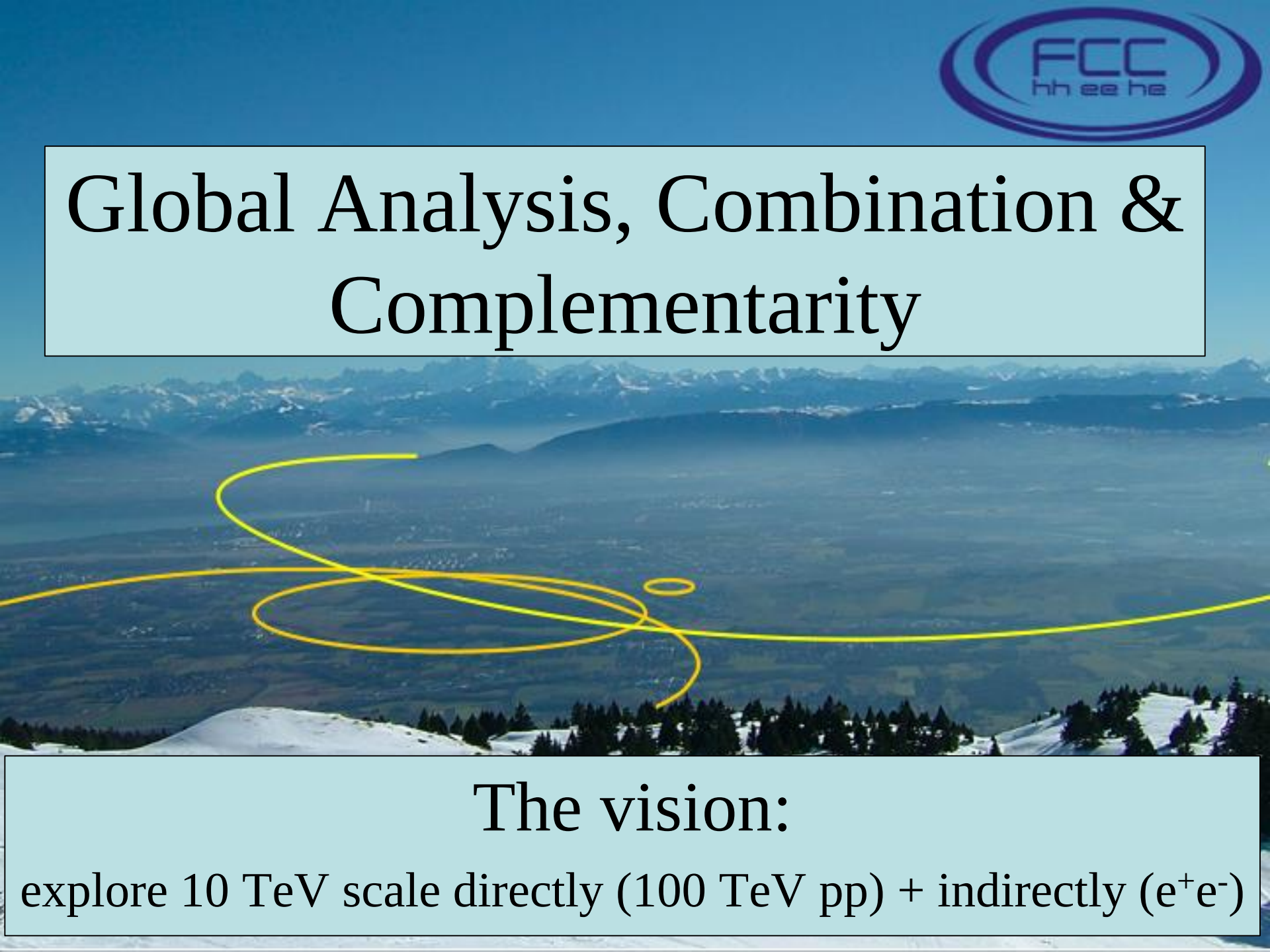


Global Analysis, Combination & Complementarity

The vision:

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

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)?
- Depend on inputs from specific FCC-xx analyses
- Broad subject: **not really started**
- Illustrate with specific physics examples
  - Higgs and precision electroweak
  - Supersymmetry
  - X(750)

Possible **FCC-ee** Precision Measurements

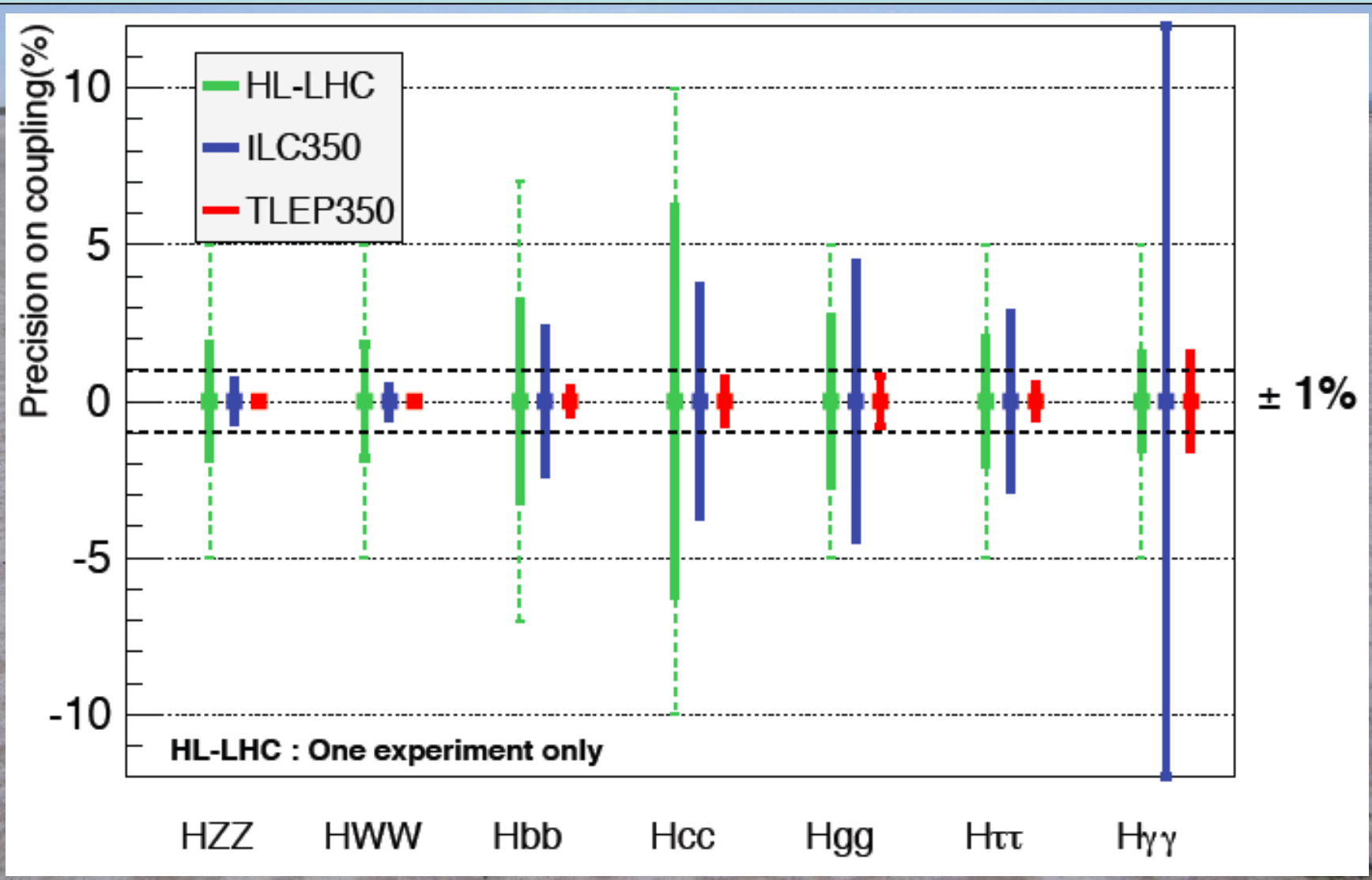
Observable	Measurement	Current precision	FCC stat.	Possible syst.	Challenge
m_Z (MeV)	Z peak ± 4 GeV for α_{EM}, line shape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)		2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l		20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b		0.21629 ± 0.00066	0.000003	< 0.00006	g → bb
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

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

- Need to reduce theoretical uncertainties to match
- Essential for new physics interpretations

Possible Future Higgs Measurements



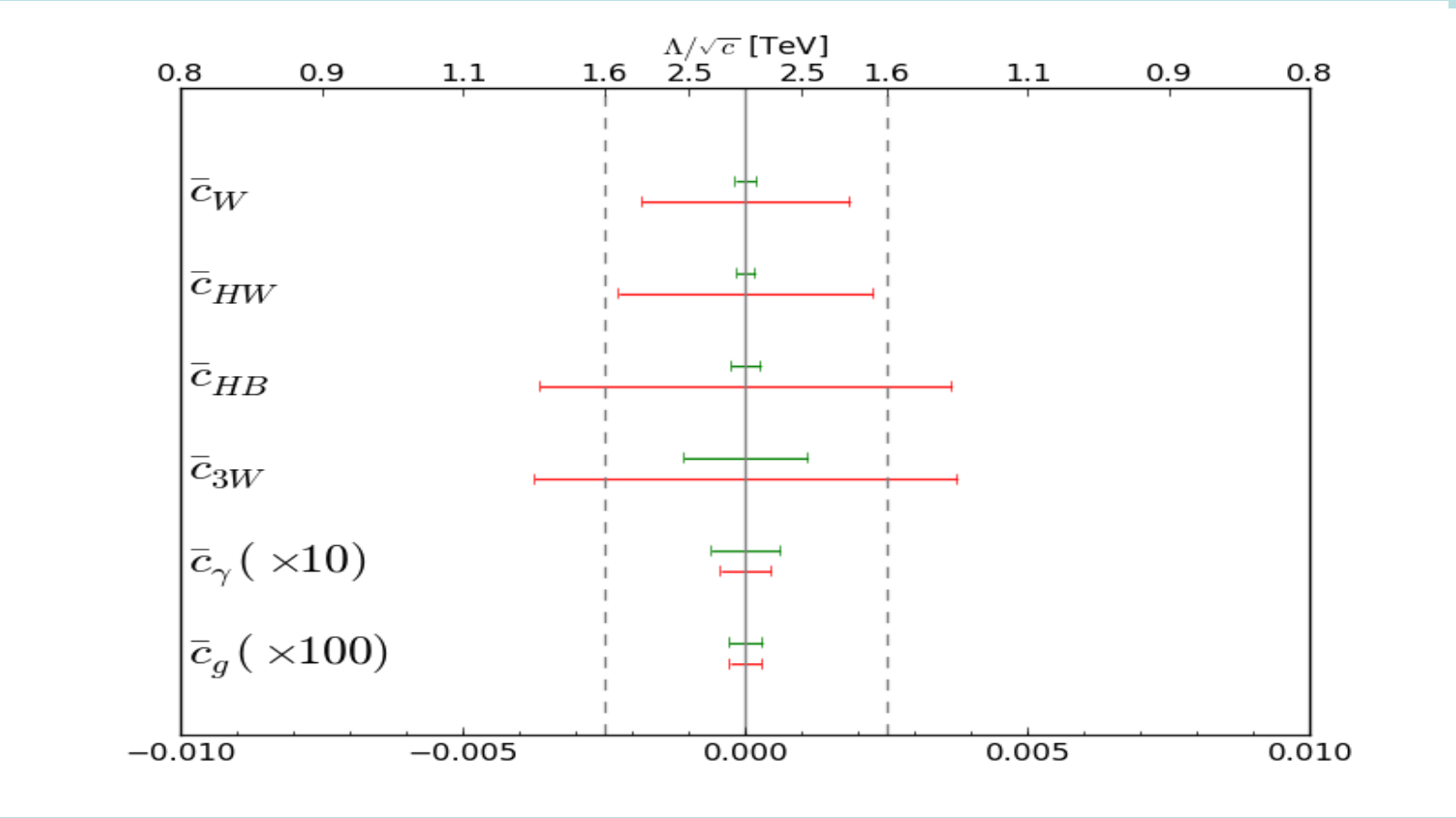
Standard Model Effective Field Theory

- 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 ...

FCC-ee Higgs & TGC Measurements



- LHC constraints

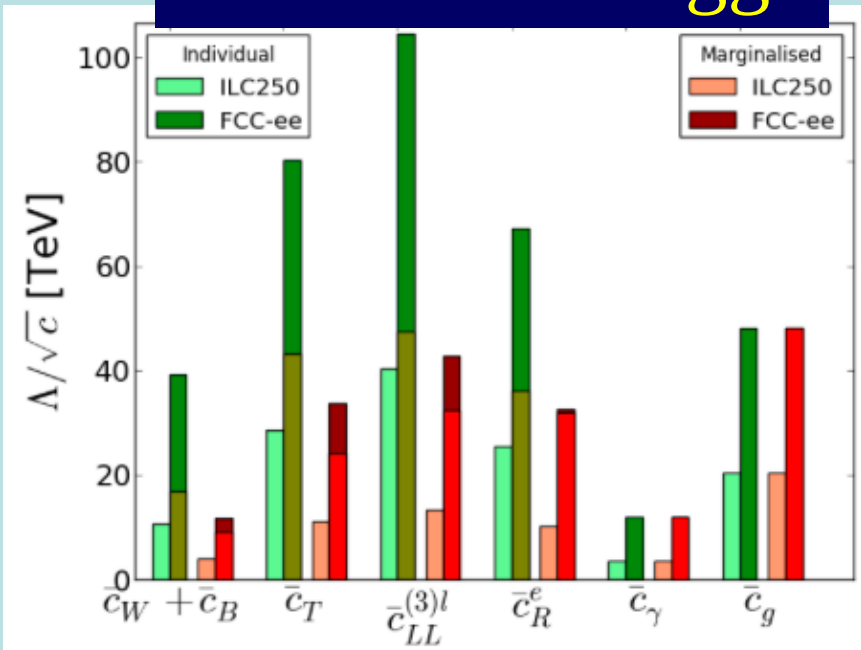
JE & Tevong You, arXiv:1510.04561

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

JE & Tevong You, arXiv:1510.04561

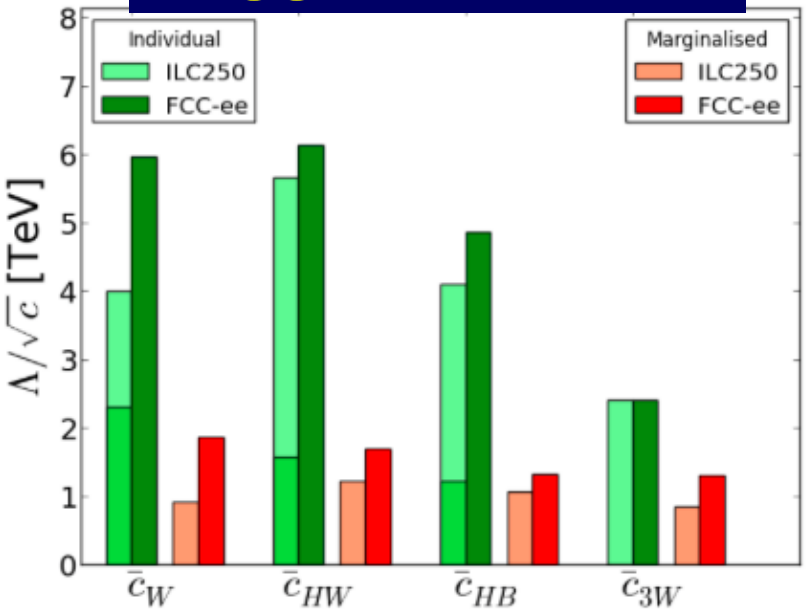
FCC-ee Higgs & TGC Measurements

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, …

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

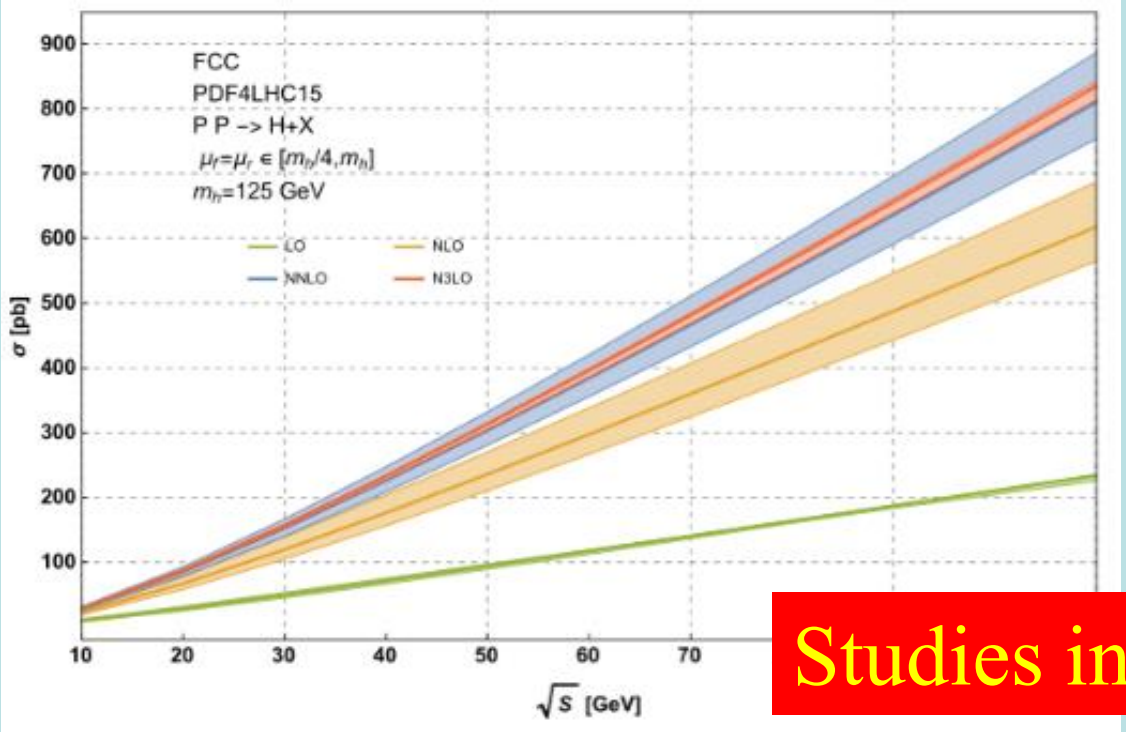
Mangano @ Hong Kong

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

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

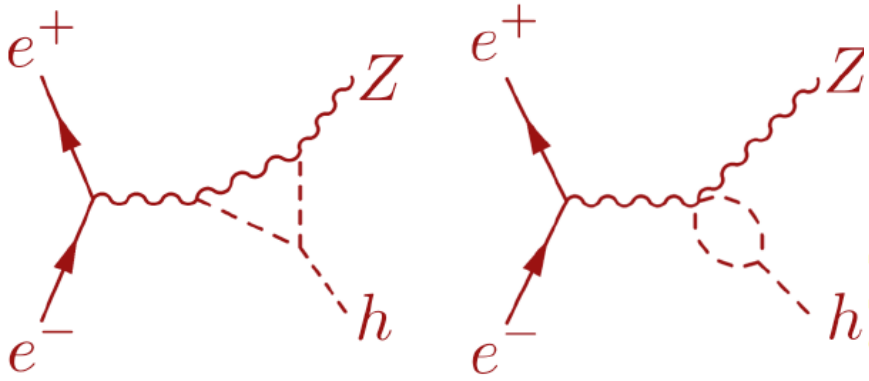
Studies in progress

$HH \to b\bar{b}\gamma\gamma$	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, .

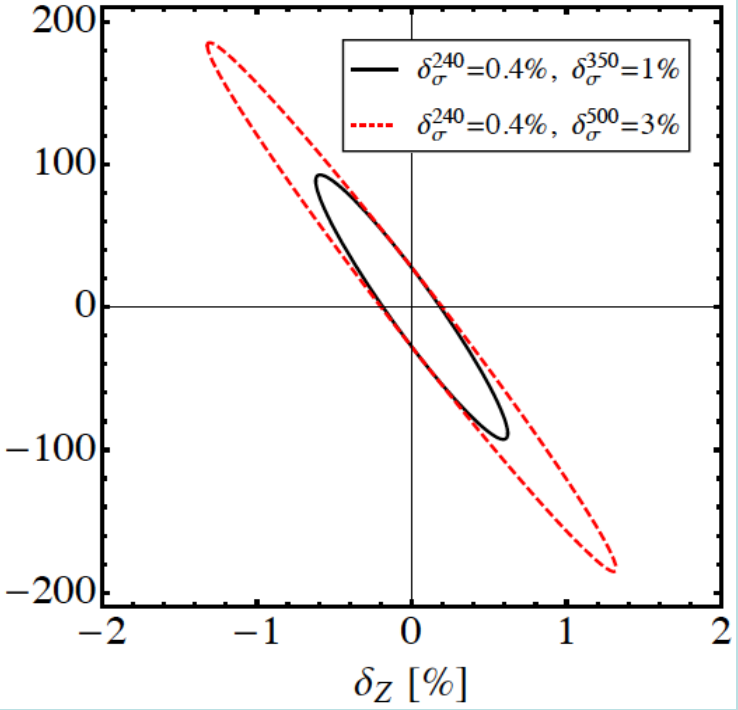
FCC-ee Sensitivity to 3h Coupling

- 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

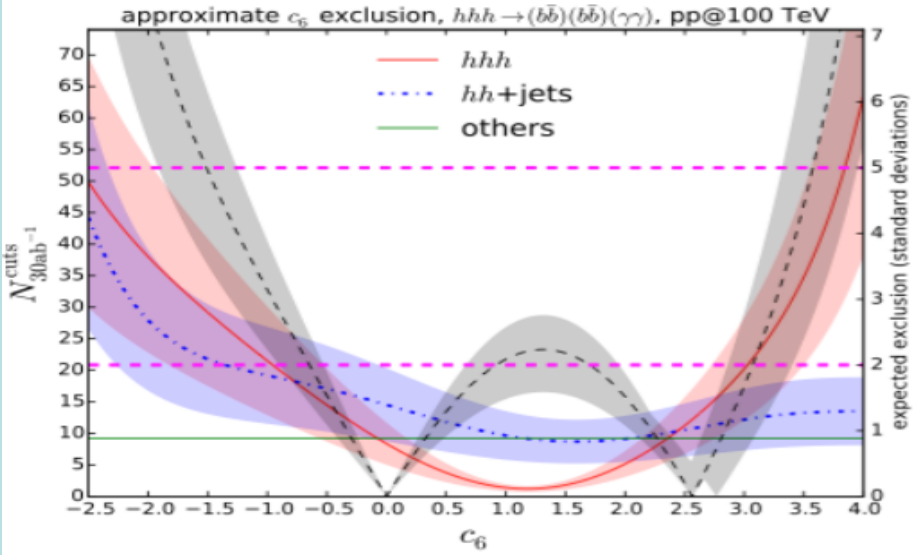
HHH production and quartic coupling constraints

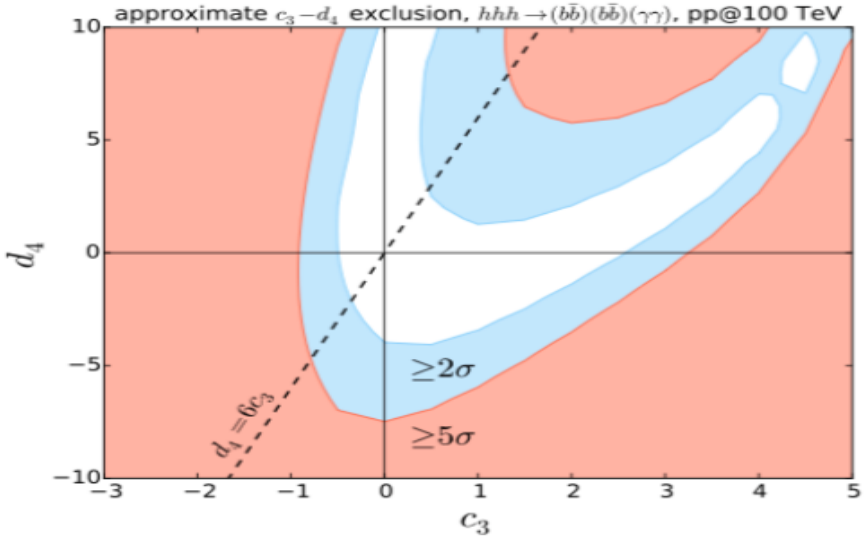
Papaefstathiou, Sakurai, arXiv:1508.06524

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

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

Is this possible?

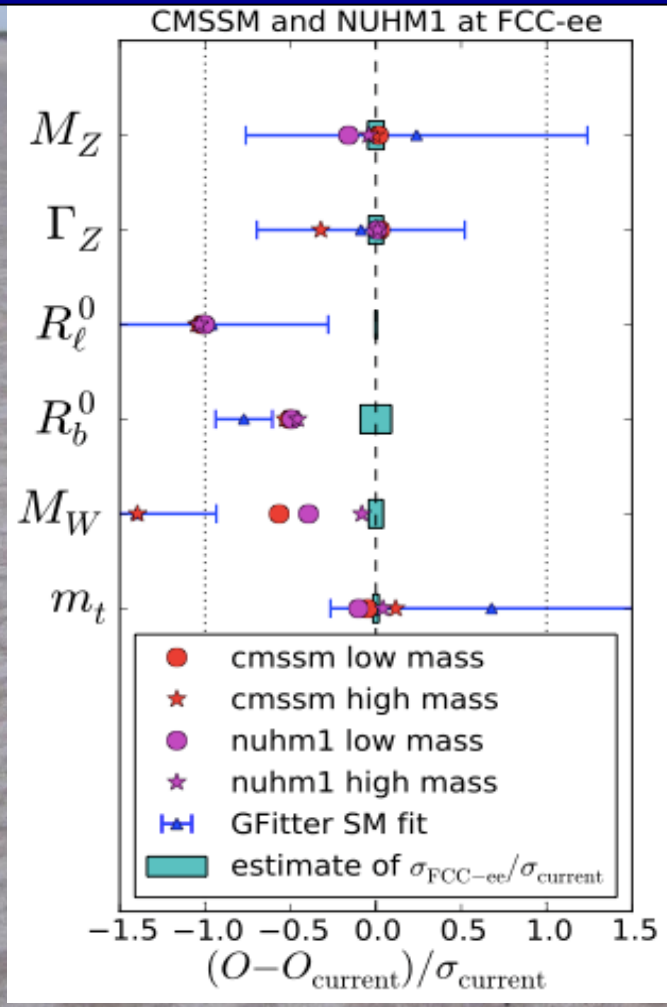




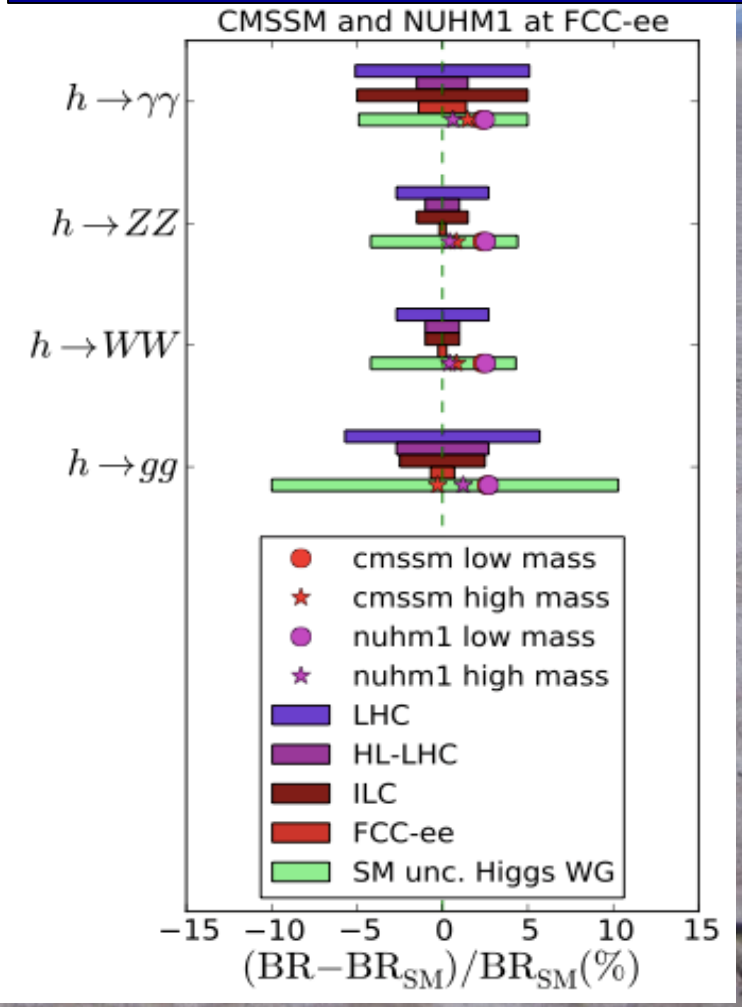
Buchmueller, JE et al: arXiv:1505.04702

Precision **FCC-ee** Measurements

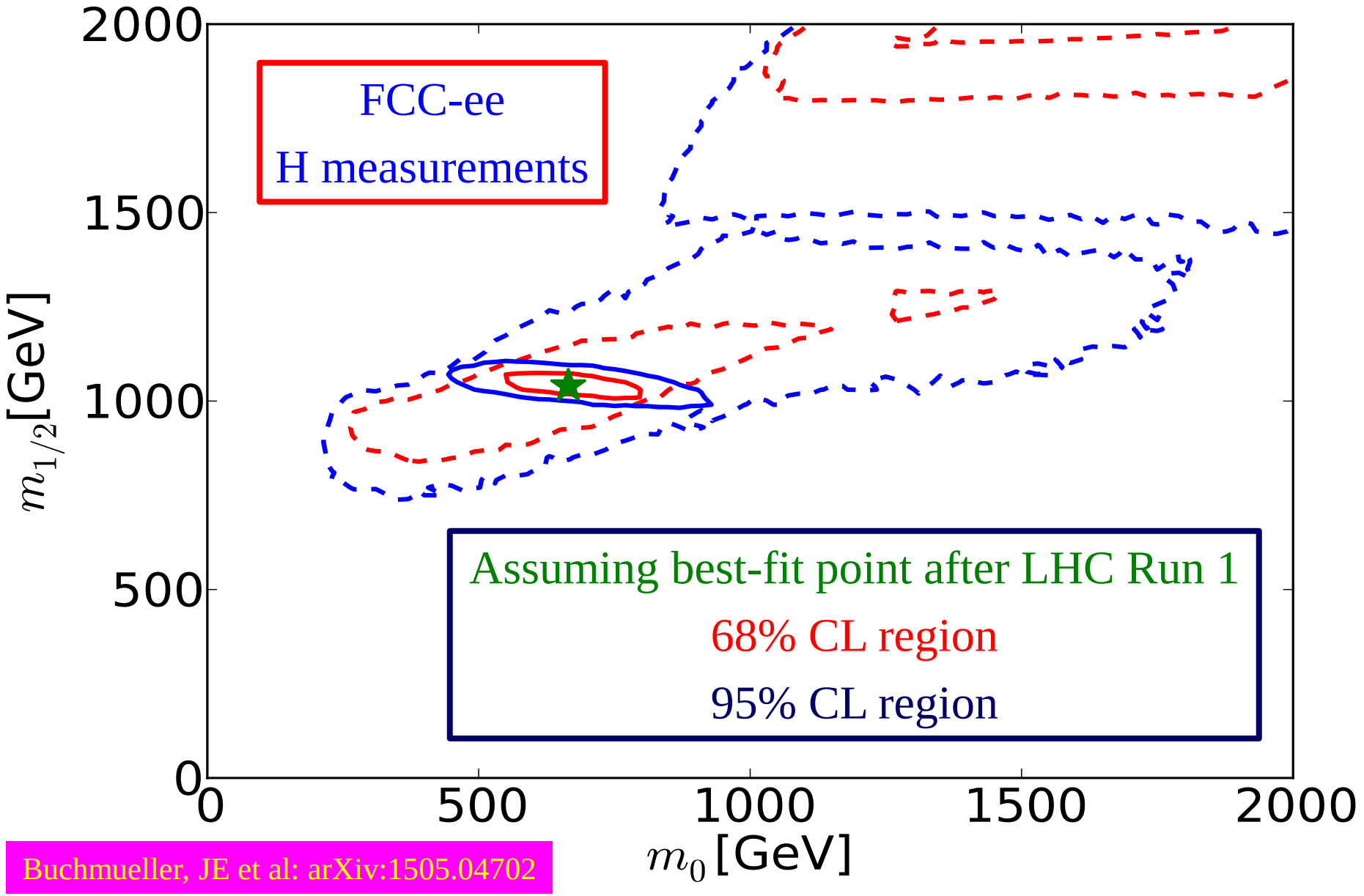
Precision Electroweak



Precision Higgs



Measuring CMSSM with FCC-ee



Buchmueller, JE et al: arXiv:1505.04702

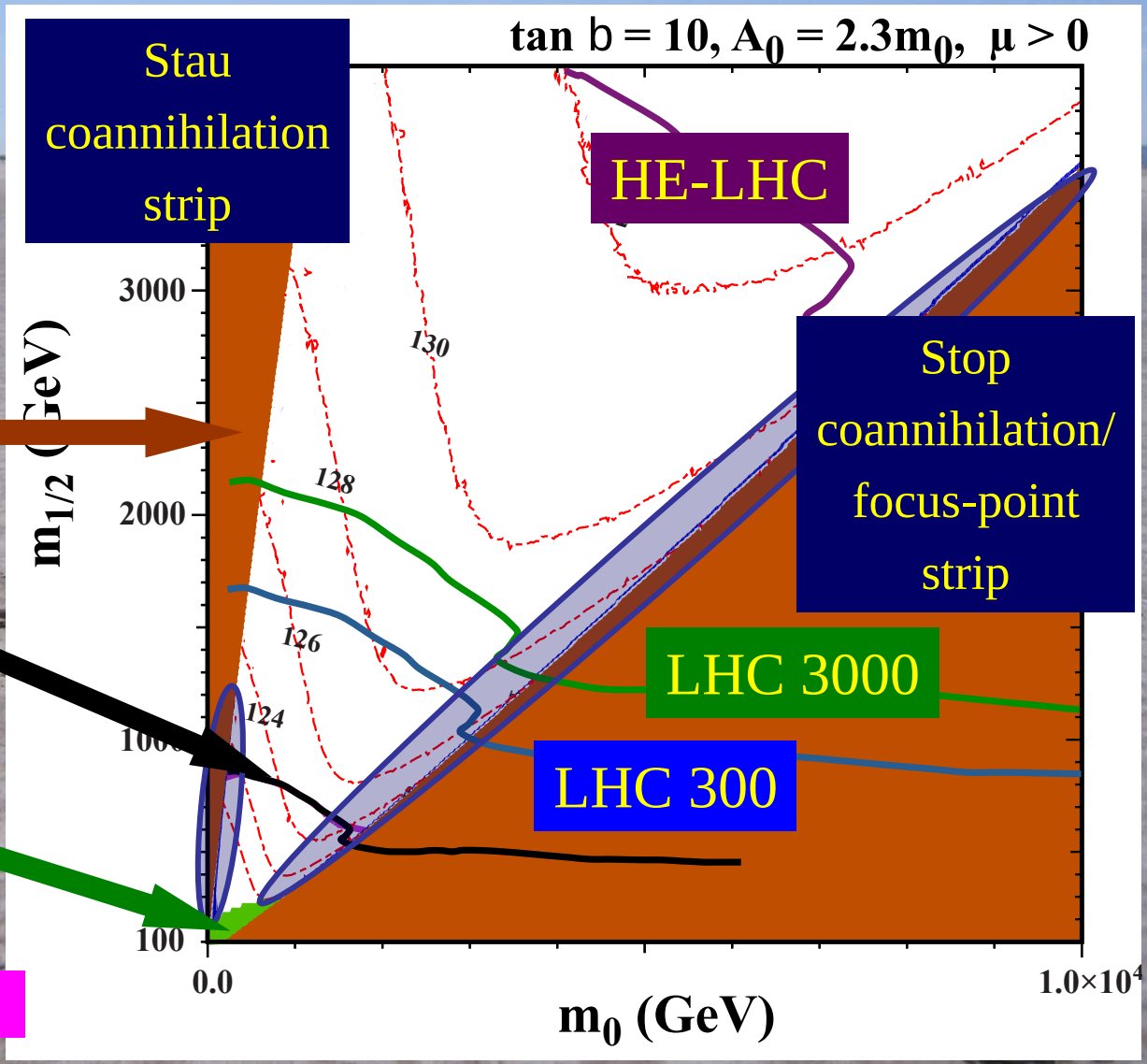
Where May CMSSM be Hiding?

Relic density constraint, assuming neutralino LSP

Excluded because stau or stop LSP

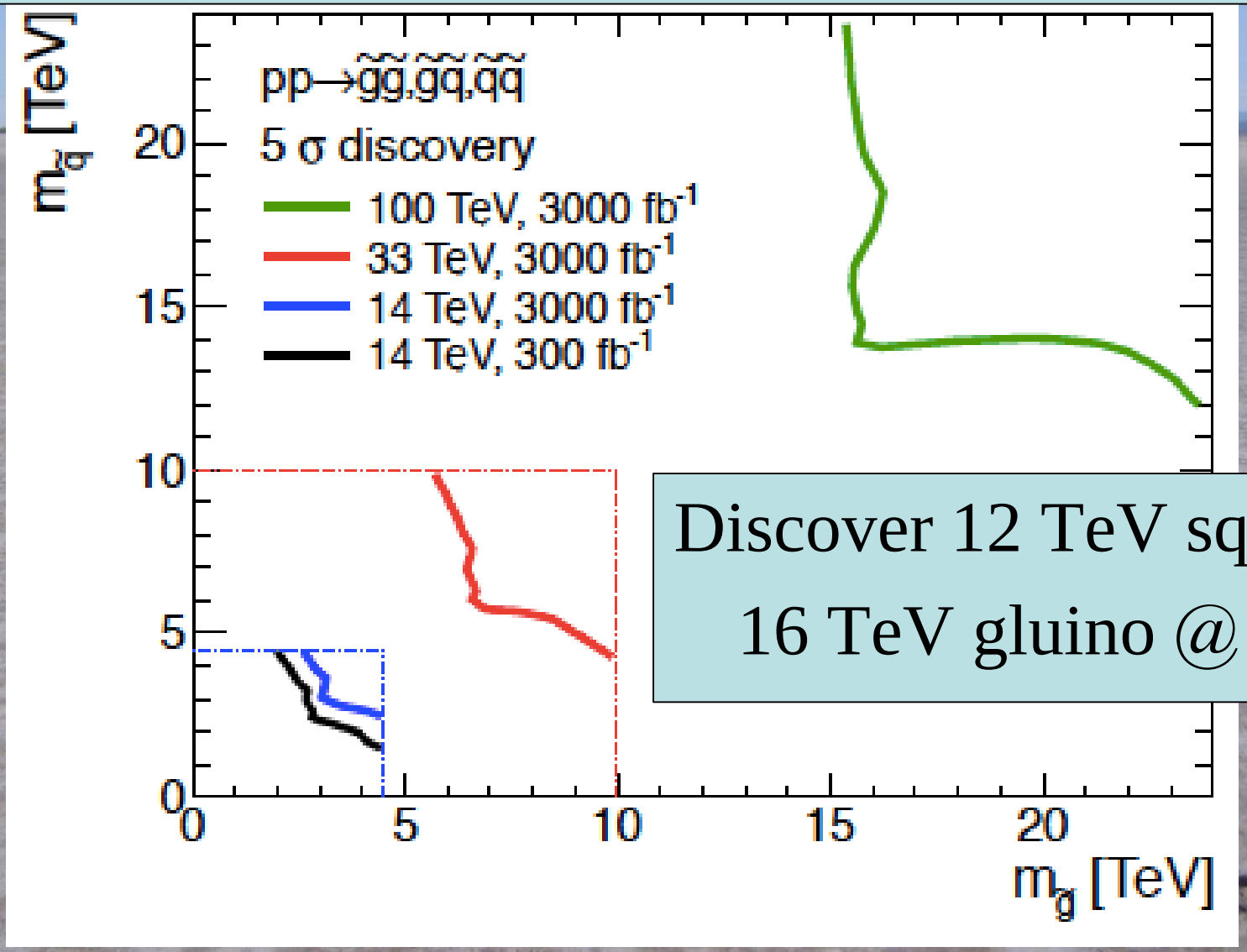
Excluded by ATLAS Jest + MET search

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



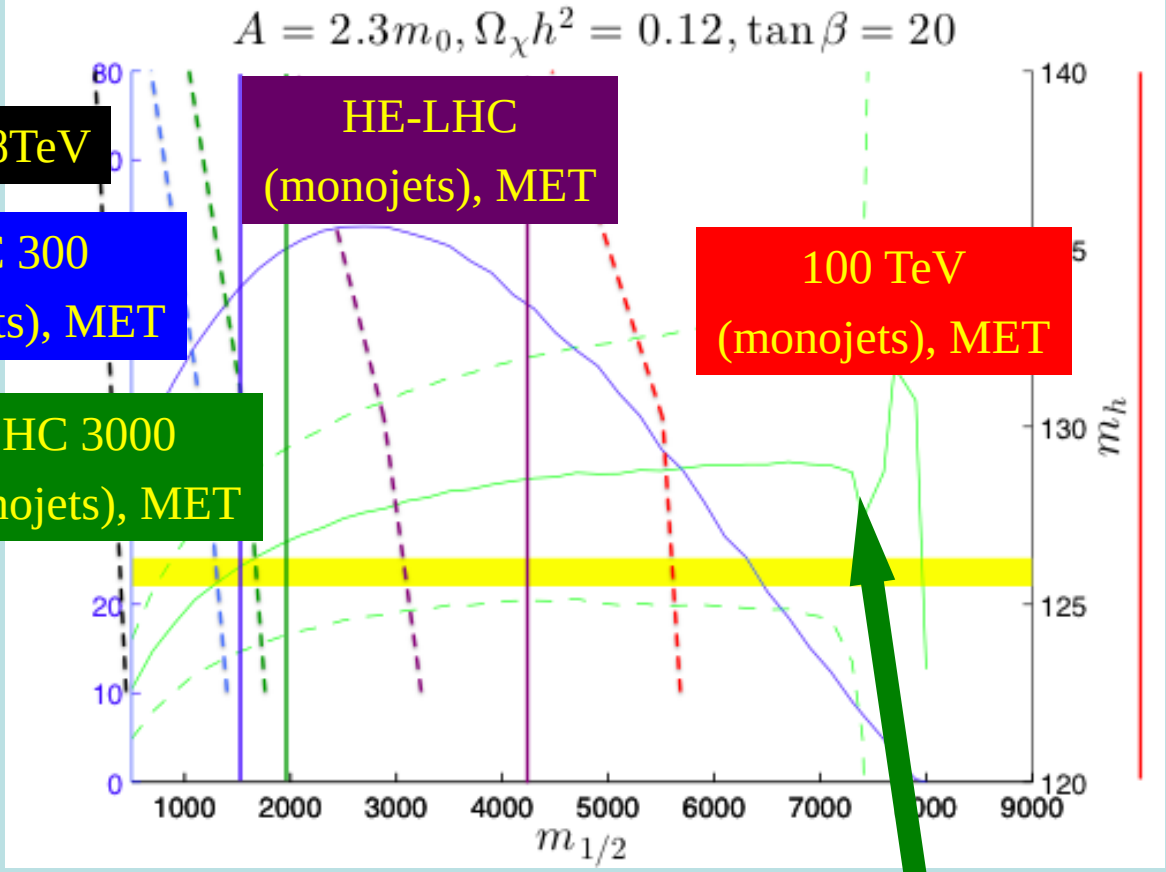
JE, Olive & Zheng: arXiv:1404.5571

Squark-Gluino Plane



Discover 12 TeV squark,
16 TeV gluino @ 5σ

Exploring the **Stop Coannihilation Strip**

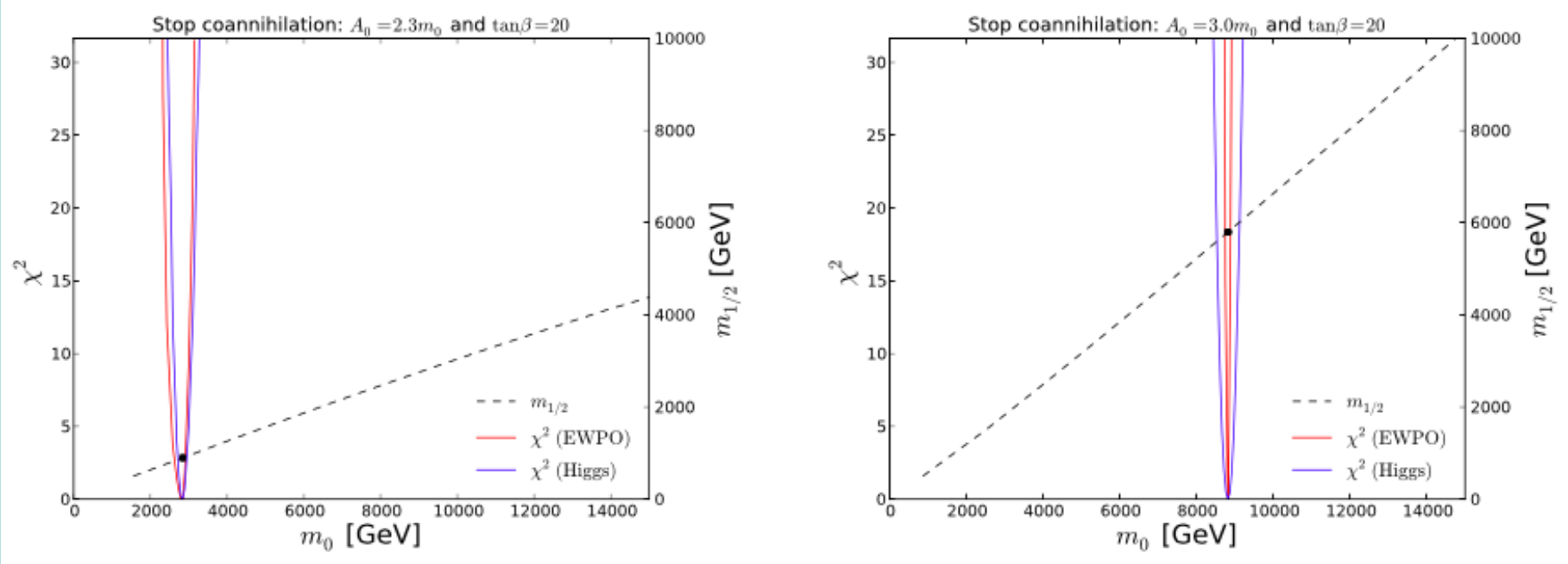


- Compatible with LHC measurement of m_h
- May extend to $m_\chi = m_{stop} \sim 6500$ GeV

JE, Olive & Zheng: arXiv:1404.5571

Impact of Precision and Higgs Measurements

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



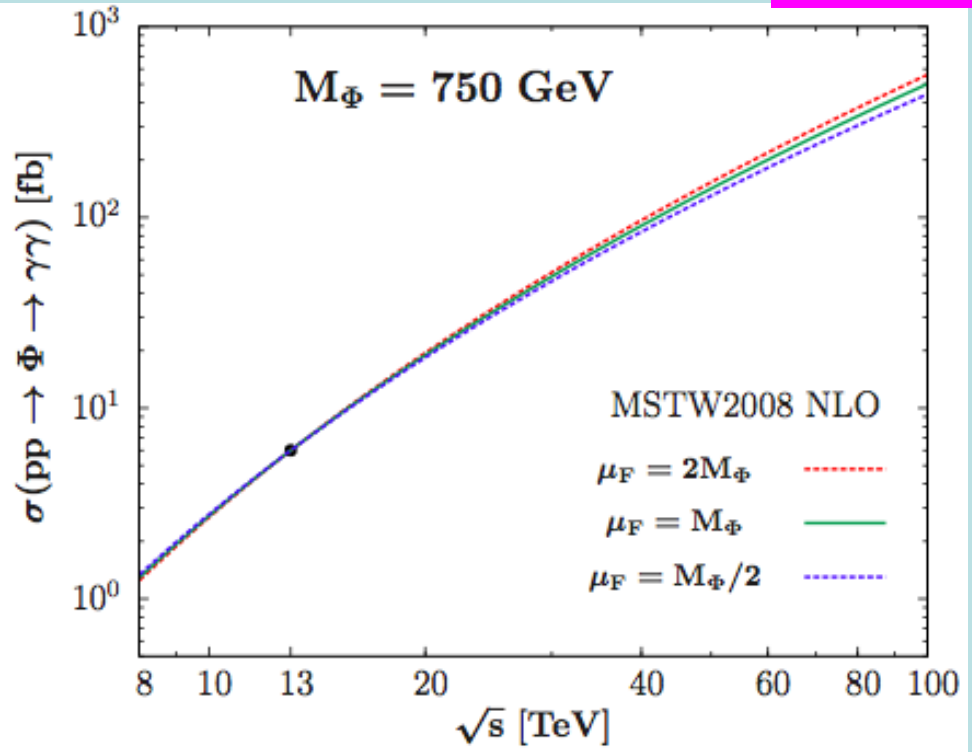
- **FCC-ee vs FCC-hh: possible test of supersymmetry at the loop level**

Buchmueller, JE et al: arXiv:1505.04702

Possible Future X Signal

- Assuming production by gluon-gluon fusion
- Normalized to $\sigma B(\gamma\gamma) = 6$ fb

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696



- PDF, ren'n scale uncertainties @ 100 TeV ~ 30%

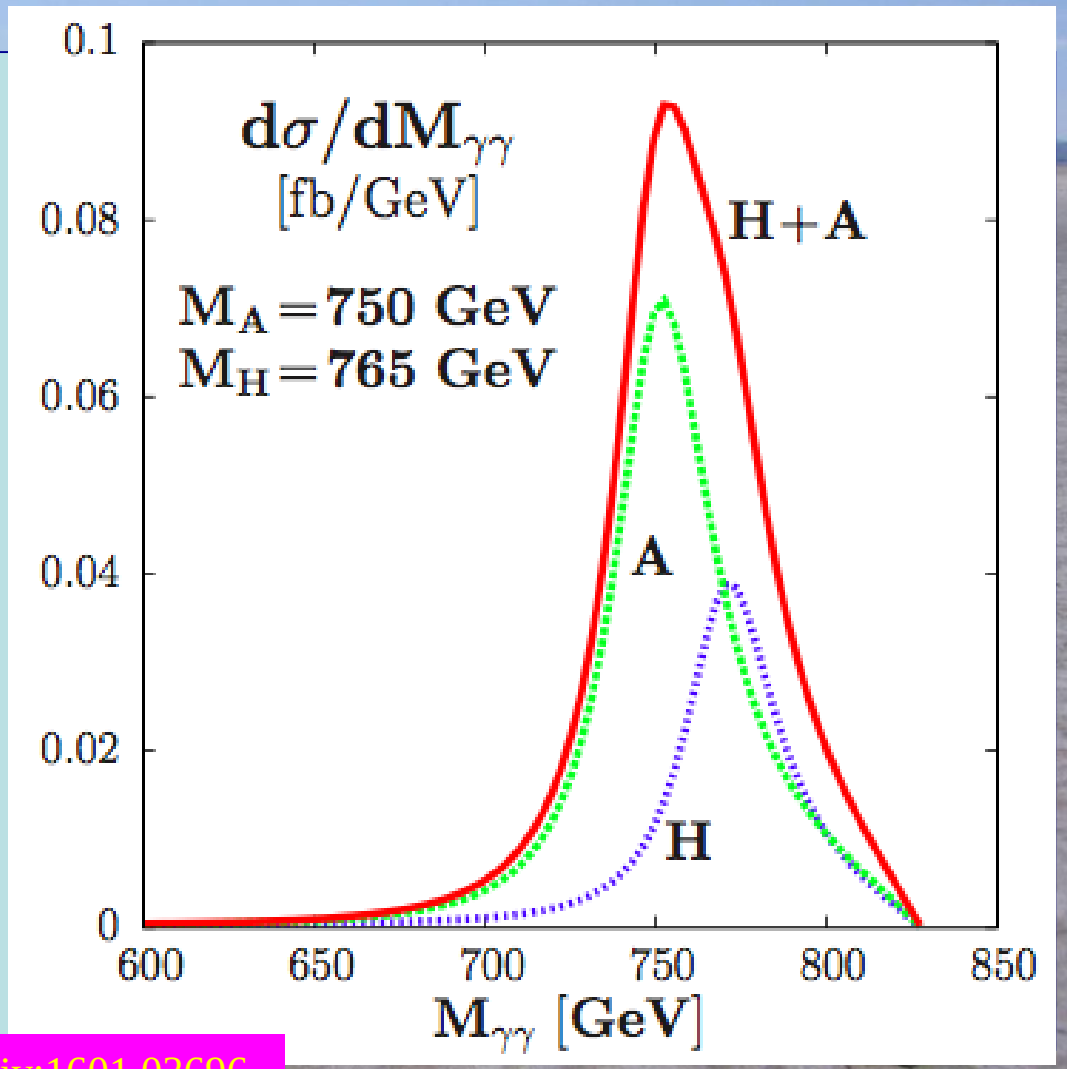
Alternative Higgs Doublet Scenario

- After singlet, doublet?
- Heavy Higgses in 2 Higgs doublet model: $\Phi = H, A$
- Nearly degenerate in many versions, e.g., SUSY
- Expect t tbar decays to dominate
- Can accommodate $\Gamma_\Phi \sim 45$ GeV (ATLAS)
- Need larger enhancement of loops compared to singlet model
- **Rich bosonic phenomenology**

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

Lineshape in *pp* Collisions

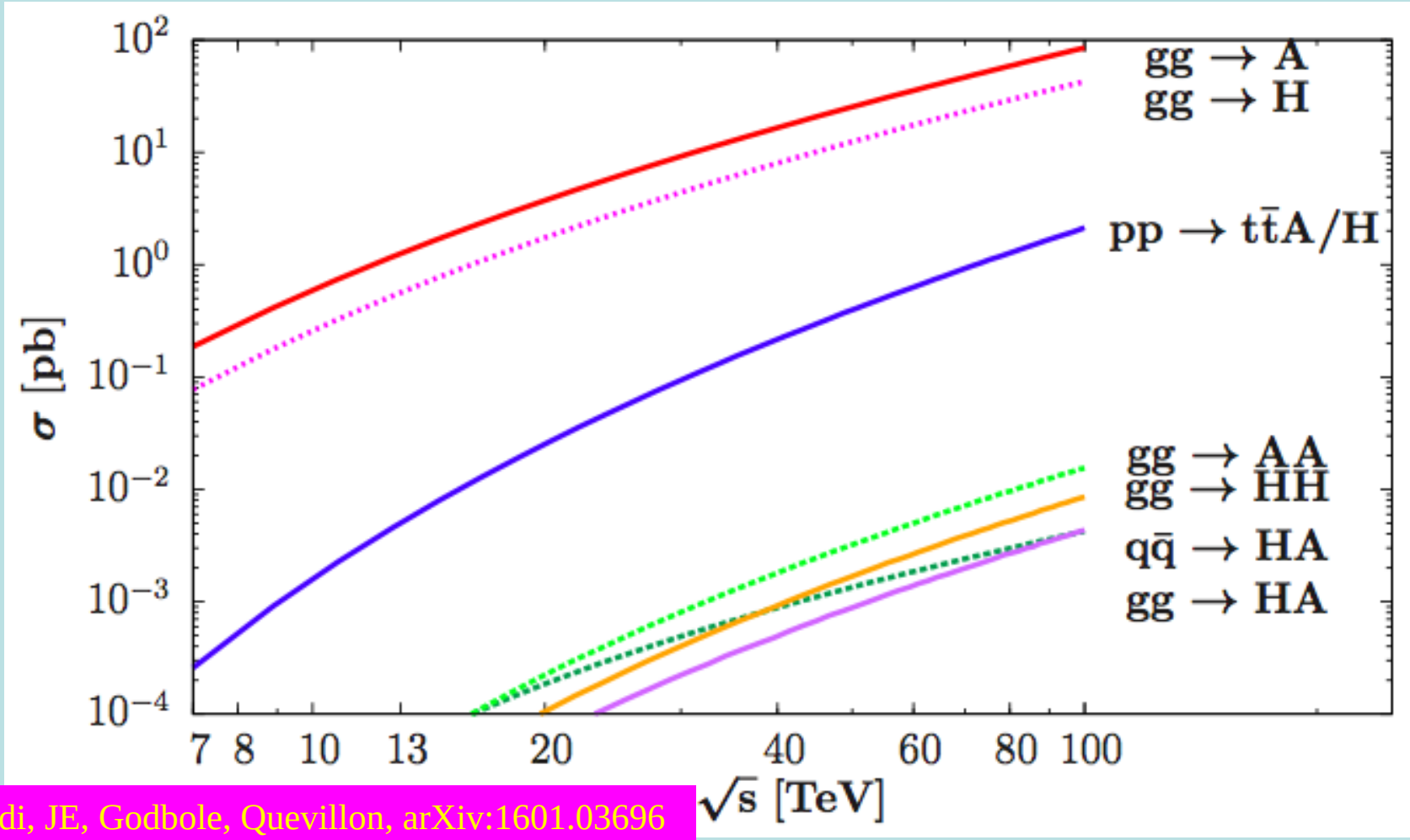
- +MSSM: tan β = 1
- $M_H - M_A \sim 15$ GeV
- $\Gamma_H, \Gamma_A \sim 32, 35$ GeV
- $\sigma B(A \rightarrow \gamma\gamma) = 2 \times \sigma B(H \rightarrow \gamma\gamma)$
- Asymmetric ‘Breit-Wigner’
- **Resolvable?**



Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

Possible Φ = H,A Signals

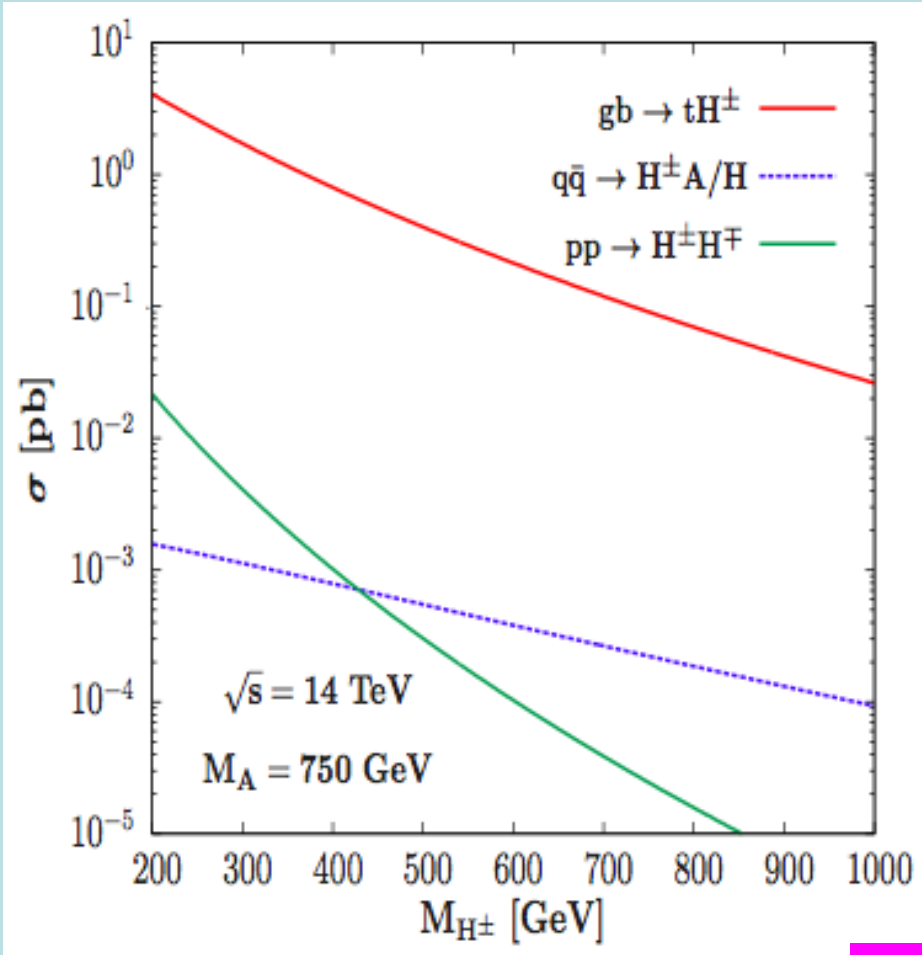
- Normalized to σB(γγ) = 6 fb @ 13 TeV

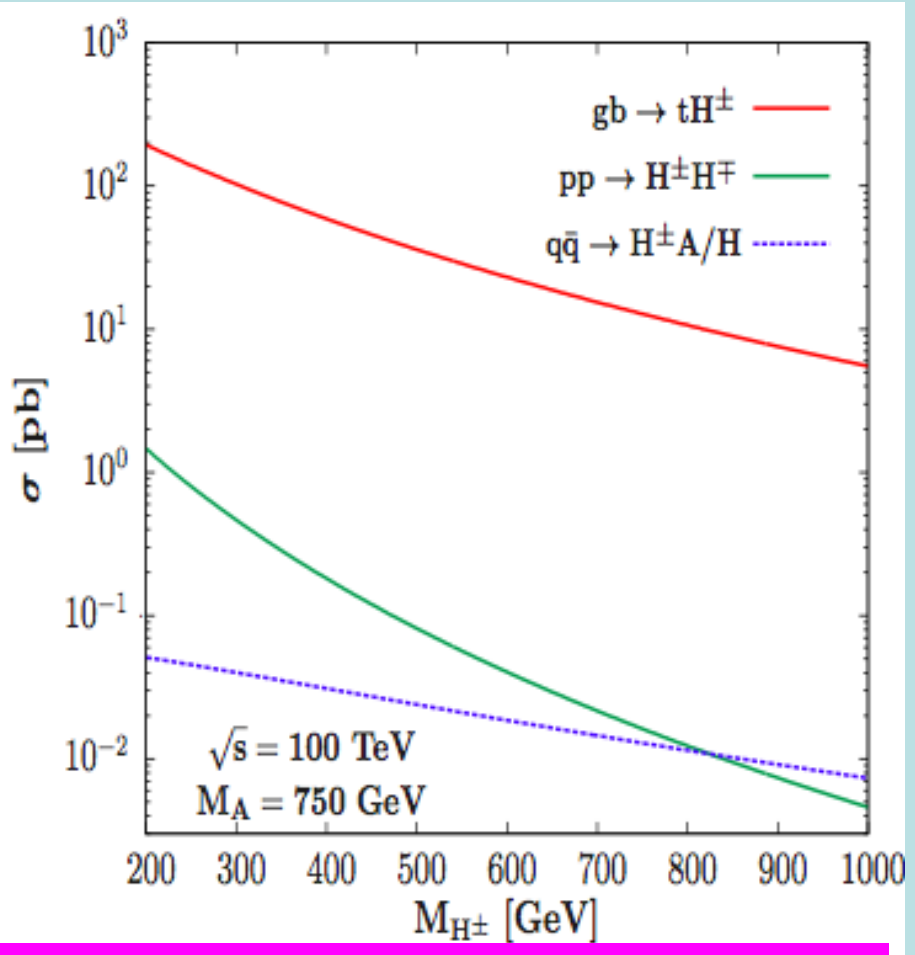


Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

Possible $H^{\pm}$ Signals

- @ 14, 100 TeV for varying $M_{H\pm} \neq M_{\Phi}$ in general

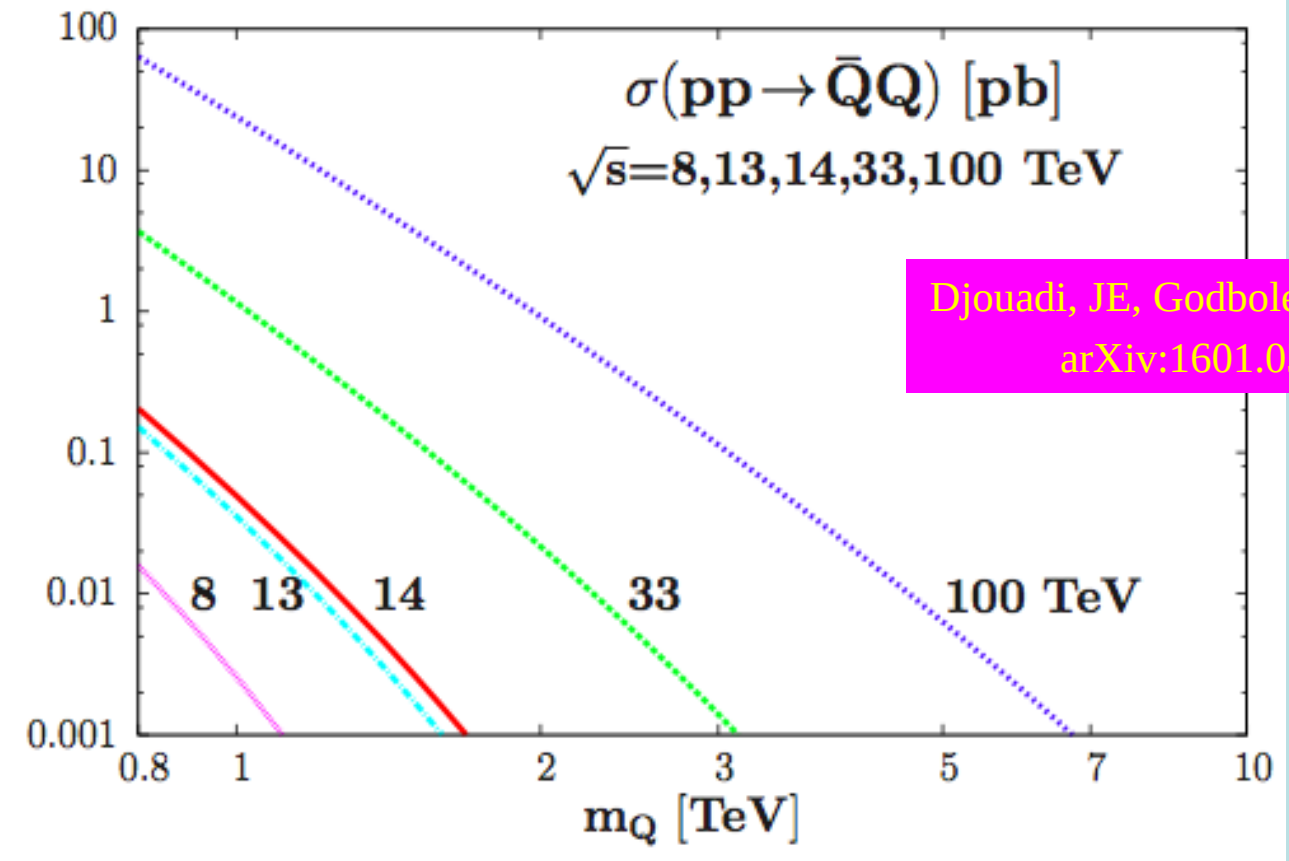




Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

Cross Sections for Vector-Like Q

- Pair-production at LHC, future circular colliders

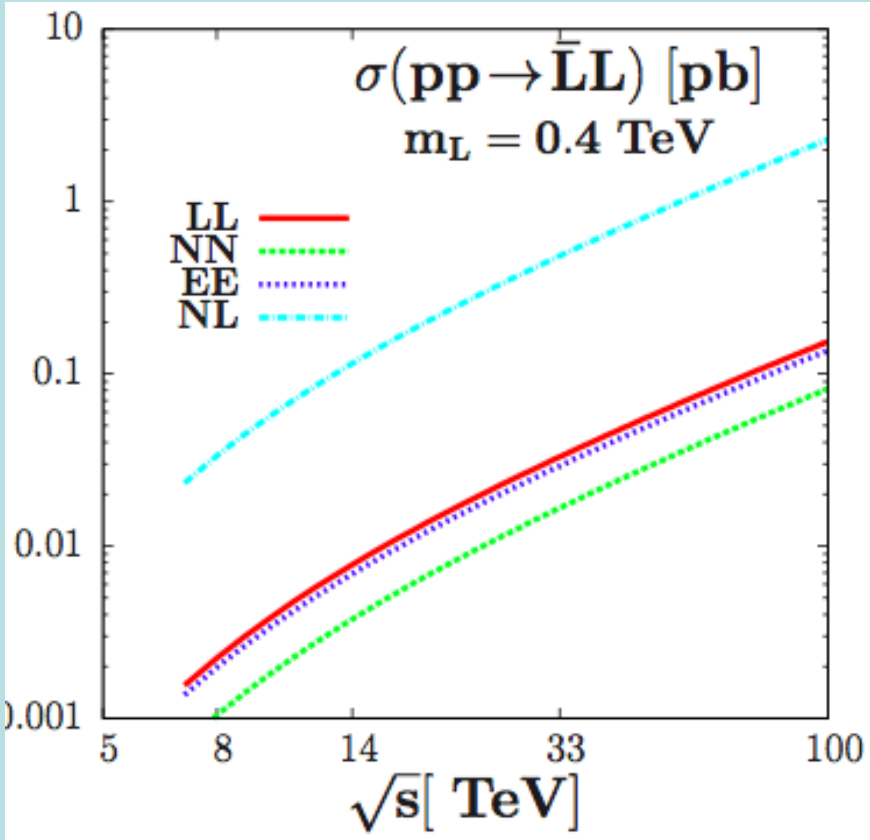


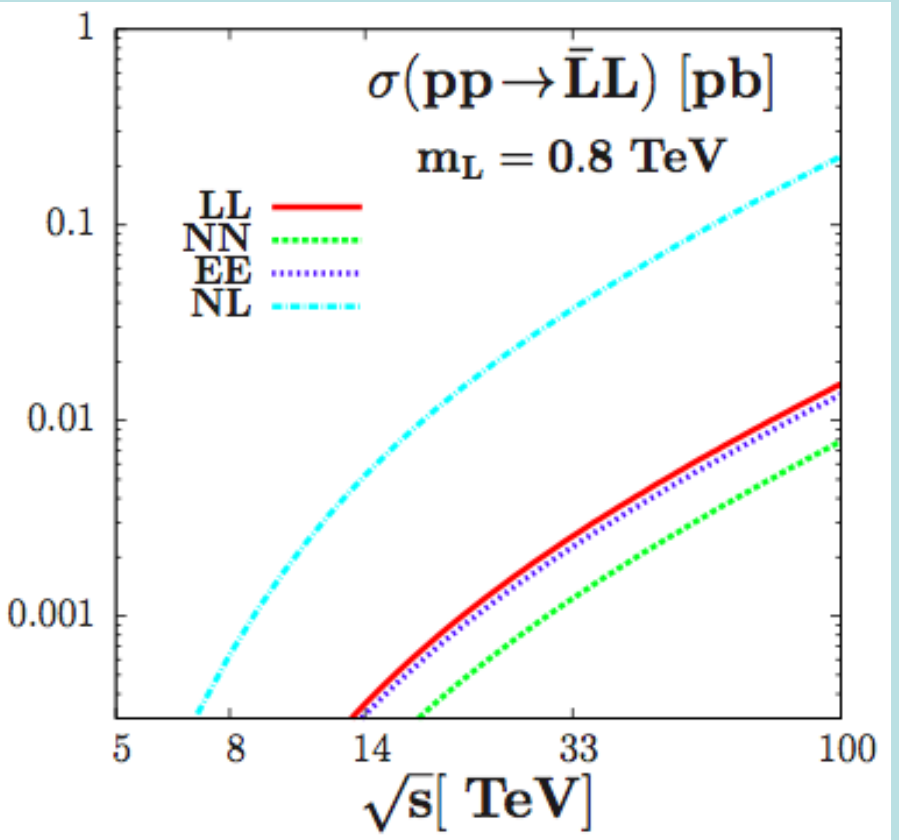
Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

- Present lower mass limit ~ 800 GeV

Cross Sections for Vector-Like L

- Pair-production at LHC, future circular colliders





- Present mass limit < 400 GeV

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

Indirect Sensitivity of FCC-ee?

- To mixing between H(125) and X(750)?
- To vector-like fermions via electroweak precision and Higgs measurements?
- To other indirect effects in two-Higgs doublet models?
- Other models?
- **Should we wait and see?**

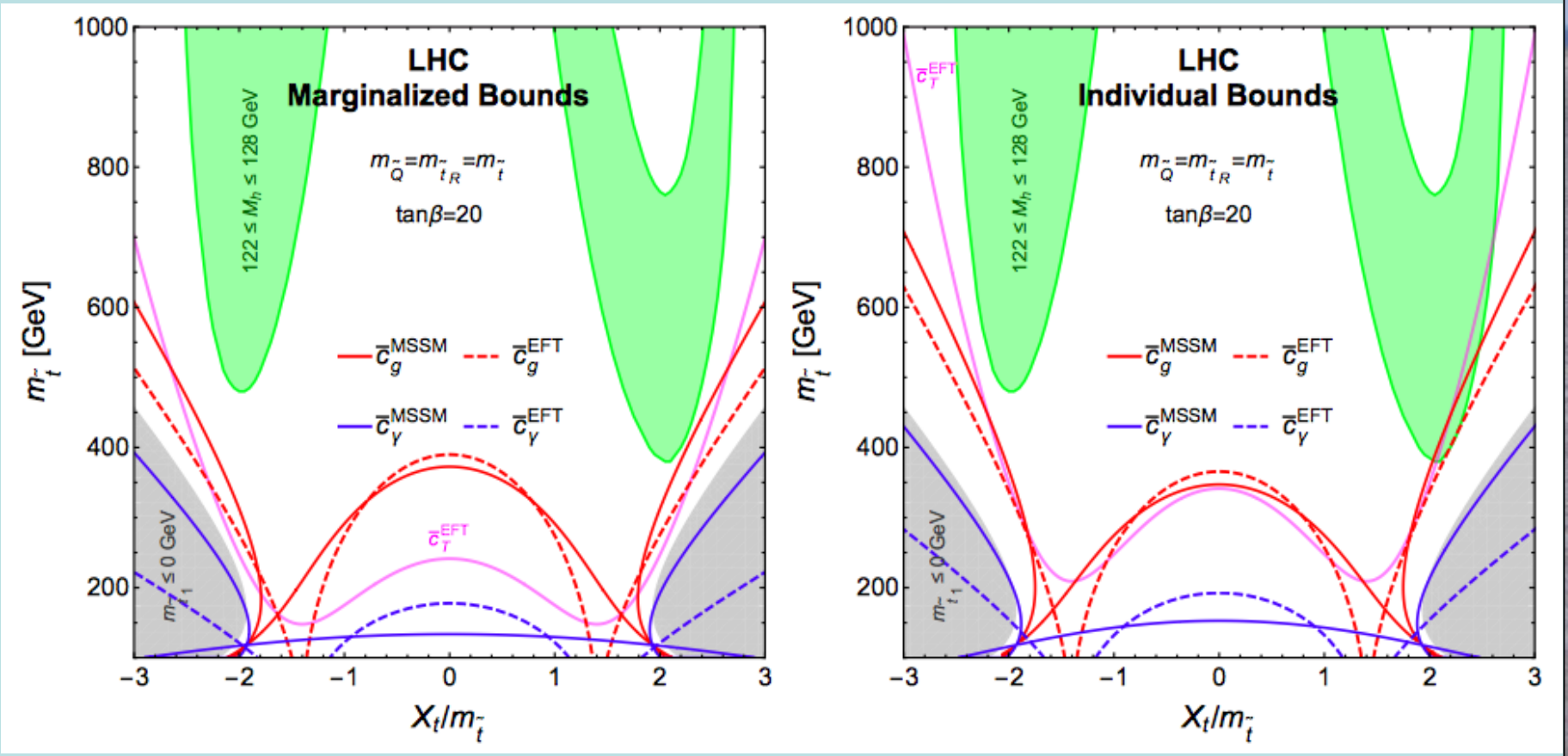
Global Analysis, Combination & Complementarity

- 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, X(750) (?)
- Effort needed from both sides:
  - Accuracy of possible FCC-hh measurements?
  - FCC-ee sensitivity to new physics ≠ H, SUSY
- **If X(750) exists, it will change everything!**

Back-ups

Indirect Stop Limits from Precision EW Data

- Solid lines = full calculation, dashed lines = EFT



Drozd, JE, Quevillon & You: arXiv:1504.02409

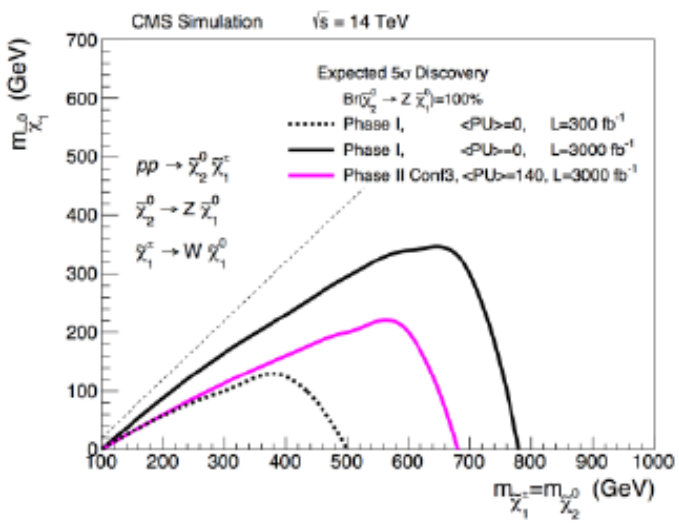
Possible FCC-ee Precision Measurements

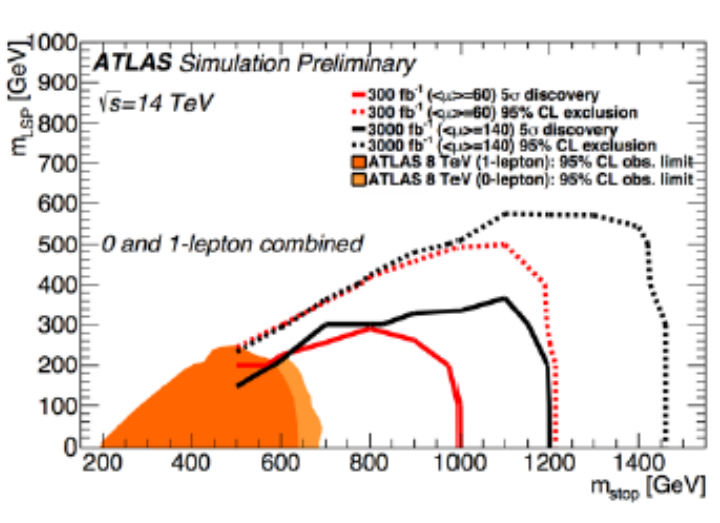
- Conservatively based on LEP experience so far – it is just a start. Much work ahead.

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%	?	$\alpha_s(m_Z)$

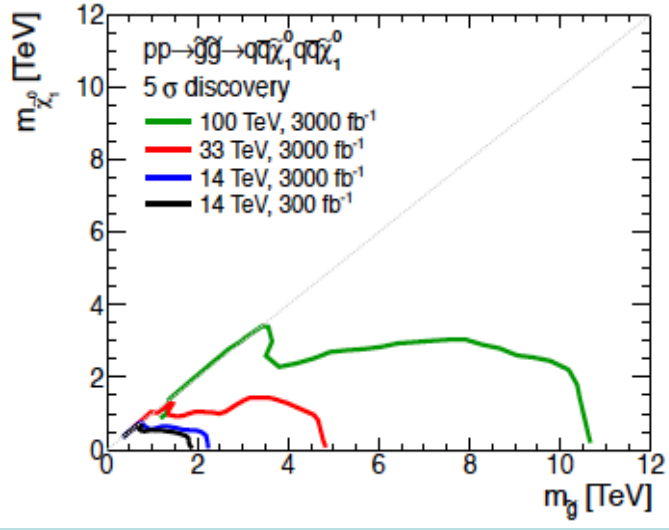
Reaches for Sparticles

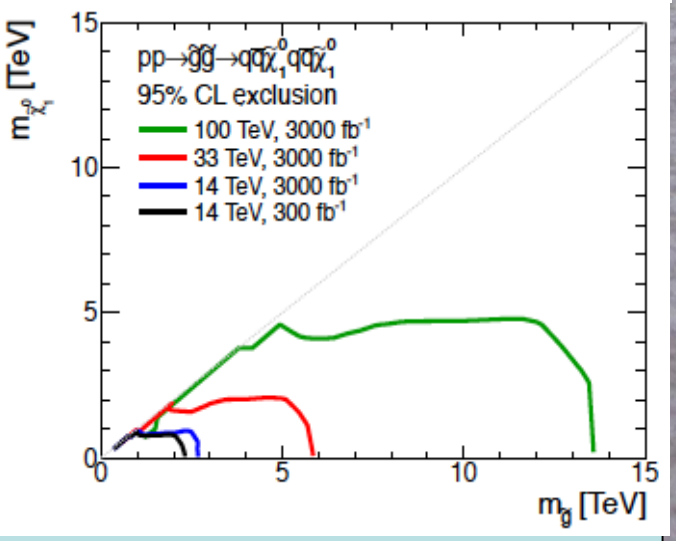
LHC:



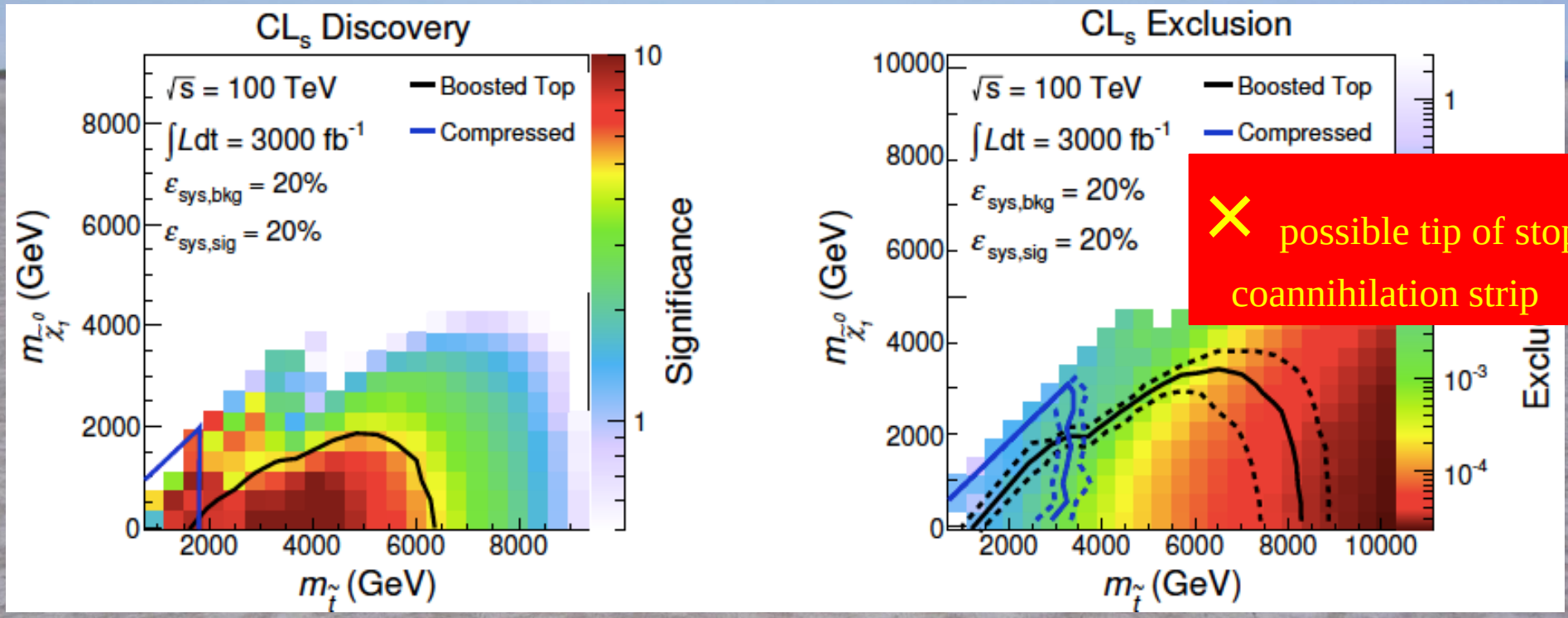


HE-LHC, FCC-hh





Reach for the Stop

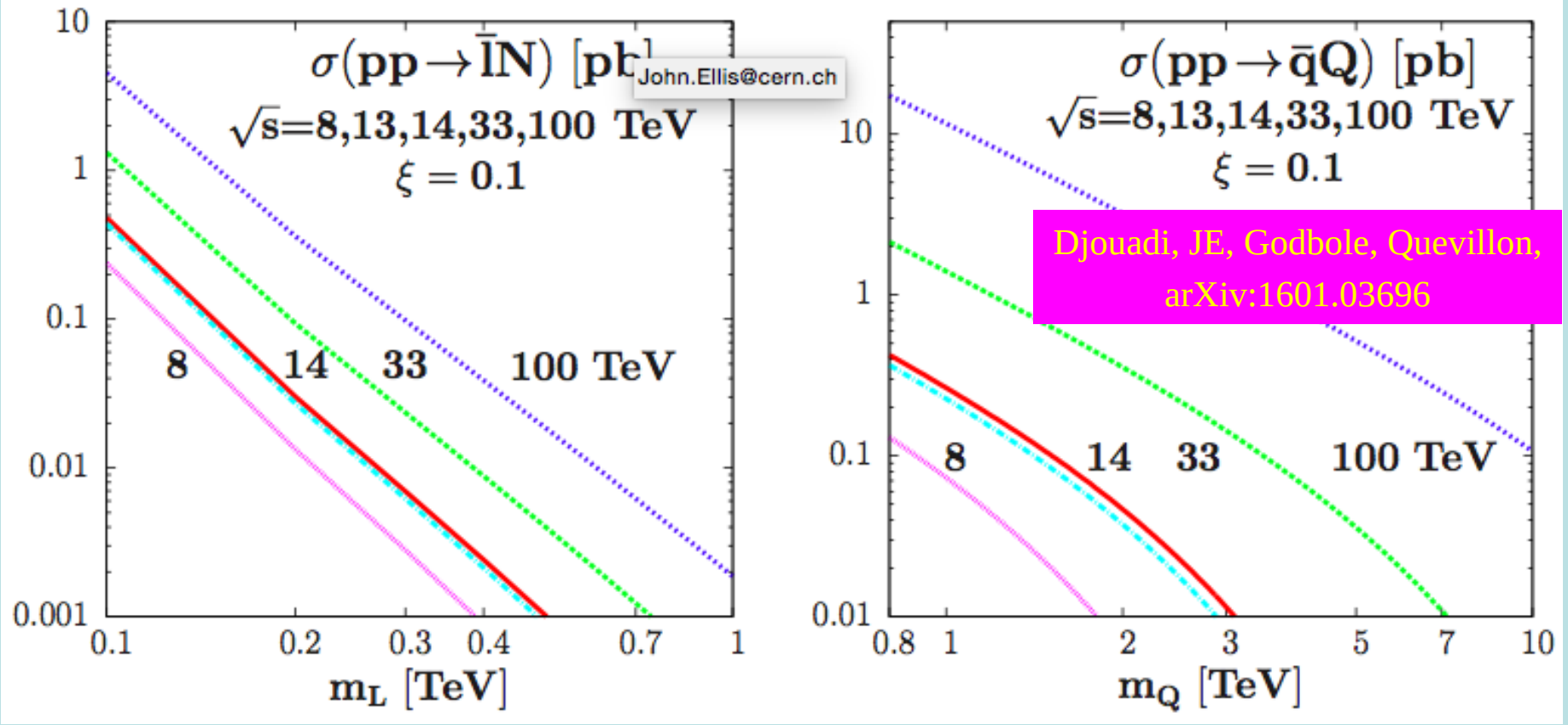


Discover 6.5 TeV stop @ 5σ, exclude 8 TeV @ 95%

Stop mass up to 6.5 TeV possible along coannihilation strip

Single Vector-Like Q, L Production

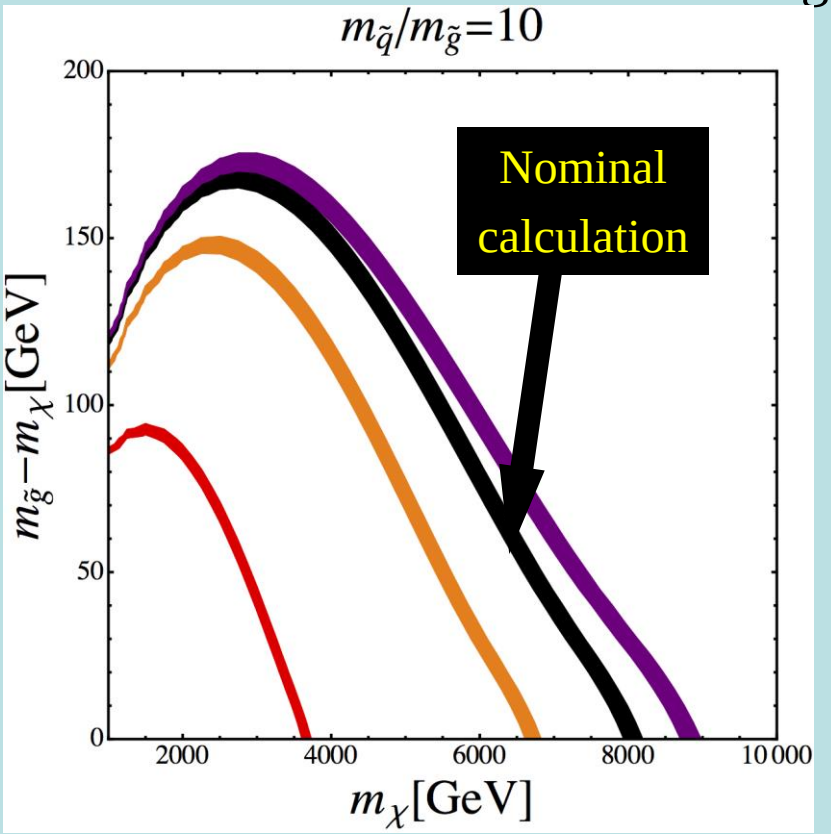
- Single production at LHC, future circular colliders

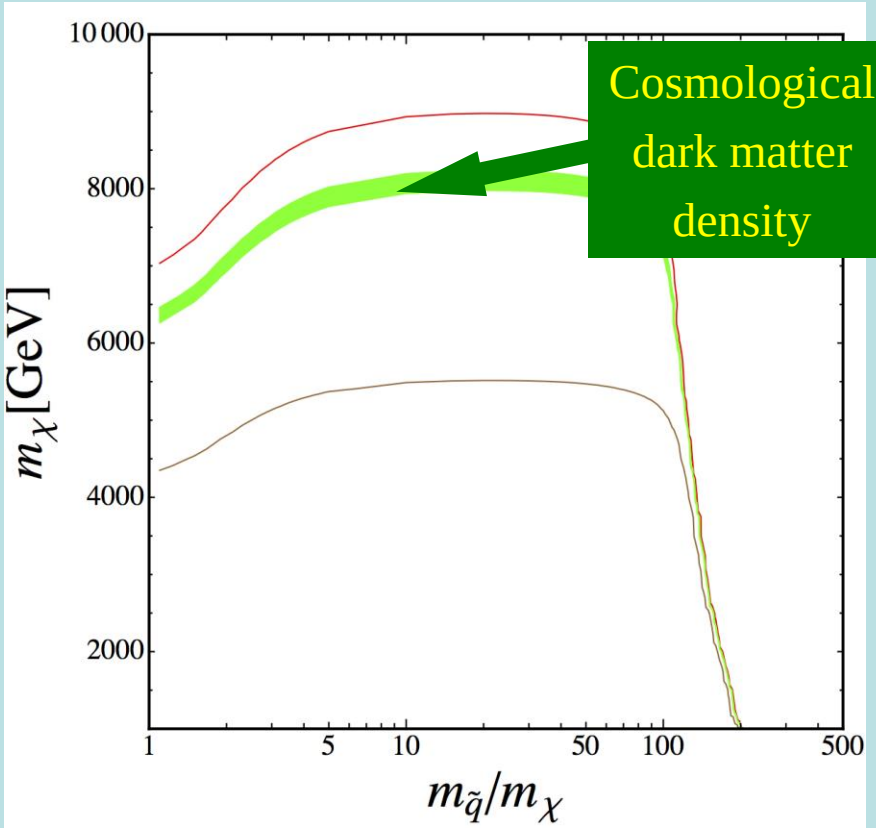


- Assuming mixing angle with light fermions $\xi = 0.1$

How Heavy could Dark Matter be in pMSSM?

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



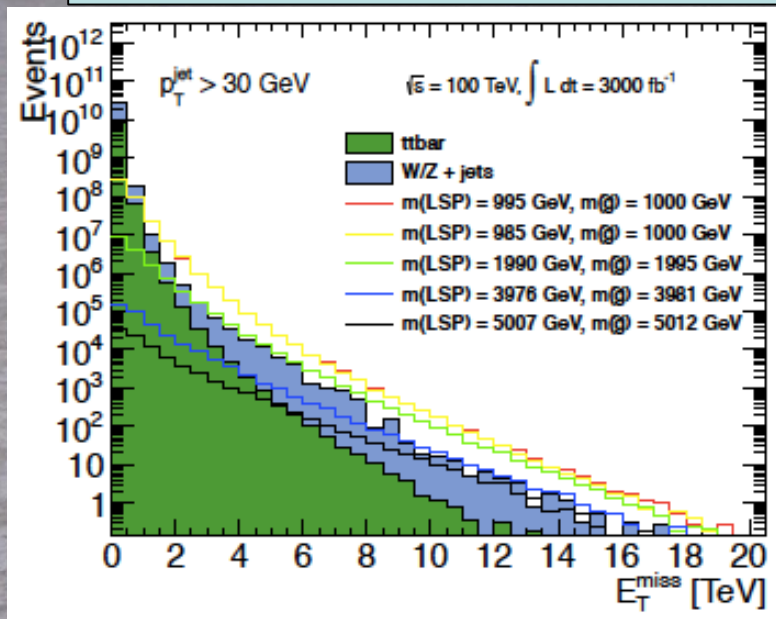


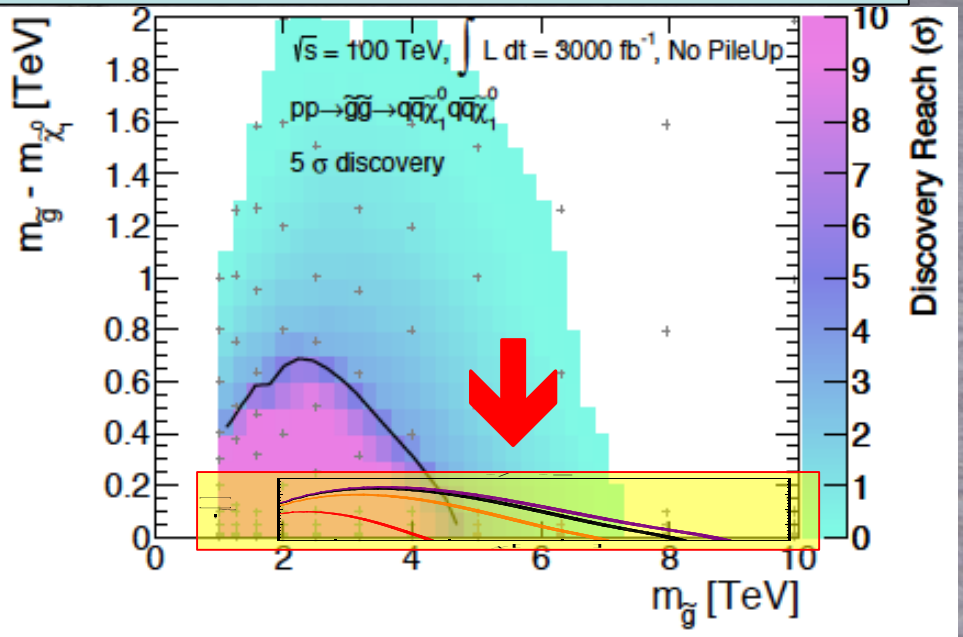
- **Extends to $m_{\chi} = m_{gluino} \sim 8$ TeV**

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