The art of collider physics

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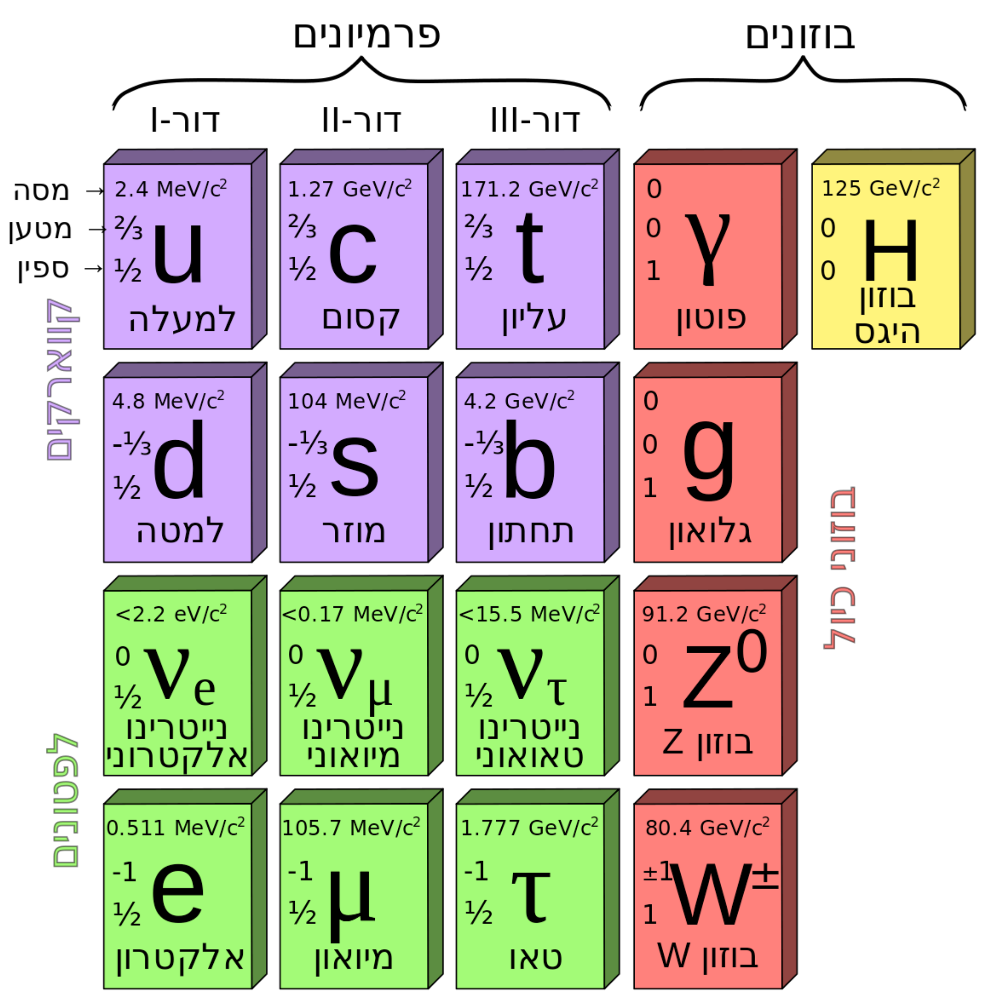
Introduction

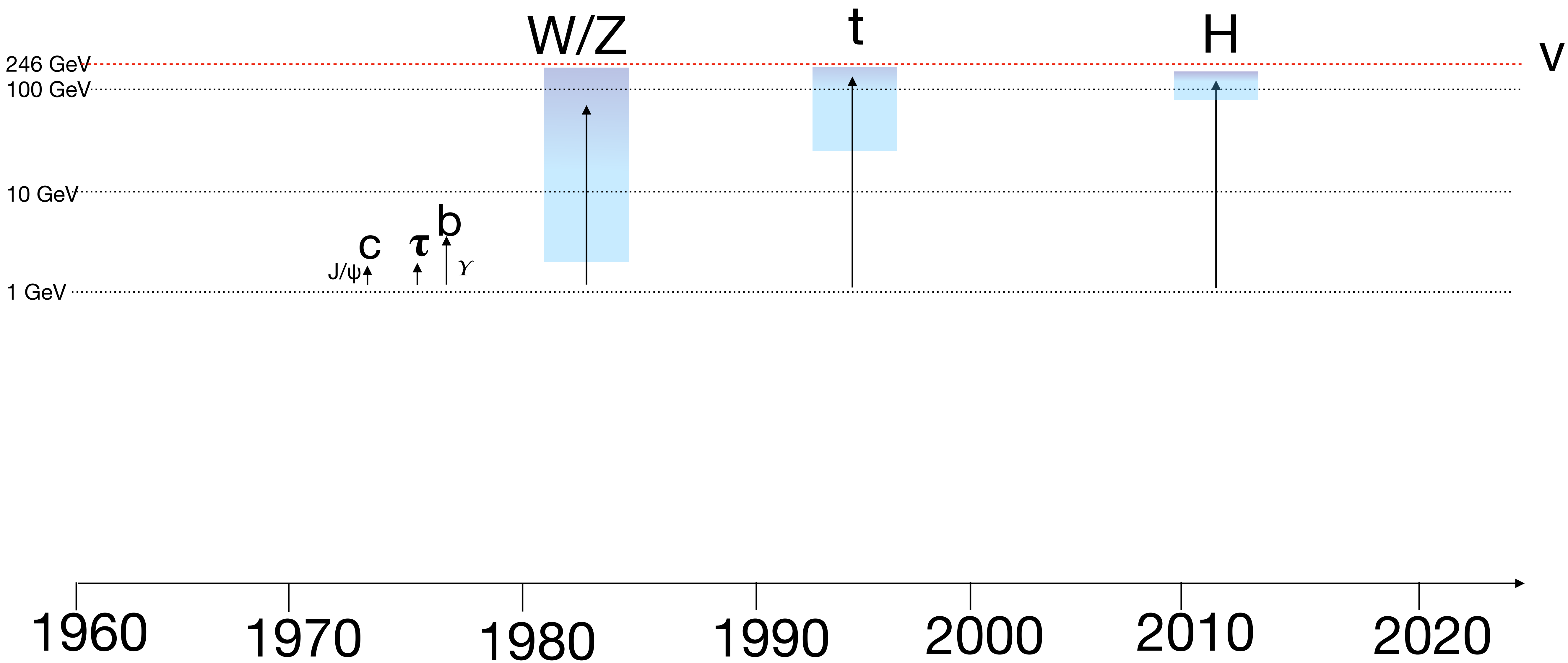
$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}^i_L \phi \psi^j_R + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$



- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fund. representation.
- The $SU(2) \times U(1)$ symmetry is spontaneously broken to $U(1)_{EM}$.
- Yukawa interactions lead to fermion masses, mixing and CP violation.
- Matter+gauge group => Anomaly free
- Renormalisable = valid to “arbitrary” high scales.
- A number of accidental symmetries seen in Nature.
- Neutrino masses can be accommodated in two distinct ways.

Experimental point of view

The story of collider physics in the last 60 years is marked by the accelerators eras and punctuated by key discoveries



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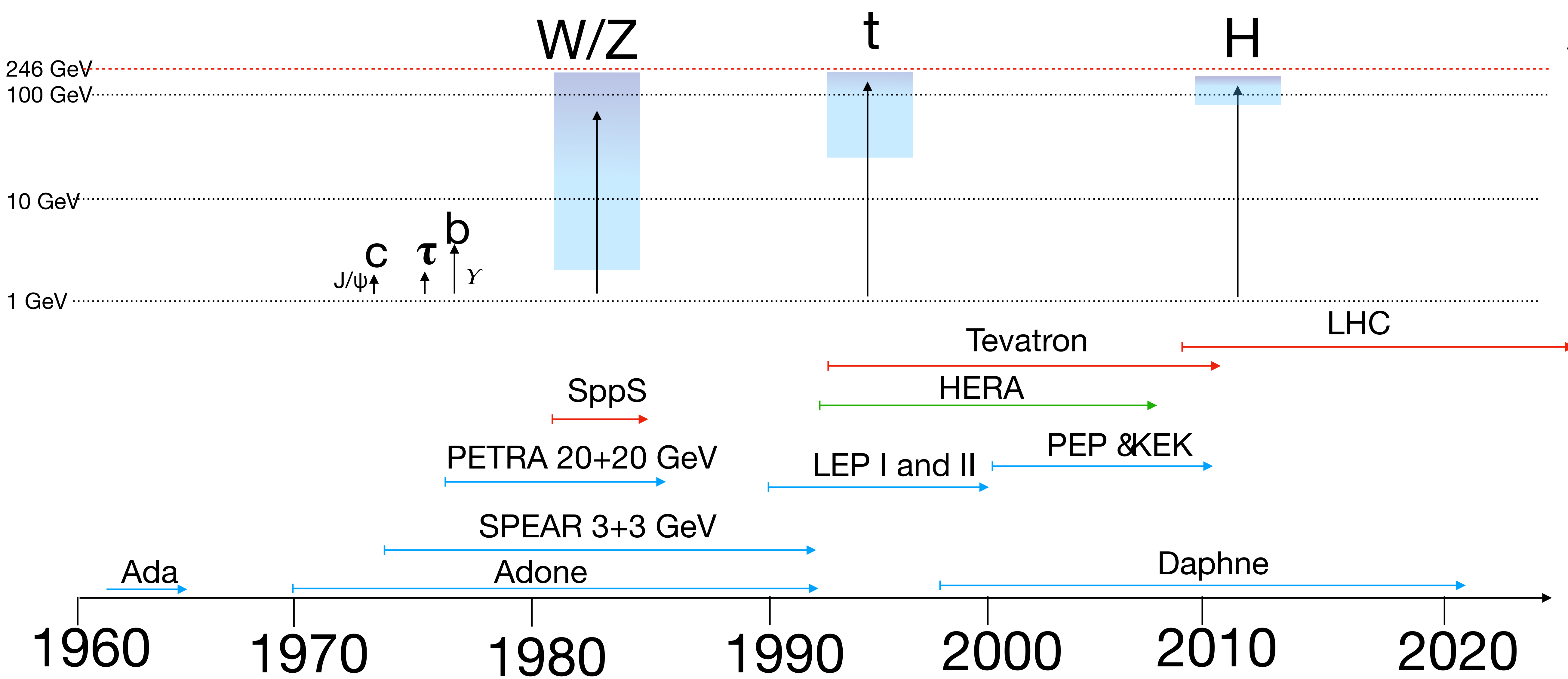
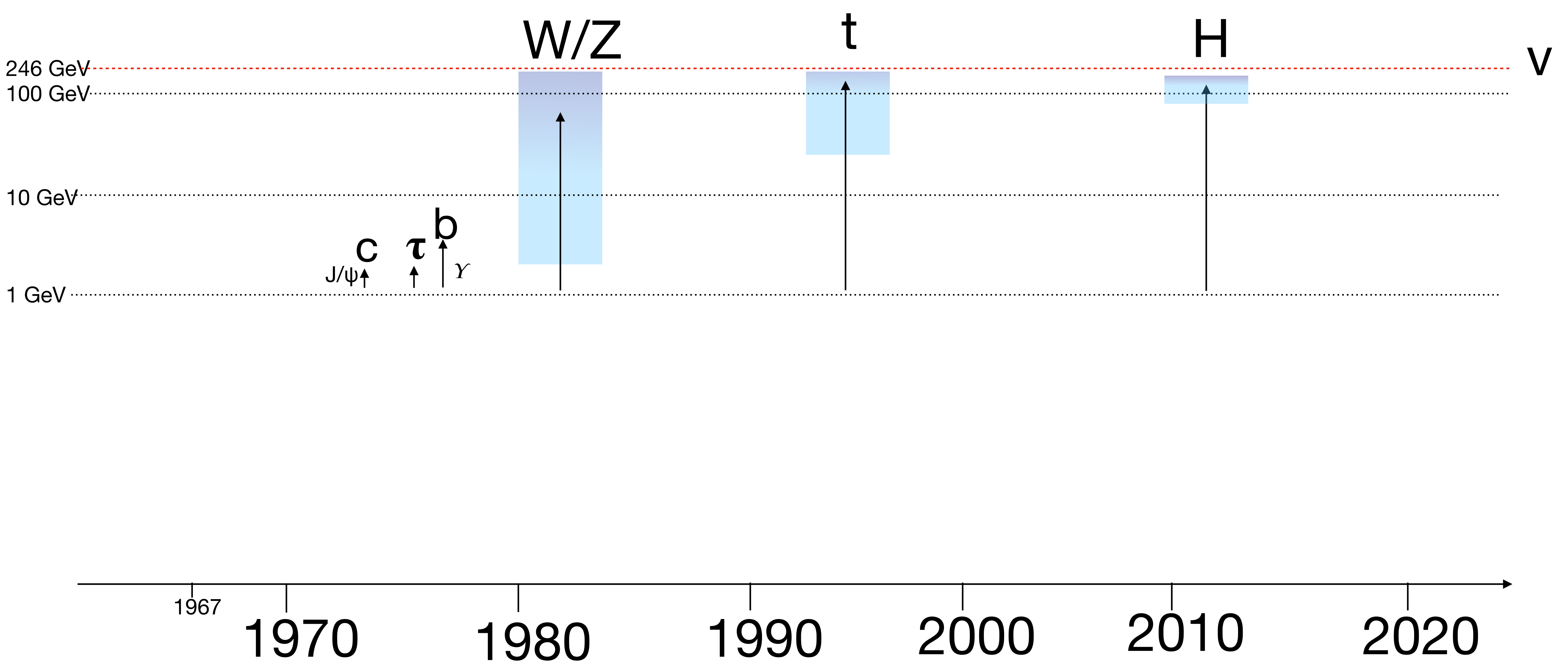


(A) theorist's point of view

The story of collider physics in the last 60 years is the slow yet steady turning of the Standard Model into a Standard Theory for Strong and EW interactions.



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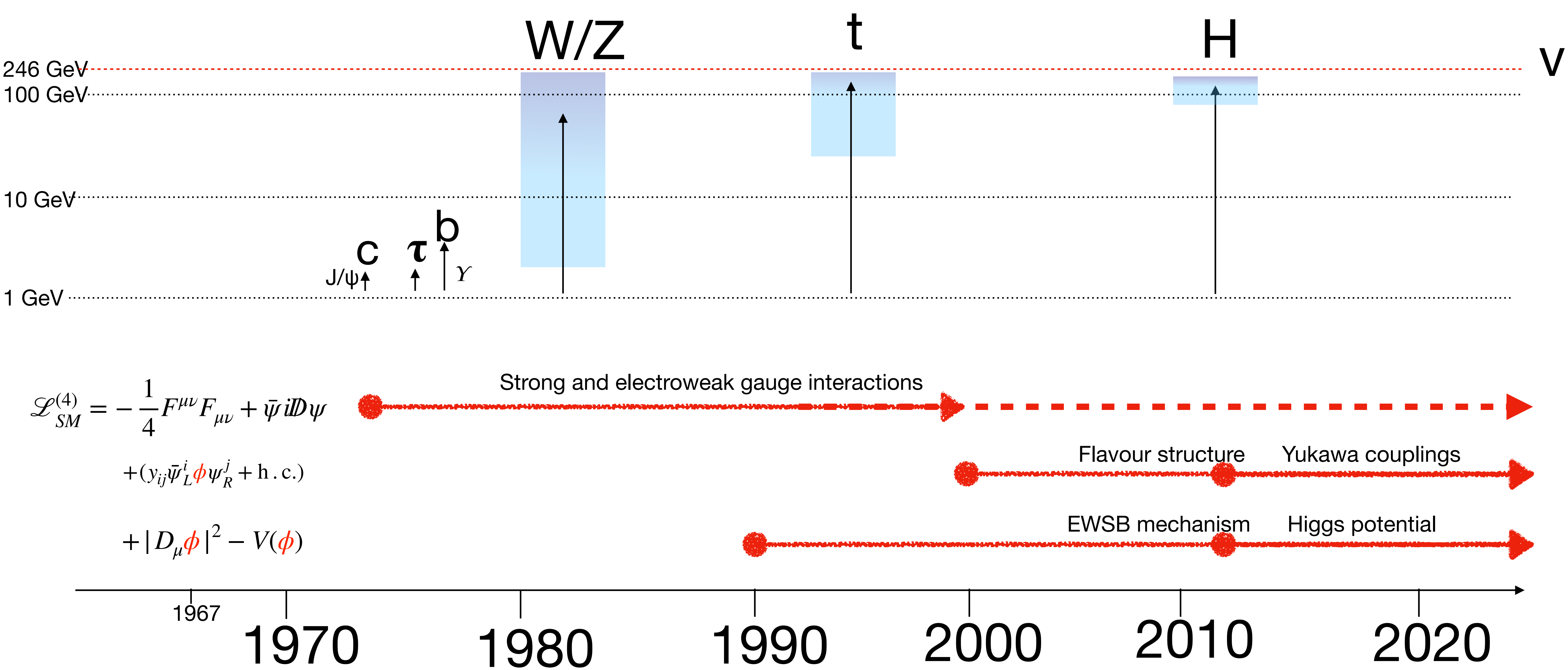
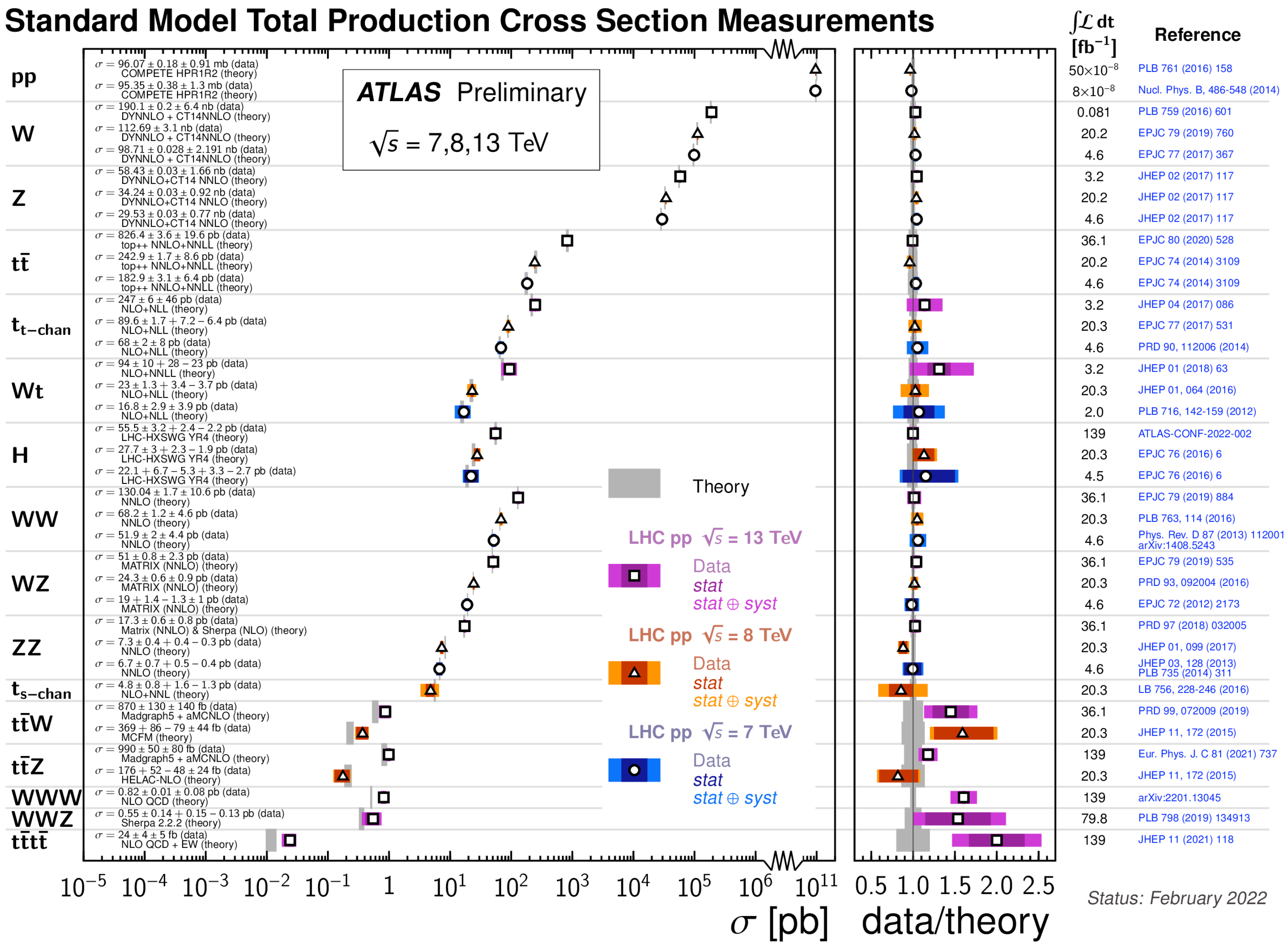


Present



- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.

- So many processes test very different sectors of the SM.

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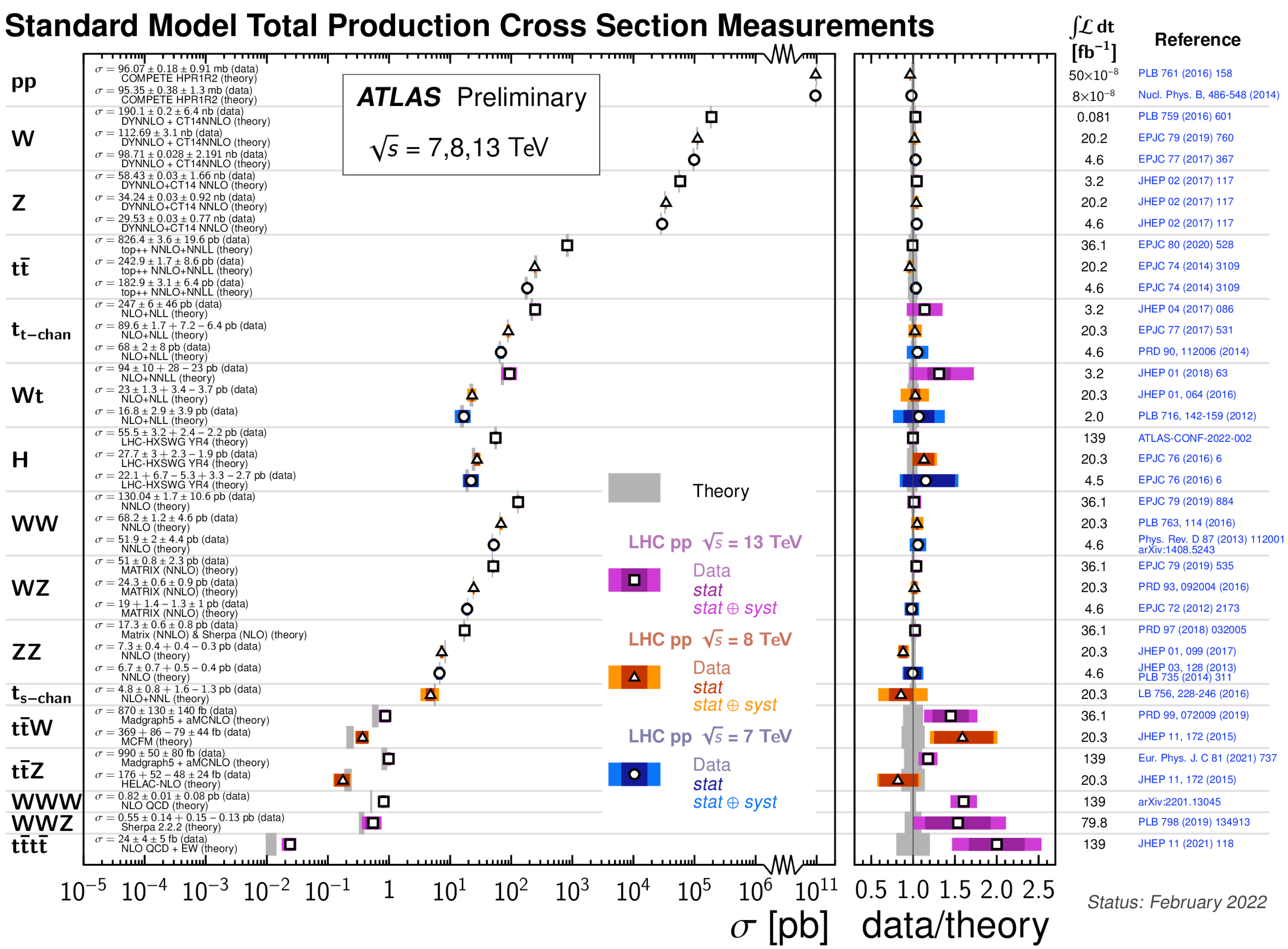

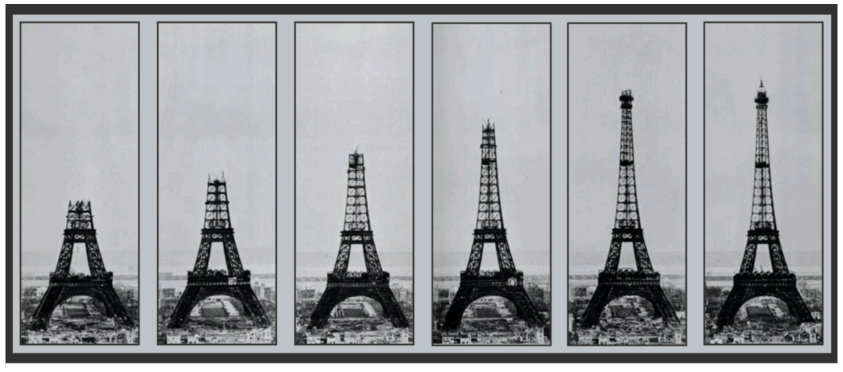

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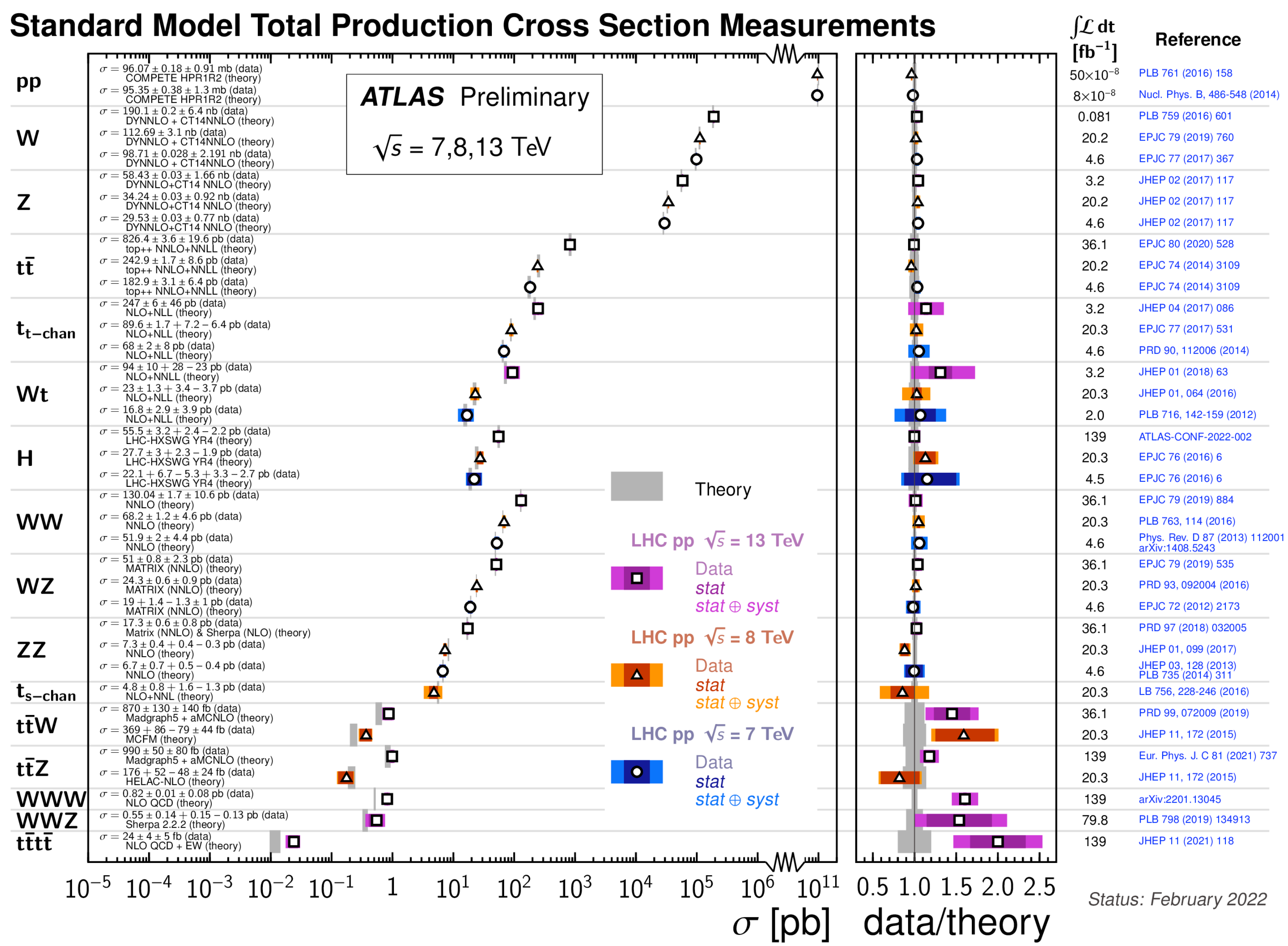

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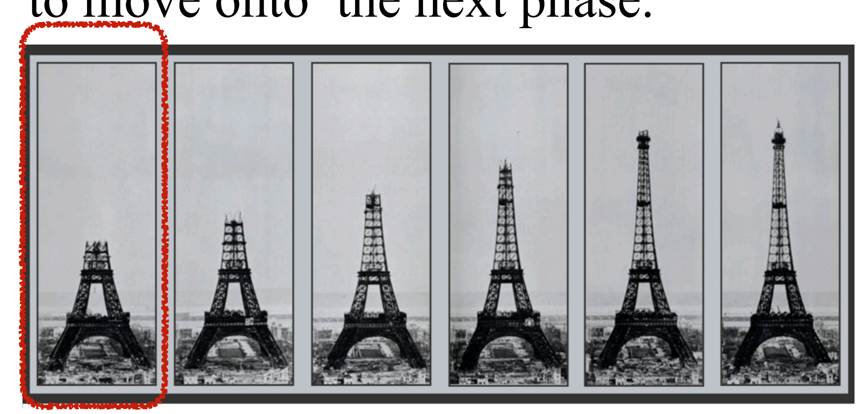
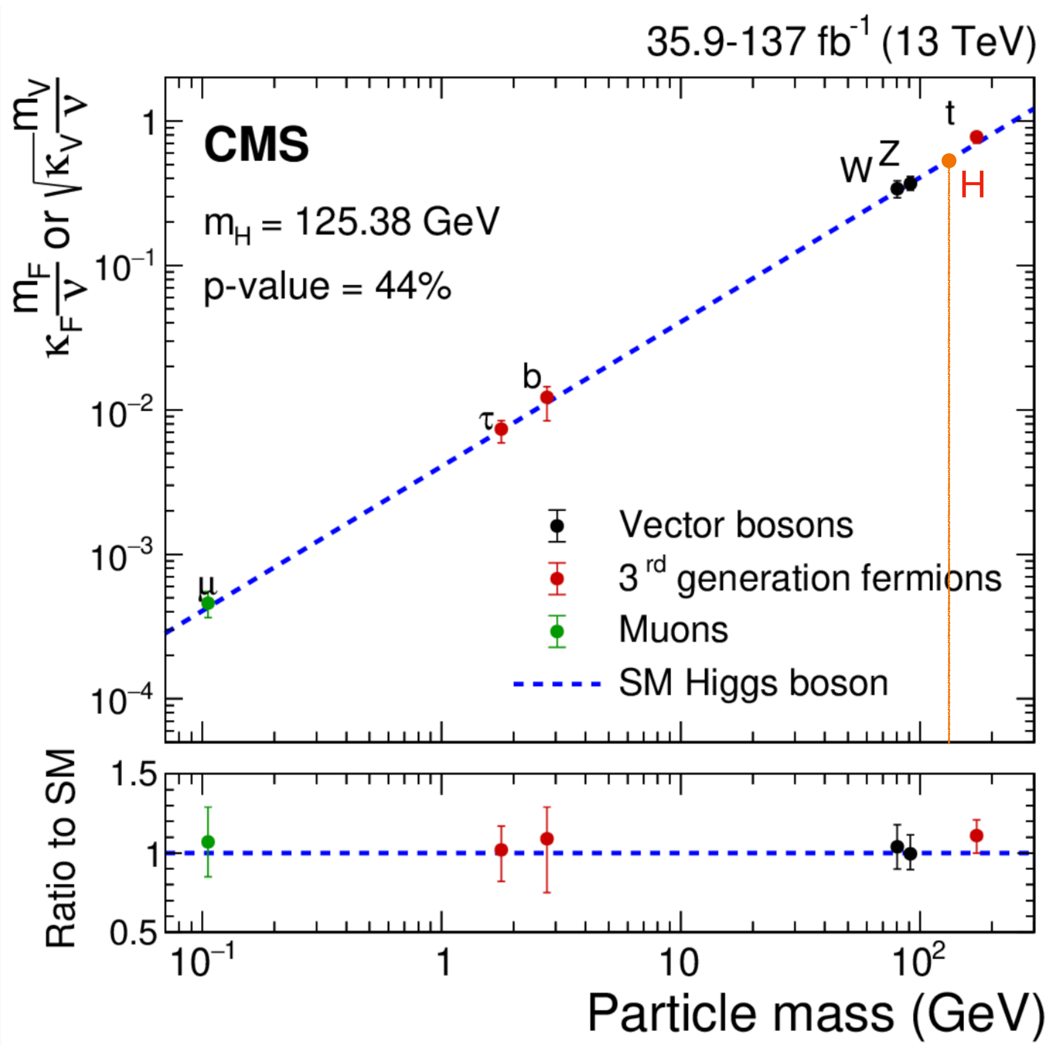
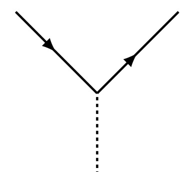


Present

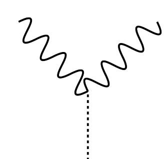
Higgs couplings



Unique mass generation mechanism for fermions/vectors and the scalar.

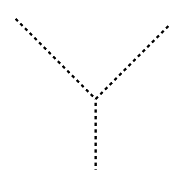


$i\, m_f/v$



$igm_W g_{\mu\nu} = 2i\, v g_{\mu\nu} \cdot m_W^2/v^2$

$ig\frac{m_Z}{\cos\theta_W} g_{\mu\nu} = 2ivg_{\mu\nu} \cdot m_Z^2/v^2$



$-3\, iv \cdot m_h^2/v^2$

+ 4 point interactions.

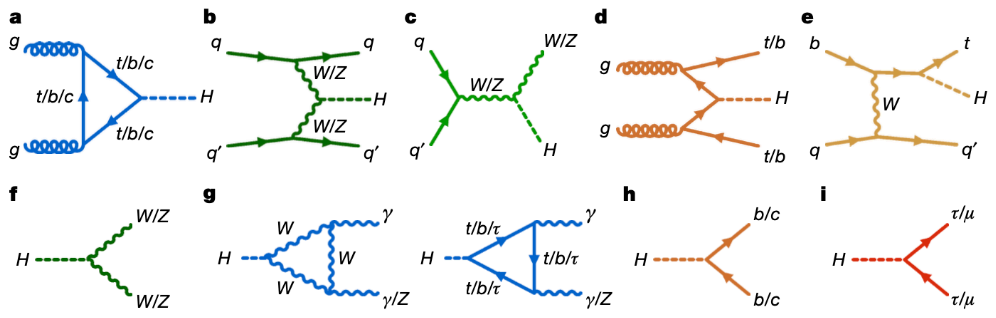
$$V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4}H^4 + \ldots$$

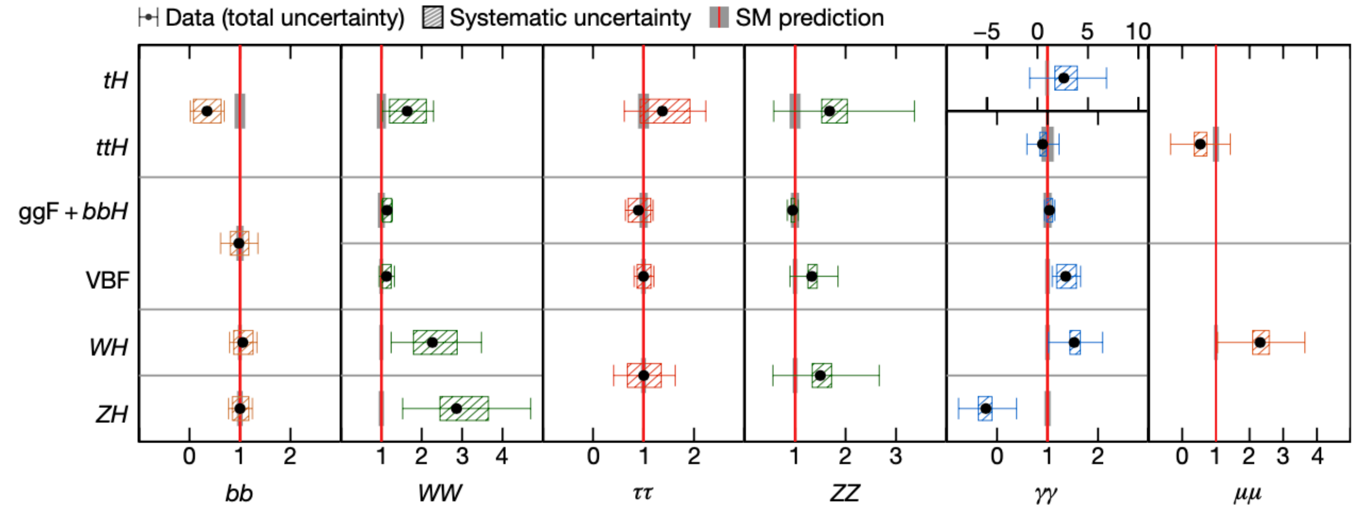
$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \quad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$

In the SM gauge invariance + SSB => constrained system. Two-point functions (propagators/masses) fix the 3-point and 4-point interactions!

Present

Higgs couplings





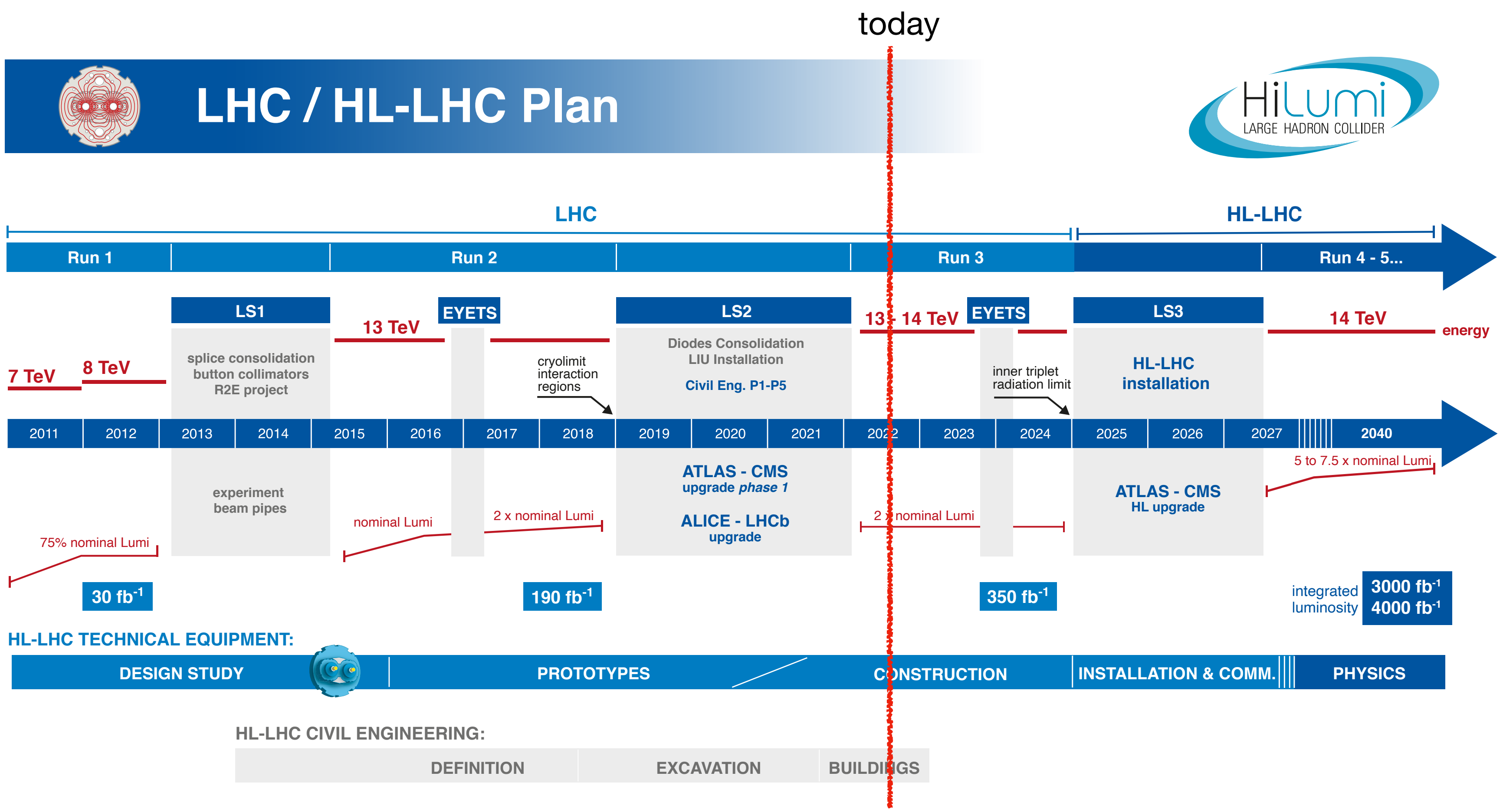
$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

Since its discovery, impressive advances in our understanding of the Higgs boson's properties have been achieved. At this moment, the new scalar seems consistent with the expectations of the SM, with different degrees of precision yet order 10%, in all measured channels.

Need to explore 2nd and 1st fermion generation and Higgs potential.

The future

The LHC reference frame and unit of time



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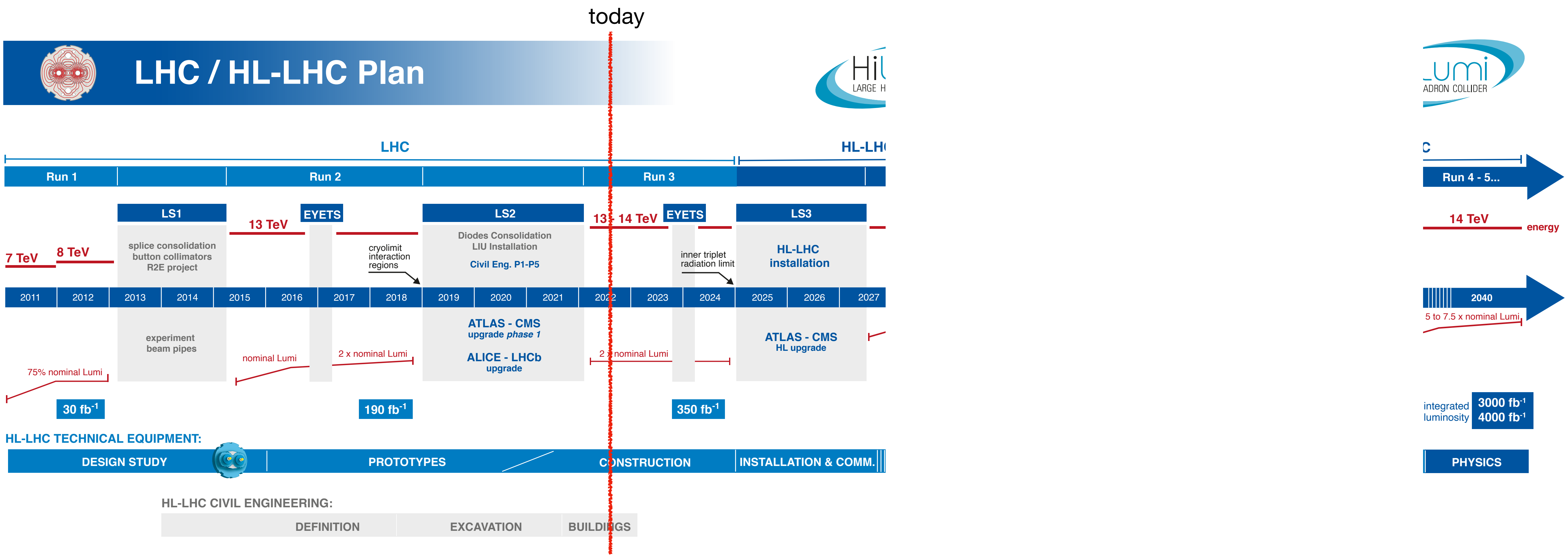

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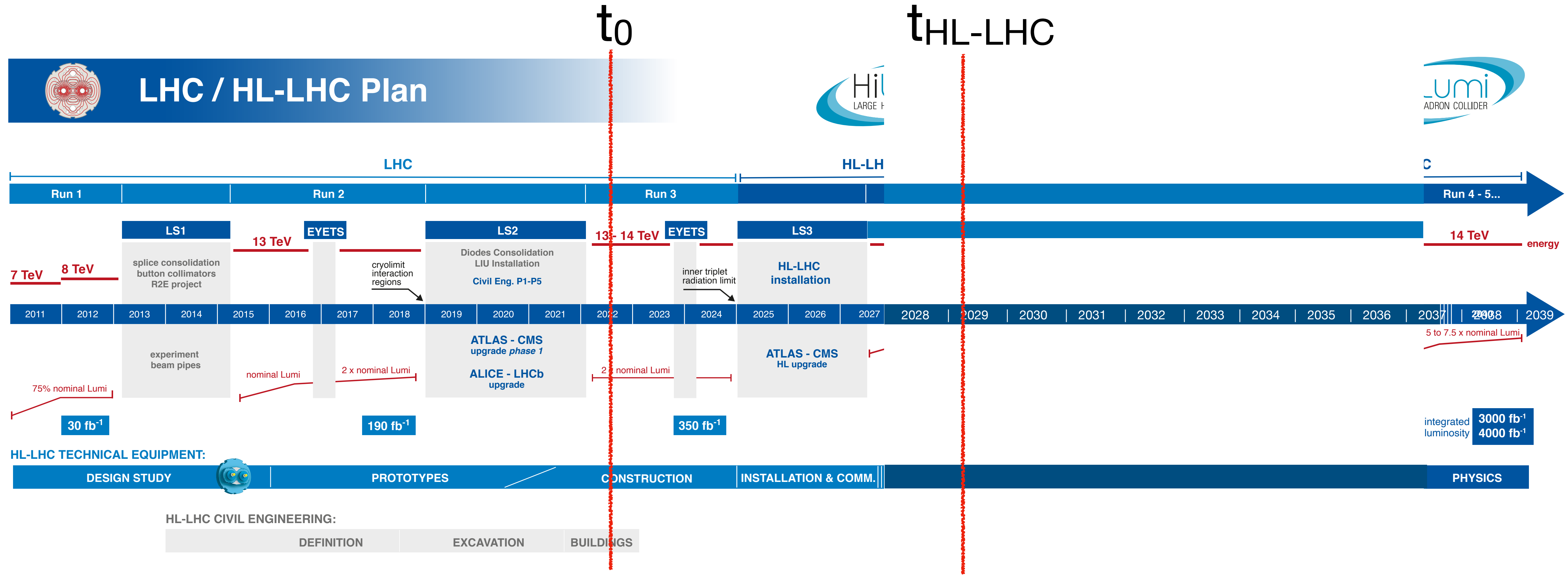


We are at 1/3 of our adventure with 1/20 of the expected data

Where do we stand?

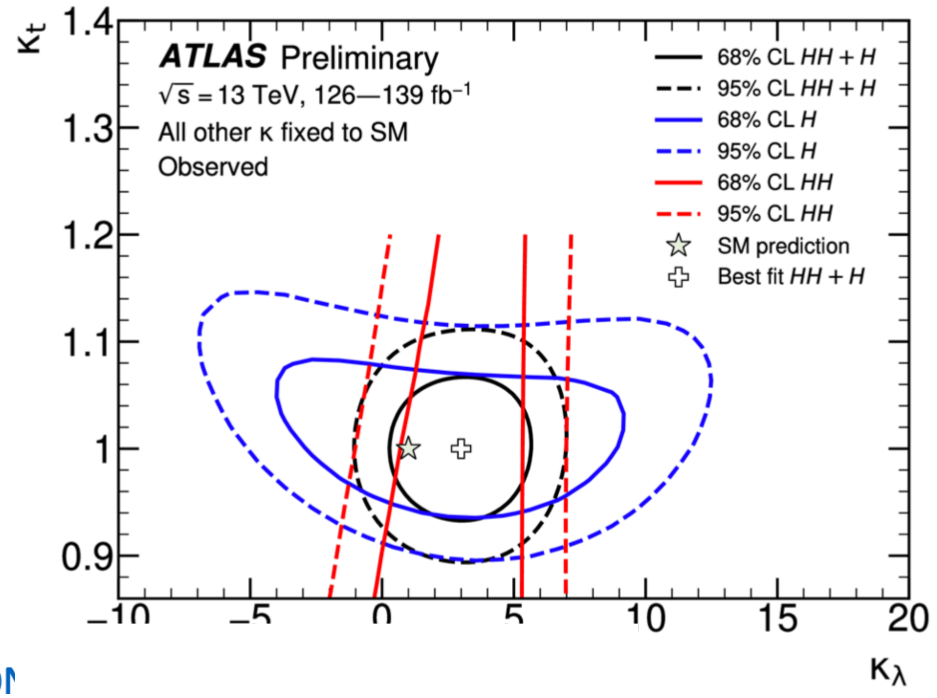
The LHC reference frame and unit of time

HL-LHC projections

Higgs self-coupling

Now

[ATLAS, 2022]



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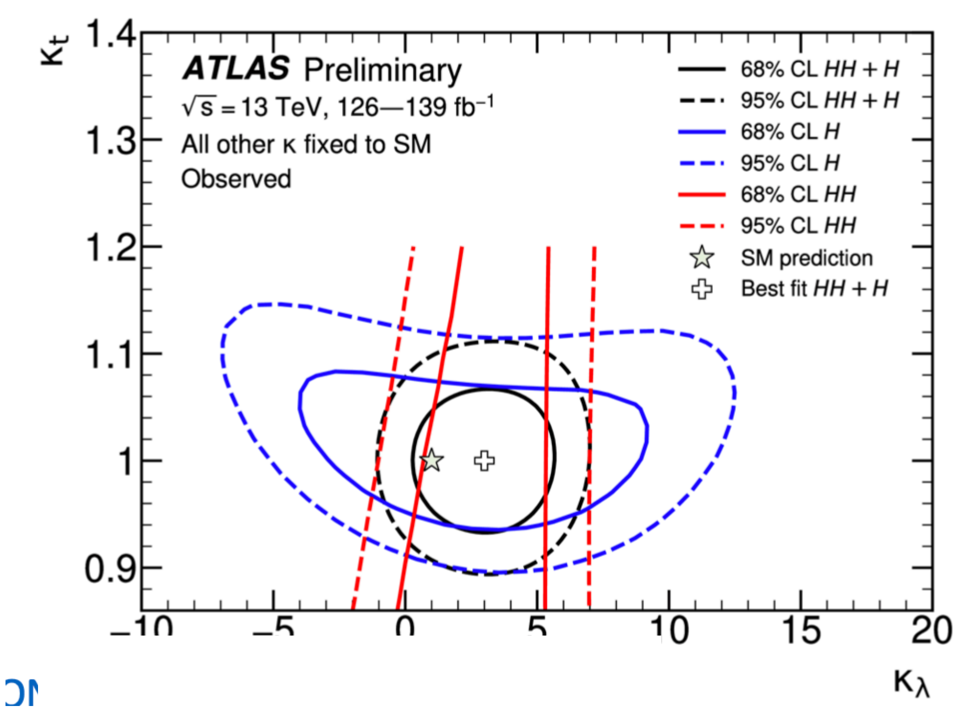
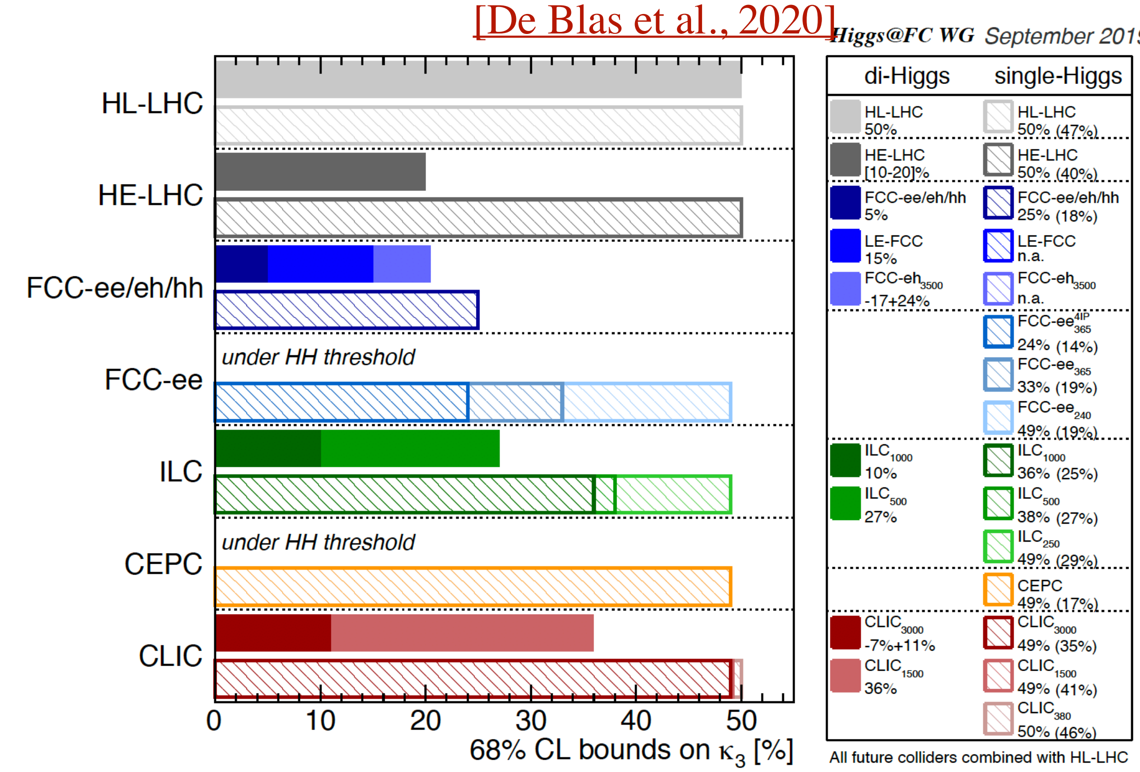


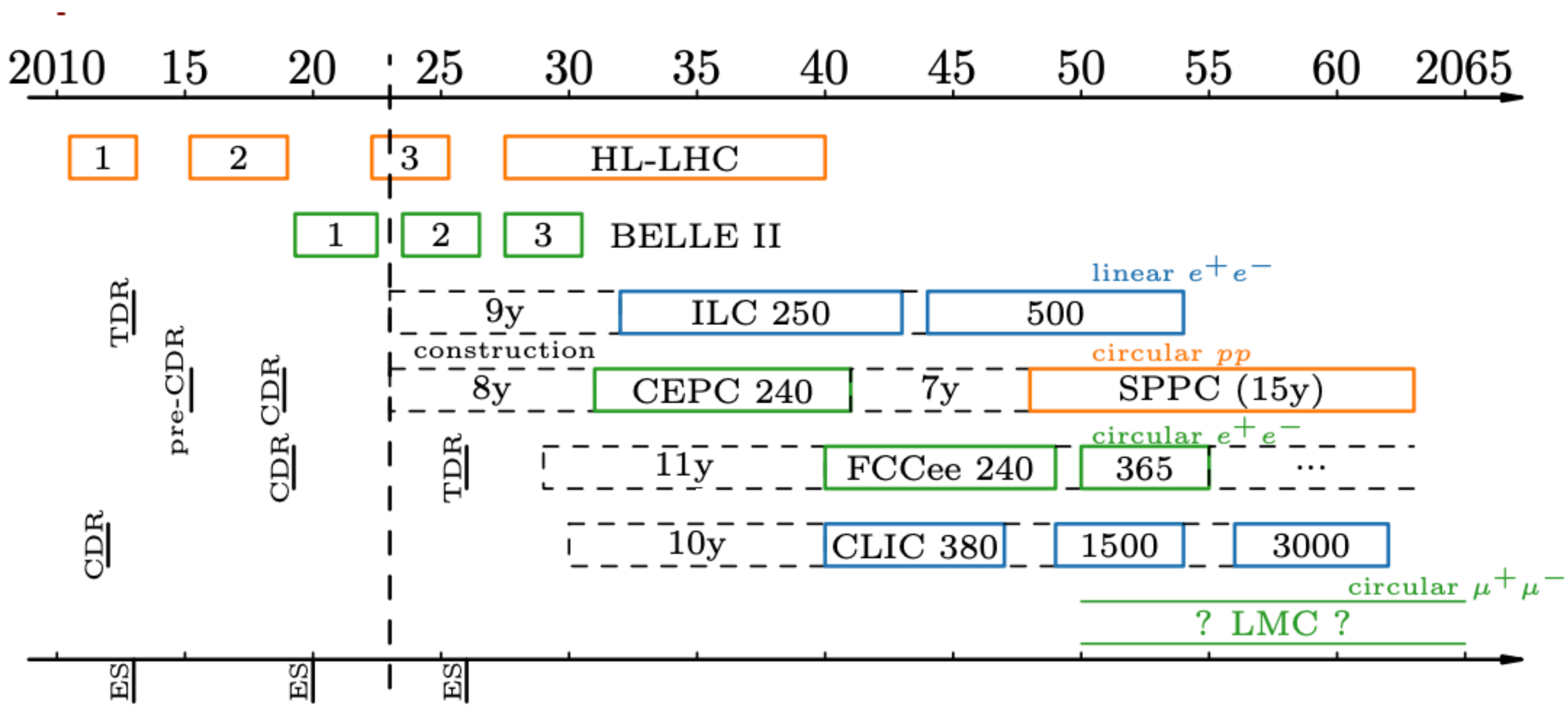
Future
[De Blas et al., 2020]



Currently limits on k_λ from H and HH are comparable and will stay so at the HL-LHC.

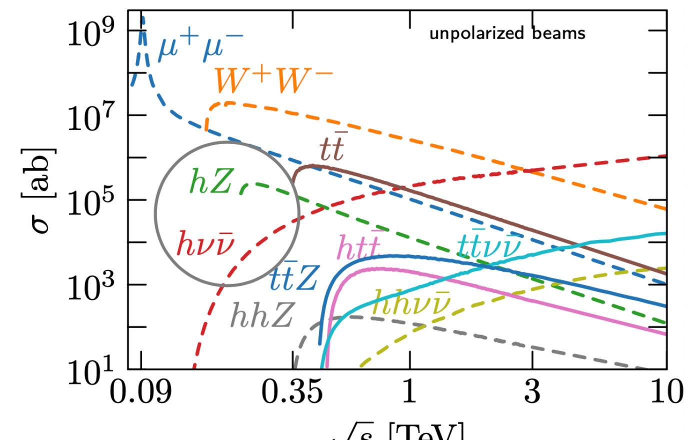
Borderline sensitivity to say something about EW baryogenesis…

Our leptonic future(s)



Extensive studies with ESU & Snowmass and now in ECFA w/ 10^6 Higgs bosons

Our leptonic future(s)



kappa-0	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 15000	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

Collider Physics

The purpose of colliders is to explore physics at small scales
in a controllable environment

$$\Delta t \cdot \Delta E \sim \hbar$$

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$\hbar c$ → QFT

Collider Physics

The purpose of colliders is to explore physics at small scales
in a controllable environment

Theory

- QFT
- Lagrangian
- Models:
  - SM
  - SUSY
  - ...
- Cross Sections

Collider (Accelerator)

Experiment

- Measurement of properties physical objects
  - momentum
  - energy
  - angles
  - ...
- Assess systematic uncertainties

Interpretation

- Signal/Background
- Statistics

The reach of collider facilities

$A + B \to M$ production in 2-particle collisions: $M^2 = (p_1 + p_2)^2$

<u>fixed target:</u>

$p_1 \simeq (E, 0, 0, E)$

$p_2 = (m, 0, 0, 0)$

before / after

$M \simeq \sqrt{2mE}$ root increase in M

- root E law: large energy loss in $E_{\rm kin}$
- dense target: large collision rate / luminosity

<u>collider target:</u>

$p_1 = (E, 0, 0, E)$

$p_2 = (E, 0, 0, -E)$

before / after

$M \simeq 2E$

- linear E law: no energy loss
- less dense bunches: small collision rates

Collider characteristics

Energy: ranges from a few GeV to several TeV (LHC)

Luminosity: measures the rate of particles in colliding bunches

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

$N_i =$ number of particles in bunches

$A =$ transverse bunch area

$f =$ bunch collision rate

$\mathcal{L}\sigma =$ observed rate for process with cross section σ

LHC (targeted): $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ➜ $300\ \mathrm{fb}^{-1}$ in 3 years

Circular vs linear collider:

charged particles in circular motion: permanently accelerated towards center -> emitting photons as synchrotron light $\Delta E \sim E^4/R$

- large loss of energy [hypothetical TeV collider at LEP: $\Delta E \simeq E$ per turn]
- no-more sharp initial state energy

LHC master formula

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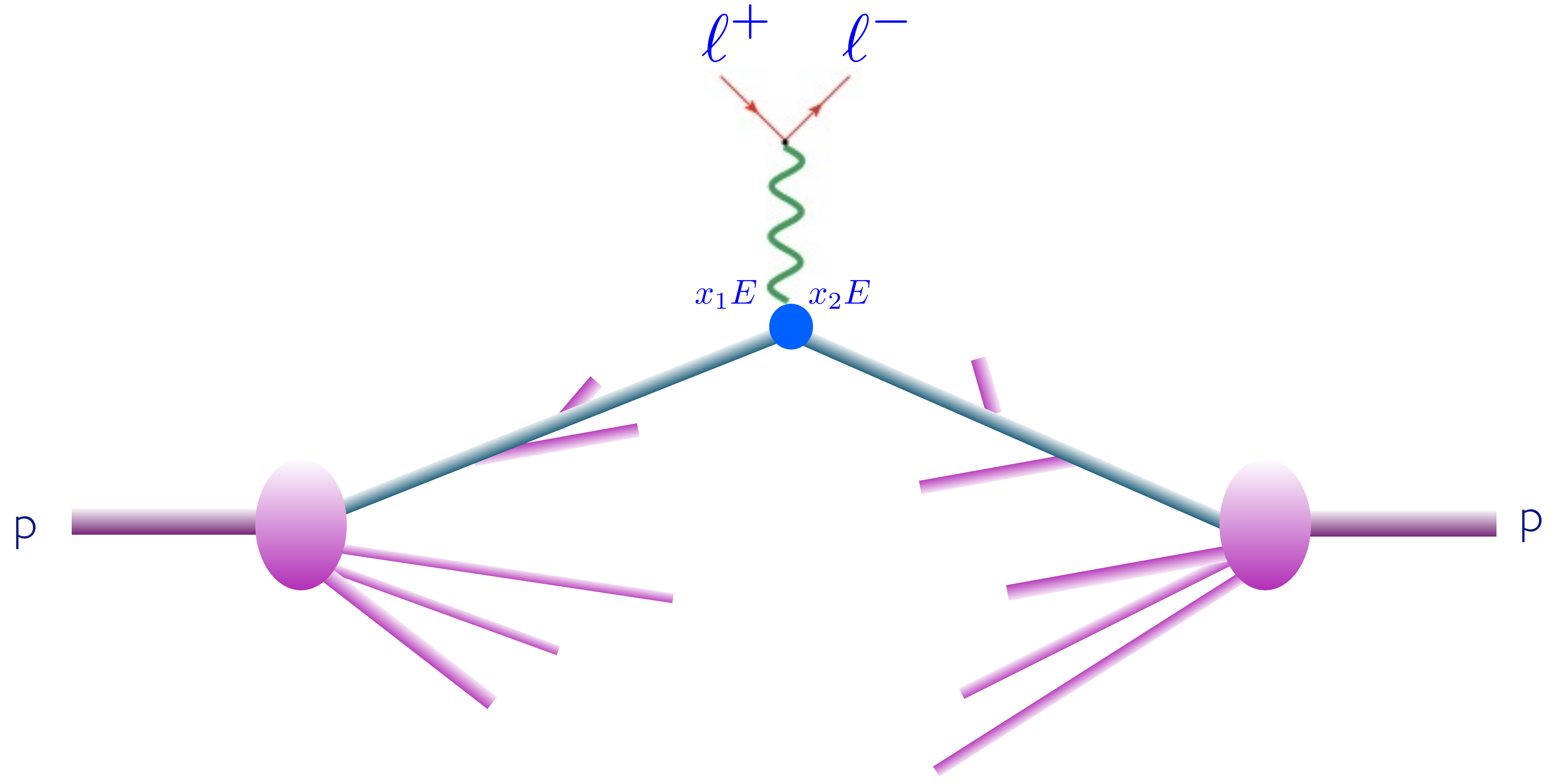
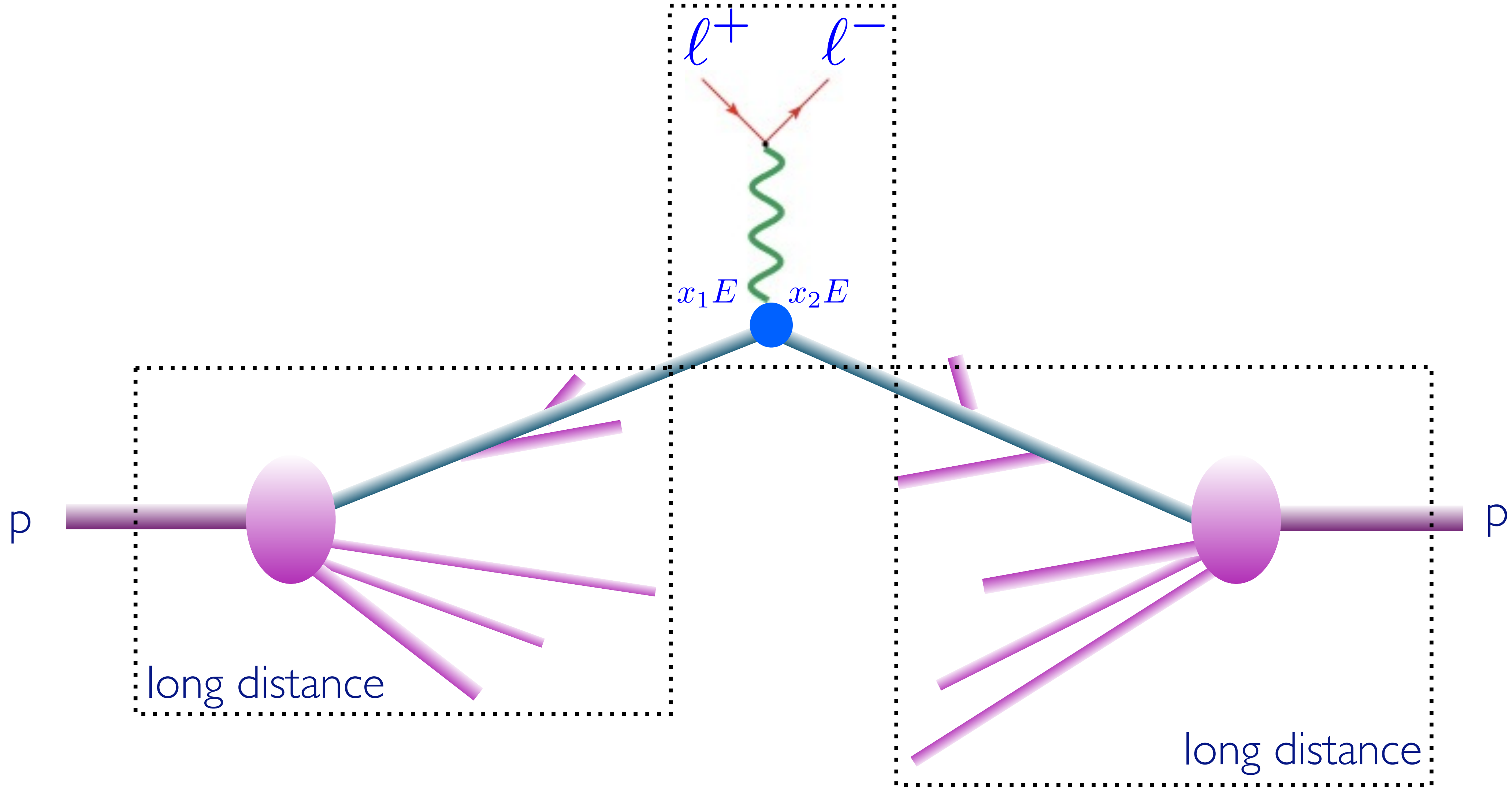


LHC master formula



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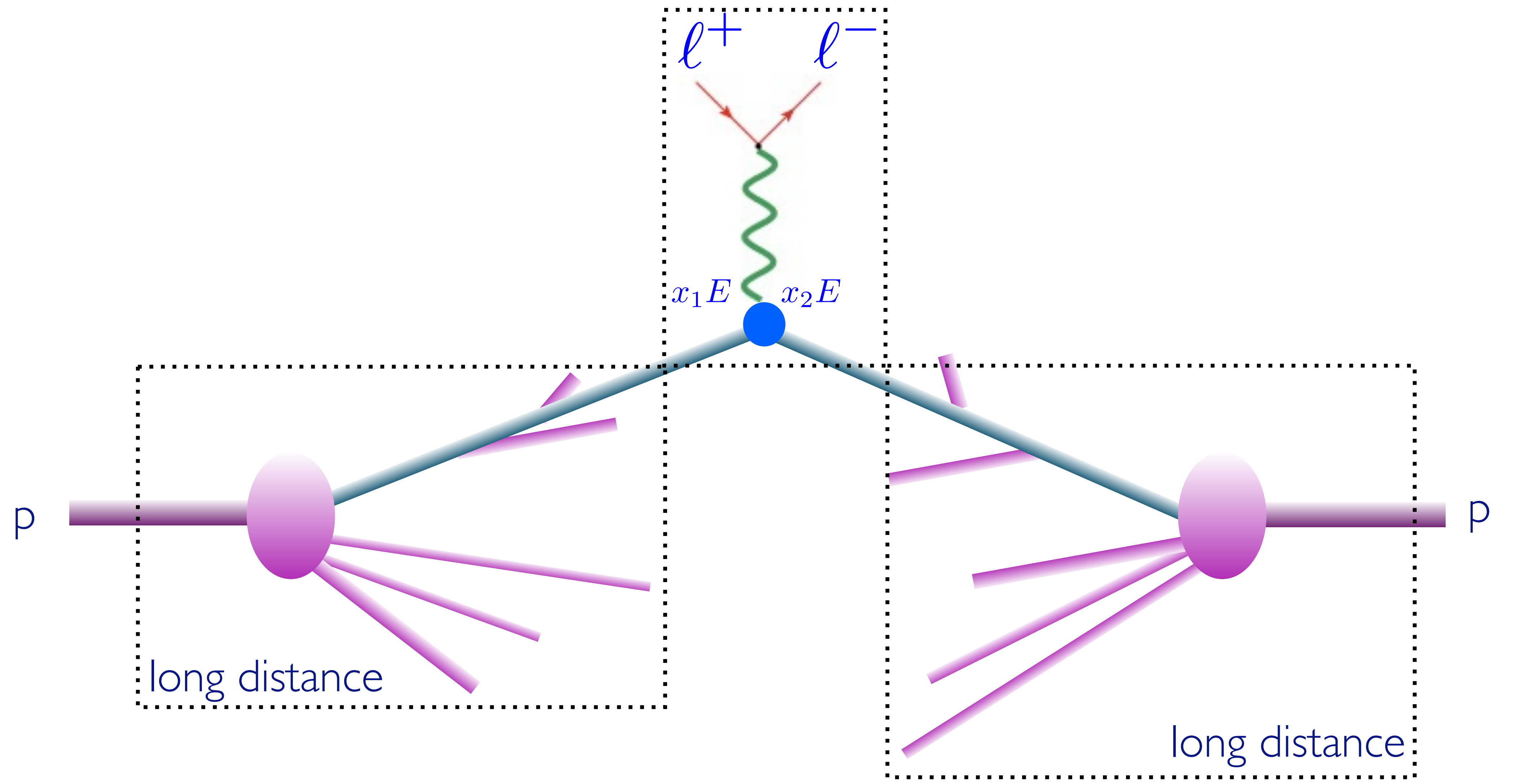
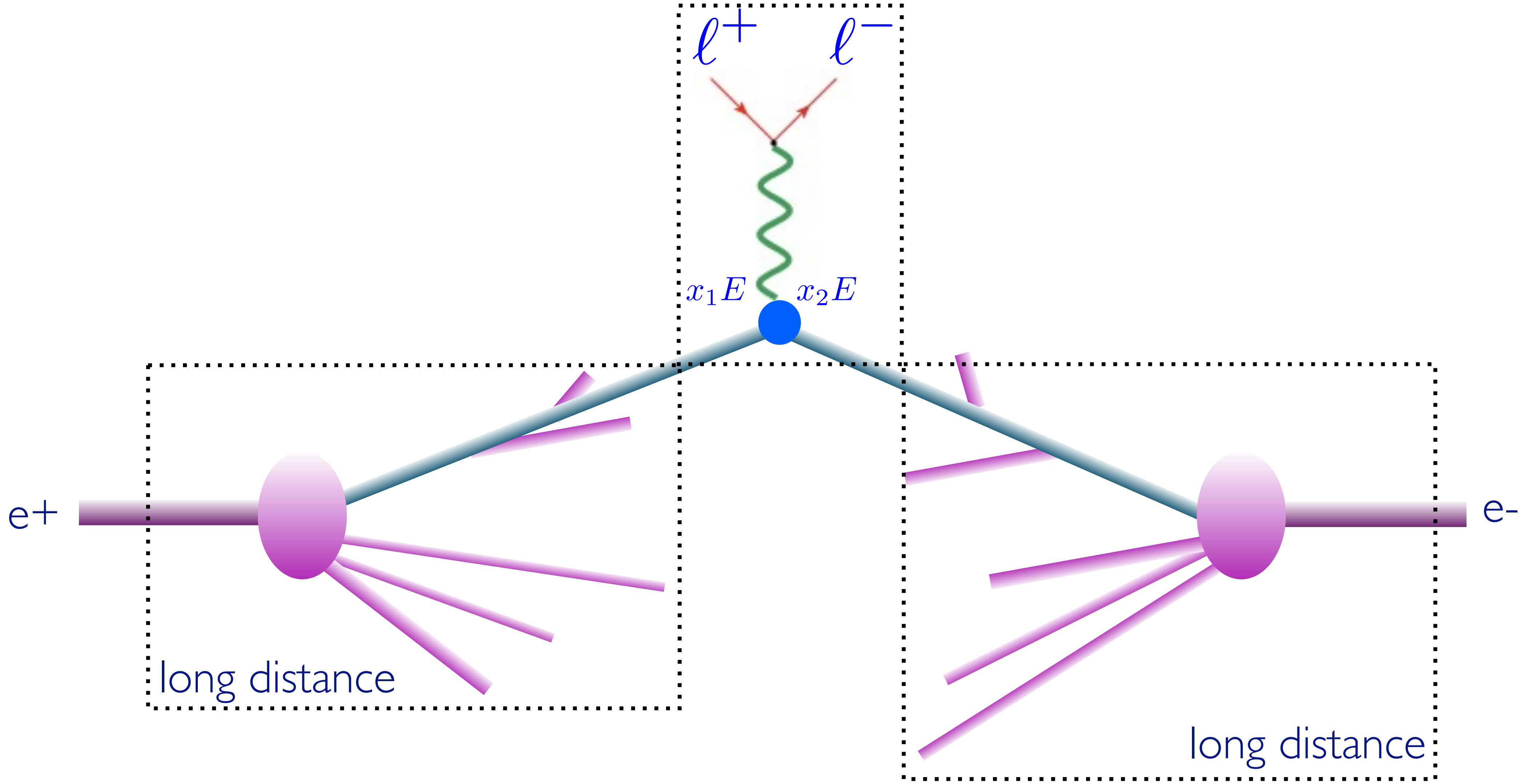


$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

e+ e- master formula



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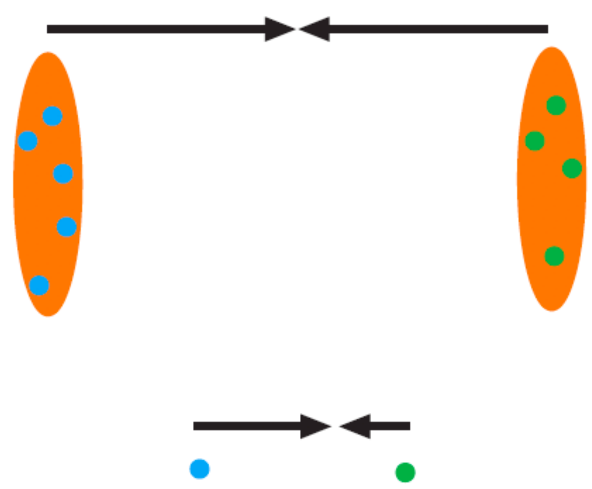
Kinematics

We describe the collision in terms of parton energies



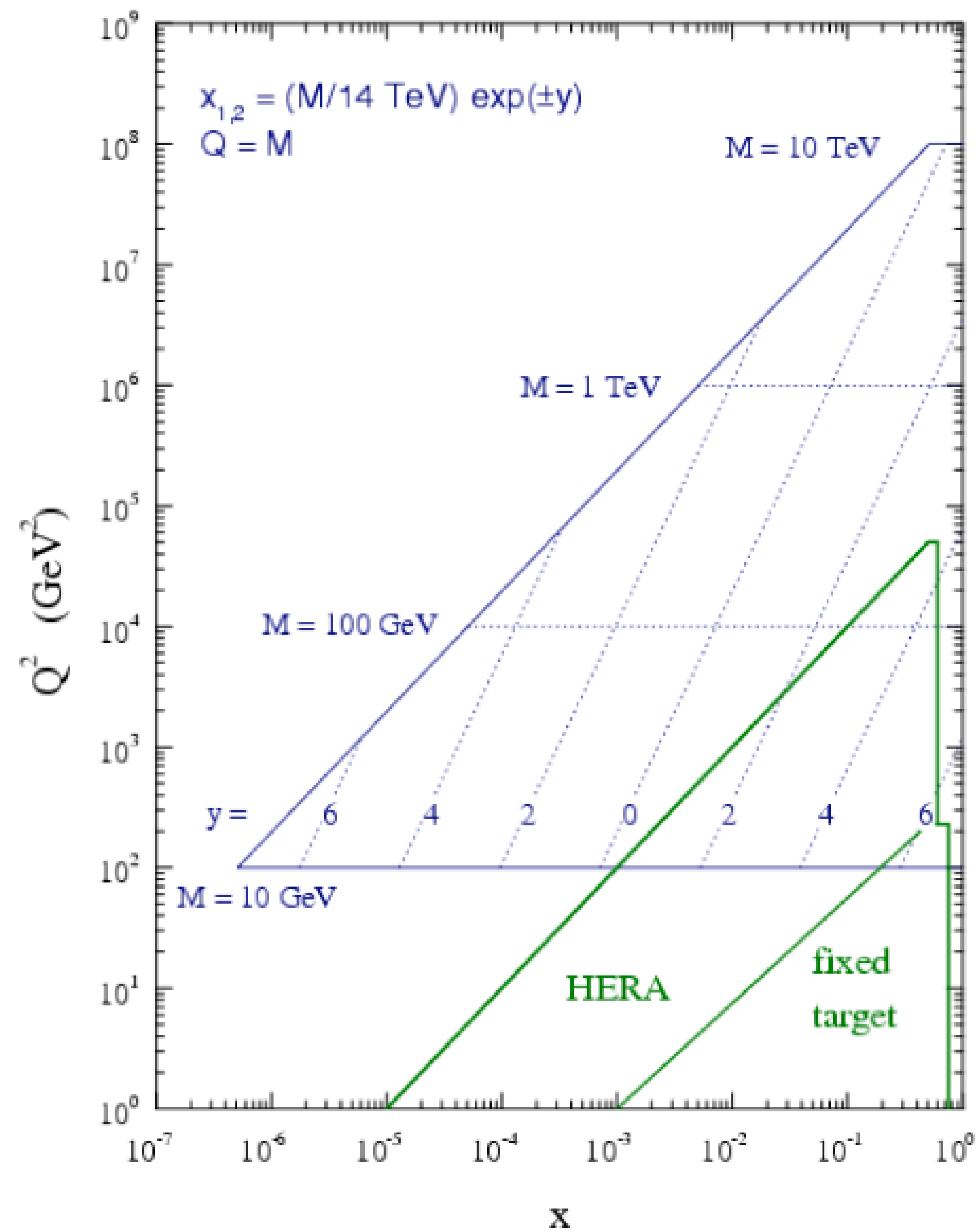
E1= x1 Ebeam
E2= x2 Ebeam

Obviously the partonic c.m.s. frame will be in general boosted. Let us say that the two partons annihilate into a particle of mass M.

$$M^2 = x_1 x_2 S = x_1 x_2 4E^2_{\rm beam}$$

$$y = \frac{1}{2}\log\frac{x_1}{x_2}$$

$$x_1 = \frac{M}{\sqrt{S}}e^{y} \quad x_2 = \frac{M}{\sqrt{S}}e^{-y}$$



LHC master formula

More exactly

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

where the partonic cross section is calculated by

$$\hat{\sigma}_{a,b\to k} = \frac{1}{2s} \int \left[\Pi_{i=1}^{n} \frac{d^3\vec{q}_i}{(2\pi)^3 2E_i}\right] \left[(2\pi)^4 \delta^4 \left(\sum_i q_i^\mu - (p_1+p_2)^\mu\right)\right] |\mathcal{M}_{ab\to k}(\mu_F, \mu_R)|^2$$

[flux factor] × [phase space (LiPS)] × [squared matrix element]

Crucial pieces for the calculation of the hadronic cross section are the **parton distribution functions** $f_{i/p}$ and the **squared matrix element** $|\mathcal{M}|^2$

A simple example: $t\bar{t}$

Let's see how to calculate the cross section for a simple process such as pp → ttbar. There are two initial states possible, gg and qqbar. For gg (which will dominate at the LHC) we obtain:

$$\frac{d\sigma}{d\hat{s}} = \int_0^1 \int_0^1 dx_1 dx_2 \, g(x_1, \mu_F) g(x_2, \mu_F) \, \hat{\sigma}(\hat{s}) \delta(\hat{s} - x_1 x_2 s)$$

We introduce the variable tau, that is proportional to x1 and x2:

$$\tau \equiv \frac{\hat{s}}{s} = x_1 x_2$$

and obtain

$$\frac{d\sigma}{d\tau} = \int_0^1 \int_0^1 dx_1 dx_2 \, g(x_1, \mu_F) g(x_2, \mu_F) \, \frac{\hat{\sigma}(\hat{s})}{\tau} \delta\left(1 - \frac{x_1 x_2}{\tau}\right)$$

A simple example: tt̄

$$\frac{d\sigma}{d\tau} = \frac{\hat{\sigma}(\hat{s})}{\tau} \boxed{\int_\tau^1 \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})}$$

We define the dimensionless partonic luminosity:

$$\frac{dL_{gg}}{d\tau} \equiv \int_\tau^1 \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})$$

and calculate the total cross section as:

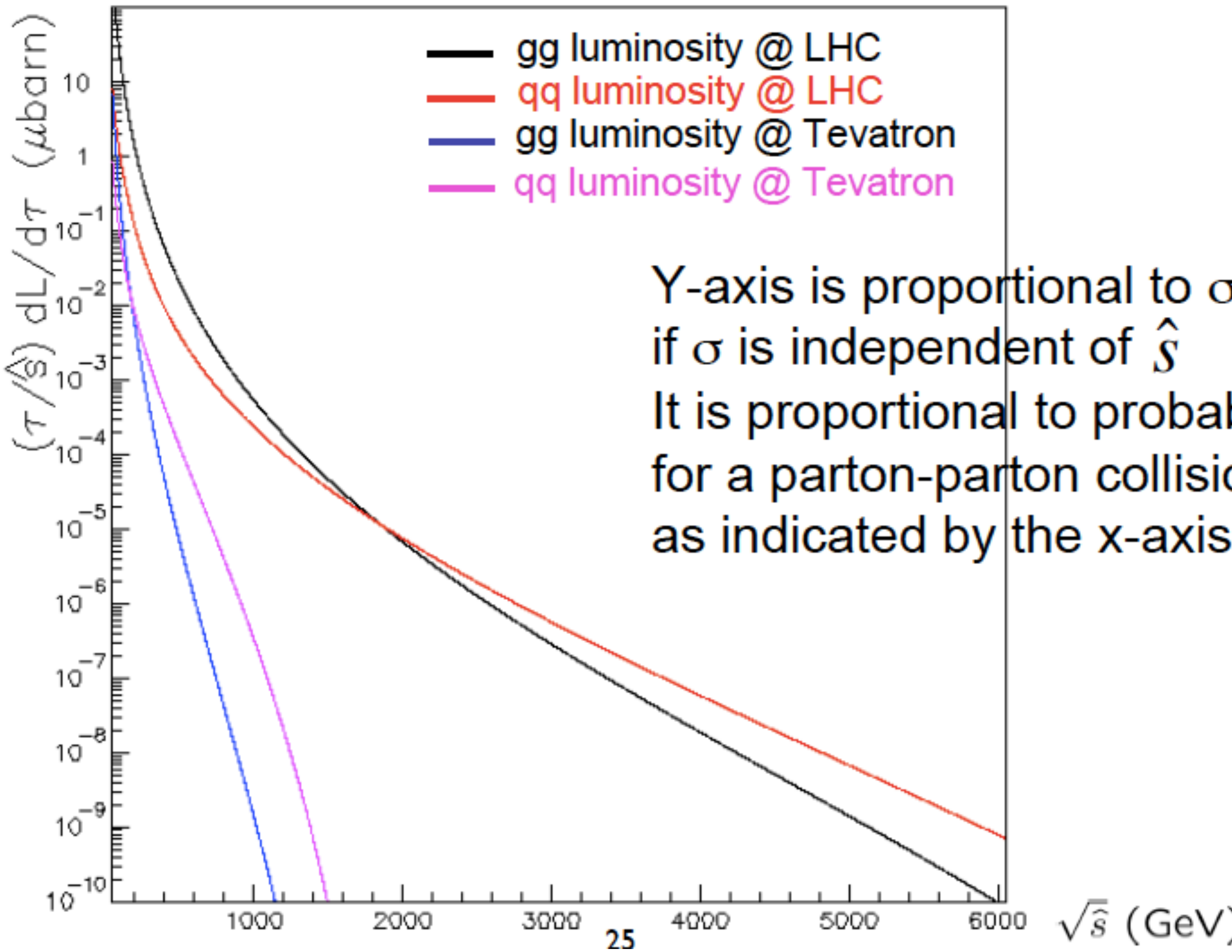
$$\sigma(pp \to t\bar{t} + X) = \int_{\tau_{\min}}^1 d\tau \cdot \hat{\sigma}_{gg\to t\bar{t}}(s\tau) \cdot \frac{dL}{d\tau}$$

$$= \int_{\tau_{\min}}^1 \frac{d\tau}{\tau} \cdot [\hat{s}\hat{\sigma}_{gg\to t\bar{t}}(\hat{s})] \cdot \frac{\tau dL}{\hat{s} d\tau}$$

CLOSE TO A CONSTANT

"CROSS SECTION"

A simple example: $t\bar{t}$



Y-axis is proportional to σ
if σ is independent of $\hat{s}$
It is proportional to probability
for a parton-parton collision with $\hat{s}$
as indicated by the x-axis.

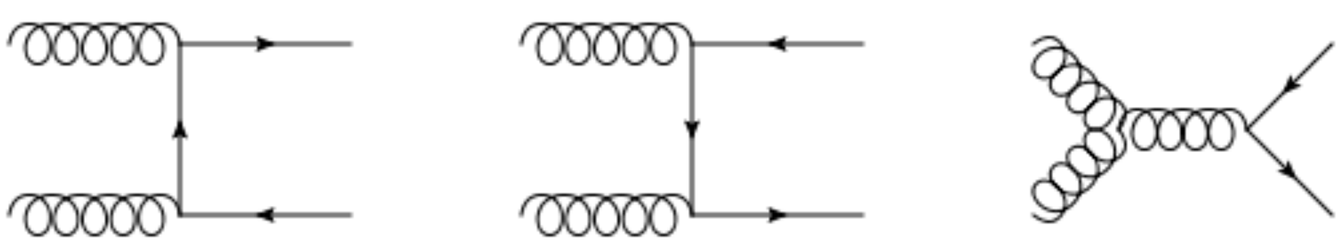
A simple example: $t\bar{t}$

$$\frac{dL_{gg}}{d\tau} \equiv \int_\tau^1 \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})$$

If we take for simplicity $$g(x) = \frac{1}{x^{1+\delta}} \Rightarrow \frac{dL_{gg}}{d\tau} = \frac{1}{\tau^{1+\delta}} \log\tau$$

i.e. the total "cross section" will scale as a power of $1/mt^{1+delta}$ Log Mt

The short distance coefficient can be easily calculated at LO via the feynman diagrams:



A simple example: $t\bar{t}$

$$\frac{1}{256}|M|^2 = \frac{3g_s^4}{4}\frac{(m^2-t)(m^2-u)}{s^2} - \frac{g_s^4}{24}\frac{m^2(s-4m^2)}{(m^2-t)(m^2-u)} + \frac{g_s^4}{6}\frac{tu-m^2(3t+u)-m^4}{(m^2-t)^2} + \frac{g_s^4}{6}\frac{tu-m^2(t+3u)-m^4}{(m^2-u)^2} - \frac{3g_s^4}{8}\frac{tu-2m^2t+m^4}{s(m^2-t)} - \frac{3g_s^4}{8}\frac{tu-2m^2u+m^4}{s(m^2-u)}$$

3 diagrams squared + the interferences. This amplitude is integrated over the phase space at fixed shat:

$$\hat{\sigma}_{gg\to t\bar{t}} = \frac{1}{2\hat{s}}\,\beta\,2\pi\int_{-1}^{+1} d\cos\theta^* \;|M|^2/256$$

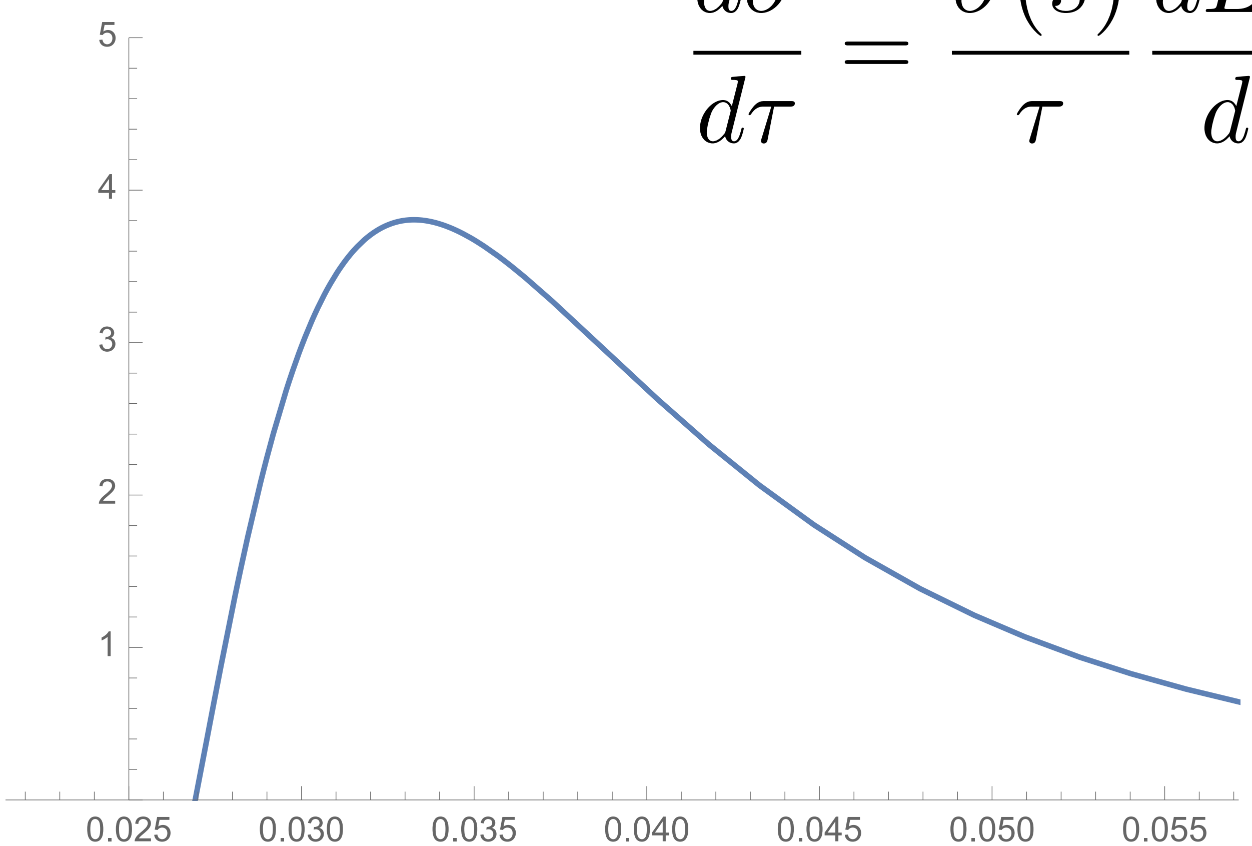
eventually giving:

$$\beta = \sqrt{1-4m_t^2/\hat{s}}$$

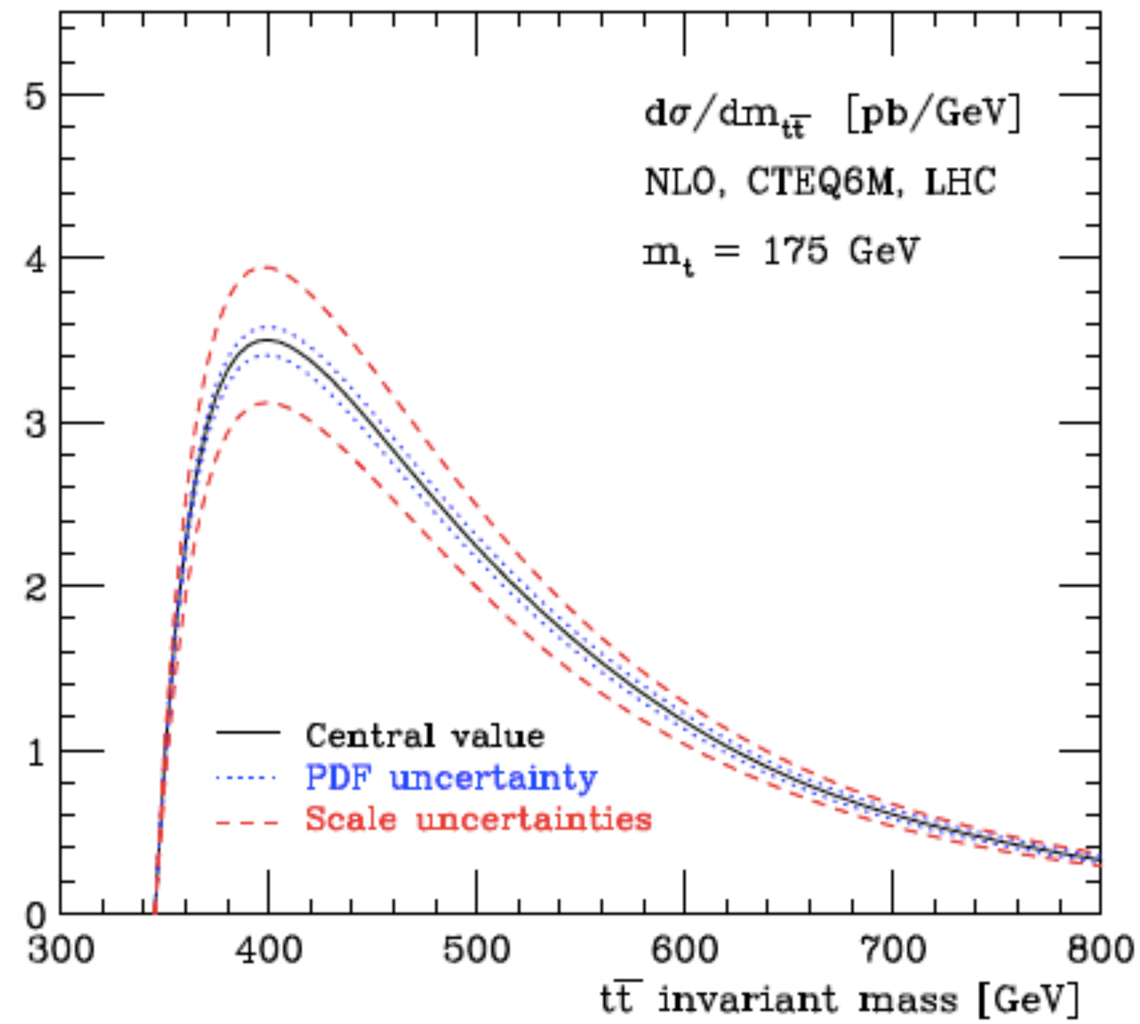
$$\hat{\sigma}_{gg\to t\bar{t}} = \frac{\pi\alpha_s^2\beta}{48\hat{s}}\left(31\beta + \left(\frac{33}{\beta} - 18\beta + \beta^3\right)\ln\left[\frac{1+\beta}{1-\beta}\right] - 59\right)$$

A simple example: $t\bar{t}$

$$\frac{d\sigma}{d\tau} = \frac{\hat{\sigma}(\hat{s})}{\tau}\frac{dL_{gg}}{d\tau}$$



LO estimation with toy pdf (δ=0.3)



NLO result with proper MC

LHC master formula

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1,x_2,\alpha_S(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:

1. Parton Distribution Functions (from exp, but evolution from th).

2. Short distance coefficients as an expansion in α_S (from th).

$$\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

Leading order

Next-to-leading order

Next-to-next-to-leading order

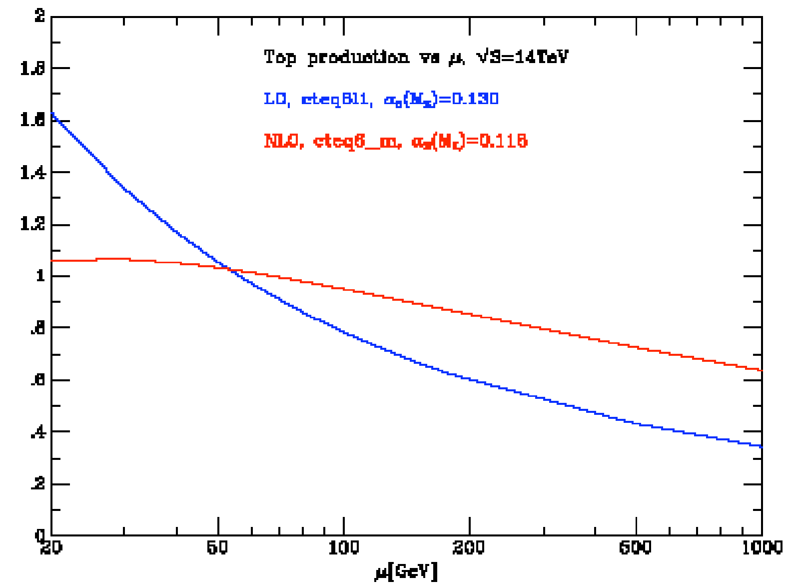
Perturbative expansion

- Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions

  - the scale of α_s is not defined
  - jets partons: jet structure starts to appear only beyond LO
  - Born topology might not be leading at the LHC

- To obtain reliable predictions at least NLO is needed

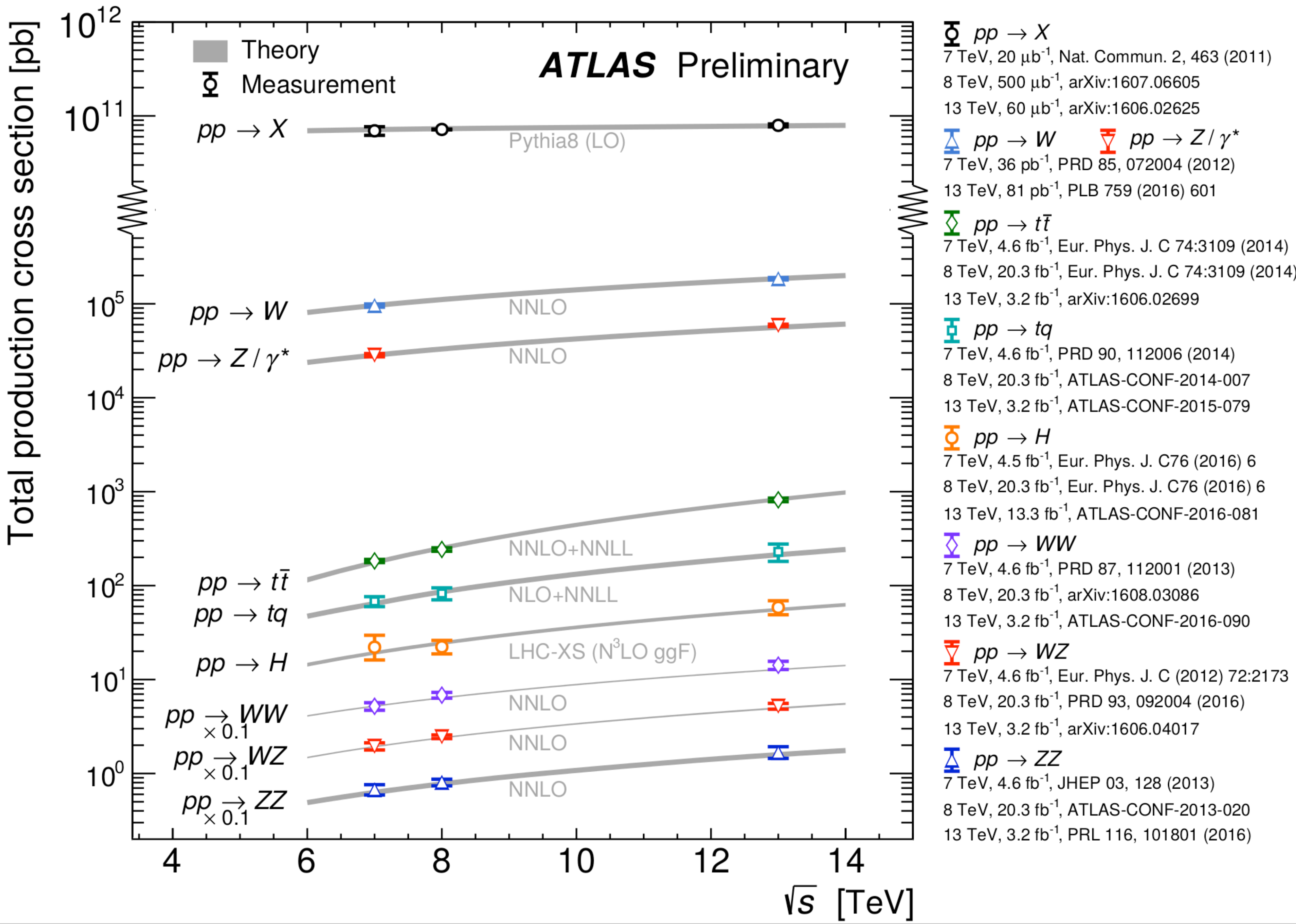
- NNLO allows to quantify uncertainties



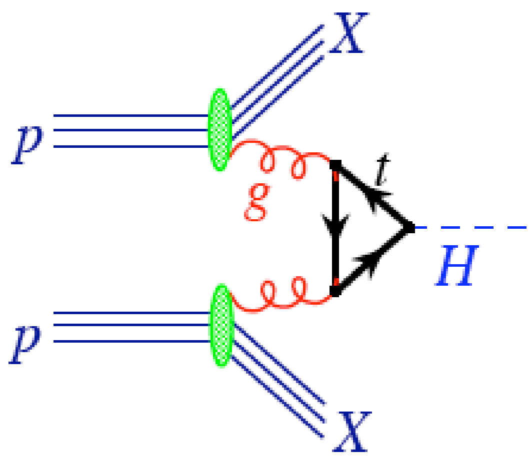
Furthermore:

- Resummation of the large logarithmic terms at phase space boundaries
- NLO ElectroWeak corrections ($\alpha_s^2 = \alpha_W$)
- Fully exclusive predictions available in terms of event simulation that can be used in experimental analysis

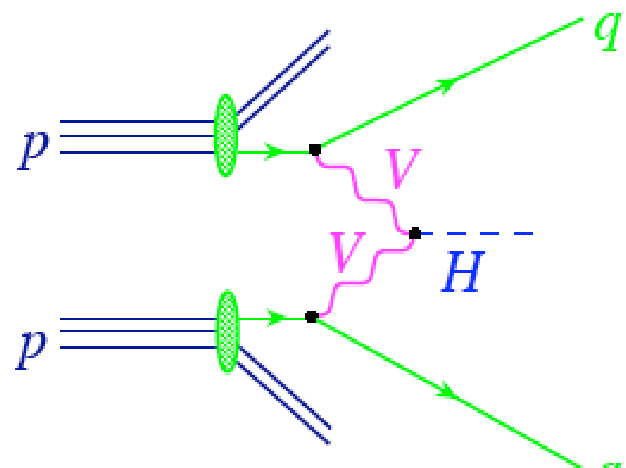
LHC Physics = QCD + ϵ



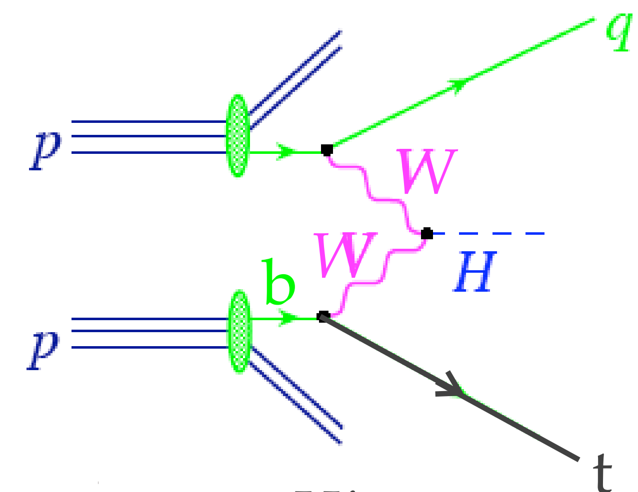
Higgs production channels



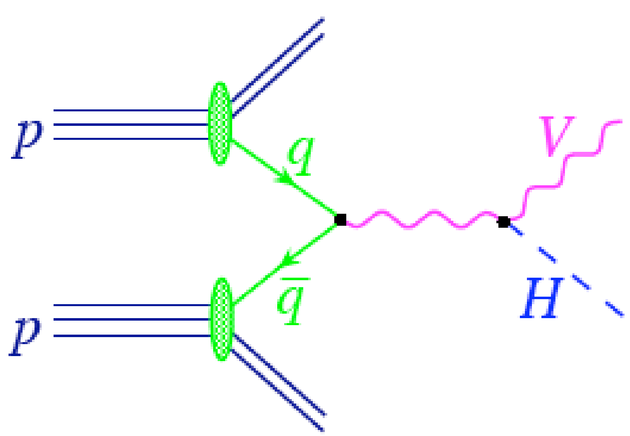
Gluon fusion



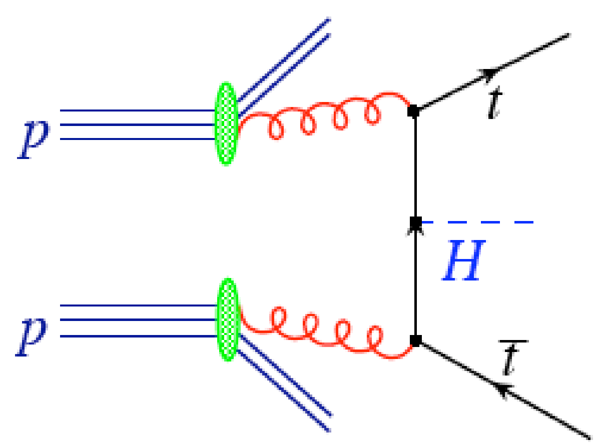
Weak-Boson Fusion



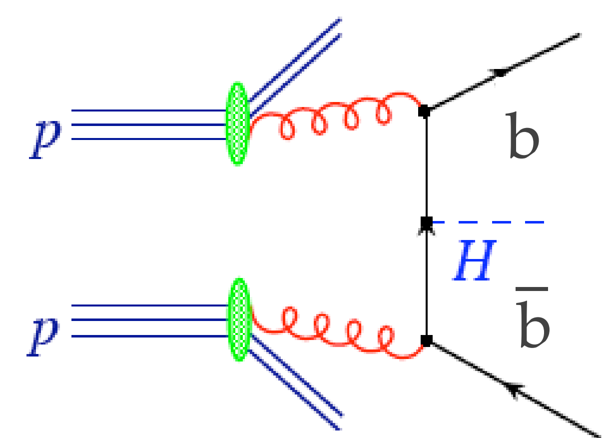
tHj



Higgs Strahlung

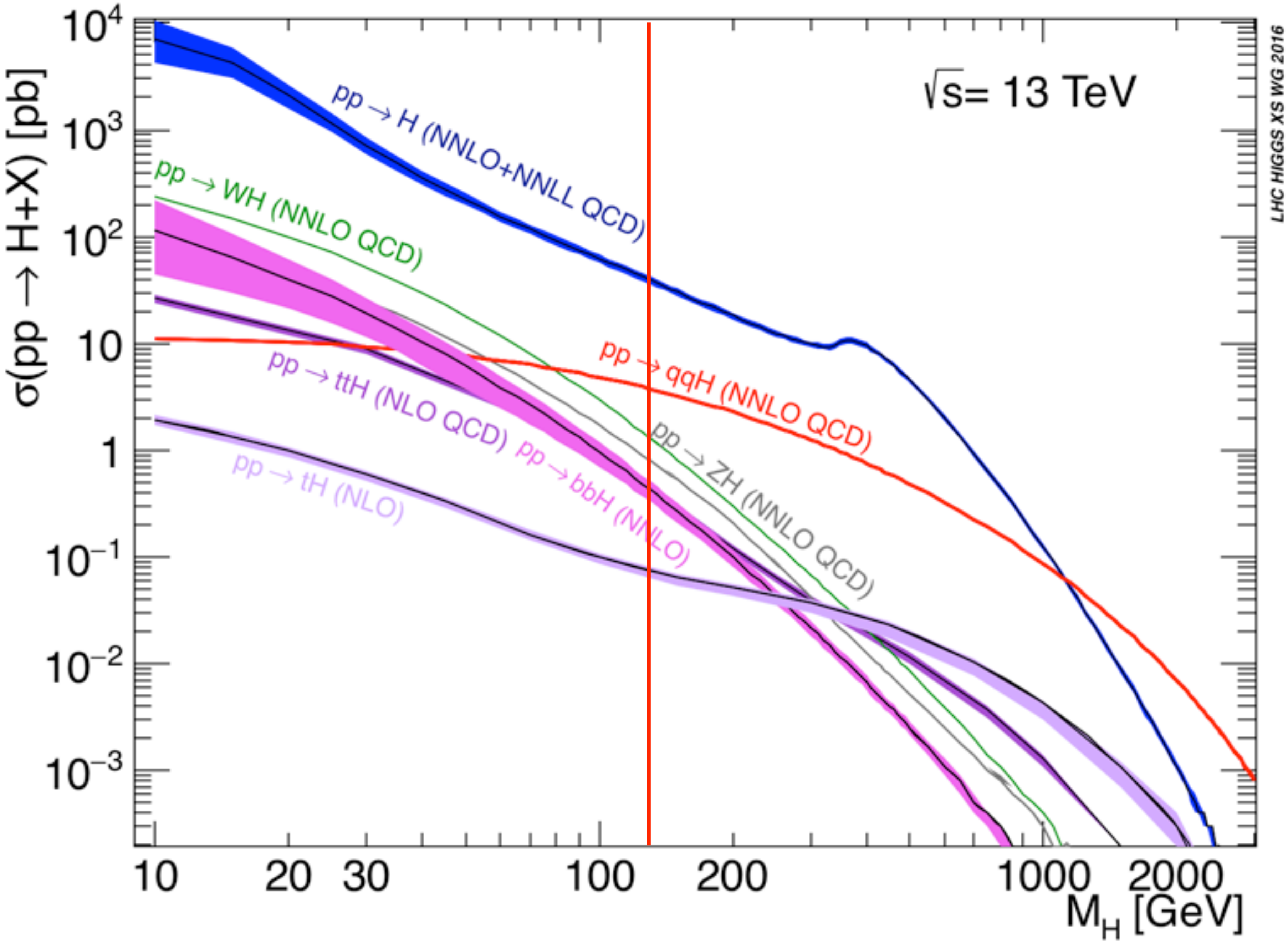


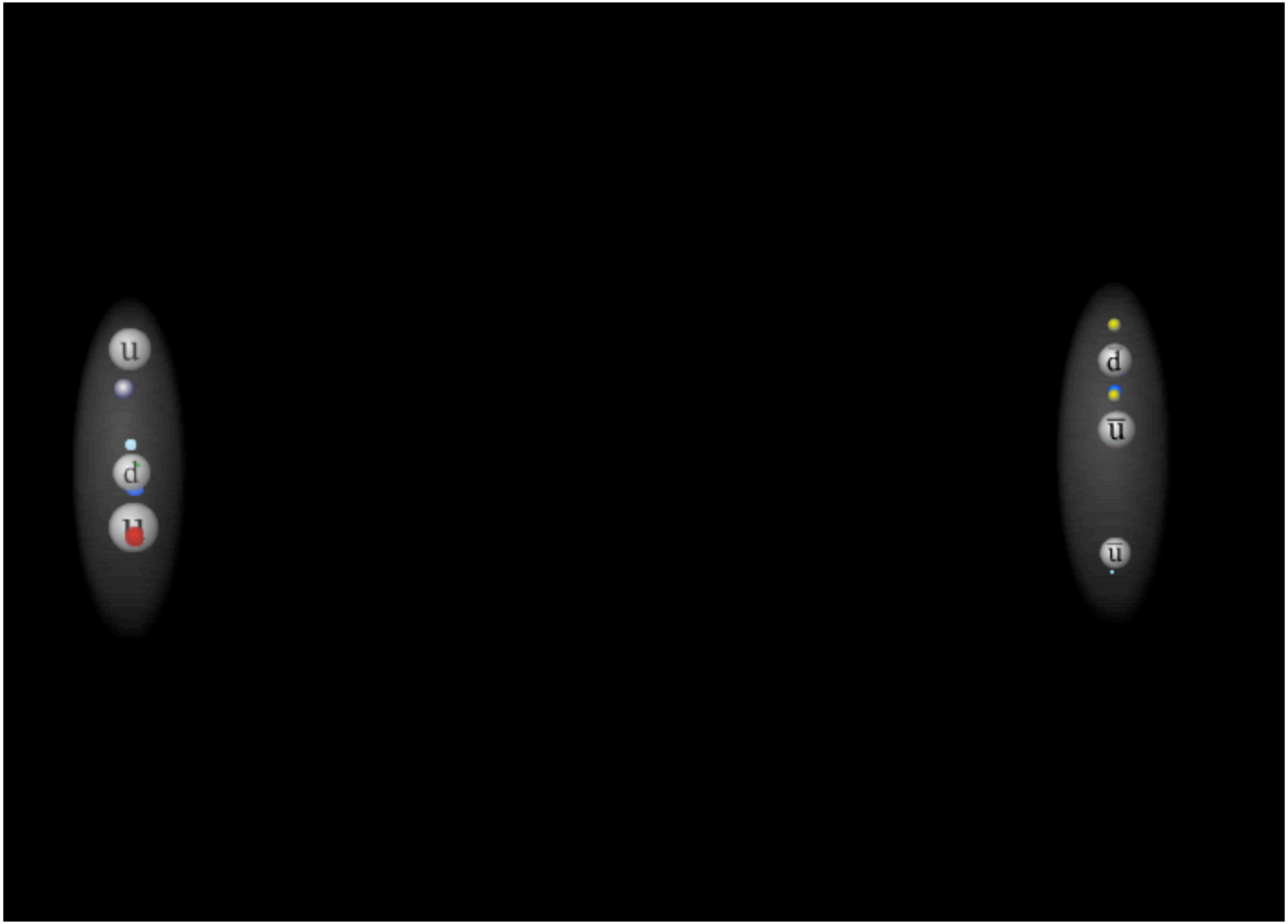
$t\bar{t}H$



bbH

Higgs production at the LHC

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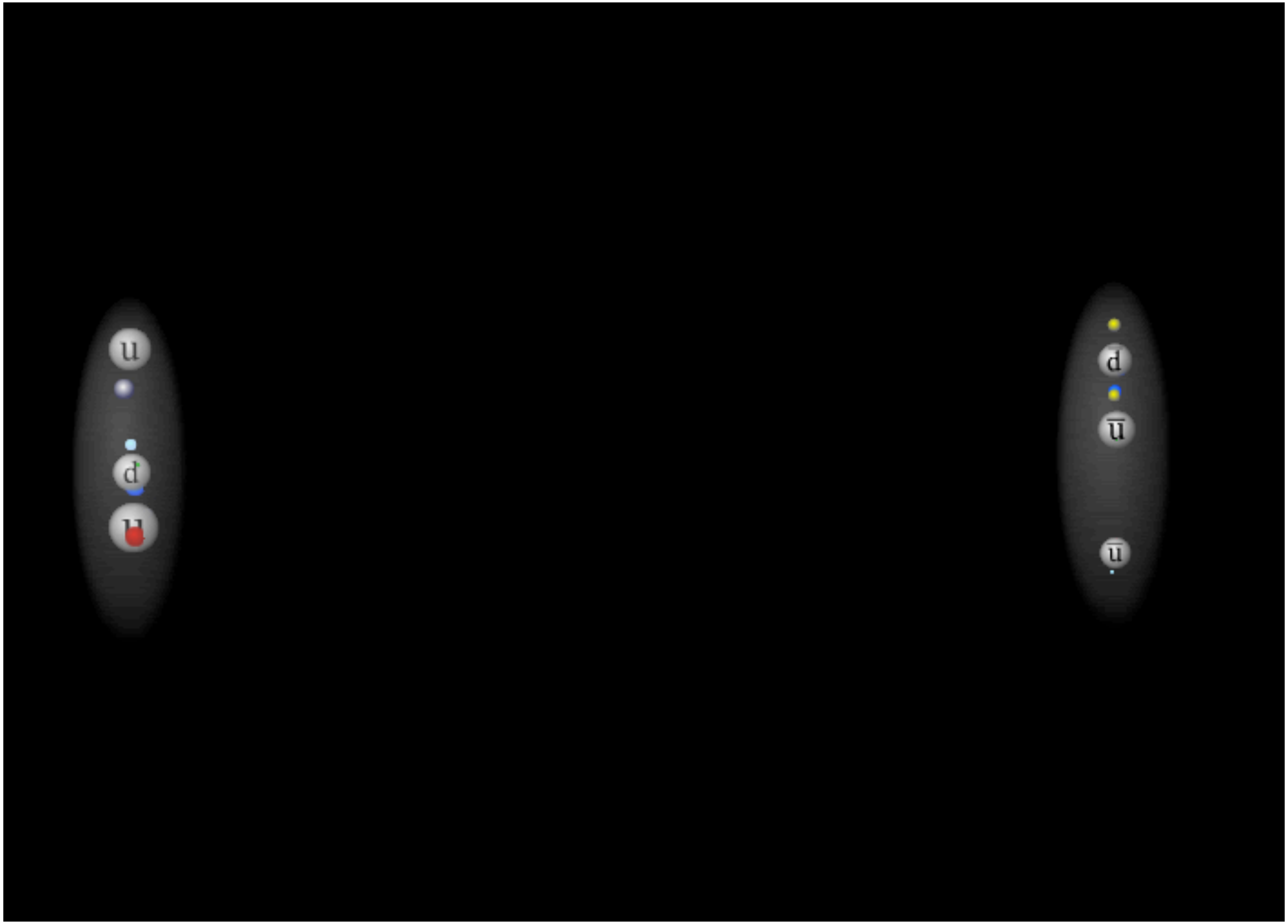
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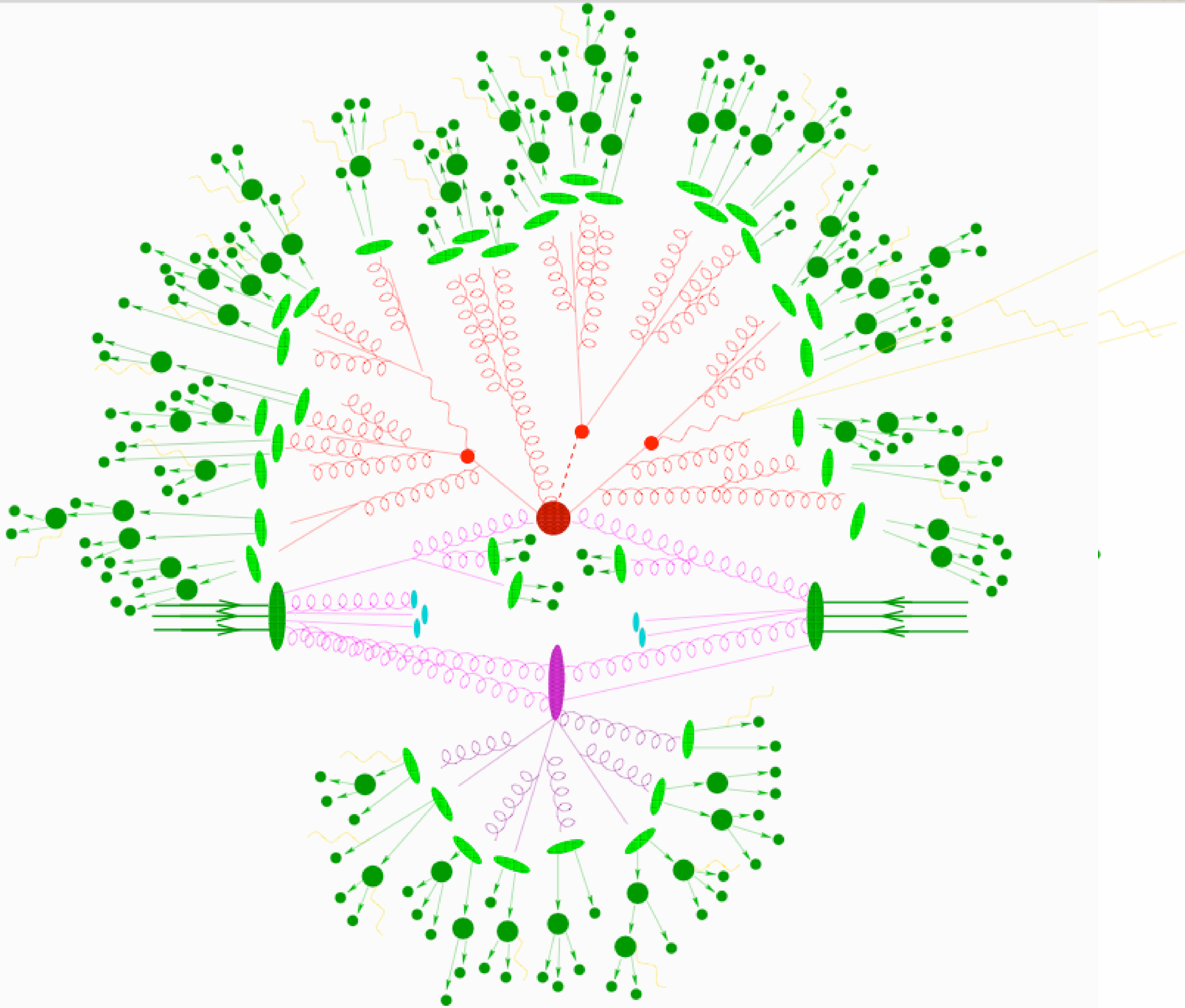
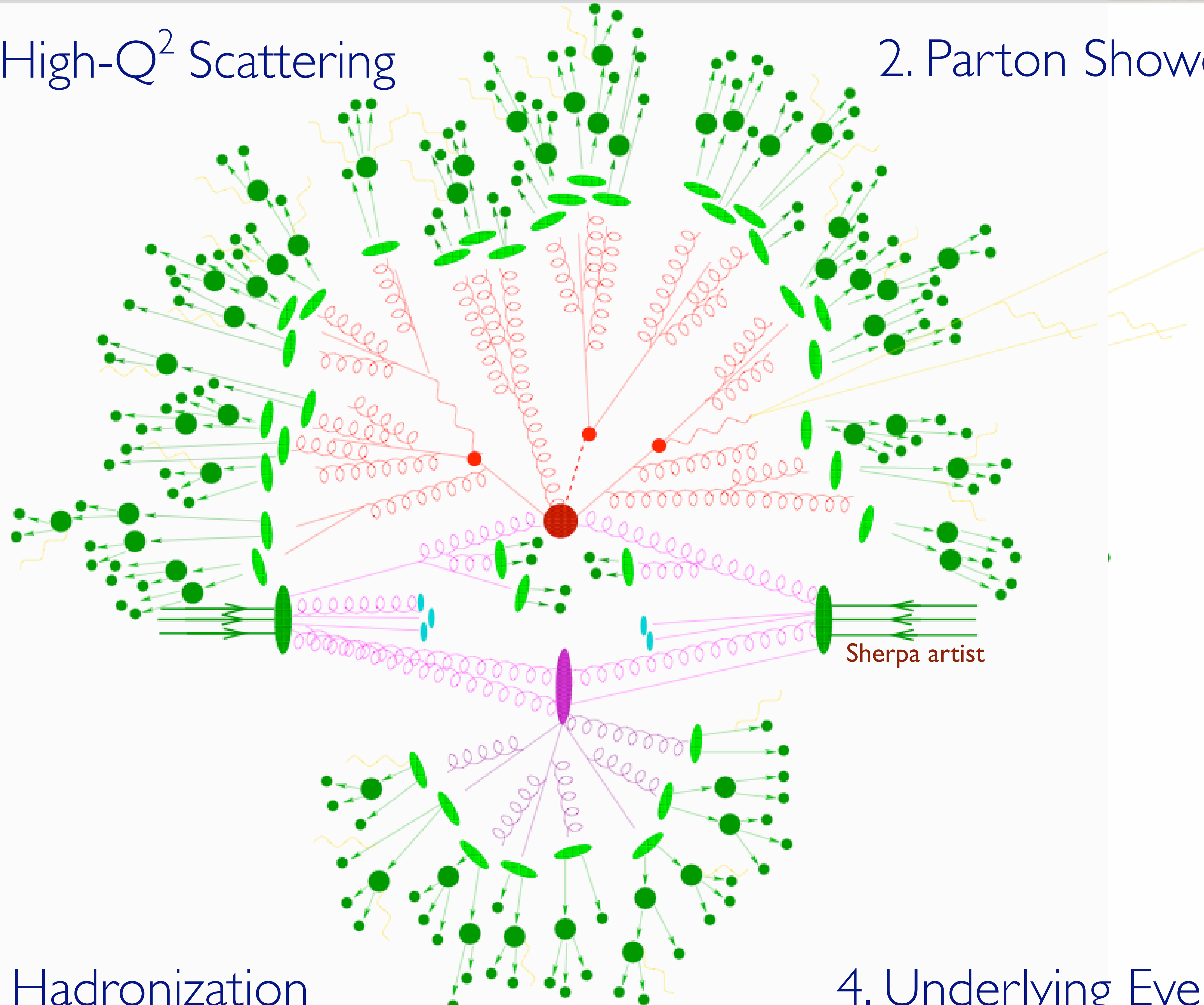


1. High-Q^2 Scattering

2. Parton Shower

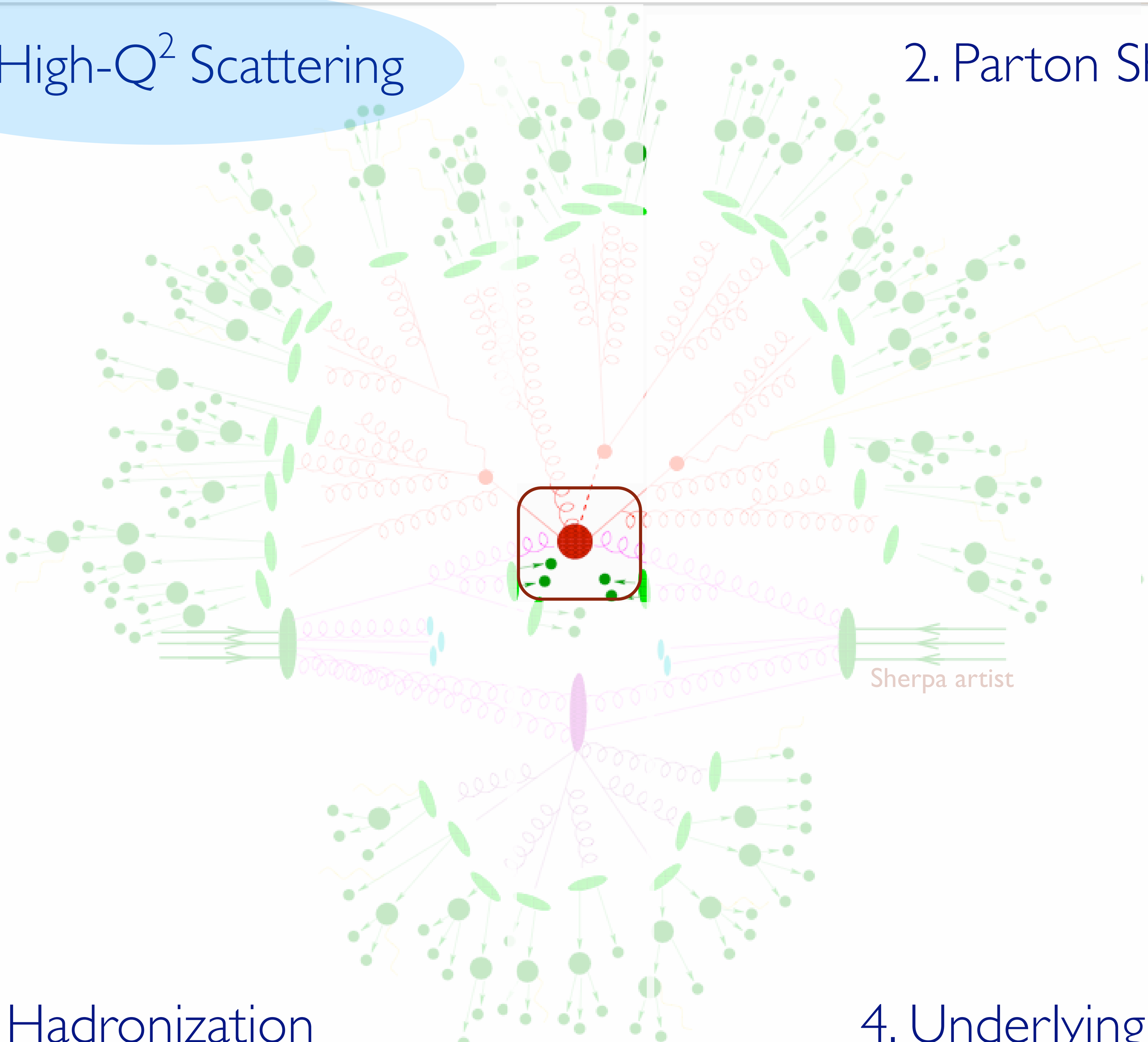


3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

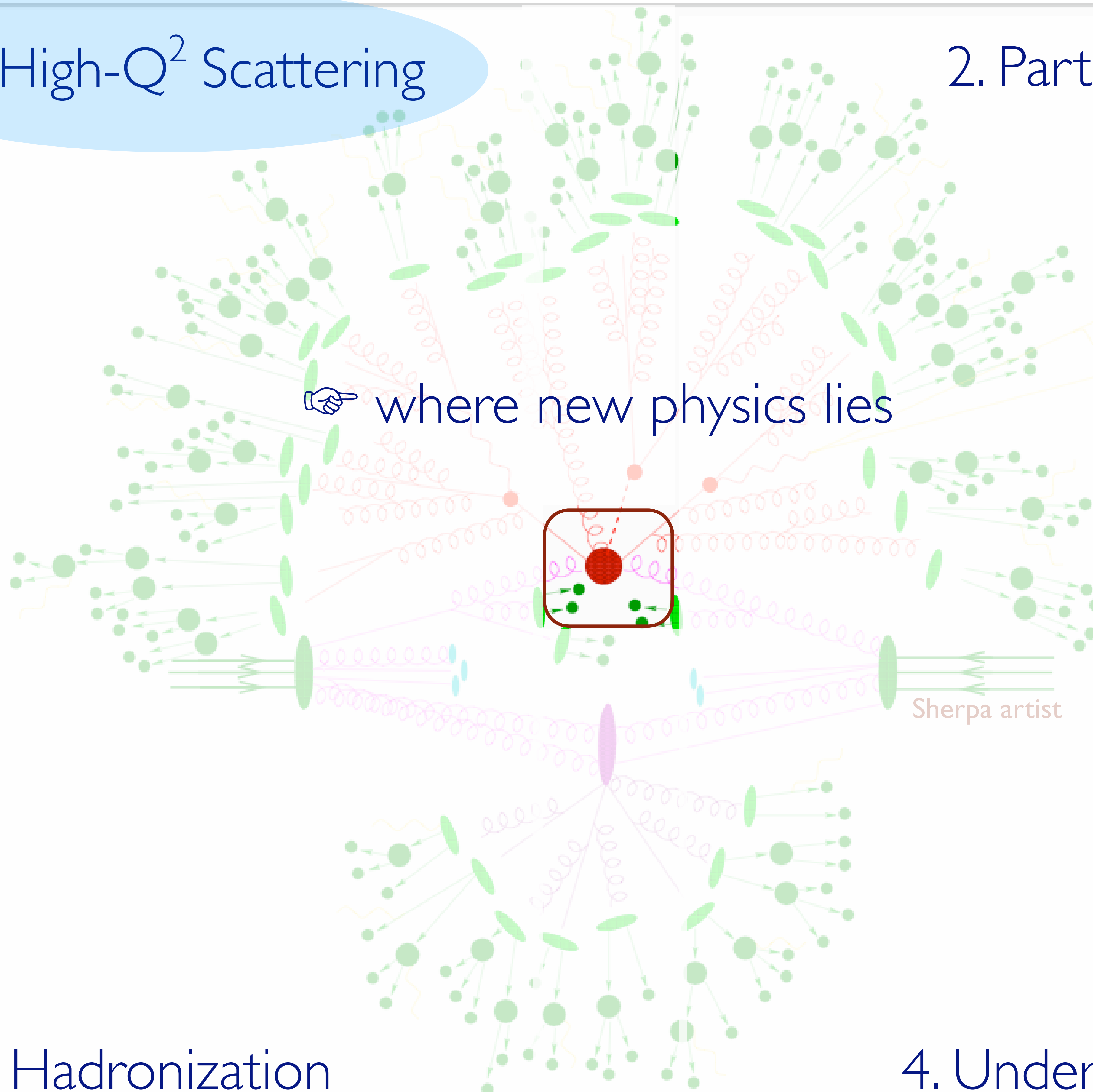


3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



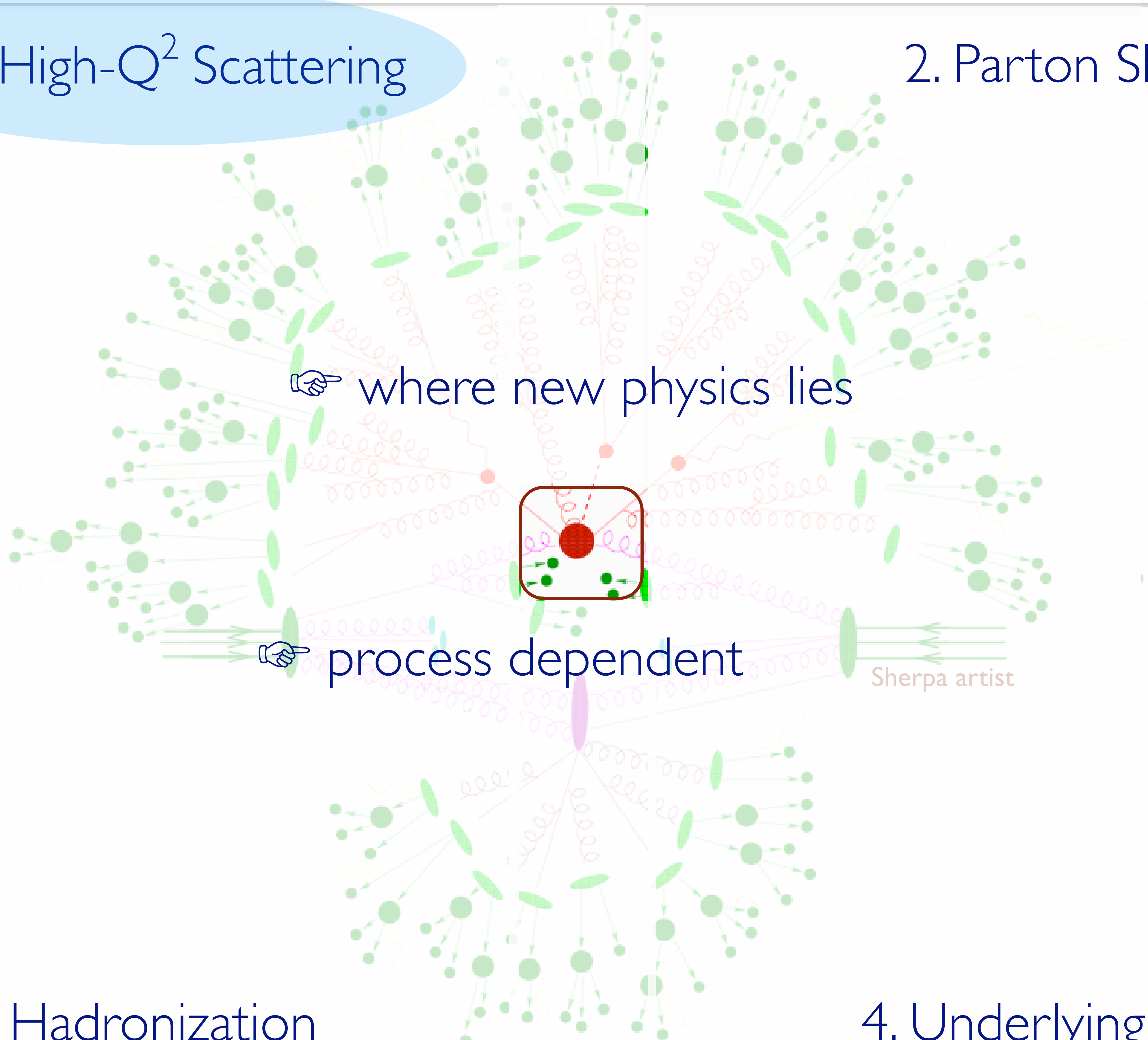
☞ where new physics lies

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ where new physics lies

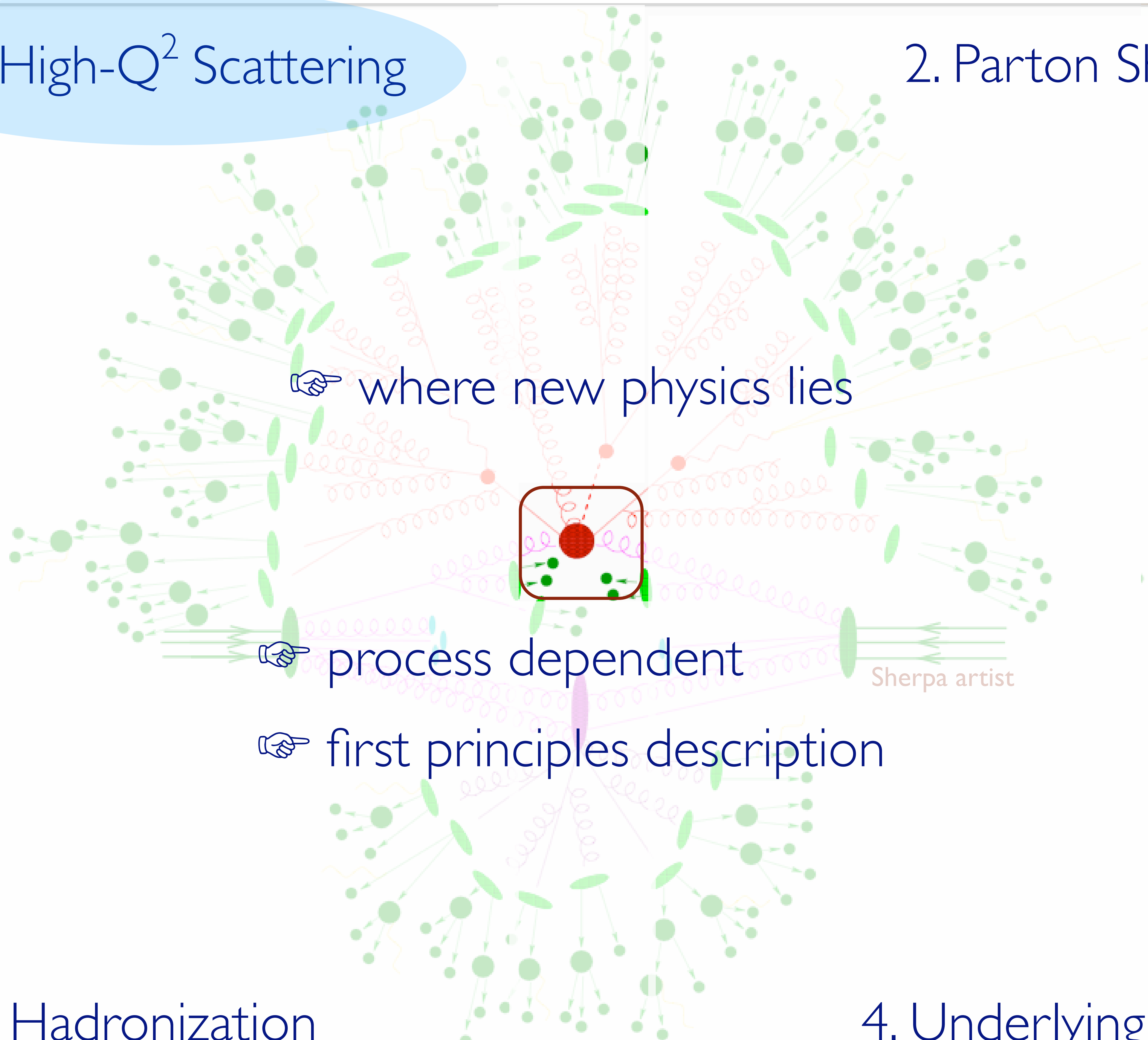
☞ process dependent

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



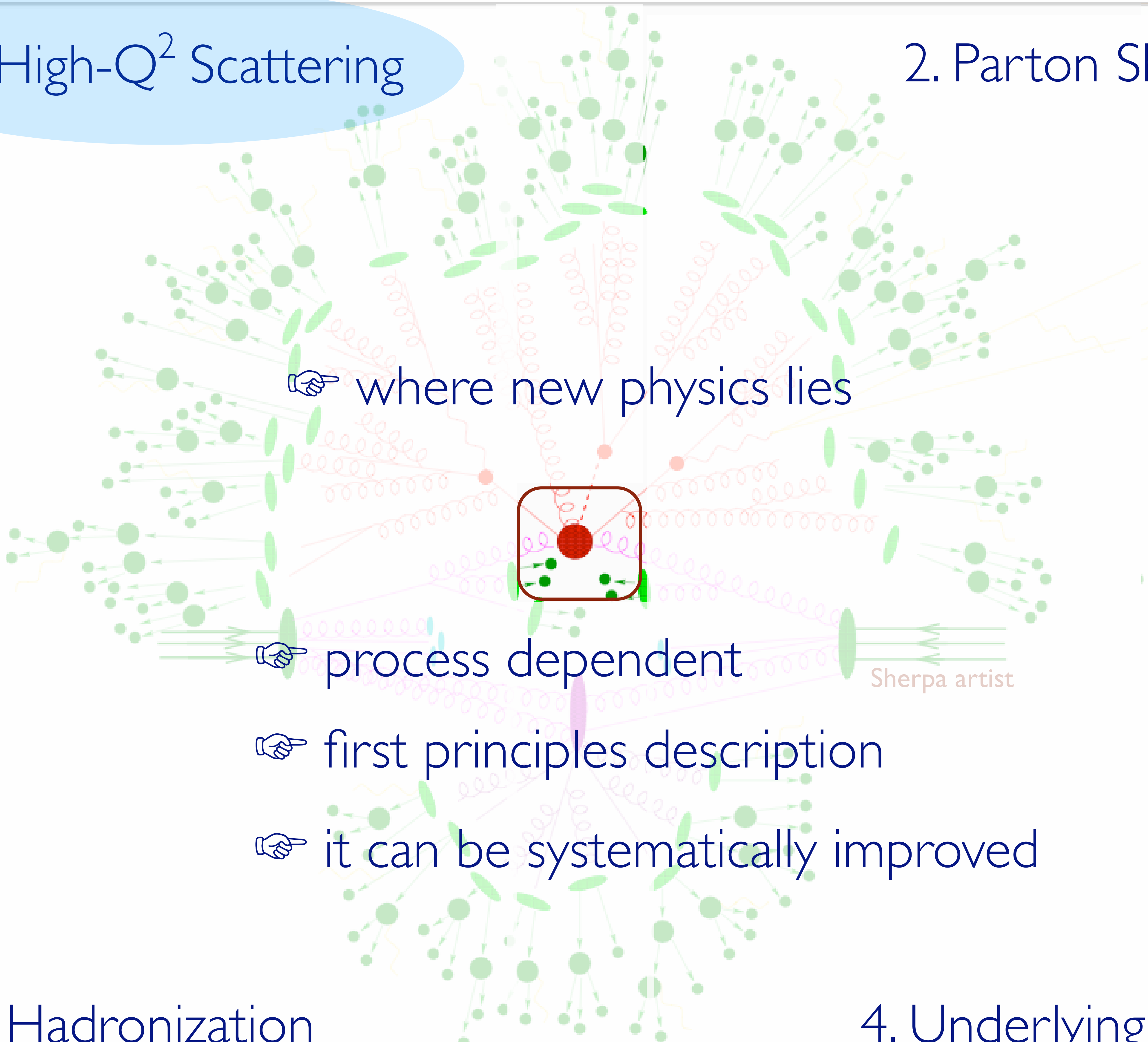
- ☞ where new physics lies
- ☞ process dependent
- ☞ first principles description

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



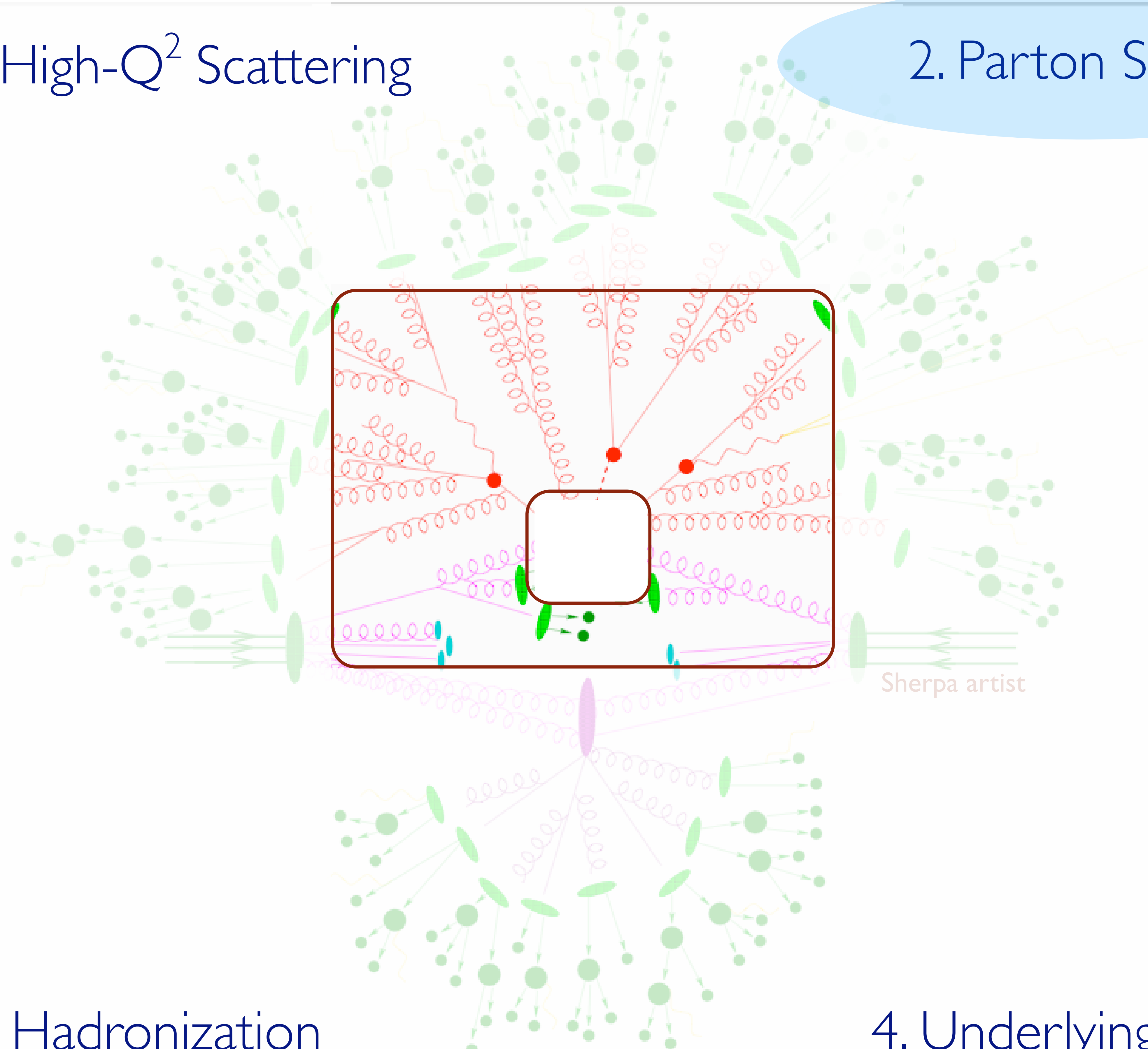
- ☞ where new physics lies
- ☞ process dependent
- ☞ first principles description
- ☞ it can be systematically improved

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

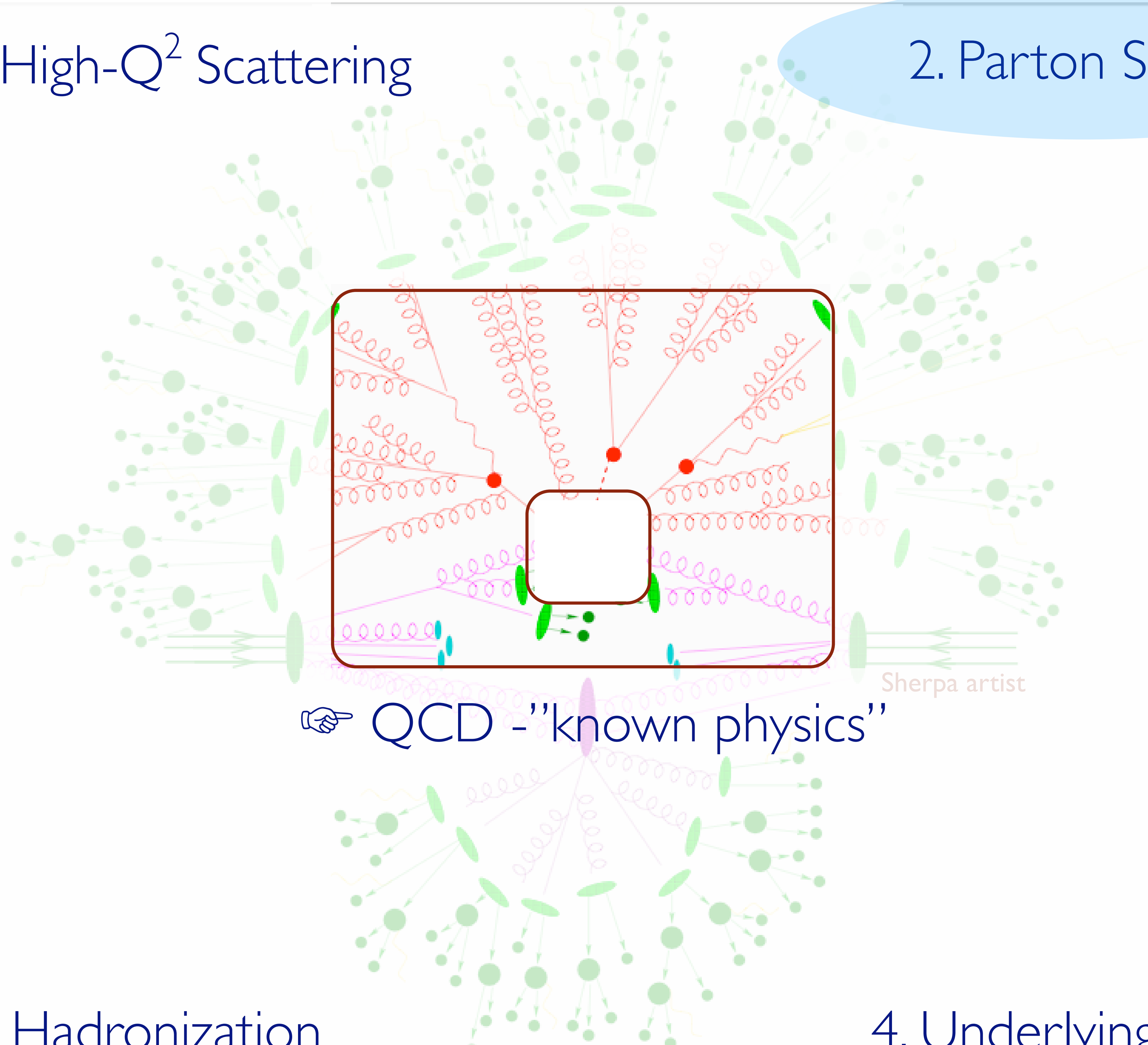


3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



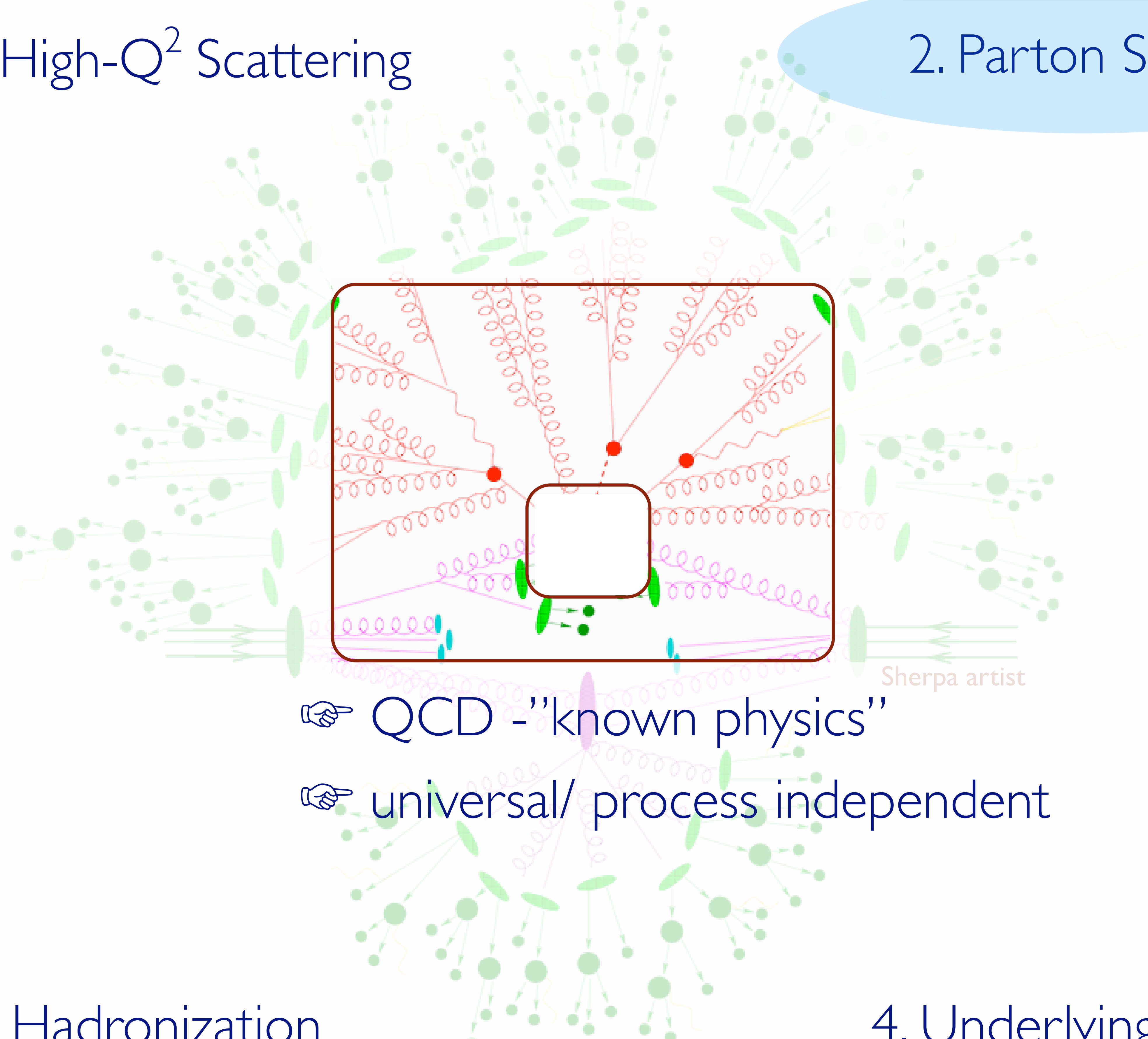
☞ QCD -"known physics"

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ QCD -"known physics"

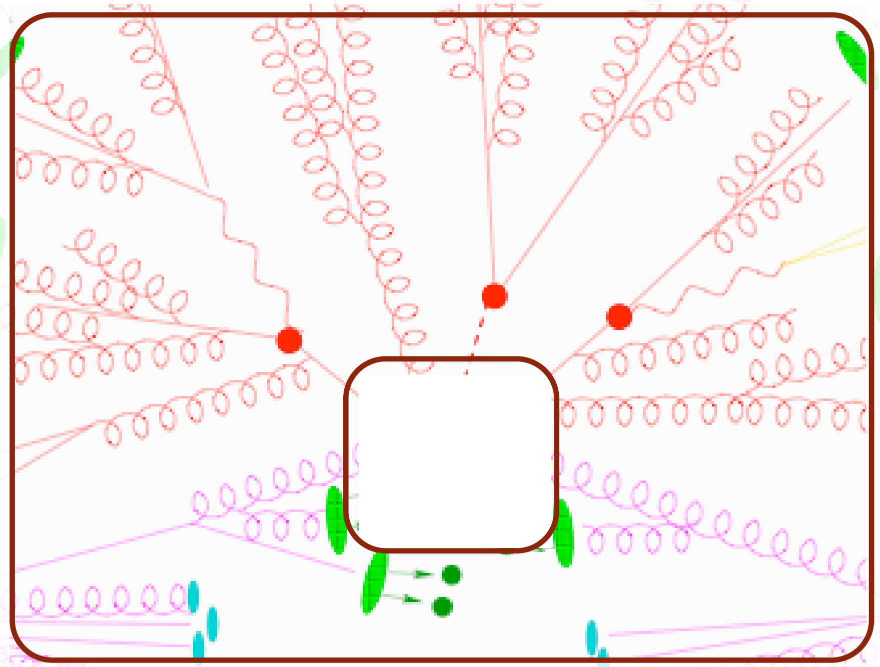
☞ universal/ process independent

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



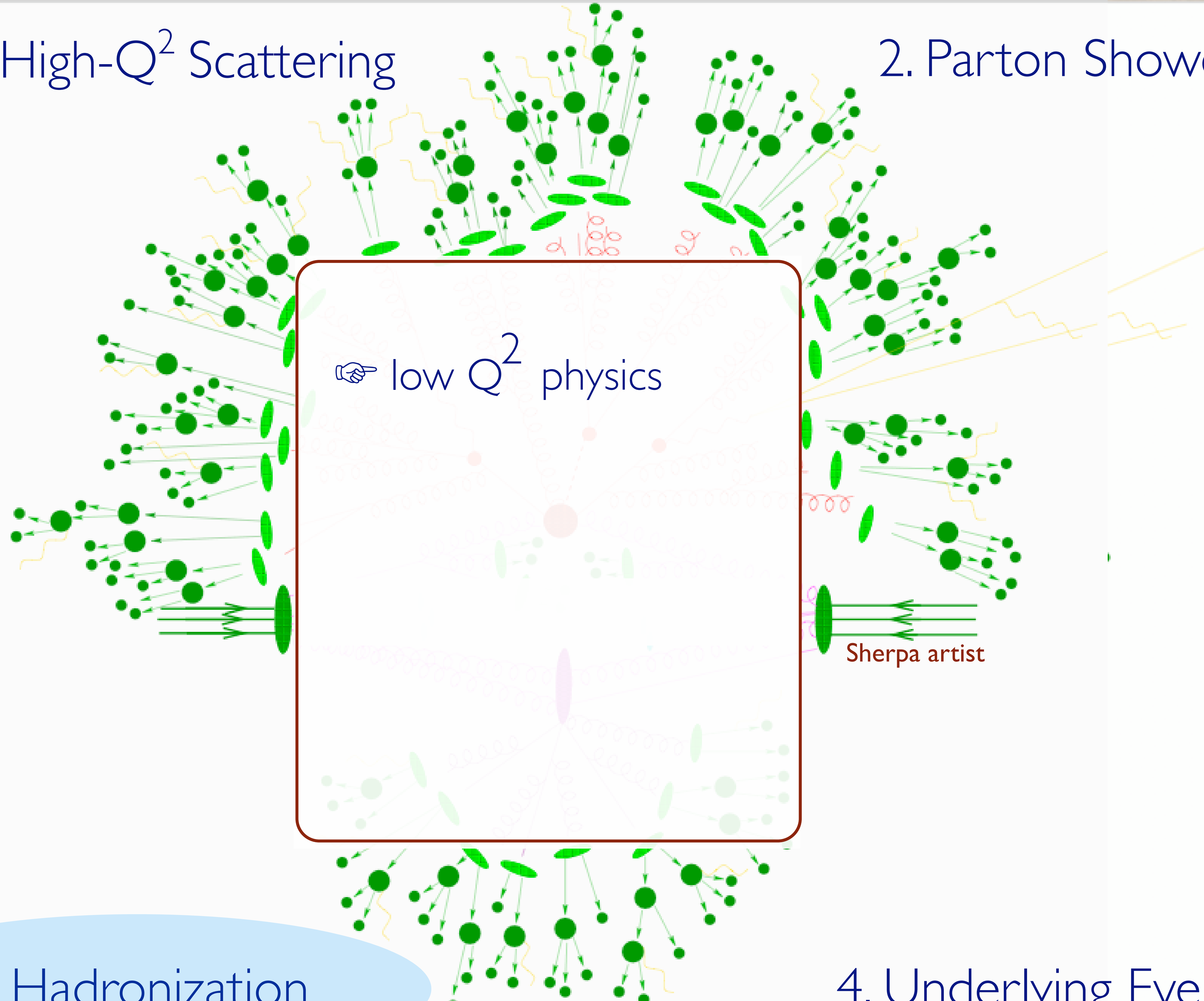
- ☞ QCD -"known physics"
- ☞ universal/ process independent
- ☞ first principles description

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

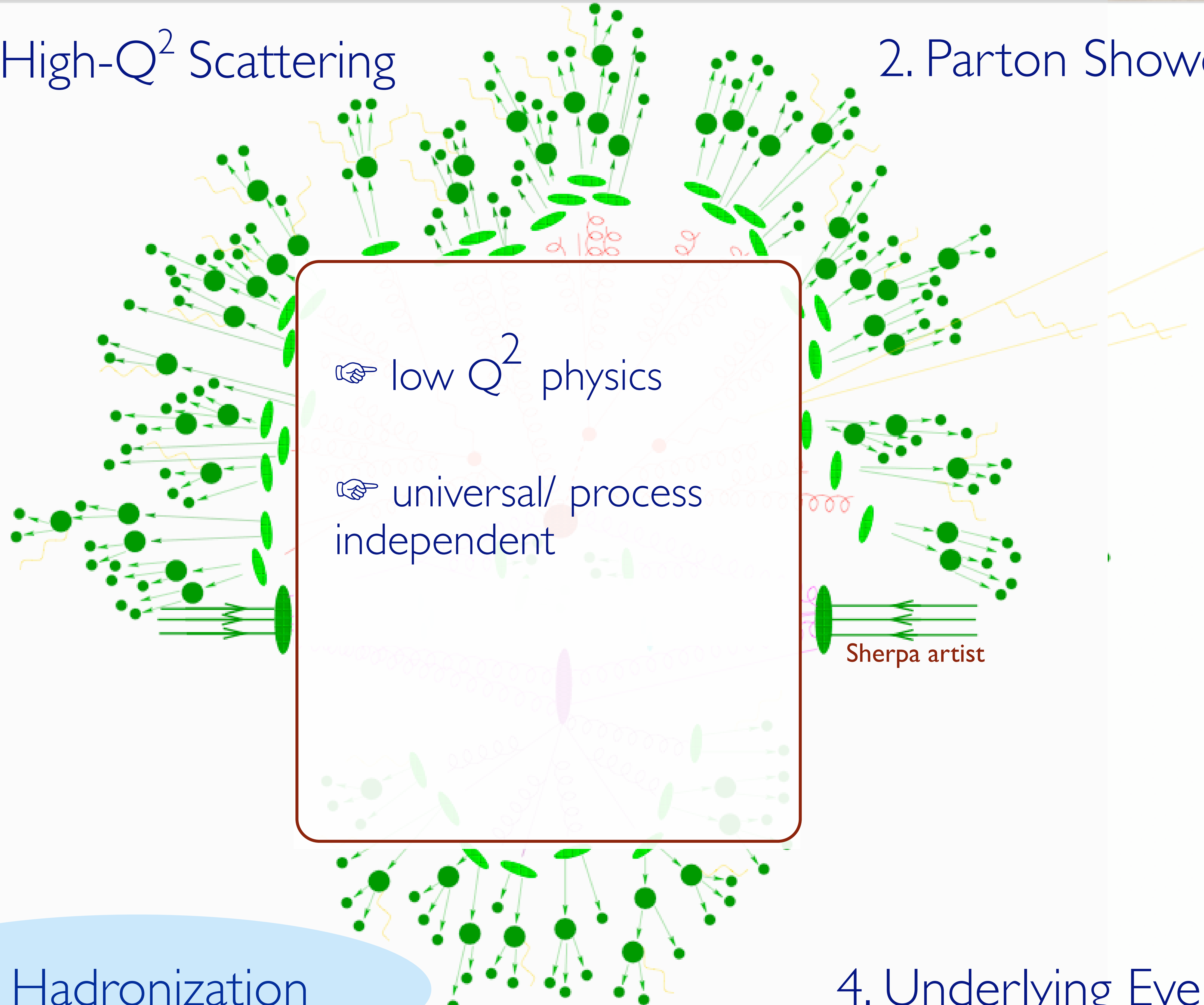


3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ low Q^2 physics

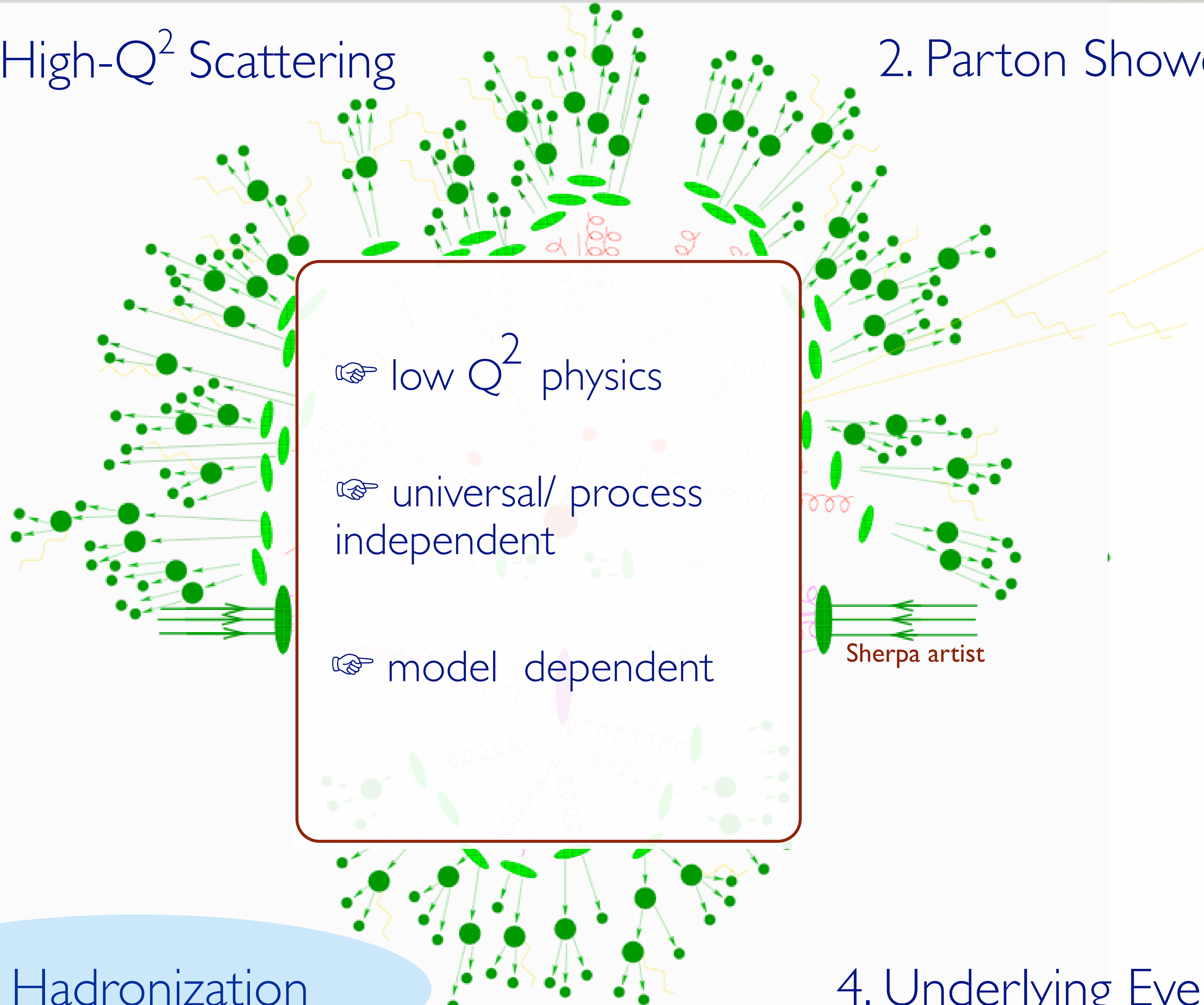
☞ universal/ process independent

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



- ☞ low Q^2 physics
- ☞ universal/ process independent
- ☞ model dependent

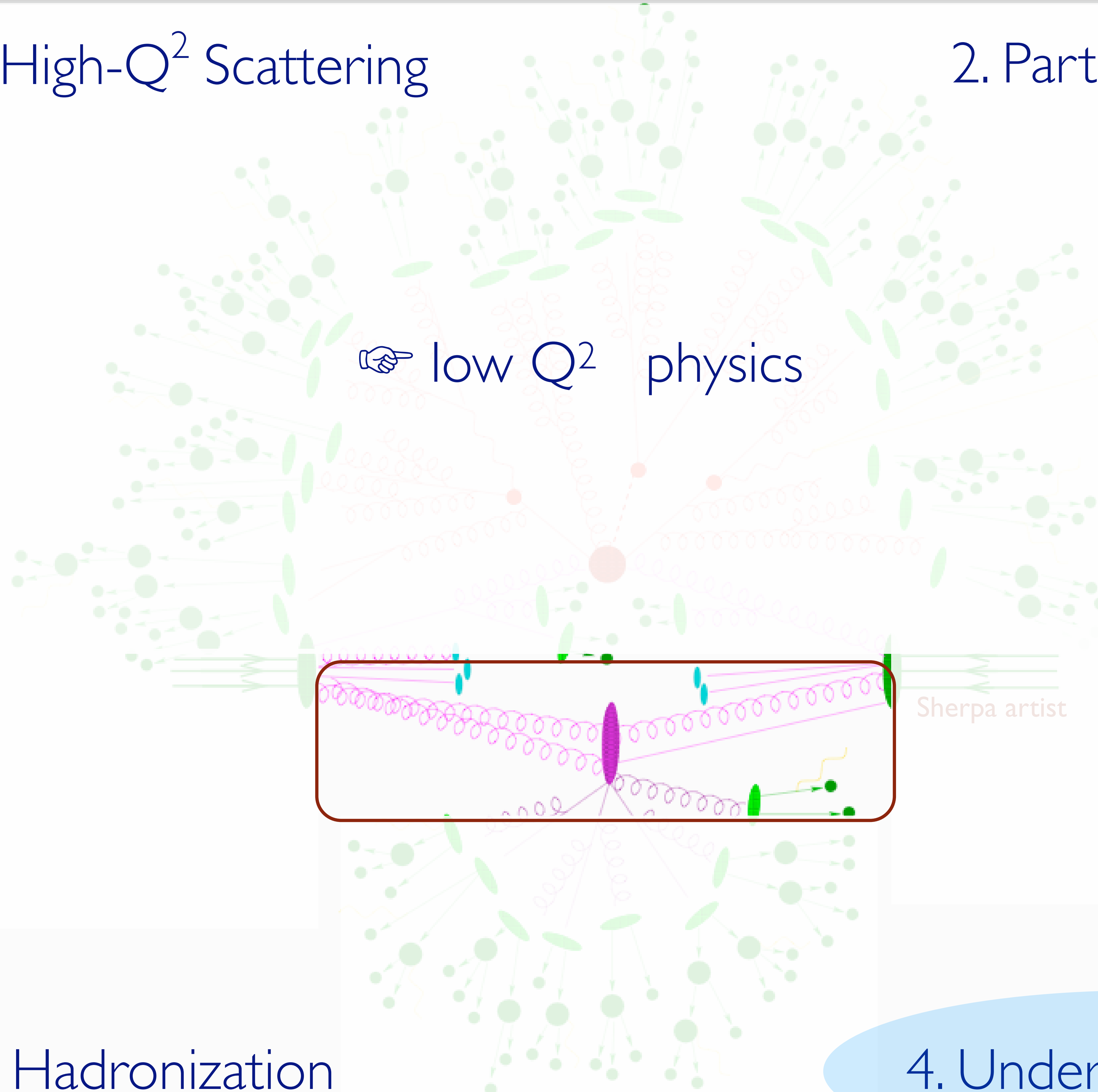
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

☞ low Q^2 physics

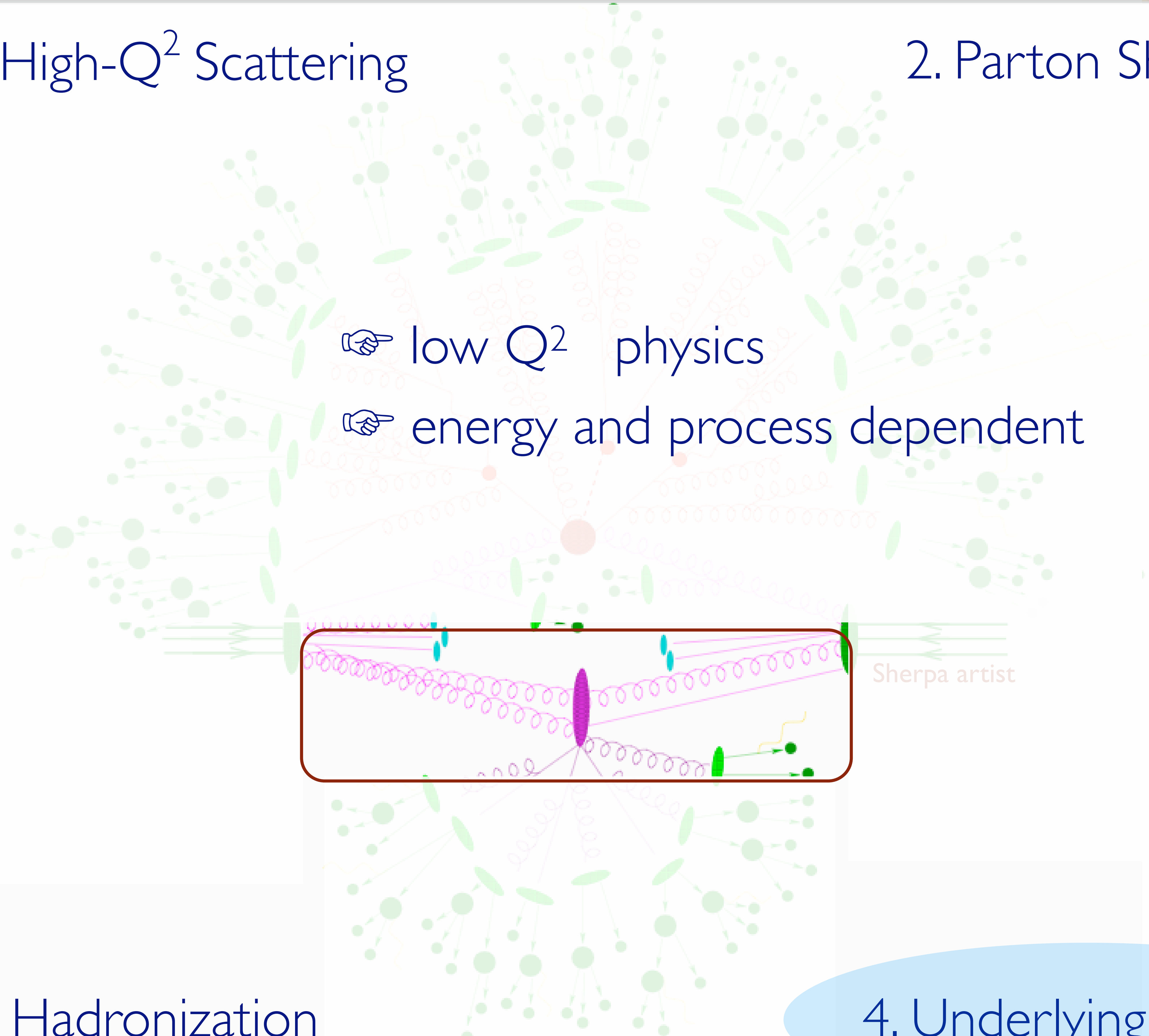


3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



- ☞ low Q^2 physics
- ☞ energy and process dependent

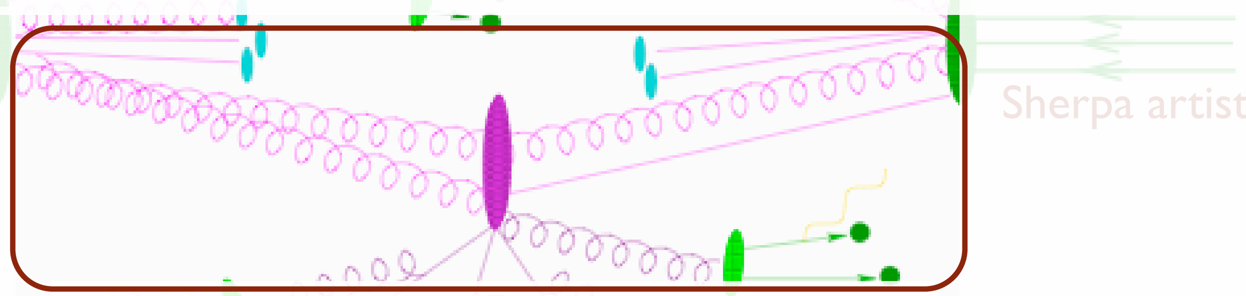
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

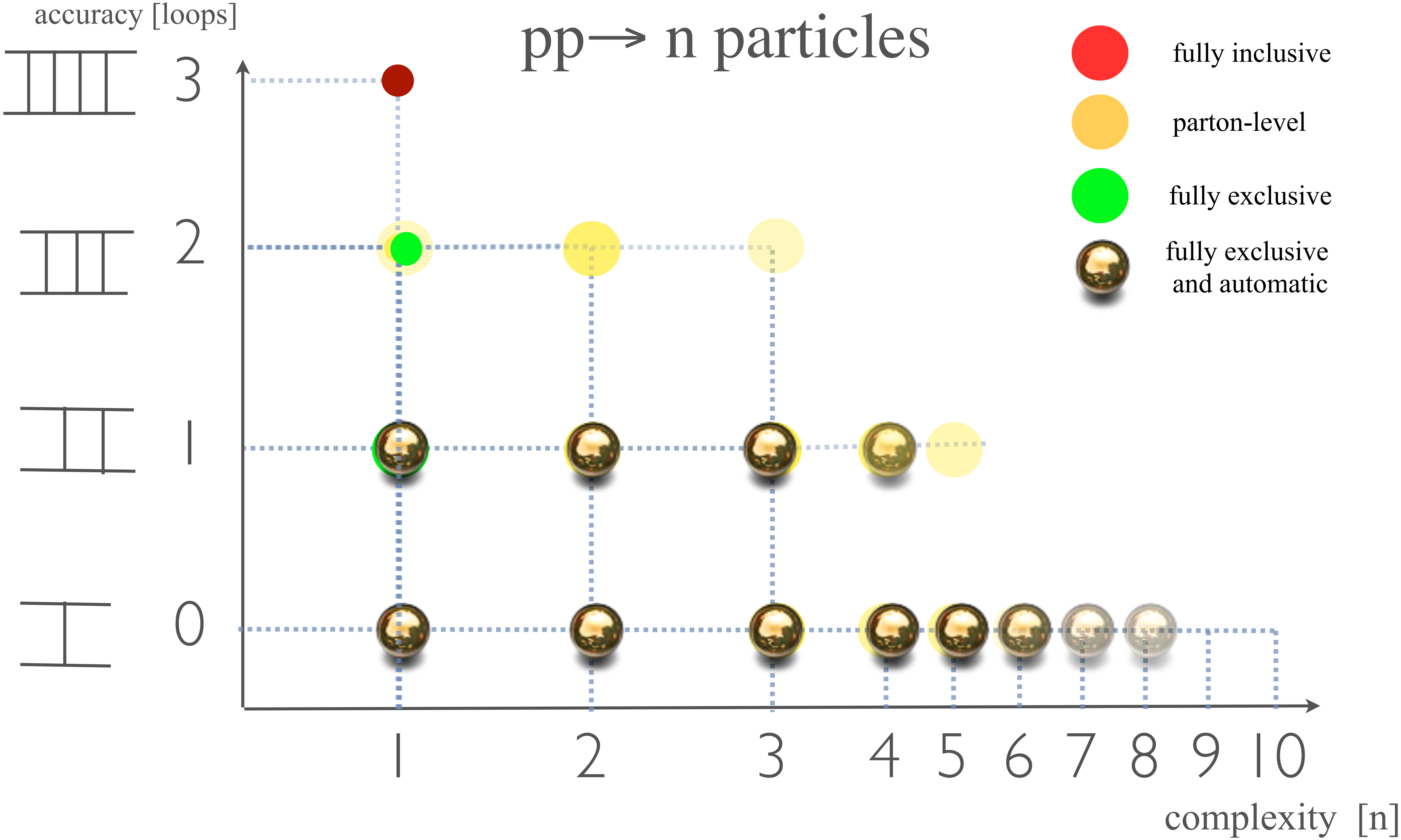
- ☞ low Q^2 physics
- ☞ energy and process dependent
- ☞ model dependent



3. Hadronization

4. Underlying Event

SM Status


accuracy [loops]
pp→ n particles
fully inclusive
parton-level
fully exclusive
fully exclusive and automatic
3
2
1
0
1 2 3 4 5 6 7 8 9 10
complexity [n]

Summary so far

- High energy collisions allow to probe interactions at very short distances, but entail SM physics that has to be described with:
  - ✦ Identify observables that can be calculated and measured reliably.
  - ✦ Accurate/Precise predictions => difficult calculations, multi-loop, QCD, EW.
  - ✦ A fully exclusive approach (associate an history to each short distance event).

Discoveries in the precision era

Question:

Precise/accurate predictions are very difficult/expensive.
Are we sure they are really needed? For what exactly?

Discoveries in the precision era

Question:

Precise/accurate predictions are very difficult/expensive.
Are we sure they are really needed? For what exactly?

Short answer:

The discovery potential of any collider working in the precision phase (fixed energy, accumulating luminosity) is directly related to our ability to make precise predictions.

New Physics

- A new force has been discovered, the first elementary of Yukawa type ever seen.
- Its mediator looks a lot like the SM scalar: H-universality of the couplings
- No sign of…..New Physics (from the LHC)!

- We have no bullet-proof theoretical argument to argue for the existence of New Physics between 8 and 13 TeV and even less so to prefer a NP model with respect to another.

New Physics

The obvious imperative:

LOOK FOR NP AT THE LHC BY COVERING THE WIDEST RANGE OF TH- AND/OR EXP-MOTIVATED SEARCHES.

Searches should aim at being sensitive to the highest-possible scales of energy

Searching for new physics

Model-dependent	⟷	**Model-independent**
SUSY, 2HDM, ED,…		simplified models, EFT, …
Search for new states	⟷	**Search for new interactions**
specific models, simplified models		anomalous couplings, EFT…
Exotic signatures	⟷	**Standard signatures**
precision measurements		rare processes

Searching for new physics

Search for new states ⟷ Search for new interactions

SUSY, EXOTICS, BSM HIGGS

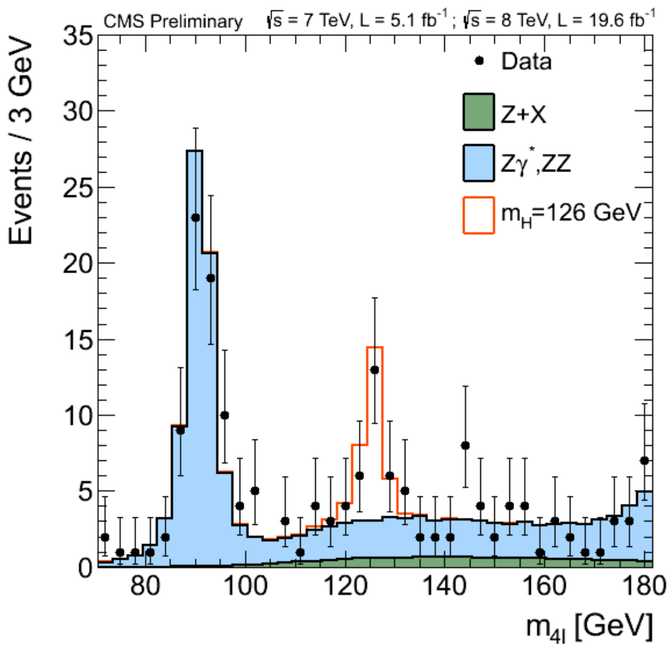
SM

Searching for new resonances

Searching for new resonances

peak

pp→H→4l



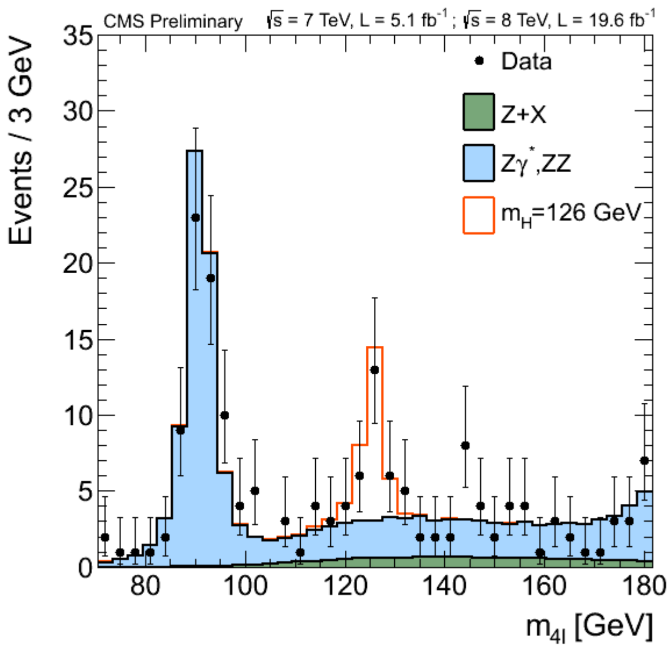
"easy"

Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)

Searching for new resonances

peak

$pp \to H \to 4l$

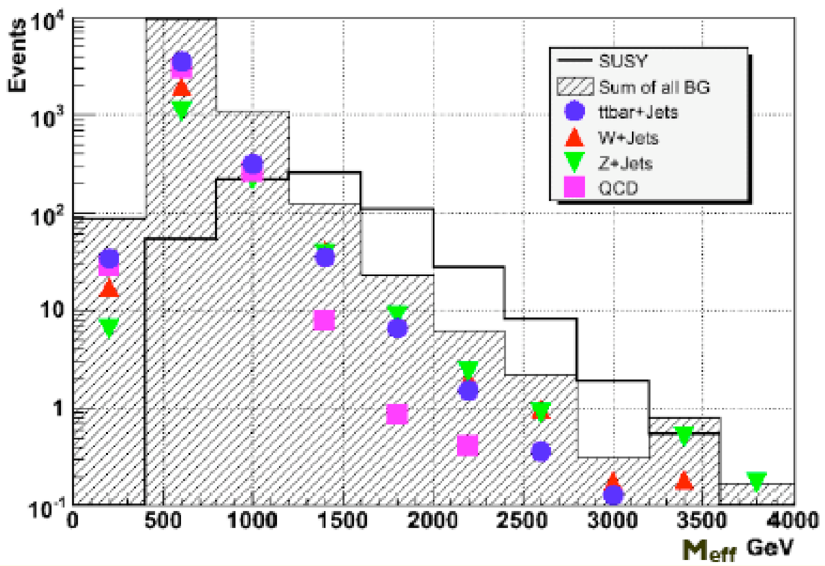


"easy"

Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)

shape

$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets + \not{E}_T$

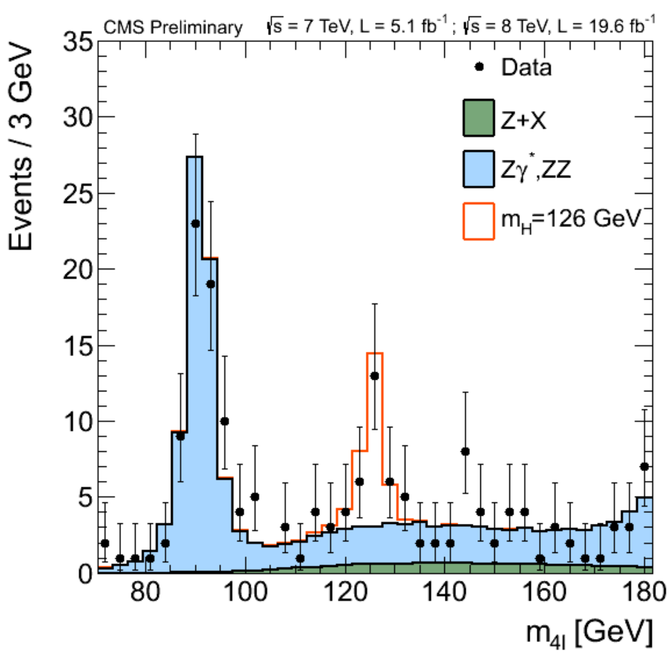


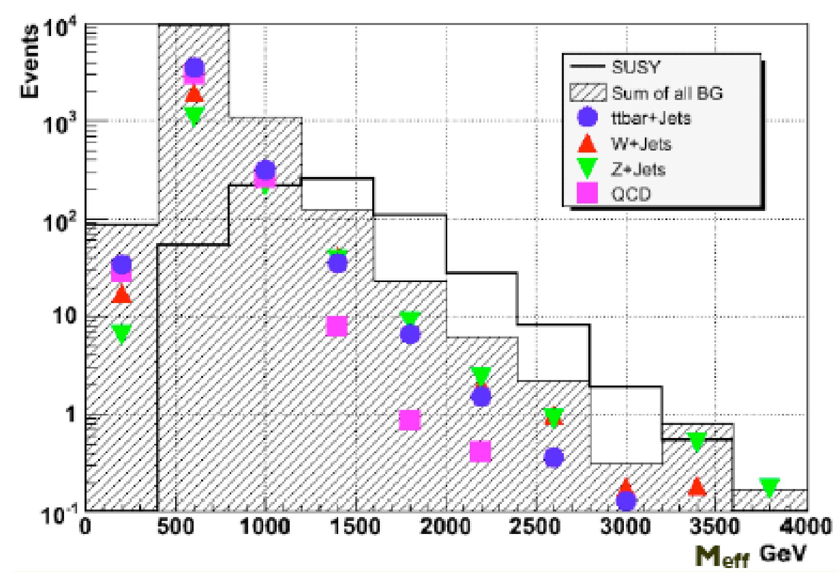
hard

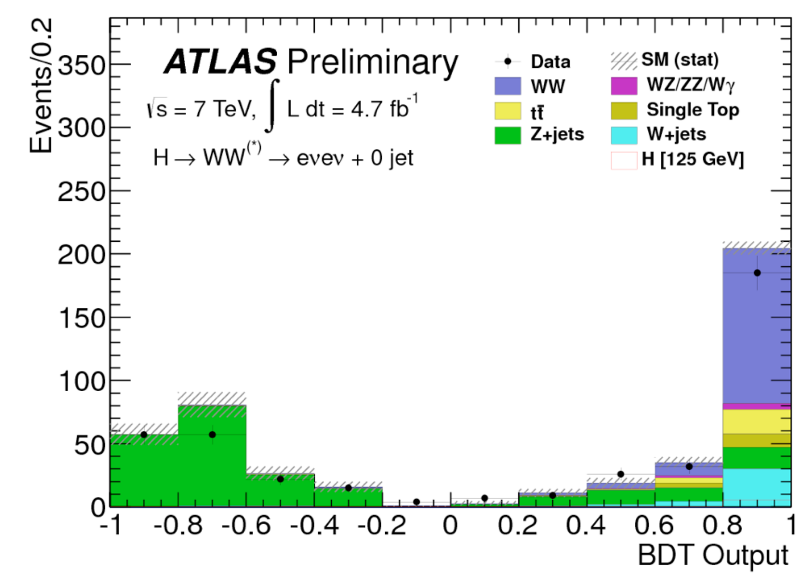
Background shapes needed. Flexible MC for both signal and background tuned and validated with data.

Searching for new resonances

peak	shape	discriminant
$pp \to H \to 4l$	$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets + \not{E}_T$	$pp \to H \to W^+W^-$



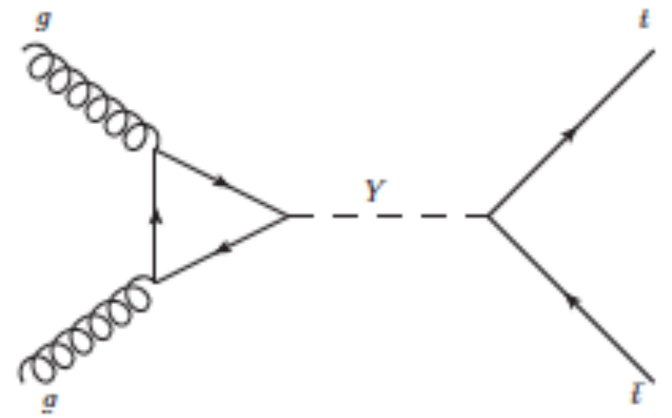




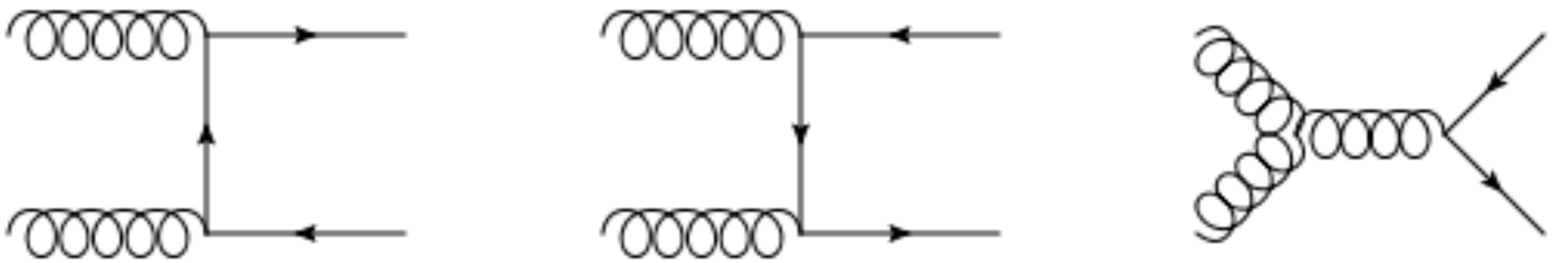
"easy"	hard	very hard
Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)	Background shapes needed. Flexible MC for both signal and background tuned and validated with data.	Background normalization and shapes known very well. Interplay with the best theoretical predictions (via MC) and data.

A simple example: $t\bar{t}$

Imagine a new scalar exists which couples mostly to top quark, similar to the SM Higgs, but it is heavier than $2m_t$. It would be produced as the SM Higgs via gluon fusion and then mostly decay to top quarks:

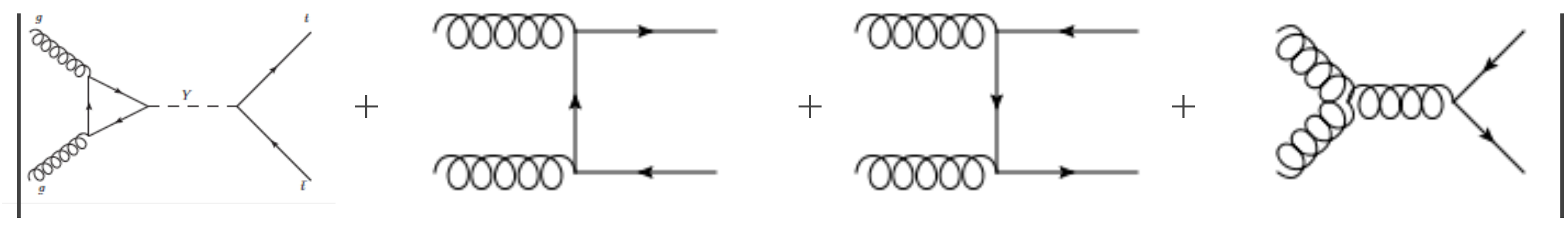


giving rise to a peak in the invariant mass distribution of m(tt). However, this process interferes with the QCD background:



A simple example: $t\bar{t}$

|Amp|^2=



Taking our previous calculation of the SM amplitude and adding the scalar production:

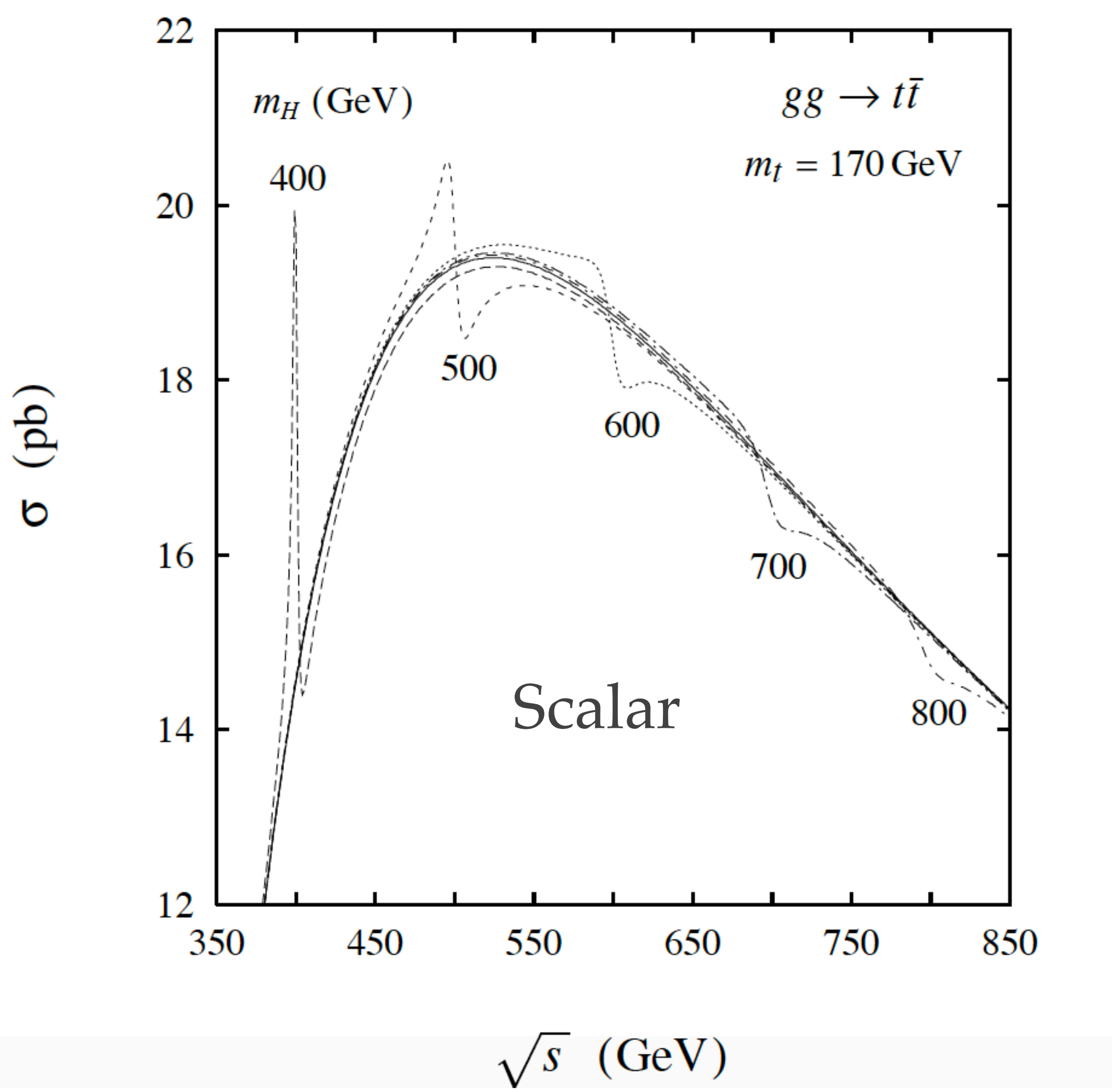
$$\hat{\sigma}(s) = \frac{\alpha_s^2 G_F^2 m^2 s^2}{768\,\pi^3}\beta^3 \left|\frac{N(s/m^2)}{s - m_H^2 + i m_H \Gamma_H(s)}\right|^2$$ ← BW resonance

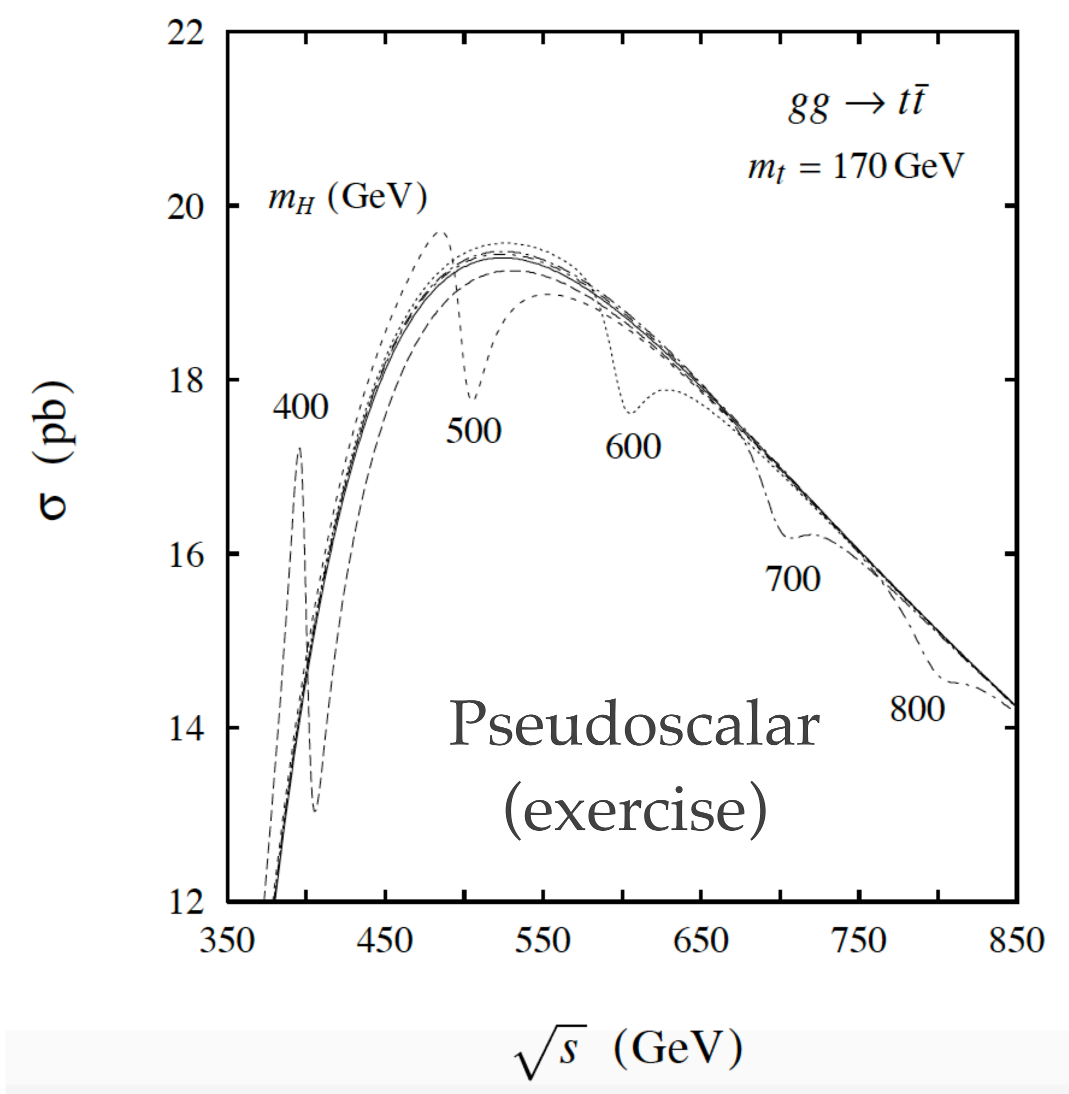
$$-\frac{\alpha_S^2 G_F m^2}{48\pi\sqrt{2}}\beta^2 \ln\frac{1+\beta}{1-\beta}\ \mathrm{Re}\left[\frac{N(s/m^2)}{s - m_H^2 + i m_H \Gamma_H(s)}\right]$$ ← Interference

$$+\hat{\sigma}_{\mathrm{SM}}(s)$$ ← SM

$$N(s/m^2) = \frac{3}{2}\frac{m^2}{s}\left[4 - \left(1 - \frac{4m^2}{s}\right) I(s/m^2)\right] \qquad I(s/m^2) = \left[\ln\frac{1+\beta}{1-\beta} - i\pi\right]^2 \qquad (s > 4m^2)$$

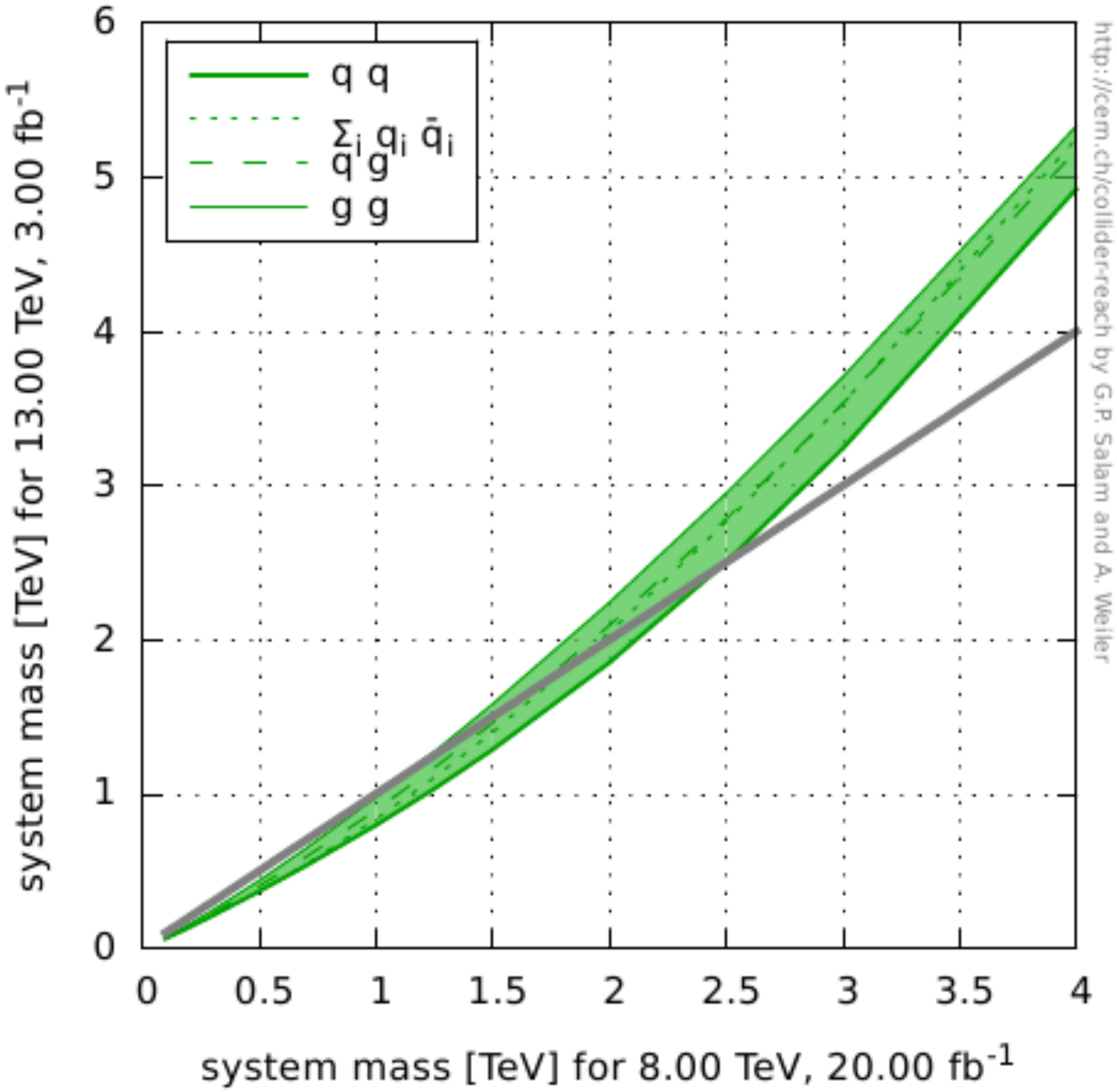
A simple example: $t\bar{t}$

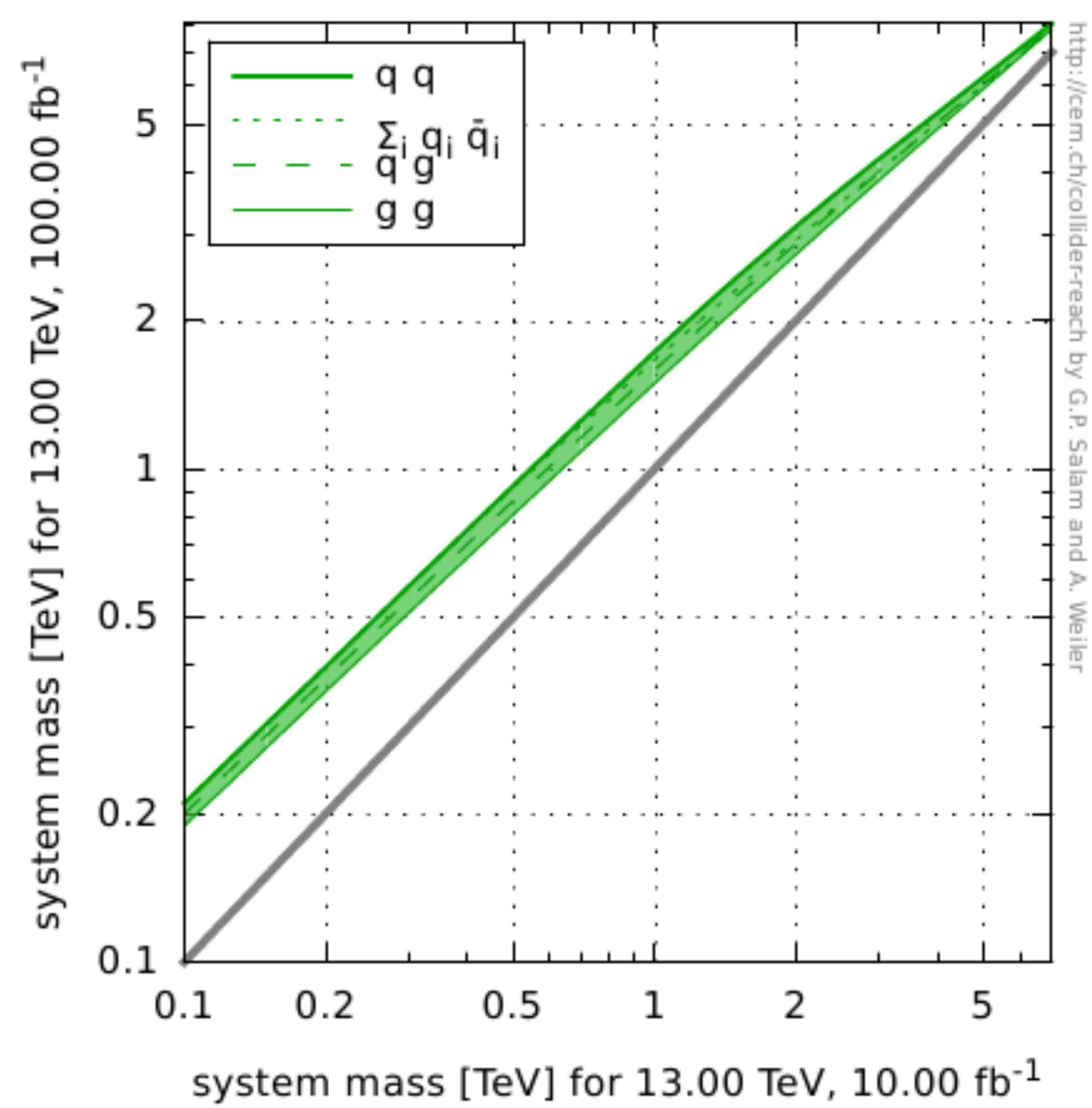




Peaks but also peak-dip and dip only structures. "Easy" to discover independently of the precise knowledge of the SM. However, needs accurate theory to characterise it.

Collider reach





Increasing the energy of a collider gives a big boost to the reach of resonance searches, while the gain due to the increase of luminosity is marginal (beware of assumptions here).

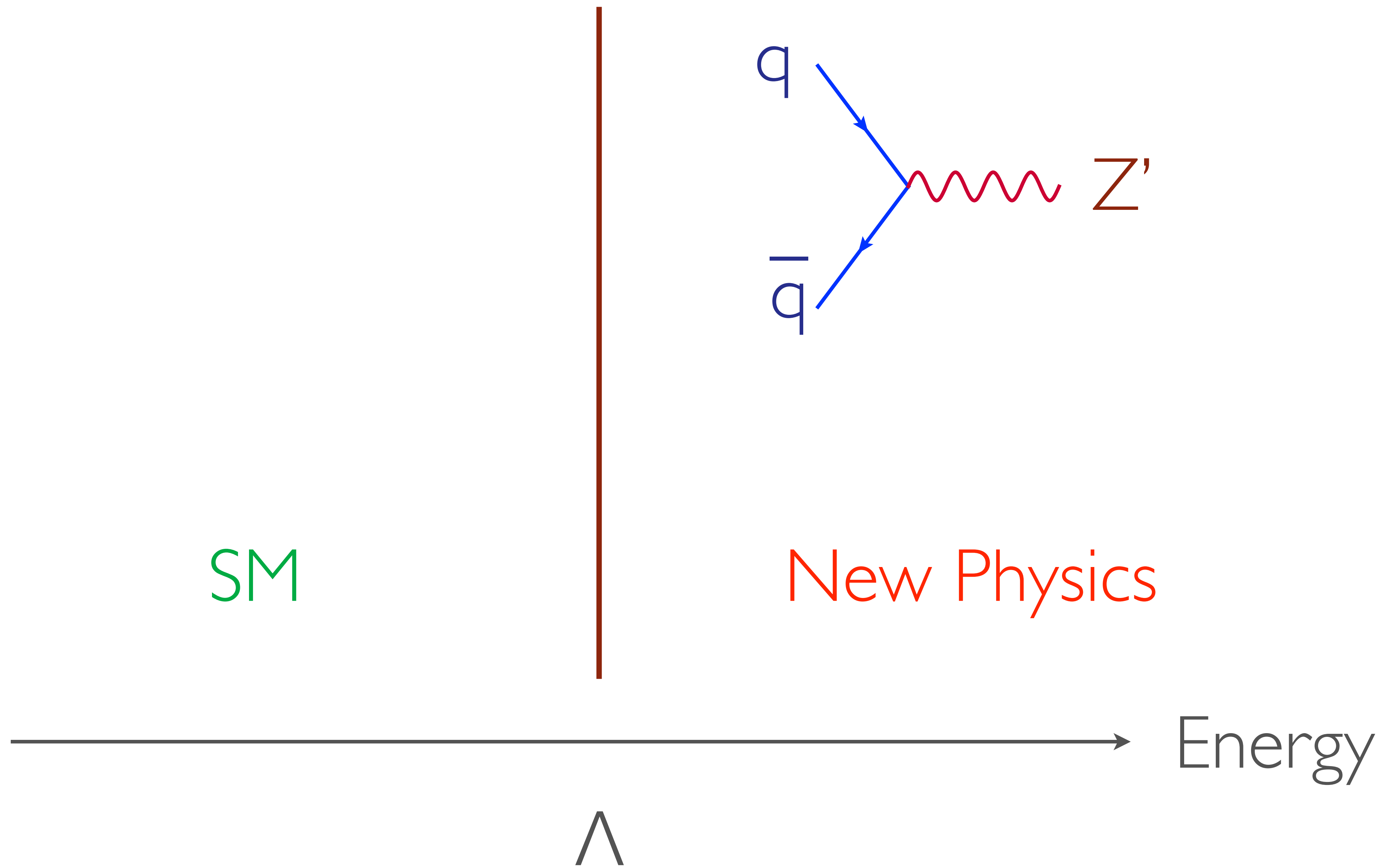
Searching for new physics

Search for new states ⟷ Search for new interactions

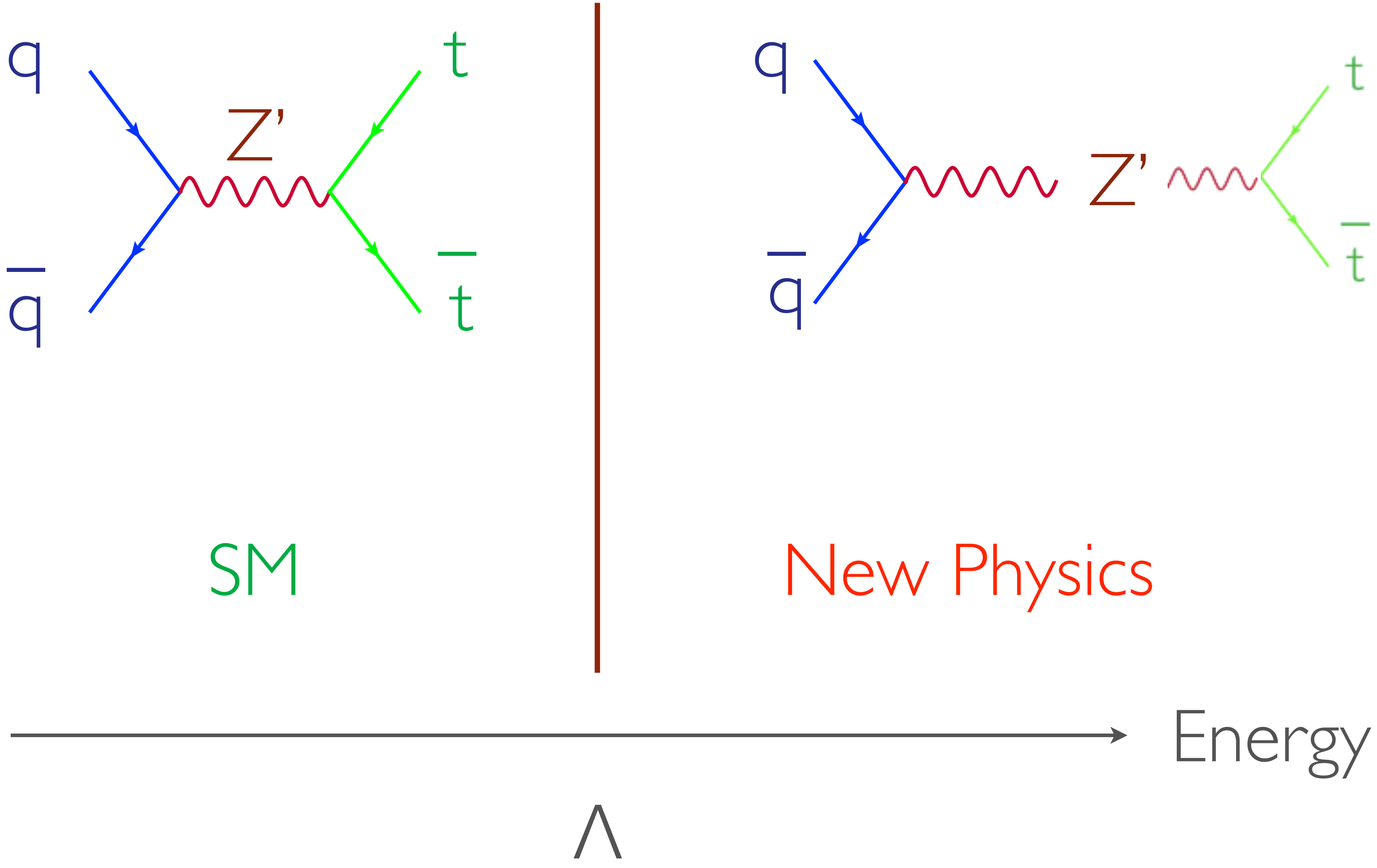
SUSY, EXOTICS, BSM HIGGS

SM

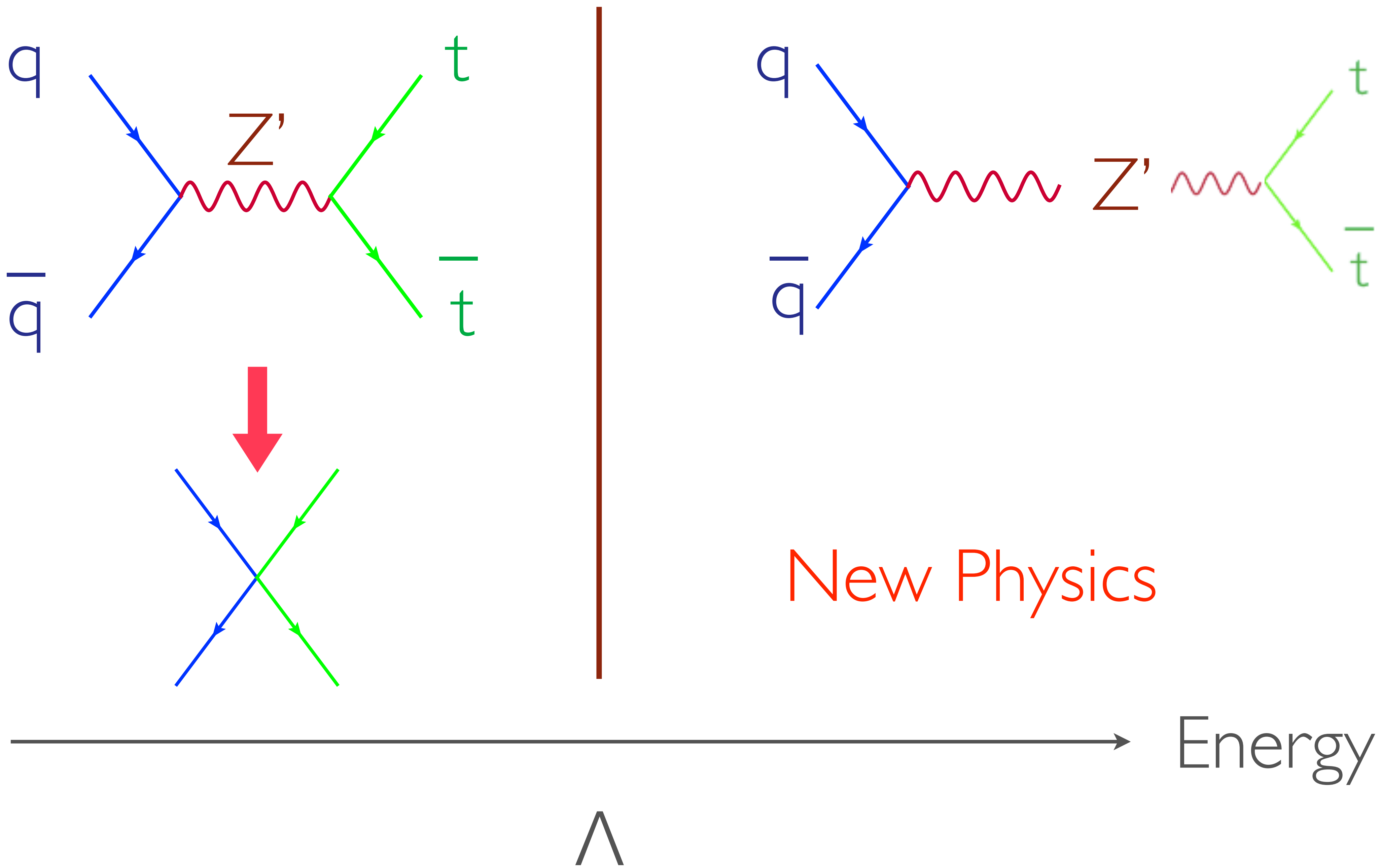
Search for New Interactions



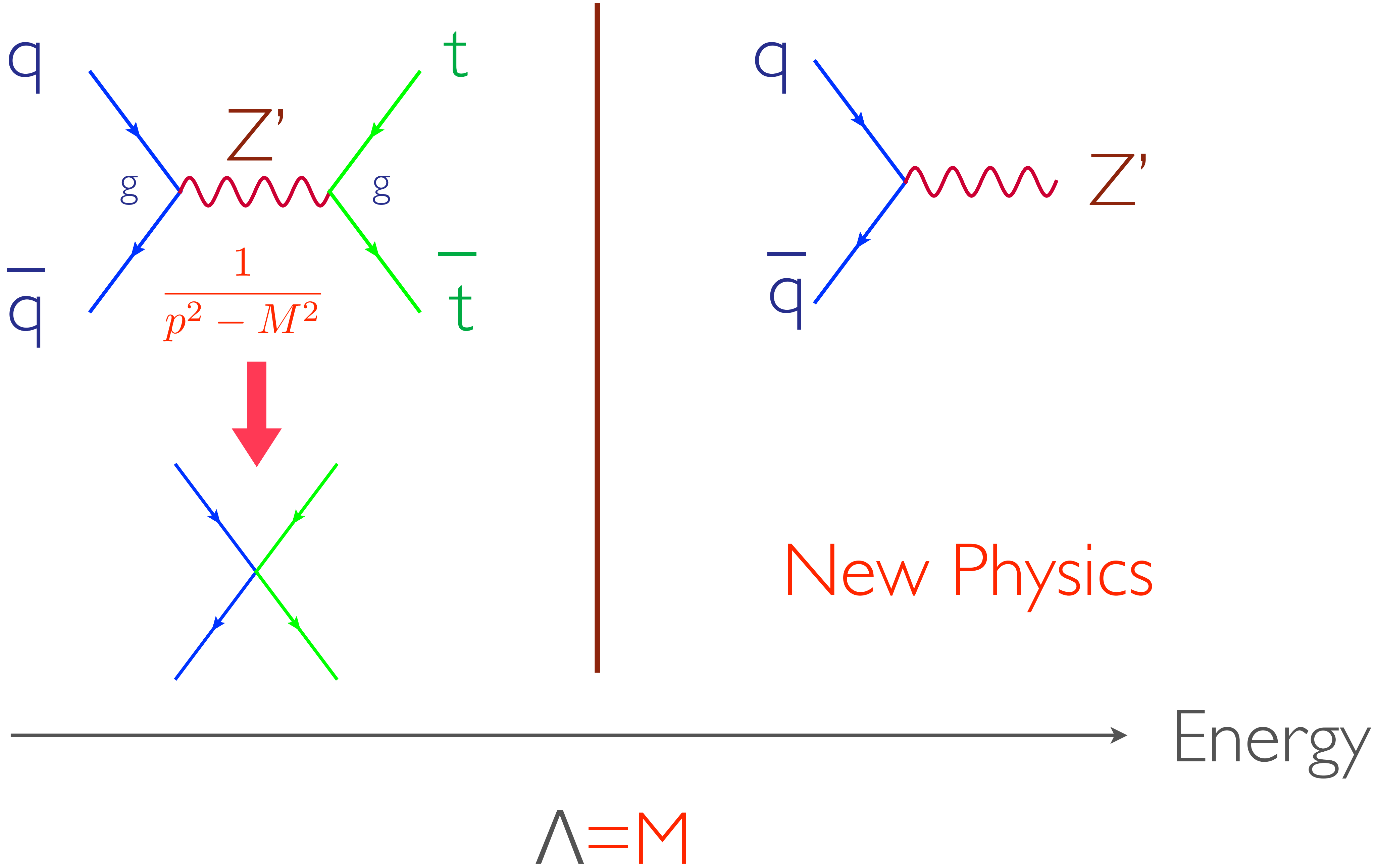
Search for New Interactions



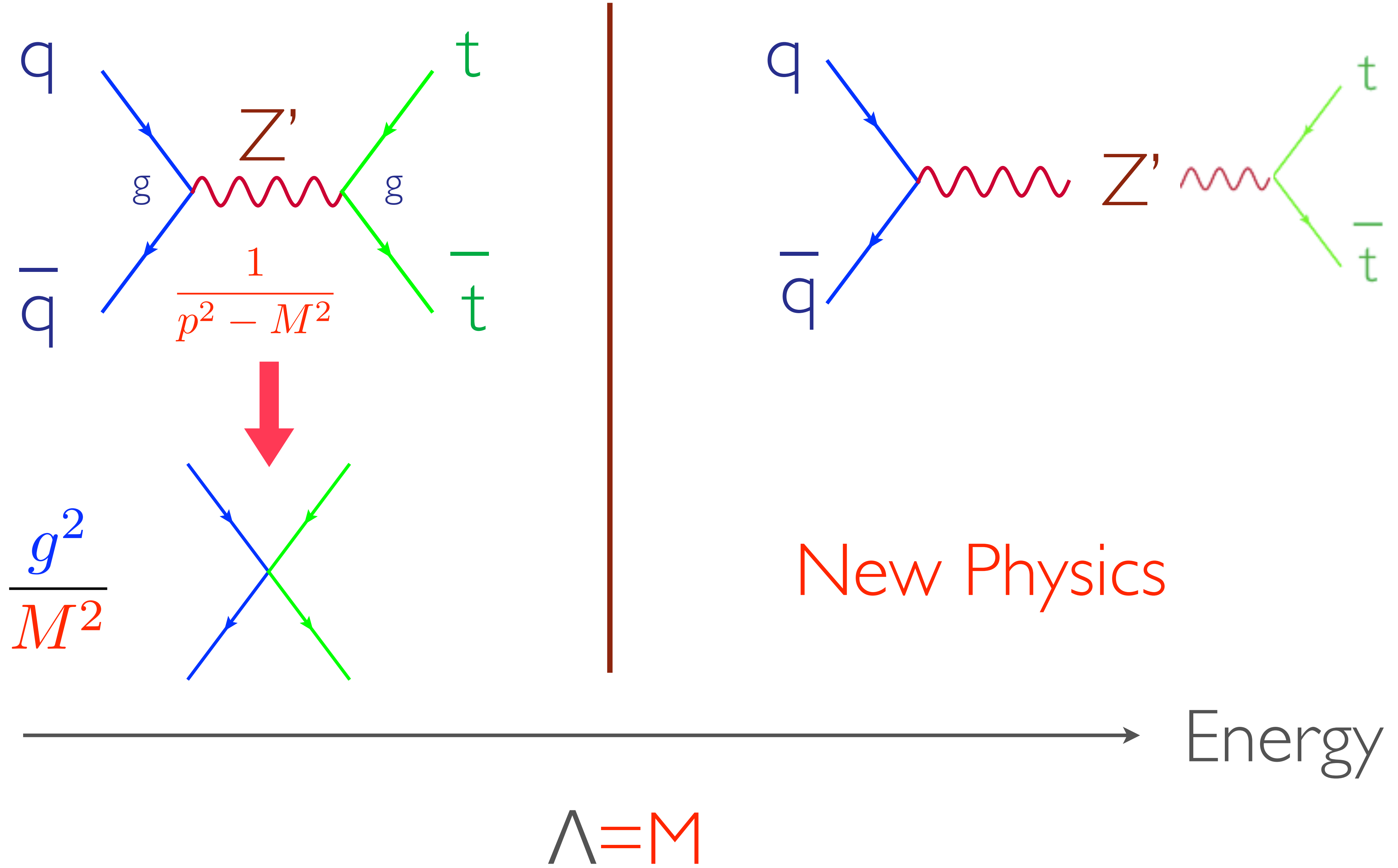
Search for New Interactions



Search for New Interactions

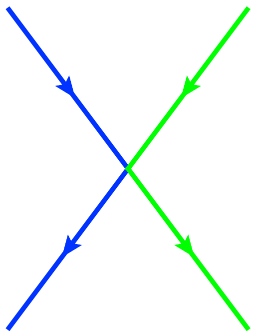


Search for New Interactions



Search for New Interactions

$$\frac{g^2}{M^2}$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{g^2}{M^2}\bar{\psi}\psi\bar{\psi}\psi$$

$$M^2 = g^2 v^2 \Rightarrow \Lambda = v$$

Λ is an upper bound on the scale of new physics

Search for New Interactions

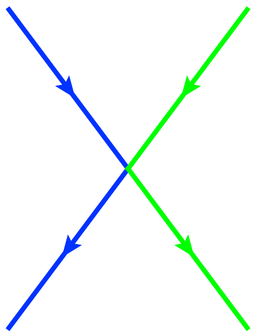
$$\hbar = c = 1$$

$$\dim A^\mu = 1$$

$$\dim \phi = 1$$

$$\dim \psi = 3/2$$

$$\frac{g^2}{M^2}$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\text{dim}=6}$$

59 operators *[Buchmuller, Wyler, 1986]*

The way of SMEFT

The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

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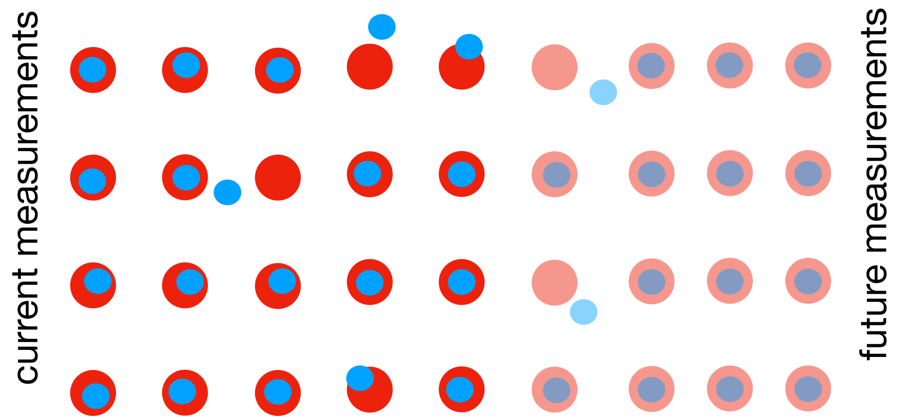

⇒ increased NP Sensitivity

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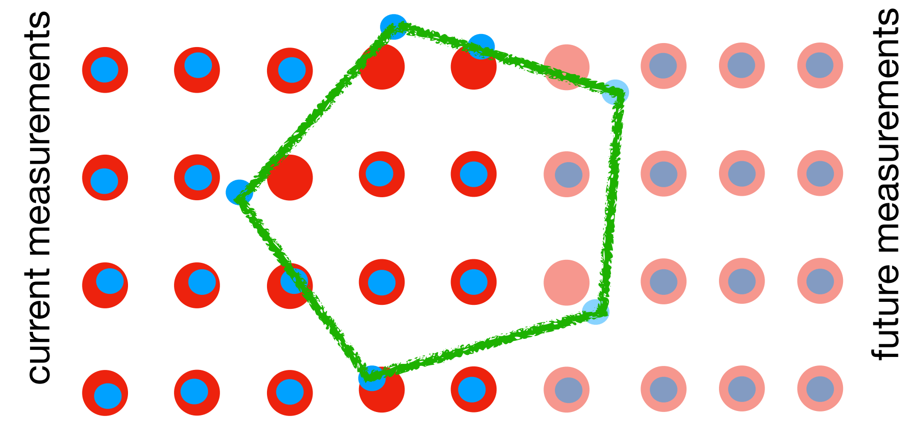

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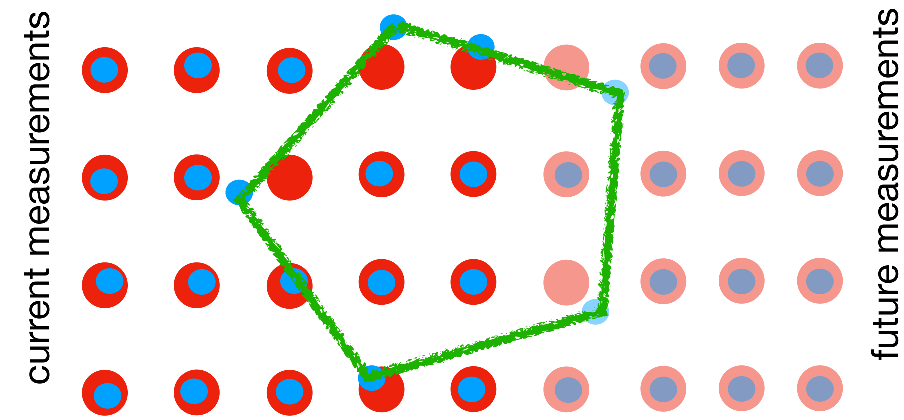
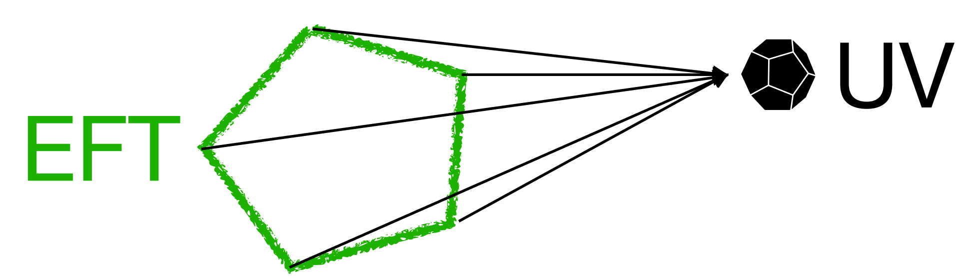


⇒ increased NP Sensitivity

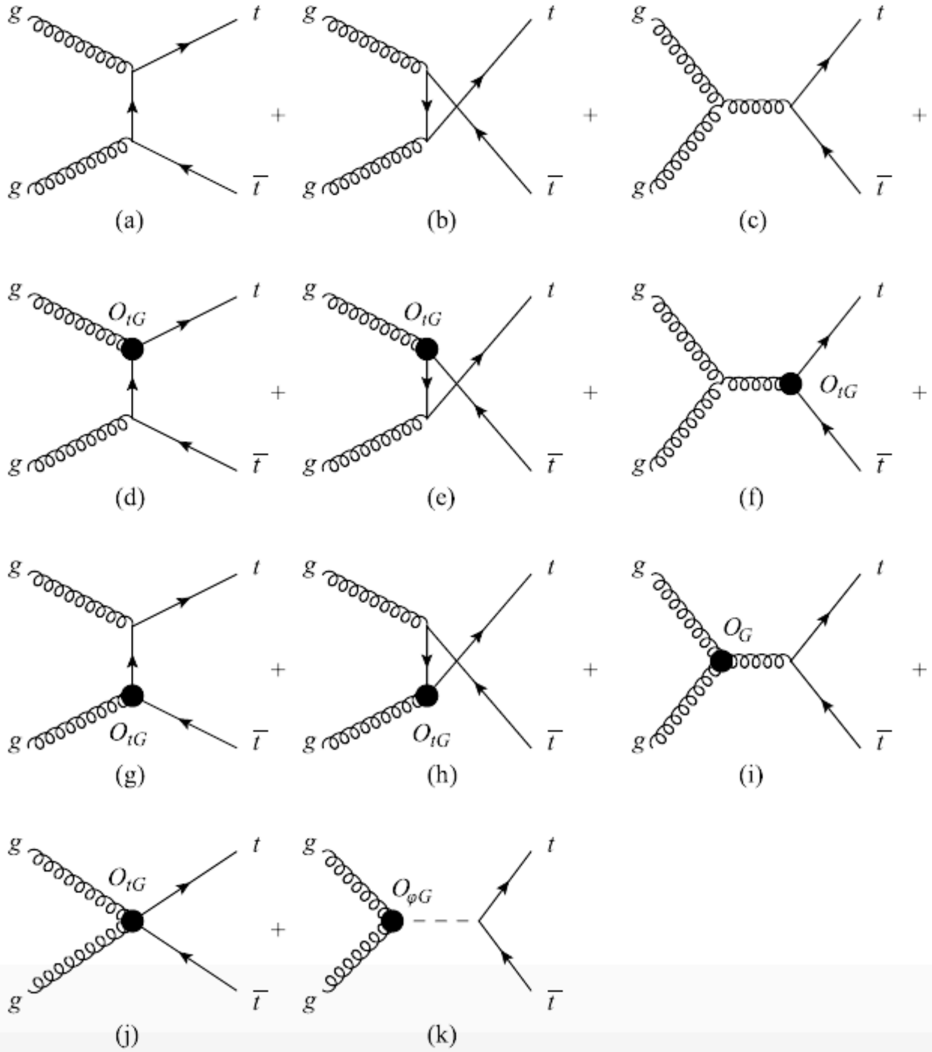
⇒ increased UV identification power



A simple example: $t\bar{t}$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$$
$$O_G = f_{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$$
$$O_{\phi G} = \frac{1}{2}(\phi^+\phi)G^A_{\mu\nu}G^{A\mu\nu}$$

Three operators of dim=6 that enter tt



$$\beta = \sqrt{1-4m_t^2/\hat{s}}$$
$$\hat{\sigma}_{gg\to t\bar{t}} = \frac{\pi\alpha_s^2\beta}{48\hat{s}}\left(31\beta + \left(\frac{33}{\beta} - 18\beta + \beta^3\right)\ln\left[\frac{1+\beta}{1-\beta}\right] - 59\right)$$

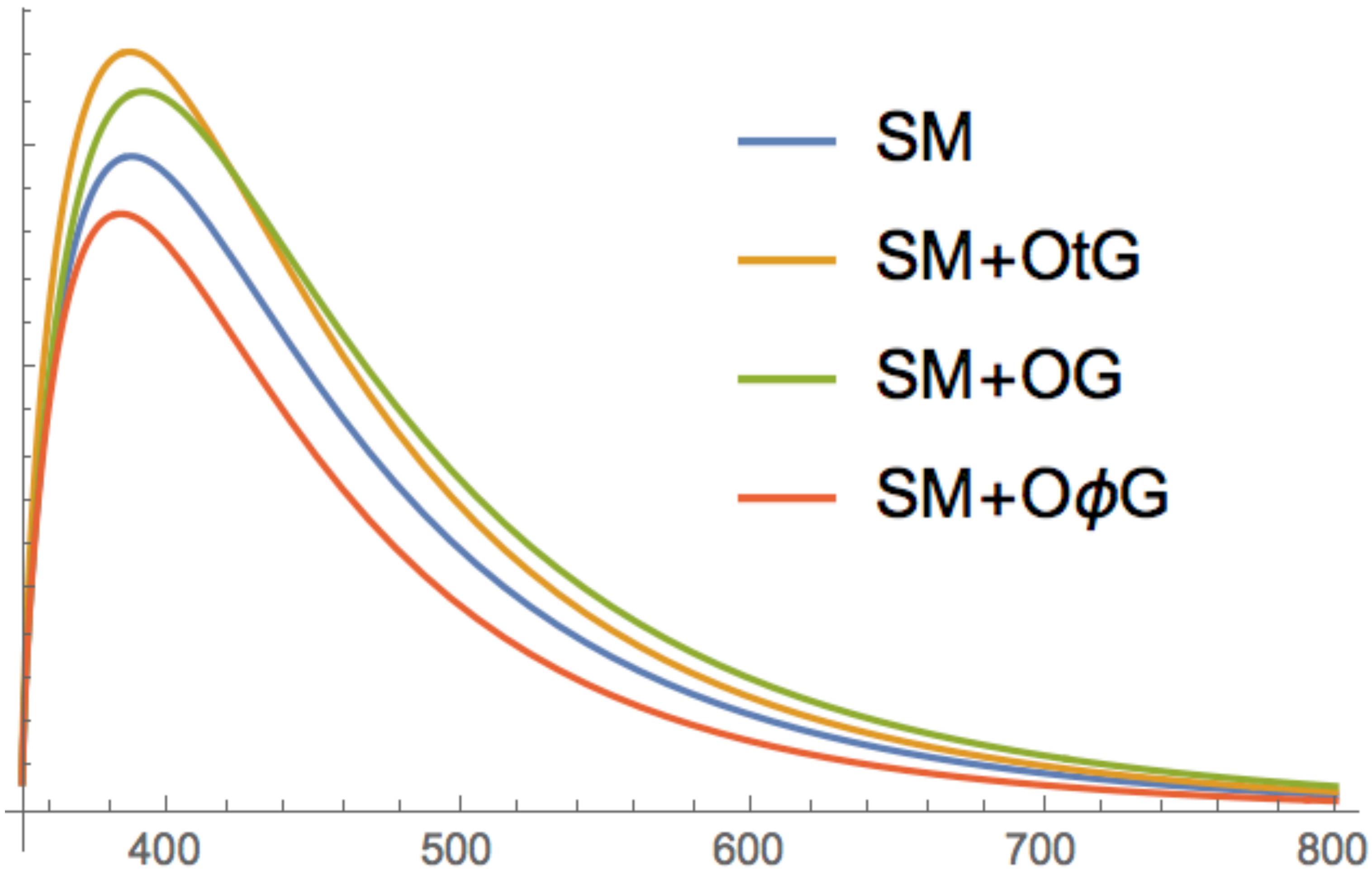
$$+\,\mathrm{Re}C_{tG}\frac{g_s^3 v\sqrt{1-\beta^2}}{48\sqrt{2}\pi\Lambda^2\sqrt{s}}\left(8\ln\frac{1+\beta}{1-\beta} - 9\beta\right)$$

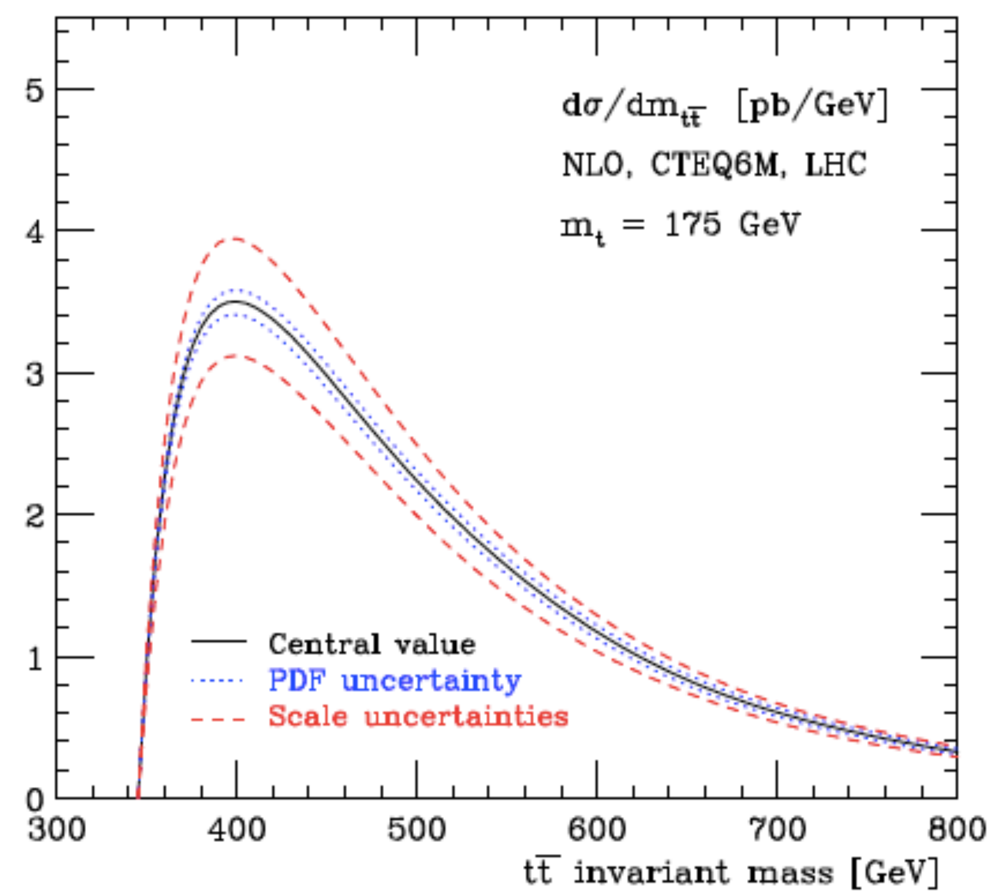
$$+C_G\frac{9g_s^3(1-\beta^2)}{256\pi\Lambda^2}\left(\ln\frac{1+\beta}{1-\beta} - 2\beta\right)$$

$$-\,C_{\phi G}\frac{g_s^2 s\beta^2(1-\beta^2)}{256\pi\Lambda^2(s-m_h^2)}\ln\frac{1+\beta}{1-\beta}$$

A simple example: $t\bar{t}$

These new interactions lead to deformations of the SM distributions.



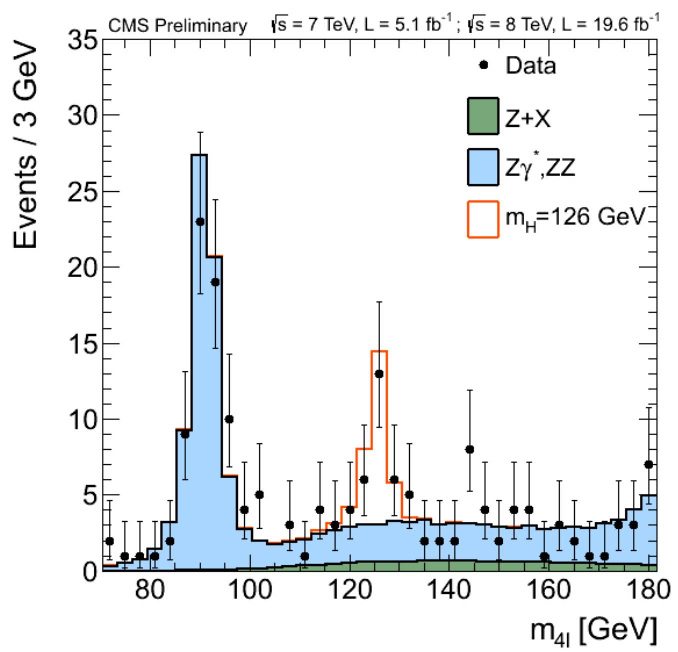


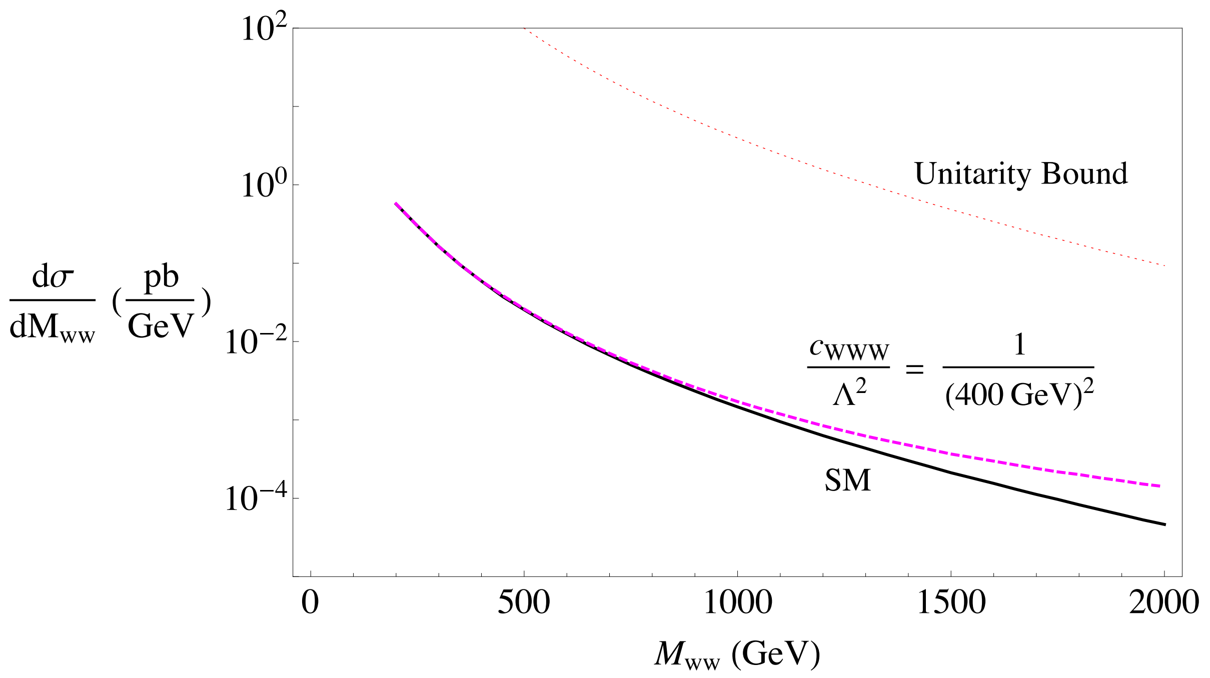
Need to know the SM distributions extremely well as well as the EFT ones!

Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states ⟷ Search for new interactions





"Peak" or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

New generation of MC tools

Theory

Lagrangian
Gauge invariance
QCD
Partons
NLO
Resummation
...

Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
...

Experiment

New generation of MC tools

Theory

Lagrangian
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Experiment

New generation of MC tools

- Idea
- Lagrangian
- FeynRules
- ME Generator
- Signal & Bkg
- Events
- PS+Had
- Detect. Sim.
- Data

Aims of the week

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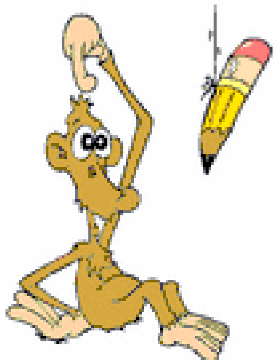
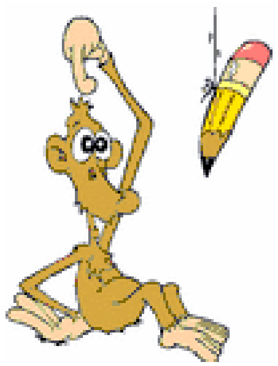


THINK

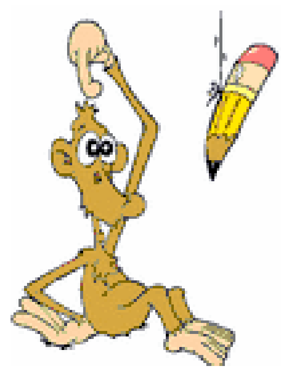
Aims of the week



THINK

PARTICIPATE

Aims of the week

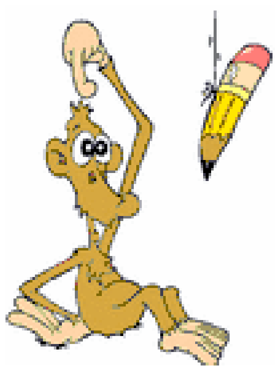


Think

Participate

Work

Aims of the week



THINK PARTICIPATE WORK

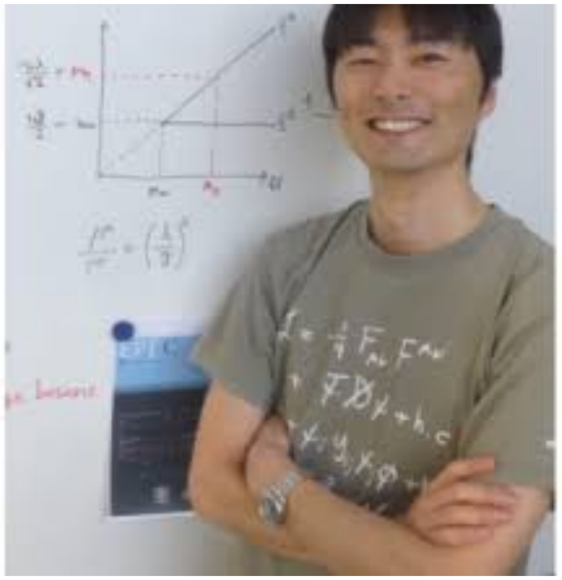
- The morning lectures for reviewing or introducing new concepts
- The afternoons, the most important part of the school, will be devoted to the tutorials

Aims of the week

- Master the basic concepts of collider physics
- Learn about the latest techniques that allow to make accurate and predictions for events at the LHC in the SM and Beyond.
- Install the full chain of tools on your laptop.
- Apply and use the tools to make your own New Physics search, simulating signal and background.
- At the end of the week you'll be ready to roll

Mad Hosts

Karou Hagiwara



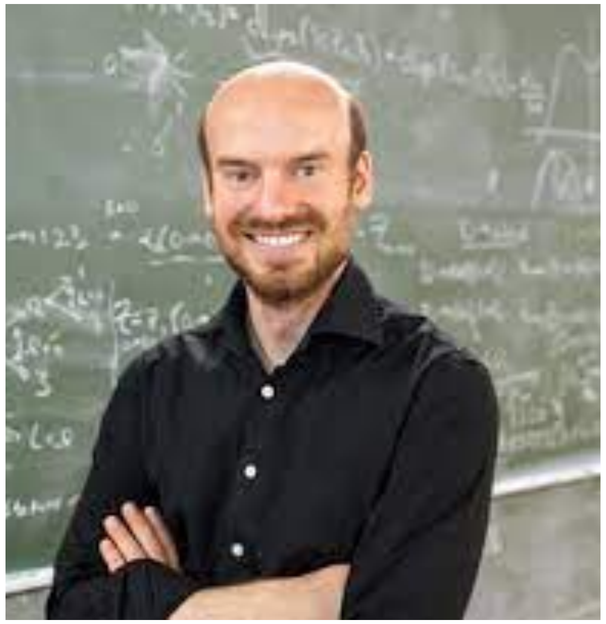
Kentarou Mawatari

Mad Teachers


Davide Pagani


Olivier Mattelaer


Benjamin Fuks


Rikkert Frederix

We are here for you!