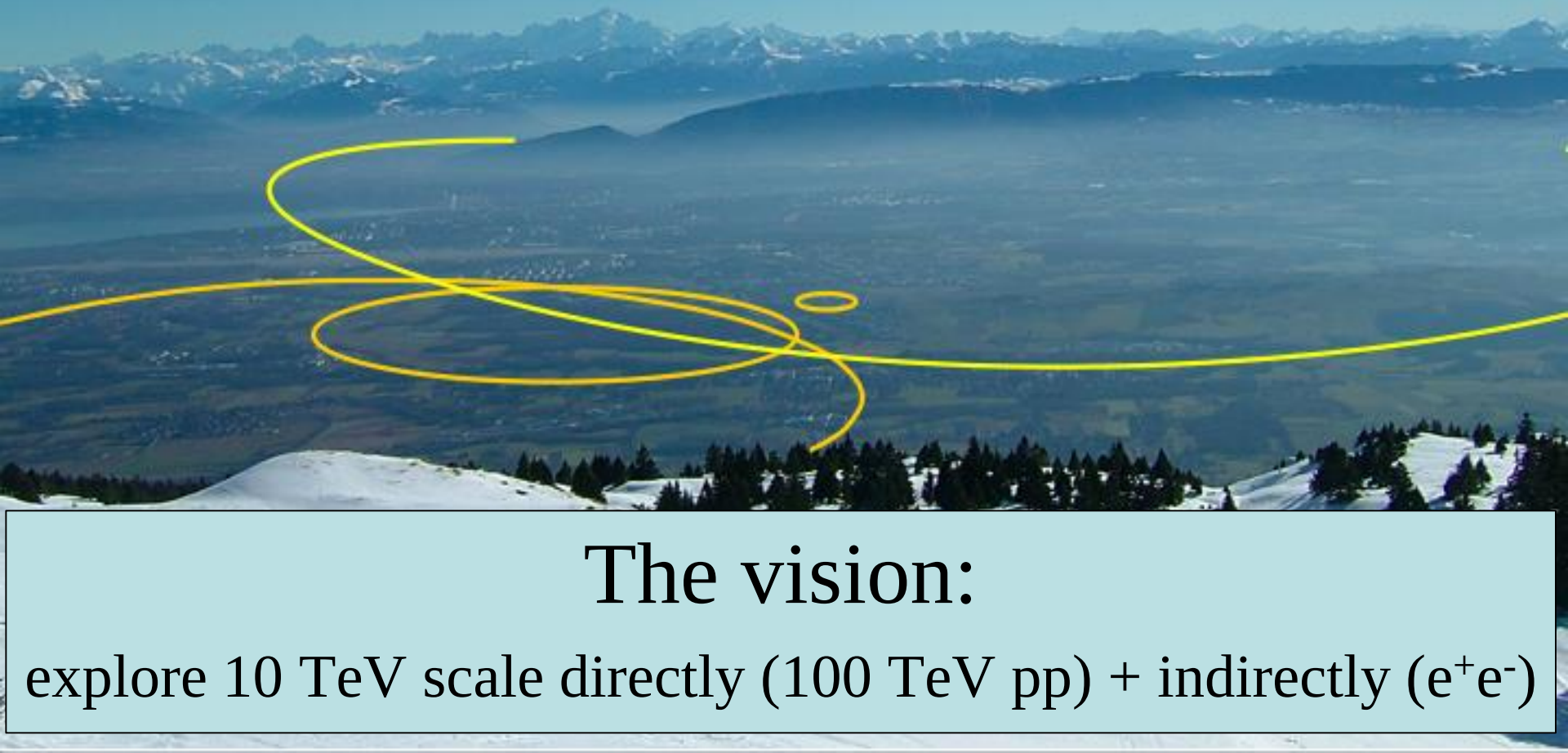
KING'S College LONDON

John Ellis

FCC hh ee he

Complementarity between FCC-ee and FCC-hh Searches for BSM Physics

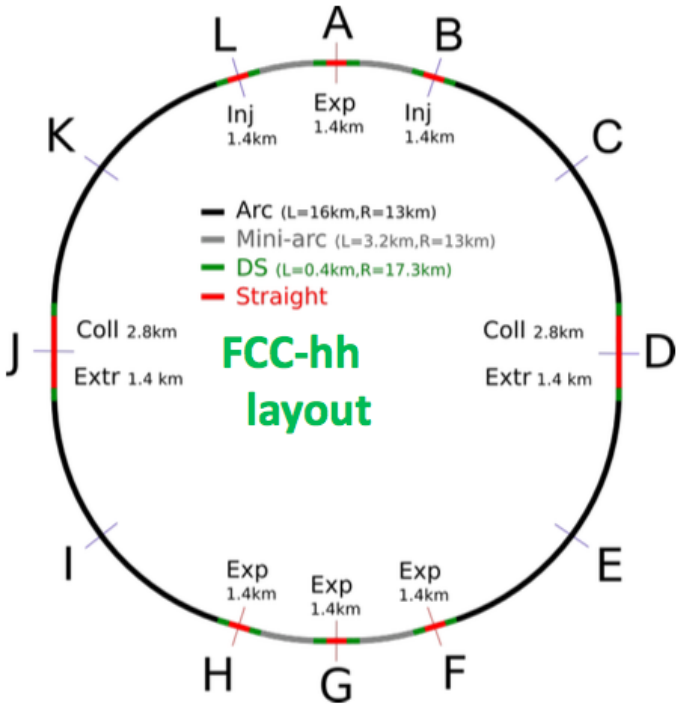


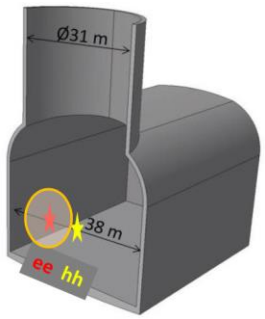
The vision:

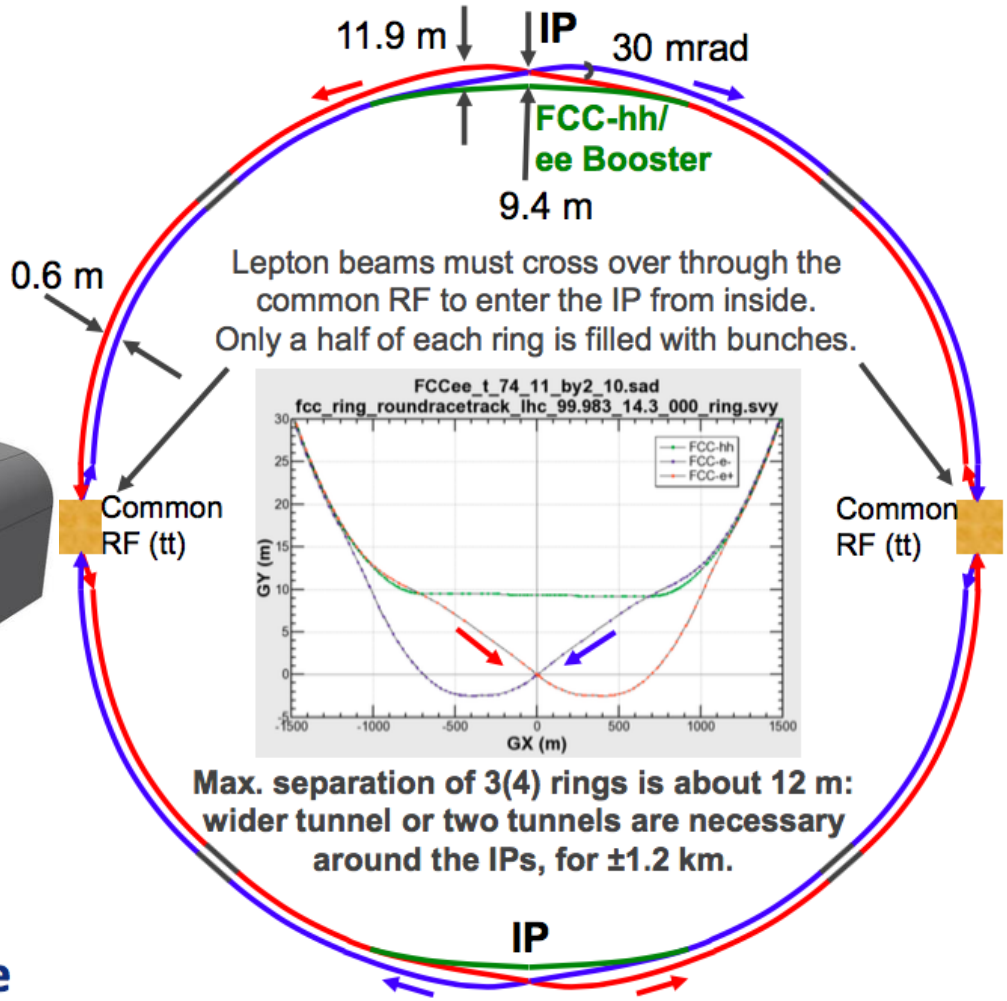
explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

Cohabitation/Serial Monogamy

FCC-hh







- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

FCC-ee Physics & Experiments Coordination

Physics Studies coordination
A. Blondel, P. Janot (EXP), C. Grojean, M. McCullough, J. Ellis (TH)

EW Physics with Z's and W's
R. Tenchini, F. Piccinini
S. Heinemeyer, A. Freitas

Higgs properties
M. Klute, K. Peters
S. Heinemeyer, A. Freitas

Top quark physics
P. Azzi (F. Blekman)
S. Heinemeyer, A. Freitas

Synergies with FCC-hh physics, LC studies, LEP legacy

QCD and γγ physics
D. d'Enterria
P. Skands

Flavours physics
S. Monteil
J. Kamenik

New physics
M. Pierini, C. Rogan
M. McCullough

Global Analysis Synergies
J. Ellis

Physics software
C. Bernet, B. Hegner,
C. Helsens

Synergy with FCC-hh, LC, LHC

Online selection & DAQ
C. Leonidopoulos
E. Perez

Polarization, √s measurments
A. Blondel
J. Wenninger

Joint with FCC-ee Accelerator

MDI, Exp'tal environment
M. Boscolo
N. Bacchetta

Adapt (to) the interaction region
Joint with FCC-ee Accelerator

Detector designs
A. Cattai, G. Rolandi,
M. Dam

Synergy with LC and CEPC
Set constraints on designs
to match statistical precision
Propose detector designs

The Objectives

- How do FCC-hh, FCC-ee and FCC-he complement each other? Cf, LEP and LHC
- What are the synergies between them?
  - And between them and other accelerators (LHC)?
- Requires inputs from specific FCC-xx analyses
- Broad subject: **just starting**
- Illustrate with specific physics examples
  - Higgs and precision electroweak
  - Supersymmetry

The Objectives

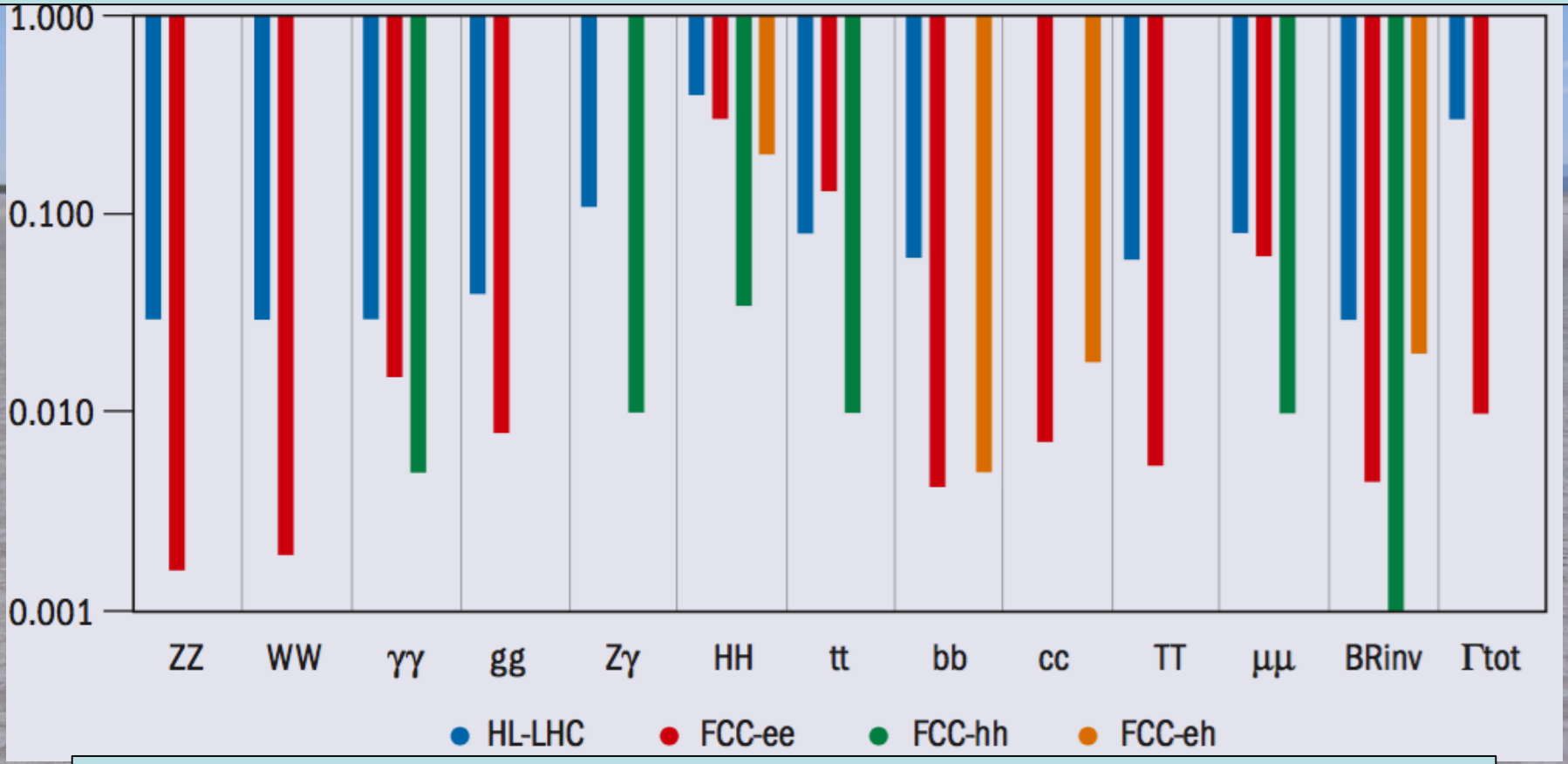
Subject		ee	hh	he
Higgs Physics	precision studies higher dimension operators composite Higgs rare and exotic decays multiple Higgs production extra Higgs bosons			
Interface with Cosmology	Dark matter baryogenesis right-handed/(almost) sterile neutrinos			
Electroweak Sym. Breaking	WW scattering supersymmetry extra dimensions composite models			
Flavour Changing	rare H,Z,W,top decays lepton flavor violation			
Extensions of the SM	extra vector-like fermions $SU(2)_R$ models leptoquarks			
QCD	Perturbation theory, structure functions Modelling final states			
EW/SM precision issues	precision measts (m_Z,m_W,m_t,α,$\alpha_s(m_Z)$,$\sin^2\theta_W$,R_b... higher-order EW corrections W,Z triple and quadruple couplings top (anomalous) couplings charm/bottom flavor studies			

TLEP (FCC-ee) study, arXiv:1308. 6176

Possible **FCC-ee** Precision Measurements

Observable	Measurement	Current precision	FCC stat.	Possible syst.	Challenge
m_Z (MeV)	Z peak ± 4 GeV for α_{EM}, line shape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)		2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l		20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b		0.21629 ± 0.00066	0.000003	< 0.00006	g → bb
N_ν		2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\alpha_s(m_Z)$		0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_W (MeV)	WW threshold	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν		2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$		B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	t tbar threshold	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)		?	12	?	$\alpha_s(m_Z)$
λ_{top}		μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

Possible Future Higgs Measurements



- Need to reduce theoretical uncertainties to match experimental errors
  - Needed for BSM interpretations

High precision at FCC-ee
Big statistics at FCC-hh

One way to look for BSM physics

Standard Model Effective Field Theory

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6:

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

- Operators constrained by SU(2) × U(1) symmetry:

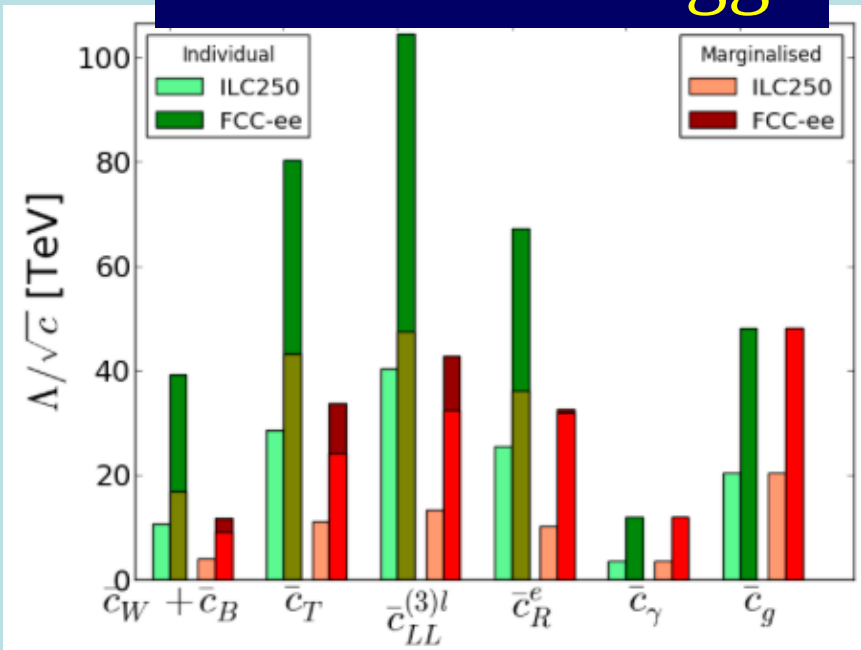
$$\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\,\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
& + \frac{2ig\,\bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k} D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\,\bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\
& + \frac{ig\,\bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\,\bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
& + \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\ \Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\ \Phi^\dagger\Phi\ \Phi\cdot\bar{L}_L\tau_R
\end{aligned}$$

- Constrain with precision EW, Higgs data, TGCs ...

JE & Tevong You, arXiv:1510.04561

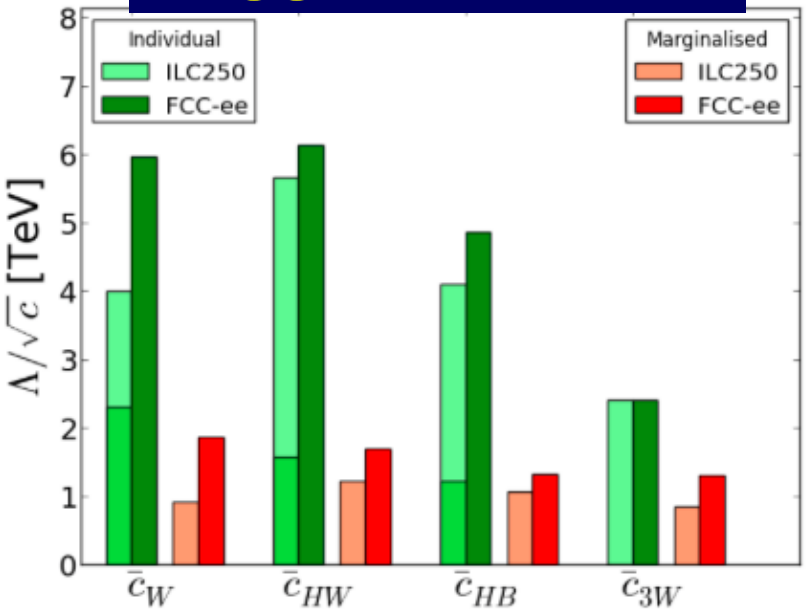
FCC-ee Higgs & TGC Measurements

EWPTs and Higgs



- Shadings:
  - With/without theoretical EWPT uncertainties

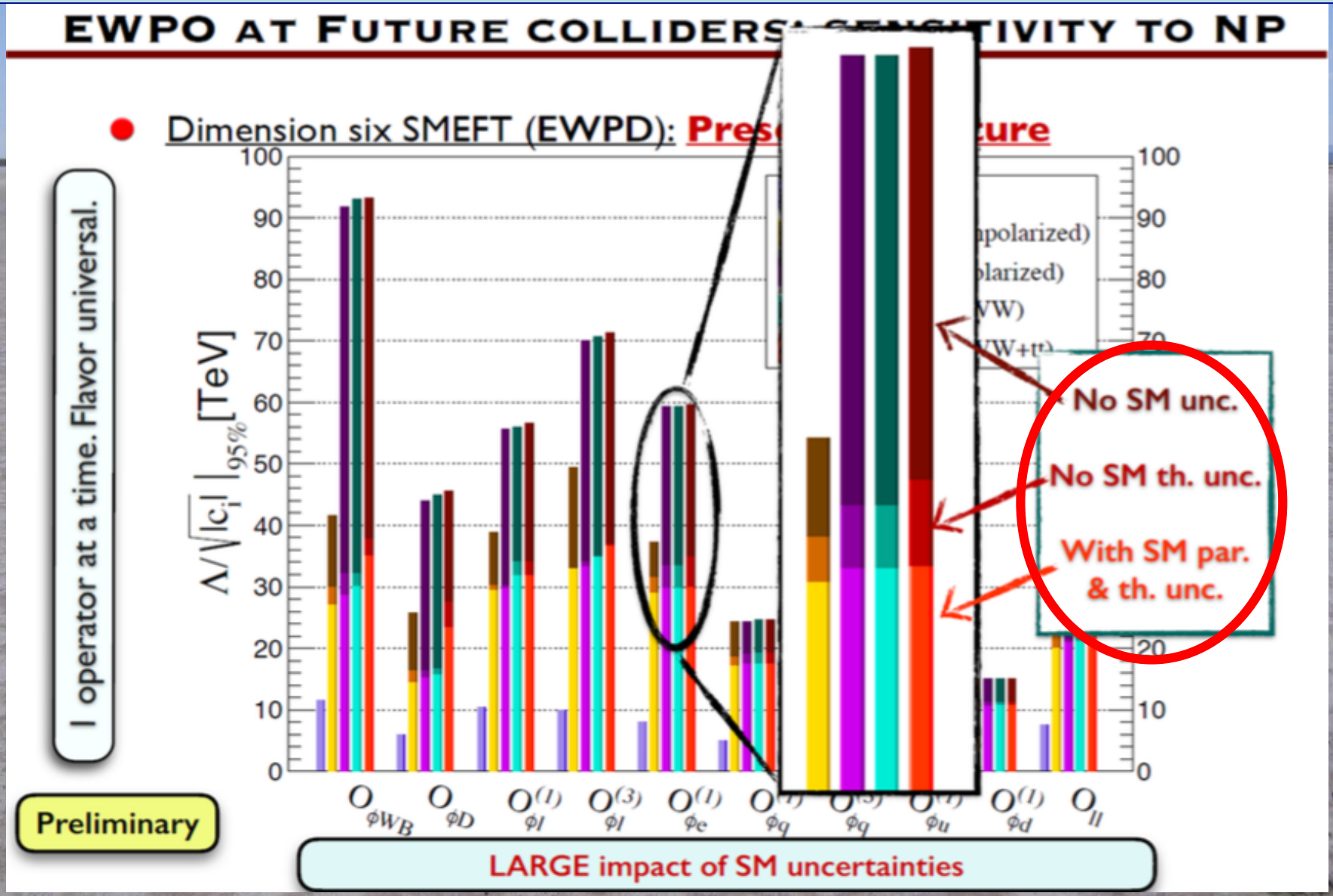
Higgs and TGCs



- Shadings of green:
  - Effect of including TGCs at ILC

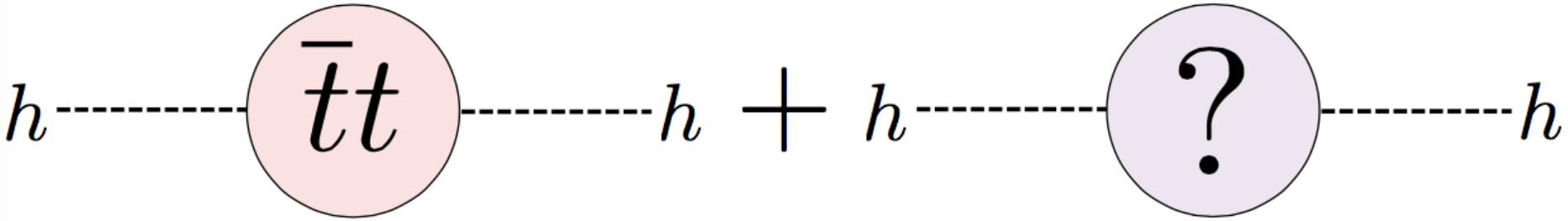
Should extend to include prospective FCC-hh measurements of TGCs, …

Important to Control TH and SM Uncertainties



What lies Beyond the Standard Model?

Could there be a hidden "Top Partner"?



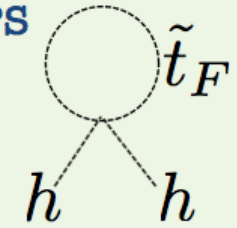
Much attention now to alternative ideas:

McCullough

Folded SUSY

hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners



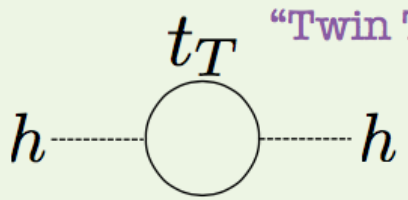
"Folded Stops"

...but they must be charged under new hidden QCD'.

Twin Higgs

hep-ph/0506256

Theory where top partners are SM gauge neutral fermions



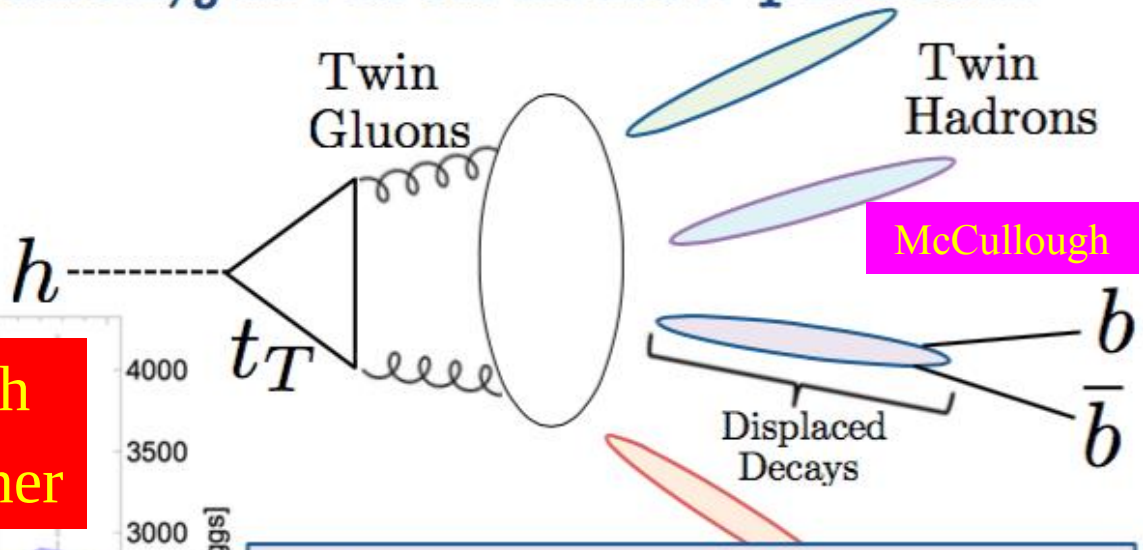
"Twin Tops"

...but they must be charged under new hidden QCD'.

Evil Twins of the Higgs?

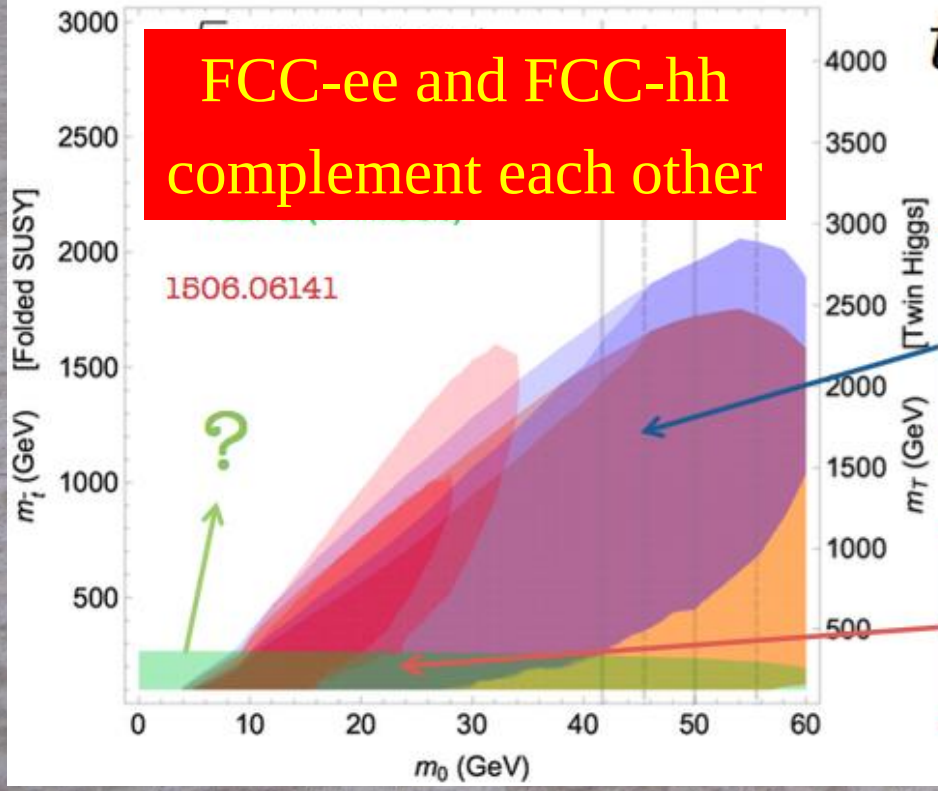
Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:



McCullough

FCC-ee and FCC-hh complement each other



FCC-hh can thoroughly probe larger Twin confinement scales through displaced searches.

FCC-ee has access for light top partners, including for well-motivated low confinement scales.

What lies beyond the Standard Model?

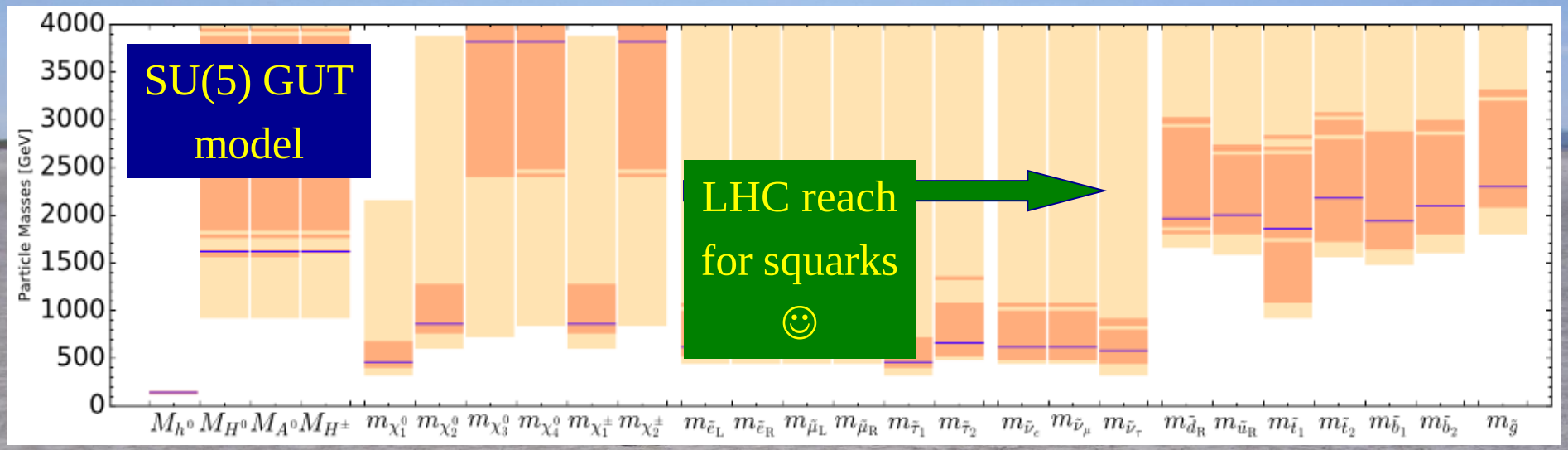
Supersymmetry

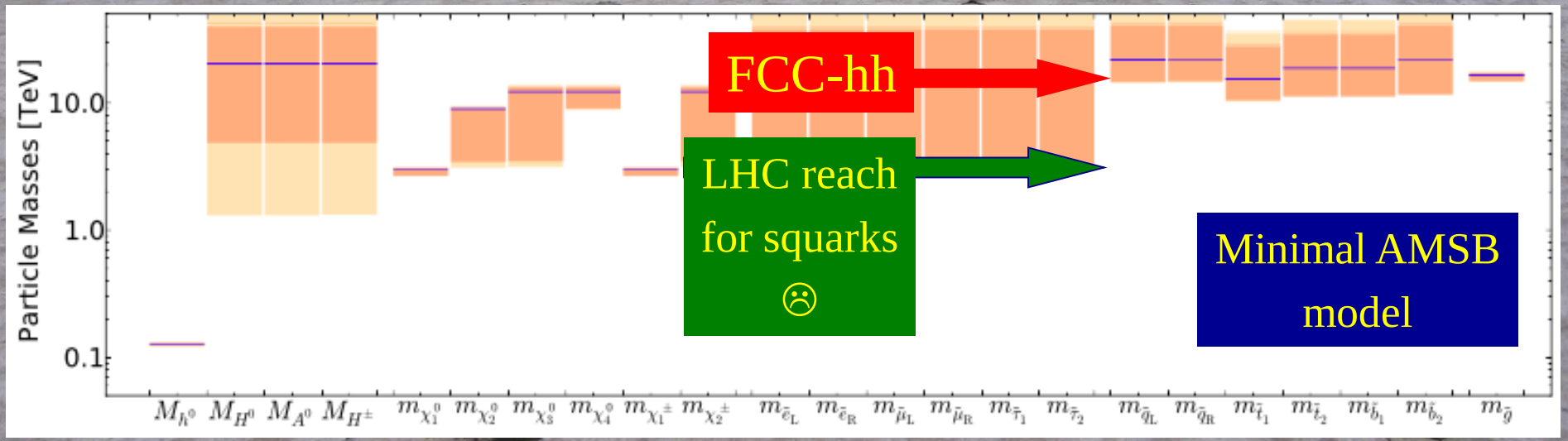
New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

Where May Supersymmetry be Hiding?

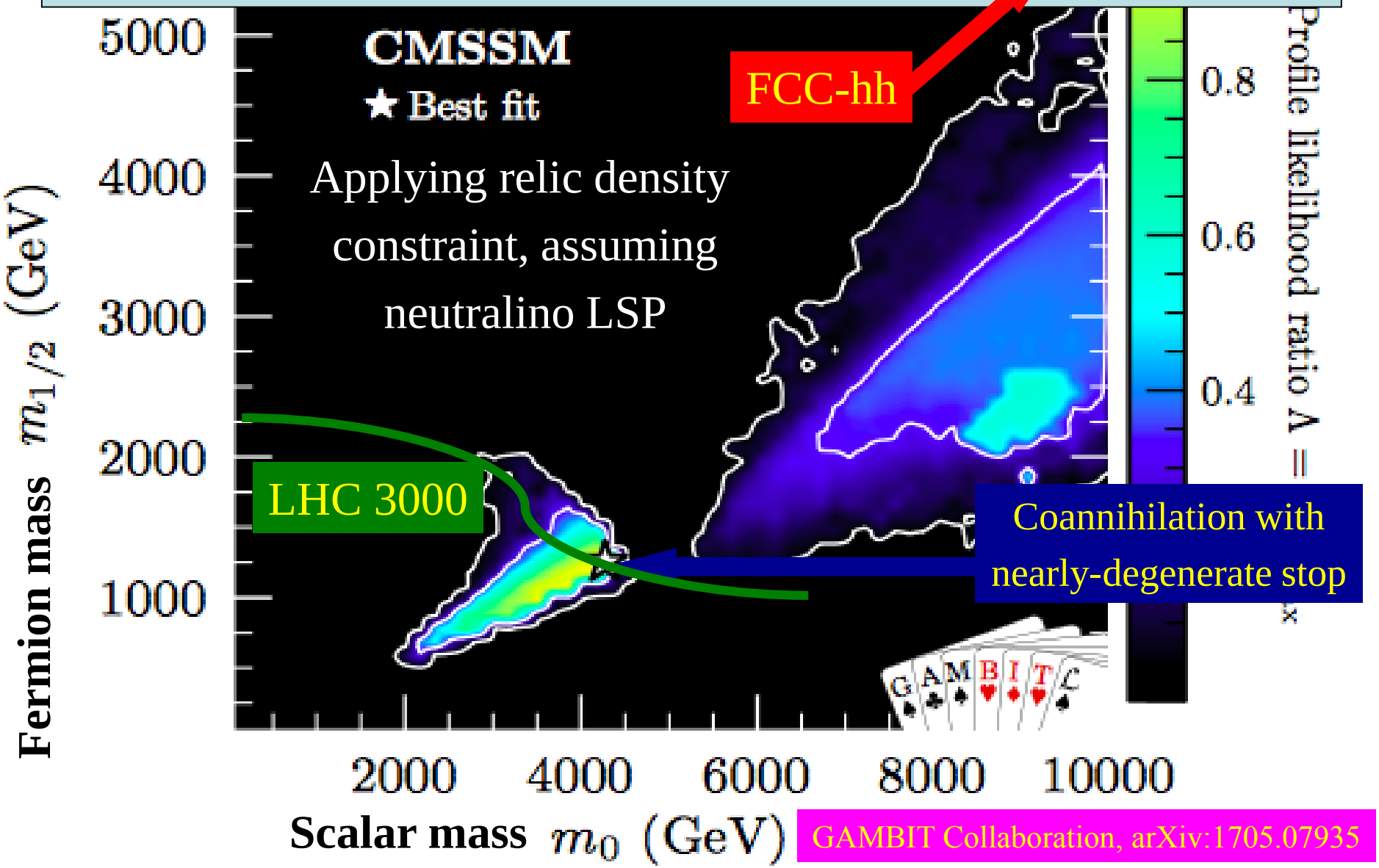
FCC-hh





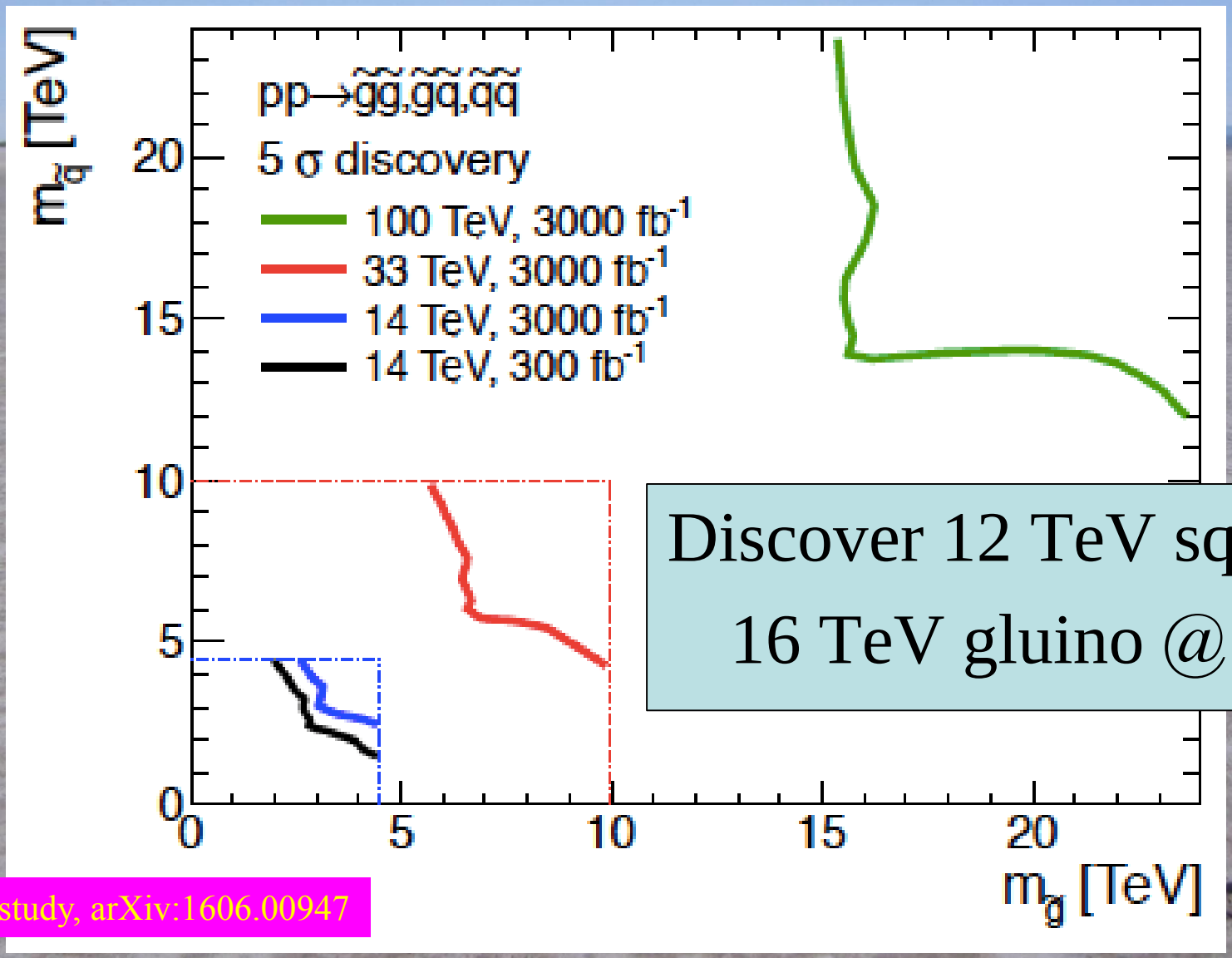
MasterCode Collaboration, arXiv:1610.10084, 1612.05210

Where May Supersymmetry be Hiding?



GAMBIT Collaboration, arXiv:1705.07935

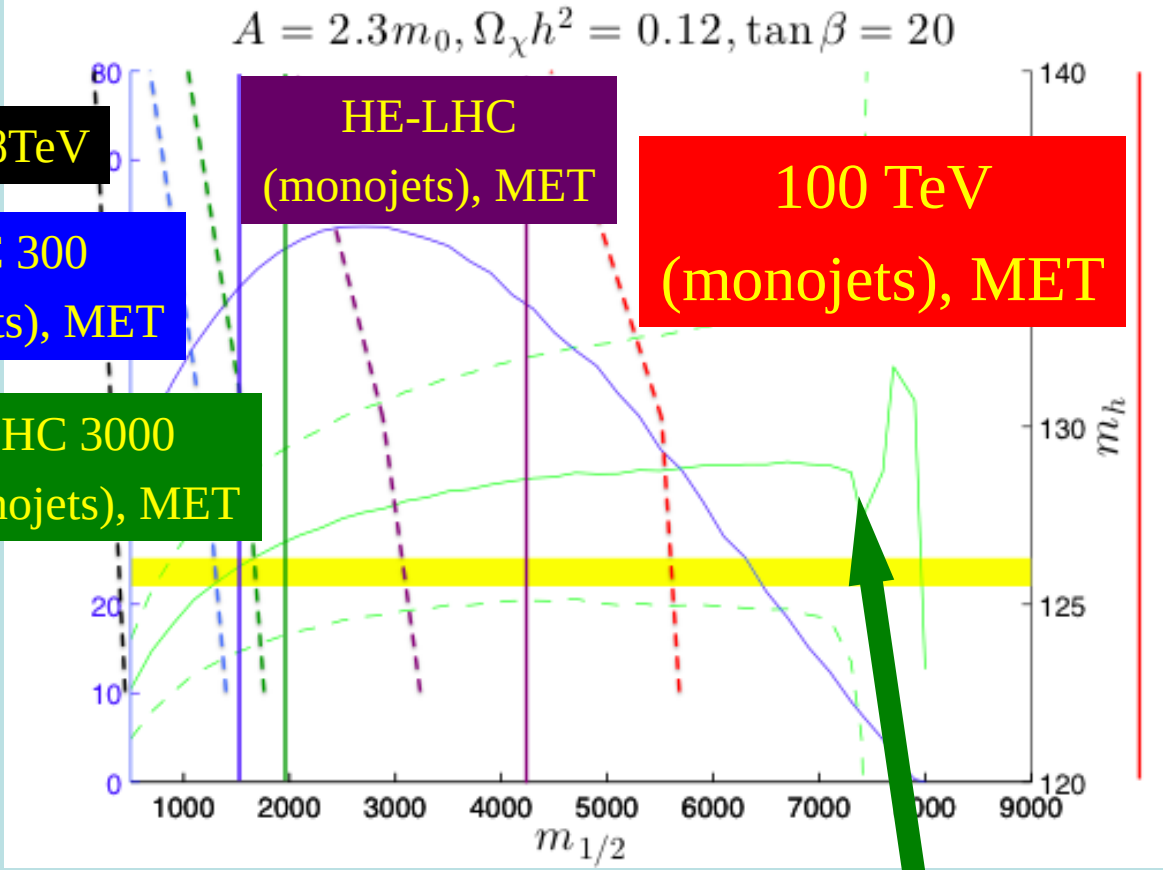
FCC-hh Reach in Squark-Gluino Plane



Discover 12 TeV squark,
16 TeV gluino @ 5σ

FCC-hh study, arXiv:1606.00947

Exploring the **Stop Coannihilation Strip**



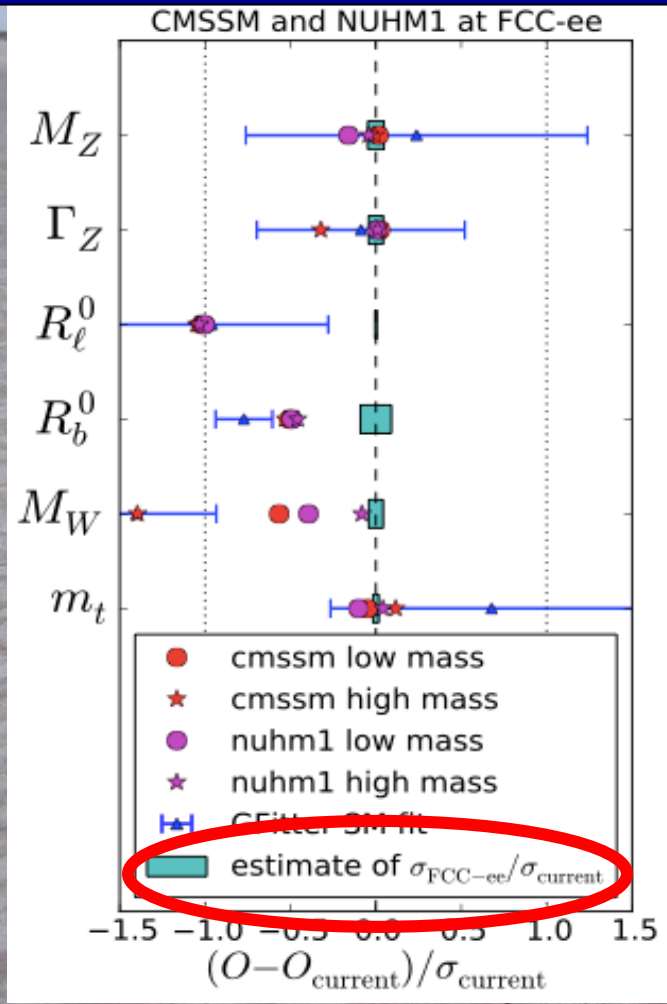
- Compatible with LHC measurement of m_h
- May extend to $m_\chi = m_{stop} \sim 6500$ GeV

JE, Olive & Zheng: arXiv:1404.5571

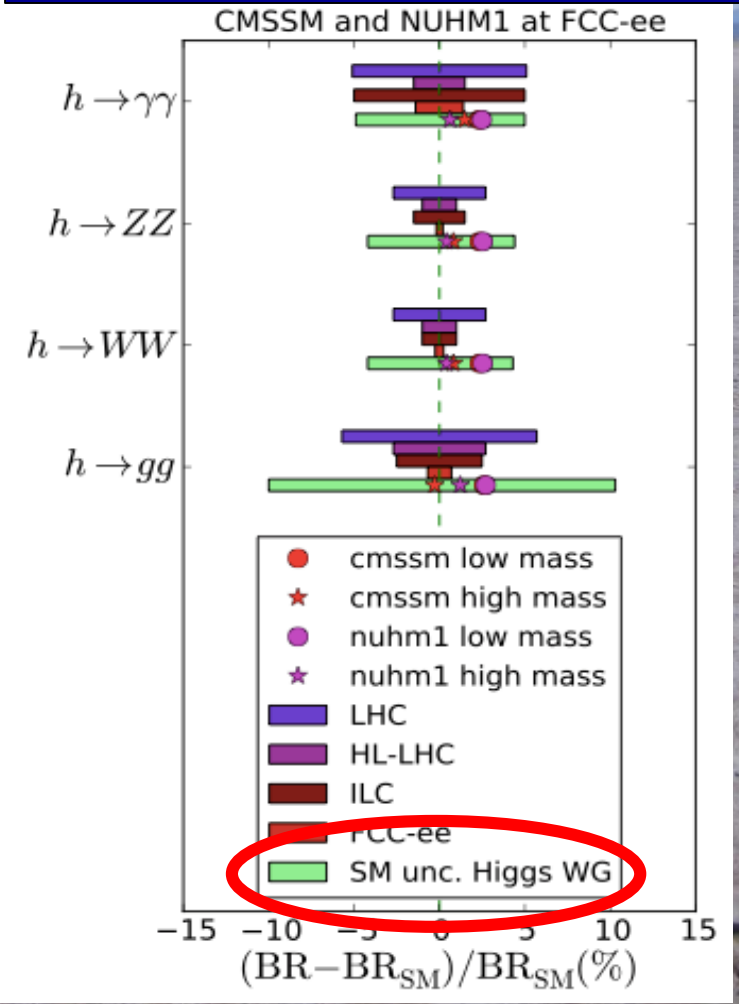
Buchmueller, JE et al: arXiv:1505.04702

Precision **FCC-ee** Measurements

Precision Electroweak

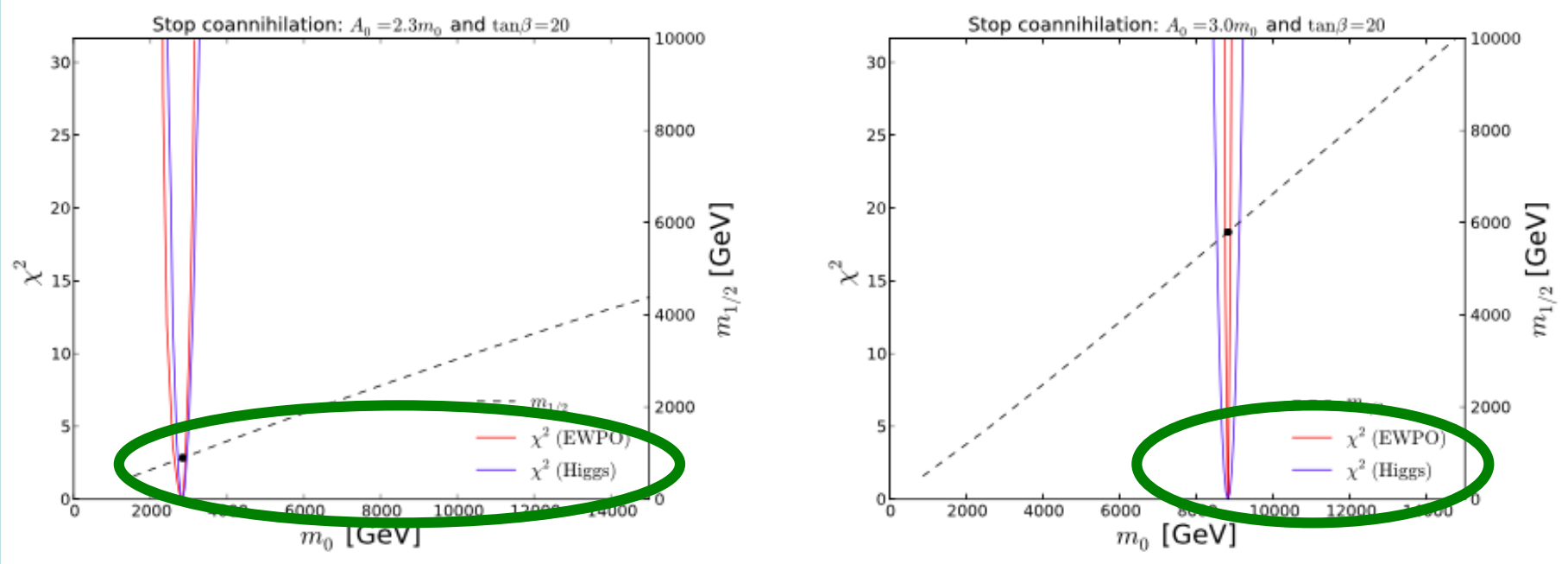


Precision Higgs



Impact of Precision and Higgs Measurements

- Contributions of Higgs and electroweak precision observables to global χ^2 function along stop coannihilation strip



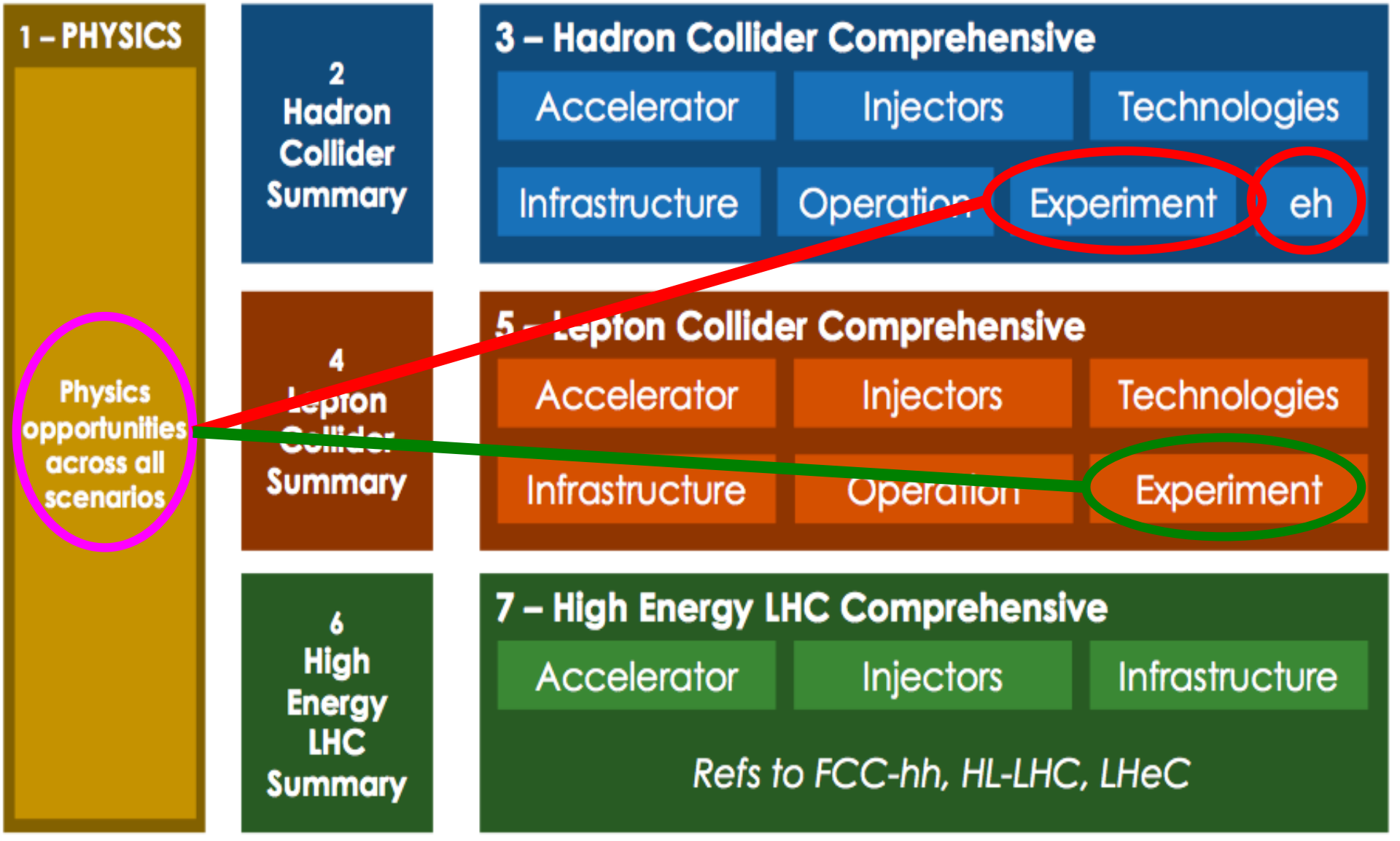
- **FCC-ee vs FCC-hh: possible test of supersymmetry at the loop level**

Buchmueller, JE et al: arXiv:1505.04702

Global Analysis, Combination & Complementarity

- Will depend upon inputs from both FCC-ee and FCC-hh (and FCC-he)
- Core business: probes of any new physics at the quantum level
  - E.g., Higgs, supersymmetry
  - Effort needed from all sides
  - Important to work on systematic, theoretical errors
  - Accuracy of possible FCC-hh measurements?
  - Explore further sensitivity to BSM > H, SUSY

Structure of FCC CDR



Work Plan Towards FCC CDR

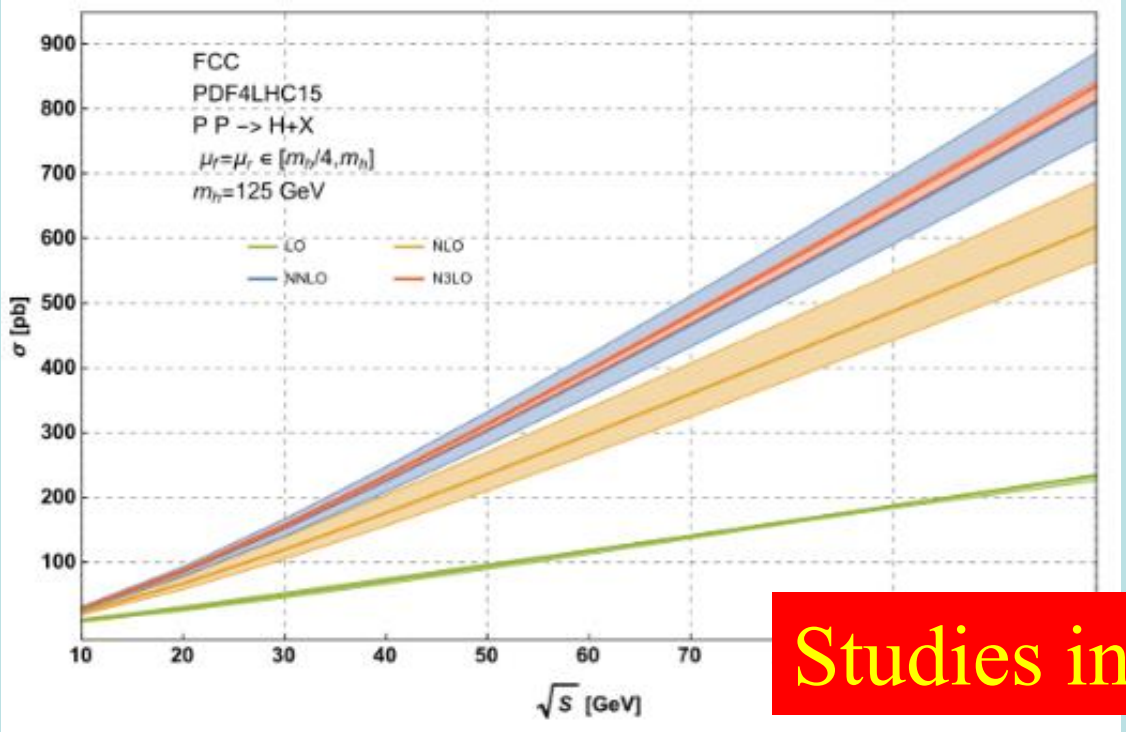
- Continue ongoing studies & document
  - Particularly hh and he, but also ee
- Need to prioritize topics?
  - Precision electroweak & TGCs
  - Higgs
  - Specific BSM scenarios
    - Supersymmetry? Composite models? Neutrinos?
- To be largely in place for FCC meeting in Jan. 18
- Can then compile & document complementarities & synergies

Back-ups

What H Physics can FCC-hh do?

- One thing is to have a large σ

Mangano @ Hong Kong



Studies in progress

- Another is to have small uncertainties

δ_{PDF}	δ_{α_S}	δ_{scale}	$\delta_{\text{PDF-theo}}$	δ_{EW}	δ_{tbc}	$\delta_{\frac{1}{m_t}}$
$\pm 2.5\%$	$\pm 2.9\%$	$^{+0.8\%}_{-1.9\%}$	$\pm 2.5\%$	$\pm 1\%$	$\pm 0.8\%$	$\pm 1\%$

Measurement of 3-H Coupling

- The story so far

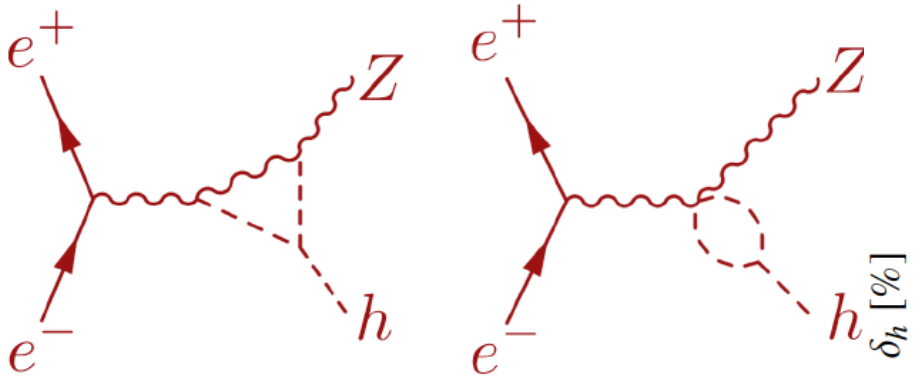
Studies in progress

$HH \to b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren Yao arXiv:1506.03302
$FCC_{@100TeV}$ 3/ab	30~40%	30%	15%
$FCC_{@100TeV}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \to b$ & $j \to \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet /W_{had} veto	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

- More decay modes, improved selections, .

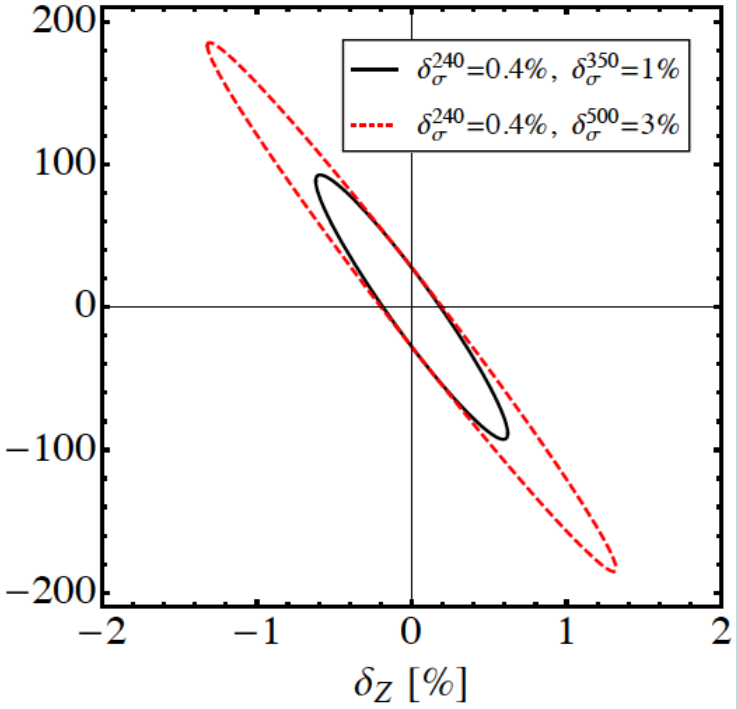
FCC-ee Sensitivity to 3h Coupling

- Loop corrections to σ(H+Z):



And also: 

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$



McCullough

- 3h correction δ_h energy-dependent
- δ_Z energy-independent: can distinguish

A First Look at 4-H Coupling

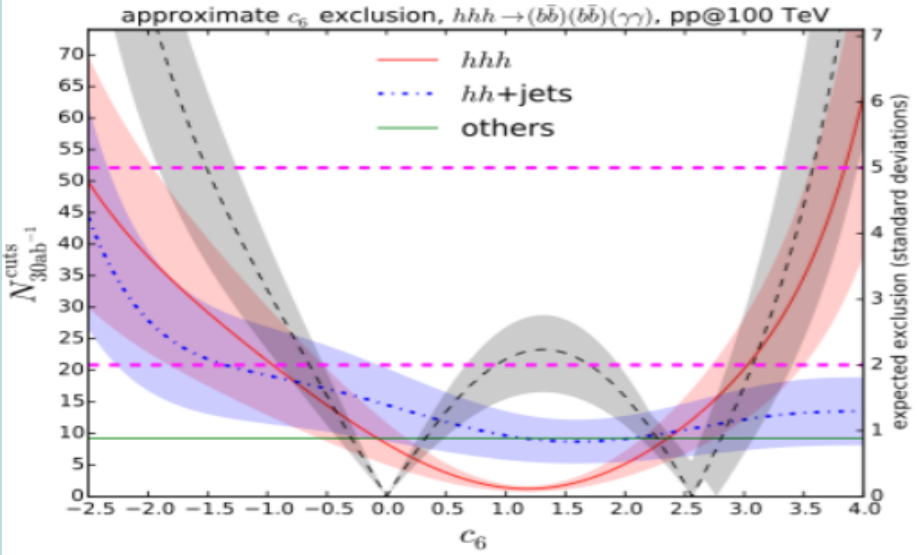
HHH production and quartic coupling constraints

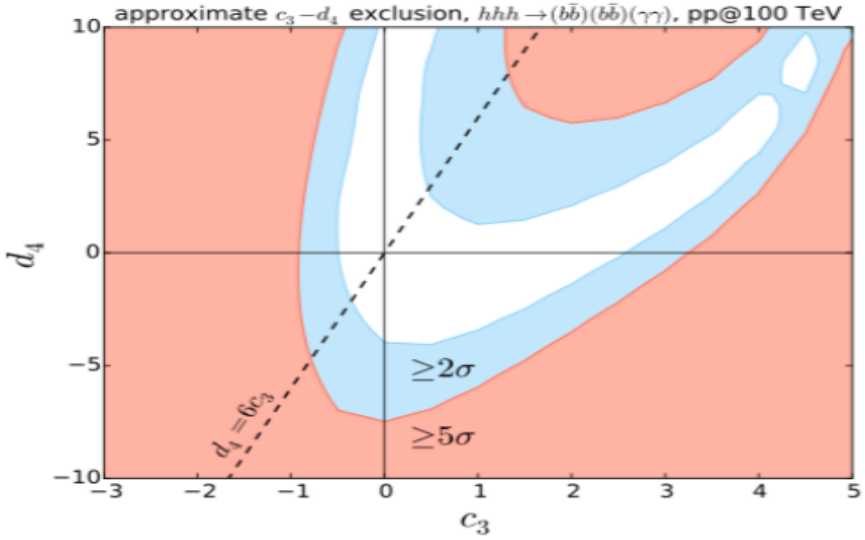
Papaefstathiou, Sakurai, arXiv:1508.06524

$$V_{\text{self}} = \mu^2|H|^2 + \lambda|H|^4 + \mathcal{O}_6,\ \mathcal{O}_6 \equiv \frac{c_6}{\Lambda^2}\lambda|H|^6 \qquad \mathcal{V}_{\text{self}} = \frac{m_h^2}{2v}(1+c_3)\,h^3 + \frac{m_h^2}{8v^2}(1+d_4)\,h^4 \qquad c_3 = c_6,\ d_4 = 6c_6$$

$$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$$

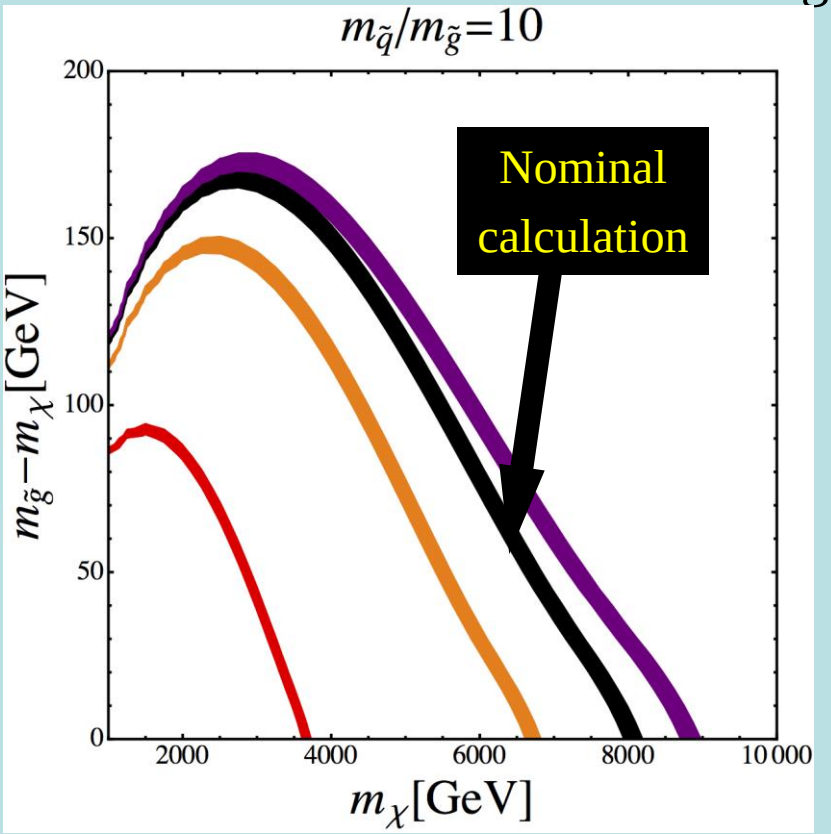
Is this possible?

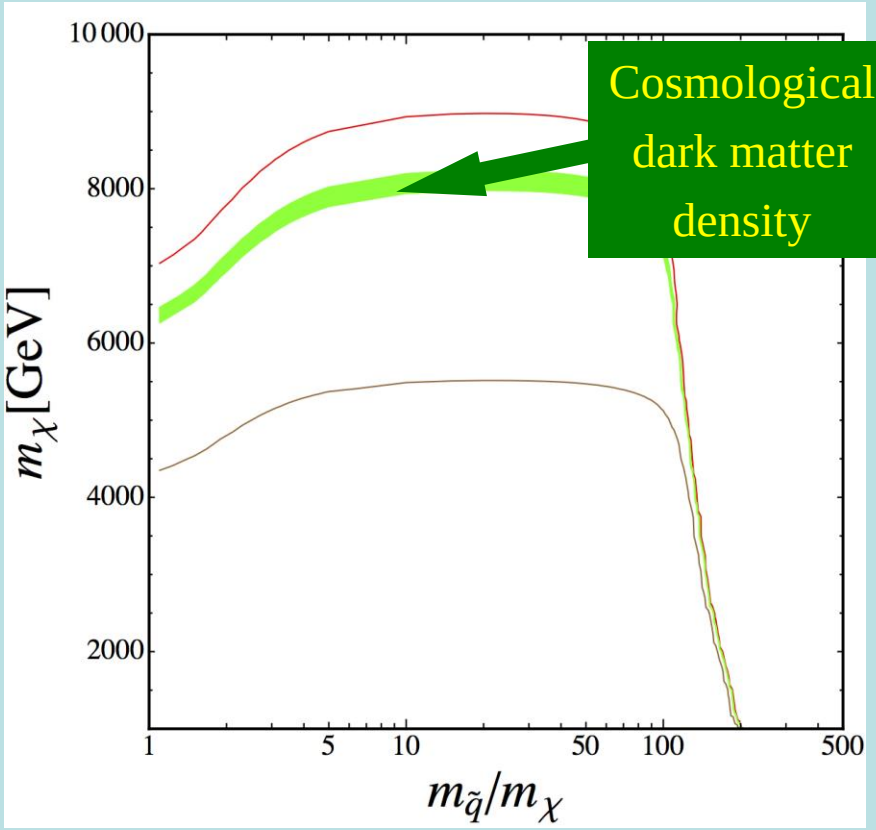




How Heavy could Dark Matter be in pMSSM?

- Largest possible mass in pMSSM is along gluino coannihilation strip: $m_{gluino} \sim m_{neutralino}$



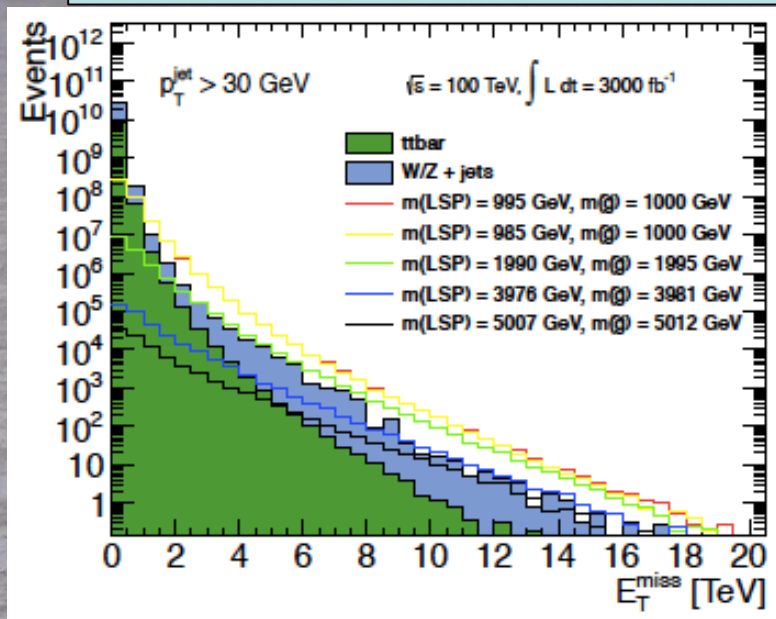


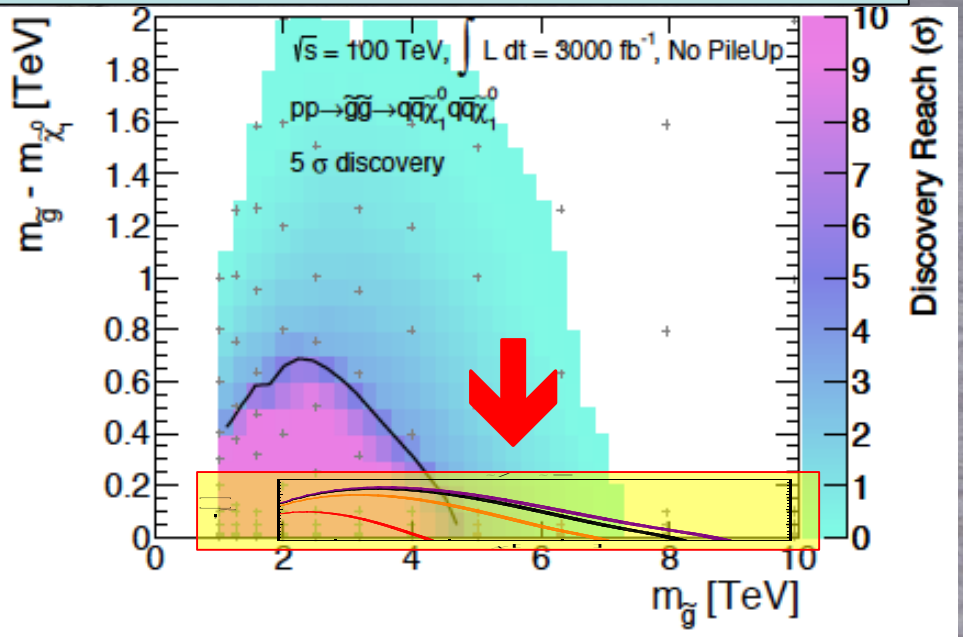
- **Extends to $m_{\chi} = m_{gluino} \sim 8$ TeV**

JE, Luo & Olive: arXiv: 1503.07142

Reaches for Sparticles

Model with compressed spectrum: small gluino-neutralino mass difference

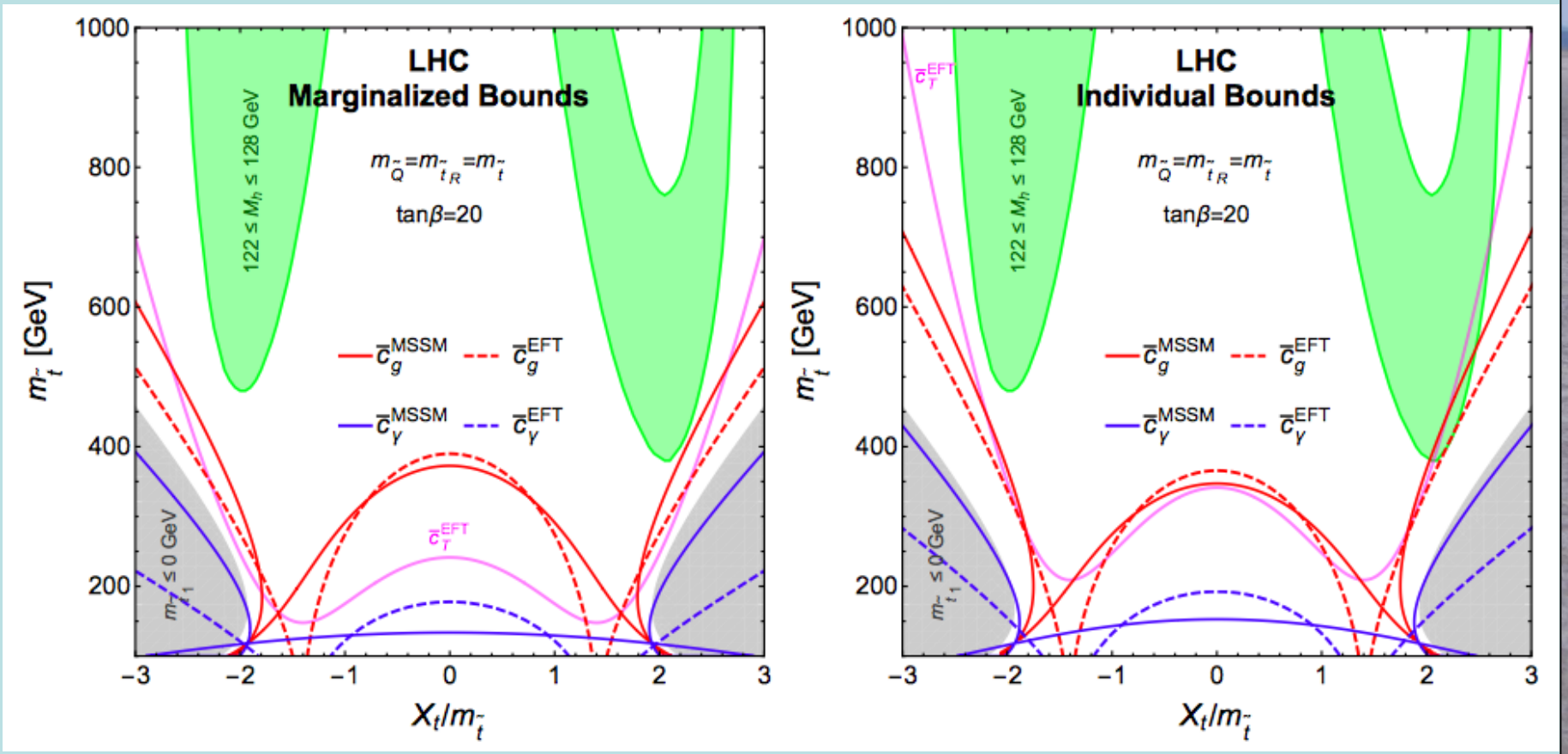




Large mass possible in gluino coannihilation scenario for dark matter

Indirect Stop Limits from Precision EW Data

- Solid lines = full calculation, dashed lines = EFT



Drozd, JE, Quevillon & You: arXiv:1504.02409

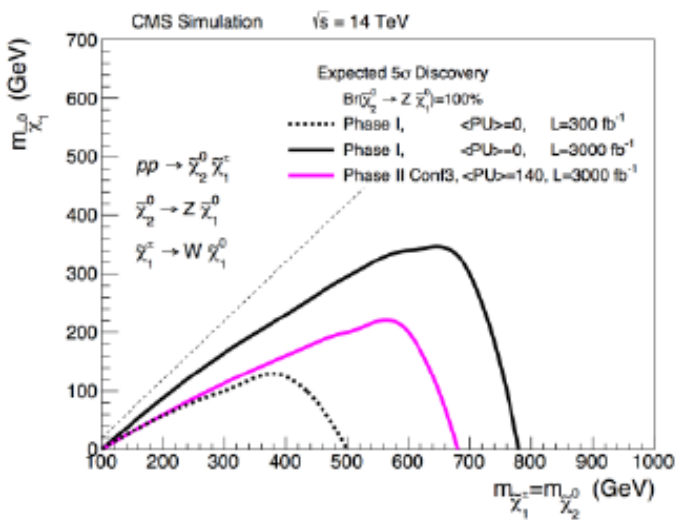
Possible FCC-ee Precision Measurements

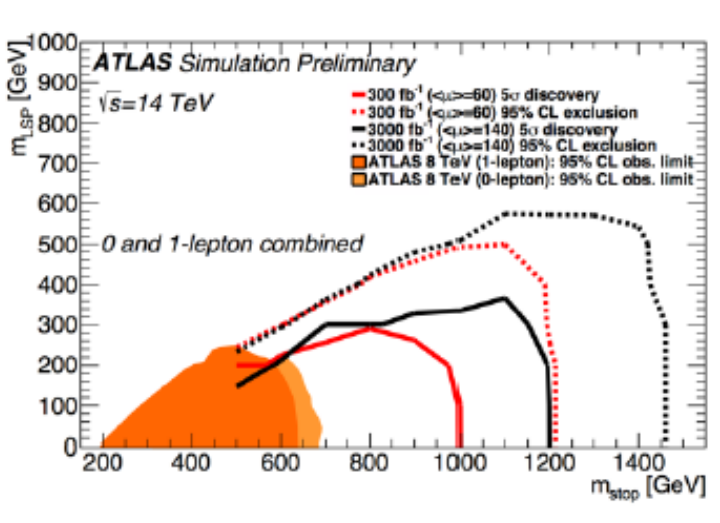
- Conservatively based on LEP experience so far – it is just a start. Much work ahead.

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g → bb
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

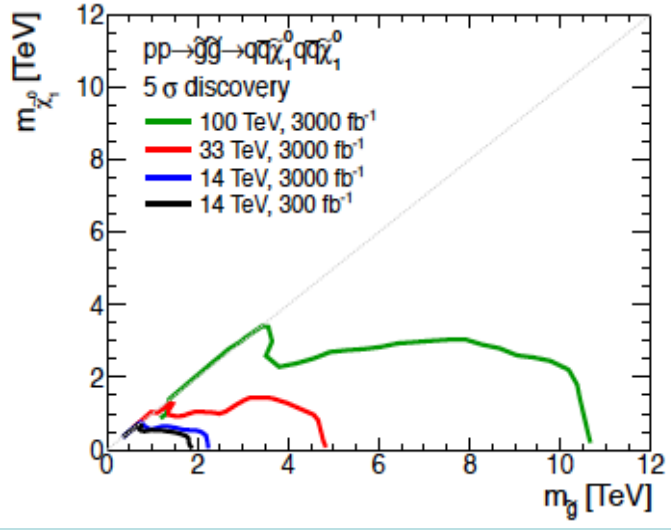
Reaches for Sparticles

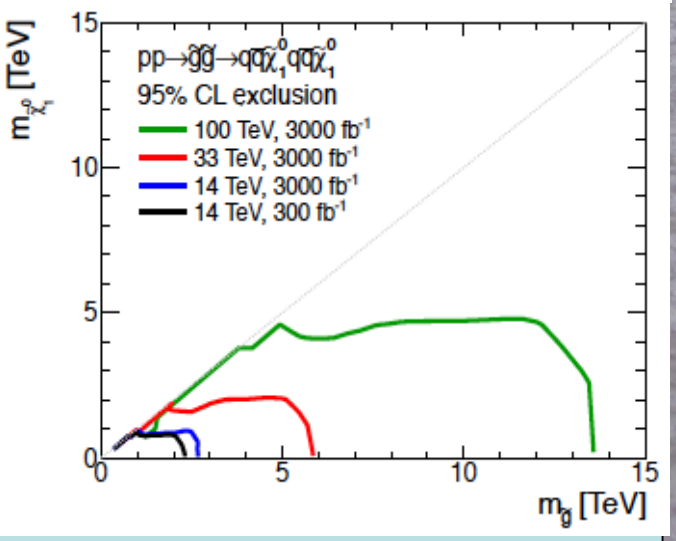
LHC:





HE-LHC, FCC-hh





What H Physics can FCC-hh do?

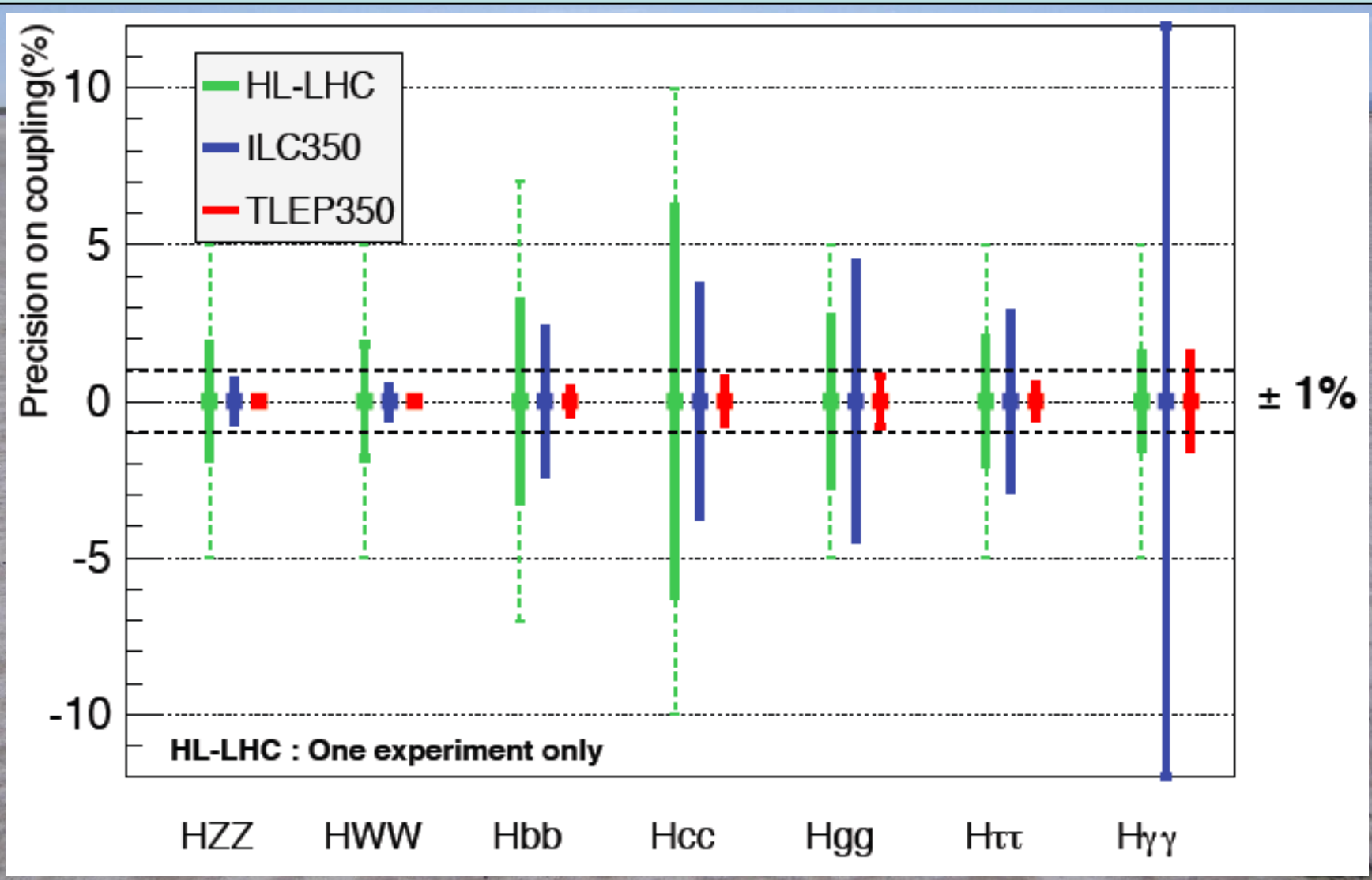
Big statistics!

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
gg→H	16 G	4.2×10^4	110
VBF	1.6 G	5.1×10^4	120
WH	320 M	2.3×10^4	66
ZH	220 M	2.8×10^4	84
ttH	760 M	29×10^4	420
gg→HH	28 M		280

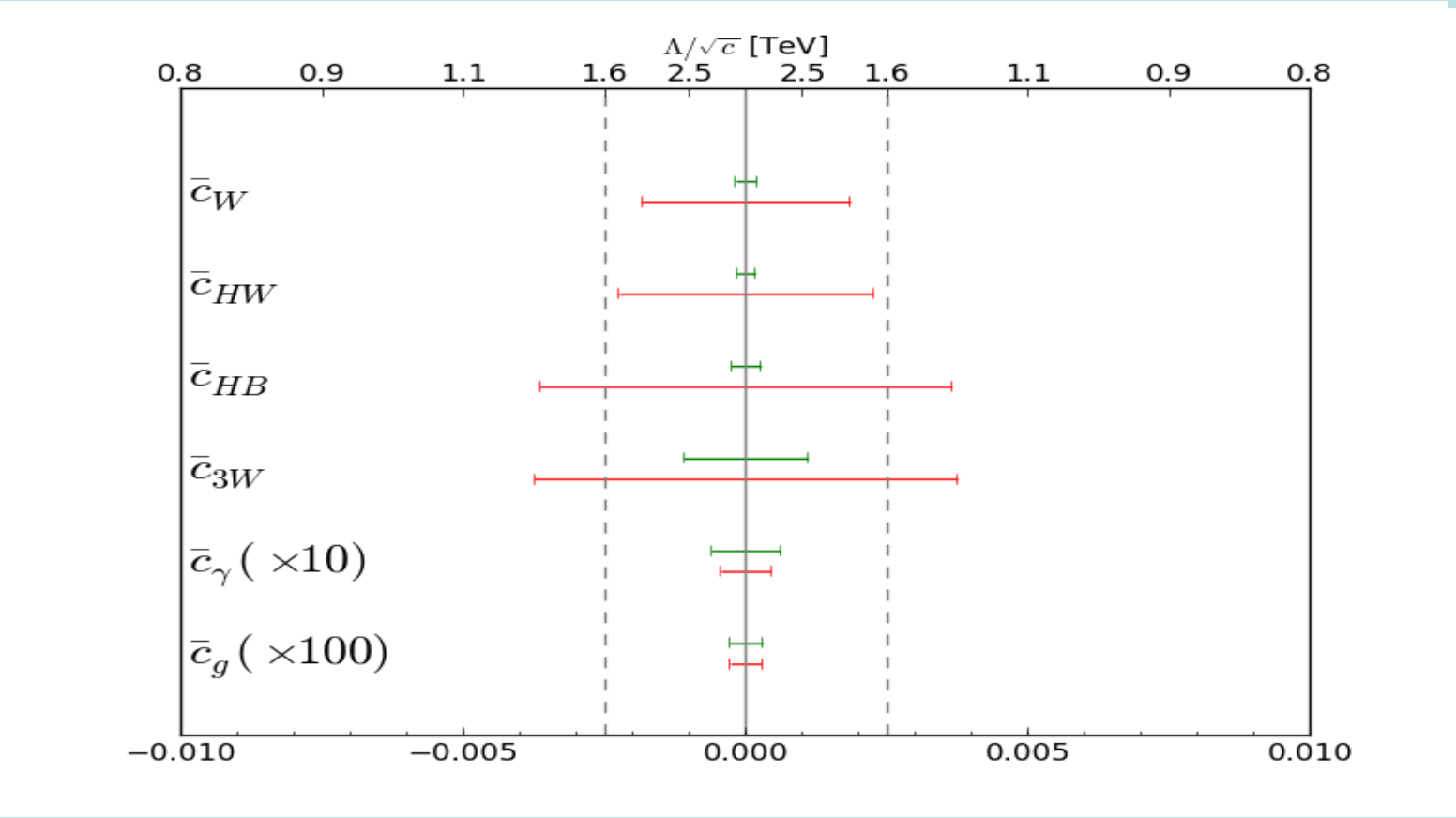
Mangano @ Hong Kong

- Sub-% measurement of H to 4l/γγ?
- 1% measurement of H to μμ
- 5% measurement of 3-H coupling?
- Sensitive to 4-H coupling?

Possible Future Higgs Measurements



FCC-ee Higgs & TGC Measurements

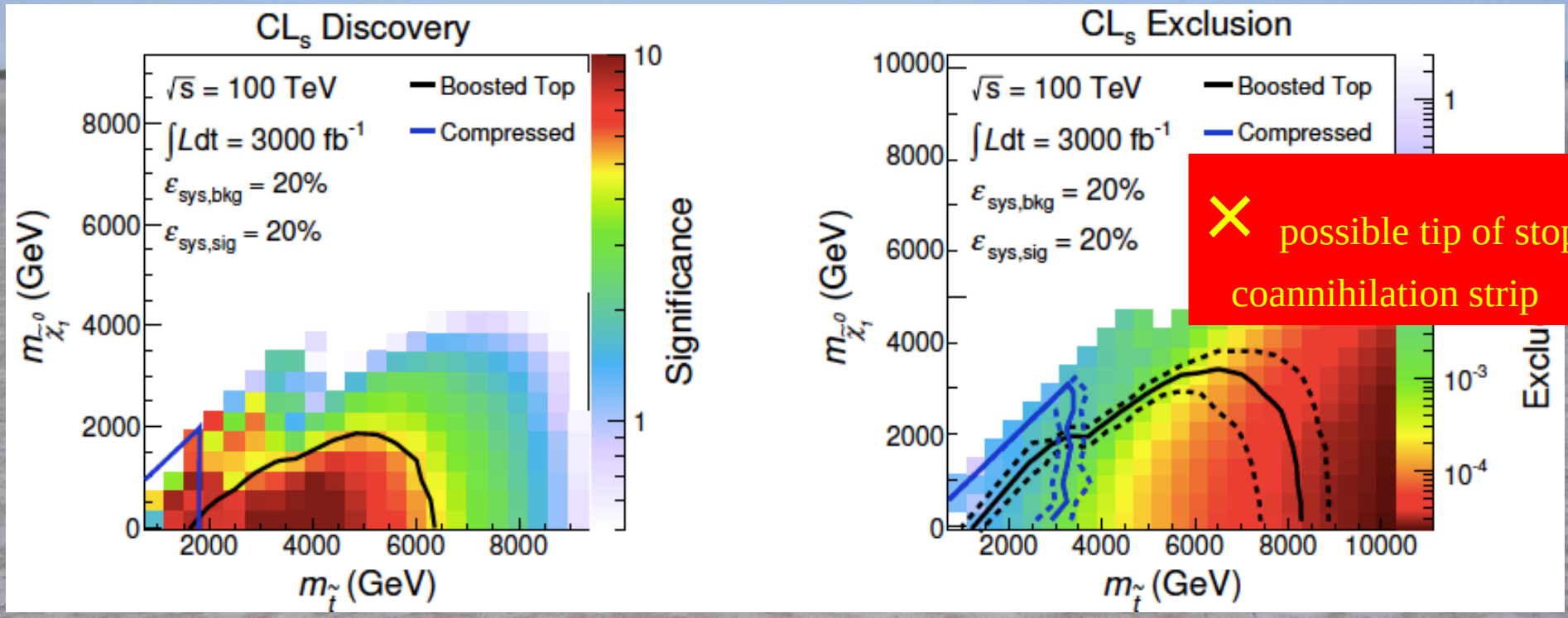


- LHC constraints

JE & Tevong You, arXiv:1510.04561

- **FCC-ee** constraints: see $\Lambda \sim 10$ TeV?

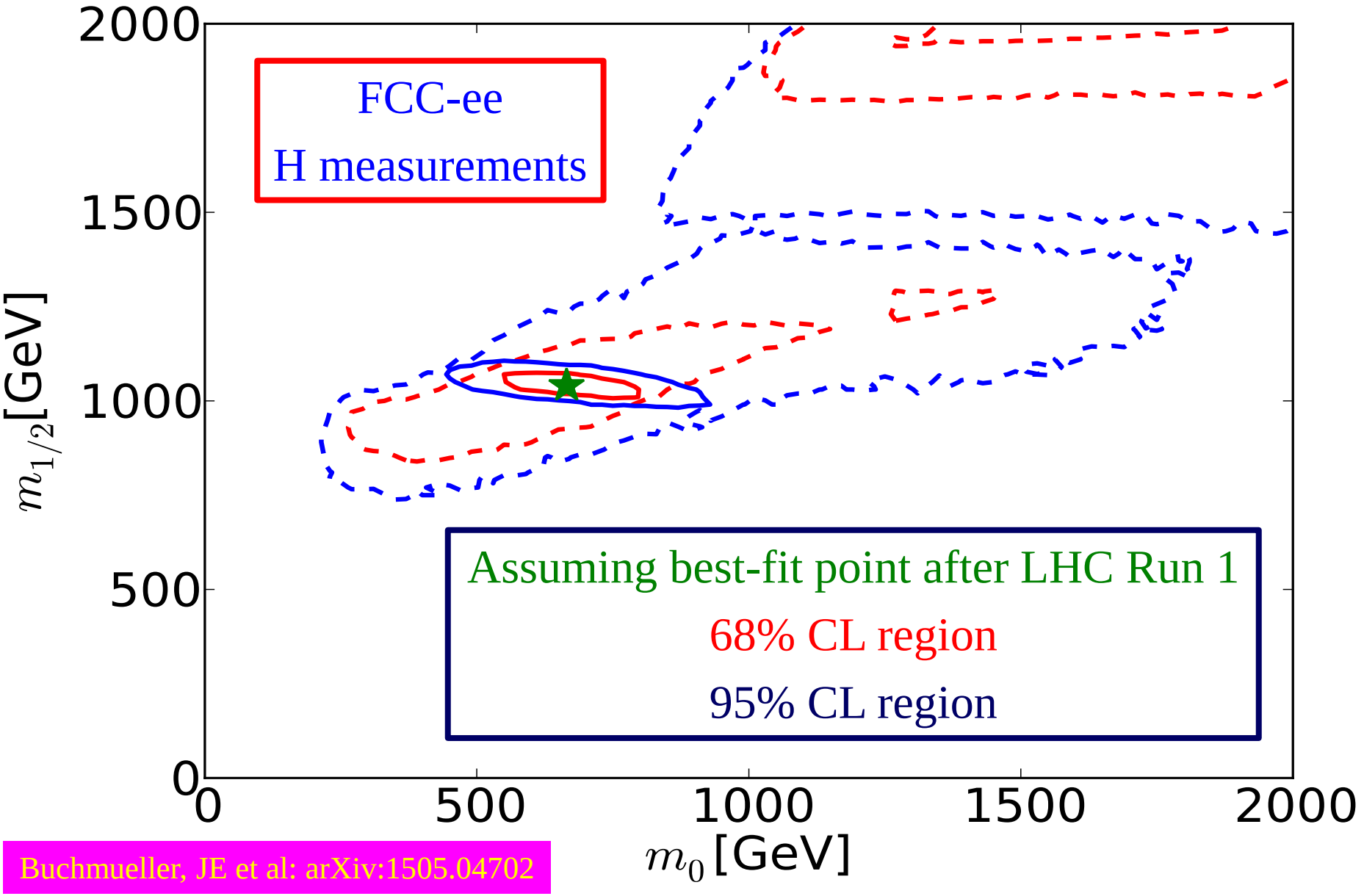
Reach for the Stop



Discover 6.5 TeV stop @ 5σ, exclude 8 TeV @ 95%

Stop mass up to 6.5 TeV possible along coannihilation strip

Measuring CMSSM with FCC-ee



Buchmueller, JE et al: arXiv:1505.04702

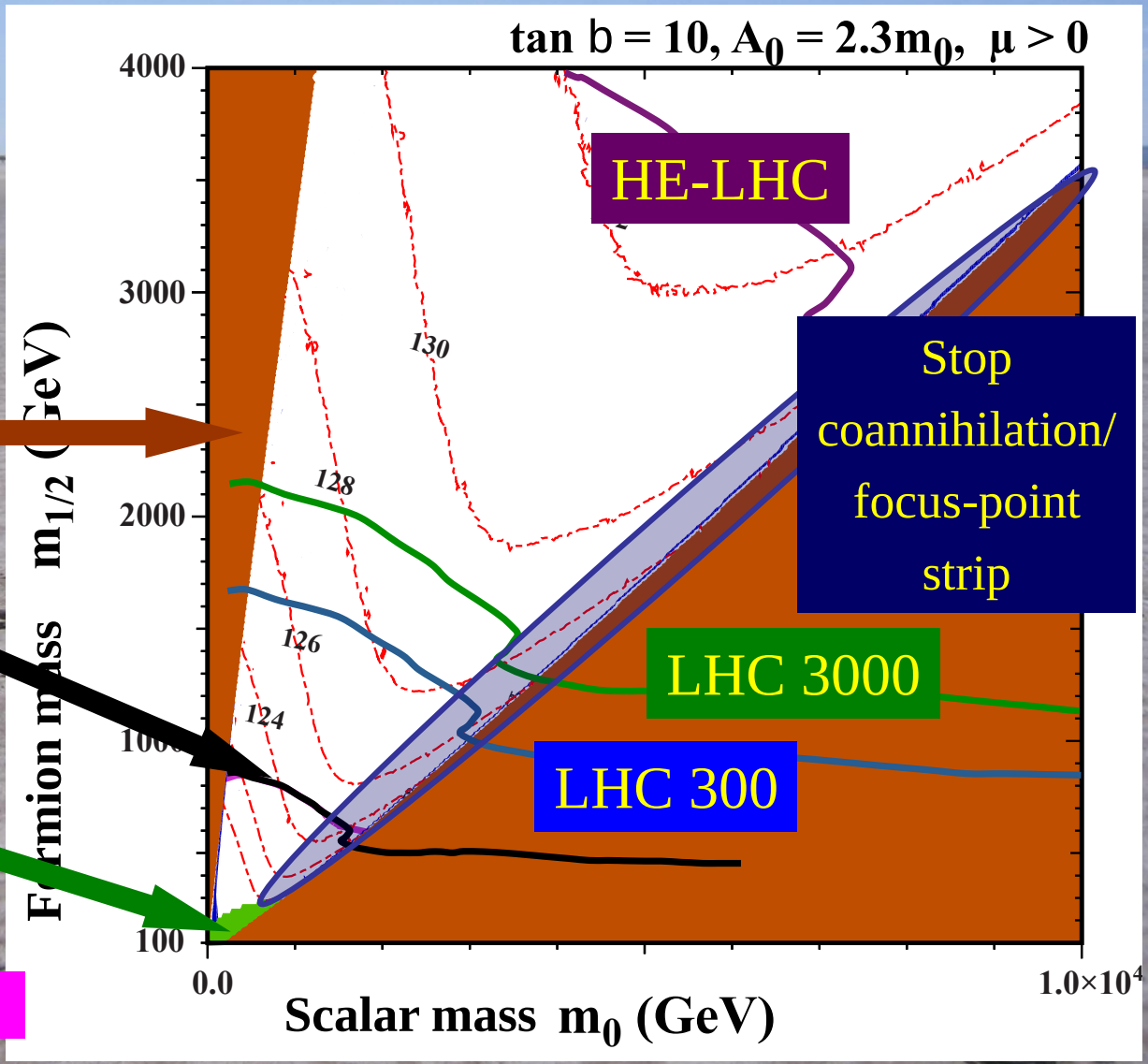
Where May Supersymmetry be Hiding?

Relic density constraint, assuming neutralino LSP

Excluded because stau or stop LSP

Excluded by LHC1 Jets + MET search

Excluded by $b \rightarrow s\,\gamma$, $B_s \rightarrow \mu^+\mu^-$



JE, Olive & Zheng: arXiv:1404.5571