Programme of Lectures

- The road to the Higgs discovery
- Characterizing the new particle
- What else?
  - Supersymmetry?
  - Future accelerators?
  - Cosmological inflation?

JE "Higgs Physics": arXiv:1312.5672

Elementary Higgs or Composite?

- Higgs field:

  <0|H|0> ≠ 0

- Quantum loop problems

Cut-off Λ ~ 1 TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS

New technicolour force?

-Heavy scalar resonance?

-Inconsistent with precision electroweak data?

No visible hint of anything beyond the Standard Model

Theoretical Confusion

- High mortality rate among theories
- (M_H, M_t) close to stability bound
- Λ close to Weinberg upper 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!**

No BSM? Beware Historical Hubris

- ***"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"* - Spanish Royal Commission, rejecting Christopher Columbus proposal to sail west, < 1492**
- *"The more important fundamental laws and facts of physical science have all been discovered"* – Albert Michelson, 1894
- *"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"* - Lord Kelvin, 1900
- *"Is the End in Sight for Theoretical Physics?"* – Stephen Hawking, 1980

The Dog(s) that did not Bark

- To Sherlock Holmes:

  "Is there any other point to which you would wish to draw my attention?"
- Holmes:

  "To the curious incident of the dog in the night-time."
- To Holmes:

  "The dog did nothing in the night-time."
- Holmes:

  "That was the curious incident."
- We have many clues:

Waiting for our Holmes: maybe a string player?

Why is there Nothing rather than Something?

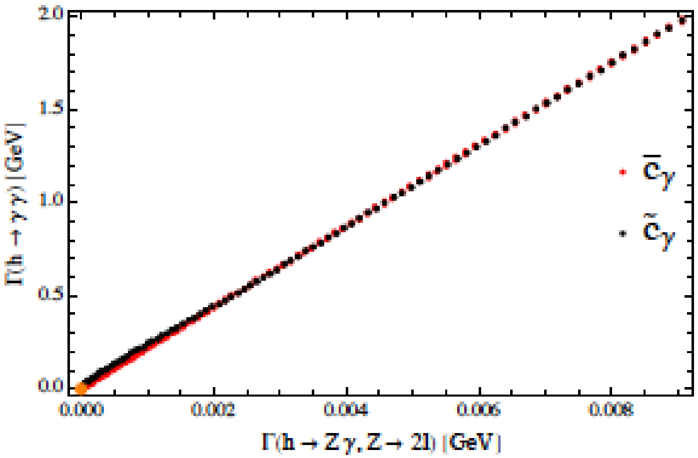
- Higher-dimensional operators as relics of higher-energy physics: $\mathcal{L}_{\mathrm{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

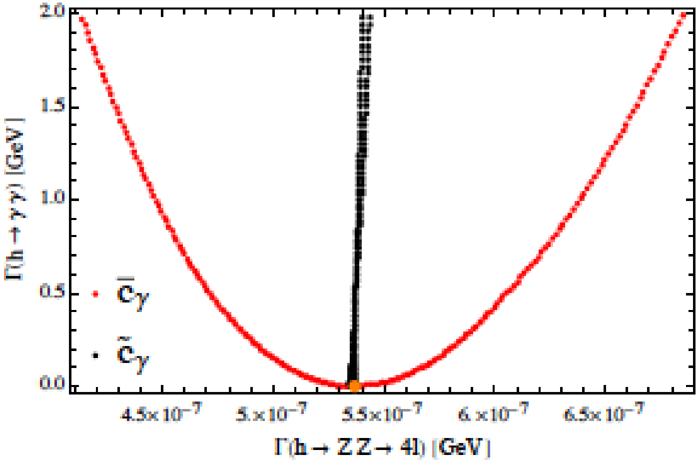
$$\begin{aligned}
\mathcal{L}_{\mathrm{SILH}} = {} & \frac{\bar{c}_H}{2v^2} \partial^\mu \left[\Phi^\dagger \Phi\right] \partial_\mu \left[\Phi^\dagger \Phi\right] + \frac{\bar{c}_T}{2v^2} \left[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right] \left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] - \frac{\bar{c}_6 \lambda}{v^2} \left[H^\dagger H\right]^3 \\
& - \left[\frac{\bar{c}_u}{v^2} y_u \Phi^\dagger \Phi \ \Phi^\dagger \cdot \bar{Q}_L u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger \Phi \ \Phi \bar{Q}_L d_R + \frac{\bar{c}_l}{v^2} y_\ell \ \Phi^\dagger \Phi \ \Phi \bar{L}_L e_R + \mathrm{h.c.}\right] \\
& + \frac{ig \ \bar{c}_W}{m_W^2} \left[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi\right] D^\nu W^k_{\mu\nu} + \frac{ig' \ \bar{c}_B}{2m_W^2} \left[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right] \partial^\nu B_{\mu\nu} \\
& + \frac{2ig \ \bar{c}_{HW}}{m_W^2} \left[D^\mu \Phi^\dagger T_{2k} D^\nu \Phi\right] W^k_{\mu\nu} + \frac{ig' \ \bar{c}_{HB}}{m_W^2} \left[D^\mu \Phi^\dagger D^\nu \Phi\right] B_{\mu\nu} \\
& + \frac{g'^2 \ \bar{c}_\gamma}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g_s^2 \ \bar{c}_g}{m_W^2} \Phi^\dagger \Phi G^a_{\mu\nu} G_a^{\mu\nu}
\end{aligned}$$

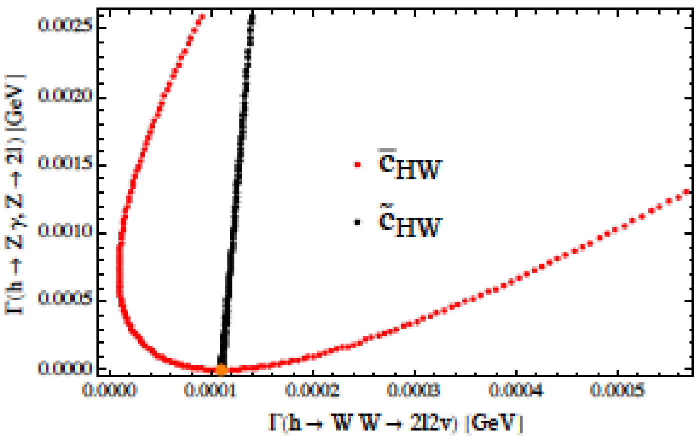
Alloul, Fuks & Sanz, arXiv:1310.5150

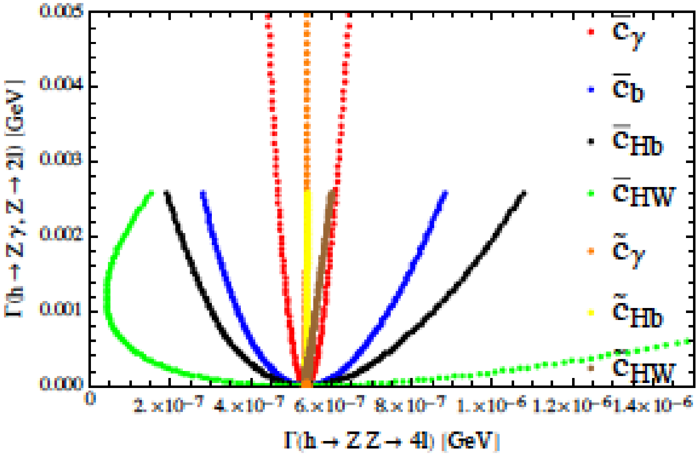
- Constrain with Higgs data, triple-gauge couplings…

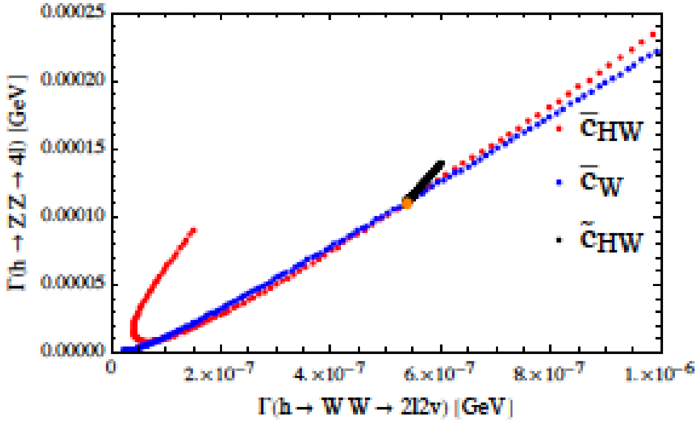
Examples of Possible Effects on Higgs Decays











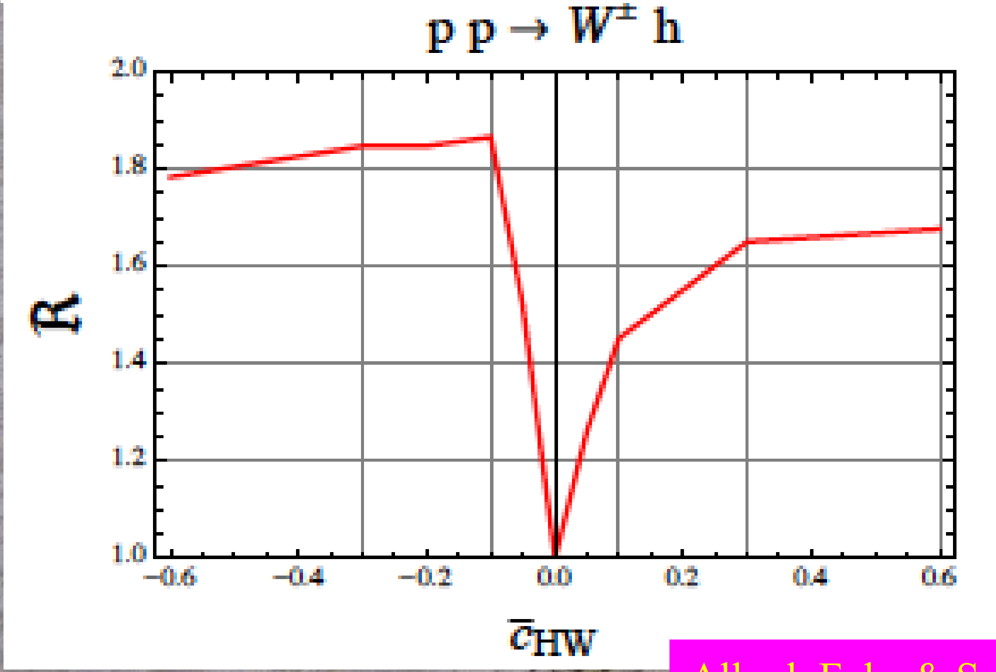
Alloul, Fuks & Sanz, arXiv:1310.5150

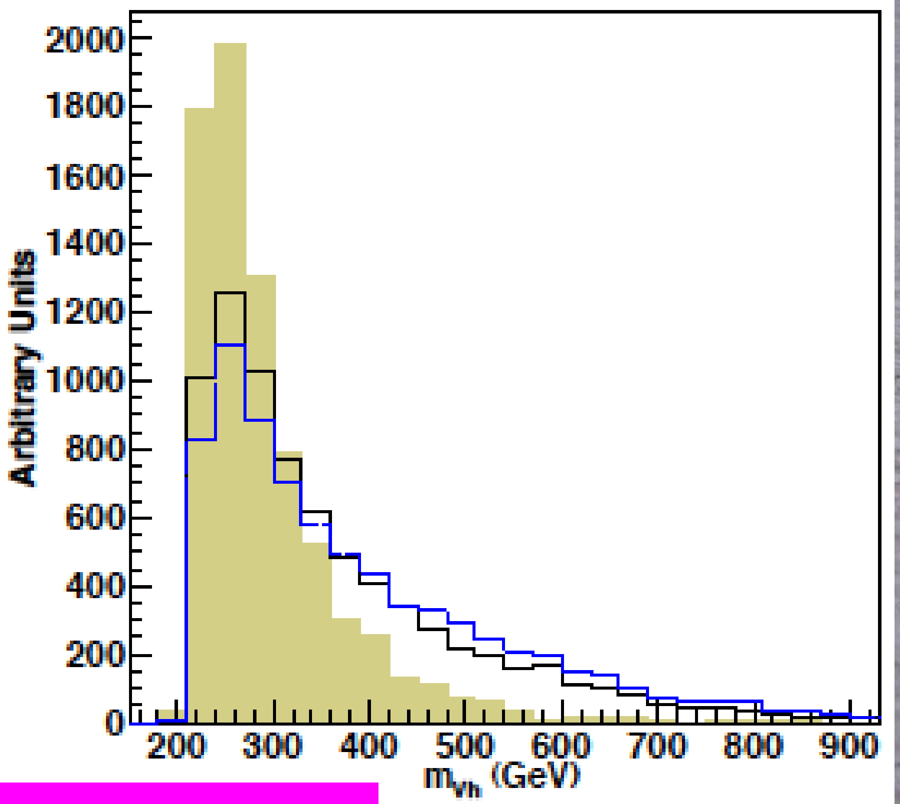
Examples of Possible Effects in H Production

V+H production cross section

V+H production distribution

$$\mathcal{R} \equiv \left(\frac{\sigma(\sqrt{S}=14\text{ TeV})}{\sigma(\sqrt{S}=8\text{ TeV})}\right)_{\bar{c}_i} \Big/ \left(\frac{\sigma(\sqrt{S}=14\text{ TeV})}{\sigma(\sqrt{S}=8\text{ TeV})}\right)_{SM}$$





Alloul, Fuks & Sanz, arXiv:1310.5150

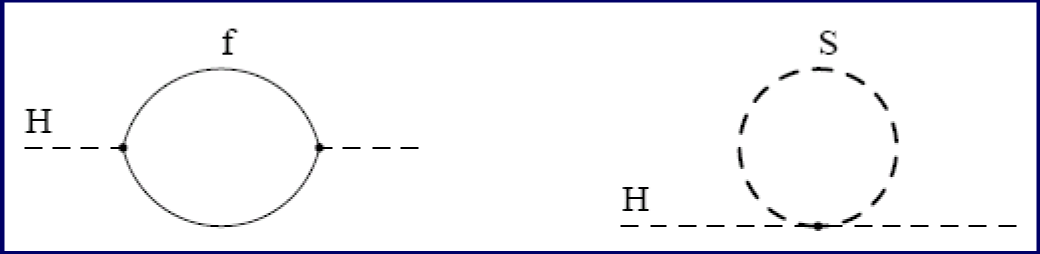
What else is there?

Supersymmetry

- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for Higgs couplings
  - Should be within few % of SM values
- Could explain the dark matter
- Naturalness, GUTs, string, … (???)

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

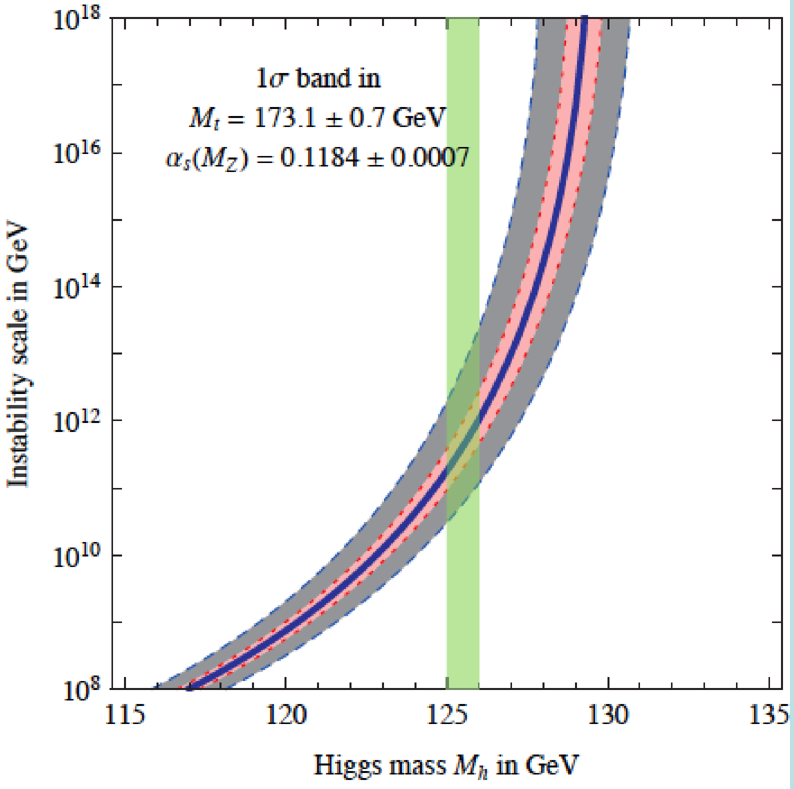
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergen $\lambda_S =$ x 2

Supersymmetry!

Theoretical Constraints on Higgs Mass

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



- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ
→ vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

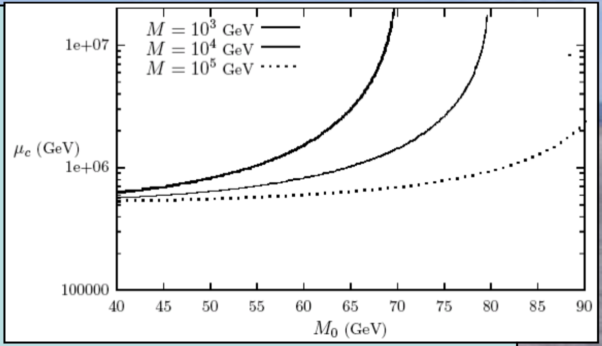
Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

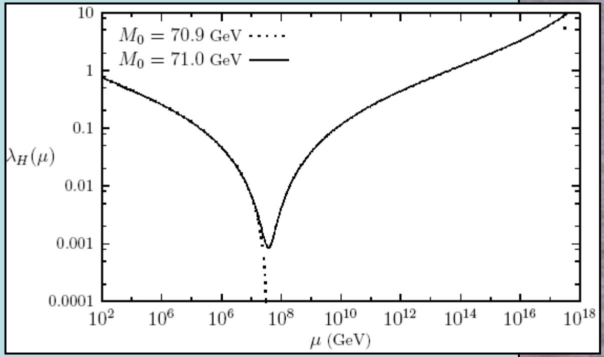
How to Stabilize a Light Higgs Boson?

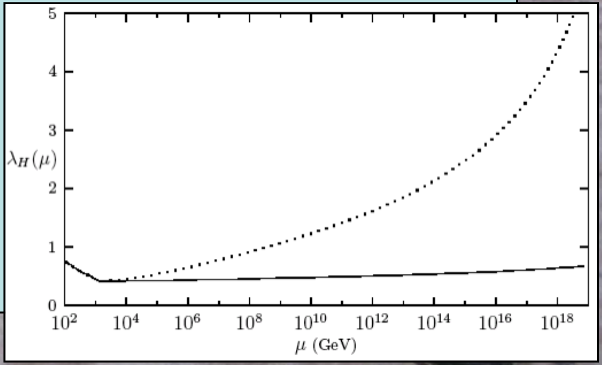
- Top quark destabilizes potential: introduce stop-like scalar:

$$\mathcal{L} \supset \; M^2 |\phi|^2 + \frac{M_0}{v^2} |H|^2 \, |\phi|^2$$

- Can delay collapse of potential:
- But new coupling must be fine-tuned to avoid blow-up:
- Stabilize with new fermions:
  - – just like Higgsinos
- Very like **Supersymmetry!**





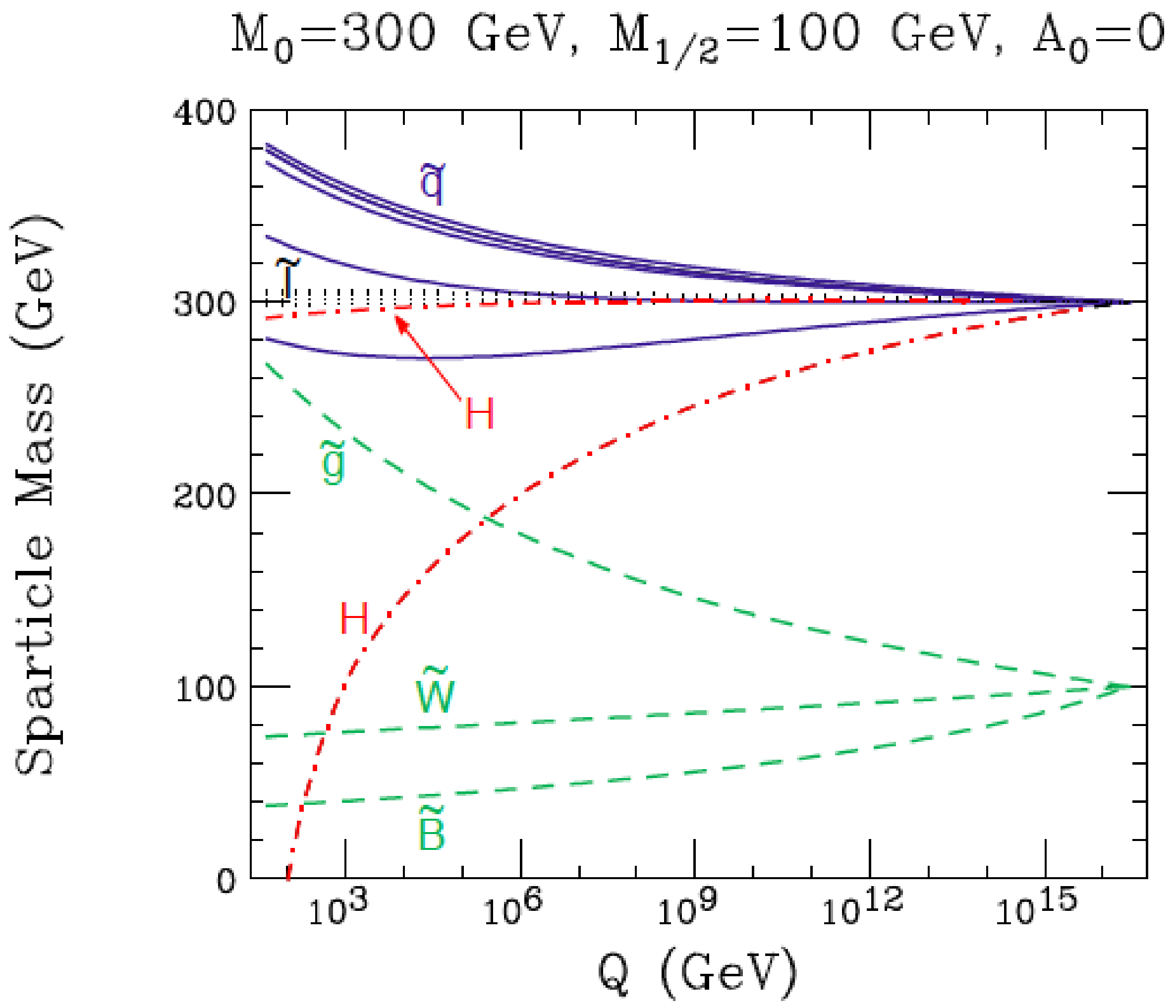


JE + D. Ross

Electroweak Symmetry Breaking

Could be driven by radiative corrections due to top quark

A bonus: supersymmetry may explain why $\mu^2 < 0$



Higgs Bosons in Supersymmetry

- Need 2 complex Higgs doublets

  (cancel anomalies, form of SUSY couplings)
- 8 – 3 = 5 physical Higgs bosons

  Scalars h, H; pseudoscalar A; charged $H^{\pm}$
- Lightest Higgs < MZ at tree level:

$$M^2_{\mathrm{H,h}} = \frac{1}{2}\left[M^2_{\mathrm{A}} + M^2_{\mathrm{Z}} \pm \sqrt{(M^2_{\mathrm{A}} + M^2_{\mathrm{Z}})^2 - 4M^2_{\mathrm{Z}}M^2_{\mathrm{A}}\cos^2 2\beta}\right]$$

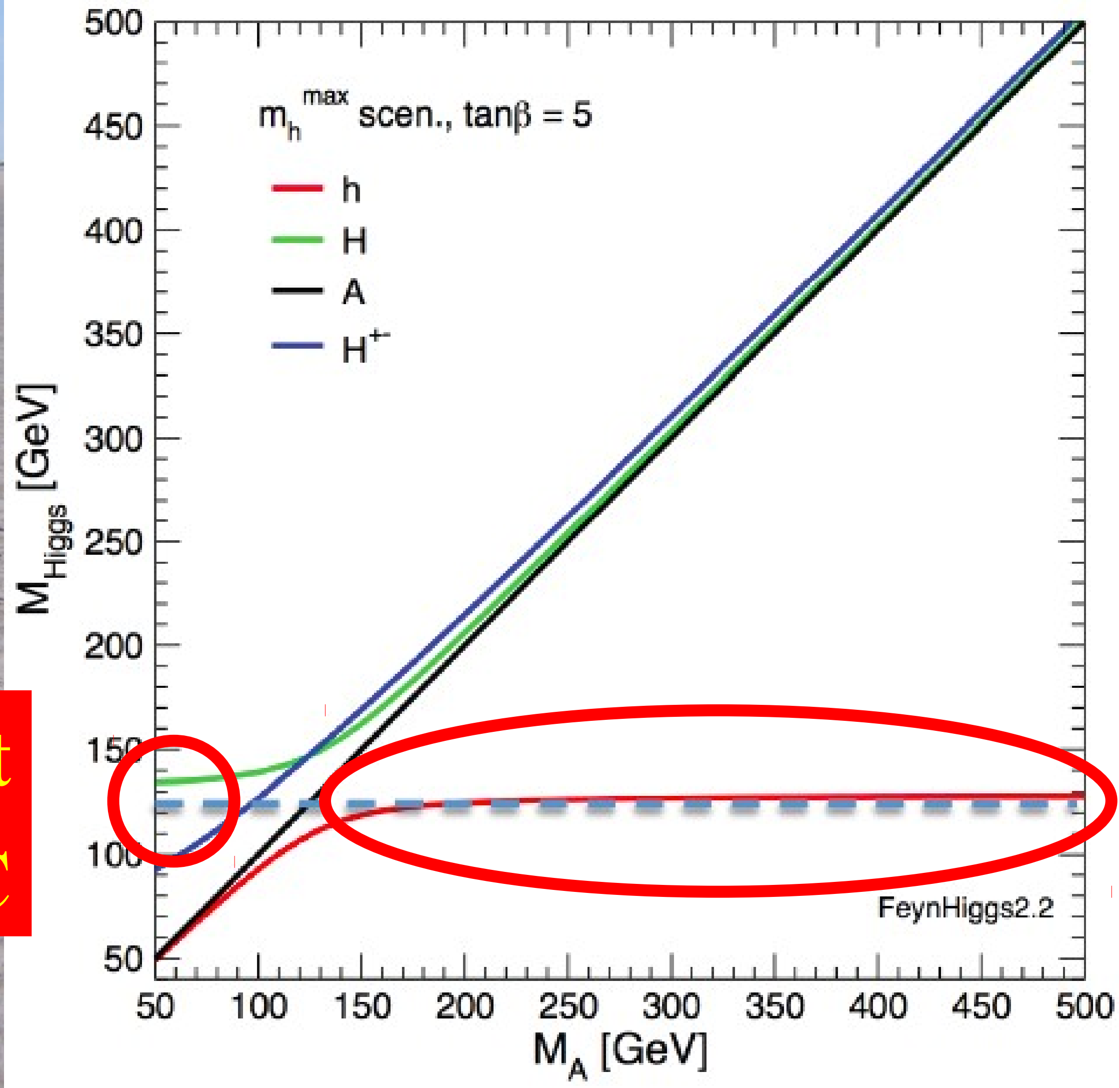
- Important radiative corrections to mass:

$$G_\mu m_{\mathrm{t}}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_{\mathrm{t}}^2}\right)$$

H ~ 1.5 GeV

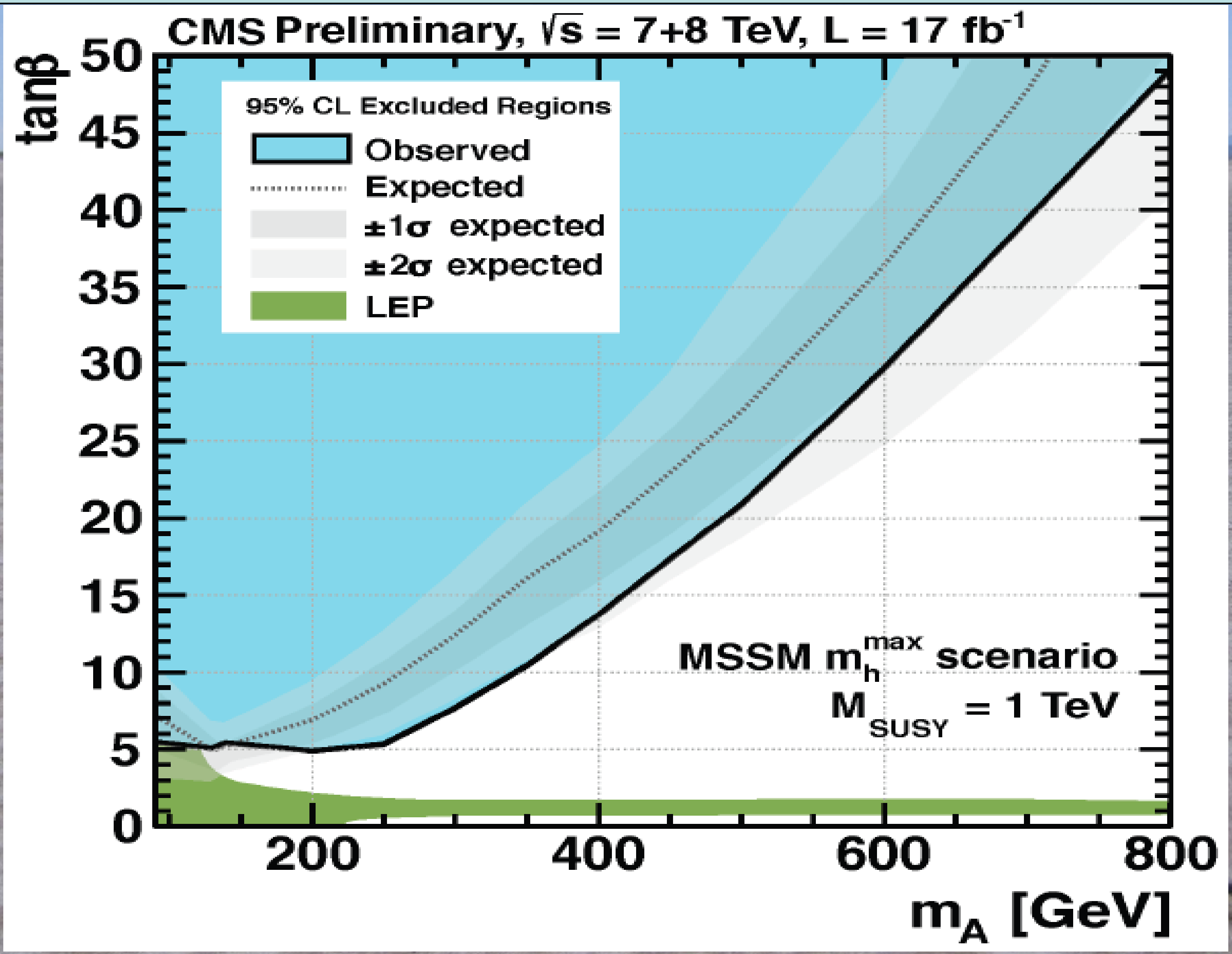
MSSM Higgs Masses & Couplings

Lightest Higgs mass
up to ~ 130 GeV
Heavy Higgs masses
quite close



Consistent
With LHC

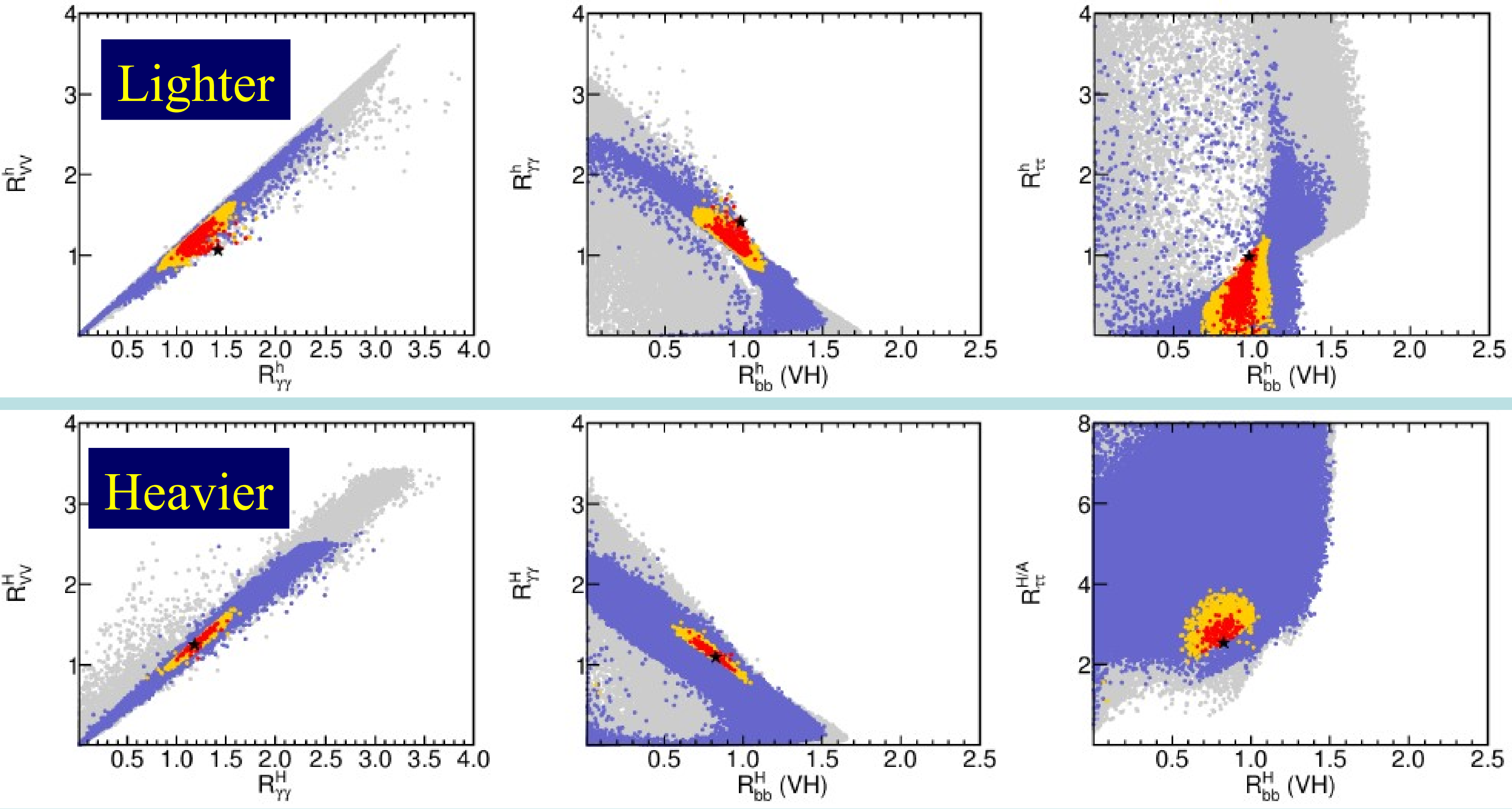
Limits on Heavy MSSM Higgses



Bechtle et al., arXiv:1211.1955

Maybe it is a Supersymmetric Duck?

- Fits with lighter/heavier scalar Higgs at 125 GeV

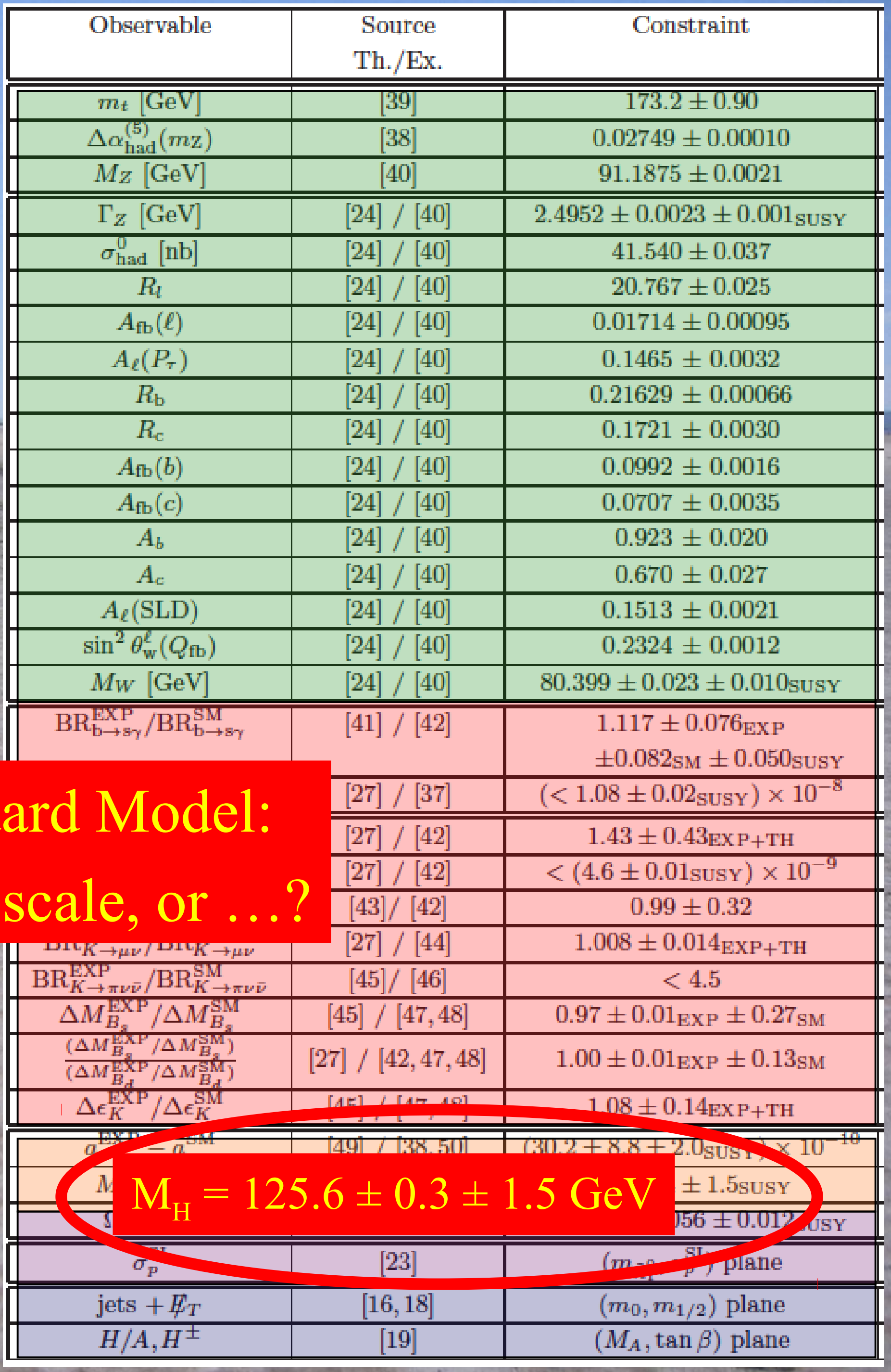


Data

- **Electroweak precision observables**
- **Flavour physics observables**
- **g_{μ} - 2**
- **Higgs mass**
- **Dark matter**
- **LHC**

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

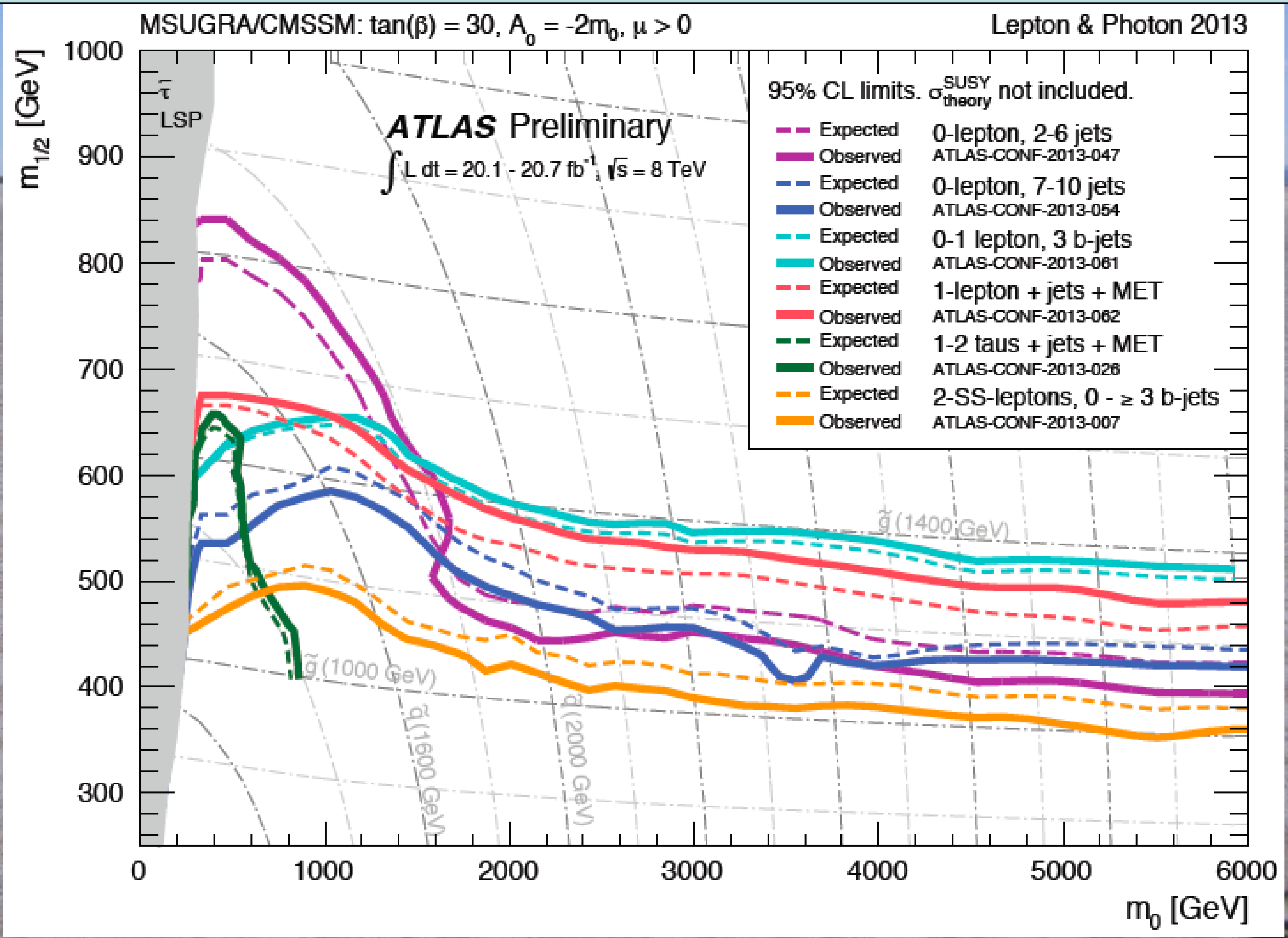
$M_H = 125.6 \pm 0.3 \pm 1.5$ GeV



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]	$1.117 \pm 0.076_{\rm EXP}$ $\pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$
	[27] / [37]	$(< 1.08 \pm 0.02_{\rm SUSY}) \times 10^{-8}$
	[27] / [42]	$1.43 \pm 0.43_{\rm EXP+TH}$
	[27] / [42]	$< (4.6 \pm 0.01_{\rm SUSY}) \times 10^{-9}$
	[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]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
M		$\pm 1.5_{\rm SUSY}$
		$056 \pm 0.012_{\rm SUSY}$
$\sigma^{\rm SI}_p$	[23]	$(m_{\tilde\chi^0_1}, \sigma^{\rm SI}_p)$ plane
jets + $\not{E}_T$	[16, 18]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[19]	$(M_A, \tan\beta)$ plane

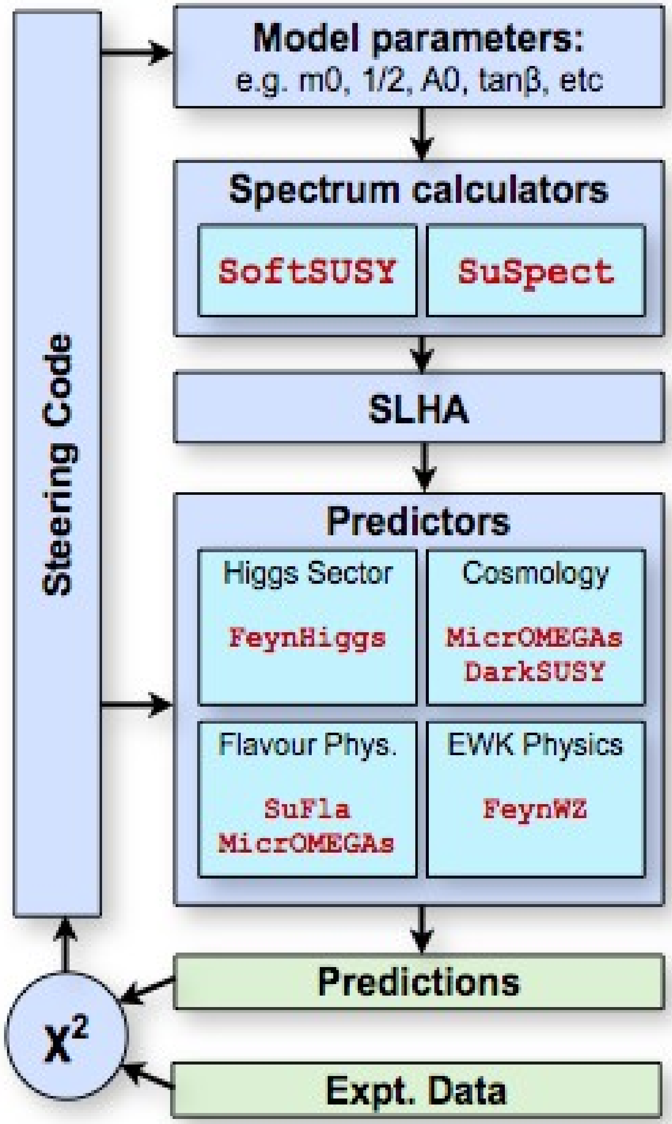
MasterCode: O.Buchmueller, JE et al.

Search with ~ 5/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



Steering Code

Model parameters:
e.g. m0, 1/2, A0, tanβ, etc

Spectrum calculators
SoftSUSY
SuSpect

SLHA

Predictors
Higgs Sector
FeynHiggs
Cosmology
MicrOMEGAs
DarkSUSY
Flavour Phys.
SuFla
MicrOMEGAs
EWK Physics
FeynWZ

Predictions

χ^2

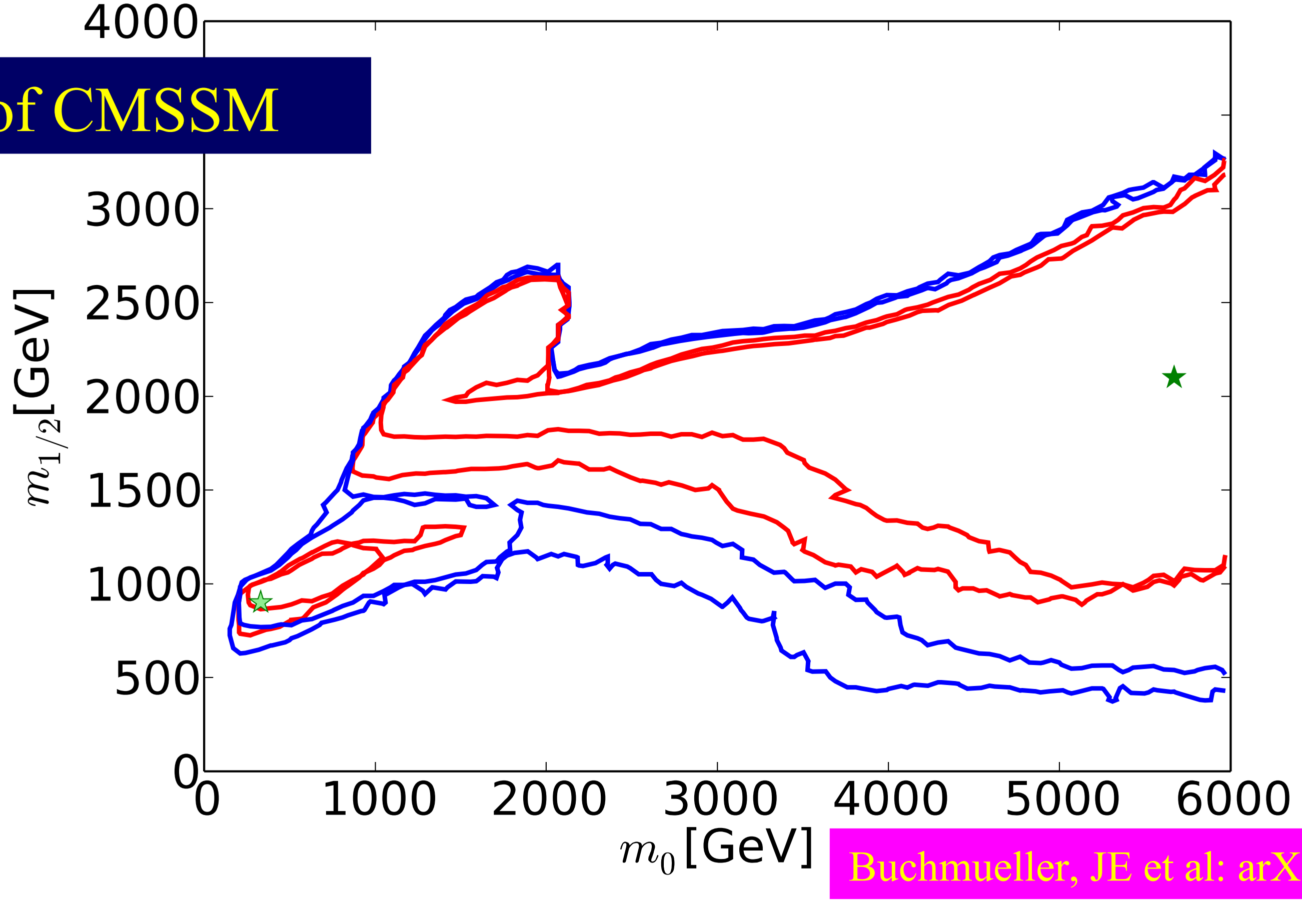
Expt. Data

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

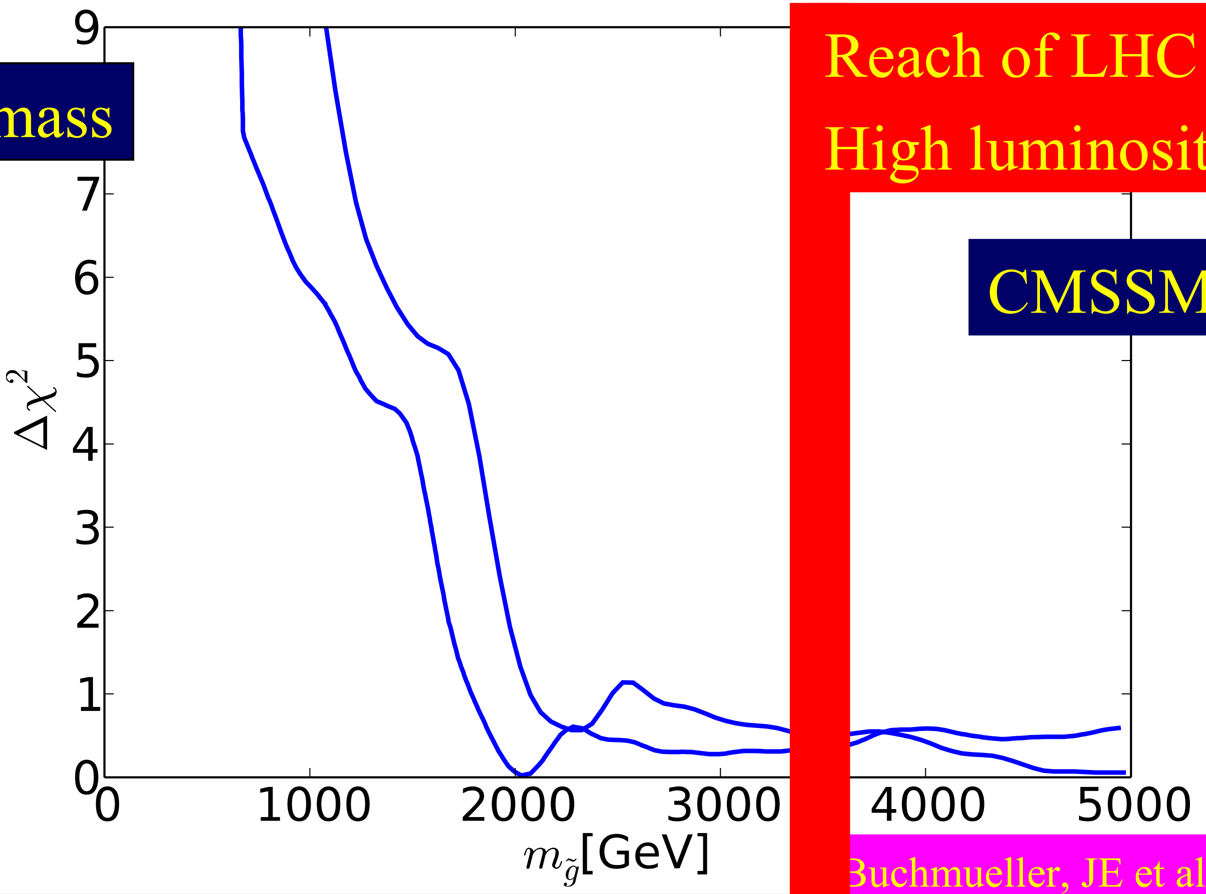
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

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

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

Gluino mass



Reach of LHC at High luminosity

CMSSM

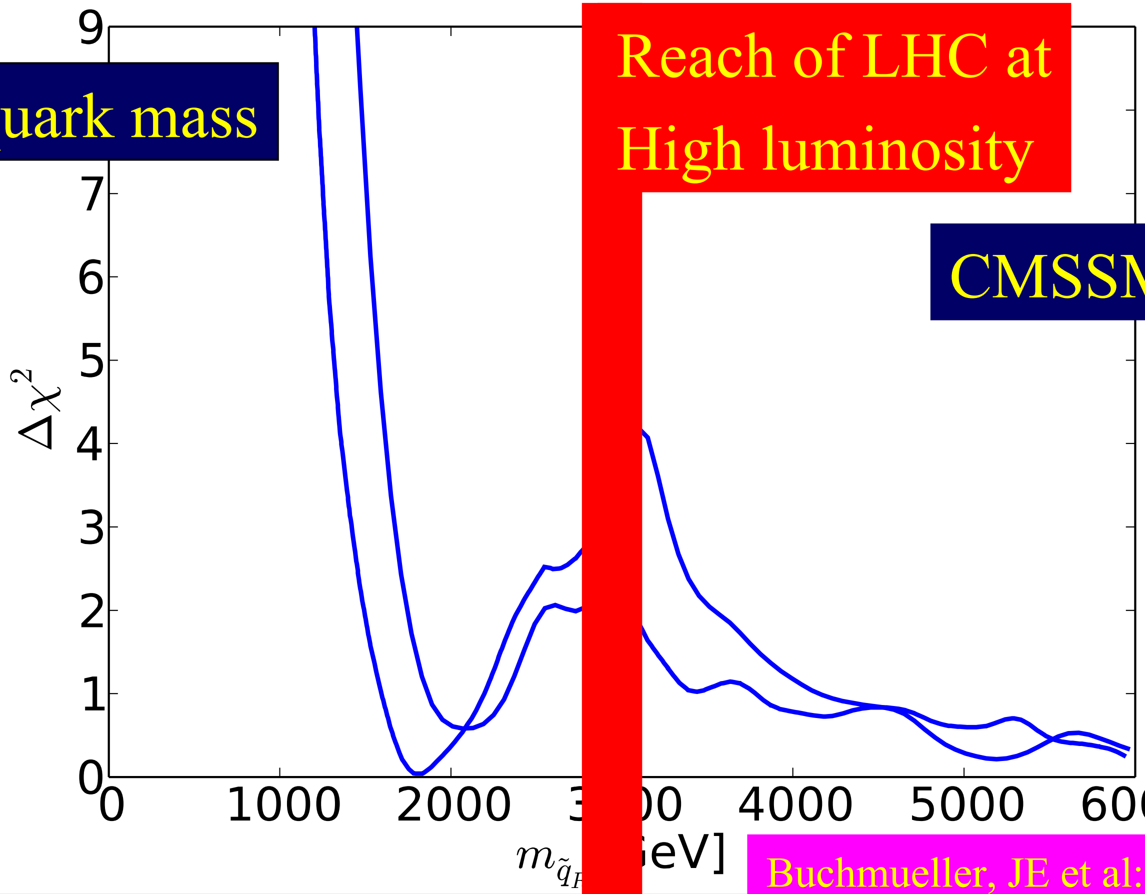
1

Buchmueller, JE et al: arXiv:1312.5250

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

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data



Squark mass

Reach of LHC at High luminosity

CMSSM

1

Buchmueller, JE et al: arXiv:1312.5250

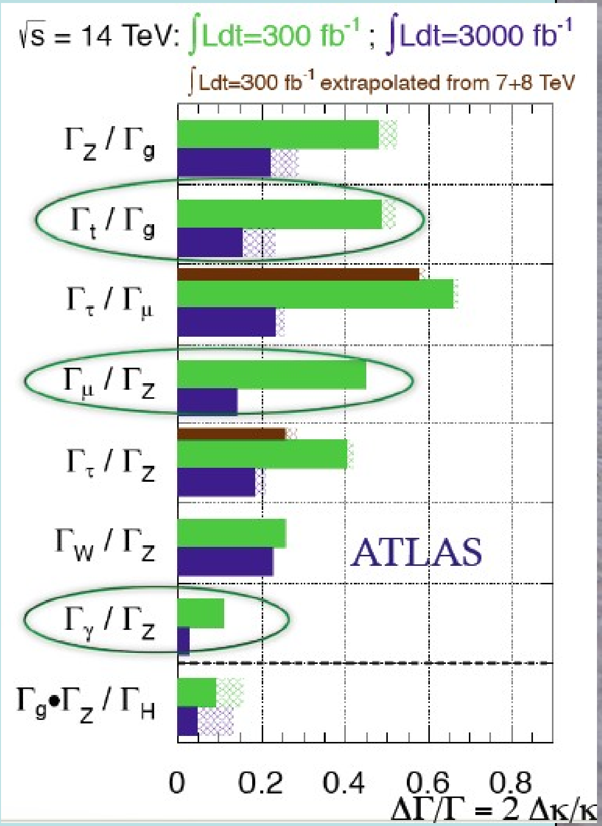
Favoured values of squark mass also significantly above pre-LHC, > 1.6 TeV

What Next: A Higgs Factory?

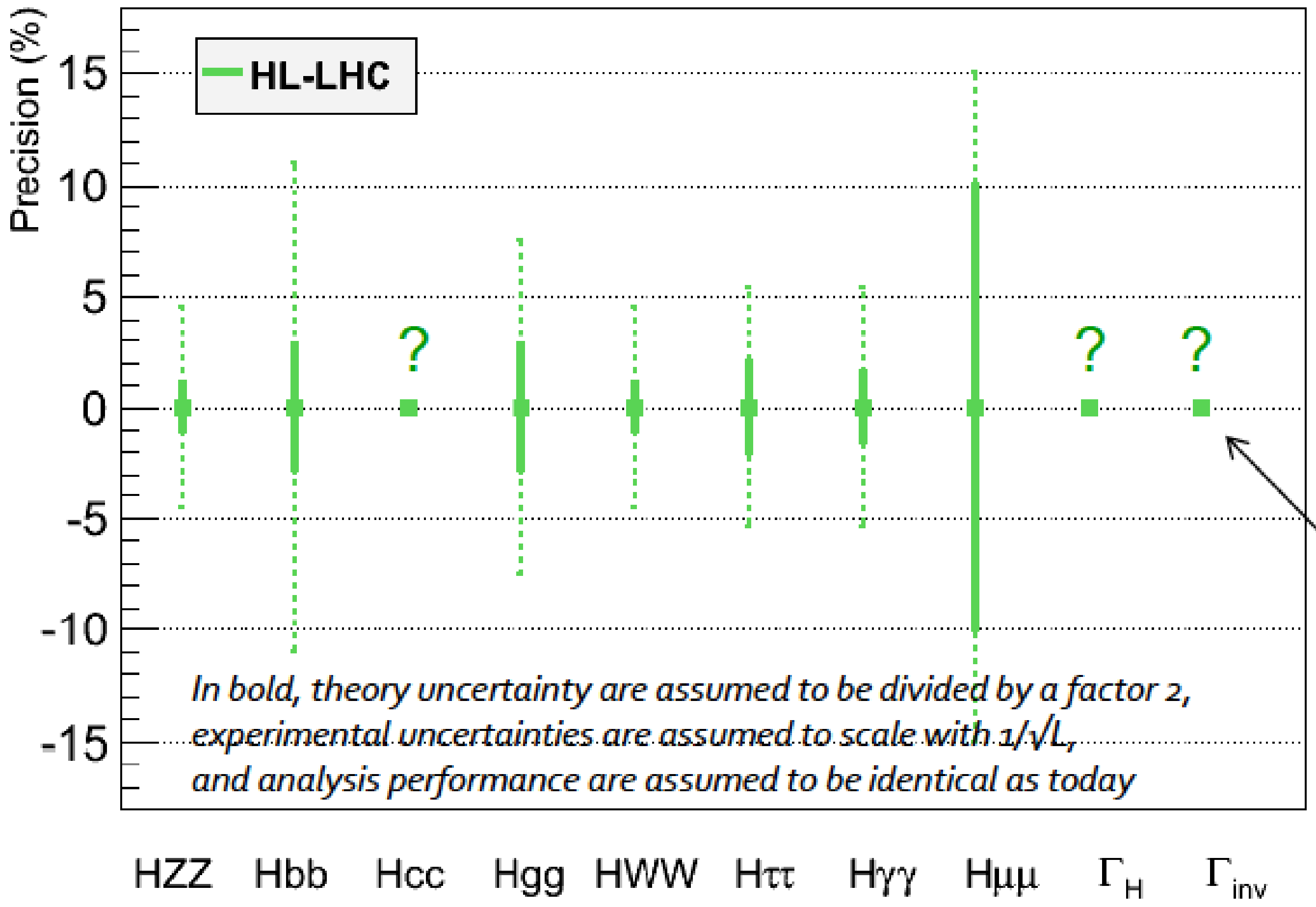
To study the ‘Higgs’ in detail:

- 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, TLEP
  - A photon-photon collider: SAPPHiRE
- A muon collider



Possible High-Luminosity LHC Measurements



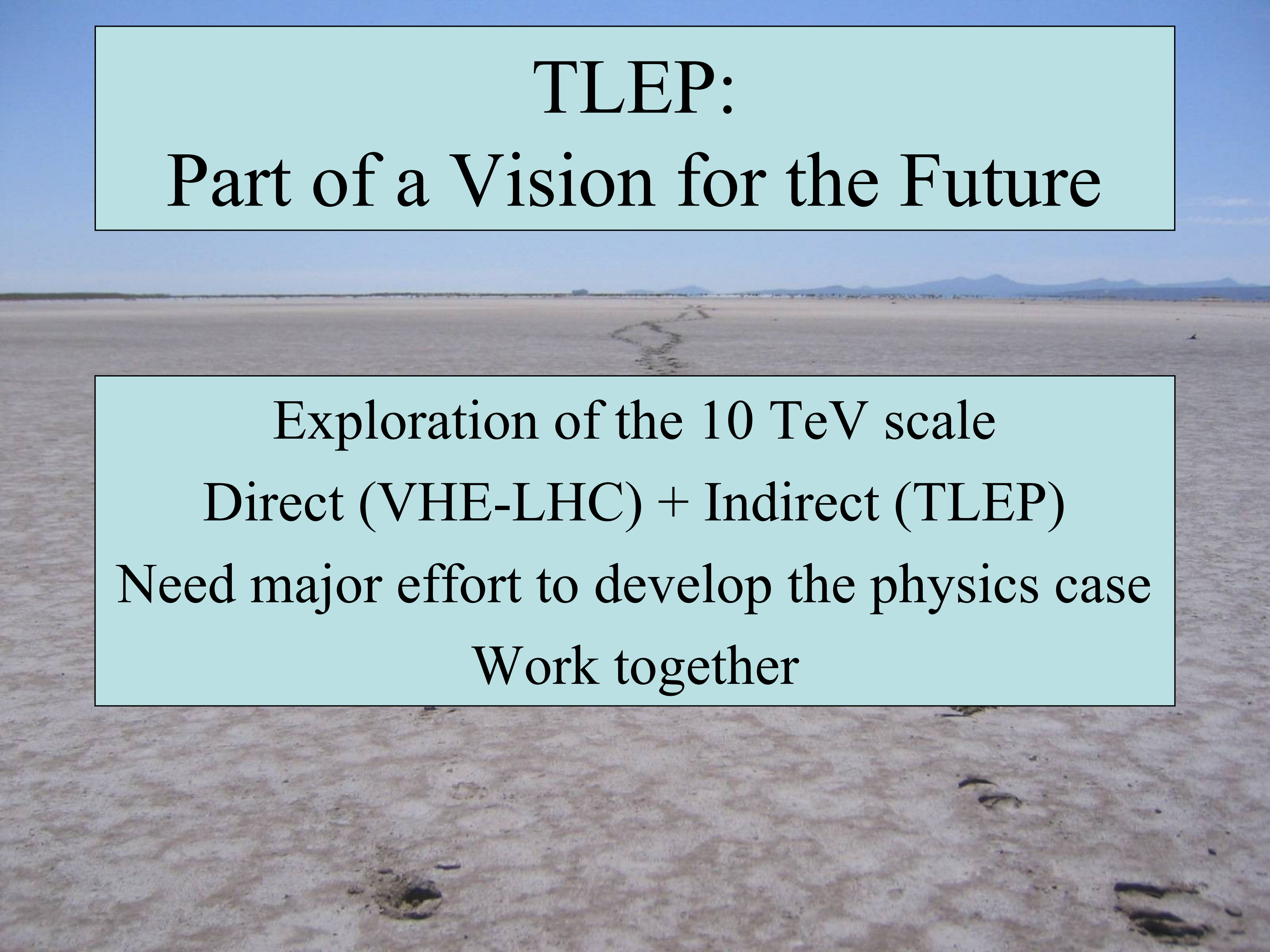
In bold, theory uncertainty are assumed to be divided by a factor 2, experimental uncertainties are assumed to scale with 1/√L, and analysis performance are assumed to be identical as today

Assumptions :

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

ATLAS upper limit at 65%
(Moriond EW 2013)

TLEP:
Part of a Vision for the Future



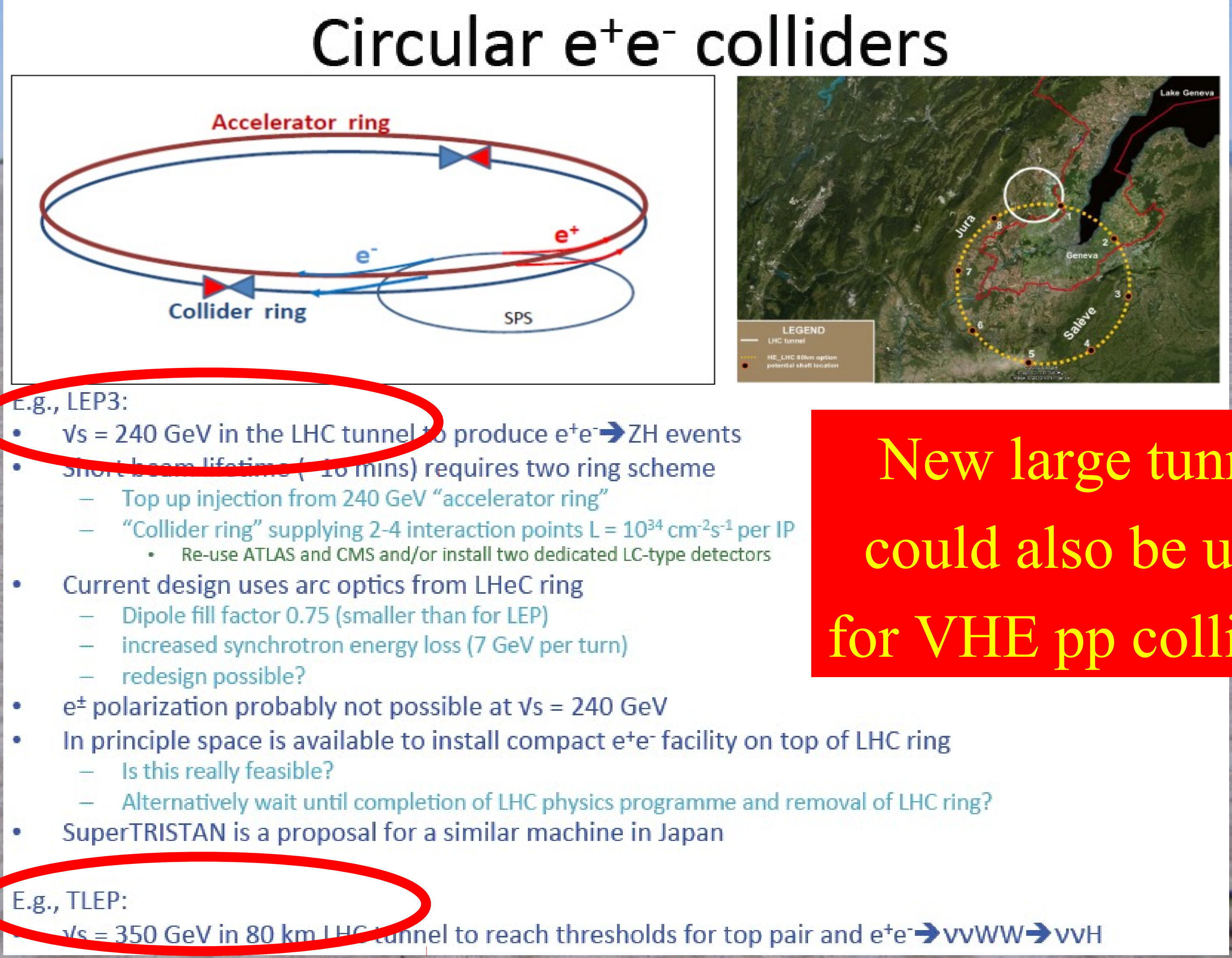
Exploration of the 10 TeV scale

Direct (VHE-LHC) + Indirect (TLEP)

Need major effort to develop the physics case

Work together

What Higgs Factory?



Circular e^+e^- colliders

E.g., LEP3:

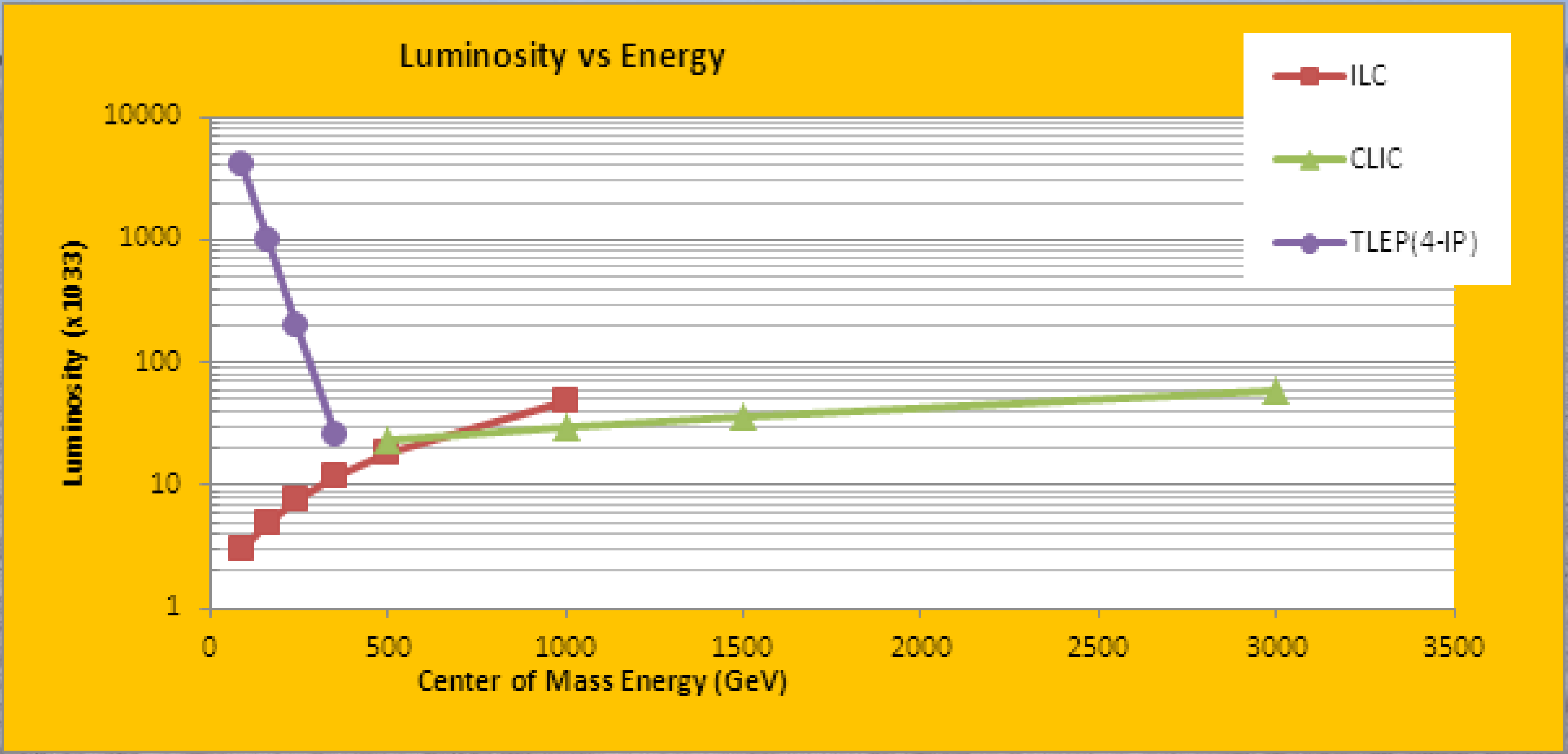
- $\sqrt{s} = 240$ GeV in the LHC tunnel to produce $e^+e^- \rightarrow ZH$ events
- Short beam lifetime (~10 mins) requires two ring scheme
  - Top up injection from 240 GeV "accelerator ring"
  - "Collider ring" supplying 2-4 interaction points $L = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ per IP
    - Re-use ATLAS and CMS and/or install two dedicated LC-type detectors
- Current design uses arc optics from LHeC ring
  - Dipole fill factor 0.75 (smaller than for LEP)
  - increased synchrotron energy loss (7 GeV per turn)
  - redesign possible?
- $e^\pm$ polarization probably not possible at $\sqrt{s} = 240$ GeV
- In principle space is available to install compact e^+e^- facility on top of LHC ring
  - Is this really feasible?
  - Alternatively wait until completion of LHC physics programme and removal of LHC ring?
- SuperTRISTAN is a proposal for a similar machine in Japan

E.g., TLEP:

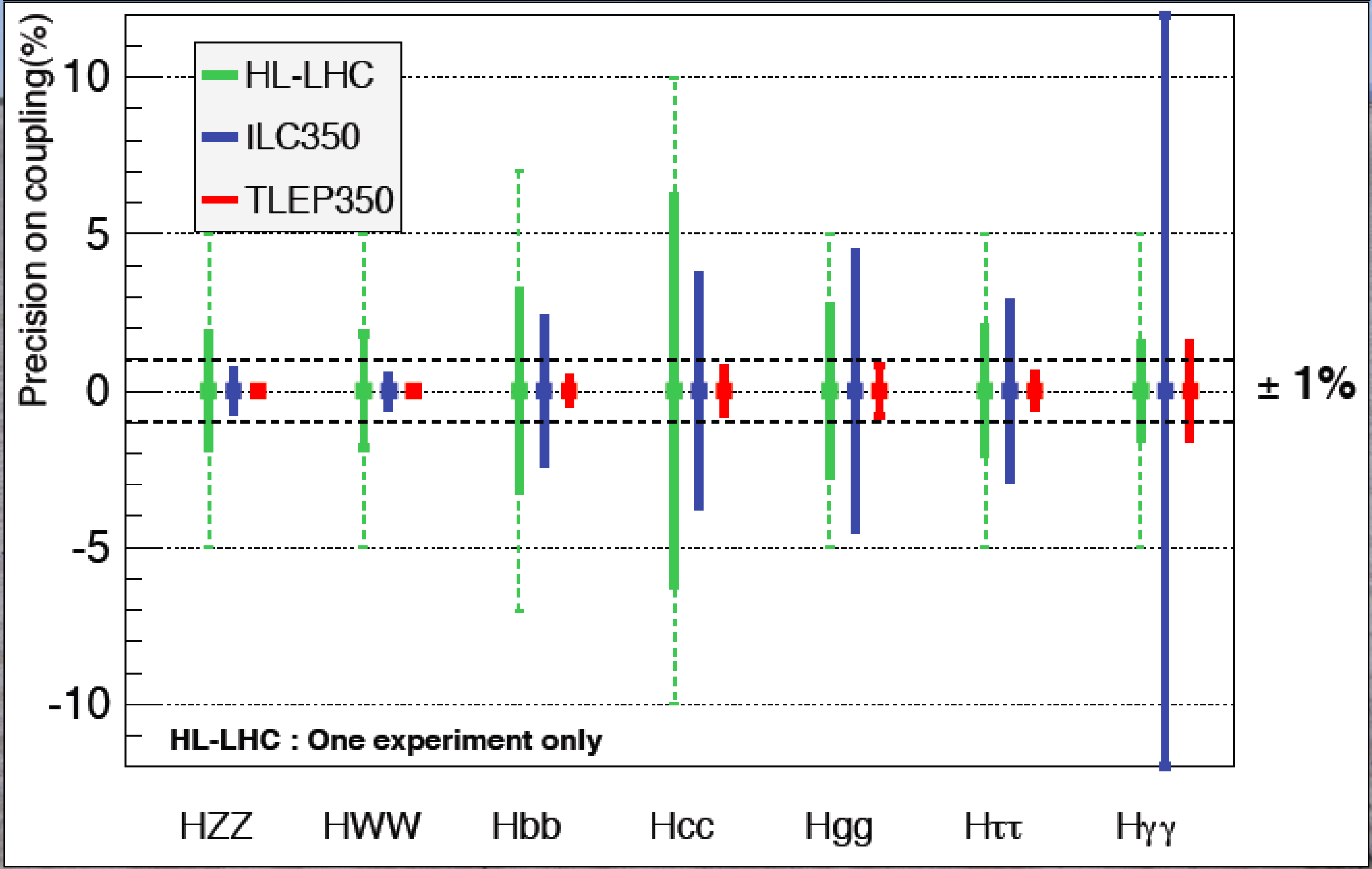
- $\sqrt{s} = 350$ GeV in 80 km LHC tunnel to reach thresholds for top pair and $e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu H$

New large tunnel
could also be used
for VHE pp collisions

Possible Luminosities of e^+e^- Colliders



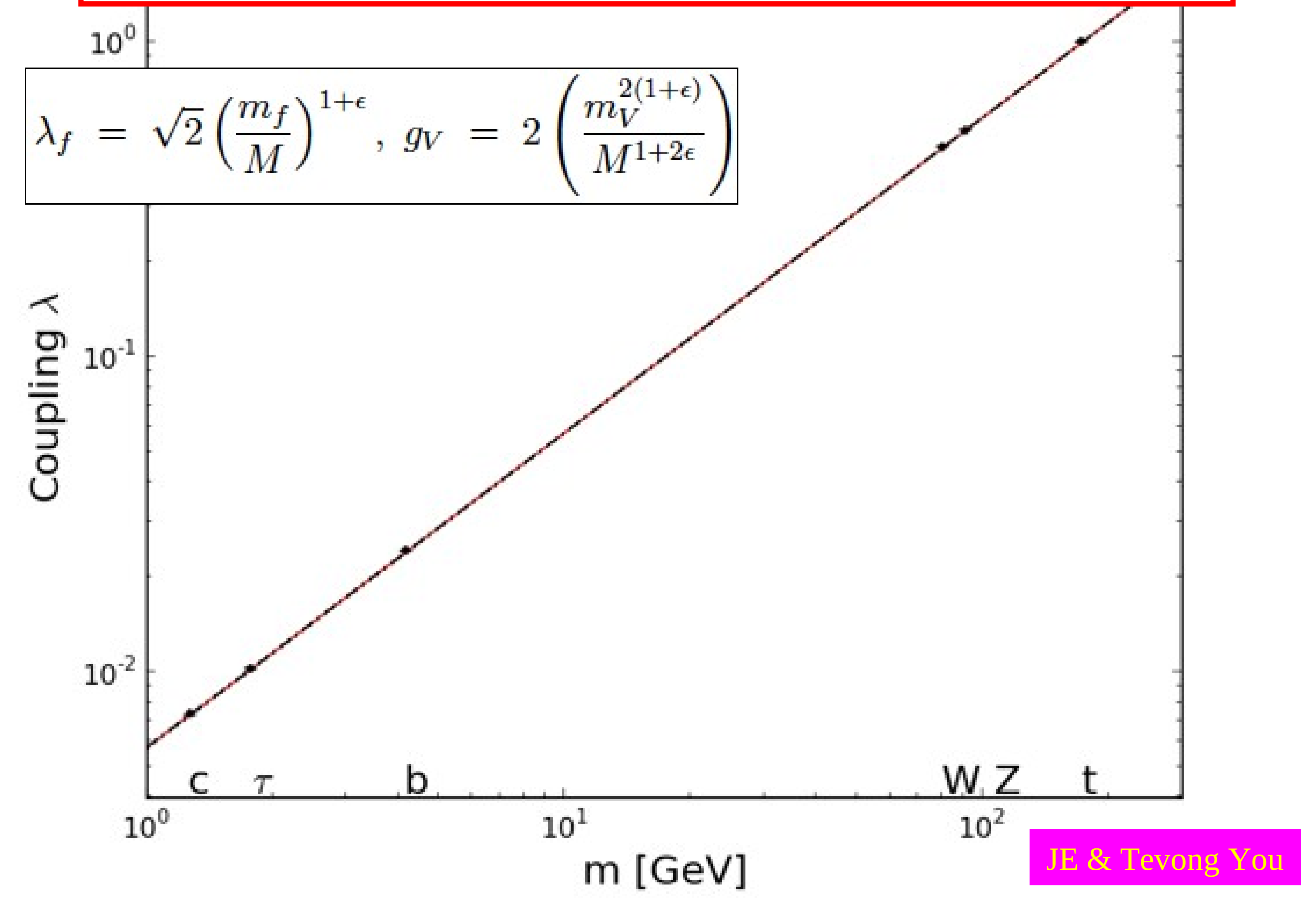
Comparison of Possible Higgs Factory Measurements



H Coupling Measurements @TLEP

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

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



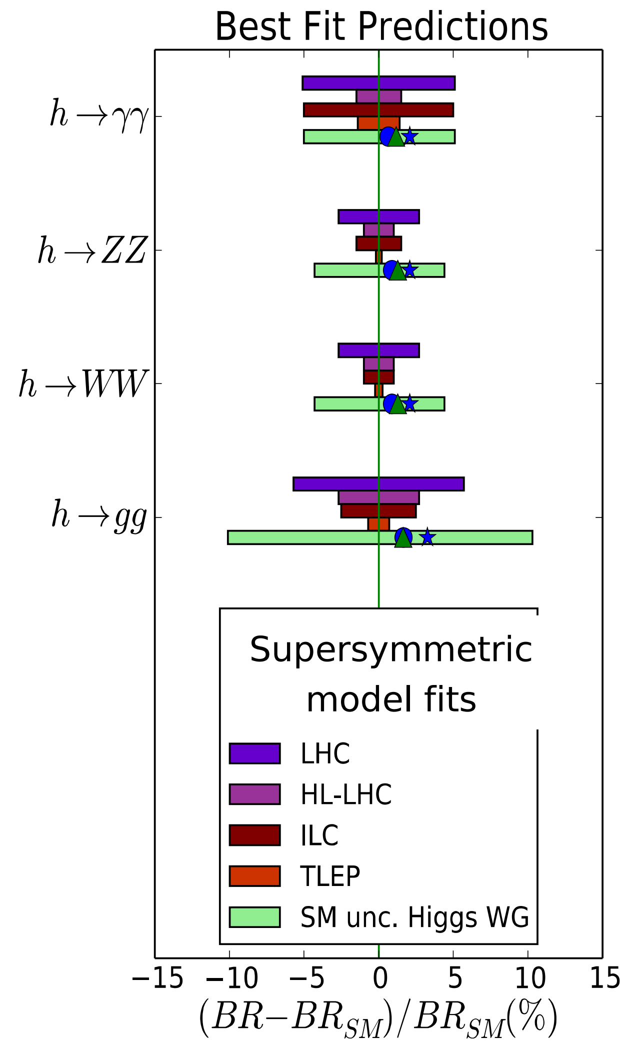
JE & Tevong You

Future Accelerators

- (What) precision, (how) high energy, neutrinos?
- Which is THE top priority accelerator?
  - Precision: HL-LHC, ILC/CLIC, TLEP, MC, γγ
  - 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 collaborative R&D needed

Impact of Higgs Factory?

- 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**



Summary

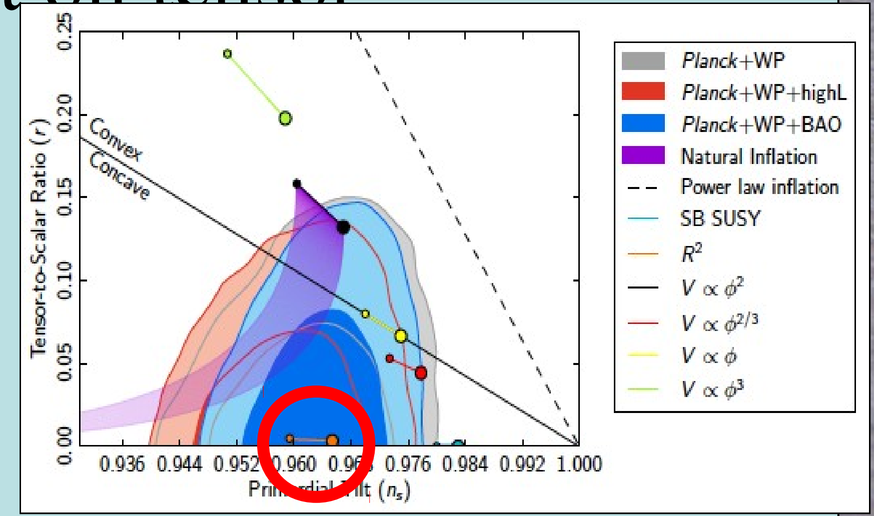
- Beyond any reasonable doubt, the LHC has discovered a (the) Higgs boson
- A big challenge for theoretical physics!
- The LHC may discover physics beyond the SM when it restarts at ~ 13 TeV
- If it **does**, priority will be to study it
- If it does **not**, natural to focus on the Higgs
- In this case, TLEP offers the best prospects
  - and also other high-precision physics

Inflationary Models in Light of Planck

- Planck CMB observations consistent with inflation
- Tilted scalar perturbation spectrum (rolling down):

$$n_s = 0.9585 \pm 0.070$$

- **BUT** strengthen upper limit on tensor perturbations: $r < 0.10$
- Challenge for simple inflationary models
- **Starobinsky R^2 to rescue?**
- **Higgs/supersymmetry/supergravity to rescue?**



Starobinsky Model

- Non-minimal general relativity (singularity-free cosmology):

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)$$

- **No scalar!?**

Starobinsky, 1980

- Inflationary interpretation, calculation of perturbations:

Mukhanov & Chibisov, 1981

$$\delta S_b = \frac{1}{2}\int d^4x \left[\phi'^2 - \nabla_a\phi\nabla^a\phi + \left(\frac{a''}{a} + M^2a^2\right)\phi^2\right]$$

- **Conformally equivalent to scalar field model:**

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2\right]$$

Whitt, 1984

Higgs Inflation: a Single Scalar?

Bezrukov & Shaposhnikov, arXiv:0710.3755

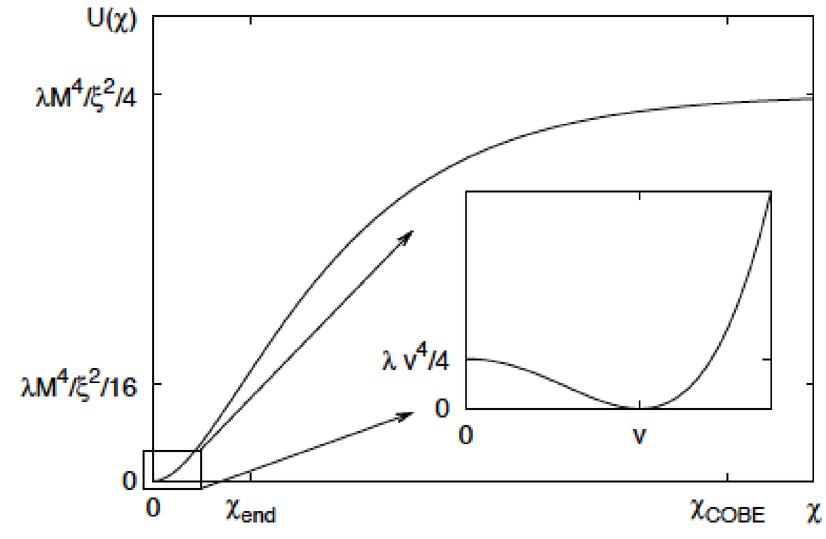
- Standard Model with non-minimal coupling to gravity:
$$S_J = \int d^4x\sqrt{-g}\left\{ -\frac{M^2+\xi h^2}{2}R + \frac{\partial_\mu h\partial^\mu h}{2} - \frac{\lambda}{4}\left(h^2-v^2\right)^2 \right\}$$
- Consider case $1 \ll \sqrt{\xi} \lll 10^{17}$: in Einstein frame
$$S_E = \int d^4x\sqrt{-\hat{g}}\left\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu\chi\partial^\mu\chi}{2} - U(\chi)\right\}$$
- With potential: $U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$

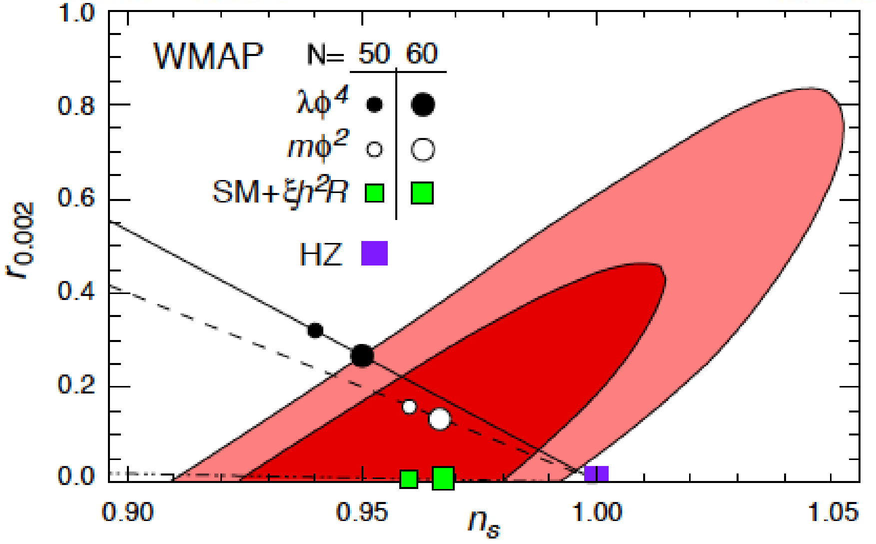
  Similar to Starobinsky, but not identical
- Successful inflationary potential at $\chi \gg M_P$

Higgs Inflation: a Single Scalar?

- Successful inflation for

$$\xi \simeq \sqrt{\frac{\lambda}{3}\frac{N_{\rm COBE}}{0.027^2}} \simeq 49000\sqrt{\lambda} = 49000\frac{m_H}{\sqrt{2}v}$$





Bezrukov & Shaposhnikov, arXiv:0710.3755

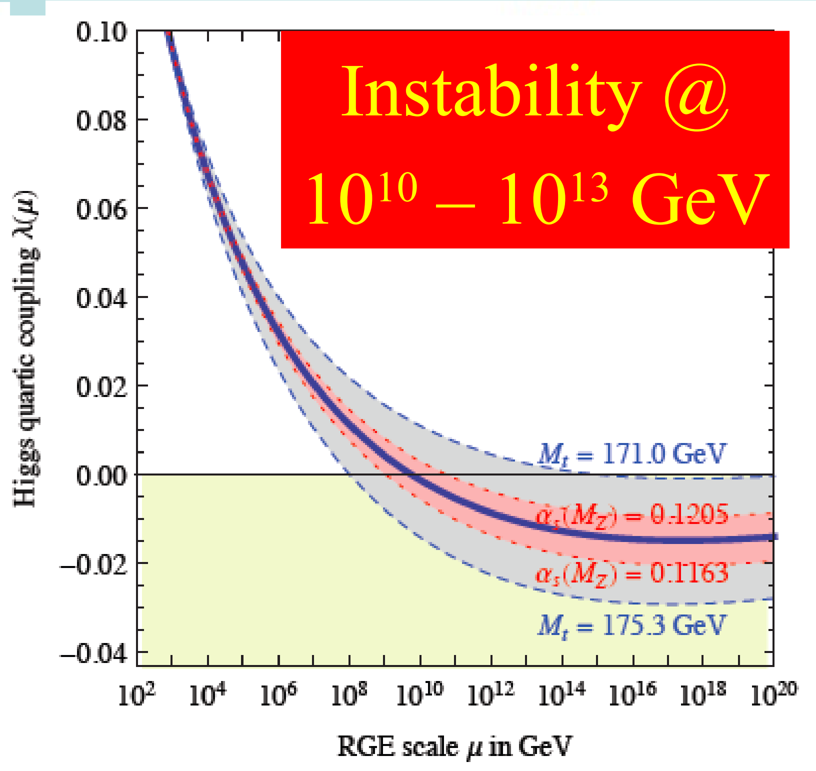
- **BUT:**
  - – Need to take into account ≥ 2-loop corrections
  - – Requires λ > 0 beyond M_P: need M_H > 127 GeV?
  - – Question of naturalness

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



Instability @ 10^{10} – 10^{13} GeV

- Vacuum could be stabilized by **Supersymmetry**

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

Inflation Cries out for Supersymmetry

- Want “elementary” scalar field

  (at least looks elementary at energies << M_P)
- To get right magnitude of perturbations
- Prefer mass << M_P

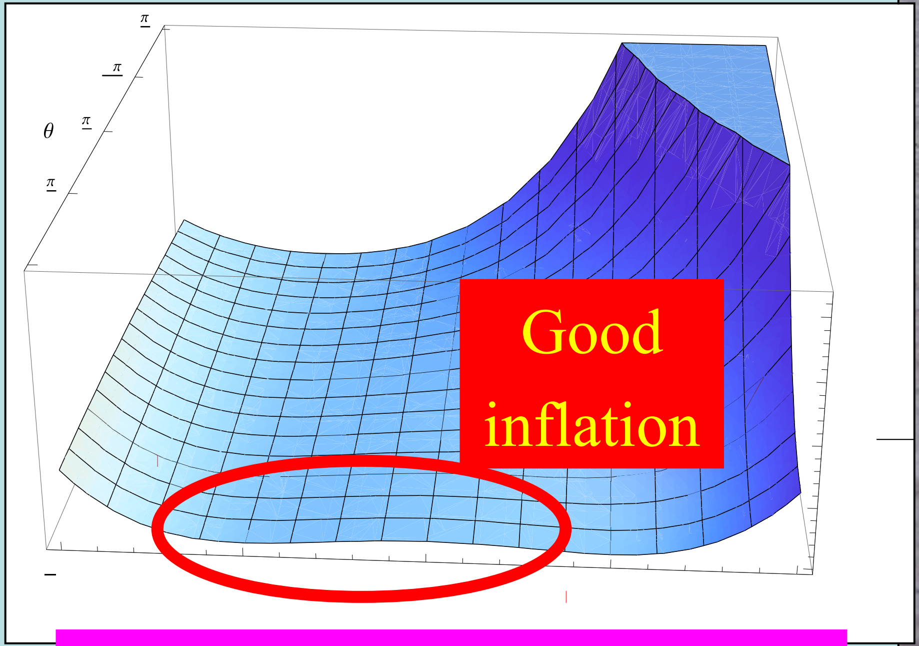
  (~ 10^{13} GeV in simple φ^2 models)
- And/or prefer small self-coupling $\lambda << 1$
- **Both technically natural with supersymmetry**

JE, Nanopoulos, Olive, & Tamvakis: 1983

Effective Potential in Wess-Zumino Model

$$W = \frac{\mu}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

- Effective potential: $V = \left|\frac{\partial W}{\partial \phi}\right|^2 = Av^4(x^4 - 2\cos\theta x^3 + x^2)$
- Equivalent to single-field model for $\theta = 0$ (good)
- Combination of $\varphi^2 + \varphi^4$ for $\theta = \pi/2$ (no good)
- **Good inflation for suitable μ, λ**

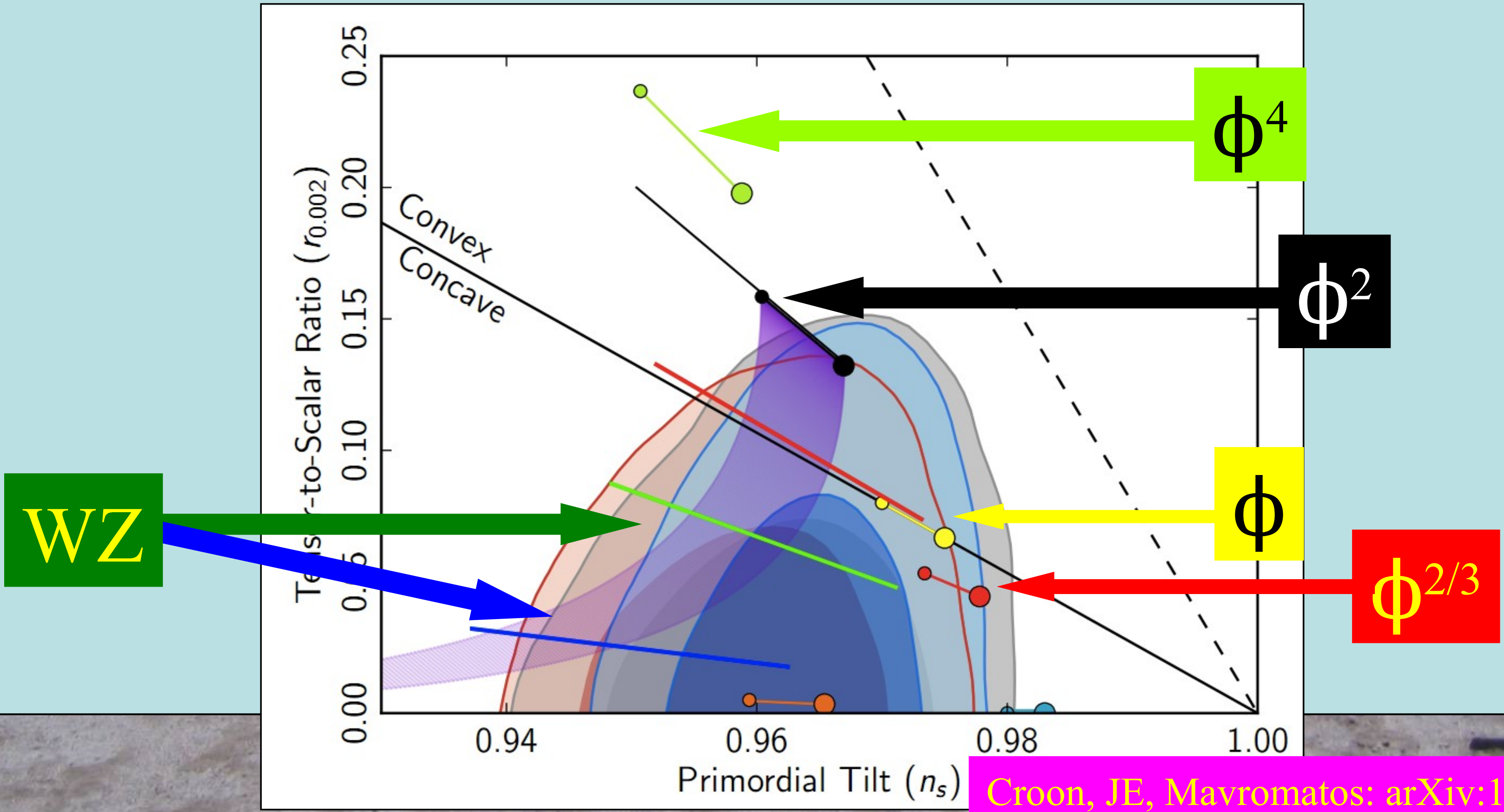


Good inflation

Croon, JE & Mavromatos: arXiv:1303.6253

Supersymmetric Inflation in Light of Planck

- Supersymmetric Wess-Zumino (WZ) model consistent with Planck data



Croon, JE, Mavromatos: arXiv:1303.6253

From Supersymmetry to Supergravity

- The only good symmetry is a local symmetry (cf, gauge symmetry in Standard Model)
- **Local supersymmetry = supergravity**
- Early Universe cosmology needs gravity
- **Supersymmetry + gravity = supergravity**
- Superpartner of graviton is gravitino fermion
- Gravitino condensation? (cf, quarks in QCD)
- **Mechanism for inflation?**

JE & Mavromatos, arXiv:1308.1906

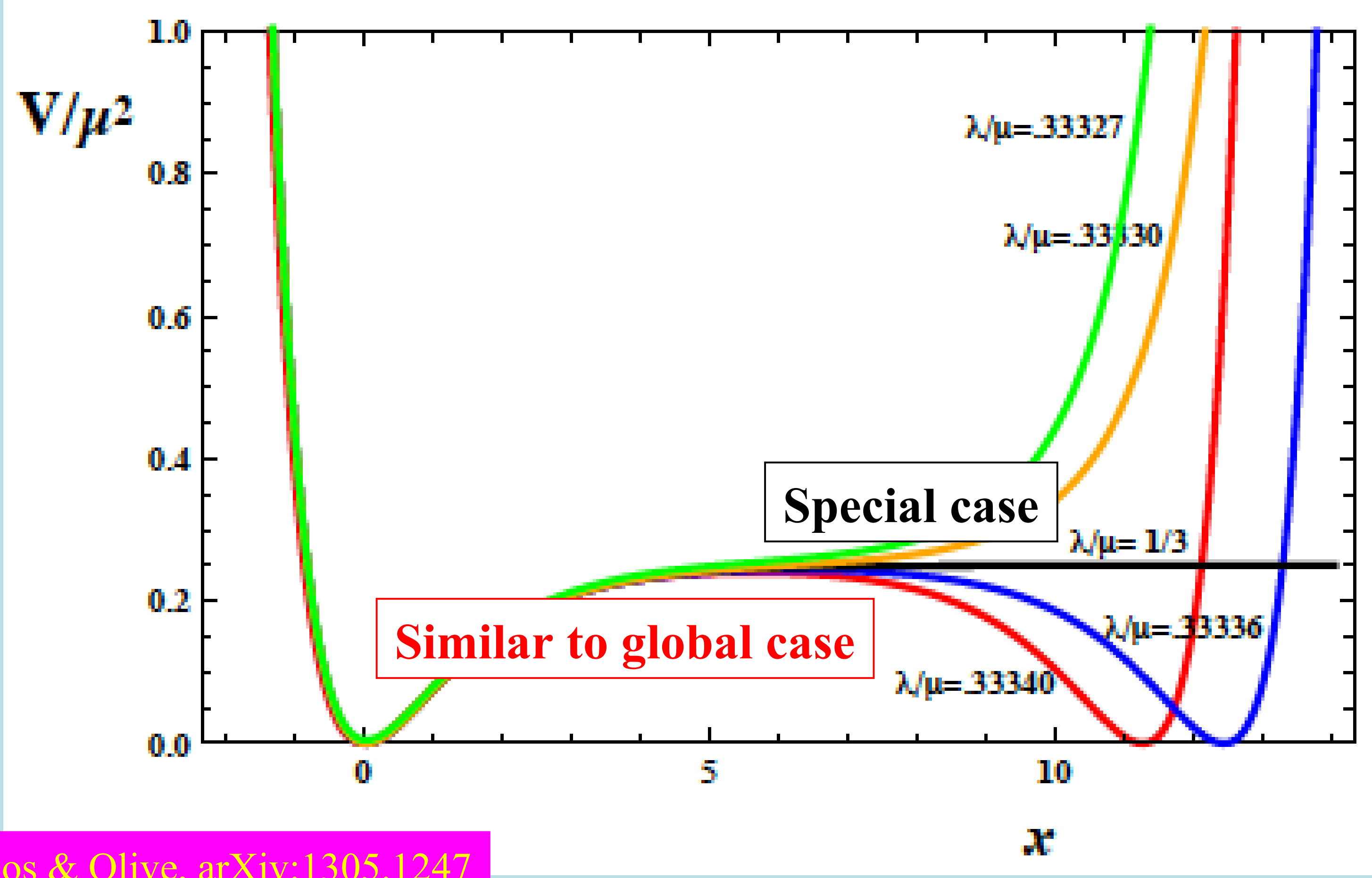
No-Scale Supergravity Inflation

- **Supersymmetry + gravity = Supergravity**
- Include conventional matter?
- Potentials in generic supergravity models have 'holes' with depths ~ – M_P^4
- Exception: **no-scale supergravity**
- Appears in compactifications of string
- Flat directions, scalar potential ~ global model + controlled corrections

JE, Nanopoulos & Olive, arXiv:1305.1247, 1307.3537

No-Scale Supergravity Inflation

- Inflationary potential for $\lambda \simeq \mu/3$



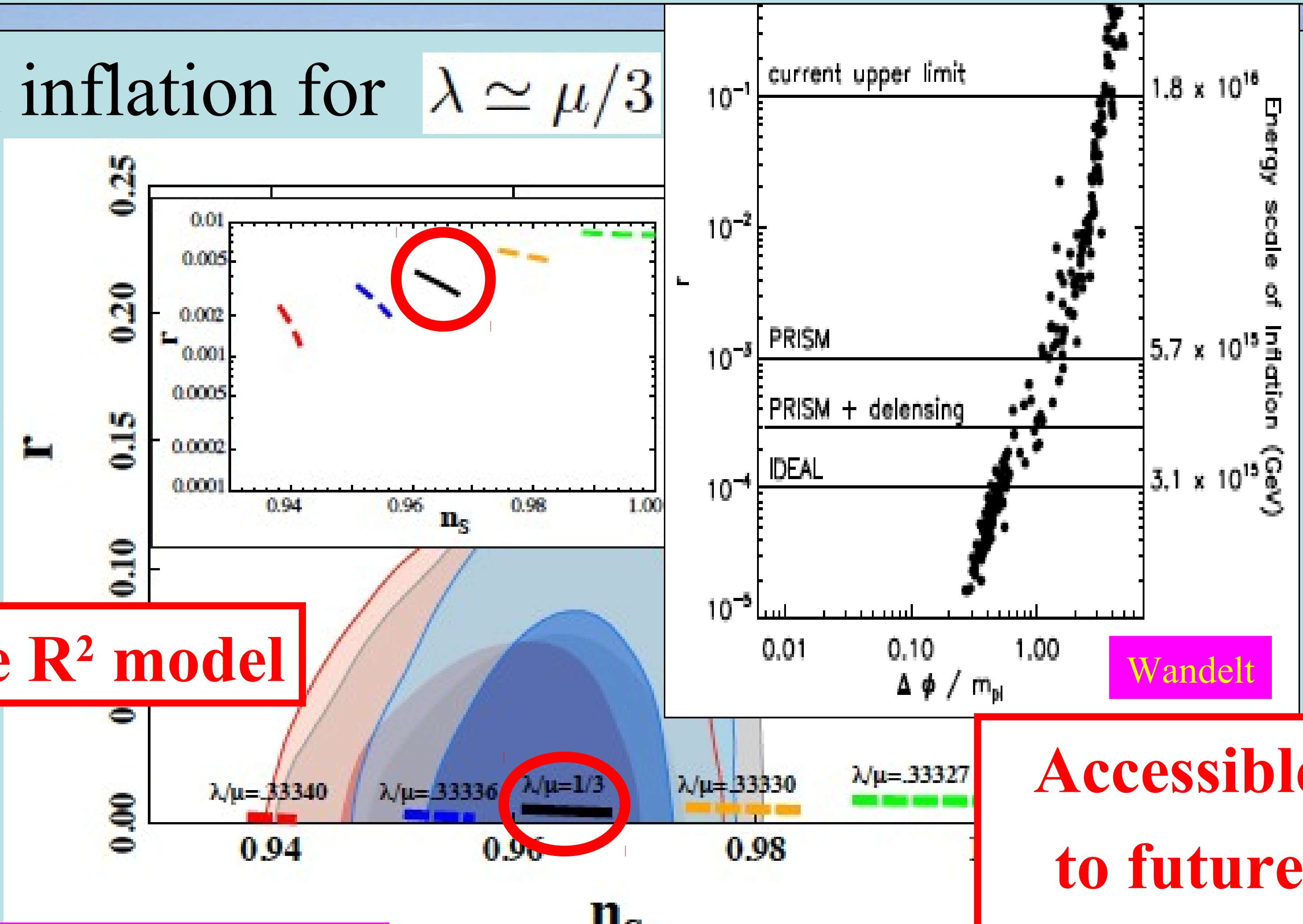
Special case

Similar to global case

JE, Nanopoulos & Olive, arXiv:1305.1247

No-Scale Supergravity Inflation

- Good inflation for $\lambda \simeq \mu/3$



Looks like R² model

Wandelt

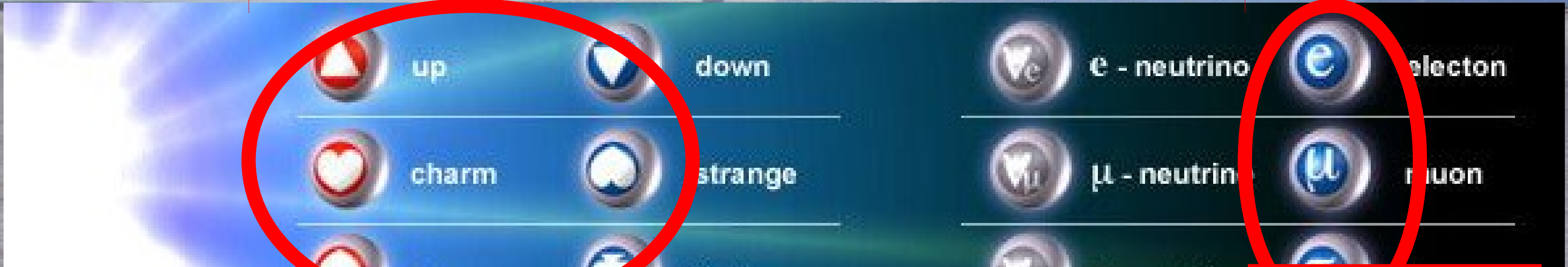
Accessible to future Experiment?

JE, Nanopoulos & Olive, arXiv:1305.1247

The Standard Model

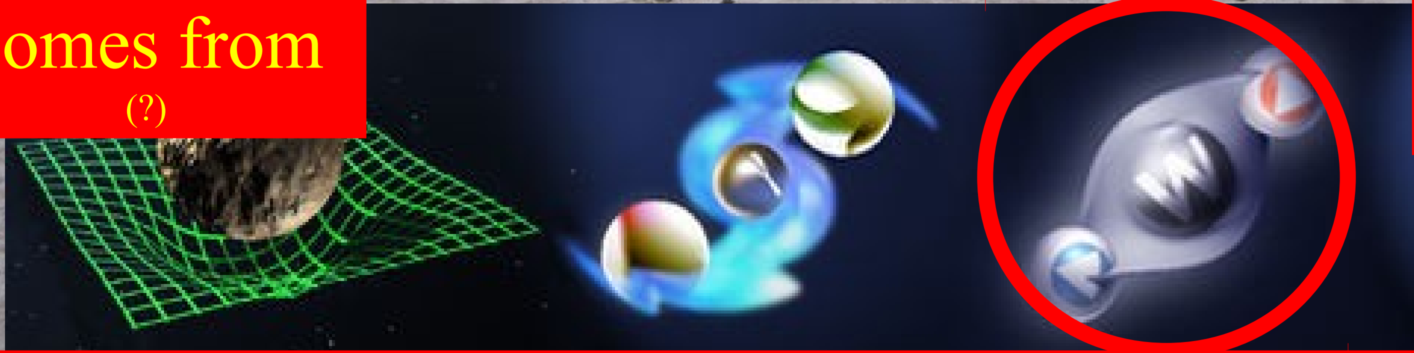
= Cosmic DNA

The matter particles



Where the mass comes from
(?)

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force