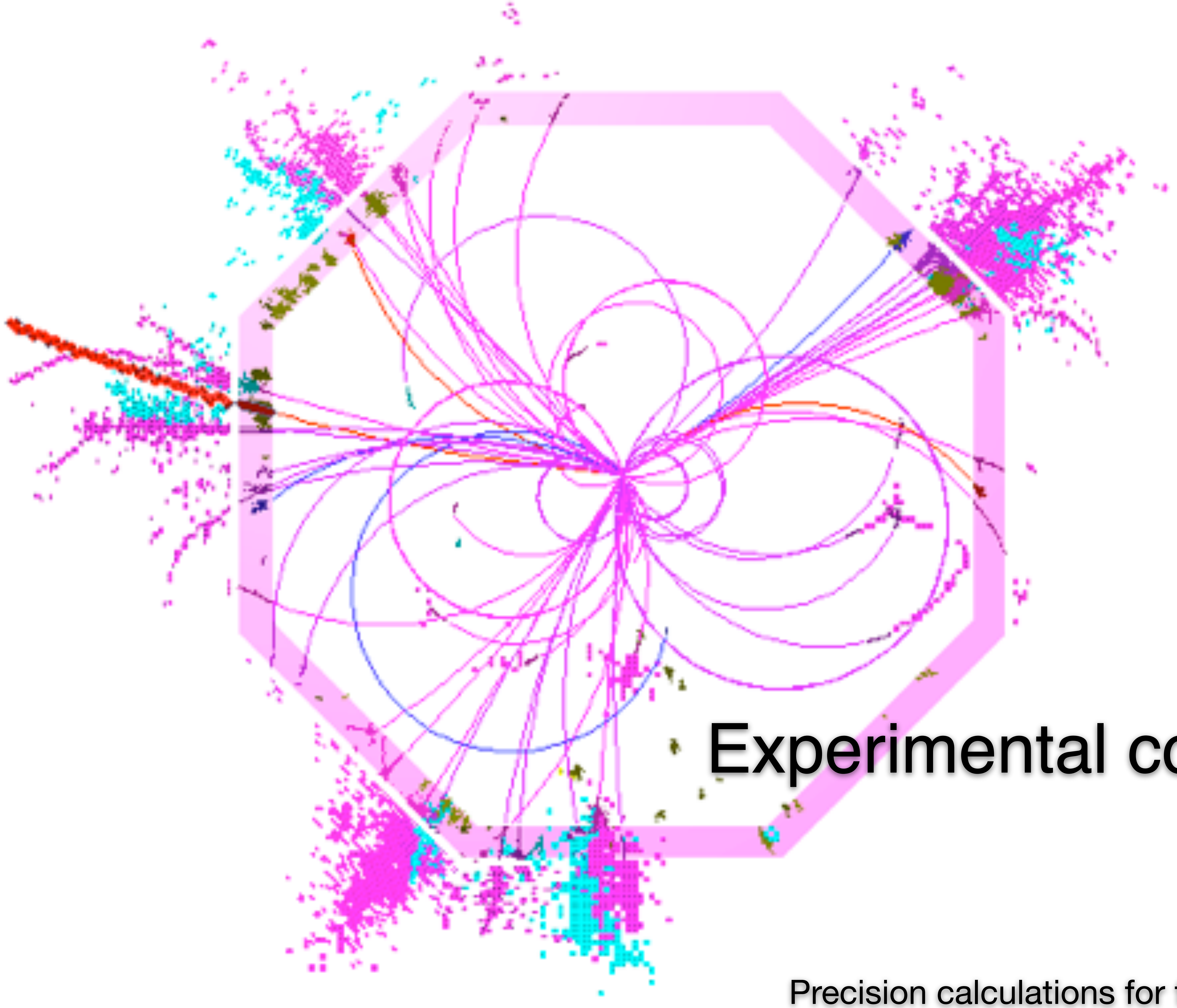
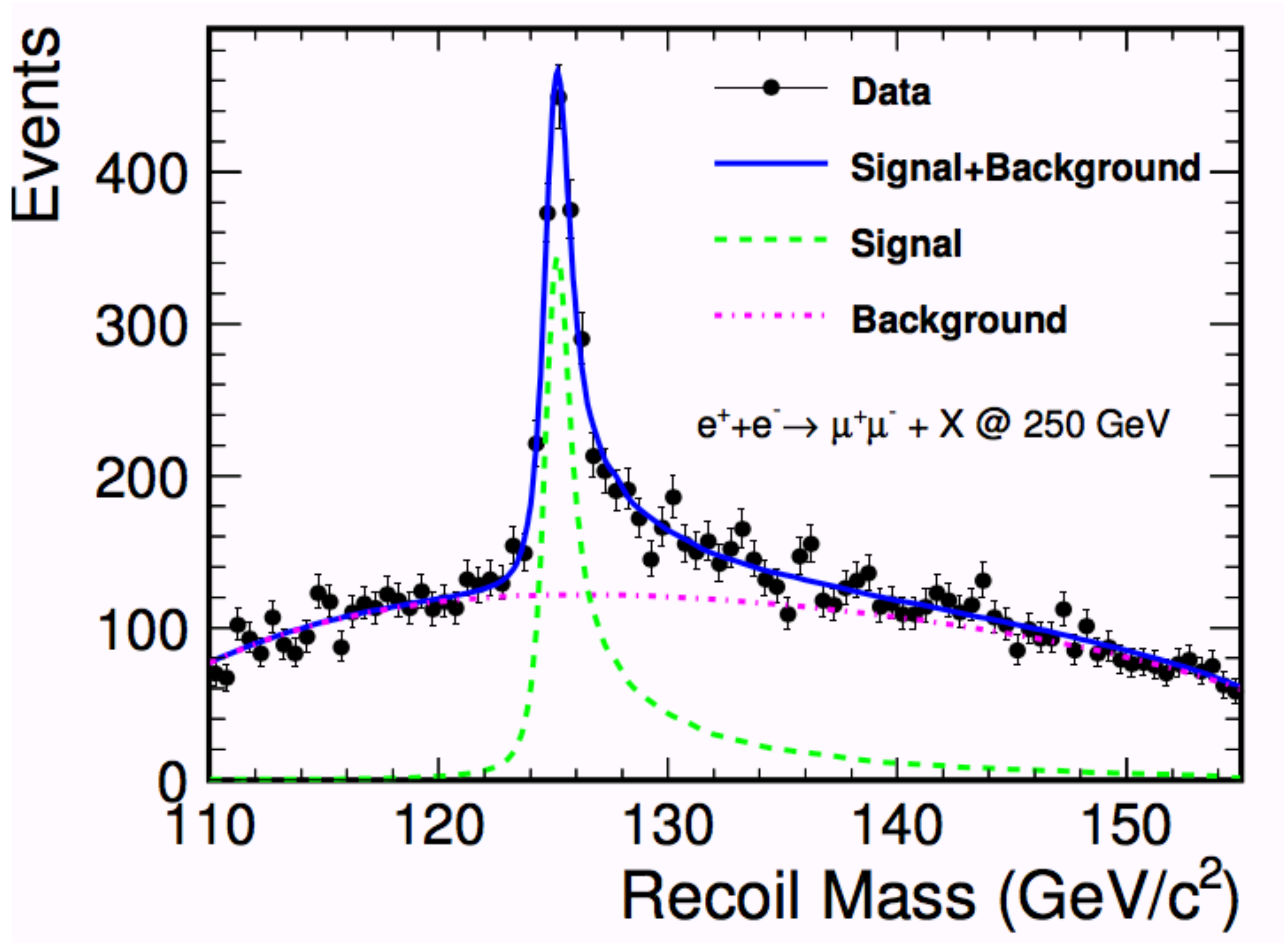




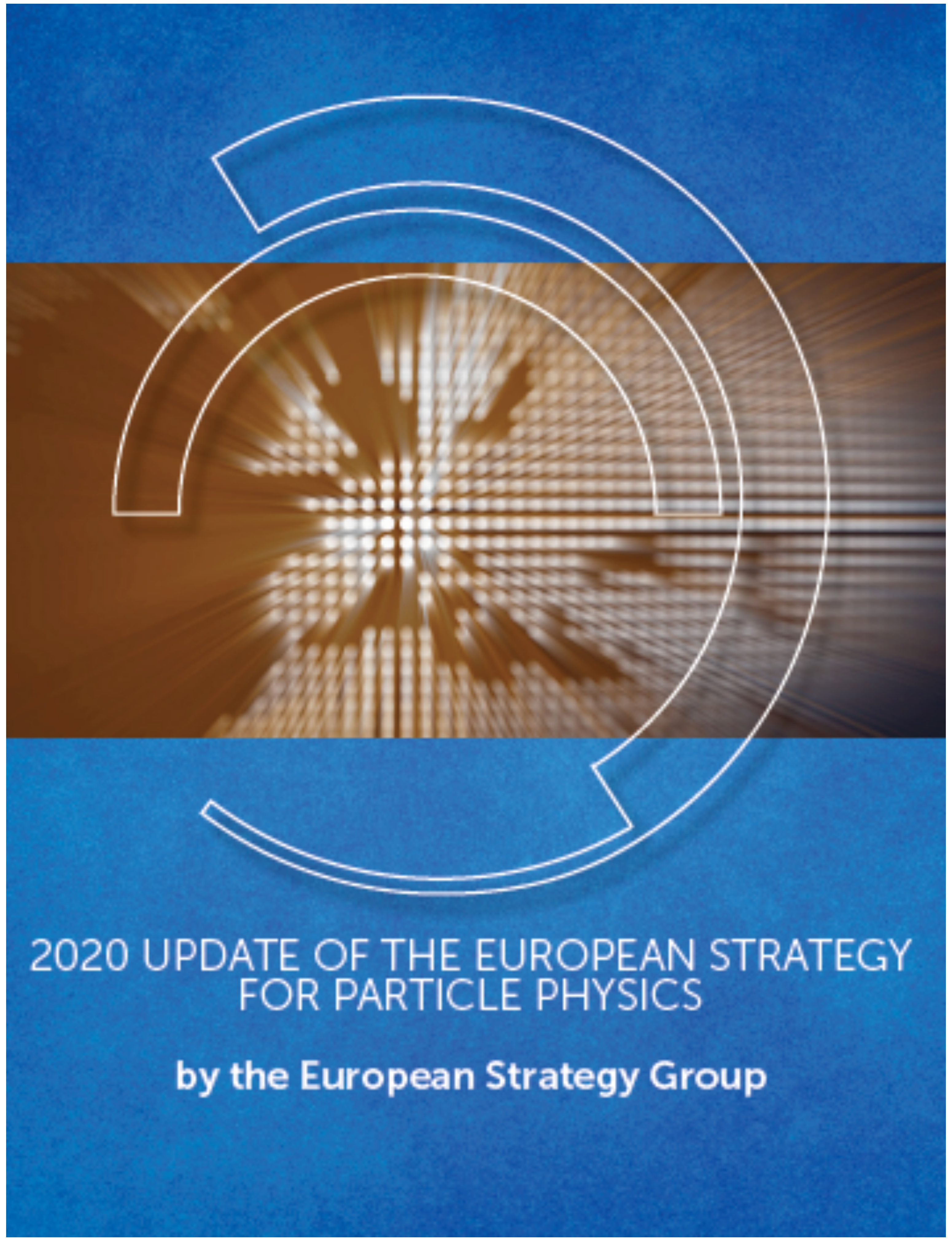
Experimental constraints on Higgs properties from future e+e- colliders

Precision calculations for future e+e– colliders: targets and tools, CERN, June 9, 2022

European Strategy for Particle Physics

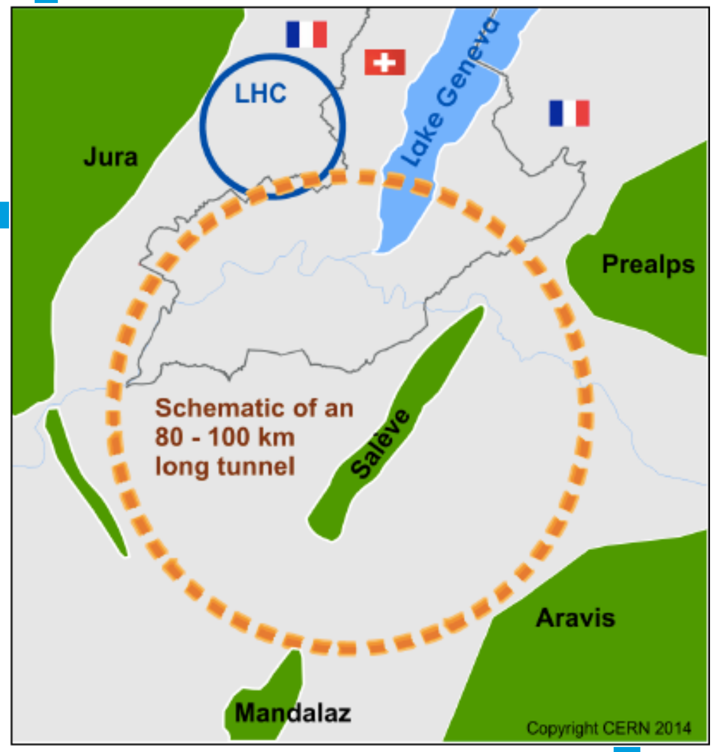
2020 Update - Future Colliders

"An electron-positron Higgs factory is the highest-priority next collider."



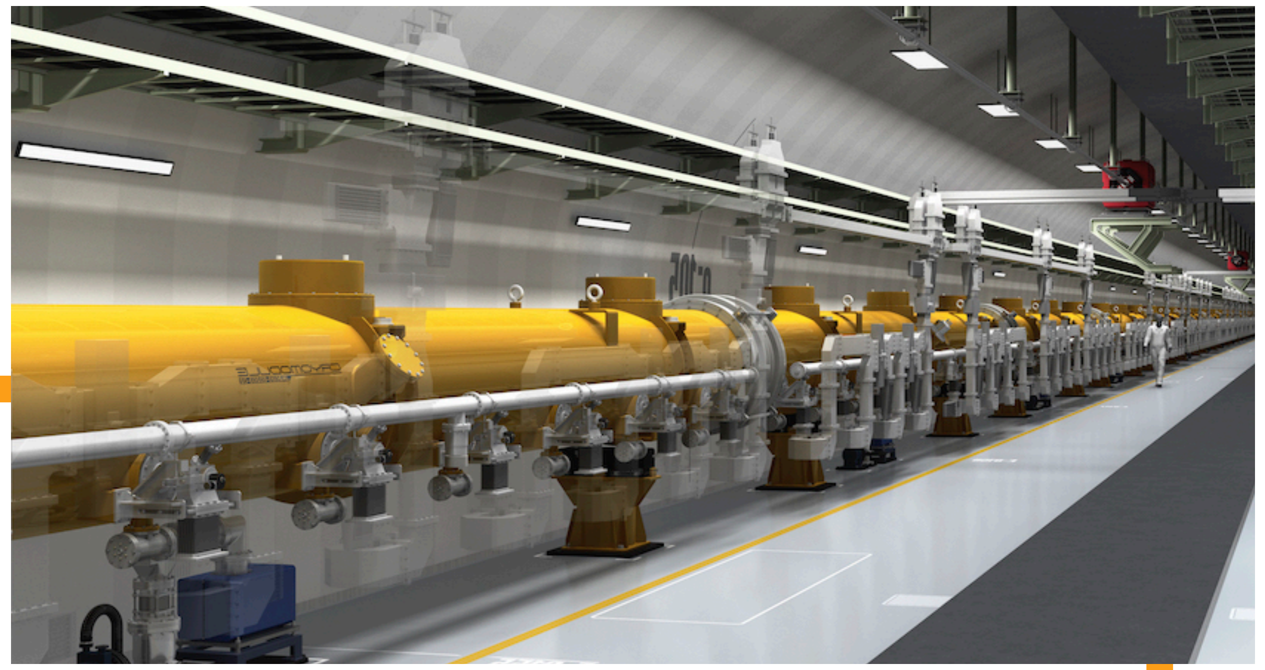
There are several proposed Higgs factories

Each have their advantages



Circular e+e- Colliders

- FCCee, CEPC
- length 250 GeV: ~100km
- high luminosity & power efficiency at **low energies**
- **multiple interaction regions**
- very clean: little beamstrahlung etc



Linear Colliders

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- **spin-polarised beam(s)**

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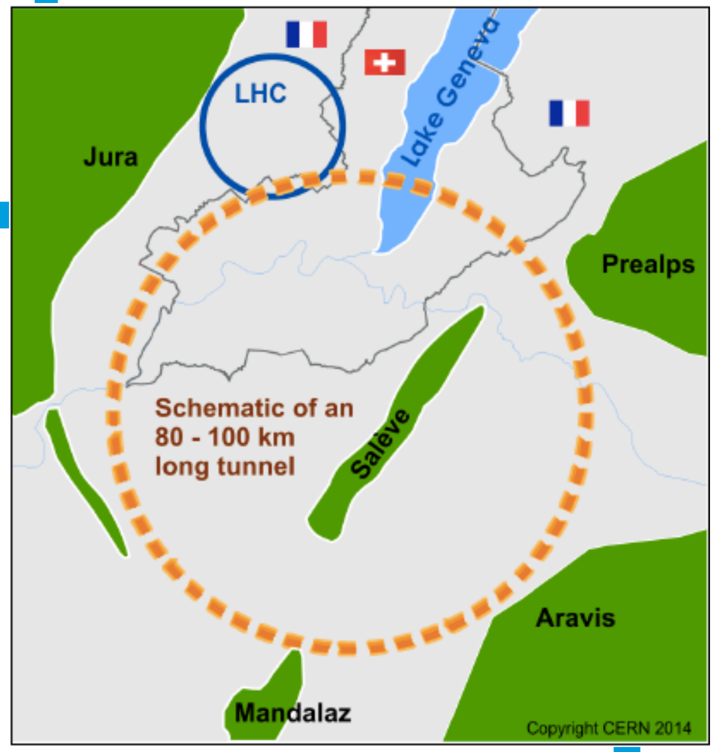

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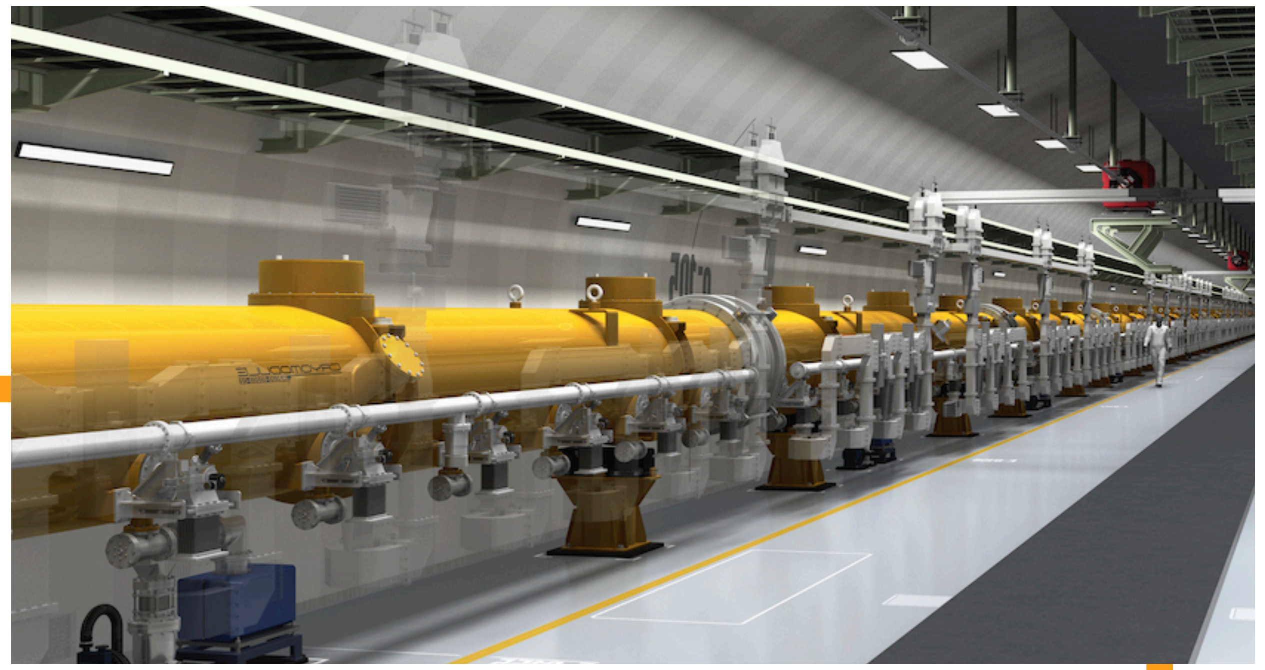
Long-term vision: re-use of tunnel for pp collider

- to measure eg Higgs self-coupling, top Yukawa incl CP properties, search for new particles
- **to explore uncharted territory at highest energies**
- **driving HTSC magnet R&D**



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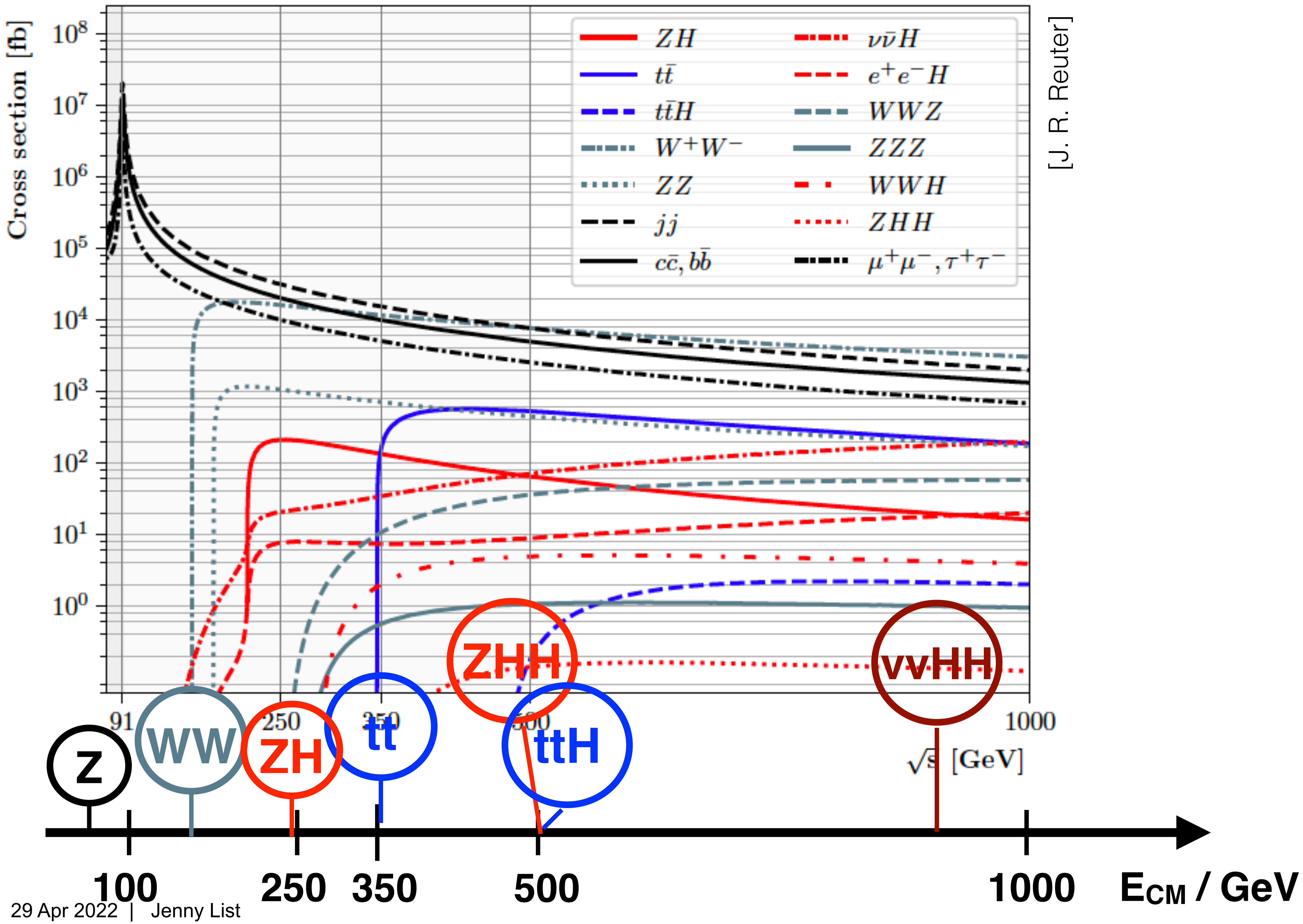
- length 250 GeV: ~10…20 km
- high luminosity & power efficiency at **high energies**
- **spin-polarised beam(s)**

Long-term vision: energy extendability

- to measure eg top axial-vector couplings, Higgs self-coupling, top Yukawa incl CP properties, search for new particles
- by increasing length
- ***or by replacing accelerating structures with advanced technologies***

Particle production thresholds in e+e- collisions

Production rates vs collision energy



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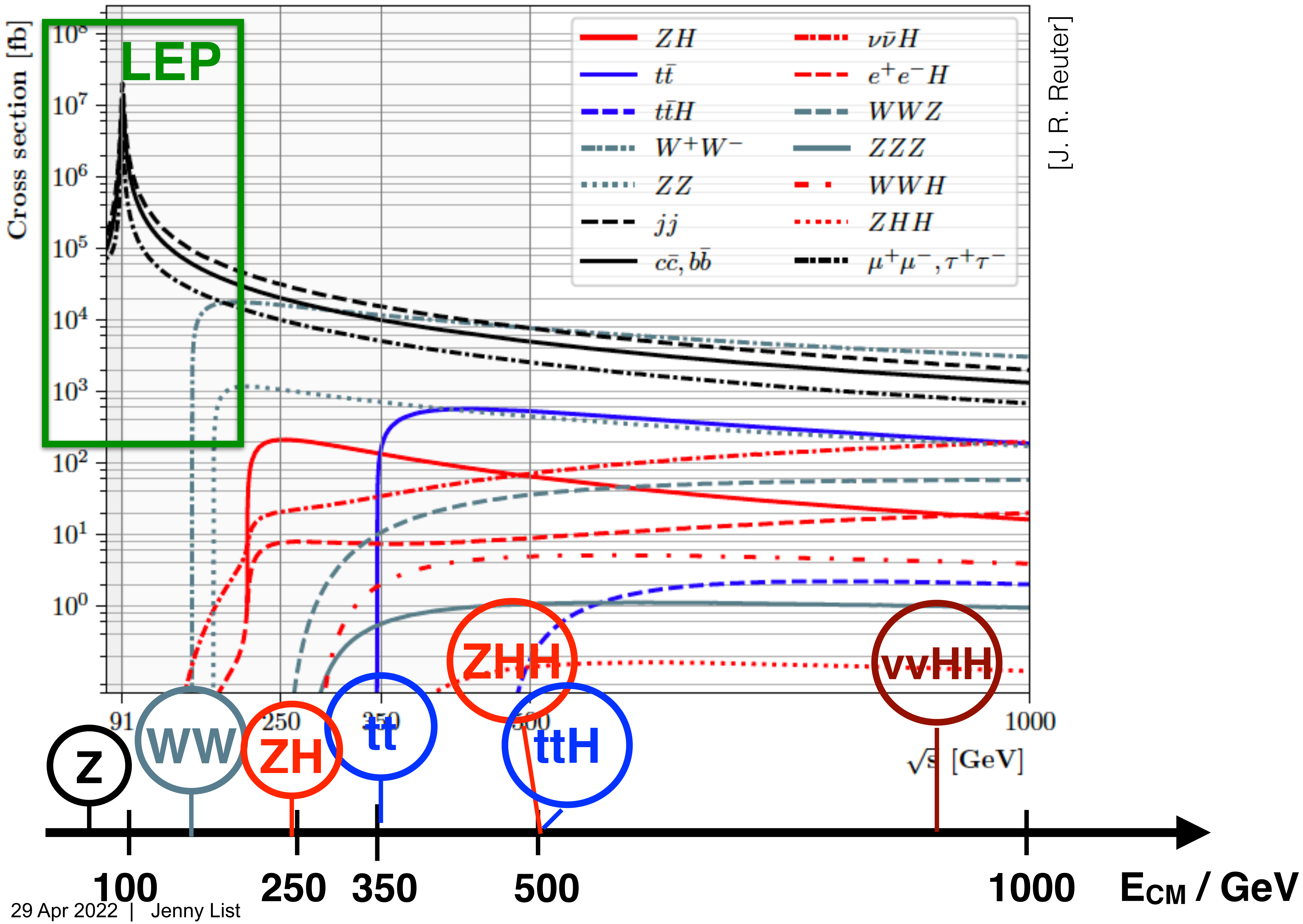
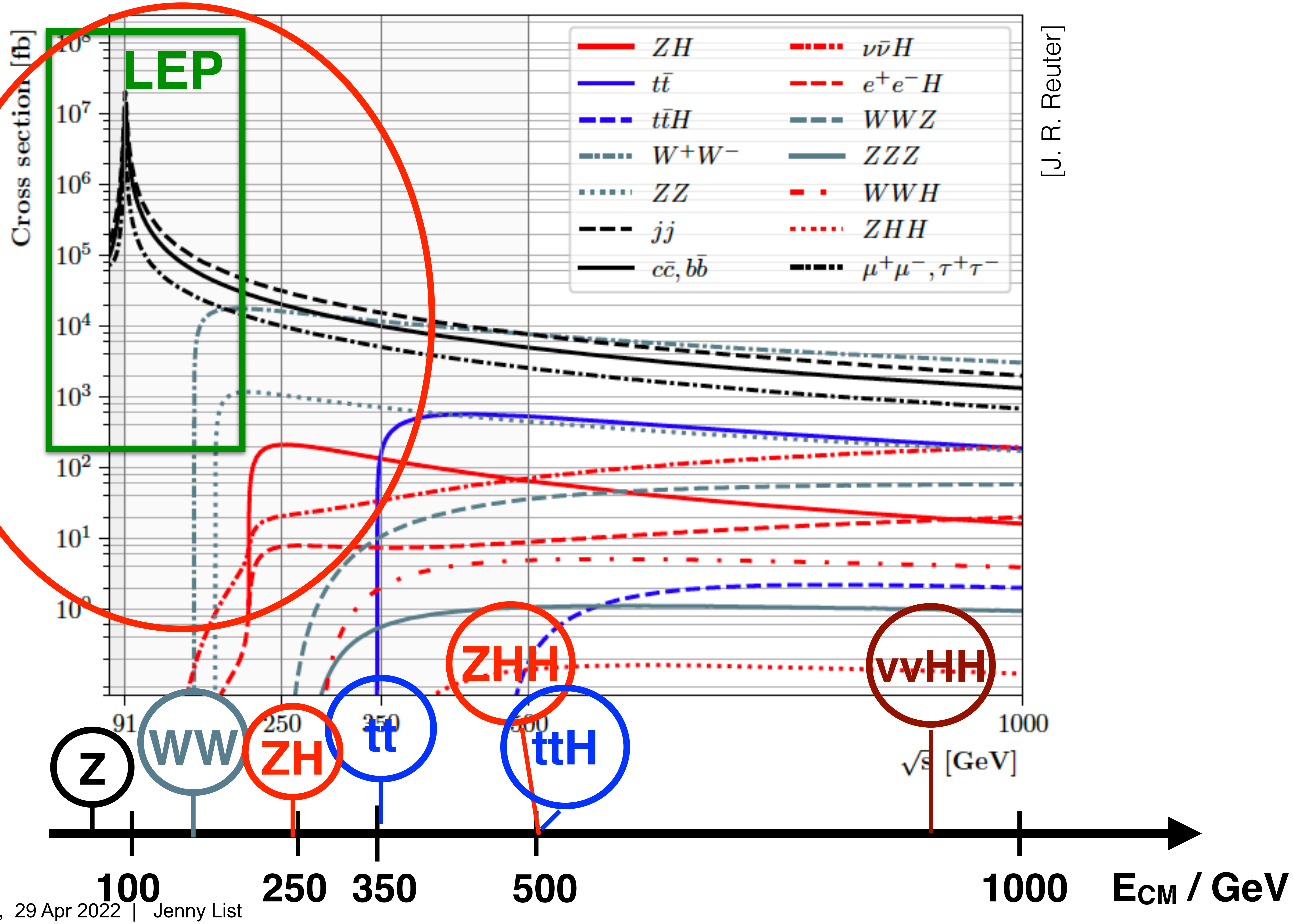


Particle production thresholds in e+e- collisions

Production rates vs collision energy

considered
by all proposed
e+e- projects



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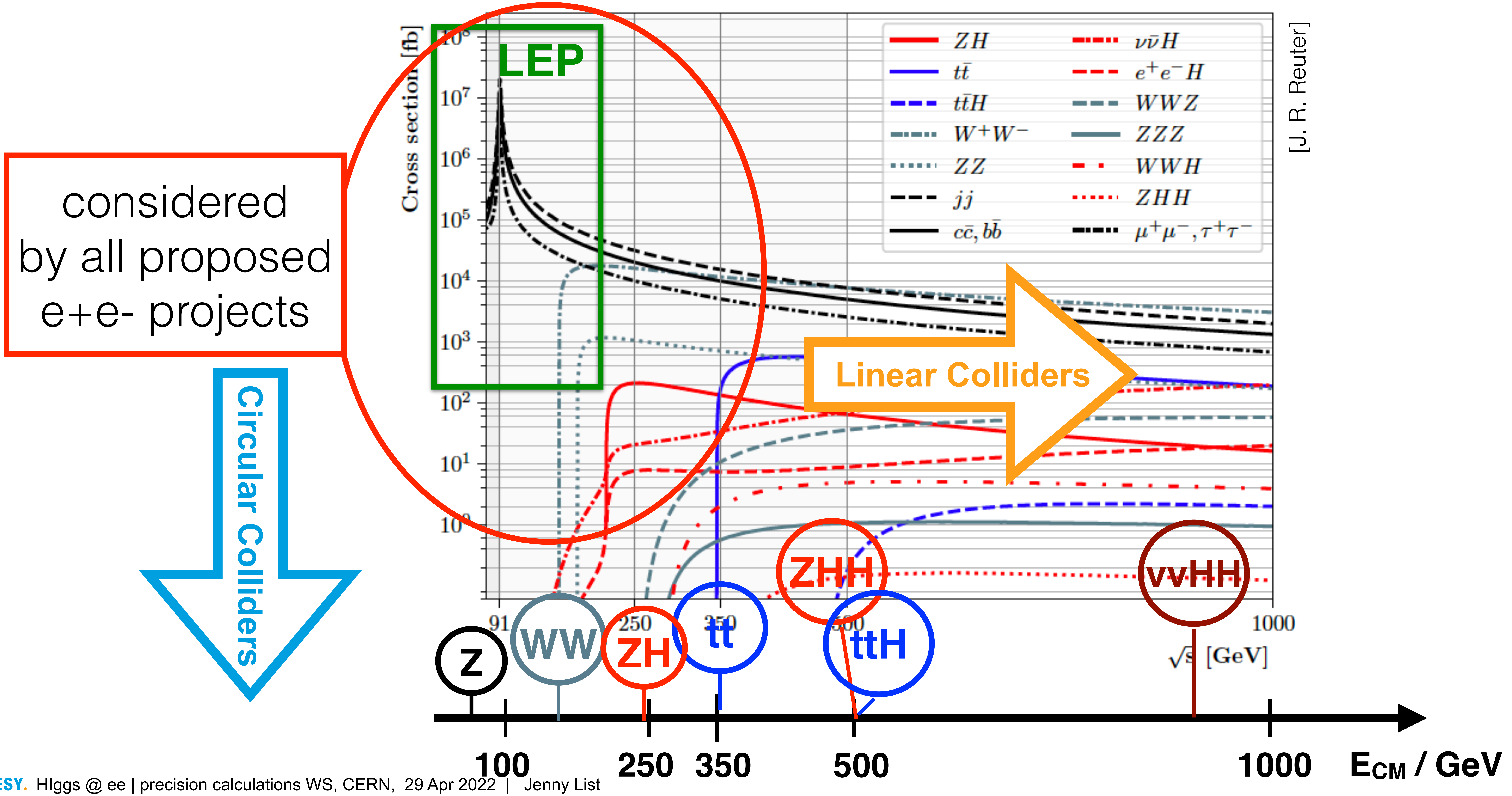

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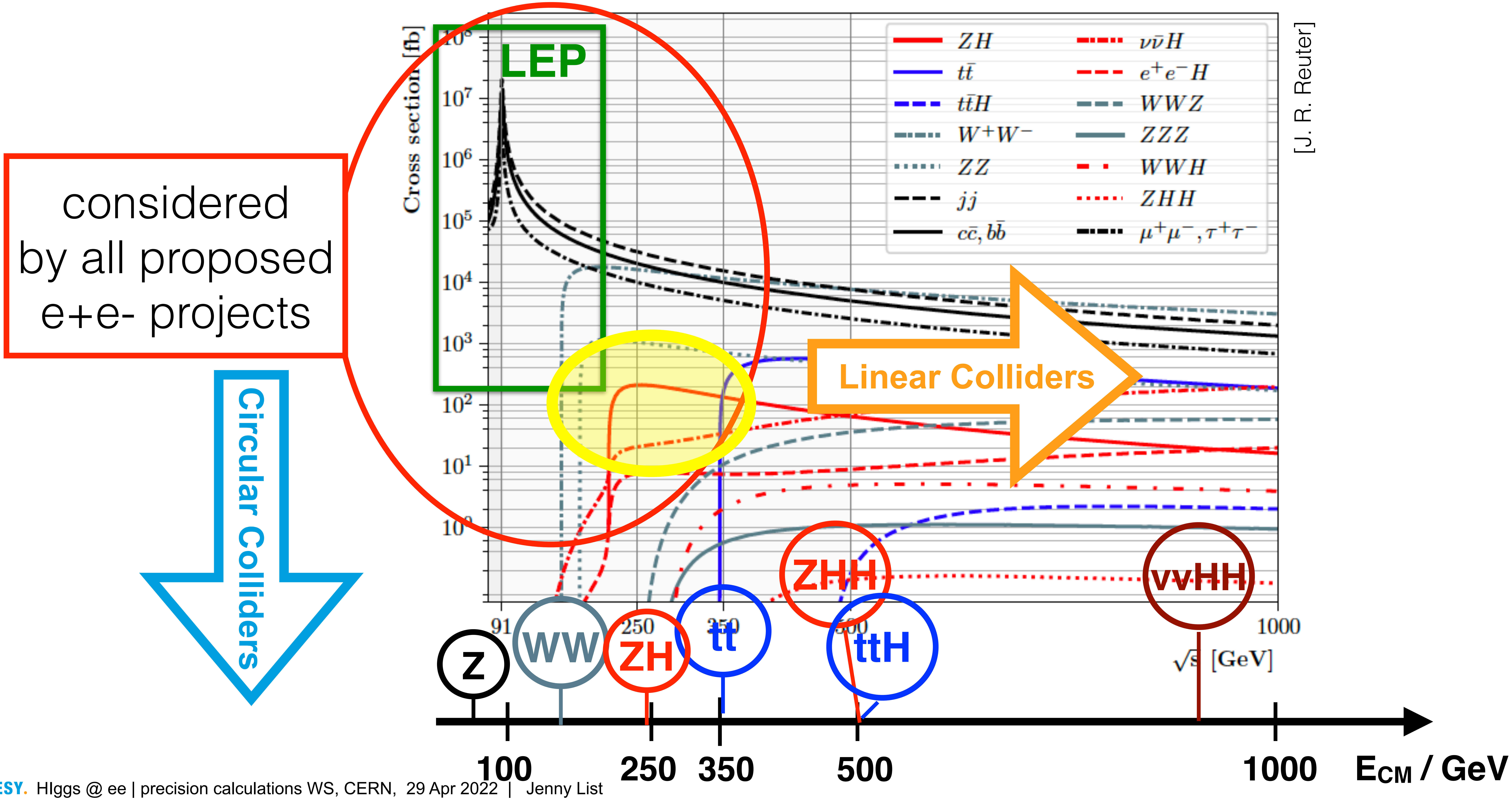
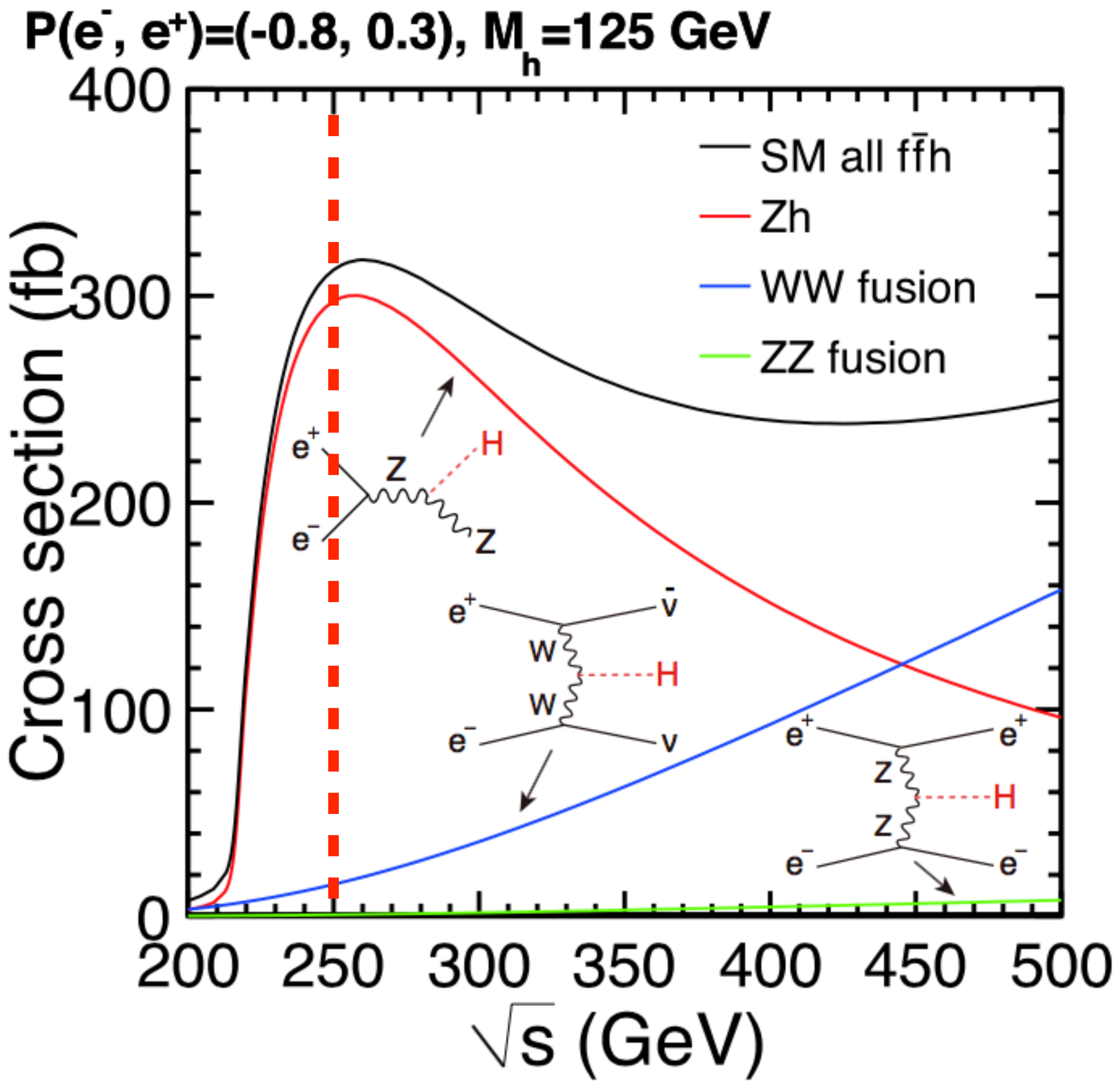


Higgs production in e+e-

Focus on single Higgs production

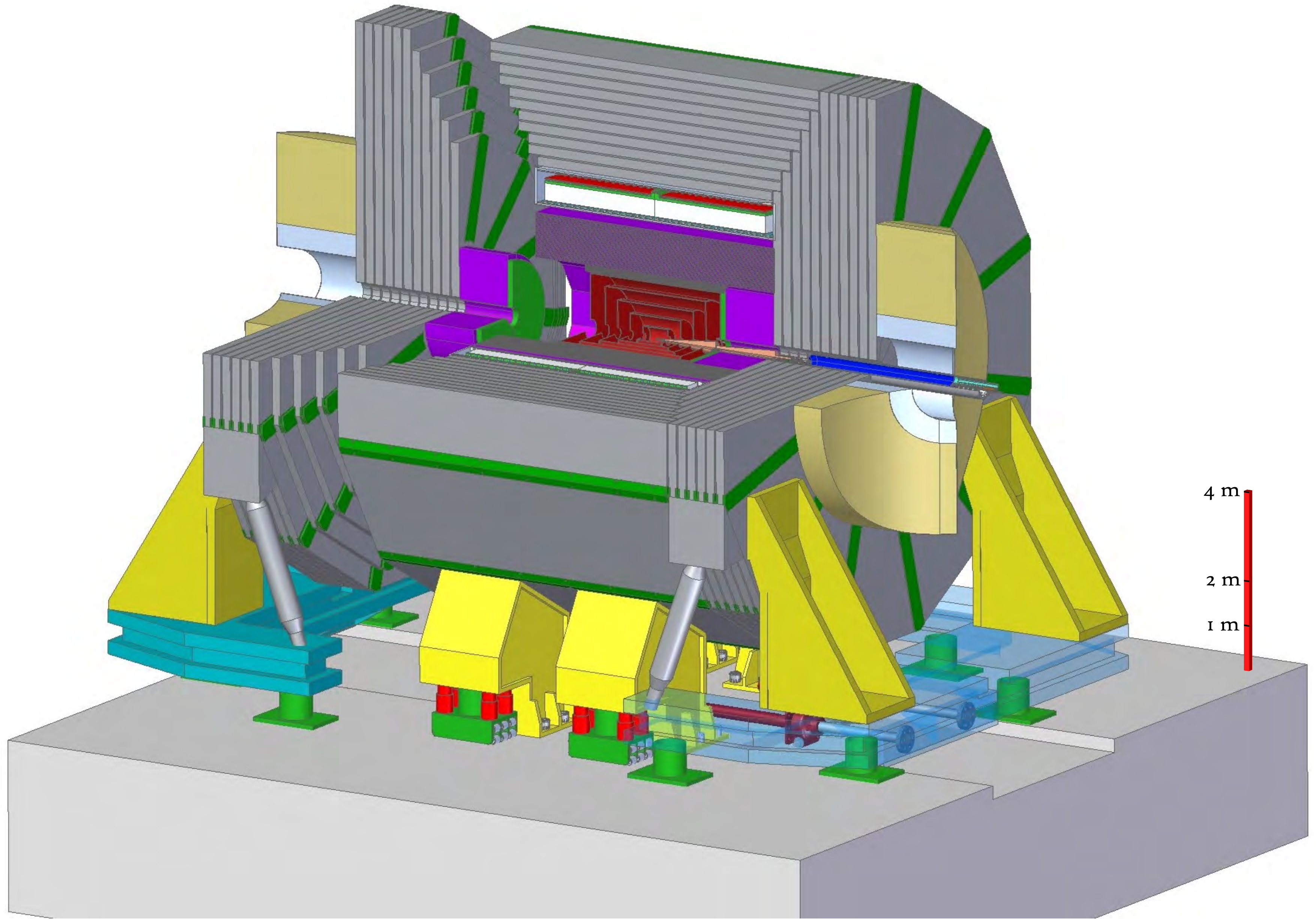
- ~250 GeV:
  e+e- → ZH
  => total cross section, coupling to Z
- ~350 GeV and above:
  e+e- → vvH
  => total width, coupling to W
- decay modes: total number of Higgses produced, regardless of production mode / ECM
- >= 500 GeV :
  e+e- → ttH, ZHH, vvHH
  => not covered today…

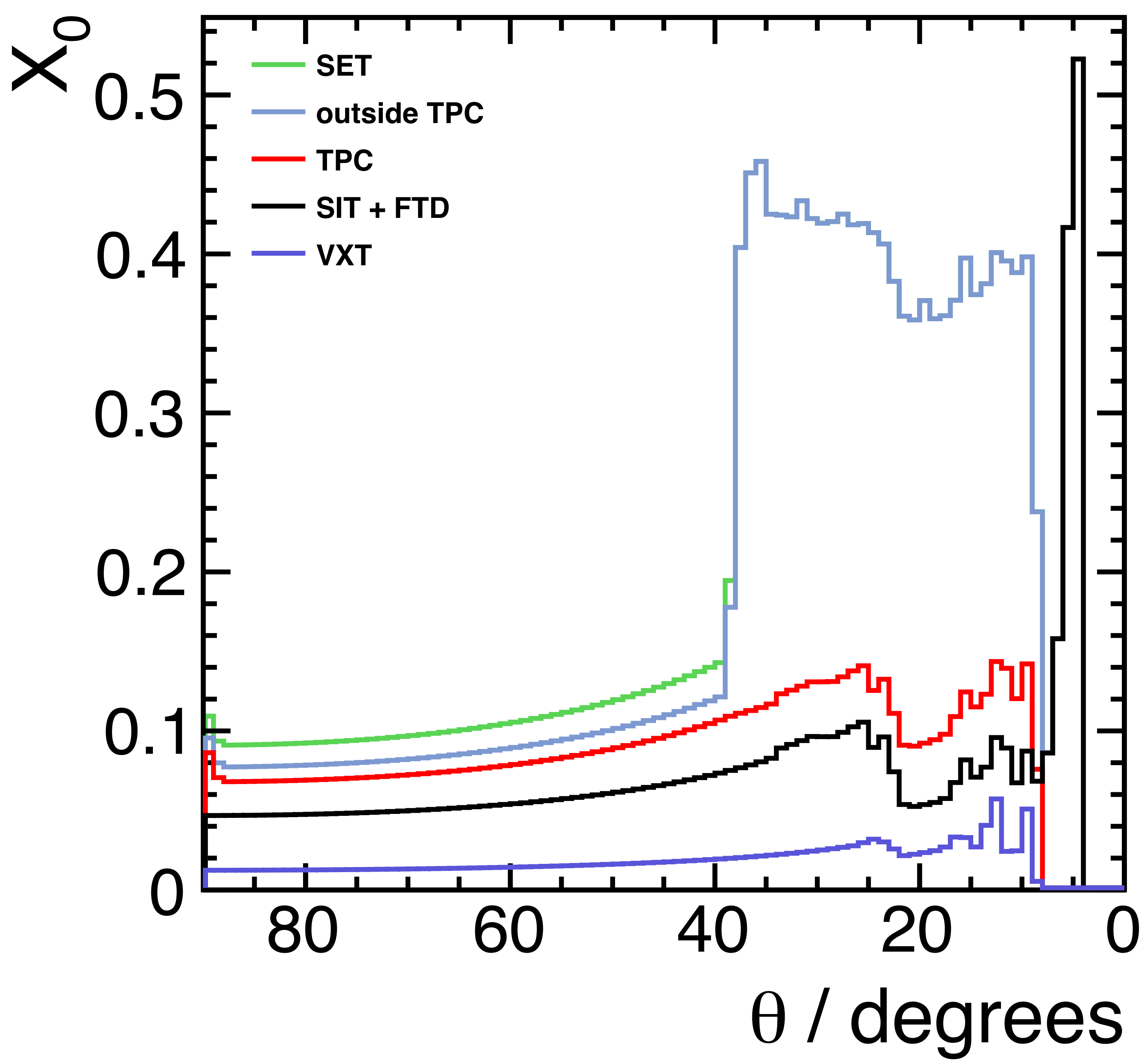


Experimental Simulation Studies

Precision requires realistic level of detail

- will not comment on differences between various detector concepts today
- however: will show results corresponding to *current* “experimental gold standard” for e+e- projections:
  - Whizard (LO ME) + Pythia 6 (PS & LEP-tuned hadronisation) MC
  - including beam energy spectrum & ISR
  - full, Geant4-based simulation of the detectors
  - gauged against test beam performance of prototypes
  - inclusion of machine and full SM background
  - in some cases full sim analyses are extrapolated to other center-of-mass energies
- sophistication of reconstruction and analyses, coverage of channels etc: limited by person power, not (yet) by ideas!





Overview of Experimental Projections

and how they are presented

- σxBR projections from full simulation are usually given for a reference value of integrated luminosity which corresponds to the *actually used MC statistics*
- e+e- colliders measure σxBR at various energy stages - and some for different settings of the beam polarisation
- all these are then directly thrown into global (SMEFT) fits

=> the pure experimental precision is often not seen directly from the σxBR inputs

=> take coupling precision from SMEFT fit as reference here

- **Sneakpreview into the still preliminary Snowmass SMEFT fit:**
  - a lot of effort went into making inputs as comparable as possible
    - extrapolating missing channels from other colliders
    - common set of (experimental) systematics
    - common HL-LHC and low-E experiment input
  - particularly suitable for our purpose today: currently, neither intrinsic theory nor parametric uncertainties are included => **"pure experimental target"**

Example of inputs to Snowmass fit (in brackets extrapolation to FCC lumi from ILC full sim)

	FCCee240 $5\mathrm{ab}^{-1}$	
Prod.	ZH	$\nu\nu H$
σ	0.5(0.537)	-
$\sigma \times BR_{bb}$	0.3(0.380)	3.1(2.78)
$\sigma \times BR_{cc}$	2.2(2.08)	-
$\sigma \times BR_{gg}$	1.9(1.75)	-
$\sigma \times BR_{ZZ}$	4.4(4.49)	-
$\sigma \times BR_{WW}$	1.2(1.16)	-
$\sigma \times BR_{\tau\tau}$	0.9(0.822)	-
$\sigma \times BR_{\gamma\gamma}$	9(8.47)	-
$\sigma \times BR_{\gamma Z}$	(17^*)	-
$\sigma \times BR_{\mu\mu}$	19(17.9)	-
$\sigma \times BR_{inv.}$	0.3(0.226)	-

in %

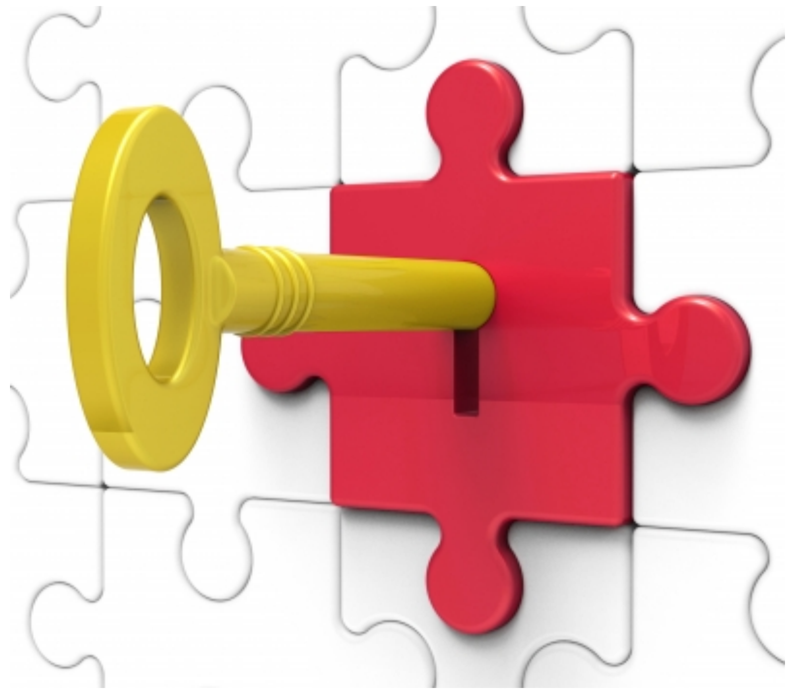


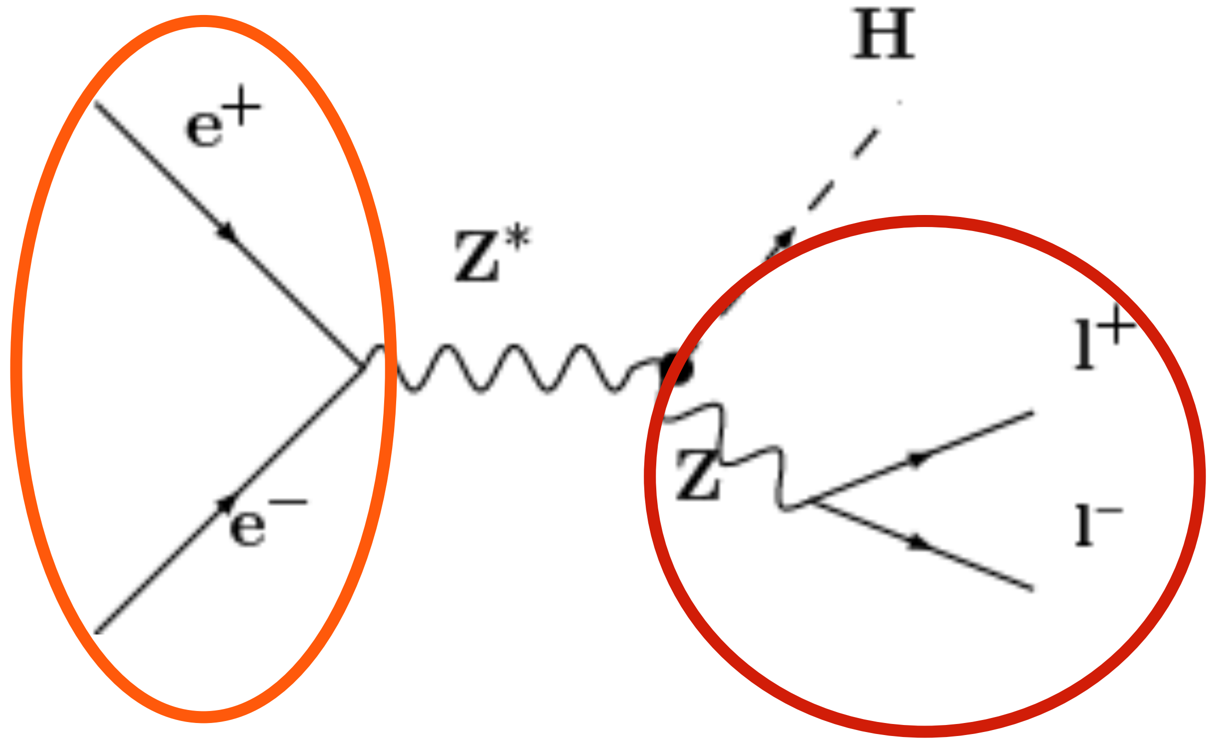
Image courtesy of Stuart Miles at FreeDigitalPhotos.net

THE key: the total ZH cross-section measurement via the recoil technique

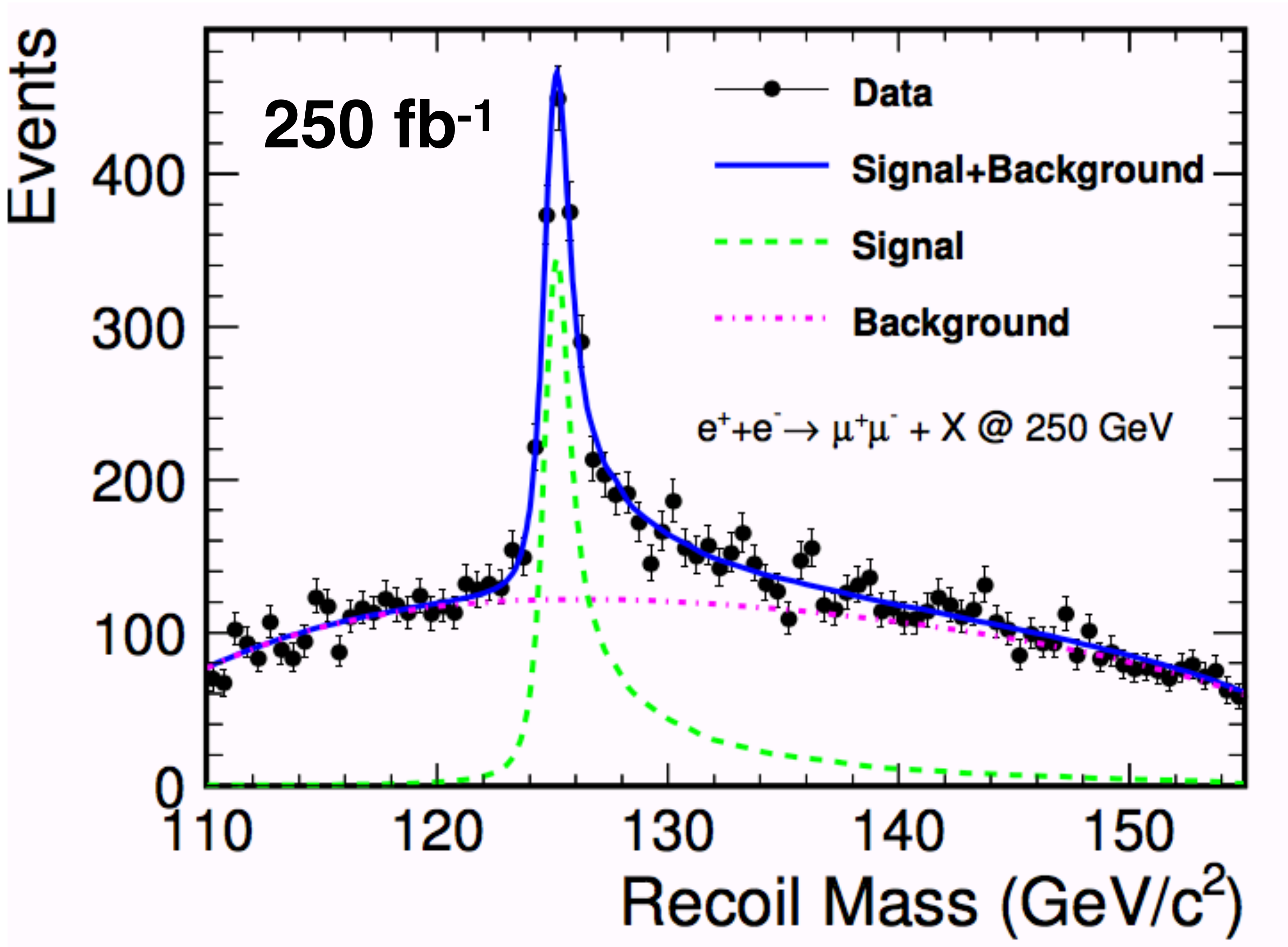
THE speciality of e+e- Collider

Absolute normalisation of Higgs couplings & total decay width

- knowledge of initial-state 4-momentum enables reconstruction of Higgs 4-momentum without measuring its decay products
- need:
  - precise prediction of exact initial state from accelerator conditions, incl. beam energy spectrum, ISR
  - precise measurement of Z momenta, plus modeling of FSR, bremsstrahlung / hadronisation etc
  - a truely Higgs-decay-mode independent event selection
- **easiest case: Z-> μ+μ-**



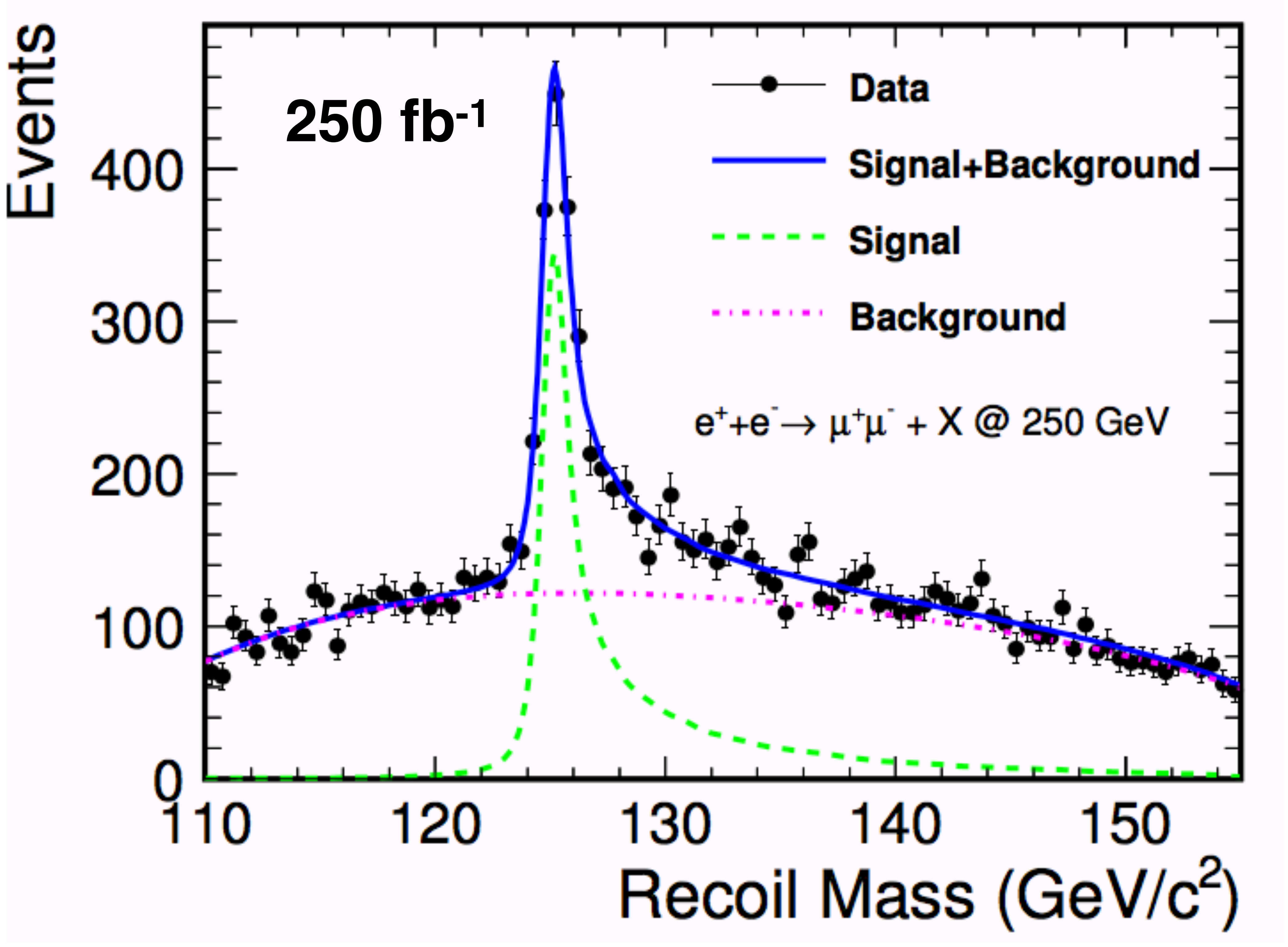
$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$



From plot to cross section…

…potential systematics

- **extract number of signal events:**
  - best possible prediction of shape of recoil peak
  - **modelling of ISR, beamstrahlung etc crucial**
  - recognized as major theory work-item, c.f. ECFA 1st Topical Meeting on Event Generators and talk by Stefano yesterday
- **from N_{evt} to σ_{tot}:**
  - knowledge of efficiency, backgrounds, luminosity => mostly “experimental problems”?
  - **lumi measurement: low-angle Bhabha scattering predictions**
  - efficiency, backgrounds: MC generators incl. hadronisation etc…



Current projections

relative precisions on σ_{tot}

- **ILC**:
  - full detector simulation, full backgrounds [Phys.Rev.D 94 (2016) 11, 113002]
  - 250fb-1 (= statistics of full sim MC) : 2%, for P(e-,e+) = (-80%,+30%) and (+80%,-30%)
  - full luminosity: **1%** for P(e-,e+) = (-80%,+30%) and (+80%,-30%), **each** (2 independent measurements!)
- **FCCee**:
  - Delphes + extrapolations, limited backgrounds [Eur. Phys. J. Special Topics 228 (2019) 261]
  - 5 ab-1, P(e-,e+) = (0%,0%): **0.5%**
- **interesting study of Snowmass EF04, as mentioned previously:**
  - **scale ILC to FCCee conditions => 0.54% [EF04 report in prep.]**
  - **effect of realistic detector / backgrounds etc on "easy & clean" final states ~ 10%** (note: for mutli-jet final-states, differences of 100% and larger have been observed in the past)

From cross section to coupling

…current state-of-the-art

- tree-level (SM)EFT fits
- g(HZZ) coupling depends on **> 1 operators** (eg c_{WW} and c_H):
  - **c_H** is determined by σ(ZH)
  - **c_{WW}** can be determined either by
    - the polarisation asymmetry of σ(ZH) i.e. A_{LR}(ZH)
    - or by angular distributions
- naive extraction from single measurement of σ_{tot} (ZH) **not** sufficient

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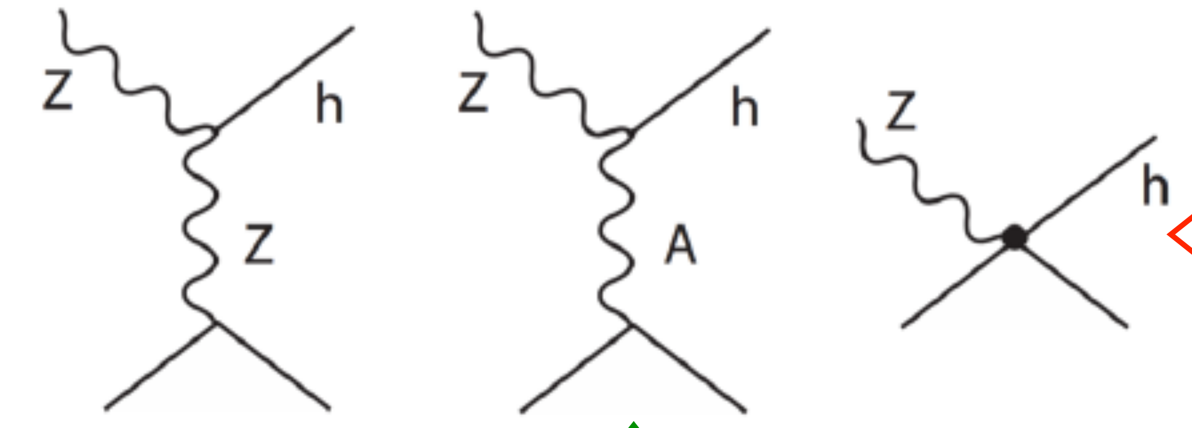

constrained by EWPOs (*)

only diagram allowed in SM

$\sim c_{WW}$

spin reversal $e^-_R \leftrightarrow e^-_L$:

- 1st diagram **flips** sign
- 2nd diagram **keeps** sign

⇒ A_{LR} lifts degeneracy between operators!

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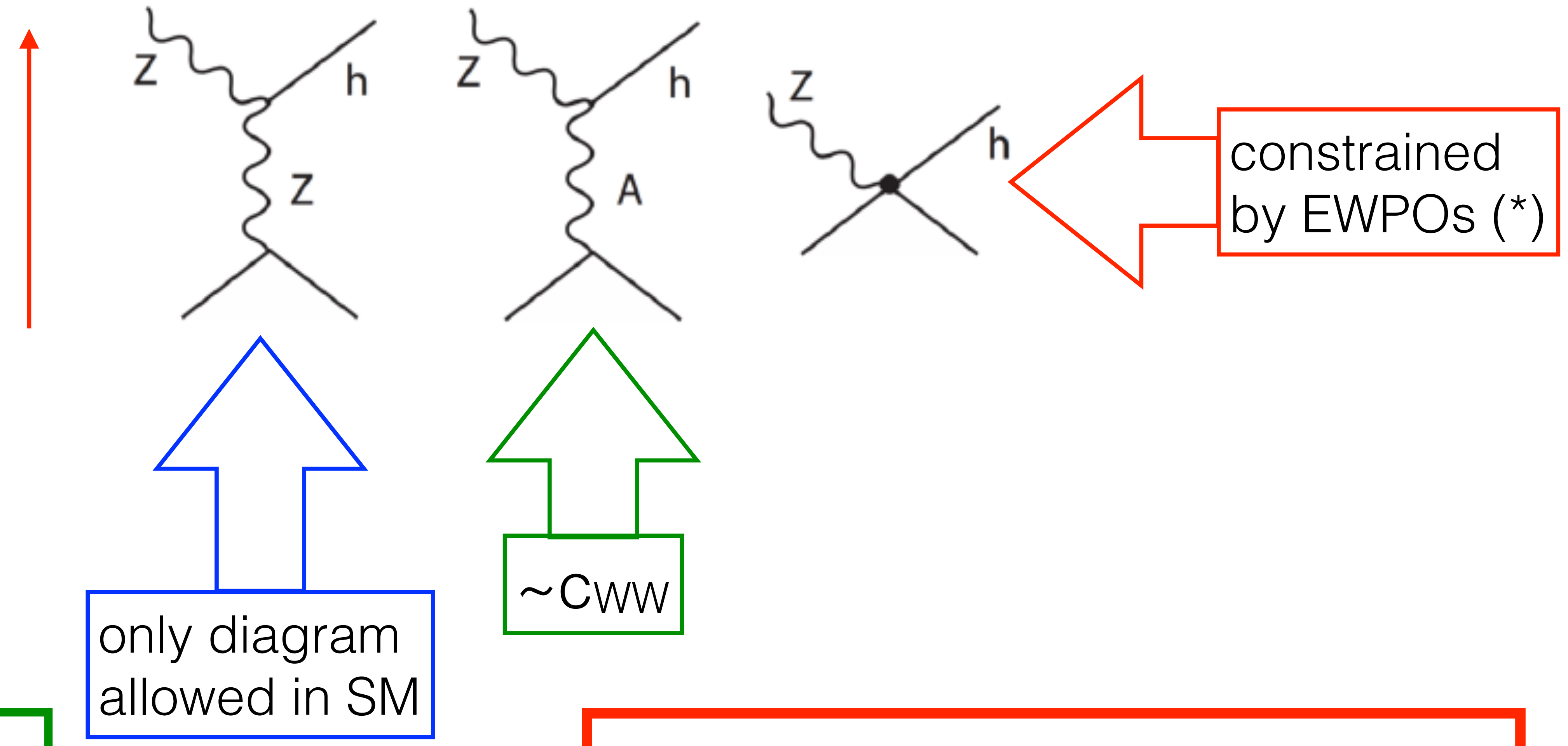

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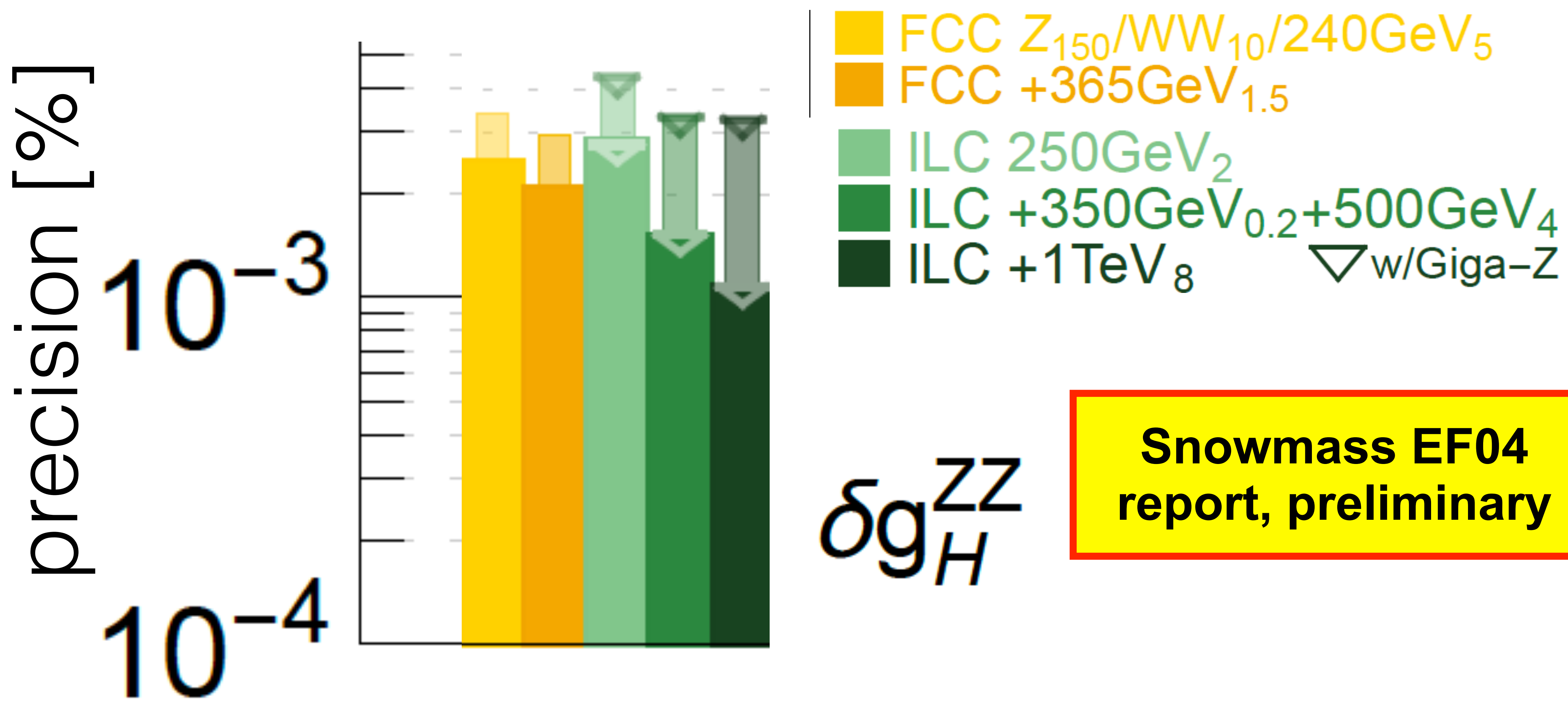

Snowmass EF04 report, preliminary

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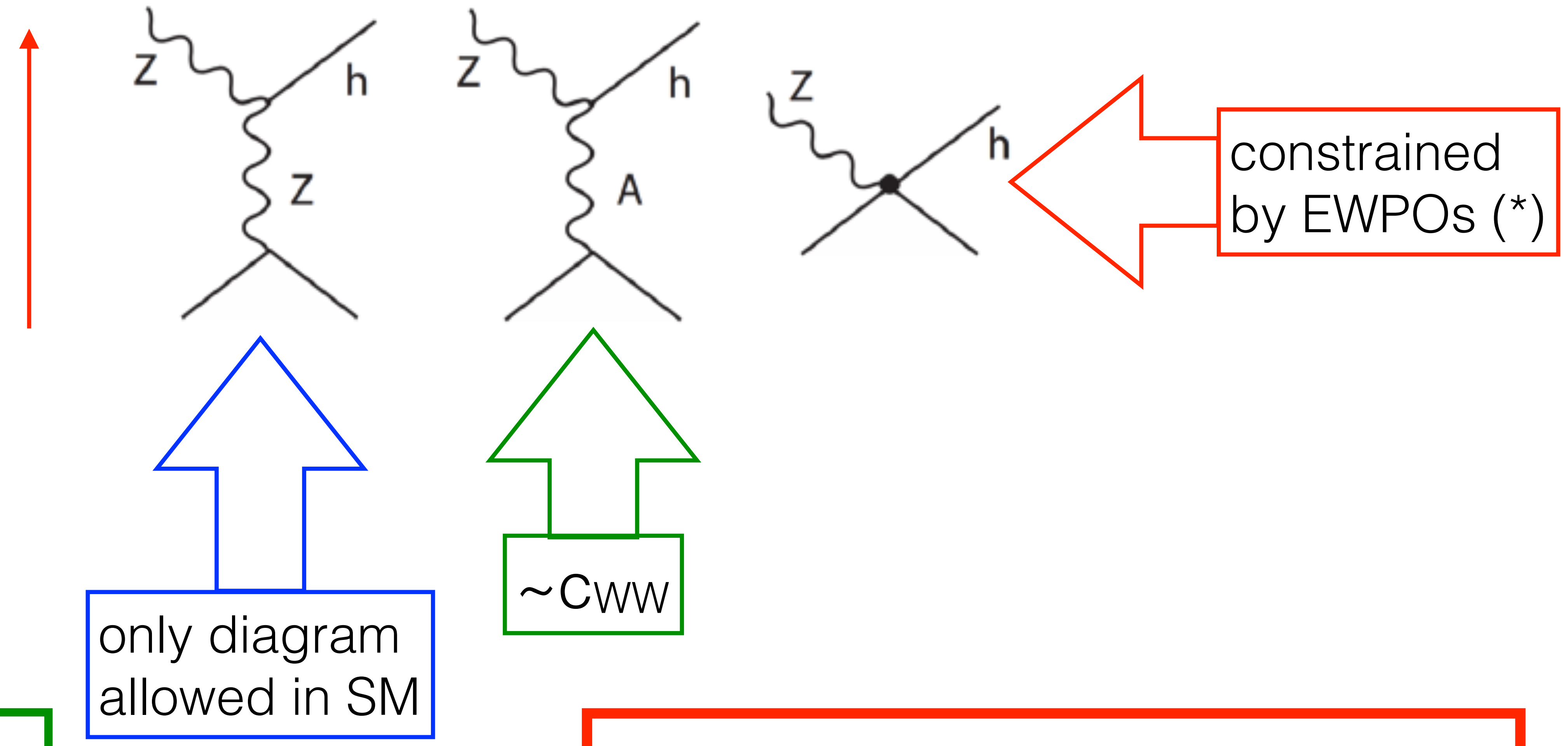

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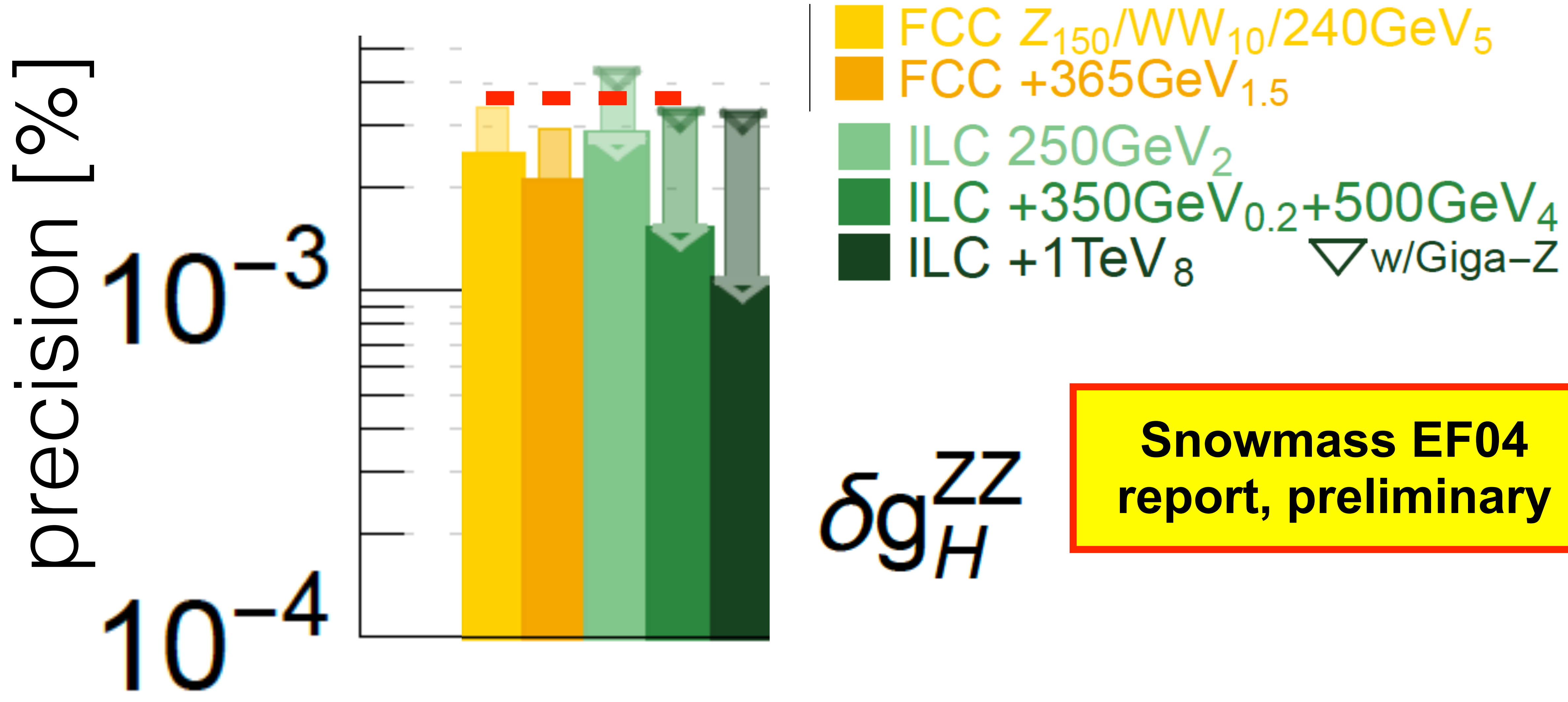

Snowmass EF04 report, preliminary

=> 2 polarised measurements with 1% and 1 unpolarised measurement with 0.5% give same coupling precision
— any difference in theory needs???

What about intrinsic theory uncertainties?

…not yet the end of the story

- ILC (LCC) SMEFT fit included **0.1%** theory uncertainty [arXiv:1903.01629]:
  - assumes **full 2-loop ew** for all relevant processes
  - considered **achievable with today's technology**
  - **and a lot of work!**
- similar conclusion has been drawn for FCCee [arXiv:1906.05379]

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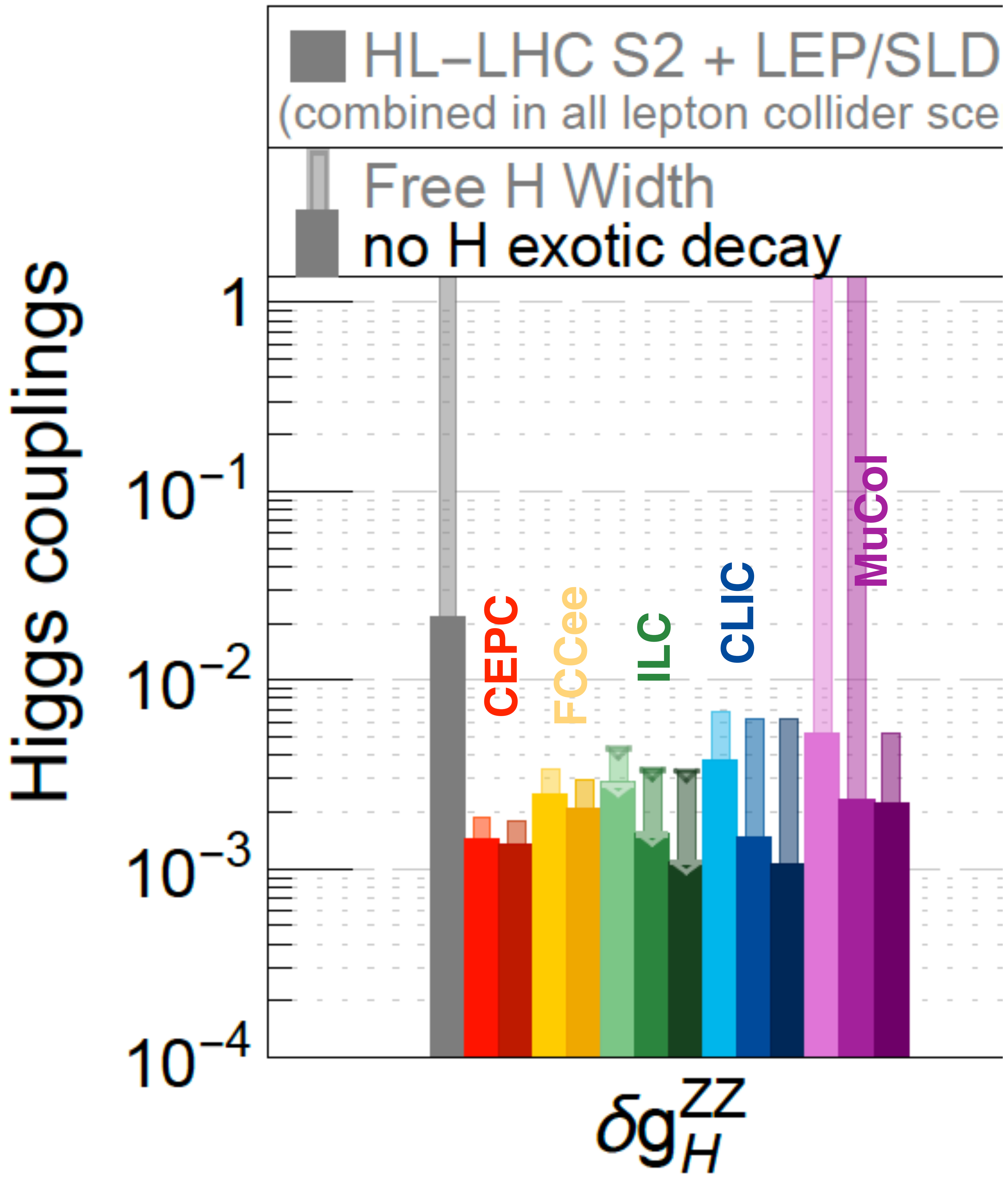
  - level of precision reaching 0.2%
  - theory uncertainty *not* included
  - will 2-loop ultimately still be sufficient?



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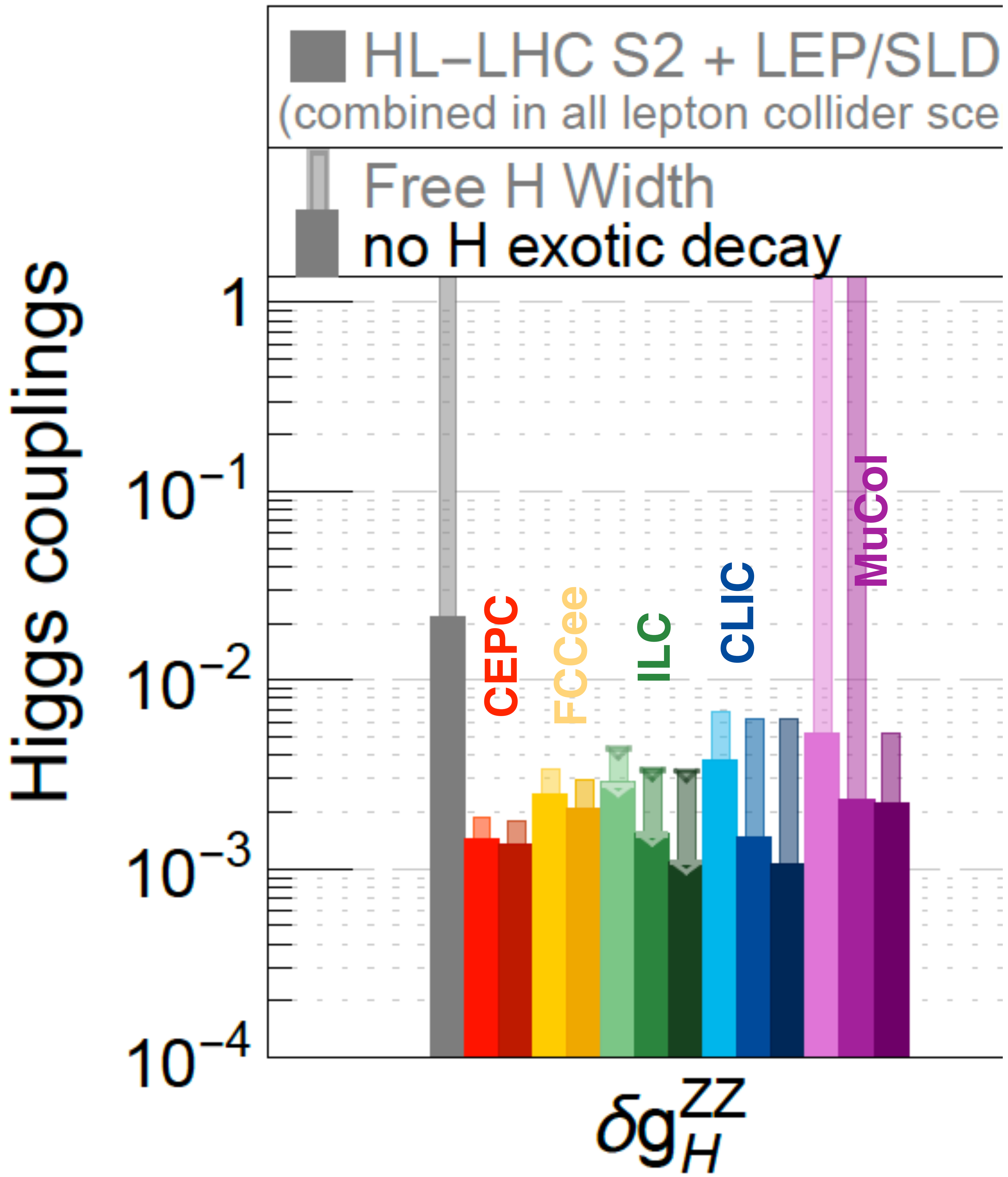
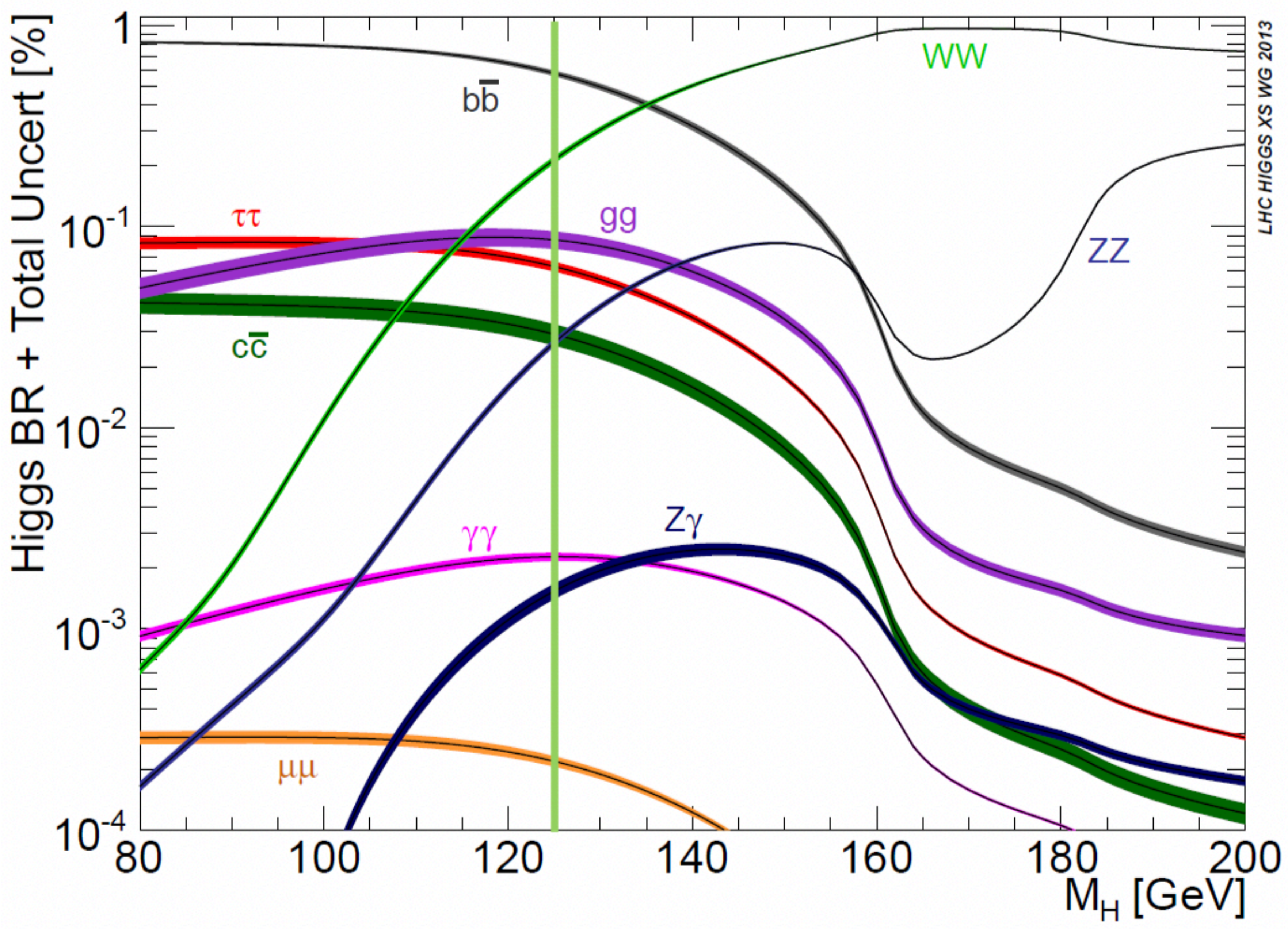


Finally: note that all this is within SM only — but we aim to find deviation from SM => same level of precision needed in (then favoured) BSM models!



Branching fractions

Higgs decay to jets

…the experimental situation

- use all visible decay modes of Z and ννH
- H->jets and Z->jets play important role

=> QCD, non-perturbative effects, hadronisation, b-/c-fragmentation, …

- Example from ILD IDR:
  - **σxBR(bb) to ~0.4%** from one channel & data set alone
  - σxBR(cc) shows lot of room for improvement by smarter flavour tag algorithm
- experimental systematics:
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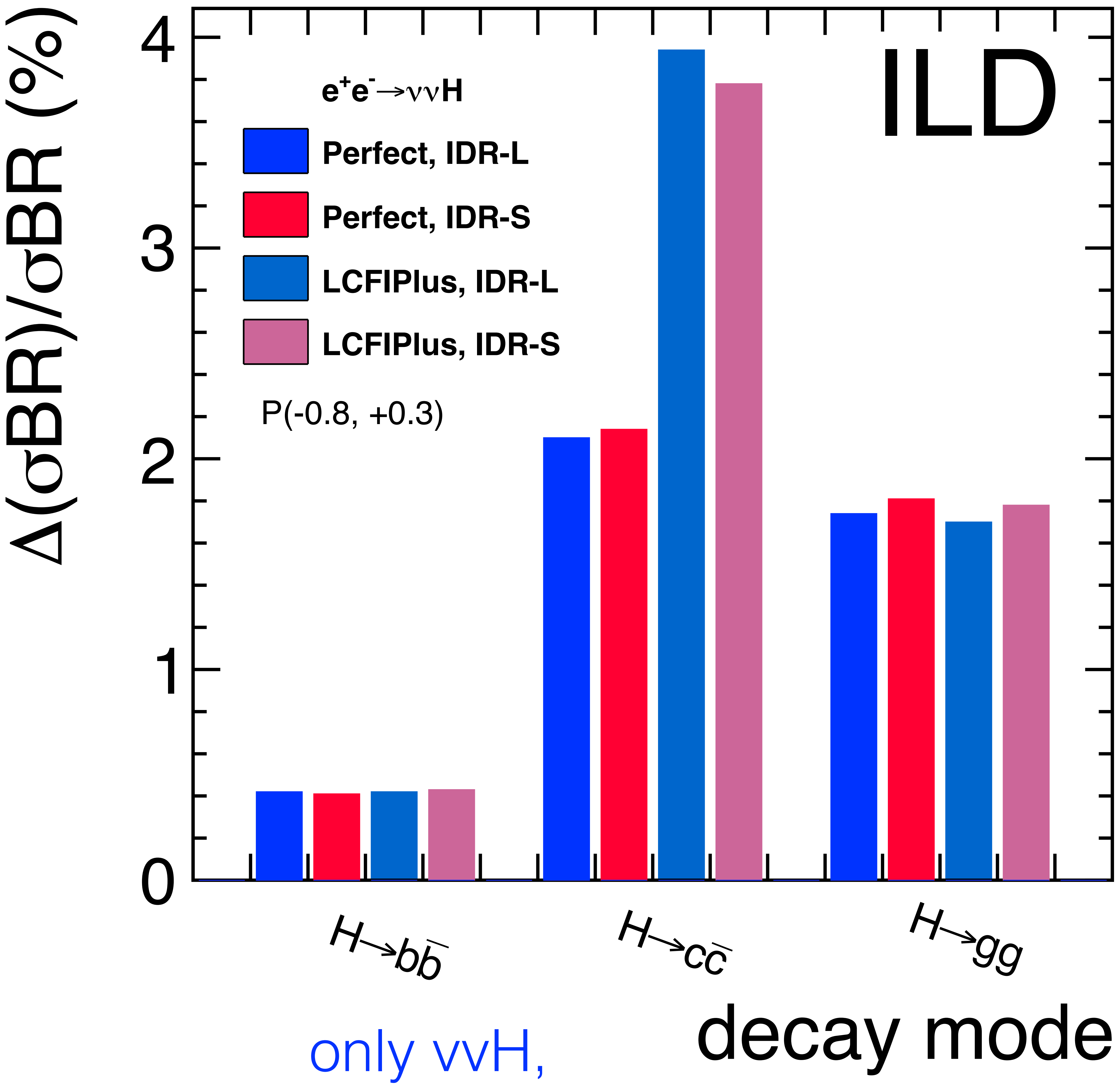

only ννH,
1.6ab-1
P(-0.8,+0.3)
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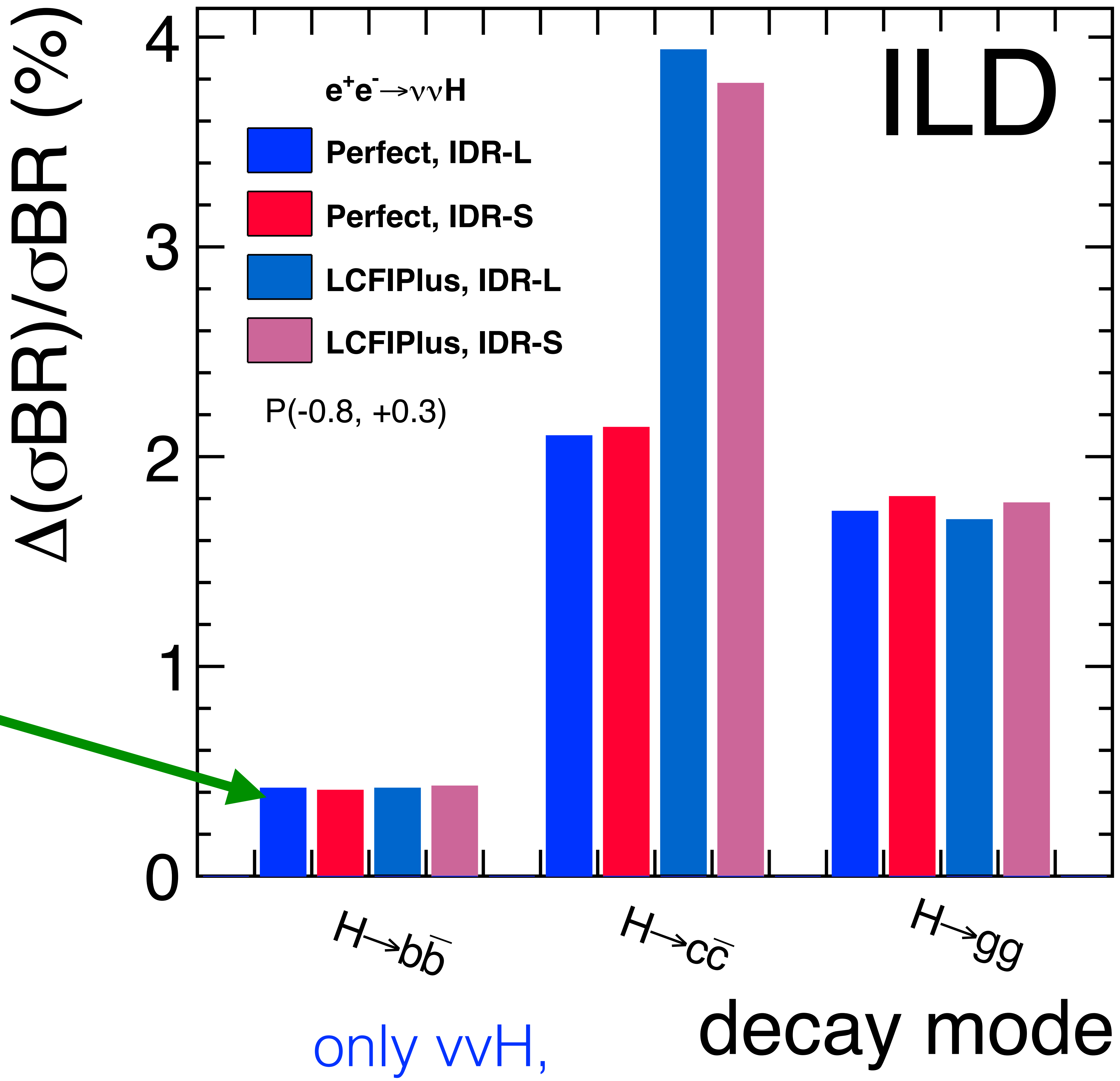

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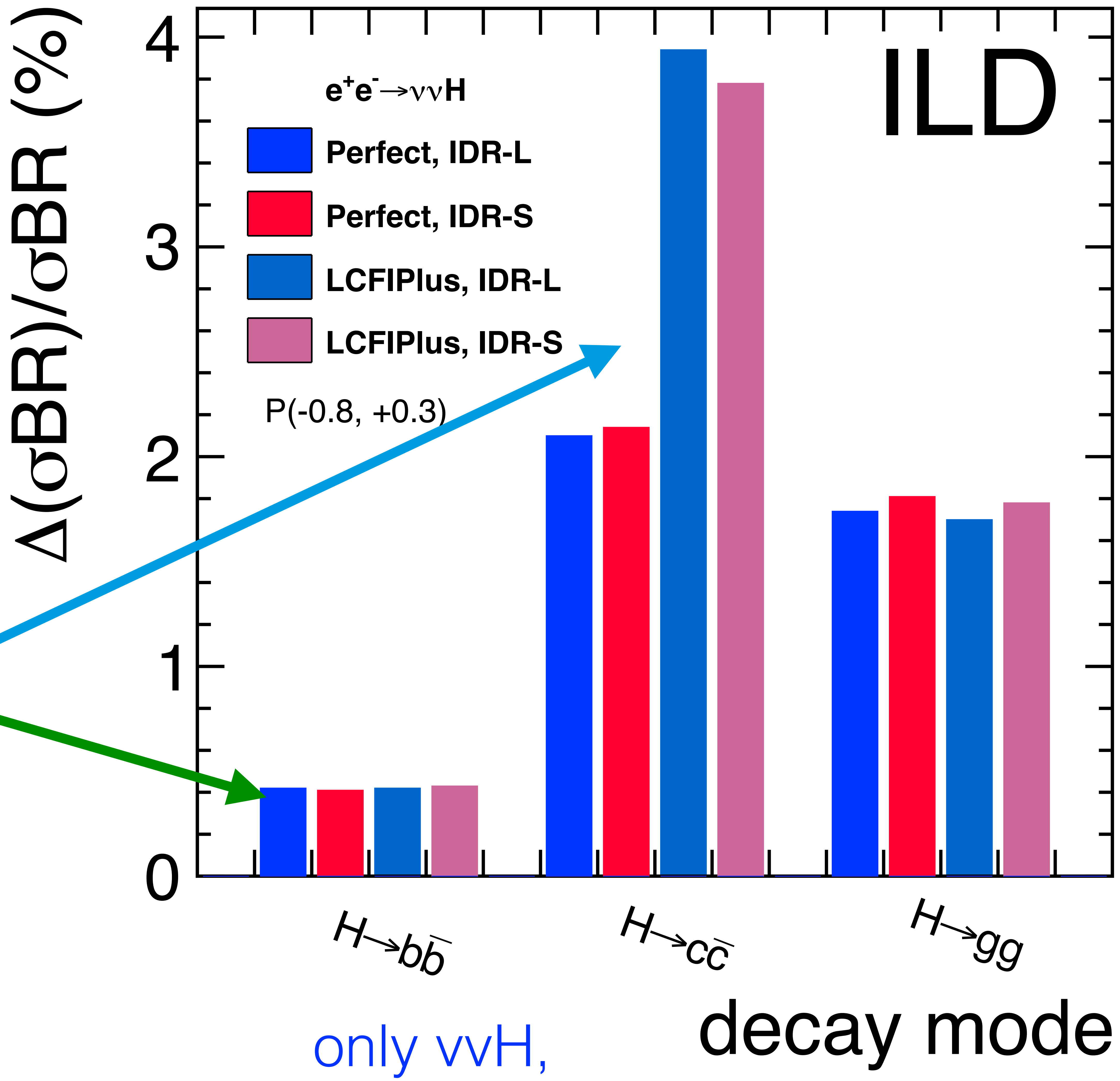

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…in SMEFT fit

preliminary Snowmass fit result:

- recall: neither intrindic theory nor parametric uncertainties included

future estimates (on Γ_{partial}) from arXiv:1906.05379:

decay	intrinsic	para. m_q	para. α_s	para. M_H
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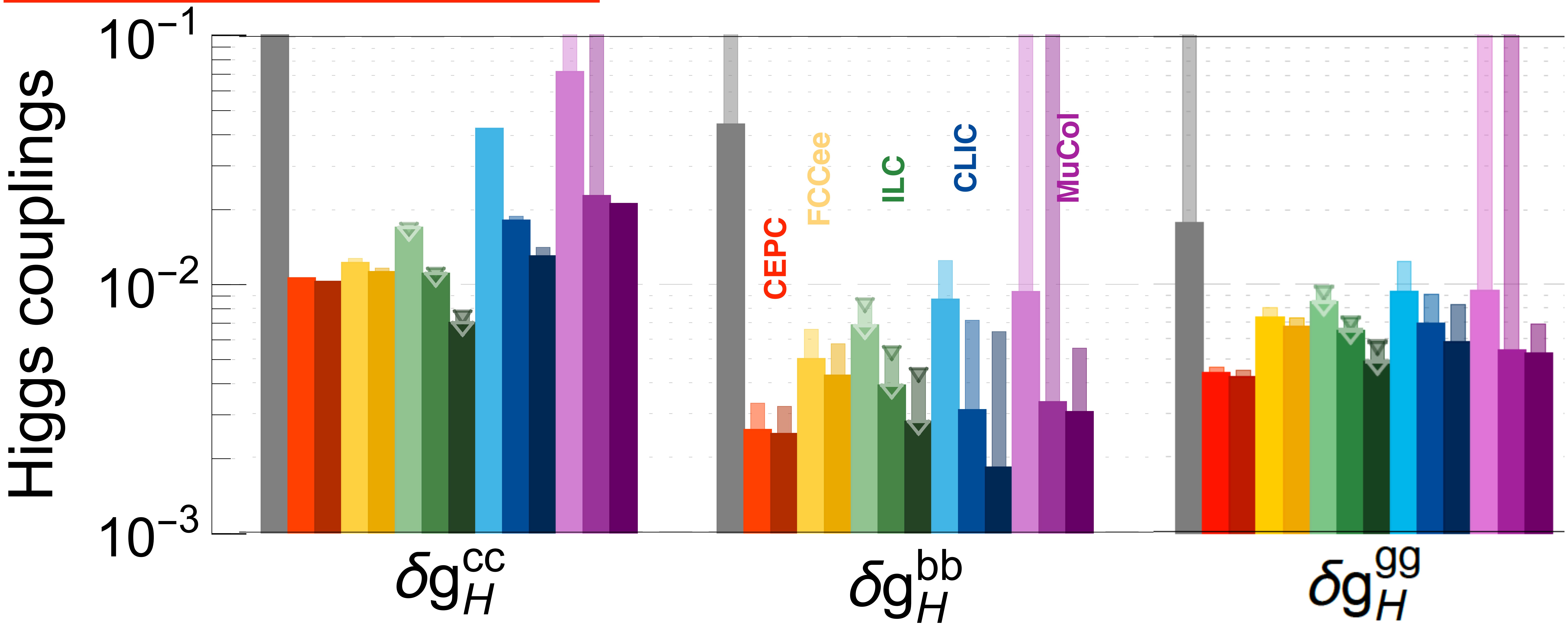

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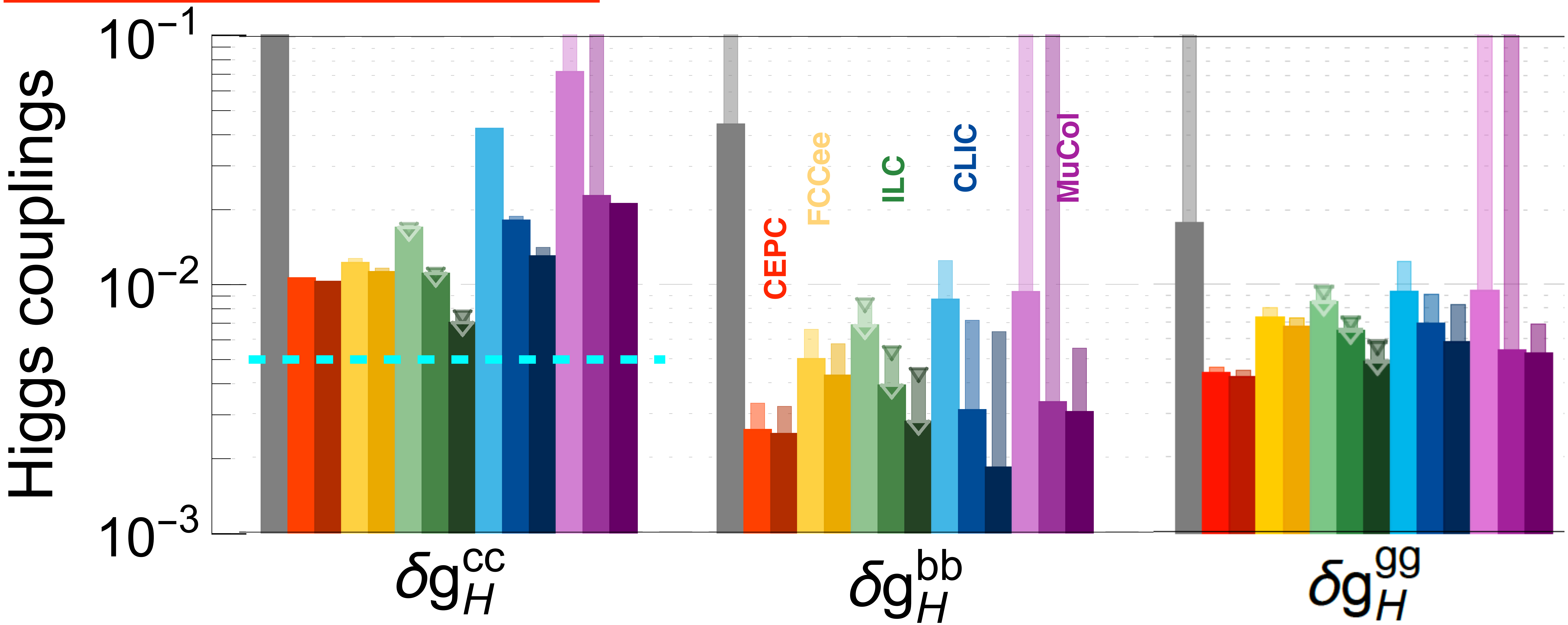

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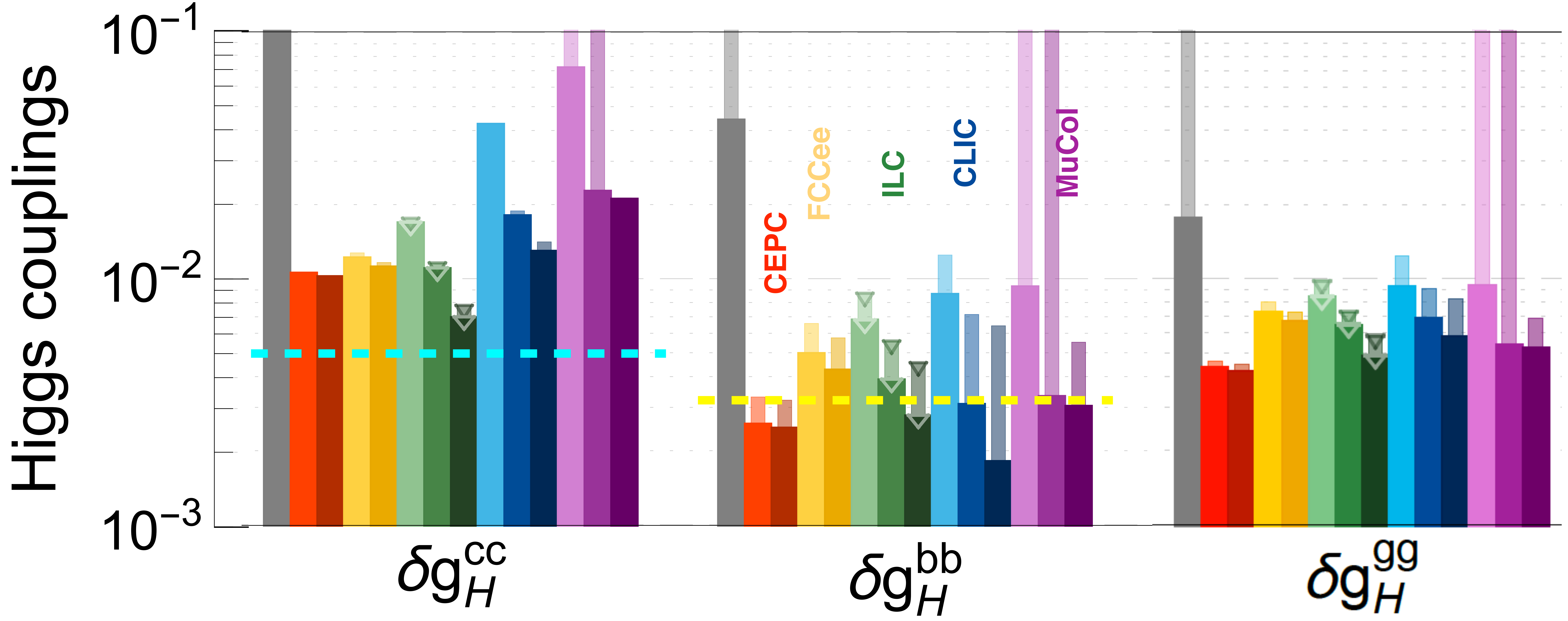


Higgs decay to jets

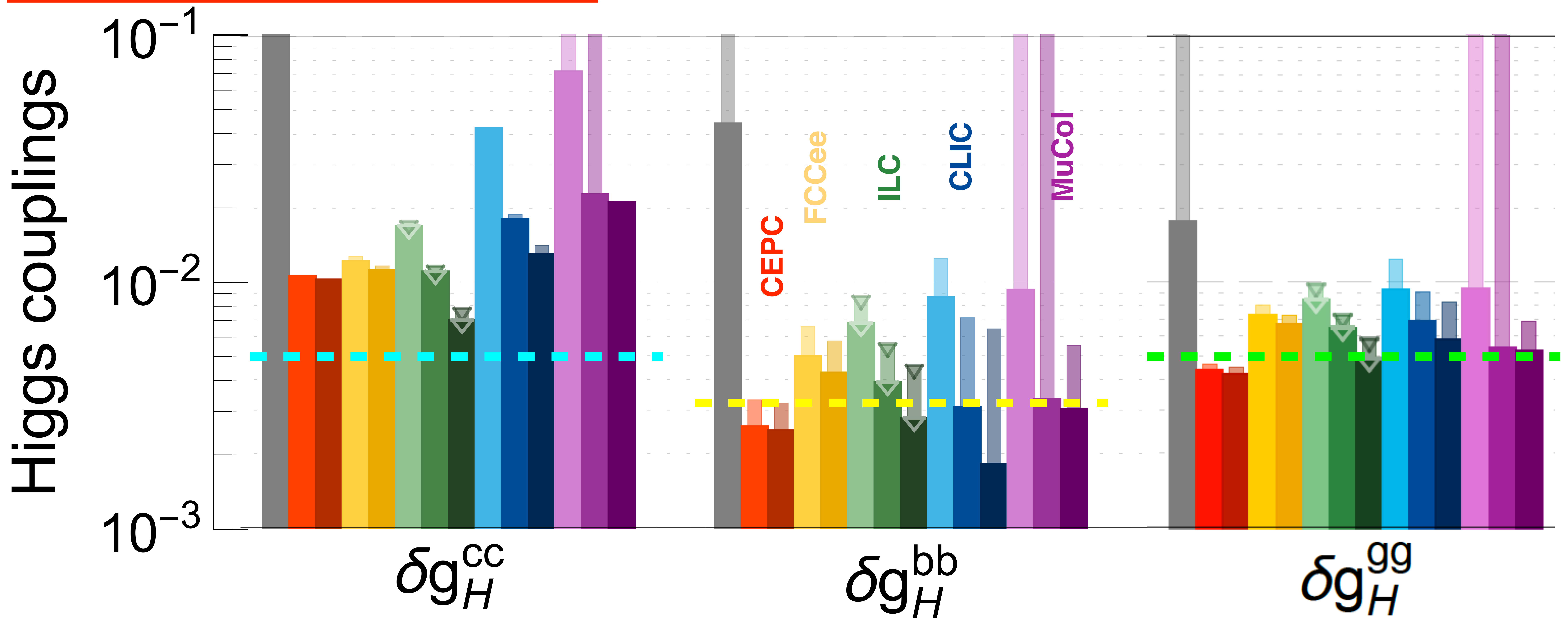
…in SMEFT fit

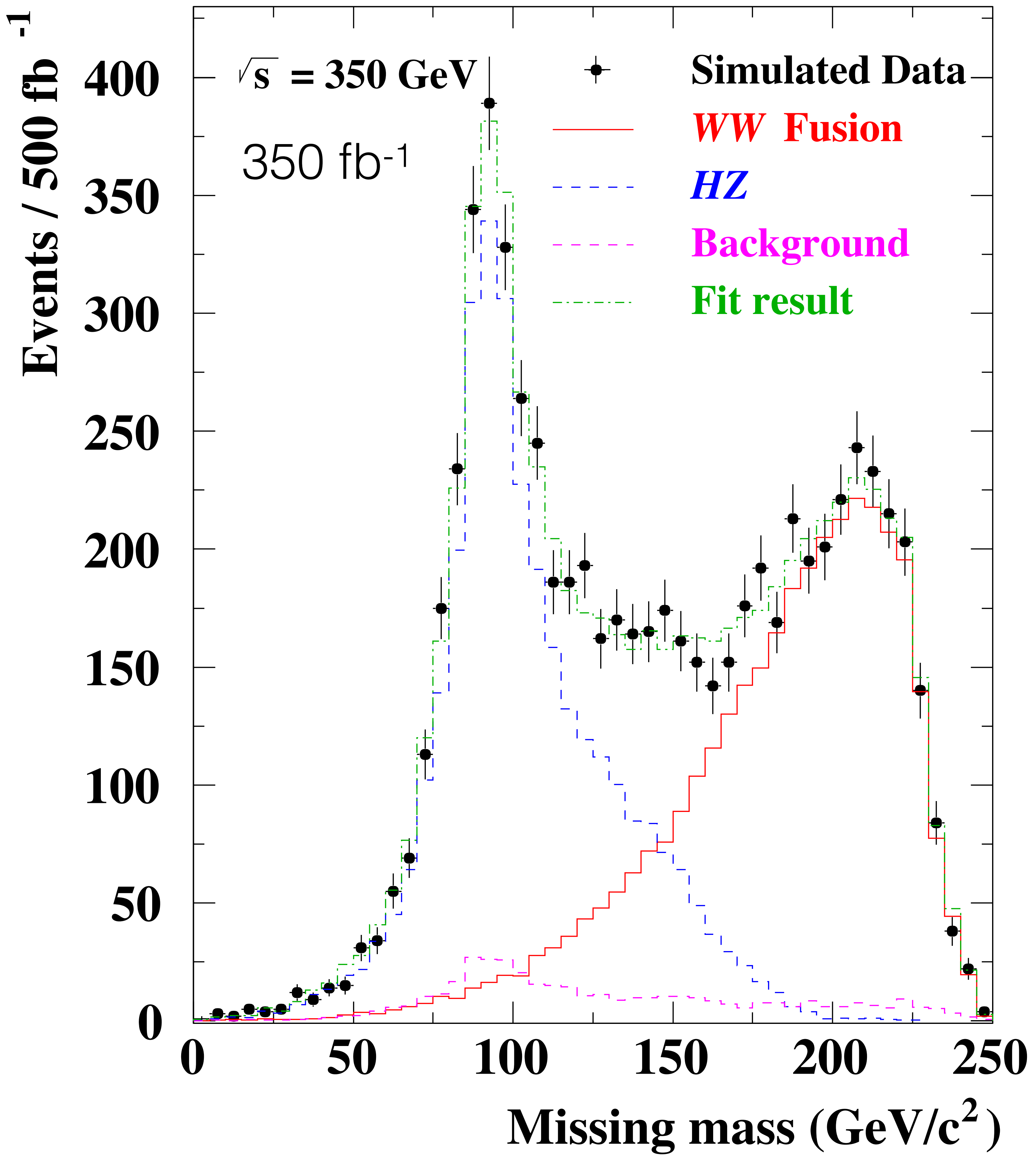
preliminary Snowmass fit result:

- recall: neither intrindic theory nor parametric uncertainties included

future estimates (on Γ_{partial}) from arXiv:1906.05379:

decay	intrinsic	para. m_q	para. α_s	para. M_H
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–
$H \to gg$	$\sim 1\%$		0.5% (0.3%)	–



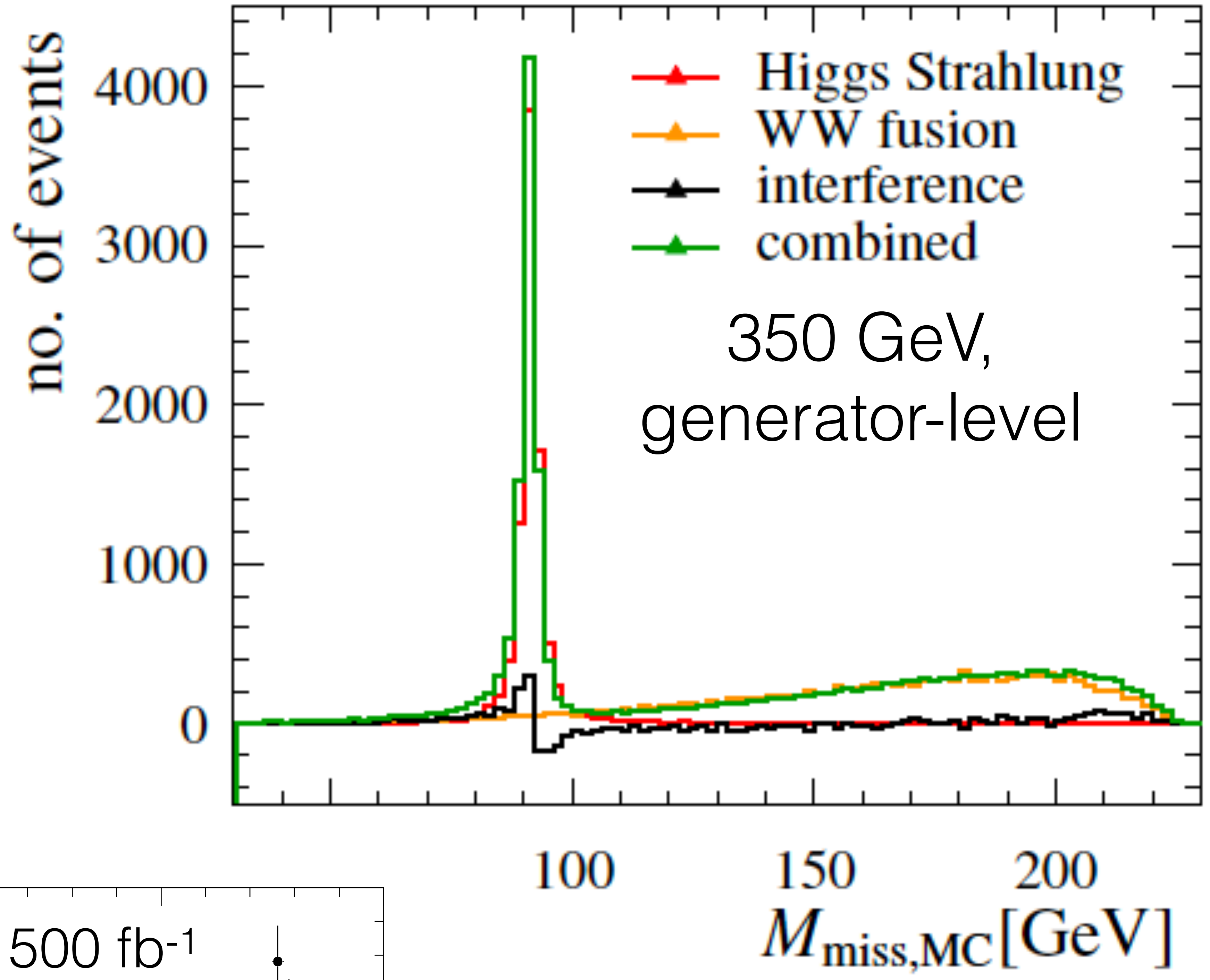


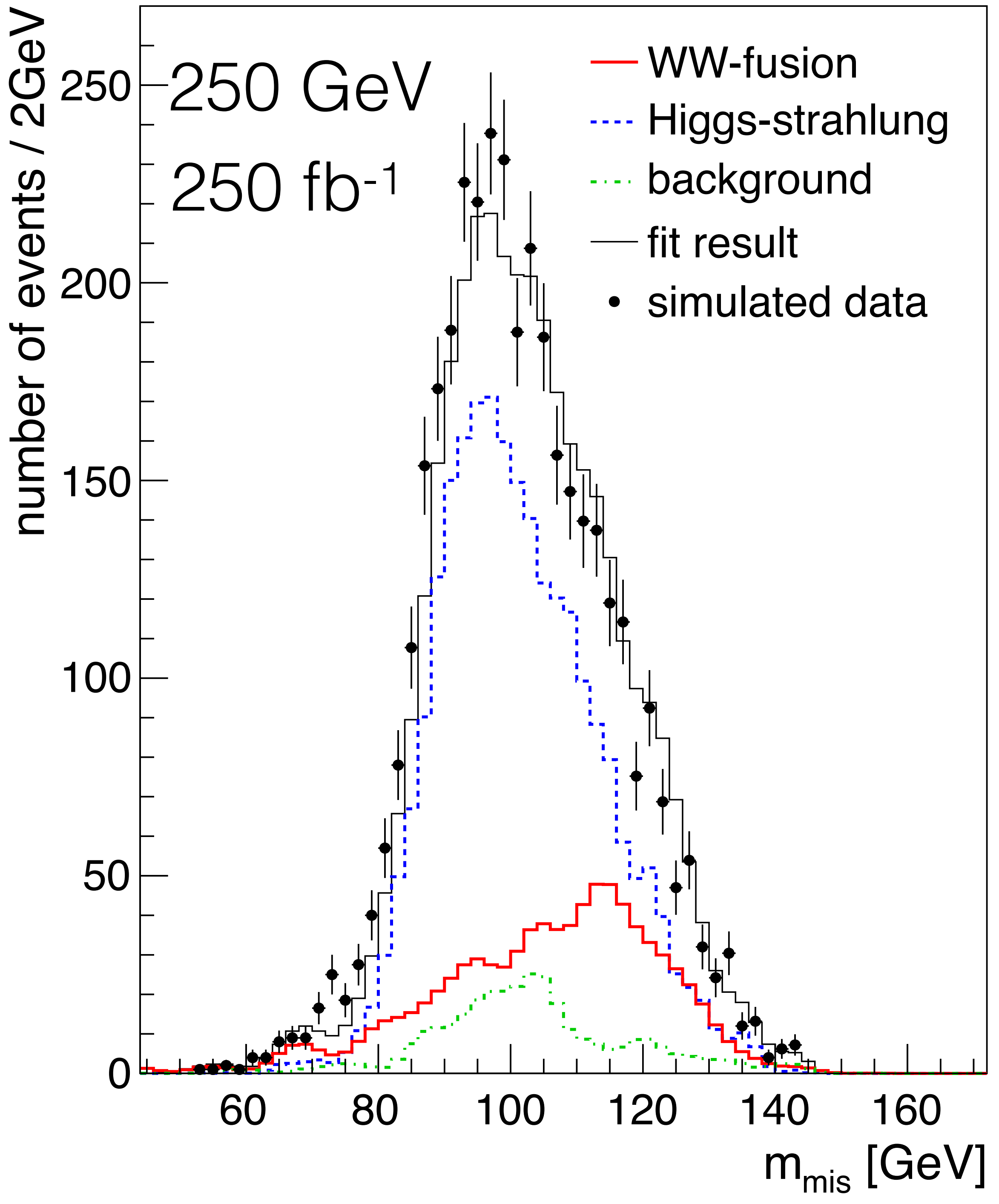
WW fusion & Total width

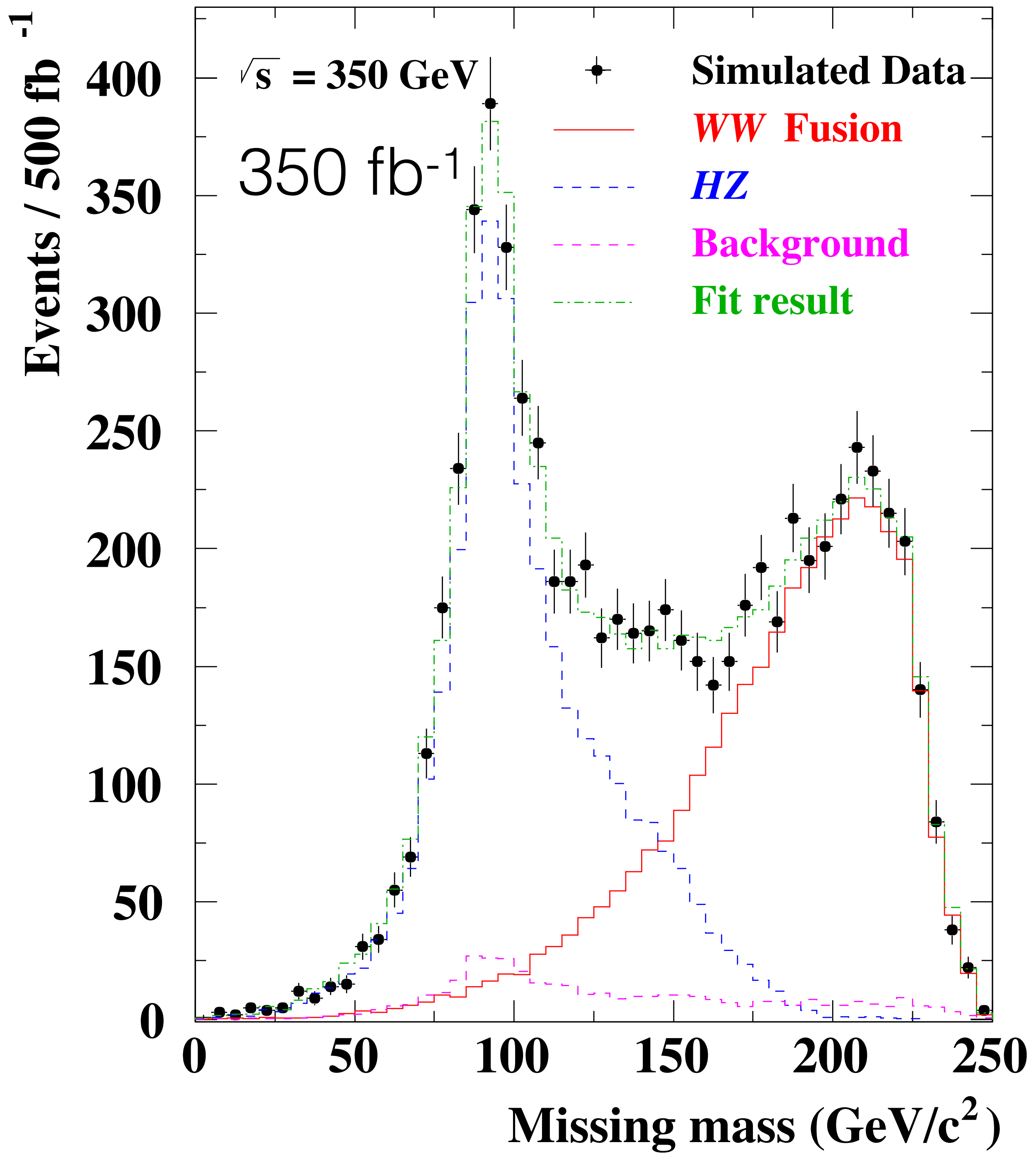
WW fusion cross section

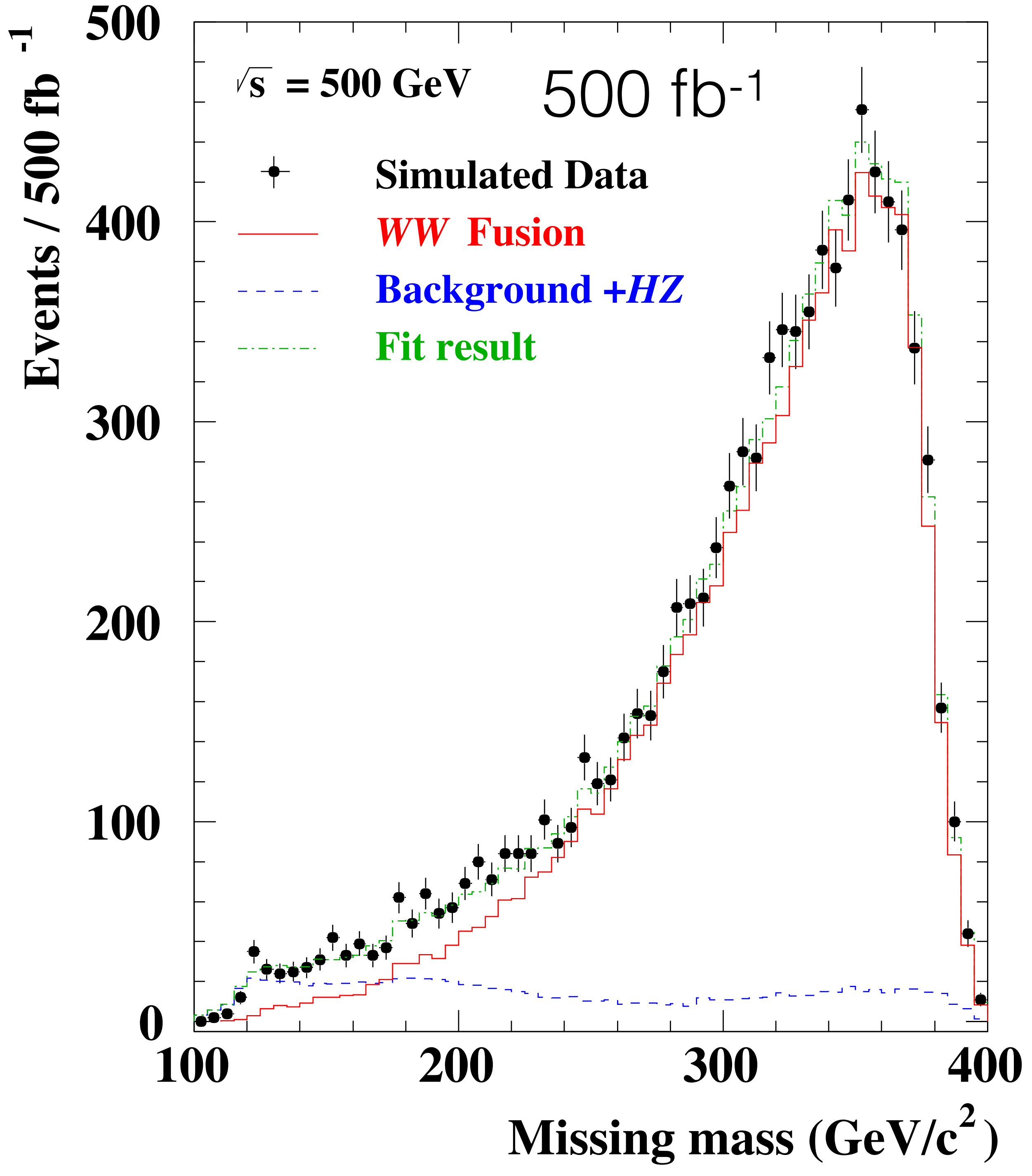
…precision energy dependent

- most important measurement: ee->ννH -> ννbb
- use BR(H->bb) from ZH to obtain σ(ννH)
- b-specifc systematics, e.g. from m(b), b-tagging, etc "cancel"
- analogously smaller contributions from all other decay modes in global fit
- however: non-negligible interference in ννH with Z(->νν)H









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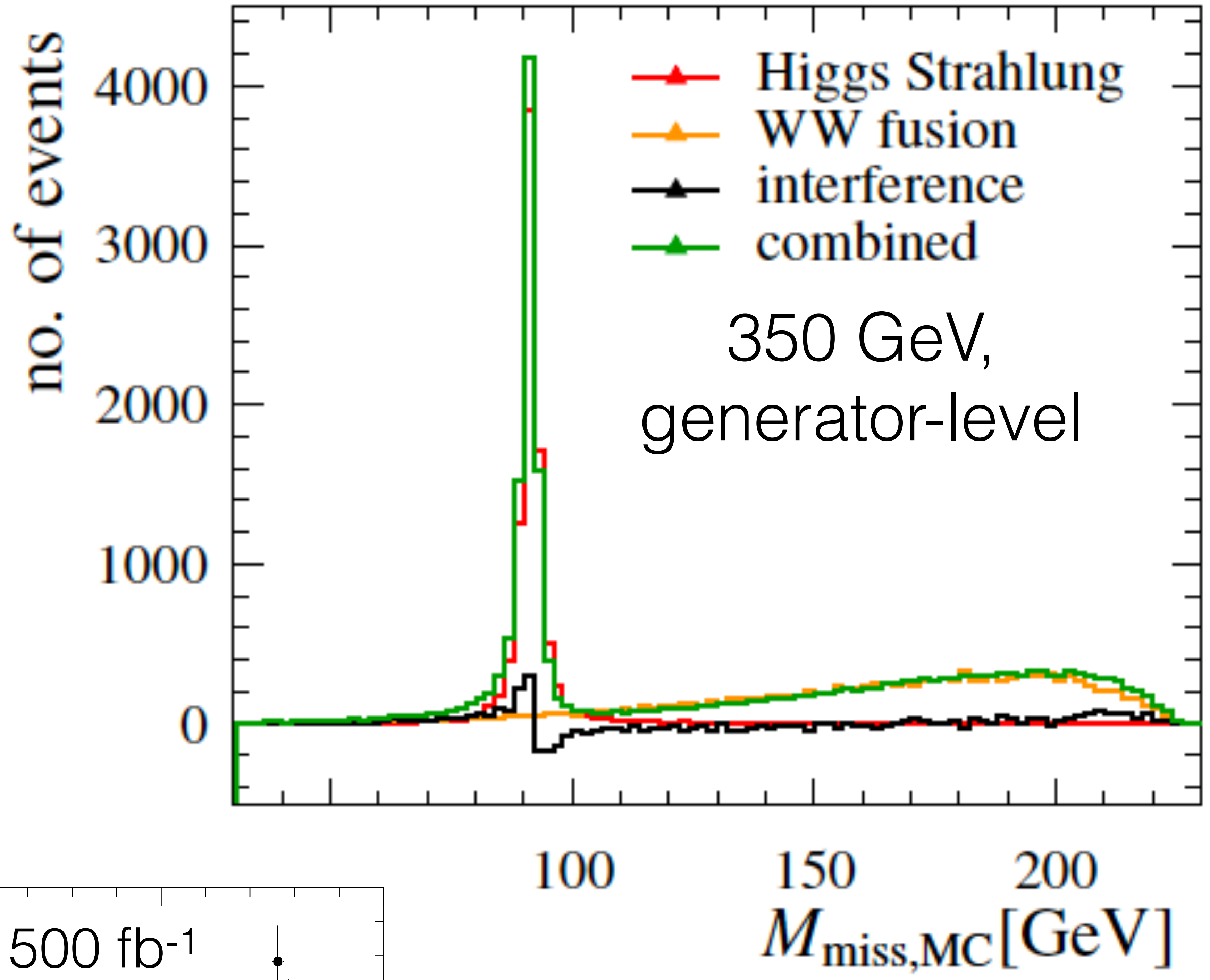
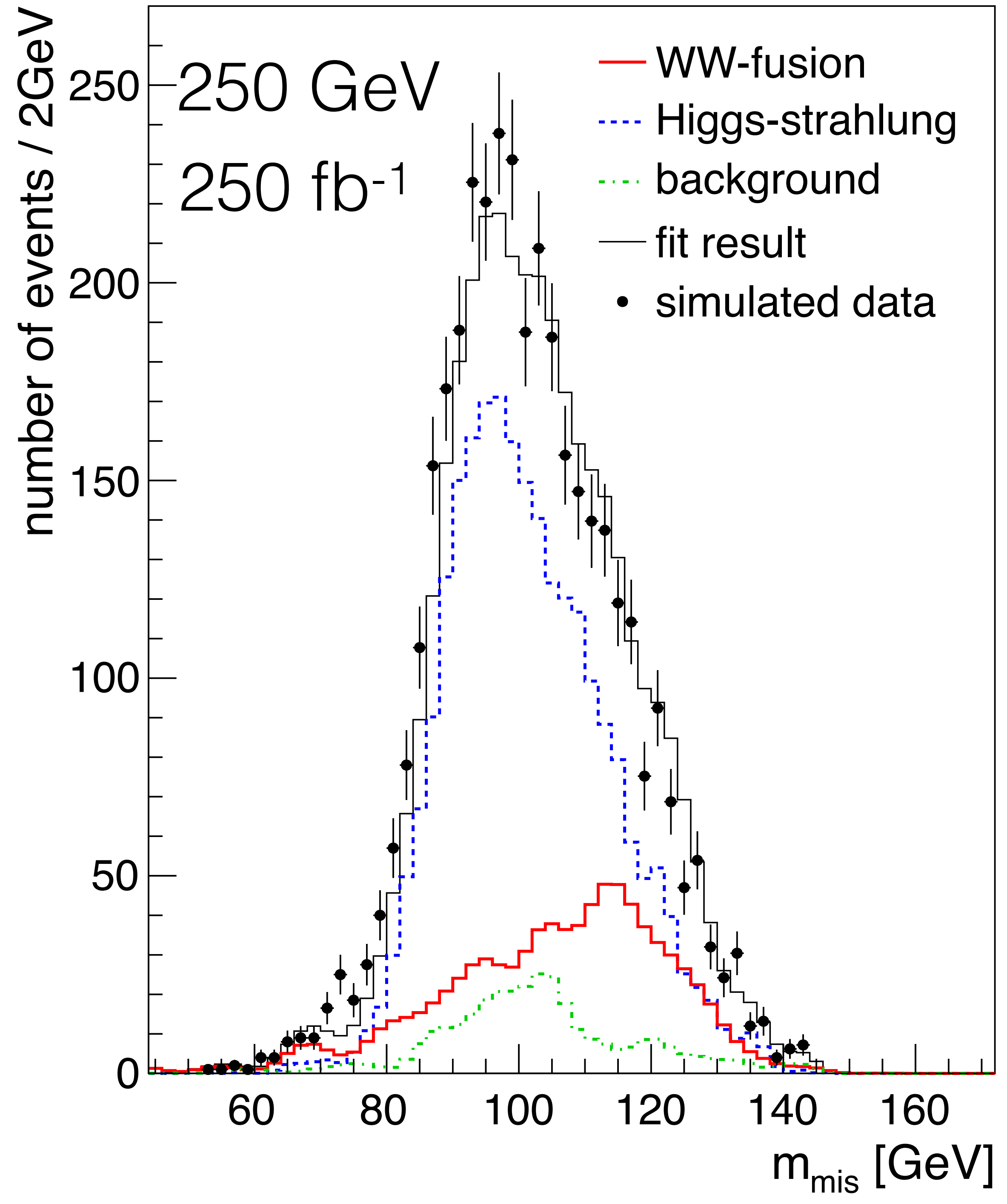
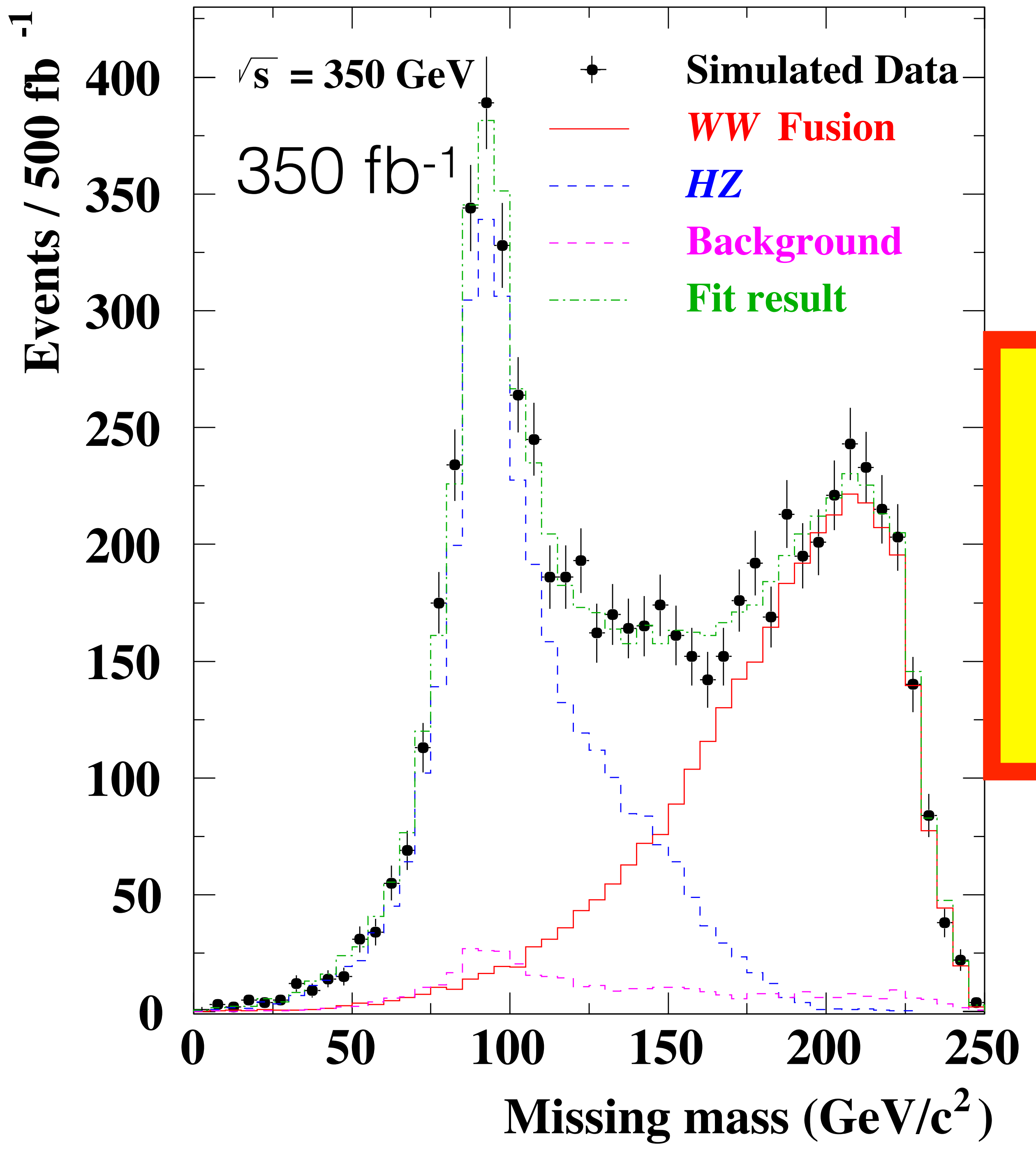
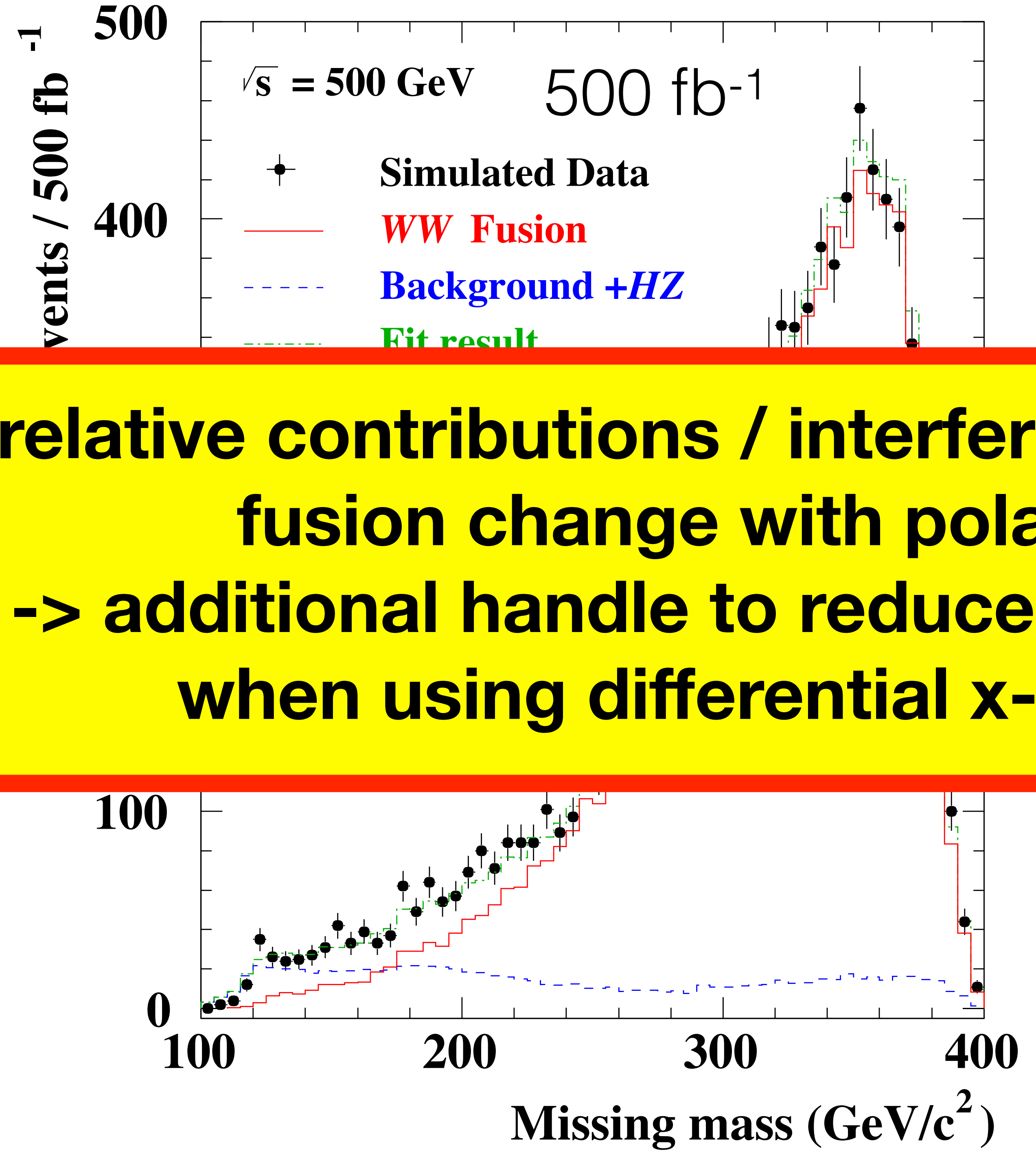








relative contributions / interference from ZH and WW fusion change with polarisation & ECM -> additional handle to reduce impact of systematics when using differential x-section in M_{miss} ?

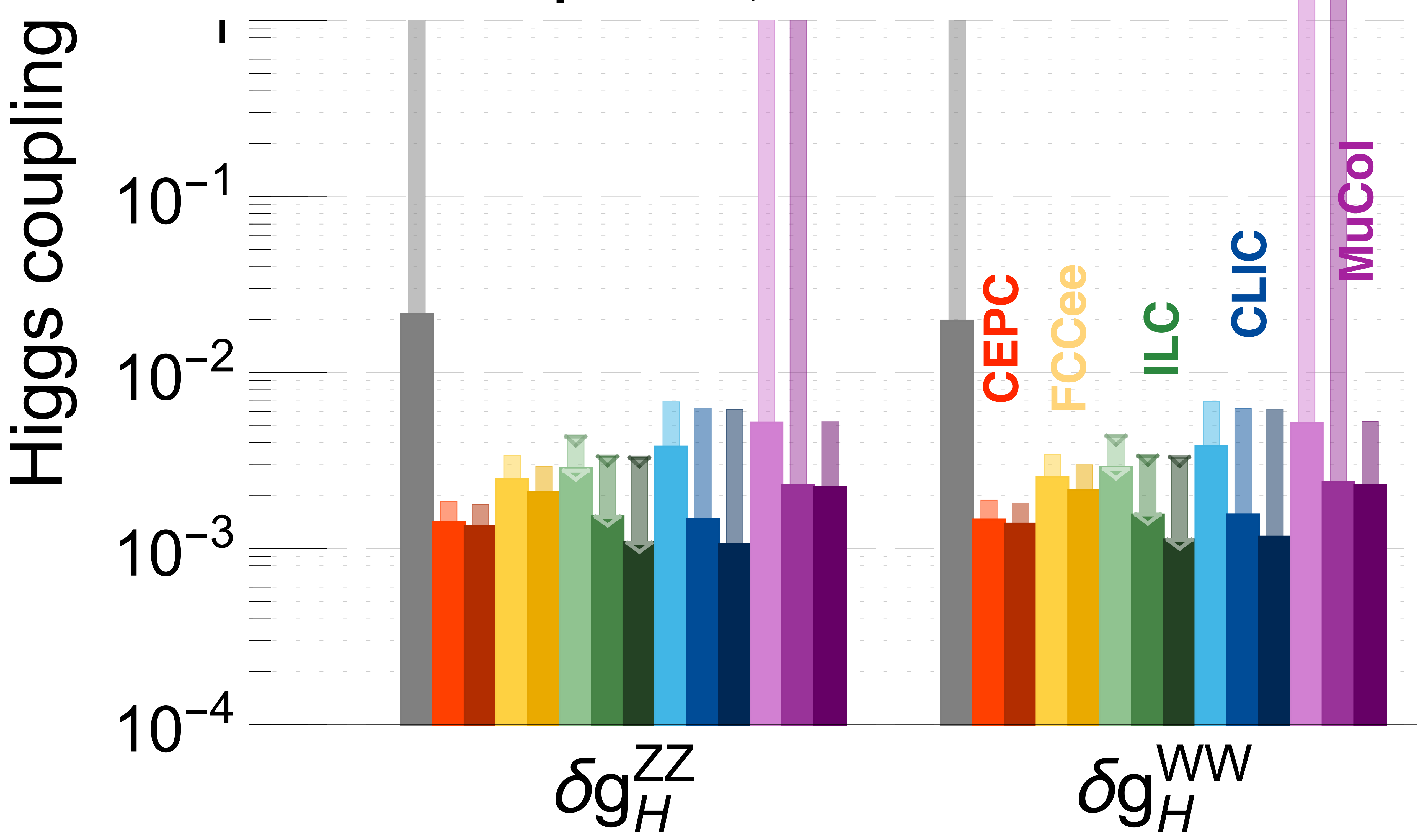
HWW coupling

a challenge?

- interpretation of σ(ννH) requires 2-loop ew - like for ZH
- BUT: now for a 2 -> 3 process => significantly more difficult than 2 -> 2
- suggestion from arXiv:1906.05379:
  - partial result with closed light-fermion loops
  - and top-loops in large-m_t approximation

=> “below the 1%-level”

Snowmass sneakpreview, no theo uncert



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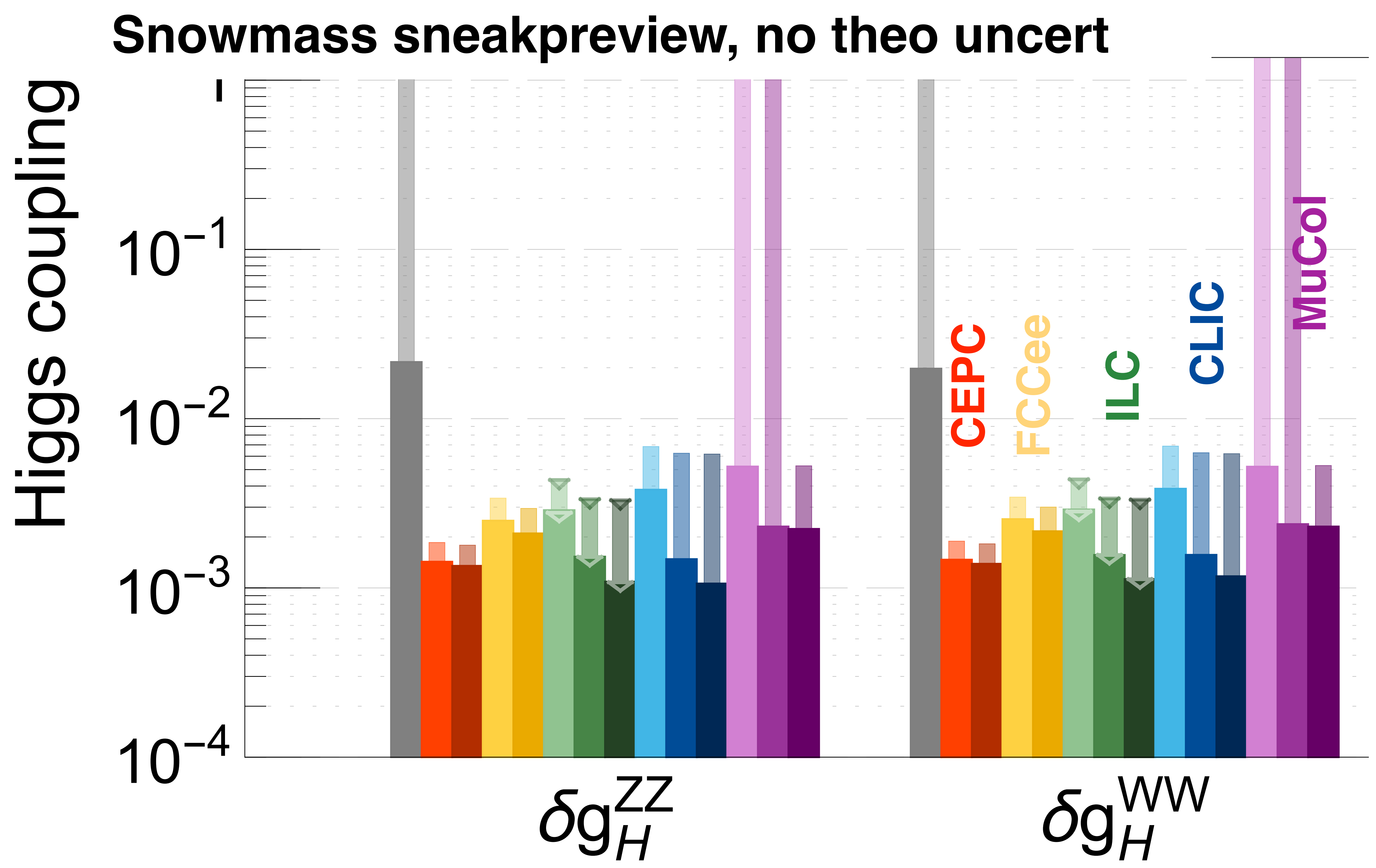

Contrast with expected g_{HWW} precisions ~ 0.35%
=> “below 1%-level” good enough?

What about differential distributions, e.g. dσ/dM_{miss} ?

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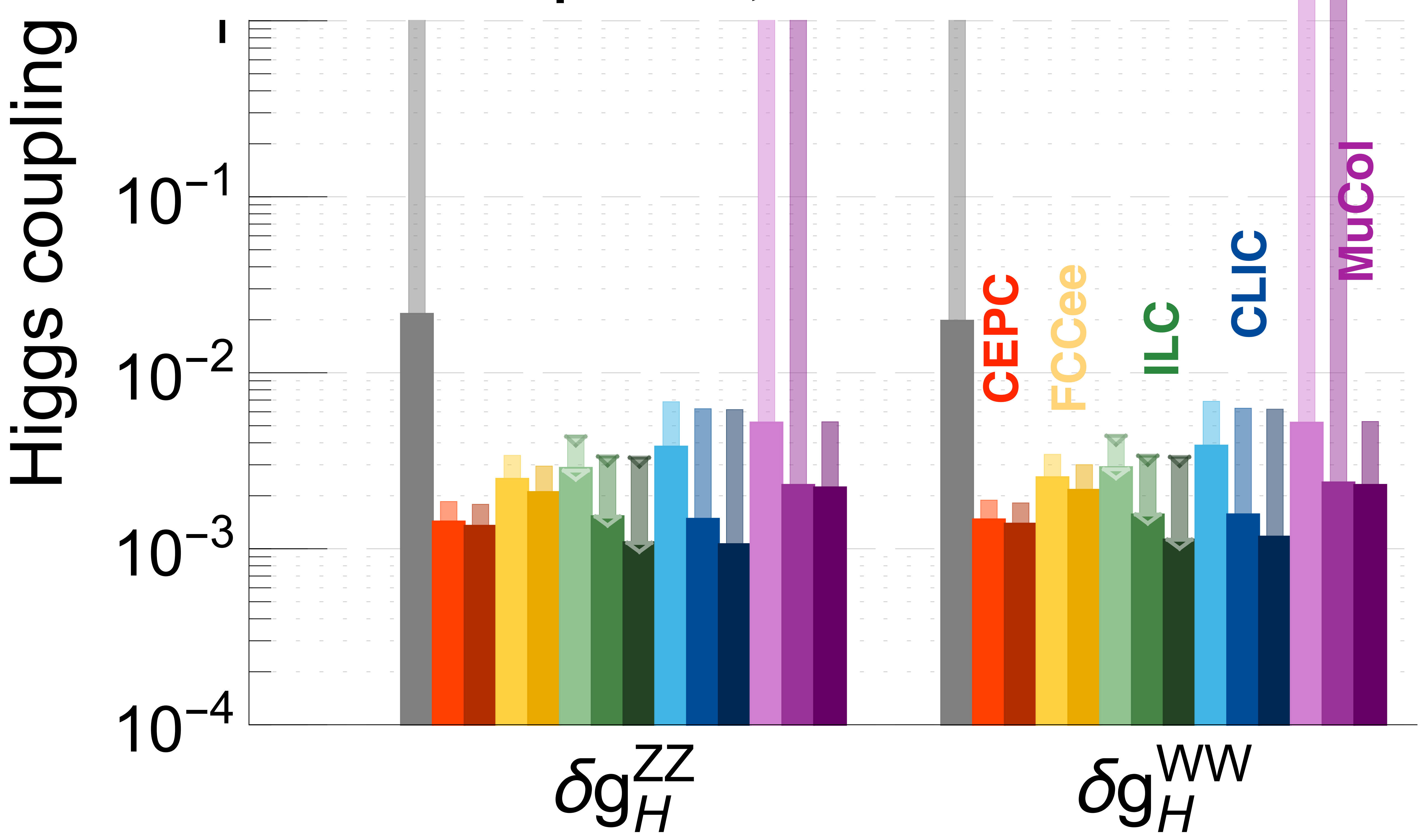

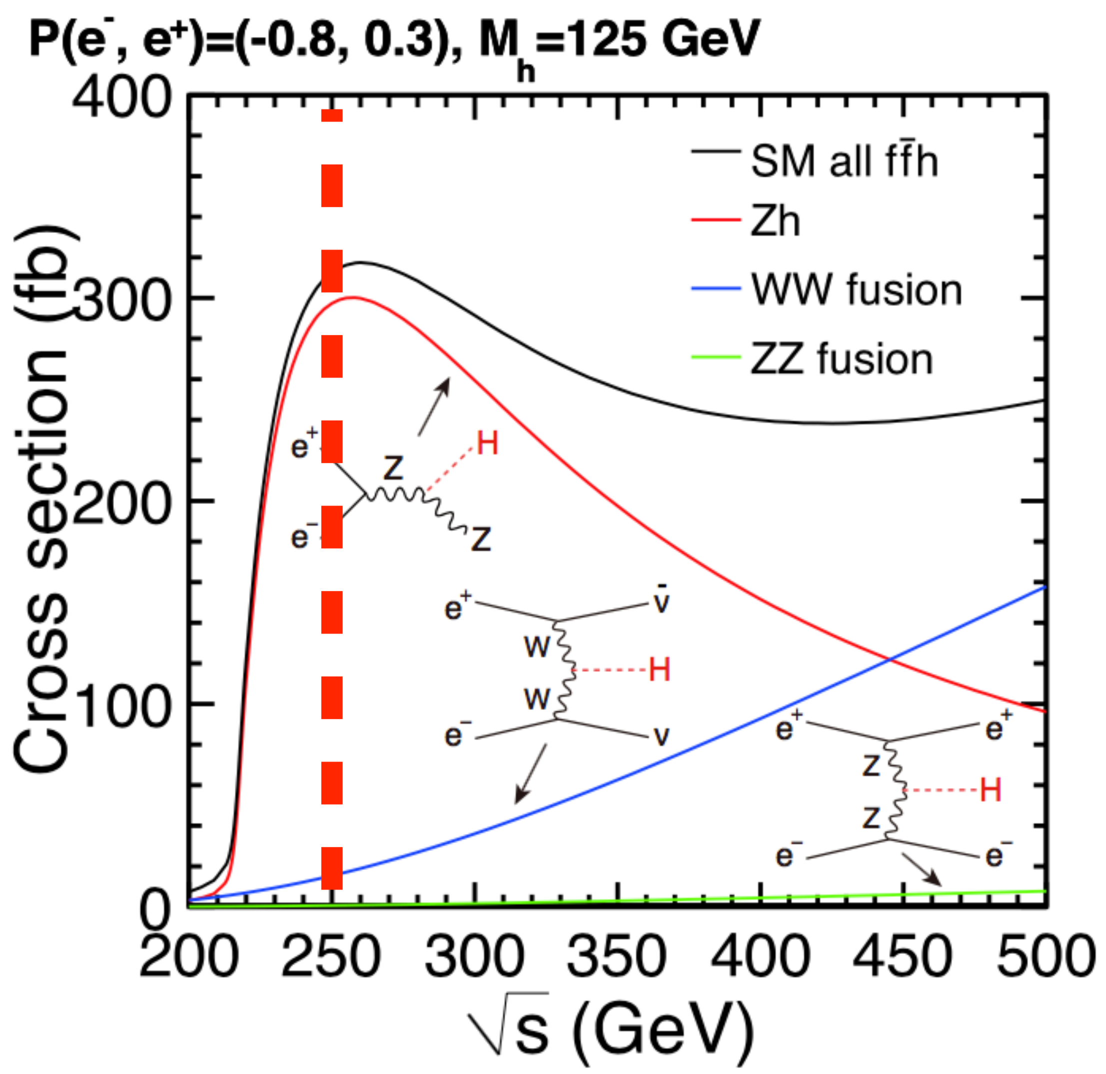

240 GeV/250 GeV: gHWW mostly from H->WW* decay? => 350 GeV upwards, fusion important !

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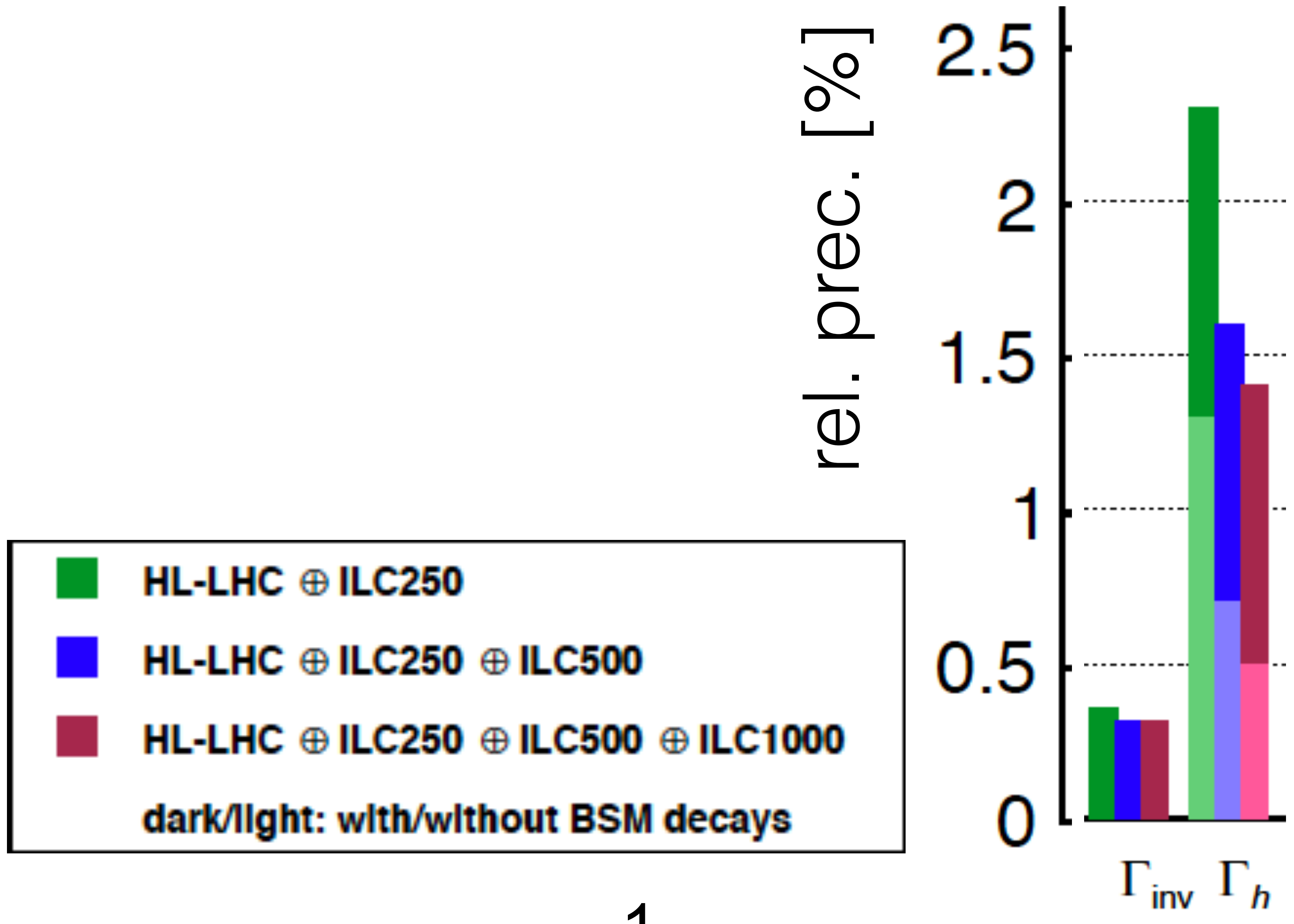
What about differential distributions, e.g. $d\sigma/dM_{miss}$?

Total width

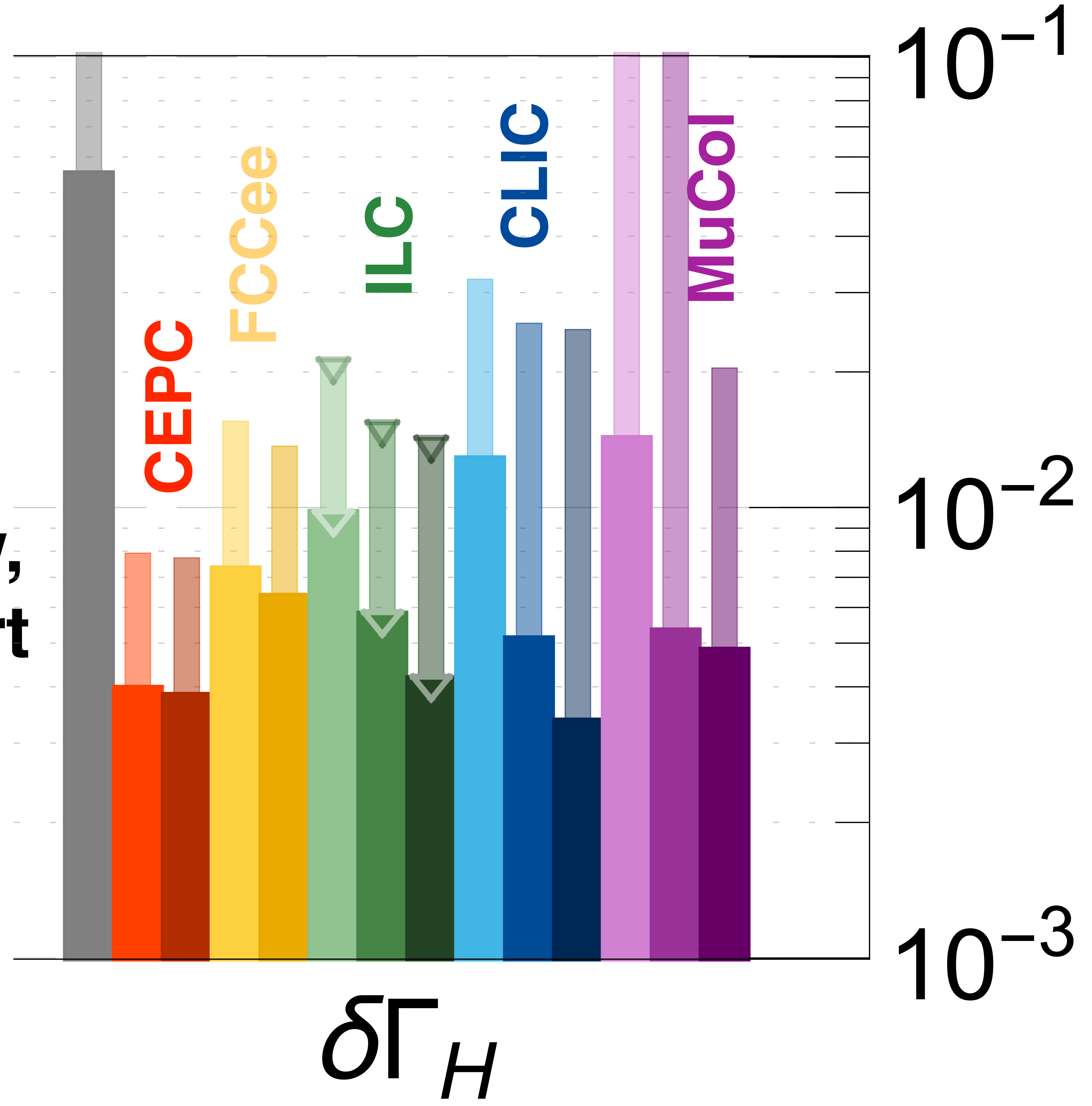
more relaxed requirements if invis. / BSM decays allowed

- if BSM/invis. decays allowed => 1.5…2%
- arXiv:1906.05379 - ok?:
  - intrinsic theo: ~0.3%
  - parametric $m_{b,c}$ (13 MeV, 7 MeV): ~0.4%
  - parametric α_S (0.0002) : ~0.1%
  - parametric m_H (10 MeV) : ~0.1%



arXiv:1903.01629

Snowmass sneakpreview, no theo uncert

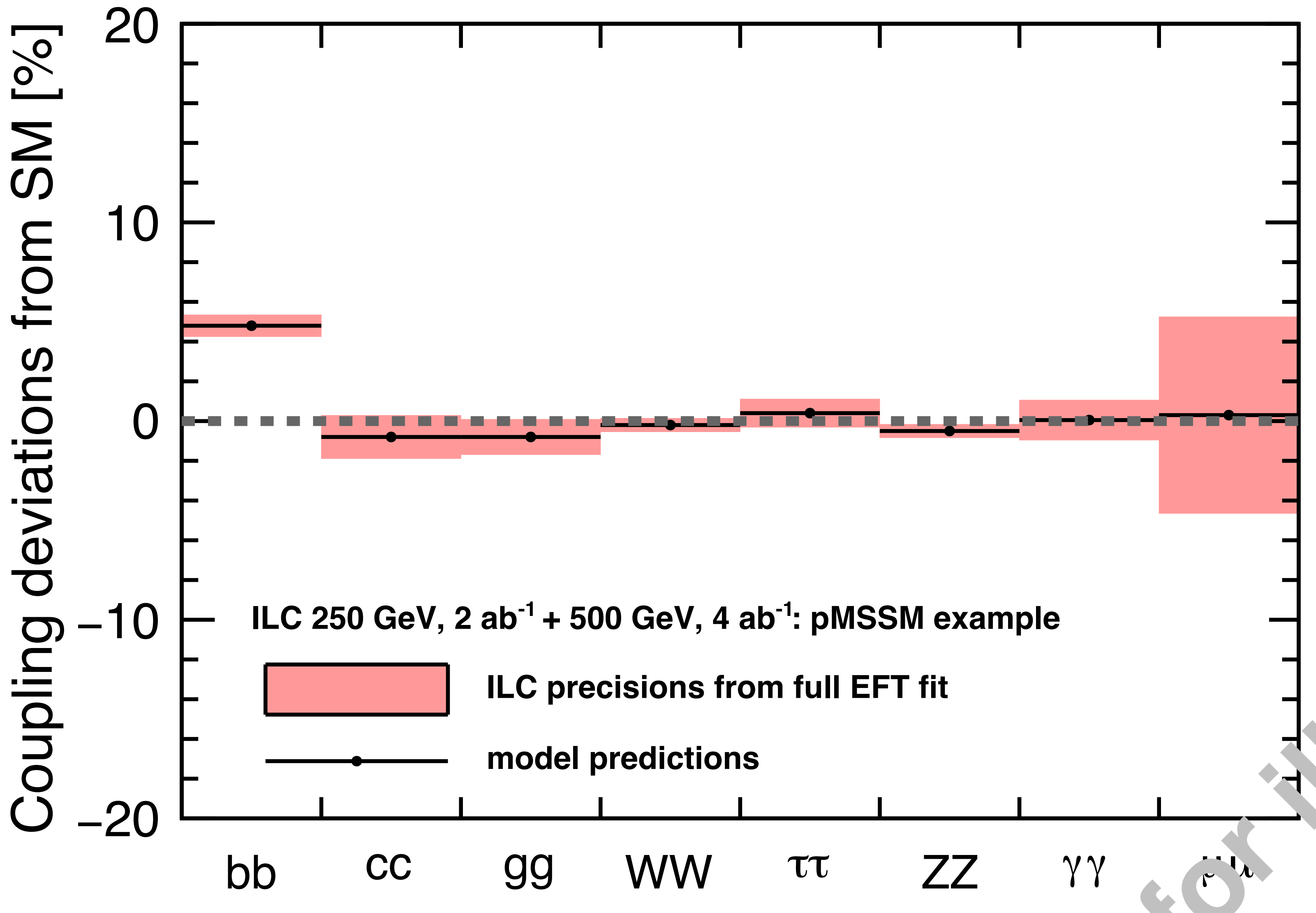


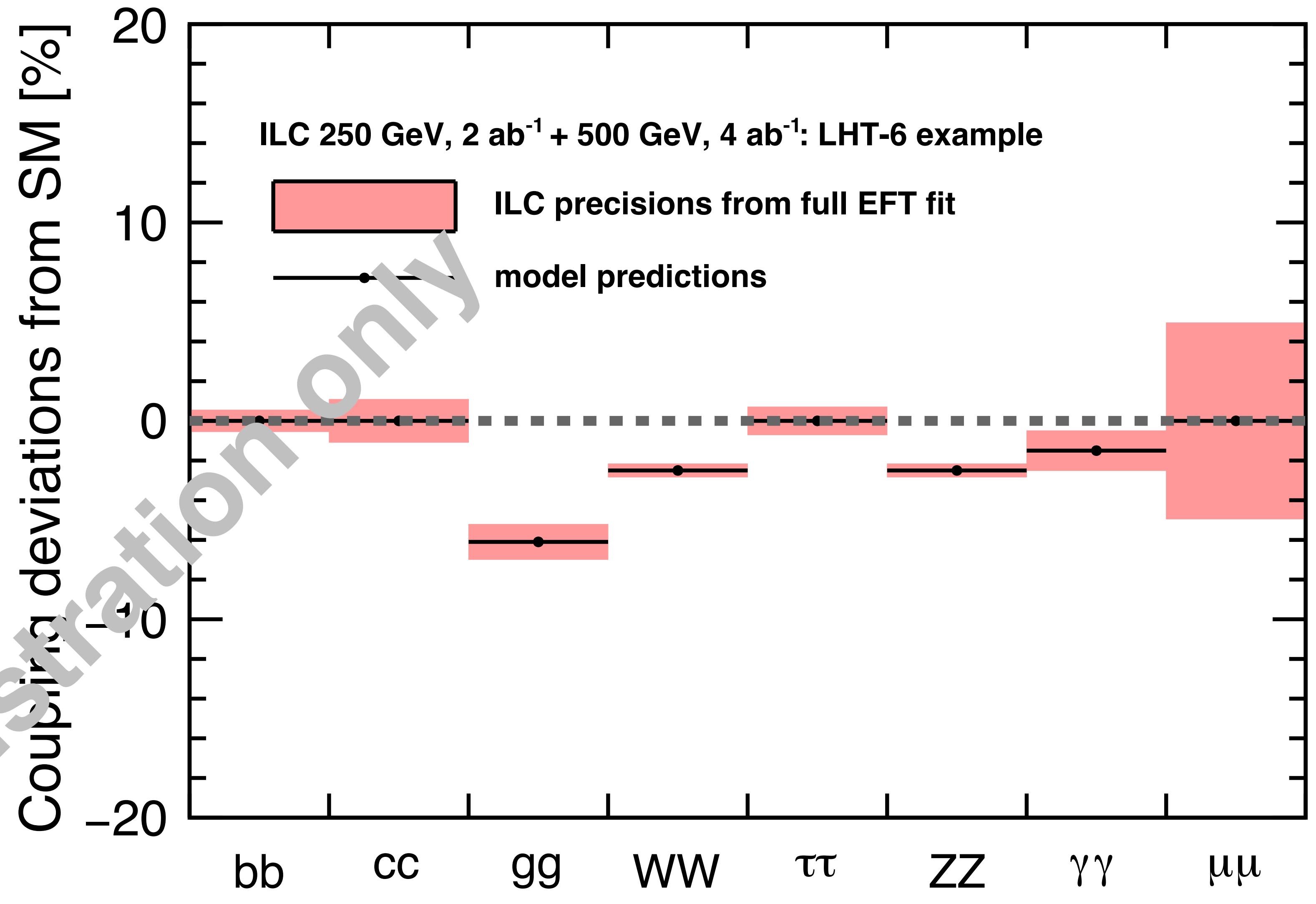
And what about BSM ?

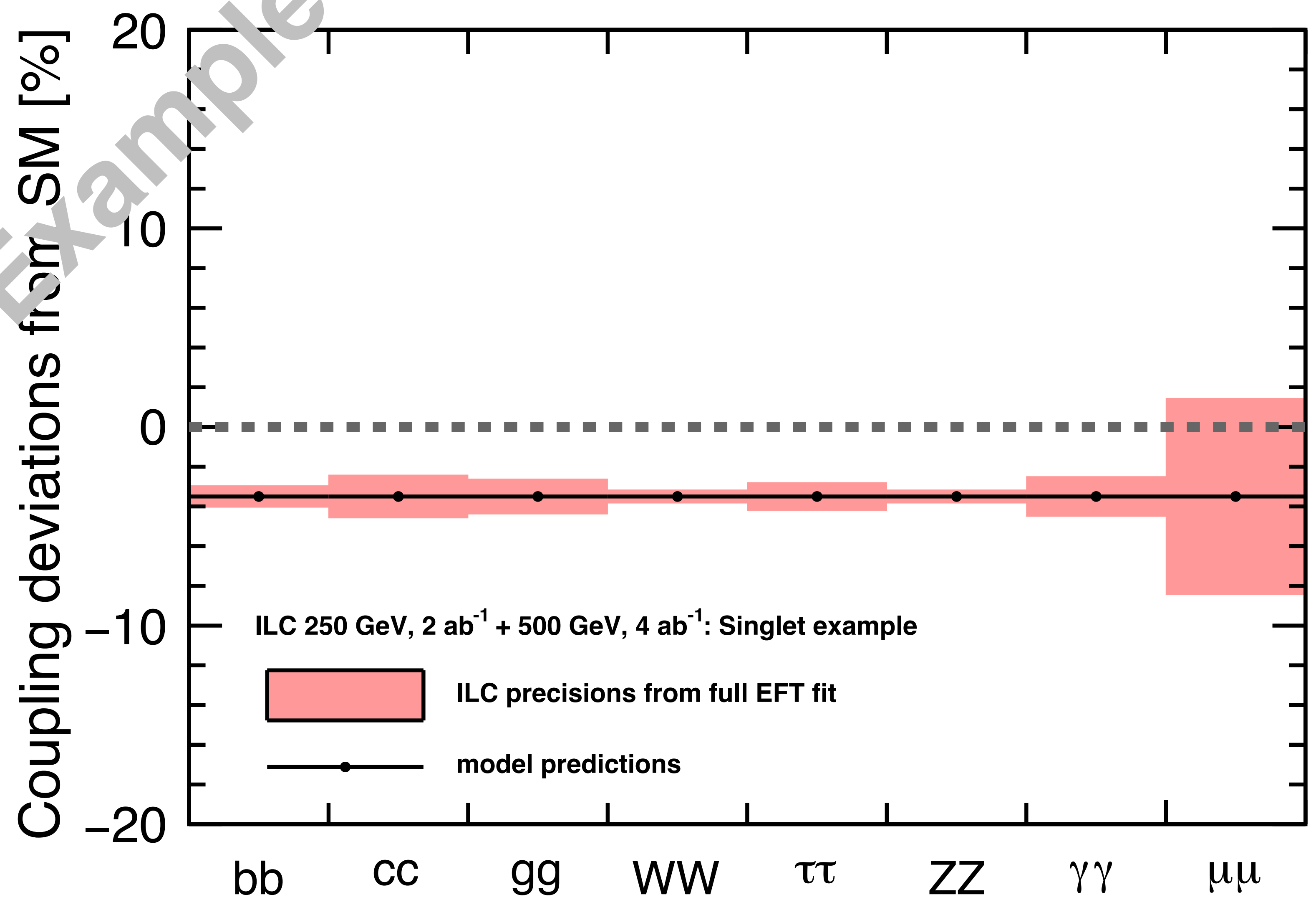
What we actually would like to see…

…is *beyond* the SM

- **finger-printing BSM**
  - **SUSY** ?
  - 2HDM ?
  - composite Higgs?
  - **Higgs singlet** ?
  - **little Higgs** ?
  - …







Examples for illustration only

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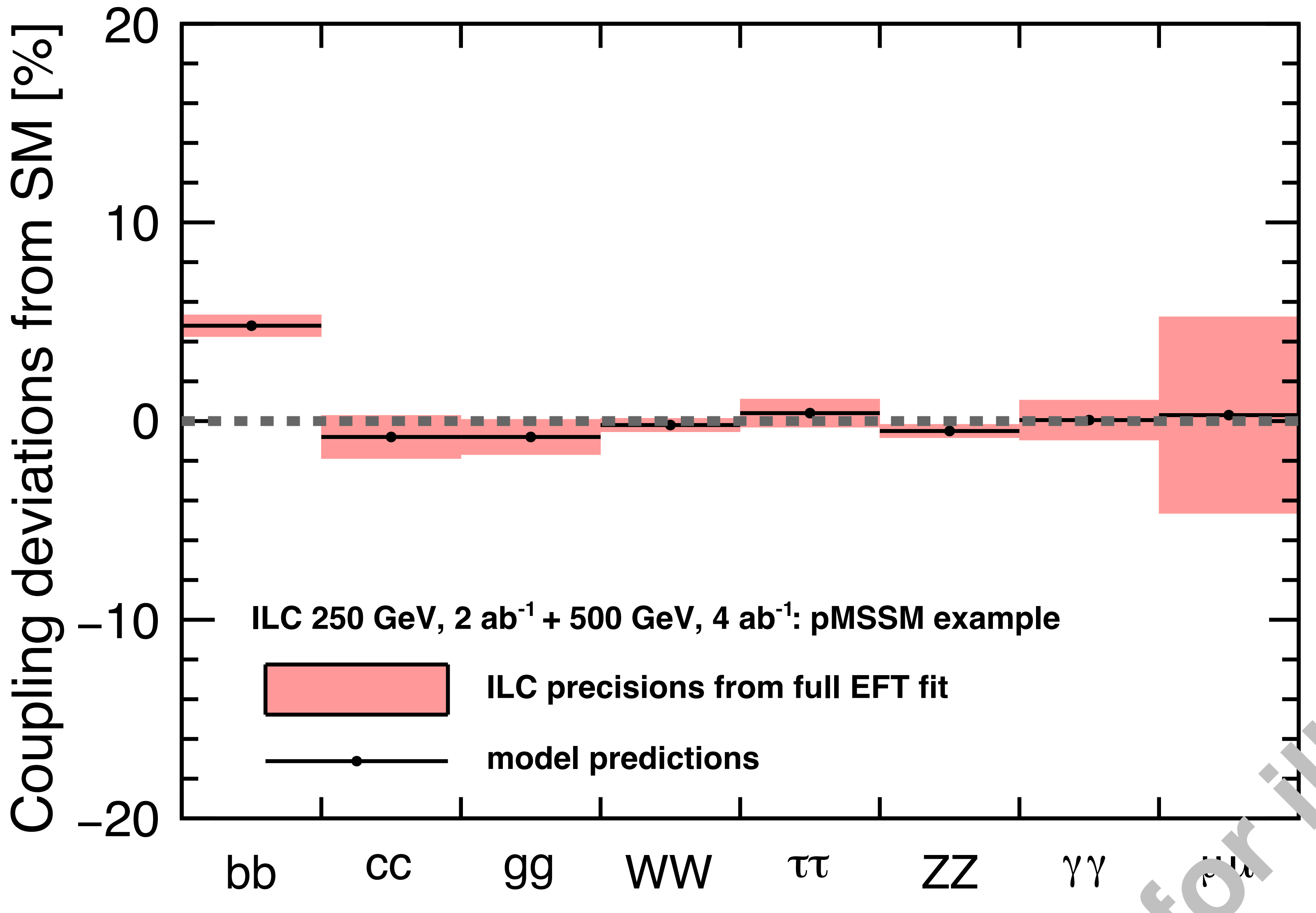
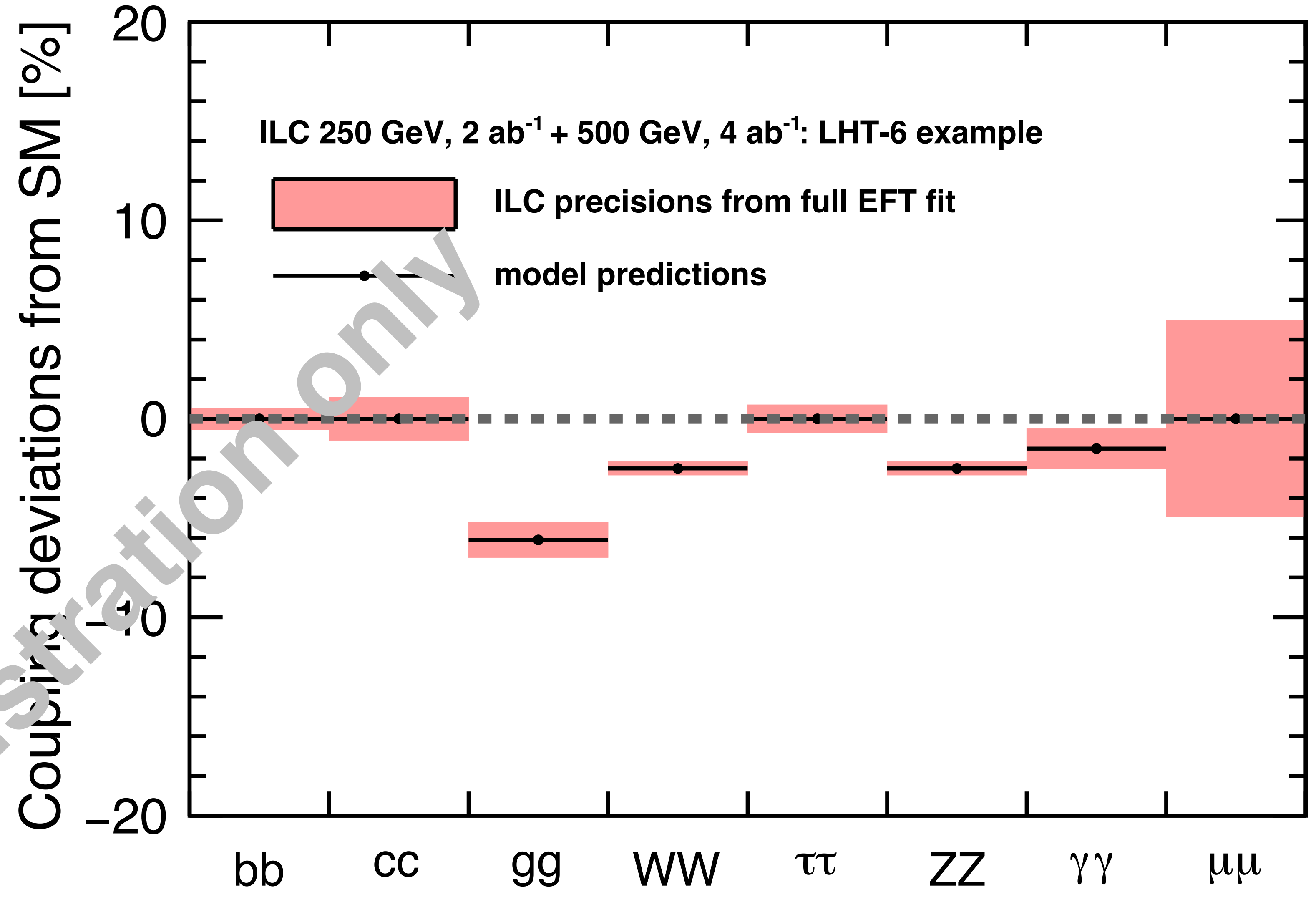
=> need same level of theory precision for the BSM models favoured by first data!
=> also: need BSM loop contribtions to quantify BSM constraints in case of no deviation from SM





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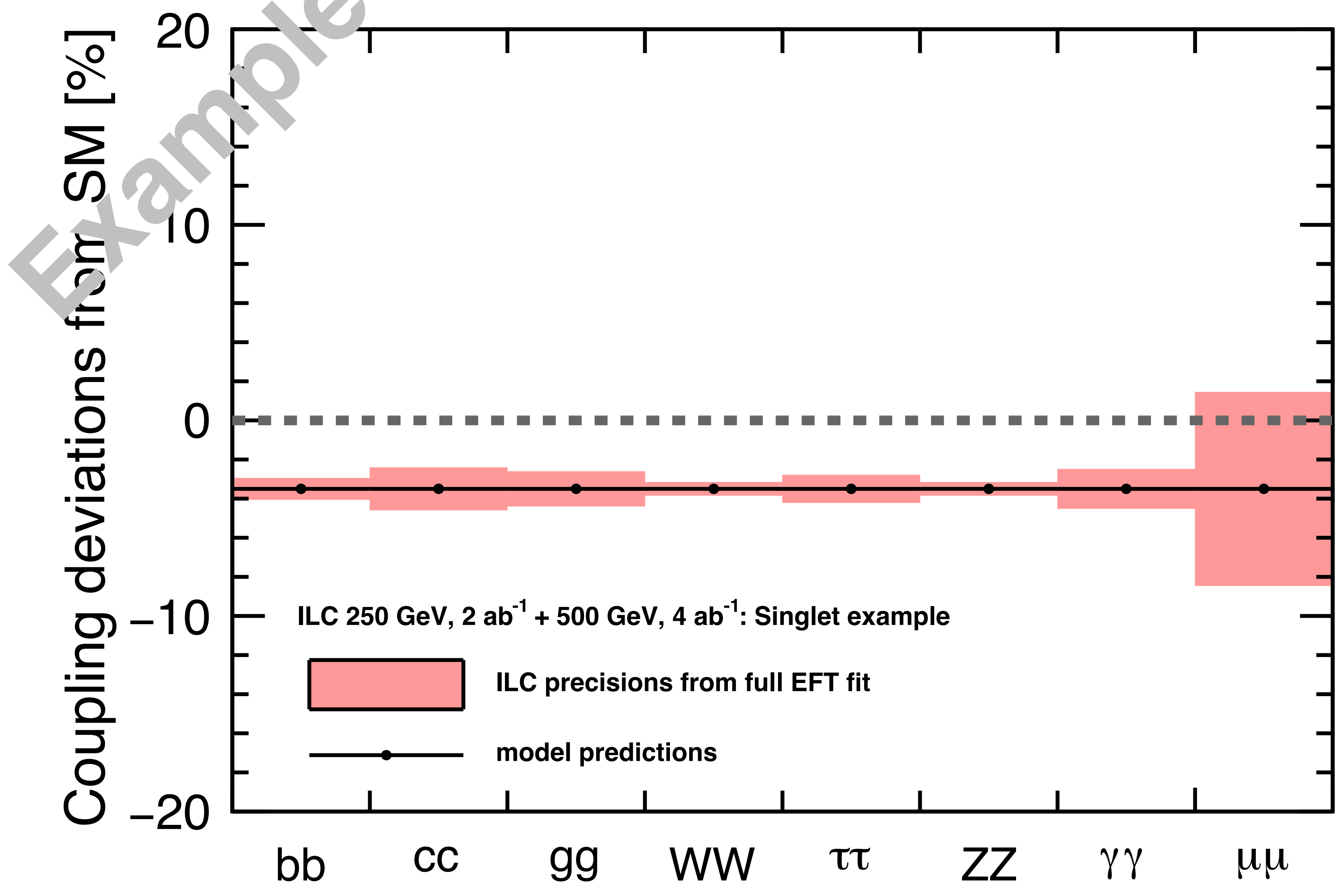


More thoughts about interpretation strategy

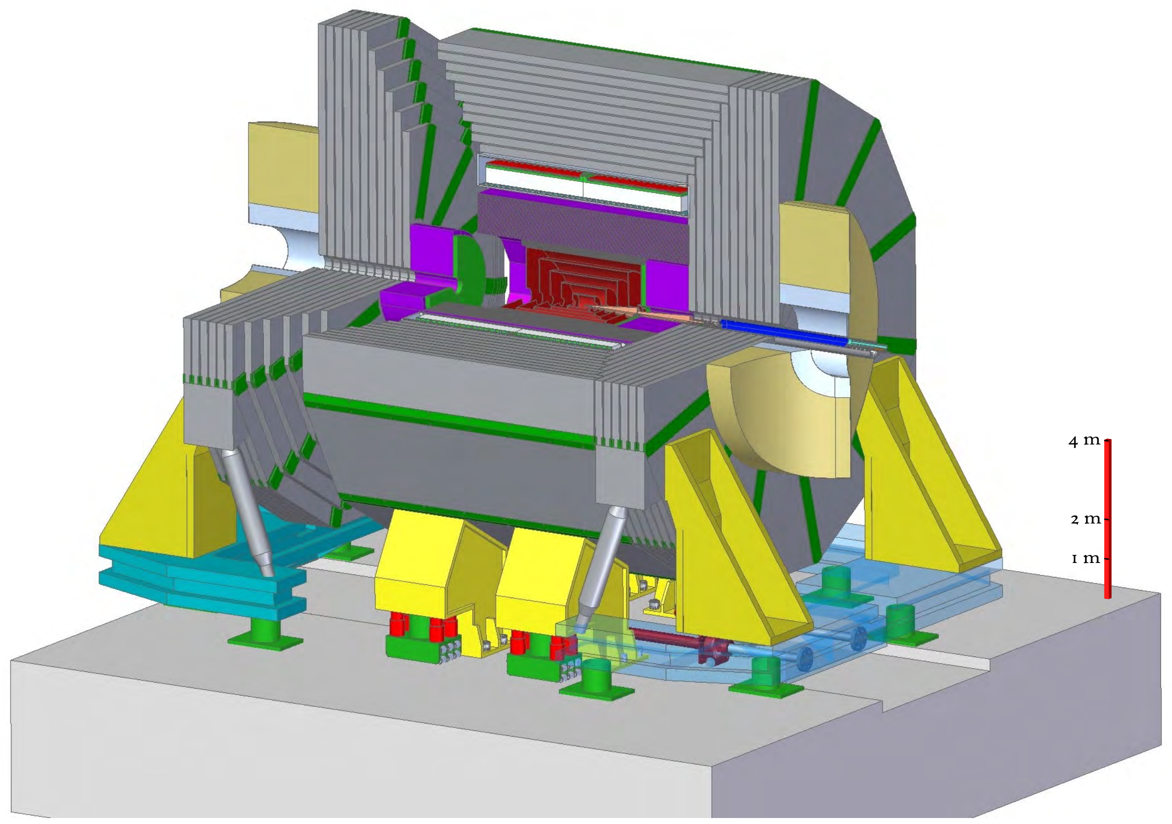
…and BSM

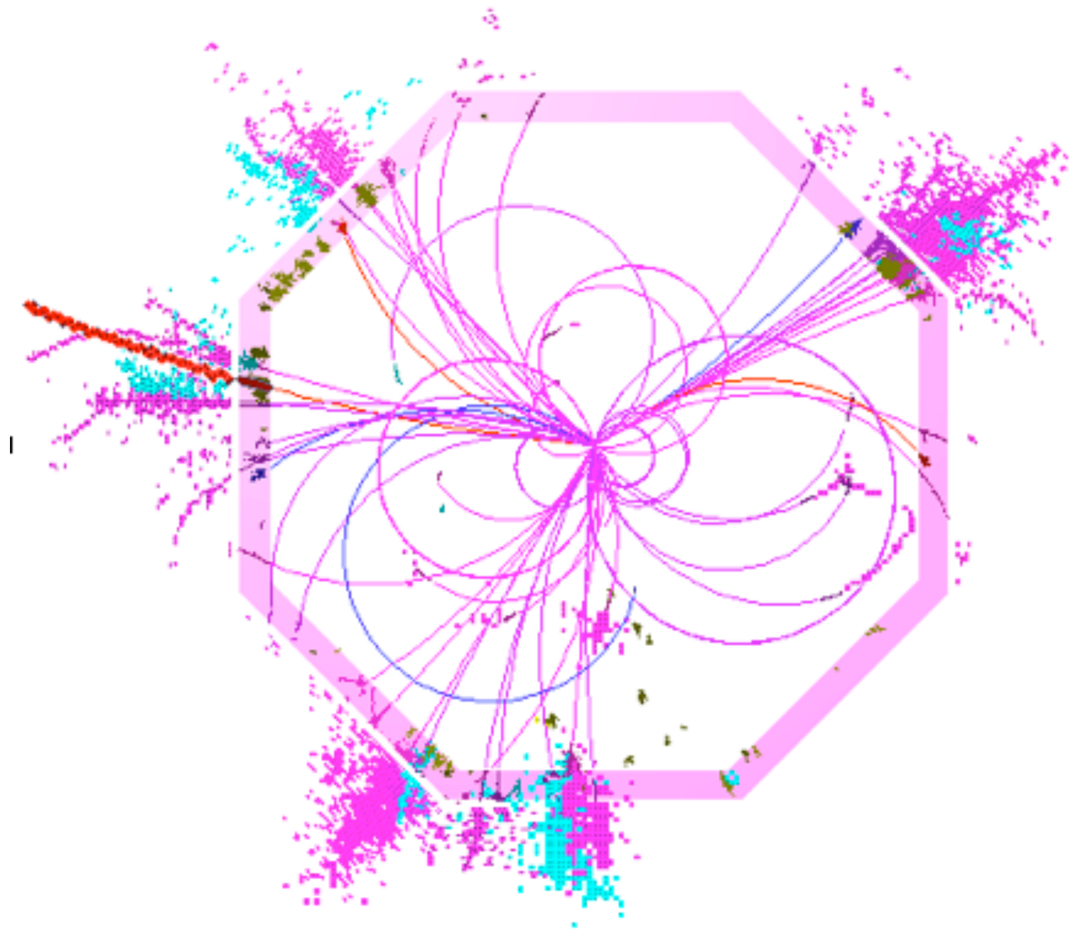
- what are the best observables to interface theory & experiment in the Higgs sector?
- currently, most emphasis is on global SMEFT fit
- a powerful tool, but combining a lot of measurements at a high abstraction level
- don't we want to do "good old" cross-section (x BR) vs ECM plots as individual observables
- and **compare to all kinds of predictions, including BSM**, at that level?
- Is the benchmark for theory requirements the coupling uncertainty from a SMEFT fit (which is what I mostly did here) - or should the benchmark rather be the individual cross-section (x BR) measurements?
- what about differential cross-sections?
  - only looked sofar at in few cases, eg TGCs, CPV / anomalous Hττ and HVV couplings, ννH@ 350 GeV, ννHH@ 3 TeV
  - a lot of uncharted territory here?

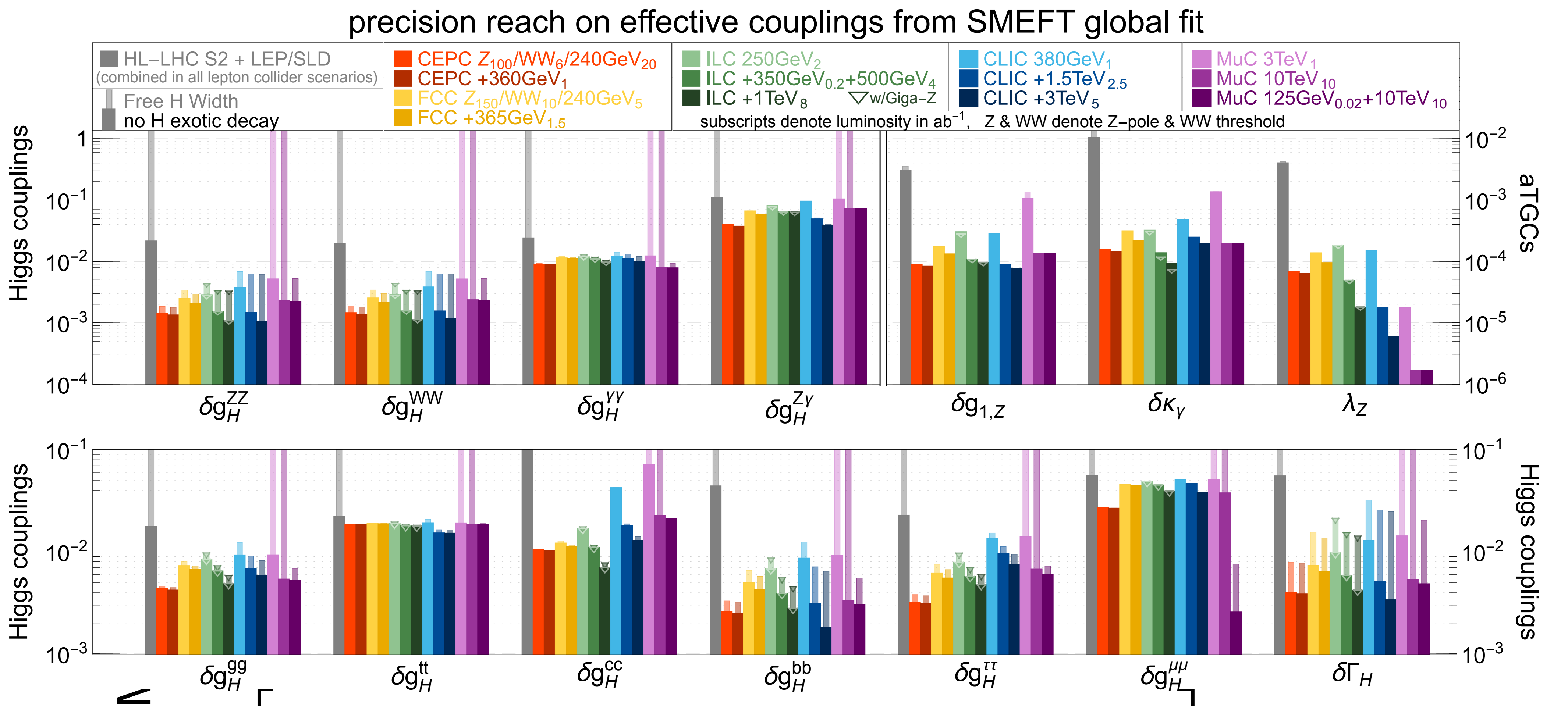
Conclusions

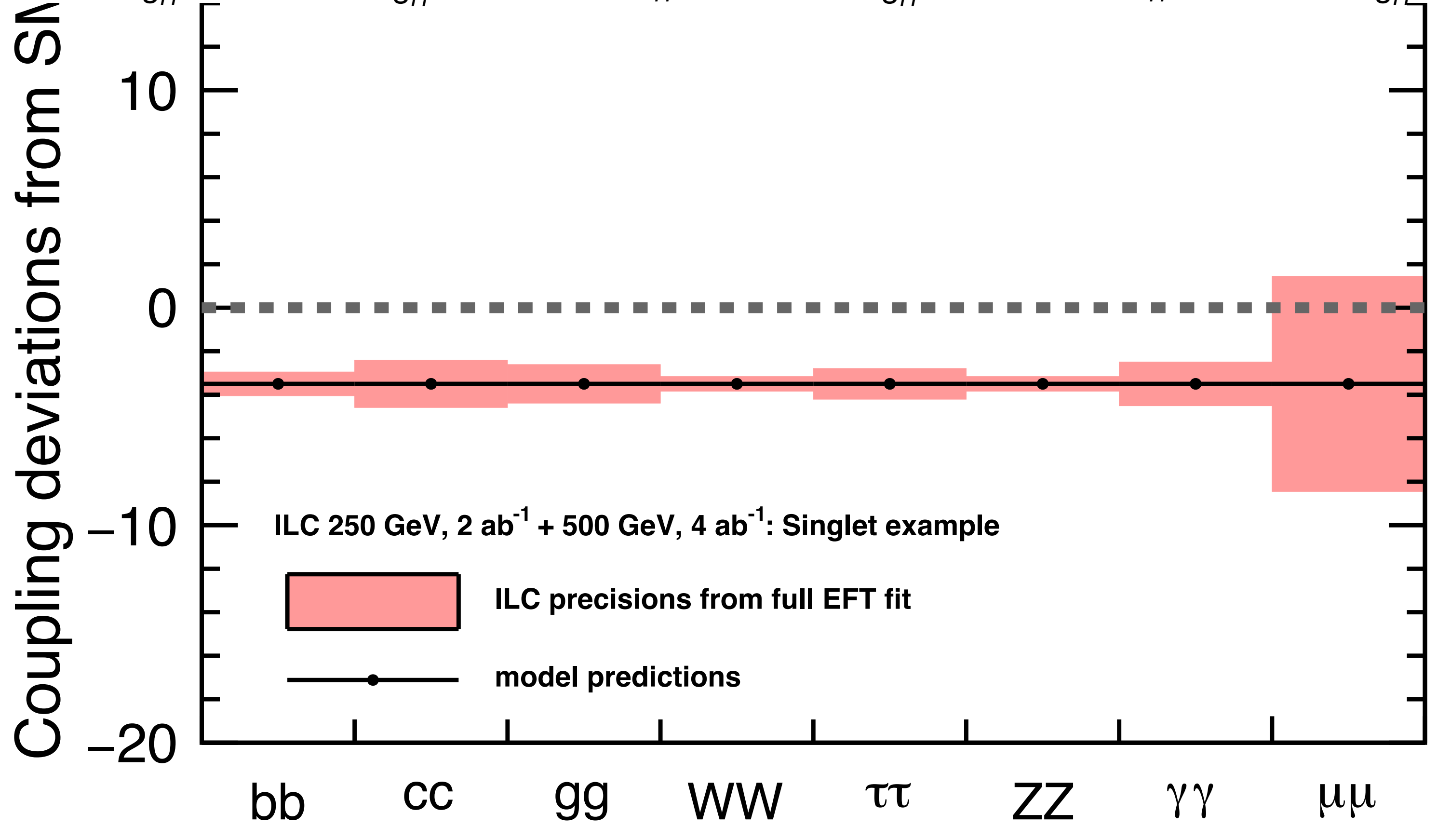
on experimental precisions & theory uncertainties

- experimental precision
  - approaching 0.1%-level in many cases
- intrinsic theory
  - ZH σ_{tot}: “only” a lot of work?
  - ννH as 2 -> 3: partial 2-loop enough?
  - differential, eg in M_{miss} ??
- non-Higgs, but essential for Higgs precision
  - ISR/FSR
  - beamstrahlung modeling
  - heavy quark fragmentation & hadronisation
  - low angle Bhabha for luminosity
- AND don’t forget:
  Implementation in Monte-Carlo event generators!









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and the SM is only the beginning
— need same level of precision in relevant BSM models!