한국물리학회
The Korean Physical Society

Korean Physical Society, 2023 Fall meeting
Changwon, 24-27 October 2023
KPS Pioneer session - Present and Future of the LHC Program at CERN

FCC Physics Prospects

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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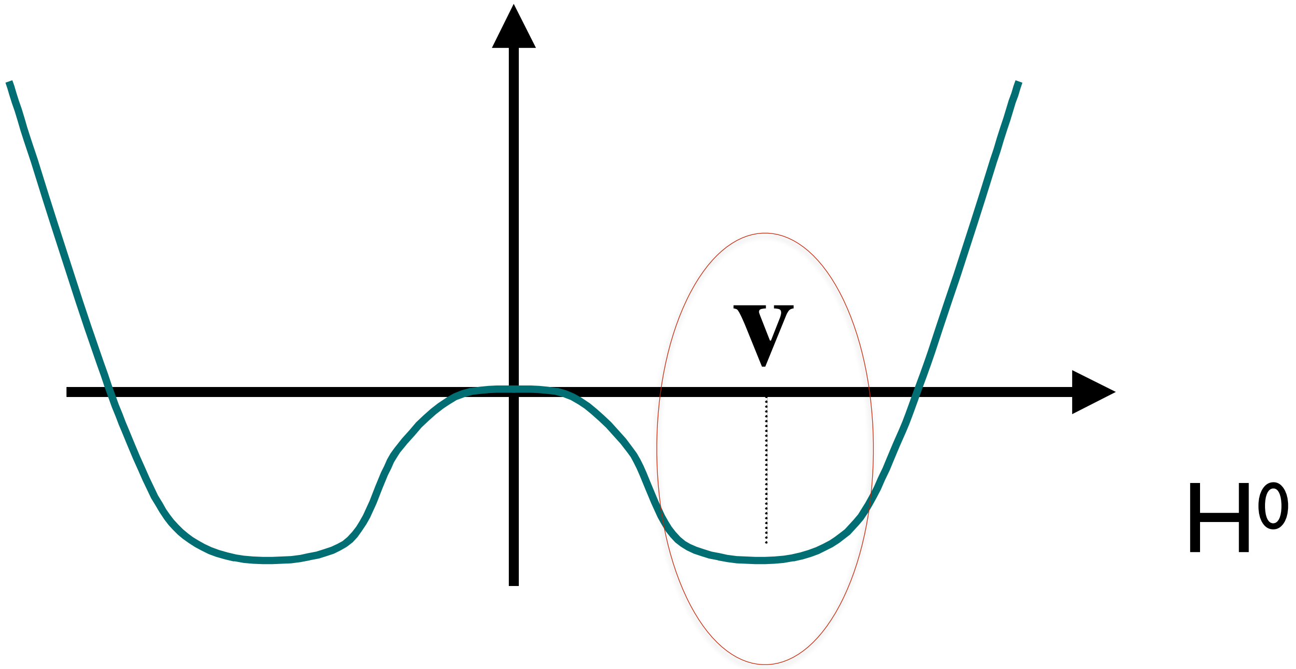

$$V(H) = -\mu^2\,|H|^2 + \lambda\,|H|^4$$

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.**

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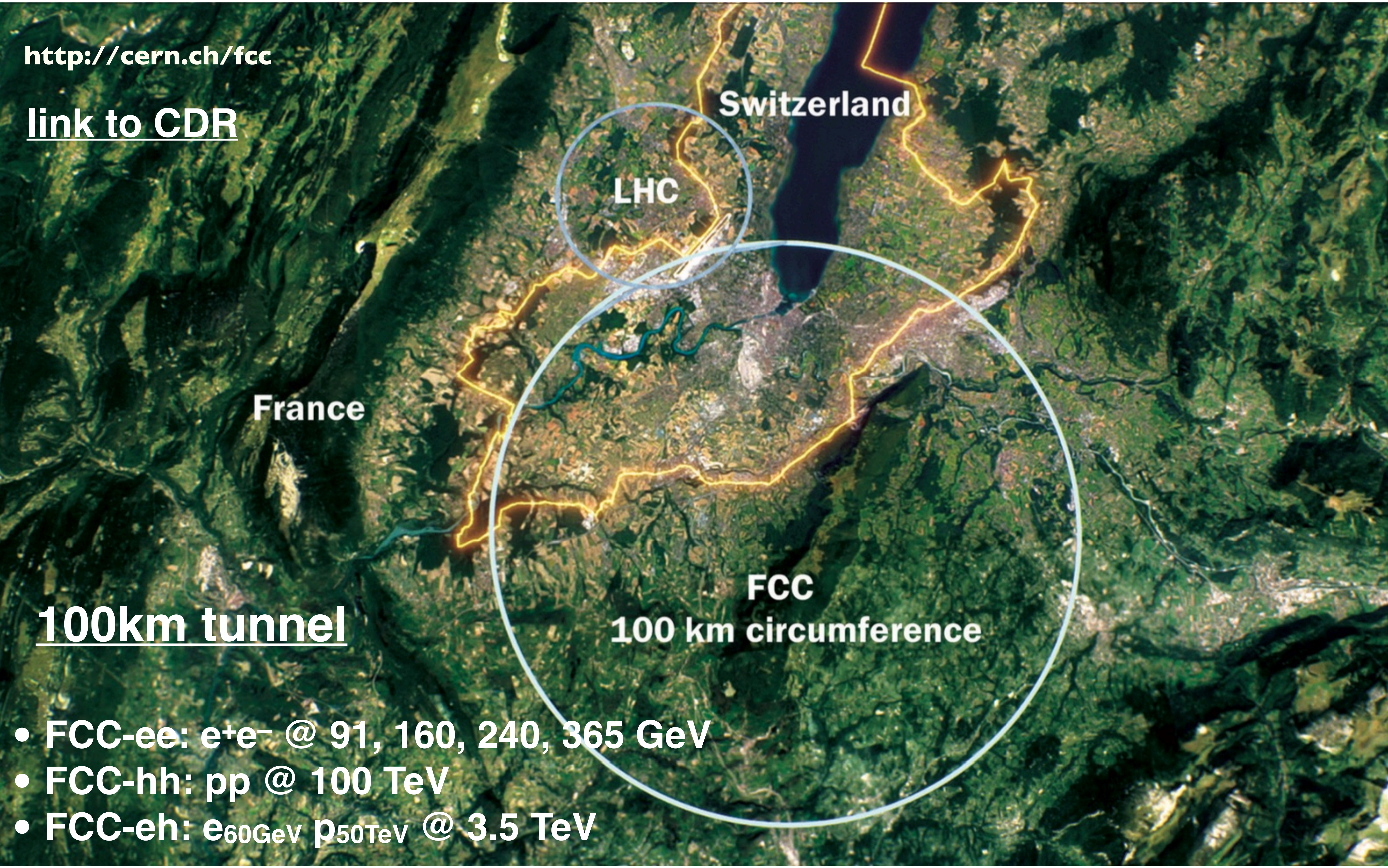
These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

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

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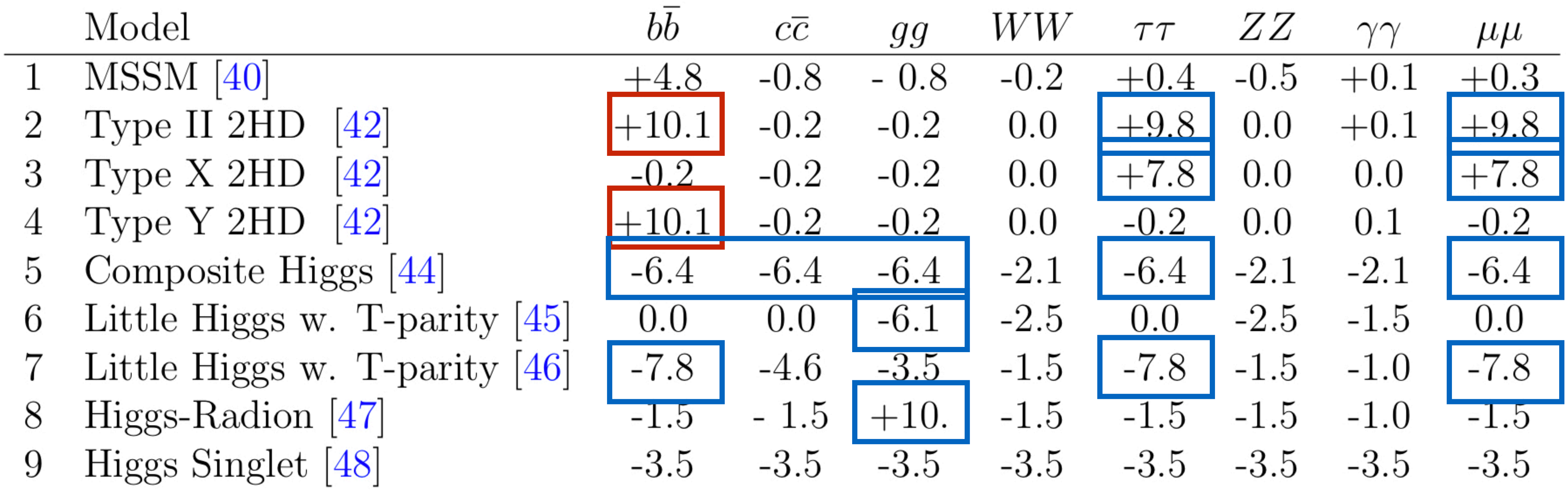
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*
- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase 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

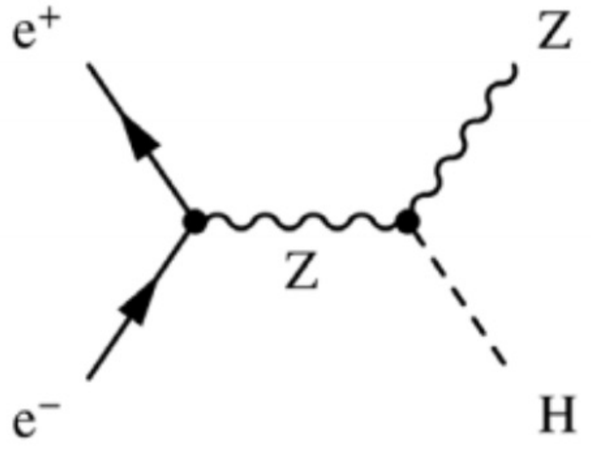
🟦	5 – 10 %
🟥	> 10%

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 $e^+e^- \rightarrow ZH$ (circular or linear):

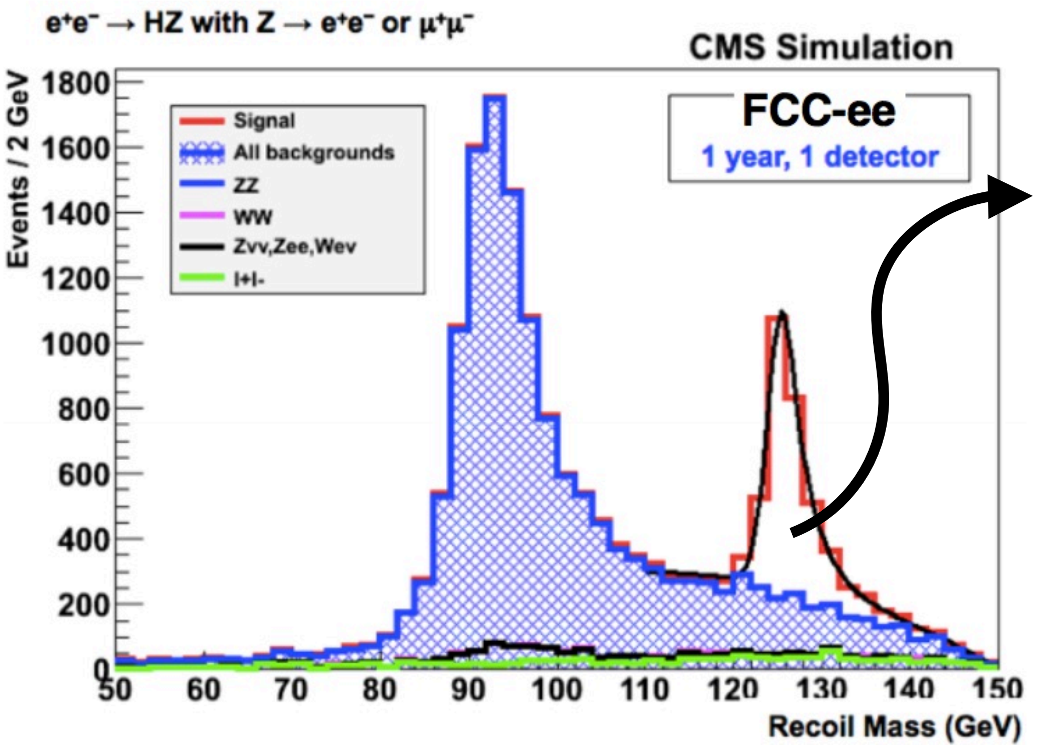
- the model independent absolute measurement of **HZZ** coupling, which allows the subsequent:
  - sub-% measurement of couplings to W, Z, b, τ
  - % measurement of couplings to gluon and charm



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

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

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

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

The absolutely unique power of pp → H+X:

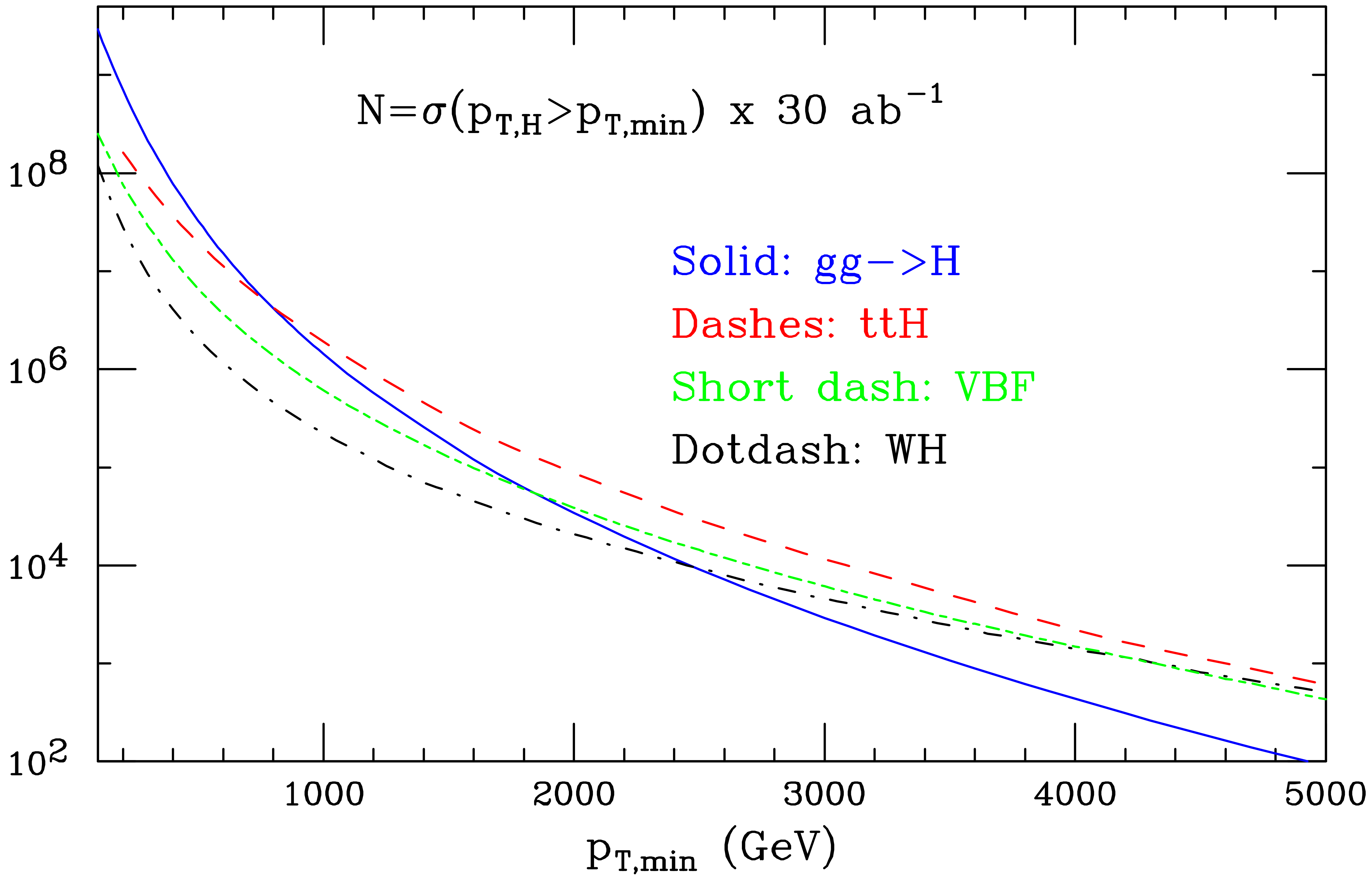
- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→ZZ*), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4 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}	24×10^9	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

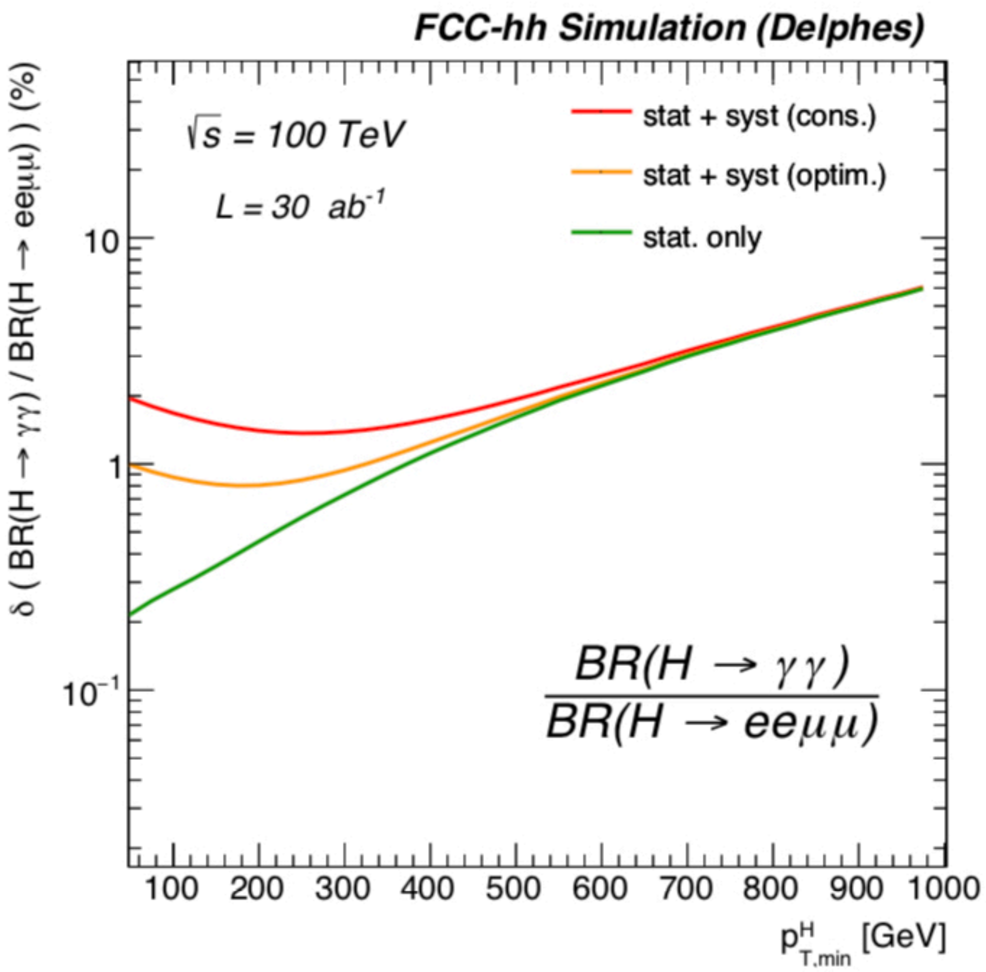
$N_{100} = \sigma_{100\,\text{TeV}} \times 30\ \text{ab}^{-1}$

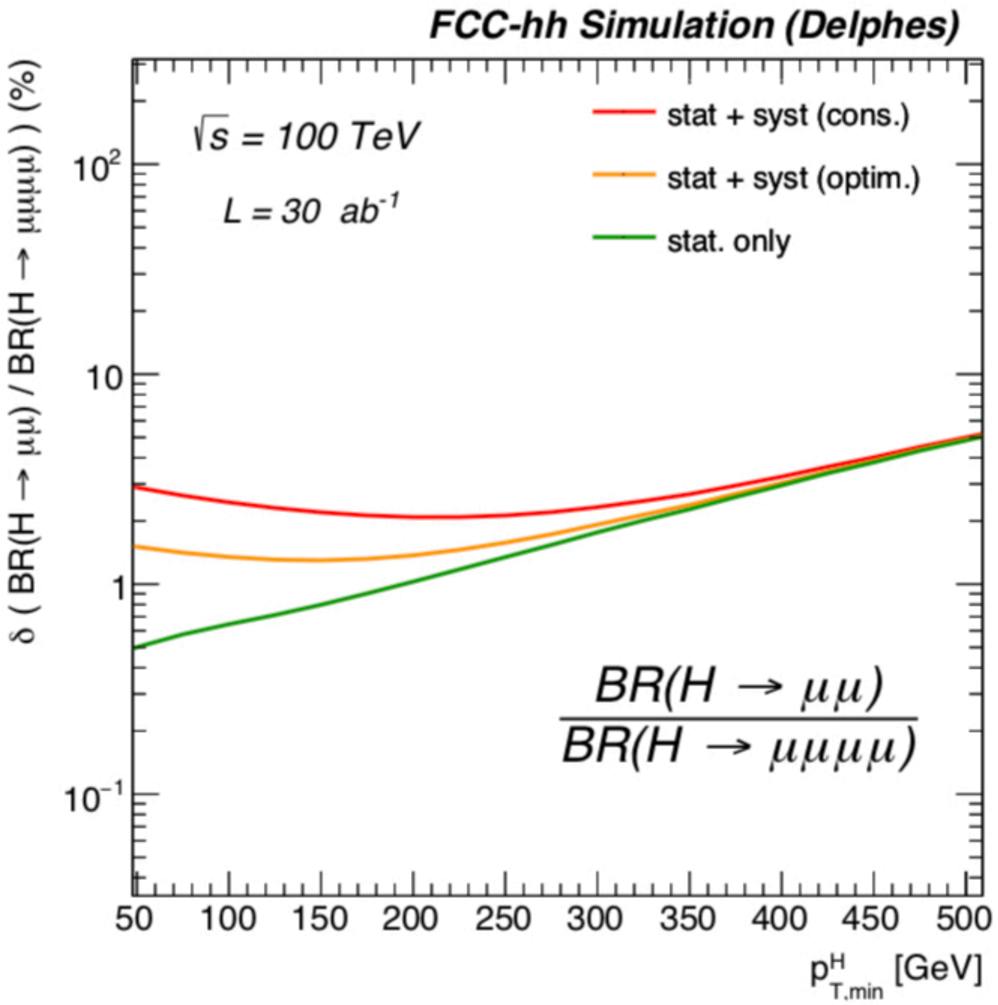
$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

H at large p_T

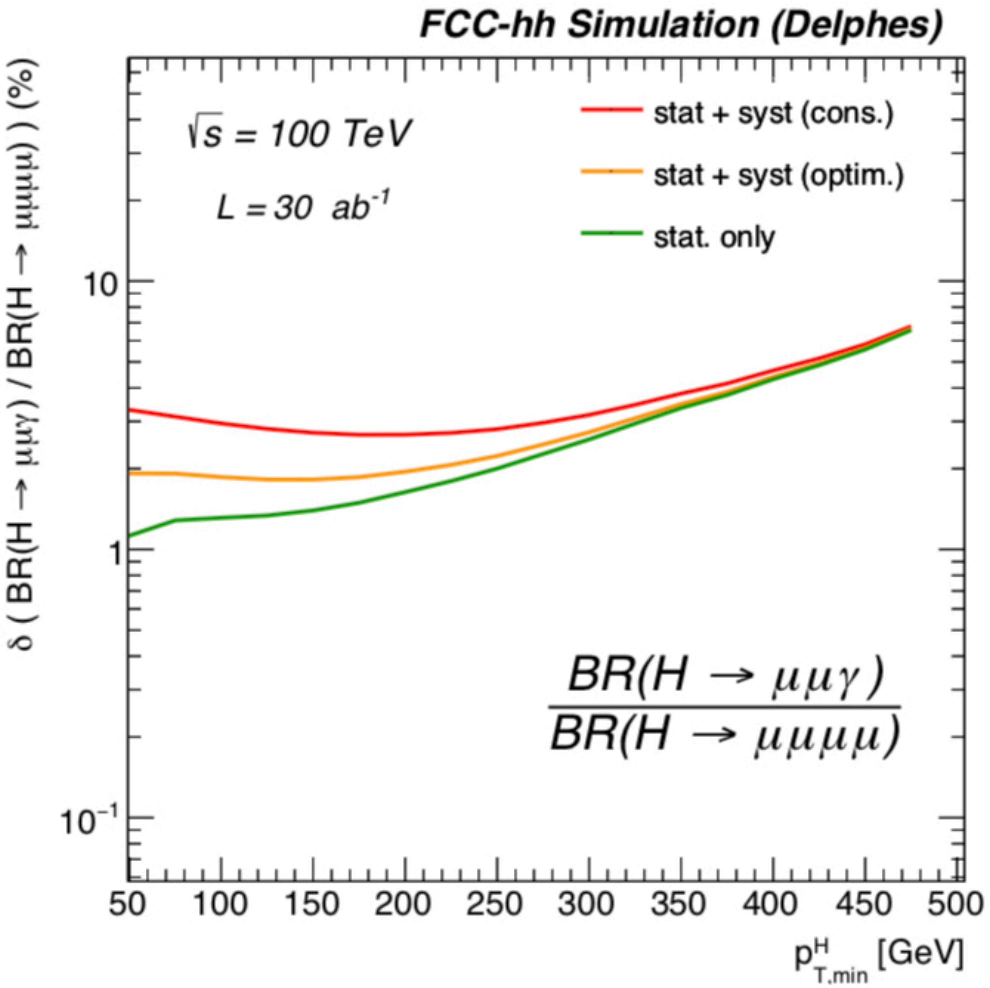


- Hierarchy of production channels changes at large $p_T(H)$:
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV





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

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

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

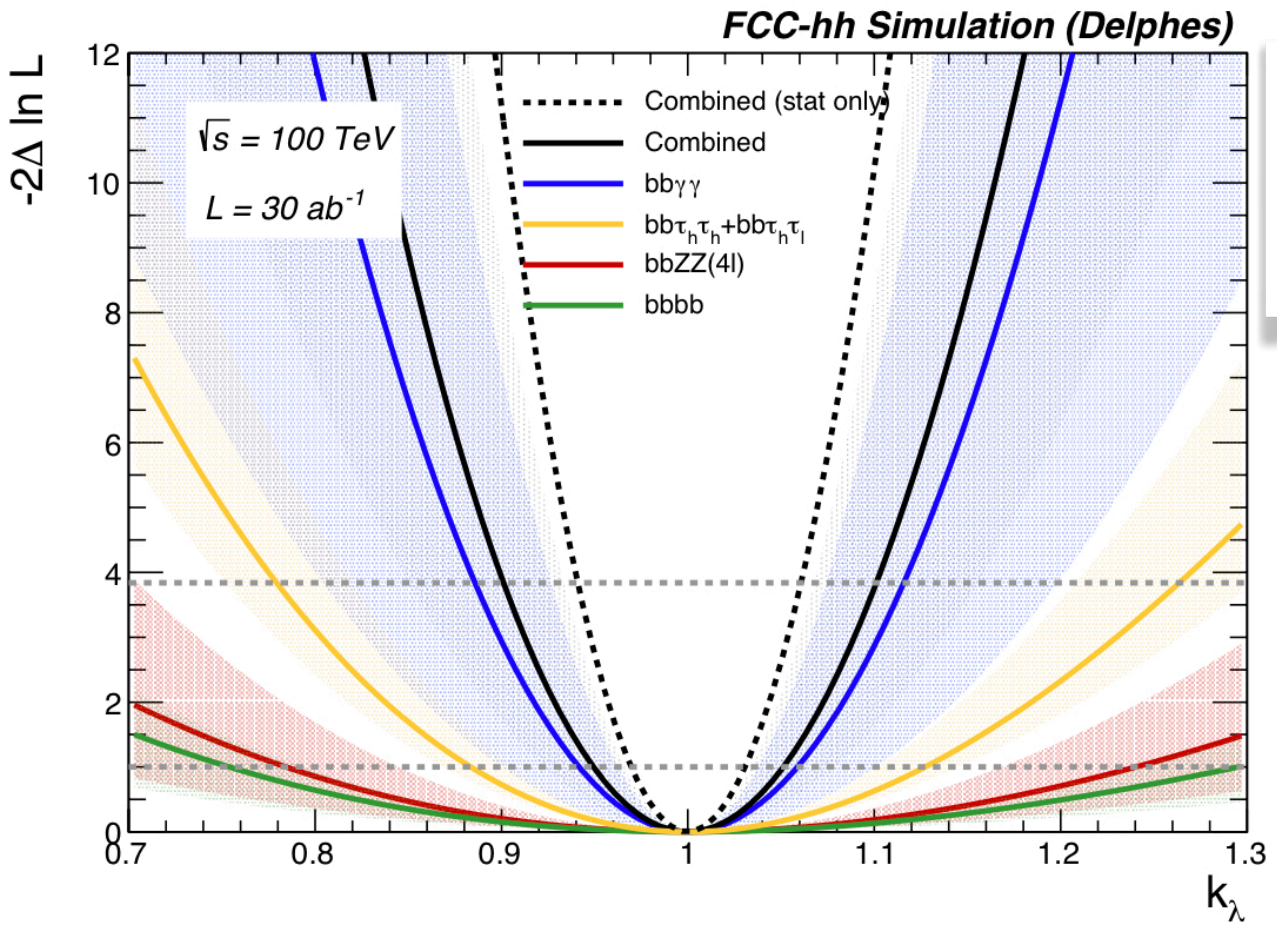
pp collider is essential to beat the % target, since no proposed ee collider can produce more than $O(10^6)$ H's

* From BR ratios wrt B(H→ZZ*) @ FCC-ee

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

The Higgs self-coupling at FCC-hh

https://arxiv.org/abs/2004.03505



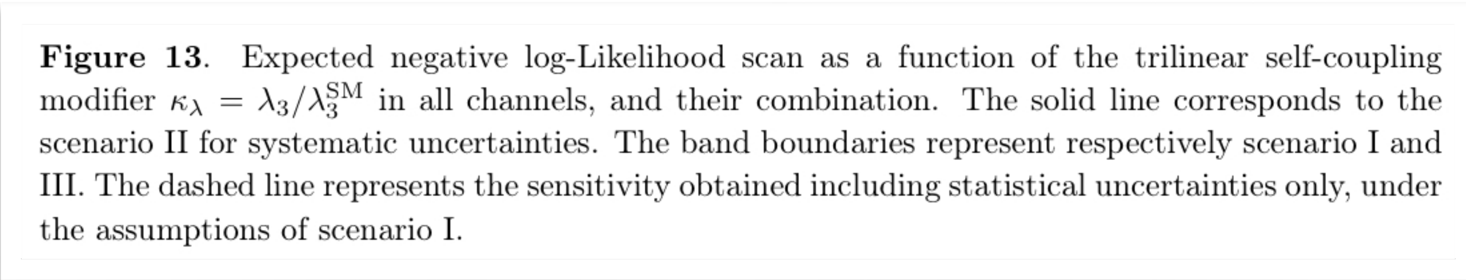
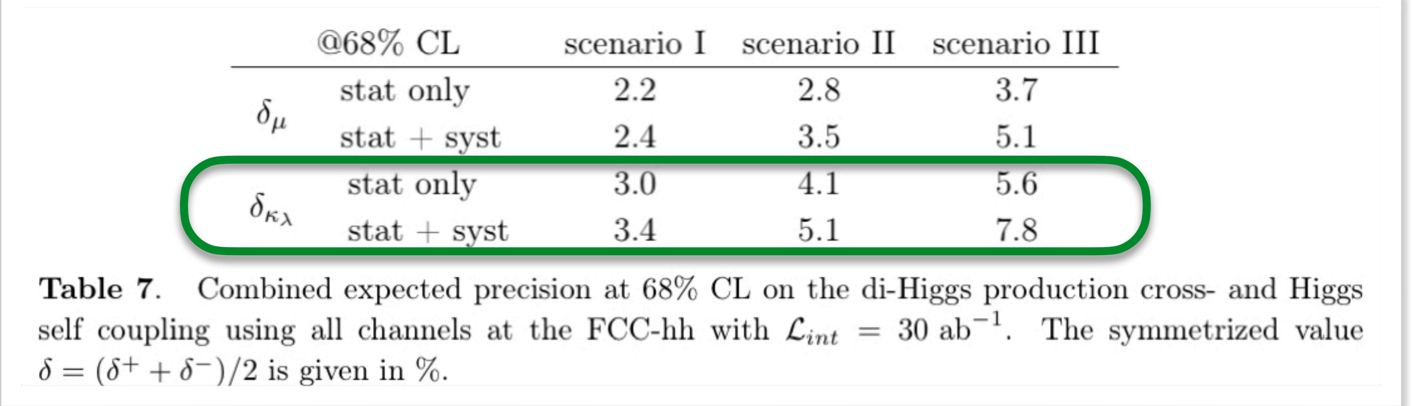


Figure 13. Expected negative log-Likelihood scan as a function of the trilinear self-coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{\rm SM}$ in all channels, and their combination. The solid line corresponds to the scenario II for systematic uncertainties. The band boundaries represent respectively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

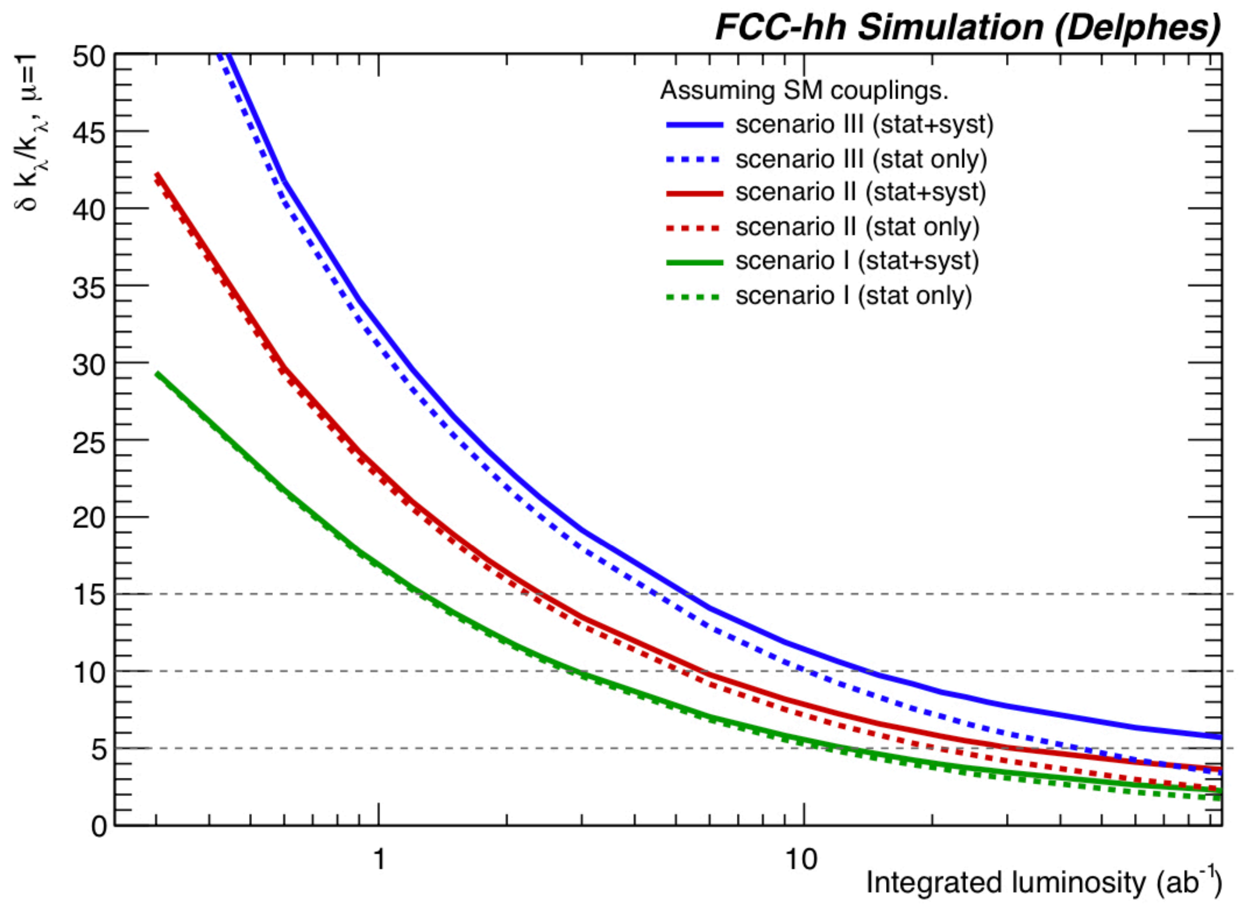
Syst scenarios



@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

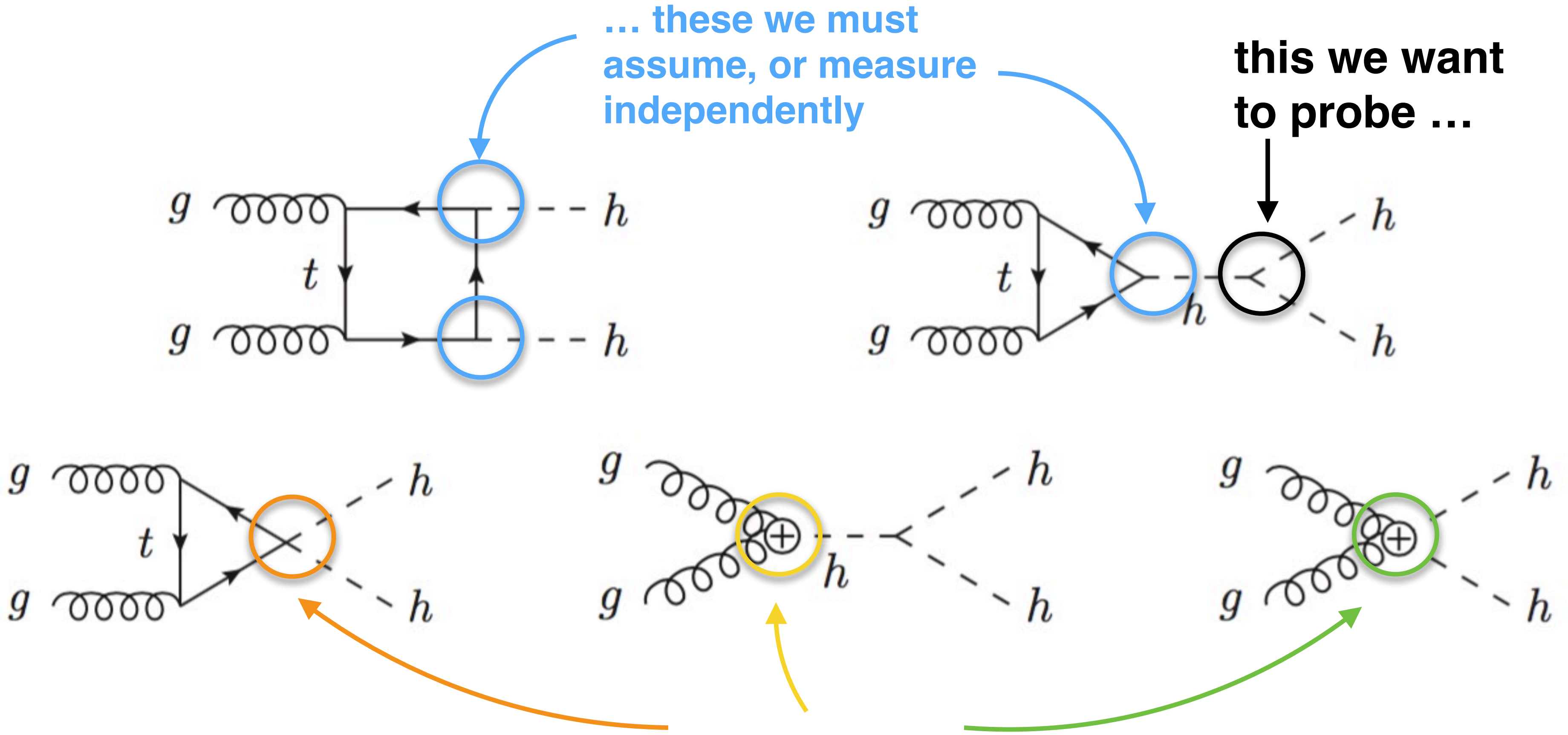
=> within the reach of the first 5yrs of FCC-hh running, in the "low" luminosity / low pileup phase

=> 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:



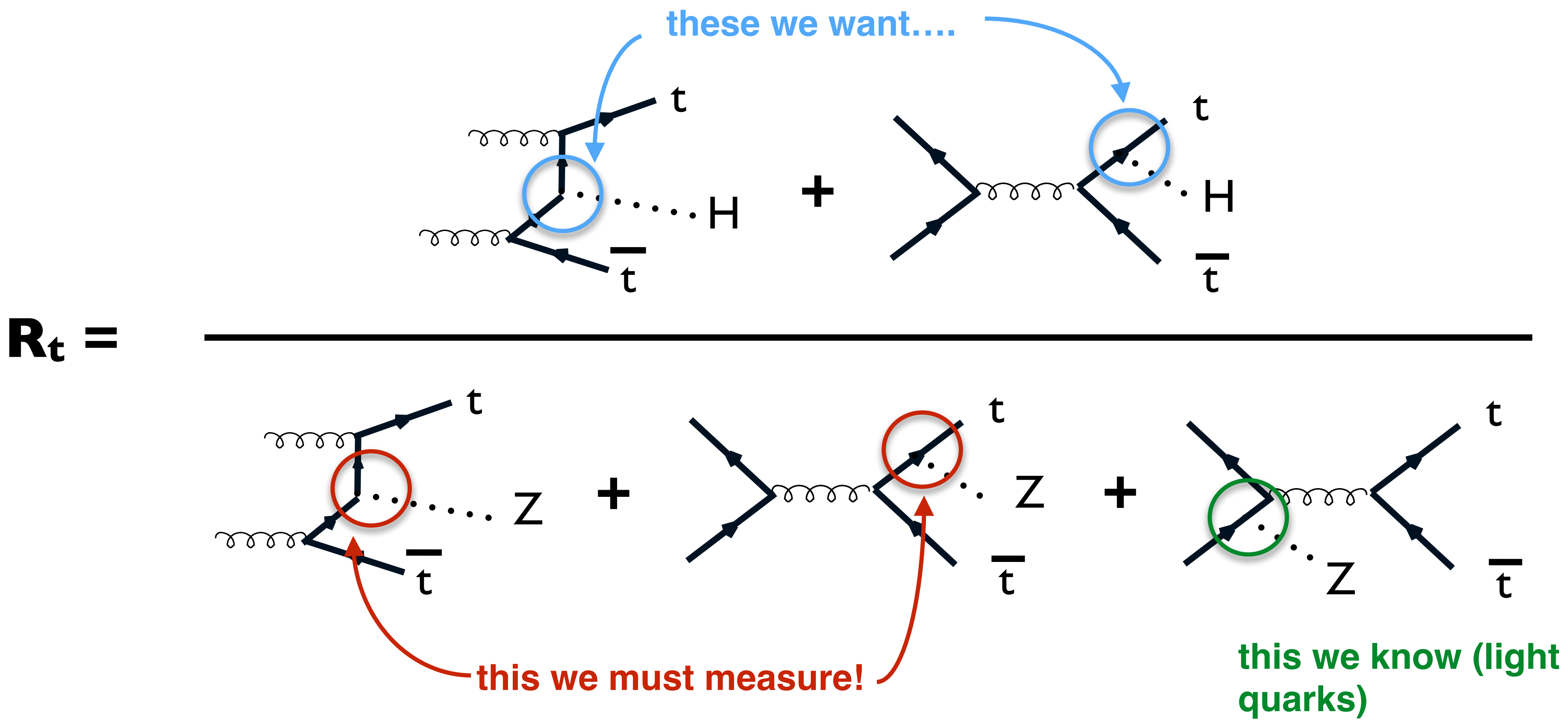
… these we must assume, or measure independently

this we want to probe …

… these would come into play if we eventually need to decode the origin of a deviation, as possible alternative sources of new physics

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:



these we want….

this we must measure!

this we know (light quarks)

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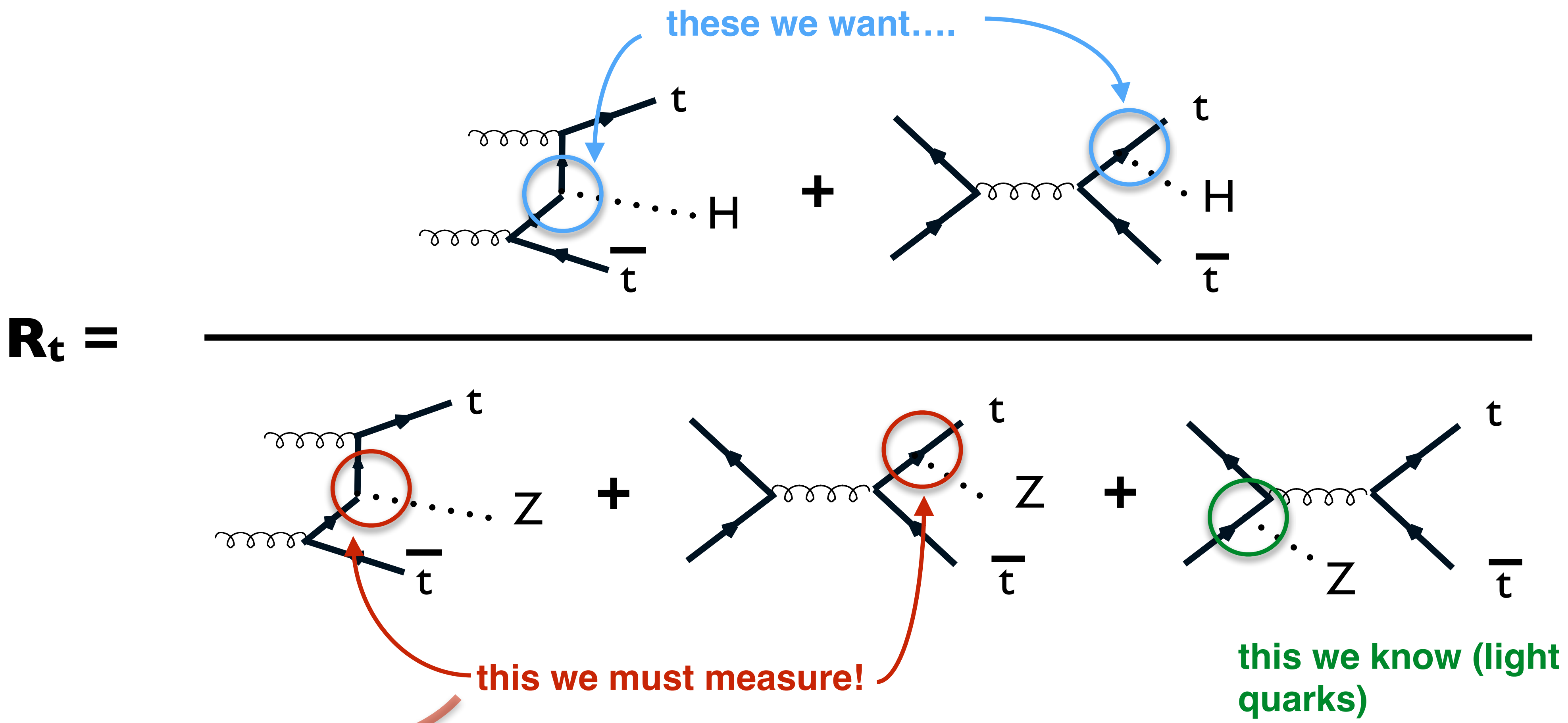

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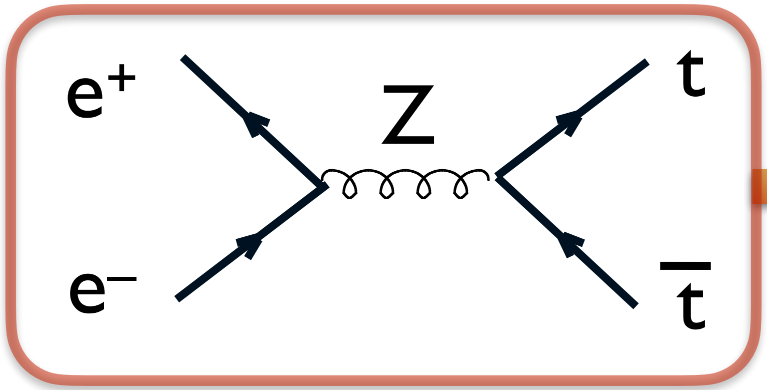
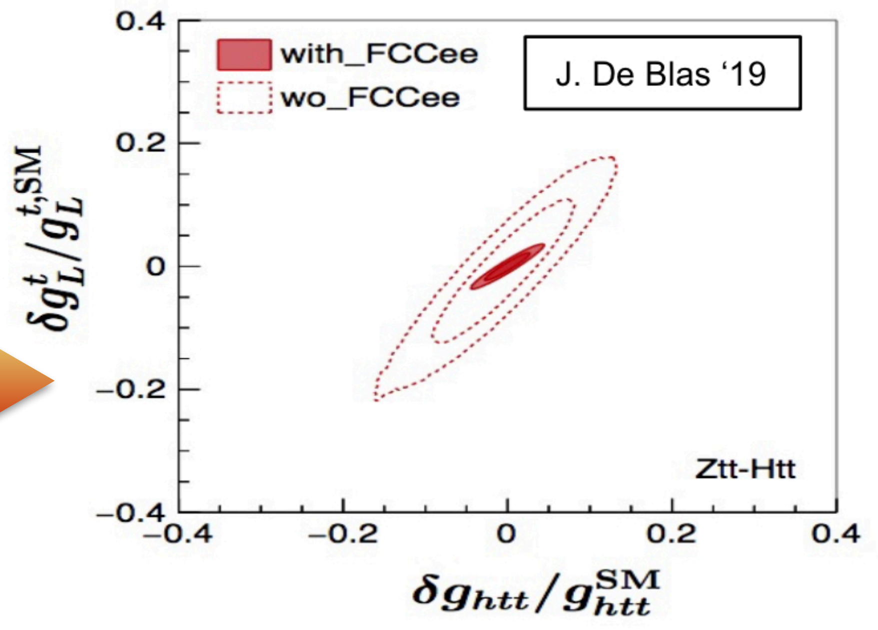
FCC-ee





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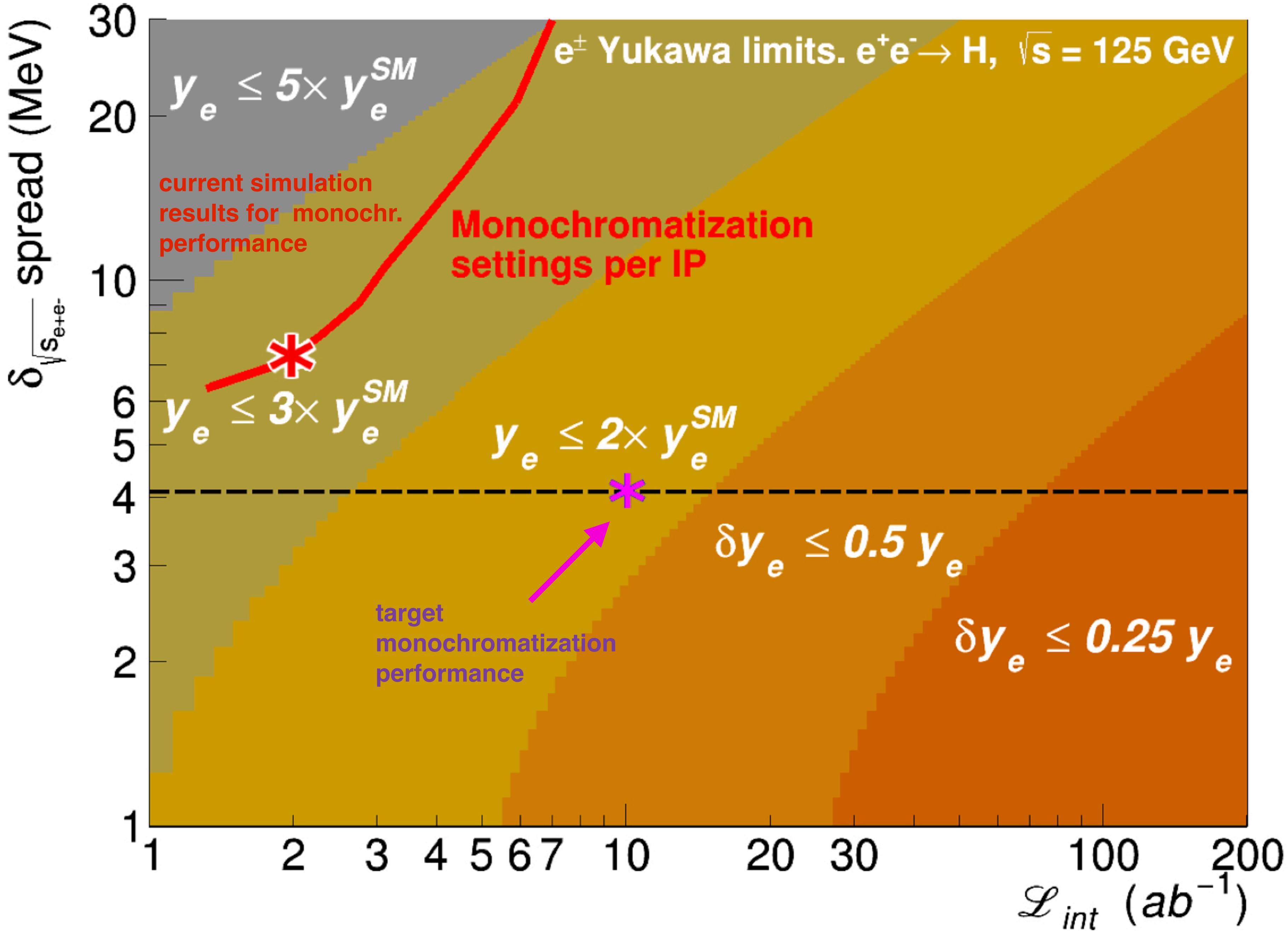
FCC-ee is a necessary pre-requisite to fully exploit the precision potential of FCC-hh

Unique at FCC-ee: $e^+e^- \rightarrow H$

D.D'Enterria et al, arXiv:2107.02686



expected lum/yr

Table 6. Individual significances (in std. deviations σ) expected per decay channel for s-channel Higgs boson production in e^+e^- collisions at FCC-ee for $\mathcal{L}_{\rm int} = 10\,\rm ab^{-1}$ and $\delta_{\sqrt{s}} = 4.1$ MeV. The last column quotes the combined significance.

$H \rightarrow gg$	$H \rightarrow WW^* \rightarrow \ell\nu\, 2j;\ 2\ell\, 2\nu;\ 4j$	$H \rightarrow ZZ^* \rightarrow 2j\, 2\nu;\ 2\ell\, 2j;\ 2\ell\, 2\nu$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau_{\rm had}\tau_{\rm had};\ c\bar{c};\ \gamma\,\gamma$	Combined
1.1σ	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

(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

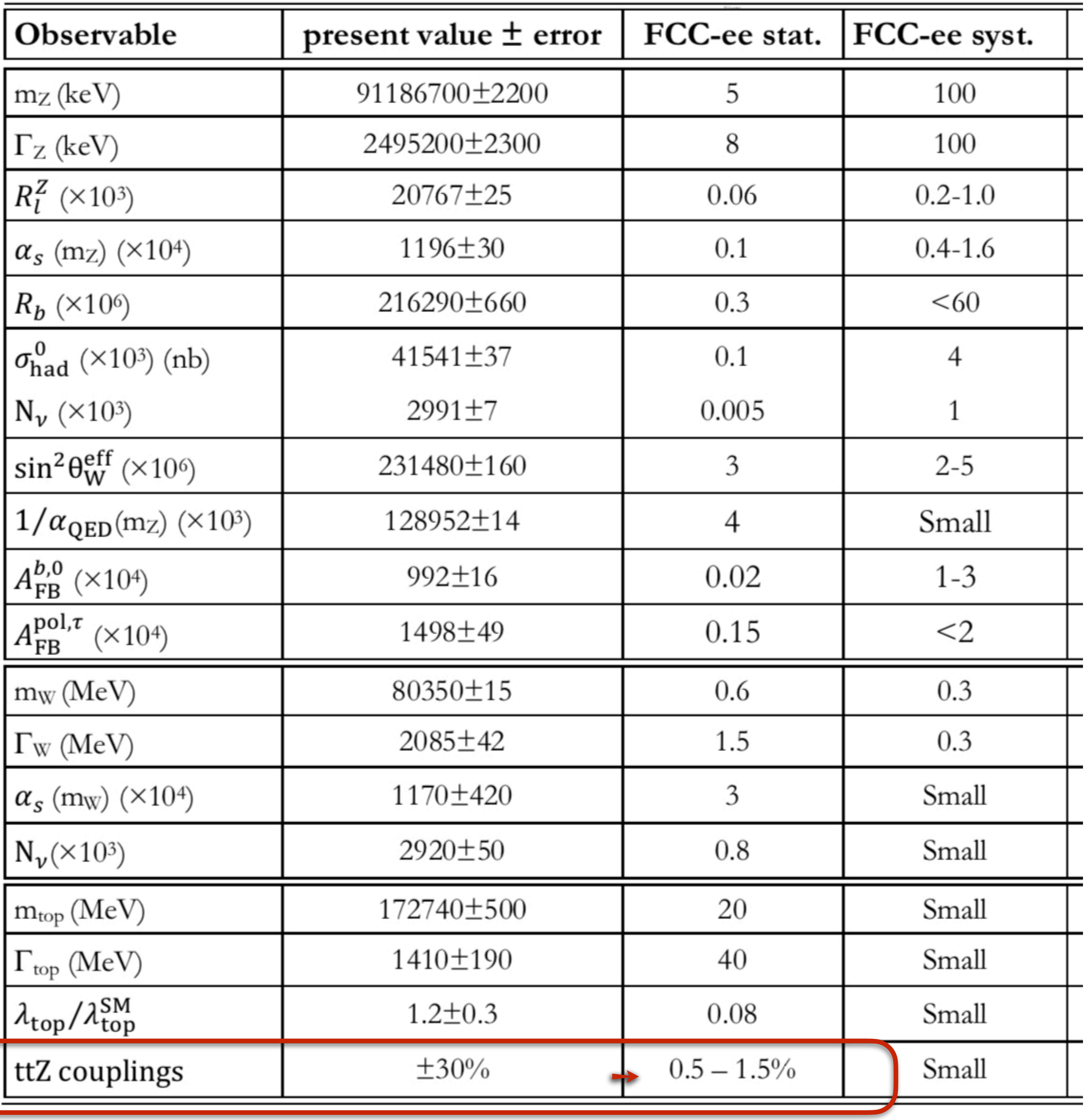
Additional bonus wrt B factory: (i) Lorentz boost (ii) B hadrons not accessible at the Y(4S,5S) thresholds

EW parameters @ FCC-ee

Improvement wrt current total uncertainties:

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

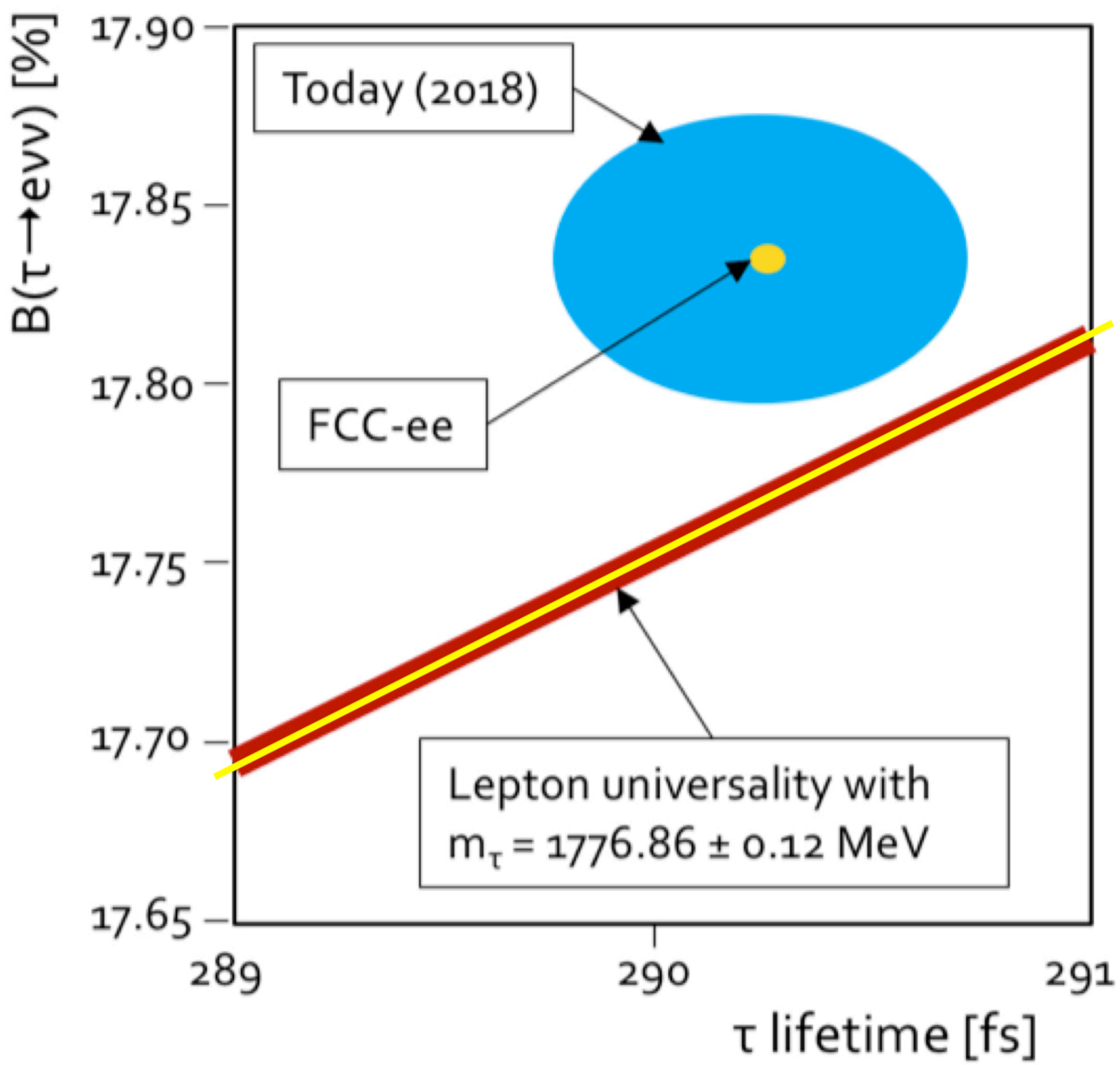
Currently limited by TH systematics => work ongoing



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
$A_{\mathrm{FB}}^{b,0}$ ($\times 10^4$)	992±16	0.02	1-3
$A_{\mathrm{FB}}^{\mathrm{pol},\tau}$ ($\times 10^4$)	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
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{\mathrm{SM}}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	0.5 – 1.5%	Small

crucial for ttH and HHH couplings at FCC-hh

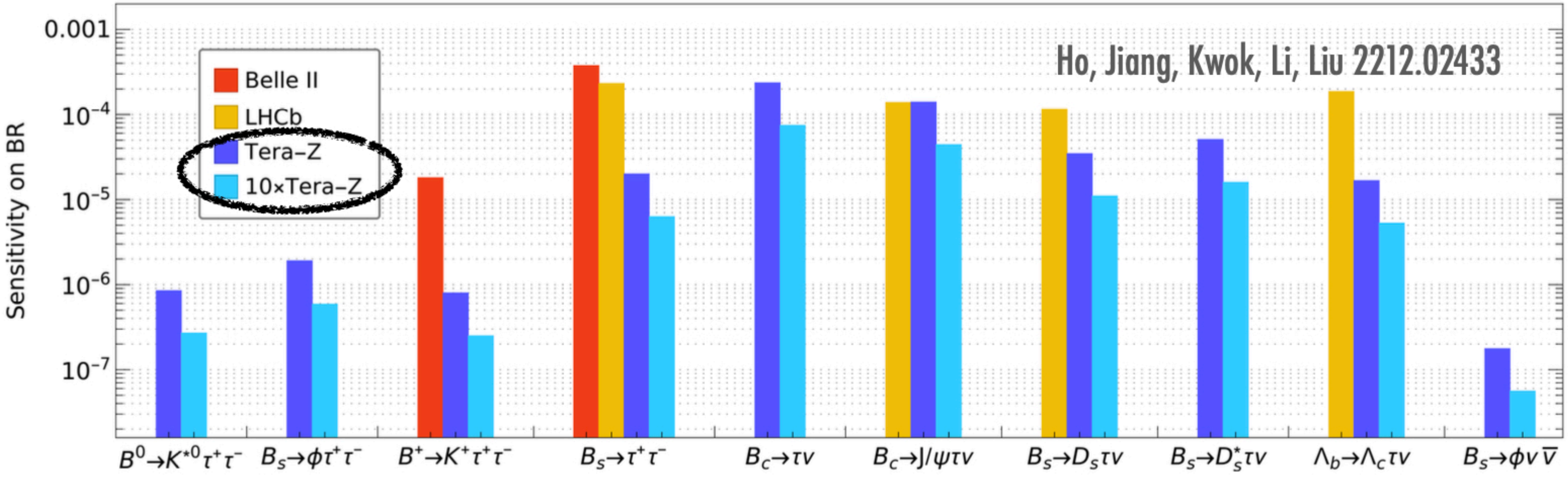
Flavour probes: eg lepton universality in tau decays



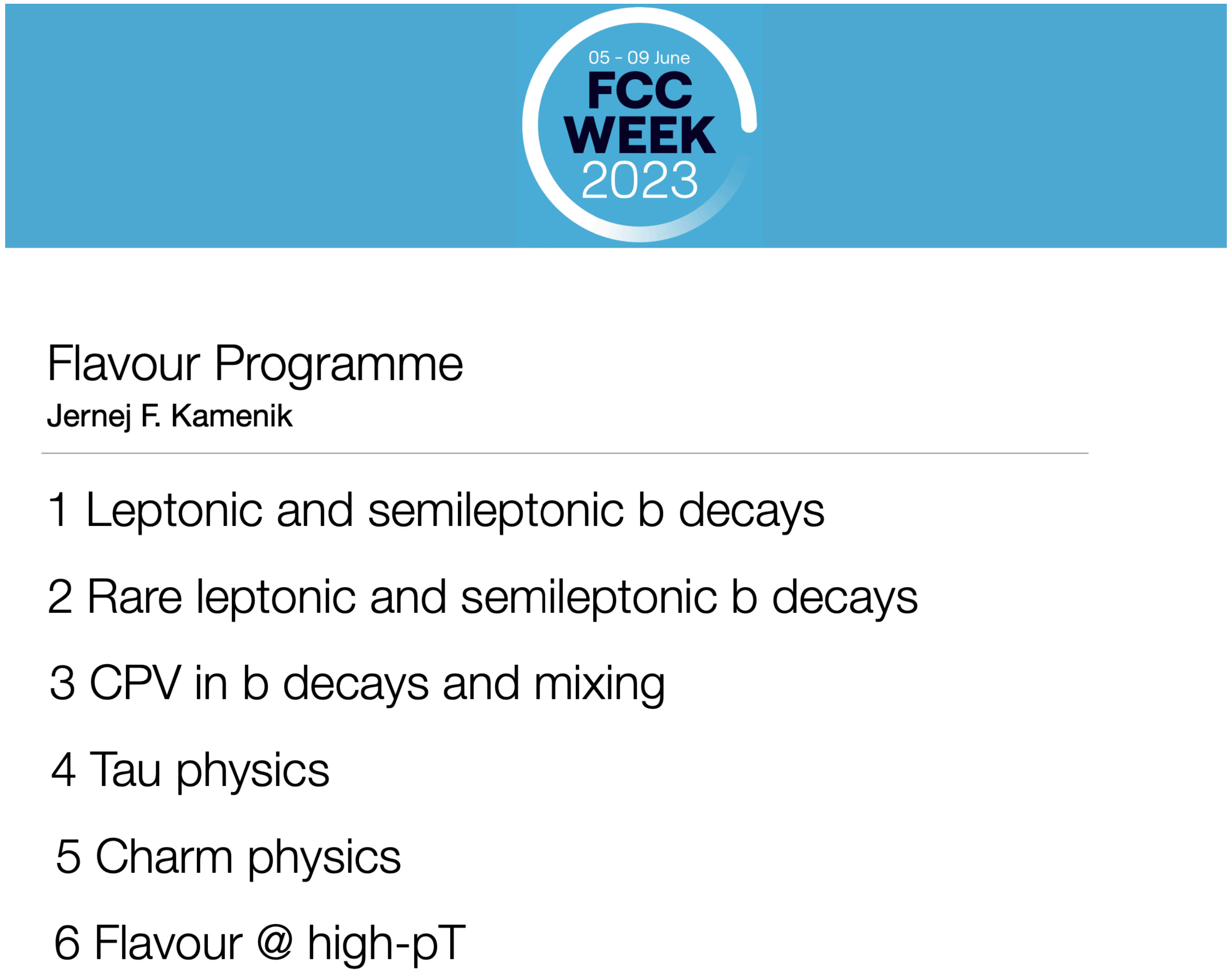
Lorentz boost crucial!

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($\tau \to e\nu\nu$) [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	0.003	Efficiency, bkg, Particle ID
B($\tau \to \mu\nu\nu$) [%]		17.39 ± 0.05			

© M. Dam



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



Flavour Programme

Jernej F. Kamenik

1 Leptonic and semileptonic b decays

2 Rare leptonic and semileptonic b decays

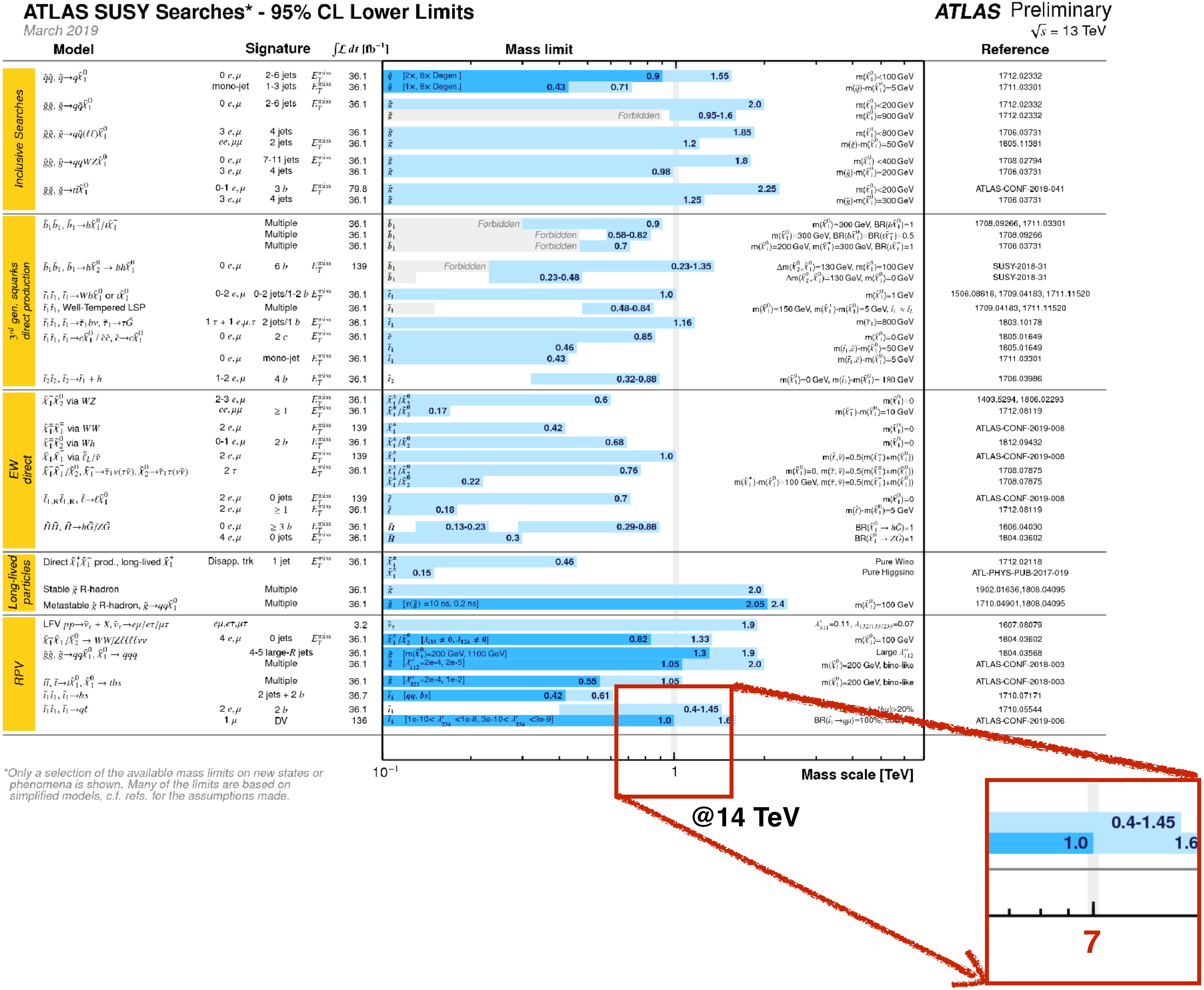
3 CPV in b decays and mixing

4 Tau physics

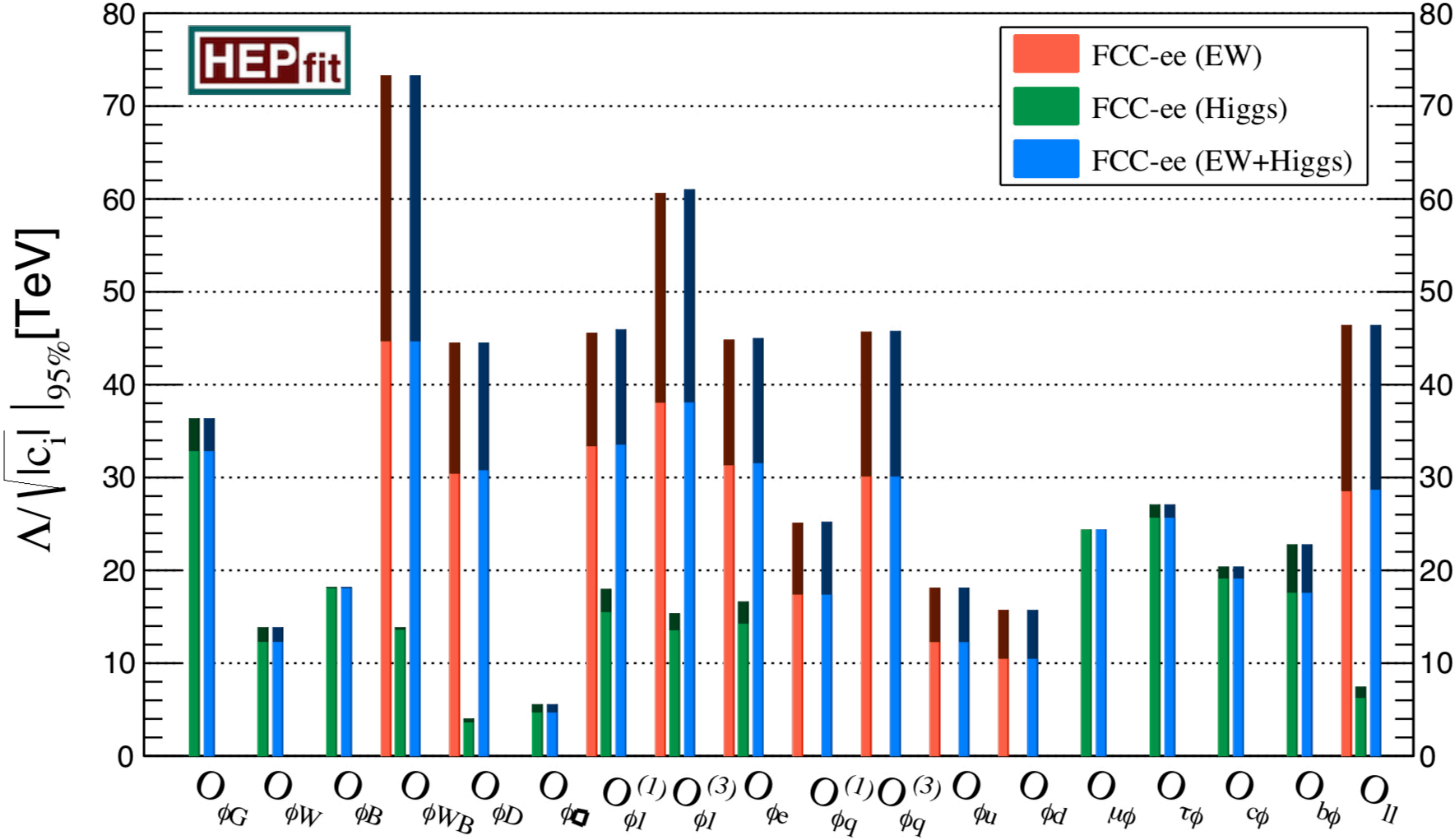
5 Charm physics

6 Flavour @ high-pT

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

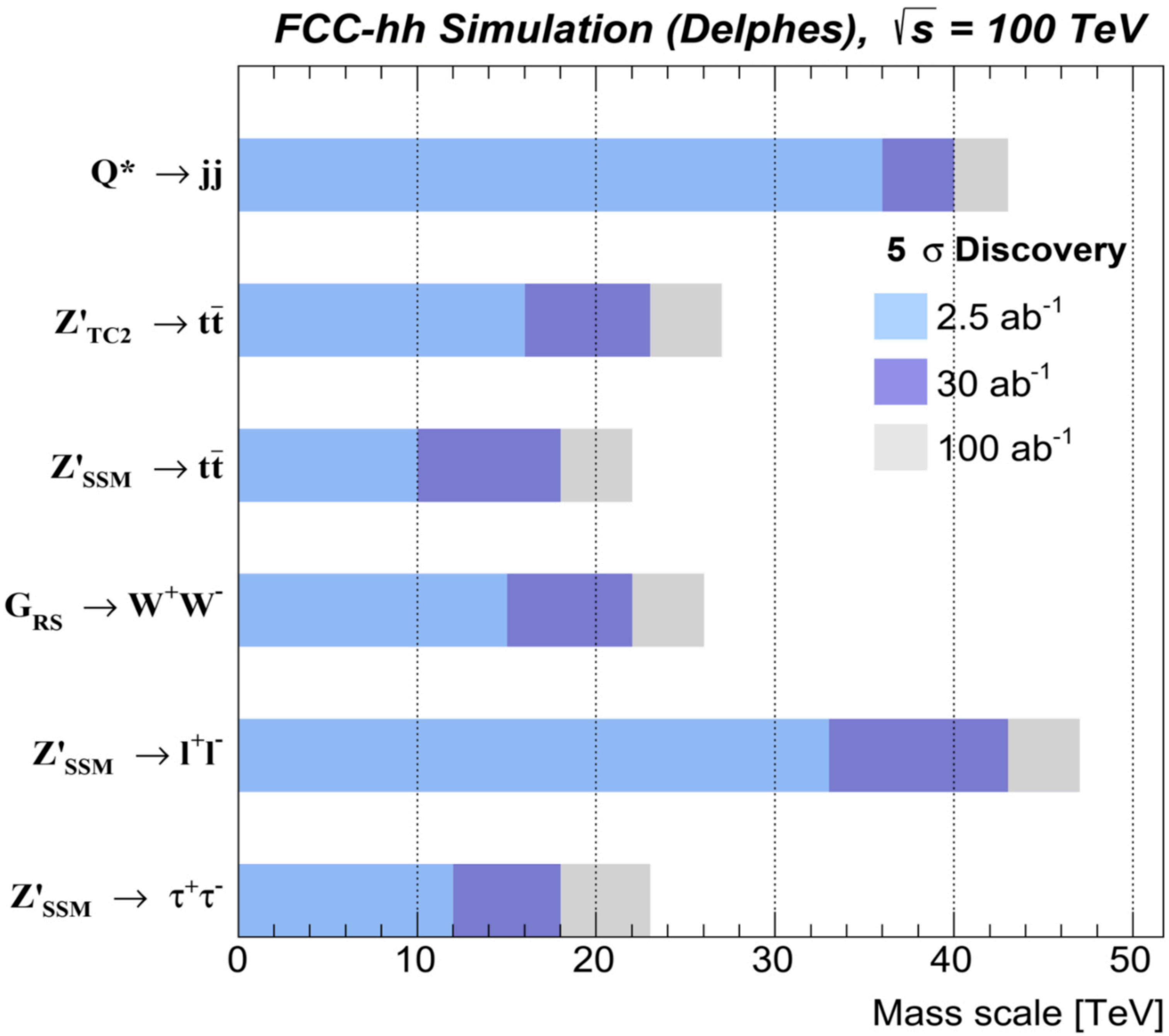

ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
√s = 13 TeV
Model
Signature
∫L dt [fb⁻¹]
Mass limit
Reference
Inclusive Searches
q̃q̃, q̃→qχ̃⁰₁ | 0 e,μ 2-6 jets E_T^miss 36.1 | q̃ [2×, 8× Degen.] 0.9 1.55 | m(χ̃⁰₁)<100 GeV | 1712.02332
mono-jet 1-3 jets E_T^miss 36.1 | q̃ [1×, 8× Degen.] 0.43 0.71 | m(q̃)-m(χ̃⁰₁)=5 GeV | 1711.03301
g̃g̃, g̃→qq̄χ̃⁰₁ | 0 e,μ 2-6 jets E_T^miss 36.1 | g̃ 2.0 | m(χ̃⁰₁)<200 GeV | 1712.02332
g̃ Forbidden 0.95-1.6 | m(χ̃⁰₁)=900 GeV | 1712.02332
g̃g̃, g̃→qq̄(ℓℓ)χ̃⁰₁ | 3 e,μ 4 jets 36.1 | g̃ 1.85 | m(χ̃⁰₁)<800 GeV | 1706.03731
ee,μμ 2 jets E_T^miss 36.1 | g̃ 1.2 | m(g̃)-m(χ̃⁰₁)=50 GeV | 1805.11381
g̃g̃, g̃→qqWZχ̃⁰₁ | 0 e,μ 7-11 jets E_T^miss 36.1 | g̃ 1.8 | m(χ̃⁰₁)<400 GeV | 1708.02794
3 e,μ 4 jets 36.1 | g̃ 0.98 | m(g̃)-m(χ̃⁰₁)=200 GeV | 1706.03731
g̃g̃, g̃→tt̄χ̃⁰₁ | 0-1 e,μ 3 b E_T^miss 79.8 | g̃ 2.25 | m(χ̃⁰₁)<200 GeV | ATLAS-CONF-2018-041
3 e,μ 4 jets 36.1 | g̃ 1.25 | m(g̃)-m(χ̃⁰₁)=300 GeV | 1706.03731
3rd gen. squarks direct production
b̃₁b̃₁, b̃₁→bχ̃⁰₁/tχ̃±₁ | Multiple 36.1 | b̃₁ Forbidden 0.9 | m(χ̃⁰₁)=300 GeV, BR(bχ̃⁰₁)=1 | 1708.09266, 1711.03301
Multiple 36.1 | b̃₁ Forbidden 0.58-0.82 | m(χ̃⁰₁)=300 GeV, BR(bχ̃⁰₁)=BR(tχ̃±₁)=0.5 | 1708.09266
Multiple 36.1 | b̃₁ Forbidden 0.7 | m(χ̃⁰₁)=200 GeV, m(χ̃±₁)=300 GeV, BR(tχ̃±₁)=1 | 1706.03731
b̃₁b̃₁, b̃₁→bχ̃⁰₂→bhχ̃⁰₁ | 0 e,μ 6 b E_T^miss 139 | b̃₁ Forbidden 0.23-1.35 | Δm(χ̃⁰₂,χ̃⁰₁)=130 GeV, m(χ̃⁰₁)=100 GeV | SUSY-2018-31
b̃₁ 0.23-0.48 | Δm(χ̃⁰₂,χ̃⁰₁)=130 GeV, m(χ̃⁰₁)=0 GeV | SUSY-2018-31
t̃₁t̃₁, t̃₁→Wbχ̃⁰₁ or tχ̃⁰₁ | 0-2 e,μ 0-2 jets/1-2 b E_T^miss 36.1 | t̃₁ 1.0 | m(χ̃⁰₁)=1 GeV | 1506.08616, 1709.04183, 1711.11520
t̃₁t̃₁, Well-Tempered LSP | Multiple 36.1 | t̃₁ 0.48-0.84 | m(χ̃⁰₁)=150 GeV, m(χ̃±₁)-m(χ̃⁰₁)=5 GeV, t̃₁ ≈ t̃_L | 1709.04183, 1711.11520
t̃₁t̃₁, t̃₁→τ̃₁bν, τ̃₁→τG̃ | 1 τ + 1 e,μ,τ 2 jets/1 b E_T^miss 36.1 | t̃₁ 1.16 | m(τ̃₁)=800 GeV | 1803.10178
t̃₁t̃₁, t̃₁→cχ̃⁰₁ / c̃c̃, c̃→cχ̃⁰₁ | 0 e,μ 2 c E_T^miss 36.1 | c̃ 0.85 | m(χ̃⁰₁)=0 GeV | 1805.01649
t̃₁ 0.46 | m(t̃₁,c̃)-m(χ̃⁰₁)=50 GeV | 1805.01649
0 e,μ mono-jet E_T^miss 36.1 | t̃₁ 0.43 | m(t̃₁,c̃)-m(χ̃⁰₁)=5 GeV | 1711.03301
t̃₂t̃₂, t̃₂→t̃₁ + h | 1-2 e,μ 4 b E_T^miss 36.1 | t̃₂ 0.32-0.88 | m(χ̃⁰₁)=0 GeV, m(t̃₁)-m(χ̃⁰₁)= 180 GeV | 1706.03986
EW direct
χ̃±₁χ̃⁰₂ via WZ | 2-3 e,μ E_T^miss 36.1 | χ̃±₁/χ̃⁰₂ 0.6 | m(χ̃⁰₁)=0 | 1403.5294, 1806.02293
ee,μμ ≥ 1 E_T^miss 36.1 | χ̃±₁/χ̃⁰₂ 0.17 | m(χ̃±₁)-m(χ̃⁰₁)=10 GeV | 1712.08119
χ̃∓₁χ̃∓₁ via WW | 2 e,μ E_T^miss 139 | χ̃±₁ 0.42 | m(χ̃⁰₁)=0 | ATLAS-CONF-2019-008
χ̃±₁χ̃⁰₂ via Wh | 0-1 e,μ 2 b E_T^miss 36.1 | χ̃±₁/χ̃⁰₂ 0.68 | m(χ̃⁰₁)=0 | 1812.09432
χ̃±₁χ̃±₁ via ℓ̃_L/ν̃ | 2 e,μ E_T^miss 139 | χ̃±₁ 1.0 | m(ℓ̃,ν̃)=0.5(m(χ̃±₁)+m(χ̃⁰₁)) | ATLAS-CONF-2019-008
χ̃±₁χ̃∓₁/χ̃⁰₂, χ̃+₁→τ̃₁ν(τν̃), χ̃⁰₂→τ̃₁τ(νν̃) | 2 τ E_T^miss 36.1 | χ̃±₁/χ̃⁰₂ 0.76 | m(χ̃⁰₁)=0, m(τ̃,ν̃)=0.5(m(χ̃±₁)+m(χ̃⁰₁)) | 1708.07875
χ̃±₁/χ̃⁰₂ 0.22 | m(χ̃±₁)-m(χ̃⁰₁)=100 GeV, m(τ̃,ν̃)=0.5(m(χ̃±₁)+m(χ̃⁰₁)) | 1708.07875
ℓ̃_{L,R}ℓ̃_{L,R}, ℓ̃→ℓχ̃⁰₁ | 2 e,μ 0 jets E_T^miss 139 | ℓ̃ 0.7 | m(χ̃⁰₁)=0 | ATLAS-CONF-2019-008
2 e,μ ≥ 1 E_T^miss 36.1 | ℓ̃ 0.18 | m(ℓ̃)-m(χ̃⁰₁)=5 GeV | 1712.08119
H̃H̃, H̃→hG̃/ZG̃ | 0 e,μ ≥ 3 b E_T^miss 36.1 | H̃ 0.13-0.23 0.29-0.88 | BR(χ̃⁰₁ → hG̃)=1 | 1806.04030
4 e,μ 0 jets E_T^miss 36.1 | H̃ 0.3 | BR(χ̃⁰₁ → ZG̃)=1 | 1804.03602
Long-lived particles
Direct χ̃+₁χ̃−₁ prod., long-lived χ̃±₁ | Disapp. trk 1 jet E_T^miss 36.1 | χ̃±₁ 0.46 | Pure Wino | 1712.02118
χ̃±₁ 0.15 | Pure Higgsino | ATL-PHYS-PUB-2017-019
Stable g̃ R-hadron | Multiple 36.1 | g̃ 2.0 | 1902.01636, 1808.04095
Metastable g̃ R-hadron, g̃→qqχ̃⁰₁ | Multiple 36.1 | g̃ [τ(g̃) =10 ns, 0.2 ns] 2.05 2.4 | m(χ̃⁰₁)=100 GeV | 1710.04901, 1808.04095
RPV
LFV pp→ν̃τ + X, ν̃τ→eμ/eτ/μτ | eμ,eτ,μτ 3.2 | ν̃τ 1.9 | λ′311=0.11, λ132/133/233=0.07 | 1607.08079
χ̃±₁χ̃∓₁/χ̃⁰₂ → WW/Zℓℓℓℓνν | 4 e,μ 0 jets E_T^miss 36.1 | χ̃±₁/χ̃⁰₂ [λi33 ≠ 0, λ12k ≠ 0] 0.82 1.33 | m(χ̃⁰₁)=100 GeV | 1804.03602
g̃g̃, g̃→qqχ̃⁰₁, χ̃⁰₁ → qqq | 4-5 large-R jets 36.1 | g̃ [m(χ̃⁰₁)=200 GeV, 1100 GeV] 1.3 1.9 | Large λ″112 | 1804.03568
Multiple 36.1 | g̃ [λ″112=2e-4, 2e-5] 1.05 2.0 | m(χ̃⁰₁)=200 GeV, bino-like | ATLAS-CONF-2018-003
t̃t̃, t̃→tχ̃⁰₁, χ̃⁰₁ → tbs | Multiple 36.1 | g̃ [λ″323=2e-4, 1e-2] 0.55 1.05 | m(χ̃⁰₁)=200 GeV, bino-like | ATLAS-CONF-2018-003
t̃₁t̃₁, t̃₁→bs | 2 jets + 2 b 36.7 | t̃₁ [qq, bs] 0.42 0.61 | 1710.07171
t̃₁t̃₁, t̃₁→qℓ | 2 e,μ 2 b 36.1 | t̃₁ 0.4-1.45 | BR(t̃₁→be/bμ)>20% | 1710.05544
1 μ DV 136 | t̃₁ [1e-10< λ′23k <1e-8, 3e-10< λ′23k <3e-9] 1.0 1.6 | BR(t̃₁→qμ)=100%, cosθt=1 | ATLAS-CONF-2019-006
10⁻¹
1
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



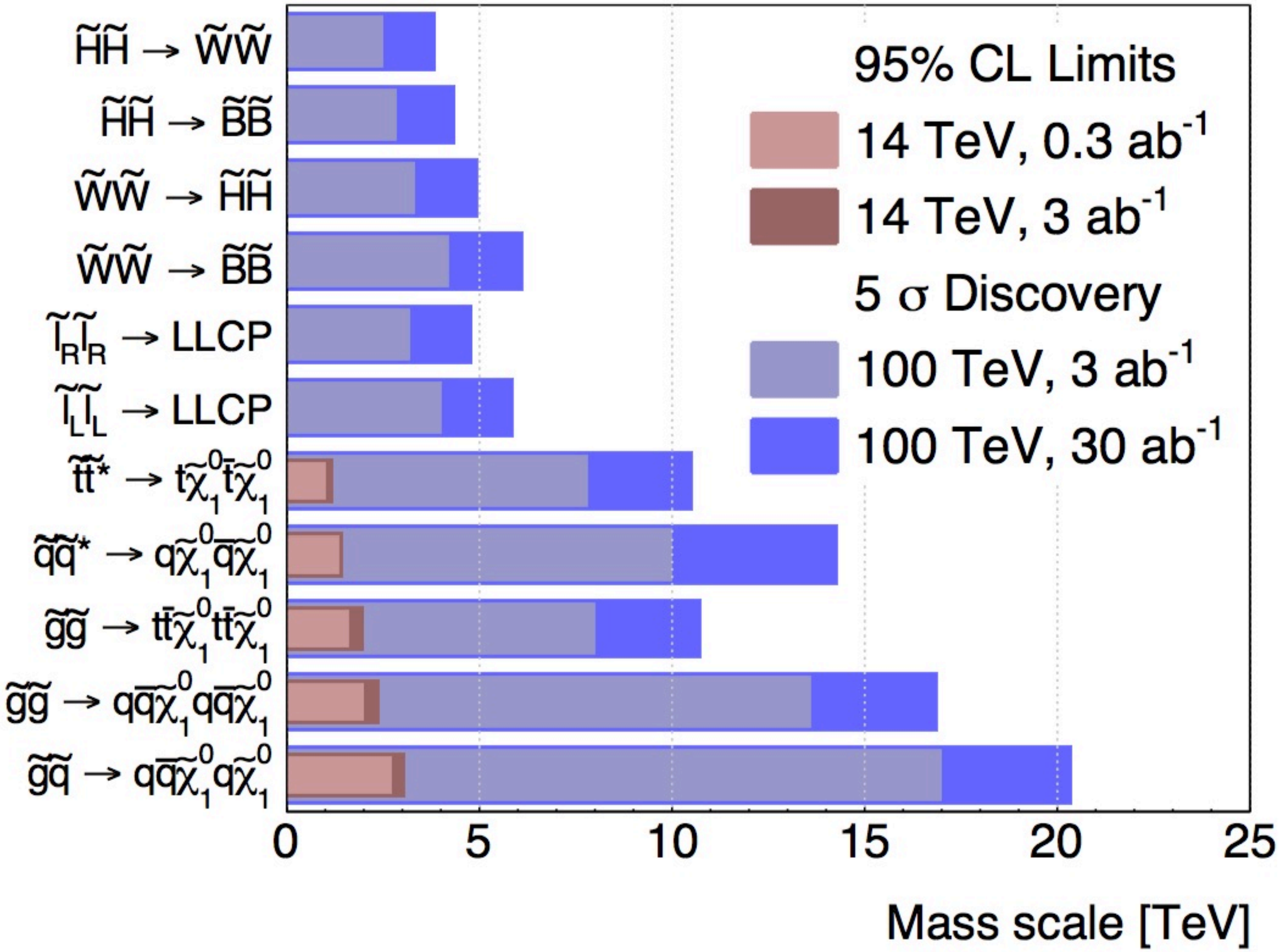
Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

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/

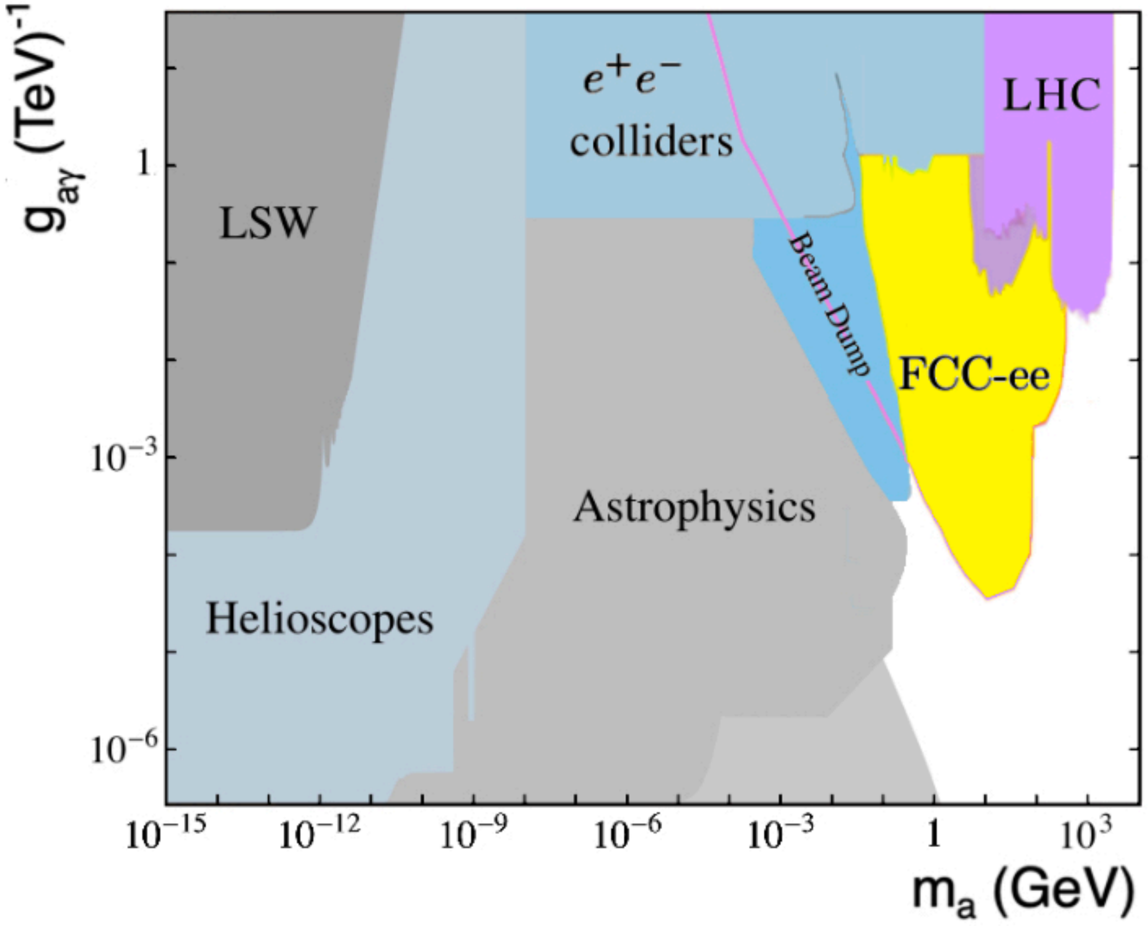
Axion-like particles

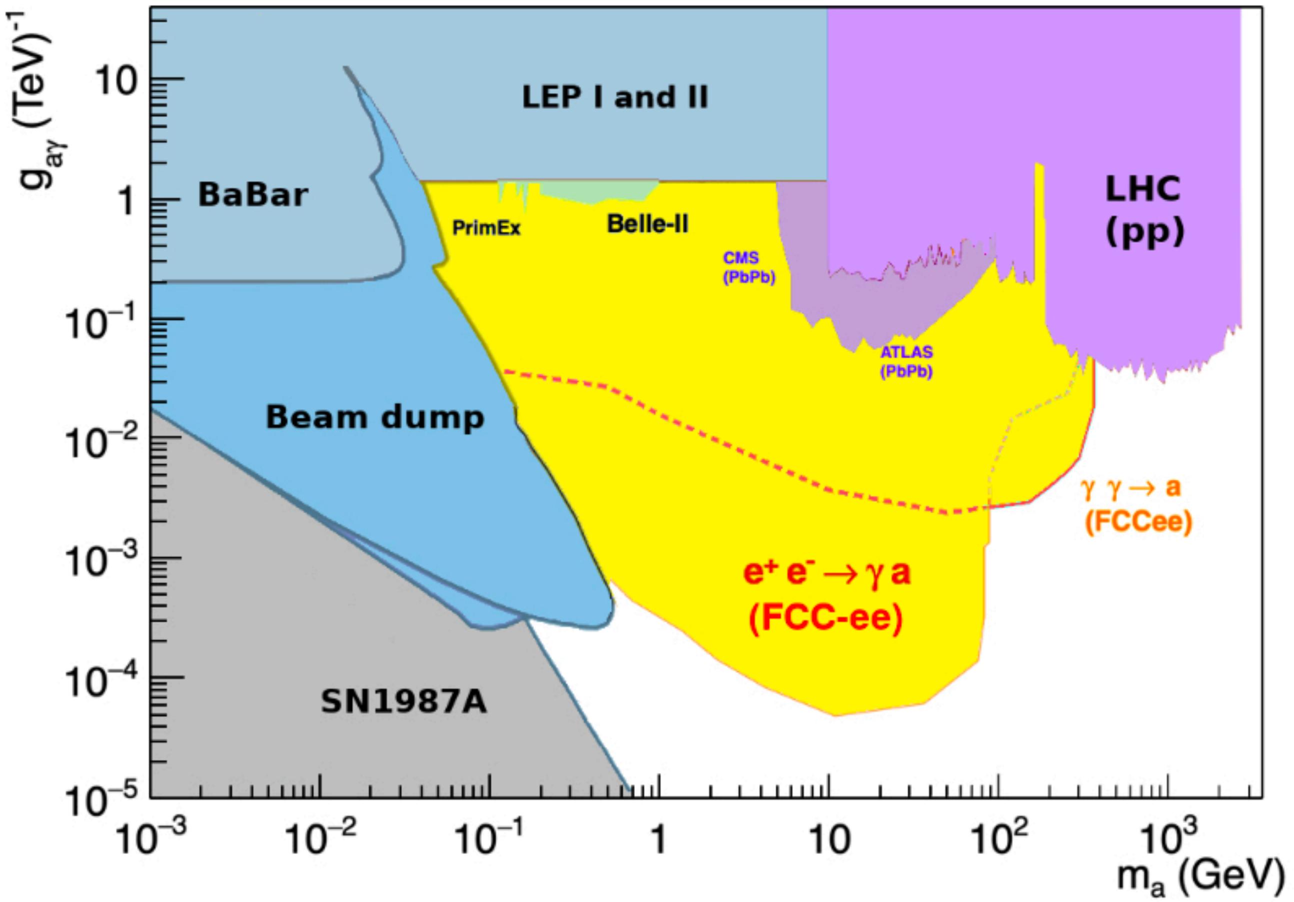
In the run at the Z pole, exploit possible channels such as

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

with

$$a \to \gamma\gamma$$

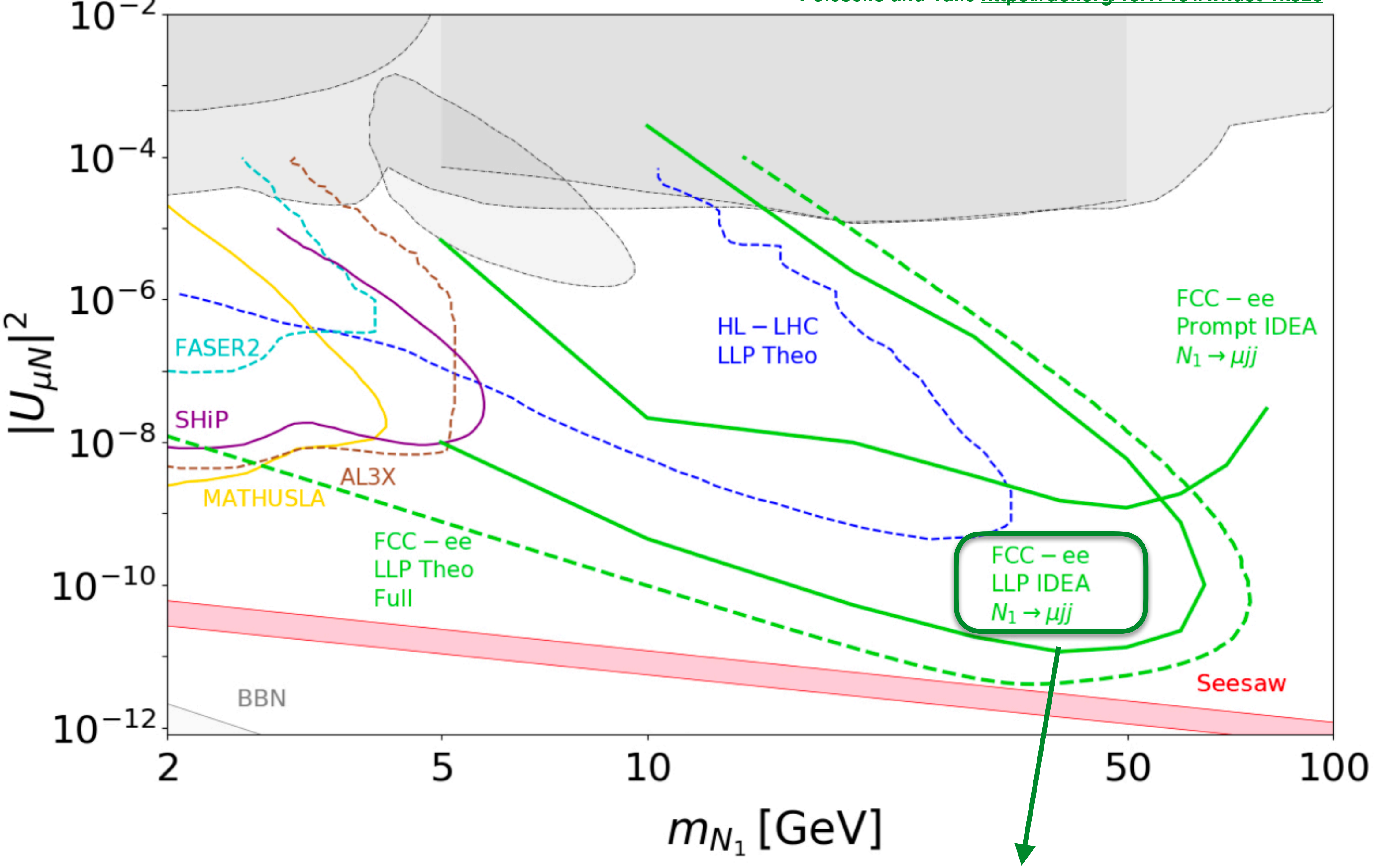




P. Rebello-Teles et al, to appear

Heavy Neutral Leptons

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



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:

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

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

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

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

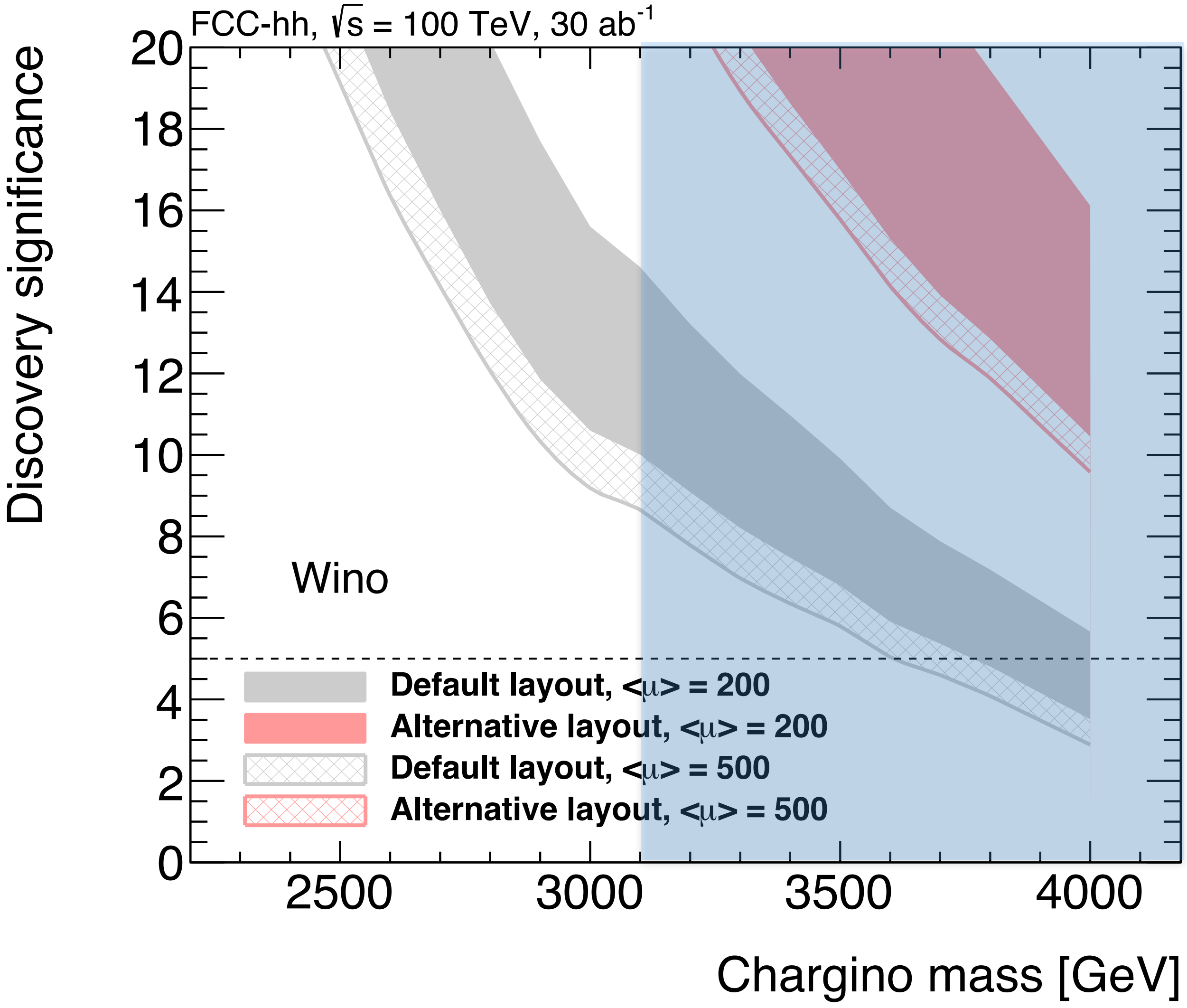
Disappearing charged track analyses

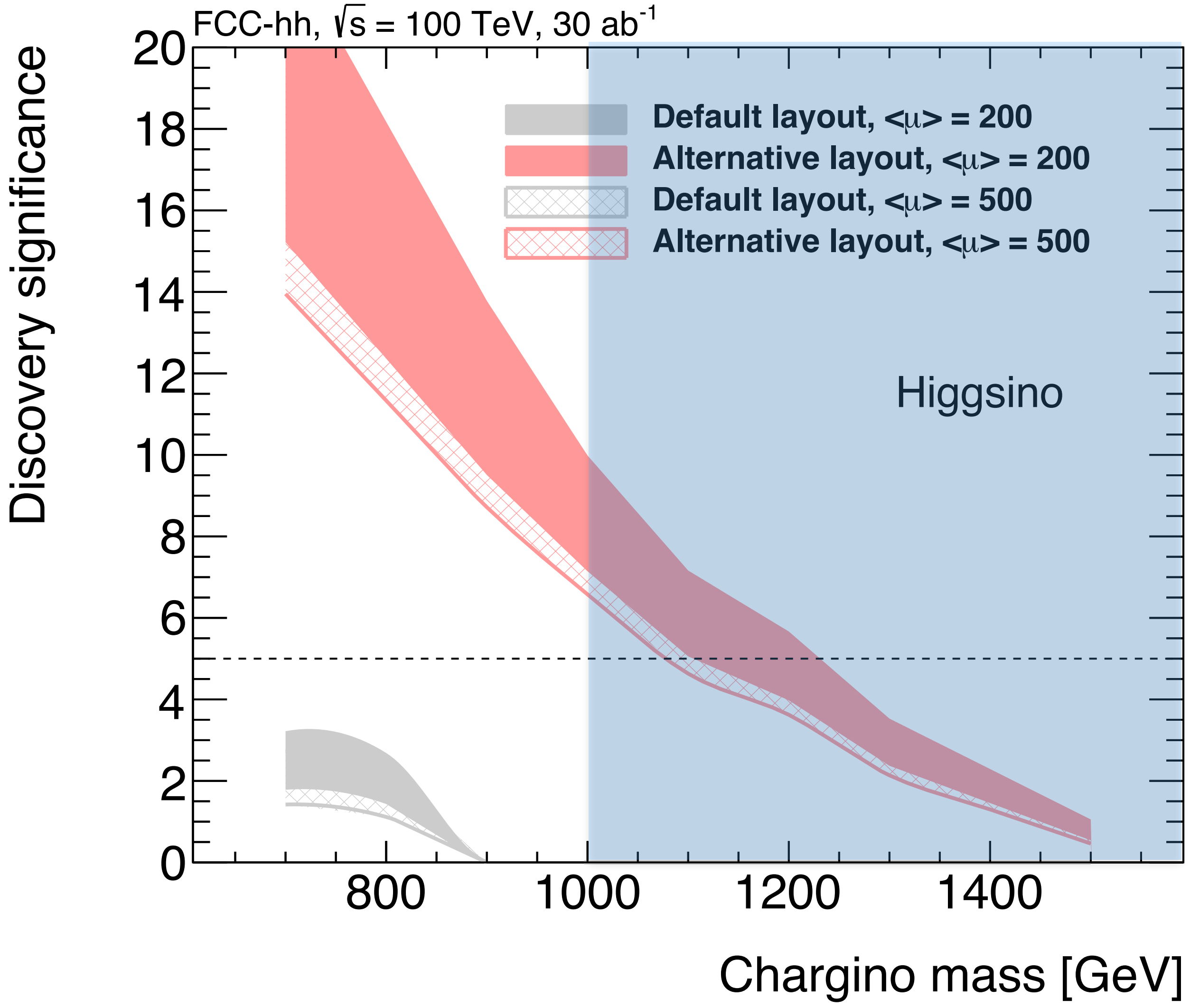
(at ~full pileup)

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

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

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 …

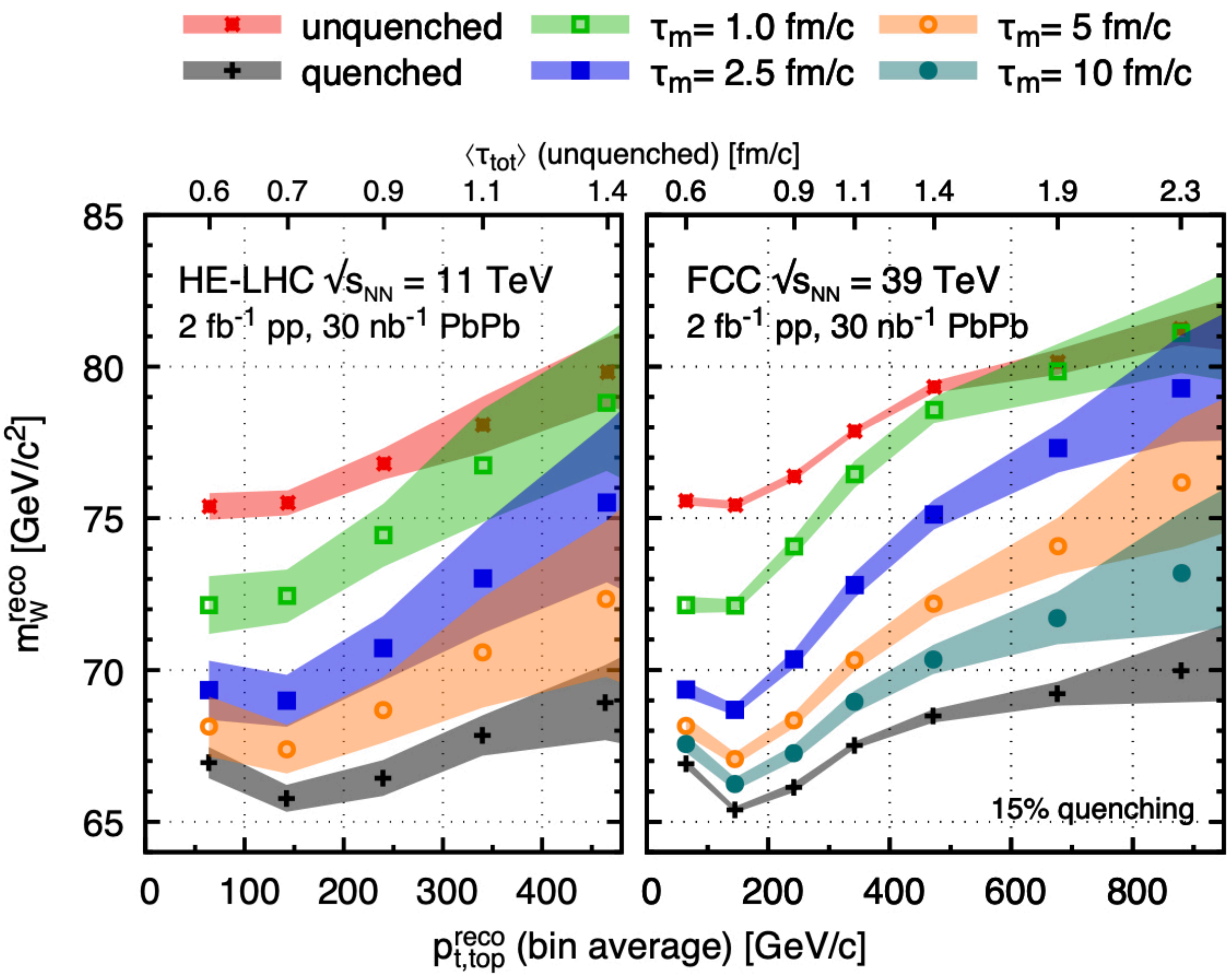
- Countless studies of discovery potential for multiple BSM scenarios, from SUSY to heavy neutrinos, from very low masses to very high masses, LLPs, DM, etcetcetc, with plenty of opportunities for direct discovery even at FCC-ee and FCC-eh
- Sensitivity studies to SM deviations in the properties of top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