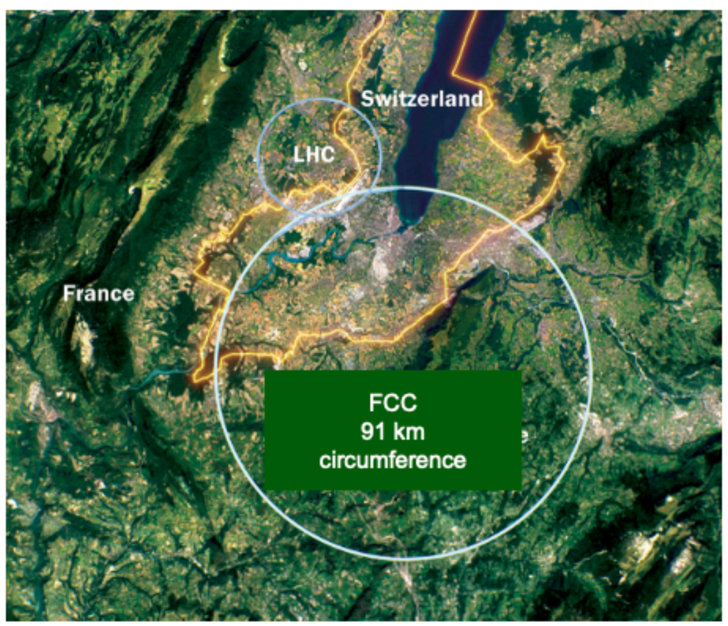
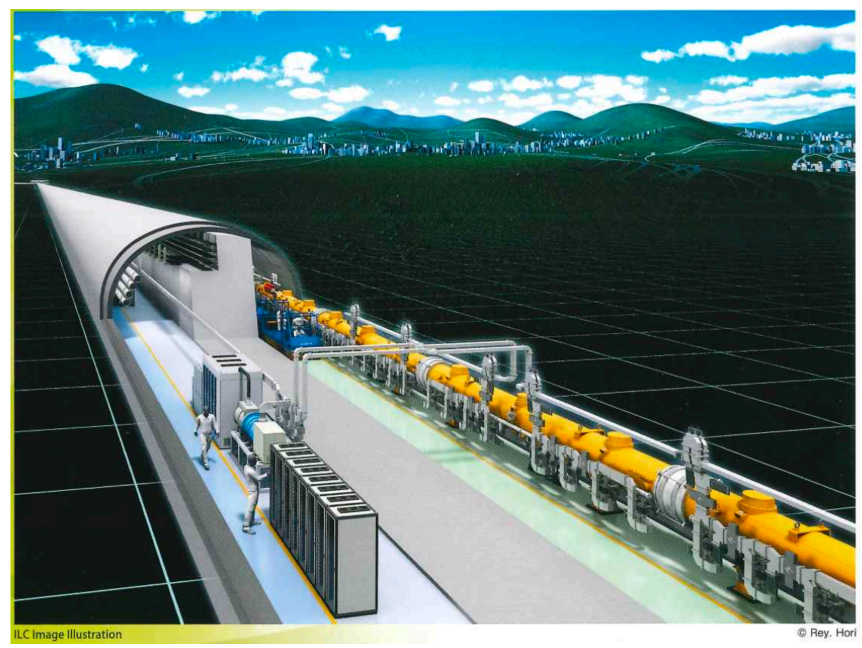
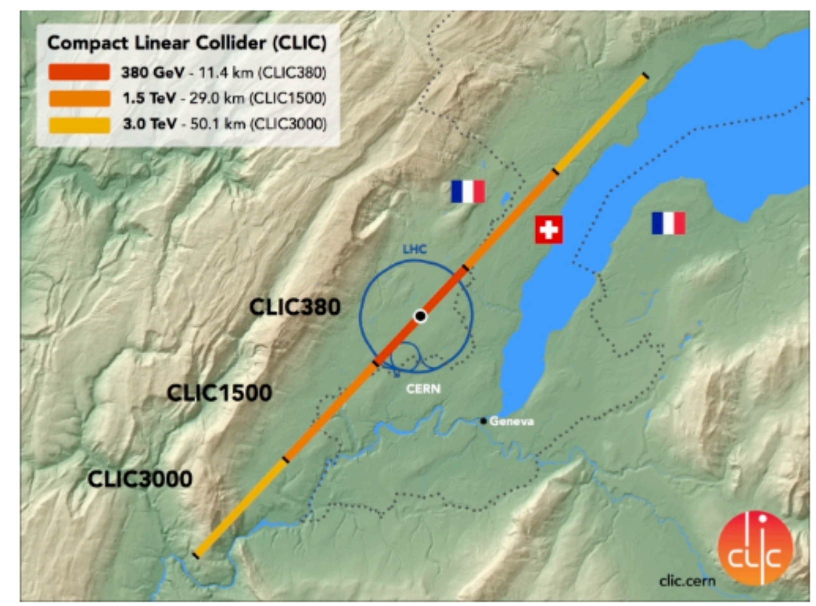
Introduction to Collider Experiments
— physics at future e+e-







Junping Tian (U. Tokyo)

Iwate Collider School @ Appi Kogen, Mar 2-6, 2026

About me: Junping Tian (田 俊平)

affiliation ICEPP, The University of Tokyo

GOAL

Advance our understanding of the universe in my area of interest and expertise.

EDUCATION

2001-2005 Tsinghua University

B.S. in Physics Thesis: *Study of Heavy Quarkonium*

2005-2011 Tsinghua University

Ph.D. in Physics Thesis: *Study of the Higgs Self-coupling at the ILC*

ACADEMIC POSITIONS

2019–Present Assistant Professor (tenured)

U. Tokyo Work on the physics at the International Linear Collider (ILC) and the detector optimization for the International Large Detector (ILD).

2016 – 2019 Project Assistant Professor / Project Researcher

U. Tokyo Work on the physics at the ILC and the detector optimization for ILD.

2011– 2016 Researcher

KEK Work on the physics at the ILC and the detector optimization for the ILD; R&D on the Time Projection Chamber (TPC).

the HEP school I joined: FAPPS 2009 @ Mt. Fujii

I was a PhD student then, and was told ILC will be realized soon

hope it won't take another 16 years…

plan

(i) Mini-intro to future e+e- experiments

Lecture 1

(ii) Higgs Property Measurements

(iii) New Particle Searches

(iv) Top-quark & EW Measurements

Lecture 2

(v) Global Interpretation in SM EFT

focus will be on experimental concepts “why / what / how”
please learn theoretical concepts “why” from other lectures

(i) proposals of future “Higgs Factories”

$\sqrt{s}$ / GeV \ $\int L$ / ab^{-1}	91	160	240-250	350-365	550	1000-3000	Beam Polarization
LCF	0.1	0.5*	3	0.4	8	8	(80%, 30%)
CEPC	100	6.9	21.6	1*			(0, 0)
FCC-ee	205	19.2	10.8	3.16			(0, 0)

(+ emerging Muon Colliders, μTristen, HELEN, HALHF, ReLiC, ALEGRO, XCC, etc)

LCF: Linear Collider Facility @ CERN; identical to scenarios proposed by LC Vision Team up to 550 GeV; representing ILC, CLIC, C³

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- O(10^6) Higgs; O(10^9-10^{12}) Z; O(10^8) W; O(10^6) t-quark; ? #BSM; etc
- What physics can be advanced? Roles played by $\sqrt{s}$, $\int L$, Polarisation?

(i-1) basic concepts on accelerators

know better our tools which often constrain physics exploration

what behind $\sqrt{s}$ L $(\int L\mathrm{d}t)$ P ?

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what behind $\sqrt{s}$ L ($\int L\mathrm{d}t$) P ?

- **Radio-Frequency acceleration**

Electromagnetic fields oscillate at a perfect timing $l_i = \beta_i \frac{\lambda_{\mathrm{RF}}}{2}$

Gradient: ILC 31.5 MV/m; CLIC 100 MV/m

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- **Magnetic field (transverse acceleration)** $R = \frac{E}{ecB}$

SPPC / FCC-hh: E = 50TeV, C = 100km; B ~ 16T

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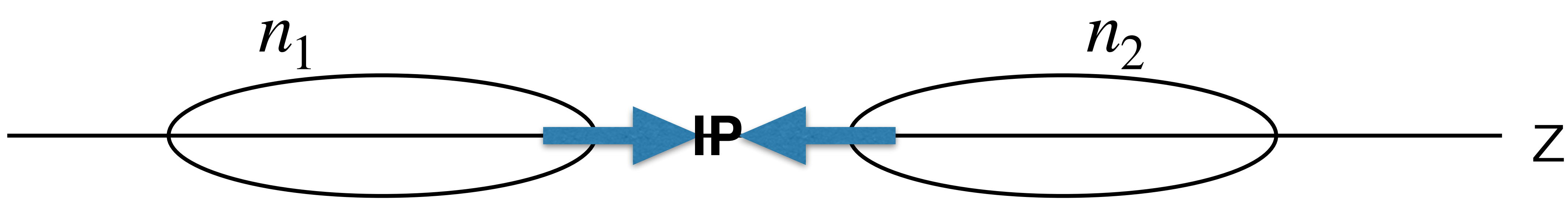
- **Plasma Wakefield acceleration (~10 GV/m)** long way to go

- **Luminosity (beam dynamics)**



$$L = f_{coll}\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*}F$$

f_{coll}	average collision frequency	(large in storage ring)
σ_x^*, σ_y^*	bunch size in transverse direction	(“Nano Beam”)
n_1, n_2	# of particles in a beam bunch	

- **Synchrotron Radiation**

$$P = \frac{e^2 c}{6\pi\epsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

radiation power

(—> muon collider)

$$\Delta E[\mathrm{keV}] = 88.5 \frac{E^4[\mathrm{GeV}]^4}{R[\mathrm{m}]}$$

E loss per turn for electron

(~5GeV! for C=100km E=175GeV)

- **Beam Polarisation**

$$P = \frac{N_R - N_L}{N_R + N_L}$$

spinning particles precess around B-field direction

hard to preserve longitudinal polarisation in a ring; transverse possible

(i-2) basic concepts on detectors

what behind

Vertex / timing resolution
Momentum / Jet Energy Resolution
Flavor-tagging Efficiency
Particle Identification Efficiency

?

(i-2) basic concepts on detectors

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Vertex / timing resolution
Momentum / Jet Energy Resolution
Flavor-tagging Efficiency
Particle Identification Efficiency

?

- **passage of particles through matter**
  - ionization / atom excitation
  - multiple scattering
  - bremsstrahlung / pair production
  - nuclear interaction
  - Cherenkov radiation

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- **passage of particles through matter**
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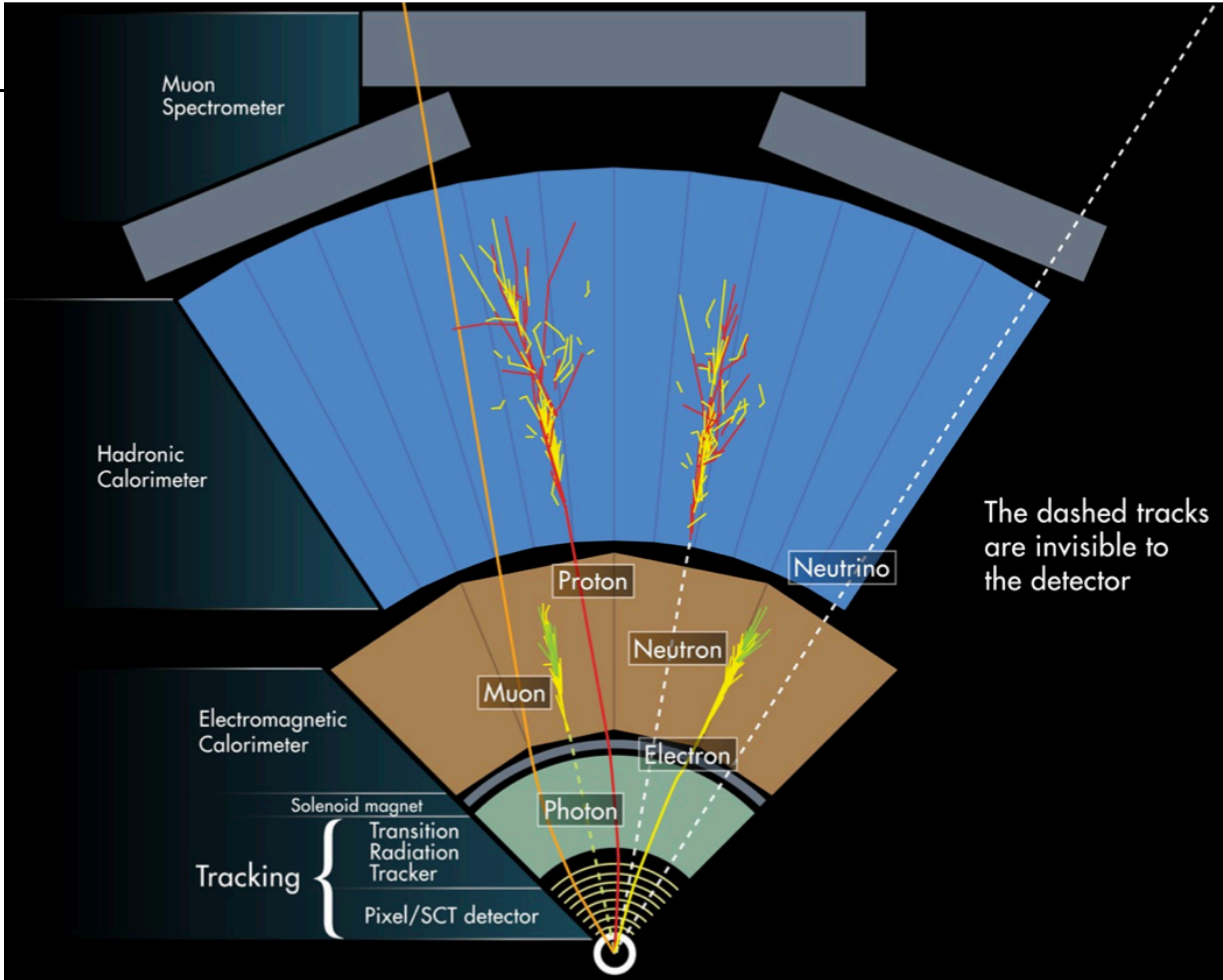
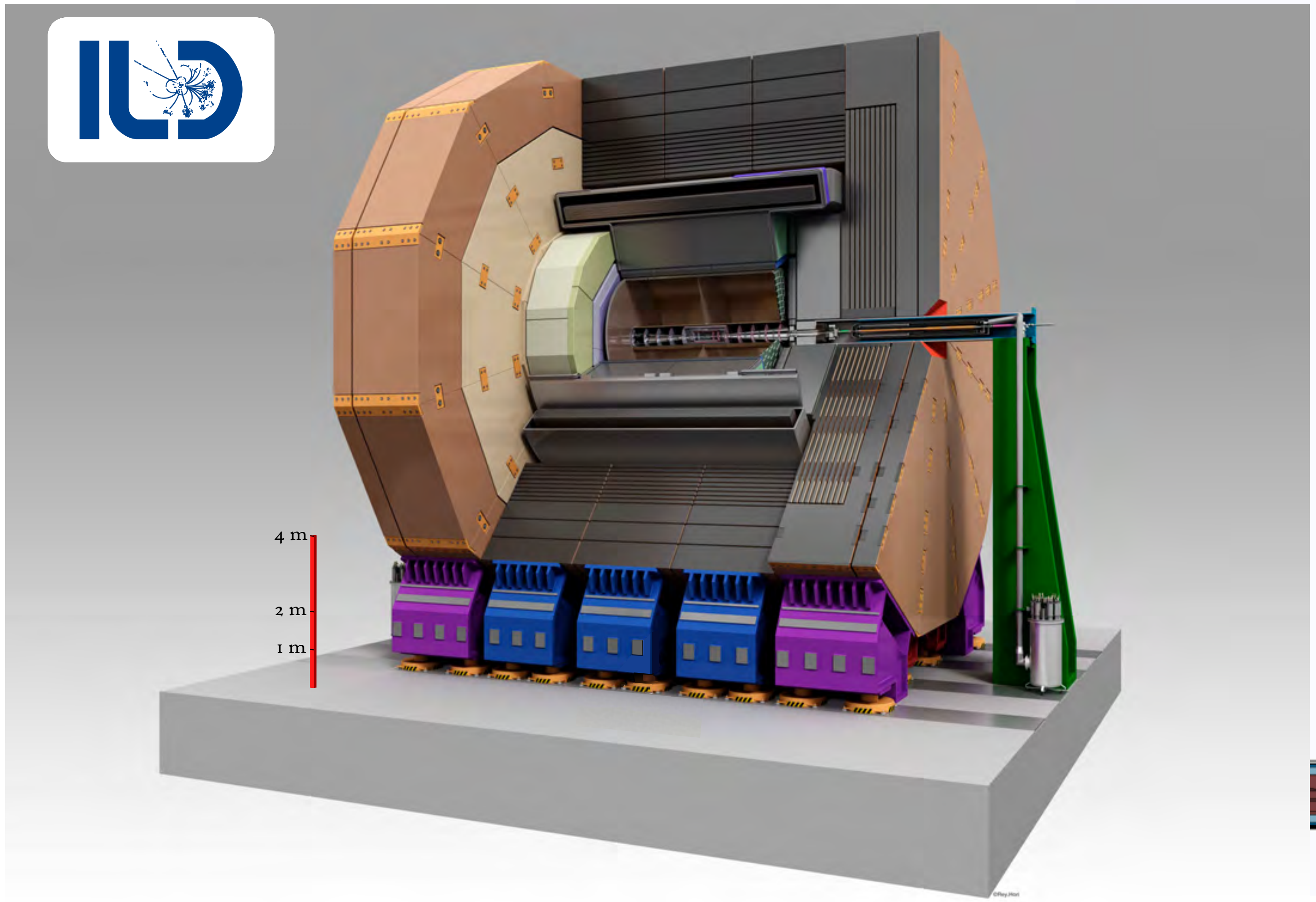
- **type of detectors**
  - vertex / tracking
  - sampling calorimeters
  - homogeneous calorimeters
  - timing detectors
  - …

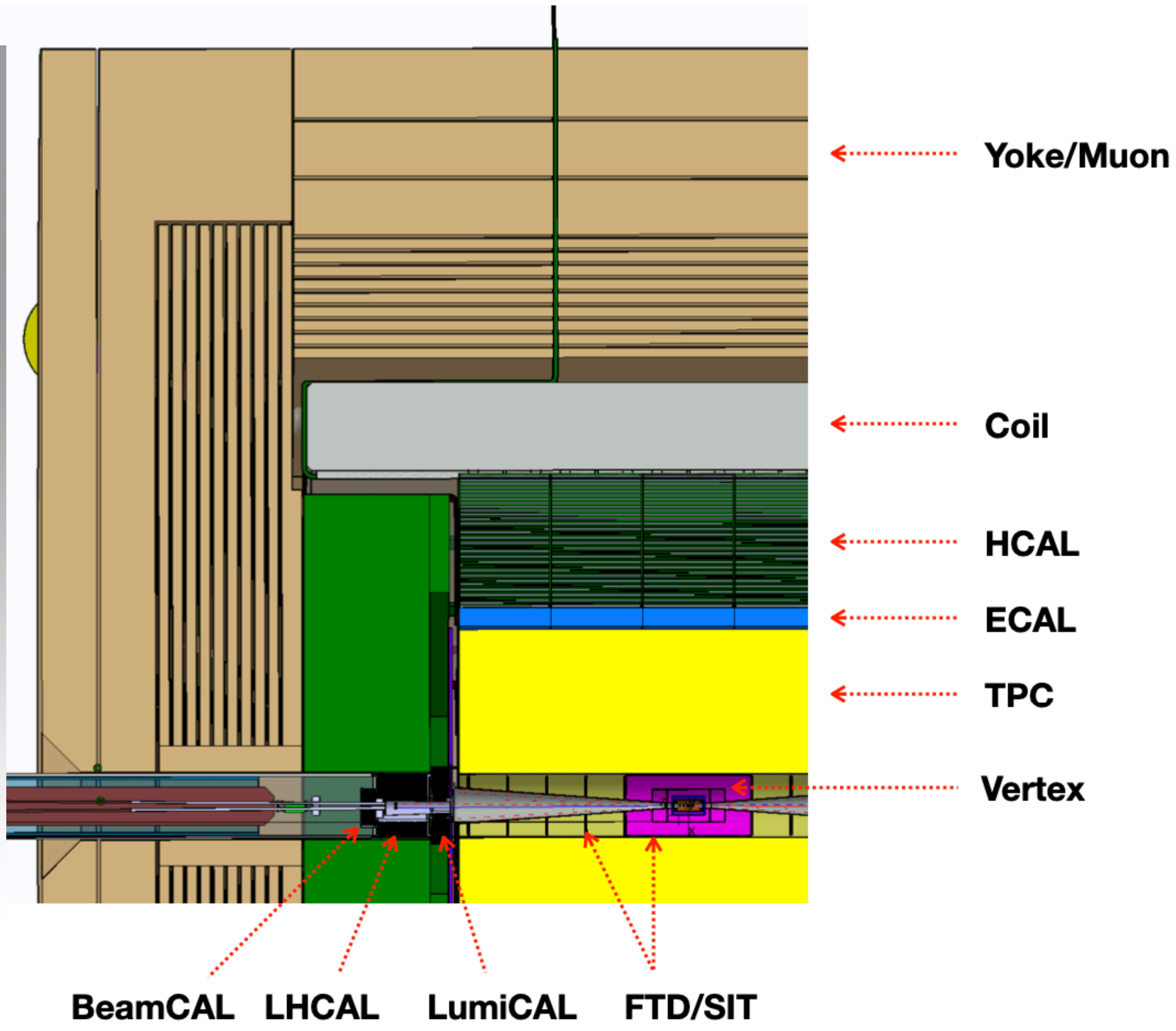
{ gaseous, silicon, scintillator, … }

{ digital, analog, semi-digi, … }


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector

(i-2) basic concepts on detectors

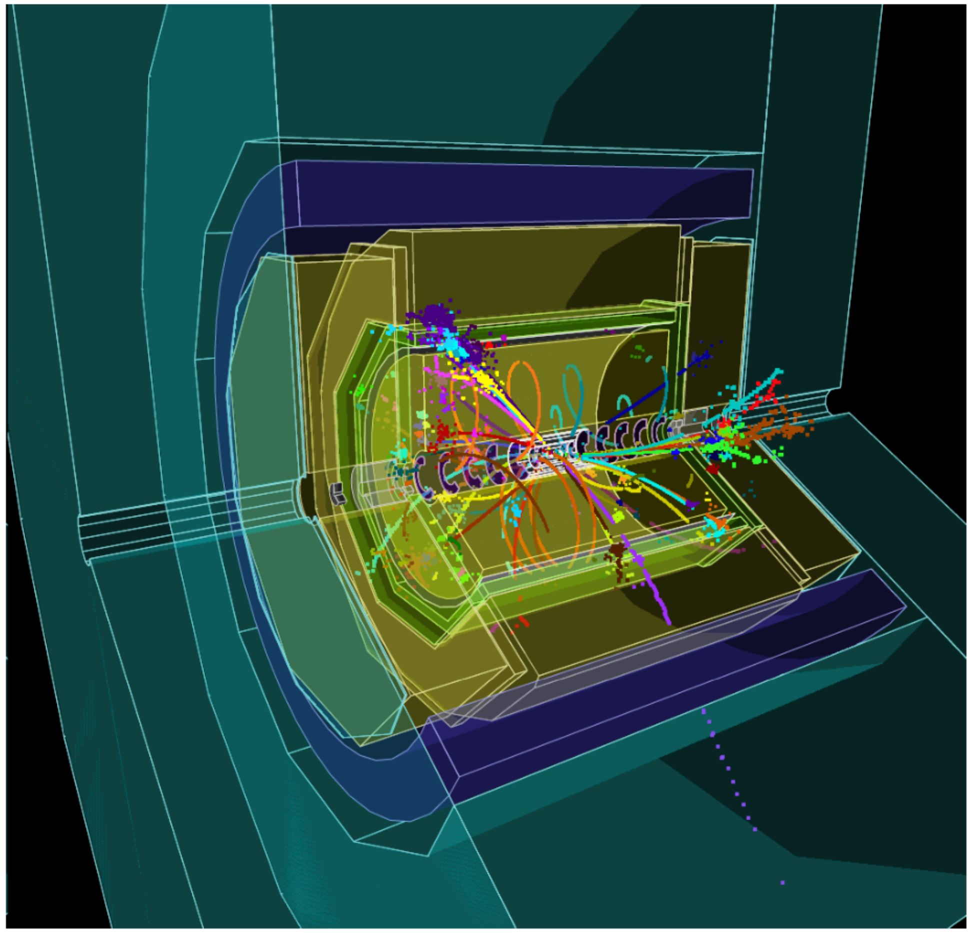




Particle Flow Detector

particle flow approach tries to reconstruct every individual particle produced in an event

key challenge is to separate the showers produced by particles from a same jet
—> highly granular calorimeters



Component	Detector	Energy Fract.	Energy Res.	Jet Energy Res.
Charged Particles ($X^{\pm}$)	Tracker	$\sim 0.6\, E_j$	$10^{-4}\, E^2_{X^{\pm}}$	$< 3.6 \times 10^{-5}\, E^2_j$
Photons (γ)	ECAL	$\sim 0.3\, E_j$	$0.15\,\sqrt{E_\gamma}$	$0.08\,\sqrt{E_j}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1\, E_j$	$0.55\,\sqrt{E_{h^0}}$	$0.17\,\sqrt{E_j}$

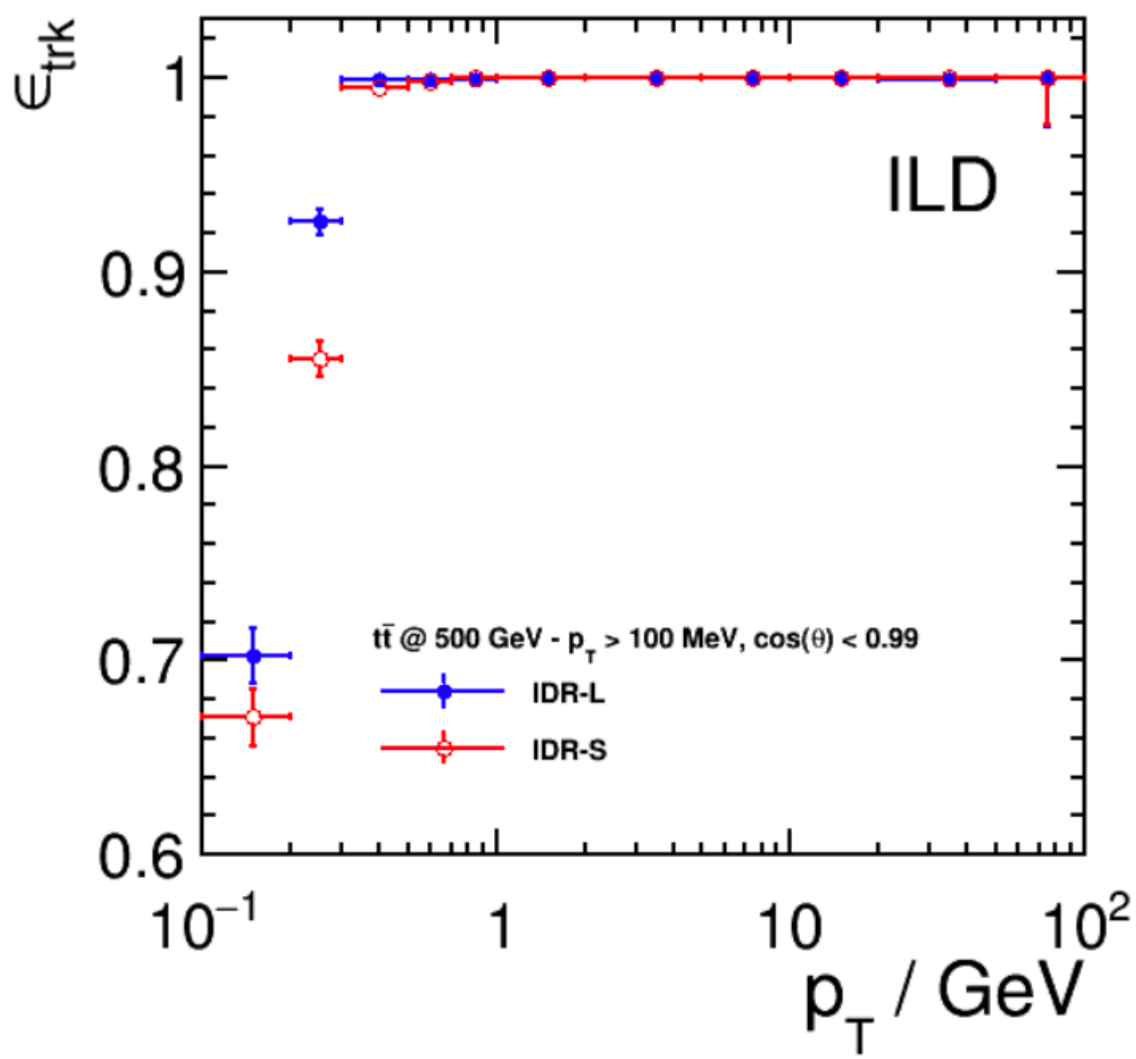
- **typical tracking performance**

momentum resolution $\Delta_{1/P_t} = \frac{\Delta P_t}{P_t^2} \sim 2 \times 10^{-5} [\mathrm{GeV}^{-1}]$

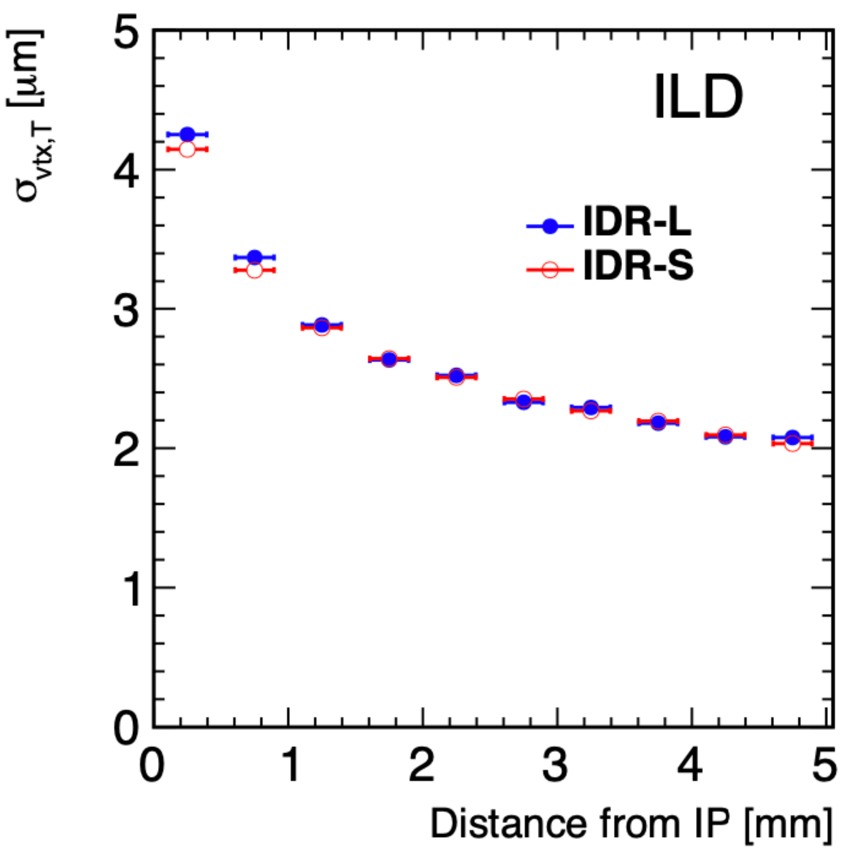
~0.2% for Pt~100GeV

tracking efficiency

~100% for P_T > 300 MeV

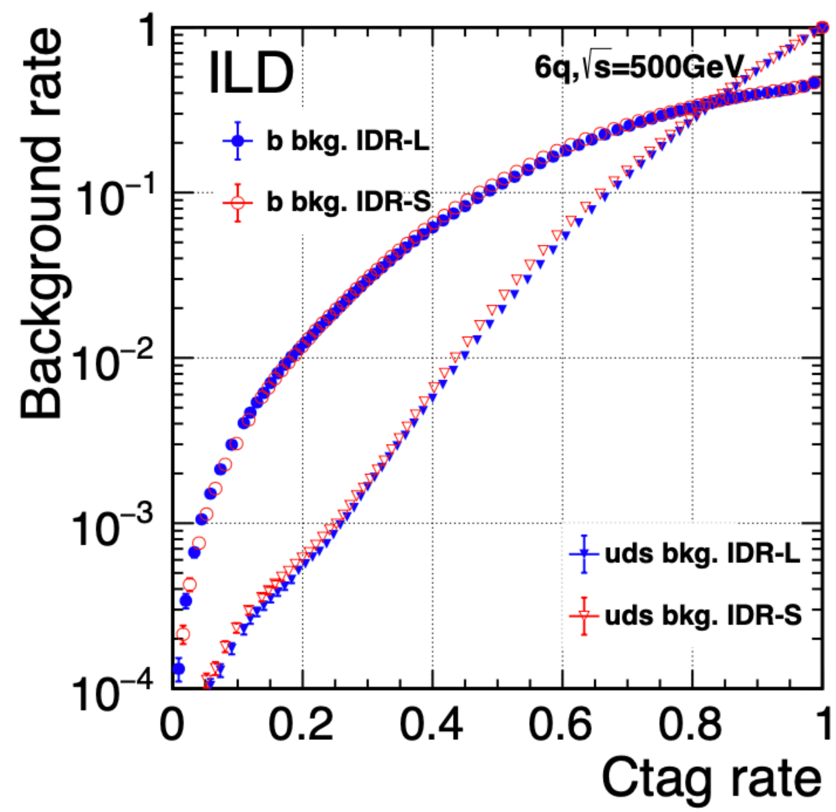


- **vertex / flavor-tagging performance**



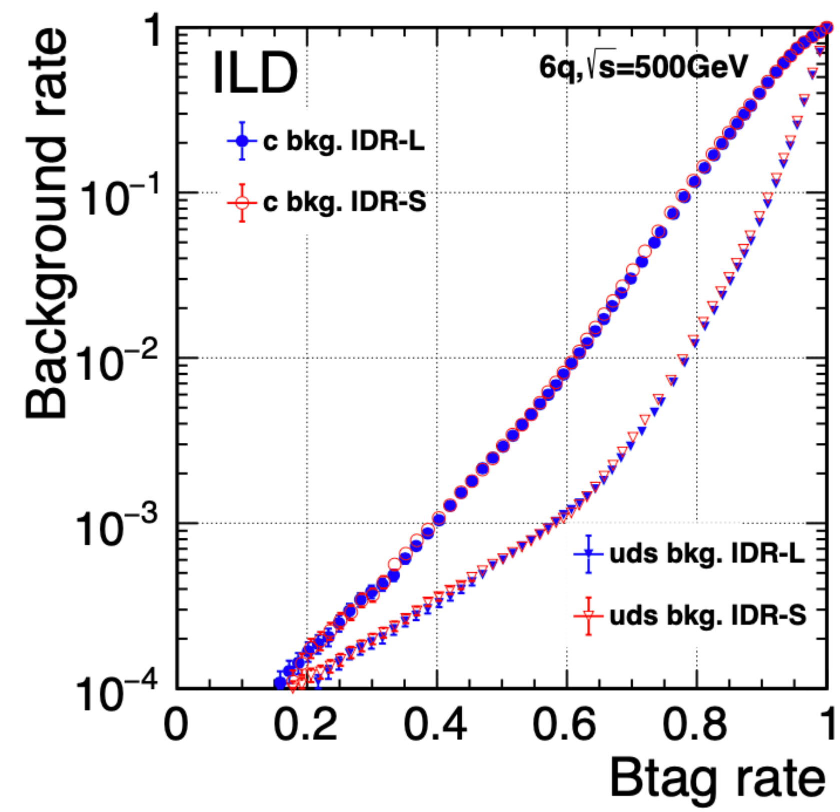
secondary vertex position from c-jets

Δr ~ 2μm



flavor-tagging c-jet

ε ~ 50% (10% b)



flavor-tagging b-jet

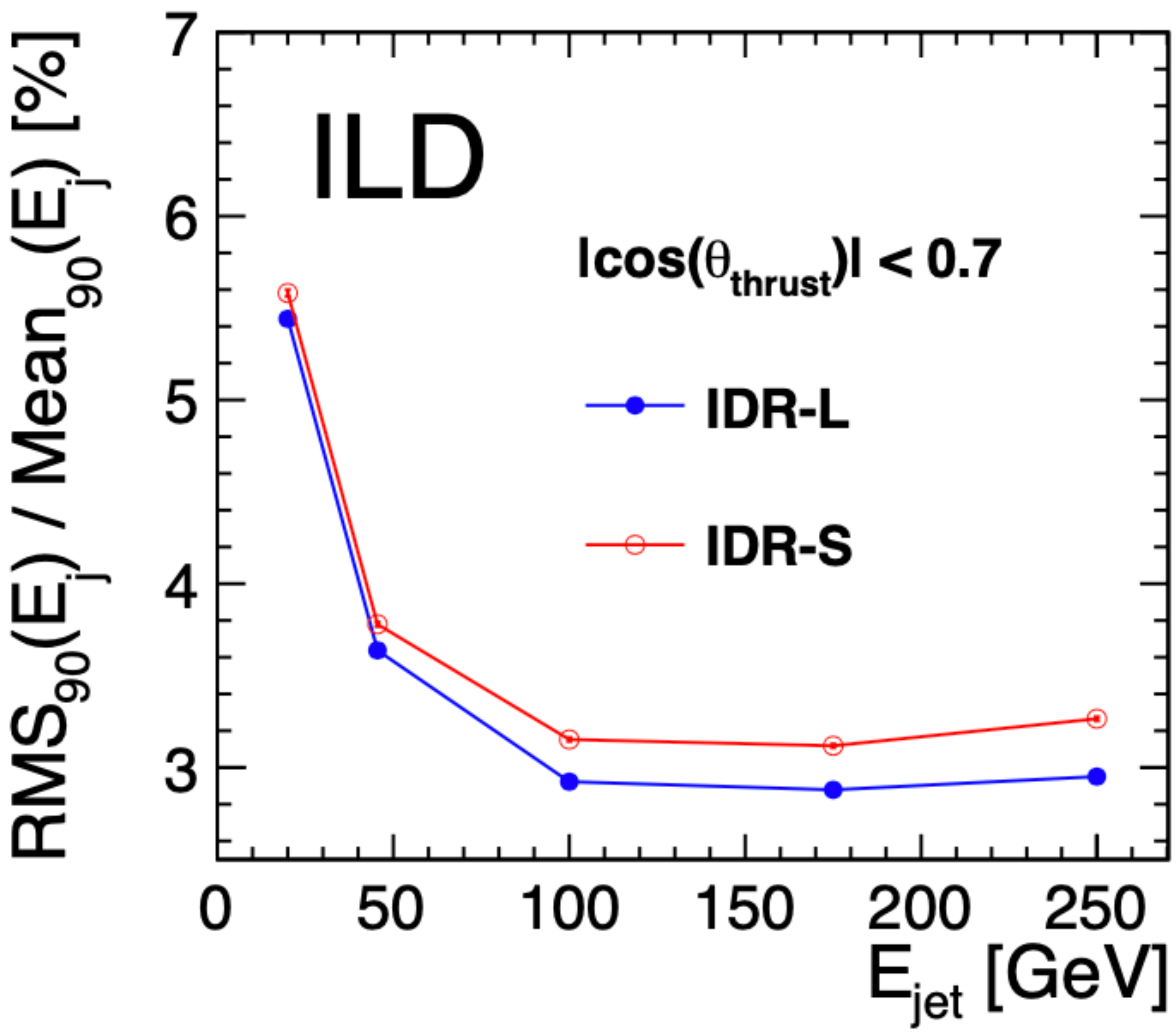
ε ~ 80% (10% c)

- **performance on jet energy resolution**

$$\frac{\Delta E}{E} = \frac{30\,\%}{\sqrt{E}} + c$$

(E in GeV)

$\Delta E / E \sim 3\text{-}4\%$



(i) from event generators to real life

- **event generator: WHIZARD / MadGraph / Sherpa / Pythia…**

  hard interaction; ISR; beamstralung

  parton showering; hadronization; decay

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  full detector simulation; pile-up; (GEANT4)

  fast simulation; simple smearing; (DELPHES / SGV)

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- **physics analysis**

(ii) e+e- physics: big questions

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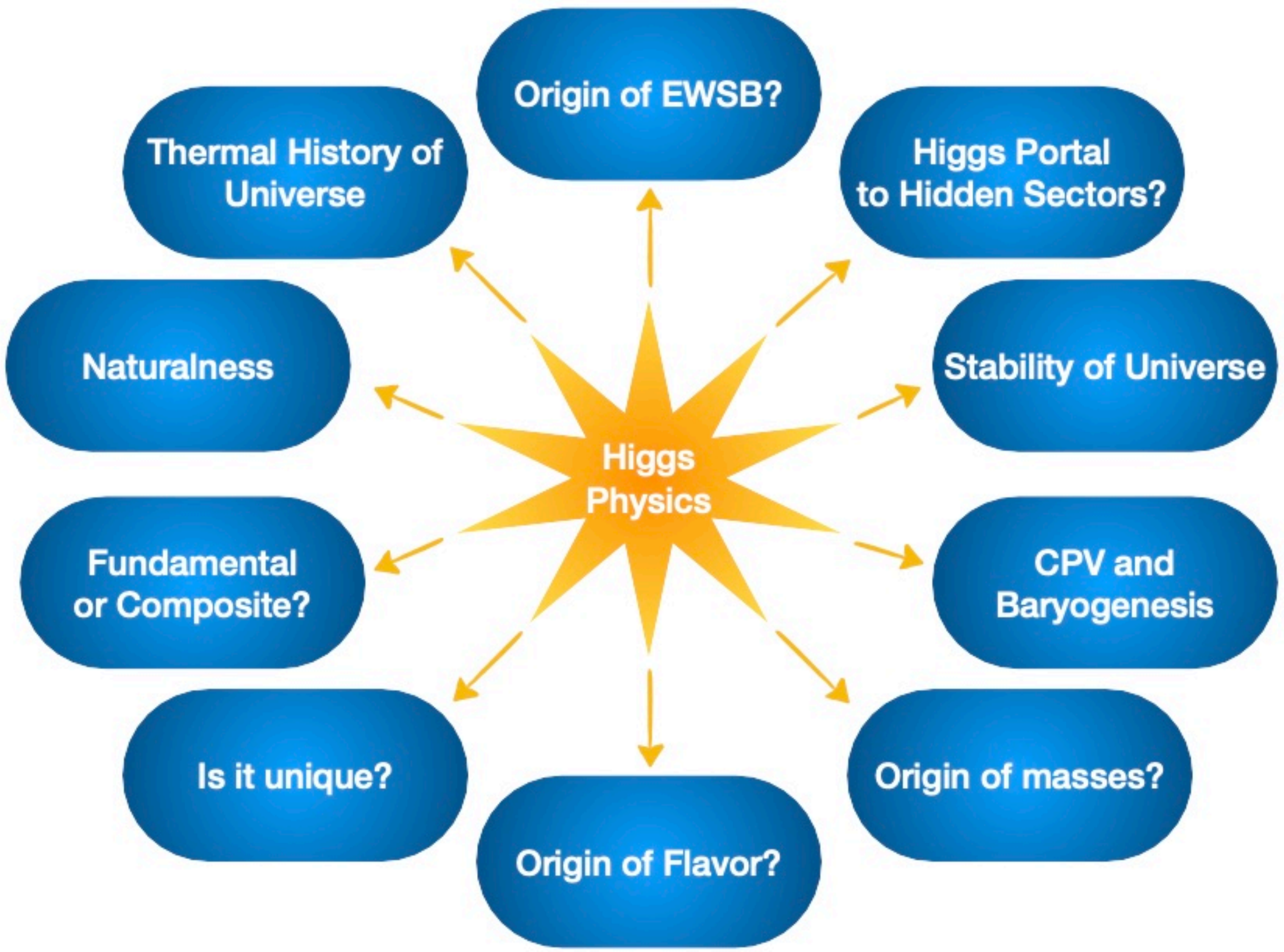
- data say there are at least five missing pieces in the SM

[H. Murayama]

  - dark matter (2003)
  - neutrino mass (1998)
  - dark energy (1998)
  - inflation (2003)
  - matter anti-matter asymmetry (2003)

how can future e+e- colliders help?

Higgs: a unique window for new physics



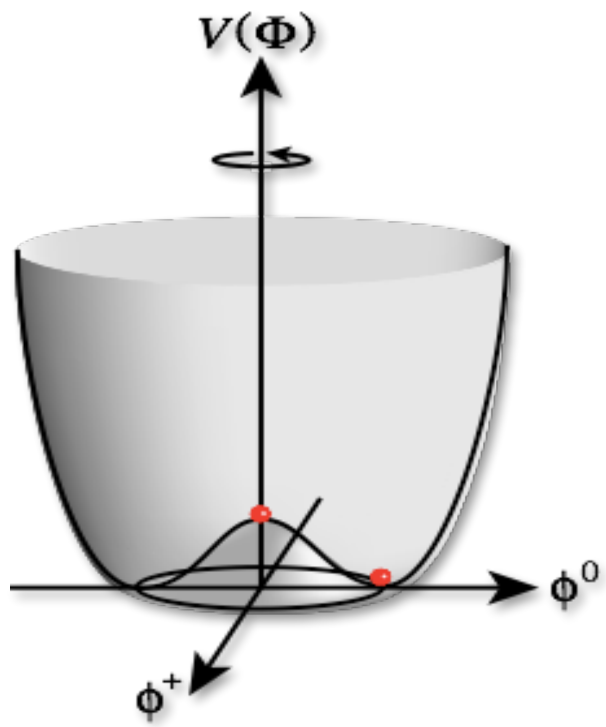
[Snowmass EF01/02 Report]

- the least understood sector of SM, theoretically or experimentally
- portal to many other big questions of our universe

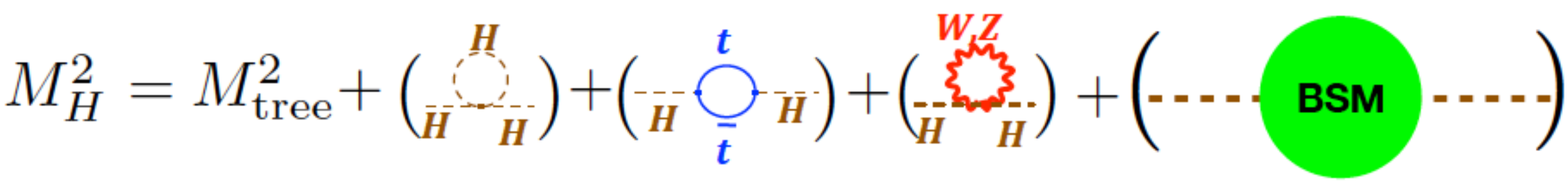
[“Higgs isn’t everything. It’s the only thing.” M. Peskin arXiv:2601.02729]

(ii) Higgs physics: mystery in Electroweak Symmetry Breaking

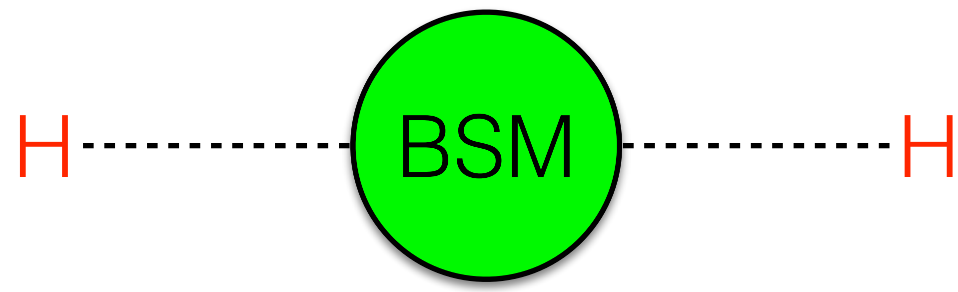
$$V(|\Phi|) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$



- H(125) discovery
  - elementary or composite? any siblings?
- What is the origin of EWSB?
  - why $\mu^2<0$? underlying dynamics?
- What BSM protects m_H?
- Connection to big questions?



golden time: BSM hunting



direct searches

future e+e-… | **LHC**

↓

$\tilde{t}, \tilde{g}, \tilde{\chi}, H^{\pm}, Z', \ldots$

indirect searches

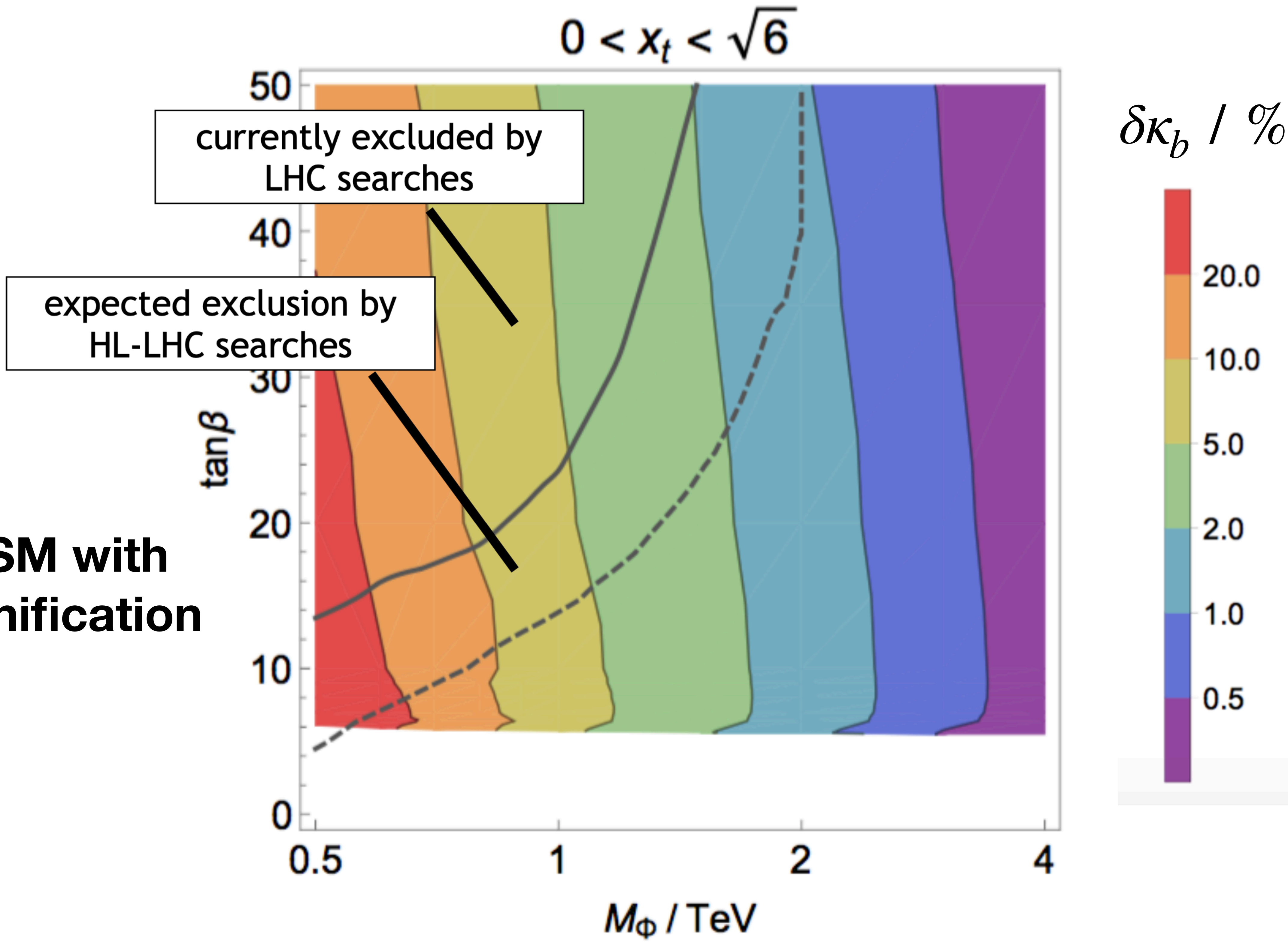
LHC | **future e+e- …**

↓

precision Higgs & SM couplings

- there must be BSM around EW scale, we just need to find it out

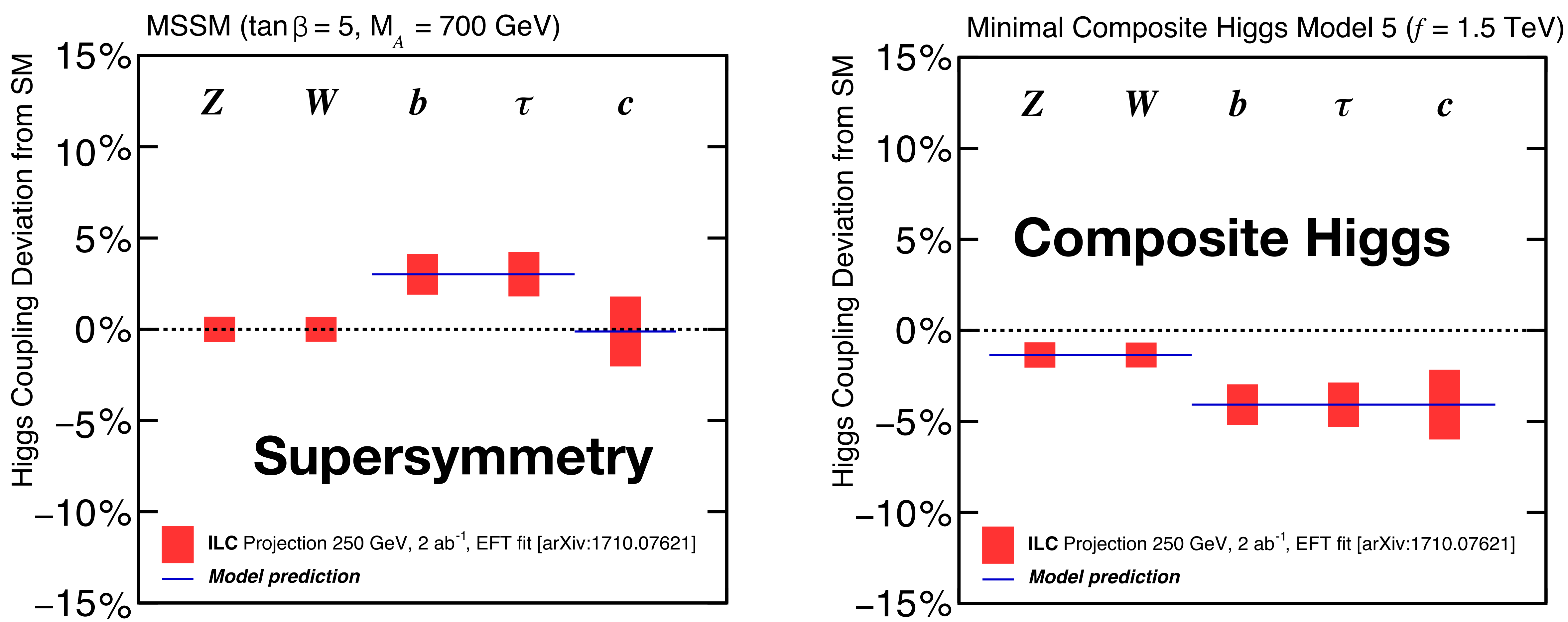
direct vs indirect searches: complementarity



MSSM with b-τ unification

[Wells, Zhang, arXiv:1711.04774]

opportunities from precision Higgs couplings



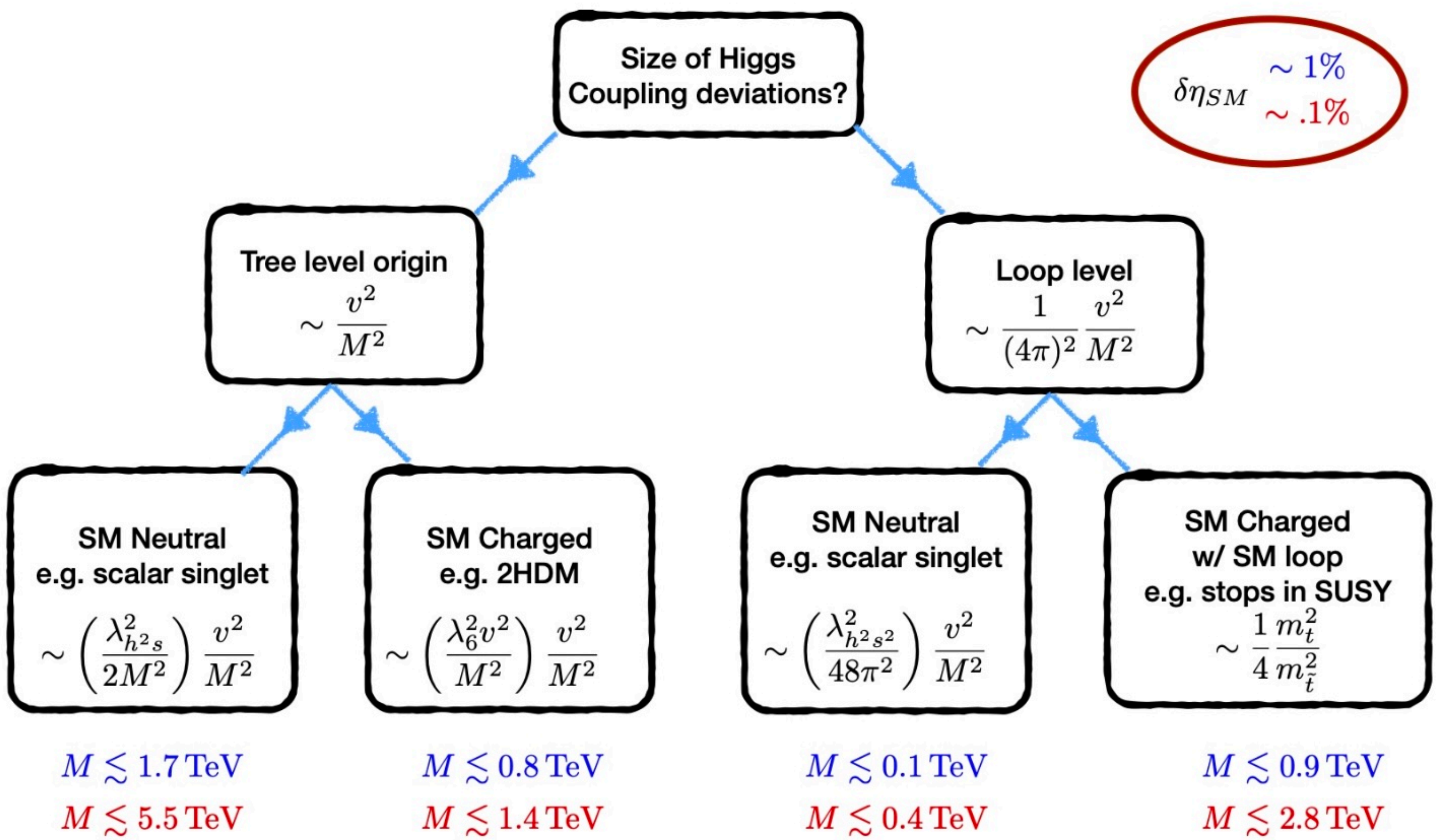
[Barklow et al, arXiv: 1708.08912]

- can not only *discover* BSM physics, but also identify the *nature of BSM* by precisely measuring the *deviation pattern*

Why not yet seen, why need future e+e-

—in light of what have been found at LHC

- deviation is small for m_{BSM}~1TeV: need *1% precision* or below
- measurements / searches better to be as *model-independent* as possible, as *loop-hole free* as possible



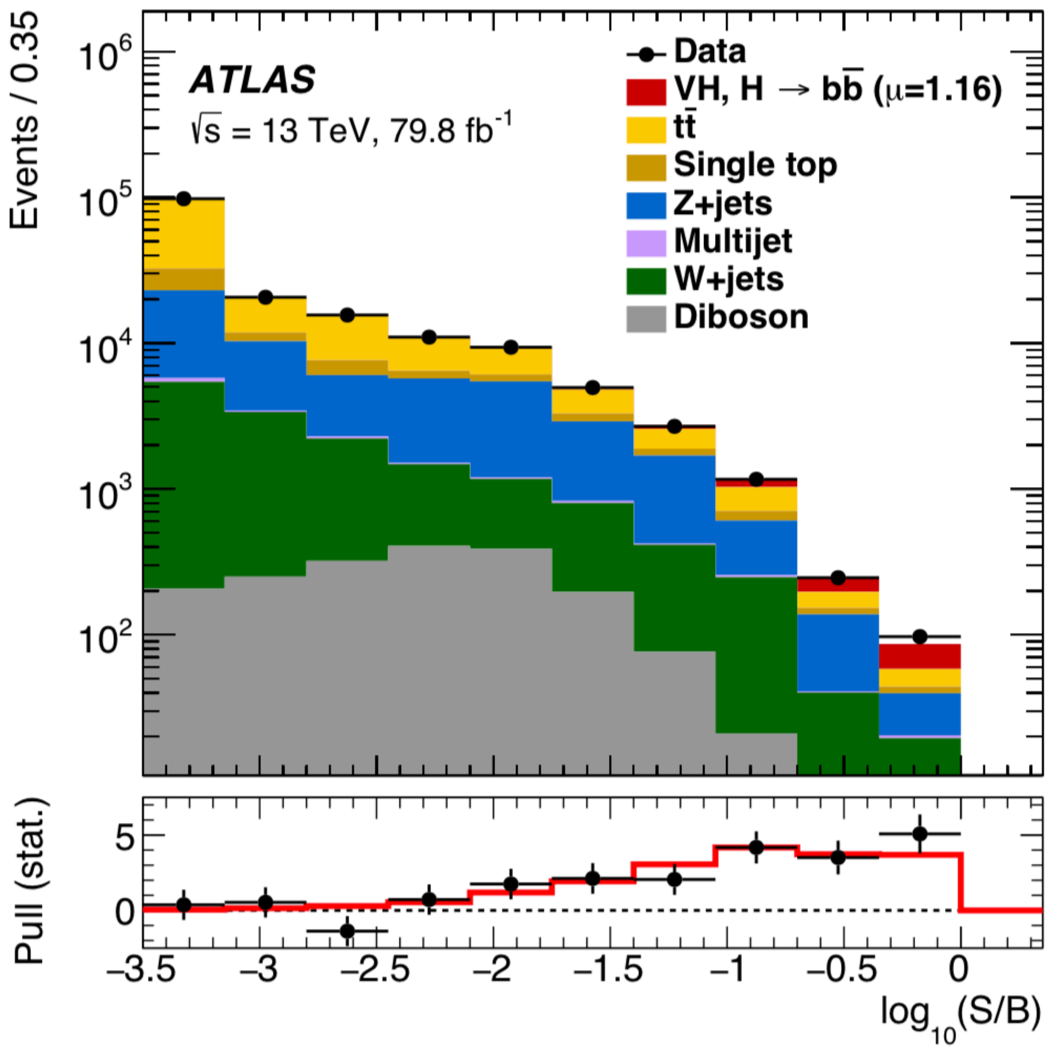
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

[Snowmass EF01/02 Report]

statistics vs S/B: example on H→bb discovery

LHC (super Higgs factory #10^8)

e+e- (Higgs factory #10^6)



# of Higgs produced: ~4,000,000

significance: 5.4σ

[ATLAS, 1808.08238; CMS, 1808.08242]

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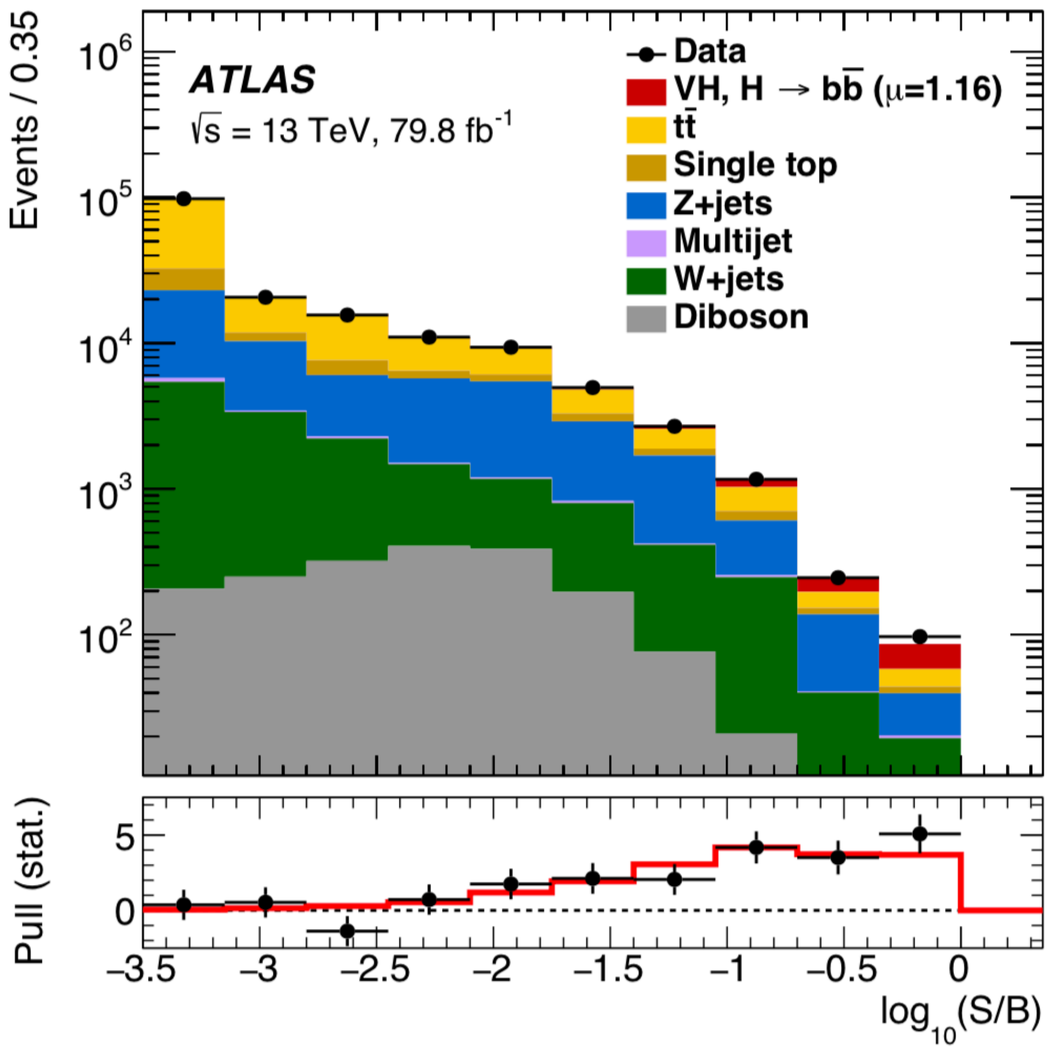
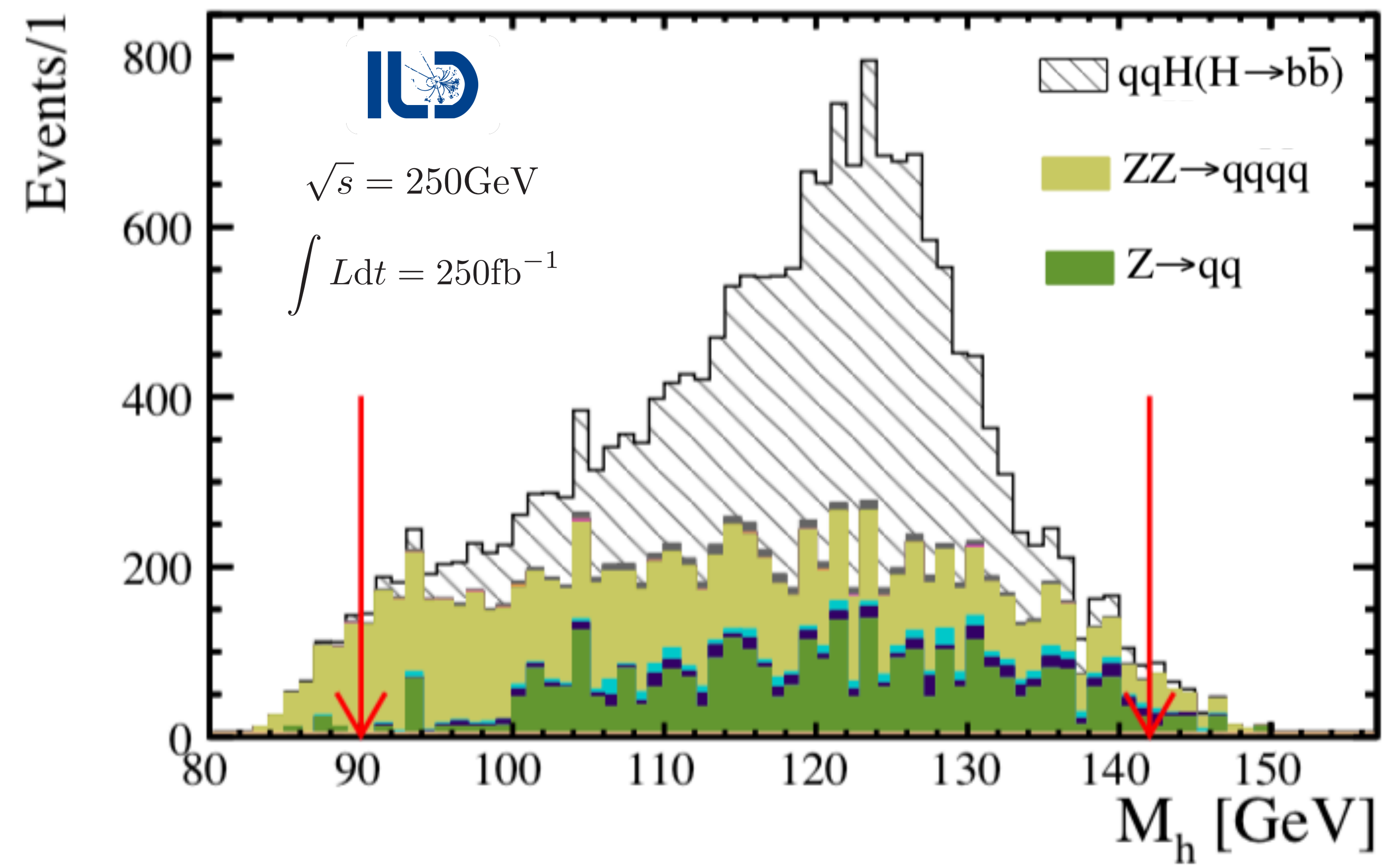




full detector simulation

# of Higgs produced: ~4,000,000 | ~400

significance: 5.4σ | 5.2σ

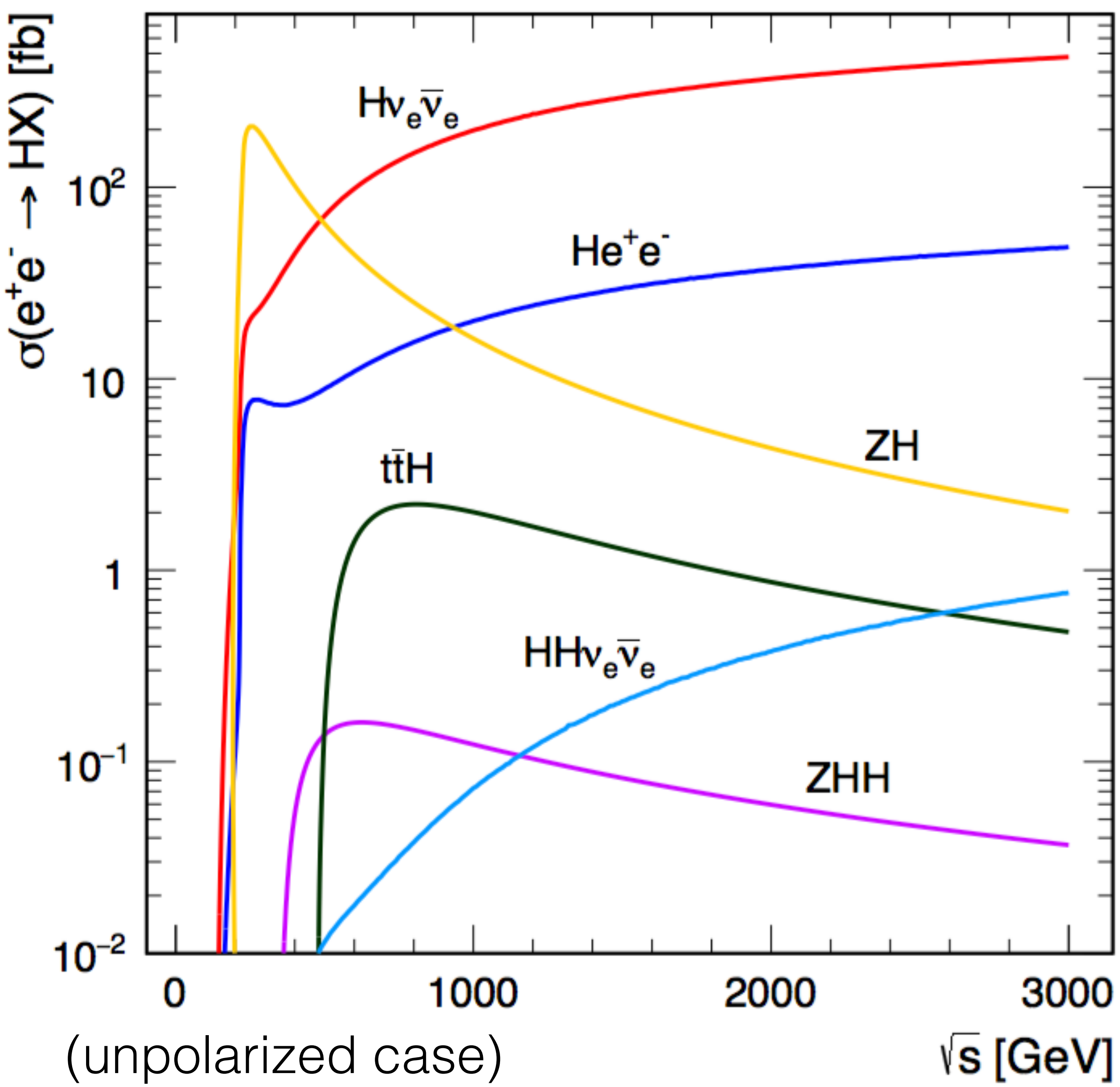
[ATLAS, 1808.08238; CMS, 1808.08242]

[Ogawa, PhD Thesis (Sokendai)]

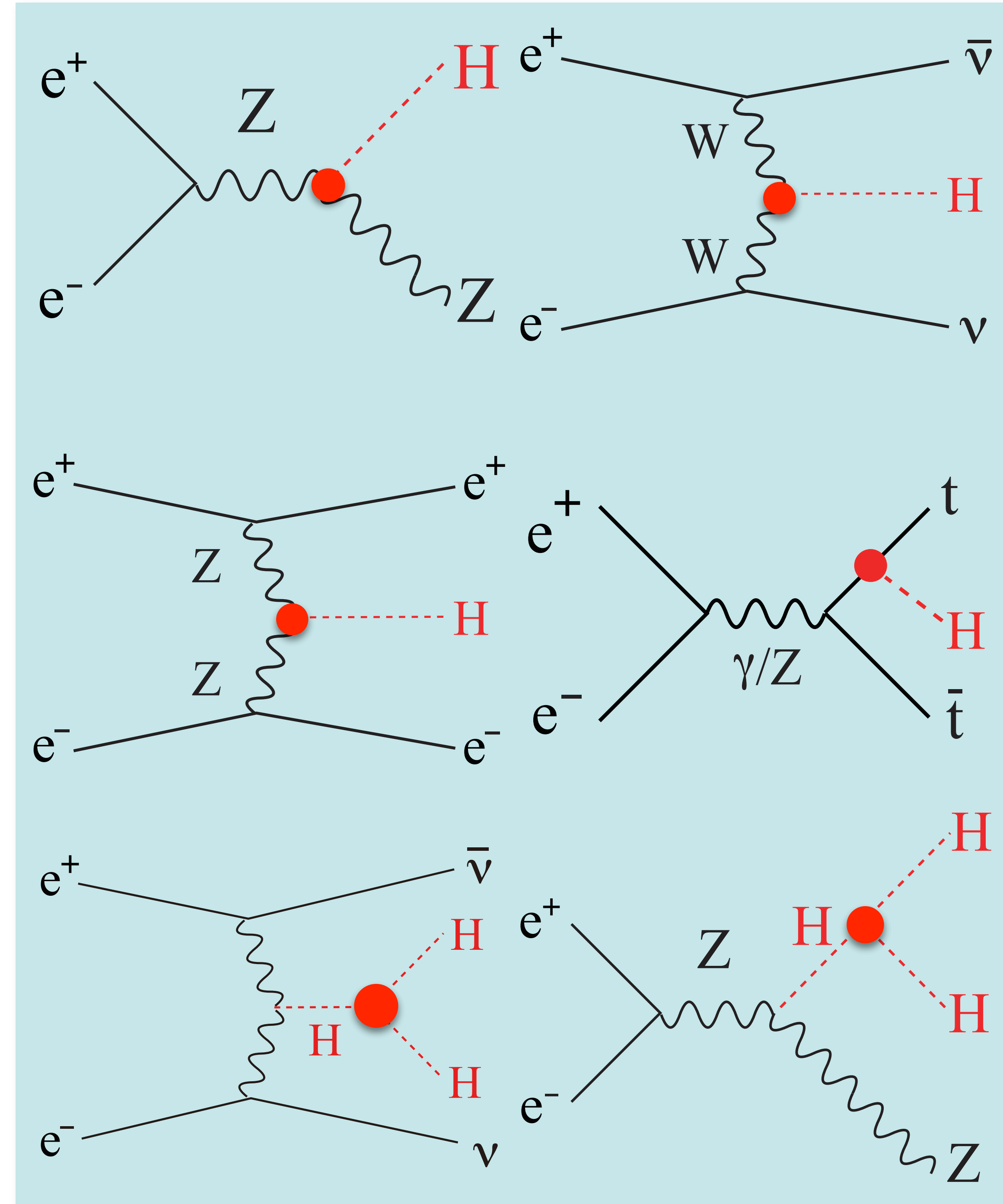
"that is much much easier, infinitely easier,
on a e+e- machine than on a proton machine"

youtube: Burton Richter #mylinearcollider, 2015

Higgs productions at e+e-



(unpolarized case)



- two apparent important thresholds: √s ~ **250** GeV for ZH, ~**500** GeV for ZHH and ttH
- + another threshold for t t-bar, important for vacuum stability

Higgs properties: what we would like to measure

reconstruct the Higgs sector in a bottom-up and model independent way

Mass & J^{CP} $\quad M_h \quad \Gamma_h \quad J^{\mathrm{CP}}$	new CP violating source?
L_{Higgs} $\quad hhh: \; -6i\lambda v = -3i\frac{m_h^2}{v}, \quad hhhh: \; -6i\lambda = -3i\frac{m_h^2}{v^2}$	probe Higgs potential, EWBG?
L_{Gauge} $\quad W_\mu^+ W_\nu^- h: \; i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}, \quad W_\mu^+ W_\nu^- hh: \; i\frac{g^2}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu},$ $\quad Z_\mu Z_\nu h: \; i\frac{g^2+g'^2 v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \; i\frac{g^2+g'^2}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$	SU(2) nature? m_V from SSB?
L_{Yukawa} $\quad h\bar{f}f: \; -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$	m_f from Yukawa coupling? 2HDM?
L_{Loop} $\quad h\gamma\gamma \quad hgg \quad h\gamma Z$	new particles in the loop?

+ possible exotic/anomalous interactions of Higgs

what are the direct experimental observables

- ☑ σ_{ZH}
- ☑ $\sigma_{ZH}\times Br(H \rightarrow bb)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow bb)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow cc)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow cc)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow gg)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow gg)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow WW^*)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow WW^*)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow ZZ^*)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow ZZ^*)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow \tau\tau)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow \tau\tau)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow \gamma\gamma/\gamma Z)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow \gamma\gamma/\gamma Z)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow \mu\mu)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow \mu\mu)$
- ☑ $\sigma_{ZH}\times Br(H \rightarrow inv./exotic)$
- ☑ $\sigma_{ttH}\times Br(H \rightarrow bb)$
- ☑ $\sigma_{ZHH}\times Br^2(H \rightarrow bb)$, $\sigma_{\nu\nu HH}\times Br^2(H \rightarrow bb)$

what are the direct experimental observables

- σ_{ZH}
- $\sigma_{ZH} \times Br(H \to bb)$, $\sigma_{\nu\nu H} \times Br(H \to bb)$
- $\sigma_{ZH} \times Br(H \to cc)$, $\sigma_{\nu\nu H} \times Br(H \to cc)$
- $\sigma_{ZH} \times Br(H \to gg)$, $\sigma_{\nu\nu H} \times Br(H \to gg)$
- $\sigma_{ZH} \times Br(H \to WW^*)$, $\sigma_{\nu\nu H} \times Br(H \to WW^*)$
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- $\sigma_{ZH} \times Br(H \to \tau\tau)$, $\sigma_{\nu\nu H} \times Br(H \to \tau\tau)$
- $\sigma_{ZH} \times Br(H \to \gamma\gamma/\gamma Z)$, $\sigma_{\nu\nu H} \times Br(H \to \gamma\gamma/\gamma Z)$
- $\sigma_{ZH} \times Br(H \to \mu\mu)$, $\sigma_{\nu\nu H} \times Br(H \to \mu\mu)$
- $\sigma_{ZH} \times Br(H \to inv./exotic)$
- $\sigma_{ttH} \times Br(H \to bb)$
- $\sigma_{ZHH} \times Br^2(H \to bb)$, $\sigma_{\nu\nu HH} \times Br^2(H \to bb)$

- note the important complementarity with LHC

(ii) Higgs property measurements at e+e-

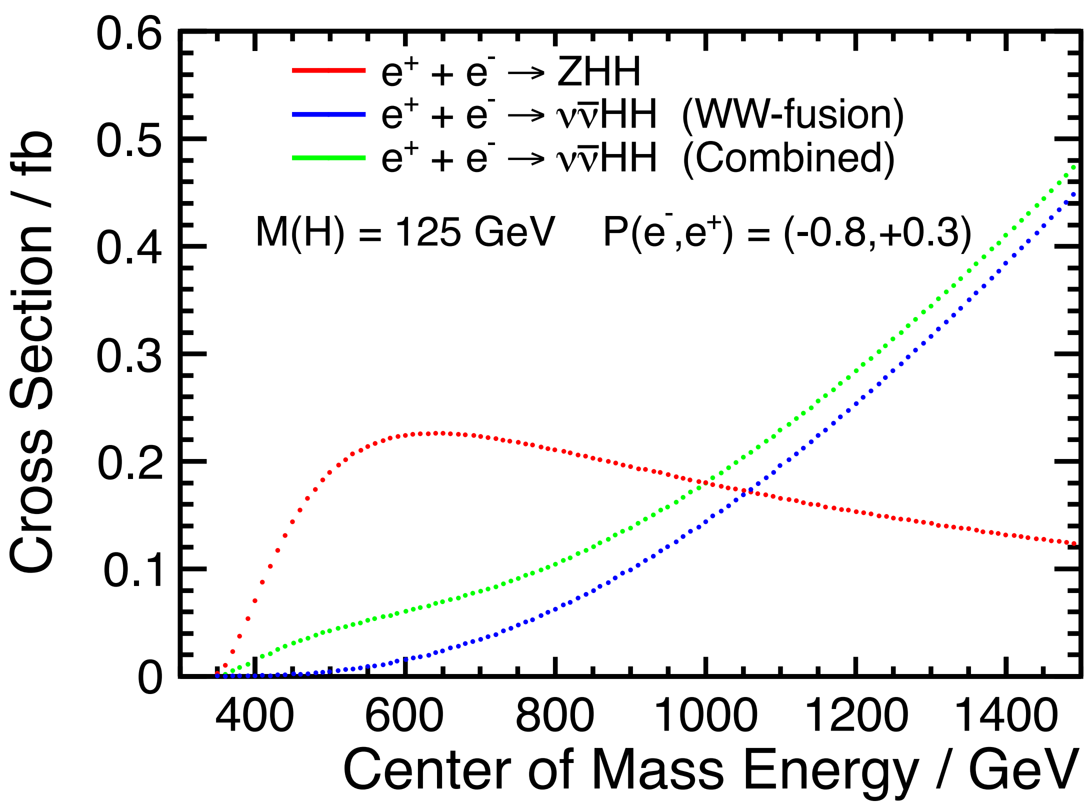
I will explain in fare details for 1-2 analyses, talk very briefly in other ones; mainly focus on physics issues instead of analysis techniques, which are important as well and can be learned from the references.

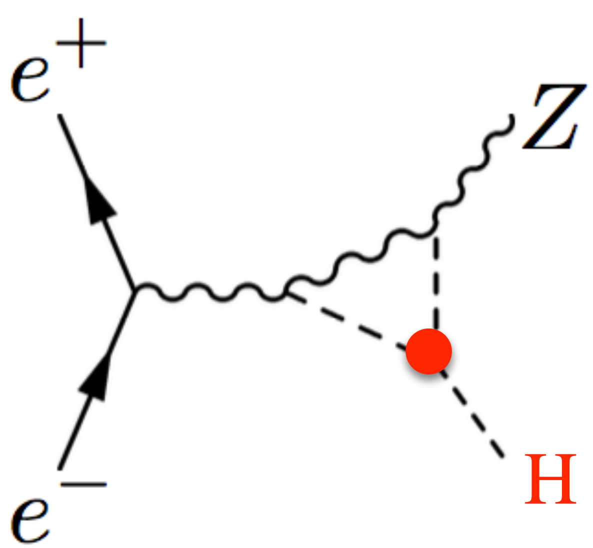
(1) Higgs self-coupling analysis
(2) recoil mass analysis
(3) Higgs CP
(4) H->bb/cc/gg
(5) Higgs total width
(6) top-Yukawa coupling
(7) …

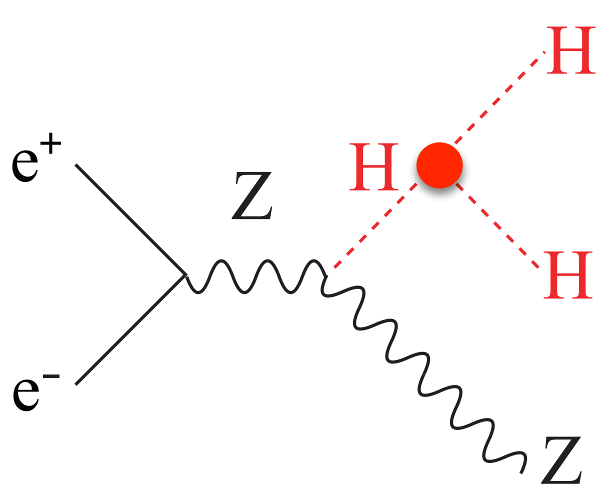
as usual, selection is always biased

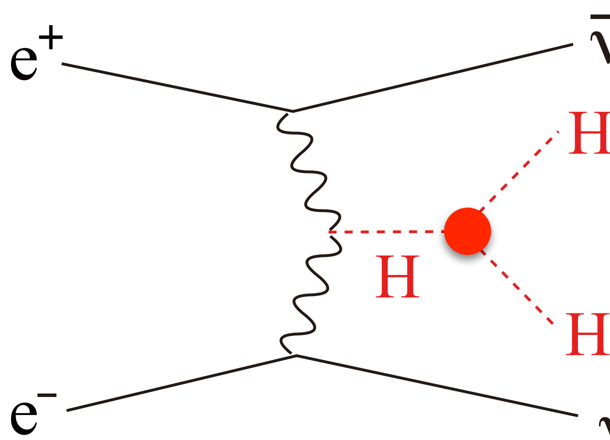
(ii-1) Higgs self-coupling

- direct probe of the Higgs potential
- large deviation (> 20%) motivated by electroweak baryogenesis, could be ~100%
- direct access via di-Higgs
- indirect access via single-Higgs
- both are challenging



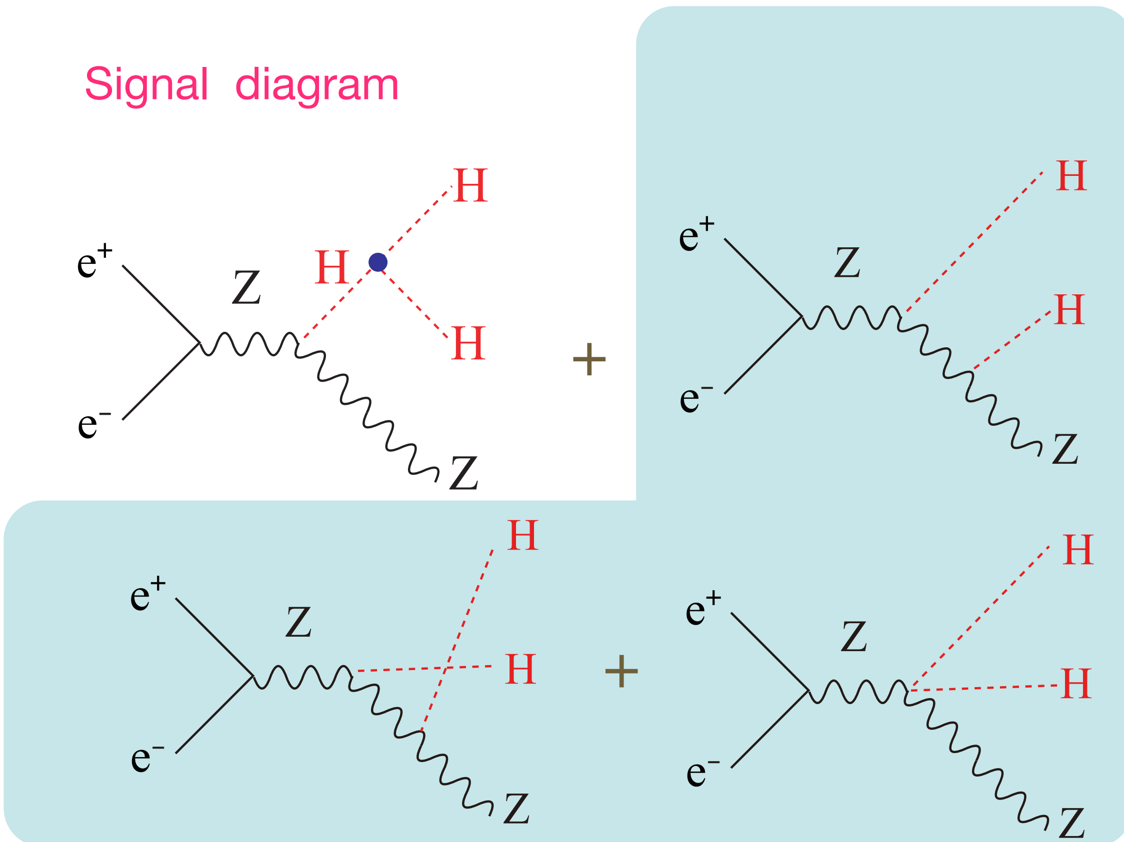


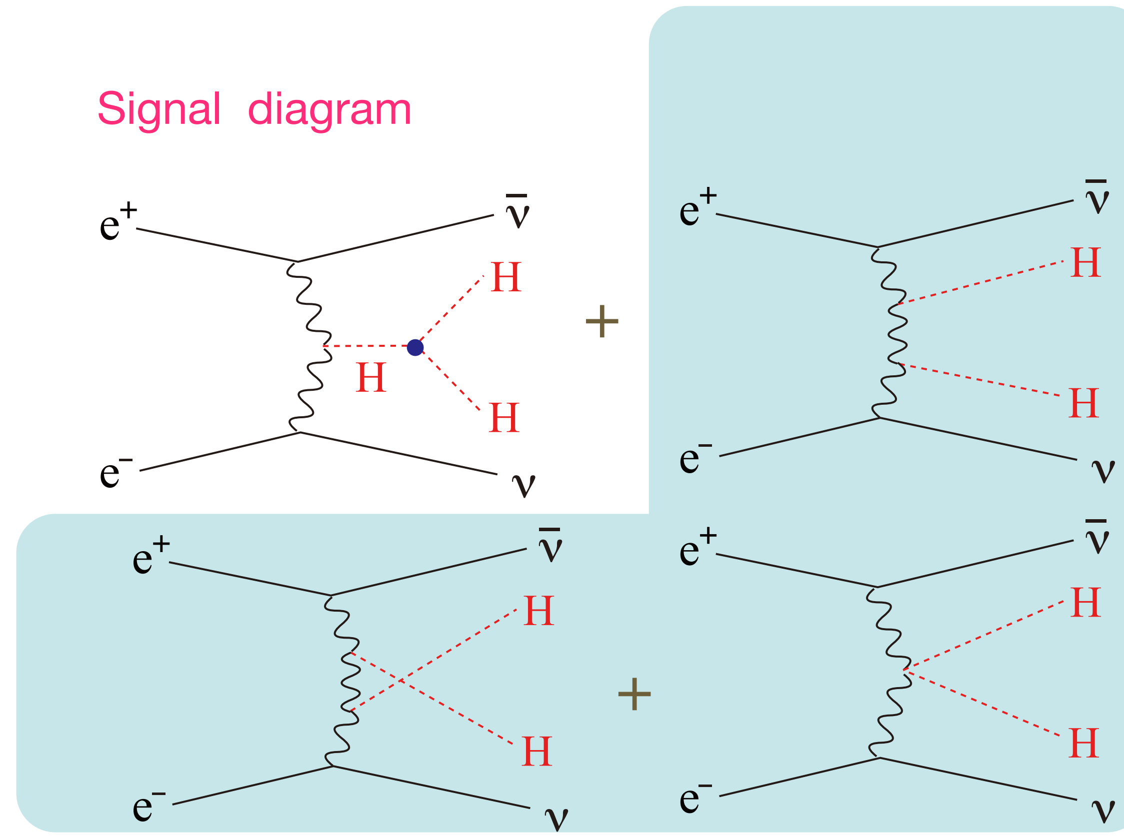




$\sqrt{s} \gtrsim 250$ GeV $\sqrt{s} \gtrsim 500$ GeV $\sqrt{s} \gtrsim 1$ TeV

physics issues: diagrams for double Higgs production





$$\sigma = S\lambda^2 + I\lambda + B$$

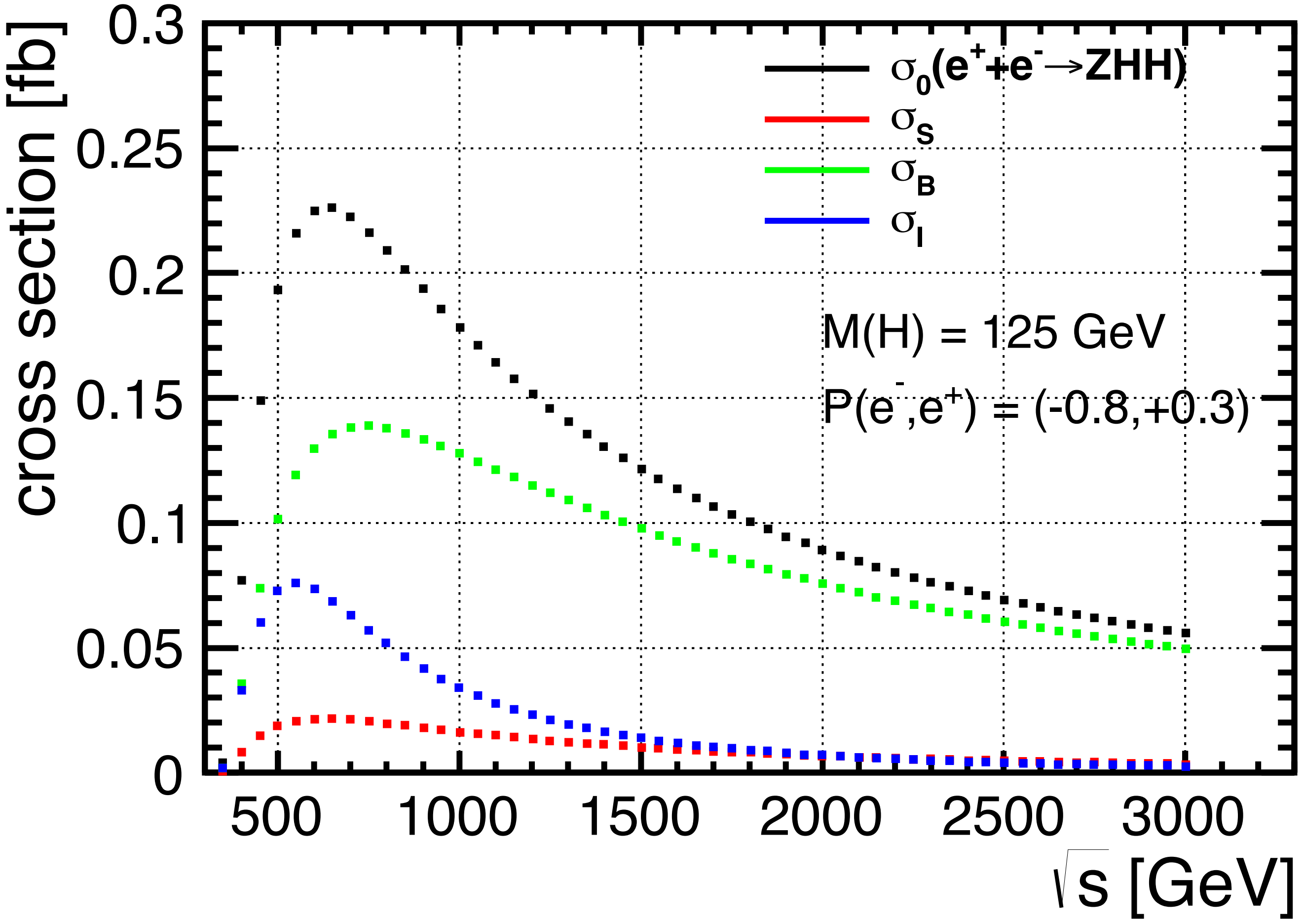
(signal diagram) (interference) (background diagram)

- the sensitivity of λ is determined not just by the apparent total cross section, in fact is determined by S and I term;
- if B term dominates, measurement would be very difficult

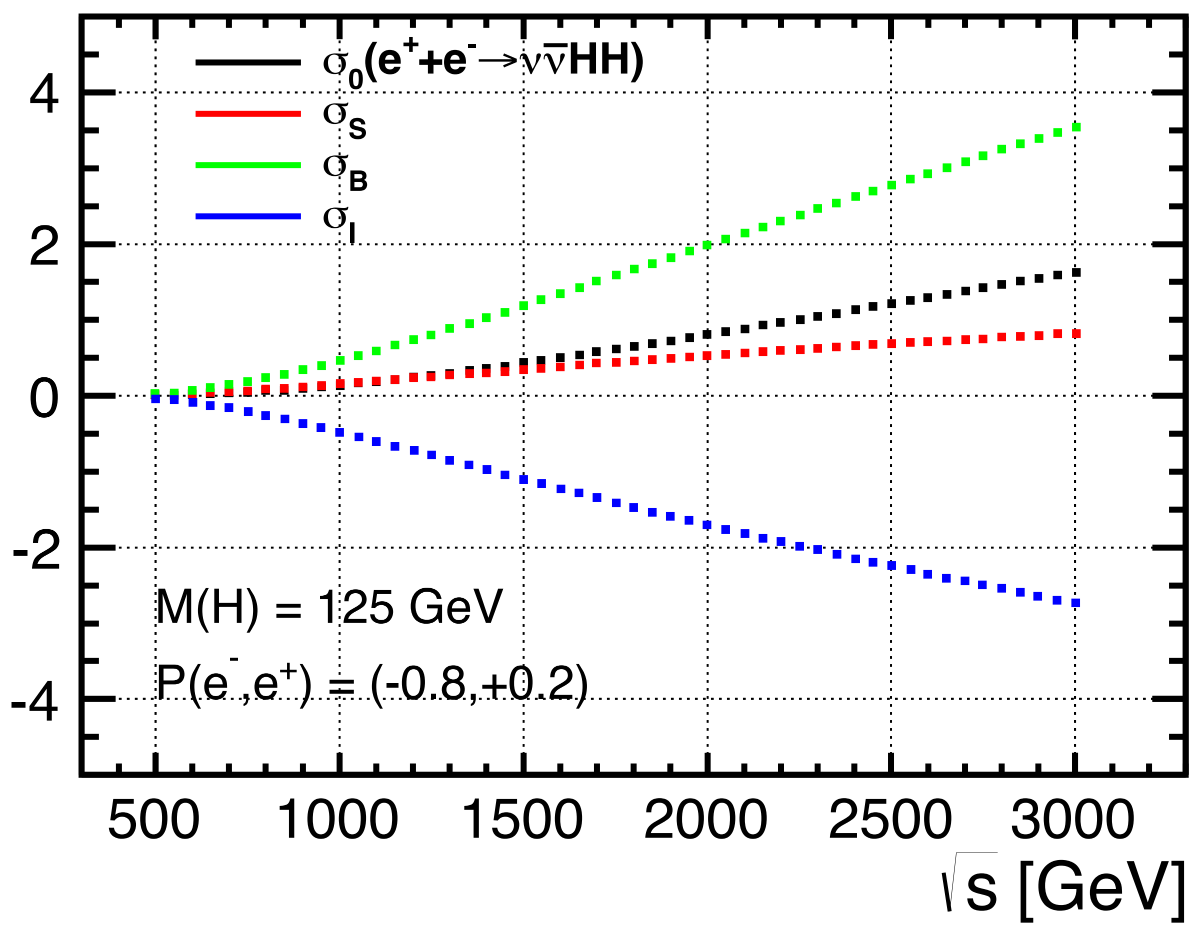
double Higgs x-section: breakdown for each diagram

$$\sigma = S\lambda^2 + I\lambda + B$$

ZHH



ννHH

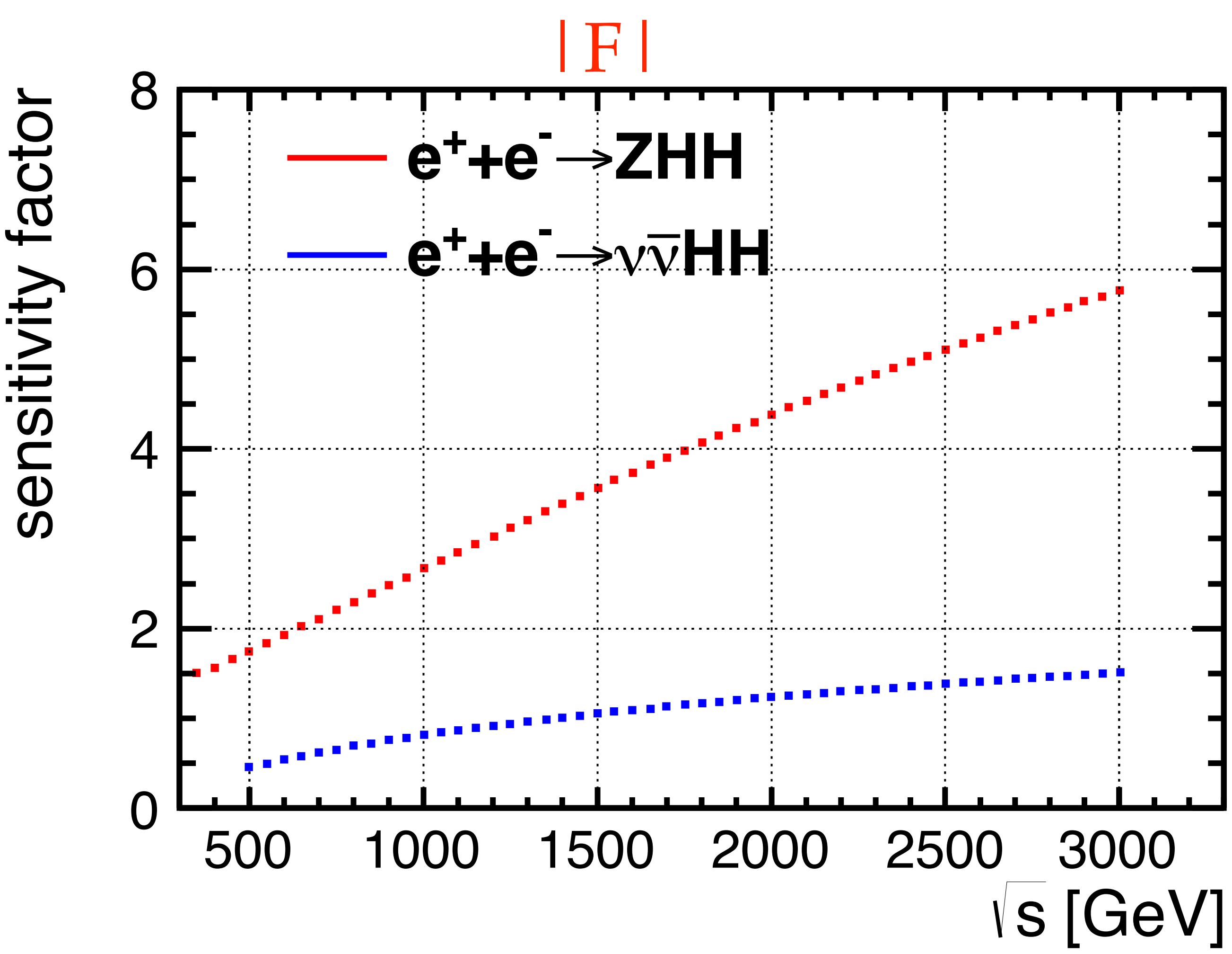


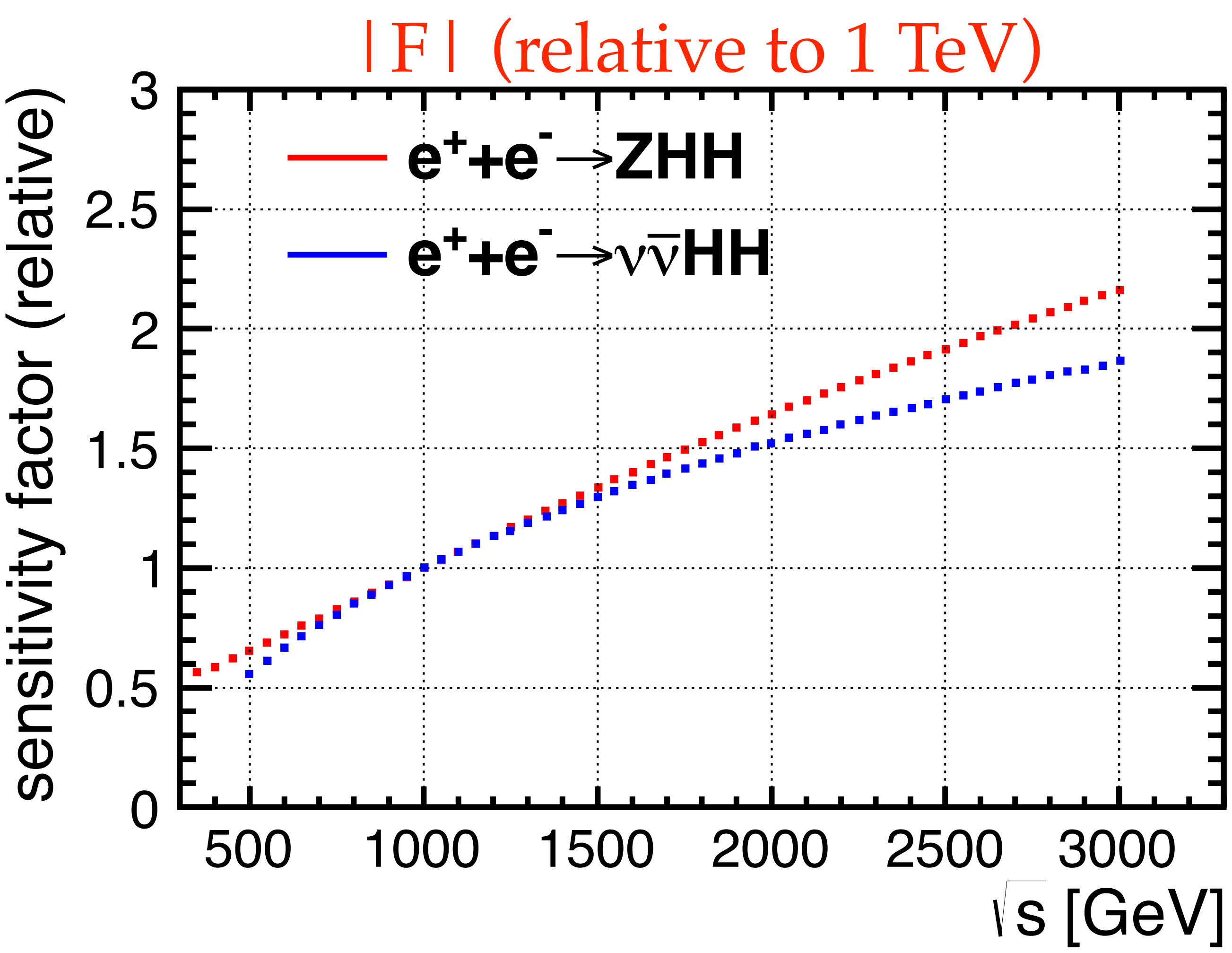
Higgs self-coupling: from σ to λ

$$\frac{\delta\lambda}{\lambda} = F \cdot \frac{\delta\sigma}{\sigma}$$

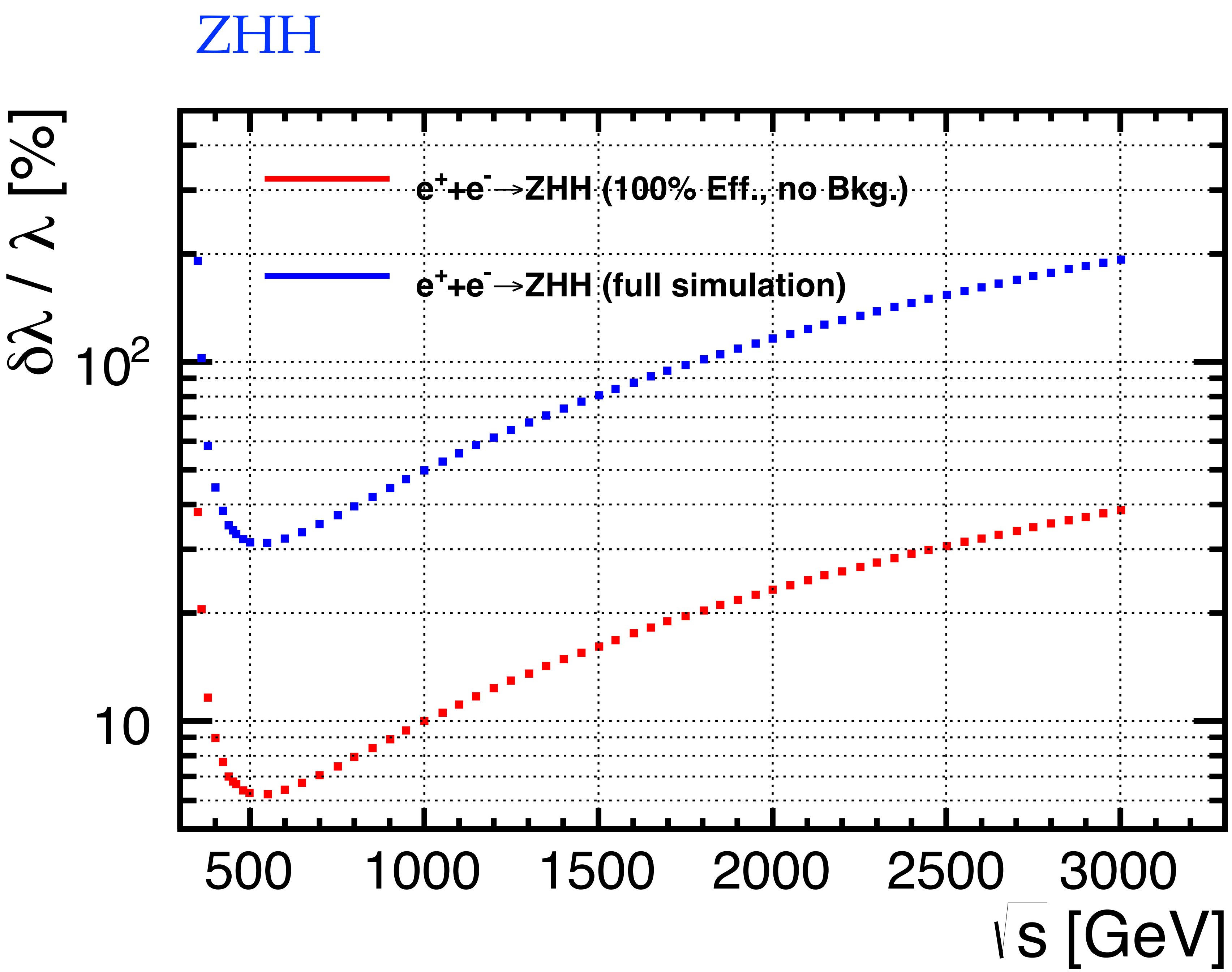
$$F = \frac{\sigma}{2S\lambda^2 + I\lambda}$$

sensitivity factor



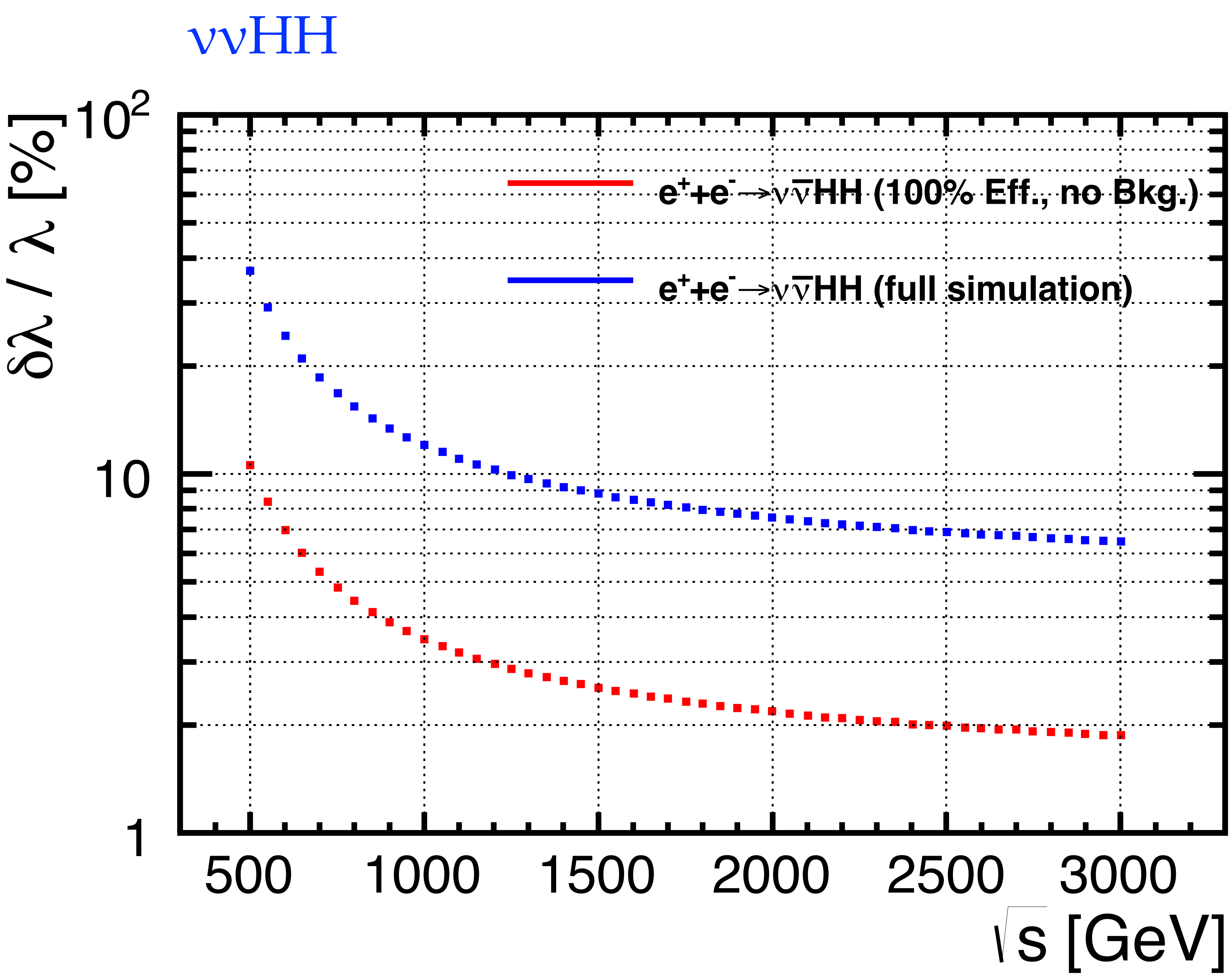


expected precision of λ: impact from analysis & √s



- **for ZHH**: **500 GeV** is optimal, **δλ/λ ~ 6% : 30%**, mild dependence between around **500-600** GeV, significantly worse at much lower or higher √s
- **huge room for improvement** (waiting for you to narrow down the gap)

expected precision of λ: impact from analysis & √s

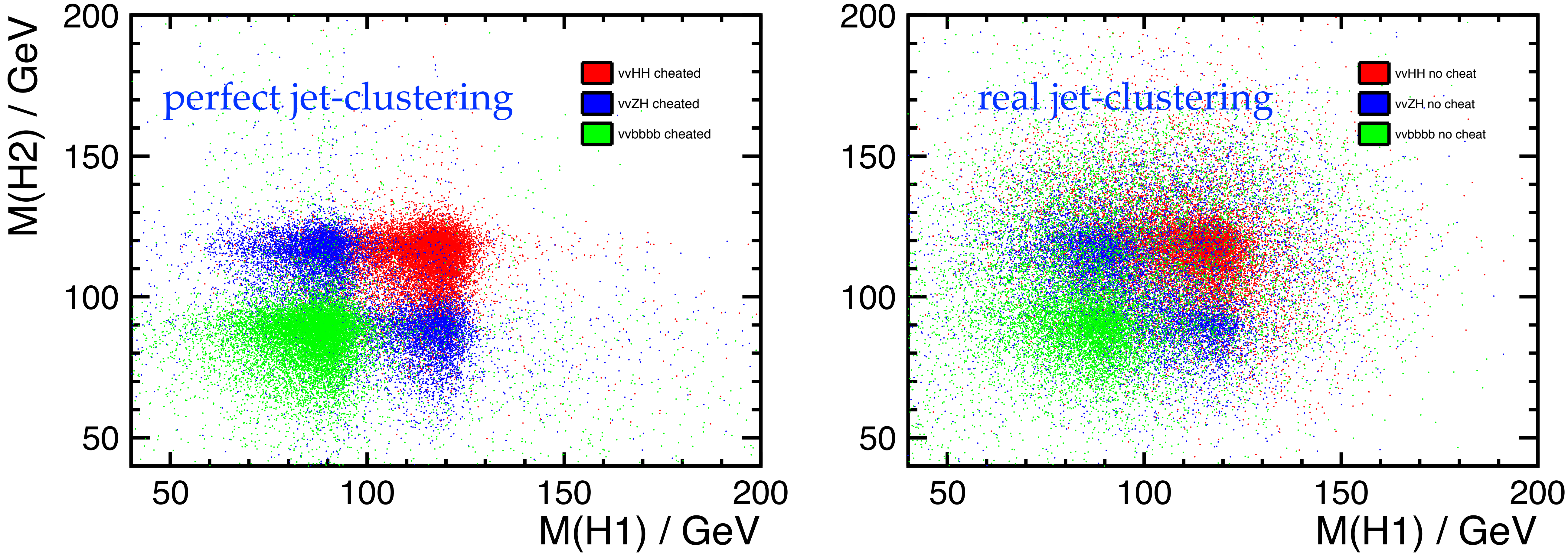


- **for vvHH**: significantly better going from 500 GeV to **1 TeV, δλ/λ~10%** achievable when √s >= 1TeV;
- better at higher √s, not drastically, from 1 TeV to 3 TeV, improved by 50%

one limiting factor: jet-clustering algorithm

ZHH->ννbbbb (BG: ZZH and ZZZ)

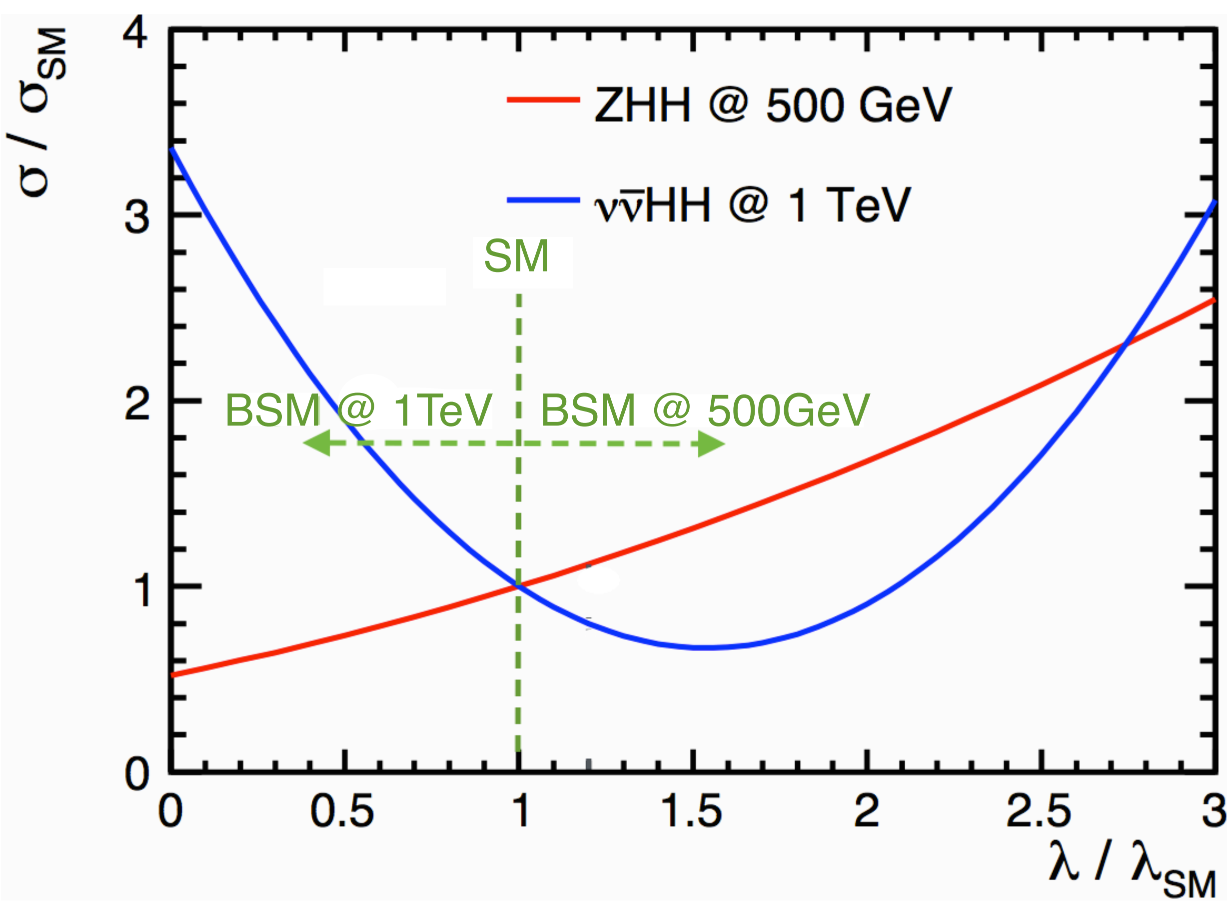
scatter plot of two Higgs masses

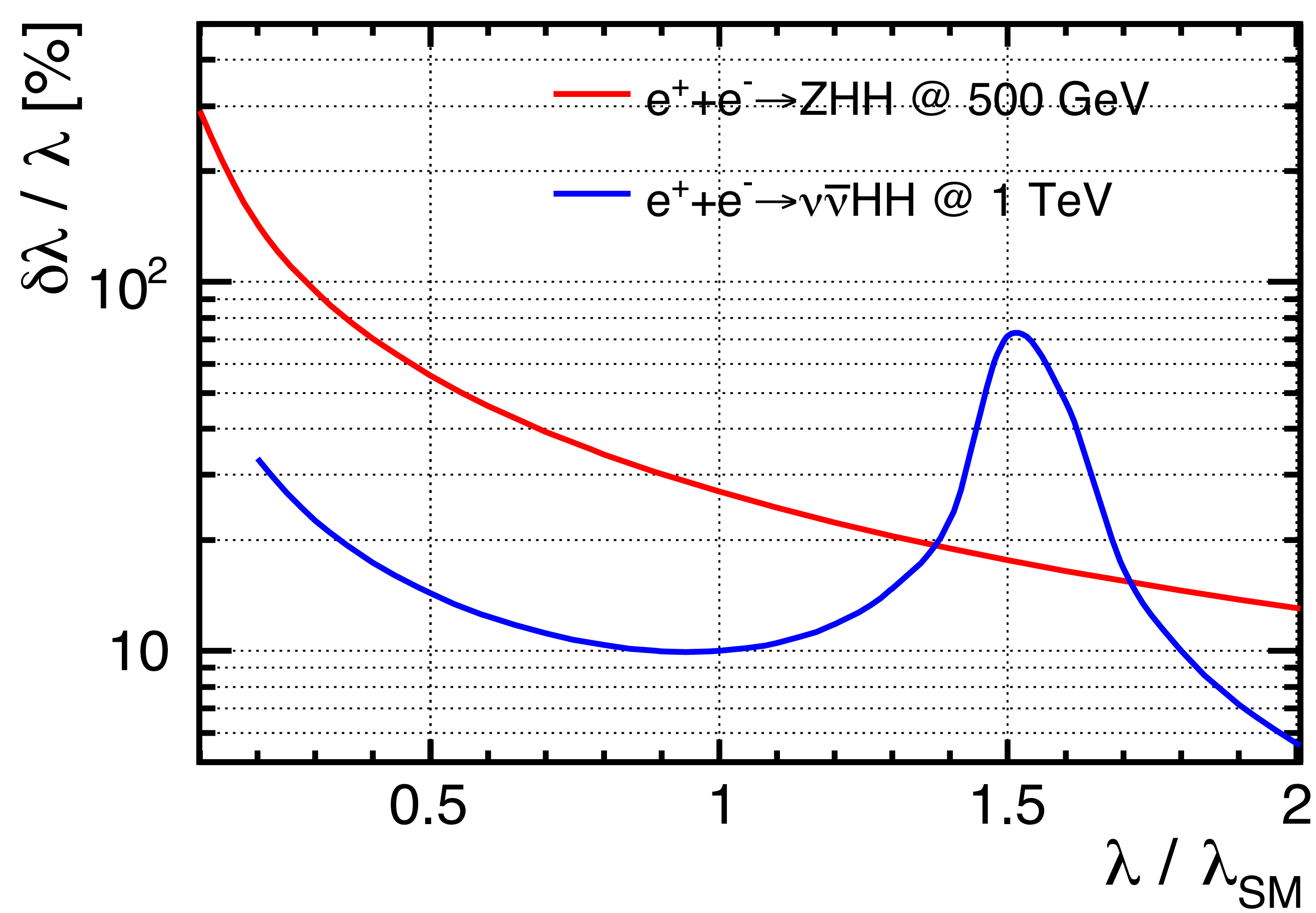


- the **mis-clustering** of particles degrades significantly the separation between signal and BG.
- it is studied that using perfect **color-singlet jet-clustering** can improve δλ/λ by **40%**!

Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

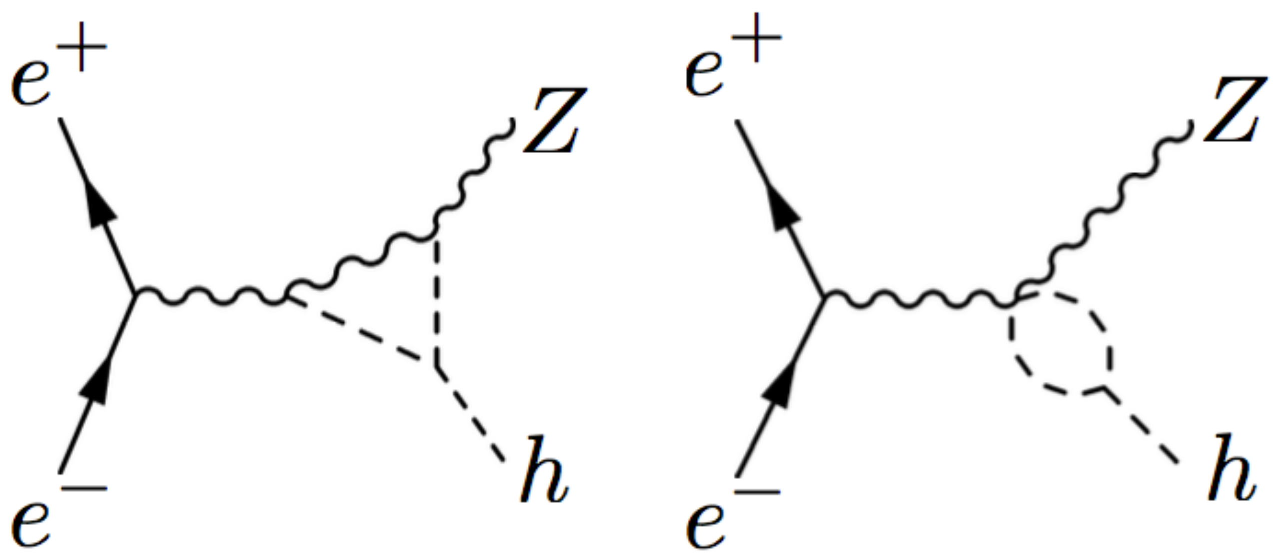
- **constructive** interference in **ZHH**, while **destructive** in **vvHH** (& LHC): **complementarity** between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\boldsymbol{\lambda_{HHH} / \lambda_{SM} = 2}$, Higgs self-coupling can be measured to ~**15%** using ZHH at 500 GeV e+e-





references for large deviations e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

Higgs self-coupling: indirect determination



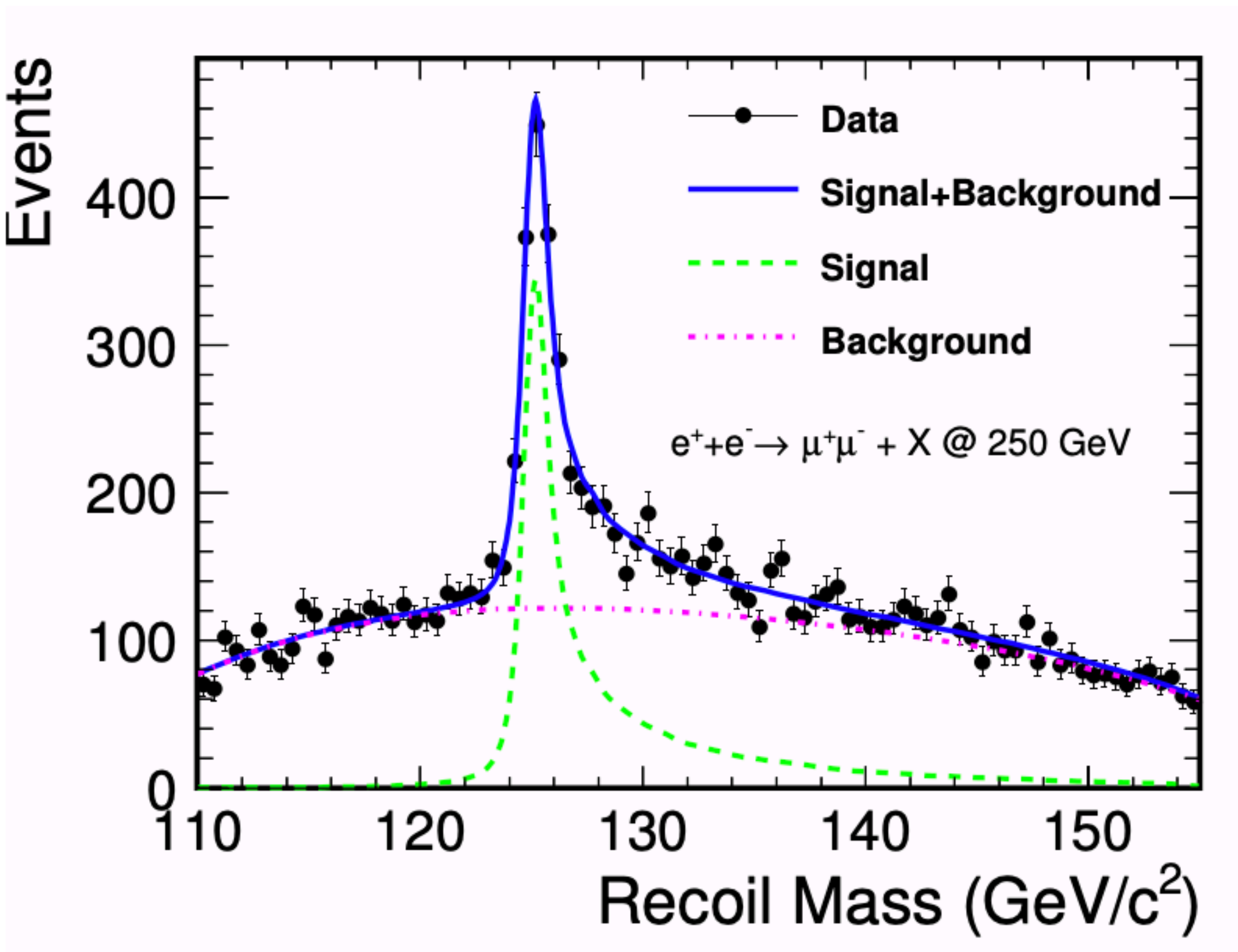
McCullough, arXiv:1312.3322

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

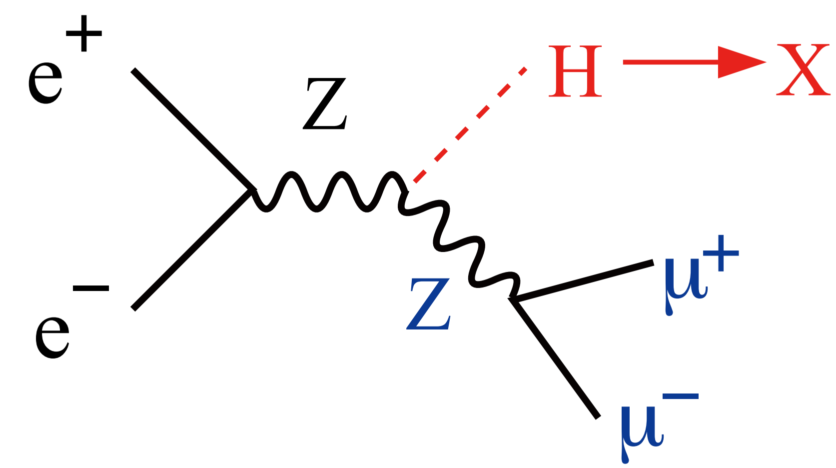
- if only δh is deviated —> δh ~ 28%
- if both δz and δh deviated —> δh ~ 90%
- δσ could receive contributions from many other sources
- open question: what happens after taking into account all possible modifications? (Lecture 2)

  - can we measure quartic Higgs self-coupling?

(ii-2) inclusive σ_{ZH}: unique key @ e+e-



$\Delta m_H = 14\text{MeV}$

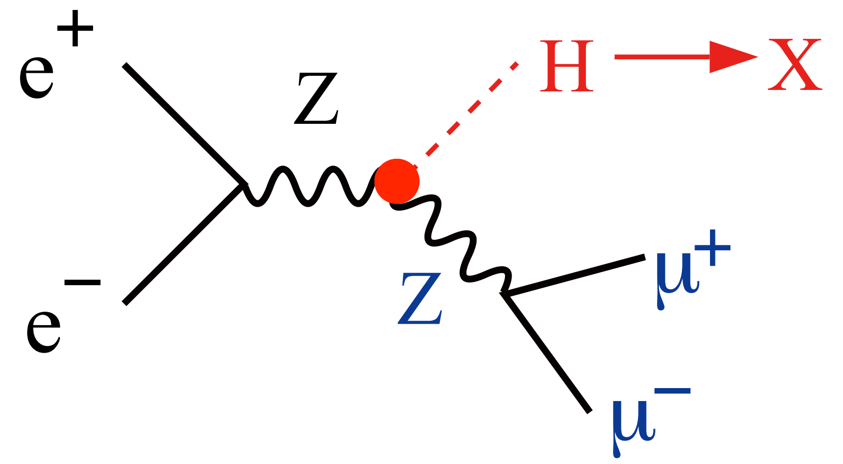


$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- well defined initial states at e+e-
- recoil mass technique —> tag Z only
- Higgs is tagged without looking into H decay
- **absolute cross section** of e^+e^- —> ZH

[for Z->ll (leptonic recoil), Yan et al, arXiv:1604.07524;
for Z->qq (hadronic recoil), Thomson, arXiv:1509.02853]

what does model independence mean?



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- meas. of σ_{ZH} doesn't depend on how Higgs decays
- meas. of σ_{ZH} doesn't depend on underlying HZZ vertex

is it really possible?

independent of H decay modes?

$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + X$$

- this question is almost equivalent to whether we can tag the Z decay products unambiguously
- might be easy in Z->ll, certainly not trivial in Z->qq
- even in Z->ll mode, we know there can be isolated leptons from Higgs decay, e.g. H->WW*/τ τ/ZZ, which get mis-identified as leptons from Z decay
- keep in mind we are targeting 0.1-1% precision measurement

efficiencies breakdown (leptonic recoil)

$H \to XX$	bb	cc	gg	$\tau\tau$	WW^*	ZZ^*	$\gamma\gamma$	γZ
BR (SM)	57.8%	2.7%	8.6%	6.4%	21.6%	2.7%	0.23%	0.16%
Lepton Finder	93.70%	93.69%	93.40%	94.02%	94.04%	94.36%	93.75%	94.08%
Lepton ID+Precut	93.68%	93.66%	93.37%	93.93%	93.94%	93.71%	93.63%	93.22%
$M_{l^+l^-} \in [73, 120]$ GeV	89.94%	91.74%	91.40%	91.90%	91.82%	91.81%	91.73%	91.47%
$p_T^{l^+l^-} \in [10, 70]$ GeV	89.94%	90.08%	89.68%	90.18%	90.04%	90.16%	89.99%	89.71%
$\lvert\cos\theta_{miss}\rvert < 0.98$	89.94%	90.08%	89.68%	90.16%	90.04%	90.16%	89.91%	89.41%
BDT > - 0.25	88.90%	89.04%	88.63%	89.12%	88.96%	89.11%	88.91%	88.28%
$M_{rec} \in [110, 155]$ GeV	88.25%	88.35%	87.98%	88.43%	88.33%	88.52%	88.21%	87.64%

- every cut is applied very carefully to avoid large bias, still ~1%
- nevertheless, it becomes almost a paradox:
  - ☑ no cut, no bias; looser cuts, less bias
  - ☑ extremely tighter cuts, less bias;
  - ☑ too loose or too tight cuts -> remain too much background or too little signal -> bad precision measurement

efficiencies breakdown (hadronic recoil)

Decay mode	$\varepsilon^{\text{vis.}}_{\mathscr{L}>0.65}$	$\varepsilon^{\text{invis.}}_{\mathscr{L}>0.60}$	$\varepsilon^{\text{vis.}} + \varepsilon^{\text{invis.}}$
$H \to$ invis.	<0.1 %	23.5 %	23.5 %
$H \to q\bar{q}/gg$	22.6 %	<0.1 %	22.6 %
$H \to WW^*$	22.1 %	0.1 %	22.2 %
$H \to ZZ^*$	20.6 %	1.1 %	21.7 %
$H \to \tau^+\tau^-$	25.3 %	0.2 %	25.5 %
$H \to \gamma\gamma$	25.7 %	<0.1 %	25.7 %
$H \to Z\gamma$	18.6 %	0.3 %	18.9 %
$H \to WW^* \to q\bar{q}q\bar{q}$	20.8 %	<0.1 %	20.8 %
$H \to WW^* \to q\bar{q}\ell\nu$	23.3 %	<0.1 %	23.3 %
$H \to WW^* \to q\bar{q}\tau\nu$	23.1 %	<0.1 %	23.1 %
$H \to WW^* \to \ell\nu\ell\nu$	26.5 %	0.1 %	26.5 %
$H \to WW^* \to \ell\nu\tau\nu$	21.1 %	0.5 %	21.6 %
$H \to WW^* \to \tau\nu\tau\nu$	16.3 %	2.3 %	18.7 %

- relative bias can be as large as ~**15%**

a nice trick: categorization

$$\sigma_{ZH} = \sigma^{cat1} + \sigma^{cat2} + \sigma^{cat3} + \sigma^{cat4} + \cdots$$

- if we have a complete list of categories
- then we only need to keep all selection cuts independent of decay mode in each category;
- selections cuts among categories can be very different

for example

$$\sigma_{ZH} = \sigma^{H\to\text{invisible}} + \sigma^{H\to\text{visible}}$$

a realistic solution: make use of individual BR measurement

$$\sigma_{ZH} = \frac{N_S}{R_f L \bar{\epsilon}} \qquad \bar{\epsilon} \equiv \sum_i B_i \epsilon_i$$

N_S: # of signal
R_f: BR of Z->ff
L: int. luminosity
Bi: BR of H decay mode i
εi: efficiency of mode i

- if every ε_i is same -> $\Sigma B_i = 1$; no need for any knowledge about B_i
- nevertheless, we can measure many of the $\sigma x B_i$; assume i=1..n is known with ΔBi; i=n+1,… is unknown, sum up to Bx;

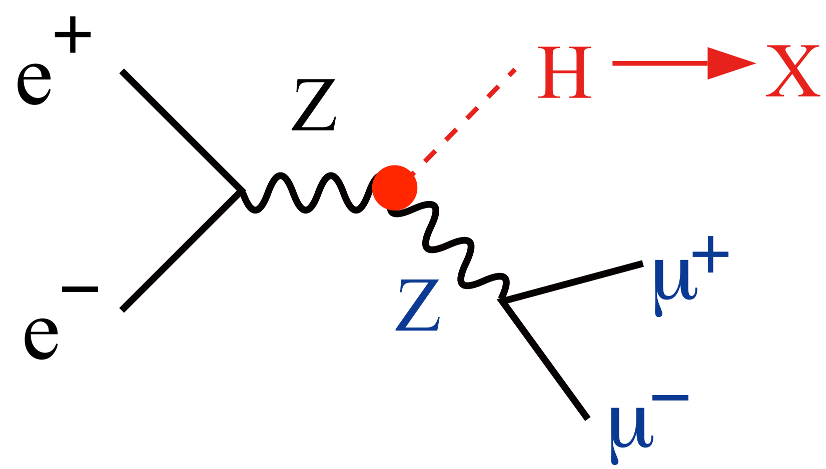
known modes | systematic error to σ_{ZH} | unknown modes

$$\frac{\Delta\sigma_{\rm ZH}}{\sigma_{\rm ZH}} = \frac{\Delta\bar{\varepsilon}}{\bar{\epsilon}} = \sqrt{\sum_{i=1}^{n} \Delta B_i^2 \left(\frac{\varepsilon_i}{\varepsilon_0} - 1\right)^2}.$$

$$\frac{\Delta\sigma_{\rm ZH}}{\sigma_{\rm ZH}} = \frac{\Delta\bar{\varepsilon}}{\bar{\epsilon}} < \sum_{i=n+1} B_i \frac{\delta\varepsilon_{\rm max}}{\varepsilon_0} = B_x \frac{\delta\varepsilon_{\rm max}}{\varepsilon_0}$$

- leptonic recoil, demonstrated possible $\delta\sigma_{ZH}$~0.1% for Bx<10%
- hadronic recoil, still need more work for $\delta\sigma_{ZH}$ <1% for Bx<10%

independent of HZZ vertex?



- different HZZ vertex might change angular distributions of Z

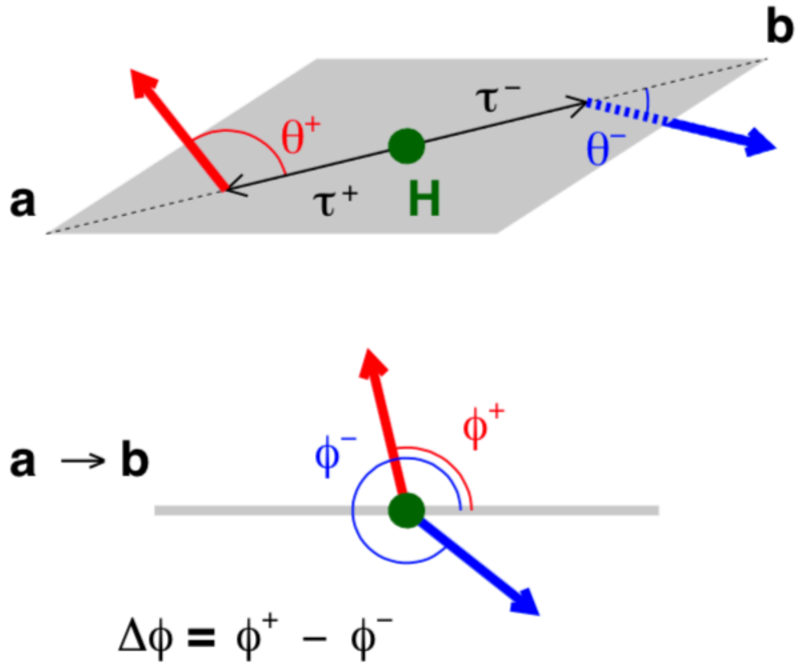
- hence, this question is equivalent to whether the selections cuts are democratic for all production angles of Z

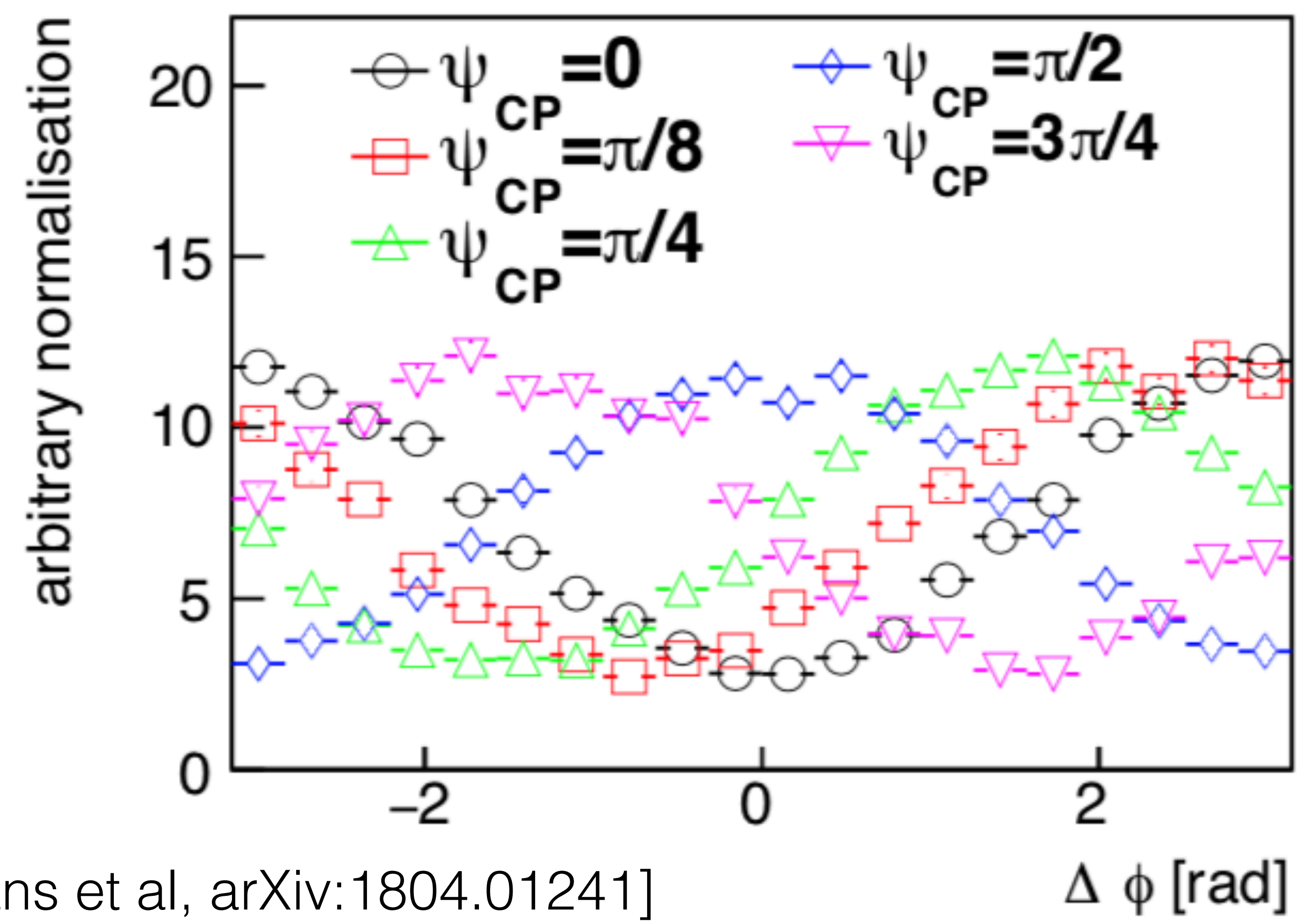
- **open question, this is not sufficiently studied yet**

(ii-3) Higgs CP in H—>τ⁺τ⁻

- CP is essential to understand structures of all Higgs couplings

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos\Phi_{CP} + i\gamma^5 \sin\Phi_{CP}) f$$





$\Delta\Phi_{CP} \sim 4.3^\circ$ [Jeans et al, arXiv:1804.01241]

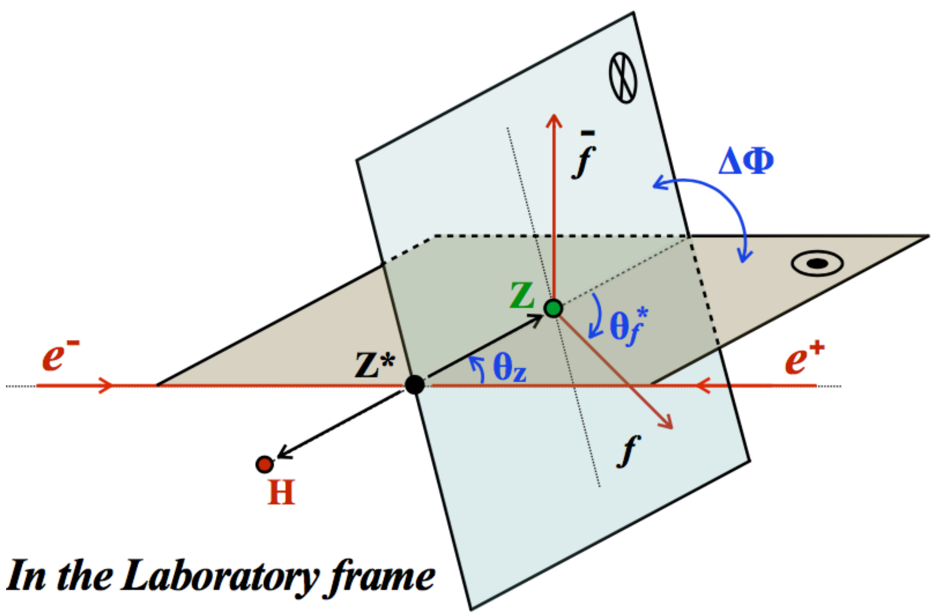
- ❑ **is it good enough for discovering EW Baryogengesis?**
- ❑ **large room to improve in experiment**

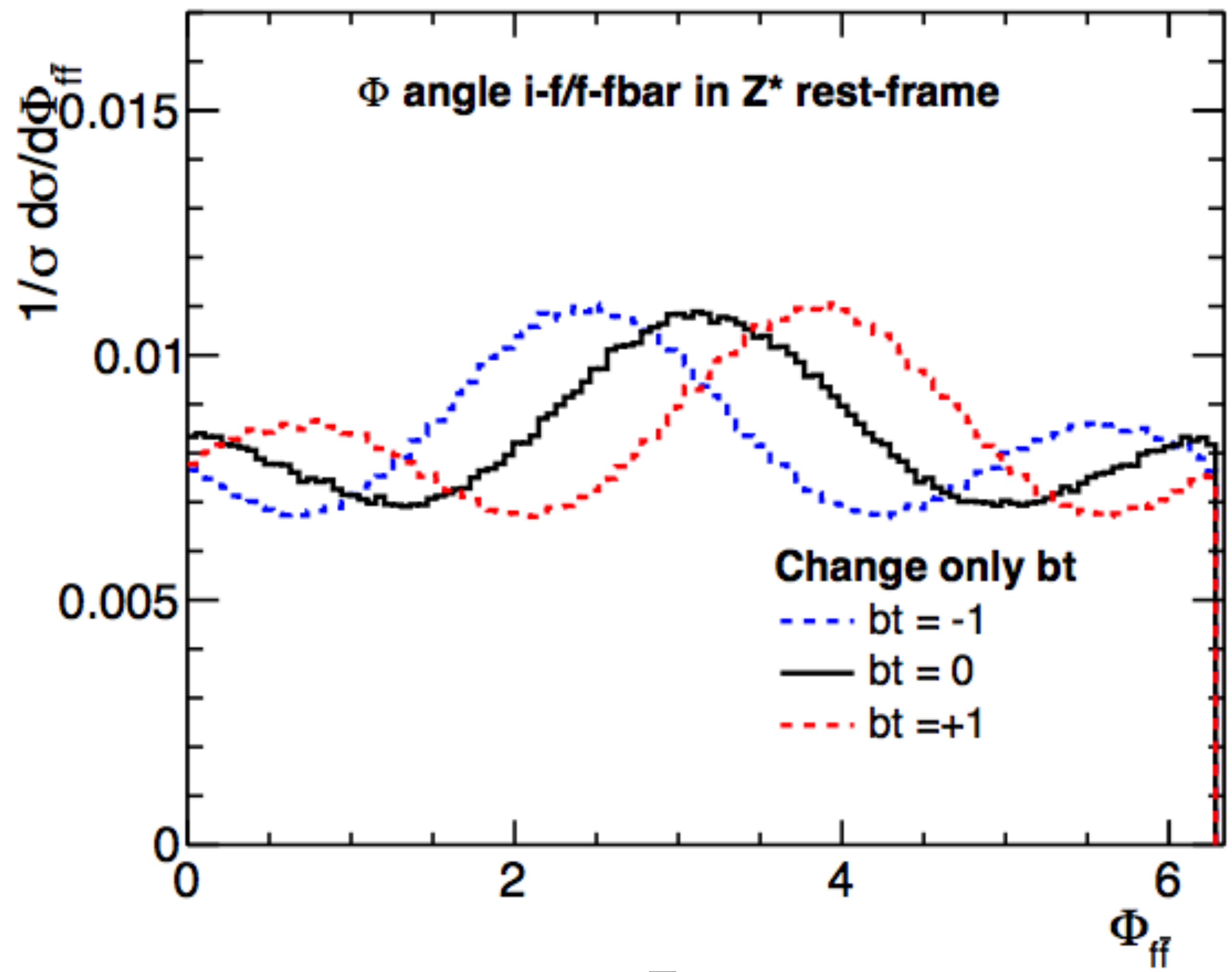
(ii-3) Higgs CP in HZZ coupling

$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda})hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}$$

(CP-odd)

$$e^+ + e^- \to Zh \to f\bar{f}h$$





@ $\sqrt{s} = 250\text{GeV}$

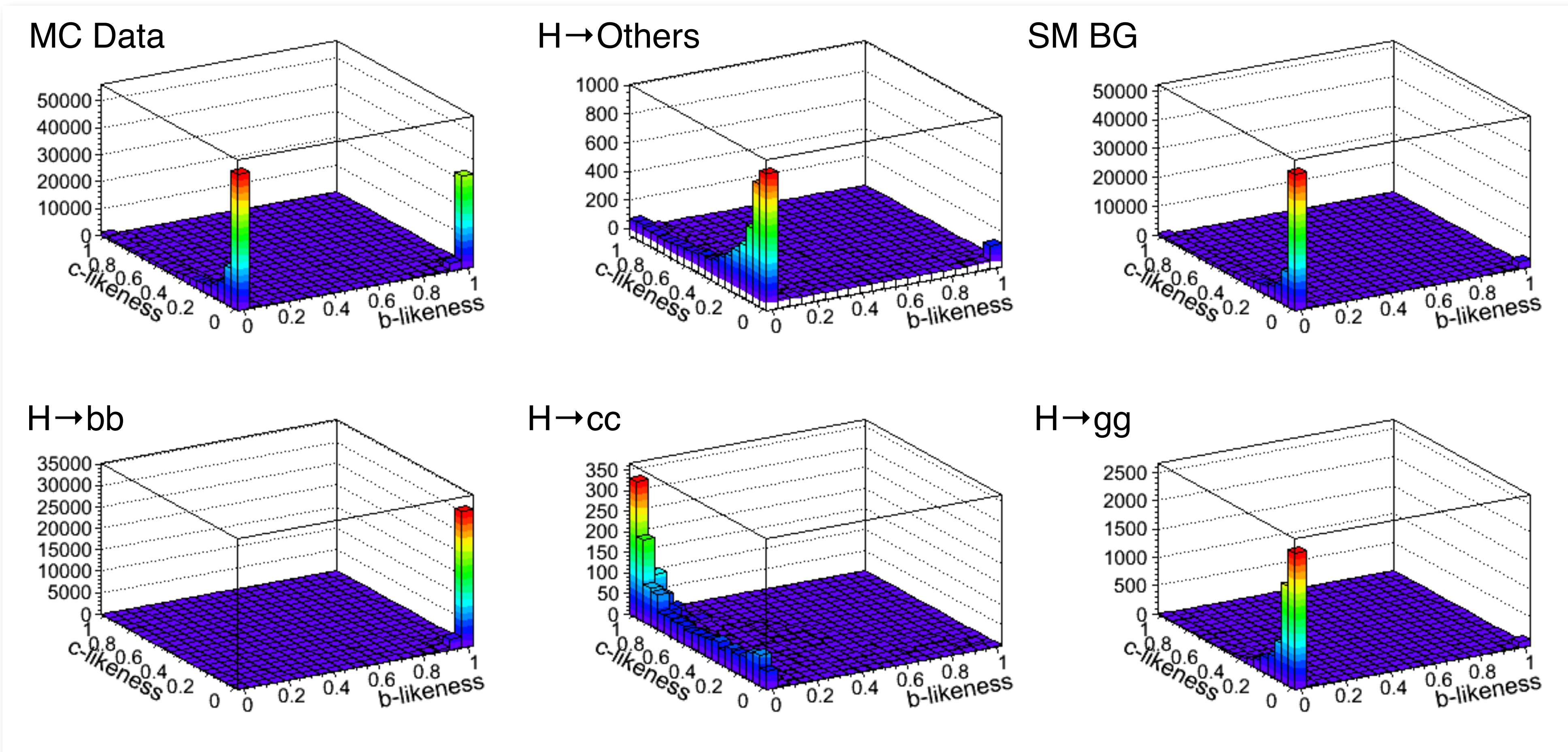
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

[Ogawa et al, arXiv:1712.09772]

(ii-4) Higgs direct couplings to bb, cc and gg

- clean environment at e+e-; excellent b- and c-tagging performance
- bb/cc/gg modes can be separated simultaneously by template fitting

e+e- —> ZH —> ff(jj): b-likeness .vs. c-likeness



directly measured

$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} g^2_{Hbb} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c}) \propto g^2_{HZZ} g^2_{Hcc} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to gg) \propto g^2_{HZZ} g^2_{Hgg} / \Gamma_H$$

with Γ_H

δg_{Hbb}

δg_{Hcc}

δg_{Hgg}

[Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY)]

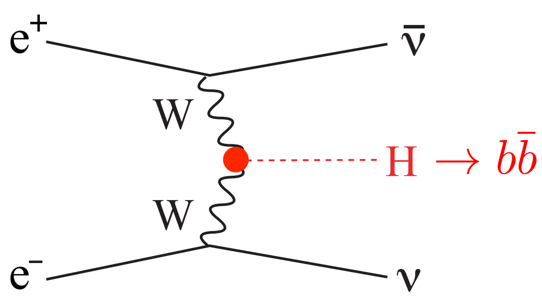
(ii-5) WW-fusion channel & Higgs total width Γ_H

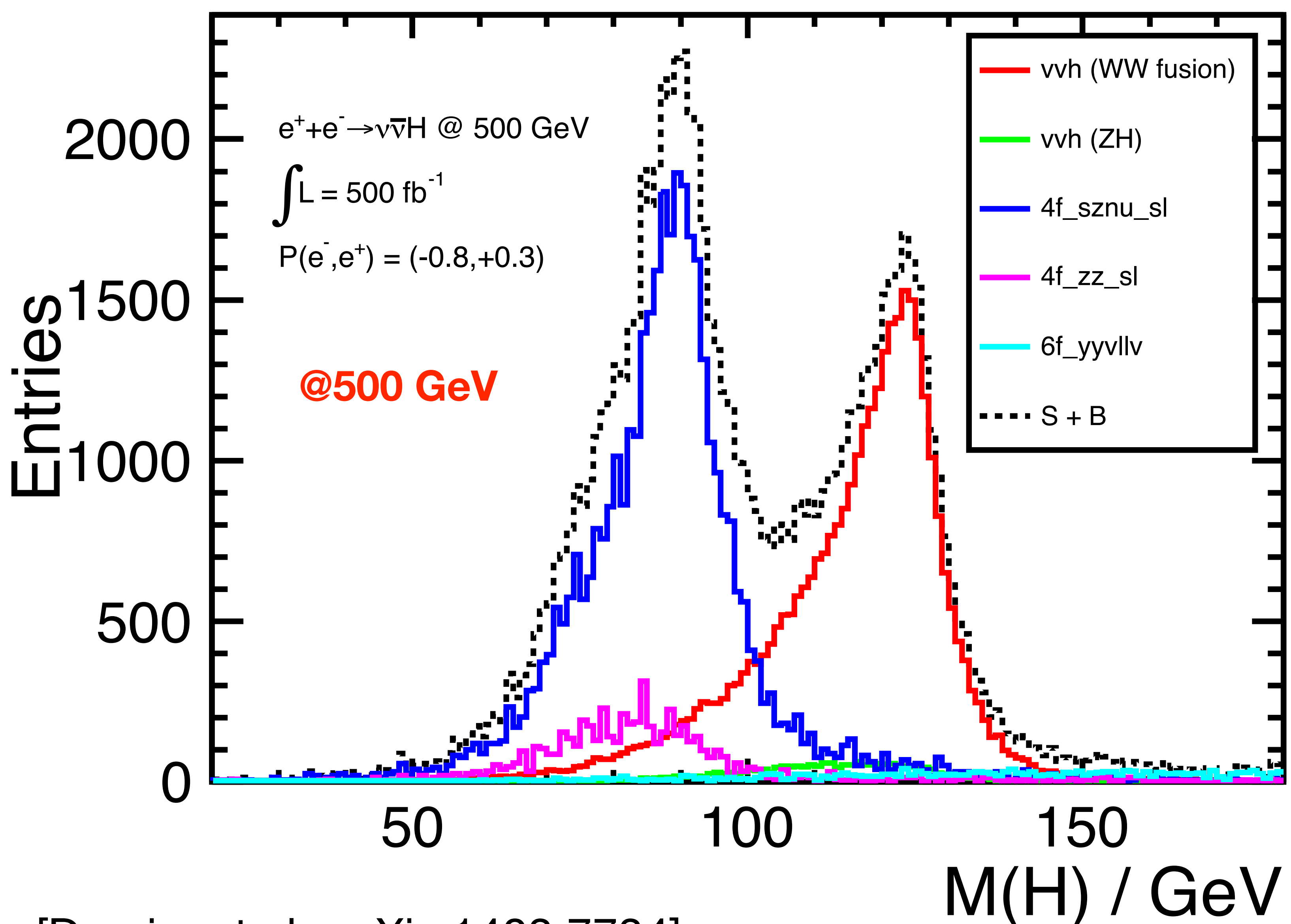
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

★ $$\Gamma_H = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

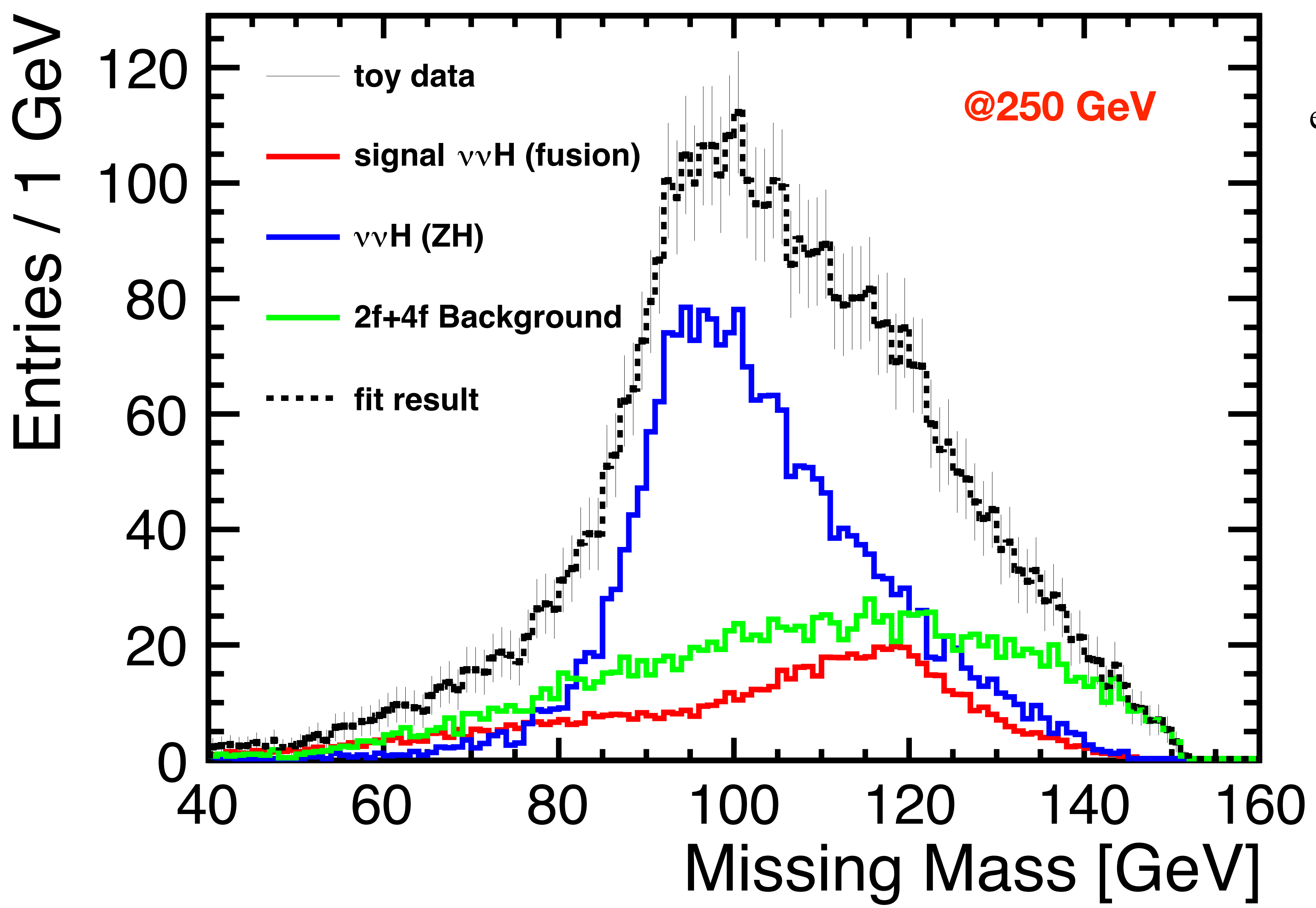
—> better option!

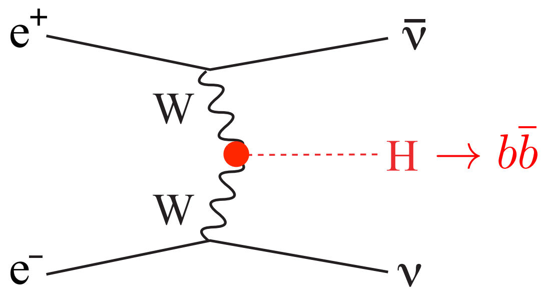




[Duerig, et al., arXiv:1403.7734]

very different at √s=250 GeV



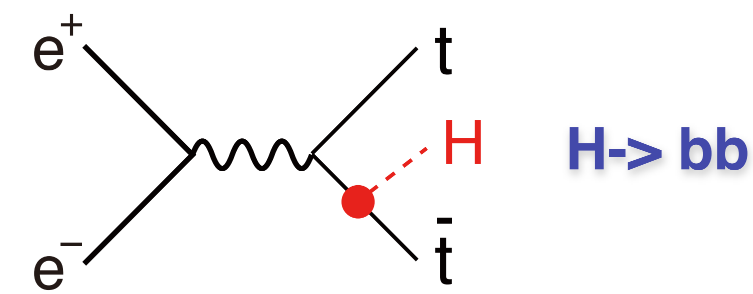


ρ = -34% correlation between

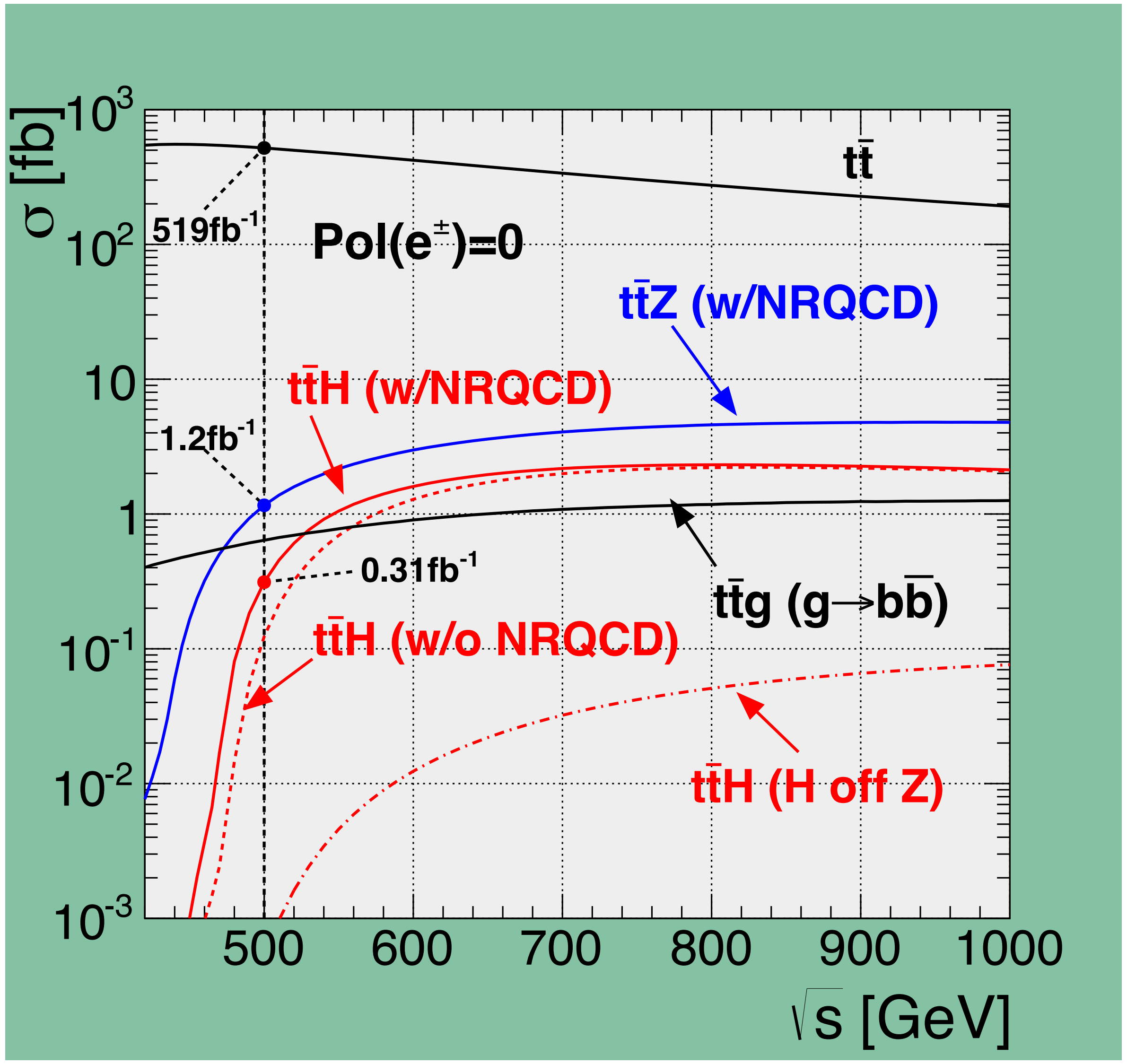
$\sigma_{\nu\nu H}$xBR(H—>bb) and σ_{ZH}xBR(H—>bb)

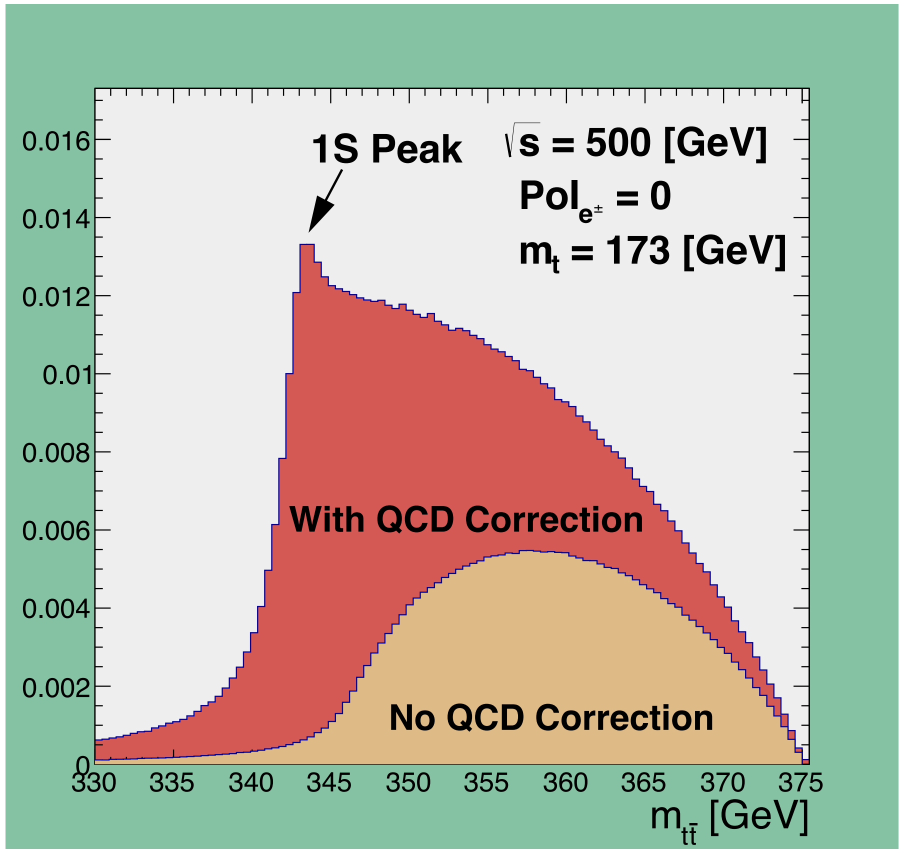
(ii-6) Top-Yukawa coupling

- largest Yukawa coupling; crucial role
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



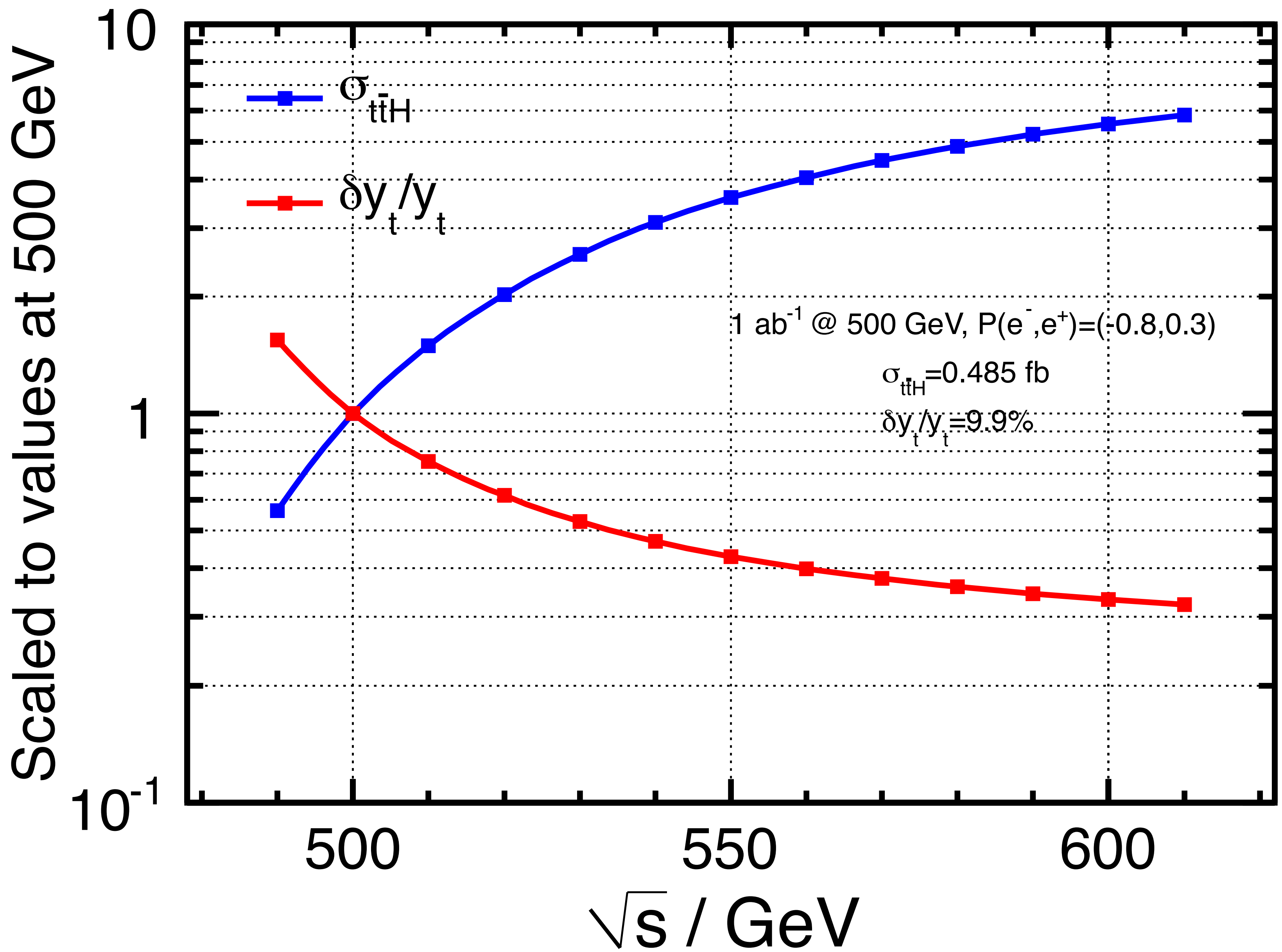
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
ILC	6.3%	1.5%





Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309

Top-Yukawa coupling: impact of √s



[Y. Sudo]

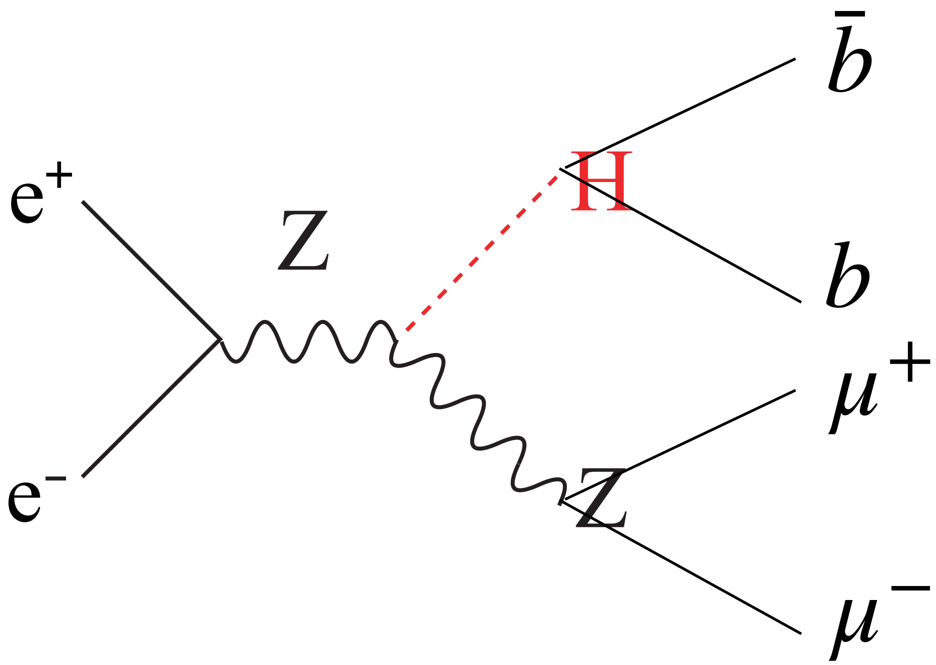
- increase $\sqrt{s}$ slightly by 50GeV can improve δy_t by a factor of 2

(ii-7) how do we actually determine Higgs couplings?

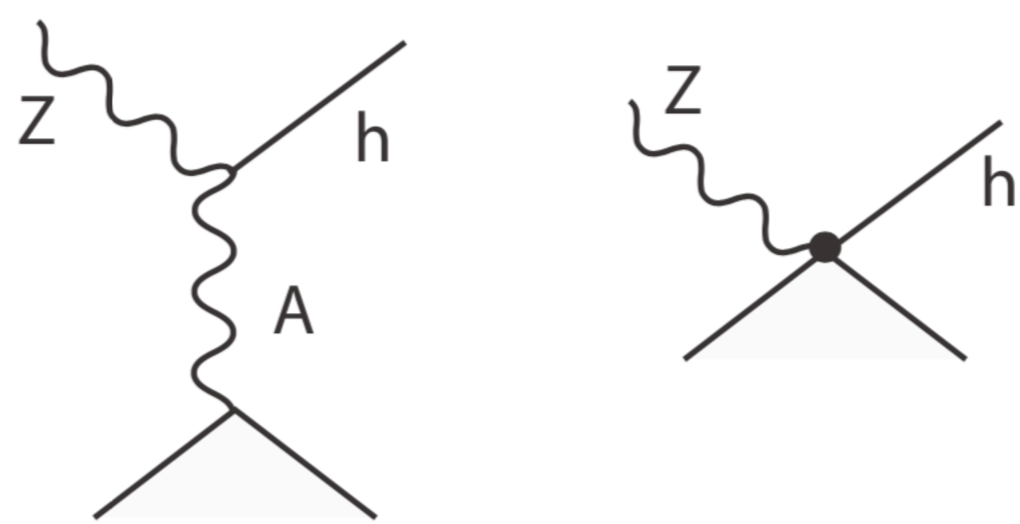
suppose we discover a deviation in, e.g. cross section of

e+e- -> ZH -> (μμ) (bb)

then we would like to know which coupling is deviated:



- hbb coupling?
- hZZ coupling?
- Zμμ coupling?
- Zee coupling?
- new diagrams?



From observables to couplings — Global Fit

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2$$

Yi: measured values by experiments

Yi': predicted values by underlying theory

ΔYi: measurement uncertainty

n: number of independent observables

- **kappa formalism**

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t) \quad (B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

$$g_{HXX} = \kappa_X \cdot g^{SM}_{HXX}$$

- **effective field theory formalism (Lecture 2)**

From observables to couplings — Global Fit

in case there are correlated observables

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2 + (Y_j - Y_j')^T C_j^{-1} (Y_j - Y_j')$$

Y_j: column vector of correlated observables

C_j: covariance matrix for those observables

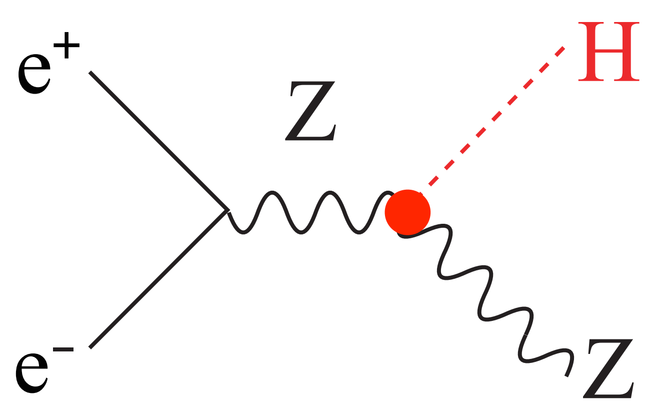
Higgs coupling determination — kappa formalism

1) recoil mass technique —> inclusive $\boldsymbol{\sigma_{Zh}}$
2) σ_{Zh} —> $\boldsymbol{\kappa_Z}$ —> Γ(h->ZZ*)
3) W-fusion $\nu_e\nu_e$h —> $\boldsymbol{\kappa_W}$ —> Γ(h->WW*)
4) total width $\boldsymbol{\Gamma_h}$ = Γ(h—>ZZ*)/BR(h->ZZ*)
5) or $\boldsymbol{\Gamma_h}$ = Γ(h—>WW*)/BR(h->WW*)
6) then all other couplings BR(h->XX) *Γ_h -> $\boldsymbol{\kappa_X}$

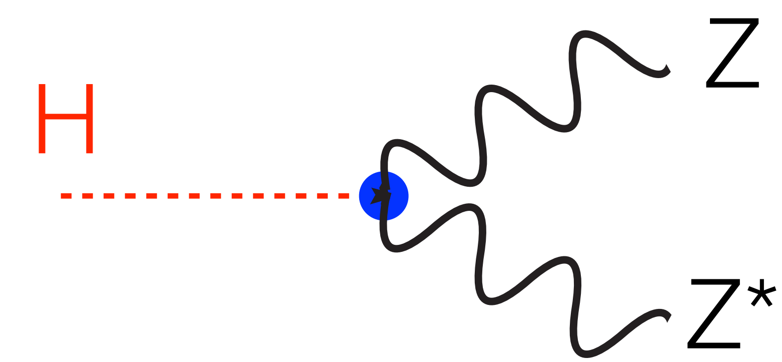
JT, et al, PoS EPS-HEP2013 (2013) 316 Nucl.Part.Phys.Proc. 273-275 (2016) 826-833

question in kappa formalism:

$$\frac{\sigma(e^+e^- \to Zh)}{SM} = \frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \qquad \textbf{?}$$



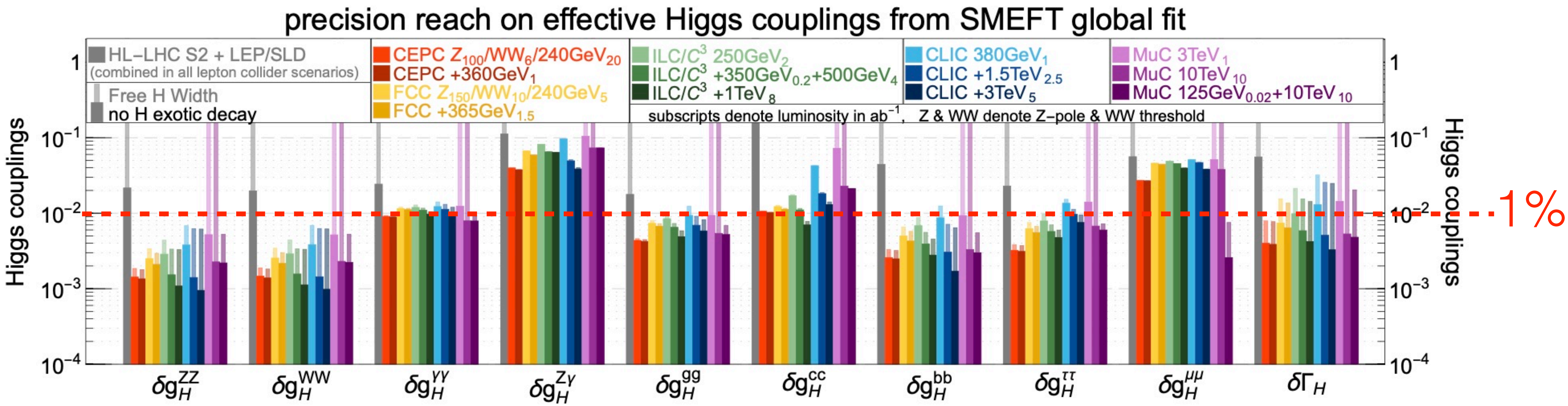
$\propto \quad \kappa_Z^2\,? \quad \propto$



- BSM territory: can deviations be represented by single κ_Z?
- How to include radiative corrections in kappa formalism?

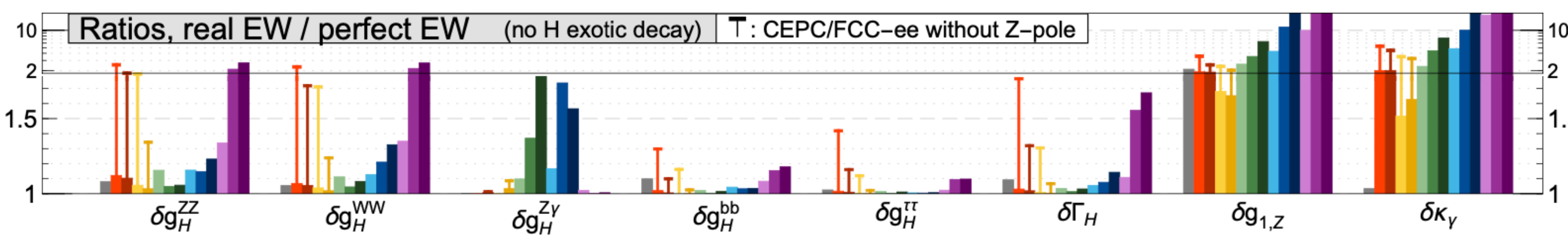
Projections of Higgs coupling precisions

[Snowmass White Paper on Global SMEFT Fits, arXiv:2206.08326]



gauge bosons .... H .... ***fermions***

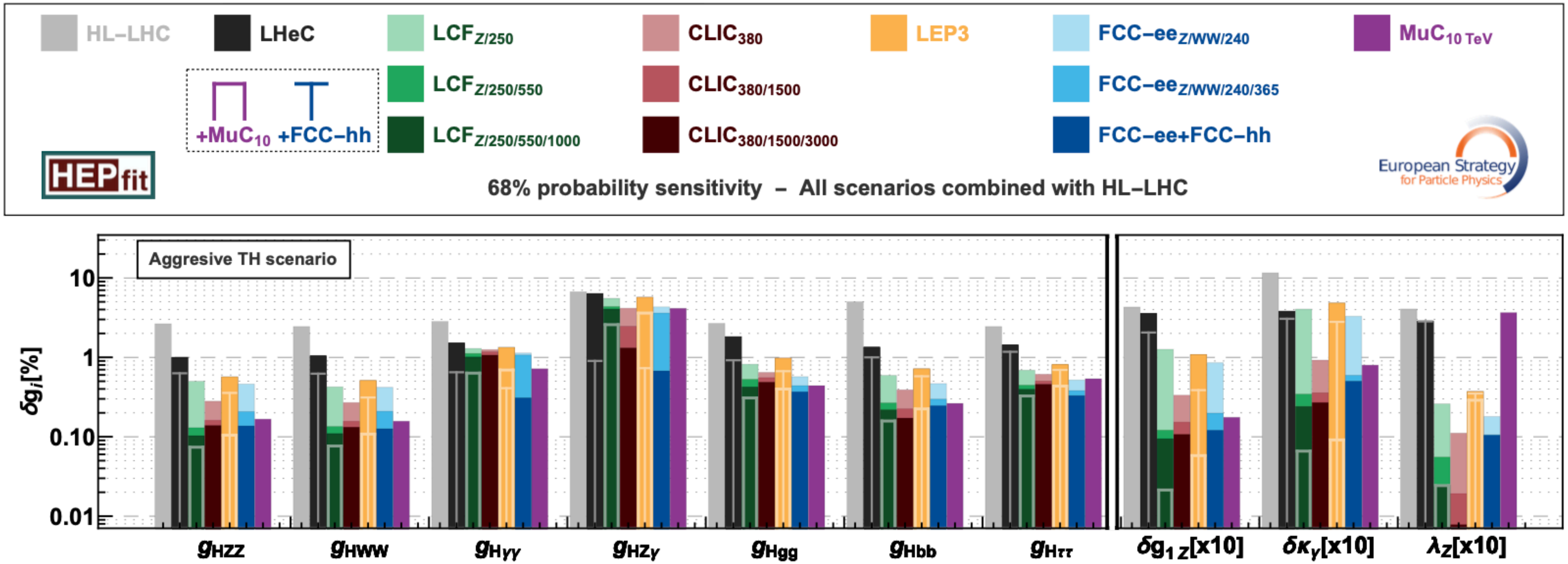
- Goal in reach: many couplings 1% or below; similar among all e+e-



- Interplay with EWPOs: Z-pole crucial for circular e+e-

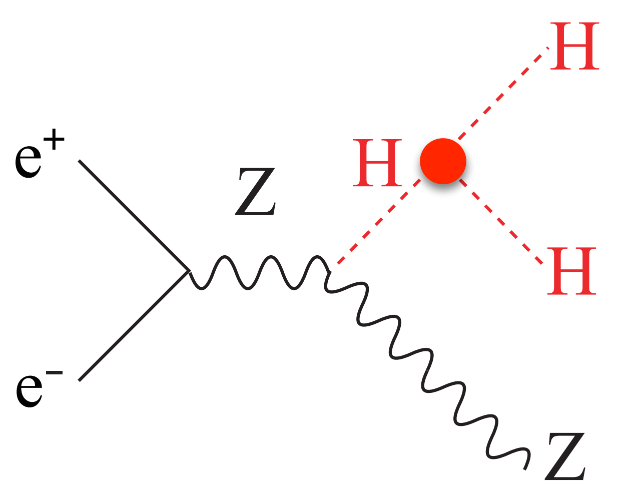
Projections of Higgs coupling precisions

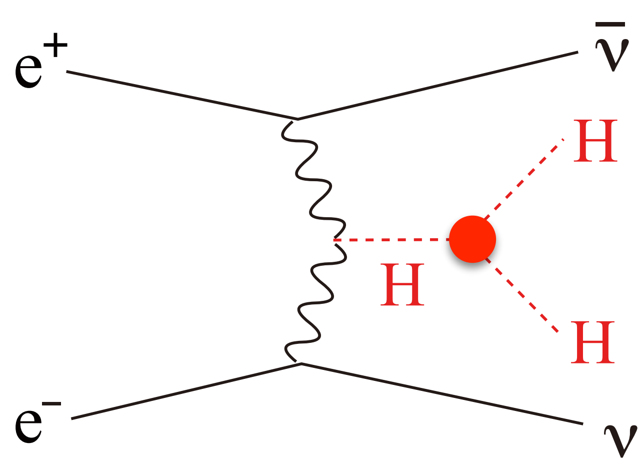
[Physics Briefing Book 2025, arXiv:2511.03883]



λ_{HHH}: di-Higgs & single-Higgs processes

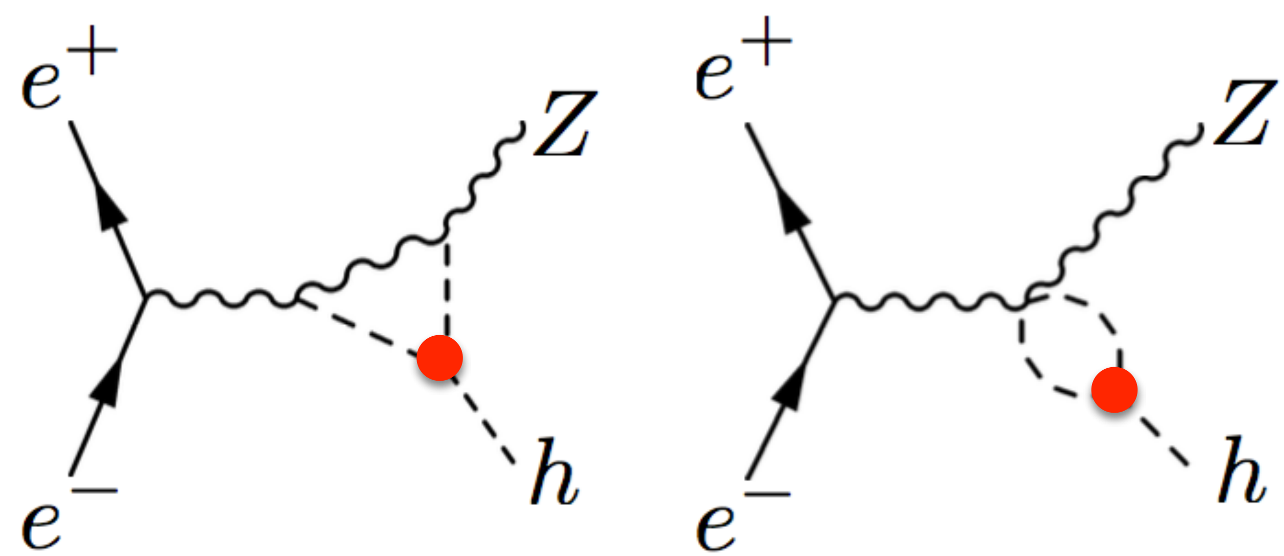
$\sqrt{s} \gtrsim 500$ GeV





$\sigma_{HH} \sim O(0.1)$ fb

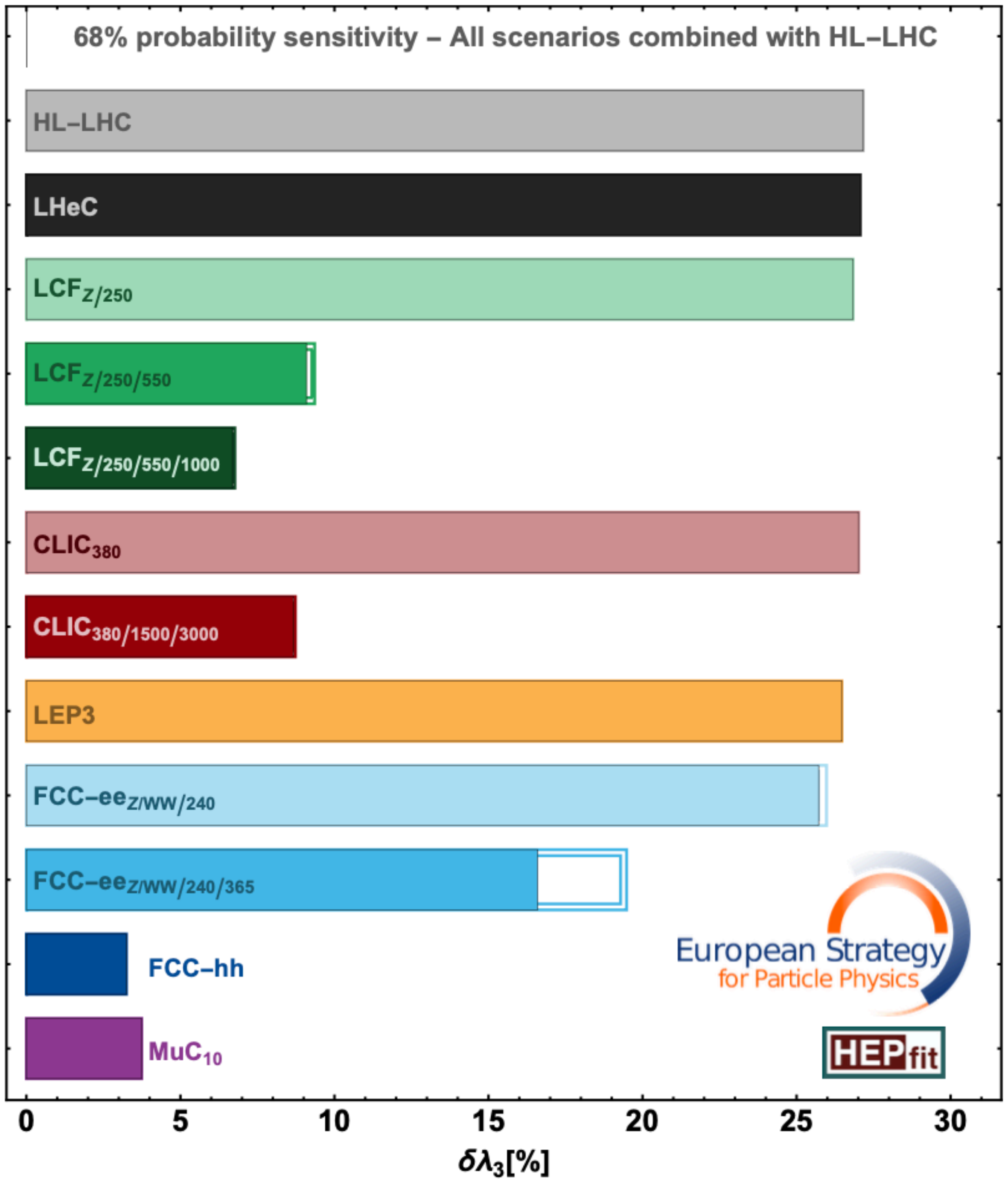
$\sqrt{s} \gtrsim 240\text{–}250$ GeV



$\delta\sigma_{ZH} \sim O(1\%)$

Projections of Higgs self-coupling precisions

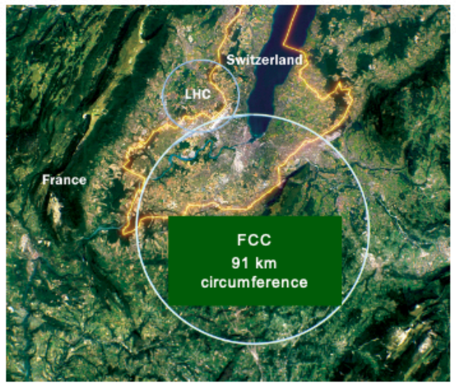
[Physics Briefing Book, arXiv:2511.03883]



- both single-Higgs and di-Higgs meas. are used
- HL-LHC di-Higgs contribution was always combined
- linear e+e- have “clear” advantages

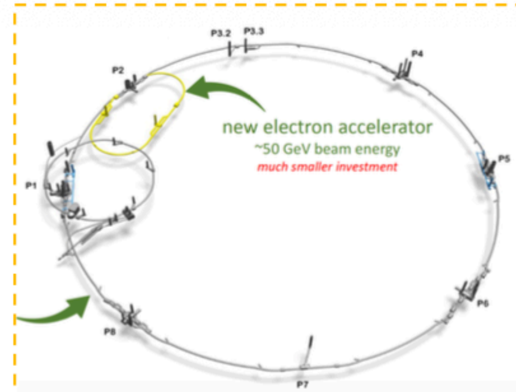
Potential for development: future 10 TeV parton-scale collider options

FCC-ee



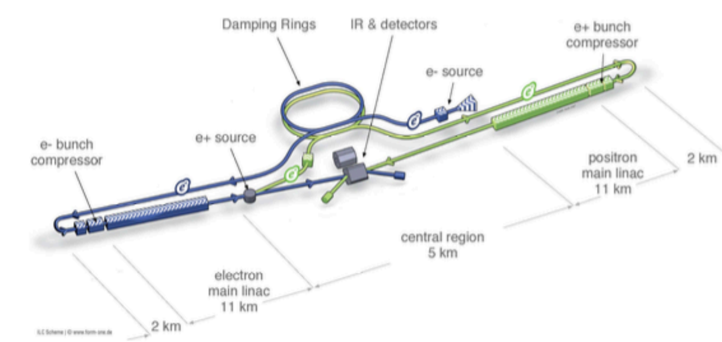
LEP3

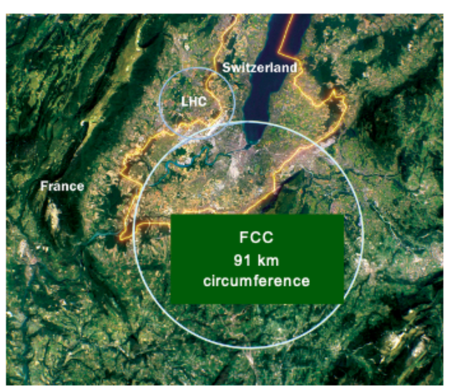
LHeC



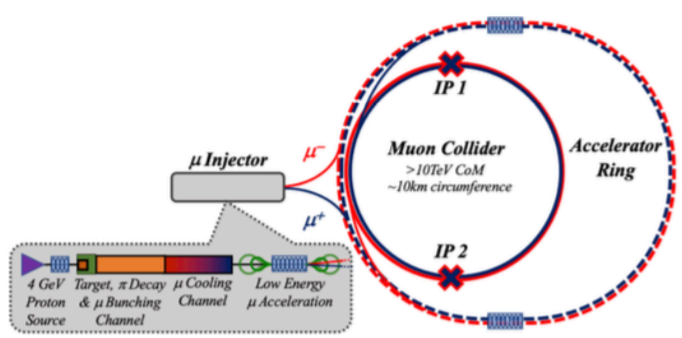
PERLE

LCF, CLIC



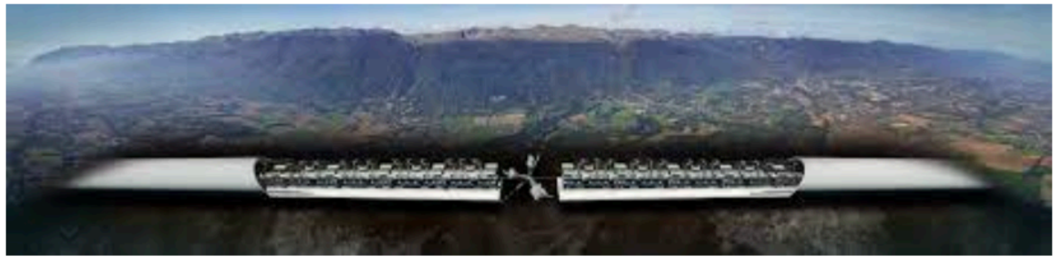


FCC-hh,
baseline 85 TeV (→ 120 TeV)
+ possibility for HI collisions



Muon Collider (3, 10 TeV)

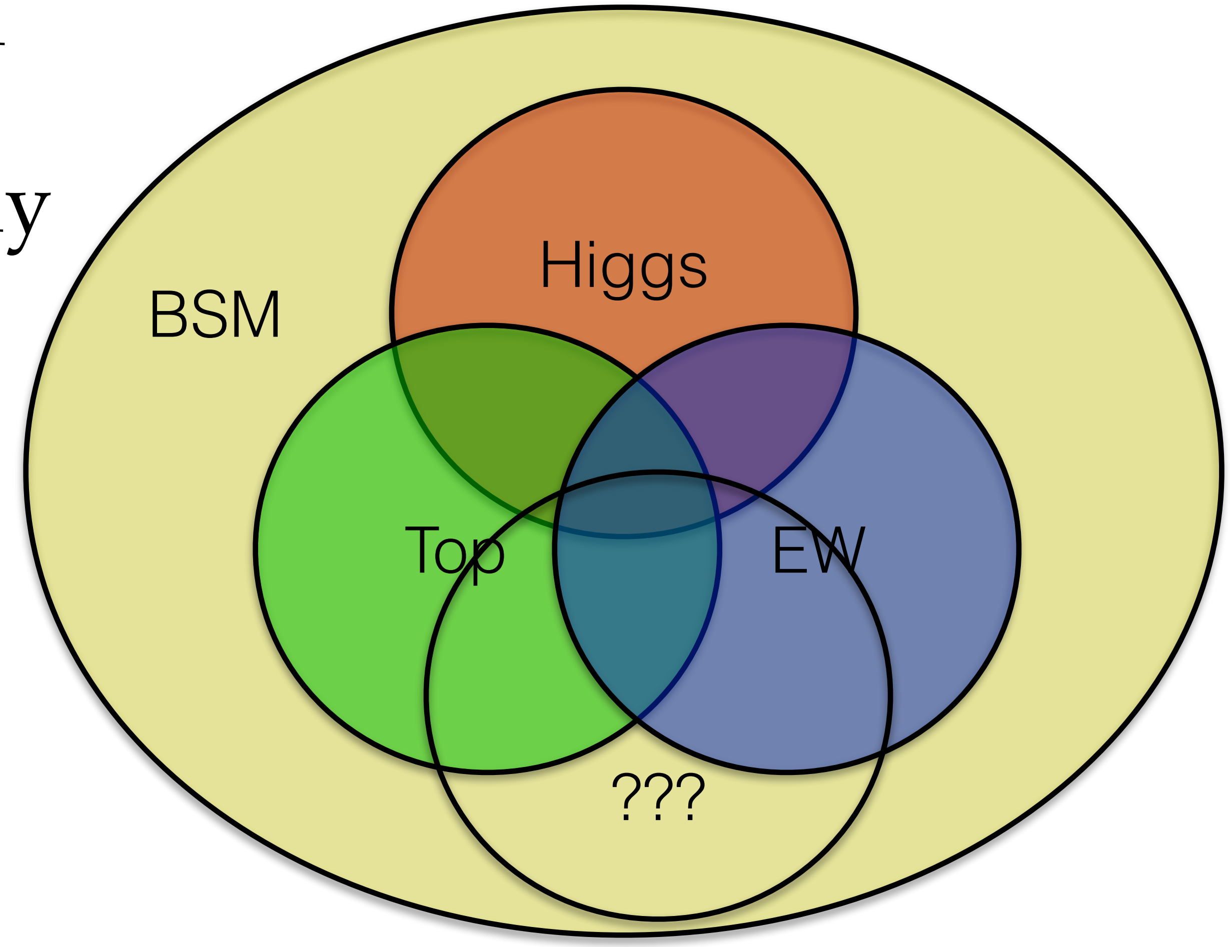
R&D



e^+e^- with improved acceleration technologies
LCF, C^3 (→ 1 TeV), CLIC (1.5 TeV), HALHF, …
→ plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)

summary

- physics at future e+e- is very rich
- discover BSM directly & indirectly
- Higgs is unique but not alone
- in addition to a Higgs factory
  - HH factory
  - Z/W factory
  - Top-quark factory
  - flavor factories
  - in the end: new particles factory
- let's get prepared for the realization



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