সাহা ইনস্টিটিউট অফ নিউক্লিয়ার ফিজিক্স
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An Institution of Basic Research and Training in Physical and Biophysical Sciences under Dept. of Atomic Energy, Govt. of India

International Conference on High Energy Particle & Astroparticle Physics
Calcutta, 11-15 December 2023

Physics Prospects of Future circular Colliders

Michelangelo L. Mangano
Theory Department,
CERN, Geneva

For recent overviews of progress in the study of the FCC physics potential, see

- the Physics-Experiments-Detector sessions at the 2023 FCC week, https://indico.cern.ch/event/1202105/timetable/
- the presentations at the 2023 FCC Phenomenology Workshop, https://indico.cern.ch/event/1278845/timetable/

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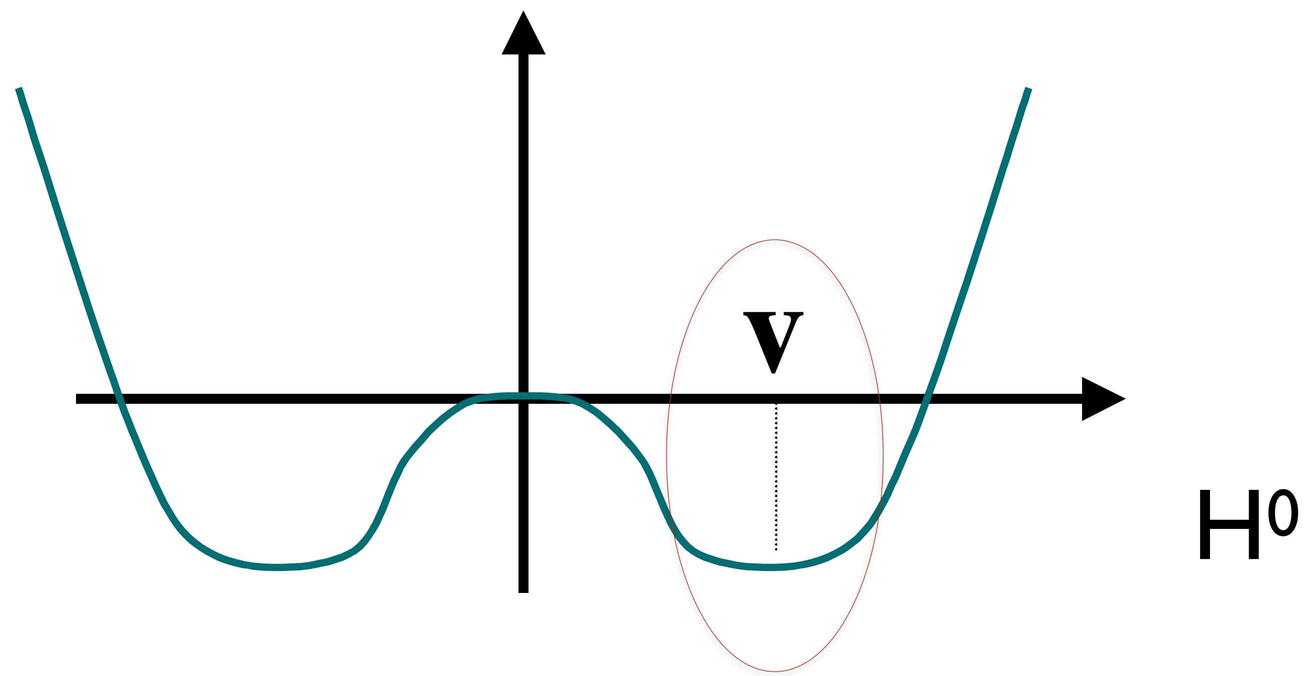

$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

a historical example: superconductivity

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- 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.

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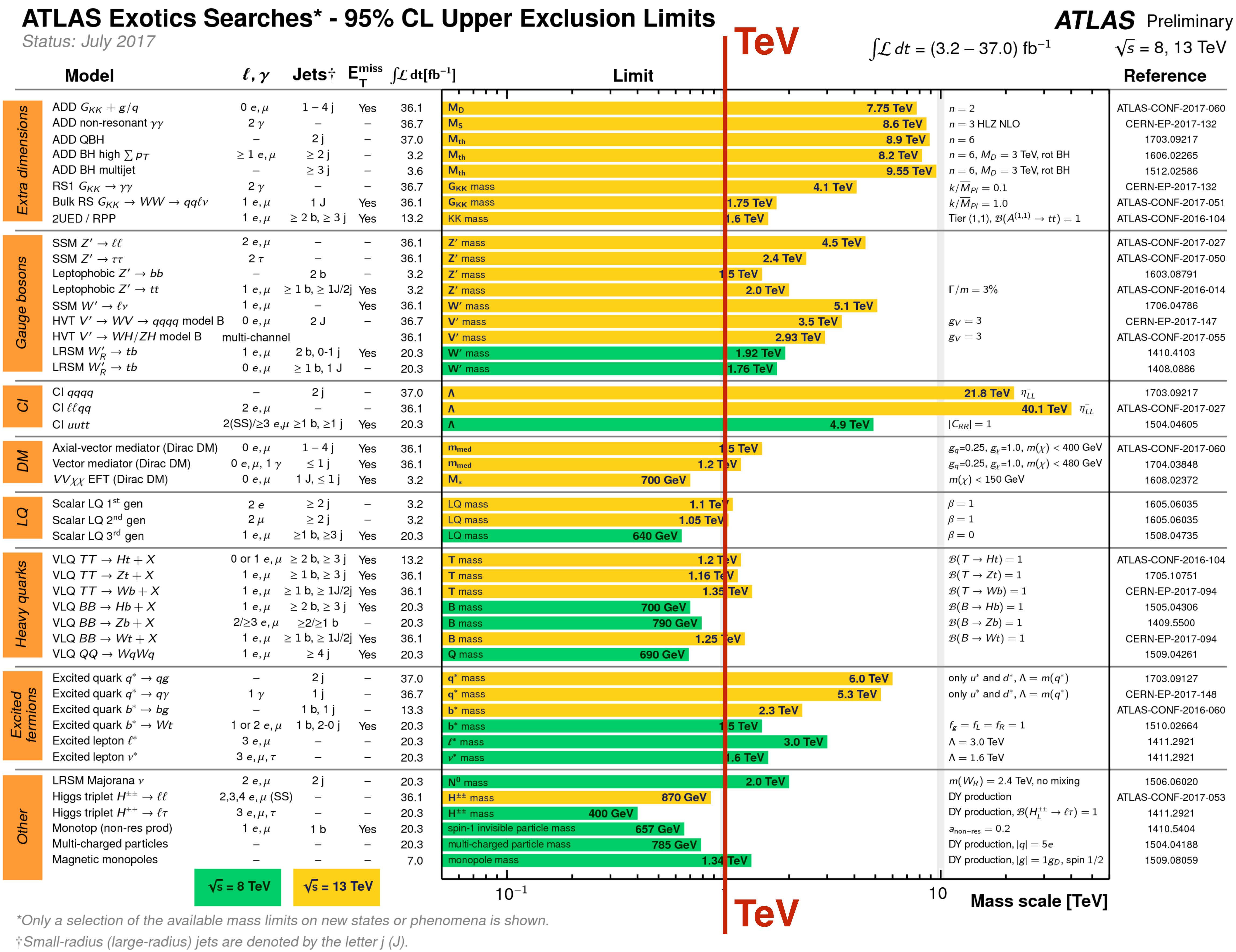
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases 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
- …

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



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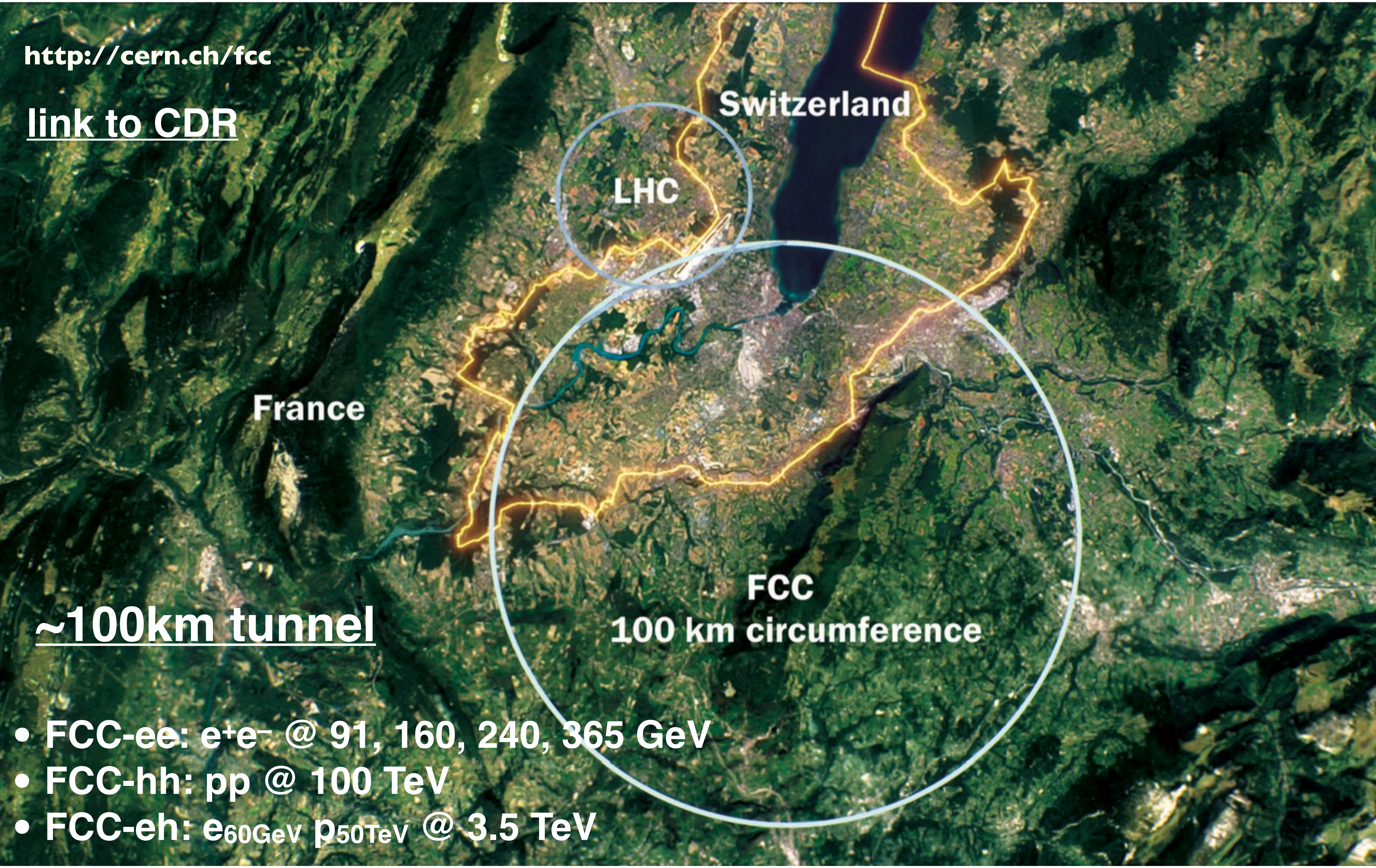
These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

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***

Future Circular Collider



http://cern.ch/fcc

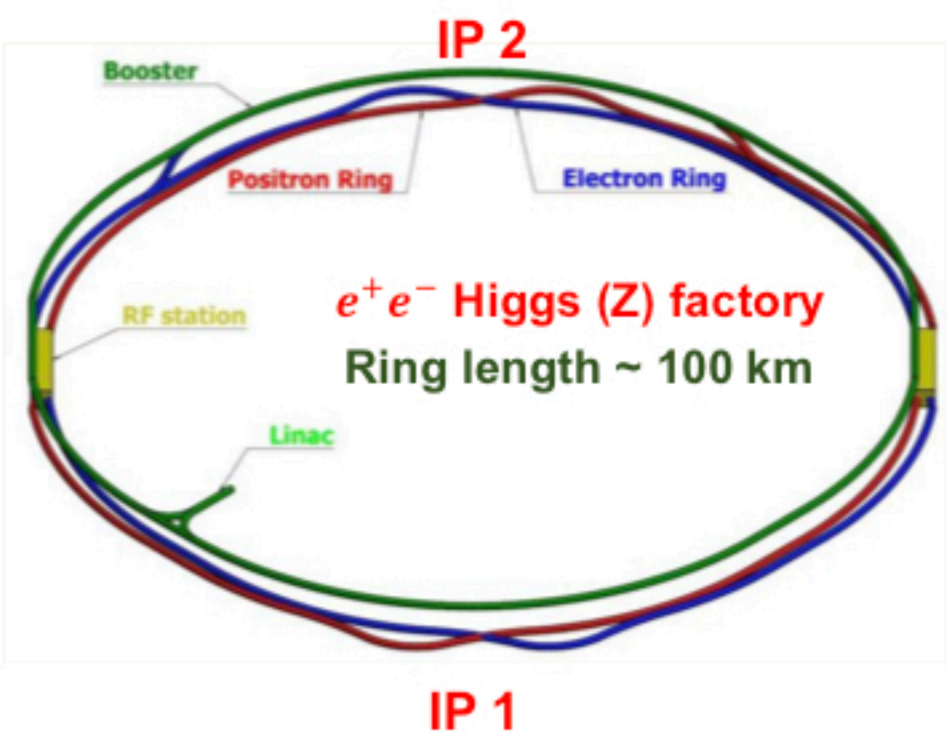
link to CDR

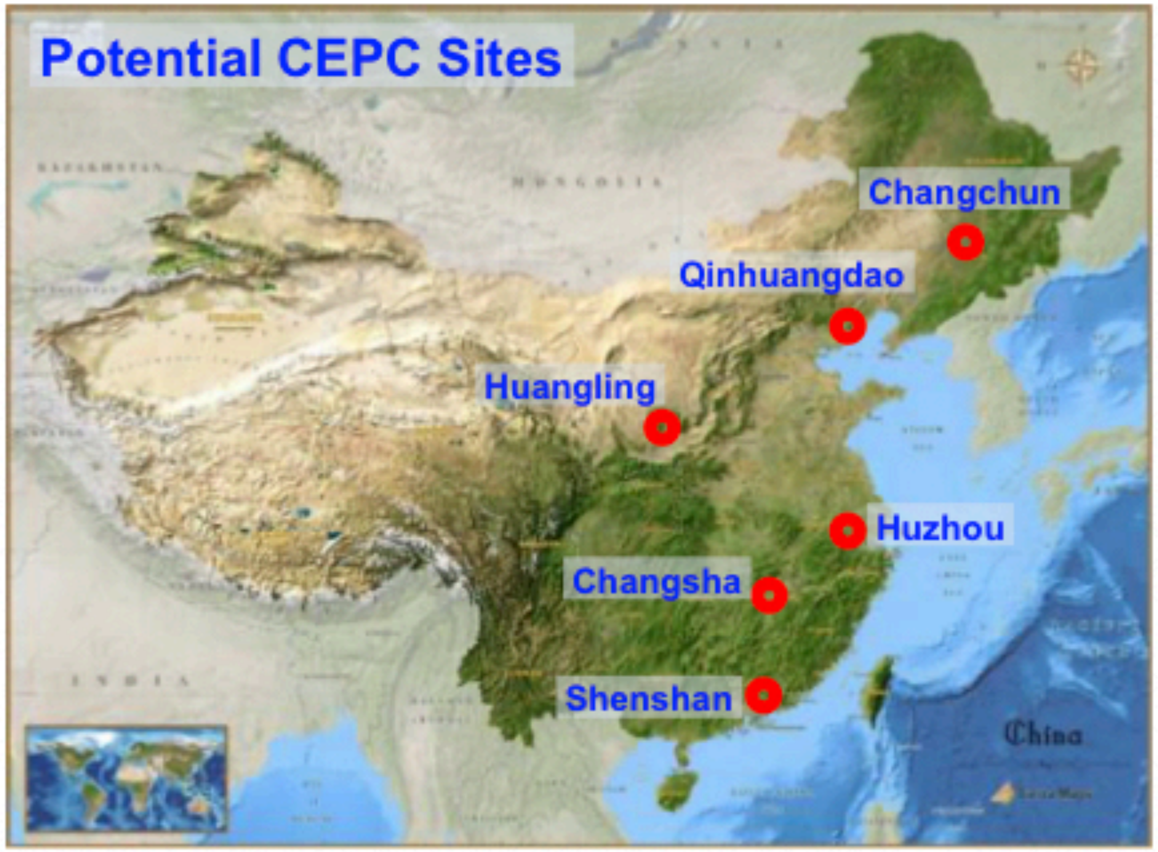
~100km tunnel

- 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

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- Provide firm Yes/No answers 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?
  - …

(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

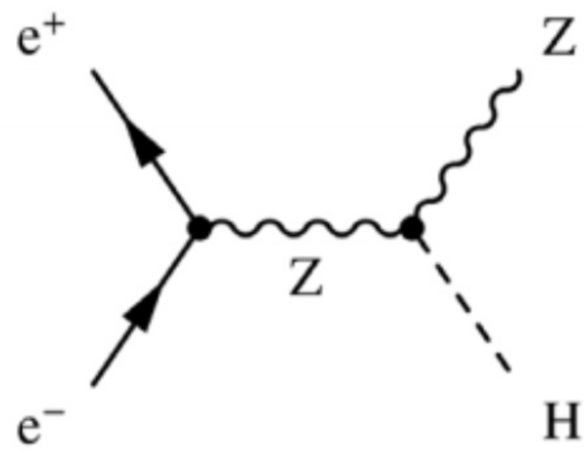
Legend: blue box: 5 – 10 %; red box: > 10%

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):

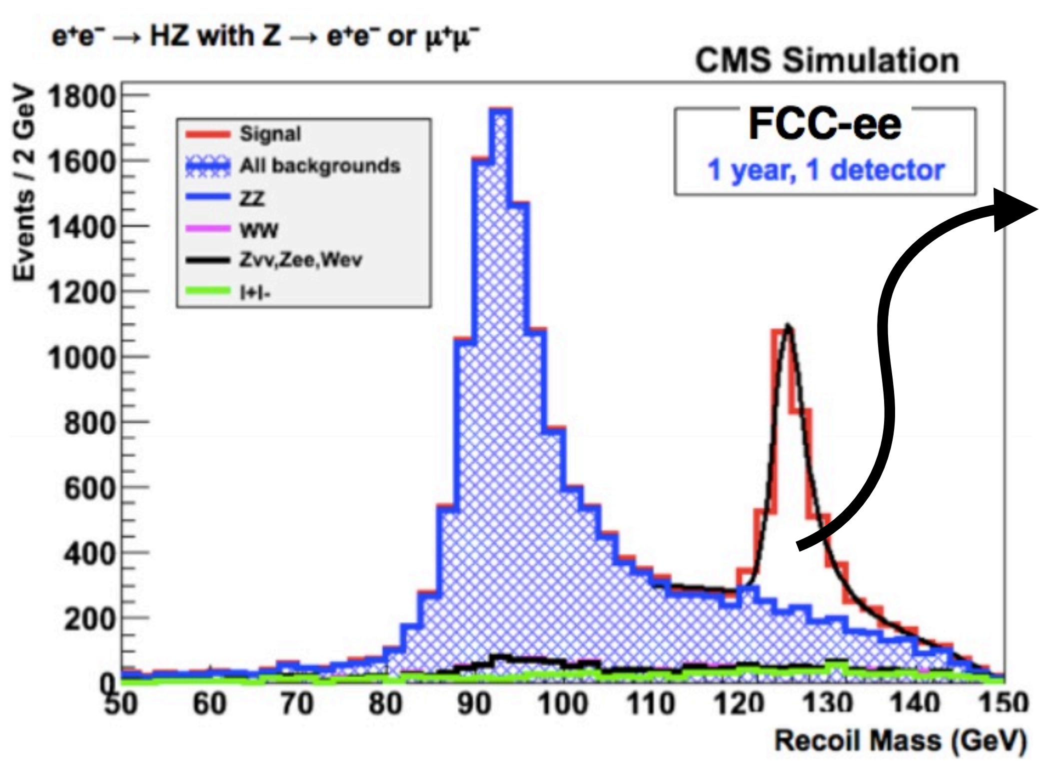
- the model independent absolute measurement of **HZZ** coupling, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

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

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

=> absolute measurement of width and couplings

The absolutely unique power of pp →H+X:

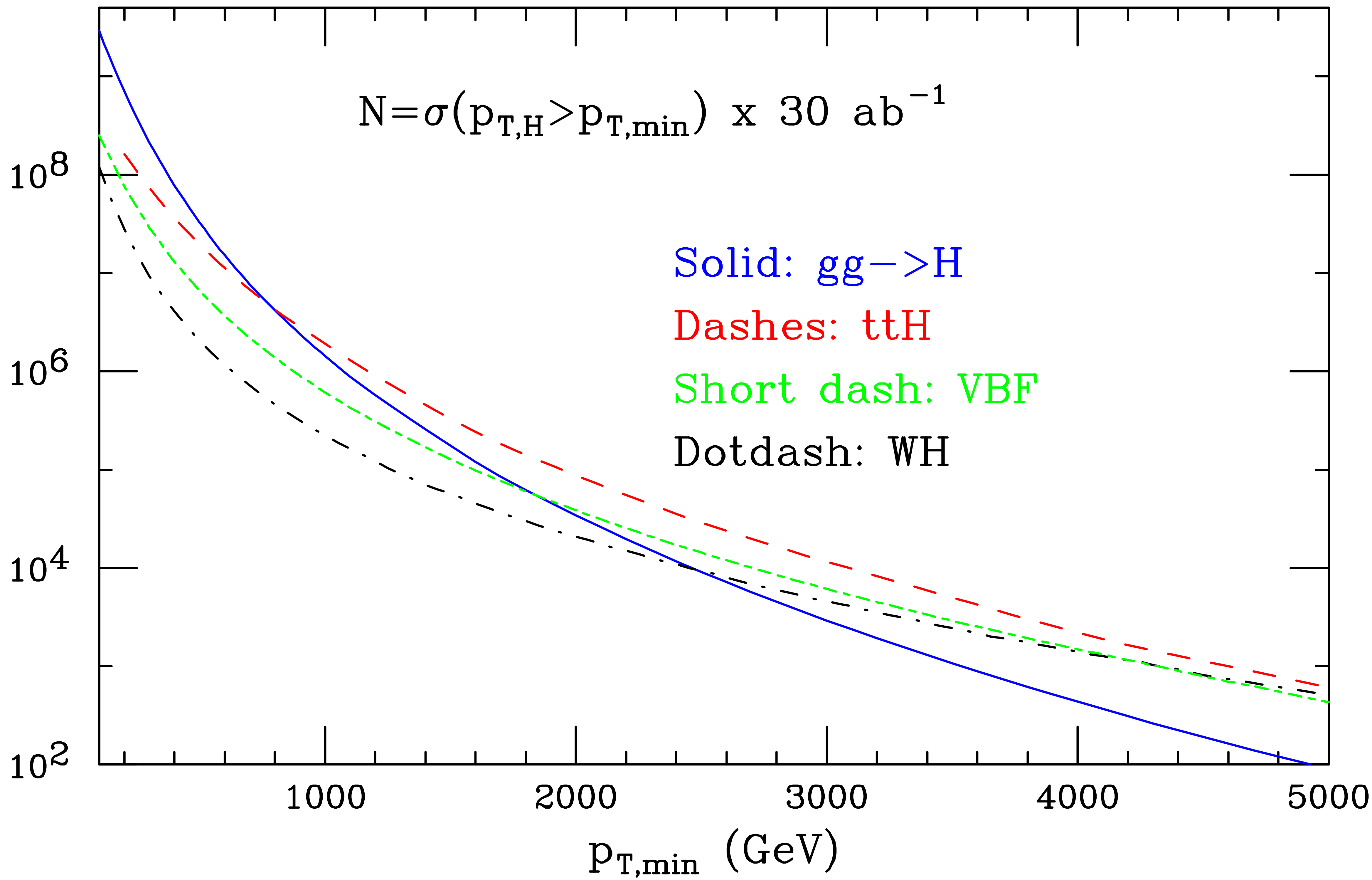
- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→ZZ*), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4 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 x 10^9	2.1 x 10^9	4.6 x 10^8	3.3 x 10^8	9.6 x 10^8	3.6 x 10^7
N_{100}/N_{14}	180	170	100	110	530	390

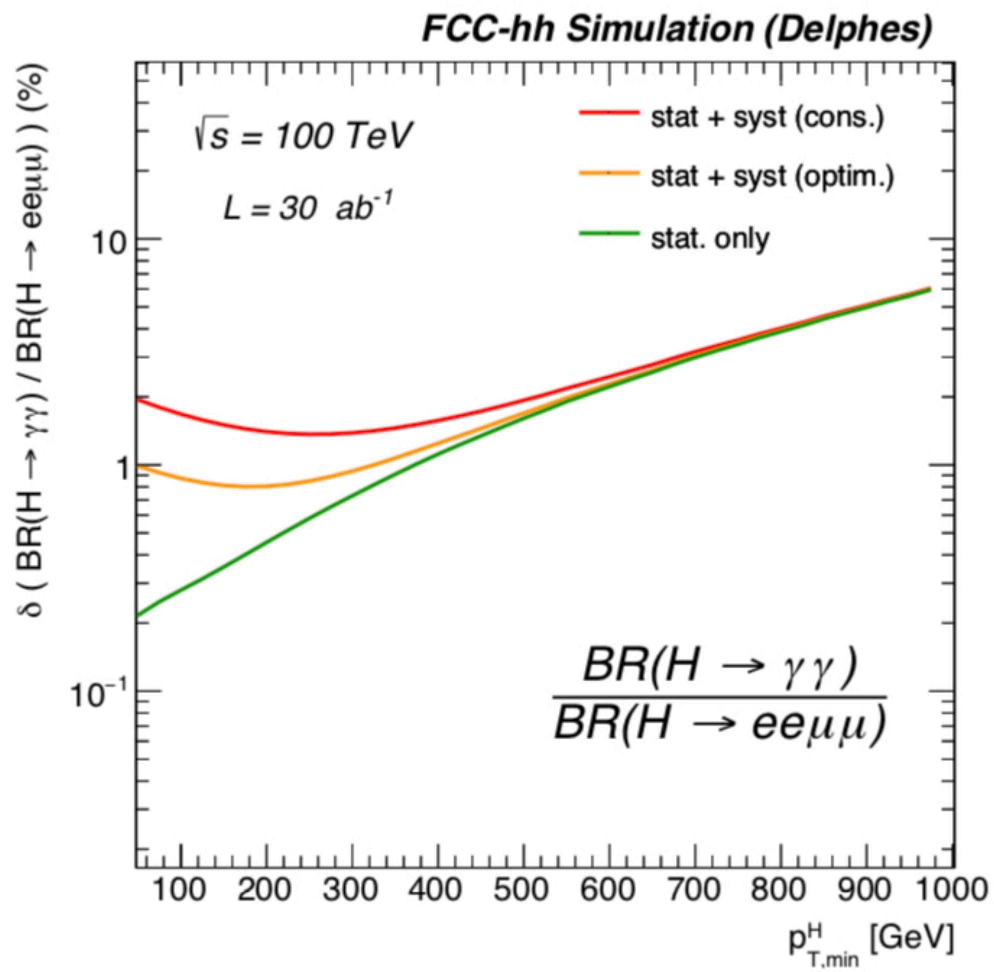
$N_{100} = \sigma_{100\,TeV} \times 30\ ab^{-1}$

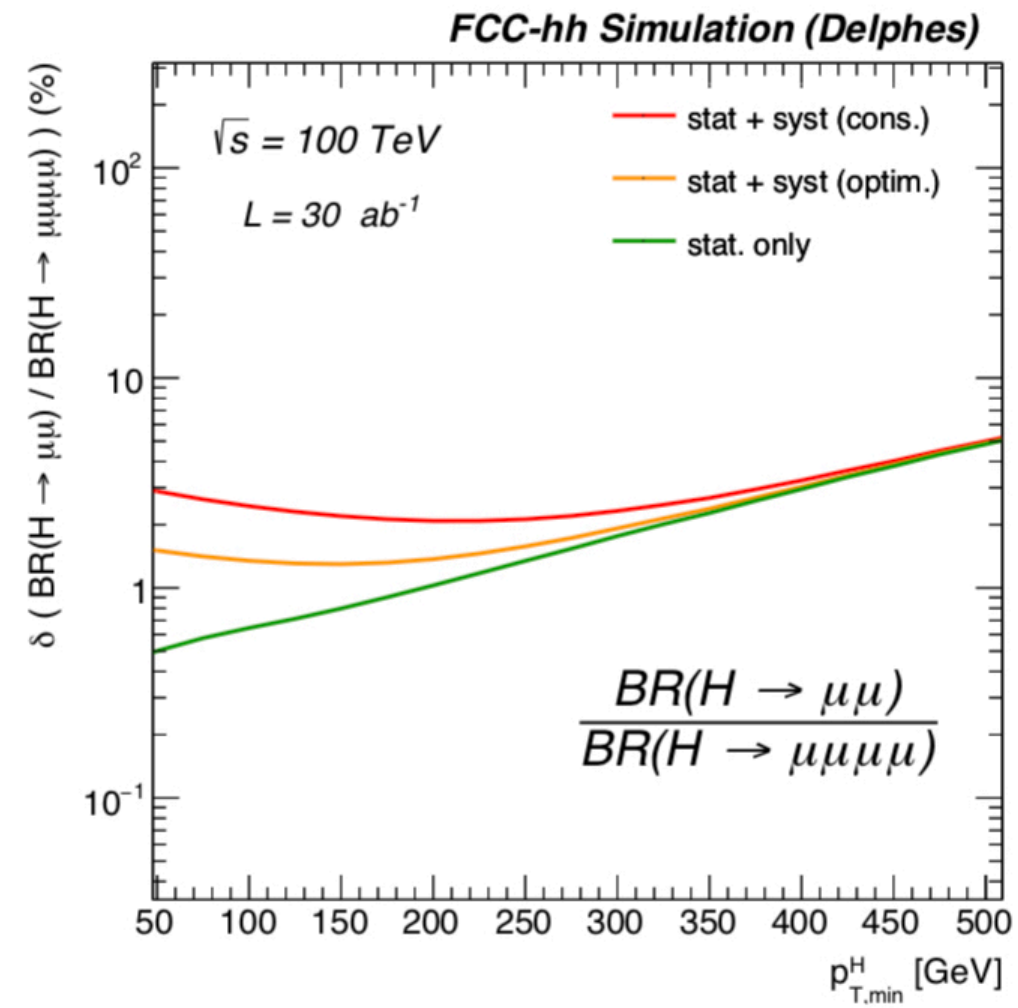
$N_{14} = \sigma_{14\,TeV} \times 3\ ab^{-1}$

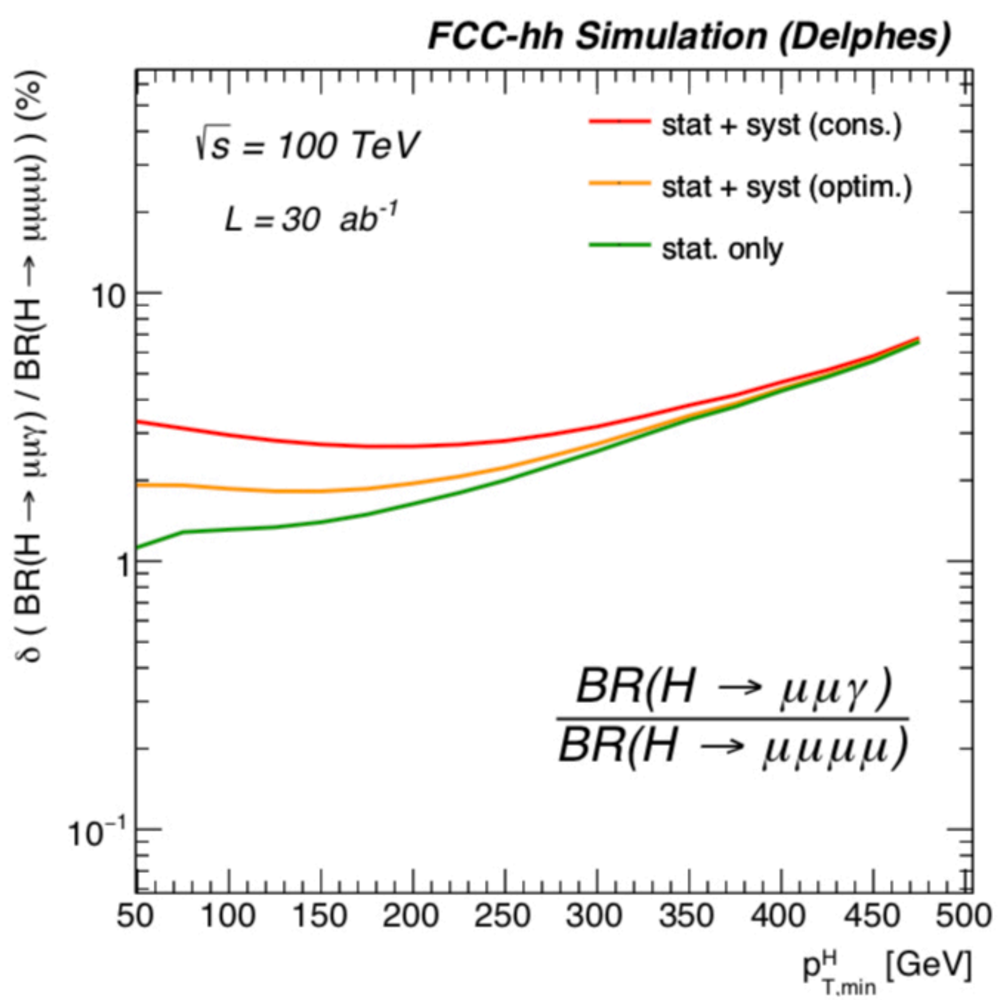
H at large p_T



- 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







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

Future work: explore in more depth data-based techniques, to validate and then reduce 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)	**3.5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

NB

BR(H→Zγ,γγ) ~O(10^{-3}) ⇒ **O(10^7) evts for Δ_{stat}~%**

BR(H→μμ) ~O(10^{-4}) ⇒ **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

The Higgs self-coupling at FCC-hh

https://arxiv.org/abs/2004.03505

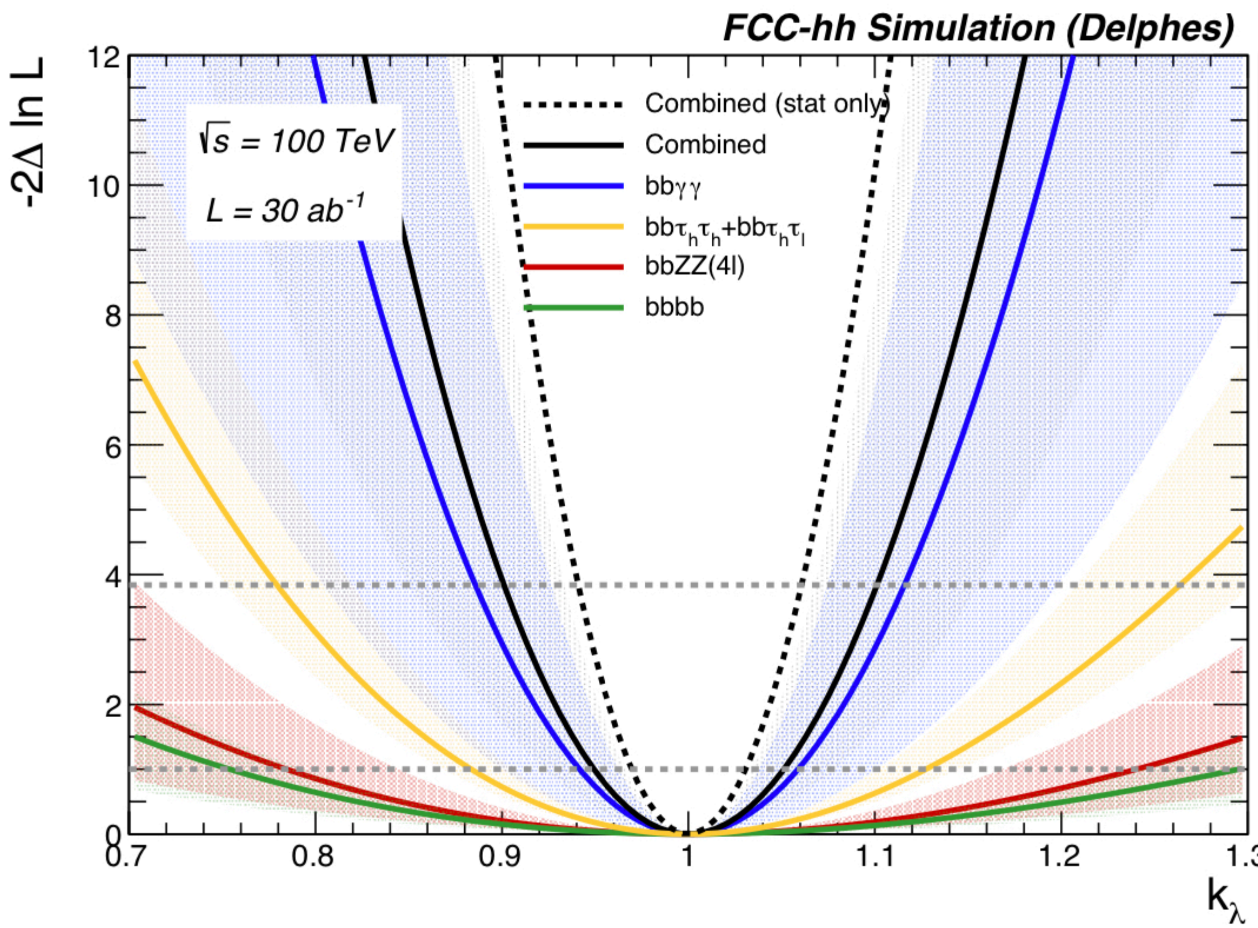


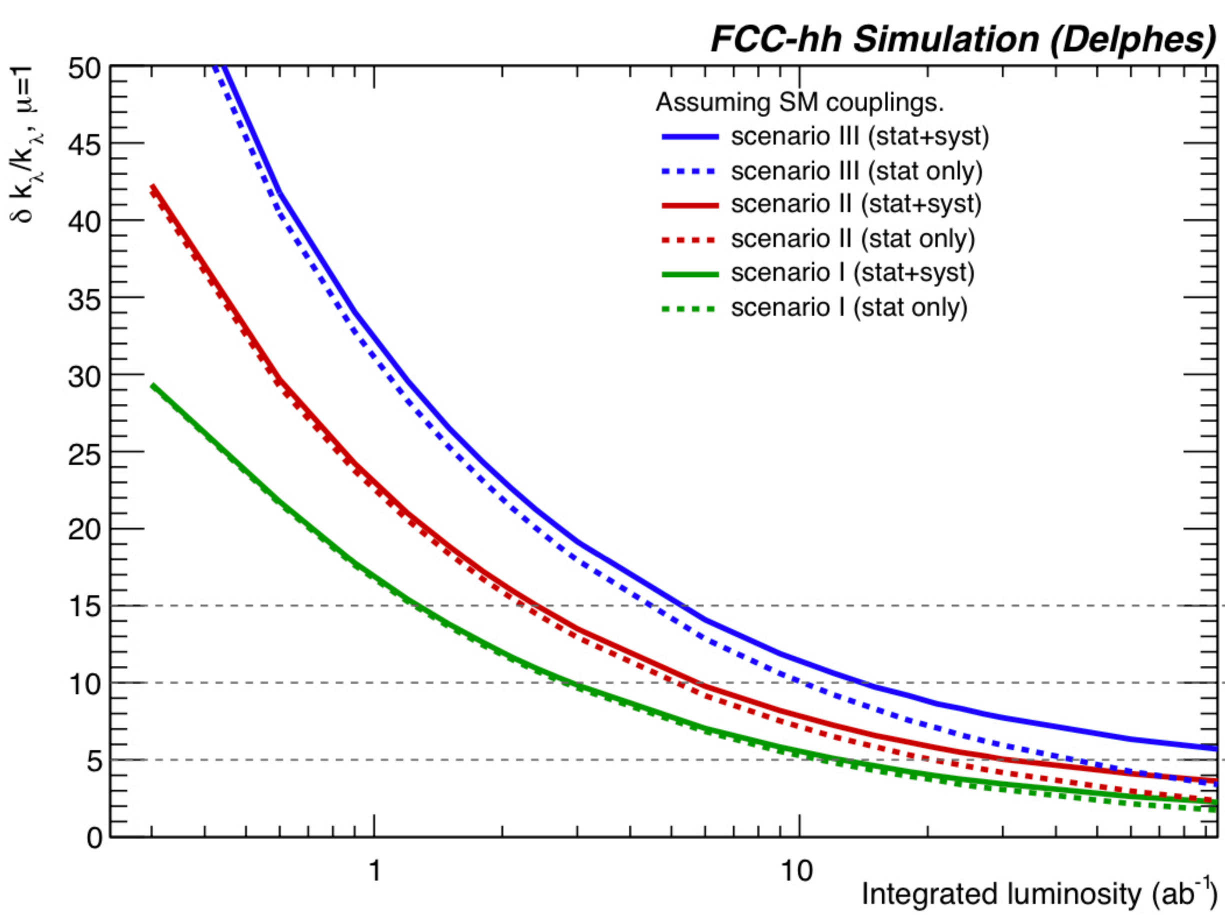
Figure 13. Expected negative log-Likelihood scan as a function of the trilinear self-coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$ in all channels, and their combination. The solid line corresponds to the scenario II for systematic uncertainties. The band boundaries represent respectively scenario I and III. The dashed line represents the sensitivity obtained including statistical uncertainties only, under the assumptions of scenario I.

Syst scenarios

@68% CL		scenario I	scenario II	scenario III
δ_μ	stat only	2.2	2.8	3.7
	stat + syst	2.4	3.5	5.1
δ_{κ_λ}	stat only	3.0	4.1	5.6
	stat + syst	3.4	5.1	7.8

Table 7. Combined expected precision at 68% CL on the di-Higgs production cross- and Higgs self coupling using all channels at the FCC-hh with $\mathcal{L}_{int} = 30$ ab^{-1}. The symmetrized value $\delta = (\delta^+ + \delta^-)/2$ is given in %.

I. Target det performance: LHC Run 2 conditions
II. Intermediate performance
III. Conservative: extrapolated HL-LHC performance, with today's algo's (eg no timing, etc)



Expected precision on the Higgs self-coupling as a function of the integrated luminosity.

3-5 ab^{-1} are sufficient to get below the 10% level

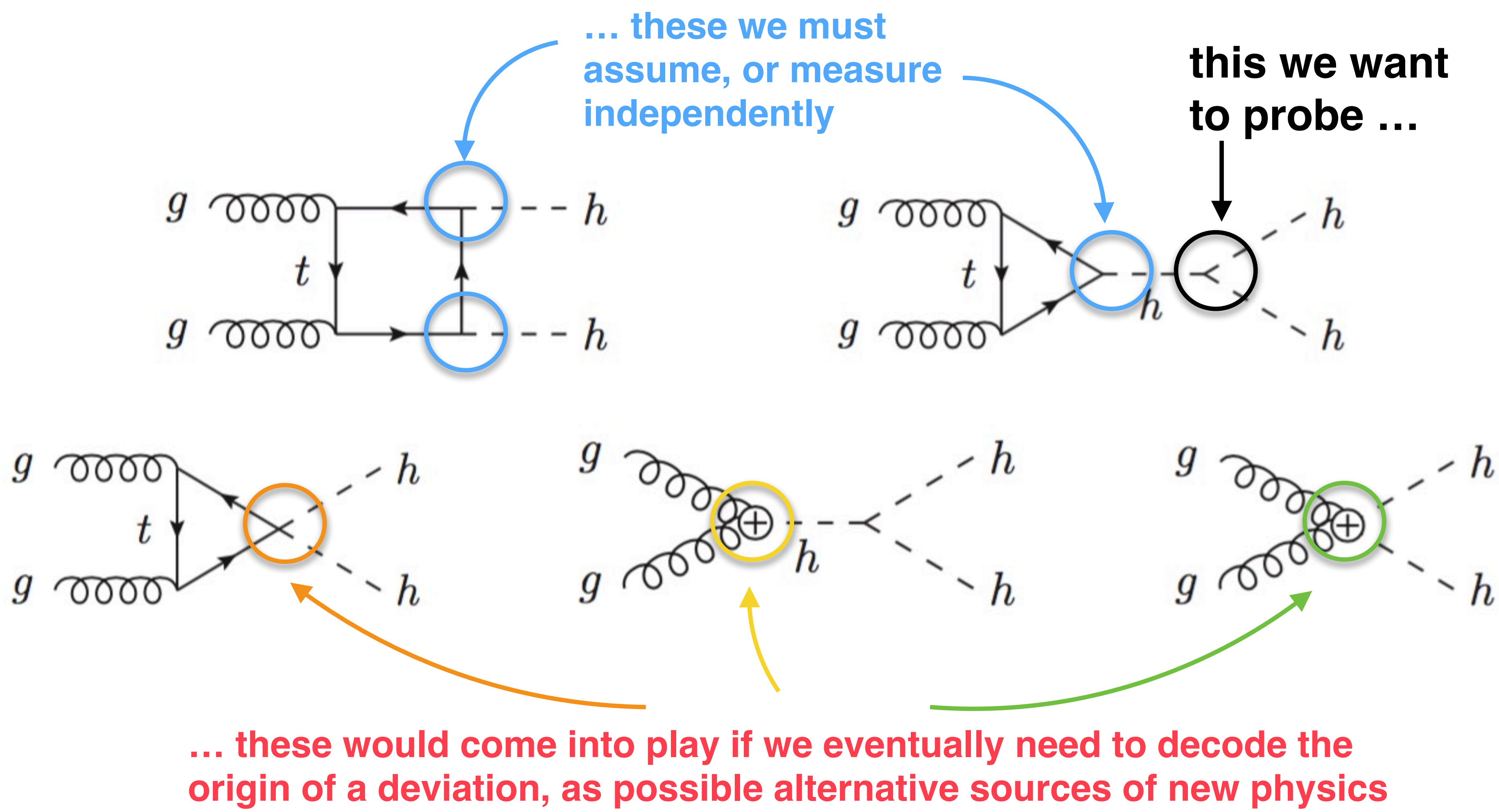
=> within the reach of the first 5yrs of FCC-hh running, in the "low" luminosity / low pileup phase

=> the 10% precision threshold can be reached within the timescale of a similar measurement by CLIC @ 3 TeV

Extracting Higgs self-coupling from HH at FCC:

the power of ee/hh synergy & complementarity

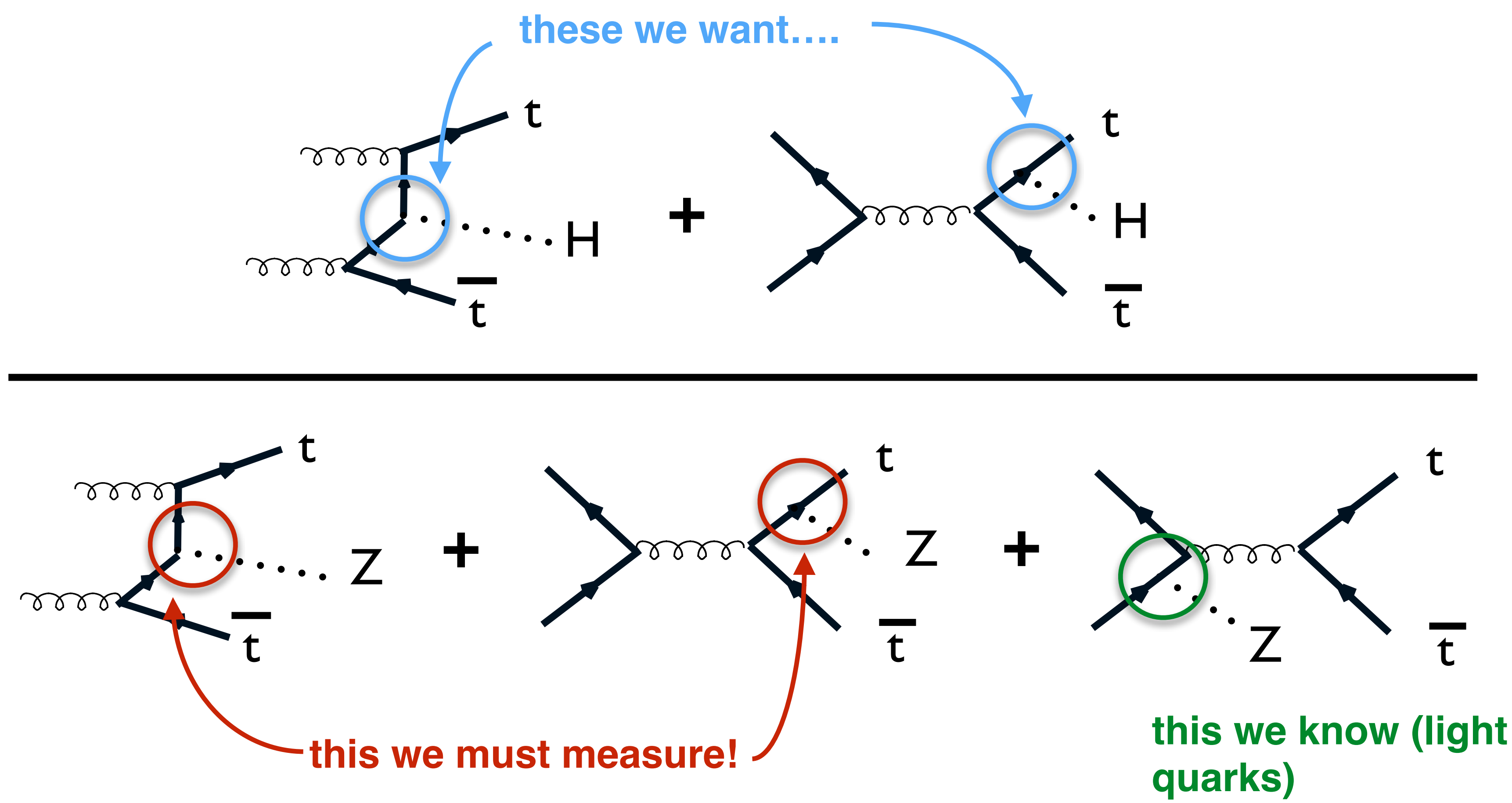
At FCC-hh we can precisely measure HH rate … but,
to interpret this as H selfcoupling:



Direct measurement of ttH coupling: from $R_t = \sigma(ttH)/\sigma(ttZ)$

FCC-hh can measure R_t with $\Delta R_t/R_t < 2\%$ …. but:

R_t =



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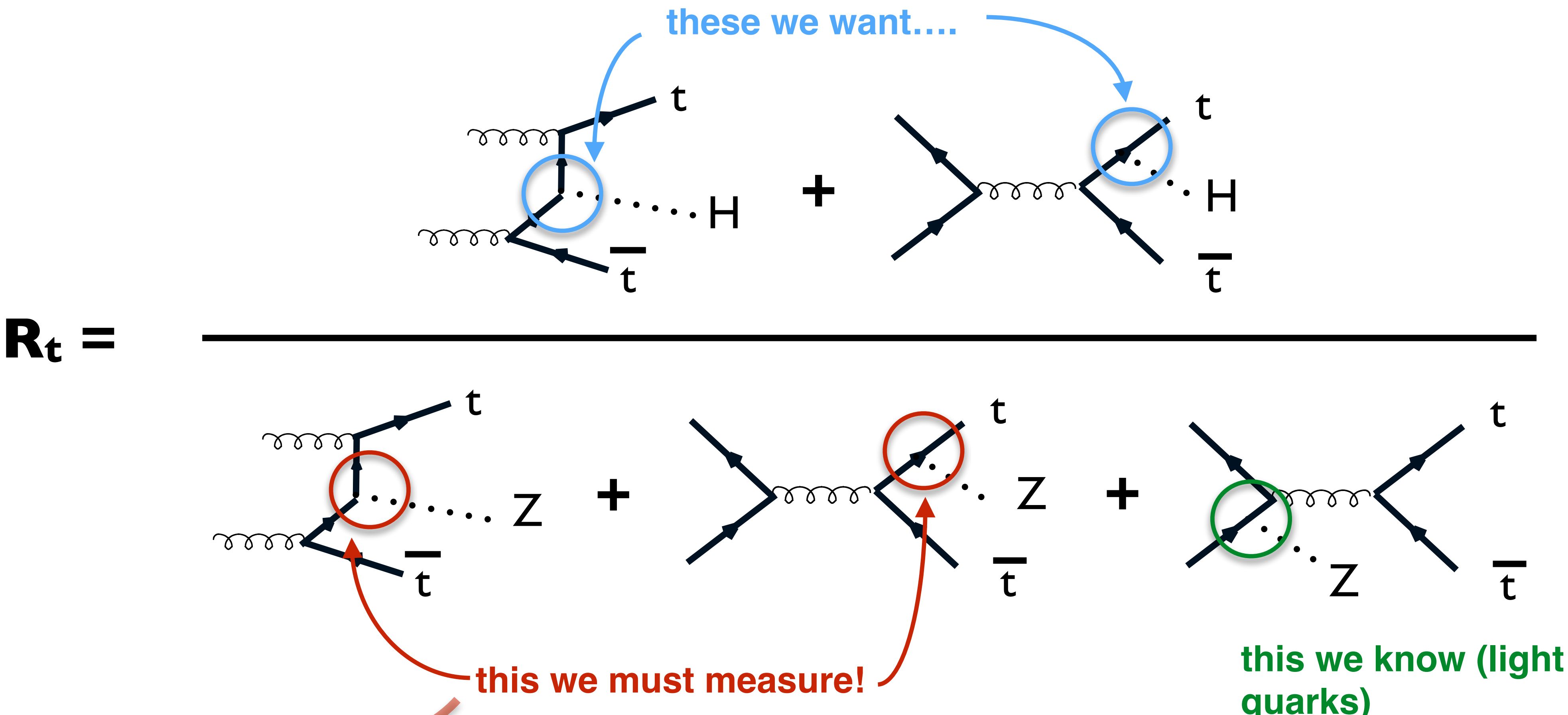
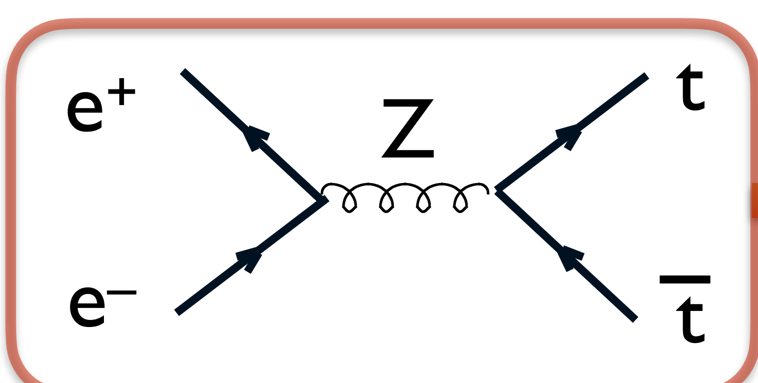
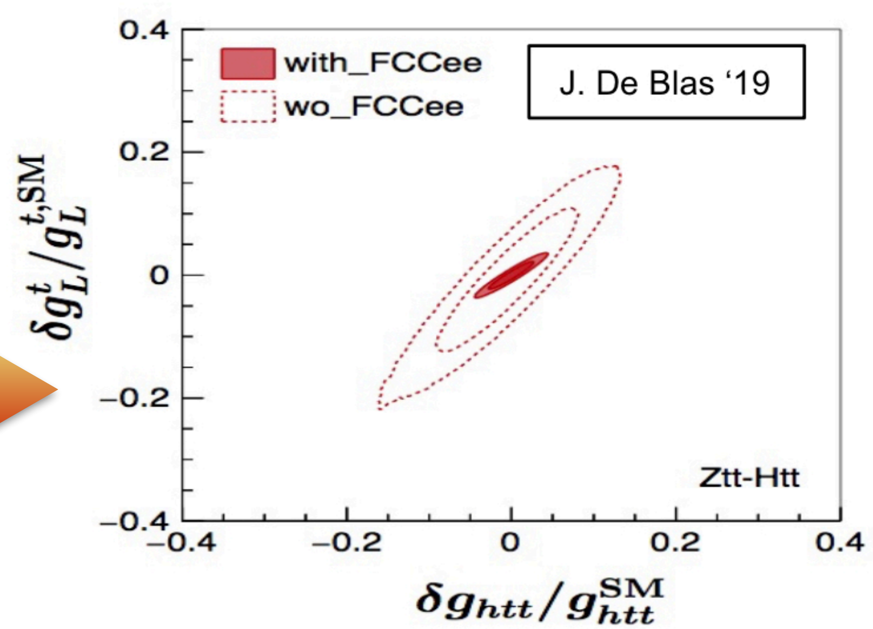


FCC-ee





FCC-ee is a necessary pre-requisite to fully exploit the precision potential of FCC-hh

(1) guaranteed deliverables: EW&flavour observables

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

$e^+e^- \to Z$	$e^+e^- \to WW$	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$	$e^+e^- \to tt$
$5\ 10^{12}$	10^8	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}	10^6

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

Flavour statistics from Z decays:

S. Monteil, FCC PED Week 2023

Working point	Lumi. / IP $[10^{34}\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}]$	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

Additional bonus wrt B factory: (i) Lorentz boost (ii) B hadrons not accessible at the Y(4S,5S) thresholds

EW parameters @ FCC-ee

Improvement wrt current total uncertainties:

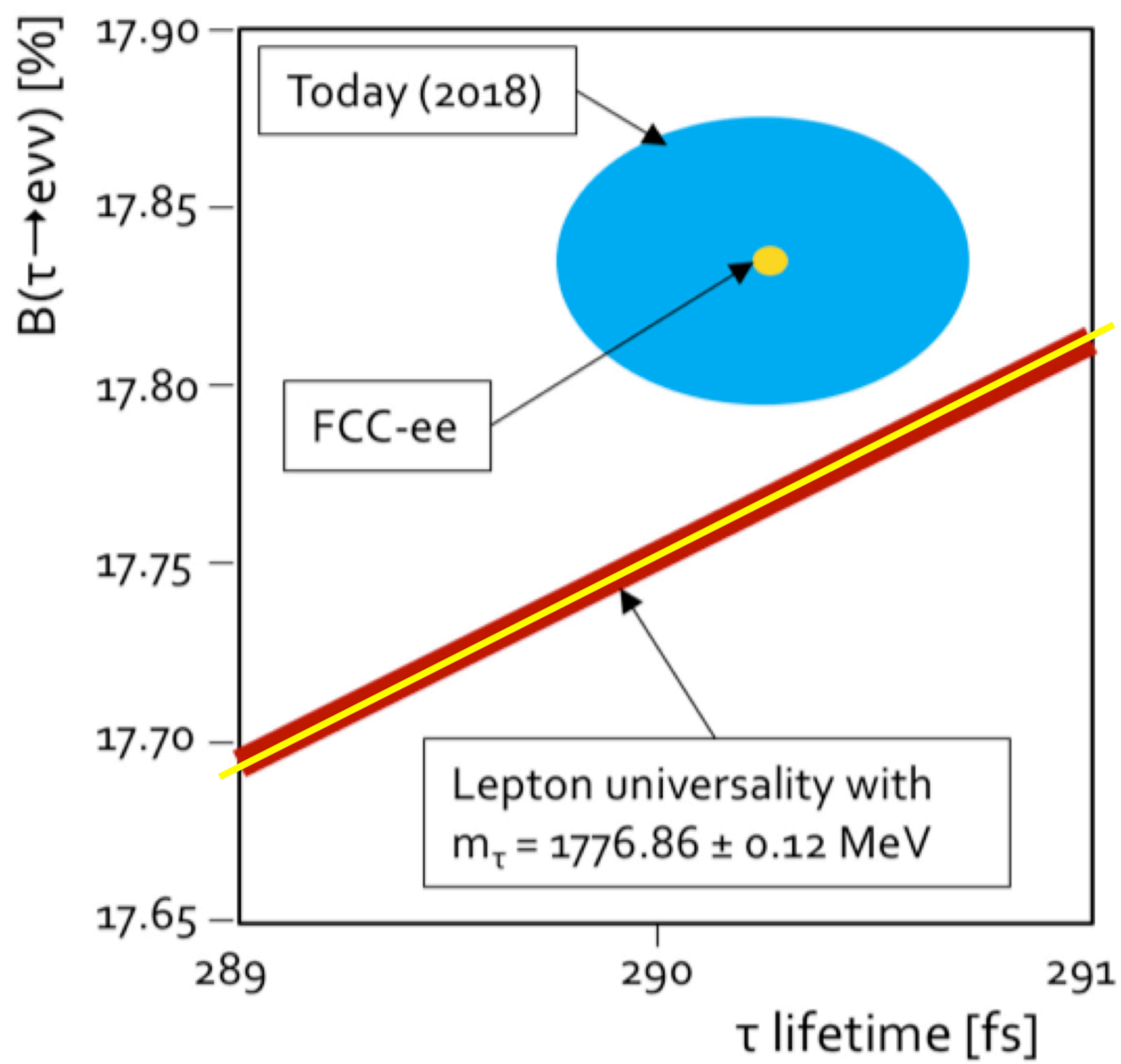
- stat precision ~ 10-1000 smaller
- with exptl syst ~ > 10-50 smaller

Currently limited by TH systematics => work ongoing

Observable	present value ± error	FCC-ee stat.	FCC-ee syst.
m_Z (keV)	91186700±2200	5	100
Γ_Z (keV)	2495200±2300	8	100
R_l^Z ($\times 10^3$)	20767±25	0.06	0.2-1.0
α_s (m_Z) ($\times 10^4$)	1196±30	0.1	0.4-1.6
R_b ($\times 10^6$)	216290±660	0.3	<60
σ^0_{had} ($\times 10^3$) (nb)	41541±37	0.1	4
N_ν ($\times 10^3$)	2991±7	0.005	1
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	231480±160	3	2-5
$1/\alpha_{\mathrm{QED}}(m_Z)$ ($\times 10^3$)	128952±14	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992±16	0.02	1-3
$A_{FB}^{\mathrm{pol},\tau}$ ($\times 10^4$)	1498±49	0.15	<2
m_W (MeV)	80350±15	0.6	0.3
Γ_W (MeV)	2085±42	1.5	0.3
α_s (m_W) ($\times 10^4$)	1170±420	3	Small
N_ν ($\times 10^3$)	2920±50	0.8	Small
m_{top} (MeV)	172740±500	20	Small
Γ_{top} (MeV)	1410±190	40	Small
$\lambda_{top}/\lambda_{top}^{SM}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	→ 0.5 – 1.5%	Small

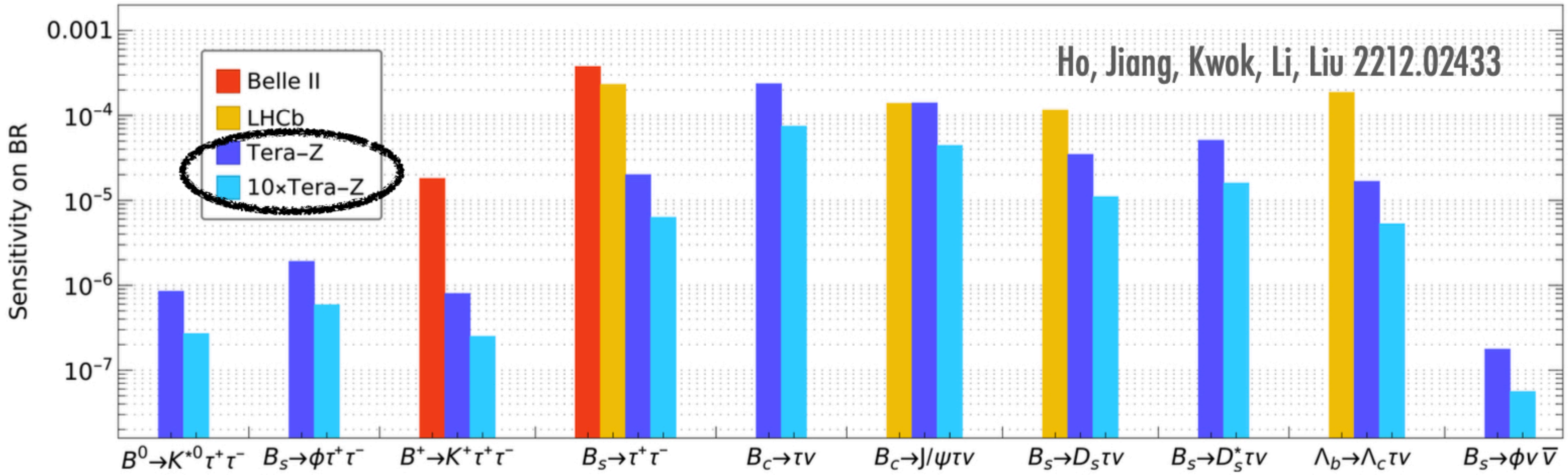
crucial for ttH and HHH couplings at FCC-hh

Flavour probes: eg lepton universality in tau decays



Lorentz boost crucial!

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.004	0.04–0.1	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.001	0.04	Vertex detector alignment
B(τ→eνν) [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	0.003	Efficiency, bkg, Particle ID
B(τ→μνν) [%]		17.39 ± 0.05			



For details about the potential of the flavour programme at the Z pole, see Jernej's overview at the 2023 FCC week

05 - 09 June
FCC WEEK 2023

Flavour Programme

Jernej F. Kamenik

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

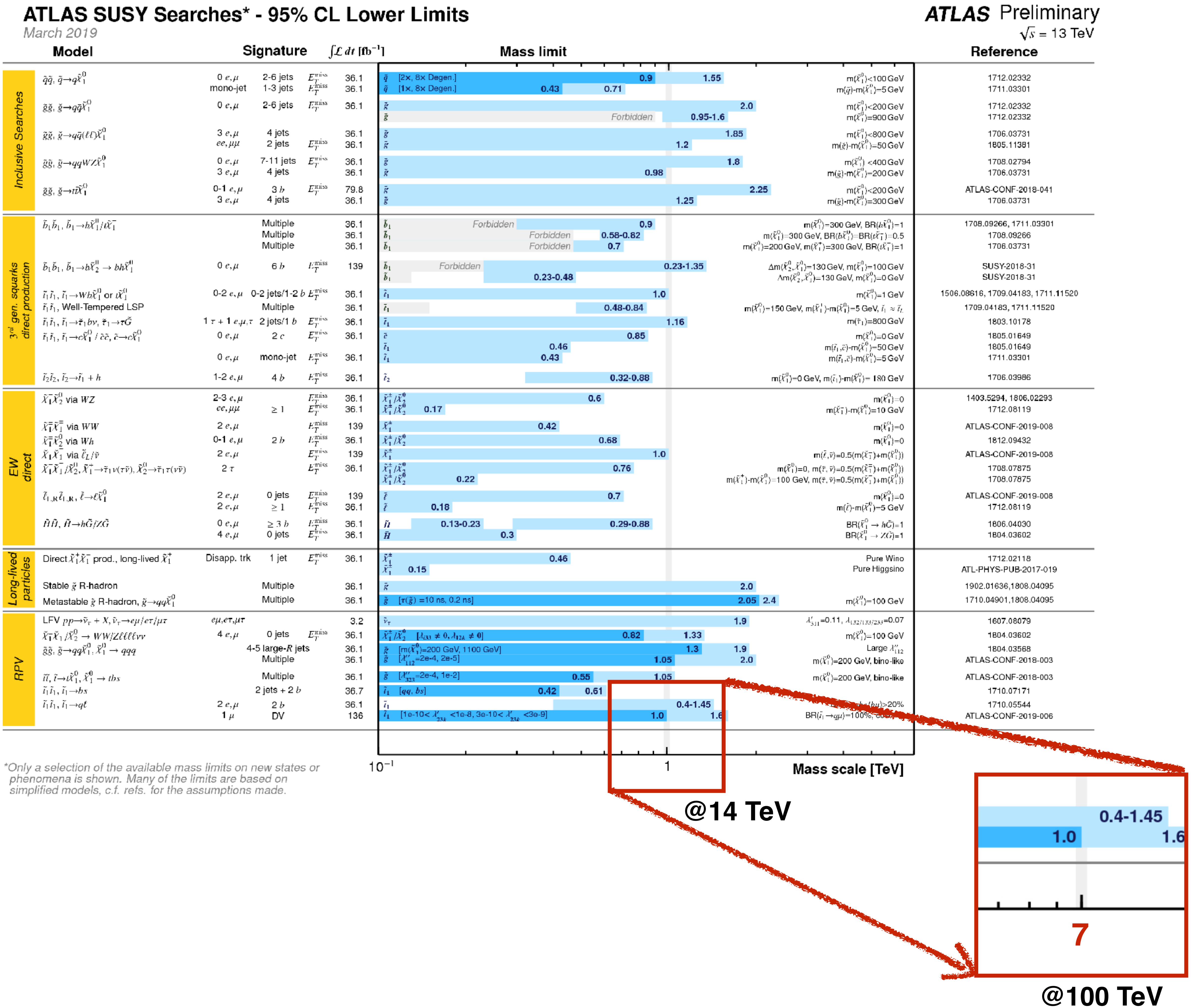
3 CPV in b decays and mixing

4 Tau physics

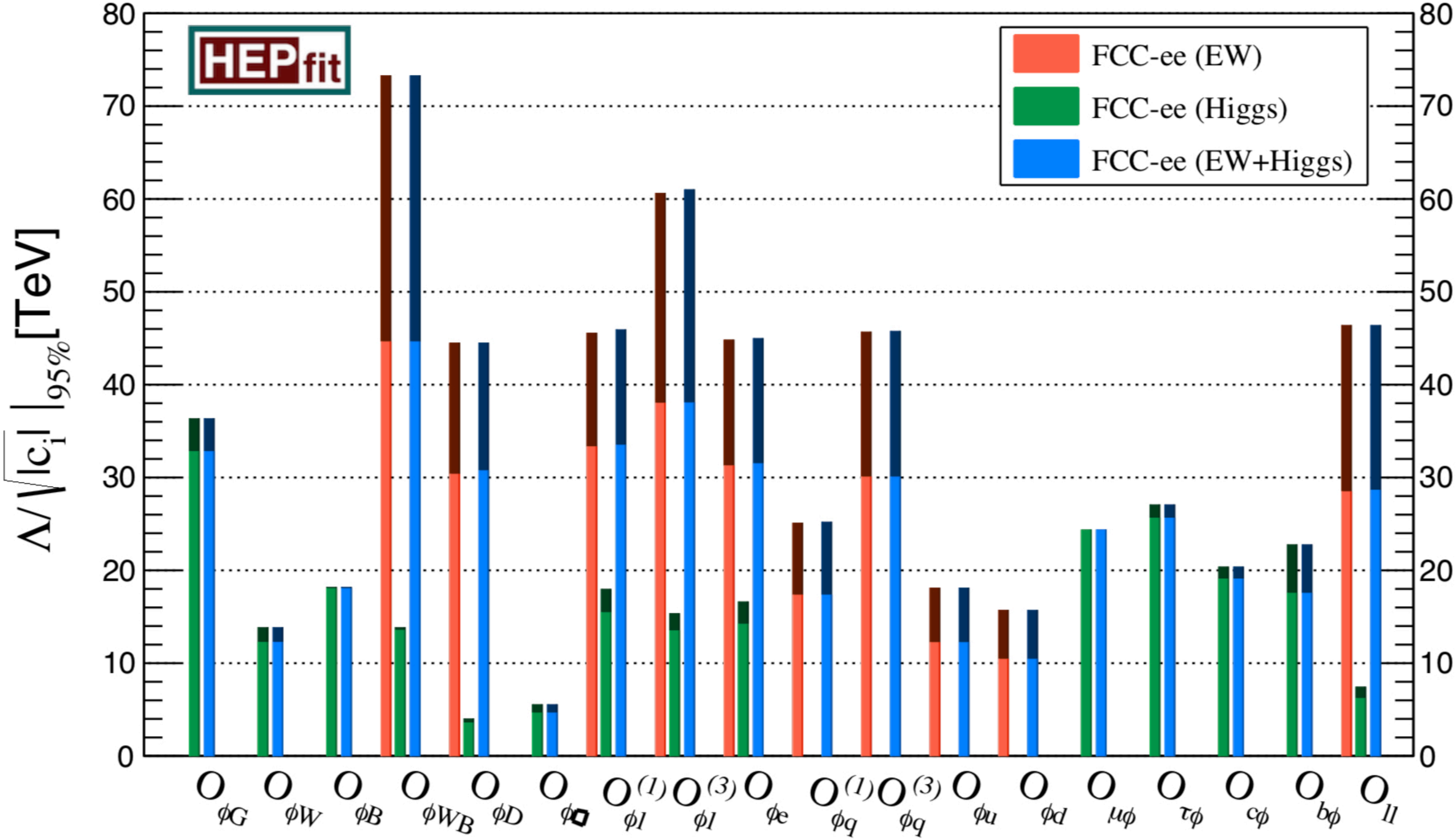
5 Charm physics

6 Flavour @ high-pT

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

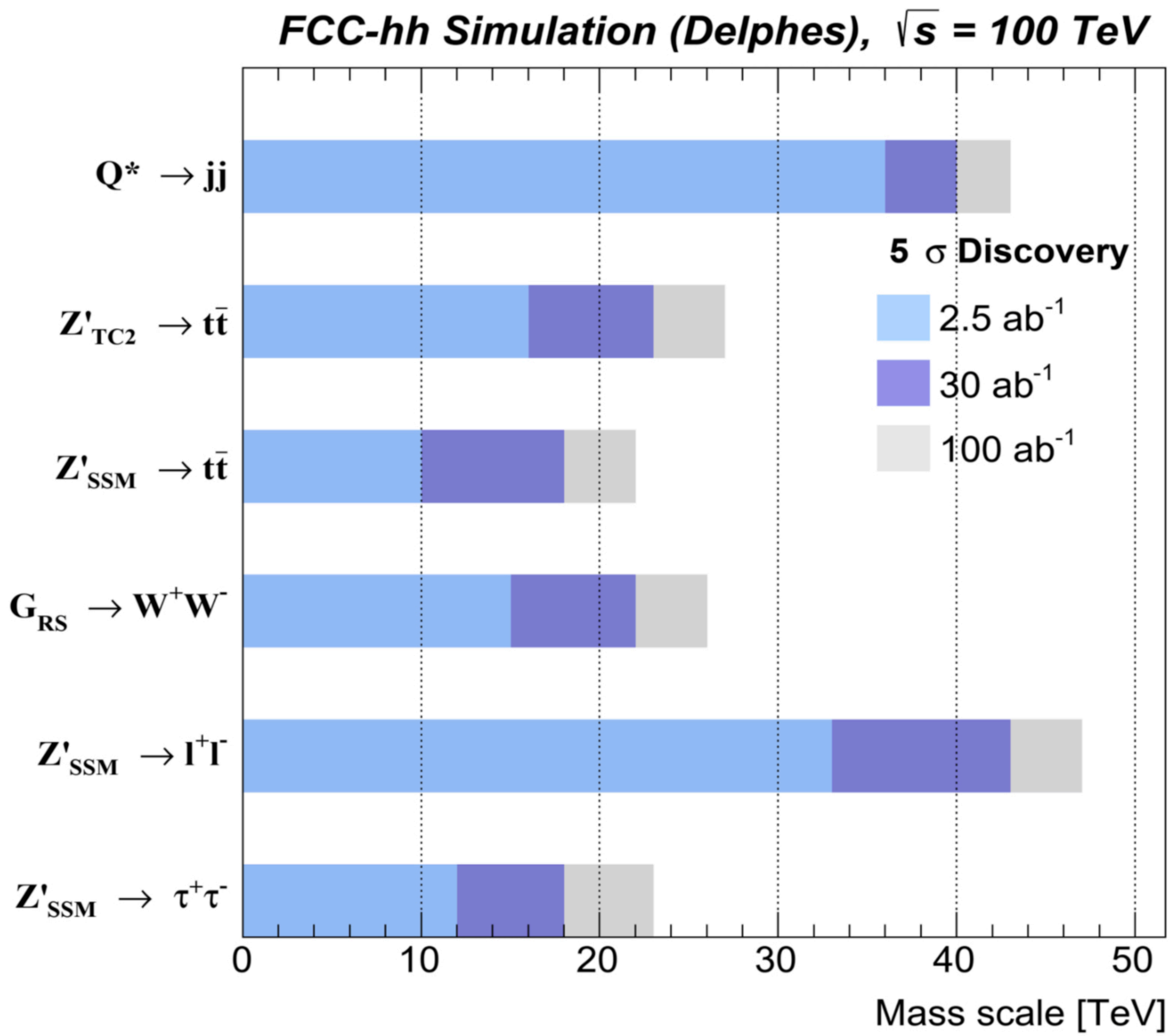

ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int \mathcal{L}\, dt$ [fb^{-1}]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
@14 TeV
0.4-1.45
1.0
1.6
7
@100 TeV

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



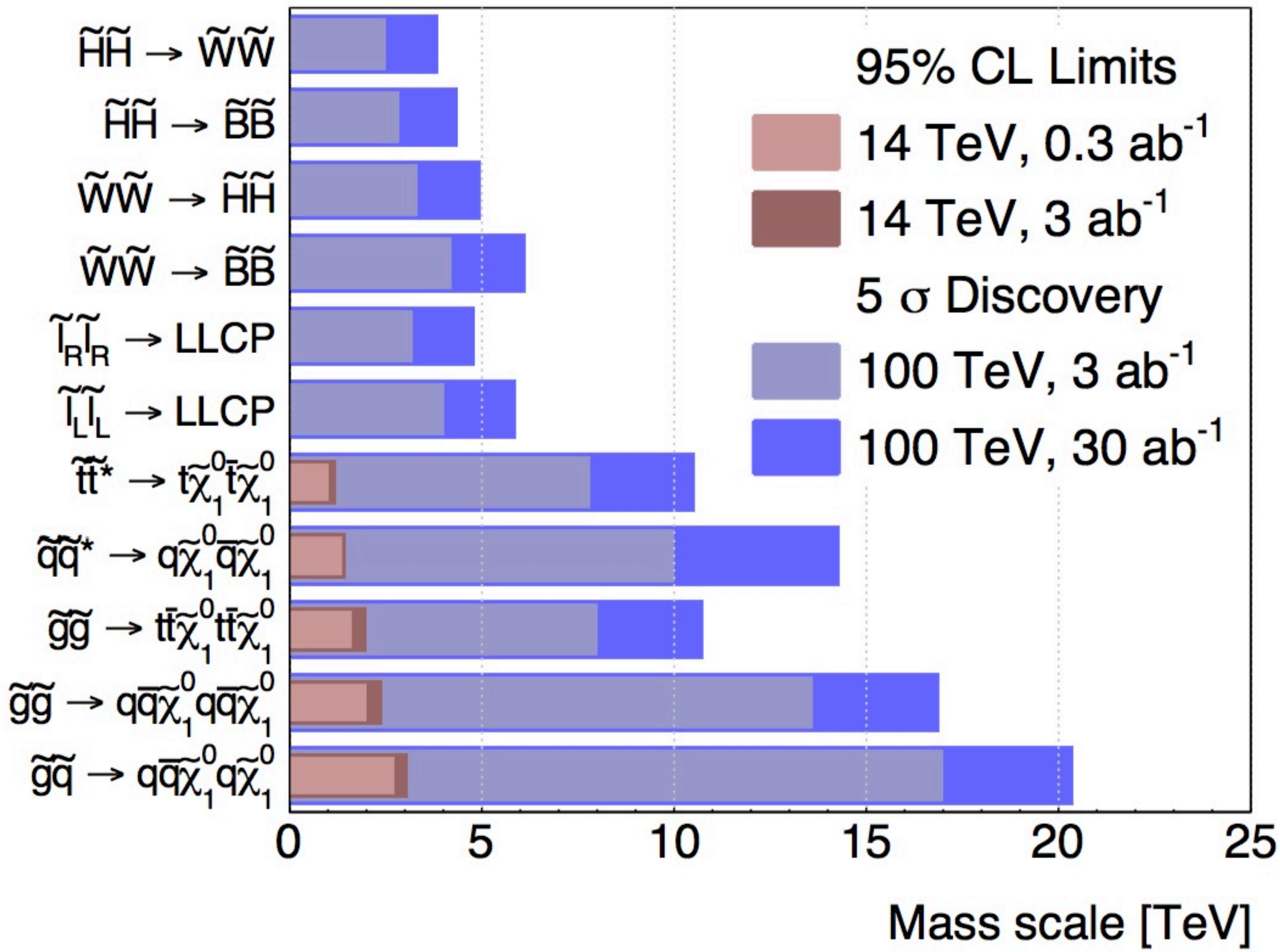
Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

s-channel resonances



100 TeV allow to directly access the mass scales revealed indirectly by precision EW and H measurements at the future e+e– factory

SUSY reach at 100 TeV



15-20 TeV squarks/gluinos would require a lepton collider in the ECM range of 30-50 TeV

(2) **Direct discovery: the “low-mass-but-elusive” scenarios —** LLP, ALPs, HNL and exotic H decays

See e.g.
LLP: Blondel, et al.. https://doi.org/10.3389/fphy.2022.967881
HNL: Blondel et al., https: //doi.org/10.1016/j.nuclphysbps.2015.09.304
FCC LLP working group: https://indico.cern.ch/category/5664/

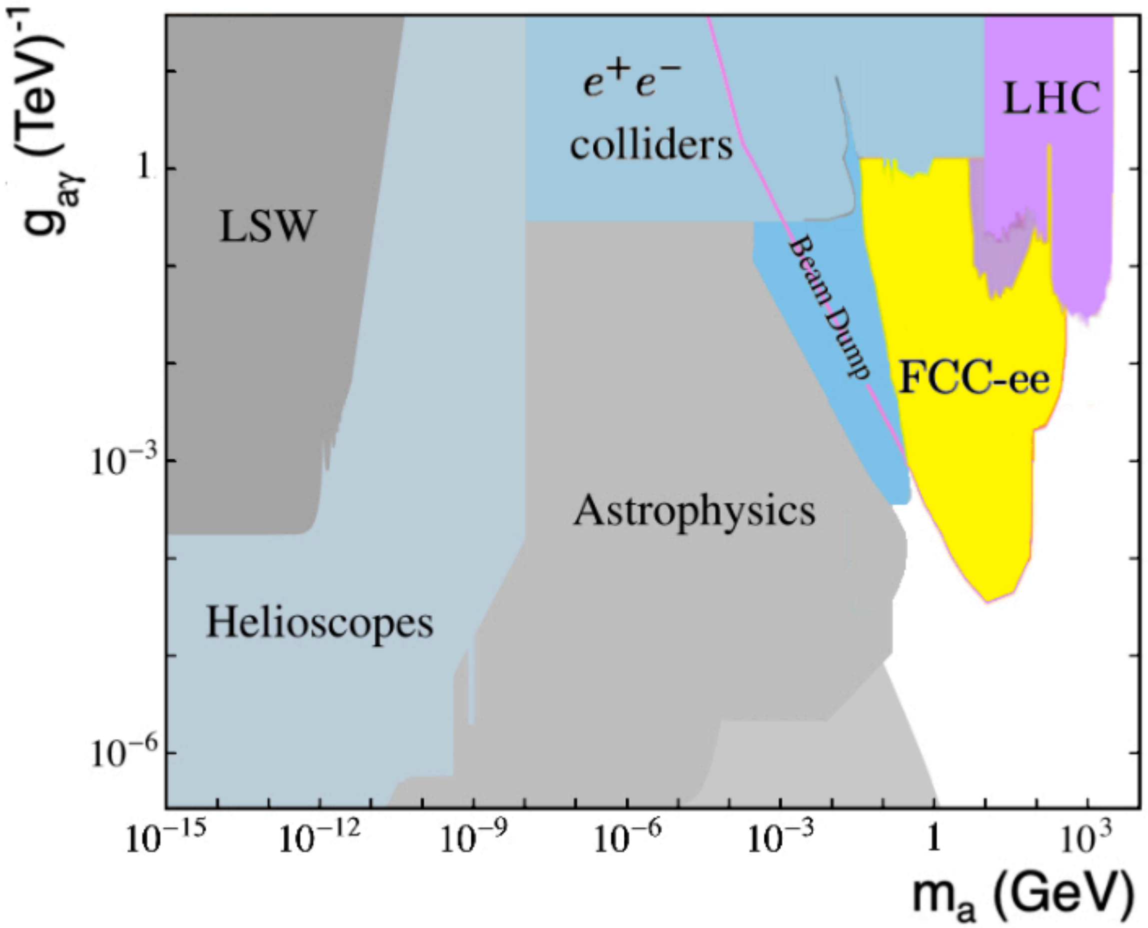
Axion-like particles

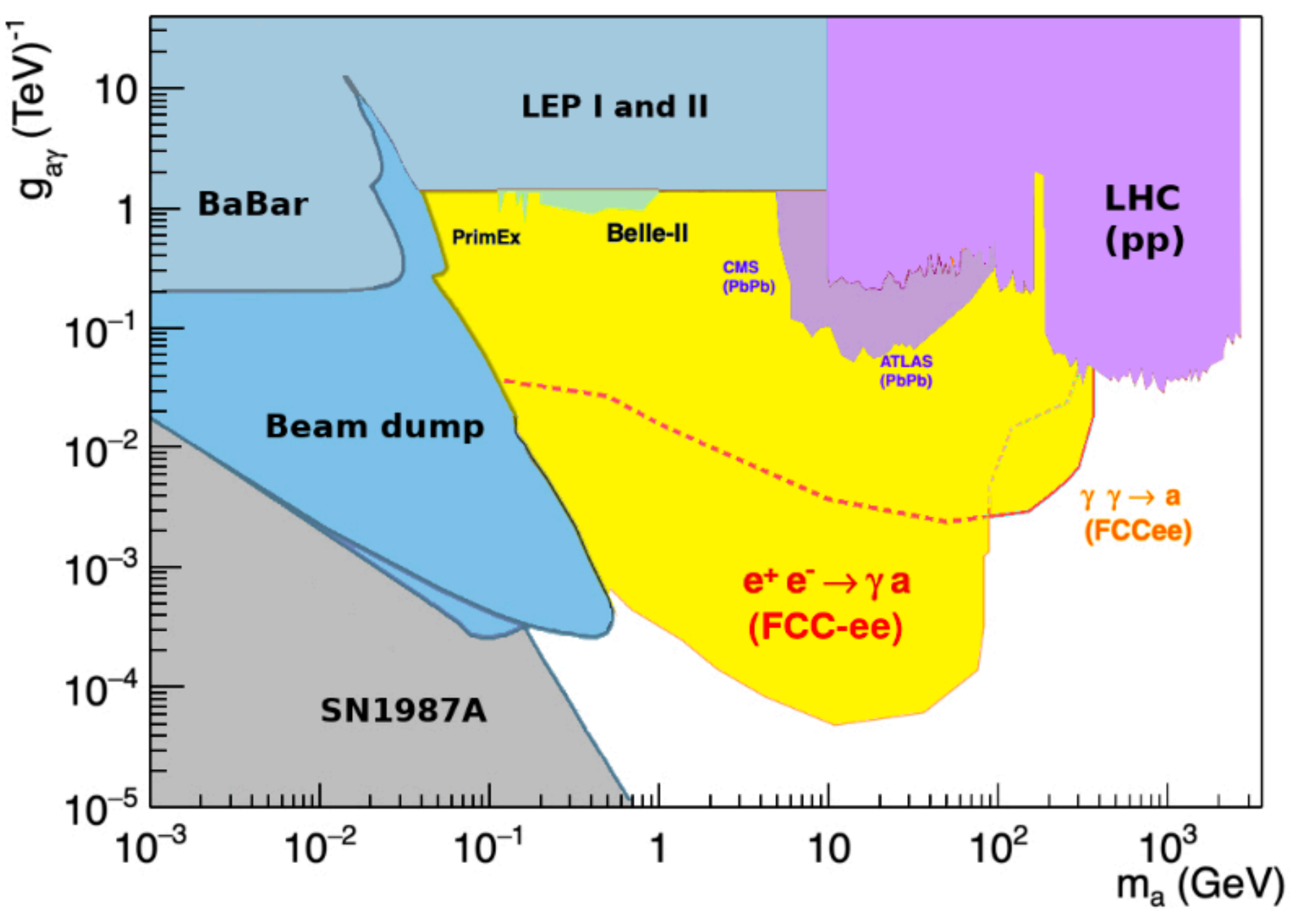
In the run at the Z pole, exploit possible channels such as

$$e^+e^- \to a\gamma \qquad\qquad e^+e^- \to e^+e^-a$$

with

$$a \to \gamma\gamma$$



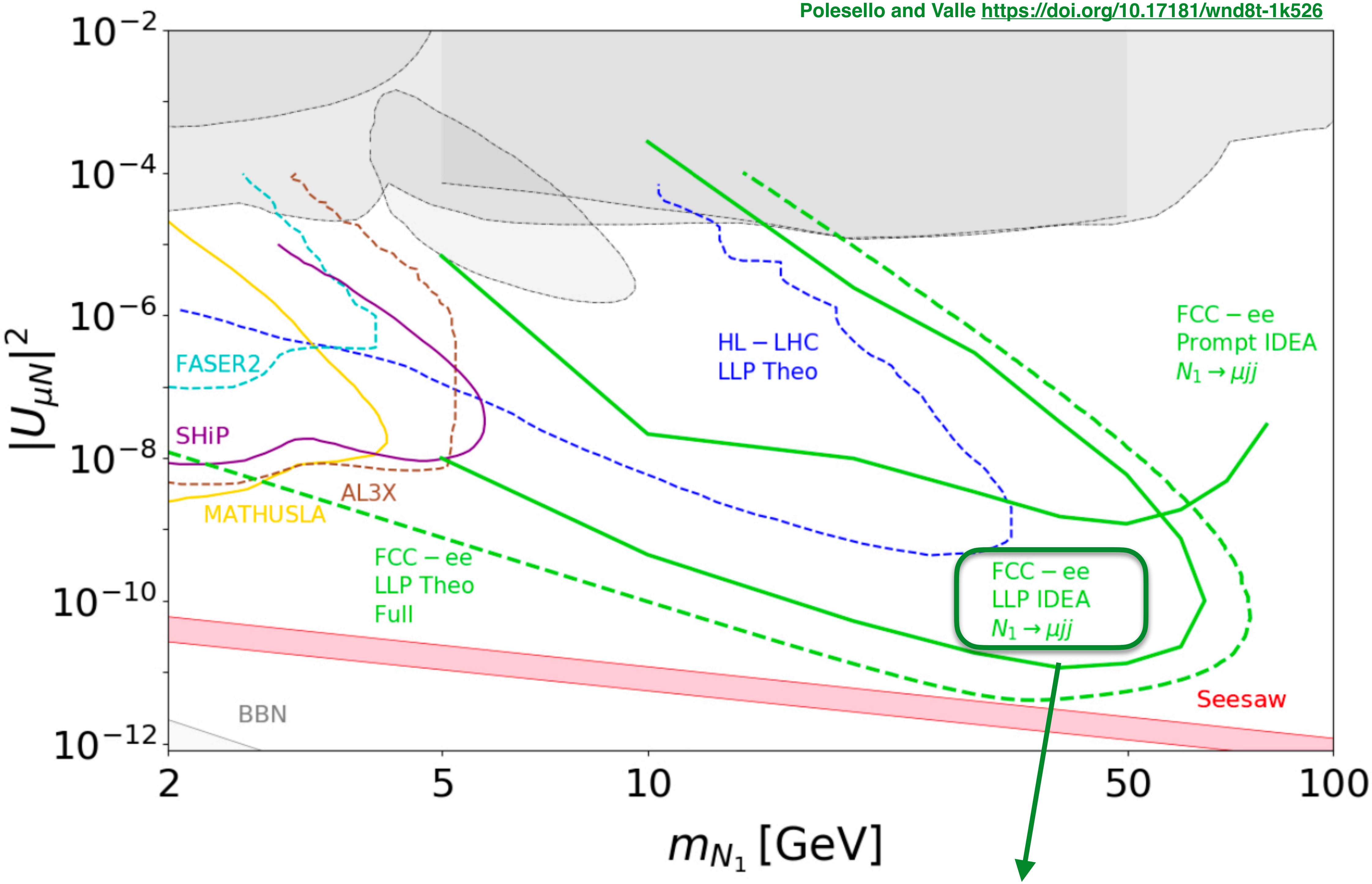


P. Rebello-Teles et al, to appear

Heavy Neutral Leptons

$$e^+e^- \to Z \to \nu N \qquad N \to \ell W^* \to \ell jj$$

Polesello and Valle https://doi.org/10.17181/wnd8t-1k526



dedicated search for decay lengths in the 1mm-2m range

(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:

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

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

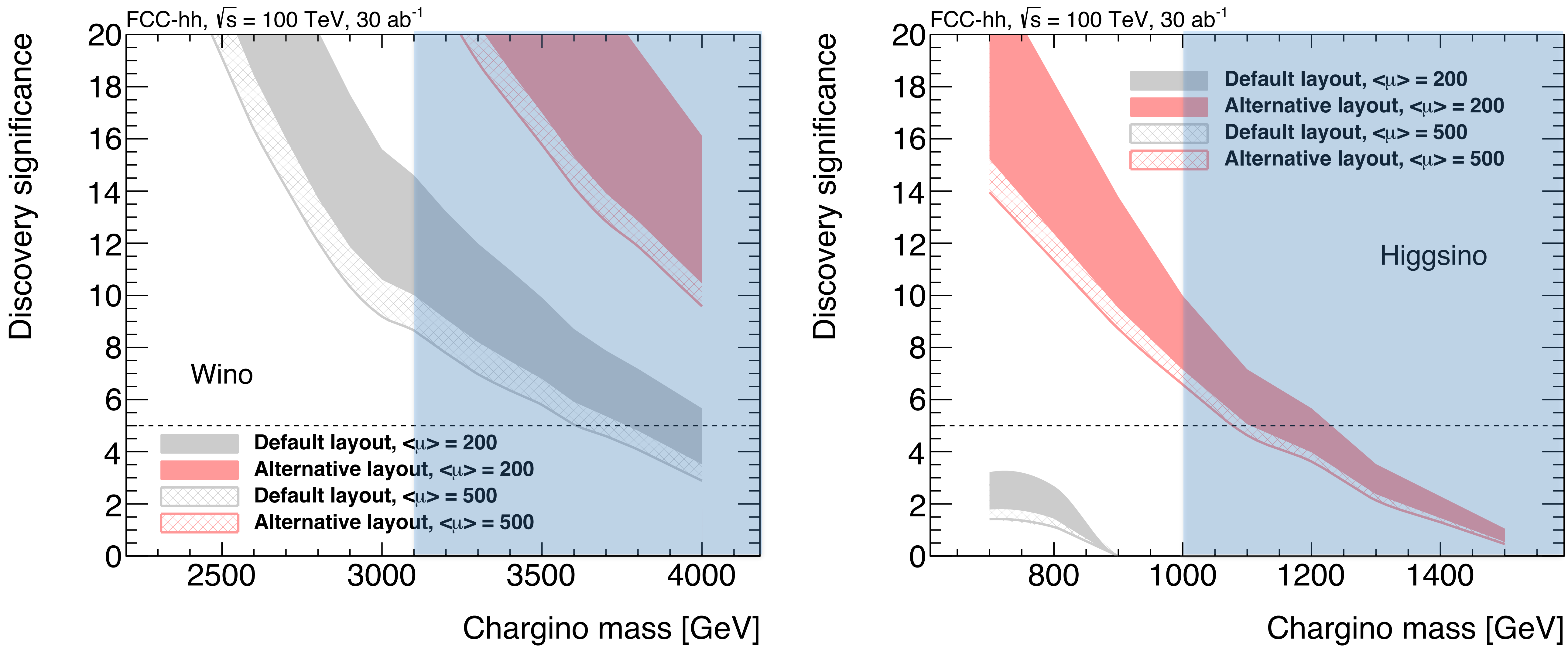
$$\Omega_{wimp}\, h^2 \lesssim 0.12 \quad \Rightarrow \quad M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3} \right)^2$$

Disappearing charged track analyses
(at ~full pileup)

K. Terashi et al,
https://cds.cern.ch/record/2642474

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

Excluded region for thermal WIMP DM



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

… and much more …

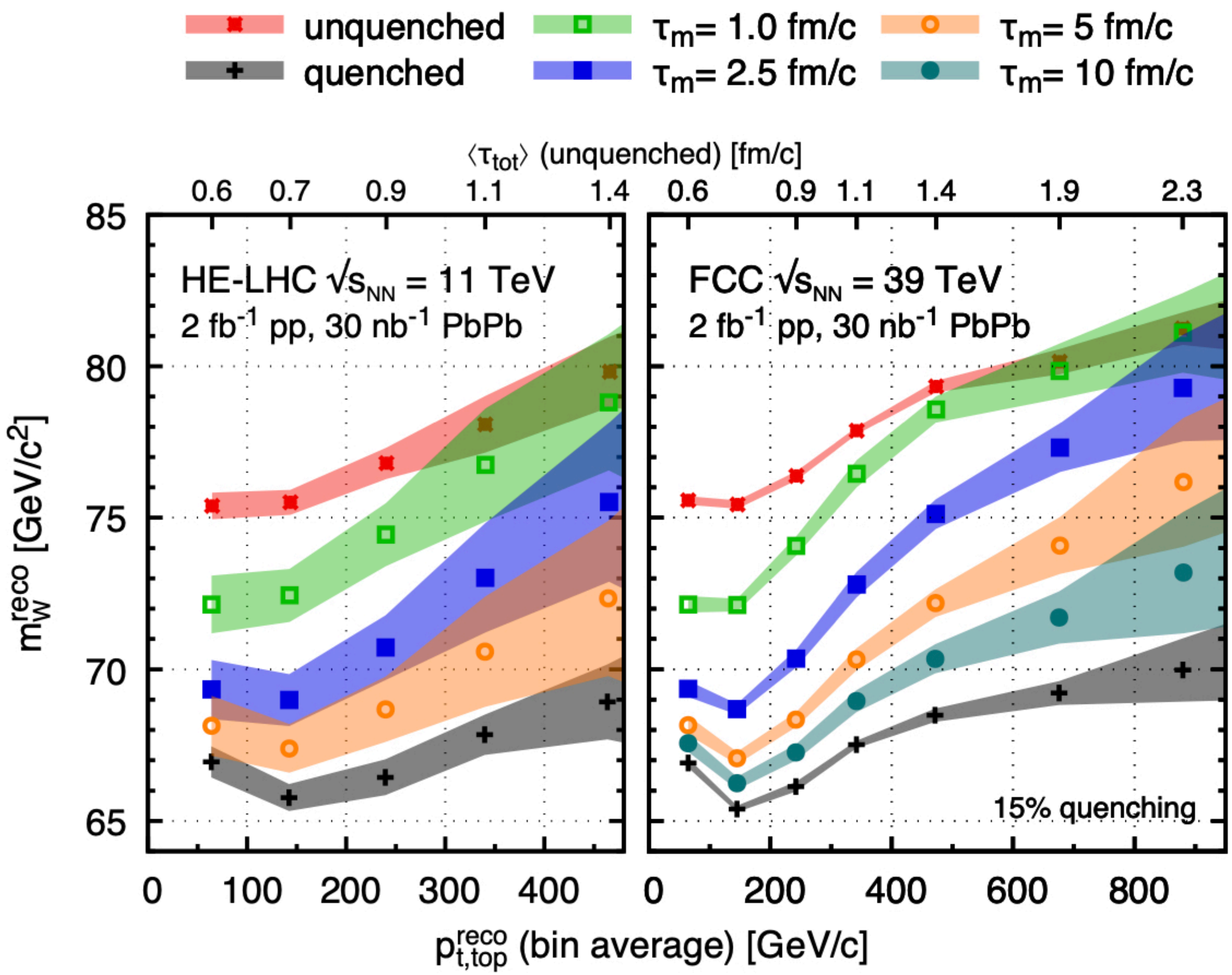
- Countless studies of discovery potential for multiple BSM scenarios, from SUSY to heavy neutrinos, from very low masses to very high masses, LLPs, DM, etcetcetc, with plenty of opportunities for direct discovery even at FCC-ee and FCC-eh
- Sensitivity studies to SM deviations in the properties of top 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

Ex: medium modification of top-decay properties in PbPb @ FCC

Apolinario et al, https://arxiv.org/pdf/1711.03105.pdf

$t \to bW \to bjj$

τ_{top} = 0.15 fm/c , τ_W (from top decay) = 0.09 fm/c … both are increased if the top is boosted, modifying the time the final state jets spend inside the thermalized medium, subject to quenching



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 circular 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 next 3-4 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