S. Stone

Heavy Flavor & Rare Decays

GGI, Nov. 11, 2011

What is Heavy Flavor Physics ?

- Define Heavy Flavor Physics
  - Flavor Physics: Study of interactions that differ among flavors
  - Heavy: Not SM neutrino's or u or d quarks, maybe s quarks, concentrate here on b quarks (some c), t too heavy

u, d, ν's

too light

s, μ

maybe

c & b, τ; ν_M's ?

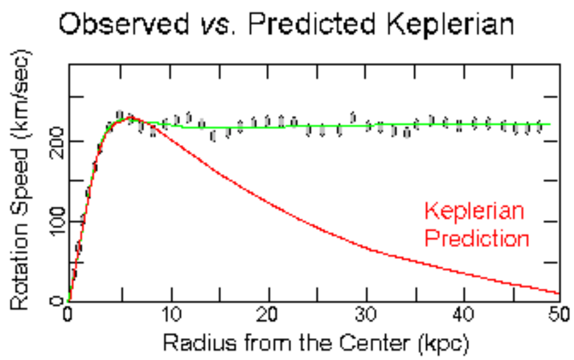
just right

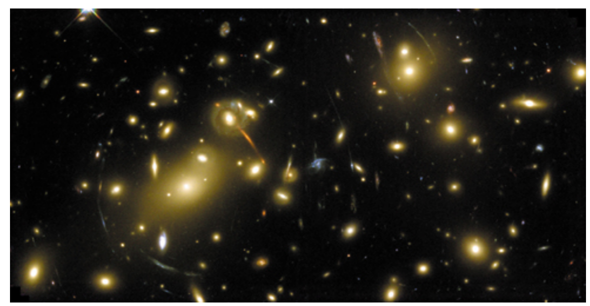
t

too heavy

Physics Beyond the Standard Model

- Baryogenesis: From current measurements can only generate $(n_B-\bar{n}_B)/n_\gamma$ =~10^{-20} but ~6×10^{-10} is needed. Thus New Physics must exist to generate needed CP Violation
- Dark Matter



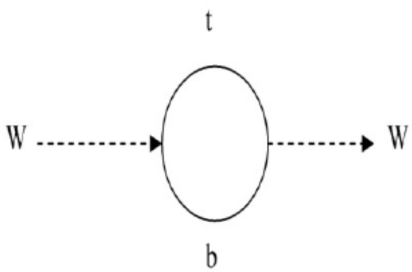


Gravitational lensing

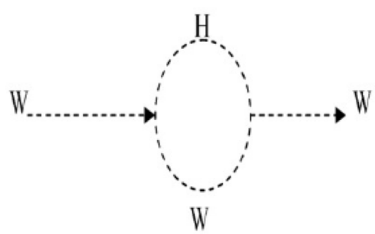
- Hierarchy Problem: We don't understand how we get from the Planck scale of Energy ~10^{19} GeV to the Electroweak Scale ~100 GeV without "fine tuning" quantum corrections

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 extracting the Higgs mass
  - M_w changes due to m_t $\frac{dM_W}{dm_t} \alpha \frac{m_t}{M_w}$

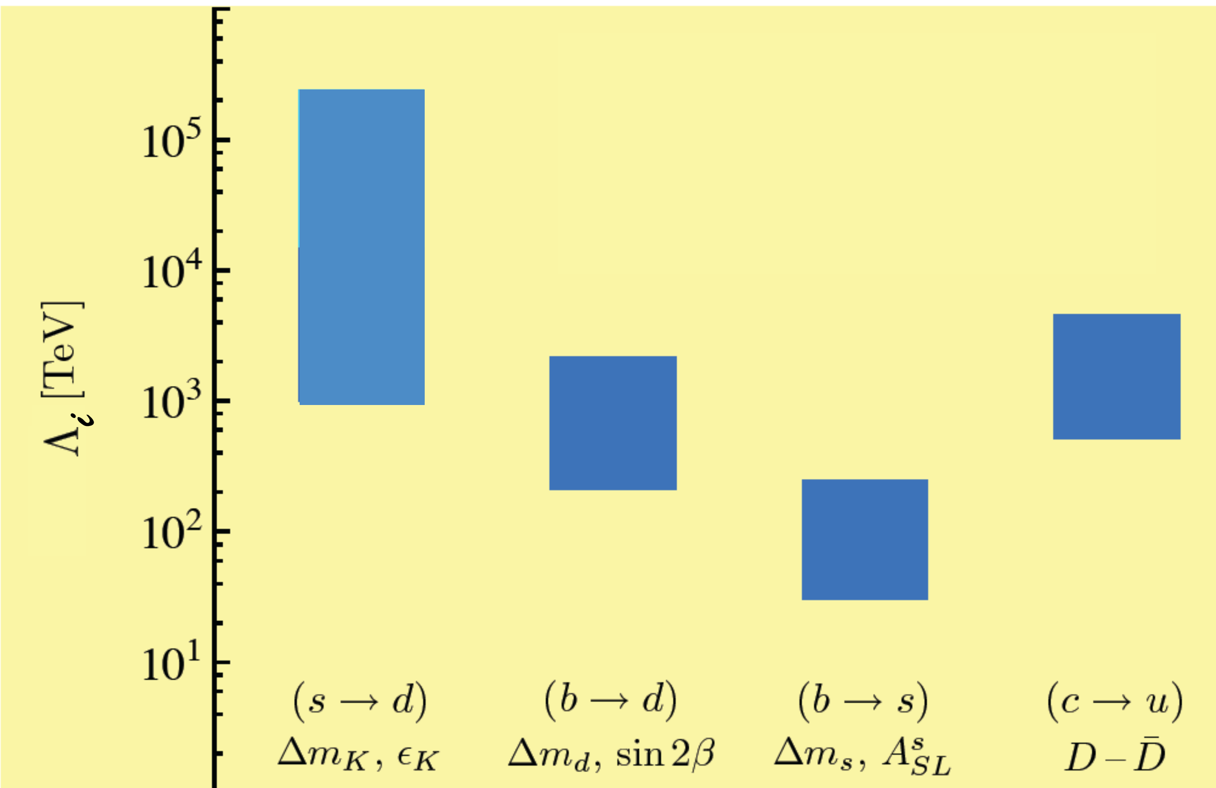


  - M_w changes due to m_H $\frac{dM_W}{dm_H} \alpha - \frac{dm_H}{M_H}$



Flavor as a High Mass Probe

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



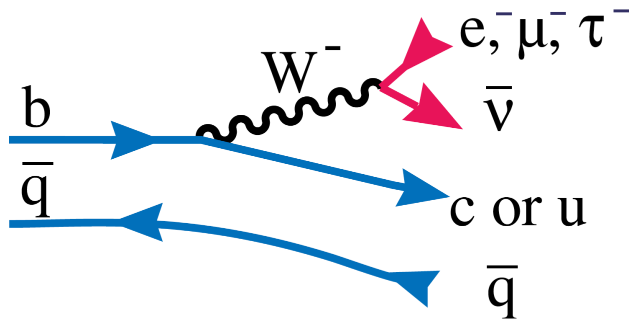
Ways out

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

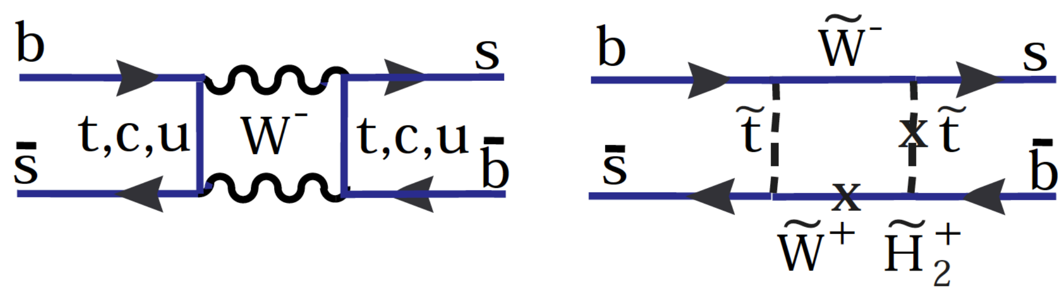
See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk

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



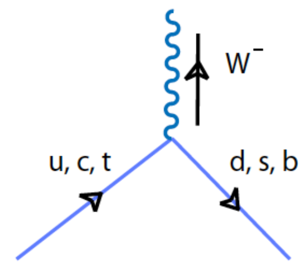
Tree diagram example



Loop diagram example

Quark Mixing & CKM Matrix

- In SM charge -1/3 quarks (d, s, b) are mixed
- Described by CKM matrix (also ν are mixed)



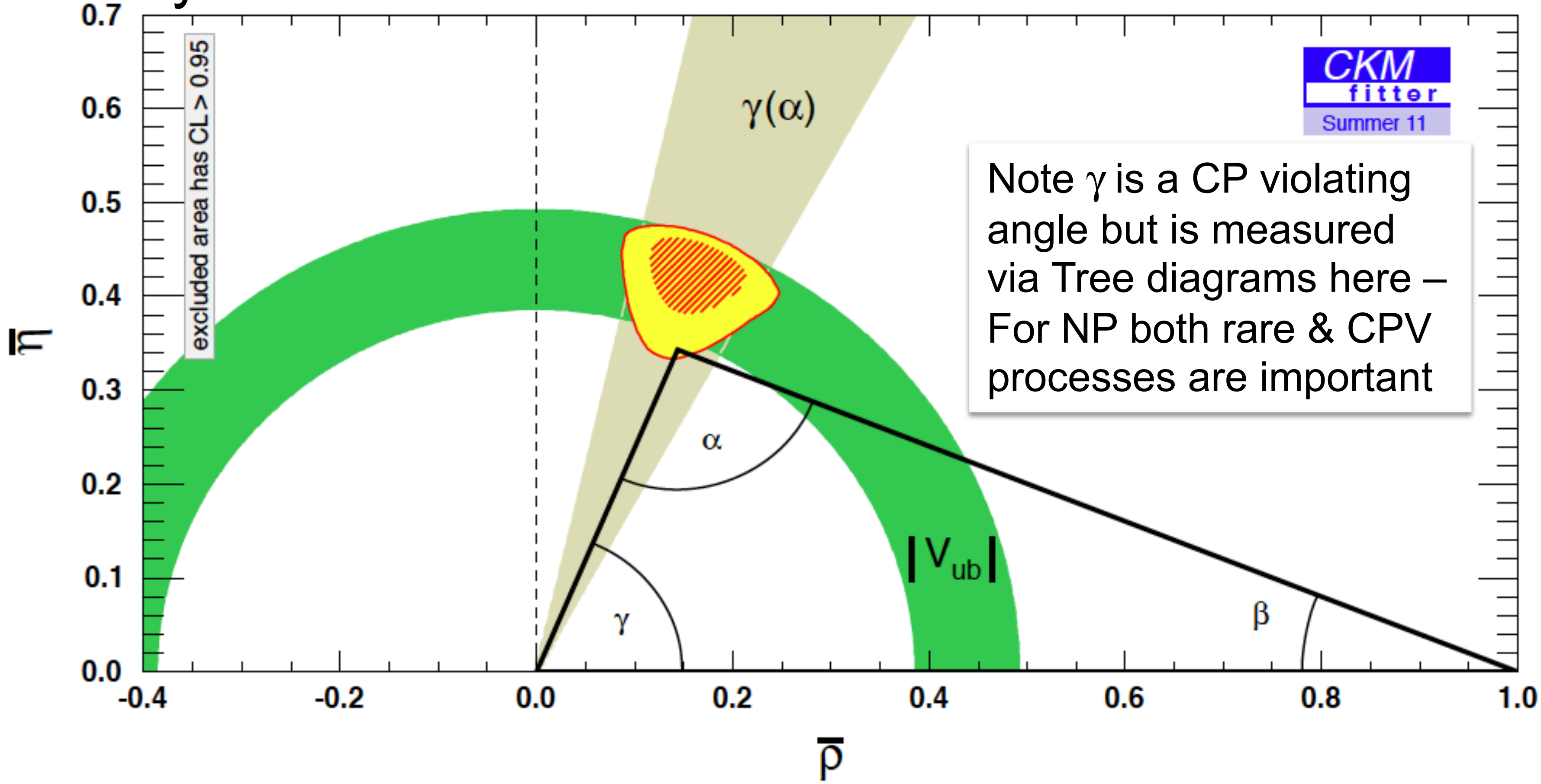
$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

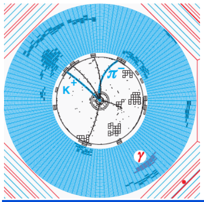
$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- λ=0.225, A=0.8, constraints on ρ & η
- These are fundamental constants in SM

What are limits on NP from quark decays?

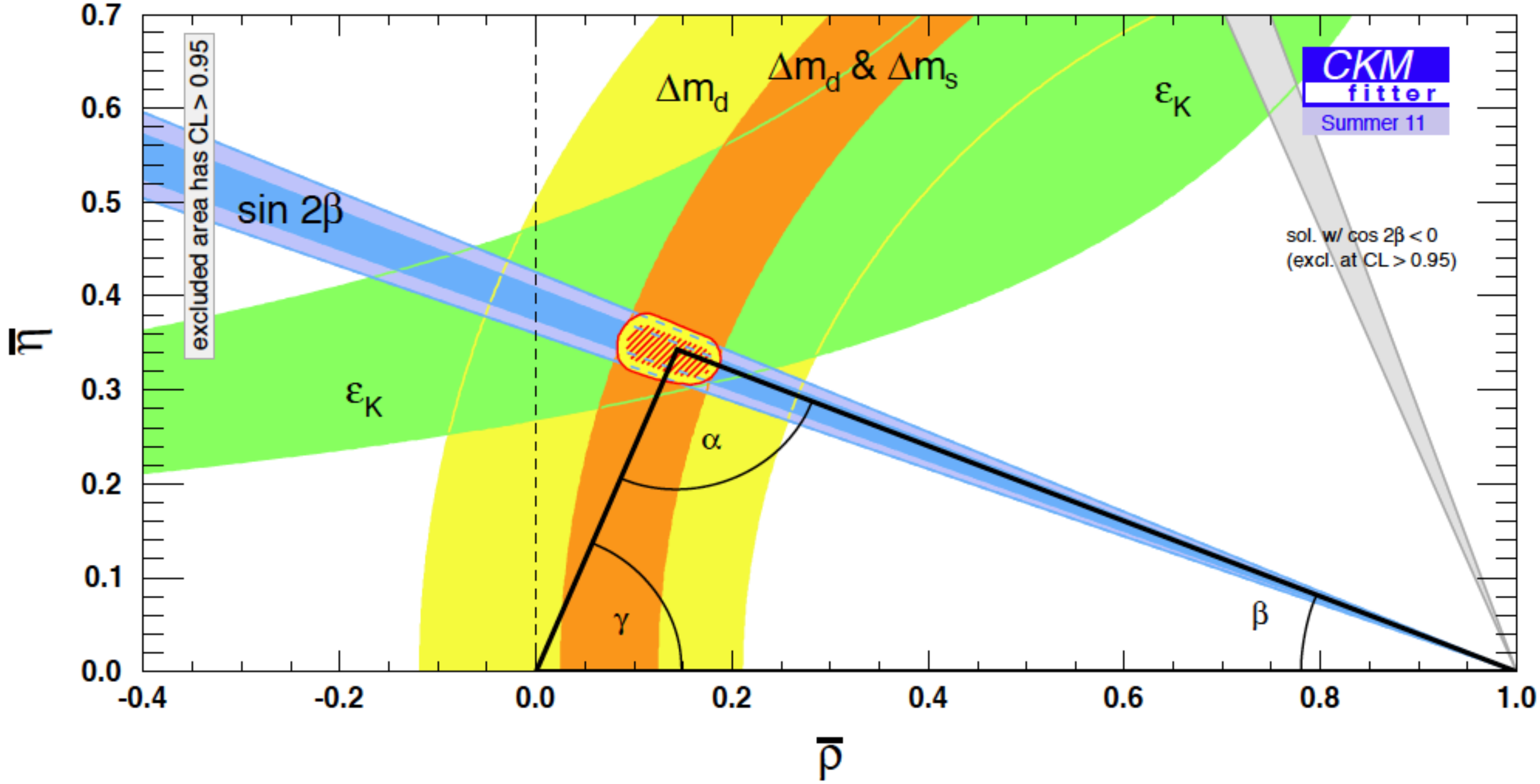
- Tree diagrams are unlikely to be affected by physics beyond the Standard Model



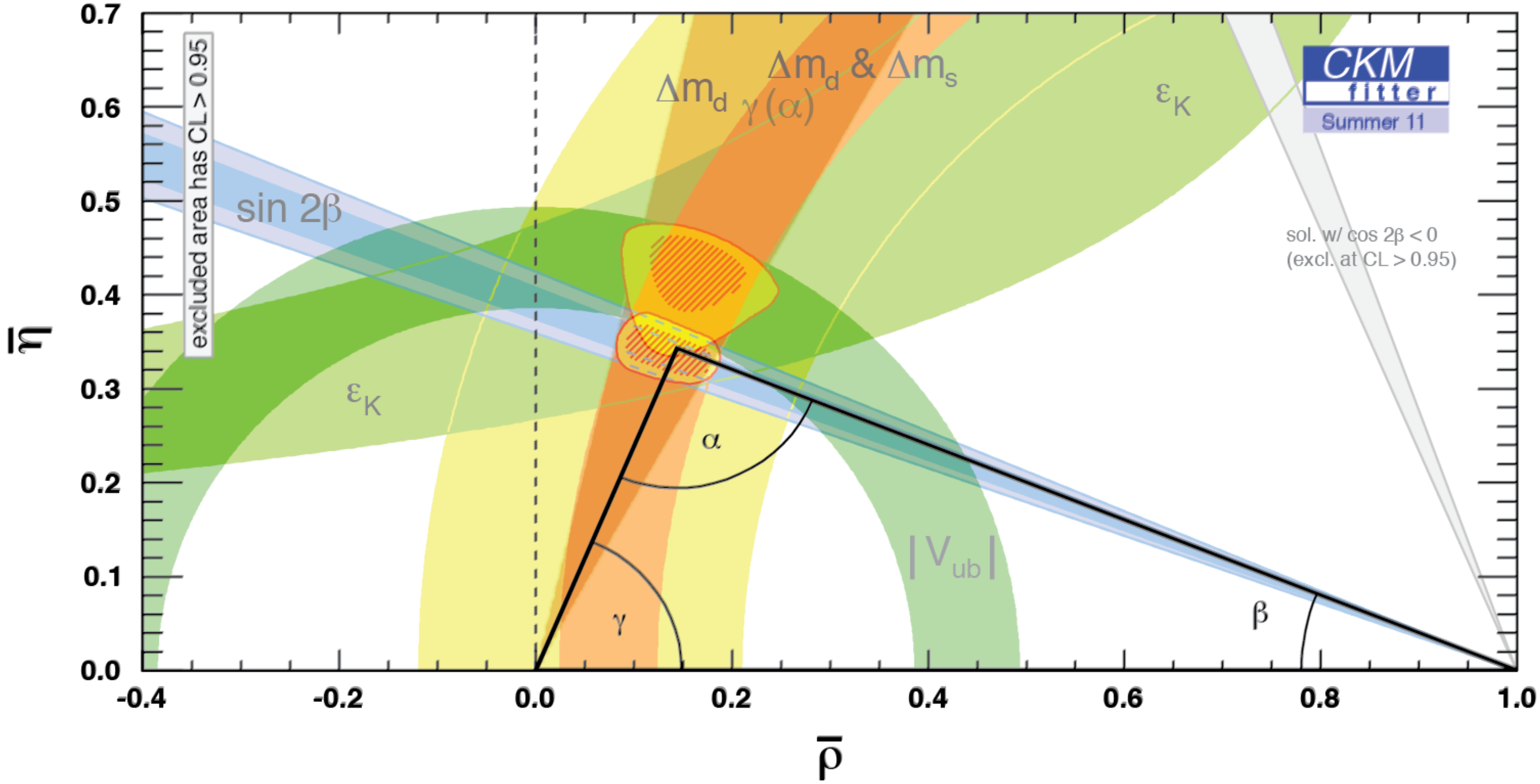


CP Violation in B° & K° Only

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



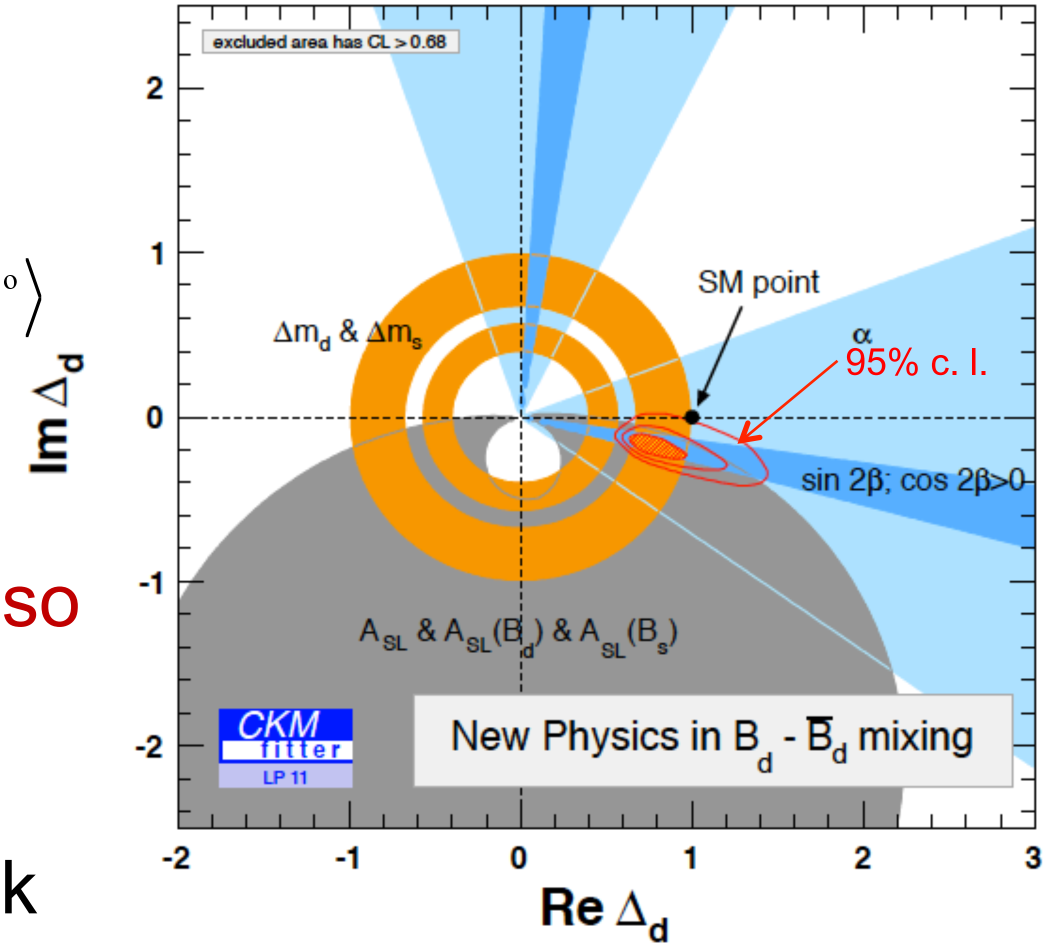
They are Consistent



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

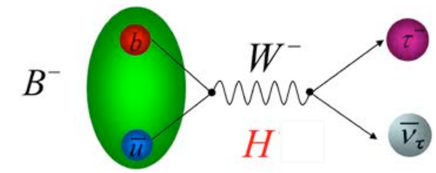
Limits on New Physics From B^o Mixing

- Is there NP in B^o-$\bar{B}^o$ mixing?
- $\langle B^o | H^{SM+NP}_{\Delta B=2} | \bar{B}^o \rangle = \Delta_d^{NP} \langle B^o | H^{SM}_{\Delta B=2} | \bar{B}^o \rangle$
  $\Delta_d^{NP} = \mathrm{Re}\,\Delta_d + i\mathrm{Im}\Delta_d$
- Assume NP in tree decays is negligible, so no NP in $|V_{ij}|$, γ from $B^- \rightarrow D^o K^-$
- Allow NP in Δm, weak phases, A_{SL}, & $\Delta\Gamma$



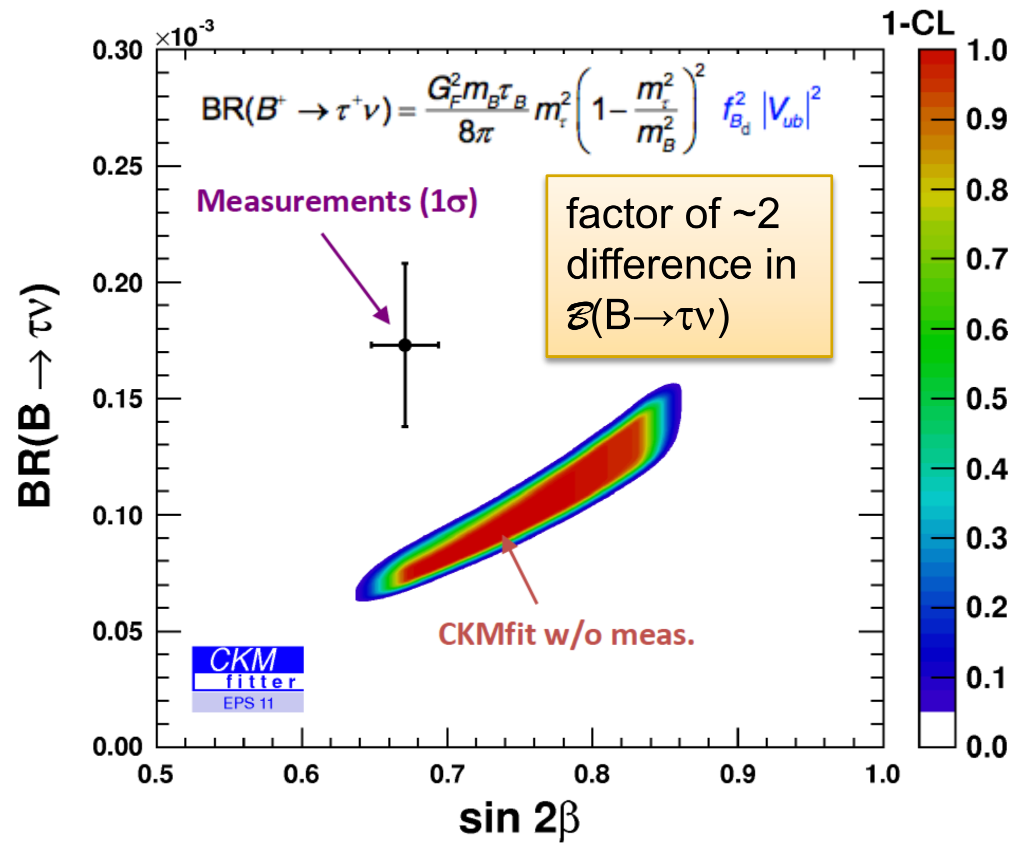
- Room for new physics, in fact SM is only at 5% c.l.

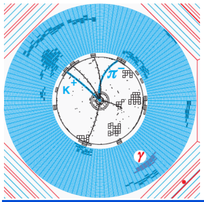
One Clear Problem

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

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

- $\sin 2\beta$, CPV in e.g. $B^o \to J/\psi\ K_s$: Box diagram
- Source of most of the CKM discrepancy
  - See: E. Lunghi & A. Soni, "Demise of CKM & its aftermath," [arXiv:1104.2117], they advocate a 4th generation

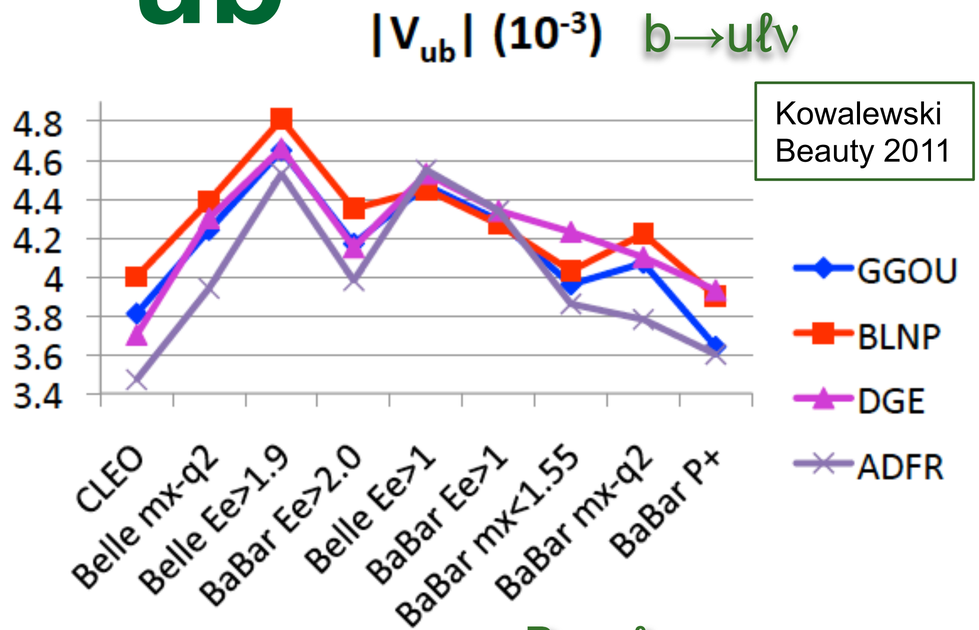


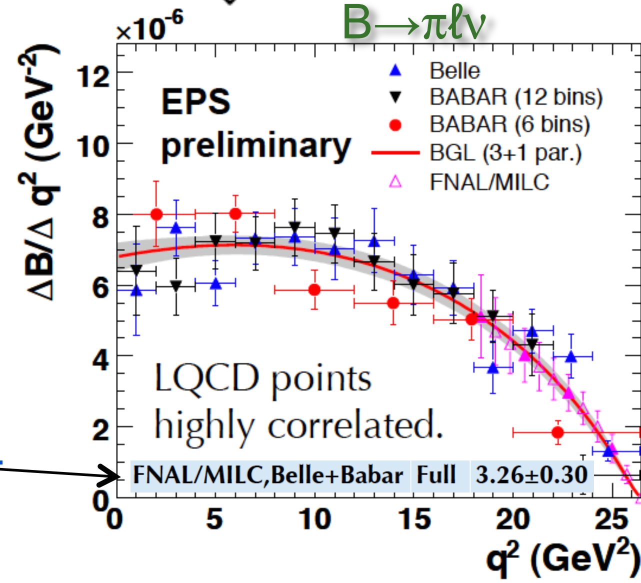


V_{ub}

- An irritating problem: Lingering difference between inclusive $b \to u \ell \nu$, & exclusive $B \to \pi \ell \nu$,
- Values $|V_{ub}| \times 10^{-3}$
  - Inclusive: 4.25±0.15±0.20
  - Exclusive: 3.25±0.12±0.28

New

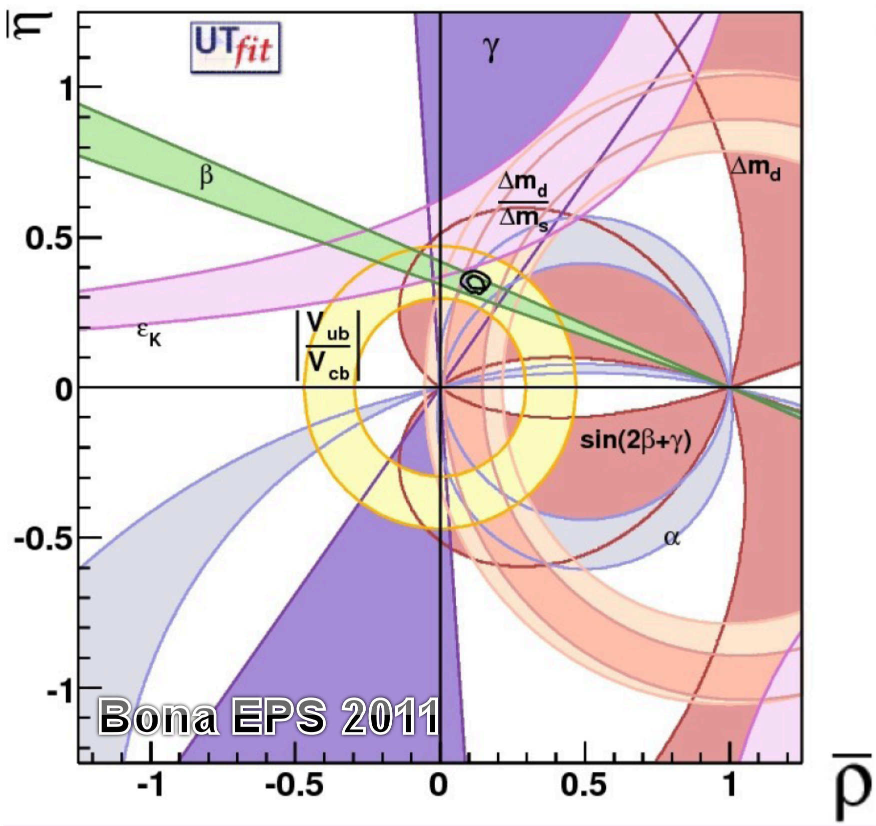


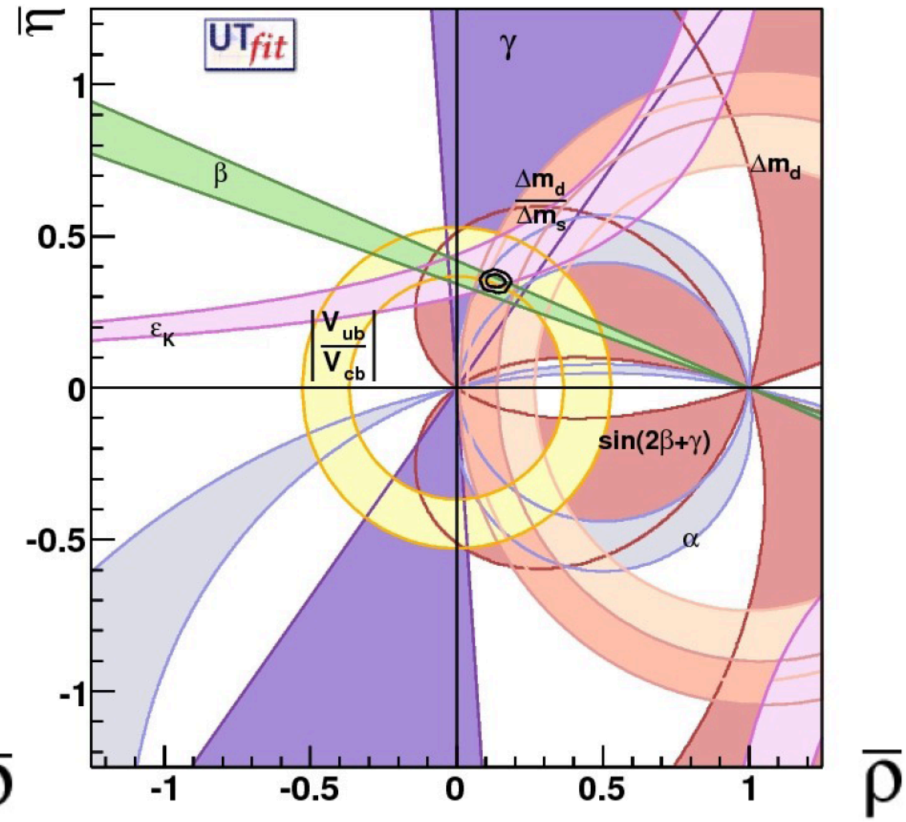


See Urquijo EPS 2011

V_{ub} Consequences

Exclusive | Inclusive



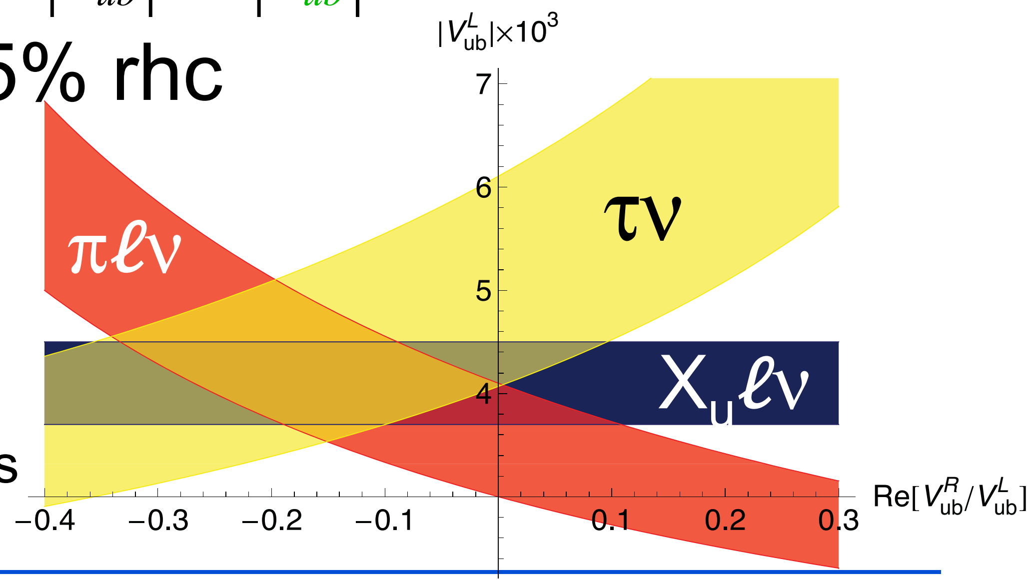


Use of Exclusive would increase τν sin2β discrepancy, use of Inclusive would not solve the problem

A V_{ub} fix?

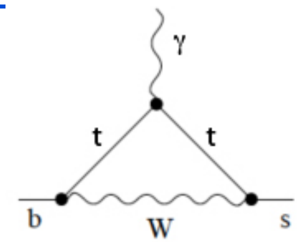
- Add new physics: right handed currents with coupling V_{ub}^R
  - B→πℓν rate goes as $\left|V_{ub}^L + V_{ub}^R\right|^2$
  - B→τν rate goes as $\left|V_{ub}^L - V_{ub}^R\right|^2$
  - B→X_uℓν rate goes as $\left|V_{ub}^L\right|^2 + \left|V_{ub}^R\right|^2$
- Agreement with ~15% rhc
  - Can arise in SUSY
  - Not in loops
  - See Crivellin

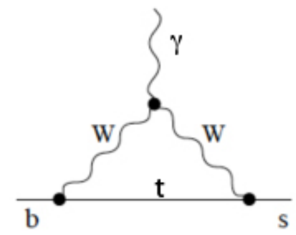
 [arXiv:0907.2461], also Buras et.al, [arXiv: 1007.1993]

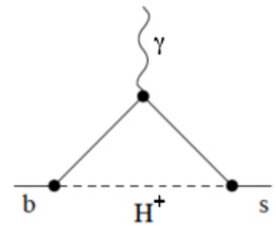


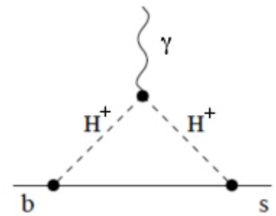
Ex. of Strong Constraints on NP

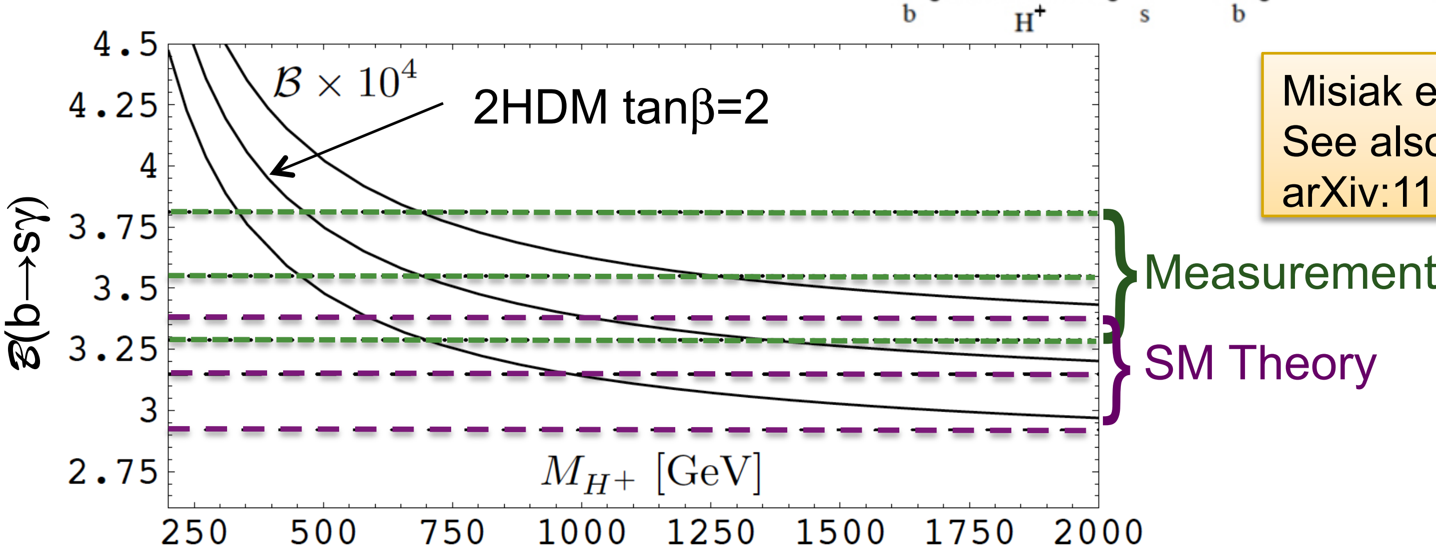
- Inclusive $b \to s\gamma$, ($E\gamma > 1.6$ GeV)
  - Measured $(3.55 \pm 0.26) \times 10^{-4}$ (HFAG)
  - Theory $(3.15 \pm 0.23) \times 10^{-4}$ (NNLL) Misiak arXiv:1010.4896
  - Ratio = 1.13±0.11, Limits most NP models
  - Example 2HDM
  - $m(H^+) < 316$ GeV



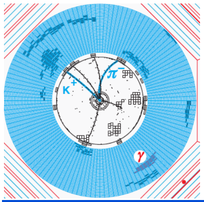






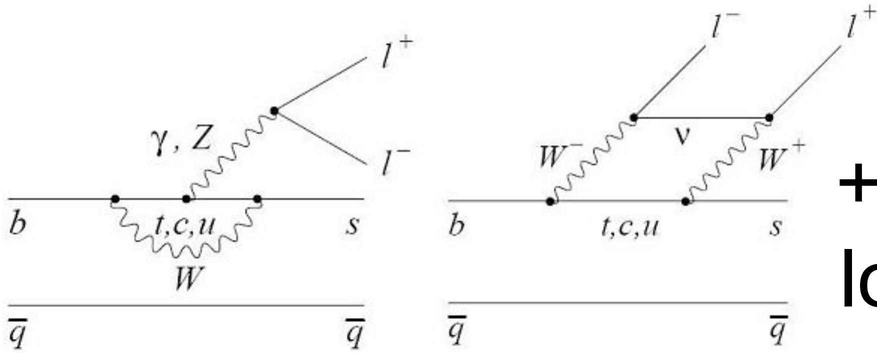


Misiak et. al hep-ph/0609232,
See also A. Buras et. al,
arXiv:1105.5146



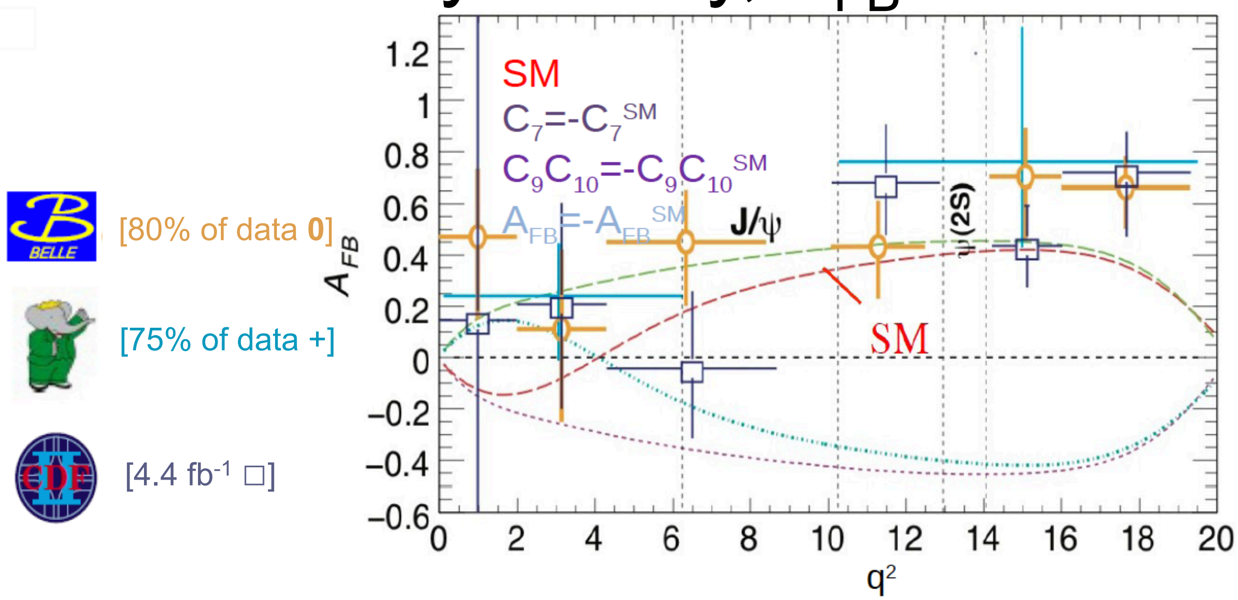
$B^o \rightarrow K^{*o}\mu^+\mu^-$

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



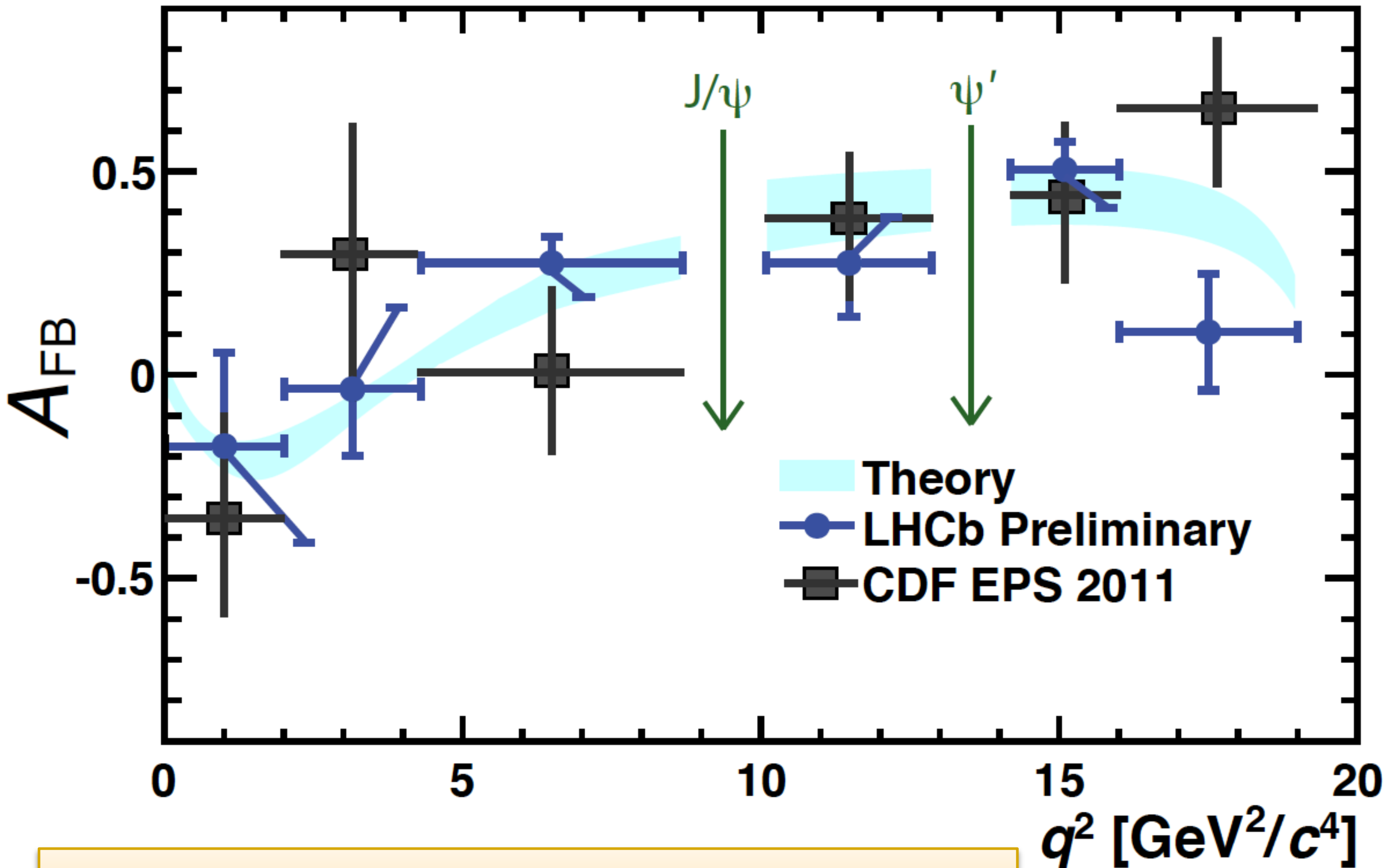
+ new particles in loops

- Several variables can be examined, e.g. muon forward-backward asymmetry, A_{FB} is well predicted
- Situation as of July 26



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

- New results from CDF 6.8 fb^{-1} & LHCb 0.3 fb^{-1}



No evidence of deviation from SM so far

Rare Decays - Generic

- $$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + {\rm h.c.}\ .$$
- $C_i O_i$ 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 $P_{R,L} \rightarrow P_{L,R}$
- $\mathcal{B}(b \rightarrow s\gamma)$ depends on O_7 & thus limits C_7'

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

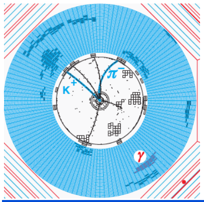
$$\frac{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) - \Gamma(B^0(t) \to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) + \Gamma(B^0(t) \to K^{*0}\gamma)} = S_{K^*\gamma}\sin(\Delta M_d t) - C_{K^*\gamma}\cos(\Delta M_d t)$$

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

- For Generic NP

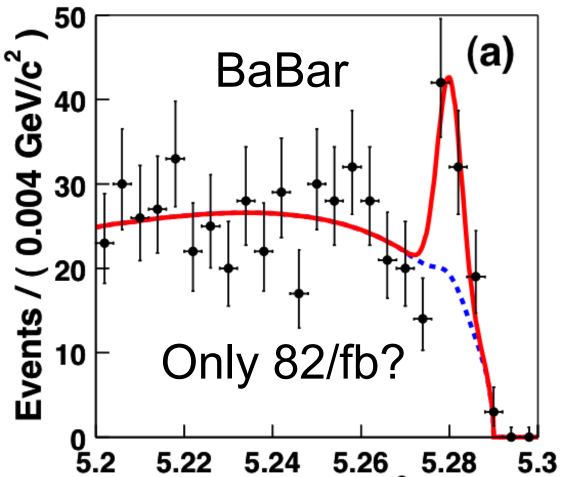
$$S_{K^*\gamma} \simeq \frac{2}{|C_7|^2 + |C_7'|^2}\,\mathrm{Im}\left(e^{-2i\beta}C_7C_7'\right)$$

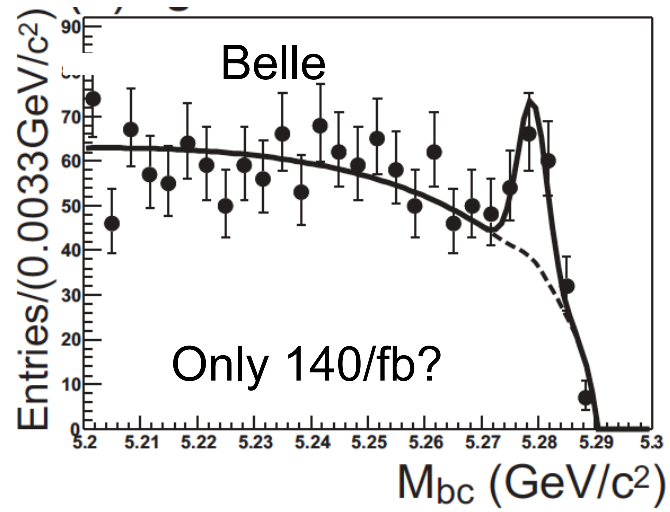
- Data, BaBar & Belle (-16±22)%, still useful even with the large error



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

- Define two q^2 regions: low 1-6, high >14.4 GeV^2
- Low again probes C_7, while high C_9 & C_{10}
- Data

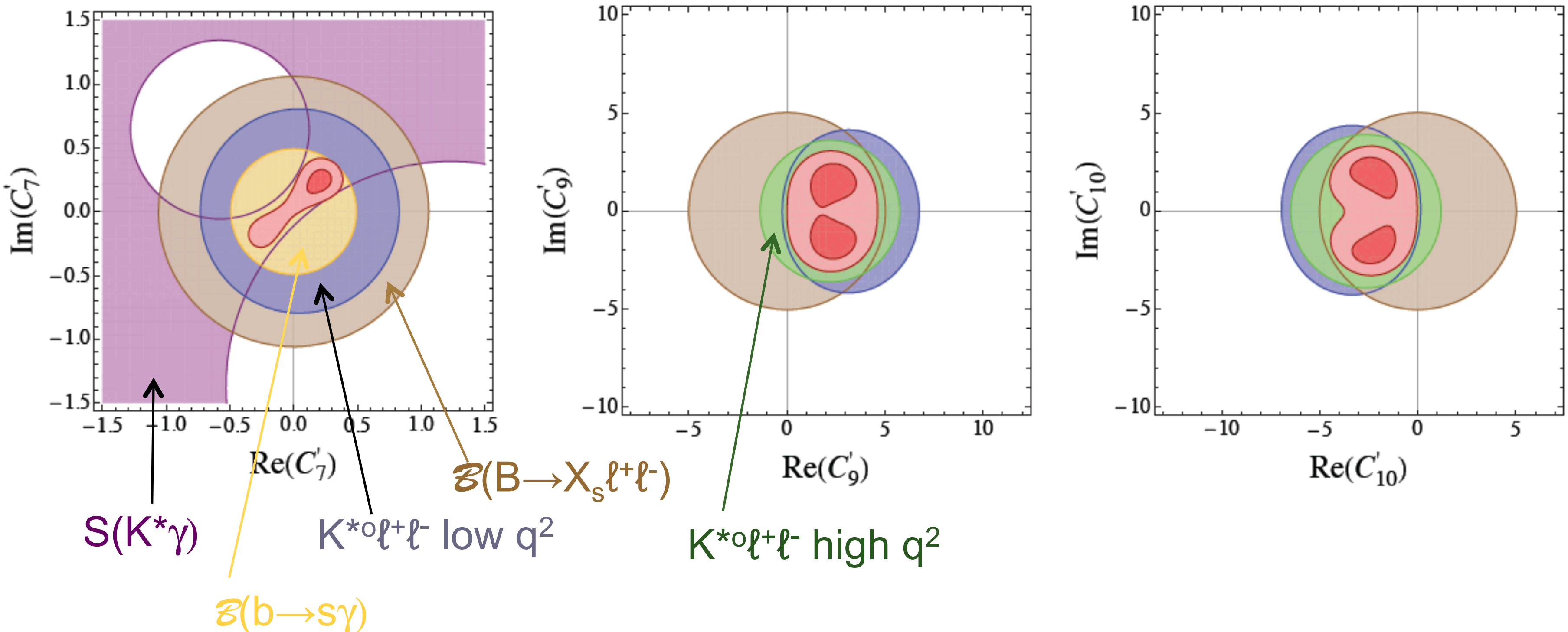




- High q^2:
  $\mathcal{B}(B \to X_s \ell^+ \ell^-) = (4.3 \pm 1.2) \times 10^{-7}$, SM 2.3×10^{-7}
- Low q^2: $\mathcal{B}(B \to X_s \ell^+ \ell^-) = (1.63 \pm 0.50) \times 10^{-6}$, SM 1.59×10^{-7}
- $B^o \to K^{*o} \ell^+ \ell^-$, is also sensitive to C_7 at low q^2, C_9 & C_{10} at high q^2

Common Analysis

- APS ≡ W. Altmannshofer, P. Paradisi & D. M. Straub arXiv:111.1257



- Many more such generic constraints

Another Analysis

arXiv:1111.2558 [pdf, other] The Decay $B \to K \ell^+ \ell^-$ at Low Hadronic Recoil and Model-Independent Delta B = 1 Constraints

Christoph Bobeth, Gudrun Hiller, Danny van Dyk, Christian Wacker

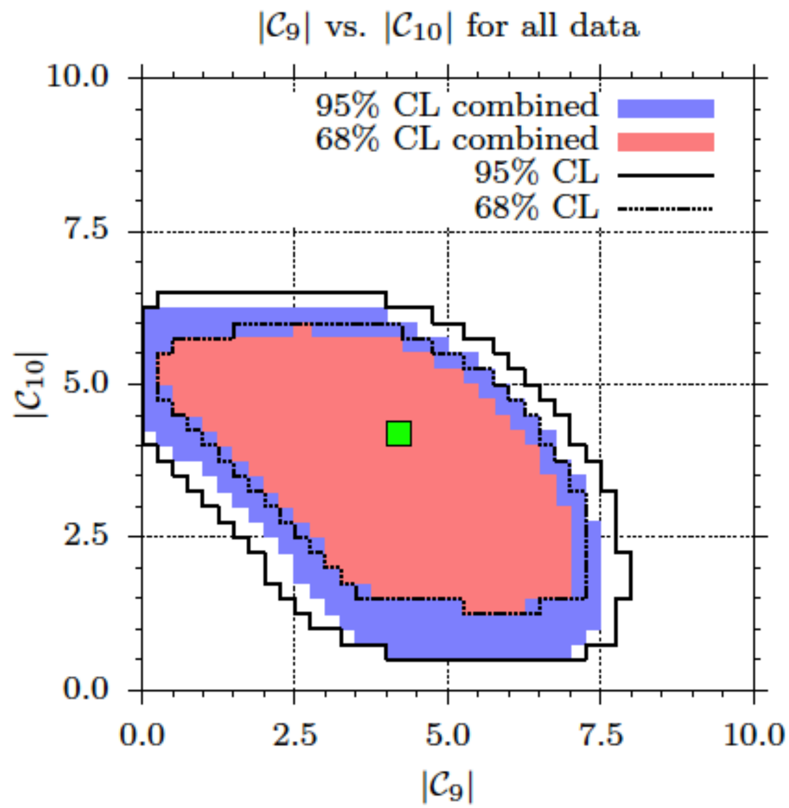
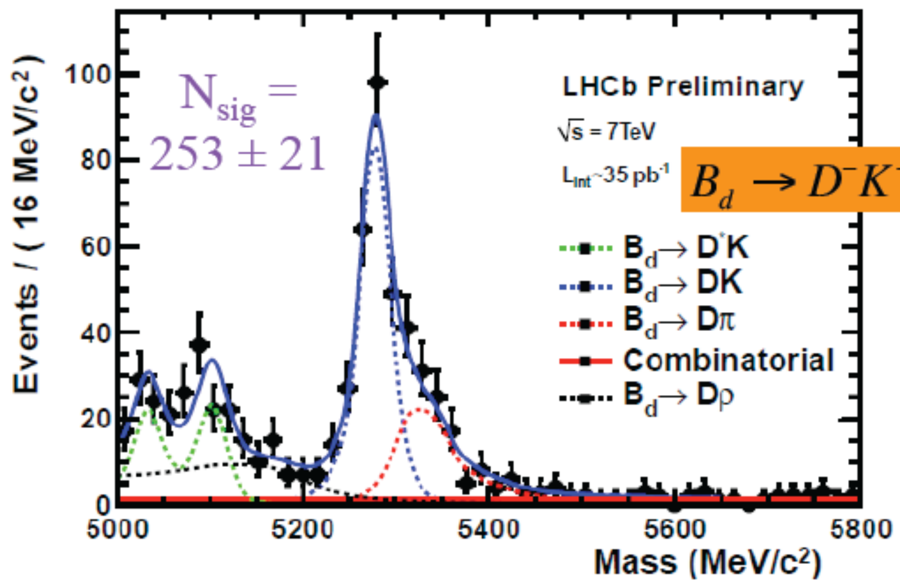


FIG. 5. Constraints on $|\mathcal{C}_9|$ and $|\mathcal{C}_{10}|$ from the combined analysis of $\bar{B} \to \{\bar{K}, \bar{K}^*, X_s\}\, \ell^+\ell^-$ decays at 68% CL (red area) and 95% CL (blue area). The 68% CL (dotted) and 95% CL (solid) contours without using $\bar{B} \to \bar{K}\ell^+\ell^-$ decays are shown as well. The green square marks the SM prediction.

b Fractions (LHCb)

- Important to set normalization scale for B_s
- f_s/f_d using hadronic decays

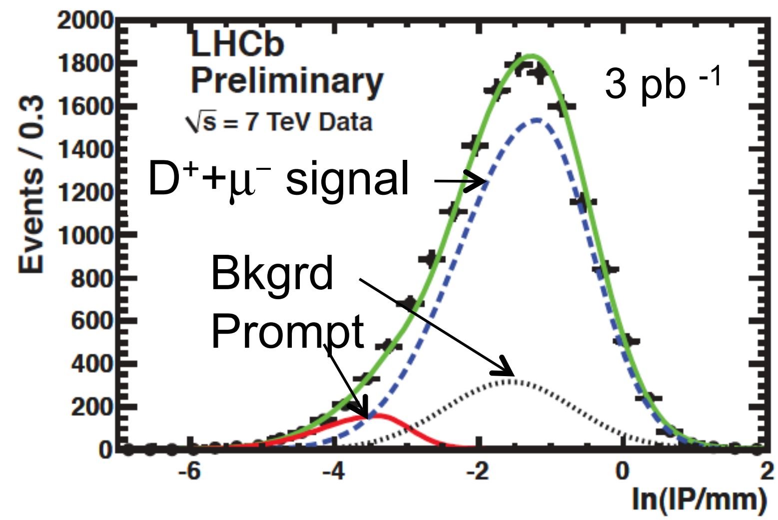
$B_d \to D^- K^+ / B_s \to D_s^- \pi^+$, & $B_d \to D^- \pi^+ / B_s \to D_s^- \pi^+$



$$f_s / f_d = 0.253 \pm 0.017 \pm 0.017 \pm 0.020$$

Theory error

- Using Semileptonics: $b \to (D^o, D^+, D_s, \Lambda_b)\, X\mu\upsilon$

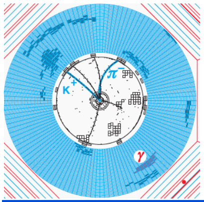


$$f_s / f_d = 0.268 \pm 0.008^{+0.022}_{-0.020}$$

- independent of η & p_t

$$f_s / f_d = 0.267^{+0.021}_{-0.020}$$

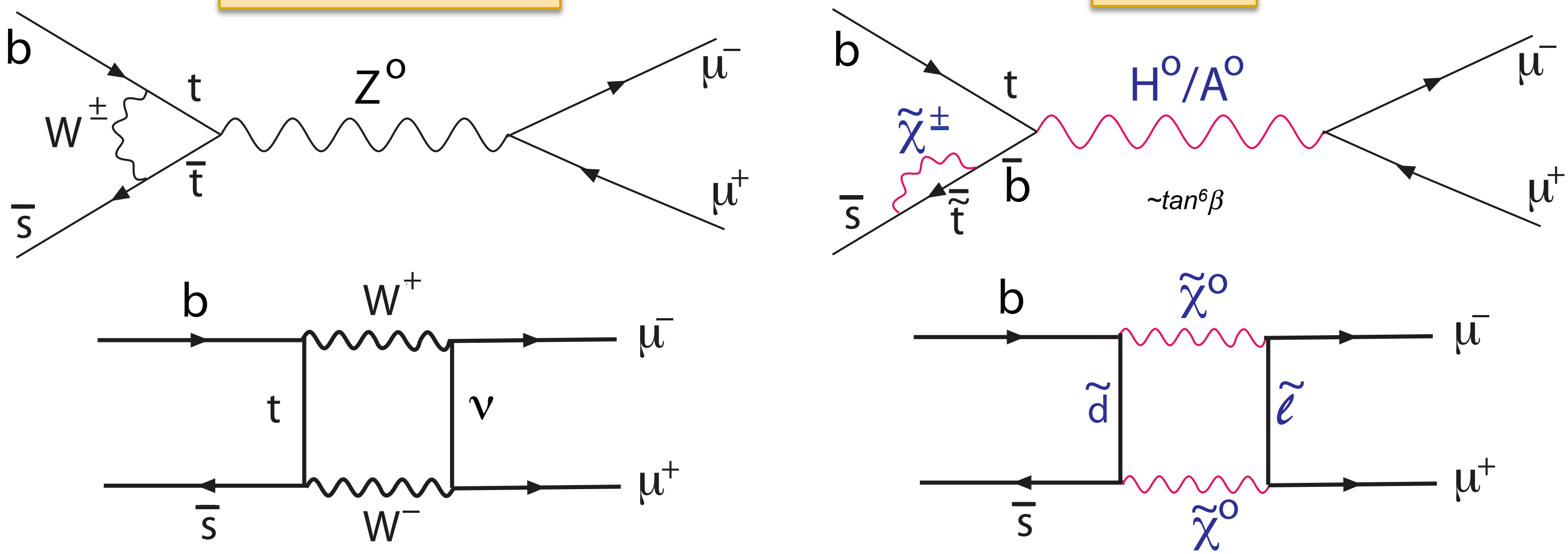
LHCb-CONF-2011-028



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

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

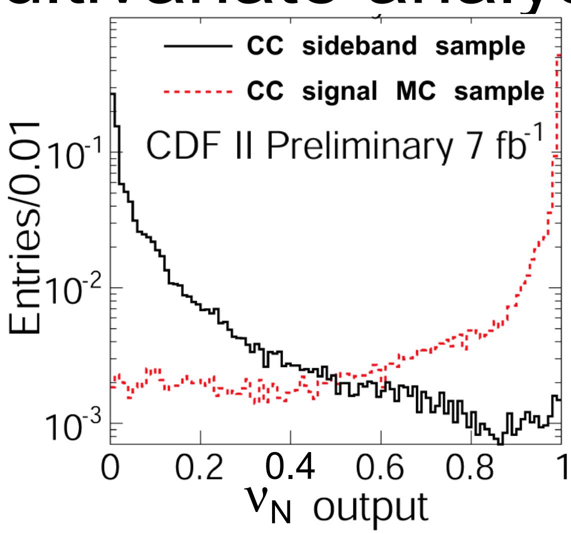
Standard Model | MSSM

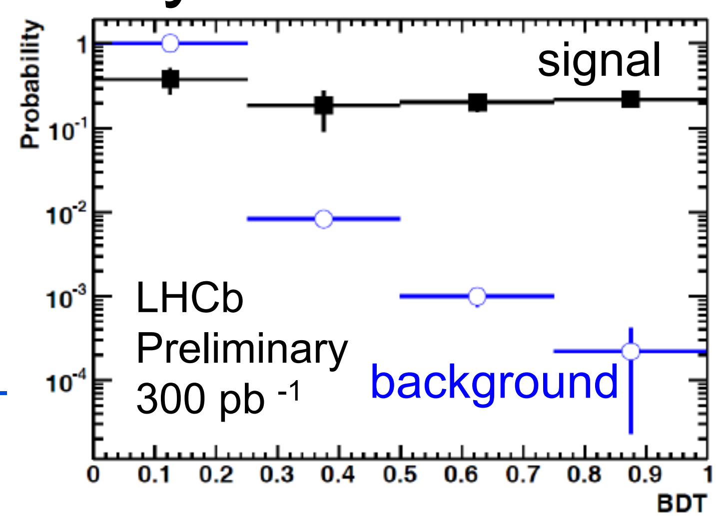


- Many NP models possible, not just Super-Sym

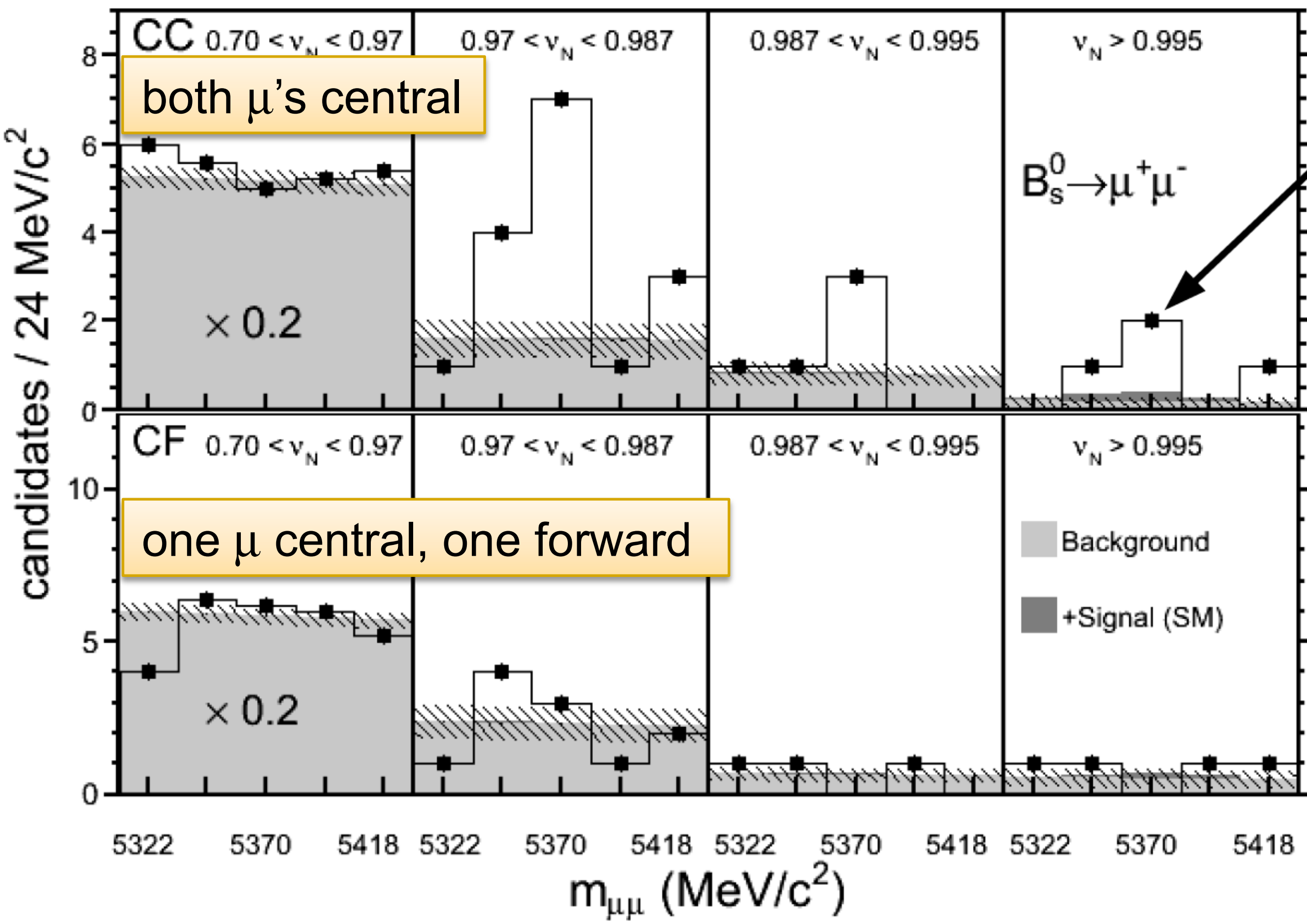
Discrimination

- Select same topology as $B \to h^+h^-$, add μ ID
- Lots of other variables to discriminate against bkgrd : B impact parameter, B lifetime, B p_t, B isolation, muon isolation, minimum impact parameter of muons, muon polarization…
- Can use $B \to h^+h^-$ to tune cuts or form a multivariate analysis, used by CDF & LHCb





CDF Result



Example:
Obs: 2
Bkg. exp:
0.16±0.12

$B(B_s \to \mu^+\mu^-)$

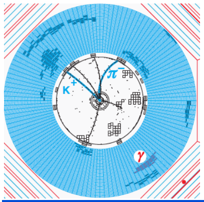
$= (1.8^{+1.1}_{-0.9})x10^{-8}$

5.6 x SM expectation

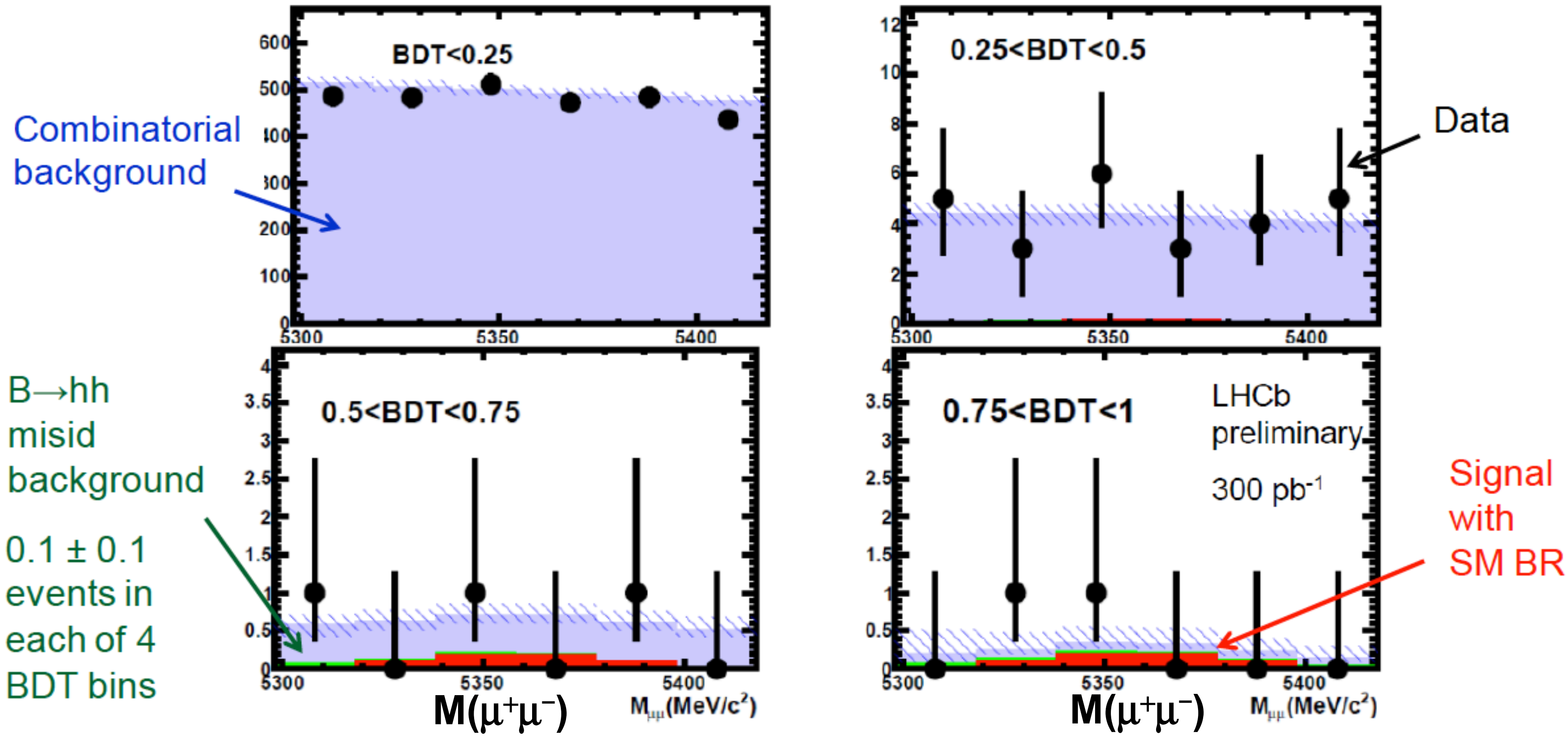
p value for bkgrnd + SM is 2.9%

Set a "two sided limit @ 90% CL" $4.6\times10^{-9} < \mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.9\times10^{-8}$

This means to me that there isn't a statistically significant result



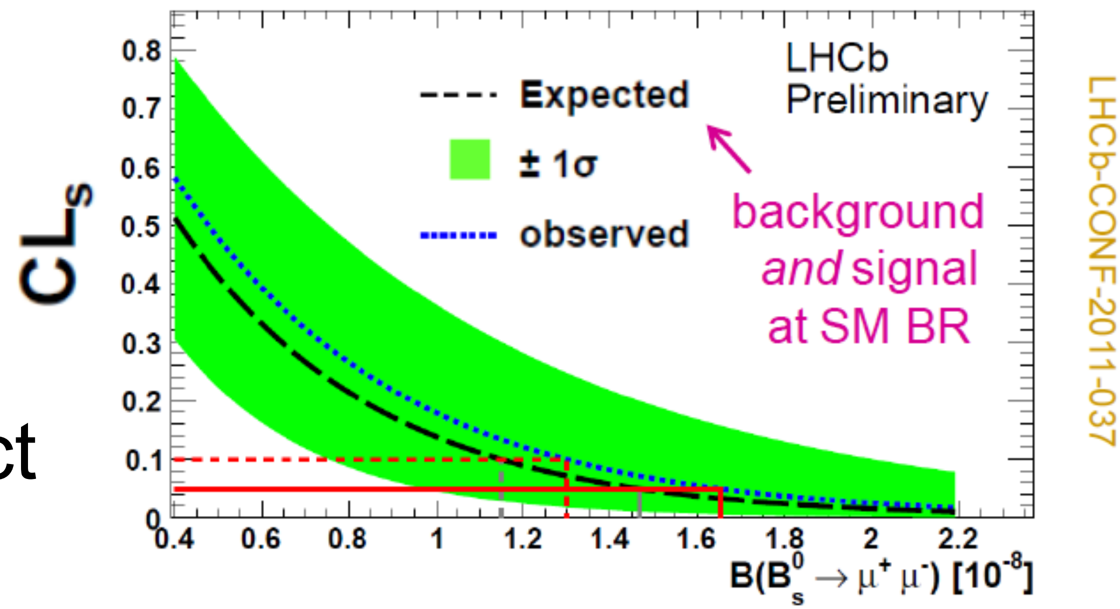
LHCb



	BDT<1/4	1/4<BDT<1/2	½<BDT<3/4	¾<BDT<1
# expected bkgrd	2968±69	25.0±2.5	2.99±0.89	0.66±0.40
# expected signal	1.26±0.13	0.61±0.06	0.67±0.07	0.72±0.07
Sum expected	2969±69	25.6±2.5	3.66±0.89	1.38±0.41
Observed	2872	26	3	2

LHCb

- LHCb does not observe any excess
- In the two BDT signal bins expect 5.1 events if $\mathcal{B}$ is at SM level, see 5



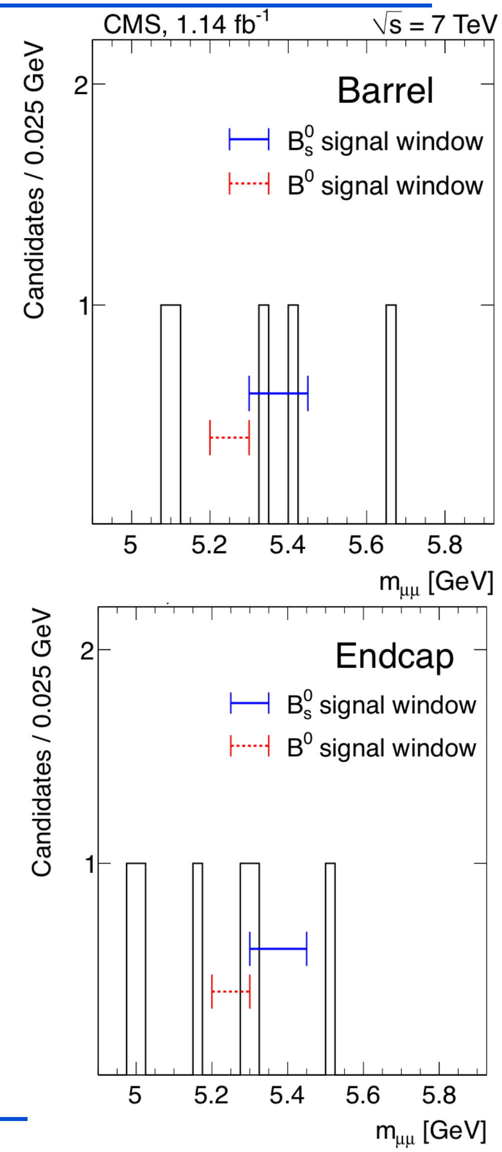
- Expected limit @95% (90%) $1.5(1.2)\times10^{-8}$
- Observed limit @95% (90%) $1.6(1.3)\times10^{-8}$
- p-value of bkgrnd only hypothesis 14%
- Observed limit with 2010 data $1.5(1.2)\times10^{-8}$

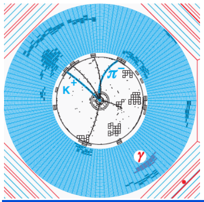
CMS

- Cut based analysis

	Barrel	Endcap
# expected bkgrd	0.60±0.35	0.80±0.40
# bkgrd $B \to h^+h^-$	0.07±0.02	0.04±0.01
# expected signal	0.80±0.16	0.36±0.07
Sum expected	1.47±0.39	1.20±0.41
Observed	2	1

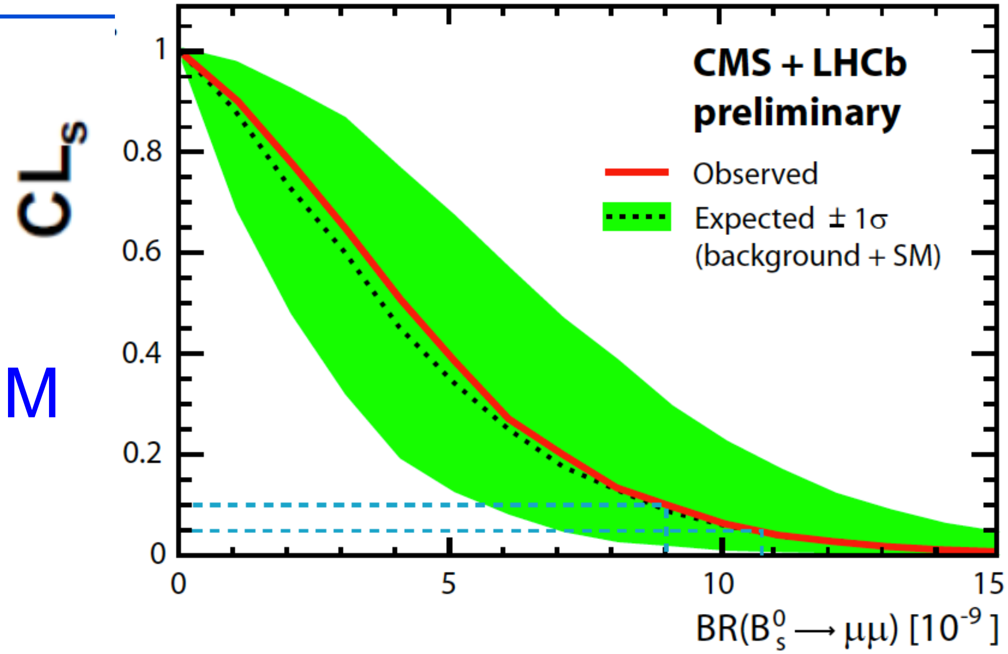
- Upper limits:
  - 1.9×10^{-8} @95% CL
  - 1.6×10^{-8} @90% CL

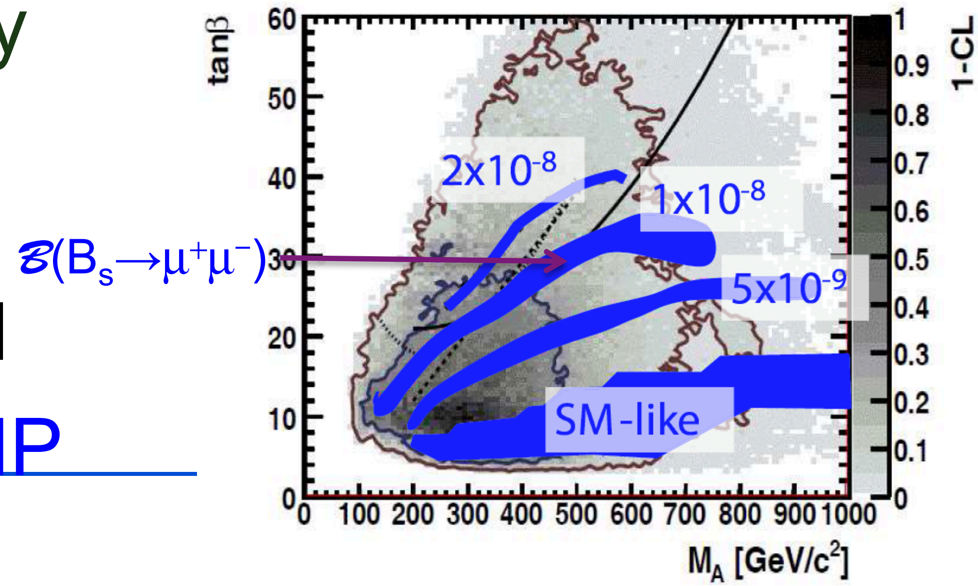




LHC Combined

- Observed limits
  - 1.1×10^{-8} @95% CL
  - 0.9×10^{-8} @90% CL,
  - This is 3.4(2.8) times SM value
- LHC consistent with CDF with a probability of 0.3%
- Set serious limits in NUHM1 SUSY model
- Still lots of room for NP





APS Model Predictions

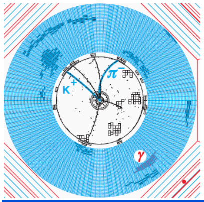
$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = |S|^2 \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + |P|^2,$$

$$S = \frac{m_{B_s}^2}{2m_\mu} \frac{(C_S - C_S')}{|C_{10}^{\mathrm{SM}}|}, \qquad P = \frac{m_{B_s}^2}{2m_\mu} \frac{(C_P - C_P')}{C_{10}^{\mathrm{SM}}} + \frac{(C_{10} - C_{10}')}{C_{10}^{\mathrm{SM}}}$$

- Using information from other modes predict NP based on different schemes

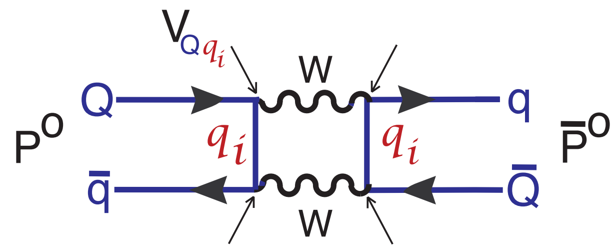
Model	Real LH	Cmpx LH	Cmpx RH	Generic NP	LH Z Peng	RH Z Peng	Generic Z peng	Scalar current
$\mathcal{B}$x10^{-9}	1.0-5.6	1.0-5.4	<5.6	<5.5	1.4-5.5	<3.8	<4.1	<11

- Recall SM $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2)\mathrm{x}10^{-9}$



Neutral Meson Mixing

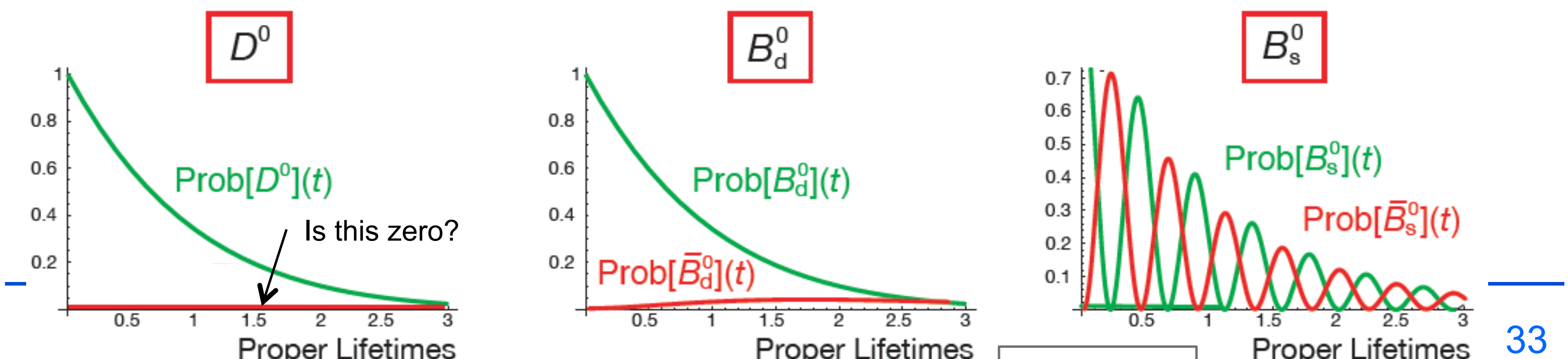
- Neutral mesons can transform into their anti-particles via 2nd order weak interactions
- Short distance transition rate depends on
  - mass of intermediate q_i, the heavier the better, favors s & b since t is allowed, while for c, b is the heaviest
  - CKM elements V_{ij}



New particles possible in loop

+ "long distance" for D^o

$D^0 \Longrightarrow \pi\pi,.. \Longrightarrow \bar{D}^0$

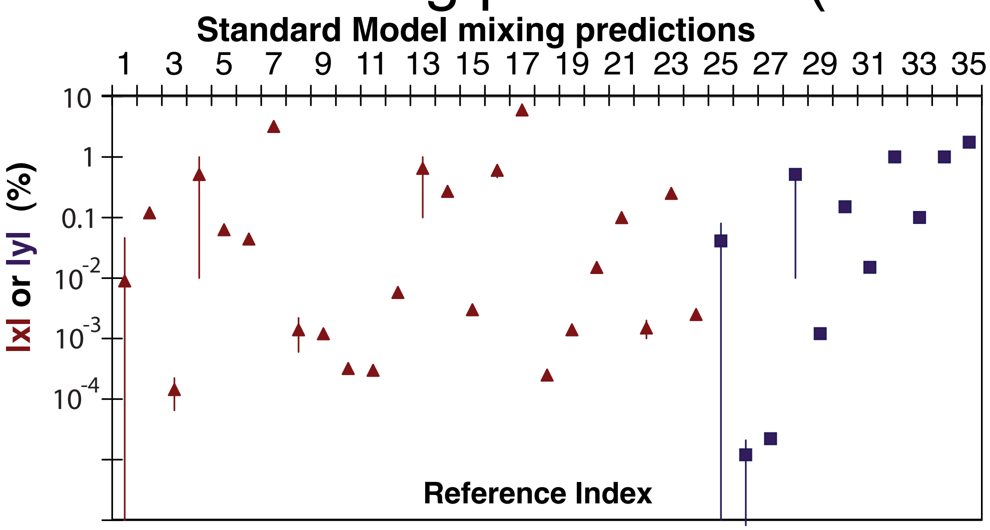


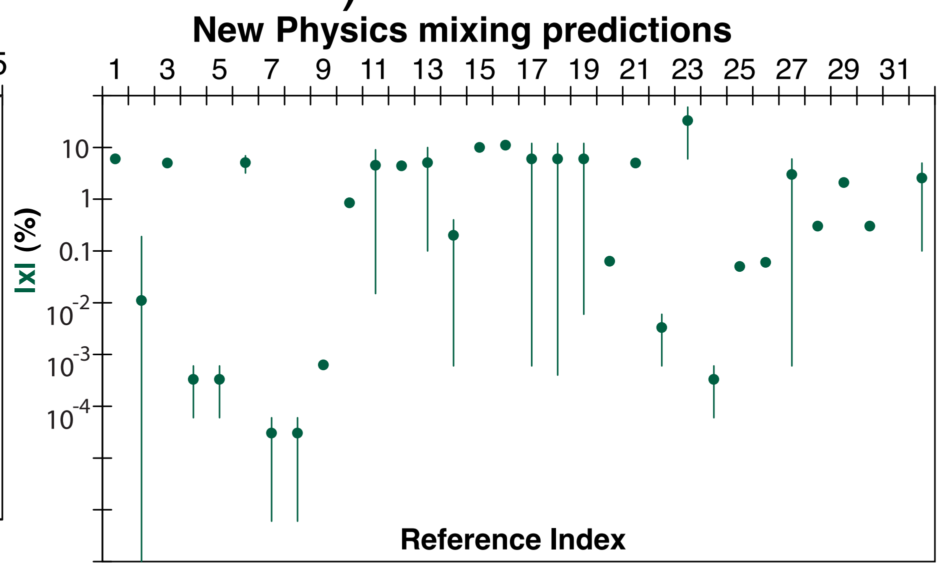
from Van Kooten

Some Definitions

- Weak interaction eigenstates are different that strong interaction eigenstates
- $|M_L\rangle = p|M^o\rangle + q|\overline{M}^o\rangle$, $|M_H\rangle = p|M^o\rangle - q|\overline{M}^o\rangle$,
- Since we observe the mesons via their weak decays, $m = (M_H+M_L)/2$, $\Delta M = M_H - M_L$,

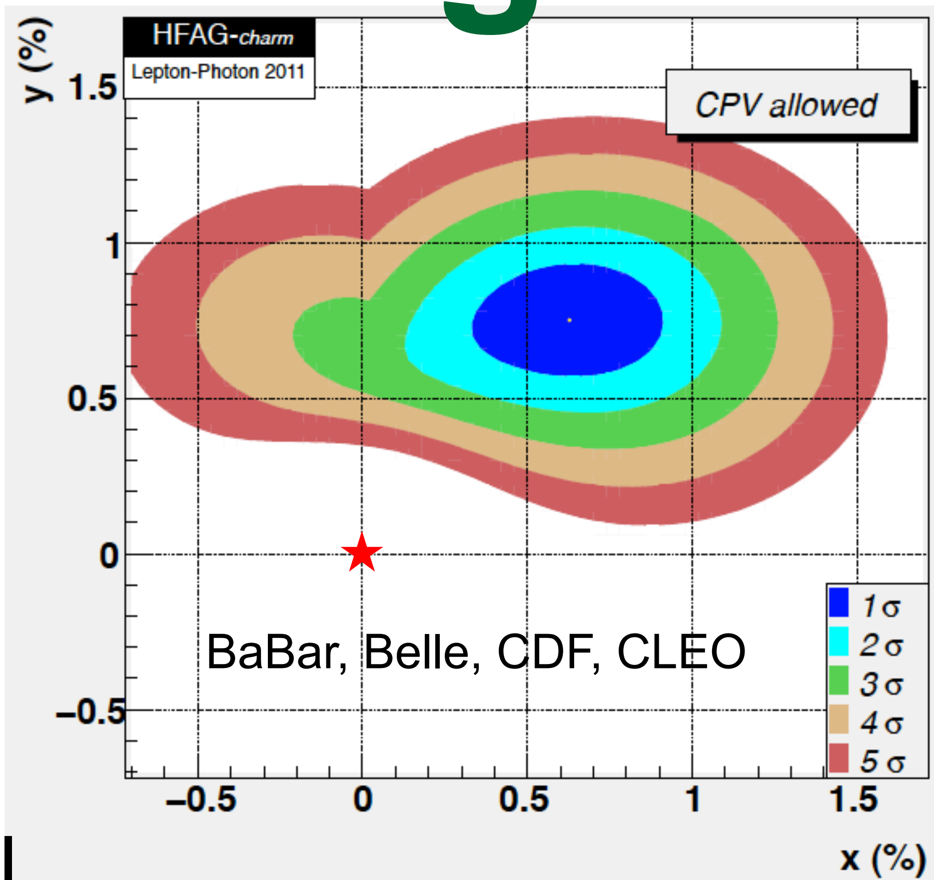
  $1/\tau = \Gamma = (\Gamma_H + \Gamma_L)/2$, $\Delta\Gamma = \Gamma_L - \Gamma_H$,
- Useful quantities are $x = \Delta M/\Gamma$, $y = \Delta\Gamma/2\Gamma$
- D^o mixing predictions (from Petrov 2006):

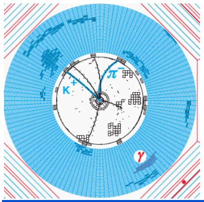




D° Mixing

- Data from BaBar, Belle, CDF, CLEO
- Result 10.1σ from no mixing, though no single measurement is better than 5σ
- Non-zero value allows for indirect CPV, as well as direct CPV in decay, or a mixture of the two





CPV in Charm

- Expect largest effects in Cabibbo Suppressed Decays. COULD REVEAL NP (see Grossman Kagan & Nir)
- Nothing yet observed, limits at <1% level
- Experiments, in some cases, now measuring differences in CP asymmetries to cancel systematic effects
- Examples (define $A(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$) if $f = \bar{f}$, CP eigenst
  - Belle $A(D^+ \to \phi\pi^+) - A(D_s^+ \to \phi\pi^+) = (-0.51 \pm 0.28 \pm 0.05)\%$ [arXiv: 1110.0694]
  - CDF $A(D^o \to \pi^+\pi^-) = (-0.22 \pm 0.24 \pm 0.11)\%$ & $A(D^o \to K^+K^-) = (-0.24 \pm 0.22 \pm 0.10)\%$ [CDF Public Note 10269]
  - LHCb 35 pb^{-1} Direct CPV $A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.28 \pm 0.70 \pm 0.25)\%$, LHCb-CONF-2011-02. To be updated next Friday, I expect something like a 3.5σ effect

CPV Time Evolution

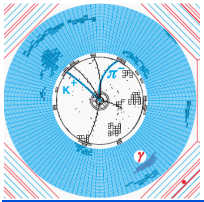
- Consider $$a[f(t)] = \frac{\Gamma\left(\bar{M} \to f\right) - \Gamma\left(M \to f\right)}{\Gamma\left(\bar{M} \to f\right) + \Gamma\left(M \to f\right)}$$
- Define $$A_f \equiv A(M \to f),\ \bar{A}_f \equiv A(\bar{M} \to f),\quad \lambda_f = \frac{p}{q}\frac{\bar{A}_f}{A_f}$$
- Only 1 A_f & $\Delta\Gamma=0$ $\Gamma\left(M \to f\right) = N_f \left|A_f\right|^2 e^{-\Gamma t}\left(1 - \mathrm{Im}\,\lambda_f \sin\left(\Delta M t\right)\right)$
- Then $a[f(t)] = -\mathrm{Im}\,\lambda_f$, & λ_f is a function of V_{ij} in SM
- For B^o, $\Delta\Gamma\approx 0$, but there can be multiple A_f

$$\Gamma\left(M \to f\right) = N_f \left|A_f\right|^2 e^{-\Gamma t}\left(\frac{1-\left|\lambda_f\right|^2}{2}\cos\left(\Delta M t\right) - \mathrm{Im}\,\lambda_f \sin\left(\Delta M t\right)\right)$$

- If in addition $\Delta\Gamma\neq 0$, eg. B_s

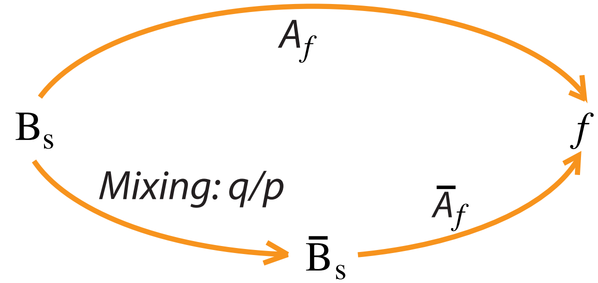
$$\Gamma\left(M \to f\right) = N_f \left|A_f\right|^2 e^{-\Gamma t}\left(\frac{1+\left|\lambda_f\right|^2}{2}\cosh\frac{\Delta\Gamma t}{2} + \frac{1-\left|\lambda_f\right|^2}{2}\cos\left(\Delta M t\right) - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} - \mathrm{Im}\,\lambda_f \sin\left(\Delta M t\right)\right)$$

See Nierste
arXiv:0904.1869 [hep-ph]

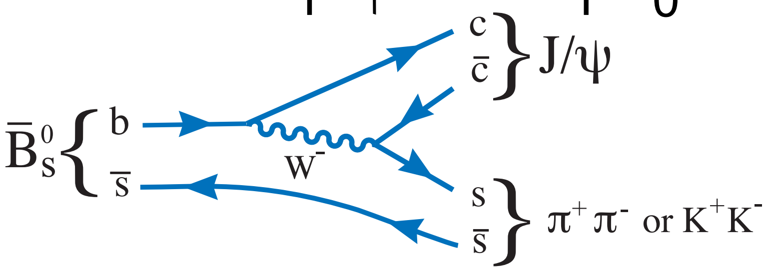


CPV in $B_s \to J/\psi X$

- Interference between mixing & decay



- For f =$J/\psi\ \phi$ or $J/\psi\ f_0$

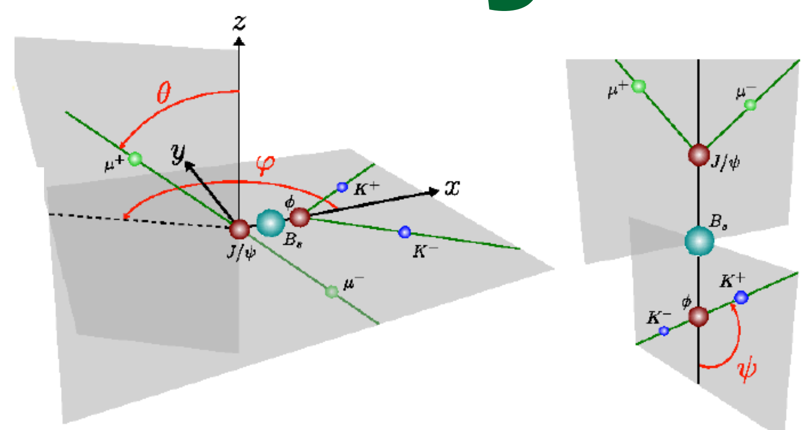


$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.04\ \text{rad}$$

- 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

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	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

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

Transversity II

$$|A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right],$$

$$|A_\|(t)|^2 = |A_\||^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right],$$

$$|A_\perp(t)|^2 = |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right],$$

$$\Im(A_\|^*(t)\,A_\perp(t)) = |A_\||A_\perp|e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\|)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta\_\|)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\|)\cos(\Delta m t)\right],$$

$$\Re(A_0^*(t)\,A_\|(t)) = |A_0||A_\||e^{-\Gamma_s t}\cos(\delta_\| - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right],$$

$$\Im(A_0^*(t)\,A_\perp(t)) = |A_0||A_\perp|e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)\right],$$

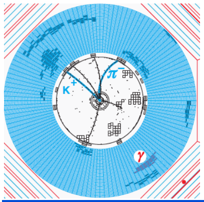
$$|A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right],$$

only term for $f=f_{cp}$

$$\Re(A_s^*(t)A_\|(t)) = |A_s||A_\||e^{-\Gamma_s t}\left[-\sin(\delta_\| - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\| - \delta_s)\ \cos\phi_s \sin(\Delta m t) + \cos(\delta_\| - \delta_s)\cos(\Delta m t)\right],$$

$$\Im(A_s^*(t)A_\perp(t)) = |A_s||A_\perp|e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right],$$

$$\Re(A_s^*(t)A_0(t)) = |A_s||A_0|e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s)\cos(\Delta m t)\right].$$



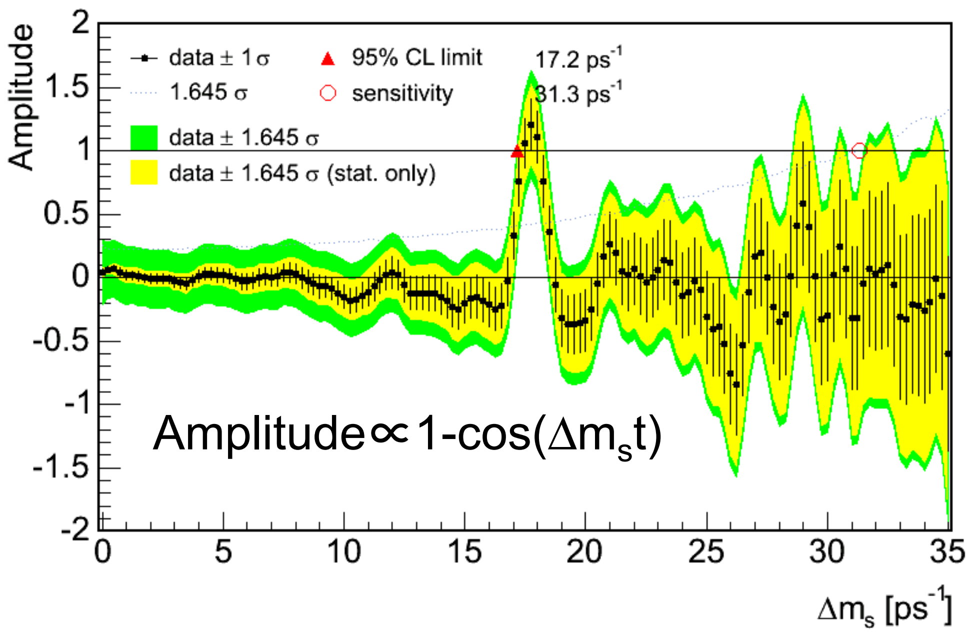
ΔM_s

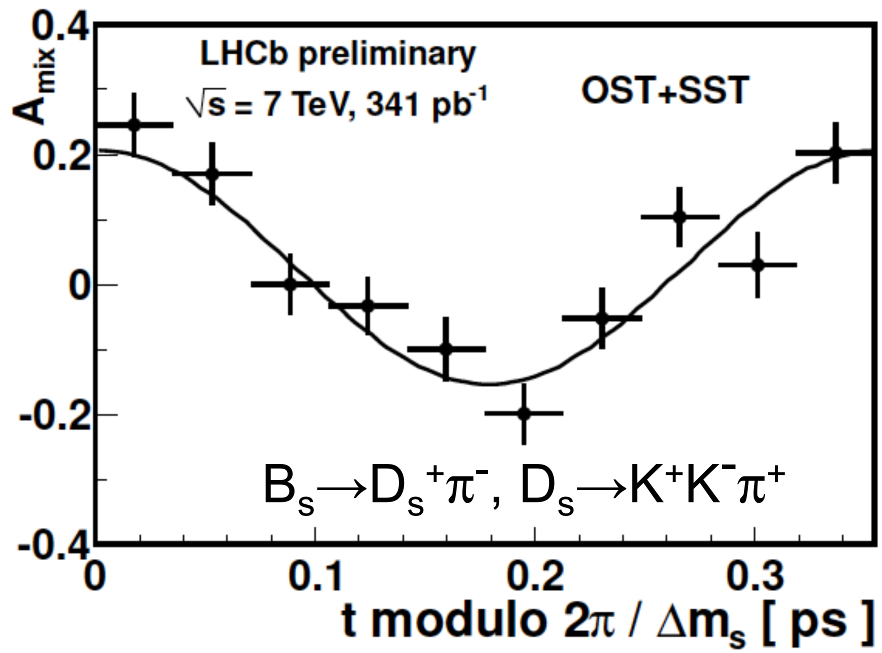
CDF 1 fb^{-1} (2006)

17.77±0.10±0.07 ps^{-1}

LHCb 0.34 fb^{-1} (2011)

17.725±0.041±0.026 ps^{-1}

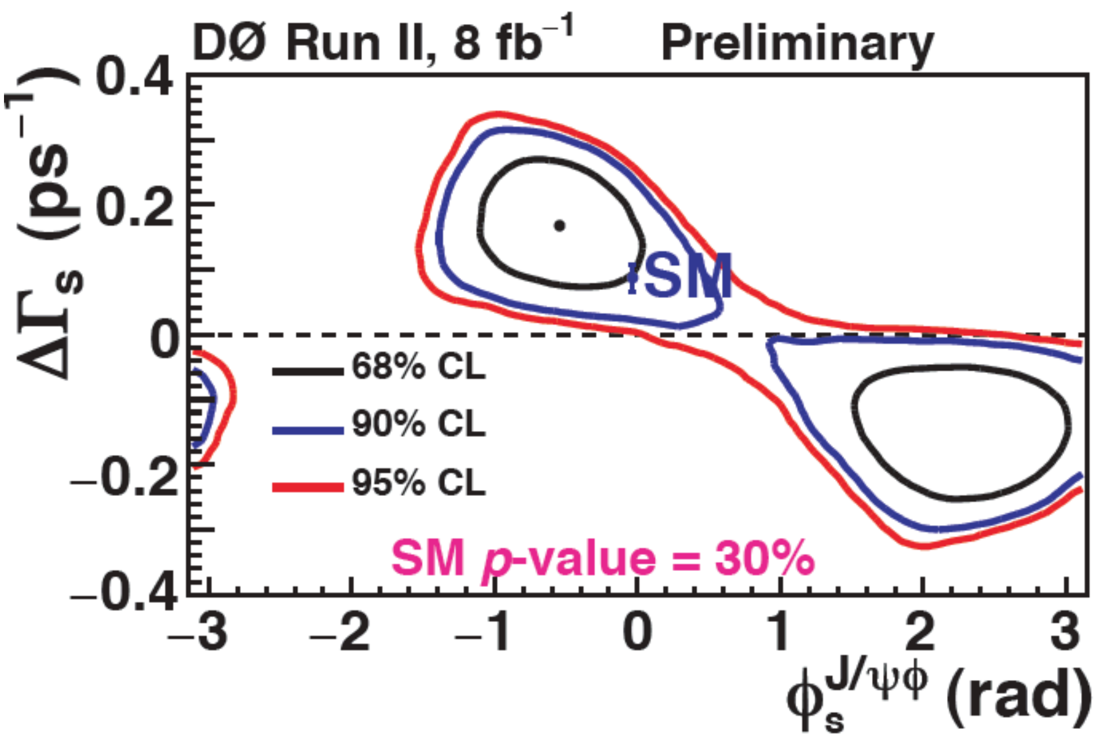


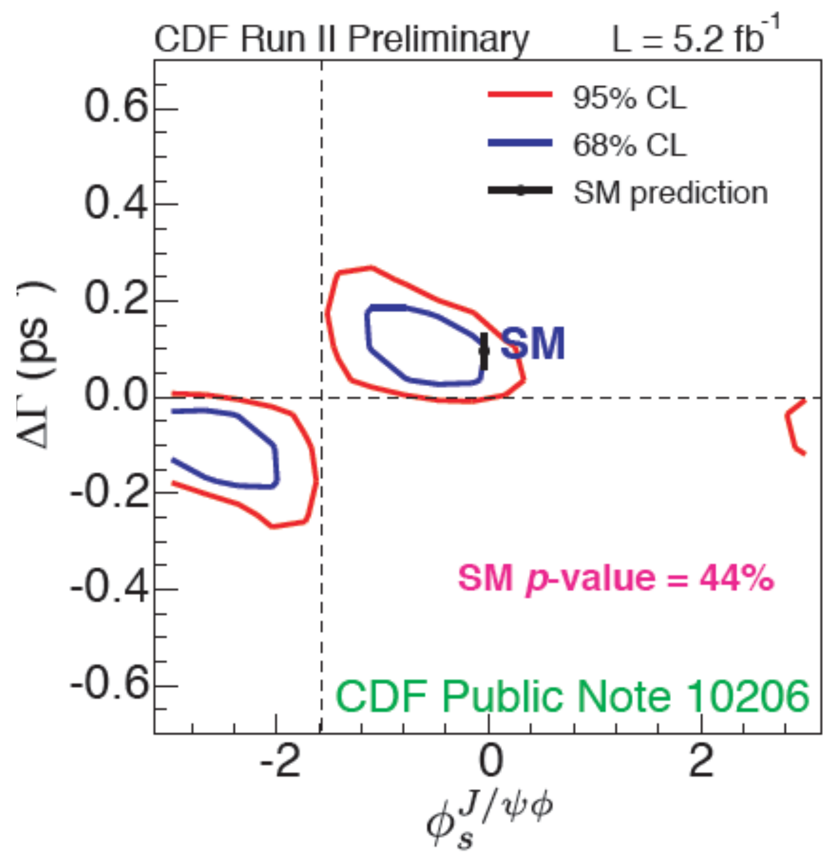


- Used to calibrate the flavor tagging

CPV in $B_s \rightarrow J/\psi\phi$

- Correlated constraints on $\Delta\Gamma_s$ versus CP violating phase ϕ_s
- Ambiguous solution for $\Delta\Gamma_s \rightarrow -\Delta\Gamma_s$, $\phi_s \rightarrow \pi - \phi_s$.



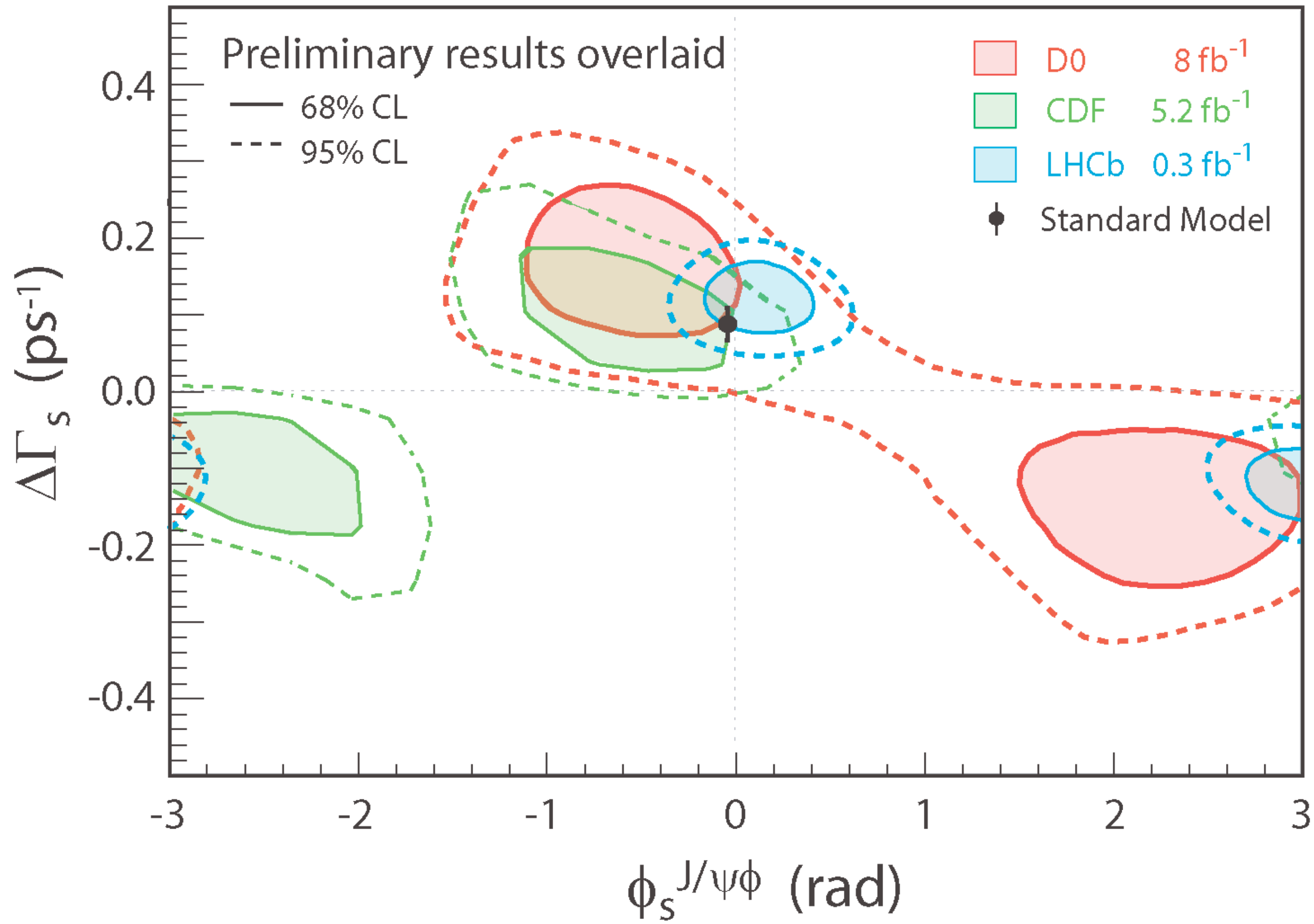


New LHCb ϕ_s result

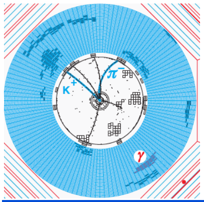
$\Gamma = 0.656 \pm 0.009 \pm 0.008$ (ps^{-1})

$\Delta\Gamma = 0.123 \pm 0.029 \pm 0.011$ (ps^{-1})

$\phi_s = 0.13 \pm 0.18 \pm 0.07$ (rad)

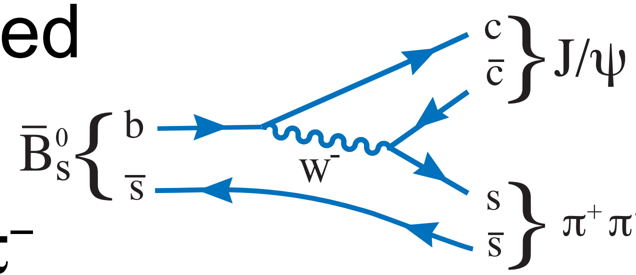


- All measurements consistent with SM value



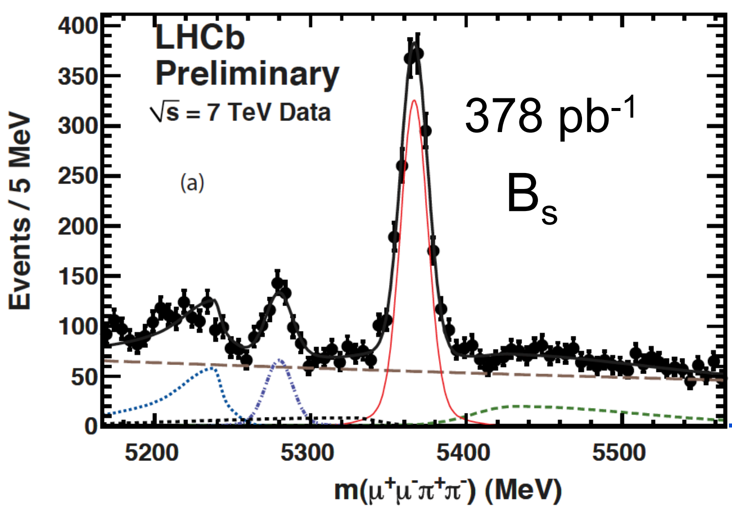
1^{st} Observation of $B_s \to J/\psi\, f_0(980)$

- In $B_s \to J/\psi\,\phi$ the S-wave predicted (& now observed) under the ϕ could manifest itself as a $0^+\ \pi^+\pi^-$ system, the $f_0(980)$ [Stone & Zhang PRD 79, 074024 (2009)]. As a CP eigenstate can be used to measure ϕ_s without angular analysis

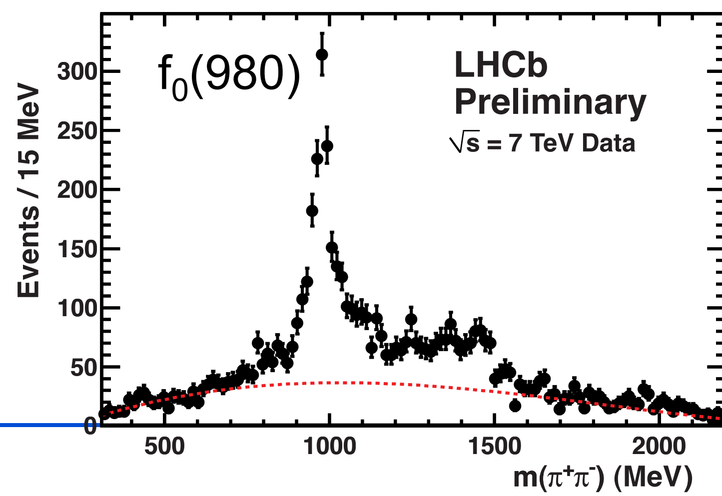


$$\frac{\Gamma\left(J/\psi f_0;\, f_0 \to \pi^+\pi^-\right)}{\Gamma\left(J/\psi\phi;\, \phi \to K^+K^-\right)} \approx 0.25$$

m(J/ψ π⁺π⁻) within 90 MeV of 980 MeV

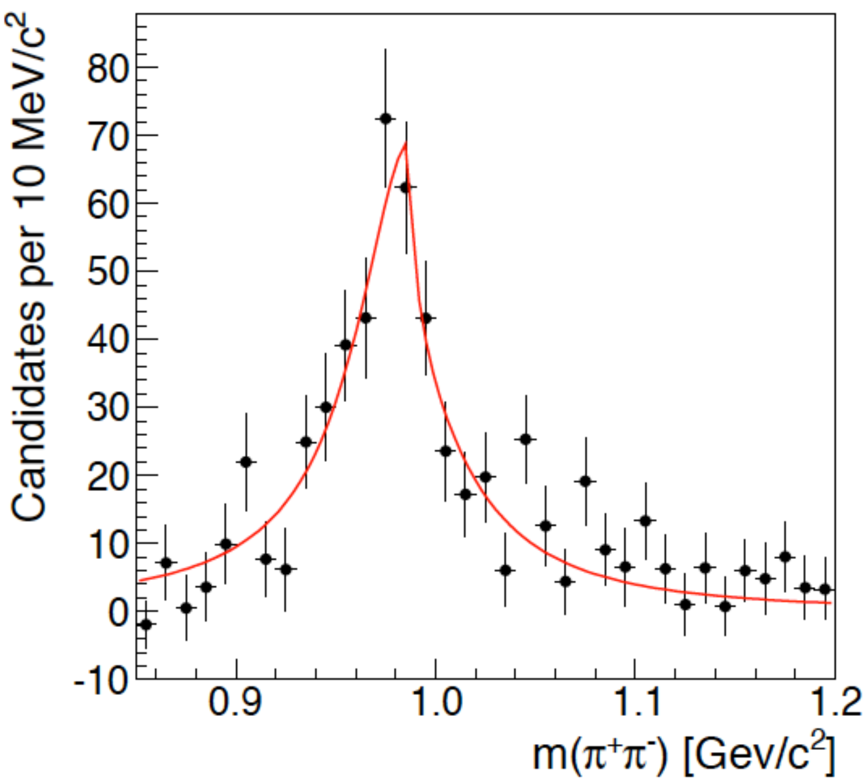


m(π⁺π⁻) within 30 MeV of B_s mass

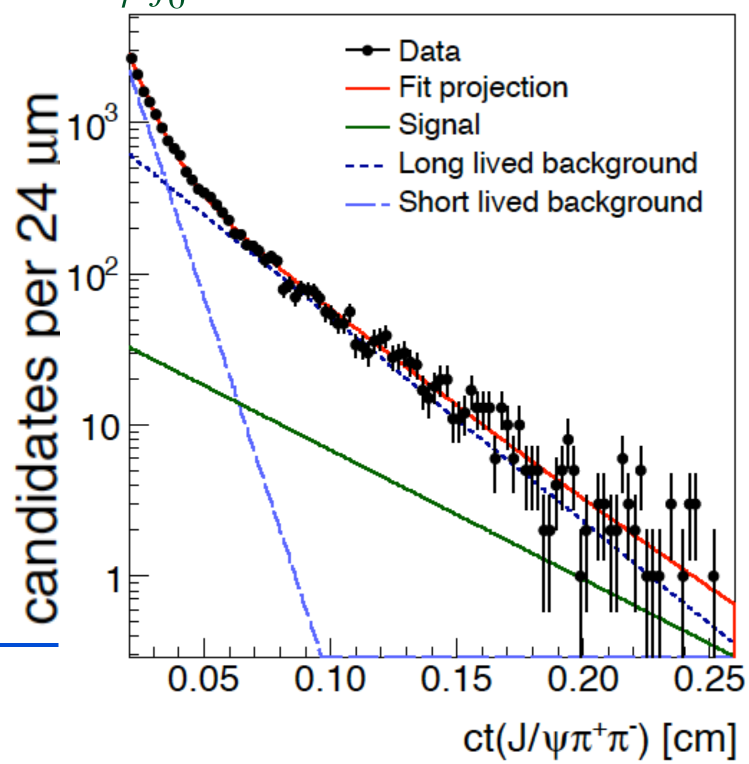


Confirmations

- Belle, CDF & D0
- CDF measures τ also, ignoring CP violation, in this CP odd eigenstate. $<\tau_{Bs}>=1.43\pm0.04$ ps (PDG)

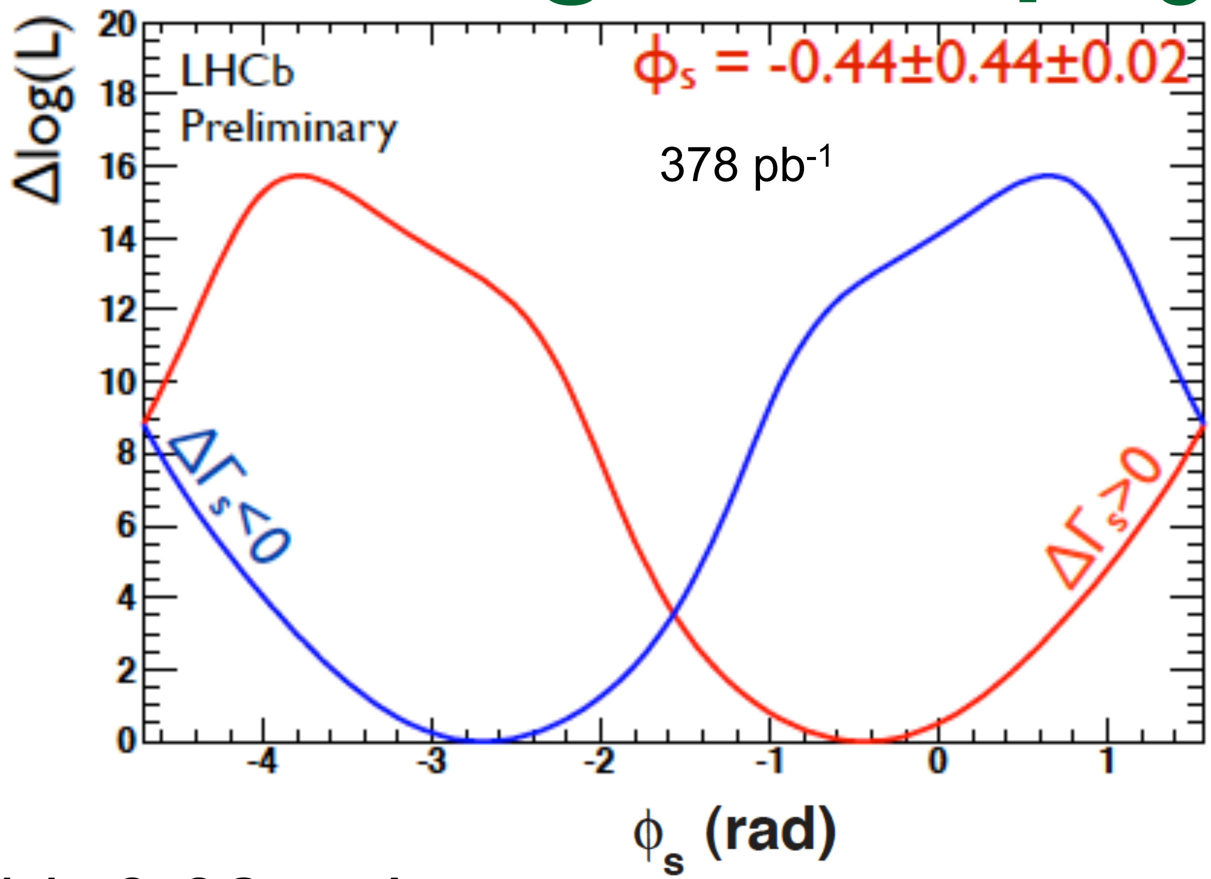


$$\tau_{J/\psi f_0} = 1.70^{+0.12}_{-0.11} \pm 0.03\,\mathrm{ps}$$



CPV in $B_s \to J/\psi f_0$

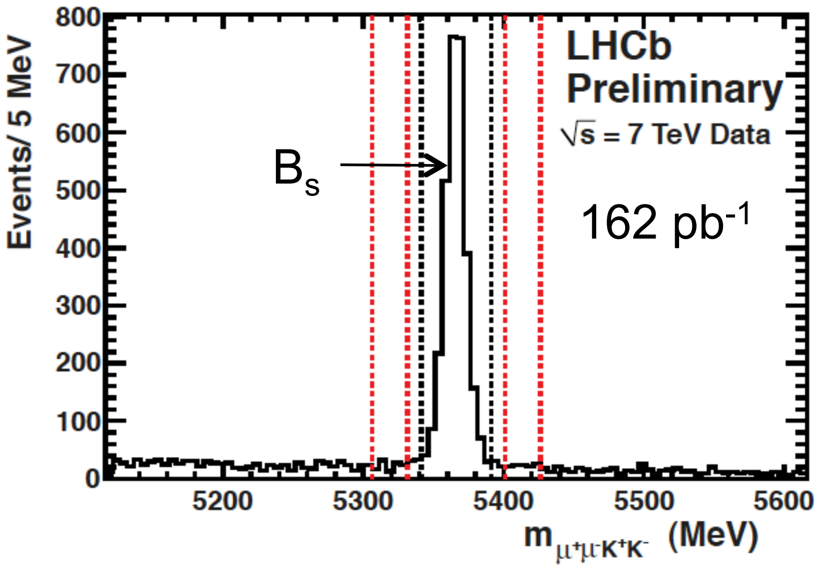
Log-likelihood profile

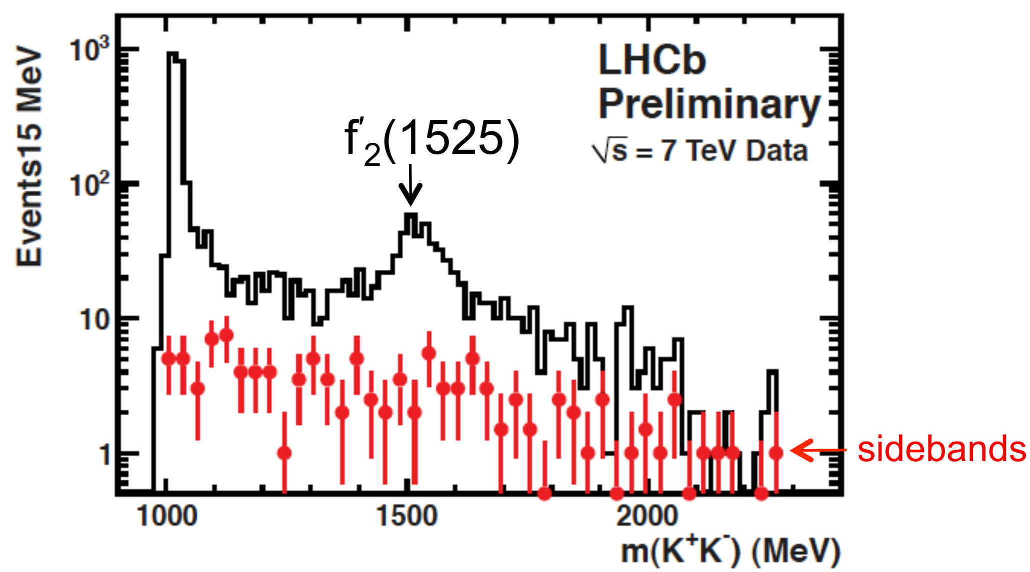


- ϕ_s=-0.44±0.44±0.02 rad
- Combined with $J/\psi\phi$, ϕ_s=0.03±0.16±0.07 rad

1^{st} Observation of $B_s \to J/\psi\, f'_2(1525)$

- $B_s \to J/\psi K^+K^-$

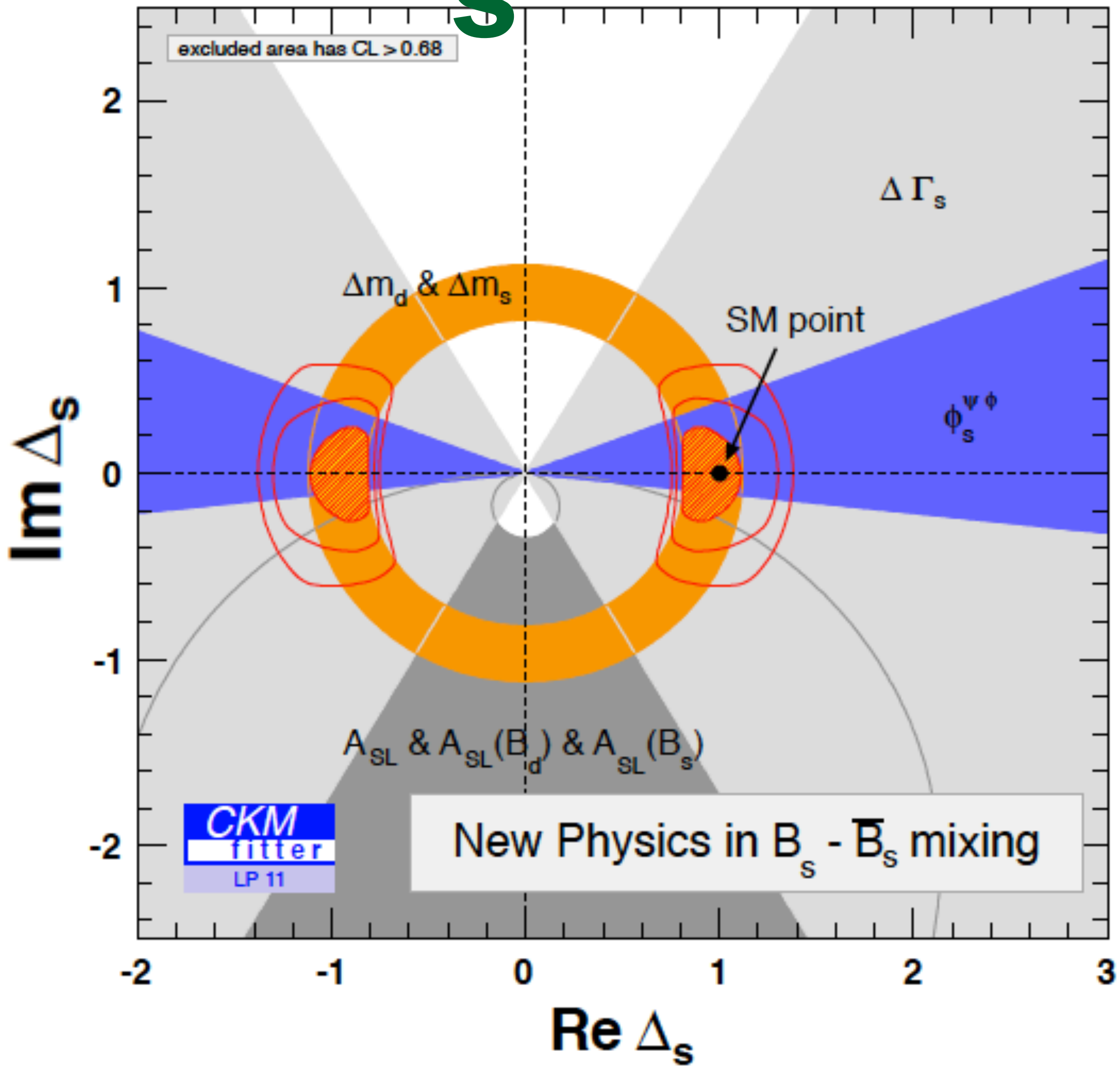


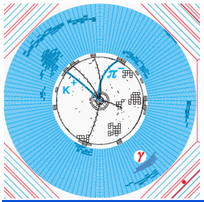


- $$R^{f'_2}_{\text{effective}} \equiv \frac{\mathcal{B}(B^0_s \to J/\psi f'_2(1525),\ f'_2(1525) \to K^+K^-)}{\mathcal{B}(B^0_s \to J/\psi\phi,\ \phi \to K^+K^-)} = (19.4 \pm 1.8 \pm 1.1)\%$$
  $$\text{for } \left|m(K^+K^-) - 1525\ \text{MeV}\right| < 125\ \text{MeV}.$$

CKM B_s Fit

- Now even better consistency with SM than B_d
- However, much more room for NP than in B_d system due to less precise measurements





a_{sl}

- By definition $|q/p| = 1-a_{sl}$

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

- Here *f* is by construction flavor specific, $f \neq \bar{f}$
- Can measure eg. $\bar{B}_s \rightarrow D_s^+ \mu^- \nu$, 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, $a_{sl}=(\Delta\Gamma/\Delta M) \tan \phi$, for B^o -7.6×10^{-4} for B_s $+3.4\times10^{-5}$

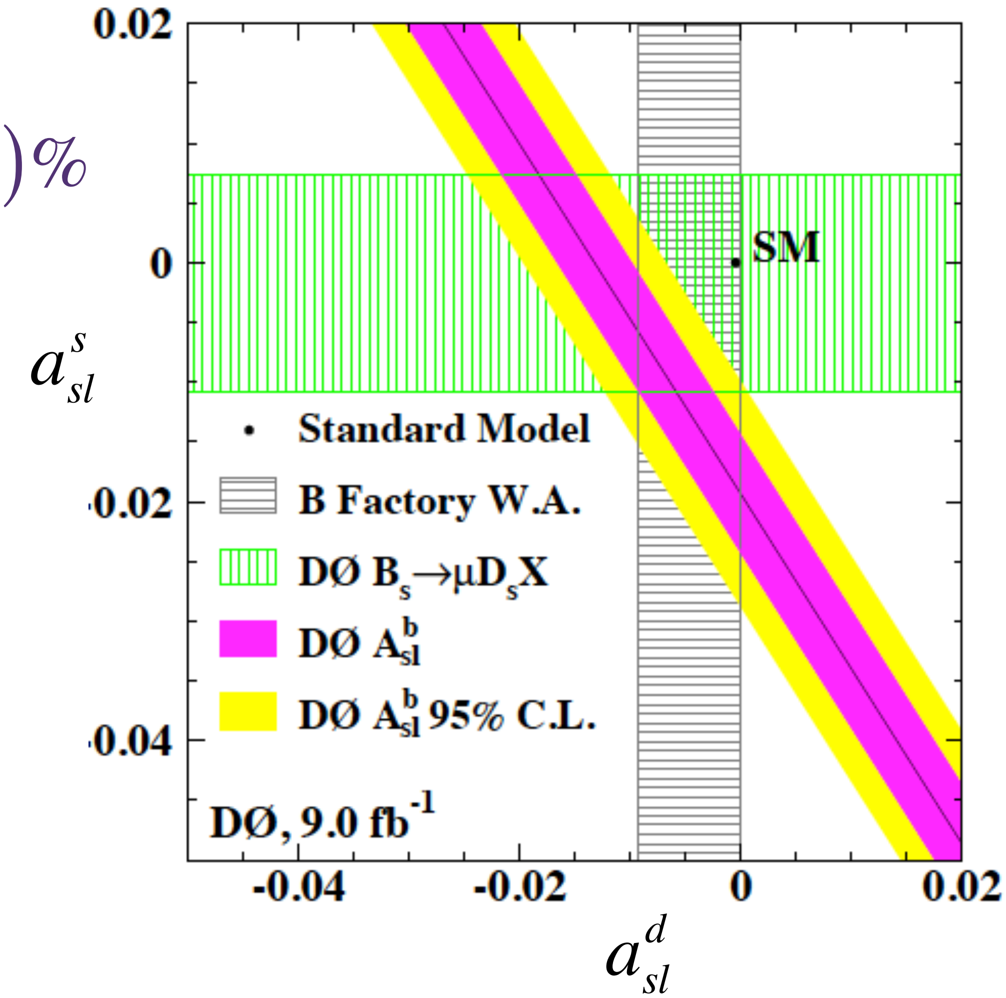
arXiv:1008.1593 [hep-ph]

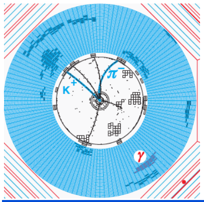
DØ result on a_{sl}

- Using dimuons

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

3.9σ from zero



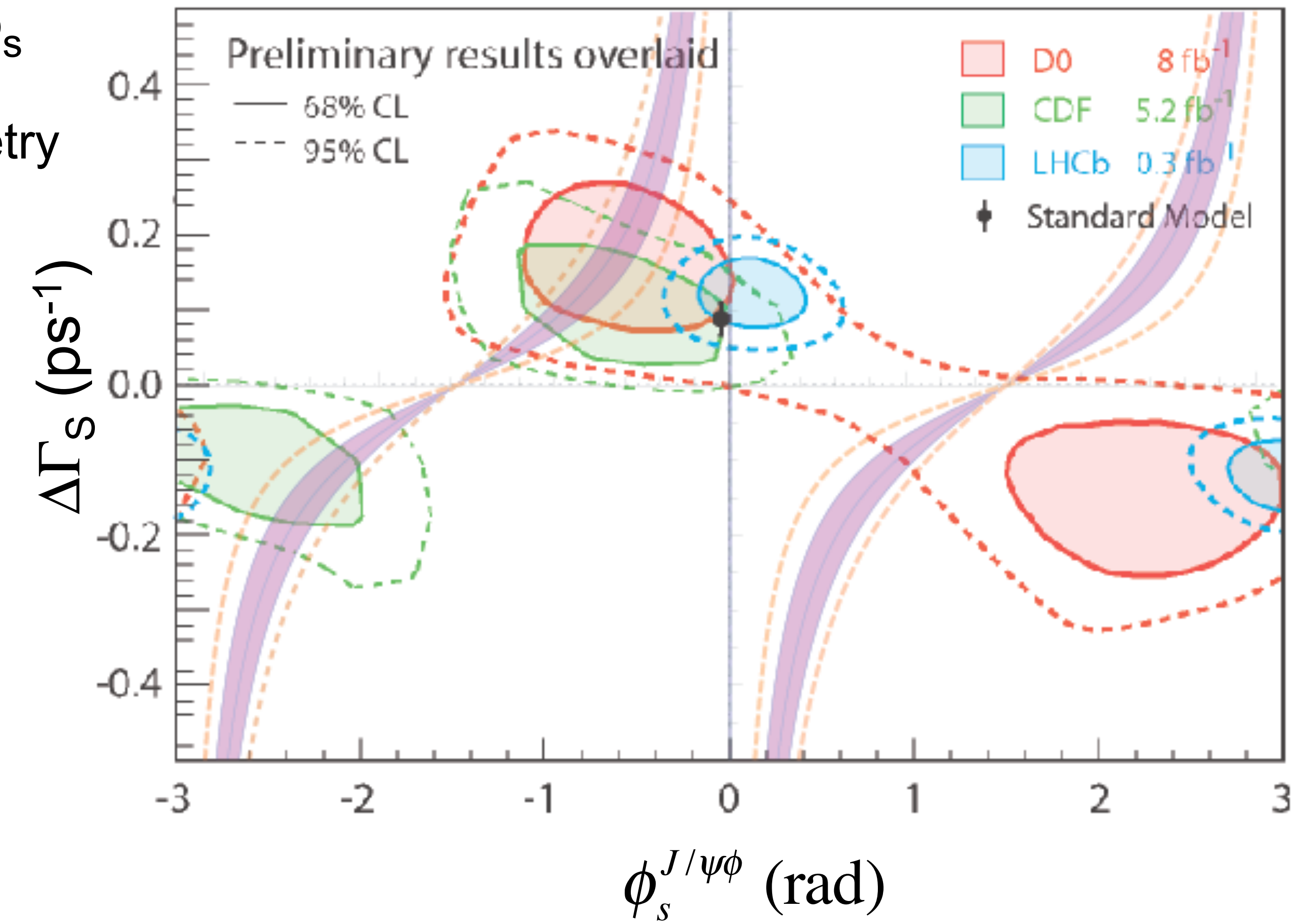


a_{sl} vs ϕ_s

$a^s_{sl}=(\Delta\Gamma/\Delta M)\tan\phi_s$

Assume all asymmetry is due to B_s

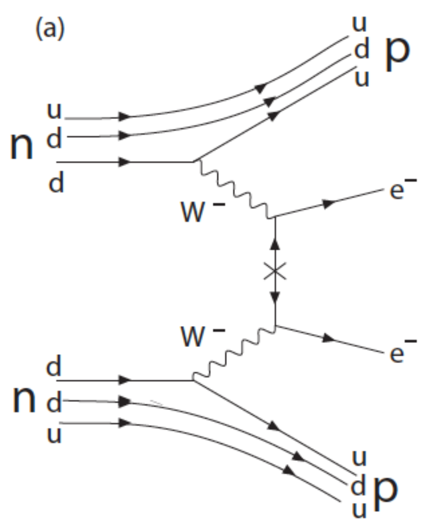
$a^s_{sl}=(-0.787\pm0.196)\%$

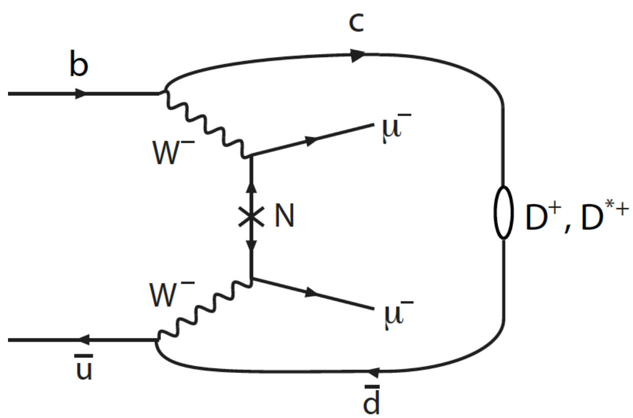


Majorana ν's

- 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}
$B^-\rightarrow D^+e^-e^-$	Belle	< 2.6
$B^-\rightarrow D^+e^-\mu^-$	Belle	< 1.8
$B^-\rightarrow D^+\mu^-\mu^-$	Belle	< 1.0
$B^-\rightarrow D^+\mu^-\mu^-$	LHCb	< 0.69
$B^-\rightarrow D^{*+}\mu^-\mu^-$	LHCb	< 3.6

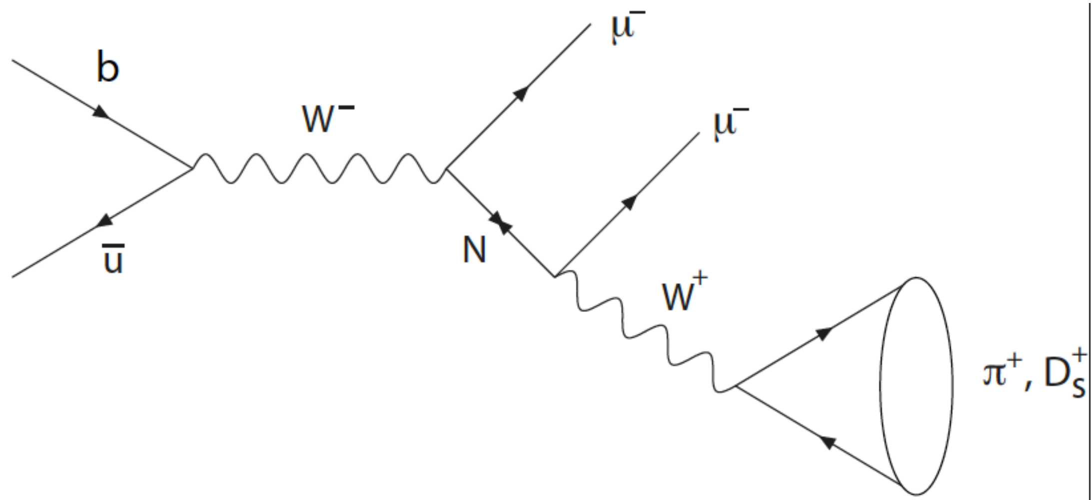
Belle [arXiv:1107.064]

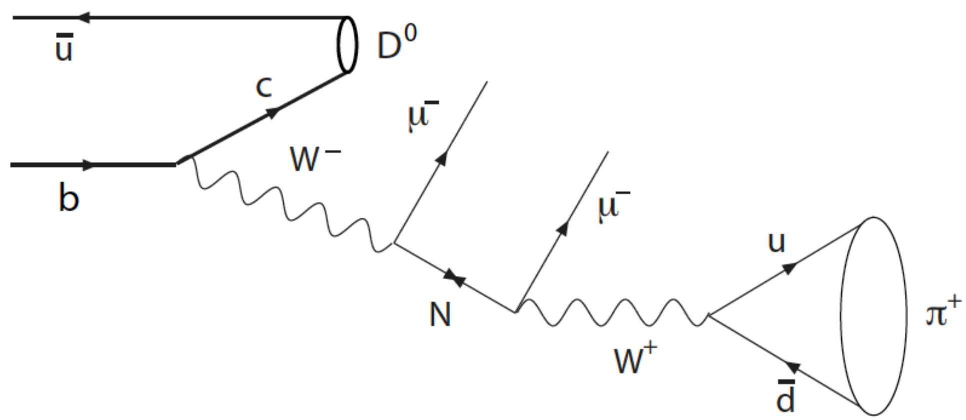
On-Shell ν

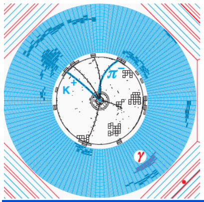
- Can also look for Majorana ν (N), where $N \to W^+ \mu^-$
- Several ways
- A. Atre, T. Han,

S. Pascoli, & B. Zhang [arXiv:0901.3589]

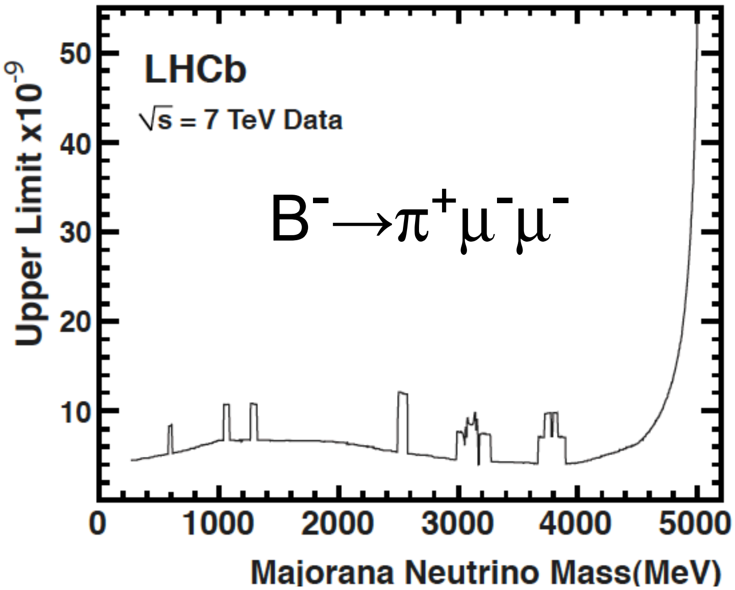
- N. Quintero, G. Lopez & Castro, [arXiv:1108.6009]



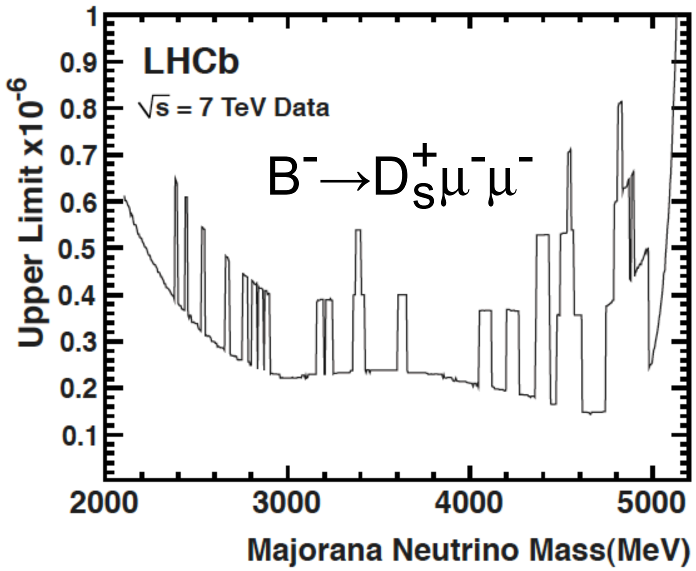


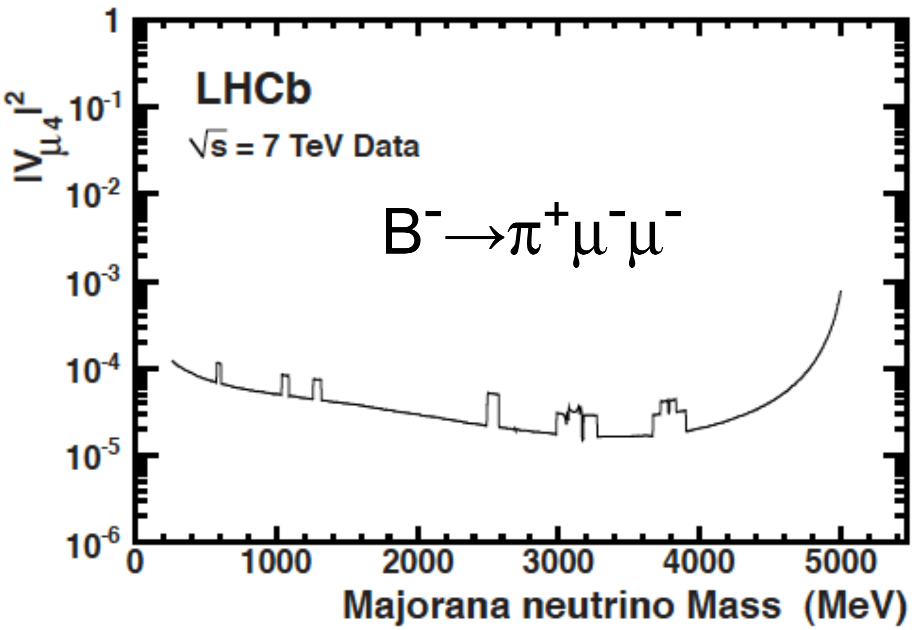


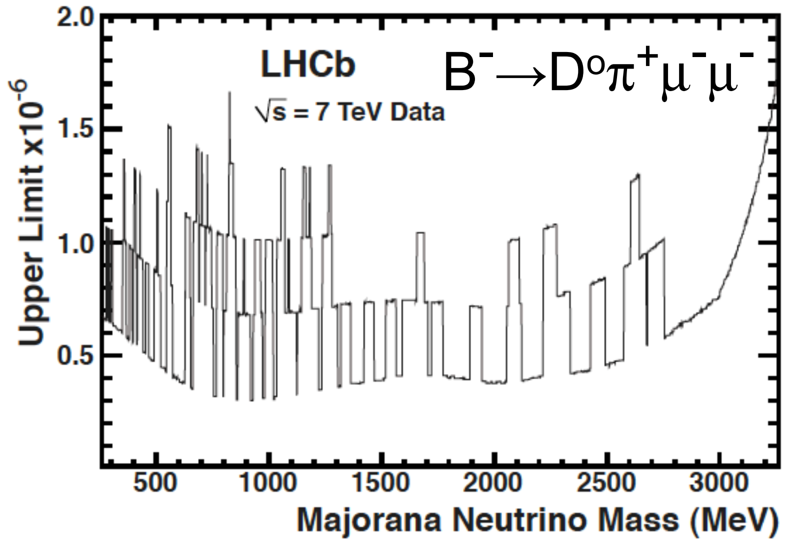
LHCb searches



Nothing yet

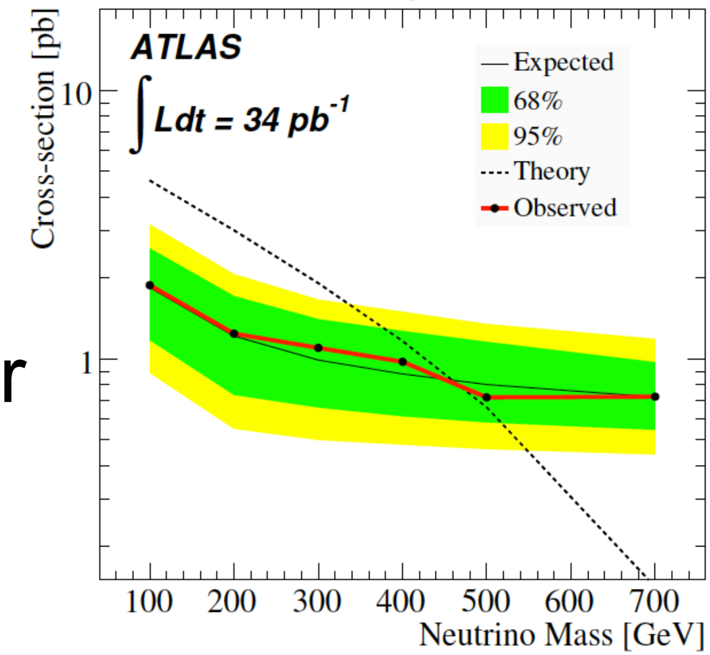






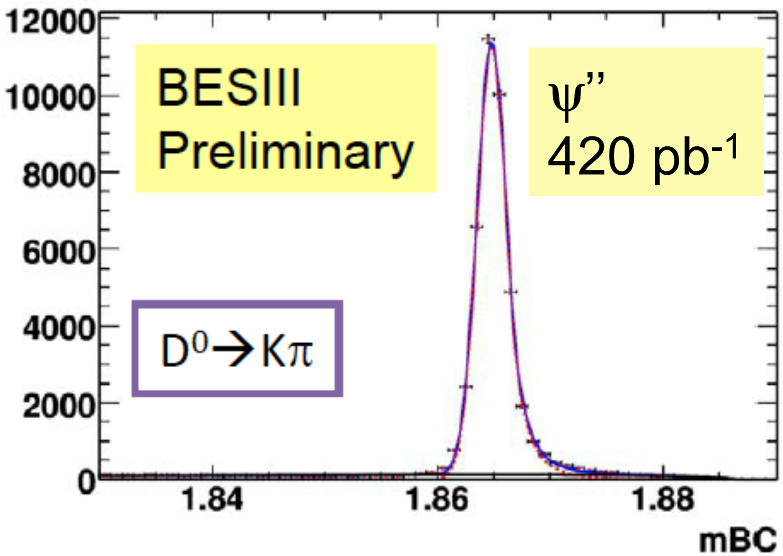
Searches at higher masses

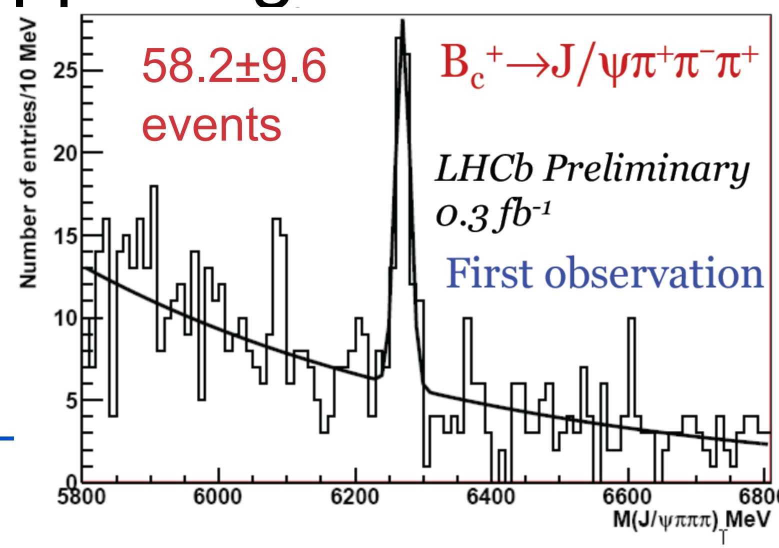
- CDF general search for like-sign dileptons [A. Abulencia et. al, Phys. Rev. Lett. 98, 221803 (2007)]
- CMS search for events with two isolated like-sign leptons, hadronic jets & missing E_T [arXiv:1104.3168]
- ATLAS [arXiv:1108.0366]
- If seen could also be interpreted in terms of other NP, ie. supersymmetery….

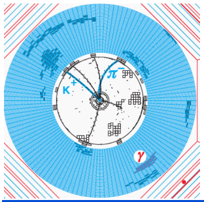


Future Acts

- LHCb Upgrade: run at 10^{33} cm^{-2}/s (x5), & double trigger efficiency on purely hadronic final states
- Super B factories
- Time scales are on the order of 6 years
- BES III, LHCb are happening now







Conclusions

- Heavy Flavor physics is now very sensitive to potential New Physics effects at high mass scales
- LHC experiments have shown their ability by already making world class 1st measurements of flavor physics. They are ready!
- Heavy Flavor experiments are ready to search for and limit New Physics, especially in rare and CP violating b & c decays at the LHC with the 2011 data and beyond
- Many other interesting flavor results have not been mentioned – apologies

The End

APS Predictions

- Instead of CiOi use a new basis $O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell)$, & $O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)$
- Then

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{S}}}$$

$$S = \frac{m_{B_s}^2}{2m_\mu}\frac{(C_S - C_S')}{|C_{10}^{\mathrm{SM}}|} \qquad P = \frac{m_B^2}{2m}$$

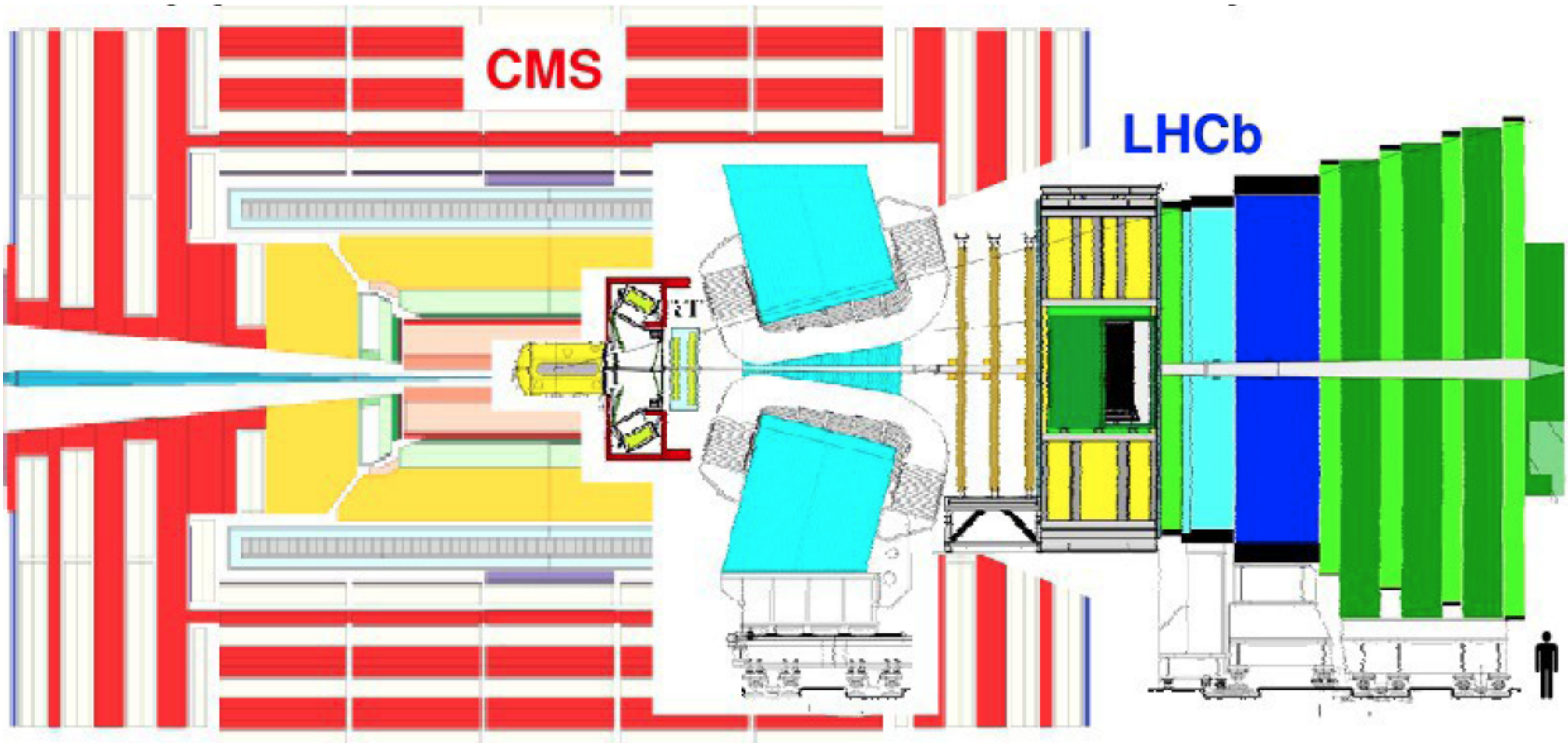
- In SM P=1, S=0

Scenario	$\mathrm{BR}(B_s \to \mu^+\mu^-)$
Real LH	$[1.0, 5.6] \times 10^{-9}$
Complex LH	$[1.0, 5.4] \times 10^{-9}$
Complex RH	$< 5.6 \times 10^{-9}$
Generic NP	$< 5.5 \times 10^{-9}$
LH Z peng.	$[1.4, 5.5] \times 10^{-9}$
RH Z peng.	$< 3.8 \times 10^{-9}$
Generic Z p.	$< 4.1 \times 10^{-9}$
scalar current	$< 1.1 \times 10^{-8}$

2

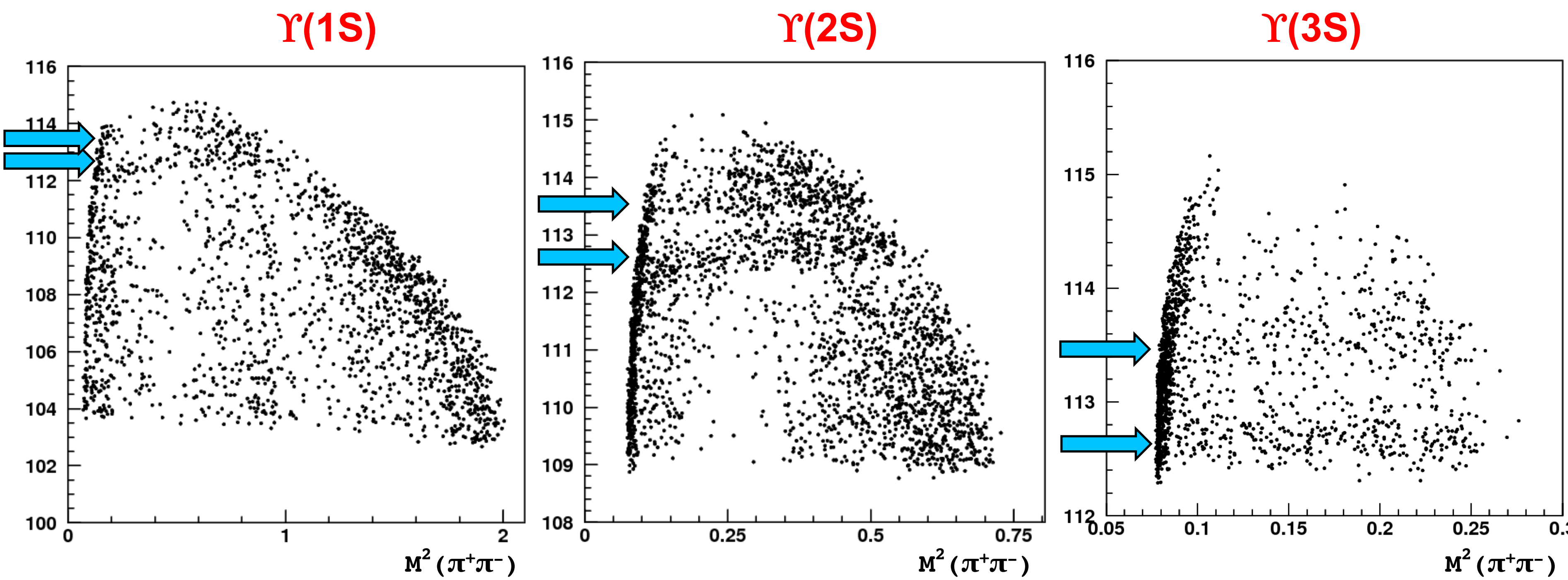
Recent Results

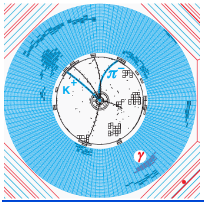
- NP **must** affect every process; the amount tells us what the NP is ("DNA footprint")
- New data from CDF, D0, BaBar BES, BELLE, ATLAS, CMS & LHCb – Not nearly enough time to cover



New Exotic States

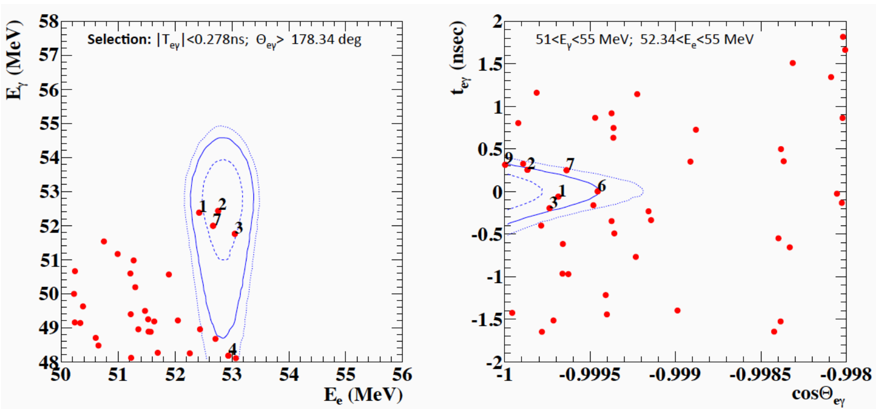
- Belle discovery of $Z_b(10610)$ and $Z_b(10650)$
- $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ Dalitz plots. See $\Upsilon(nS)\pi^\pm$ states
- Also seen in $h_b(1P)\pi^\pm$ & $h_b(2P)\pi^\pm$ decays arXiv:1105.4583

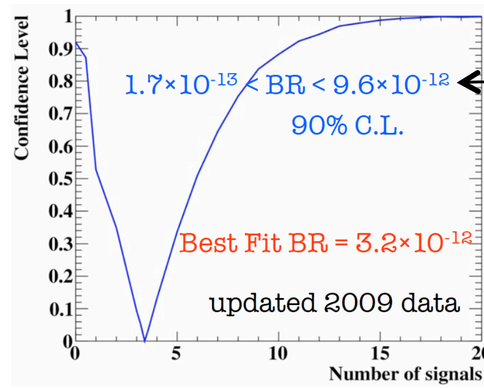




Lepton Flavor Violation

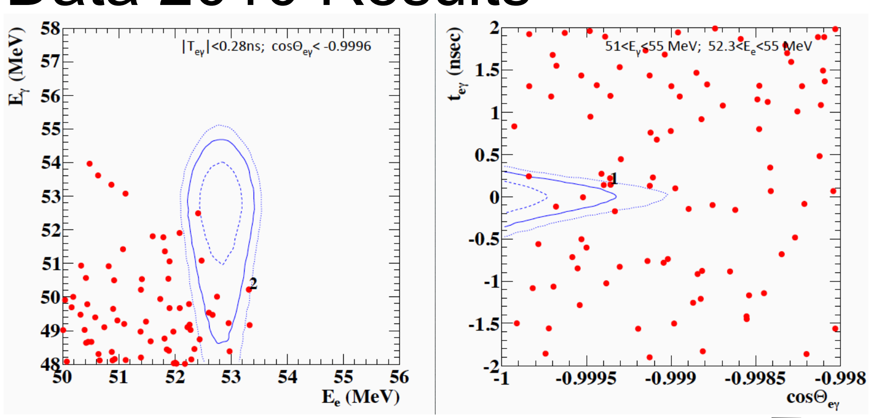
- μ→eγ MEG data 2009 results (Mori EPS2011)

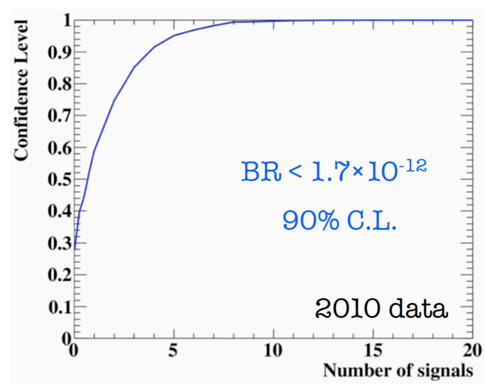




Note 2-sided limit

- Data 2010 Results





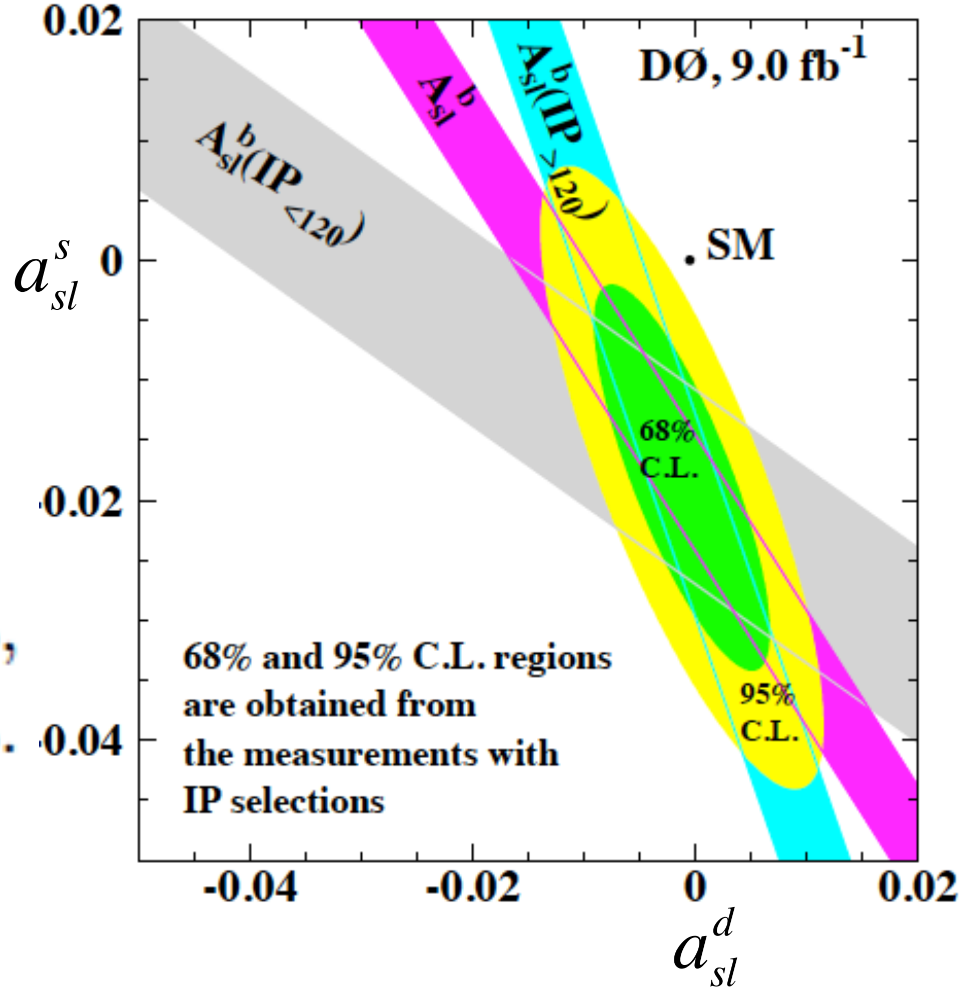
Combined $\mathcal{B}<2.4\times10^{-12}$

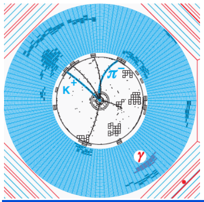
- Many limits on τ→ℓhh, Λh, $\bar{\Lambda}$h, μγ, μh, 3μ, best limits near 10^{-8} (Belle, BaBar)

DØ a_{sl}

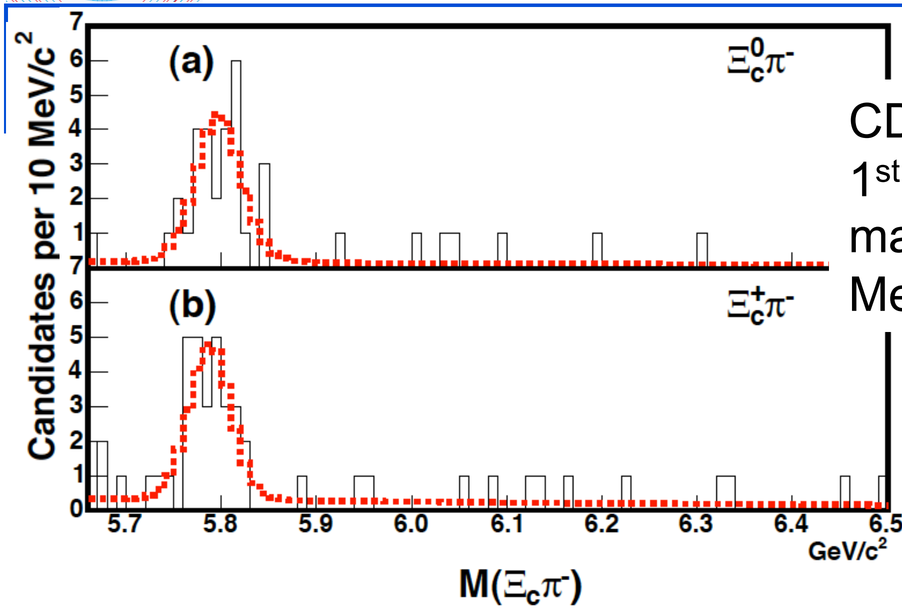
- Separate into B_d and B_s samples using impact parameter of muons
- Find

$$a^d_{\rm sl} = (-0.12 \pm 0.52)\%,$$
$$a^s_{\rm sl} = (-1.81 \pm 1.06)\%.$$

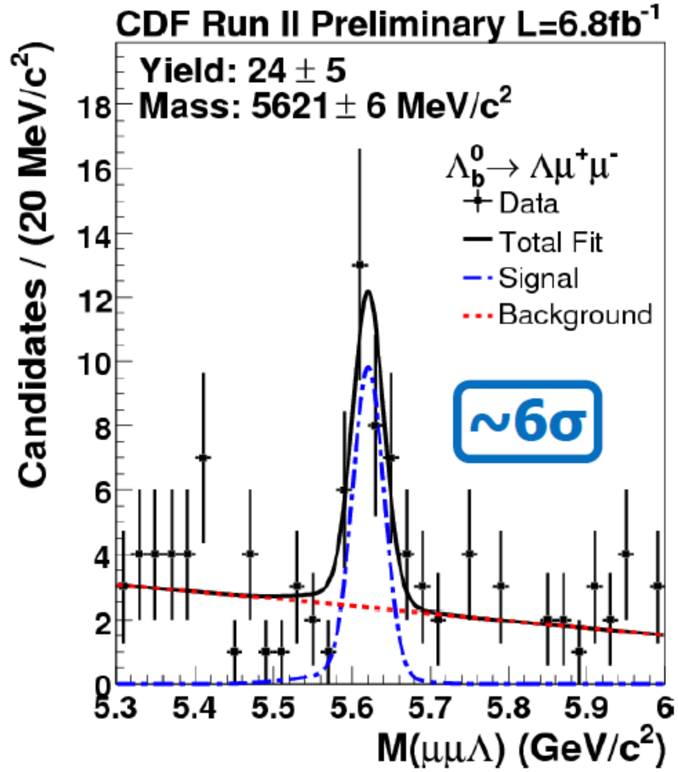




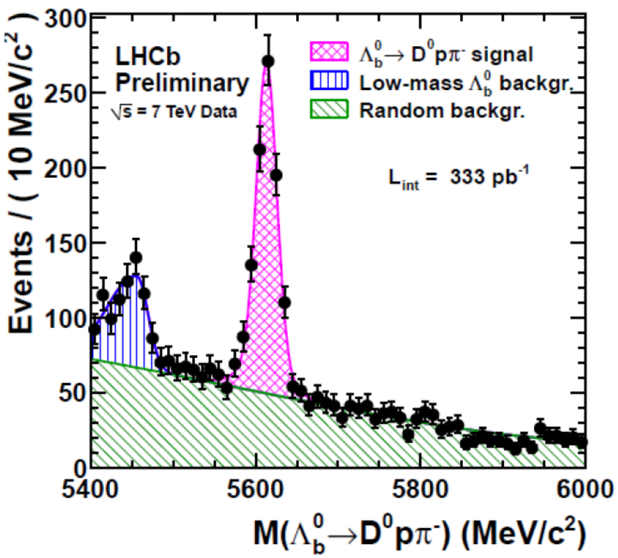
New b-Baryon Decays



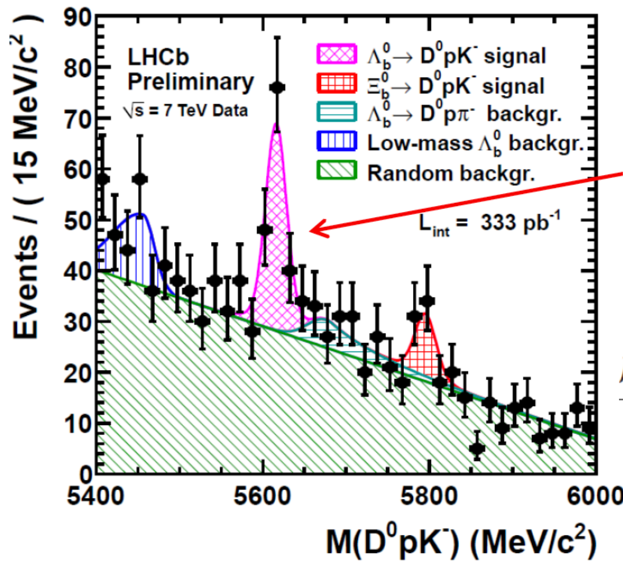
CDF Ξ_b^o
1[st] observation
mass 5787.8±5.0 MeV



$D^0p\pi^-$



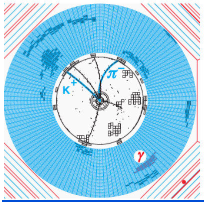
D^0pK^-



$\Lambda_b \rightarrow D^0pK$

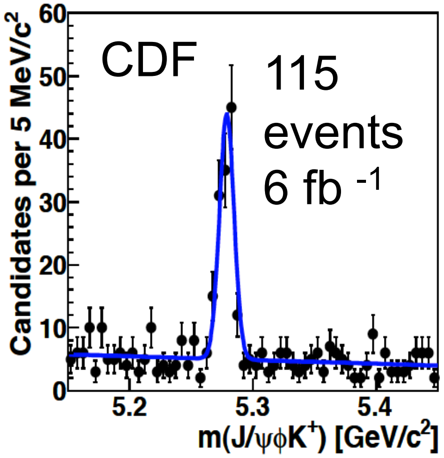
$\Lambda_b \rightarrow D^0pK$ observed for first time with significance of 6.3σ

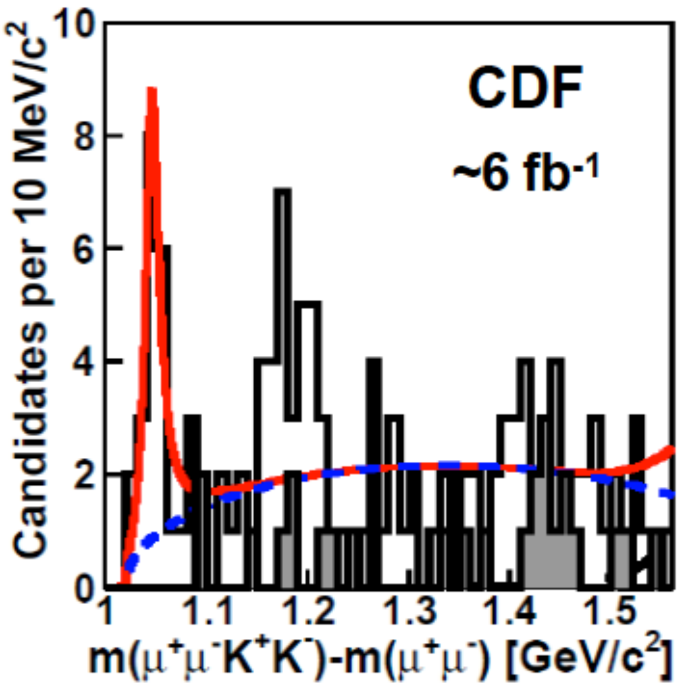
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^0pK^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow D^0p\pi^-)} = 0.112 \pm 0.019^{+0.011}_{-0.014}$$

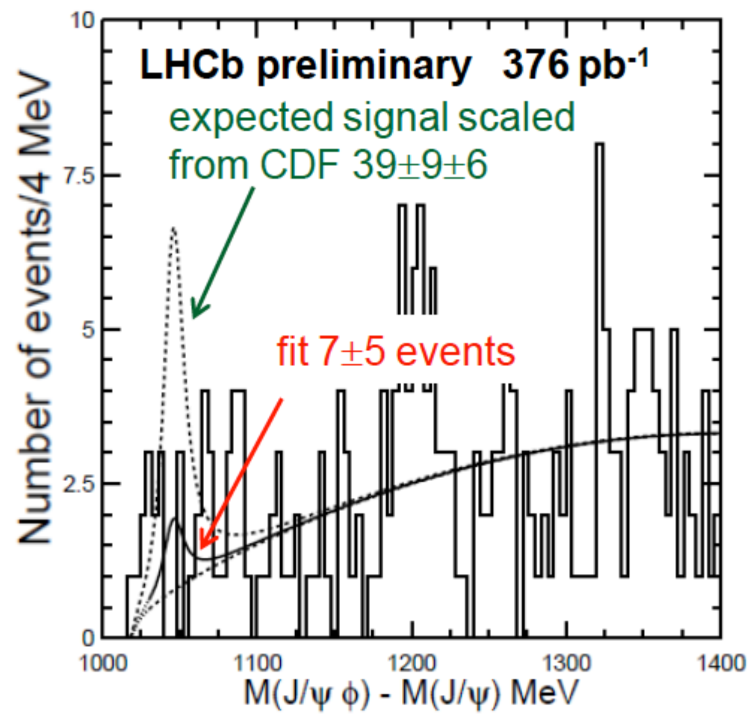


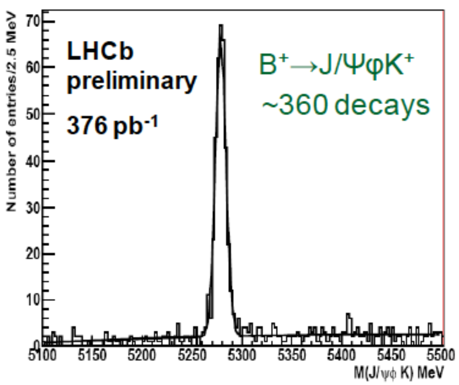
X(4140)?

- In $B^- \to J/\psi\,\phi\, K^-$ decays, CDF reported a narrow structure in $m(J/\psi\,\phi)$ mass [arXiv:1101.6058]



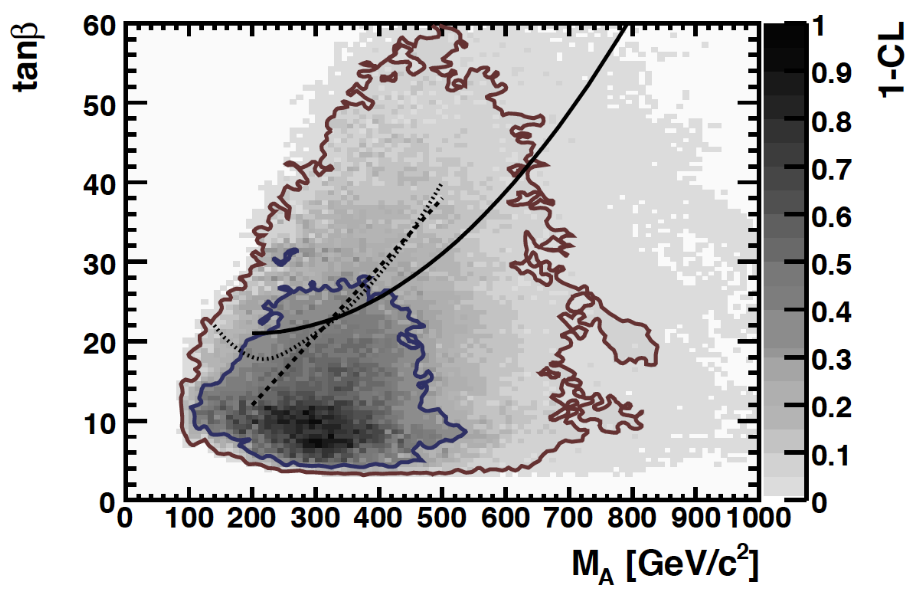


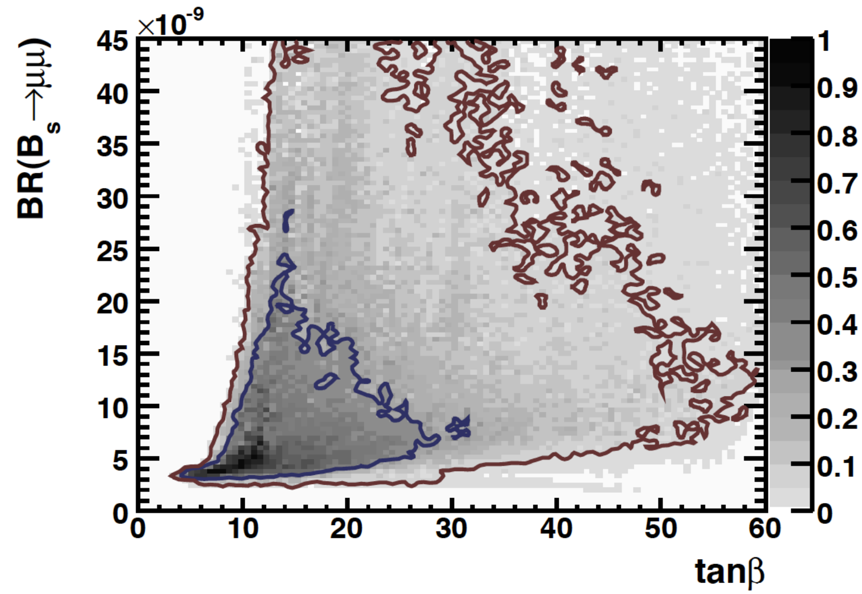




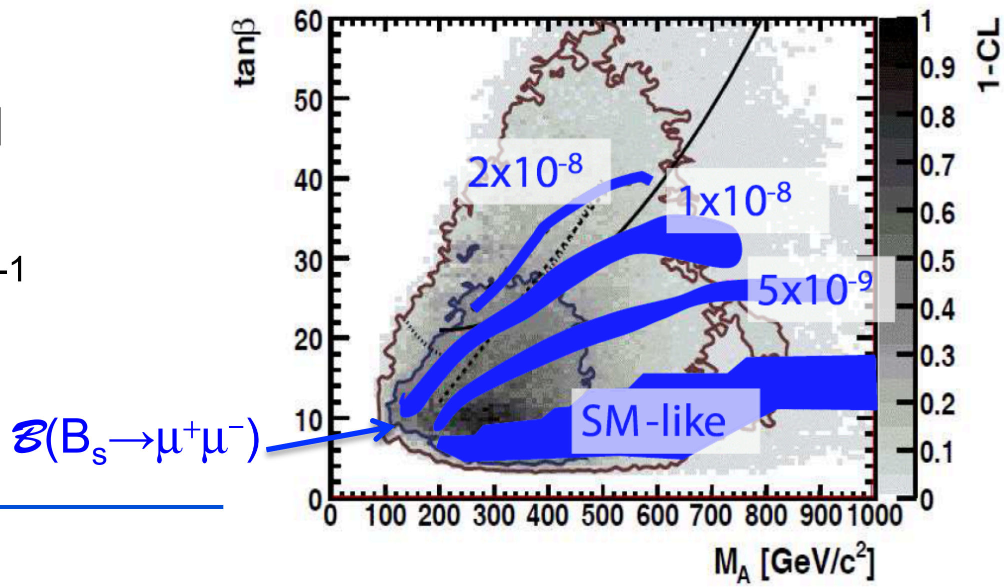
No signal evident in LHCb data

Exp: $\mathcal{B}(B_s \to \mu^+\mu^-)$ in NUHM1



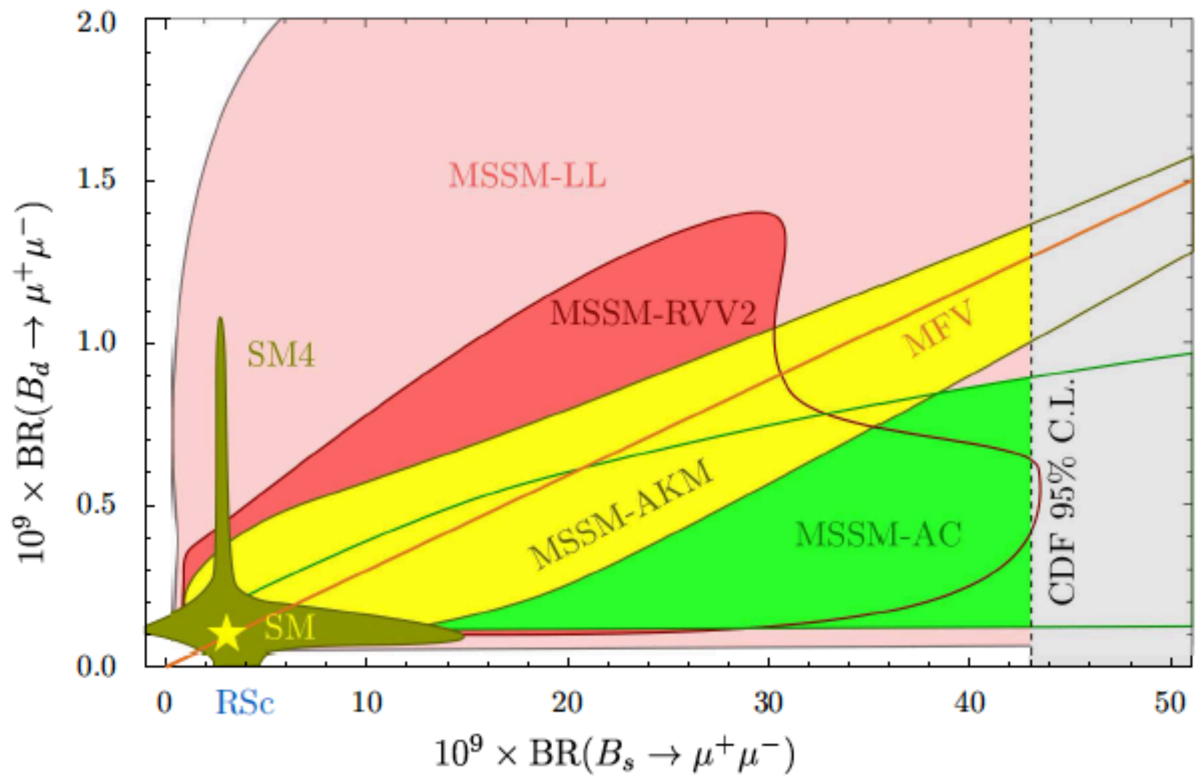


- CMS discovery contours for H, A $\to \tau^+\tau^- \to$jets (solid line), jet + μ (dashed), jet + e (dotted) using 30-60 fb^{-1}
- (From O. Buchmueller et al., arXiv:0907.5568)



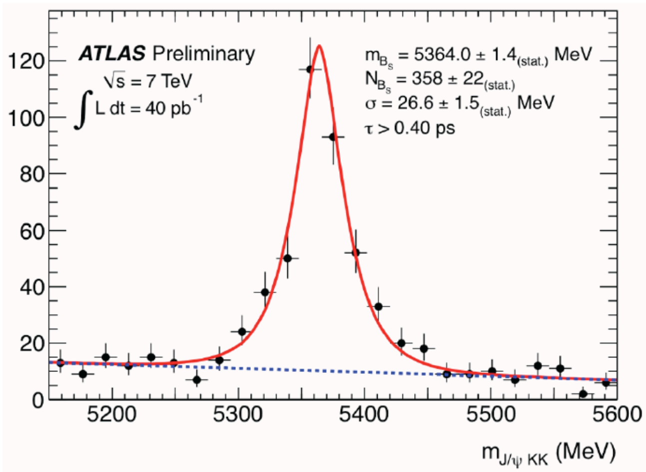
$B^o \rightarrow \mu^+\mu^-$

- In fact correlation between B_d & B_s $\mu^+\mu^-$ could be crucial

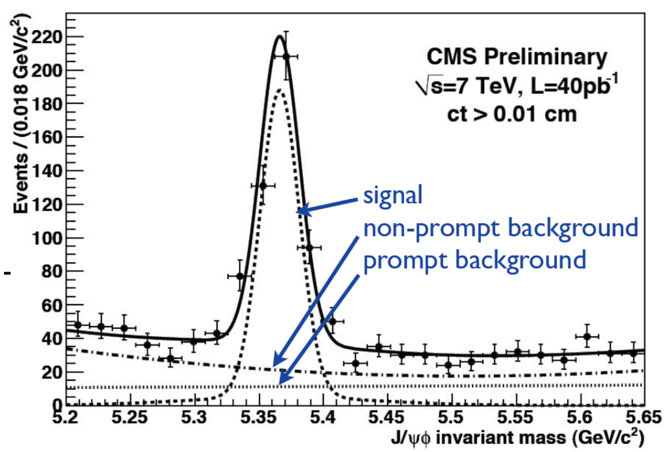


- This can only be done with the LHCb Upgrade

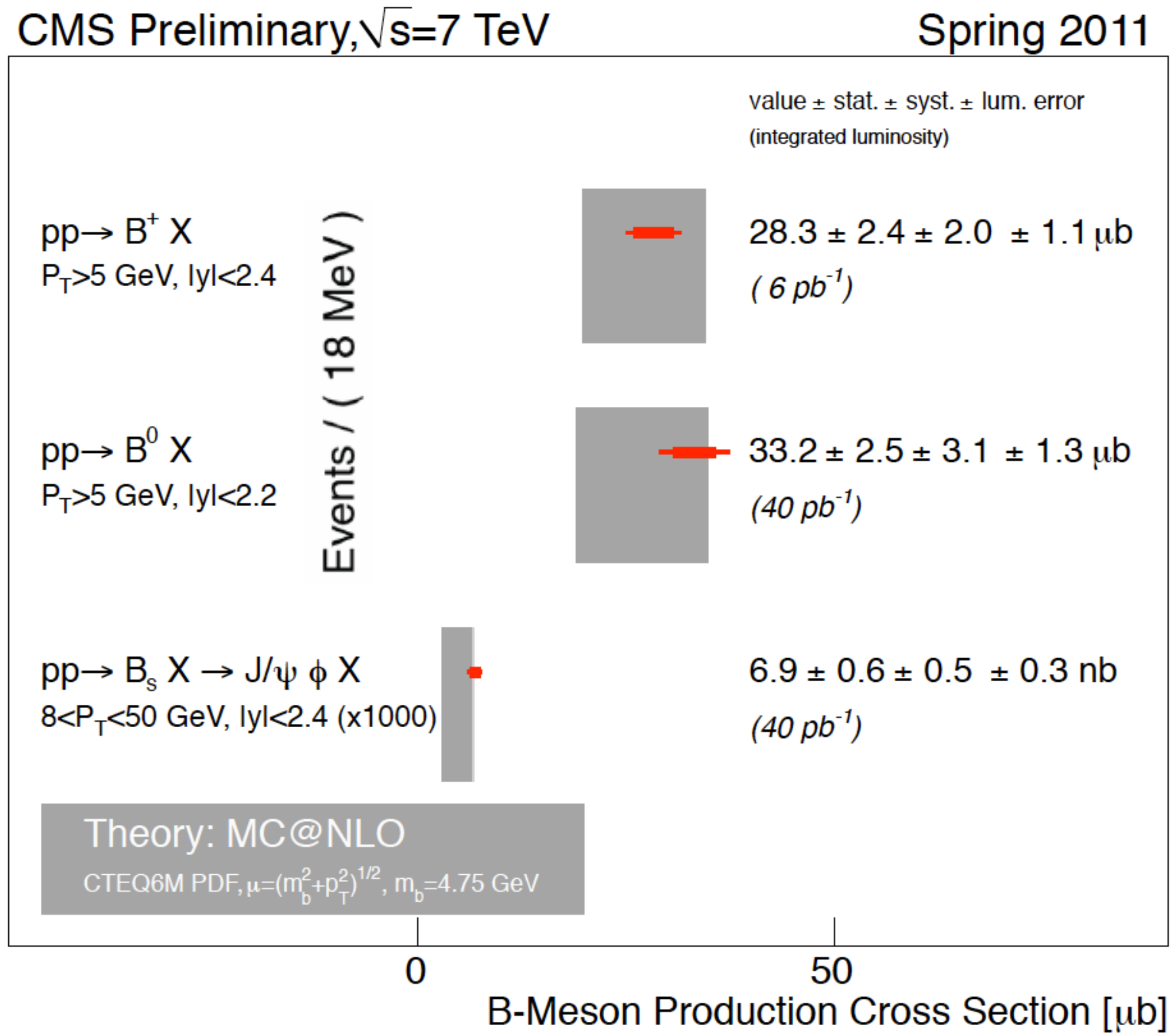
ATLAS B σ's



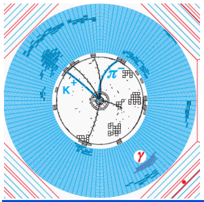
ATLAS Preliminary
√s = 7 TeV
∫L dt = 40 pb⁻¹
m_Bs = 5364.0 ± 1.4(stat.) MeV
N_Bs = 358 ± 22(stat.)
σ = 26.6 ± 1.5(stat.) MeV
τ > 0.40 ps
0
20
40
60
80
100
120
5200
5300
5400
5500
5600
m_J/ψ KK (MeV)



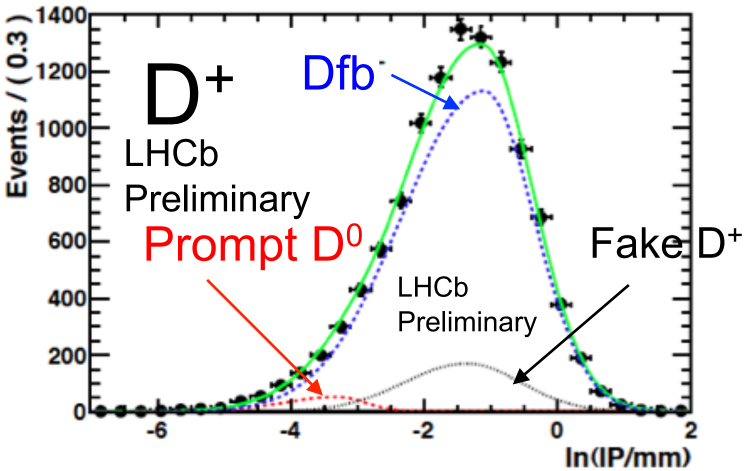
CMS Preliminary
√s=7 TeV, L=40pb⁻¹
ct > 0.01 cm
signal
non-prompt background
prompt background
Events / (0.018 GeV/c²)
0
20
40
60
80
100
120
140
160
180
200
220
5.2
5.25
5.3
5.35
5.4
5.45
5.5
5.55
5.6
5.65
J/ψφ invariant mass (GeV/c²)

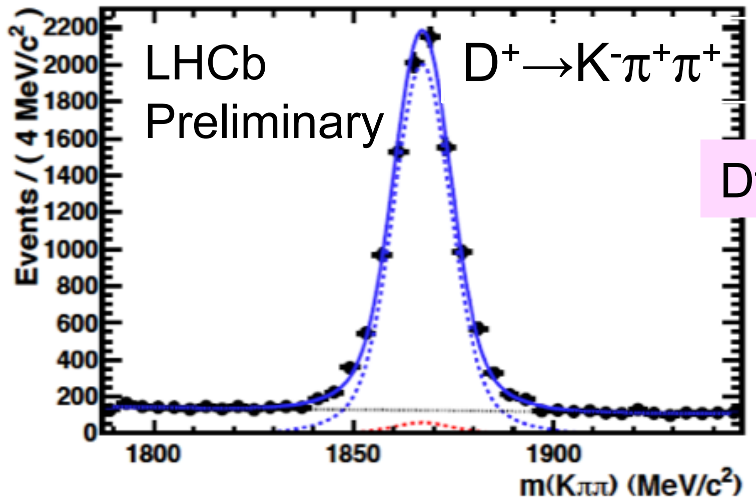


CMS Preliminary,√s=7 TeV
Spring 2011
value ± stat. ± syst. ± lum. error
(integrated luminosity)
pp→ B⁺ X
P_T>5 GeV, lyl<2.4
28.3 ± 2.4 ± 2.0 ± 1.1 μb
(6 pb⁻¹)
pp→ B⁰ X
P_T>5 GeV, lyl<2.2
33.2 ± 2.5 ± 3.1 ± 1.3 μb
(40 pb⁻¹)
pp→ B_s X → J/ψ φ X
8<P_T<50 GeV, lyl<2.4 (x1000)
6.9 ± 0.6 ± 0.5 ± 0.3 nb
(40 pb⁻¹)
Events / (18 MeV)
Theory: MC@NLO
CTEQ6M PDF, μ=(m_b²+p_T²)^1/2, m_b=4.75 GeV
0
50
B-Meson Production Cross Section [μb]

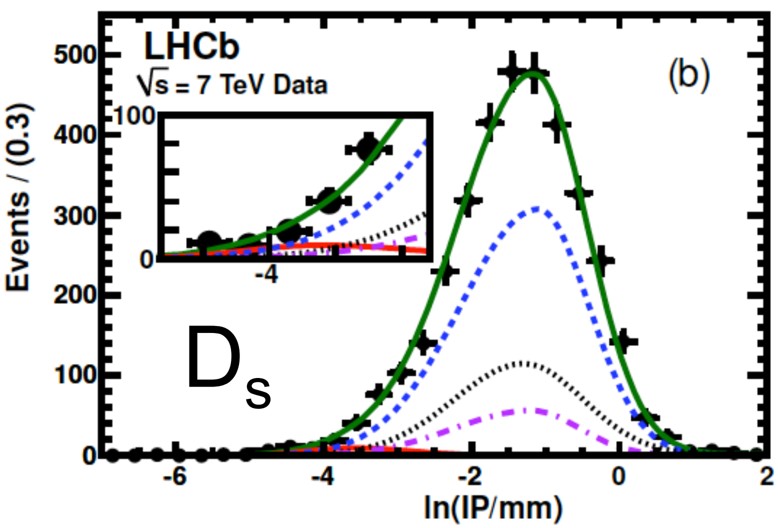


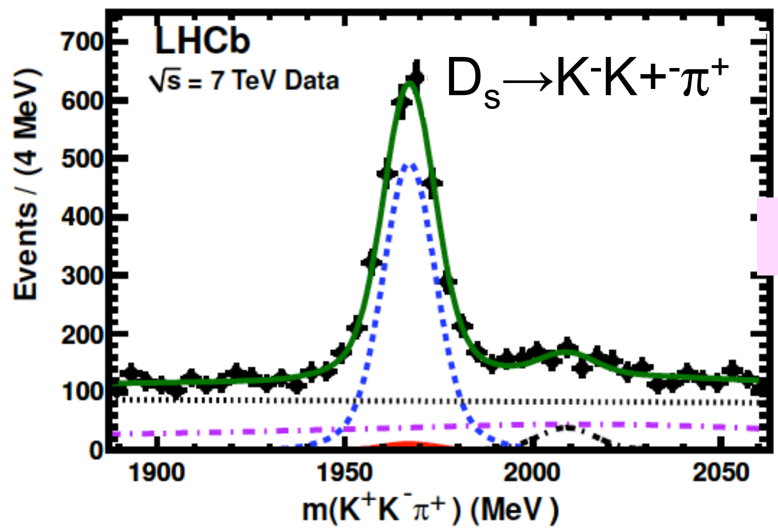
Also D^+, D_s, Λ_b





Dfb: 9406±110



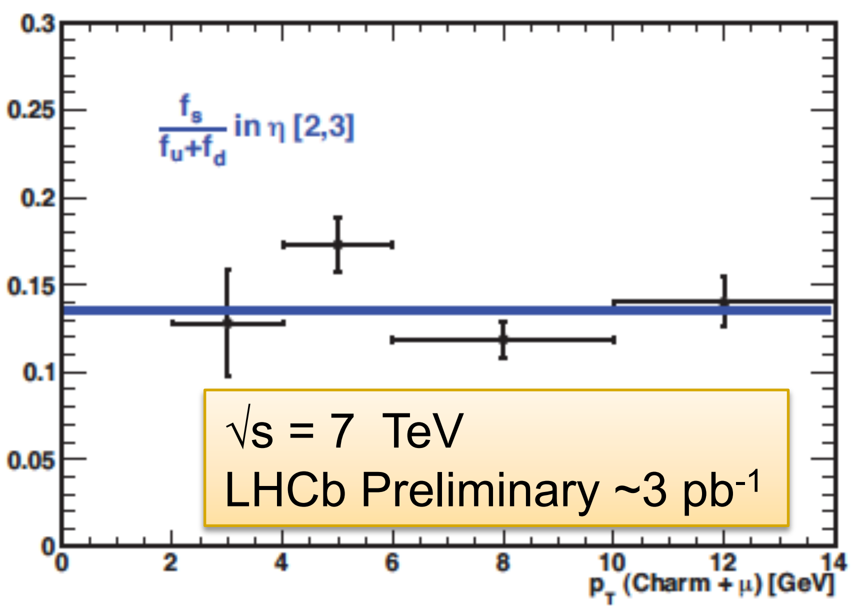


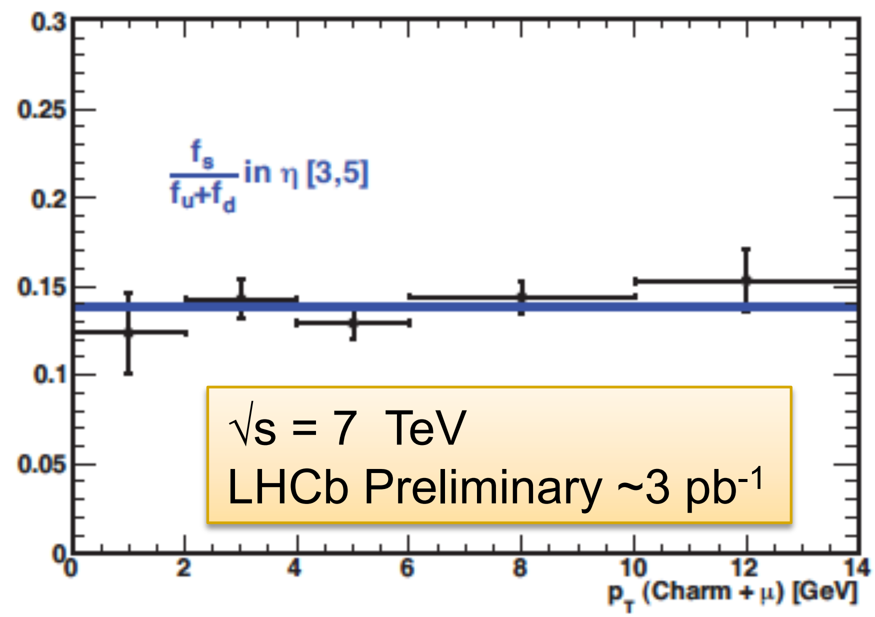
Dfb: 2446±60

Extract B_s fractions

- Crucial to set absolute scale for B_s rates, since not given by e^+e^- machines.
- Must correct for $B_s \rightarrow D^o K^+ X\mu\nu$, also $\Lambda_b \rightarrow D^o p X\mu\nu$

$$f_s/(f_u+f_d) = 0.136 \pm 0.004^{+0.012}_{-0.011}$$

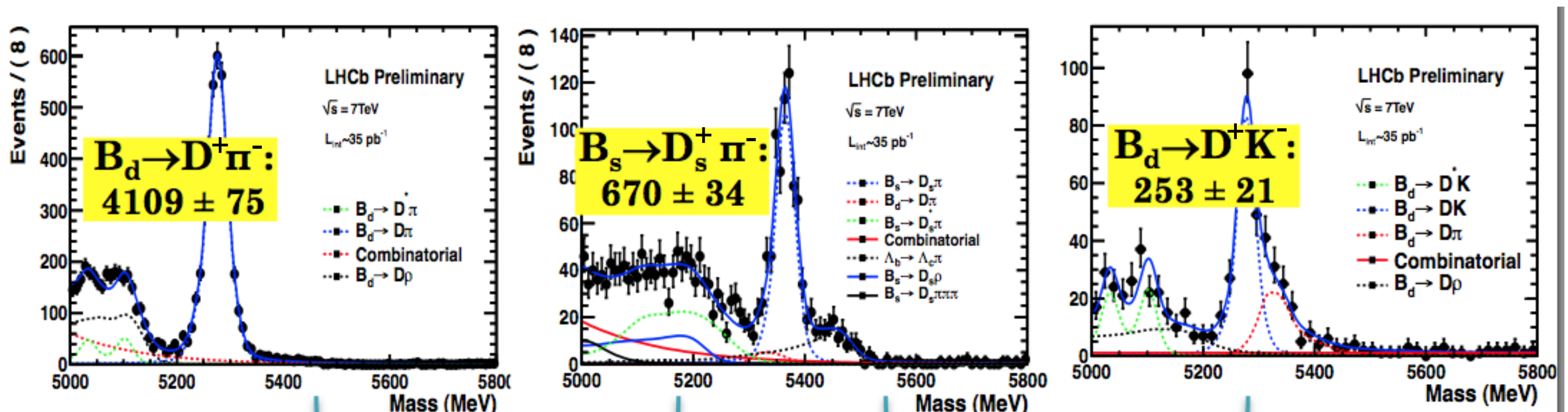




B_s fraction - hadronic

- Also can use hadronic decays + theory ~35 pb^{-1}

$\sqrt{s}$ = 7 TeV
LHCb Preliminary



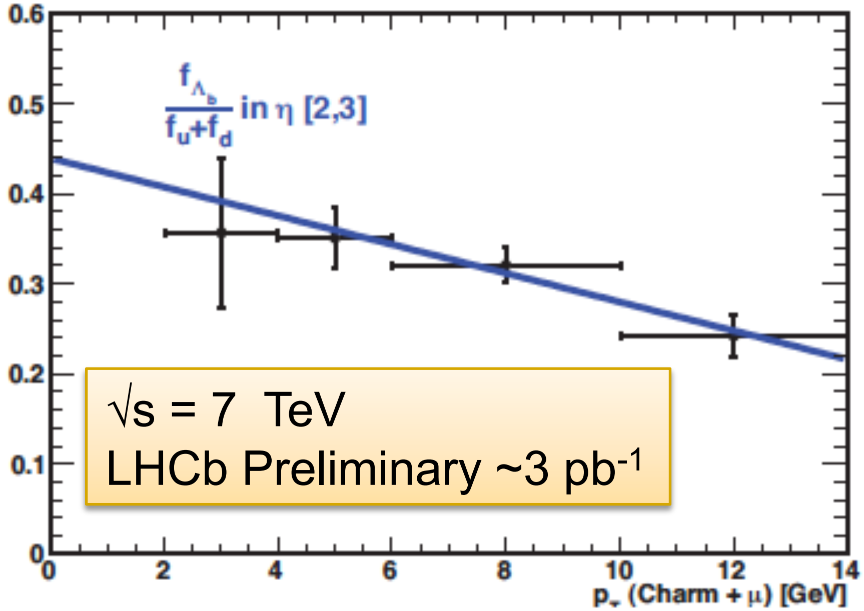
$$\frac{f_s}{f_d} = 0.249 \pm 0.013^{\text{stat}} \pm 0.020^{\text{syst}} \pm 0.025^{\text{theor}}$$

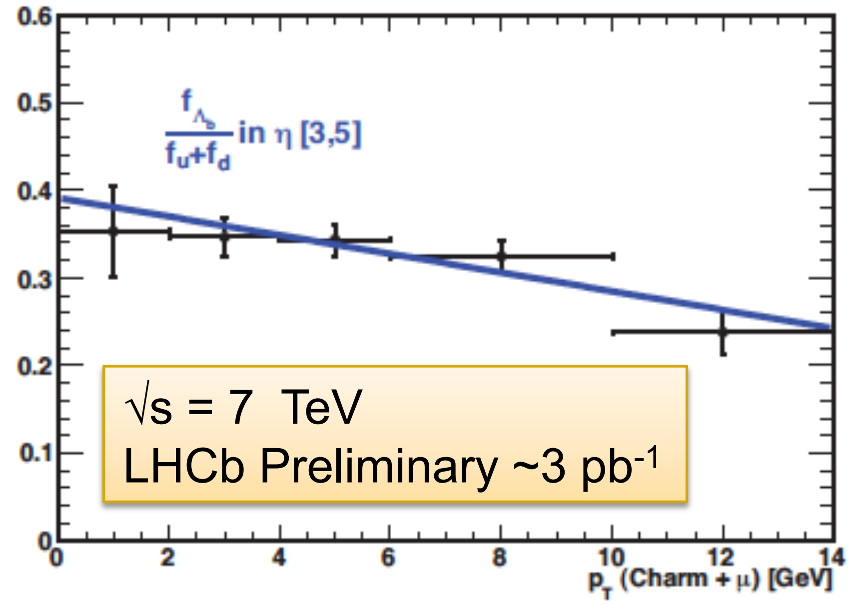
$$\frac{f_s}{f_d} = 0.242 \pm 0.024^{\text{stat}} \pm 0.018^{\text{syst}} \pm 0.016^{\text{theor}},$$

Semileptonics: $f_s / f_d = 0.272 \pm 0.008^{+0.024}_{-0.022}$

Λ_b Fraction

- Significant p_t dependence





$$[f_{\Lambda_b}/(f_u + f_d)] = 0.401 \pm 0.019 \pm 0.106 - (0.012 \pm 0.0025 \pm 0.0012) \times p_t(\mathrm{GeV})$$

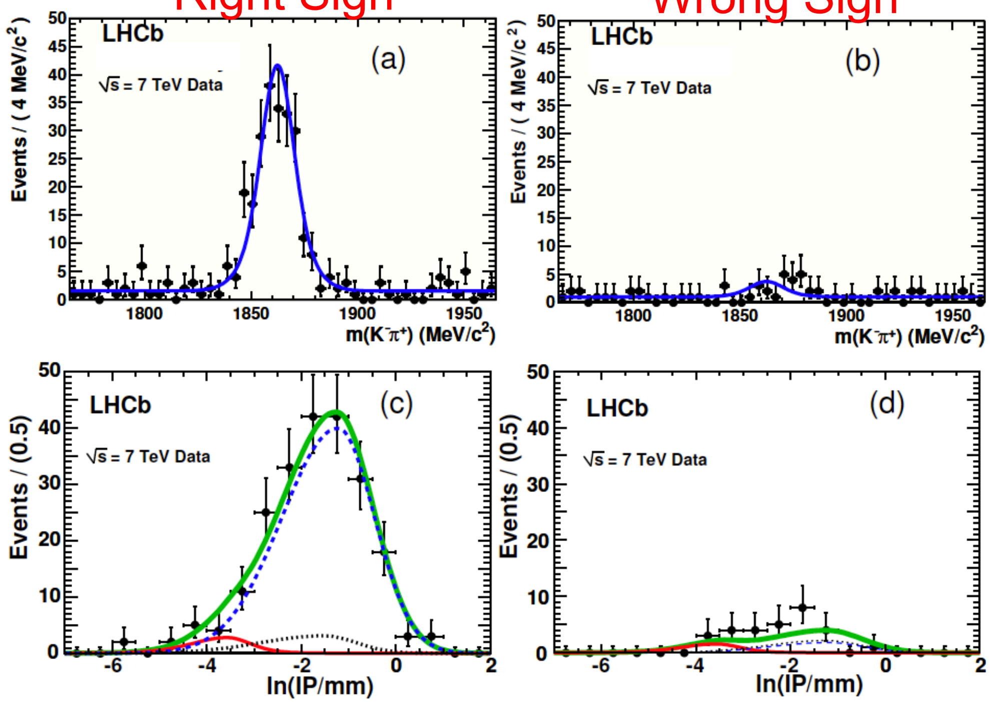
- In general agreement with CDF measured at $<p_t>$~10 GeV/c $f_{\Lambda_b}/(f_u + f_d) = 0.281 \pm 0.012^{+0.011+0.128}_{-0.056-0.086}$

$\sigma(pp\rightarrow b\bar{b}X)$ using 15 nb^{-1}

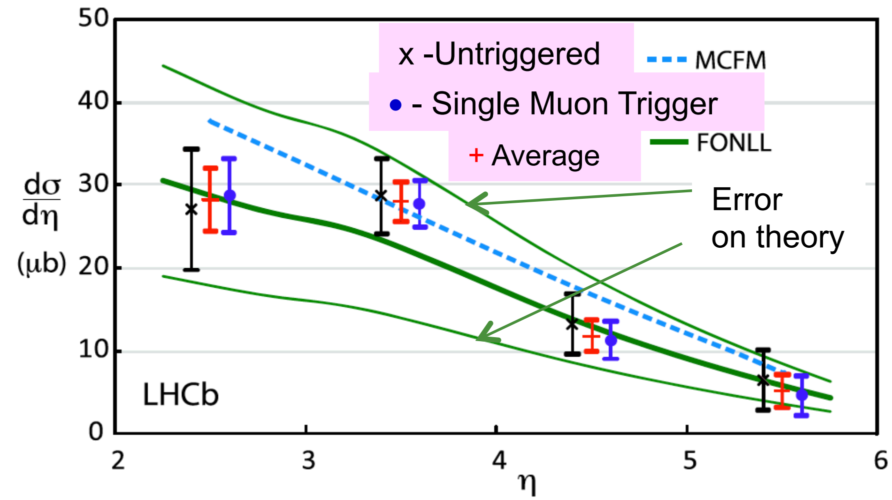
- $b\rightarrow D^0X\mu^-\nu$, $D^o\rightarrow K^-\pi^+$, ~280 events

Infancy

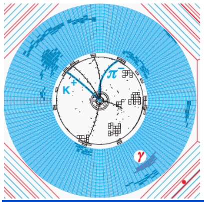
Right Sign   Wrong Sign



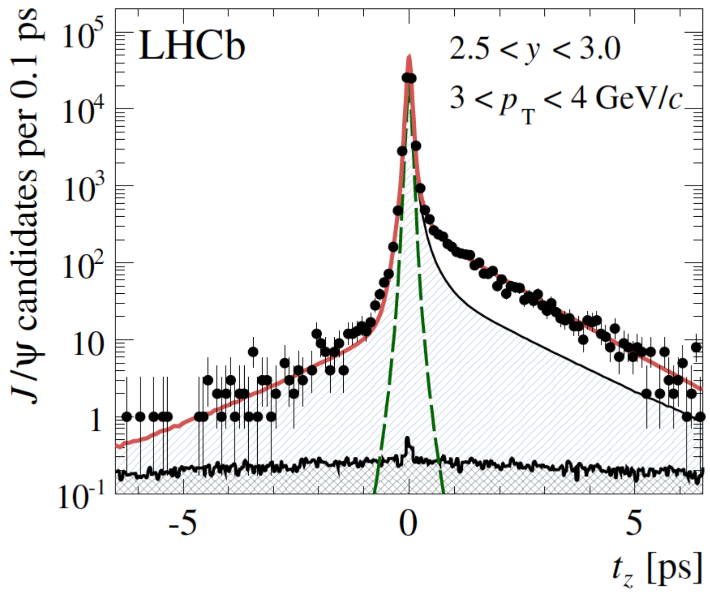
$$\sigma = \frac{\#\text{ of detected } D^0\mu^- \ \&\ \bar{D}^0\mu^+}{L \text{ x efficiency x } 2}$$

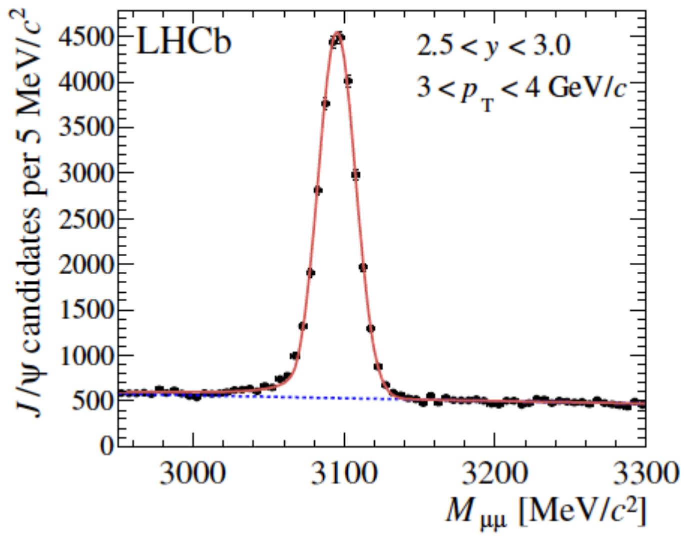


- In 2<η<6, (75.3±5.4±13.0) μb LEP frag ⇒ 284±20±49 μb
- In 2<η<6, 89.6 μb Tevatron frag ⇒ 338±24±58 μb
- Also measured charm cross-section, ~20x b



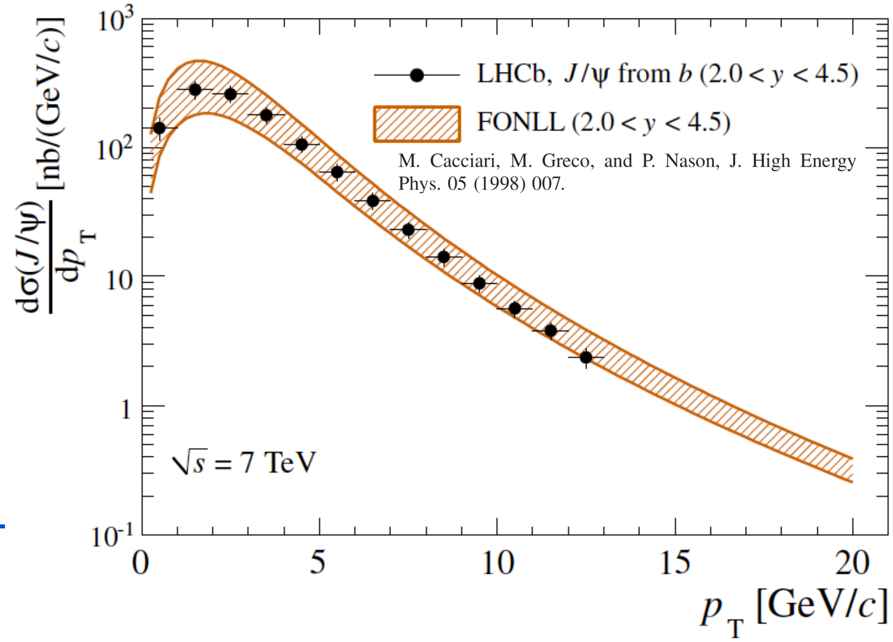
b xsect from b→J/ψX



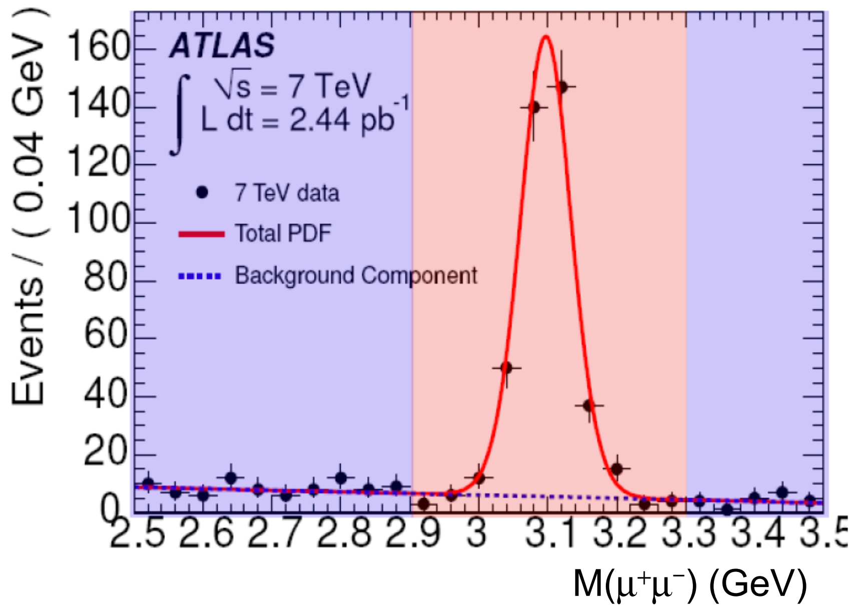


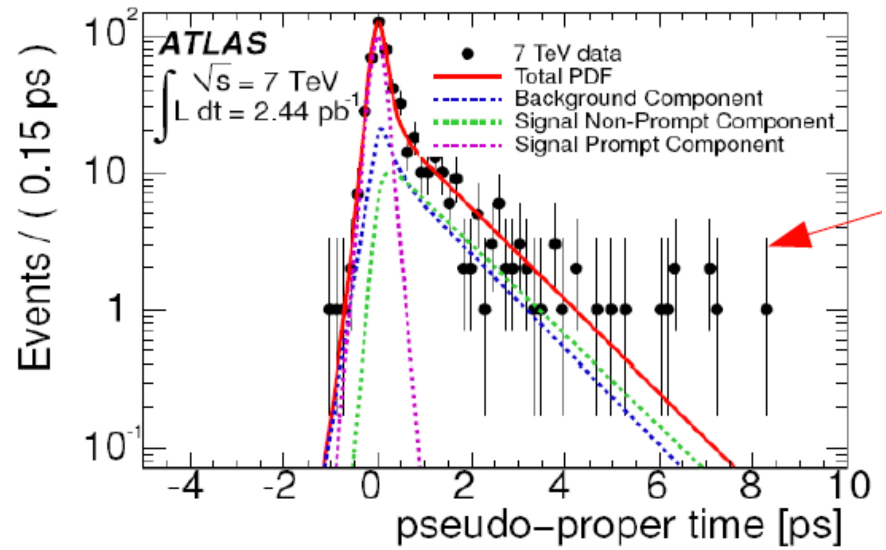
$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$

- Here use 5.2 pb^{-1}
- σ= 288±4±48 μb

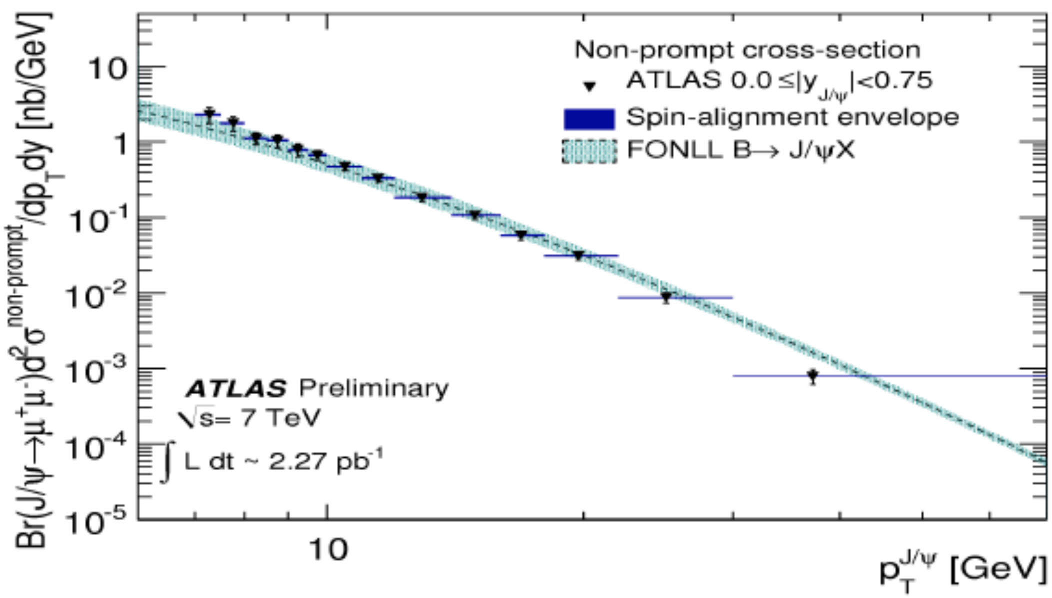


ATLAS σ from b→J/ψX

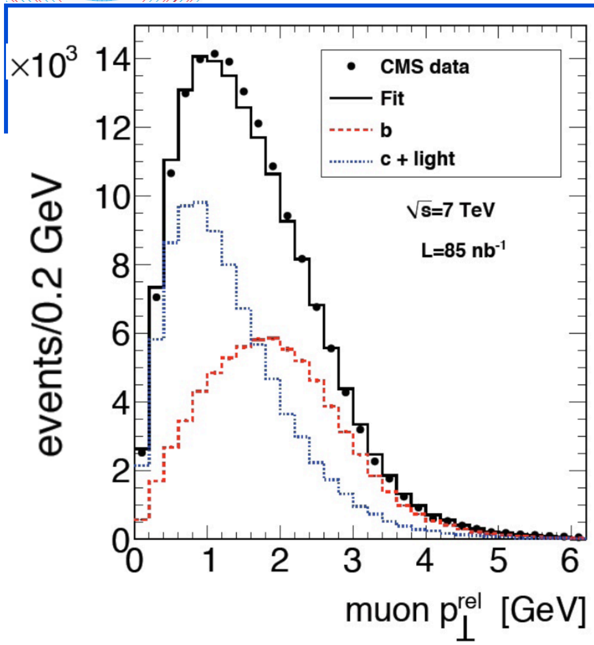




- ATLAS also in agreement with FONLL for p_t>5 GeV/c

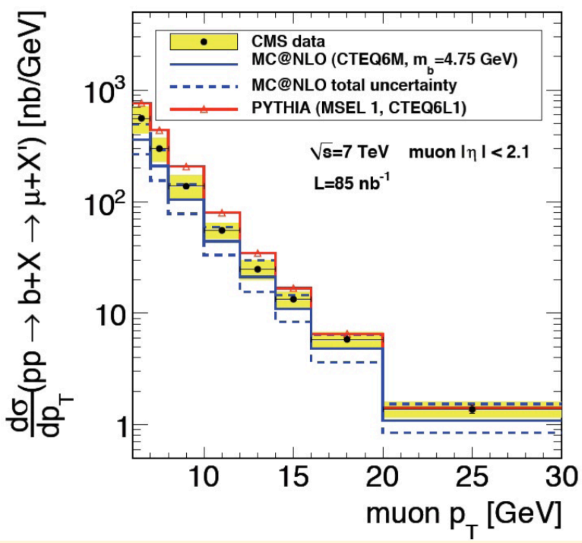


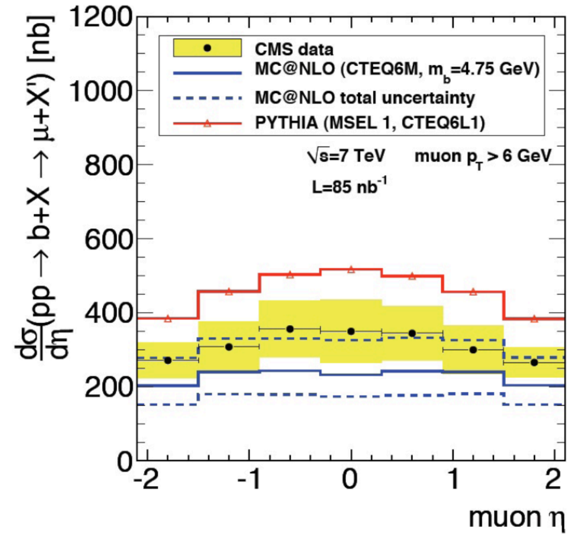
CMS σ from b→Xμν



$$\sigma = 1.32 \pm 0.01(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.15(\mathrm{lumi})\ \mu\mathrm{b}$$

$$\sigma_{MC@NLO} = 0.84^{+0.36}_{-0.19}(\mathrm{scale}) \pm 0.08(\mathrm{m_b}) \pm 0.04(\mathrm{pdf})\mu\mathrm{b} \qquad \sigma_{PYTHIA} = 1.8\mu\mathrm{b}$$





- In all cases generally good agreement with NLO calculations, within large errors

CPV Time Evolution

- In general with $A_f \equiv A(M \to f), \bar{A}_f \equiv A(\bar{M} \to f), \quad \lambda_f = \frac{p}{q}\frac{\bar{A}_f}{A_f}$

$$\Gamma(M(t) \to f) \;=\; \mathcal{N}_f\,|A_f|^2 e^{-\Gamma t}\left\{\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma\, t}{2} + \frac{1-|\lambda_f|^2}{2}\cos(\Delta M\, t) - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma\, t}{2} - \mathrm{Im}\,\lambda_f \sin(\Delta M\, t)\right\},$$

See Nierste arXiv:0904.1869 [hep-ph]

- For B°, $\Delta\Gamma \approx 0$

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(\frac{1}{2}\left(1-|\lambda_f|\right)\cos(\Delta M t) - \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$$

- if only 1 A_f $\quad \Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(1 - \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$

- and a CP eigenstates

$$a[f_{CP}(t)] = \frac{\Gamma(\bar{M} \to f_{CP}) - \Gamma(M \to f_{CP})}{\Gamma(\bar{M} \to f_{CP}) + \Gamma(M \to f_{CP})} = -2\,\mathrm{Im}\,\lambda_f$$

λ_f a function of V_{ij} in SM & thus to α,β or γ