S. Stone

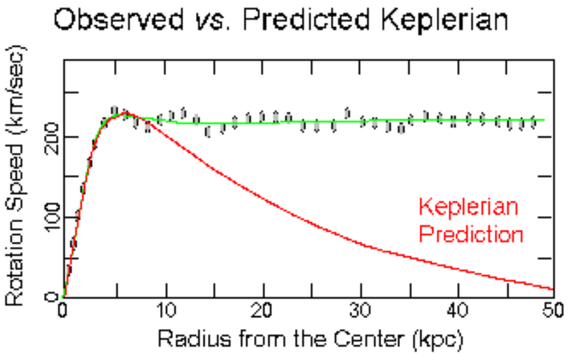
SYRACUSE UNIVERSITY FOUNDED AD 1870

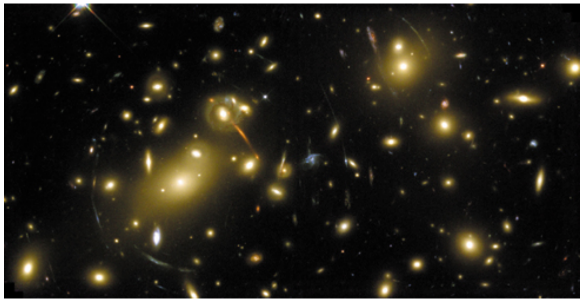
New Physics from Flavour

ICHEP2012
Melbourne

Reasons for Physics Beyond the Standard Model

- Dark Matter





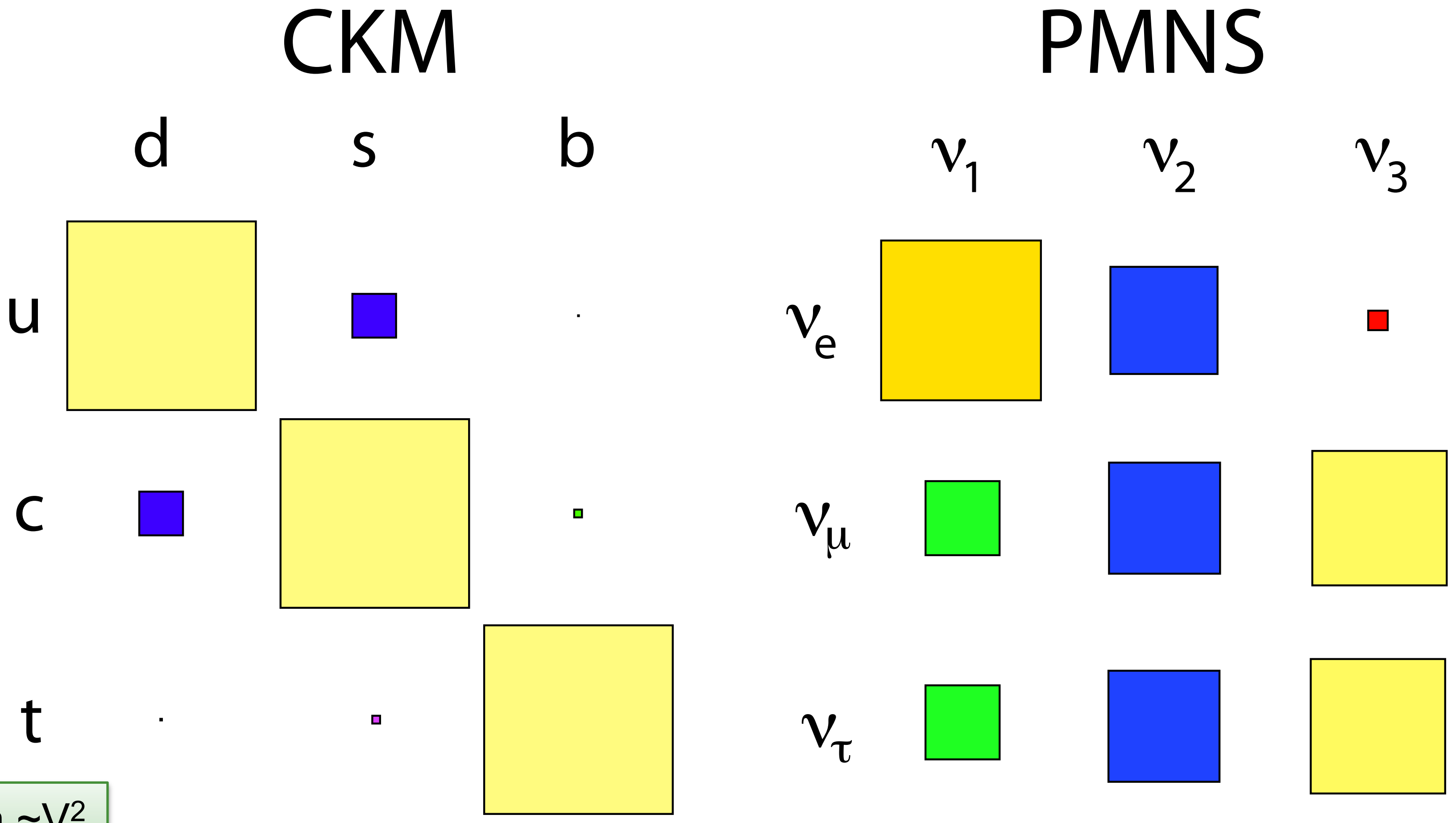
Gravitational lensing

- Dark Energy: Cosmological constant
- Hierarchy Problem: Divergent quantum corrections to go from Electroweak scale ~100 GeV to Planck scale of Energy ~10^{19} GeV without "fine tuning" quantum corrections
- *All of the above may only be related to Gravity*

Reasons for NP

- Flavor problem: Why 3 replications of quarks & leptons?
- Baryogenesis: The amount of CP Violation observed thus far in the quark sector is too small: $(n_B-n_{\bar{B}})/n_\gamma =\sim 10^{-20}$ but $\sim 6\times10^{-10}$ is needed. Thus New Physics must exist to generate needed CP Violation
- To explain the values of CKM couplings, V_{ij}, (both neutrino & quark)
- To explain the masses of fundamental objects. Are they related to the V_{ij}'s?

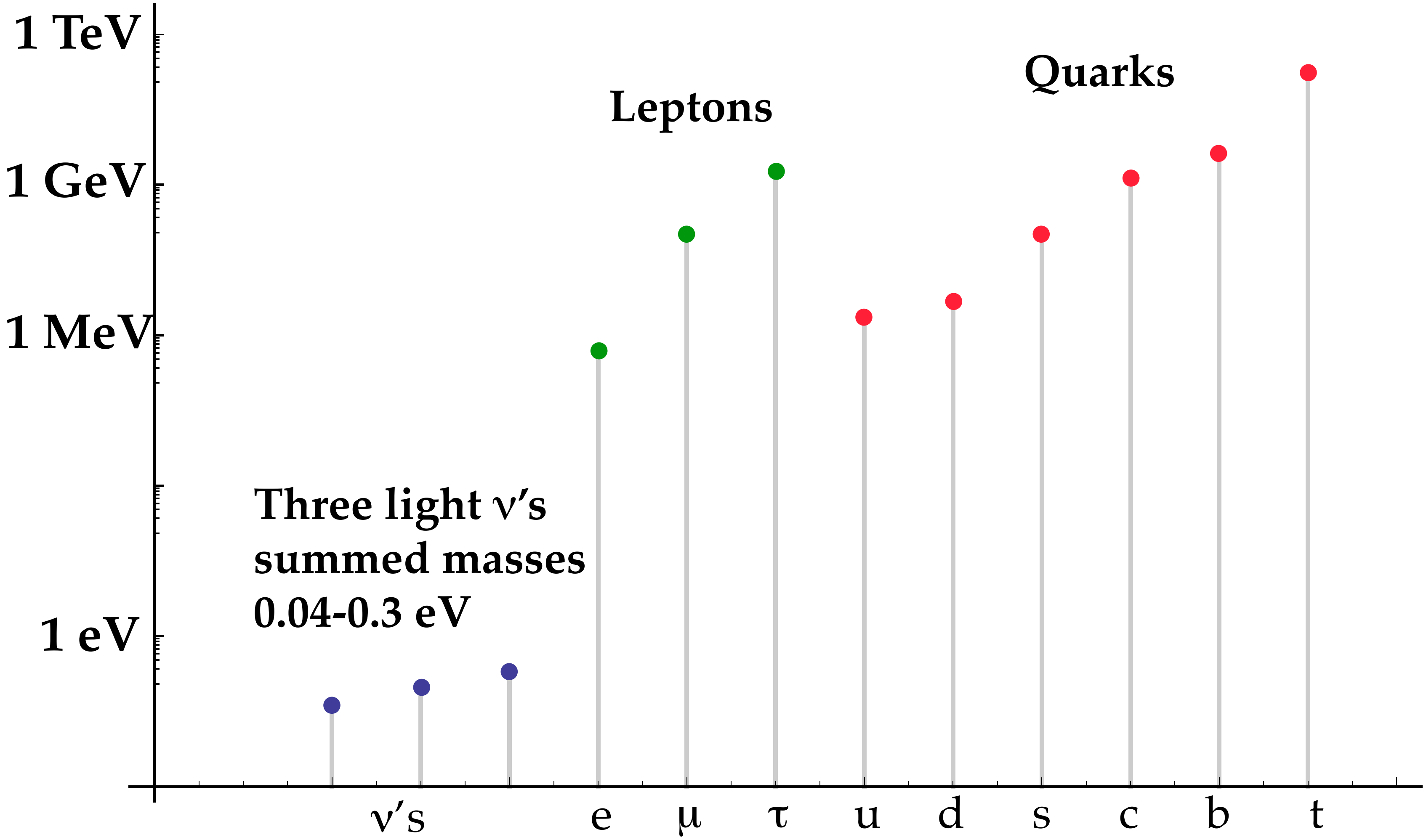
CKM vs. PMNS



Area ~V^2

Why these values? Are the two related? Are they related to masses?

Masses



Three light ν's
summed masses
0.04-0.3 eV

12 orders of magnitude differences not explained; t quark as heavy as Tungsten

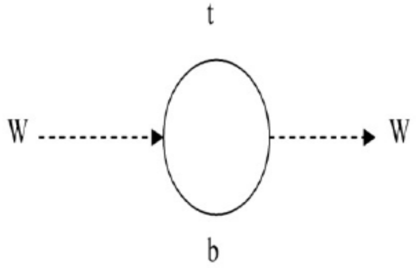
Theorists task

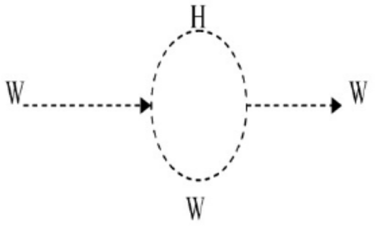
- A given theoretical model must explain all the data

Model must thread through all experimental constraints (12 axe handles). One measurement can, in principle, defeat the theorist, but we seek a consistent pattern.

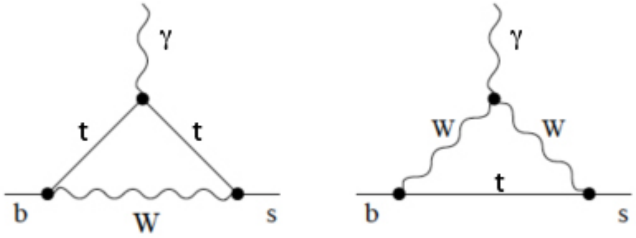
Flavor Physics as a NP discovery tool

- While measurements of CKM parameters & masses are fun, the main purpose of Flavor Physics is to find and/or define the properties of physics beyond the SM
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass
  - M_w changes due to m_t $\frac{dM_W}{dm_t} \alpha \frac{m_t}{M_w}$
  - M_w changes due to m_H $\frac{dM_W}{dm_H} \alpha - \frac{dm_H}{M_H}$



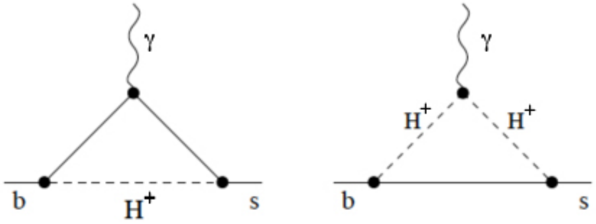


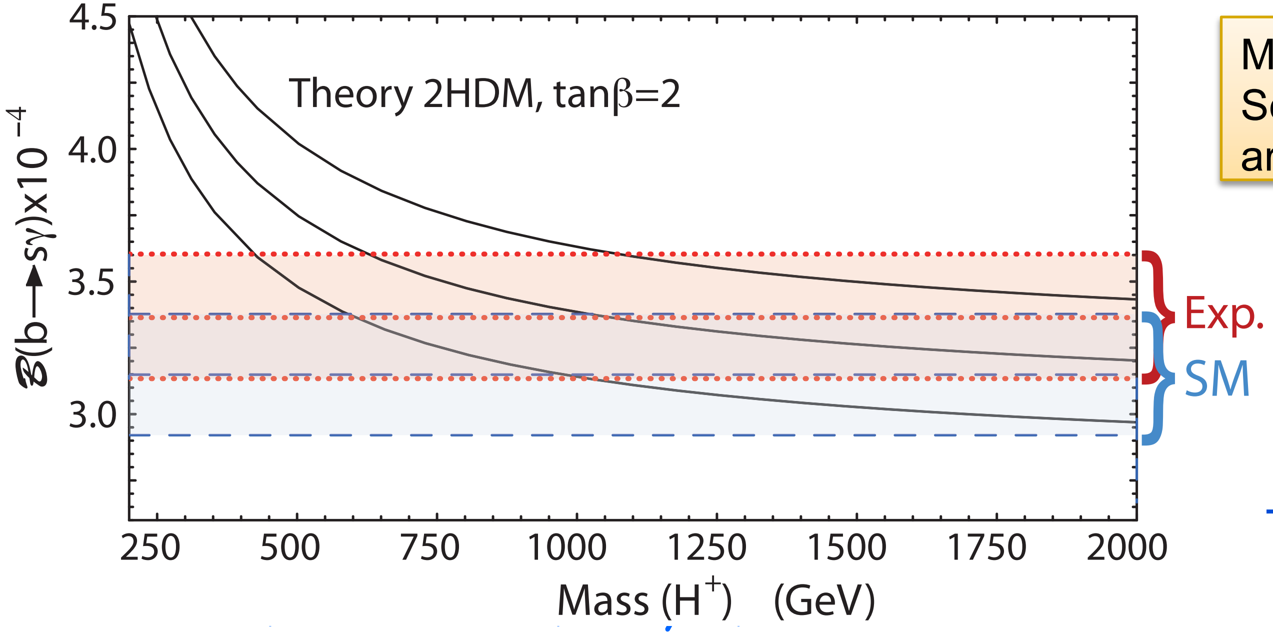
Ex. of Strong Constraints on NP



- Inclusive b→sγ, (Eγ > 1.6 GeV)
  - Measured (3.37±0.23)x10^{-4}
  - Theory (3.15±0.23)x10^{-4} (NNLL) Misiak arXiv:1010.4896
  - Ratio = 1.07±0.10, Limits most NP models
  - Example 2HDM
    m(H^+) > 385 GeV

New BaBar
(3.31±0.35)x10^{-4}
See G. Eigen's talk

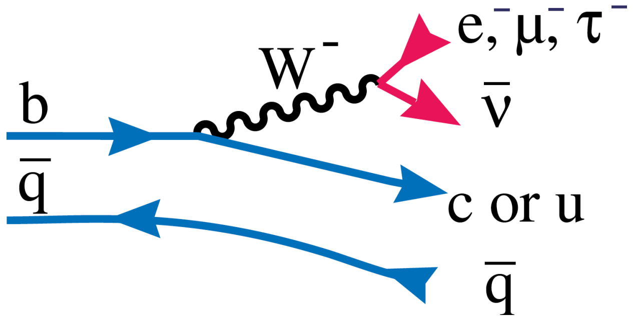




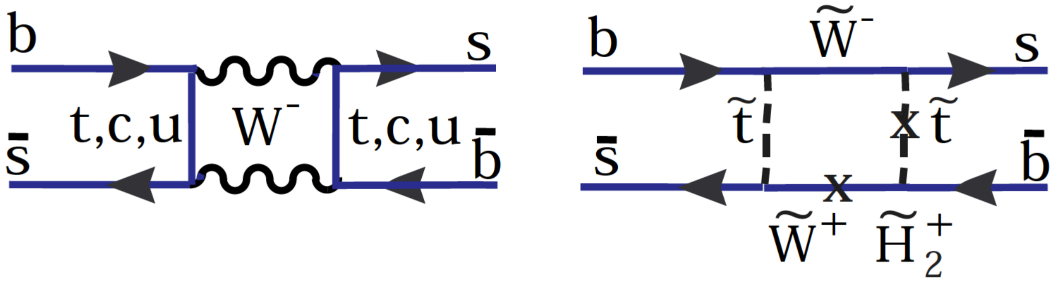
Misiak et. al hep-ph/0609232,
See also A. Buras et. al,
arXiv:1105.5146

Limits on New Physics

- It is oft said that we have not seen New Physics, yet what we observe is the sum of Standard Model + New Physics. How to set limits on NP?
- One hypothesis: assume that tree level diagrams are dominated by SM and loop diagrams could contain NP



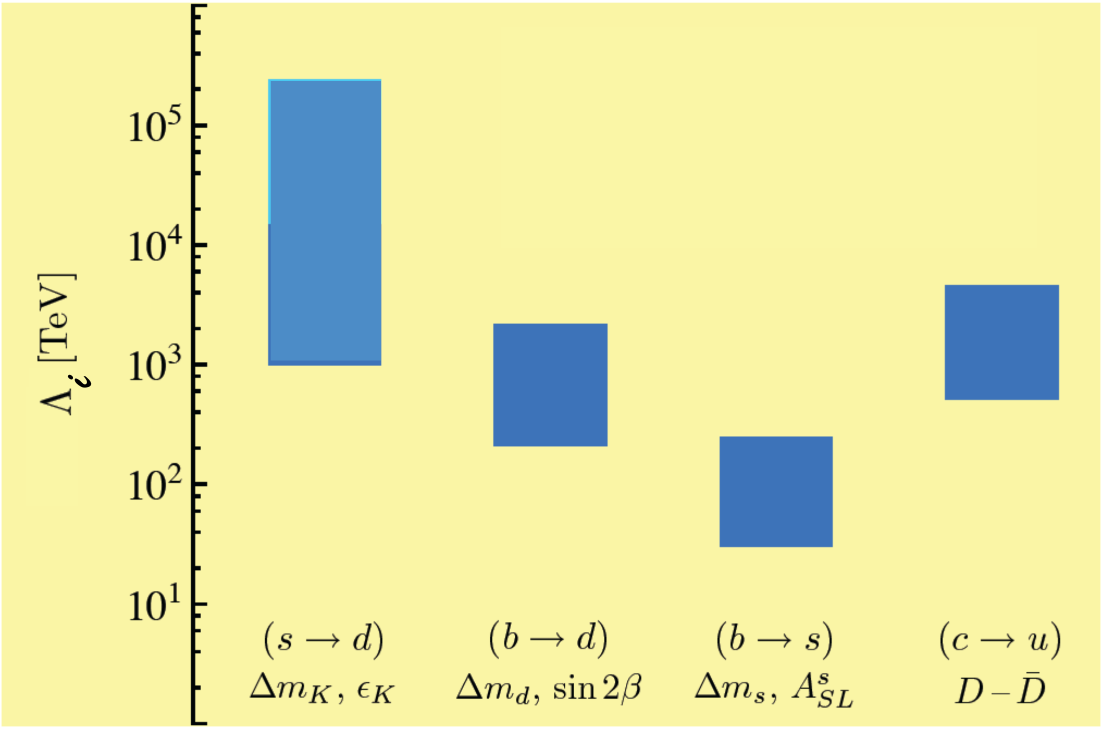
Tree diagram example



Loop diagram example

Flavor as a High Mass Probe

- Already excluded ranges from box diagrams
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i} O_i$, take c_i ~1



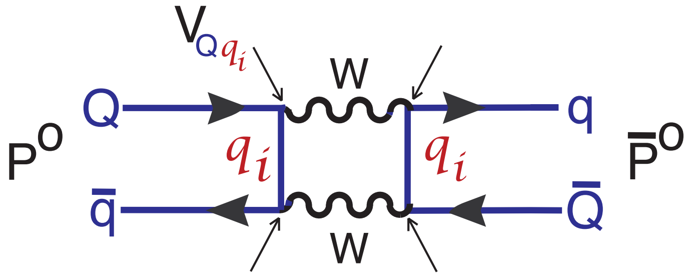
Ways out

1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

See: Isidori, Nir
& Perez arXiv:1002.0900;
Neubert EPS 2011 talk

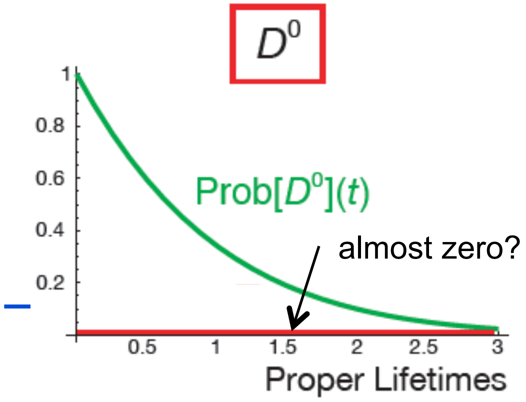
Neutral Meson Mixing

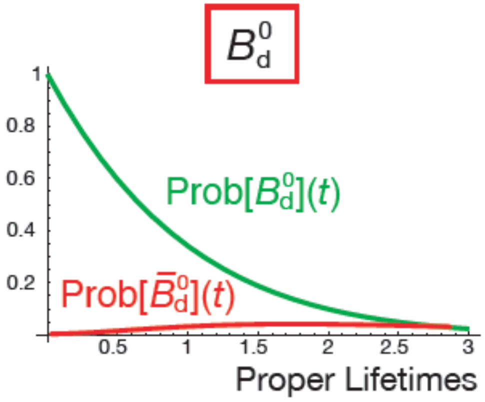
- Neutral mesons can transform into their anti-particles via 2nd order weak interactions

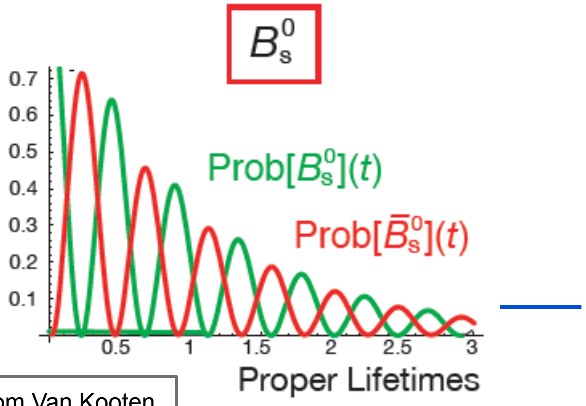


New particles possible in the loop

- Short distance transition rate depends on
  - mass of intermediate q_i, the heavier the larger, favors s & b since t is allowed
  - CKM elements V_{ij}



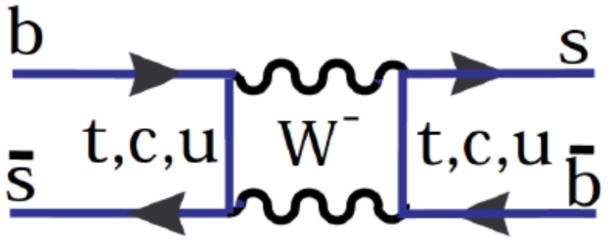




from Van Kooten

Mixing &CPV Definitions

- Mixing & Decay:



$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11}-\Gamma_{11}/2 & M_{12}-i\Gamma_{12}/2 \\ M_{12}^*-i\Gamma_{12}^*/2 & M_{22}-i\Gamma_{22}/2 \end{pmatrix}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix}$$

- $|M_L\rangle = p|M^o\rangle + q|\overline{M}^o\rangle$, $|M_H\rangle = p|M^o\rangle - q|\overline{M}^o\rangle$,
- $mB_s = (M_H+M_L)/2$, $\Delta M = M_H - M_L$,

  $1/\tau_{Bs} = \Gamma = (\Gamma_H+\Gamma_L)/2$, $\Delta\Gamma = \Gamma_L - \Gamma_H$,
- $y \equiv \Delta\Gamma/2\Gamma$

CPV Time Evolution

- Consider $a[f(t)] = \dfrac{\Gamma\left(\bar{M} \to f\right) - \Gamma\left(M \to f\right)}{\Gamma\left(\bar{M} \to f\right) + \Gamma\left(M \to f\right)}$ where *f* is a CP eigenstate
- Define $A_f \equiv A(M \to f), \bar{A}_f \equiv A(\bar{M} \to f), \quad \lambda_f = \dfrac{p}{q}\dfrac{\bar{A}_f}{A_f}$
- λ_f is a function of V_{ij} in SM

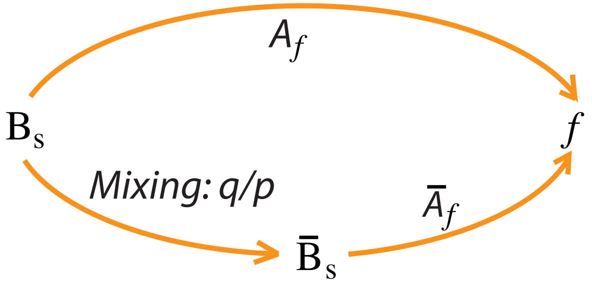
$$\Gamma\left(M \to f\right) = N_f \left|A_f\right|^2 e^{-\Gamma t}\left(\cosh\frac{\Delta\Gamma t}{2} - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} - \mathrm{Im}\,\lambda_f \sin\left(\Delta M t\right)\right)$$

$$\Gamma\left(\bar{M} \to f\right) = N_f \left|A_f\right|^2 e^{-\Gamma t}\left(\cosh\frac{\Delta\Gamma t}{2} - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} + \mathrm{Im}\,\lambda_f \sin\left(\Delta M t\right)\right)$$

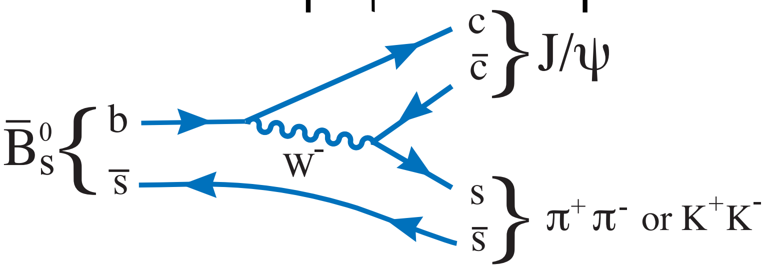
See Nierste
arXiv:0904.1869 [hep-ph]

CPV in $B_s \to J/\psi X$

- Interference between mixing & decay



- For f = $J/\psi\,\phi$ or $J/\psi\pi^+\pi^-$

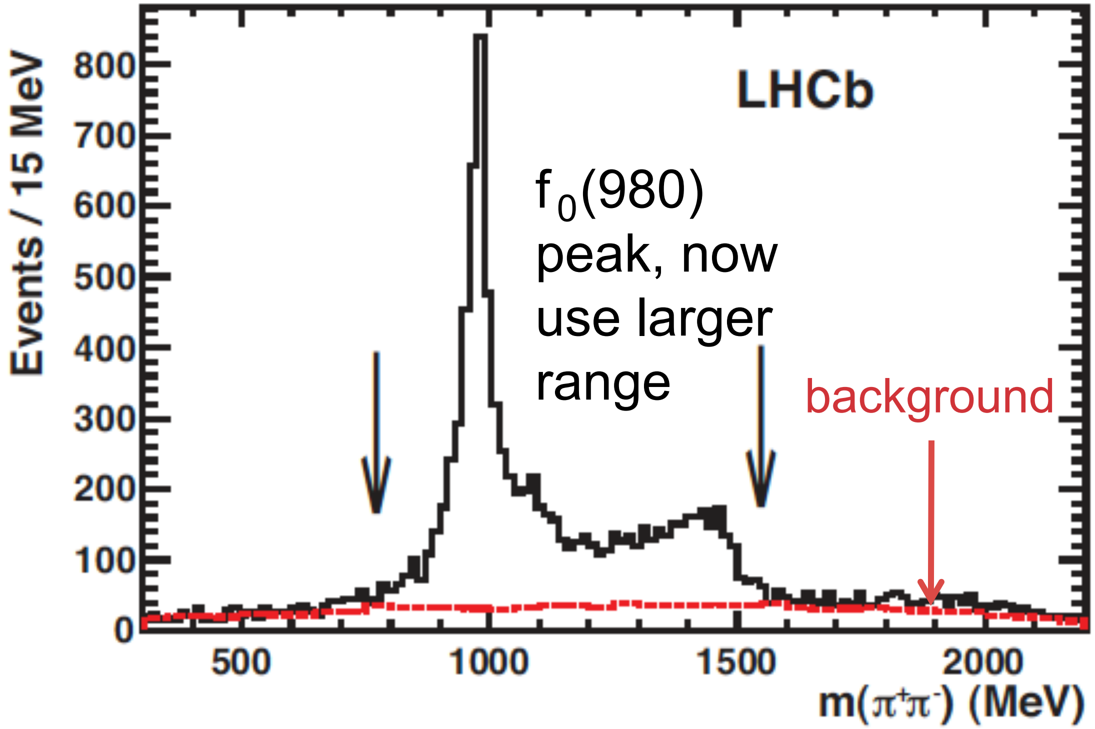


$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right) = -0.04 \text{ rad}$$

- Small CPV expected, good place for NP to appear
- $B_s \to J/\psi\phi$ is not a CP eigenstate, as it's a vector-vector final state, so must do an angular analysis to separate the CP+ and CP- components

ϕ_s from $J/\psi\pi^+\pi^-$

- Reconstructed $\pi^+\pi^-$ mass spectrum
- In region between arrows, measured to be >97.7% CP-odd @95% cl
- $a[f(t)] \sim 2\sin\phi_s \sin(\Delta M t)$
- $\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$ rad
- See || talk of G. Cowan

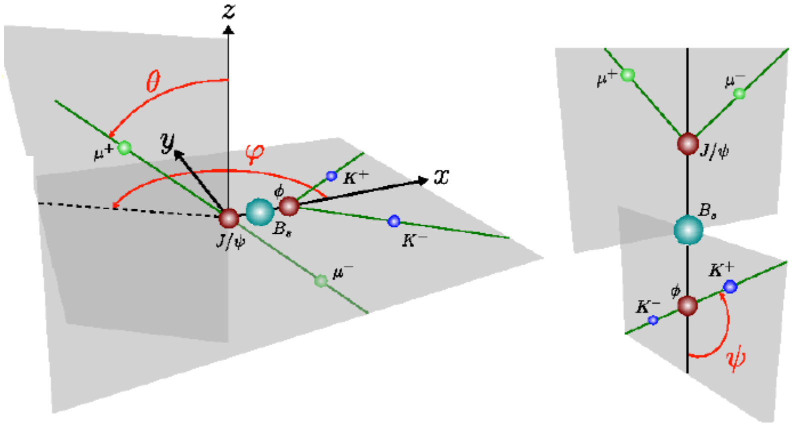


$f_0(980)$ peak, now use larger range

background

J/ψφ: Transversity

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4\Gamma}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)$$



k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

$\Big\}$ for S-wave under ϕ predicted by Stone & Zhang PRD 79, 074024 (2009)

Transversity II

$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\parallel(t)|^2 &= |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_\parallel^*(t)\, A_\perp(t)) &= |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. -\cos(\delta_\perp - \delta_{-}\|) \cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel) \cos(\Delta m t)\right], \\
\Re(A_0^*(t)\, A_\parallel(t)) &= |A_0||A_\parallel| e^{-\Gamma_s t} \cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. + \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_0^*(t)\, A_\perp(t)) &= |A_0||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. -\cos(\delta_\perp - \delta_0) \cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0) \cos(\Delta m t)\right], \\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right], \\
\Re(A_s^*(t) A_\parallel(t)) &= |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_s) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_s)\ \cos\phi_s \sin(\Delta m t)\right. \\
&\quad \left. + \cos(\delta_\parallel - \delta_s) \cos(\Delta m t)\right], \\
\Im(A_s^*(t) A_\perp(t)) &= |A_s||A_\perp| e^{-\Gamma_s t} \sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin\phi_s \sin(\Delta m t)\right], \\
\Re(A_s^*(t) A_0(t)) &= |A_s||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin(\delta_0 - \delta_s) \cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s) \cos(\Delta m t)\right].
\end{aligned}
$$

only term for $f=f_{cp}$

ϕ_s results from $J/\psi\phi$

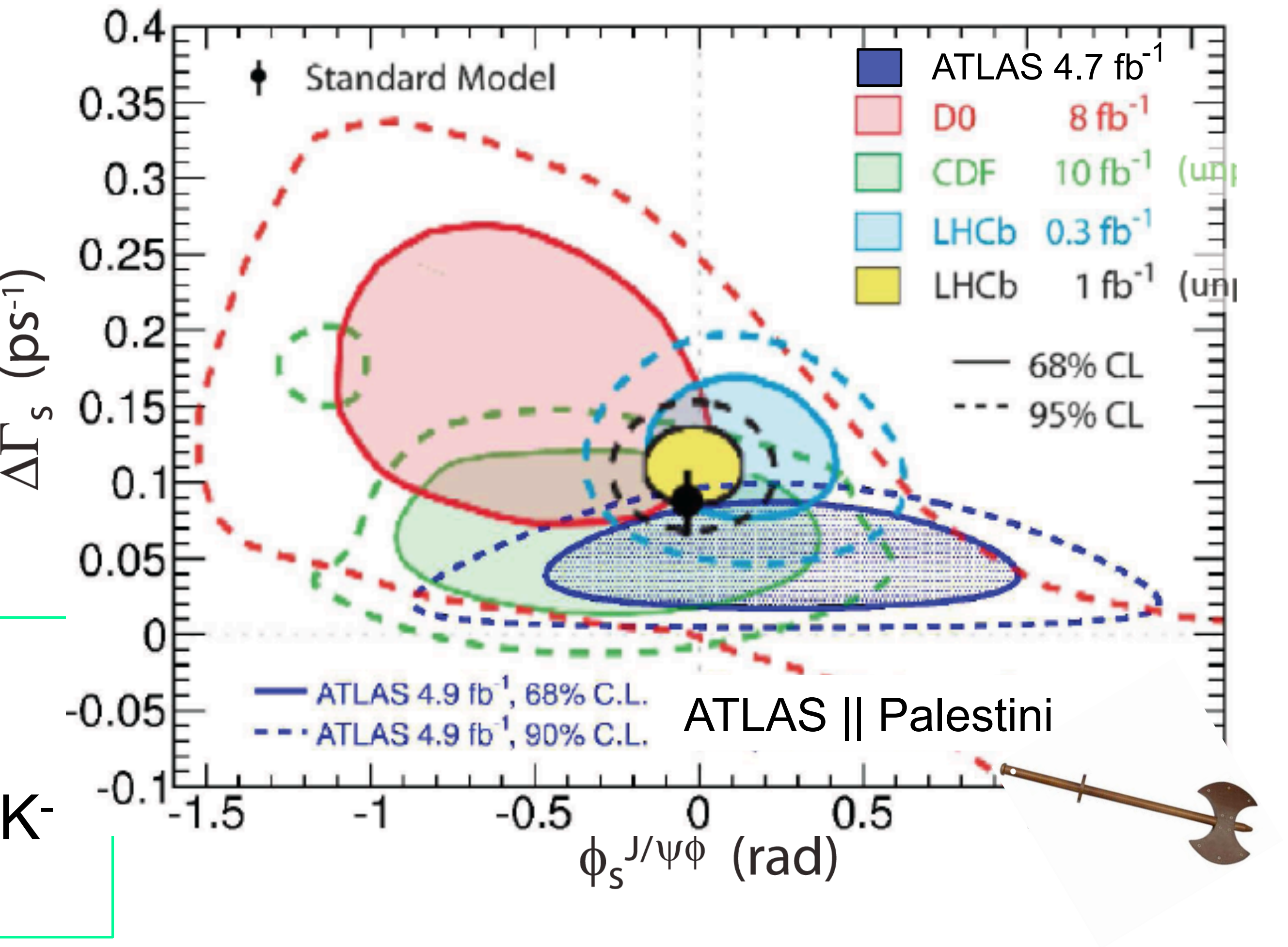
LHCb values

$\Gamma = 0.6580 \pm 0.0054 \pm 0.0066$ (ps^{-1})

$\Delta\Gamma = 0.116 \pm 0.018 \pm 0.006$ (ps^{-1})

$\phi_s = 0.001 \pm 0.101 \pm 0.027$ (rad)

Ambiguity removed using interference with K^+K^- S-wave

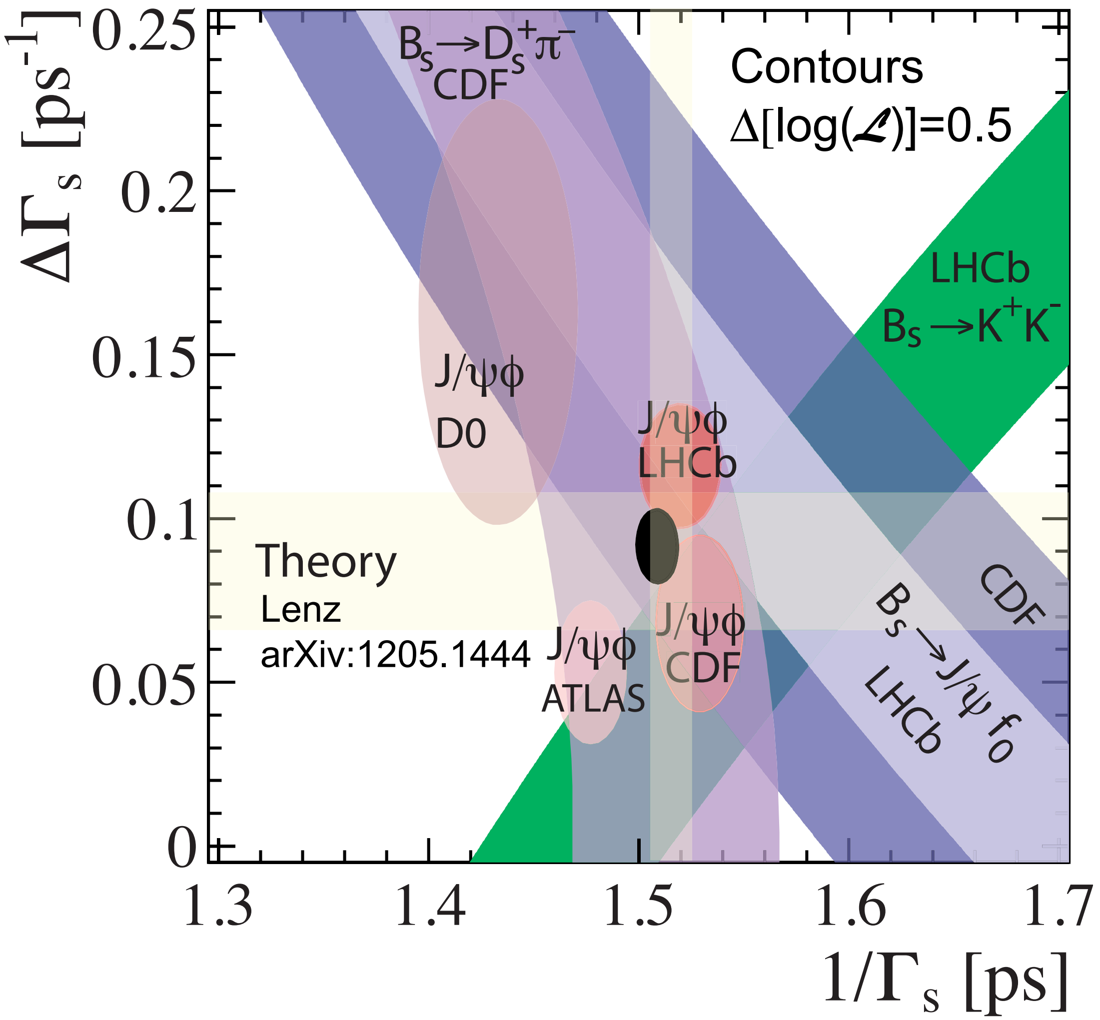


ATLAS || Palestini

- Combining LHCb results: $\phi_s = -0.002 \pm 0.083 \pm 0.027$ rad

Γ_s & $\Delta\Gamma_s$

- B_s lifetime measurements using fully reconstructed decays
- For K^+K^- $A_{\Delta\Gamma}=-1$
- Ovals show 39% cl, while bands 68% cl
- $\tau_s=1.509\pm0.010$ ps, $\Delta\Gamma_s = 0.092\pm0.011$ ps^{-1}, $y_s=\Delta\Gamma_s/2\Gamma_s=$ 0.07 ± 0.01 (from Anna Phan)



only full reconstructed B_s decays used

a_{sl}

- By definition

$$a_{sl}=\frac{\Gamma\left(\bar{M}\rightarrow f\right)-\Gamma\left(M\rightarrow \bar{f}\right)}{\Gamma\left(\bar{M}\rightarrow f\right)+\Gamma\left(M\rightarrow \bar{f}\right)}$$

  at t=0 $\overline{\mathrm{M}}\rightarrow \mathrm{f}$ is zero as is $\mathrm{M}\rightarrow\overline{\mathrm{f}}$

- Here *f* is by construction flavor specific, $f \neq \bar{f}$
- Can measure eg. $\overline{B}_s\rightarrow D_s^+\mu^-\nu$, versus $B_s\rightarrow D_s^-\mu^+\nu$,
- Or can consider that muons from two B decays can be like-sign when one mixes and the other decays, so look at $\mu^+\mu^+$ vs $\mu^-\mu^-$
- a_{sl} is expected to be very small in the SM, $a_{sl}=(\Delta\Gamma/\Delta M)\tan\phi_{12}$, where $\tan\phi_{12}=\mathrm{Arg}(-\Gamma_{12}/M_{12})$
- In SM (B^o) $a^d_{sl}=-4.1\times10^{-4}$, ($B_s$) $a^s_{sl}=+1.9\times10^{-5}$

arXiv:1205.1444 [hep-ph]

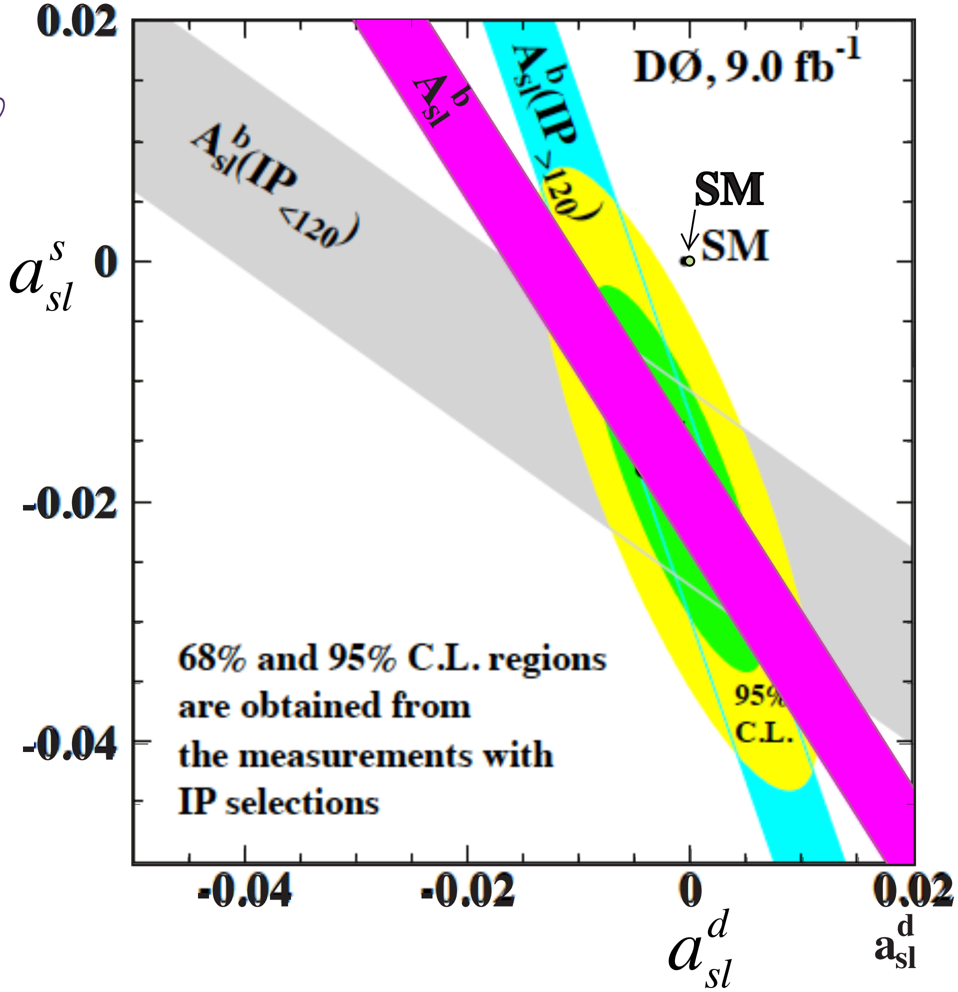
D$^{\mathrm{o}}$ a_{sl}

- Using dimuons (3.9σ)

$$A_{sl}^{b}=(-0.787\pm0.172\pm0.093)\%$$

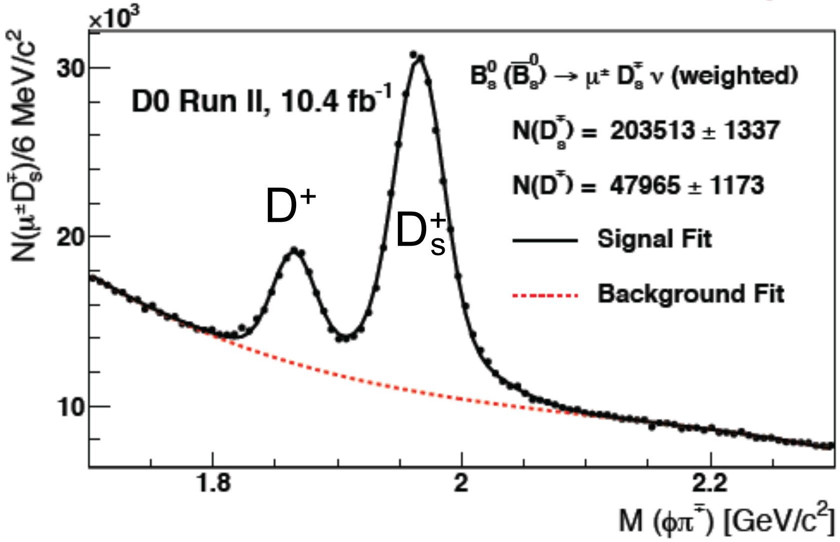
- Indication from D0 that its B_s
- Separate dimuons into B_d and B_s samples using muon impact parameter
- Find

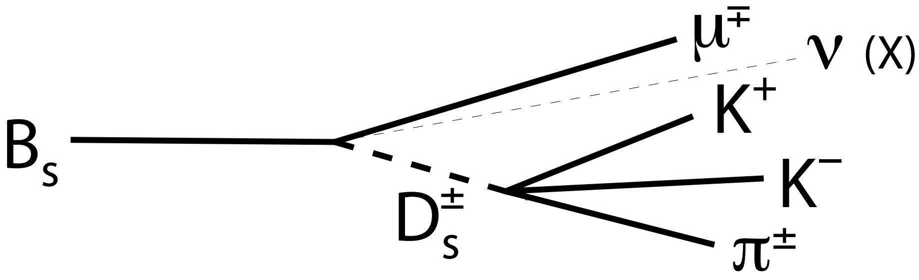
$$a_{sl}^{d}=(-0.12\pm0.52)\%$$
$$a_{sl}^{s}=(-1.81\pm1.06)\%$$



New D0 Analysis

- Measure a^s_{sl} using $D_s\mu^-\nu$ events, $D_s\rightarrow\phi\pi^\pm$
- Detect a μ associated with a D_s decay



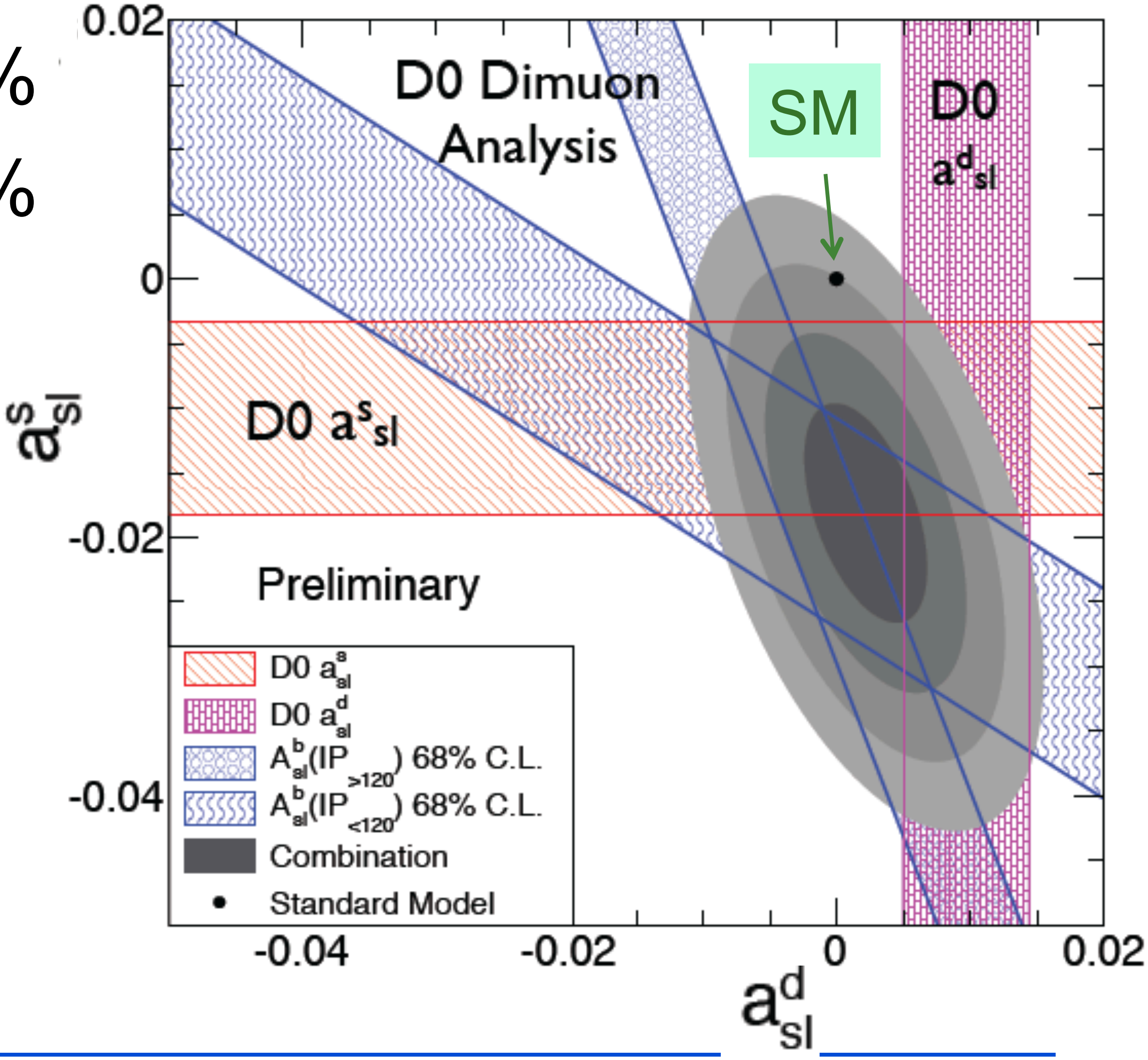


- Find a^s_{sl}=(-1.08±0.72±0.17)%
- Also measure a^d_{sl} using $D^+\mu^-\nu, D^+\rightarrow K\pi^+\pi^+$
- a^d_{sl}=(0.93±0.45±0.14)%

a_{sl} according to D0

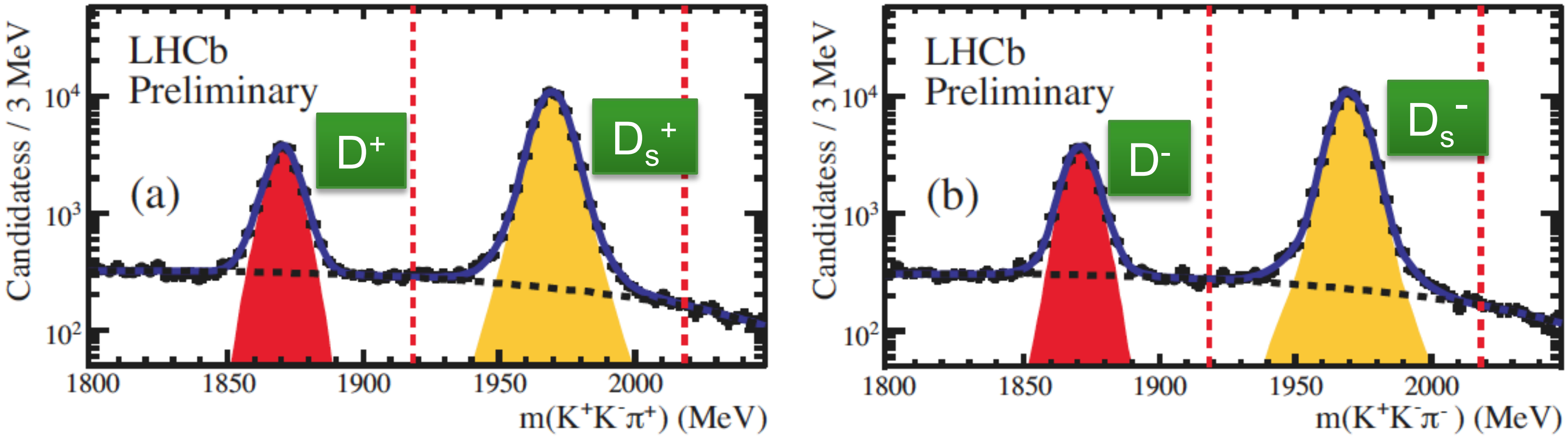
- a^s_{sl}=(-1.81±0.56)%
- a^d_{sl}=(-0.22±0.30)%
- 3σ from SM

(see || talk of Bertram)



LHCb measurement

- Use $D_s\mu^-\nu$, $D_s\to\phi\pi^\pm$, magnet is periodicaly reversed. For magnet down:



- Effect of B_s production asymmetry is reduced to negligible level by rapid mixing oscillations
- Calibration samples (J/ψ, D^{*+}) used to measure detector trigger, track & muon ID biases

a_{sl} not D0

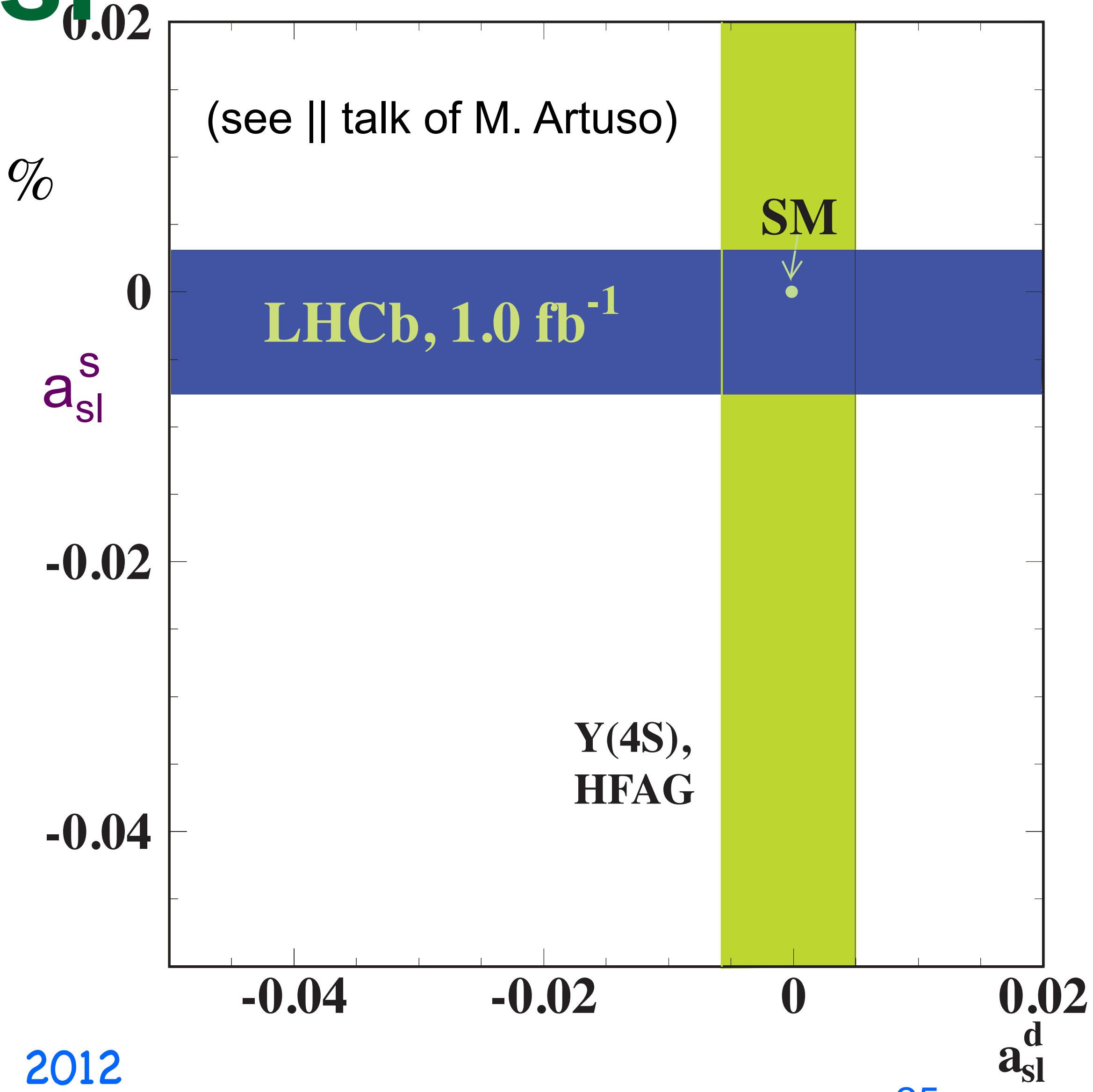
- LHCb finds

$$a_{sl}^{s} = (-0.24 \pm 0.54 \pm 0.33)\%$$

- B-factory

$$a_{sl}^{d} = (-0.05 \pm 0.56)\%$$

- Results consistent with SM
- Expect ϕ_s to grow as $\sin[2|\beta_s|+\arg(M_{12}^{s})]$ for finite a_{sl}.



CPV in Charm

- Expect largest effects in Cabibbo Suppressed Decays. COULD REVEAL NP (see Grossman Kagan & Nir arXiv:1204.3557)
- Define: $A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$, if *f* is a CP eigenstate then $f = \bar{f}$
- Current data mainly from LHCb, CDF & Belle show

$$\Delta A_{CP} \equiv A_{CP}\left(K^+K^-\right) - A_{CP}\left(\pi^+\pi^-\right) = \left(-0.74 \pm 0.15\right)\%$$

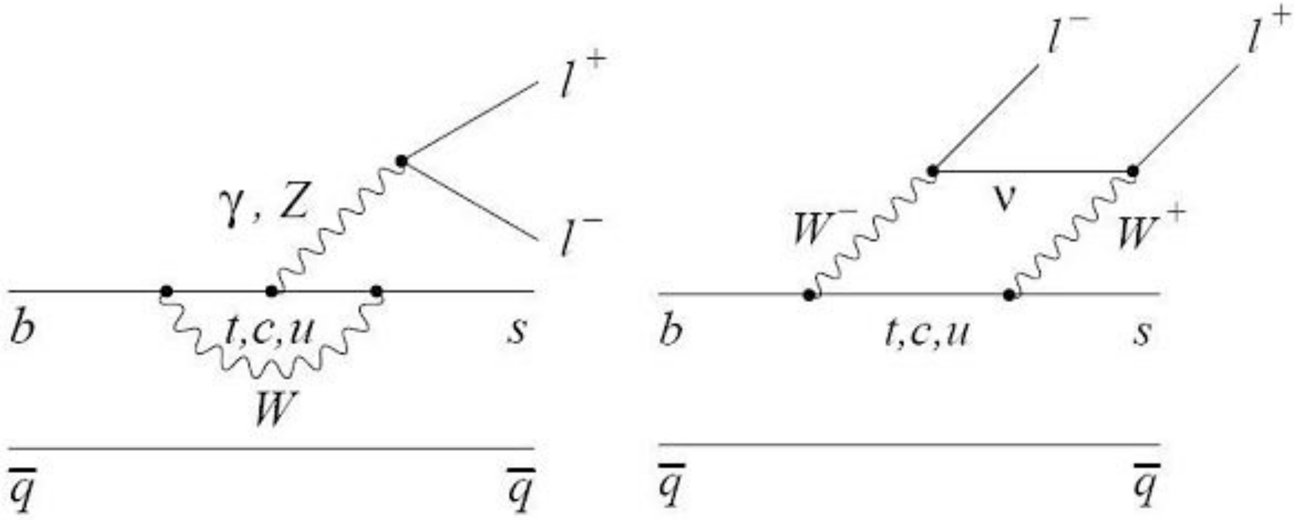
- A 4.9 σ effect

(|| talks Tico, Tonelli) & Ko

- Both SM & NP explanations are prolific
- Choose to treat this as a limit on NP: 1%>-ΔA_{CP}>0%

$B \to K^{(*)}\ell^+\ell^-$

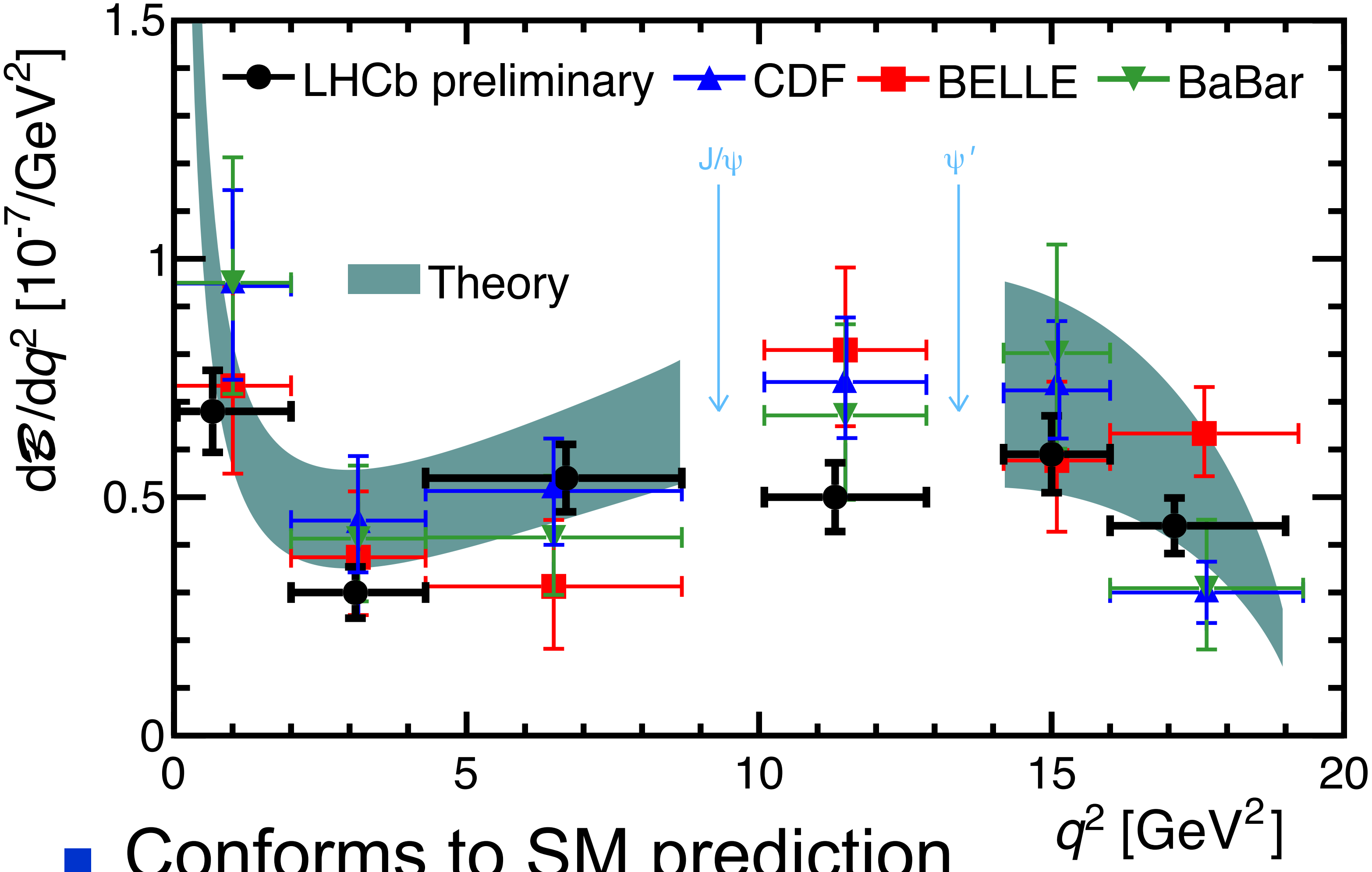
- Similar to $K^*\gamma$, but more decay paths



+ new particles in loops

- Several variables can be examined, e.g. muon forward-backward asymmetry, A_{FB} is well predicted in SM

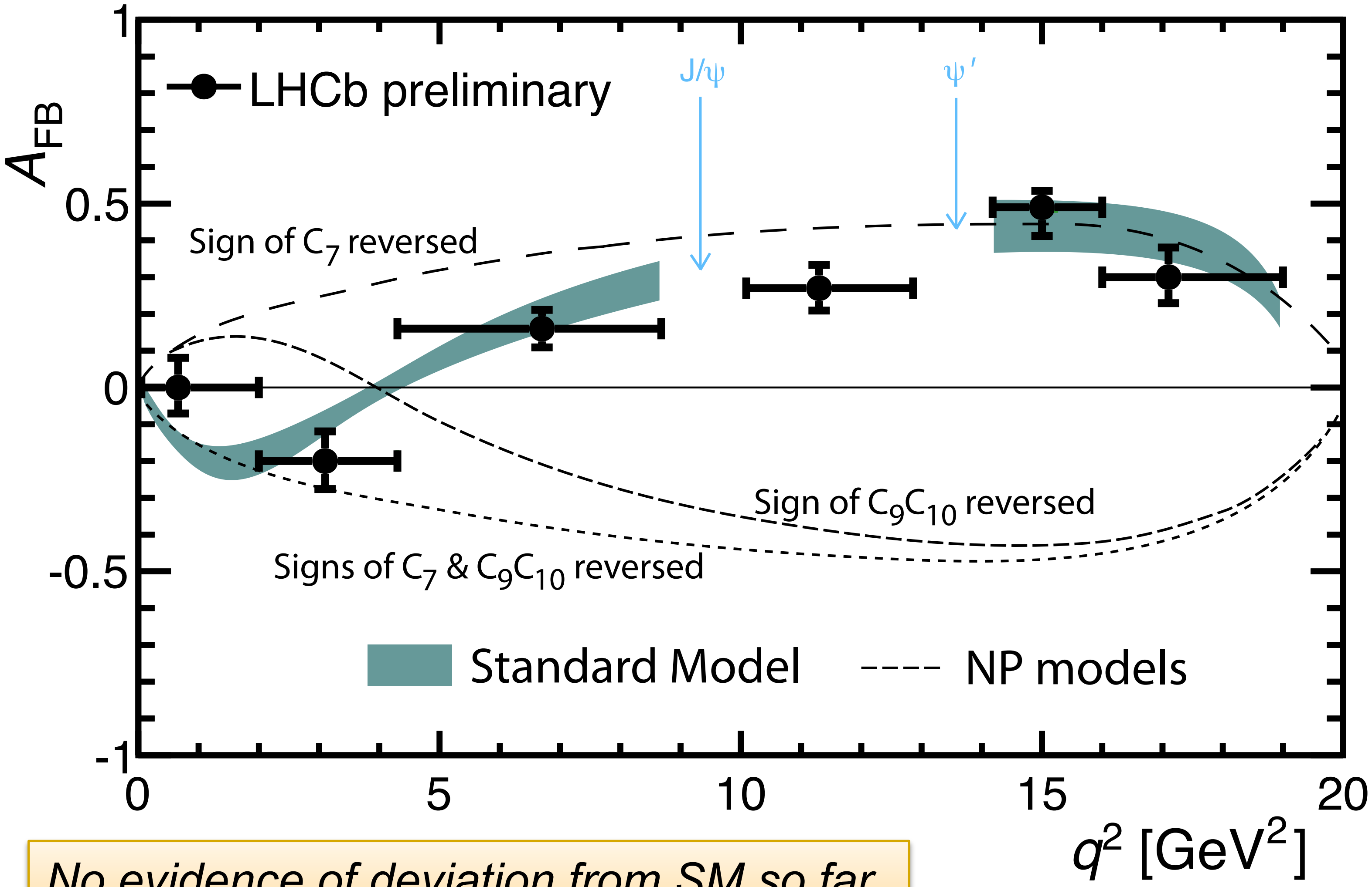
$B^o \rightarrow K^{*o} \ell^+ \ell^-$



LHCb || Gallas Torreira, BaBar || Eigen, CDF|| Miyake, Belle PRL 103, 171801 (2009)

- Conforms to SM prediction

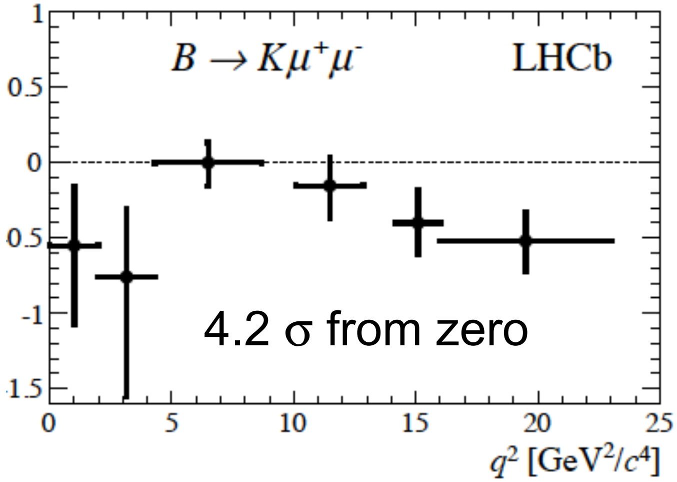
Forward-Backward asymmetry

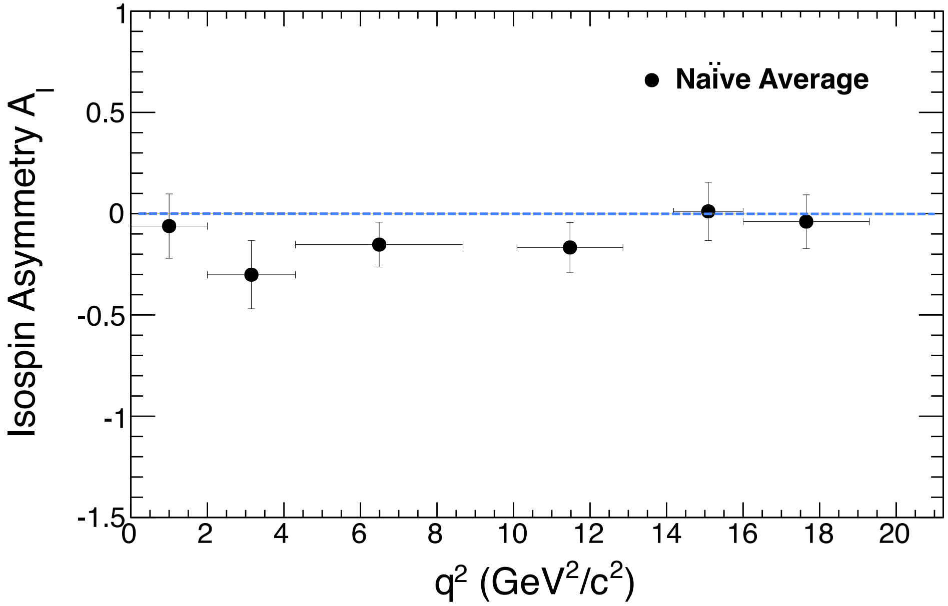


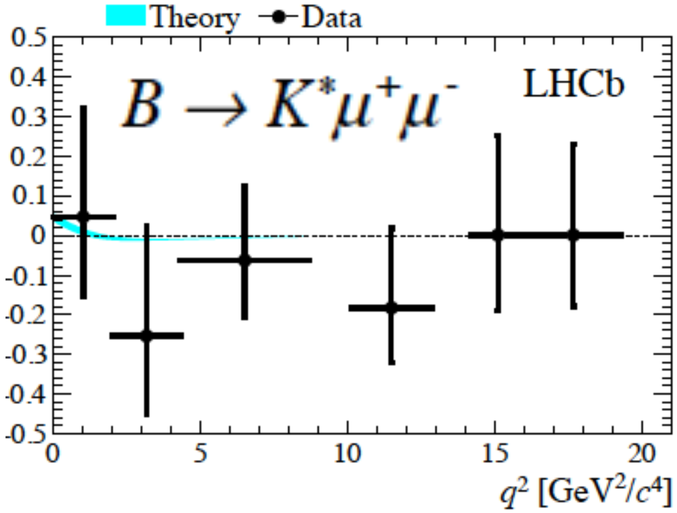
No evidence of deviation from SM so far

Isospin asymmetry

$$\frac{\Gamma(B^0\to K^{(*)0}\mu^+\mu^-)-\Gamma(B^+\to K^{(*)+}\mu^+}{\Gamma(B^0\to K^{(*)0}\mu^+\mu^-)+\Gamma(B^+\to K^{(*)+}\mu^+}$$







Not SM, but no NP model yet. Annihilation diagram only for B^-, but why the difference for K* & K?

Other Processes

- Other processes probe different operators
  - Time dependent CPV in $B^o \to K^*\gamma$, $K^* \to K_s\pi^o$, is given by

$$\frac{\Gamma(\bar{B}^0(t)\to \bar{K}^{*0}\gamma)-\Gamma(B^0(t)\to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t)\to \bar{K}^{*0}\gamma)+\Gamma(B^0(t)\to K^{*0}\gamma)} = S_{K^*\gamma}\sin(\Delta M_d t) - C_{K^*\gamma}\cos(\Delta M_d t)$$

where $S_{K^*\gamma}$= -2.3% in SM

- For Generic NP

$$S_{K^*\gamma} \simeq \frac{2}{|C_7|^2+|C_7'|^2}\mathrm{Im}\left(e^{-2i\beta}C_7C_7'\right)$$

- Data, BaBar & Belle (-16±22)%, still useful even with the large error

Rare Decays - Generic

- $$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}\ .$$
- C_iO_i for SM, $C_i'O_i'$ are for NP. Operators are for $P_{R,L} = (1 \pm \gamma_5)/2$

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O_8 = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\,a},$$

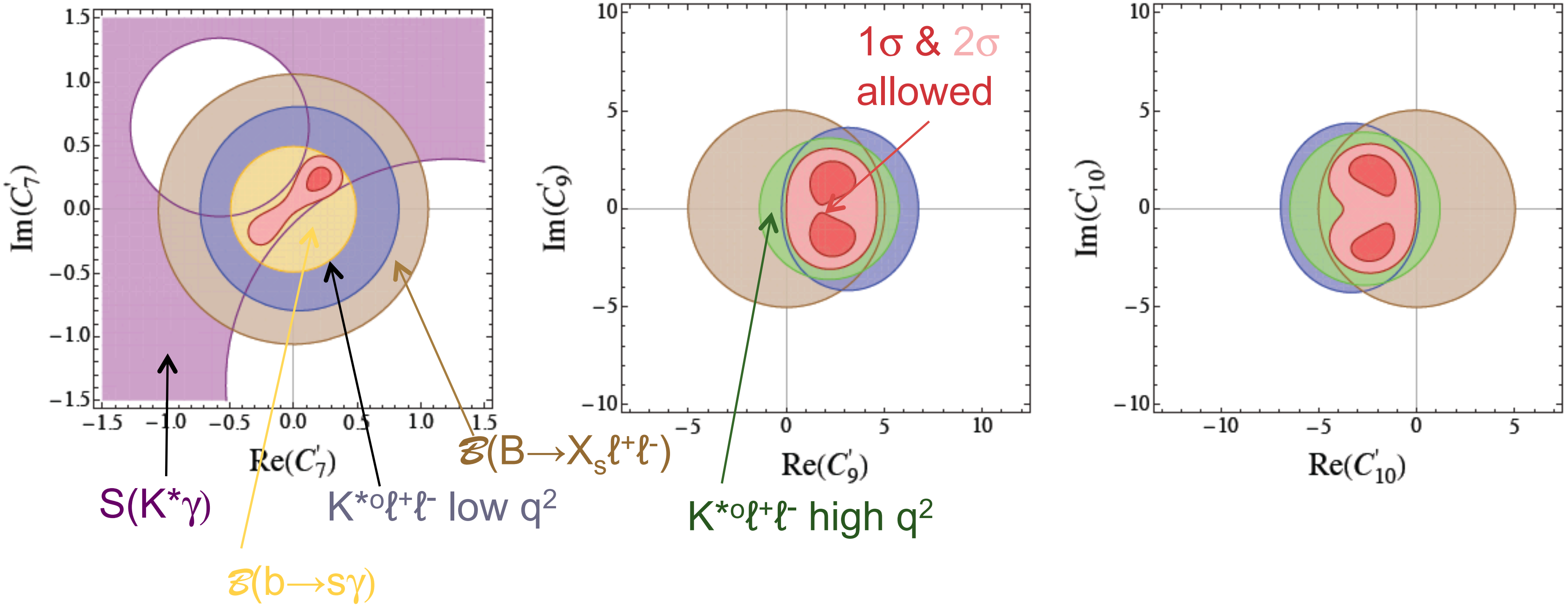
$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell)\,, \qquad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)\,,$$

- O'=O with $P_{R,L} \rightarrow P_{L,R}$
- Each process depends on a unique combination

Common Analysis

- APS ≡ W. Altmannshofer, P. Paradisi & D. M. Straub arXiv:1111.1257v2



- Many more such generic constraints

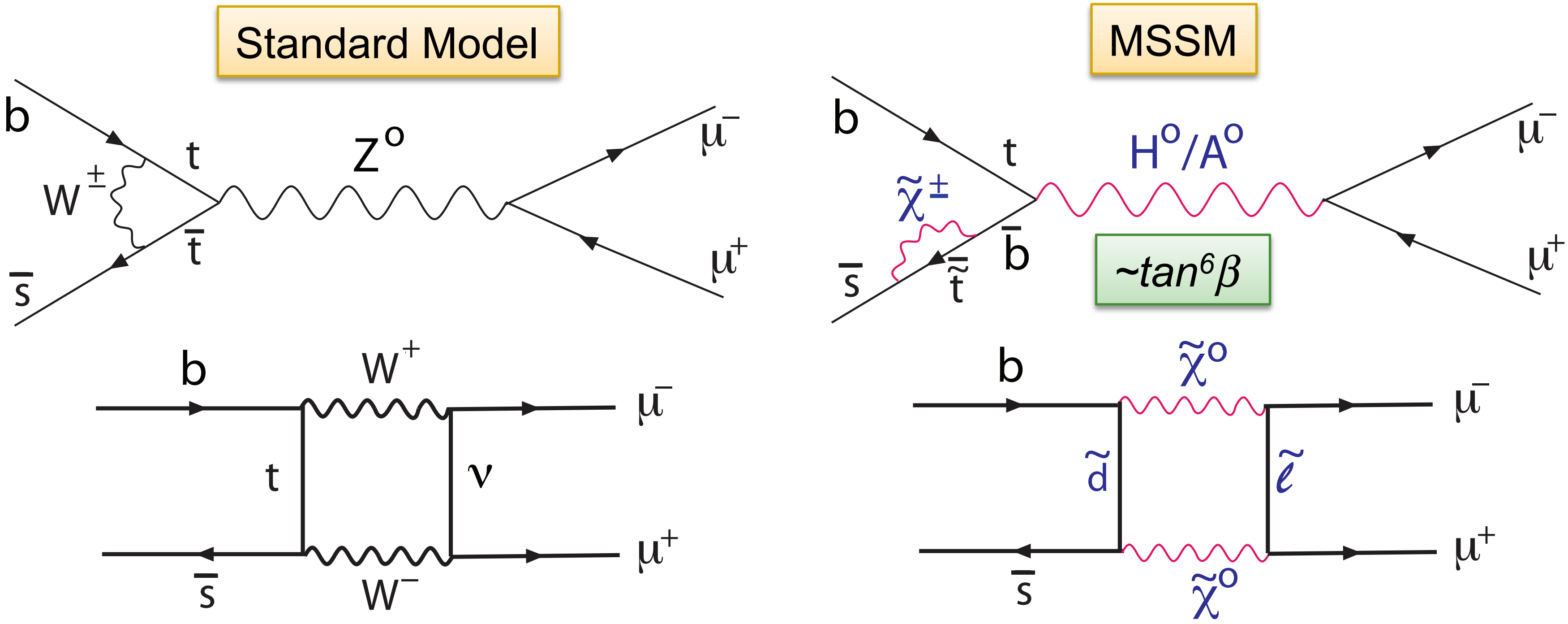
$B_s \rightarrow \mu^+\mu^-$

- SM branching ratio is $(3.2\pm0.2)\times10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

Note, K. De Brun arXive:1204.1737 show that B theory needs to be raised by $1/(1-y_s)$

Standard Model

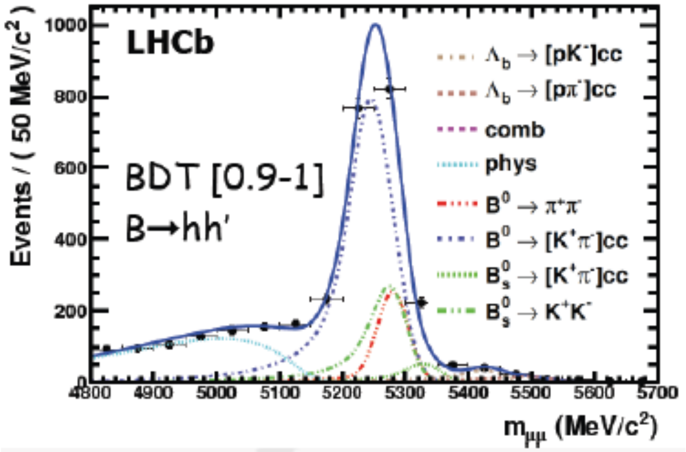
MSSM

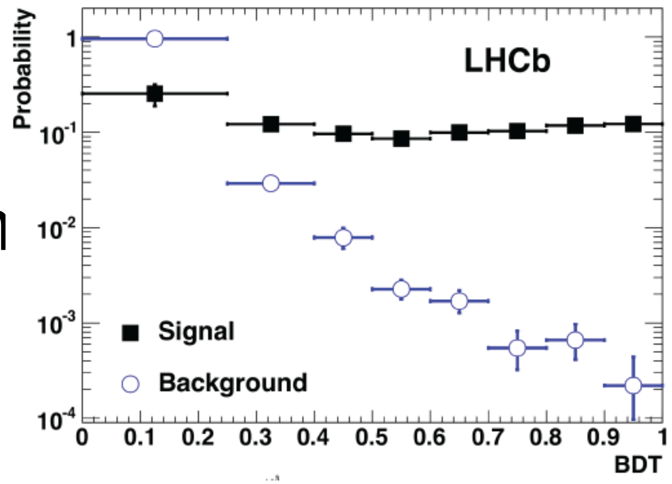


- Many NP models possible, not just Super-Sym

Discrimination

- LHCb & CDF use $B \to h^+h^-$ to tune cuts. They use a multivariate analysis
- Other variables to discriminate against bkgrd : B impact parameter, B lifetime, B p_t, B isolation, muon isolation, minimum impact parameter of muons, …
- CMS & ATLAS use f_s/f_d from LHCb

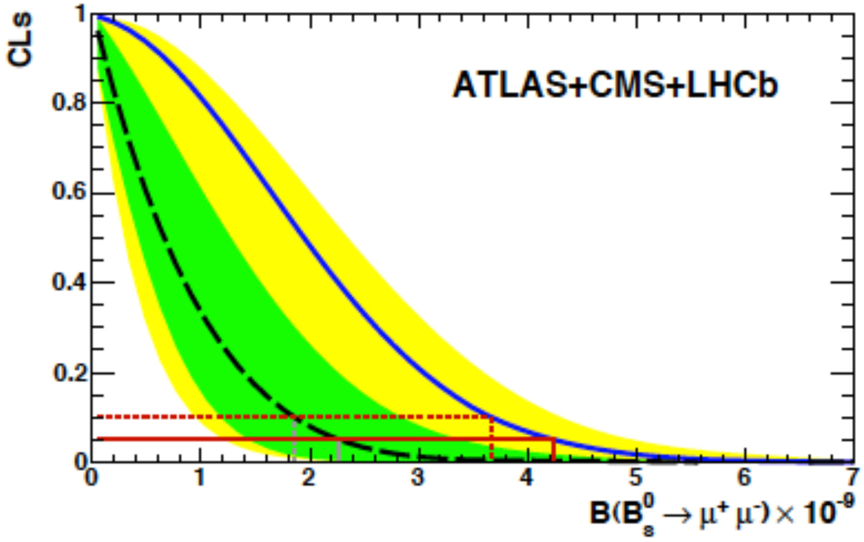


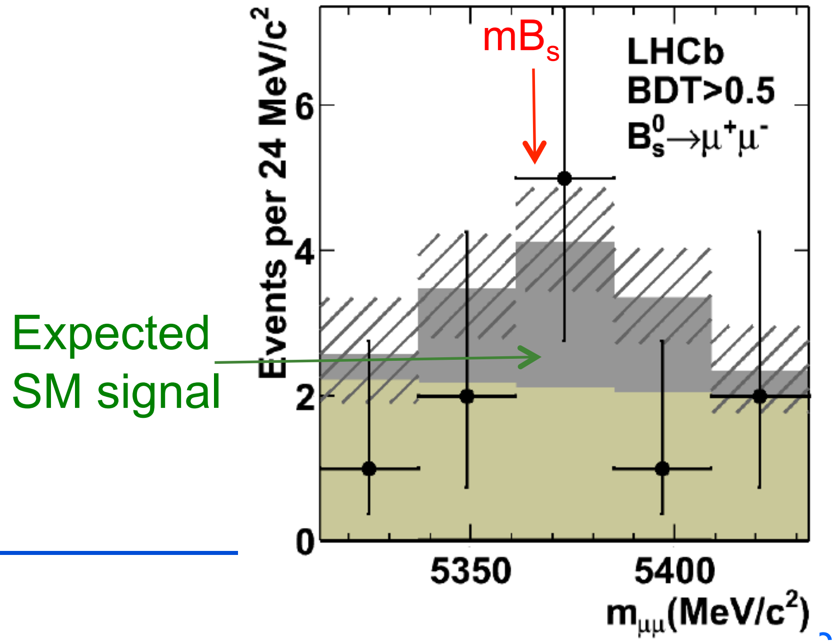


See || talk of M. Perrin-Terrin

ATLAS+CMS+LHCb

- CLs for bkgrnd only, dashed line is the expectation, blue curve show the measurement, red the 95% cl limit
- LHCb data show slight excess consistent with SM
- Also
  $\mathcal{B}(B_d \to \mu^+\mu^-) < 8.1\times10^{-10}$

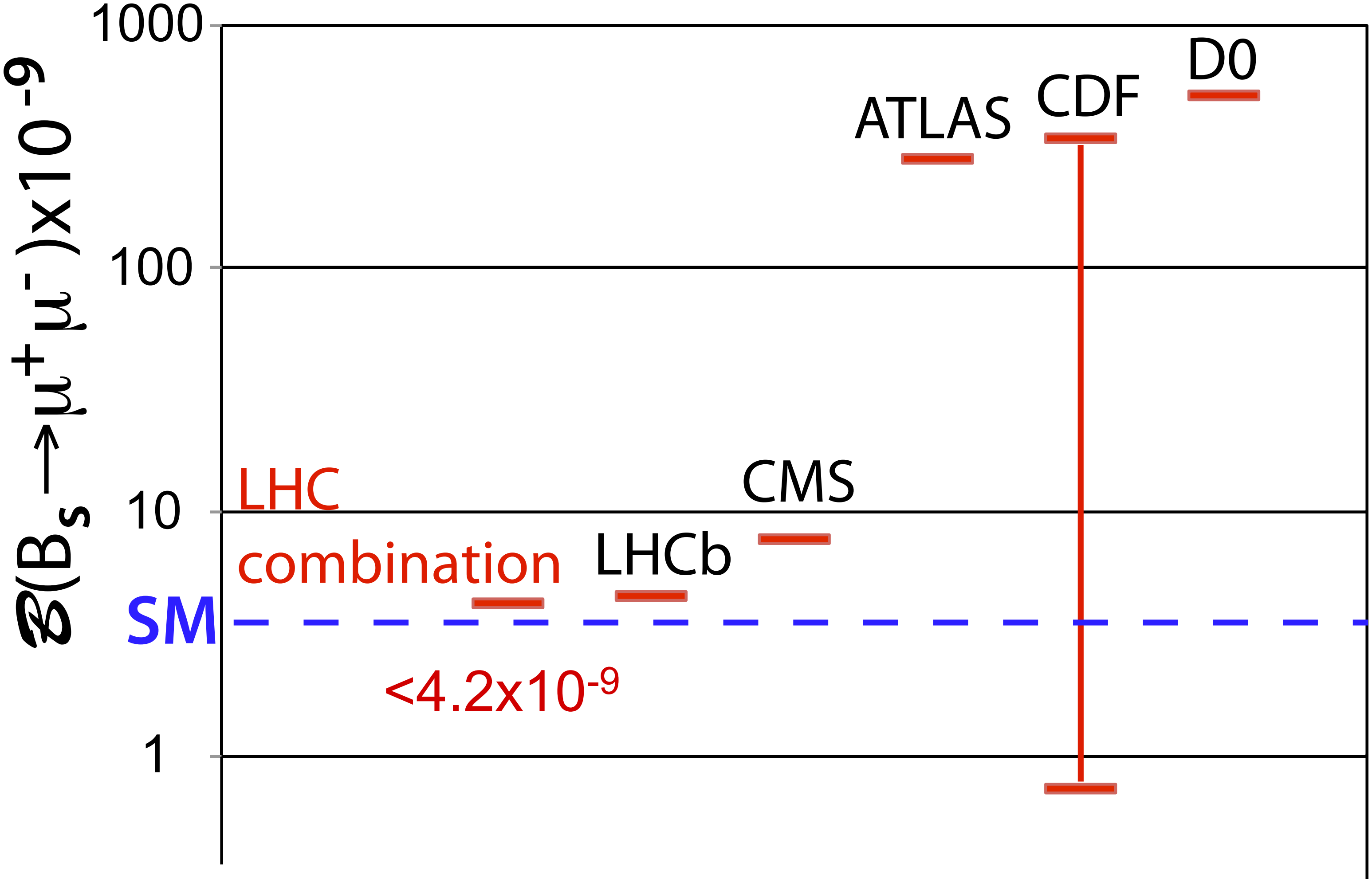




Expected SM signal

Results

95% confidence level limits



Implications

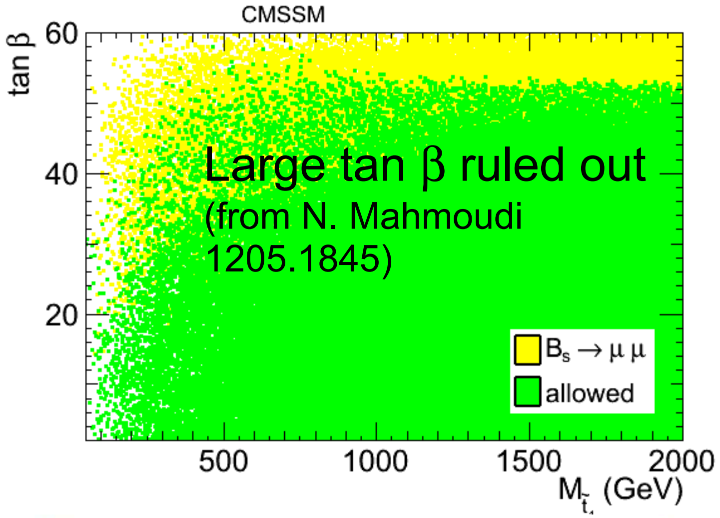
- "LHC" limit
  - <4.2x10^{-9} @95% CL
  - This is 1.2 times SM value
- Set serious limits in NUHM1 SUSY model
- Other LHCb results

$\mathcal{B}(B_s\to\mu^+\mu^-\mu^+\mu^-)<1.3\times10^{-8}$

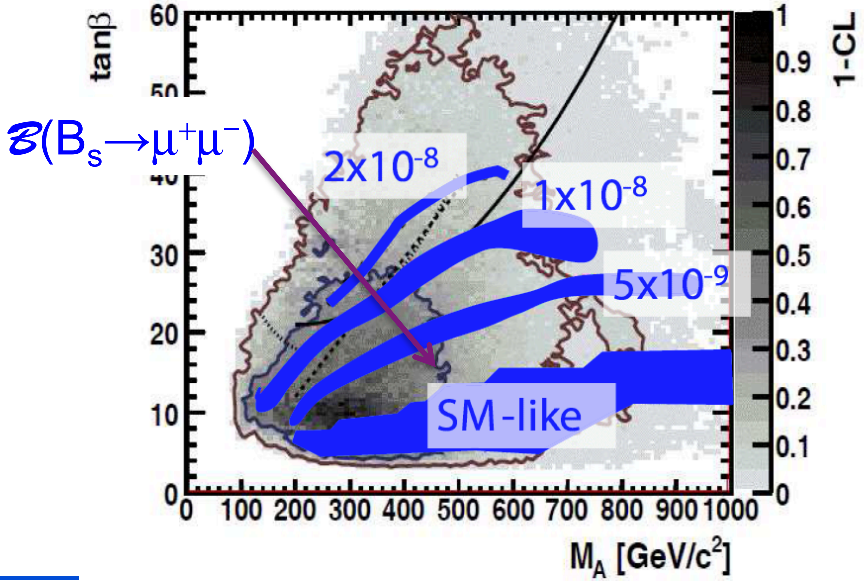
$\mathcal{B}(B_d\to\mu^+\mu^-\mu^+\mu^-)<5.4\times10^{-9}$

Predicted via "portals"

see arXiv:0911.4938

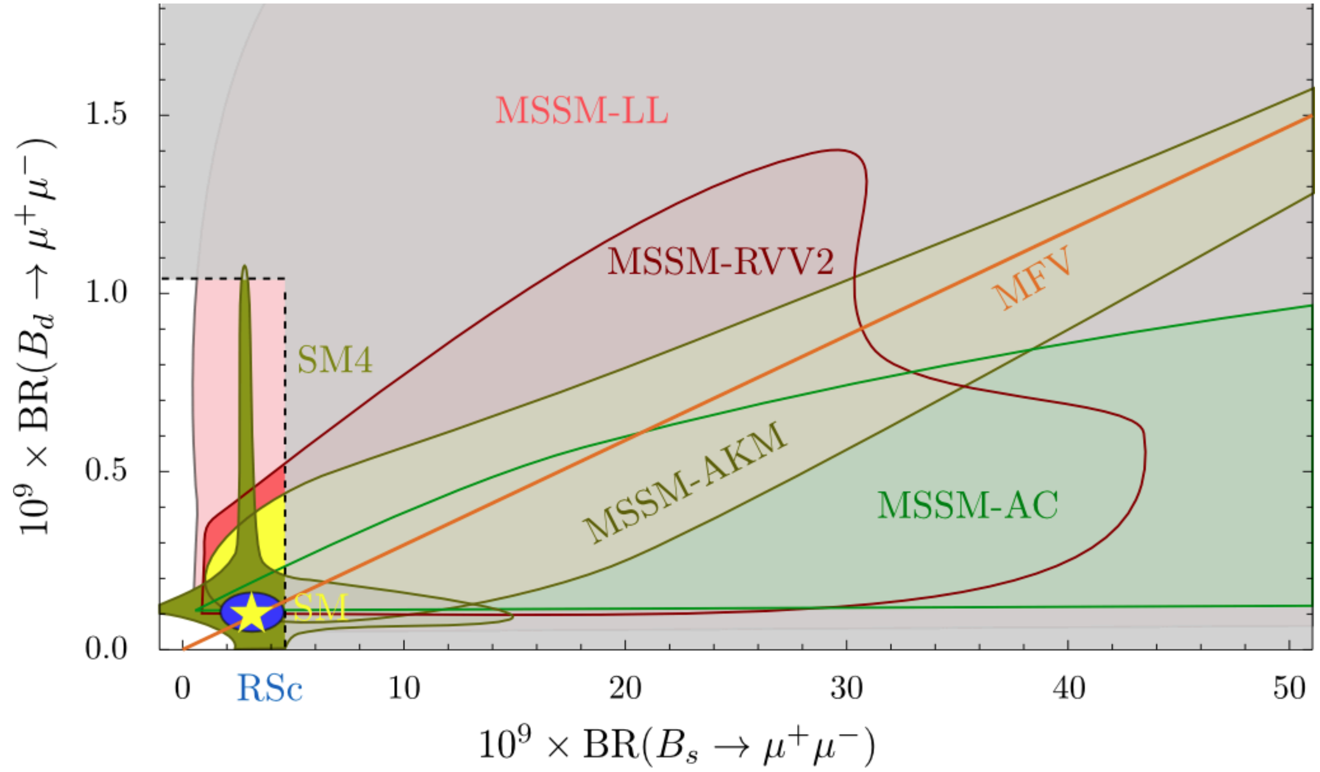


Large tan β ruled out (from N. Mahmoudi 1205.1845)



Implications II

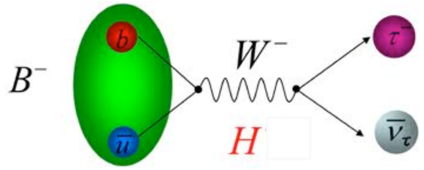
David Straub, Rencontres de Moriond EW, La Thuile (2012)



The 125 GeV Higgs observations kills off 4th generation models as the production cross-section would be 9x larger & decays to $\gamma\gamma$ suppressed

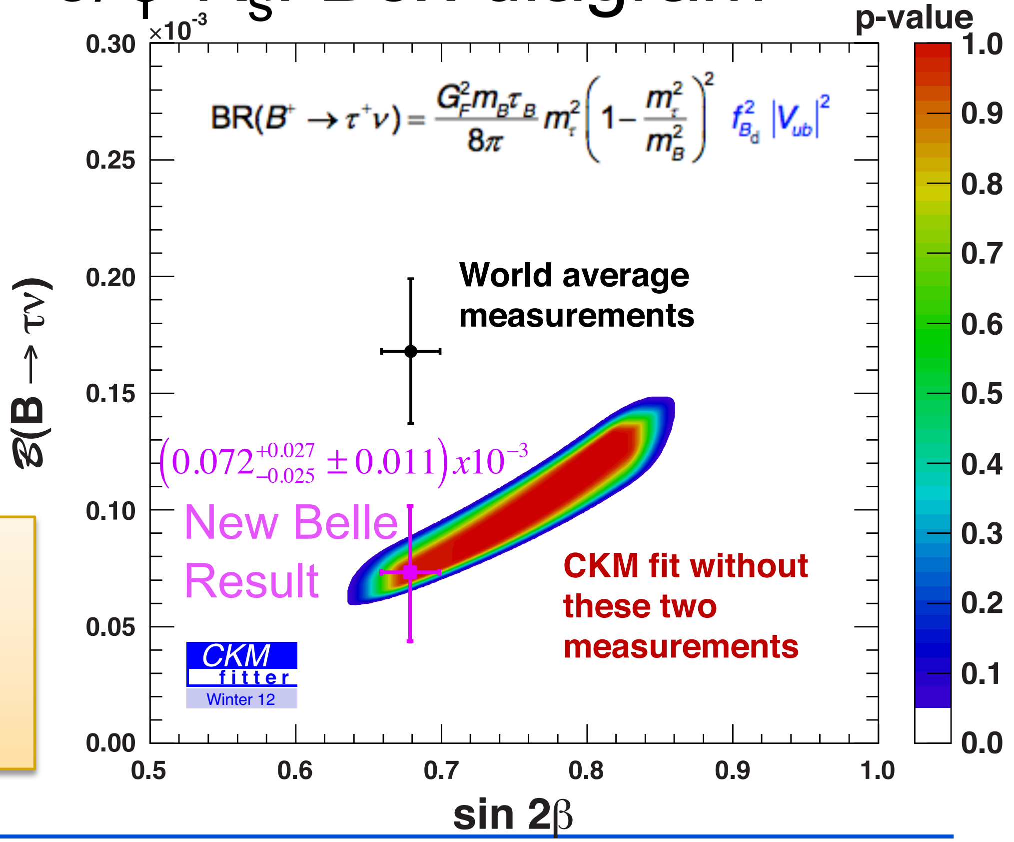
$B^-\to\tau^-\bar{\nu}$ problem?

- $B^-\to\tau^-\nu$, tree process:



Can be new particles instead of W^- but why not also in $D^+_{(s)}\to\ell^+\nu$?

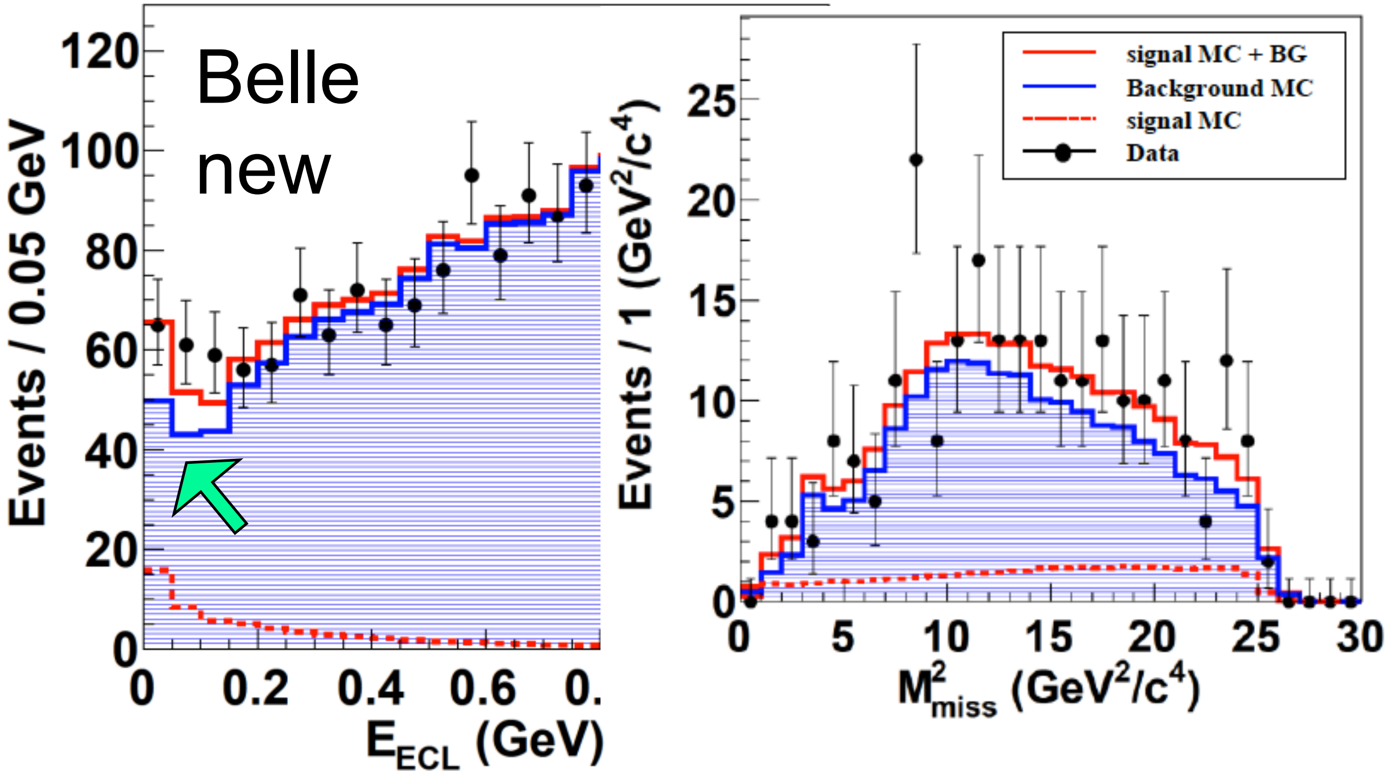
- sin2β, CPV in e.g. $B^o\to J/\psi\ K_s$: Box diagram
- Measurement not in good agreement with SM prediction based on CKM fit (Yook || talk)



Discrepancy may be resolved; what caused the change?

Peaking Backgrounds

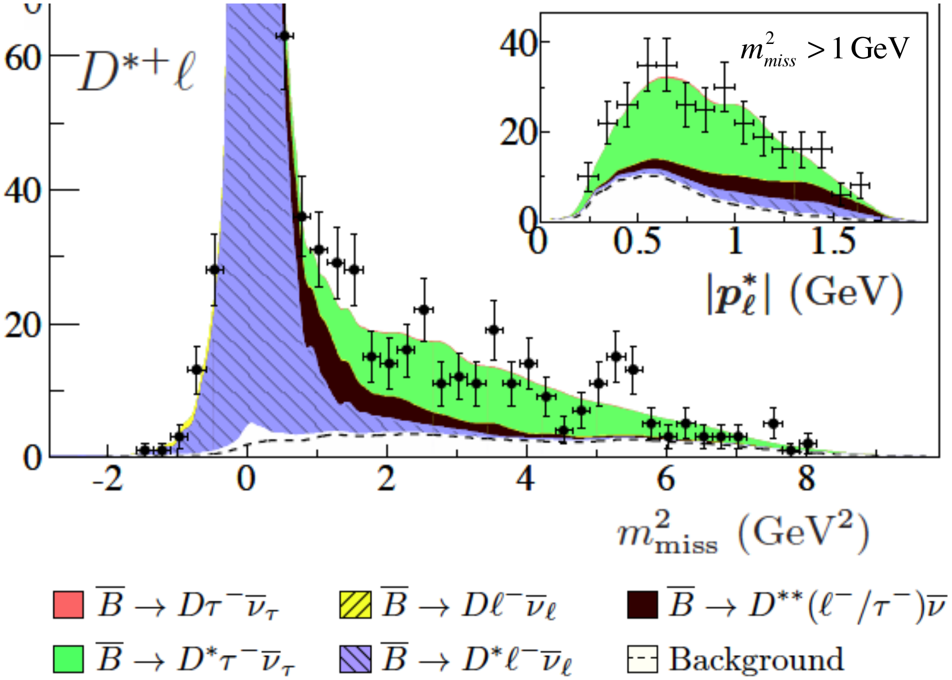
- Since $e^+e^- \rightarrow B^+B^-$, analysis uses reconstruction of B^+, detection of $\tau^- \rightarrow$ one track & small extra E



See || talk of Y. Yook

$B\to D^{(*)}\tau\nu$

- Also, tree level –new BaBar result
- Similar to $B^-\to\tau^-\nu$ analysis: fully reconstruct one B, keep events with an additional $D^{(*)}$ plus an e^- or μ^-.



- Signal is wide, background, especially $D^{**}\ell\,\nu$, needs careful estimation

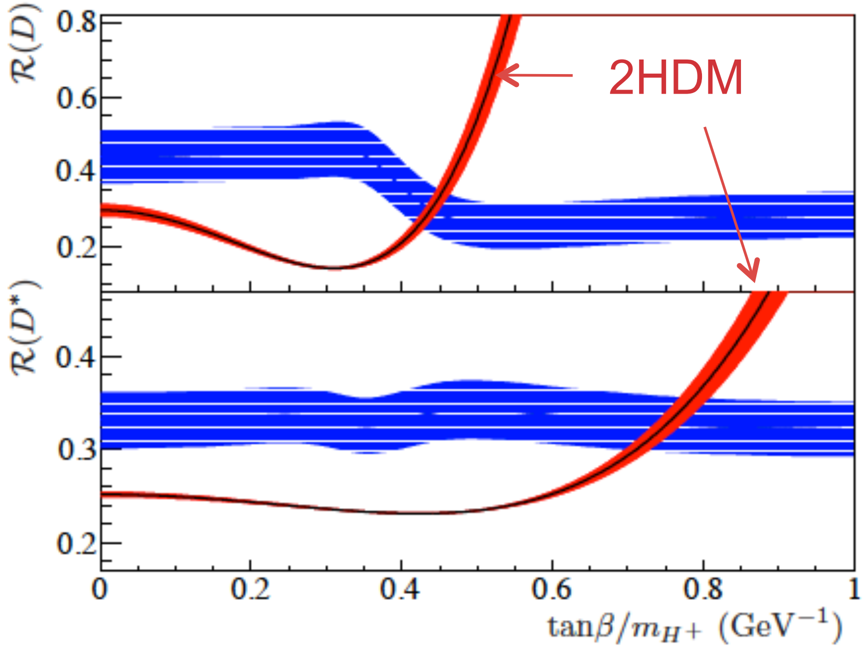
BaBar results

- Results given in terms of ratio to $B\rightarrow D^{(*)}\ell\nu$

	SM Theory	**BaBar value**	**Diff.**
R(D)	0.297±0.017	0.440±0.058±0.042	+2.0σ
R(D*)	0.252±0.003	0.332±0.024±0.018	+2.7σ

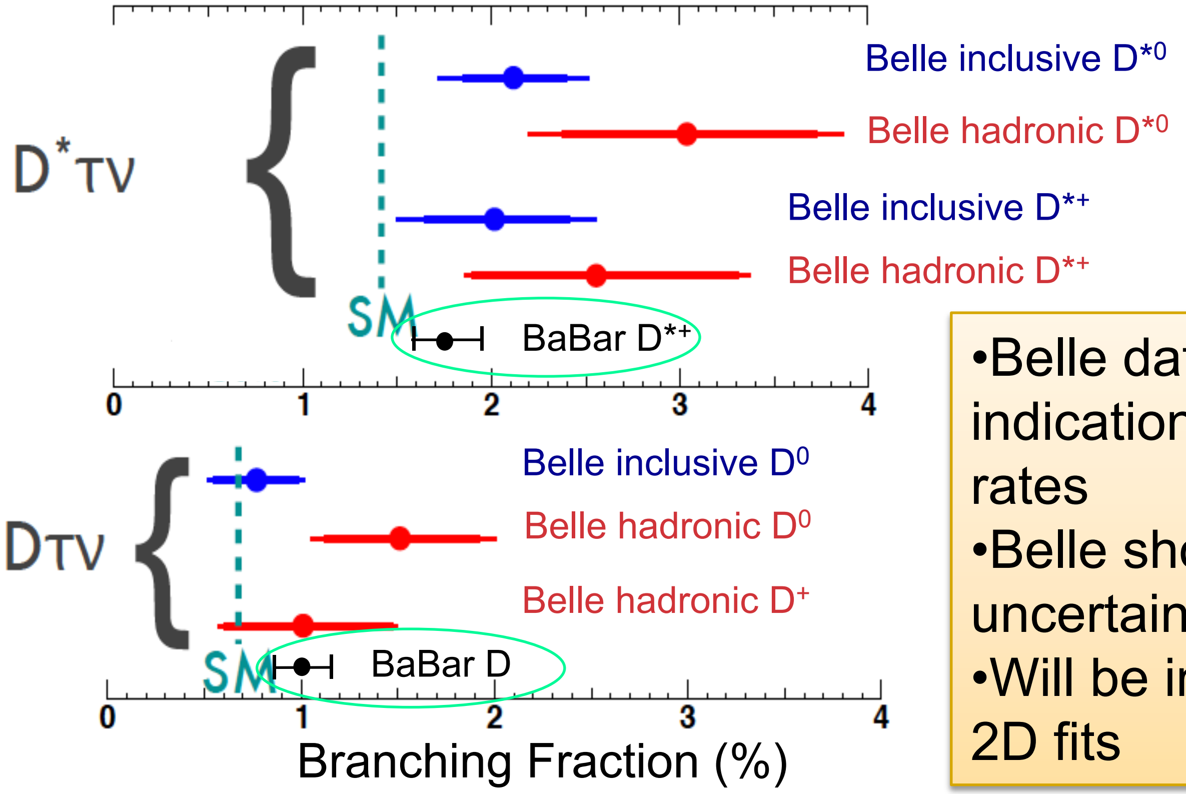
- Sum is 3.4σ above SM
- Also inconsistent with type II 2HDM

  (see De Nardo || talk)



Belle Results

- Two types of analysis, hadronic tags (arXiv: 0910.4301) similar to BaBar and also “inclusive tags” (A. Matyja et. al, PRL 99,191807 (2007)).



•Belle data currently support BaBar indication of larger than expected rates

•Belle should be able to reduce uncertainties to the BaBar level

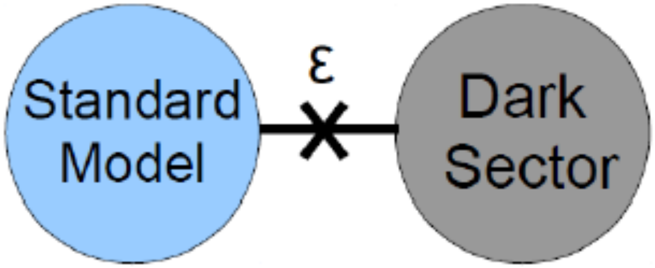
•Will be interesting to see results of 2D fits

The Dark Sector

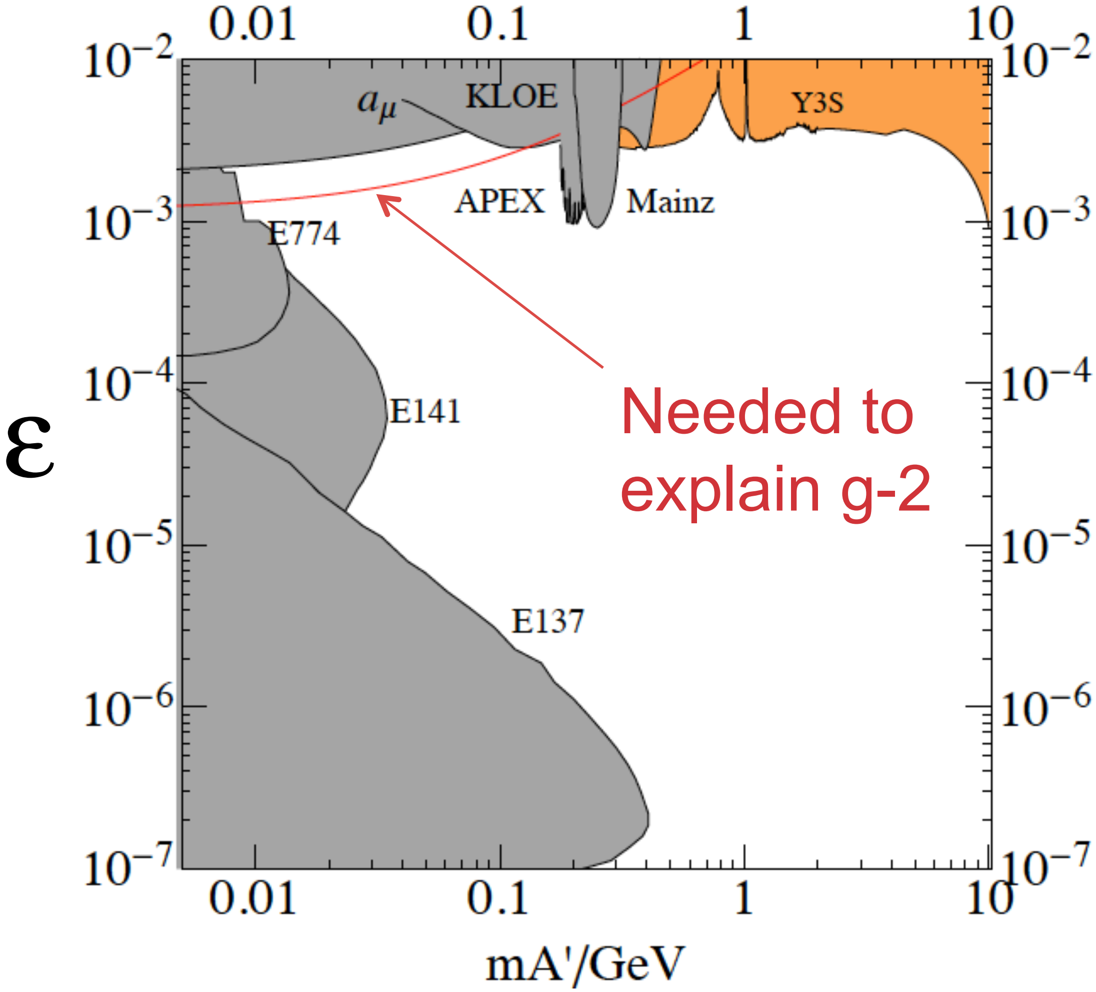
- Could it be that there are 3 classes of matter?
  - SM particles with charges [SU(3)xSU(2)xU(1)]
  - Dark matter particles with “dark” charges
  - Some matter having both (“mediators”)
- Searches for “dark photons”
  - A mediator, couples to b-quarks (see arXiv:056151 hep/ph)
  - BaBar $\mathcal{B}(Y(1S)\rightarrow \text{invisible}) < 3\text{x}10^{-4}$ @ 90% cl
  - Other experiments

Search Summary

- Parameterize by mixing ε



- Dark photon mass mA´

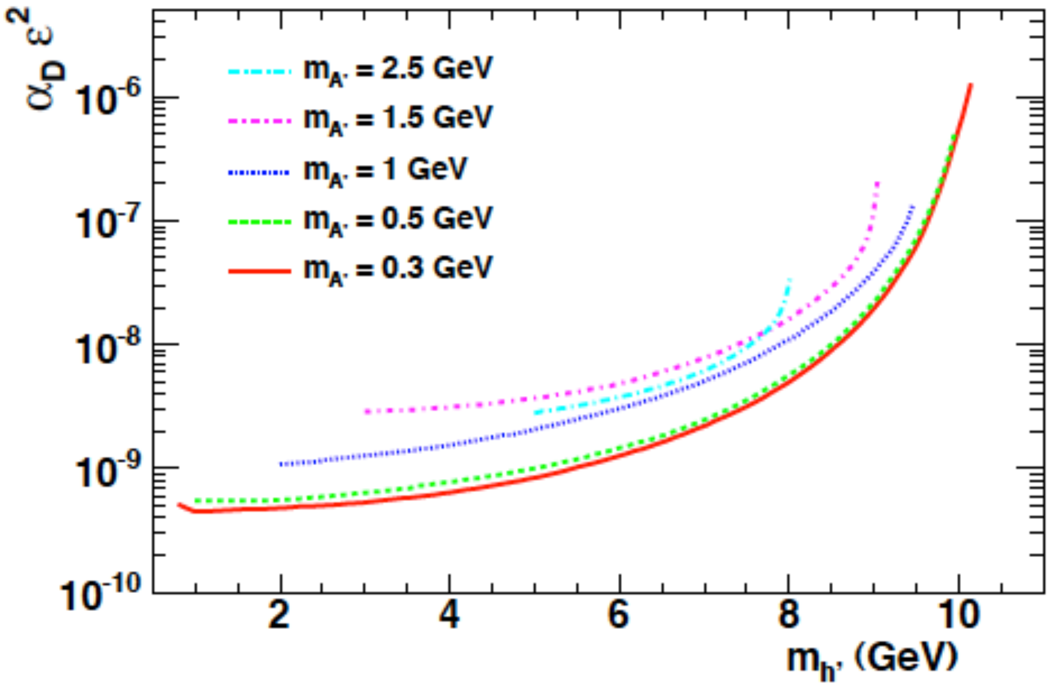


Needed to explain g-2

From B. Echenard arXiv:1205.3505

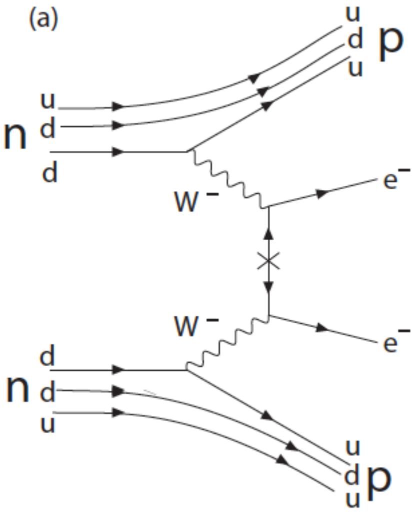
Dark Higgs

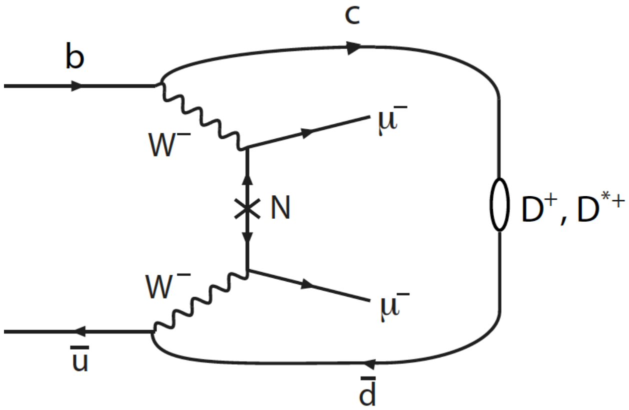
- BaBar search for $e^+e^-\rightarrow h'A'$, $h'\rightarrow A'A'$
- A' is looked for in e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ & hadrons
- Limits parameterized in terms of mixing ε & dark matter coupling α_D
- Nothing found, upper limits set at 90% cl:



Majorana ν's

- Several ways of looking for presence of heavy ν's (N) in heavy quark decays if they Majorana (their own anti-particles) and couple to "ordinary" ν's
- Modes analogous to ν–less nuclear β decay





Simplest Channels:
$B^- \rightarrow D^+ \ell^- \ell'^-$ &
$B^- \rightarrow D^{*+} \ell^- \ell'^-$
ℓ^- & ℓ'^- can be
e^-, μ^- or τ^-.

Limits on $D^{(*)+}\ell^- \ell'^-$

- Upper limits in e^-e^- mode not competitive with nuclear β decay
- Others unique since measure coupling of Majorana ν to μ^-

Mode	Exp.	u. l. x 10^{-6}
$B^- \to D^+ e^- e^-$	Belle	< 2.6
$B^- \to D^+ e^- \mu^-$	Belle	< 1.8
$B^- \to D^+ \mu^- \mu^-$	Belle	< 1.0
$B^- \to D^+ \mu^- \mu^-$	LHCb	< 0.69
$B^- \to D^{*+} \mu^- \mu^-$	LHCb	< 3.6

Belle [arXiv:1107.064]

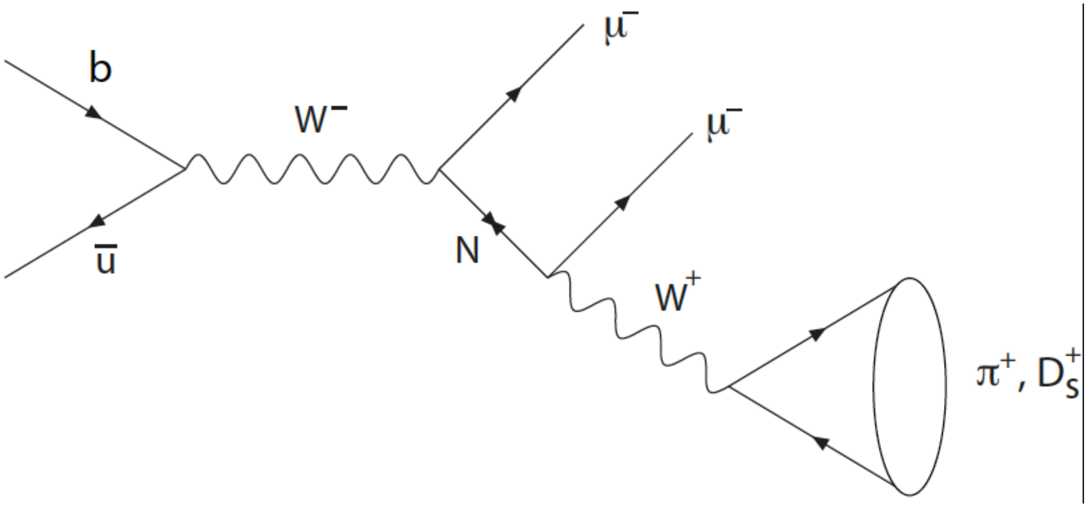
On-Shell ν

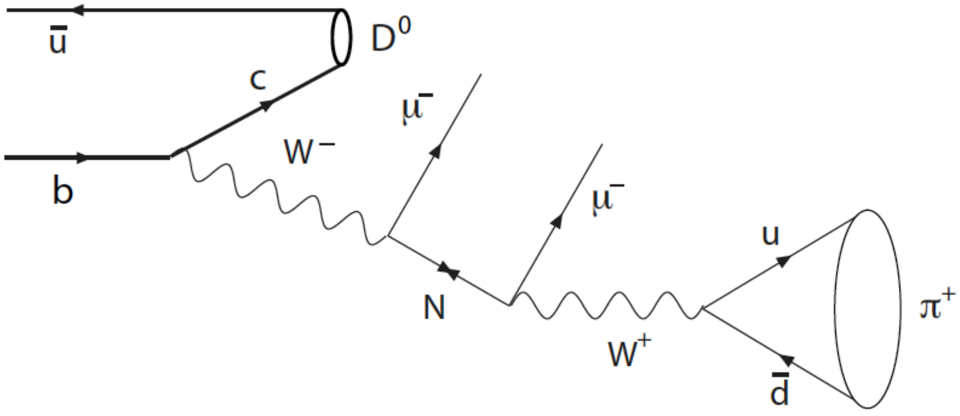
- Can also look for Majorana ν (N), where N→$W^+\mu^-$
- Several ways
- A. Atre, T. Han,

S. Pascoli, & B. Zhang

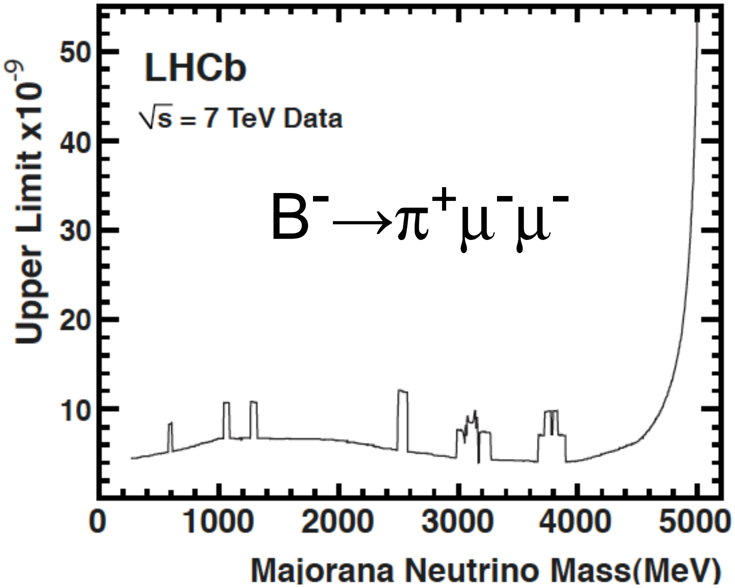
[arXiv:0901.3589]

- N. Quintero, G. Lopez & Castro, [arXiv:1108.6009]





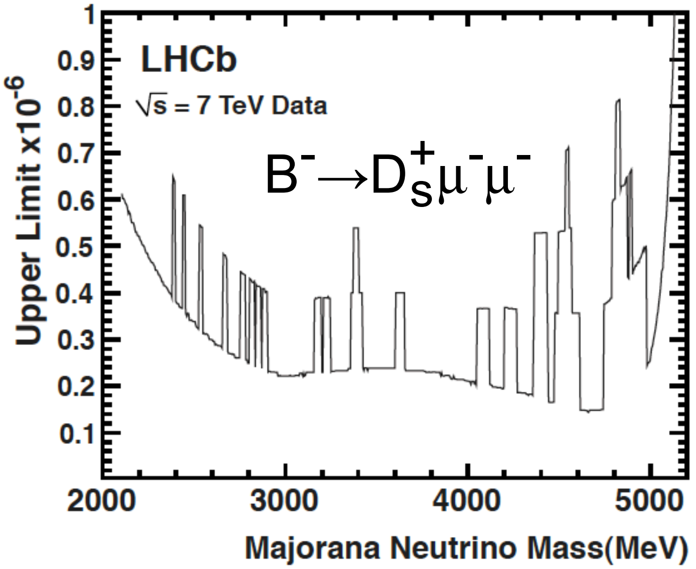
LHCb searches



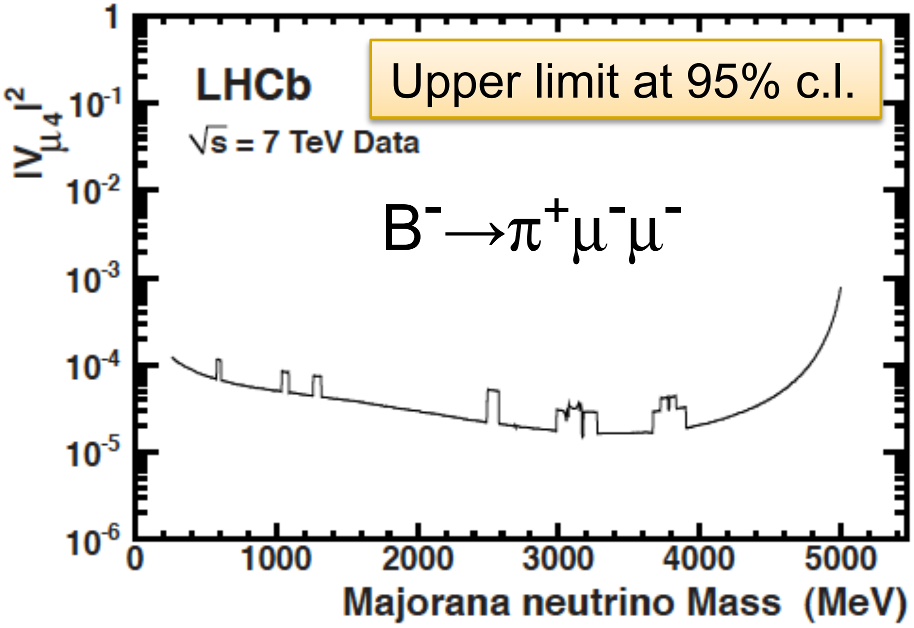
$B^- \to \pi^+ \mu^- \mu^-$

Nothing yet

Aaij, PRD 85, 112004 (2012)

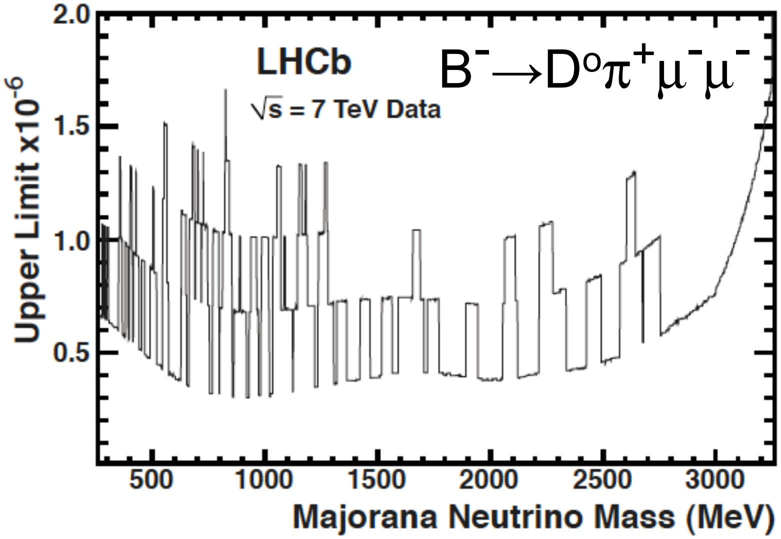


$B^- \to D_s^+ \mu^- \mu^-$



Upper limit at 95% c.l.

$B^- \to \pi^+ \mu^- \mu^-$



$B^- \to D^o \pi^+ \mu^- \mu^-$

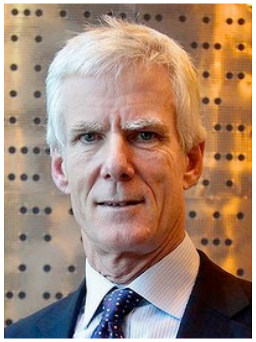
Conclusions

- Although there is no compelling evidence yet for NP, Heavy Flavor physics is very sensitive to potential effects at high mass scales. All NP theories must satisfy stringent experimental constraints
- Experiments have been very effective at dispelling effects with marginal statistical significance, although a few remain. Will some stand when precision improves?
- Improving measurements such as $B_s \to \mu^+\mu^-$, $B \to K\mu^+\mu^-$, CPV: ϕ_s, etc.., may show NP effects, & need to be aggressively pursued
- We are looking forward to new flavor physics discoveries from the LHC & its upgrades, BESIII, and Super B factories
- We are looking forward to defining the next theory beyond the SM

Theory conquers

Thanks!

- To my scientific secretary Antonio Limosani
- Conference organizers:
  - Geoffrey TAYLOR Raymond VOLKAS



  - Paul HOGAN

- Apologies for all the interesting results, I left out

The End