Title: Where is particle physics going?

Date: Feb 08, 2017 02:00 PM

URL: http://pirsa.org/17020013

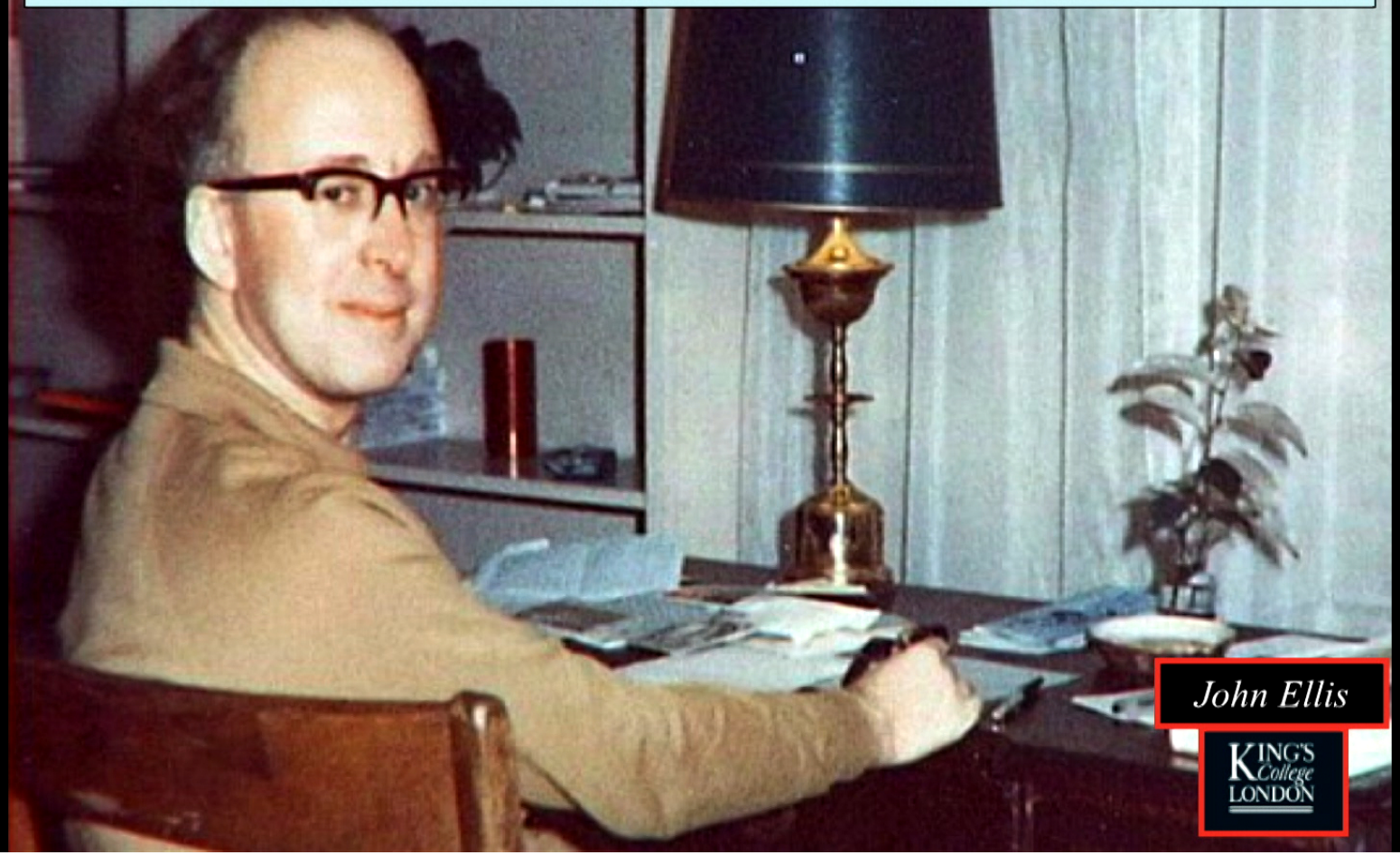
Abstract: The discovery of the Higgs boson at the LHC in 2012 was a watershed in particle physics. Its existence focuses attention on the outstanding questions about physics beyond the Standard Model: is `empty' space unstable? what is the dark matter? what is the origin of matter? what is the explanation for the small masses of the neutrinos? how is the hierarchy of mass scales in physics established and stabilized? what drove inflation? how to quantize gravity Many of these issues will be addressed by future runs of the LHC, e.g., by studies of the Higgs boson, and also motivate possible future colliders.

Where is Particle Physics Going?

John Ellis

KING'S College LONDON

Where is Particle Physics Going?



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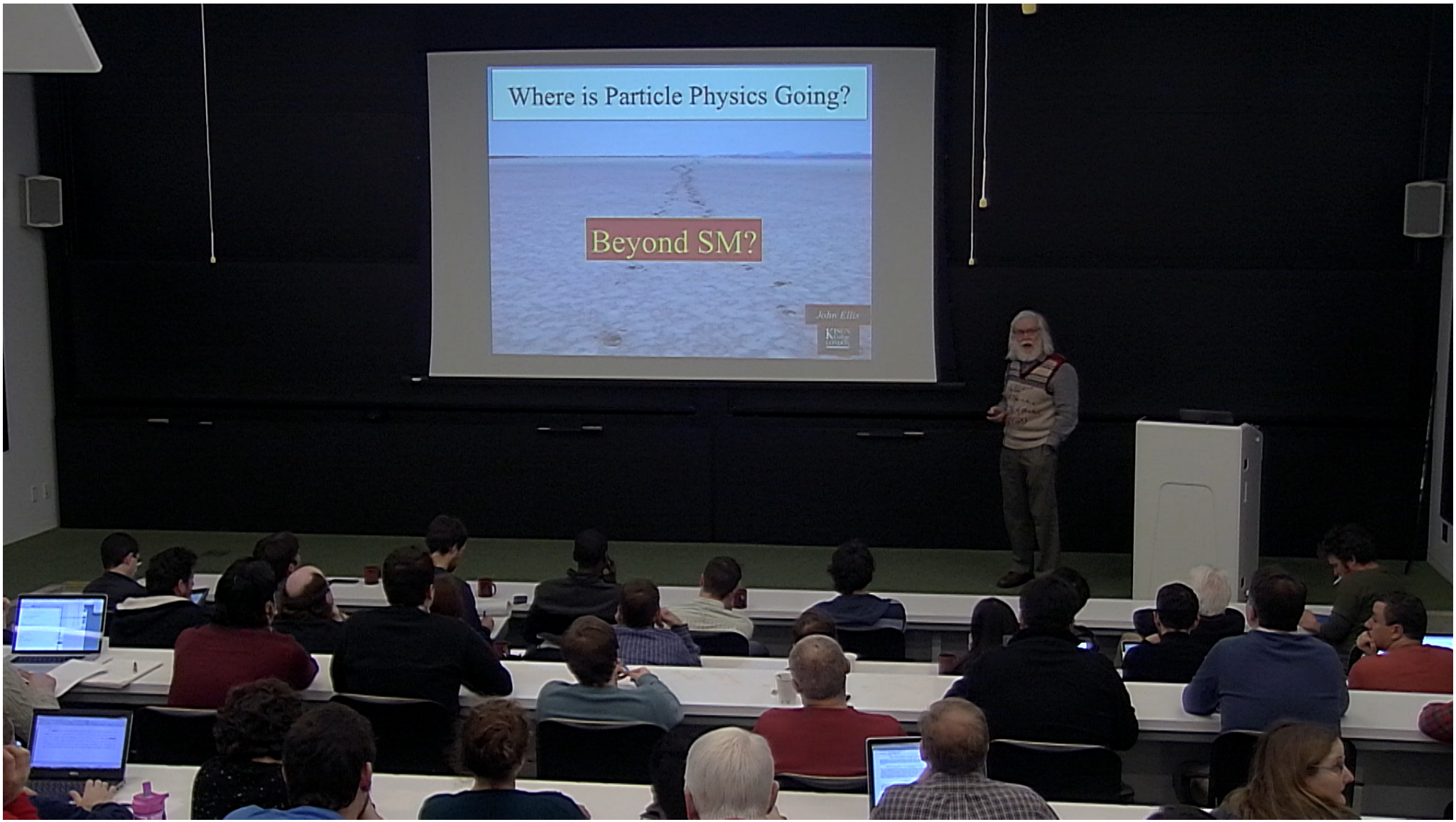
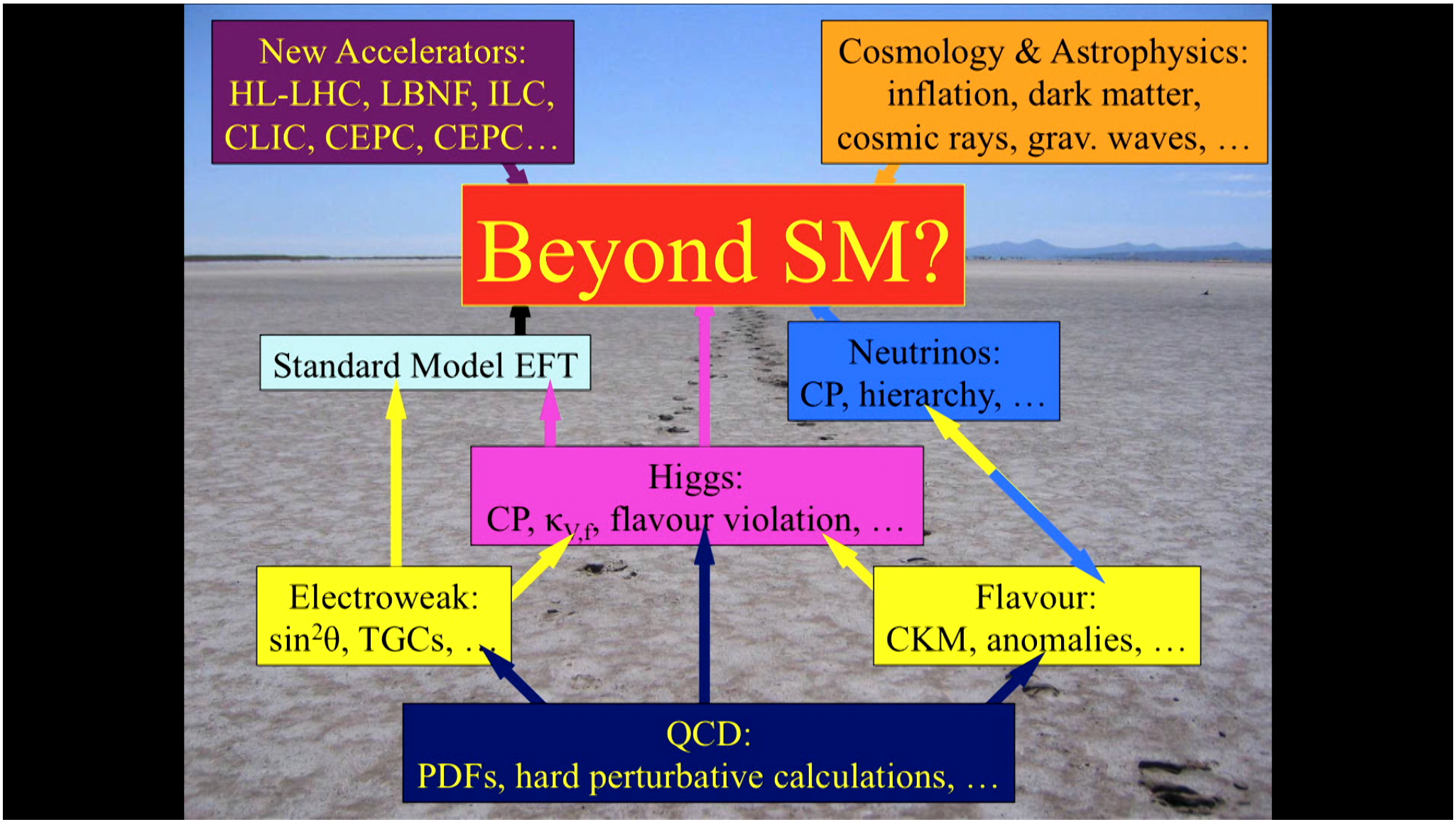

Where is Particle Physics Going?
Beyond SM?
John Ellis

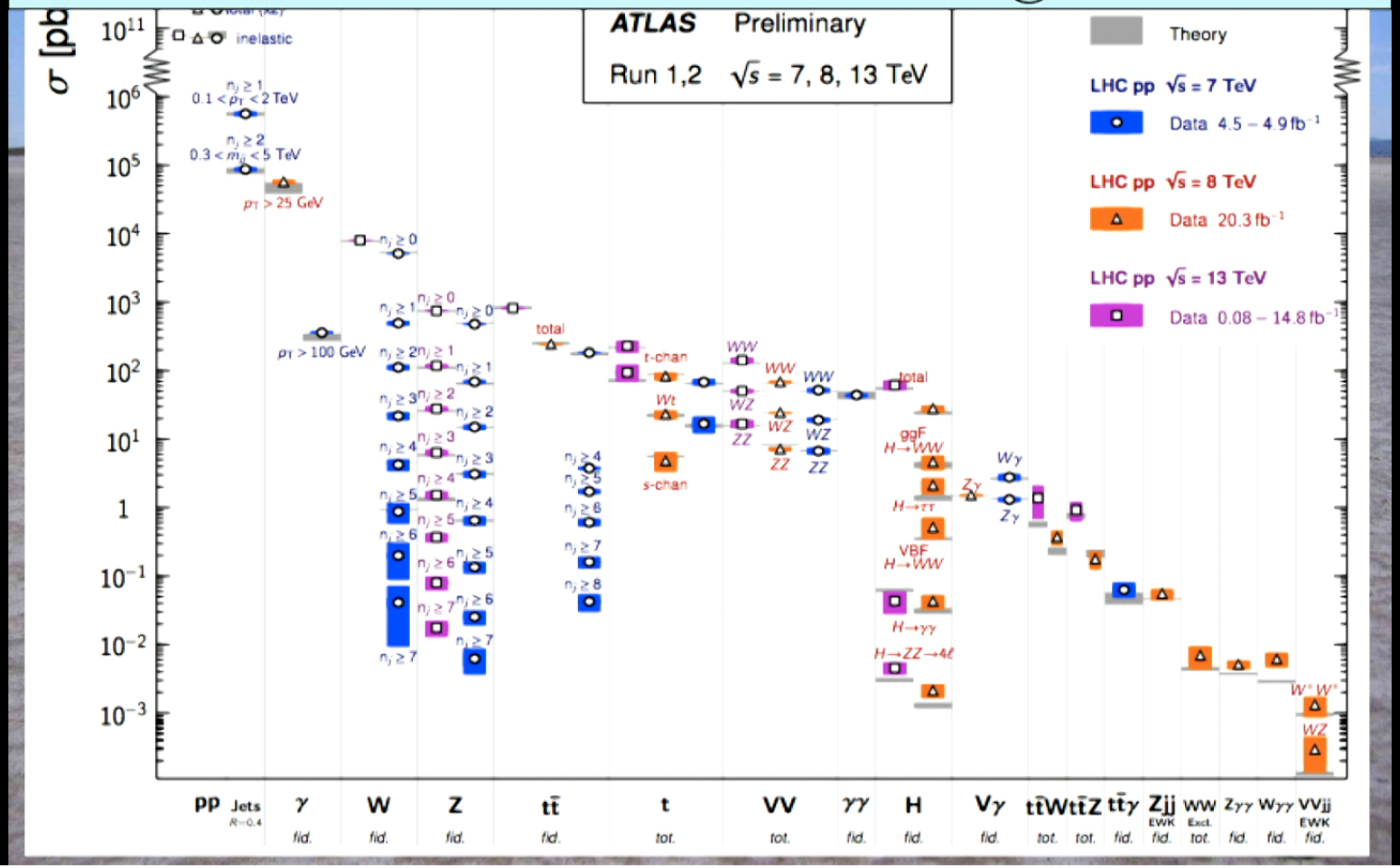
Quoting George Harrison

If you don’t know where you’re going,
Any road will take you there


New Accelerators:
HL-LHC, LBNF, ILC,
CLIC, CEPC, CEPC…
Cosmology & Astrophysics:
inflation, dark matter,
cosmic rays, grav. waves, …
Beyond SM?
Standard Model EFT
Neutrinos:
CP, hierarchy, …
Higgs:
CP, $\kappa_{V,f}$, flavour violation, …
Electroweak:
$\sin^2\theta$, TGCs, …
Flavour:
CKM, anomalies, …
QCD:
PDFs, hard perturbative calculations, …

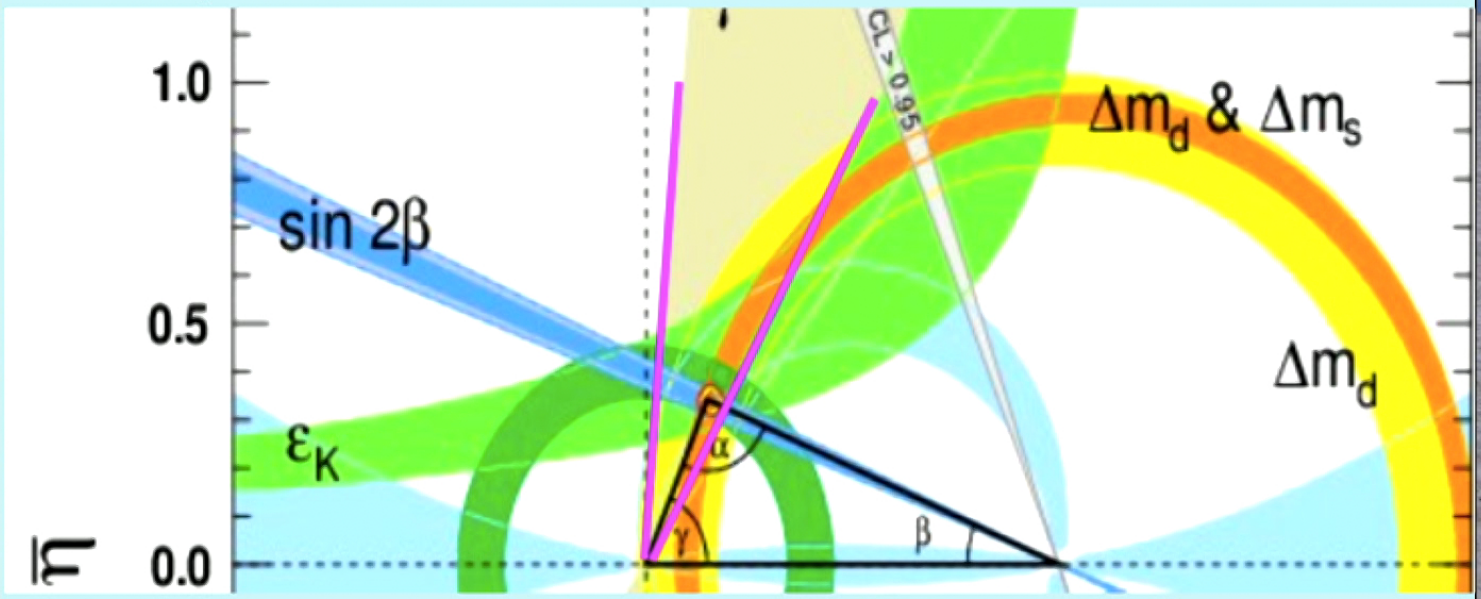
“Stairway to Heaven”

Standard Model Cross-Sections @ LHC



CKM Unitarity Triangle

- Many consistent measurements



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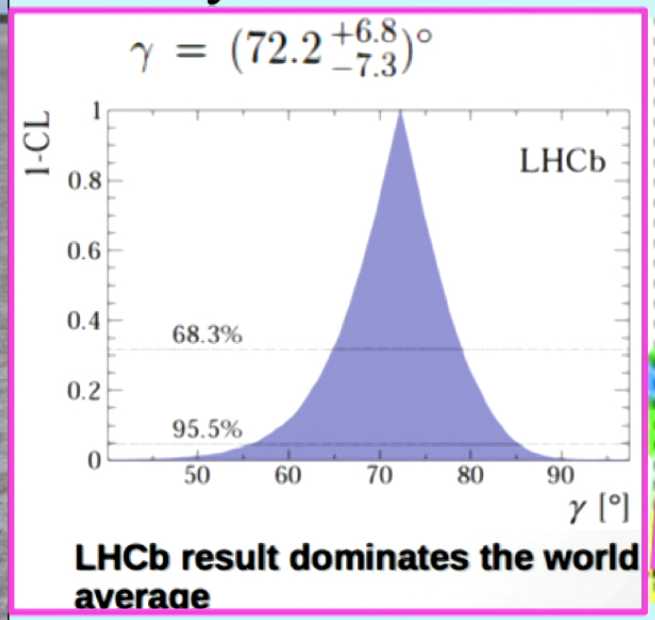
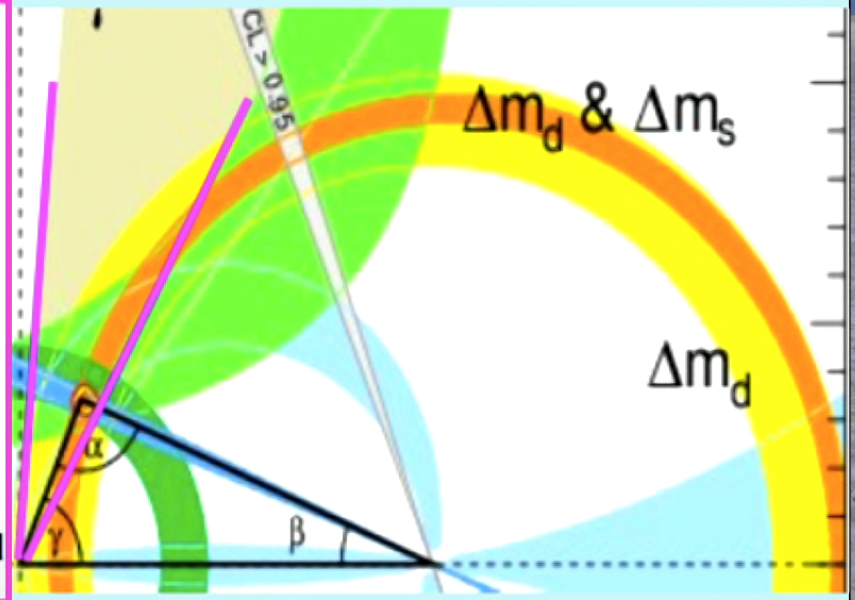
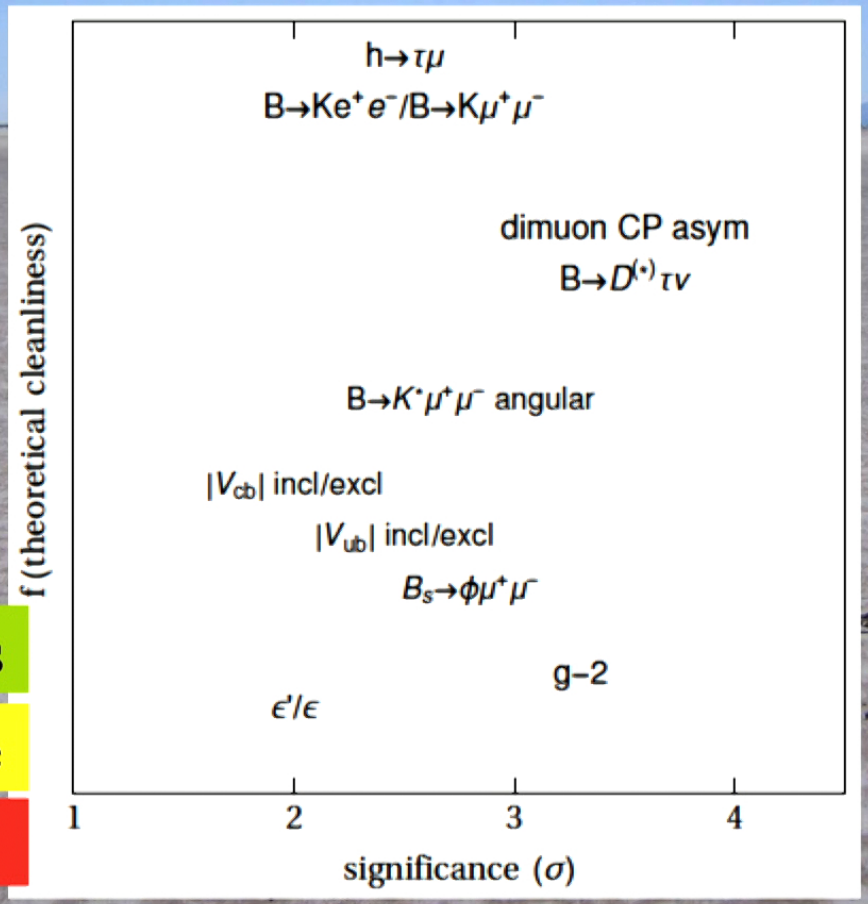


LHCb result dominates the world average



- **Least well-known angle: γ**
- Important new result from LHCb

Flavour Anomalies

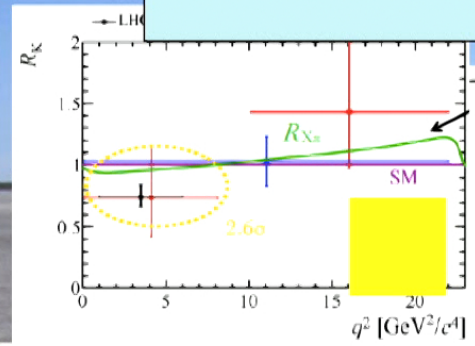


No worries

Wait & See

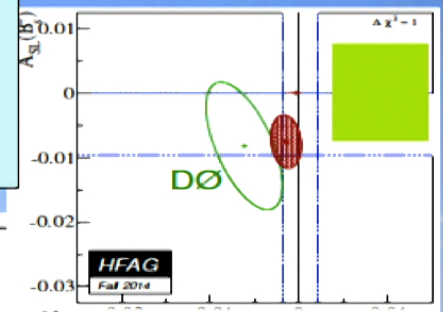
Serious?

Flavour Anomalies



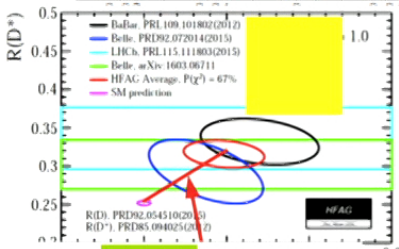
h→τμ

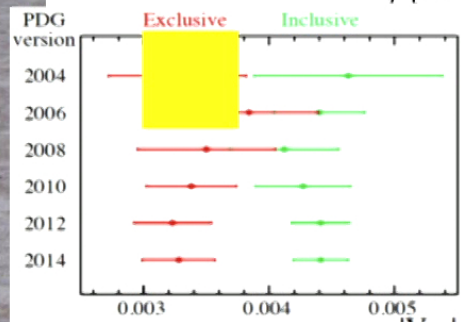
B→Ke⁺e⁻/B→Kμ⁺μ⁻



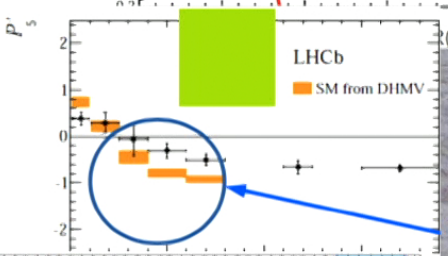
dimuon CP asym

B→D^(*)τν





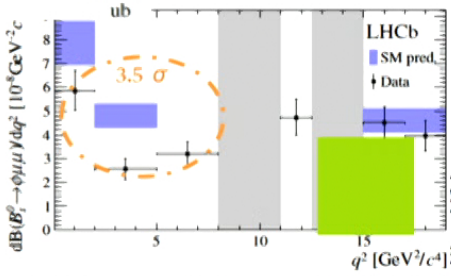
B→K*μ⁺μ⁻ angular



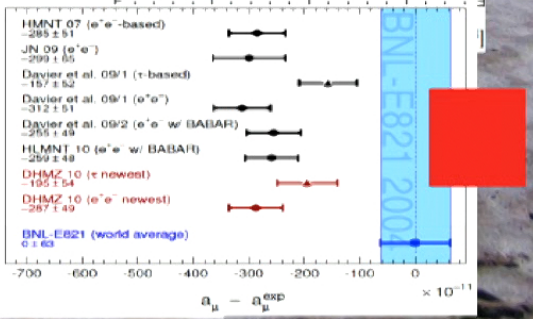
V_{cb}| incl/excl

|V_{ub}| incl/excl

B_s→φμ⁺μ⁻



g−2



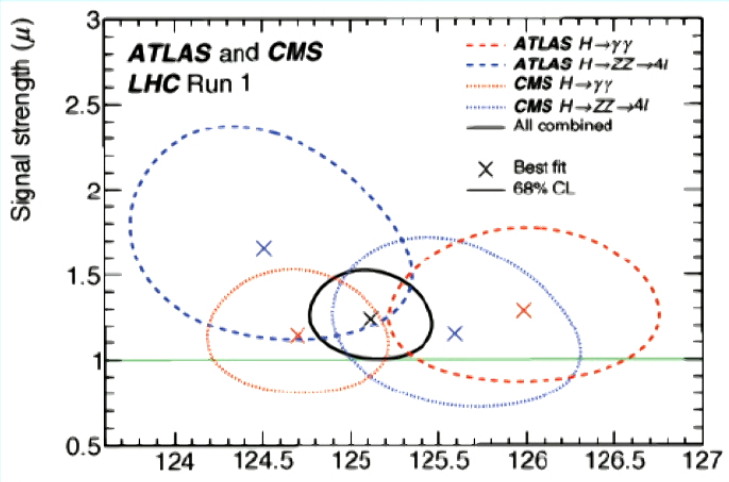
No worries

Wait & See

Serious?

Higgs Mass Measurements

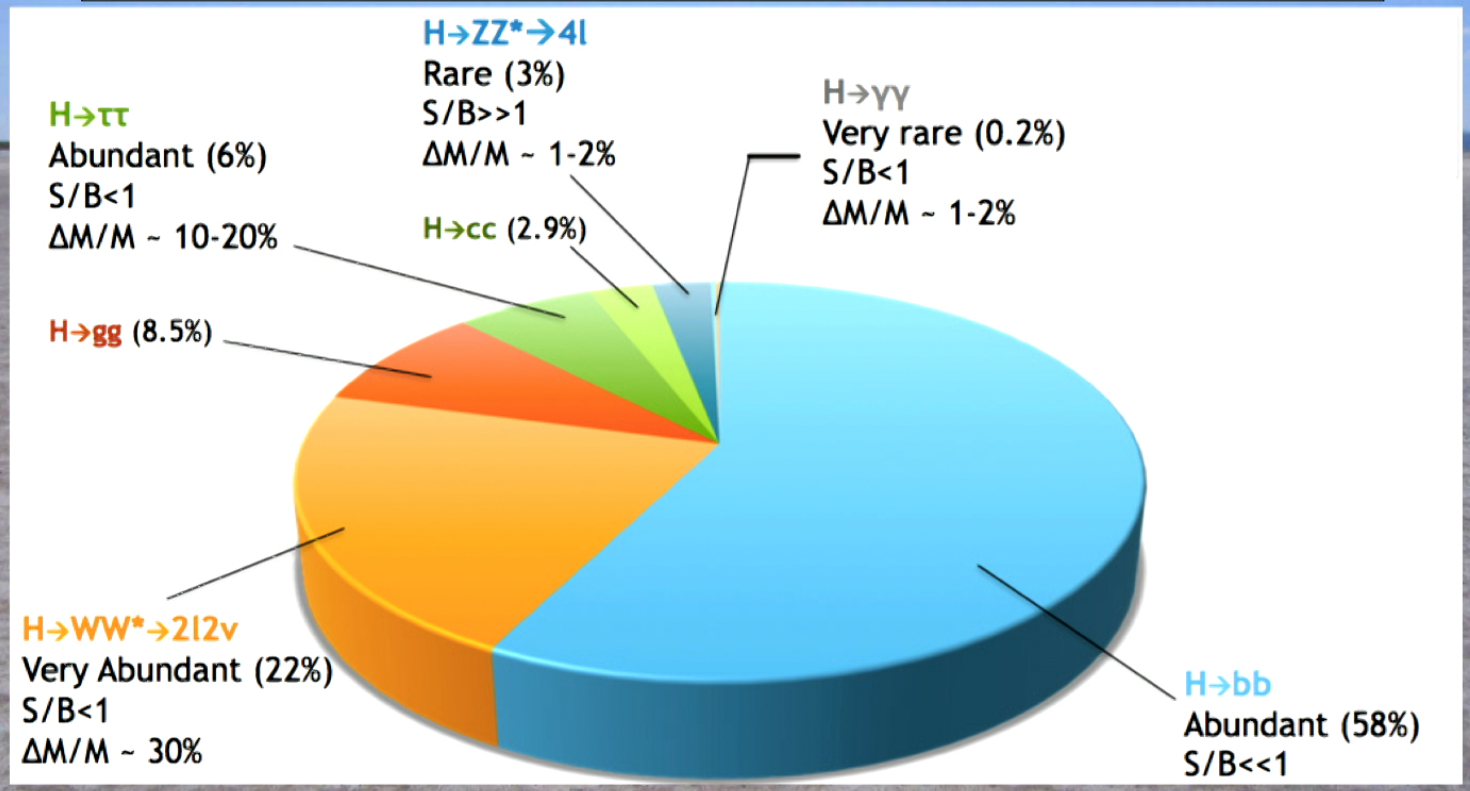
- ATLAS + CMS ZZ* and γγ final states



125.09 ± 0.21 (stat) ± 0.11 (syst)

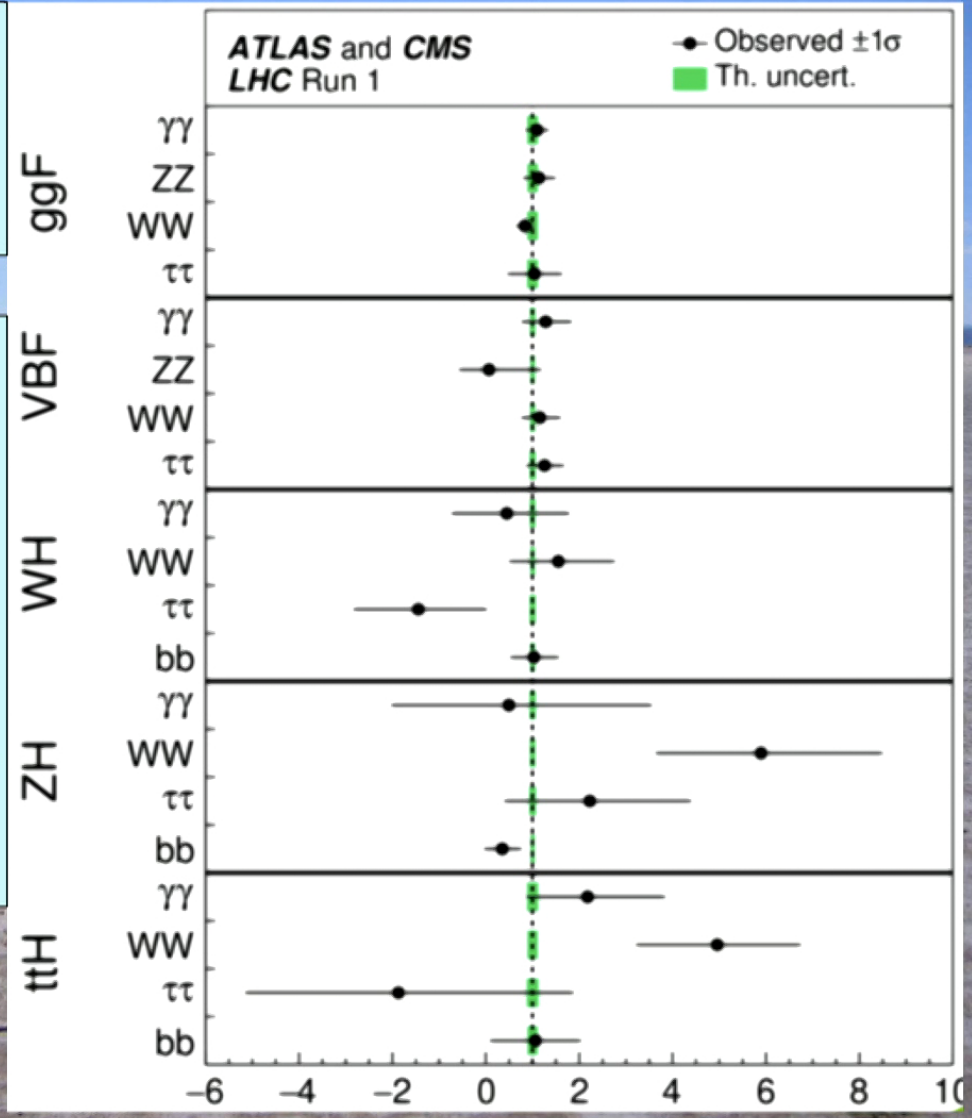
- Statistical uncertainties dominate
- Allows precision tests
- **Crucial for stability of electroweak vacuum**

What we Expect



Measurements in Run 1

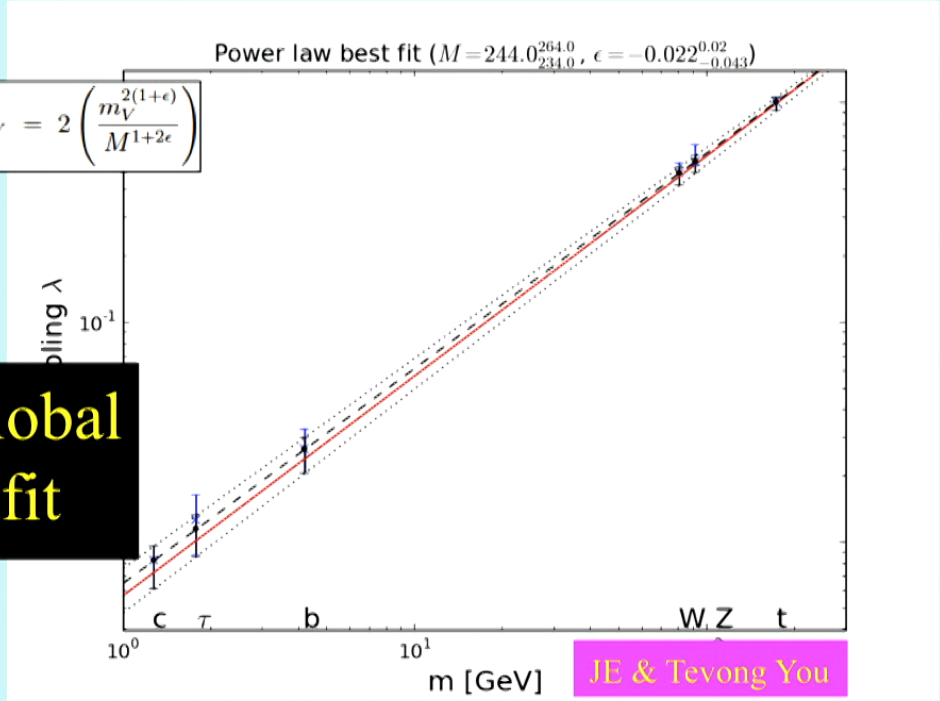
- Open questions:
  - H➔bb?
    - 2.6σ @ LHC
    - 2.8σ @ FNAL
  - H➔μμ?
  - ttH production?



It Walks and Quacks like a Higgs

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

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



Global fit

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

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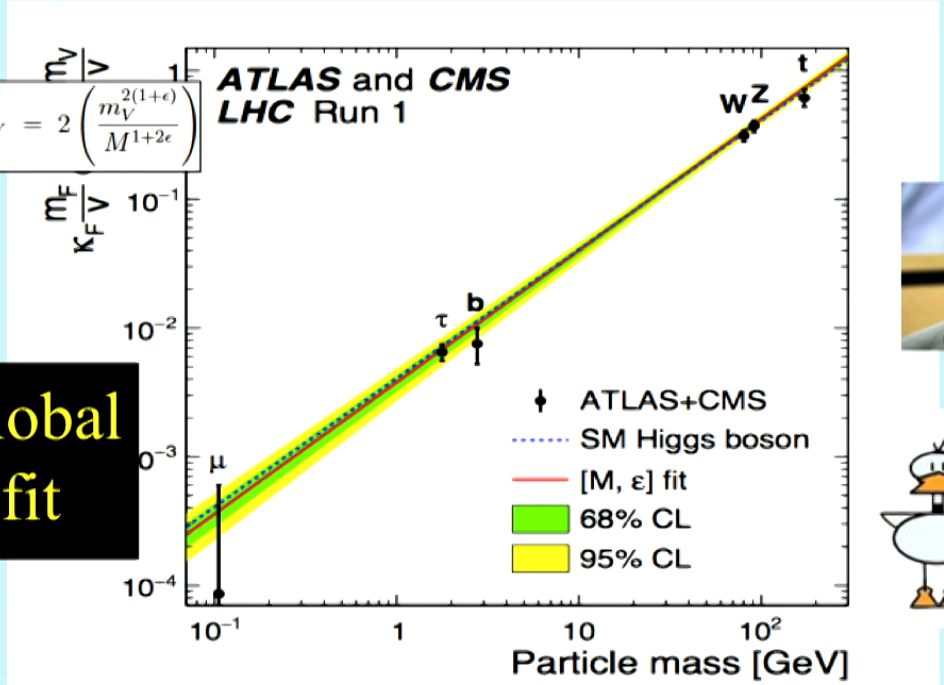
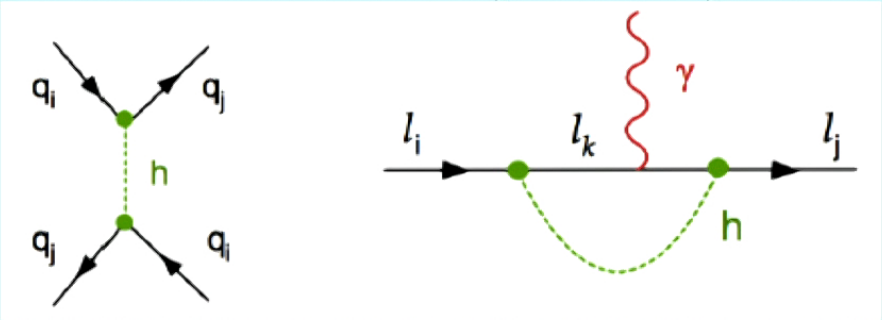


Global fit

- **Blue** dashed line = Standard Model

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



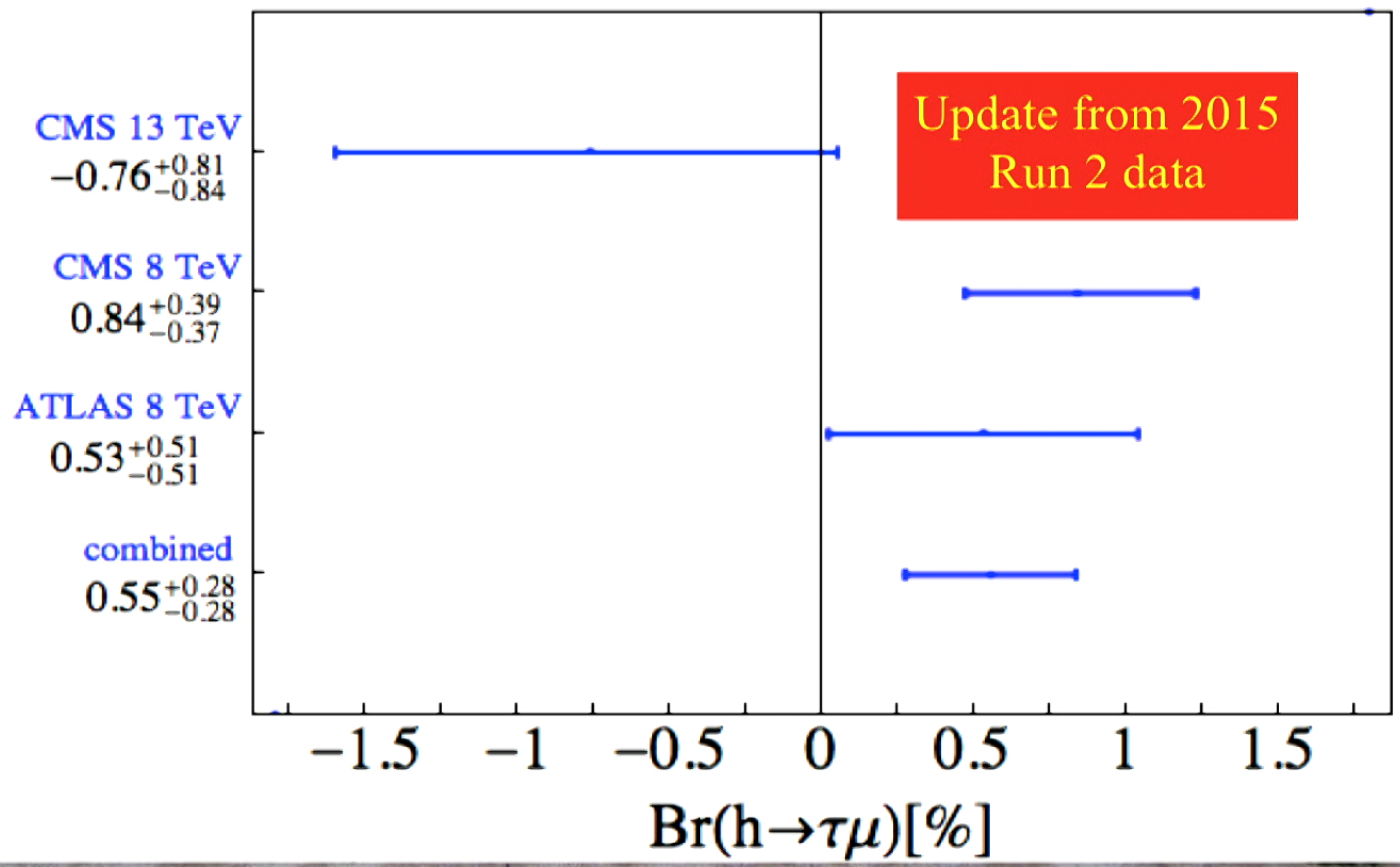
- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

Either BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704
Harnik, Kopp, Zupan: arXiv:1209.1397

B BR(μe) must be $< 2 \times 10^{-5}$

Flavour-Changing Higgs Coupling?

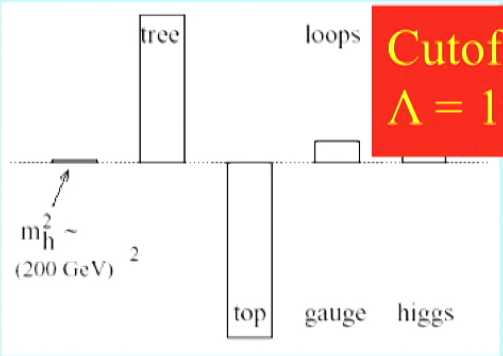


Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff
$\Lambda = 10$ TeV

Cut-off $\Lambda \sim 1$ TeV with
Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed $m_t > 200$ GeV

New strong interactions?
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?
- Pseudo-Nambu-Goldstone?

Phenomenological Framework

- Assume custodial symmetry:

$$SU(2) \times SU(2) \to SU(2)_V \qquad (\rho \equiv M_W/M_Z \cos\theta_w \sim 1)$$

- Parameterize gauge bosons by 2 × 2 matrix Σ:

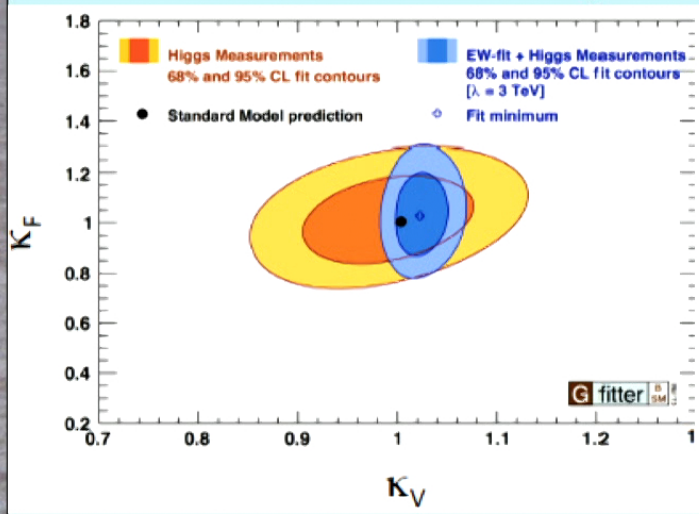
$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) - m_i\bar{\psi}^i_L\Sigma\left(1 + c\frac{h}{v} + \ldots\right)\psi^i_R + \mathrm{h.c.}$$
$$+ \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2 h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \quad ,$$

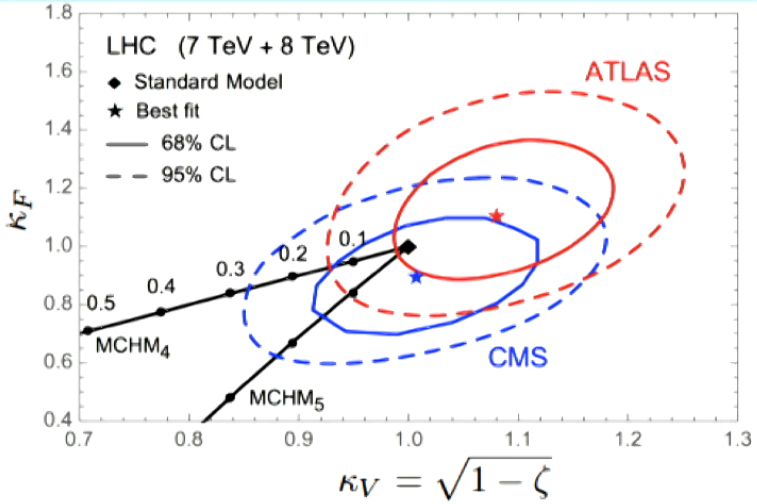
$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right) \quad \mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi}b_s G_{a\mu\nu}G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

- Coefficients ***a = c = 1*** in Standard Model

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by κ_V, to fermions by κ_f
- Standard Model: $\kappa_V = \kappa_f = 1$





- Consistency between Higgs and EW measurements
- Must tune composite models to look like SM

Assuming H(125) is SM-like: Model-independent search for new physics

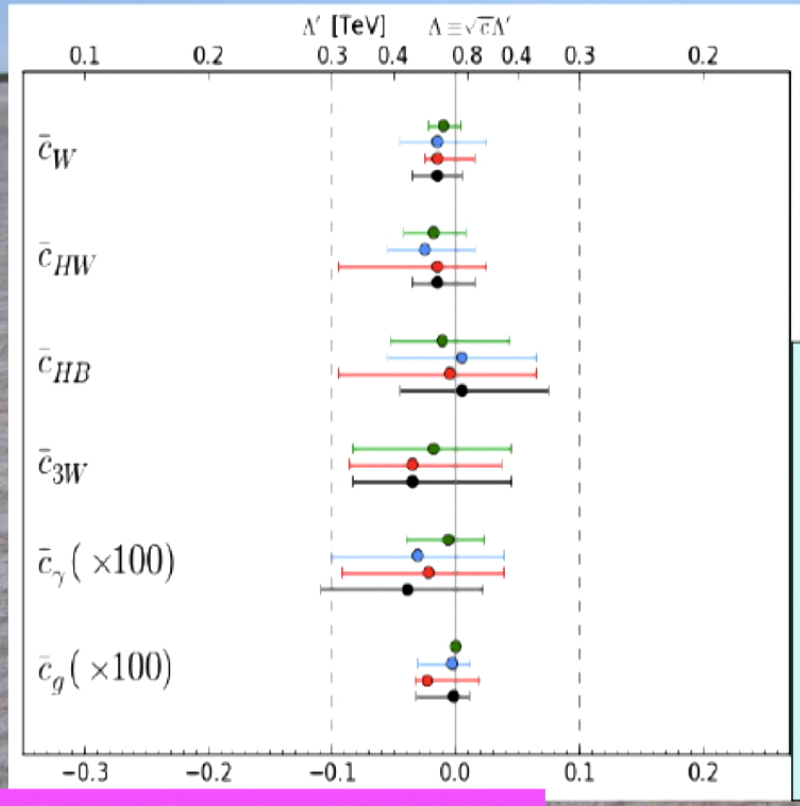
Standard Model Effective Field Theory

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

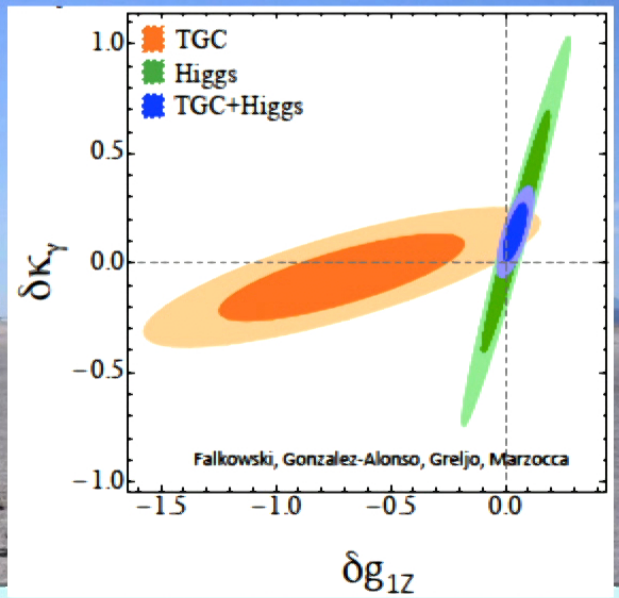
$$\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\ \bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
+\ &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

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

Global Fits including LHC Higgs, TGCs



JE, Sanz & Tevong You, arXiv:1410.7703



- **Higgs production**
- **LHC Triple-gauge couplings**
- Global combination
- **Individual operators**

Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at low-energy scale Λ due to renormalization

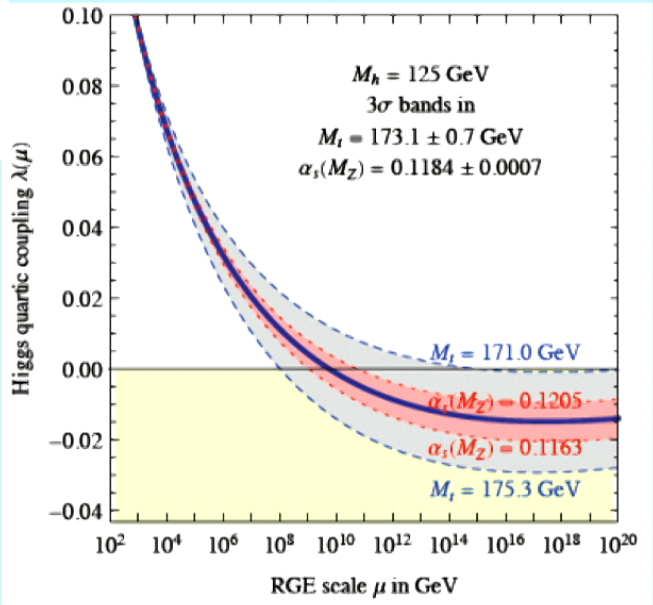
$$\lambda(Q) = \frac{\lambda(v)}{1 - \frac{3}{4\pi^2}\lambda(v)\log\frac{Q^2}{v^2}}$$

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

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



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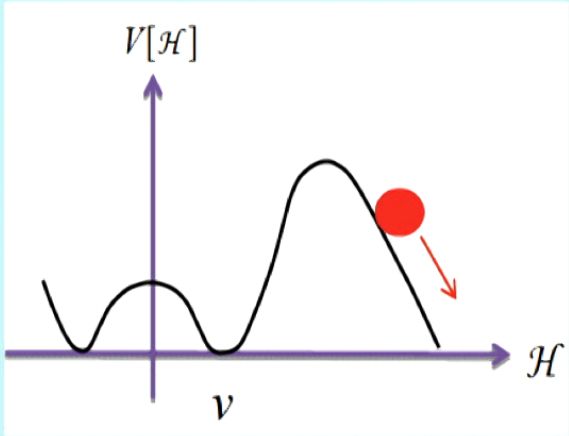
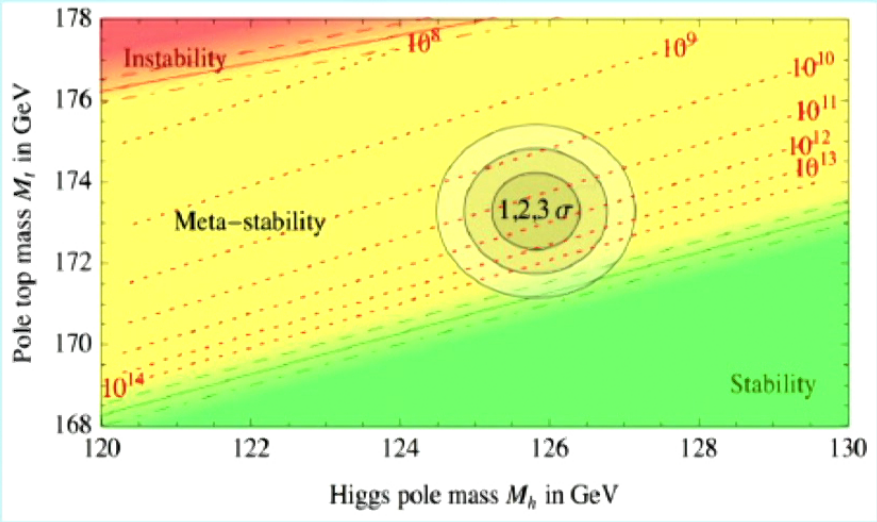
Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H





- Instability scale: Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

$$\log_{10}\frac{\Lambda_I}{\mathrm{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\mathrm{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\mathrm{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

Vacuum Instability in the Standard Model

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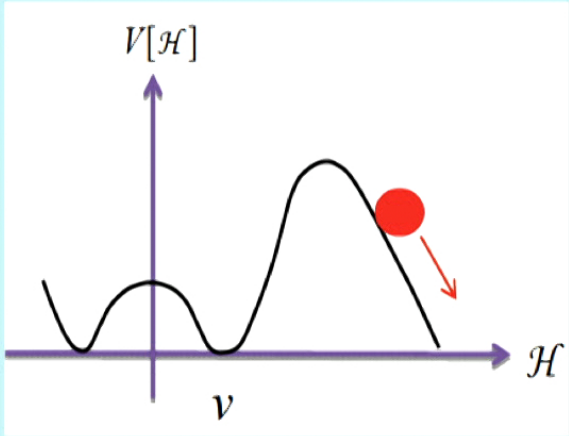

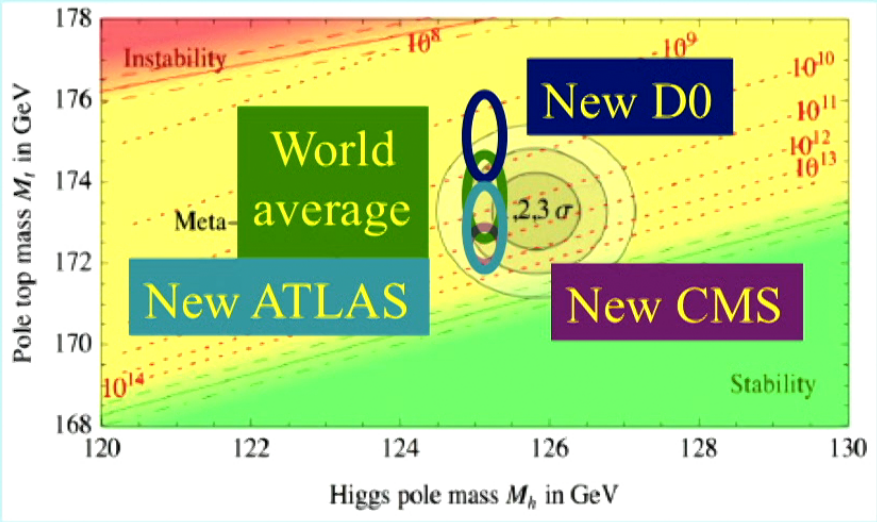

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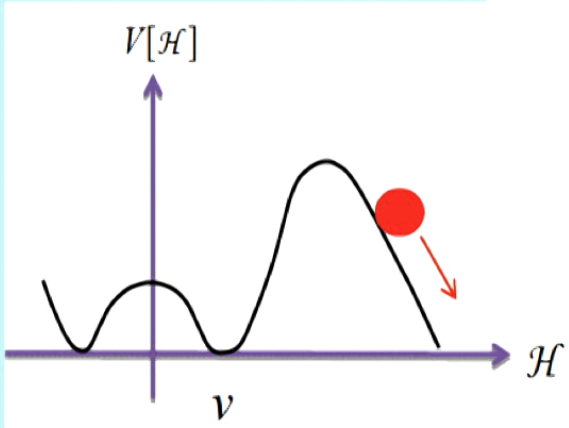
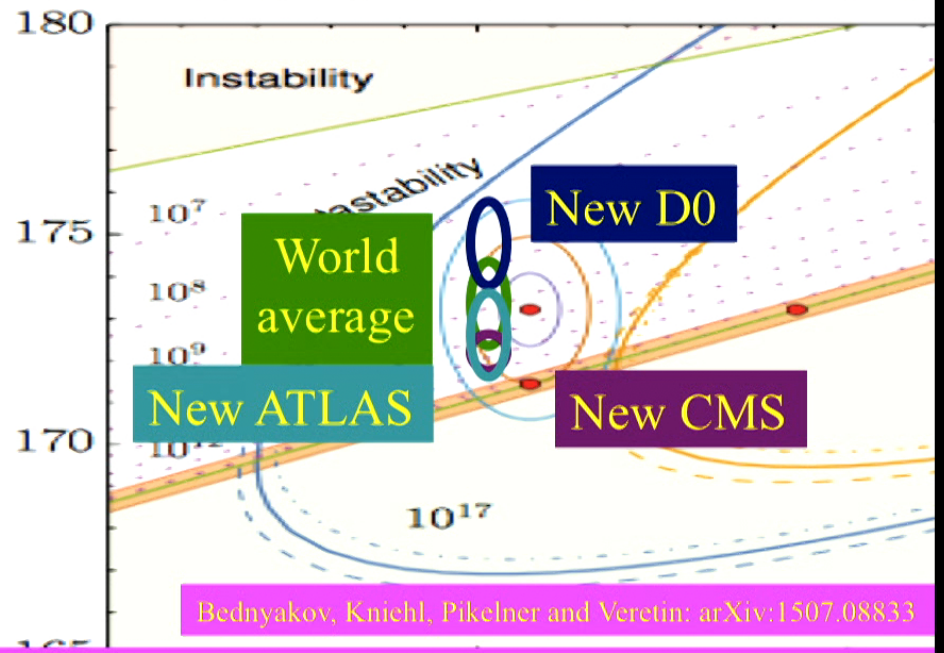
$m_t = 173.3 \pm 1.0$ GeV ➔ $\log_{10}(\Lambda/\mathrm{GeV}) = 11.1 \pm 1.3$

Vacuum Instability in the Standard Model

- Very sensitive t





Bednyakov, Kniehl, Pikelner and Veretin: arXiv:1507.08833

- Instability scale

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

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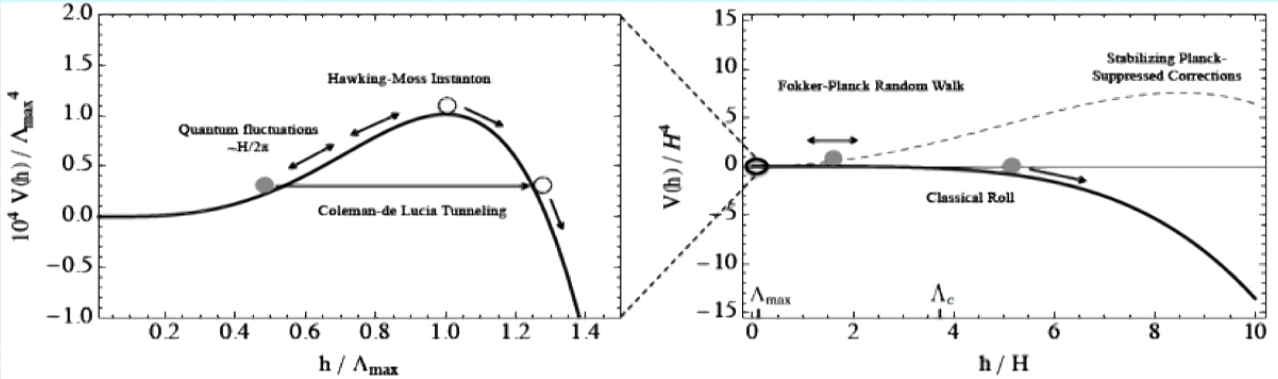
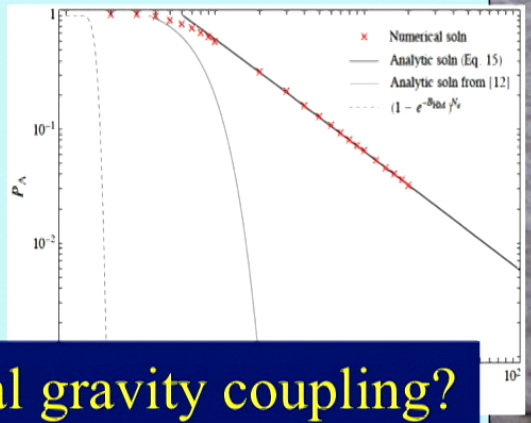
Instability during Inflation?

Hook, Kearney, Shakya & Zurek: arXiv:1404.5953

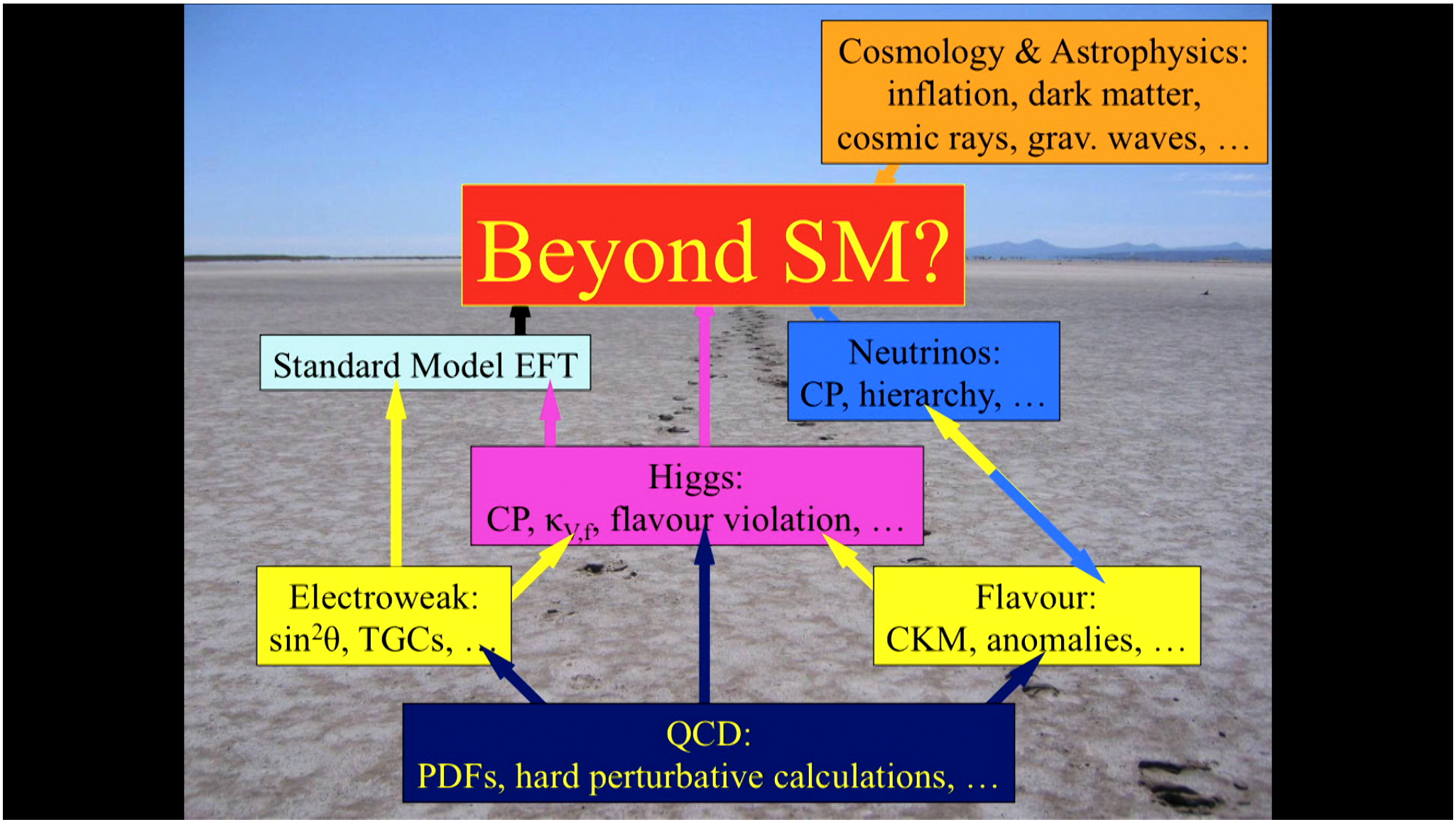
- Do inflation fluctuations drive us over the hill?

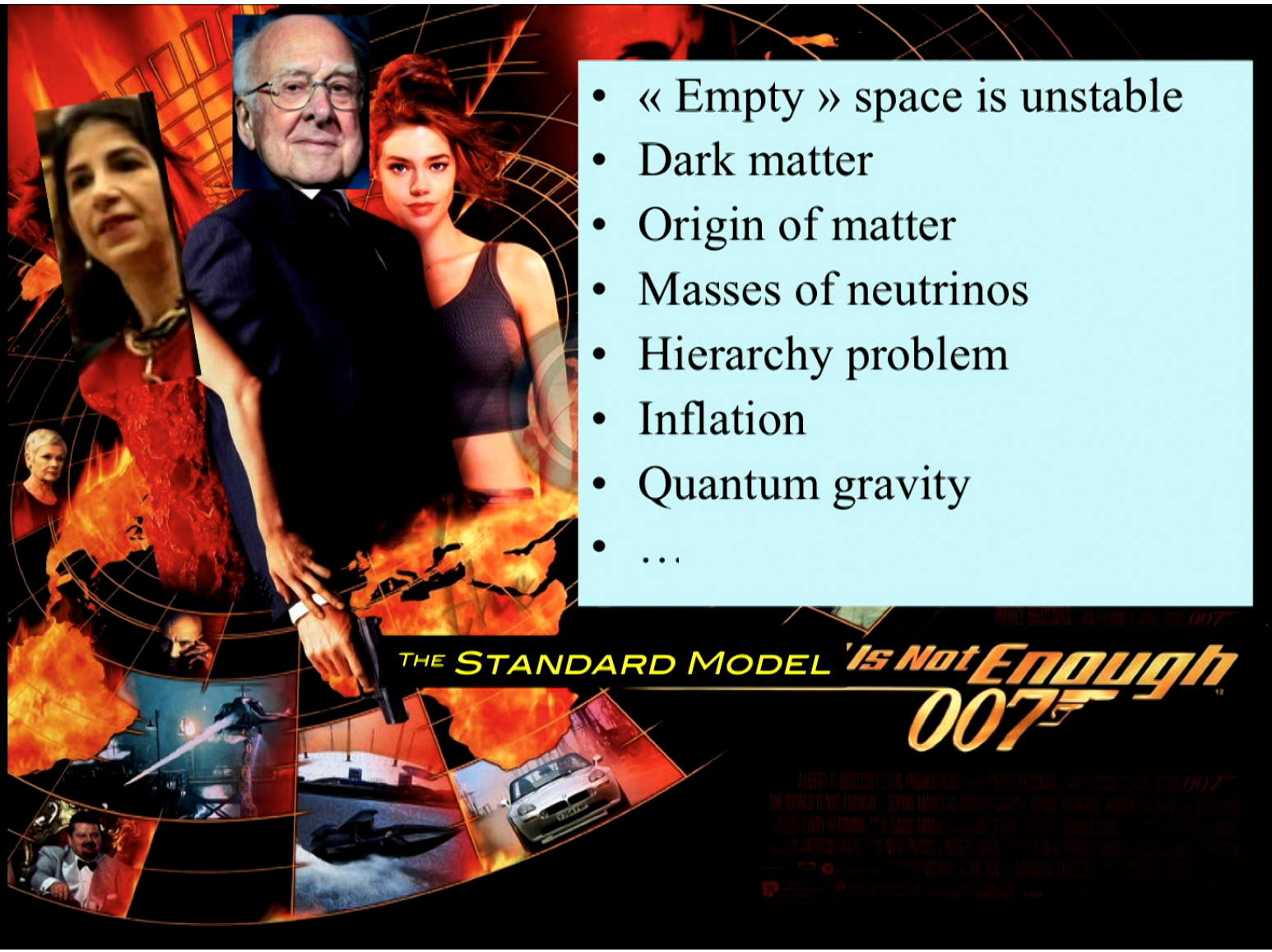


- Then Fokker-Planck evolution
- Do AdS regions eat us?
  - Disaster if so
  - If not, OK if more inflation

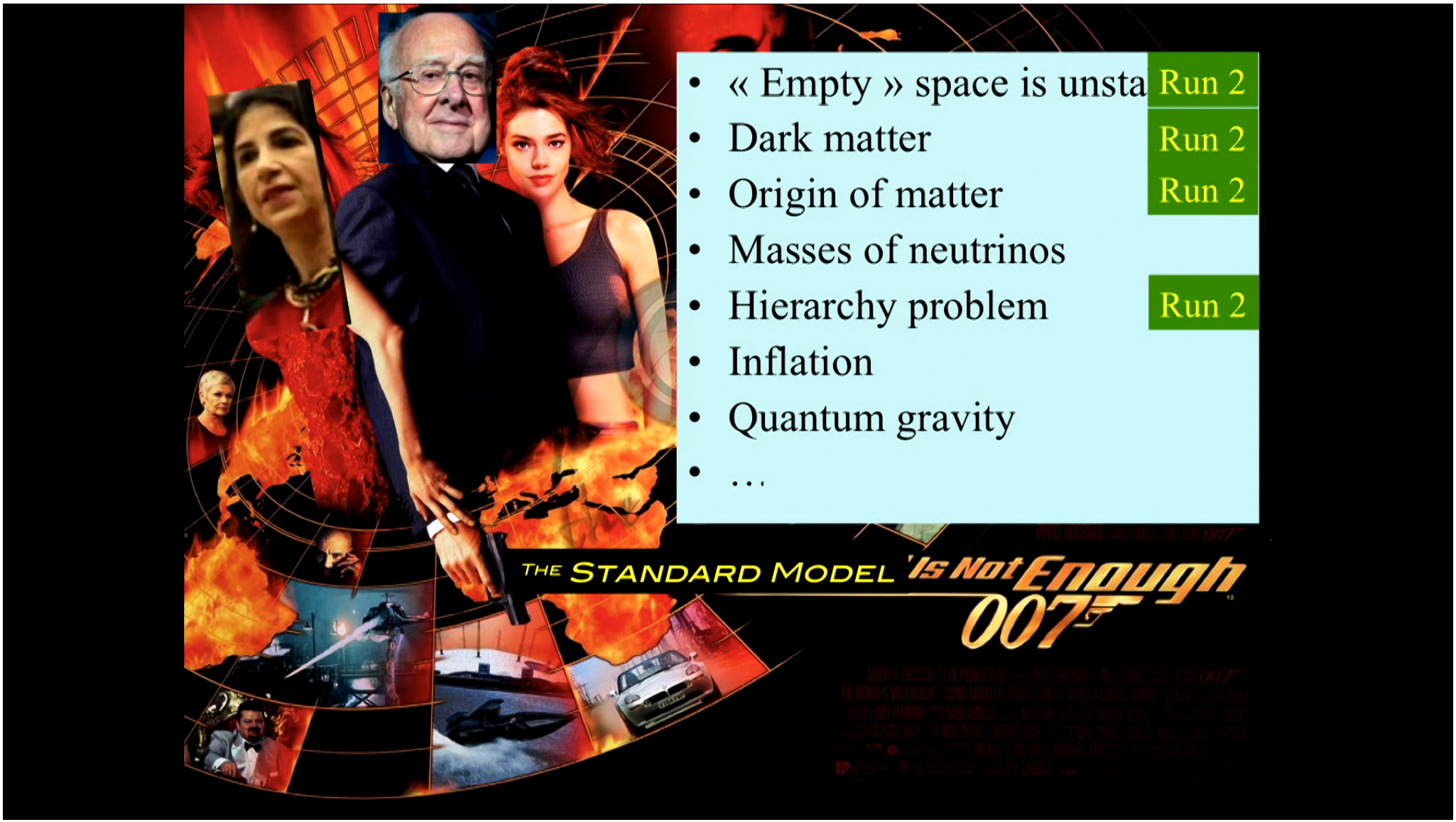


OK if dim-6 operator? Non-minimal gravity coupling?

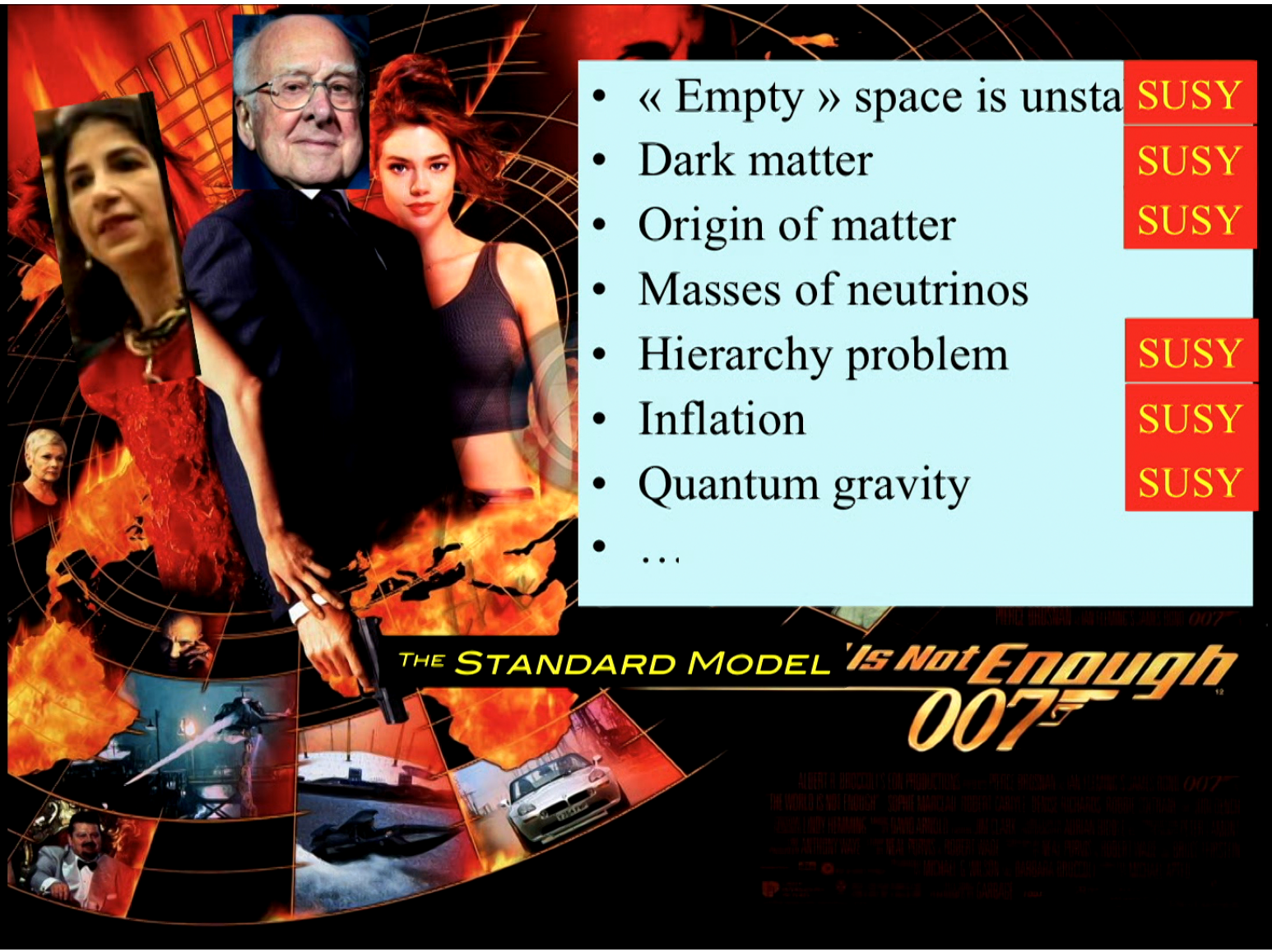

Cosmology & Astrophysics:
inflation, dark matter,
cosmic rays, grav. waves, …
Beyond SM?
Standard Model EFT
Neutrinos:
CP, hierarchy, …
Higgs:
CP, $\kappa_{V,f}$, flavour violation, …
Electroweak:
$\sin^2\theta$, TGCs, …
Flavour:
CKM, anomalies, …
QCD:
PDFs, hard perturbative calculations, …



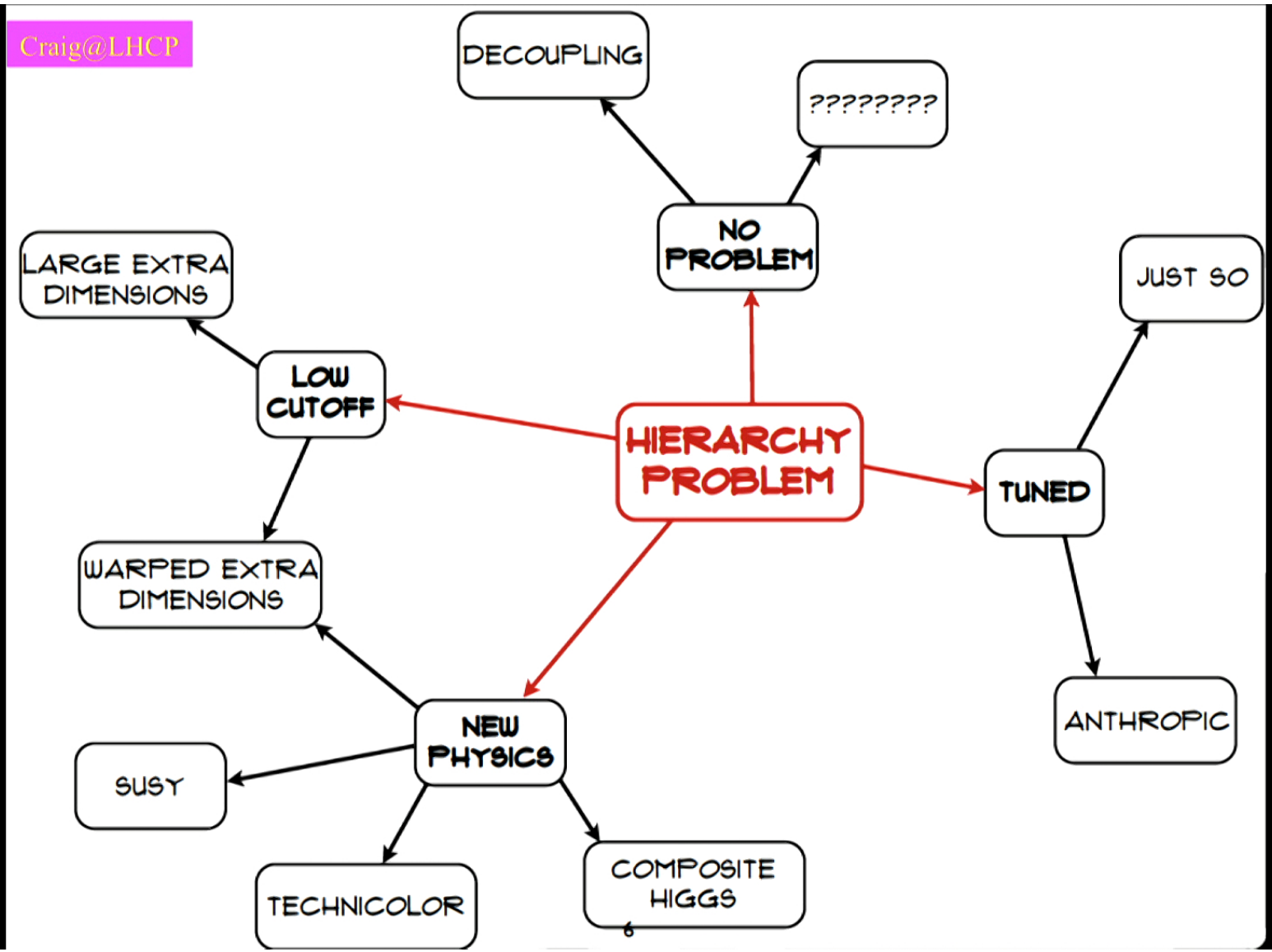
- « Empty » space is unstable
- Dark matter
- Origin of matter
- Masses of neutrinos
- Hierarchy problem
- Inflation
- Quantum gravity
- …



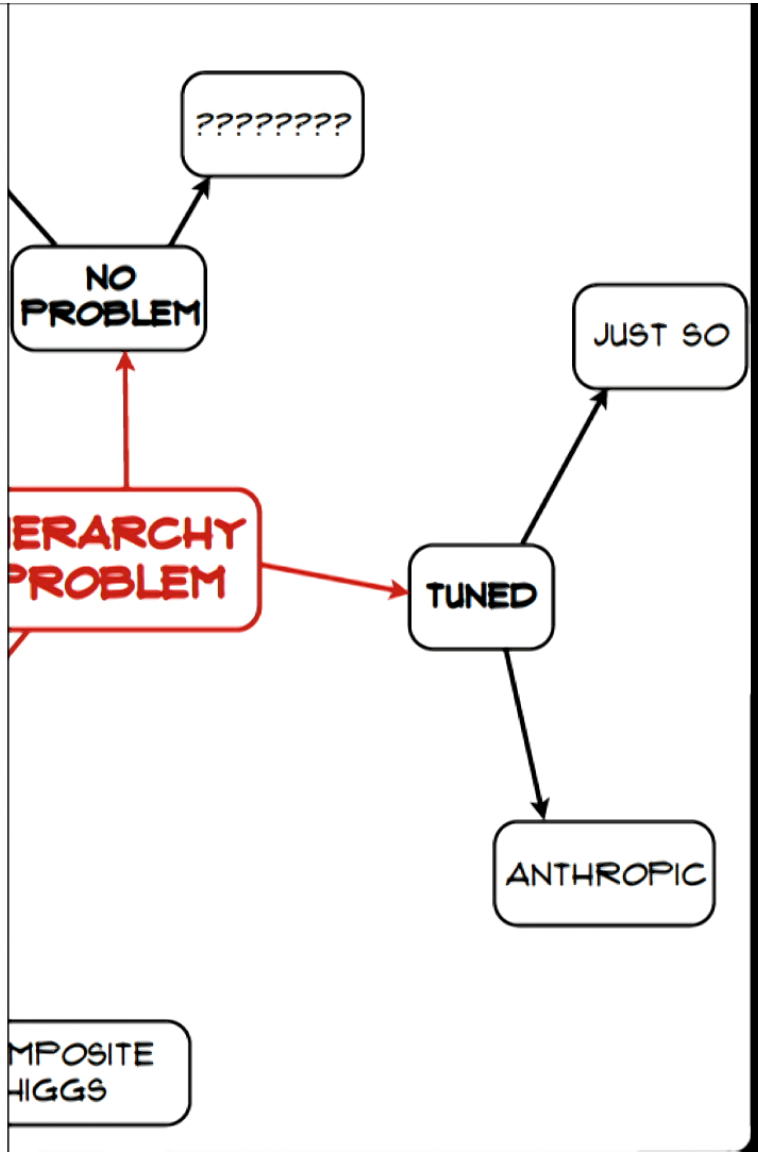
- « Empty » space is unsta Run 2
- Dark matter Run 2
- Origin of matter Run 2
- Masses of neutrinos
- Hierarchy problem Run 2
- Inflation
- Quantum gravity
- …



- « Empty » space is unsta SUSY
- Dark matter SUSY
- Origin of matter SUSY
- Masses of neutrinos
- Hierarchy problem SUSY
- Inflation SUSY
- Quantum gravity SUSY
- …


Craig@LHCP
DECOUPLING
????????
NO PROBLEM
LARGE EXTRA DIMENSIONS
JUST SO
LOW CUTOFF
HIERARCHY PROBLEM
TUNED
WARPED EXTRA DIMENSIONS
ANTHROPIC
NEW PHYSICS
SUSY
TECHNICOLOR
COMPOSITE HIGGS
6

If you know of a better hole, go to it



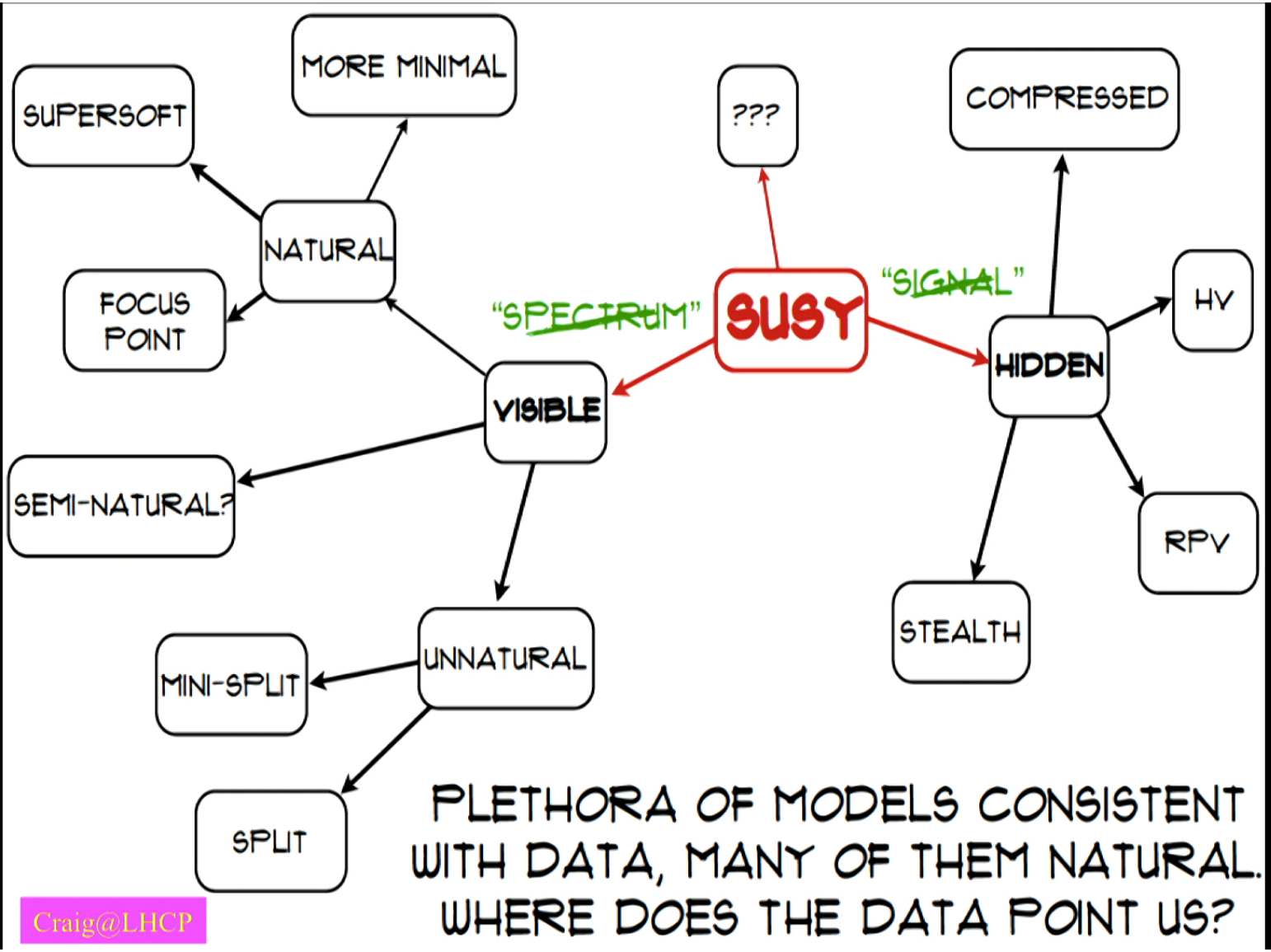
What lies beyond the Standard Model?

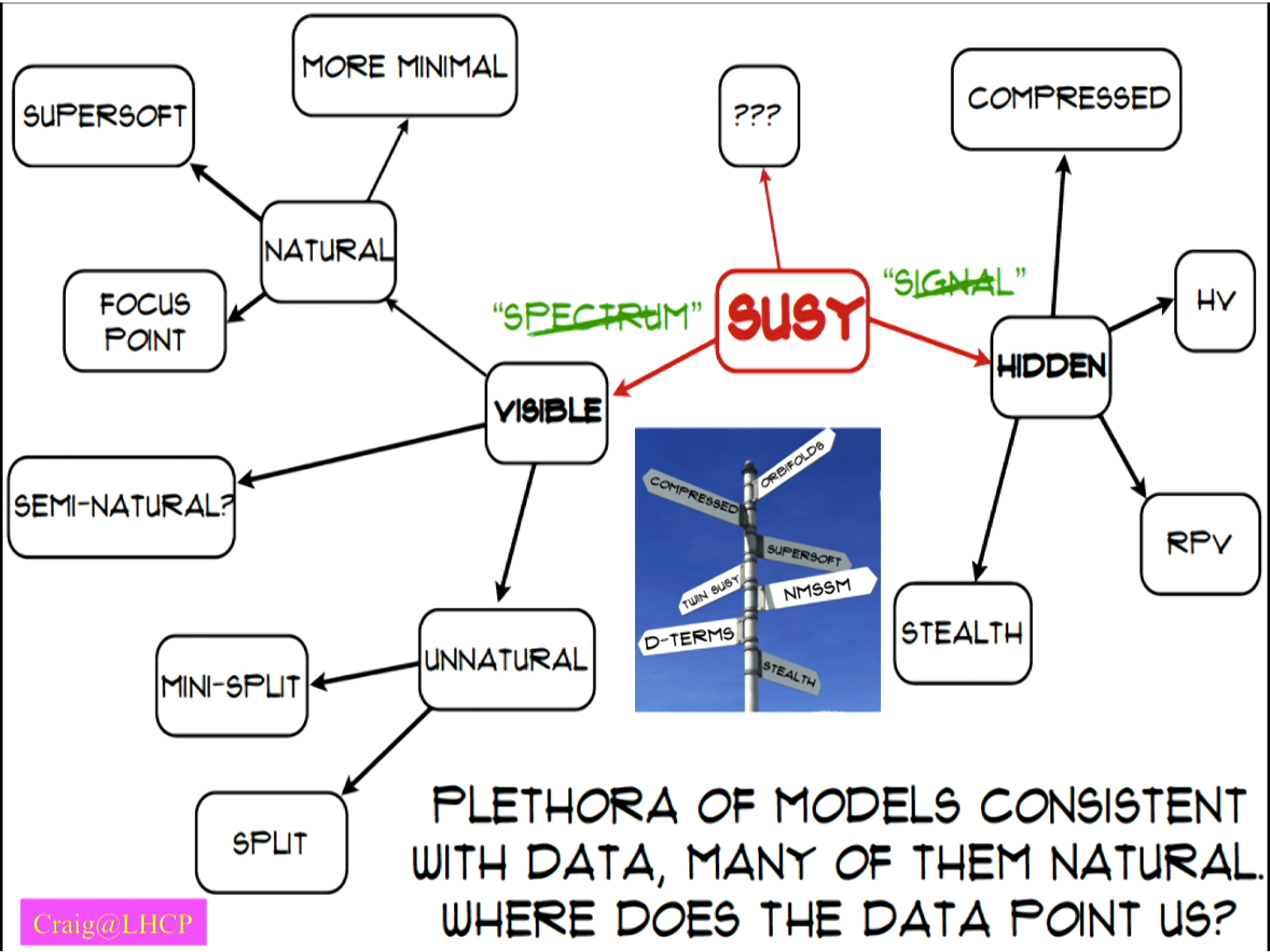
Supersymmetry

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**

SUSY: Dusk or Dawn?


SUPERSOFT
MORE MINIMAL
???
COMPRESSED
NATURAL
FOCUS POINT
"SPECTRUM"
SUSY
"SIGNAL"
HV
HIDDEN
VISIBLE
SEMI-NATURAL?
RPV
STEALTH
UNNATURAL
MINI-SPLIT
SPLIT
PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL.
WHERE DOES THE DATA POINT US?
Craig@LHCP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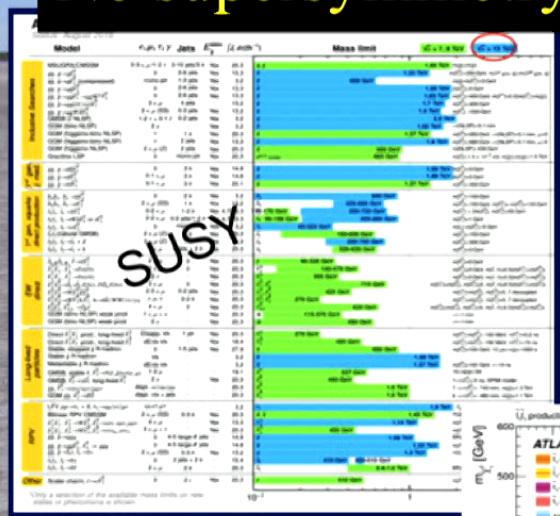
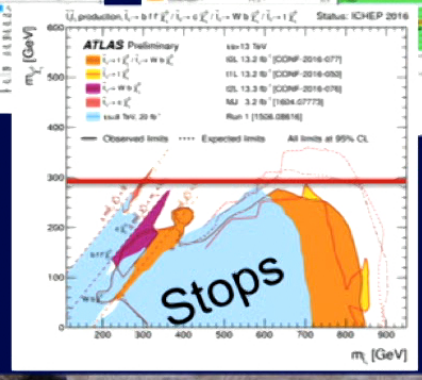
TWIN SUSY
NMSSM
D-TERMS
STEALTH
PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL.
WHERE DOES THE DATA POINT US?
Craig@LHCP

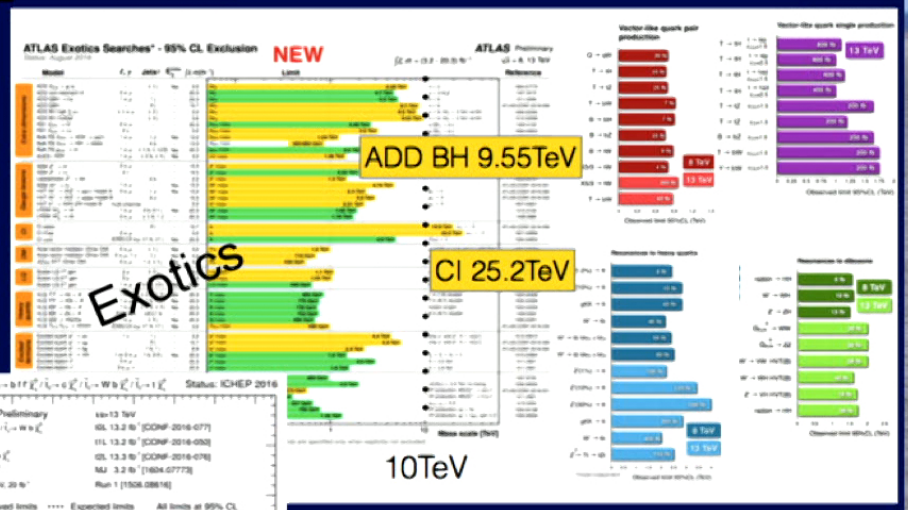
Nothing (yet) at the LHC

No supersymmetry

Nothing else, either





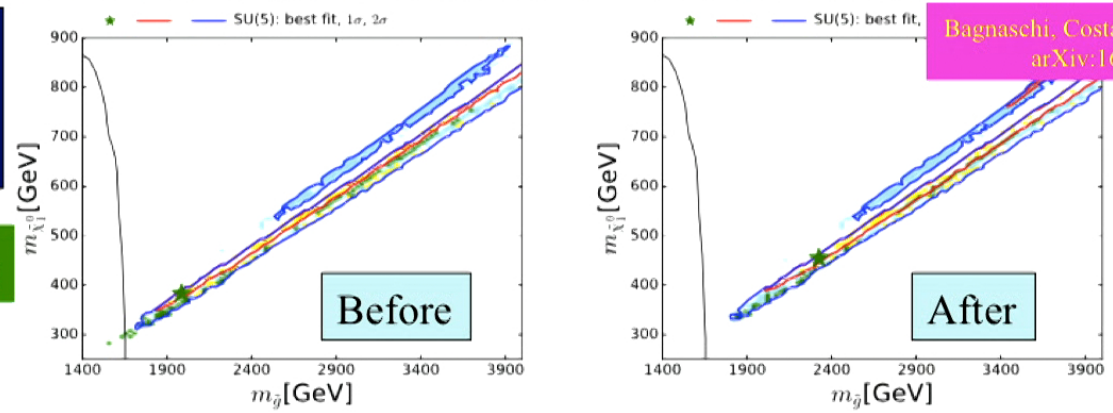


More of same?
Unexplored nooks?
Novel signatures?

Impact of 13 TeV Data so far

SU(5) GUT

Gluino

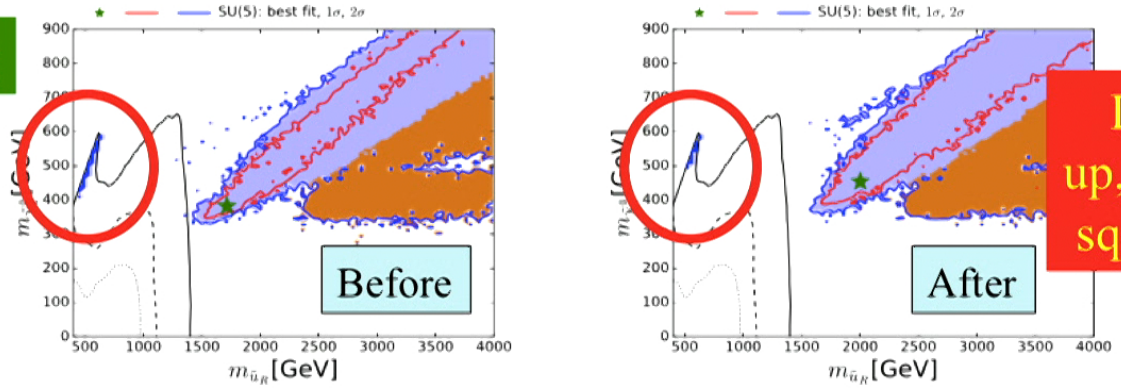


Bagnaschi, Costa, Sakurai, JE et al: arXiv:1610.10084

$\tilde{g} \to \tilde{q}_R\, q_{12}$ $\tilde{g} \to \tilde{b}_1\, b$ $\tilde{g} \to \tilde{b}_2\, b$ $\tilde{g} \to \tilde{t}_1\, t$

Important to take decay branching ratios into account

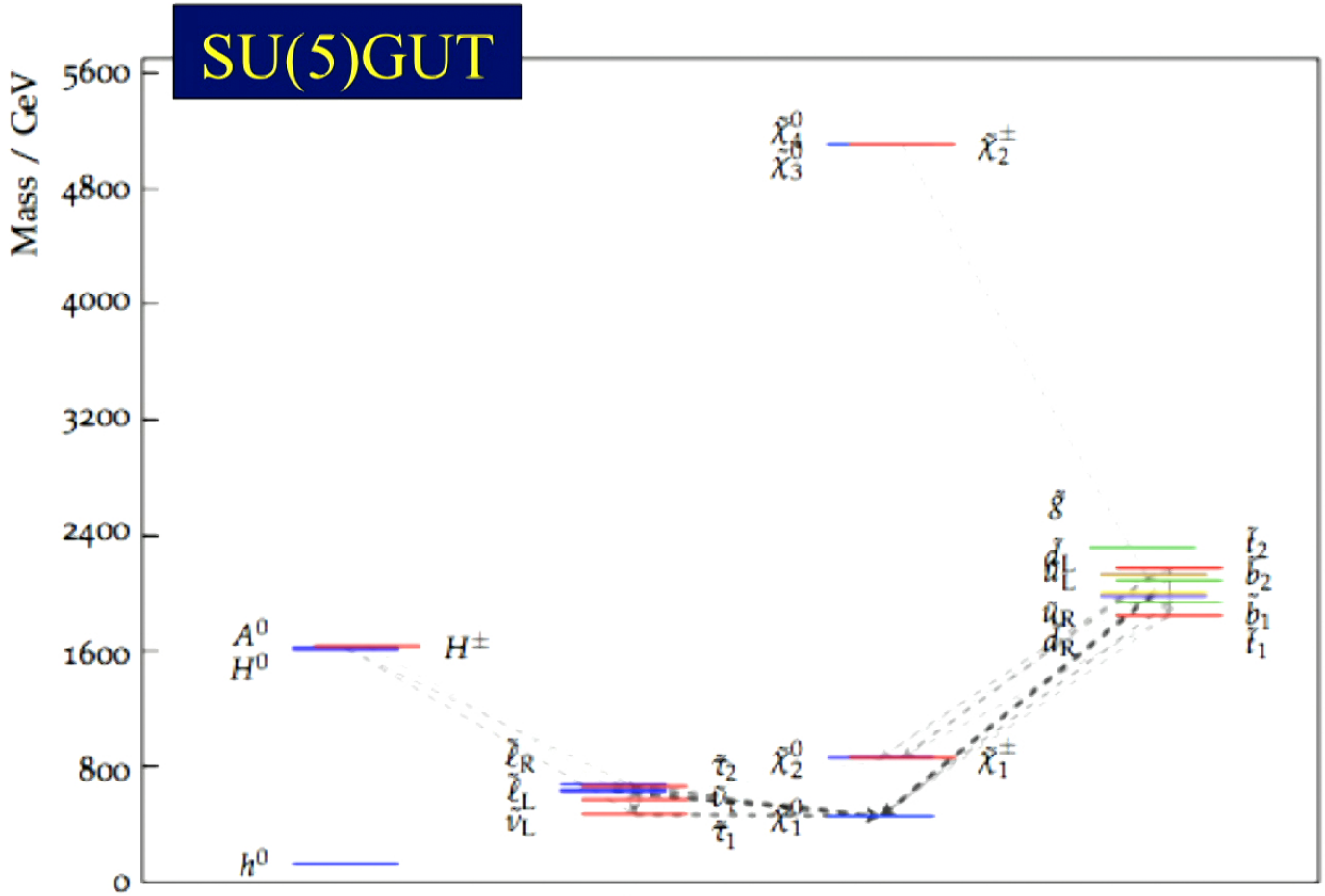
Squark



Light up, charm squarks?

$\tilde{u}_R \to \tilde{\chi}_1^0 q$ $\tilde{u}_R \to \tilde{g} q$

Best-Fit Sparticle Spectrum



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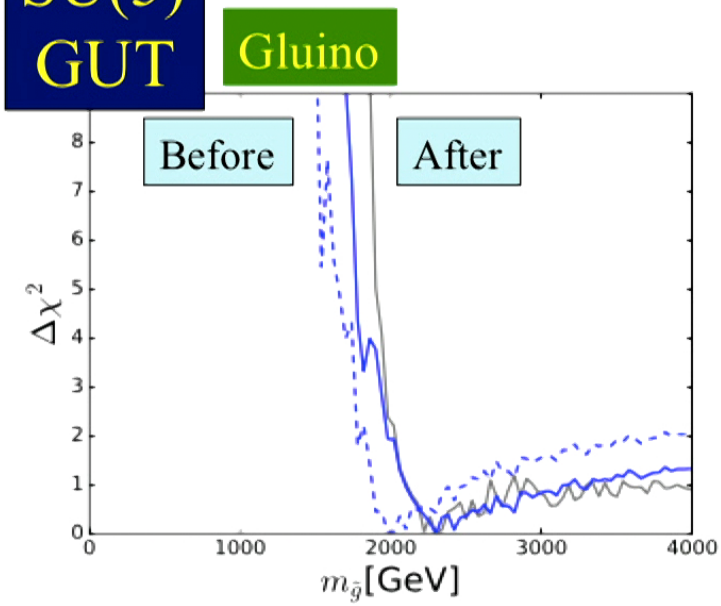
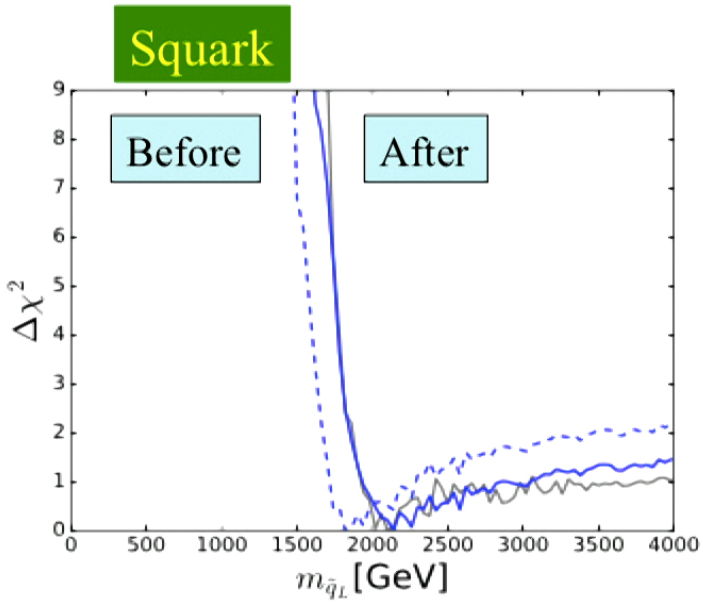
Impact of 13 TeV Data so far

SU(5) GUT

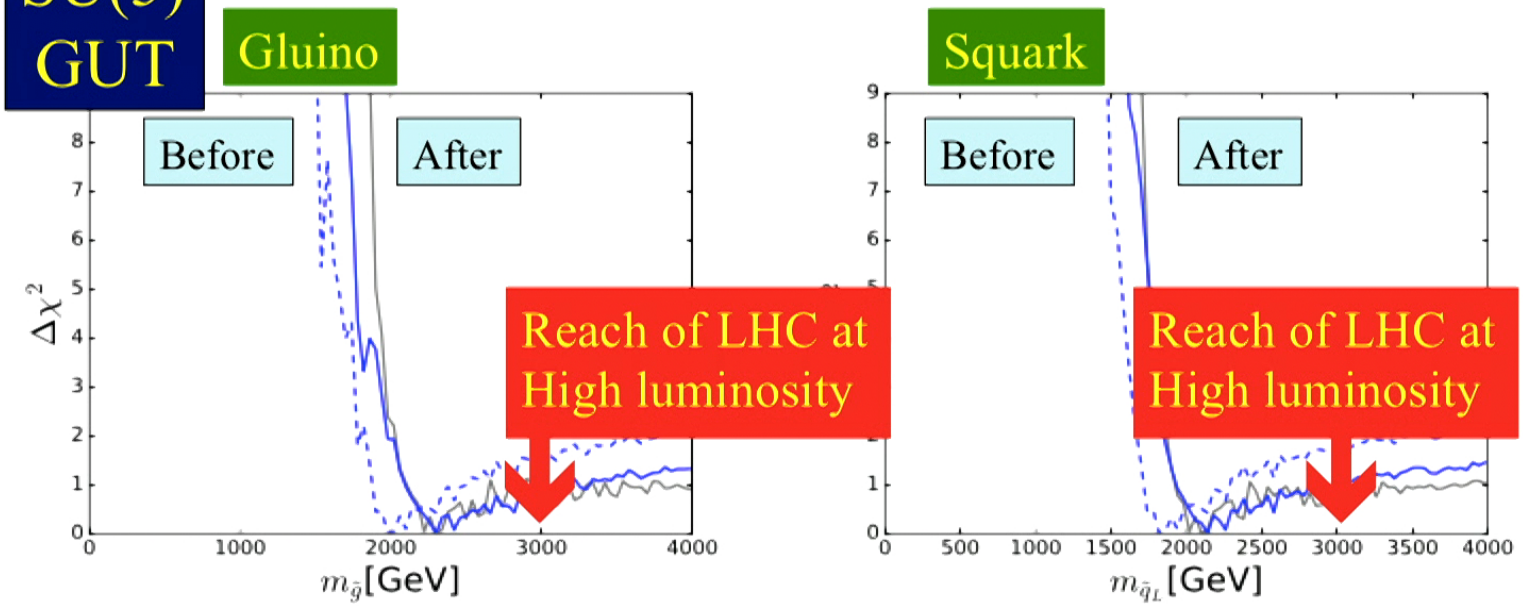




Bagnaschi, Costa, Sakurai, JE et al: arXiv:1610.10084

Impact of 13 TeV Data so far

SU(5) GUT

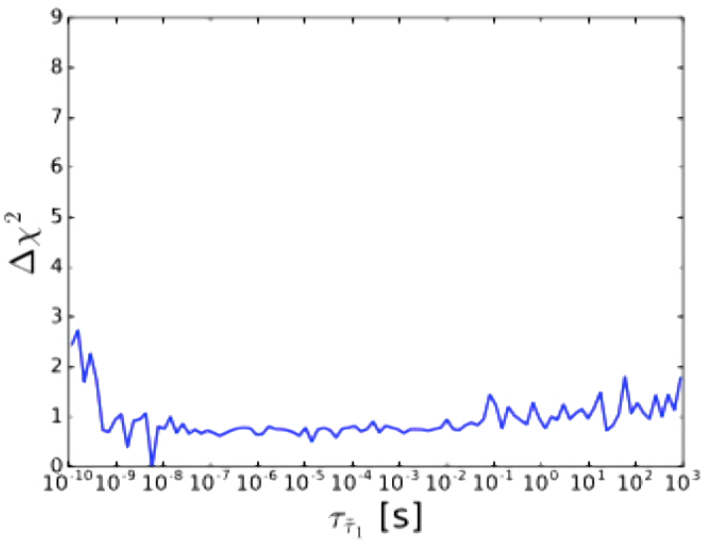


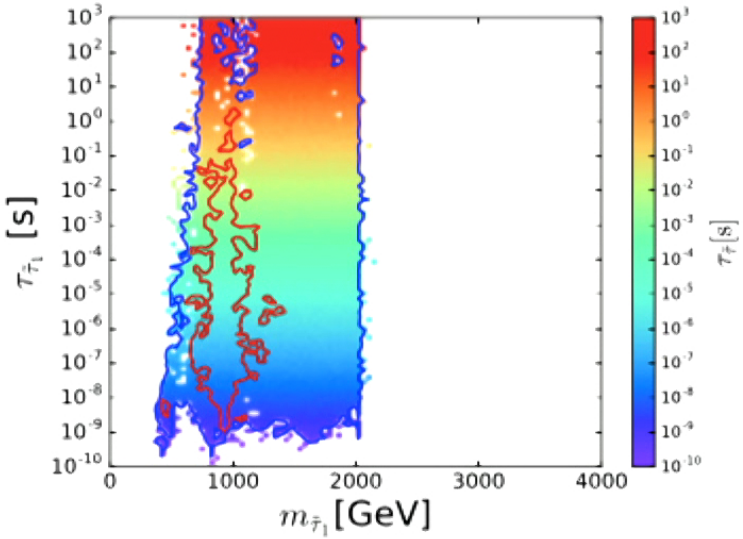
Limited impact of first 13/fb of 13 TeV data
Plenty of room for supersymmetry in future LHC runs
No guarantees!

Bagnaschi, Costa, Sakurai, JE et al: arXiv:1610.10084

Long-Lived Stau?

Possible if $m_{stau} - m_{LSP} < m_\tau$
Generic possibility in CMSSM, NUHM, SU(5)
(stau coannihilation region)

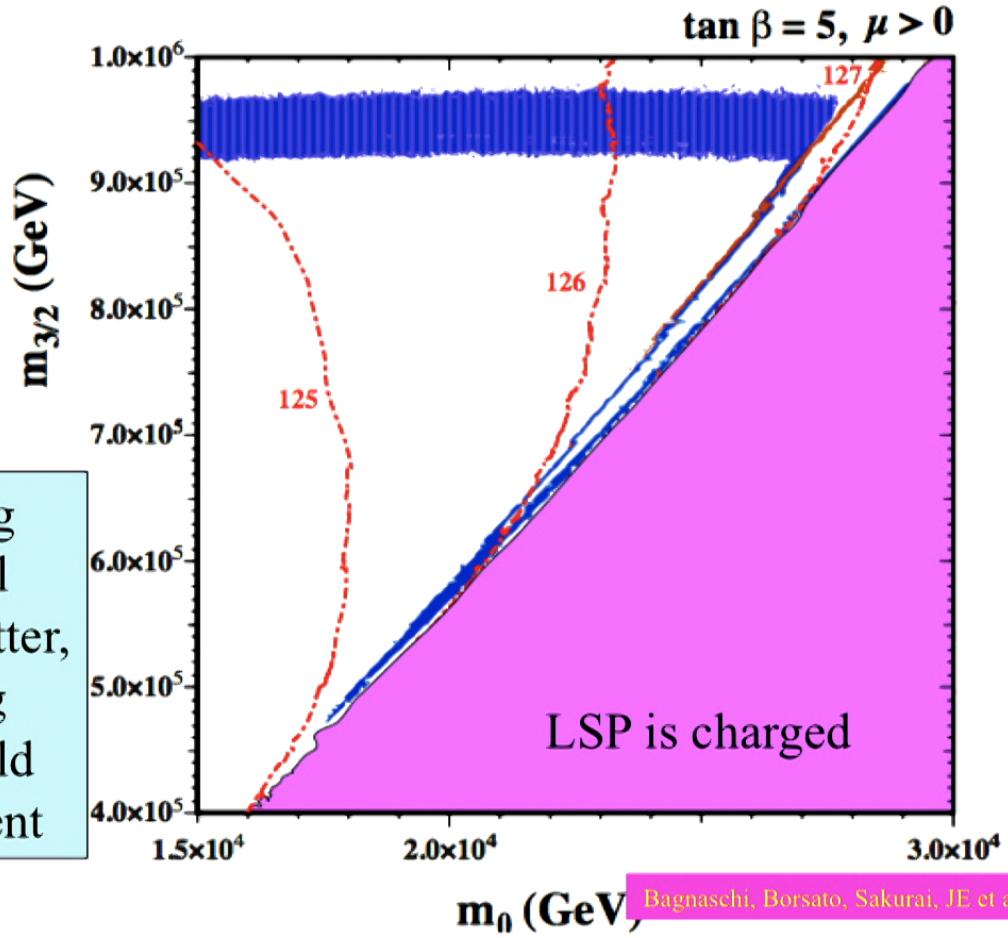




$\tau_{stau} > 10^3$ s gives problems with nucleosynthesis
$\tau_{stau} > 10^{-7}$ s gives separated vertex signature **for τ-like decays**

Bagnaschi, Costa, Sakurai, JE et al: arXiv:1610.10084

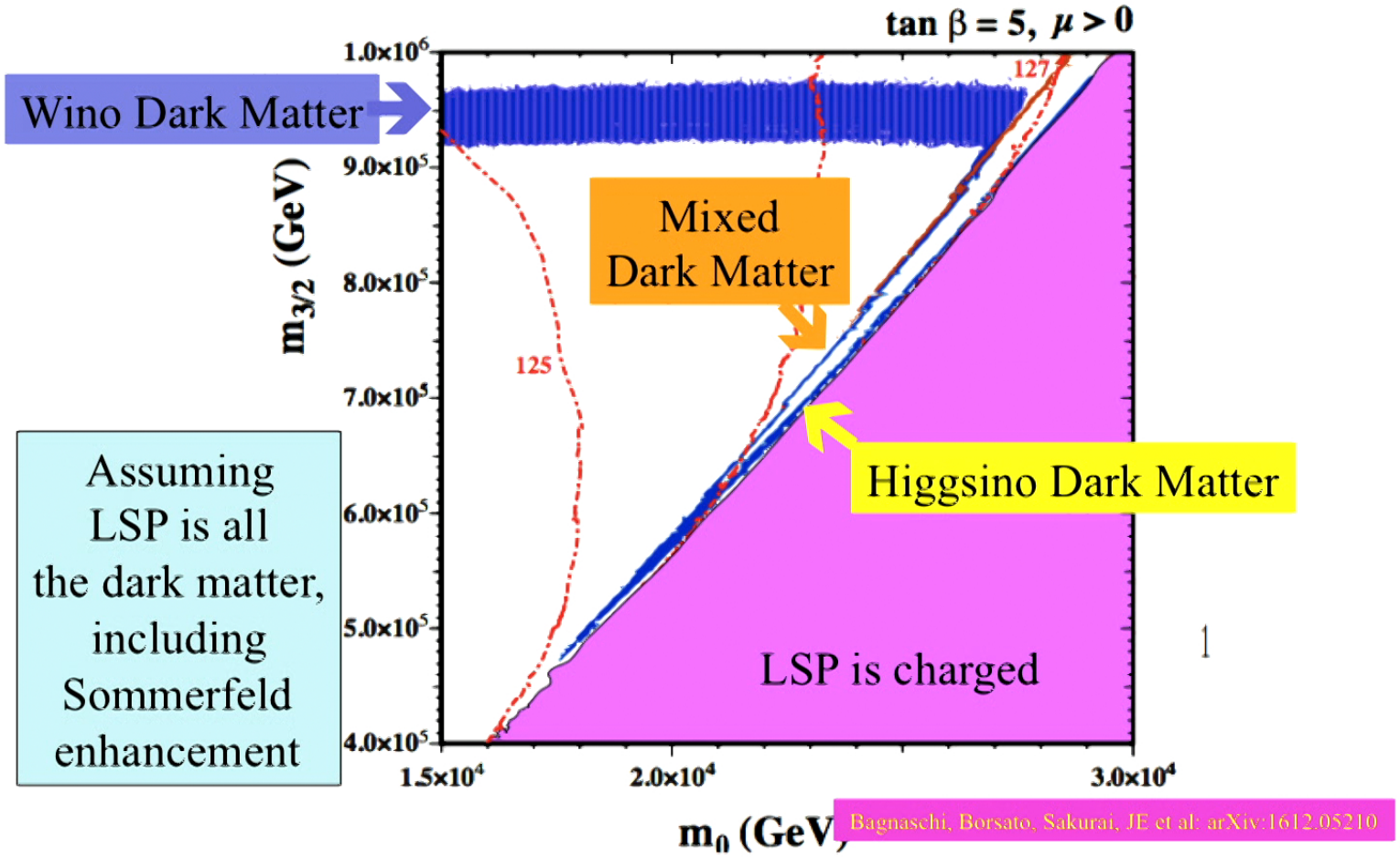
Minimal Anomaly-Mediated Supersymmetry-Breaking Model



Assuming LSP is all the dark matter, including Sommerfeld enhancement

Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210

Minimal Anomaly-Mediated Supersymmetry-Breaking Model



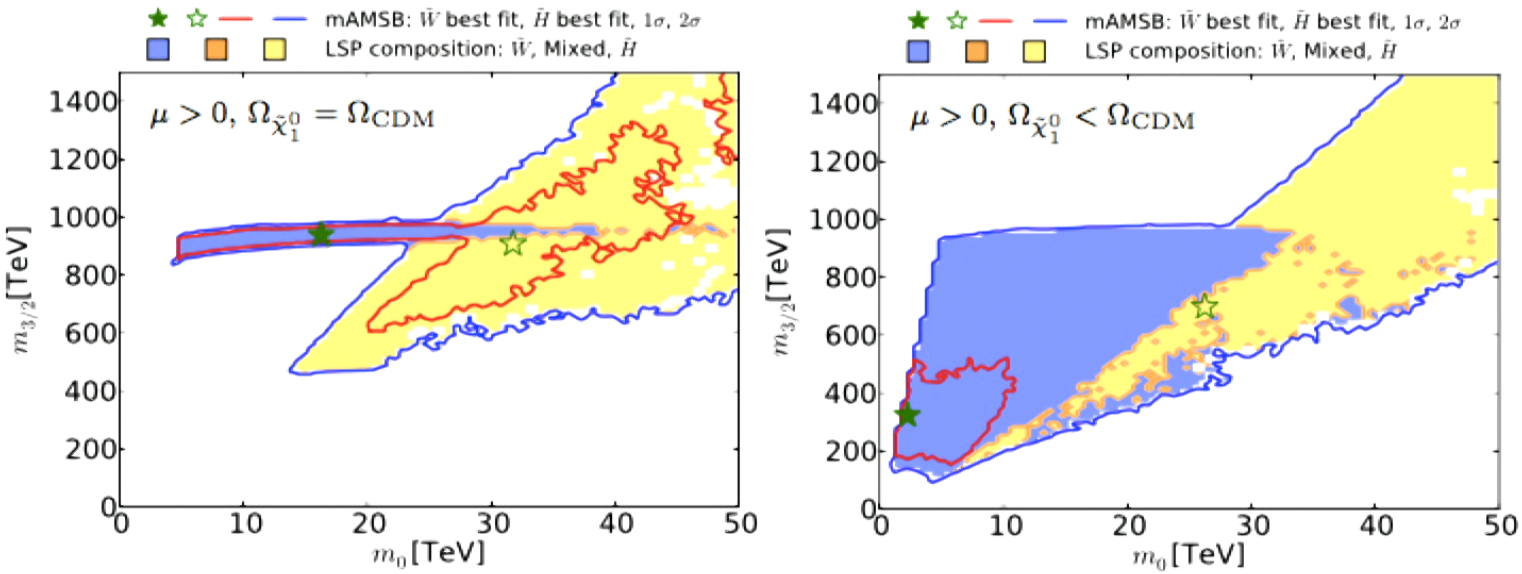
Assuming LSP is all the dark matter, including Sommerfeld enhancement

Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210

Minimal Anomaly-Mediated Supersymmetry-Breaking Model

LSP provides all the dark matter

LSP provides only some dark matter



Wino Dark Matter

Mixed Dark Matter

Higgsino Dark Matter

Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210

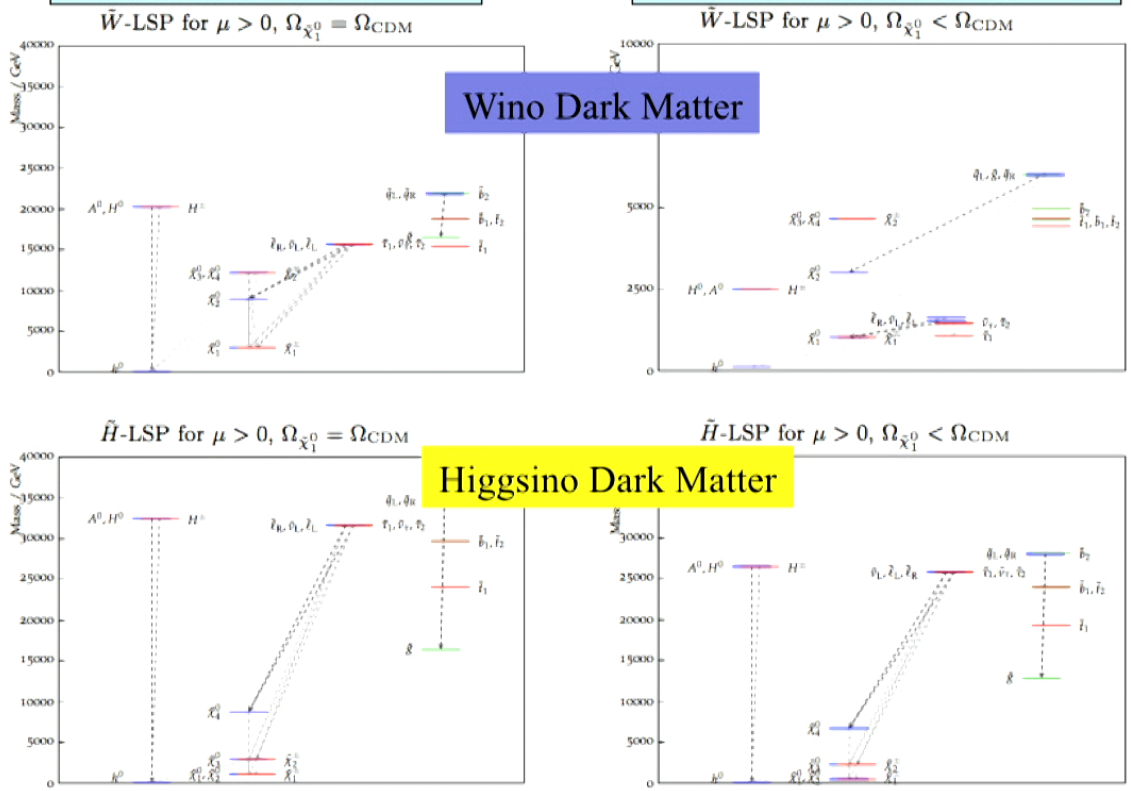
Minimal Anomaly-Mediated Supersymmetry-Breaking Model

LSP all dark matter

LSP some dark matter

Wino Dark Matter

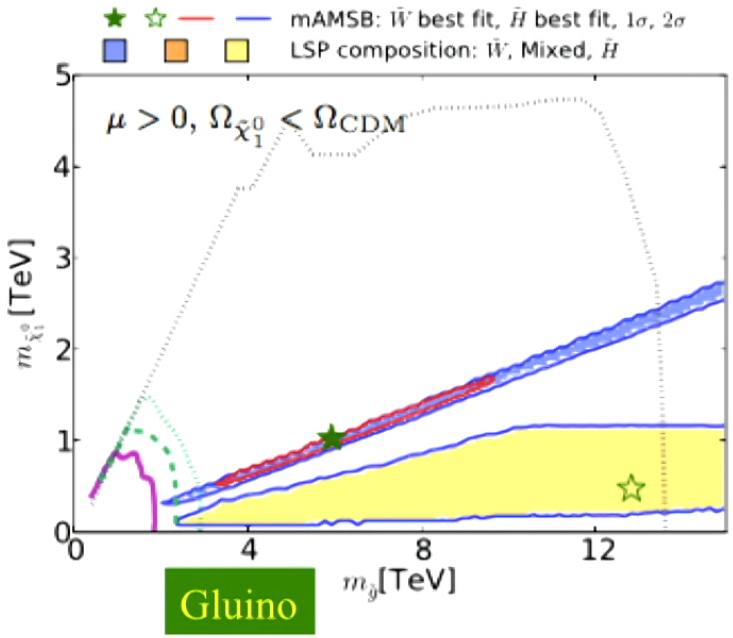
Higgsino Dark Matter

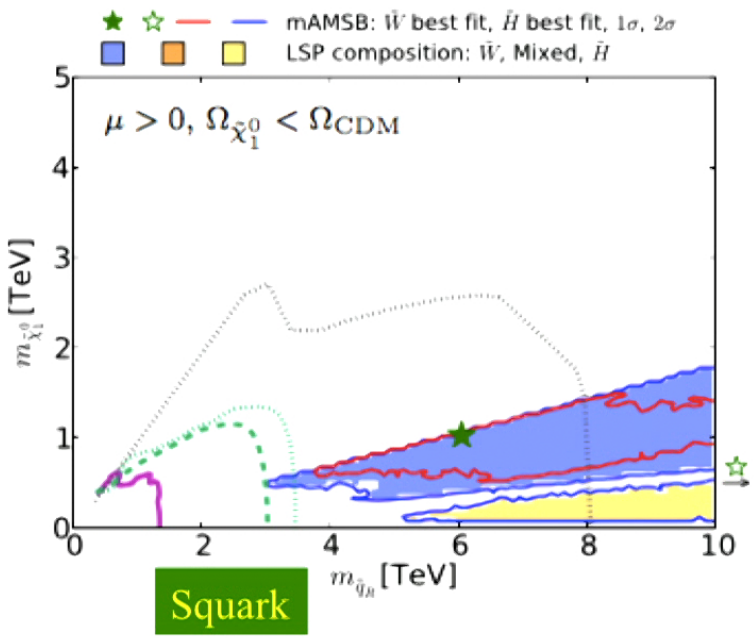


Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210

Minimal Anomaly-Mediated Supersymmetry-Breaking Model

LSP some of the dark matter





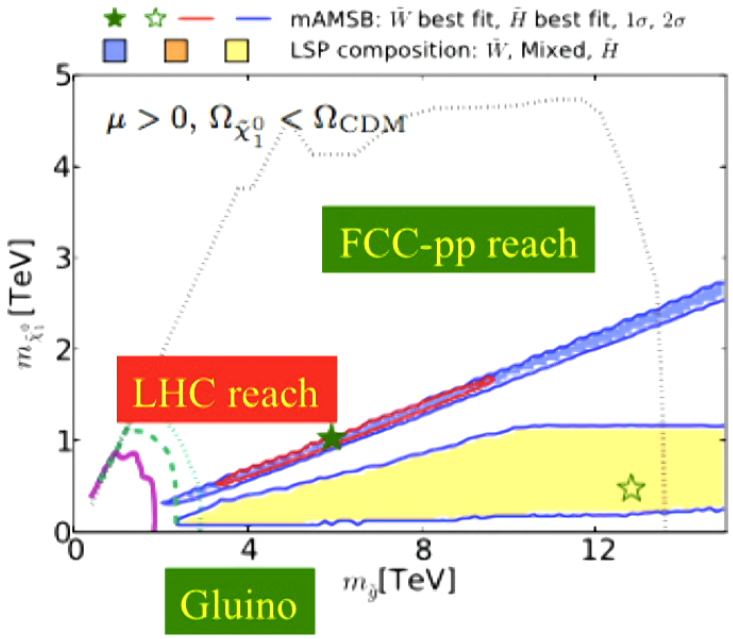
Wino Dark Matter

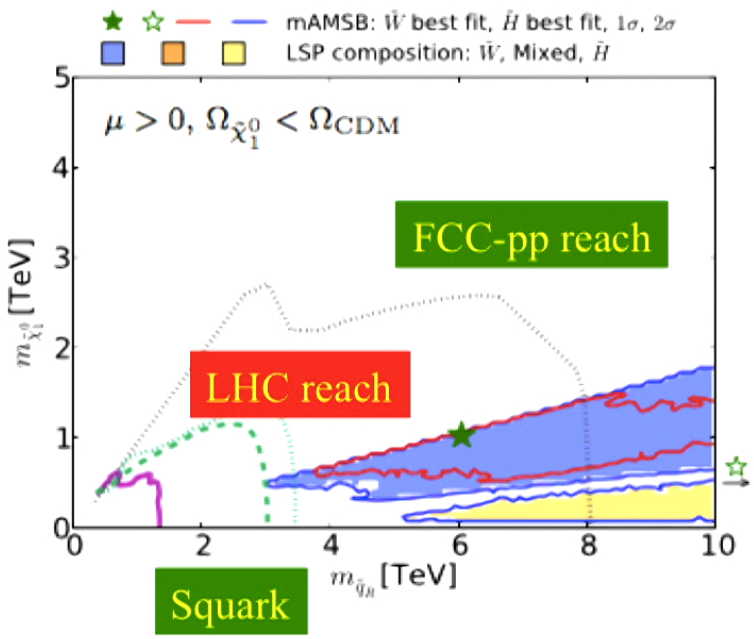
Higgsino Dark Matter

Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210

Minimal Anomaly-Mediated Supersymmetry-Breaking Model

LSP some of the dark matter





Wino Dark Matter

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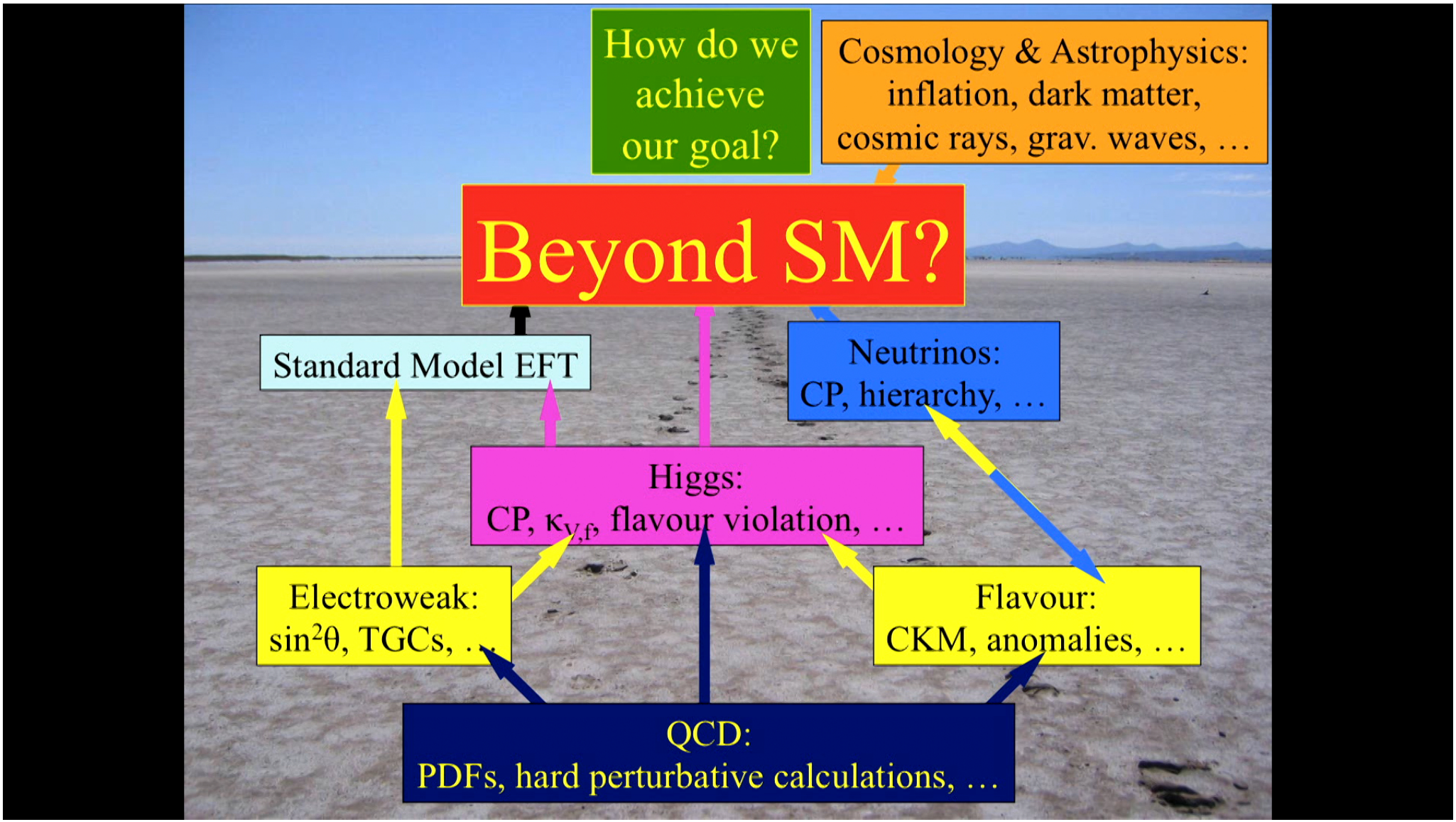
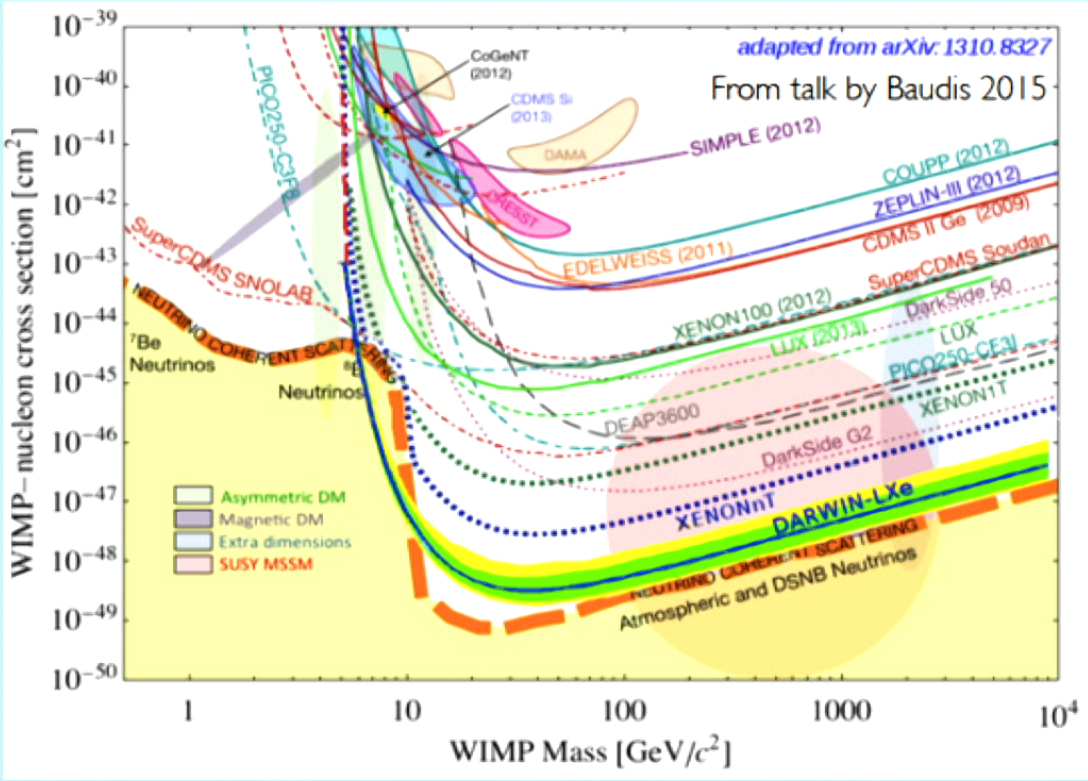
Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210


How do we achieve our goal?
Cosmology & Astrophysics: inflation, dark matter, cosmic rays, grav. waves, …
Beyond SM?
Standard Model EFT
Neutrinos: CP, hierarchy, …
Higgs: CP, $\kappa_{V,f}$, flavour violation, …
Electroweak: $\sin^2\theta$, TGCs, …
Flavour: CKM, anomalies, …
QCD: PDFs, hard perturbative calculations, …

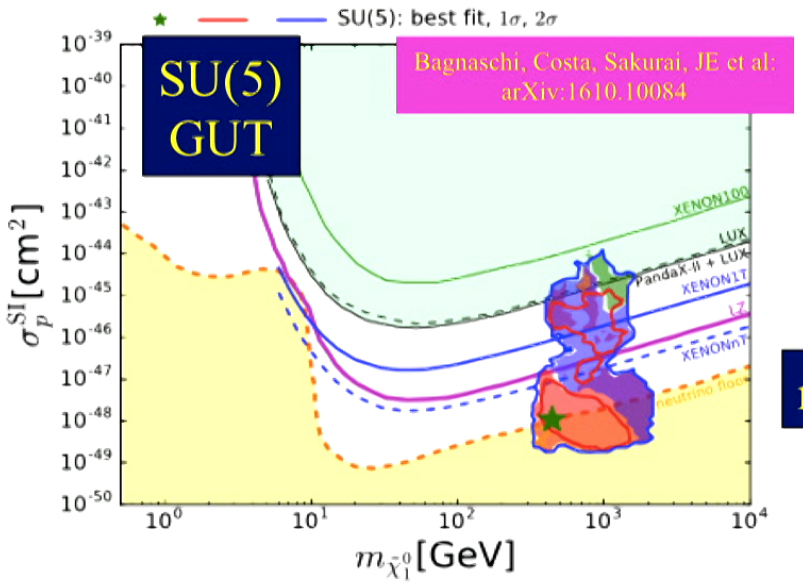
Direct Dark Matter Searches

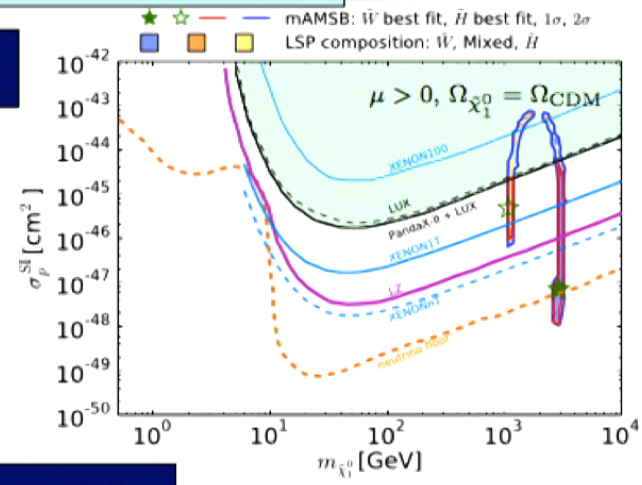
- Compilation of present and future sensitivities



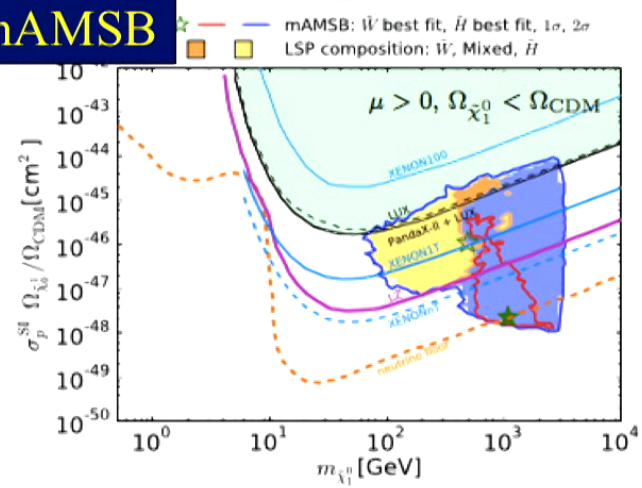
Direct Dark Matter Searches

Spin-independent dark matter scattering





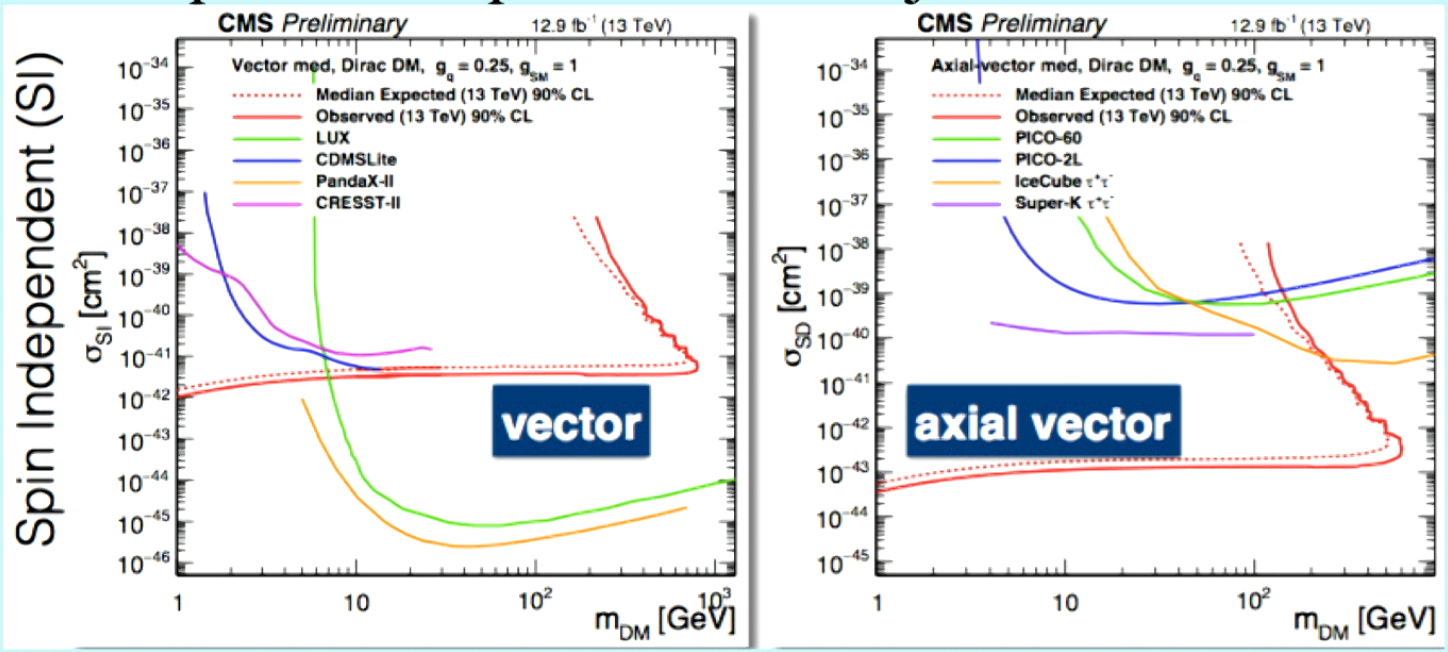
mAMSB



Bagnaschi, Borsato, Sakurai, JE et al: arXiv:1612.05210

LHC vs Dark Matter Searches

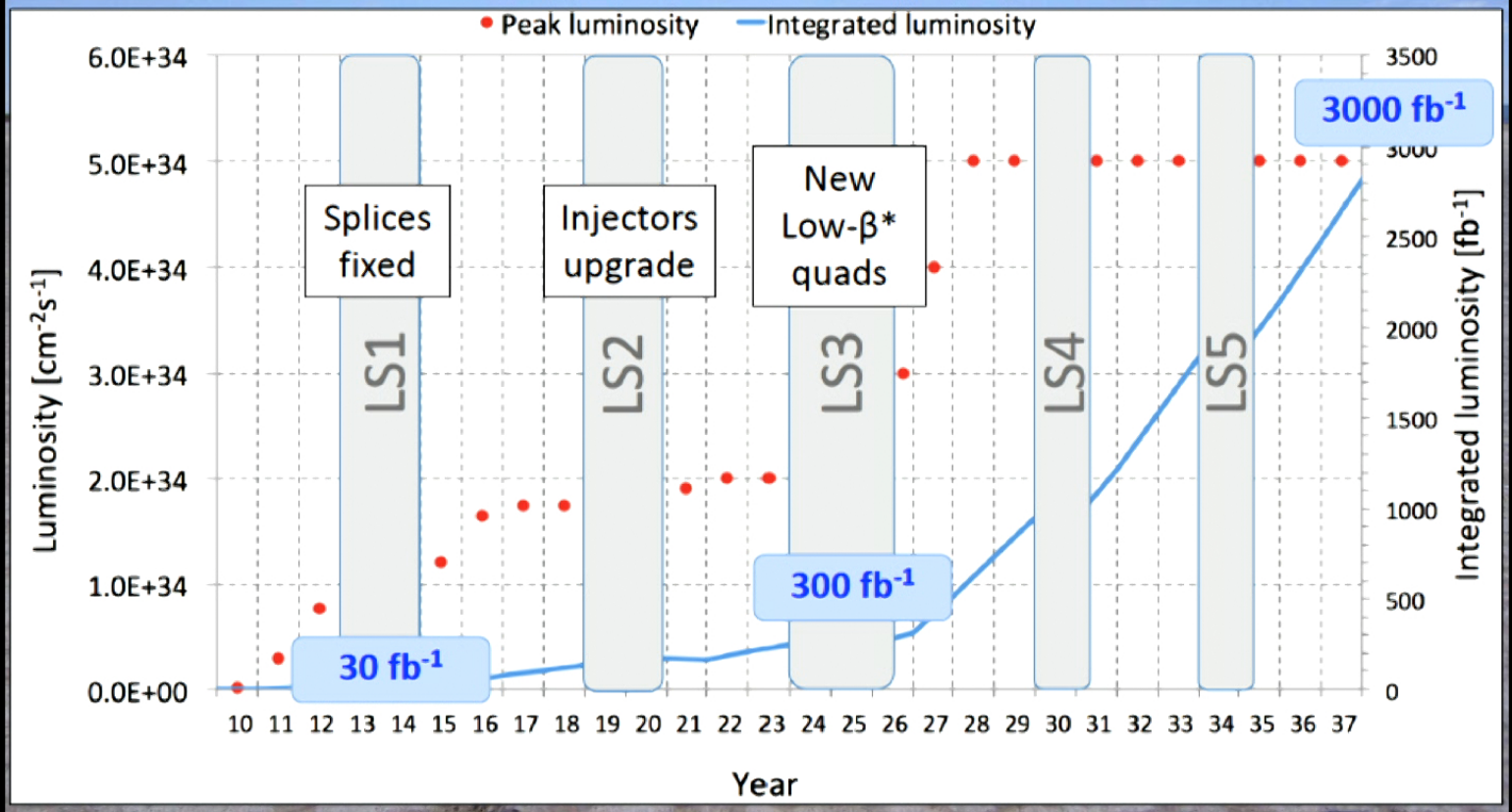
- Compilation of present "mono-jet" sensitivities



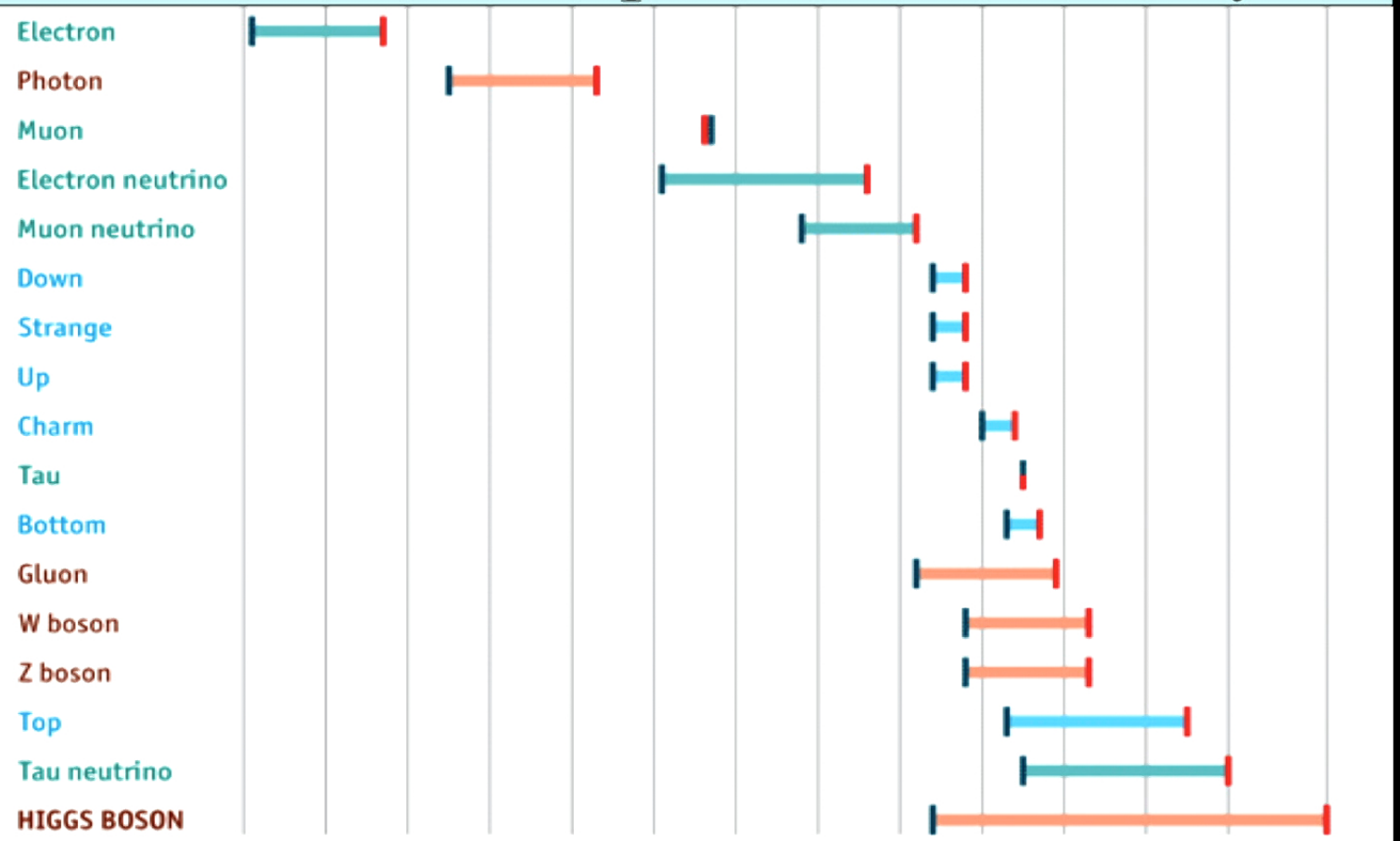
- LHC loses for vector, except small m_{DM}

NB: Model dependence

The LHC in Future Years

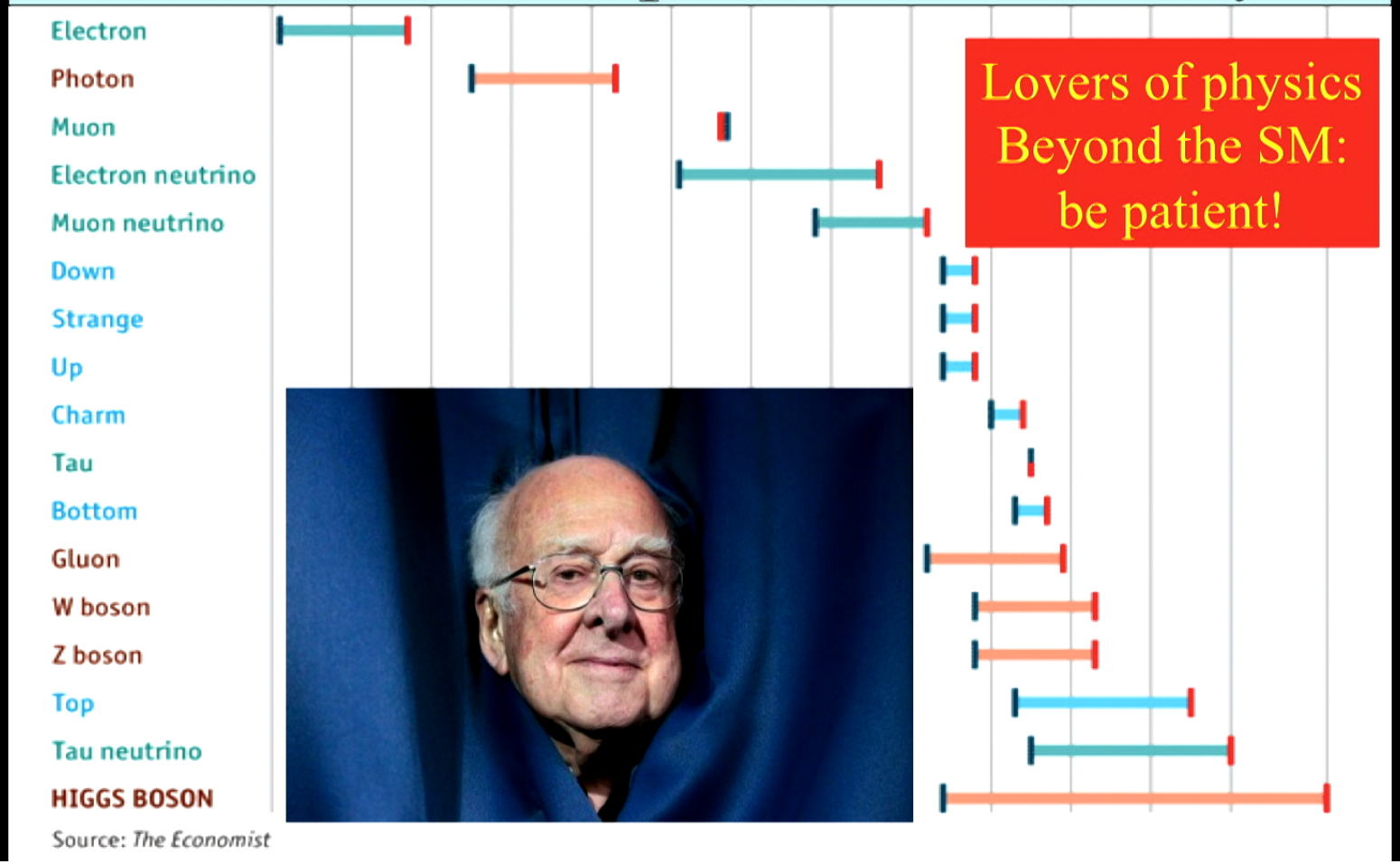


Standard Model Particles:
Years from Proposal to Discovery



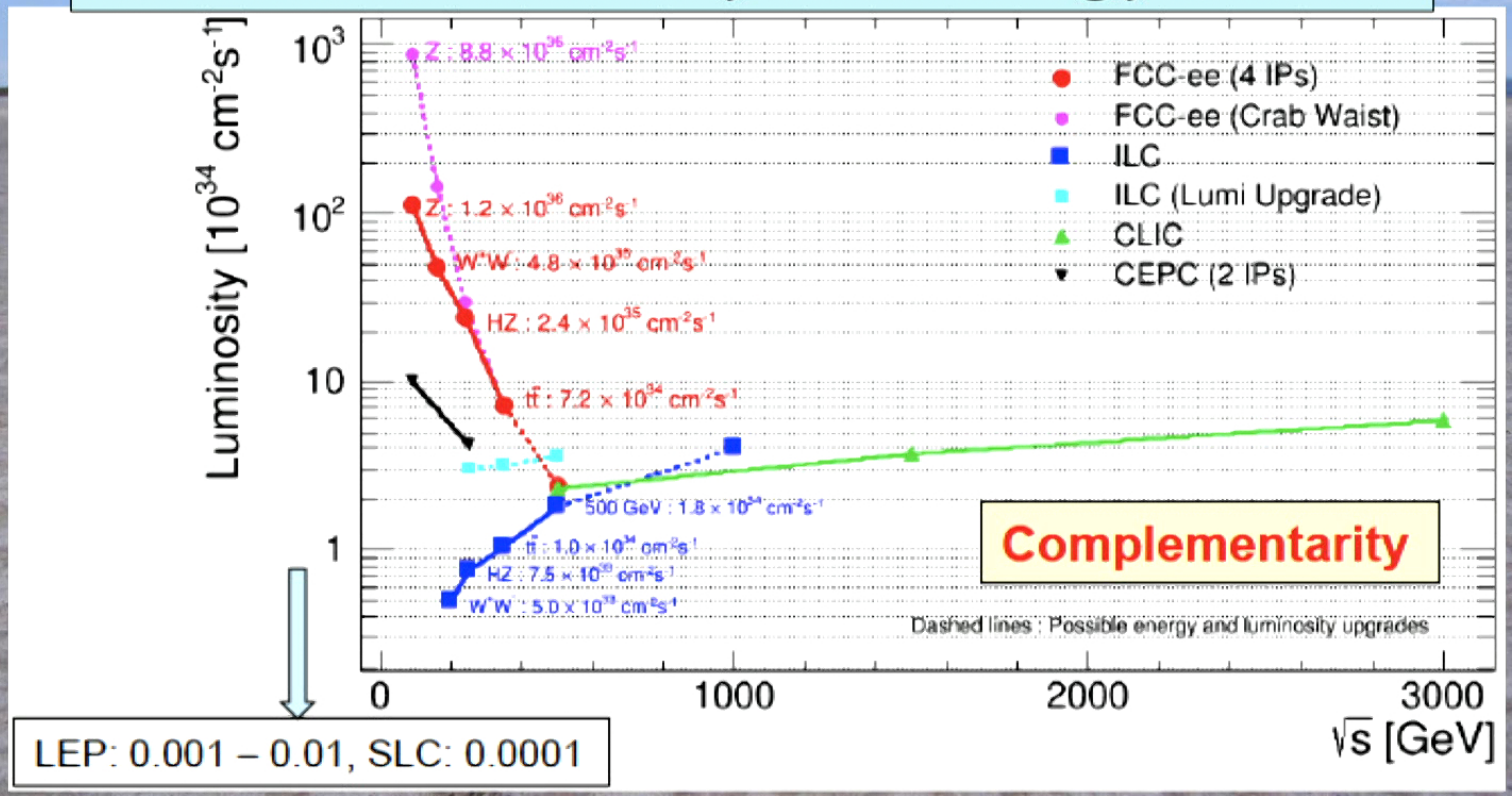
Source: *The Economist*

Standard Model Particles:
Years from Proposal to Discovery



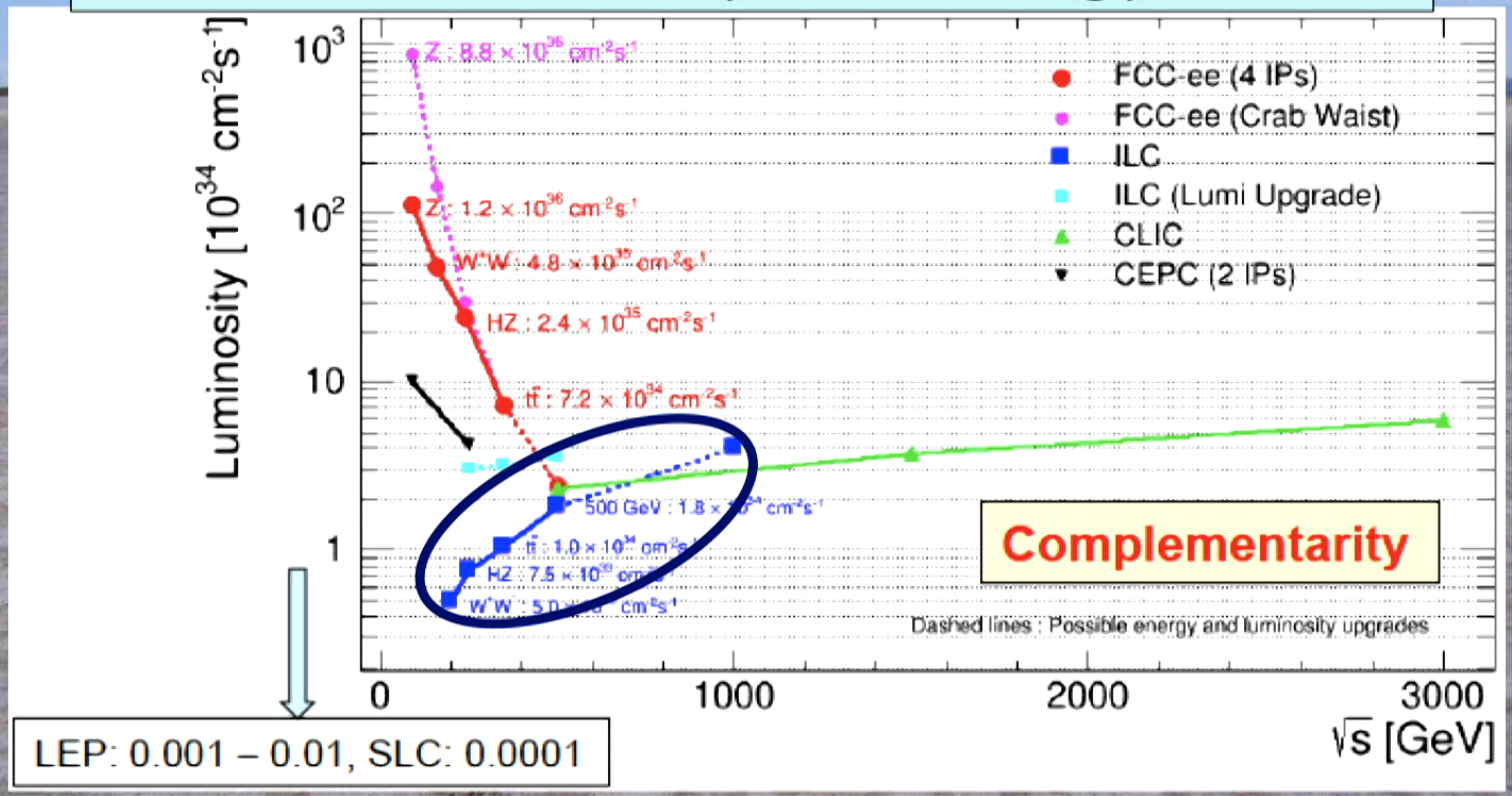
Lovers of physics
Beyond the SM:
be patient!

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



LEP: 0.001 – 0.01, SLC: 0.0001

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



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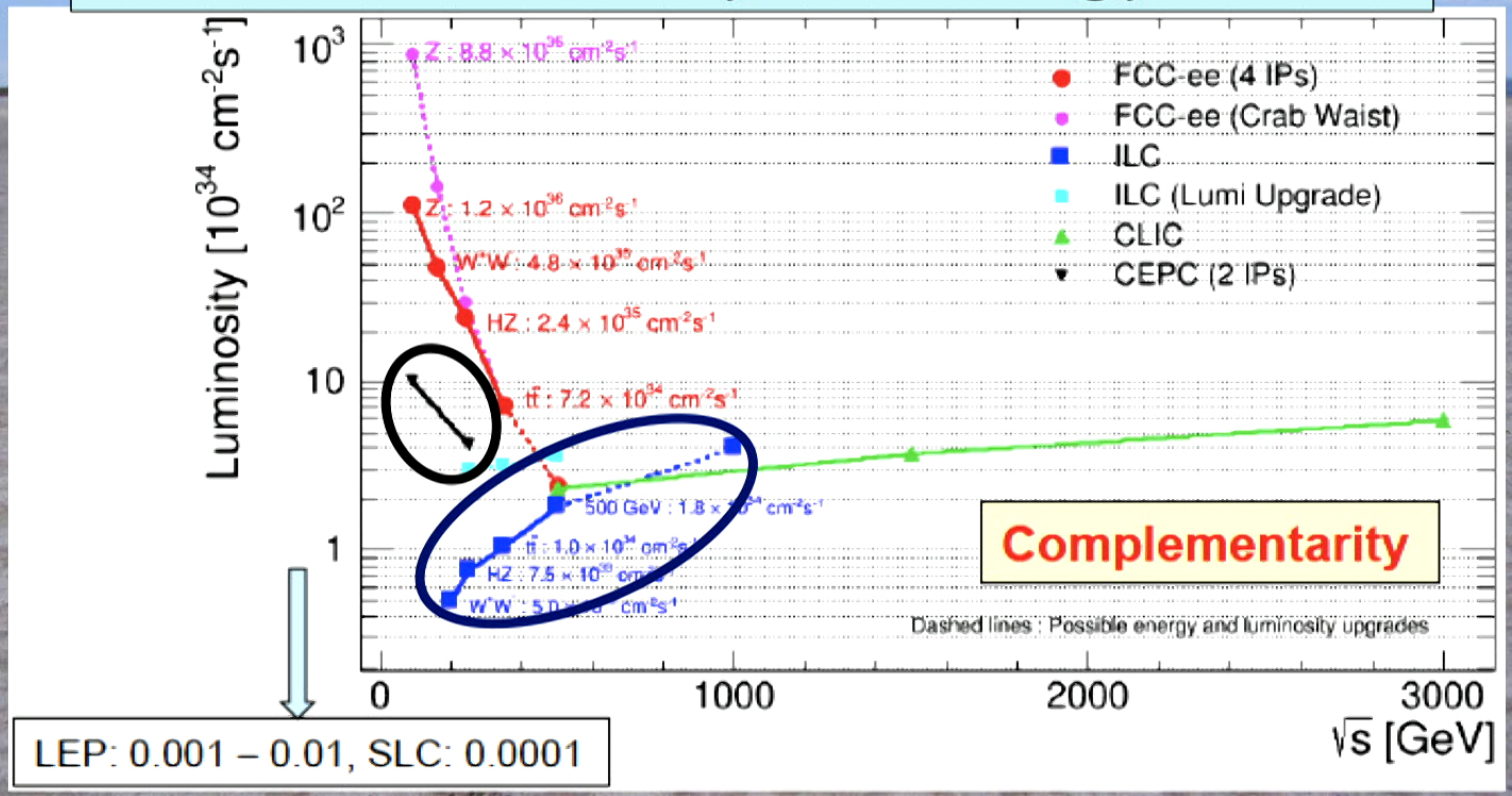

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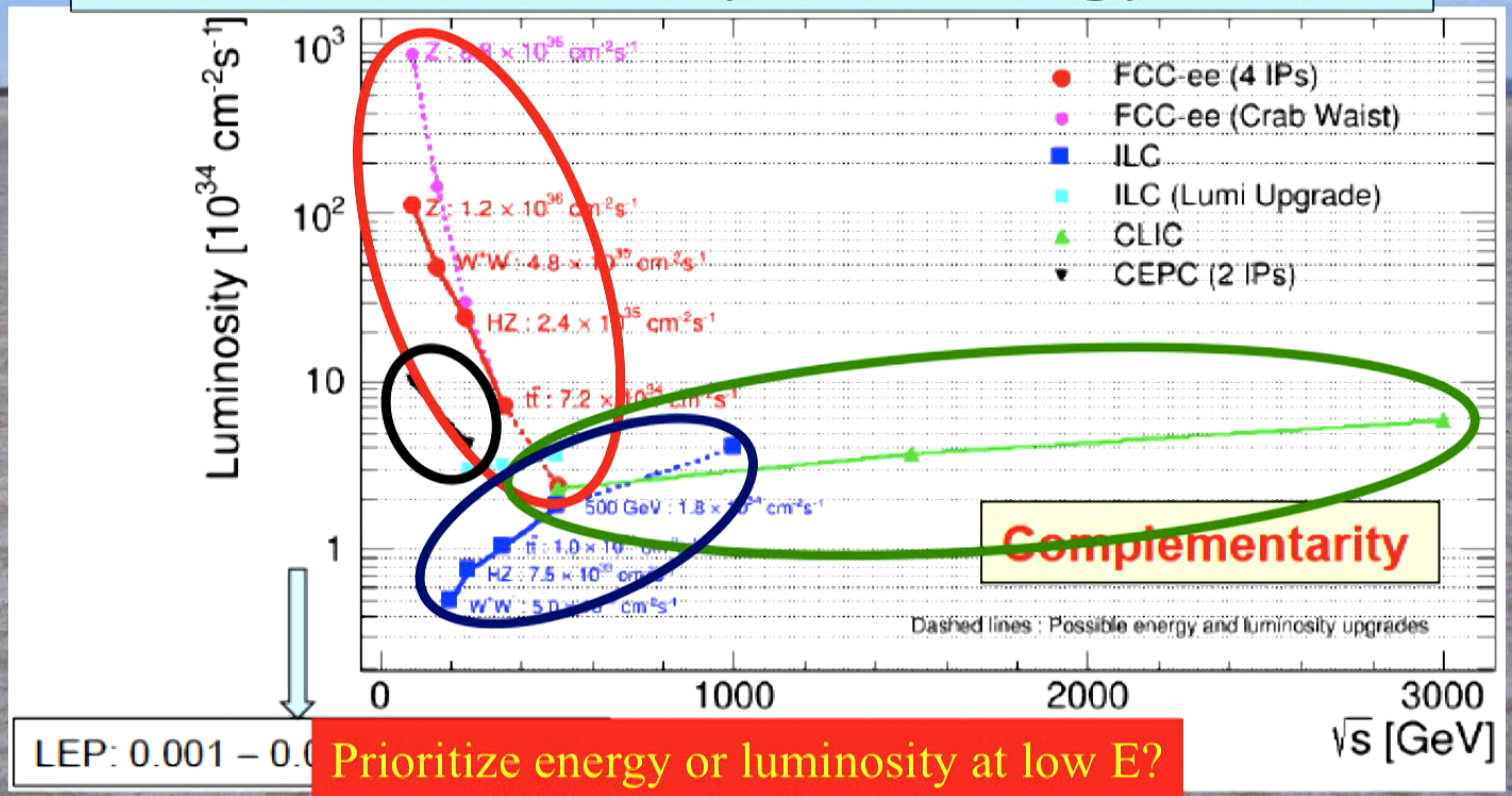
Projected e^+e^- Colliders: Luminosity vs Energy

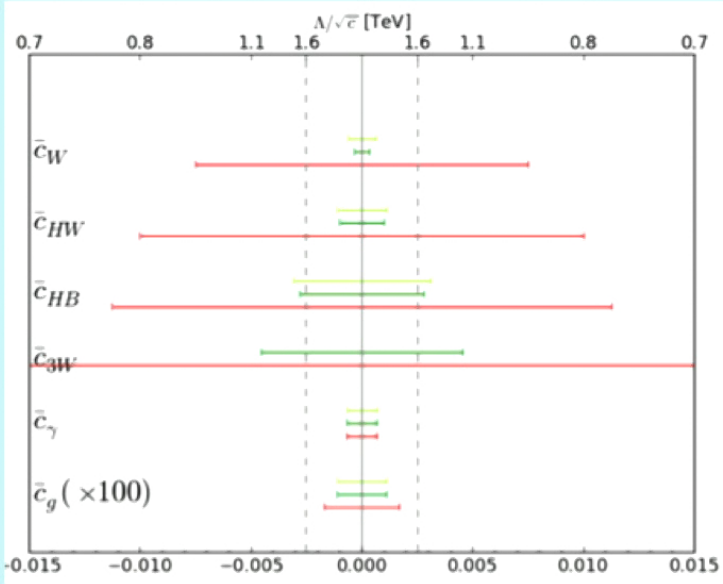


LEP: 0.001 – 0.0

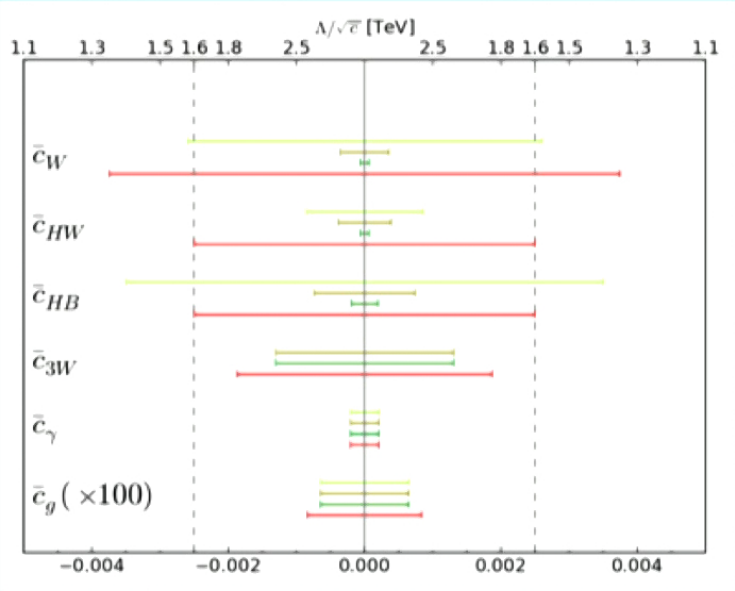
Prioritize energy or luminosity at low E?
LHC Run 2 will guide us

CLIC Sensitivities to Dimension-6 Operators

350 GeV



3 TeV



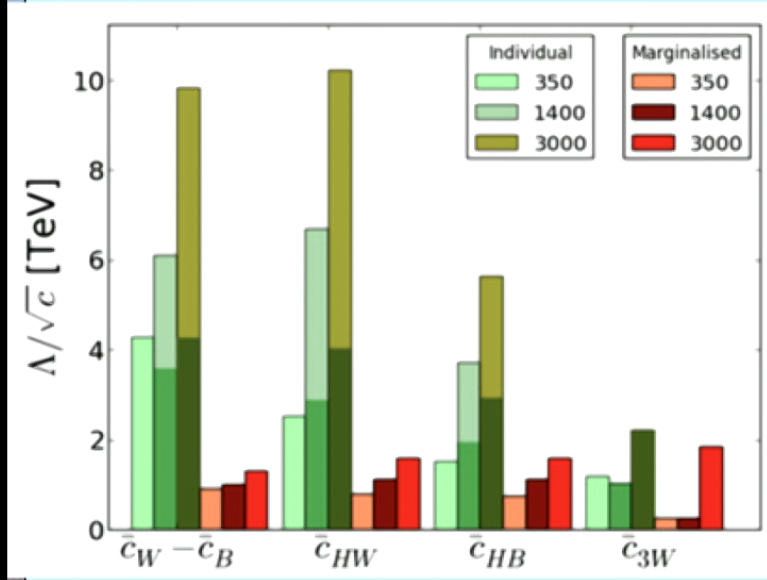
Global fit | Individual operators | Omitting W^+W^-

Sensitivity enhanced by higher centre-of-mass energy

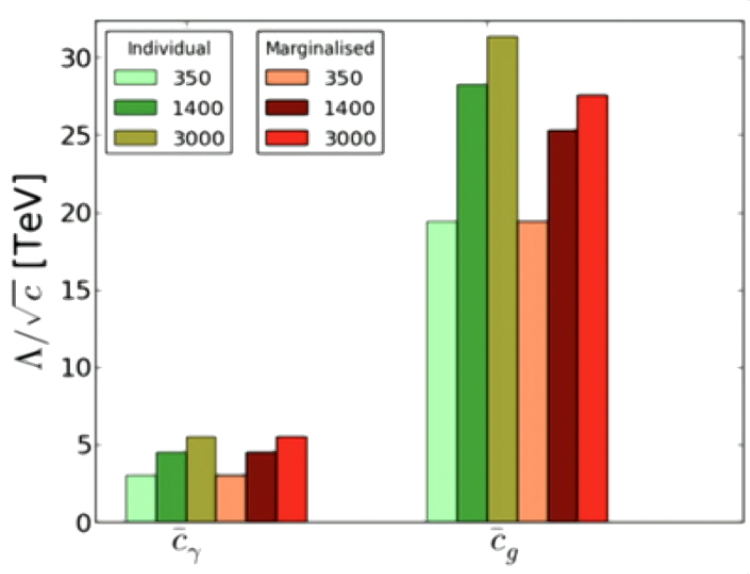
JE, Roloff, Sanz & Tevong You, arXiv:1701.04804

CLIC Sensitivities to Dimension-6 Operators

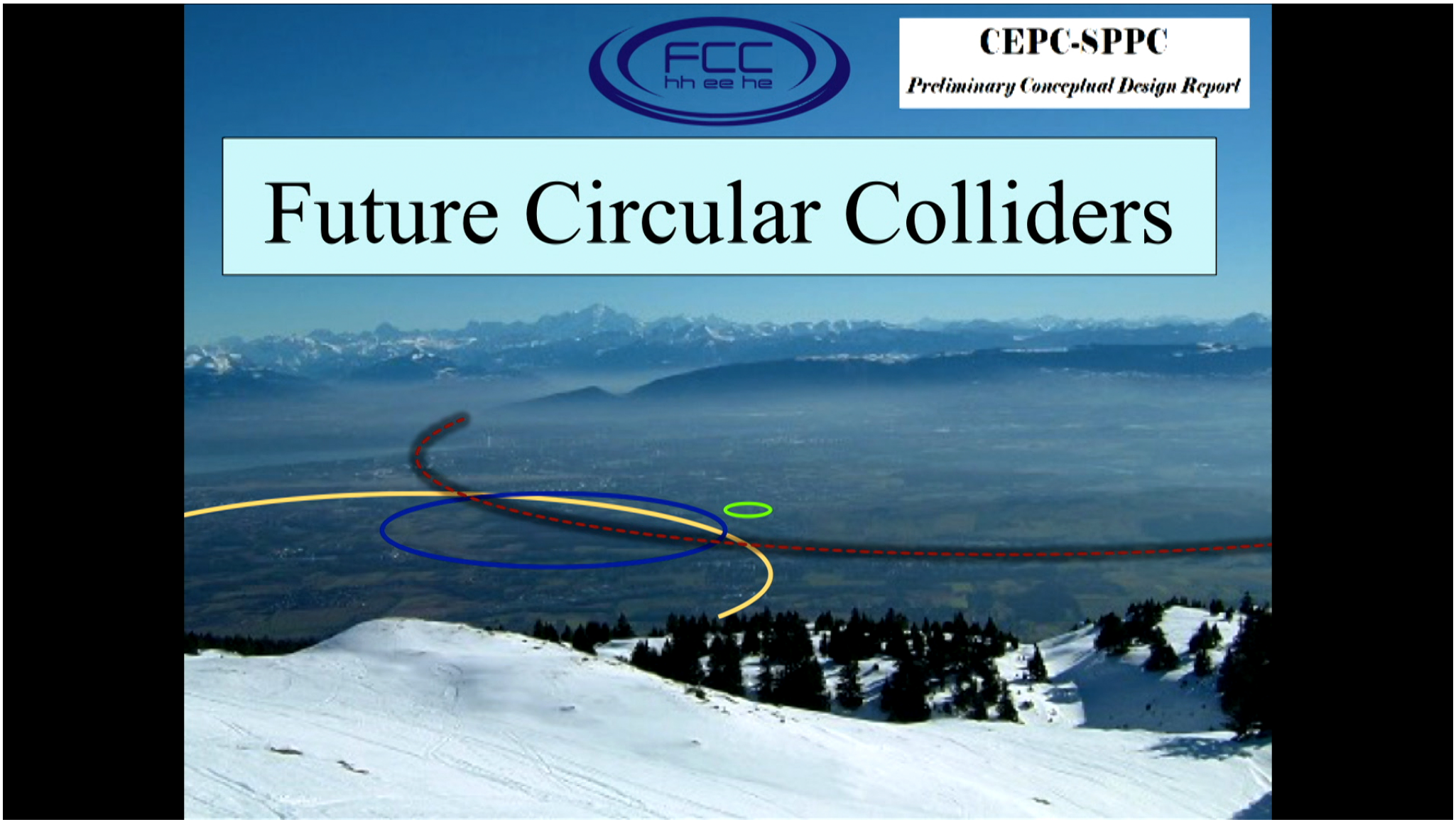
Individual operators

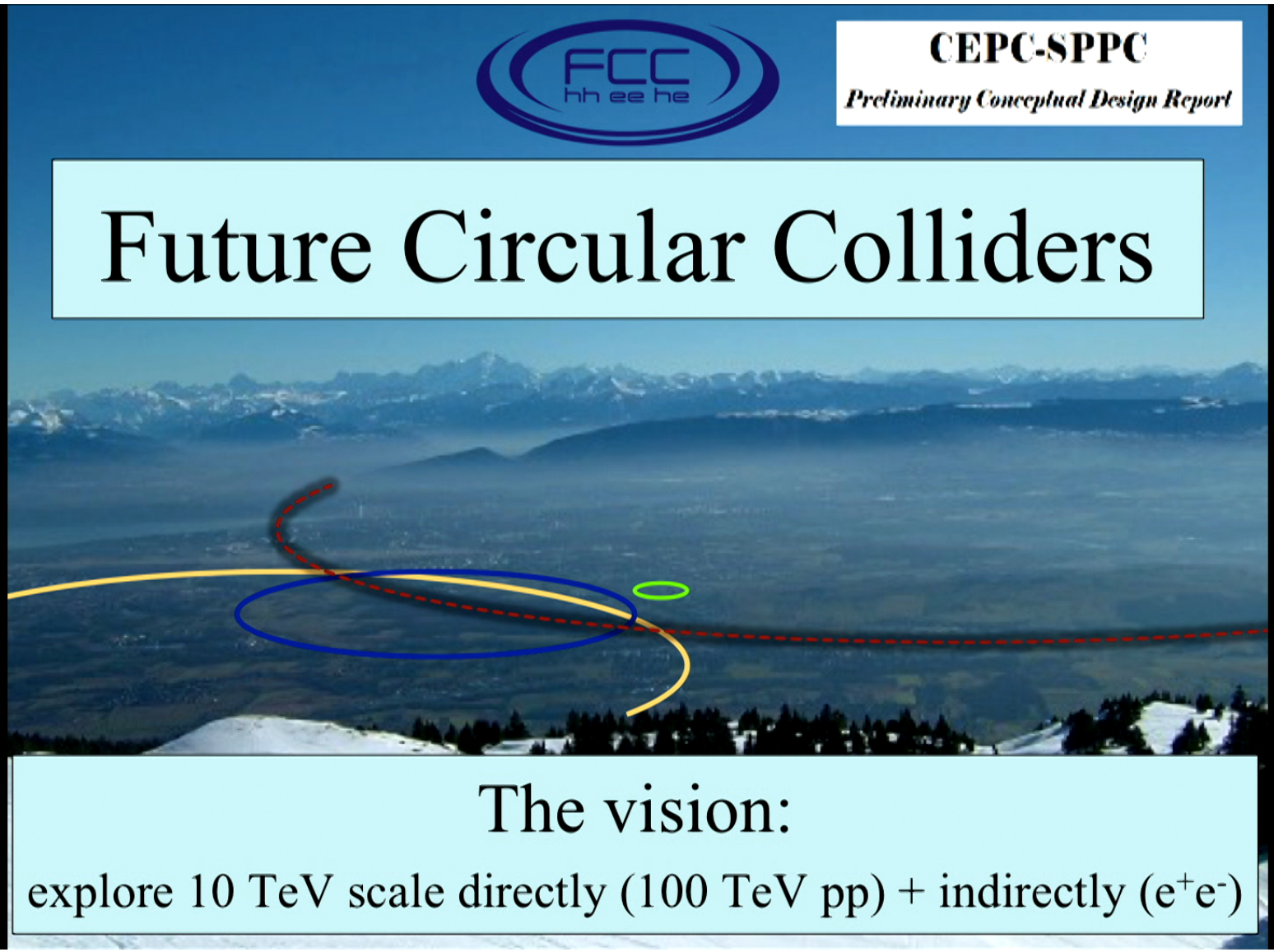


Global fit



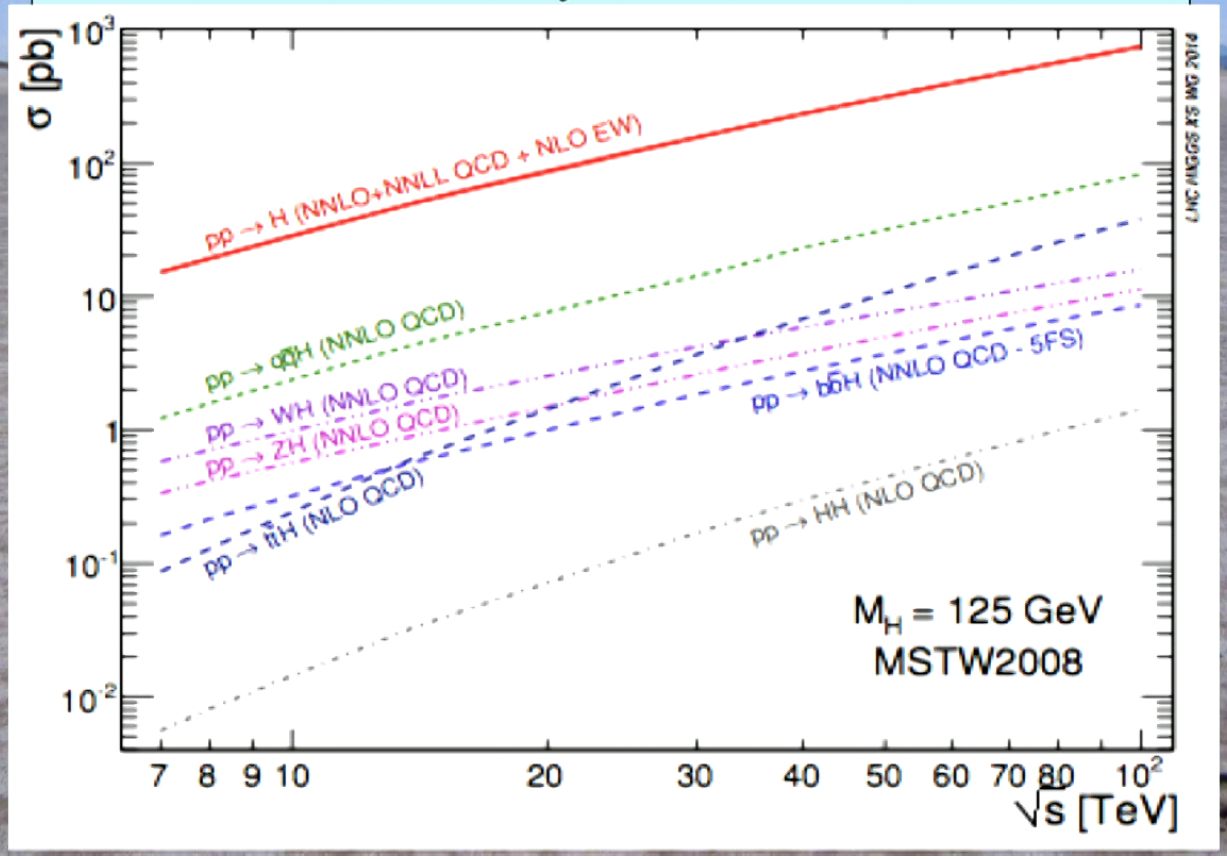
JE, Roloff, Sanz & Tevong You, arXiv:1701.04804


FCC
hh ee he
CEPC-SPPC
Preliminary Conceptual Design Report
Future Circular Colliders

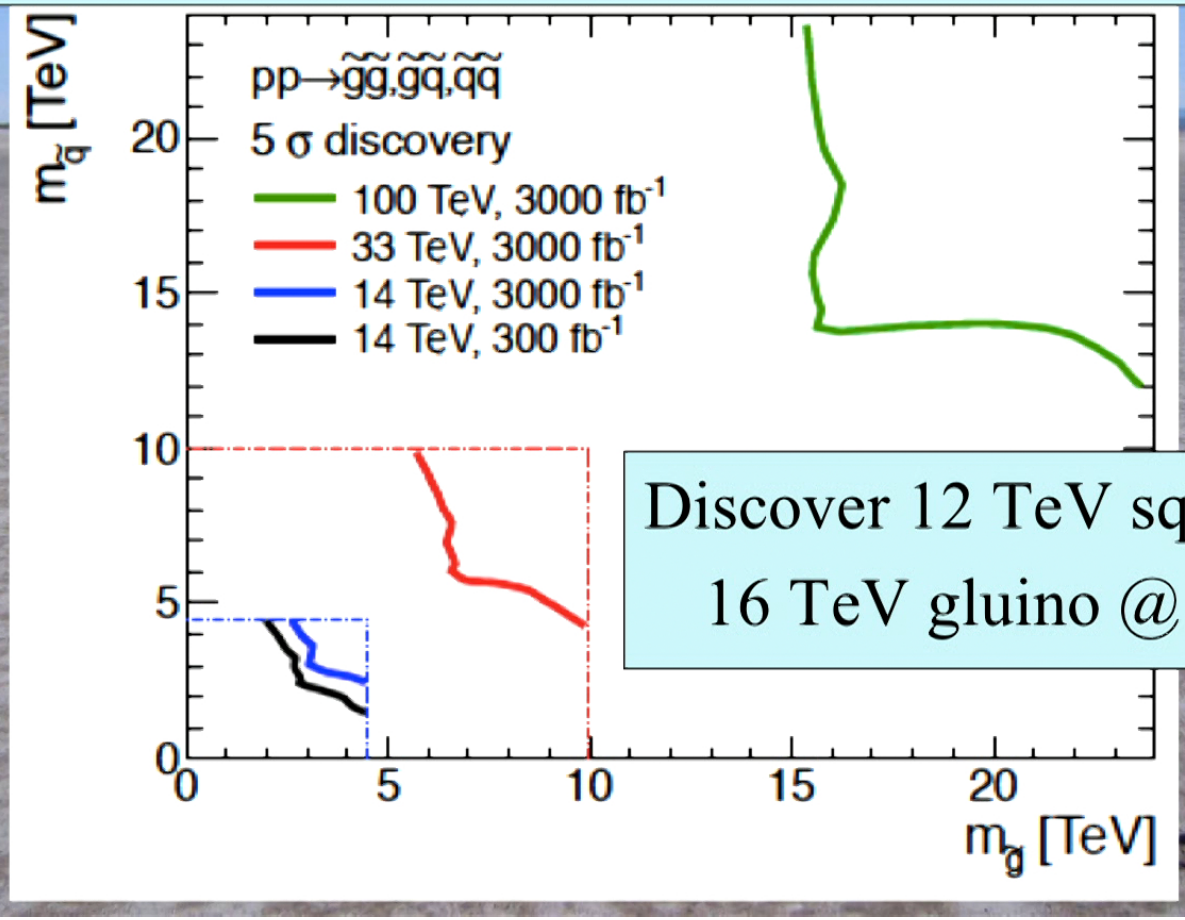

FCC
hh ee he
CEPC-SPPC
Preliminary Conceptual Design Report
Future Circular Colliders
The vision:
explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

Higgs Cross Sections

- At the LHC and beyond:



Squark-Gluino Plane



Discover 12 TeV squark,
16 TeV gluino @ 5σ

Summary

- Much still to be learnt about Higgs boson
- Rumours of the death of SUSY are exaggerated
  - Still the best framework for TeV-scale physics
- Simple models (CMSSM, etc.) under pressure
  - More general models quite healthy
- Good prospects for LHC Run 2 and for direct dark matter detection
  - But no guarantees
- **Await full Run 2 before choosing next collider**