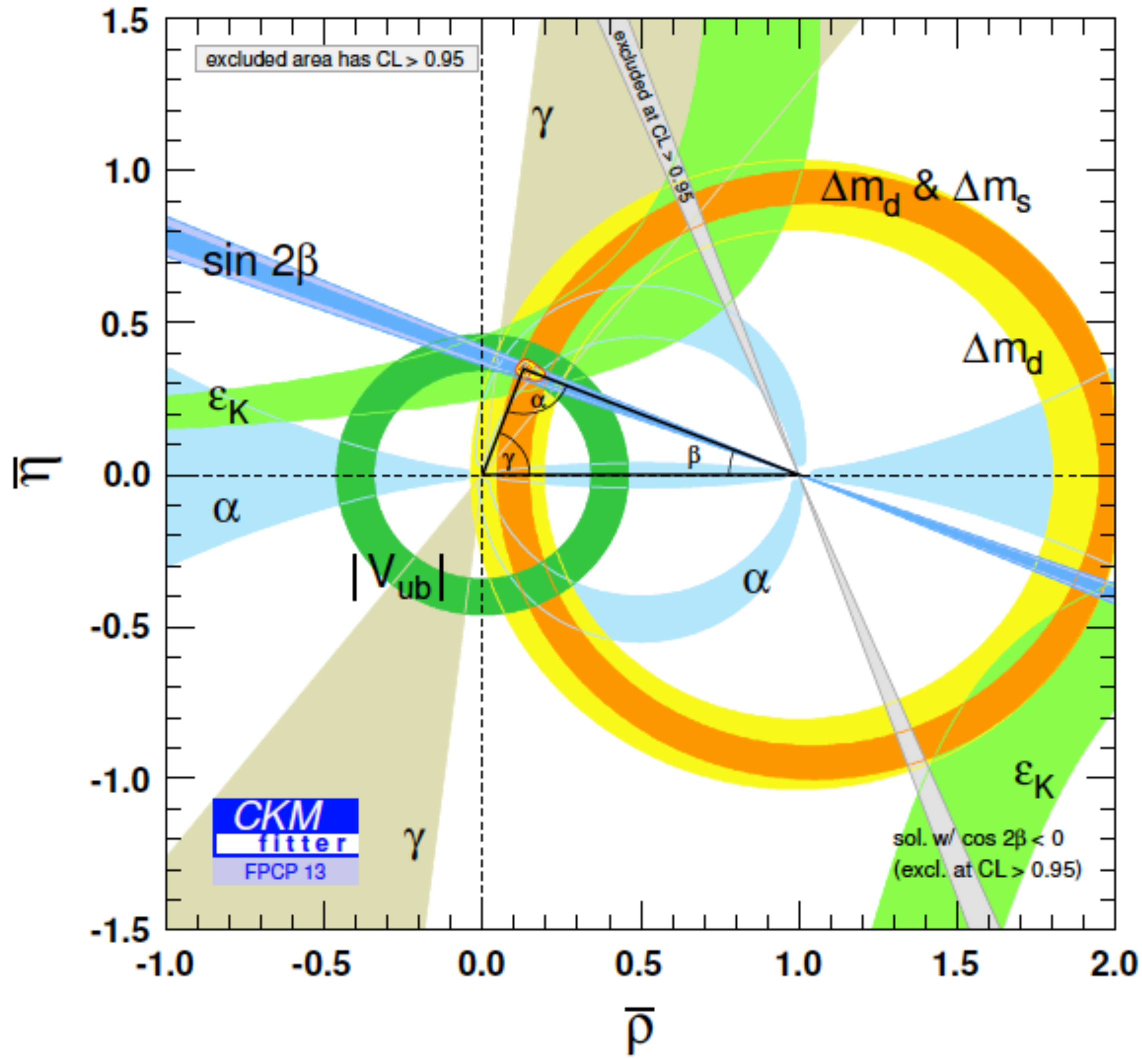
Are these measurements consistent?

- CKM fitter group
- Does a "frequentist" analysis
- Also UT fit group does a "Bayesian analysis

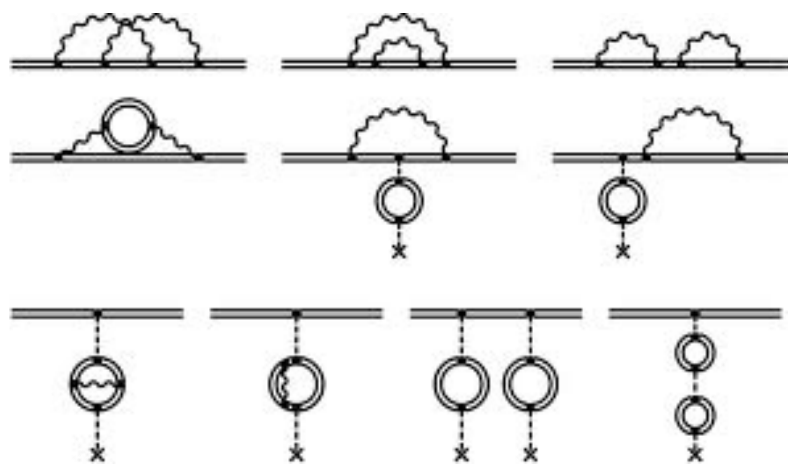


Homework

- Explain how each of the constraint bands in the $\eta-\rho$ plane (previous slide) are generated

Seeking New Physics

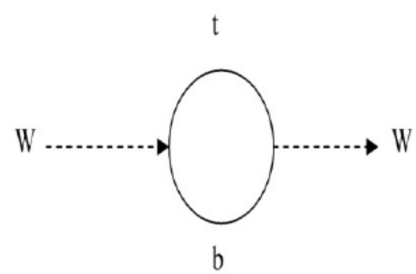
- HFP as a tool for NP discovery
  - While measurements of fundamental constants are fun, the main purpose of HFP is to find and/or define the properties of physics beyond the SM
  - HFP probes large mass scales via virtual quantum loops. An example, of the importance of such loops is the Lamb shift in atomic hydrogen
  - A small difference in energy between $2S_{1/2}$ & $2P_{1/2}$ that should be of equal energy at lowest order



Flavor Physics as a NP discovery tool

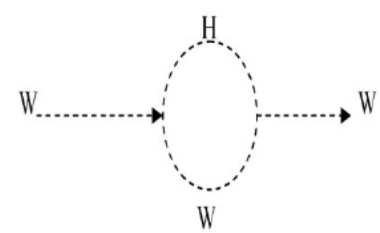
- Another example:
- FP probes large mass scales via virtual quantum loops. An example, of the importance of such loops are changes in the W mass
  - M_w changes due to m_t

$$\frac{dM_W}{dm_t} \alpha \frac{m_t}{M_w}$$



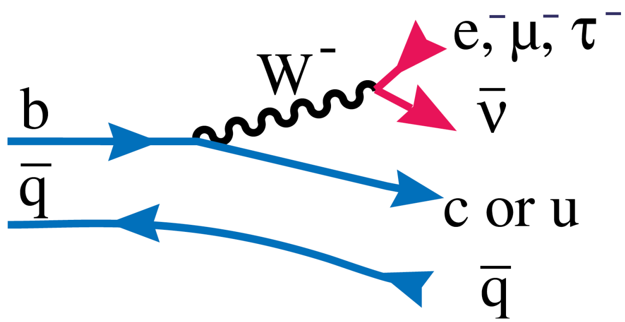
  - M_w changes due to m_H

$$\frac{dM_W}{dm_H} \alpha - \frac{dm_H}{M_H}$$

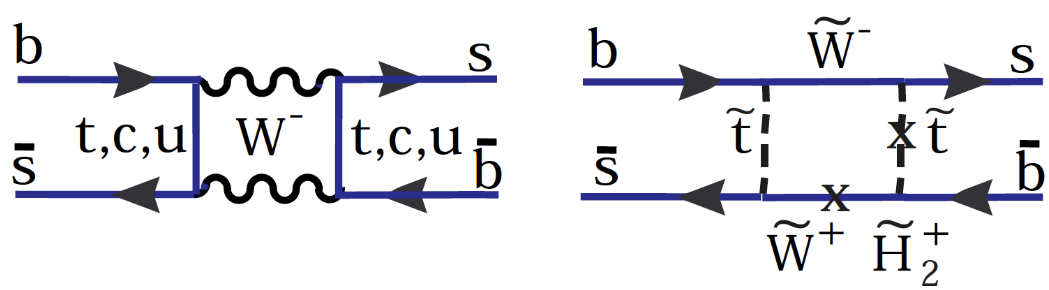


Limits on New Physics

- 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



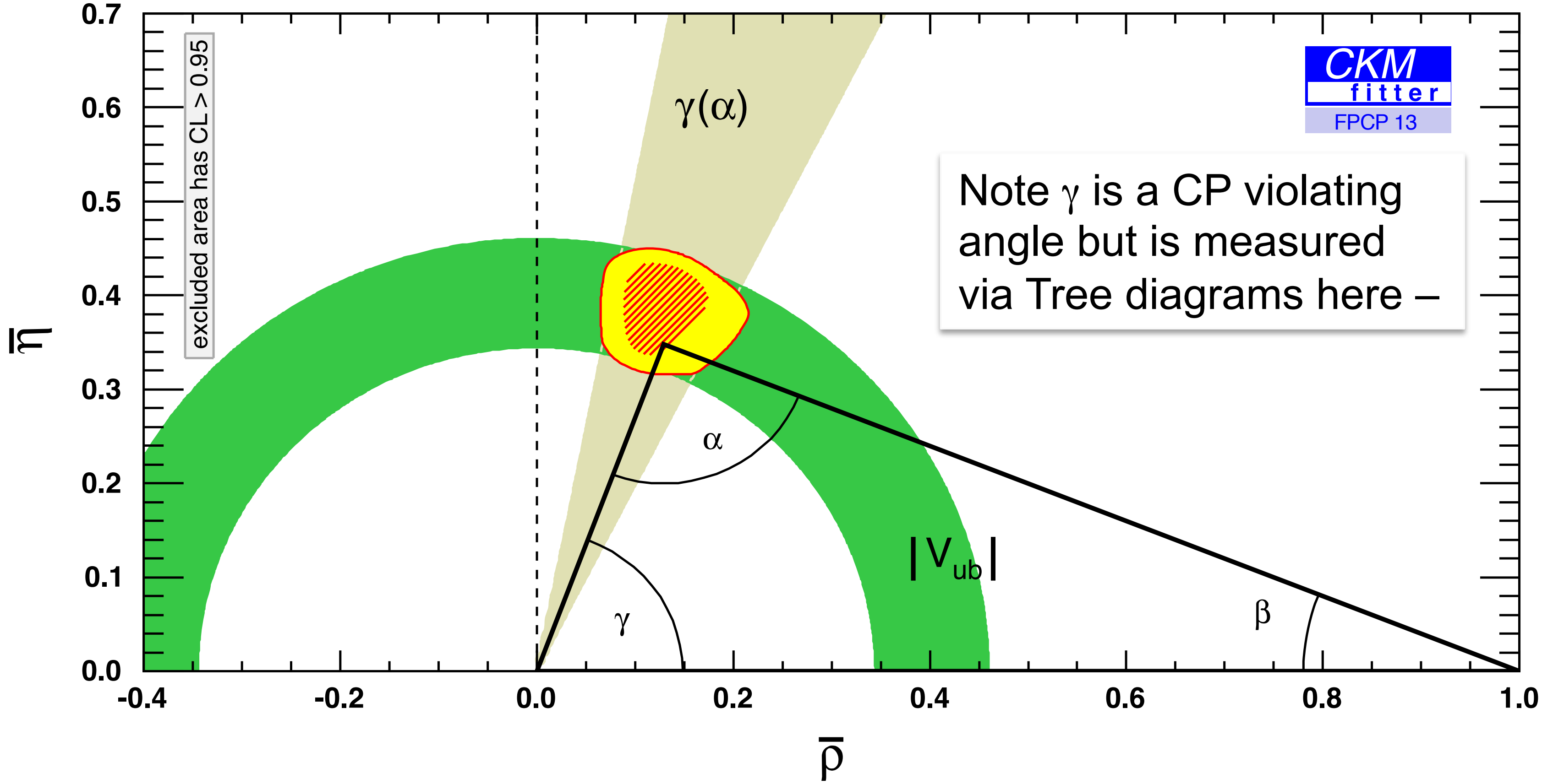
Tree diagram example



Loop diagram example

What are limits on NP from quark decays?

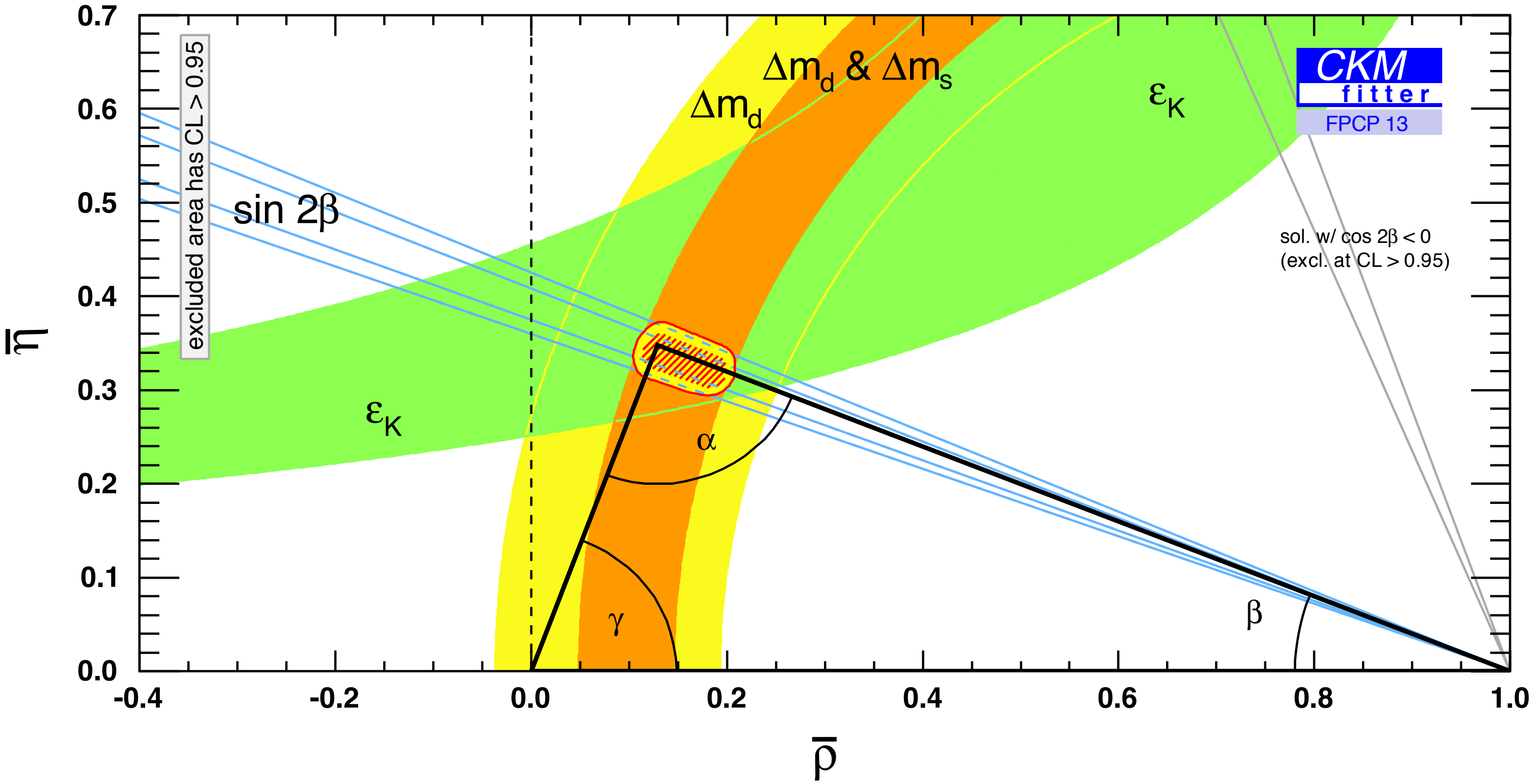
- Tree diagrams are unlikely to be affected by physics beyond the Standard Model



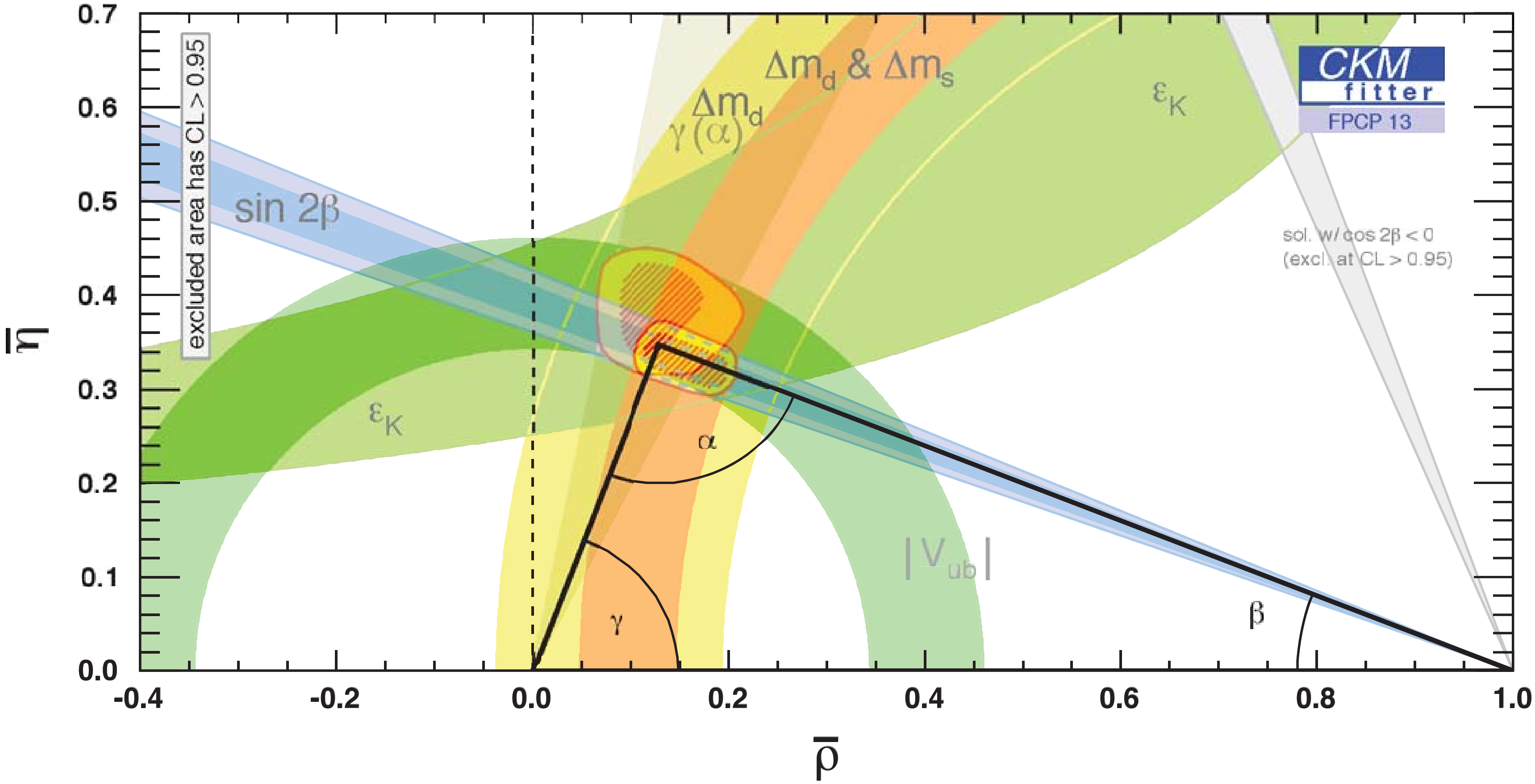
Note γ is a CP violating angle but is measured via Tree diagrams here –

CP Violation in B° & K° Only

- Absorptive (Imaginary) part of mixing diagram should be sensitive to New Physics. Lets compare



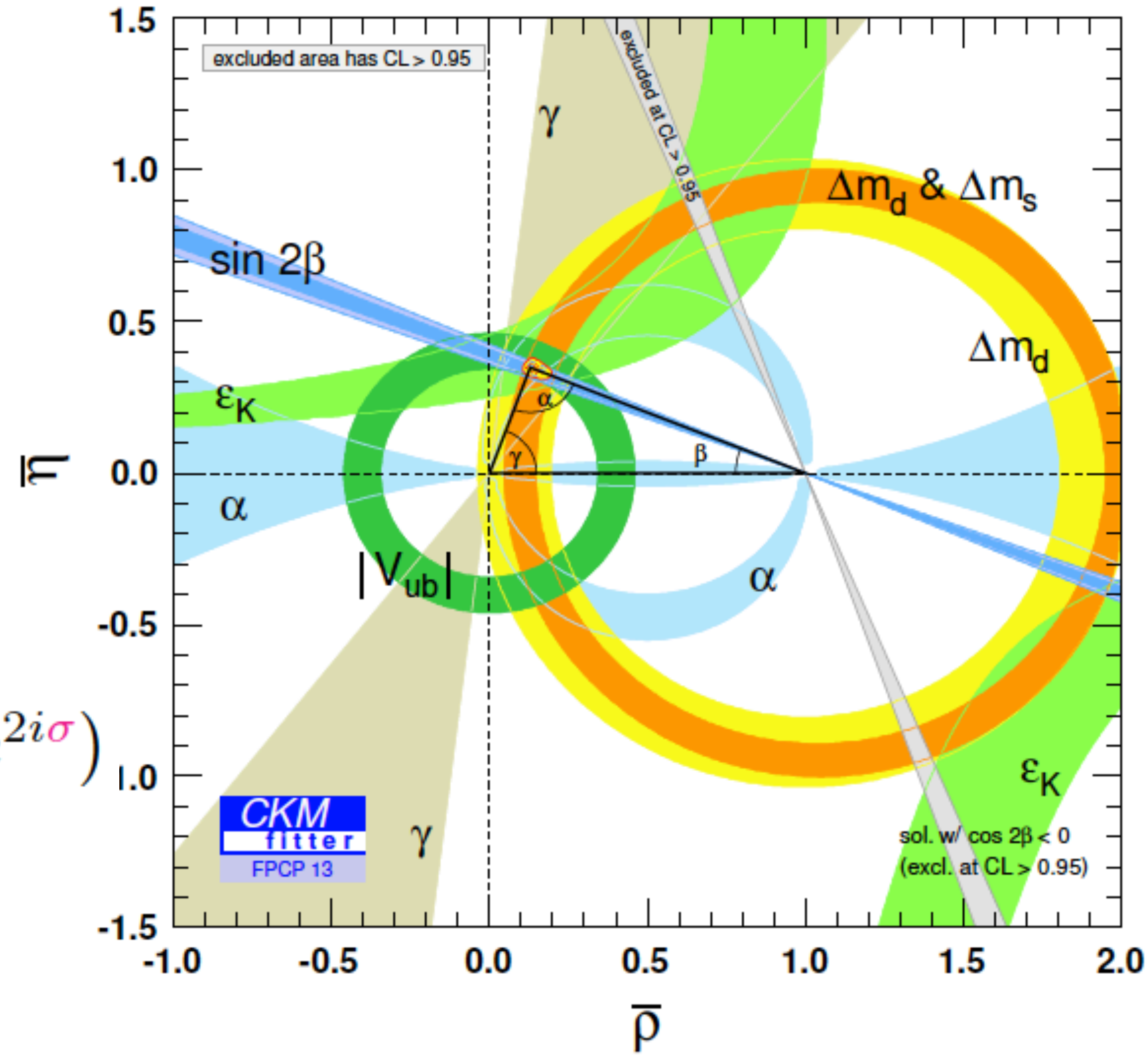
They are Consistent



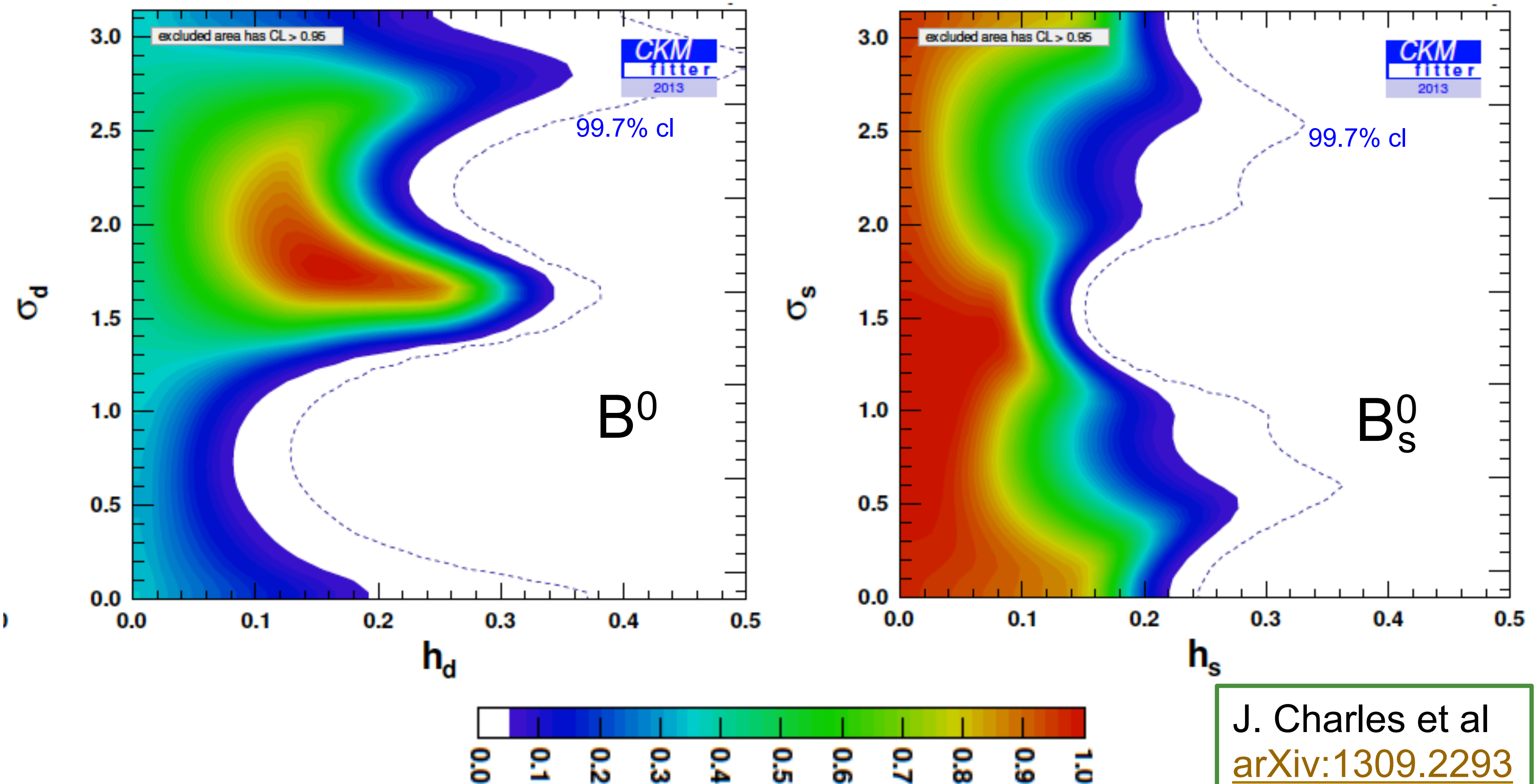
- But consistency is only at the 5% level
- Limits on NP are not so strong

Generic Analyses

- Compare measurements look for discrepancies
- $B^o_{(s)}$ mixing and CP. Parameterize NP as h & σ
- $M_{12} = M_{12}^{\rm SM} \times \left(1 + h\, e^{2i\sigma}\right)$



Limits on New Physics

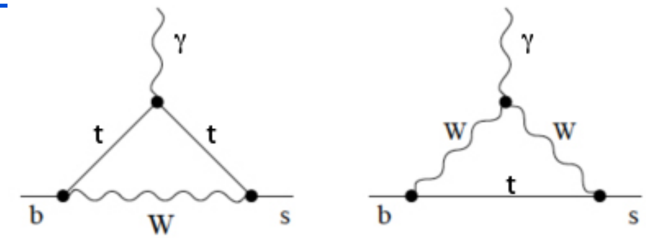


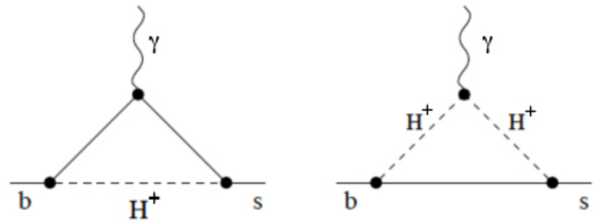
J. Charles et al
arXiv:1309.2293

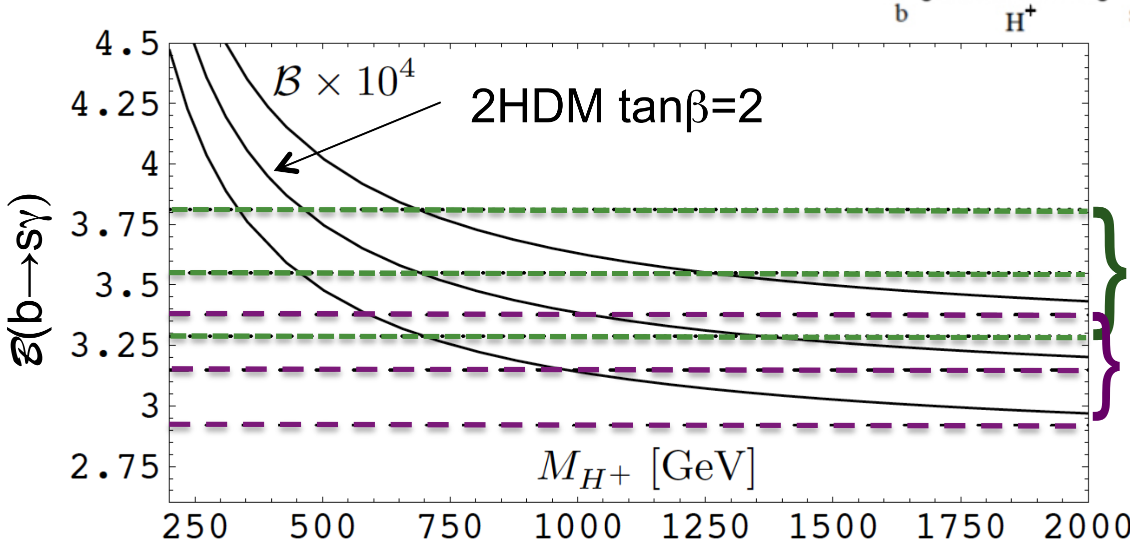
New Physics amplitudes could be ~20% of Standard Model

Ex. of Strong Constraints on NP

- Inclusive $b \to s\gamma$, ($E\gamma > 1.6$ GeV)
  - Measured $(3.55\pm0.26)\times10^{-4}$ (HFAG)
  - Theory $(3.15\pm0.23)\times10^{-4}$ (NNLL) Misiak arXiv:1010.4896
  - Ratio = 1.13±0.11, Limits most NP models
  - Example 2HDM
  - $m(H^+) < 316$ GeV







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

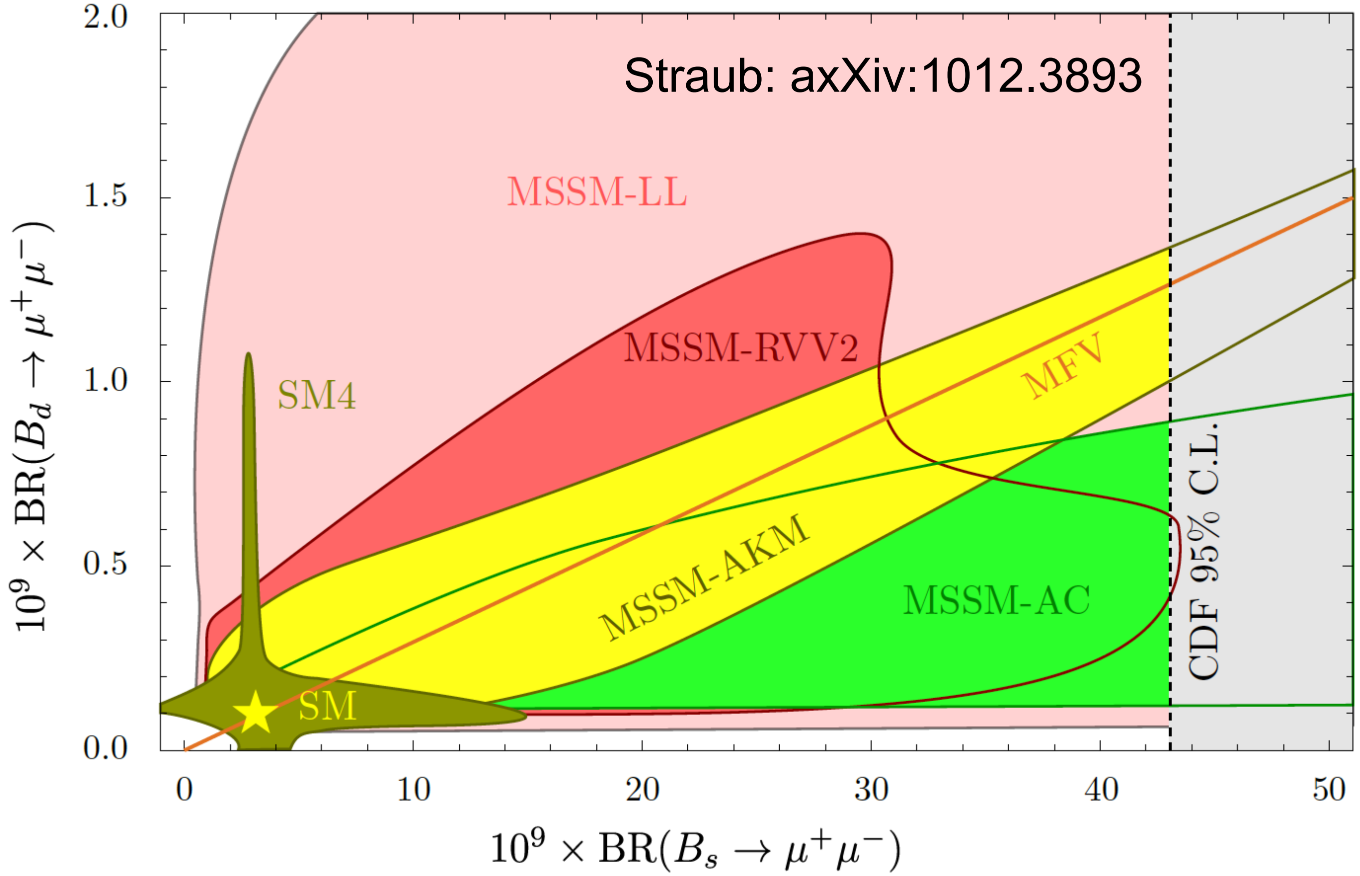
Theorists task

- 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.

Top Down Analyses

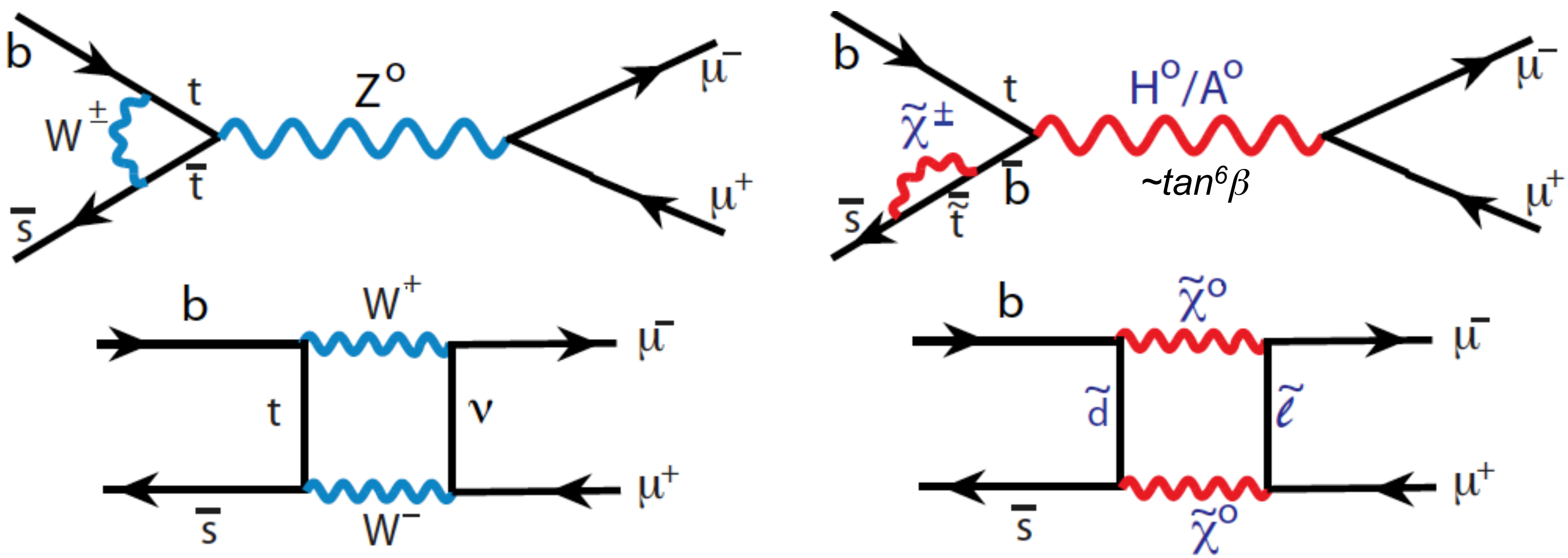
- Here we pick models and work out their consequences in many modes. Ex. (circa 2010):



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

- SM branching ratio is $(3.5\pm0.2)\times10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

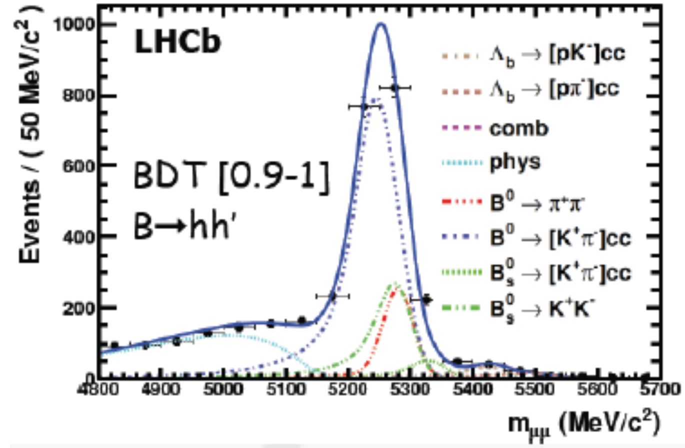
Standard Model | MSSM

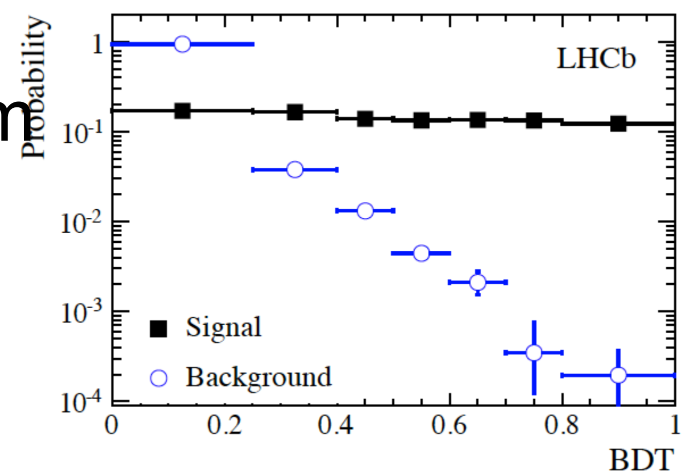


- Many NP models possible, not just Super-Sym

Discrimination

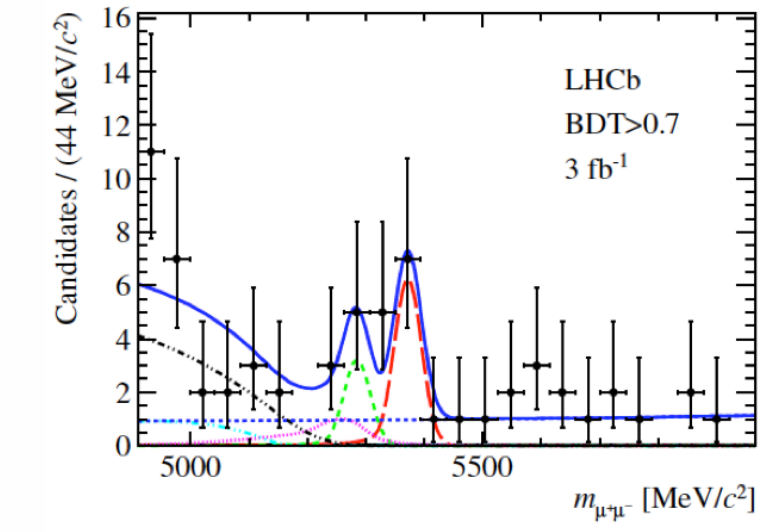
- LHCb uses $B \to h^+h^-$ to tune cuts for a multivariate analysis
- Other variables to discriminate against bkgrd : B impact parameter, B lifetime, B p_t, B isolation, muon isolation, minimum impact parameter of muons, …
- B_s production is measured by using the LHCb measured ratio f_s/f_d. New value of 0.259±0.015





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

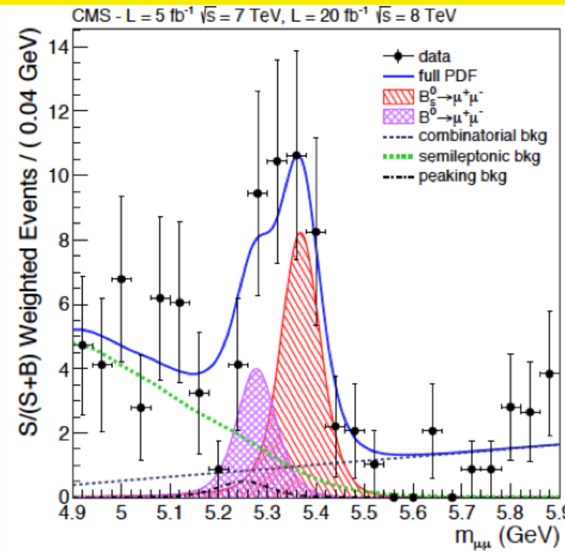
LHCb: arXiv:1307.5024, PRL.111.101805 (2013)



$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}) \times 10^{-10}$$

--> 4.0σ

CMS: arXiv:1307.5025, PRL. 111.101804 (2013)

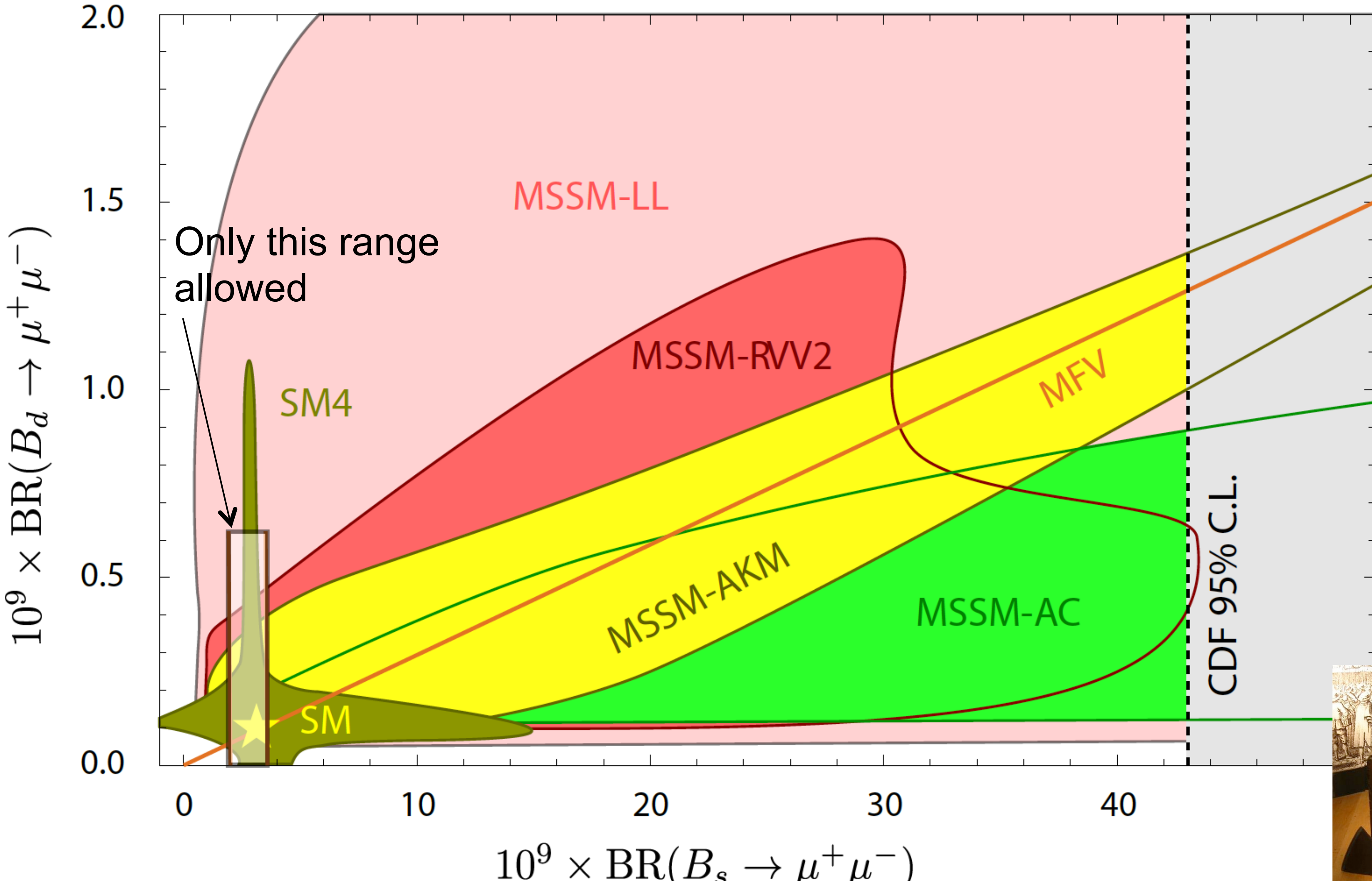


$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.0\,^{+1.0}_{-0.9}) \times 10^{-9},$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.5\,^{+2.1}_{-1.8}) \times 10^{-10}$$

--> 4.3σ

- Avg: $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$
- Avg: $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}$ (not significant)

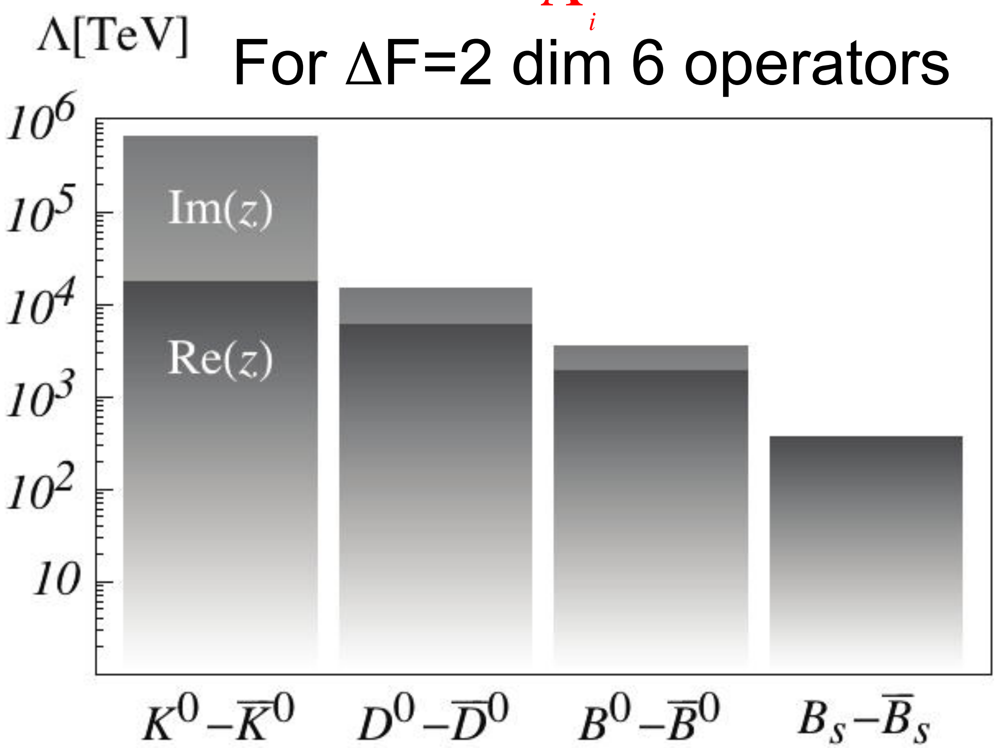
Implications



Flavor as a High Mass Probe

- Already excluded ranges from box diagrams
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$, take c_i ~1

For ΔF=2 dim 6 operators



Ways out

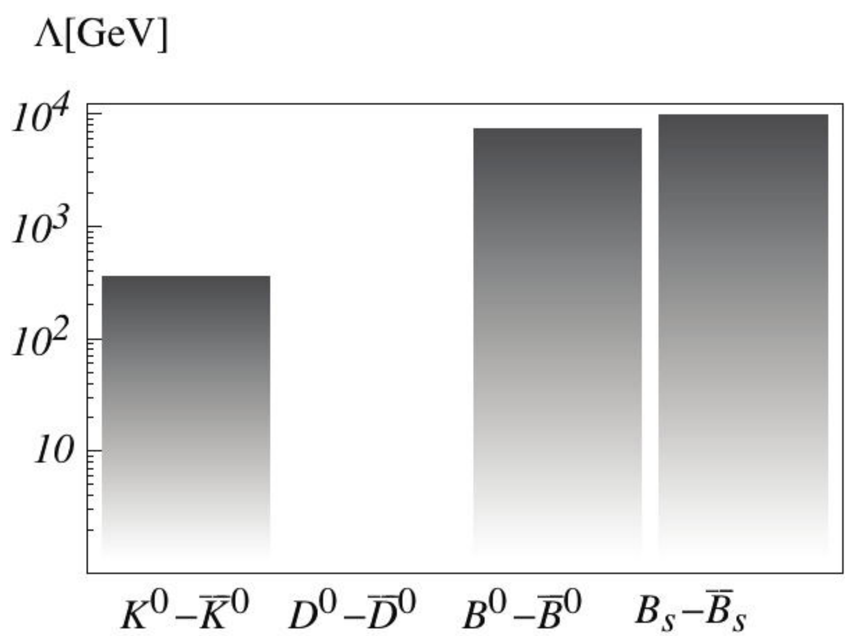
1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk; Kamenik Mod Phys Lett A201429

Minimum flavor violation

- Assumes all flavor violating and CP-violating transitions are governed by the CKM matrix and the only relevant local operators are the ones that are relevant in the SM
- Not a theoretical model

Constraints on NP in terms of effective operator scale in MFV

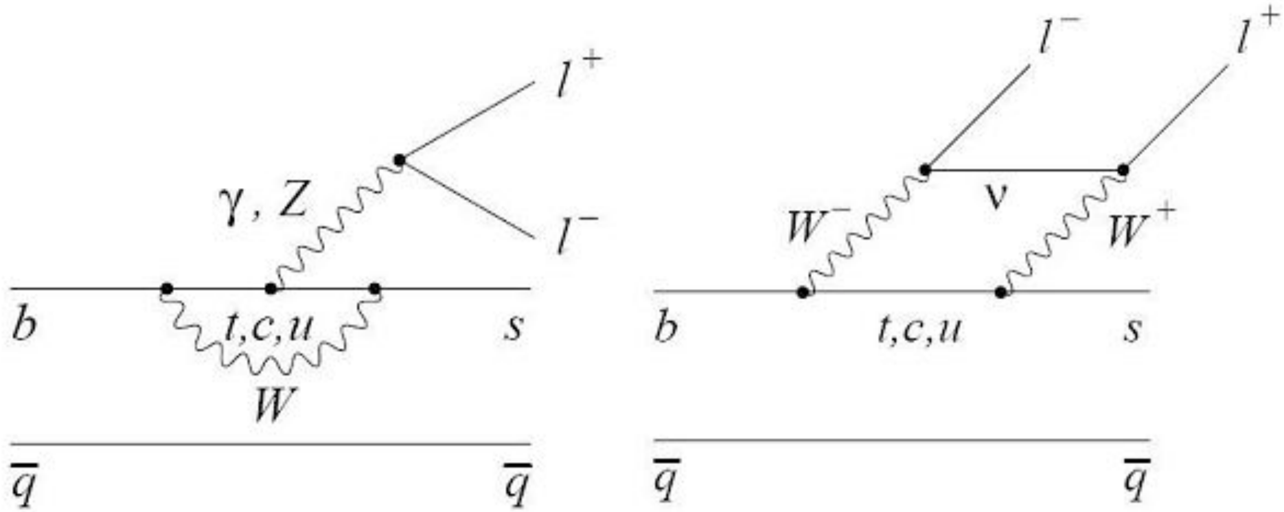


Kamenik, Mod Phys Lett A201429

Some hints of discrepancies with SM

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

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

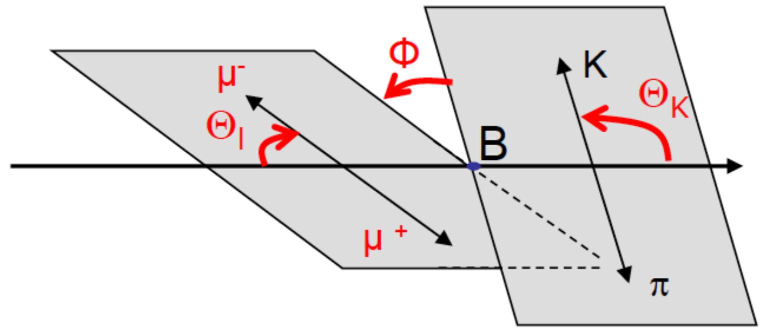


+ new particles in loops

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

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

- Decay described by 3 angles & dimuon invariant mass (q^2)

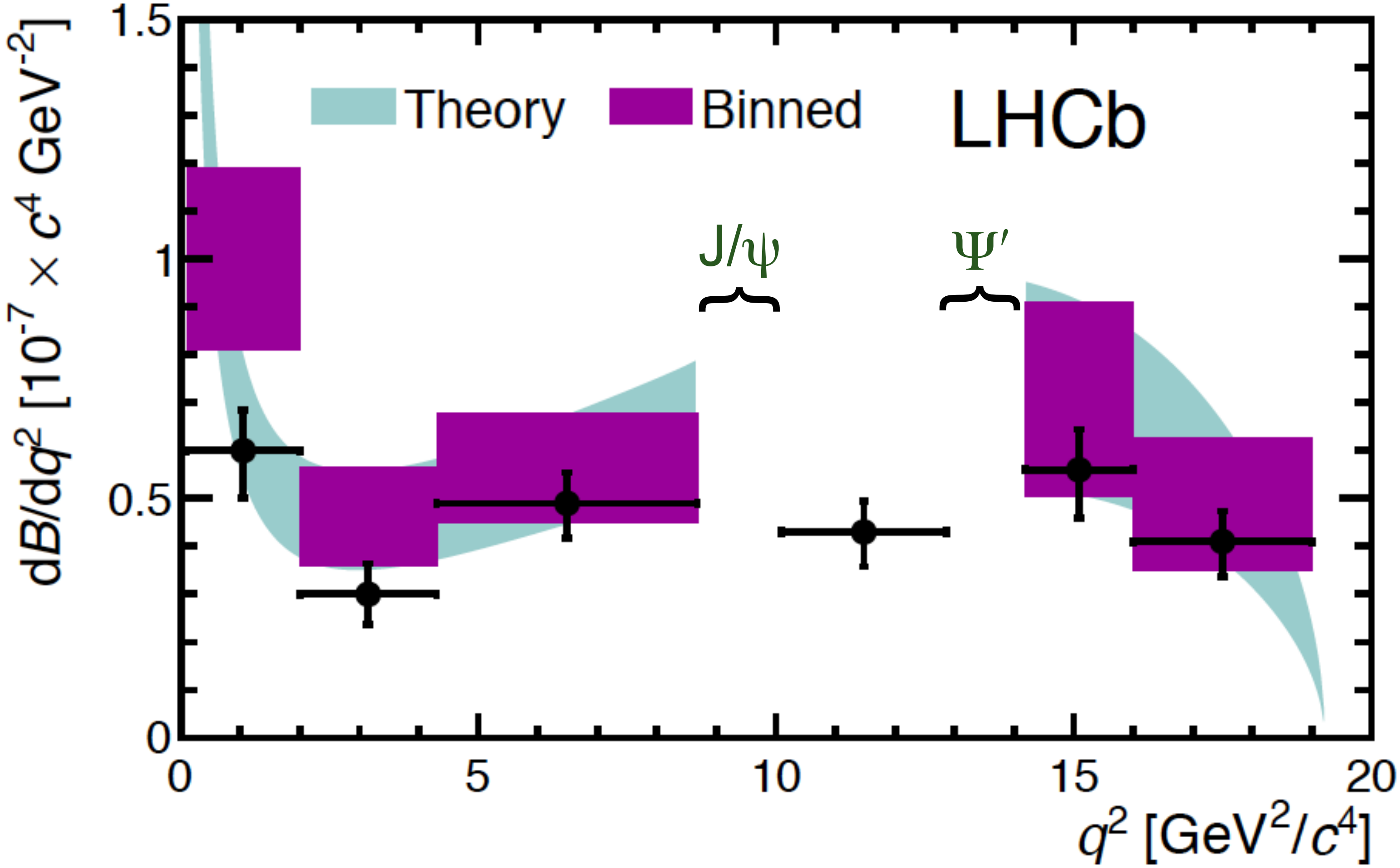


- For each bin in q^2

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{16\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \frac{1}{2}(1-F_L)A_T^{Re}\sin^2\theta_K\cos\theta_\ell + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- F_L is fraction of longitudinally polarized K^{*0}
- A_{FB}, forward-backward asymmetry $=\frac{3}{4}(1-F_L)A_T^{\mathrm{Re}}$
- SM prediction of q^2 for A_{FB} crossing 0 is $q_0^2 = 4.36^{+0.33}_{-0.31}\, GeV^2$ (Beneke)

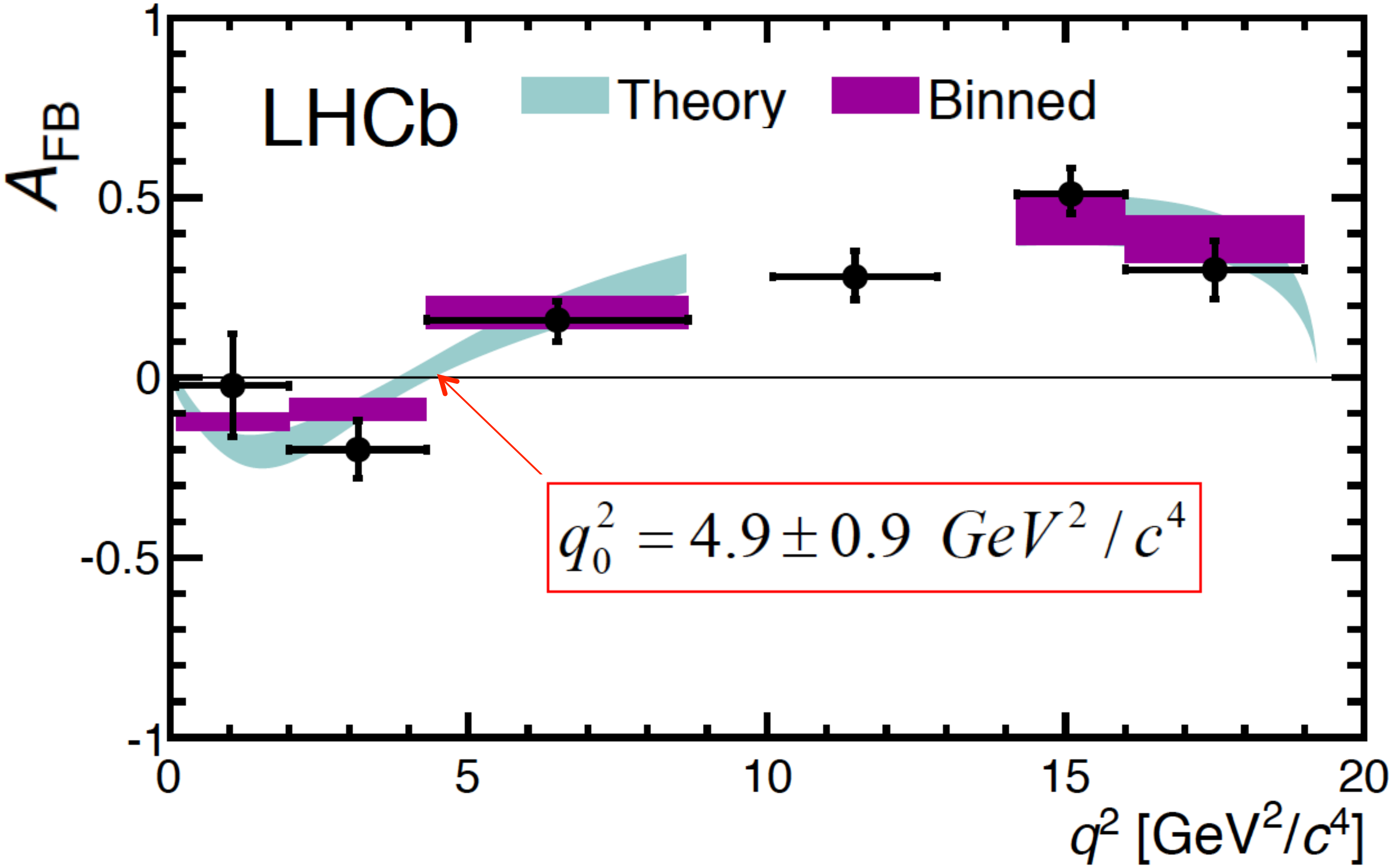
$B^o \rightarrow K^{*o}\ell^+\ell^-$



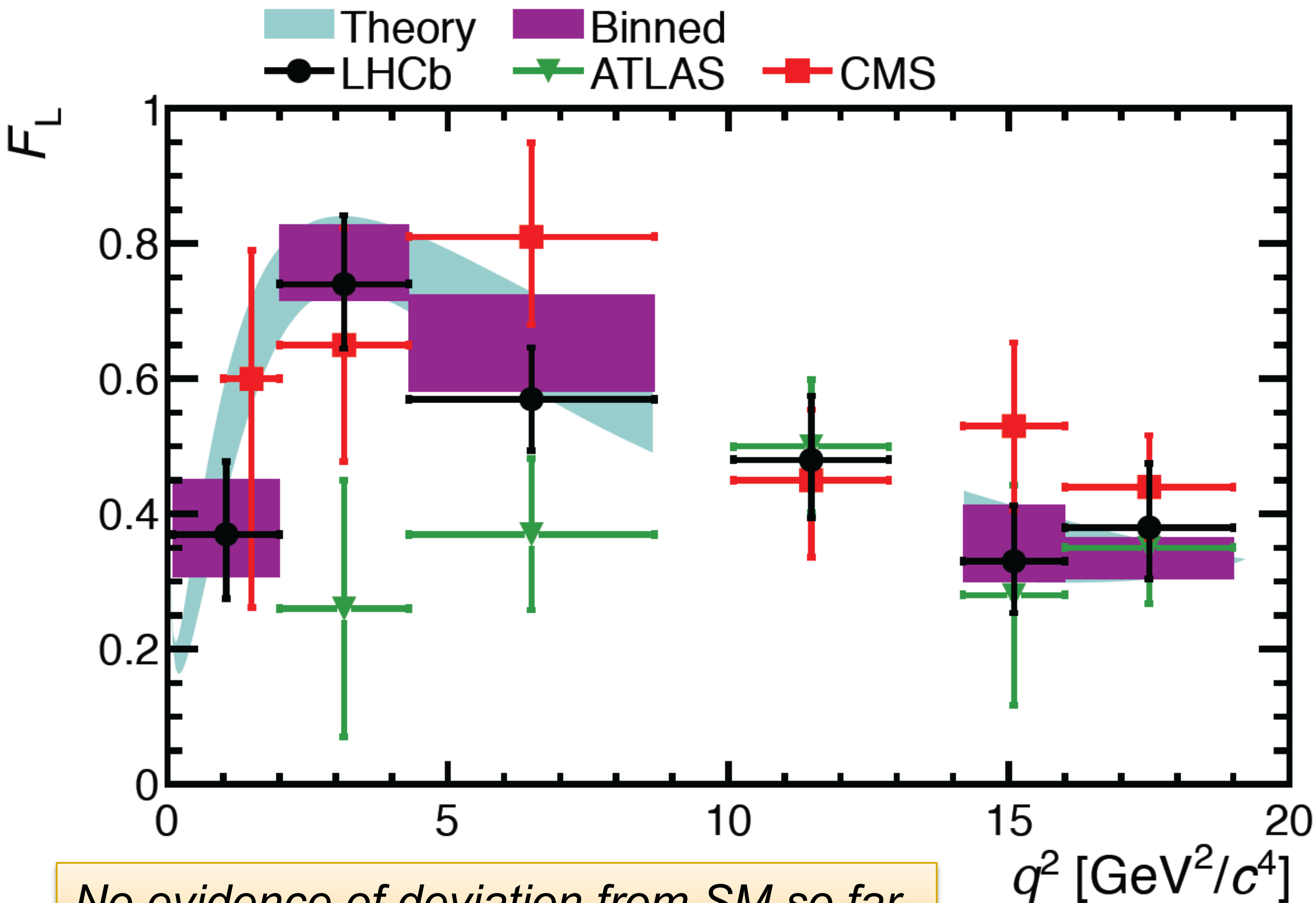
Other data from ATLAS, CDF, CMS BaBar & Belle

- Conforms to SM predictions by Bobeth et al. & Matias et al

Forward-Backward asymmetry



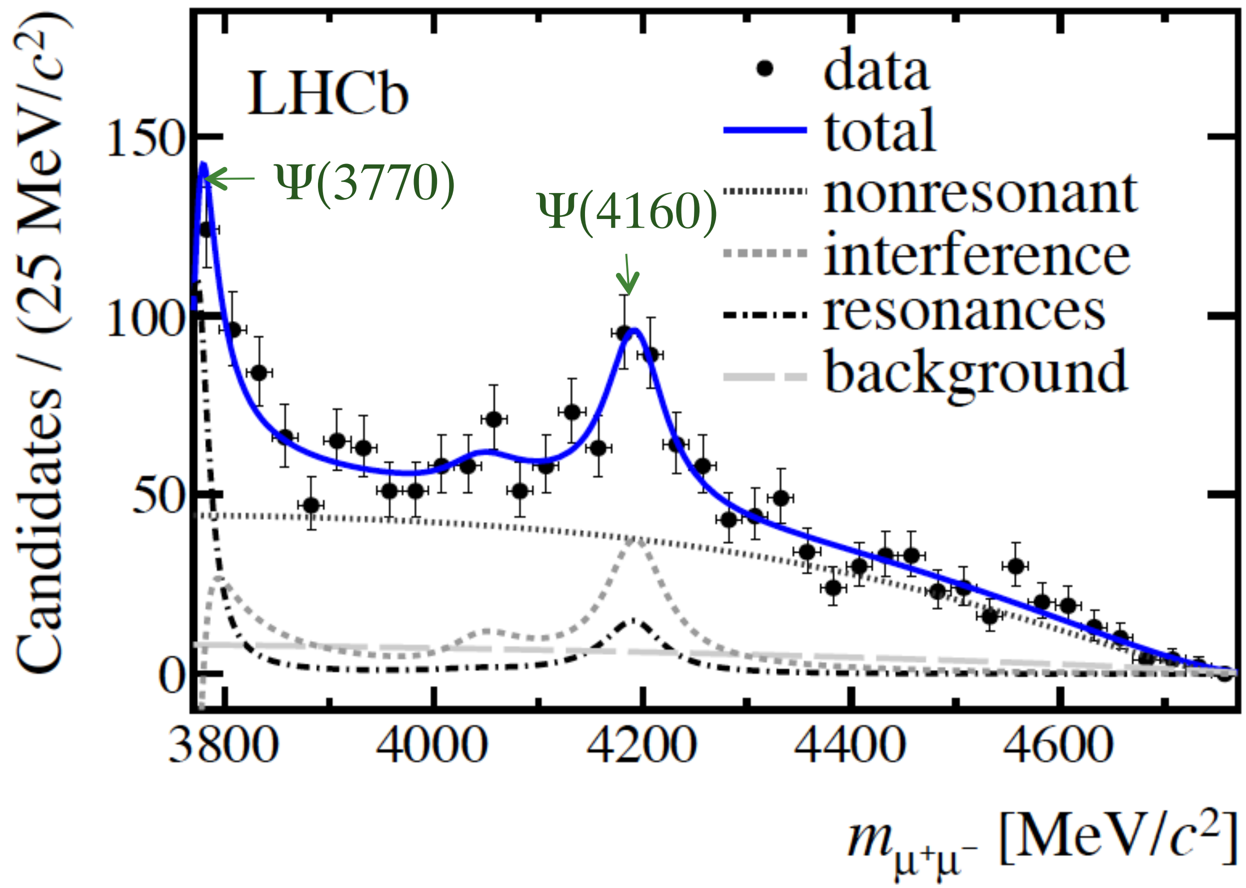
A_{FB} with ATLAS & CMS



No evidence of deviation from SM so far

$B^- \to K^- \ell^+ \ell^-$

- Resonances found in high q^2 region
- One would think they would be in $K^{*o}\ell^+\ell^-$ also
- Should affect theory predictions



More ∠variables

- Back to $K^{(*)}\ell^+\ell^-$, new observables in formalism designed to less sensitive to hadronic form-factors

Descotes-Genon et al arXiv:1303.5794

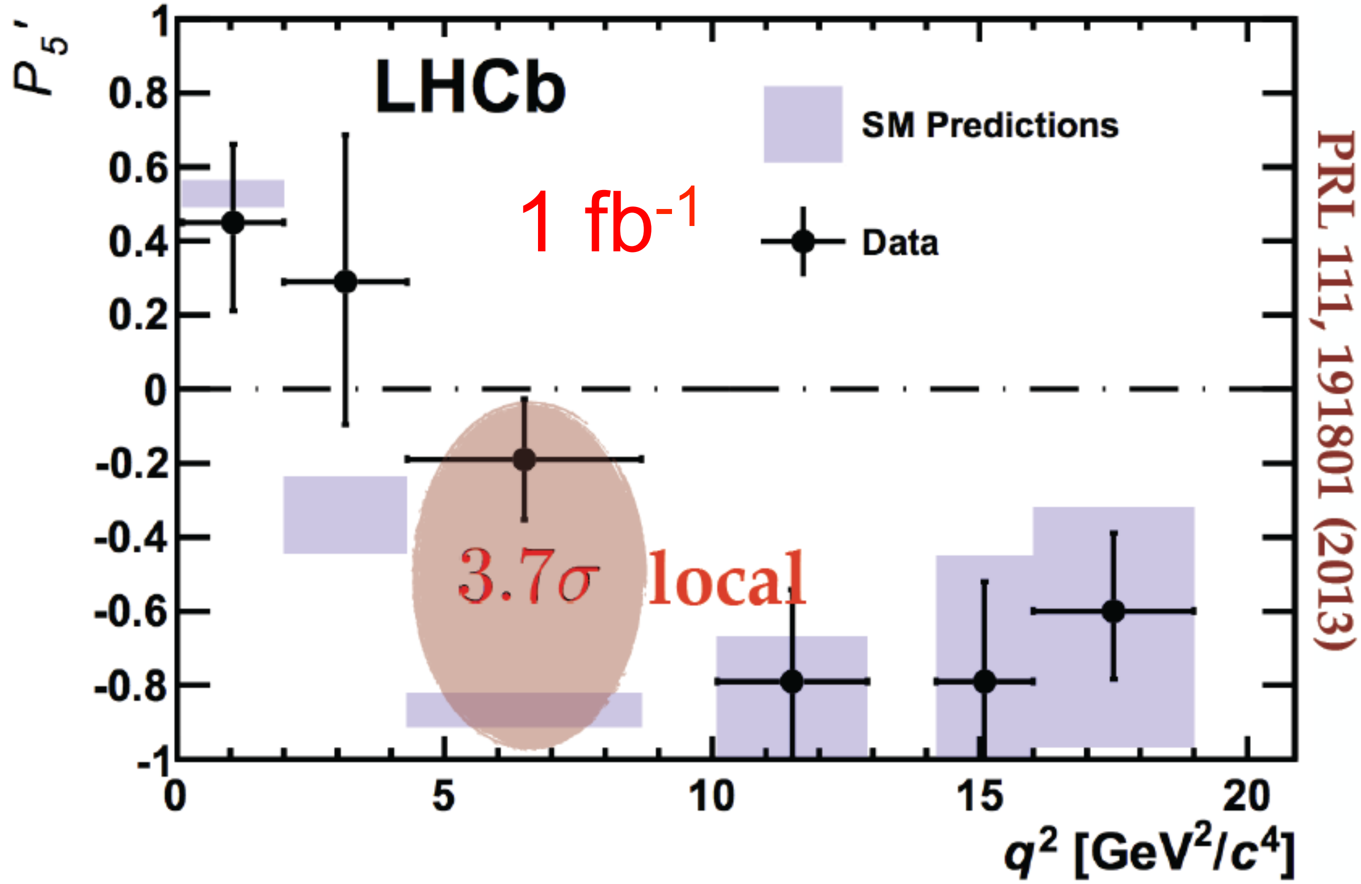
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Possible deviation

- Could be something,

but significance depends on theoretical model, &

deviation is only in one place



Test of lepton universality

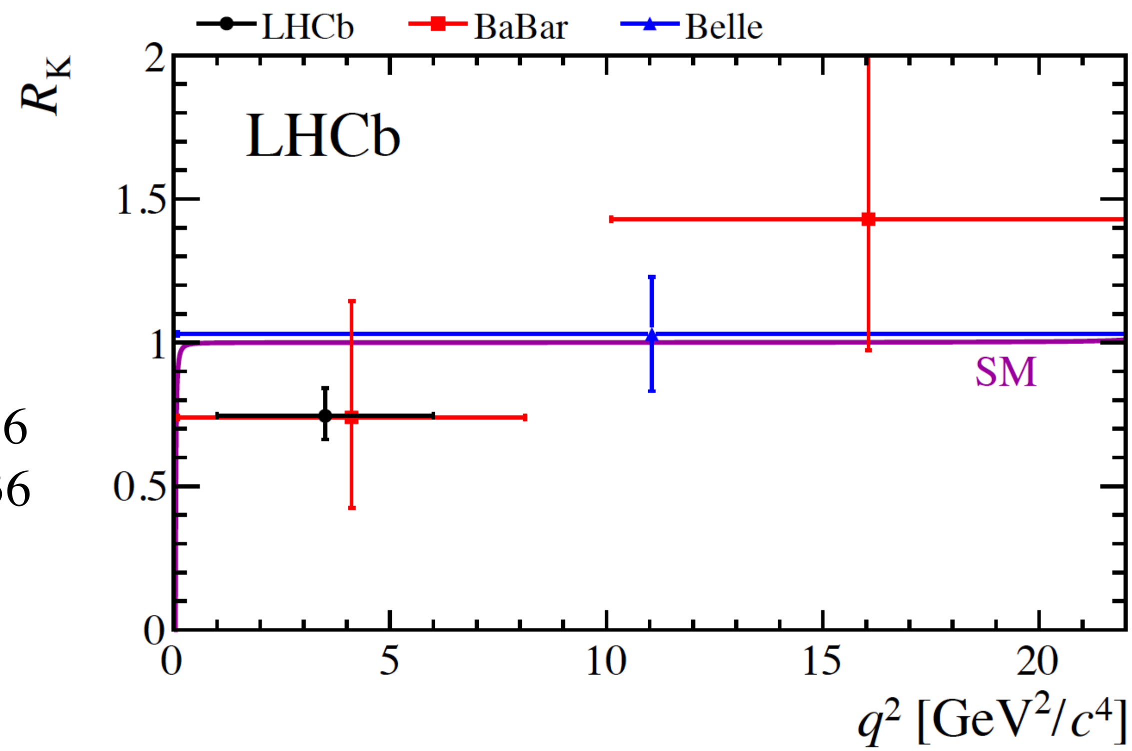
- The ratio of branching fractions

$$R_K \equiv \frac{\mathcal{B}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathcal{B}\left(B^+ \to K^+e^+e^-\right)}$$ is expected to be $1+\mathcal{O}(10^{-3})$

- Data
- LHCb result for $6>q^2>1$ GeV^2

$$R_K = 0.745^{+0.090+0.036}_{-0.074-0.036}$$

2.6 σ from SM



Rare Decays - Generic

- $$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.} \ .$$
- $C_i O_i$ 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

Other Processes

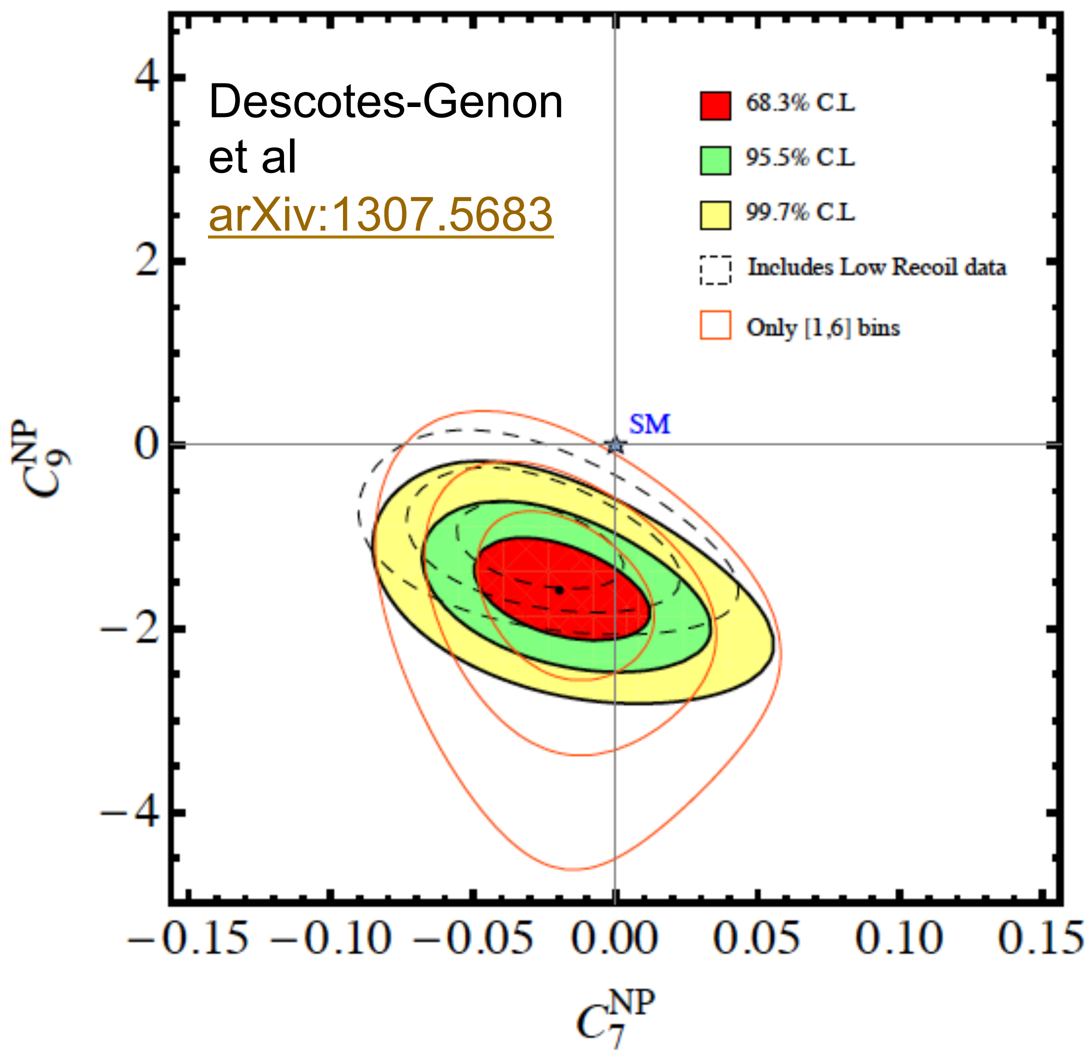
- Other processes probe different operators
- Let $\delta Ci = C_i(NP) - C_i(SM)$
- Examples:

$$\mathcal{B}(B \to X_s \mu^+ \mu^-) = 10^{-7} \times \left[\sum_{i,j=0,7,7',9,9',10,10'} b_{(i,j)} \delta C_i \delta C_j \pm \delta_b \right]$$

$$\mathcal{B}(\bar{B} \to X_s \gamma)_{E_\gamma > 1.6\,\mathrm{GeV}} = \Big[a_{(0,0)} \pm \delta_a + a_{(7,7)} \left[(\delta C_7)^2 + (\delta C_{7'})^2 \right] + \\ + a_{(0,7)}\, \delta C_7 + a_{(0,7')}\, \delta C_{7'} \Big] \cdot 10^{-4}$$

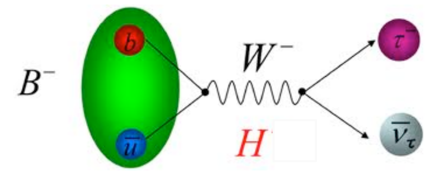
Maximizing deviations

- Filled bands: $B \to K^* \mu^+ \mu^-$, $K^* \gamma$ & $B_s \to \mu^+ \mu^-$
- Dashed: all q^2 for $K^* \mu^+ \mu^-$
- Orange: only $1 < q^2 < 6$ GeV^2 for $K^* \mu^+ \mu^-$



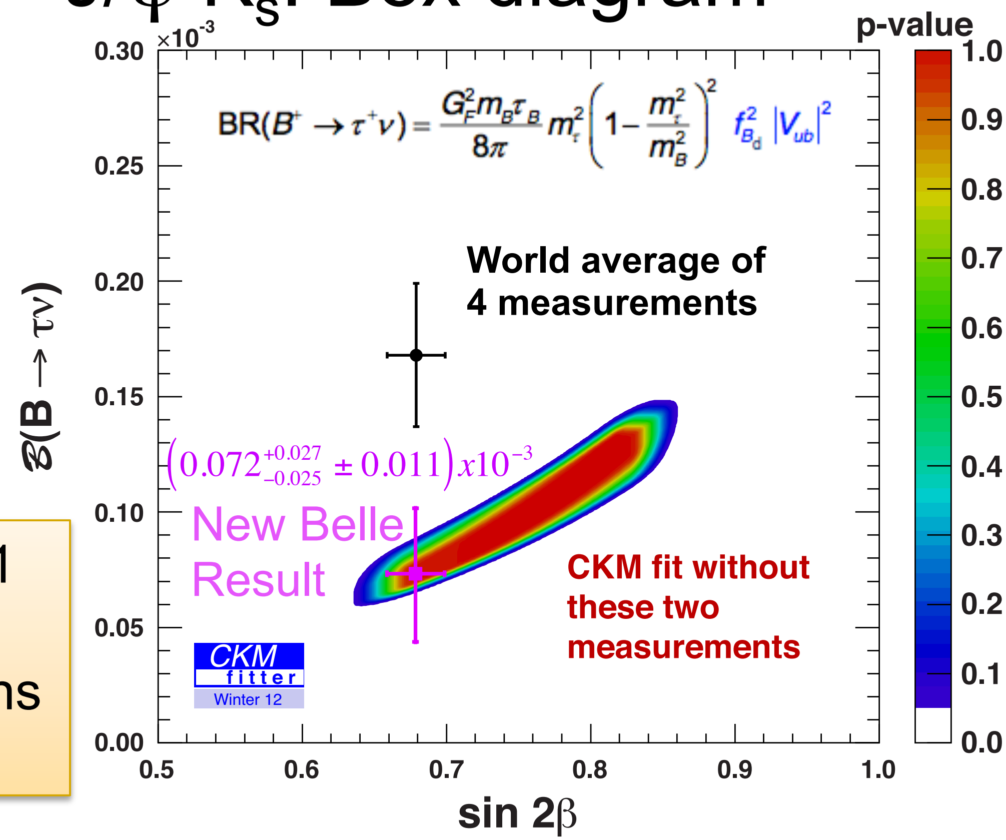
$B^- \to \tau^- \bar{\nu}$ problem?

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



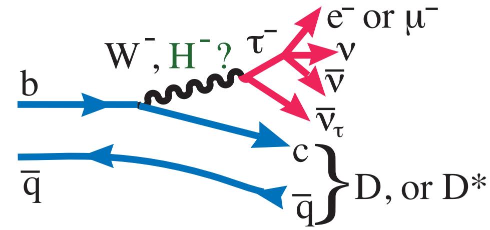
Can be new particles instead of W^- but why not also in $D^+_{(s)} \to \ell^+ \nu$?

- 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



New Belle measurement in using 1 method. Discrepancy may be resolved, but 3 other determinations need to be checked

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

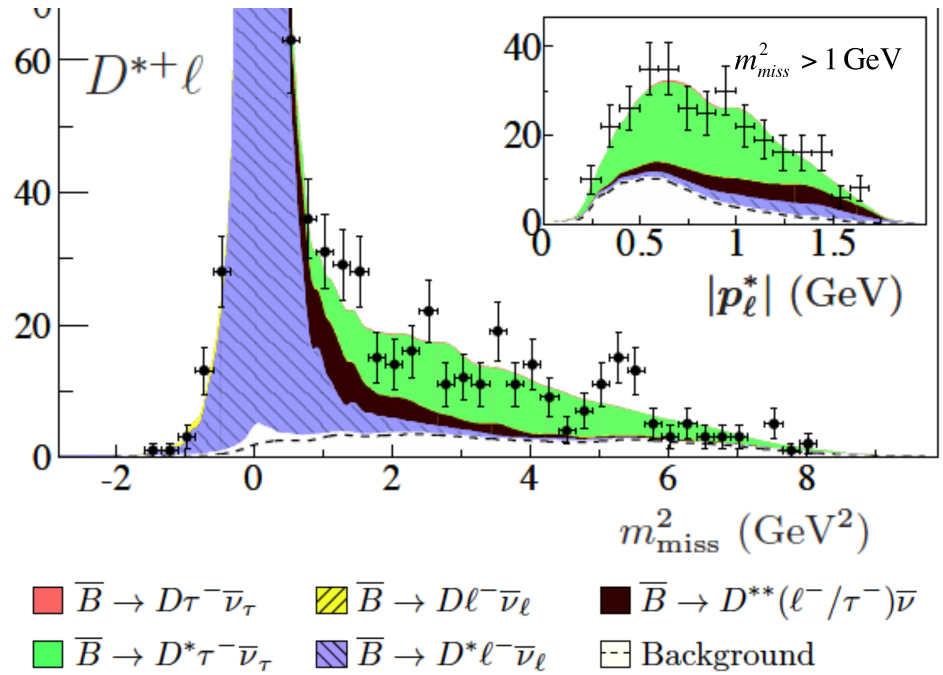


- Also, tree level – BaBar result
- Similar to $B^- \rightarrow \tau^- \nu$ analysis
- Fully reconstruct

one B, keep events with an additional $D^{(*)}$ plus an e^- or μ^-.

- Signal is wide,

background, especially $D^{**}\ell\,\nu$, needs careful estimation

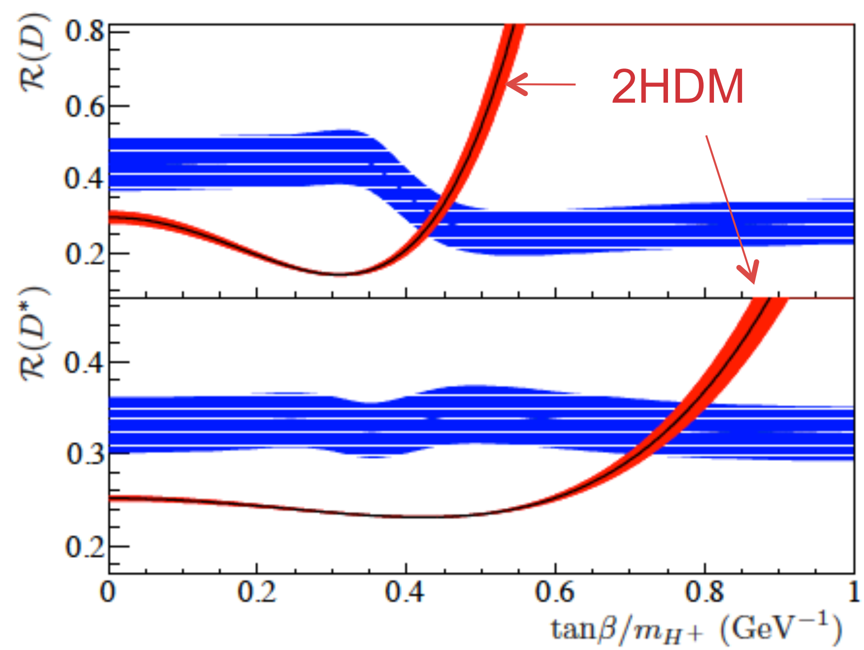


$B \to D^{(*)}\tau\nu$ II

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

	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

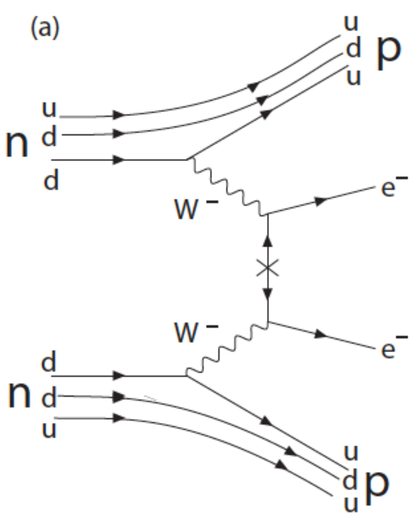


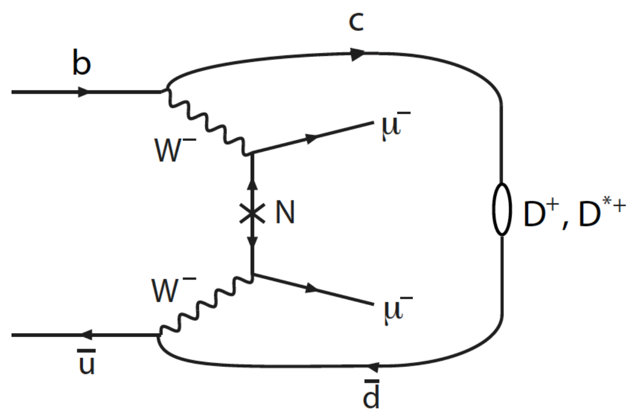
Other searches

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

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

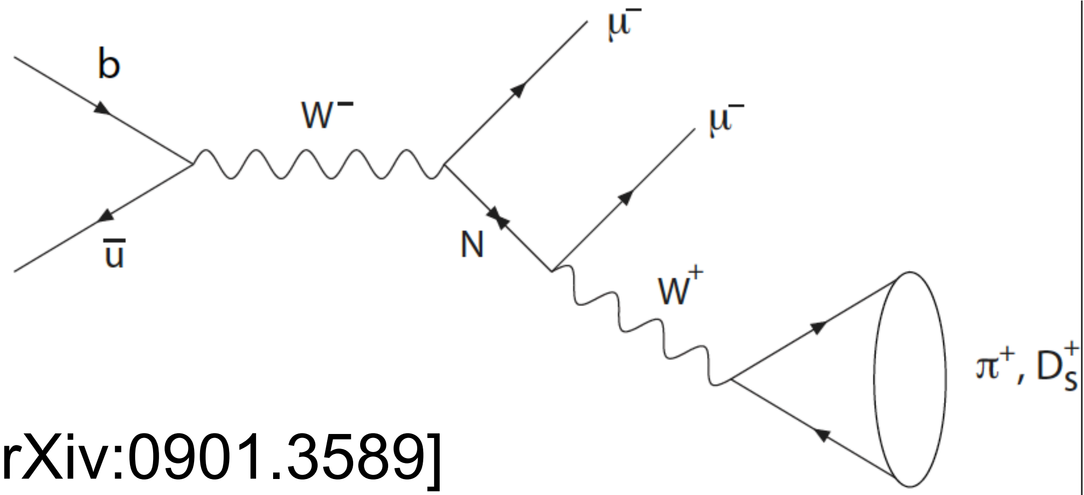
- Upper limits in e^-e^- mode not competitive with nuclear β decay
- Others unique since measure coupling of Majorana ν to μ^-

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

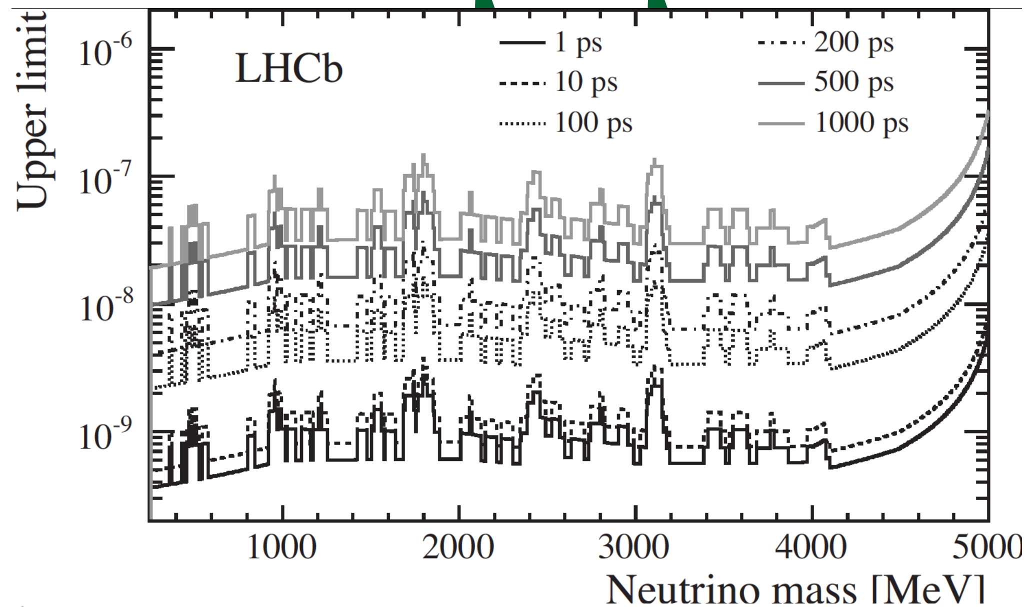
- Can also look for Majorana ν (N), where $N \rightarrow W^{+}\mu^{-}$
- A. Atre, T. Han, S. Pascoli, & B. Zhang [arXiv:0901.3589]

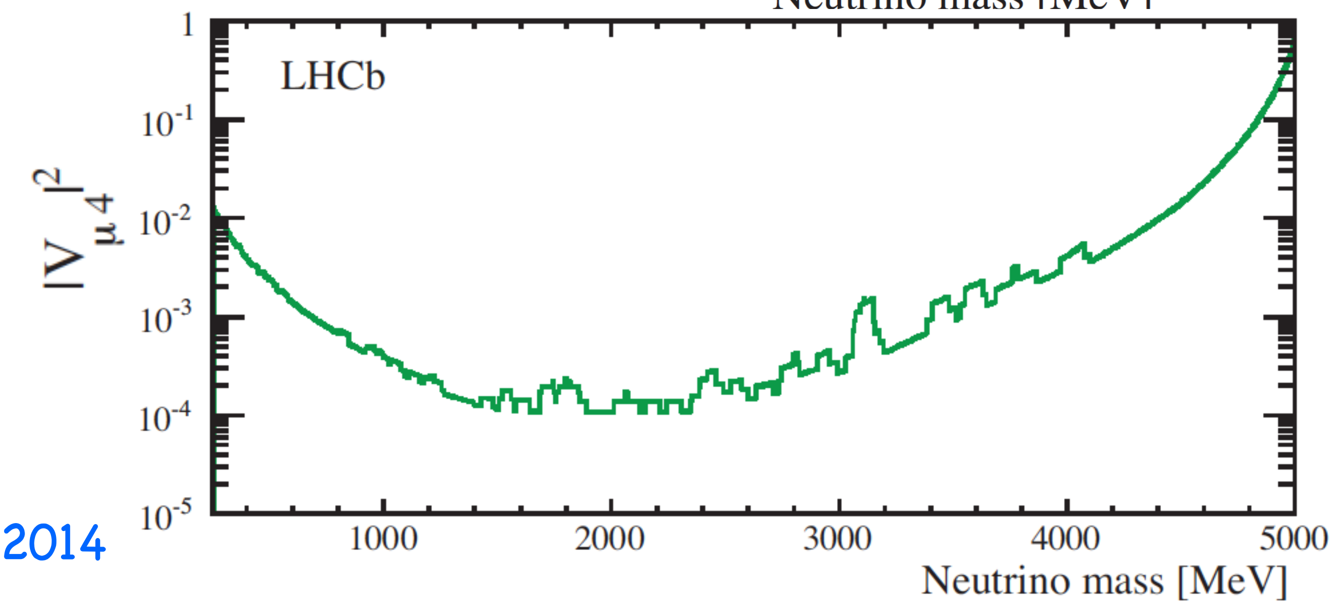


- Many other ways of searching:
  - $K^{-} \rightarrow \pi^{-} N$
  - $\mu^{-} \rightarrow e^{-} \gamma$
  - $\tau^{-} \rightarrow \mu^{+} \pi^{-} \pi^{-}$
  - …..

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

LHCb search as a function of Majorana neutrino mass and lifetime



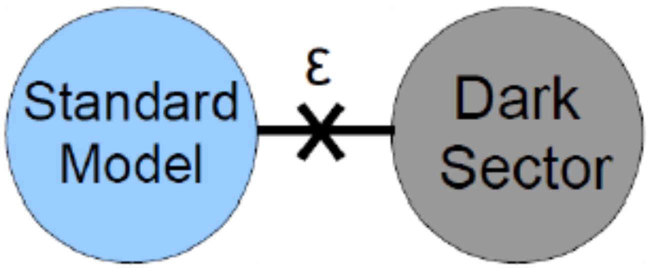


The Dark Sector

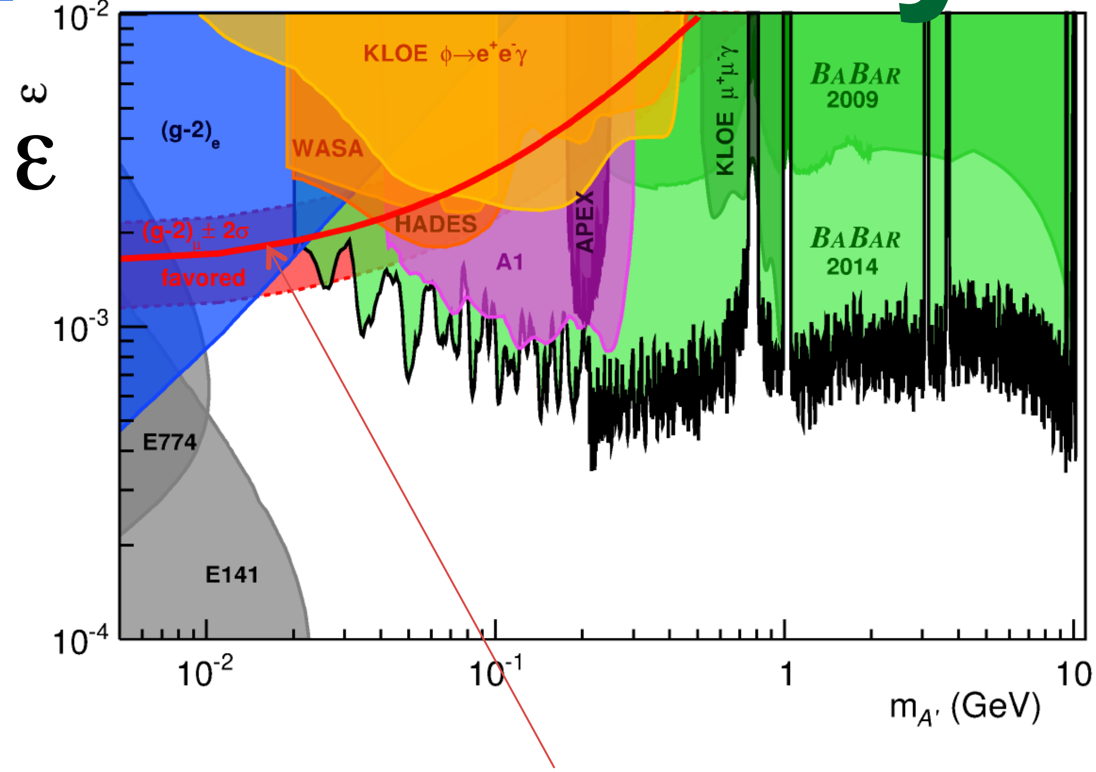
- Could it be that there are 3 classes of matter?
  - SM particles with charges [SU(3)xSU(2)xU(1)]
  - Dark matter particles with "dark" charges
  - Some matter having both ("mediators")
- Searches for "dark photons"
  - A mediator, couples to b-quarks (see arXiv:056151 hep/ph)
  - BaBar $\mathcal{B}(\Upsilon(1S)\rightarrow \text{invisible}) < 3\times10^{-4}$ @ 90% cl
  - Other experiments

Search Summary

- Parameterize by mixing ε



- Dark photon mass mA´



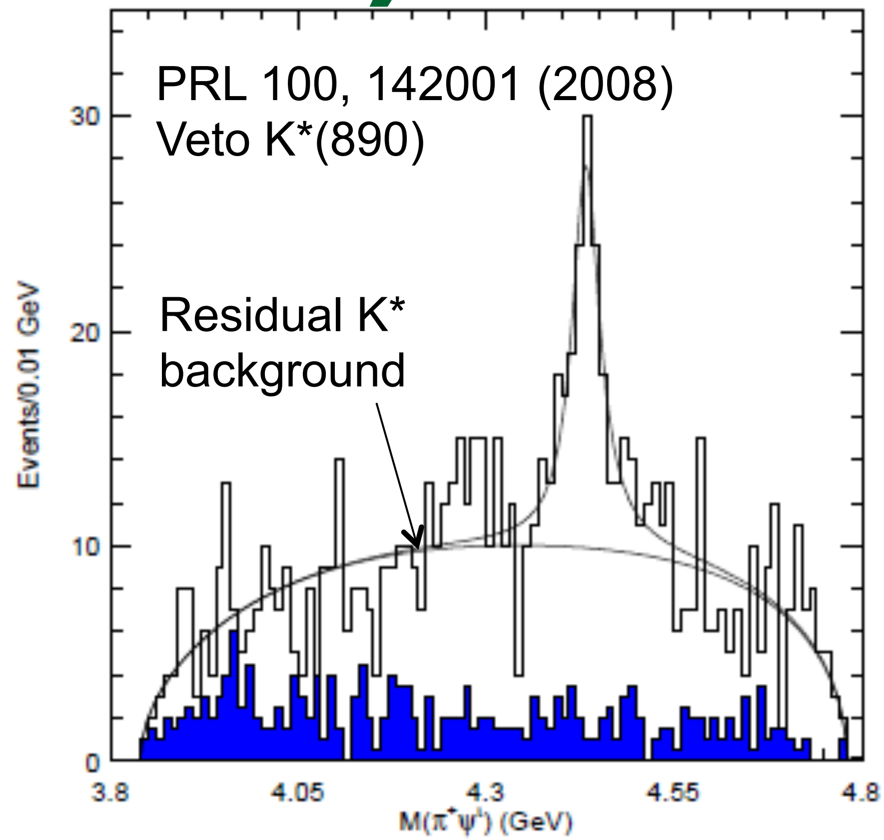
Needed to explain g-2

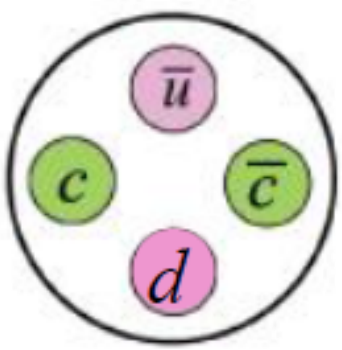
From arXiv:1406.2980

Tetraquarks, both heavy & light

Z (4430)$^-$

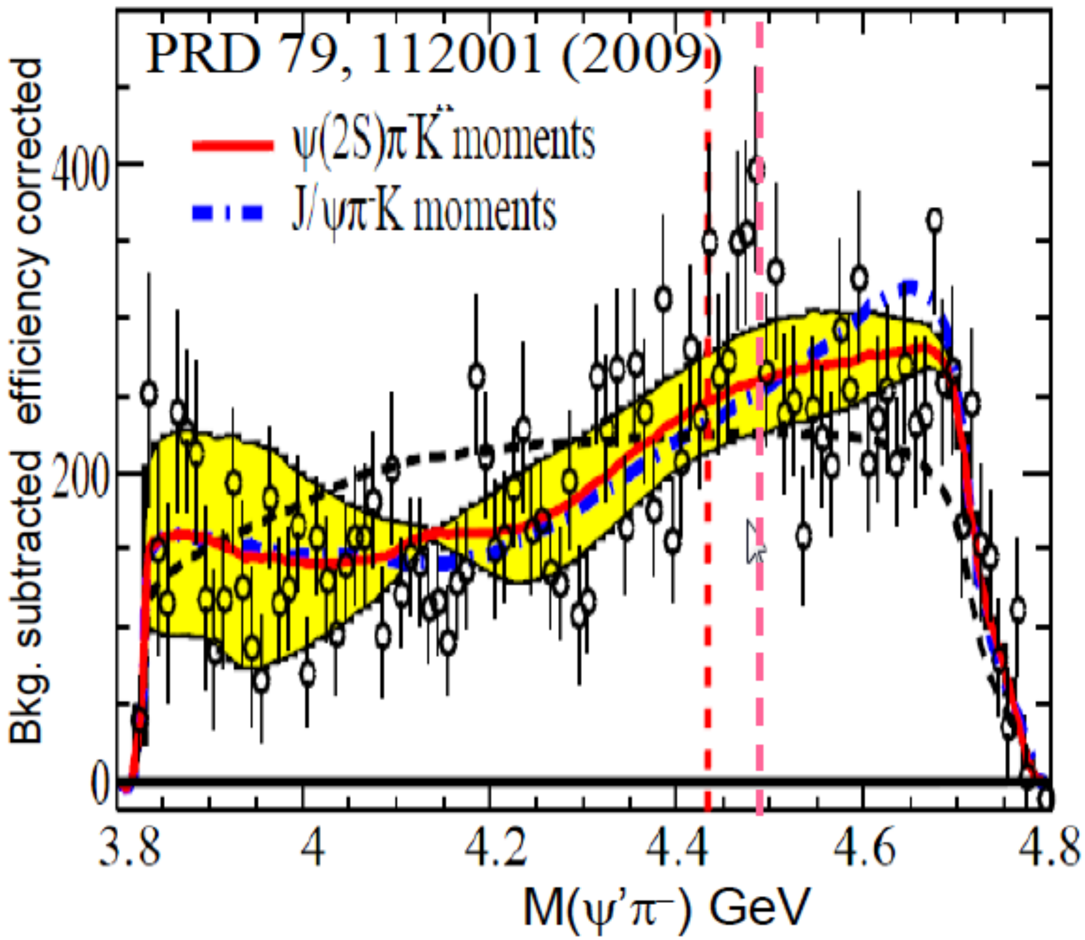
- Belle 2008: $B^0 \rightarrow \psi' \pi^- K^+$. Claimed resonant signal decaying into $\psi' \pi^-$ at 4430 MeV ⇒ a charged "charmonium" state, not possible with only $c\bar{c}$
- Tetraquark candidate





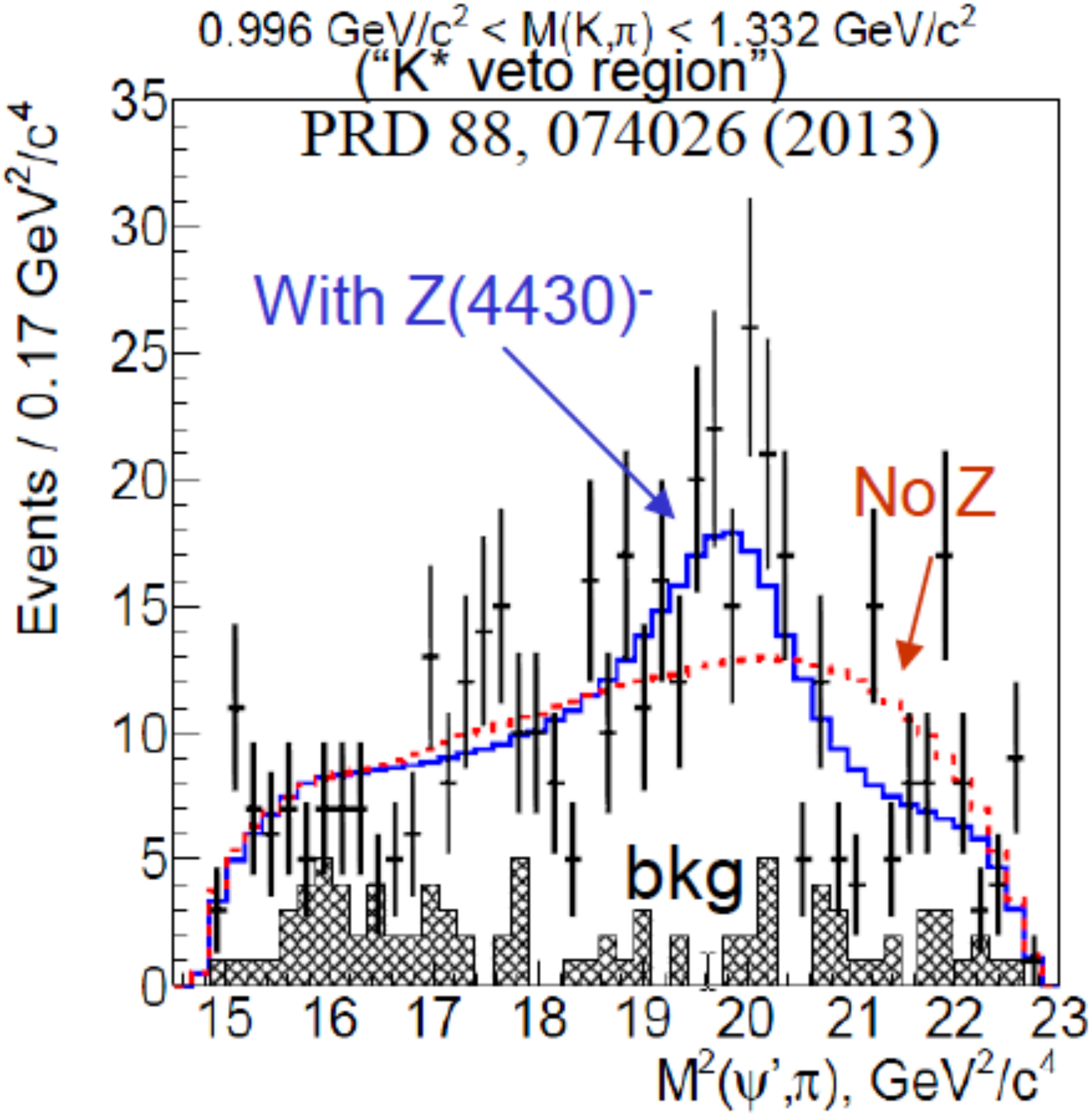
But not BaBar

- BaBar shows that moments of $K^+\pi^-$ resonances can reflect in mass peak
- Data are compatible with Belle
- Difference is in interpretation

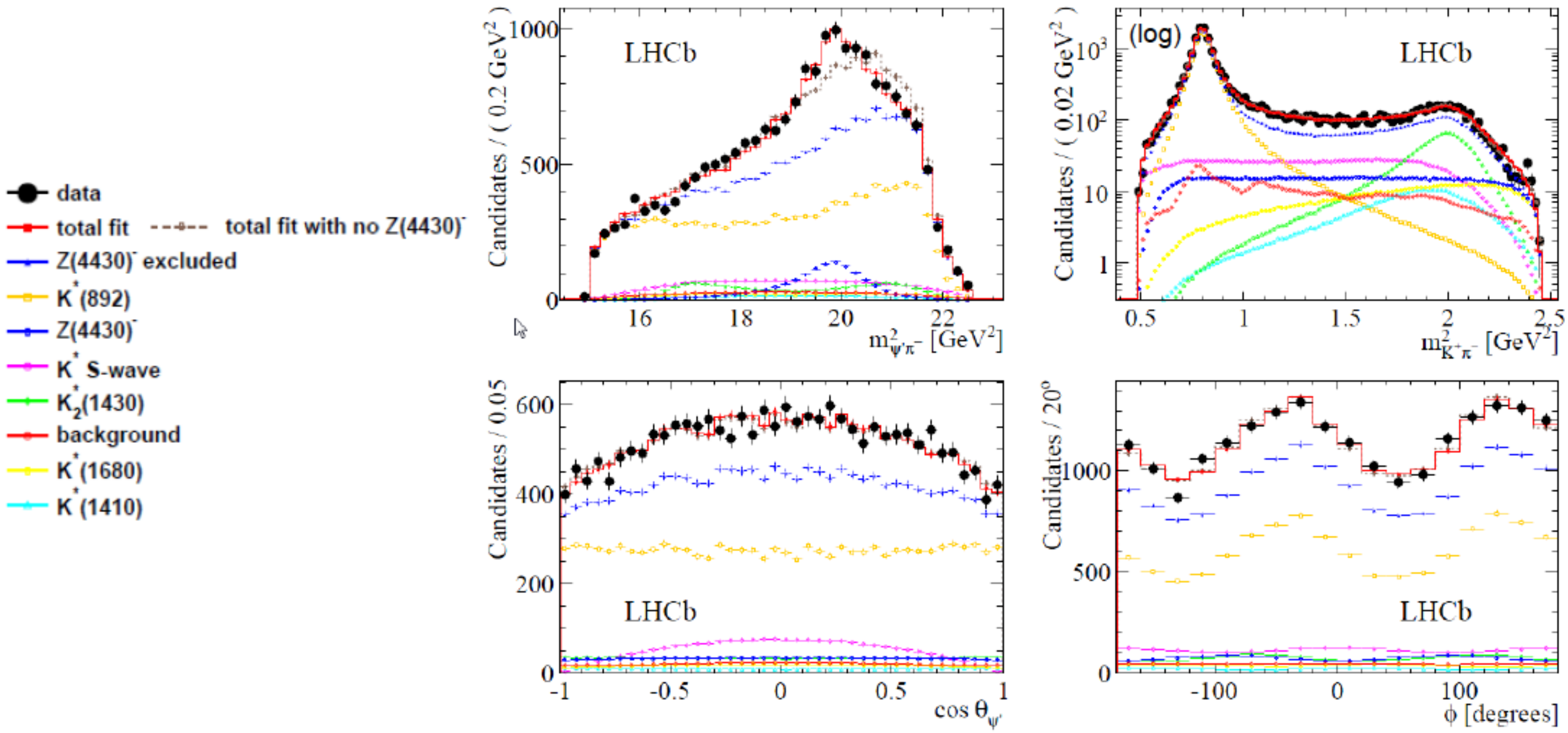


Belle does 4D amplitude fit

- New fit confirms observation, but questions remain



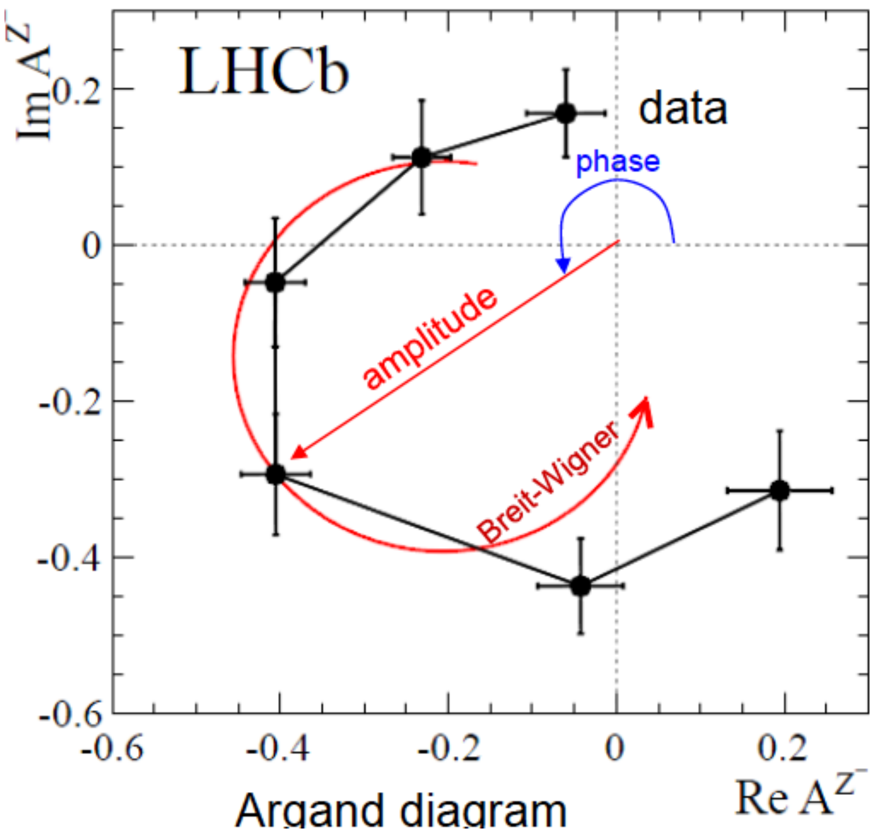
LHCb full fit for 1^+ Z



- p value of 12% arXiv:1404.1903

Argand diagram

- Replace the Breit-Wigner amplitude for $Z(4430)^-$ by 6 independent amplitudes in $m_{\psi'\pi^-}{}^2$ bins in its peak region



Argand diagram

Rapid phase transition at the peak of the amplitude → resonance!

First time ever the resonant character of the four-quark candidate has been demonstrated this way!

arXiv:1404.1903

Scalar octet problem

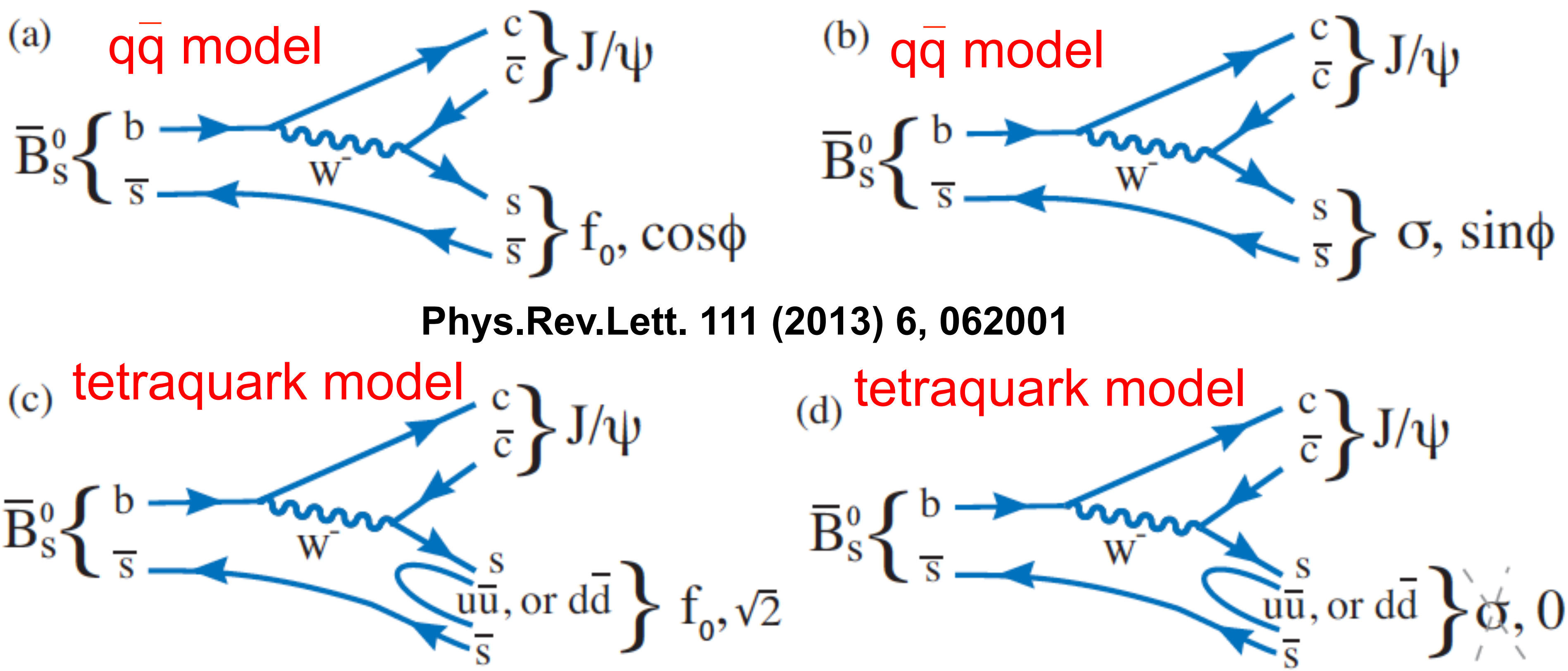
- 0^+ vs 1^- meson masses (charge = 0)

$$
\begin{aligned}
I=0: m[f_0(600)] &\approx 500\,\text{MeV} & I=1: m[\rho(776)] &\approx 776\,\text{MeV} \\
I=1/2: \quad m[\kappa] &\approx 800\,\text{MeV} & I=0: m[\omega(783)] &\approx 783\,\text{MeV} \\
I=0: m[f_0(980)] &\approx 980\,\text{MeV} & I=1/2: m[K^*(892)] &\approx 892\,\text{MeV} \\
I=1: m[a_0(980)] &\approx 980\,\text{MeV} & I=0: m[\phi(1020)] &\approx 1020\,\text{MeV}
\end{aligned}
$$

- For 1^-, adding an s quark increases meson mass
- Suggestions that 0^+ mesons are tetraquarks

Suggested B_s test

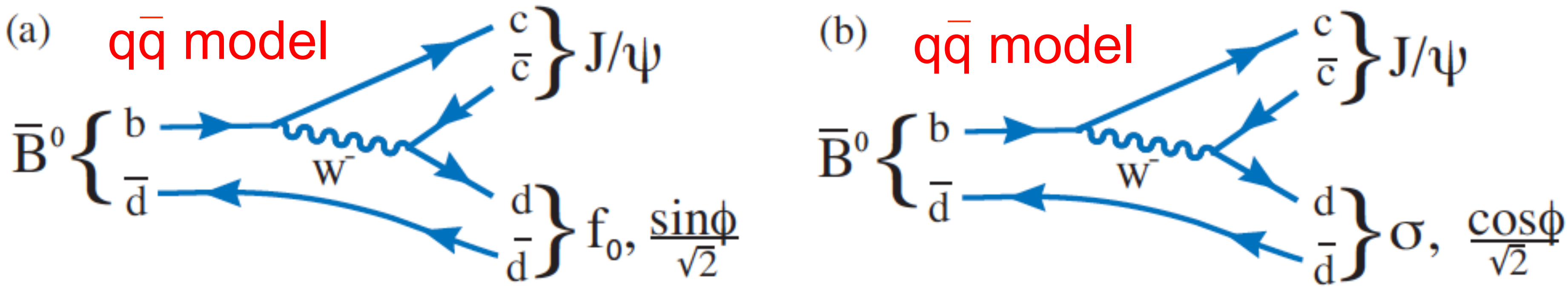
- Here $f_0 \equiv f_0$ (980), $\sigma = f_0$ (500)



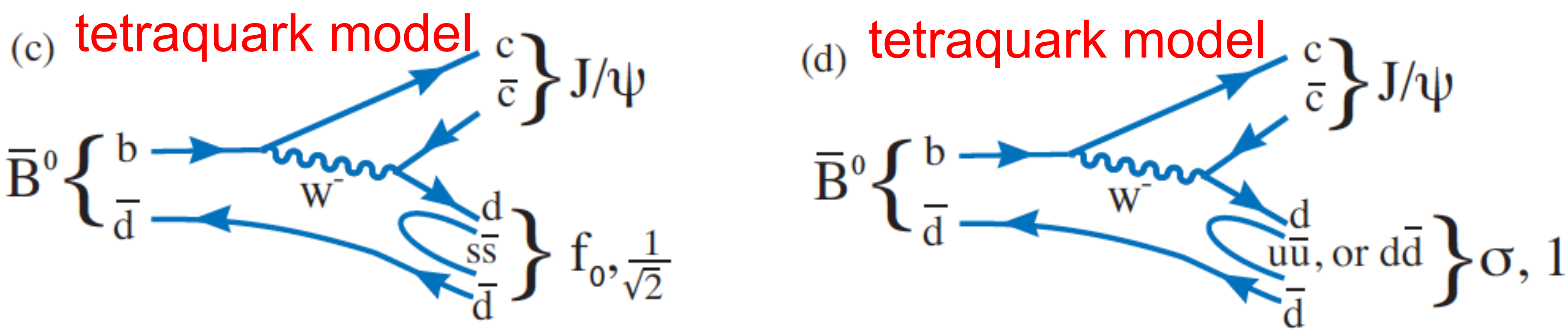
- Large f_0 expected in $q\bar{q}$, no σ rate for tetraquark

Suggested B^0 test

- Here $f_0 \equiv f_0\,(980)$, $\sigma = f_0\,(500)$

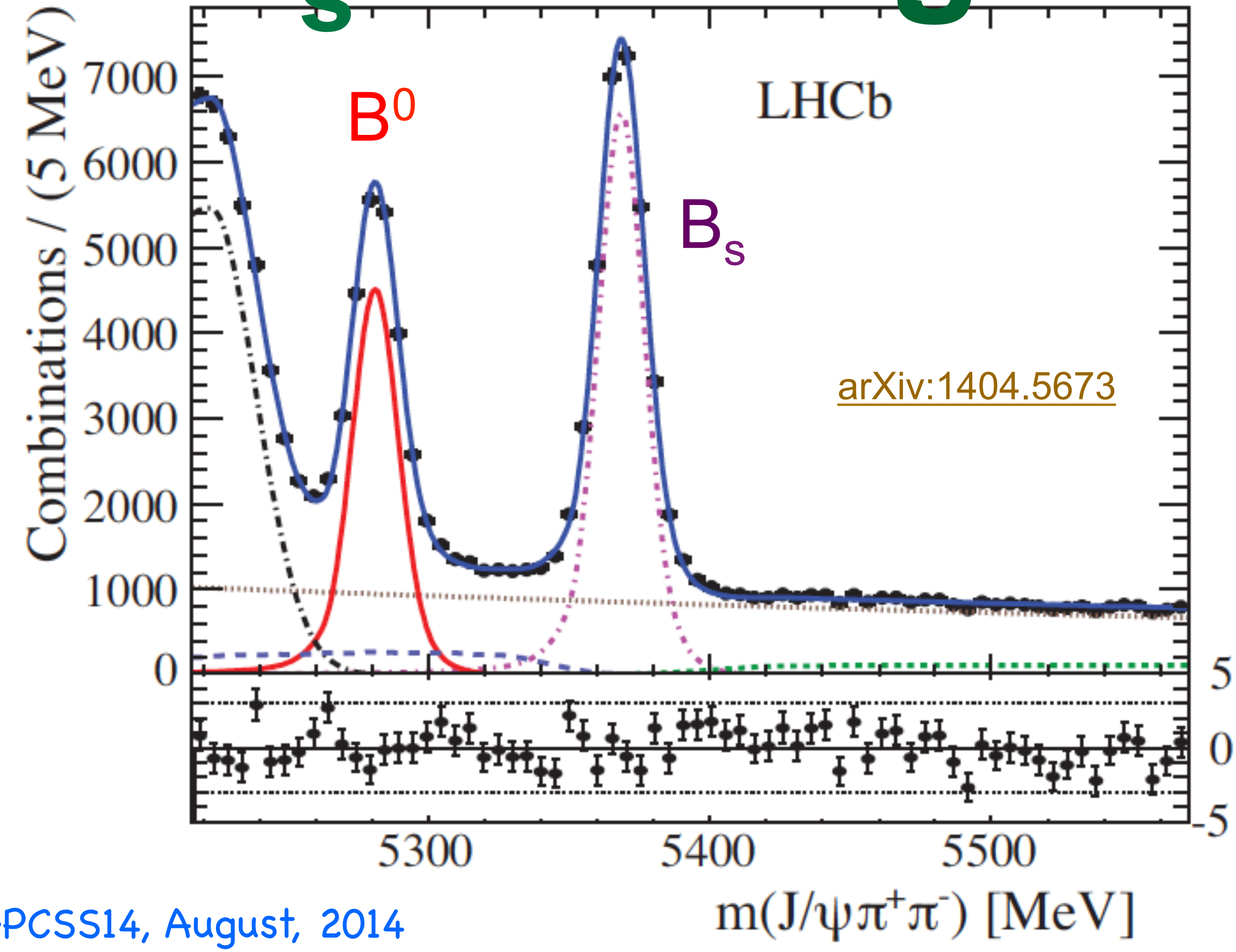


Phys.Rev.Lett. 111 (2013) 6, 062001



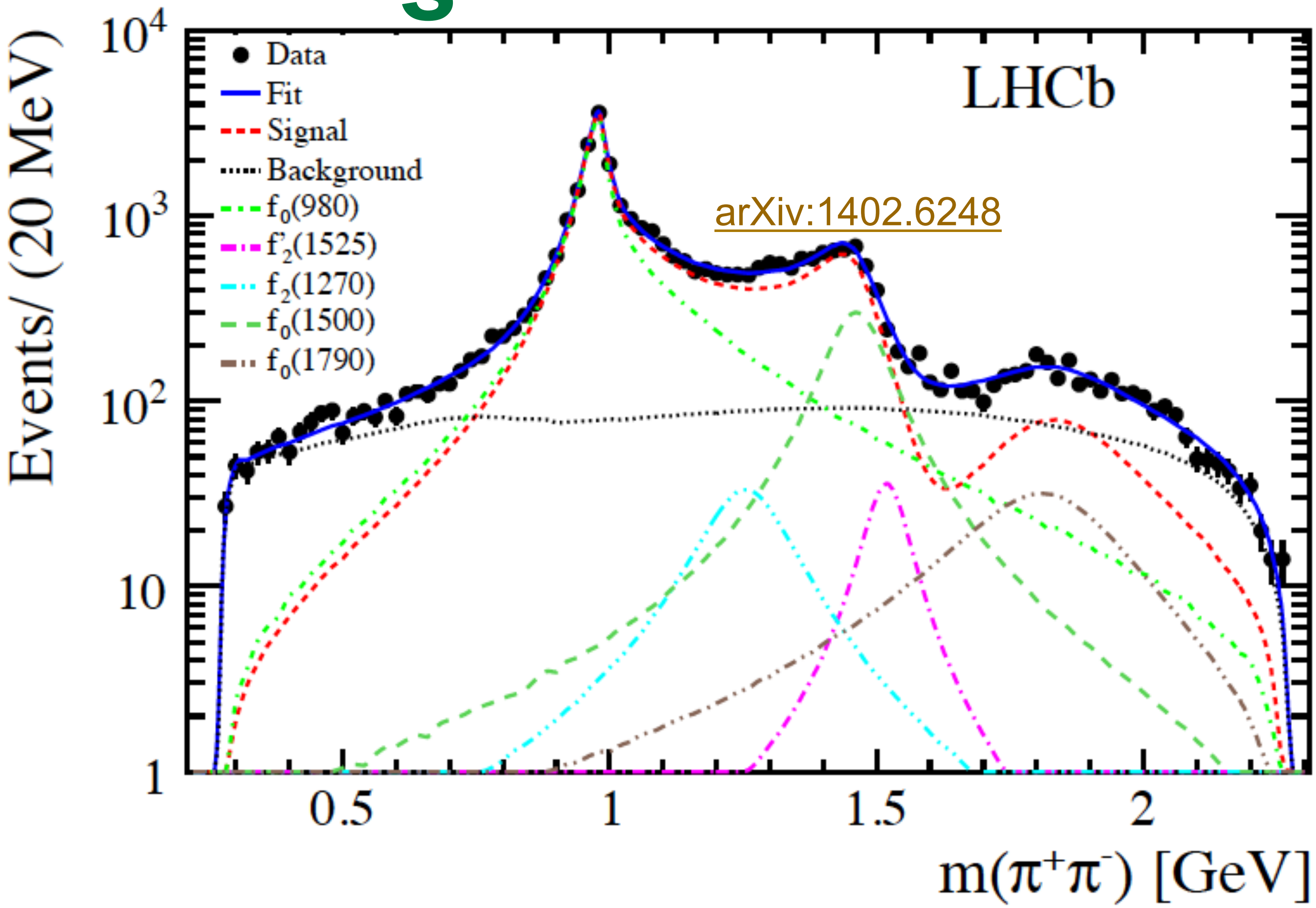
- Small f_0 expected in $q\bar{q}$, half of σ rate in tetraquark

B_s & B^0 signals



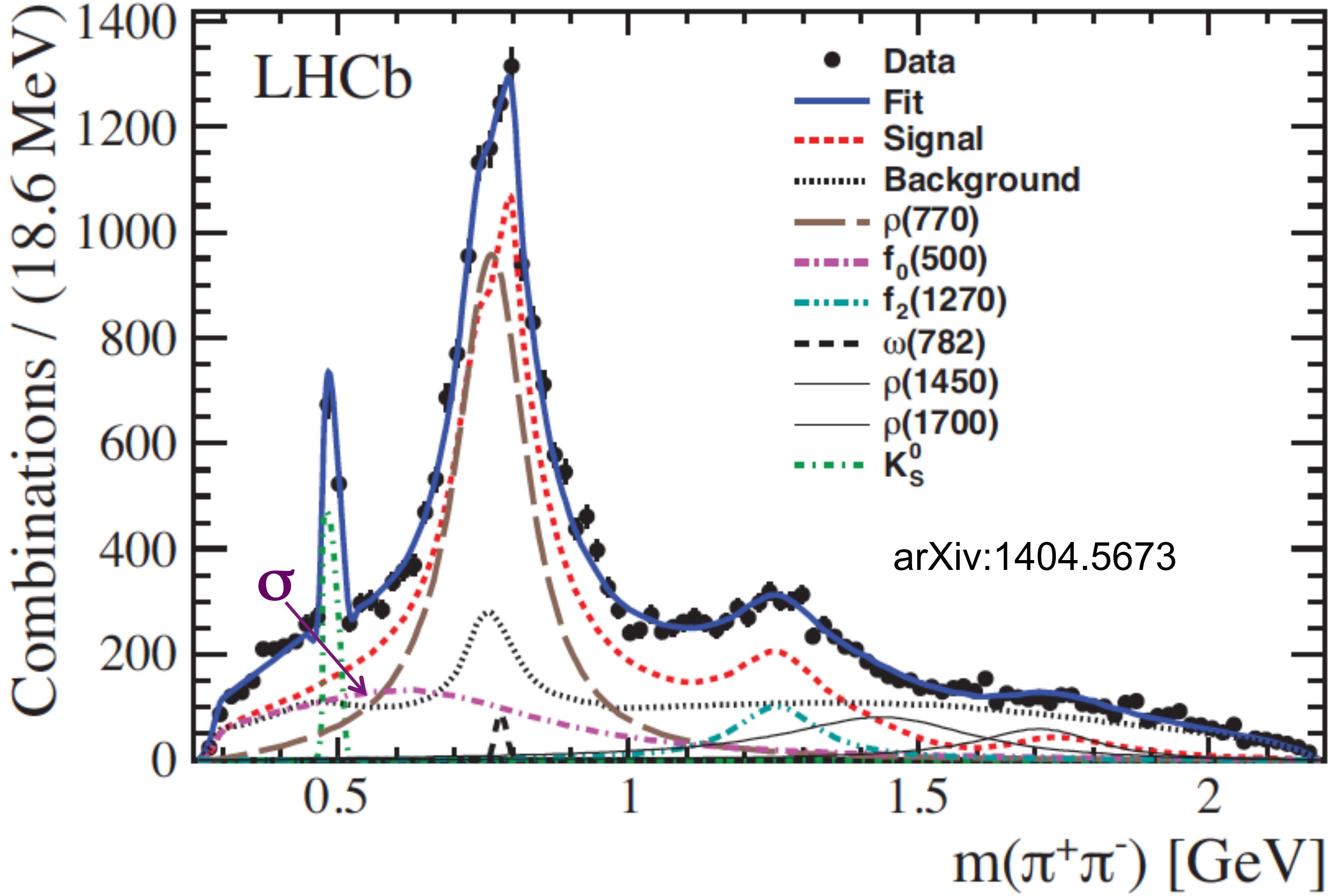
B_s results

Huge f_0, no σ



B^0 results

Nice σ
no f_0



Results

- $$\tan^2\varphi_m \equiv r_\sigma^f = \frac{\mathcal{B}\left(\overline{B}^0 \to J/\psi\, f_0(980)\right)}{\mathcal{B}\left(\overline{B}^0 \to J/\psi\, f_0(500)\right)} \frac{\Phi(500)}{\Phi(980)}$$

$$\frac{\mathcal{B}\left(\overline{B}^0 \to J/\psi\, f_0(980),\; f_0(980) \to \pi^+\pi^-\right)}{\mathcal{B}\left(\overline{B}^0 \to J/\psi\, f_0(500),\; f_0(500) \to \pi^+\pi^-\right)} = (0.6^{+0.7+3.3}_{-0.4-2.6})\%$$

$$\tan^2\varphi_m \equiv r_\sigma^f = \left(1.1^{+1.2+6.0}_{-0.7-0.7}\right) \times 10^{-2} < 0.098 \text{ at } 90\% \text{ C.L}$$

- In $q\bar{q}$ model mixing $\angle|\varphi_m| < 17^\circ$ at 90% CL
- Tetraquark prediction of 0.5 ruled out at 8σ

Future Acts

- LHCb Upgrade: run at 10^{33} cm^{-2}/s (x5), & double trigger efficiency on purely hadronic final states. Much improved sensitivities to New Physics at higher mass
  - Implemented by having a purely software trigger
  - Requires entire detector to be read-out at 40 MHz
- e^+e^- Super Belle
- Time scales are on the order of 5 years

Conclusions

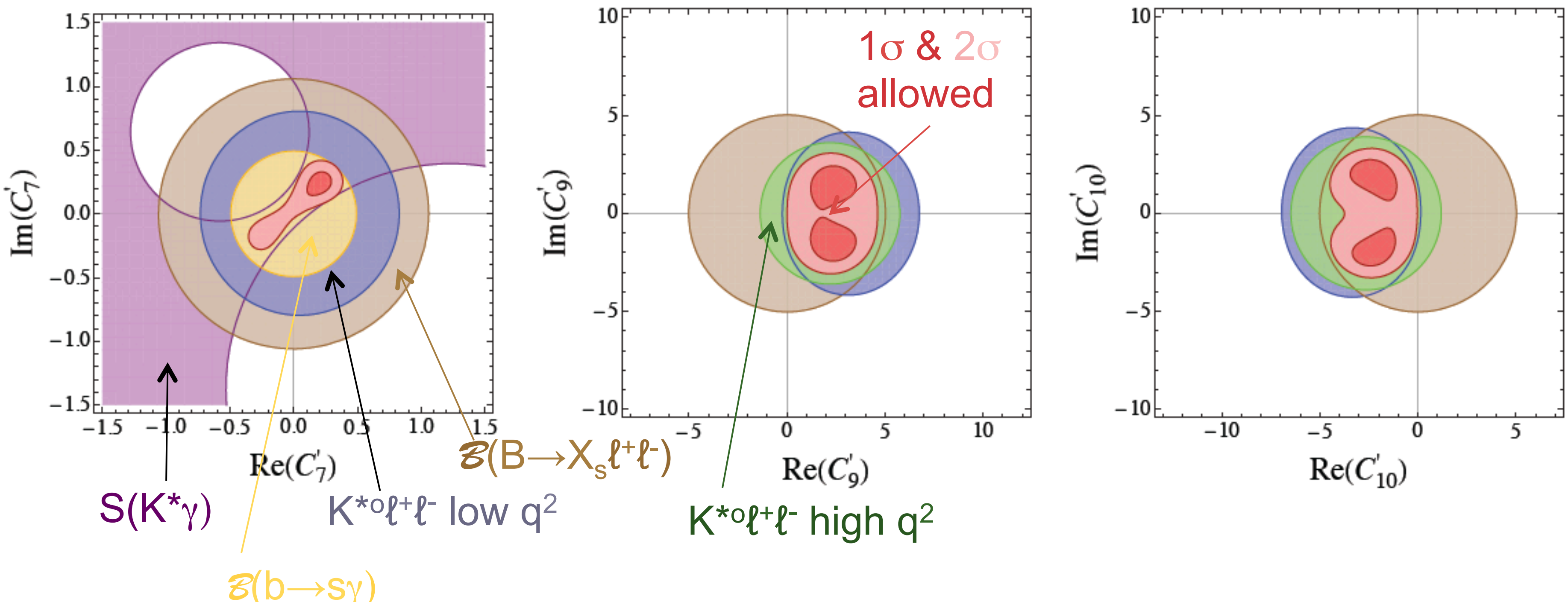
- Heavy Flavor physics is very sensitive to potential New Physics effects at high mass scales
- LHCb has started to make world class measurements of flavor physics.
- We hope to find physics beyond the Standard Model or derive limits that strongly constrains theories of New Physics.
- The LHCb upgrade is necessary to improve sensitivities.
- Many other interesting results have not been mentioned

Theory conquers

The End

Common Analysis

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



- Many more such generic constraints

a_{sl}

- By definition $a_{sl} = \frac{\Gamma(\bar{M}\to f) - \Gamma(M\to \bar{f})}{\Gamma(\bar{M}\to f) + \Gamma(M\to \bar{f})}$

  at t=0 $\bar{M}\to f$ is zero as is $M\to\bar{f}$
- Here *f* is by construction flavor specific, $f \neq \bar{f}$
- Can measure eg. $\bar{B}_s \to D_s^+ \mu^- \nu$, versus $B_s \to D_s^- \mu^+ \nu$,
- 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 $\tan\phi_{12}=\text{Arg}(-\Gamma_{12}/M_{12})$
- In SM (B^o) $a_{sl}^d=-4.1\times10^{-4}$, ($B_s$) $a_{sl}^s=+1.9\times10^{-5}$

arXiv:1205.1444 [hep-ph]

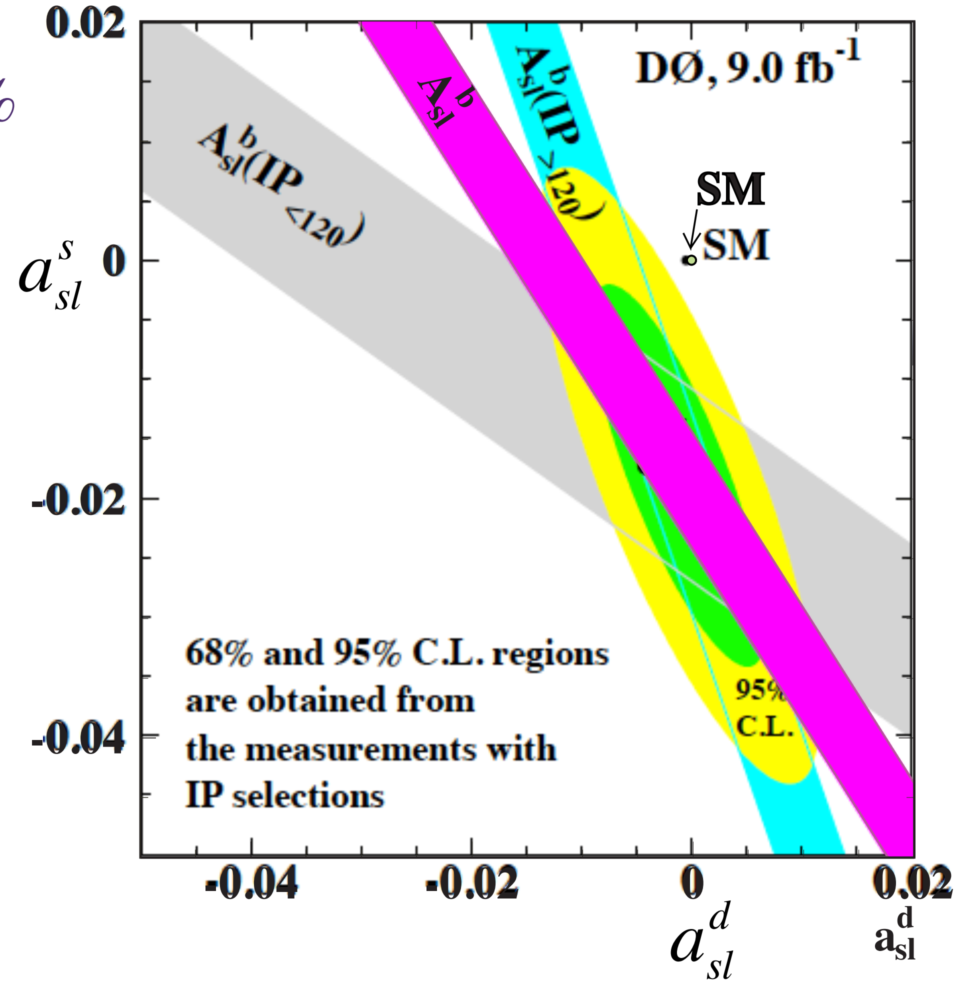
DO a_{sl}

- Using dimuons (3.9σ)

$$A_{sl}^{b} = \left(-0.787 \pm 0.172 \pm 0.093\right)\%$$

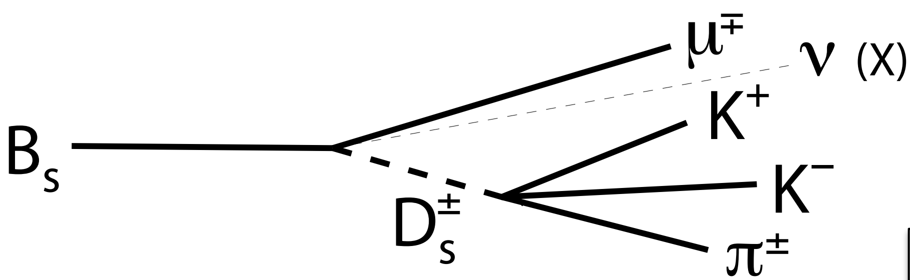
- Indication from D0 that its B_s
- Separate dimuons into B_d and B_s samples using muon impact parameter
- Find

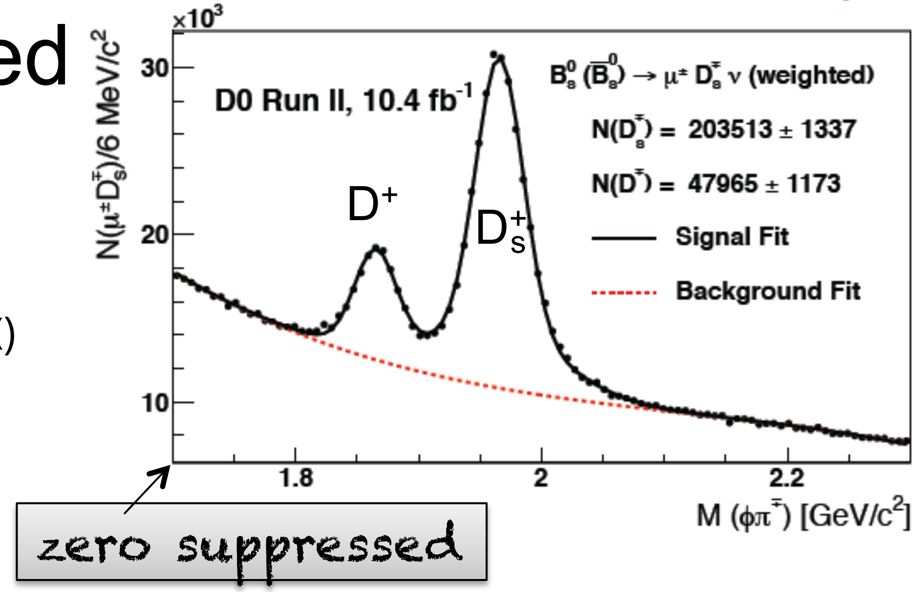
$$a_{sl}^{d} = \left(-0.12 \pm 0.52\right)\%$$
$$a_{sl}^{s} = \left(-1.81 \pm 1.06\right)\%$$



New D0 Analysis

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

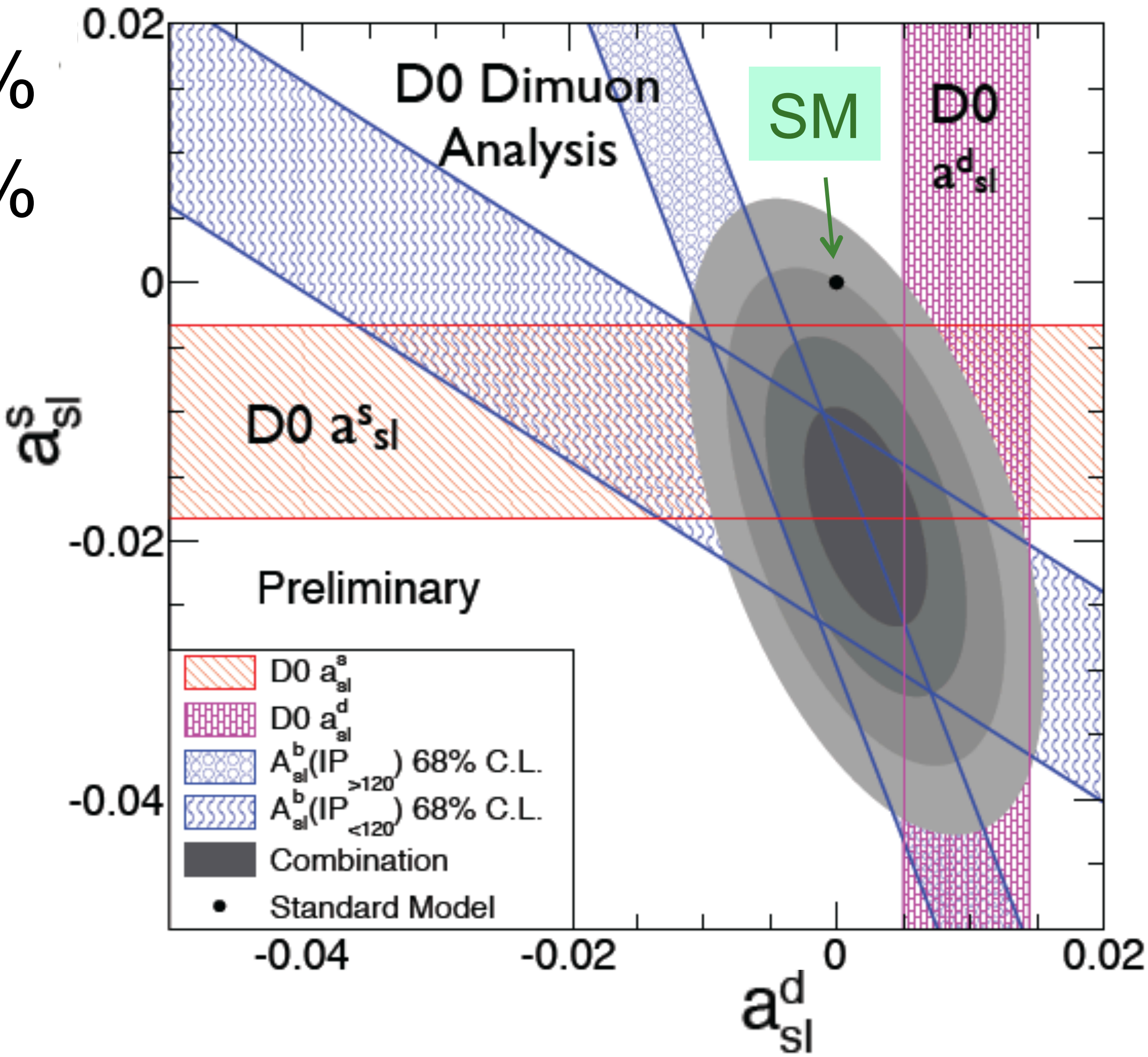




- Find a_{sl}^{s}=(-1.08±0.72±0.17)%
- Also measure a_{sl}^{d} using $D^+\mu^-\nu$, $D^+\rightarrow K\pi^+\pi^+$
- a_{sl}^{d}=(0.93±0.45±0.14)%

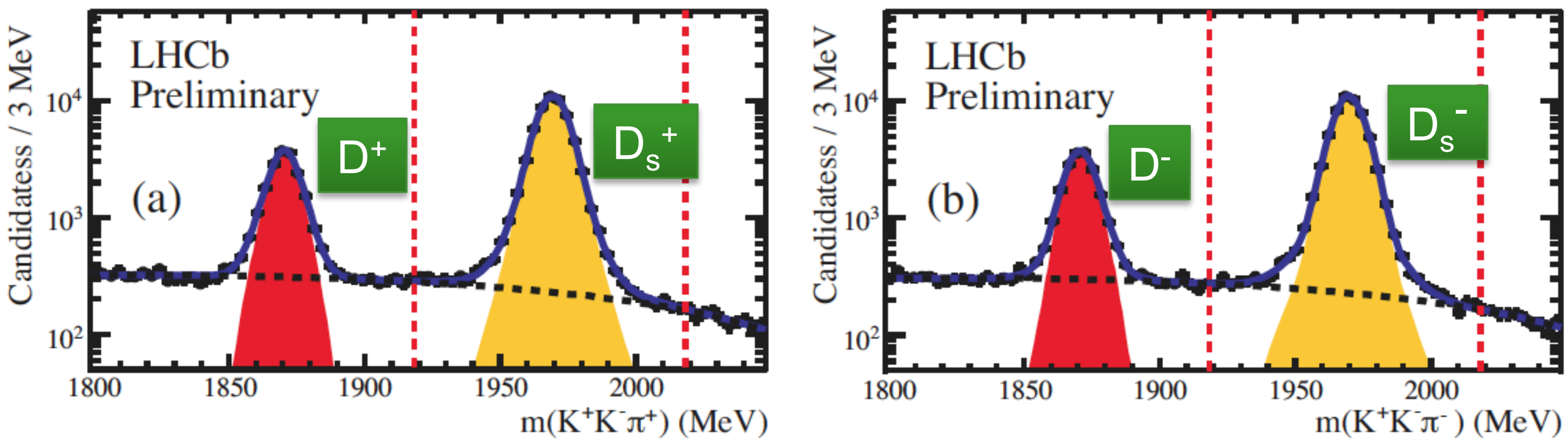
a_{sl} according to D0

- a^s_{sl}=(-1.81±0.56)%
- a^d_{sl}=(-0.22±0.30)%
- 3σ from SM
- arXiv:1208.5813



LHCb measurement

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



- Effect of B_s production asymmetry is reduced to a 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}.