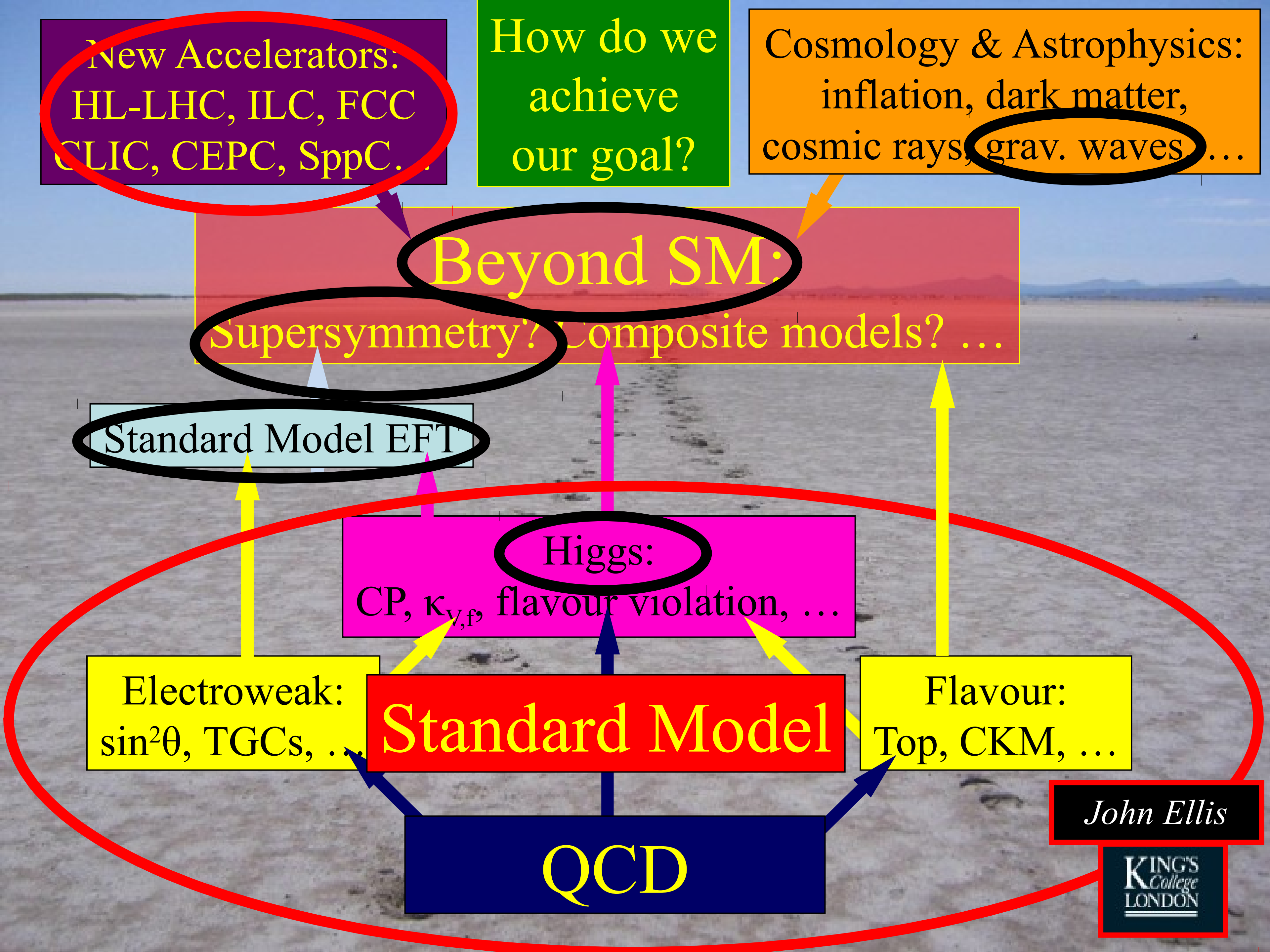
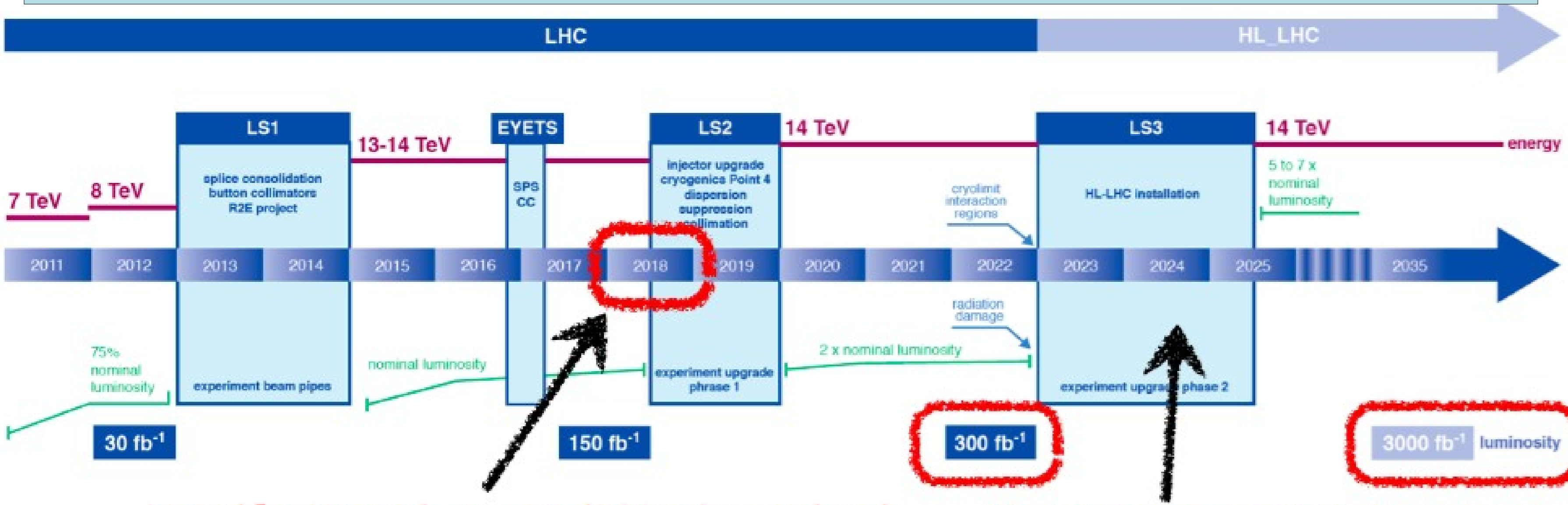

New Accelerators:
HL-LHC, ILC, FCC
CLIC, CEPC, SppC…
How do we achieve our goal?
Cosmology & Astrophysics:
inflation, dark matter,
cosmic rays, grav. waves, …
Beyond SM:
Supersymmetry? Composite models? …
Standard Model EFT
Higgs:
CP, $\kappa_{V,f}$, flavour violation, …
Electroweak:
$\sin^2\theta$, TGCs, …
Standard Model
Flavour:
Top, CKM, …
QCD
John Ellis
KING'S College LONDON

HL-LHC Plans



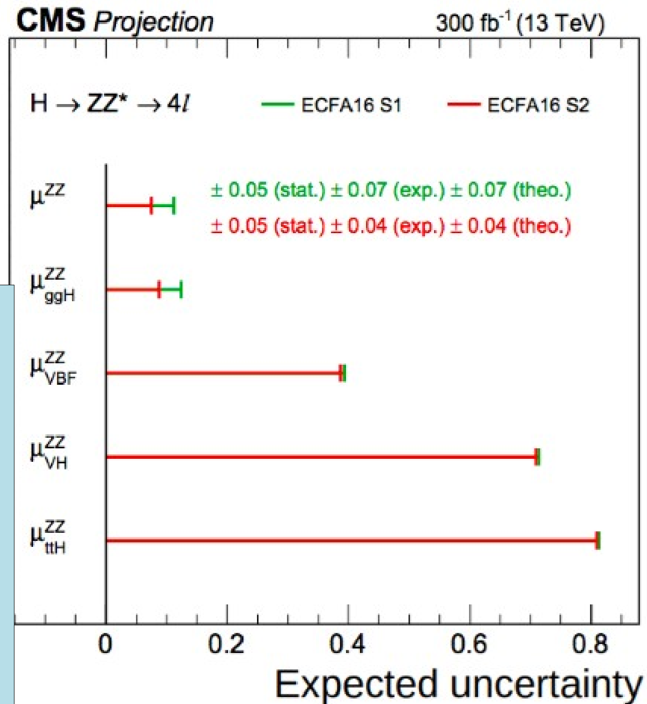
Now (√s=13 TeV), <μ>~38 (2017 data-taking)

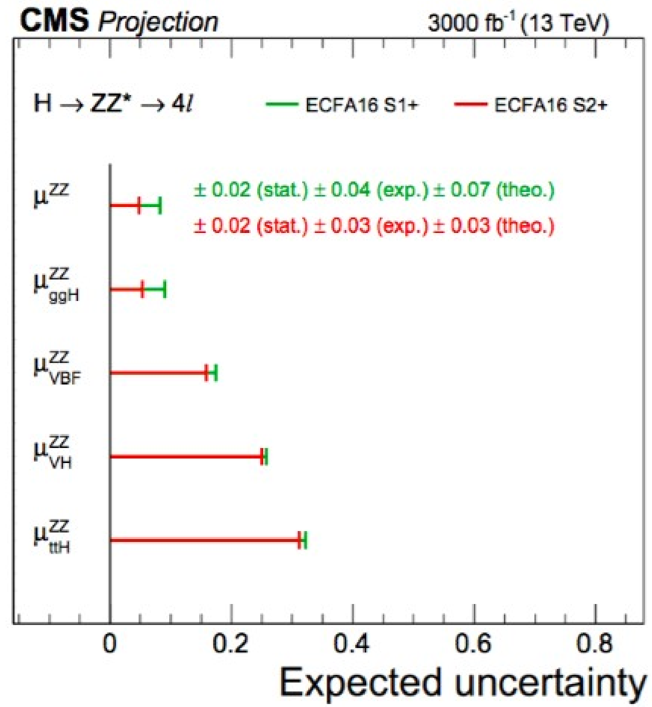
Phase-II Atlas and CMS Upgrade

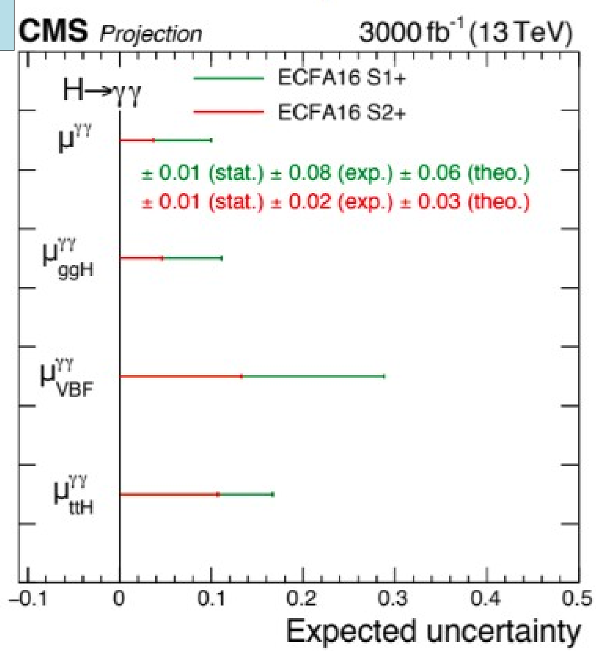
	Peak luminosity (cm^{-2} s^{-1})	μ (pile-up)
Current	$1.3 \cdot 10^{34}$	~40
HL-LHC baseline	$5 \cdot 10^{34}$	140
HL-LHC ultimate	$7.5 \cdot 10^{34}$	200

- Increased instantaneous luminosity and mean number of interactions per bunch-crossing (pile-up)
- Integrated luminosity collected during HL-LHC ~ 3000 fb^{-1}
- Precision measurements on the Higgs sector (couplings, self-couplings, VBF production), rare-decays

H ➔ZZ*, γγ @HL-LHC

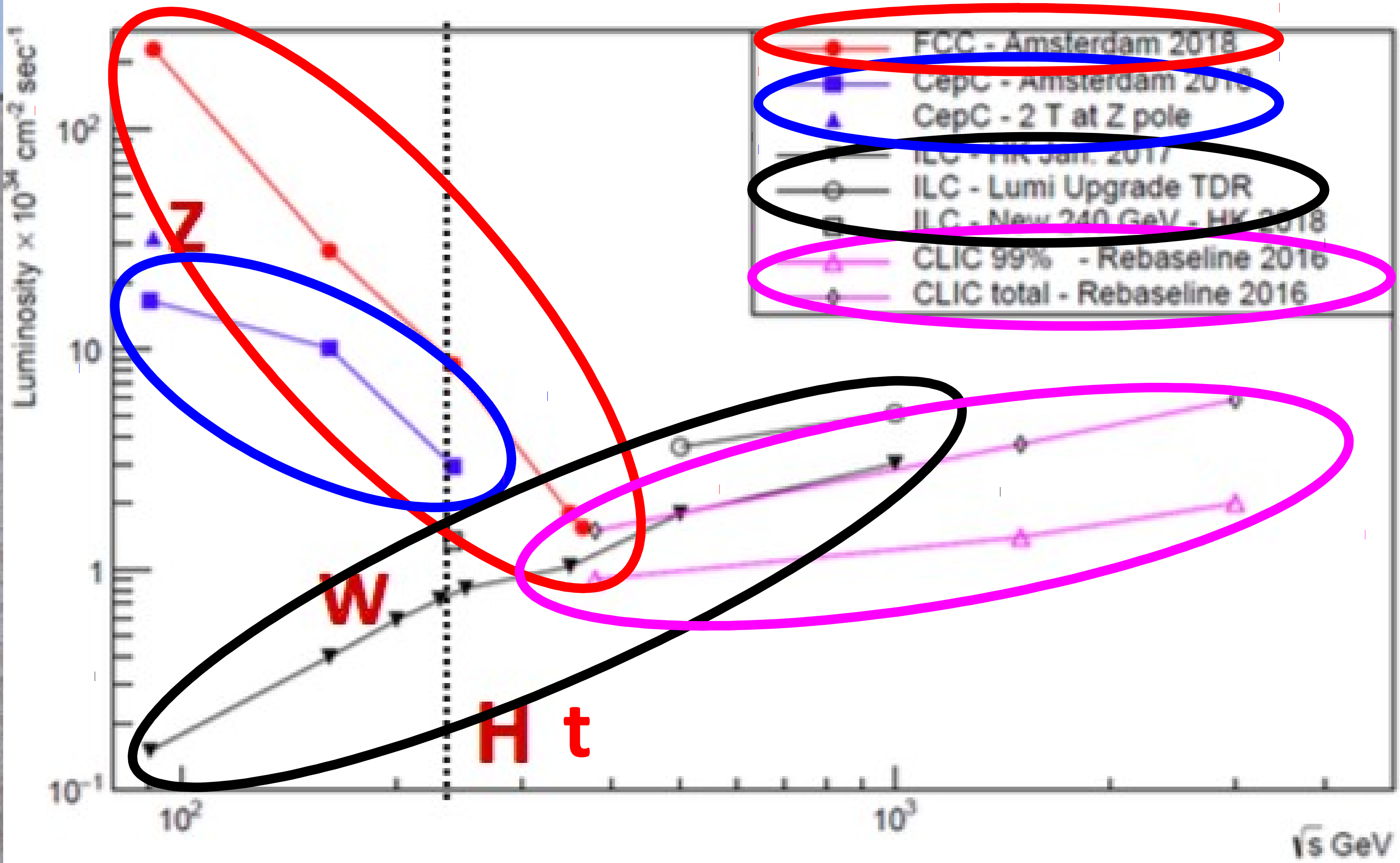




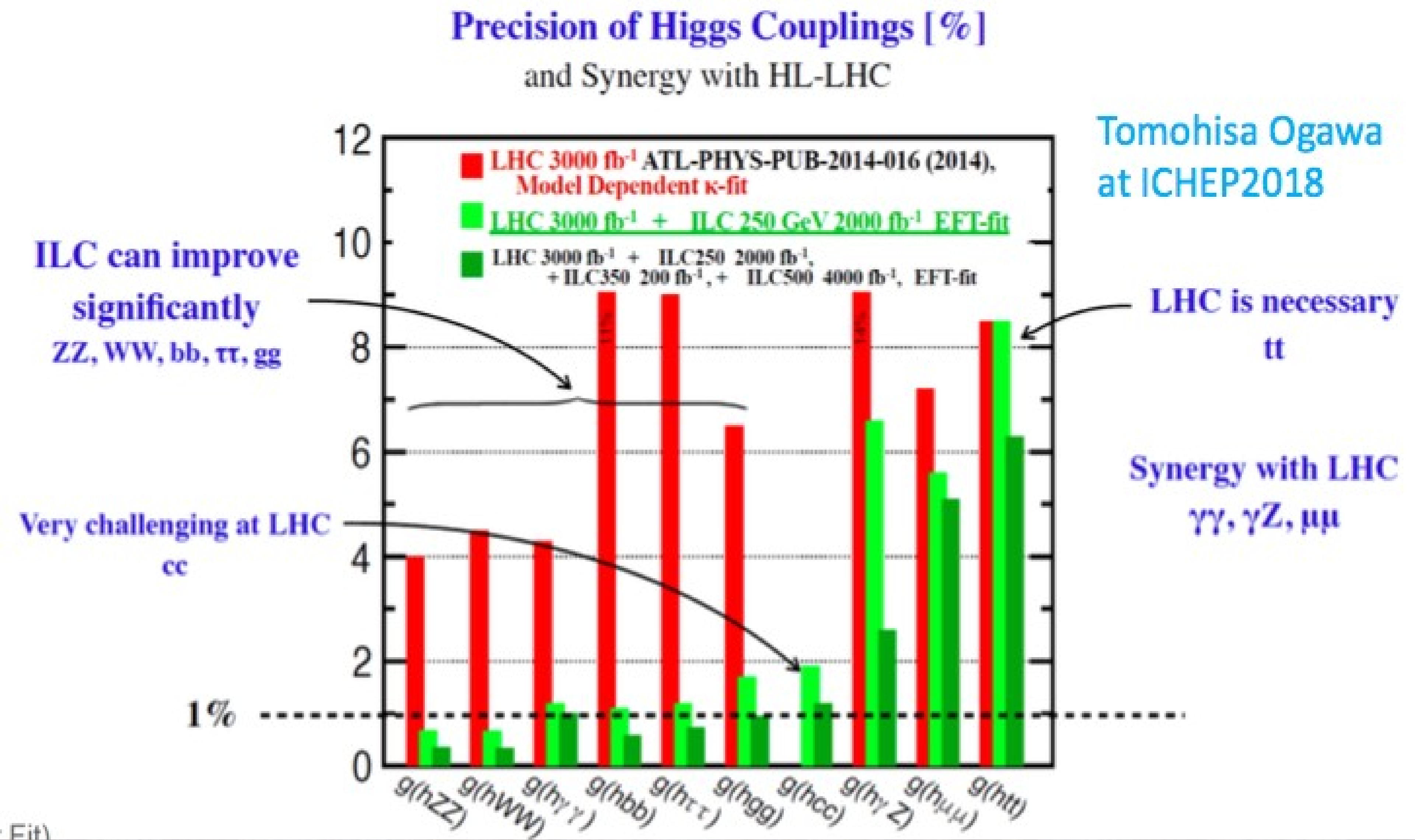


- Scenario 1+: All systematics remain constant with luminosity + some detector upgrade effects included
- Scenario 2+: Experimental nuisances scale with √L, theory uncertainties halved + some detector upgrade effects included

Projected e+e- Colliders: Luminosity vs Energy



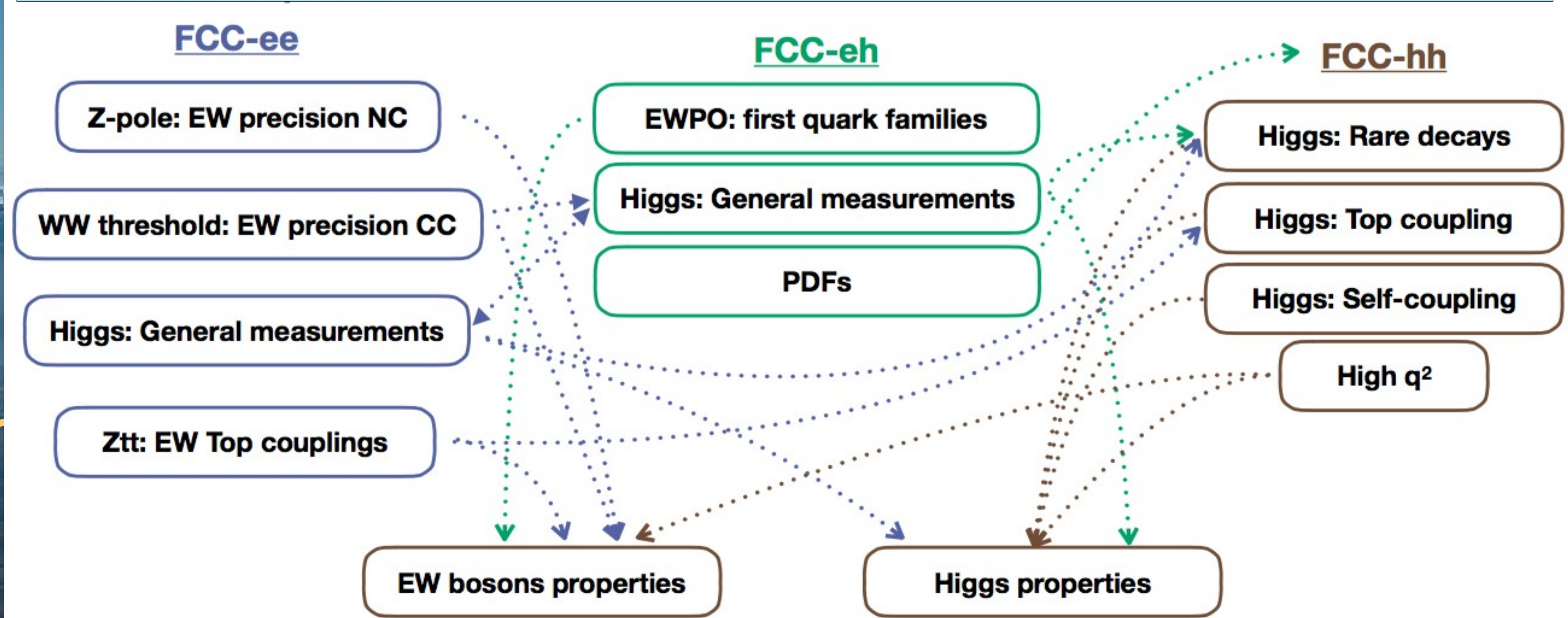
ILC Measurements of H Couplings



CEPC-SPPC

Preliminary Conceptual Design Report

Future Circular Colliders



The vision:

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

FCC-ee CDR

FCC-ee Parameters & Run Plan

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold	365 GeV
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	31	7.5	0.85	1.5
Lumi/year (2 IP)	26 ab^{-1}	52 ab^{-1}	8.1 ab^{-1}	1.95 ab^{-1}	0.22 ab^{-1}	0.39 ab^{-1}
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	1	4

FCC-ee CDR

Possible FCC-ee Precision Measurements

	Observable	Measurement	Current precision	FCC-ee stat.	FCC-ee syst.	Dominant exp. error
Z pole	m_Z (keV)	Z Lineshape	91187500 ± 2100	5	< 100	Beam energy
	Γ_Z (MeV)		2495200 ± 2300	8	< 100	Beam energy
	R_l ($\times 10^3$)		20767 ± 25	0.06	0.2 – 1	Detector acceptance
	R_b ($\times 10^6$)		216290 ± 660	0.3	< 60	$g \to bb$
	N_ν ($\times 10^3$)		2984 ± 8	0.005	1	Lumi measurement
	$\sin^2\theta_W^{eff}$ ($\times 10^6$)		231480 ± 160	3	2 – 5	Beam energy
	$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)		128952 ± 14	4	< 1	Beam energy
	$\alpha_s(m_Z)$ ($\times 10^4$)	R_l	1196 ± 30	0.1	0.4 – 1.6	Same as R_l
WW thresh.	m_W (MeV)	WW Threshold scan	80385 ± 15	0.6	0.3	Beam energy
	Γ_W (MeV)	n	2085 ± 42	1.5	0.3	Beam energy
	N_ν ($\times 10^3$)	ll	2920 ± 50	0.8	small	?
	$\alpha_s(m_W)$ ($\times 10^4$)		1170 ± 420	2	small	CKM Matrix
$t\bar{t}$ thresh.	m_{top} (MeV)	Top Threshold scan	173340 ± 760 ± 500	17	< 40	QCD corr.
	Γ_{top} (MeV)	n	?	45	< 40	QCD corr.
	λ_{top}	n	μ = 1.28 ± 0.25	0.10	< 0.05	QCD corr.
	ttZ couplings		± 30%	0.5 – 1.5 %	< 2%	QCD corr

Z peak ± 4 GeV for α_{EM}, line shape

WW threshold

t tbar threshold

Precision Electroweak Measurements with FCC-ee

Blondel et al, arXiv:1809.01830

BU-HEPP-18-04, CERN-TH-2018-145, IFJ-PAN-IV-2018-09, KW 18-003
MITP/18-052, MPP-2018-143, SI-HEP-2018-21

Standard Model Theory for the FCC-ee: The Tera-Z

Report on the 1st Mini workshop: Precision EW and QCD calculations for the FCC studies: methods and tools, 12-13 January 2018, CERN, Geneva

https://indico.cern.ch/event/669224/

arXiv:1809.01830v1 [hep-ph] 6 Sep 2018

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Precision Electroweak Measurements

Present and future EWPO errors

Blondel et al, arXiv:1809.01830

	$\delta\Gamma_Z$ [MeV]	δR_l $[10^{-4}]$	δR_b $[10^{-5}]$	$\delta\sin^2\theta^{\rm l}_{\rm eff}$ $[10^{-6}]$	$\delta\sin^2\theta^{\rm b}_{\rm eff}$ $[10^{-5}]$
Present EWPO errors					
EXP1	2.3	250	66	160	1600
TH1	0.5	50	15	45	5
FCC-ee-Z EWPO error estimations					
EXP2	0.1	10	$2 \div 6$	6	70

Comparison of future EWPO errors with TH estimates

FCC-ee-Z EWPO error estimations				
	$\delta\Gamma_Z$ [MeV]	δR_l $[10^{-4}]$	δR_b $[10^{-5}]$	$\delta\sin^2\theta^{\rm l}_{\rm eff}$ $[10^{-5}]$
EXP2 [40]	0.1	10	$2 \div 6$	6
TH1-new	0.4	60	10	45
TH2	0.15	15	5	15
TH3	< 0.07	< 7	< 3	< 7

Numbers of Diagrams to be Calculated

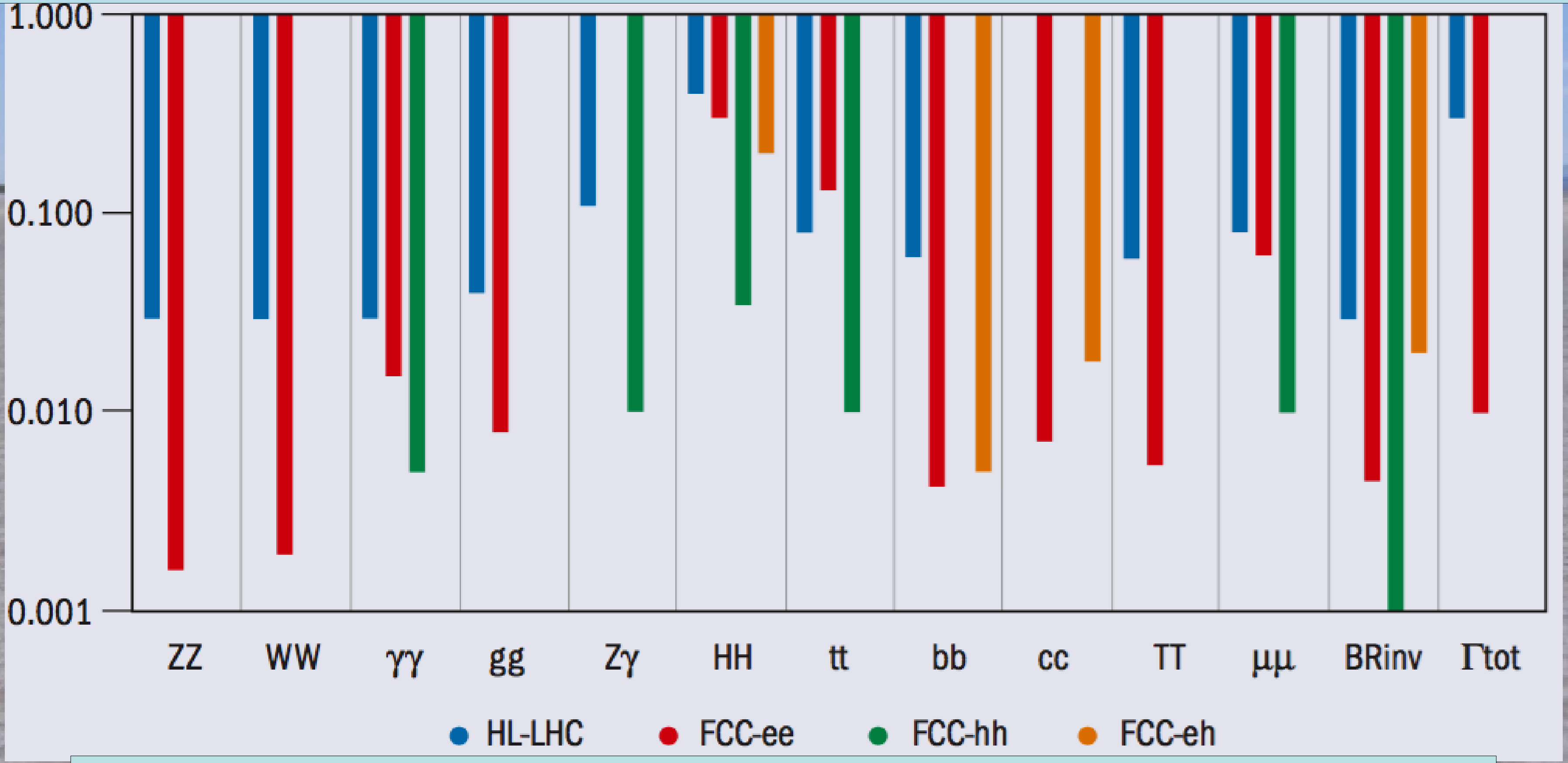
Blondel et al, arXiv:1809.01830

$Z \to b\bar{b}$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \overset{(A)}{\to} 7 \overset{(B)}{\to} 5$	$211 \overset{(A)}{\to} 84 \overset{(B)}{\to} 51$
Number of diagrams	15	$2383 \overset{(A,B)}{\to} 1074$	$490387 \overset{(A,B)}{\to} 120472$
Fermionic loops	0	150	17580
Bosonic loops	15	924	102892
Planar / Non-planar	15 / 0	981/133	84059/36413
QCD / EW	1 / 14	98 / 1016	10386/110086

$Z \to e^+e^-, \ldots$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \overset{(A)}{\to} 7 \overset{(B)}{\to} 5$	$211 \overset{(A)}{\to} 84 \overset{(B)}{\to} 51$
Number of diagrams	14	$2012 \overset{(A,B)}{\to} 880$	$397690 \overset{(A,B)}{\to} 91472$
Fermionic loops	0	114	13104
Bosonic loops	14	766	78368
Planar / Non-planar	14 / 0	782/98	65487/25985
QCD / EW	0 / 14	0 / 880	144/91328

A lot of work for theorists, but feasible!

Possible Future Higgs Measurements



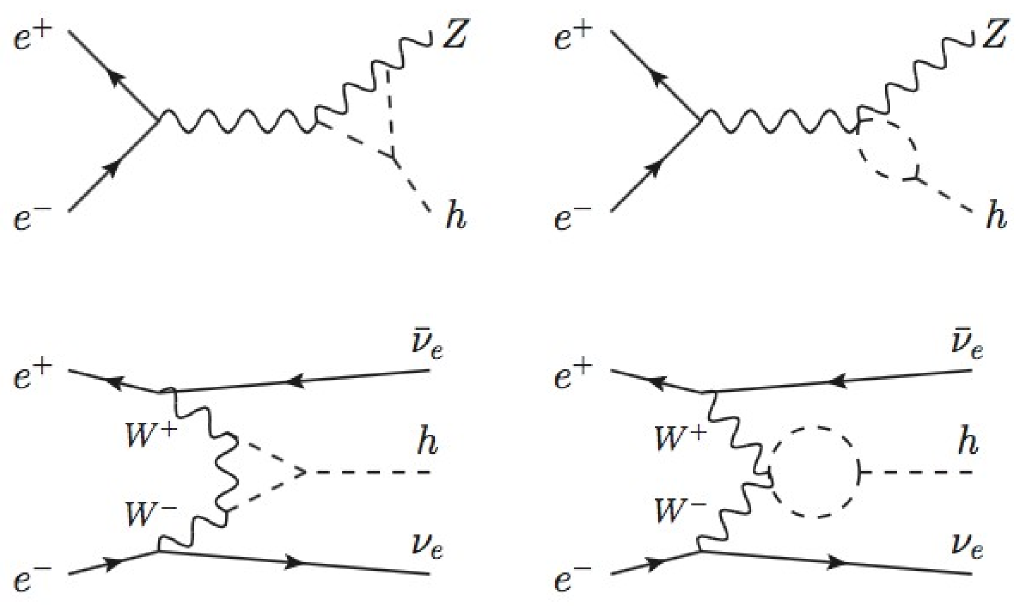
- Need to reduce theoretical uncertainties to match experimental errors
  - Needed for BSM interpretations

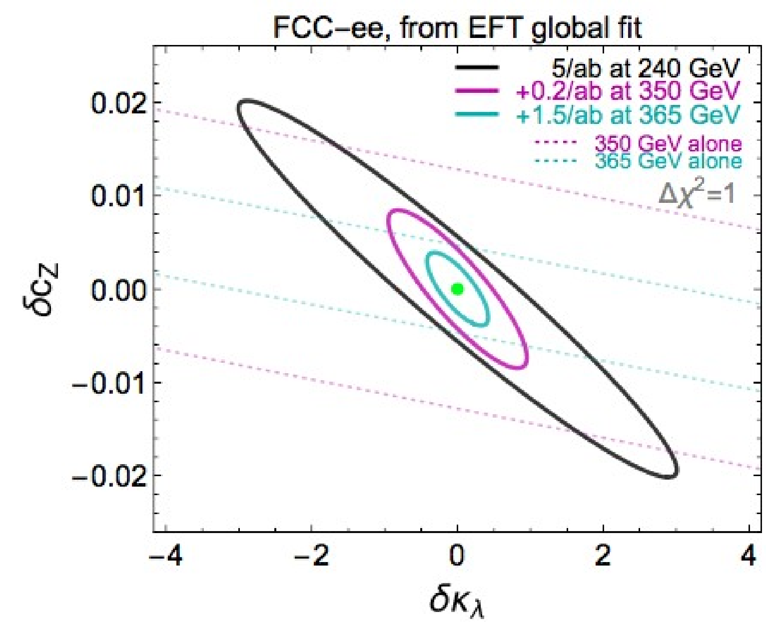
High precision at FCC-ee
Big statistics at FCC-hh

FCC-ee CDR

Sensitivity to HHH Coupling

Sensitivity through radiative corrections



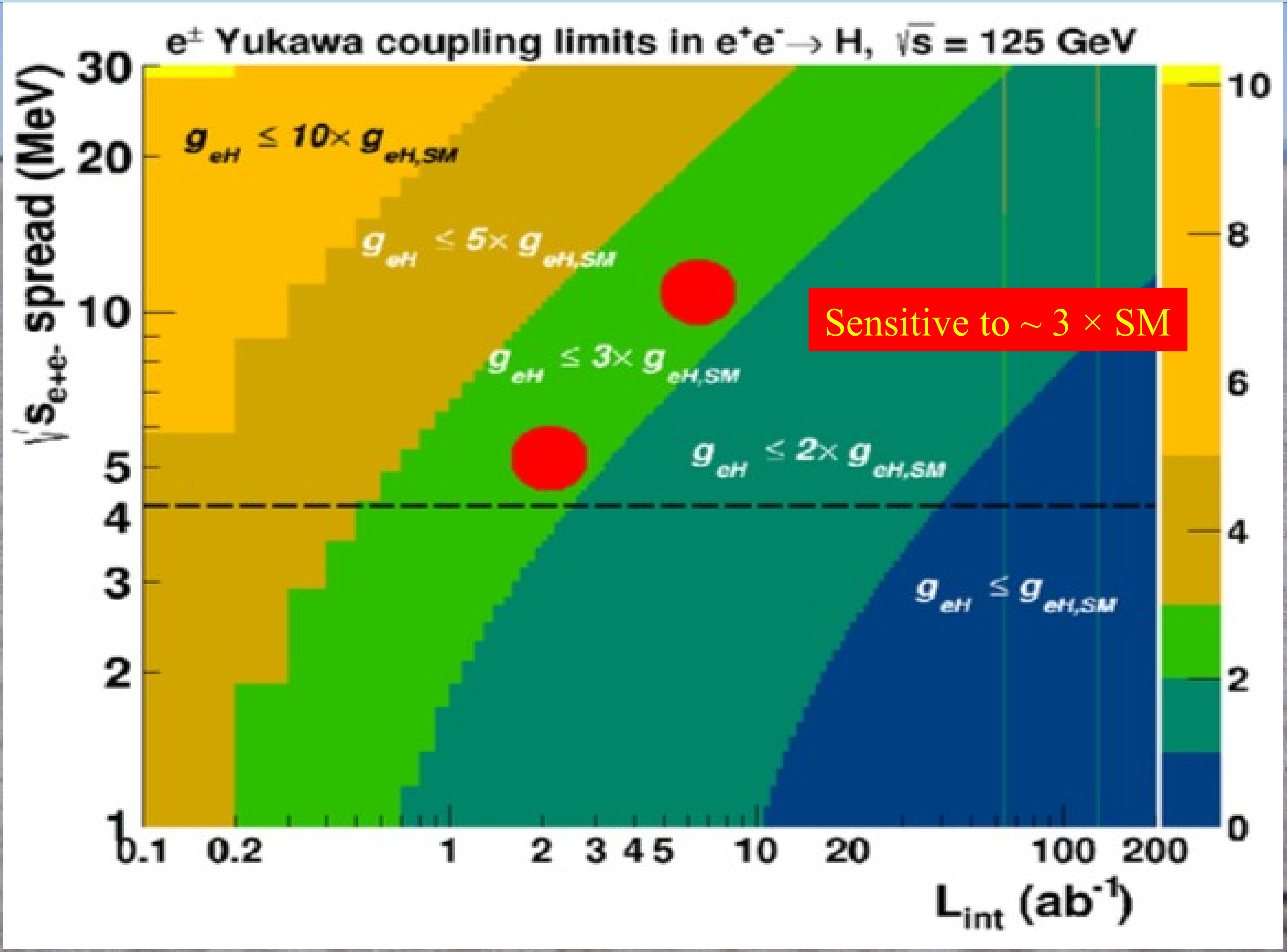


Combining all FCC-ee centre-of-mass energies: precision in κ_λ of ±40%

Improved to ±35% in combination with HL-LHC

Further improved to ±25% when c_Z fixed to SM value.

Sensitivity to e^+e^-H Coupling

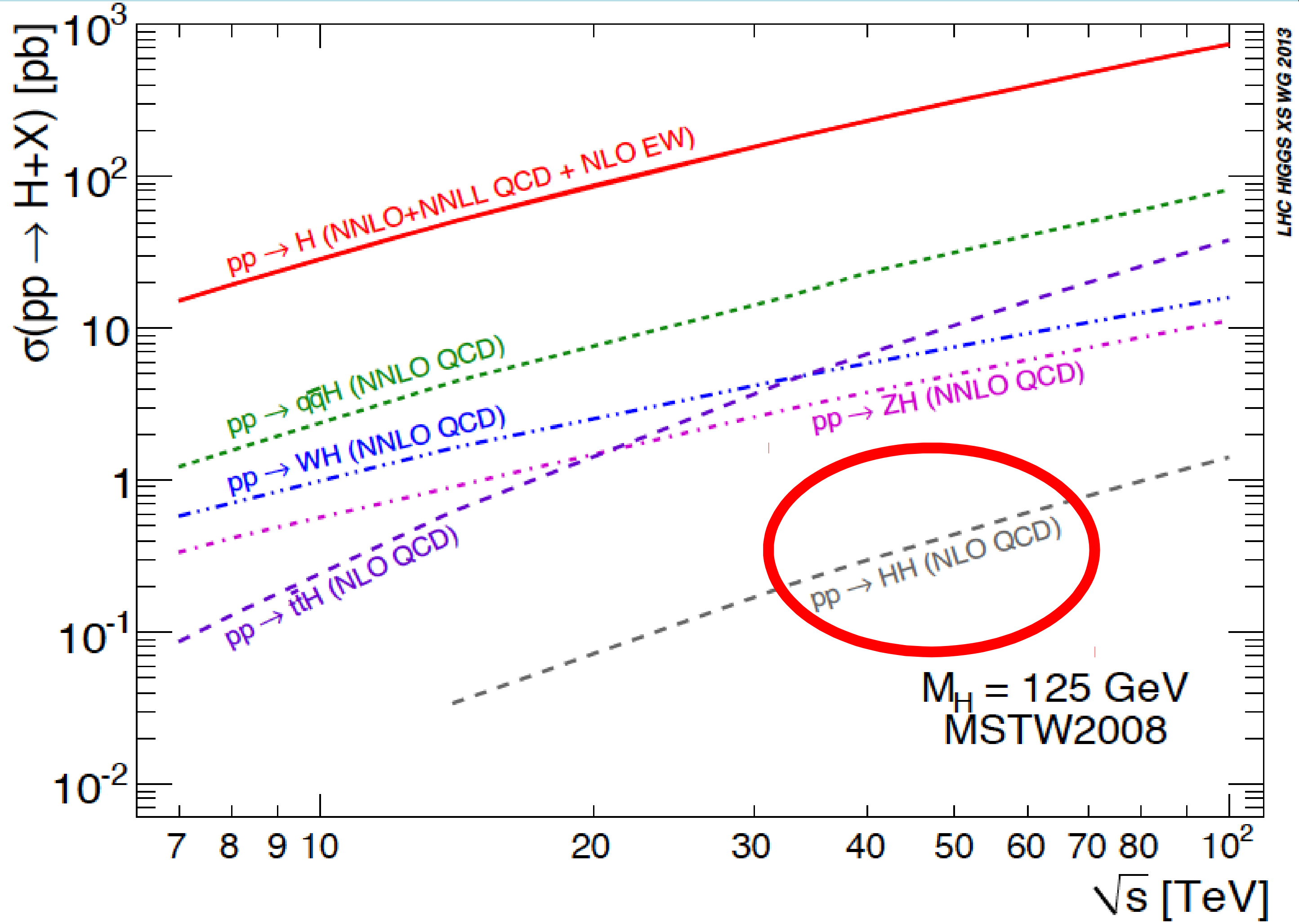


Parameters of FCC-hh & HL/HE-LHC

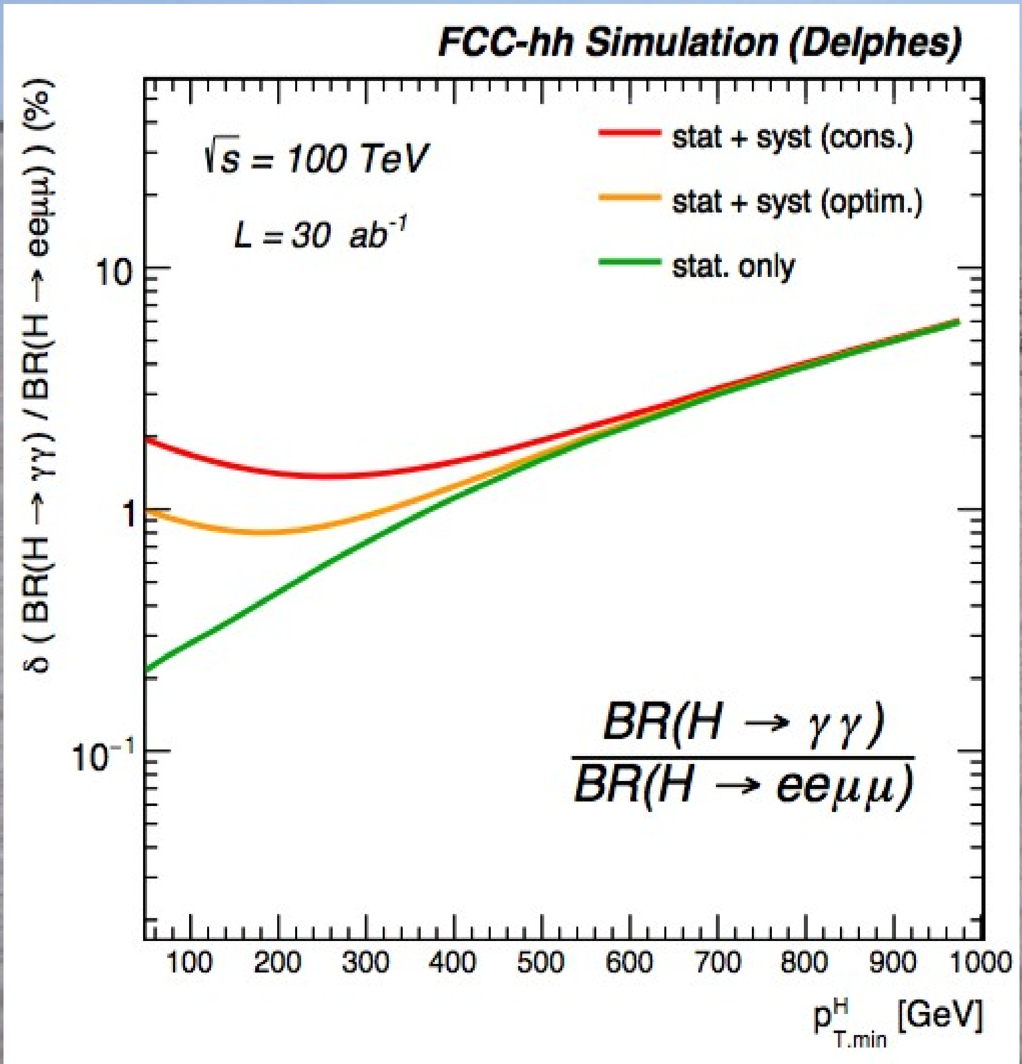
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

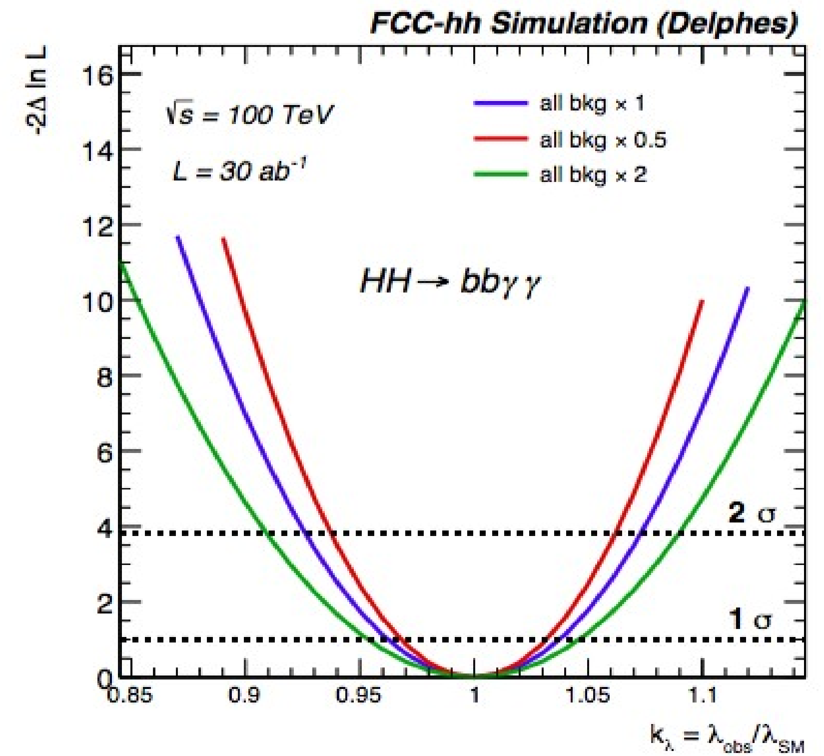
Higgs Cross Sections

- At the LHC and beyond:



Examples of Higgs Measurements





varying (0.5x-2x) background yields:

$\delta\kappa_\lambda(\text{stat}) \approx$ 3 - 5 %

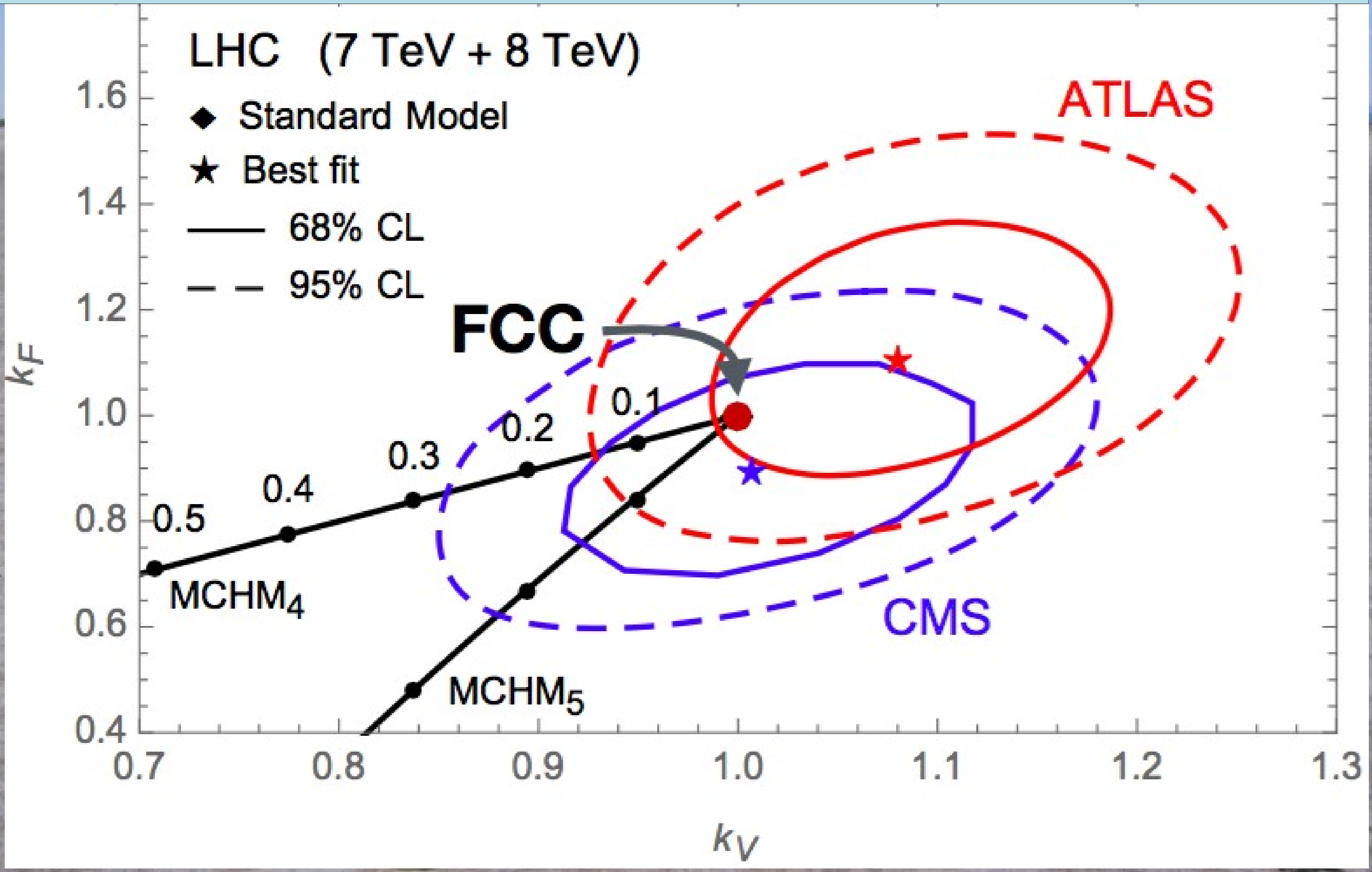
$\delta r(\text{stat}) \approx$ 2 - 3%

FCC Accuracy in H Couplings

HLLH+FCC-ee/FCC-eh	
Coupling	Relative precision
κ_b	0.39%
κ_t	5.16%
κ_τ	0.59%
κ_c	0.79%
κ_μ	5.17%
κ_Z	0.14%
κ_W	0.17%
κ_g	0.74%
κ_γ	1.19%
$\kappa_{Z\gamma}$	14.3%

HLLHC + FCC	
Coupling	Relative precision
κ_b	0.38%
κ_t	0.51%
κ_τ	0.58%
κ_c	0.79%
κ_μ	0.42%
κ_Z	0.14%
κ_W	0.17%
κ_g	0.74%
κ_γ	0.40%
$\kappa_{Z\gamma}$	0.52%

FCC Constraints on $\kappa_{V,F}$



SM Effective Field Theory: Tool to Search for BSM

- D=6 operators in electroweak, diboson data

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{Hl}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}_{Hl}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$
$$+ \frac{\bar{C}_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar{C}_{HWB}}{v^2}H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$$
$$+ \frac{\bar{C}_{He}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e) + \frac{\bar{C}_{Hu}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u) + \frac{\bar{C}_{Hd}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$
$$+ \frac{\bar{C}_{Hq}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q) + \frac{\bar{C}_{Hq}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q) + \frac{\bar{C}_W}{v^2}\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$$

$$\bar{C} \equiv \frac{v^2}{\Lambda^2}C$$

- D=6 operators affecting Higgs observables

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{eH}}{v^2}(H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2}(H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2}(H^\dagger H)(\bar{q}u\widetilde{H})$$
$$+ \frac{\bar{C}_G}{v^2}f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu} + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar{C}_{uG}}{v^2}(\bar{q}\sigma^{\mu\nu}T^A u)\widetilde{H}\, G_{\mu\nu}^A$$
$$+ \frac{\bar{C}_{HW}}{v^2}H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu} + \frac{\bar{C}_{HB}}{v^2}H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{\bar{C}_{HG}}{v^2}H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}\,.$$

Updated Global SMEFT Fit
to Higgs, Diboson and Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, Higgs and diboson data from LHC Runs 1 and 2
- Results in Warsaw and SILH bases
- Improvements in the constraints from Run 2
- Constraints on BSM models
  - Some contribute to operators at tree level
  - Stops that contribute at loop level

Murphy, JE, Sanz & You, arXiv:1803.03252

Run 2 Higgs Measurements used in SMEFT Fit

Include all available kinematical information + W^+W^- measurement at high p_T

Probe 12 SMEFT directions

CMS

Production	Decay	Sig. Stren.
1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$
Zh	$b\bar{b}$	0.9 ± 0.5
Wh	$b\bar{b}$	1.7 ± 0.7
$t\bar{t}h$	$b\bar{b}$	$-0.19^{+0.80}_{-0.81}$
$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$
$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$
$t\bar{t}h$	$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$
$t\bar{t}h$	$2\ell ss$	$1.7^{+0.6}_{-0.5}$
$t\bar{t}h$	3ℓ	[illegible]
$t\bar{t}h$	4ℓ	[illegible]
0-jet	WW	[illegible]
1-jet	[illegible]	[illegible]
2-jet	[illegible]	[illegible]
VBF 2-j[illegible]	[illegible]	[illegible]
Vh	[illegible]	$2.1^{+2.3}_{-2.2}$
[illegible]	[illegible]	-1.4 ± 1.5
[illegible]	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$
[illegible]	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$
[illegible]	$\gamma\gamma$	2.2 ± 0.9
Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$
ggF	4ℓ	$1.20^{+0.22}_{-0.21}$
0-jet	$\tau\tau$	0.84 ± 0.89
boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$
VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$

ATLAS

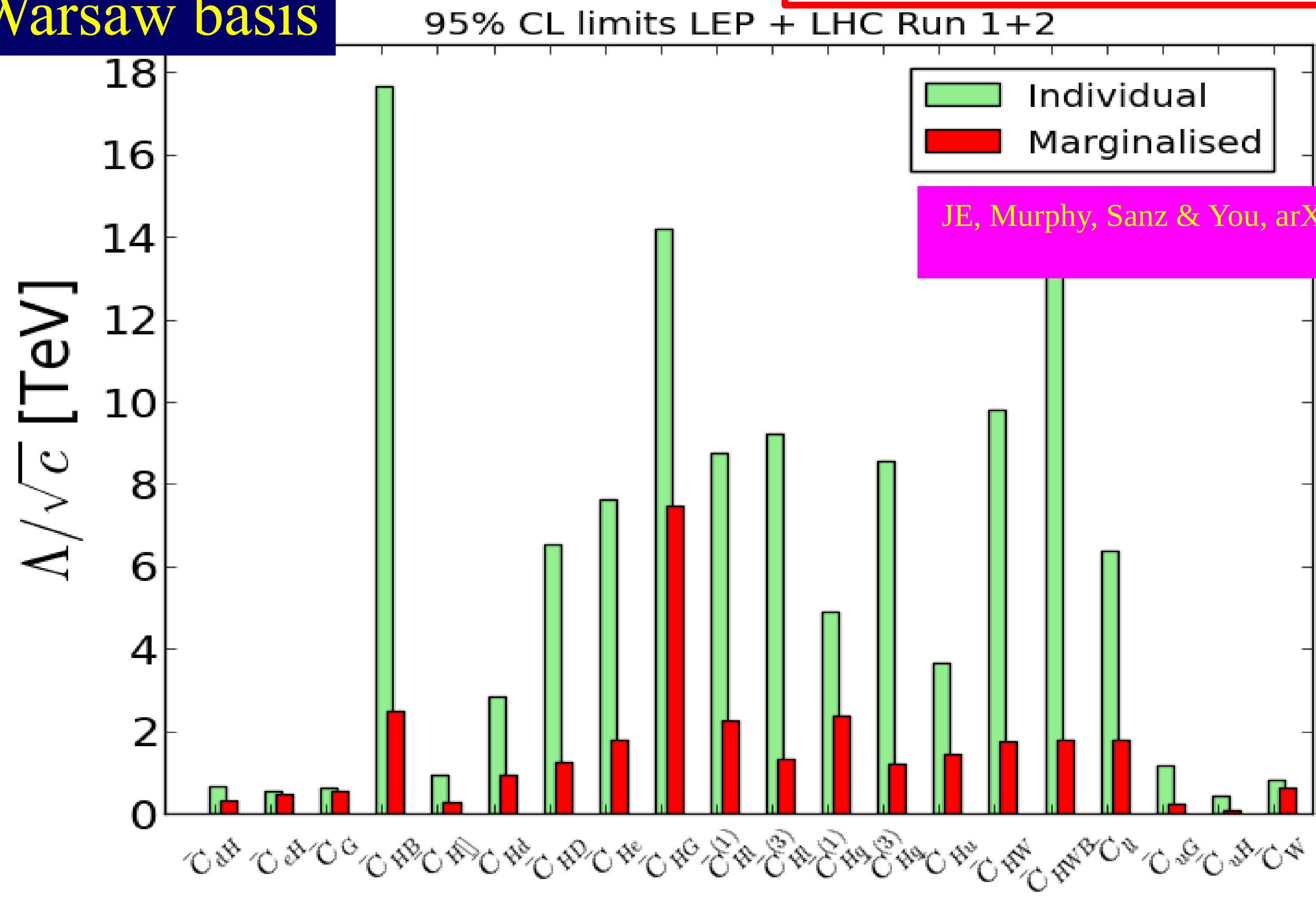
Production	Decay	Si[illegible]en.
pp	$\mu\mu$	[illegible]
Zh	[illegible]	[illegible]
Wh	[illegible]	[illegible]
$t\bar{t}h$	[illegible]	[illegible]
$t\bar{t}h$	[illegible]	$1.7^{+2.1}_{-1.9}$
[illegible]	[illegible]	$-0.6^{+1.6}_{-1.5}$
[illegible]	[illegible]	$1.6^{+1.8}_{-1.3}$
[illegible]	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[illegible]	3ℓ	$1.8^{+0.9}_{-0.7}$
[illegible]	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
ggF	WW	$1.21^{+0.22}_{-0.21}$
VBF	WW	$0.62^{+0.37}_{-0.36}$
$B(h \to \gamma\gamma)/B(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
Wh	WW	$3.2^{+4.4}_{-4.2}$

Murphy, JE, Sanz & You, arXiv:1803.03252

Summary

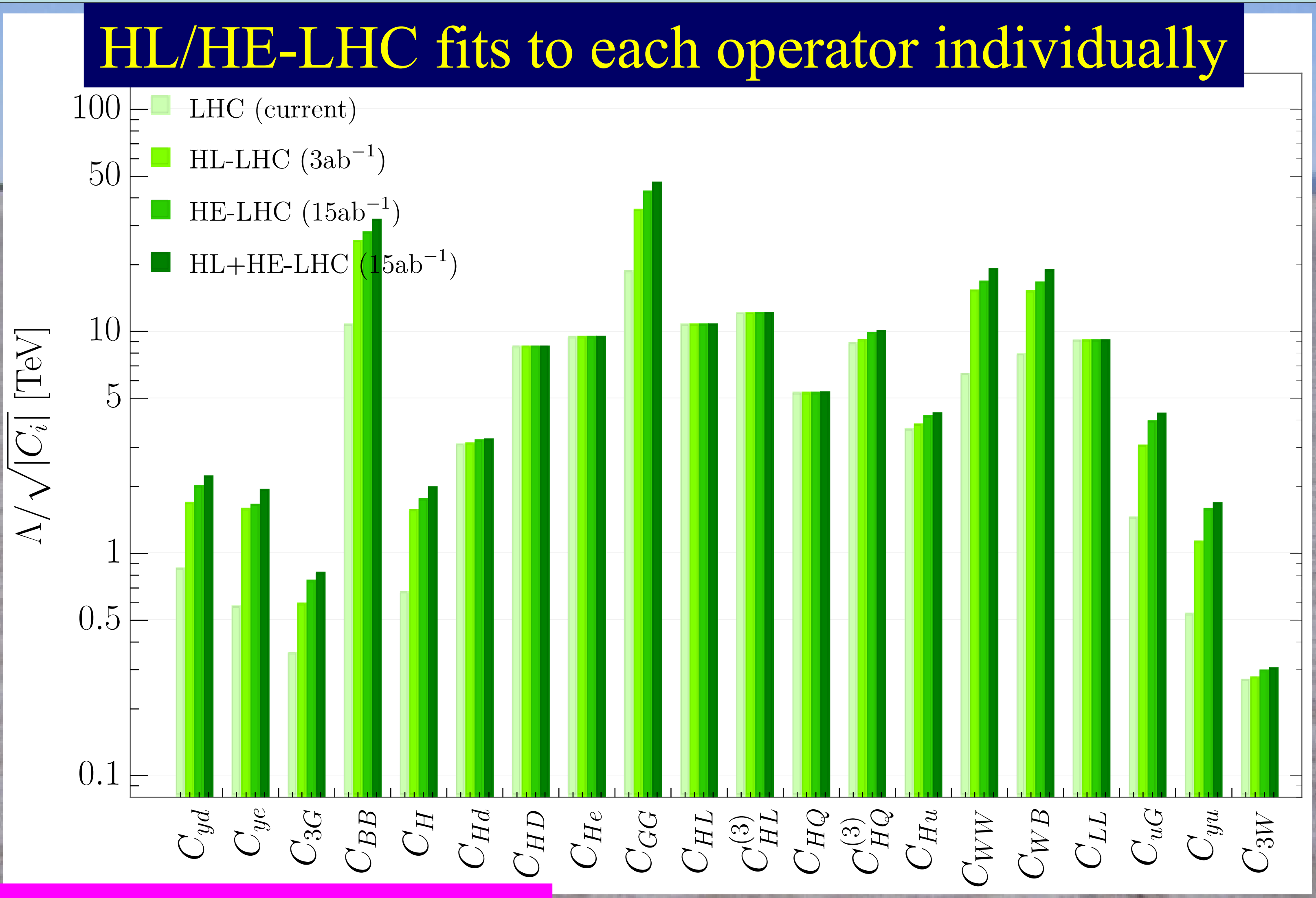
Theory	χ^2	χ^2/n_d	p-value
SM	157	0.987	0.532
SMEFT	137	0.987	0.528
SMEFT*	143	0.977	0.564

Warsaw basis



JE, Murphy, Sanz & You, arXiv:1803.03252

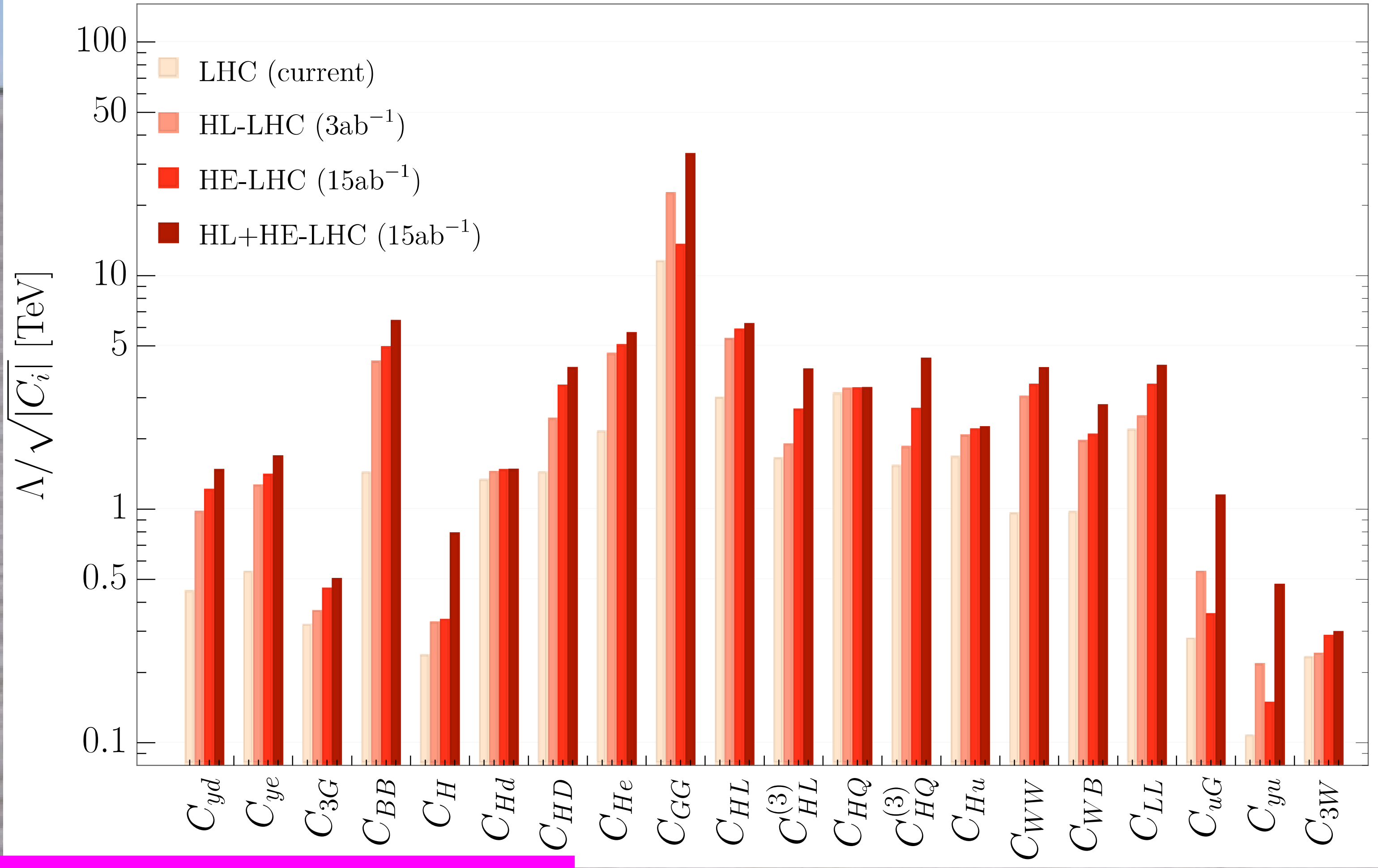
Extrapolating Global Fit in Warsaw Basis



EMSY, based on arXiv:1803.03252

Extrapolating Global Fit in Warsaw Basis

HL/HE-LHC fits to all operators simultaneously

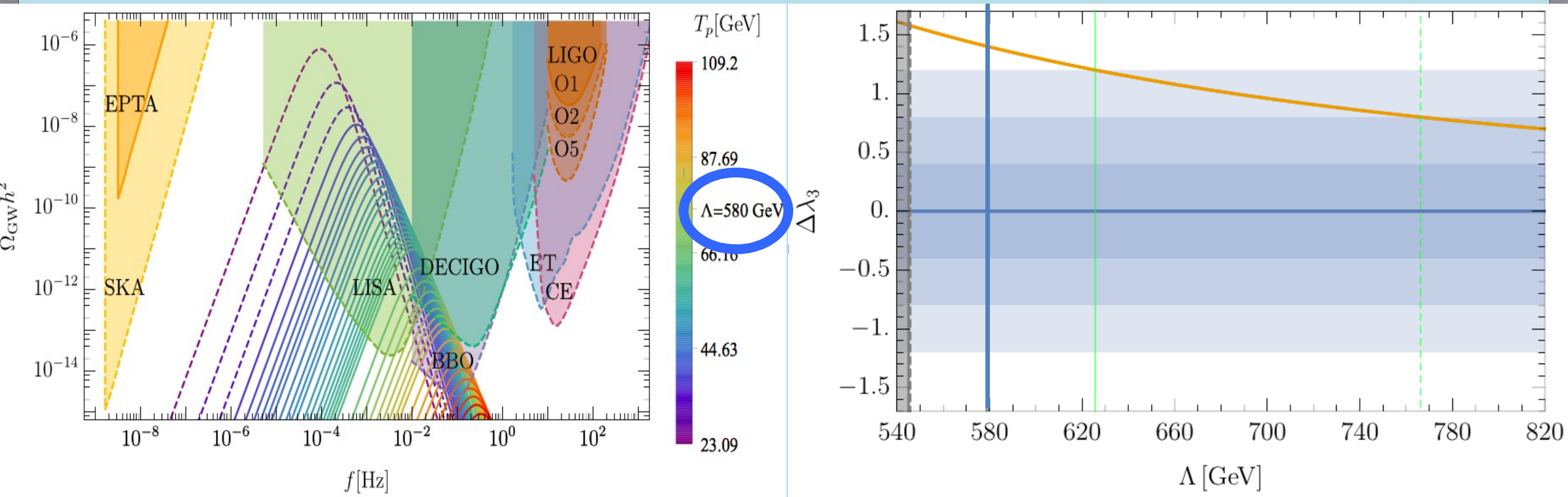


EMSY, based on arXiv:1803.03252

Remark on Primordial Gravitational Waves

Generated by first-order electroweak phase transition

Observable if $|\Phi|^6/\Lambda^2$, Λ small, also at HL-LHC



Reach of HL-LHC: **625 GeV @ 3σ, 766 GeV 2σ**

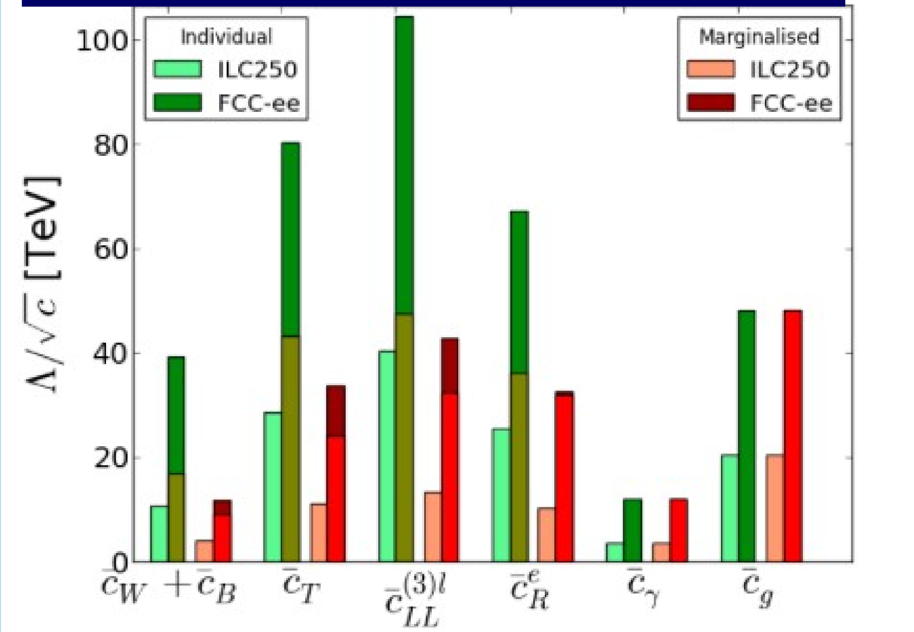
Reach of LISA: **580 GeV**

JE, Lewicki & No, arXiv:1809.08242

JE & Tevong You, arXiv:1510.04561

e^+e^- H, Electroweak & TGC Measurements

Higgs and electroweak



- Shadings:
  - With/without theoretical electroweak uncertainties

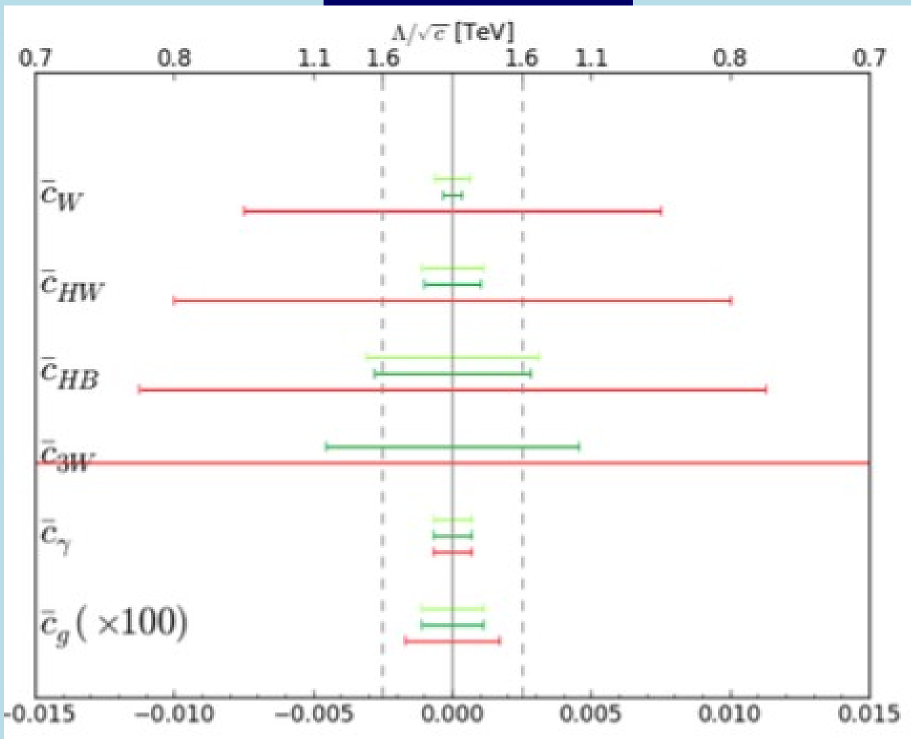
Shadings of green:

- Effect of including TGCs at ILC

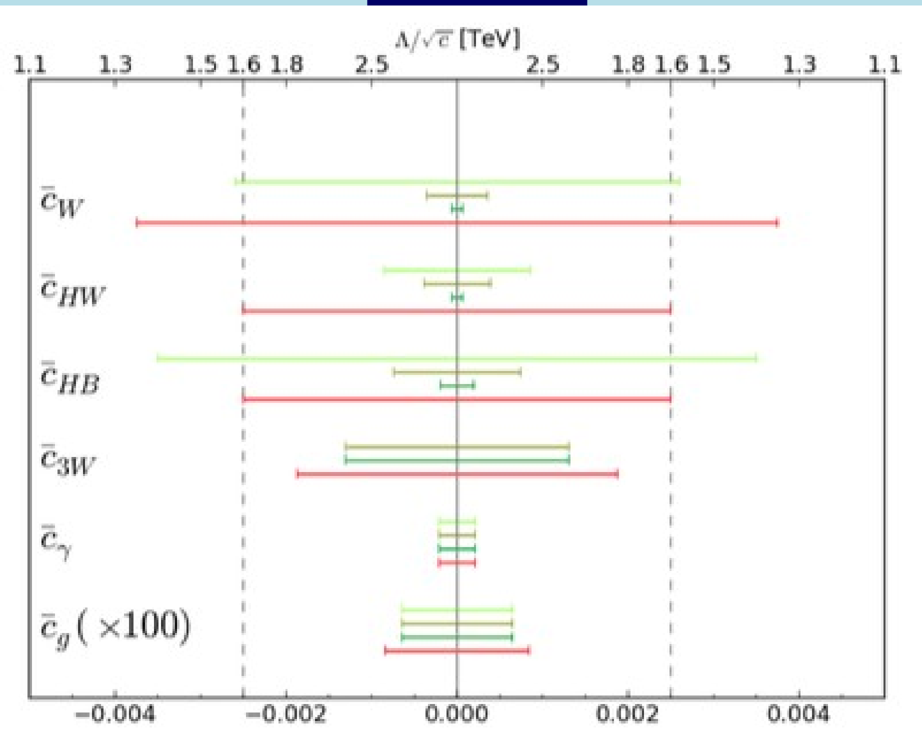
Should extend to include prospective FCC-hh measurements of TGCs, …

CLIC Sensitivities to Dimension-6 Operators

350 GeV



3 TeV



Global fit | Individual operators | Omitting W^+W^-

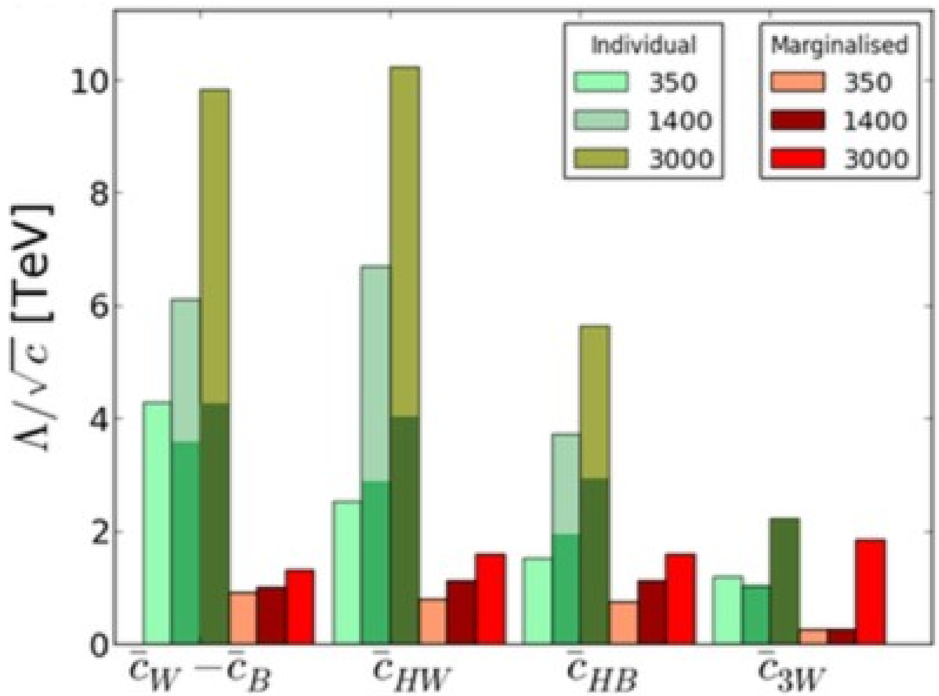
Sensitivity enhanced by higher centre-of-mass energy

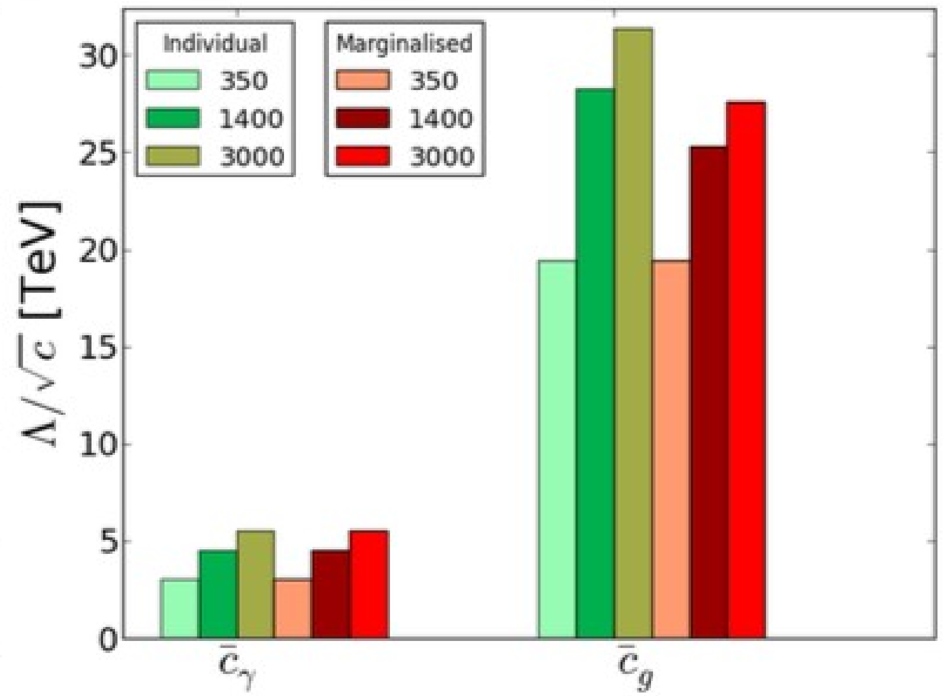
JE, Roloff, Sanz & Tevong You, arXiv:1701.04804

CLIC Sensitivities to Dimension-6 Operators

Individual operators

Global fit





Sensitivity enhanced by higher centre-of-mass energy

JE, Roloff, Sanz & Tevong You, arXiv:1701.04804


We still believe in supersymmetry
You must be joking

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

Inputs to Global Fits for New Physics

Electroweak observables | **Flavour observables: Interpretation requires lattice inputs** | **Dark Matter** | **LHC observables**

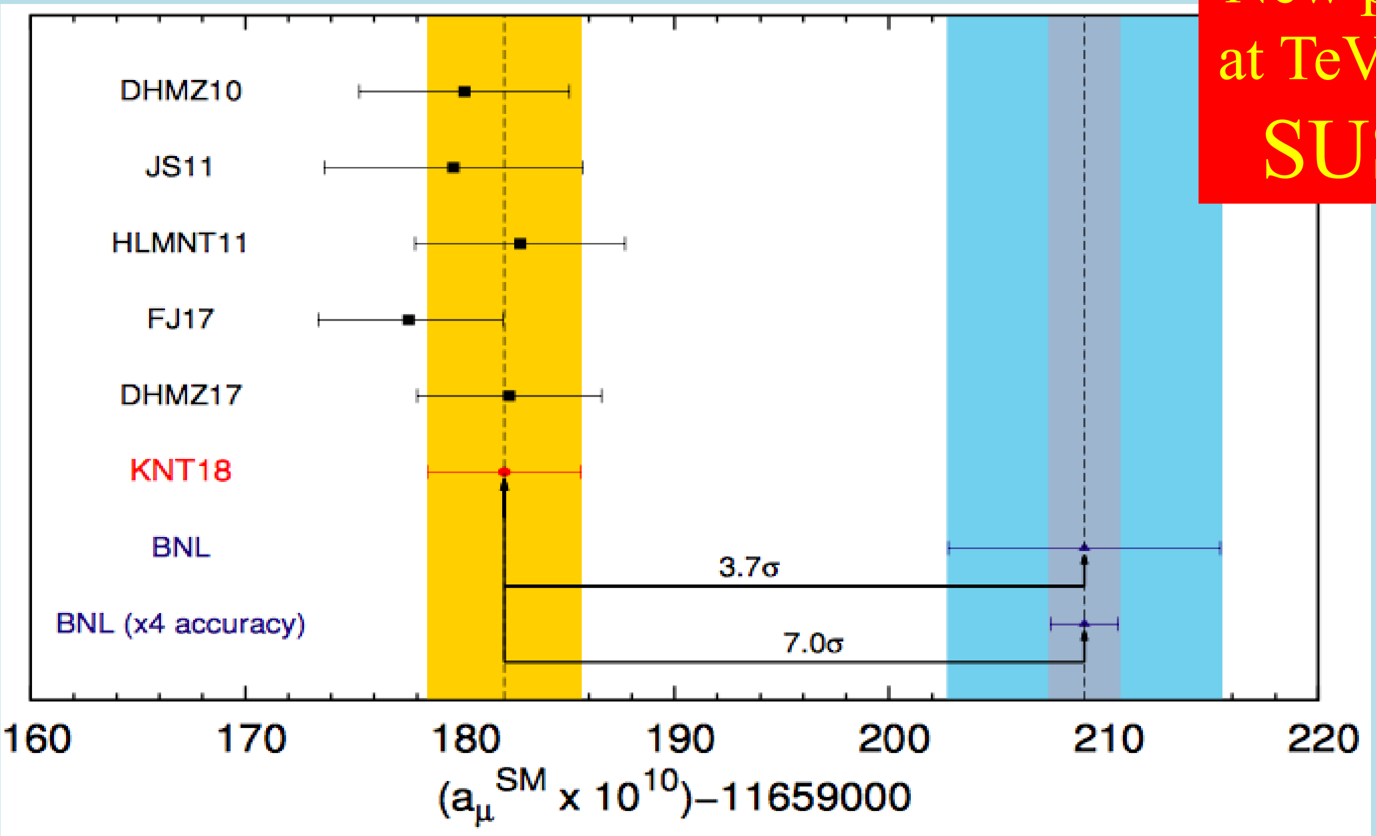
Observable	Source Th./Ex.	Constraint
M_W [GeV]	[33] / [57,58]	$80.379 \pm 0.012 \pm 0.010_{\rm MSSM}$
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[59] / [60]	$(30.2 \pm 8.8 \pm 2.0_{\rm MSSM}) \times 10^{-10}$
$R_{\mu\mu}$	[61–63]	2D likelihood, MFV
$\tau(B_s \to \mu^+\mu^-)$	[63]	$2.04 \pm 0.44(\text{stat.}) \pm 0.05(\text{syst.})$ ps
$\mathrm{BR}^{\rm EXP/SM}_{b\to s\gamma}$	[65]/ [66]	$0.988 \pm 0.045_{\rm EXP} \pm 0.068_{\rm TH,SM} \pm 0.050_{\rm TH,SUSY}$
$\mathrm{BR}^{\rm EXP/SM}_{B_u\to\tau\nu}$	[66,67]	$0.883 \pm 0.58_{\rm EXP} \pm 0.096_{\rm SM}$
$BR^{\rm EXP/SM}_{B\to X_s\ell\ell}$	[68]/ [66]	$0.966 \pm 0.278_{\rm EXP} \pm 0.037_{\rm SM}$
$\Delta M^{\rm EXP/SM}_{B_s}$	[34,69] / [66]	$0.968 \pm 0.001_{\rm EXP} \pm 0.078_{\rm SM}$
$\frac{\Delta M^{\rm EXP/SM}_{B_s}}{\Delta M^{\rm EXP/SM}_{B_d}}$	[34,69] / [66]	$1.007 \pm 0.004_{\rm EXP} \pm 0.116_{\rm SM}$
$BR^{\rm EXP/SM}_{K\to\mu\nu}$	[34,70] / [71]	$1.0005 \pm 0.0017_{\rm EXP} \pm 0.0093_{\rm TH}$
$BR^{\rm EXP/SM}_{K\to\pi\nu\bar\nu}$	[72]/ [73]	$2.01 \pm 1.30_{\rm EXP} \pm 0.18_{\rm SM}$
$\sigma_p^{\rm SI}$	[3,5,6]	Combined likelihood in the $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SI})$ plane
$\sigma_p^{\rm SD}$	[4]	Likelihood in the $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SD})$ plane
$\tilde g \to q\bar q\tilde\chi^0_1, b\bar b\tilde\chi^0_1, t\bar t\tilde\chi^0_1$	[16,17]	Combined likelihood in the $(m_{\tilde g}, m_{\tilde\chi^0_1})$ plane
$\tilde q \to q\tilde\chi^0_1$	[16]	Likelihood in the $(m_{\tilde q}, m_{\tilde\chi^0_1})$ plane
$\tilde b \to b\tilde\chi^0_1$	[16]	Likelihood in the $(m_{\tilde b}, m_{\tilde\chi^0_1})$, plane
$\tilde t_1 \to t\tilde\chi^0_1, c\tilde\chi^0_1, b\tilde\chi^\pm_1$	[16]	Likelihood in the $(m_{\tilde t_1}, m_{\tilde\chi^0_1})$, plane
$\tilde\chi^\pm_1 \to \nu\ell^\pm\tilde\chi^0_1, \nu\tau^\pm\tilde\chi^0_1, W^\pm\tilde\chi^0_1$	[18]	Likelihood in the $(m_{\tilde\chi^\pm_1}, m_{\tilde\chi^0_1})$ plane
$\tilde\chi^0_2 \to \ell^+\ell^-\tilde\chi^0_1, \tau^+\tau^-\tilde\chi^0_1, Z\tilde\chi^0_1$	[18]	Likelihood in the $(m_{\tilde\chi^0_2}, m_{\tilde\chi^0_1})$ plane
Heavy stable charged particles	[74]	Fast simulation based on [74, 75]
$H/A \to \tau^+\tau^-$	[28,29,76,77]	Likelihood in the $(M_A, \tan\beta)$ plane

Quo Vadis g_μ - 2?

- Strong discrepancy between BNL experiment and e^+e^- data now ~ 3.7 σ

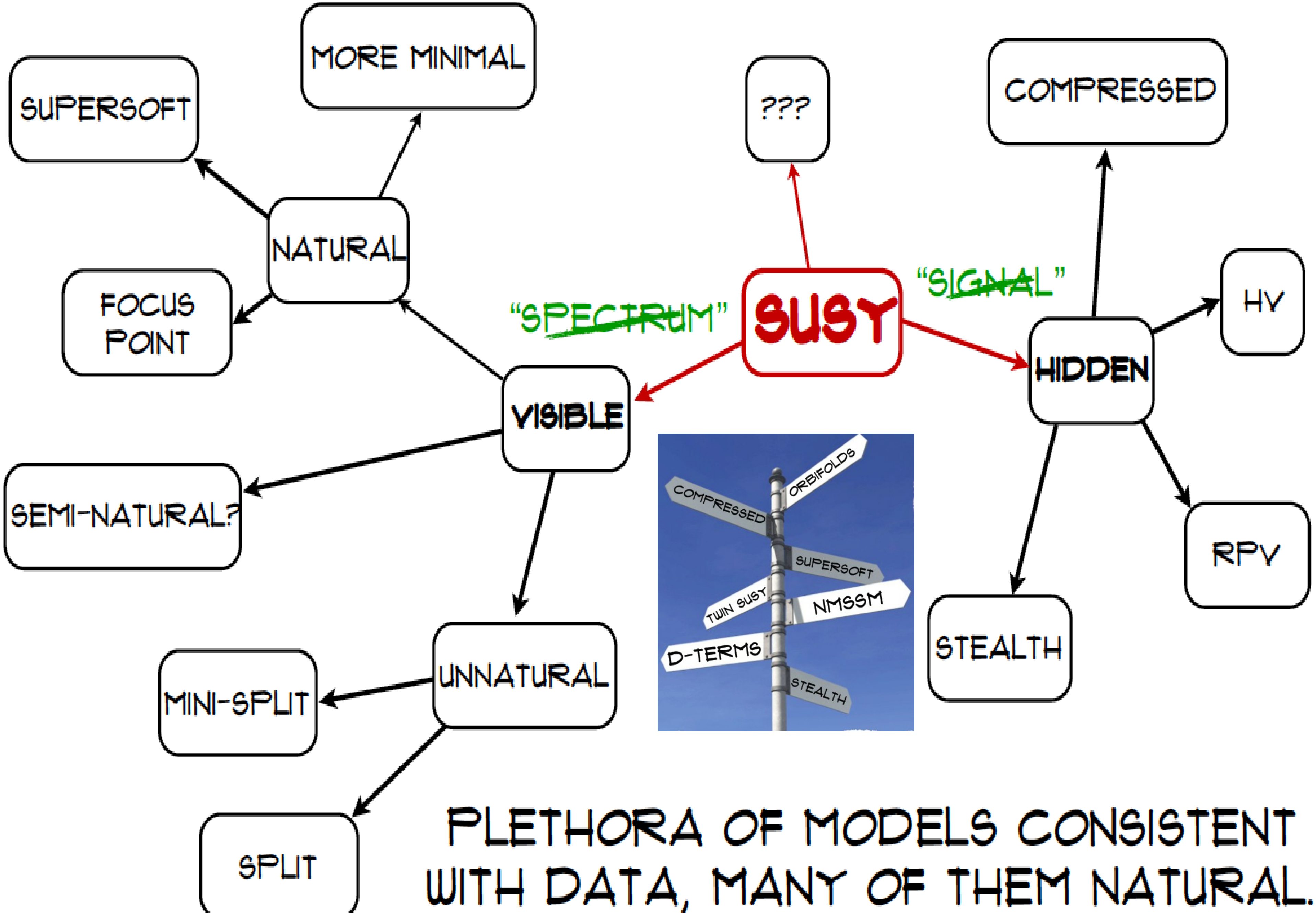
$$\Delta a_\mu = (27.05 \pm 7.26) \times 10^{-10}$$

New physics at TeV scale? SUSY?



- **New experiment at FNAL (J-PARC)**

Keshavarrzi, Nomura & Teubner, arXiv:1802.02995



PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL.
WHERE DOES THE DATA POINT US?

Craig@LHCP

Analysis of pMSSM11

- Phenomenological MSSM with 11 parameters
- Sample parameter space using Multinest technique
- Sampling with/without g-2
- Dedicated sampling of Dark Matter regions
- Sample 2×10^9 points

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

$$\begin{aligned}
\text{3 gaugino masses}: &\quad M_{1,2,3}\,, \\
\text{2 squark masses}: &\quad m_{\tilde{q}} \equiv m_{\tilde{q}_1}, m_{\tilde{q}_2} \\
&\quad \neq m_{\tilde{q}_3} = m_{\tilde{t}}, m_{\tilde{b}}, \\
\text{2 slepton masses}: &\quad m_{\tilde{\ell}} \equiv m_{\tilde{\ell}_1} = m_{\tilde{\ell}_2} = m_{\tilde{e}}, m_{\tilde{\mu}} \\
&\quad \neq m_{\ell_3} = m_{\tilde{\tau}}, \\
\text{1 trilinear coupling}: &\quad A\,, \qquad\qquad (1) \\
\text{Higgs mixing parameter}: &\quad \mu\,, \\
\text{pseudoscalar Higgs mass}: &\quad M_A\,, \\
\text{ratio of vevs}: &\quad \tan\beta\,,
\end{aligned}$$

Parameter	Range	Number of segments
M_1	(-4 , 4) TeV	6
M_2	(0 , 4) TeV	2
M_3	(-4 , 4) TeV	4
$m_{\tilde{q}}$	(0 , 4) TeV	2
$m_{\tilde{q}_3}$	(0 , 4) TeV	2
$m_{\tilde{\ell}}$	(0 , 2) TeV	1
$m_{\tilde{\tau}}$	(0 , 2) TeV	1
M_A	(0 , 4) TeV	2
A	(-5 , 5) TeV	1
μ	(-5 , 5) TeV	1
$\tan\beta$	(1 , 60)	1
Total number of boxes		384

SUSY Dark Matter Mechanisms

- Bringing relic density into cosmological range often requires **specific relation** between sparticle masses, such as:
  - Near-degeneracy, e.g..:

"Blind spots"

$$\tilde{\tau} \text{ coann. } : \quad \left(\frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} - 1 \right) < 0.15 \qquad \text{Chargino coann. } : \quad \left(\frac{m_{\tilde{\chi}_1^\pm}}{m_{\tilde{\chi}_1^0}} - 1 \right) < 0.25$$

  - Direct-channel resonance, e.g.:

$$H/A \text{ funnel } : \quad \left| \frac{M_A}{m_{\tilde{\chi}_1^0}} - 2 \right| < 0.4$$

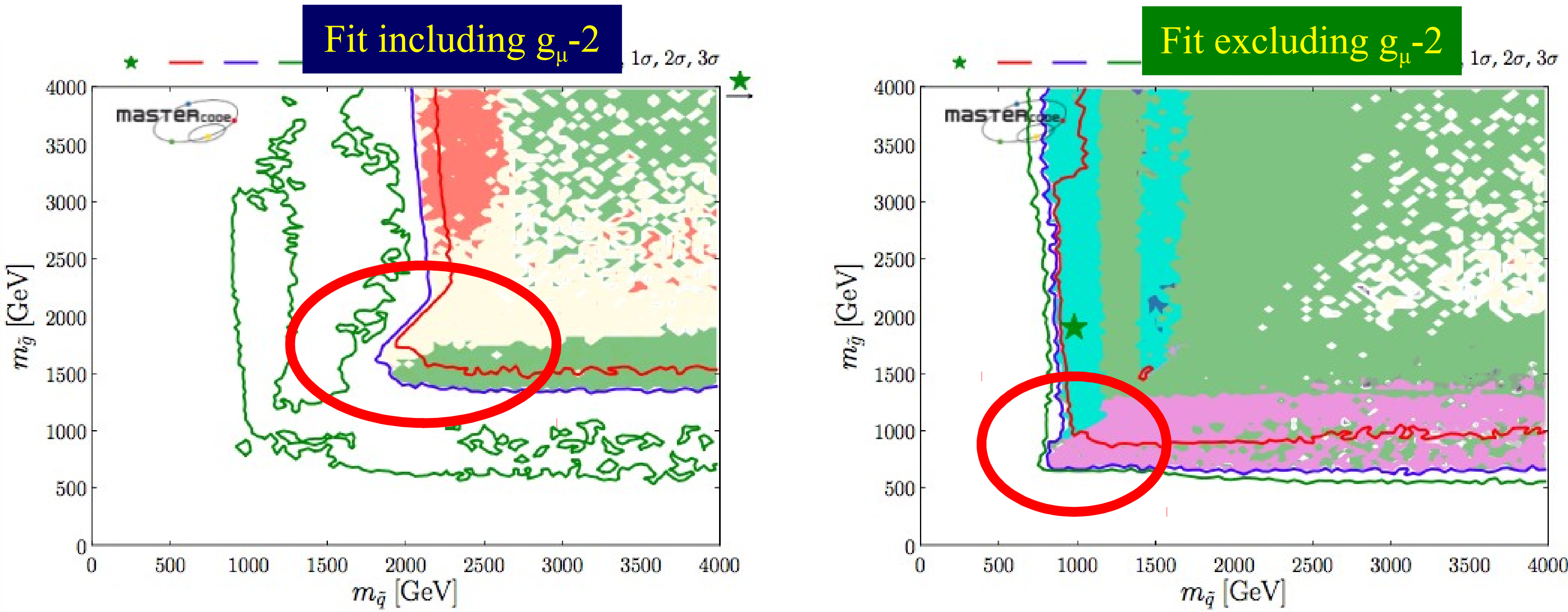
- Indicate by following shadings

$\tilde{\tau}$ coann. $\tilde{\tau}_1$ coann. + H/A $\tilde{\chi}_1^\pm$ coann. A/H funnel

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Squark & Gluino Mass Planes

Phenomenological MSSM



'Nose' regions where LHC sensitivity reduced because of compressed spectrum

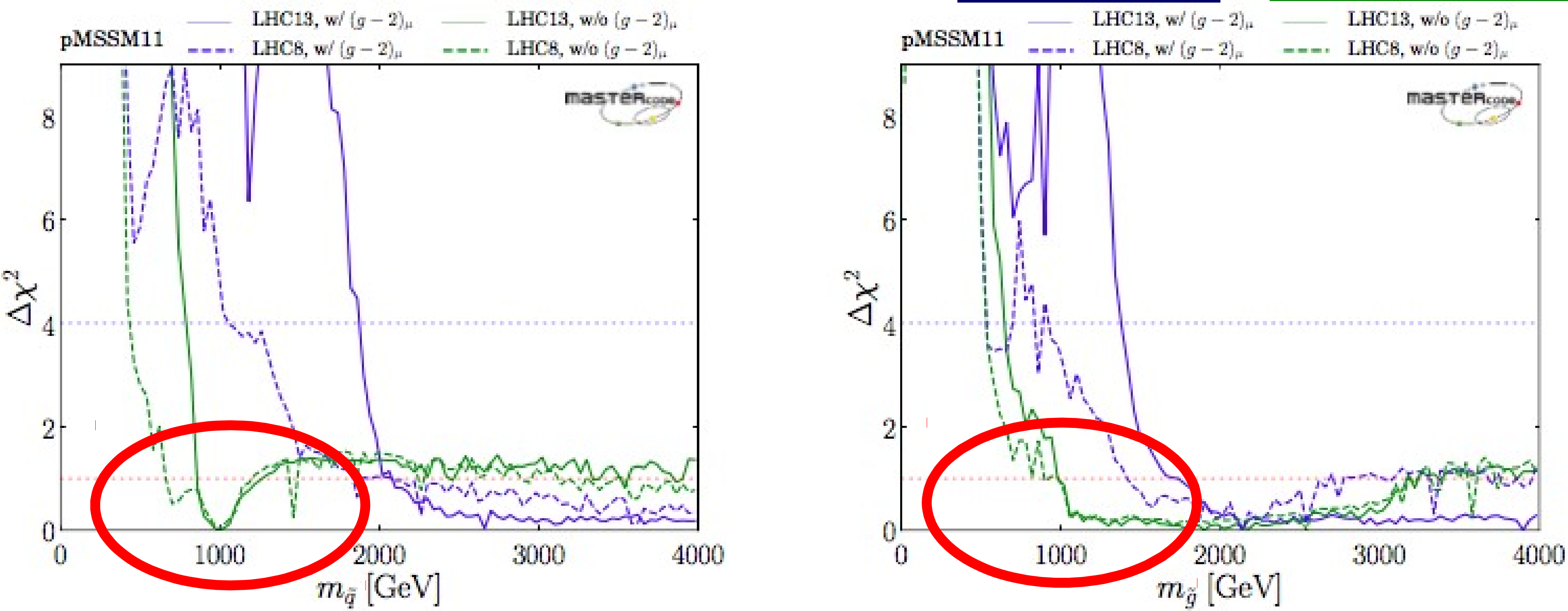
Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

How Light can Squarks & Gluinos be?

Phenomenological MSSM

Fit with g_μ-2

Fit without g_μ-2



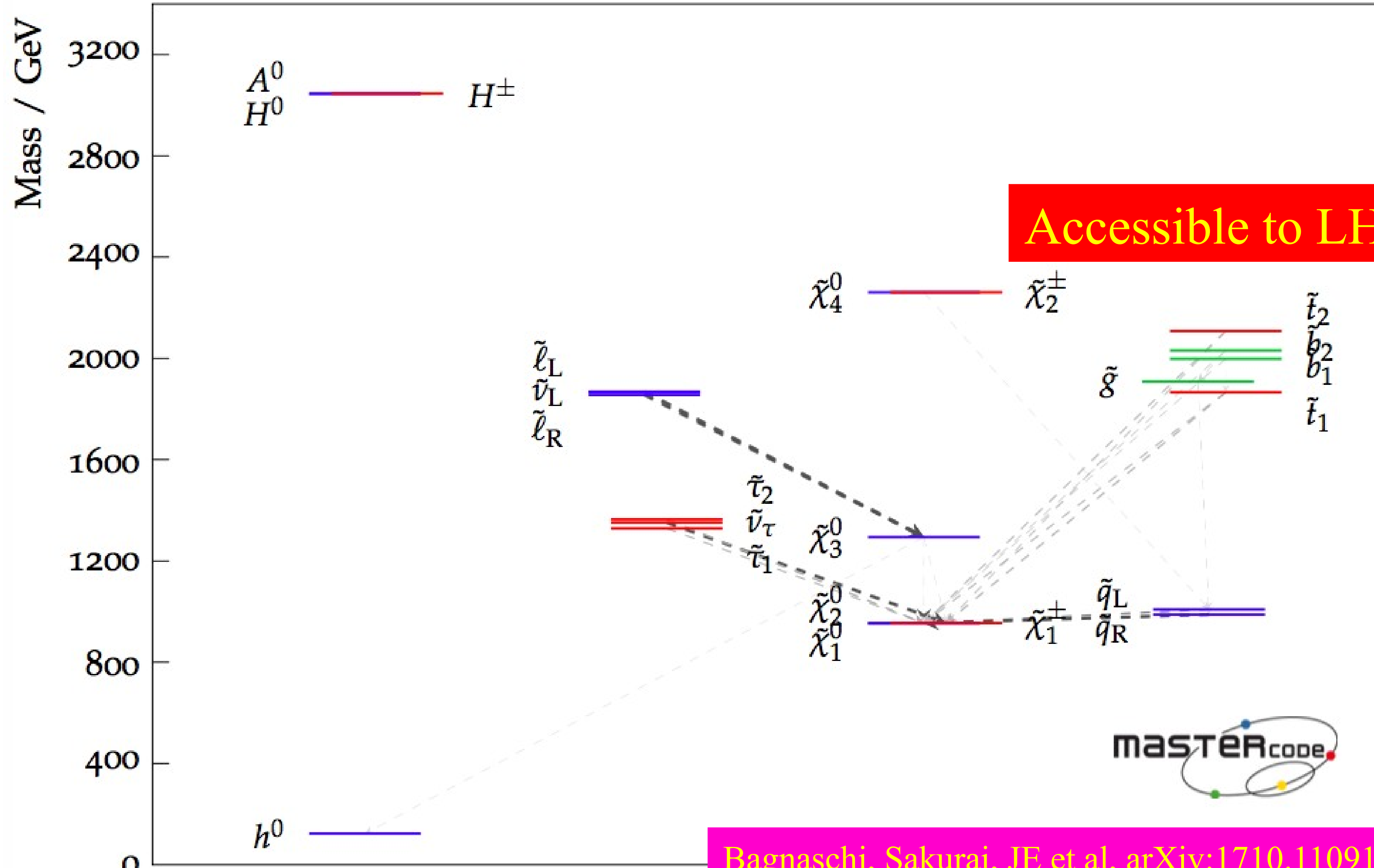
Squarks, gluinos could weigh ~ 1 TeV if drop g_μ-2

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Best-Fit Sparticle Spectrum

Phenomenological MSSM

Fit without g_μ-2



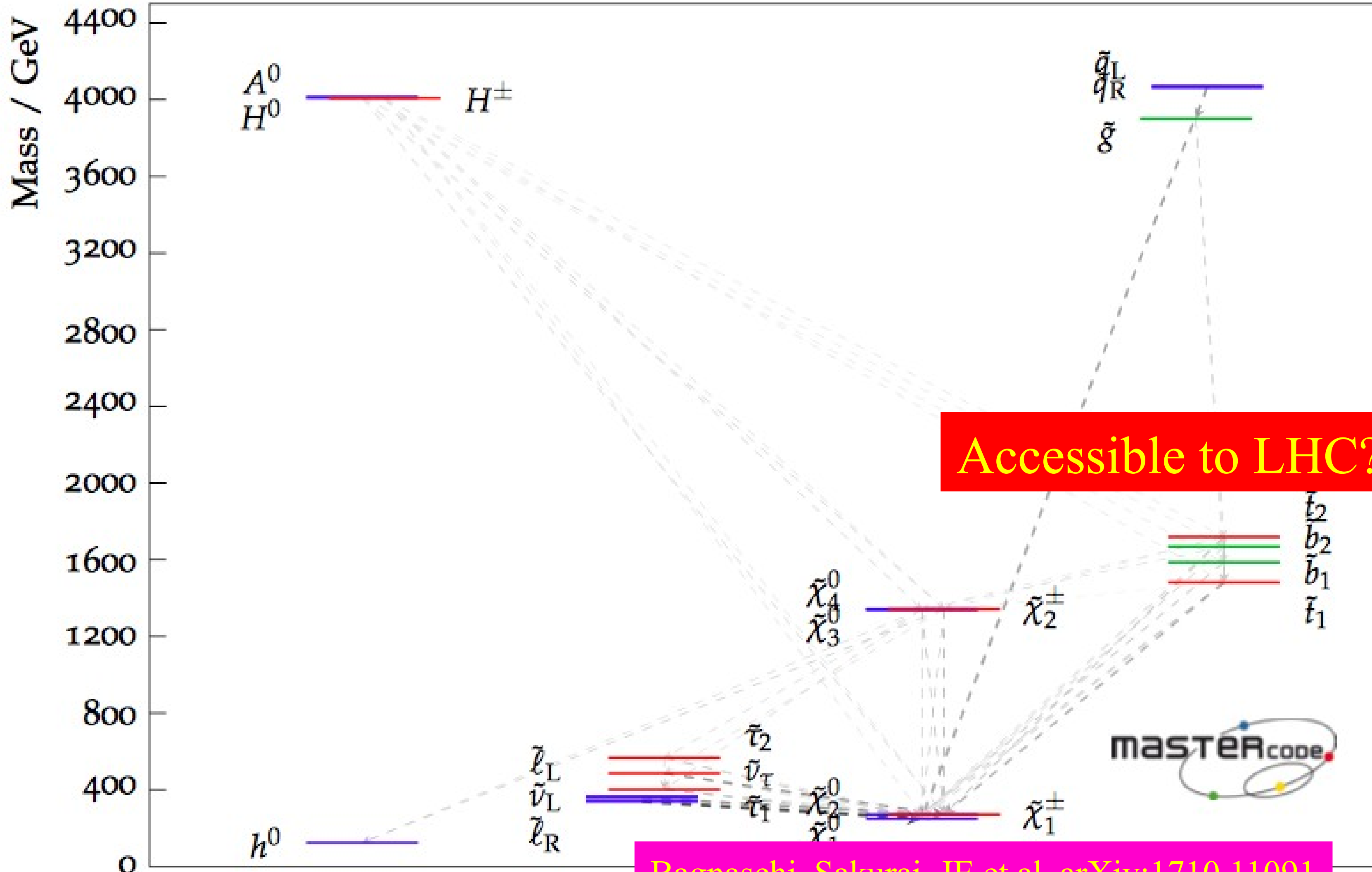
Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Best-Fit Sparticle Spectrum

Phenomenological MSSM

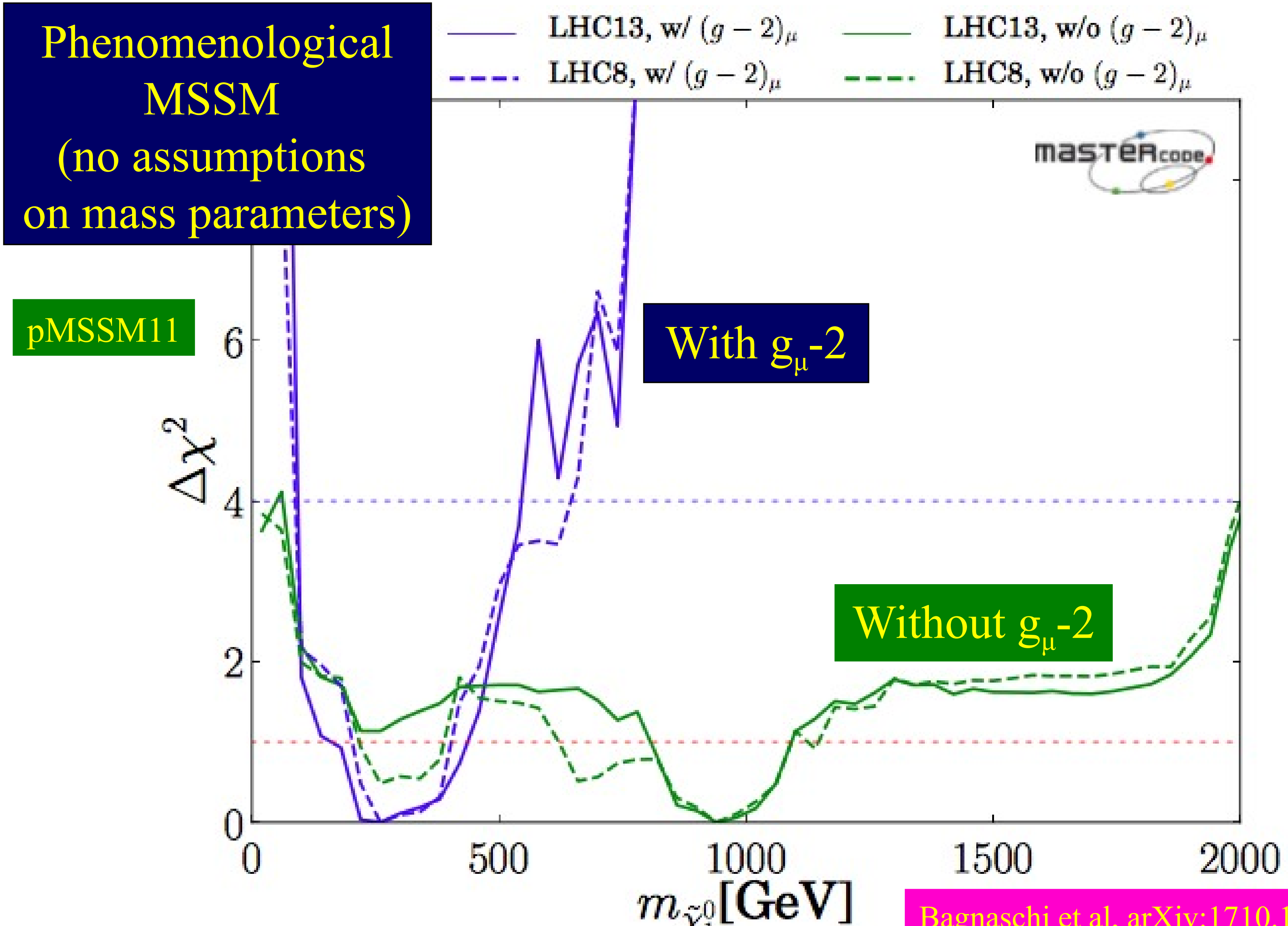
Fit with g_μ-2



Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

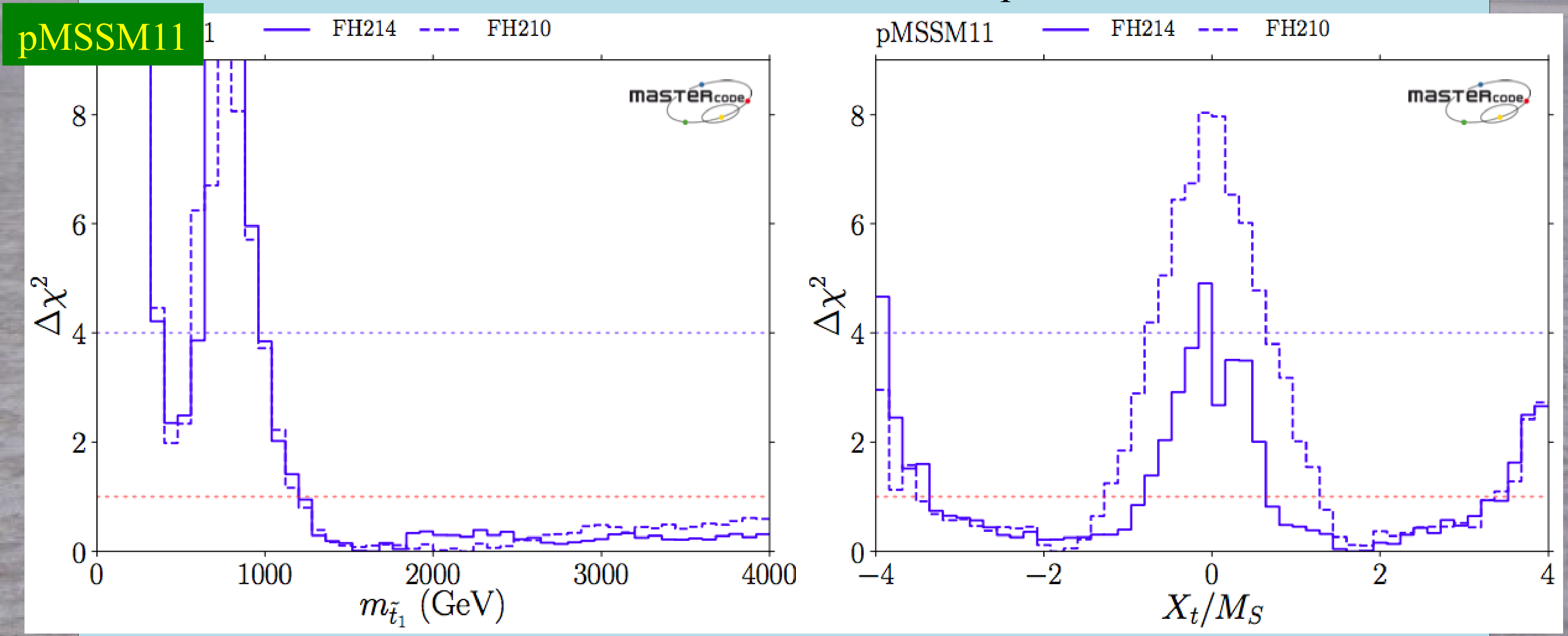
Likelihood for LSP Mass



Bagnaschi et al. arXiv:1710.11091

The Lighter Stop may be Light

- χ^2 likelihood functions for m_{stop}, stop mixing



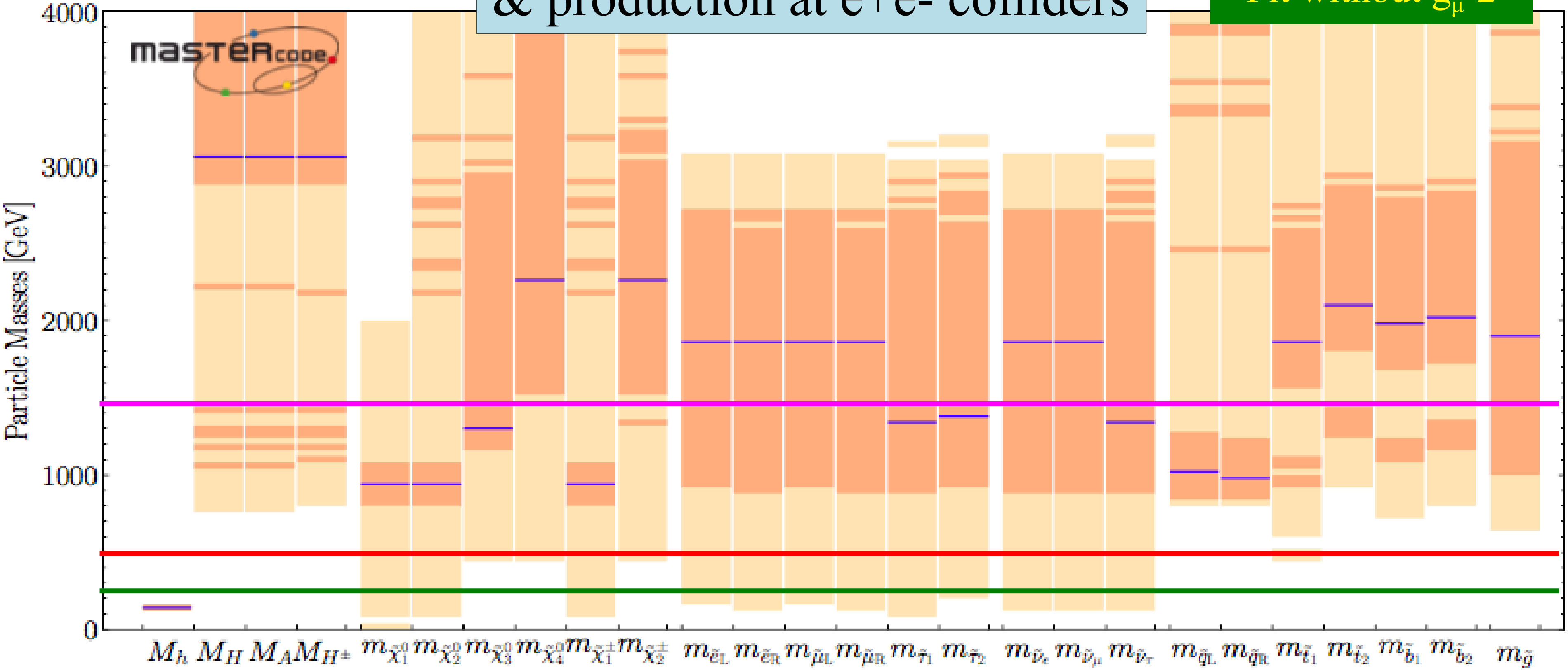
- **M_{stop} < 500 GeV allowed with $\Delta\chi^2 \sim 2$**

Bagnaschi, Bahl, JE et al, arXiv:1810.10905

Sparticle Masses in the pMSSM

& production at e+e- colliders

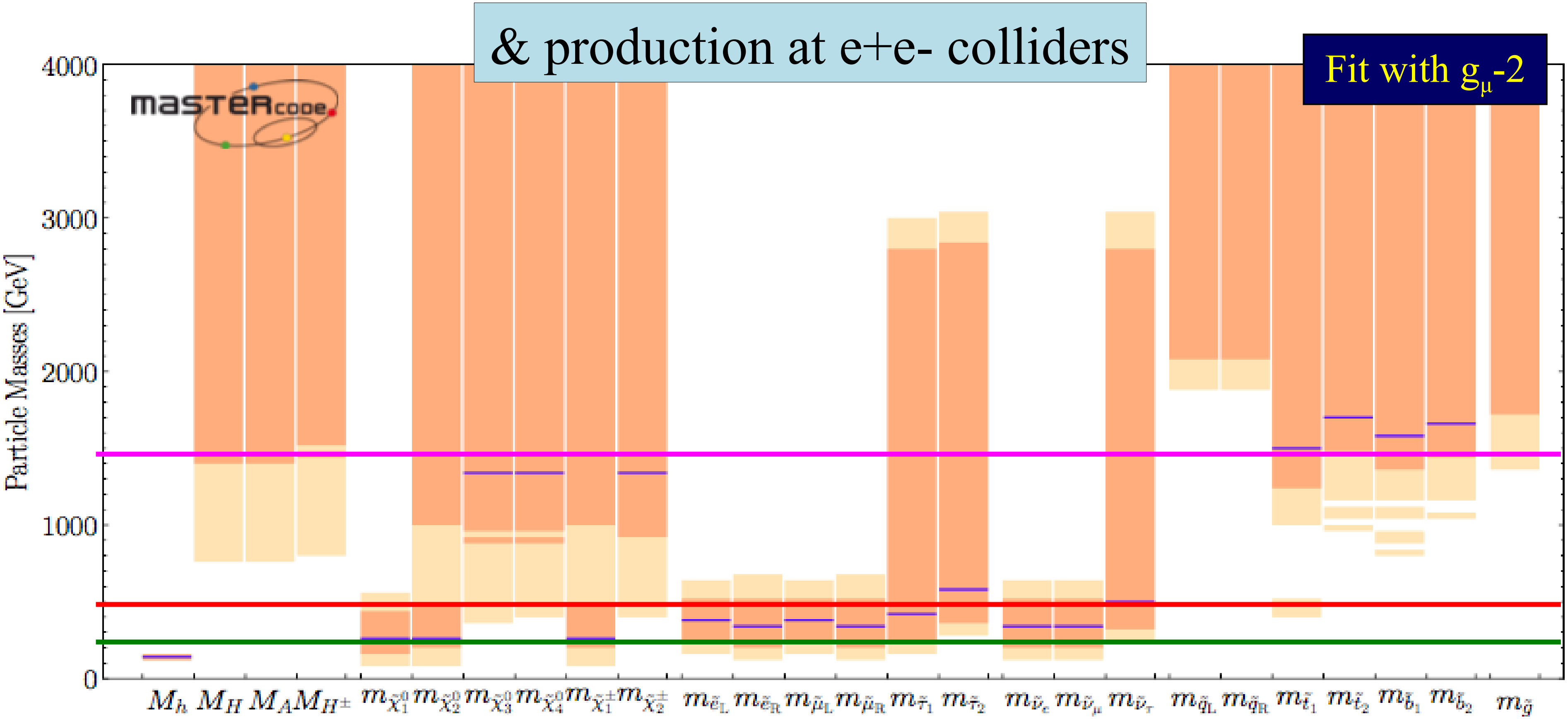
Fit without g_μ-2



- 68 & 95% CL ranges
- Best-fit values
- Accessible in pair production at ILC500, ILC1000, CLIC

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Sparticle Masses in the pMSSM



- **68 & 95% CL ranges**
- **Best-fit values**
- Accessible in pair production at **((ILC500))**, **(ILC1000)**, **CLIC**

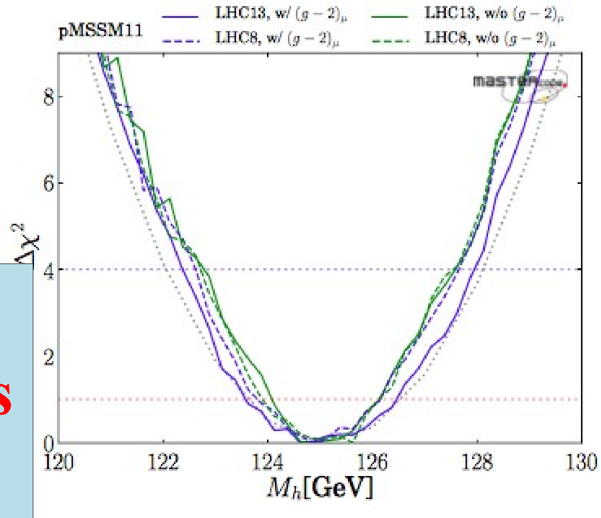
Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

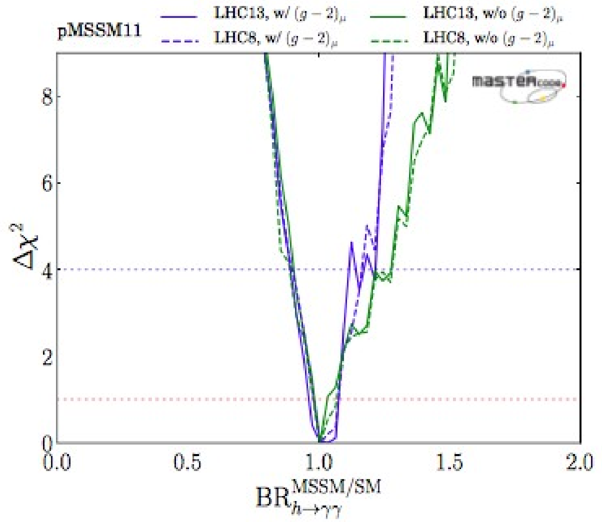
Higgs properties in the pMSSM

Fit with g_μ-2

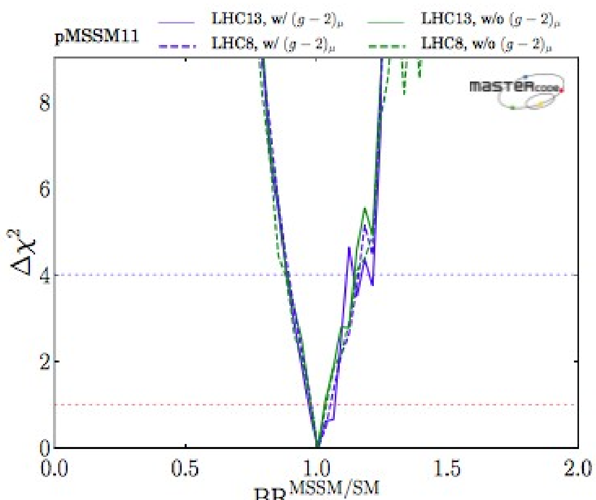
Fit without g_μ-2

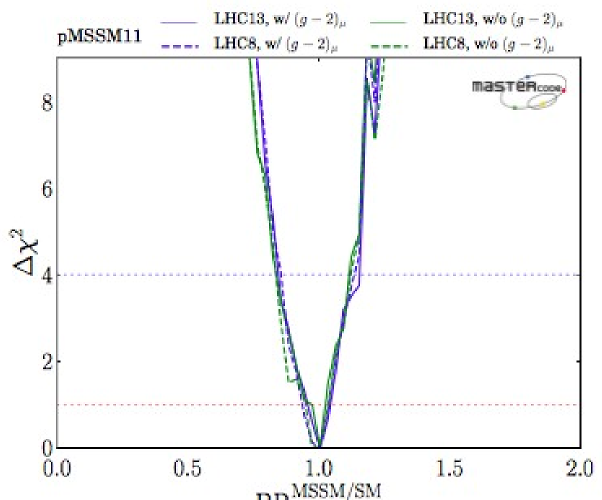
- **No issue with measured Higgs mass**
- Central values of decay BRs similar to SM
- **Substantial deviations possible**





Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

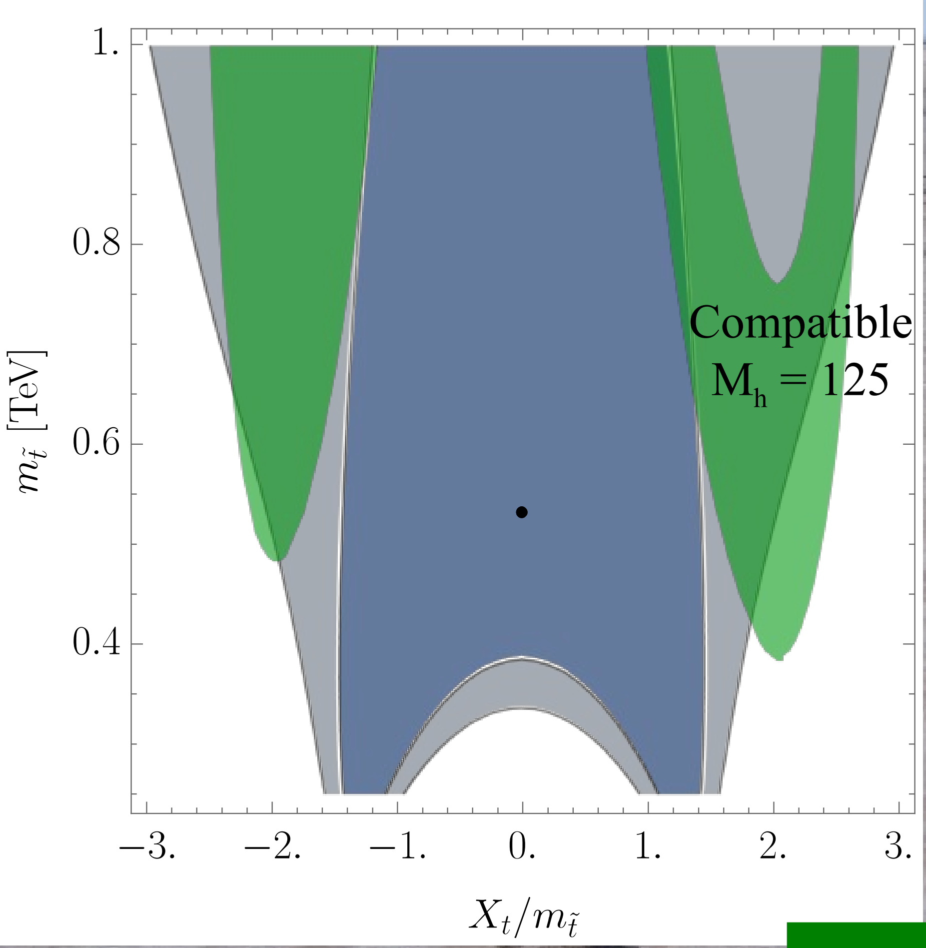




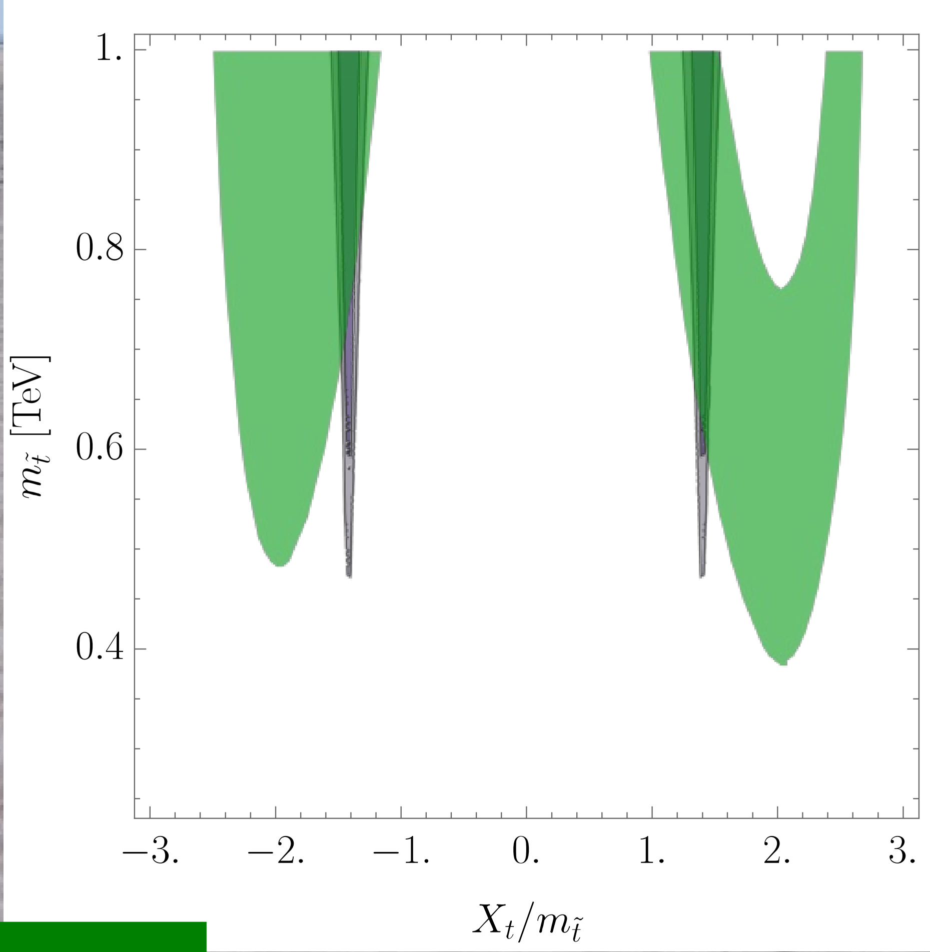
EMSY, arXiv:1803.03252

SMEFT Constraints on Light Stops

Current bounds



Possible HE-LHC bounds



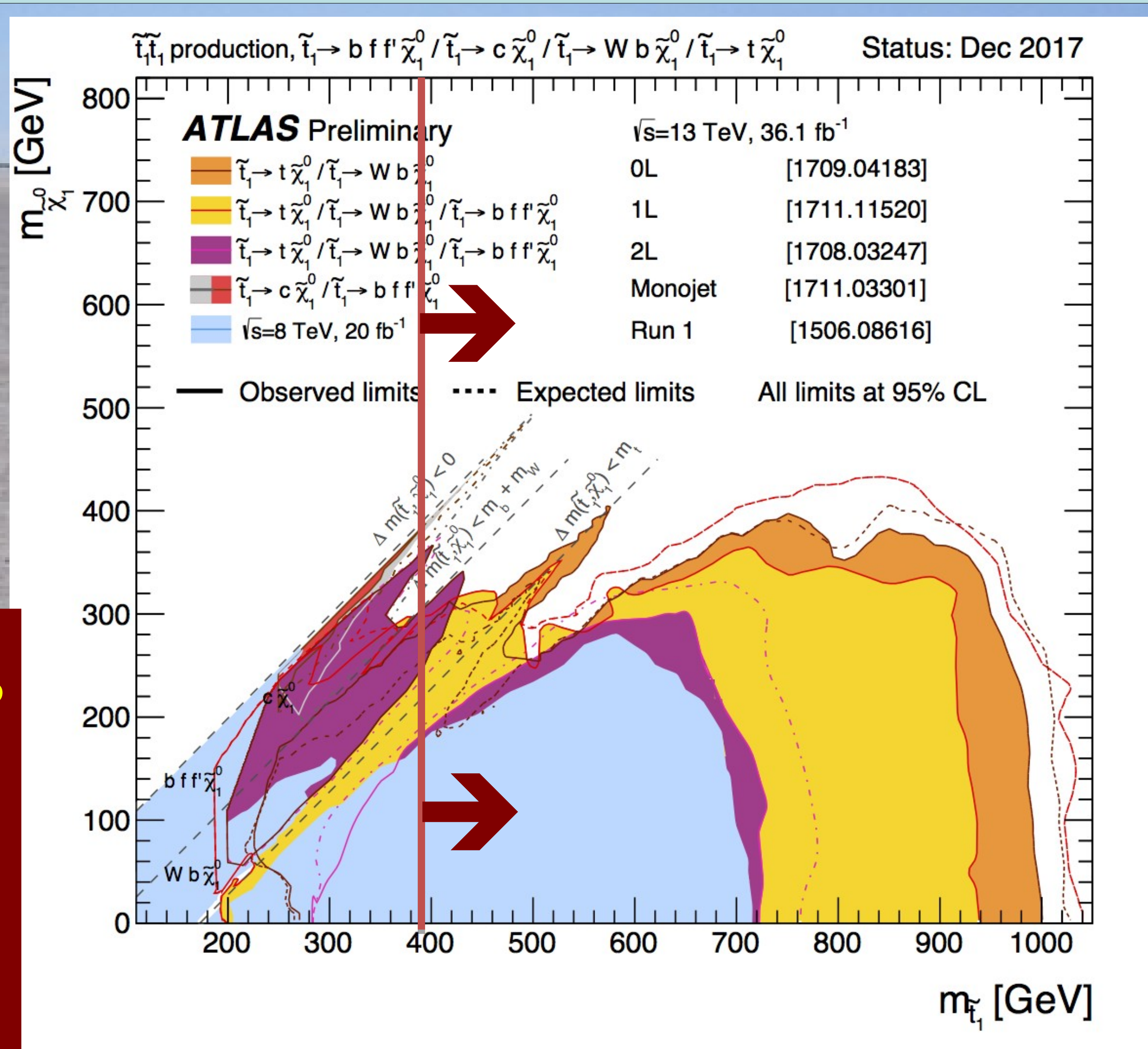
$\tan\beta = 20$

Direct Constraints on Light Stops

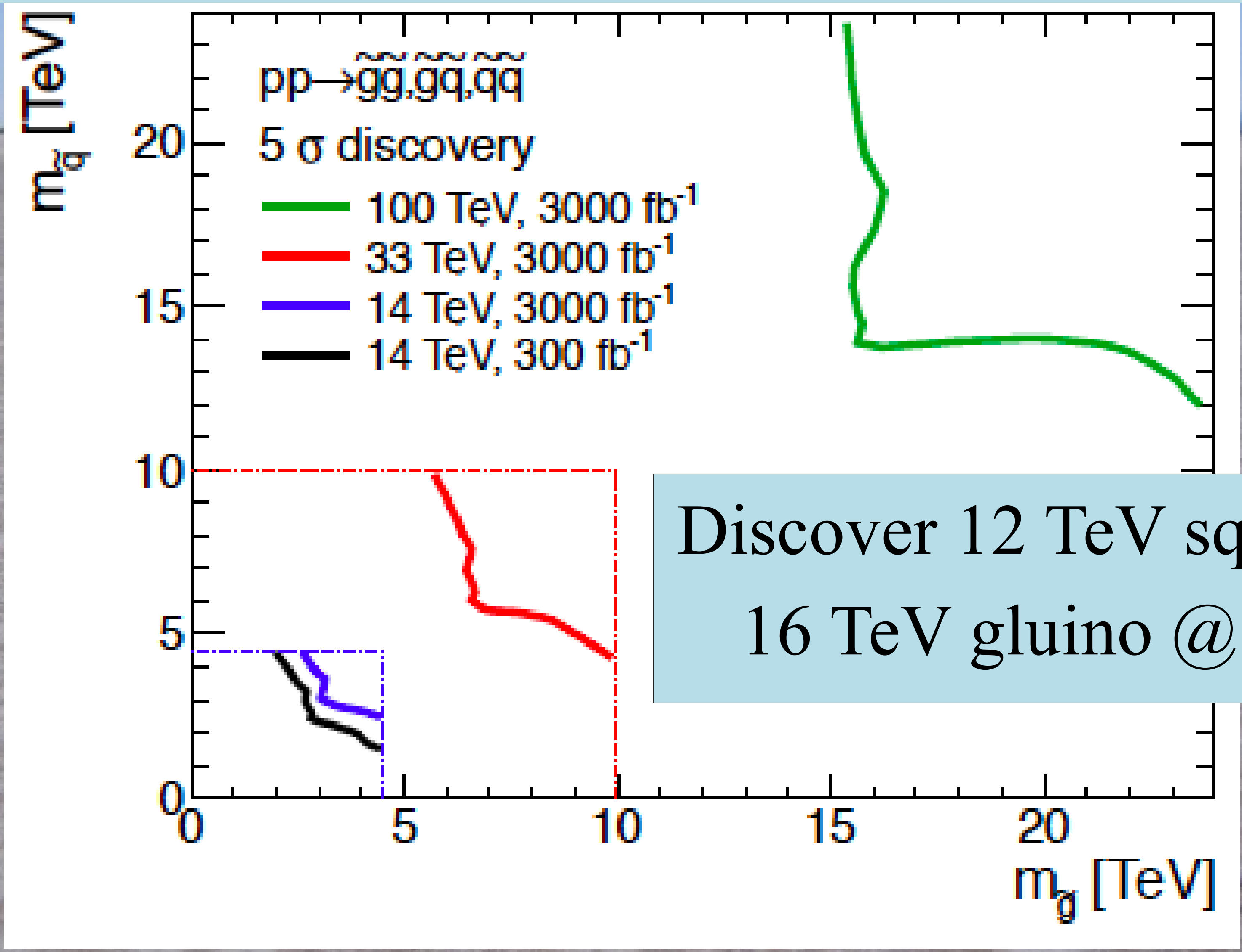
Depend on m_{LSP} not on tan β

Comparison with SMEFT depends on mixing X_t

Range of m_{stop} compatible with SMEFT and m_H constraints

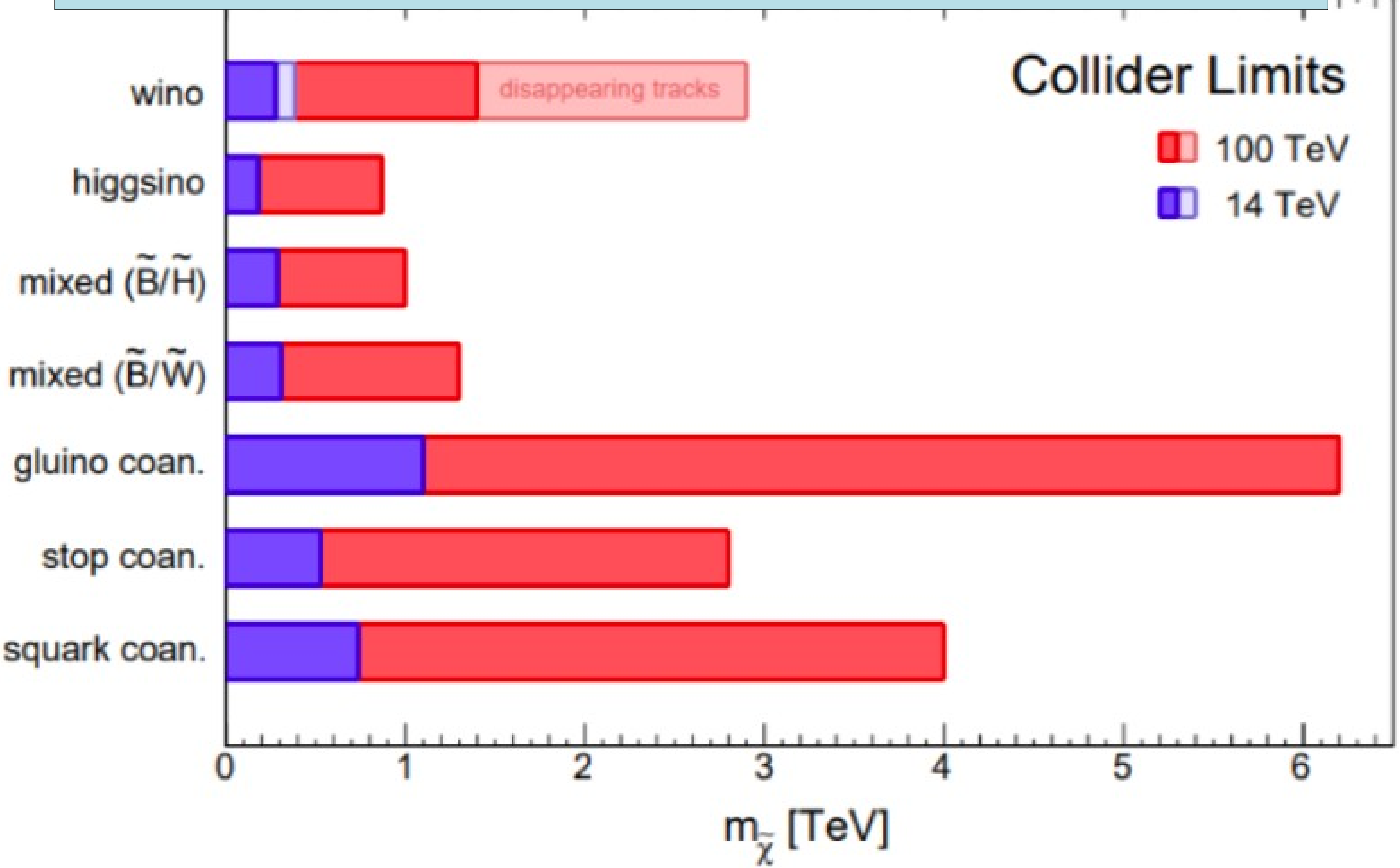


Squark-Gluino Plane



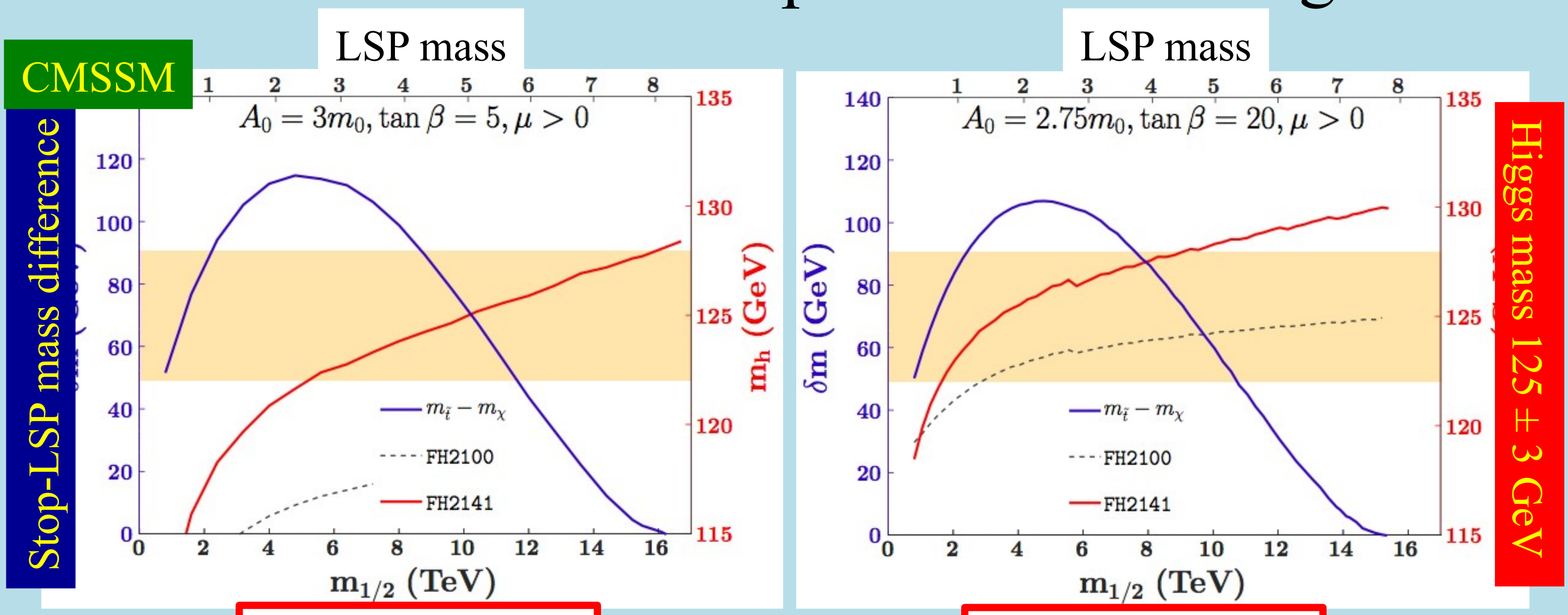
Discover 12 TeV squark, 16 TeV gluino @ 5σ

Neutralino Reach



Where could it be hiding?

- Near-degeneracy of LSP and heavier sparticle(s)?
- Coannihilation increases possible mass range



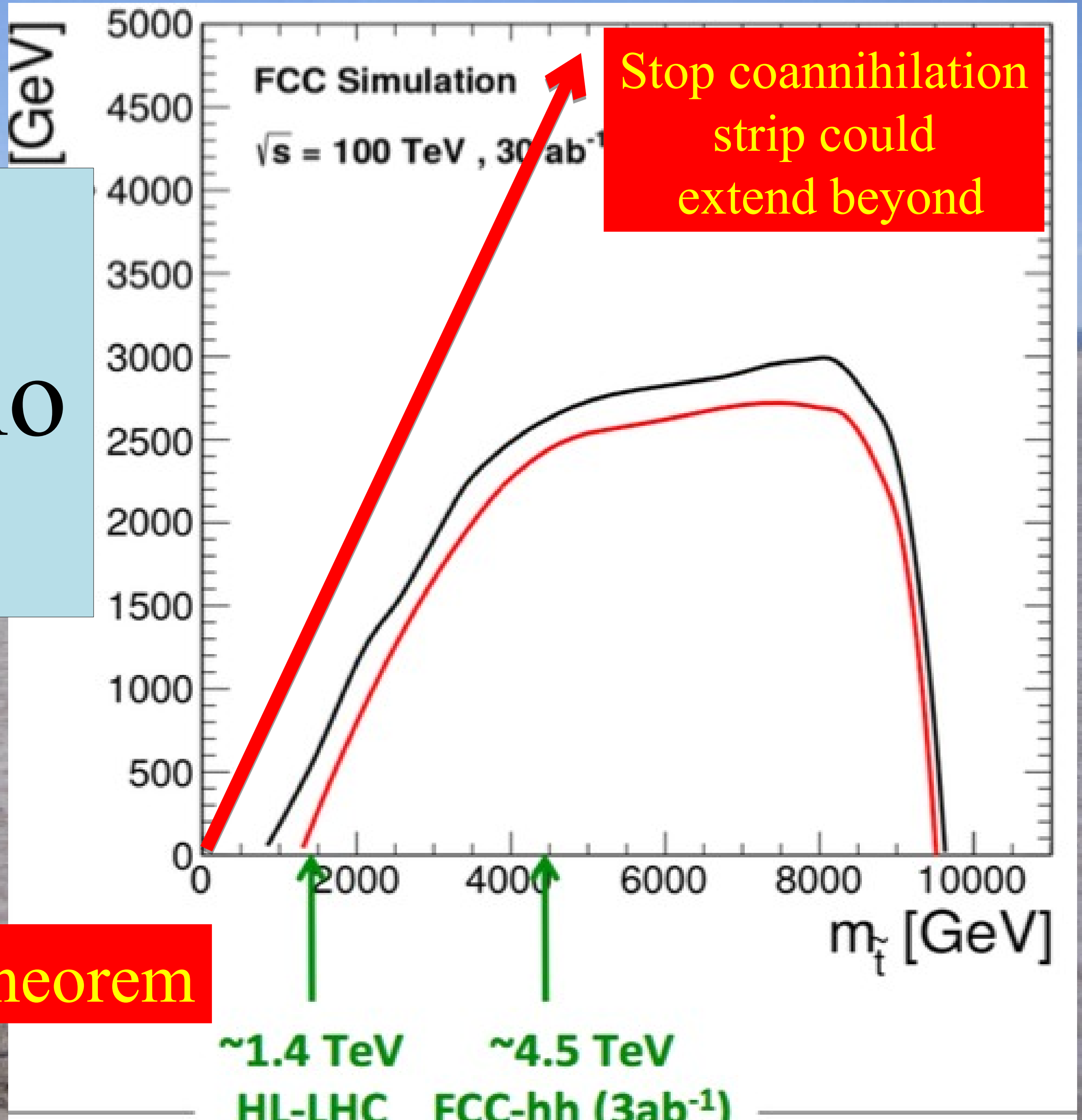
LSP mass ≤ 8 TeV

LSP mass ≤ 5 TeV

- Experimental MET signature more difficult

Bagnaschi, Bahl, JE et al, arXiv:1810.10905

Stop-Neutralino Plane



No 'no-lose' theorem


LIFE HAS REALLY GOT ME DOWN.
WELL, THINGS MIGHT GET BETTER..

- « Empty » space is unstable
- Dark matter
- Origin of matter
- Hierarchy/naturalness
- Masses of neutrinos
- Inflation
- Quantum gravity
- …

- HL-LHC is on its way
- ILC might be next
- CLIC's energy advantageous
- FCC most versatile