The Physics context: theory and phenomenology

INFN Roma

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assessing a future accelerator facility project is by now a multi-dimensional task !

* feasibility → maturity → technical risk
* innovation
* construction/operation costs (vs constraints from funding agencies)
* power consumption /carbon footprint
* start-up time
* total operation time (staging, expandibility)
* location vs infrastructures vs politics (global context !)
* HEP community support (both regional and international)
* fraction of present HEP community involved

* plus (of course) the Physics Case (direct and indirect reach) on which we focus in this talk

CAVEAT !

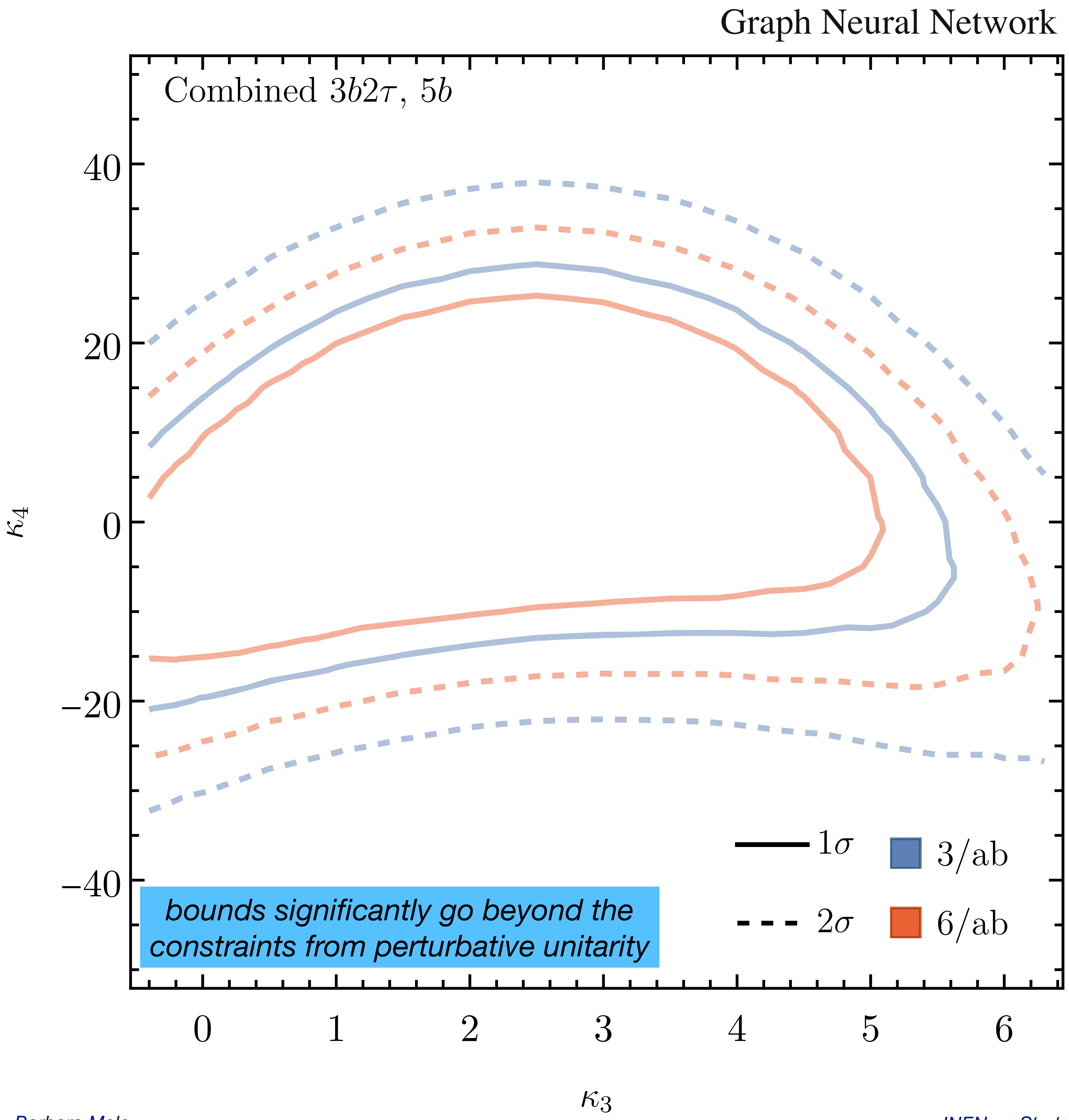
today we can give just a tentative picture of what could be the actual potential of a project that will be realized in ~ 20 years (or more)

LHC has largely proved that...
just compare the expectations of initial LHC exps TDRs with what has actually been reached... the impossible became possible...
even more to come for HL-LHC !

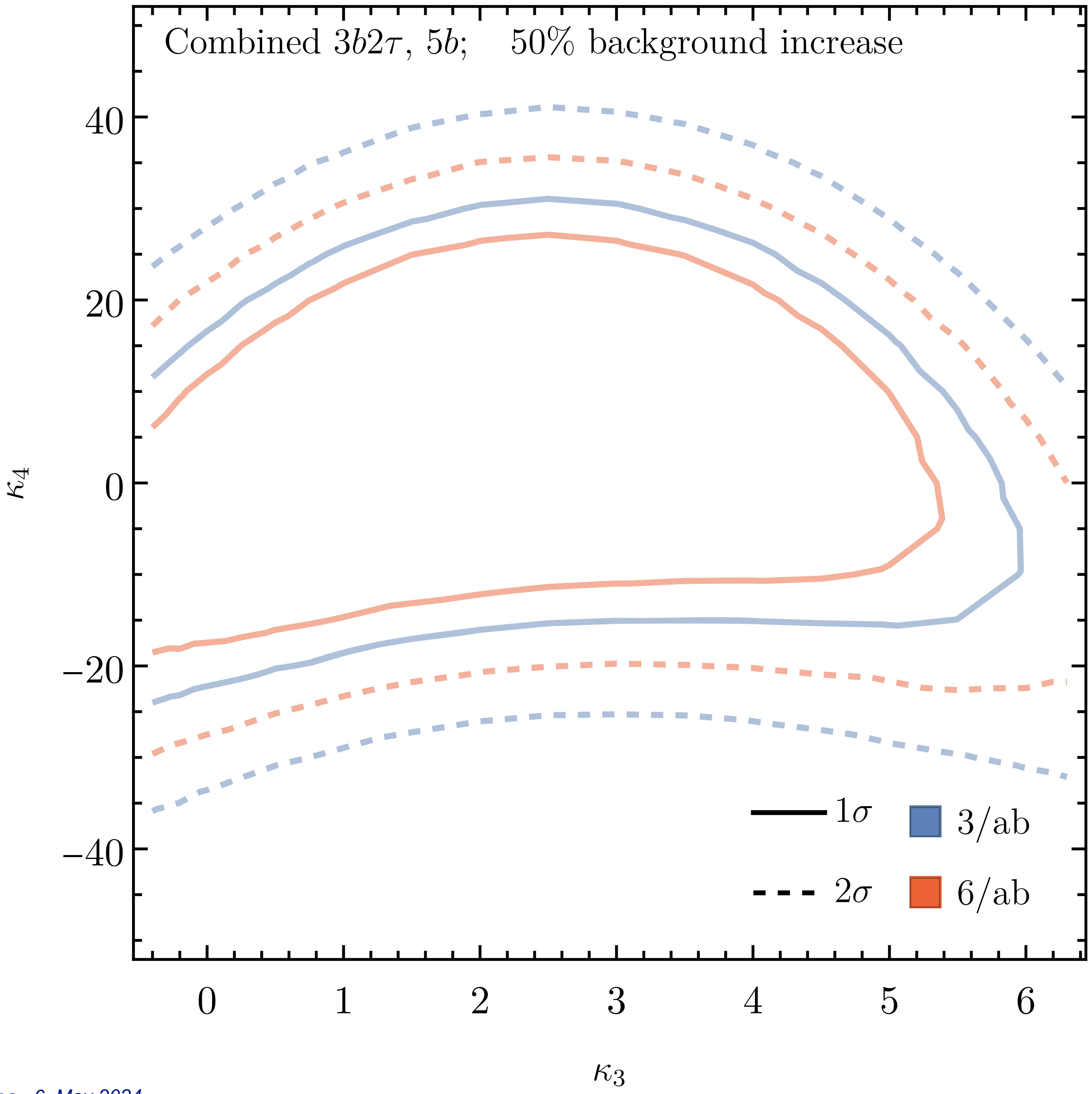
→→→ a recent example of previously unthinkable LHC potential →→→

bounding the quartic Higgs coupling via triple Higgs production at the HL-LHC

2312.04646 (see also 2312.13562)



bounds significantly go beyond the constraints from perturbative unitarity



Outline

- HEP Theory : present status
- Collider Experiments : main strategies
- a few great options for "beyond HL-LHC" Physics !
  - FCC-ee, FCC-hh, Muon Colliders
- extremely rich programme...
  just a few examples of physics potential...
- much more in D. Buttazzo' and R. Franceschini' talks tomorrow

our boundary condition → LHC [+ HL-LHC]

impressive amount of results !

testing present knowledge of fundamental interactions

in many many directions with unforeseen accuracy...

will expand enormously in the high-luminosity phase (~2029 - ~2041)

our present Physics vision...

WHERE DO WE STAND ?

[THEORY + EXP's]

SM works !

- * huge amount of LHC data fits SM predictions at amazing level of accuracy !
- * no real hint of BSM
- * bounds on new heavy states predicted by many BSM models widely extended
- * Simplest Versions of different BSM models look quite Fine-Tuned

nevertheless...

great (although quite foggy) expectations for new BSM phenomena at colliders !

* two kinds of issues with the SM :

  * existence of "external" phenomena :

    (quantum ?) Gravity

    + empirical evidences :
      - Dark Matter
      - Barion asymmetry
      - neutrino masses
      - . . .

  * "internal" poor consistency :

    mainly connected to the EWSB/Higgs sector

what's so challenging about the Higgs (TH)

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi^\dagger\phi) - \bar{\psi}_L\Gamma\psi_R\phi - \bar{\psi}_R\Gamma^\dagger\psi_L\phi^\dagger$$

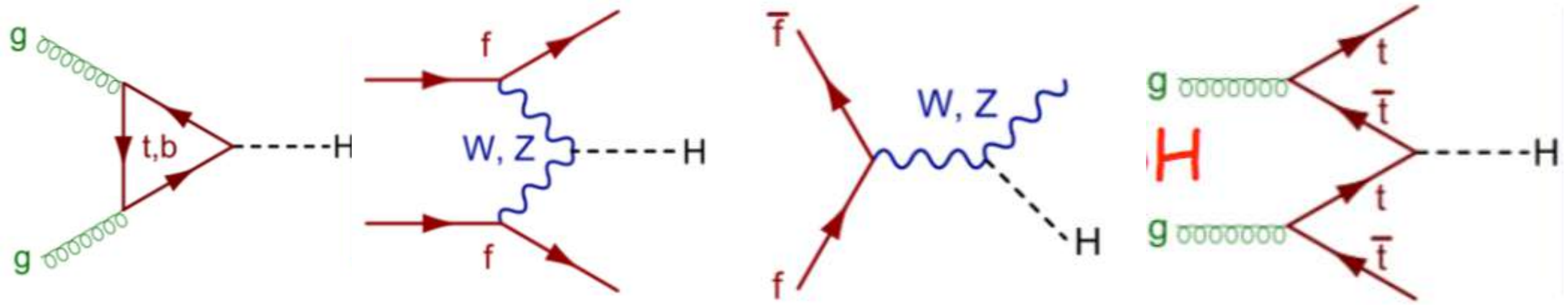
$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \frac{1}{2}\lambda(\phi^\dagger\phi)^2$$

$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

- the only "fundamental" scalar particle (microscopic interpretation ?)
- not protected by symmetries (the less constrained SM sector):
  - naturalness problem : $m_H \sim g \times \Lambda_{cutoff}$
- many different couplings all fixed by masses (?)
  - proliferation of parameters historically leads to breakdown in TH models
- fermion masses/Yukawa's hierarchy (?)
  - have neutrinos a special role ?!!!
- λ determines shape and evolution of Higgs potential → cosmology !

what's so challenging about the Higgs (EXP)

- very difficult experimental studies in general !!!
  - tiny x-sections in direct production from light states
    → must excite heavy states (t,W,Z) radiating Higgs
    → small cross sections → harsh separation from backgrounds



- the measured (and unpredicted) m_H value comes as a bonus, since it opens many explorable decay channels (with relatively unsuppressed production x-sections) how to proceed beyond HL-LHC ?

→→→ colliders are still by far the most powerful instrument we know to probe physics at smaller length scales...

presently four main strategies to advance in HEP at colliders

→ → →

four paths to advance in HEP at colliders:

- by exploring the characteristics of the Higgs sector and confirming/spoiling the SM picture (primary relevance since the Higgs sector is so critical !)
- by searching for new heavy states coupled to the SM, [acting as a cut-off for the SM, possibly solving the naturalness issues and/or non-SM phenomena (dark matter, …)] [searched for but not yet found at LHC in minimal version !]
- by looking for new "DARK" states (i.e., uncoupled to SM at tree level) either in production or/and heavy-state (H,top…) decays (elusive signatures, may be long-lived p.les)
- by exploring $\Lambda >> o(1\text{TeV})$ indirect effects through high-accuracy studies of SM x-sections/distributions and searches for rare processes (EFT parametrization)

four paths to advance in HEP at colliders:

* Higgs
* new particles
* "Dark" signals
* indirect effects

* at this stage, every single method is of fundamental importance to make progress !
* e+e- colliders can have great opportunities in all sectors (cleanness [→ model independence], accuracy…)
* quite general consensus on e^+e^- Higgs factory as next collider to build !

precision needed in Higgs measurements ?

BSM impact on Higgs couplings

- up to few percent for natural model
  not showing up by heavy states production at LHC

	$\Delta g(hVV)$	$\Delta g(ht\bar{t})$	$\Delta g(hb\bar{b})$
Composite Higgs	10%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	tens of %
Mixed-in Singlet	6%	6%	6%

- different patterns of deviations from SM for different NP models

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [38]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [39]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [39]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [39]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [40]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [41]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [42]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [43]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [44]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

arXiv:1710.07621

λ H³ coupling most exposed to BSM !

(impact on vacuum stability, Baryogenesis from cosmological EWPT ?)

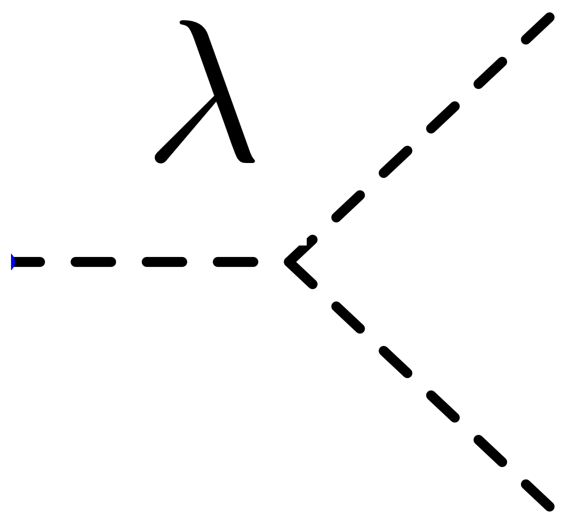
- in the SM :

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda' H^4$$

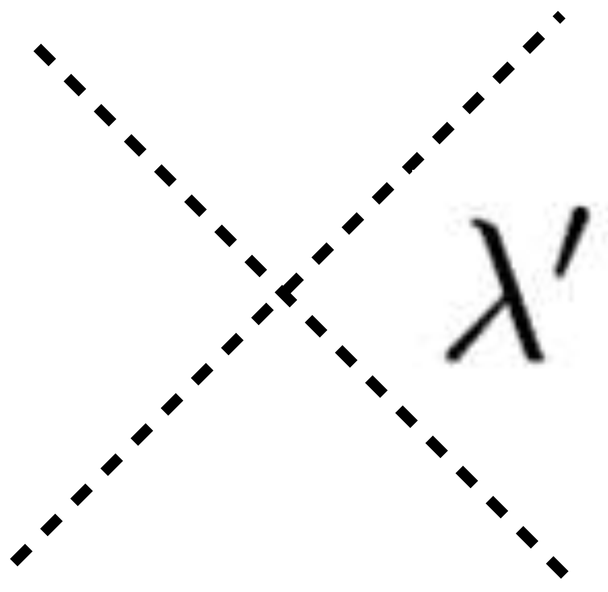
$$\lambda = \lambda' = M_H^2/(2v^2) = 0.13$$

→ m_H directly related to Higgs dynamics !

- direct exploration needs HH in final states (tiny x-sections)



or HHH



out of reach ??

- BSM : Max λ deviations compatible with no other BSM observation:

→ few % to ~20%

1305.6397

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^{a}$ $-15\,\%^{b}$
NMSSM	$-25\,\%$

- target for both TH and EXP accuracies !

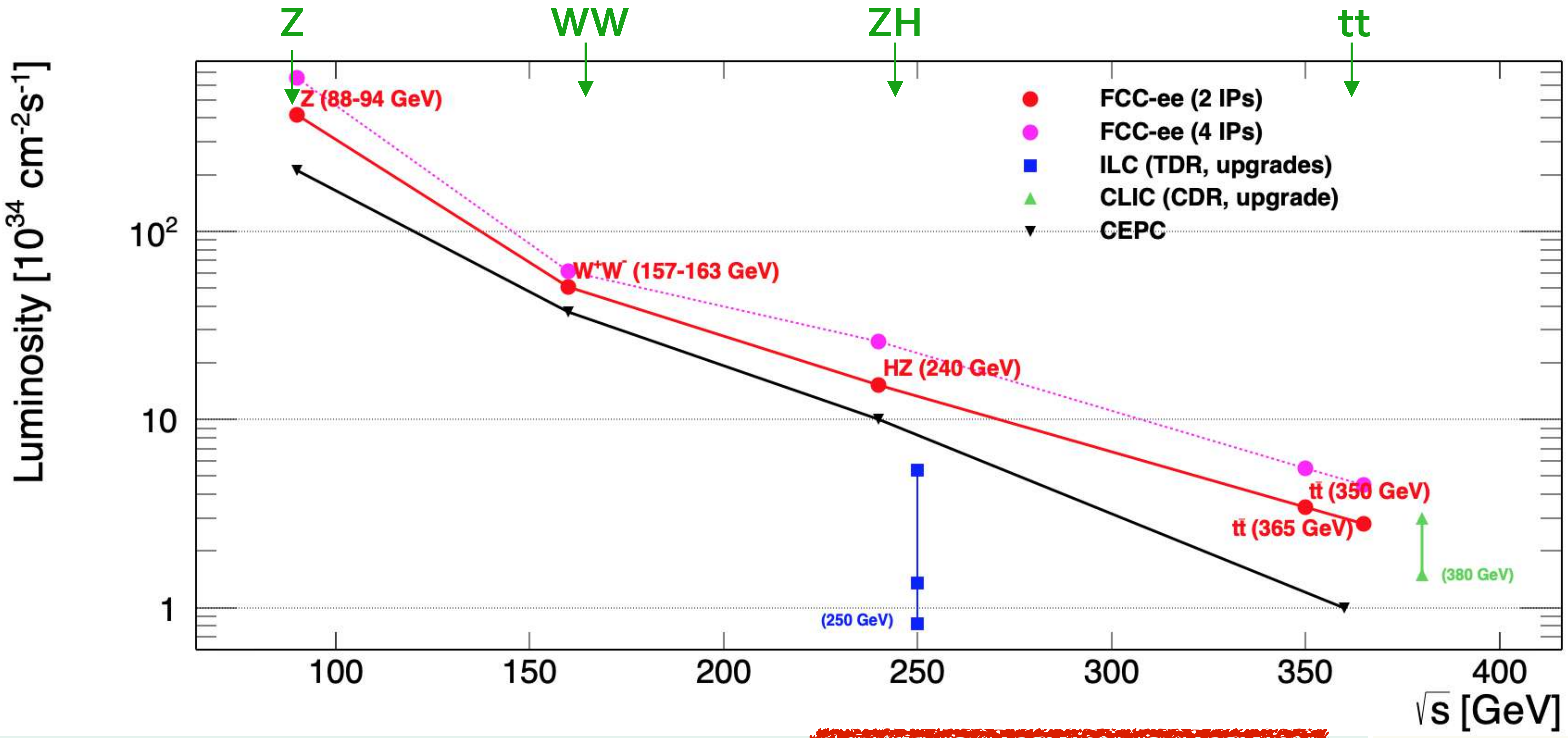
FCC research infrastructure for the 21st century

A new 91 km tunnel to host multiple colliders
100 – 300 m under ground, 8 surface sites
FCC-ee: electron-positron @ 91, 160, 240, 365 GeV
FCC-hh: proton-proton @ 100 TeV, and heavy-ions (Pb) @39 TeV
FCC-eh: electron-proton@ 3.5 TeV

going from hadron to lepton colliders : life gets much easier !

* as if fixing the parton cm Energy at hadron collider
* complexity of collisions collapses
* well defined kinematics
* dramatic background drop
* clean (simple) events
* pile-up →→ 0

FCC-ee: Lumi and event # at different stages



						$\sqrt{s}$ errors
ZH maximum	$\sqrt{s}$ ~ 240 GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$\bar{t}t$ threshold	$\sqrt{s}$ ~ 350 GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s}$ ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 100 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$	LEP x 10^3	< 300 keV
s-channel H	$\sqrt{s}$ = 125 GeV	? Years	~5000	$e^+e^- \to H$	Never done	< 200 keV

Event statistics (with 2 IPs, x1.7 for 4 IPs)

exact sequence and duration for stages to be elaborated !

in each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

two brand new collision setups at FCC-ee

* **Higgs factory** : $e^+e^- \rightarrow H\ Z$ ⟶ m_{Higgs}, Γ_{Higgs}
  Higgs couplings
  self-coupling

* **Top factory** : $e^+e^- \rightarrow t\ t_{bar}$ ⟶ m_{top}, Γ_{top}
  EW top couplings

[both circular and linear colliders]

plus two well know collision setups at hugely higher statistics !!

* "intensity frontier" : $e^+e^- \to Z, WW$ [→ super LEP]

* EW & QCD →

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

* direct searches of "light new physics" →

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

* Flavor Factory (10^{12} bb/cc; $1.7\times10^{11}\tau\tau$)

* B physics →

- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

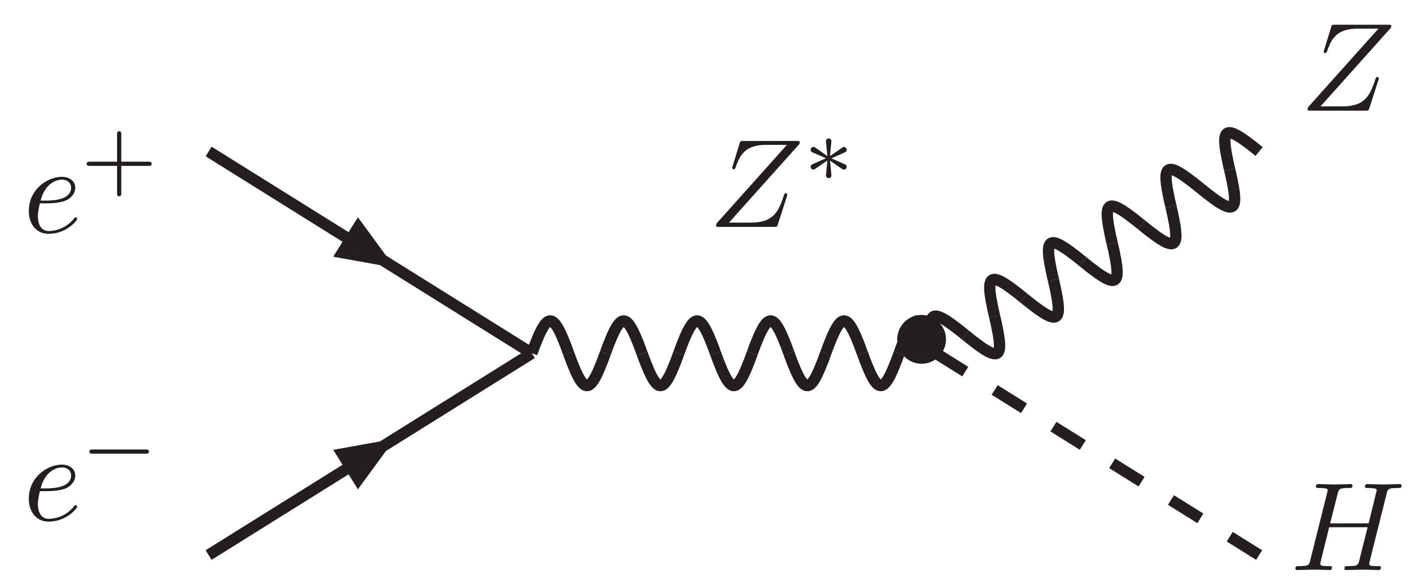
→ Belle II x 15

tau physics →

- τ-based EWPOs
- lept. univ. violation tests

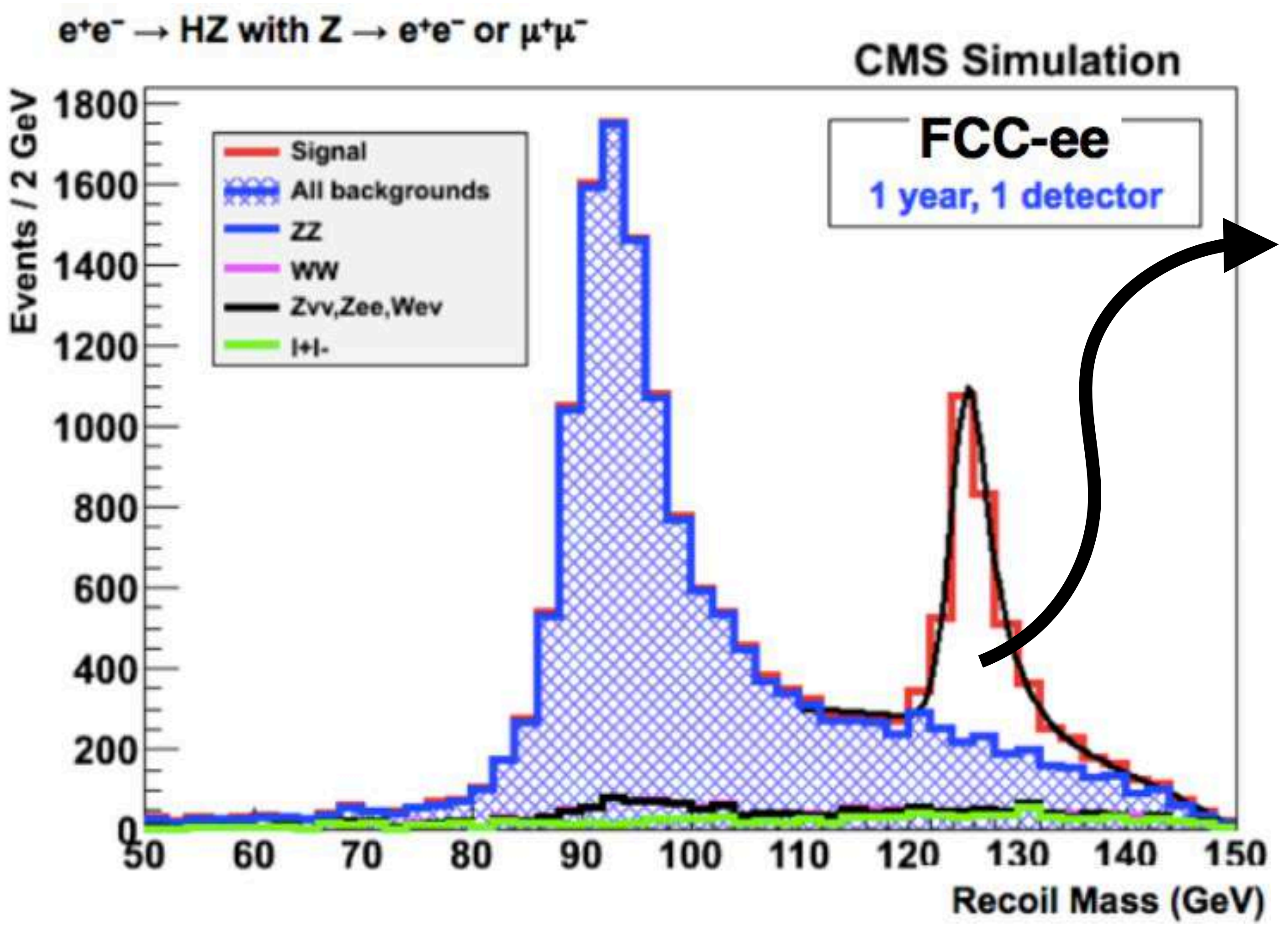
ee → HZ allows model-independent g_{HXX} measurem.s

- selected by just identifying Z decay products
  → absolute σ_{tot} ($\sim g_{HZZ}^2$) measurement → model independent g_{HZZ}



> by identifying Higgs final states X
> → absolute measurement of BR_X
> → g_{HXX}

- direct access to inv. H decays, H → cc, H → ss (?), H → gg



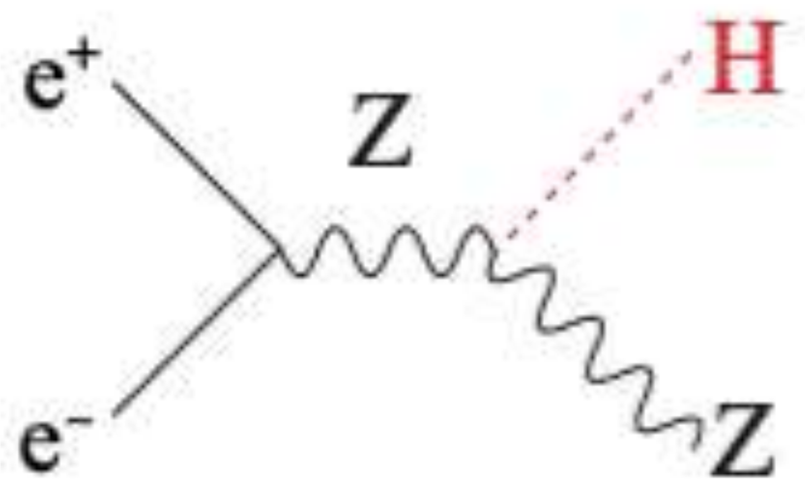
N(ZH) ∝ σ(ZH) ∝ g_{HZZ}^2

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.0 / 0.88

1905.03764 + 4 IP

- sub-% accuracy of couplings to W, Z, b, τ
- % accuracy of couplings to gluon and charm

don't need to reach HH threshold to have access to H^3 coupling



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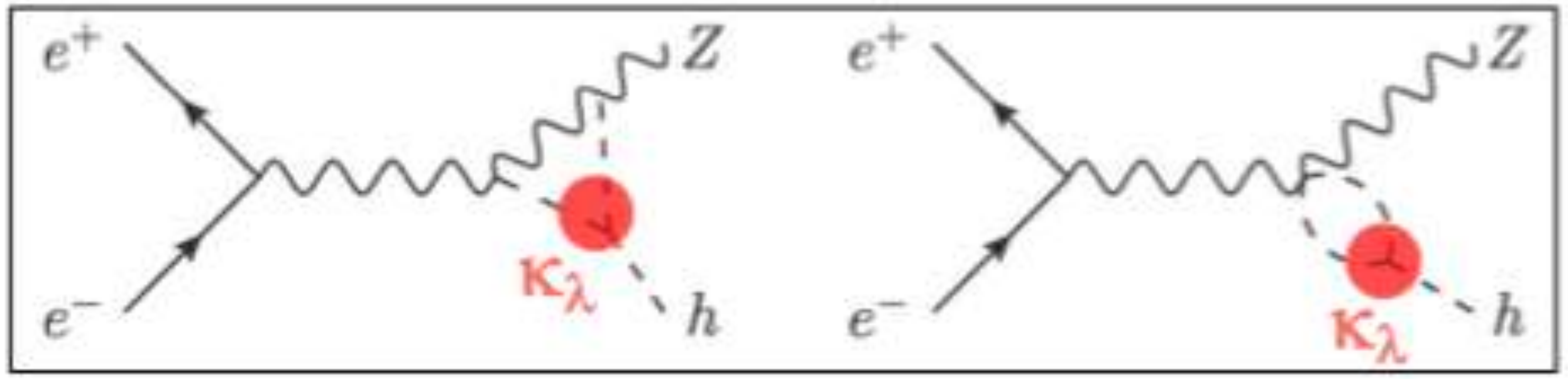
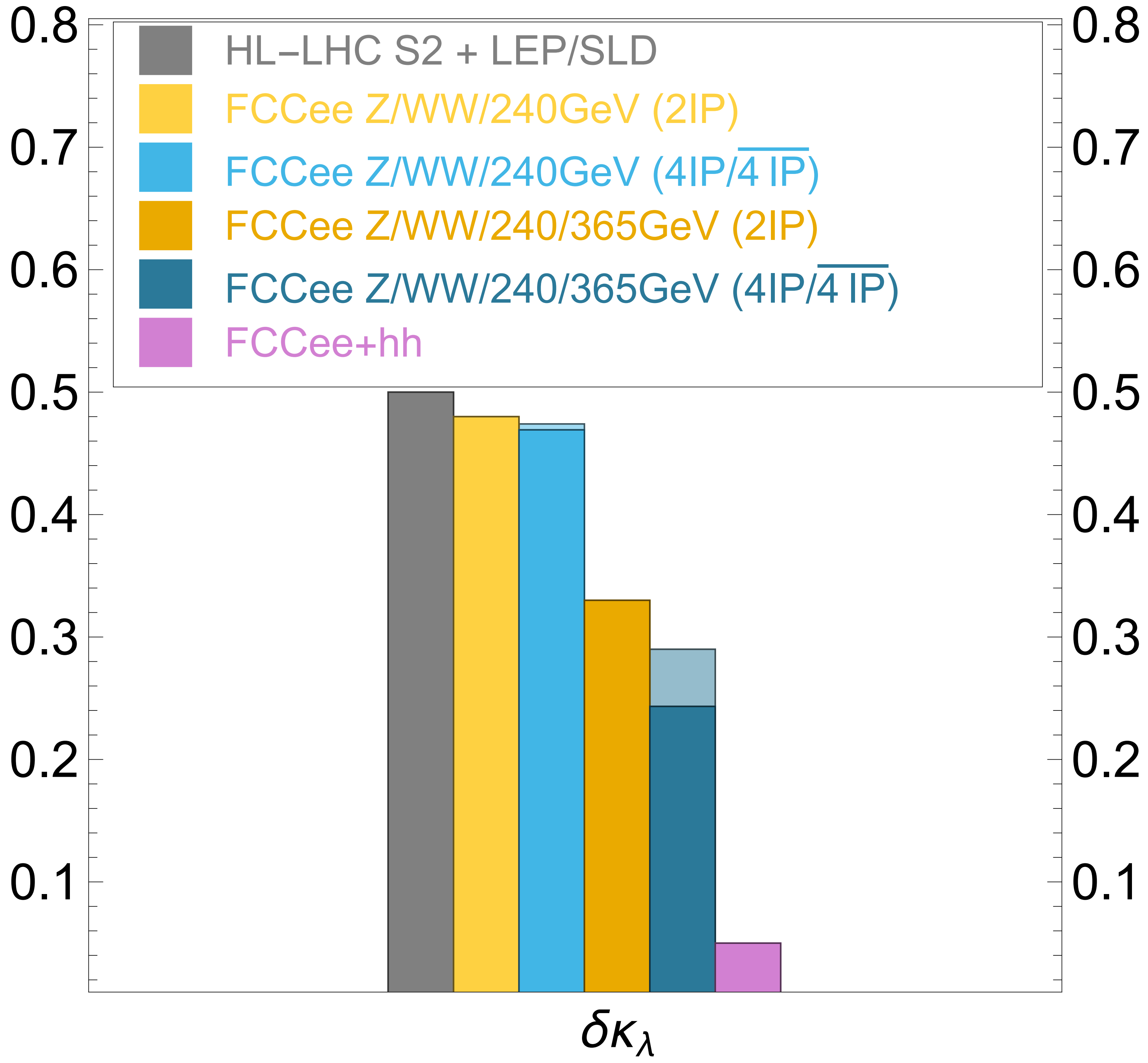
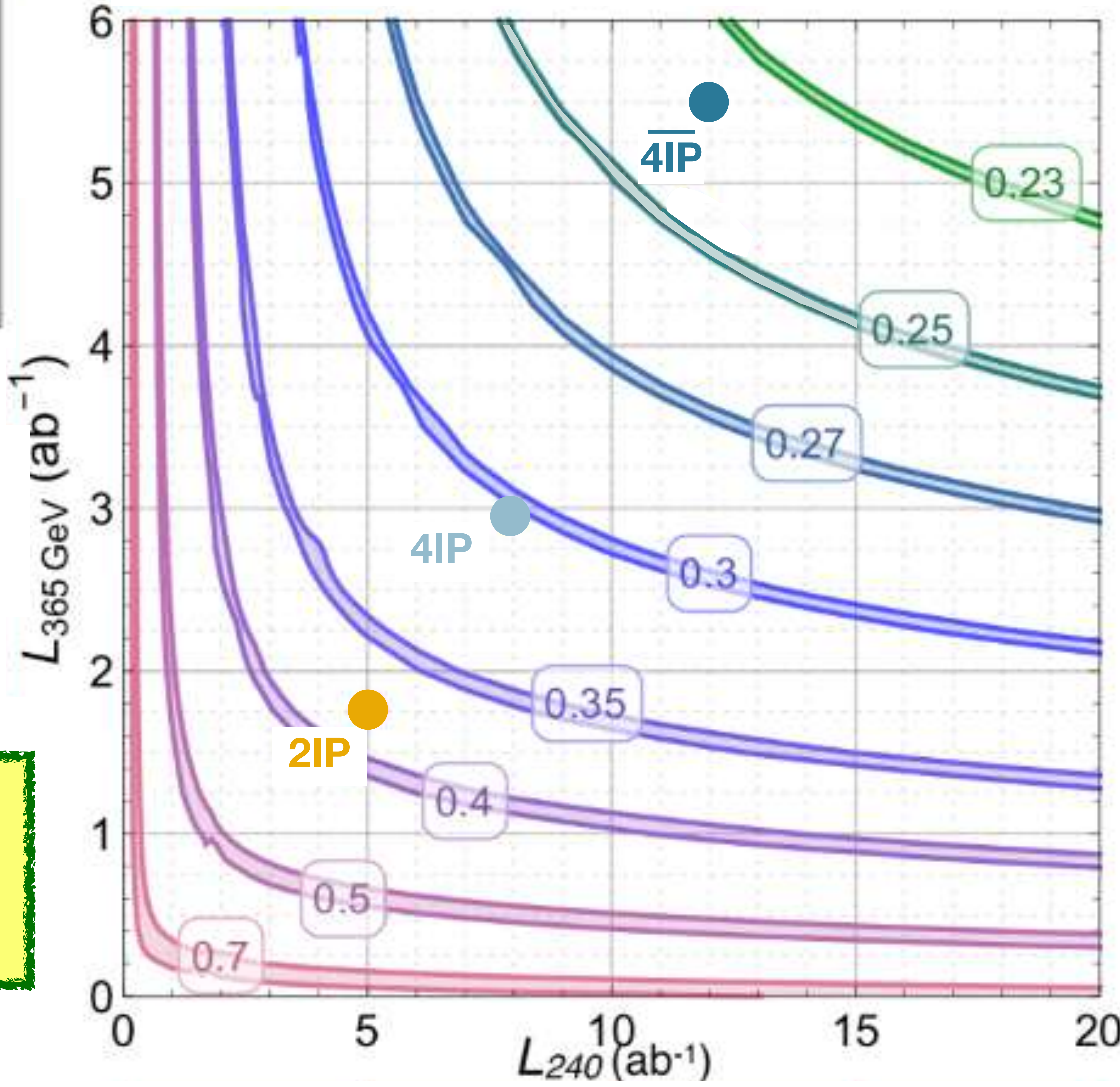




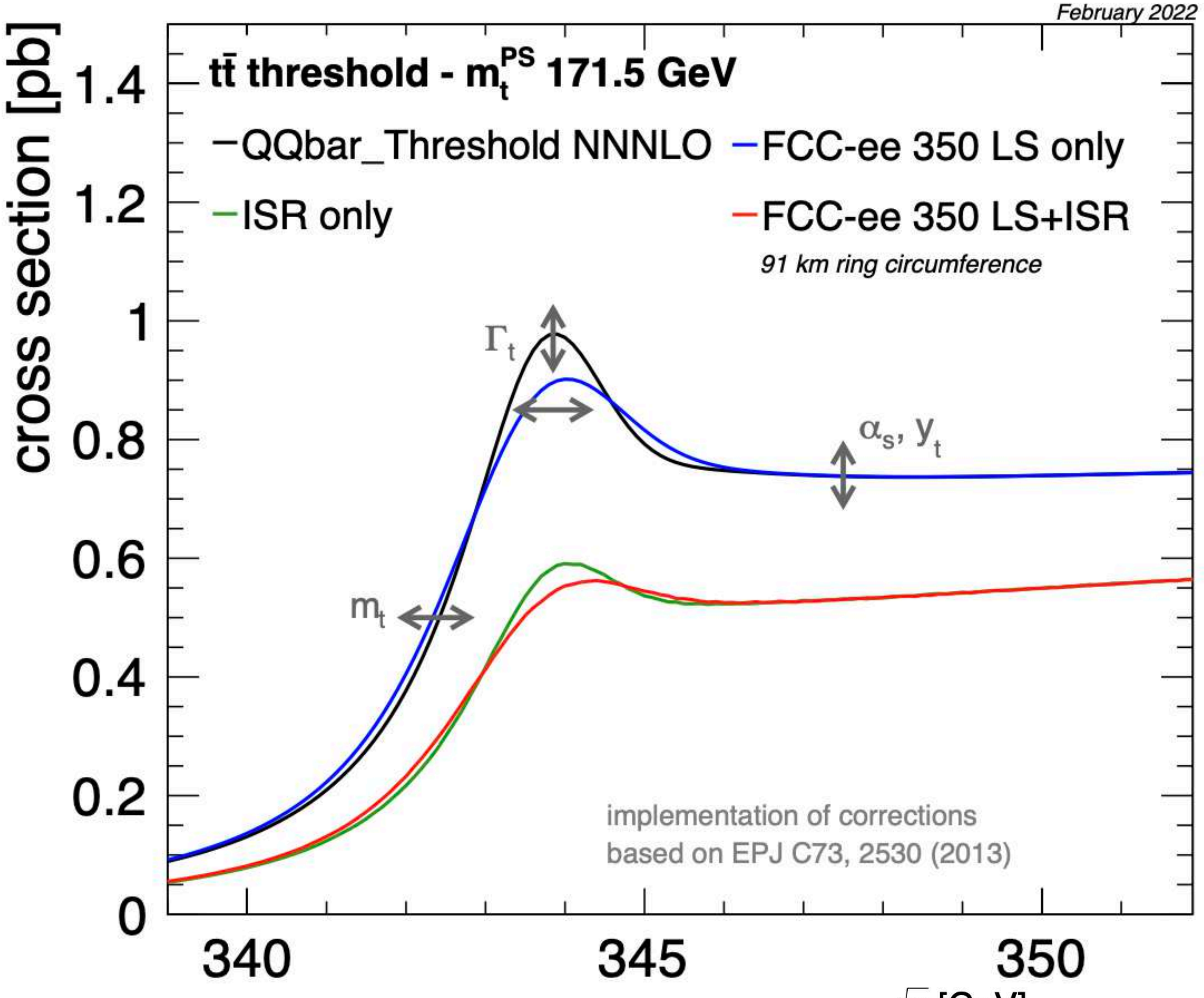
$\delta\kappa_\lambda$ precision vs Lumi at 240 and 365 runs ➔➔



including FCC-hh ➔ direct HH production ➔ $\delta\kappa_\lambda \sim$ few %

FCC-ee at ttbar threshold (a top Factory !)

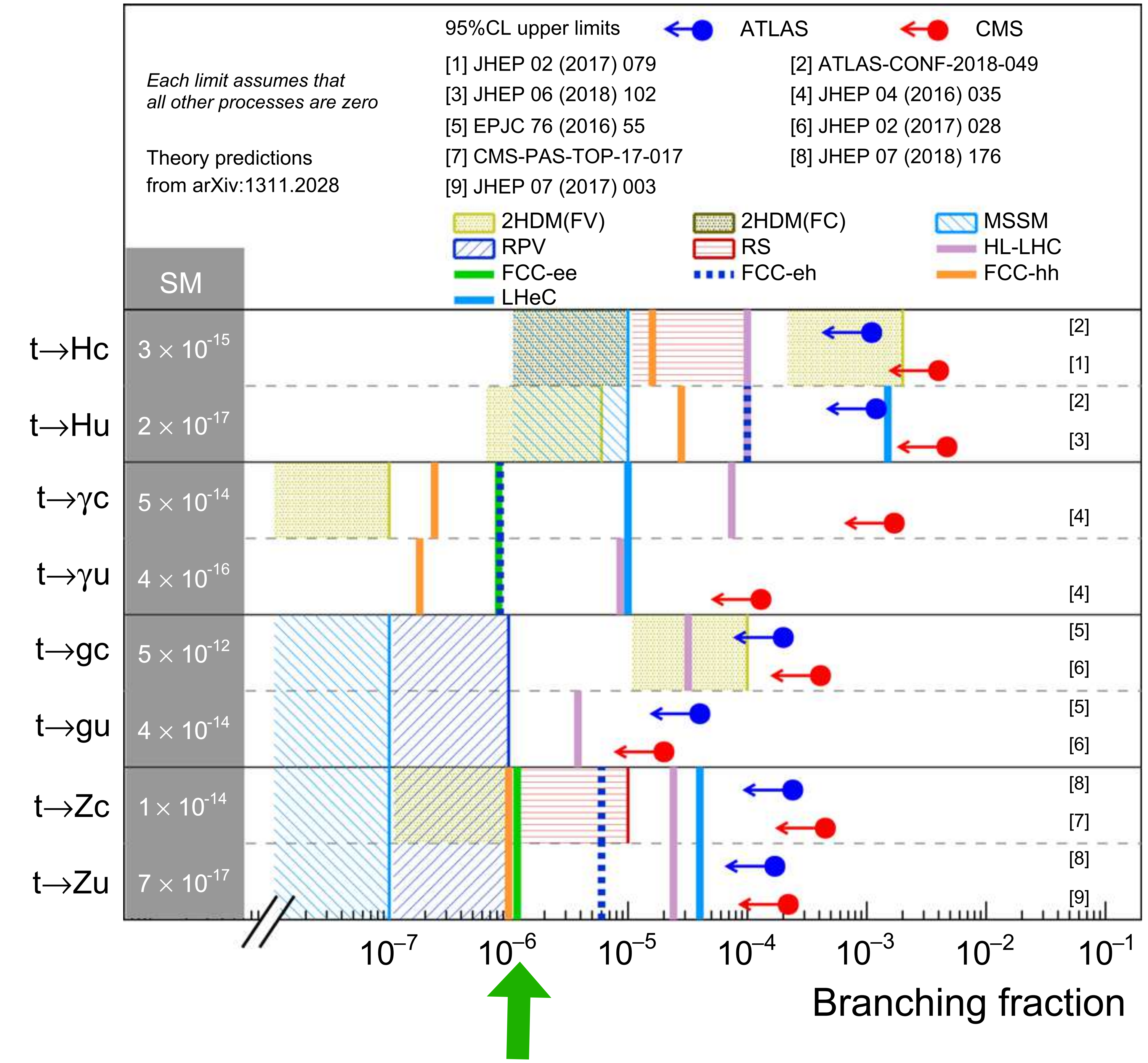
- up to per-mille accuracy on x-sections and asymmetries !
- access to top mass and width, and strong and Yukawa top couplings
- exps aims at $\delta m_t \sim 20$ MeV
- challenge for theory ‼



[Plot from F. Simon's talk @ CERN FC workshop 2022]

bounds on top FCNC from 10^6 ttbar

Future Circular Collider Conceptual Design Report Volume 1



EW param.s at FCC-ee → 6×10^{12} Z

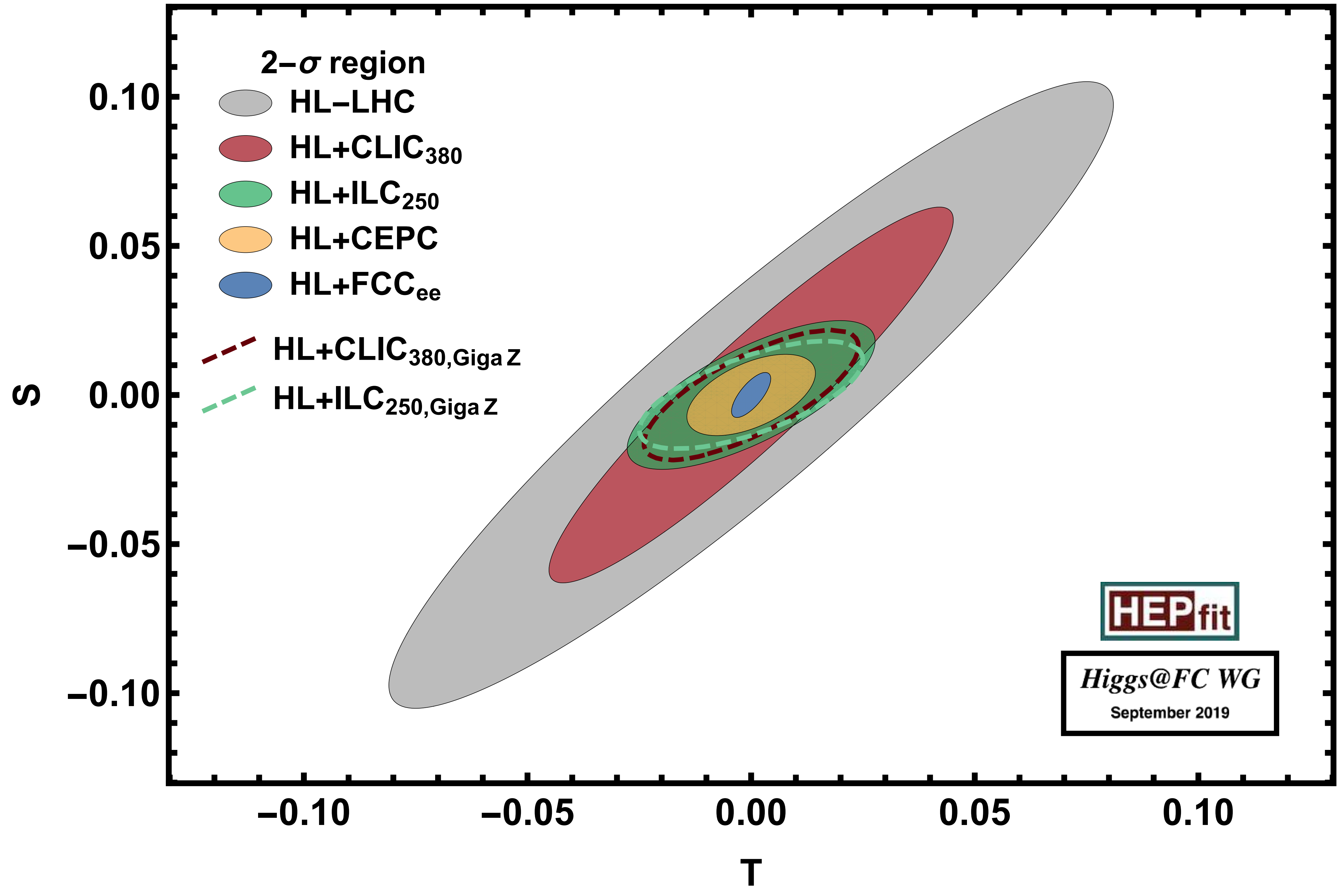
- stat precision up to 1000 times better than LEP
- (exp) syst precision "10÷50" times better
- total precision currently limited by TH syst (!!!)

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

[mid-term report]

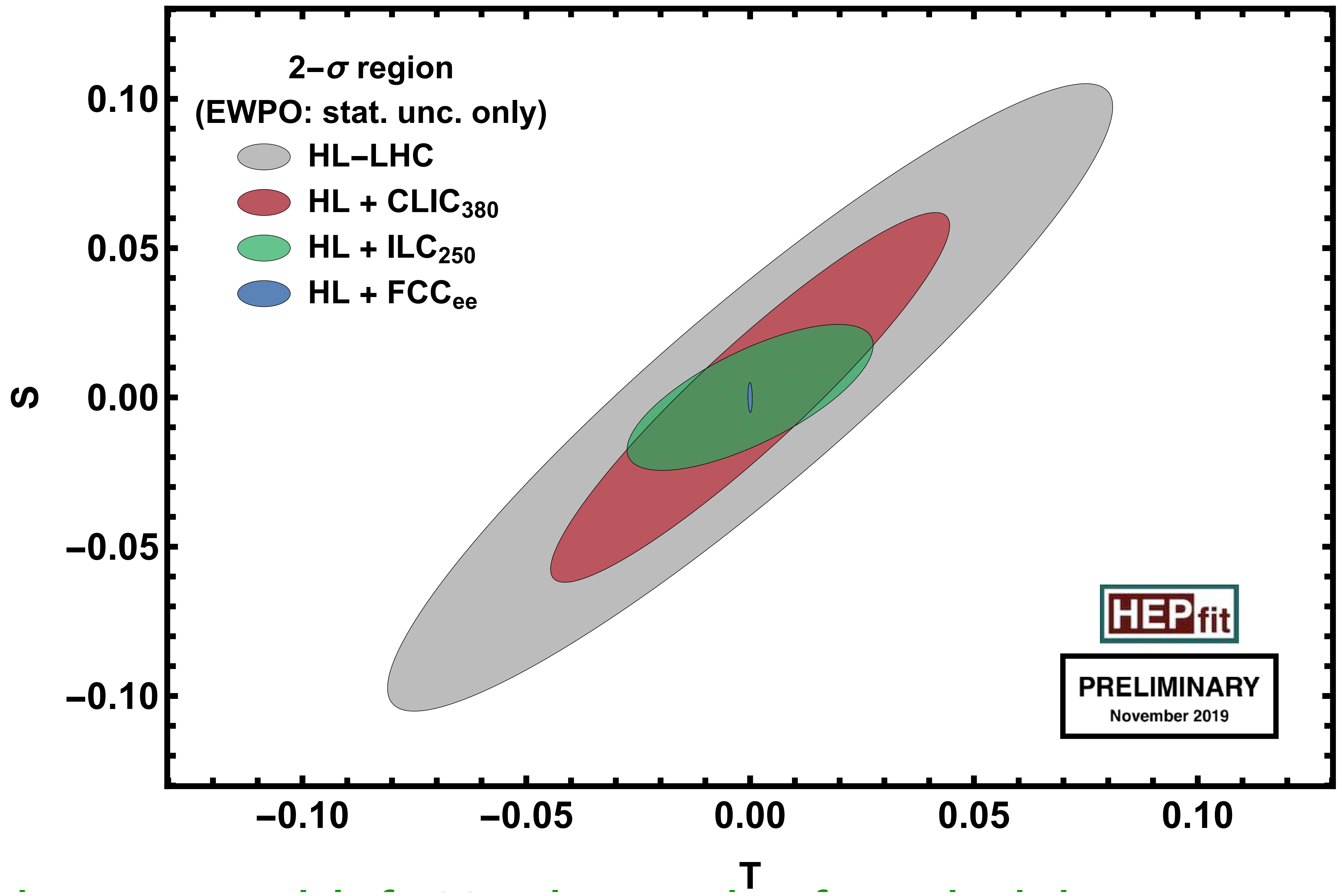
Global EW fits at FCC-ee

w/. stat.+ param. + th-exp syst.



w/ stat. and param. only

2106.13885

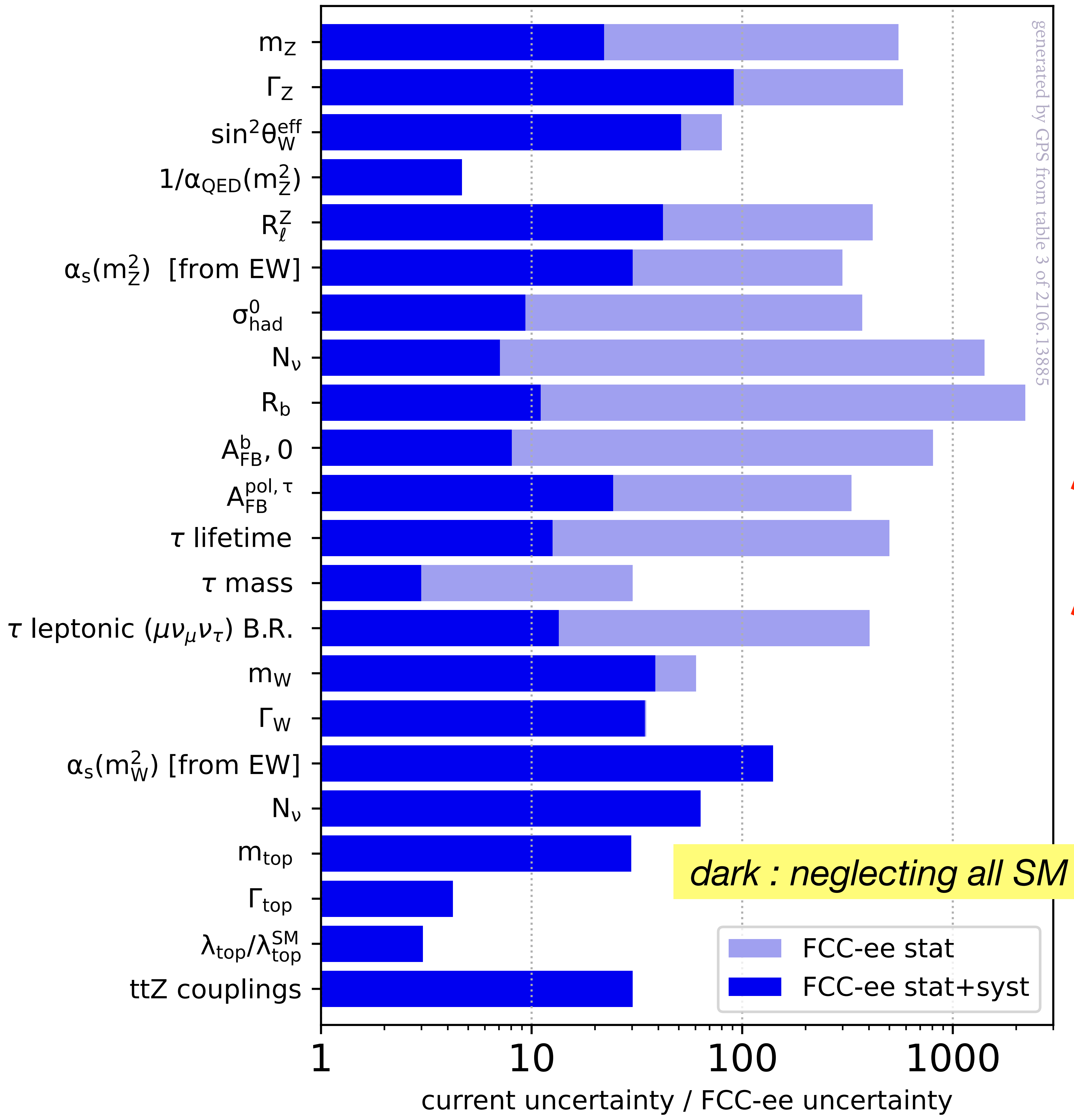


- ✱ oblique S,T,U parameters as an indirect probe of NP
- ✱ improve mass reach in indirect search for NP [$S \sim 10^{-2} \to M \sim 70$ TeV]
- ✱ in general, increase by X in accuracy gives increase by $\sqrt{X}$ in mass reach !!

Precision vs Energy reach

FCC precision gain

G. Salam

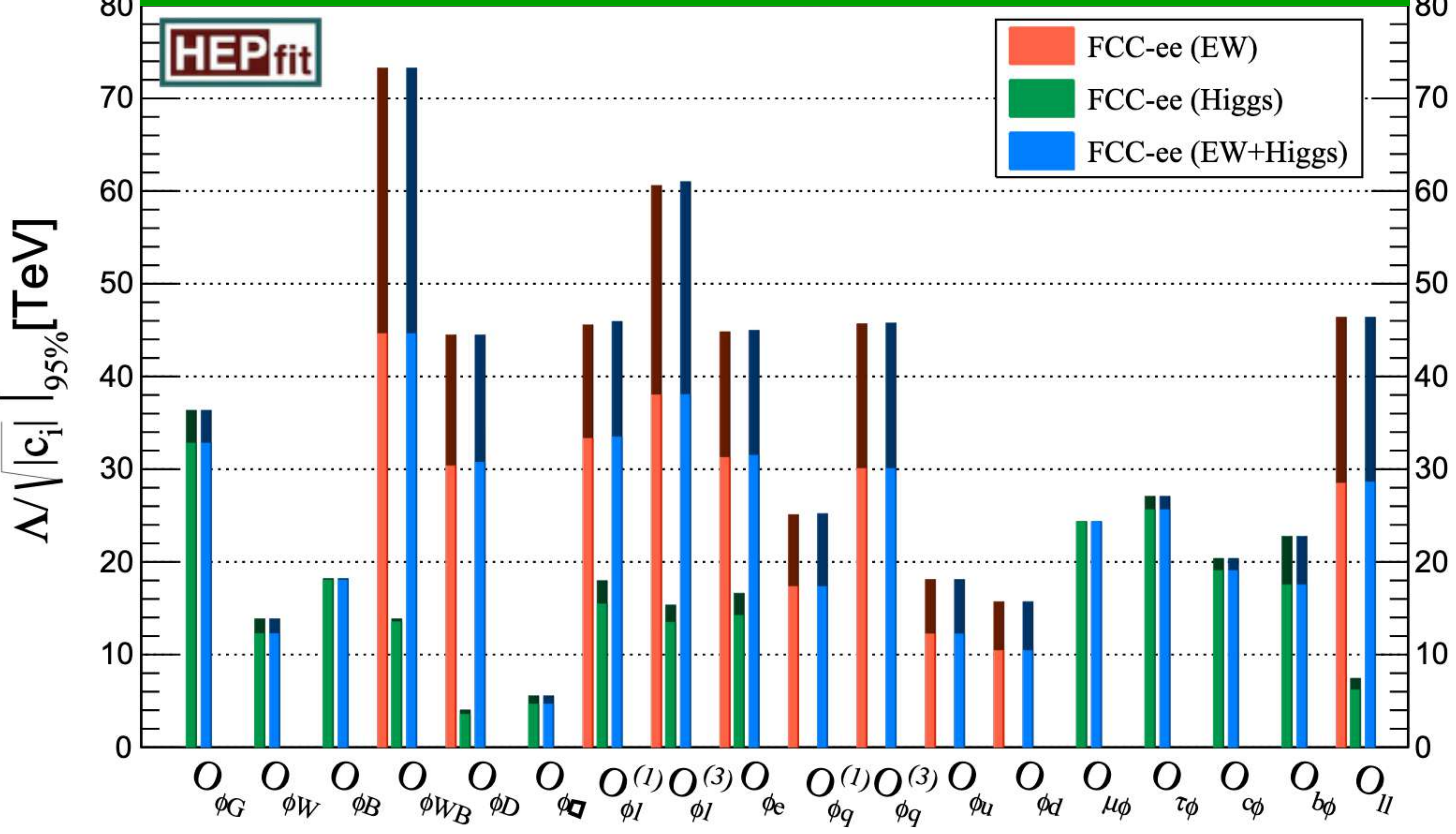


dark : neglecting all SM theory uncertainties

✱ **crucial to improve systematics !**

4÷5 increase in EFT energy reach at FCC-ee !

maximum scale probed indirectly — up to 70 TeV



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FCC-ee searches for BSM feebly coupled particles

can benefit from huge Z-pole luminosity !

* Heavy Neutral Leptons (HNL)
* Exotic Z decays
* Light SUSY scenarios and scenarios with light scalars
* Axion-like particles (ALP)
* Z', dark photons and other light-mediator scenarios
* Exotic Higgs boson decays

[models inspired by dark matter, baryon asymmetry, neutrino masses ...]

* also involving Long Lived Particles (LLP) !

Let's assume we find a deviation in H couplings…

deviaton from SM : $\delta_i \sim v^2/M^2$ (M scale of New Physics)

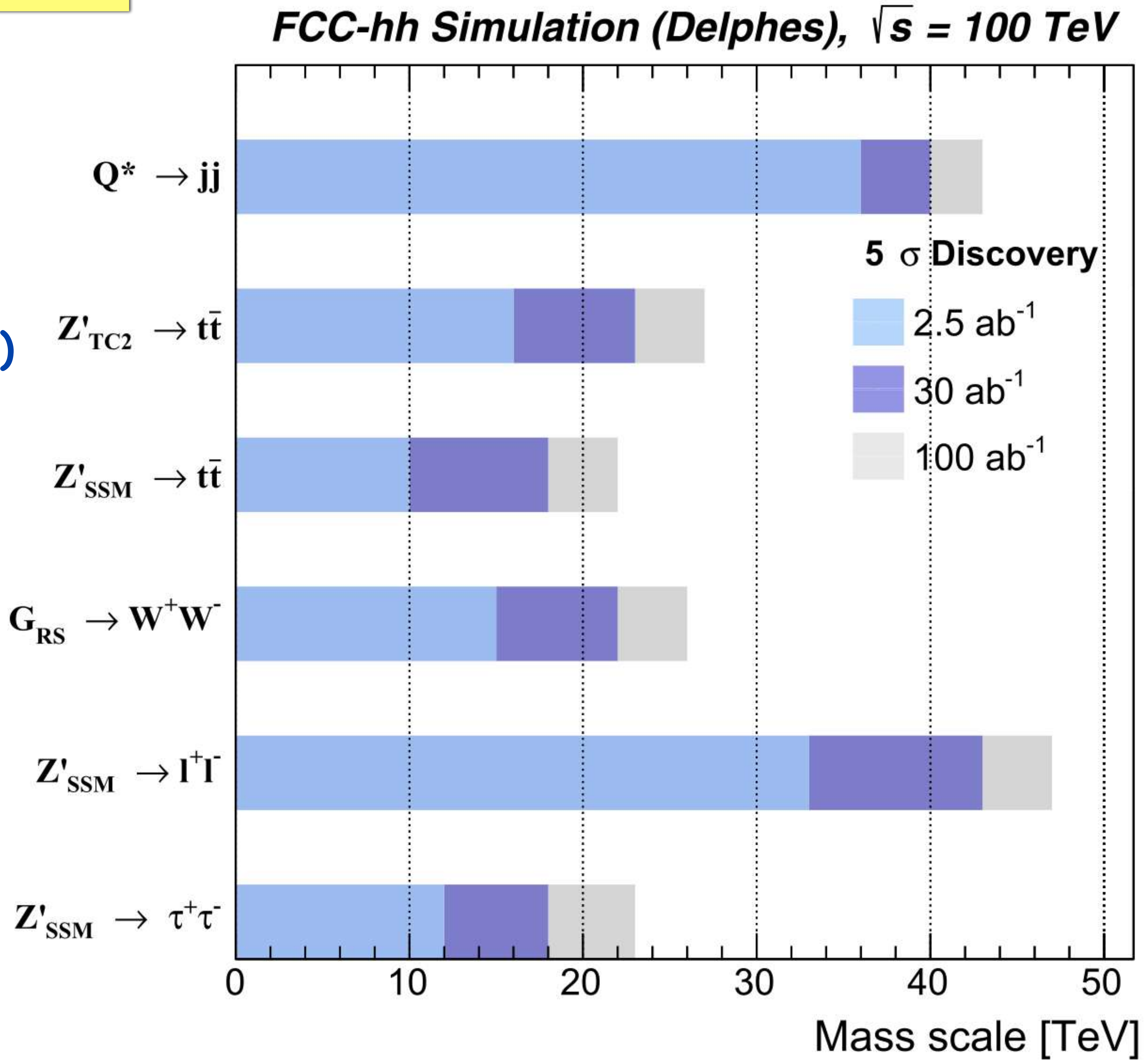
$\delta_i \sim$ [6-0.06] % ➜ M ~ [1-10] TeV

* in order to figure out what's going on we will need an energy-frontier facility to explore the corresponding M scale in a direct way
* R&D for future high-energy colliders needed (new technologies ?)
  FCC-hh [natural follow-on to FCC-ee]
  higher energy linear collider ? multi-TeV muon collider ?
  plasma acceleration ?

FCC-hh : 30 ab^{-1} at ~100 TeV

Resonance production

- mass reach in BSM searches ~ (4÷6) × $M_{[HL-LHC]}$
- for multiple-heavy-p.le final states n(H,W,Z,t) N_{100}/N_{14} >100 (e.g. ~500 for ttH, ~400 for HH)
- large Higgs rates (>10^{10}H, >10^{7} HH)
- unique sensitivity to rear decays
- explores extreme (clean) phase-space with high statistics
- much higher gain at high-P_T and large invariant masses !



M. Lamont, IMCC and MuCol Annual Mtg 2024, 12 March

lepton collisions are great ... what about a Multi-TeV muon collider ?

μ^+ → ← μ^-

$\sqrt{S_{\mu\mu}} \sim$ 3, 10, 14 ...TeV

$$\mathcal{L} = (E_{\rm CM}/10\ {\rm TeV})^2 \times 10\,{\rm ab}^{-1}$$

point x-section
(~ rate for new p.le pair production)

$$\sigma_{EW} \sim \sigma(\mu^+\mu^- \to \gamma^* \to e^+e^-) \sim \frac{4\pi\alpha^2}{3\,S}$$

$$\to 1\,fb\,(\frac{10\,TeV}{\sqrt{S}})^2$$

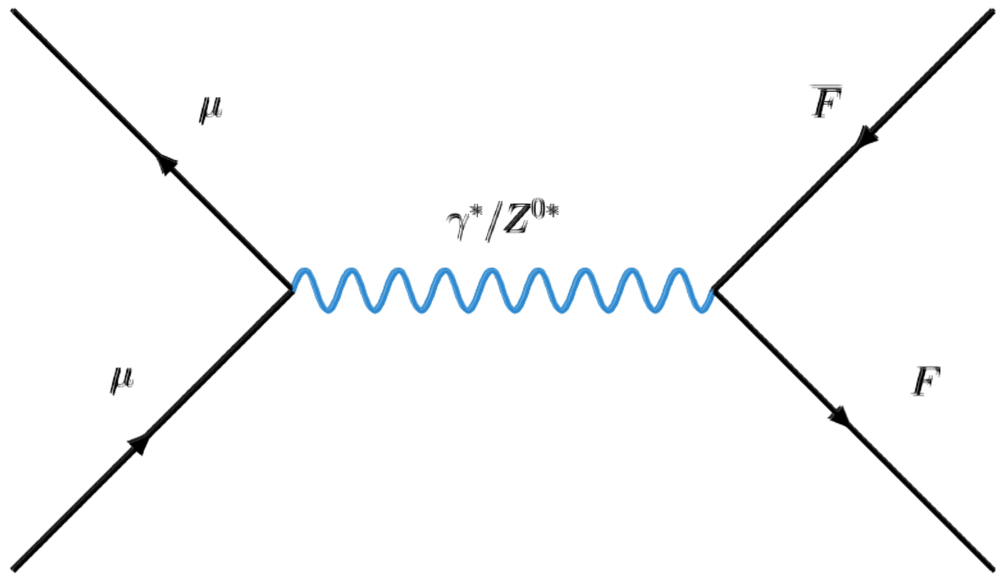
$\sigma_{EW} \times \int L \sim 10^4$ evts

→ $\delta_{stat} \sim 1\%$

allows precision on whatever is discovered !

* direct pair production of new heavy states...

$$\mu^+\mu^- \to F\bar{F}$$



$m_F \lesssim \sqrt{S_{\mu\mu}}/2$

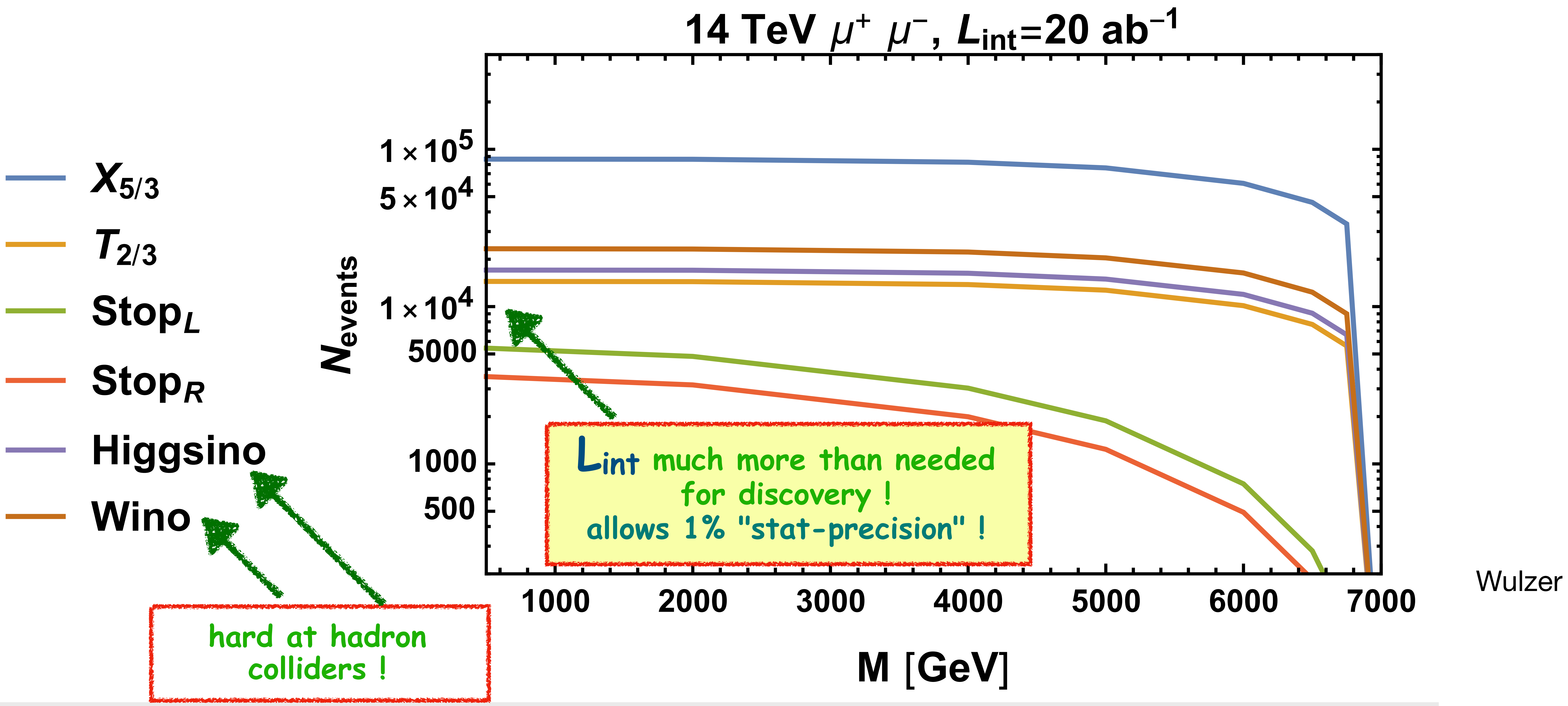
~1.5,5,7 TeV !!!

* as at LEP, it would cover searches up to almost the kinematic limit !
* huge discovery potential for $\sqrt{S_{\mu\mu}} \sim$ 10+TeV !

warning:
new kind of machine bckgr from muon beam decays...!!

Direct pair production $\mu\mu \to XX$

$\sigma_{\mu\mu\to XX}$ ~ uniform up to threshold ⟶ $m_F \sim \sqrt{S_{\mu\mu}}/2$!

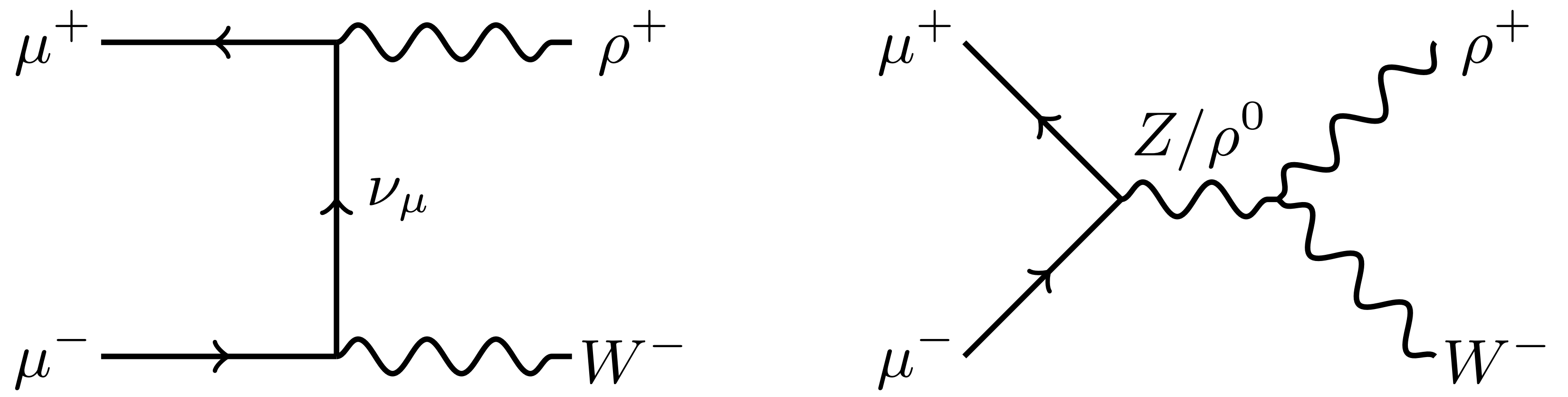


$\int L$ /100 would be enough for discovering pairs of new EW multi-TeV particles !

a vast physics case for multi-TeV muon colliders

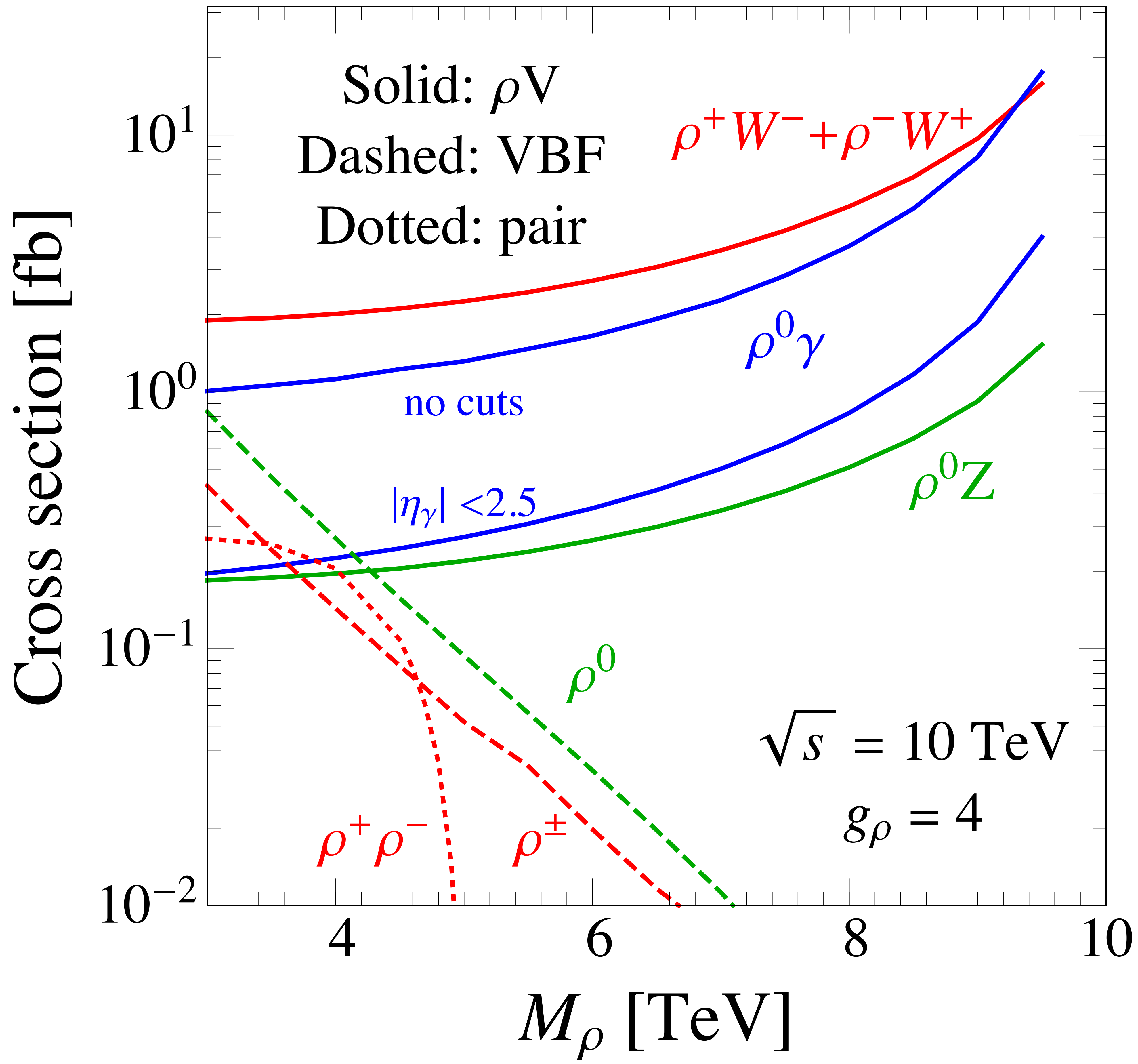
* heavy-pair production
* heavy-resonance production [$X^{0/+/-}$]
* a "WW collider" ⟶ $\mu\mu \to W^*W^*\nu\nu$
* precision reach (Higgs and beyond)
* . . .

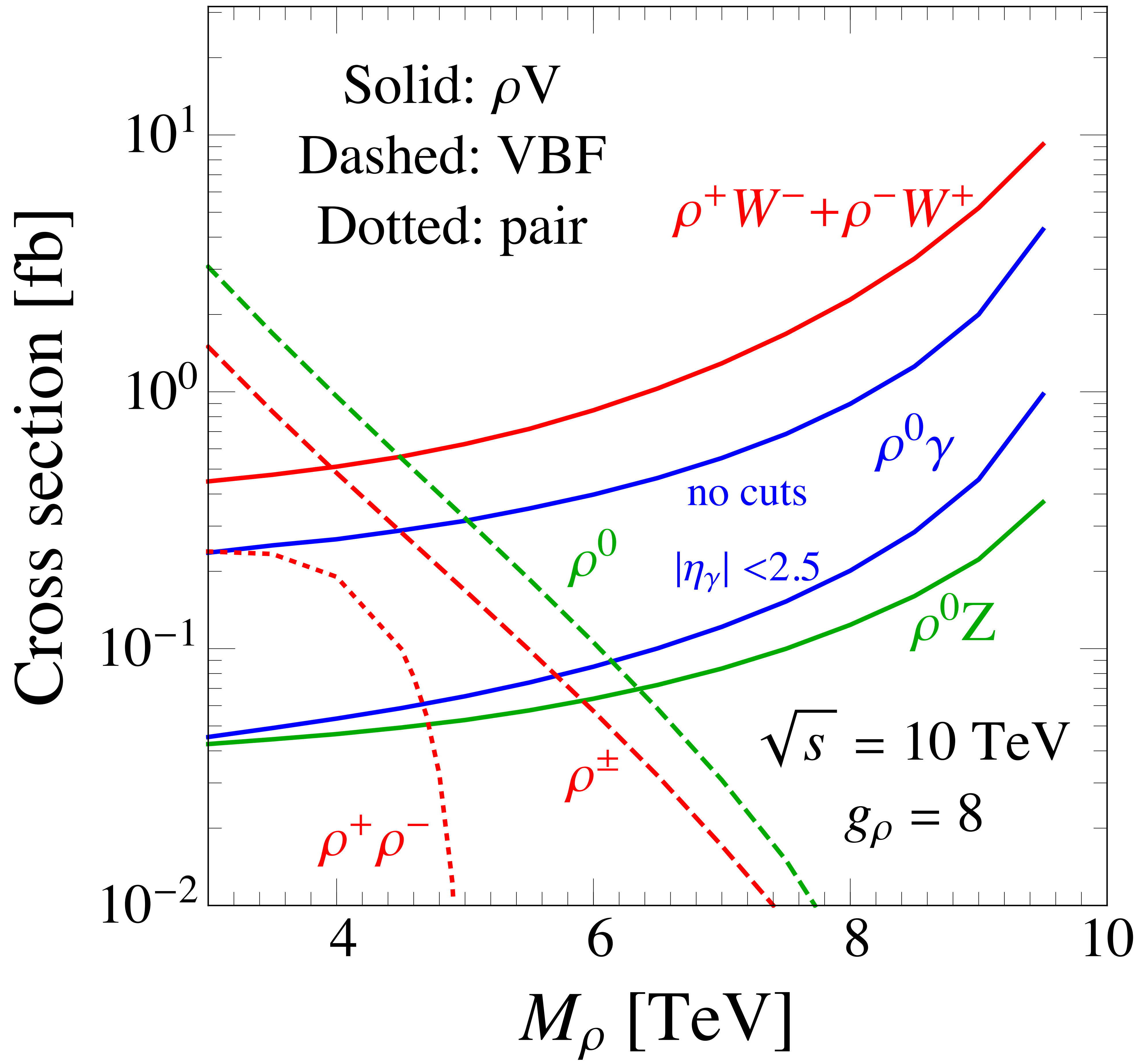
charged resonance real production via W radiation



composite Higgs Model

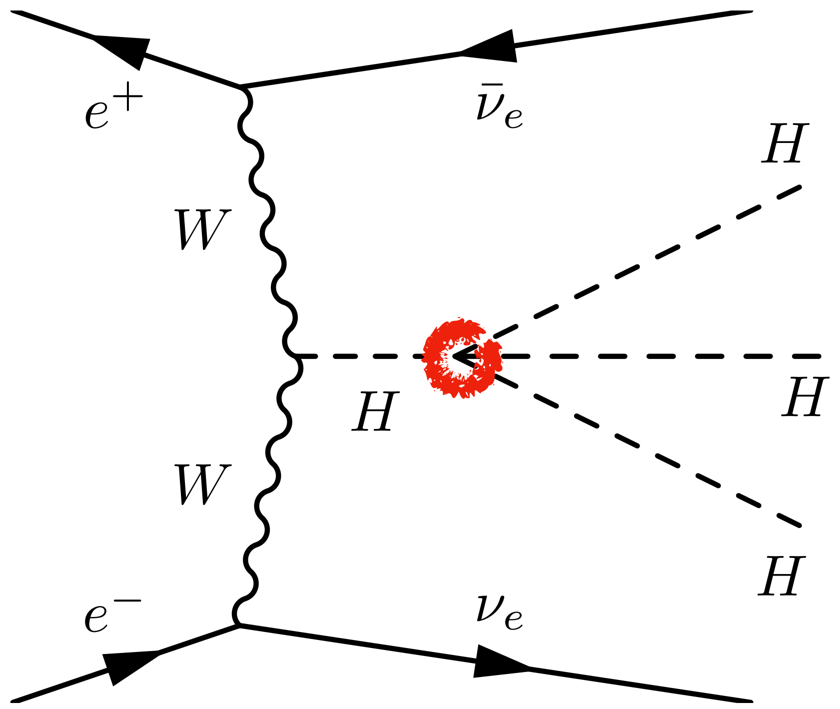
2312.09117, see also 2304.12362

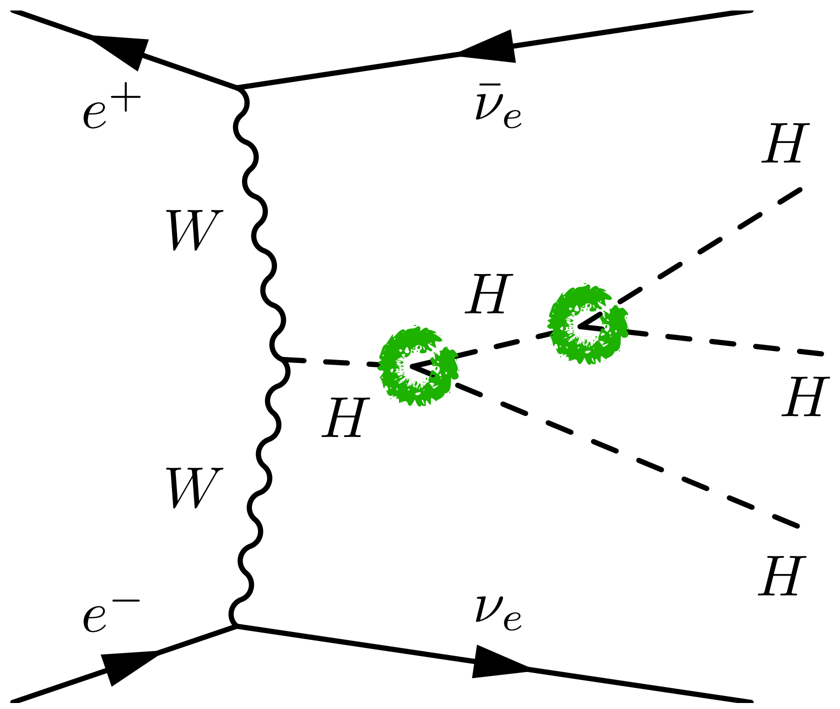




a multi-TeV MC could make a robust measurement of λ'H⁴ !!

$$V_{\rm h} = \frac{m_h^2}{2} h^2 + (1 + \boxed{\kappa_3}) \lambda_{hhh}^{\rm SM} v h^3 + \frac{1}{4} (1 + \boxed{\kappa_4}) \lambda_{hhhh}^{\rm SM} h^4$$





$$\mu^+ \mu^- \to HHH\nu\bar{\nu}, \ (\nu = \nu_e, \nu_\mu, \nu_\tau)$$

(2003.13628)

(κ_i ➔ δ_i)

$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	Constraints on δ_4 (with $\delta_3 = 0$) x-sec only 1 σ	x-sec only 2 σ	threshold + $M_{HHH} > 1$ TeV 1 σ
6	12	$[-0.60, 0.75]$	$[-0.90, 1.00]$	$[-0.55, 0.85]$
10	20	$[-0.50, 0.55]$	$[-0.70, 0.80]$	$[-0.45, 0.70]$
14	33	$[-0.45, 0.50]$	$[-0.60, 0.65]$	$[-0.35, 0.55]$
30	100	$[-0.30, 0.35]$	$[-0.45, 0.45]$	$[-0.20, 0.40]$
3	100	$[-0.35, 0.60]$	$[-0.50, 0.80]$	$[-0.45, 0.65]$

bckgr can be tamed by b-tagging (soft?) / Higgs reconstruction / Z,W vetoes !

Table 5: Summary of the constraints on the quartic deviations δ_4, assuming $\delta_3 = 0$, for various muon collider energy/luminosity options, as obtained from the total expected cross sections (1σ and 2σ CL). The third column shows the bounds obtained from the combination of the constraints corresponding to the setups $M_{HHH} < 1$ TeV and $M_{HHH} > 1$ TeV.

Outlook

- an e^+e^- circular collider running at ZH, $t\bar{t}$, WW, Z, (H) with L ~ $10^{(34-36)}$ $cm^{-2}s^{-1}$ can go well beyond the (HL-) LHC reach in many many different physics sectors...

- it is "not just" a wonderful Higgs precision probe !

- EWPT : order of magnitudes improvements wrt LEP
  (badly needed : advances in theory accuracies !)

- ideal setup for discovering (very) weakly interacting particles

- whatever deviation from SM predictions will be observed will require an Energy Frontier machine to be clarified !

- presently a few great options...no one technogically mature yet...

- much more on Physics potential tomorrow by Dario and Roberto