The Future of High Energy Physics

Luciano Maiani, Universita' di Roma "La Sapienza" and INFN, Roma, Italy

Pierre Fayet Fest
ENS, Paris, 8-9 December 2016

Prediction is very difficult, especially about the future
Niels Bohr

feature article

Particle physics, from Rutherford to the LHC

Steven Weinberg

August 2011 Physics Today 33

Not the last word

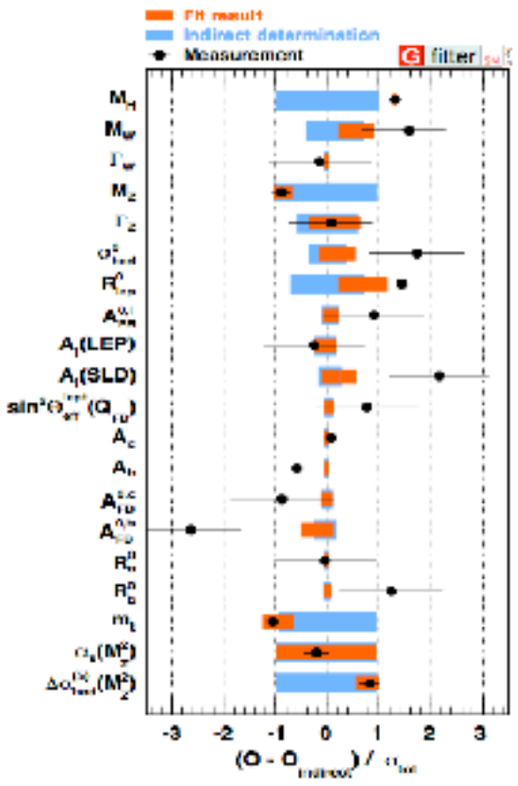
It is clearly necessary to go beyond the standard model. There is a mysterious spectrum of quark and lepton masses and mixing angles that we have been staring at for decades, as if they were symbols in an unknown language, without our being able to interpret them. Also, something beyond the standard model is needed to account for cosmological dark matter.

Electroweak Fit – SM Fit Results

- Results drawn as *pull values:*
  → deviations to the *indirect* determinations, divided by *total error.*
- Total error:
  error of direct measurement plus error from indirect determination.

- Black: direct measurement (data)
- Orange: full fit
- Light-blue: fit excluding input from the row

- The prediction (light blue) is often more precise than the measurement!



1. Electroweak fit updated

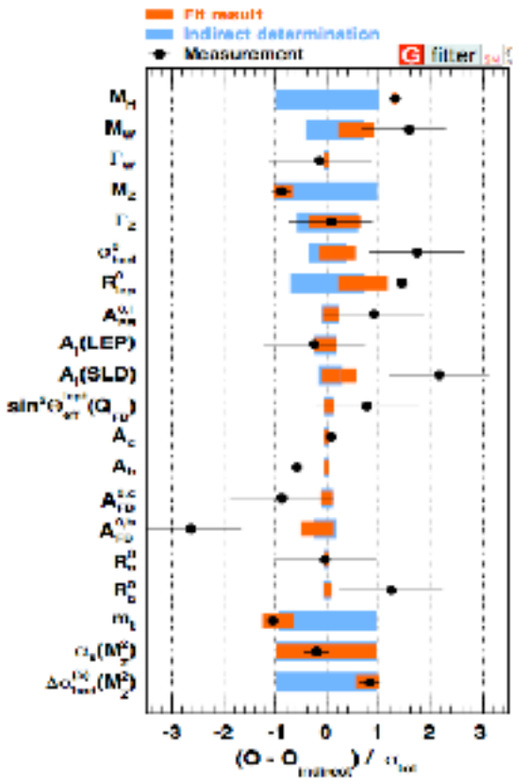
M. Baak *et al.*, PoS EPS **HEP 2015** (2015) 100

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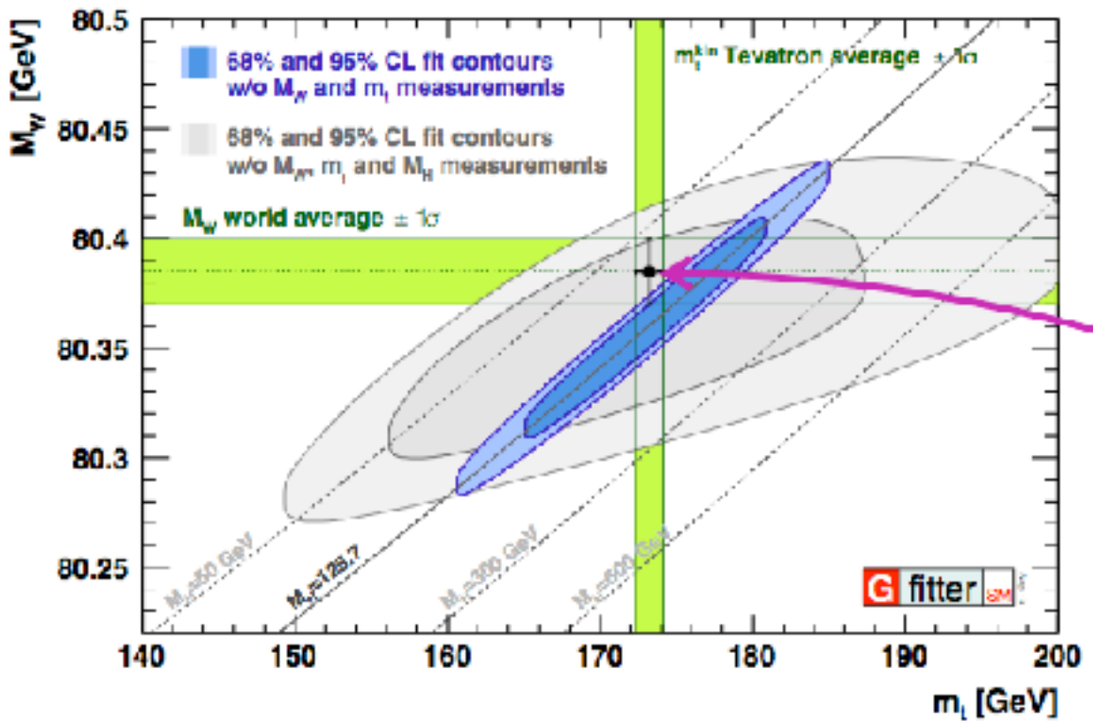


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W versus top mass

M_W vs m_t, with the direct measurements excluded from the fit.
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- Observed agreement demonstrates impressive consistency of the SM!

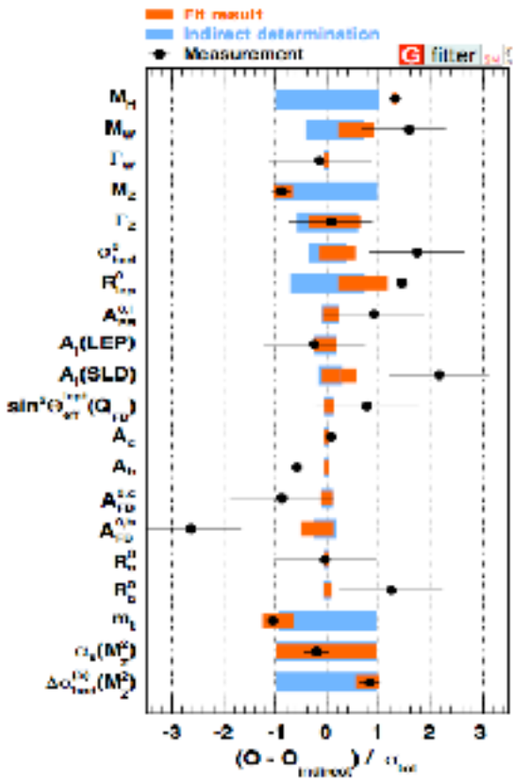
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- Fit result:

	S	T	U
S	1	+0.89	-0.54
T		1	-0.80
U			1

S = 0.03 ± 0.10 ,
T = 0.05 ± 0.12 ,
U = 0.03 ± 0.10

- Stronger constraints from fit with U=0.
- Also available for Z→bb correction.

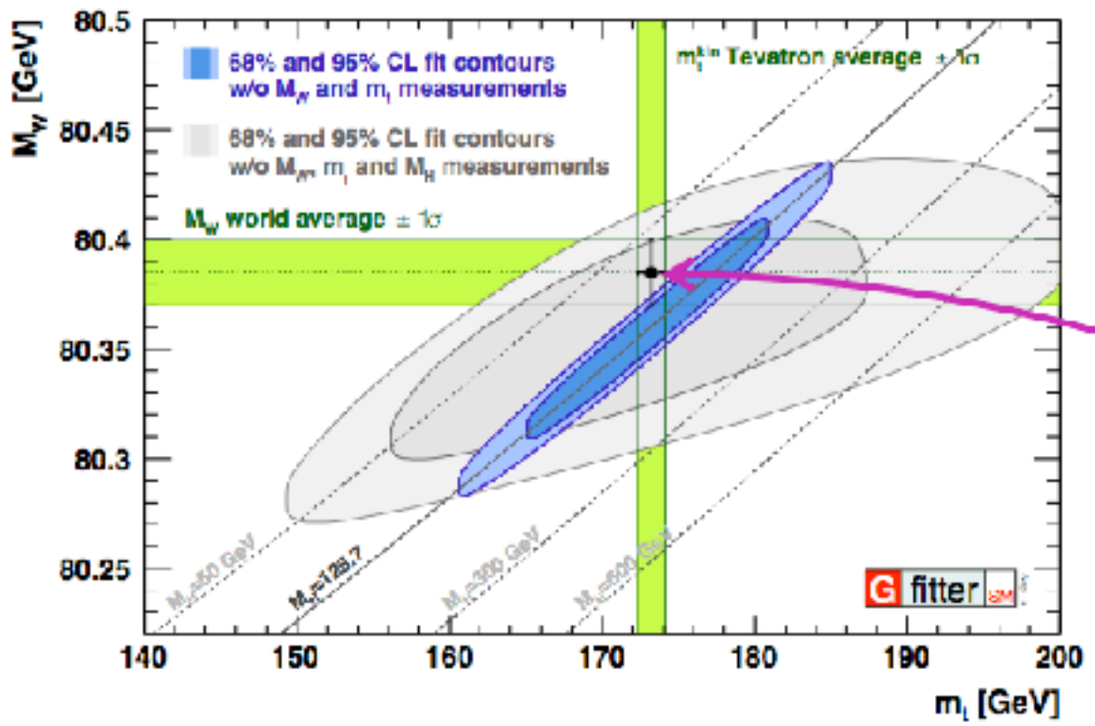
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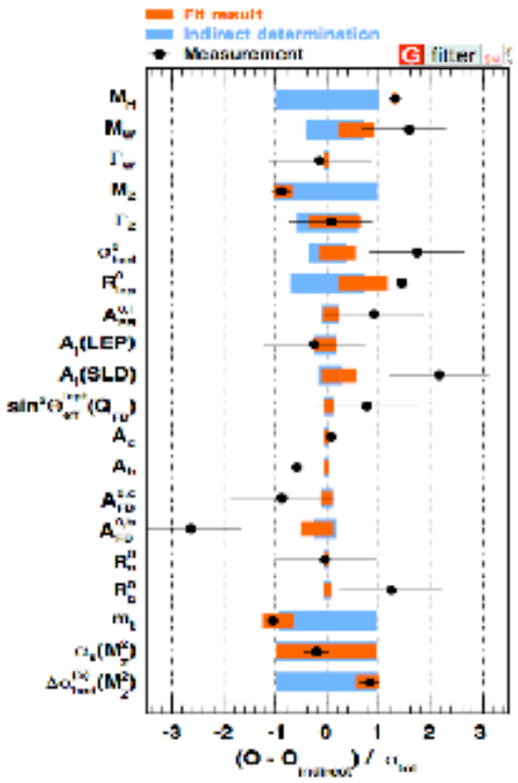
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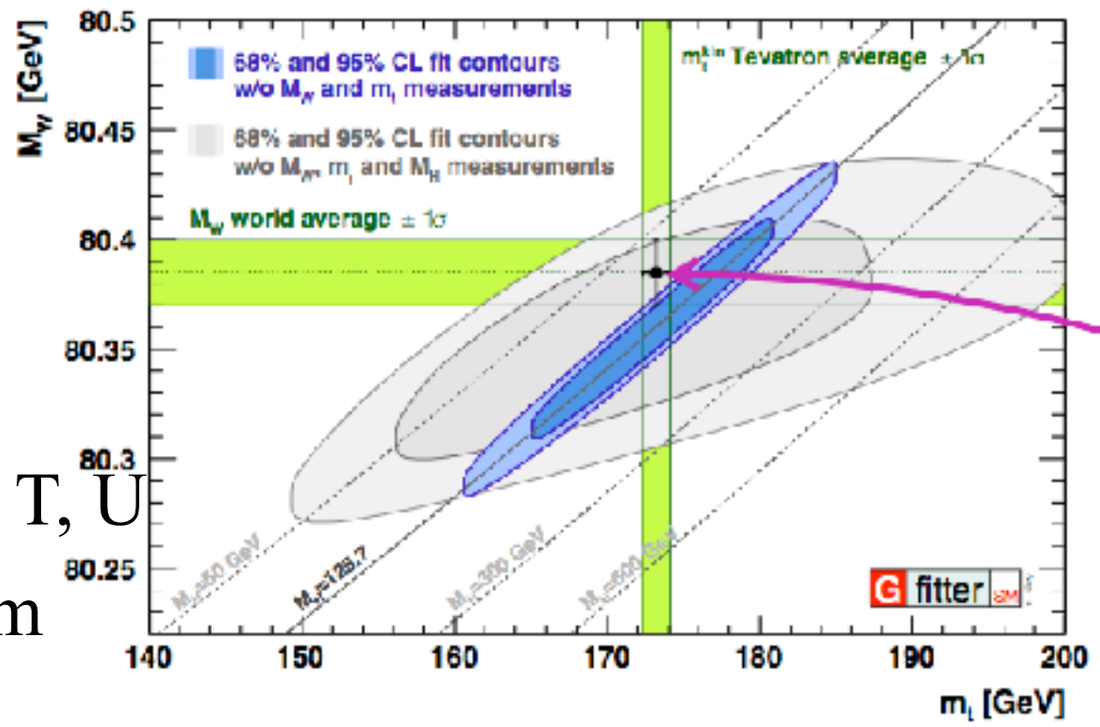
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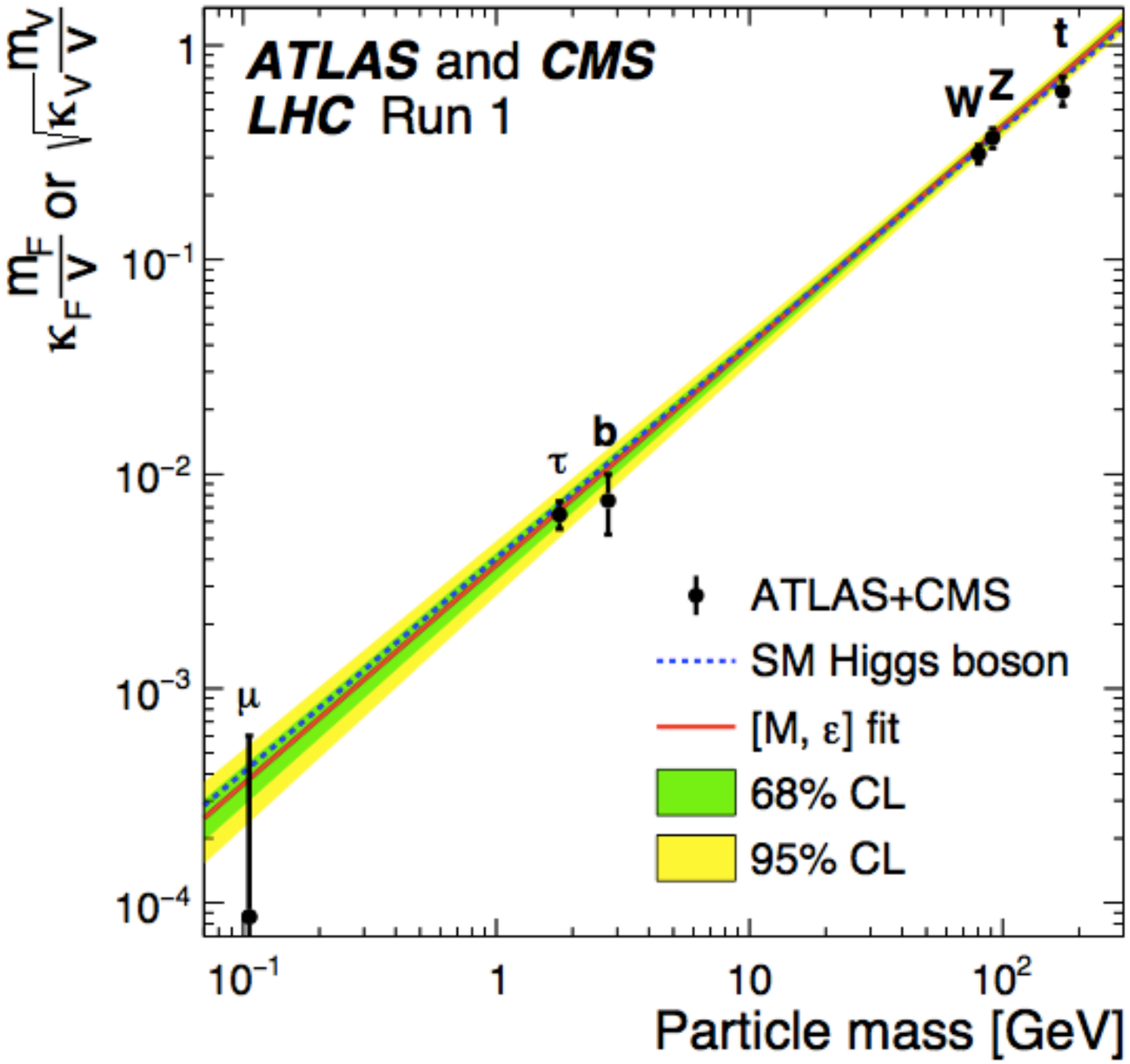
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- No detectable oblique corrections: S, T, U
- At most, perturbative corrections from physics Beyond the Standard Model
- Too early to say, ...but

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Higgs boson branching ratios vs. particle masses

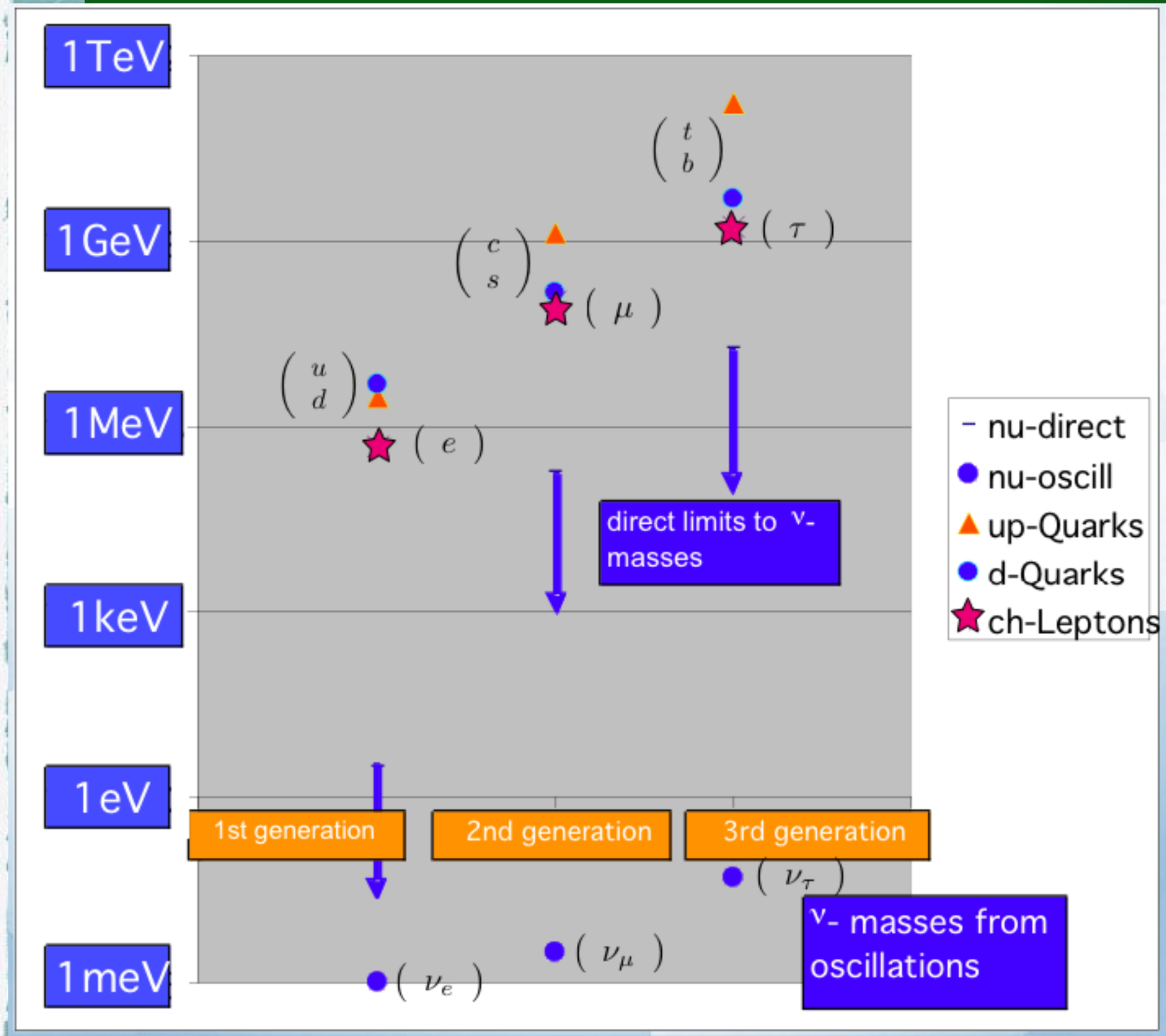
- The dashed (blue) line indicates the predicted dependence on the particle mass in the case of the SM Higgs boson.



- As expected…but very unconventional
- the first ***scalar*** elementary particle
- coupled not to currents but to masses
- ***the true signature of the Higgs mechanism***

The Higgs boson ***is*** the new physics!!!!
Higher energy is needed to study its interactions and self-interactions (Nima Arkani-Ahmed)

2. Neutrinos are different



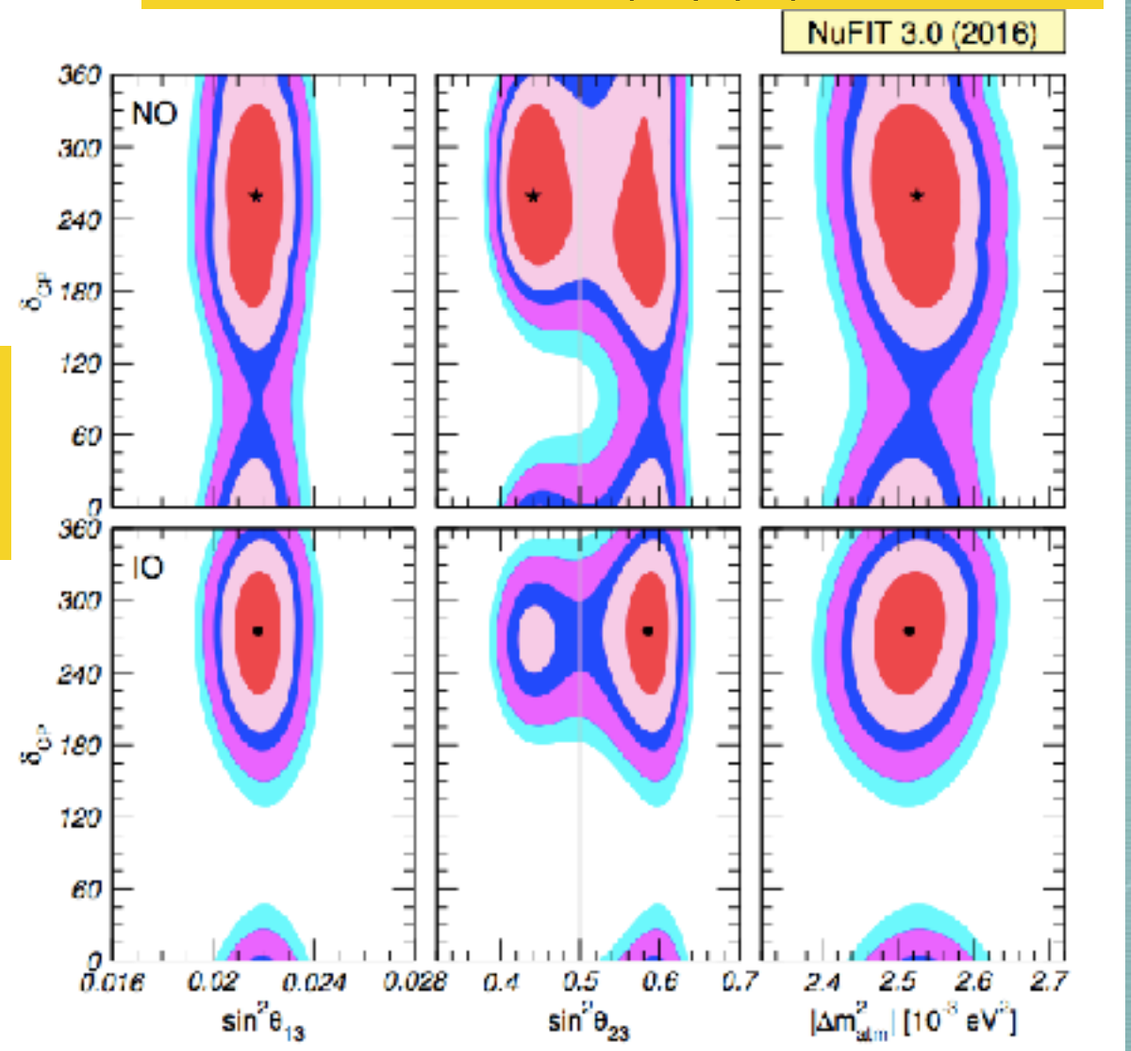
Neutrinos

★ **Combined Fit** (nuFit2016)

- $\Delta m^2_{21} = +(7.5 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2$
- $|\Delta m^2_{32}| \approx (2.5 \pm 0.4) \times 10^{-3}\ \mathrm{eV}^2$
- $\theta_{12} = 33.6 \pm 0.8°$
- $\theta_{13} = 8.4 \pm 0.2°$
- $\theta_{23} = (38 - 50)°\ (3\sigma)$

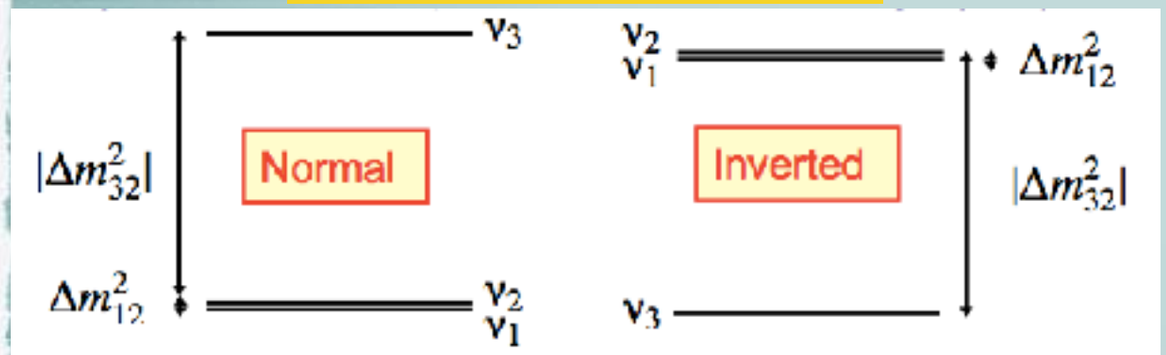
Ivan Esteban,[a] M. C. Gonzalez-Garcia,[a,b,c] Michele Maltoni,[d] Ivan Martinez-Soler,[d] Thomas Schwetz[e]

arXiv:1611.01514v1 [hep-ph] 4 Nov 2016

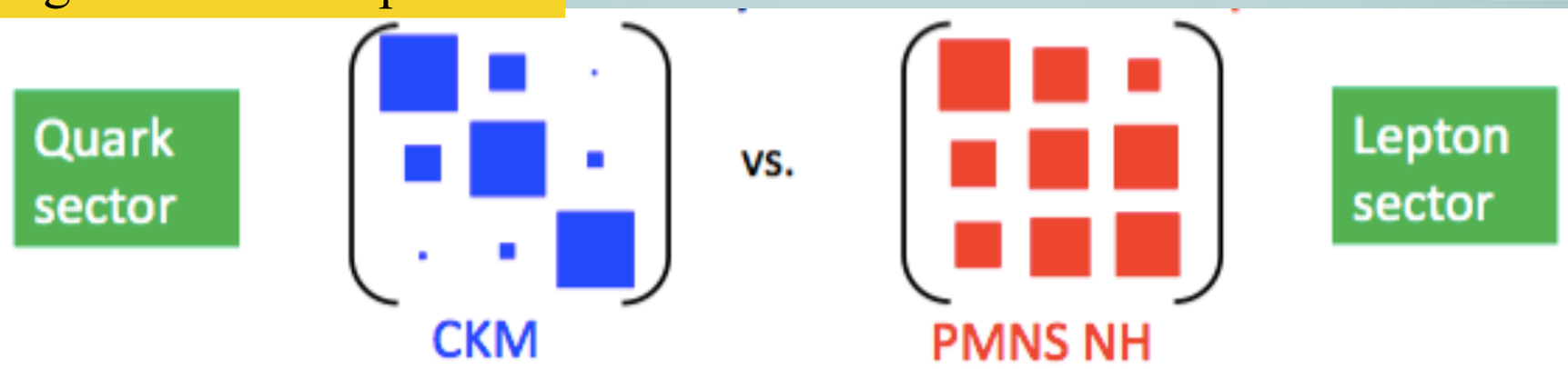


CP violation in neutrinos
N. Cabibbo Phys. Lett. **B72** (1978) 333
seen??

Mass Hierarchies (MH)



A striking difference of patterns



Majorana neutrinos vs. quarks

- In the ST there is a large, global, flavour group commuting with the gauge group, SU(3)⊗SU(2)⊗U(1), and broken by the Yukawa couplings;
- with 3 generations of left-handed quark and leptons, Q_L, L_L, and right-handed singlets, U_R, D_R, E_R, flavor group is: $\mathcal{G}=U(3)^5$
- However with the see-saw mechanism, to produce naturally small Majorana neutrino masses, the flavour group of leptons is different from the flavour group of quarks
  - quarks: $\mathcal{G}_q = SU(3) \otimes SU(3) \otimes SU(3)$ (Q_L, U_R, D_R)
  - leptons: $\mathcal{G}_l = SU(3) \otimes SU(3) \otimes O(3)$ (L_L, E_R, N)

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- Could the difference in the flavour groups be the origin of the difference in the mixing patterns? Impossible, if Ys are just renormlized coupling constants
- An idea pioneered by Froggat & Nielsen (arXiv:hep-ph/9905445): Yukawa couplings are themselves the VEVs of new fields, which break spontaneously the Flavour Symmetry.

•natural minima of a $\mathcal{G}_q \otimes \mathcal{G}_l$ symmetric potential can be found by group-theoretical methods (devised in the 60' by Cabibbo and by Michel & Radicati)

• a striking difference is found between quarks and neutrinos

•one finds:

$$\text{quarks, charged leptons : hierarchical masses, } U_{CKM} = 1;$$

$$\text{neutrinos : degenerate masses}$$

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \times U(\theta_{12}) \times \text{ Majorana phases.}$$

•introducing first order perturbations in the solutions, one finds

•hierarchical quarks with small mixings

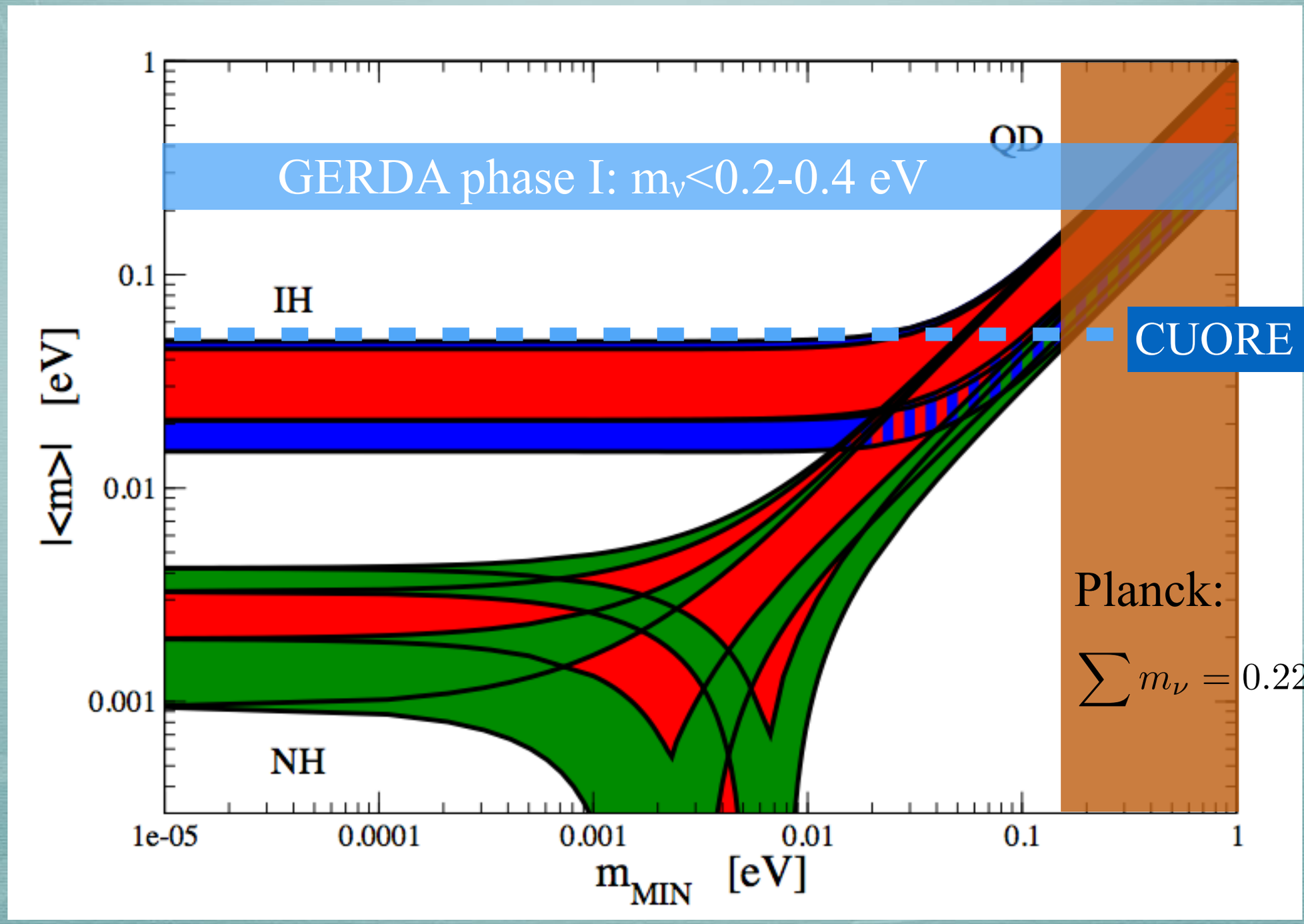
•mixing of neutrinos the bimaximal or tribimaximal form

•, and an estimate of the masses: m~0.1 eV

R. Alonso, B. Gavela, G. Isidori and L. Maiani, *Neutrino Mixing and Masses from a Minimum Principle*, JHEP **1311,** (2013) 187

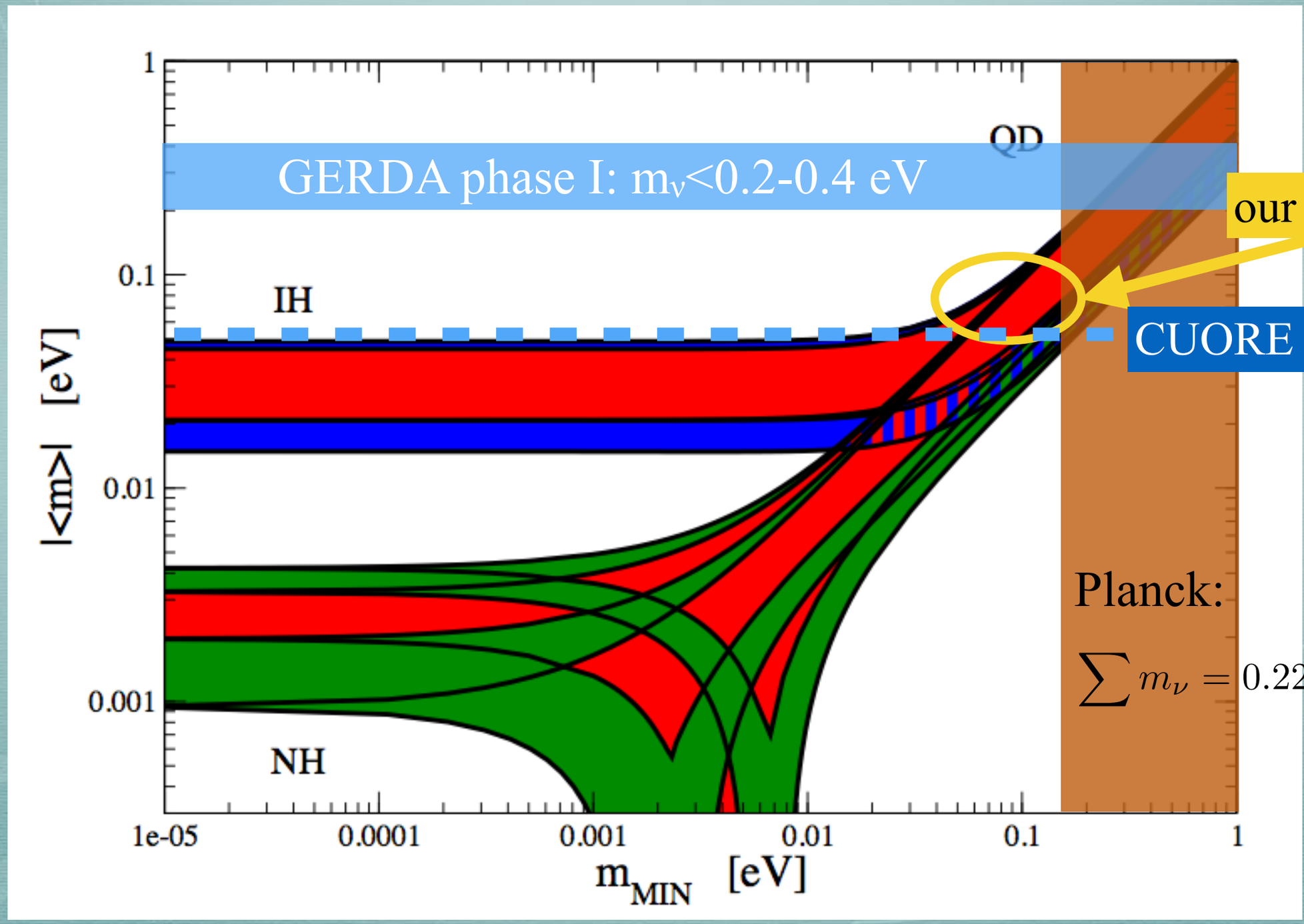
Majorana-natural neutrinos vs quarks

• almost degenerate Majorana neutrinos with m ~ 0.1 eV are not so far from present limits of GERDA (ββ neutrinoless) and the cosmological PLANCK determination.



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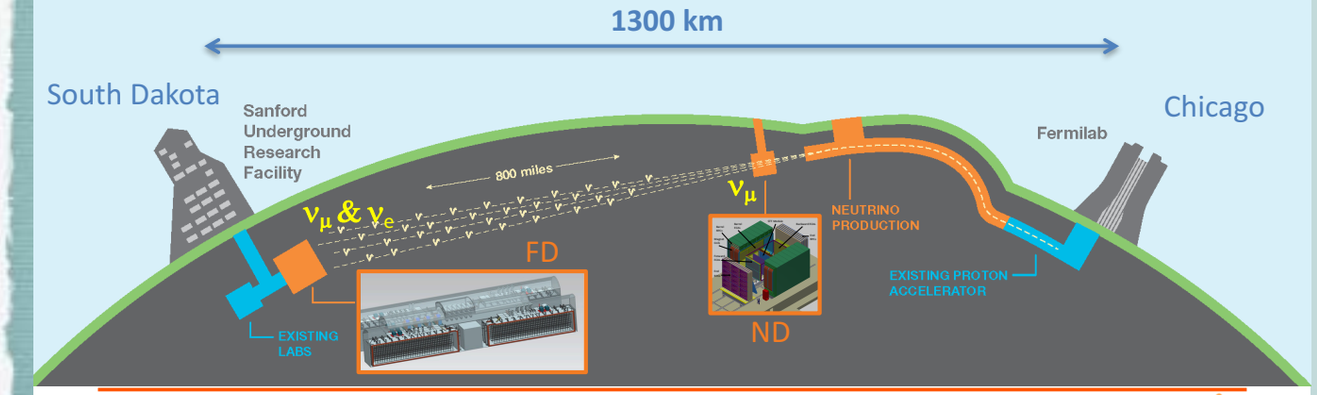


To measure CP violation in neutrinos

DUNE in a Nutshell

★LBNF/DUNE

- Muon neutrinos/antineutrinos from high-power proton beam
  - **1.2 MW** from day one (upgradeable)
- Large underground **Liquid Argon Time Projection Chamber**
  - **4 x 17 kton ⇨ fiducial (useable) mass of >40 kton**
- Near detector to characterize the beam



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- **2017:** start of construction in South Dakota
- **2026:** start of beam operation (1.2 MW)

JPARC Beam for Hyper-K

★ **Upgraded JPARC beam**

★ **Assume 1.3 MW at start of experiment**

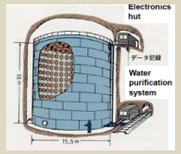
★ **Hyper-K is off-axis**

- Narrow-band beam, centered on first oscillation maximum
- Baseline = 295 km ⇨ **matter effects are small**

Far Detector

Hyper-K is the proposed third generation large water Cherenkov detector in the Kamioka mine

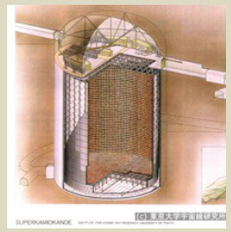
Kamiokande (1983-1996)



3 kton

⇨

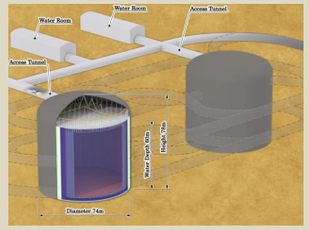
Super-Kamiokande (1996-)



50 kton

⇨

Hyper-Kamiokande (2026?-)



0.52 Mton

- Inner detector volume = 0.74 Mton
- Fiducial volume = 0.56 Mton
- Photomultiplier tubes: 80,000 20” inner detector

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Panorama of planned neutrino experiments for the 2020s

K.~Abe *et al*. [Hyper-Kamiokande Working Group Collaboration], arXiv:1412.4673

MH=Mass Hierarchy

Experiment (Place)	ν source	Fiducial mass (kt)	Energy (MeV)	baseline (km)	physics targets
Hyper-K (Japan)	beam	560	600	295	CP, MH, θ_{23}, θ_{13}, Δm^2_{32}
	atm.	560	$100 \sim 10^5$	$10 \sim 10,000$	MH, CP, θ_{23}, Δm^2_{32}
LBNE (US)	beam	34	$1,000 \sim 5,000$	1300	MH, CP, θ_{23}, θ_{13}, Δm^2_{32}
LBNO (EU)	beam	$20 \rightarrow 100$	$1,000 \sim 10,000$	2300	MH, CP, θ_{23}, θ_{13} , Δm^2_{32}
JUNO (China)	reactor	20	$1 \sim 10$	~ 50	MH, θ_{12}, Δm^2_{21}, Δm^2_{31}
RENO50 (Korea)	reactor	10	$1 \sim 10$	47	MH, θ_{12}, Δm^2_{21}, Δm^2_{31}
PINGU (South pole)	atm.	$\sim 6,000$	$1,000 \sim 10^6$	$10 \sim 10,000$	MH, θ_{23} and , Δm^2_{32}
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DUNE~2 times LBNE

3. Low energy riddles in Flavor physics

recent review: A. Hoecker, W.J. Marciano, PdG 2013.

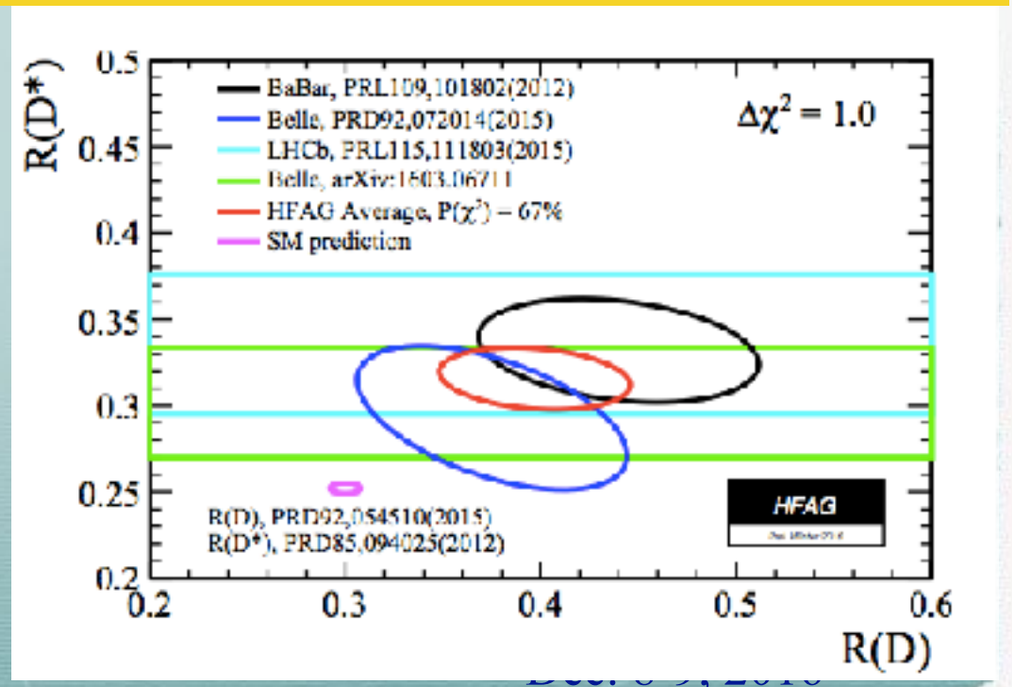
- The muon g-2

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 288(63)(49) \times 10^{-11},$$

  - 3-4 σ discrepancy of experiment at BNL from Standard Theory prediction
  - could be due to strong interactions in light-by-light scattering
  - new experiment at FermLab (E989) to reduce the experimental error, but to improve on theoretical prediction is very hard (***lattice QCD?***)
  - rather large (EW corrections are ~150 x 10^{-11}): if due to new particles, e.g a new vector boson, they should be around the corner

- Anomalies in semileptonic B decays in D and D*
- there are also anomalies in Flavor Changing Neutral Current transitions: b → s μ+ μ-
- leptoquarks????

see: D. Straub in: *Implications of LHCb measurements and future prospects*, Workshop at CERN, 2016.

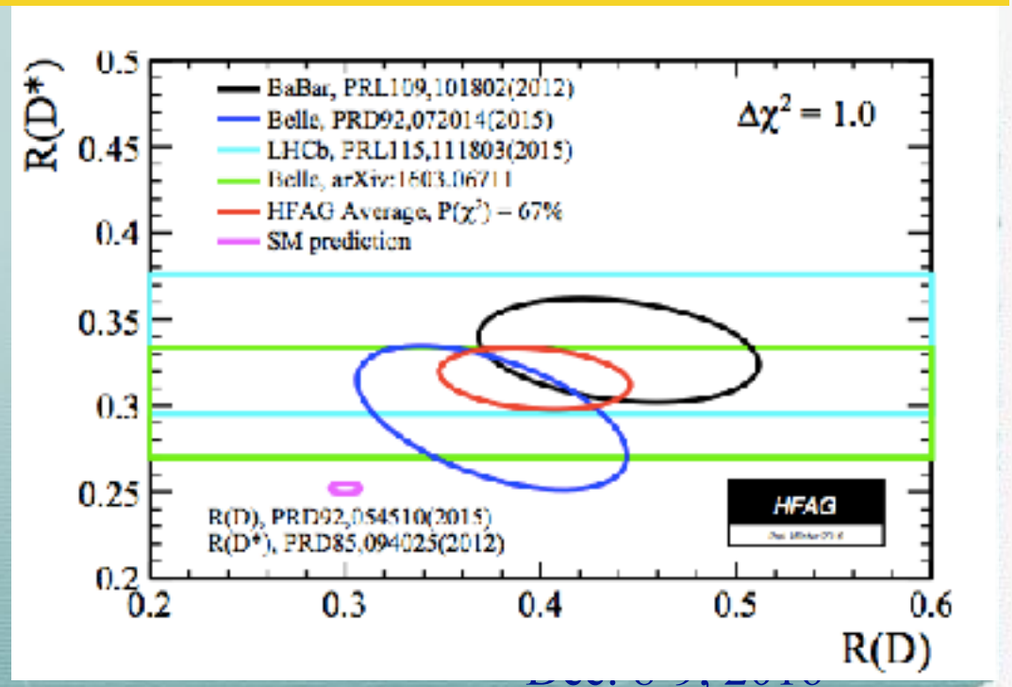


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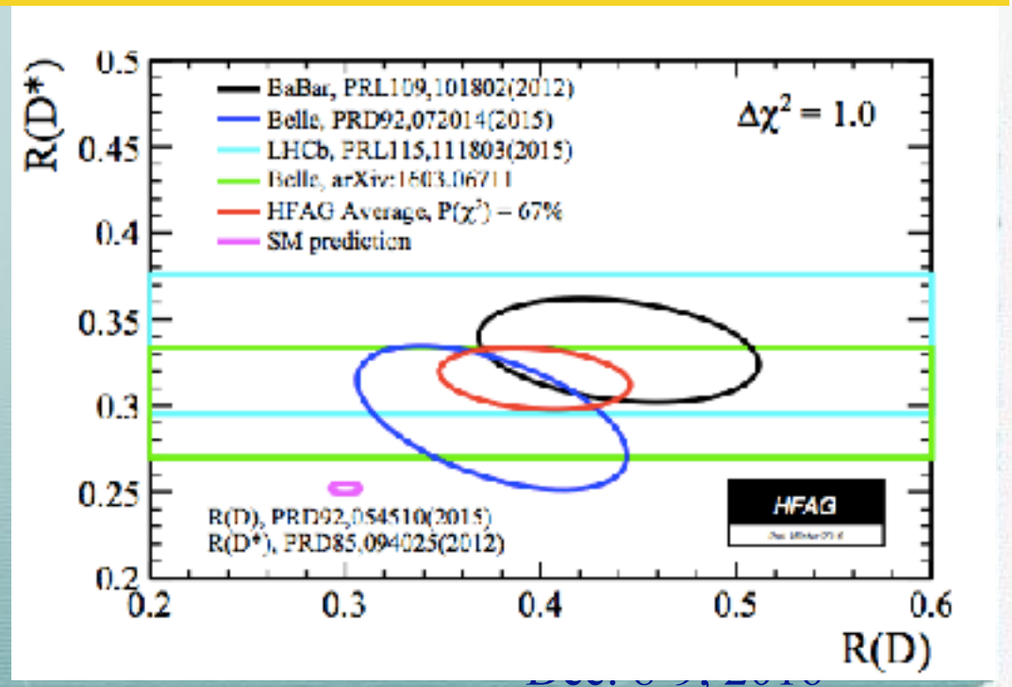
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à suivre !!!

4. Is there life beyond the LHC ?
The hierarchy problem

•The Standard Theory is incomplete:

• missing parts imply very large mass scale >> proton mass

-Gravity: regulated by the Planck mass $M_P=1/\sqrt{G_{Newton}} = 10^{19}$ GeV

-Unification of the three gauge interactions of ST, Grand Unification mass $M_{GUT} = 10^{14}$ GeV

• How is it possible to have a low energy sector almost decoupled from the high energy scales?

• Spin 1/2 and 1 particles,: in the zero mass limit a new symmetry is gained (chiral symmetry for spin 1/2, gauge symmetry for spin 1)

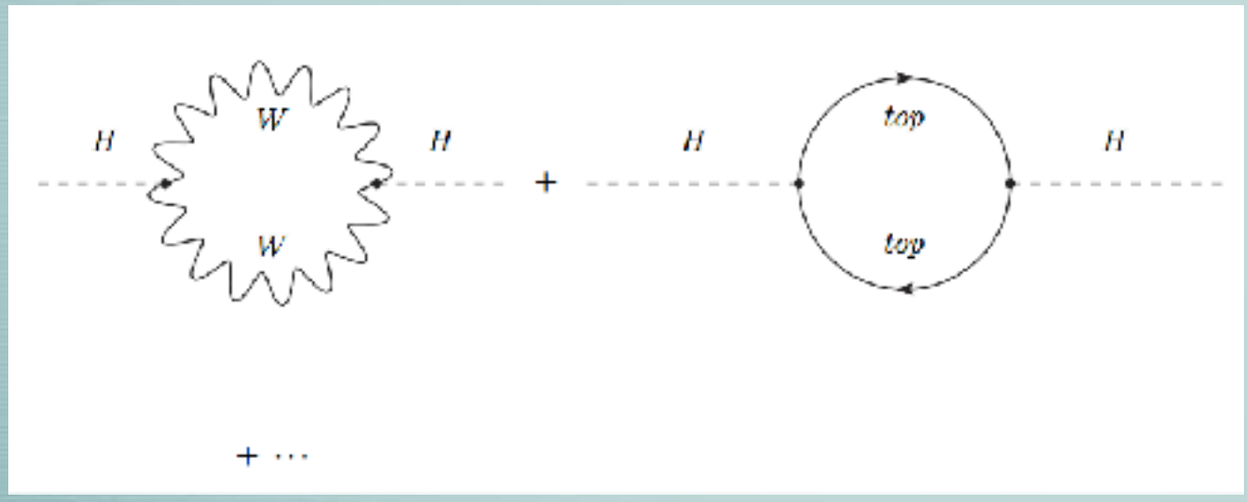
•This implies that higher order corrections to the mass do vanish in the limit where the bare mass vanishes

•thus, e.g. for the electron mass: $m_e(q^2)=m_0$ Log(q^2/M_{GUT}) and the large mass is locked into Logs.

•In the Standard Theory: no increased symmetry is gained by letting the mass of the scalar field to vanish, ST is “unnatural” (K. Wilsons, 1973, G. ’t-Hooft, 1979).

quadratic divergences

•Sometime unnaturalness of the Higgs is associated to quadratic divergences of quantum corrections and unnatural tuning between bare mass and rad corrections



$$\mu^2 = \mu_0^2 + \frac{\alpha}{\pi} \times Cost \times \Lambda^2 + \cdots$$

•this is however not necessary: even in regularization schemes with no quad div (e.g. dimensional reg. or Lee-Wick ghosts) the large mass will end up into the finite corrections, unless a symmetry reason does not prevent it.

Alternatives

- ***Alternative 1: there are no elementary scalars***, the Higgs boson is a composite of fermion fields, $\Lambda=\Lambda_{Techn} \sim O(1\ TeV)$;
- to make H much lighter than the high energy strong interactions scale, the Higgs could be the ***would-be-Goldstone boson*** of some global symmetry.
- ***Alternative 2: Low energy supersymmetry*** relates scalars to fermions, whose mass is protected by chiral symmetry, and reduces the cutoff scale to ΔM_{SUSY}
  - for not too unnatural tuning: $\Lambda \sim \Delta M_{SUSY} \sim O(1\ TeV)$

- New strong-interactions at high energy are not particularly favoured by electroweak precision data (which are becoming high-precision data).
- The value found for the Higgs boson mass speaks in favour of SUSY

- But we should keep ***both options*** open...for the time being

A1. Minimal Composite Higgs Models

For a review, see for example, R. Contino, arXiv:1005.4269 [hep-ph]; B. Bellazzini, C. Csáki and J. Serra, Eur. Phys. J. **C 74** (2014) 2766

- Assume new quarks (Techniquark) confined in hadron by Technicolor forces at a mass scale $\Lambda=\Lambda_{Techn}$
- Λ_{Techn} acts as the cutoff of the quadratic divergences which arise if we treat h as an elementary field: it is the mass scale where h "feels" that it is just made of fermions and gauge bosons
- Presently favoured is a modification of the old Technicolor model which has two mass scales, inspired by QCD, where one particle, the pion, is much lighter than normal hadrons, e.g. the proton: the reason being that the pion is a quasi-Goldstone boson of the chiral symmetry
- Suppose that the Technicolor sector has a global symmetry, broken spontaneously to a group which contains the electroweak $SU(2)_L$x $U(1)_Y$ and that there is one scalar doublet, H, of Goldstone fields (composite but massless, like the Nambu-Goldstone pion in QCD);

- ST particles (quarks and gauge boson) couple to H and generate (via loops) a potential which breaks spontaneously the $SU(2)_L \otimes U(1)_Y$ symmetry, giving mass to W & Z and generating a mass to the neutral component of H:

$$H_0 = \frac{1}{\sqrt{2}}(v + h(x)),$$

$$v = \sqrt{2} < H >_0 \sim 246 \text{ GeV}$$

- the mass scale, Λ_{Tech}, can be larger that the mass acquired by h;
- there is another mass scale, f, which describes the coupling of h to the currents, the analog of f_π, and the deviations from the Standard Theory of h couplings are parametrised by $\xi = v^2/f^2$

  - $f \sim g^* \Lambda$, where g^* is the Technicolor coupling constant
  - $\xi \to 0$ means $\Lambda \to \infty$, h elementary and we recover the Standard Theory

$$\xi = v^2/f^2$$

$$\frac{g^h_{VV}}{g^{ST}_{VV}} = \sqrt{1-\xi}$$

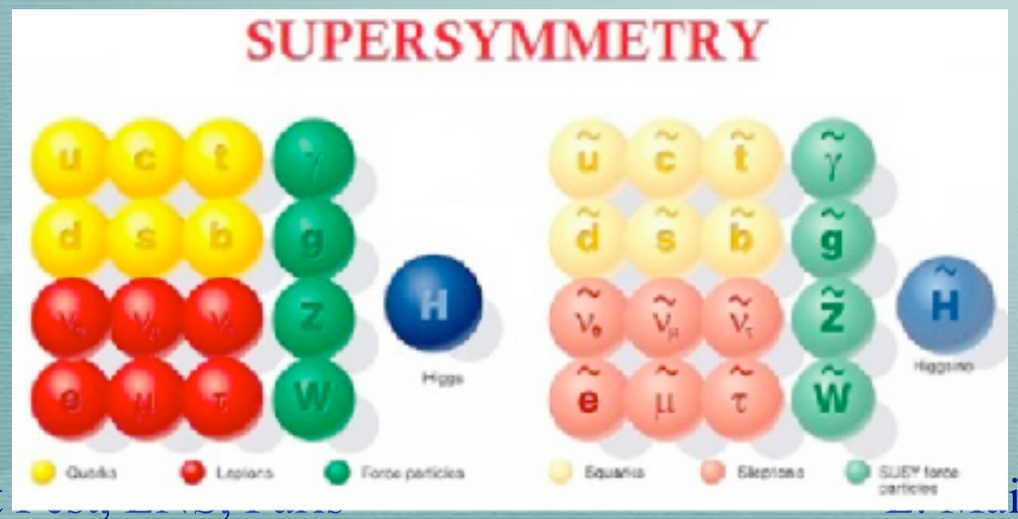
$$\frac{g^h_{ff}}{g^{ST}_{ff}} = \frac{1-(1+n)\xi}{\sqrt{1-\xi}}$$

A2. Supersymmetry and the LHC

- Pierre Fayet was among the firsts to produce a Supersymmetric Electroweak model and spell out signatures of SUSY particles
- Fayet-Iliopoulos term: to give mass to the Higgs boson by spontaneous EW symmetry breaking
- Georgi&Dimopoulos: MSSM with explicit soft breaking, two Higgs doublets (also Fayet)
- Lot of work in the 80's to determine upper limits to the lightest Higgs boson, h, mass: m_h<135 GeV in Minimal SUSY (MSSM)
- The particle seen at CERN is relatively light, 125 GeV: good news for Supersymmetry
- MSSM predicts a total of 5 scalars: h(125), H, A, $H^{\pm}$, the heavier bosons have undetermined masses: $m_H \sim m_{H\pm} \sim m_A$; and a duplication of the other particles of the ST, with a change of 1/2 unit of spin.

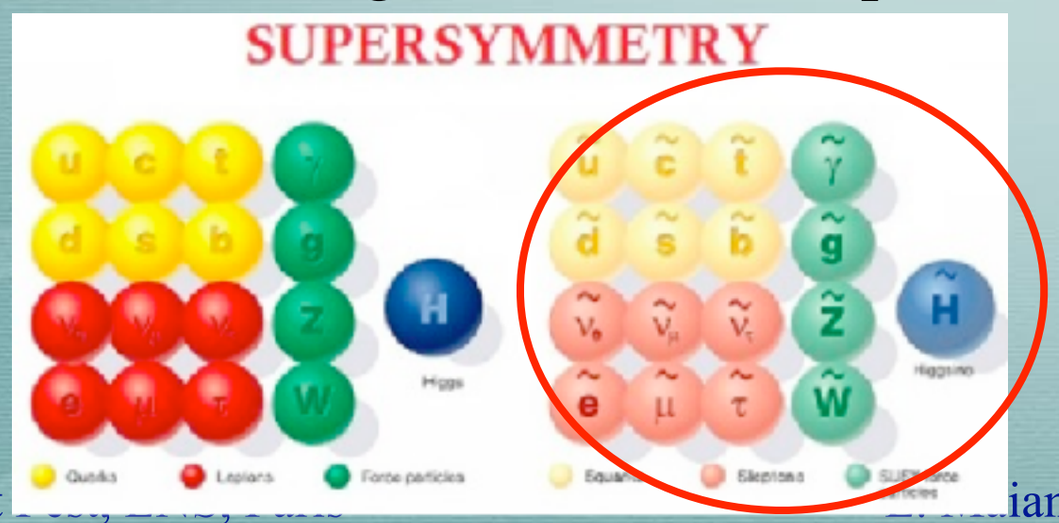
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An entire world of new particles to discover!!

Dark Matter be a parallel world and SUSY particles may be heavier than expected !!

Riccardo Barbieri, Fayet Fest

A (the only) common solution

Minimal Mirror Twin Higgs

B, Hall, Gregoire 2006
B, Hall, Harigaya 2016

$$y_t = y_{t'} \approx 1$$

$$y_{f' \neq t'} \; > (>>) \; y_{f \neq t}$$

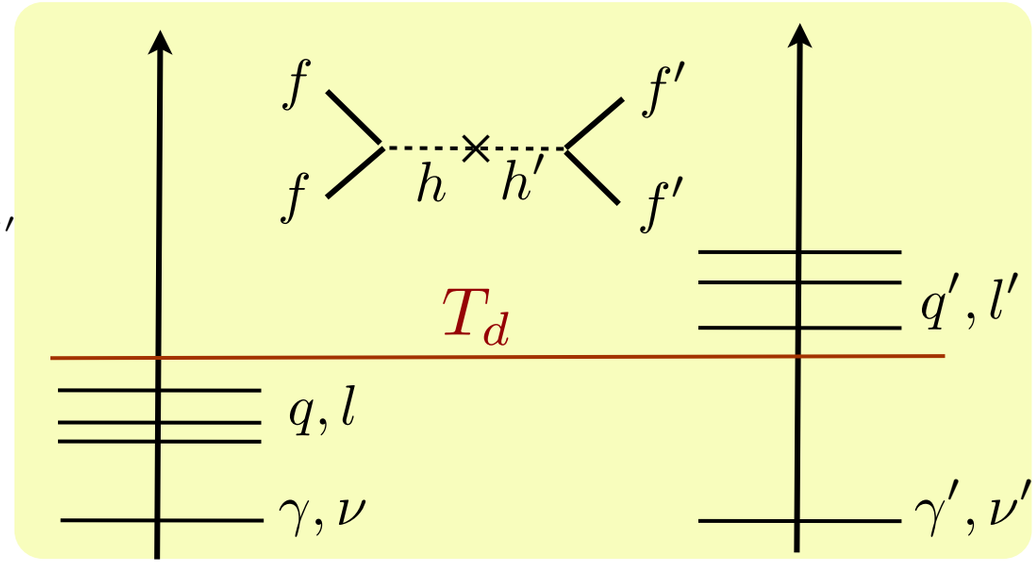
as in a Froggatt-Nielsen picture of flavour

$$y_{f \neq t} = (\phi/M)^{q_f} \quad y_{f' \neq t'} = (\phi'/M)^{q_{f'}}$$

$$y_t \approx 1 \qquad y_{t'} \approx 1$$

with

$$< \phi' > \; \gg \; < \phi >$$



$$\Delta V = \Delta m^2 H^+ H$$

$$\Delta m^2 \simeq \sum_{f \neq t} \frac{N_{f'}}{8\pi^2} y_{f'}^2(\Lambda)\, \Lambda^2 \simeq \frac{1}{4} \frac{v'^2}{v^2} m_h^2$$

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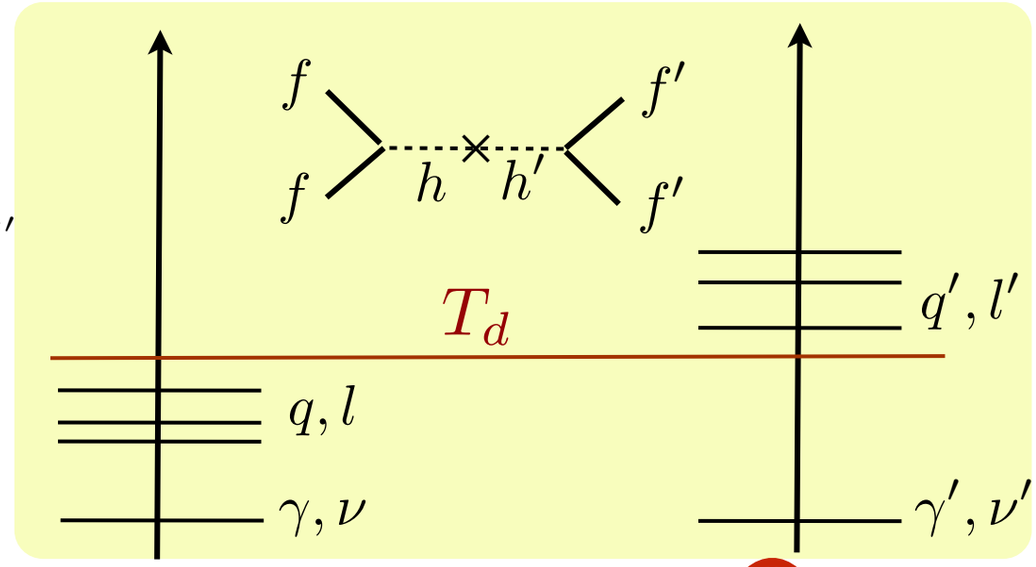
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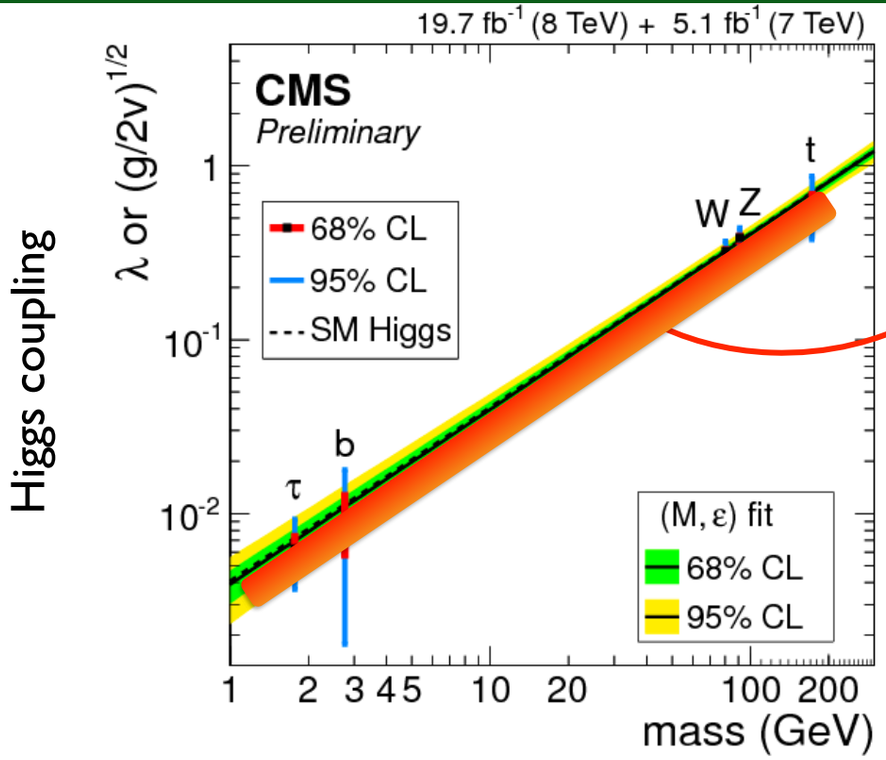
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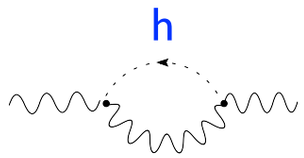
5. Looking for precursor signals in h decay



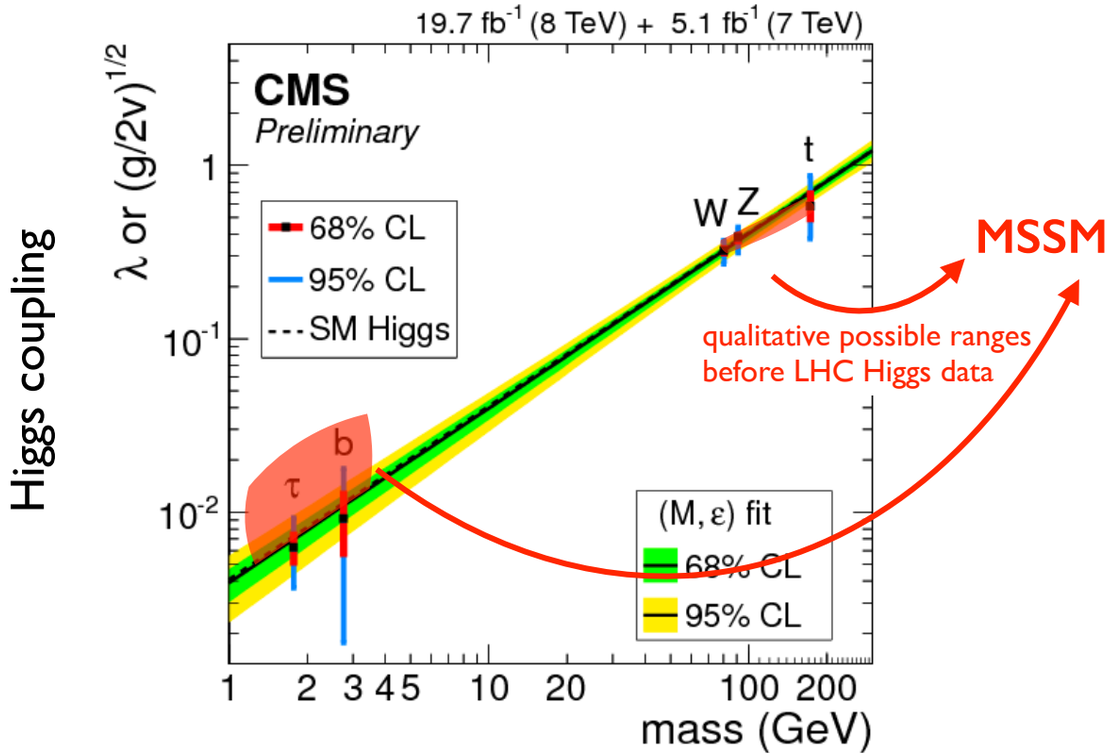
A. Pomerol in *The Standard Theory of Particle Physics*, L. Maiani, L. Rolandi eds., World Scientific, 2016.

Composite Higgs
(reduction of couplings)

small effects already expected,
as EWPT (LEP1) put strong limits
to the coupling hVV
since it affects the Z propagator:



A better perspective to understand how close to a SM Higgs:

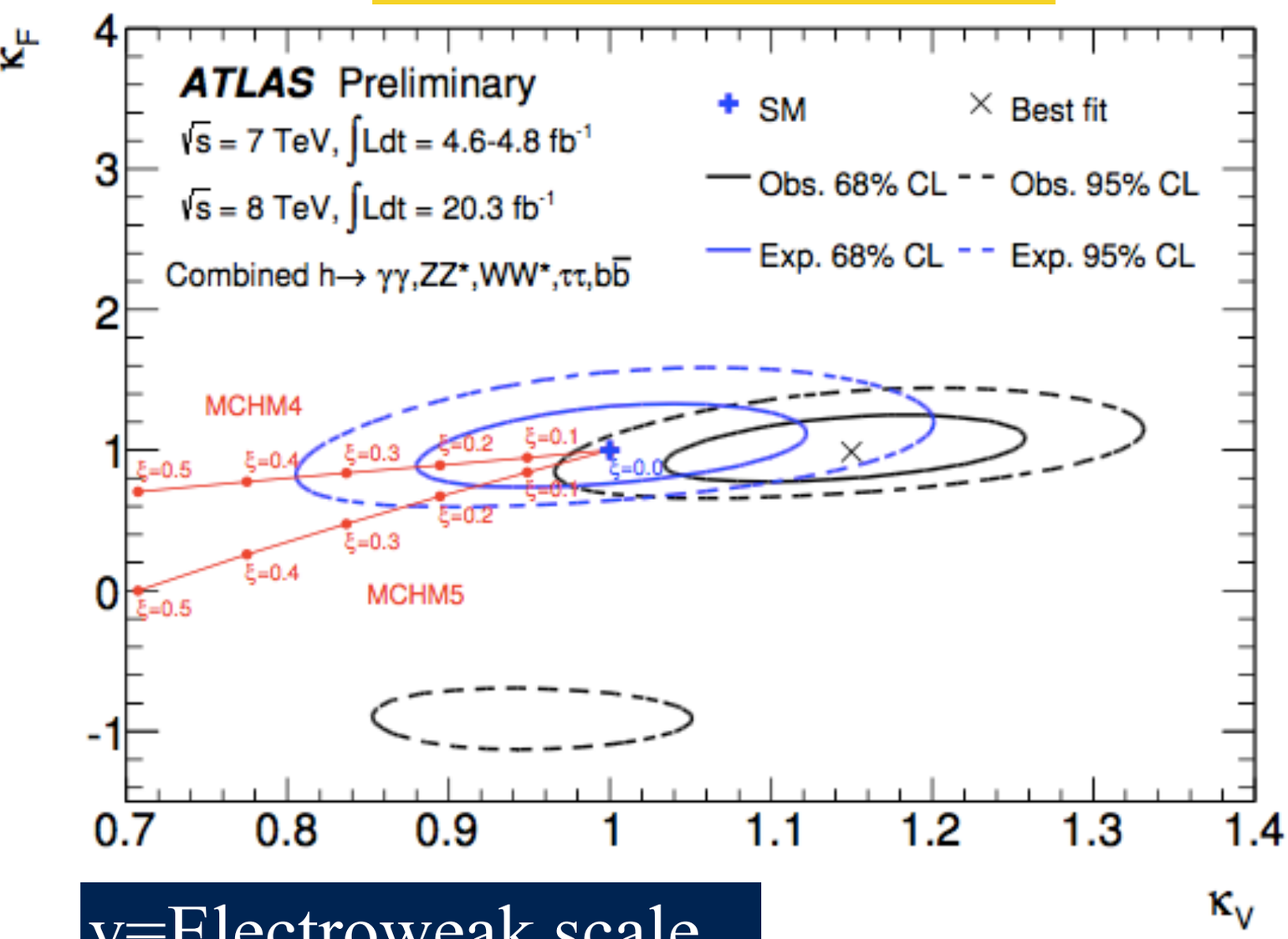


MSSM light Higgs

qualitative possible ranges
before LHC Higgs data

Minimal Composite Higgs Models (MCHMn)

ATLAS CONF- 2014 - 010



see e.g.
A. Pomarol, *Higgs Physics*, arXiv:1412.4410 [hep-ph].

$$\xi = v^2/f^2$$

$$\frac{g^h_{VV}}{g^{ST}_{VV}} = \sqrt{1-\xi}$$

$$\frac{g^h_{ff}}{g^{ST}_{ff}} = \frac{1-(1+n)\xi}{\sqrt{1-\xi}}$$

v=Electroweak scale
Λ= New Physics scale

$$v \sim 246 \text{ GeV},$$

$$\Lambda \sim g^\star f \sim g^\star \frac{v}{\sqrt{\xi}}$$

$$\xi < 0.15 \;\rightarrow\; \Lambda > g^\star \cdot 640 \text{ GeV}$$

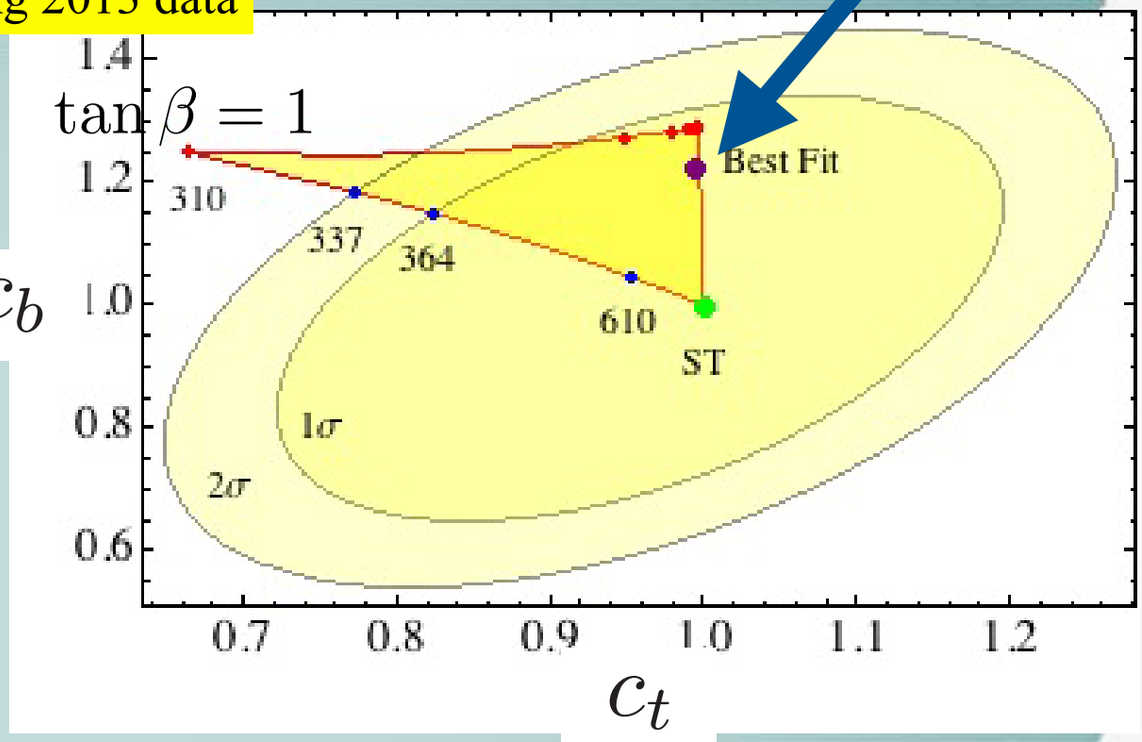
Heavy Scalar Bosons in the Minimal SUSY Standard Model (MSSM)

$$@\tan\beta = 1:$$
$$M_H > 340\ (3\sigma)$$
$$M_H > 365\ (2\sigma)$$

ATLAS CONF- 2014 - 010

Best Fit

Spring 2013 data



L. Maiani, A. D. Polosa and V. Riquer,
Phys. Lett. **B724** (2013) 274;
see also R. S. Gupta, M. Montull and F. Riva,
JHEP **1304** (2013) 132.

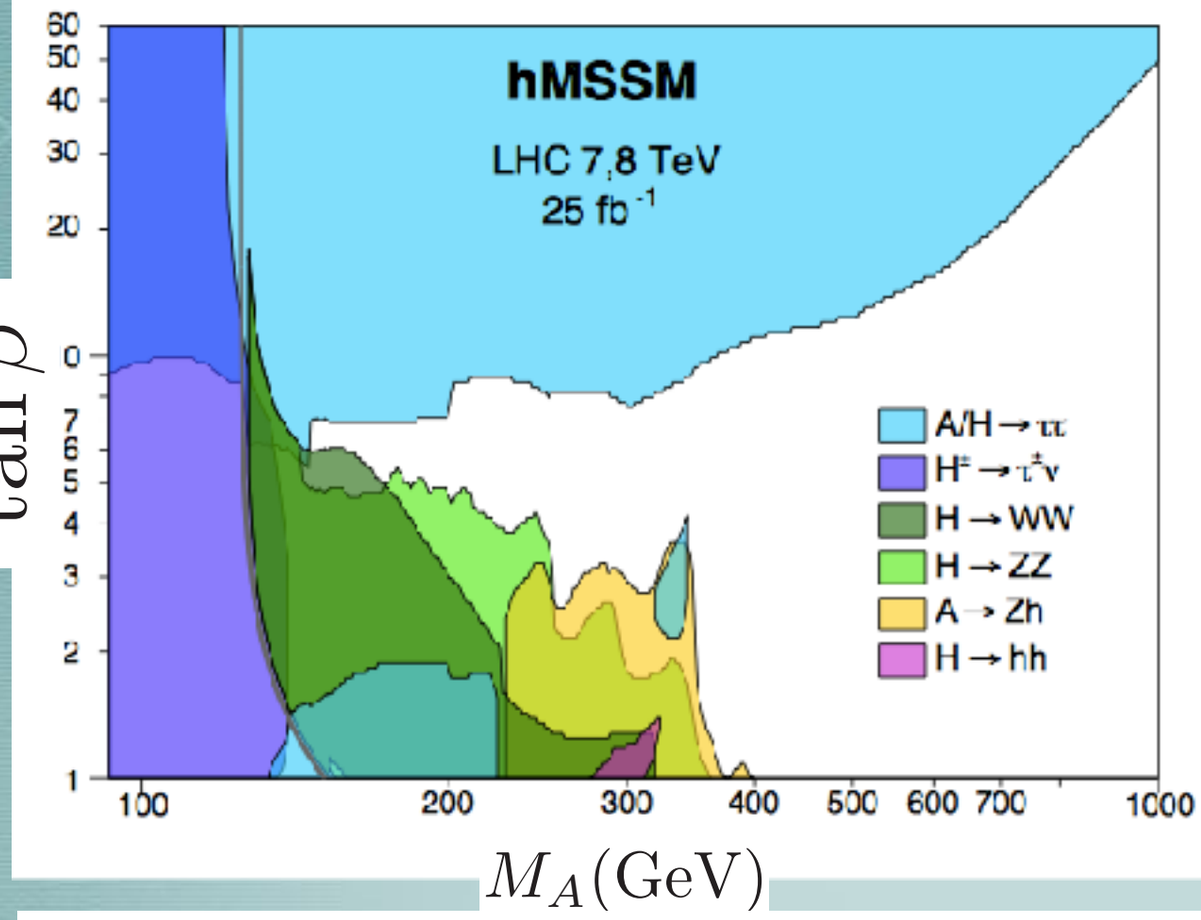
$$@\tan\beta = 1 (\text{ATLAS data } 2014):$$
$$M_H > 450\ (2\sigma)$$

Direct search for heavier scalars in MSSM

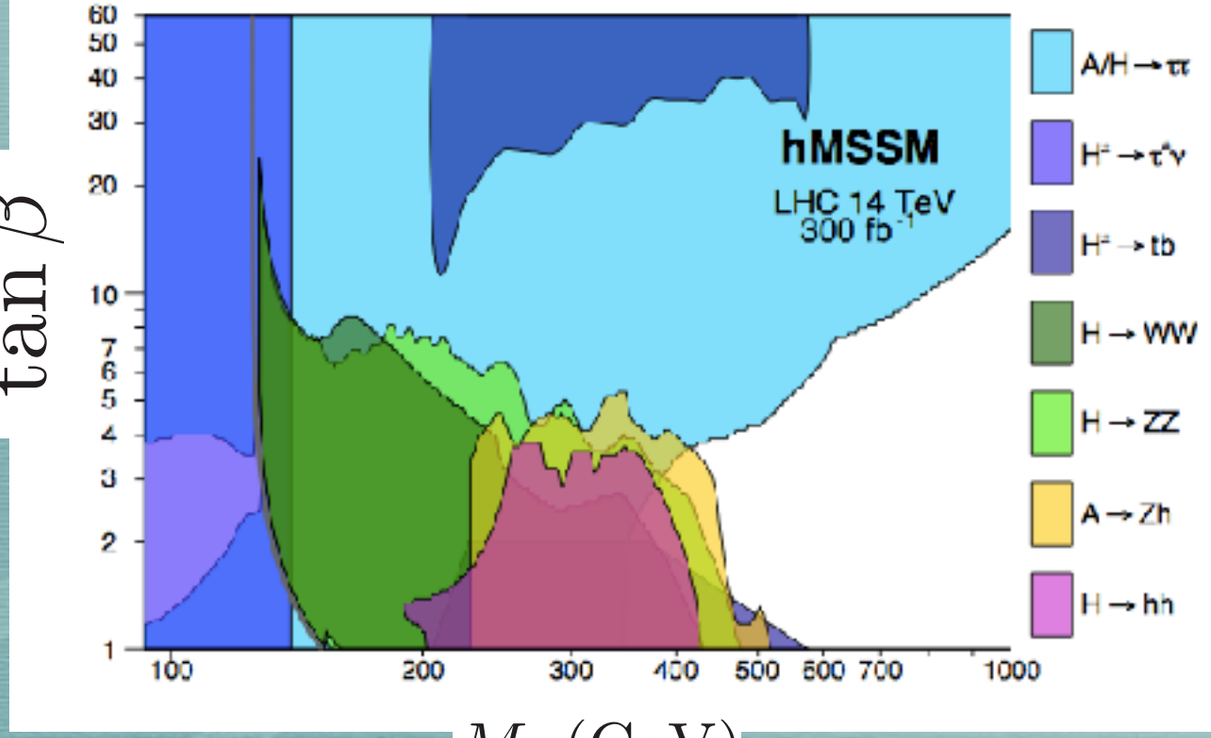
Combined constraints in the [tan β, M_A] plane of the hMSSM from searches at the LHC for the heavier H, A and H bosons decaying into either fermionic or bosonic final states. All searches performed at c.m. energies up to $\sqrt{s}$ = 8 TeV and 25 fb−1 data are included.

A. Djouadi *et al.*, JHEP **1506** (2015) 168

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Projections for the LHC with $\sqrt{s}$ = 14 TeV and 300 fb^{-1} data for the 2σ sensitivity in the hMSSM [tanβ,MA] plane when the searches for the A/H/H$^{\pm}$ states in their fermionic and bosonic decays are combined.

A. Djouadi *et al.*, JHEP **1506** (2015) 168

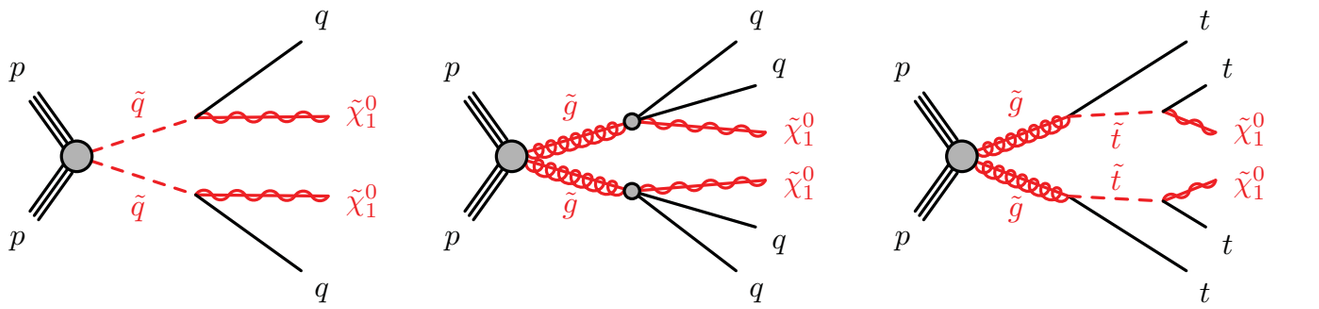
Recent limits on gluino mass

Andreas Hoecker (CERN), *Conference Summary*
Rencontres de Moriond La Thuile, 19 March 2016

Supersymmetry (I)

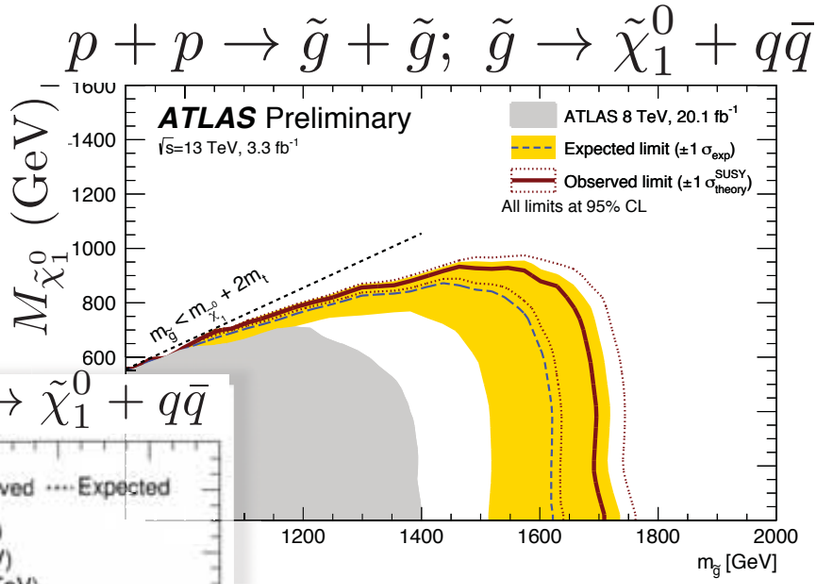
With jets & MET

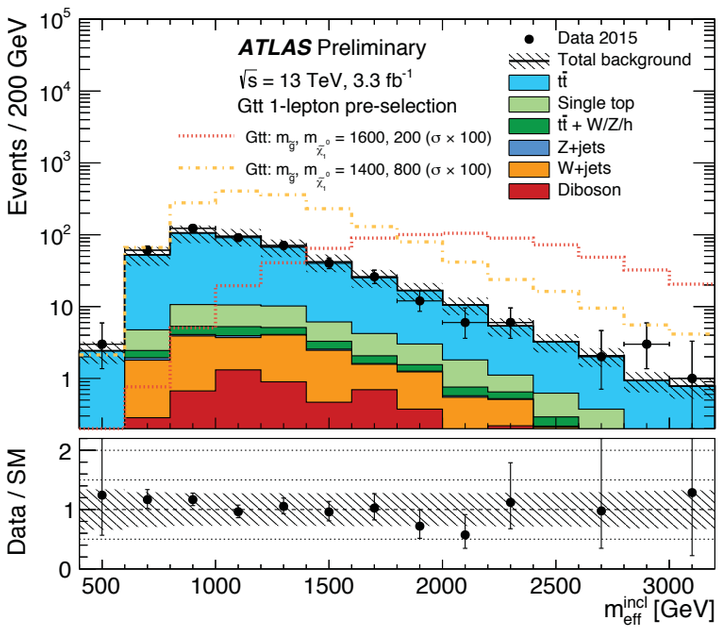
ATLAS & CMS have updated their most sensitive SUSY searches using (b-)jets and MET

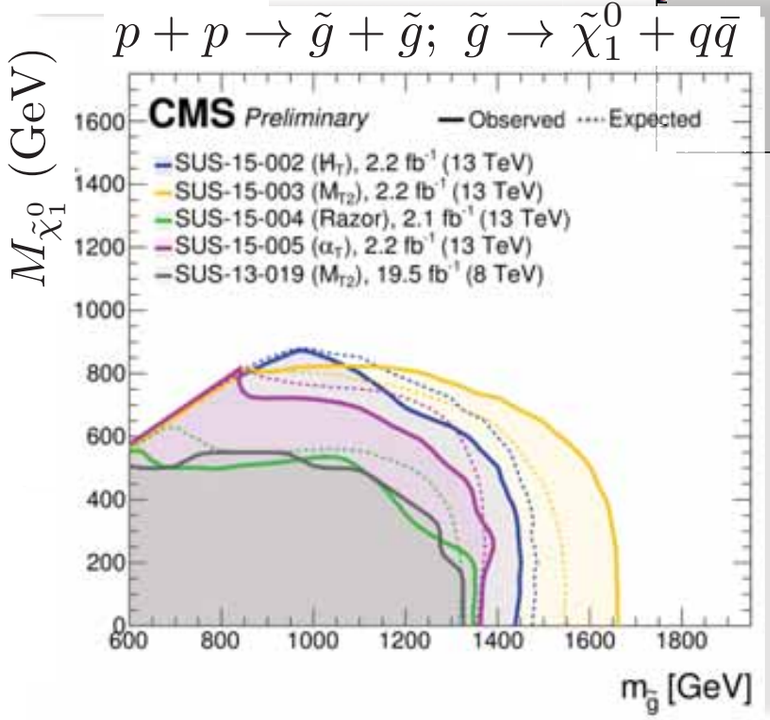


Benefit from improved background modelling (better generators & theory, better tuning), but can still find large scale factors from control region normalisation of SM processes in extreme corners of phase space

Personal remark: need to make sure our analyses are optimised for discovery (not limits)







No significant anomaly seen in 7 different jets + MET analyses presented

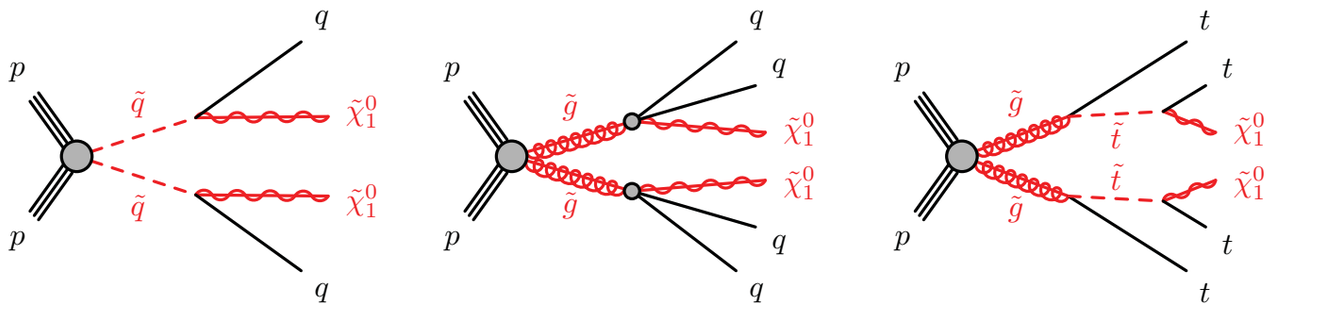
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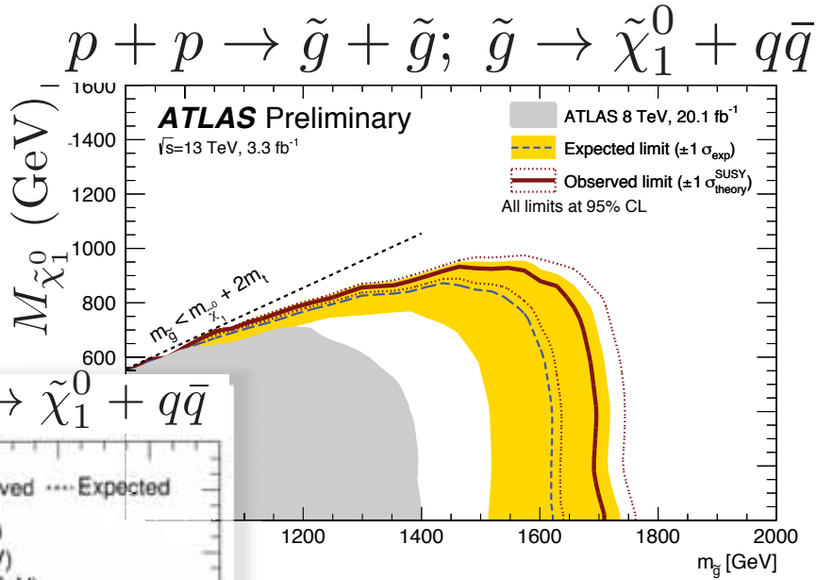
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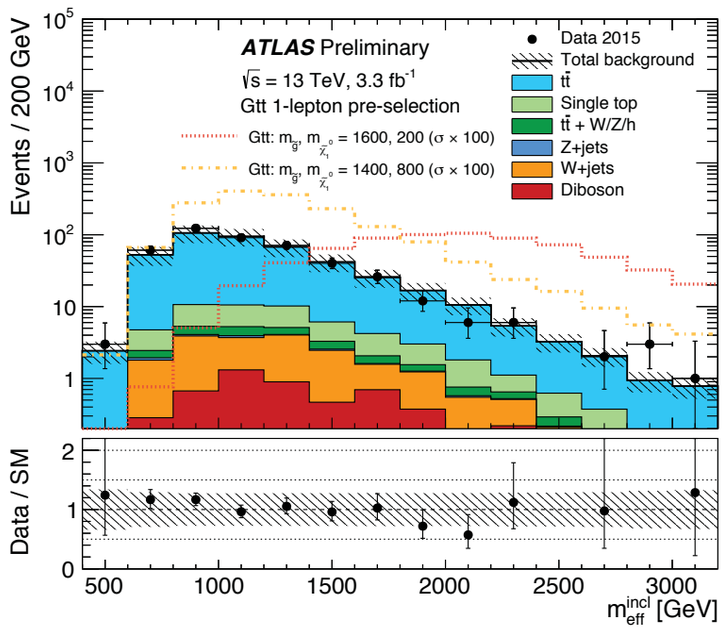
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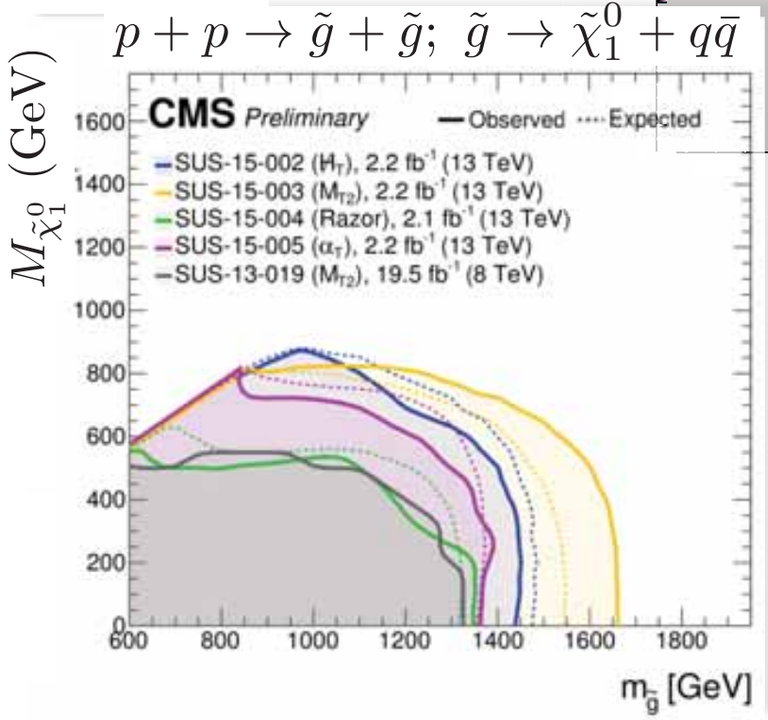


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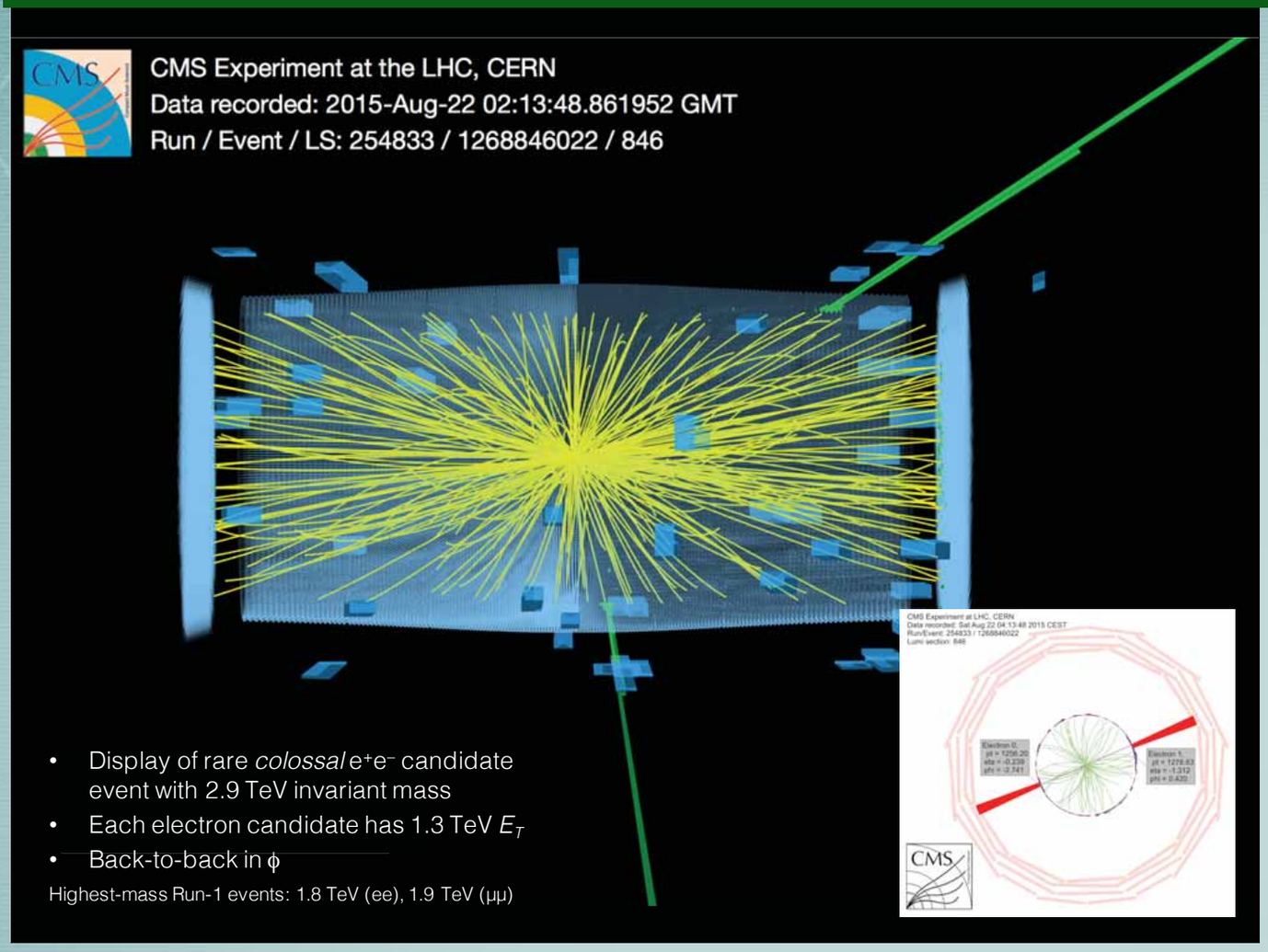




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$$M_{\tilde{g}} > (1400 - 1600)\ \text{GeV},\ \text{for}$$
$$M_{\tilde{\chi}_1^0} < 800\ \text{GeV}$$

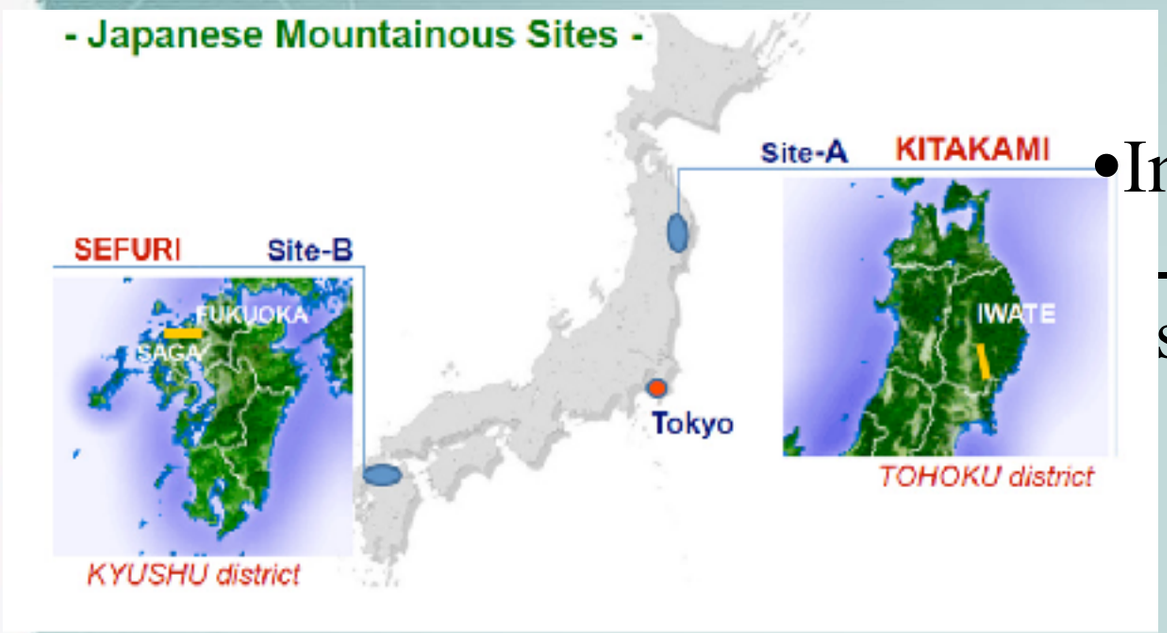
Run 2. Production of an e^+e^- pair with invariant mass of 2.9 TeV ????



- LHC Run2: ongoing
- H-LHC: a factor 10 more luminosity, will bring the discovery potential above 3 TeV (?)
- Could it be possible to replace the superconductin dipoles to bring H=15 Tesla doubling the LHC energy?

6. An electron-positron step ?

An $e^+ e^-$ Higgs boson factory, could aim at high precision to probe Higgs physics at high energies

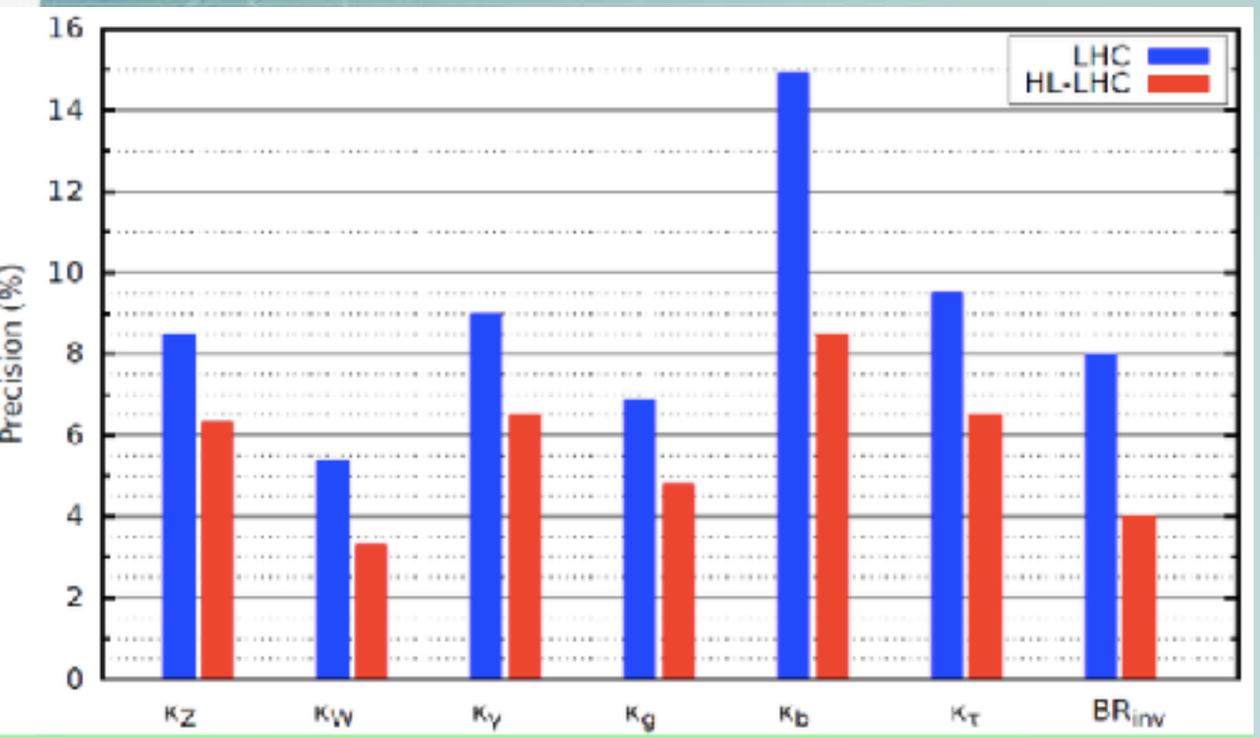


- International Linear Collider, e^+e^- @ 0.5 TeV:
  - -site approved in Japan: (Kitakami) + a reserve site (Sefuri)

- Alternatively, ***repeat the LEP-LHC strategy***
- go for a circular e^+e^- @ 250-300 GeV in a large tunnel (Higgs factory)
- 70-100 km to make radiation losses acceptable,
- tunnel may host later a p-p collider @ 80-100 TeV, to explore the region left by LHC, 3 to 10 TeV
- projects are being made at CERN, TLEP, and in China, CEPC, led by IHEP.

High precision? (very incomplete)

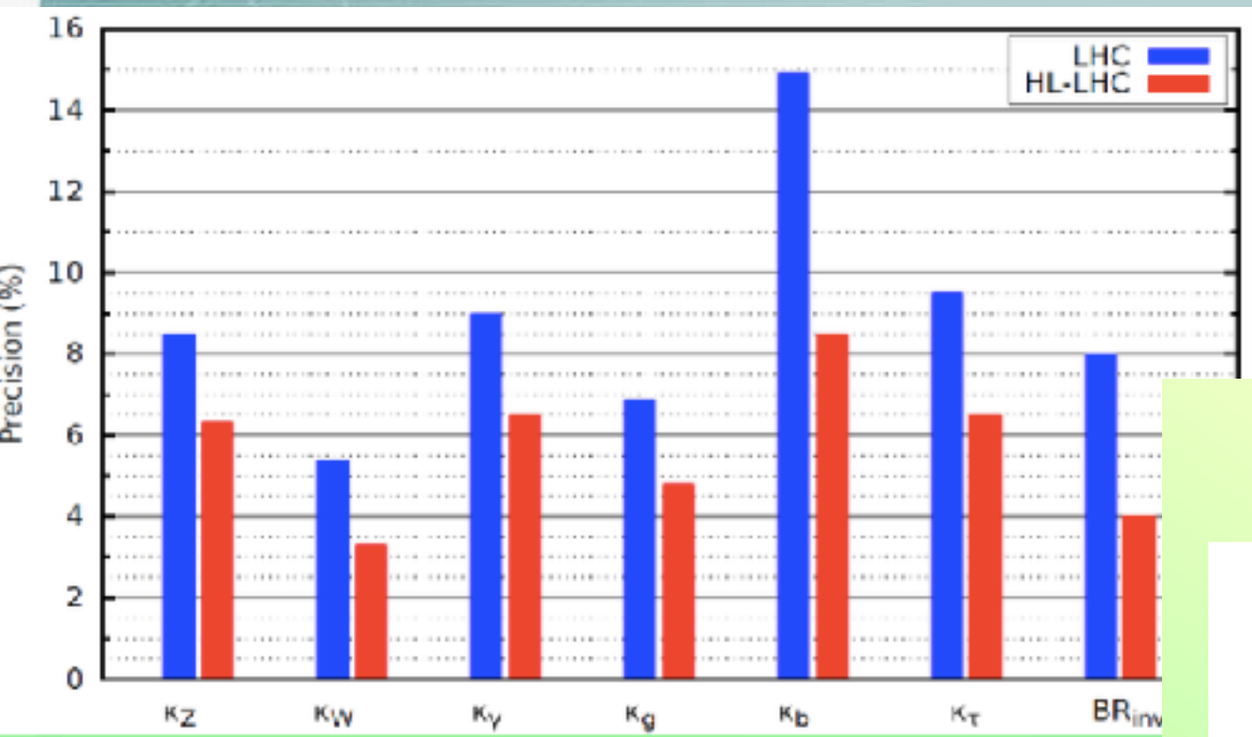
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$



LHC(300/fb) + HL-LHC(3/ab)
M. E. Peskin, Snowmass Study, arxiv:1312.4974

High precision? (very incomplete)

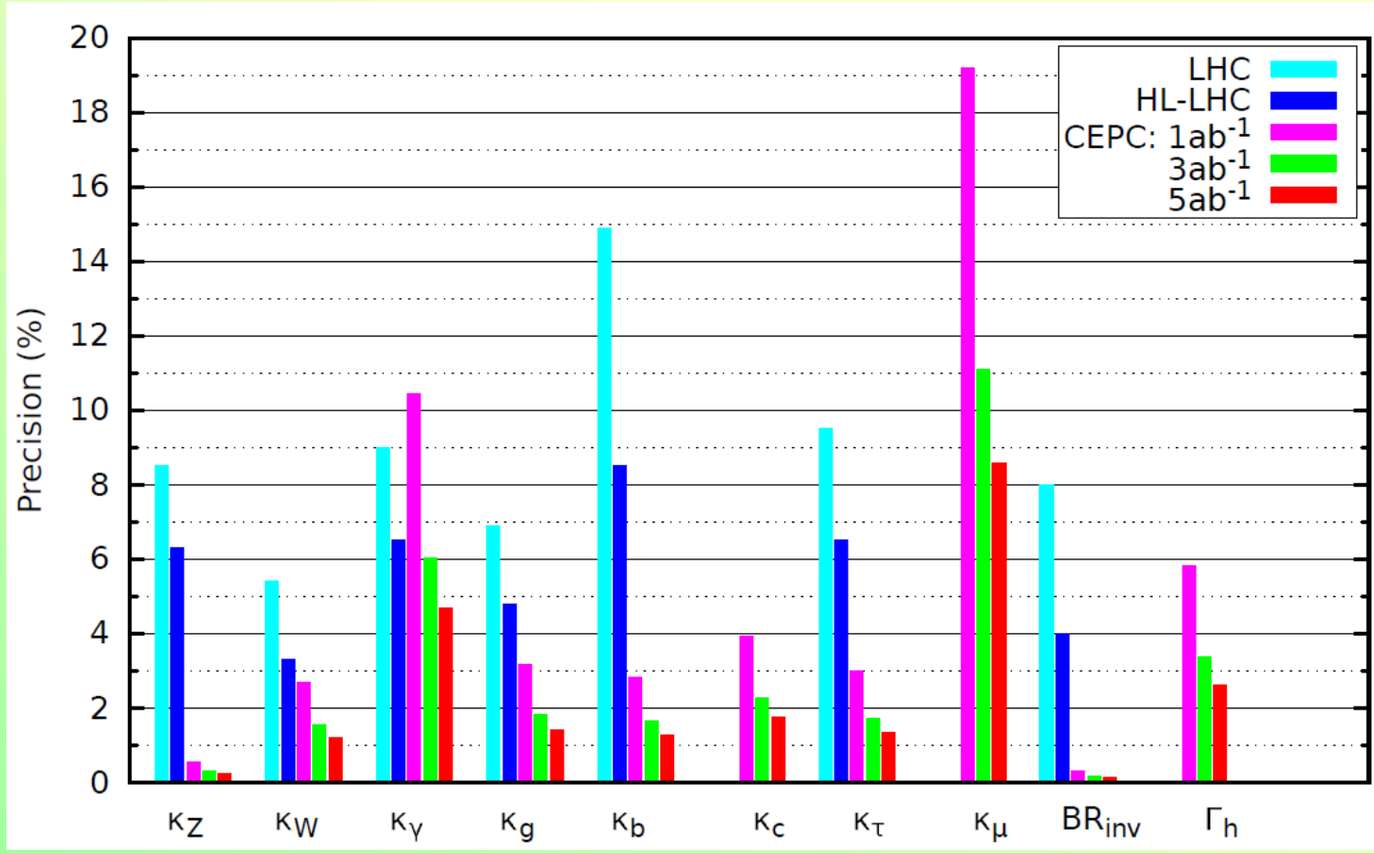
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LHC(300/fb) + HL-LHC(3/ab)
M. E. Peskin, Snowmass Study, arxiv:1312.4974

Courtesy of Hong-Jian He

Testing Higgs Couplings: CEPC vs LHC



Ge, HJH, Xiao, JHEP 10(2016)007 [arXiv:1603.03385

The trilinear h(125) coupling

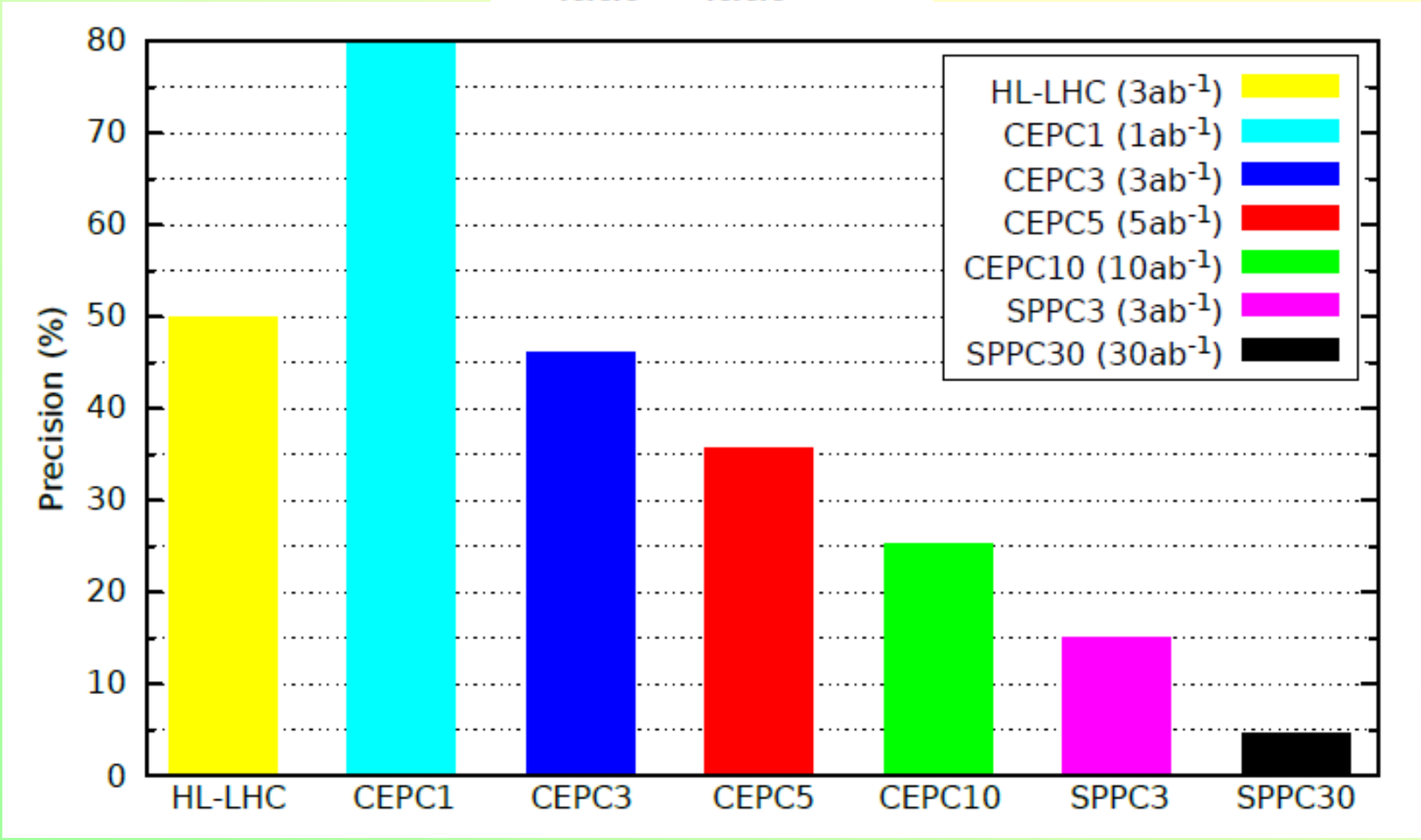
- Deviations from Standard Model would be univocal signal of New Physics
- can barely be seen at HL-LHC and electron-positron Colliders, Very Large proton Colliders needed.

Sensitivity to Higgs Self-Coupling h^3

Courtesy of Hong-Jian He

➢ **Comparison: h^3 at CEPC(1, 3, 5/ab) and SPPC(3, 30/ab), vs HL-LHC (3/ab):**

$$|\lambda_{hhh}/\lambda^{\rm sm}_{hhh} - 1|$$



-- Higgs WG Rept

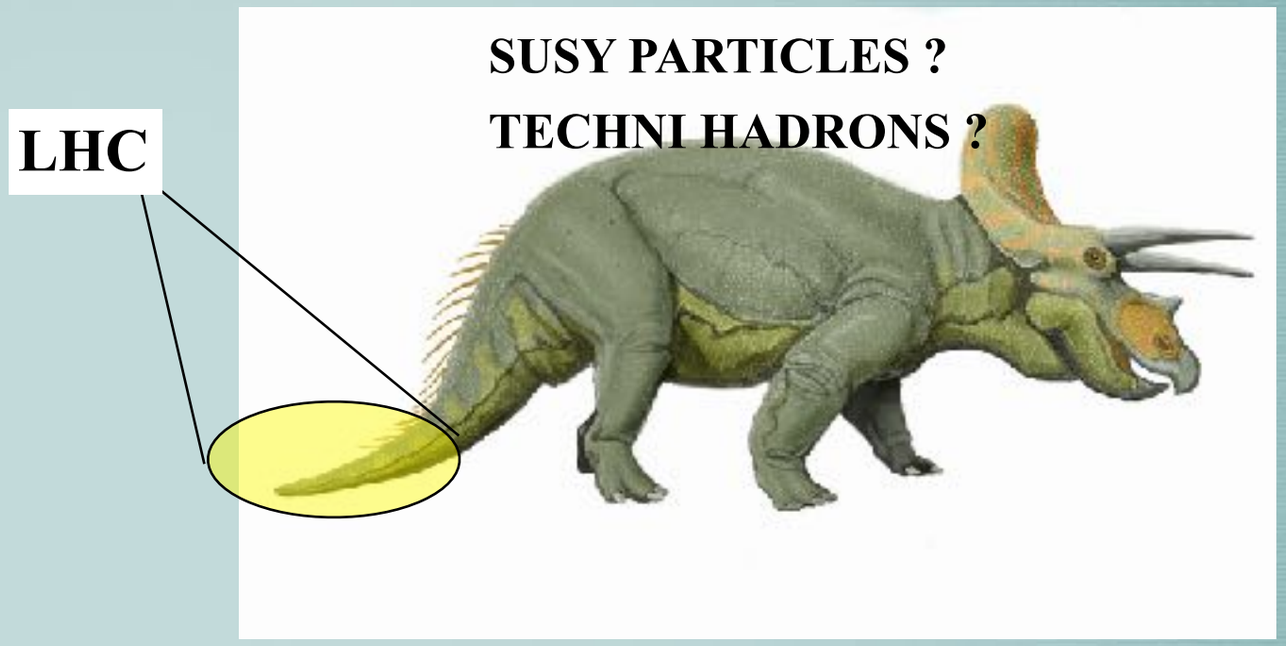
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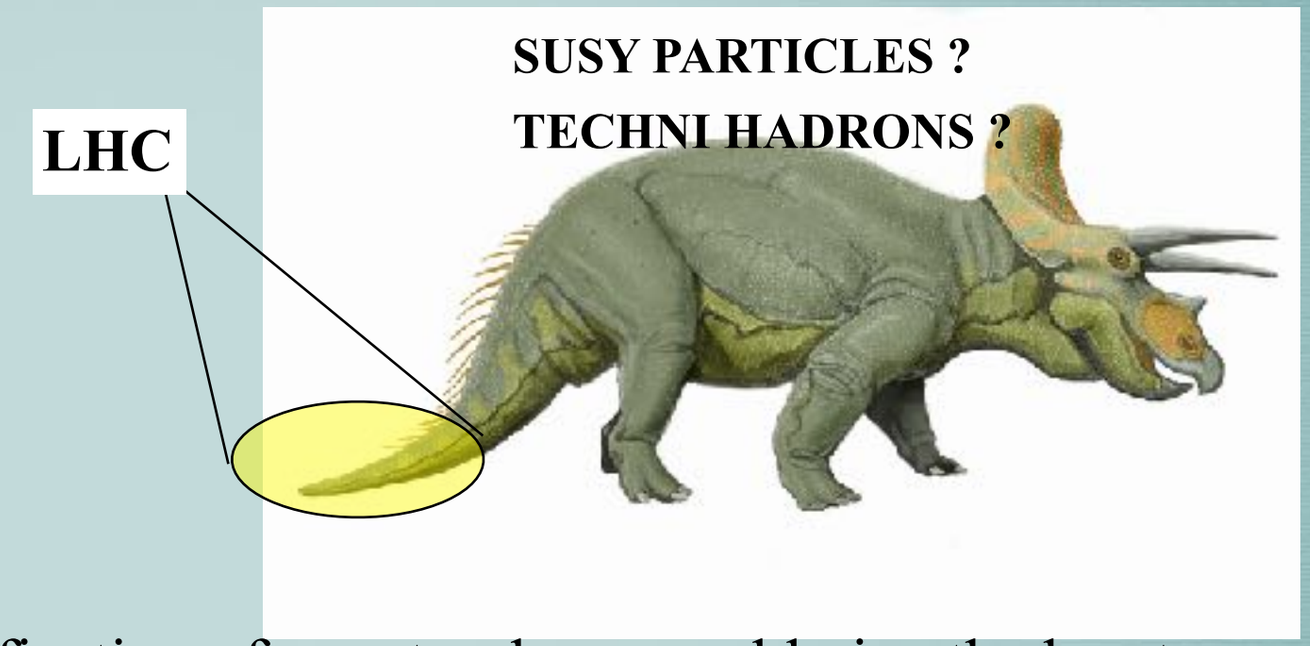
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- In the 80s it was thought that identification of unnaturalness could give the key to a complete theory of what is Beyond the Standard Theory
- we may have guessed some real point…. compositeness, supersymmetry …but there are so many things we do not fully understand (which SUSY, dark matter, hierarchy, strong interactions) that the physics we will find there will be, most likely, ***entirely new, strange and unexpected***.
- Only direct inspection will tell.

Dreams about the future??





- 100 TeV proton Collider is a fantastic challenge
- new innovative technologies: material science, low temperatures, electronics, computing, big data
- an attraction for new physics ideas and young talents to solve the hardest scientific problem which we have been confronted in the last 100 years

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1950's: National Laboratories in IT, FR, UK, DE... united forces to make CERN-Europa
2030's: Regional Laboratorie in Europe, America, Asia … will unite in a Global Accelerator Network - The World ??