سومین کارگاه

دو روز با ذرات بنیادی

۲۶و ۲۷ آبان ماه ۱۴۰۰

اعضای کمیته اجرایی

شهو عبدالسلام (دبیر اجرایی)
سید امیر رضا اجاقی
نرگس علیزاده

اعضای کمیته علمی

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موضوعات

فیزیک مدل استاندارد و ورای آن
نظریه میدان کوانتومی در دمای محدود
توابع توزیع پارتون هادرون هادرونها

نظریه ریسمان
پدیده شناسی فیزیک ذرات

لینک وب سایت جهت ثبت نام
https://indi.to/rVckX

انجمن علمی فیزیک
دانشگاه شهید بهشتی

CERN

Physics at Future Circular Colliders

Two Days with Particle Physics Workshop

Shahid Beheshti University
17-18 November 2021

Michelangelo L. Mangano
Theory Department,
CERN, Geneva

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BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

$$L = -\tfrac{1}{2}(\nabla \varphi_1)^2 - \tfrac{1}{2}(\nabla \varphi_2)^2 \boxed{- V(\varphi_1{}^2 + \varphi_2{}^2)} - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad (1)$$

Let us suppose that $V'(\varphi_0{}^2) = 0$, $V''(\varphi_0{}^2) > 0$; then spontaneous breakdown of U(1) symmetry occurs.

$m_A = e\, \phi_0$

$$\partial_\mu F^{\mu\nu} = - \boxed{e^2 \phi_o^2} A^\mu$$

2

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
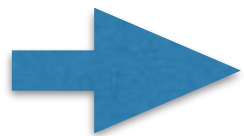Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

$$\mathcal{L} = -\tfrac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu)^2 - \tfrac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig'B_\mu)R - \bar{L}\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu - i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu \varphi - ig\vec{A}_\mu \cdot \vec{t}\varphi + i\tfrac{1}{2}g'B_\mu\varphi|^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^\dagger L) \boxed{-M_1^2\varphi^\dagger\varphi + h(\varphi^\dagger\varphi)^2.} \quad (4)$$
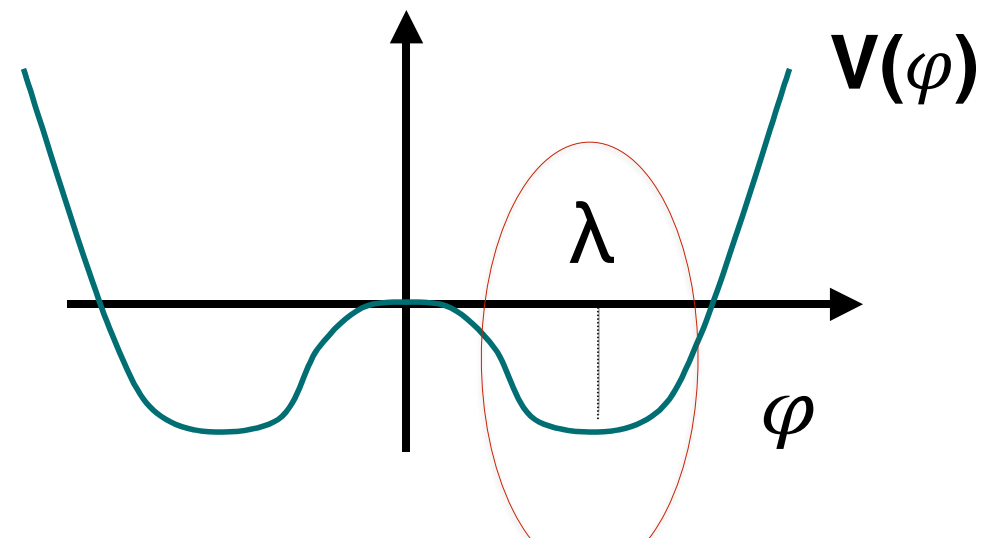
$$\mathbf{V}(\varphi)$$

$$\langle\varphi\rangle = \lambda\begin{pmatrix}1\\0\end{pmatrix}.$$

$$M_W = \tfrac{1}{2}\lambda g.$$

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2},$$

$$M_A = 0,$$

$$\mathbf{V}(\varphi)$$

$$\lambda$$

$$\varphi$$

3

Fast forward to 2012

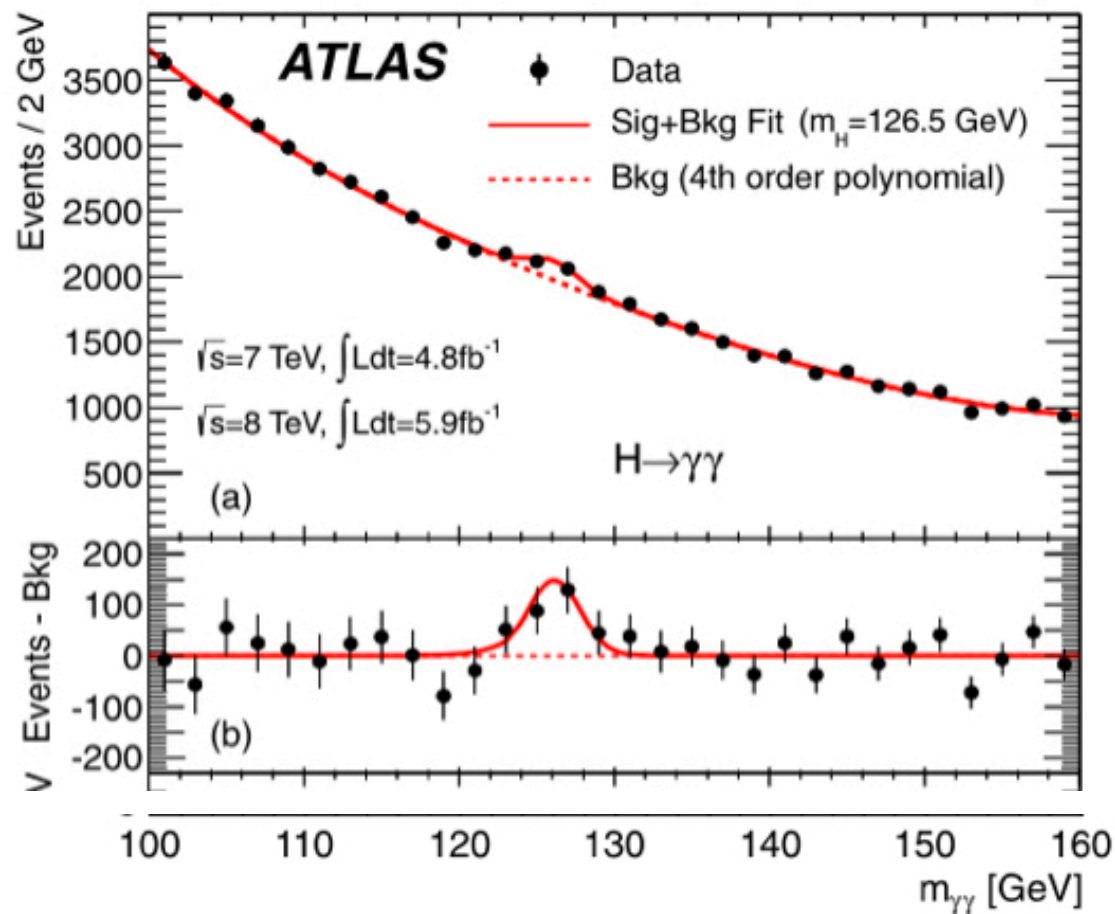**Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC** ☆
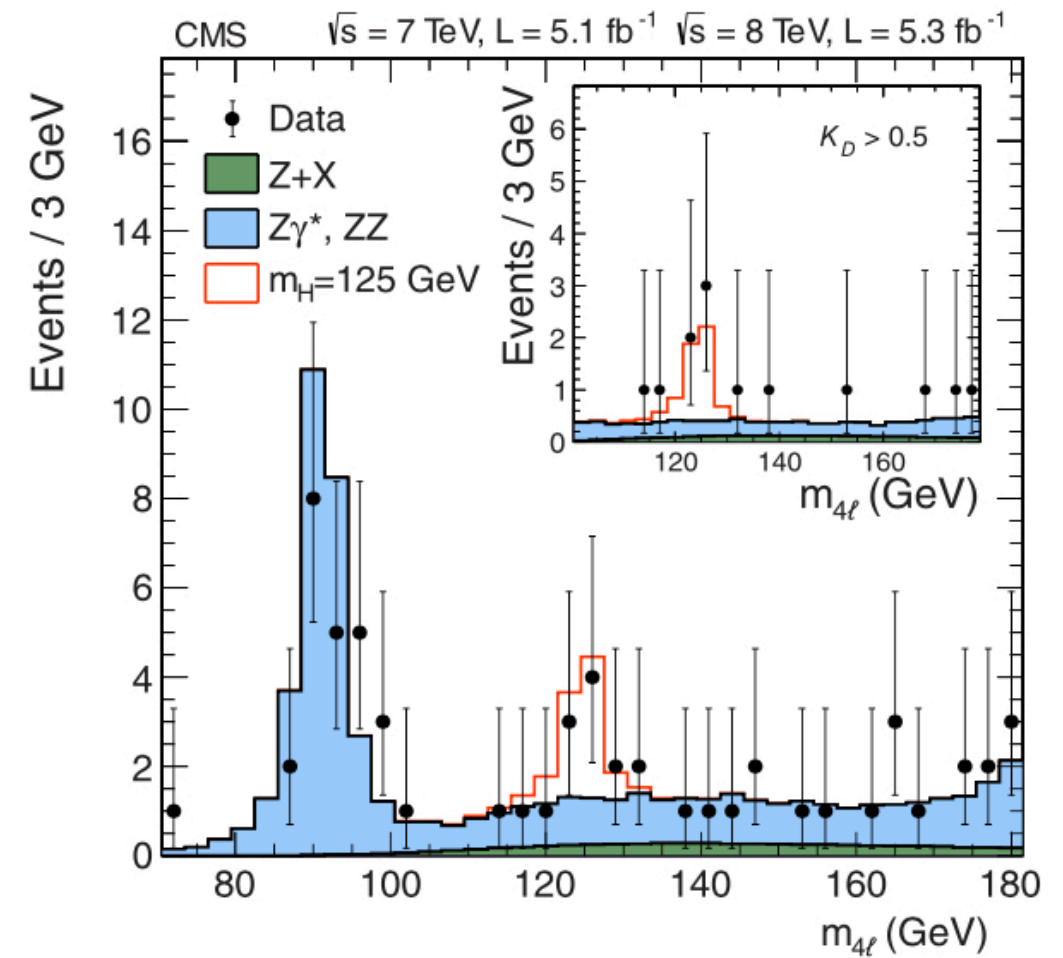
ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

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what's next?

what more do we need to explore?

# The open 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
  - …

We have no guarantees as to where answers to these questions will come from, and what are the experiments that will eventually answer them.

But there is one question that can only be addressed by colliders, and future collider efforts must focus on its thorough exploration
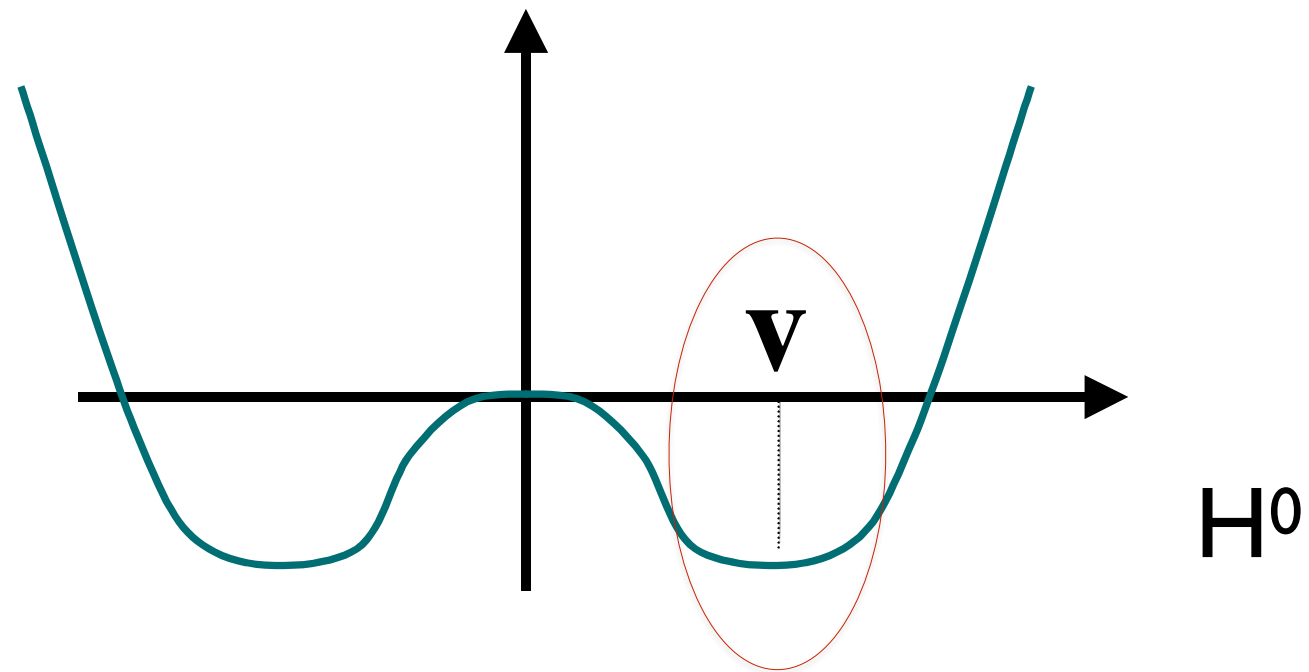
$$V(H) = - \mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

- The search for the origin of the Higgs and EW symmetry breaking is justified independently of prejudice on the relevance of theoretical puzzles like the hierarchy problem

- It is reasonable to expect that the dynamics underlying the Higgs phenomenon sits nearby the EW scale, justifying the yet unfulfilled hope that new physics should be seen by LHC…

- .. thus many theoretical ideas are emerging, postponing to much higher energies or to alternative scenarios the framework to understand the origin of the weak scale

- The detailed experimental investigation of Higgs properties remains nevertheless a sine qua non condition to make progress no matter what is our bias

The importance of the in-depth exploration of the Higgs properties was acknowledged by the 2020 update of the European Strategy for Particle Physics:

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

- The precision measurement of Higgs properties must be a guaranteed deliverable of all future colliders

- Whether the measurements will challenge or confirm the SM properties, these measurements are a key ingredient in exploration of physics beyond the SM.

- Should they show deviations from the SM, the hint to BSM will be explicit, and the correlations among the various deviations will guide the interpretation of their origin

- Should they agree with the SM, the more accurate the measurements, the more constraining their power in identifying the microscopic origin of possible BSM effects observed in other parts of the programme

  - *The LEP precision measurements are still today an essential constraint in evaluating BSM models proposed whenever some anomaly is detected in the data*

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 **<u>same</u>** Higgs field?
  - Do $I_3 = 1/2$ fermions (up-type quarks) get their mass from the **<u>same</u>** 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?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- 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 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>*

Key question for the future developments of HEP:
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* ⇒ *higher statistics, better detectors and experimental conditions*

- *sensitivity (to elusive signatures)* ⇒ *ditto*

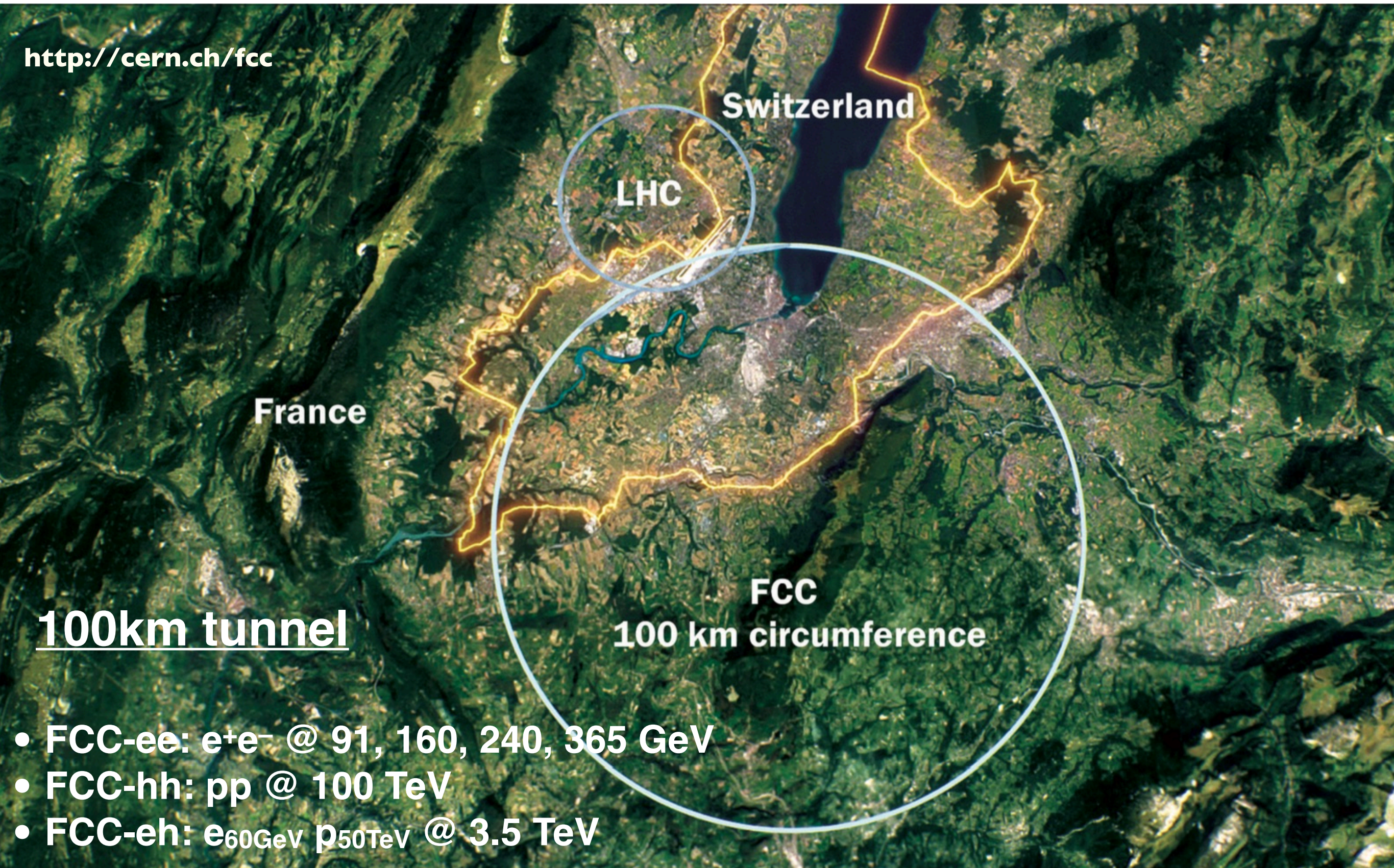- **extended energy/mass reach ⇒ higher energy**

From ESPP 2020:

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. "

Answer to these challenges: Future Circular Collider

http://cern.ch/fcc

Switzerland

LHC

France

FCC
100 km circumference

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

What the future **circular** collider can offer

- <u>Guaranteed deliverables</u>:
  - study of <u>Higgs</u> and <u>top</u> quark properties, and exploration of <u>EWSB</u> phenomena, with the best possible **precision and sensitivity**

- <u>Exploration potential</u>:
  - exploit both direct (large Q^2) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration at 100 TeV
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*

- <u>Provide firm Yes/No answers</u> to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

Event rates: examples

FCC-ee	H	Z	W	t	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
	10^6	$5 \cdot 10^{12}$	10^8	10^6	$3 \cdot 10^{11}$	$1.5 \cdot 10^{12}$	10^{12}

FCC-hh	H	b	t	$W(\leftarrow t)$	$\tau(\leftarrow W \leftarrow t)$
	$2.5 \cdot 10^{10}$	10^{17}	10^{12}	10^{12}	10^{11}

FCC-eh	H	t
	$2.5 \cdot 10^6$	$2 \cdot 10^7$

(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
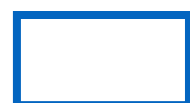
5 – 10 %

> 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
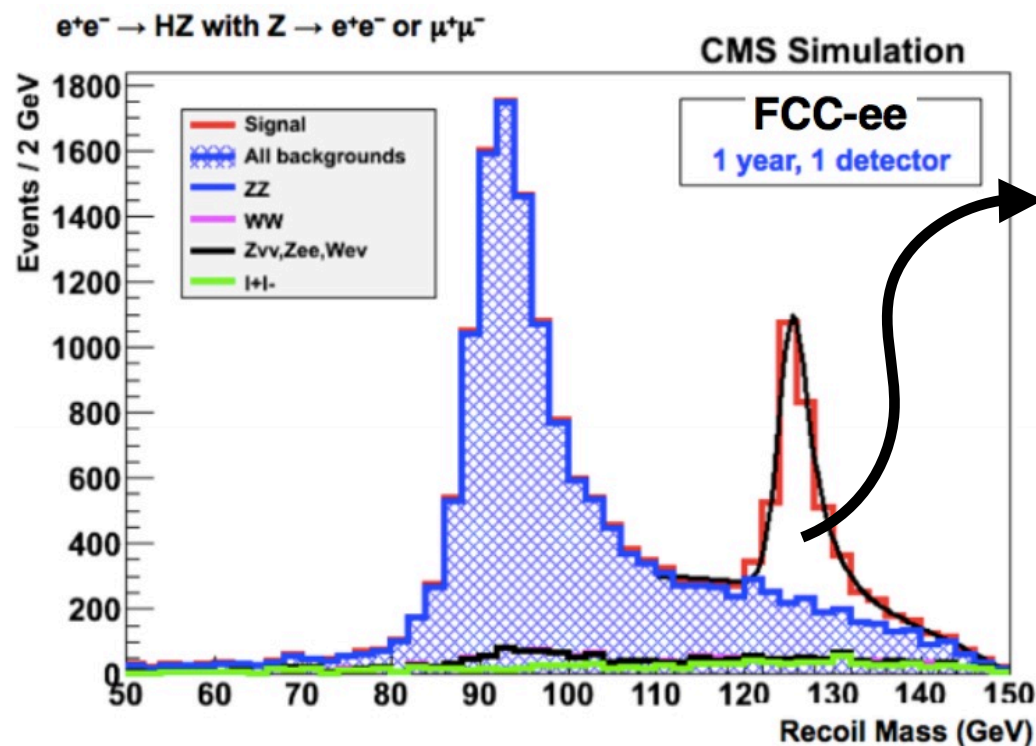
The absolutely unique power of e⁺e⁻ →ZH (circular or linear):

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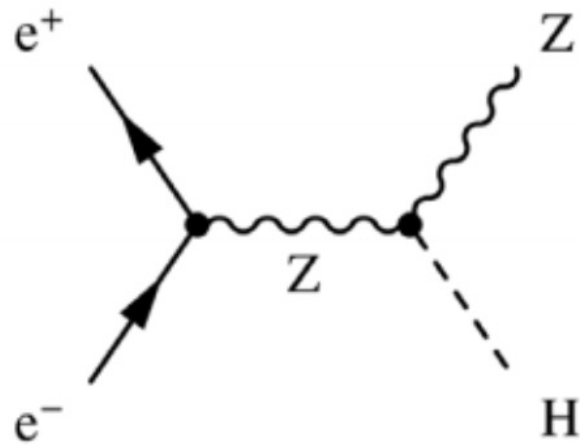
$p(H) = p(e^-e^+) - p(Z)$

$\Rightarrow [\, p(e^-e^+) - p(Z) \,]^2$ **peaks at m²(H)**

reconstruct Higgs events independently of the Higgs decay mode!

e⁺e⁻ → HZ with Z → e⁺e⁻ or μ⁺μ⁻

CMS Simulation

FCC-ee
1 year, 1 detector

Legend:
- Signal
- All backgrounds
- ZZ
- WW
- Zνν, Zee, Wev
- l+l-

Recoil Mass (GeV)

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

N(ZH) $\propto$ **σ(ZH)** $\propto$ **g$_{HZZ}$²**

N(ZH[→ZZ]) $\propto$
σ(ZH) x BR(H→ZZ) $\propto$
g$_{HZZ}$² x g$_{HZZ}$² / **Γ(H)**

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

The absolutely unique power of pp →H+X:

- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→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
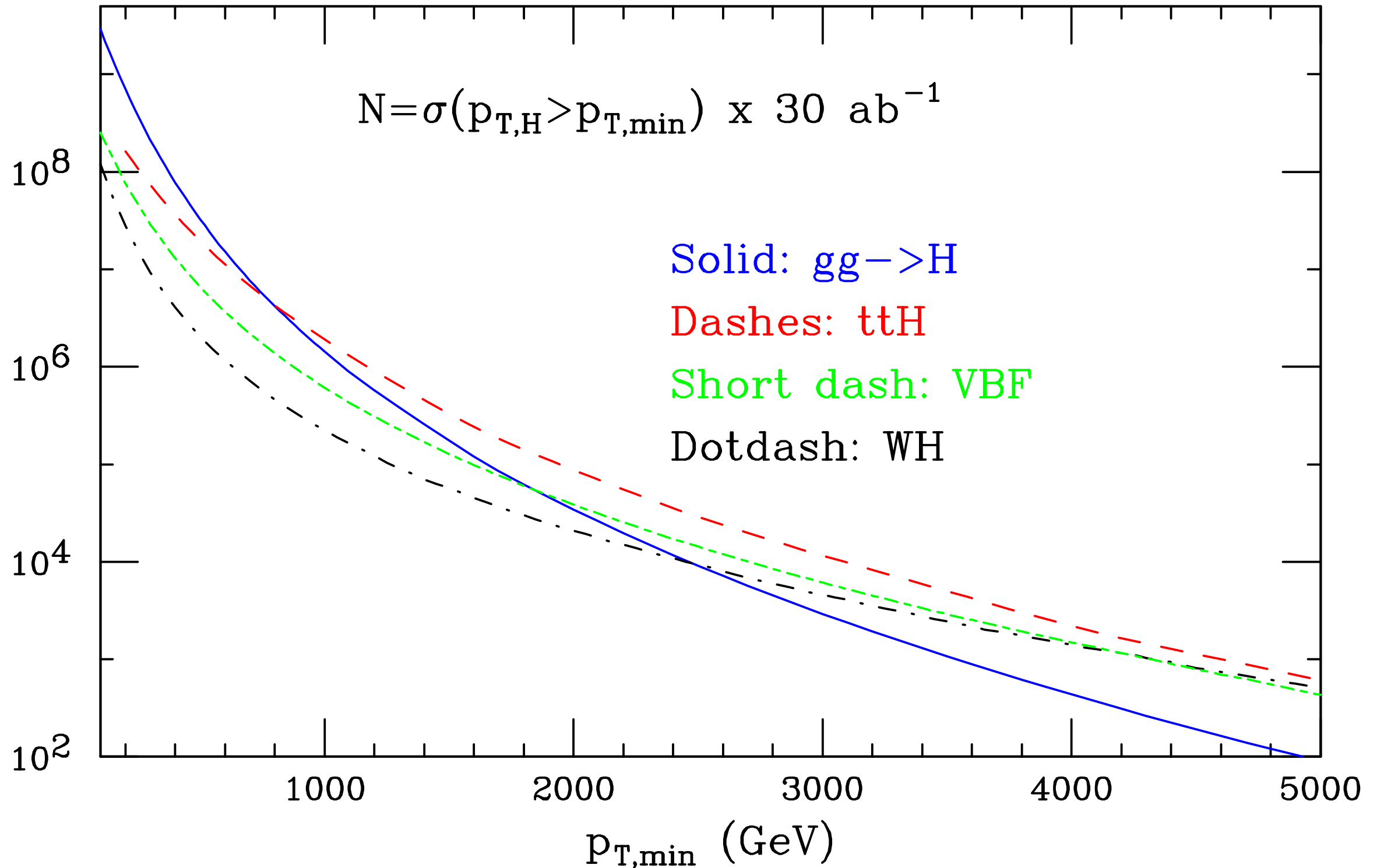 - search for multi-TeV resonances decaying to H, or extensions of the Higgs sector

	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

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

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

H at large p$_T$

$$N = \sigma(p_{T,H} > p_{T,min}) \times 30 \ ab^{-1}$$

Solid: gg−>H
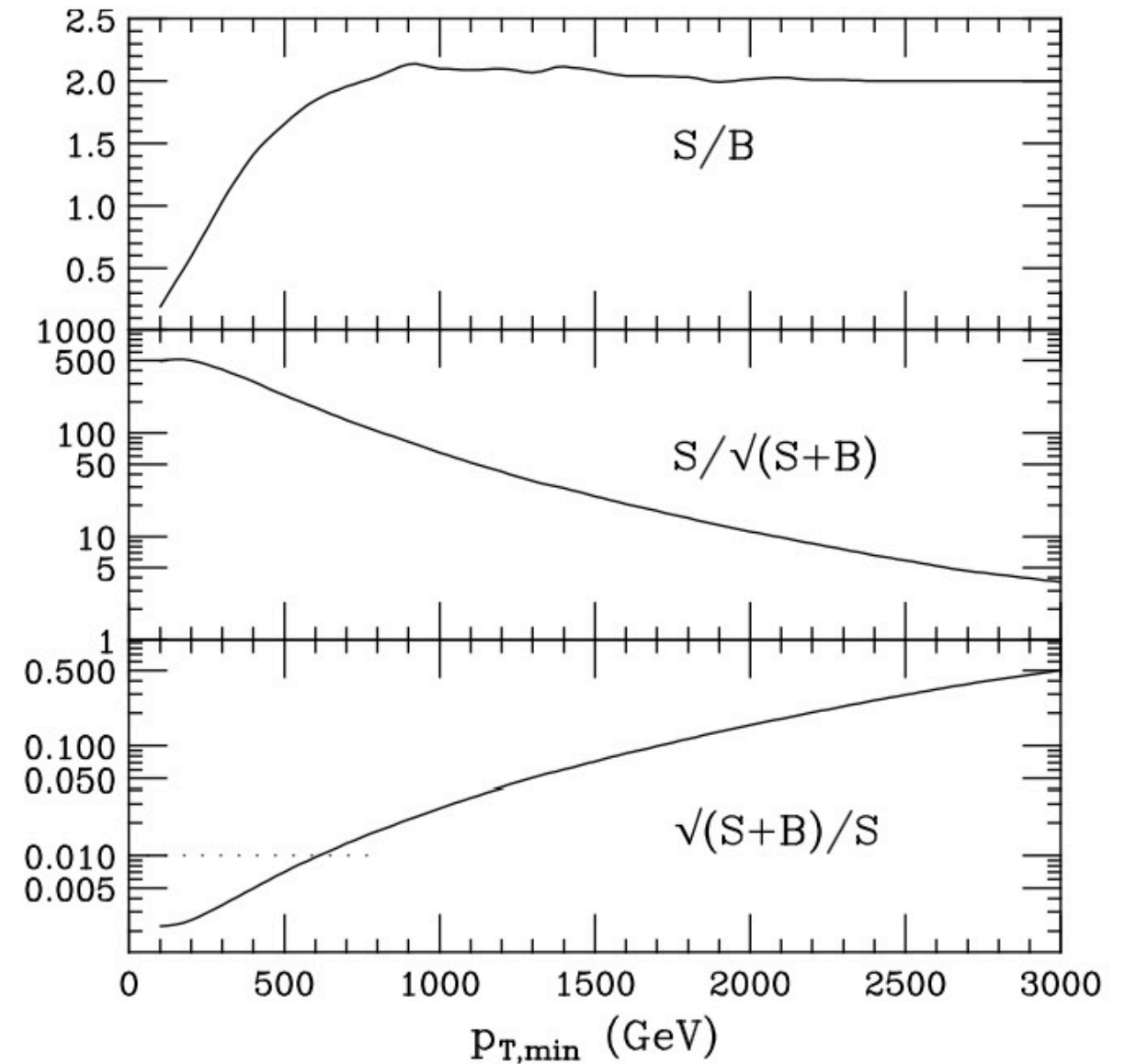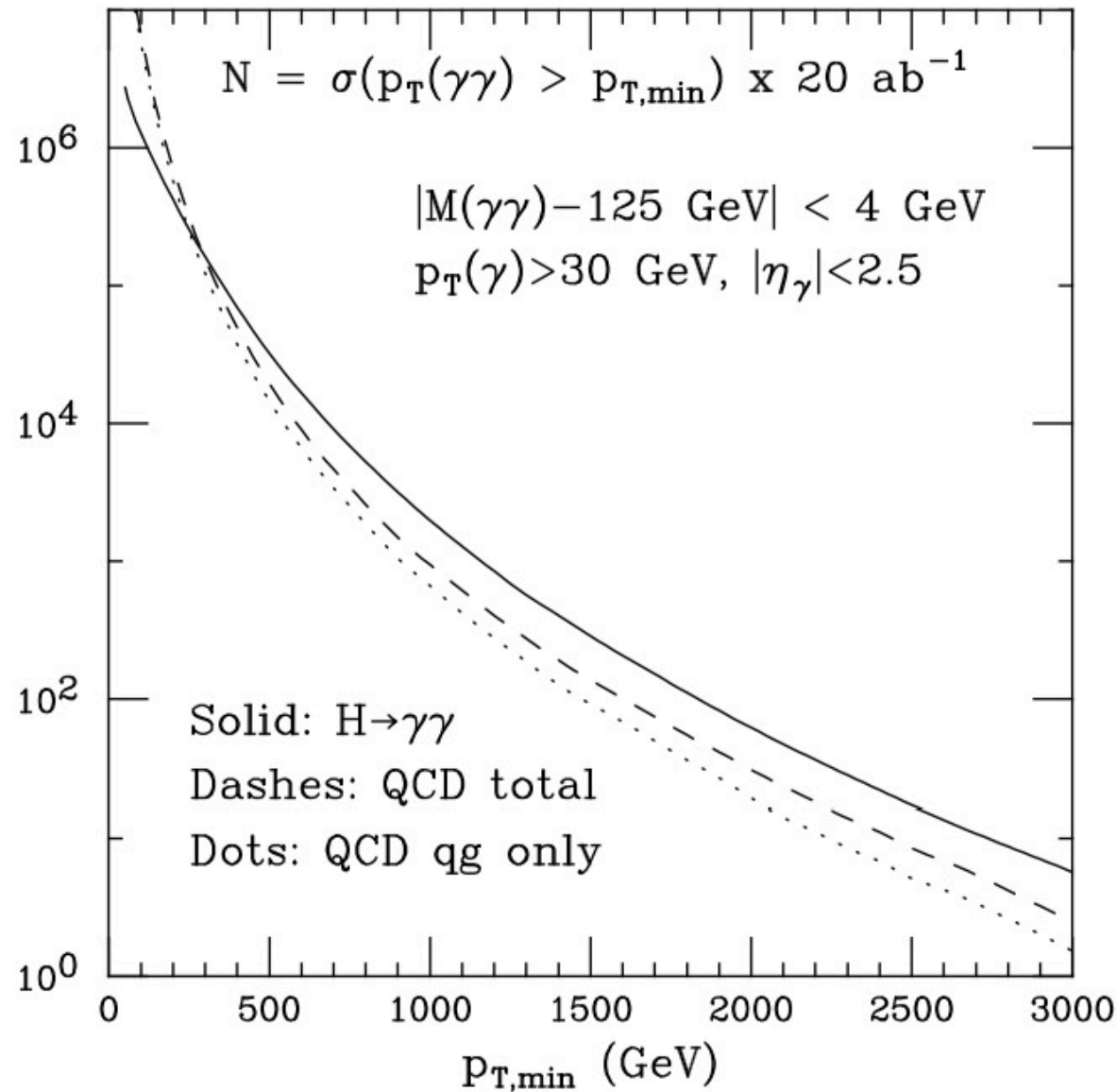Dashes: ttH
Short dash: VBF
Dotdash: WH

$p_{T,min}$ (GeV)

- 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 $\Rightarrow$ low efficiency, large systematics

  ➡ det simulations challenging, likely unreliable $\Rightarrow$ regime not studied so far

- <u>$p_T \gtrsim 100$ GeV :</u>
  - stat uncertainty ~few $\times$ 10^{-3} for H$\rightarrow$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$\rightarrow$4l, $\gamma\gamma$ (H$\rightarrow$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~m_H

gg→H→γγ at large p$_T$

$N = \sigma(p_T(\gamma\gamma) > p_{T,min}) \times 20\ ab^{-1}$

$|M(\gamma\gamma) - 125\ GeV| < 4\ GeV$
$p_T(\gamma) > 30\ GeV, |\eta_\gamma| < 2.5$

Solid: H→γγ
Dashes: QCD total
Dots: QCD qg only

S/B

S/√(S+B)

√(S+B)/S

- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p$_T$(H)>300 GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

p$_{T,min}$ (GeV)	δ$_{stat}$
100	0.2%
400	0.5%
600	1%
1600	10%
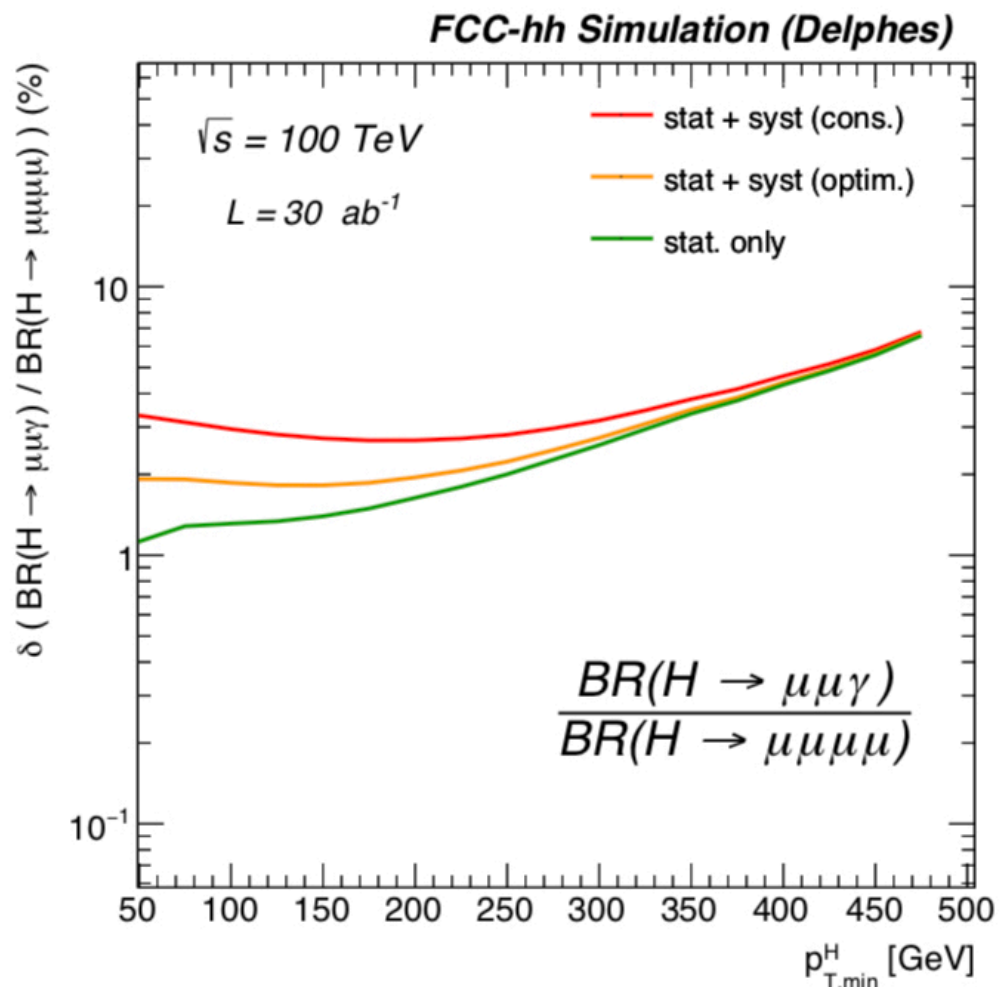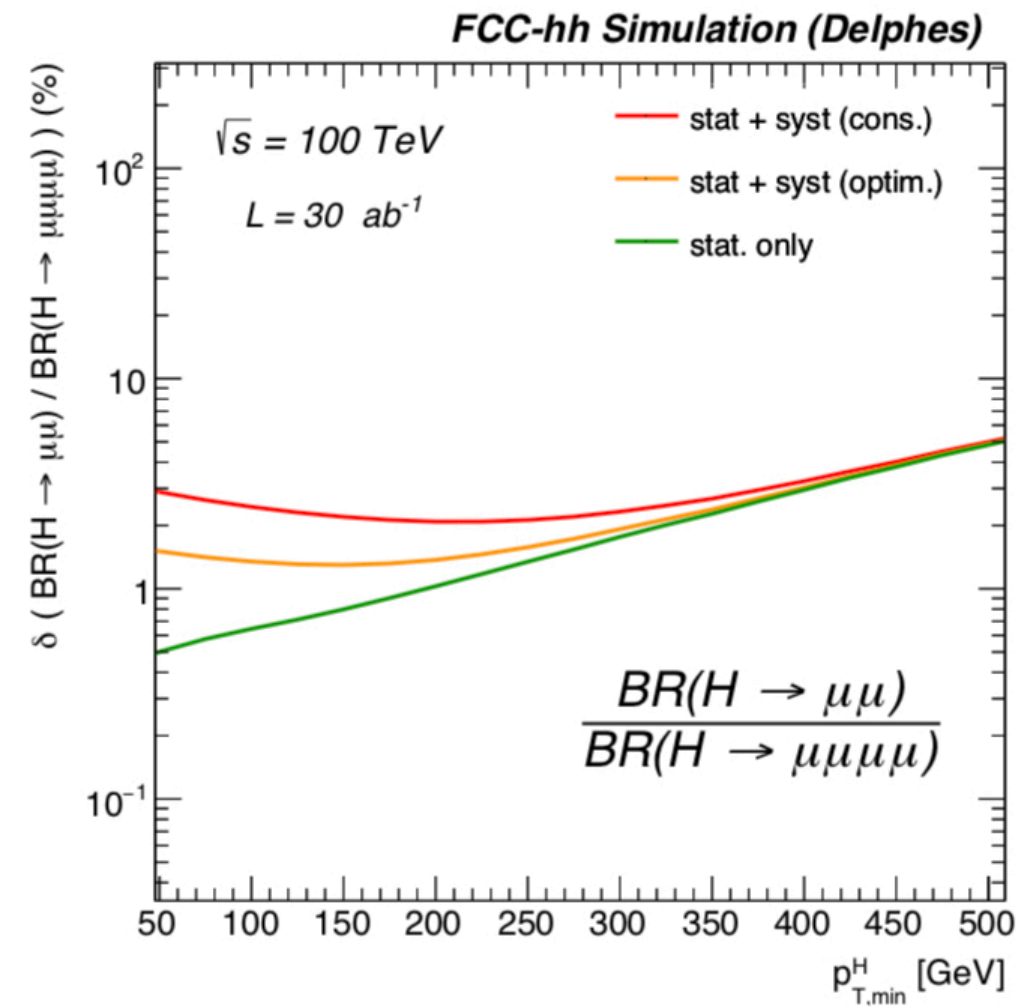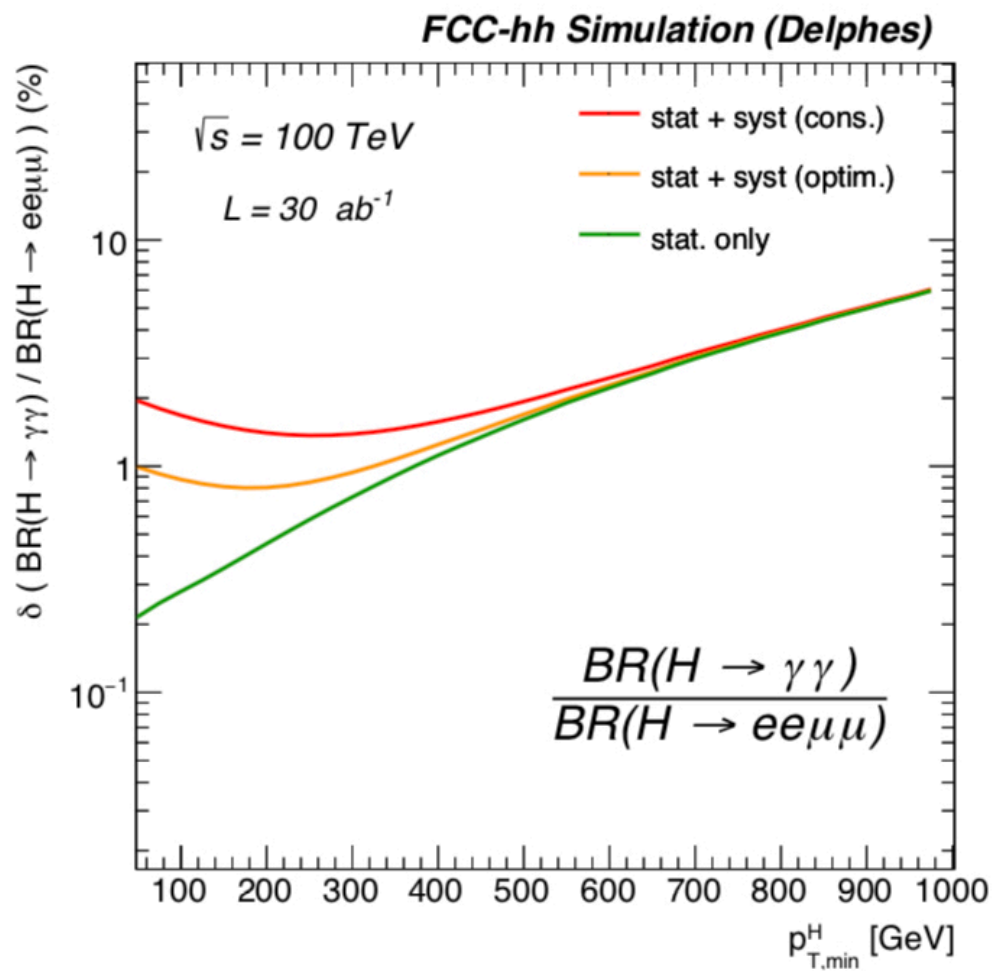
Normalize to BR(4l) from ee => sub-% precision for absolute couplings

Future work: explore in more depth data-based techniques, to <u>validate and then reduce</u> the systematics in these ratio measurements, possibly moving to lower pt's and higher stat
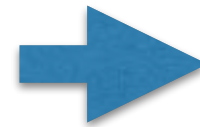
Higgs couplings after FCC-ee / hh

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

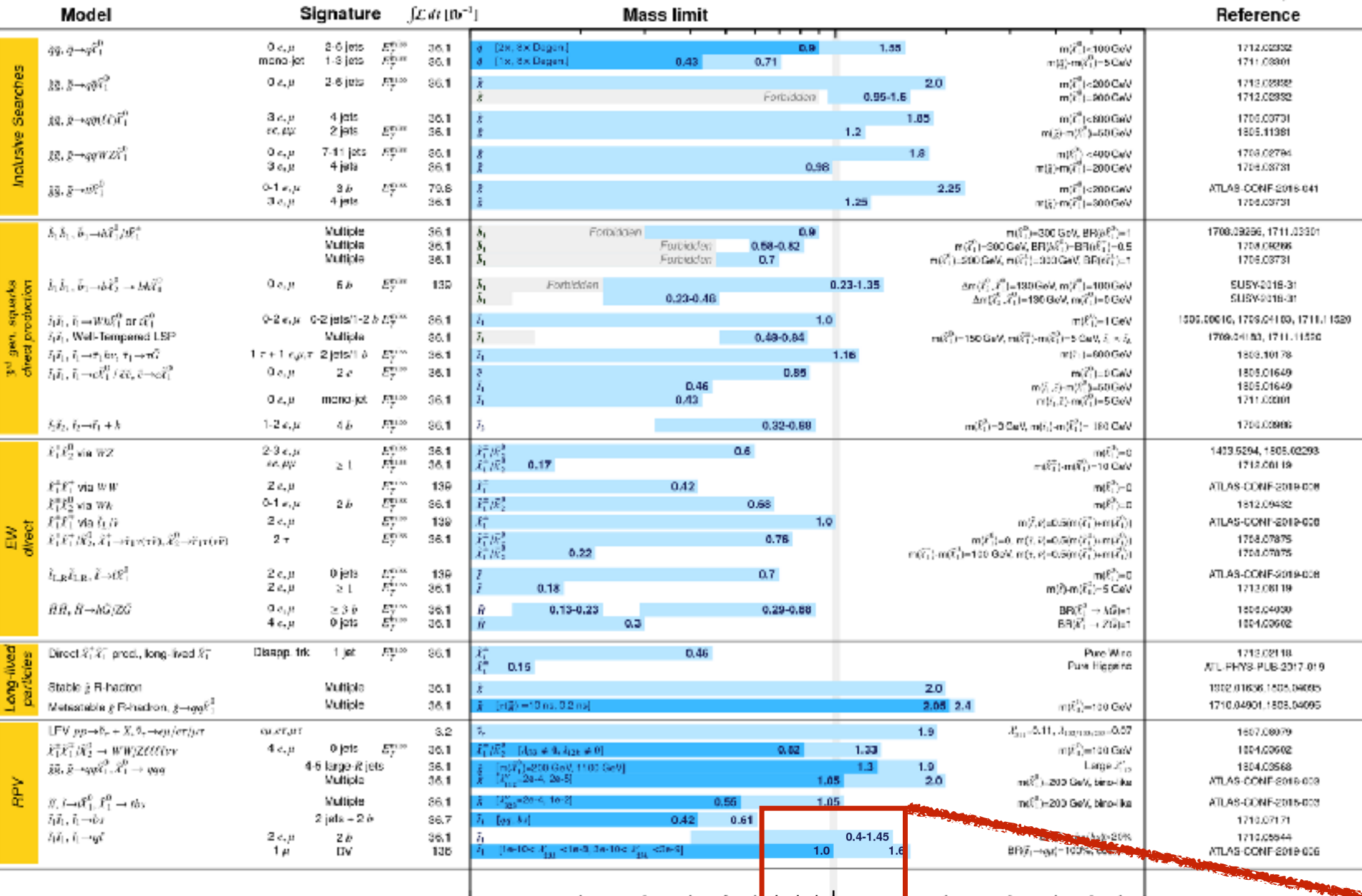$BR(H\rightarrow\mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for Δ_{stat}~%**

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→ZZ*) @ FCC-ee

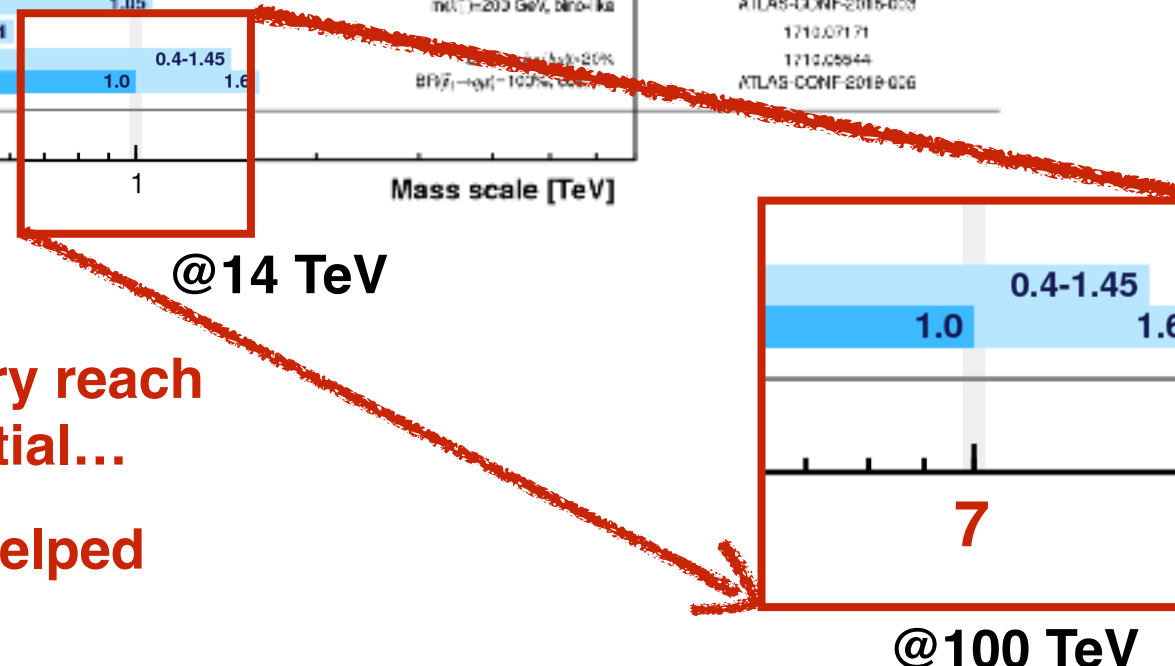** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

(2) **Direct discovery reach at high mass: the power of 100 TeV**

ATLAS SUSY Searches* - 95% CL Lower Limits (March 2019) — ATLAS Preliminary, √s = 13 TeV
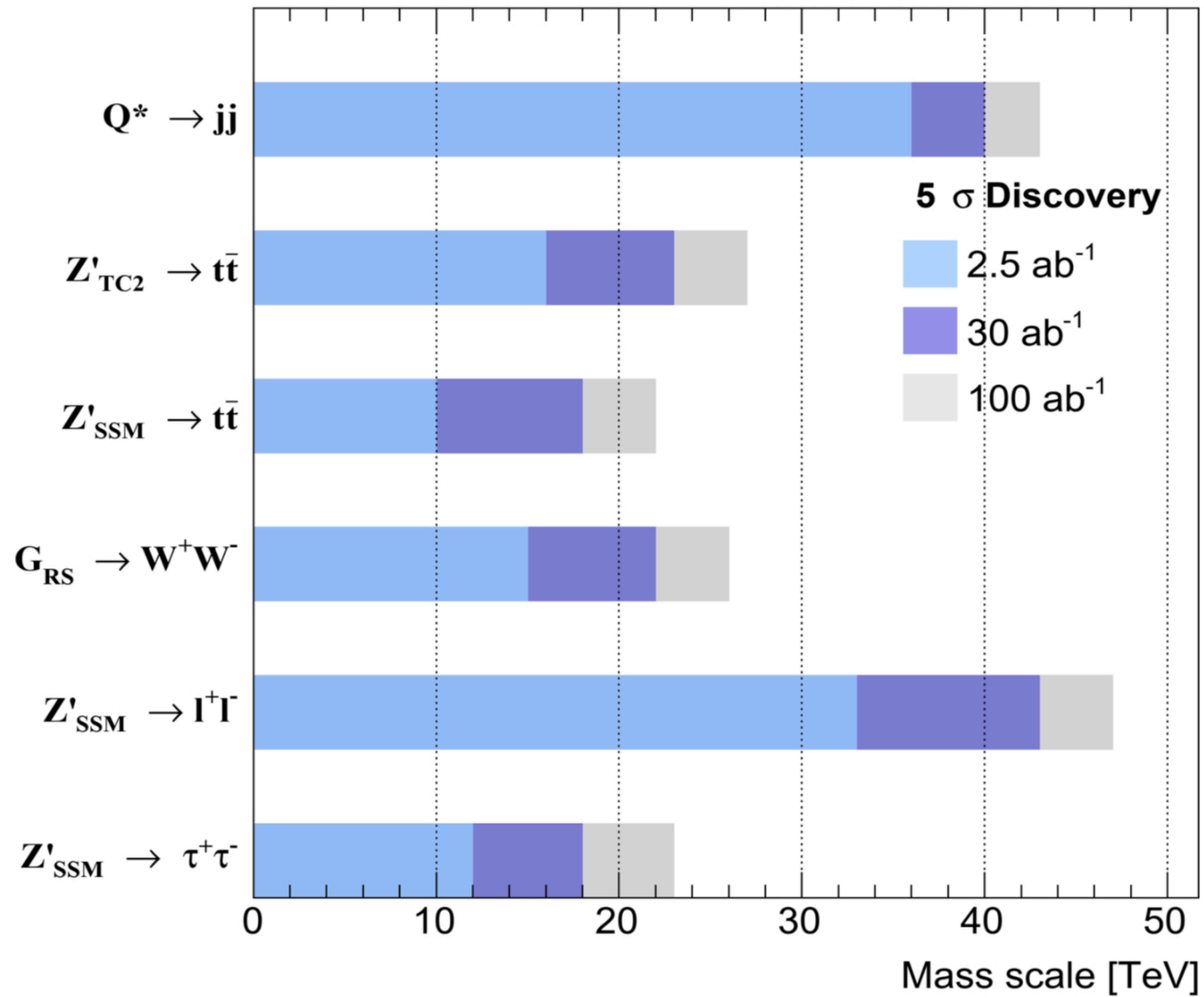
Good rule of thumb to estimate FCC discovery reach at high mass: scale up by ~6x the LHC potential…

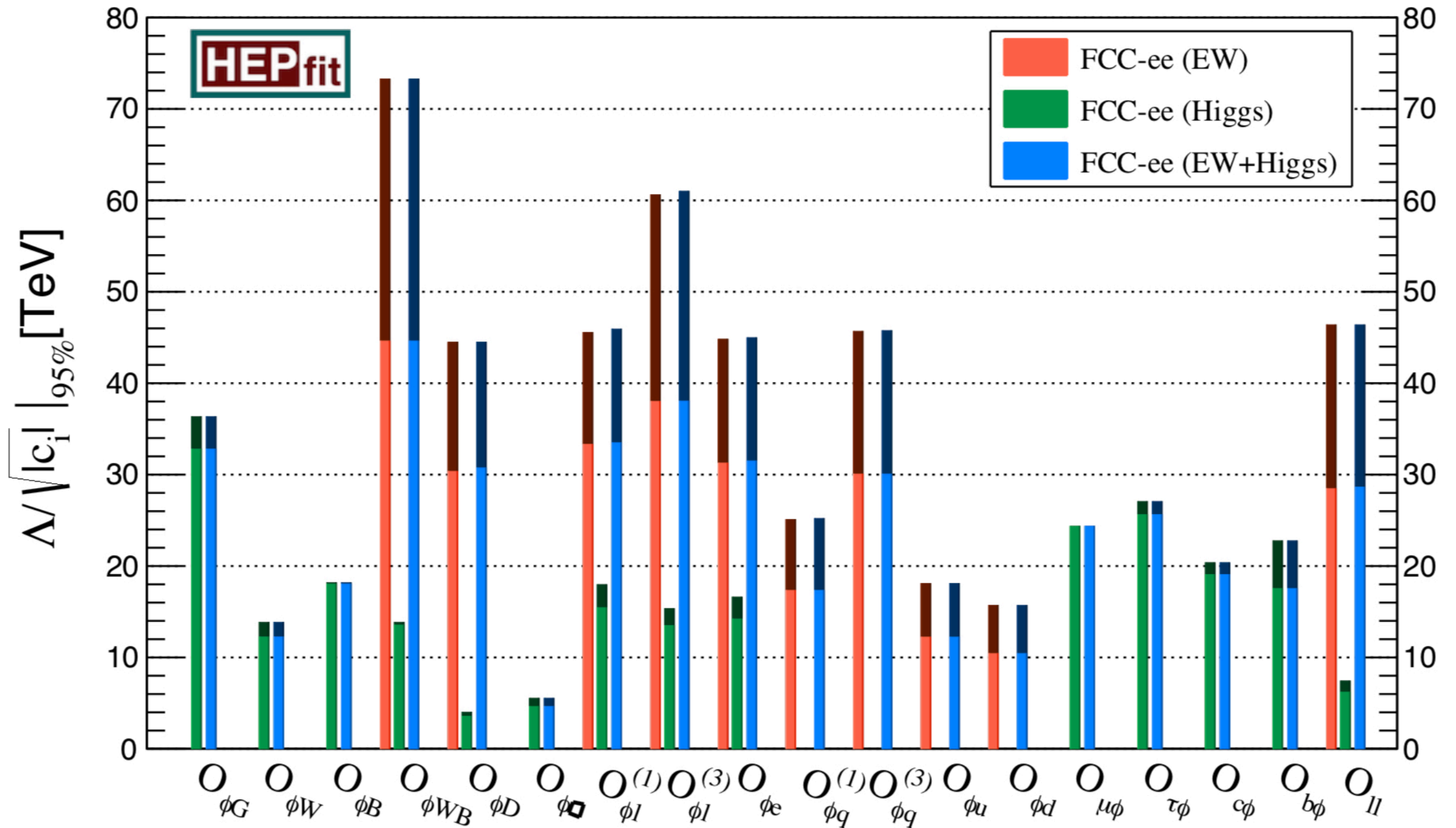**Explicitly verified in many examples, which helped setting detector performance targets**

@14 TeV

@100 TeV

s-channel resonances

FCC-hh Simulation (Delphes), $\sqrt{s} = 100$ TeV

Legend: 5 σ Discovery — 2.5 ab^{-1}, 30 ab^{-1}, 100 ab^{-1}

Rows: $Q^* \to jj$, $Z'_{TC2} \to t\bar{t}$, $Z'_{SSM} \to t\bar{t}$, $G_{RS} \to W^+W^-$, $Z'_{SSM} \to l^+l^-$, $Z'_{SSM} \to \tau^+\tau^-$
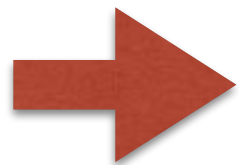
Mass scale [TeV]

FCC-hh reach ~ 6 x HL-LHC reach

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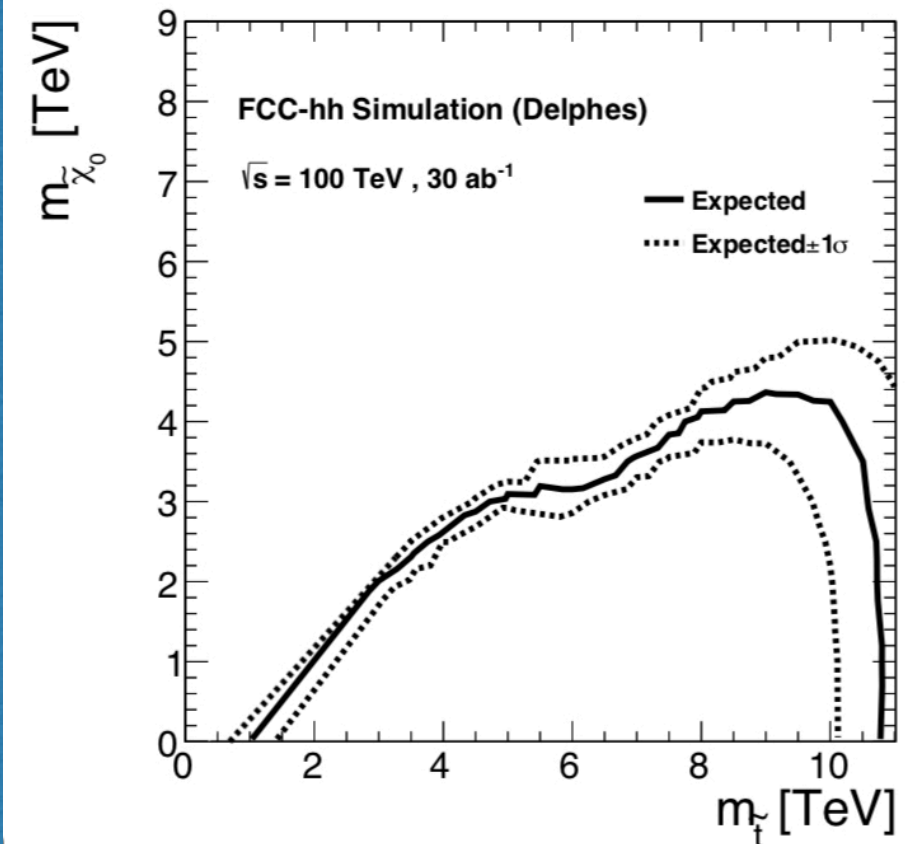
100 TeV is the appropriate CoM energy to directly search for new physics appearing indirectly through precision EW and H measurements at the future ee collider

SUSY reach at 100 TeV

Early phenomenology studies
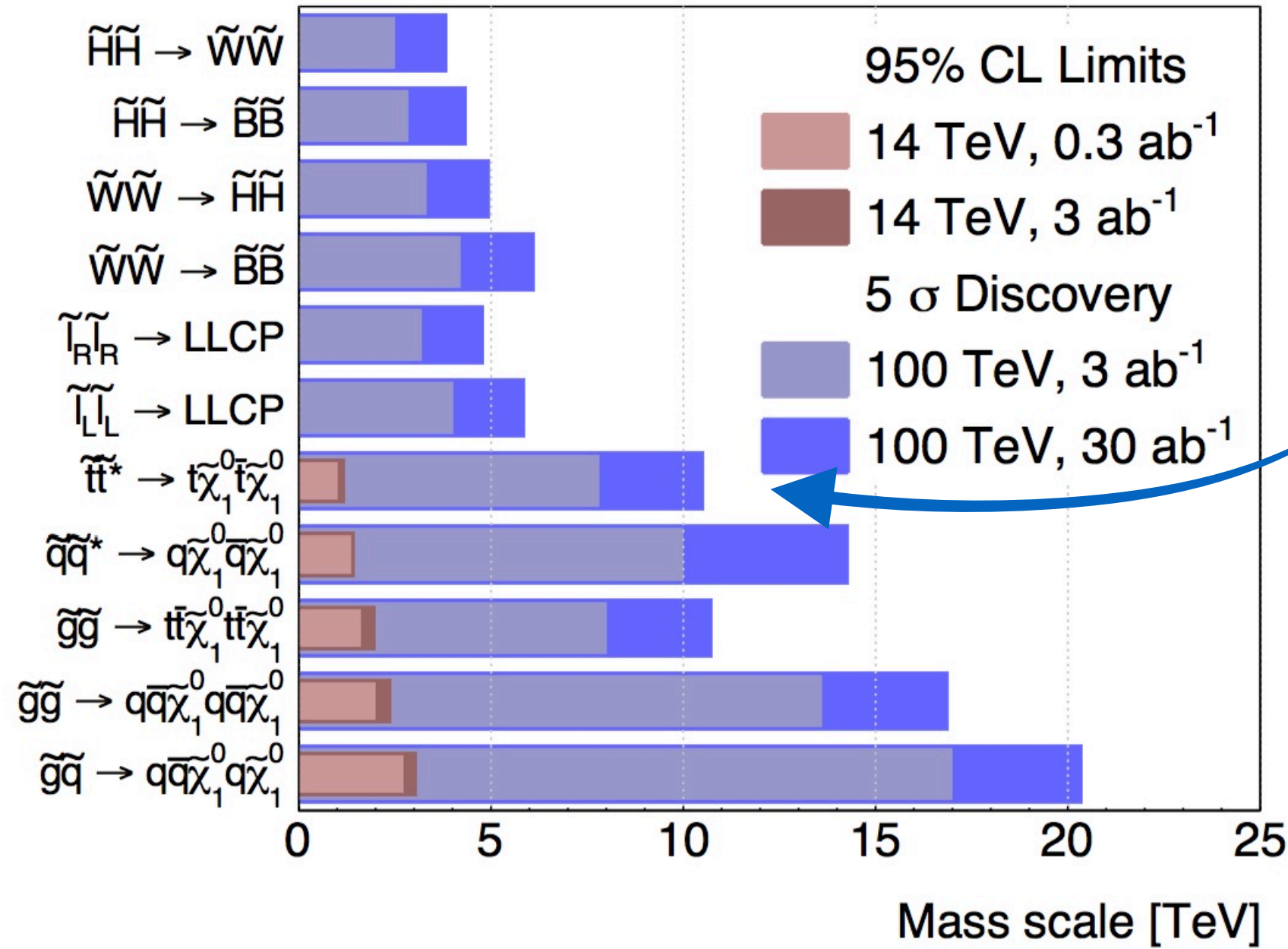
New detector performance studies

(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, ($\chi \chi \leftrightarrow$ SM)

$$\Omega_{\mathrm{DM}} h^2 \sim \frac{10^9 \mathrm{GeV}^{-1}}{M_{\mathrm{pl}}} \frac{1}{\langle \sigma v \rangle}$$
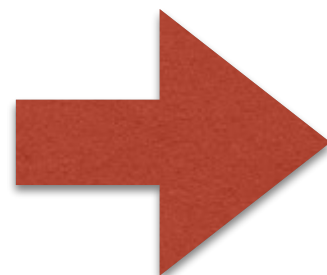
For a particle annihilating through processes which do not involve any larger mass scales:

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

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

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

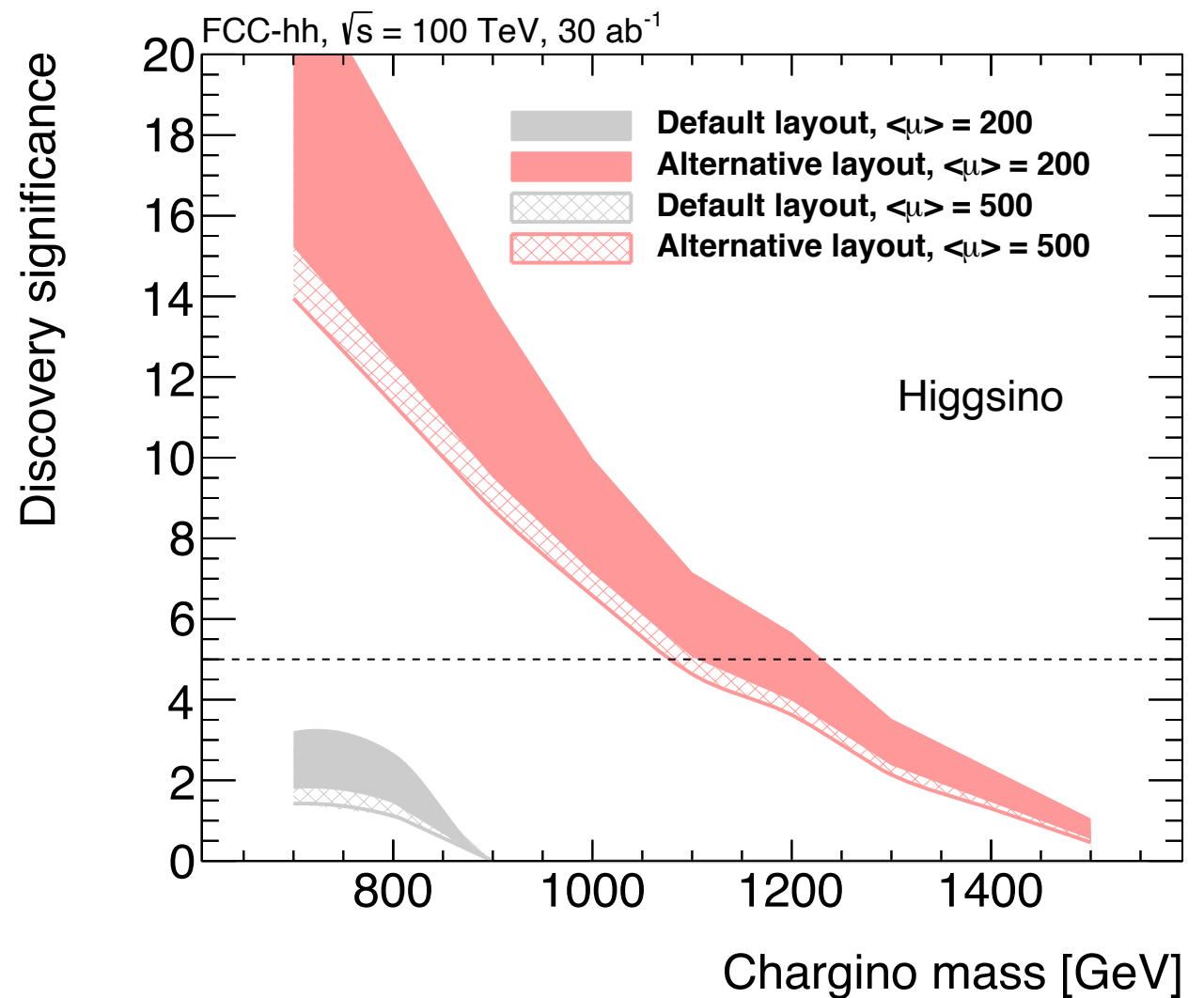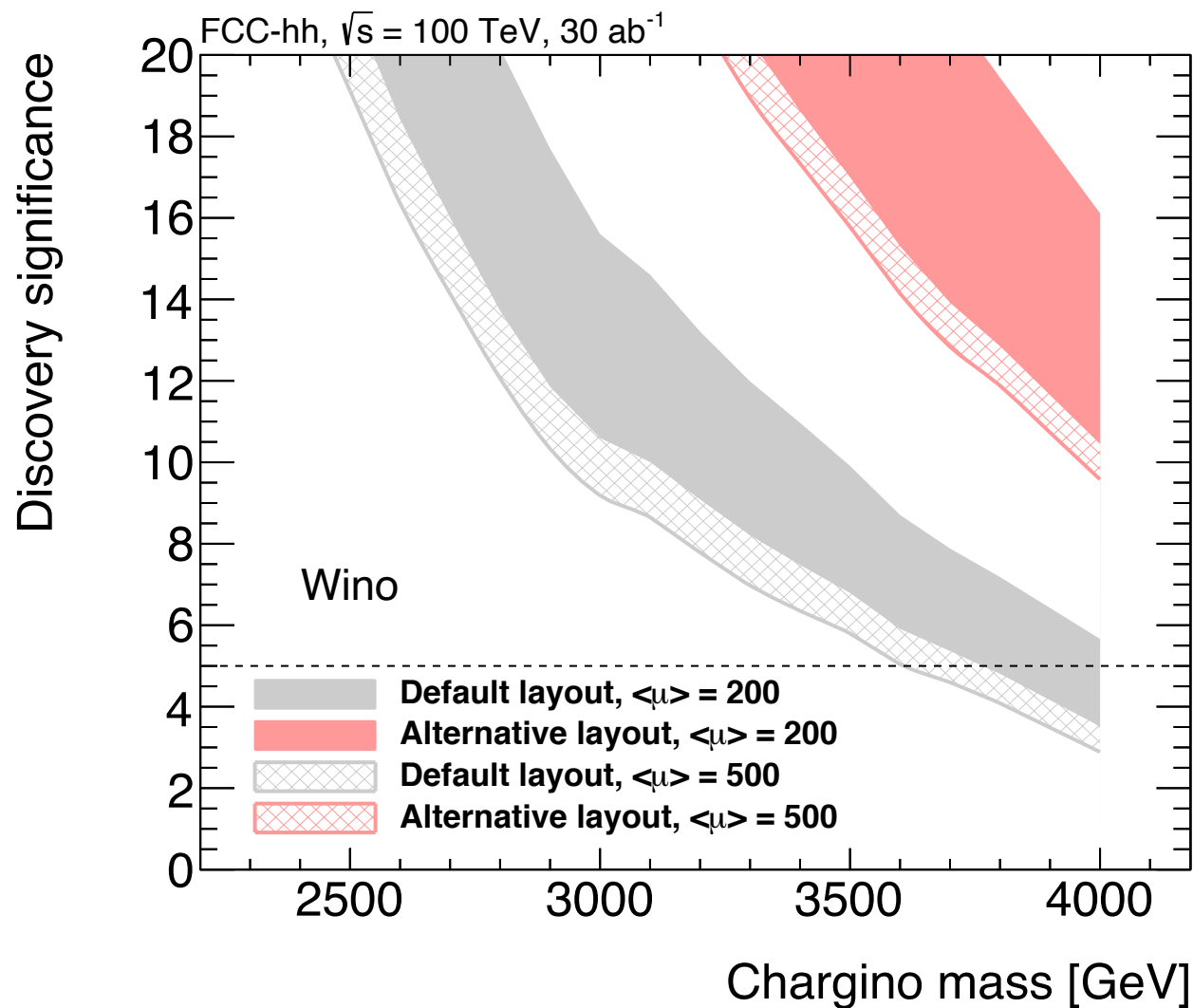$$M_{wimp} \lesssim 2\,\mathrm{TeV} \left(\frac{g}{0.3} \right)^2$$

DM WIMP searches in the most elusive, compressed scenarios:

Disappearing charged track analyses (at ~full pileup)

=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

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

Not covered

- Countless studies of discovery potential for multiple BSM scenarios, from SUSY to heavy neutrinos, from very low masses to very high masses, LLPs, DM, etcetcetc, at FCC-ee, FCC-hh and FCC-eh

- Sensitivity studies to SM deviations in the properties of top quarks, flavour physics in Z decays: huge event rates offer unique opportunities, that cannot be matched elsewhere

- …

- Operations with heavy ions: new domains open up at 100 TeV in the study of high-T/high-density QCD. Broaden the targets, the deliverables, extend the base of potential users, and increase the support beyond the energy frontier community

Final remarks

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.

- The exptl program possible at a future collider facility, combining a versatile high-luminosity e^+e^- circular collider, with a follow-up pp collider in the 100 TeV range, offers unmatchable breadth and diversity: concrete, compelling and indispensable Higgs & SM measurements enrich a unique direct & indirect discovery potential

- The unique feature of a circular ee + pp collider is the possibility to match the indirect high-mass-scale sensitivity of precision measurements to the direct search potential at large mass

- The next 5-6 years, before the next review of the European Strategy for Particle Physics, will be critical to reach the scientific consensus and political support required to move forward

Additional material: recent reports on Future Circular Colliders

- **FCC CDR**:
  - Vol.1: Physics Opportunities (CERN-ACC-2018-0056) http://cern.ch/go/Nqx7
  - Vol.2: The Lepton Machine (CERN-ACC-2018-0057) http://cern.ch/go/7DH9
  - Vol.3: The Hadron Machine (CERN-ACC-2018-0058), http://cern.ch/go/Xrg6
  - Vol.4: High-Energy LHC (CERN-ACC-2018-0059) http://cern.ch/go/S9Gq

- **"Physics at 100 TeV"**, CERN Yellow Report: https://arxiv.org/abs/1710.06353

- **CEPC CDR**: Physics and Detectors