LISHEP 2023
International School on High Energy Physics

Physics at the high-energy frontier:
the LHC and beyond

LISHEP 2023, Rio de Janeiro, Brazil

6 March 2023

Michelangelo L. Mangano
Theory Department,
CERN, Geneva

Probes of high energy

astrophysical (eg cosmic rays, GWs, …)

colliders

high energy

indirect lab (proton decay, neutrino mass, gauge coupling unification…)

The next steps in HEP build on

- having important questions to pursue
- creating opportunities to answer them
- … while being able to constantly add to our knowledge, while seeking those answers

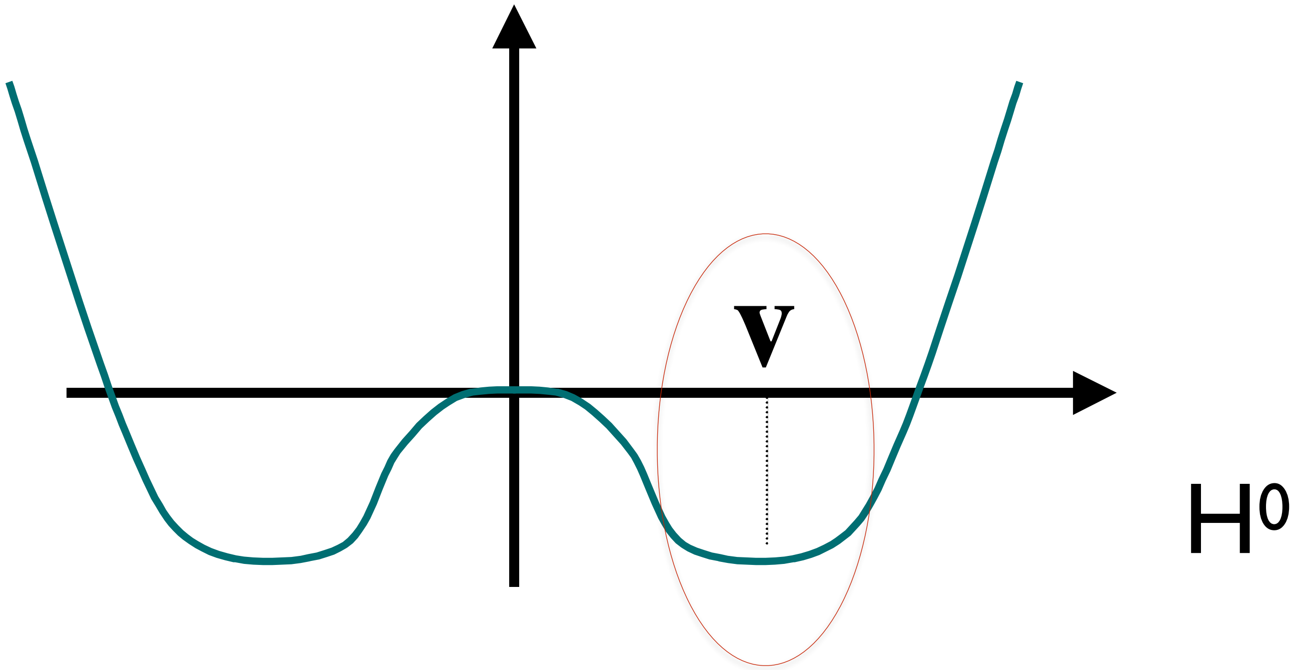
The important questions in HEP

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - …

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- *Two examples:*
  - **DM:** could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_{\odot}$ primordial BHs, passing through axions and sub-GeV DM
    - ***a vast array of expts*** is needed, even though most of them will end up empty-handed…
  - **Neutrino masses:** could originate anywhere between the EW and the GUT scale
    - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \to e\gamma$, $H \to \mu\tau$, …): as for DM, ***a broad range of options*** to explore, to find the right clues
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/inflation/dark energy, …)

But there is one central question to the progress of HEP, which can only be addressed by colliders



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

The SM Higgs mechanism provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us ...

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- …

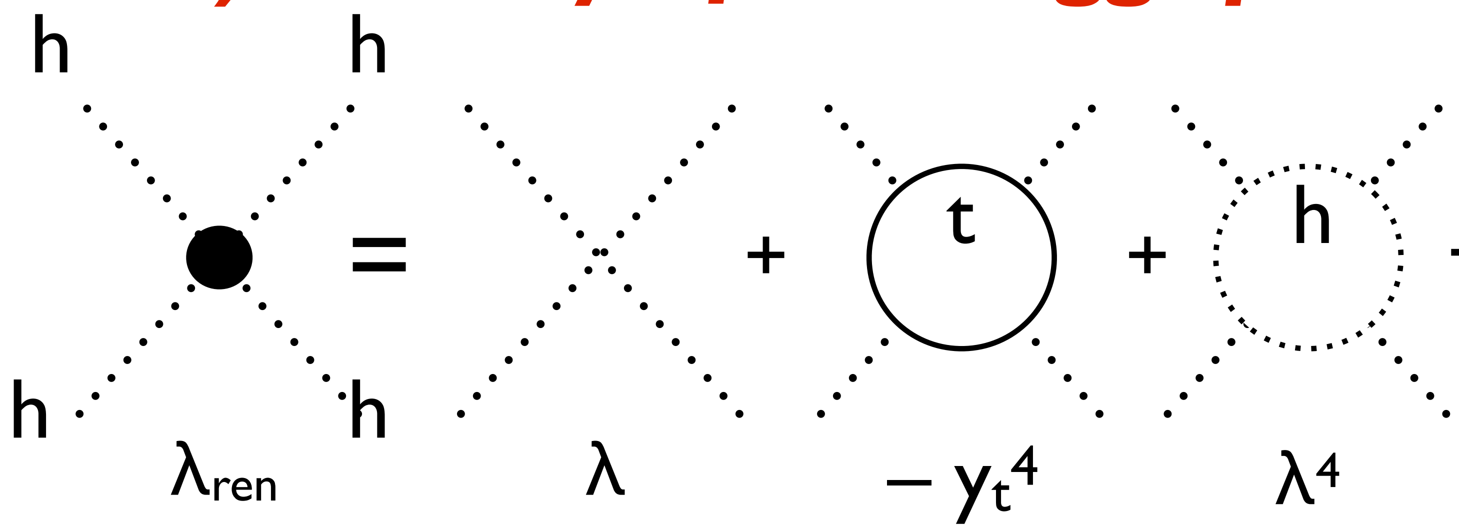
Other important open issues on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?

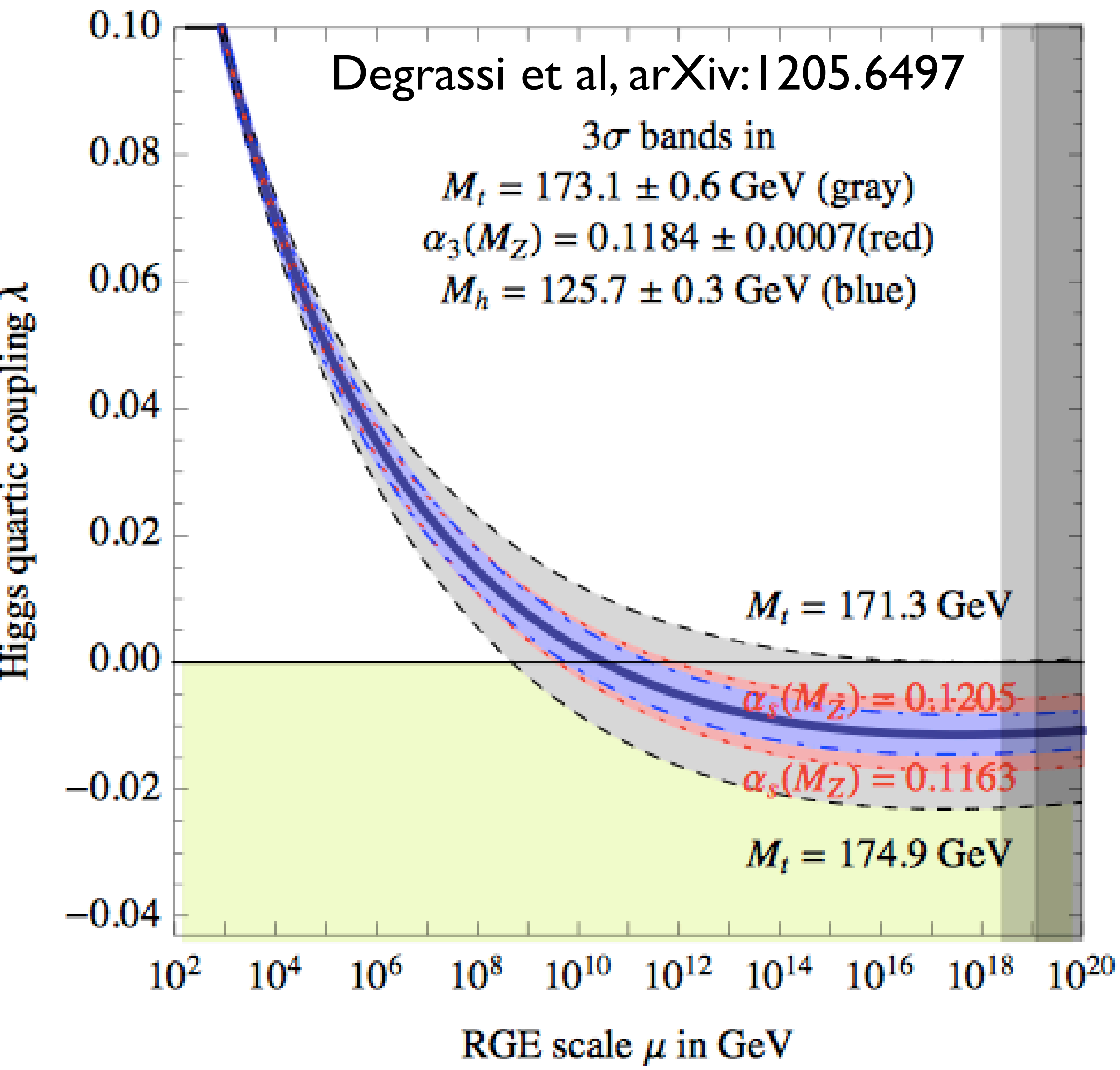
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

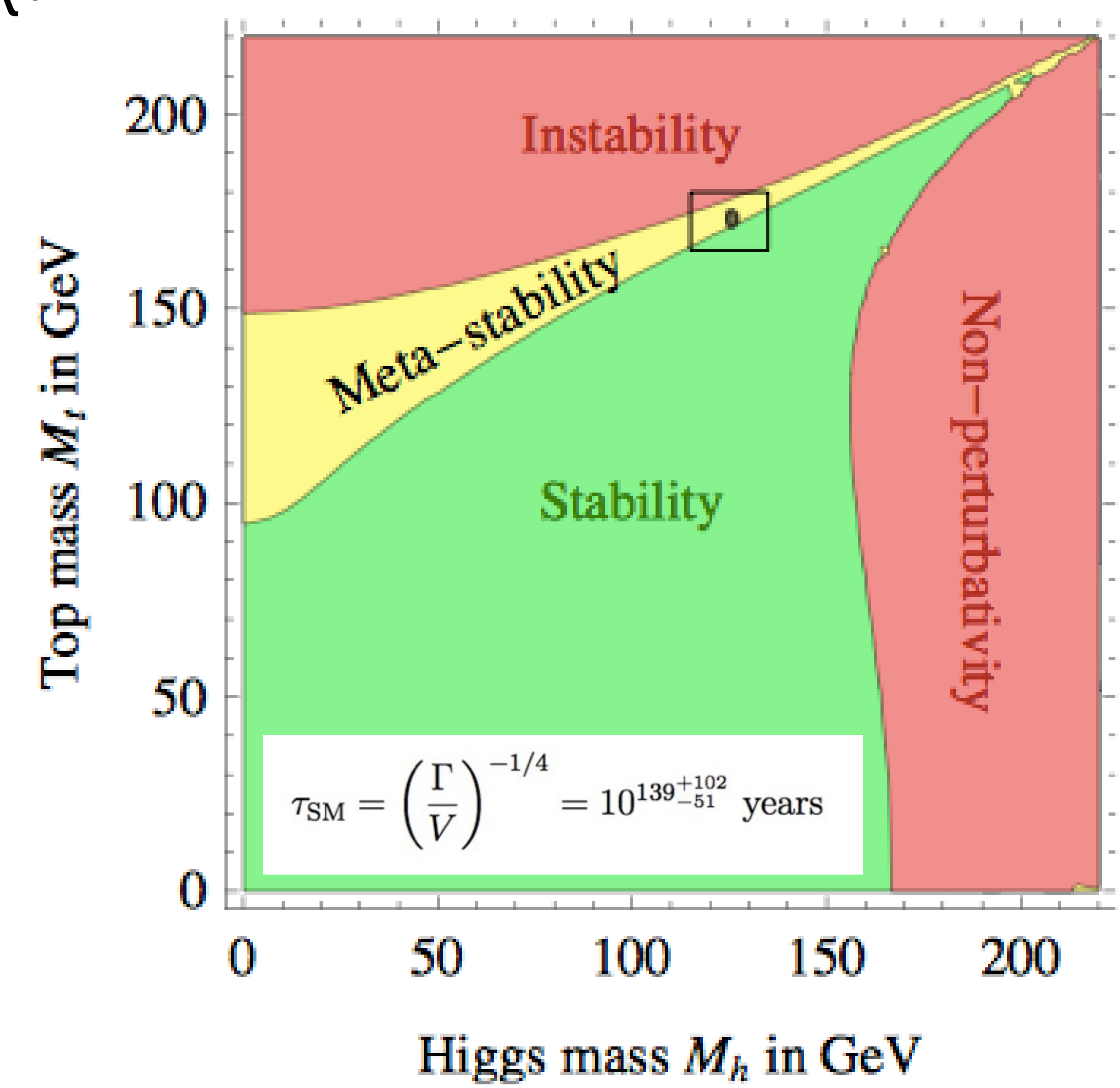
(meta)Stability of the Higgs potential

Higgs selfcoupling and coupling to the top are the key elements to define the stability of the Higgs potential



$$\Longrightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4$$
$$\propto a\, m_H^4 - b\, m_t^4$$



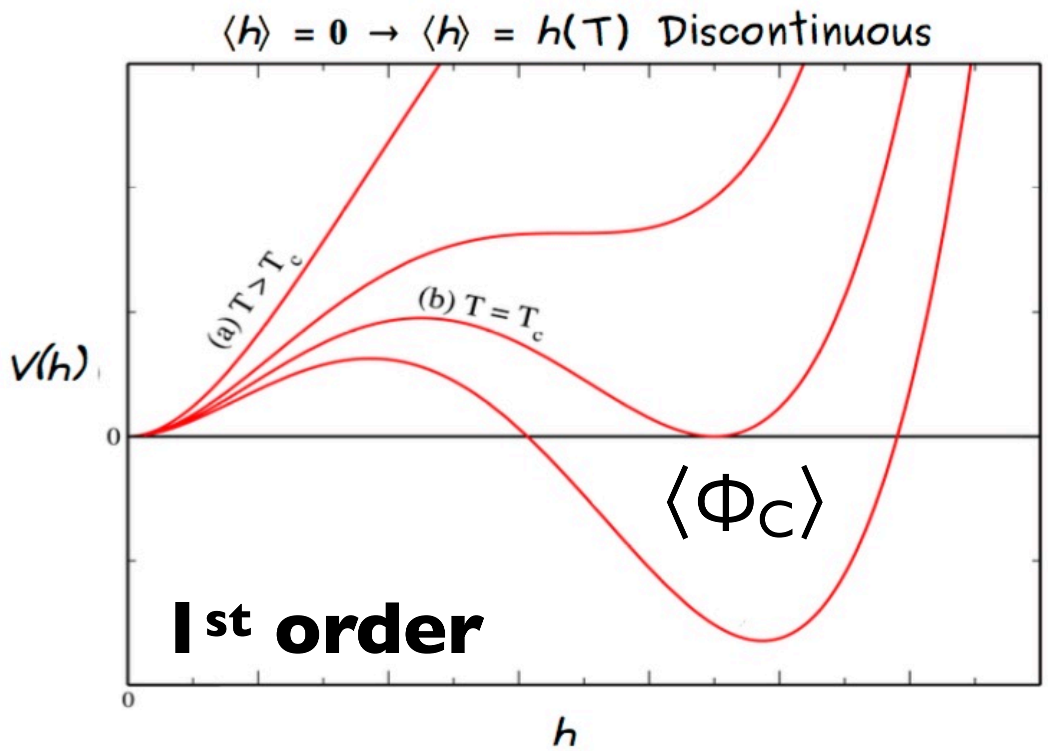


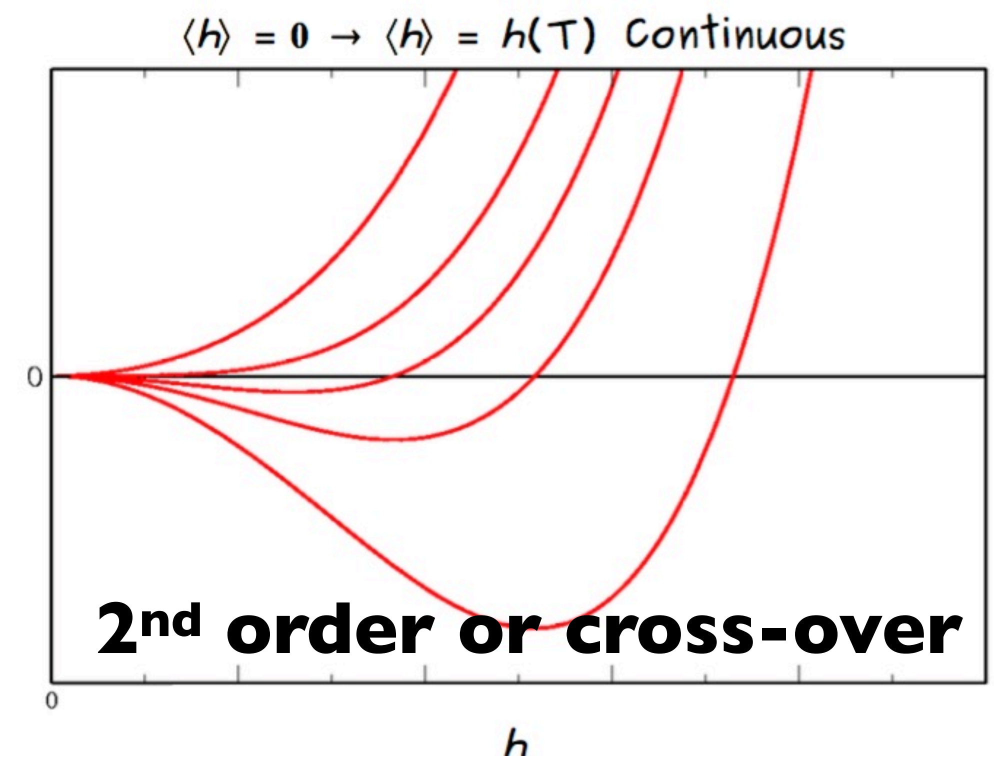
Not an issue of concern for the human race…. but the closeness of mtop to the critical value where the Higgs selfcoupling becomes 0 at M_{Planck} (namely 171.3 GeV) might be telling us something fundamental about the origin of EWSB … incidentally, y_{top}=1 (?!)

Other important open issues on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

The nature of the EW phase transition





Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

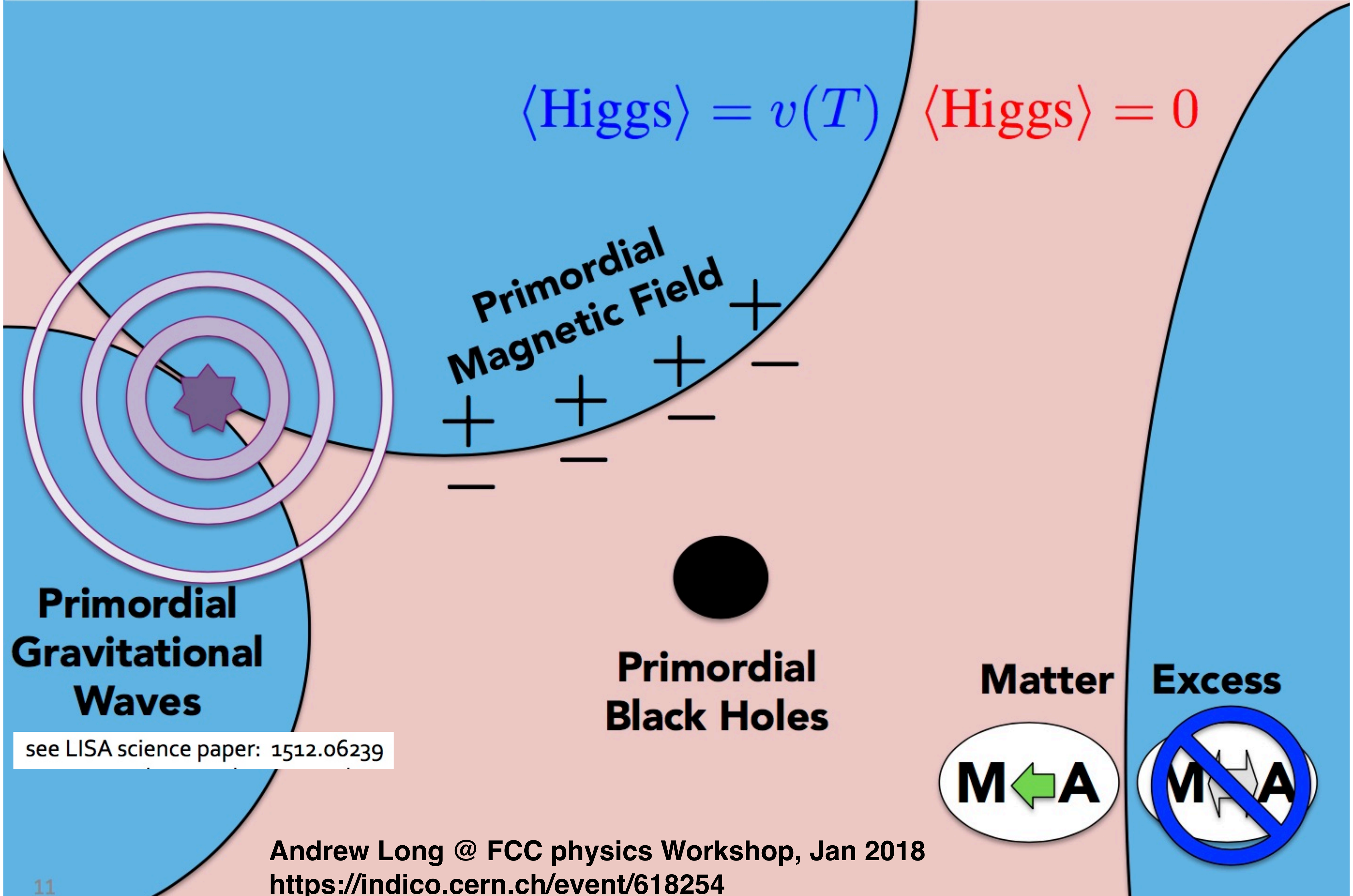
Strong 1st order phase transition $\Rightarrow$ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV, else transition is a smooth crossover.

Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**

1st Order EWPT has profound implications for cosmology



Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254

Other important open issues in the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^\pm$, A^0, $H^{\pm\pm}$, … , EW-singlets, ….) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?

- Is there a deep reason for the apparent metastability of the Higgs vacuum?

- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?

➡ *the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, <u>which can only rely on a future generation of colliders</u>*

What are we talking about when

we talk about future colliders?

Linear ...

e^+e^- @ 250, 350, 500 GeV

TDR 2012,
decision pending in Japan

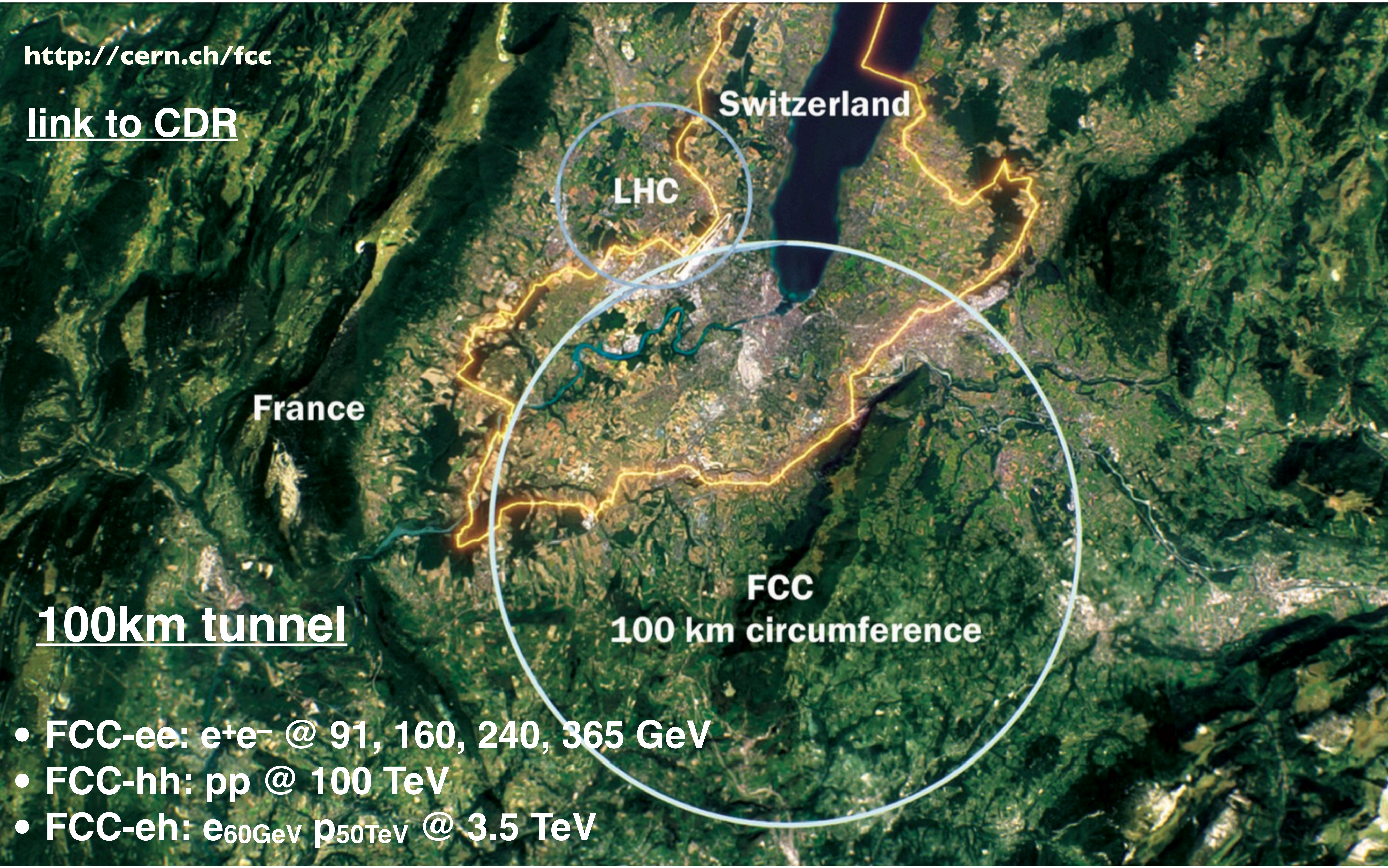
TDR: Technical Design Report

e^+e^- @ 380 GeV, 1.5 & ~3 TeV

CDR 2012+
<u>update</u> '16

CDR: Conceptual Design Report

Future Circular Collider



http://cern.ch/fcc

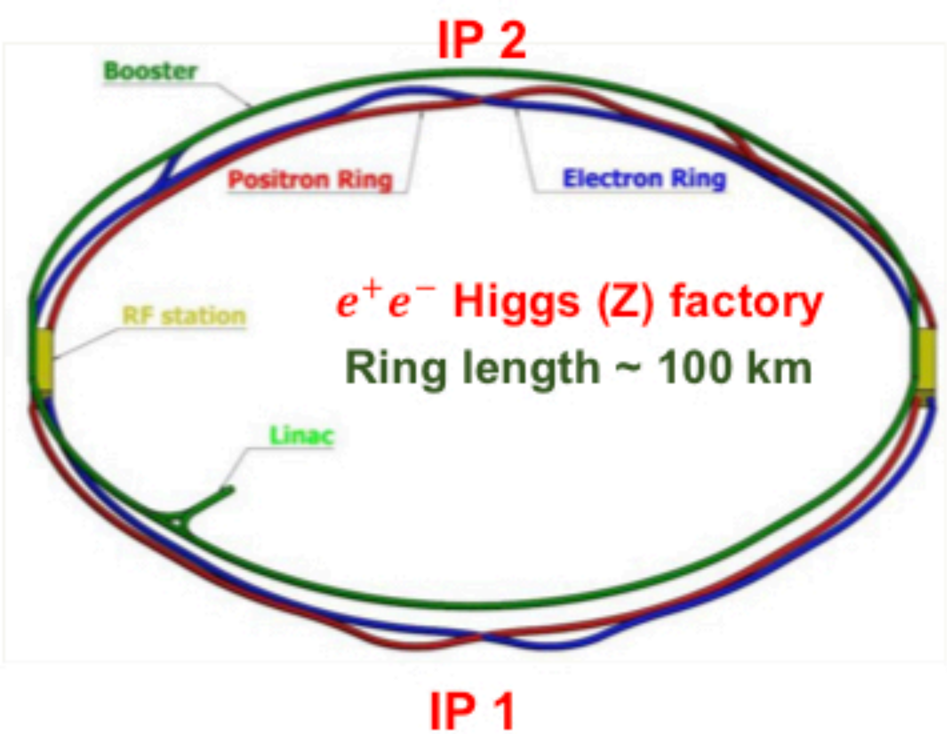
link to CDR

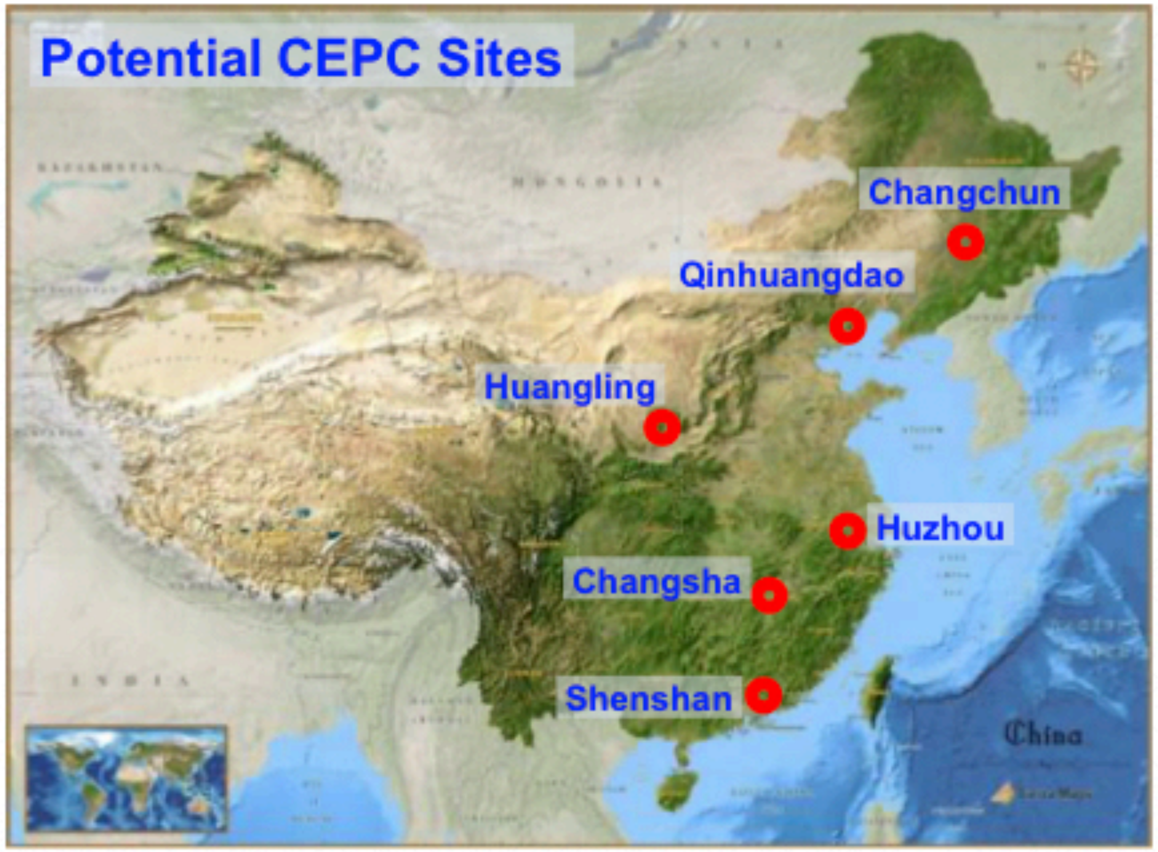
100km tunnel

- FCC-ee: e^+e^- @ 91, 160, 240, 365 GeV
- FCC-hh: pp @ 100 TeV
- FCC-eh: e_{60GeV} p_{50TeV} @ 3.5 TeV

Circular electron-positron Collider

- The CEPC aims to start operation in 2030's, as a Higgs (Z / W) factory in China.
- To run at $\sqrt{s}$ ~ 240 GeV, above the **ZH** production threshold for ≥1 M Higgs; at the **Z** pole for ~Tera Z; at the **W^+W^-** pair and possible $t\bar{t}$ pair production thresholds.
- Higgs, EW, flavor physics & QCD, probes of physics BSM.
- Possible *pp* collider (SppC) of $\sqrt{s}$ ~ 50–100 TeV in the far future.





link to CDR

beyond, with electrons (linear)

Multi-TeV e^+e^- colliders, from plasma wakefield acceleration

The ALEGRO collaboration

https://www.lpgp.u-psud.fr/icfaana/alegro

Reference documents:

https://arxiv.org/pdf/1901.08436.pdf https://arxiv.org/pdf/1901.08436.pdf

Table 2.4: LWFA single stage parameters operating at a plasma density of $n_0 = 10^{17}$ cm^{-3}.

Plasma density (wall), n_0[cm^{-3}]	10^{17}
Plasma wavelength, λ_p[mm]	0.1
Plasma channel radius, r_c[μm]	25
Laser wavelength, λ[μm]	1
Normalized laser strength, a_0	1
Peak laser power, P_L[TW]	34
Laser pulse duration (FWHM), τ_L[fs]	133
Laser energy, U_L[J]	4.5
Normalized accelerating field, E_z/E_0	0.14
Peak accelerating field, E_L[GV/m]	4.2
Plasma channel length, L_c[m]	2.4
Laser depletion, η_{pd}	23%
Bunch phase (relative to peak field)	$\pi/3$
Loaded gradient, E_z[GV/m]	2.1
Beam beam current, I[kA]	2.5
Charge/bunch, $eN_b = Q$[nC]	0.15
Length (triangular shape), L_b[μm]	36
Efficiency (wake-to-beam), η_b	75%
e$^-$/e$^+$ energy gain per stage [GeV]	5
Beam energy gain per stage [J]	0.75

Example parameter sets for 0.25, 1, 3, 30 TeV center-of-mass LWFA-based colliders.

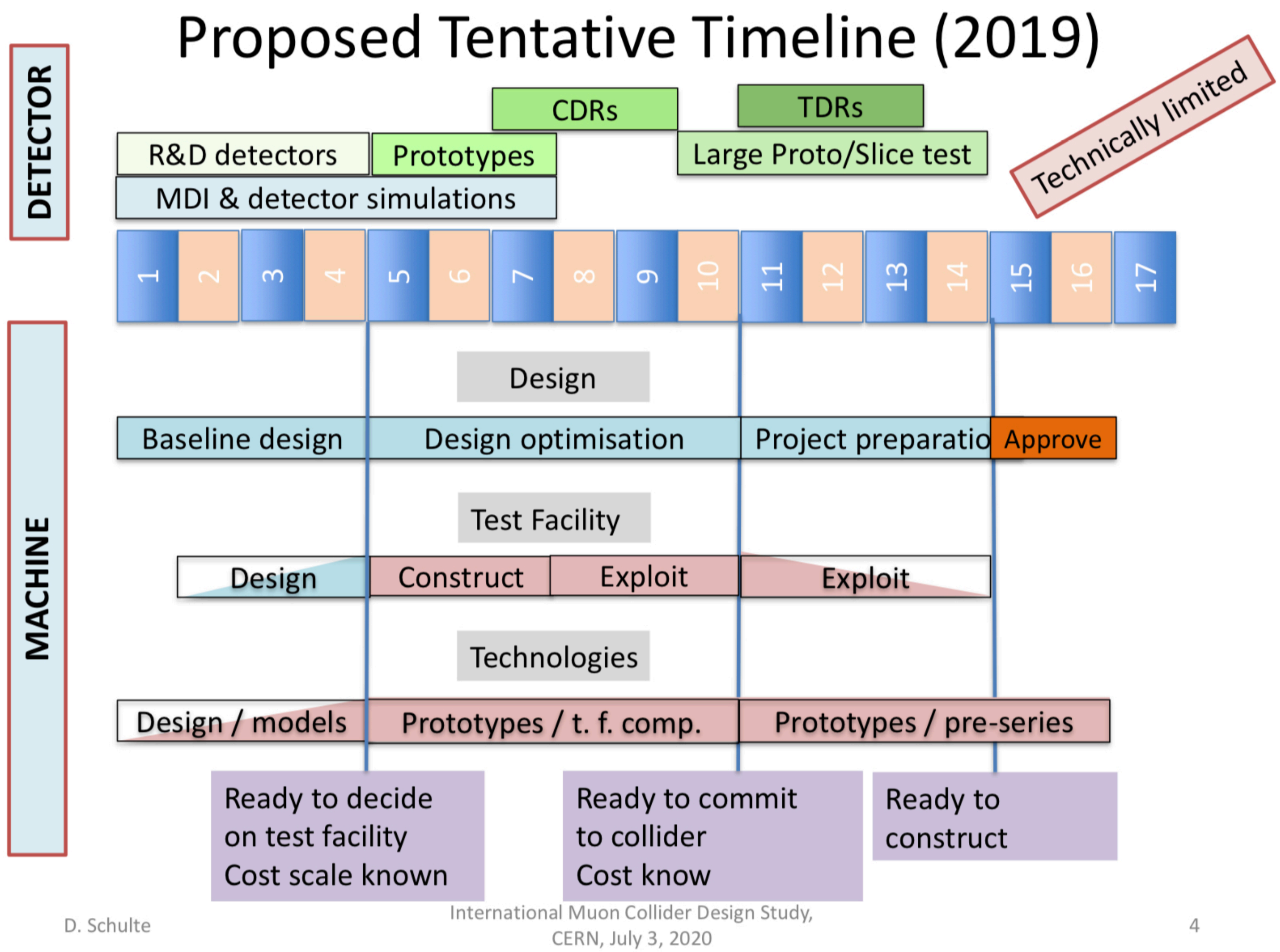
Energy, center-of-mass, U_{cm}[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}[10^{34}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}]$	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert. beam size at IP, σ_y^*[nm]	1	1	0.5	0.5
Beamstrahlung parameter, Υ	0.5	2	16	2890
Beamstrahlung photons, n_γ	0.6	0.5	0.8	2.8
Beamstrahlung energy spread, δ_γ	0.06	0.08	0.2	0.8
Disruption paramter, D_x	0.07	0.02	0.05	3.0
Number of stages (1 linac), N_{stage}	25	100	300	3000
Distance between stages [m]	0.5	0.5	0.5	0.5
Linac length (1 beam), L_{total}[km]	0.07	0.3	0.9	9.0
Average laser power, P_{avg}[MW]	0.3	0.3	0.6	0.17
Efficiency (wall-to-beam)[%]	9	9	13	13
Wall power (linacs), P_{wall}[MW]	30	120	450	1250

peak accelerating field: 4.2 GeV/meter

beyond, with muons (circular)

=> International Muon Collider Design Study* recently set up

Kick-off meeting: https://indico.cern.ch/event/930508/



** building on 2 decades of preliminary work, notably within the US Muon Accelerator Program (MAP)*

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

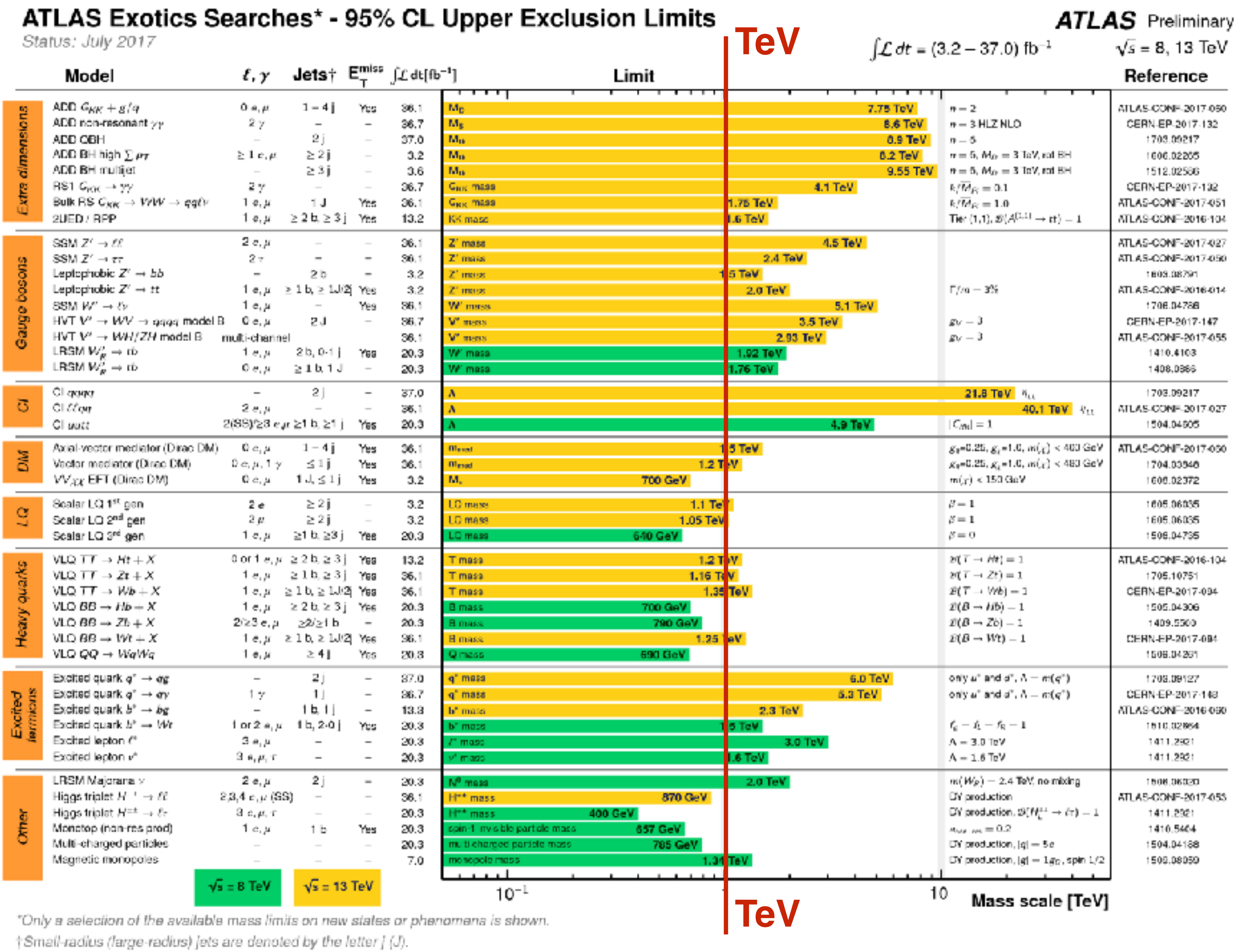
In search of the origin of known departures from the SM

- **Dark matter, long lived particles**
- **Neutrino masses**
- **Matter/antimatter asymmetry of the universe**

To explore alternative extensions of the SM

- **New gauge interactions (Z', W') or extra Higgs bosons**
- **Additional fermionic partners of quarks and leptons, leptoquarks, ...**
- **Composite nature of quarks and leptons**
- **Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, ...)**
- **Extra dimensions**
- **New flavour phenomena**
- **unanticipated surprises ...**

So far, no *conclusive* signal of physics beyond the SM



<u>Key question for the future developments of HEP:</u> Why don't we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**

- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision* $\Rightarrow$ *higher statistics, better detectors and experimental conditions*
- *sensitivity (to elusive signatures)* $\Rightarrow$ *ditto*
- *extended energy/mass reach* $\Rightarrow$ *higher energy*

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

The physics potential (the "case") of a future facility for HEP should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

The value of diversity and guaranteed deliverables in collider physics

LHC scientific production

Over 3000 papers published/submitted to refereed journals by the 7 experiments (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)

Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~30% on searches for new physics (35% if ATLAS+CMS only)

~60% of the papers on SM measurements (jets, EW, top, b, HIs, …)

Not only Higgs and BSM !

Flavour physics

- B(s) $\to \mu\mu$
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase ϕ_s, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

QCD dynamics

- Countless precise measurements of hard cross sections, and improved determinations of the proton PDF
- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in "small" systems (pA and pp)

EW param's and dynamics

- m_W, m_{top}, $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)

Remarks

- These 3000 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities
- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities
  - HERA→PDFs, B-factories→flavour, RHIC→HIs, LEP/SLC→EWPT, etc
- Even in the perspective of new dedicated facilities, eg SuperKEKB or EIC, LHC maintains a key role of competition and complementarity

I have a broad concept of "*new physics*", which includes SM phenomena, emerging from the data, that are unexpected, surprising, or simply poorly understood.

I consider as "new", and as a discovery, everything that is not obviously predictable, or that requires deeper study to be clarified, even if it belongs to the realm of SM phenomena.

"New physics" is emerging every day at the LHC!

(1) guaranteed deliverables: Higgs properties

Coupling deviations for various BSM models, likely to remain unconstrained by direct searches at HL-LHC

https://arxiv.org/pdf/1708.08912.pdf

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

5 – 10 %

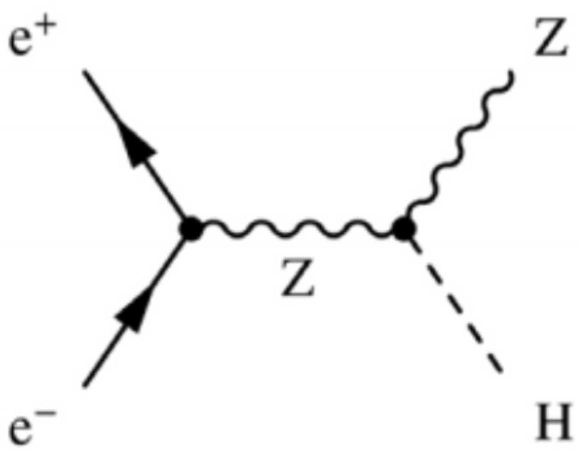
> 10%

NB: when the b coupling is modified, BR deviations are smaller than the square of the coupling deviation. Eg in model 5, the BR to b, c, tau, mu are practically SM-like

(sub)-% precision must be the goal to ensure 3-5σ evidence of deviations, and to cross-correlate coupling deviations across different channels

The absolutely unique power of $e^+e^- \to ZH$ (circular or linear):

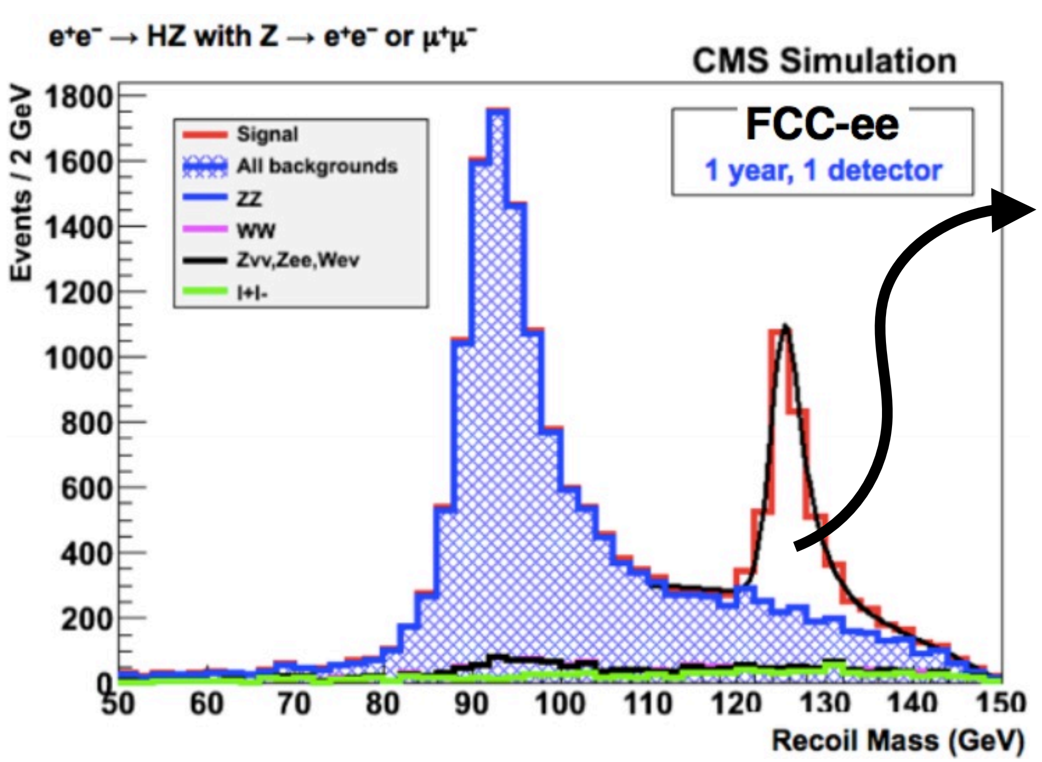
- the model independent absolute measurement of **HZZ** coupling, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



$p(H) = p(e^-e^+) - p(Z)$

$\Rightarrow [\, p(e^-e^+) - p(Z) \,]^2$ peaks at $m^2(H)$

reconstruct Higgs events independently of the Higgs decay mode!



$N(ZH) \propto \sigma(ZH) \propto g_{HZZ}^2$

$N(ZH[\to ZZ]) \propto$
$\sigma(ZH) \times BR(H\to ZZ) \propto$
$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

=> **absolute measurement of width and couplings**

$m_{recoil} = \sqrt{[\, p(e^-e^+) - p(Z) \,]^2}$

(more details in Christophe Grojean talk)

The absolutely unique power of pp → H+X:

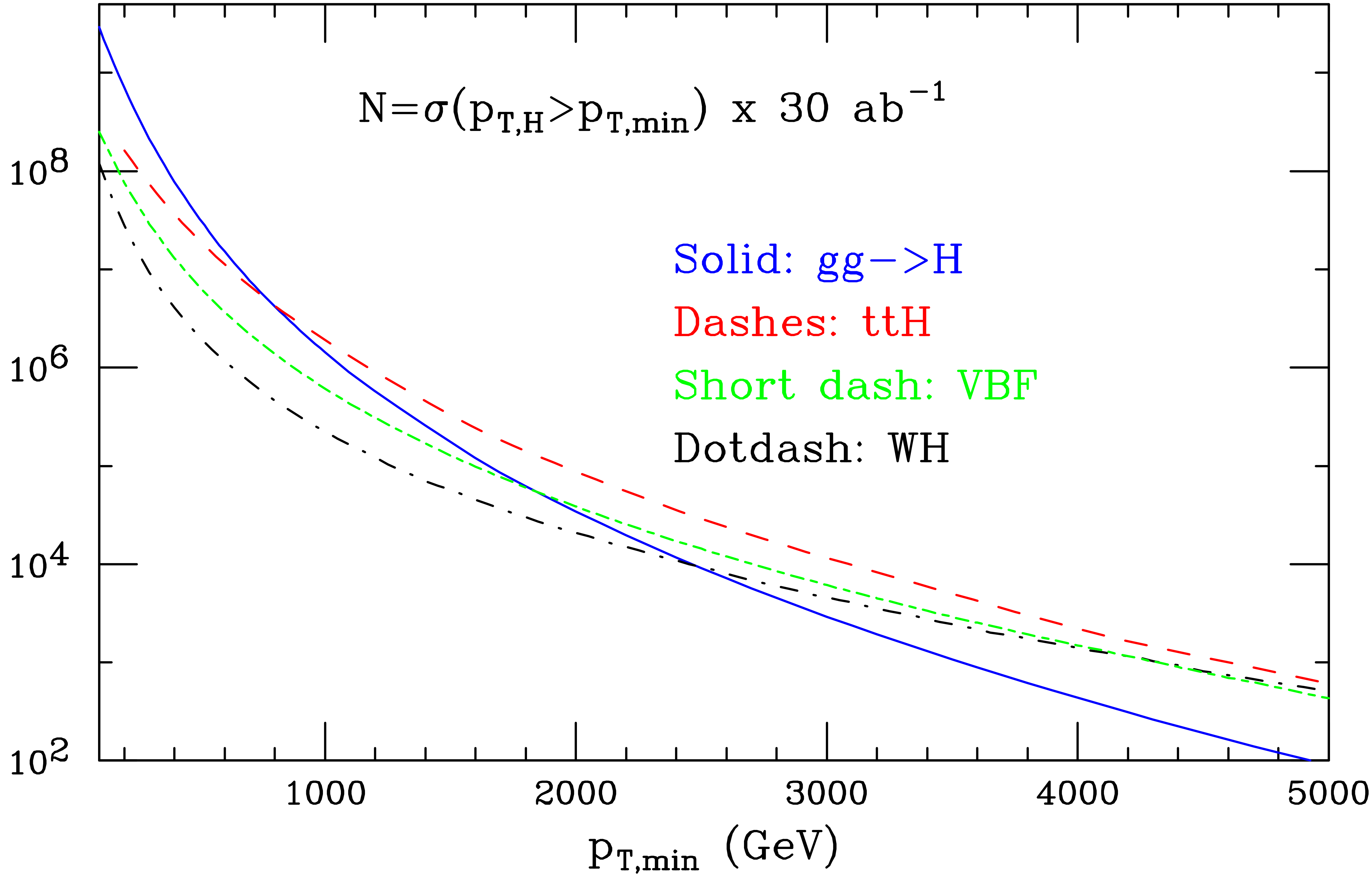
- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR($H \to ZZ^*$), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4 EFT operators up to scales of several TeV
  - search for multi-TeV resonances decaying to H, or extensions of the Higgs sector

	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\text{TeV}} \times 30\ \text{ab}^{-1}$

$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

Three kinematic regimes

- <u>Inclusive production, $p_T > 0$:</u>
  - largest overall rates
  - most challenging experimentally:
    - triggers, backgrounds, pile-up ⇒ low efficiency, large systematics

  ➡ det simulations challenging, likely unreliable ⇒ regime not studied so far

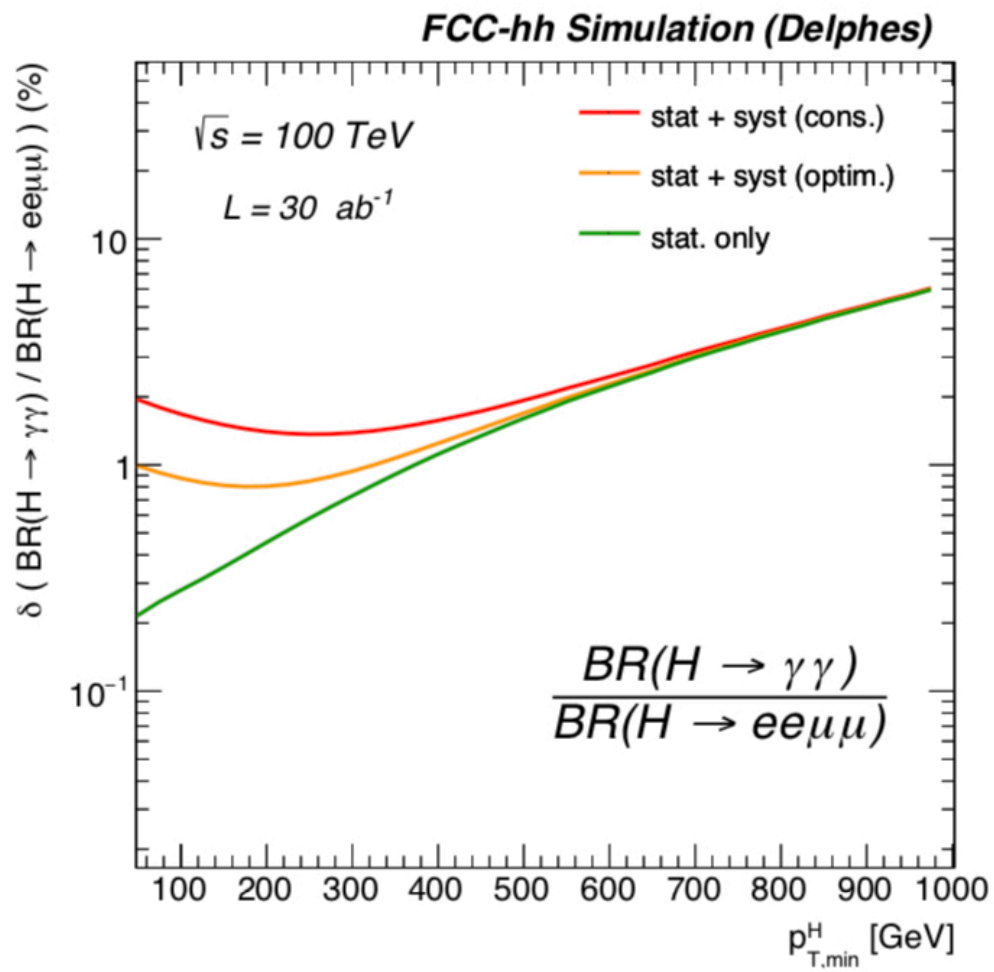
- <u>$p_T \gtrsim 100$ GeV :</u>
  - stat uncertainty ~few × 10^{-3} for $H \to 4l$, $\gamma\gamma$, …
  - improved S/B, realistic trigger thresholds, reduced pile-up effects ?

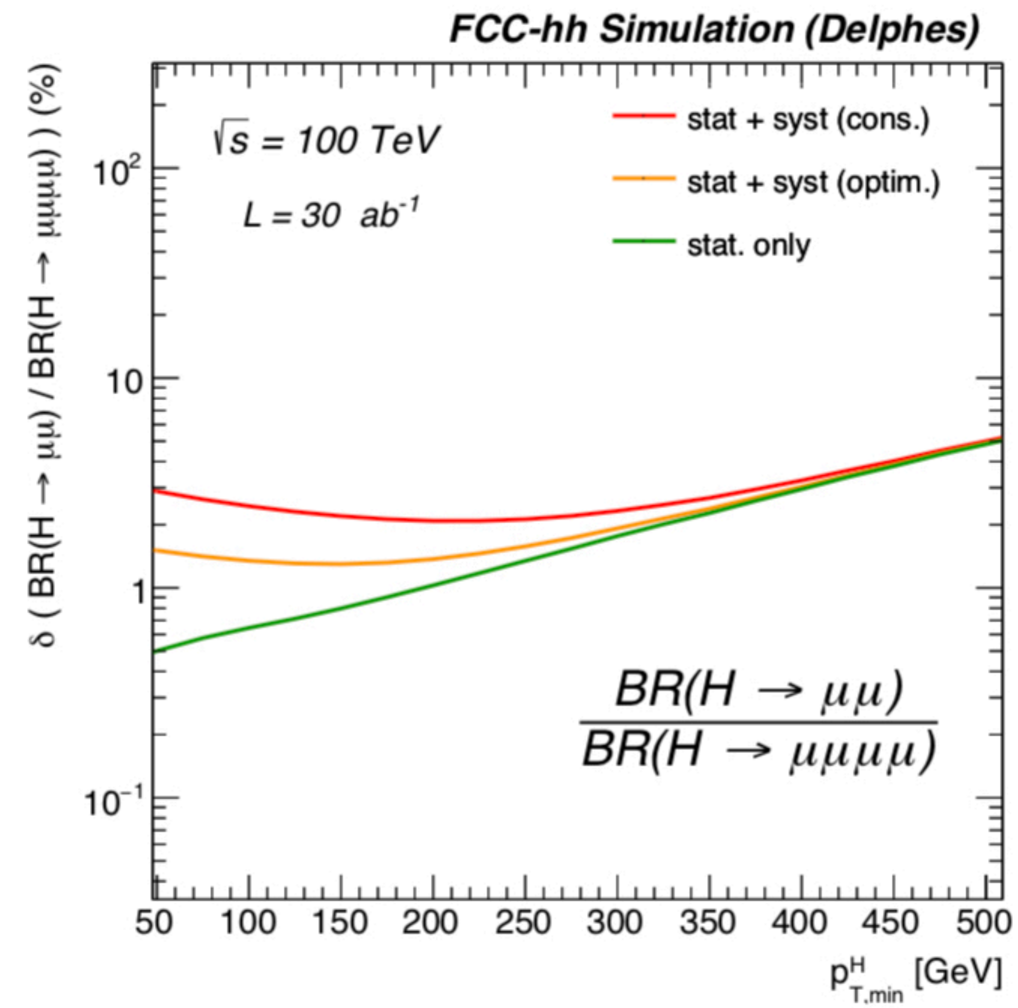
  ➡ current det sim and HL-LHC extrapolations more robust

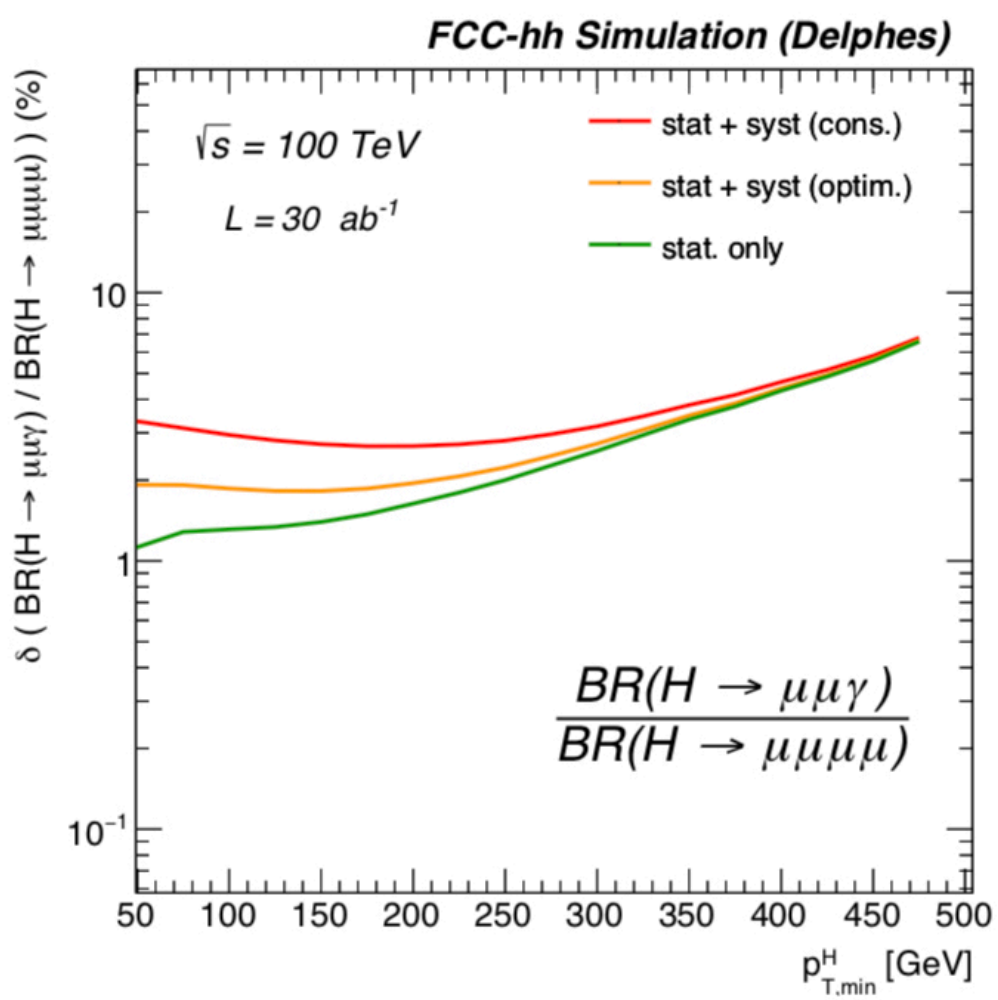
  ➡ focus of FCC CDR Higgs studies so far

  ➡ sweet-spot for precision measurements at the sub-% level

- <u>$p_T \gtrsim$ TeV :</u>
  - stat uncertainty O(10%) up to 1.5 TeV (3 TeV) for $H \to 4l$, $\gamma\gamma$ ($H \to bb$)
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$







Normalize to BR(4l) from ee => sub-% precision for absolute couplings

Higgs couplings after a ee Higgs factory and a 100TeV pp collider (eg FCC-ee/hh)

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

NB

$BR(H\to Z\gamma,\gamma\gamma) \sim O(10^{-3}) \Rightarrow$ **$O(10^7)$ evts for $\Delta_{stat}\sim\%$**

$BR(H\to\mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for $\Delta_{stat}\sim\%$**

pp collider is essential to beat the % target, since no proposed ee collider can produce more than $O(10^6)$ H's

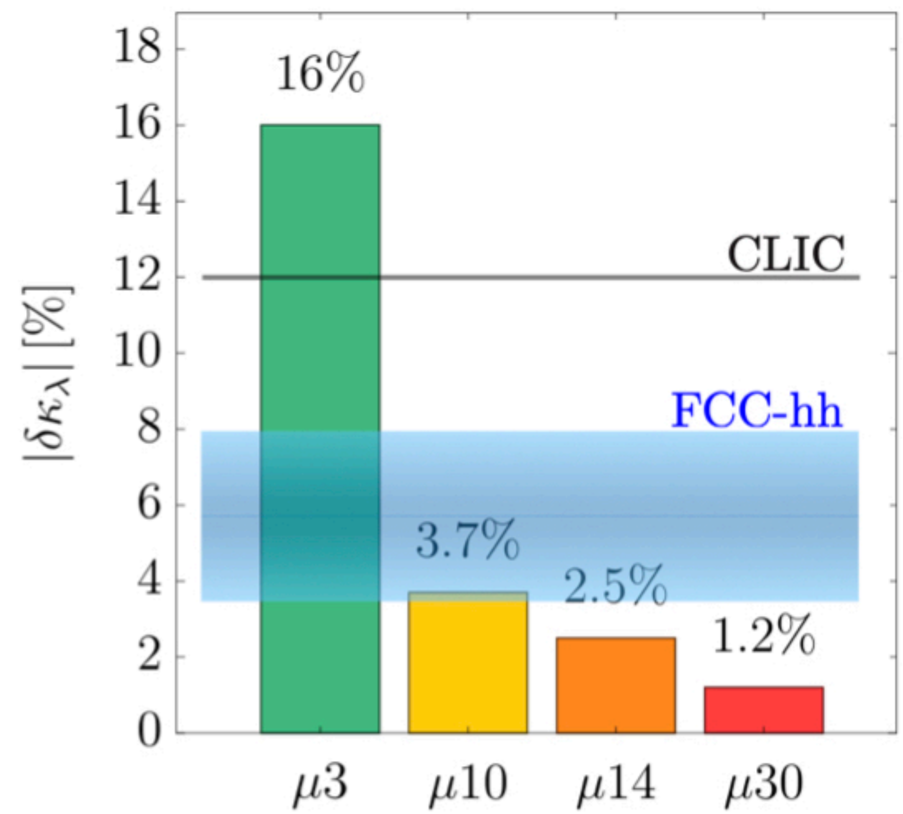
* From BR ratios wrt $B(H\to ZZ^*)$ @ FCC-ee

** From $pp\to ttH$ / $pp\to ttZ$, using $B(H\to bb)$ and ttZ EW coupling @ FCC-ee

vs high-energy μ collider

	10 TeV mucol	FCC-ee	FCC-hh
$\delta g_{HZZ} / g_{HZZ}$	0.4	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$	0.1	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$	0.4	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	2.3	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$	0.6	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	0.6	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$	3.4	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	0.8	3.9	**0.4 (*)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$	7.2	–	**0.9 (*)**

Higgs self-coupling:



(1) guaranteed deliverables: EW observables

The absolutely unique power of **circular** e^+e^-:

$e^+e^- \to Z$	$e^+e^- \to WW$	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
$5\ 10^{12}$	10^{8}	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

=> $O(10^5)$ larger statistics than LEP at the Z peak and WW threshold

For the interpretation and impact of the combined EW and higgs precision measurements, see Christophe's talk

Beyond guaranteed deliverables: the discovery potential

- Discovery-reach comparison among different colliders is by and large subjective
  - statements like *"collider A is more/less/as powerful as collider B"* are meaningless, unless they refer to specific new-physics scenarios
- Studies typically focus on new-physics scenarios best suited for discovery at your preferred collider …
- Typical criteria to characterize search scenarios for new physics:
  - direct vs indirect discovery
  - strong vs weak coupling new interactions,

exposing the complementarity/synergy between energy and precision

Sequential Z' reach: comparison across colliders, direct vs indirect reach

Indirect observation through EW precision observables

Direct observation

Machine	Type	$\sqrt{s}$ (TeV)	$\int Ldt$ (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	pp	14	3	RH [395]	$Z'_{SSM} \to$ dijet	4.2	**5.2**
				ATLAS [396]	$Z'_{SSM} \to l^+l^-$	6.4	**6.5**
				CMS [397]	$Z'_{SSM} \to l^+l^-$	–	**6.8**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**6**
ILC250, CLIC380 or FCC-ee	e^+e^-	0.25	2	ILC [398]	$Z'_{SSM} \to f^+f^-$	4.9	**7.7**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**7**
HE-LHC	pp	27	15	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**11**
				ATLAS [396]	$Z'_{SSM} \to e^+e^-$	12.8	**12.8**
ILC	e^+e^-	0.5	4	ILC [398]	$Z'_{SSM} \to f^+f^-$	8.3	**13**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**13**
CLIC	e^+e^-	1.5	2.5	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**19**
Muon Collider	$\mu^+\mu^-$	3	1	IMCC [392]	$Z'_{Univ}(g_{Z'} = 0.2)$	10	**20**
ILC	e^+e^-	1	8	ILC [398]	$Z'_{SSM} \to f^+f^-$	14	**22**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**21**
CLIC	e^+e^-	3	5	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**24**
FCC-hh	pp	100	30	RH [395]	$Z'_{SSM} \to$ dijet	25	**32**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**35**
				EPPSU [399]	$Z'_{SSM} \to l^+l^-$	43	**43**
Muon Collider	$\mu^+\mu^-$	10	10	IMCC [392]	$Z'_{Univ}(g_{Z'} = 0.2)$	42	**70**

(1)

(2)

Table 2-14. *For each collider we list the operating point and mass reach, for 5σ discovery and 95% CL exclusion, of the SSM Z' model taken from Refs. [395, 399, 396, 397, 398], and the mass reach of the universal Z' model with a coupling $g_{Z'} = 0.2$ from Refs. [392, 384] that we determined from Fig. 2-32.*

1. A TeV-scale ee collider already sets (indirect) limits well above the direct discovery potential from a 10-TeV scale lepton collider

2. A 100 TeV pp collider extends the direct search well beyond the sensitivity of indirect evidence from ILC, CLIC and a 3 TeV muon collider. With a discovery reach at over 40 TeV, and sensitivity to lepton and quark decays above 25 TeV, this collider would allow a direct exploration of the coupling properties of the object responsible for the SM deviations to EW observables induced in a 10-TeV scale lepton collider

3. For direct observation of a charged resonance (eg W') the HL-LHC is as powerful as a 13 TeV lepton collider (pair production)

International MUON Collider Collaboration

May 30, 2022
https://muoncollider.web.cern.ch

Muon Collider Physics Summary

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/pdf/2203.07256.pdf

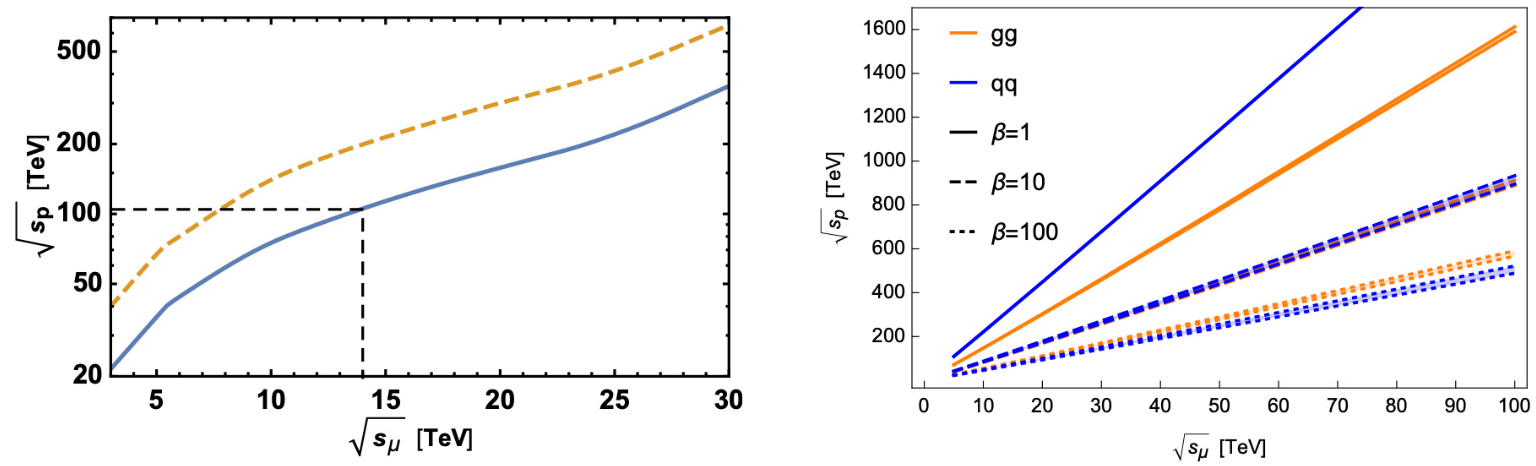


Fig. 1: Equivalent proton collider energy. The left plot [1], assumes that qq and gg partonic initial states both contribute to the production. In the orange and blue lines, $\beta = 1$ and $\beta = 10$, respectively. In the right panel [4], production from qq and from gg are considered separately.

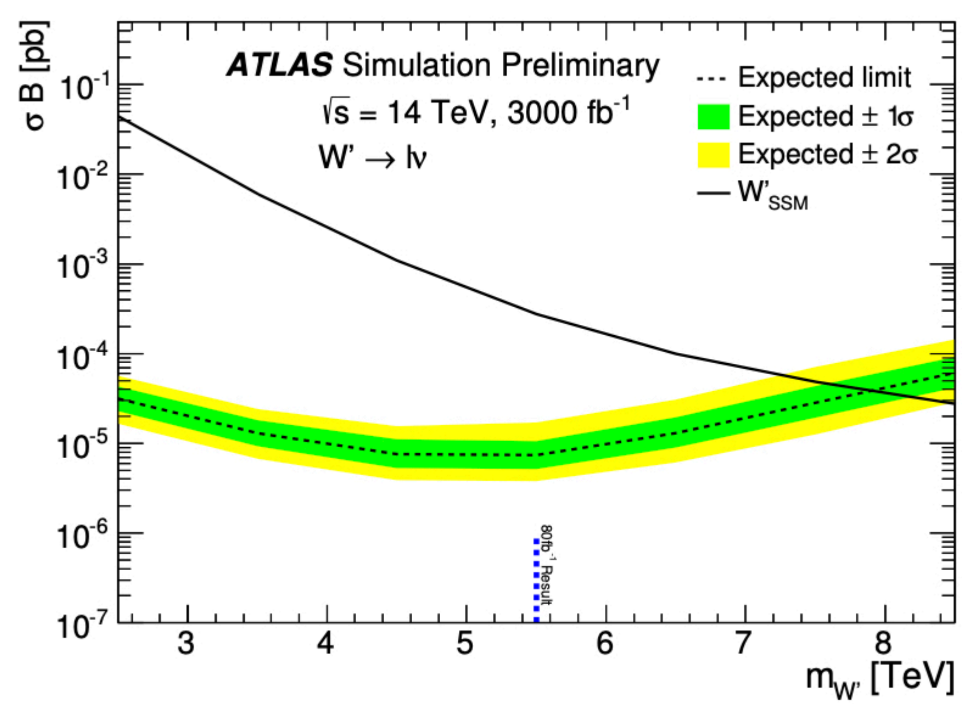
this leads to the often quoted statement

*"a 14 TeV μ collider is '**equivalent**' to a 100 TeV pp collider"*

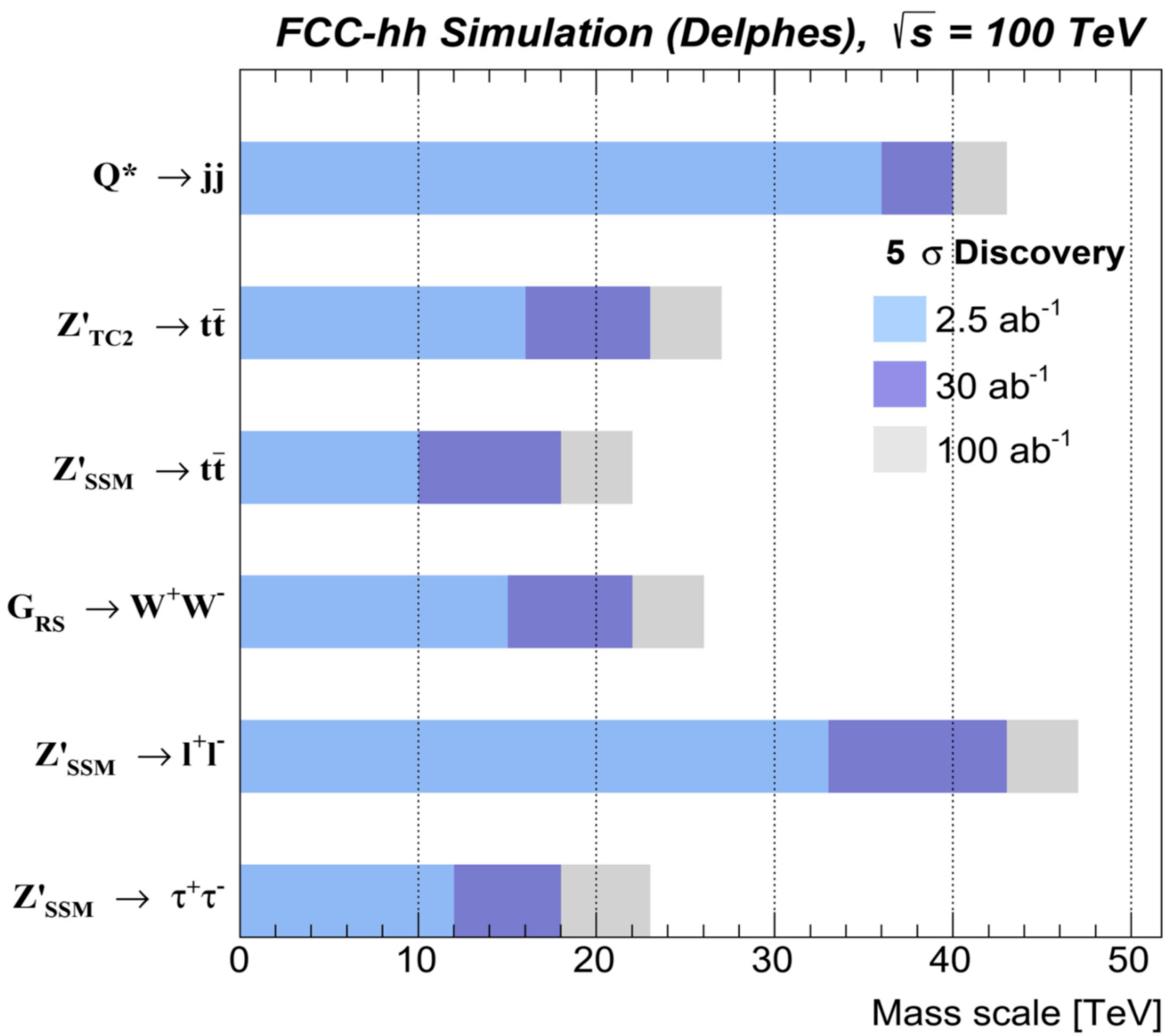
But let's take eg the search for a W' (heavy partner of charged W boson)

- reach at μ collider: $M_W < \sqrt{s}/2$ (=>**7 TeV** at √s=14 TeV)
- reach at **LHC**: **7.9 TeV !!**

similar counter-examples to the above statement can be found, eg in the context of new particles coupling only to gluons…



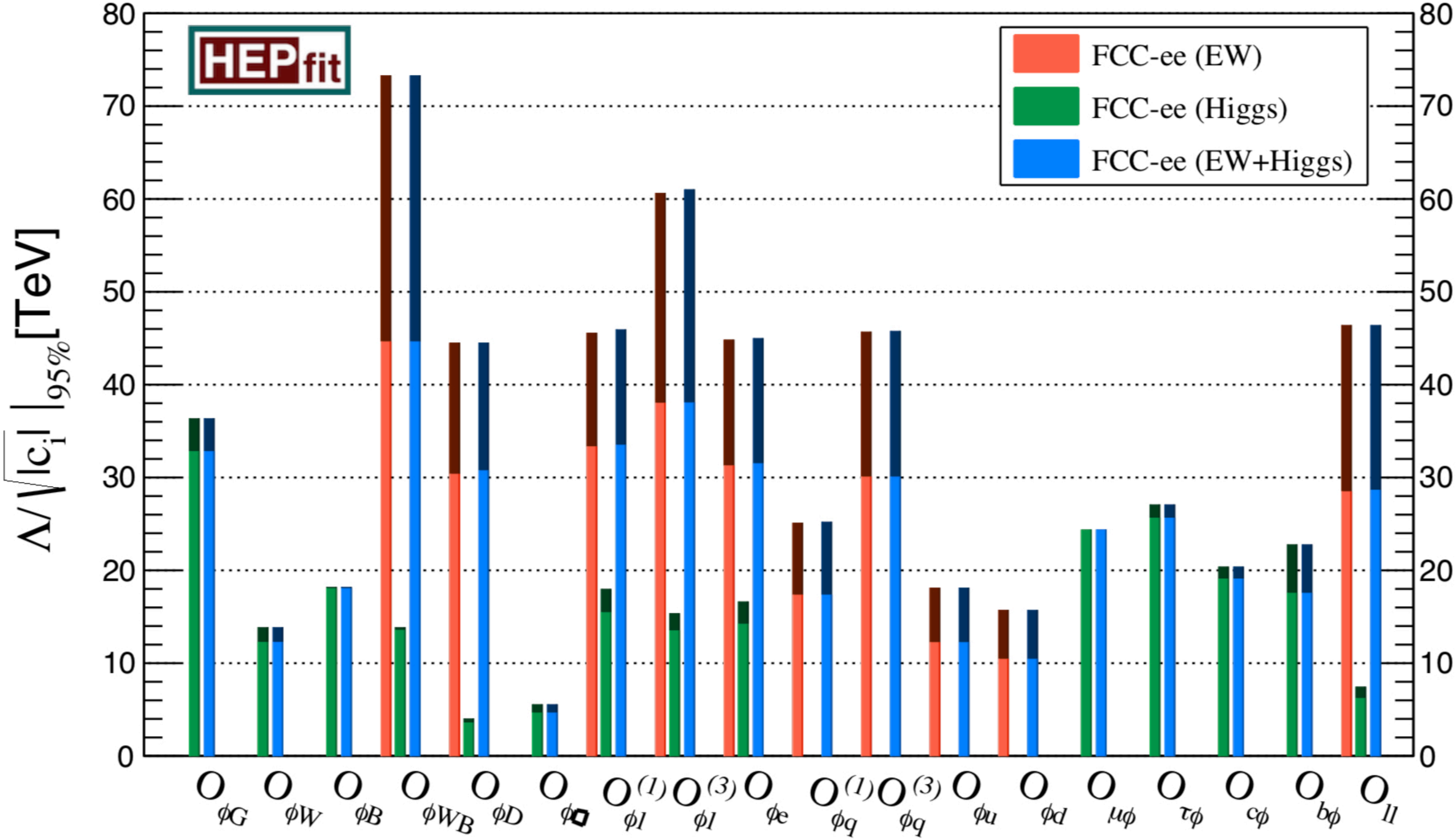
Direct sensitivity to s-channel resonances



FCC-hh reach ~ 6 x HL-LHC reach

for the direct discovery reach at FCC-ee (eg light dark sectors, …) see Christophe's talk

Global EFT fits to EW and H observables at FCC-ee

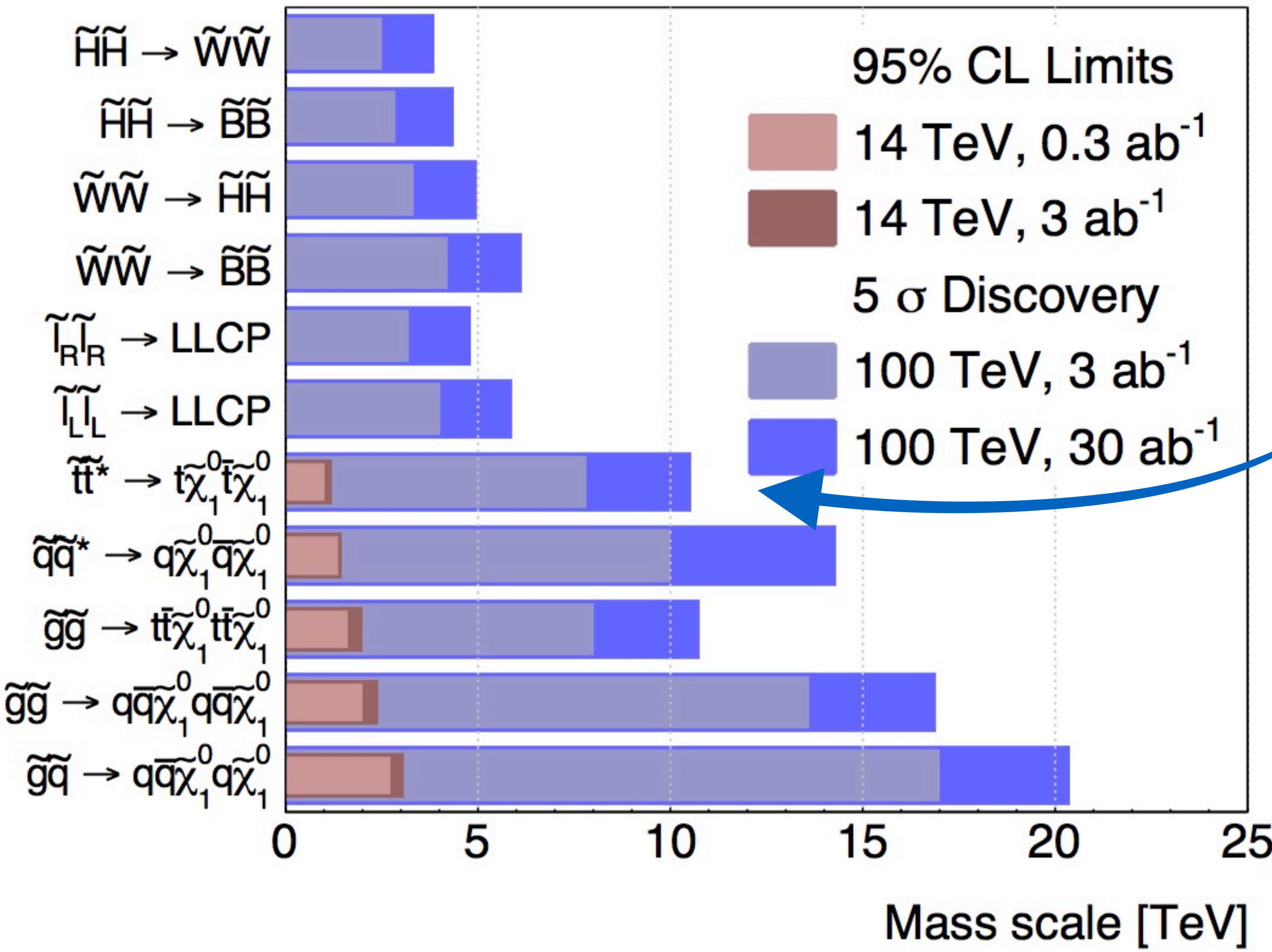


Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

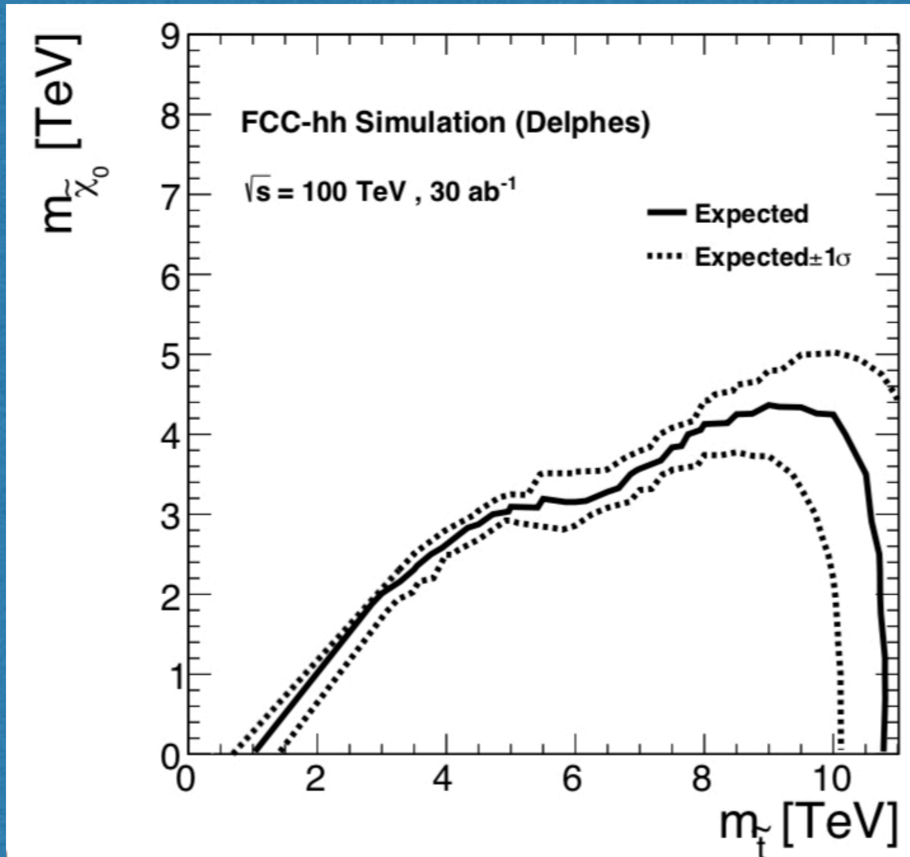
100 TeV is the appropriate CoM energy to directly search for new physics appearing indirectly through precision EW and H measurements at the future ee collider

SUSY reach at 100 TeV

Early phenomenology studies



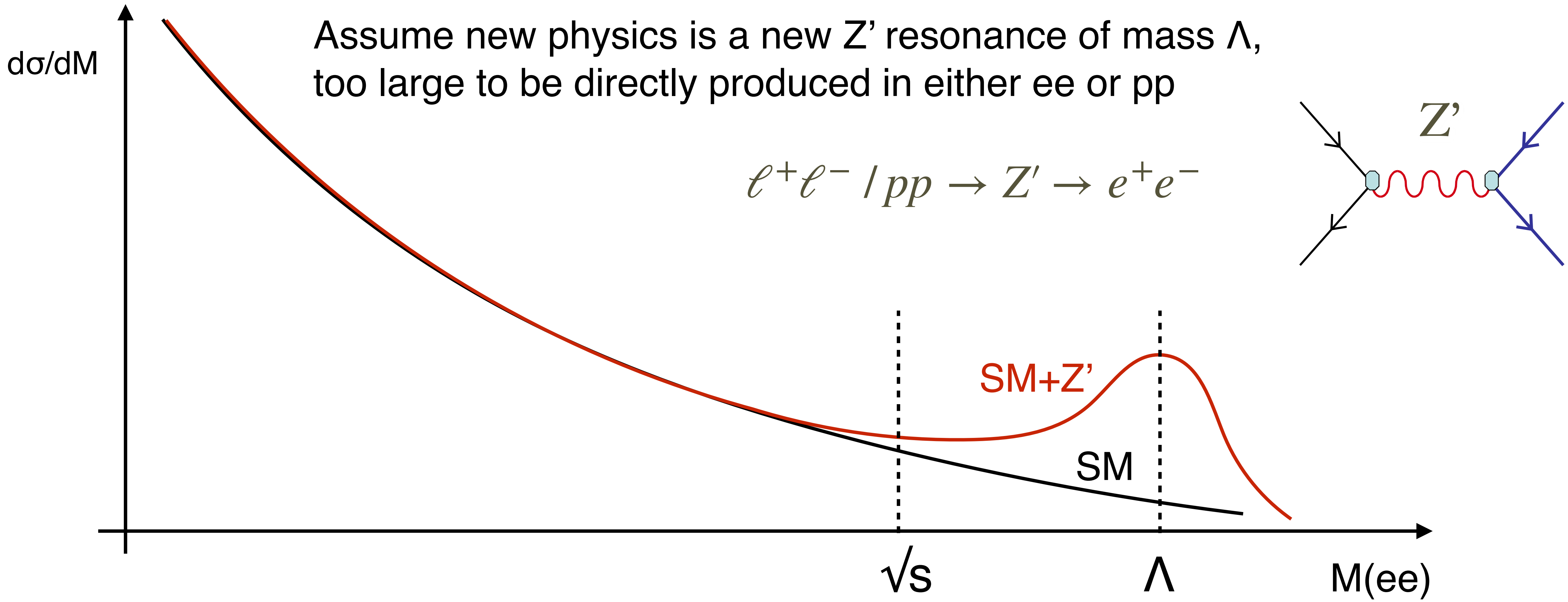
New detector performance studies



Indirect sensitivity: precision vs dynamic reach

Assume new physics is a new Z' resonance of mass Λ, too large to be directly produced in either ee or pp

$$\ell^+\ell^- \,/\, pp \to Z' \to e^+e^-$$



For M(ee) below the production threshold Λ:

$$\sigma = \sigma_{SM} \times \left(1 + g^2 \frac{M_{ee}^2}{\Lambda^2}\right)$$

Indirect discovery reach on Λ:

$$\Lambda_{max} \sim g \frac{M_{max}}{\sqrt{\Delta\sigma/\sigma}}$$

M_{max} → kinematic reach

$\sqrt{\Delta\sigma/\sigma}$ → precision

- Higher E (eg LHC) can compete with better precision (eg LEP)
- Reach depends on the strength of interaction **g**:
  - if **g** large $\Lambda_{max} \gg \sqrt{S}$ and ee colliders can have an edge
  - if **g** small $\Lambda_{max} < \sqrt{S}$ and direct search at pp collider can be more powerful

Example: high mass dilepton production

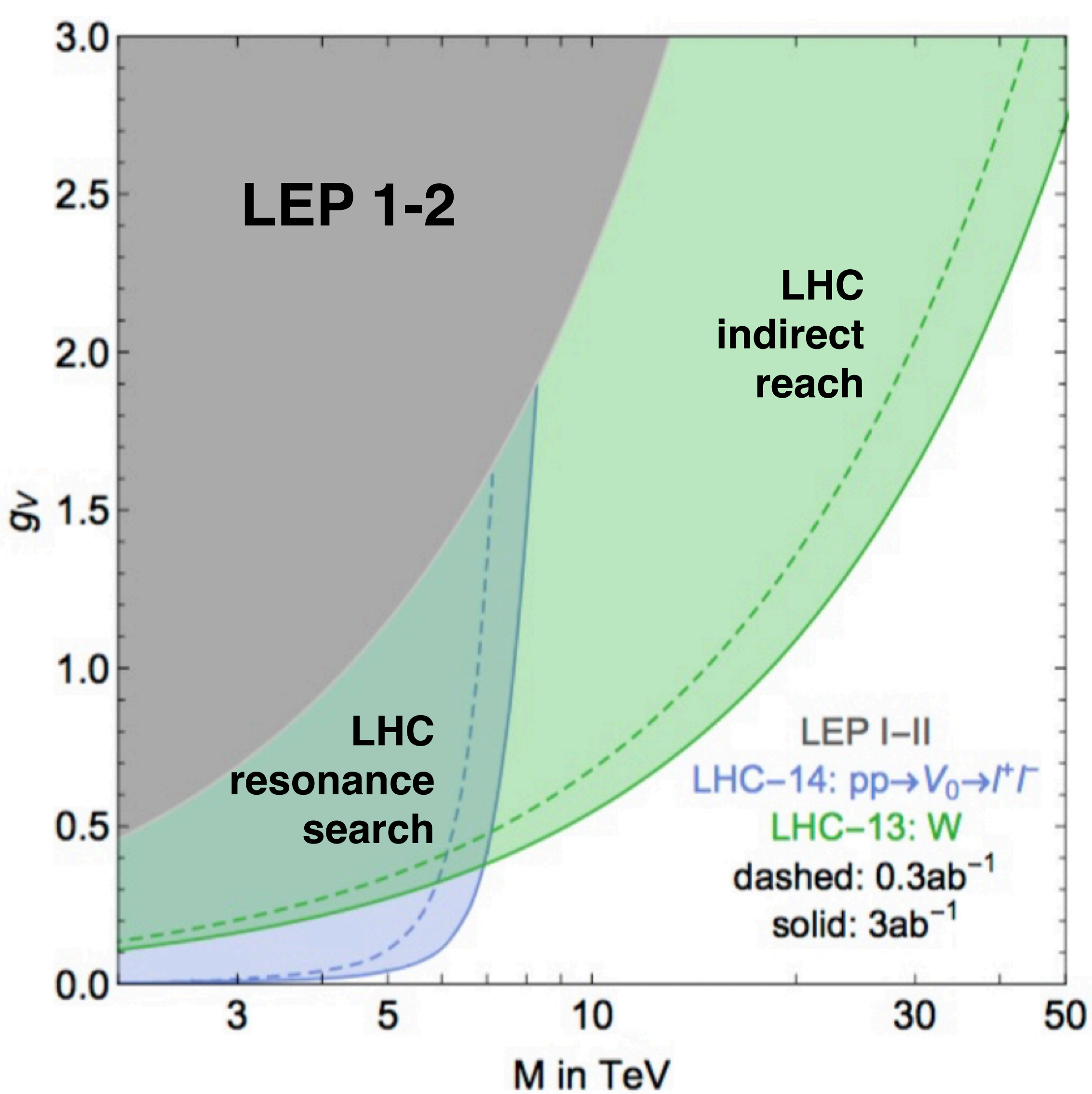
Farina et al, arXiv:1609.08157

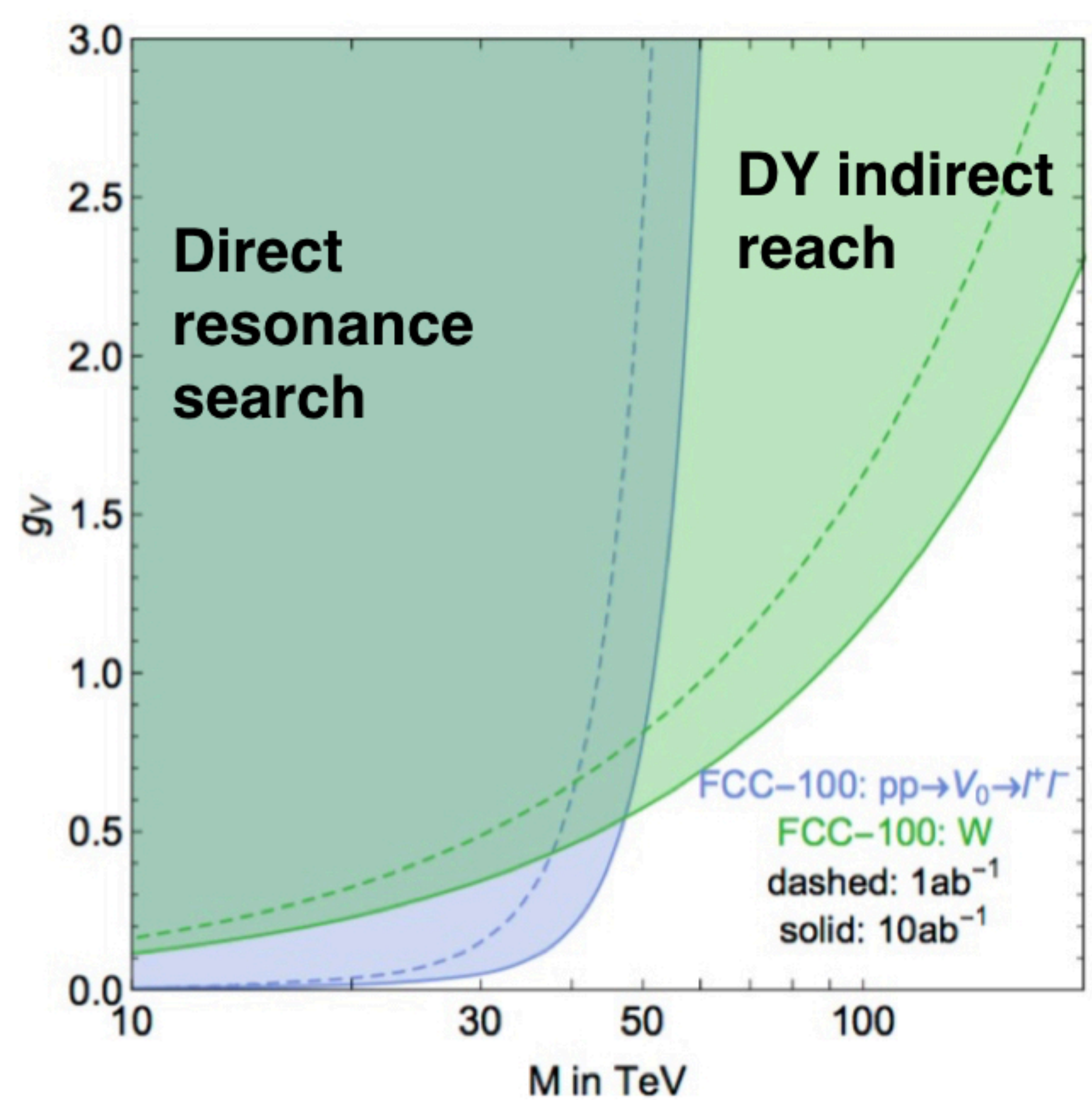
Constraints on Higher-dim op's

$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

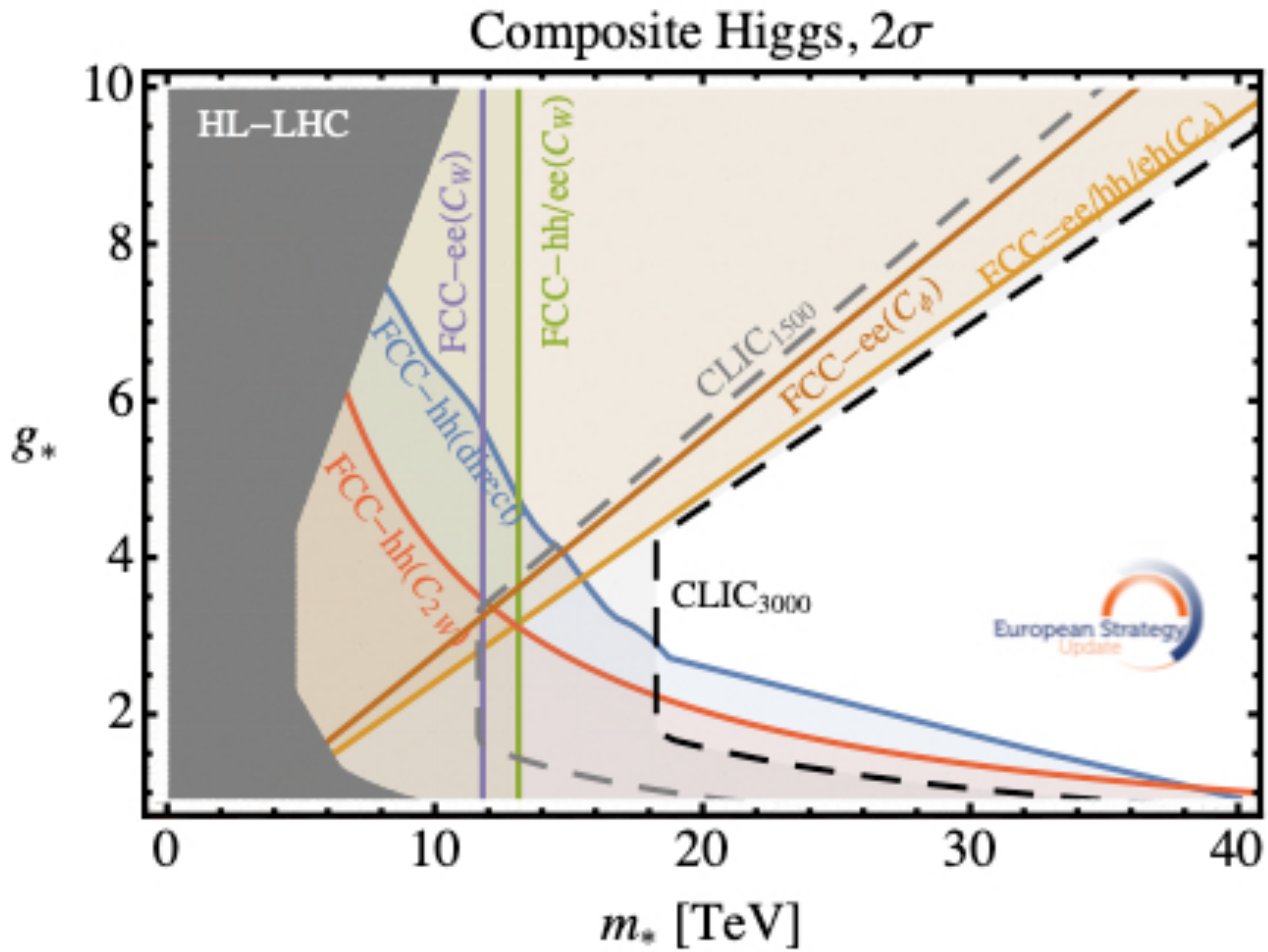
	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2\times10^7\,Z$	0.3/ab	3/ab	10/ab	$10^9\,Z$	$10^{12}\,Z$	$10^{10}\,Z$	3/ab	1/ab	1/ab
W $\times10^4$	[−19, 3]	±0.7	±0.45	±0.02	±4.2	±1.2	±3.6	±0.3	±0.5	±0.15
Y $\times10^4$	[−17, 4]	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2	∼ ±0.5	∼ ±0.15

$W / 4m_W^2 \;<\; 1/(100\ \text{TeV})^2$



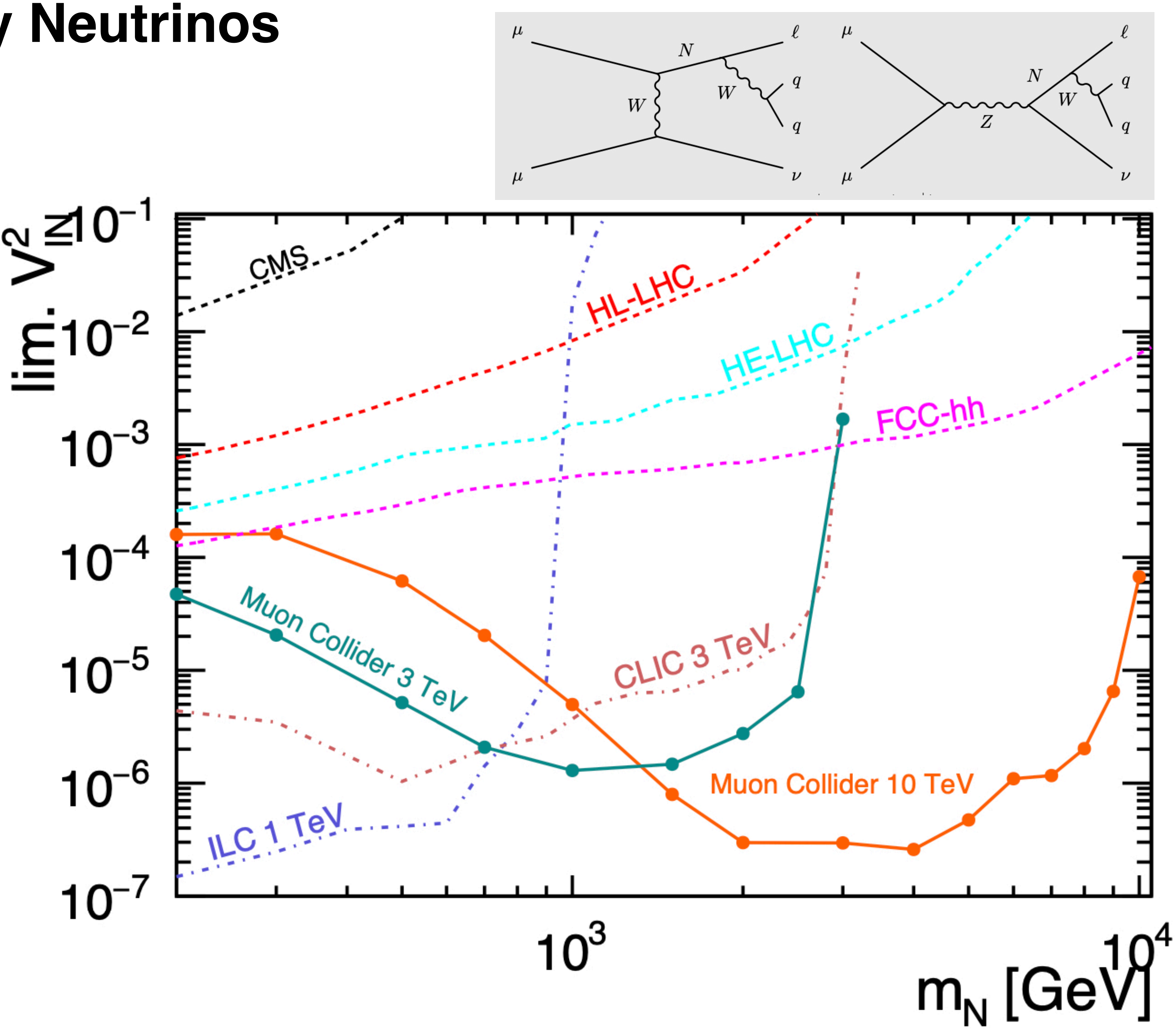


Example of sensitivity to composite-Higgs scenarios, from direct and indirect Higgs and EW measurements



For **direct** searches of very weakly coupled particles, whose final states can be subject to large backgrounds at hadron colliders, lepton colliders have a net advantage. For ex:

Heavy Neutrinos



Mekala et al, arxiv:2301.02602

(3) The potential for yes/no answers to important questions

WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, (χ χ ↔ SM)

$$\Omega_{\rm DM}h^2 \sim \frac{10^9 {\rm GeV}^{-1}}{M_{\rm pl}} \frac{1}{\langle\sigma v\rangle}$$

For a particle annihilating through processes which do not involve any larger mass scales:

$$\langle\sigma v\rangle \sim g_{\rm eff}^4 / M_{\rm DM}^2$$

$$\Omega_{\rm DM}h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}}\right)^2 \left(\frac{0.3}{g_{\rm eff}}\right)^4$$

$$\Omega_{wimp}\, h^2 \lesssim 0.12$$

$$M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3}\right)^2$$

Sensitivity to higgsino **dark matter** candidates: comparison across colliders for direct reach

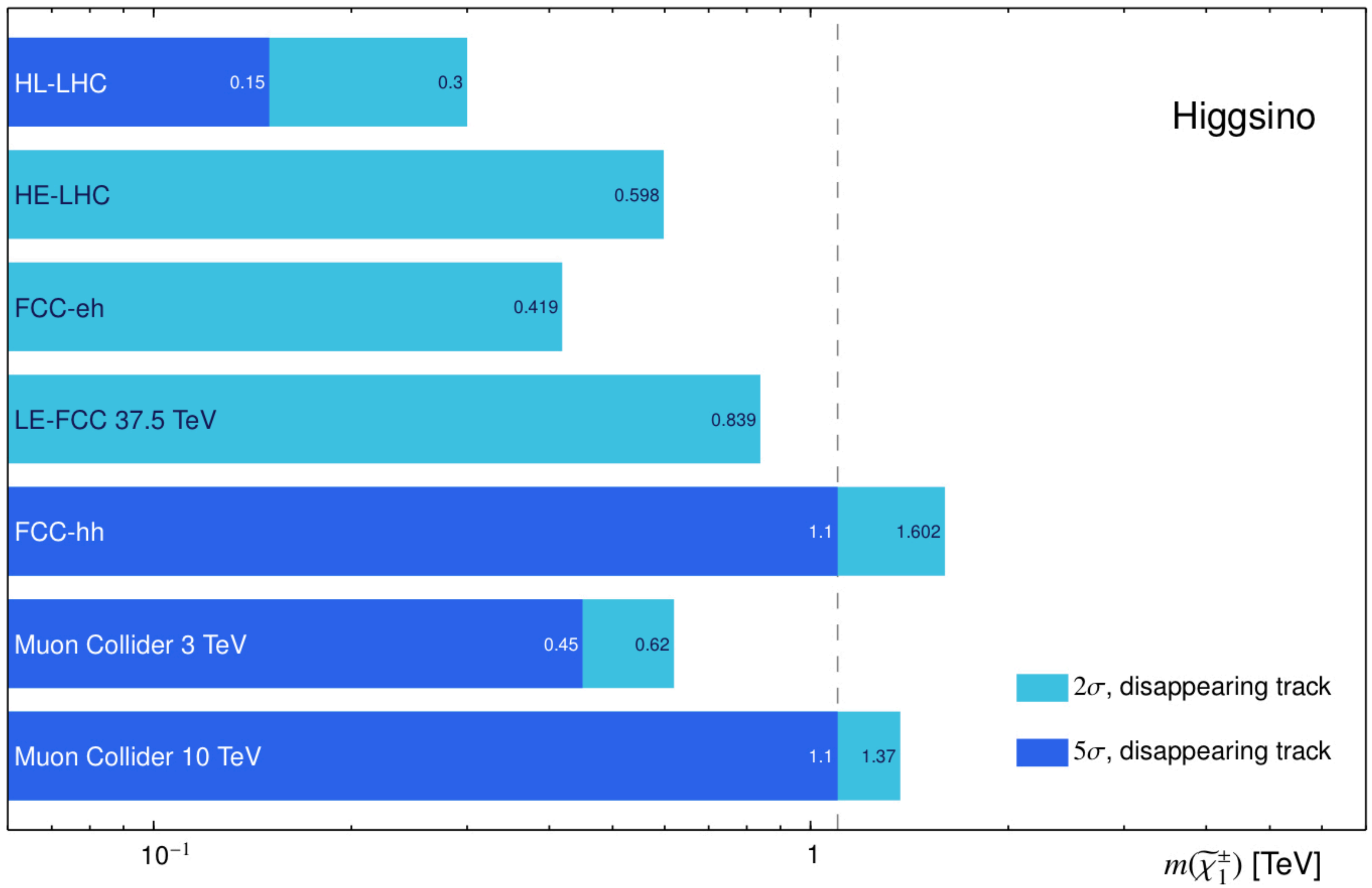


Figure 2-34. *Overview plot for the sensitivity to the pure Higgsino, assuming its natural mass splitting, for various future colliders. Figure adapted from [410].*

The direct discovery reach for an elusive weakly interacting particle at a lepton collider with CM energy E compete with that of a pp collider at ~ 10xE CM energy

FCC-ee/hh, or a multi-TeV muon collider, could conclusively search for WIMPS in T_3^W = 1/2, 1 reps

Key wrap-up messages:

- The Higgs mechanism hints at the existence of a more fundamental landscape of interactions, at the origin of EW symmetry breaking
- Contrary to the search for the origin of other signals of new physics (DM, neutrino masses, baryon asymmetry of the universe), the exploration of Higgs properties can only be pursued at colliders
- The potential to improve the Higgs knowledge is a mandatory guaranteed deliverable and a key criterion to assess the value of a future facility
- Judging the value of the discovery potential of different colliders relies in part on prejudice and on how specific features of different new-physics models resonate with the distinctive qualities of different colliders (E vs precision, direct vs indirect discovery, signal strength vs background reduction, …)
- The diversity of the opportunities offered by different collider facilities should be a major selection criterion. The experience of LEP/LHC singles out FCCs as the most versatile and far-reaching evolution beyond the LHC