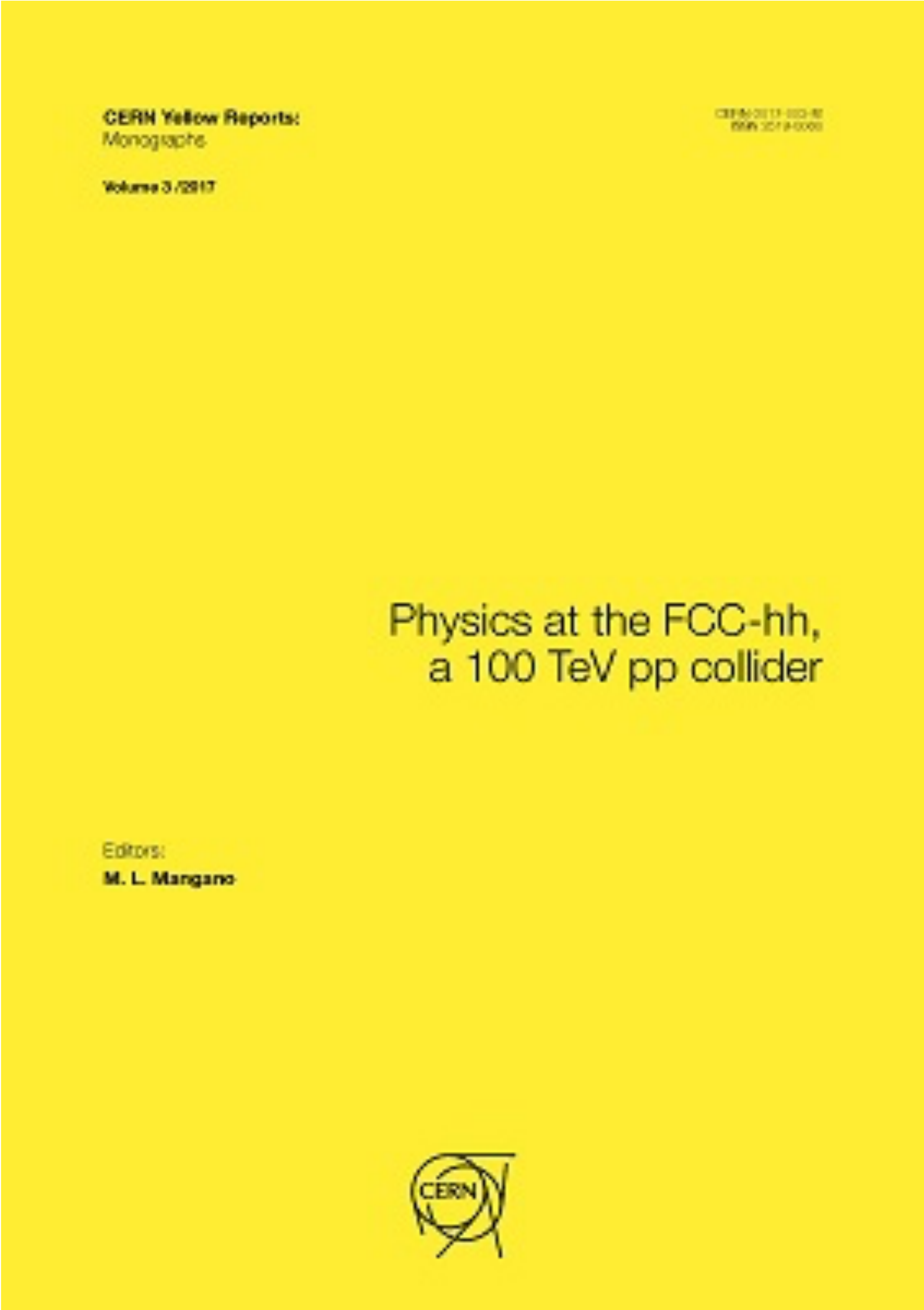
FCC-hh physics potential: status and next steps

Michelangelo Mangano, CERN TH

The work so far:

Physics at the FCC-hh
https://e-publishing.cern.ch/index.php/CYRM/issue/view/35
Chapter 1: Standard Model Processes
Chapter 2: Higgs and EW Symmetry Breaking Studies
Chapter 3: Beyond the Standard Model Phenomena
Chapter 4: Heavy Ions at the Future Circular Collider
Chapter 5: Physics Opportunities with the FCC-hh Injectors



FCC Conceptual Design Report:
Volume 1: Physics Opportuniities, Eur.Phys.J.C 79 (2019) 6, 474
Volume 3: The FCC-hh, Eur.Phys.J.ST 228 (2019) 4, 755

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THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

FCC-hh: The Hadron Collider

Future Circular Collider Conceptual Design Report Volume 3

Recent developments motivated by

- Continued progress in the exploration of the general physics potential
  - synergy/complementarity between FCC-ee and FCC-hh
  - experimental opportunities beyond general-purpose detectors **-> Rojo**
- Changes in baseline accelerator configuration (layout and dipole field targets -> **Todesco**)
- Contributions to the ESPP

➡

FCC-hh physics and performance WG (https://indico.cern.ch/category/18813/) =>

Birgit's talk

Presentations at the 4 general mtgs:

- Energy/luminosity/operation scenarios - Frank Zimmermann
- 100TeV -> 80/120 TeV CDR projections: results so far - Michelangelo Mangano
- FCC-hh simulation studies: the work ahead - Michele Selvaggi
- Update on longitudinal same-sign WW scattering studies - Marc-Andre Pleier
- Heavy Neutral Leptons at the FCC-hh: Where do we stand? - Stefan Antusch
- DM in mono-X and VBF - Giulio Marino
- Heavy vector singlets at future colliders - Timothy Martonhelyi
- Higgs without Higgs - Francesco Riva
- Exploring the Flavour Symmetry Landscape - Riccardo Rattazzi
- ALPs and massive gravitons in $\gamma\gamma$ - David d'Enterria
- FASER-like experiments for FCC-hh - Juan Rojo
- 4D tracking algorithms to improve pile-up robustness - Valentina Cairo
- Update on HH->bb$\gamma\gamma$ studies - Angela Taliercio
- Status/plans for updated HH->bb$\tau\tau$ studies - Monica D’Onofrio
- Single Higgs studies, DESY team - Daina Leyva Pernia
- Search for ttHZ - Shankha Banerjee
- Improving the sensitivity of the Higgs self-coupling by exploiting the kinematical properties - Bastien Voirin
- Towards updated Higgs coupling projections at the FCC-hh - Juan Rojo
- High-level comparisons of energy and luminosity scenarios - Elliot Lipeles
- UHE atmospheric neutrinos and FCC-hh, Maria Vittoria Garzelli

Slides from Frank Zimmermann (link), see also Frank's note

Assumptions & possible parameter range

With present layout of the FCC, and after diligent optimization (by Massimo, Gustavo, and Thys), the following energies can be reached according to the dipole field:

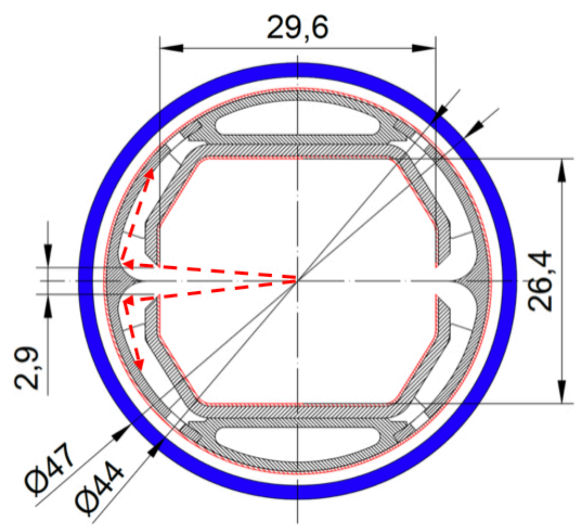
Dipole field [T]	c.m. energy	Comment
12	72	not far above peak field of HL-LHC Nb_3Sn quadrupoles
14	84	Nb_3Sn or HTS
17	102	HTS
20	120	HTS

Increasing the c.m. energy beyond ~100 TeV, **we will assume that the synchrotron-radiation power could not increase, beyond a total of about 4 MW** (which must be removed from inside the cold magnets) **

On the other hand, **when decreasing the beam energy, one can hold either the synchrotron-radiation power** (increasing current up to HL-LHC values) **or the beam current constant**. Also, the **pile-up might need to be limited, e.g. to ~1000 events/crossing**. We thus consider three scenarios for 12 T (0.5 A and 1.12 A beam current, the latter without or with pile-up levelling).

Finally, **further overall lowering the synchrotron radiation power, by reducing the number of bunches, in order to restrict the total power consumption of the future FCC-hh, would decrease peak and integrated luminosity by the same factor.**

** 30 W/m/beam => 5 MW total, released inside magnets operating at 1.9K !!
Absorption by beam screen at 50K to room T => 100MW cryo plant …



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new baseline (see Todesco)

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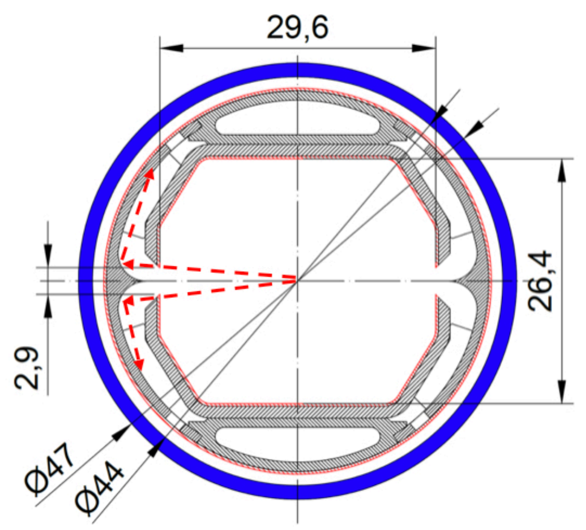

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Six scenarios

1) A machine based on 12 T dipoles, with a beam current of 0.5 A as considered for the 16 T FCC-hh machine (F12LL).
2) A machine based on the same 12 T technology close to deployment, but with a higher beam current of 1.1 A, as considered for the HL-LHC (F12HL).
3) The same case as F12HL but limiting the pile up not to exceed a value of 1000 (F12PU).
4) A machine based on 14 T dipoles, and 0.5 A current (F14).
5) A machine based on High Temperature Superconductor (HTS) dipole magnets with a field of 17 T, just exceeding 100 TeV c.m., still with 0.5 A (F17).
6) A machine also based on High Temperature Superconductor (HTS) dipole magnets with a field of 20 T, and a beam current of 0.2 A, so that the synchrotron-radiation power is limited to about 2 MW / beam (F20).

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new baseline (F14)

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
initial L	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
opt. run time	h	3.8	3.3	6.3	3.8	3.4	4.2	(18-13) ~10

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
ideal $\int L\,dt$ /day	fb^{-1}	7.9	17.1	10.8	7.7	7.7	3,1	(1.9) 0.4
$\int L\,dt$ / year	fb^{-1}	950	2000	1300	920	920	370	240 (55)

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Early assessment of new energy scenarios for benchmark projections: Higgs

(assuming equal luminosity)

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Higgs couplings beyond precision reach of H factory

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	0.9	1.0	0.8

Higgs self-coupling

Det performance/systematics scenarios

https://arxiv.org/abs/2004.03505

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)

$$\frac{\sigma_{HH}(80\text{TeV})}{\sigma_{HH}(100\text{TeV})} \sim 0.72$$ => reduce δ_{stat} by 15%

$$\frac{\sigma_{HH}(120\text{TeV})}{\sigma_{HH}(100\text{TeV})} \sim 1.3$$ => increase δ_{stat} by 15%

$\delta\kappa_{HHH}(\,\%\,)$

100 TeV	s I	s II	s III
stat	3.0	4.1	5.6
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80 TeV	s I	s II	s III
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Final assessment, including updated analyses: ongoing work by Performance WG, Birgit's talk

Disappearing charged track analyses (at ~full pileup)

Saito, Sawada, Terashi, Asai, *https://arxiv.org/abs/1901.02987* w. 80 TeV study by Saito

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

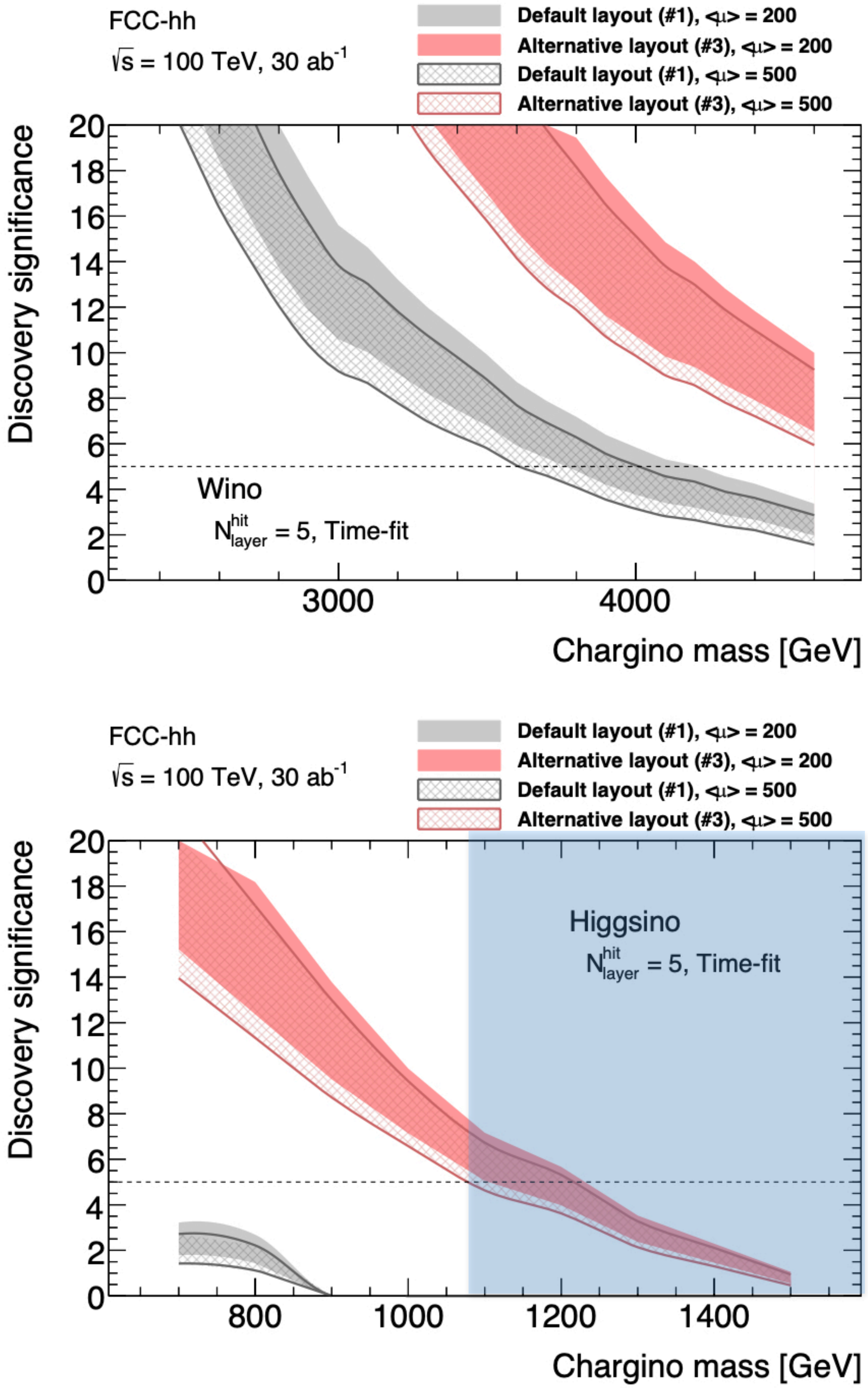
Excluded region for thermal WIMP DM

80 TeV study, vs 100 TeV:

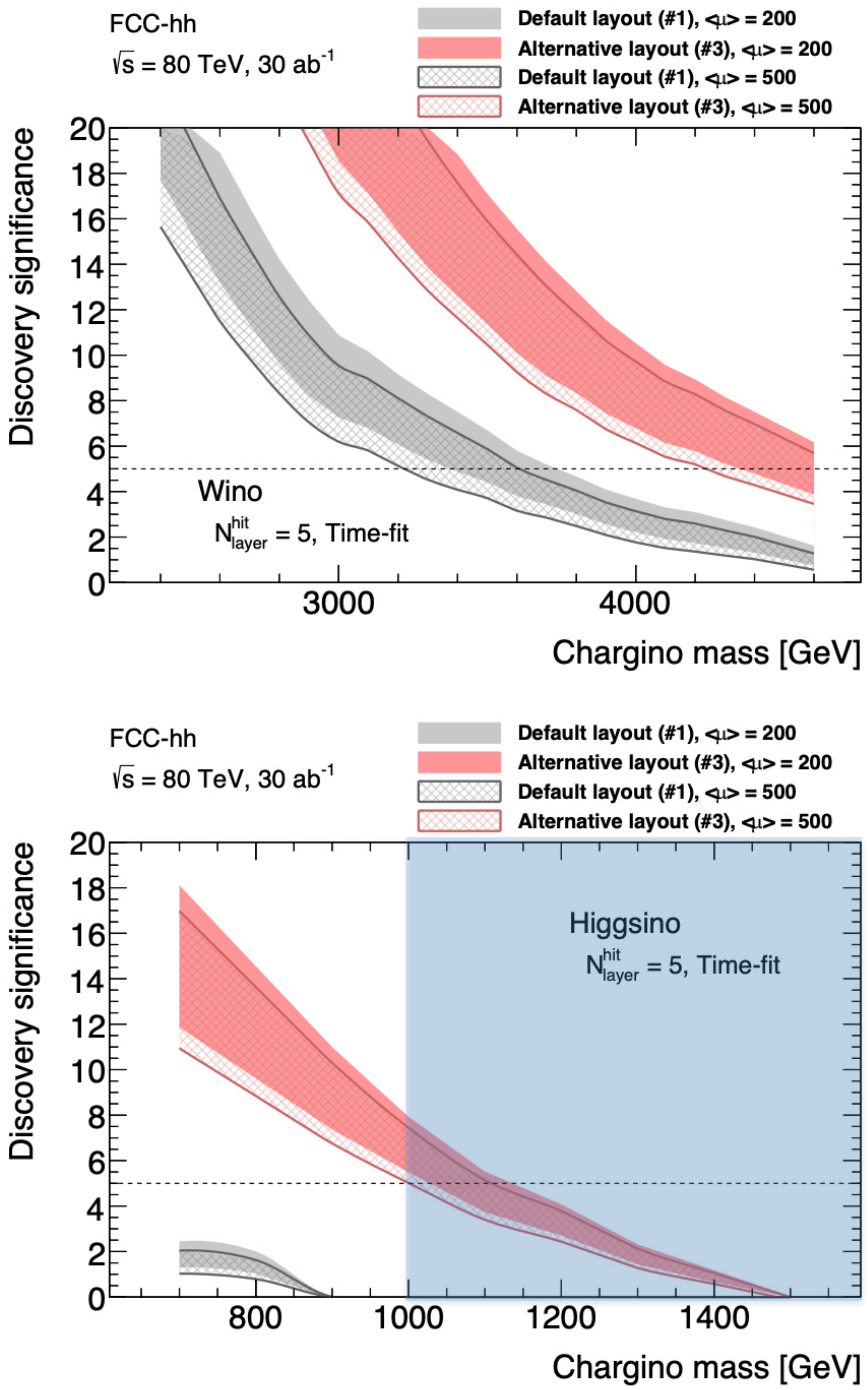
- signal rates @ 80 TeV
- kinematic selection reoptimised
- bgd rates unchanged

➡ discovery reach **conservative**

5σ higgsino reach drops from 1150 GeV to 1000 GeV

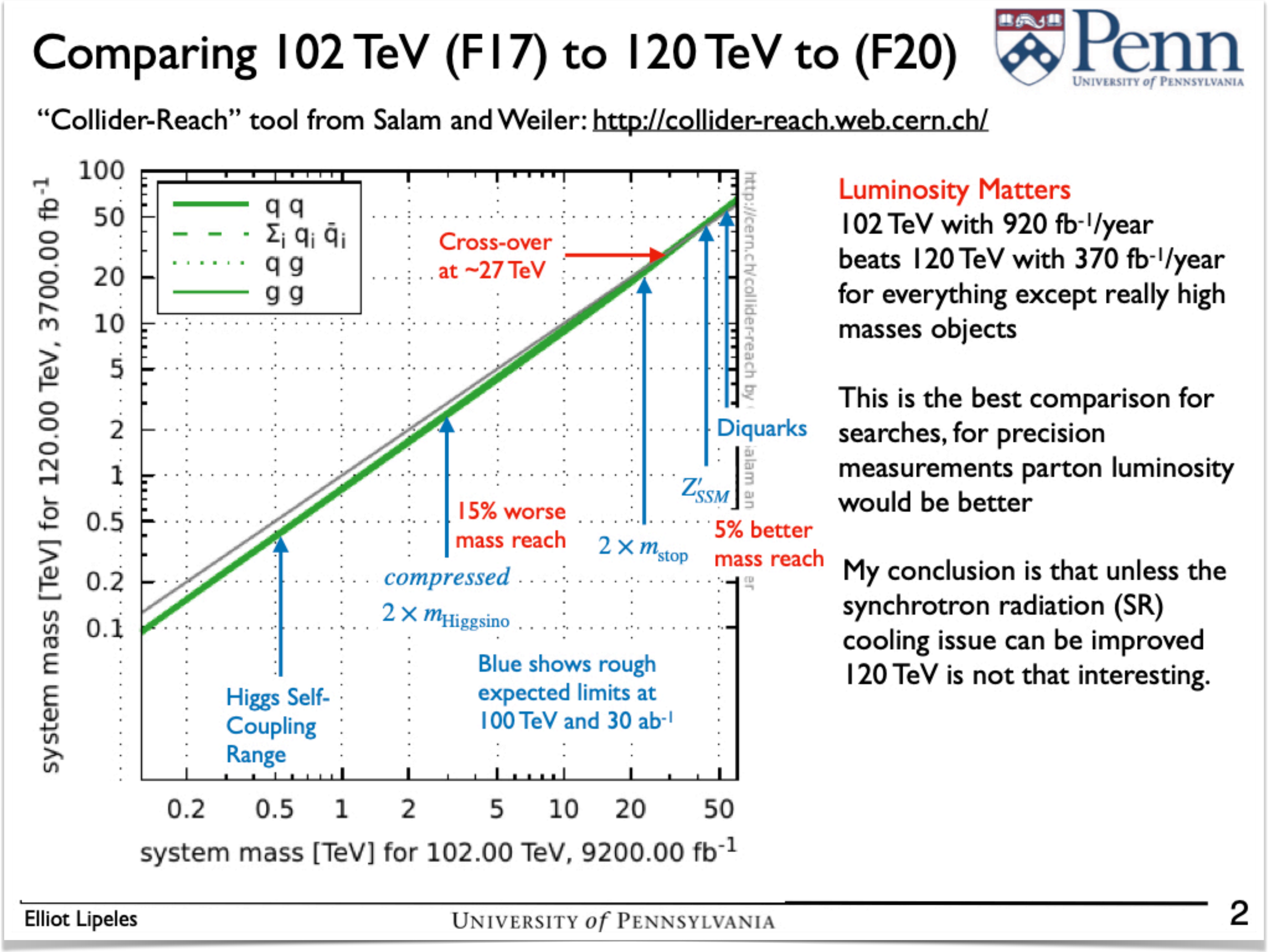


100 TeV



80 TeV

Significant impact of potential luminosity loss at the highest energy



Elliot @ https://indico.cern.ch/event/1461211/

Significant impact of potential luminosity loss at the highest energy

change of discovery reach w.r.t. canonical 100 TeV CDR scenario,
in different mass regions:

Scenario name	Energy	Lumi/year	Cross-over	DM/ Compress EWK 3.0 →	Change in stop mass limit [TeV] 12.5 →	Change in Z' limit [TeV] 40→
F12LL	72 TeV	950 fb^{-1}	~always worse	~2.6	~9.6	~30
F12HL	72 TeV	2000 fb^{-1}	~3 TeV	~3.2	~10.4	~32
F12PU	72 TeV	1300 fb^{-1}	~125 GeV	~2.8	~10.0	~31
F14	84 TeV	950 fb^{-1}	~always worse	~2.8	~10.8	~34
F20	120 TeV	370 fb^{-1}	~25 TeV	~2.5	~12.6	~42

Collider-reach extrapolations, Elliot @ https://indico.cern.ch/event/1461211/

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- 100 -> O(80) TeV
  - the reduced rates for physics in the O(TeV) mass region (eg Higgs, EW, EWinos) can be compensated by higher luminosity or improved detector performance
  - mass reach at the highest masses ($\sqrt{\hat{s}} \sim 0.5 \sqrt{S}$) is reduced by 15-20%, depending on luminosity
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- 100 -> 120 TeV
  - if drop in luminosity wrt baseline remains significant, O(2-3):
    - potential loss for precision measurement in the TeV region (to be evaluated however in the context of reduced pileup, which might improve systematics limitations)
    - marginal gain in mass reach only at the highest possible masses

Next steps: short-term (< 31 March 2025)

- Document latest studies for the ESPP submission
  - impact of various energy scenarios
  - updated Higgs studies (Birgit talk), including updated impact on global EW/H fits (Tentori, de Blas talks)
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Next steps: medium-term (< 23 June 2025)

- Complete ongoing studies for contributions to the ESPP Symposium in Venice

Next steps: longer term — follow up of ESPP conclusions

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2. Review and keep uptodate detector performance potential, in view of
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   - etc.etc.
3. Expand landscape of complementary experiments/detectors (Forward, HI, Flavour)

Expanding the scope of ee-hh synergy studies

Key question to address:

given a discovery at FCC-ee (whether **direct,** *eg ALPs, HNL, BSM H decays, …,* or **indirect,** *eg deviations in EWPO or in Higgs properties*), how will FCC-hh contribute to the interpretation of this discovery?

- What information will it add to the study of the properties of new particles observed at FCC-ee?
- How will it uncover the microscopic origin of SM deviations see at FCC-ee?

Examples

- Higgs
  - detailed studies for the complete spectrum of SM Higgs decays (eg only basic studies available for $H\rightarrow WW^*$, ττ, cc) and production modes (VH, VBF, large pt, …)
  - reach for rare/forbidden/exotic Higgs decays possibly accessible to FCC-ee, and beyond (*Gallen's talk*)

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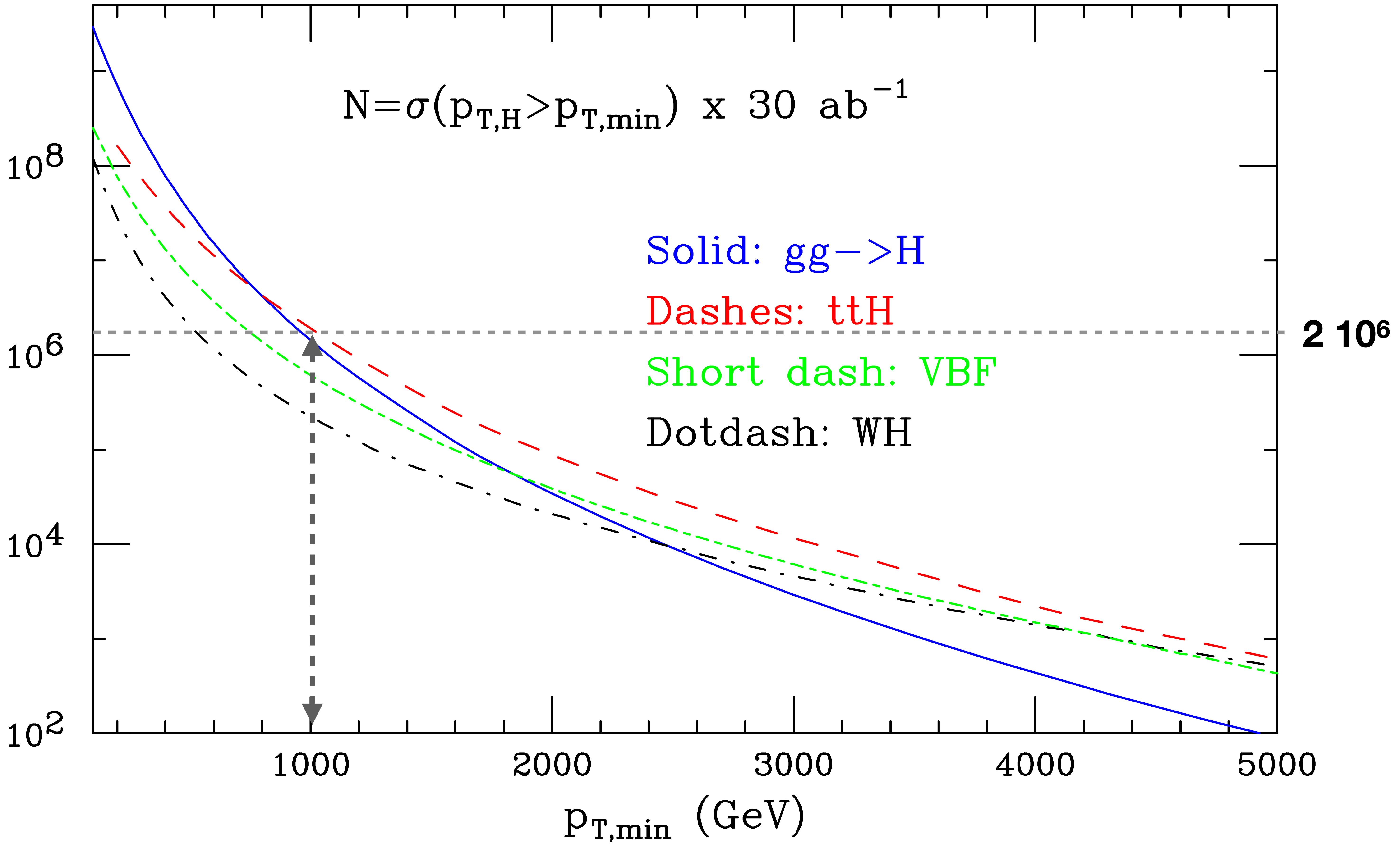
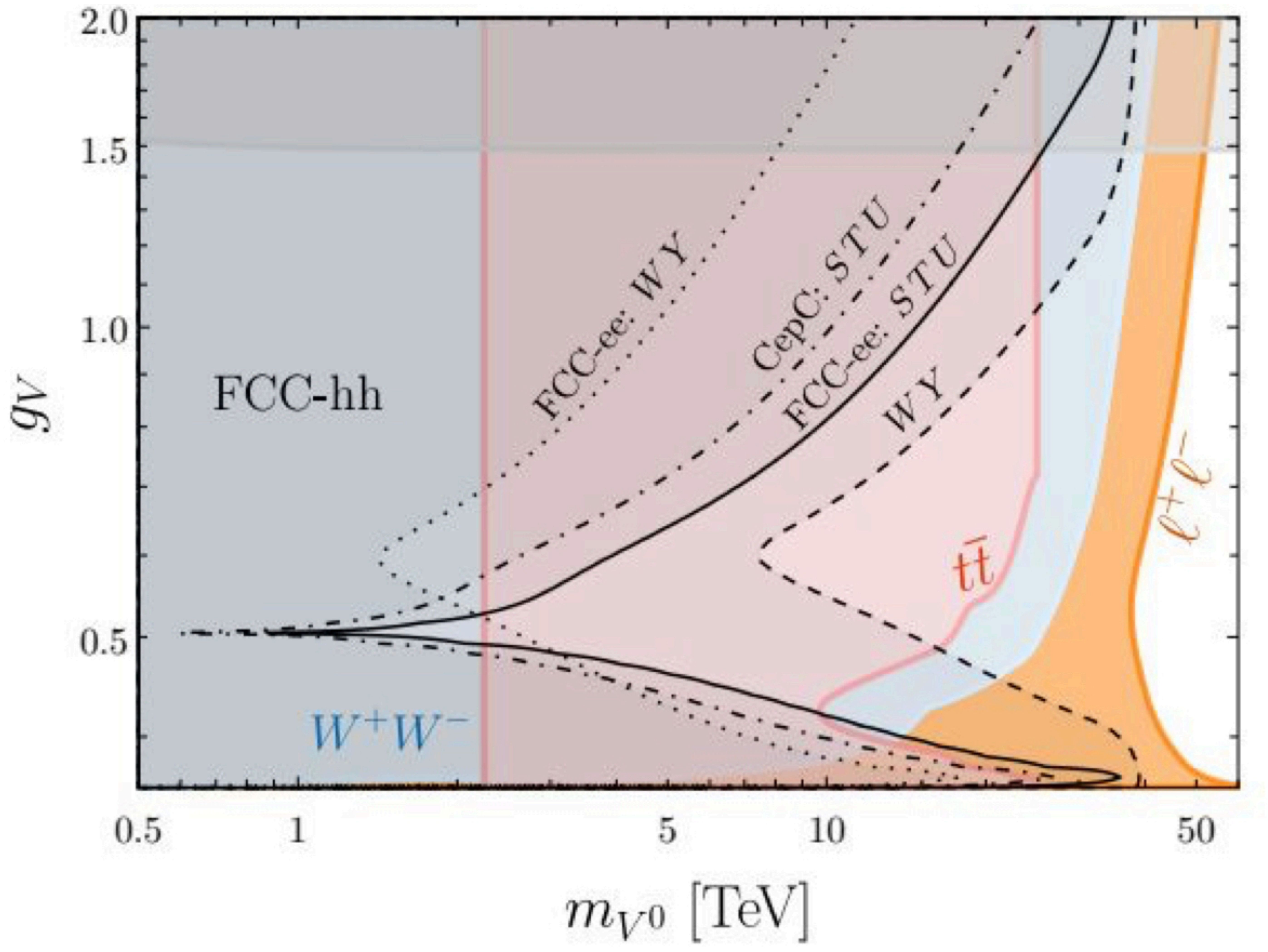


FCC-hh will have a Higgs sample larger than the full FCC-ee statistics produced at p_T larger than 1 TeV: are there opportunities to probe exotic Higgs decays?

Examples

- EWPO: heavy vector resonances (see *Torre's talk*)



Plots like this should not be read in terms of "which facility promises the best constraint", but in terms of "should FCC-ee find a 3σ deviation in S/T/U, which handles will the FCC-hh have to fully decode the source of this deviation"

Examples

- Single-particle SM extensions, the Granada dictionary (*Allwicher, Vuong talks*)

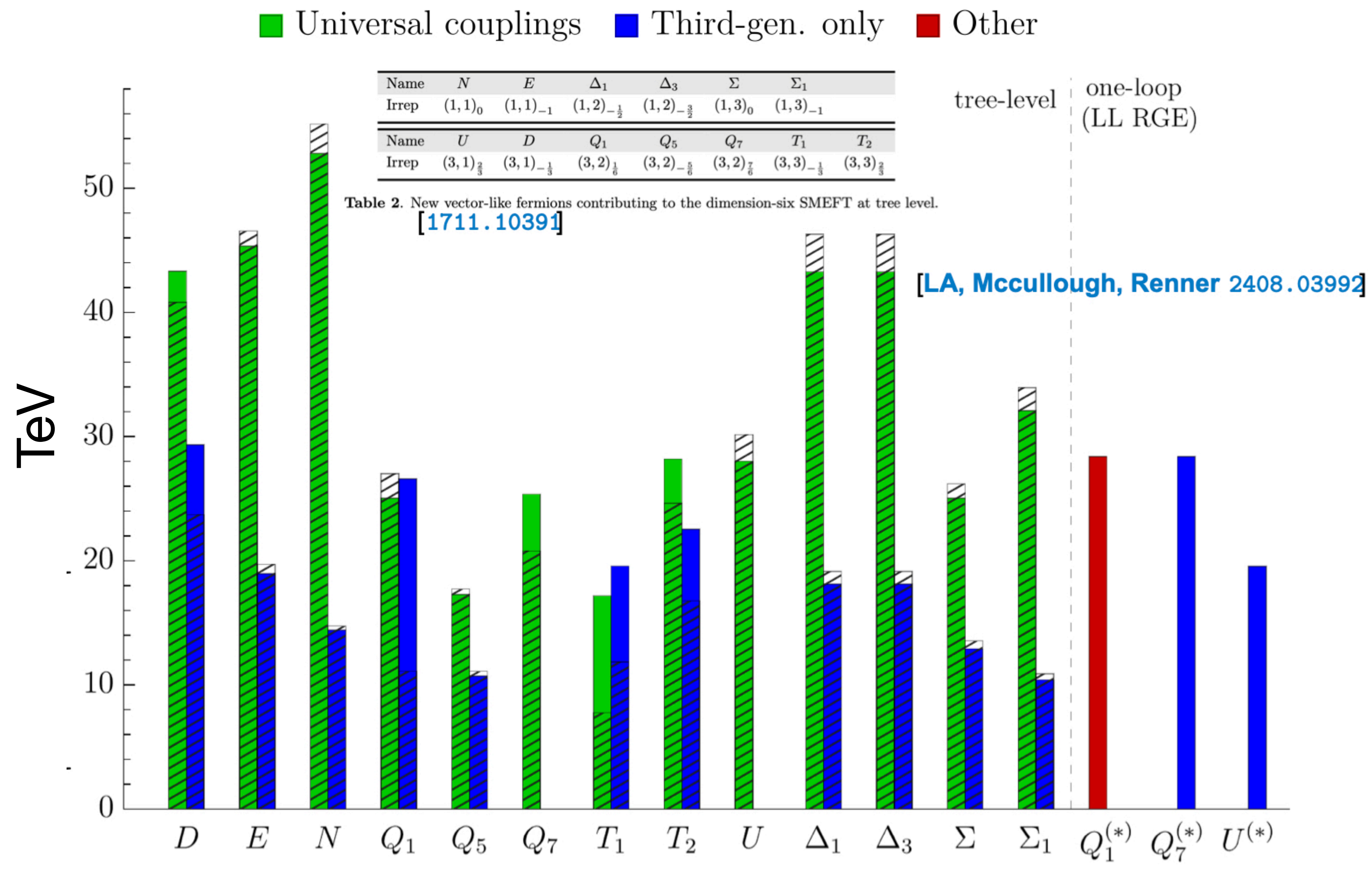
Linear extensions of the Standard Model

[De Blas et al. 1711.10391]

> Finite number of new states can couple linearly to the SM fields: *Granada dictionary*
> Matching to SMEFT at $d = 6$ well known

Scalar	$\mathcal{S}$ $(1,1)_0$	$\mathcal{S}_1$ $(1,1)_1$	$\mathcal{S}_2$ $(1,1)_2$	φ $(1,2)_{\frac{1}{2}}$	Ξ $(1,3)_0$	Ξ_1 $(1,3)_1$	Θ_1 $(1,4)_{\frac{1}{2}}$	Θ_3 $(1,4)_{\frac{3}{2}}$
	ω_1 $(3,1)_{-\frac{1}{3}}$	ω_2 $(3,1)_{\frac{2}{3}}$	ω_4 $(3,1)_{-\frac{4}{3}}$	Π_1 $(3,2)_{\frac{1}{6}}$	Π_7 $(3,2)_{\frac{7}{6}}$	ζ $(3,3)_{-\frac{1}{3}}$		
	Ω_1 $(6,1)_{\frac{1}{3}}$	Ω_2 $(6,1)_{-\frac{2}{3}}$	Ω_4 $(6,1)_{\frac{4}{3}}$	Υ $(6,3)_{\frac{1}{3}}$	Φ $(8,2)_{\frac{1}{2}}$			
Fermion	N $(1,1)_0$	E $(1,1)_{-1}$	Δ_1 $(1,2)_{-\frac{1}{2}}$	Δ_3 $(1,2)_{-\frac{3}{2}}$	Σ $(1,3)_0$	Σ_1 $(1,3)_{-1}$		
	U $(3,1)_{\frac{2}{3}}$	D $(3,1)_{-\frac{1}{3}}$	Q_1 $(3,2)_{\frac{1}{6}}$	Q_5 $(3,2)_{-\frac{5}{6}}$	Q_7 $(3,2)_{\frac{7}{6}}$	T_1 $(3,3)_{-\frac{1}{3}}$	T_2 $(3,3)_{\frac{2}{3}}$	
Vector	$\mathcal{B}$ $(1,1)_0$	$\mathcal{B}_1$ $(1,1)_1$	$\mathcal{W}$ $(1,3)_0$	$\mathcal{W}_1$ $(1,3)_1$	$\mathcal{G}$ $(8,1)_0$	$\mathcal{G}_1$ $(8,1)_1$	$\mathcal{H}$ $(8,3)_0$	$\mathcal{L}_1$ $(1,2)_{\frac{1}{2}}$
	$\mathcal{L}_3$ $(1,2)_{-\frac{3}{2}}$	$\mathcal{U}_2$ $(3,1)_{\frac{2}{3}}$	$\mathcal{U}_5$ $(3,1)_{\frac{5}{3}}$	$\mathcal{Q}_1$ $(3,2)_{\frac{1}{6}}$	$\mathcal{Q}_5$ $(3,2)_{-\frac{5}{6}}$	$\mathcal{X}$ $(3,3)_{\frac{2}{3}}$	$\mathcal{Y}_1$ $(\bar{6},2)_{\frac{1}{6}}$	$\mathcal{Y}_5$ $(\bar{6},2)_{-\frac{5}{6}}$

All (except very few) new states are probed by EWPOs at one-loop

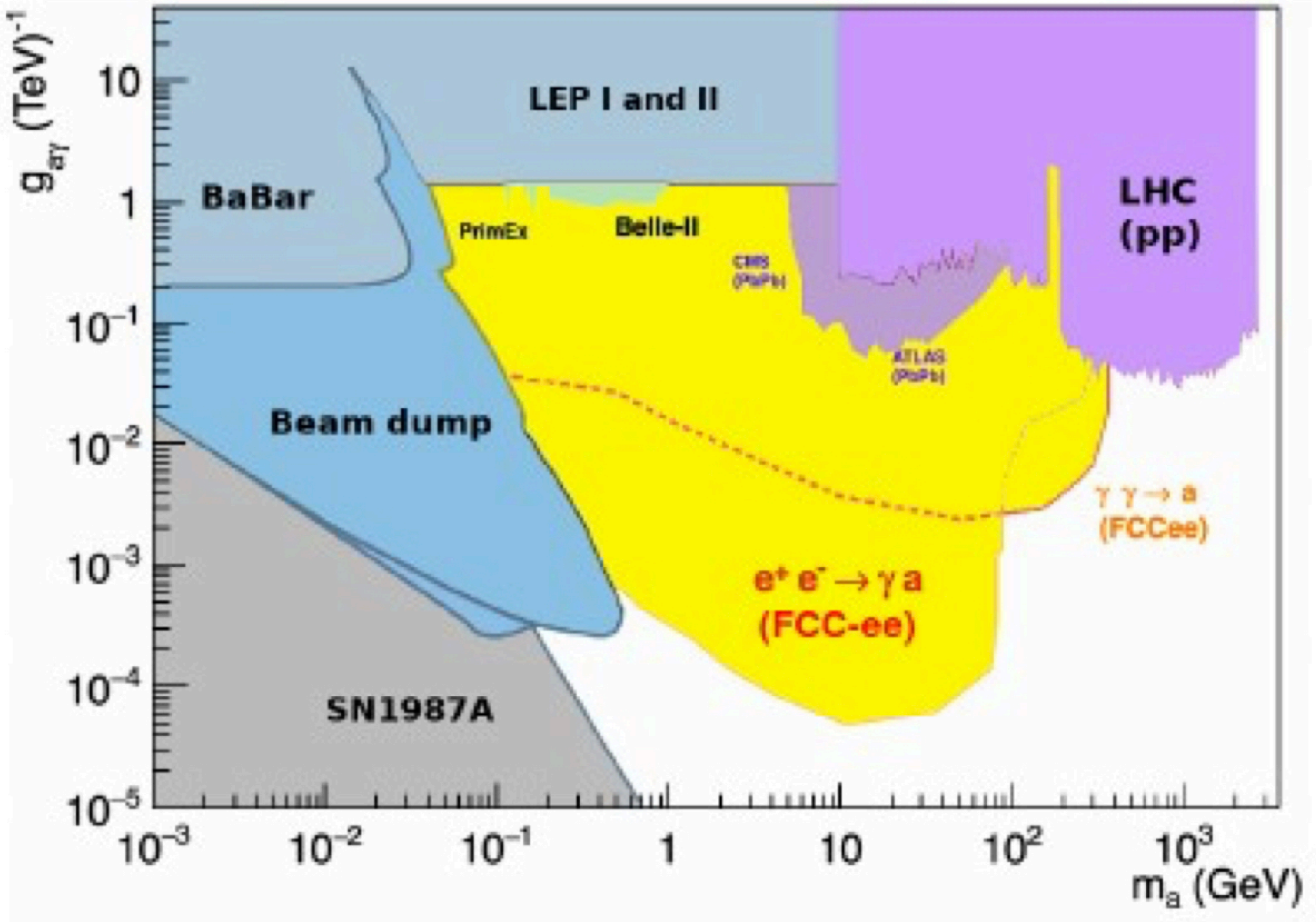


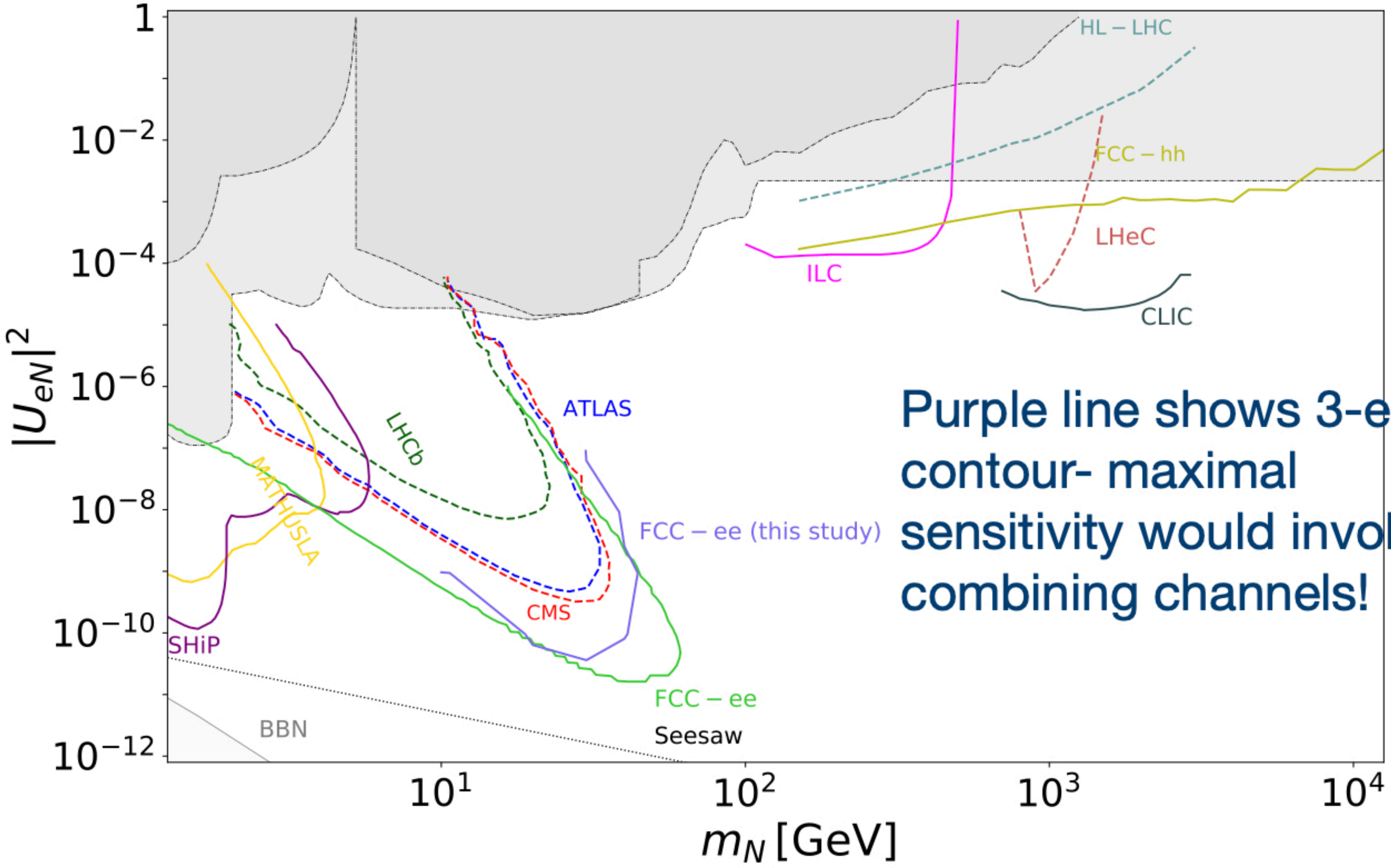
[LA, Mccullough, Renner 2408.03992]

What are the actual prospects to detect these particles at FCC-hh, in the relevant mass ranges?

Examples

- ALPs and HNLs (*Polesello, Kontaxakis talks*)





Purple line shows 3-event contour- maximal sensitivity would involve combining channels!

- **Include FCC-hh reach**
- **Explore implications at FCC-hh of concrete models for ALPs and HNLs, considering potential signals of other manifestations of such models**