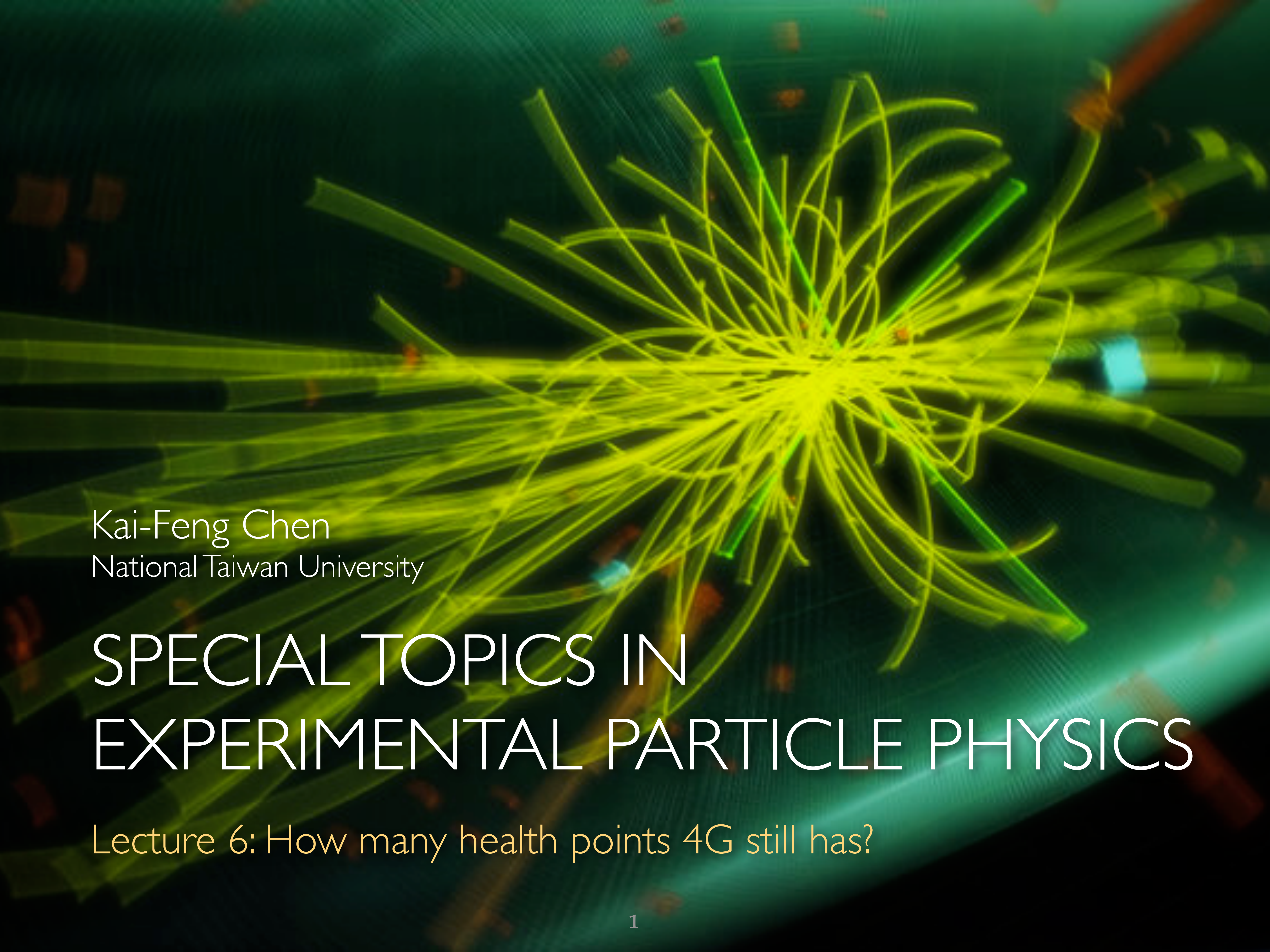


Kai-Feng Chen
National Taiwan University

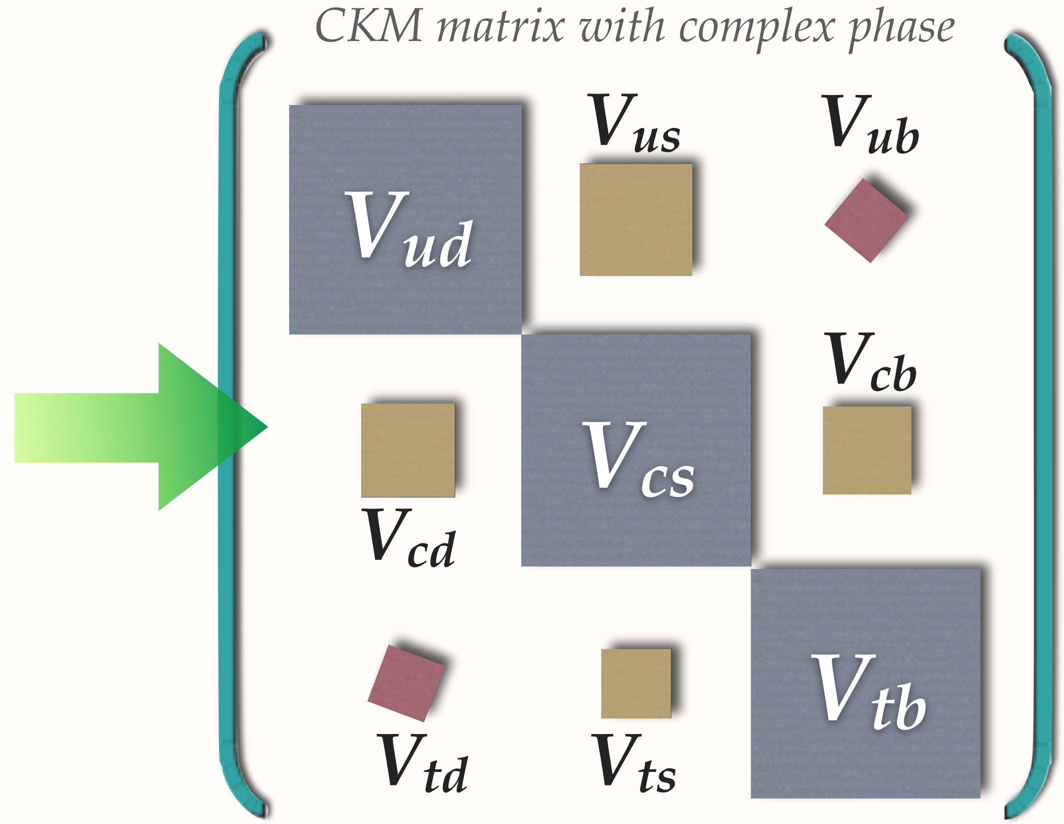
SPECIAL TOPICS IN EXPERIMENTAL PARTICLE PHYSICS

Lecture 6: How many health points 4G still has?


You on
3G
You on
4G

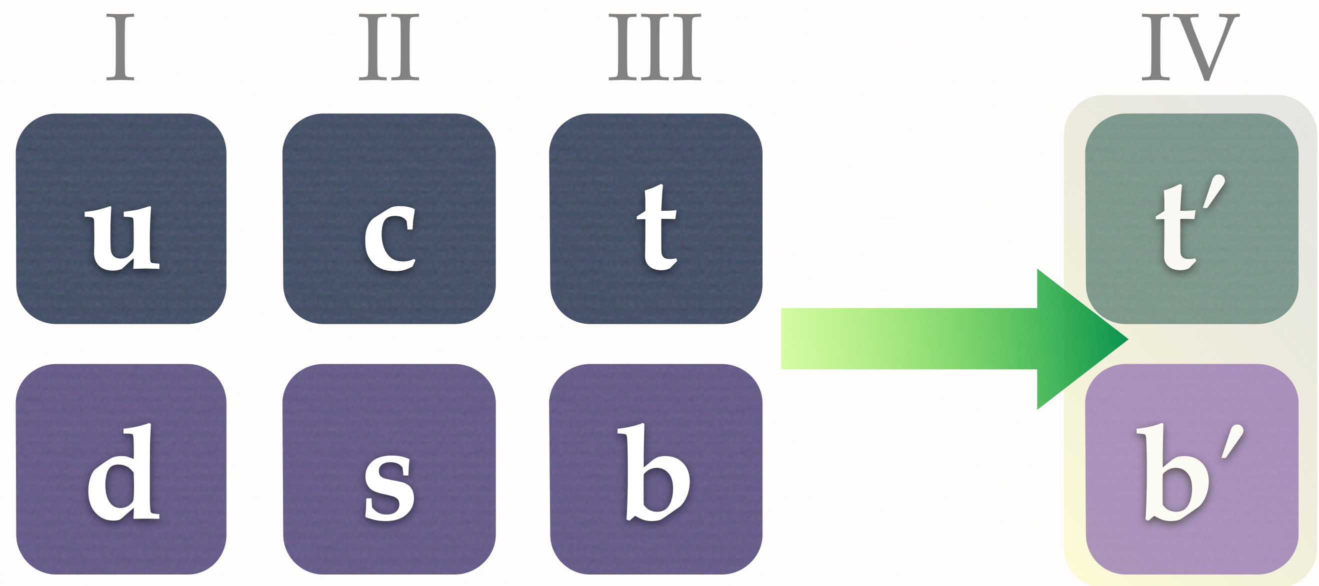
WHY 3 GENERATIONS?

- In Kobayashi-Maskawa model:
  We need **THREE** generations of quarks to produce **ONE** irreducible complex phase representing for the *CP* violation and explain the tiny difference between **matter** and **antimatter**.



*But this model does not limit the number of generations to be exactly **3**!*

ADDING 4G TO THE WORLD

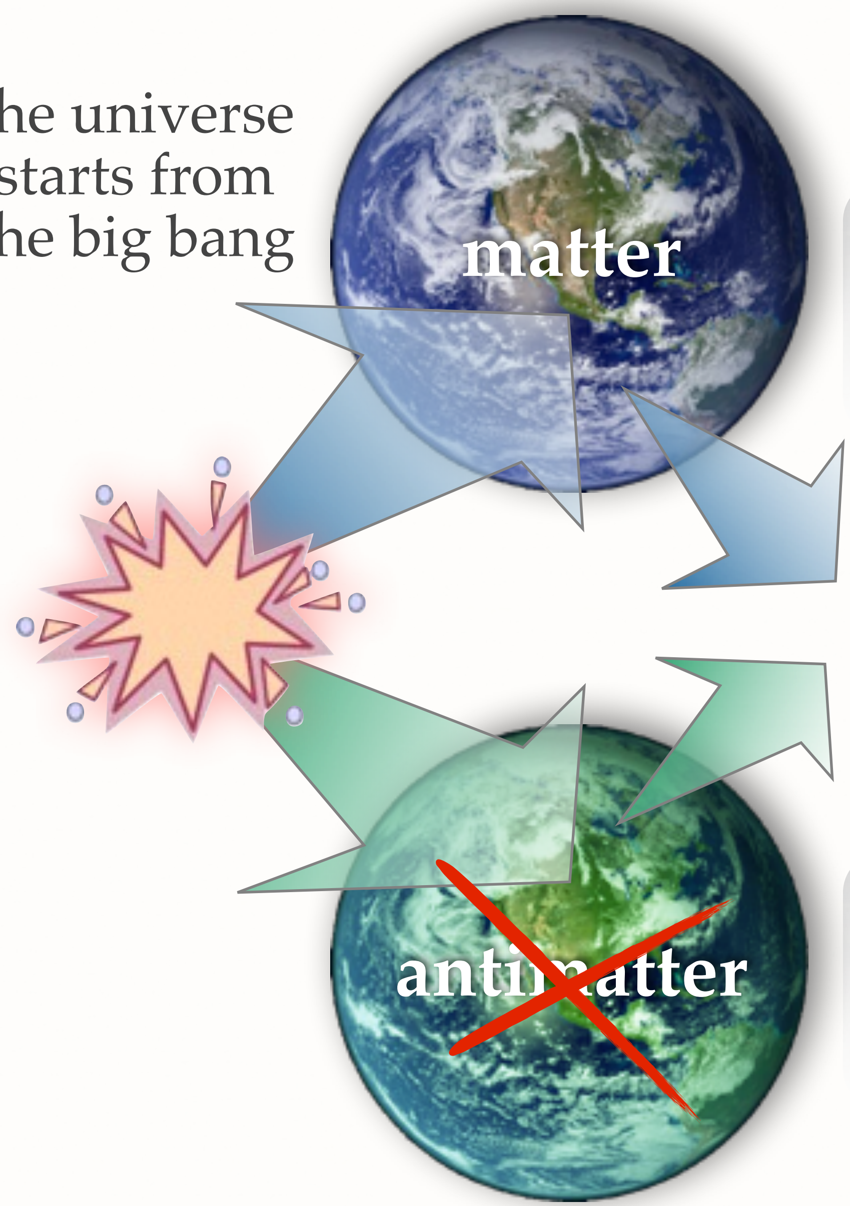


Adding a couple of heavy quarks to the SM?

- Adding one more generation of quarks is **an obvious extension** to the SM, and this is not really excluded by the electroweak precision data.
- Small mass splitting between b′ and t′ is preferred: $|M_{t'}-M_{b'}|<M_W$.
- Flavor physics data for unitarity triangle provide some information regarding the "CKM4" matrix, but it is only weakly constrained due to the uncertainties.

A BIG MOTIVATION: BAU

the universe starts from the big bang



Although, the known baryon-antibaryon asymmetry is already quite small:

$$\frac{n(B)}{n(\gamma)} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$

(WMAP)

Pair Annihilation

$$\frac{n(\overline{B})}{n(\gamma)} \approx 0$$

The Kobayashi-Maskawa phase only contributes ~10^{-20}

The CP violation in the Standard Model is far too small for accommodating the "matter-dominated" Universe!

"Something" is definitely necessary to enlarge the asymmetry by $O(10^{10})$!

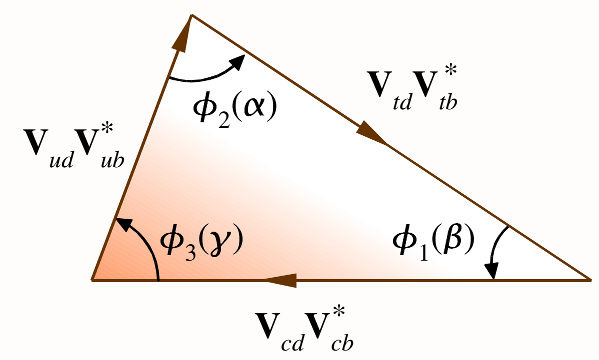
A BIG MOTIVATION: BAU

Ingredients of CPV in the Standard Model:

#1: At least THREE generations;

#2: Non-trivial *CP* phase; Non-trivial unitarity triangle.

#3: Non-degenerate like-charge quarks.



If we simply shift the invariant by one generation:

$$\begin{bmatrix} u & c & t \\ d & s & b \end{bmatrix} \begin{matrix} t' \\ b' \end{matrix} \rightarrow \begin{matrix} u \\ d \end{matrix} \begin{bmatrix} c & t & t' \\ s & b & b' \end{bmatrix}$$

$$\frac{J'}{J} \approx \boxed{\frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}}\,\boxed{\frac{A'}{A}}$$

References:
Jarlskog PRL 55, 1039 (1985)
Hou arXiv: CJP 47, 134 (2009)

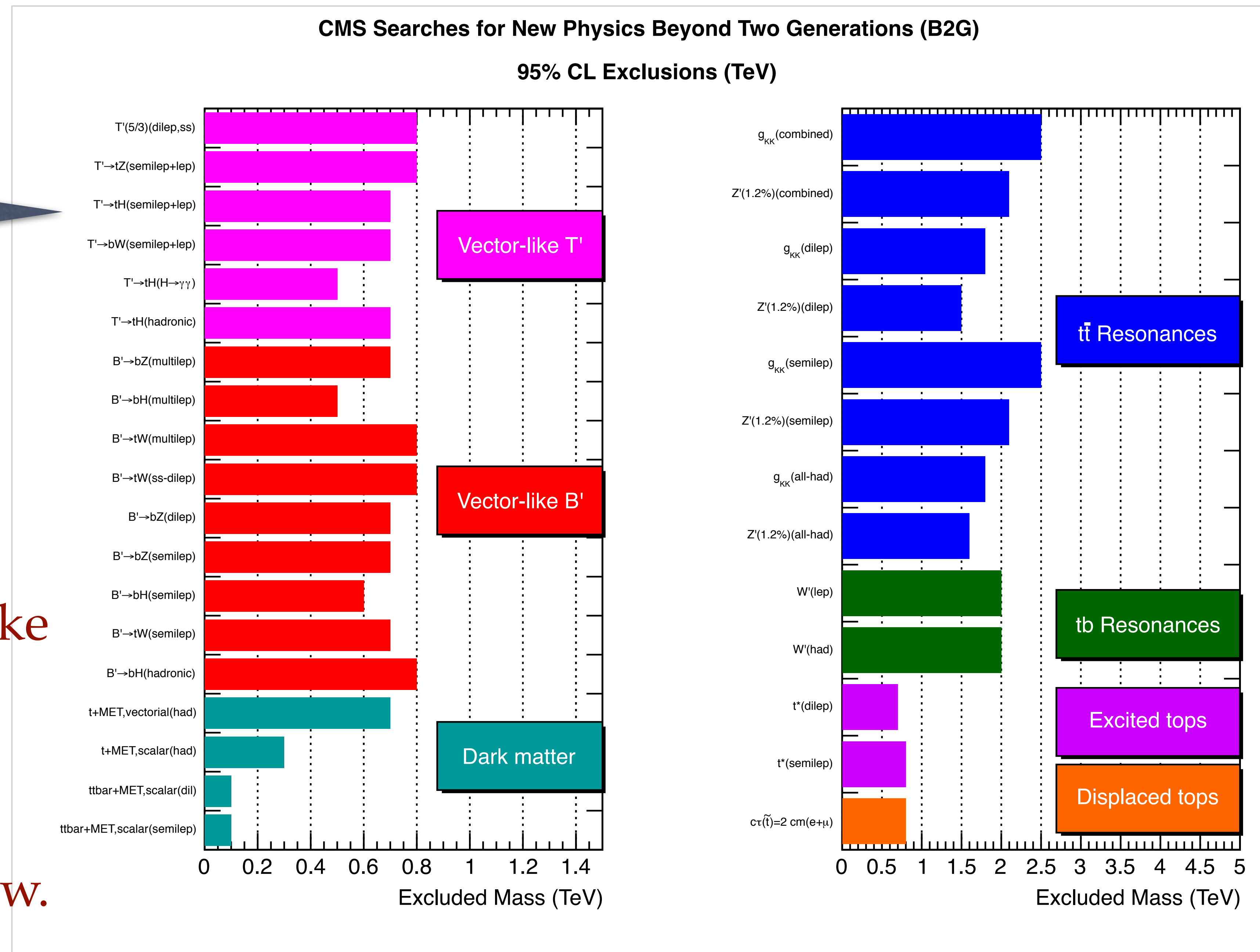
By inserting M(b′,t′) ~ 300~600 GeV/c^2, it already gives us a huge boost on *J*, of $O(10^{13}{\sim}10^{15})$

Replacing the unitary triangle contributes a factor of 30.

A **low cost** solution to BAU!

FROM DIRECT SEARCHES

Nothing found yet...



The searches for vector-like quarks and chiral 4G quarks are not really different in terms of experimental point of view.

THE CLASSICAL "DEATH OF 4G"

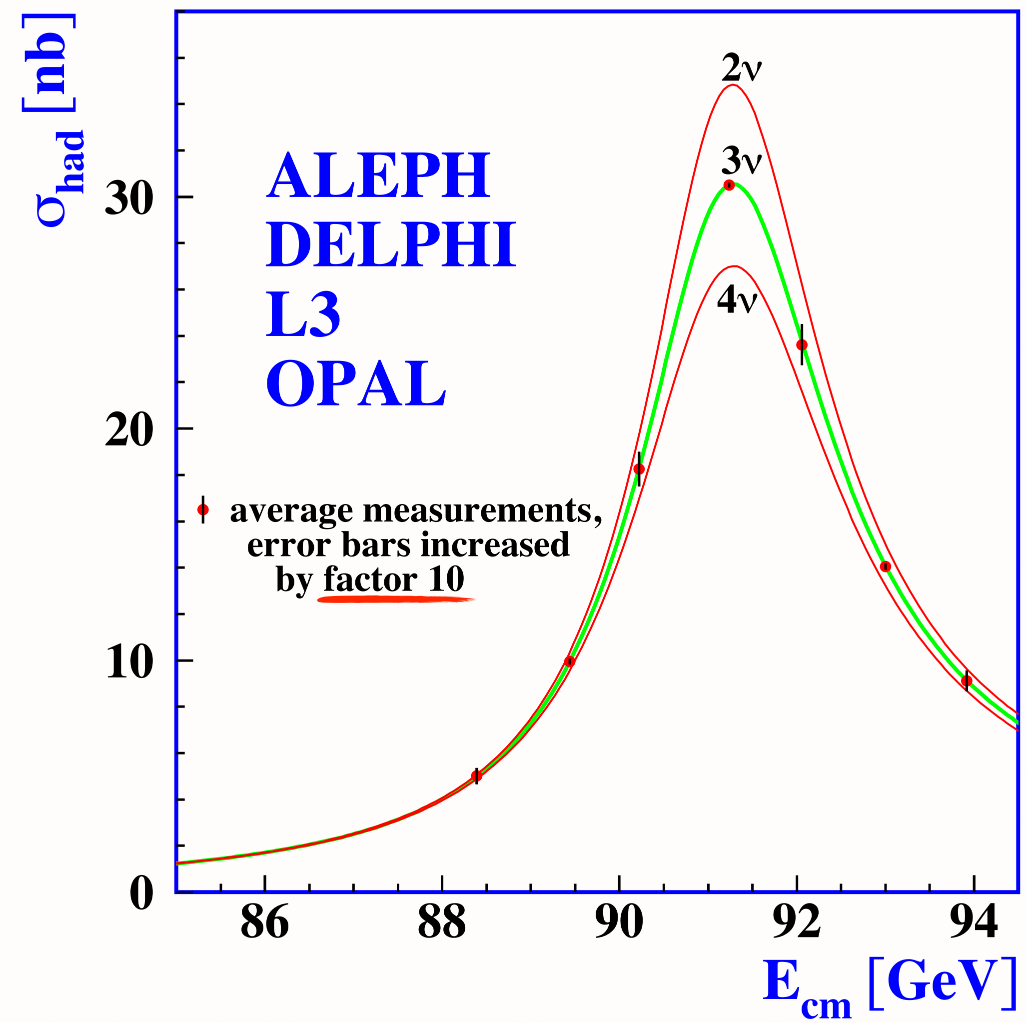
The PDG after 2010 explicitly states that "An extra generation of ordinary fermions is excluded at the 6σ level on the basis of the S parameter alone"...

THE FIRST DEATH OF 4G

- The most precise measurements of the number of *light* neutrino types, N_ν, come from studies of Z production:

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\text{SM}} = 2.984 \pm 0.008$$

Γ_{inv} = the invisible partial width; determined by subtracting the measured visible partial widths from the total Z width.



A very precise measurement — the only issue is that this does not exclude the possibility of heavy neutrinos (ie. $M_\nu > M_Z/2$).

HISTORY OF PDG REVIEWS

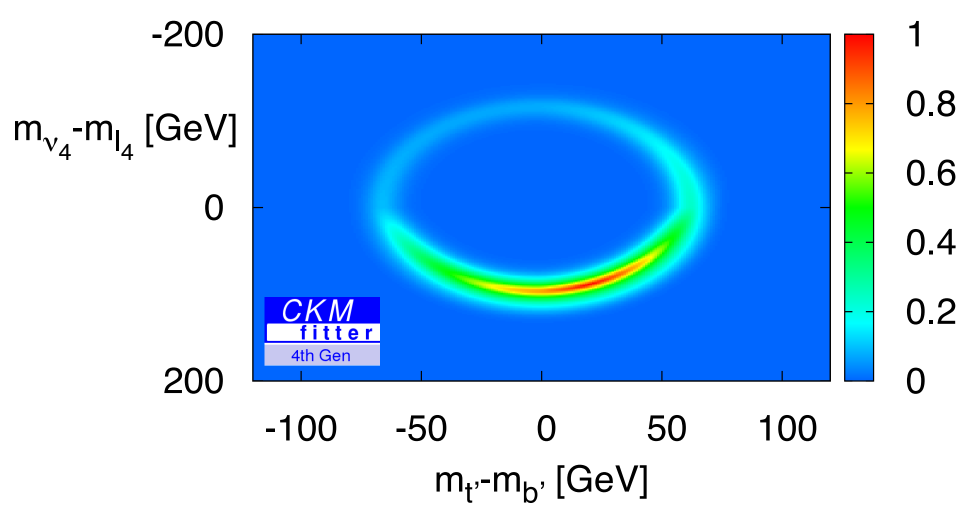
- **1994**: "one heavy generation of ordinary fermions is allowed at 95% CL".
- **1998**: "an extra generation of ordinary fermions is now excluded at the 99.2% CL"
- **2002**: "an extra generation of ordinary fermions is excluded at the 99.8% CL on the basis of the S parameter alone. [...] This result assumes [...] that any new families are degenerate. This restriction can be relaxed [...] to 95%."
- **2010**: "an extra generation of ordinary fermions is excluded at the **6σ** level on the S parameter alone. This result assumes [...] that any new families are degenerate. [...] a fourth family is disfavored but not excluded by current data."

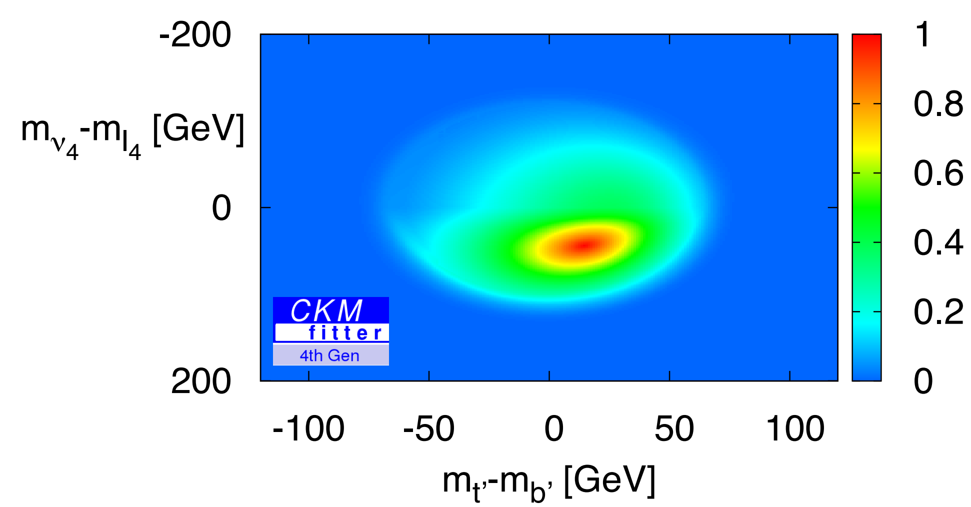
THE CLASSICAL "DEATH OF 4G"

- In PDG, the "inaccurate" statement for the exclusion of 4G is based on electroweak constraints on the oblique parameter ***S***.

$$\delta S = \frac{2}{3\pi} - \frac{1}{3\pi}\left[\log\frac{m_{t'}}{m_{b'}} - \log\frac{m_{\nu'_\tau}}{m_{\tau'}}\right]$$

This exclusion only works with **degenerate 4G** and **unity CKM4**:



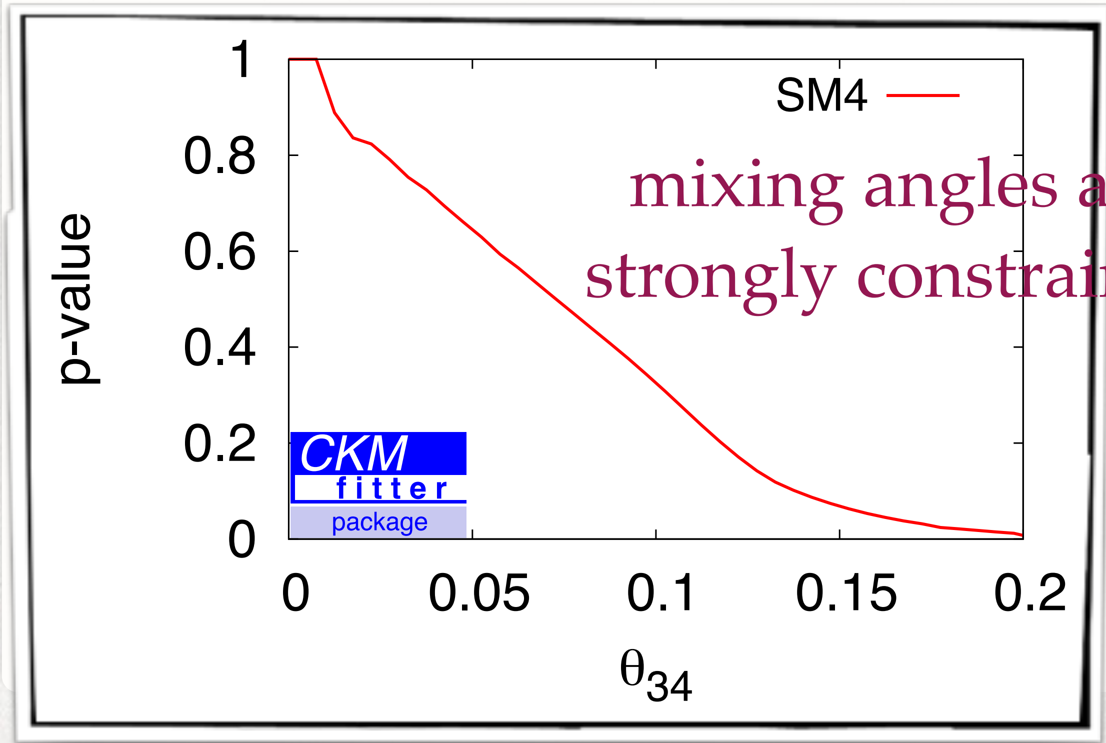


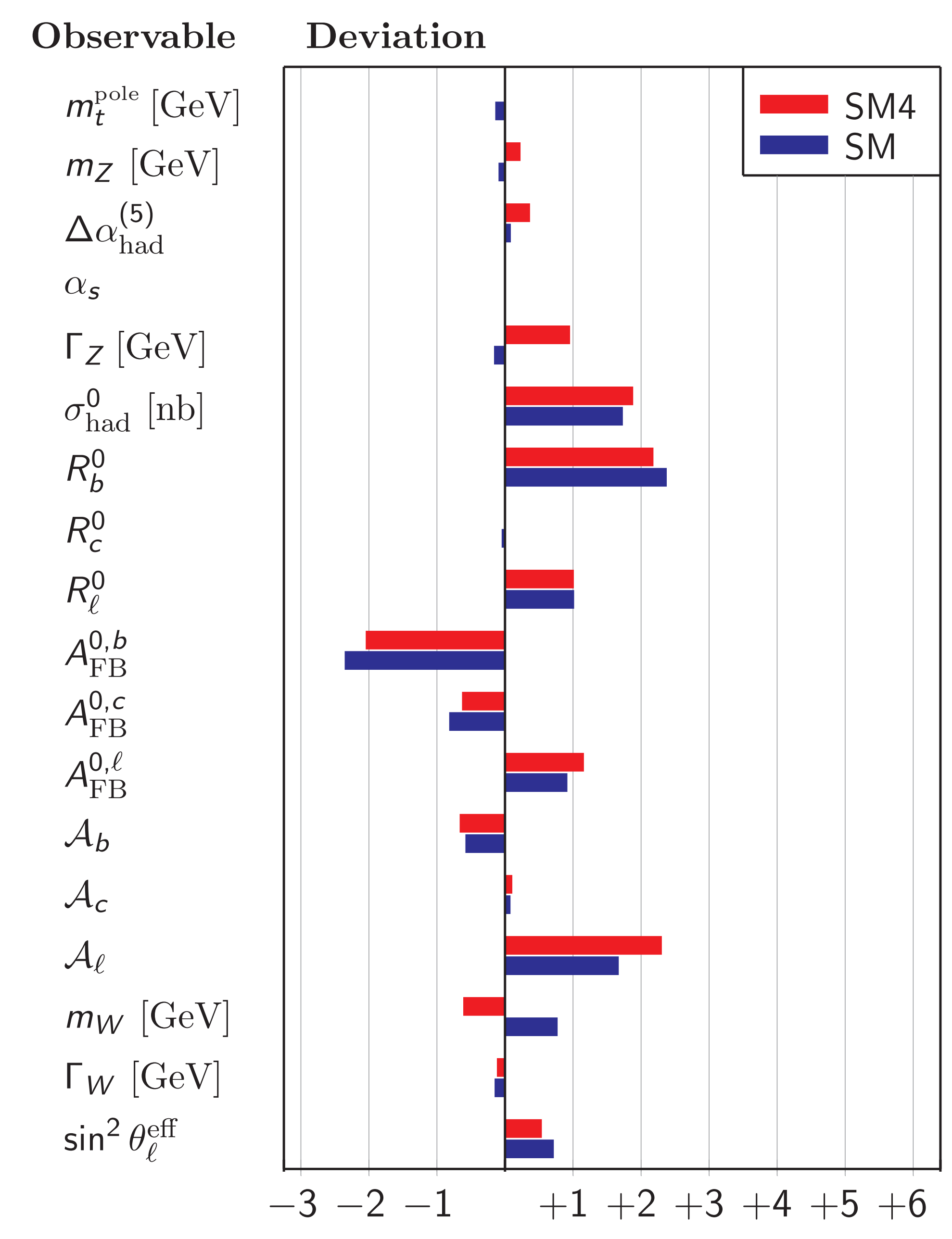
Not a real constraint any more...

$V_{CKM4} = I$ $\qquad$ $V_{CKM4} \neq I$

ELECTROWEAK CONSTRAINTS

- Note the oblique parameters S and T are only applicable if
  - $M_{NP} \gg M_Z$
  - no NP vertex contributions
- Also, it is better to use all electroweak precision observables.

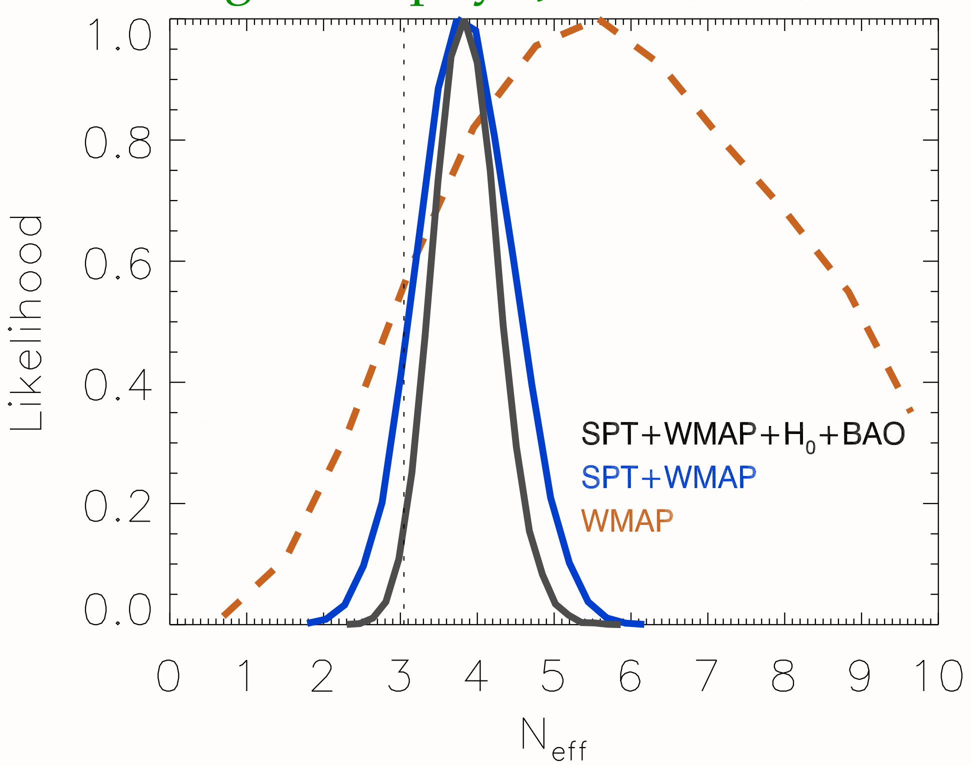





Hints from something above us...

EFFECTIVE NEUTRINO NUMBER (N_{eff}) FROM CMB

e.g. Astrophys.J. 743 (2011) 28



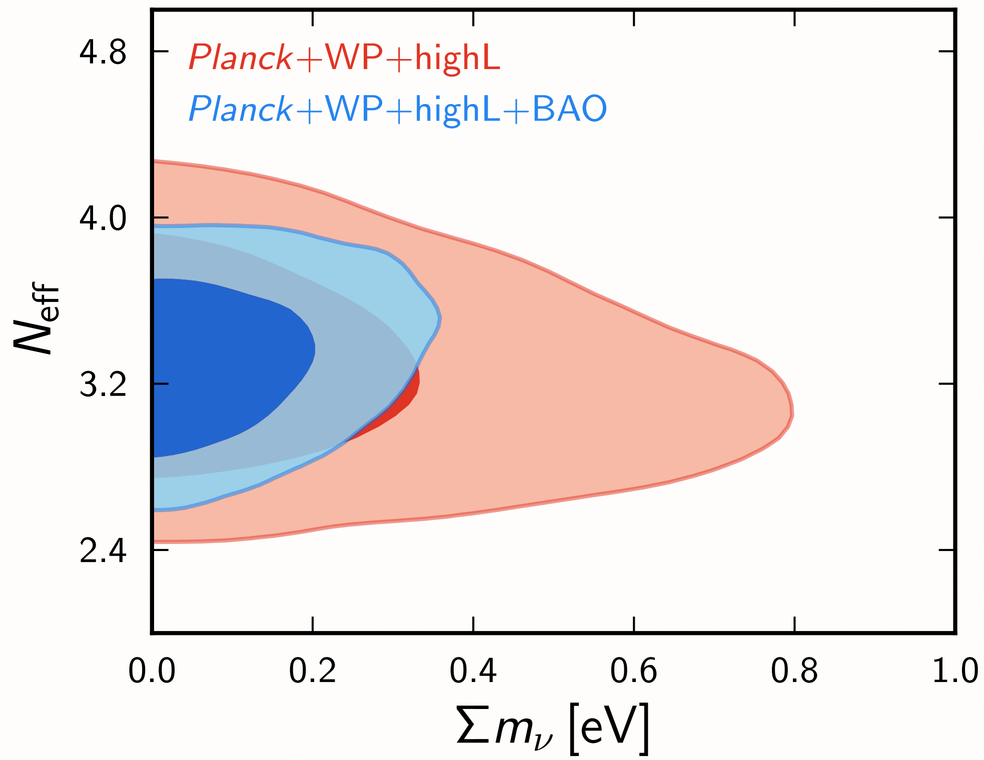
= Neff > 3 @ >95% C.L.

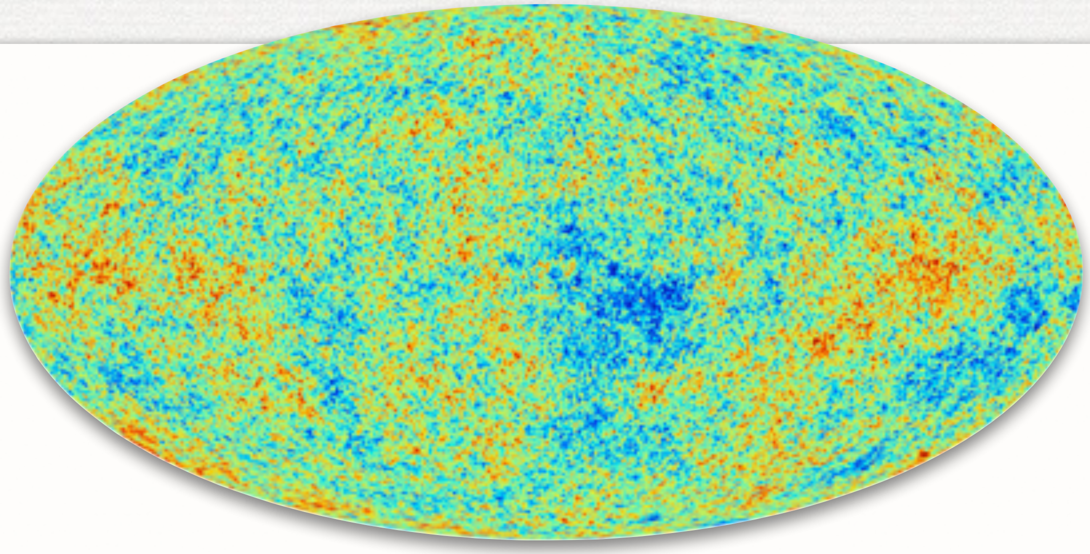
Ref. Light Sterile Neutrinos: A White Paper (arXiv:1204.5379)

Model	Data	N_{eff}
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$
	W-7+ACT	5.3 ± 1.3
	W-7+ACT+BAO+H_0	4.56 ± 0.75
	W-7+SPT	3.85 ± 0.62
	W-7+SPT+BAO+H_0	3.85 ± 0.42
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$

- N_{eff}>3 trend was there since WMAP.
- Exact numbers depend on the cosmological models, the central value is around ~4.

EFFECTIVE NEUTRINO NUMBER (N_{eff}) FROM CMB

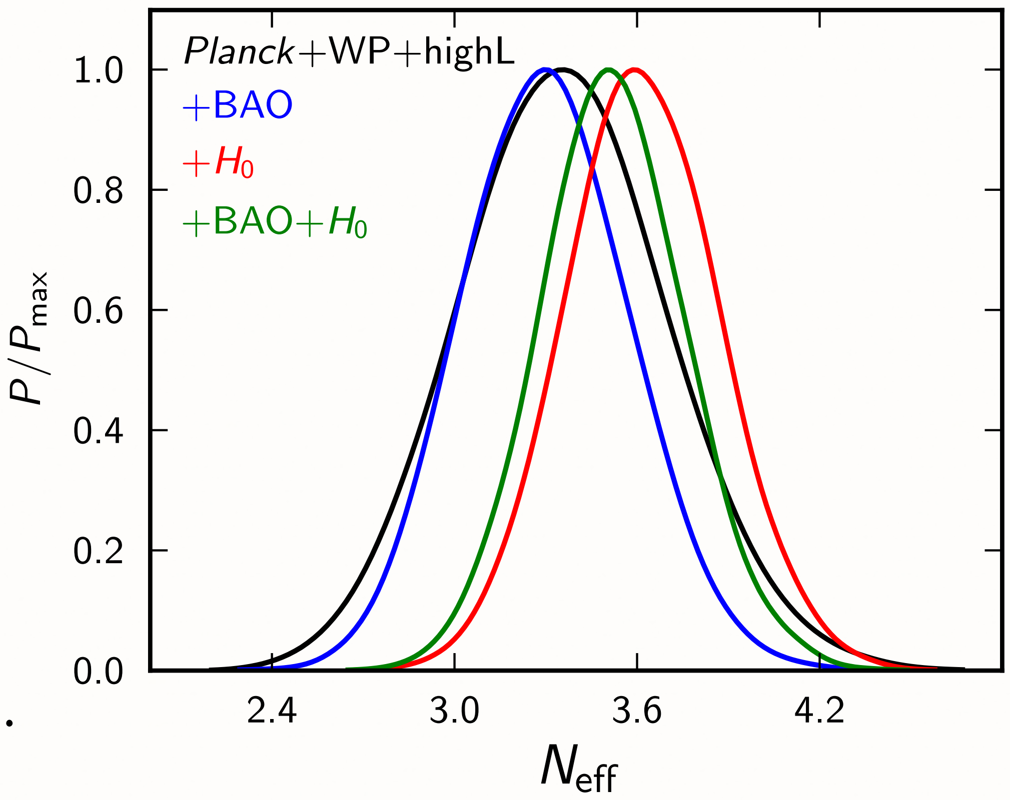




Planck 2013 results. XVI (arXiv:1303.5076)

- However with the new planck data (*hot releases last year*), pushes it back to **N_{eff}~3** now:

$$N_{\rm eff} = 3.30^{+0.54}_{-0.51} \quad (95\%;\, Planck\text{+WP+highL+BAO}).$$




Hints from something smells strong...

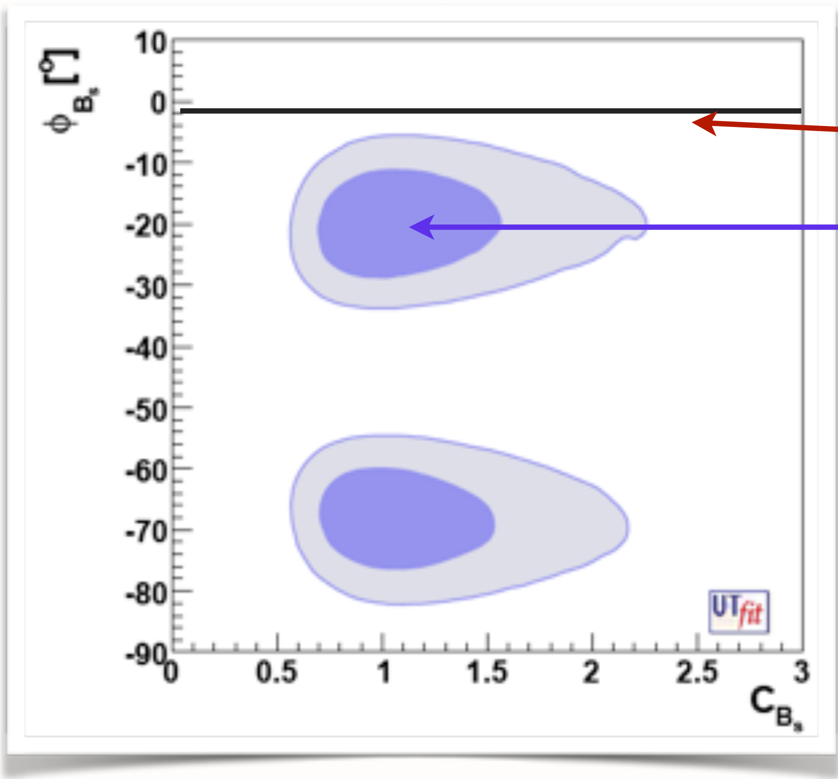
AN INDIRECT HINT : Φ_{Bs}

A hint of non-vanished B_s mixing phase has been seen in 2008:

FIRST EVIDENCE OF NEW PHYSICS IN $b \leftrightarrow s$ TRANSITIONS

(UT*fit* Collaboration)

M. Bona,[1] M. Ciuchini,[2] E. Franco,[3] V. Lubicz,[2,4] G. Martinelli,[3,5] F. Parodi,[6] M. Pierini,[1]
P. Roudeau,[7] C. Schiavi,[6] L. Silvestrini,[3] V. Sordini,[7] A. Stocchi,[7] and V. Vagnoni[8]



Standard Model value (<2 degree)

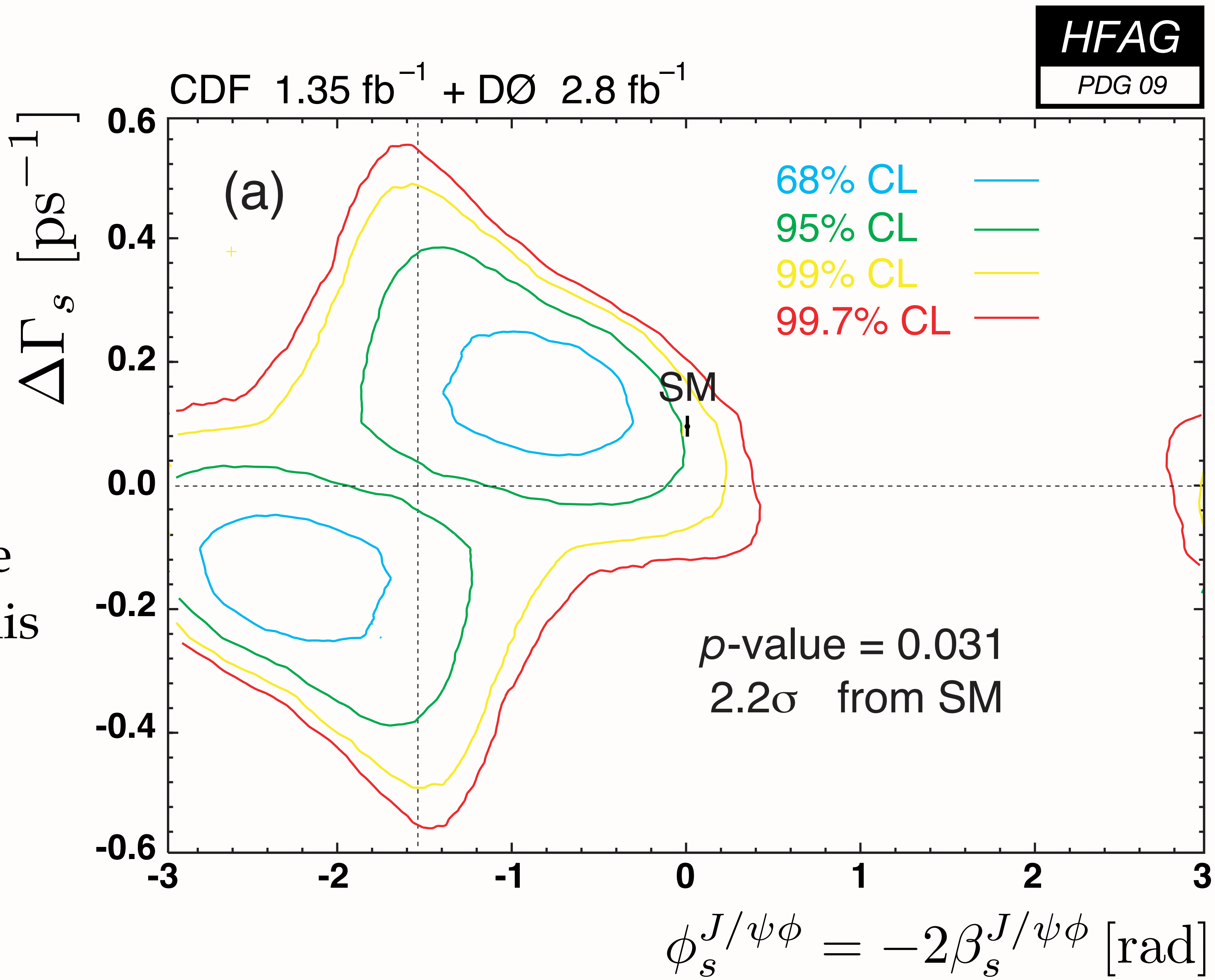
Central value ~20 degrees, 3.7σ deviation

Adding 4th generation quarks can pull down the Φ_{Bs} value from the SM easily!
e.g. add ~500 GeV t': $\sin 2\Phi_{Bs}$~-0.33

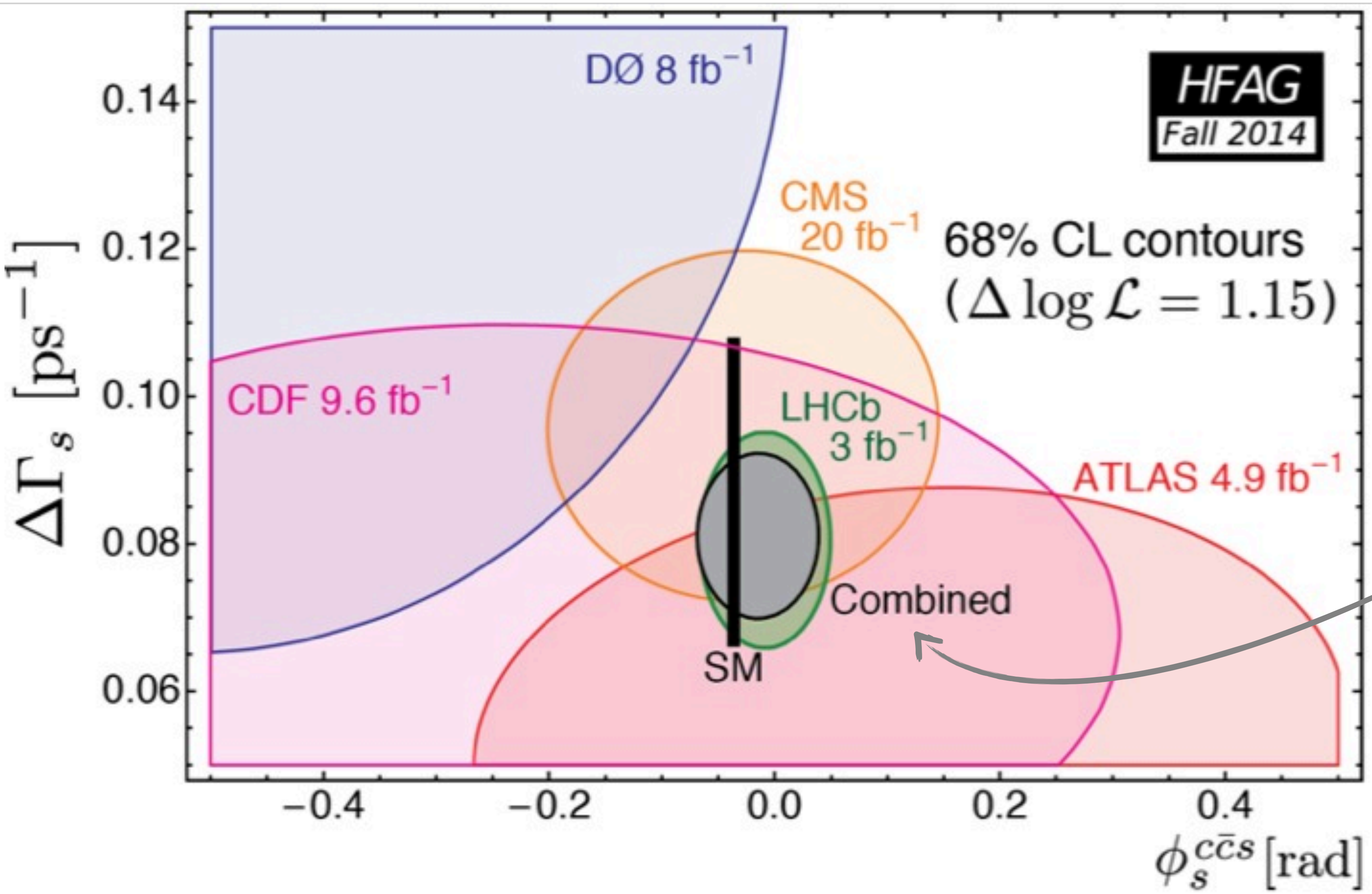
Hou et. al. PRD 76, 016004 (2007);
Hou et. al. PRD 82, 036002 (2010)

IT WAS SOMETHING!

- It was saying that probably 4G is the best solution to this deviation. It was very exciting...



NEVER ESCAPE FROM THE SM



world average 2014
(not yet published)

Fully agree with the SM; no hint of NP anymore...

Experiment	$\Delta\Gamma_s$ (ps^{-1})	ϕ_s (rad)
ATLAS (4.9/fb)	0.053±0.021±0.010	0.12±0.25±0.05
CMS (20/fb)	0.096±0.014±0.007	−0.03±0.11±0.03
LHCb (3/fb)	0.0805±0.0091±0.0032	−0.058±0.049±0.006

http://www.nobelprize.org

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert

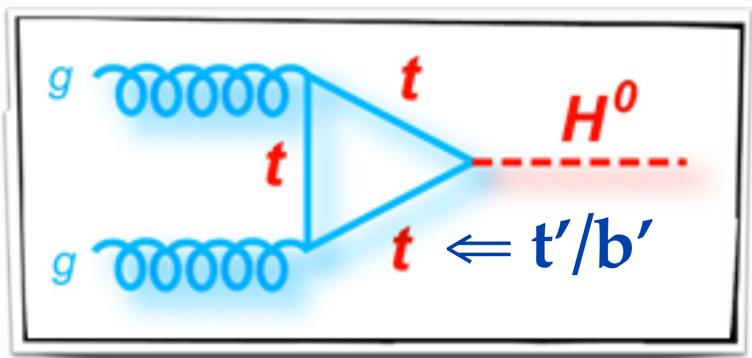
Photo: A. Mahmoud
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Finally, it's the killer application – the observed "Higgs" boson…

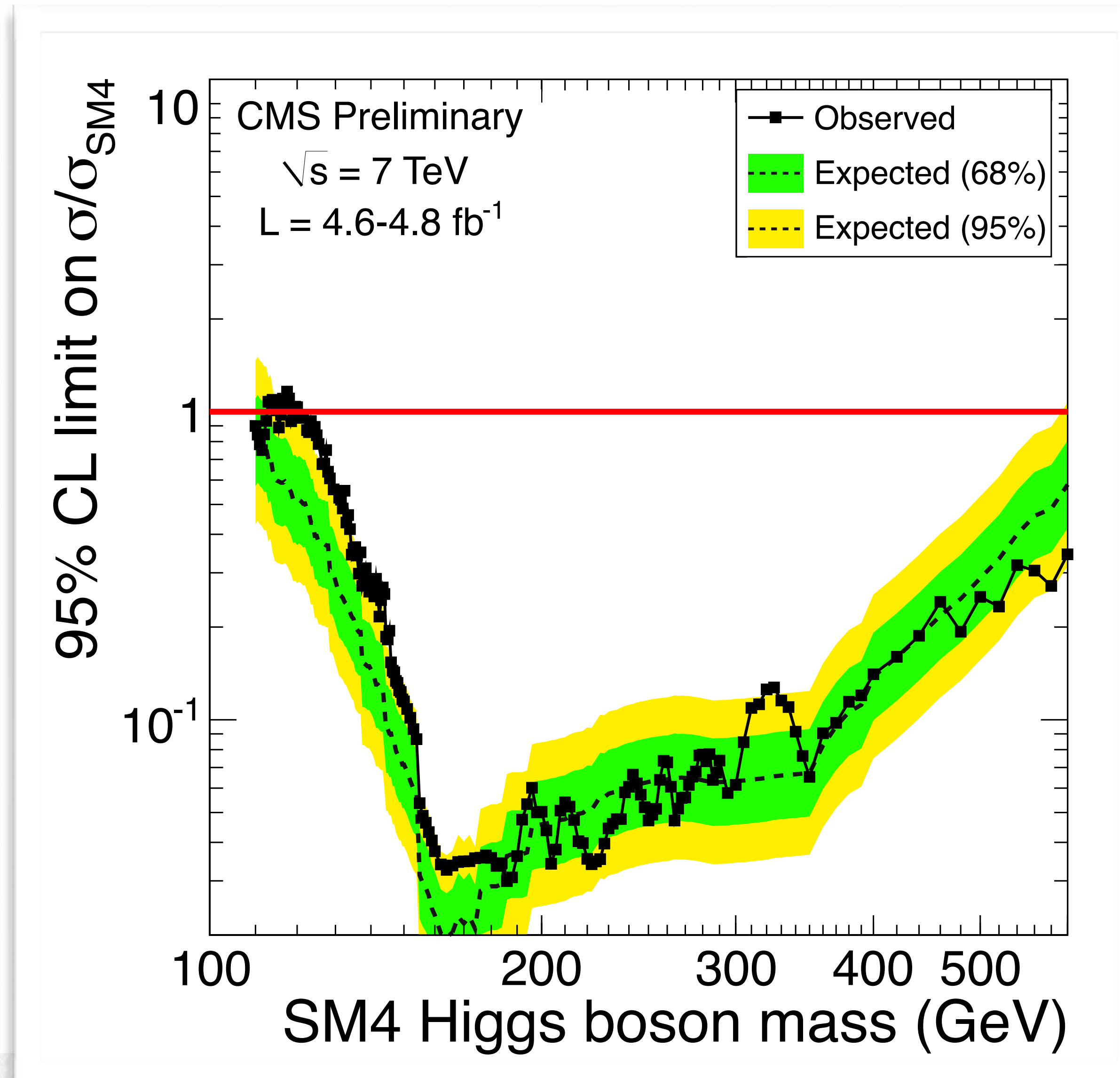
THE HIGGS AND SM4

- Since the ***new quarks are suppose to be heavy*** (at least heavier than the top quark). Large impact on the Higgs sector is expected:

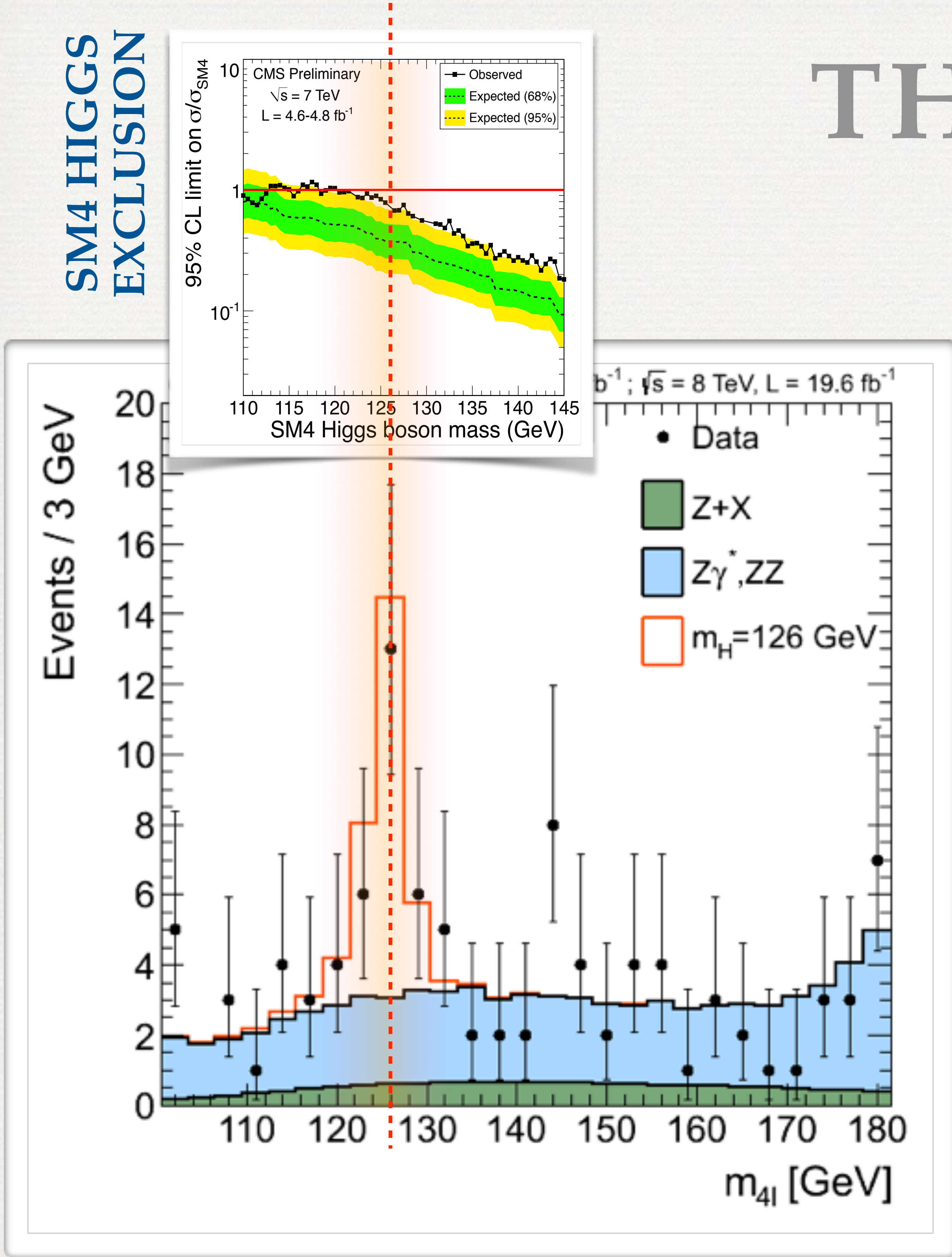


Enlarge the Higgs production rate by a factor 4~9

If 4G fermions exist,
the SM Higgs boson should have been fully excluded:
Pure 4G ⇔ SM Higgs cannot coexist.



SM4 HIGGS EXCLUSION

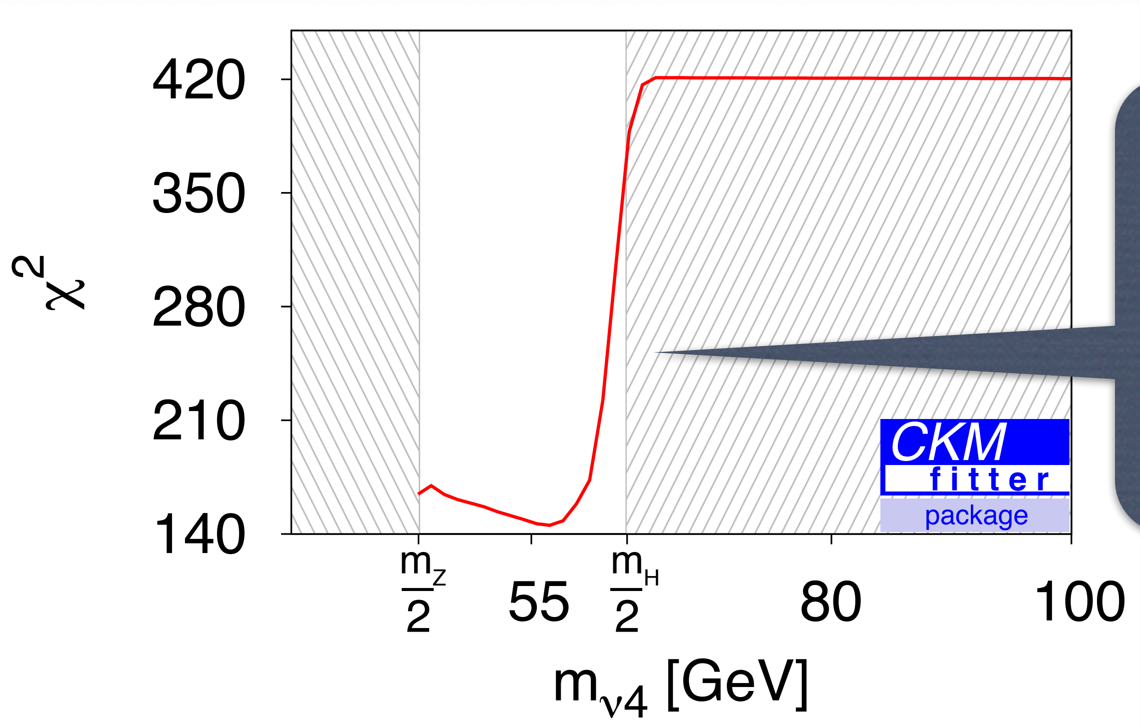


THE "HIGGS" BOSON

- The particle at 126 GeV / c^2 is clearly seen.
- Almost all of the properties (decays, J^{PC}) are consistent with the hypothesis of SM Higgs at this moment; contradict to the SM4 hypothesis.
- If the observed "Higgs" boson is **pure SM Higgs**, then the assumption of pure SM4 is difficult.

WAIT…CAN WE STILL RECOVER IT BACK?

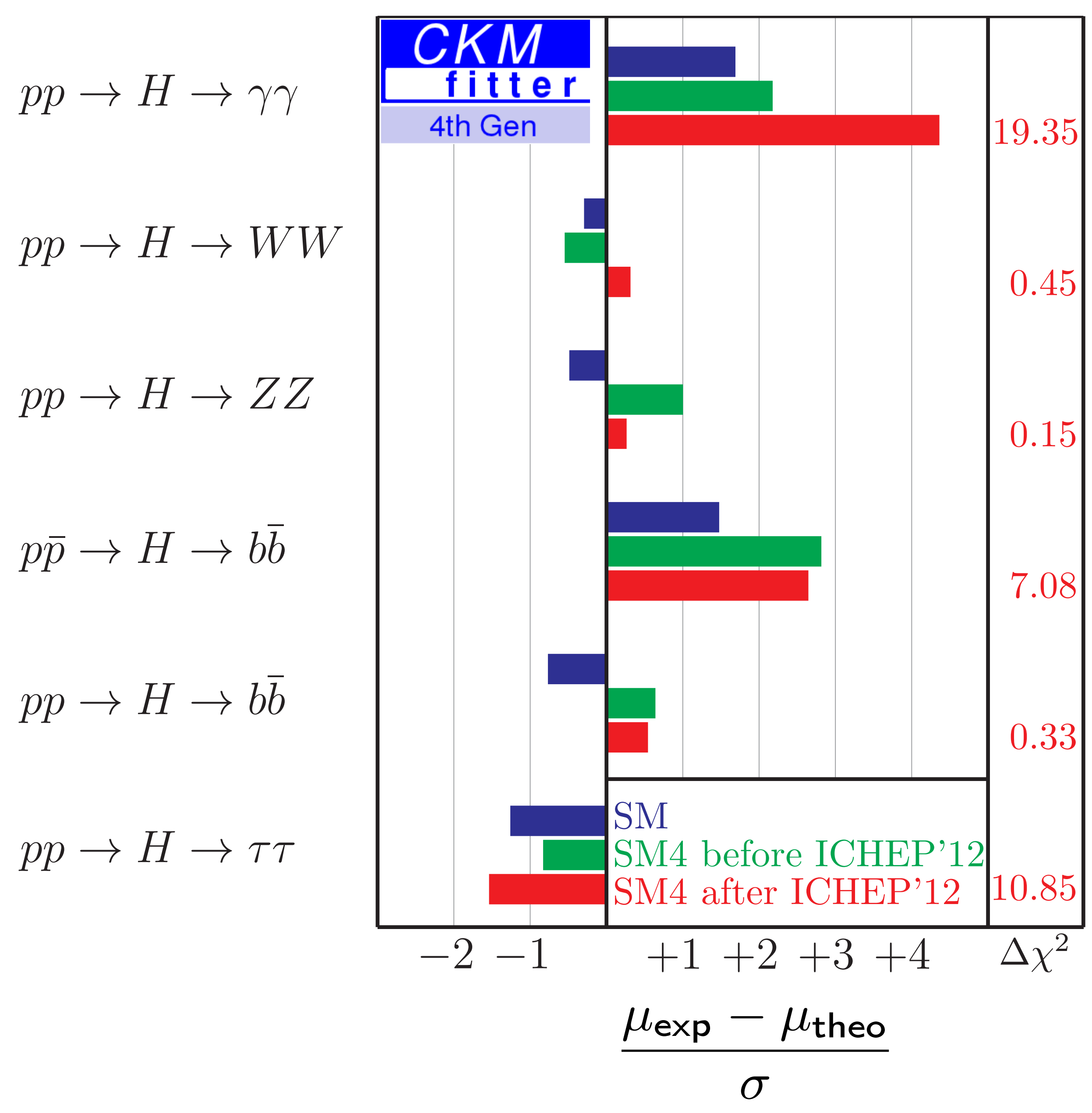
- One can always think of something that might rescue the situation, for example, if there is a **dark matter** (or heavy neutrino) candidate that allow Higgs to decay. Since the decay product is basically invisible so that we somehow finds the resulting Higgs production is very close to the SM (e.g. take over the factor of 4 production rate?)



Well, it might happen but also very limited phase space. The heavy neutrino mass must be between **$M_Z/2$** and **$M_H/2$**…

A MORE "STATISTICAL" VIEW

- You may want to ask, how many **"sigma's"** we are able to kill the 4G based on the pure Higgs results only.
- Based on some statistics analysis, the SM4 is roughly excluded at **5.3σ**.
  [O. Eberhardt, et al, arXiv:1209.1101]

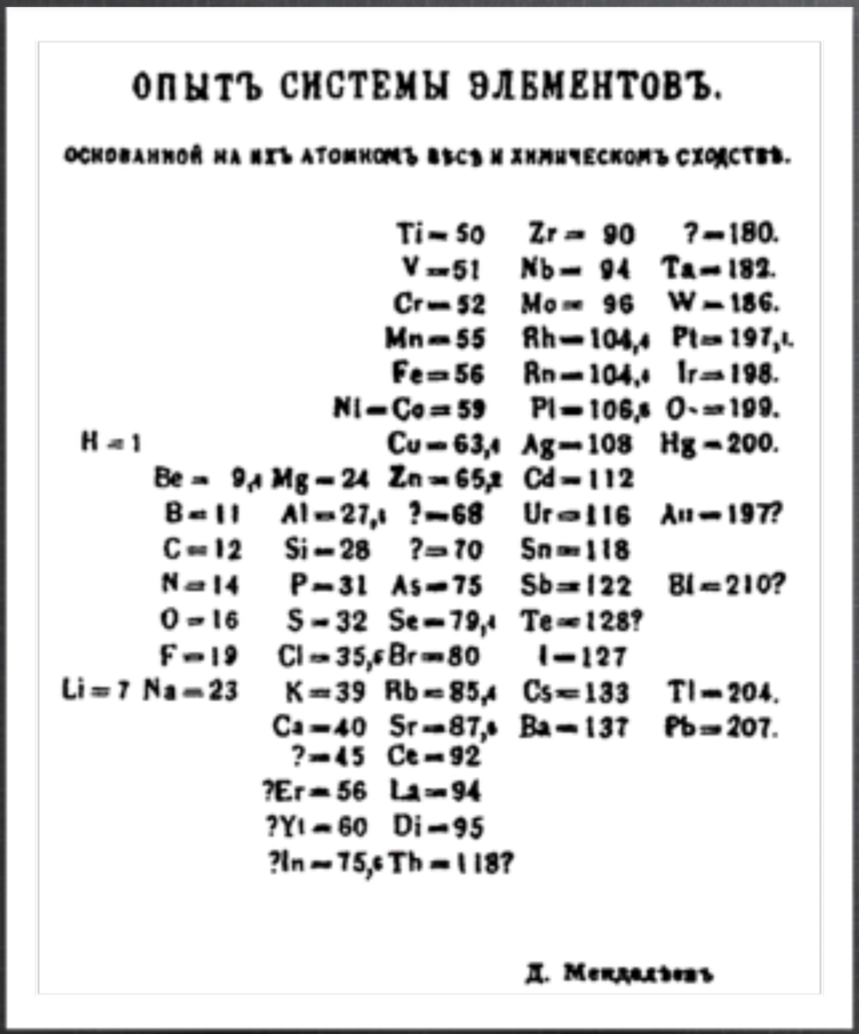


SUMMARY

- Sequential 4th generation quarks are constrained with EWK precision data, but not fully excluded yet; **SM4 (pure SM+4G) hypothesis is not compatible the SM Higgs**, due to its strong contribution in the loop.
- Pure SM4 is very difficult, but any BSM contribution may “rescue” the situation, e.g. getting SUSY also in the consideration.
- Other new quark models *(such a vector-like quarks, exotic quarks)* do not have the same constraint. It can be an alternative solution to the fine-tuning problem in Higgs sector.

In any case, finding new fermions is still a “must-done” task at the LHC!

HISTORY MIGHT REPEAT ITSELF?

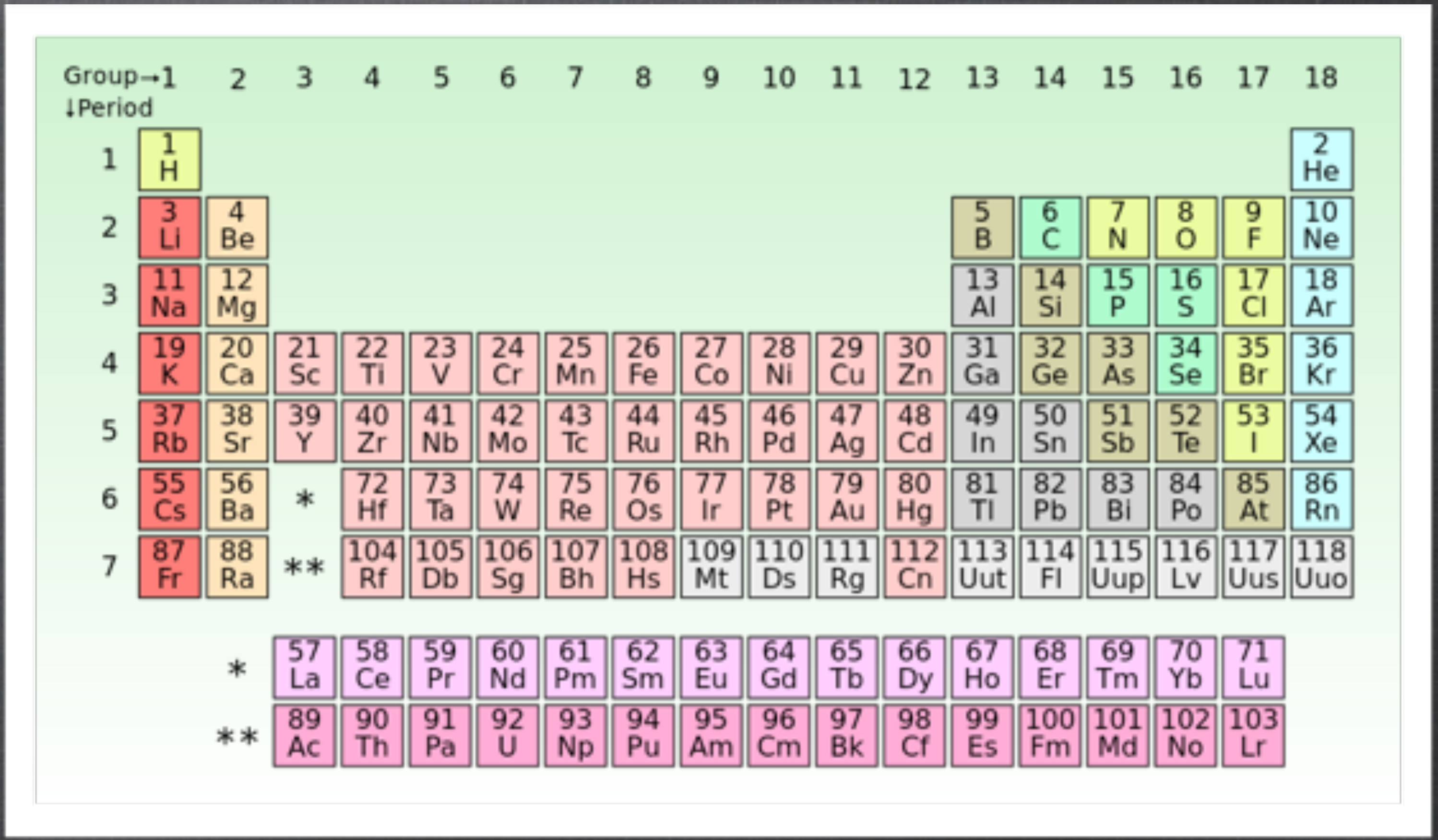

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

Ti=50 Zr=90 ?=180.
V=51 Nb=94 Ta=182.
Cr=52 Mo=96 W=186.
Mn=55 Rh=104,4 Pt=197,4.
Fe=56 Rn=104,4 Ir=198.
Ni=Co=59 Pl=106,6 Os=199.
H=1 Cu=63,4 Ag=108 Hg=200.
Be=9,4 Mg=24 Zn=65,2 Cd=112
B=11 Al=27,4 ?=68 Ur=116 Au=197?
C=12 Si=28 ?=70 Sn=118
N=14 P=31 As=75 Sb=122 Bi=210?
O=16 S=32 Se=79,4 Te=128?
F=19 Cl=35,5 Br=80 I=127
Li=7 Na=23 K=39 Rb=85,4 Cs=133 Tl=204.
Ca=40 Sr=87,6 Ba=137 Pb=207.
?=45 Ce=92
?Er=56 La=94
?Yt=60 Di=95
?In=75,6 Th=118?

Д. Менделѣевъ

Mendeleev's 1869 periodic table



Periodic table today

Finding more particles and understand the real picture behind?

BACKUP SLIDES