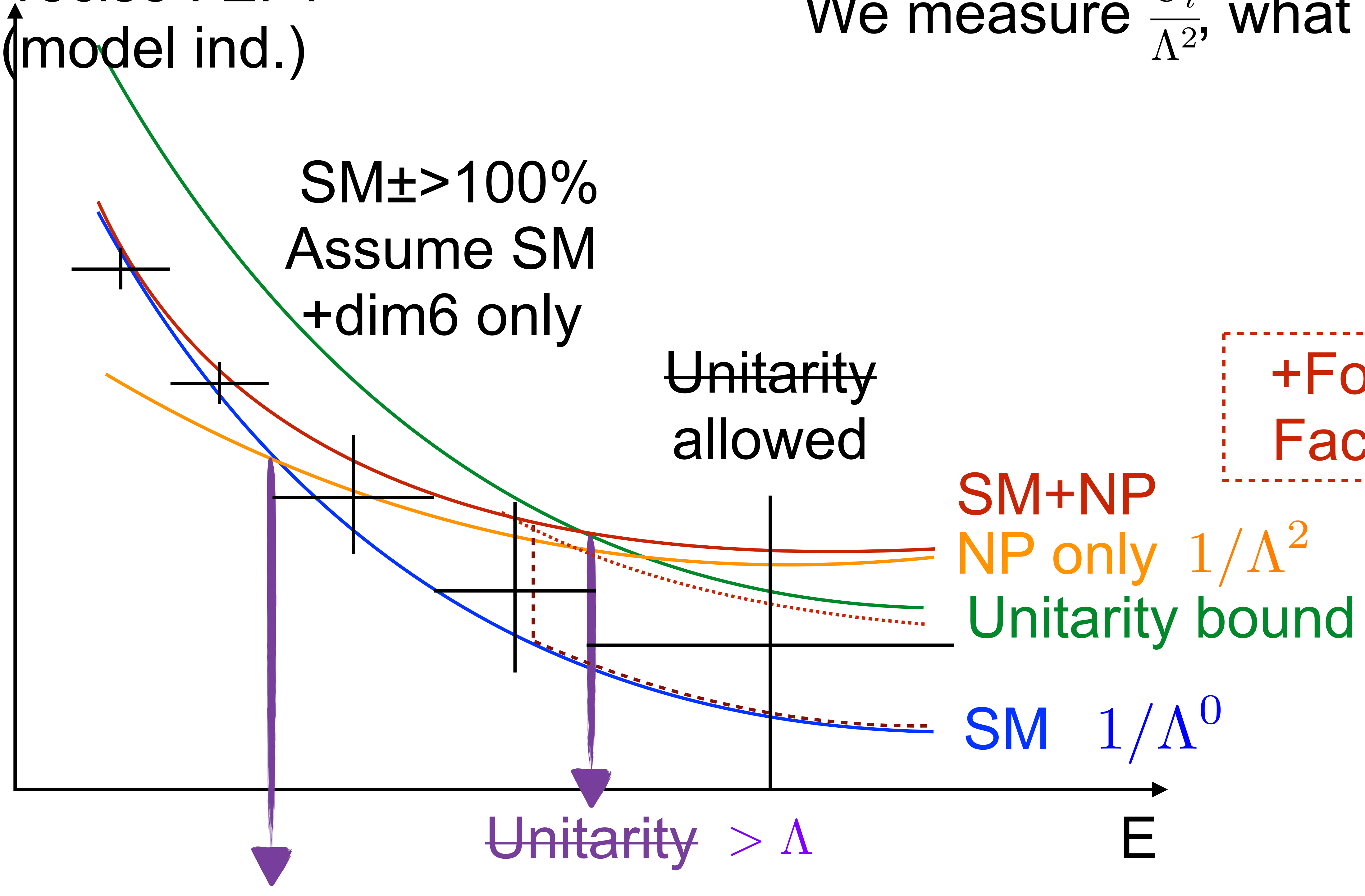
C. Degrande

EFT & scales

We measure $\frac{C_i}{\Lambda^2}$, what is Λ?



Precise : EFT
(model ind.)

SM±>100%
Assume SM
+dim6 only

~~Unitarity~~
allowed

+Form
Factor

~~Unitarity~~ $> \Lambda$

~~Perturbativity~~ $\sim \Lambda$

C. Degrande

(SM-like) Top decay

$t \to bW$

$$\mathcal{O}_{\phi q}^{(3)} = i\left(\phi^\dagger \tau^i D_\mu \phi\right)\left(\bar{Q}\gamma^\mu \tau^i Q\right) + h.c.$$
$$\mathcal{O}_{tW} = \bar{Q}\sigma_{\mu\nu}\tau^i t\tilde{\phi}W_i^{\mu\nu}.$$

C. Zhang, S Willenbrock, PRD83, 034008

$t \to bl\nu_l$

$$\mathcal{O}_{ql}^{(3)} = \left(\bar{Q}\gamma^\mu \tau^i Q\right)\left(\bar{l}\gamma_\mu \tau^i l\right)$$

J.A. Aguilar-Saavedra, NPB843, 683

+ one four-fermion operator for the hadronic decay

$$\frac{1}{2}\Sigma|M|^2 = \frac{V_{tb}^2 g^4 u(m_t^2-u)}{2(s-m_W^2)^2}\left(1+2\frac{C_{\phi q}^{(3)} v^2}{V_{tb}\Lambda^2}\right) + \frac{4\sqrt{2}\mathrm{Re}C_{tW}V_{tb}m_t m_W}{\Lambda^2}\frac{g^2 su}{(s-m_W^2)^2}$$
$$+\frac{4C_{ql}^{(3)}}{\Lambda^2}\frac{g^2 u(m_t^2-u)}{s-m_W^2} + \mathcal{O}\left(\Lambda^{-4}\right)$$

Width, W helicities and …

$$\frac{\Gamma\left(t\to be^{+}\nu_e\right)}{GeV}=0.1541+\left[0.019\frac{C^{(3)}_{\phi q}}{\Lambda^2}+0.026\frac{C_{tW}}{\Lambda^2}+0\frac{C^{(3)}_{ql}}{\Lambda^2}\right]\text{TeV}^2$$

$$\left.\begin{aligned}\frac{\Gamma_t}{GeV}&=\Gamma_{SM}+\left[0.17\frac{C^{(3)}_{\phi q}}{\Lambda^2}+0.23\frac{C_{tW}}{\Lambda^2}\right]\text{TeV}^2\\ \Gamma^{meas}&=1.42^{+0.19}_{-0.15}\text{ GeV}\\ \Gamma^{**}_{SM}&=1.33\,\text{GeV}\end{aligned}\right\}\frac{C^{(3)}_{\phi q}}{\Lambda^2}+1.35\frac{C_{tW}}{\Lambda^2}=4^{+2.8}_{-2.5}\text{TeV}^{-2}$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta}=\frac{3}{8}(1+\cos\theta)^2F_R+\frac{3}{8}(1-\cos\theta)^2F_L+\frac{3}{4}\sin^2\theta F_0$$

$$\begin{aligned}F_0&=\frac{m_t^2}{m_t^2+2m_W^2}-\frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2V_{tb}}\frac{m_tm_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2}\\ F_L&=\frac{2m_W^2}{m_t^2+2m_W^2}+\frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2V_{tb}}\frac{m_tm_W(m_t^2-m_W^2)}{(m_t^2+2m_W^2)^2}\\ F_R&=0\end{aligned}$$

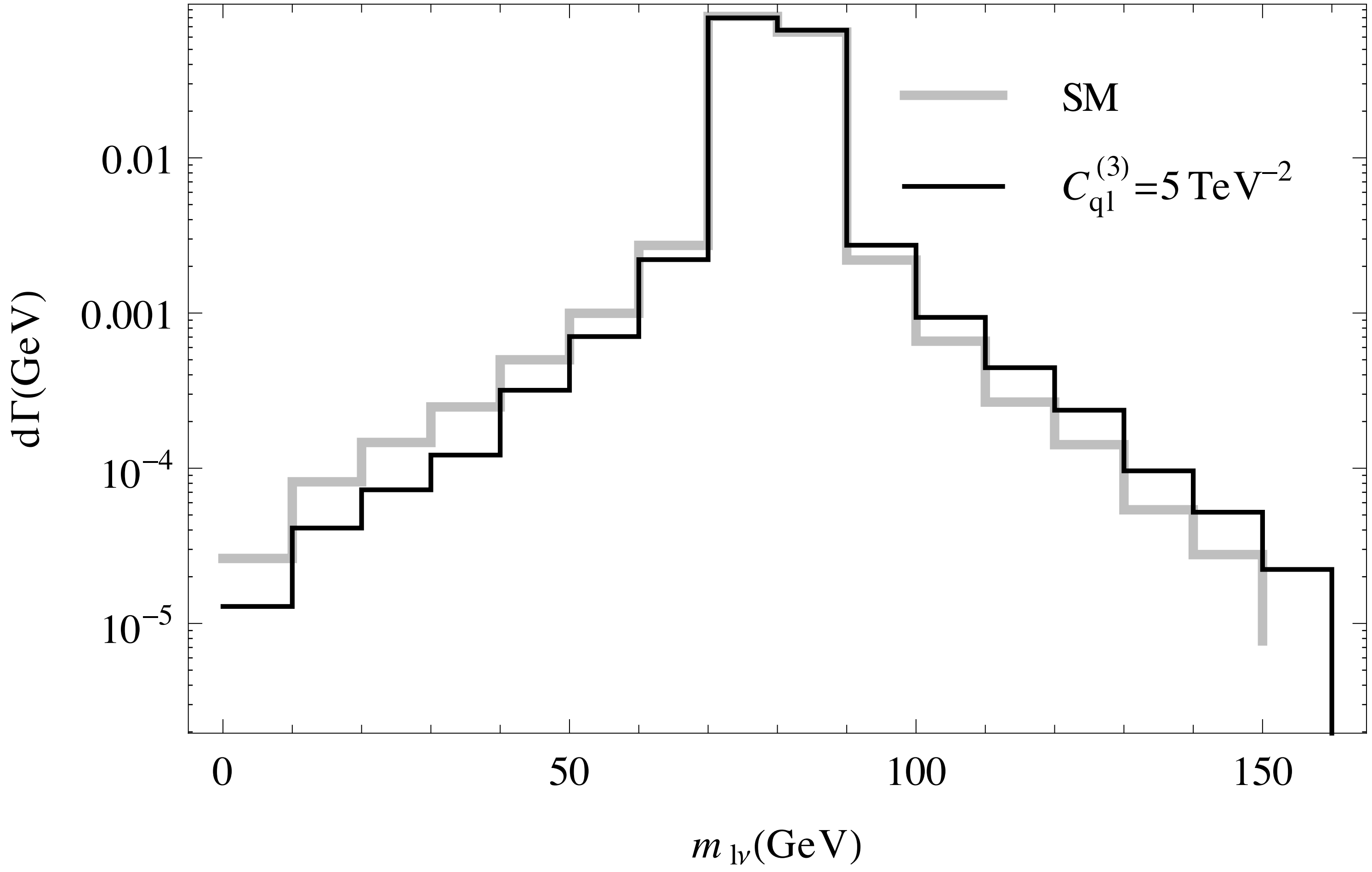
$$\left.\begin{aligned}F_0^{SM*}&=0.687\pm5\\ F_0^{meas**}&=0.66\pm5\end{aligned}\right\}\frac{C_{tW}}{\Lambda^2}=0.44\pm0.9\text{TeV}^{-2}$$

$$\frac{C^{(3)}_{\phi q}}{\Lambda^2}=1.1^{+2.3}_{-2.1}\text{TeV}^{-2}$$

C. Degrande

Width, W helicities and …

$$\frac{1}{2}\Sigma|M|^2 = \frac{V_{tb}^2 g^4 u(m_t^2 - u)}{2(s - m_W^2)^2} + \frac{4C_{ql}^{(3)}}{\Lambda^2}\frac{g^2 u(m_t^2 - u)}{s - m_W^2}$$



C. Degrande

interference suppression

Azatov et al., Helicity Selection Rules and Non-Interference for BSM Amplitudes, 1607.05236

A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

interference suppression

Azatov et al., Helicity Selection Rules and Non-Interference for BSM Amplitudes, 1607.05236

A_4	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
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$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

$$|M(x)|^2 = \underset{\Lambda^0}{\boxed{|M_{SM}(x)|^2}} + \underset{\Lambda^{-2}}{\boxed{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}} + \underset{\Lambda^{-4}}{\boxed{|M_{d6}(x)|^2 + \ldots}} \quad + \mathcal{O}(\Lambda^{-6})$$

$\mathcal{O}(1)$ ~0 $\mathcal{O}(0.1)$ ⟷ 30% $\mathcal{O}(0.03)$

C. Degrande

interference suppression

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$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

$$|M(x)|^2 = \boxed{\begin{array}{c}|M_{SM}(x)|^2\\ \Lambda^0\end{array}} + \boxed{\begin{array}{c}2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)\\ \Lambda^{-2}\end{array}} + \boxed{\begin{array}{c}|M_{d6}(x)|^2 + \ldots\\ \Lambda^{-4}\end{array}} \quad + \mathcal{O}(\Lambda^{-6})$$

$\mathcal{O}(1)$ ~0 $\mathcal{O}(0.1)$ 30% $\mathcal{O}(0.03)$

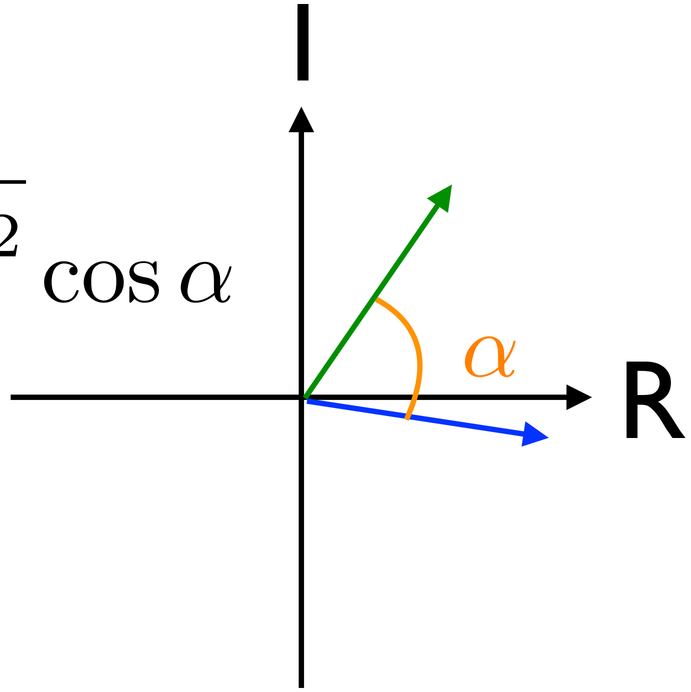
Assuming ~0

C. Degrande

Interference

$$|M(x)|^2 = \boxed{\underset{\Lambda^0}{|M_{SM}(x)|^2}} + \boxed{\underset{\Lambda^{-2}}{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}} + \boxed{\underset{\mathcal{O}\left(\Lambda^{-4}\right)}{|M_{d6}(x)|^2 + \ldots}}$$

$$\Re\left(M_{SM}(x)M^*_{d6}(x)\right) = \sqrt{|M_{SM}(x)|^2\,|M_{d6}(x)|^2}\cos\alpha$$



mom&spin

Not always positive

Can be suppressed

$$\sigma \propto \sum_x |M(x)|^2$$

if

$$M_{SM}(x_1) = 1,\ M_{SM}(x_2) = 0$$

$$M_{d6}(x_1) = 0,\ M_{d6}(x_2) = 1$$

$$\sigma_{int} = 0$$

Observable dependent

C. Degrande

Interference

$$|M(x)|^2 = \boxed{\begin{array}{c}|M_{SM}(x)|^2\\ \Lambda^0\end{array}} + \boxed{\begin{array}{c}2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)\\ \Lambda^{-2}\end{array}} + \boxed{\begin{array}{c}|M_{d6}(x)|^2 + \ldots\\ \mathcal{O}\left(\Lambda^{-4}\right)\end{array}}$$

$$\Re\left(M_{SM}(x)M^*_{d6}(x)\right) = \sqrt{|M_{SM}(x)|^2\,|M_{d6}(x)|^2}\cos\alpha$$

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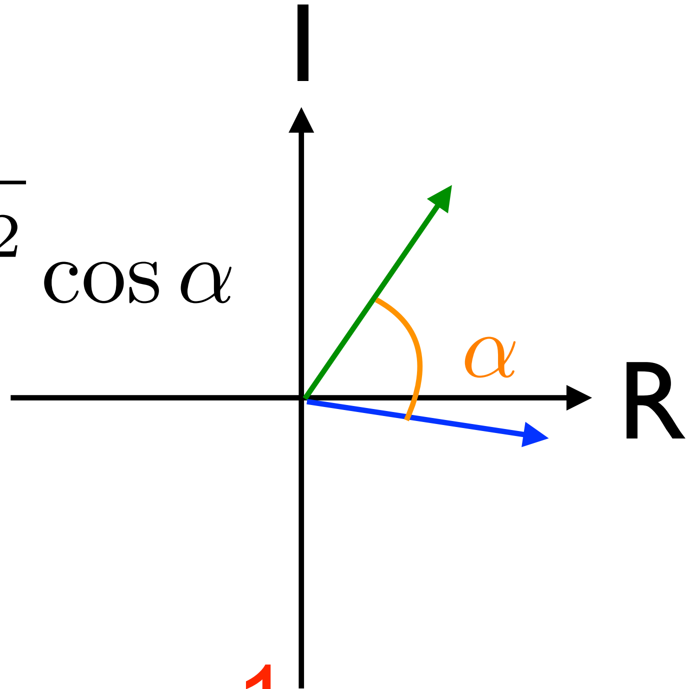
Not always positive



Can be suppressed

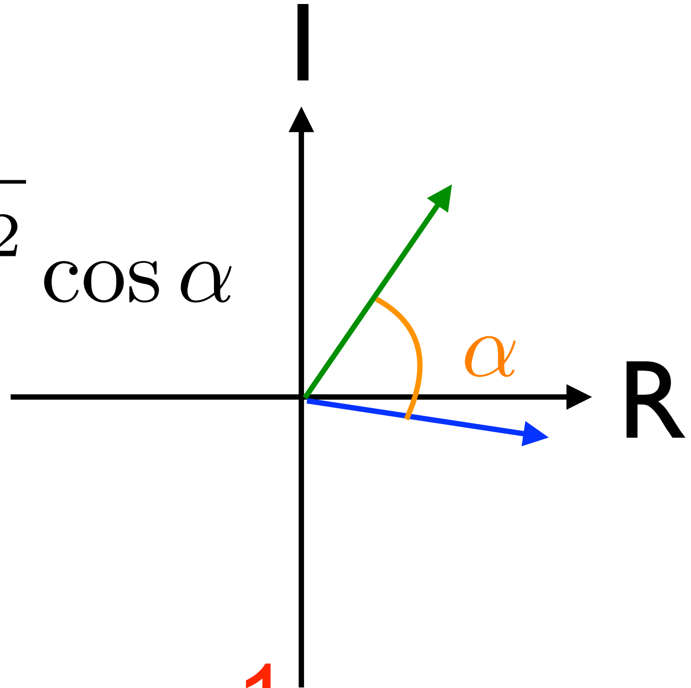
$$\sigma \propto \sum_x |M(x)|^2 \quad \textbf{if} \quad \begin{array}{l} M_{SM}(x_1) = 1,\ M_{SM}(x_2) = \overset{1}{\cancel{0}} \\ M_{d6}(x_1) = \underset{-1}{\cancel{0}},\ M_{d6}(x_2) = 1 \end{array} \qquad \sigma_{int} = 0$$

Observable dependent

C. Degrande

Interference

$$|M(x)|^2 = \boxed{\underset{\Lambda^0}{|M_{SM}(x)|^2}} + \boxed{\underset{\Lambda^{-2}}{2\Re\left(M_{SM}(x)M^*_{d6}(x)\right)}} + \boxed{\underset{\mathcal{O}\left(\Lambda^{-4}\right)}{|M_{d6}(x)|^2 + \ldots}}$$



$$\Re\left(M_{SM}(x)M^*_{d6}(x)\right) = \sqrt{|M_{SM}(x)|^2\,|M_{d6}(x)|^2}\cos\alpha$$

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Observable dependent

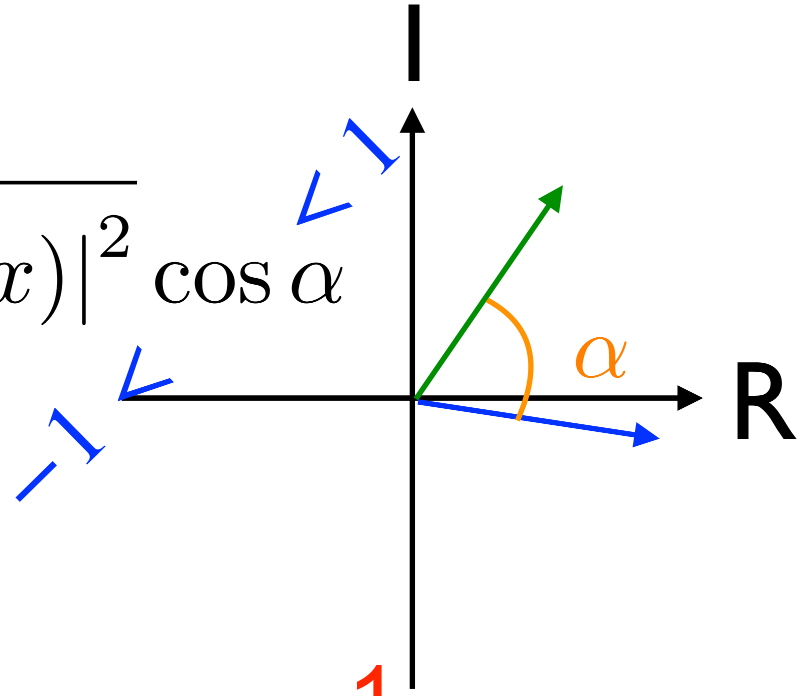
or $\alpha \approx \pi/2$ $\quad M^2 \rightarrow M^2 - i\Gamma M \quad$ $\sigma_{int} \propto \Gamma$

C. Degrande

Interference

$$|M(x)|^2 = \boxed{\begin{matrix}|M_{SM}(x)|^2 \\ \Lambda^0\end{matrix}} + \boxed{\begin{matrix}2\Re\left(M_{SM}(x)M^*_{d6}(x)\right) \\ \Lambda^{-2}\end{matrix}} + \boxed{\begin{matrix}|M_{d6}(x)|^2 + \dots \\ \mathcal{O}\left(\Lambda^{-4}\right)\end{matrix}}$$

$$\Re\left(M_{SM}(x)M^*_{d6}(x)\right) = \sqrt{|M_{SM}(x)|^2\,|M_{d6}(x)|^2}\cos\alpha$$



mom&spin

Not always positive

Can be suppressed

$$\sigma \propto \sum_x |M(x)|^2$$

if

$$M_{SM}(x_1) = 1,\ M_{SM}(x_2) = \overset{1}{\cancel{0}}$$

$$M_{d6}(x_1) = \underset{-1}{\cancel{0}},\ M_{d6}(x_2) = 1$$

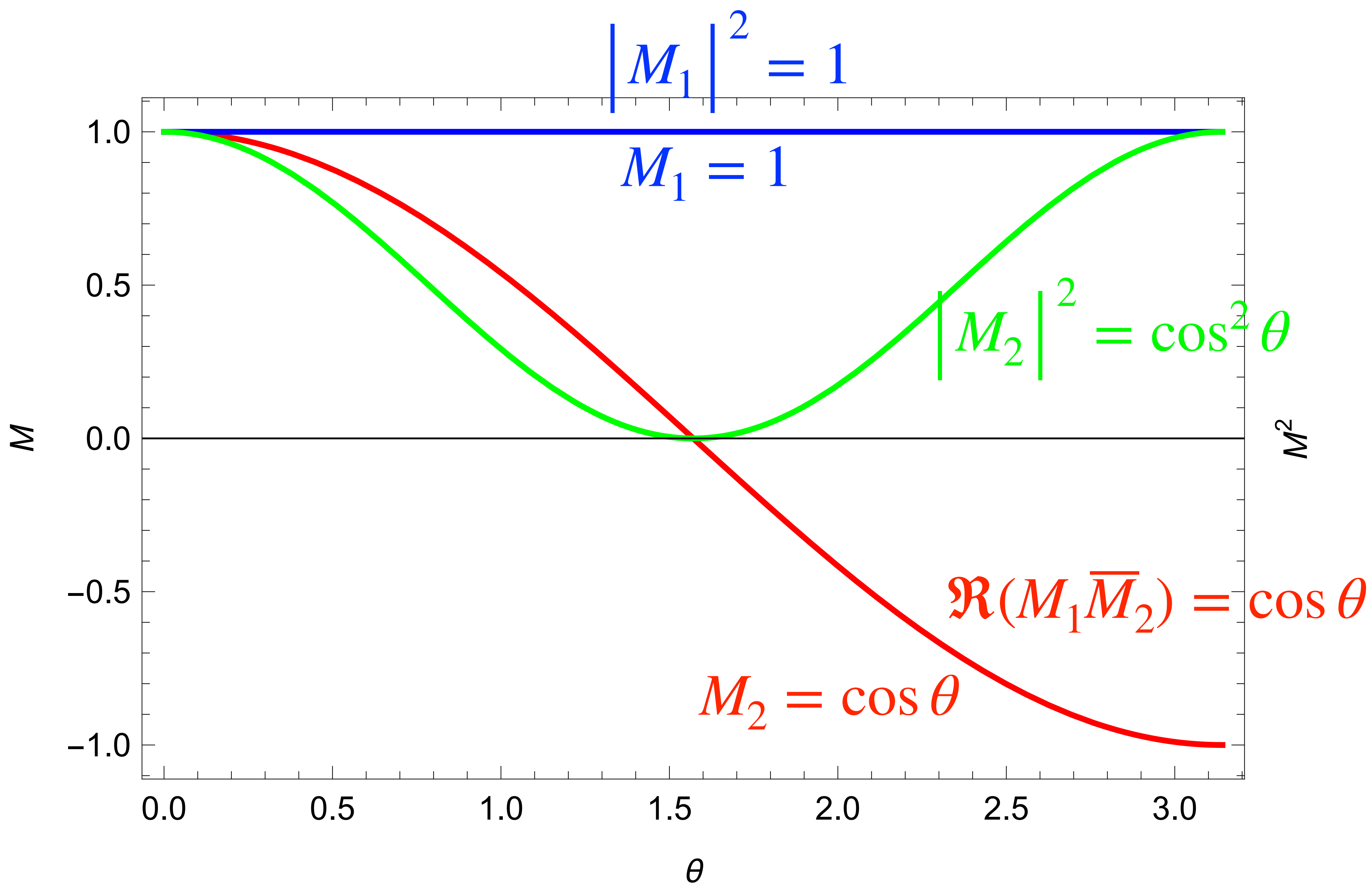
$$\sigma_{int} = 0$$

Observable dependent

or $\alpha \approx \pi/2$ $\quad M^2 \to M^2 - i\Gamma M \quad \sigma_{int} \propto \Gamma$

C. Degrande

Interference suppression from phase space



$$\sigma_{int} = \int_0^{\pi} 2\Re(M_1\overline{M}_2)d\theta = \int_0^{\pi} 2\cos\theta d\theta = 0$$

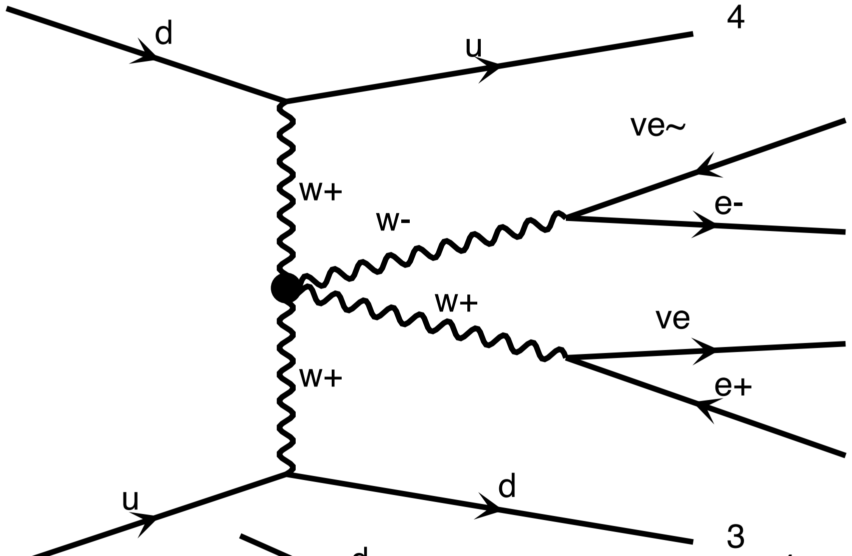
C. Degrande

VBS

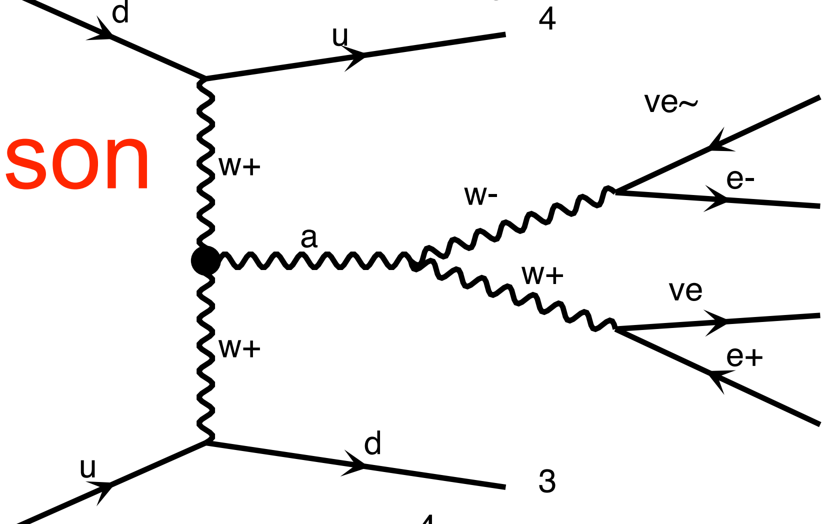
Operators → ↓ Processes	Q_{HD}	$Q_{H\Box}$	Q_{HWB}	$Q_{Hq}^{(1)}$	$Q_{Hq}^{(3)}$	Q_{HW}	Q_{W}	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{ll}^{(1)}$	$Q_{qq}^{(3)}$	$Q_{qq}^{(3,1)}$	$Q_{qq}^{(1,1)}$	$Q_{qq}^{(1)}$	Q_{ll}
WW	✓		✓	✓	✓		✓	(✓)	✓	✓					
SSWW+2j EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
OSWW+2j EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
WZ+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZZ+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZV+2j EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
OSWW+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					
WZ+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					(✓)
ZZ+2j QCD	✓		✓	✓	✓			✓	✓	✓					(✓)
ZV+2j QCD	✓		✓	✓	✓		✓	✓	✓	✓					

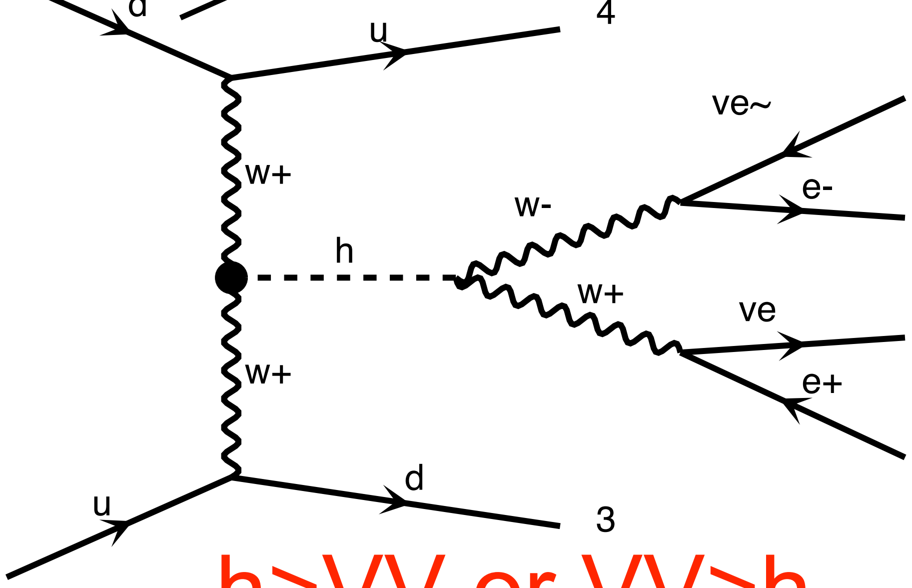
Bellan et al., 2108.03199

VBS



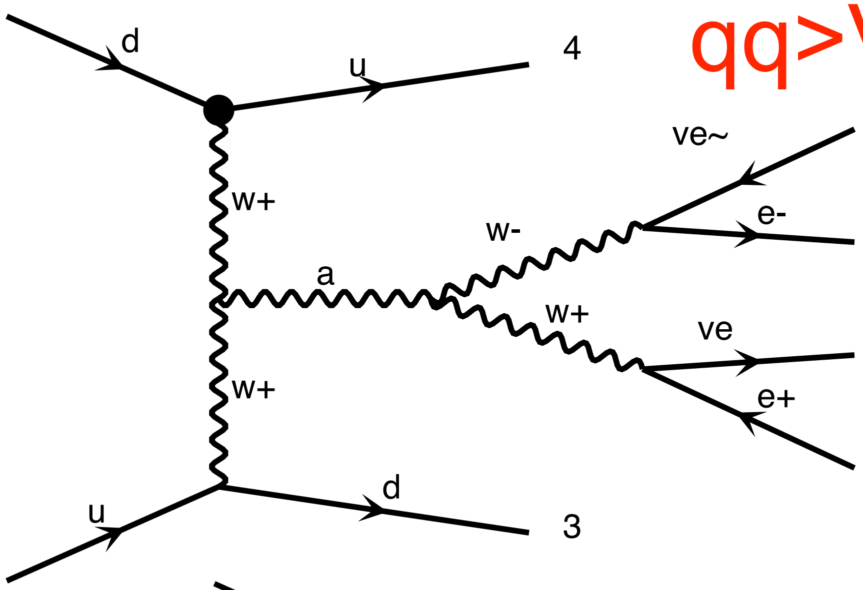
Diboson



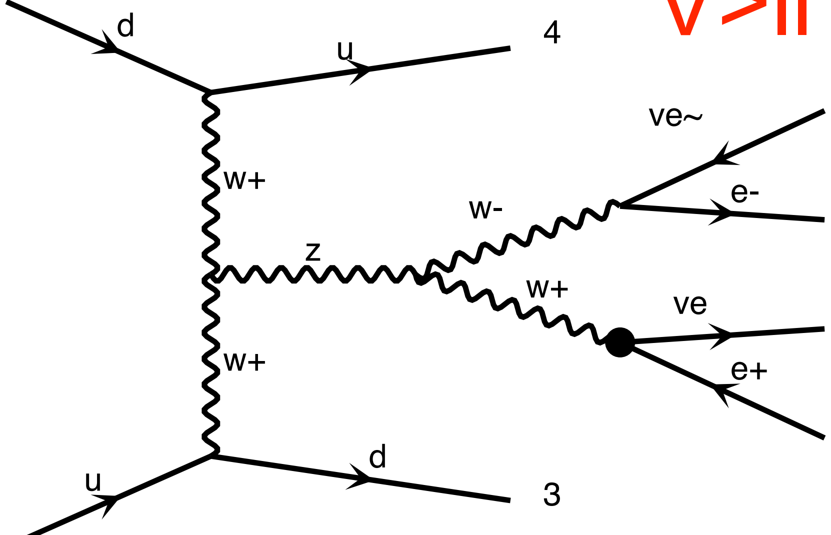


h>VV or VV>h

qq>V or V>qq



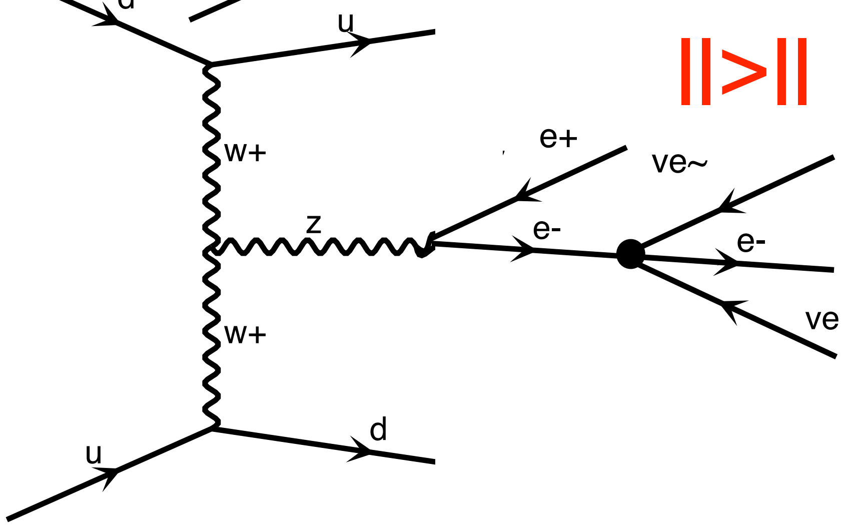
V>ll or ll>V



ll>ll

qq>qq

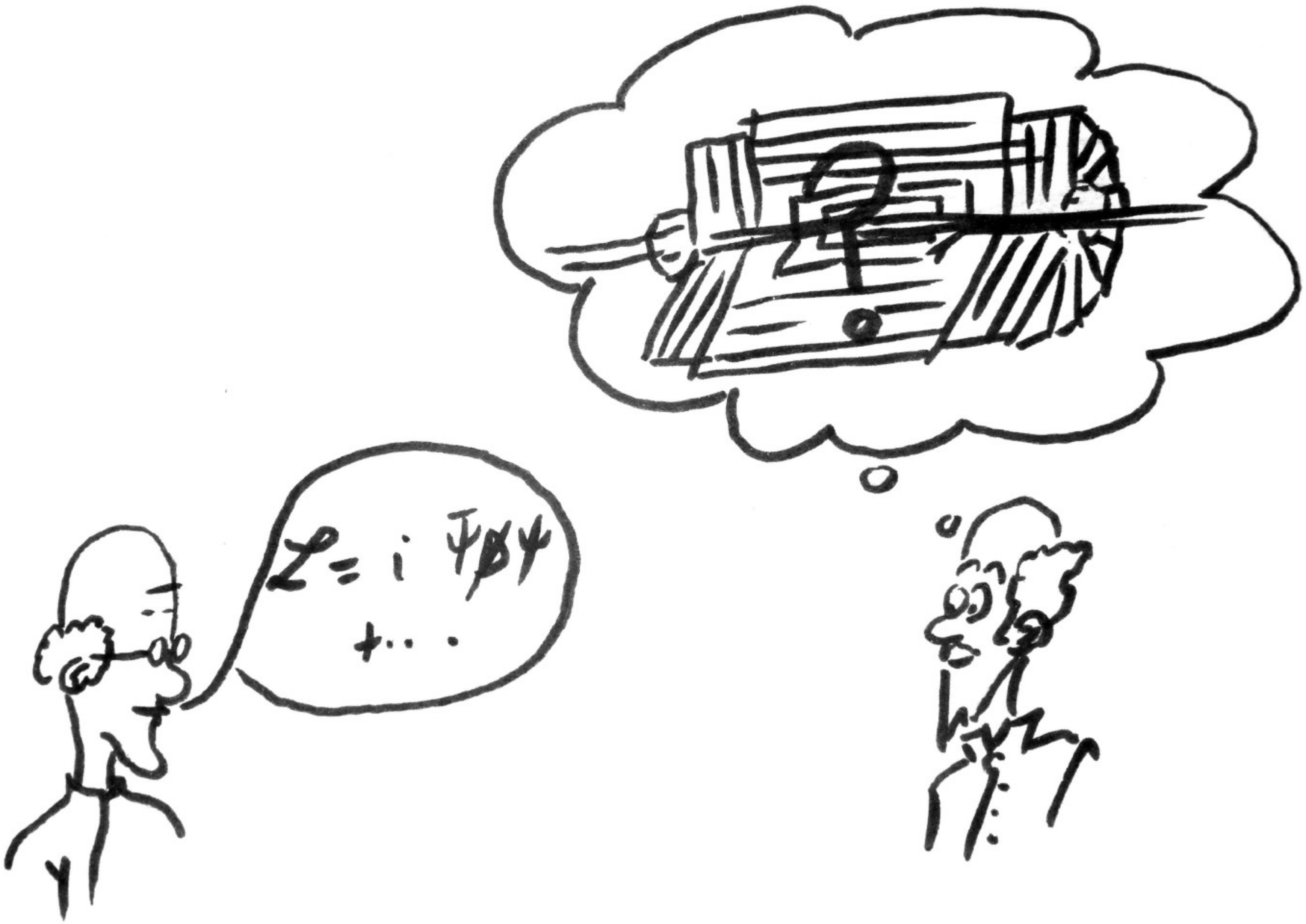
+ with 4q



C. Degrande

Automated computation for BSM

Why BSM simulation?



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Why automated tools

- Algorithmic
- Less error prone
- Long $f^{abc}G^a_{\mu\nu}G^{b\nu\rho}G^{c\mu}_{\rho} \ni$ 4 gluons vertex

$$
\begin{aligned}
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_4} \mathrm{p}_2^{\mu_3} \eta_{\mu_1,\mu_2} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_3} \mathrm{p}_2^{\mu_4} \eta_{\mu_1,\mu_2} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_3} \mathrm{p}_3^{\mu_4} \eta_{\mu_1,\mu_2} + \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_2^{\mu_3} \mathrm{p}_3^{\mu_4} \eta_{\mu_1,\mu_2} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_1^{\mu_4} \mathrm{p}_4^{\mu_3} \eta_{\mu_1,\mu_2} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_2^{\mu_4} \mathrm{p}_4^{\mu_3} \eta_{\mu_1,\mu_2} - \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \eta_{\mu_3,\mu_4} \mathrm{p}_1{\cdot}\mathrm{p}_3 \eta_{\mu_1,\mu_2} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \eta_{\mu_3,\mu_4} \mathrm{p}_1{\cdot}\mathrm{p}_4 \eta_{\mu_1,\mu_2} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \eta_{\mu_3,\mu_4} \mathrm{p}_2{\cdot}\mathrm{p}_3 \eta_{\mu_1,\mu_2} - \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \eta_{\mu_3,\mu_4} \mathrm{p}_2{\cdot}\mathrm{p}_4 \eta_{\mu_1,\mu_2} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_2} \mathrm{p}_2^{\mu_4} \eta_{\mu_1,\mu_3} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_4} \mathrm{p}_3^{\mu_2} \eta_{\mu_1,\mu_3} - \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_2^{\mu_4} \mathrm{p}_3^{\mu_2} \eta_{\mu_1,\mu_3} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_2} \mathrm{p}_3^{\mu_4} \eta_{\mu_1,\mu_3} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_1^{\mu_4} \mathrm{p}_4^{\mu_2} \eta_{\mu_1,\mu_3} + \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_3^{\mu_4} \mathrm{p}_4^{\mu_2} \eta_{\mu_1,\mu_3} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_2} \mathrm{p}_2^{\mu_3} \eta_{\mu_1,\mu_4} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_3} \mathrm{p}_3^{\mu_2} \eta_{\mu_1,\mu_4} + \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_1^{\mu_3} \mathrm{p}_4^{\mu_2} \eta_{\mu_1,\mu_4} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_2^{\mu_3} \mathrm{p}_4^{\mu_2} \eta_{\mu_1,\mu_4} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_1^{\mu_2} \mathrm{p}_4^{\mu_3} \eta_{\mu_1,\mu_4} - \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_3^{\mu_2} \mathrm{p}_4^{\mu_3} \eta_{\mu_1,\mu_4} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_4} \mathrm{p}_2^{\mu_1} \eta_{\mu_2,\mu_3} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_4} \mathrm{p}_3^{\mu_1} \eta_{\mu_2,\mu_3} + \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_2^{\mu_4} \mathrm{p}_3^{\mu_1} \eta_{\mu_2,\mu_3} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_2^{\mu_1} \mathrm{p}_3^{\mu_4} \eta_{\mu_2,\mu_3} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_2^{\mu_4} \mathrm{p}_4^{\mu_1} \eta_{\mu_2,\mu_3} - \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_3^{\mu_4} \mathrm{p}_4^{\mu_1} \eta_{\mu_2,\mu_3} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_3} \mathrm{p}_2^{\mu_1} \eta_{\mu_2,\mu_4} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_2^{\mu_3} \mathrm{p}_3^{\mu_1} \eta_{\mu_2,\mu_4} - \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_1^{\mu_3} \mathrm{p}_4^{\mu_1} \eta_{\mu_2,\mu_4} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_2^{\mu_3} \mathrm{p}_4^{\mu_1} \eta_{\mu_2,\mu_4} - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_2^{\mu_1} \mathrm{p}_4^{\mu_3} \eta_{\mu_2,\mu_4} + \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_3^{\mu_1} \mathrm{p}_4^{\mu_3} \eta_{\mu_2,\mu_4} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_1^{\mu_2} \mathrm{p}_3^{\mu_1} \eta_{\mu_3,\mu_4} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_2^{\mu_1} \mathrm{p}_3^{\mu_2} \eta_{\mu_3,\mu_4} + \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \mathrm{p}_1^{\mu_2} \mathrm{p}_4^{\mu_1} \eta_{\mu_3,\mu_4} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_3^{\mu_2} \mathrm{p}_4^{\mu_1} \eta_{\mu_3,\mu_4} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \mathrm{p}_2^{\mu_1} \mathrm{p}_4^{\mu_2} \eta_{\mu_3,\mu_4} - \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \mathrm{p}_3^{\mu_1} \mathrm{p}_4^{\mu_2} \eta_{\mu_3,\mu_4} + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} \mathrm{p}_1{\cdot}\mathrm{p}_2 - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} \mathrm{p}_1{\cdot}\mathrm{p}_2 + \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} \mathrm{p}_1{\cdot}\mathrm{p}_3 + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} \mathrm{p}_1{\cdot}\mathrm{p}_4 + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a} f_{\mathrm{a}_2,\mathrm{a}_3,a} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} \mathrm{p}_2{\cdot}\mathrm{p}_3 + \\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a} f_{\mathrm{a}_2,\mathrm{a}_4,a} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} \mathrm{p}_2{\cdot}\mathrm{p}_4 + 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} \mathrm{p}_3{\cdot}\mathrm{p}_4 - 6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a} f_{\mathrm{a}_3,\mathrm{a}_4,a} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} \mathrm{p}_3{\cdot}\mathrm{p}_4
\end{aligned}
$$

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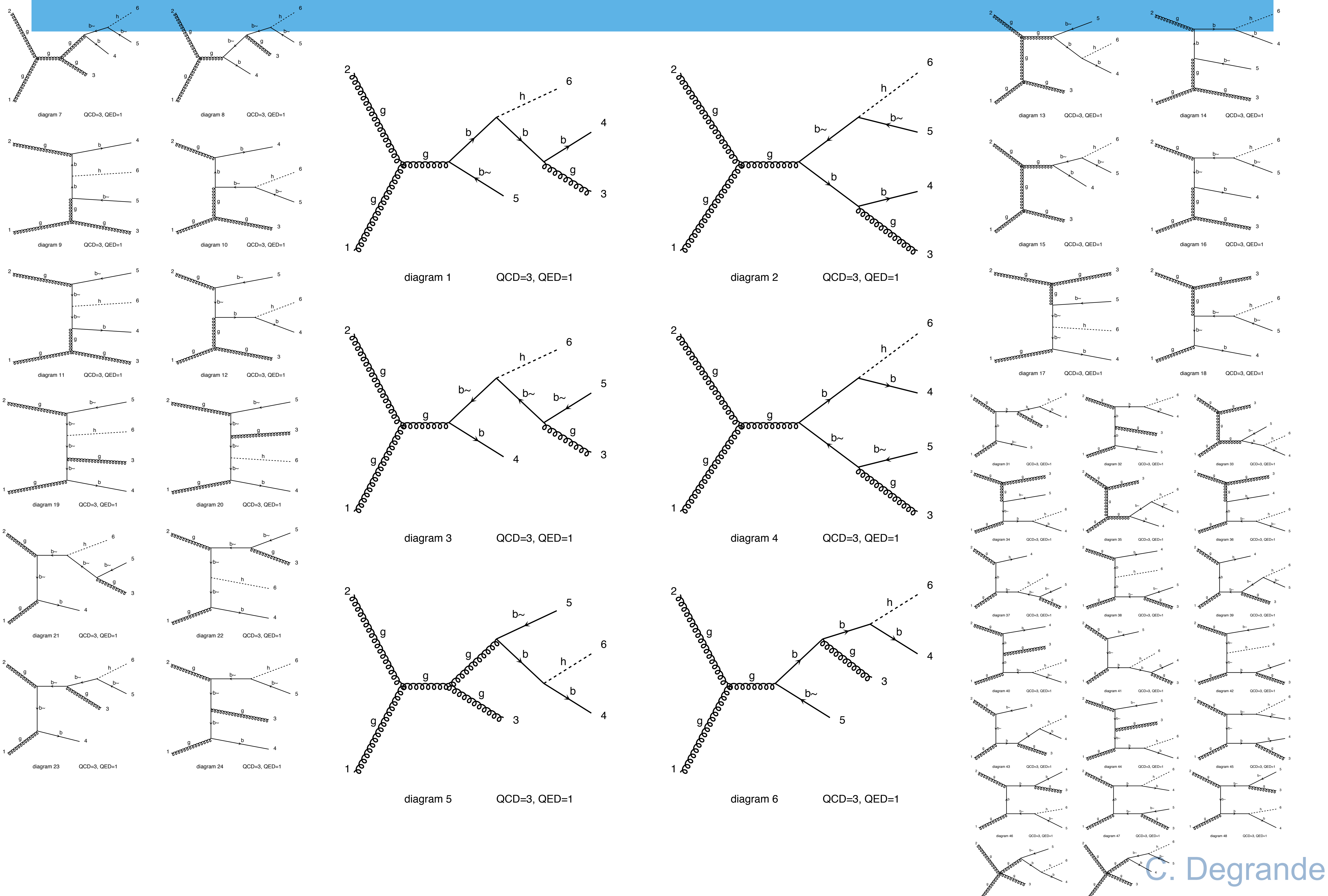
Many diagrams



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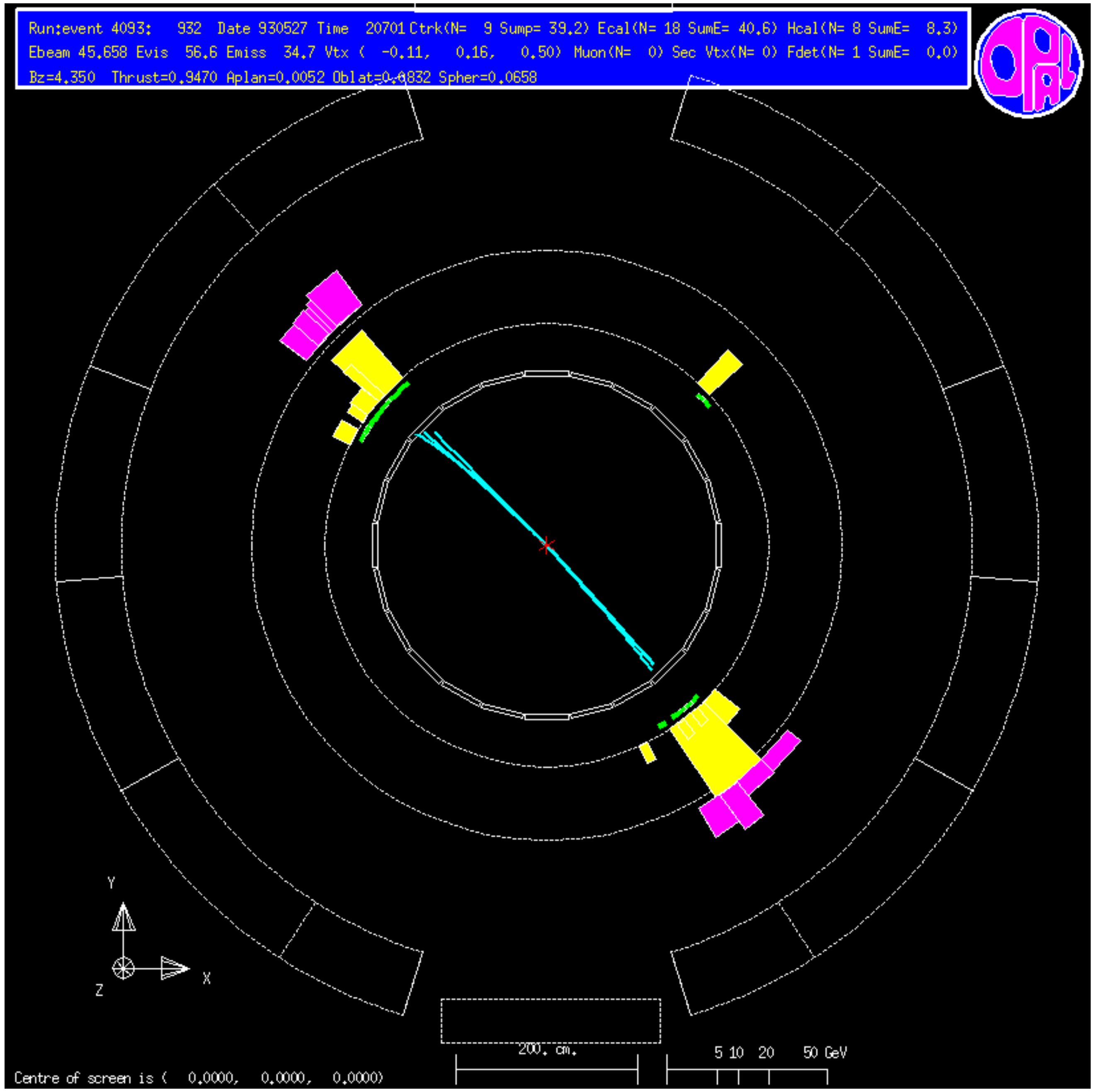
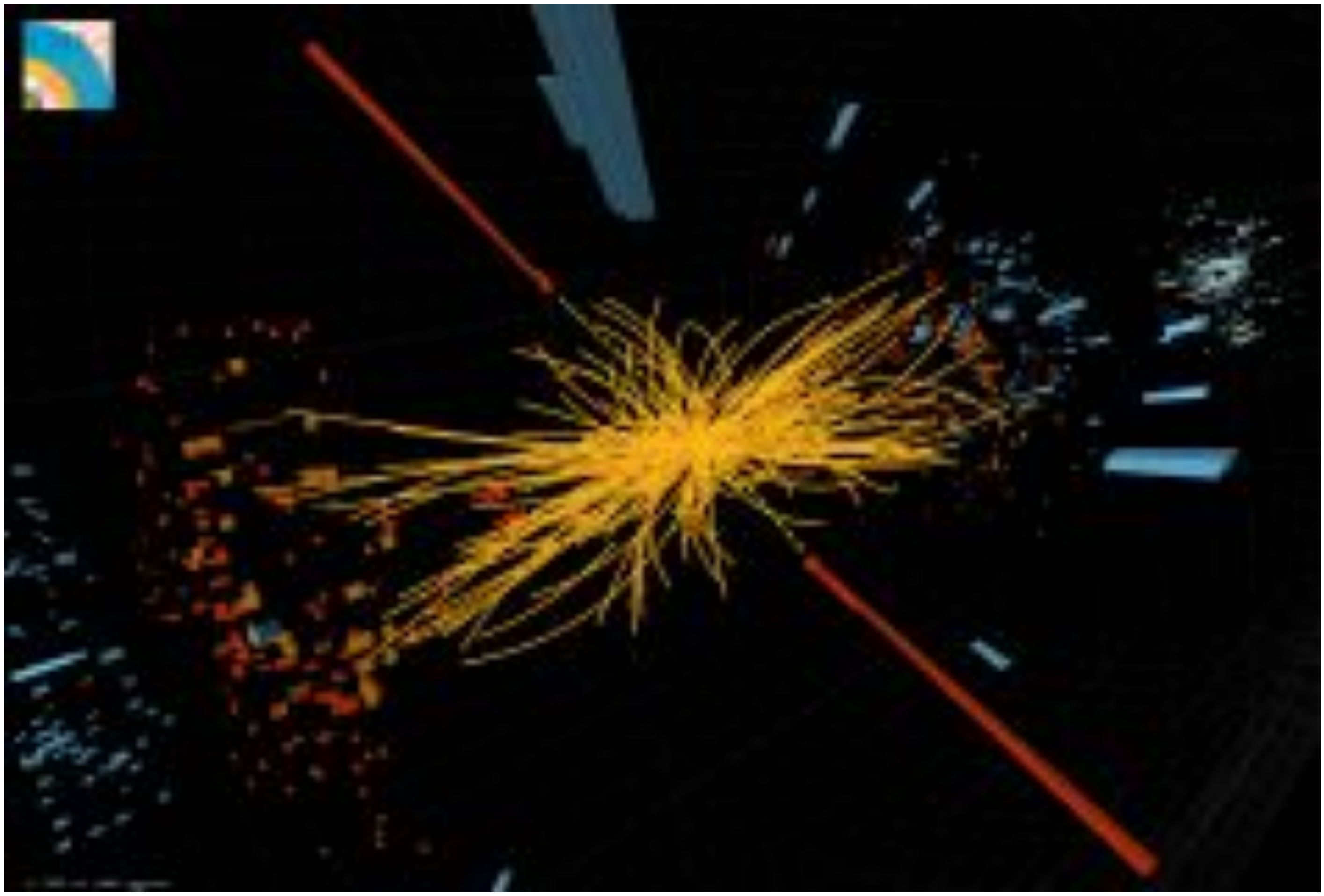
Hadron colliders

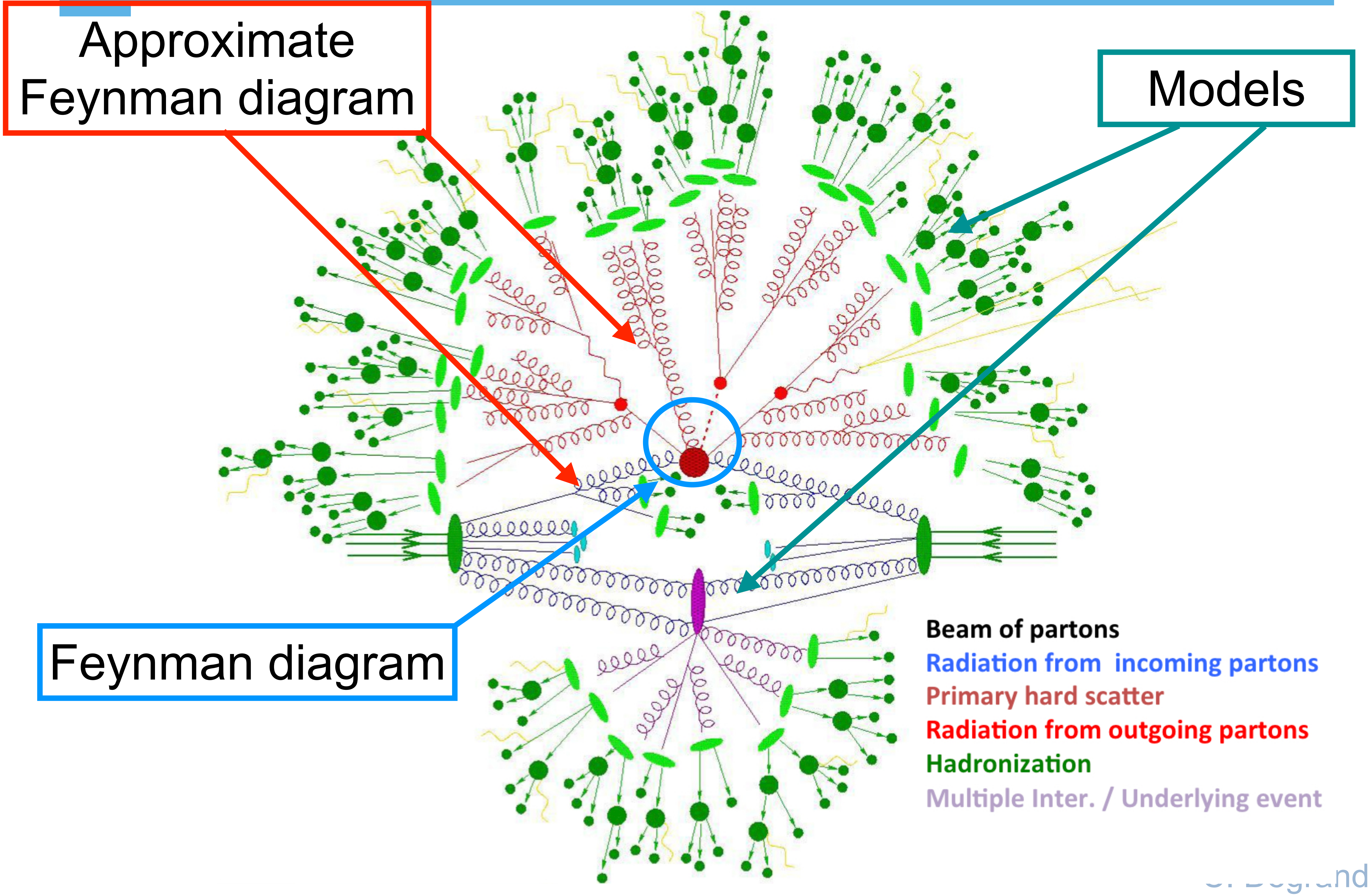
LEP

LHC





Hadron collider event



Approximate Feynman diagram

Models

Feynman diagram

Beam of partons

Radiation from incoming partons

Primary hard scatter

Radiation from outgoing partons

Hadronization

Multiple Inter. / Underlying event

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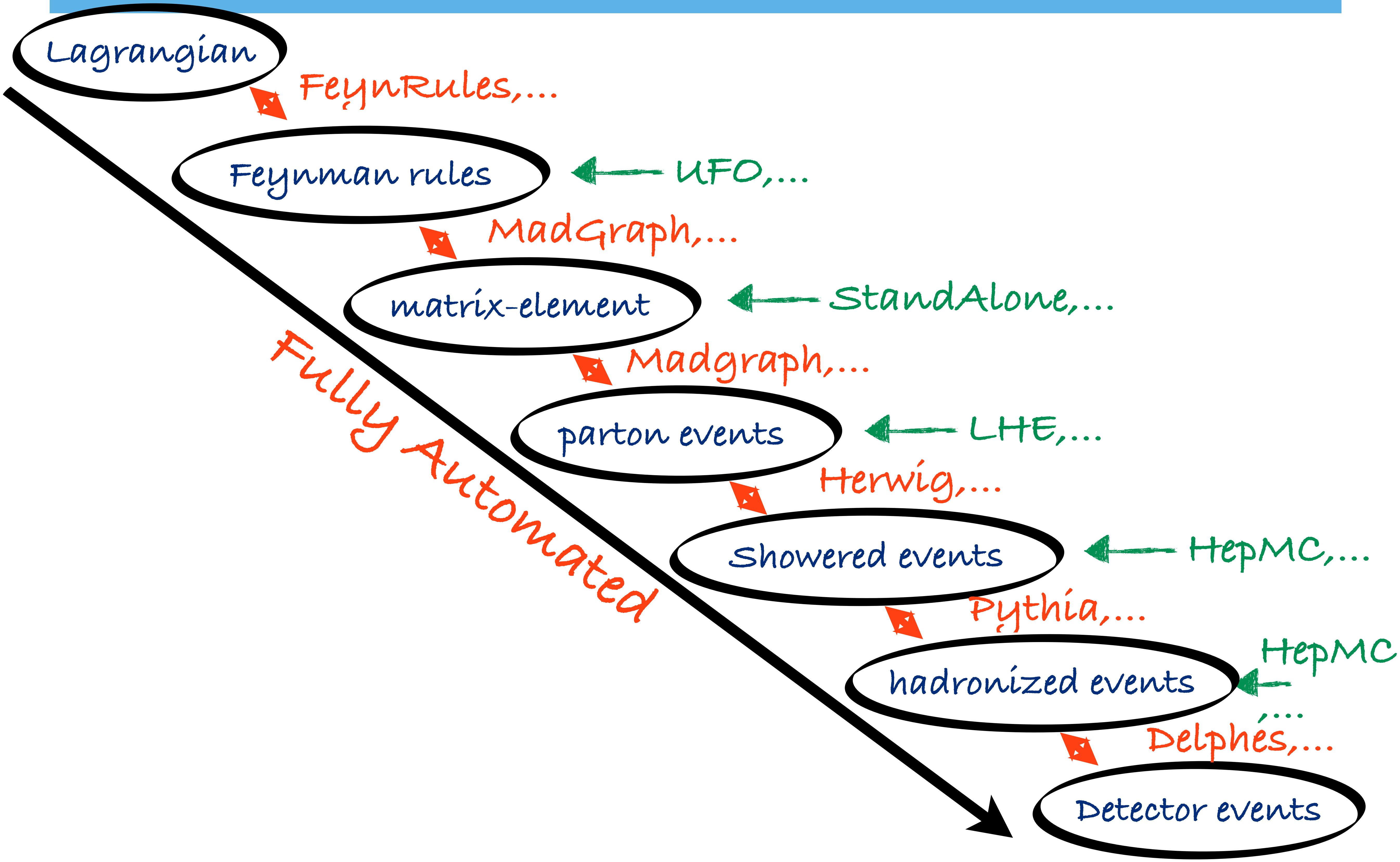
BSM simulation



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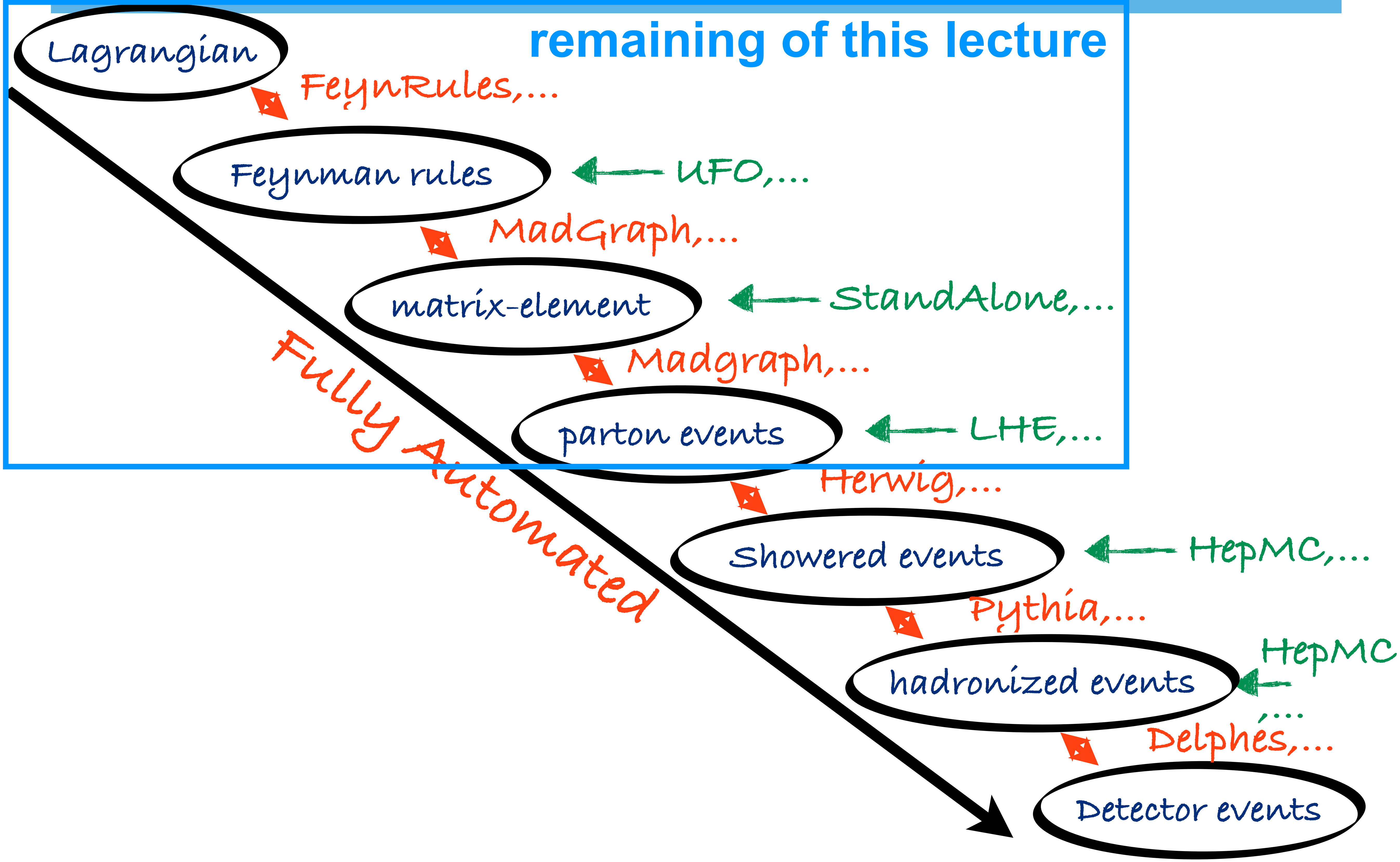
BSM simulation



remaining of this lecture

Lagrangian

FeynRules,...

Feynman rules

UFO,...

MadGraph,...

matrix-element

StandAlone,...

Madgraph,...

parton events

LHE,...

Herwig,...

Showered events

HepMC,...

Pythia,...

hadronized events

HepMC ,...

Delphes,...

Detector events

Fully Automated

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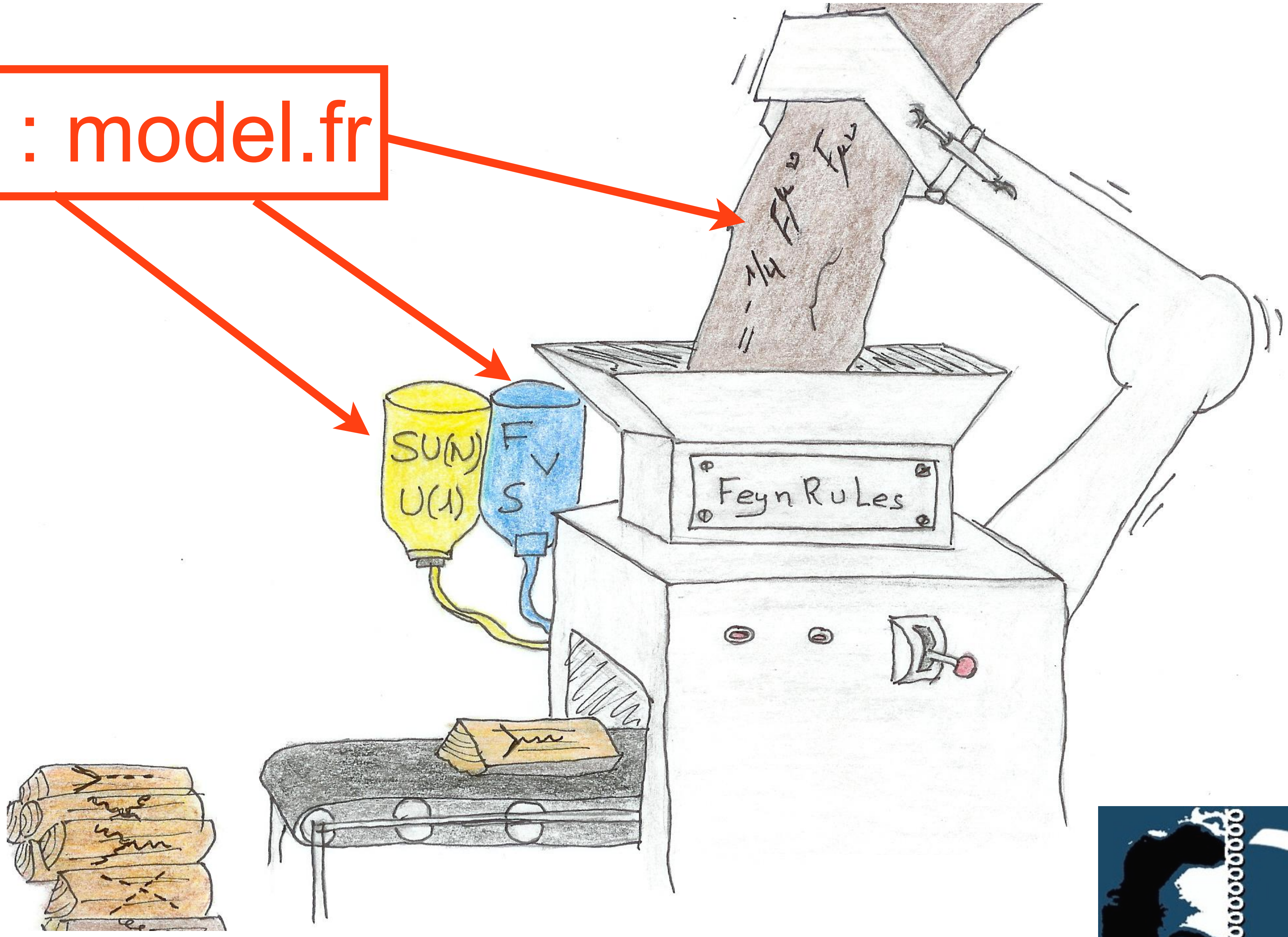
FeynRules in a nutshell



Input : model.fr

Output : vertices

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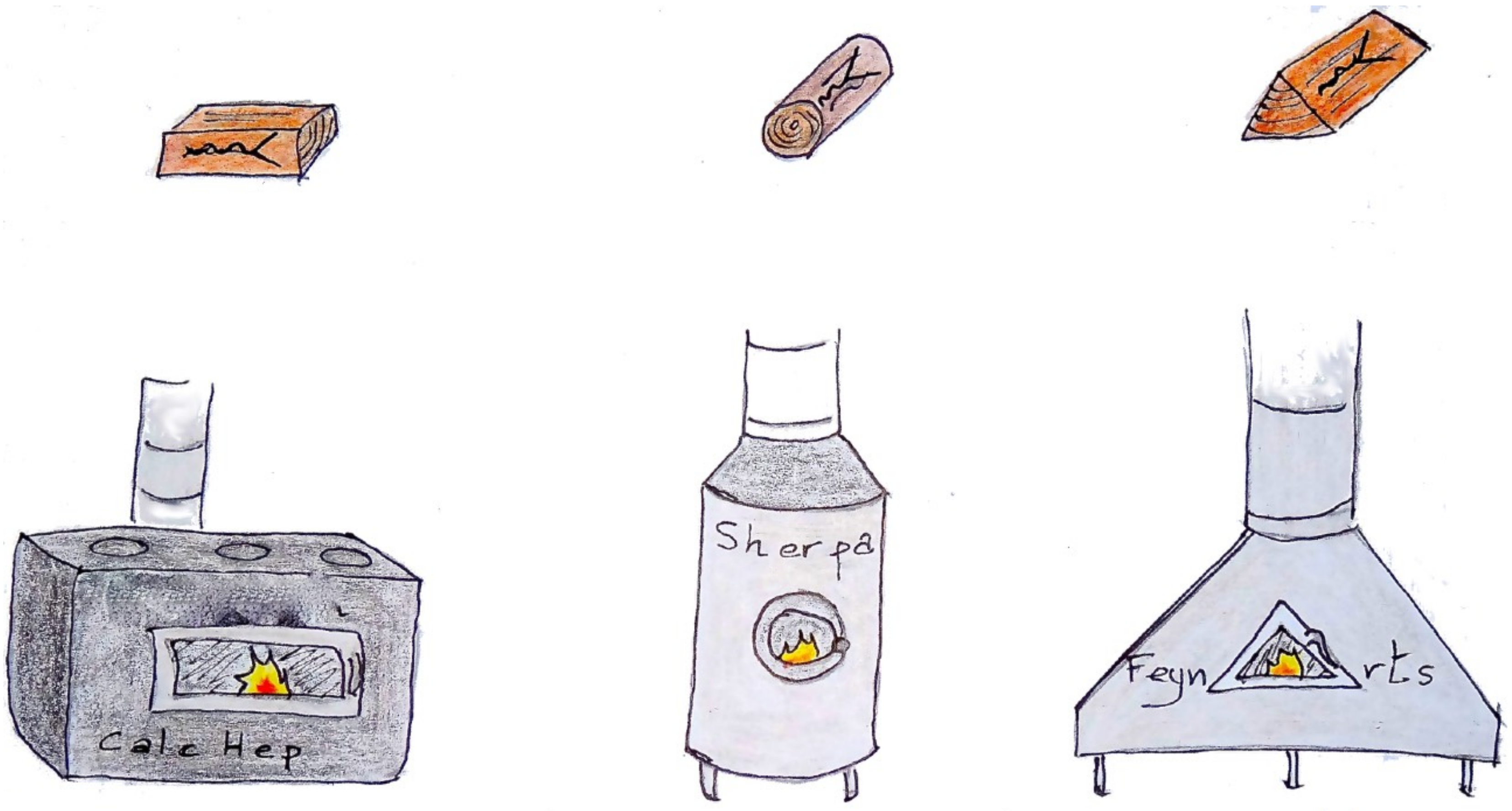
Feynman rules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

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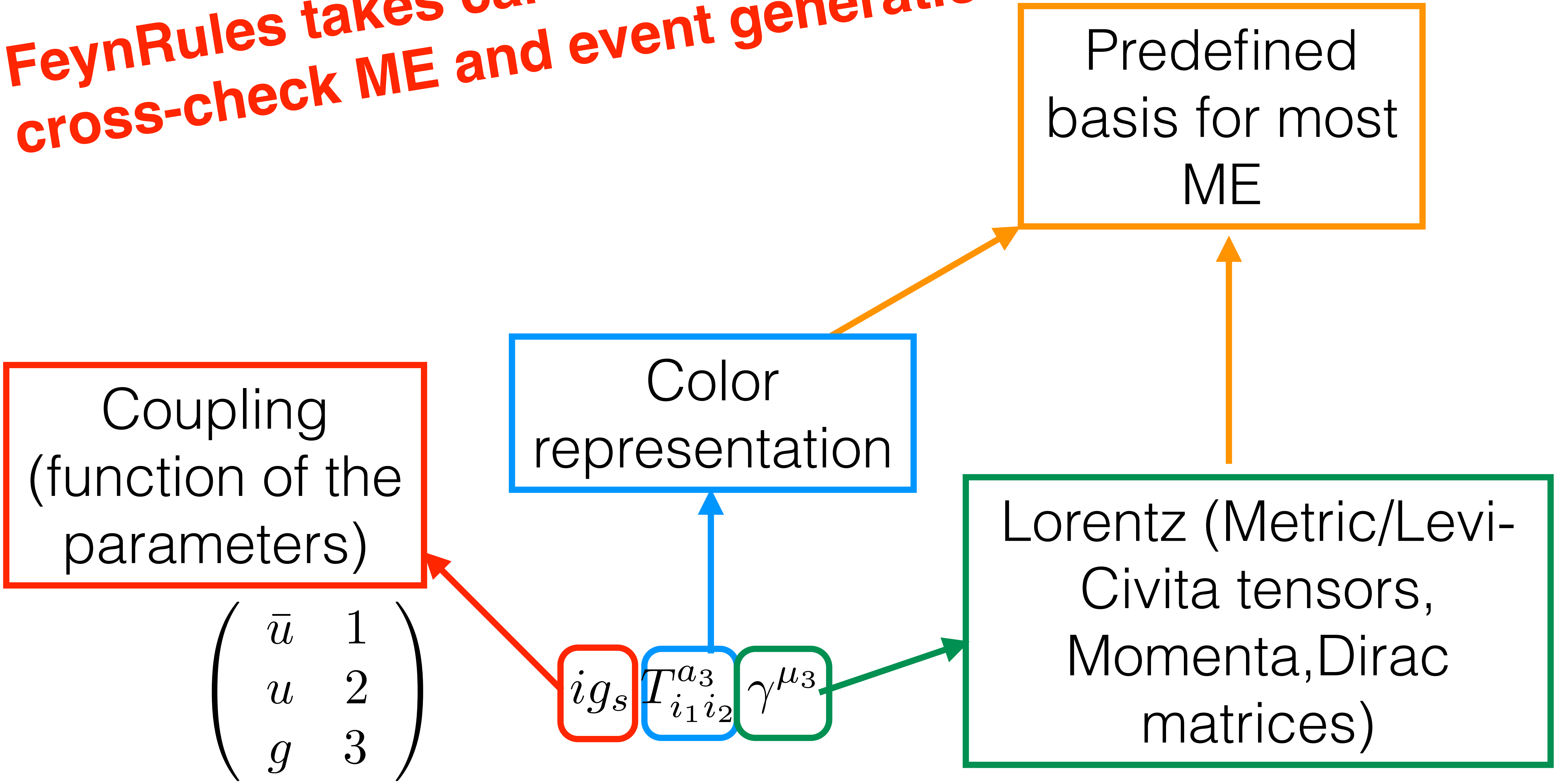
Feynman Rules

FeynRules takes care of all the conventions
cross-check ME and event generation



Predefined basis for most ME

Color representation

Coupling (function of the parameters)

Lorentz (Metric/Levi-Civita tensors, Momenta,Dirac matrices)

$$\begin{pmatrix} \bar{u} & 1 \\ u & 2 \\ g & 3 \end{pmatrix}$$

$$\boxed{ig_s}\,\boxed{T^{a_3}_{i_1 i_2}}\,\boxed{\gamma^{\mu_3}}$$

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UFO

- Generic output with the **full** model information
  - coupling_orders.py, parameters.py, particles.py, write_param_card.py, __init__.py,
  - vertices.py, couplings.py, lorentz.py

$ig_s T^a \gamma^\mu$

No basis, all the lorentz structures of the model

  - decays.py
  - CT_vertices.py, CT_couplings.py (For NLO)
- Python module used in MadGraph, Herwig, Gosam, Sherpa

model file

```
(***************** This is a template model file for FeynRules ***********)

(********** Index definition *********)

IndexRange[ Index[Generation] ] = Range[3]

IndexFormat[Generation, f]

(***** Parameter list ******)

M$Parameters = {
}
(***** Gauge group list ******)

M$GaugeGroups = {
}
(***** Particle classes list ******)

M$ClassesDescription = {
}
```

Definition of variables
in Mathematica syntaxe

Model information

```
M$ModelName = "my_new_model";

M$Information = {
          Authors      -> {"Mr. X", "Ms. Y"},
          Institutions -> {"UC Louvain"},
          Emails       -> {"X@uclouvain.be", "Y@uclouvain.be},
          Date         -> "01.03.2013",
          References   -> {"reference 1", "reference 2"},
          URLs         -> {"http://feynrules.irmp.ucl.ac.be"},
          Version      -> "1.0"
                };
```

Good practice for credit, issue(s) tracking

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Indices definition

Used in parameters, gauge groups and fields

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]  = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FR to remplace summed indices by the explicite sum

Tells FA/FC **not** to remplace summed indices by the explicite sum

Indices definition

Used in parameters, gauge groups and fields

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]  = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FR to remplace summed indices by the explicite sum

Tells FA/FC **not** to remplace summed indices by the explicite sum

Format:

```
IndexStyle[ Colour, i ];
IndexStyle[ Gluon, a ];
```

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Indices definition

Used in parameters, gauge groups and fields

Tells FR to remplace summed indices by the explicite sum

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]  = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FA/FC **not** to remplace summed indices by the explicite sum

Format:

```
IndexStyle[ Colour, i ];
IndexStyle[ Gluon, a ];
```

Predefined indices: Lorentz, Spin, Spin1, Spin2

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
              ...
};
```

```
aEWM1 == {
  ParameterType    -> External,
  BlockName        -> SMINPUTS,
  OrderBlock       -> 1,
  Value            -> 127.9,
  InteractionOrder -> {QED,-2},
  Description      -> "Inverse of the EW coupling constant at the Z
pole"
 },
```

Numerical value

Compulsory!

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
              ...
};
```

Expression

```
MW == {
  ParameterType -> Internal,
  Value       -> Sqrt[MZ^2/2+Sqrt[MZ^4/4-Pi/Sqrt[2]*aEW/
Gf*MZ^2]],
  TeX         -> Subscript[M,W],
  Description   -> "W mass"
 },
```

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
              ...
};
```

```
aEWM1 == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 1,
   Value            -> 127.9,
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z
pole"
 },
```

For the LHA cards

Dependence in the expansion parameters

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
              ...
};
```

```
aEWM1 == {
  ParameterType    -> External,
  BlockName        -> SMINPUTS,
  OrderBlock       -> 1,
  Value            -> 127.9,
  InteractionOrder -> {QED,-2},
  Description      -> "Inverse of the EW coupling constant at the Z pole"
 },
```

For the LHA cards

Dependence in the expansion parameters

Interaction order

In the SM : QCD the power of g_s

QED the power of e

```
aEWM1 == { ...
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z pole"
  },

vev == {...
   InteractionOrder -> {QED,-1},
   Description      -> "Higgs vacuum expectation value"
  },
```

Interaction order

In the SM : QCD the power of g_s

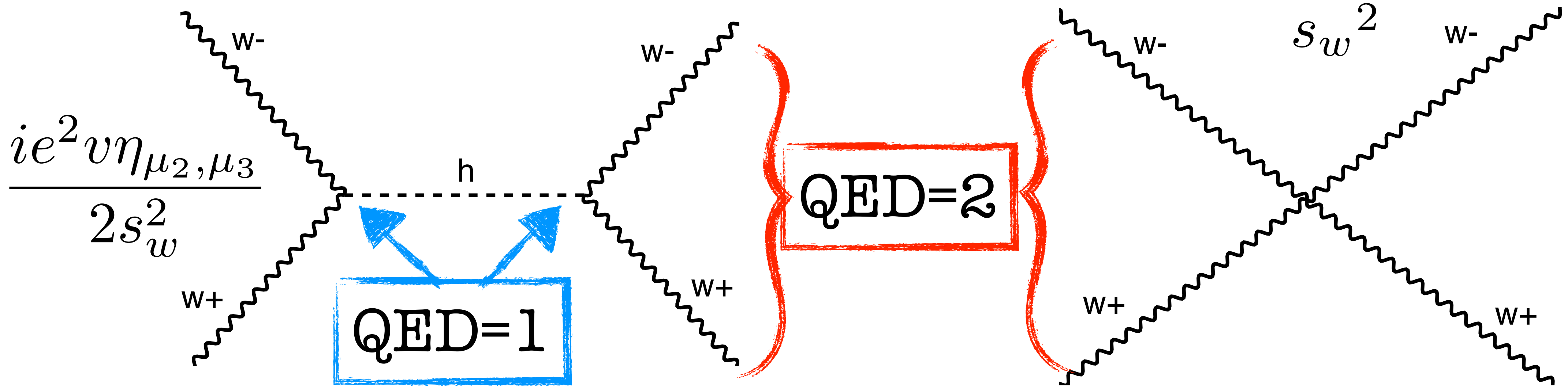
QED the power of e

```
aEWM1 == { ...
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z pole"
 },

vev == {...
   InteractionOrder -> {QED,-1},
   Description      -> "Higgs vacuum expectation value"
 },
```

$$-\frac{ie^2\left(\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}+\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}-2\eta_{\mu_1,\mu_2}\eta_{\mu_3,\mu_4}\right)}{{s_w}^2}$$

$$\frac{ie^2 v\eta_{\mu_2,\mu_3}}{2s_w^2}$$



C. Degrande

Interaction order

In the SM : QCD the power of g_s

QED the power of e

```
vev == {...
   InteractionOrder -> {QED,-1},
   Description      -> "Higgs vacuum expectation value"
  },

yu == {...
   InteractionOrder -> {QED, 1},
   Description      -> "Up-type Yukawa couplings"
  },
```

Such that masses have QED=0

However y_t is not a small parameter!

C. Degrande

Interaction order

```
M$InteractionOrderHierarchy = {  {QCD, 1},
                                 {QED, 2}};
```

$$g_s \sim e^2$$

Interaction order

```
M$InteractionOrderHierarchy = {  {QCD, 1},
                                 {QED, 2}};
```

$$g_s \sim e^2$$

$$\mathcal{L} = \mathcal{L} + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

`NP` the power of Λ^{-2}

```
,{NP, 2}
```

Interaction order

```
M$InteractionOrderHierarchy = {  {QCD, 1},
                                 {QED, 2} };
```

$$g_s \sim e^2$$

$$\mathcal{L} = \mathcal{L} + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

`NP` the power of Λ^{-2}

```
,{NP, 2}
```

```
M$InteractionOrderLimit = { {NP,1} };
```

Max power per diagram of Λ^{-2} is 1

C. Degrande

Fields definition I

```
M$ClassesDescription = {
   spin1[1] == { options1 },
   spin1[2] == { options2 },
   spin2[1] == { options3 },
   ...}
```

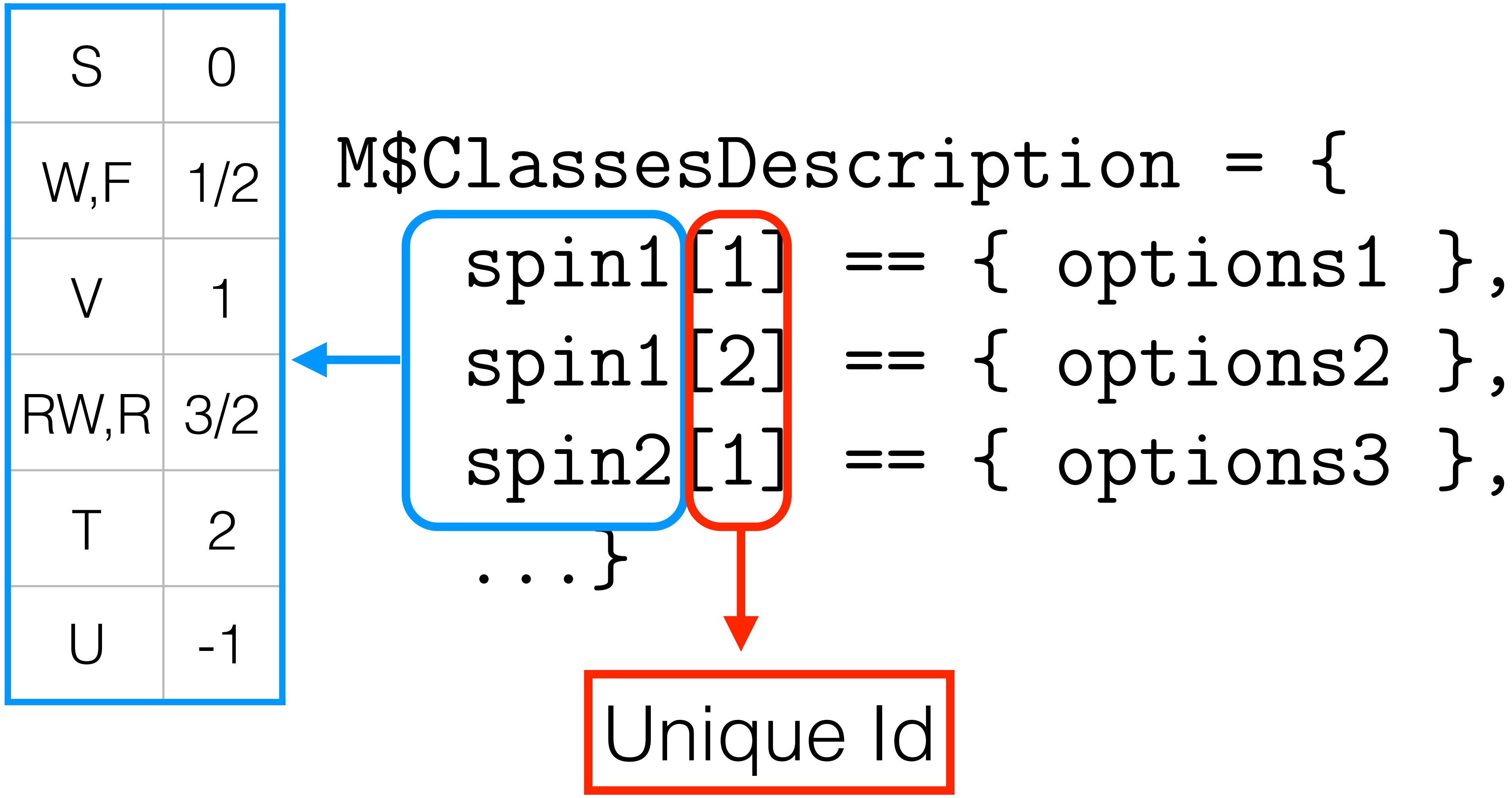
Fields definition I

S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

```
M$ClassesDescription = {
   spin1[1] == { options1 },
   spin1[2] == { options2 },
   spin2[1] == { options3 },
   ...}
```

C. Degrande

Fields definition I



S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

```
M$ClassesDescription = {
   spin1[1]  == { options1 },
   spin1[2]  == { options2 },
   spin2[1]  == { options3 },
   ...}
```

Unique Id

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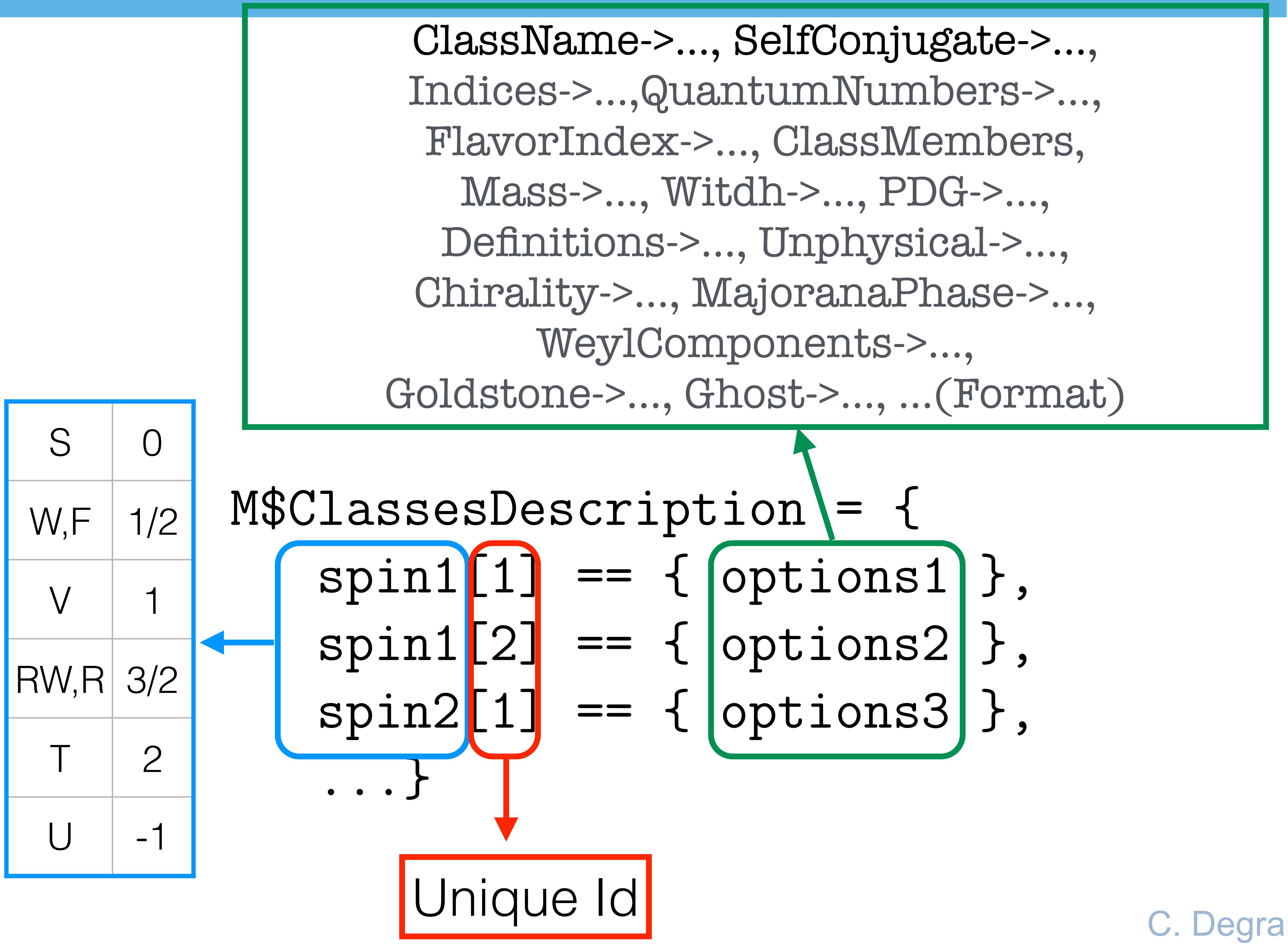
Fields definition I



ClassName->..., SelfConjugate->...,
Indices->...,QuantumNumbers->...,
FlavorIndex->..., ClassMembers,
Mass->..., Witdh->..., PDG->...,
Definitions->..., Unphysical->...,
Chirality->..., MajoranaPhase->...,
WeylComponents->...,
Goldstone->..., Ghost->..., ...(Format)

```
M$ClassesDescription = {
   spin1[1]  == { options1 },
   spin1[2]  == { options2 },
   spin2[1]  == { options3 },
   ...}
```

S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

Unique Id

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Fields definition II

```
F[3] == {   ClassName        -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

Fields definition II

Spin index

```
F[3] == {    ClassName          -> uq,
   ClassMembers      -> {u, c, t},
   Indices           -> {Index[Generation], Index[Colour]},
   FlavorIndex       -> Generation,
   SelfConjugate     -> False,
   Mass              -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width             -> {0, 0, {WT,1.50833649}},
   QuantumNumbers    -> {Q -> 2/3},
   PDG               -> {2, 4, 6},
   ...
  }
```

Fields definition II

Generation index distinguishes the class members

```
F[3] == {    ClassName        -> uq,
   ClassMembers      -> {u, c, t},
   Indices         -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass           -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width          -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG           -> {2, 4, 6},
   ...
  }
```

Fields definition II

```
F[3] == {    ClassName        -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

Same representation

Fields definition II

```
F[3] == {   ClassName        -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

External parameters

Fields definition II

```
F[3] == {    ClassName        -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

External parameters

Generic label

```
Mass -> {MW, Internal}
Mass -> {MZ, 91.188}
Mass -> {{MU,0}, {MC,0}, {MT, 174.3}}
Mass -> {Mu, {MU, 0}, {MC, 0}, {MT, 174.3}}
```

C. Degrande

Fields definition II

```
F[3] == {    ClassName        -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

Not used in FR but by following codes

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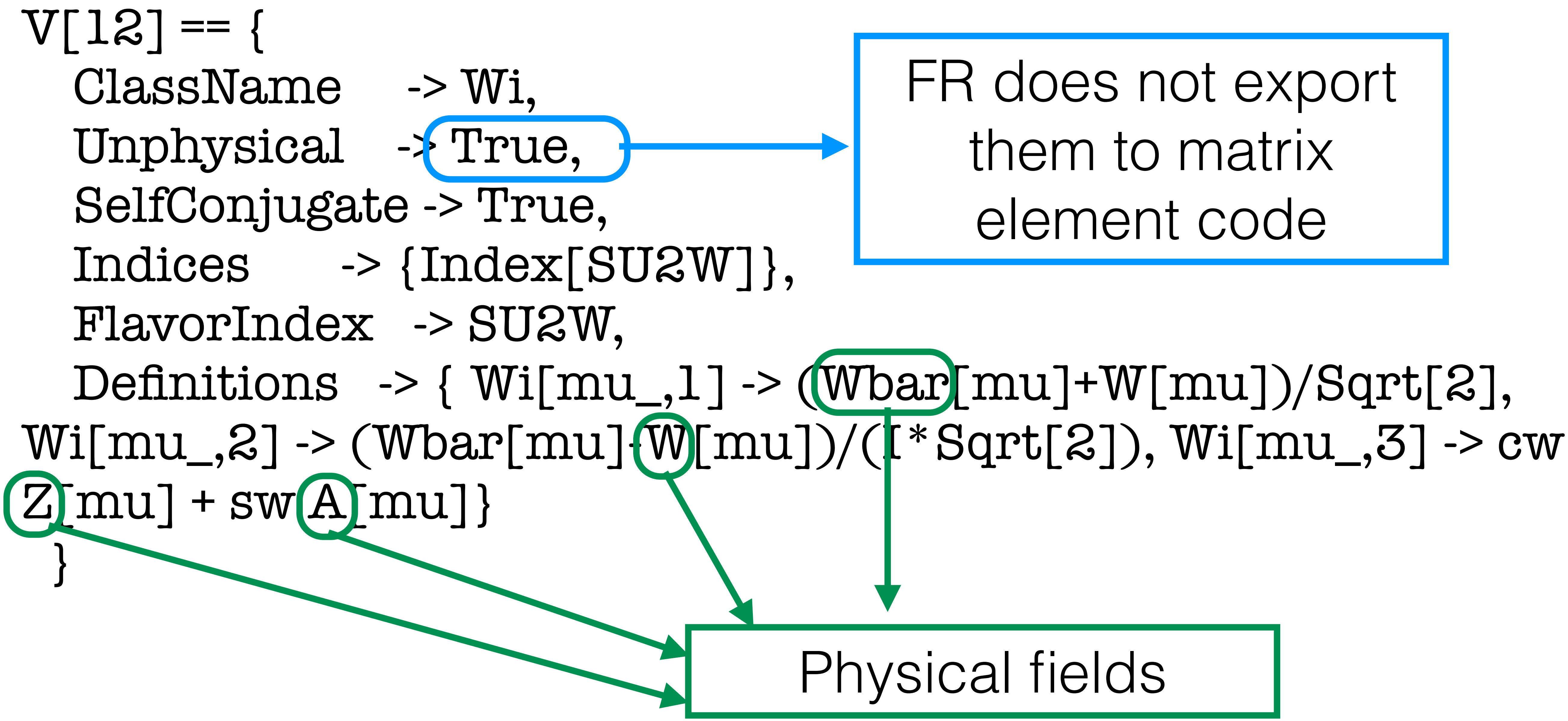
Fields definition III

Interaction eigenstates



```
V[12] == {
   ClassName     -> Wi,
   Unphysical    -> True,
   SelfConjugate -> True,
   Indices       -> {Index[SU2W]},
   FlavorIndex   -> SU2W,
   Definitions   -> { Wi[mu_,1] -> (Wbar[mu]+W[mu])/Sqrt[2],
Wi[mu_,2] -> (Wbar[mu]-W[mu])/(I*Sqrt[2]), Wi[mu_,3] -> cw
Z[mu] + sw A[mu]}
  }
```

FR does not export them to matrix element code

Physical fields

Fields definition IV

```
U[11] == {
   ClassName     -> ghB,
   Unphysical    -> True,
   SelfConjugate -> False,
   Ghost         -> B,
   Definitions   -> { ghB -> -sw ghZ + cw ghA}
  },

S[2] == {
   ClassName       -> G0,
   SelfConjugate   -> True,
   Goldstone       -> Z,
   ...
  },
```

ClassName of the boson

C. Degrande

Gauge Groups

```
M$GaugeGroups = {
 U1Y  == {
   Abelian          -> True,
   CouplingConstant -> g1,
   GaugeBoson       -> B,
   Charge           -> Y
  },...
 SU3C == {
   Abelian           -> False,
   CouplingConstant  -> gs,
   GaugeBoson        -> G,
   StructureConstant -> f,
   Representations   -> {T,Colour},
   SymmetricTensor   -> dSUN
  }
};
```

Gauge Groups

```
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 U1Y  == {
   Abelian          -> True,
   CouplingConstant -> g1,
   GaugeBoson       -> B,
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C. Degrande

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   GaugeBoson        -> G,
   StructureConstant -> f,
   Representations   -> {T,Colour}
   SymmetricTensor   -> dSUN
  }
};
```

Generator label

Associated index

Gauge groups

`FS[ A, mu, nu(, a )]` ⇨ $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a{}_{bc} A^b_\mu A^c_\nu$

abelian

DC[phi, mu] ⇨ $D_\mu \phi = \partial_\mu \phi - i g A^a_\mu T_a \phi$

Lagrangian

$$\mathcal{L}^{\mathcal{QCD}} \equiv -\frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} + i\bar{d}\not{D}d$$

```
L = -1/4 FS[G, mu, nu, a] FS[G, mu, nu, a]
          +  I dqbar.Ga[mu].DC[dq, mu]
```

FeynRules creates the “anti”-particle name

Dot to avoid commuting the fermions

```
dqbar.Ga[mu].T[a].dq
          → Ga[mu,s,r] T[a,i,j] dqbar[s,f,i].dq[r,f,j]
```

FeynRules restores the indices internally

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

Extracting the Feynman rules

```
vertsQCD = FeynmanRules[ LQCD ];
```

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

Outputting the Lagrangian

```
WriteUFO[ L ]
```

C. Degrande

Running FeynRules

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```

All the model files should be loaded at once

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```
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C. Degrande

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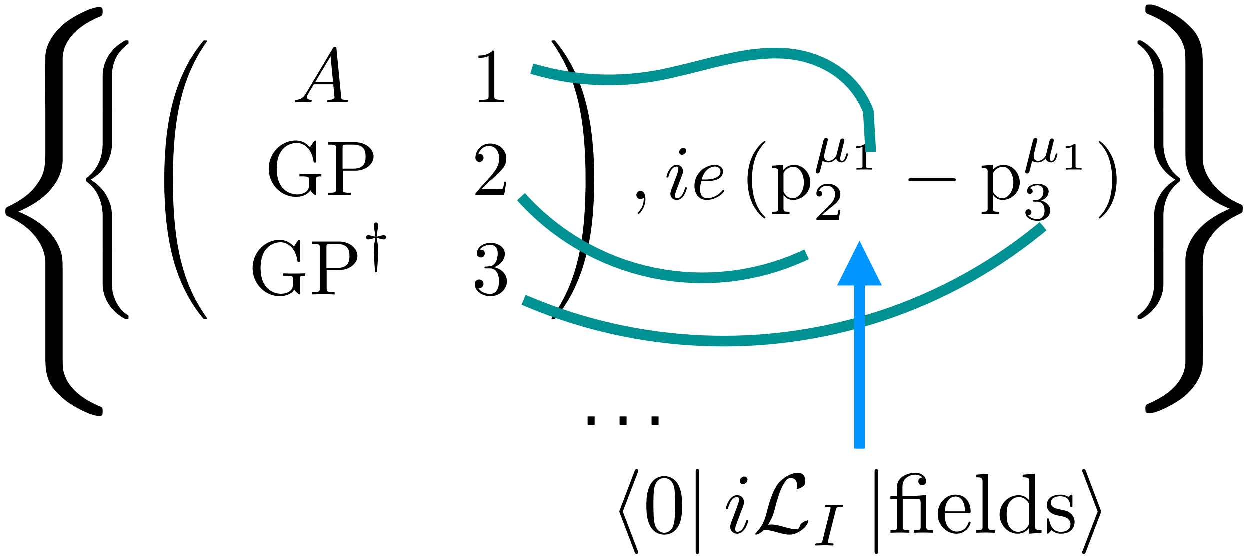

$$\left\{\left\{\begin{pmatrix} A & 1 \\ \mathrm{GP} & 2 \\ \mathrm{GP}^\dagger & 3\end{pmatrix}, ie\left(\mathrm{p}_2^{\mu_1} - \mathrm{p}_3^{\mu_1}\right)\right\} \ldots \right\}$$

$$\langle 0|\, i\mathcal{L}_I \,|\mathrm{fields}\rangle$$

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

Outputting the Lagrangian

```
WriteUFO[ L ]
```

All momenta are incoming

C. Degrande

Running FeynRules

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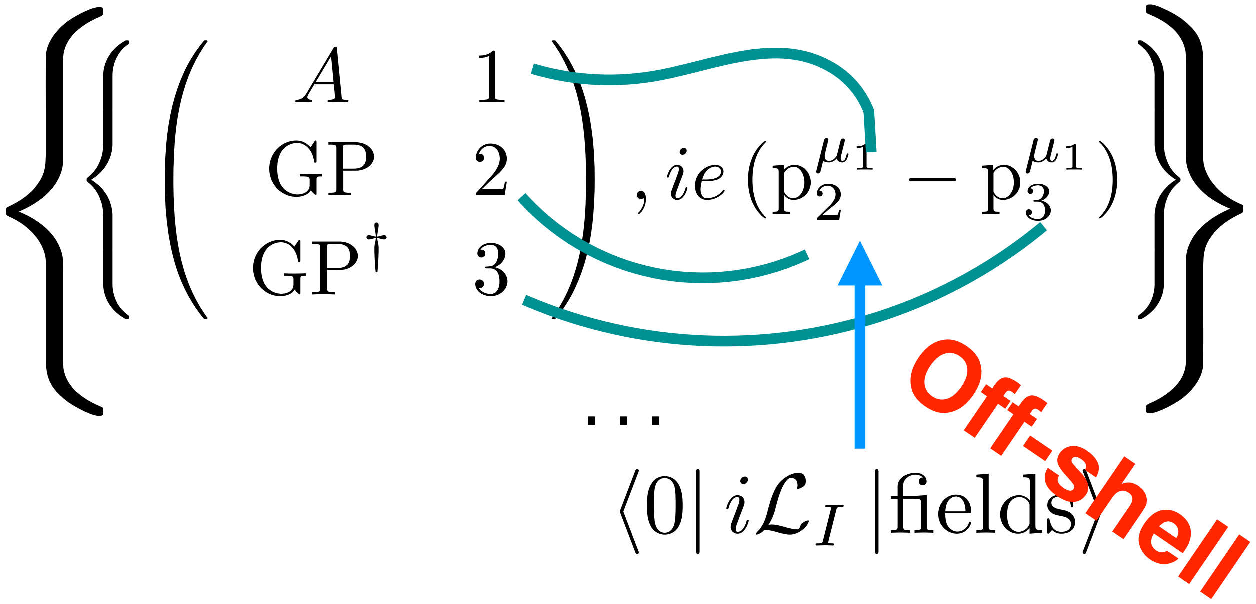


$$\left\{\left\{\begin{pmatrix} A & 1 \\ \mathrm{GP} & 2 \\ \mathrm{GP}^\dagger & 3 \end{pmatrix}, ie\left(\mathrm{p}_2^{\mu_1} - \mathrm{p}_3^{\mu_1}\right)\right\} \quad \ldots \right\}$$

$$\langle 0|\, i\mathcal{L}_I\, |\text{fields}\rangle$$

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

Outputting the Lagrangian

```
WriteUFO[ L ]
```

All momenta are incoming

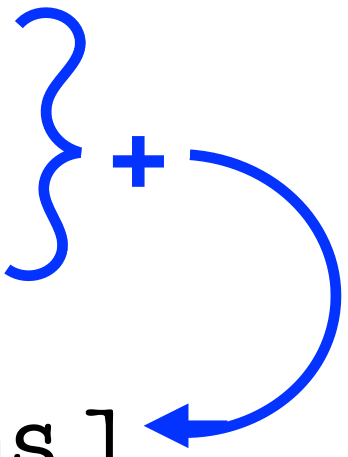
C. Degrande

Checks

CheckHermiticity[L, options]

CheckDiagonalKineticTerms[L, options]

CheckDiagonalMassTerms[L, options]



CheckDiagonalQuadraticTerms[L, options]

CheckKineticTermNormalisation[L, options]

$$\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 \qquad \frac{1}{2}\bar{\lambda}i\partial\!\!\!/\lambda - \frac{1}{2}m\bar{\lambda}\lambda \qquad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2A_\mu A^\mu$$

$$\partial_\mu\phi^\dagger\partial^\mu\phi - m^2\phi^\dagger\phi \qquad \bar{\psi}i\partial\!\!\!/\psi - m\bar{\psi}\psi \qquad -\frac{1}{2}F^\dagger_{\mu\nu}F^{\mu\nu} - m^2A^\dagger_\mu A^\mu$$

CheckMassSpectrum[L, options]

C. Degrande

Toolbox

ExpandIndices[L, options]

GetKineticTerms[L, options]

GetMassTerms[L, options]

GetQuadraticTerms[L, options]

GetInteractionTerms[L, options]

SelectFieldContent[L, list]