General Introduction into 4th Family Model & Phenomenology

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“Flavor & the 4th Family”
IPPP, Durham; 09/14/11

Outline

- **Motivation**
- **Parameters & constraints on 4G**
- **Possible hints**

Repercussions 4

- **DEWSB**
- **Baryogenesis**
- **DM**
- **High intensity Expts**
- **Colliders**
- **Summary**

Motivation [1]

- **Seen 3; why not 4?**

- **Enhanced prospects for DEWSB**
- **[Holdom('86); Bardeen et al ('90); Hung & Isidori('97); Hung & Xiong('11)]…………**

- **Enhanced prospects for baryogenesis**

[Jarlskog & Stora('88); Branco et al('98); Hou('08)]

Motivation [II]

- NFC: built in…..Recall this is a very serious problem for almost all BSMs
- Cannot be just simple SM4: DM link?
  [See e.g. Volovik(‘03); Lee, Liu & AS (‘11)]
- Readily accounts for B-CP-anomalies
  [A.S et al (’08; ’10); Buras et al (‘10)]
- Accounts also for AFB(tt)
  [Davoudiasl,McElmurry & A S]

May be the best reason

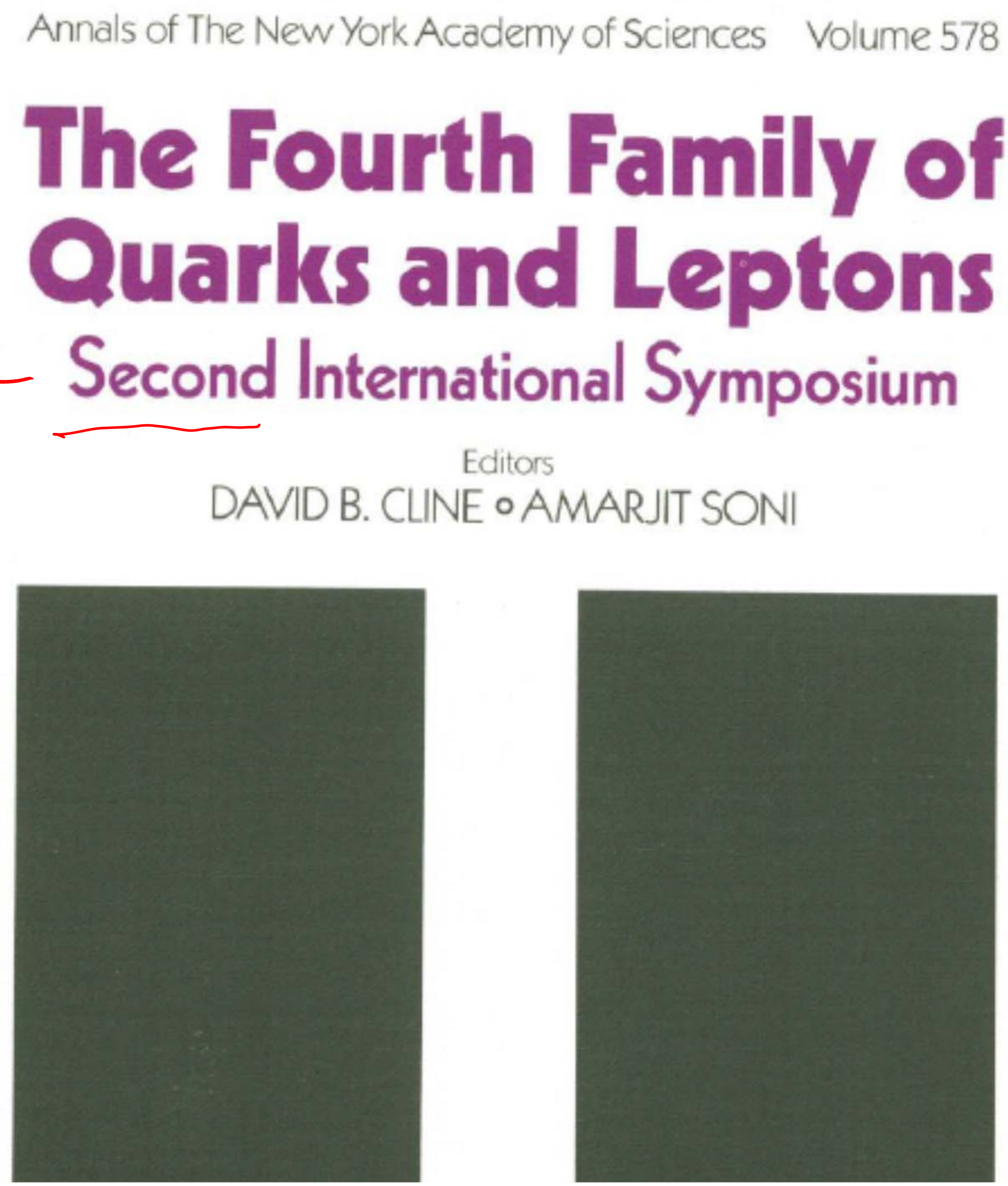
- **My license plate: udcstbgz   (since ‘89 NY)**

- **Used to be OSCILL8   (before ‘89 in CA)**

“SM4”: a revisit

- **Inspired by classic works on “SSB w/o fundamental scalars” by Cornwall and Norton [‘73], studied with Norton and students Carpenter & Siegemund-Broka, role of heavy quarks in DEWSB in [87-90]**
- **potential of B-physics forSM4 studied extensively with George Hou~86-88**

CIRCA 1989 (UCLA)



1st ~1987

Parameters & Constraints on 4G

- In the simplest version (SM4) there are quarks t', b' and leptons L_4, ν_4
- KM "theorem" tells us that every linearly independent set of 3 generations has a phase; so there will be 2 new CP-odd phases (total 3).
- The 4X4 CKM-mixing matrix will also have 3 new real parameters (total 6)
- As far as masses go, LEPII told us that

4 G charged lepton, neutrino, quarks have to be at least around 100 GeV

VCKM4

- Bearing in mind that rare B-decays are very sensitive to 4 G effects and the hierarchical structure of the Wolfenstein representation , we extend to 4X4 case → NANDI + AS '10
-

$$V_{us} = \lambda, \qquad V_{cb} = A\lambda^2, \qquad V_{ub} = A\lambda^3 C e^{-i\delta_{ub}},$$

$$V_{t's} = -Q\lambda^2 e^{i\delta_{t's}}, \quad V_{t'd} = -P\lambda^3 e^{i\delta_{t'd}}, \quad V_{t'b} = -r\lambda, \qquad (1)$$

$$
\begin{pmatrix}
1-\frac{\lambda^2}{2}+\mathcal{O}(\lambda^4) & \lambda & A\lambda^3 C e^{-i\delta_{ub}} & \begin{array}{c} P\lambda^3 e^{-i\delta_{t'd}} \\ +Q\lambda^3 e^{-i\delta_{t's}} + ACr\lambda^4 e^{-i\delta_{ub}} \\ -P\frac{\lambda^5}{2} e^{-i\delta_{t'd}} + \mathcal{O}(\lambda^7) \end{array} \\
-\lambda+\mathcal{O}(\lambda^5) & 1-\frac{\lambda^2}{2}+O(\lambda^4) & A\lambda^2 & \begin{array}{c} Q\lambda^2 e^{-i\delta_{t's}} \\ +A\lambda^3 r - P\lambda^4 e^{-i\delta_{t'd}} \\ -\frac{Q}{2}\lambda^4 e^{-i\delta_{t's}} + \mathcal{O}(\lambda^6) \end{array} \\
\begin{array}{c} A\lambda^3(1-Ce^{i\delta_{ub}}) \\ -Pr\lambda^4 e^{i\delta_{t'd}} \\ +\frac{1}{2}AC\lambda^5 e^{i\delta_{ub}} + \mathcal{O}(\lambda^7) \end{array} & \begin{array}{c} -A\lambda^2 - Qr\lambda^3 e^{i\delta_{t's}} \\ +A\lambda^4\left(\frac{1}{2} - Ce^{i\delta_{ub}}\right) \\ +\mathcal{O}(\lambda^6) \end{array} & 1-\frac{r^2\lambda^2}{2}+\mathcal{O}(\lambda^4) & r\lambda+\mathcal{O}(\lambda^4) \\
-P\lambda^3 e^{i\delta_{t'd}} & -Q\lambda^2 e^{i\delta_{t's}} & -r\lambda & 1-\frac{r^2\lambda^2}{2}+\mathcal{O}(\lambda^4)
\end{pmatrix}.
$$

Use K,B, D …experimental info such as b-> s gamma, b-> s ll, Delta Ms(Md), εK, K^+ -> π+ νν…………..[Nandi and A. S, arXiv: 1011.6091]

SEE SOUMITRA NANDI's talk

TABLE III. Allowed ranges of the CKM4 parameters obtained from our analysis.

Parameter	Allowed range	Parameter	Allowed range
λ	0.2205 ± 0.0018	$\|V_{t'b}\|$	<0.12
C	$0.32 \rightarrow 0.42$	$\|V_{t'd}\|$	<0.05
A	$0.825 \rightarrow 0.865$	$\|V_{t's}\|$	<0.11
γ	$(73 \pm 13)^{\circ}$	$\|V_{ub'}\|$	<0.05
r	<0.5	$\|V_{cb'}\|$	<0.11
P	<5.0	$\|\lambda_{db}^{t'}\|$	<0.002
Q	<2.5	$\|\lambda_{sb}^{t'}\|$	<0.01
		$\|\lambda_{uc}^{b'}\|$	<0.0025

Electroweak precision tests[EWPT]

- **Provide important constraints on SM4 (see talk by Juergen Rohrwild for details).**
- **Here we'll simply note that due EWPT in SM4 mass difference of t', b' needs to be less than ~ 70 GeV.**

  That prejudice suggests in SM4 prominent modes are t'-> b W; b' -> t W

HINTS of CKM breaking

Based on Enrico Lunghi+AS

0707.0212; **0803.4340**; 0903.5059;0912.0002

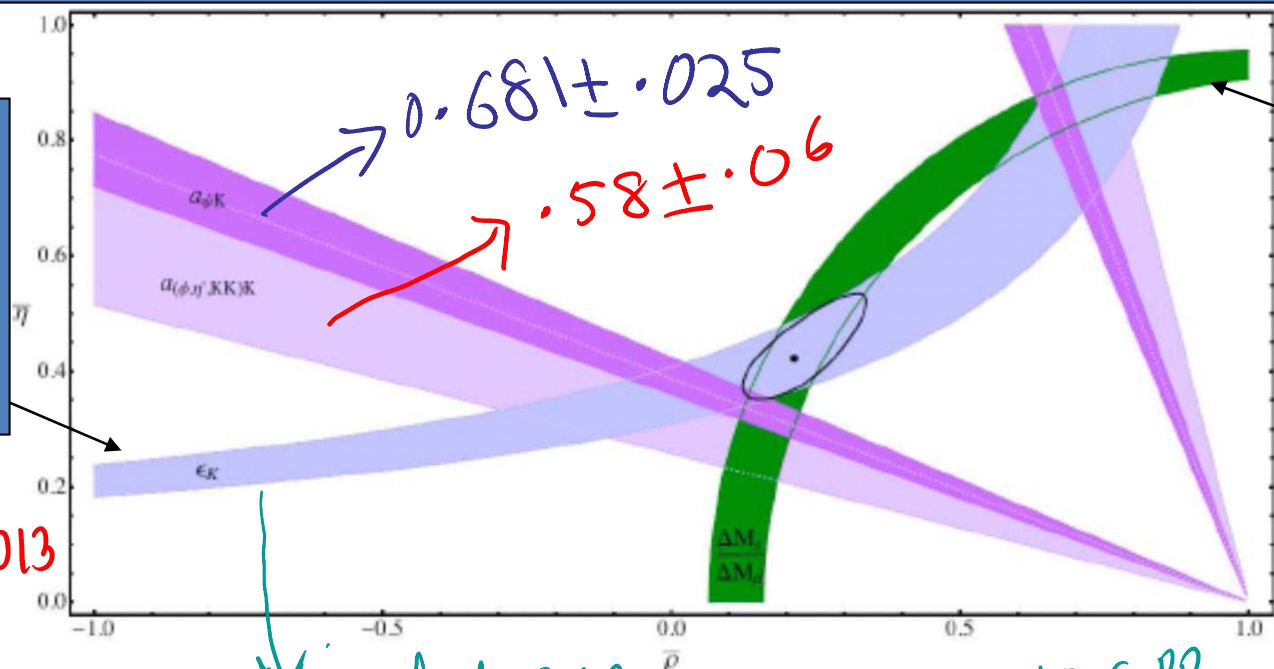
1010.6069

Important to Examine only DeltaF=2 observables:Leave out Vub
sin 2 β = 0.87+-.09{Lunghi+AS,hep-ph/08034340}
(became possible only due significantly reduced error in B_K)

Antonio et al (RBC-UKQCD) 0702042

$\hat{B}_K$ = .720 ± .013 ± .037

$|V_{cb}|$ = 40.8 ± .6 × 10^{-2}



Gamiz et al; Becirevic; Tantalo

.

ξ = 1.20 ± .06

include BURAS + GUADAGNOLI CORR. (0805.3887)

FIG. 1: Unitarity triangle fit in the SM. All constraints are imposed at the 68% C.L.. The solid contour is obtained using the constraints from ε_K and $\Delta M_{B_s}/\Delta M_{B_d}$. The regions allowed by $a_{\psi K}$ and $a_{(\phi+\eta'+2K_s)K_s}$ are superimposed.

2.1-2.7 σ- deviation from the directly measured values of sin 2 β requires careful follow-up

Continuing saga of Vub

- For past many years exclusive & inclusive show discrepancy (Latest; gotten worse)
- Exc ~ (29.7 +-3.1)X10^{-4}
- Inc ~ (40.1+-2.7+-4.0)X10^{-4}

lattice e.g. $B \to \pi l \nu$

continuum $B \to X_u l \nu$

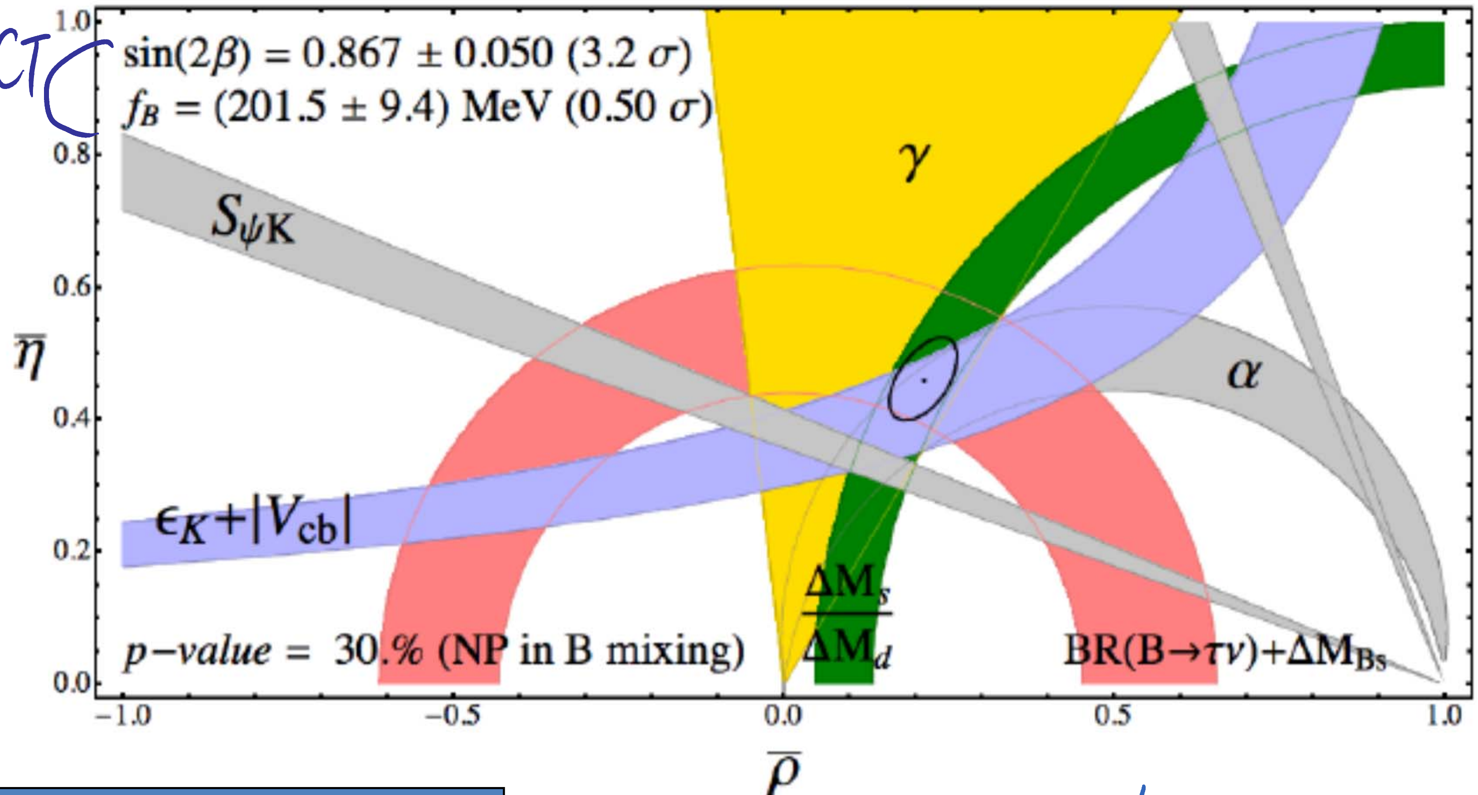
-> ***Let's try NOT use Vub: initiated in '08 (EL&AS'08)…Not just for the above reason***

ONLY BECAME VIABLE DUE TO SIGNIFICANT BETTER B_K

UPDATE 2010

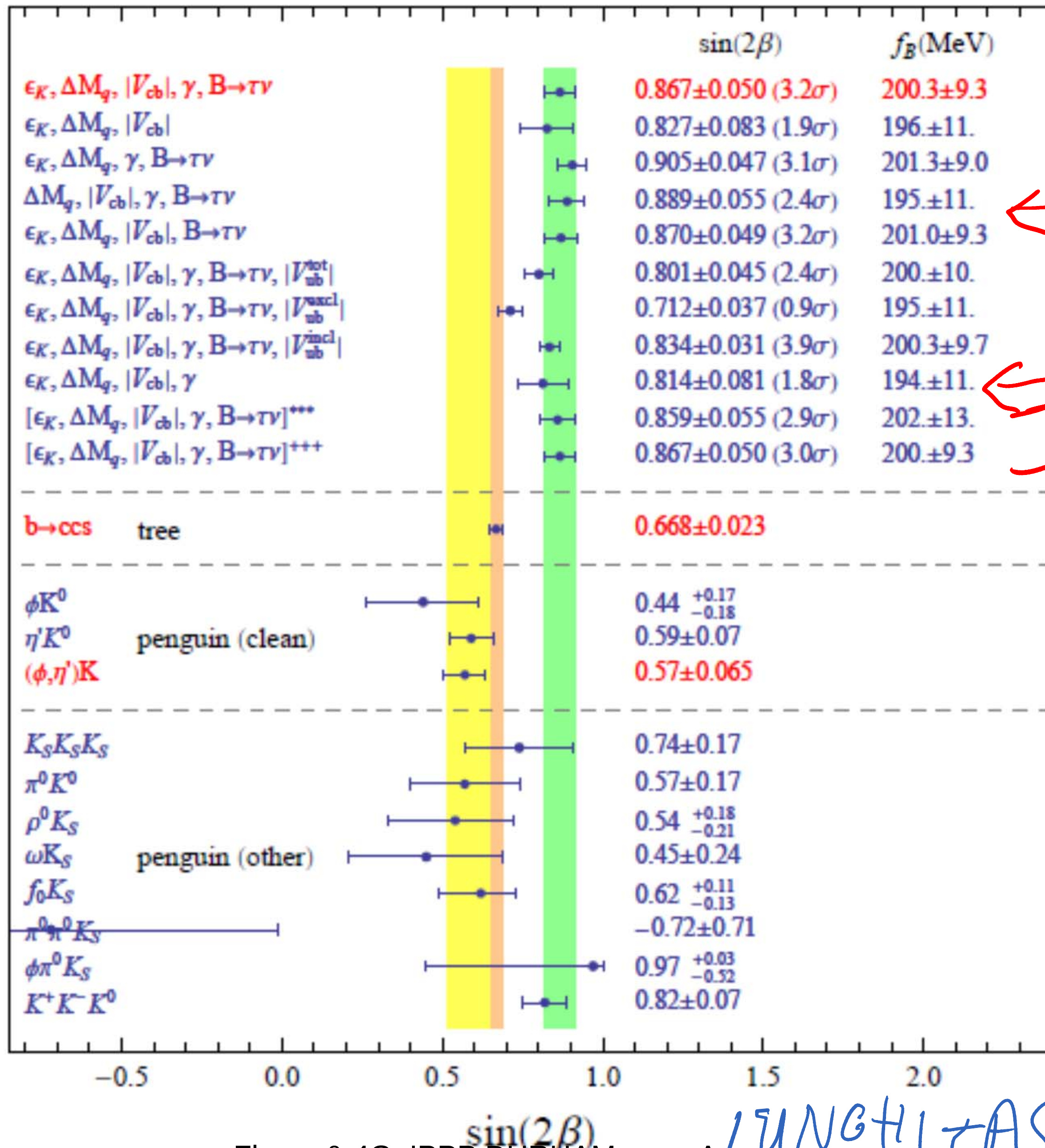
INPUTS: ϵ_K, $\Delta M_{B_s}/\Delta M_{B_d}$, ΔM_{B_s}, γ, $B \to \tau\nu$

PREDICT



LUNGHI + AS PLB'11

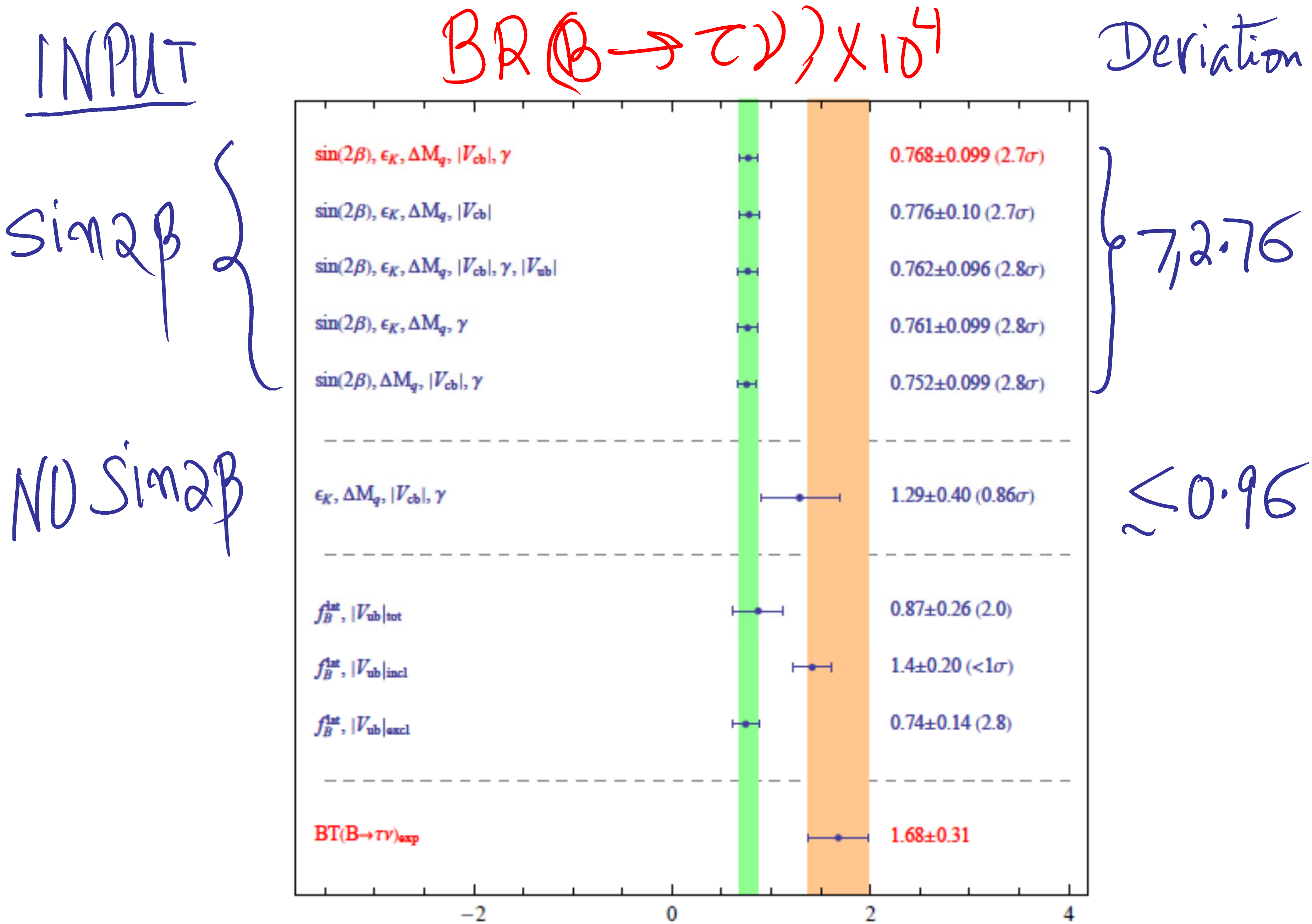
Predict sin2β & fB



"GOLD"

penguin dominated

LUNGHI+AS PLB 11

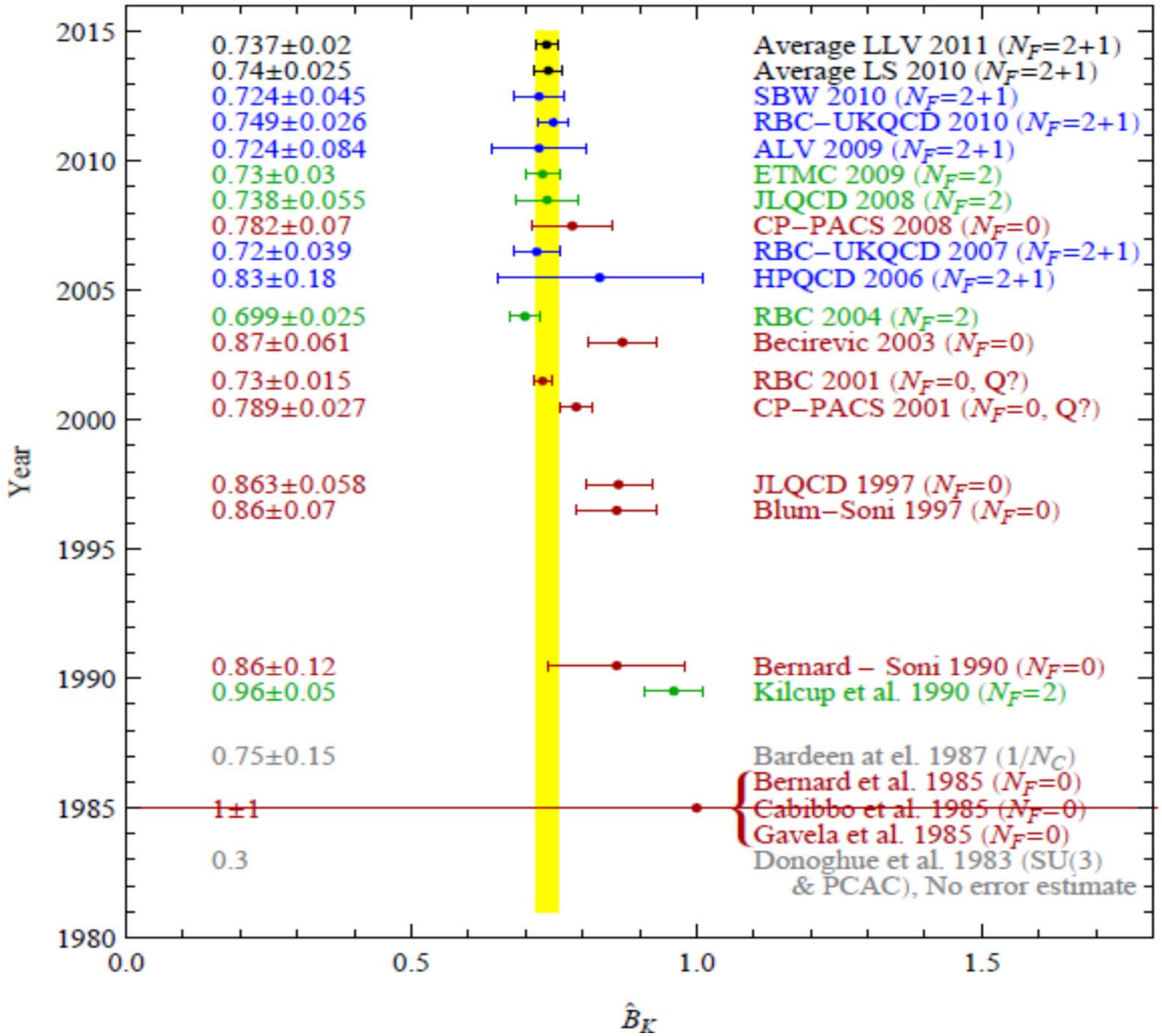

INPUT
BR(B→τν)×10⁴
Deviation
sin2β
NO sin2β
sin(2β), ε_K, ΔM_q, |V_cb|, γ
0.768±0.099 (2.7σ)
sin(2β), ε_K, ΔM_q, |V_cb|
0.776±0.10 (2.7σ)
sin(2β), ε_K, ΔM_q, |V_cb|, γ, |V_ub|
0.762±0.096 (2.8σ)
sin(2β), ε_K, ΔM_q, γ
0.761±0.099 (2.8σ)
sin(2β), ΔM_q, |V_cb|, γ
0.752±0.099 (2.8σ)
~ 2.76
ε_K, ΔM_q, |V_cb|, γ
1.29±0.40 (0.86σ)
≲ 0.96
f_B^lat, |V_ub|tot
0.87±0.26 (2.0)
f_B^lat, |V_ub|incl
1.4±0.20 (<1σ)
f_B^lat, |V_ub|excl
0.74±0.14 (2.8)
BT(B→τν)exp
1.68±0.31
−2
0
2
4

In a nutshell

- **Bulk of NP effects is in Bd,Bs mixing & in sin2β {CONFIRMS our 2008 findings}**
- **Bulk of NP NOT in B->τν, or in ε_K [Presence of subdominant effects therein certainly possible]**
- **Many, many checks for robustness of the conclusions**
- **DIFFICULT to RECONCILE**

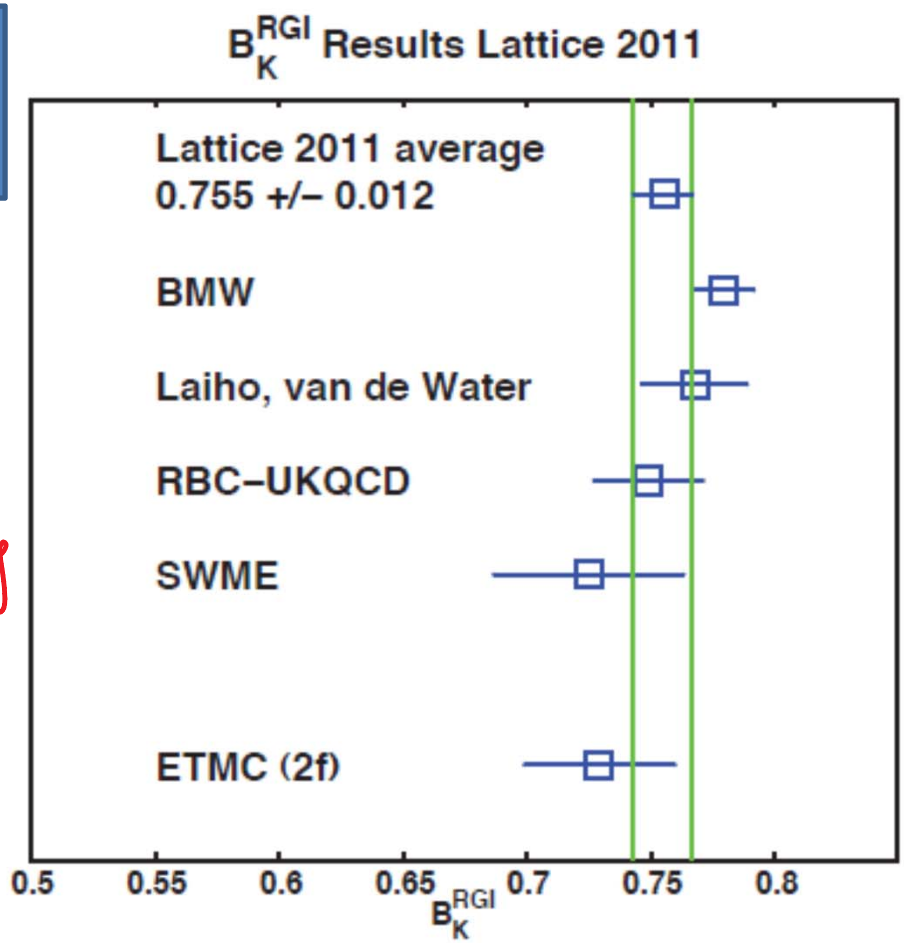
RESULTS with CKM-SM

A BRIEF ~25 years history of B_K



Mawhinney, plenary LAT'11

Several Lattice groups using completely diff methods reporting B_K with total error $\leq 3\%$!



HUGE STRIDES IN LATTICE CALCULATION OF BK!

- Average the four 2+1 flavor calculations presented
- Except for BMW, all are preliminary, although all groups have recently published B_K results from earlier datasets, so preliminary work should be fairly reliable.

See also recent summary by FLAG working group of FLAVIANET (arXiv:1011.4408)
They quote $\hat{B}_K = 0.738(20)$ for $N_f = 2+1$

Delta K pi

- $$A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+)$$

EXPT ~ 5% − (−9%)

" ~ 14.8 ± 2.8 %

LUNGHI + AS '09 2.8 ± 2.8

Numerous tests to check stability under large variation of inputs.

Possibilties for DEWSB

Burdman & Rold arXiv: 0710.0623

WARPED SPACE

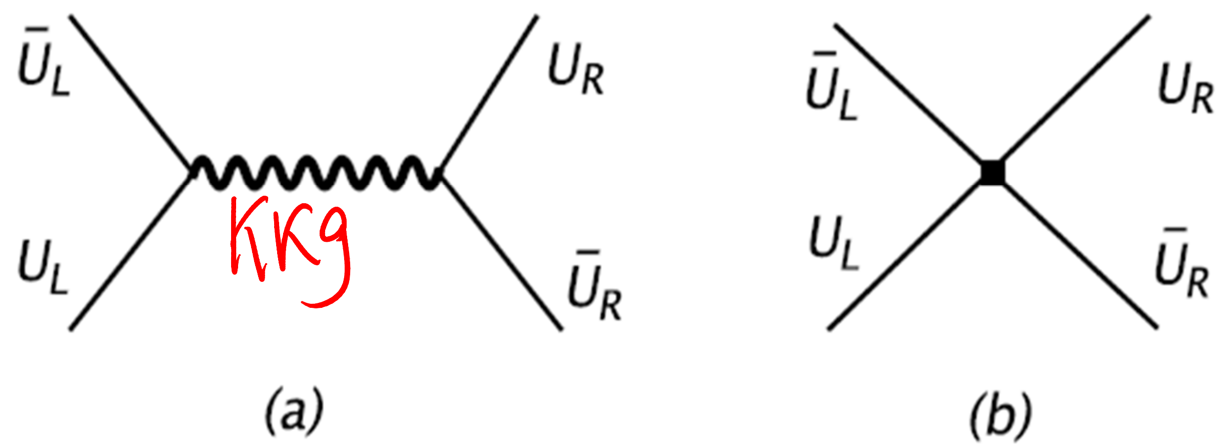


Figure 1: Two contributions to four-fermion interactions of the up-type fourth-generation quark: (a) from the interactions with a KK gluon; (b) from the four-fermion interactions induced by the bulk operators of (2.11).

$\langle \bar{u}_L u_R \rangle \neq 0$

$m_u \sim 600-700\ \text{GeV}$

$m_H \sim 2 m_u$

HEAVY fourth family cannot co-exist with light Higgs

Higgs description loses meaning

- $m_{t',b'} \approx 600$ GeV close to the unitarity upper bound
- Goldstone bosons of electroweak symmetry breaking couple strongly to t', b', so strong interactions unitarize WW scattering

Higgs is no longer needed

- strong interactions can also be responsible for the Goldstone bosons
- a fermion condensate replaces the Higgs vev

- so where do quark and lepton masses come from?

$$\langle \overline{\Psi}\Psi \rangle = \Lambda_{ew}^3 \qquad \frac{1}{\Lambda_{fl}^2}\overline{\Psi}\Psi\overline{\psi}\psi \qquad m_\psi = \frac{\Lambda_{ew}^3}{\Lambda_{fl}^2}$$

BOB HOLDOM

Heavy 4th Generation's scenario

PQ Hung

What can a heavy 4th generation do?

- A heavy Higgs-4th Yukawa system can give rise to condensates and bound states of 4th generation fermions $\Rightarrow$ Implications on the vacuum structure of the SM and the number of Higgs doublets (a mixture of fundamental and composites)
- The appearance of quasi-fixed points in the 2-loop approximation at a scale $\Lambda_{FP} \sim O(TeV)$ hints at a possible scale-invariant theory above Λ_{FP}.

CAN NOT BE JUST SM4

- Neutrino4 must be very heavy [LEP, Fermilab]
- D0,CDF mt', mb' > 350GeV [bounds in SM4]
- 4G fermions very likely play important role IN DEWSB -> likely a strongly coupled 4G
- Generic 2HDMmodels [see Bar-Shalom, Nandi and A. S '11] suggest significant differences in search strategies from SM4 and constraints of oblique parameters

Baryogenesis

- For SM3, there is unique CP invariance [Jarlskog '87]

$$J = \mathrm{Im}\det[M_u M_u^{\dagger} M_d M_d^{\dagger}]$$
$$= 2(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)$$
$$(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

→ Area of UT

⇒ exceedingly small no CP ∵ of small masses

$J/v^{12} \sim 10^{-20}$!

In 4G models

$$J_{234} = 2(m_{t'}^2 - m_t^2)(m_{t'}^2 - m_c^2)(m_t^2 - m_c^2)$$
$$(m_{b'}^2 - m_b^2)(m_{b'}^2 - m_s^2)(m_b^2 - m_s^2)A_{234}$$

$\frac{J_{234}}{J} \sim 10^{16}$!!

SHOULD FACILITATE SIGNIFICANTLY

But SM4 simple Higgs not good 4 phase transition; 2 HDM needed [c DINE + KUSENKO]

DM possibilities in 4G models

- Lee,Liu, AS arXiv: 1105.3490 [c also Volovik hep-ph/0310006]
- Link heaviness of $\nu 4$ with new abelian gauge interaction: B – 4 L4 distinguishing it from SM3 neutrinos
- Just a heavy $\nu 4$ in SM4 is NOT a viable DMcandidate …conflicts with direct detection bounds[CDMS & XENON} both for Dirac (spin independent) or Majorana (spin dependent) cases [XENON 10]

New B-xiL gauge symmetry for 4G

- [its similar to earlier 3G studies: Ma arXiv:9709.474; Lee & Ma, 1001.0768]

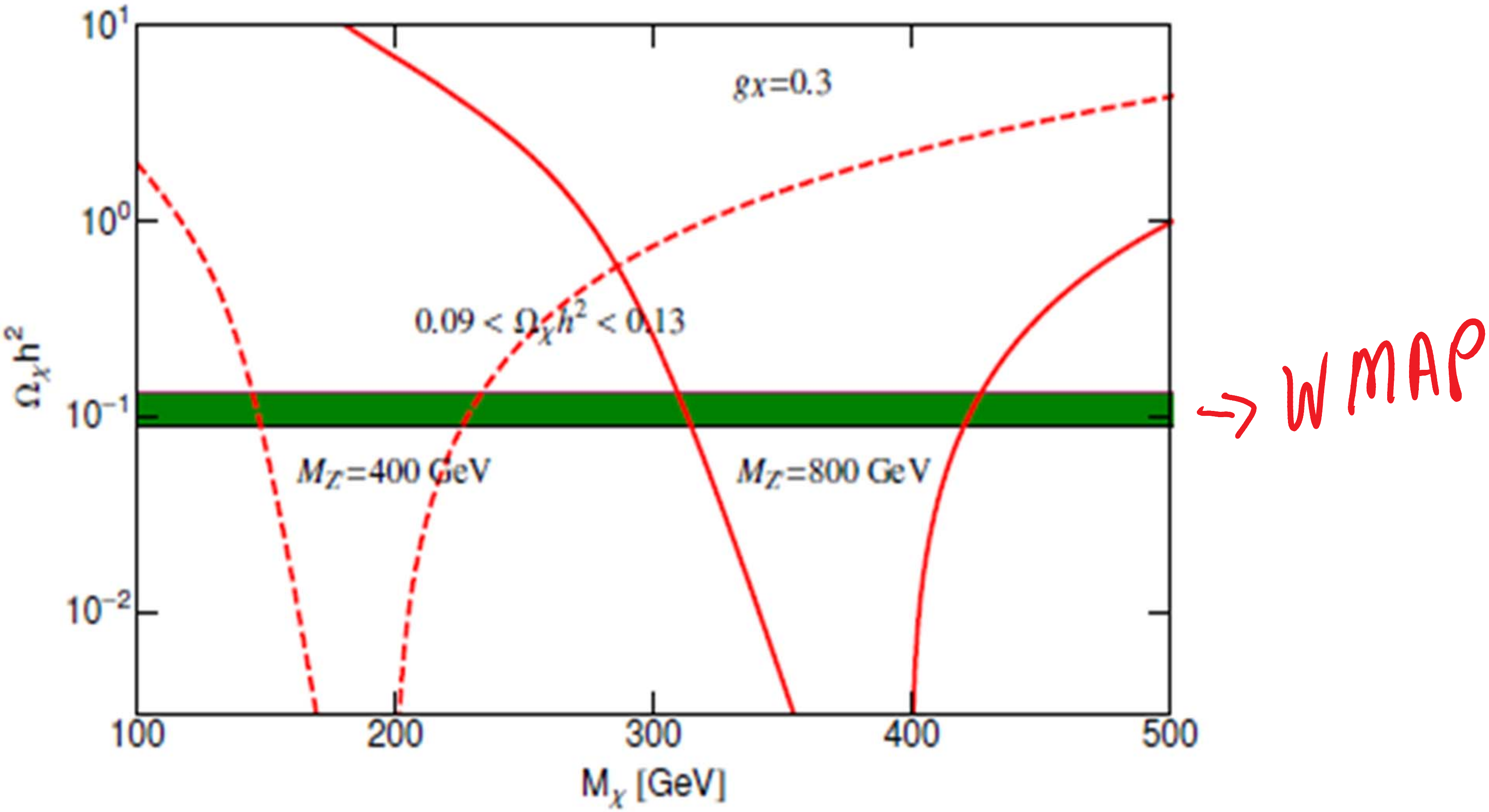
- Relevant effective new interaction is:

$$\mathcal{L}^{Z'}_{\mathrm{int}} = g_X Z'_\mu \left[\frac{1}{6}\bar{q}\gamma^\mu q - 2\bar{e}_4\gamma^\mu e_4 - 2\bar{\nu}_{4L}\gamma^\mu\gamma_5\nu_{4L} - 2\bar{\nu}_{4R}\gamma^\mu\gamma_5\nu_{4R}\right]$$

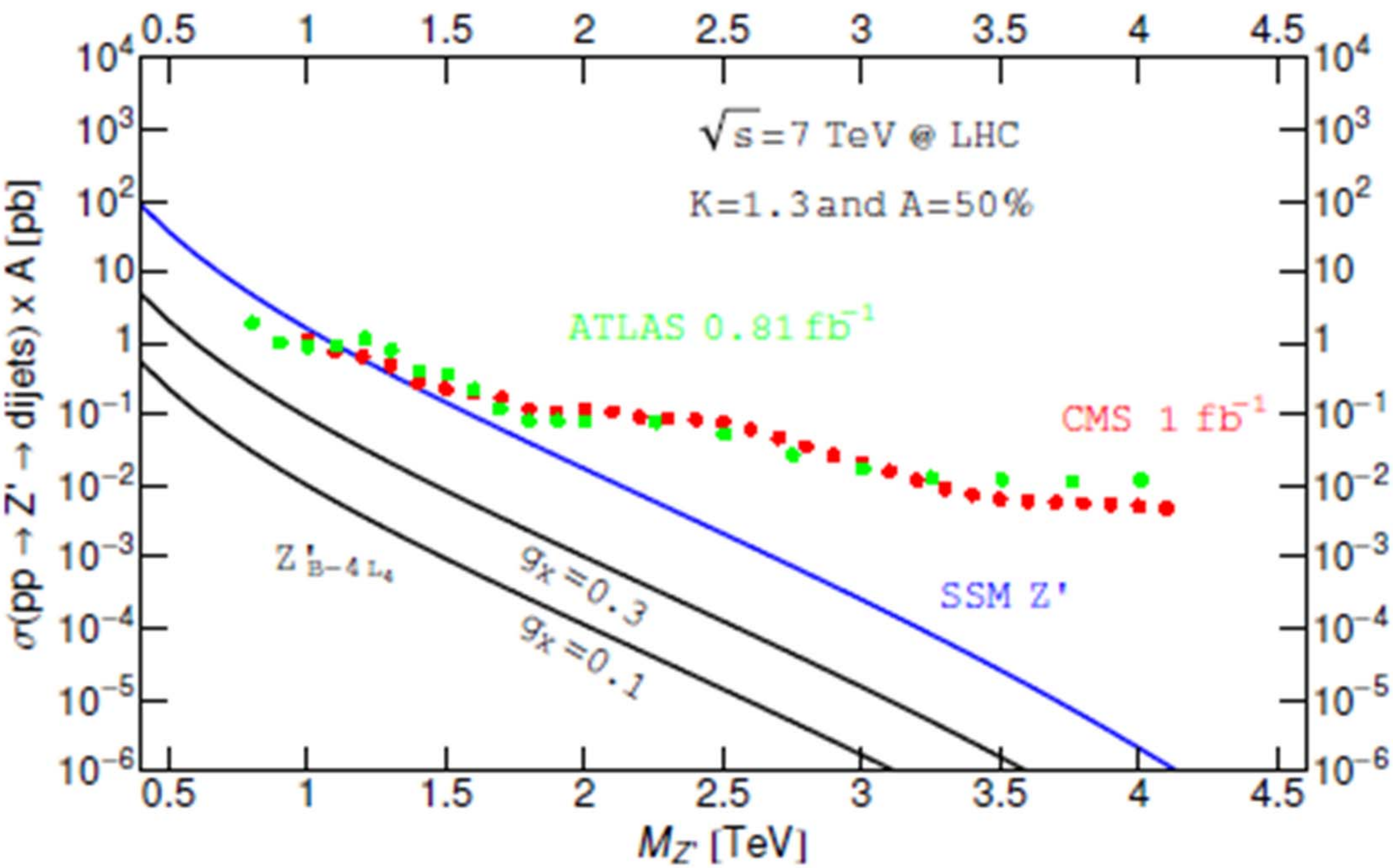
NOTE: (almost) leptophobic Z' Also couples rather weakly to quarks

DMC

RELIC DENSITY Vs DM MASS



LHC Searches NOT Yet Sensitive

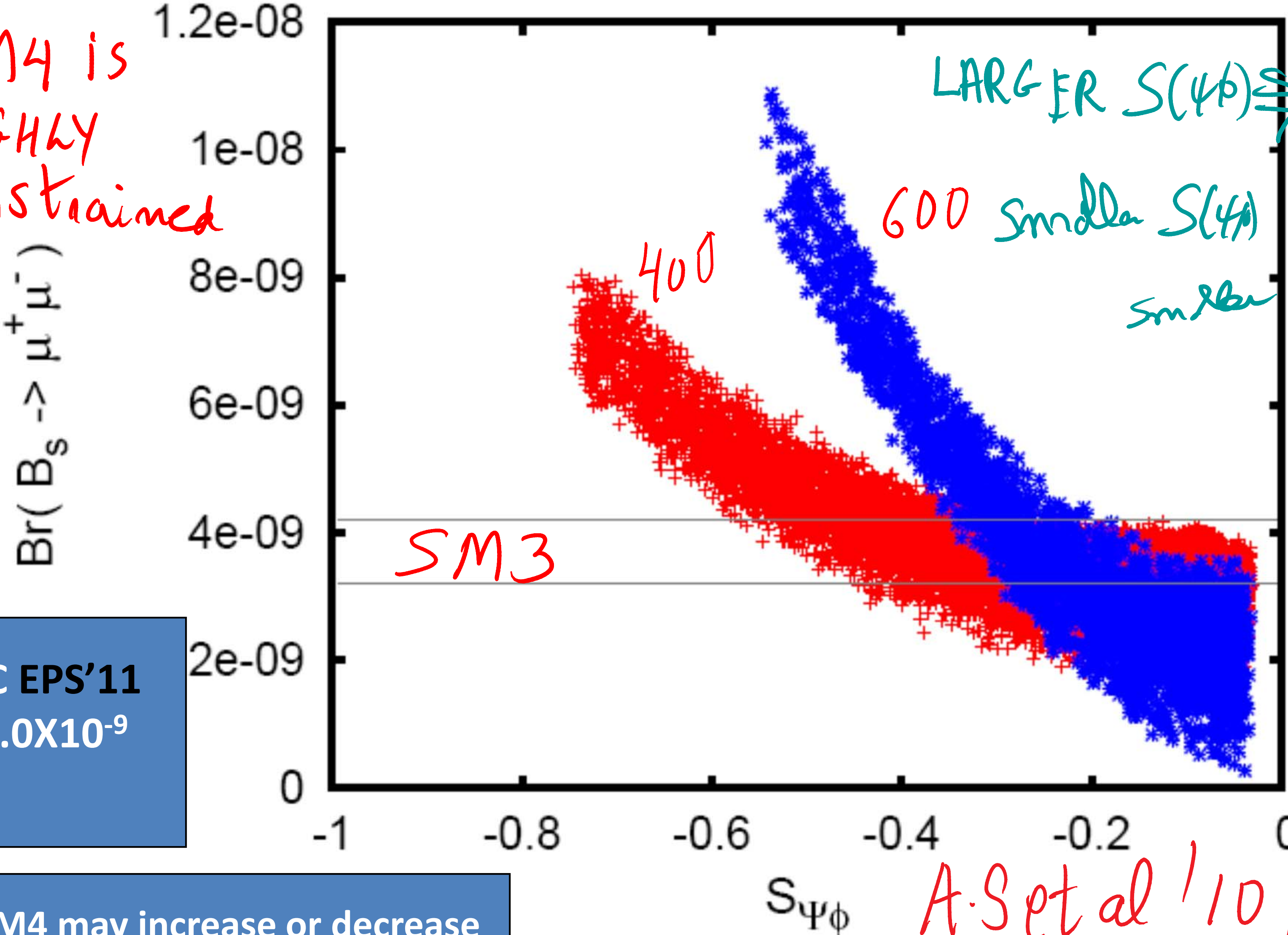


Implications for High Intensity Experiments

- Effects on CP-conserving observables are expected to be small.[e.g b s gamma; b s l l..]
- A very nice exception is Bs->mu mu
- CP-violating observables are more susceptible due to the 2 new phases.
- Using null observables of SM3 is a good idea.. [see e.g. Gershon & AS hep-ph/0607230]
- Here are some candidates: Bs-> psi phi, B(Bs) -> X(Xs) l nu, D0->phi pi0, eta' rho, ks omega; KL-> pi0 nu nu, epsilon'/epsilon
- May also appear as deviation from sin2beta

Br(Bs->μμ): a very clean process
IMPORTANT Correlation with S(psi phi)

SM4 is HIGHLY constrained

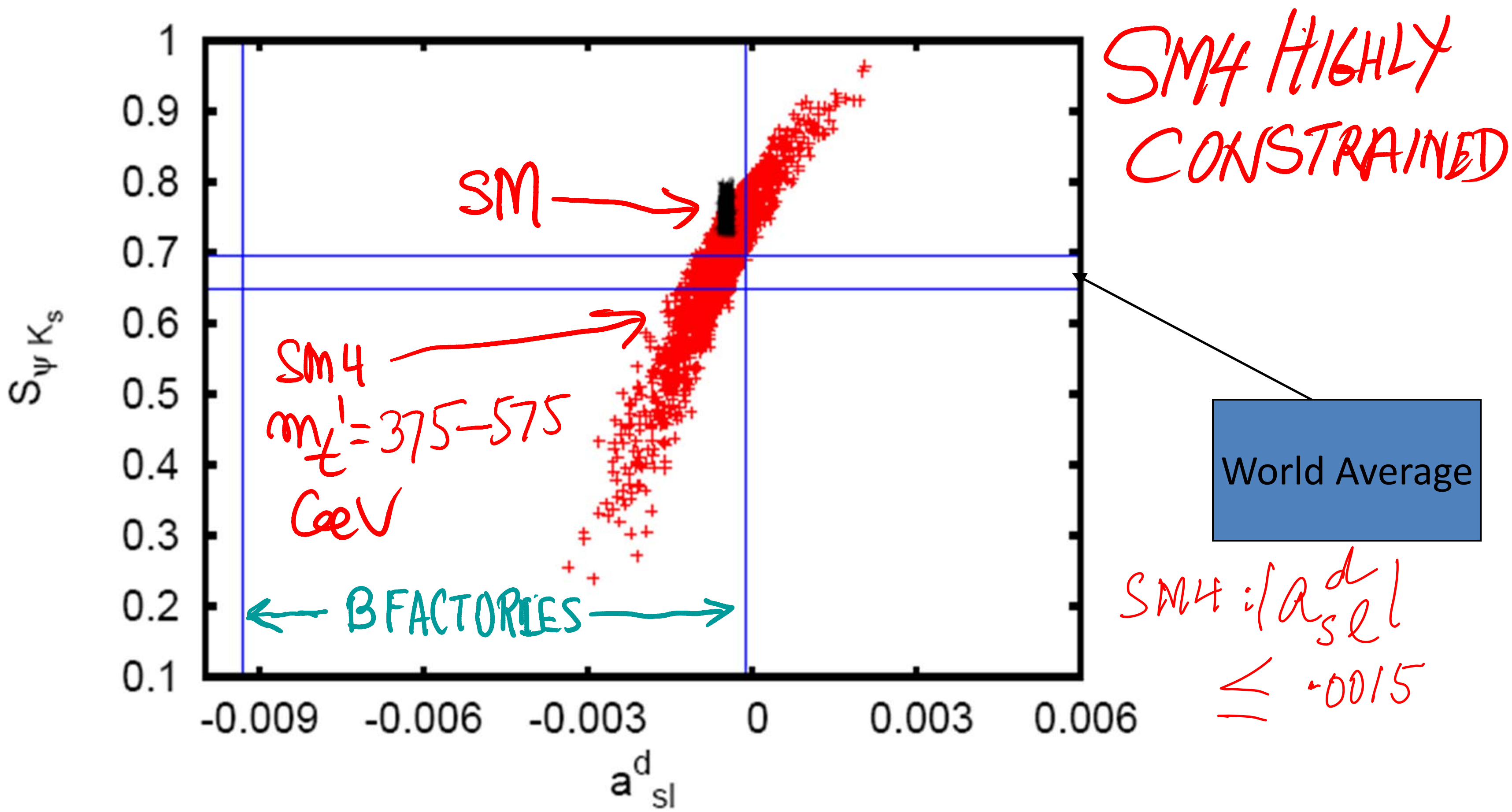


LHC EPS'11
<9.0X10^{-9}

SM4 may increase or decrease Br by ~ O(3)

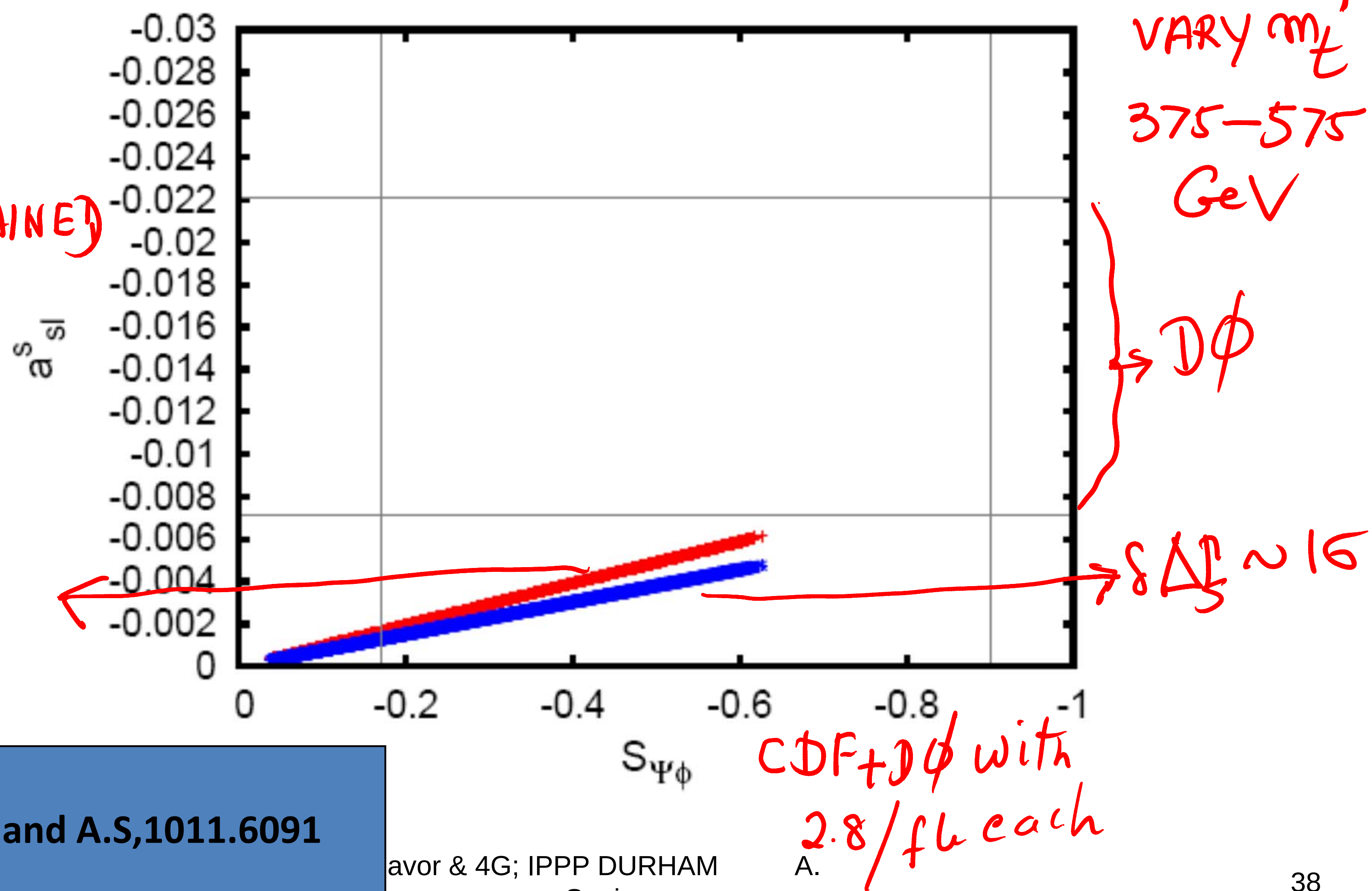
A.S et al '10; BURAS et al '10

Predicted range of S(psiKs) in SM4 (with mt’=400 GeV) is (shown in red) compared with the experimentally measured value via the psi Ks mode (1 sigma error) and with the SM (1 sigma)



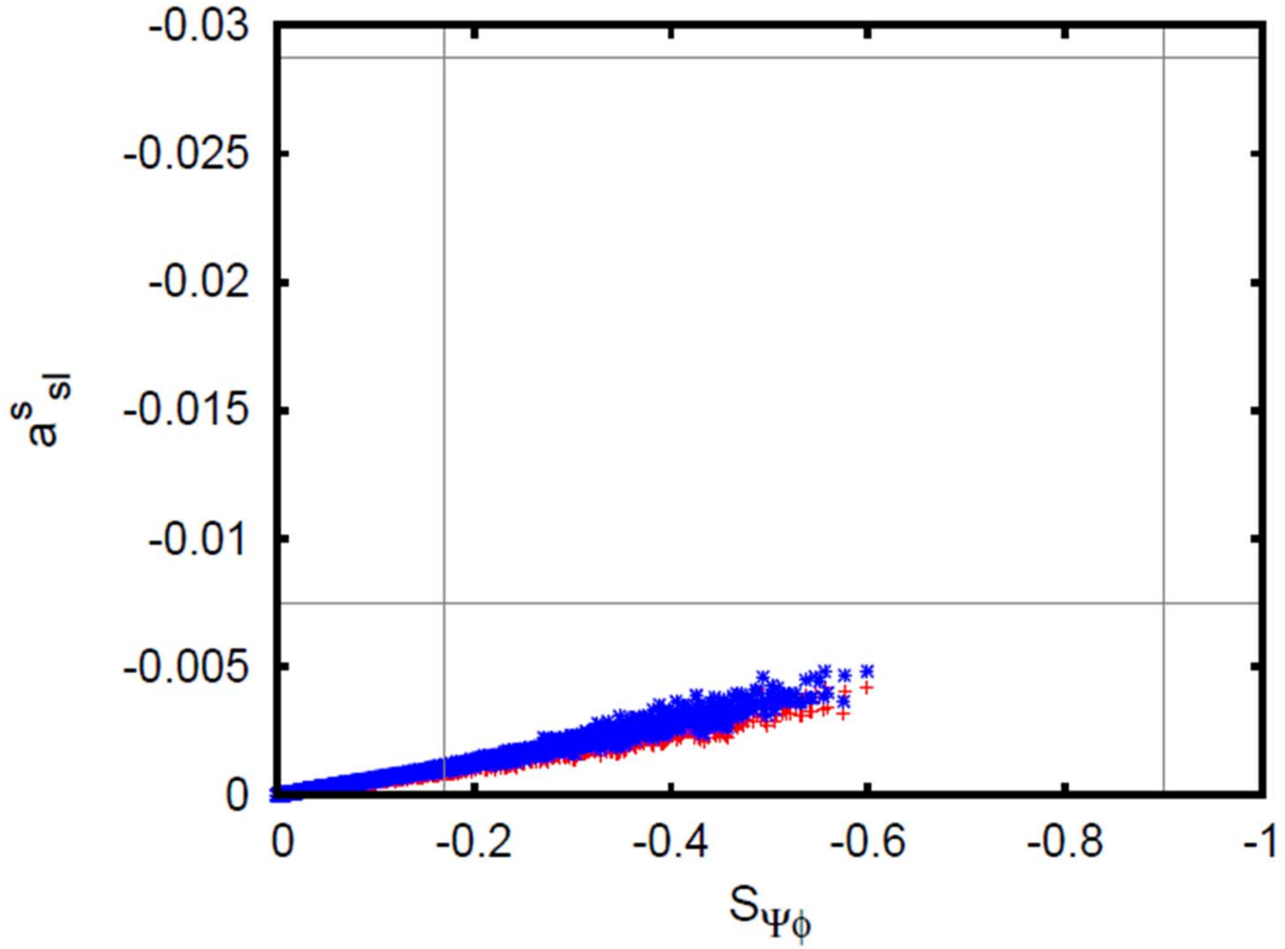
SM4 seems to predict sin2 beta around 0.70 with an error of about 0.06;
S. Nandi and A.S, 1011.6091

Recent D0 result is vertical axis and combined D0, CDF each
For SM4 error on Delta_Gamma_s is increased
by a factor of two resulting in ~50% increase in a_sl^s



S.Nandi and A.S,1011.6091

D0 update '11

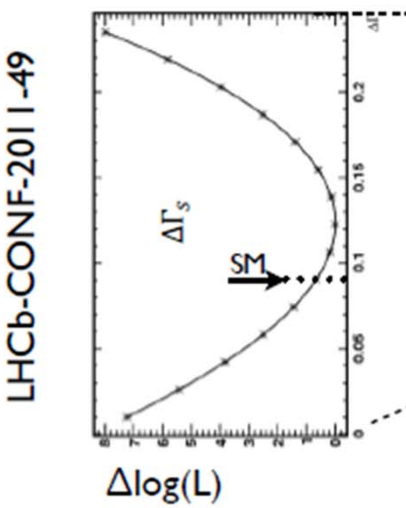


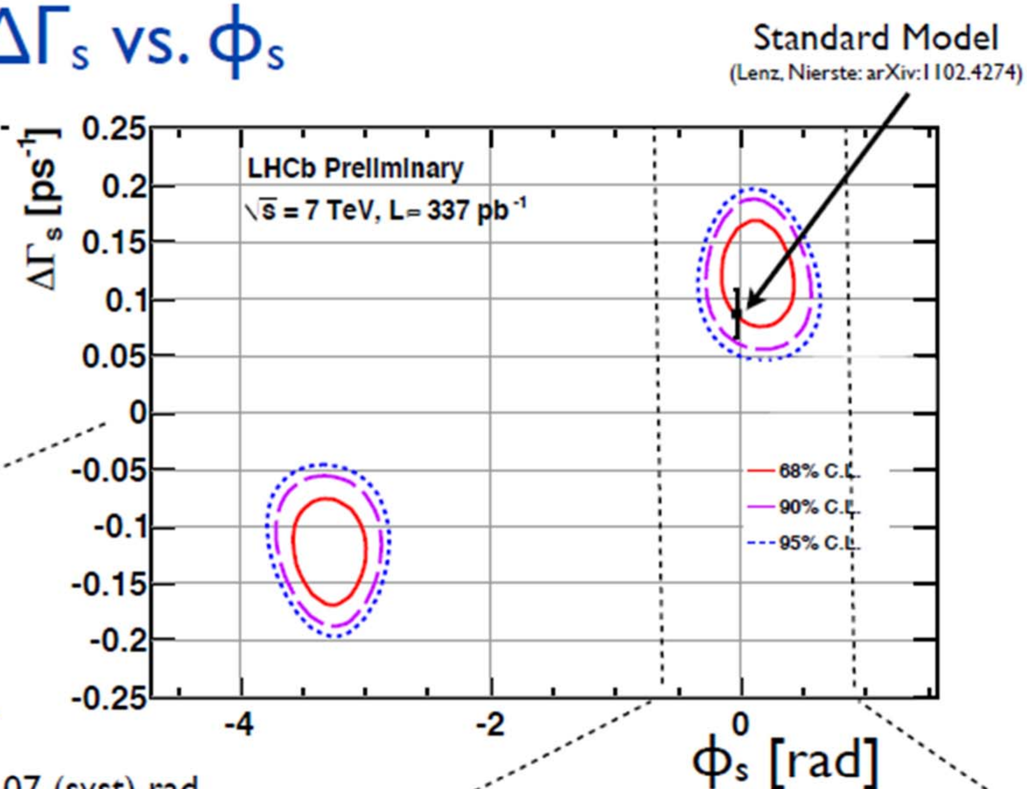
$\frac{\Delta\Gamma}{\Gamma} = 16$ RED

$= 26$ BLUE

G. Raven @ LP11

$B_s \to J/\psi\varphi$: $\Delta\Gamma_s$ vs. ϕ_s



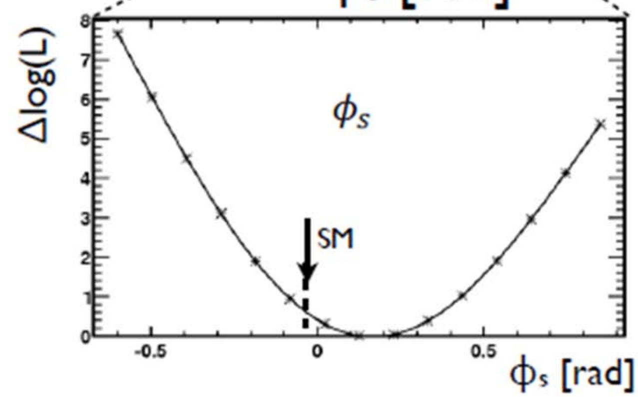


Most precise measurement of ϕ_s

- $\phi_s = 0.13 \pm 0.18$ (stat) ± 0.07 (syst) rad
- Consistent with SM

4 σ Evidence for $\Delta\Gamma_s \neq 0$:

- $\Delta\Gamma s = 0.123 \pm 0.029$ (stat) ± 0.008 (syst) ps^{-1}
- $\Gamma_s = 0.656 \pm 0.009$ (stat) ± 0.008 (syst) ps^{-1}



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(Sin2beta)tree vs (sin2beta)penguin

- The other hint is that b-> s penguin transitions have a non-vanishing BSM phase.
- Cleanest modes (eta' Ks, phi Ks) seem to show smaller value ~0.59 – 0.56
- Central value for several other modes is smaller than 0.68 [and of course practically all are well below the theory prediction ~0.85]

Note sin 42 deg = 0.67

sin 35 deg = 0.59 NEED TO TARGET such small deviation

~0.1 rad

SM: $\phi_s \sim -.04 \pm .02$

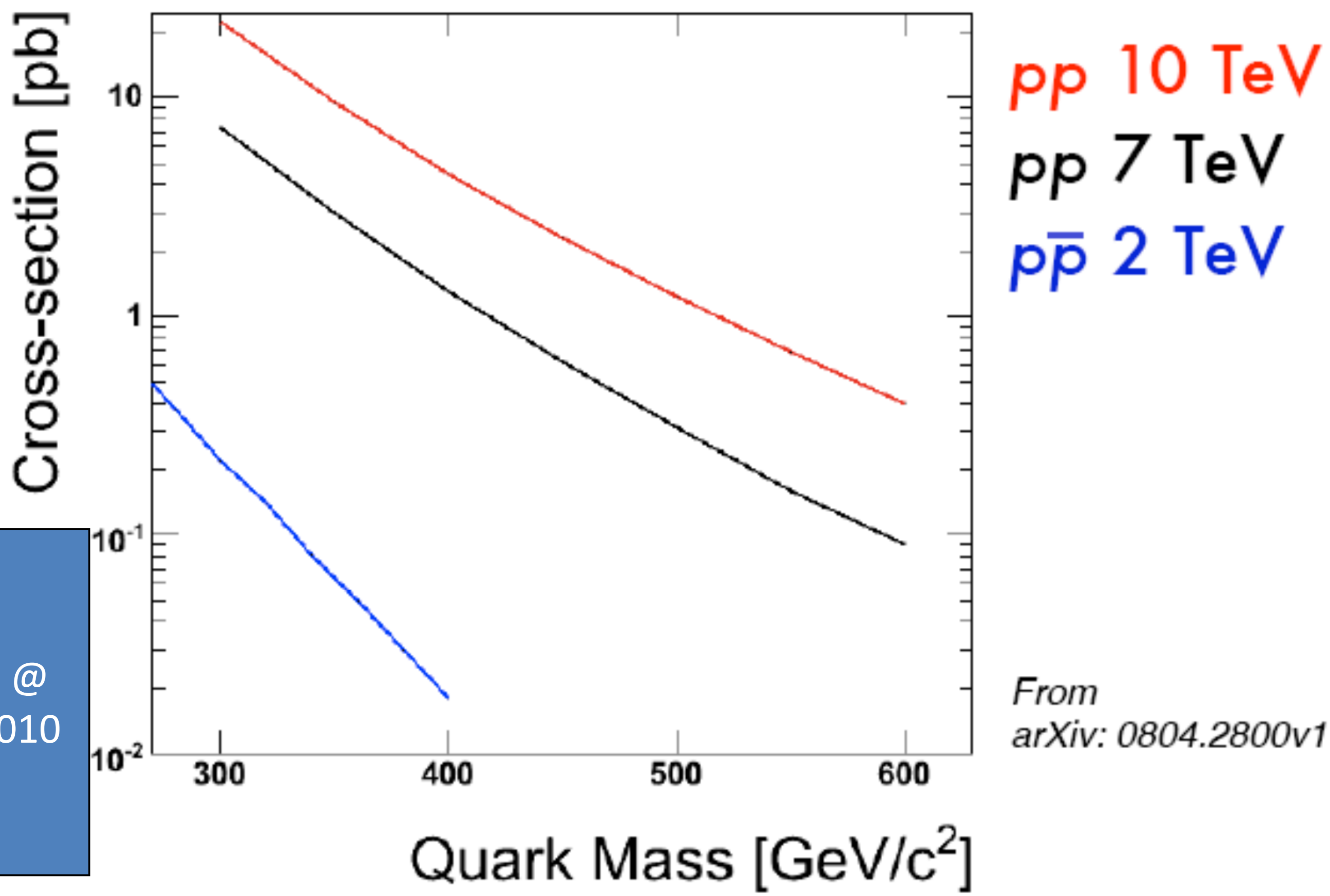
“…..but we have only just got started”, G Raven at LP11

A sentiment I enthusiastically share

@ colliders

Cross-sections

LHC has much larger rates for heavy quarks

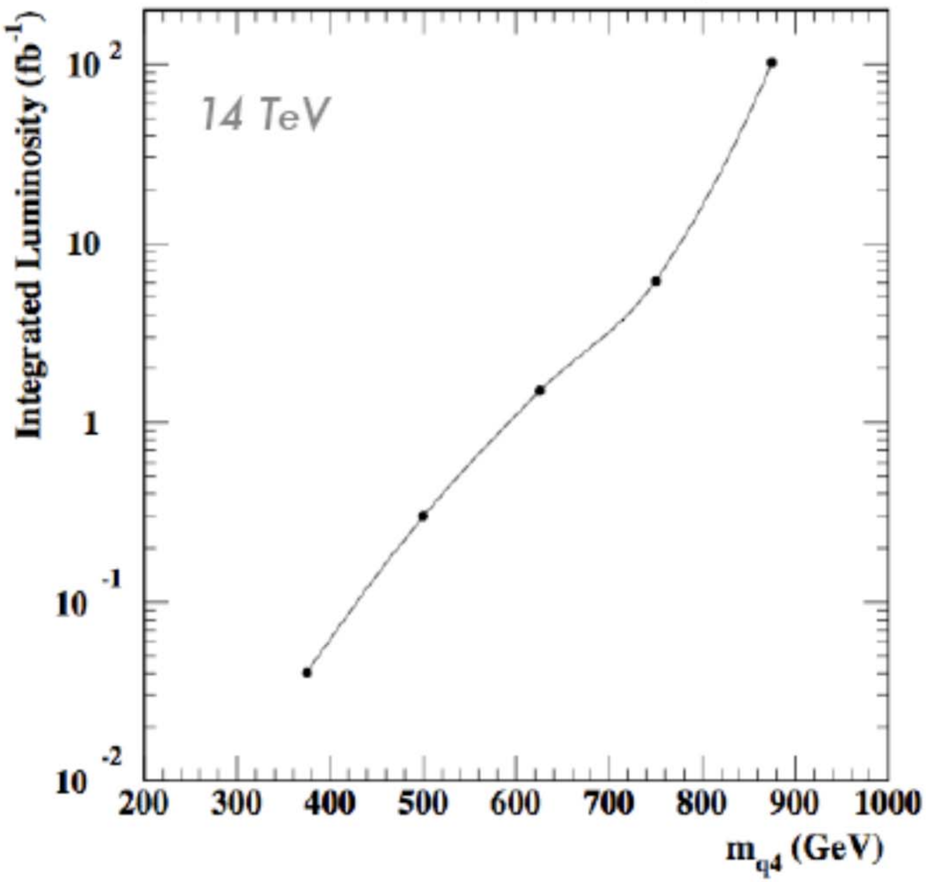


From arXiv: 0804.2800v1

Whiteson @ NTU Jan2010

Sensitivity

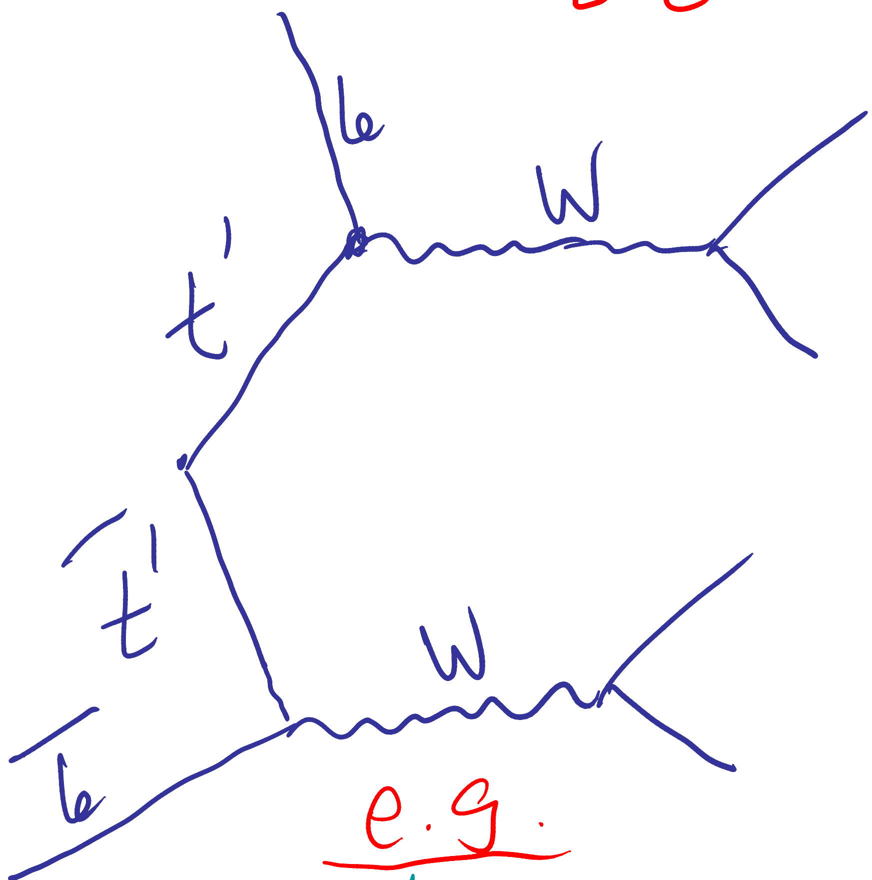
5σ discovery



Whiteson@NTU,Jan2010

From ATLAS SN-ATLAS-2008-069

$t'\bar{t}'$



e.g.

I 2 OS l, 2 b_j, MET

II 1 l, 2 b_j, MET, W_{jj}

e.g.

1. 2 OS ℓ, $2b_j$, W_{jj}, W_{jj}, MET
2. 2 SS ℓ, $2b_j$, W_{jj}, W_{jj}, MET
3. 1 ℓ, $2b_j$, W_{jj}, W_{jj}, W_{jj}, MET

Detection of 4G [SM4] quarks

[Atwood, Gupta, AS'11,arXiv:1104.3874]

- **An important feature: To a rather good approximation, pair production is**

near threshold . Using this feature showed robust signals:

1) Single lepton

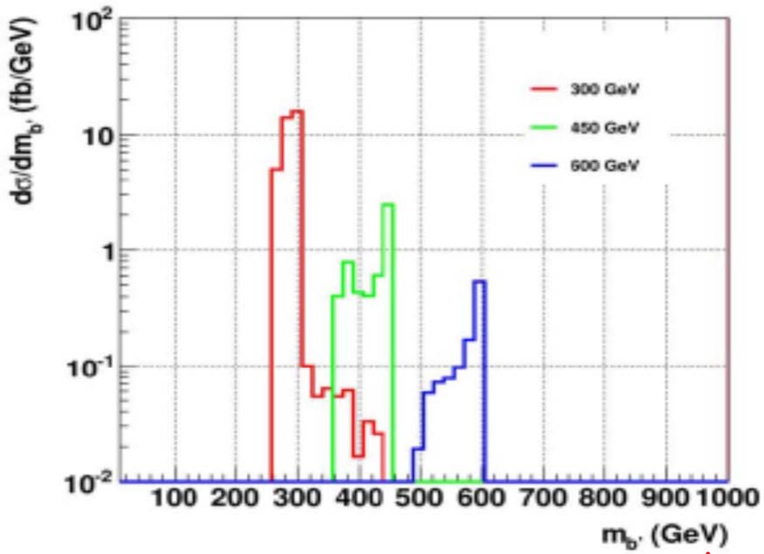
2) Opposite sign leptons

3) Same sign dileptons

All 3 viable

Search for 4th generation at hadron colliders

- Large production rates at the LHC
  - b'→tW gives same sign leptons, plus jets, E_T^{miss}
  - Small Standard Model background
  - Can reconstruct b' mass



14 TeV
1/fb

Atwood, Gupta, Soni, arXiv:1104.3874

An illustrative example

Experimental bounds

- **CDF, D0 and CMS have looked for t’, b’ assuming simple SM4 decay patterns.**
- **CDF: mb’ > 338 GeV; mt’ > 358 GeV**
- **D0:**
- **CMS (LHC7, 34/pb): mb’ between 255 GeV & 361 GeV excluded @ 95%CL.**
- **ATLAS [UCI group actively involved] talk by Michael Werth**

Theory bounds (prejudice)

- Chanowitz, Furman, Hinchliffe (`78-79) showed perturbative unitarity requires

quark mass < ~ 550 GeV; leptons < ~ 1 TeV

Important Caveat: Nature cares less above perturbation theory than many of us [e.g. QCD]

[Infact strong coupling could lead to DEWSB]

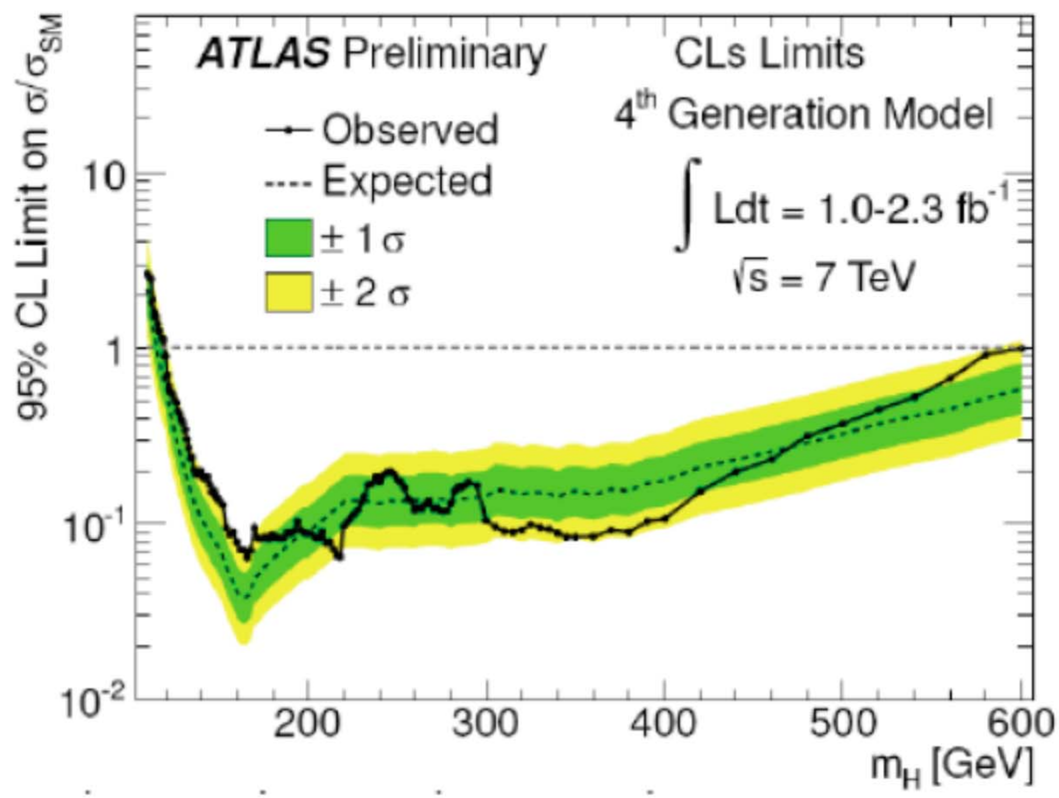
Cannot be simple SM4

- **Even if a 4th generation exists it is unlikely to be a simple replica of SM3:**
- **Neutrino mass provides a strong clue**
- **DM possibility and baryogenesis both strongly suggest 4G not in SM4**
- **Highly implausible that heavy quarks will**

not be used for DEWSB…..mH tends to be heavy in these models

- **Simple SM4 light higgs seems strongly disfavored by data**

Higgs limits assuming a 4th generation of quarks and leptons:



Other exotic fermions are still alive and interesting, but the sequential 4th generation is in deep troupble!

see Xiao-Gang He

4G2HDM:LEET for DEWSB

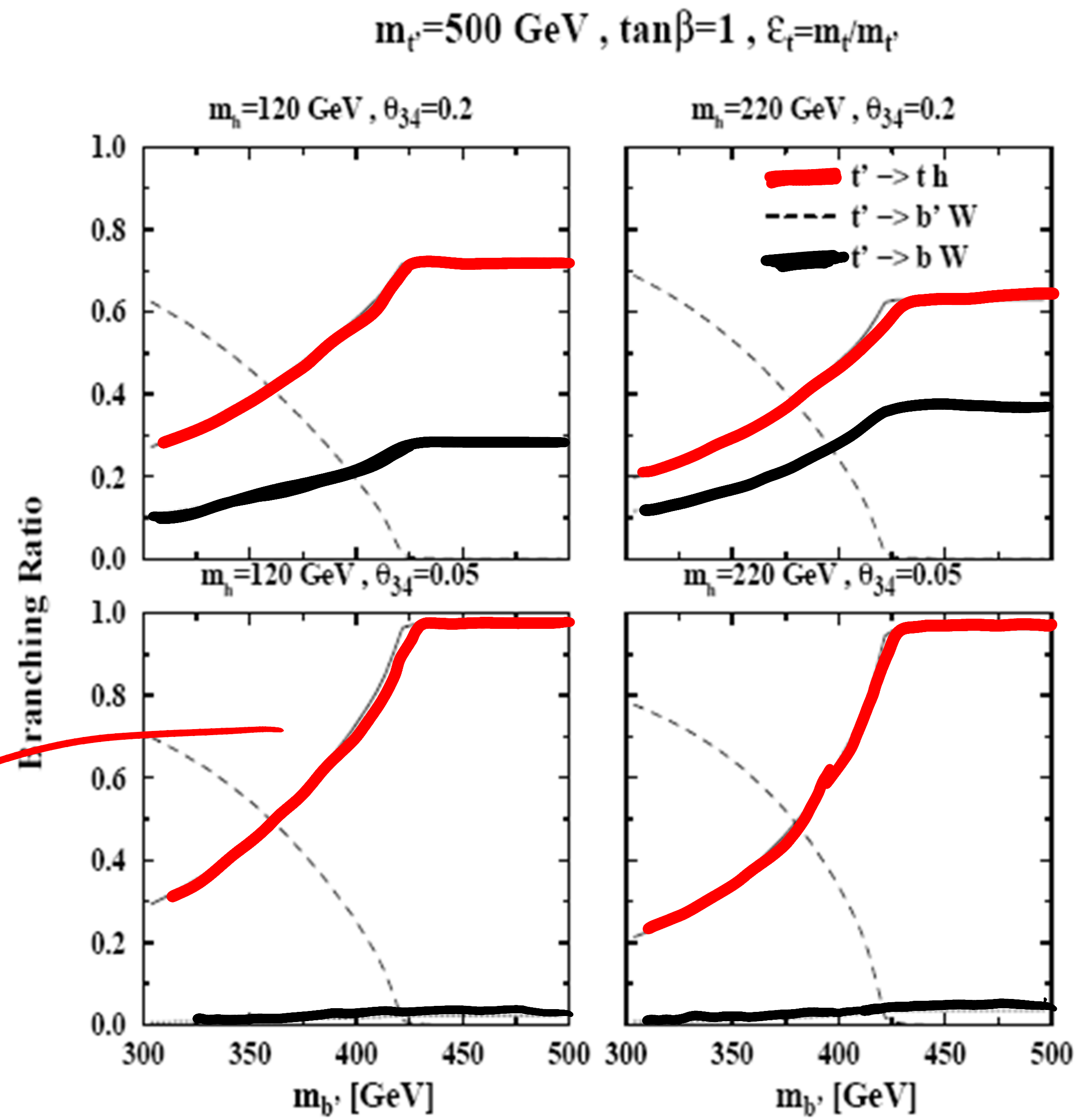
[Bar-Shalom,Nandi, A.S ’11, arXiv:1105.6095]
see also He & Valencia: arXiv:1108:0222

- **2 Higgs doublet model for the 4th ; 2nd doublet with v2/v1 >> 1 couples only to 4th gen**
- **FCNC only among 3rd and 4th gen**
- **Significant modifications to t’, b’ decays**
- **t’->t h, b h+ very large BR, similarly for b’**
- **Requires modification to search strategies**
- **Can account for tt FB asymmetry**

t’ decay pattern

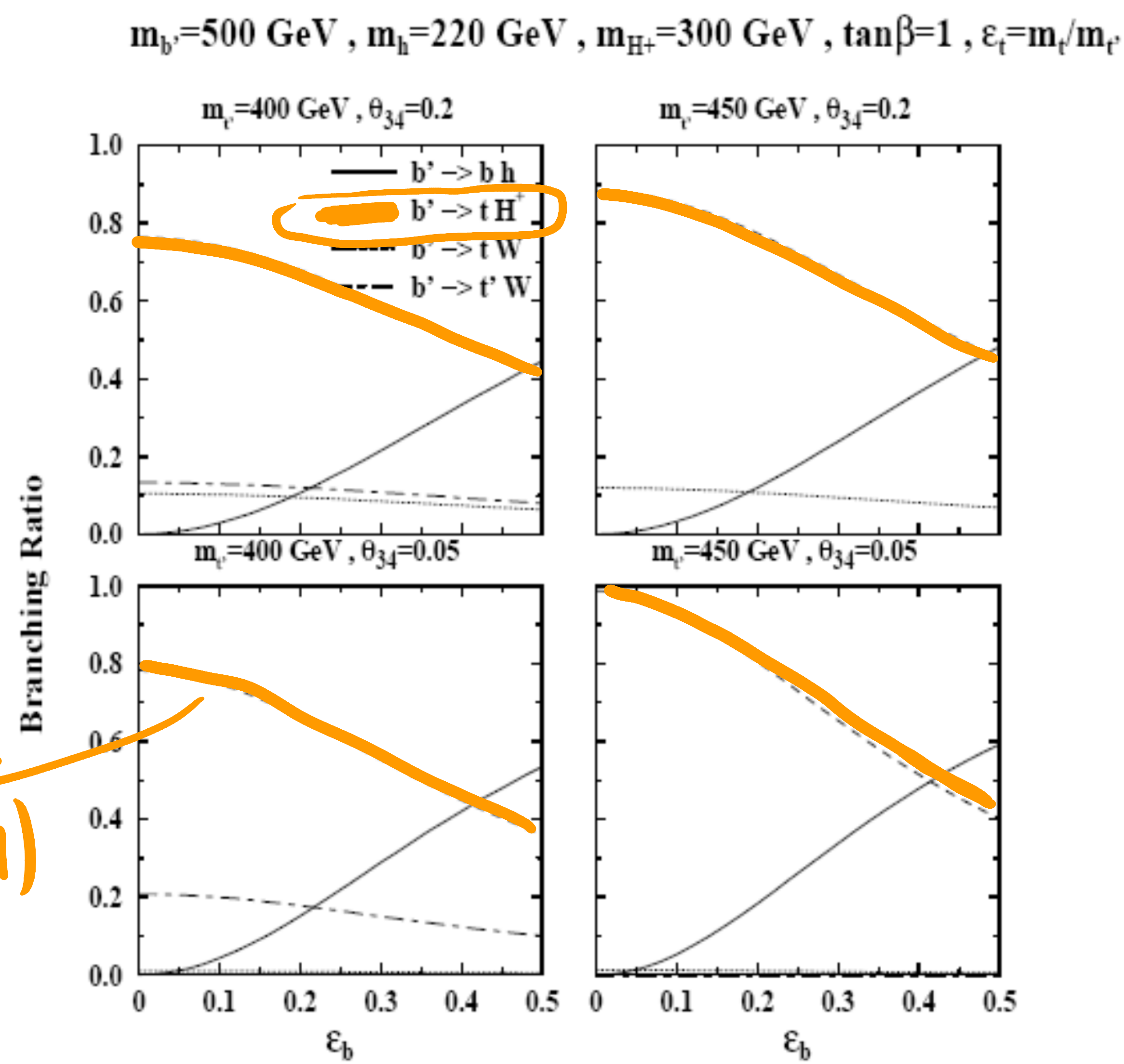
t’ decays:

BR(t’→th) ≲ 1



b’ decay pattern

b’ decays:



BR(b'→tH+) ~ O(1)

Bar-Shalom @ BNL

4G2HDM: significantly alleviates EWPC on 4G

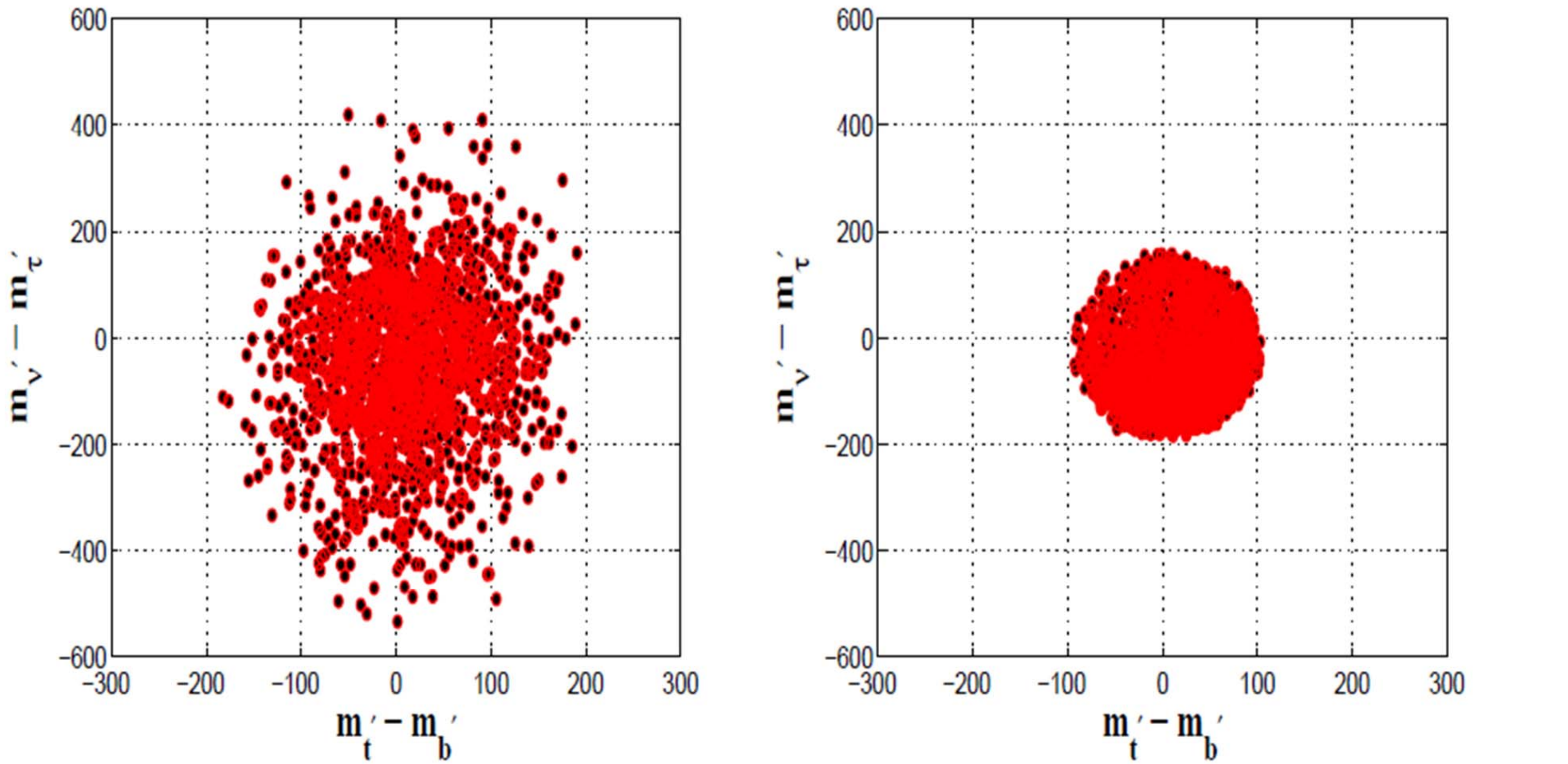


FIG. 13: *Allowed regions in the* $\Delta m_{q'} - \Delta m_{\ell'}$ *plane within the* 95%*CL contour in the S-T plane, for the 4G2HDMs (left) and for the SM4 (right). The data points are varied as in Fig. 11.*

Top pair FB asymmetry from strongly coupled 4G quarks

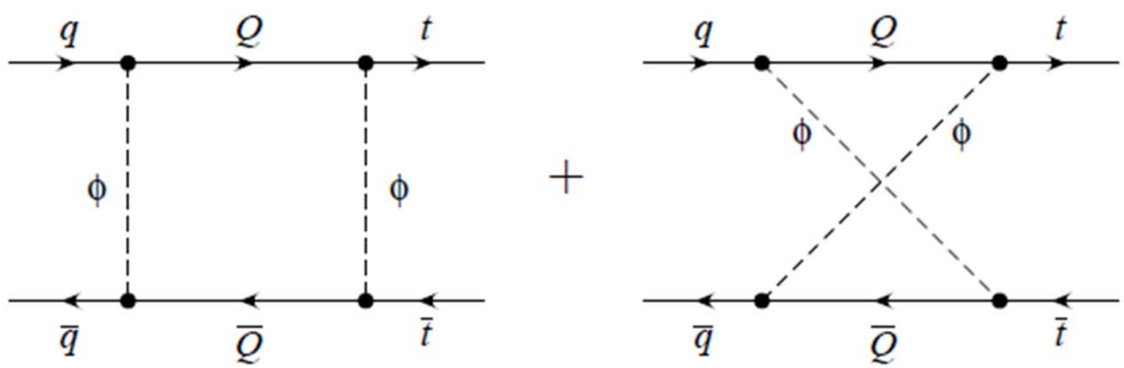
- [Davoudiasl, McElmurry and AS arXiv:1108.1173]
- CDF has been reporting ~2 sigma deviation from SM in the integrated asymm. And in the high invariant top pair mass about 3.5 sigma deviation from SM:
- 0.158 +- 0.075 vs 0.058+-0.009
- For high (>450 GeV), 0.475+-0.114 vs 0.088+-0.013
- NEW (EPS'11) D0 finds similar integrated asymmetery (a bit more significant than CDF); in the high mass region they see some increase but not so pronounced

We consider a simple toy 4G model with [FC] scalars

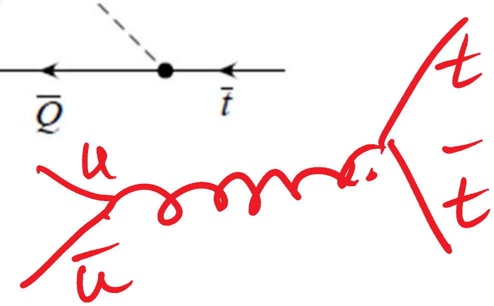
$$\mathcal{L} \supset \lambda_{ut'}\phi^0\bar{u}t' + \lambda_{ub'}\phi^+\bar{u}b' + \lambda_{dt'}\phi^-\bar{d}t'$$

$$+ \lambda_{db'}\phi^0\bar{d}b' + \lambda_{tt'}\phi^0\bar{t}t' + \lambda_{tb'}\phi^+\bar{t}b' + \text{H.C.},$$

NOTE $t' \to t\,\phi$ DOMINANT Not $t' \to bW$



ASYMMETRY from interfence with



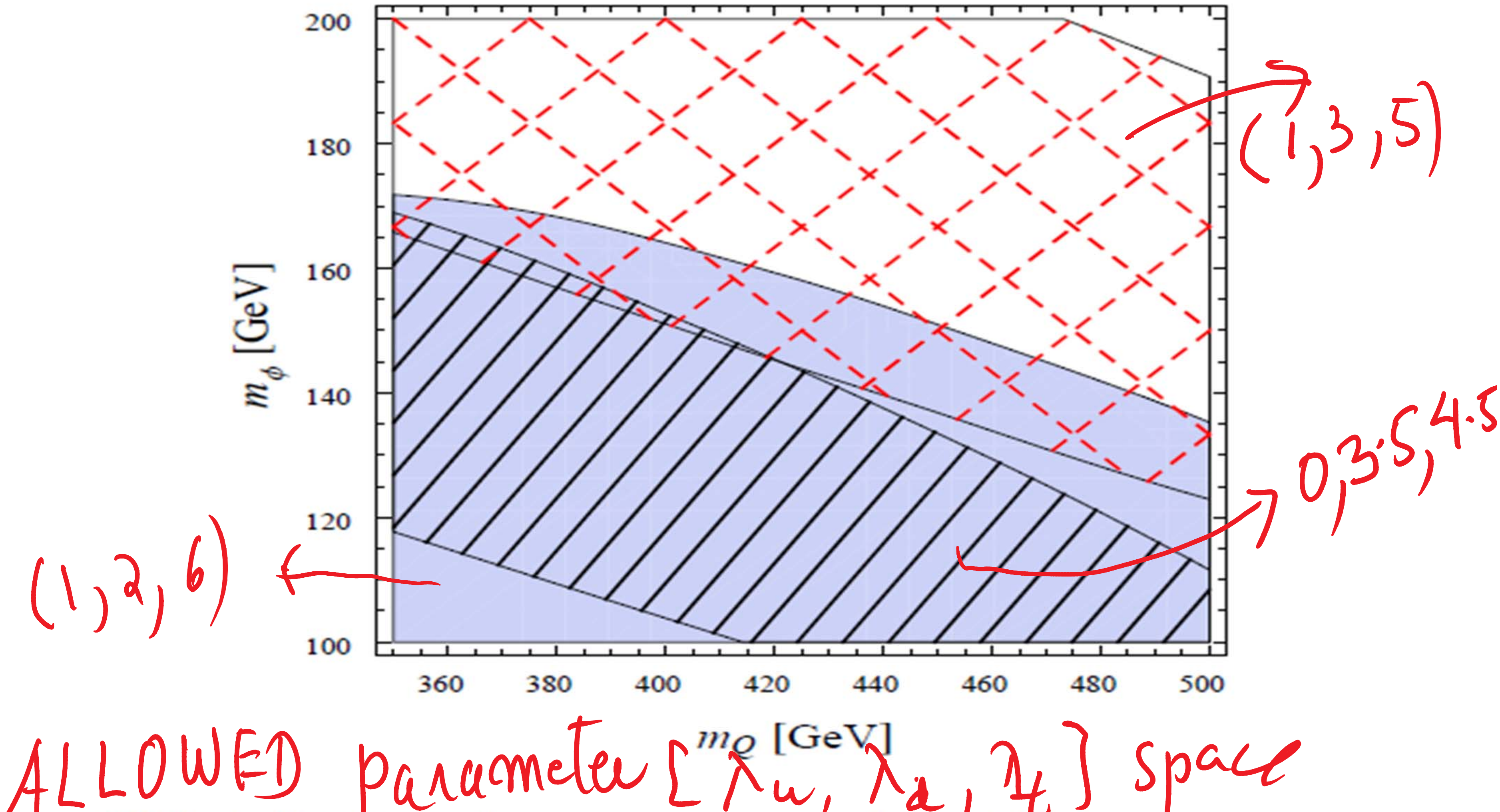


FIG. 3: Regions of parameter space that yield 2σ agreement with the CDF results [1], as well as agreement with the $t\bar{t}$ total cross section within 30%, for $(\lambda_u, \lambda_d, \lambda_t) = (1, 2, 6)$ (shaded), for $(\lambda_u, \lambda_d, \lambda_t) = (0, 3.5, 4.5)$ (hatched) and for $(\lambda_u, \lambda_d, \lambda_t) = (1, 3, 5)$ (cross-hatched).

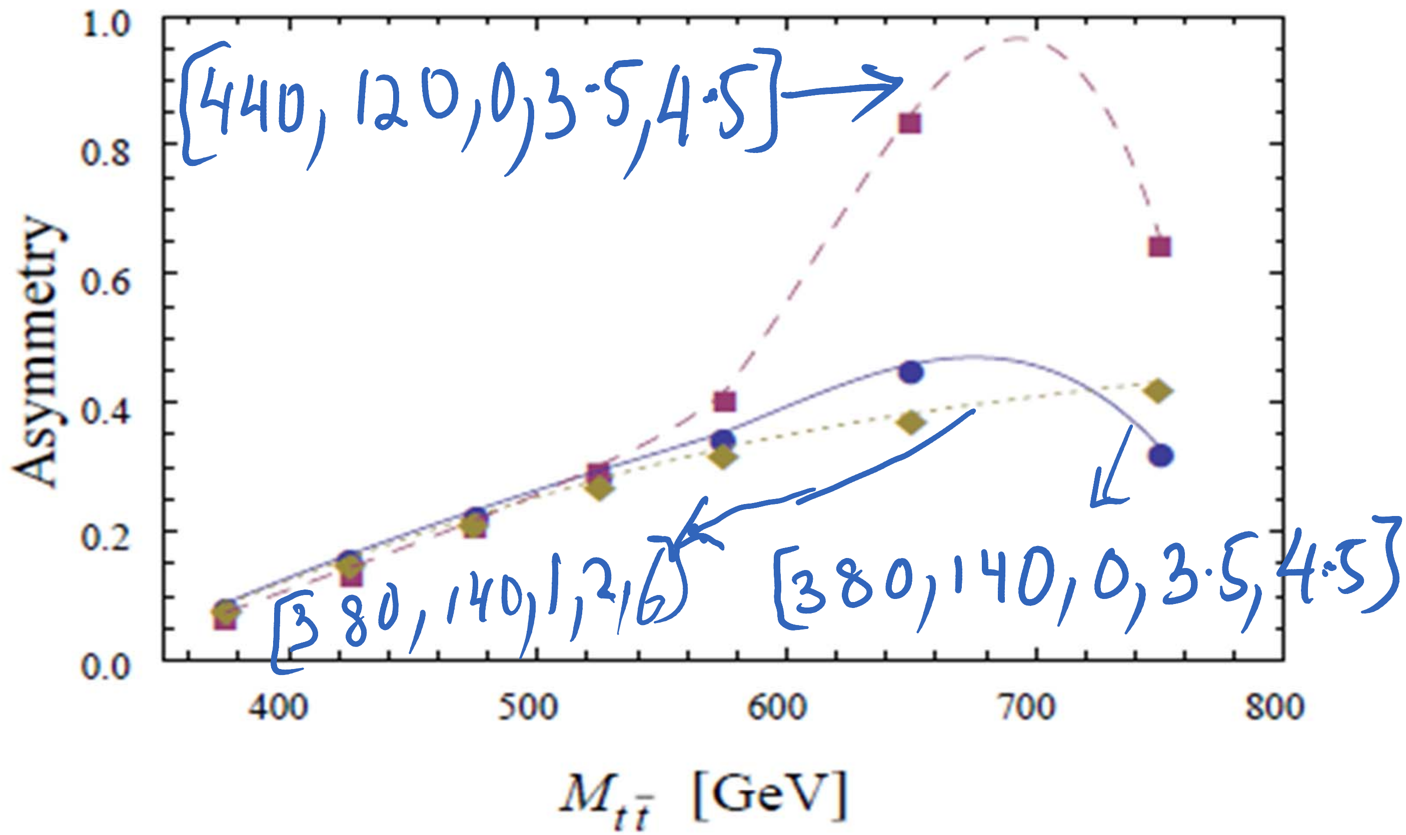


FIG. 4: Asymmetry as a function of the invariant mass $M_{t\bar{t}}$ for $(m_Q, m_\phi, \lambda_u, \lambda_d, \lambda_t) = (380\,\text{GeV}, 140\,\text{GeV}, 0, 3.5, 4.5)$ (solid), $(380\,\text{GeV}, 140\,\text{GeV}, 1, 2, 6)$ (dashed), and $(440\,\text{GeV}, 120\,\text{GeV}, 0, 3.5, 4.5)$ (dotted).

DIAGNOSTIC Power of ASYM VS MASS

Summary

- 4G extensions of SM3 should be seriously considered
- It is highly unlikely to be just SM4
- Heavier 4G quarks can trigger DEWSB and consequently can be a simpler solution to hierarchy problem w/o the need for multitude of new parameters
- It facilitates significantly baryogenesis over SM3
- Opens up new avenues for DM
- Unlike almost all BSM models, 4G extension need not cause flavor or CP problem
- (Sin2beta)tree less than SM3 and (sin2beta)penguin less than both, may be hints of 4G
- AFB (tt) may be a hint of a strongly coupled 4G
- Experimental searches for t’ -> t h, b’->t h+- should be given a high priority [in addition to conventional modes]

XTRAS

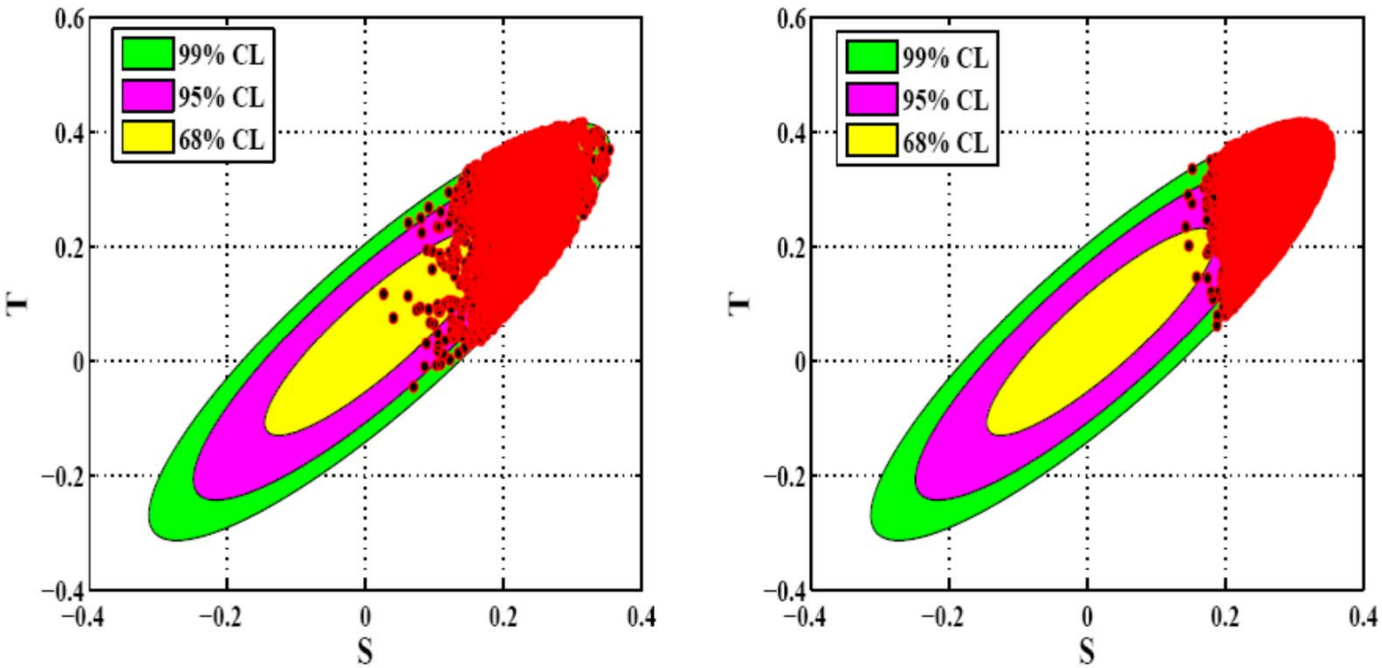

Brookhaven Forum 2011
A First Glimpse of the Tera Scale

Random scans of free-parameters:

$$0 \le \alpha \le 2\pi \quad \tan\beta \le 30 \quad \theta_{34} \le 0.3$$

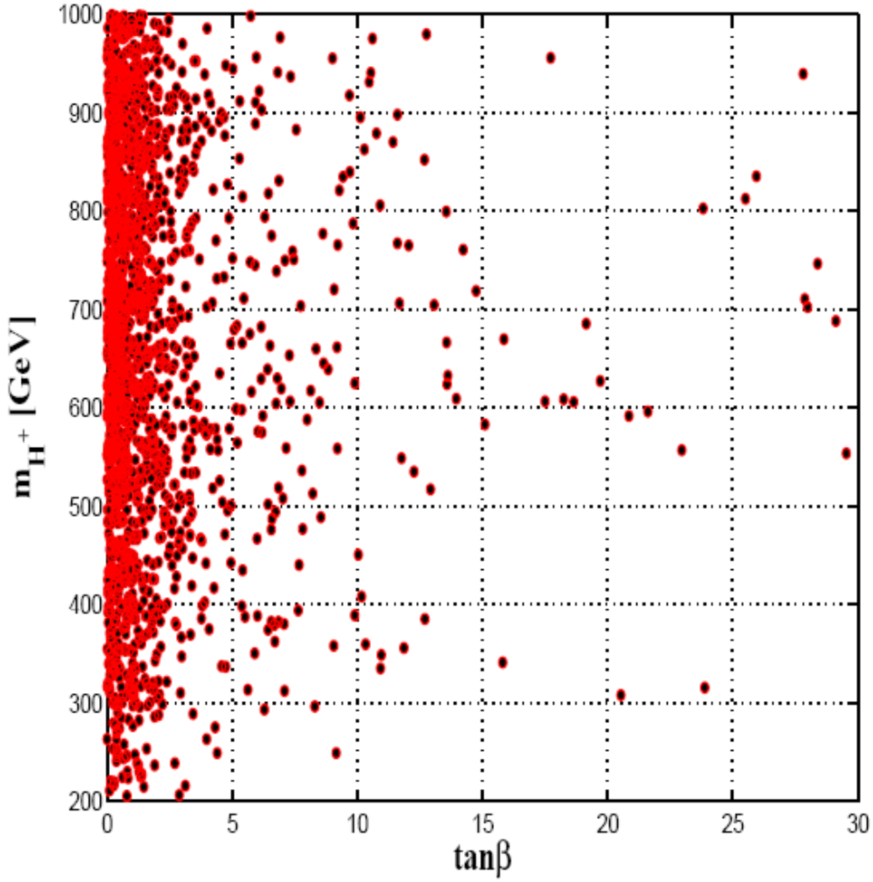
$$100\ \text{GeV} \le m_h \le 1\ \text{TeV} \quad 100\ \text{GeV} \le m_A \le 1\ \text{TeV} \quad m_h \le m_H \le 1.5\ \text{TeV}$$

$$400\ \text{GeV} \le m_{t'}, m_{b'} \le 600\ \text{GeV} \qquad 100\ \text{GeV} \le m_{\nu'}, m_{\tau'} \le 1.2\ \text{TeV}$$



Order of magnitude more points within 68%CL contour in 4G2HDMs

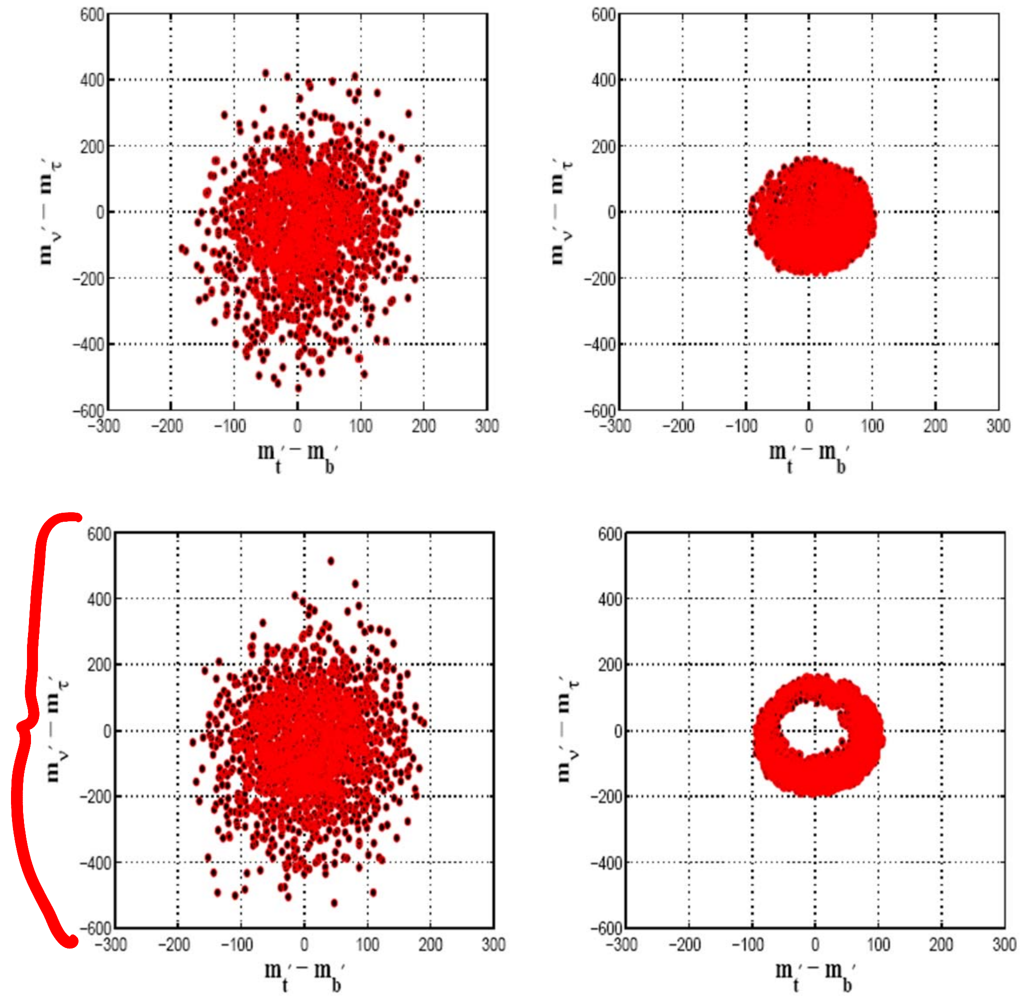
S-T & the M_{H+} - tanβ plane



Favors: low tanβ ~ O(few)

S-T & quark/lepton mass splitting:

"3+1" case ($\theta_{34}=0$)



Δm_q, $\Delta m_l \to 0$ allowed also for $\theta_{34} \sim O(0.1)$

$\Rightarrow$ **Isospin breaking required (to compensate for effects of extra fermions and Higgs particles) provided by Higgs sector; more room for a light Higgs …**

Special/interesting points that survive combined constraints from EWPD & flavor physics

e.g., for tanβ=1:

	$\tan\beta = 1,\ \epsilon_t = m_t/m_{t'}$										
Point #	Model	$m_{t'}$	$m_{b'}$	$m_{\nu'}$	$m_{\tau'}$	m_h	m_A	m_H	m_{H^+}	$\sin\theta_{34}$	α
1	4G2HDM-I,II,III	542	358	144	462	260	296	1357	654	0.153	0.74π
2	4G2HDM-I	511	353	426	455	261	296	1075	428	0.09	0.705π
3	4G2HDM-I,II,III	548	372	413	434	199	272	1088	707	0.063	1.88π
4	4G2HDM-I	367	525	829	993	347	491	1227	681	0.011	1.82π
5	4G2HDM-I	356	537	121	310	675	238	1306	542	0.056	0.97π
6	4G2HDM-I	440	456	619	634	169	332	405	479	0.082	0.82π
7[a]	4G2HDM-I,II,III	526	534	403	420	152	875	550	461	0.007	0.87π
8	4G2HDM-I	416	510	370	536	216	153	1032	333	0.14	0.96π
9	4G2HDM-II,III	520	369	738	744	102	882	238	781	0.129	1.28π
10	4G2HDM-I	500	450	302	414	220	793	1001	750	0.05	$\pi/2$
11	4G2HDM-I	500	450	424	410	120	597	1479	750	0.2	$\pi/2$
12	4G2HDM-I	500	450	147	127	350	716	506	400	0.05	$\pi/2$
13[b])	4G2HDM-I	450	500	225	235	220	782	303	300	0.2	$\pi/2$

$BR(b' \to t'W) \sim 1$ (point 5)

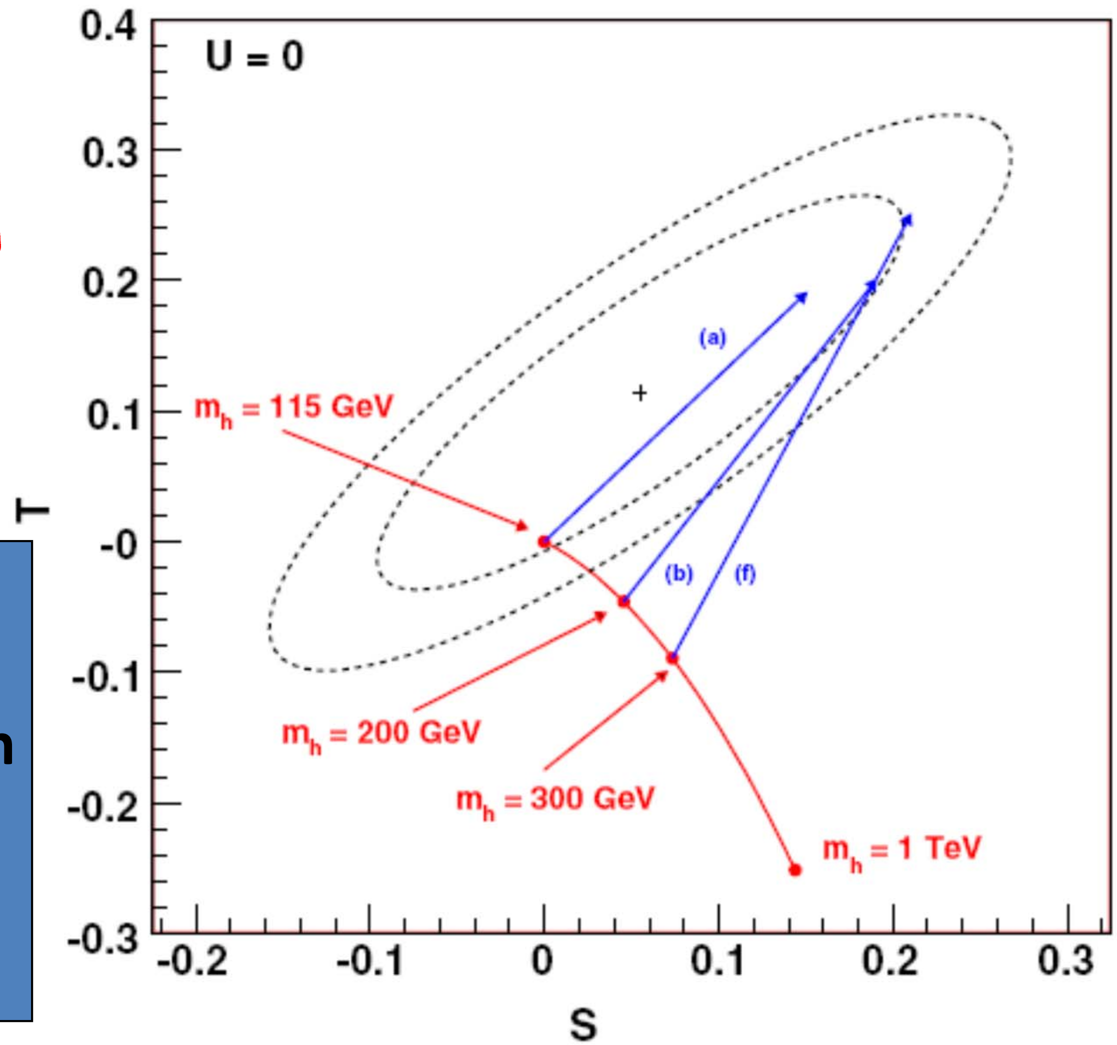
$BR(t' \to b'W) \sim 1$ (point 9)

$\mathrm{BR}(t' \to th) \sim \mathcal{O}(1)$ (points 10, 11)

$\mathrm{BR}(t' \to bH^+) \sim \mathcal{O}(1)$ (point 12)

$\mathrm{BR}(b' \to tH^+) \sim \mathcal{O}(1)$ (point 13)

Kribs, Plehn, Spannowsky & Tait, PRD'07



C also: Novikov, Rozanov, Vysotsky, 0904.4570 & earlier works

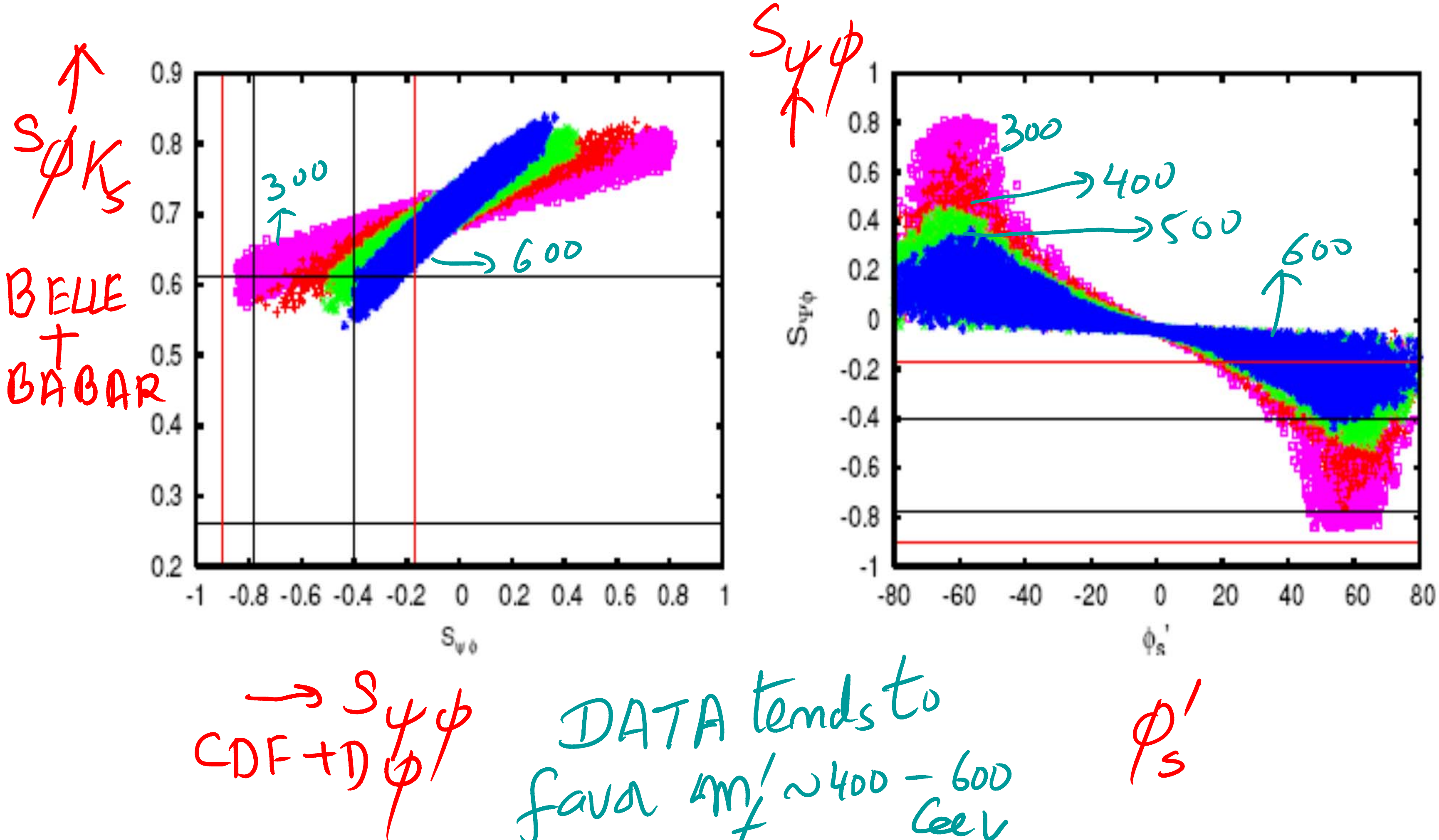
LEP EW Constraints on $m_{t'}$, $m_{b'}$, m_H

4^{th} family is not inconsistent with LEP EWPC
See also M. Chanowitz, arXiv:0903.3570; 1007.0043; Erler abd Langacker 1003.3211

TABLE I. Examples of the total contributions to ΔS and ΔT from a fourth generation. The lepton masses are fixed to $m_{\nu_4} = 100$ GeV and $m_{\ell_4} = 155$ GeV, giving $\Delta S_{\nu\ell} = 0.00$ and $\Delta T_{\nu\ell} = 0.05$. The best fit to data is $(S, T) = (0.06, 0.11)$ [35]. The standard model is normalized to $(0, 0)$ for $m_t = 170.9$ GeV and $m_H = 115$ GeV. All points are within the 68% C.L. contour defined by the LEP EWWG [35].

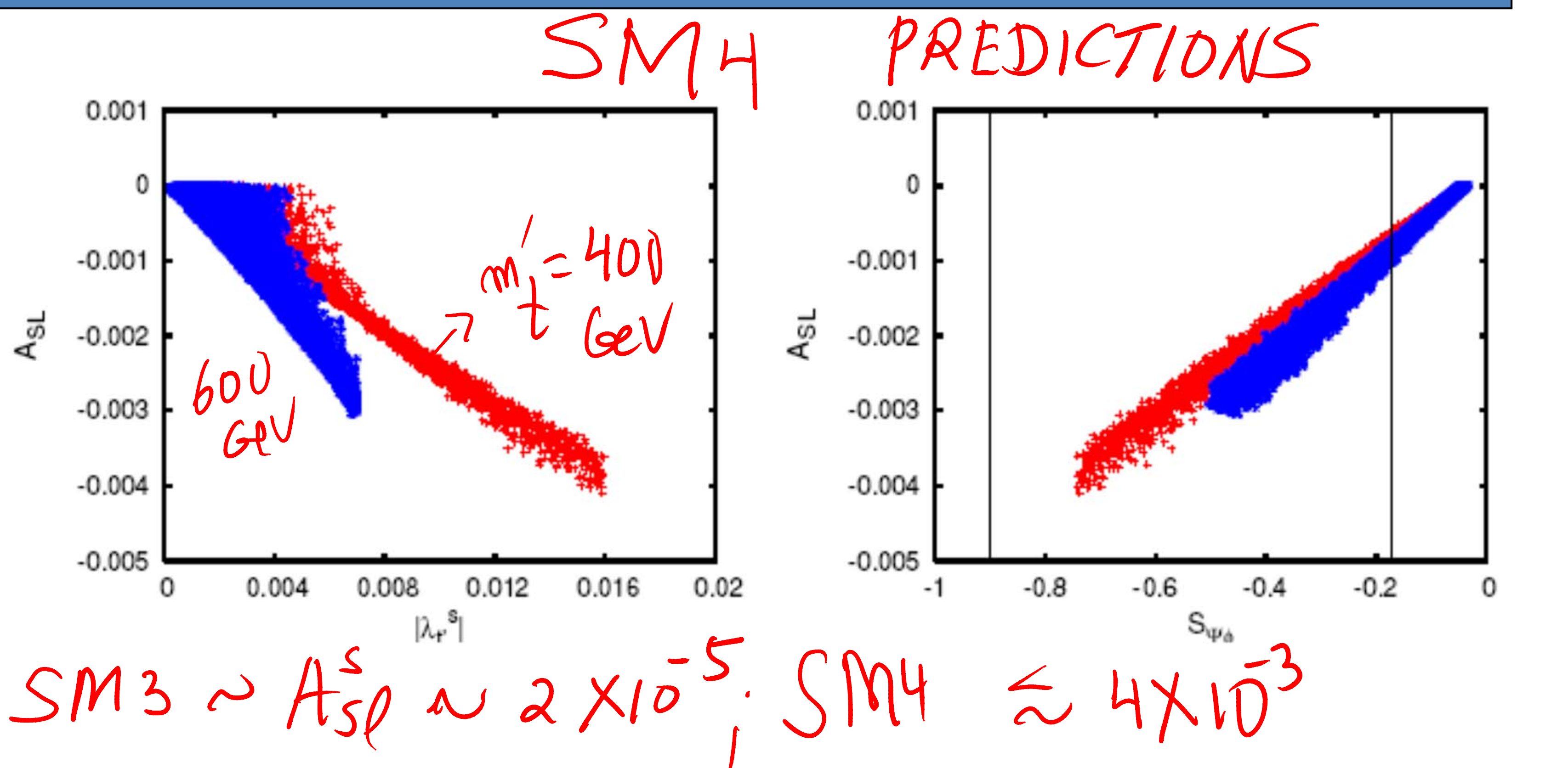
Parameter set	m_{u_4}	m_{d_4}	m_H	ΔS_{tot}	ΔT_{tot}
(a)	310	260	115	0.15	0.19
(b)	320	260	200	0.19	0.20
(c)	330	260	300	0.21	0.22
(d)	400	350	115	0.15	0.19
(e)	400	340	200	0.19	0.20
(f)	400	325	300	0.21	0.25

A. S et al 0807.1971; 1002.0595 {Note constraints from S,T, b -> s gamma, K-> pi nu nu ….are all included}



DATA tends to favor $m_{t'} \sim 400 - 600$ GeV

Semi-leptonic asymmetry (Bs-> Xs l nu) PREDICTION given in arXiv: 1002.0595 [Used here Delta_Gamma_s=0.096 +-.039 from Lenz and Nierste'07]



Recently D0 (V M Abazov et al, arXiv: 1005.2757) reported a_sl^s = -0.0146 +- 0.0075)

$\lvert V_{cb}\rvert_{\rm excl} = (39.0 \pm 1.2)10^{-3}$	$\eta_1 = 1.51 \pm 0.24$ [18]
$\lvert V_{cb}\rvert_{\rm incl} = (41.31 \pm 0.76)10^{-3}$	$\eta_2 = 0.5765 \pm 0.0065$ [19]
$\lvert V_{cb}\rvert_{\rm tot} = (40.43 \pm 0.86)10^{-3}$	$\eta_3 = 0.494 \pm 0.046$ [20, 21]
$\lvert V_{ub}\rvert_{\rm excl} = (29.7 \pm 3.1)10^{-4}$	$\eta_B = 0.551 \pm 0.007$ [22]
$\lvert V_{ub}\rvert_{\rm incl} = (40.1 \pm 2.7 \pm 4.0)10^{-4}$	$\xi = 1.23 \pm 0.04$ [23, 24]
$\lvert V_{ub}\rvert_{\rm tot} = (32.7 \pm 4.7)10^{-4}$	$\lambda = 0.2255 \pm 0.0007$
$\Delta m_{B_d} = (0.507 \pm 0.005)\ {\rm ps}^{-1}$	$\alpha = (89.5 \pm 4.3)^{\rm o}$
$\Delta m_{B_s} = (17.77 \pm 0.12)\ {\rm ps}^{-1}$	$\kappa_\varepsilon = 0.94 \pm 0.02$ [25–27]
$S_{\psi K_S} = 0.668 \pm 0.023$ [28]	$\gamma = (74 \pm 11)^{\rm o}$
$m_c(m_c) = (1.268 \pm 0.009)$ GeV	$\widehat{B}_K = 0.740 \pm 0.025$
$m_{t,pole} = (172.4 \pm 1.2)$ GeV	$f_K = (155.8 \pm 1.7)$ MeV
$f_{B_s}\sqrt{\widehat{B}_s} = (276 \pm 19)$ MeV [23]	$\varepsilon_K = (2.229 \pm 0.012)10^{-3}$
$f_B = (208 \pm 8)$ MeV [23, 24] [a]	$\widehat{B}_d = 1.26 \pm 0.10$ [23, 24]
$\mathcal{B}_{B\to\tau\nu} = (1.68 \pm 0.31) \times 10^{-4}$ [30–32]	

[a] Our value of f_B reflects the change in the overall scale (r_1) recently adopted by the Fermilab/MILC and HPQCD collaborations [29]

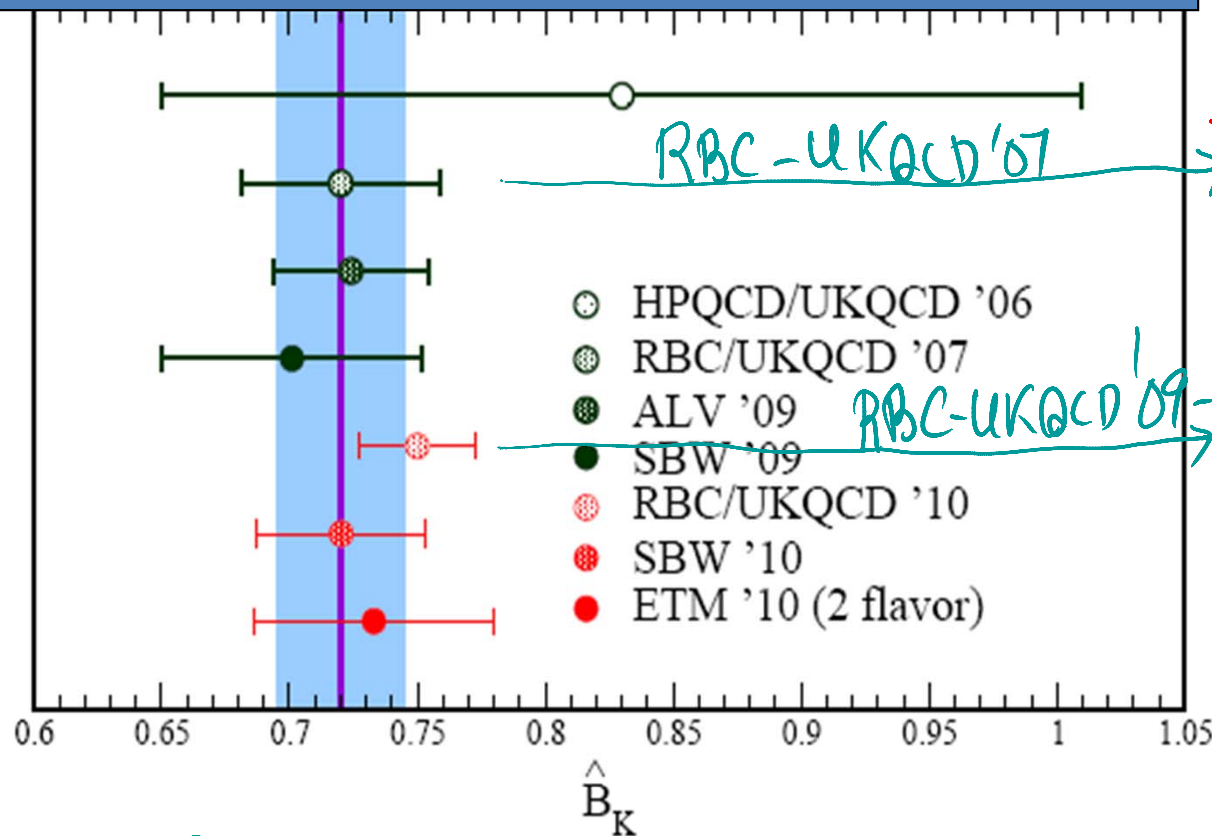
14.4% ←

→ As in 2008 we ASSERT again V_{ub} cannot be used!

B_K

Jack LAIHO @ LATTICE '10

Several diff, collabs; diff discretizations, systematics…



RBC-UKQCD '07 → 0.720 ± .013 ± .037 → USED by L&S '08

RBC-UKQCD '09-'10 → 0.750 ± .007 ± .026

Total ERROR ~3.6%

USE 0.740 ± 0.025

CKMFITTER 2010 USE
δStat ~ 5.9%; δSyst ~ 9.3% !!

NANDI + AS '10

TABLE I. Inputs that we use in order to constrain the SM4 parameter space, when not explicitly stated, we take the inputs from Particle Data Group [7]; for the lattice inputs see also [6].

$B_K = 0.740 \pm 0.025$ [35–37]	$R_{bb} = 0.216 \pm 0.001$
$f_{bd}\sqrt{B_{bd}} = 0.224 \pm 0.015$ GeV [38,39]	$\lvert V_{ub}\rvert = (32.8 \pm 2.6) \times 10^{-4}$[a]
$\xi = 1.232 \pm 0.042$ [38,39]	$\lvert V_{cb}\rvert = (40.86 \pm 1.0) \times 10^{-3}$
$\eta_c = 1.51 \pm 0.24$ [40]	$\gamma = (73.0 \pm 13.0)^\circ$
$\eta_t = 0.5765 \pm 0.0065$ [41]	$\mathcal{BR}(B \to X_s\gamma) = (3.55 \pm 0.25) \times 10^{-4}$
$\eta_{ct} = 0.494 \pm 0.046$ [42]	$\mathcal{BR}(B \to X_s\ell^+\ell^-) = (0.44 \pm 0.12) \times 10^{-6}$
$\Delta M_s = (17.77 \pm 0.12)$ ps^{-1}	$\mathcal{BR}(K^+ \to \pi^+\nu\nu) = (0.147^{+0.130}_{-0.089}) \times 10^{-9}$
$\Delta M_d = (0.507 \pm 0.005)$ ps^{-1}	$\mathcal{BR}(B \to X_c\ell\nu) = (10.61 \pm 0.17) \times 10^{-2}$
$\lvert\epsilon_k\rvert \times 10^3 = 2.32 \pm 0.007$	$T_4 = 0.11 \pm 0.14$
$\kappa_\epsilon = 0.94 \pm 0.02$ [43][b]	$m_t(m_t) = (163.5 \pm 1.7)$ GeV

[a] It is the weighted average of $V_{ub}^{\rm inl} = (40.1 \pm 2.7 \pm 4.0) \times 10^{-4}$ and $V_{ub}^{\rm exl} = (29.7 \pm 3.1) \times 10^{-4}$. In our numerical work to follow, we increase the error on $\lvert V_{ub}\rvert$ by 50% and take the total error to be around 12% because of the appreciable disagreement between the two determinations.
[b] We tacitly assume that κ_ϵ in SM4 is approximately the same as in SM3.