Maale Hachamisha - 27 May '11

A Theorist Conclusion

Not a real summary!
Very incomplete

Guido Altarelli
Roma Tre/CERN

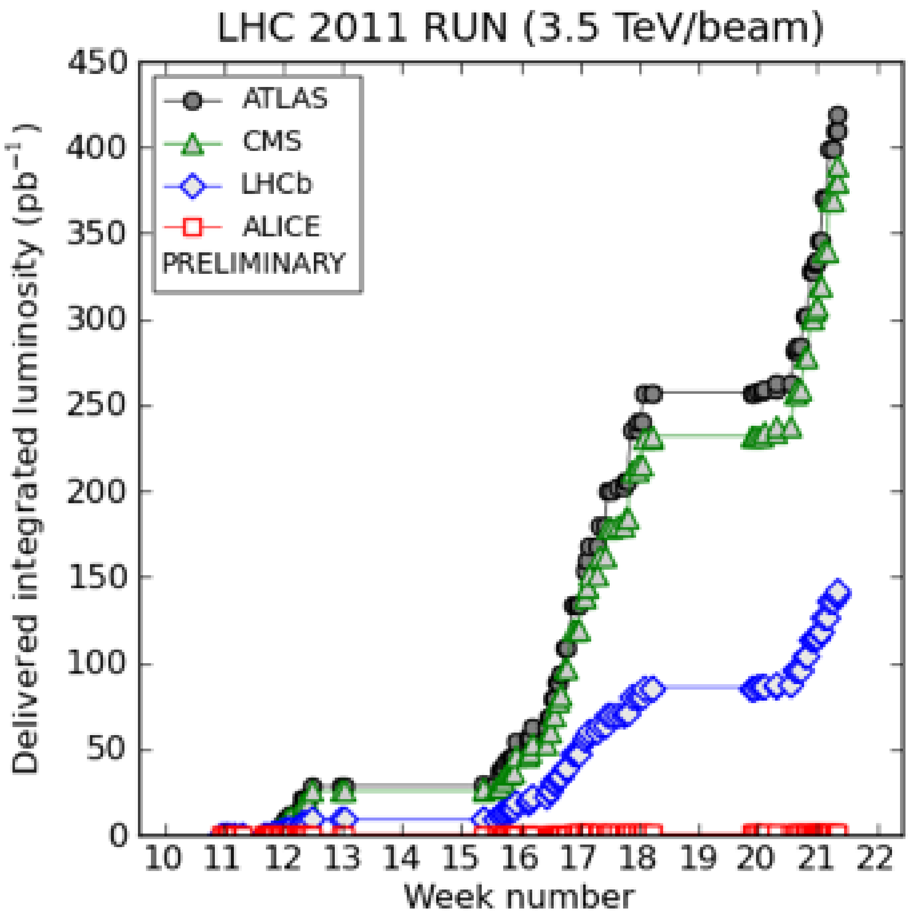
Part 1 The general context

Part 2 Highlights from FPCP'11

The LHC is working very well!

0.42 fb^{-1}

The target of 1 fb^{-1} will probably be reached soon!



This is great news because particle physics is in a deadlock and needs to be restarted

Particle physics at a glance

The SM is a low energy effective theory
(nobody can believe it is the ultimate theory)

It happens to be renormalizable, hence highly predictive.
And is well supported by the data.

However, we expect corrections from higher energies

not only from the GUT or Planck scales
but also from the TeV scale (LHC!)

In fact even just as a low energy effective theory
the SM it is not satisfactory

QCD + the gauge part of the EW theory are fine,
but the Higgs sector is so far only a conjecture

The Higgs problem is central in particle physics today

A review: G.A. ArXiv:1003.3180

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ eV)^4$

Origin of quadratic
divergences.
Hierarchy problem

Possible instability
depending on m_H

The flavour problem:
large unexplained ratios
of Y_{ij} Yukawa constants

The Standard EW theory: $\mathcal{L} = \mathcal{L}_{\text{symm}} + \mathcal{L}_{\text{Higgs}}$

$$\mathcal{L}_{symm} = -\frac{1}{4}[\partial_\mu W_\nu^A - \partial_\nu W_\mu^A - ig\varepsilon_{ABC} W_\mu^A W_\nu^B]^2 +$$

$$-\frac{1}{4}[\partial_\mu B_\nu - \partial_\nu B_\mu]^2 +$$

$$+\bar{\psi}\gamma^\mu[i\partial_\mu + g W_\mu^A t^A + g' B_\mu \frac{Y}{2}]\psi$$

$$\mathcal{L}_{Higgs} = |[\partial_\mu - ig W_\mu^A t^A - ig' B_\mu \frac{Y}{2}]\phi|^2 +$$

$$+ V[\phi^\dagger\phi] + \bar{\psi}\Gamma\psi\phi + \text{h.c}$$

with $\quad V[\phi^\dagger\phi] = \mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4$

$\mathcal{L}_{\text{symm}}$: well tested (LEP, SLC, Tevatron…), $\mathcal{L}_{\text{Higgs}}$: ~ untested

All we know from experiment about the SM Higgs:

No Higgs seen at LEP2 -> $m_H > 114.4$ GeV (95%cl)

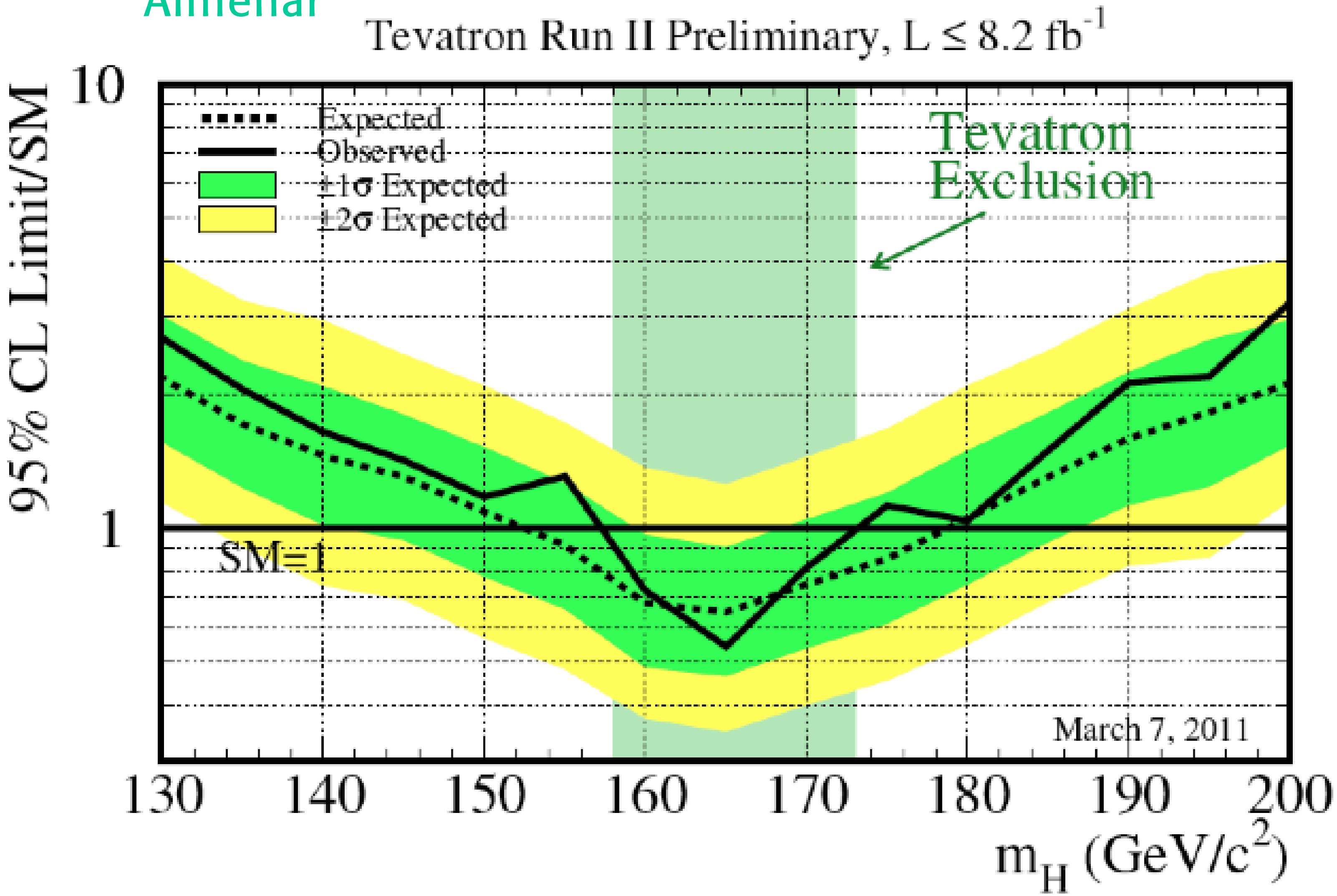
Rad. corr's -> $m_H < 186$ GeV (95%cl, incl. direct search bound)

$v = \langle\phi\rangle = \sim 174$ GeV ; $\quad m_W = m_Z \cos\theta_W \longrightarrow$ doublet Higgs

The Tevatron bounds $158 < m_H < 174$ GeV at 95%

Almenar

March'11



Depends on assumed pdf's, α_s errors ....

>11 fb^{-1} at end '11: could exclude $145 < m_H < 185$ GeV !!!

That some sort of spontaneous symmetry breaking mechanism is at work has already been established (couplings symmetric, spectrum totally non symmetric)

The question is on the nature of the Higgs mechanism/particle(s)

- One doublet, more doublets, additional singlets?
- SM Higgs or SUSY Higgses
- Fundamental or composite (of fermions, of WW....)
- Pseudo-Goldstone boson of an enlarged symmetry
- A manifestation of extra dimensions (fifth comp. of a gauge boson, an effect of orbifolding or of boundary conditions....)
- Some combination of the above

Can we do without the Higgs?

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable. One loses understanding of the observed accurate validity of gauge predictions for couplings.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

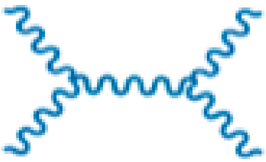
With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

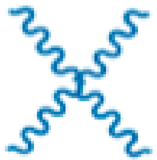
Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints
[Veltman, 1977; Lee-Quigg-Thacker, 1977; …]

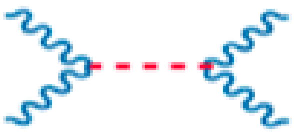
Zwirner

An example: $\mathcal{A}(W_L^+ \, W_L^- \longrightarrow Z_L \, Z_L) \quad (s \gg m_W^2)$





$$i\,\frac{s}{v^2}$$



$$-i\,\frac{s^2}{v^2(s-m_h^2)}$$

$$\rightarrow \quad -i\,\frac{m_h^2}{v^2}\,\frac{s}{s-m_h^2}$$

If no Higgs then something must happen!

Can we do without the Higgs?

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable. One loses understanding of the observed accurate validity of gauge predictions for couplings.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

To avoid this either there is one or more Higgs particles or some new states (e.g. new vector bosons)

Thus something must happen at the few TeV scale!!

A crucial question for the LHC

What saves unitarity?

- the Higgs
- some new vector boson

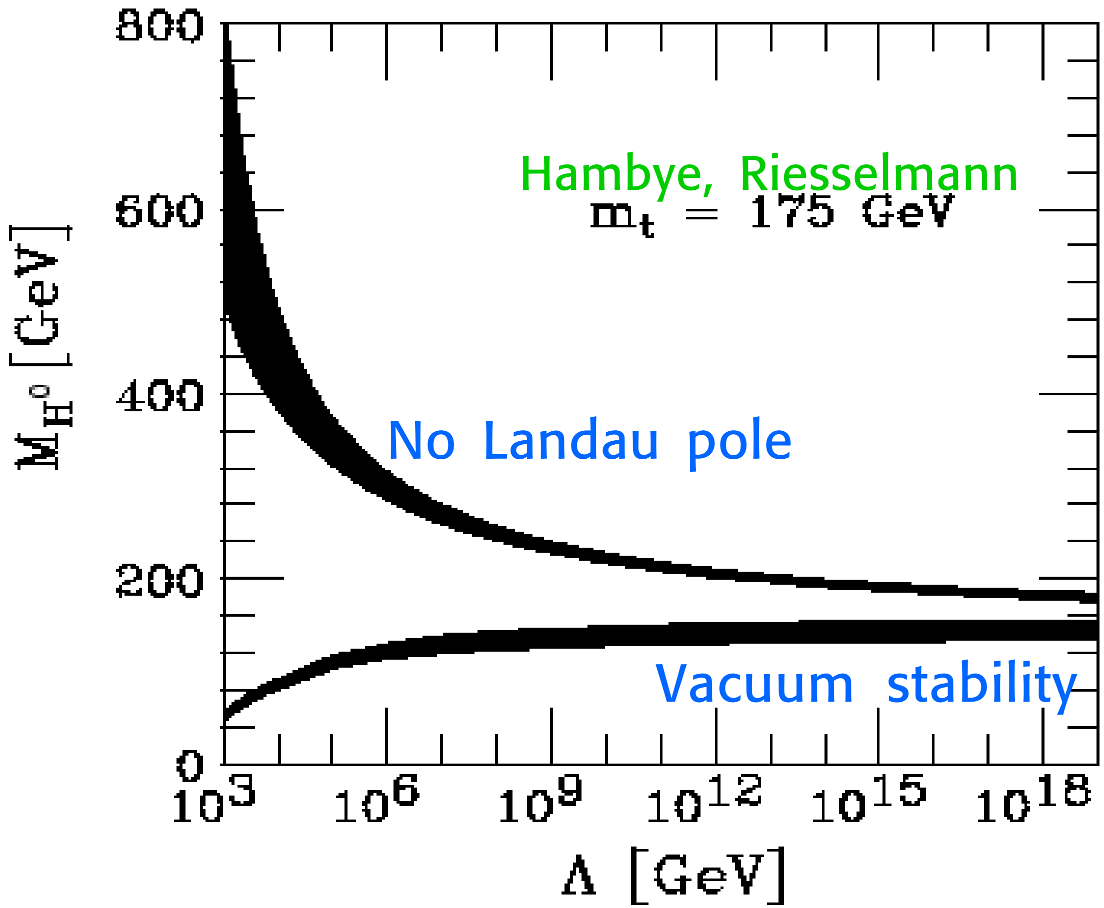
  W′, Z′
  KK recurrences
  resonances from a strong sector
  ......

Theoretical bounds on the SM Higgs mass

Λ: scale of new physics beyond the SM

Upper limit: No Landau pole up to Λ
Lower limit: Vacuum (meta)stability

The LHC was designed to cover the whole range



If the SM would be valid up to M_{GUT}, M_{Pl} then m_H would be limited in a small range

Lower now because of m_t → 128 GeV < m_H < 180 GeV

Status of the SM Higgs fit

Radiative corr's indicate a light H

Summer '09

Sensitive to log m_H

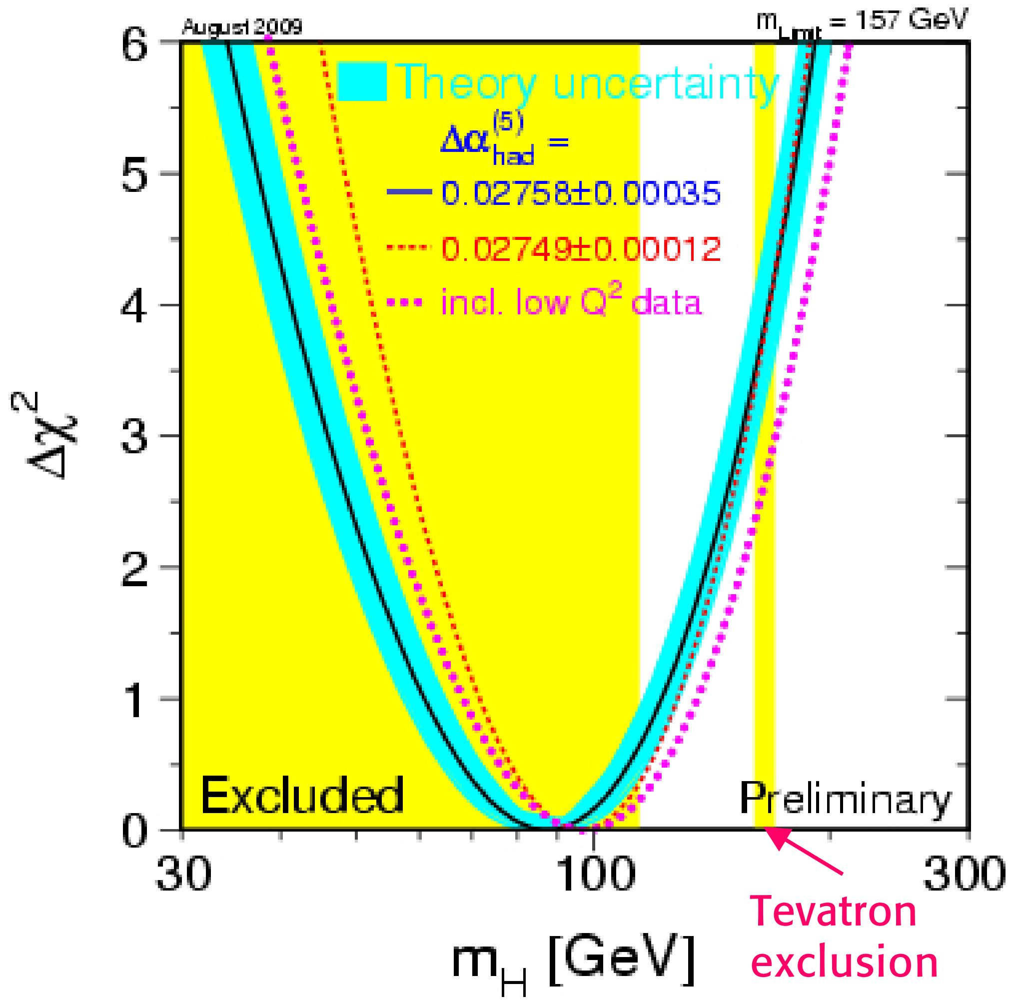
Rad Corr.s ->

$\log_{10} m_H(\mathrm{GeV}) = 1.94 \pm 0.15$

$m_H = 87 + 35 - 26$ GeV

This is a great triumph for the SM: ~right in the narrow allowed range $\log_{10} m_H \sim 2 - 3$

Direct search: $m_H > 114.4$ GeV



Tevatron exclusion

At 95 % cl

$m_H < 157$ GeV (rad corr.'s)

$m_H < 186$ GeV (incl. direct search bound)

Is it possible that the Higgs is not found at the LHC?

Here "Higgs" means the "the EW symmetry breaking mechanism"

Looks pretty unlikely!!

The LHC discovery range is large enough: $m_H < \sim 1$ TeV
the Higgs should be really heavy!

Rad. corr's indicate a light Higgs (whatever its nature)

A heavy Higgs would make perturbation theory to collapse nearby (violations of unitarity for $m_H > \sim$ TeV)

Such nearby collapse of pert. th. is very difficult to reconcile with EW precision tests plus simulating a light Higgs

The SM good agreement with the data favours forms of new physics that keep at least some Higgs light

The Standard Model works very well

So, why not find the Higgs and declare particle physics solved?

First, you have to find it!

→ LHC

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- The flavour puzzle

•••••

and experimental clues:

- Neutrino masses
- Coupling unification
- Dark matter
- Baryogenesis
- Vacuum energy

•••••

Some of these problems point at new physics at the weak scale: eg
Hierarchy
Dark matter (perhaps)

Dark Matter

WMAP, SDSS, 2dFGRS....

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.045$, $\Omega_m \sim 0.27$

Most is Dark Matter and Dark Energy

Most Dark Matter is Cold (non relativistic at freeze out)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant: $\Omega_\nu < 0.015$

SUSY has excellent DM candidates: eg Neutralinos (--> LHC)
Also Axions are still viable (introduced to solve strong CPV)
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

Identification of Dark Matter is a task of enormous importance for particle physics and cosmology

LHC?

LHC has good chances because it can reach any kind of WIMP:

WIMP: Weakly Interacting Massive Particle
with m ~ 10^1-10^3 GeV

For WIMP's in thermal equilibrium after inflation the density is:

$$\boxed{\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle}}$$

can work for typical weak cross-sections!!!

This "coincidence" is a good indication in favour of a
WIMP explanation of Dark Matter

A crucial question for the LHC

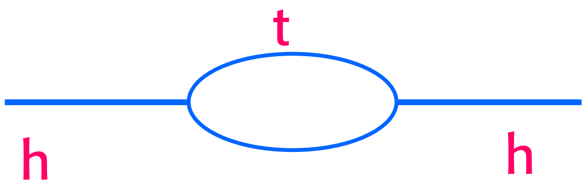
Is Dark Matter a WIMP?

LHC will tell yes or no to WIMPS

The "little hierarchy" problem

e.g. the top loop (the most pressing):

$m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

$\Lambda \sim o(1\text{TeV})$

This hierarchy problem demands new physics near the weak scale

Λ: scale of new physics beyond the SM

- $\Lambda >> m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\text{TeV})$ for a natural explanation of m_h or m_W

Barbieri, Strumia

The LEP Paradox: m_h light, new physics must be close but its effects were not visible at LEP2

The B-factory Paradox: and not visible in flavour physics

Precision Flavour Physics

Another area where the SM is good, too good.....

With new physics at ~ TeV one would expect
the SM suppression of FCNC and the CKM
mechanism for CP violation to be sizably modified.

But this is not the case

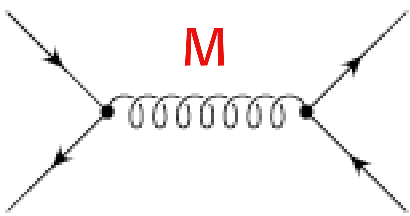
an intriguing mystery and a major challenge for models of
new physics

A lot of fine-tuning is imposed on us when our present theory is confronted with the data

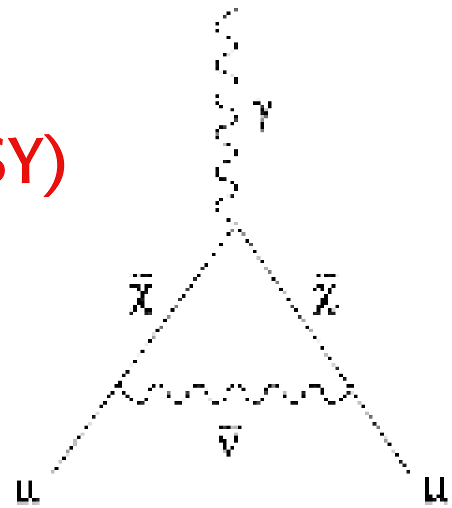
For naturalness we need new physics at ~ 1 TeV but we see no clear deviations in EW Precision Tests and in Flavour Physics

Strong constraints on model building

Typical tree level NP effects too large



Avoided by R-parity (SUSY)
T-parity (Little Higgs) etc



Loop effects preferred

The flavor problem

Grossman

In fact, we know the full theory must be non-generic!

- Many reasons to expect NP at $\Lambda \sim 1$ TeV
- Naive flavor bounds imply $\Lambda > 10^4$ TeV
- This tension is called

The NP flavor problem

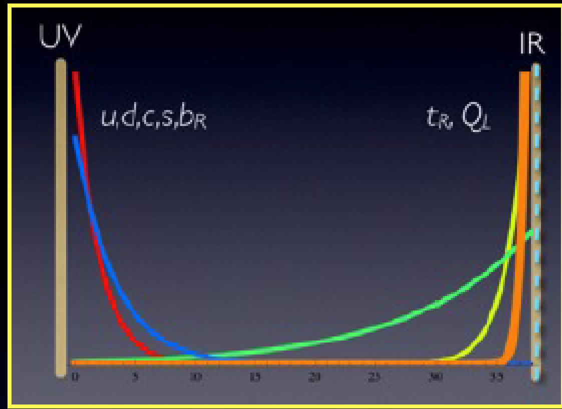
- The full theory must have a non-trivial flavor structure

MFV is a simplest recipe for this structure

[Yuval has discussed how MFV can, to some extent, replace R-parity]

Observed hierarchies suggest exp factors

Weiler



anarchic ("structure-less")

$$\text{Mass}_{ij} \propto Y_{ij} e^{-MR(c_i+c_j)}$$

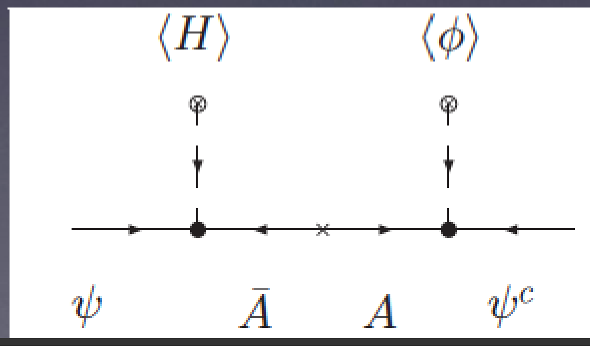
split fermions/RS

$$\propto Y_{ij} \left(\frac{\mu_{\text{low}}}{\mu_{\text{high}}} \right)^{\gamma^i+\gamma^j}$$

strong dynamics

$$\propto Y_{ij} \left(\frac{\langle \Phi \rangle}{M_{\text{mess}}} \right)^{Q^i-Q^j}$$

Froggatt-Nielsen



Hierarchy $\left\{ \begin{array}{l} \text{=> hierarchical} \\ \text{masses \& mixing angles} \end{array} \right.$

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of Λ^2 in δm_h^2

  approximate (possible): $\Lambda \sim m_{SUSY} - m_{ord}$ $\longrightarrow$ top loop $\Lambda \sim m_{stop}$

  The most widely accepted

- The Higgs is a $\bar{\psi}\psi$ condensate. No fund. scalars. But needs new very strong binding force: $\Lambda_{new} \sim 10^3 \Lambda_{QCD}$ (technicolor).

  Strongly disfavoured by LEP. Coming back in new forms

- Models where extra symmetries allow m_h only at 2 loops and non pert. regime starts at $\Lambda \sim 10$ TeV

  "Little Higgs" models. Some extra trick needed to solve problems with EW precision tests

- Extra spacetime dim's that "bring" M_{Pl} down to o(1TeV)

Exciting. Many facets. Rich potentiality. No baseline model emerged so far

- Ignore the problem: invoke the anthropic principle

A crucial question for the LHC

What damps the top loop Λ^2 dependence?

- the s-top (SUSY)
- some new fermion

  t′ (Little Higgs)

  KK recurrences of the top (Extra dim.)

  ......

Part 2 Highlights from FPCP'11

An exciting digression: progress in spectroscopy

Gradl

$h_b(9898)$, $h_b(10260)$: neutral, spin-0 P-wave bb^{bar}, $J^{PC} = 1^{+-}$

New! Belle Bondar, Santoro (h_c obs. by Cleo)

Rosner

Molecules vs tetraquarks: difficult to distinguish

X(3872) : neutral, can be interpreted as DD* with some admixture of cc^{bar}

Choi

$Z_b(10610)$, $Z_b(10650)$: charged, certainly exotic (must be $b\,b^{bar}q'q^{bar}$),can be interpreted as BB* and B*B*

New! Belle

Bondar

Z_b predicted by Karliner&Lipkin in '08!

The light scalar nonet appear as tetraquark states (inverted spectrum) but are strongly coupled to $\pi\pi, K\pi, KK$

Rosner

a light diquark behaves like an s^{bar} : $\varepsilon^{312}q_1q_2$

Neutrino oscill'ns, mass and mixing

Kayser

Recently the main development was the coming back of sterile neutrinos (and also the start of T2K) Zimmerman

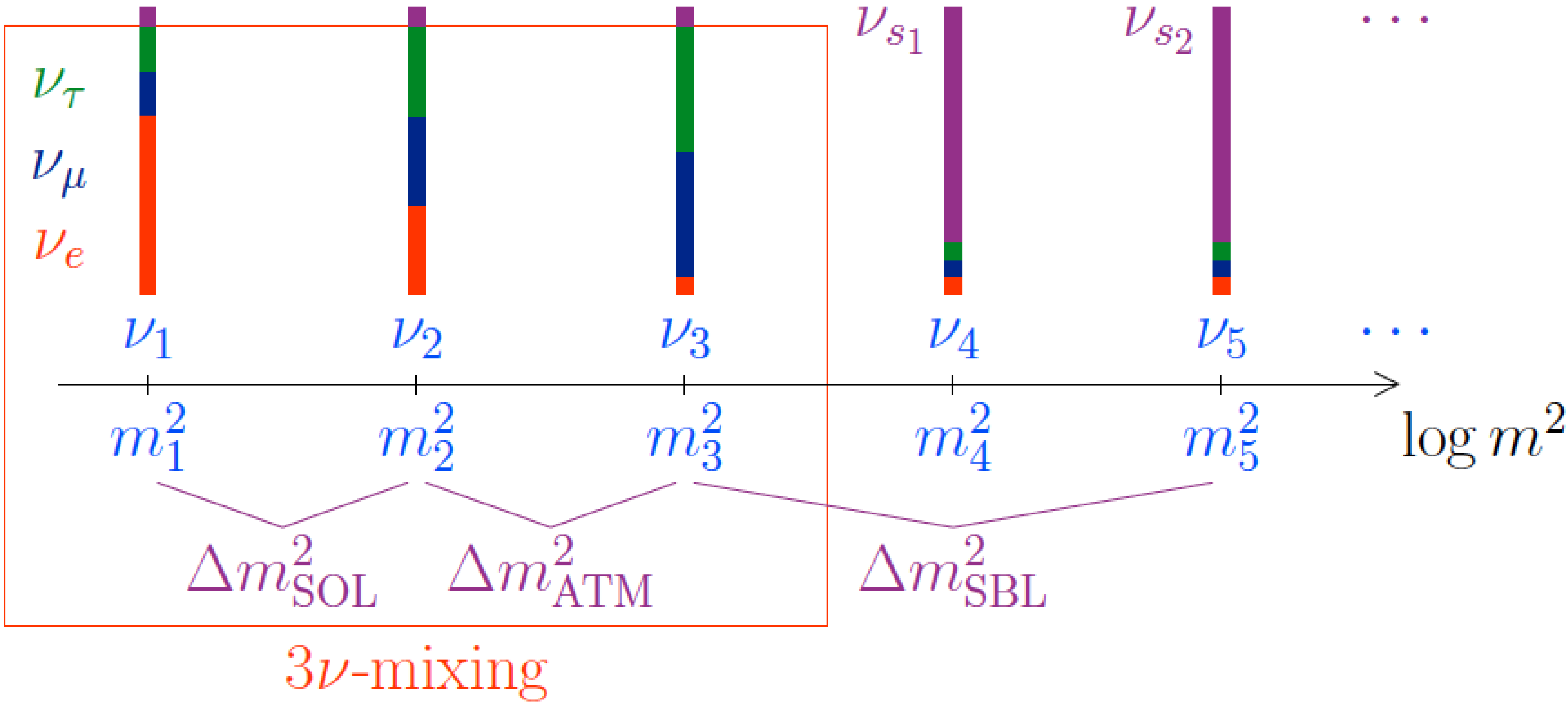
Evans

A number of "hints" (they do not make an evidence but pose an experimental problem that needs clarification)

- LSND and MiniBoone
- Reactor flux & anomaly
- Gallium ν_e disappearance vs ν_e^{bar} reactor limits
- Neutrino counting from cosmology

If all true (unlikely) then need at least 2 sterile ν's

Only a small leakage from active to sterile neutrinos is allowed by present data



Most common models BSM do not contain sterile neutrinos. But a sterile neutrino would probably be a remnant of some hidden sector. So would be a great discovery.

Some NP hints from accelerator experiments

A^b_{FB}	LEP	$\sim 3\sigma$
$(g-2)_\mu$	Brookhaven	$\sim 3\sigma$
tt^{bar} FB asymmetry	Tevatron	$\sim 3\sigma$ at large M_{tt}
Dimuon charge asymmetry	D0	$\sim 3.2\sigma$
Wjj excess at $M_{jj} \sim$ 144 GeV only candidate to open prod. of NP	CDF	$\sim 3.2\sigma$ to be confirmed
$B_s \rightarrow J/\psi\phi$	Tevatron, LHCb	$\sim 2\sigma$
$B \rightarrow \tau\nu$	BaBar, Belle	$\sim 2.5\sigma$

••••••• most of them discussed at this Conference

Muon g-2 and SUSY

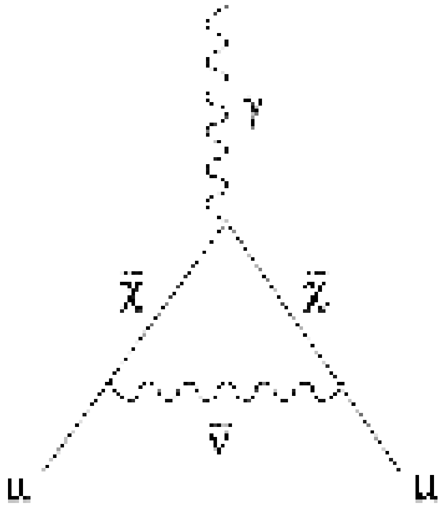
Observed Difference with Experiment:

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (27.5 \pm 8.4) \times 10^{-10}$$

➡ 3.3 ”standard deviations“

Could be new physics
eg light SUSY

$$\delta a_\mu = 13 \cdot 10^{-10} \left(\frac{100 GeV}{M_{SUSY}}\right)^2 tg\beta$$



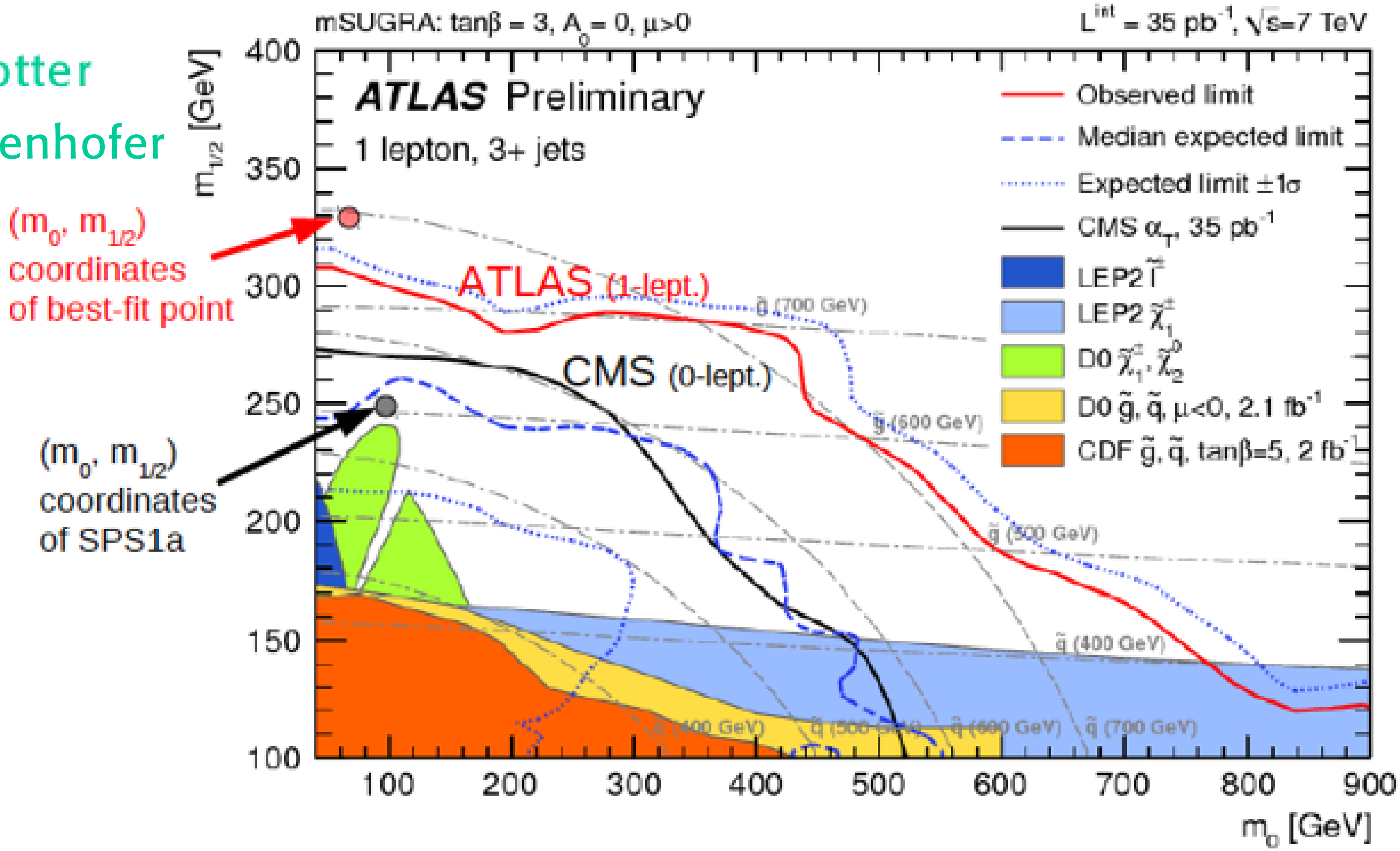
a_μ is a plausible location for a new physics signal!!

Light SUSY should soon be seen at the LHC!

SUSY Bounds at the LHC

Potter

Kiesenhofer

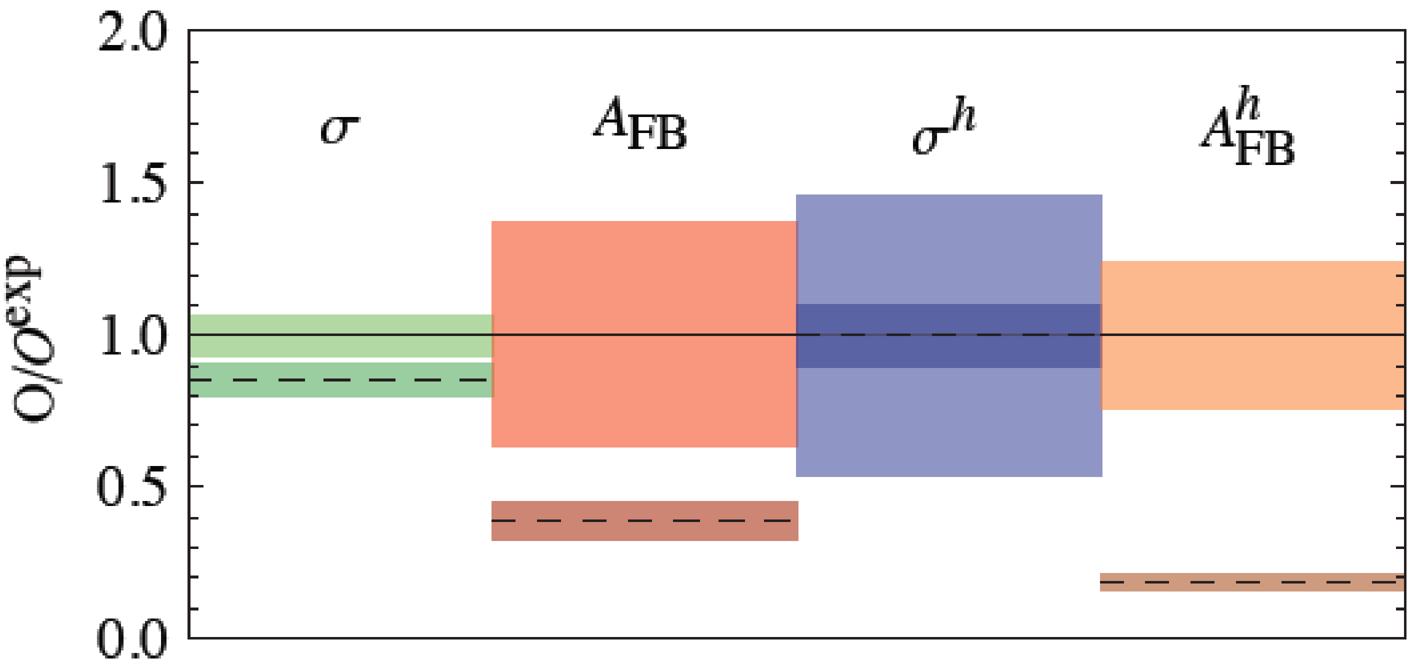


Forward-backward asymmetry in $t\bar{t}$ production

K

see also talk by !

- Measurements at the Tevatron



Kidonaki

Ahrens et al

also: $0.42 \pm 0.15 \pm 0.05 \quad 2\ell$

)ther me
CDF
DØ Note

$$\sigma = (7.50 \pm 0.48)\,\mathrm{pb}$$

$$\sigma^h = (80 \pm 37)\,\mathrm{fb}$$

$$A_{FB} = 0.158 \pm 0.074$$

$$A^h_{FB} = 0.475 \pm 0.114$$

CDI

Kuhn, Rodrigo

Is the SM prediction reliable?

Why (might need to) worry:

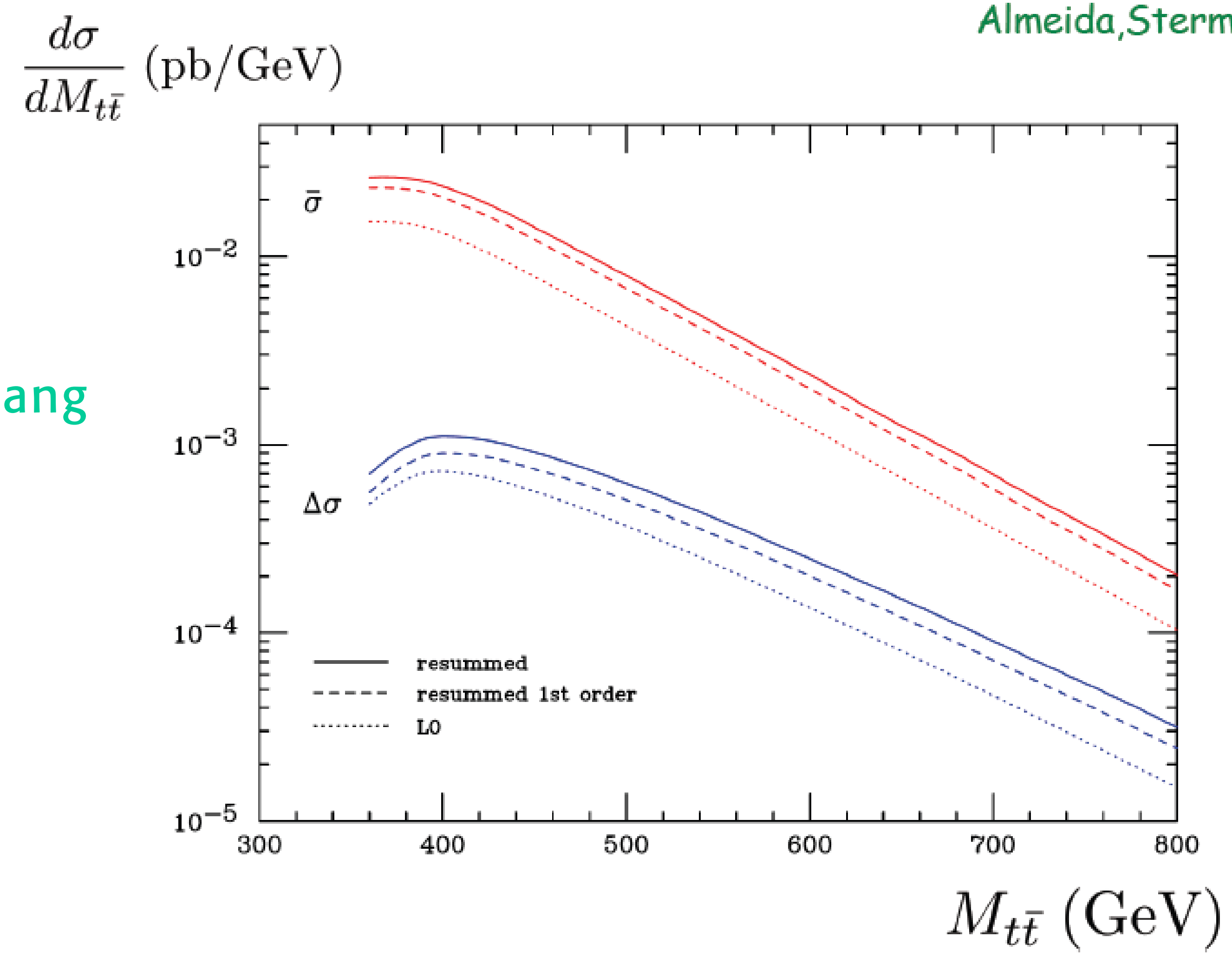
Vogelsang

- only LO
- NLO gives ~30% correction to $t\bar{t}$ cross section, significant scale uncertainty
- NLO for *charge-asymmetric* part not available (would be part of NNLO for full cross sec.)

Resummation of the leading logs affects numerator (red) and denominator (blue) in about the same way

Almeida,Sterman,WV

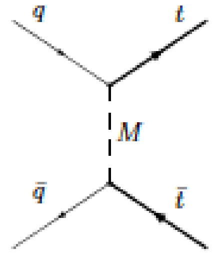
Vogelsang



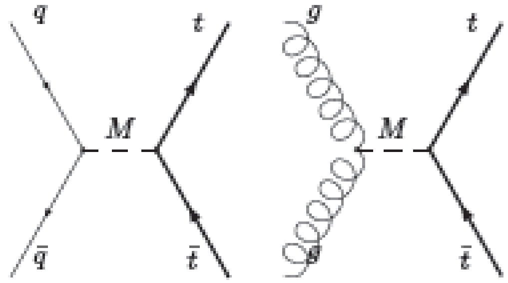
Many NP models for $t\bar{t}$ asymmetry

Kamenik

- ***Light to moderate mass t(u)-channel resonances***
  - Z', W', scalar color triplets, sextets
  - Need large FC (u-t, d-t) couplings
  - Generically predict slow rise in m_{tt} spectrum*
  - Same-sign top top production can be a problem - model-dependent

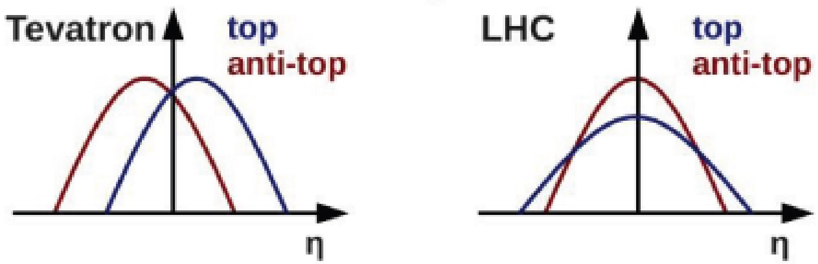


- ***Heavy (s-channel) resonances or EFT****
  - KK or "Axigluon" - need color octet axial contributions
  - Need opposite sign $u\bar{u}$ and $t\bar{t}$ couplings
  - Constrained by LHC di-jet searches



Vogelsang conclusion:

- tantalizing situation - but, too soon for conclusions
- if data persist, QCD unlikely to explain observed A_{FB}
- LHC should provide answers:



$$A_C(y_C) = \frac{\sigma_t(|y| \leq y_C) - \sigma_{\bar{t}}(|y| \leq y_C)}{\sigma_t(|y| \leq y_C) + \sigma_{\bar{t}}(|y| \leq y_C)}$$

Antunano, Kühn, Rodrigo

- Tosi's talk: $A_{\text{ch}}(|\eta_t| - |\eta_{\bar{t}}) = 0.060 \pm 0.134 \pm 0.026$

  QCD: ~1% (Rodrigo)

- plus: like-sign tops, dijets, …

D0 dimuon asymmetry

Williams

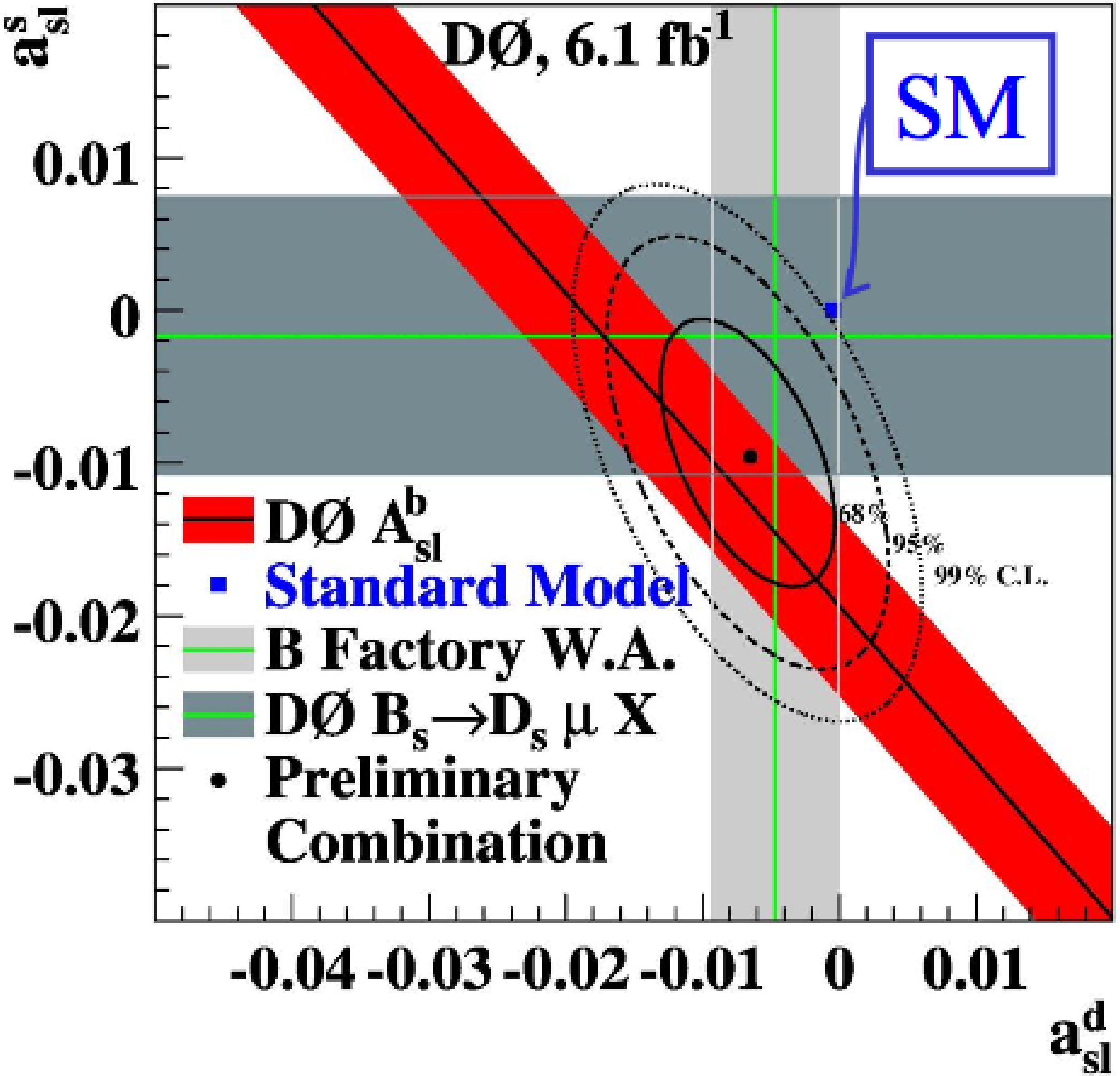
Interpreted as from semileptonic B_d, B_s decay asymm. a^d_{sl}, a^s_{sl}

D0 central value larger than th possible if Γ_{12} normal

Lenz

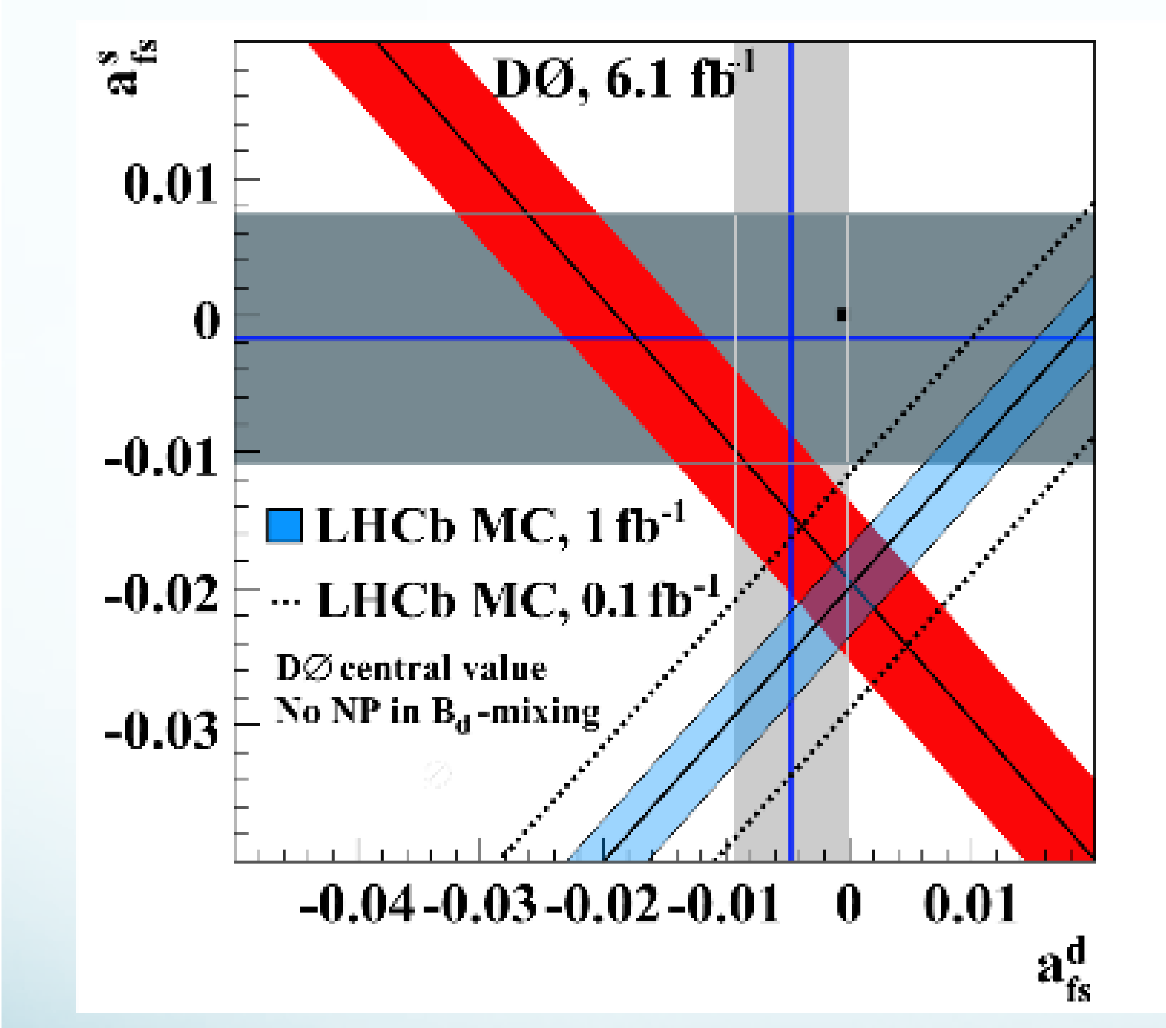
$A < -4.8 \cdot\cdot\ -6.1\ 10^{-3}$

$A^{D0} = -9.6 \pm 2.8\ 10^{-3}$



Probably LHCb will fix this issue

Calvi

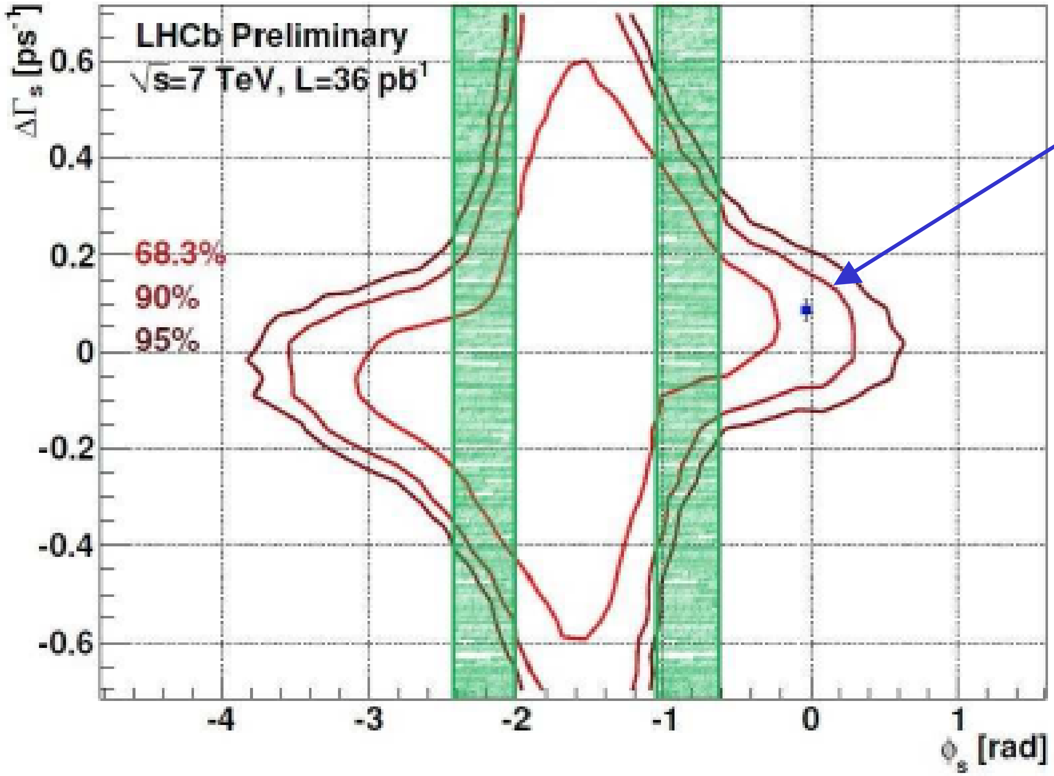


$B_s \to J/\Psi\ \phi$

All data fit

Abbot
Calvi
Muheim

SM



The situation is now closer to the SM

B_d-mixing: The golden plated mode Bigi/Sanda 1981

$$\begin{array}{ccc} \sin(2\beta)^{\text{Exp.}} & < & \sin(2\beta)^{\text{Fit}} \\ 0.678 \pm 0.020 & & 0.831^{+0.013}_{-0.030} \\ \beta = (21.4 \pm 0.8)^\circ & & \left(28.09^{+0.7}_{-1.49}\right)^\circ \end{array}$$

Exp. Talk by Himansu Sahoo

Pointed out by Lunghi, Soni 0803.4340 and then by Buras, Guadagnoli 0805.3887

Statistical significane

- 1102.3917: Laiho, Lunghi, Van de Water: $2.5 - 3.3\sigma$
- 1010.6069: Lunghi, Soni : 3.3σ
- 1010.5089: UTfit : 2.6σ
- 1008.1593: A.L., Nierste, CKMfitter : 2.8σ
- ...

V_{ub}incl = 4.35±0.18±0.23 Bernlocher
V_{ub}excl = 3.25±0.12±0.28

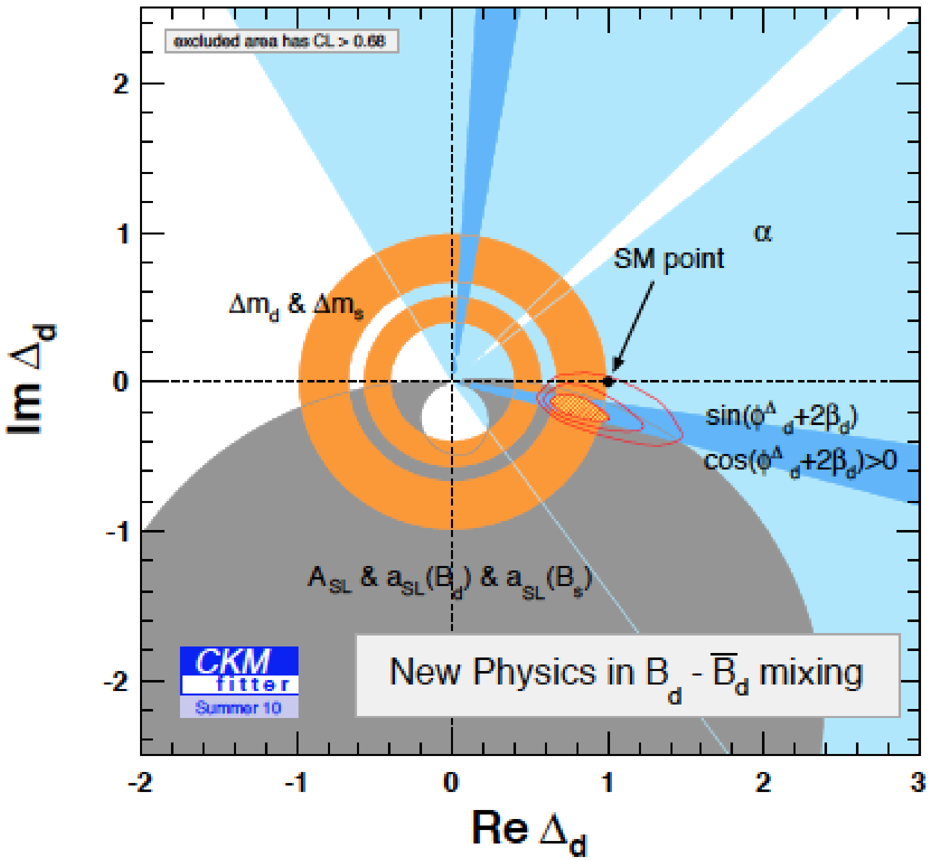
V_{ub}incl- V_{ub}excl = 1.10 ±0.42 2.6 σ

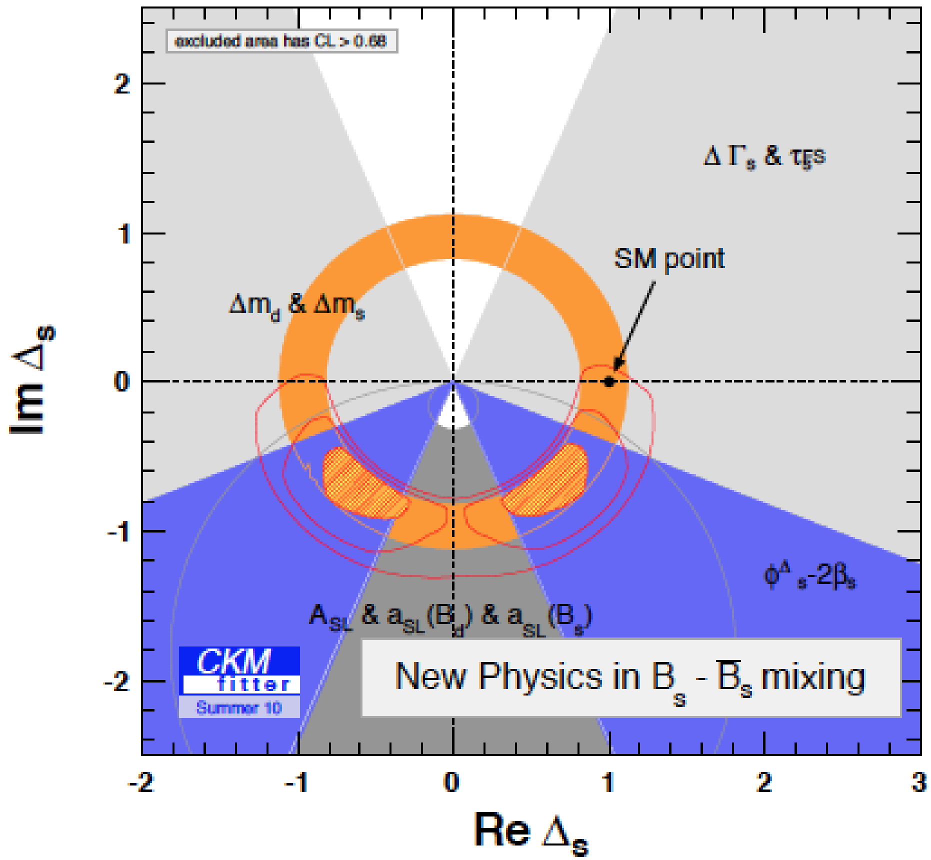
I think that this "tension" is due to the fact that over the last 30 years hundreds of theory papers have been devoted to the determination of Vub: each author claiming that his work led to a decrease of the theor. error

Combined fit of Δ_d and Δ_s

$$M_{12}^q = M_{12}^{q,\mathrm{SM}} \cdot |\Delta_q| e^{i\phi_q^\Delta}$$

$$a_{sl}^q = \frac{|\Gamma_{12}^{q,\mathrm{SM}}|}{|M_{12}^{q,\mathrm{SM}}|} \frac{\sin\left(\phi_q^{\mathrm{SM}} + \phi_q^\Delta\right)}{|\Delta_q|}$$





Lenz

Im Δ_d = 0 = Im Δ_s is excluded with 3.8 σ

Mixing and CPV in D-D^{bar} system

Recently great exp progress

$$x = \frac{m_2 - m_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

$$\mathbf{x} = (0.63 \pm 0.20)\%$$
$$\mathbf{y} = (0.80 \pm 0.13)\%$$
$$|\mathbf{q/p}| = 0.91^{+0.18}_{-0.16}$$
$$\phi(^\circ) = -10.0^{+9.4}_{-8.9}$$

still consistent with no CPV

Zupanc

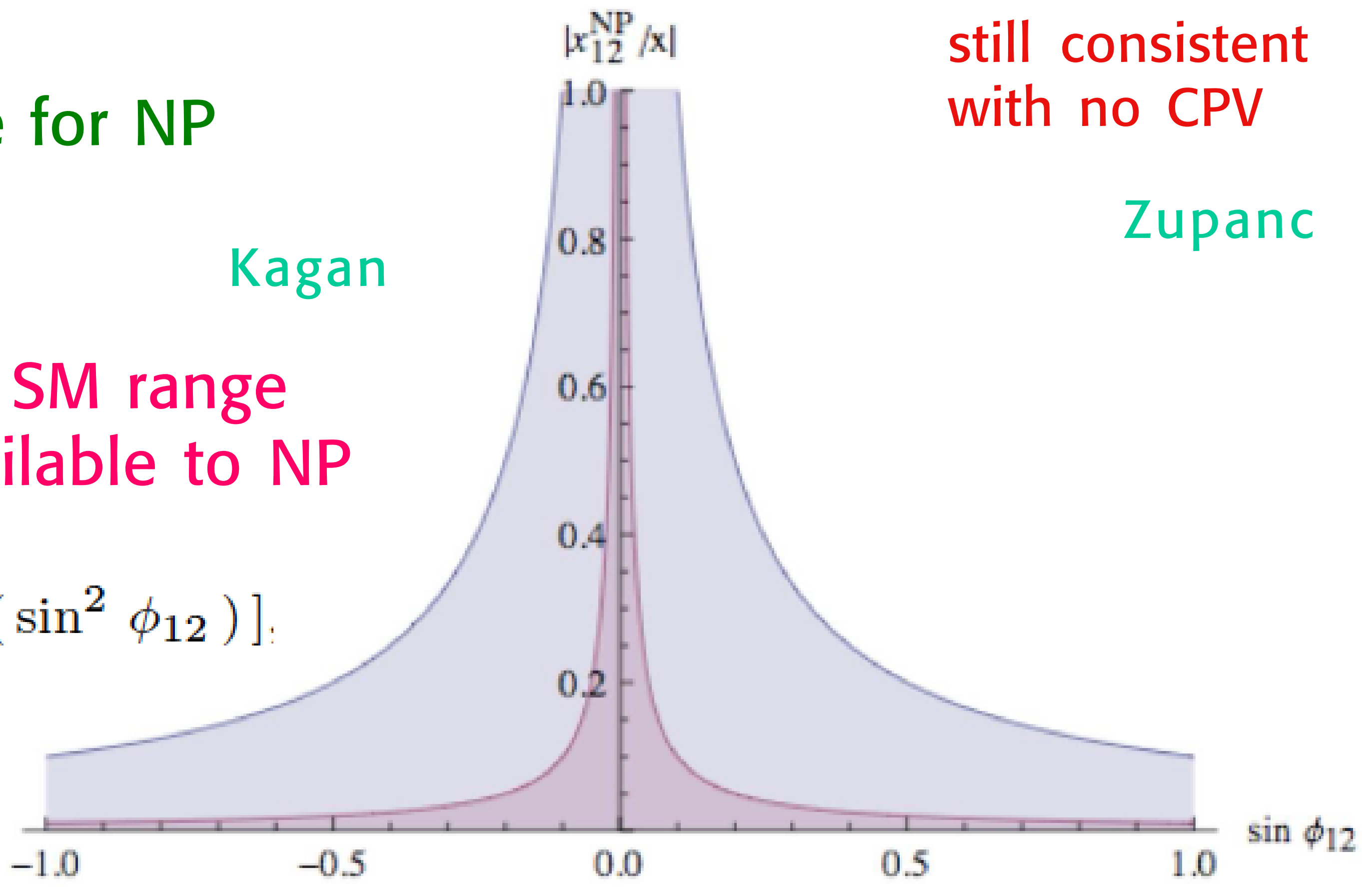
There is still space for NP but limited

Kagan

The dark area is the SM range
The light area is available to NP

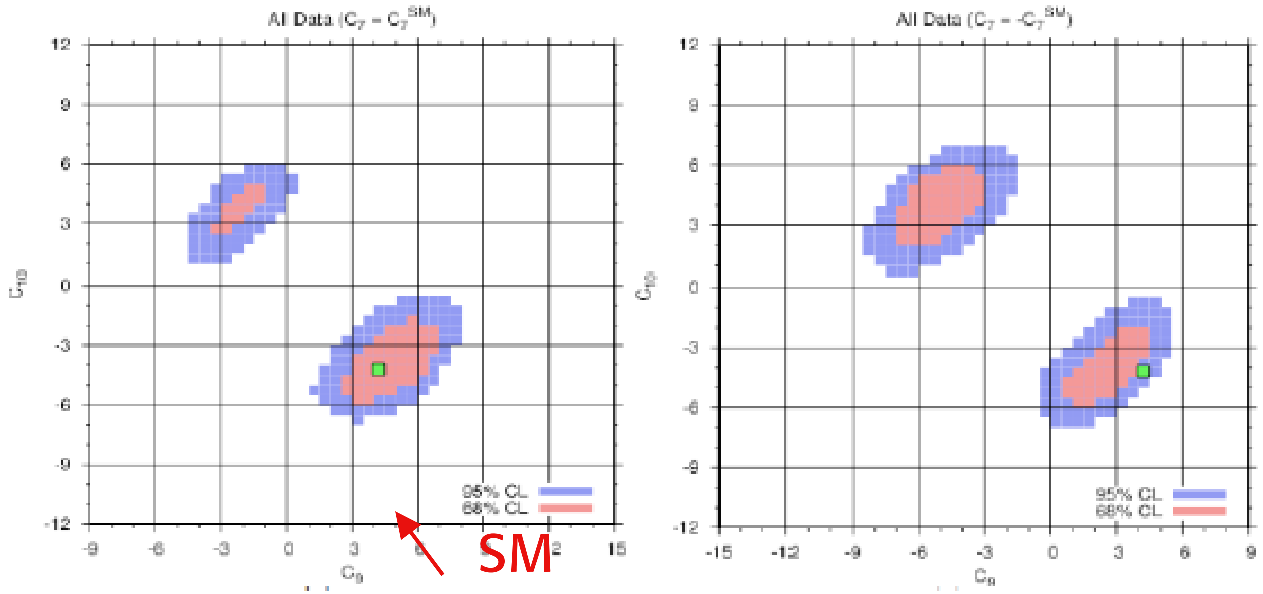
$$|x| \equiv \frac{|\Delta m|}{\Gamma} = x_{12}\,[1 + O(\sin^2 \phi_{12})]$$

$$\phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$



C_9-C_{10} Scans $B \to K^* l^+ l^-$ 2010

Including low recoil data



global fits to (real) C_9, C_{10} for $C_7 = \pm C_7^{\rm SM}$; green box: SM value of (C_9, C_{10})
EOS project: http://project.het.physik.tu-dortmund.de/eos/ Bobeth, GH,vanDyk 1006.5013 [hep-ph]

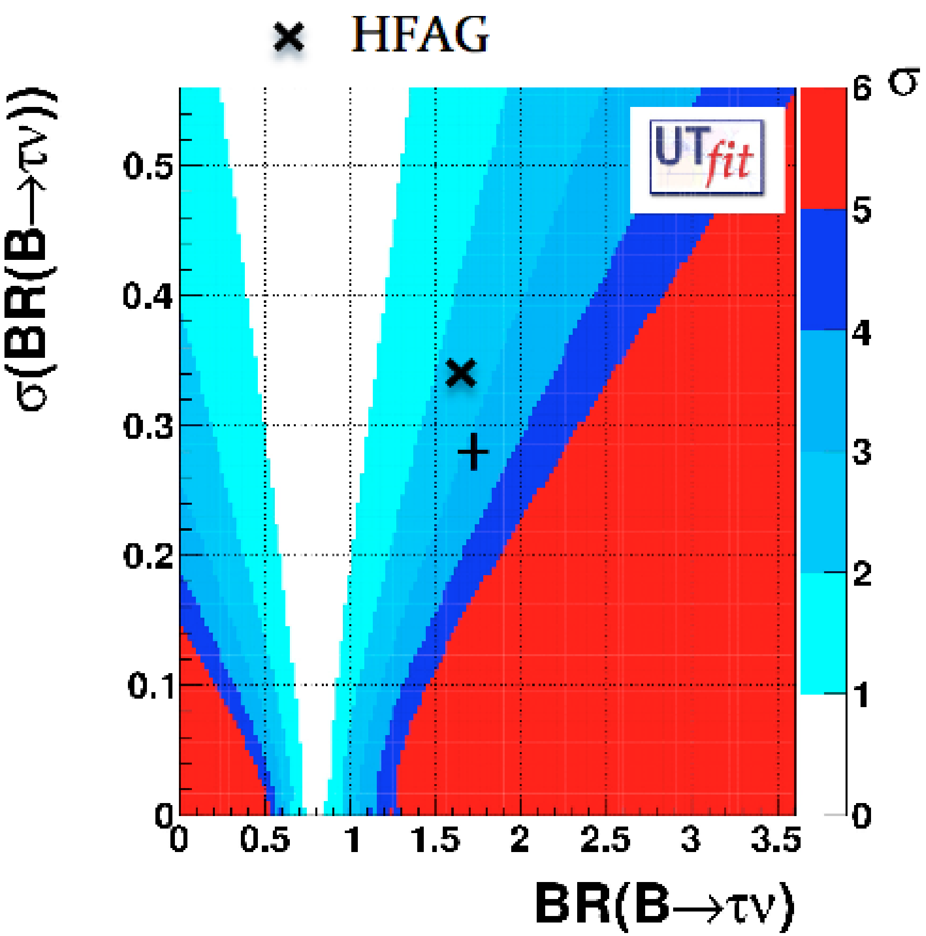
agreement with SM; order 1 BSM allowed.

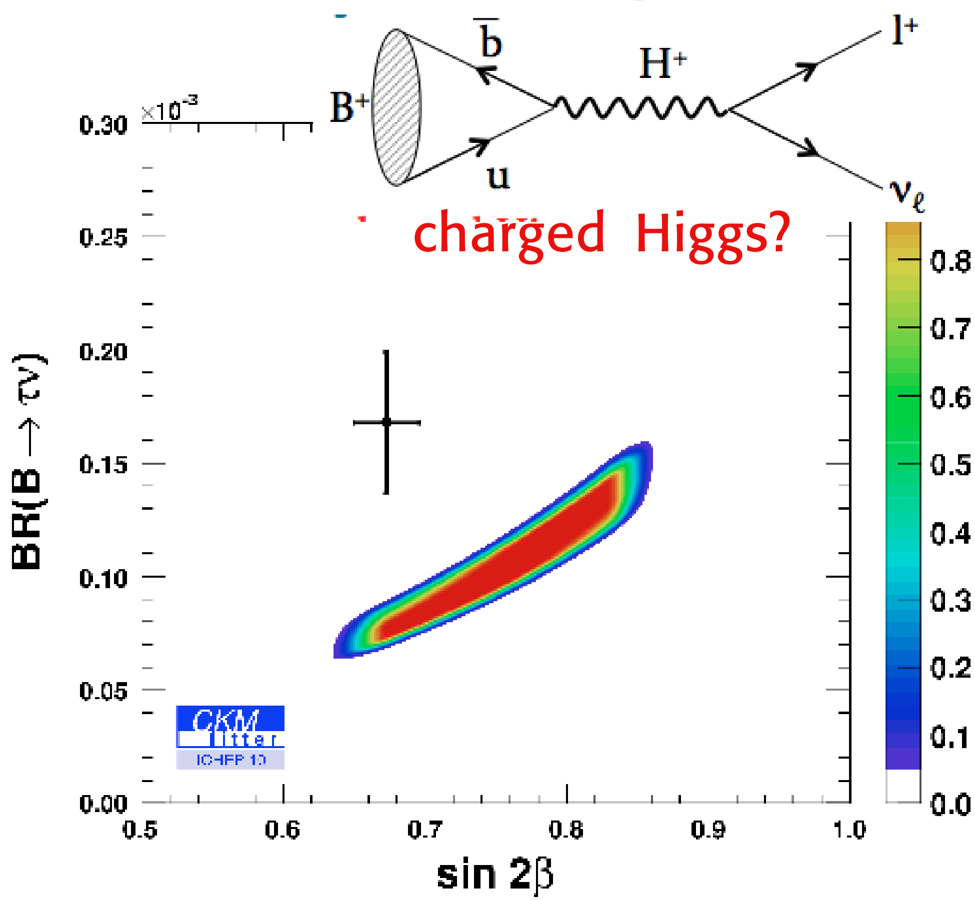
Attacking rare B decays by experiment, operator expansion, lattice calculations

HFAG average: $\mathcal{B}(B \to \tau\nu) = (1.64 \pm 0.34) \times 10^{-4}$

- Vub (exp.+theory) and f_B (theory) uncertainties dominate the SM expectation uncertainty:
  - Using $f_B = 190 \pm 13$ MeV * and $V_{ub} = (3.5 \pm 0.4) \times 10^{-3}$ ** $BF_{SM}(B \to \tau\nu) = (0.80 \pm 0.20) \times 10^{-4}$

De Nardo





Miyazaki
De Gerone

MEGA: Br < 1.2 10^{-11}
MEG: Br < 1.5 10^{-11}

90%cl

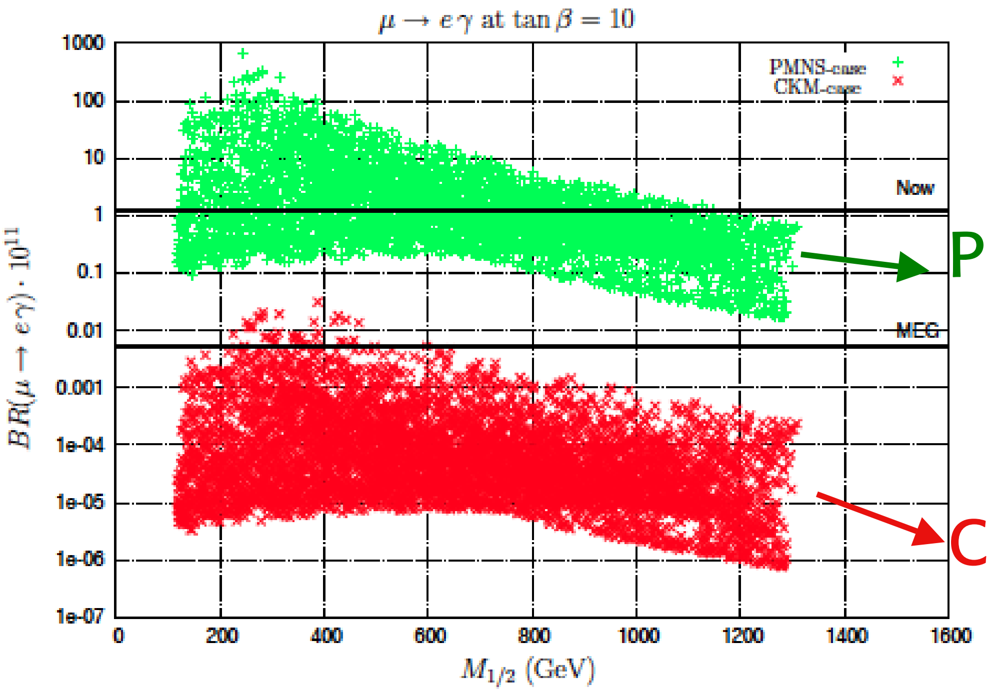
Belle: Br < 4.5 10^{-8}
BaBar: Br < 4.4 10^{-8}

$\mu \to e\gamma$

$\tan\beta = 10$

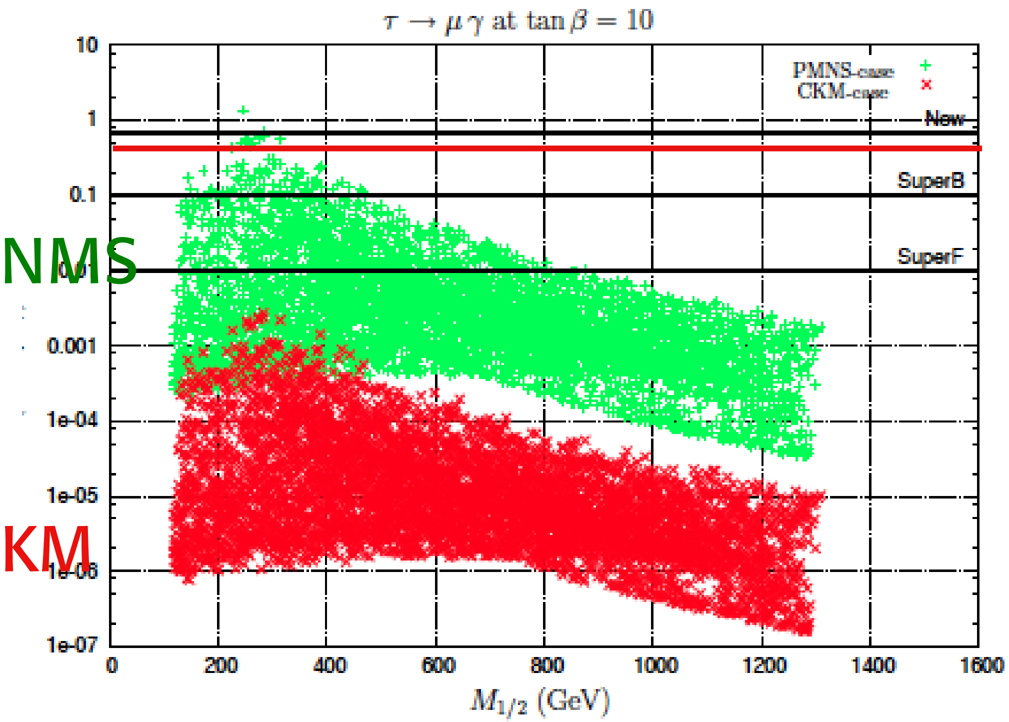
$\tau \to \mu\gamma$

Calibbi et al'06



PNMS

CKM



At present the $\mu \to e\gamma$ is more constraining

In conclusion

ATLAS and CMS have already 10 times more data than in 2010

Very soon the LHC will take the lead and pronounce its verdict

We really hope it will start a new era: not just indirect hints of NP, but direct production of new states