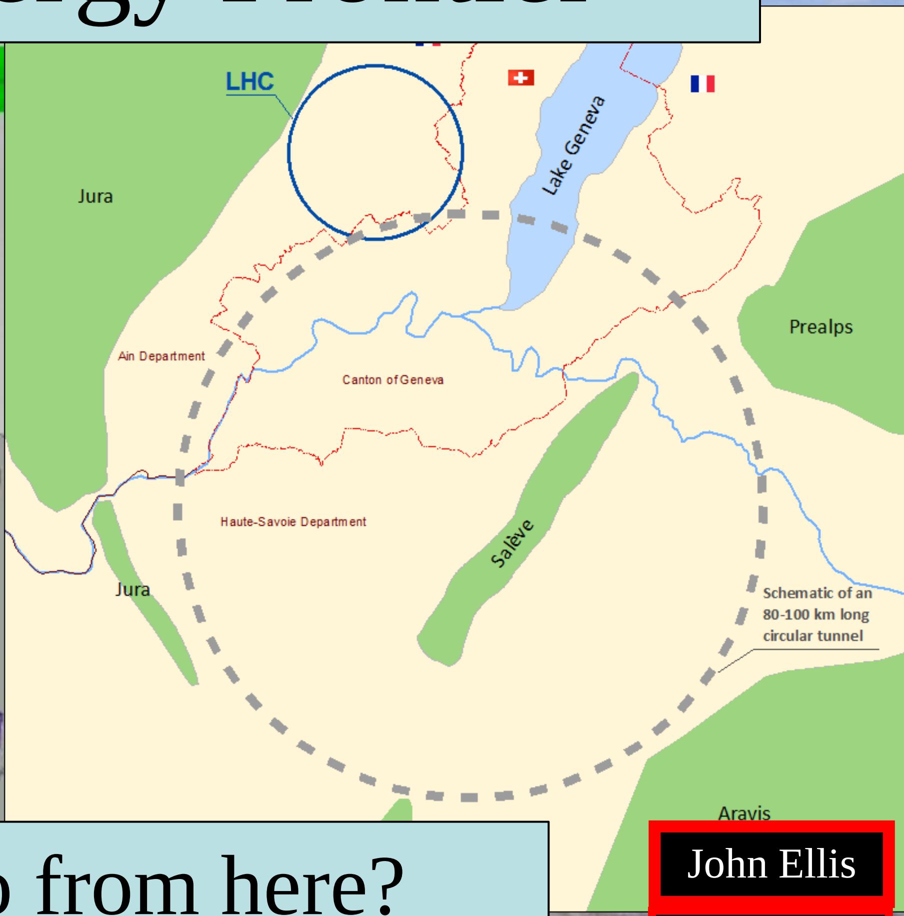
Physics Challenges at the High-Energy Frontier



Where do we go from here?
After the Higgs, LHC Run 1

John Ellis

KING'S College LONDON

Open Questions beyond the Standard Model

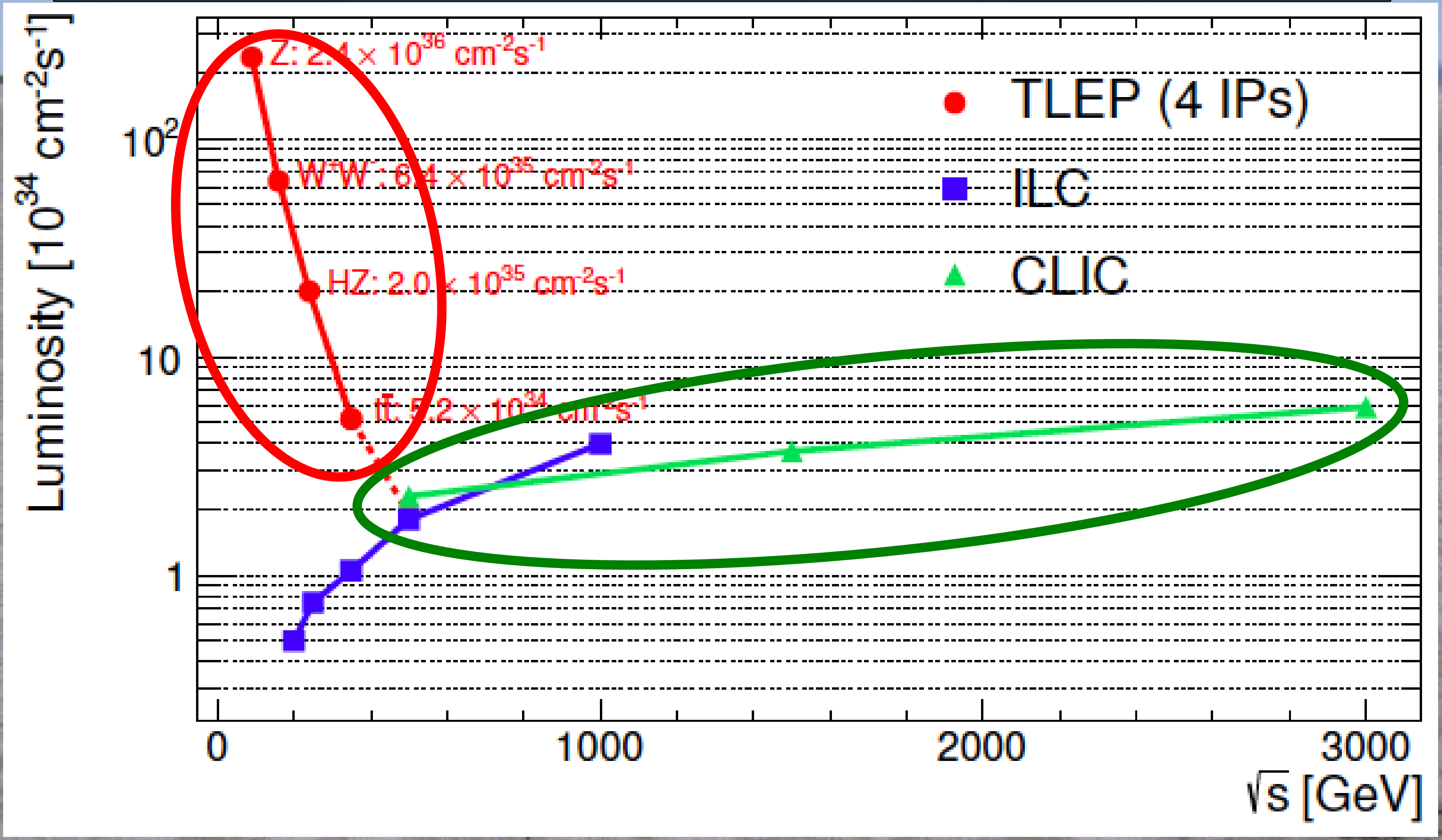
- What is the origin of particle masses?
  due to a Higgs boson?
- Why so many types of matter particles?
- What is the dark matter in the Universe?
- Unification of fundamental forces?
- Quantum theory of gravity?

LHC

Theoretical Confusion

- High mortality rate among theories
- (M_H, M_t) close to stability bound
- Split SUSY? High-scale SUSY?
- Modify/abandon naturalness? Does Nature care?
- String landscape?
- SUSY anywhere better than nowhere
- SUSY could not explain the hierarchy
- **New ideas needed!**

Projected e^+e^- Colliders: Luminosity vs Energy



Proton-Proton Colliders: Luminosity and Energy

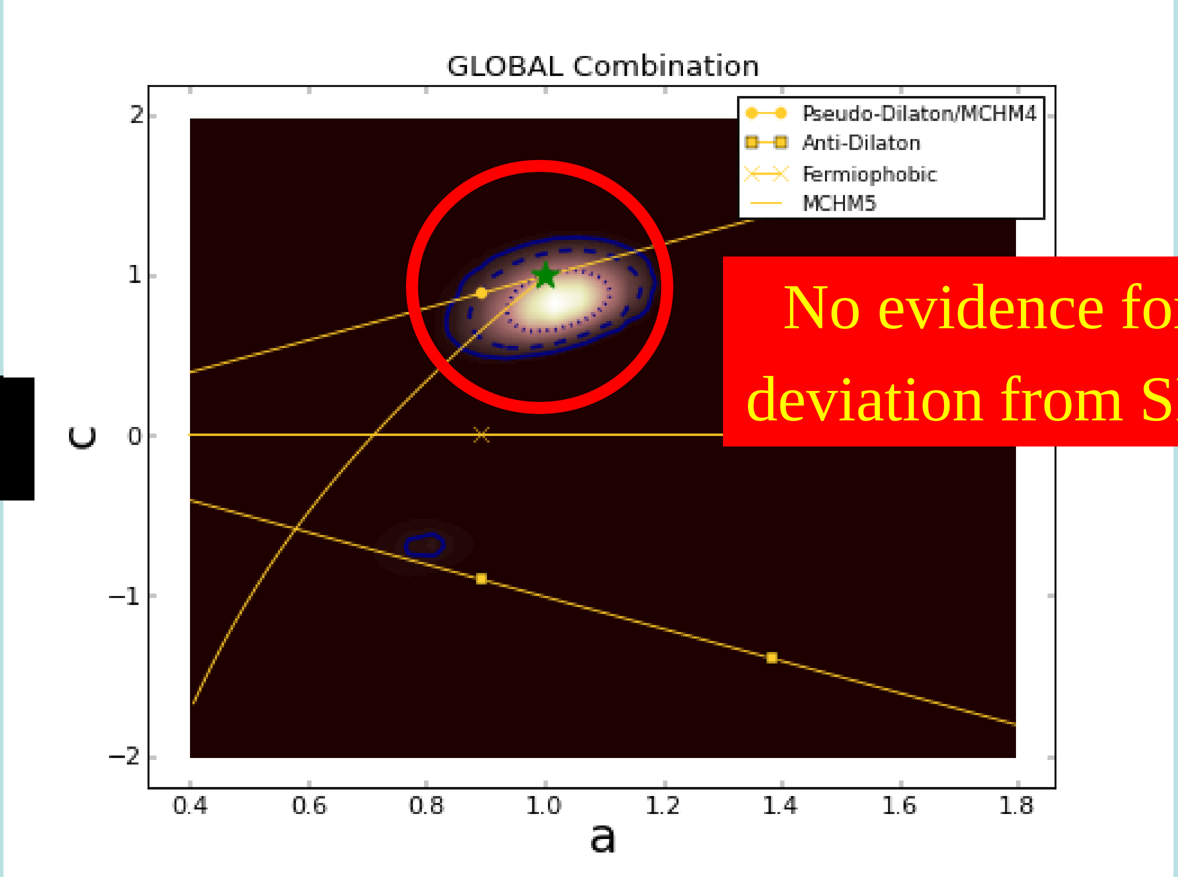
- Future runs of the LHC:
  - Run 2: 30/fb @ 13/14 TeV
  - Run 3: 300/fb @ 14 TeV
- HL-LHC: 3000/fb @ 14 TeV?
  (advanced planning, not formally approved)
- HE-LHC: 3000/fb @ 33 TeV??
  (high-field magnets in the LHC tunnel)
- VHE-LHC: 3000/fb @ 100 TeV??
  (high-field magnets in 80/100 km tunnel)

July 4th 2012

The discovery of a new particle

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*



Global

No evidence for deviation from SM

- Standard Model: $a = c = 1$

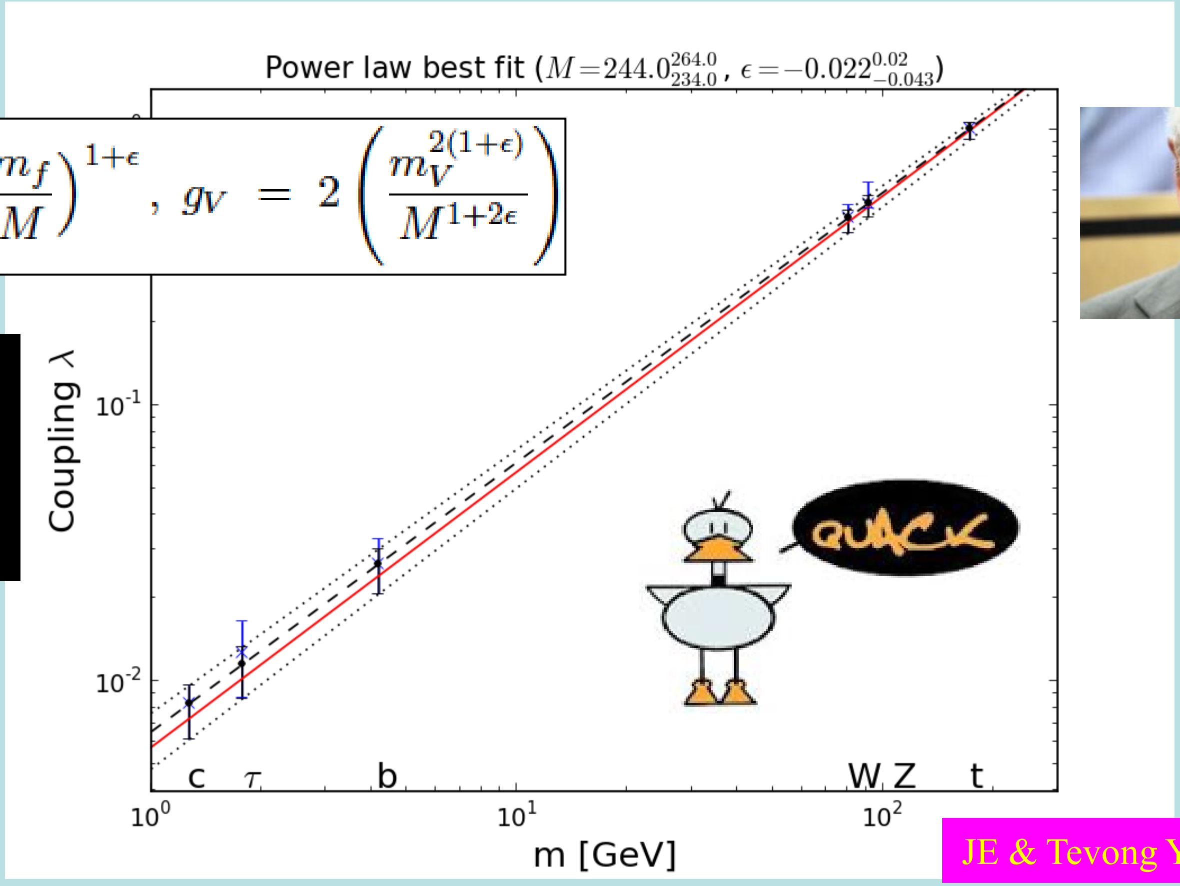
JE & Tevong You, arXiv:1303.3879

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

Global fit



JE & Tevong You, arXiv:1303.3879

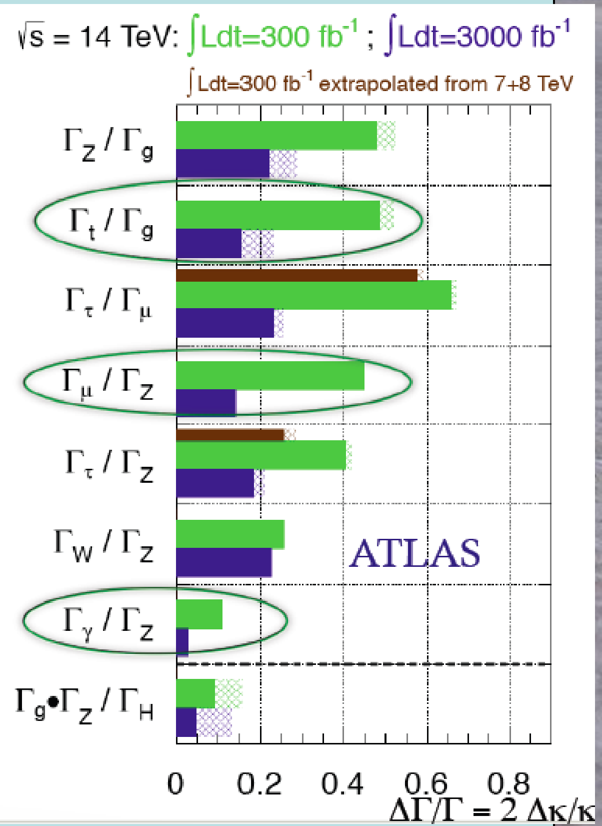
- **Red line = SM**, dashed line = best fit

What Next: A Higgs Factory?

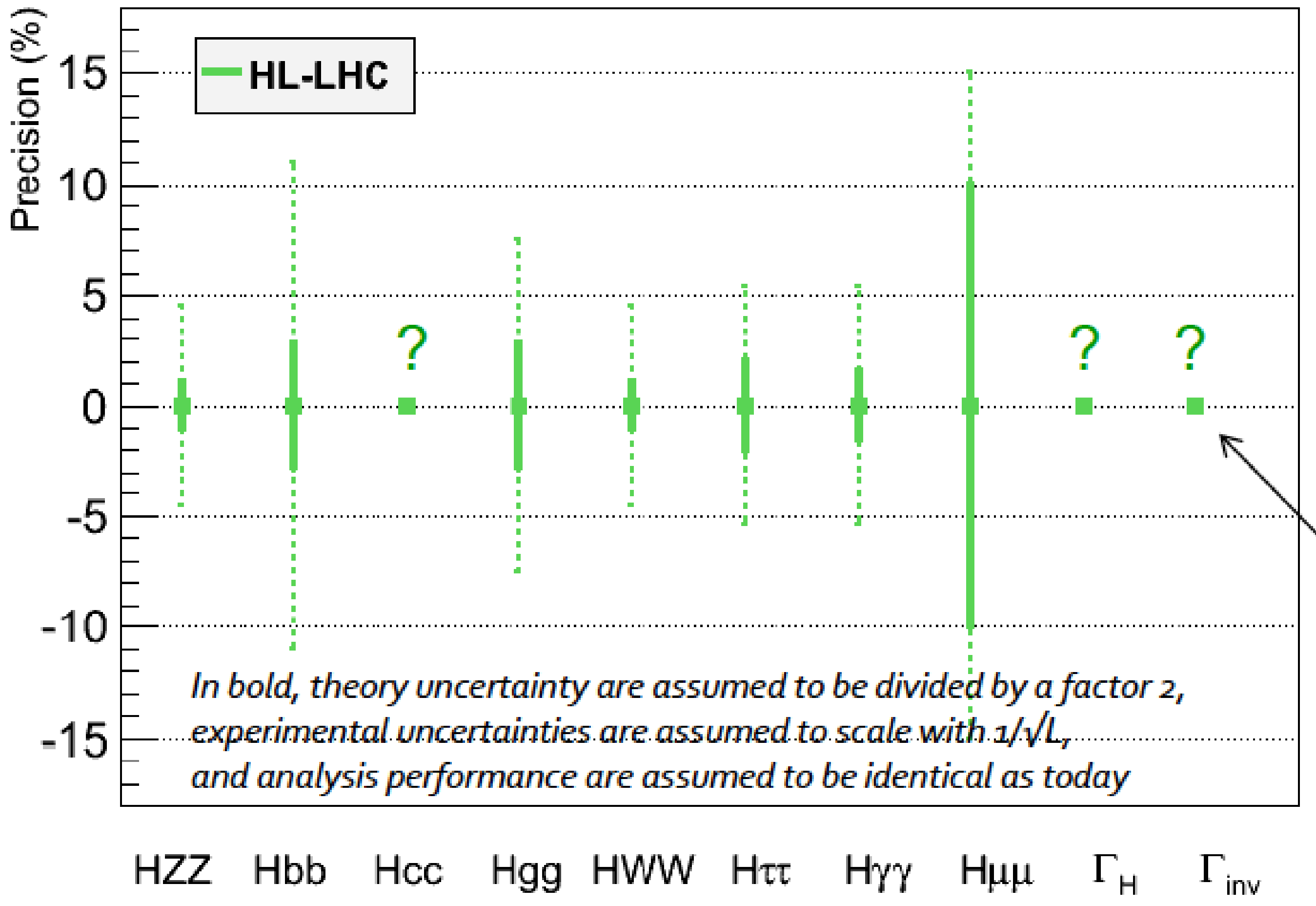
To study the 'Higgs' in detail:

- The LHC
  - Rethink LHC upgrades in this perspective?
- A linear collider?
  - ILC up to 500 GeV
  - CLIC up to 3 TeV

    (Larger cross section at higher energies)
- A circular e+e- collider: LEP3, …
  - A photon-photon collider: SAPPHiRE
- A muon collider



Possible High-Luminosity LHC Measurements



Assumptions :

1. No new decay
2. Γ_H fixed in the fit (or fixed BR(cc))

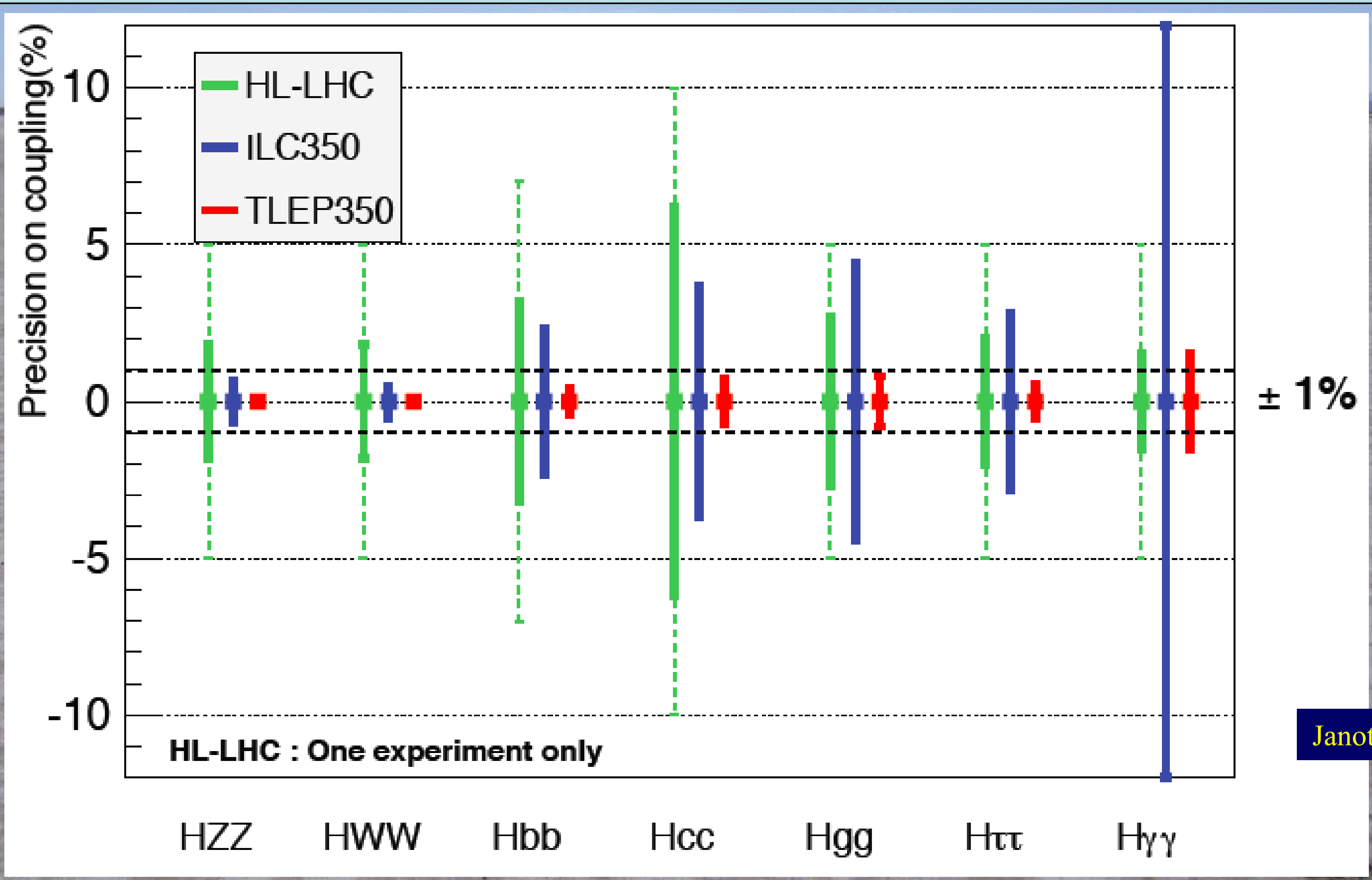
ATLAS upper limit at 65%
(Moriond EW 2013)

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

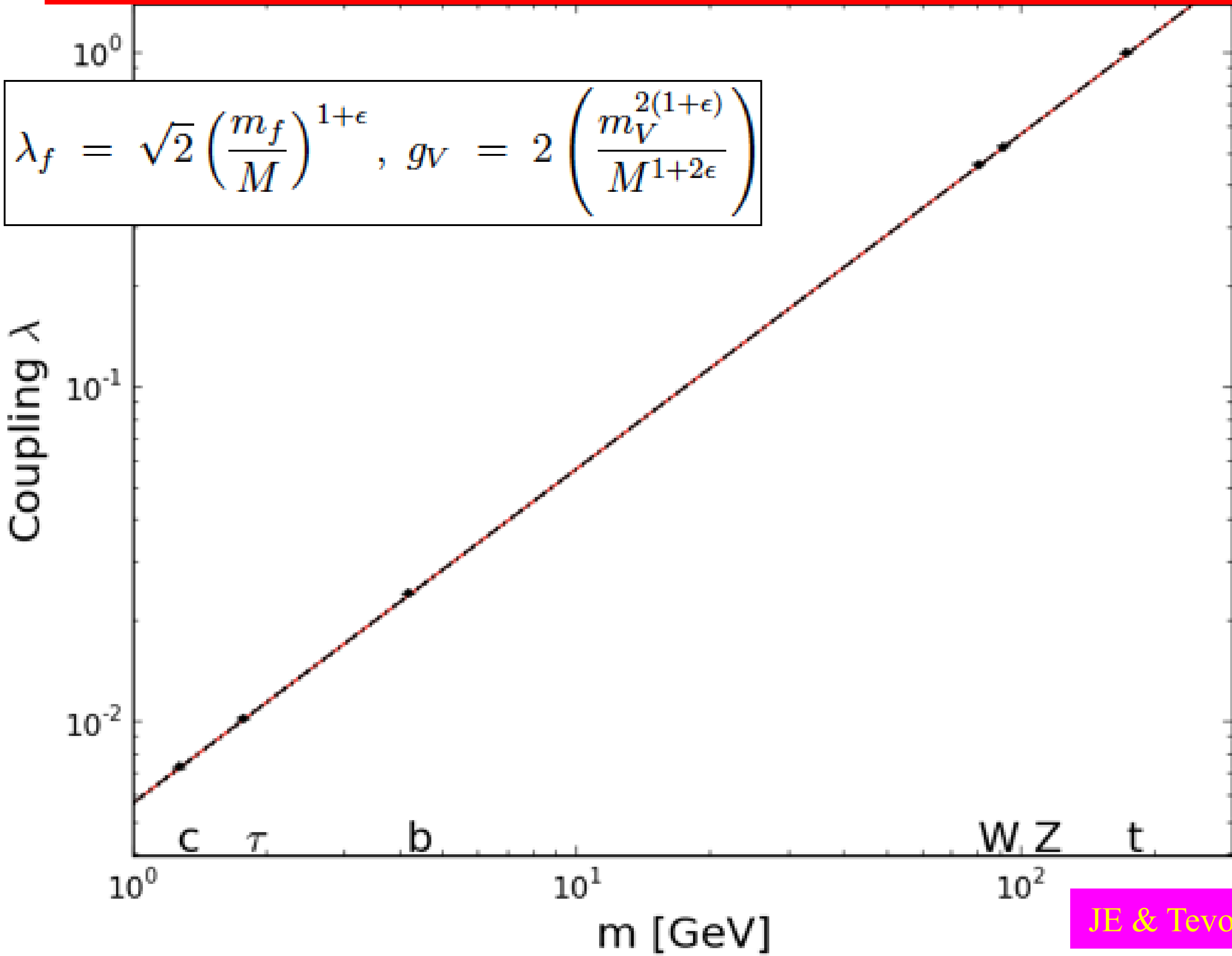


Janot

H Coupling Measurements @TLEP

$M = 246.0 \pm 0.8$ GeV, $\varepsilon = 0.0000^{+0.0015}_{-0.0010}$

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon},\; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$



JE & Tevong You

CLIC Higgs Measurements

★ **Model-independent global fits**

- **Note: updates since Snowmass**

Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
m_H	120.00 MeV	30.00 MeV	20.00 MeV
λ	–	21.00%	10.00%
Γ_H [%]	5.47	4.23	4.11
g_{HZZ} [%]	1.00	1.00	1.00
g_{HWW} [%]	1.87	1.05	1.03
g_{Hbb} [%]	2.06	1.11	1.05
g_{Hcc} [%]	3.28	1.50	1.26
g_{Htt} [%]	–	4.15	4.13
$g_{H\tau\tau}$ [%]	3.55	1.68	1.64
$g_{H\mu\mu}$ [%]	–	11.03	5.37
g_{Hgg} [%]	3.67	1.29	1.15
$g_{H\gamma\gamma}$ [%]	–	5.60	5.59

★ **Constrained "LHC-style" fits**

- **Assuming no invisible Higgs decays (model-dependent):**

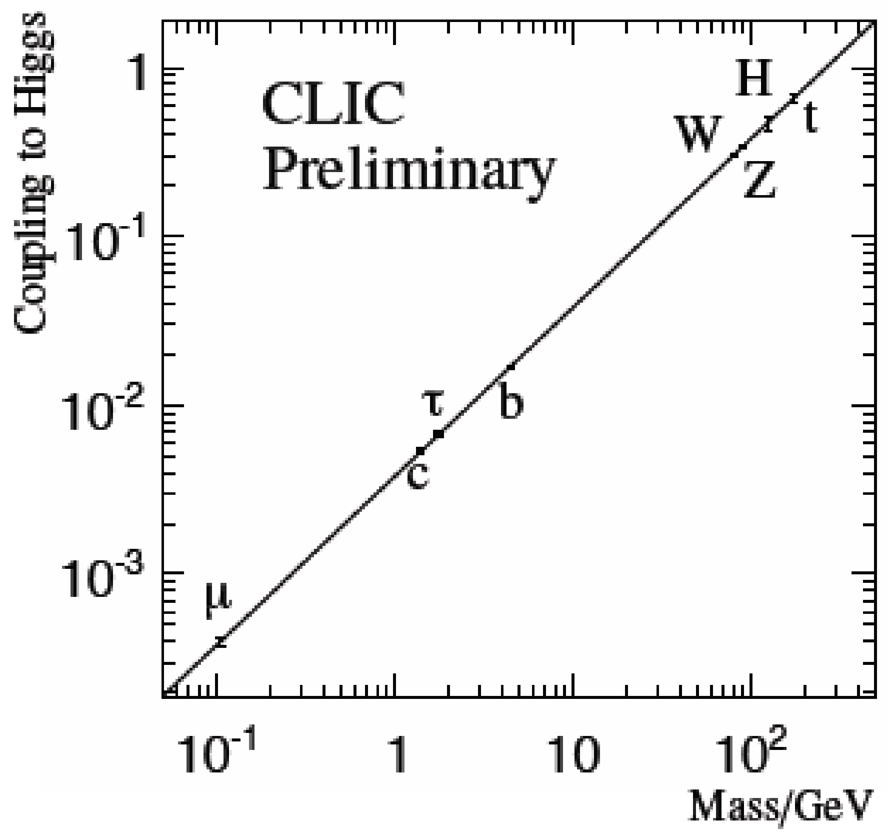
$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i|_{SM}}$$

$$\Gamma_{H,md} = \sum_i \kappa_i^2 \, BR_i$$

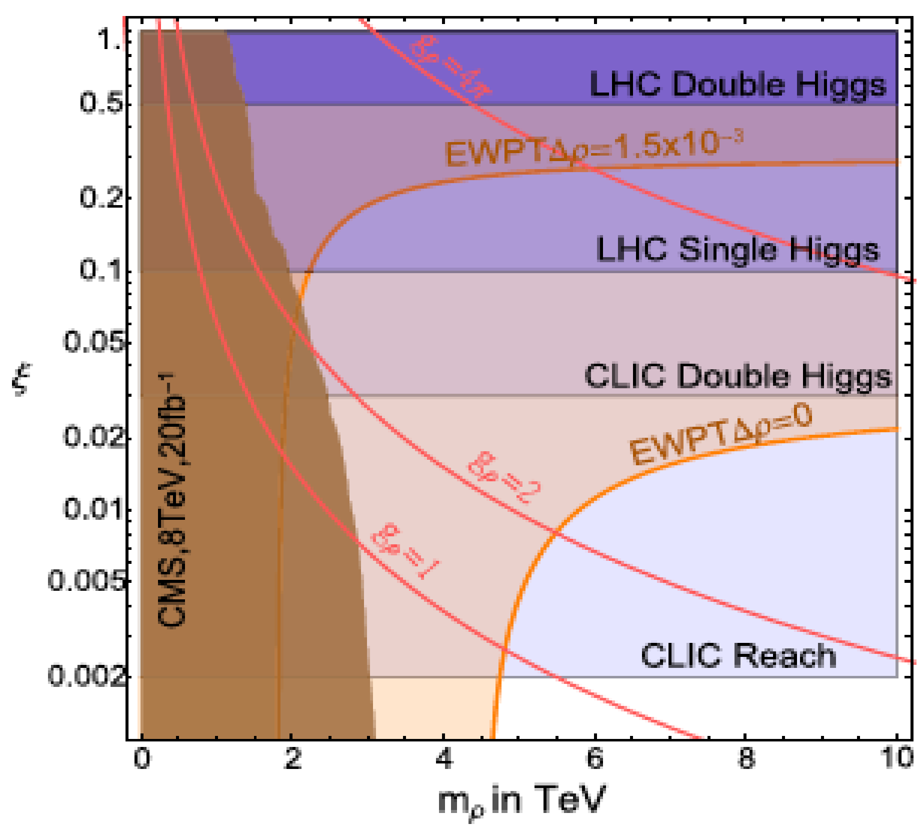
Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
$\Gamma_{H,model}$ [%]	1.62	0.29	0.22
κ_{HZZ} [%]	0.45	0.32	0.24
κ_{HWW} [%]	1.53	0.15	0.11
κ_{Hbb} [%]	1.69	0.33	0.21
κ_{Htt} [%]	3.07	1.04	0.74
$\kappa_{H\tau\tau}$ [%]	3.45	1.35	1.31
κ_{Hgg} [%]	3.62	0.79	0.56
$\kappa_{H\gamma\gamma}$ [%]	–	5.52	5.51

CLIC Higgs Measurements

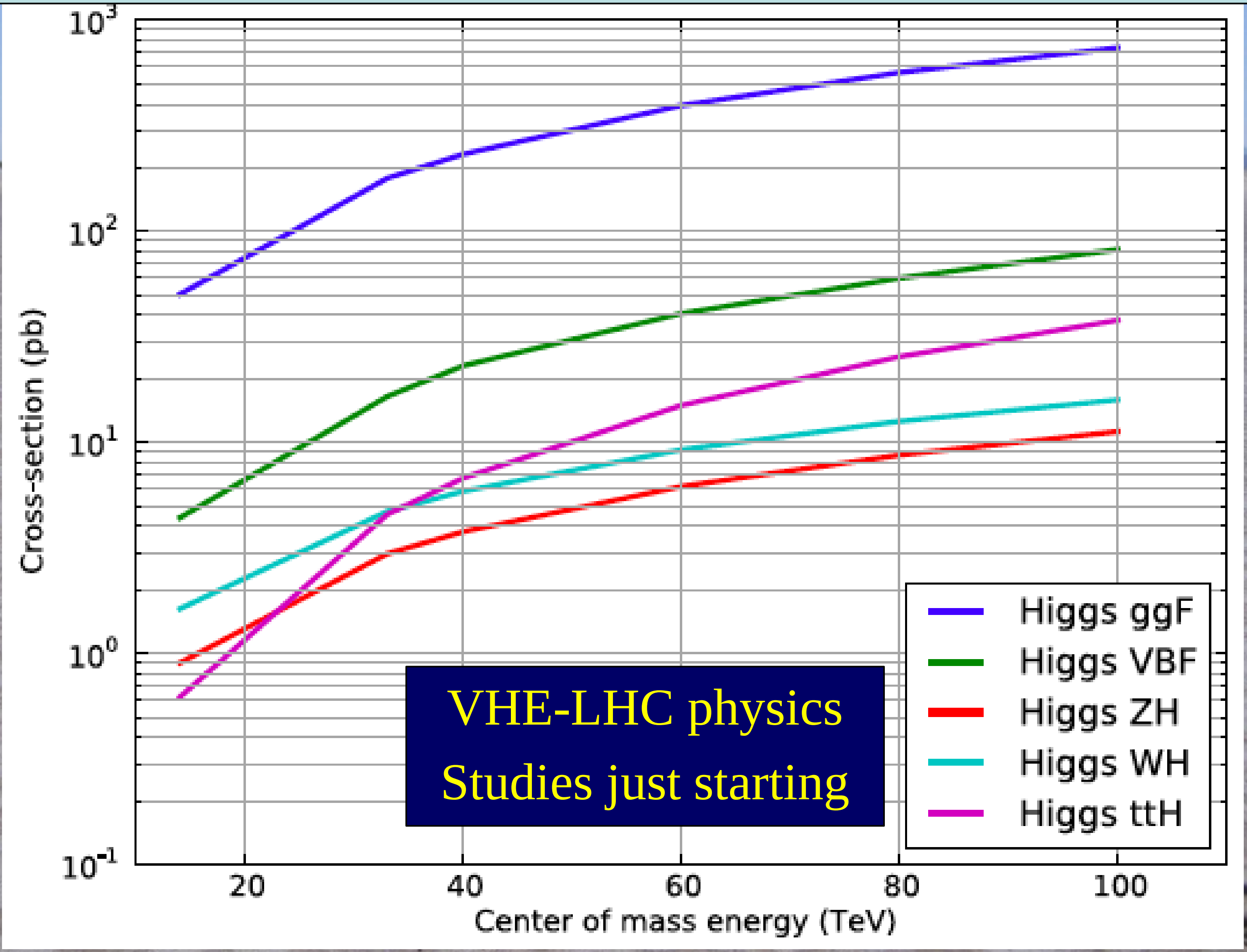
Mass dependence of H couplings



Sensitivity to composite H models



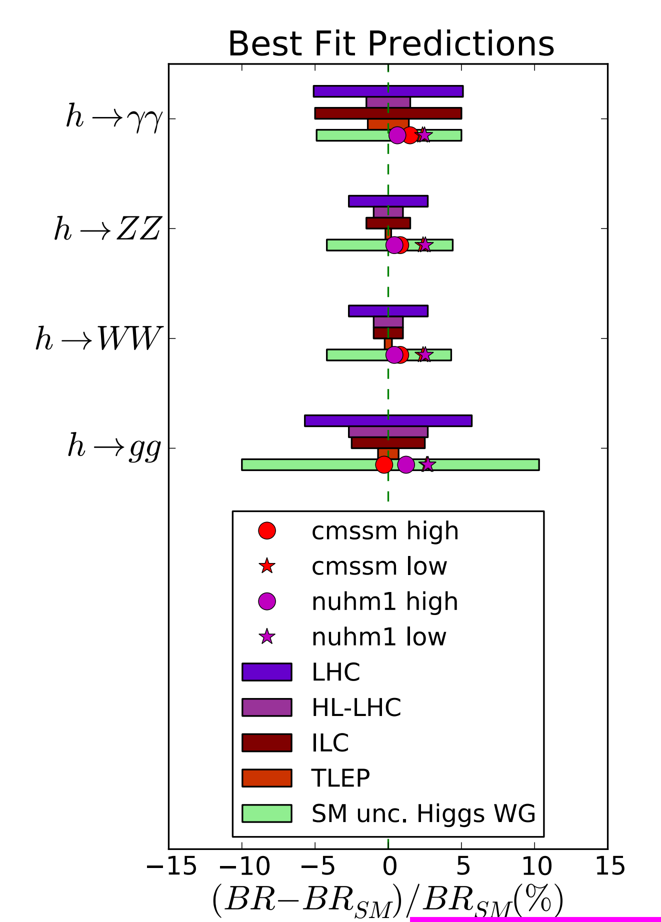
Higgs Cross-Sections @ HE/VHE-LHC



VHE-LHC physics
Studies just starting

Impact of Higgs Measurements

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - LHC
  - HL-LHC
  - ILC
  - TLEP
- **Don't decide before LHC 13/4**



K. De Vries (MasterCode)

Possible TLEP Precision Measurements

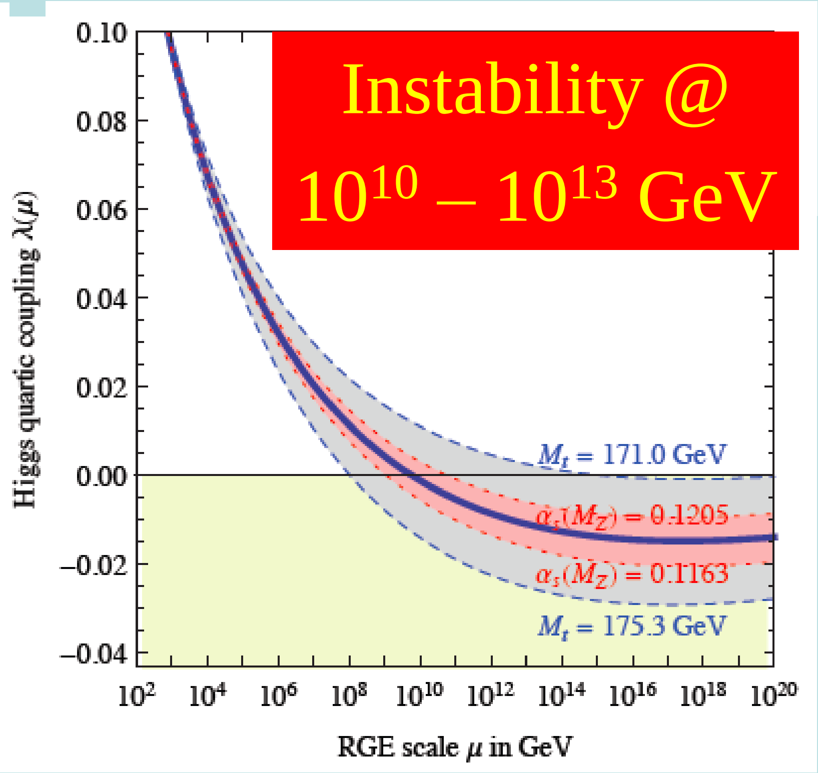
Quantity	Physics	Present precision		TLEP Stat errors	Possible TLEP Syst. Errors	TLEP key	Challenge
M_z (keV)	Input	91187500 ±2100	Z Line shape scan	5 keV	<100 keV	E_cal	QED corrections
Γ_z (keV)	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495200 ±2300	Z Line shape scan	8 keV	<100 keV	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001	<0.001	Statistics	QED corrections
N_ν	PMNS Unitarity sterile ν's	2.984 ±0.008	Z Peak	0.00008	<0.004		Bhabha scat.
N_ν	PMNS Unitarity sterile ν's	2.92 ±0.05	(γ+Z_inv) (γ+Z→ ℓℓ)	0.001 (161 GeV)	<0.001	Statistics	
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003	<0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho, \varepsilon_3, \Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	0.000015	<0.000015	4 bunch scheme, > 2exp	Design experiment
M_W MeV/c2	$\Delta\rho, \varepsilon_3, \varepsilon_2, \Delta\alpha$ (T, S, U)	80385 ± 15	Threshold (161 GeV)	0.3 MeV	<0.5 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	Input	173200 ± 900	Threshold scan	10 MeV	<10MeV	E_cal & Statistics	Theory interpretation 40 MeV?

Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$

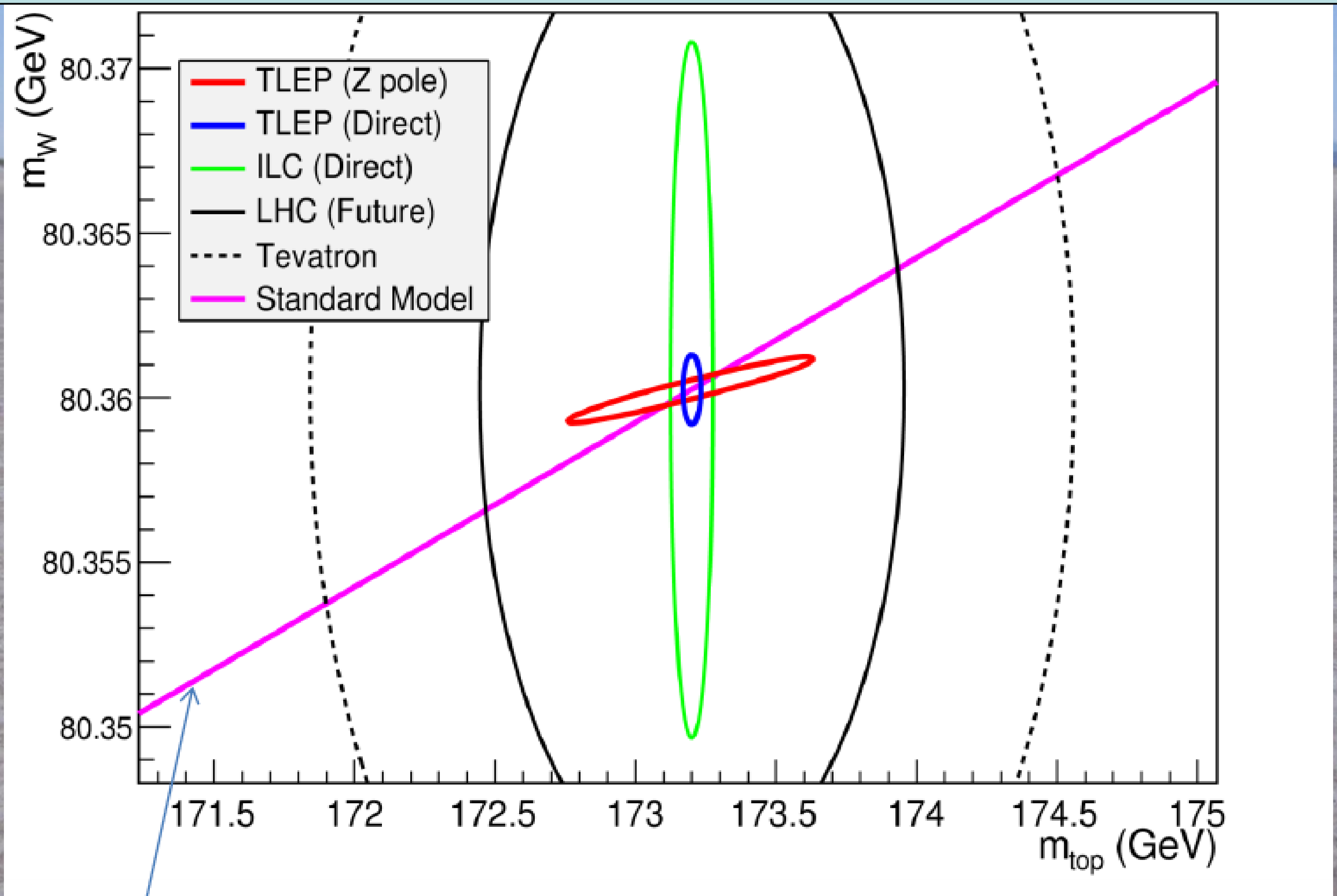
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable



- Vacuum could be stabilized by **Supersymmetry**

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

TLEP Measurements of m_t & M_W



NB without TLEP the SM line would have a 2.2 MeV width

What else is there?

Supersymmetry

- 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, … (???)

Data

- **Electroweak precision observables**
- **Flavour physics observables**
- **g_μ - 2**
- **Higgs mass**
- **Dark matter**
- **LHC**

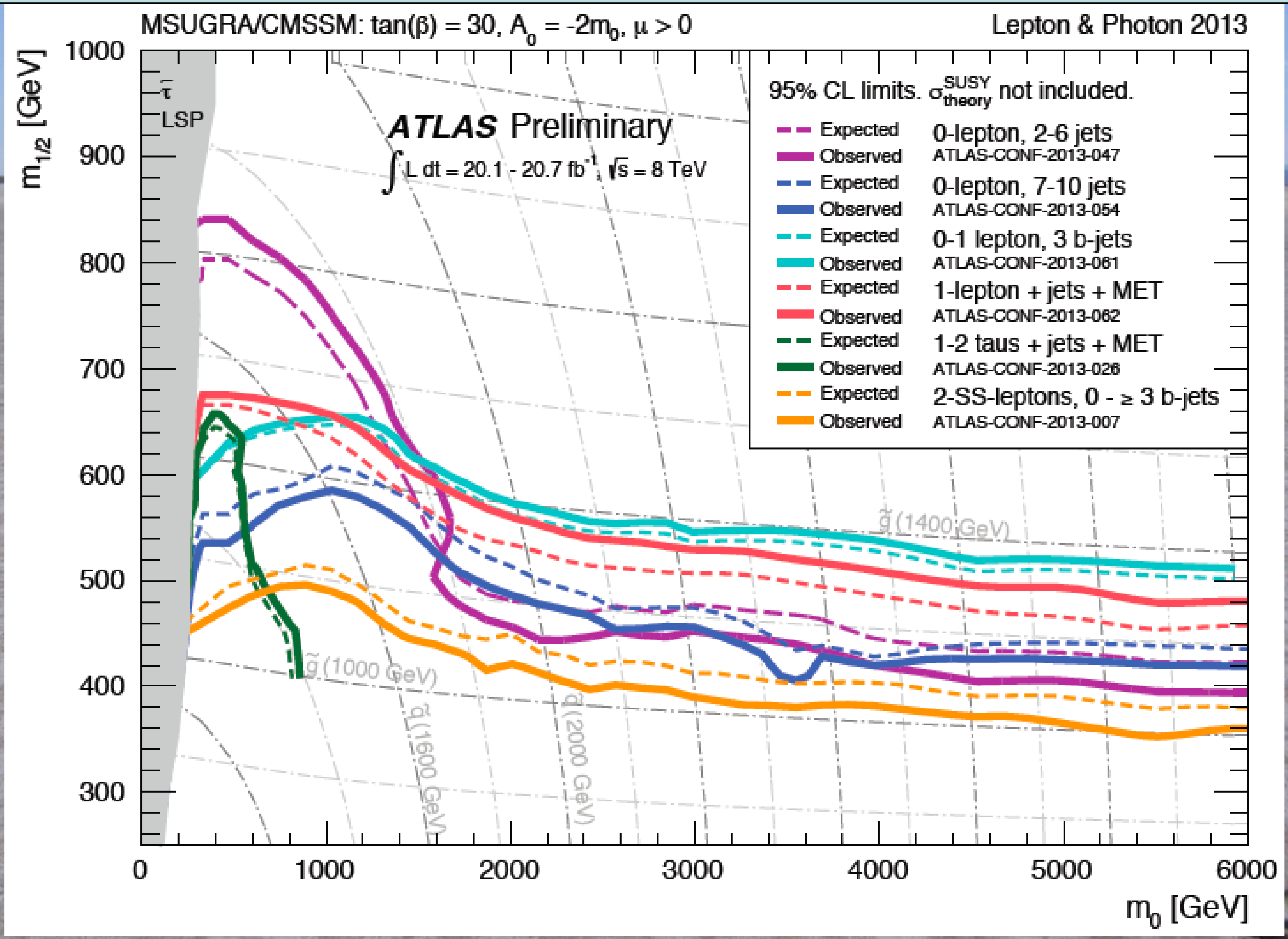
Deviation from Standard Model:
Supersymmetry at low scale, or …?

Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 0.90
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	[38]	0.02749 ± 0.00010
M_Z [GeV]	[40]	91.1875 ± 0.0021
Γ_Z [GeV]	[24] / [40]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma^0_{\rm had}$ [nb]	[24] / [40]	41.540 ± 0.037
R_l	[24] / [40]	20.767 ± 0.025
$A_{\rm fb}(\ell)$	[24] / [40]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[24] / [40]	0.1465 ± 0.0032
R_b	[24] / [40]	0.21629 ± 0.00066
R_c	[24] / [40]	0.1721 ± 0.0030
$A_{\rm fb}(b)$	[24] / [40]	0.0992 ± 0.0016
$A_{\rm fb}(c)$	[24] / [40]	0.0707 ± 0.0035
A_b	[24] / [40]	0.923 ± 0.020
A_c	[24] / [40]	0.670 ± 0.027
A_ℓ(SLD)	[24] / [40]	0.1513 ± 0.0021
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$	[24] / [40]	0.2324 ± 0.0012
M_W [GeV]	[24] / [40]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$
${\rm BR}^{\rm EXP}_{b\to s\gamma}/{\rm BR}^{\rm SM}_{b\to s\gamma}$	[41] / [42]	$1.117 \pm 0.076_{\rm EXP} \pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$
[illegible]	[27] / [37]	$(< 1.08 \pm 0.02_{\rm SUSY}) \times 10^{-8}$
[illegible]	[27] / [42]	$1.43 \pm 0.43_{\rm EXP+TH}$
[illegible]	[27] / [42]	$< (4.6 \pm 0.01_{\rm SUSY}) \times 10^{-9}$
[illegible]	[43]/ [42]	0.99 ± 0.32
${\rm BR}^{\rm EXP}_{K\to\mu\nu}/{\rm BR}^{\rm SM}_{K\to\mu\nu}$	[27] / [44]	$1.008 \pm 0.014_{\rm EXP+TH}$
${\rm BR}^{\rm EXP}_{K\to\pi\nu\bar\nu}/{\rm BR}^{\rm SM}_{K\to\pi\nu\bar\nu}$	[45]/ [46]	< 4.5
$\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s}$	[45] / [47, 48]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$
$\frac{(\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s})}{(\Delta M^{\rm EXP}_{B_d}/\Delta M^{\rm SM}_{B_d})}$	[27] / [42, 47, 48]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$
$\Delta\epsilon^{\rm EXP}_K/\Delta\epsilon^{\rm SM}_K$	[45] / [47, 48]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a^{\rm EXP}_\mu - a^{\rm SM}_\mu$	[49] / [38, 50]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
[illegible]	[illegible]	[illegible] $\pm 1.5_{\rm SUSY}$
[illegible]	[illegible]	[illegible]$56 \pm 0.012_{\rm SUSY}$
$\sigma_p^{\rm SI}$	[23]	[illegible] plane
jets + $\not{E}_T$	[16, 18]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[19]	$(M_A, \tan\beta)$ plane

$M_H = 125.6 \pm 0.3 \pm 1.5$ GeV

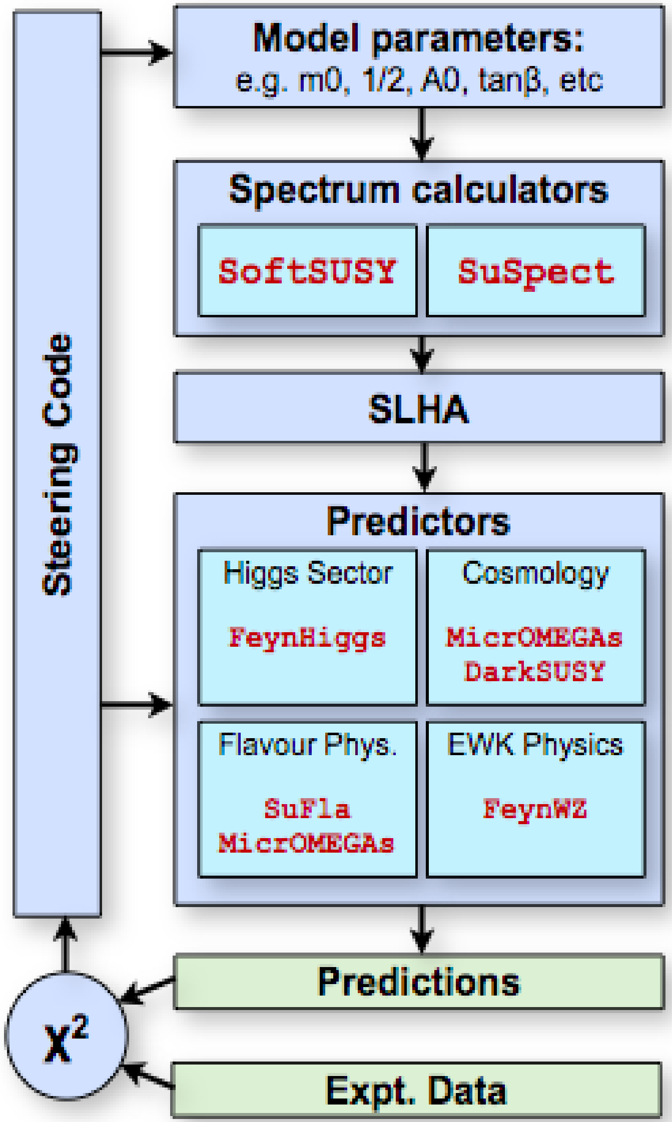
MasterCode: O.Buchmueller, JE et al.

Search with ~ 20/fb @ 8 TeV



MasterCode

- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- **Compatibility is crucial! Ensured by**
  - close collaboration of tools authors
  - standard interfaces

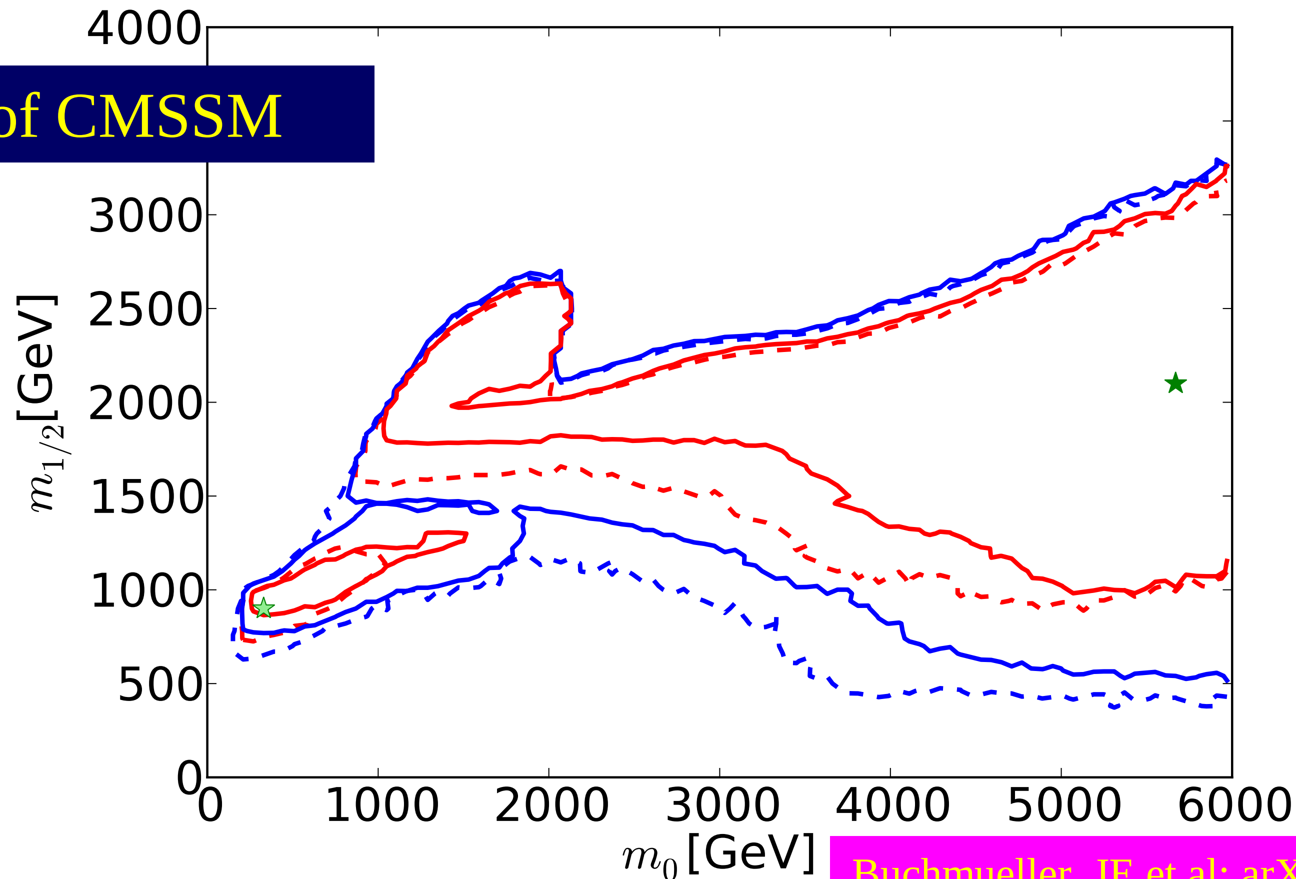


O. Buchmueller, R. Cavanaugh, *M. Citron*, A. De Roeck, M.J. Dolan, J.E., H. Flacher, S. Heinemeyer, G. Isidori, J. Marrouche, D. Martinez Santos, *S. Nakach*, K.A. Olive, *S. Rogerson*, F.J. Ronga, *K.J. de Vries*, G. Weiglein

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

Scan of CMSSM

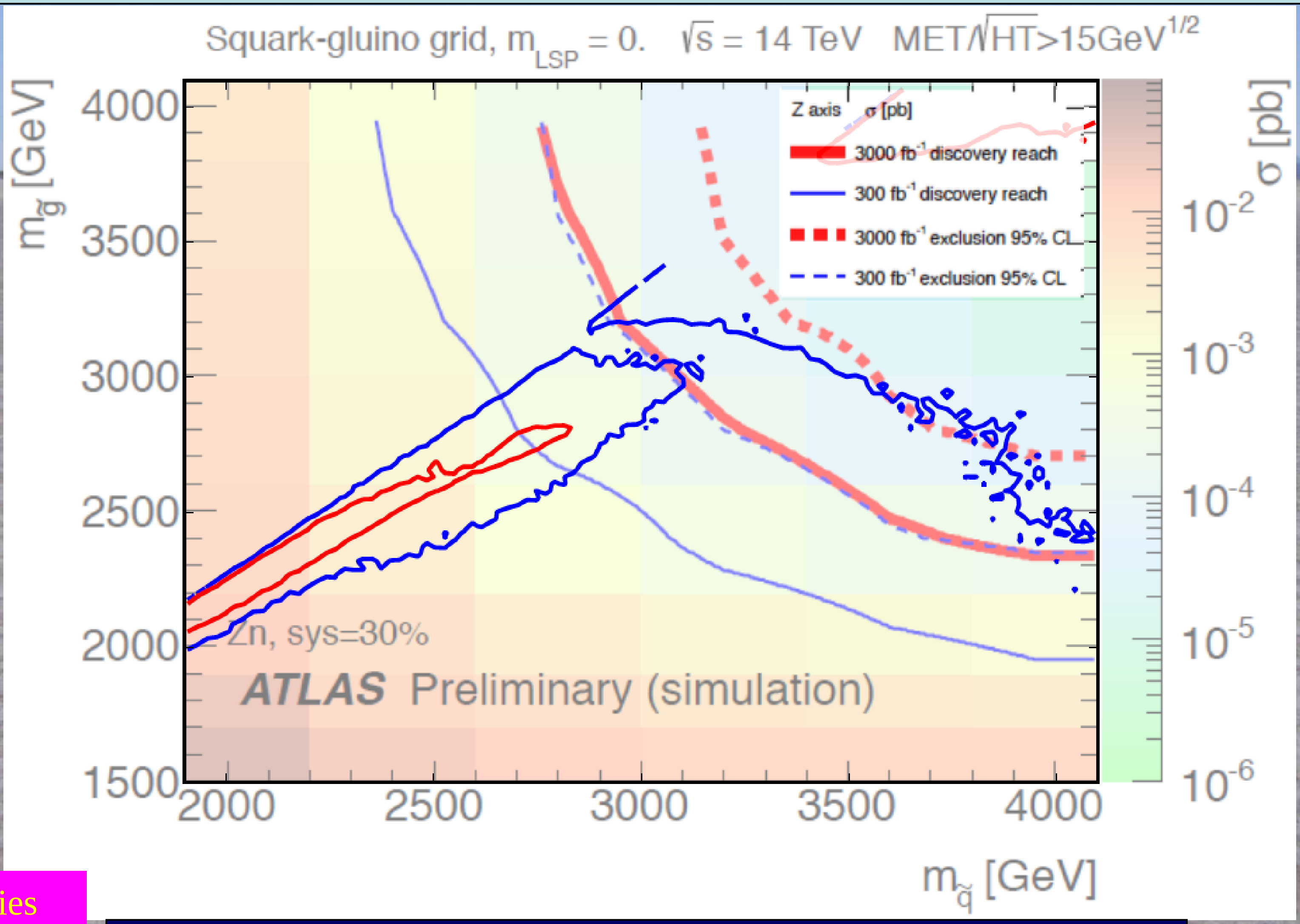


Buchmueller, JE et al: arXiv:1312.5250

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

p-value of simple models ~ 5% (also SM)

LHC Reach for Supersymmetry

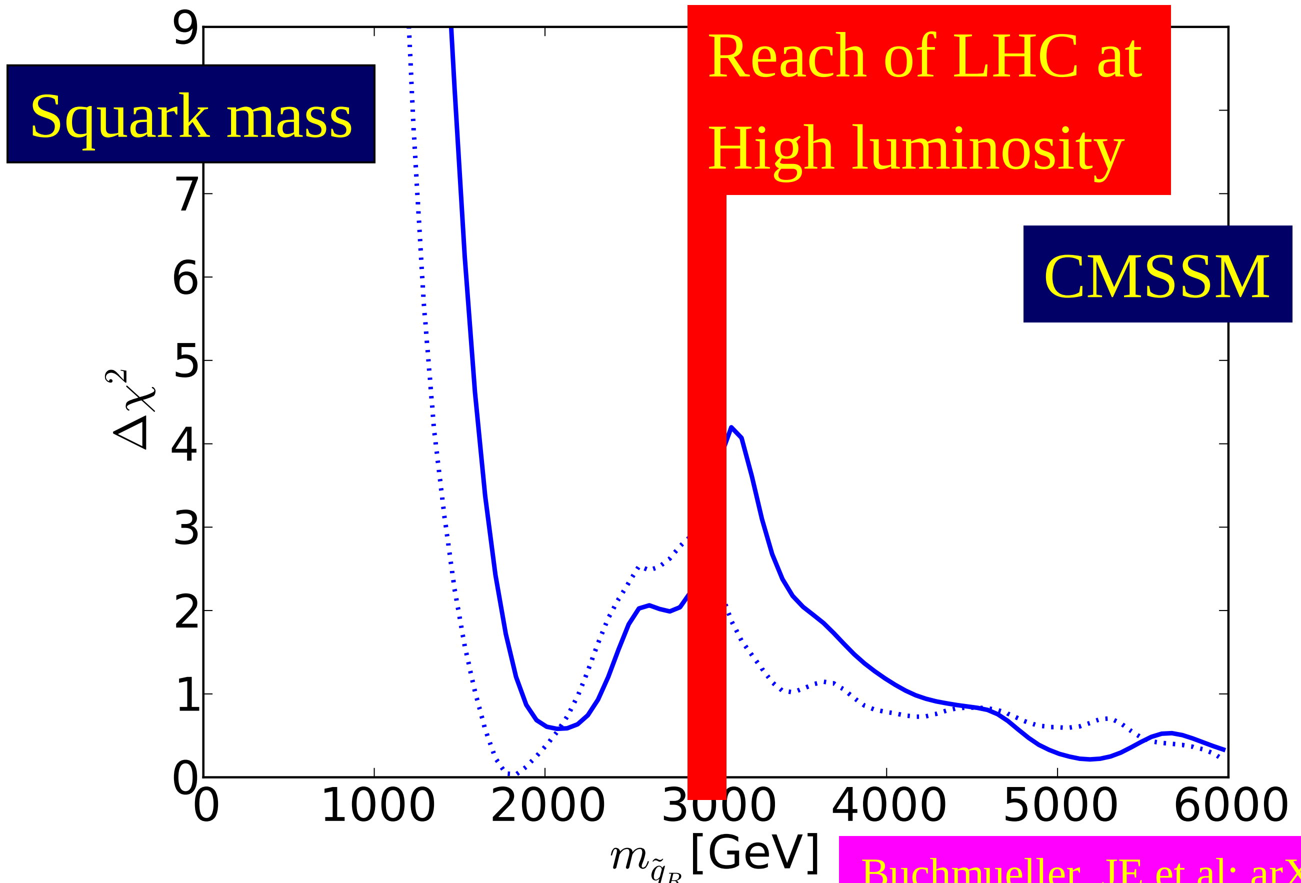


K. De Vries (MasterCode)

Confronted with likelihood analysis of CMSSM

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

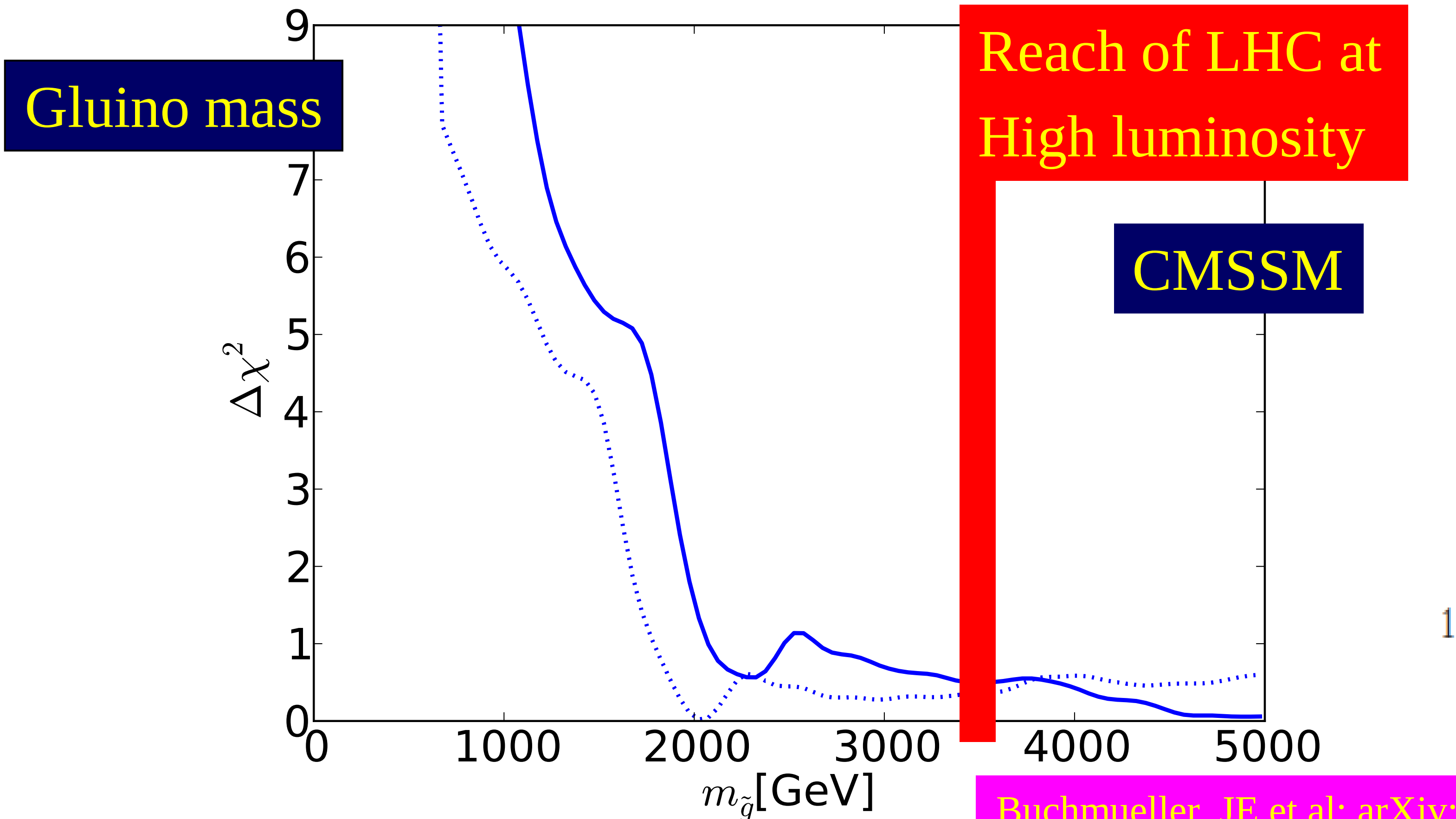


Buchmueller, JE et al: arXiv:1312.5250

Favoured values of squark mass also significantly above pre-LHC, > 1.6 TeV

Post-LHC, Post-XENON100

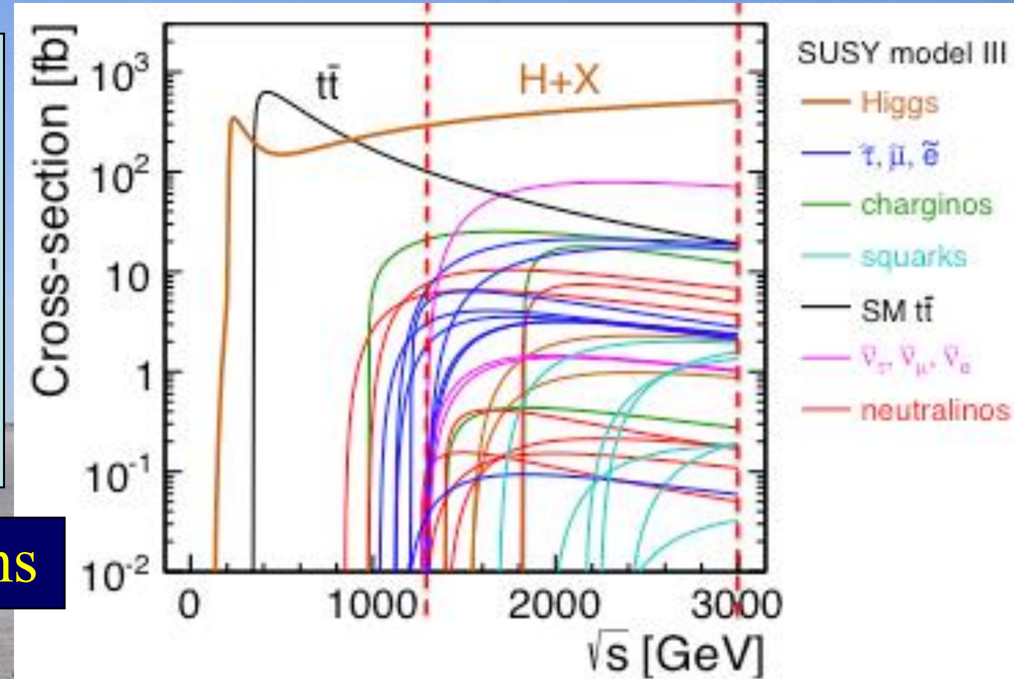
2012 ATLAS + CMS with 20/fb of LHC Data



Buchmueller, JE et al: arXiv:1312.5250

Favoured values of gluino mass significantly above pre-LHC, > 1.8 TeV

CLIC Capabilities for Supersymmetry

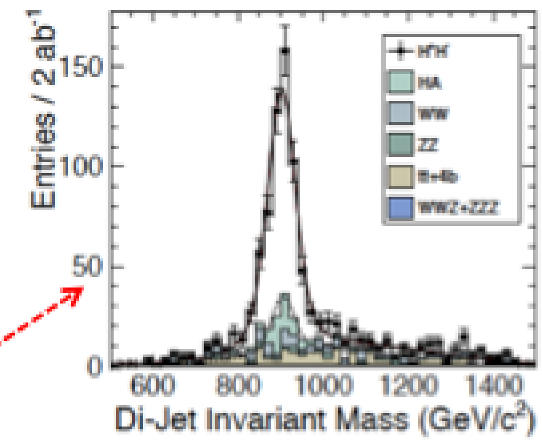


Possible cross-sections

Possible measurement errors

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\,h/Z^0\,\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%

e.g. Heavy Higgs



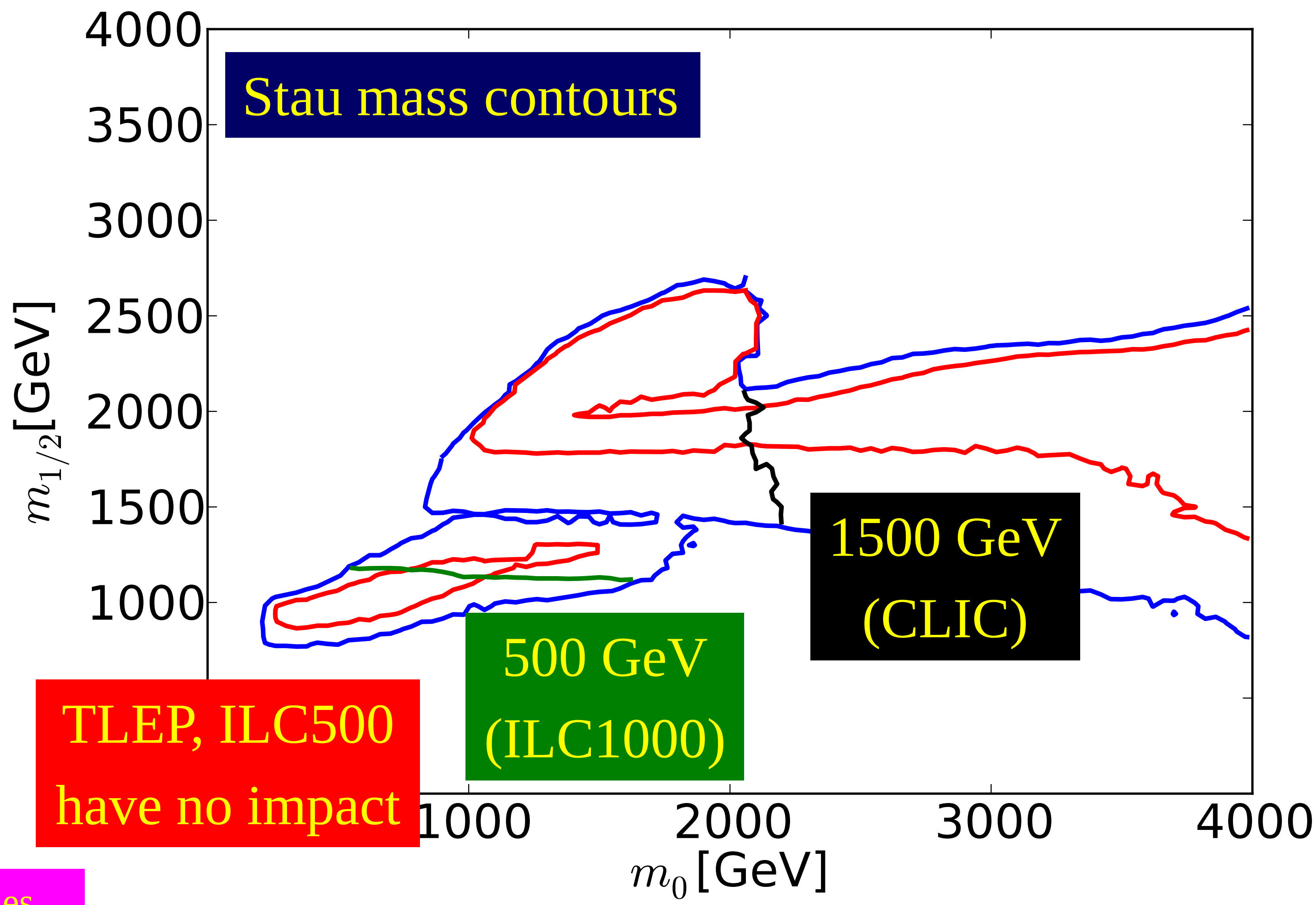
per cent level measurements of SUSY mass spectrum

unique opportunity to probe SUSY breaking mechanism

CLIC Sensitivity to BSM Physics

New particle	LHC (14 TeV)	HL-LHC	CLIC3
squarks [TeV]	2.5	3	$\lesssim$1.5
sleptons [TeV]	0.3	-	$\lesssim$1.5
Z' (SM couplings) [TeV]	5	7	20
2 extra dims M_D [TeV]	9	12	20–30
TGC (95%) (λ_γ coupling)	0.001	0.0006	0.0001
μ contact scale [TeV]	15	-	60
Higgs composite scale [TeV]	5–7	9–12	70

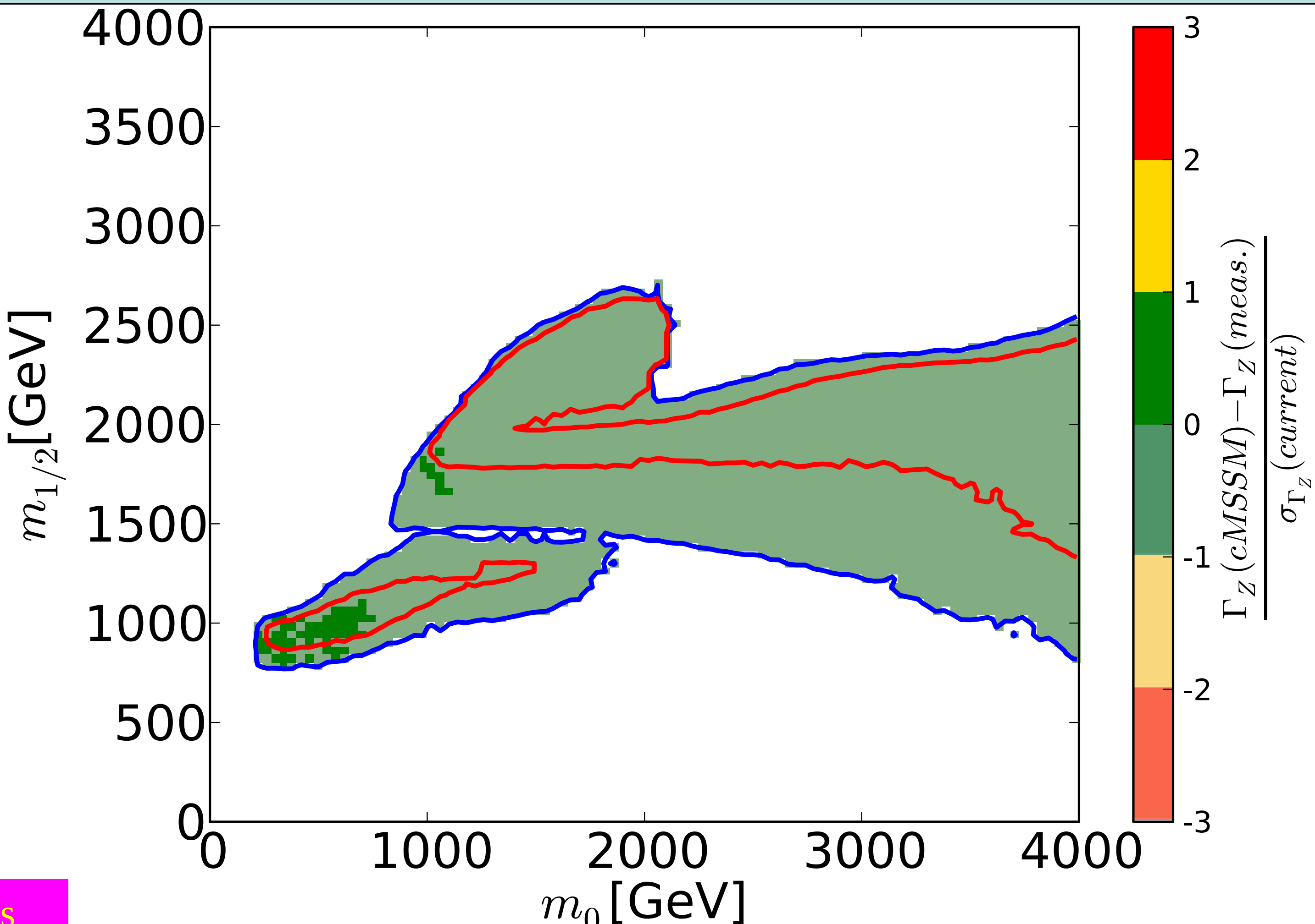
Direct Reach for Supersymmetry



K. De Vries
(MasterCode)

Confronted with likelihood analysis of CMSSM

Impact of **LEP** Precision on Susy

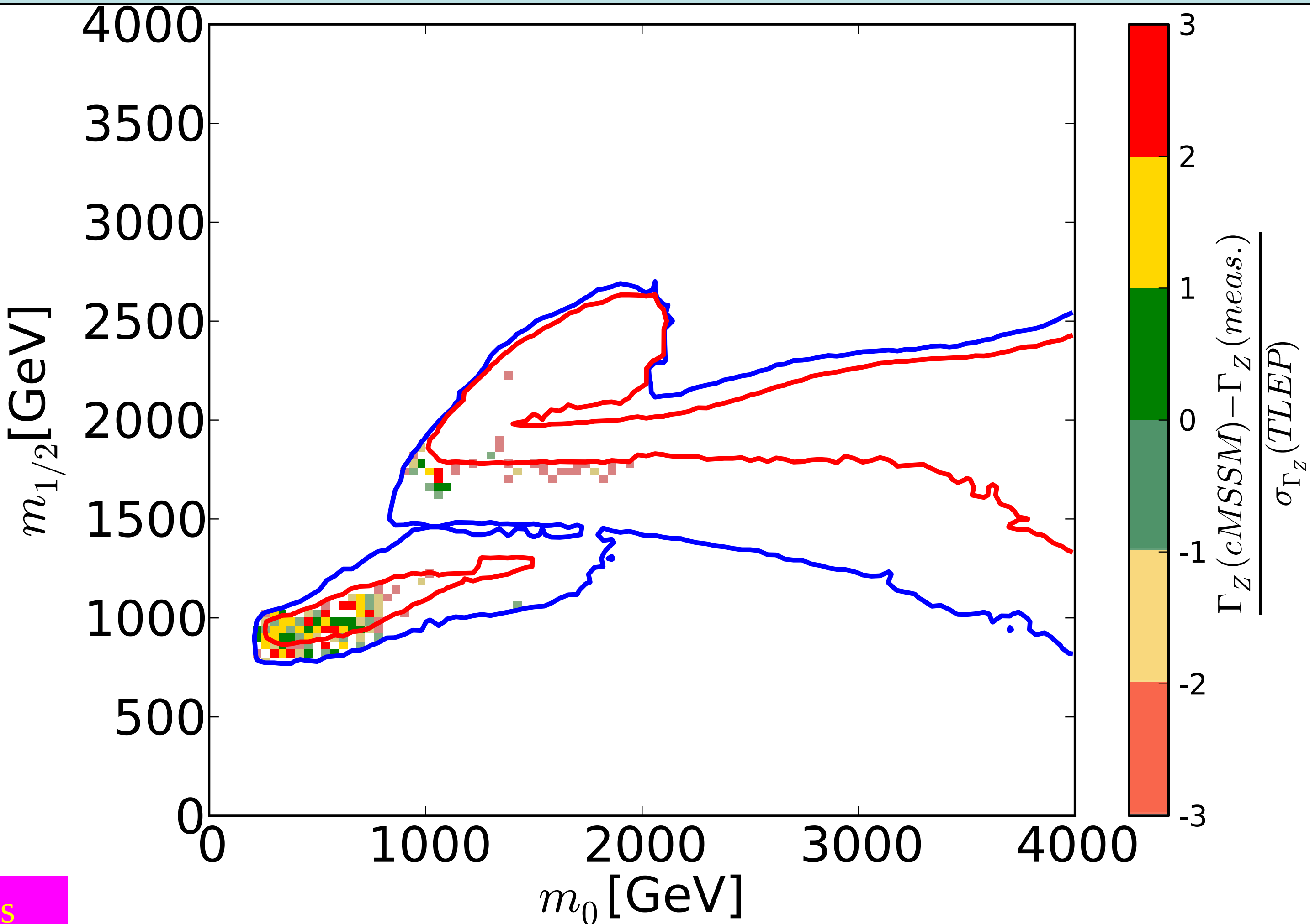


K. De Vries (MasterCode)

Γ_Z constraint on (m0, m1/2) plane in CMSSM:

All points within one current σ of present best-fit value

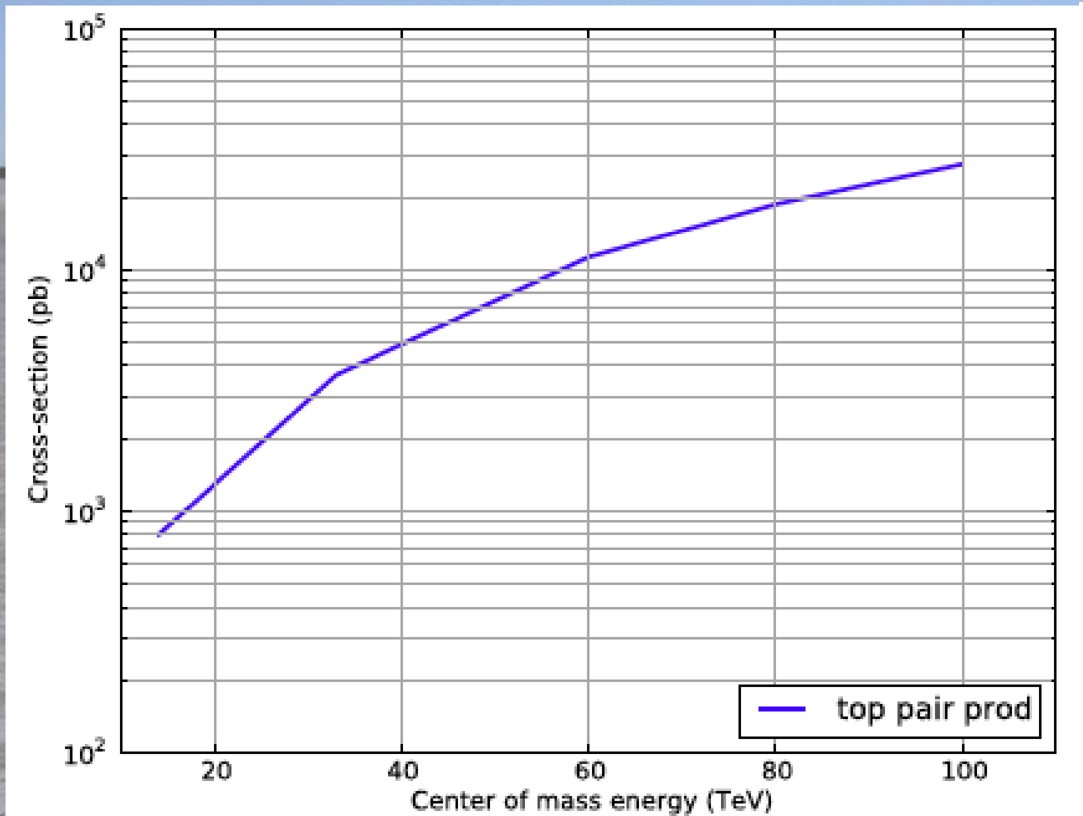
Impact of **TLEP** Precision on Susy

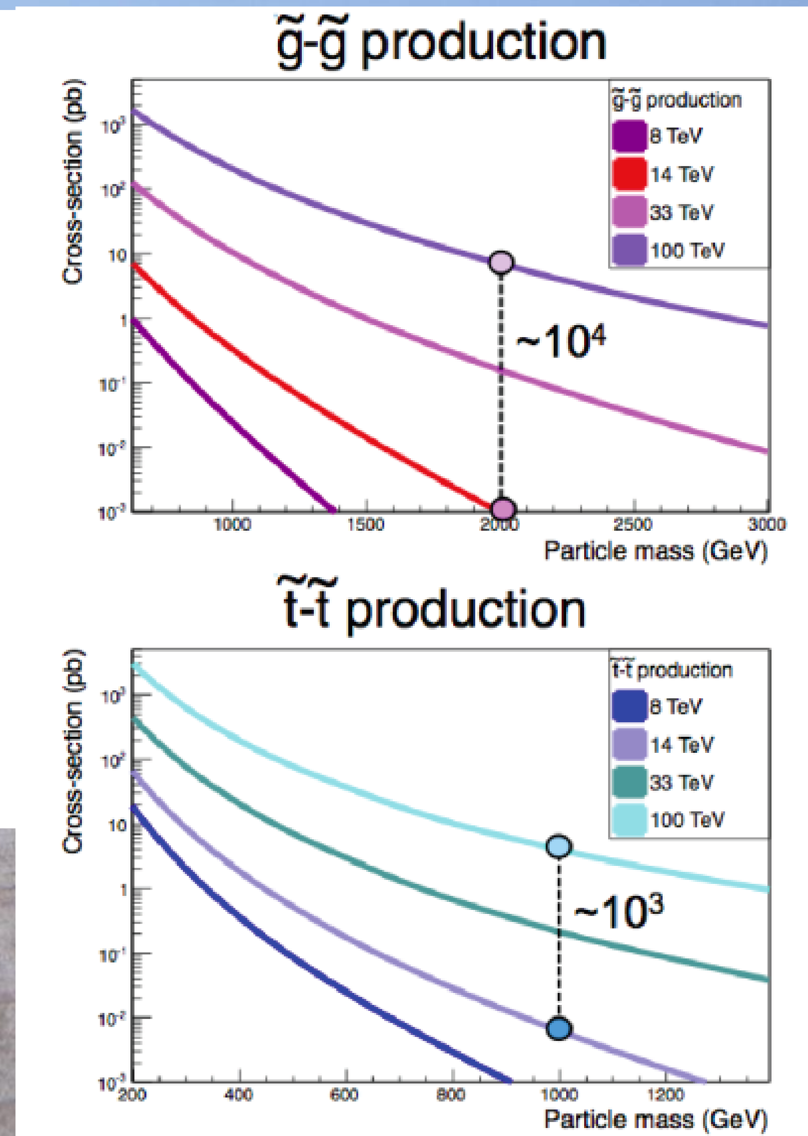


K. De Vries
(MasterCode)

Γ_Z constraint on (m_0, $m_{1/2}$) plane in CMSSM:
Points within one, two, three TLEP σ of present best-fit value

$t\bar{t}$ & Supersymmetry @ HE/VHE-LHC



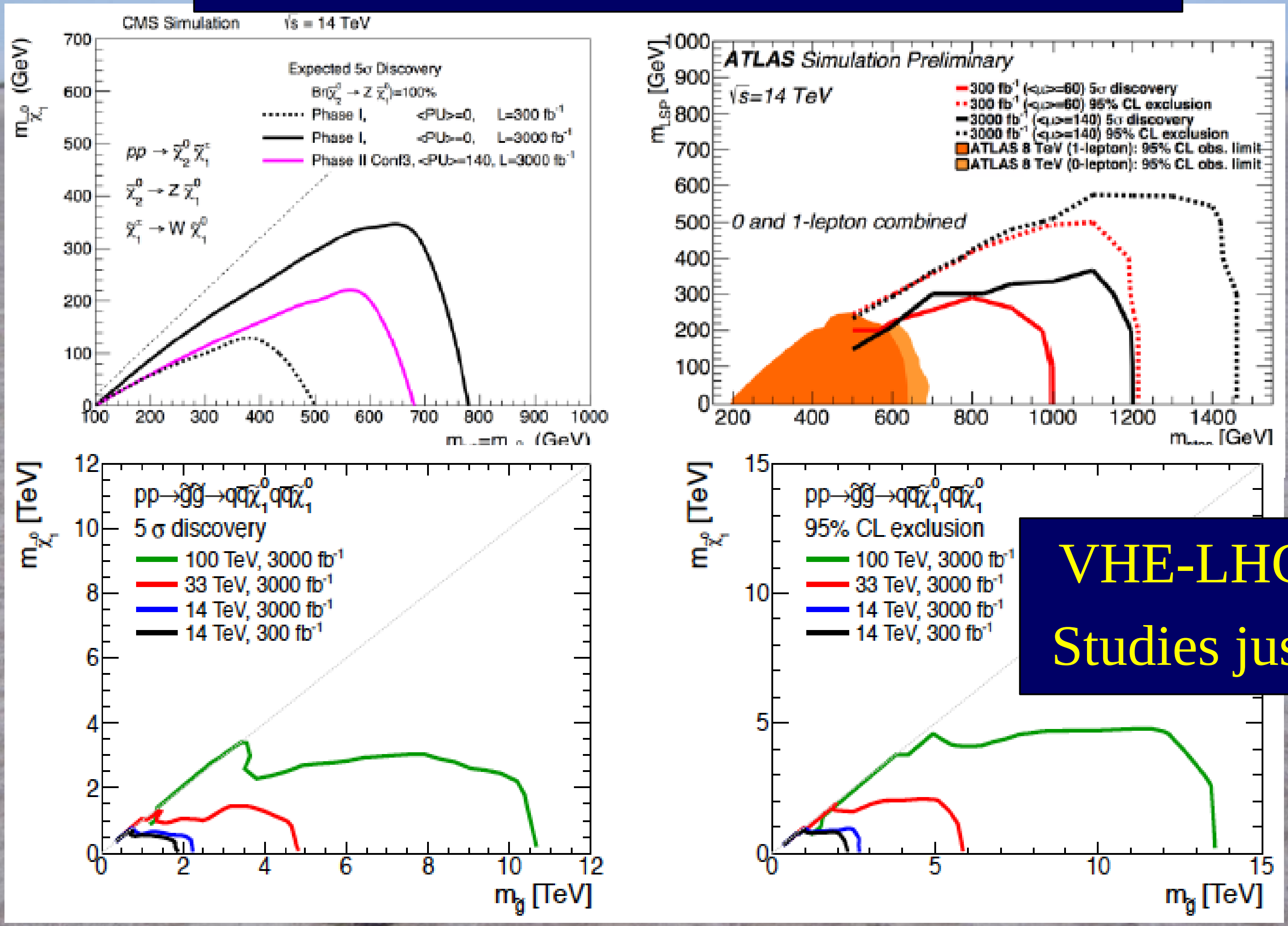


VHE-LHC physics

Studies just starting

Reaches for Sparticles

@ LHC, HE-LHC, VHE-LHC



VHE-LHC physics
Studies just starting

Future Accelerators

- (What) precision, (how) high energy, neutrinos?
- Which is THE top priority accelerator?
  - Precision: HL-LHC, ILC/CLIC, TLEP, MC, $\gamma\gamma$
  - Energy: HE-LHC, VHE-LHC, CLIC, MC
  - Neutrinos: from superbeam to ν factory
- HL-LHC is not a done deal, needs high-tech:
  - 11T dipoles, 13T quads, 500m HTS link, crab cavities
- Worldwide collaboration needed
- **No decision before LHC 13/14 TeV results**

The Twin Pillars of TLEP Physics

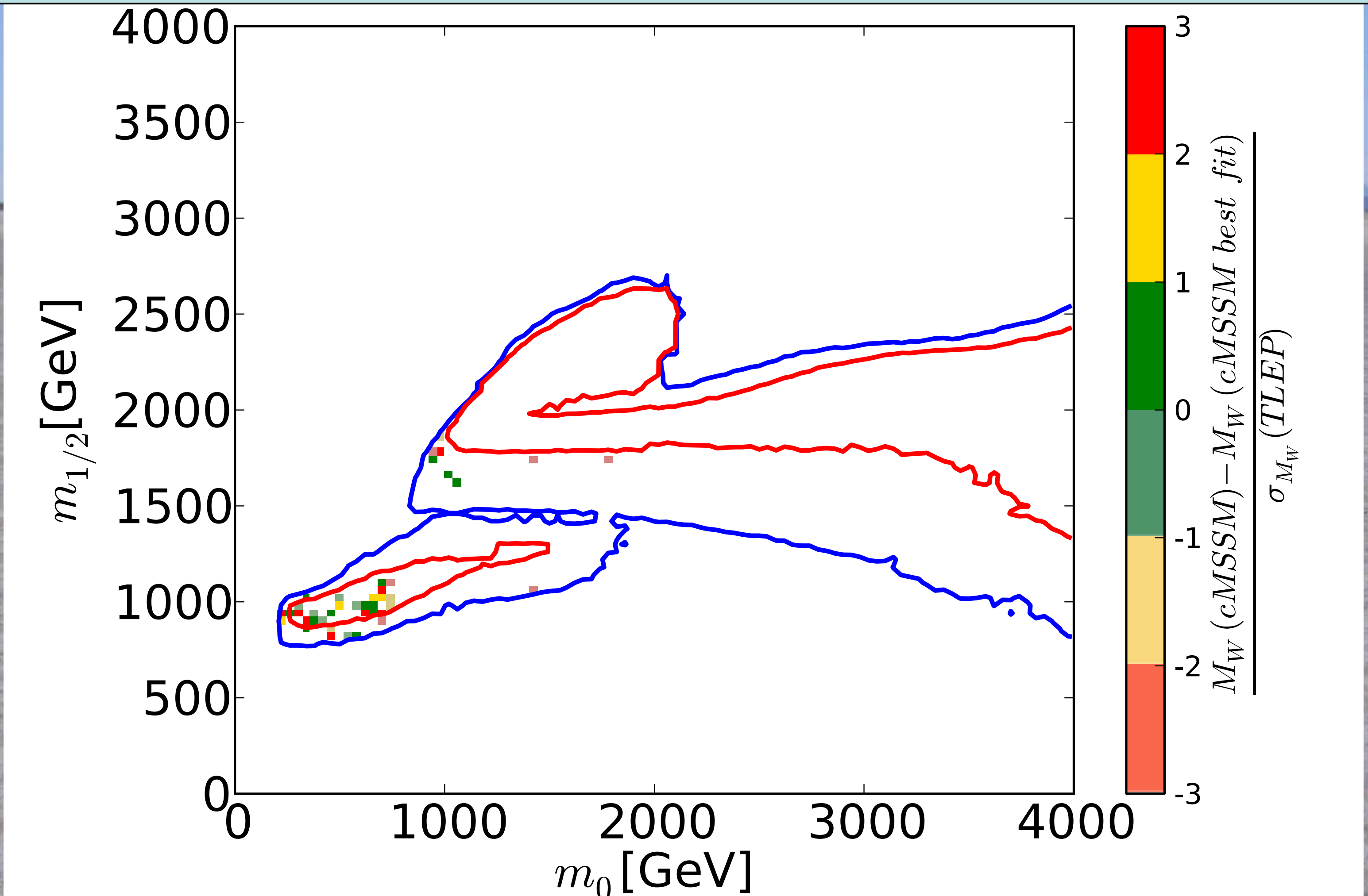
Precision Measurements

- Springboard for sensitivity to new physics
- Theoretical issues:
  - Higher-order QCD
  - Higher-order EW
  - Mixed QCD + EW
- Experimental issues
  - Patrick

Rare Decays

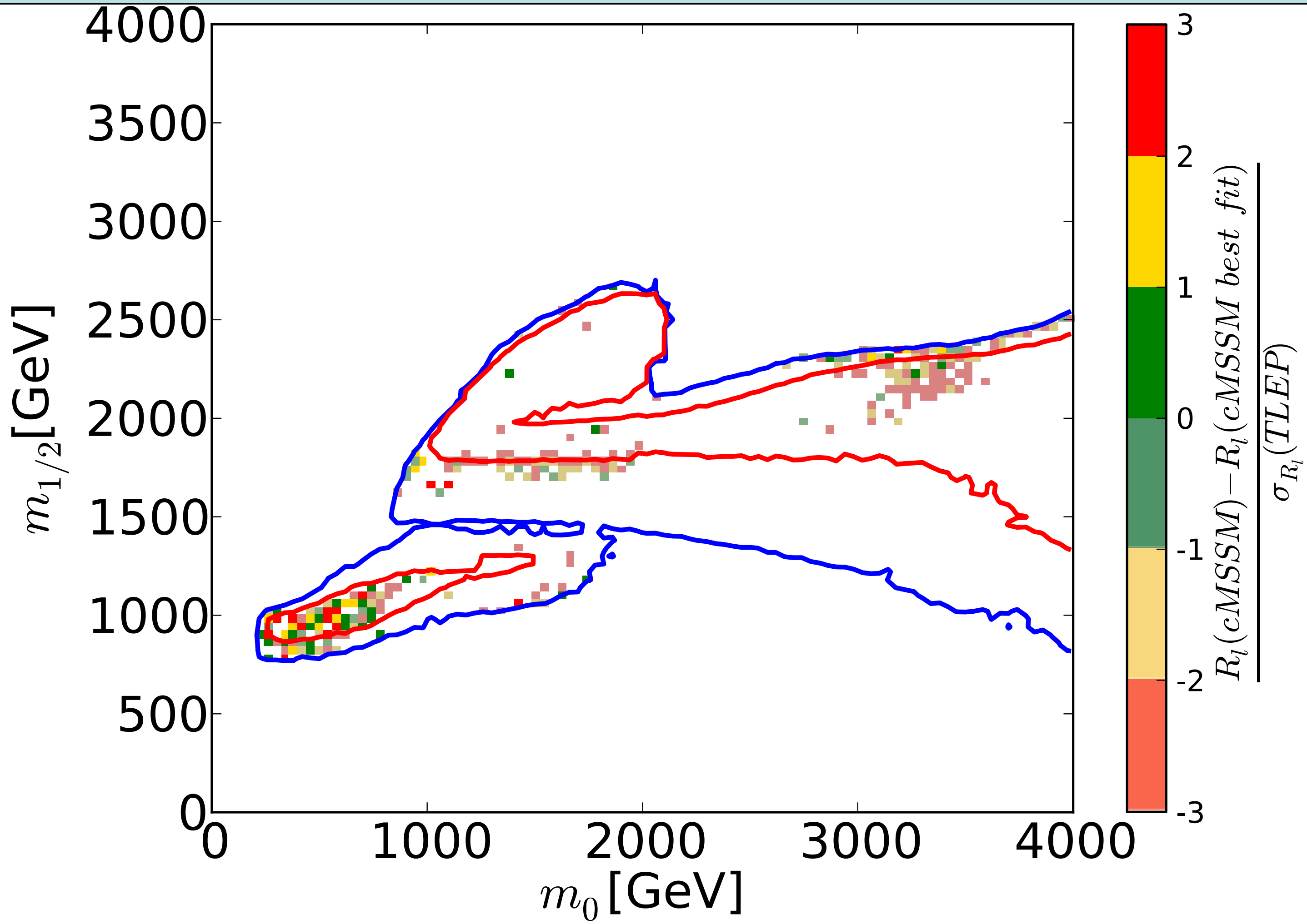
- Direct searches for new physics
- Many opportunities
- Z: 10^{12}
- b, c, τ: 10^{11}
- W: 10^{8}
- H: 10^{6}
- t: 10^{6}

Impact of TLEP Precision on Susy



M_W constraint on (m0, m1/2) plane in CMSSM:
All points within one current σ of present best-fit value

Impact of TLEP Precision on Susy

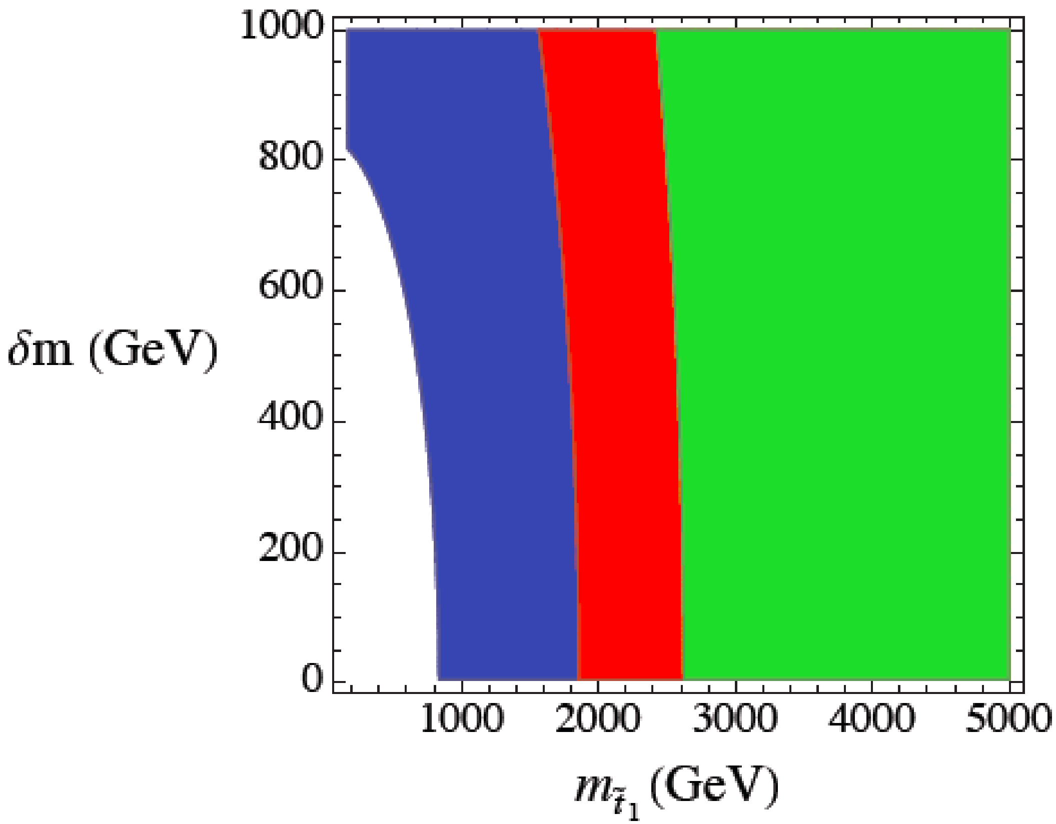


R_l constraint on (m0, m1/2) plane in CMSSM

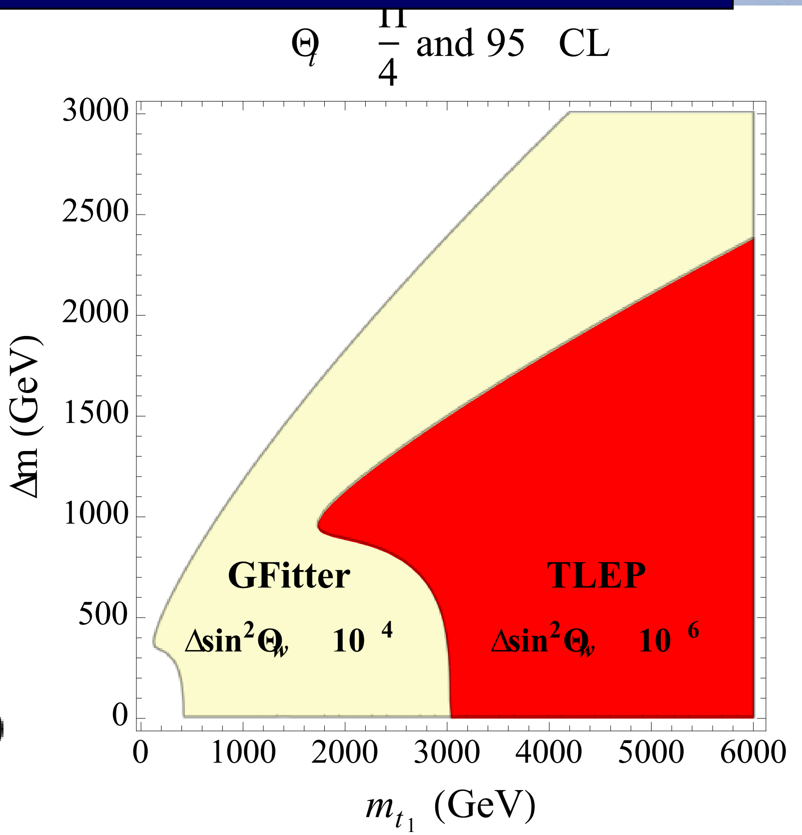
Points within one, two, three TLEP σ of present best-fit value

Impact of TLEP Precision on Susy

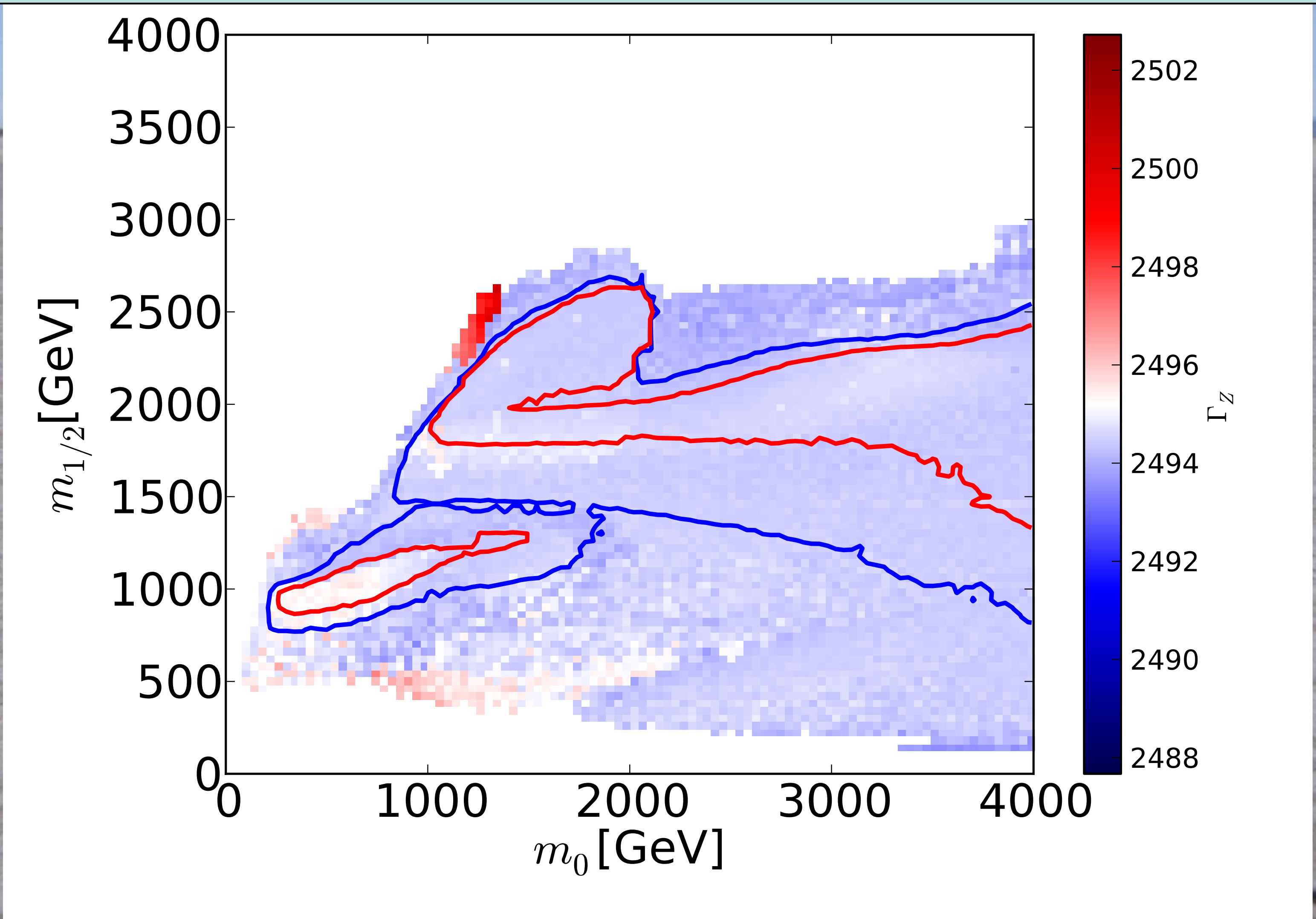
M_W constraint on stop mass



$\sin^2\theta_W$ constraint on stop mass

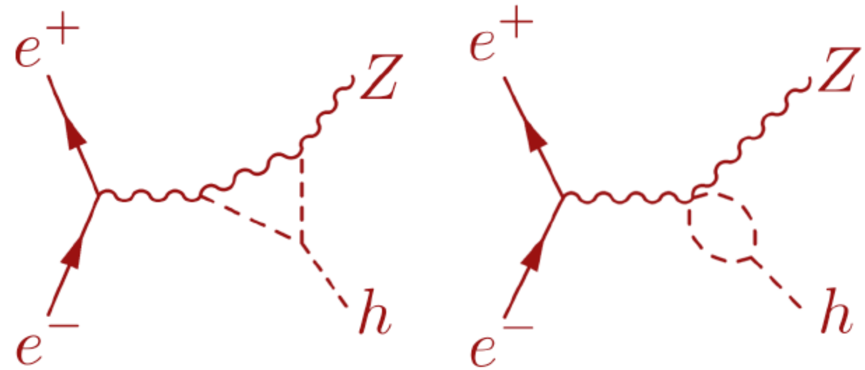


Impact of Precise Measurement of Γ_Z



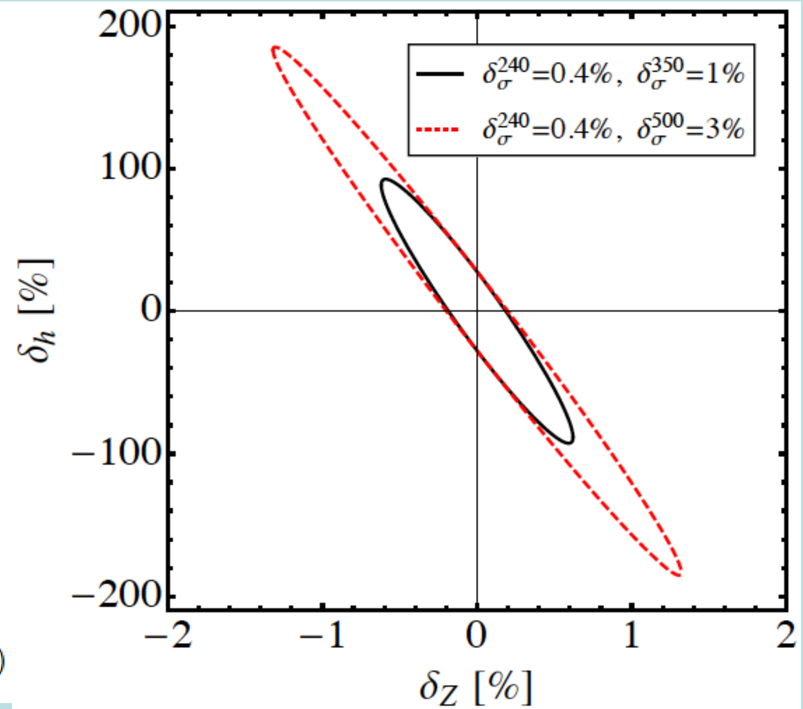
Indirect Sensitivity to 3h Coupling

- Loop corrections to σ(H+Z):



And also:

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



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

cf, LEP and LHC

- *"Those who don't know history are doomed to repeat it…"*
  - Edmund Burke
- *"... and maybe also those who do."*
- LEP: Precision Z studies ✔, W+W- ✔,
  search for Higgs ✖, anything else ✖
- LHC: search for Higgs ✔, anything else ?
- **Do not decide anything until LHC 13/4**