Workshop on High Luminosity LHC and Hadron Colliders
LNF Frascati
1-4 Oct 2024

Future hadron colliders: the physics/strategy landscape

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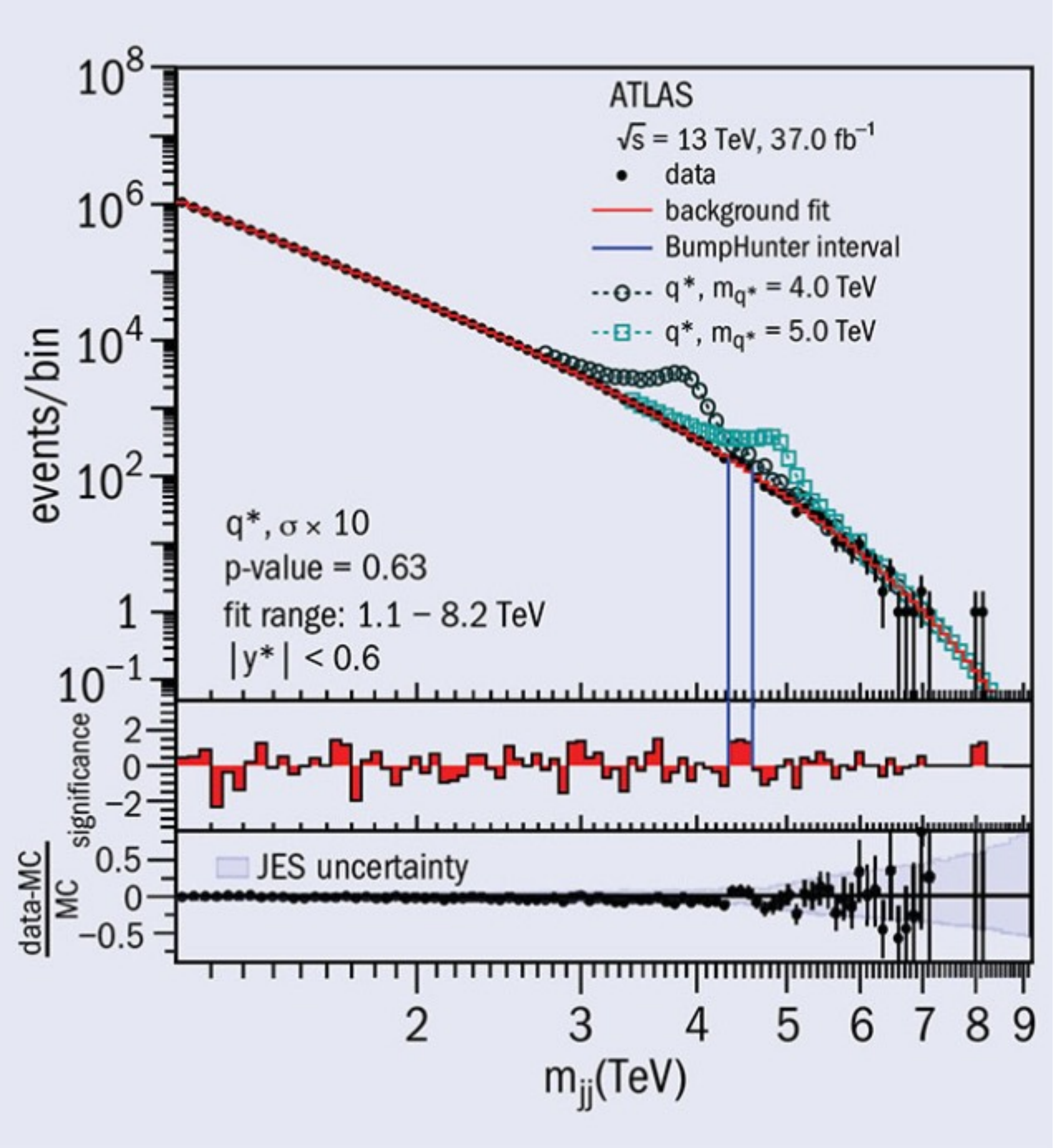
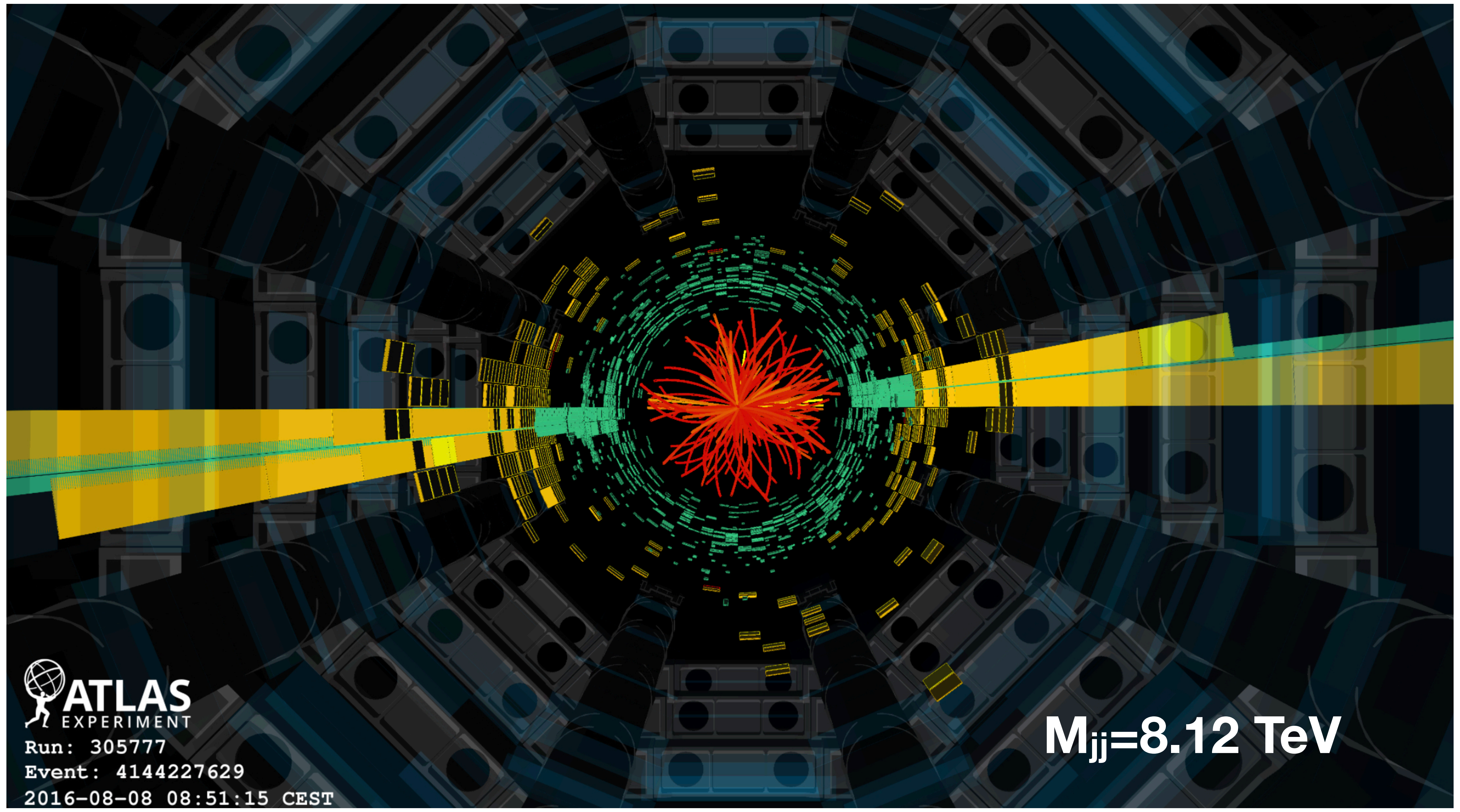
CERN TH

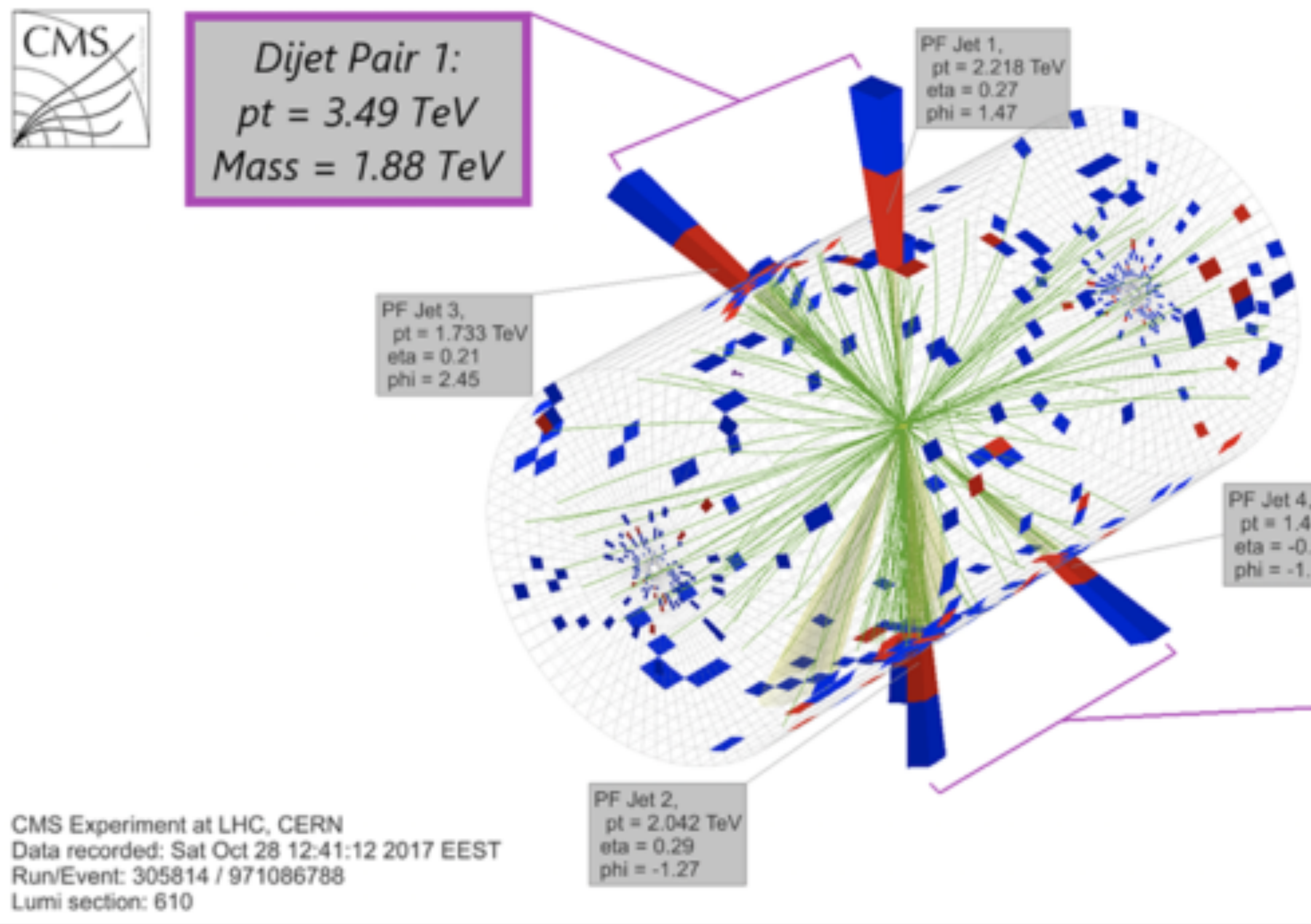
> ***“All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider”***
>
> *P5 Report (2023), p. 17*

The 10 TeV pCM holy Grail: how far are we from it, really? not much actually, already at the LHC



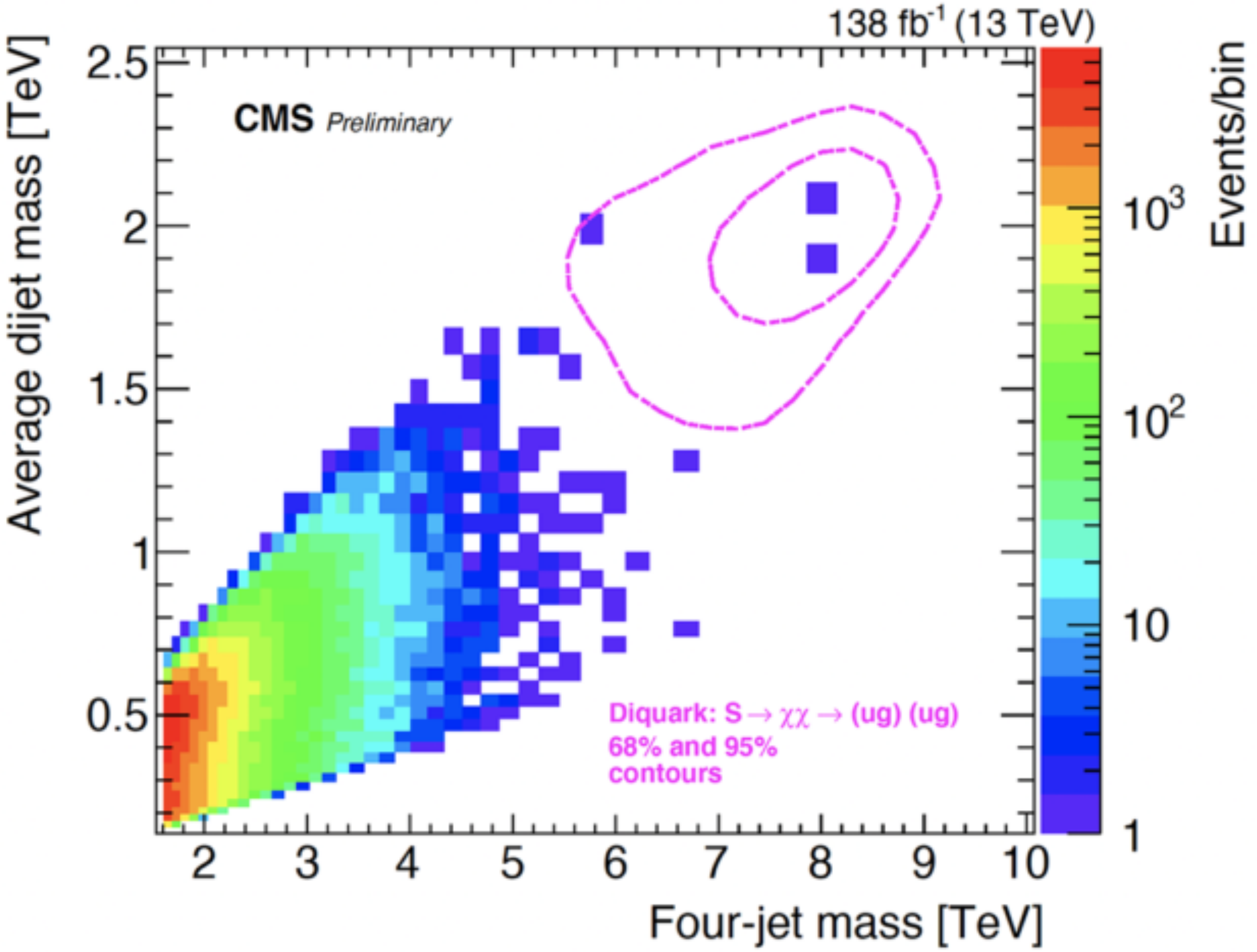


M_{jj}=8.12 TeV



M_{jjjj}=8.4 TeV

https://arxiv.org/abs/1911.03947



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- The guaranteed deliverables
  - improved measurements of fundamental constants and parameters (eg H couplings)
  - deeper exploration of dynamics of SM interactions, eg
    - EW symmetry breaking and flavour phenomena
    - QCD non-perturbative dynamics
  - *push further the boundary between* ***established*** *facts (e.g. quarks are pointlike at the scale of (10 TeV)–1) and* ***conjectures*** *(e.g. quarks are pointlike)*

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- Conclusive answers to important questions, like
  - Is DM a thermal WIMP ?
  - What was the nature of the EW phase transition ?
  - Does the origin of neutrino masses lie at the TeV scale ?
  - Are the Higgs potential and mass defined by physics at the few-TeV scale ?
  - are there BSM sources of CPV below the few-TeV scale ?

Physics potential of FCC-hh @ 100 TeV to complement FCC-ee in fulfilling these goals studied over 10 years, leading to the FCC CDR (2018) and further refinements

- "Physics at 100 TeV", CERN Yellow Report: https://arxiv.org/abs/1710.06353
- **FCC CDR:**
  - Vol.1: **Physics Opportunities** (CERN-ACC-2018-0056), http://cern.ch/go/Nqx7
  - Vol.3: The Hadron **Machine** (CERN-ACC-2018-0058), http://cern.ch/go/Xrg6
  - Conceptual design of an **experiment** at the FCC-hh: https://inspirehep.net/literature/2595883
- **Low-E FCC-hh** physics potential: M. Mangano, https://cds.cern.ch/record/2681366?ln=en

On the **HE-LHC**, see also

- HL/HE-LHC Physics Workshop reports
  - P. Azzi, et al, **SM** Physics at the HL- and HE-LHC, https://cds.cern.ch/record/2650160
  - M. Cepeda, et al, **Higgs** at the HL- and HE-LHC, https://cds.cern.ch/record/2650162
  - X. Cid-Vidal, et al, **BSM** at the HL- and HE-LHC, https://cds.cern.ch/record/2650173
  - A. Cerri, et al, **Flavour** at the HL- and HE-LHC, https://cds.cern.ch/record/2650175
  - Z. Citron,et al, Future physics opportunities for **high-density QCD** at the LHC with heavy-ion and proton beams, https://cds.cern.ch/record/2650176
- HE-LHC FCC CDR
  - FCC CDR Vol.4: (CERN-ACC-2018-0059), http://cern.ch/go/S9Gq

Examples of key FCC-hh @ 100 deliverables

- Higgs physics
- High mass reach
- Yes/no answers

Higgs

The absolutely unique power of pp →H+X:

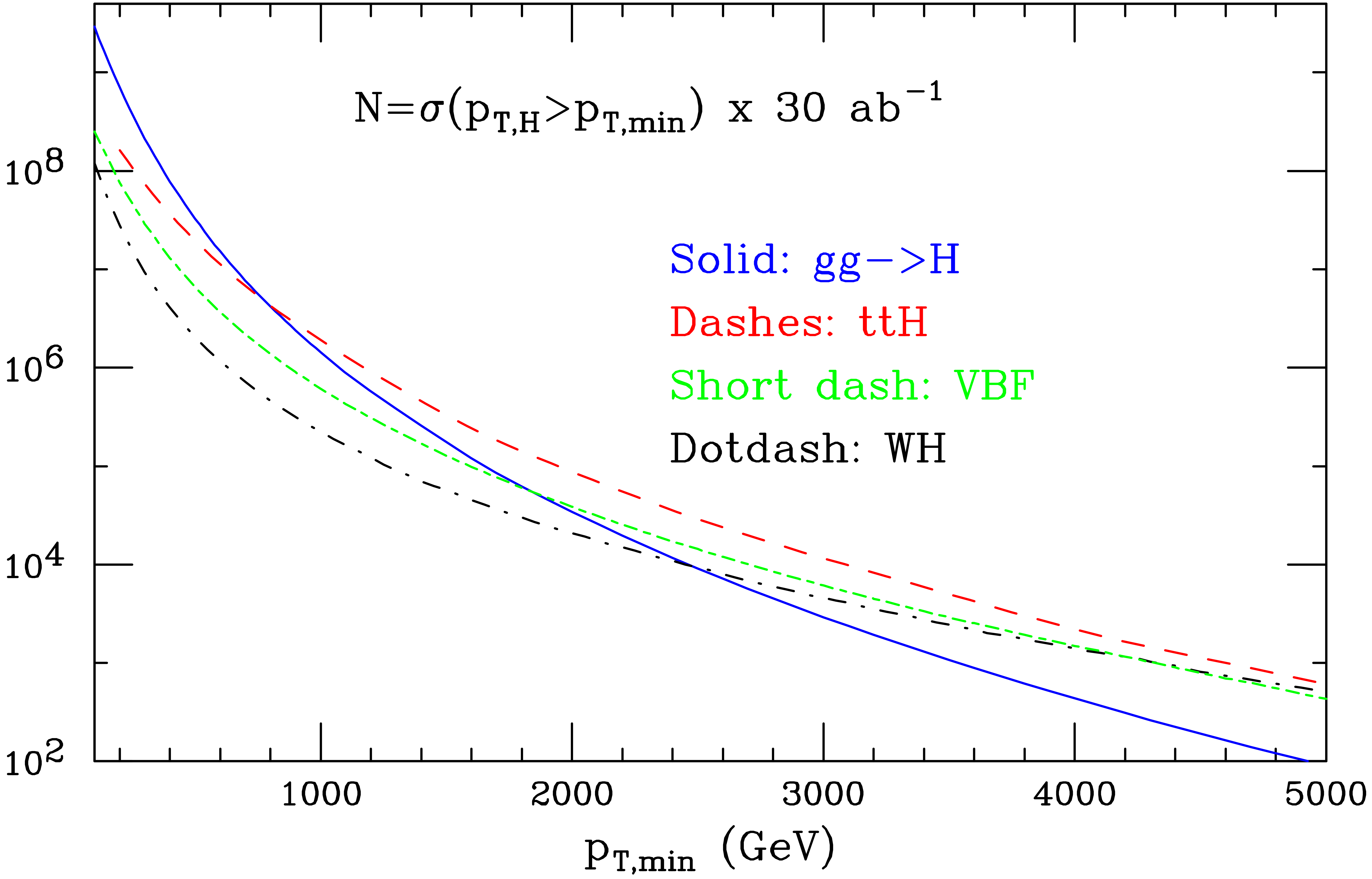
- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR(H→ZZ*), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling
- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4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

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

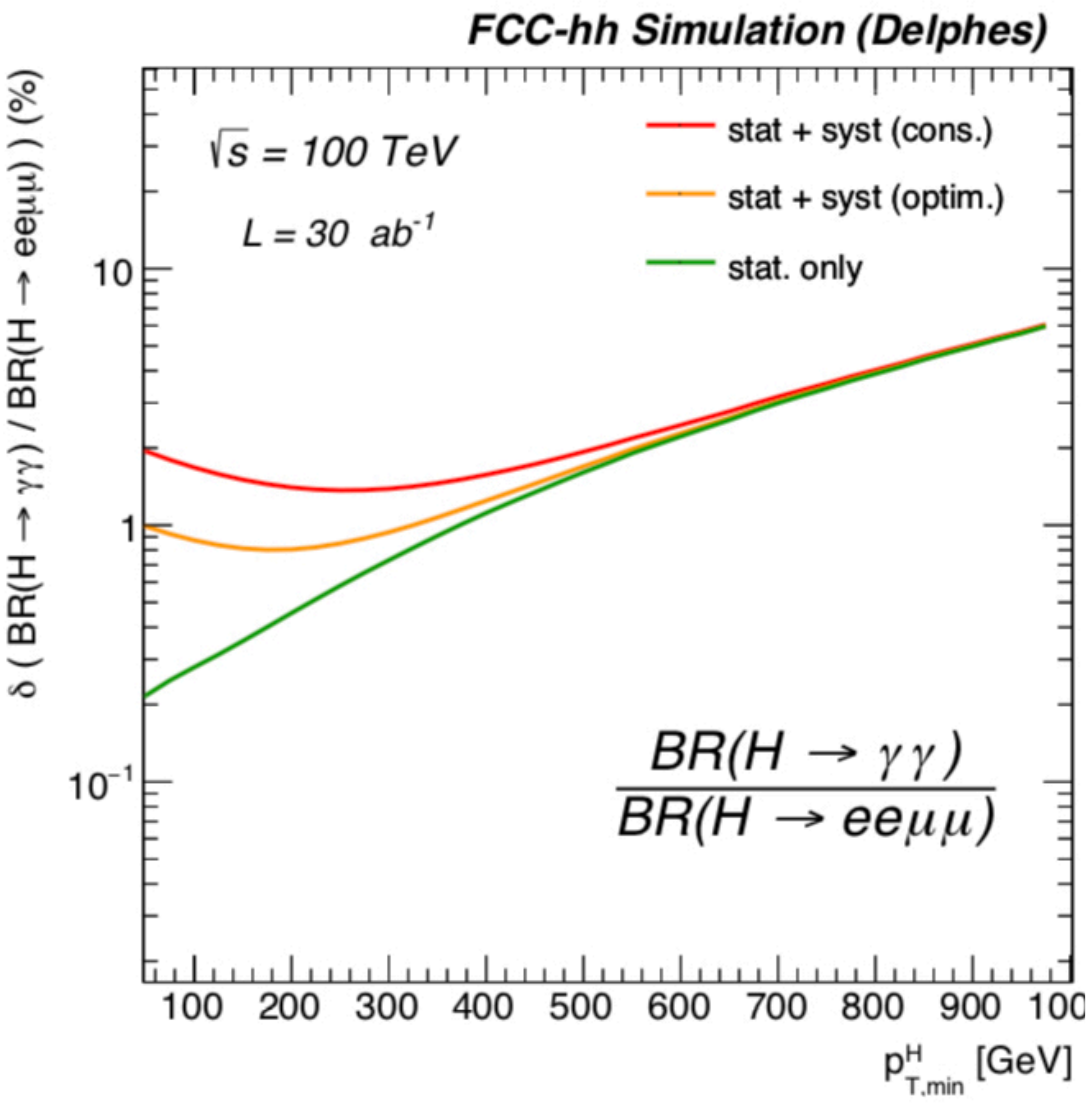
$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

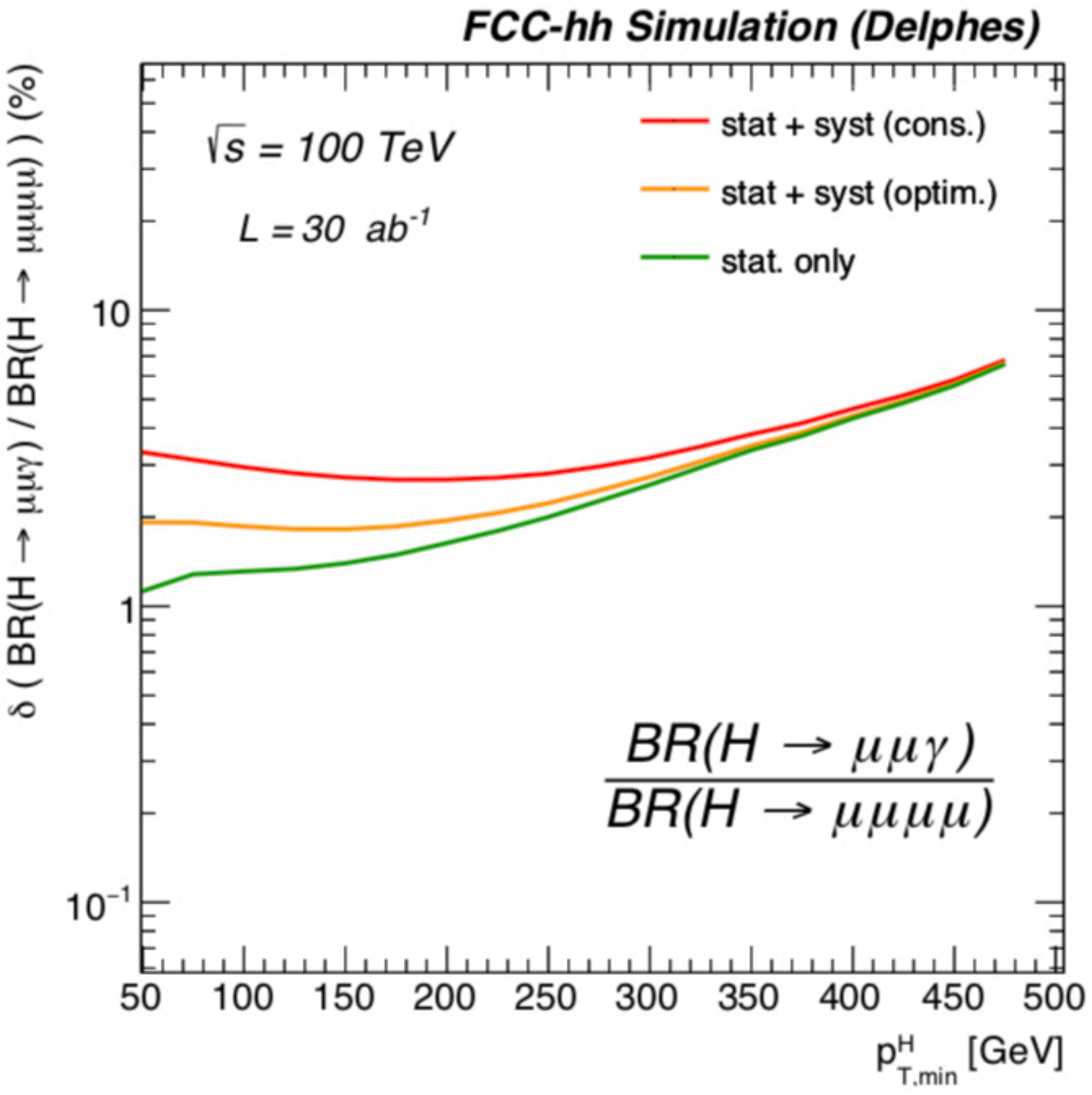
H at large p_T

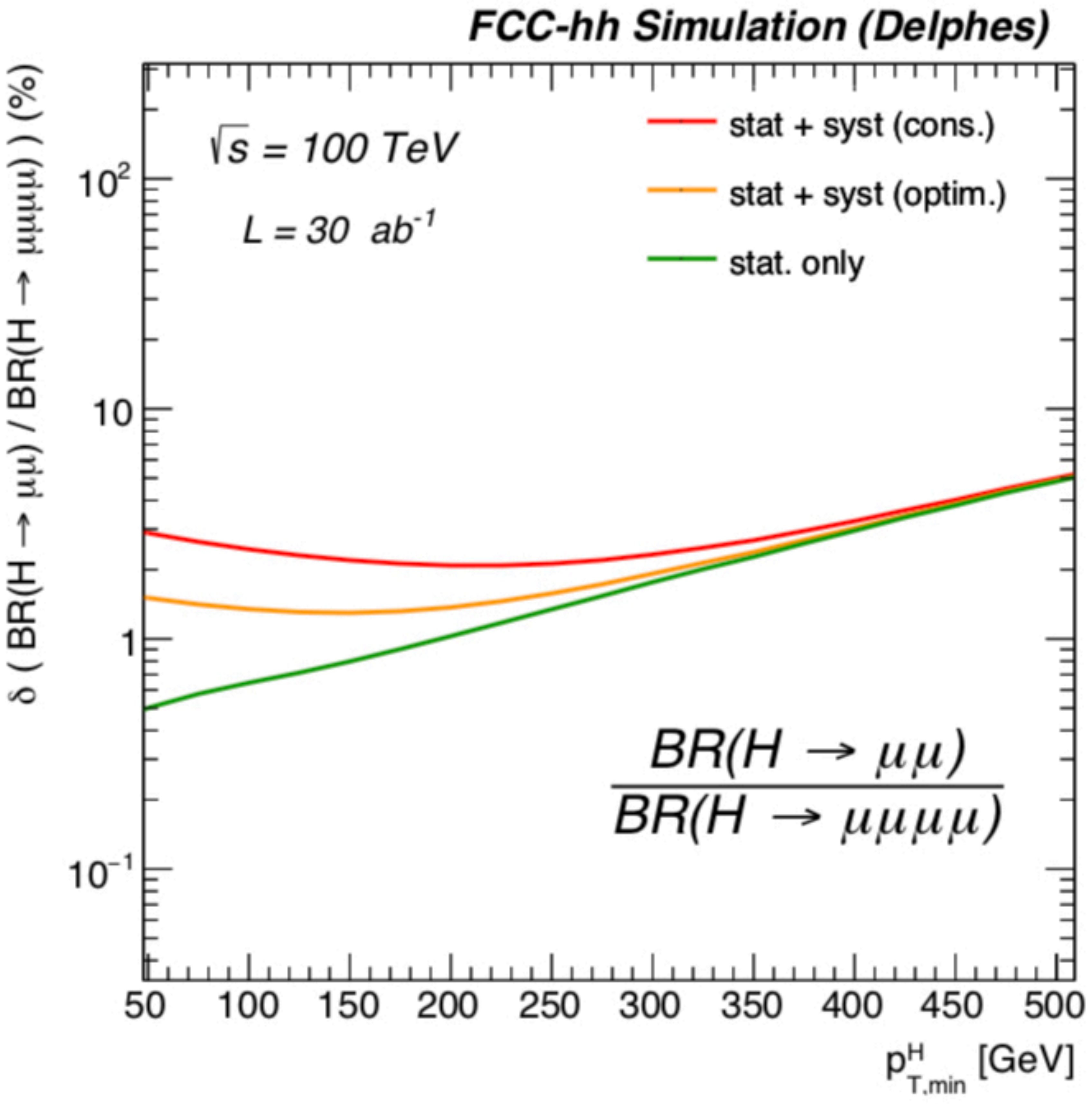


- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

Precision measurements of Higgs couplings with boosted Higgses







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

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($H \to Z\gamma,\gamma\gamma$) ~O($10^{-3}$) ⇒ **O($10^7$) evts for Δ_{stat}~%**

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

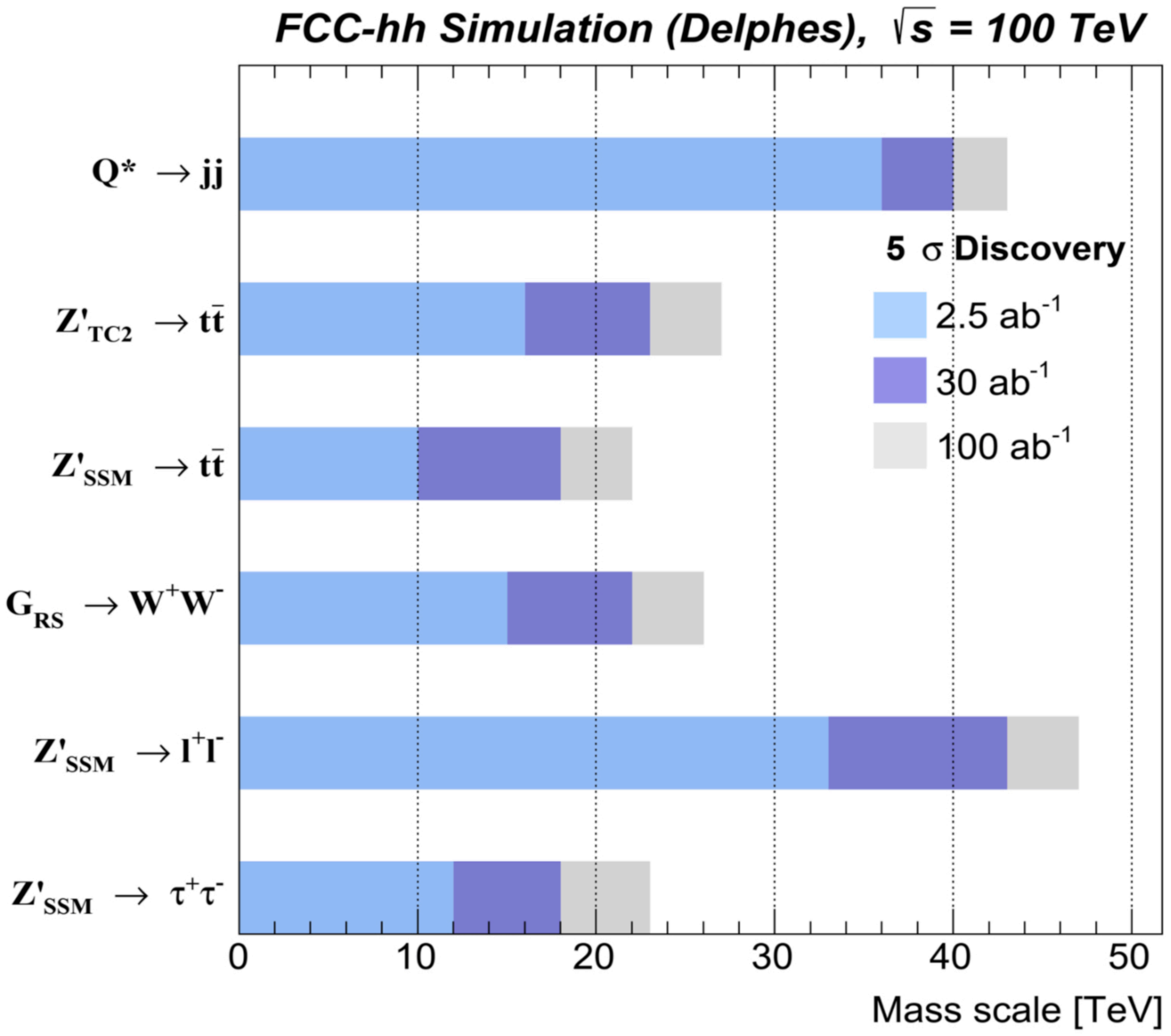
pp collider is essential to beat the % target, since no proposed ee collider can produce more than O(10^6) H's

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

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

High mass reach

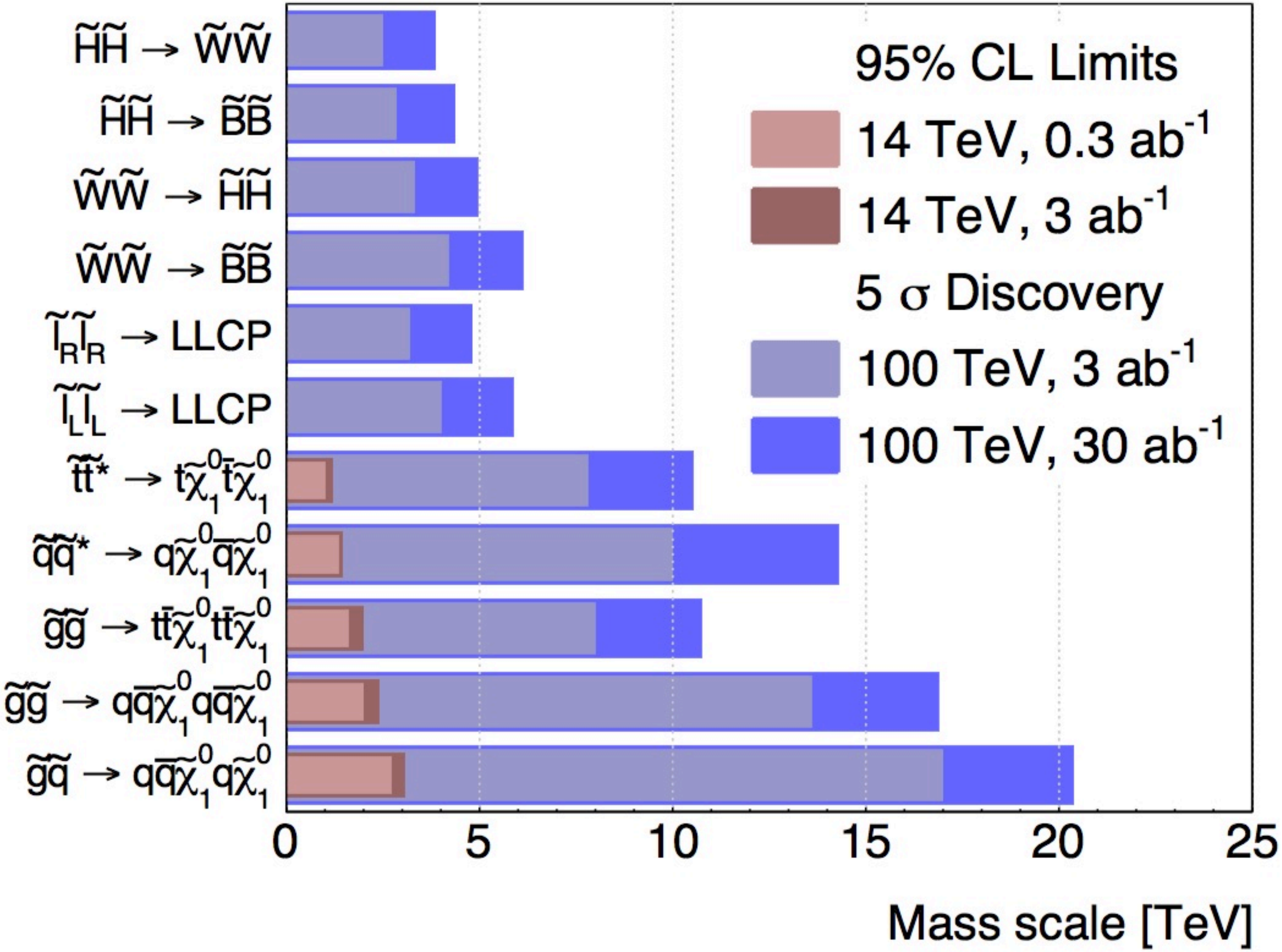
s-channel resonances



FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

Early phenomenology studies



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:

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

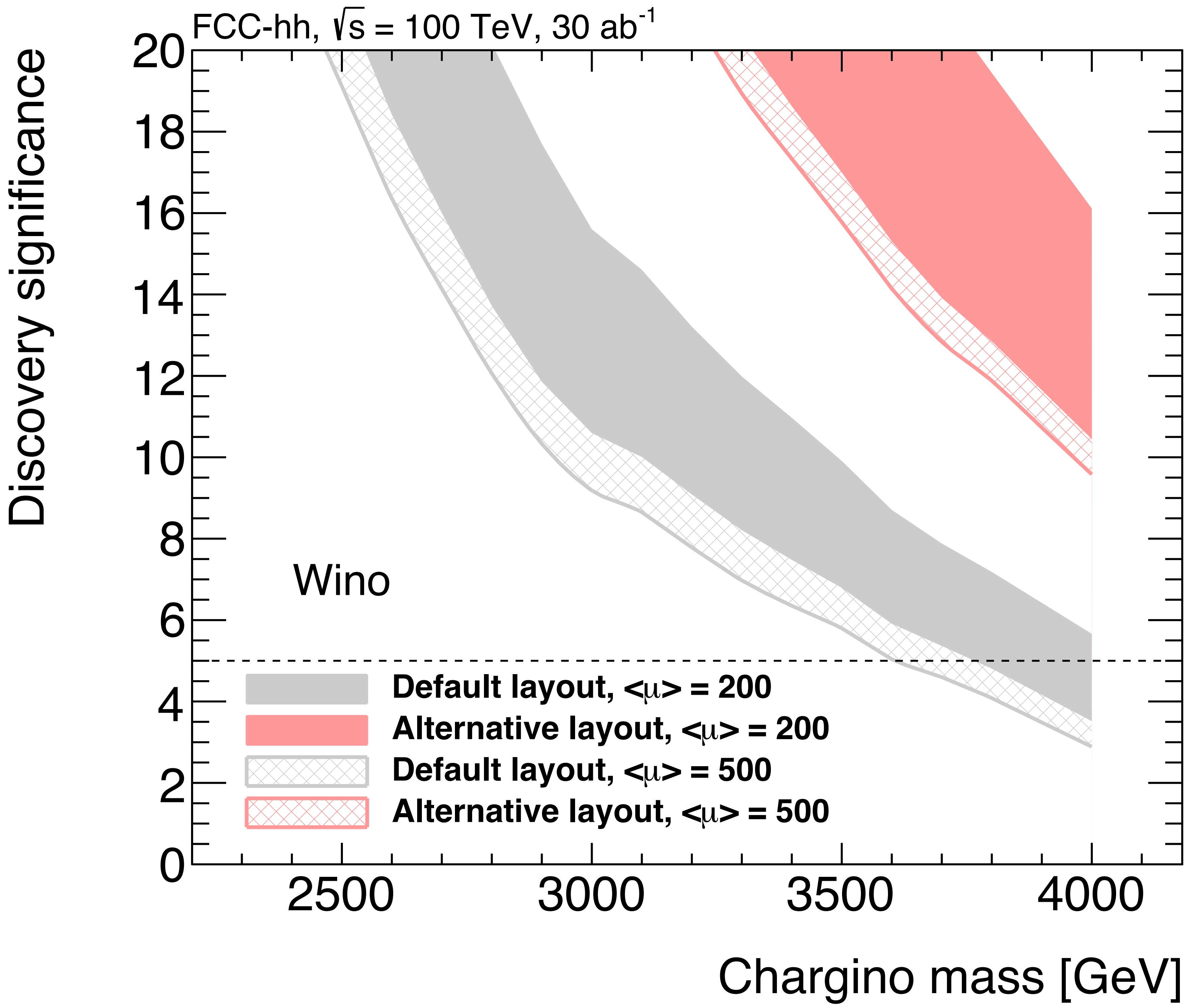
$$\Rightarrow \quad \Omega_{\rm DM}h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}}\right)^2 \left(\frac{0.3}{g_{\rm eff}}\right)^4$$

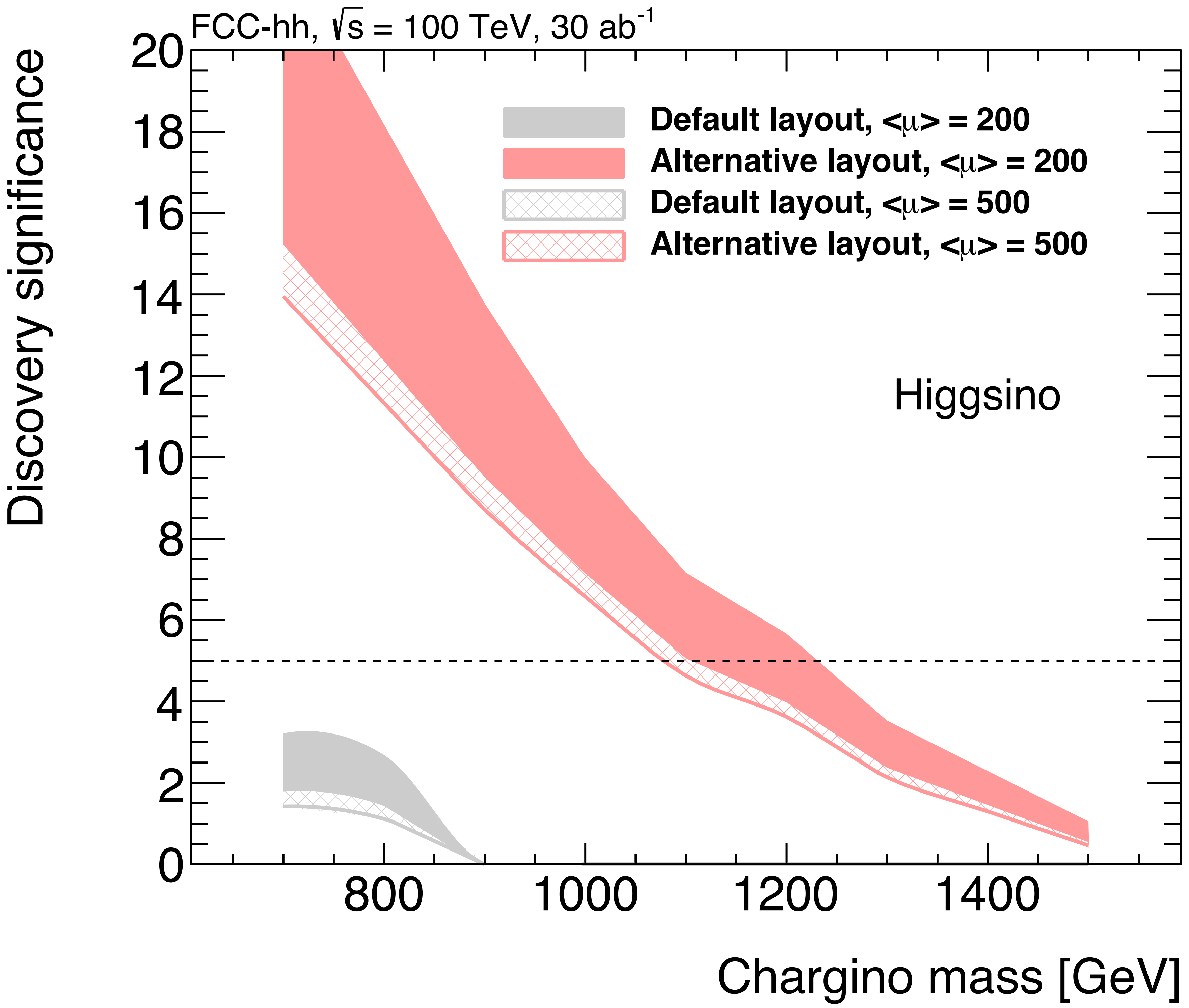
$$\Omega_{wimp}\, h^2 \lesssim 0.12 \quad \Rightarrow \quad M_{wimp} \lesssim 2\ {\rm TeV}\left(\frac{g}{0.3}\right)^2$$

Disappearing charged track analyses

(at ~full pileup)

K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.





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

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

New FCC-hh scenarios

- Driven by new accelerator layout (90.7 km ring vs 100 km, increased dipole filling factor)

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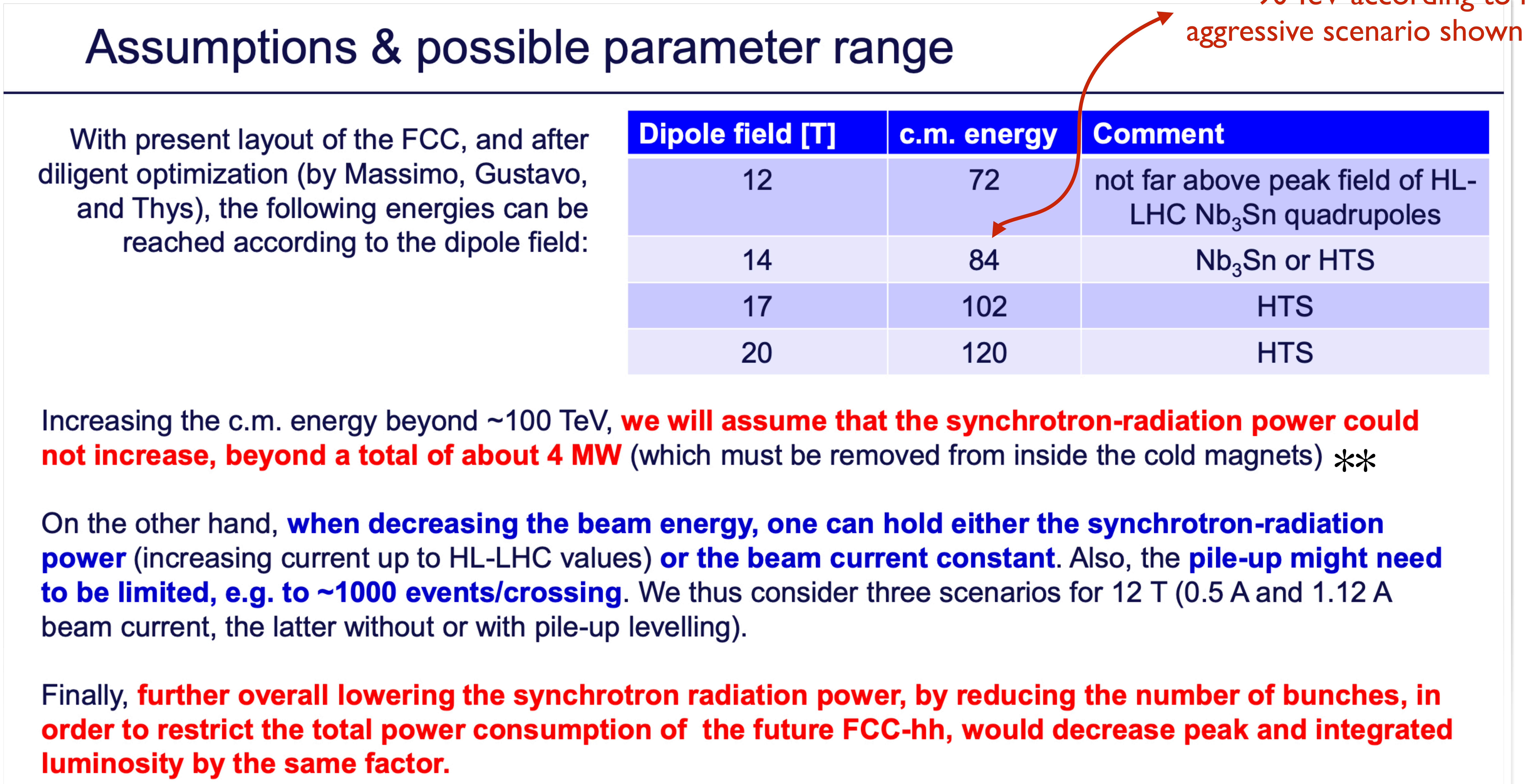
- Driven by assumptions about challenges/options in dipole technology (see L.Rossi yesterday)
- Ongoing review of CDR physics potential projections, to assess impact of new scenarios:
  - See https://indico.cern.ch/event/1439072/ and Michele's talk after this
  - Goal is NOT to push for an alternative "planA", but to provide expert answers to questions that may be raised during the Strategy process, eg in the context of "plan-B" discussions

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

~90 TeV according to more aggressive scenario shown by Lucio



Assumptions & possible parameter range

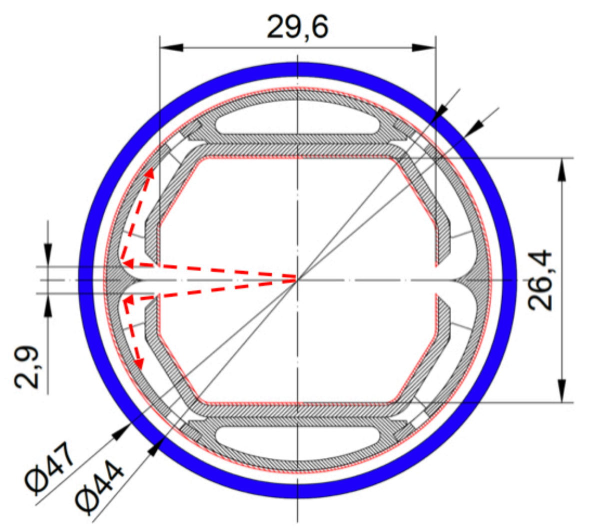
With present layout of the FCC, and after diligent optimization (by Massimo, Gustavo, and Thys), the following energies can be reached according to the dipole field:

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 …

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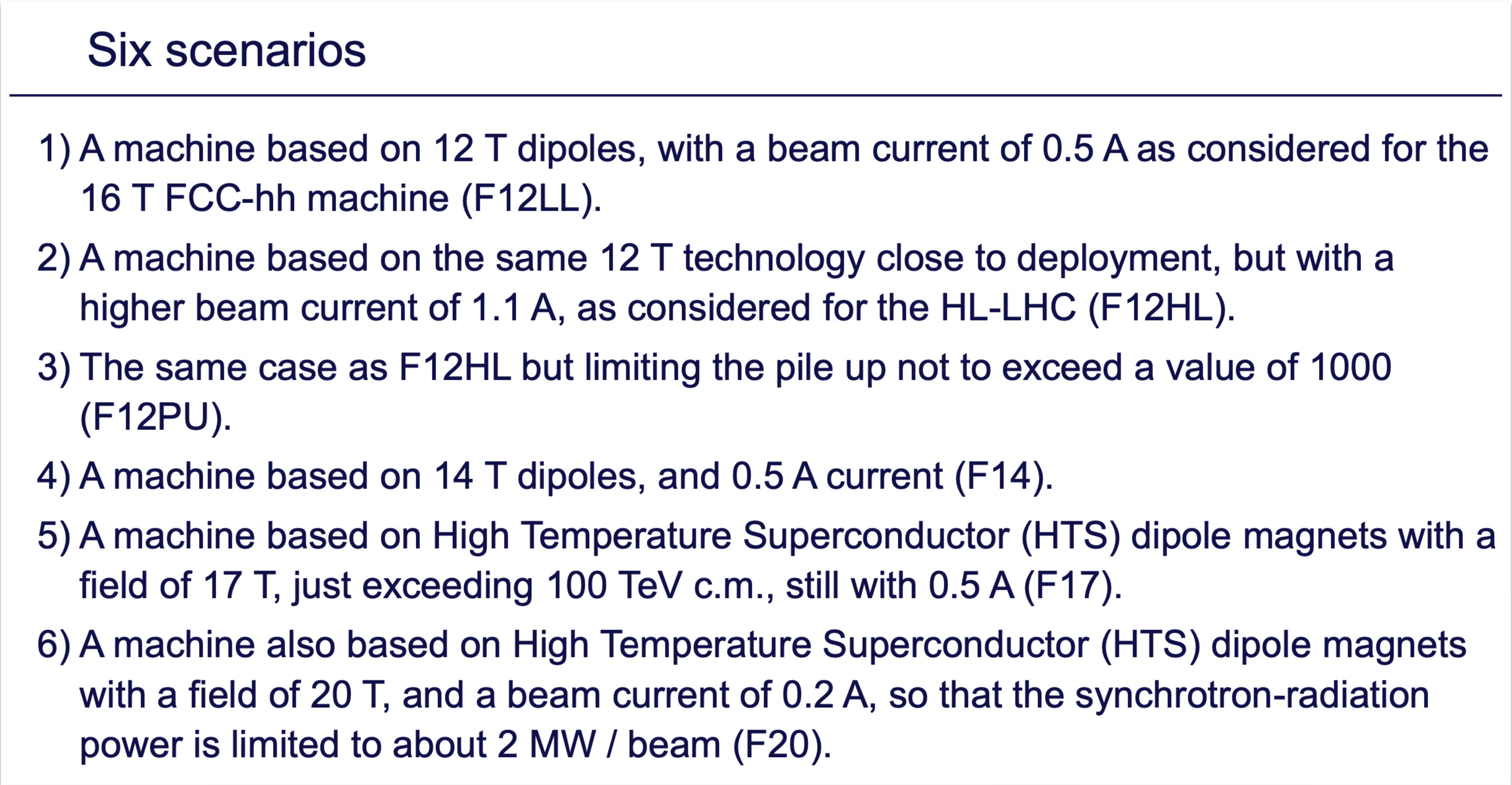
Parameter	**Unit**	**F12LL**	**F12HL**	**F12PU**	**F14**	**F17**	**F20**	**(HL-)LHC**
initial *L*	nb^{-1}s^{-1}	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
opt. run time	h	3.8	3.3	6.3	3.8	3.4	4.2	(18-13) ~10

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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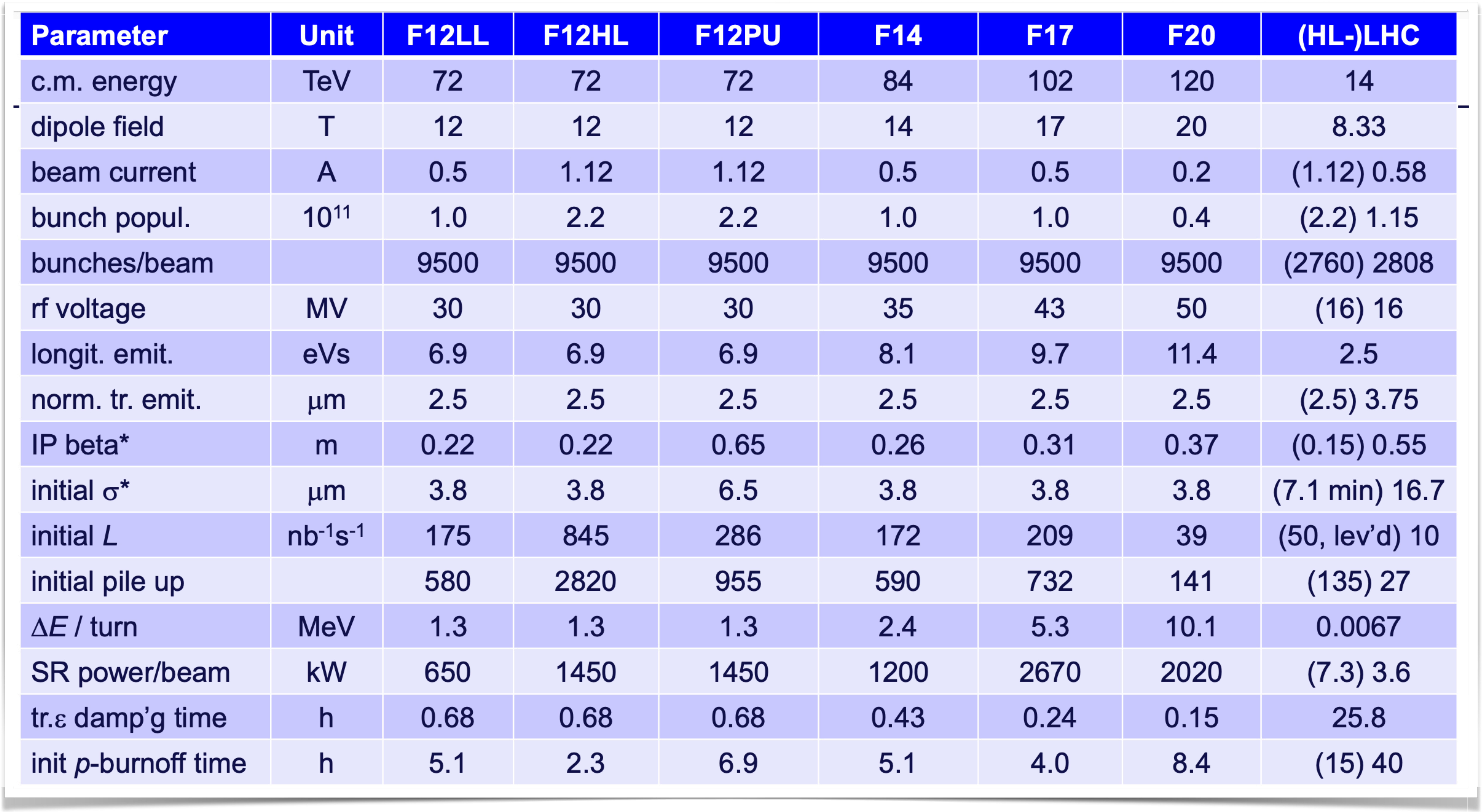
!!

More details *(see Frank's note)*



Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
c.m. energy	TeV	72	72	72	84	102	120	14
dipole field	T	12	12	12	14	17	20	8.33
beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
bunch popul.	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
bunches/beam		9500	9500	9500	9500	9500	9500	(2760) 2808
rf voltage	MV	30	30	30	35	43	50	(16) 16
longit. emit.	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
norm. tr. emit.	μm	2.5	2.5	2.5	2.5	2.5	2.5	(2.5) 3.75
IP beta*	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
initial σ^*	μm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min) 16.7
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
ΔE / turn	MeV	1.3	1.3	1.3	2.4	5.3	10.1	0.0067
SR power/beam	kW	650	1450	1450	1200	2670	2020	(7.3) 3.6
tr.ε damp'g time	h	0.68	0.68	0.68	0.43	0.24	0.15	25.8
init p-burnoff time	h	5.1	2.3	6.9	5.1	4.0	8.4	(15) 40

Preliminary assessment of 80 vs 100 vs 120 TeV evolution of key measurements

More details in talks by MLM (slides) and M.Selvaggi's (today's talk and earlier slides)

Assumptions underlying the results shown below:

(1) *exptl systematics and S/B independent of* E_{CM}

(2) *total integrated luminosity independent of* E_{CM} *(30 ab*$^{-1}$*)*

➡ E_{CM} evolution only driven by E_{CM} - dependence of production cross sections

Note:

- Zimmermann's table shows that (2) is too naive

  ➡ *to be fixed in next iterations*

- for Higgs measurements, potential handicap @ 120 TeV and advantage for 80 TeV

  ➡ *not necessarily so, play with higher boosts to optimize stat vs syst balance, to be studied in ore detail*

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**
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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
syst	1.6	3.0	5.4
tot	**3.4**	**5.1**	**7.8**

80 TeV	s I	s II	s III
stat	3.5	4.7	6.4
syst	1.6	3.0	5.4
tot	**3.8**	**5.6**	**8.4**

120 TeV	s I	s II	s III
stat	2.6	3.6	4.9
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Remarks:

- Similar +/– 15% changes for Htt coupling
- Differences within the uncertainty range of detector performance. Run 2 performance keeps $\delta\kappa_{HHH}$ well below 5%

Disappearing charged track analyses (at ~full pileup)

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

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

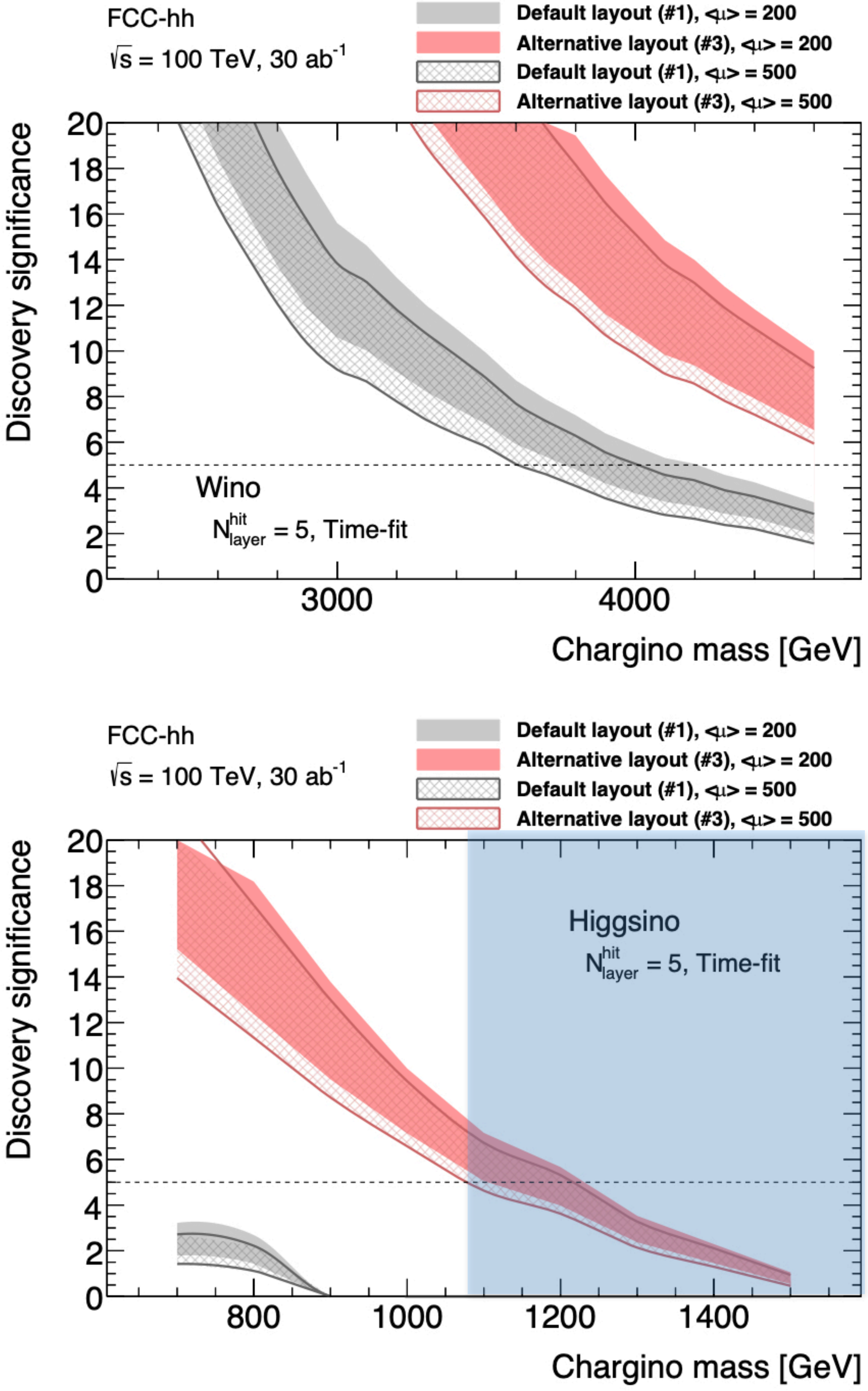
Excluded region for
thermal WIMP DM

80 TeV study, vs 100 TeV:

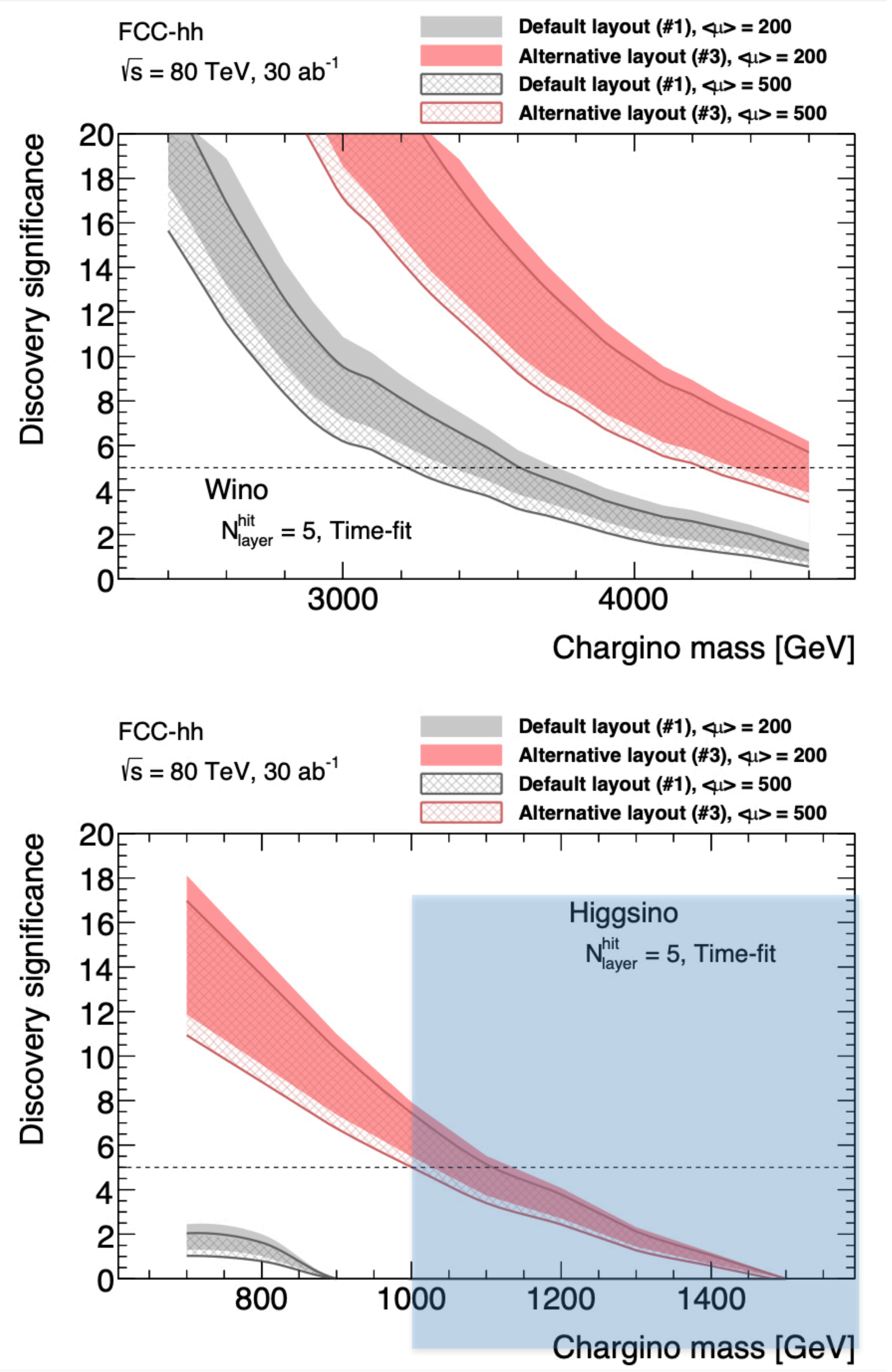
- signal rates @ 80 TeV
- kinematic selection reoptimised
- bgd rates unchanged

➡ discovery reach **conservative**

5σ higgsino reach drops from 1150 GeV to 1000 GeV

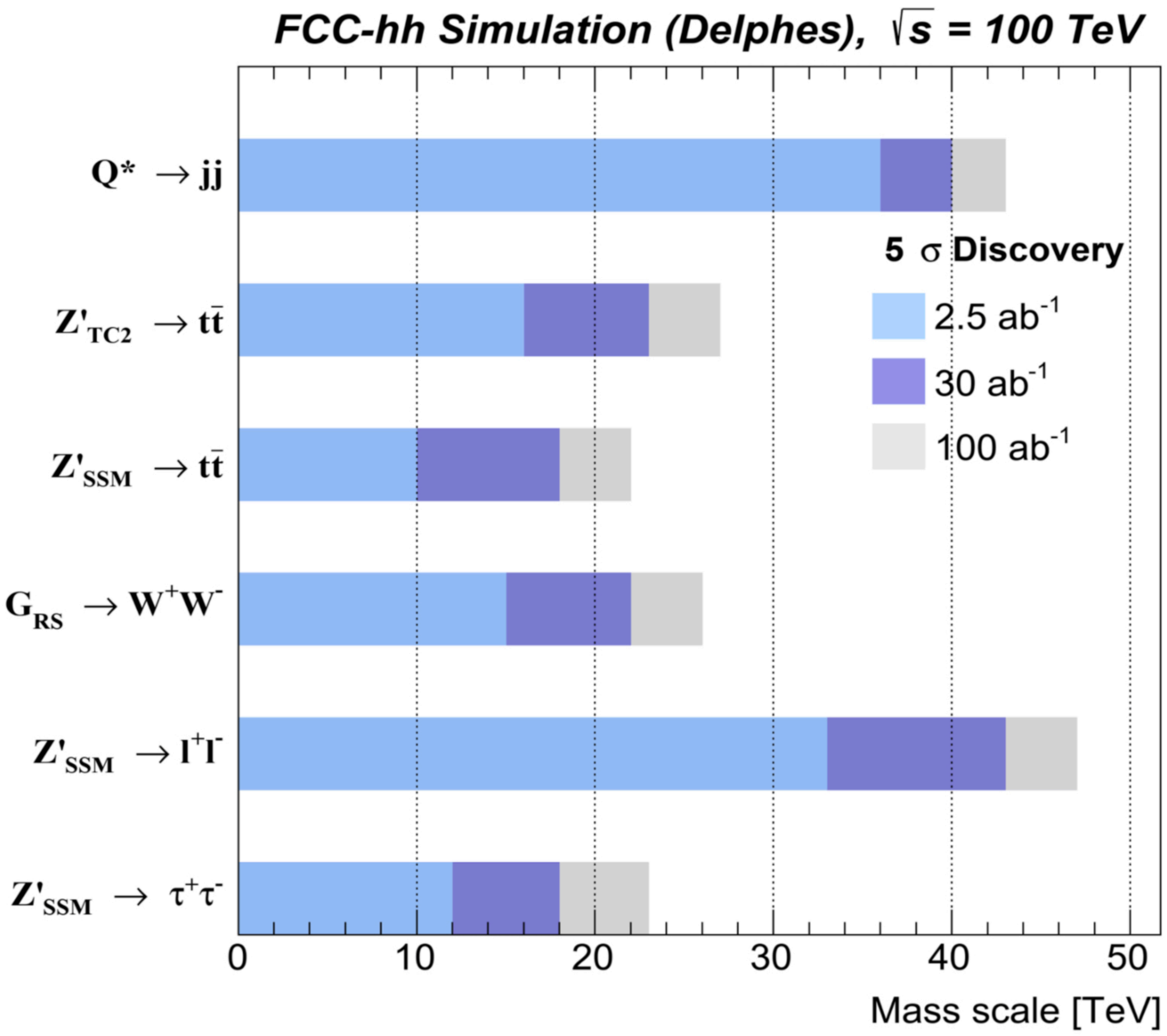


100 TeV



80 TeV

s-channel resonances



CilliderReach ECM extrapolation of 5σ 30ab^{-1} discovery reach

	100 TeV	80 TeV	120 TeV
Q*	40	33	46
$Z'_{TC2}\to tt$	23	20	26
$Z'_{SSM}\to tt$	18	15	20
$G_{RS}\to WW$	22	19	25
$Z'_{SSM}\to ll$	43	36	50
$Z'_{SSM}\to \tau\tau$	18	15	20

- 10-15% reach increase at 120 TeV
- 15-20% reach loss at 80 TeV

100 vs 80 vs 120: remarks

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- For the key "guaranteed deliverables", the difference between 100 and 80 TeV is comparable to the detector performance projection uncertainties. The loss in rate is in the range of 20-30% for key observables, with minor impact on measurements that by and large tend to be systematics-dominated

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➡ the decision of 80 vs 120 vs 100 is probably final, and unlikely to lead to an upgrade path

The HE-LHC "plan-B" option,

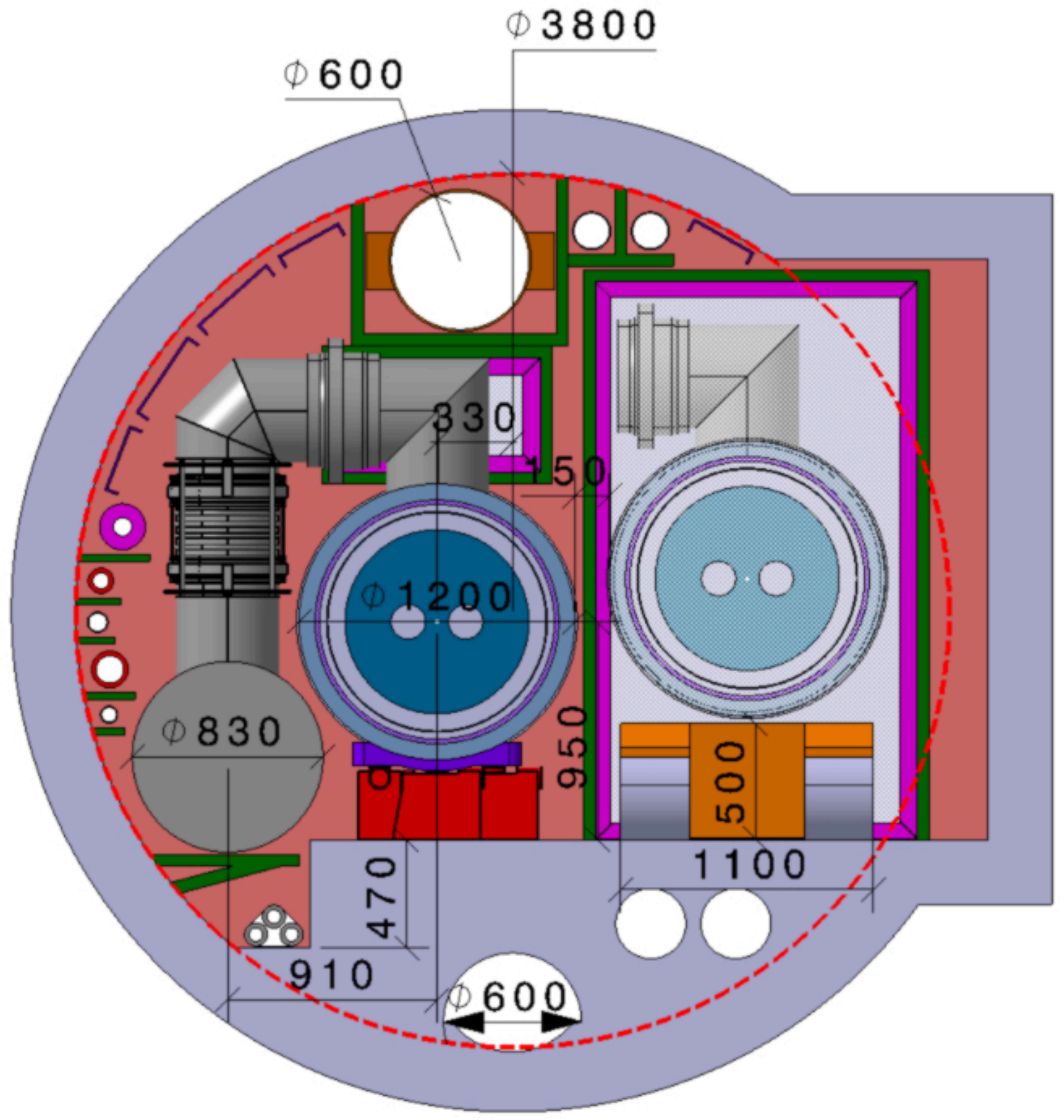
(eg to fast-track an "affordable" post-LHC hadron collider,
or to react to CEPC, or in case a 90 km tunnel is not built)

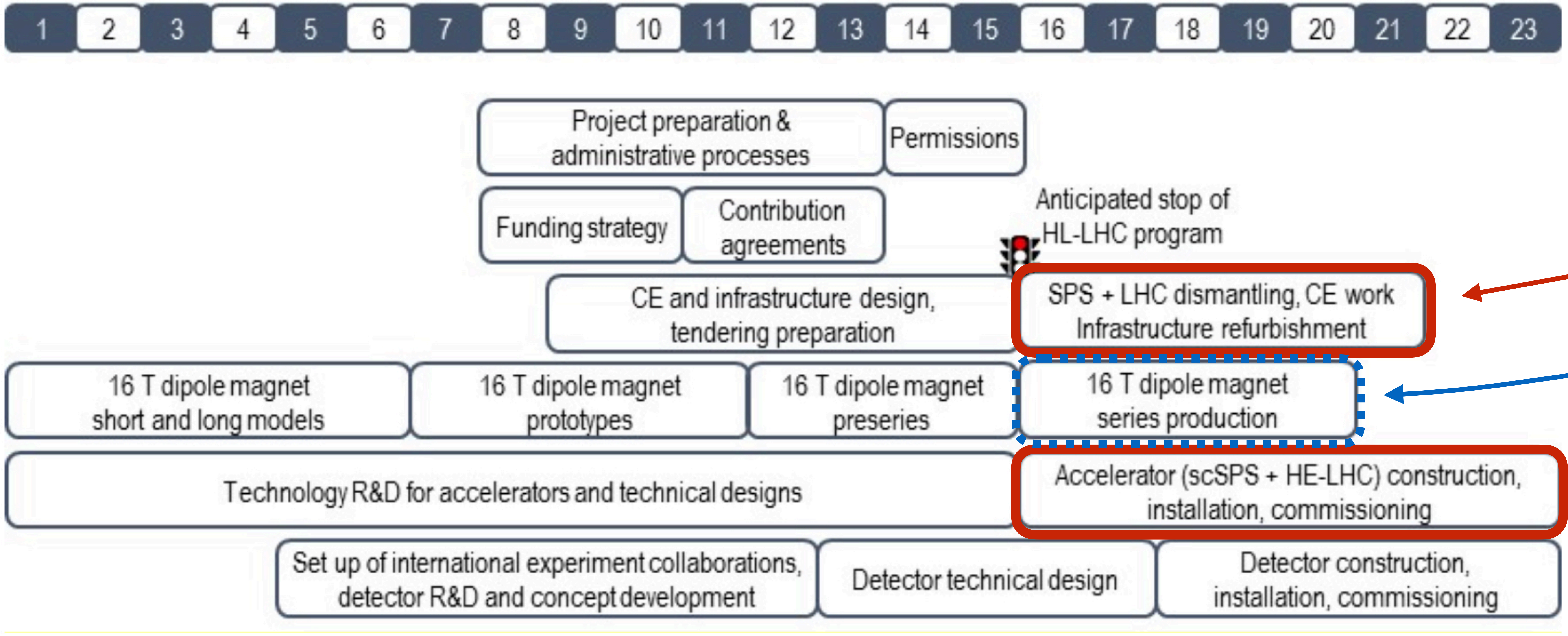
(results shown below for 16 T dipoles =~ 27 TeV)

Essential requirements:

1) total removal of current accelerator installation (magnets, QRL)
2) major infrastructure upgrade, including CE work on tunnel and ancillary surface/tunnel facilities to host enhanced power/cryo systems
3) upgrade of injector chain (eg super-conducting SPS)
4) magnets must be ready at end of HL-LHC for industrial mass-production
5) new detectors

(probably weaker demands on (2) and (3) if 12 T dipoles instead of 16 => 20 TeV)





Project preparation & administrative processes

Permissions

Funding strategy

Contribution agreements

Anticipated stop of HL-LHC program

CE and infrastructure design, tendering preparation

SPS + LHC dismantling, CE work Infrastructure refurbishment

16 T dipole magnet short and long models

16 T dipole magnet prototypes

16 T dipole magnet preseries

16 T dipole magnet series production

Technology R&D for accelerators and technical designs

Accelerator (scSPS + HE-LHC) construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

Detector technical design

Detector construction, installation, commissioning

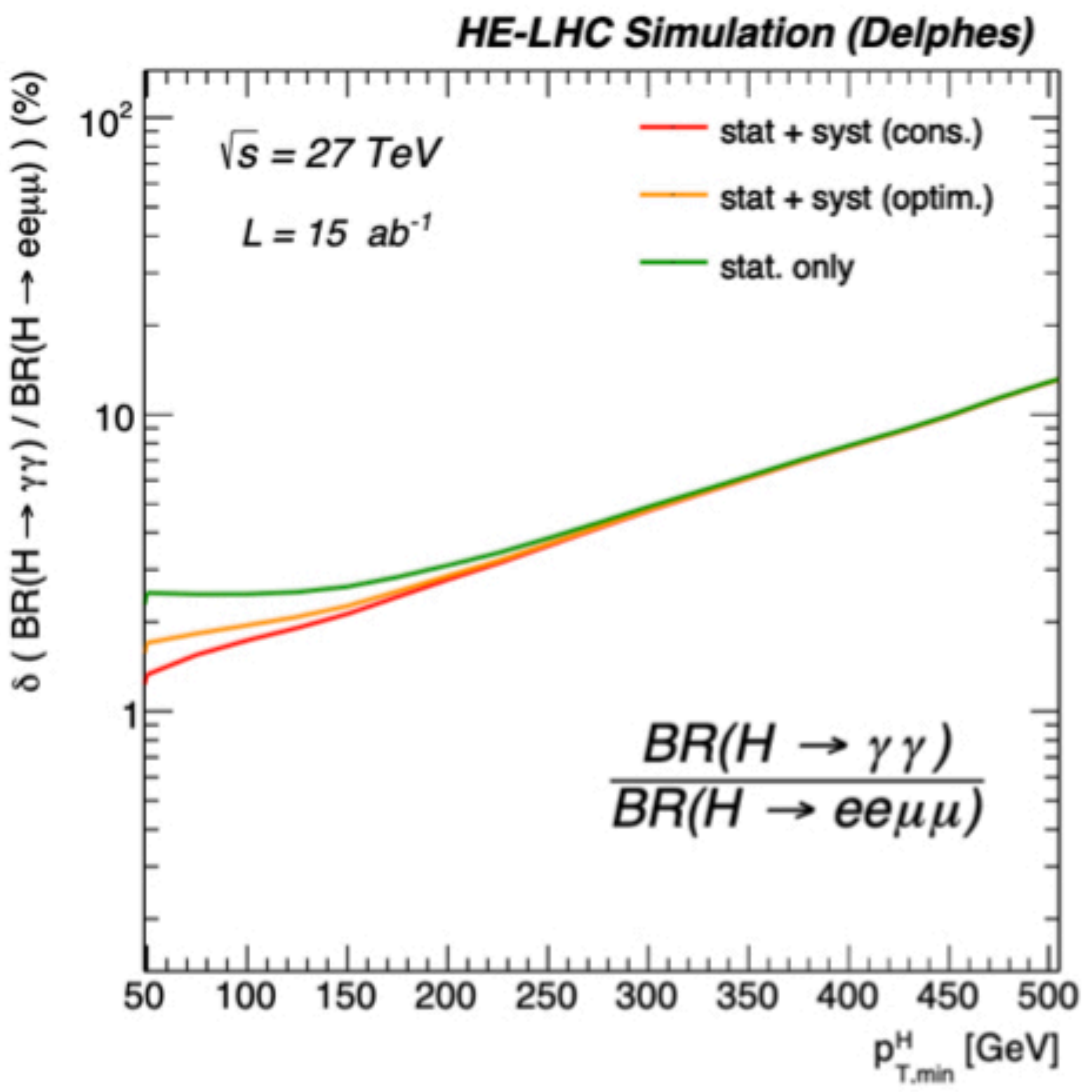
6yrs post HL-LHC just for CE and infrastructure

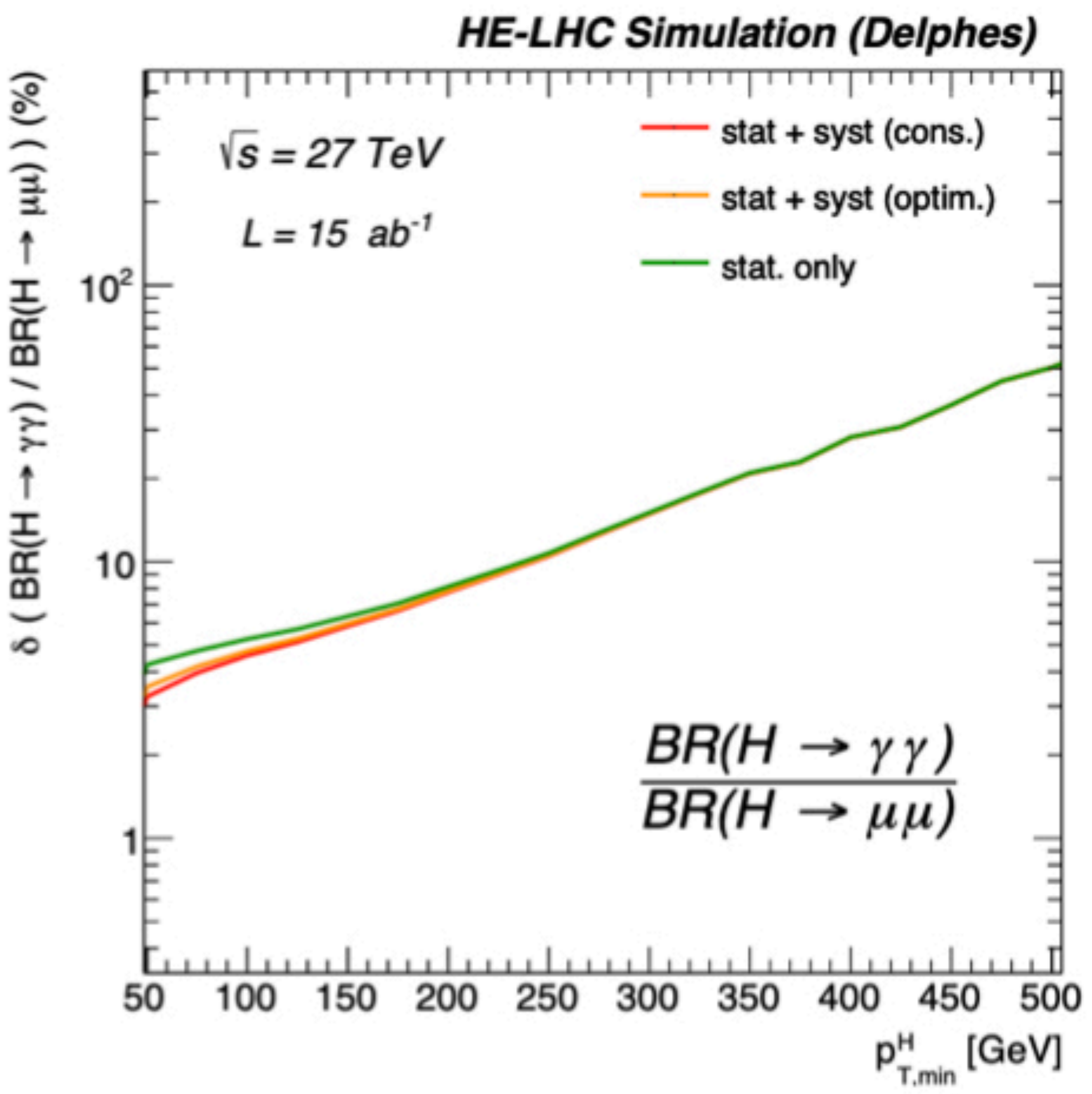
8yrs post HL-LHC to complete accelerator/inj's, assuming readiness of magnet series production before HL-LHC ends

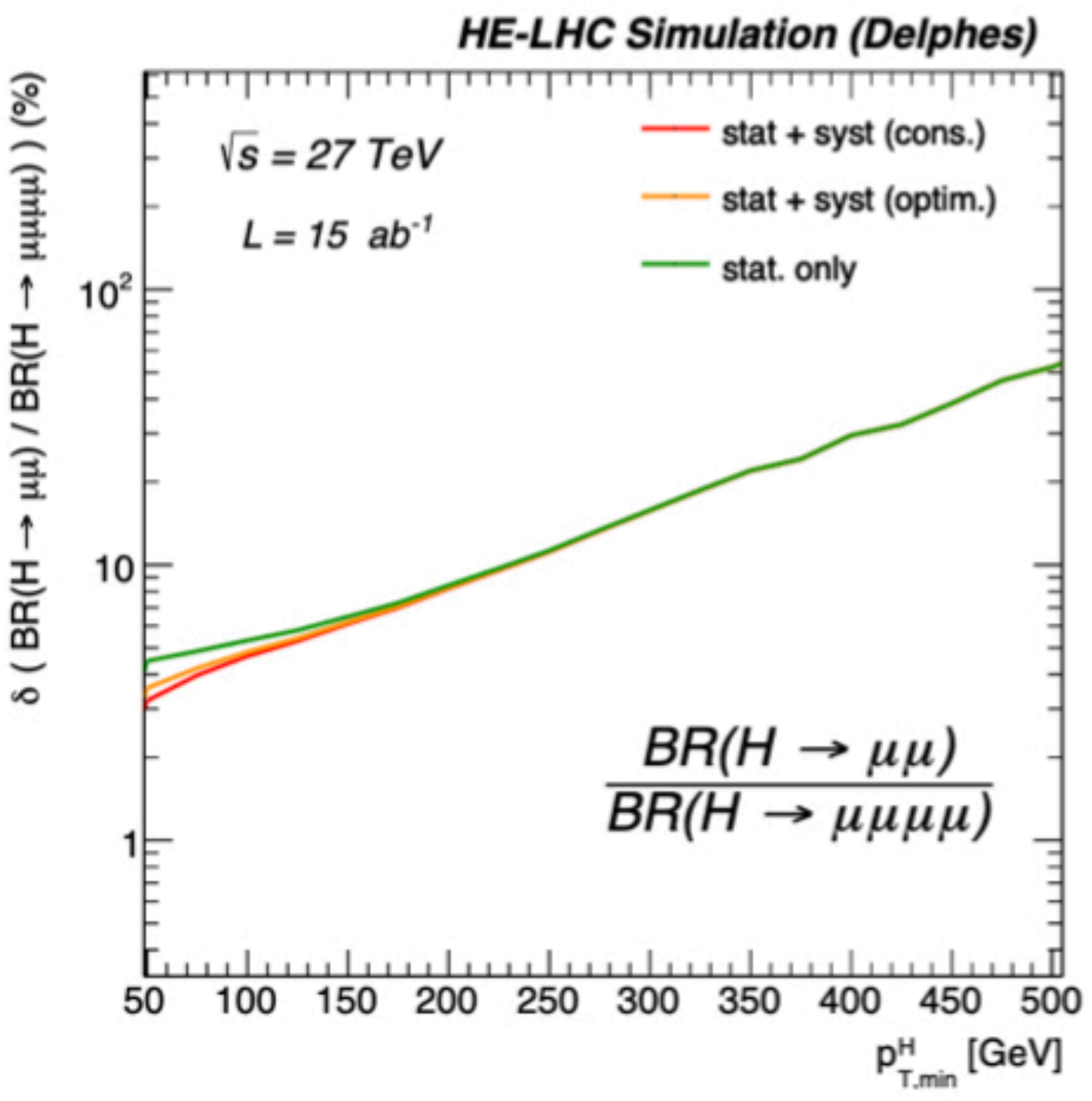
Table 4.3: Higgs production event rates for selected processes at 100 TeV (N_{100}) and 27 TeV (N_{27}), and statistical increase with respect to the statistics of the HL-LHC ($N_{100/27} = \sigma_{100/27\ \mathrm{TeV}} \times 30/15\ \mathrm{ab}^{-1}$, $N_{14} = \sigma_{14\ \mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$).

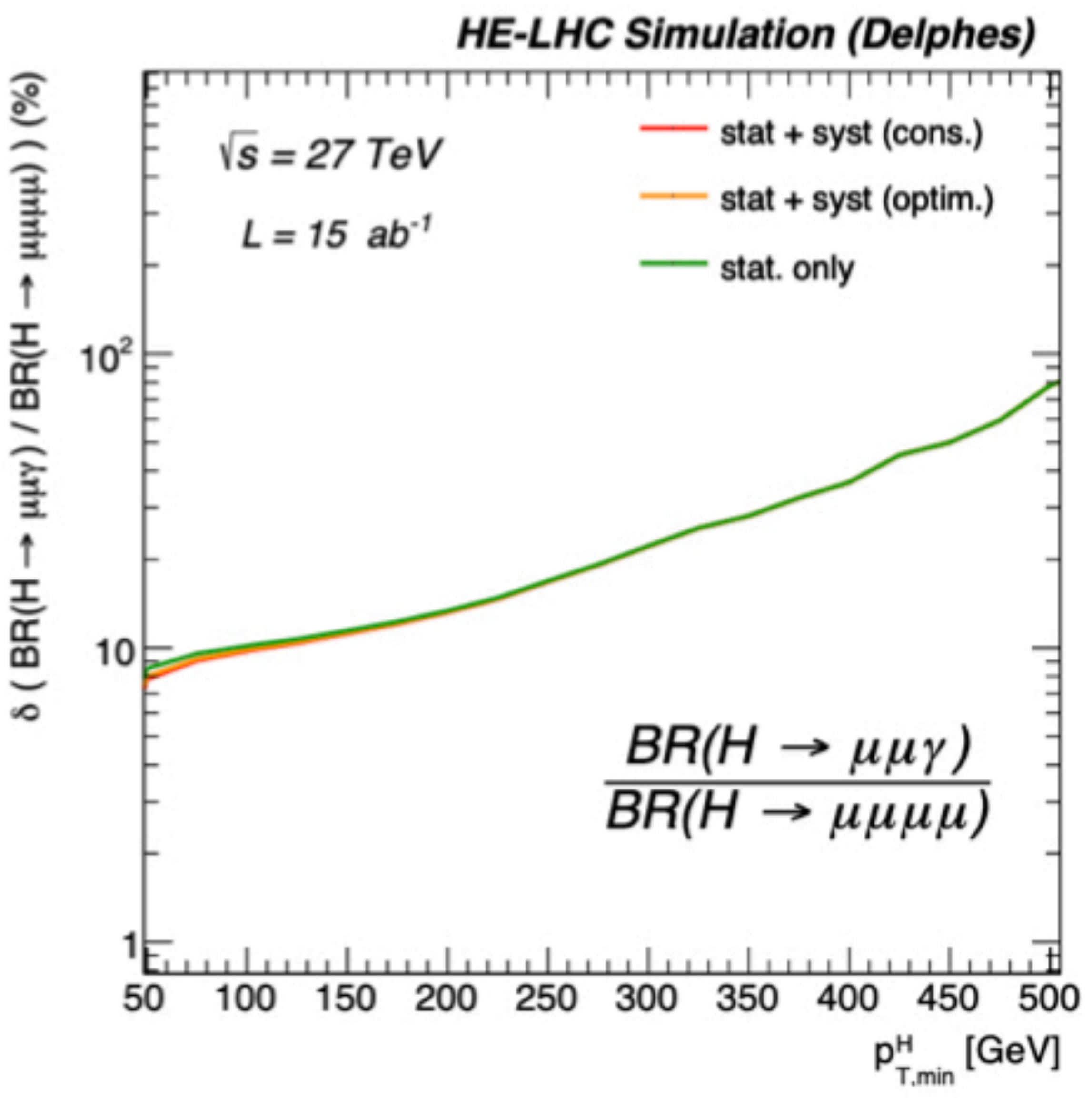
	gg→H	VBF	WH	ZH	$t\bar{t}$H	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390
N_{27}	2.2×10^9	1.8×10^8	5.1×10^7	3.7×10^7	4.4×10^7	2.1×10^6
N_{27}/N_{14}	16	15	11	12	24	19

- Loss of statistics at the level of 10-20 wrt 100 TeV
- Lack of absolute normalization of Higgs couplings to HZZ and ttH in absence of ee input

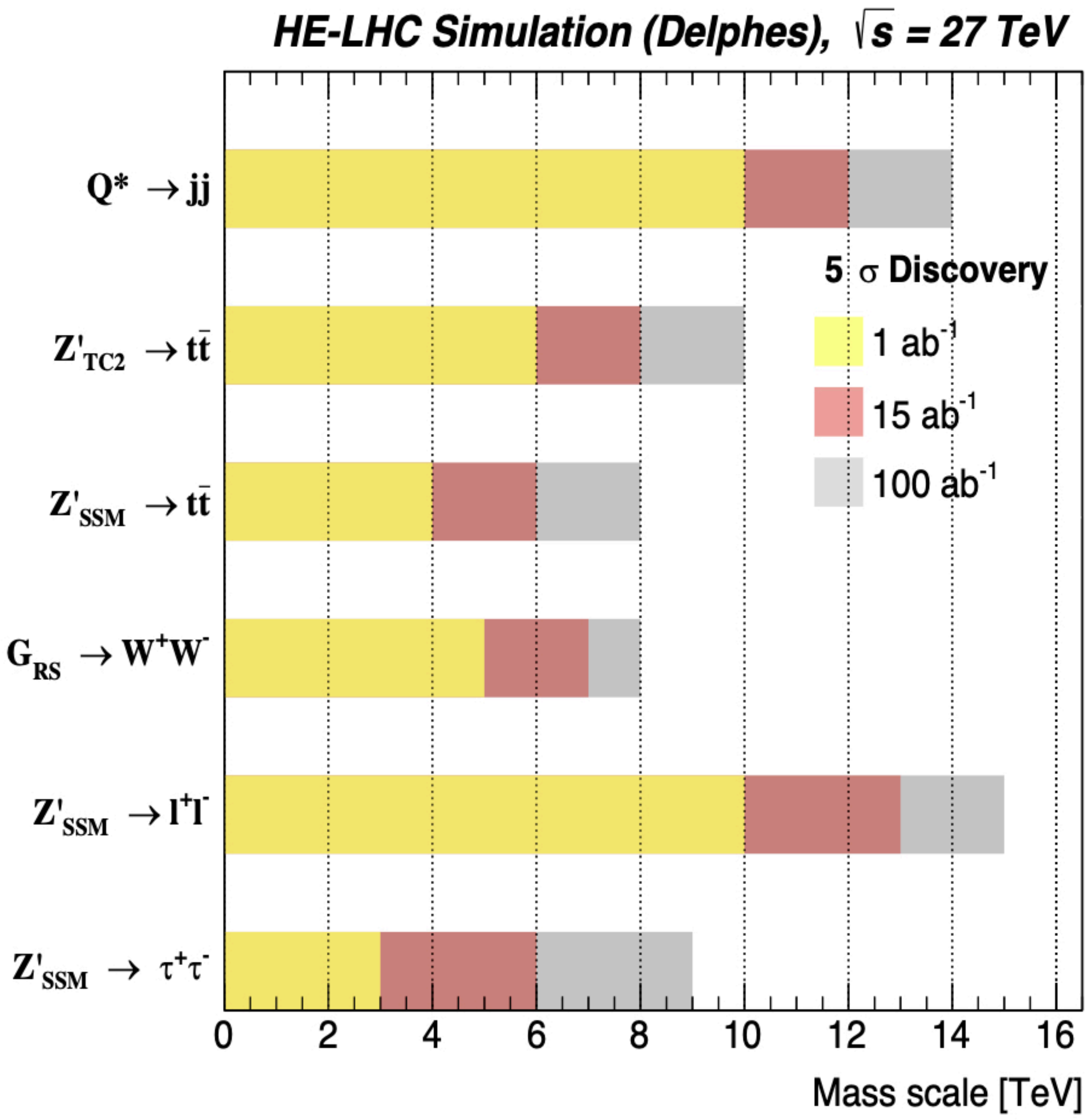








High-mass reach



WIMP DM reach

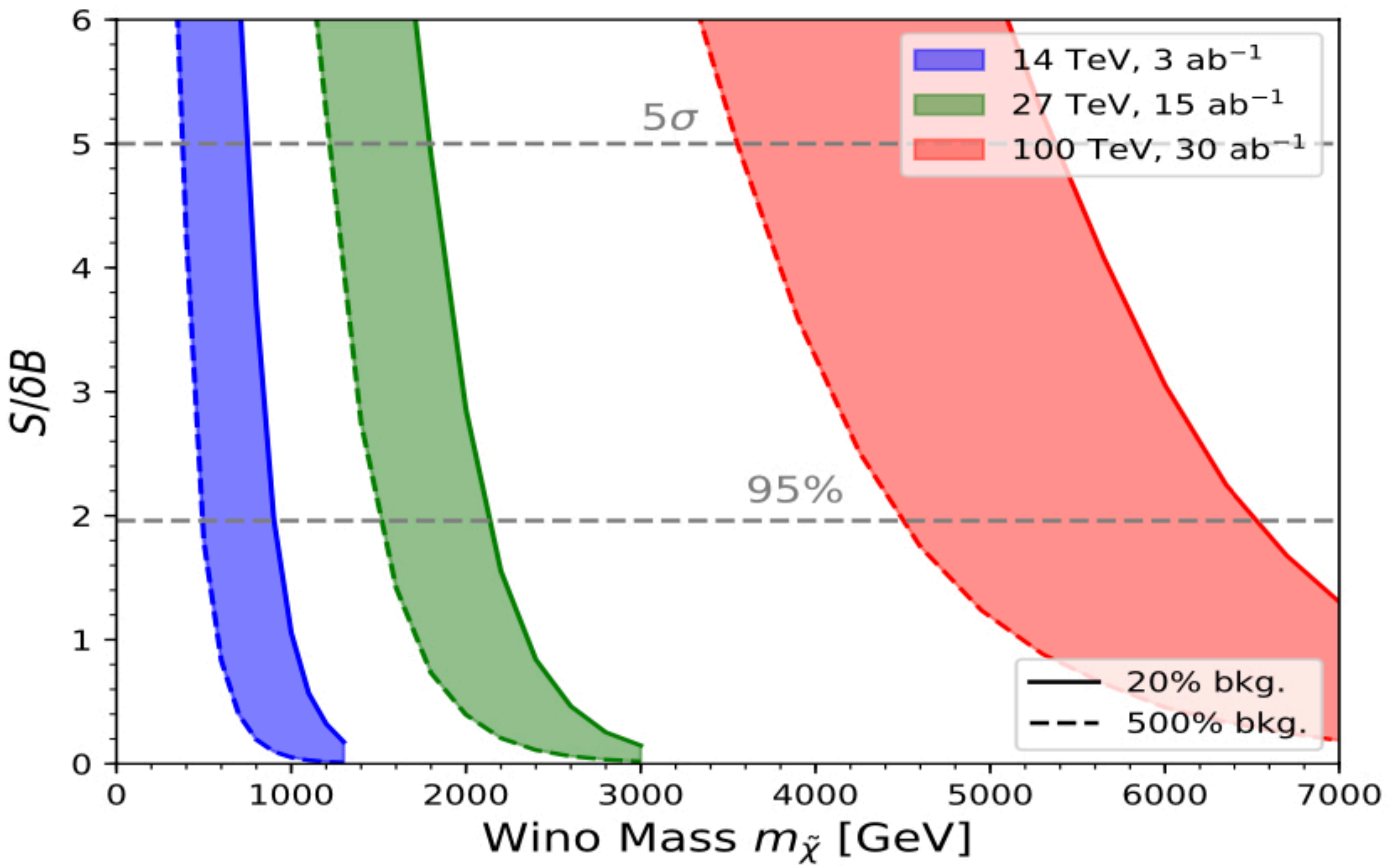
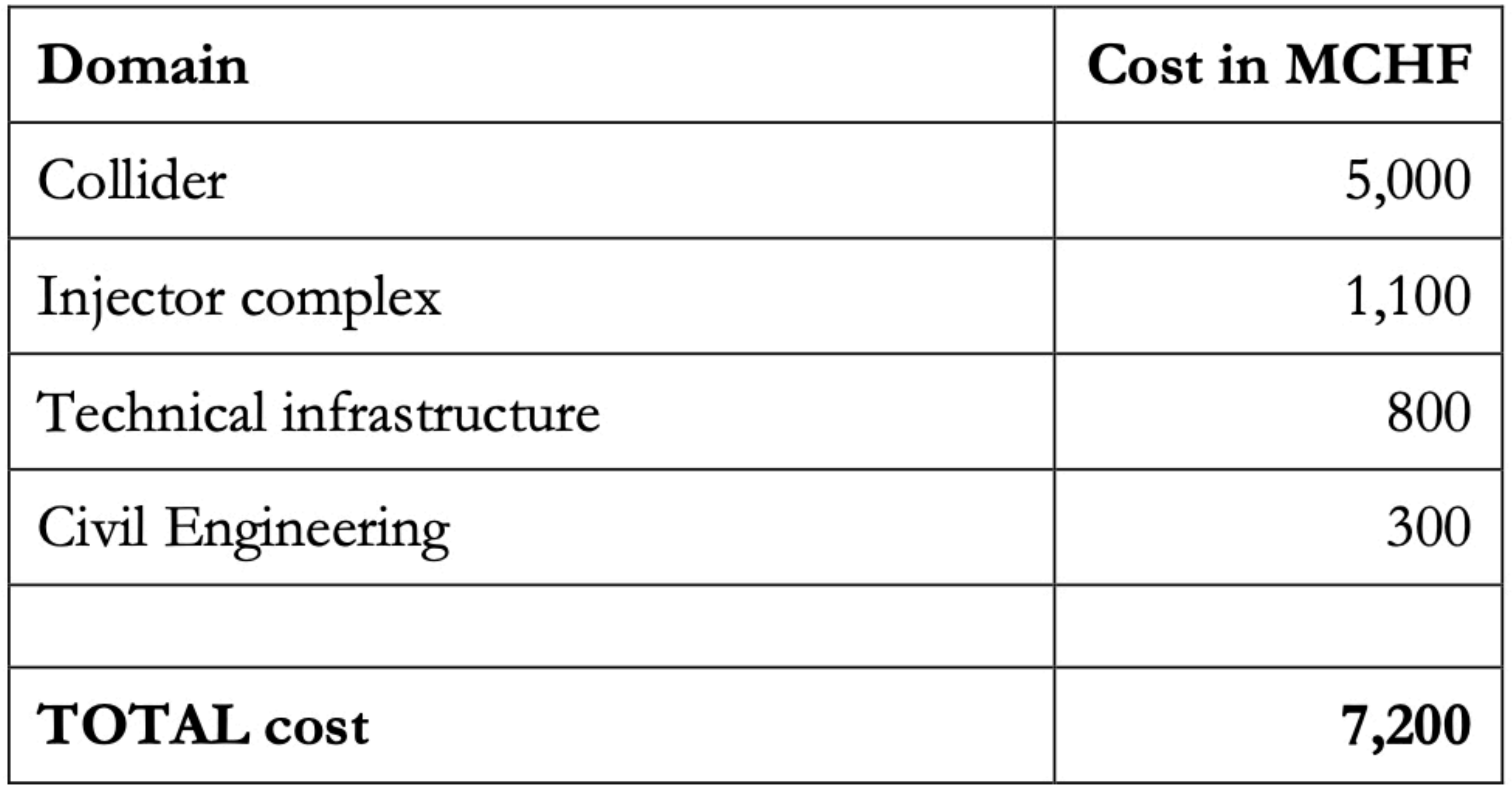


Figure 3: Sensitivity reach for wino-like DM WIMP candidates.

=> loss of yes/no answer to WIMP DM scenarios

2018 costs as documented in the FCC CDR

HE-LHC

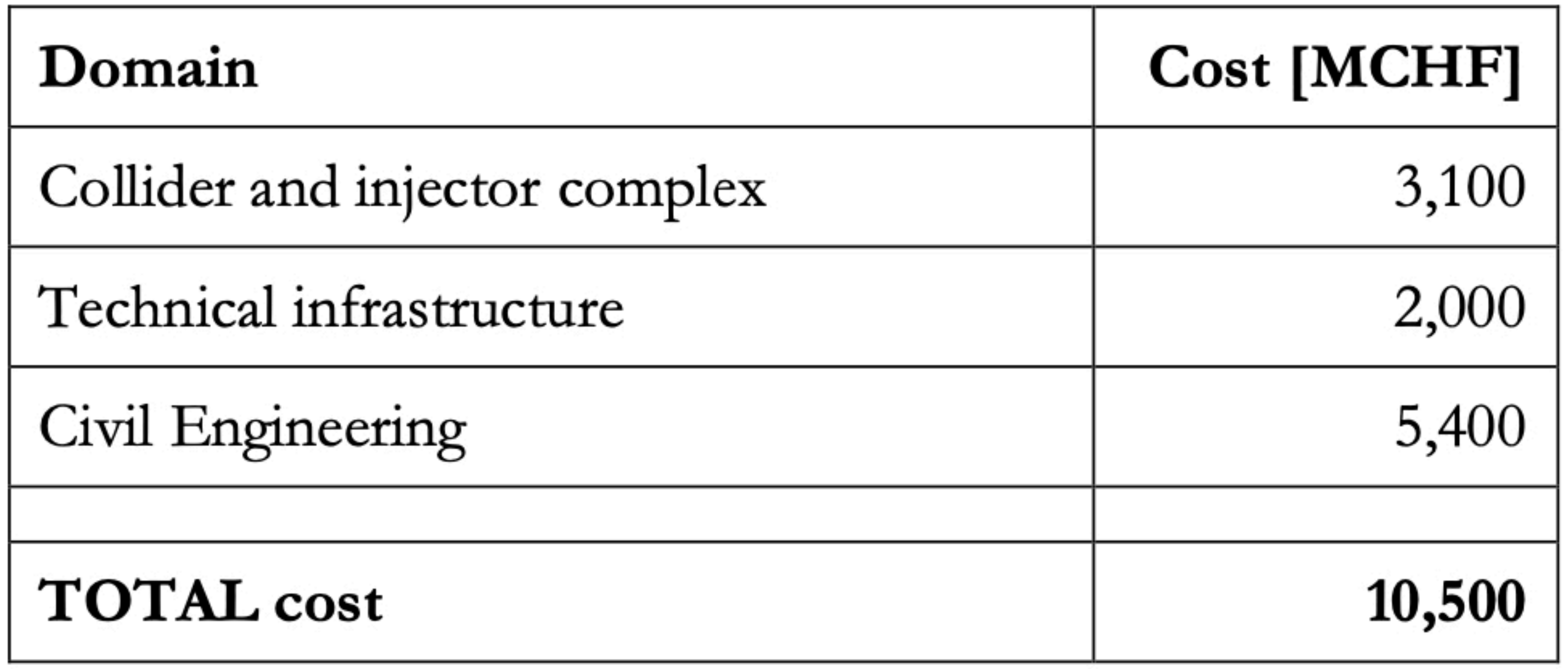


Domain	Cost in MCHF
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil Engineering	300
TOTAL cost	**7,200**

assumes 2.3 MCHF/dipole ~2.9 BCHF
(cfr ~ 1 MCHF/ LHC dipole)

includes SC SPS

FCC-ee



Domain	Cost [MCHF]
Collider and injector complex	3,100
Technical infrastructure	2,000
Civil Engineering	5,400
TOTAL cost	**10,500**

NB: FCC-ee new estimate (2024) ~13B.
No update available for HE-LHC

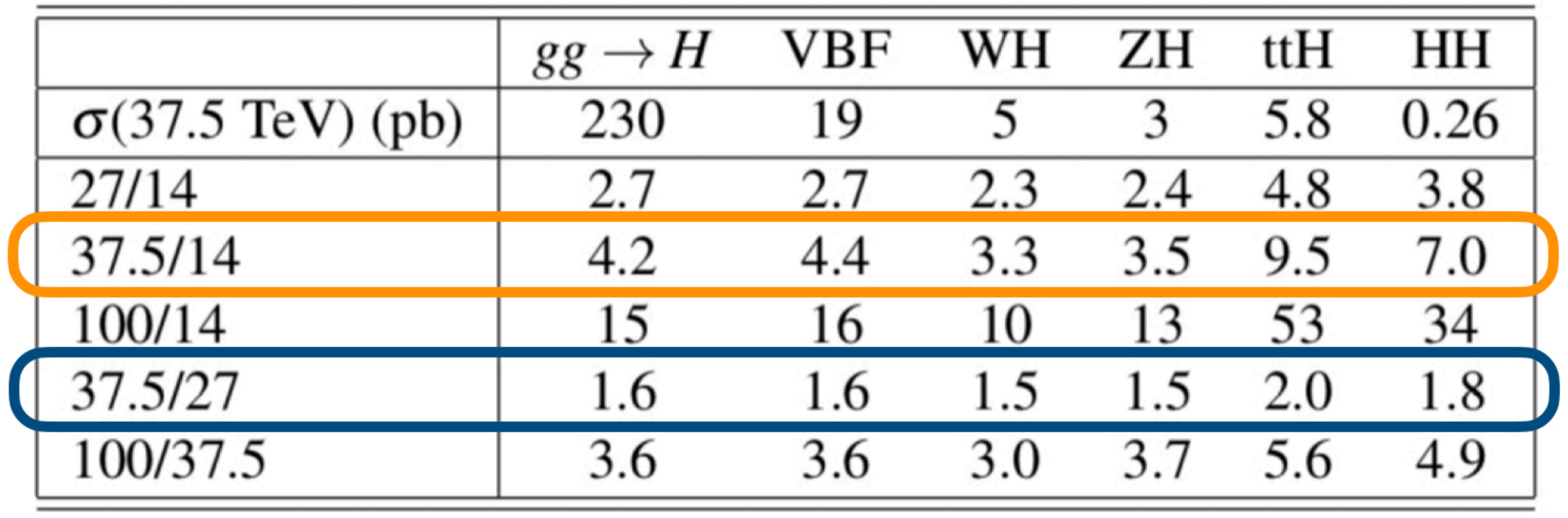
NB: If no 90km tunnel built, HE-LHC to be compared with LEP3 for prioritization: a different talk…

The low-E FCC "plan-B" option,

for a fast-track "*cheaper*" FCC-hh

(results for LHC dipoles in a 100km tunnel => 37.5 TeV)

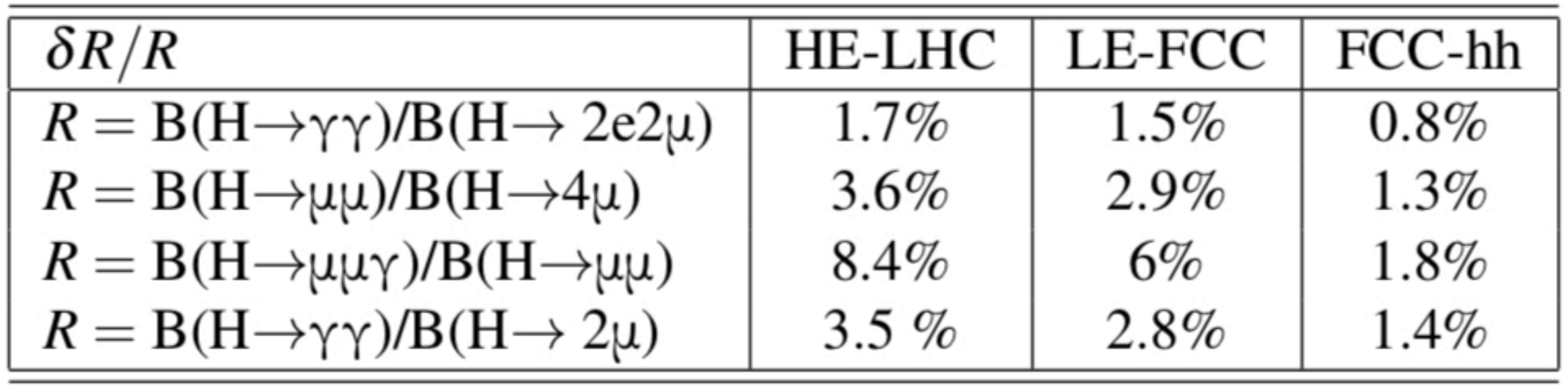
Low-E FCC-hh physics reach



	$gg \to H$	VBF	WH	ZH	ttH	HH
σ(37.5 TeV) (pb)	230	19	5	3	5.8	0.26
27/14	2.7	2.7	2.3	2.4	4.8	3.8
37.5/14	4.2	4.4	3.3	3.5	9.5	7.0
100/14	15	16	10	13	53	34
37.5/27	1.6	1.6	1.5	1.5	2.0	1.8
100/37.5	3.6	3.6	3.0	3.7	5.6	4.9

4-10 x LHC

50% - 2 x HE-LHC



$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	1.7%	1.5%	0.8%
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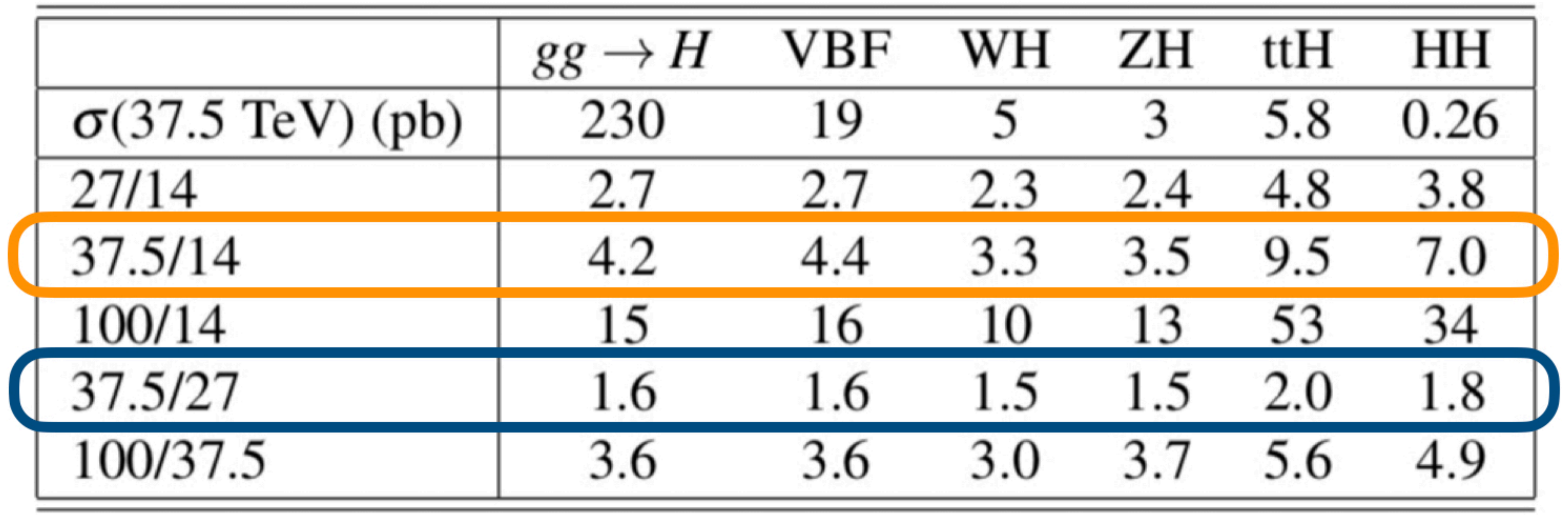
- **Minor improvement HE-LHC => LE-FCC**
- **In the region above pt~100 GeV, LE-FCC stat limited for rare decays, while FCC is still syst-dominated** ***(=> room for improvement of asymptotic precision)***

Low-E FCC-hh physics reach



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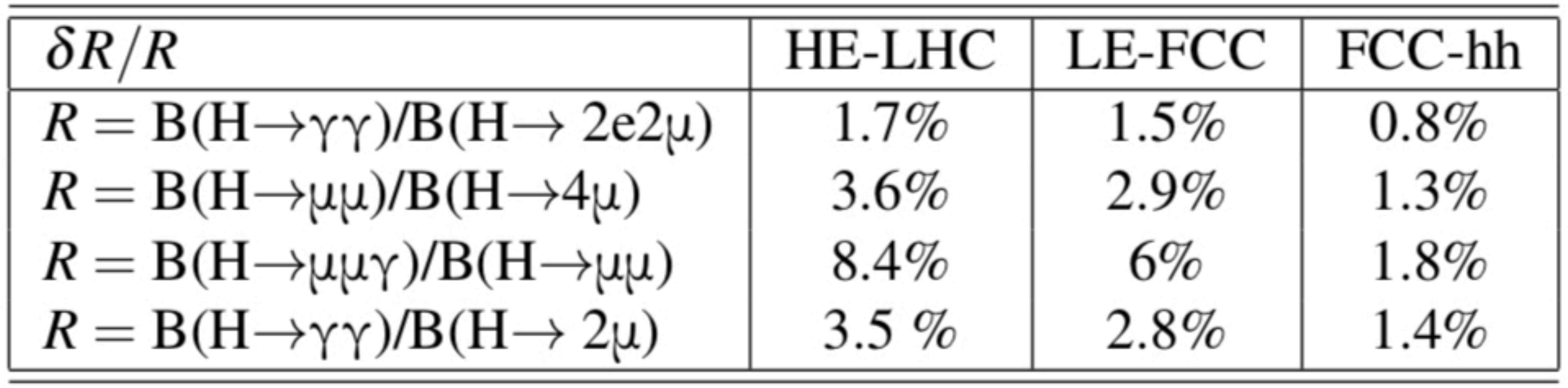

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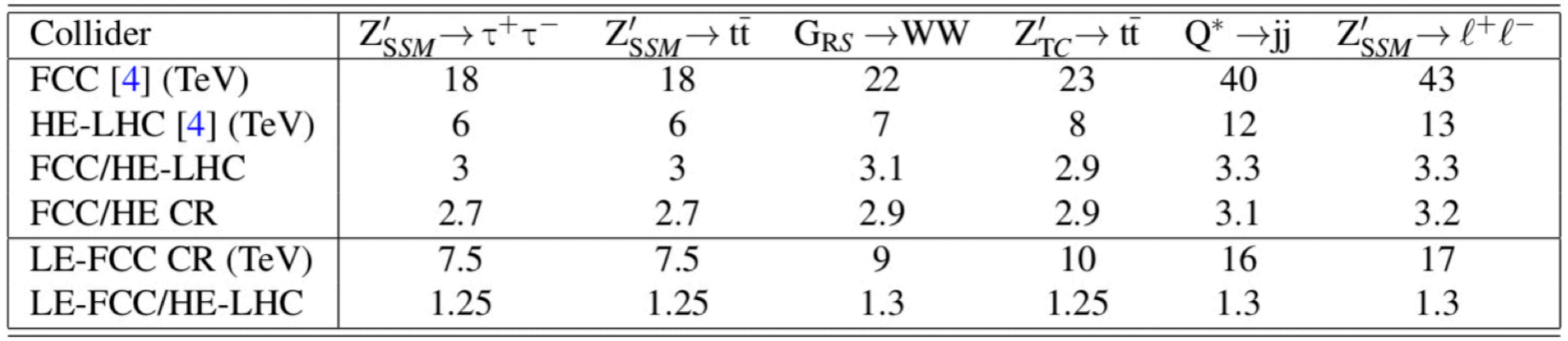
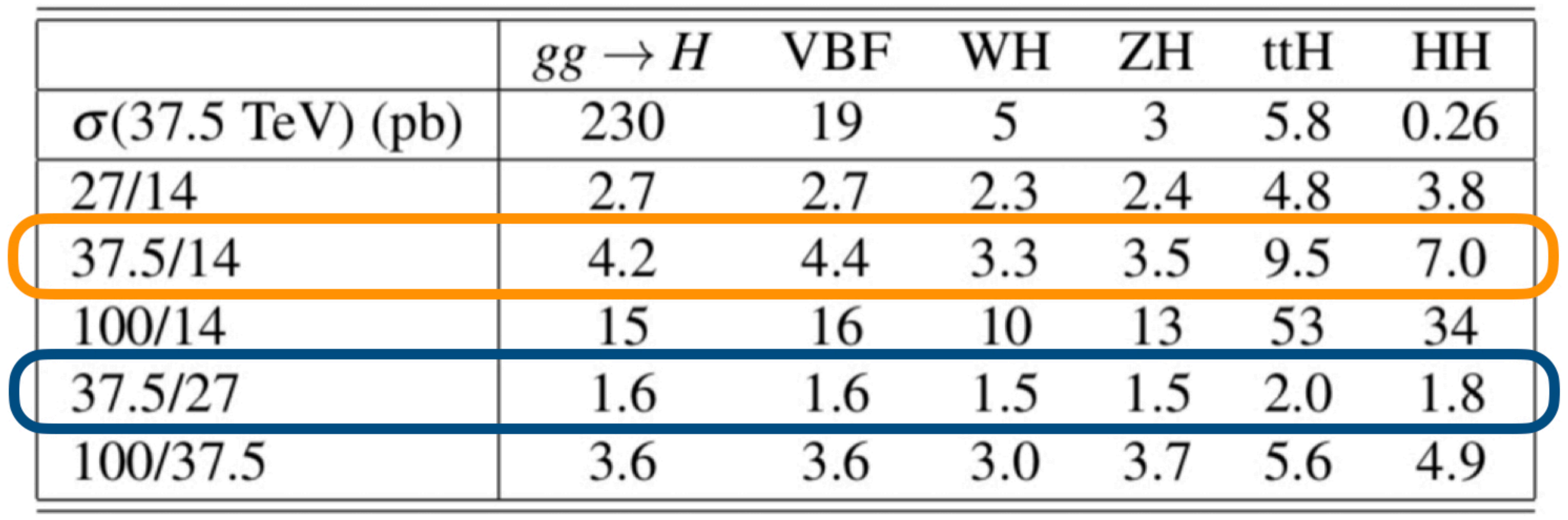
Example: s-channel resonances



Collider	$Z'_{SSM}\to\tau^+\tau^-$	$Z'_{SSM}\to t\bar{t}$	$G_{RS}\to WW$	$Z'_{TC}\to t\bar{t}$	$Q^*\to jj$	$Z'_{SSM}\to \ell^+\ell^-$
FCC [4] (TeV)	18	18	22	23	40	43
HE-LHC [4] (TeV)	6	6	7	8	12	13
FCC/HE-LHC	3	3	3.1	2.9	3.3	3.3
FCC/HE CR	2.7	2.7	2.9	2.9	3.1	3.2
LE-FCC CR (TeV)	7.5	7.5	9	10	16	17
LE-FCC/HE-LHC	1.25	1.25	1.3	1.25	1.3	1.3

- **M_{max}(37.5) ~ 0.35 M_{max}(100)**
- **M_{max}(37.5) ~ 1.25 M_{max}(27)**

Low-E FCC-hh physics reach



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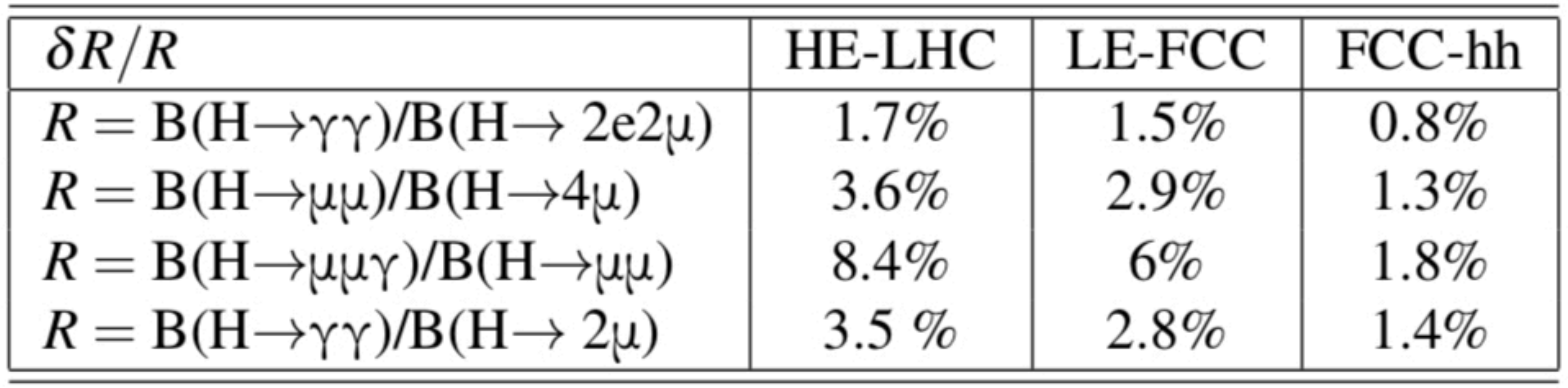

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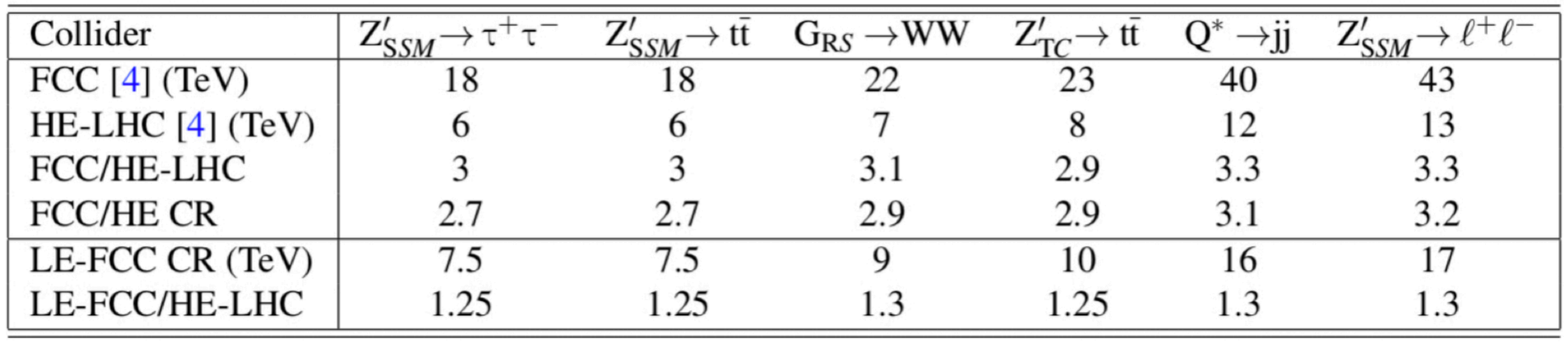

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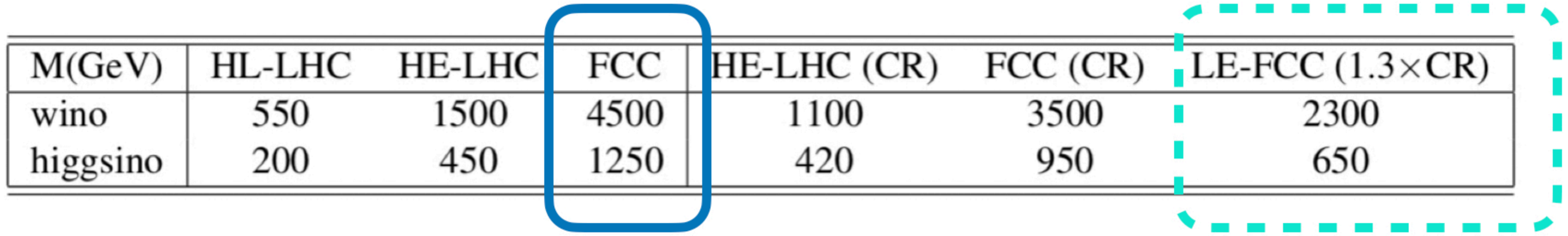
- **$M_{max}(37.5) \sim 0.35\ M_{max}(100)$**
- **$M_{max}(37.5) \sim 1.25\ M_{max}(27)$**

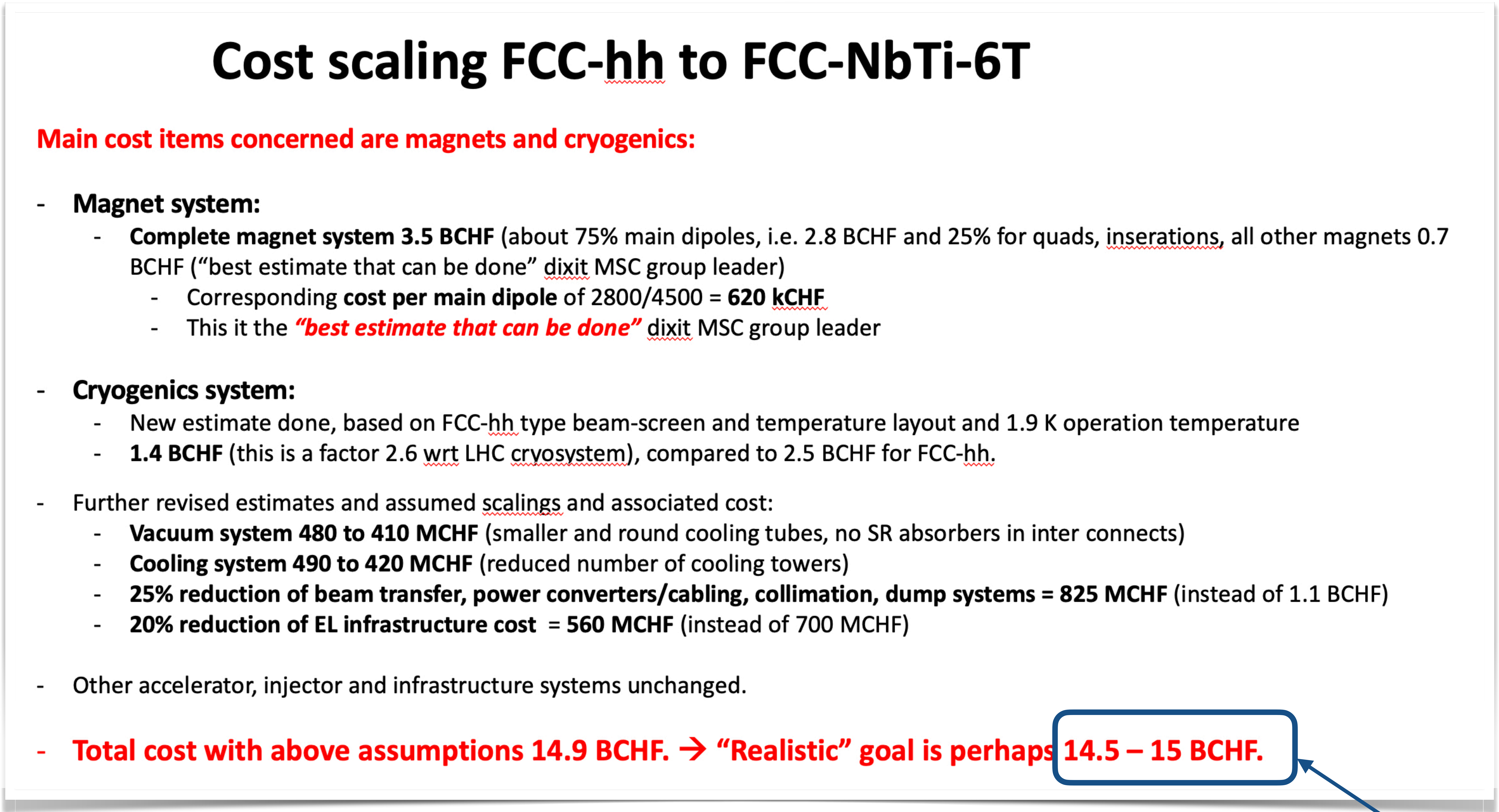
Table 3. 5σ discovery reach for WIMP DM particles at HL-LHC, HE-LHC and FCC-hh [7]. Columns 4 and 5 present the CR extrapolations from HL-LHC to HE-LHC, and from HE-LHC to FCC, respectively. Column 6 gives the extrapolation from HE-LHC to LE-FCC, augmented by a factor 1.3, as discussed in the text.



M(GeV)	HL-LHC	HE-LHC	FCC	HE-LHC (CR)	FCC (CR)	LE-FCC (1.3×CR)
wino	550	1500	4500	1100	3500	2300
higgsino	200	450	1250	420	950	650

LE-FCC comes short of the upper mass limits for a wino (higgsino) WIMP, namely 3 TeV (1 TeV)

from M. Benedikt (2019 cost projection, tunnel construction excluded)



Cost scaling FCC-hh to FCC-NbTi-6T

Main cost items concerned are magnets and cryogenics:

- **Magnet system:**
  - **Complete magnet system 3.5 BCHF** (about 75% main dipoles, i.e. 2.8 BCHF and 25% for quads, inserations, all other magnets 0.7 BCHF ("best estimate that can be done" dixit MSC group leader)
    - Corresponding **cost per main dipole** of 2800/4500 = **620 kCHF**
    - This it the ***"best estimate that can be done"*** dixit MSC group leader

- **Cryogenics system:**
  - New estimate done, based on FCC-hh type beam-screen and temperature layout and 1.9 K operation temperature
  - **1.4 BCHF** (this is a factor 2.6 wrt LHC cryosystem), compared to 2.5 BCHF for FCC-hh.

- Further revised estimates and assumed scalings and associated cost:
  - **Vacuum system 480 to 410 MCHF** (smaller and round cooling tubes, no SR absorbers in inter connects)
  - **Cooling system 490 to 420 MCHF** (reduced number of cooling towers)
  - **25% reduction of beam transfer, power converters/cabling, collimation, dump systems = 825 MCHF** (instead of 1.1 BCHF)
  - **20% reduction of EL infrastructure cost = 560 MCHF** (instead of 700 MCHF)

- Other accelerator, injector and infrastructure systems unchanged.

- **Total cost with above assumptions 14.9 BCHF. → "Realistic" goal is perhaps 14.5 – 15 BCHF.**

cfr 2018 cost of FCC-hh after FCC-ee is built: 17 B CHF

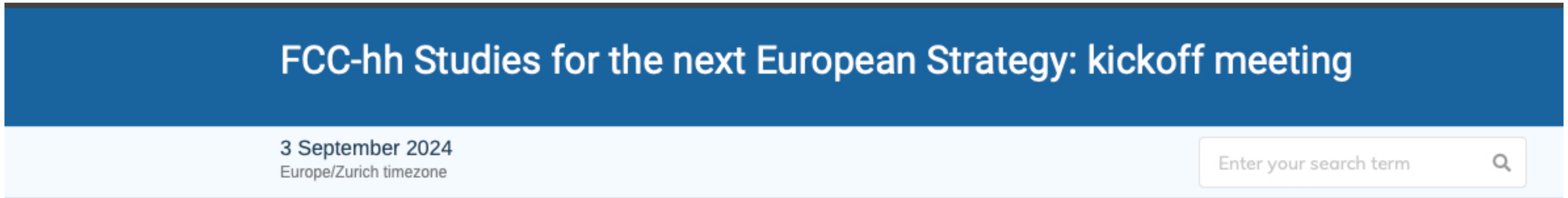

FCC-hh Studies for the next European Strategy: kickoff meeting

3 September 2024
Europe/Zurich timezone

M.L. Mangano, C. Grojean, M. McCullough, M. Selvaggi

https://indico.cern.ch/event/1439072/

Goals and scope of this effort



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  - **update reach for key processes (eg Higgs measurements)**
  - **focus on interplay between FCC-ee and FCC-hh in finding and deciphering signals of new physics** (FCC-hh potential to discover the microscopic origin of SM deviations observed in precision measurements at FCC-ee)**, mapping the FCC-hh discovery potential beyond the sensitivity of FCC-ee** (room for further discovery at FCC-hh following FCC-ee)
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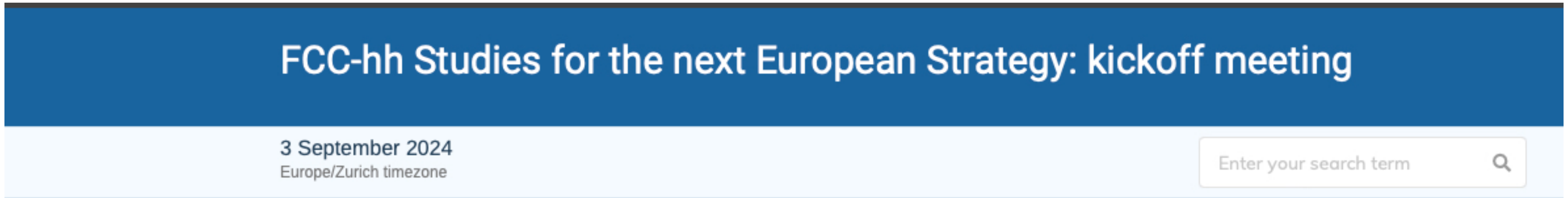
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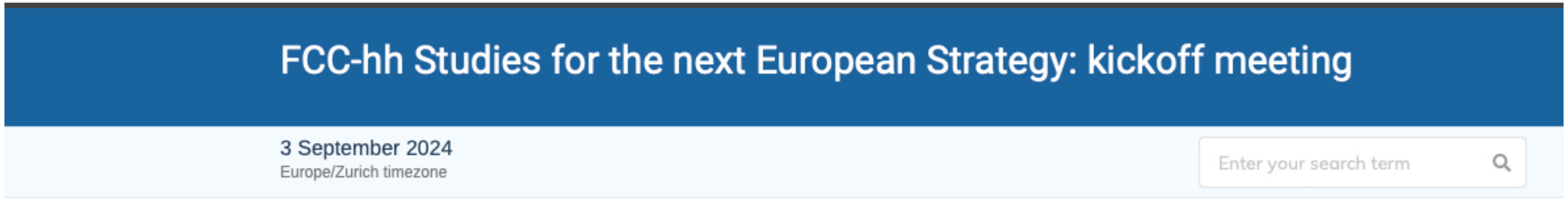
  - **review detector performance assumptions, and discuss opportunities for dedicated expts**

- **Assess the impact of the energy/luminosity scenarios introduced by the new FCC layout and by magnet technology options**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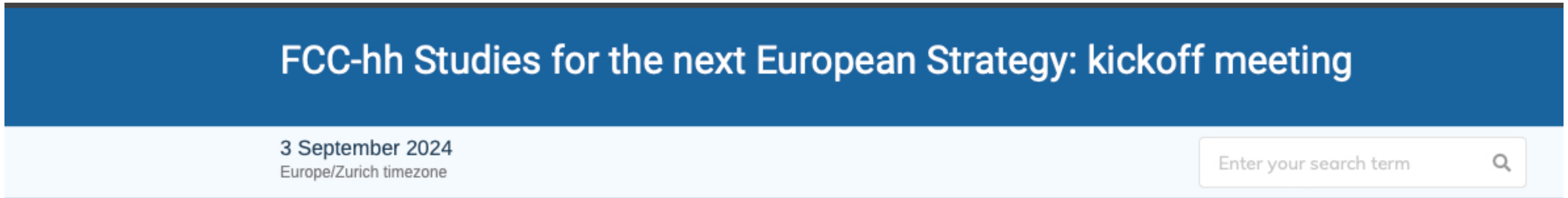
  - **focus on interplay between FCC-ee and FCC-hh in finding and deciphering signals of new physics** (FCC-hh potential to discover the microscopic origin of SM deviations observed in precision measurements at FCC-ee)**, mapping the FCC-hh discovery potential beyond the sensitivity of FCC-ee** (room for further discovery at FCC-hh following FCC-ee)
  - **review detector performance assumptions, and discuss opportunities for dedicated expts**

- **Assess the impact of the energy/luminosity scenarios introduced by the new FCC layout and by magnet technology options**

The context of this study is the baseline FCC project, with the start of FCC-ee operations by mid-40's, followed by FCC-hh after completion of the ee physics programme.


FCC-hh Studies for the next European Strategy: kickoff meeting

3 September 2024
Europe/Zurich timezone

M.L. Mangano, C. Grojean, M. McCullough, M. Selvaggi https://indico.cern.ch/event/1439072/

Goals and scope of this effort

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To join the mailing list dedicated to these studies and be kept informed about future meetings, register at http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=FCC-PED-hh-espp25