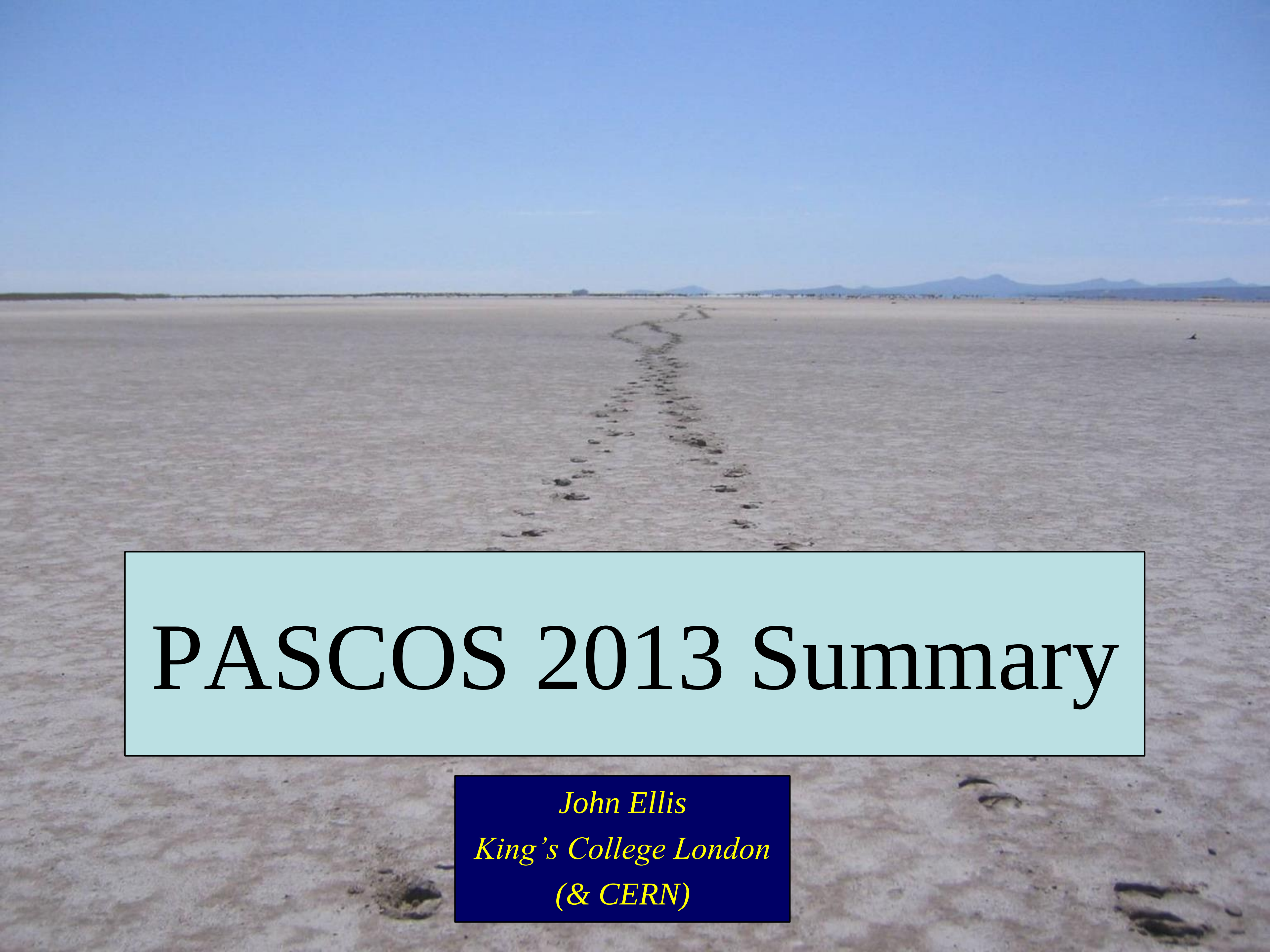
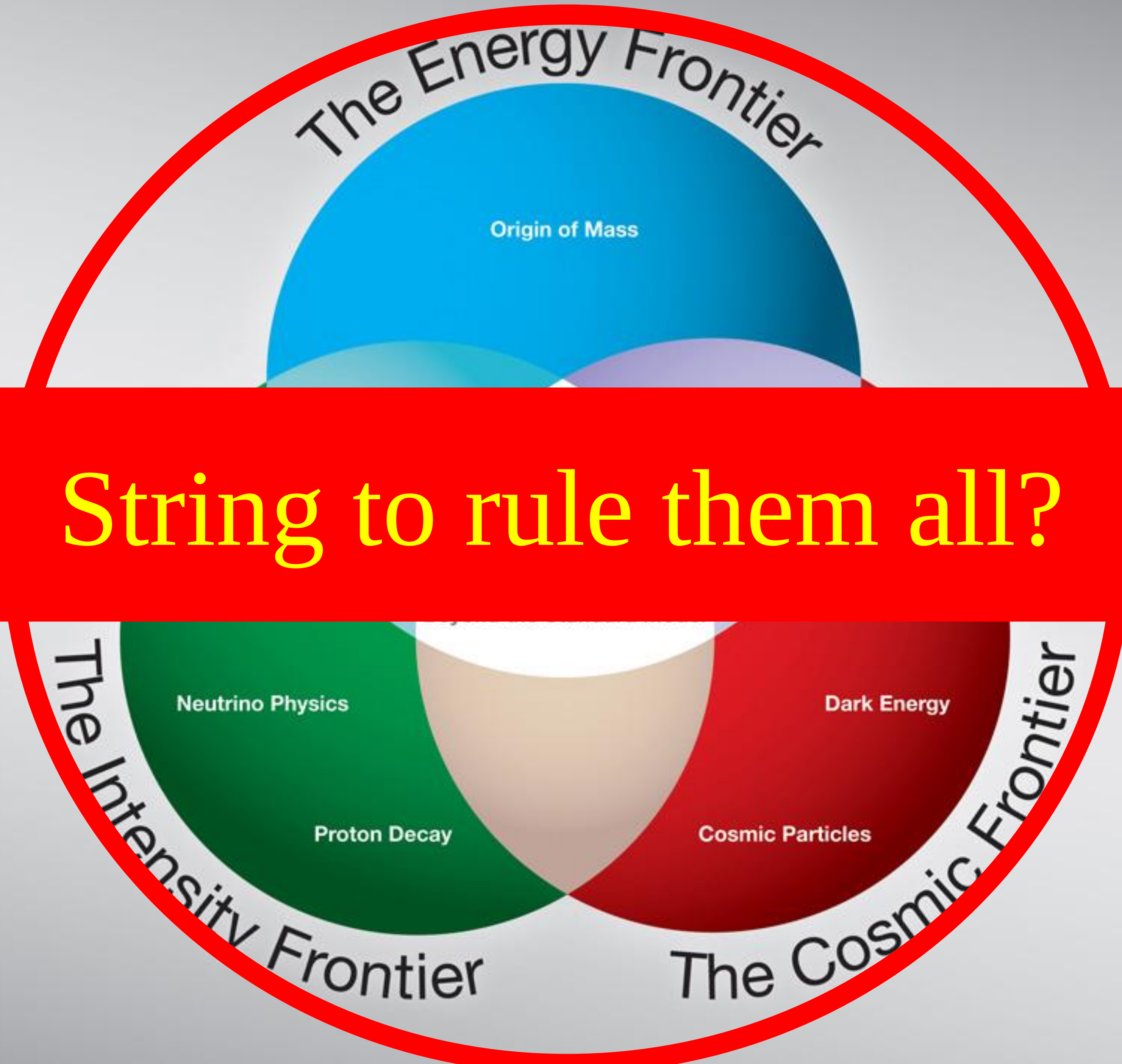


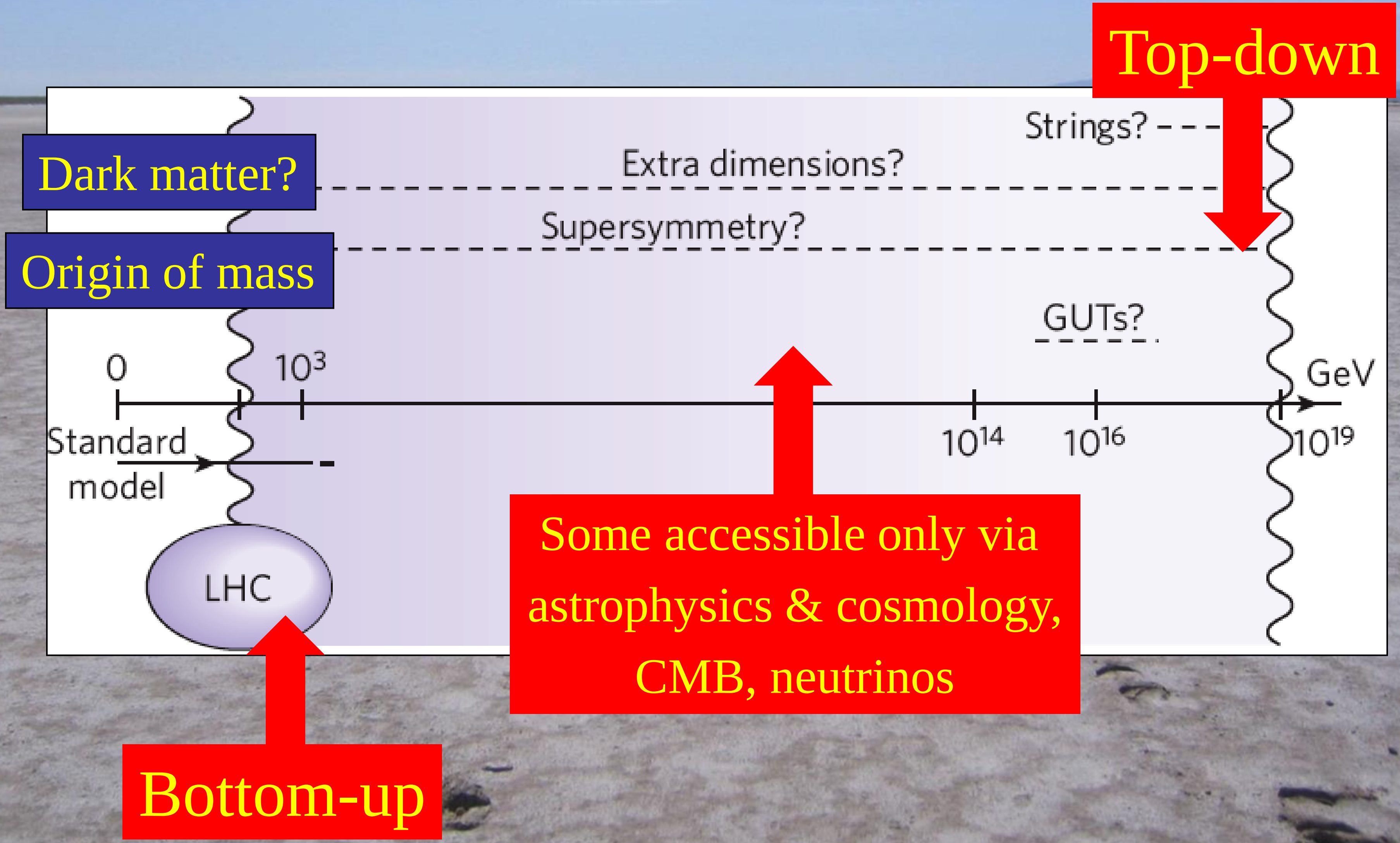
PASCOS 2013 Summary

John Ellis
King's College London
(& CERN)

String to rule them all?



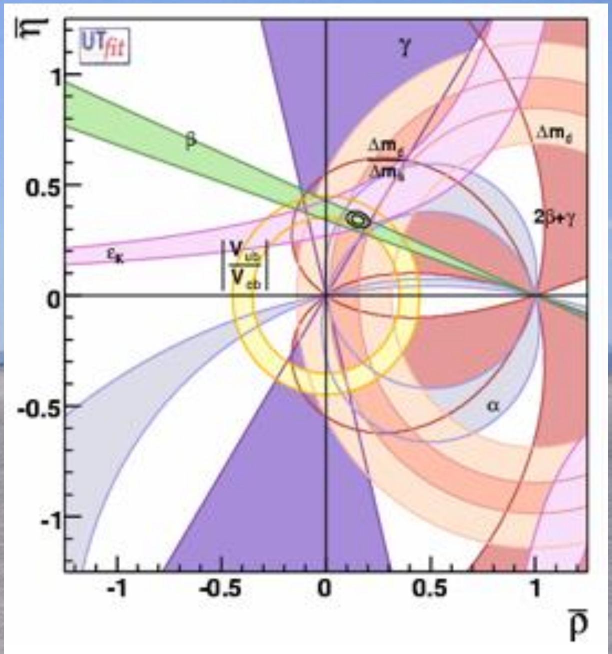
At what Energy is the New Physics?

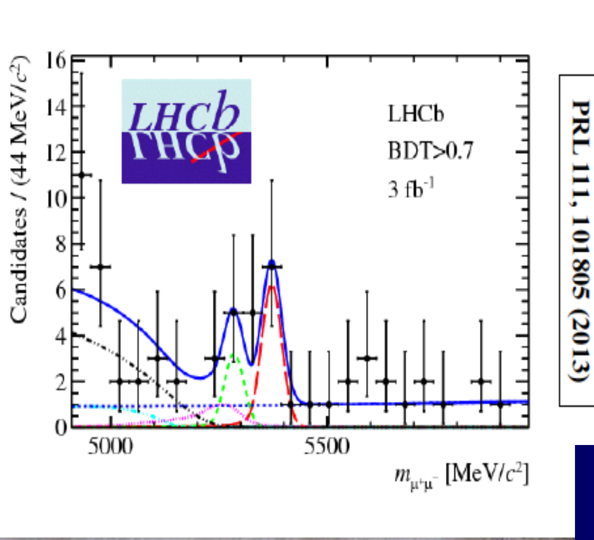


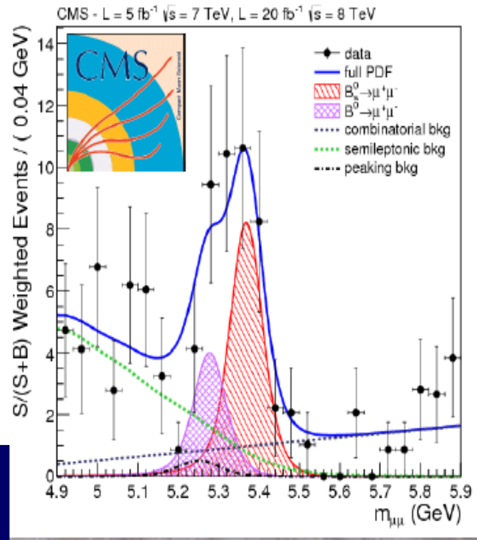
Quark Flavour Physics Successes

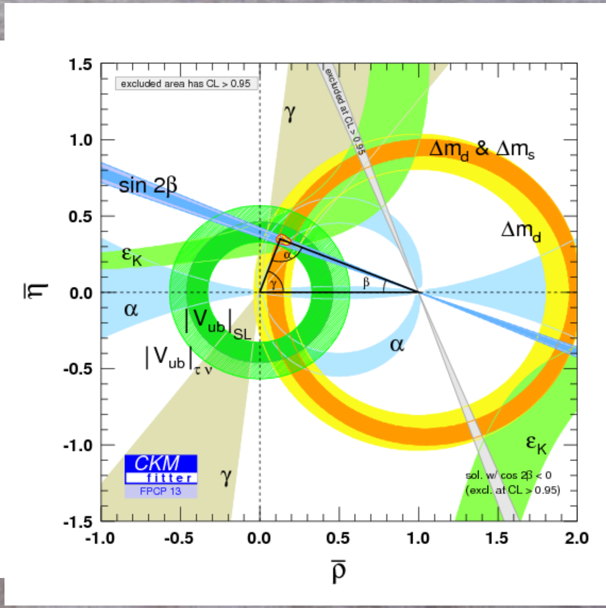
Good global fits to CKM model

Rare B decays to $\mu^+\mu^-$ observed





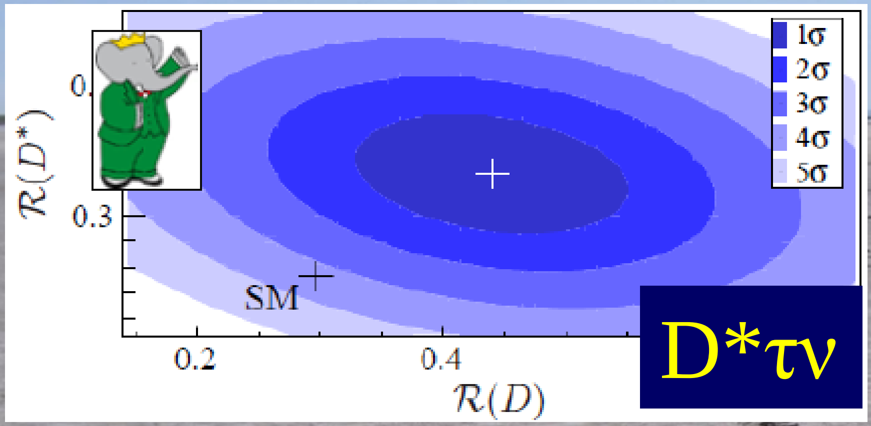


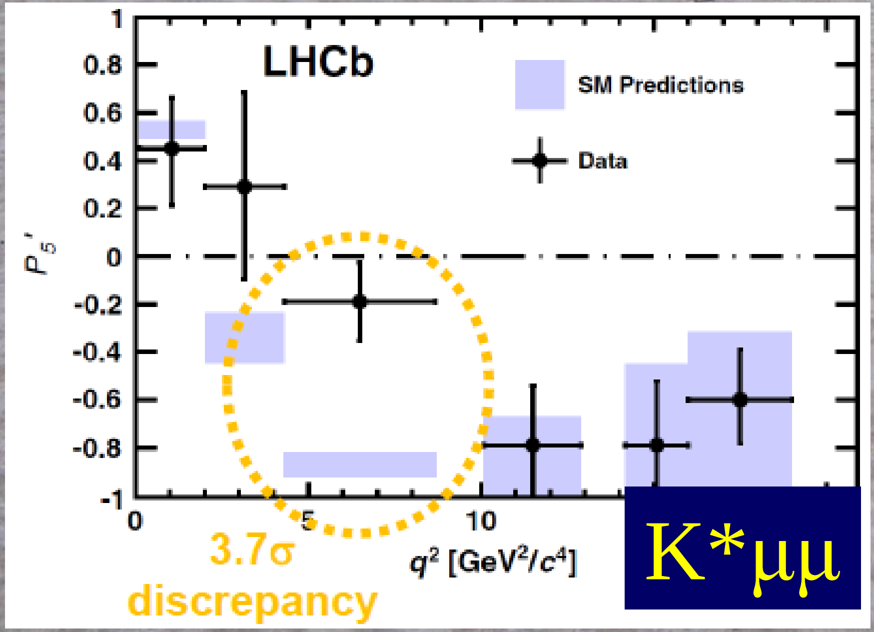


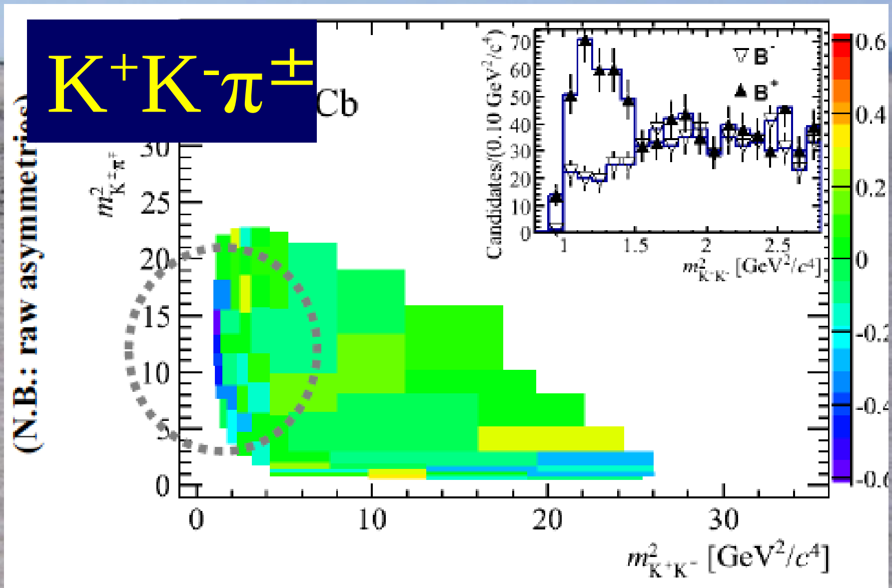
$\mu^+\mu^-$

Rodrigues

Quark Flavour Physics Puzzles





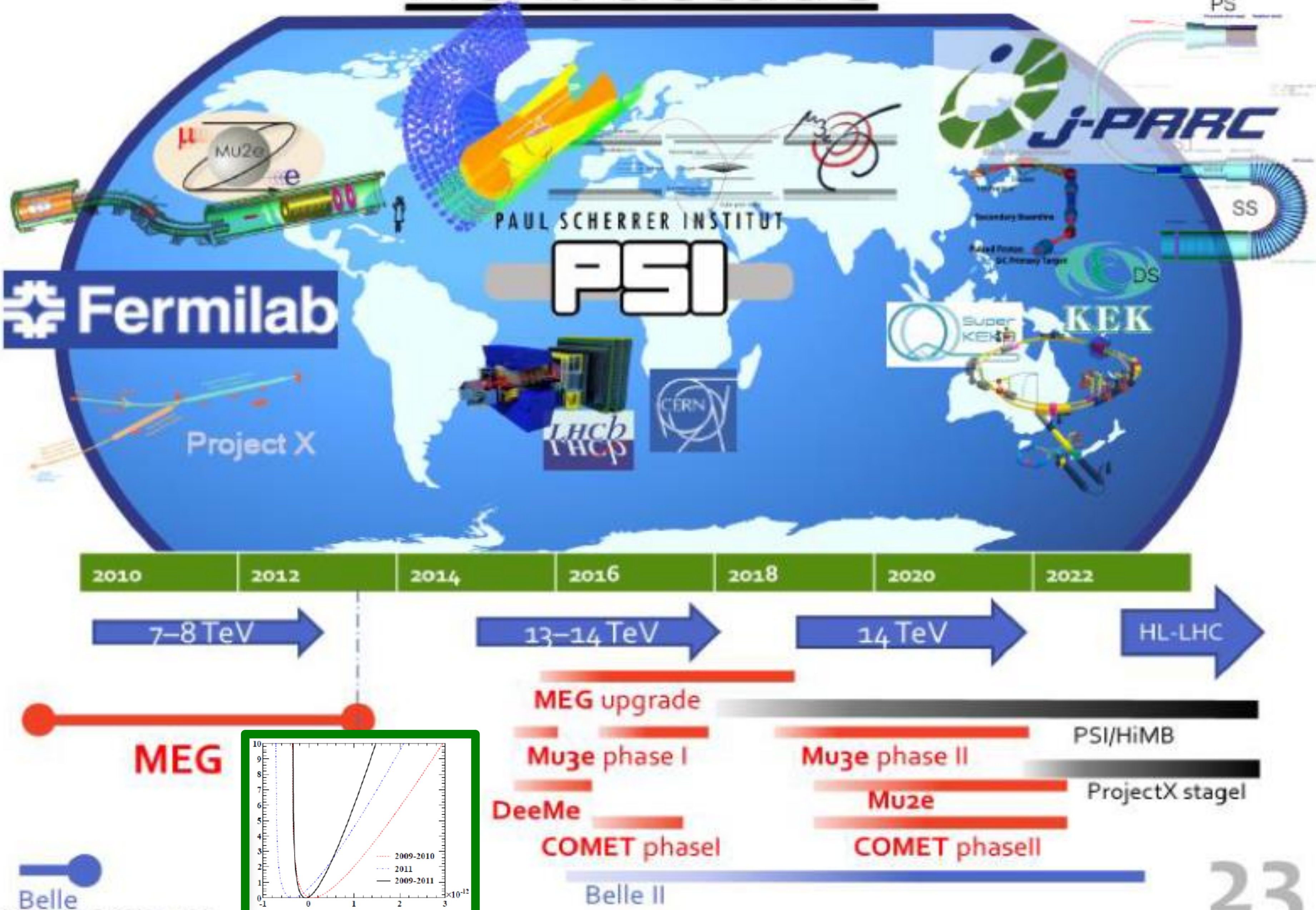


❑ **Regional CP asymmetry:**

$$A_{CP}^{\text{reg}}(B^\pm \to K^+K^-\pi^\pm) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007$$

Rodrigues

Next decade

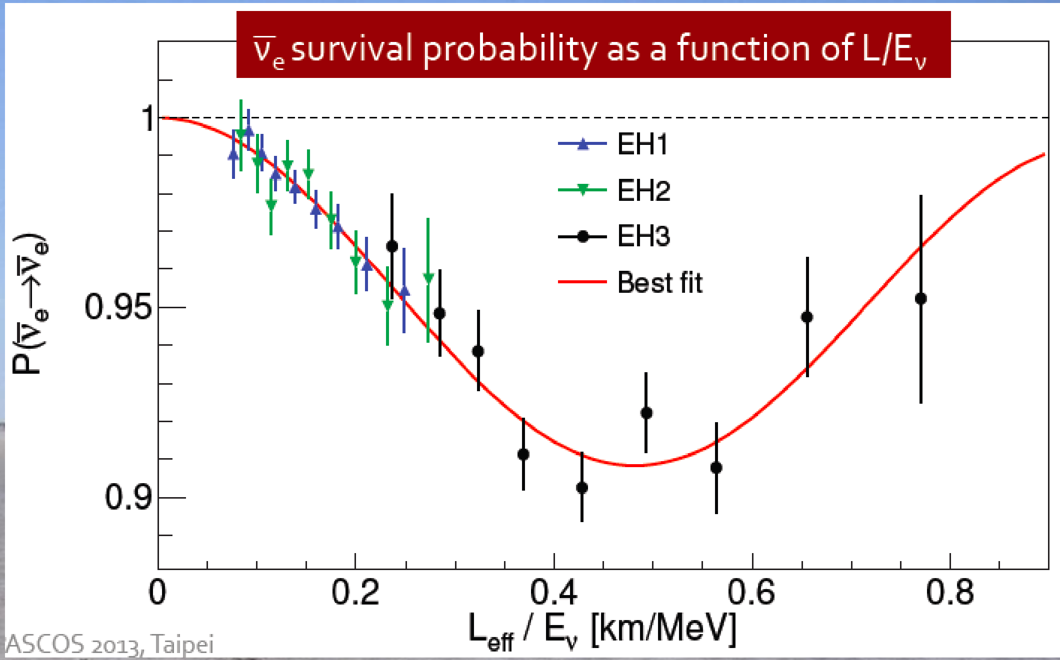


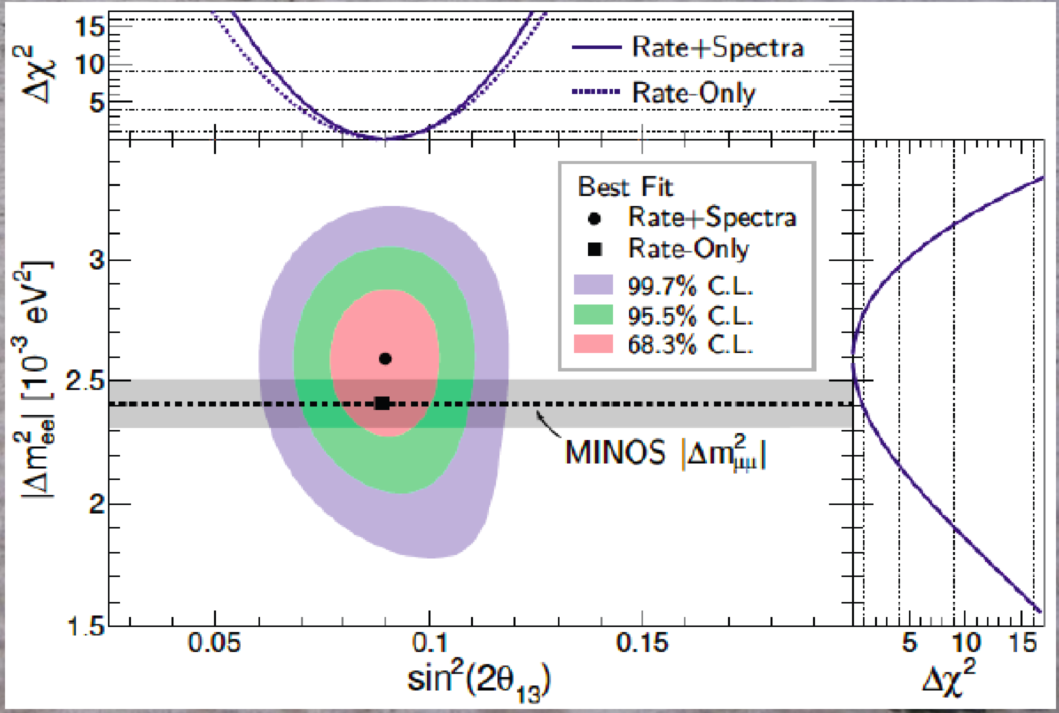
PS
SS
DS
J-PARC
KEK
Super KEKB
PAUL SCHERRER INSTITUT
PSI
Fermilab
Project X
Mu2e
μ
e
CERN
LHCb
2010
2012
2014
2016
2018
2020
2022
7–8 TeV
13–14 TeV
14 TeV
HL-LHC
MEG upgrade
PSI/HiMB
Mu3e phase I
Mu3e phase II
ProjectX stageI
DeeMe
Mu2e
COMET phaseI
COMET phaseII
Belle II
MEG
Belle
2009-2010
2011
2009-2011
×10^-12
Branching ratio

Neutrino Oscillations @ Daya Bay

- Almost a complete cycle observed
- Accurate value of θ_{13}
- Next ν step: CP violation?

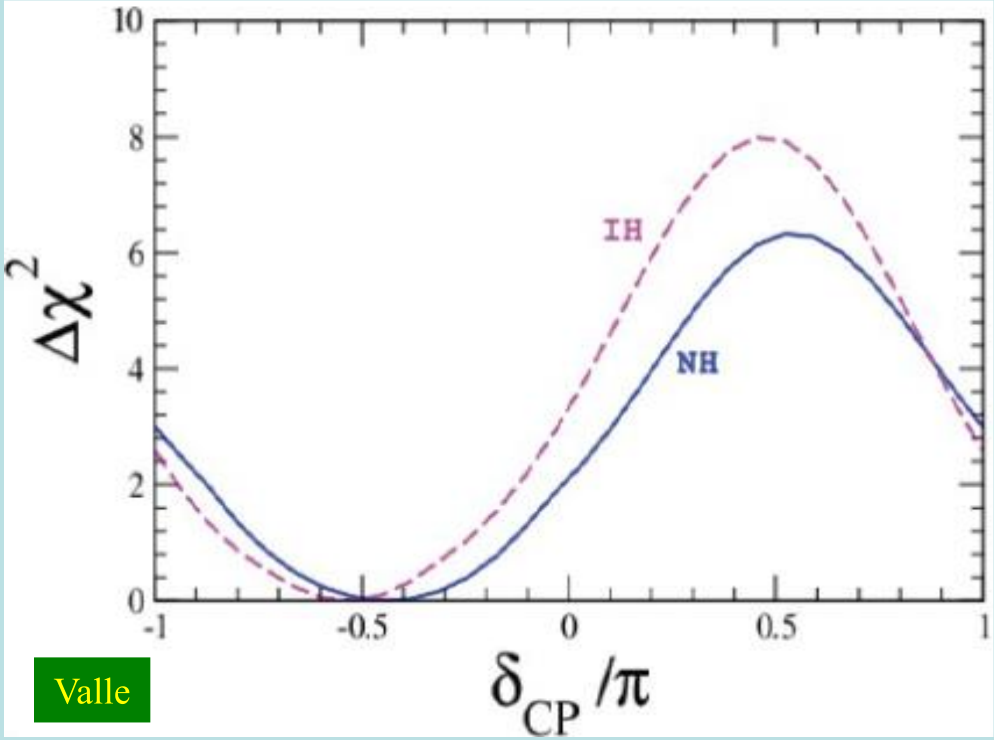
Wang



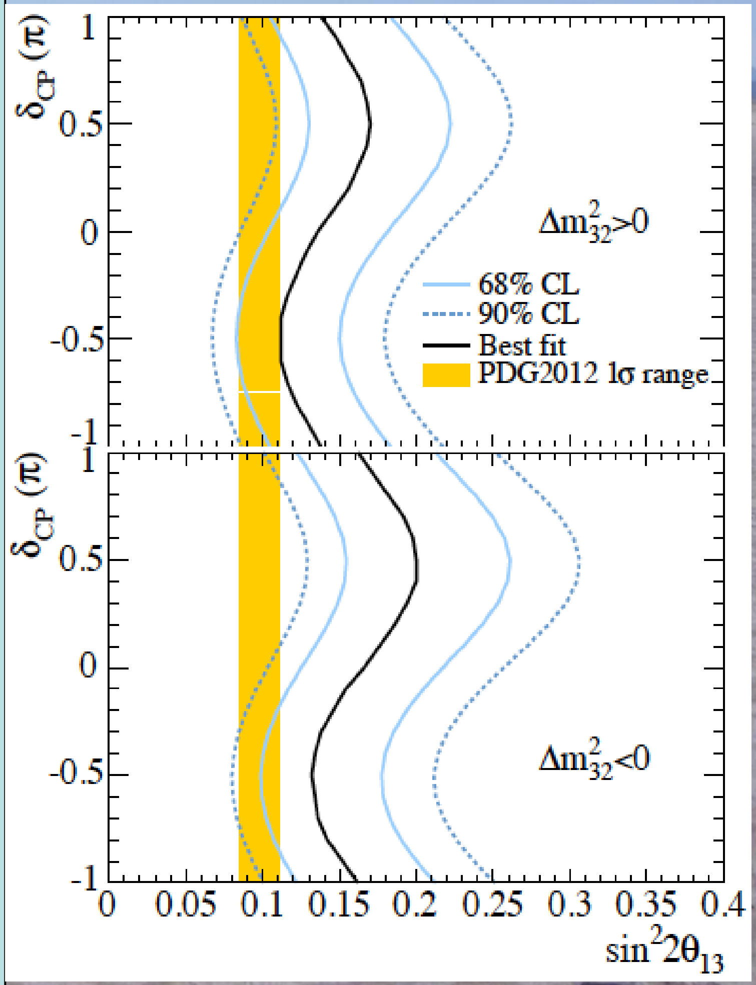


CP Violation in the Neutrino Sector?

- Not yet, but hint from T2K data on ν_e appearance

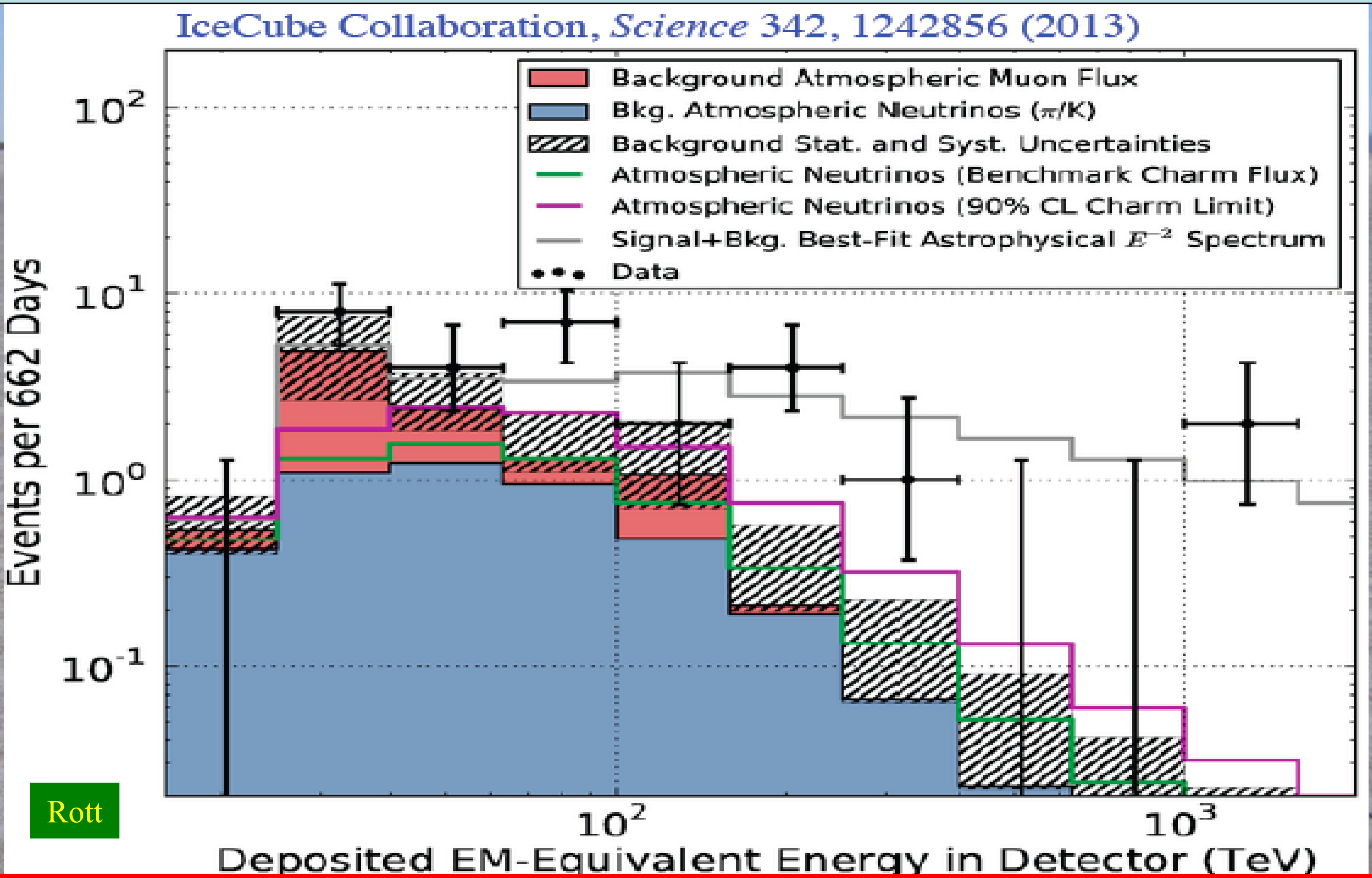


- Look forward to more data!



Nakadaira

High-Energy Neutrino Astronomy



Finally, some other particle besides the photon!

What we (don't) know What else is there? How to discover it?

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

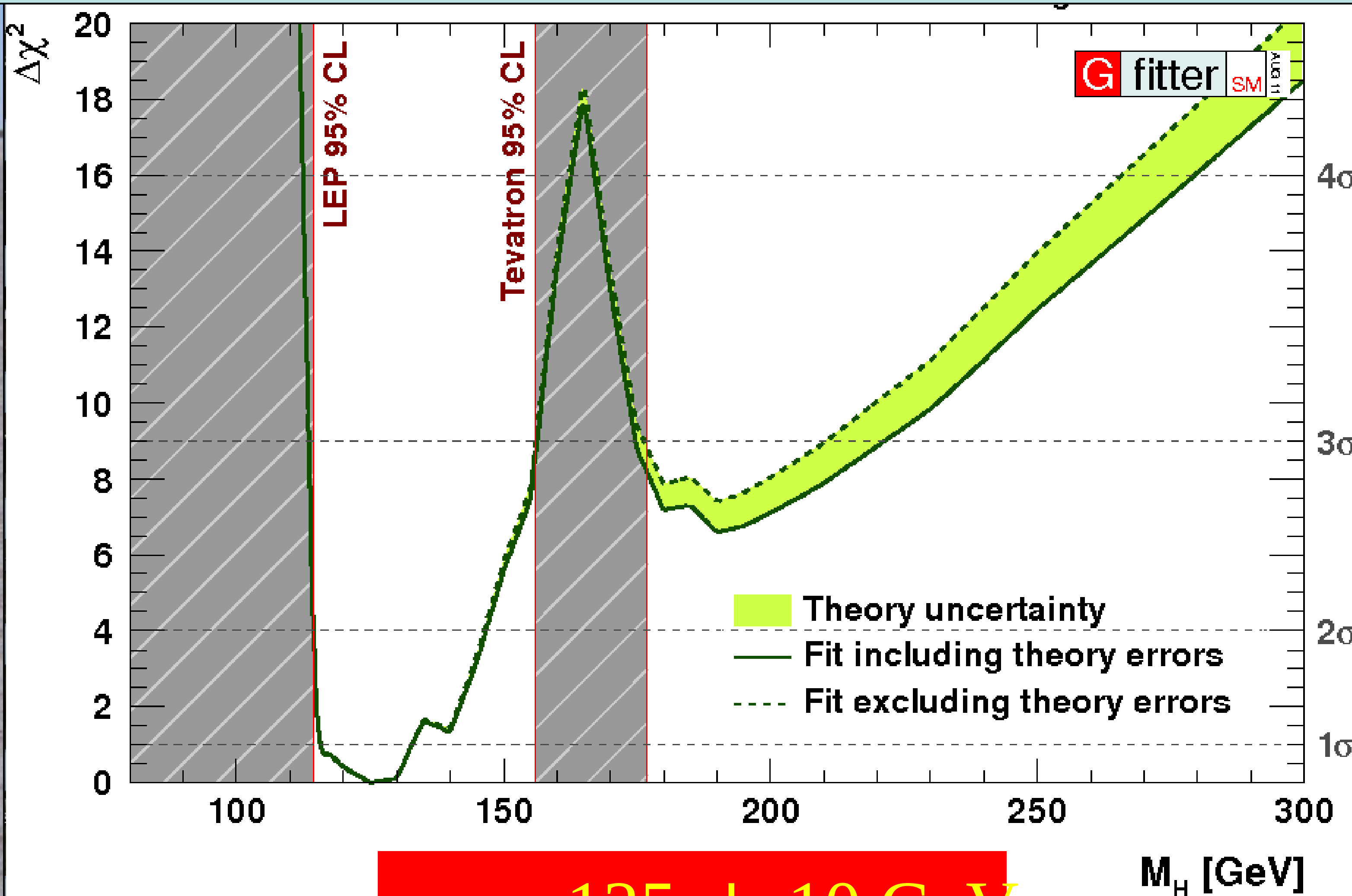
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

2011: Combining Information from Previous Direct Searches and Indirect Data

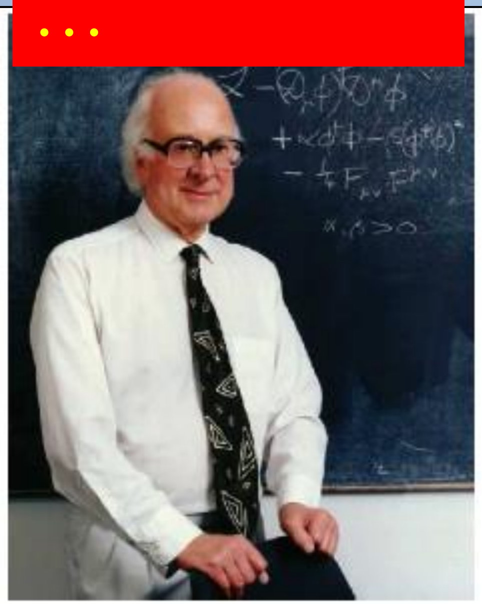


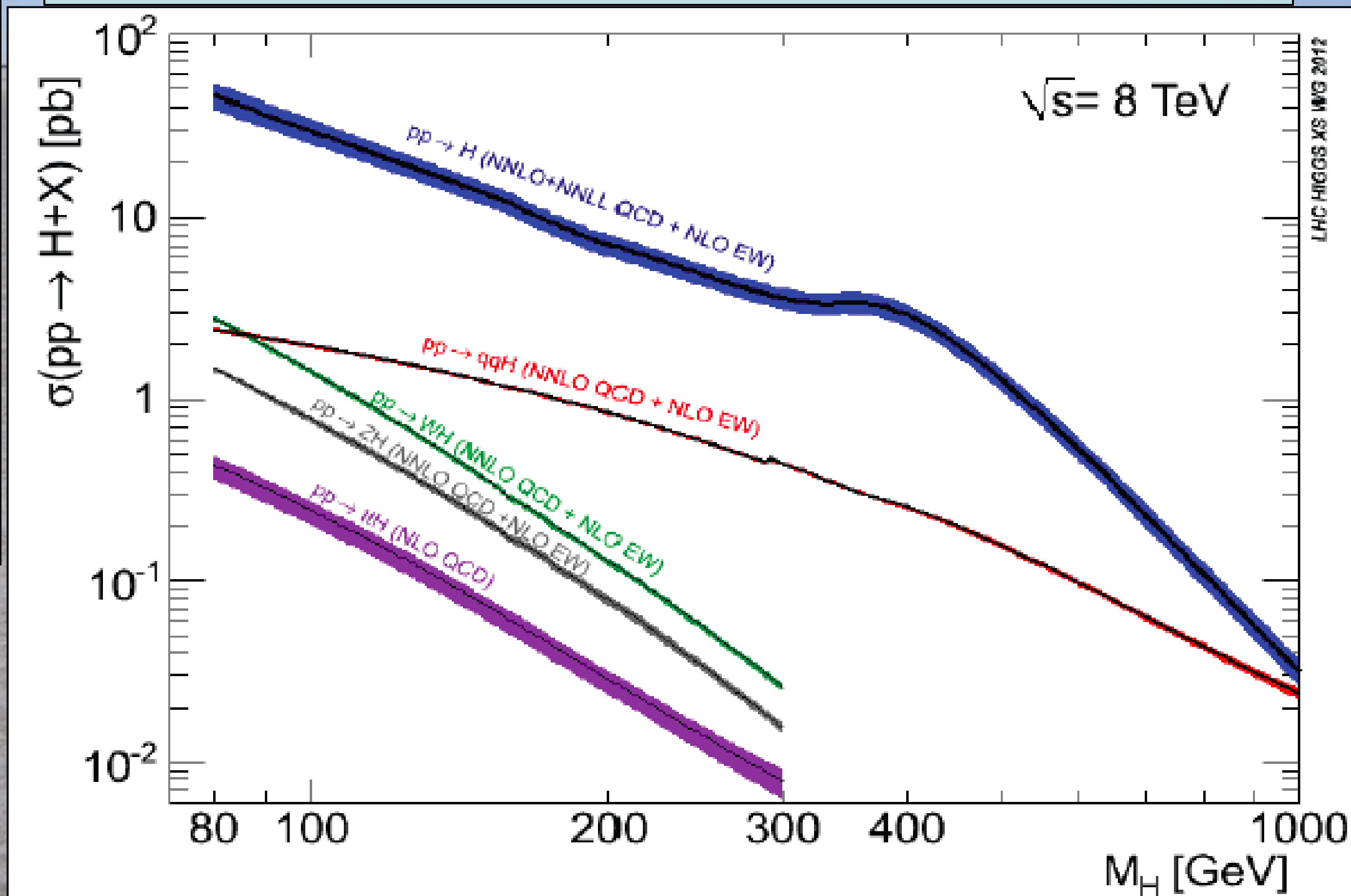
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

A la recherche du Higgs perdu …

Higgs Production at the LHC

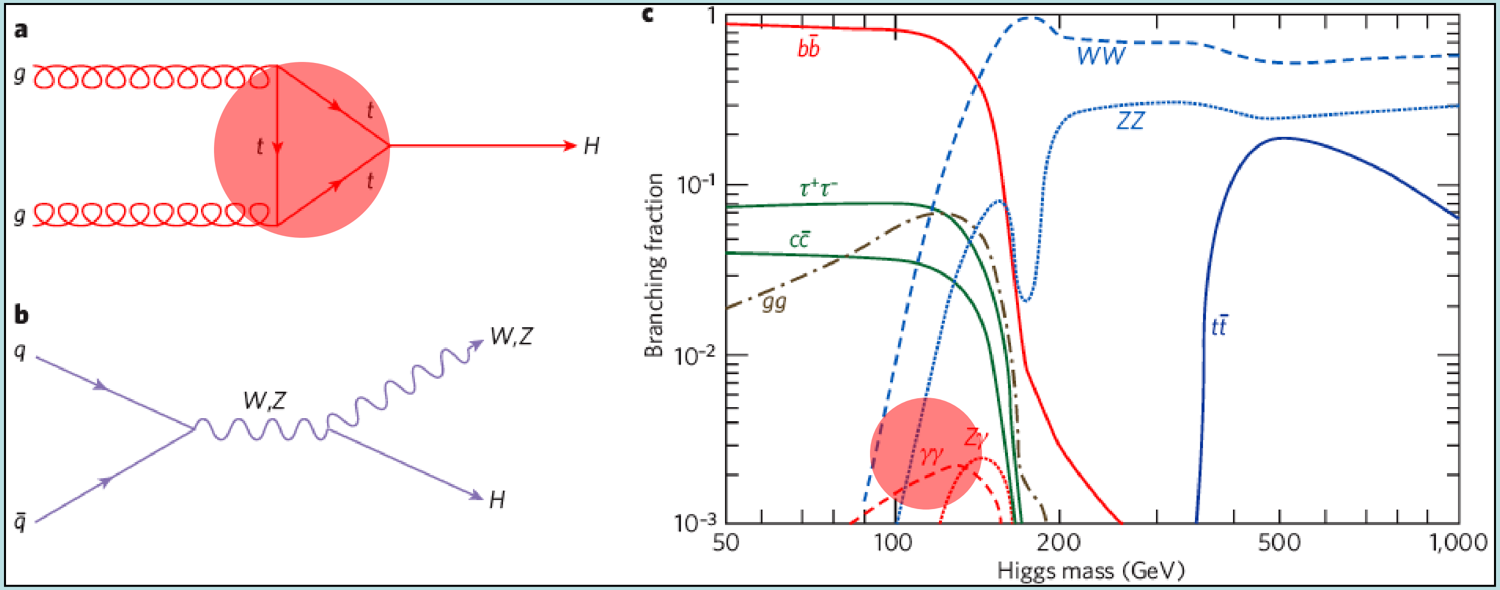




Many production modes measurable if M_h ~ 125 GeV

Higgs Decay Branching Ratios

- Couplings proportional to masses (?)



- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if $M_h \sim 125$ GeV

July 4th 2012 The Higgs discovery

The Particle Higgsaw Puzzle

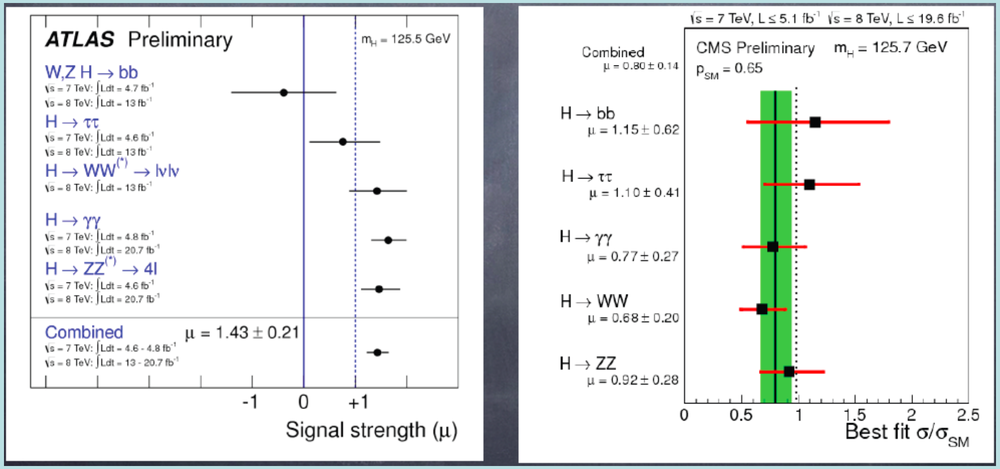
Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

From Discovery to Measurement

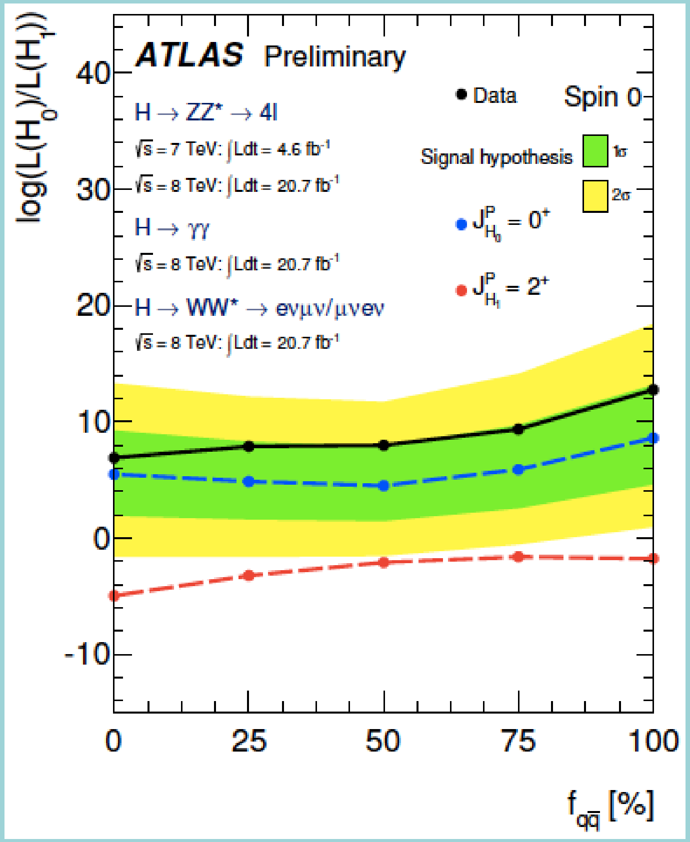
- Mass measurements:
  125.6 ± 0.3 GeV
- Signal strengths ~ SM
  in many channels

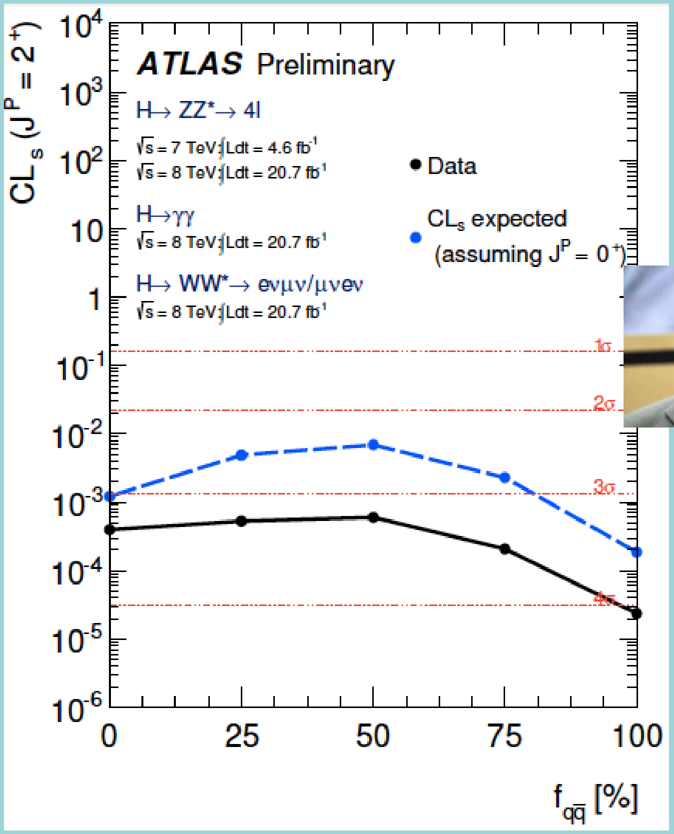


- Frontiers:
  - VBF significance 2σ in several channels, 3σ combined
  - Decay to ττ emerging
  - Decay to bbbar emerging (CMS, Tevatron)
  - Indirect evidence for ttbar coupling
  - Still to come: ttbar + H, t + H, H to Zγ, …

Wingerter-Seez
Ganjour

The 'Higgs' Spin is probably 0



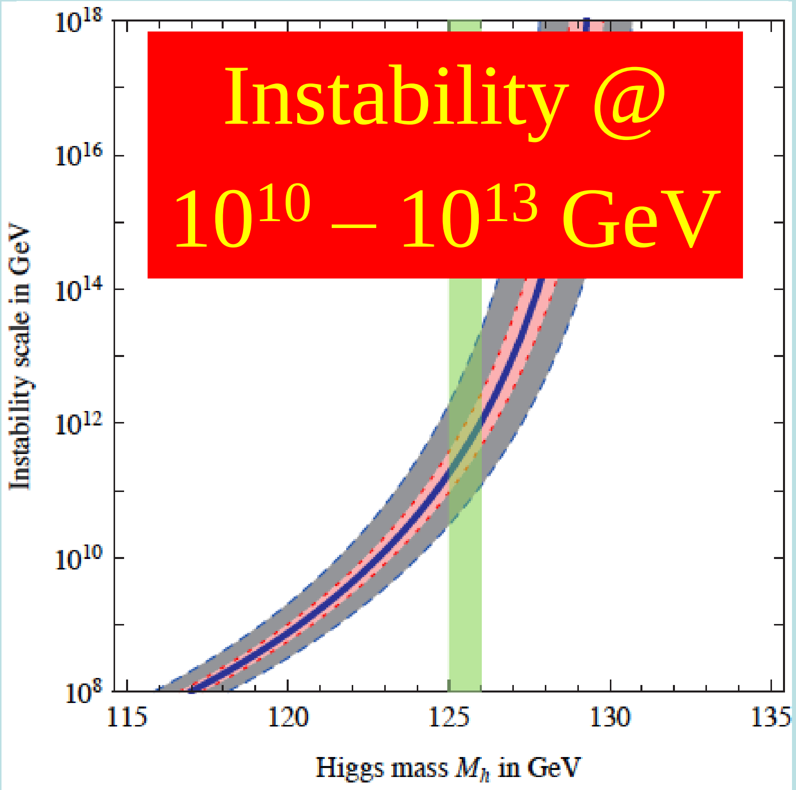


- Graviton-like spin-2 disfavoured at 99.9% CL

Theoretical Constraints on Higgs Mass

- Large $M_h \rightarrow$ large self-coupling $\rightarrow$ blow up at

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



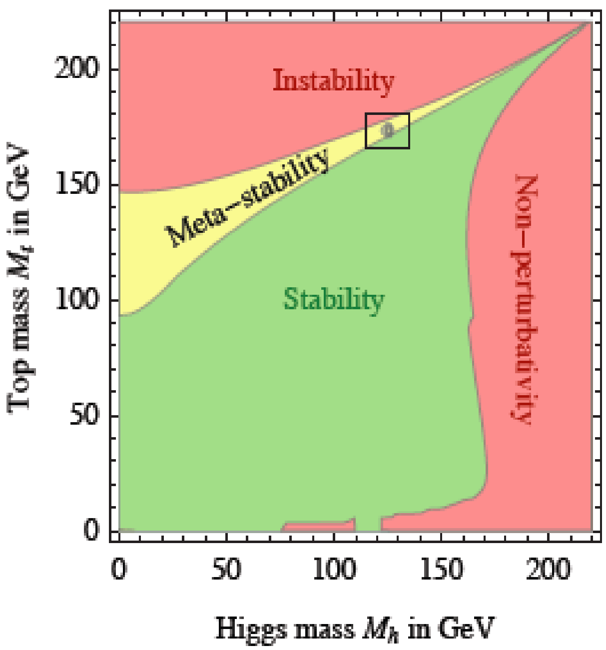
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ $\rightarrow$ vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

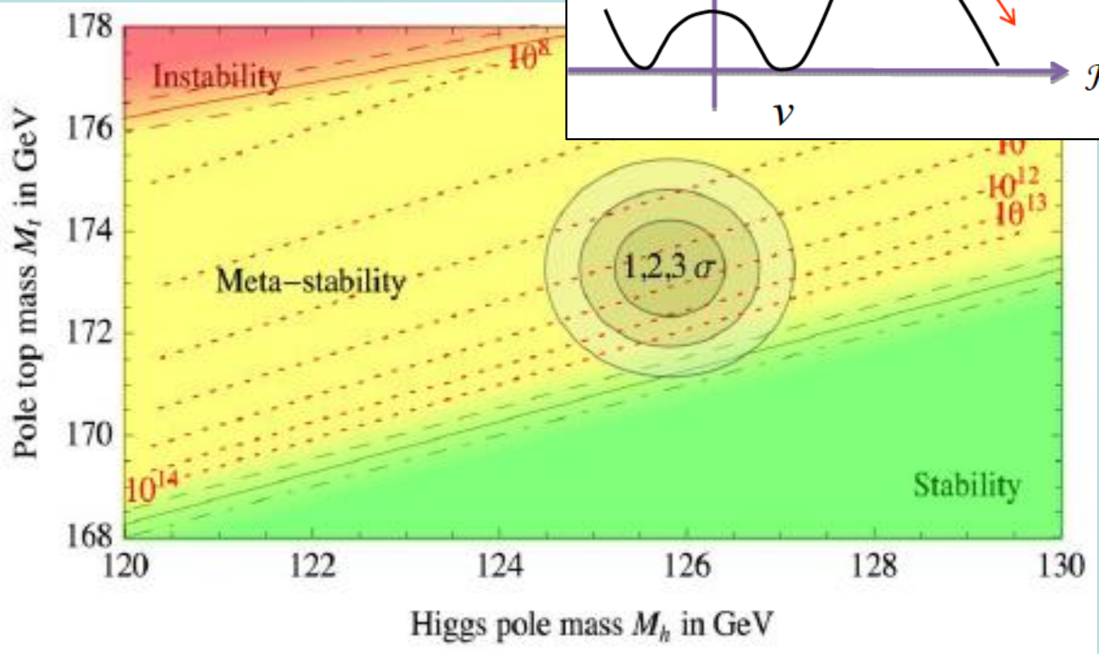
Ibanez, Kobakhidze //

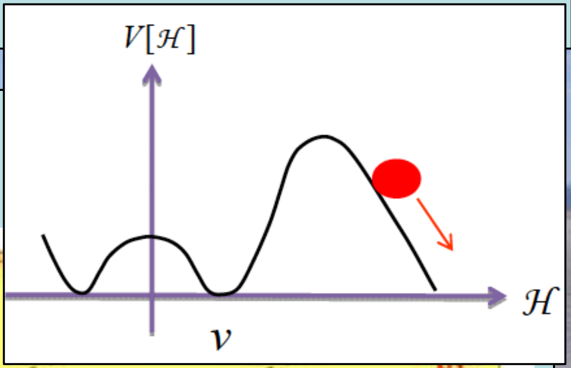
Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H







- Present vacuum probably metastable with lifetime >> age of the Universe

Ibanez, Kobakhidze //

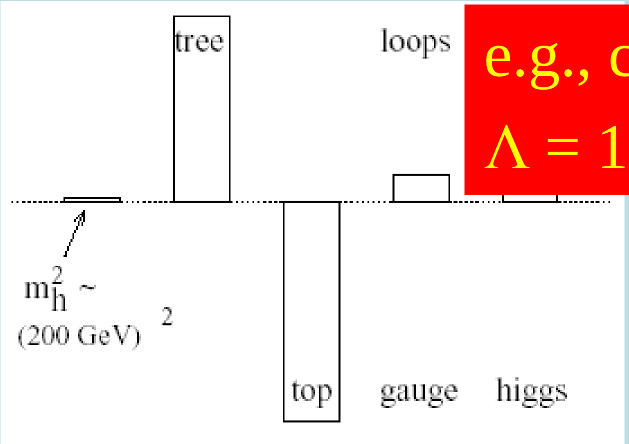
Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems



e.g., cutoff
Λ = 10 TeV

Cut-off Λ ~ 1 TeV with
Supersymmetry?

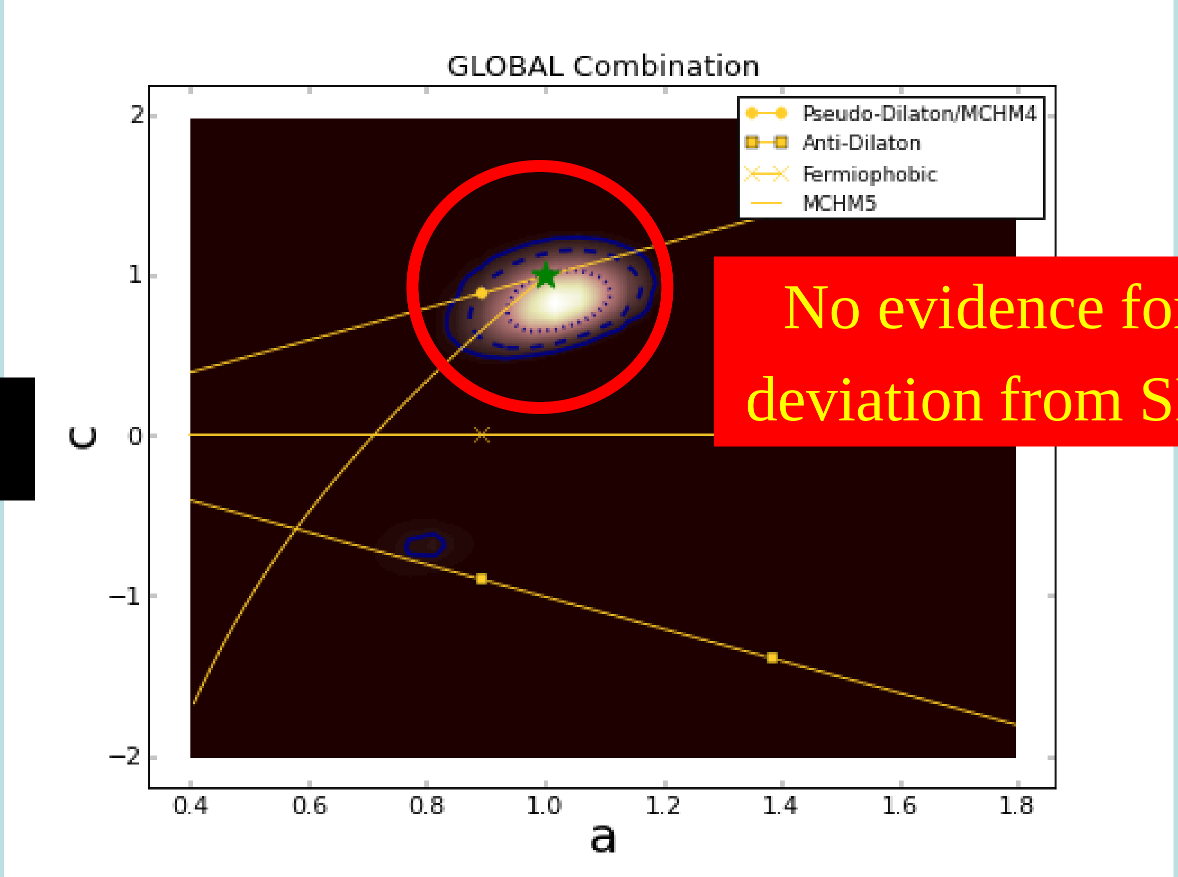
- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

New technicolour force?

- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

Global Analysis of Higgs-like Models

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



Lee

Global

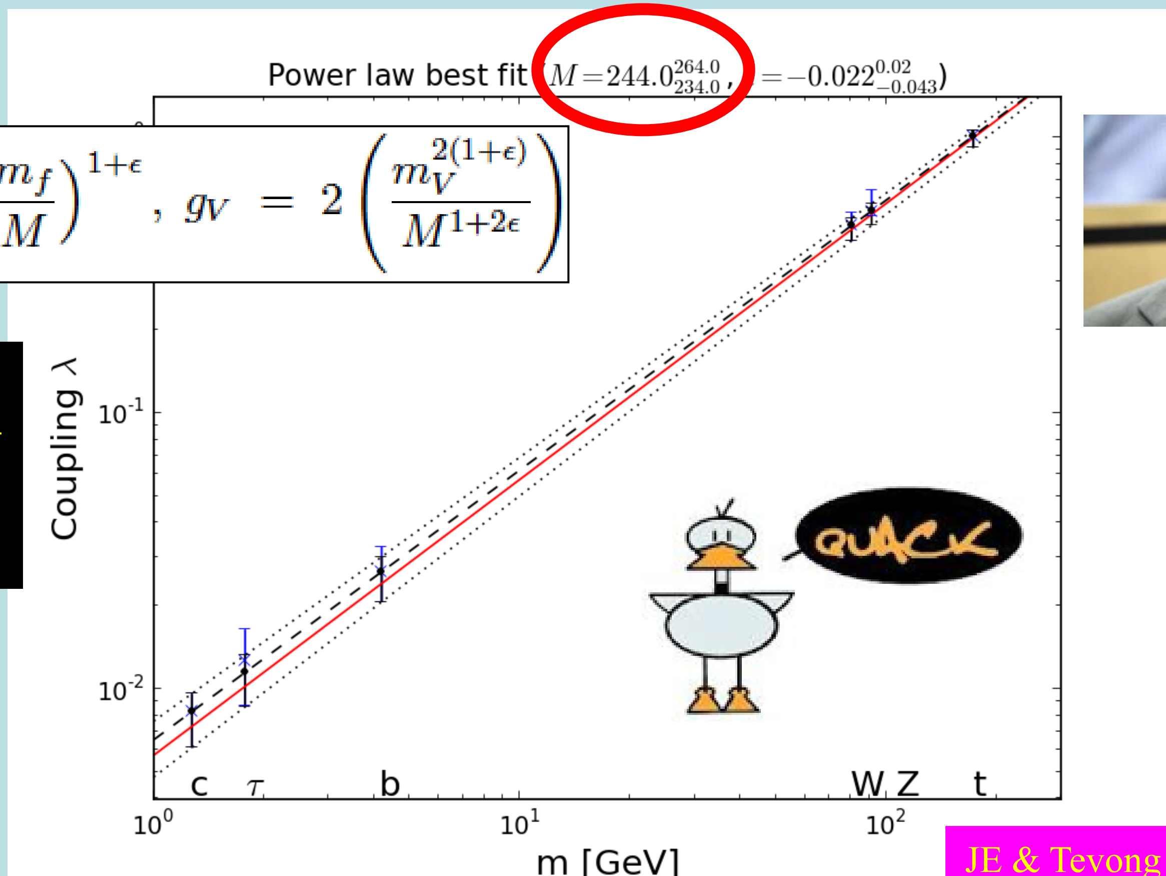
No evidence for deviation from SM

- 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?



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

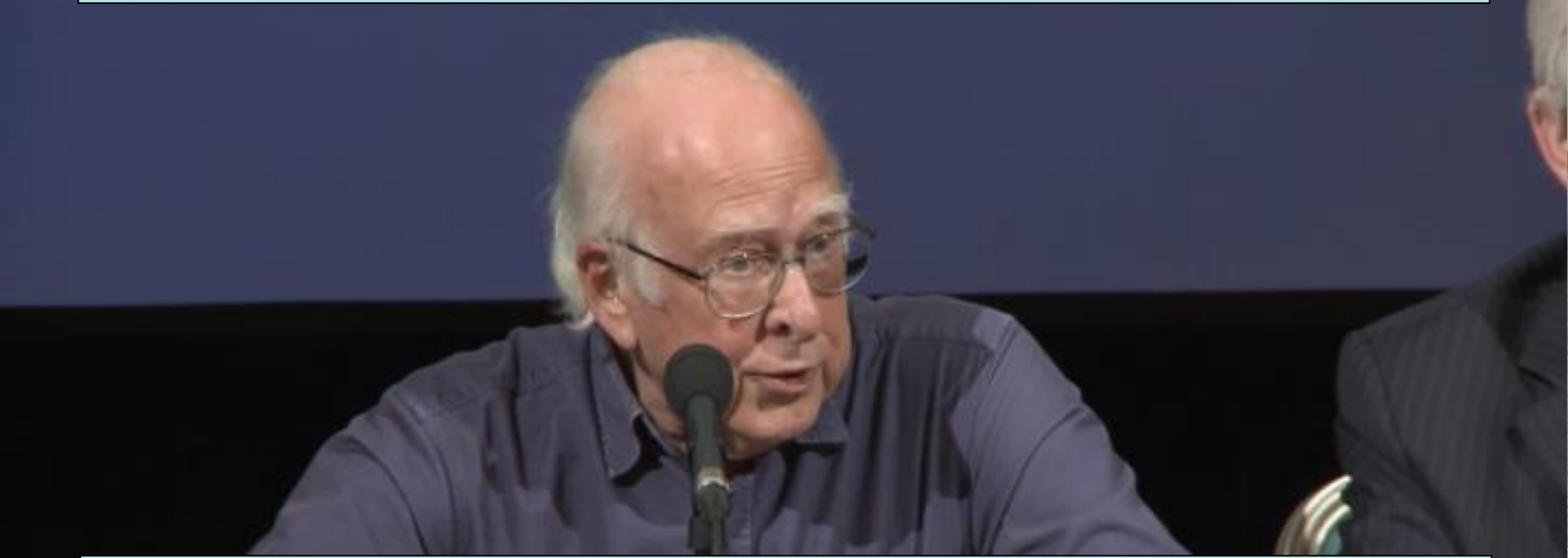
Global fit

Lee

JE & Tevong You, arXiv:1303.3879

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

Dixit Swedish Academy



Today we believe that “Beyond any reasonable doubt, it is a Higgs boson.” [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879

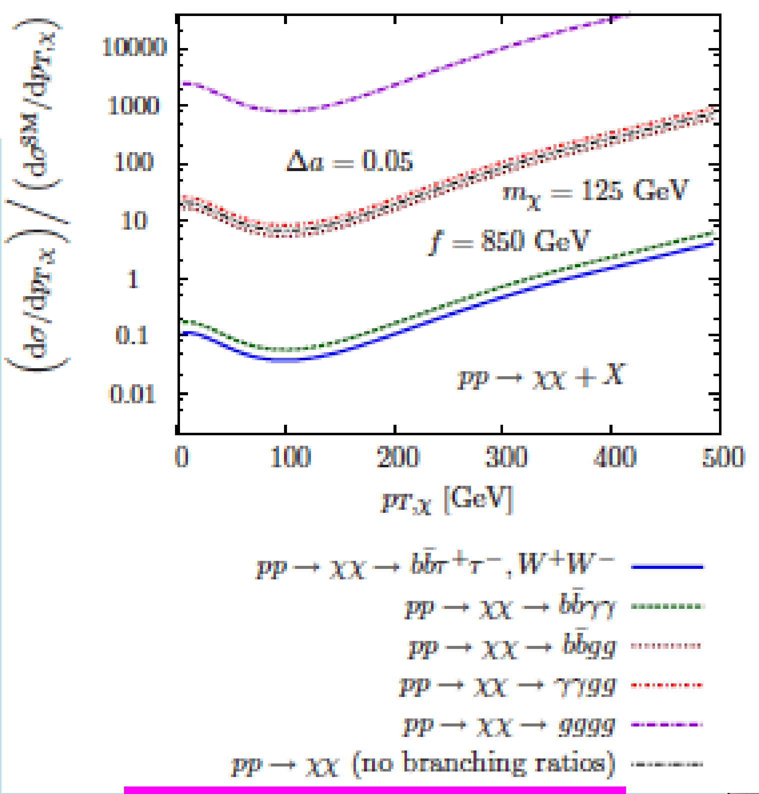
From a-Theorem to Double-Higgs Production?

- Beautiful new, fundamental result in field theory
- Infra-red scale anomaly < ultra-violet anomaly

Schwimmer

$$\int_0^\infty ds \frac{Im S(s,M)}{s^3} = a_{UV} - a_{IR}$$

- Dilaton scattering sum rule, anomalous couplings
- Higgs = electroweak dilaton
- Anomalous couplings in composite Higgs models
- Double-Higgs production?



Dolan, Englert & Spannowsky

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, … (???)

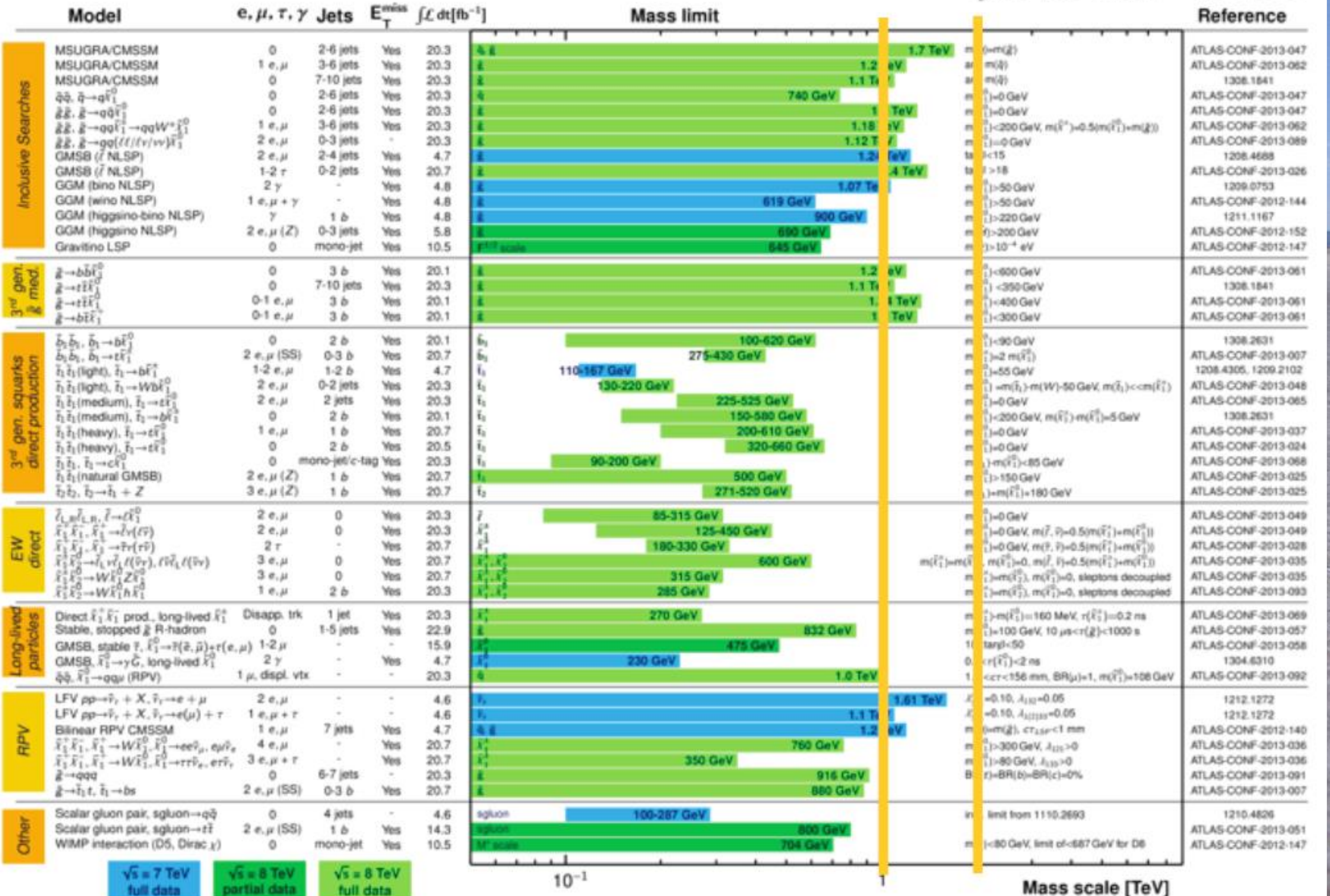
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

Wingerter-Seez

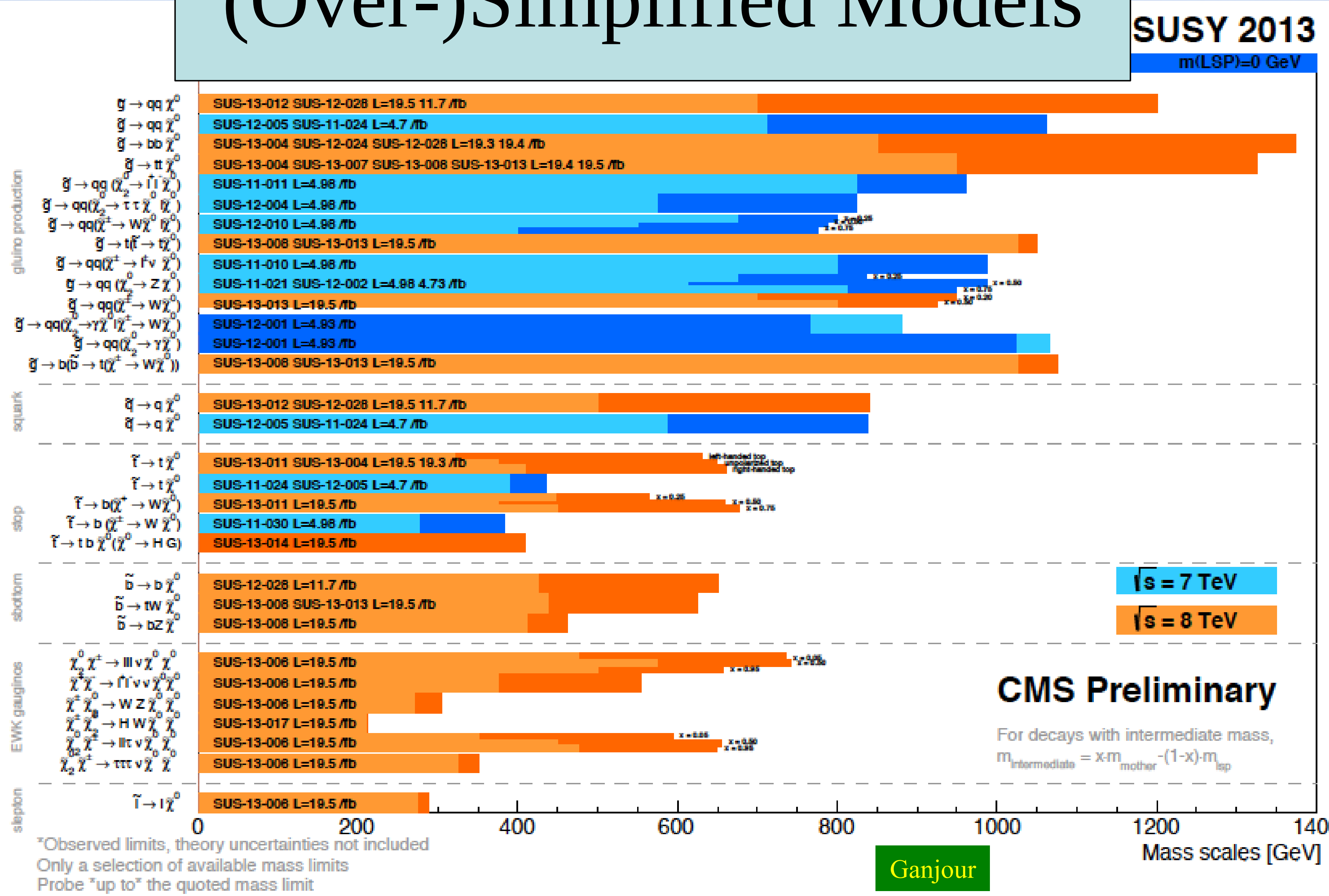
ATLAS Preliminary

$\int \mathcal{L}\,dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV



*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

(Over-)Simplified Models

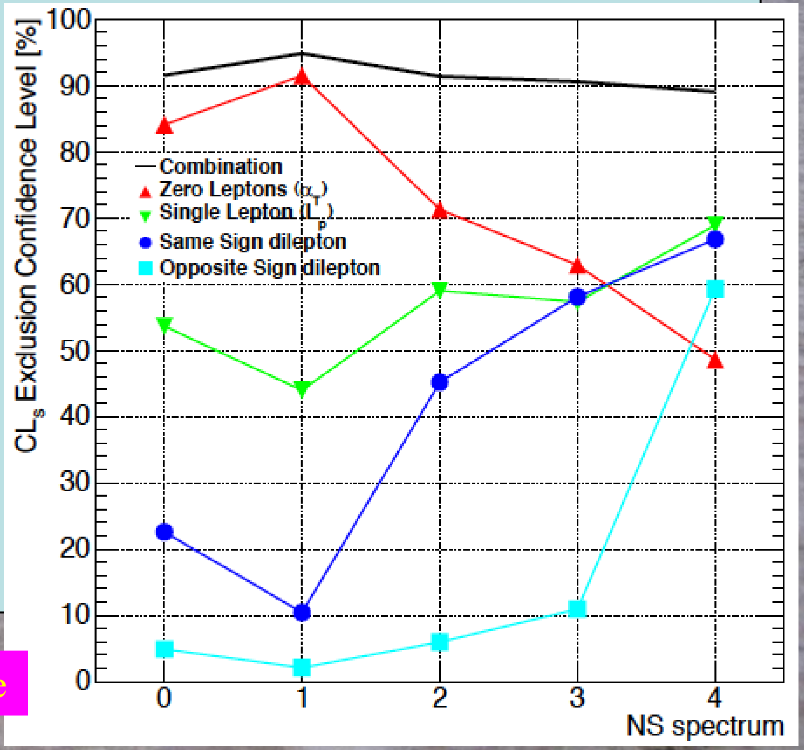


Ganjour

Simplified Models: Caveat Emptor

- Any realistic model will yield signature with probability < 100%
- Any realistic model will yield > 1 signature
- Develop tools to combine simplified signatures
- Significance may be not depend on model details

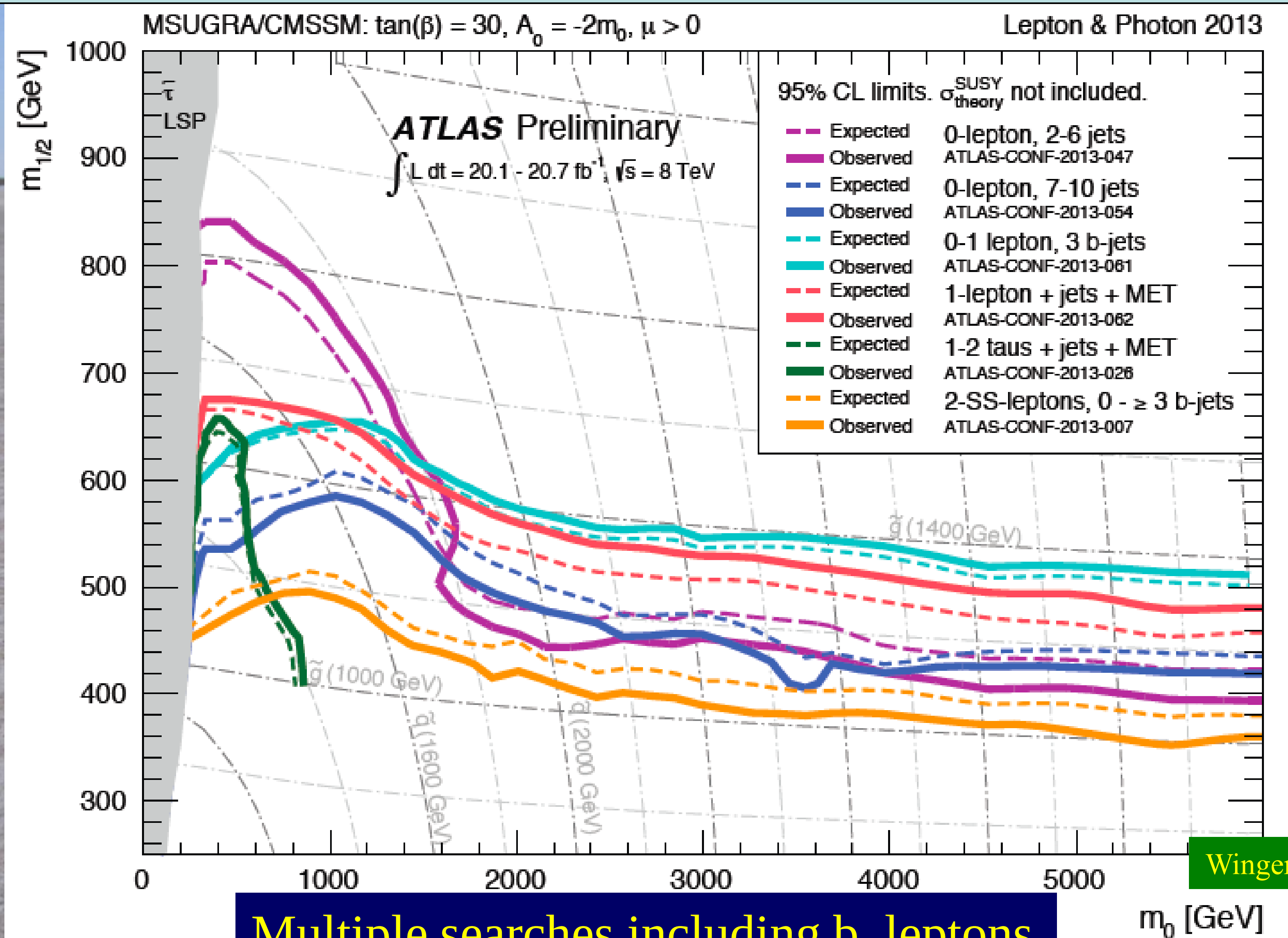
Kulkarni //



Buchmueller & Marrouche


??
Low Energy SUSY
LHC
Ibanez

Searches with 8 TeV Data



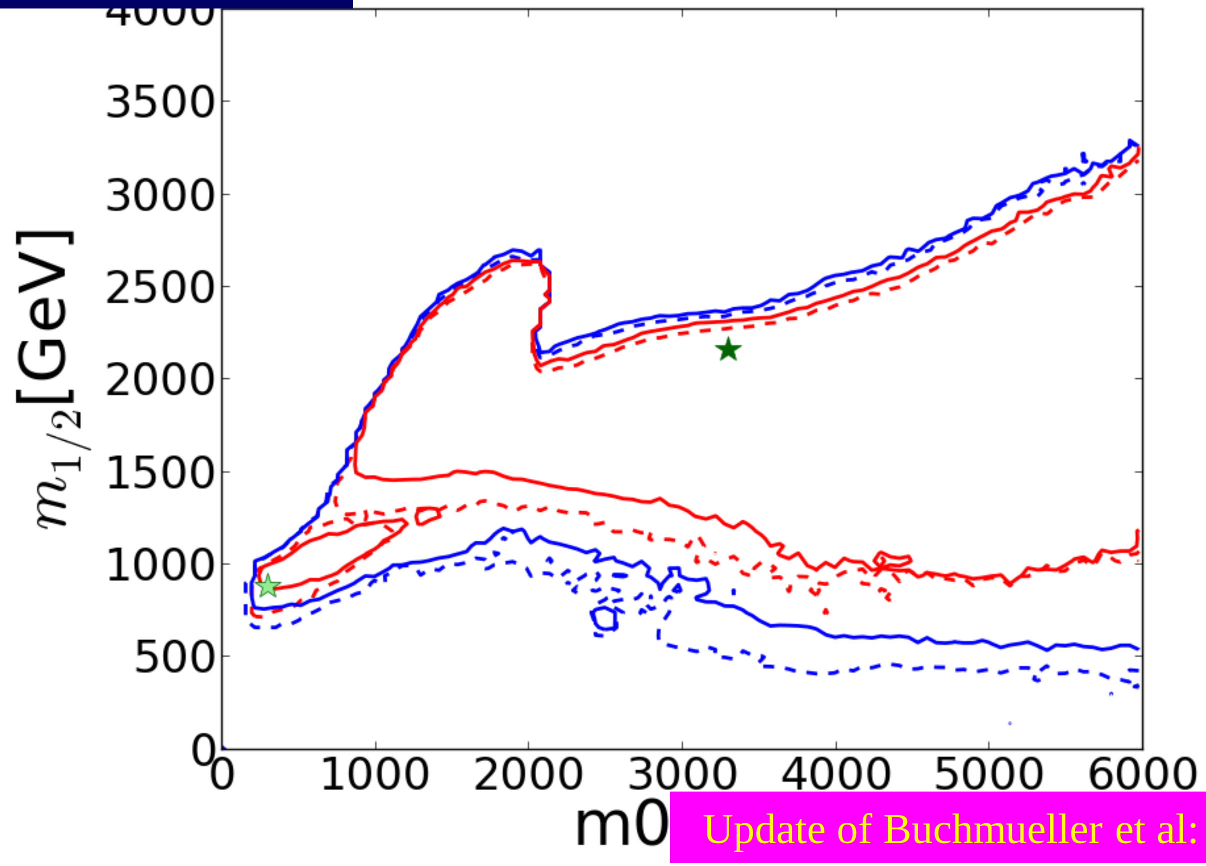
Multiple searches including b, leptons

Wingerter-Seez

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

Scan of CMSSM



Olive

Update of Buchmueller et al: arXiv:1207.3715

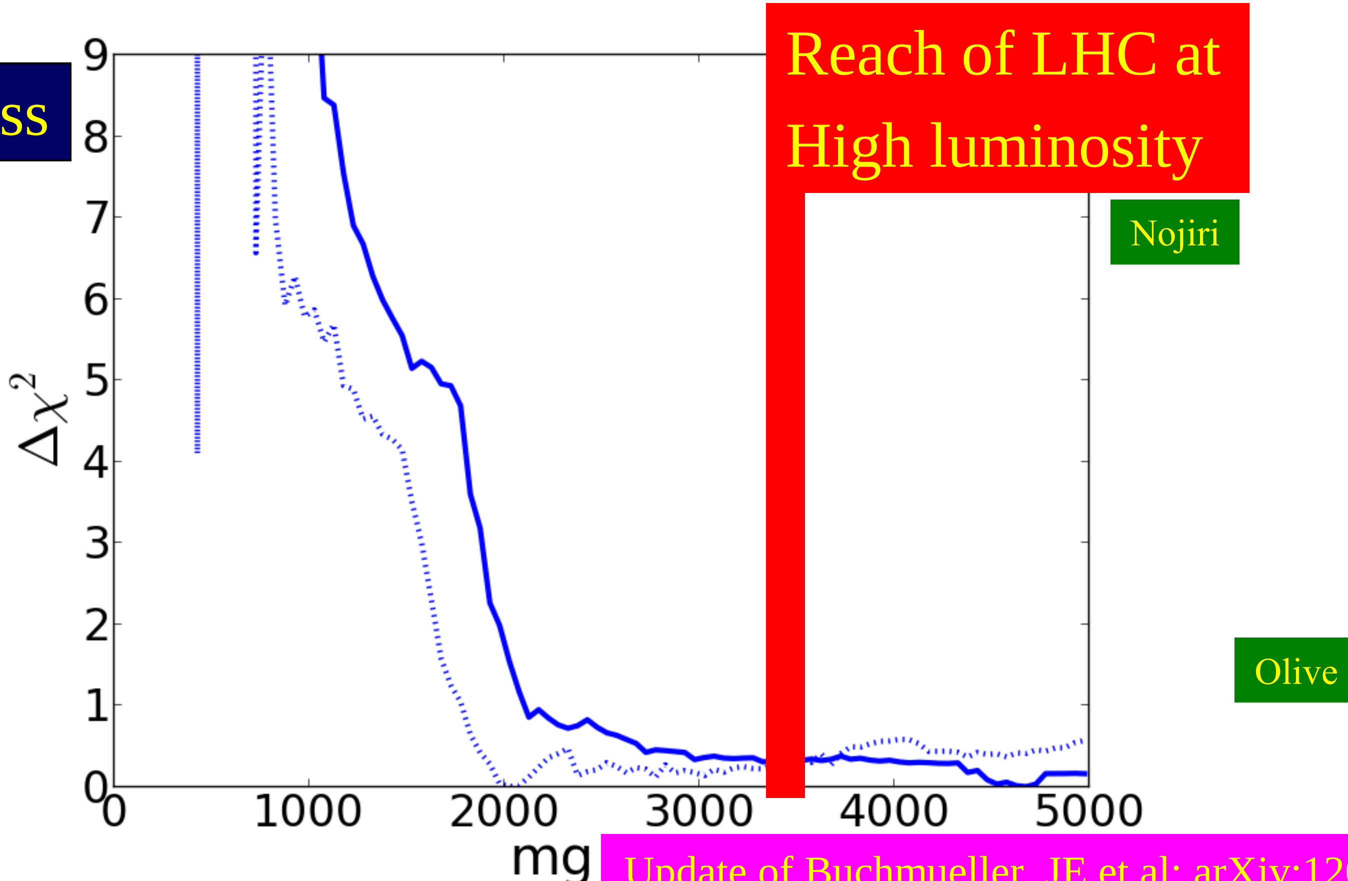
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

p-value of simple models ~ 5%, ~ SM

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

Gluino mass

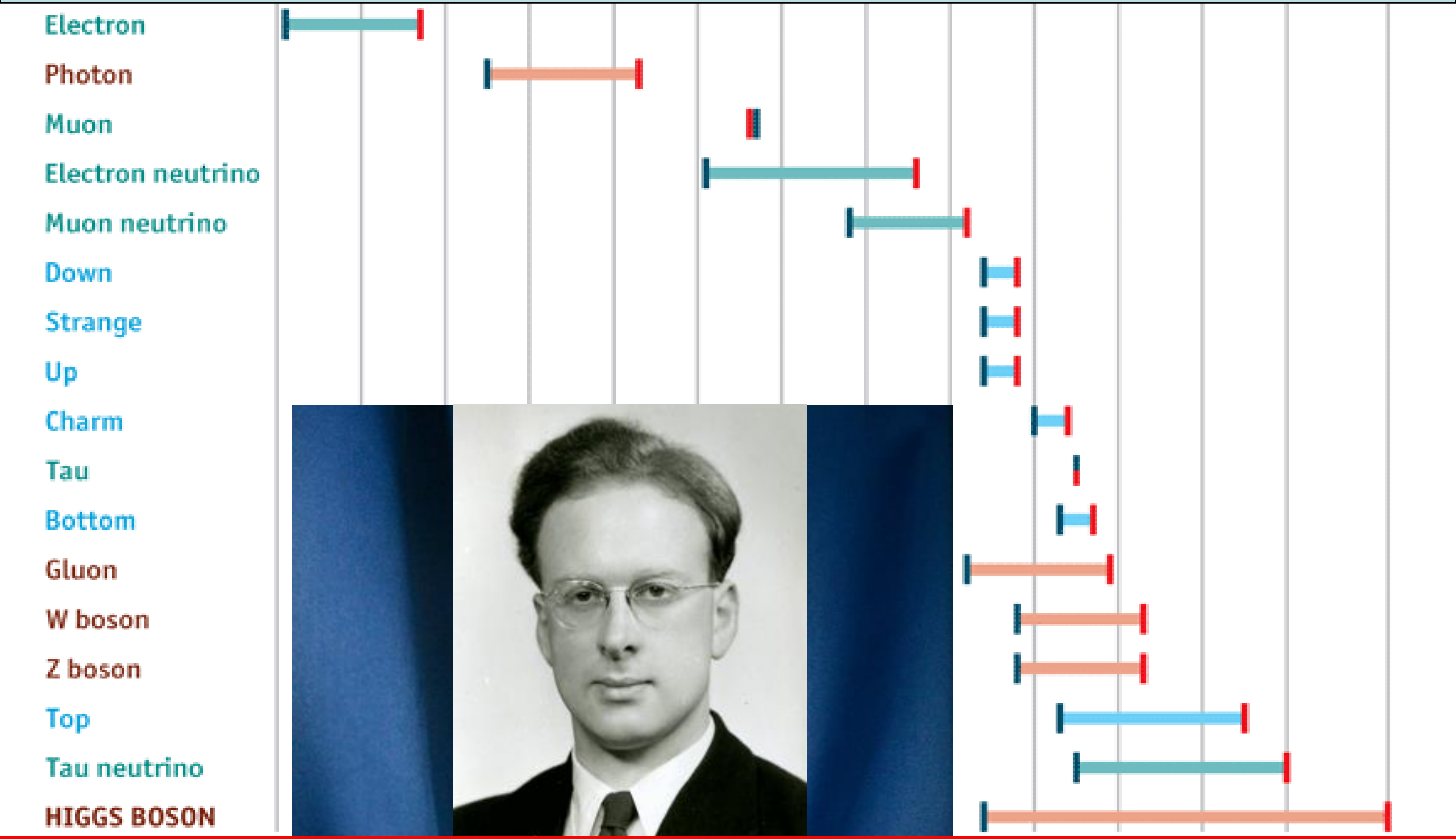


Update of Buchmueller, JE et al: arXiv:1207.3715

Favoured values of gluino mass significantly above pre-LHC, > 2 TeV

New Particles:

Years from Proposal to Discovery



Supersymmetry |------------------- ?

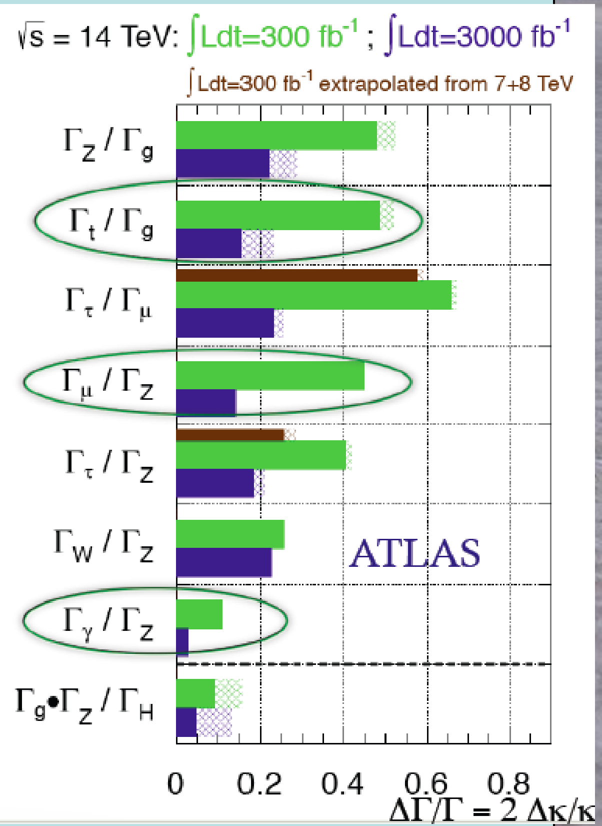
What Next: A Higgs Factory?

Nojiri

To study the 'Higgs' in detail:

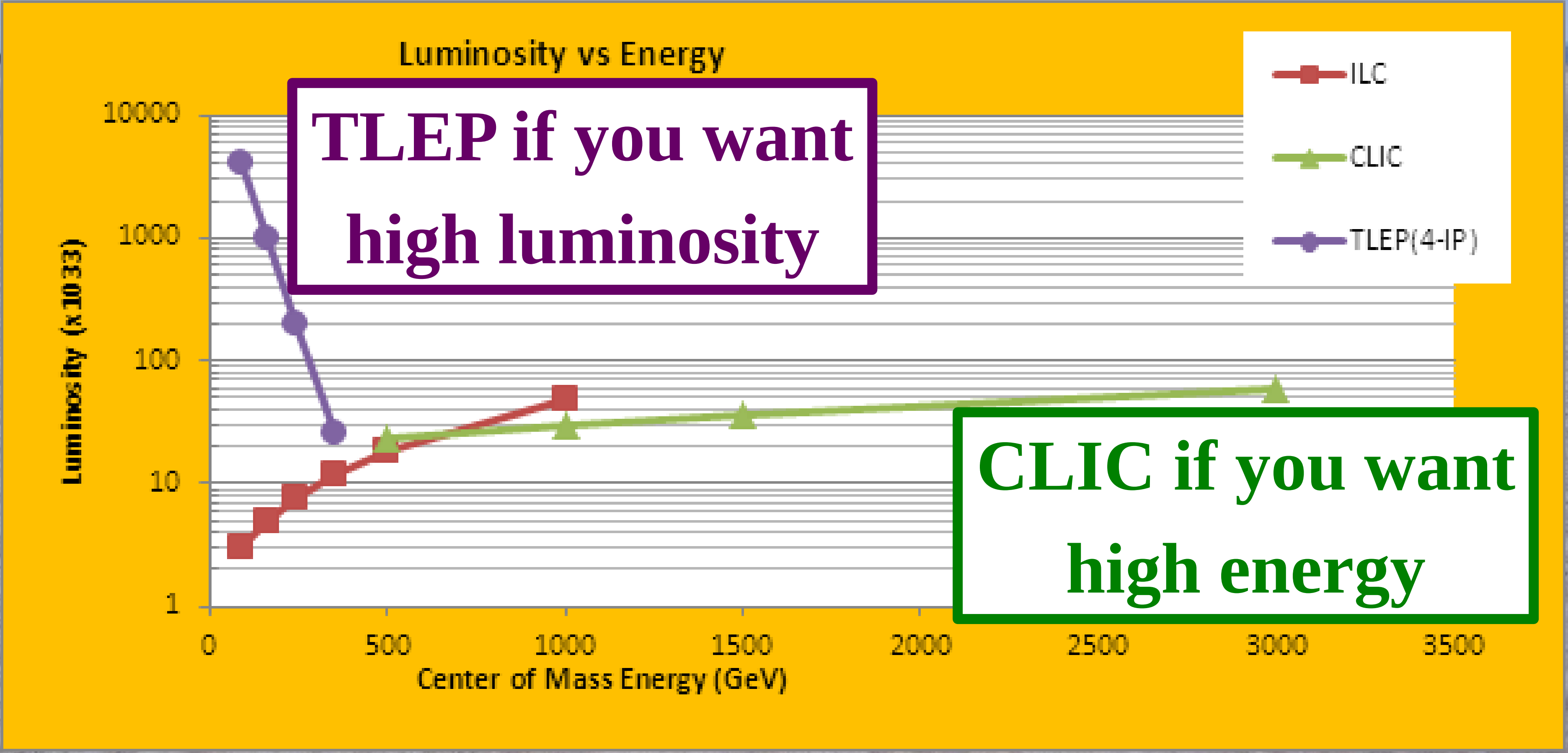
- The LHC
  - Rethink LHC upgrades in this perspective?
- A linear collider?
  - ILC up to 500 GeV
  - CLIC up to 3 TeV

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



Possible Luminosities and Energies of e^+e^- Colliders

Nojiri



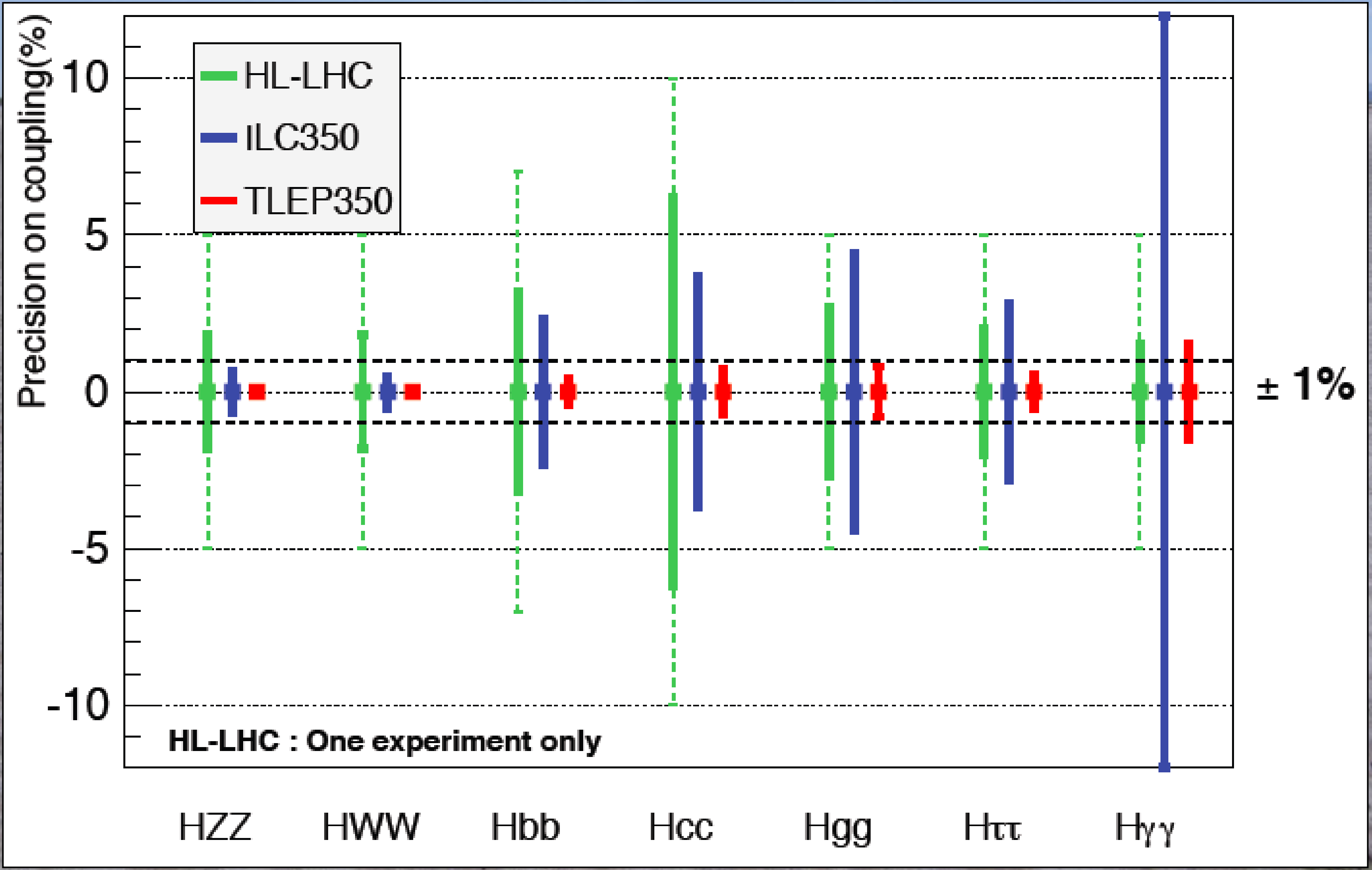
A Vision for the 21st Century

350 GeV Circular e^+e^- collider

100 TeV proton-proton collider

Similar ideas in China

Comparison of Possible Higgs Factory Measurements



TLEP:
Part of a Vision for the Future

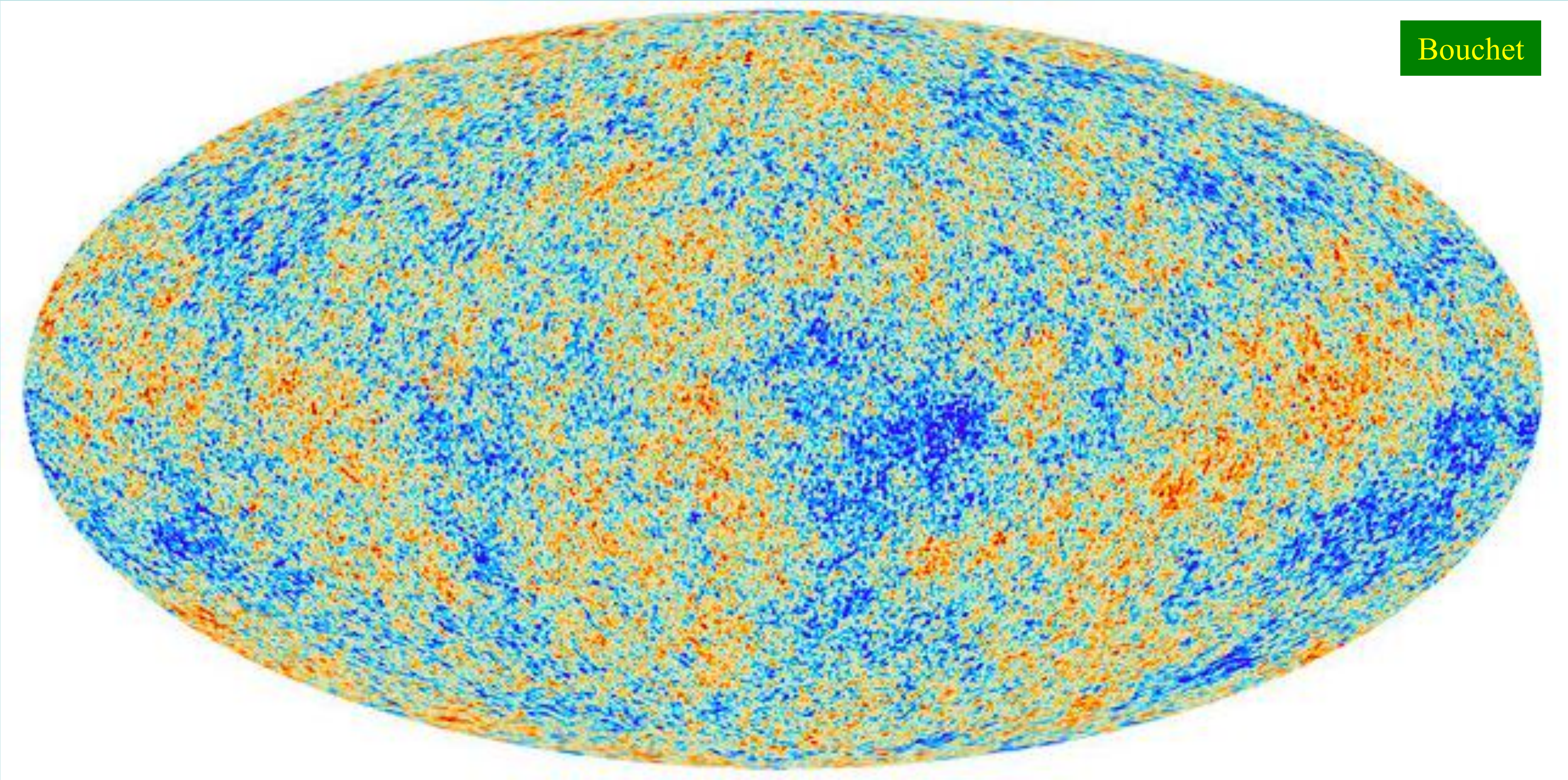
Exploration of the 10 TeV scale

Direct (VHE-LHC) + Indirect (TLEP)

Need major effort to develop the physics case

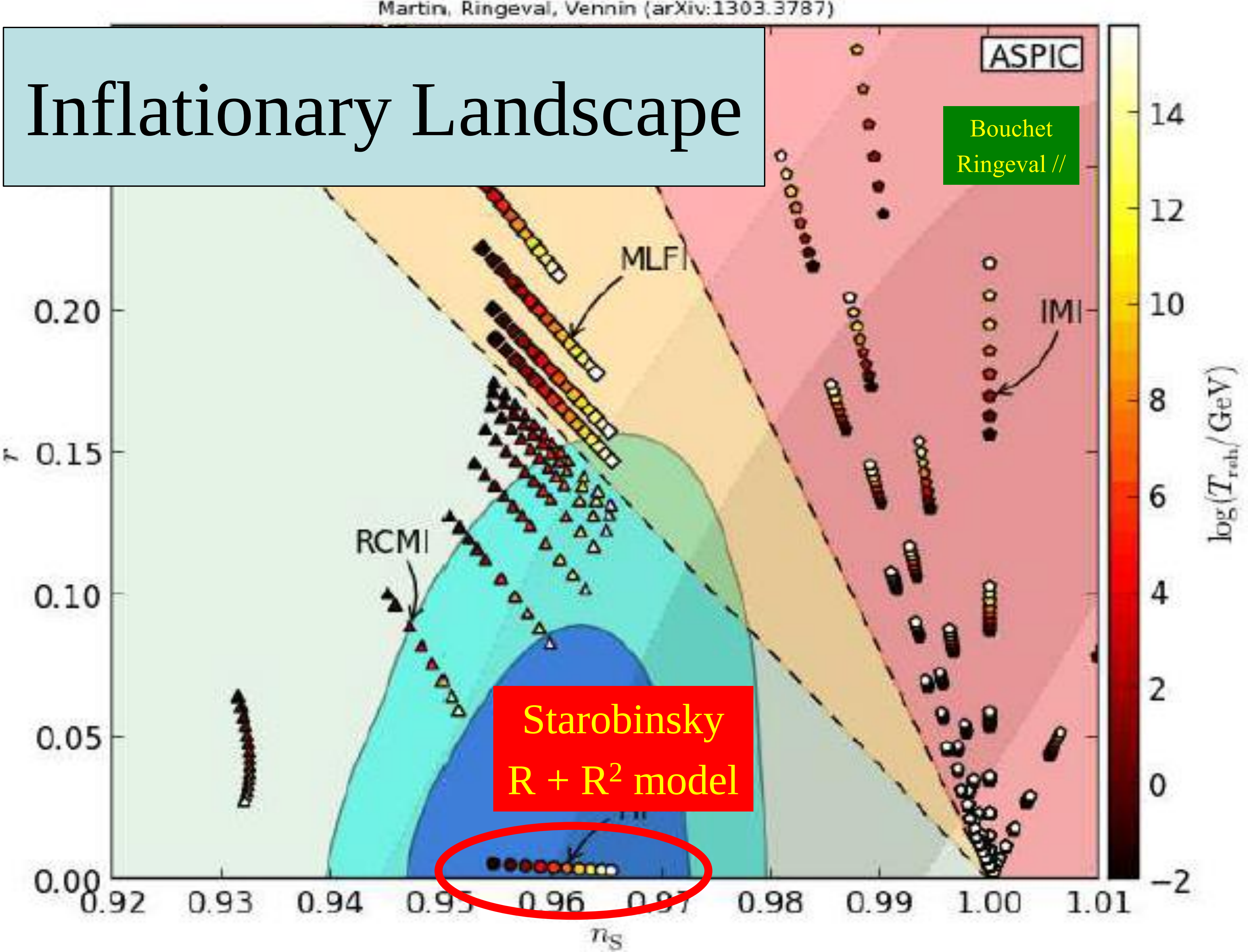
Work together

Cosmological Inflation in Light of Planck



- **A scalar in the sky? Supersymmetry/gravity?**

Inflationary Landscape



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

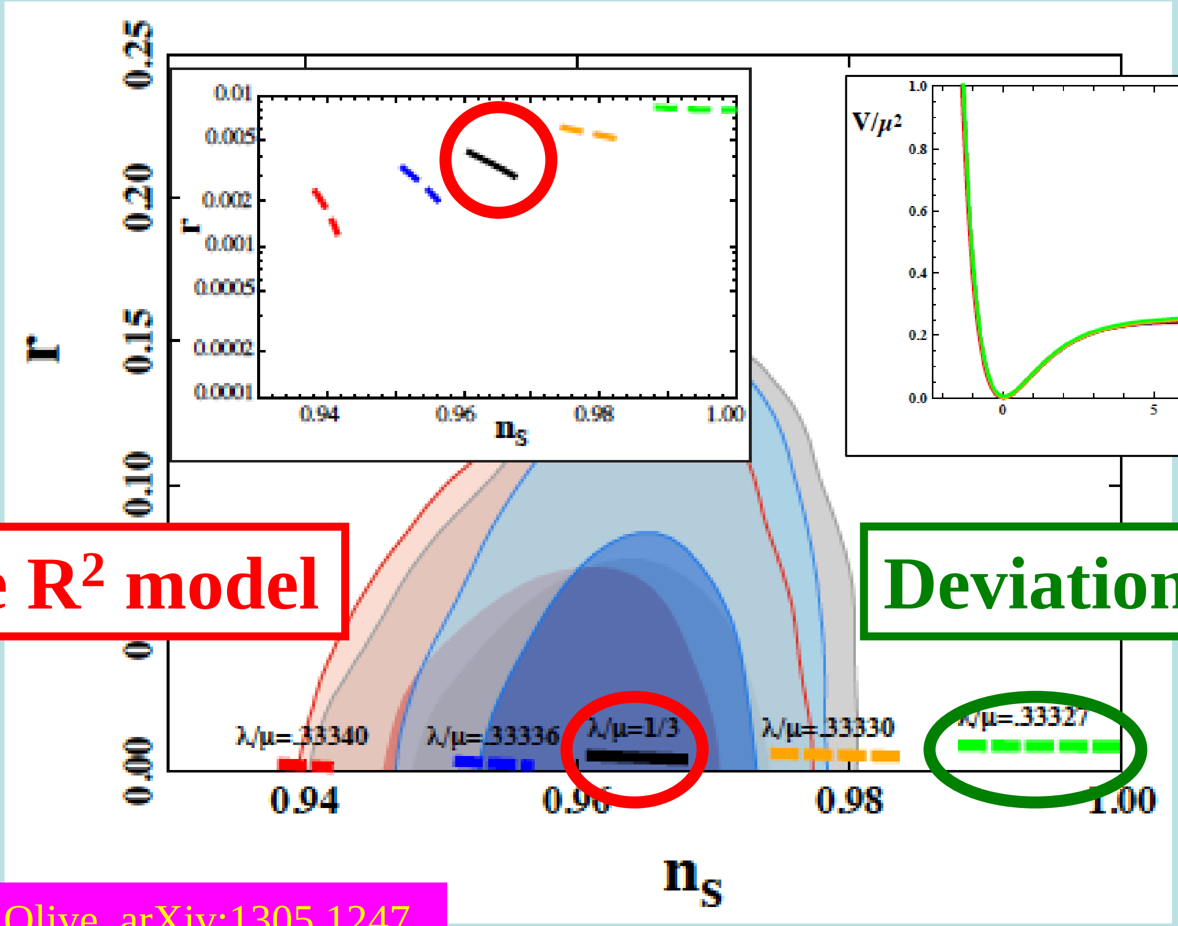
No-Scale Supergravity Inflation

- The only good symmetry is a local symmetry
- Early Universe cosmology needs gravity
- **Supersymmetry + gravity = Supergravity**
- **BUT**: potentials in generic supergravity models have potential 'holes' with depths $\sim - M_P^4$
- 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

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

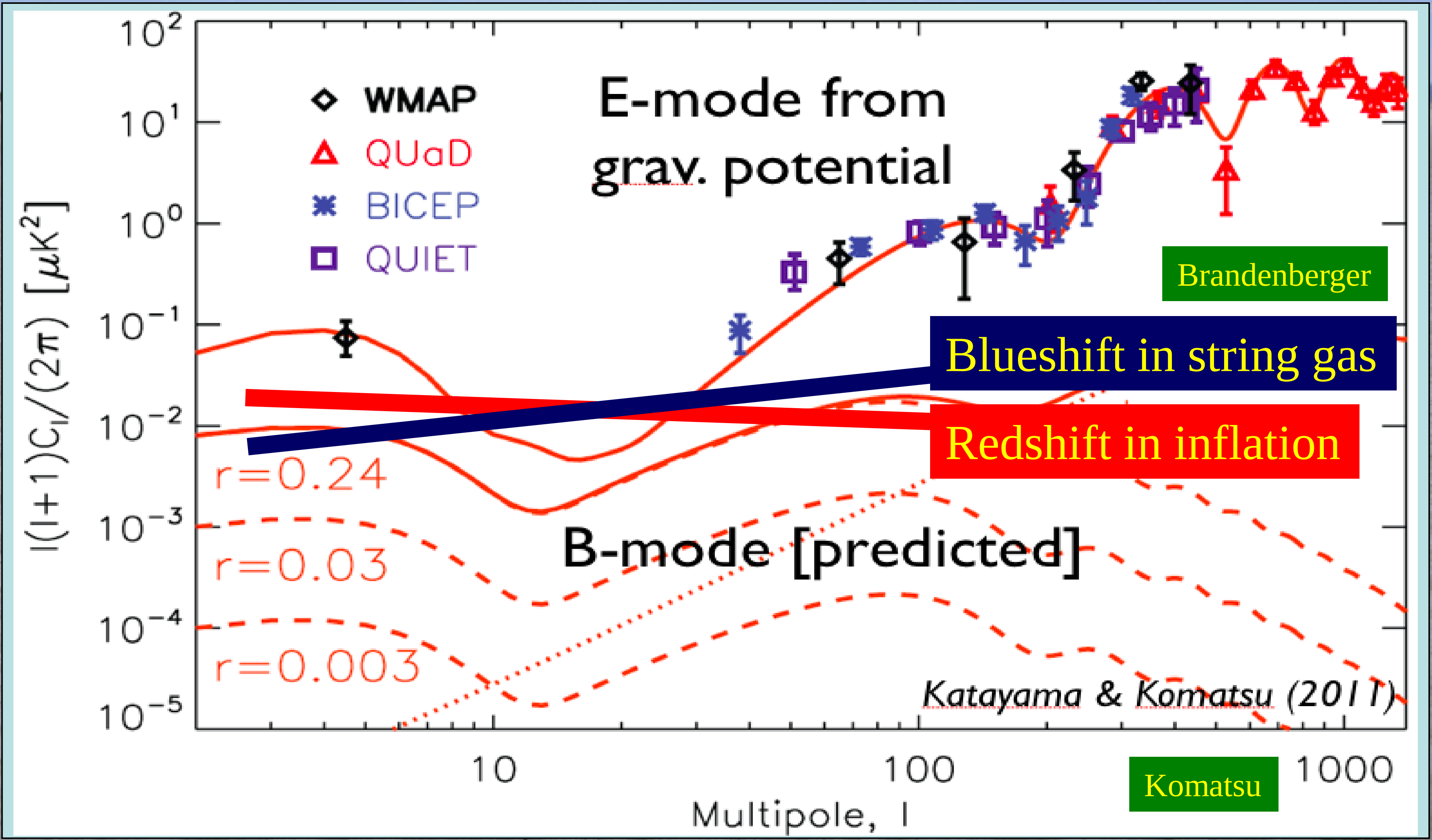


Looks like R^2 model

Deviations possible

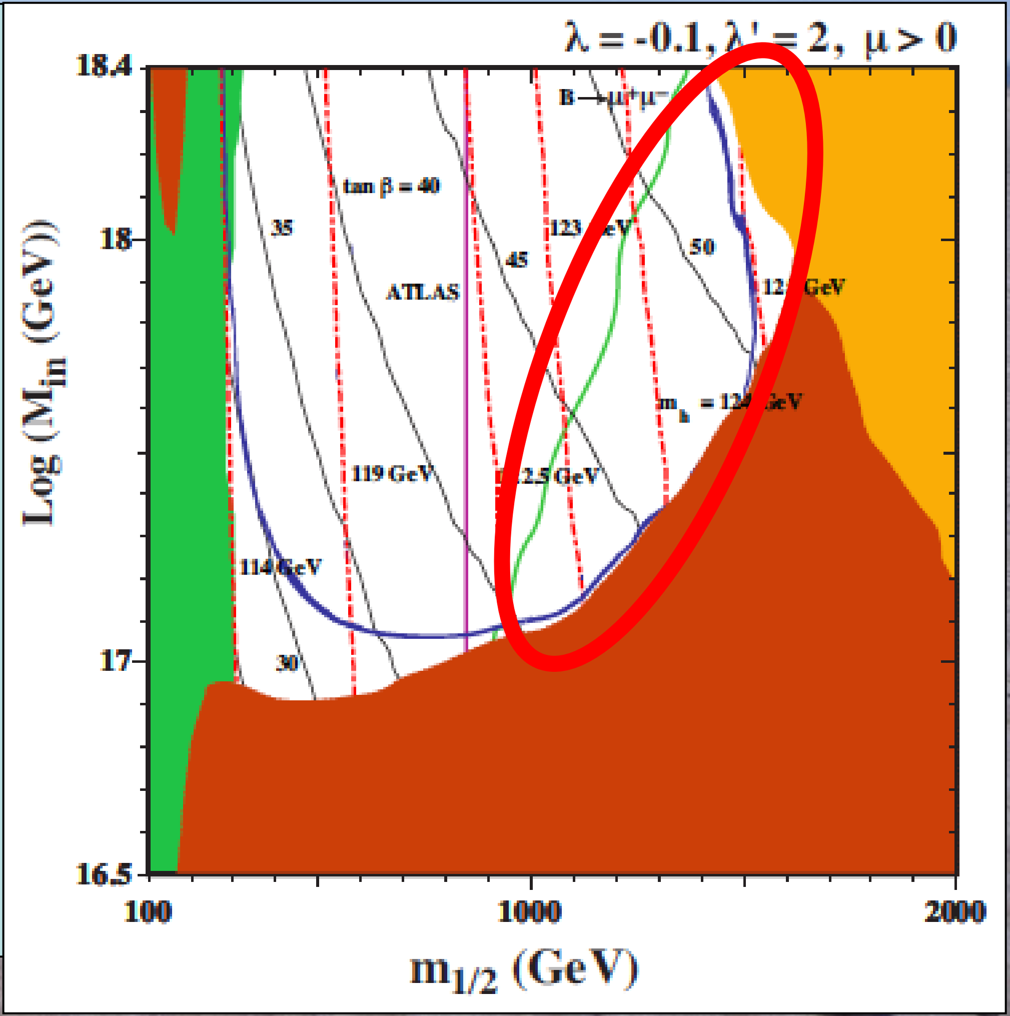
JE, Nanopoulos & Olive, arXiv:1305.1247

Look for B-Mode Polarization



No-Scale Framework for Particle Physics & Dark Matter

- Incorporating Starobinsky-like inflation, leptogenesis, neutrino masses, LHC constraints, supersymmetric dark matter,
- Stringy origin…?

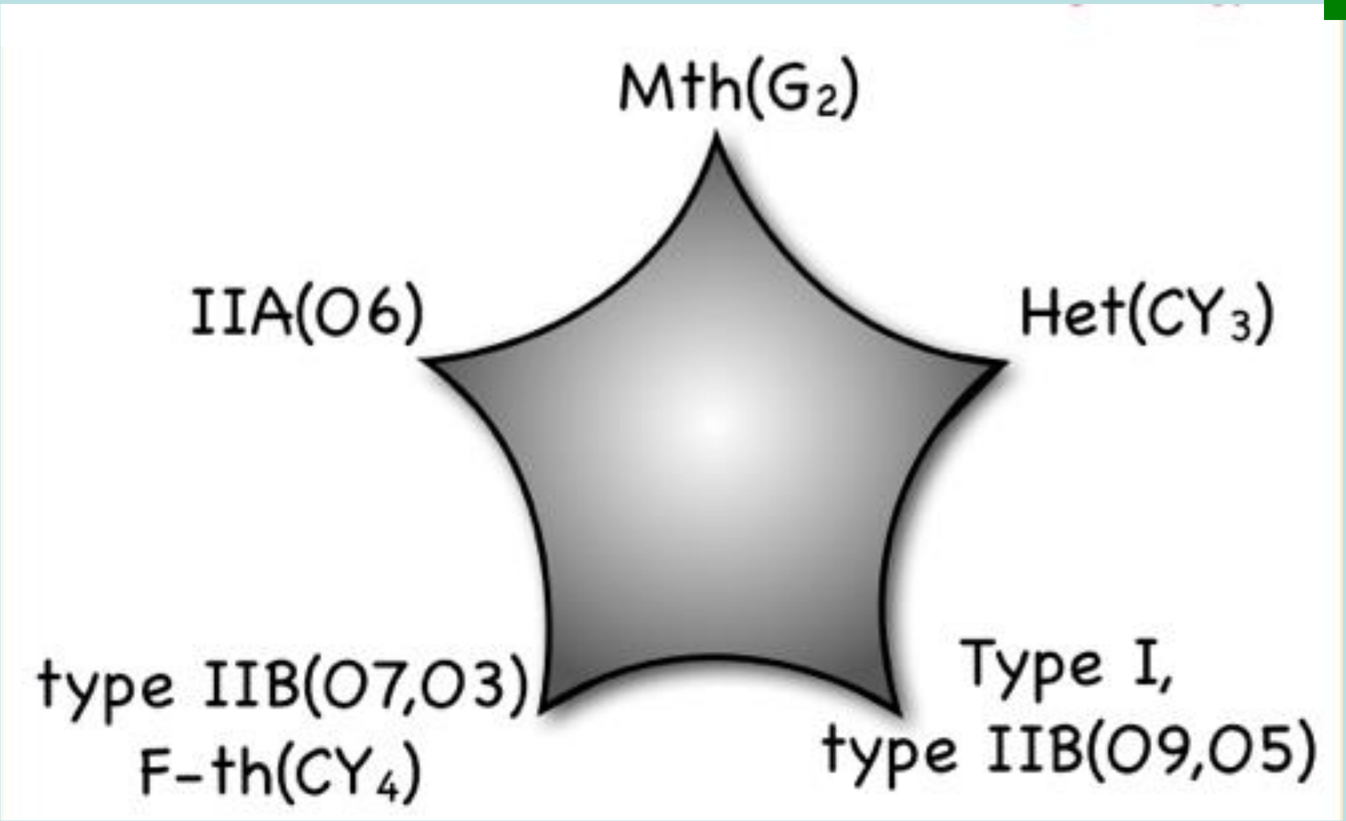


JE, Nanopoulos & Olive, arXiv:1310.4770

String Model-Building

Ibanez
Quevedo
Lukas
Shiu

- Many possible approaches:



- Many possibilities within each approach

E.g., Systematic Approach to Calabi-Yau Spaces

Number of consistent SU(5) GUT models with correct indices:

$h^{1,1}(X)$	1	2	3	4	5	6	total
#models	0	0	6	552	21731	41036	63325

After demanding absence of $\bar{10}$ and presence of $5 - \bar{5}$ pair:

34989 models

Available at:

http://www-thphys.physics.ox.ac.uk/projects/CalabiYau/linebundlemodels/index.html

Roughly, a factor 10 more models per CY for each additional Kahler parameter!

Lukas

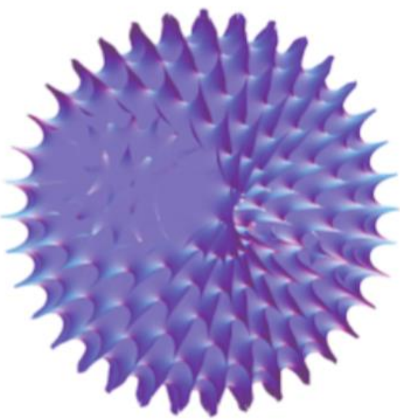
- How to choose between them?
- Optimal use of bottom-up information?
- Still ambiguity? A********* principle?

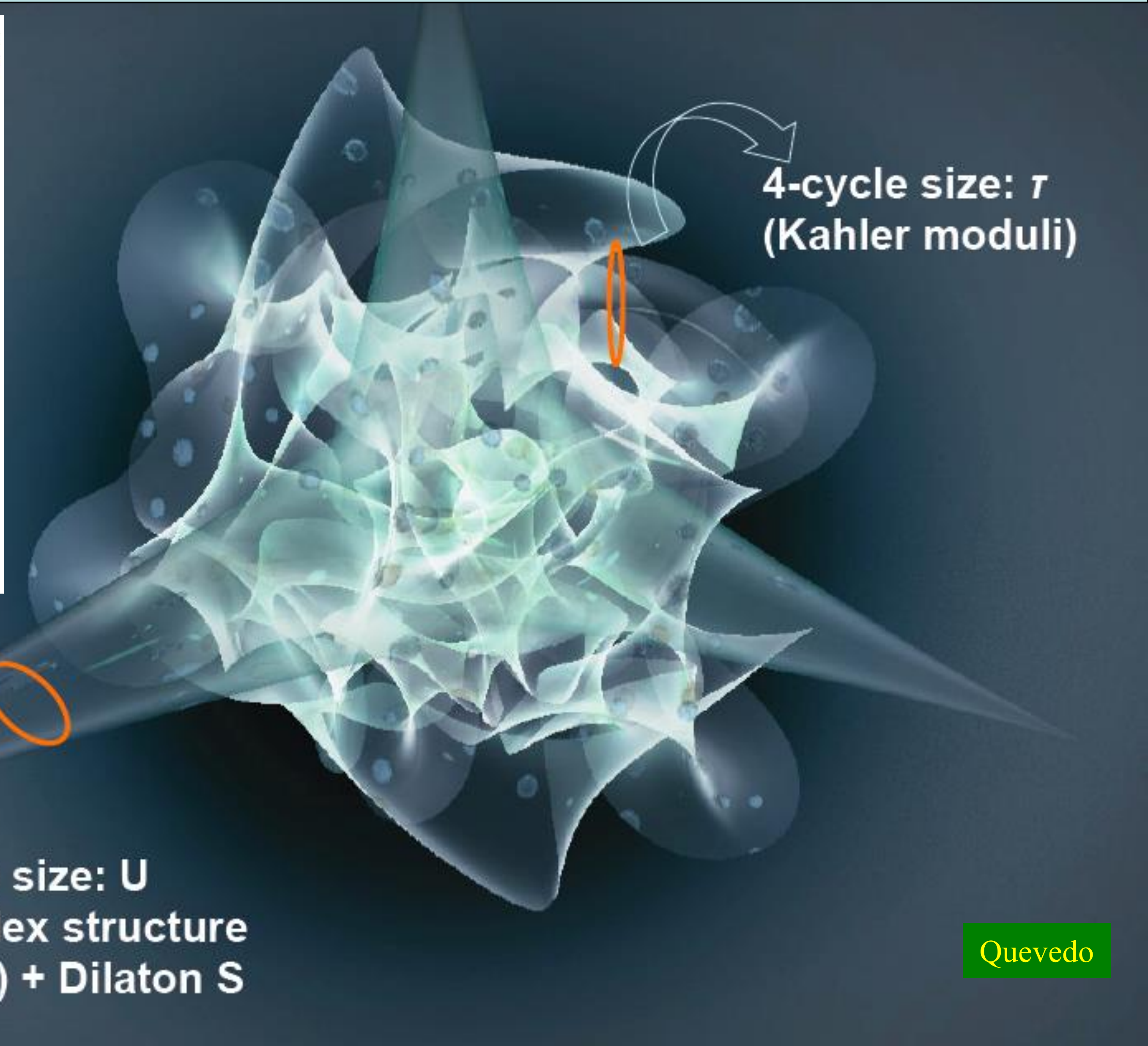
Ibanez

Calabi-Yau-Ology

Simple example:

$\mathbf{P}^4_{11169}$

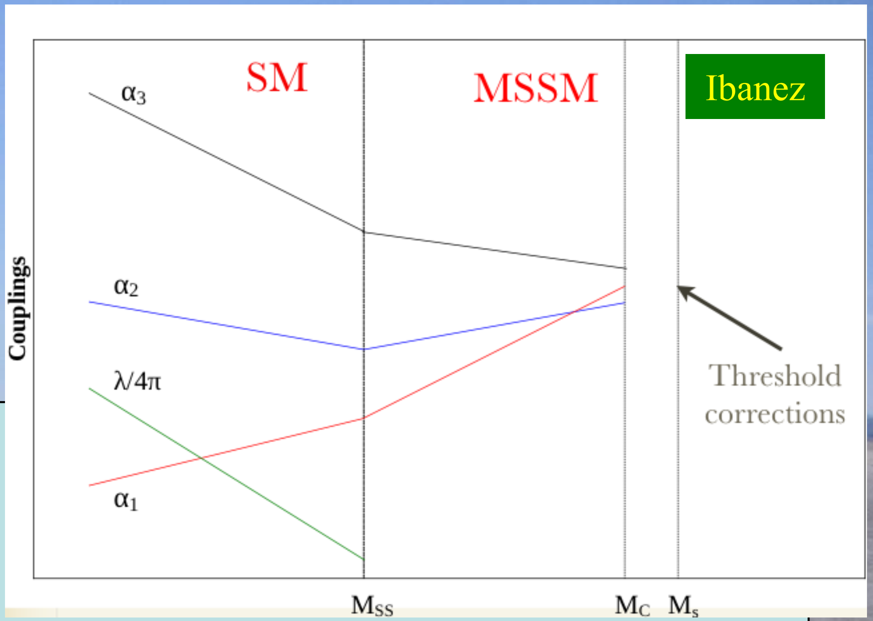


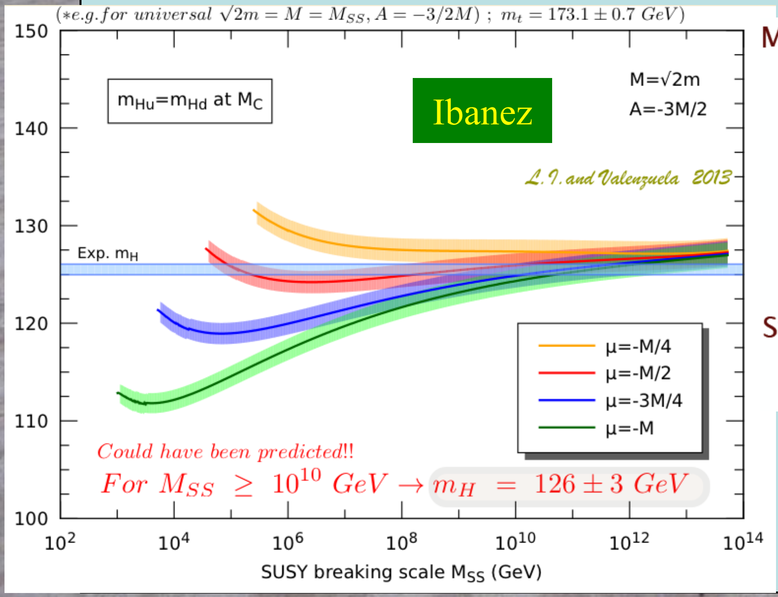


Quevedo

Sample Approaches

- High SUSY-breaking scale?
- Large volume? Quevedo
- Efforts to engage with phenomenology:
  - Higgs mass — Dark matter — Models of inflation





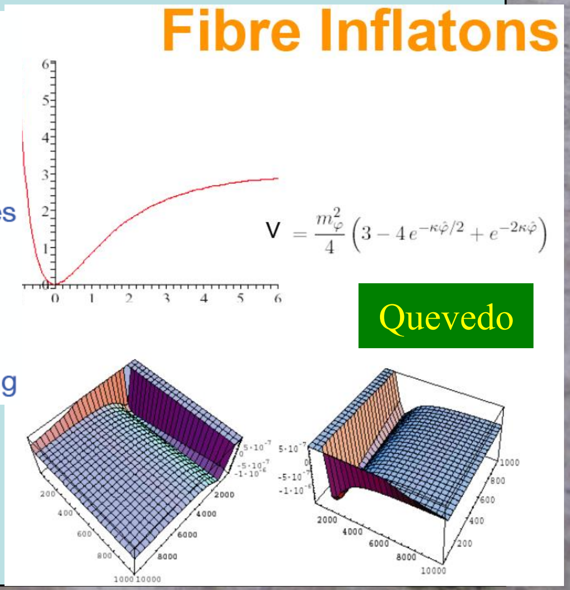
Mini-charged Dark Matter scenarios:

- Field theory construction
- Constraints from Quantum Gravity
- Charge quantization and millicharges

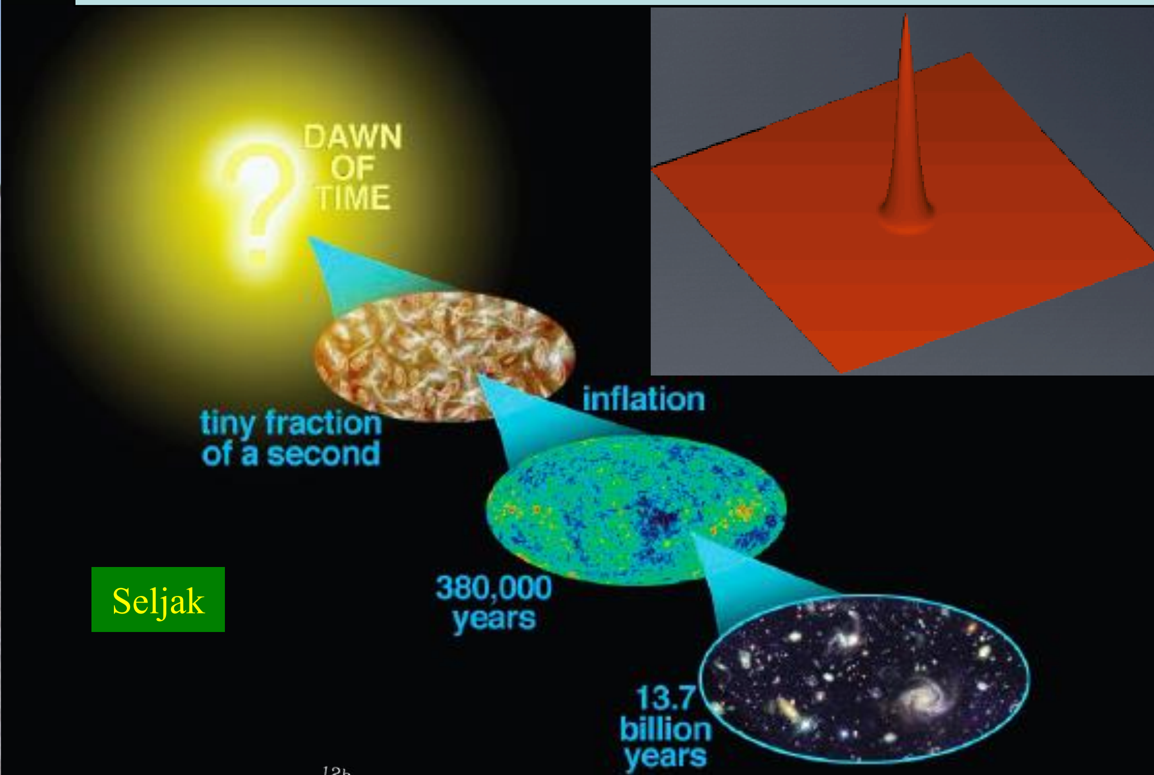
Stueckelberg portal

- Massive U(1)'s and their mass mixing

Shiu



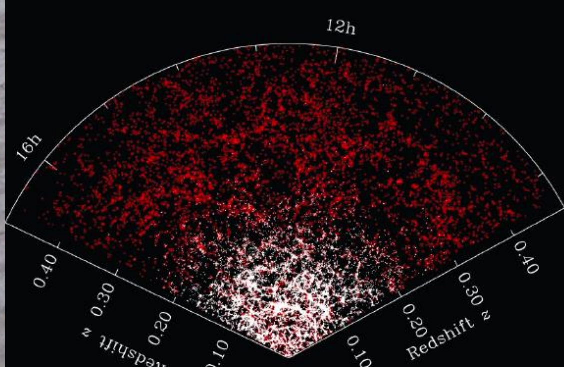
From Inflation to Structures



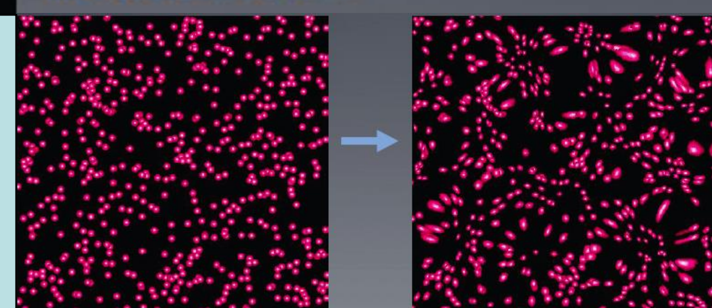
Seljak

- Perturbations can be measured at different epochs:
1. CMB z=1000
2. 21cm z=10-20 (?)
3. Ly-alpha forest z=2-4
4. Weak lensing z=0.3-2
5. Galaxy clustering z=0-2

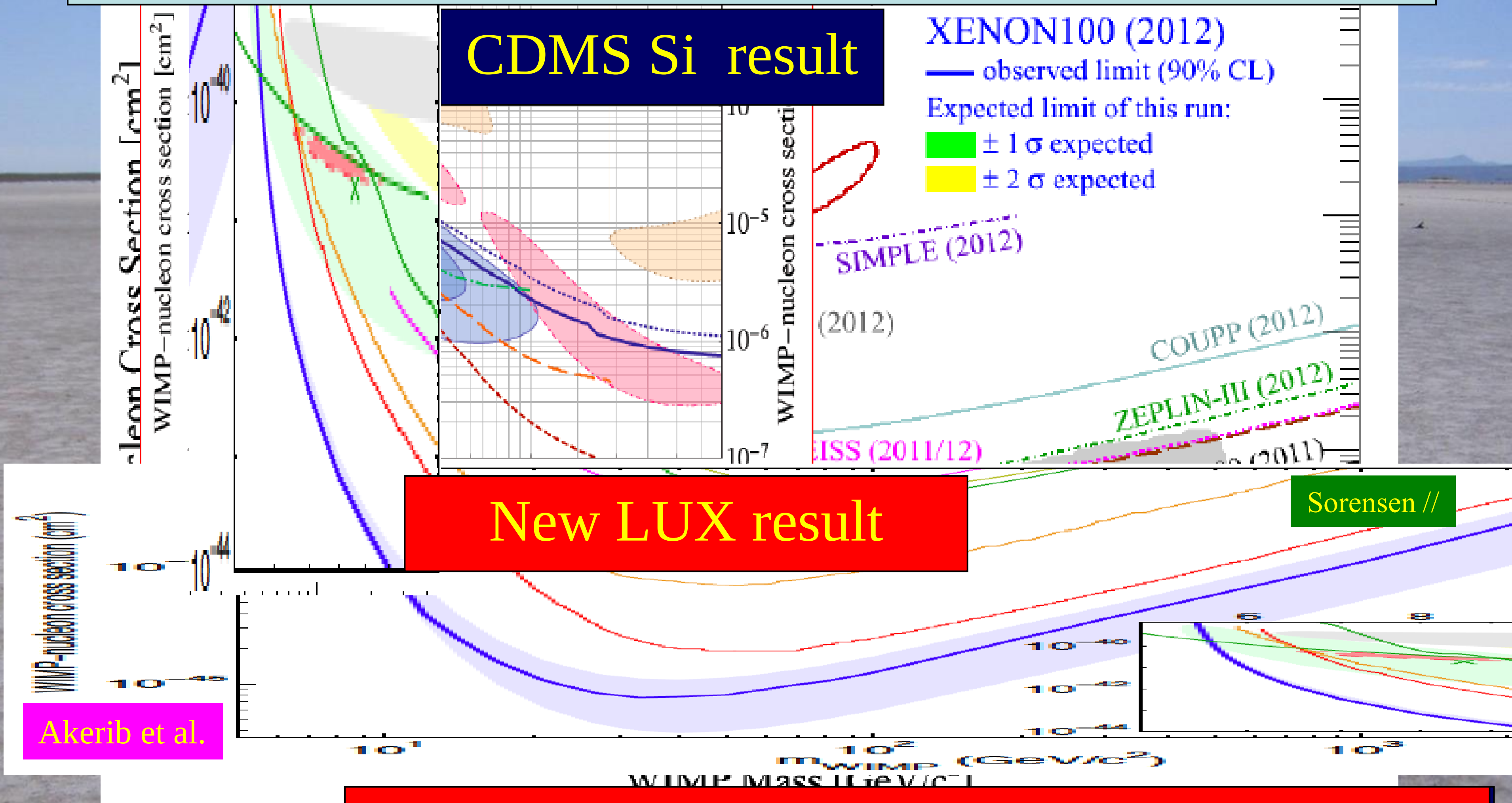
Sensitive to dark energy, neutrinos…



- Growth of structures
- Baryon acoustic oscillations



Direct Searches for Dark Matter



New best limit: LUX with 85 days of data

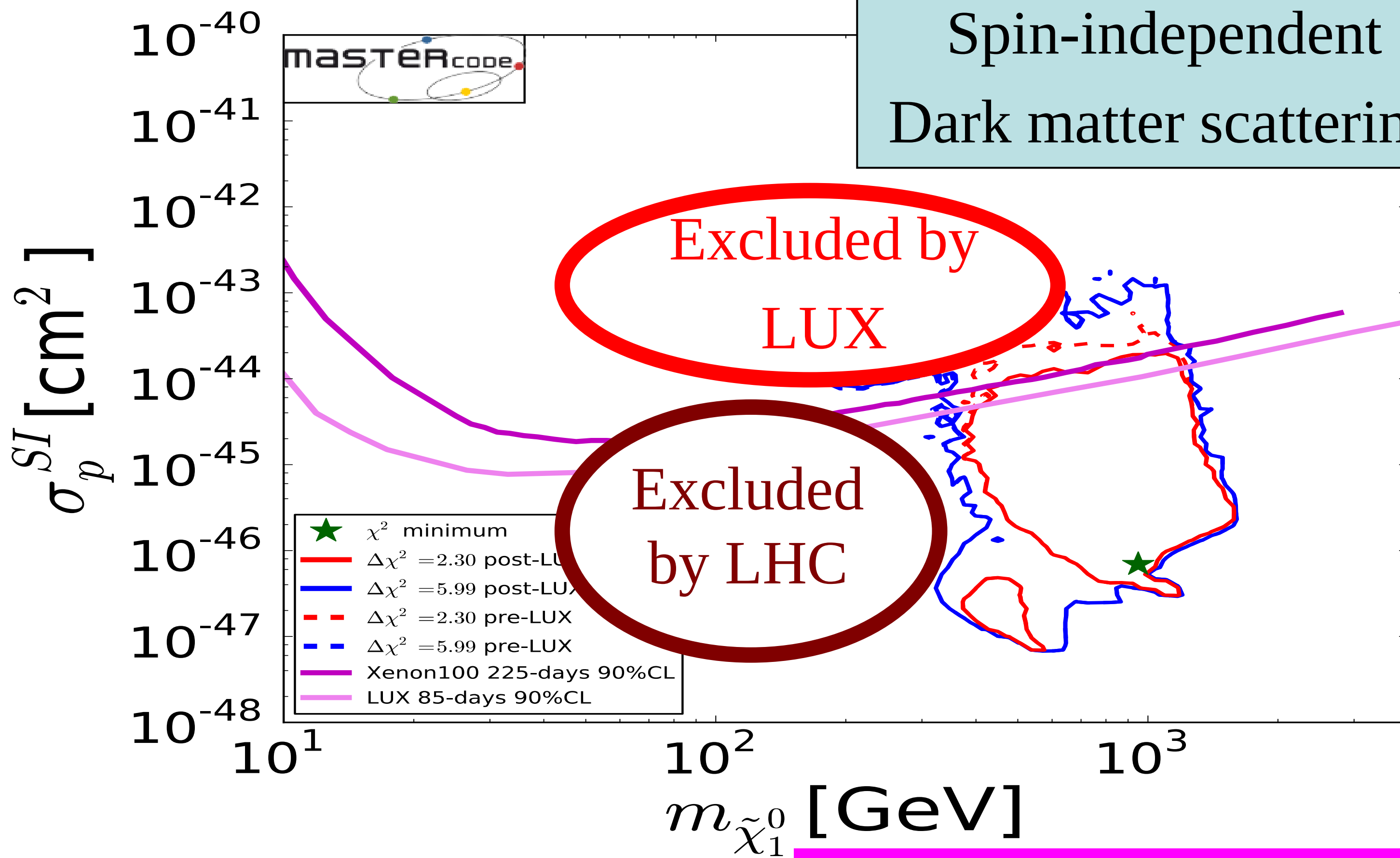
Resolves confusion at low WIMP masses?

Aprile et al.

Global Fit to Supersymmetric Model

2012 ATLAS + CMS with 20/fb of LHC Data

Spin-independent
Dark matter scattering



Olive

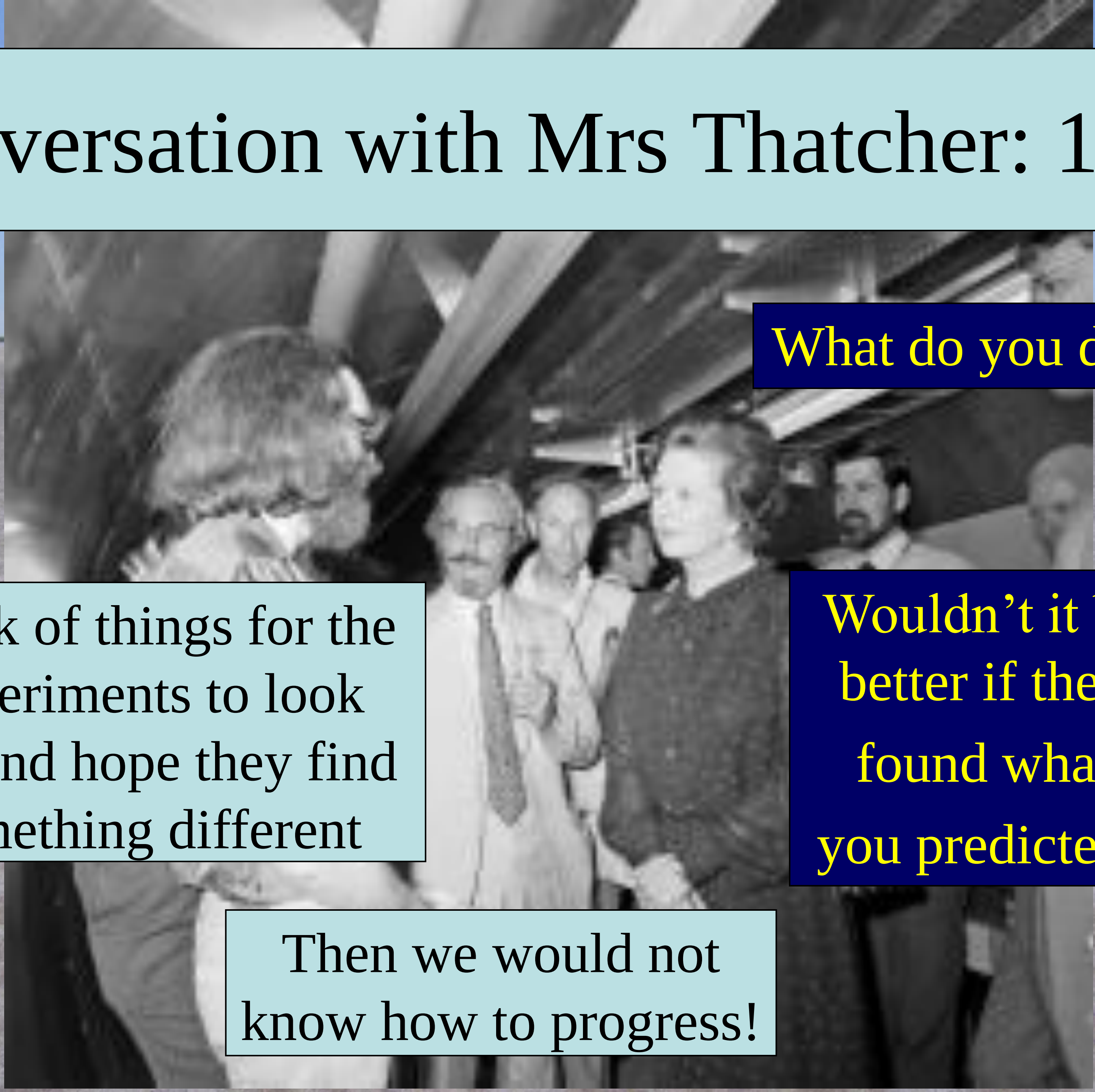
Update of Buchmueller, JE et al: arXiv:1207.3715

Favoured values of dark matter scattering cross section significantly below XENON100, LUX

No BSM? History is on our Side

- ***"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

Conversation with Mrs Thatcher: 1982



What do you do?

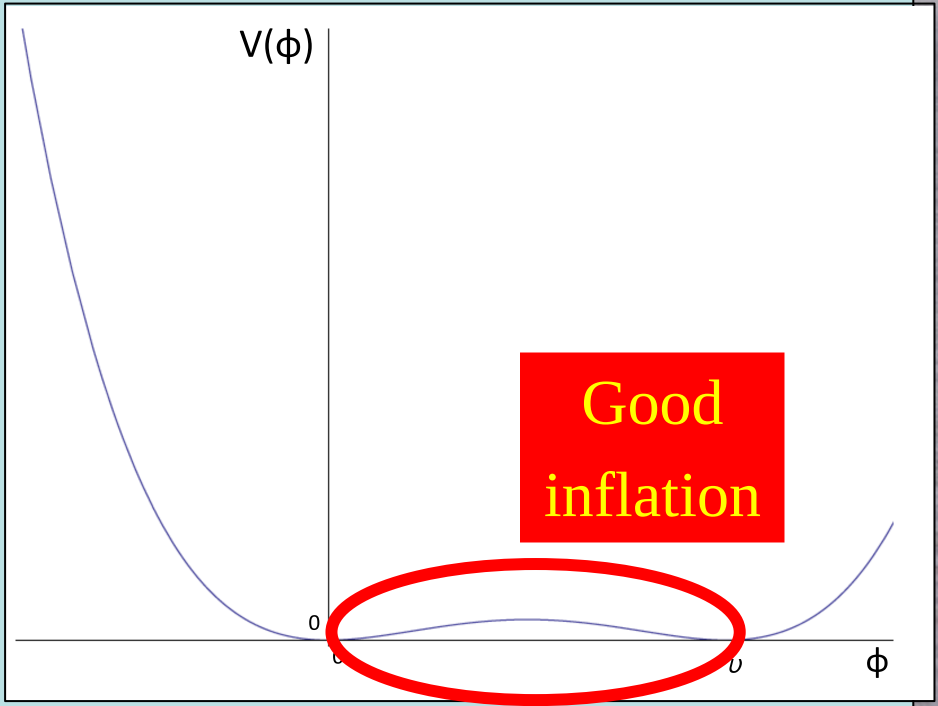
Think of things for the experiments to look for, and hope they find something different

Wouldn’t it be better if they found what you predicted?

Then we would not know how to progress!

Effective Potential in Single-Field Model

- Consider single real field with double-well potential: $V = A\phi^2(v-\phi)^2$
- Shallower than φ^2 for
  $0 < \varphi < v$
- Better tensor-to-scalar
  ratio r for $0 < \varphi < v$
- Steeper than φ^2 for
  $\varphi < 0$ or $> v$: worse r

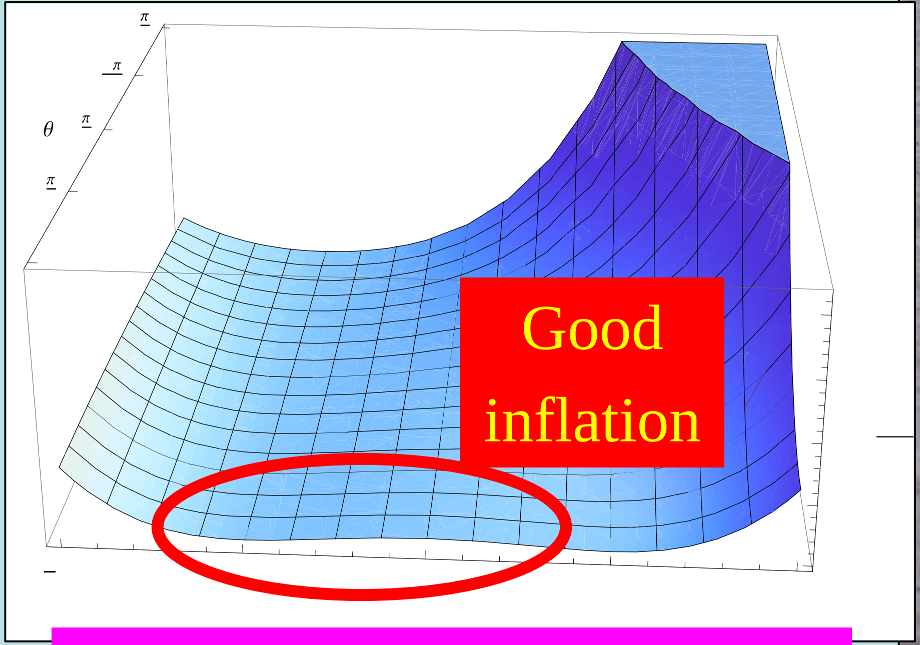


Croon, JE & Mavromatos: arXiv:1303.6253

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 θ = 0 (good)
- Combination of $\varphi^2 + \varphi^4$ for $\theta = \pi/2$ (no good)
- **Good inflation for suitable μ, λ**



Croon, JE & Mavromatos: arXiv:1303.6253

Wess-Zumino Inflation in Light of Planck

- Consistent with Planck for x_i = 0.3, 0.4

Value of x_i	0.1	0.2	0.3	0.4
Derived quantity				
$\frac{v^2}{M_{Pl}^2}$	18000	4200	1600	710
ϵ	0.0085	0.0067	0.0045	0.0020
η	0.0062	0.00074	-0.0073	-0.022
ξ	-0.000053	-0.000077	-0.000079	-0.000050
r	0.14	0.11	0.072	0.031
n_s	0.961	0.961	0.958	0.945
α_s	-1.4×10^{-6}	-1.3×10^{-6}	-1.4×10^{-6}	-1.1×10^{-6}
λ	4.3×10^{-8}	1.0×10^{-7}	2.1×10^{-7}	4.1×10^{-7}

Good inflation

- Numbers calculated for N = 50 e-folds

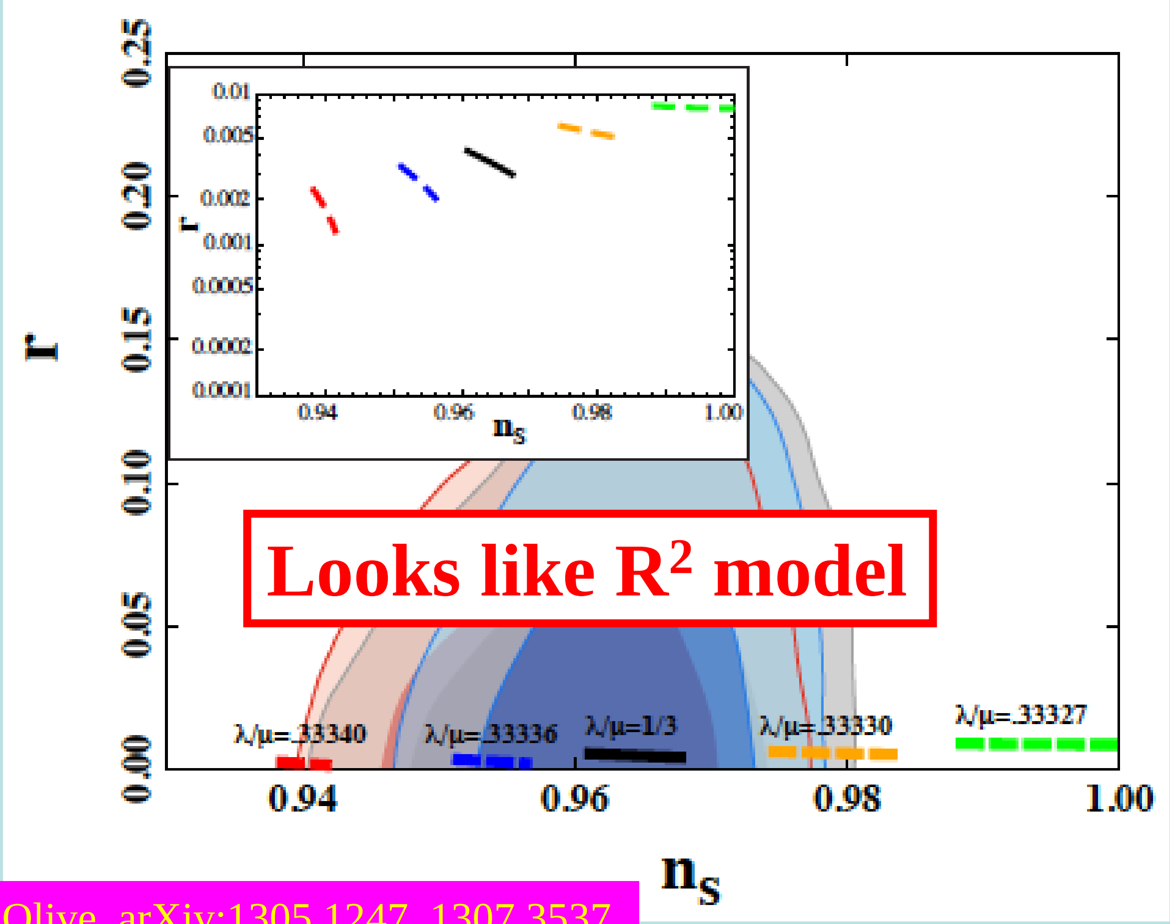
Croon, JE & Mavromatos: arXiv:1303.6253

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

No-Scale Supergravity Inflation

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



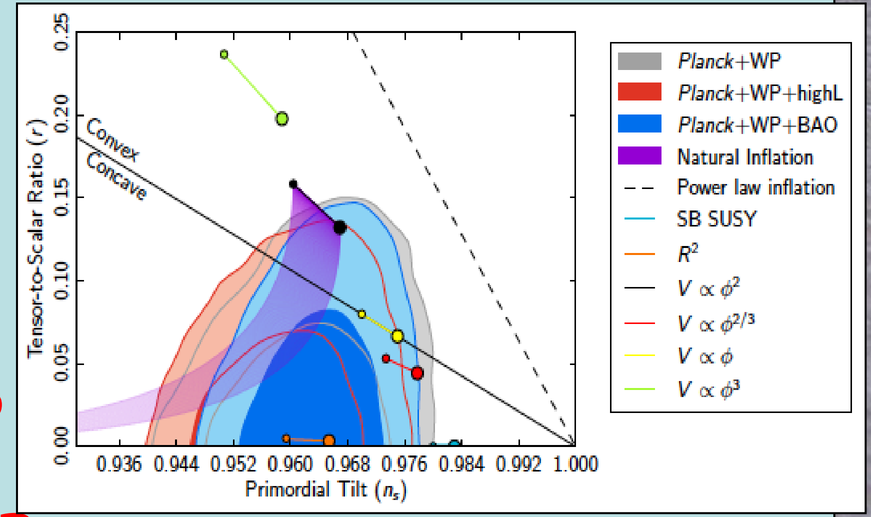
JE, Nanopoulos & Olive, arXiv:1305.1247, 1307.3537

Inflationary Models in Light of Planck

- Planck CMB observations consistent with inflation
- Tilted scalar perturbation spectrum:

$$n_s = 0.9585 \pm 0.070$$

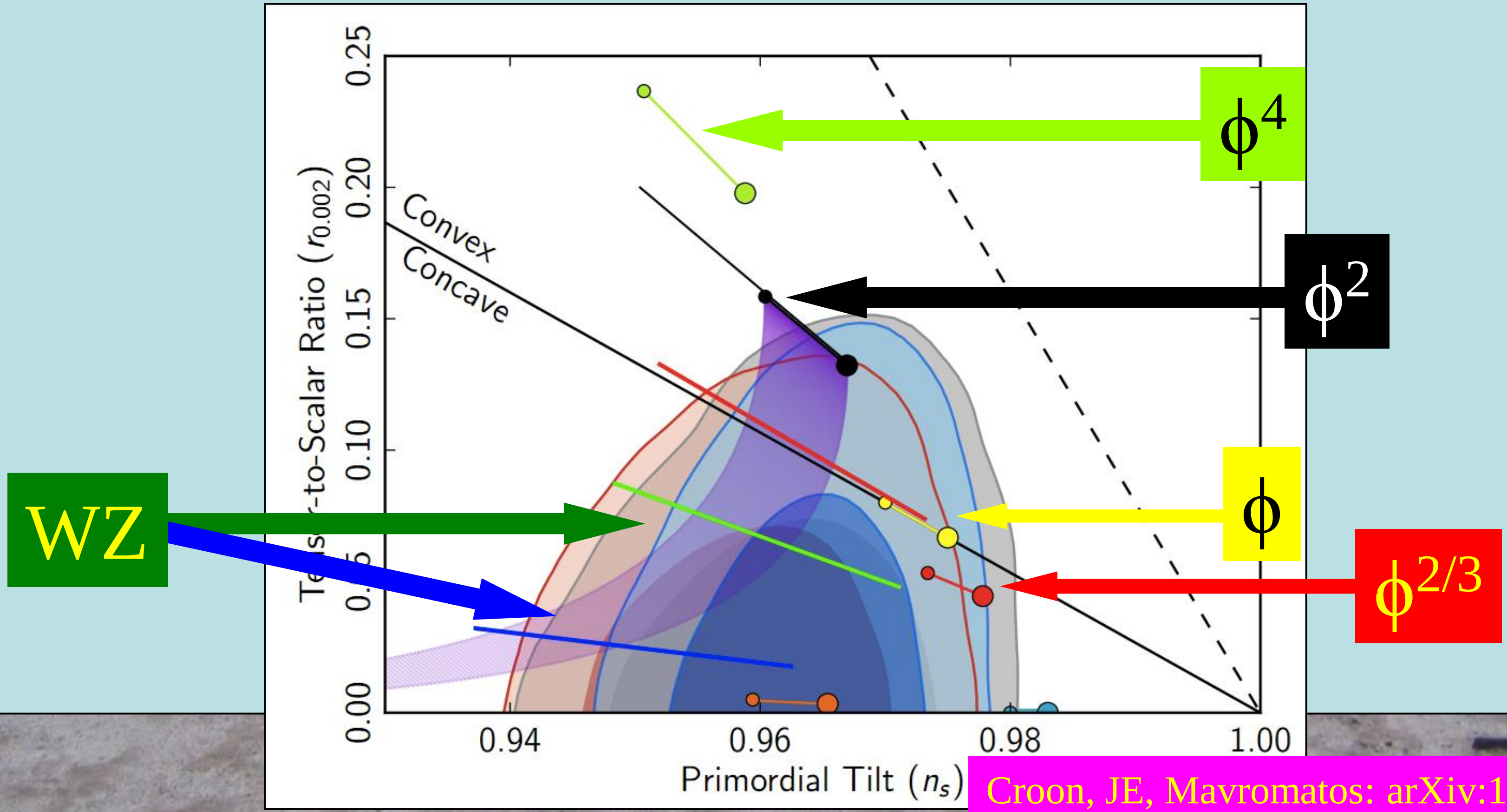
- BUT strengthen upper limit on tensor perturbations: $r < 0.10$
- Challenge for simple inflationary models
- **Starobinsky R^2 to rescue?**
- **Supersymmetry to rescue?**



Croon, JE & Mavromatos: arXiv:1303.6253

Supersymmetric Inflation in Light of Planck

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



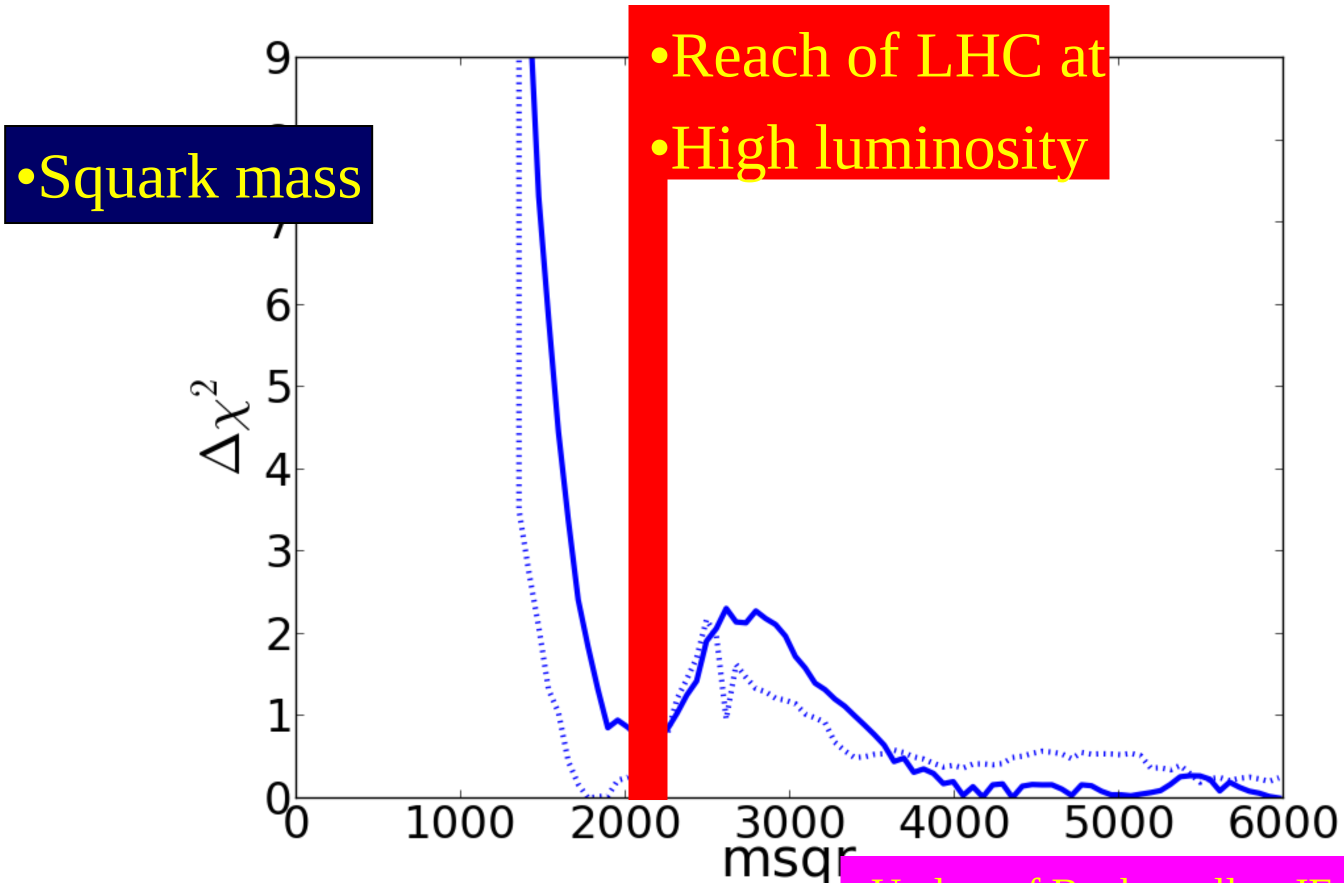
Croon, JE, Mavromatos: arXiv:1303.6253

See also …

- Nakayama, Takahashi & Yanagida – arXiv:1305.5099
- Kallosh & Linde – arXiv:1306:3214
- Buchmuller, Domcke & Kamada – arXiv:1306.3471
- Kallosh & Linde – arXiv:1306.5220
- Farakos, Kehagias and Riotto – arXiv:1307.1137
- Roest, Scalisi & Zavala – arXiv:1307.4343
- Kiritsis – arXiv:1307.5873
- Ferrara, Kallosh, Linde & Porrati – arXiv:1307.7696

Post-LHC, Post-XENON100

•2012 ATLAS + CMS with •20/fb of LHC Data



1

•Update of Buchmueller, JE et al: arXiv:1207.3715

•Favoured values of squark mass:

•~ 2000 GeV or more

The (NG)AEBHGHKMP Mechanism

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTE

BROKEN SYMMETRIES AND THE MASSES OF GA

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh,
(Received 31 August 1964)

The only one who mentioned a massive scalar boson

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

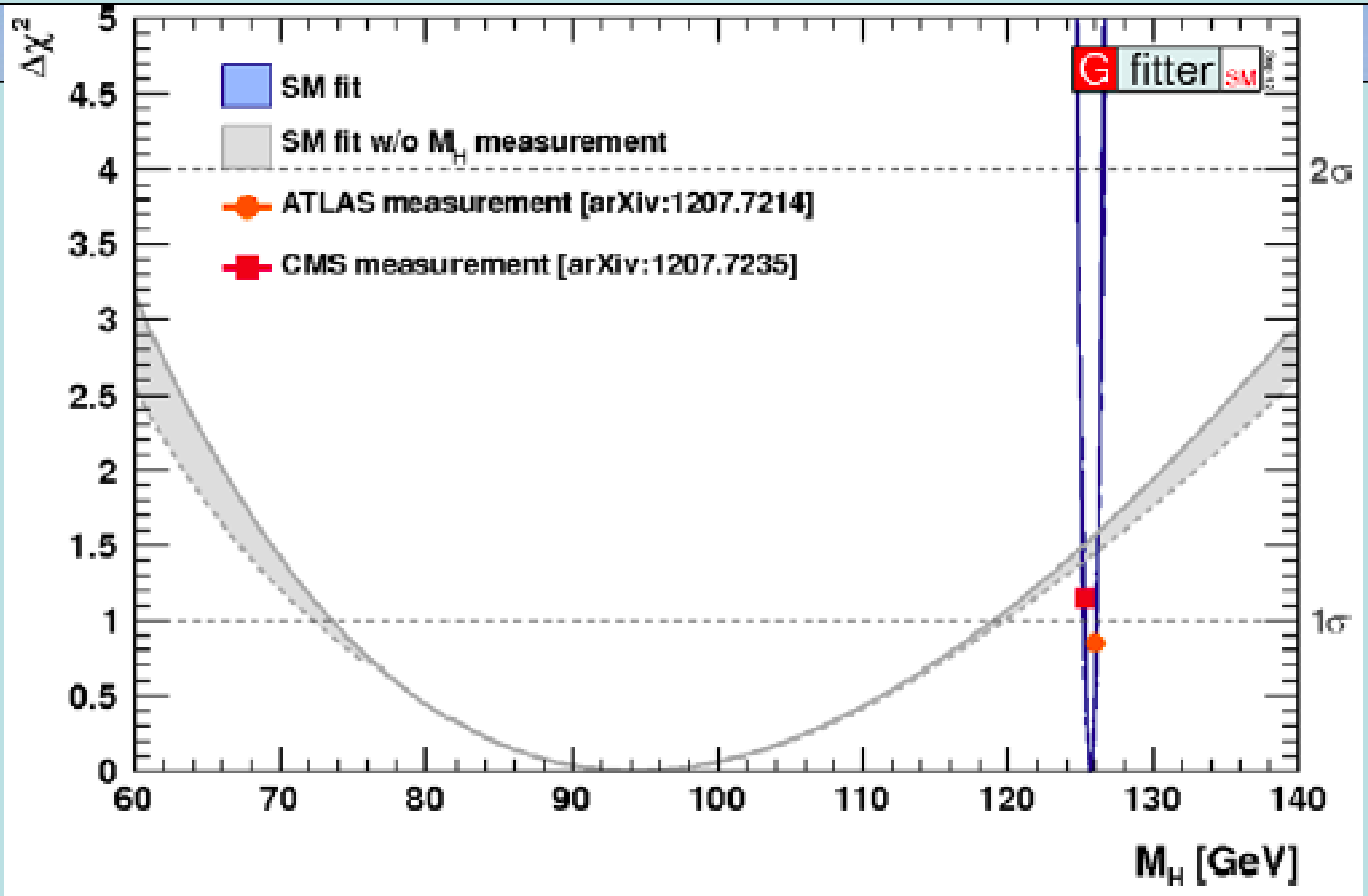
SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

A. A. MIGDAL

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966
J. Exptl.

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

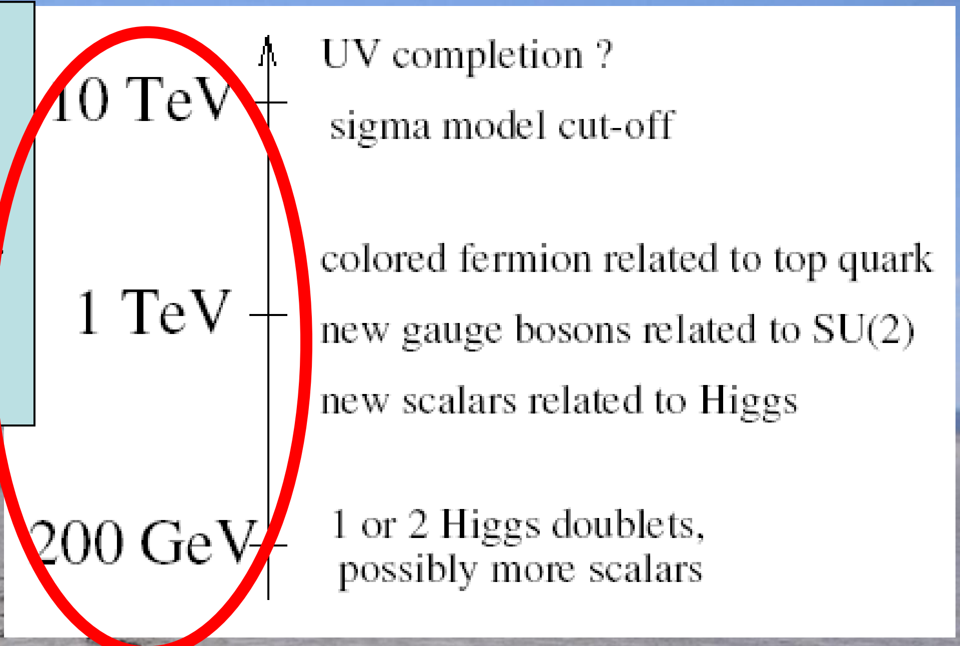
Comparison with Electroweak Fit



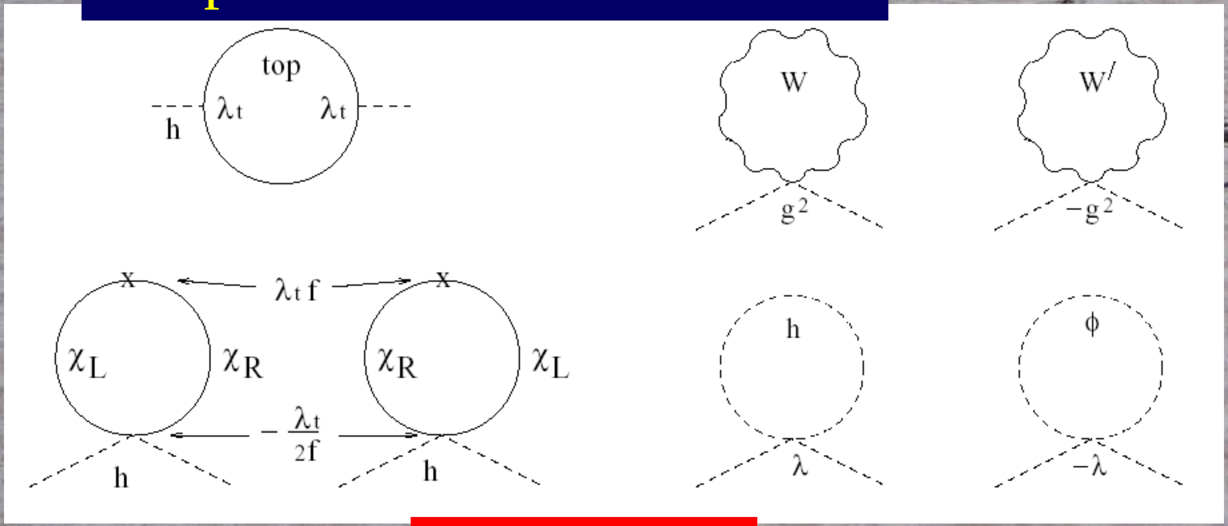
Quite consistent: $\Delta\chi^2 \sim 1.5$

Higgs as a Pseudo-Goldstone Boson

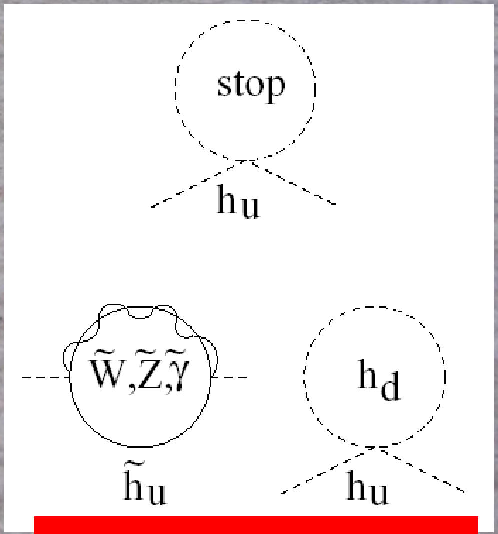
'Little Higgs' models
(breakdown of larger symmetry)



Loop cancellation mechanism



Little Higgs

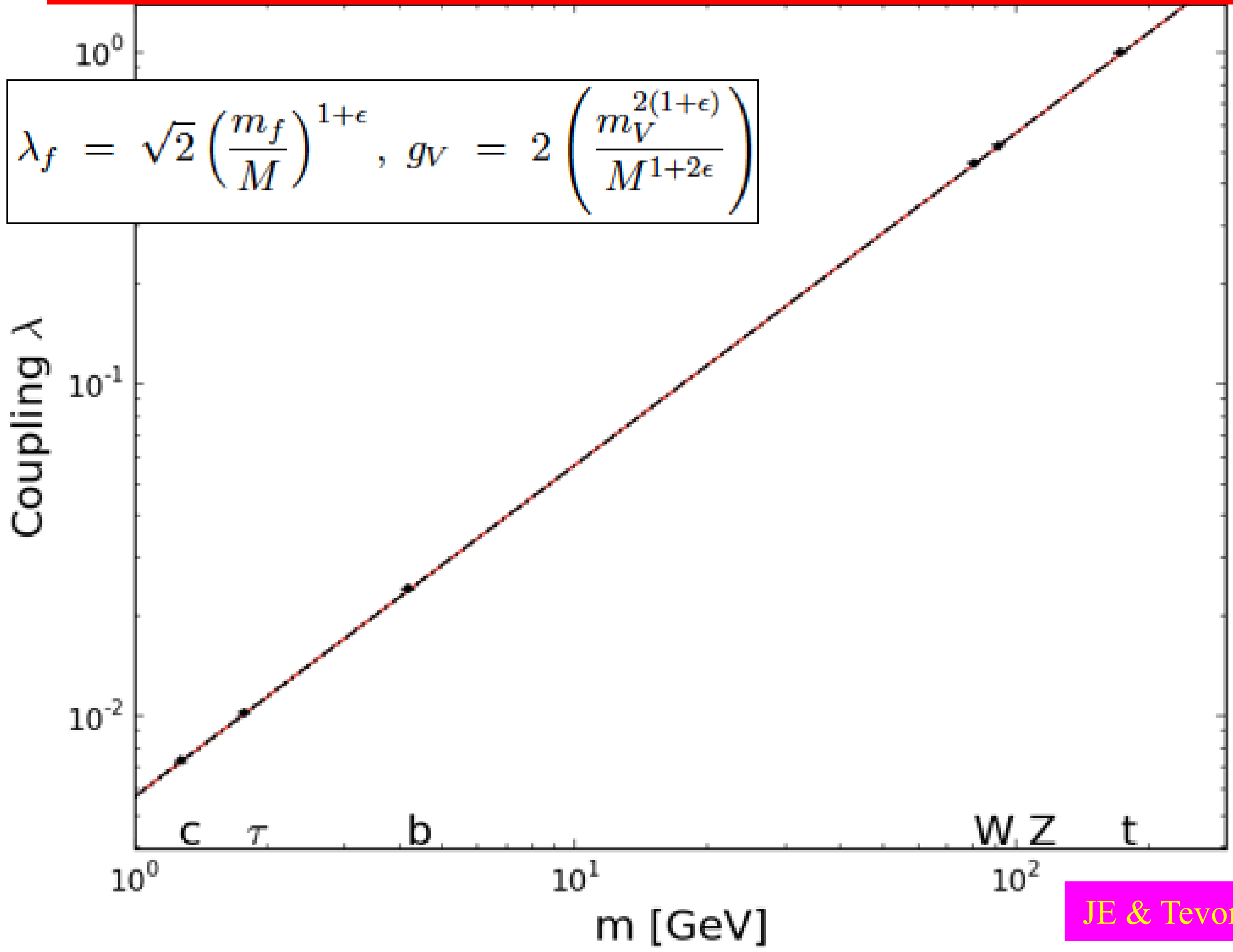


Supersymmetry

H Coupling Measurements @TLEP

M = 246.0 ± 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