



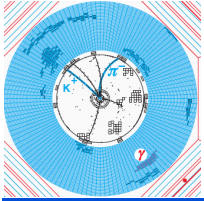
S. Stone



Heavy Flavor

Highlights

BF11, Oct. 20, 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 c & b quarks, t too heavy



u, d, ν 's

too light



s, μ

maybe



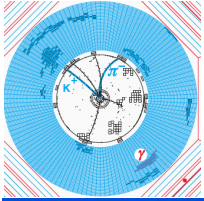
c & b, τ ; ν_M 's ?

just right



t

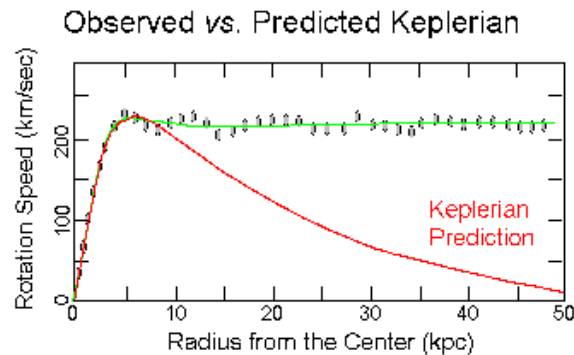
too heavy



Physics Beyond the Standard Model

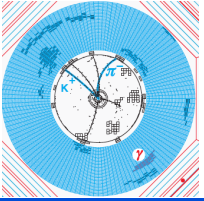
- Baryogenesis: From current measurements can only generate $(n_B - \bar{n}_B)/n_\gamma = \sim 10^{-20}$ but $\sim 6 \times 10^{-10}$ is needed. Thus New Physics must exist to generate needed CP Violation

- Dark Matter



Gravitational lensing

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



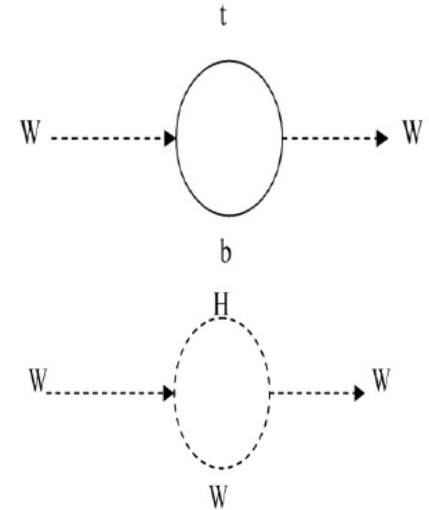
Seeking New Physics

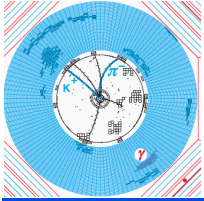
- HFP as a tool for NP discovery

- 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 $\frac{dM_W}{dm_t} \propto \frac{m_t}{M_W}$

- M_W changes due to m_H $\frac{dM_W}{dm_H} \propto -\frac{dm_H}{M_H}$

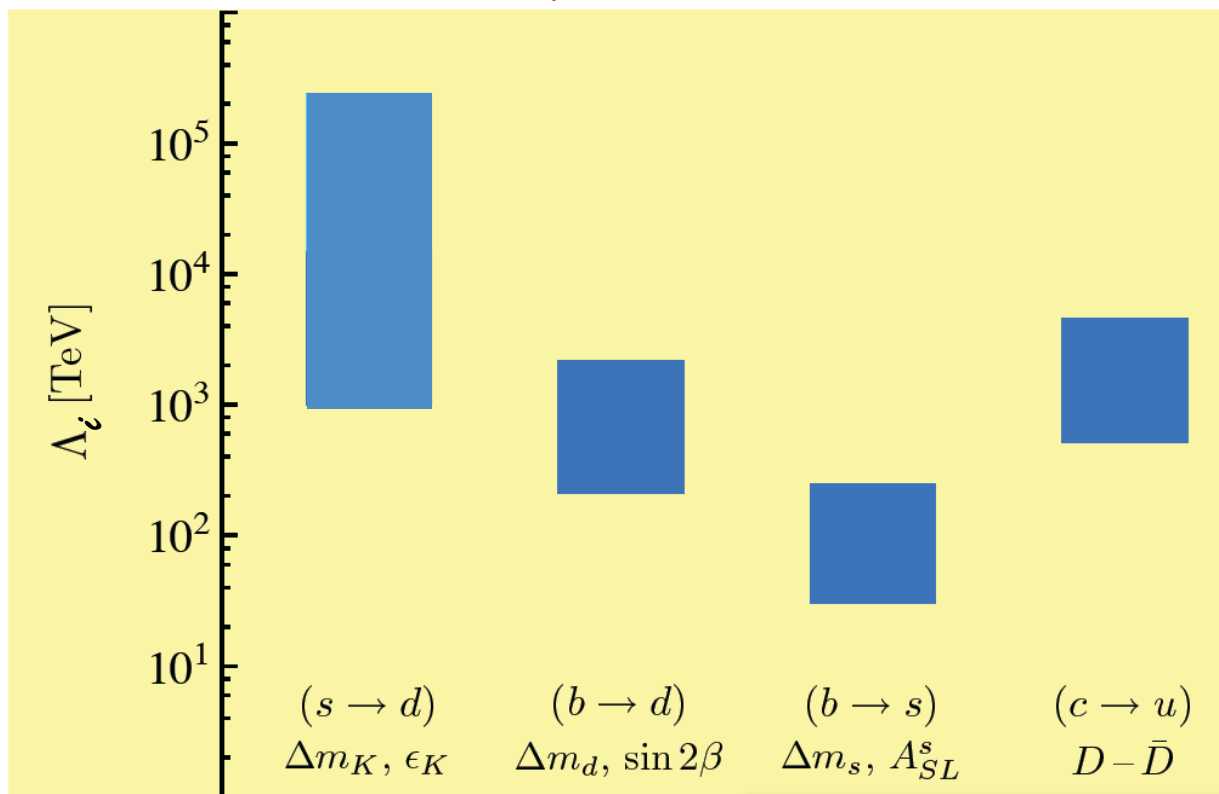




Flavor as a High Mass Probe

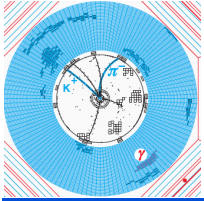
■ Already excluded ranges

□ $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i} O_i$, take $c_i = 1$



Ways out

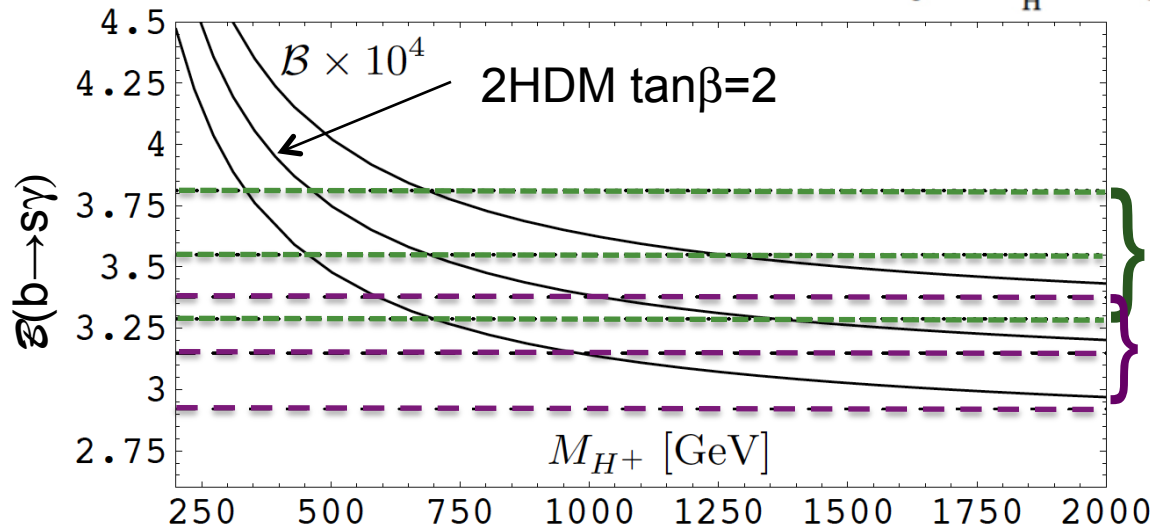
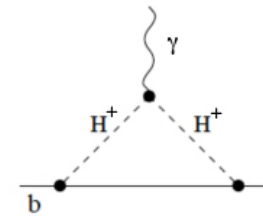
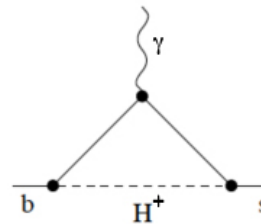
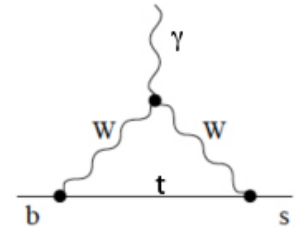
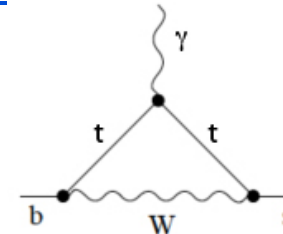
1. New particles have large masses $\gg 1$ TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constraints on NP



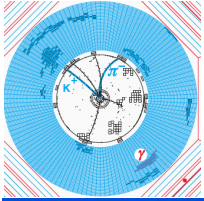
Ex. of Strong Constraints on NP

■ Inclusive $b \rightarrow s \gamma$, ($E_\gamma > 1.6$ 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

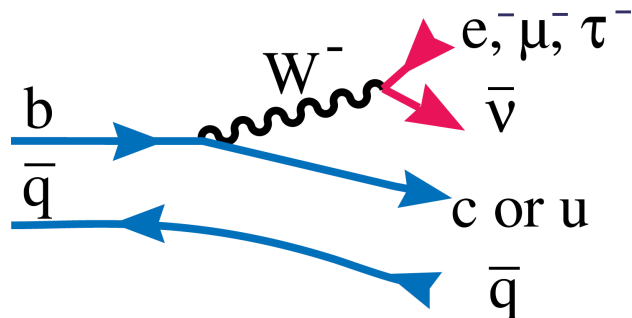


Misiak et. al hep-ph/0609232,
See also A. Buras et. al,
arXiv:1105.5146

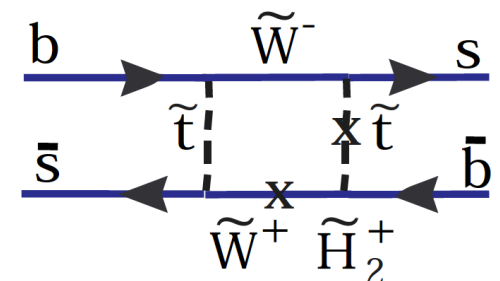
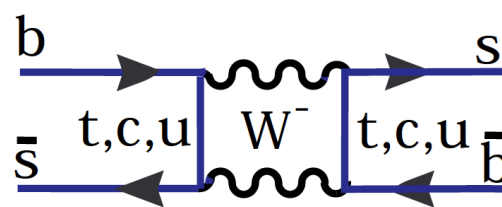


Limits on New Physics

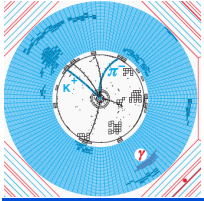
- It is oft said that we have not seen New Physics, yet what we observe is the sum of Standard Model + New Physics. How to set limits on NP?
- One hypothesis: assume that tree level diagrams are dominated by SM and loop diagrams could contain NP



Tree diagram example



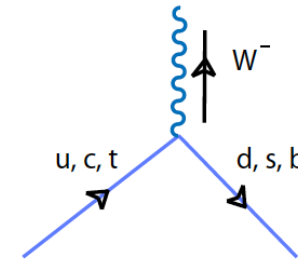
Loop diagram example



Quark Mixing & CKM Matrix

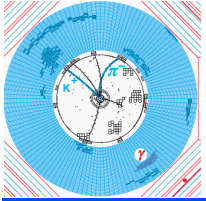
- In SM charge $-1/3$ quarks (d, s, b) are mixed
- Described by CKM matrix (also ν are mixed)

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



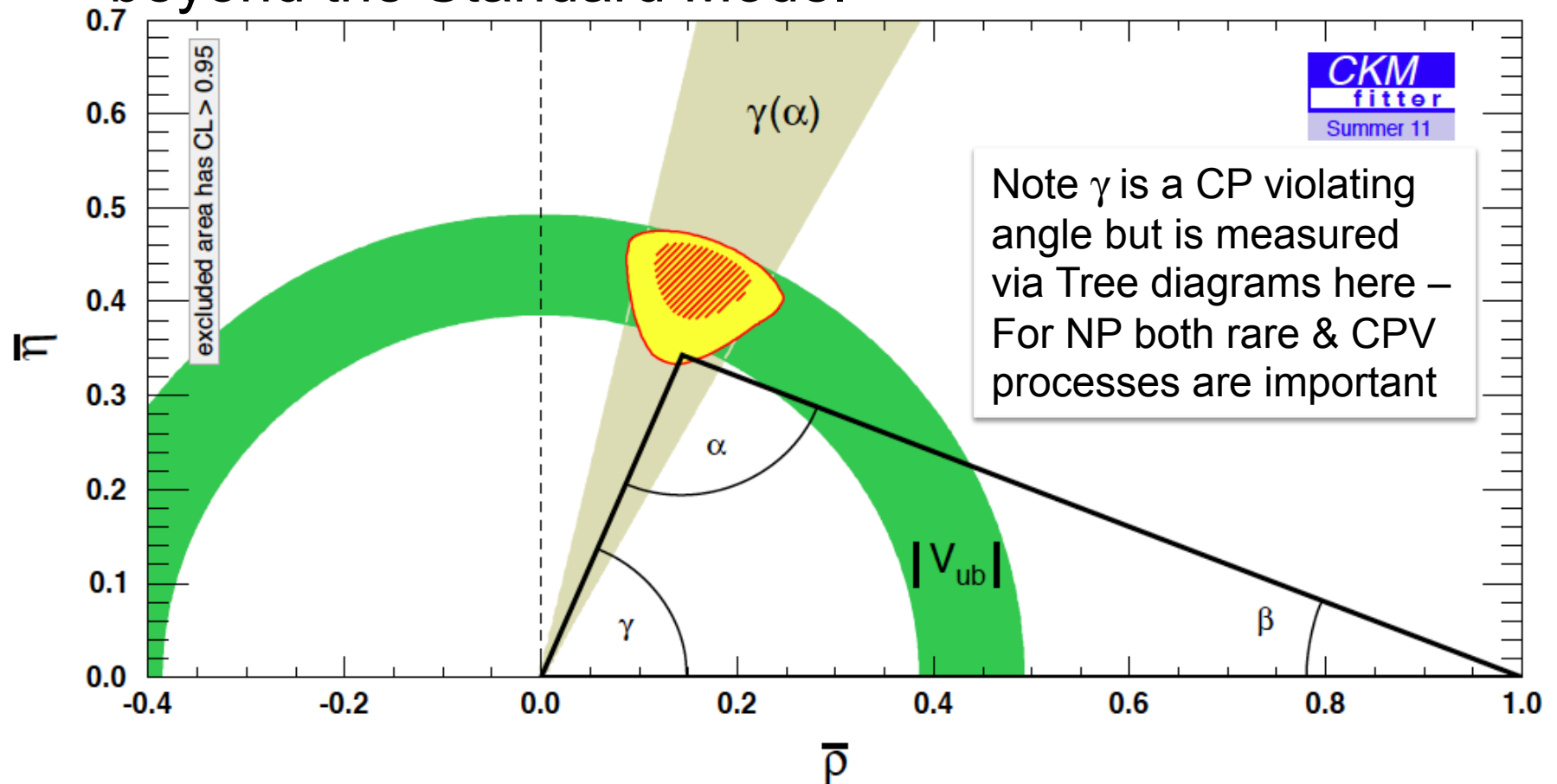
$$= \begin{pmatrix} 1 - \lambda^2 / 2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

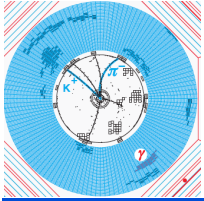
- $\lambda=0.225$, $A=0.8$, constraints on ρ & η
- These are fundamental constants in SM



What are limits on NP from quark decays?

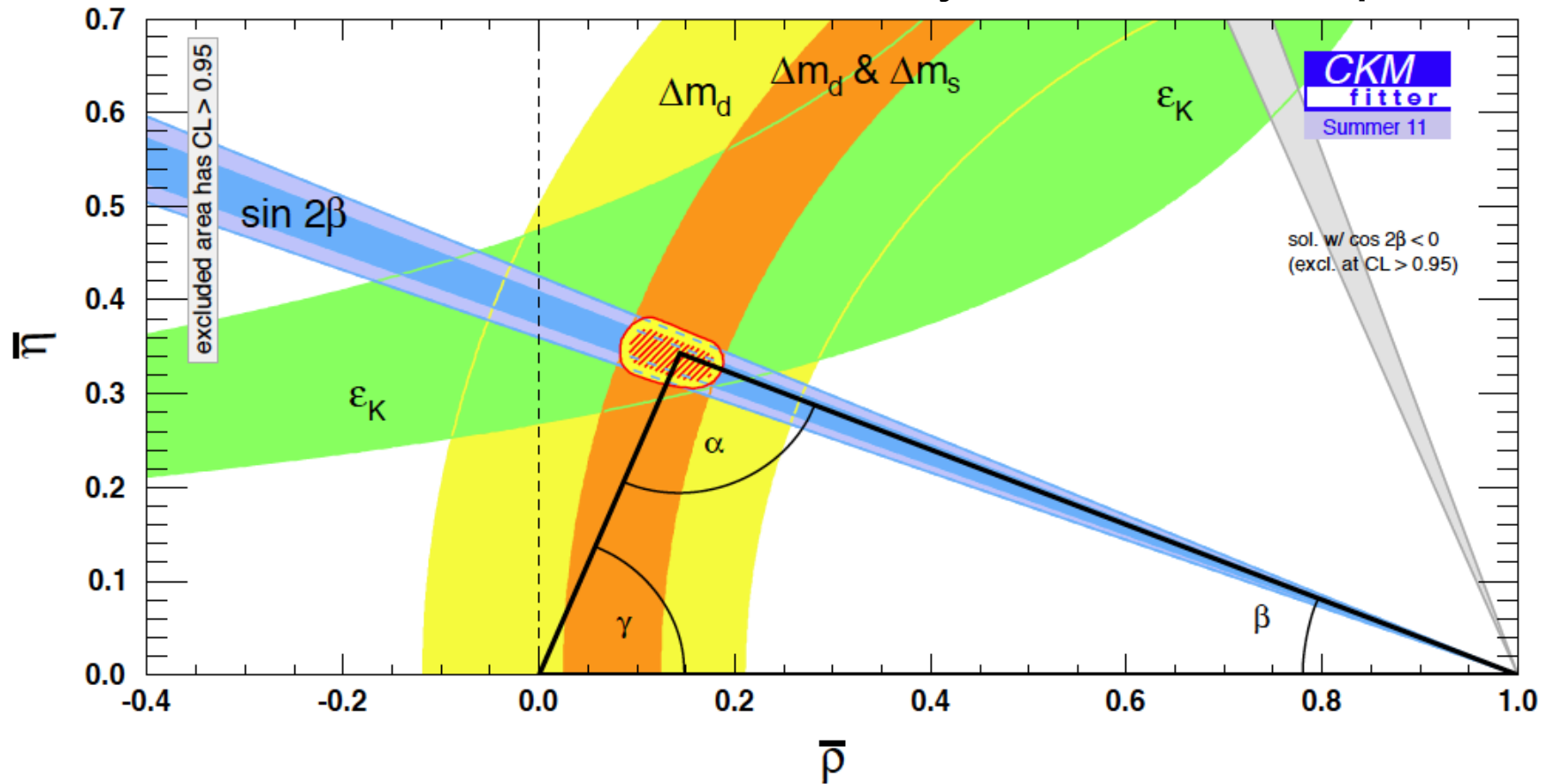
- Tree diagrams are unlikely to be affected by physics beyond the Standard Model

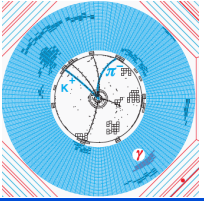




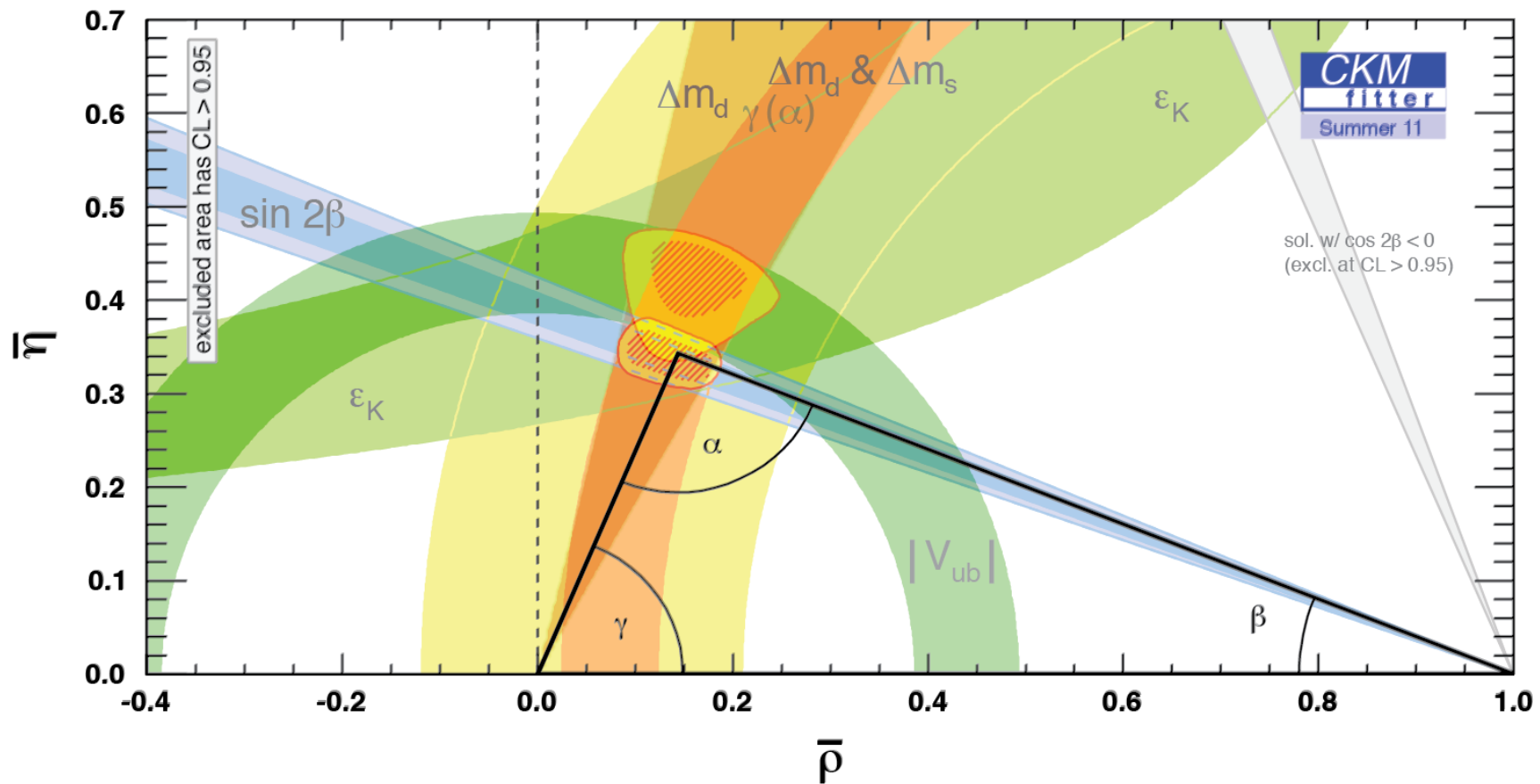
CP Violation in B^0 & K^0 Only

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

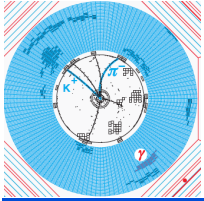




They are Consistent

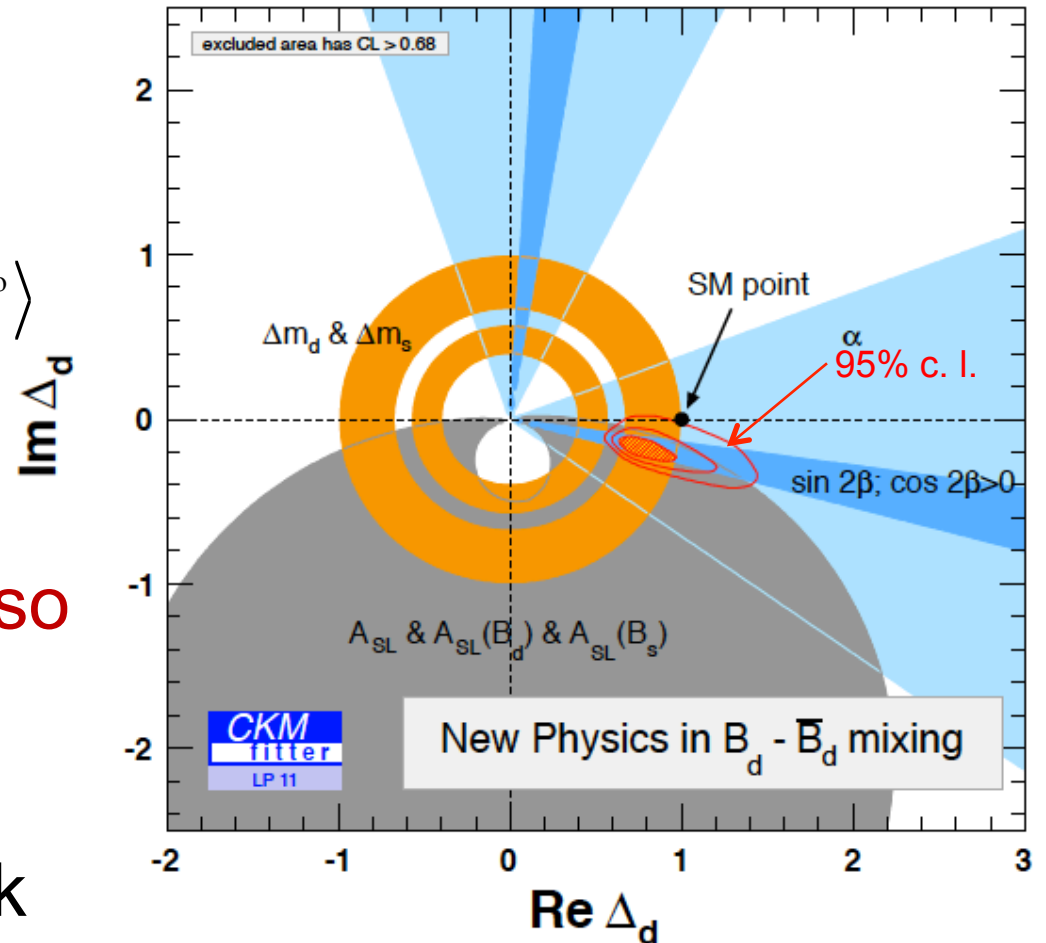


- But consistency is only at the 5% level
- Limits on NP are not so strong

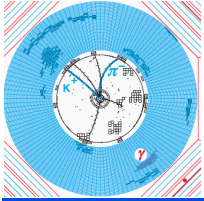


Limits on New Physics From B^0 Mixing

- Is there NP in B^0 - \bar{B}^0 mixing?
- $\langle B^0 | H_{\Delta B=2}^{SM+NP} | \bar{B}^0 \rangle = \Delta_d^{NP} \langle B^0 | H_{\Delta B=2}^{SM} | \bar{B}^0 \rangle$
 $\Delta_d^{NP} = \text{Re} \Delta_d + i \text{Im} \Delta_d$
- Assume NP in tree decays is negligible, so no NP in $|V_{ij}|$, γ from $B^- \rightarrow D^0 K^-$
- Allow NP in Δm , weak phases, A_{SL} , & $\Delta\Gamma$

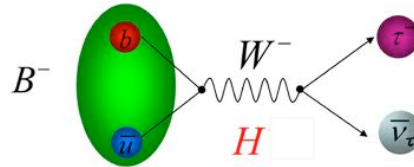


■ Room for new physics, in fact SM is only at 5% c.l.



One Clear Problem

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

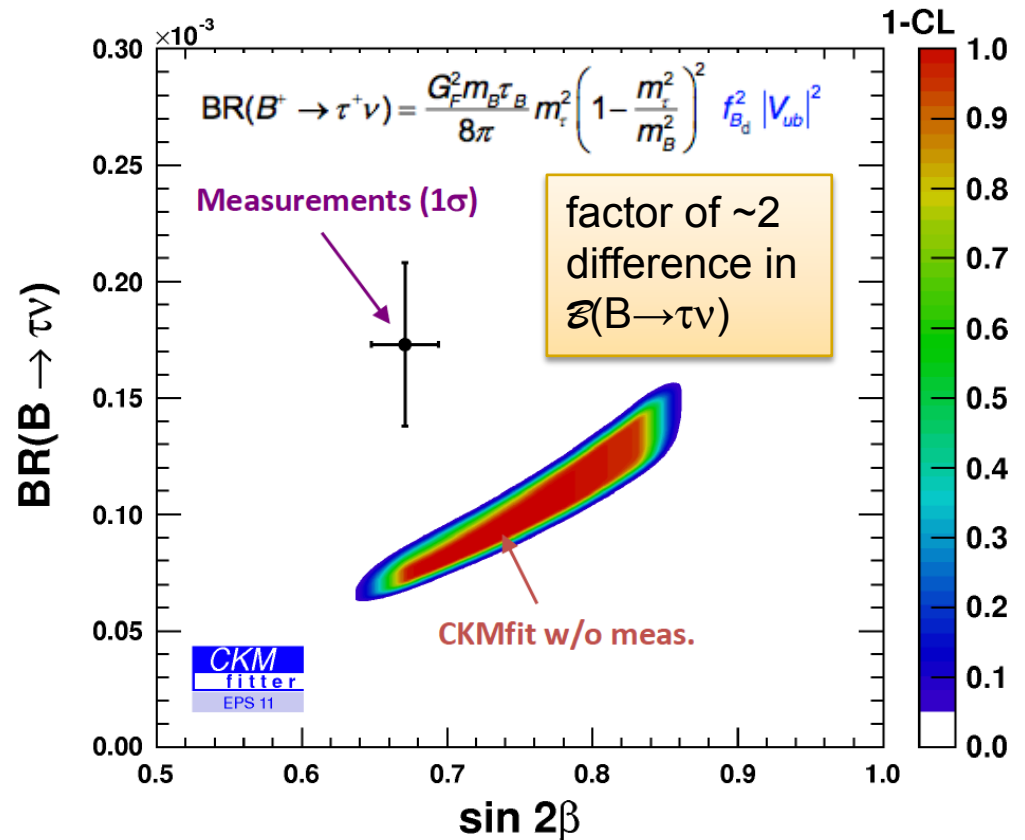


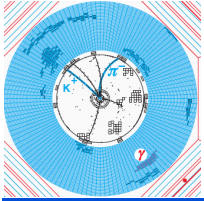
Can be new particles instead of W^- but why not also in $D_{(s)}^+ \rightarrow \ell^+ \nu$?

- $\sin 2\beta$, CPV in e.g. $B^0 \rightarrow J/\psi K_S$: 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: Lingered difference between inclusive $b \rightarrow u \ell \nu$, & exclusive $B \rightarrow \pi \ell \nu$,

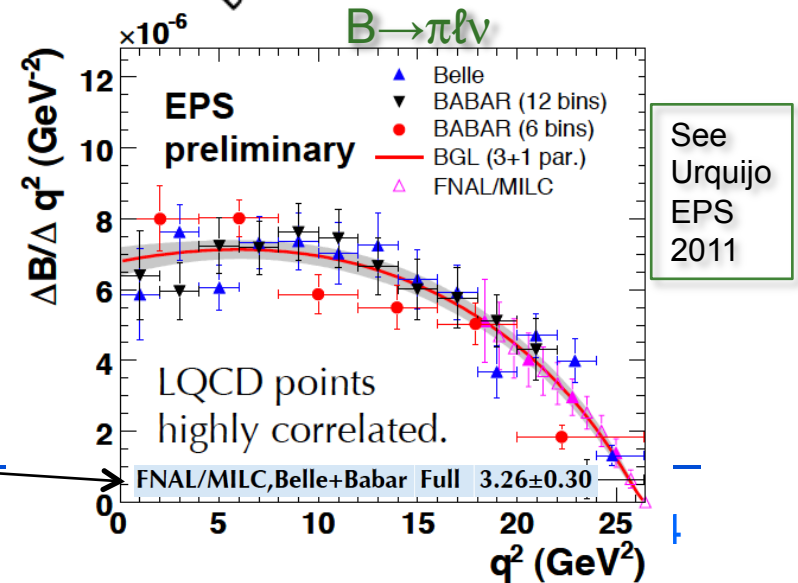
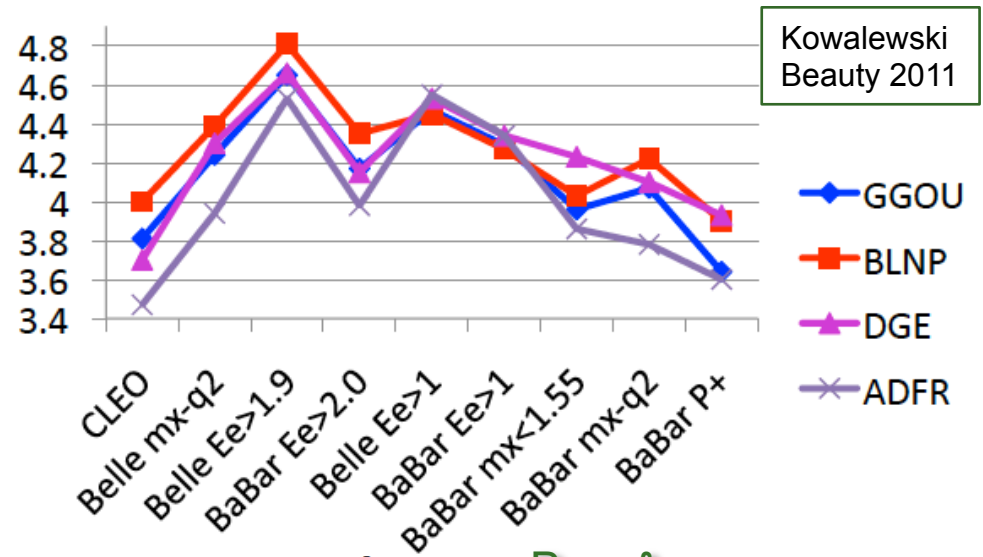
- Values $|V_{ub}| \times 10^{-3}$

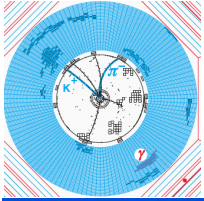
- Inclusive: $4.25 \pm 0.15 \pm 0.20$

- Exclusive: $3.25 \pm 0.12 \pm 0.28$

New

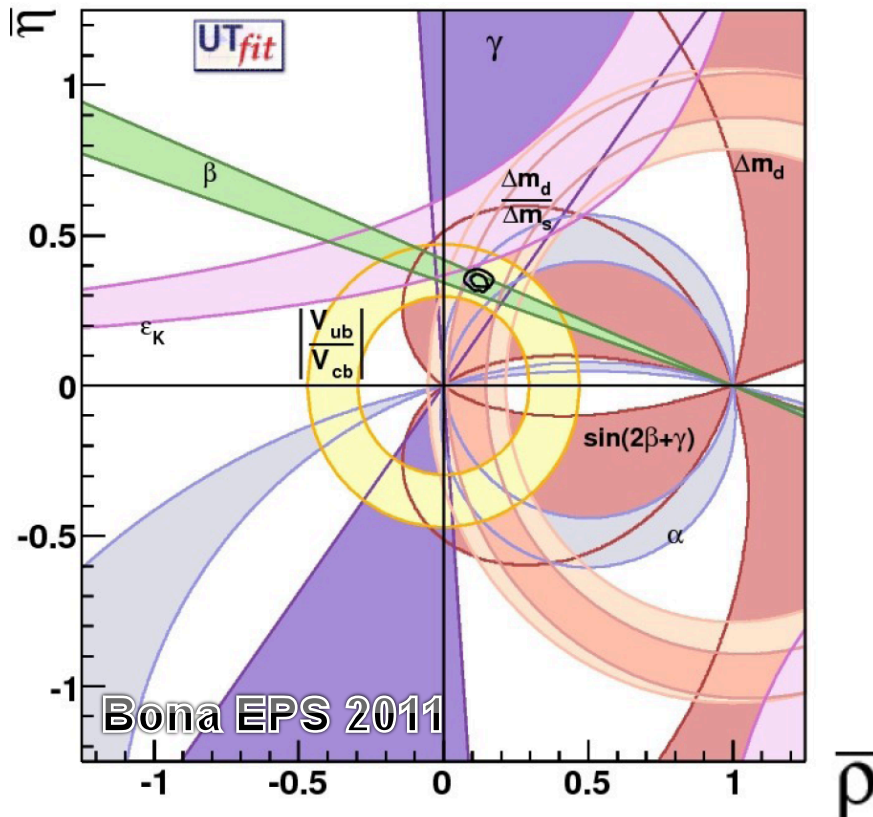
$|V_{ub}| (10^{-3})$ $b \rightarrow u \ell \nu$



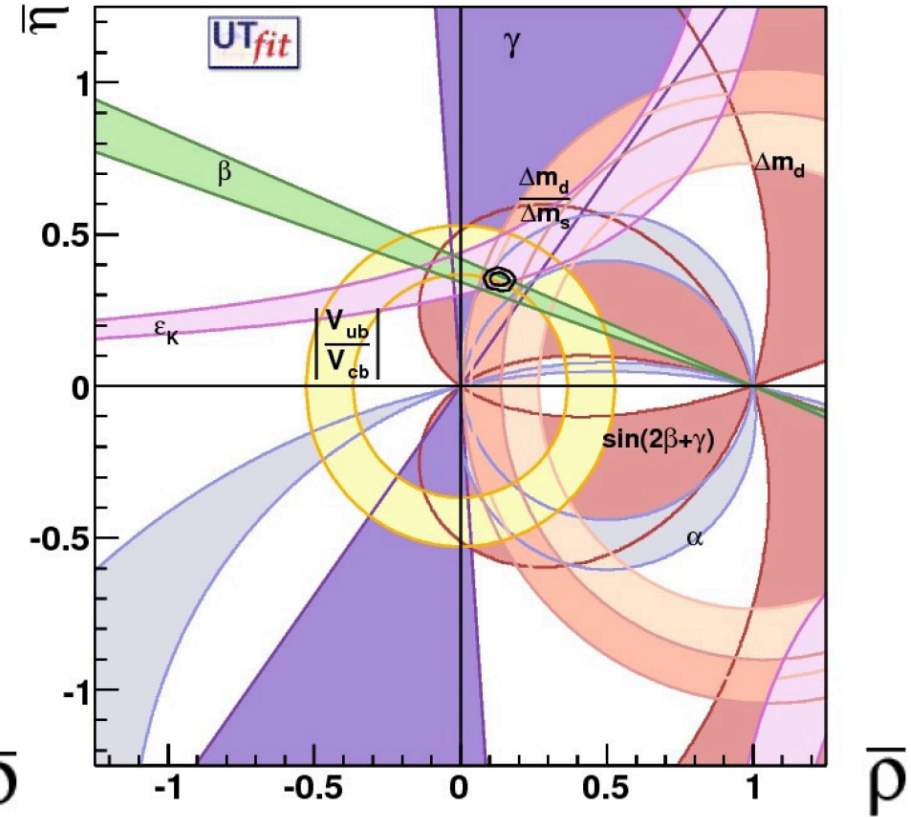


V_{ub} Consequences

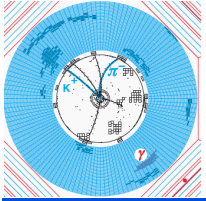
Exclusive



Inclusive



Use of Exclusive would increase $\tau\nu \sin 2\beta$ discrepancy, use of Inclusive would not solve the problem



A V_{ub} fix?

- Add new physics: right handed currents with coupling V_{ub}^R

- $B \rightarrow \pi \ell \nu$ rate goes as $|V_{ub}^L + V_{ub}^R|^2$

- $B \rightarrow \tau \nu$ rate goes as $|V_{ub}^L - V_{ub}^R|^2$

- $B \rightarrow X_u \ell \nu$ rate goes as $|V_{ub}^L|^2 + |V_{ub}^R|^2$

- Agreement with $\sim 15\%$ rhc

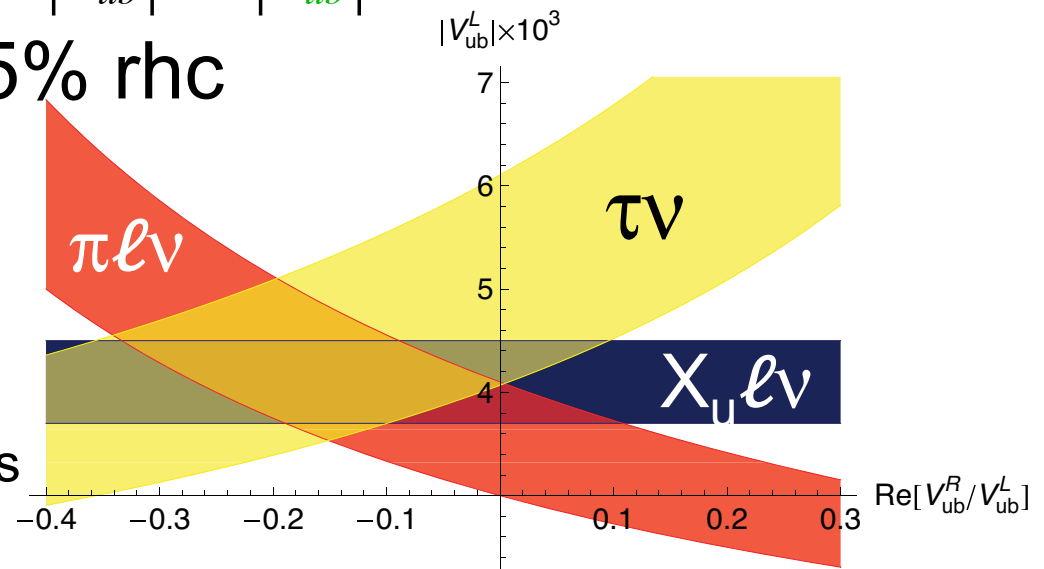
- Can arise in SUSY

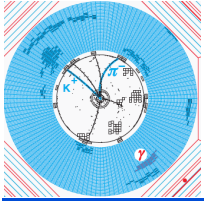
- Not in loops

- See Crivellin

[arXiv:0907.2461], also Buras

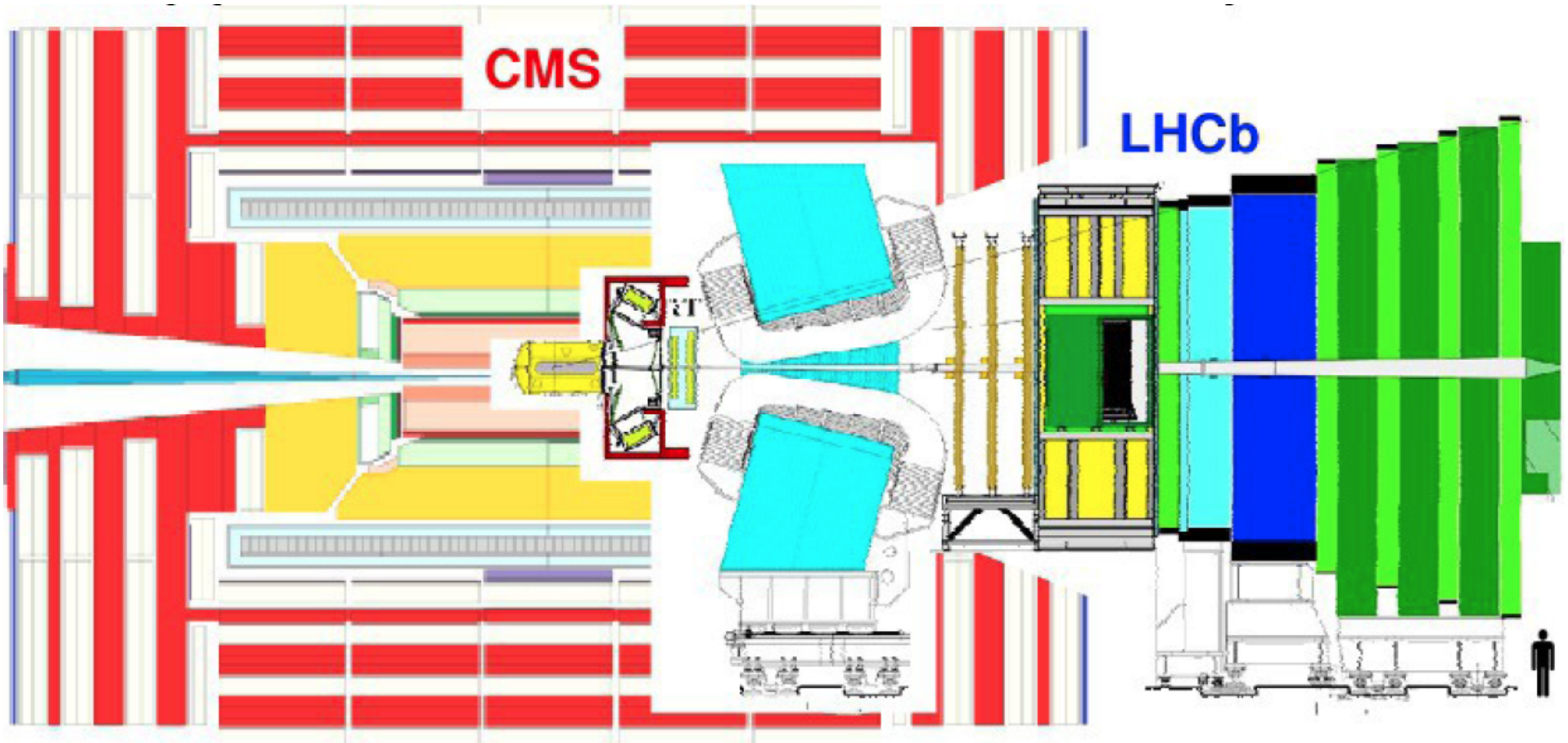
et.al, [arXiv: 1007.1993]

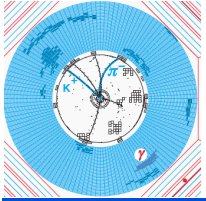




Recent Results

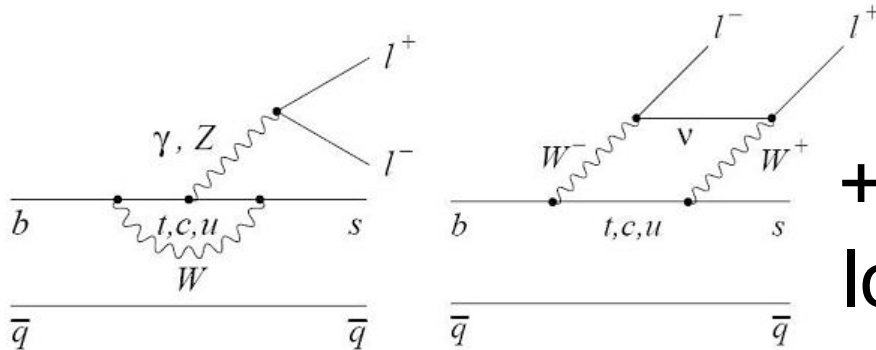
- NP **must** affect every process; the amount tells us what the NP is (“DNA footprint”)
- New data from CDF, D0, BaBar BES, BELLE, ATLAS, CMS & LHCb – Not nearly enough time to cover





$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- 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



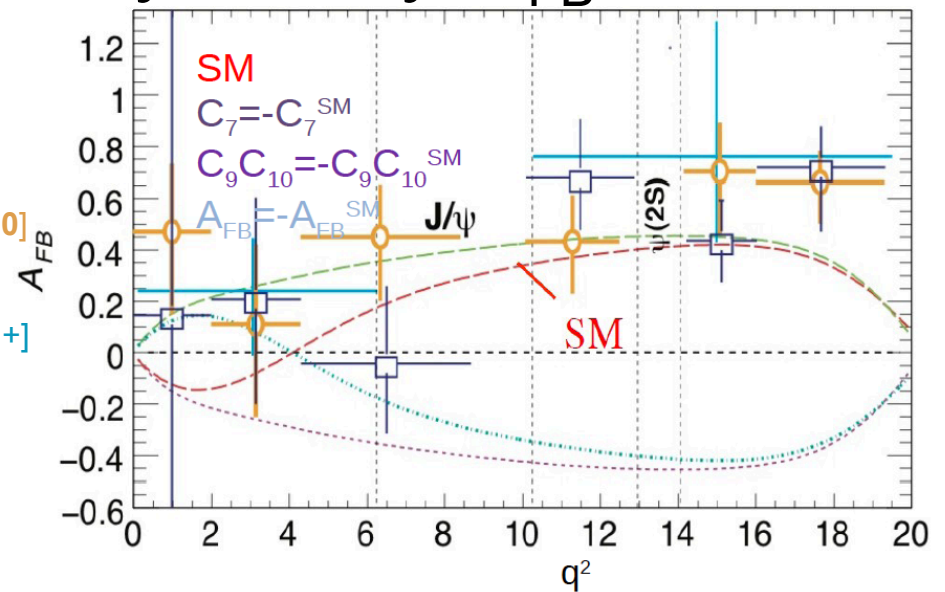
[80% of data 0]

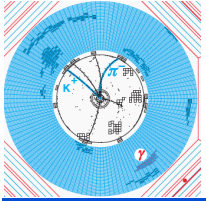


[75% of data +]



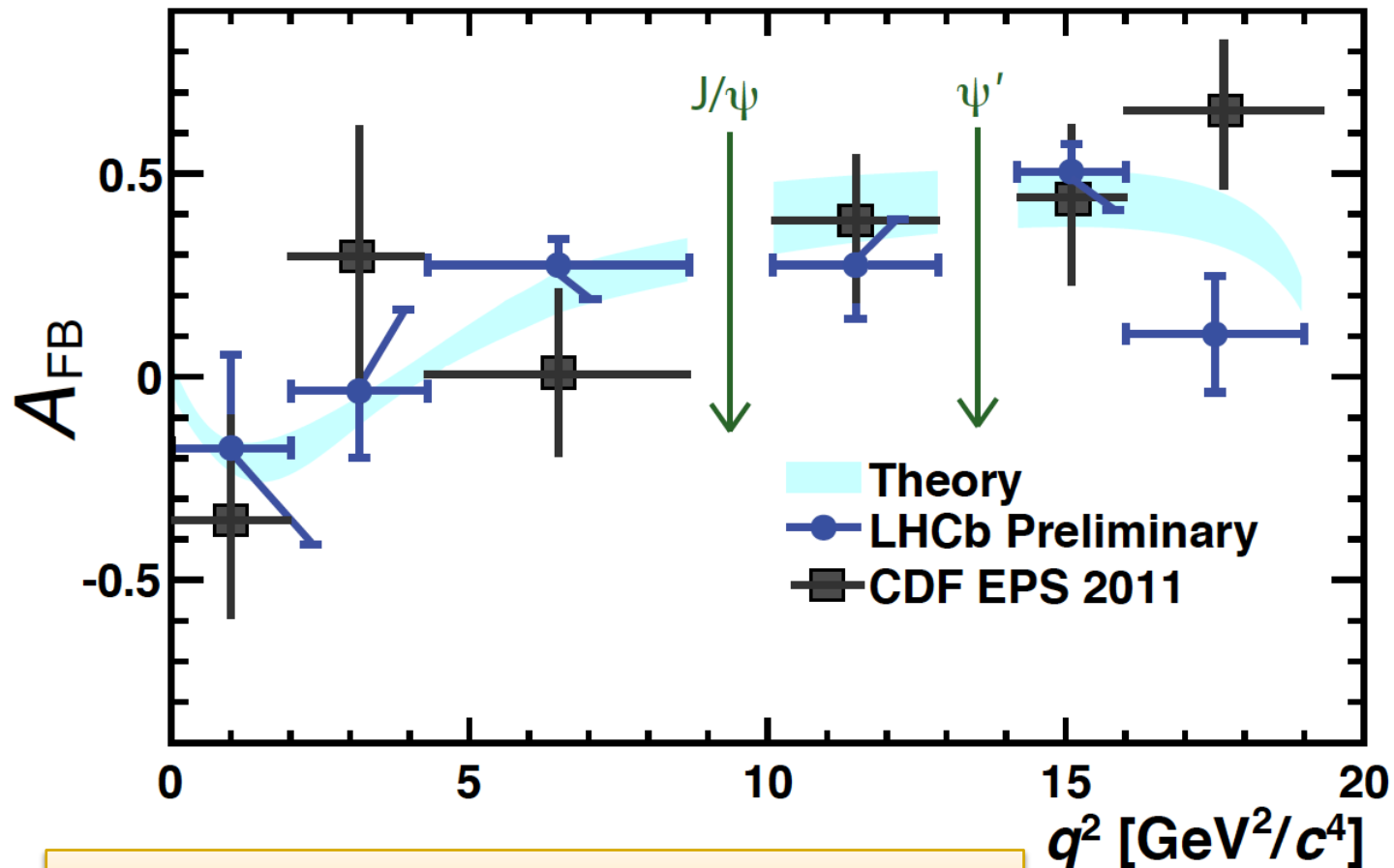
[4.4 fb⁻¹ □]



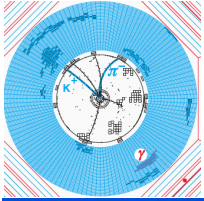


New $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- New results from CDF 6.8 fb⁻¹ & LHCb 0.3 fb⁻¹



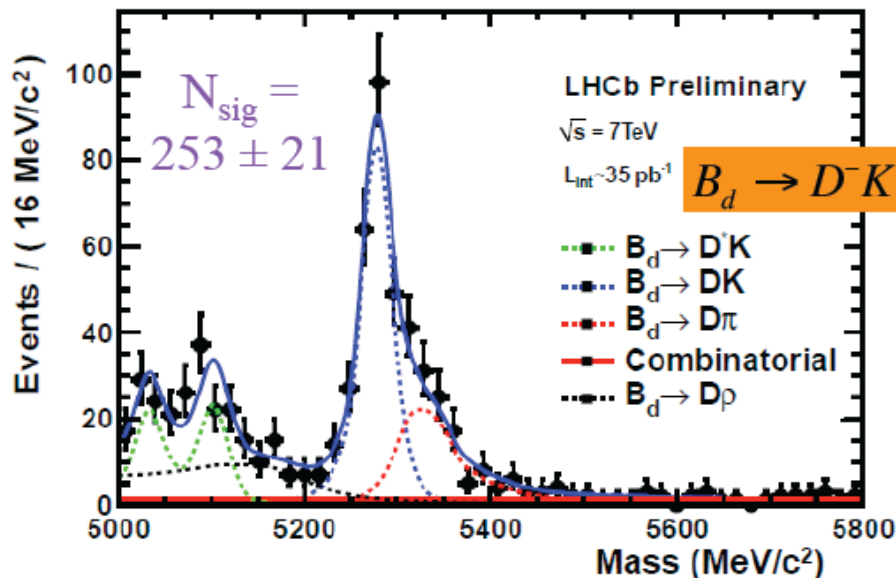
No evidence of deviation from SM so far



b Fractions (LHCb)

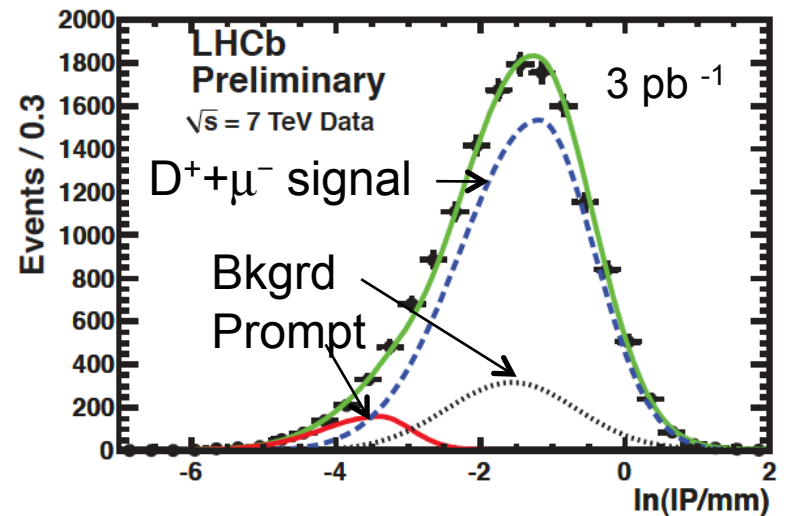
- Important to set normalization scale for B_s
- f_s/f_d using hadronic decays
- Using Semileptonic: $b \rightarrow (D^0, D^+, D_s, \Lambda_b) X \mu \nu$

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



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

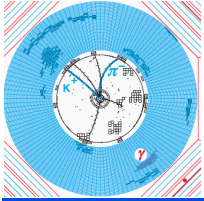
Theory error



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

- independent of η & p_t

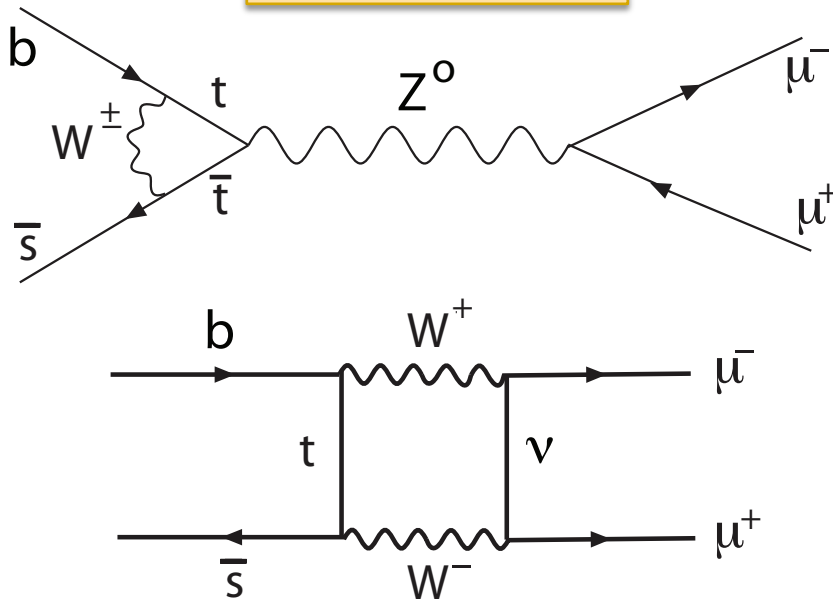
$$f_s / f_d = 0.267^{+0.021}_{-0.020}$$



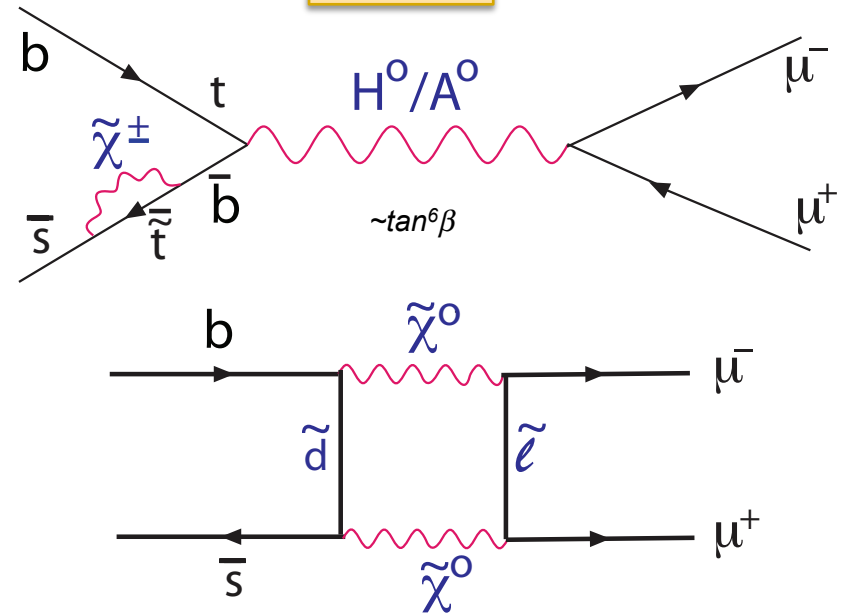
$B_s \rightarrow \mu^+ \mu^-$

- SM branching ratio is $(3.2 \pm 0.2) \times 10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

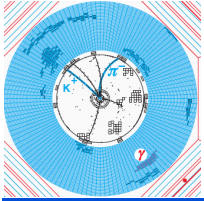
Standard Model



MSSM

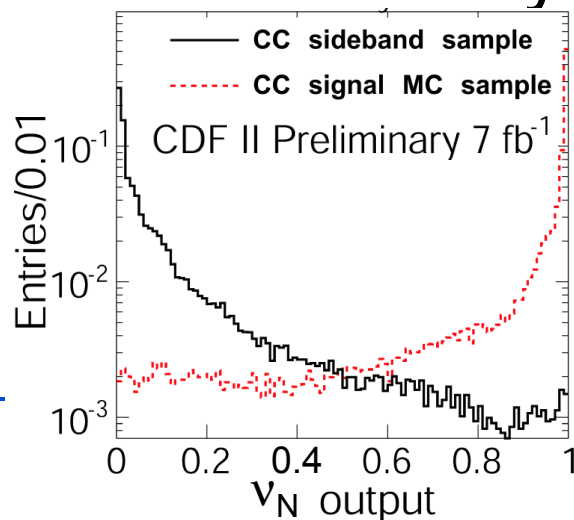


- Many NP models possible, not just Super-Sym

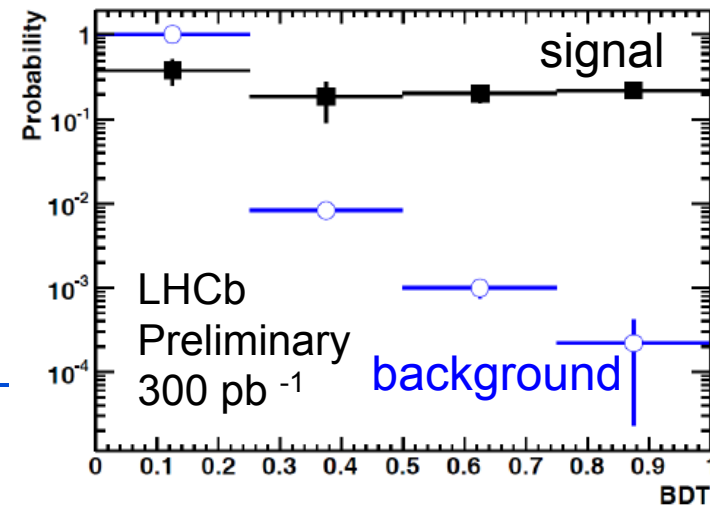


Discrimination

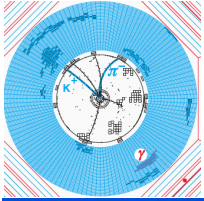
- Select same topology as $B \rightarrow h^+ h^-$, add μ ID
- Lots of other variables to discriminate against bkgd : B impact parameter, B lifetime, B p_t , B isolation, muon isolation, minimum impact parameter of muons, muon polarization...
- Can use $B \rightarrow h^+ h^-$ to tune cuts or form a multivariate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



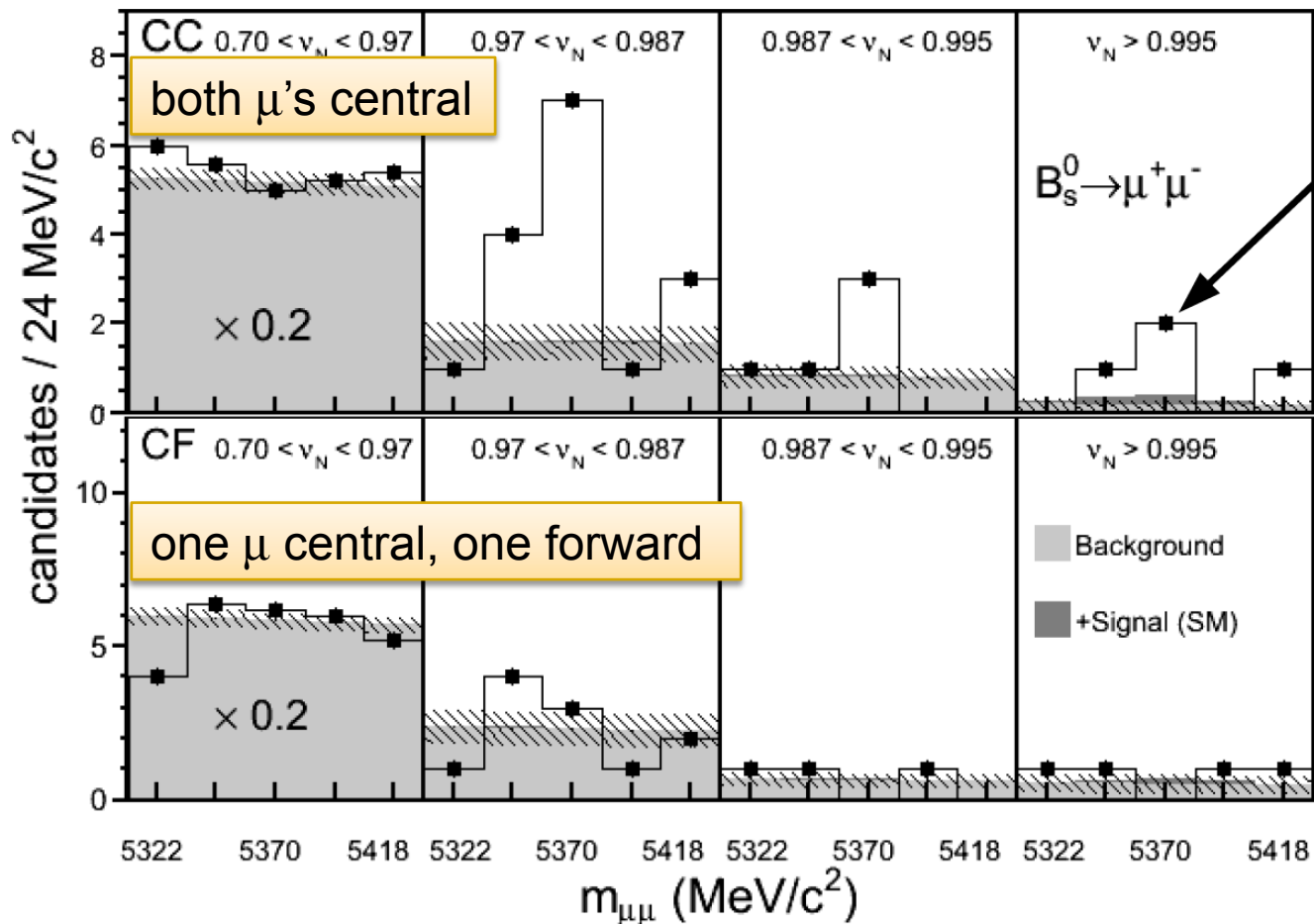
BF11,



22



CDF Result



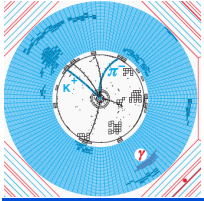
Example:
 Obs: 2
 Bkg. exp:
 0.16 ± 0.12

$$B(B_s \rightarrow \mu^+ \mu^-) = (1.8_{-0.9}^{+1.1}) \times 10^{-8}$$

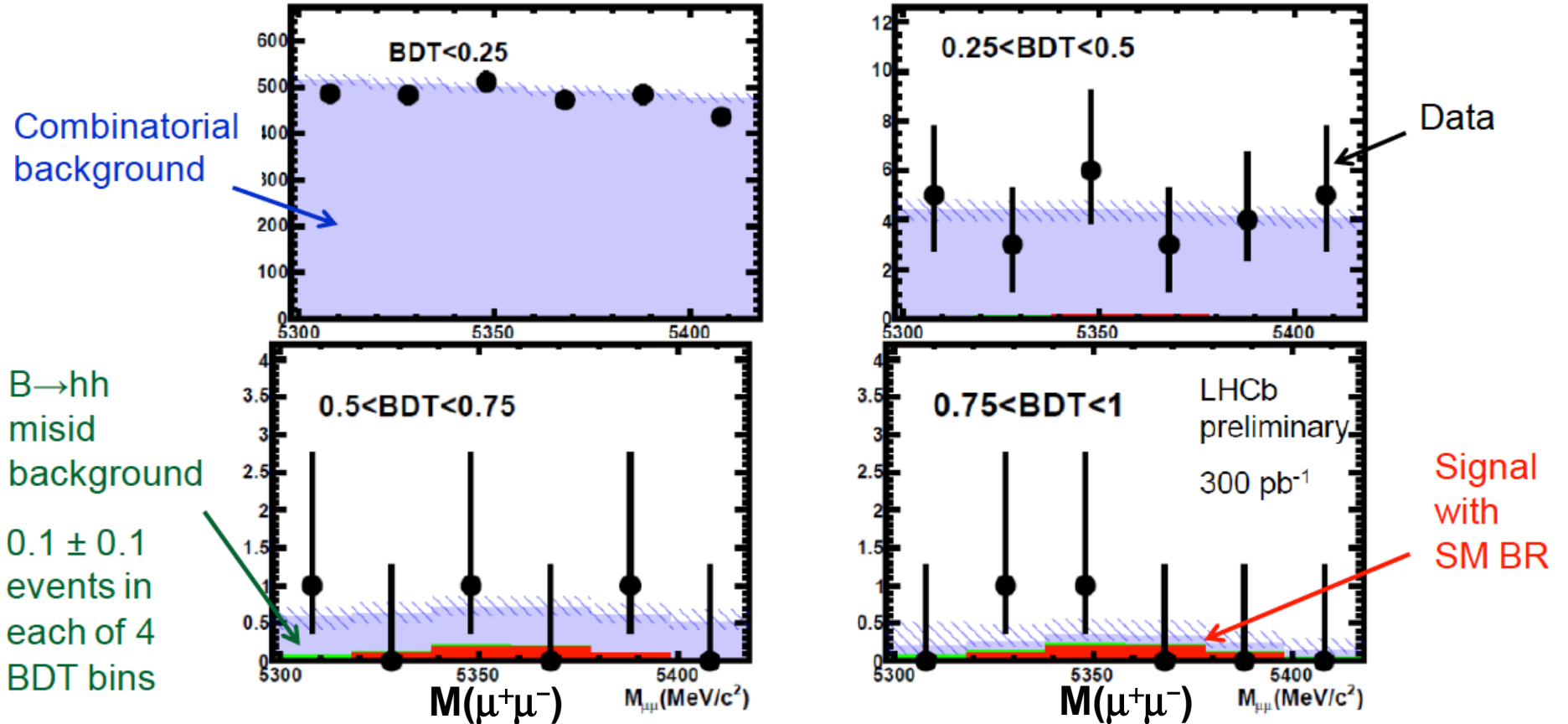
5.6 x SM expectation
 p value for bkgnd + SM is 2.9%

Set a “two sided limit @ 90% CL” $4.6 \times 10^{-9} < B(B_s^0 \rightarrow \mu^+ \mu^-) < 3.9 \times 10^{-8}$

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



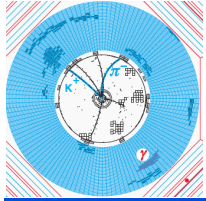
LHCb



	BDT < 1/4	1/4 < BDT < 1/2	1/2 < BDT < 3/4	3/4 < 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

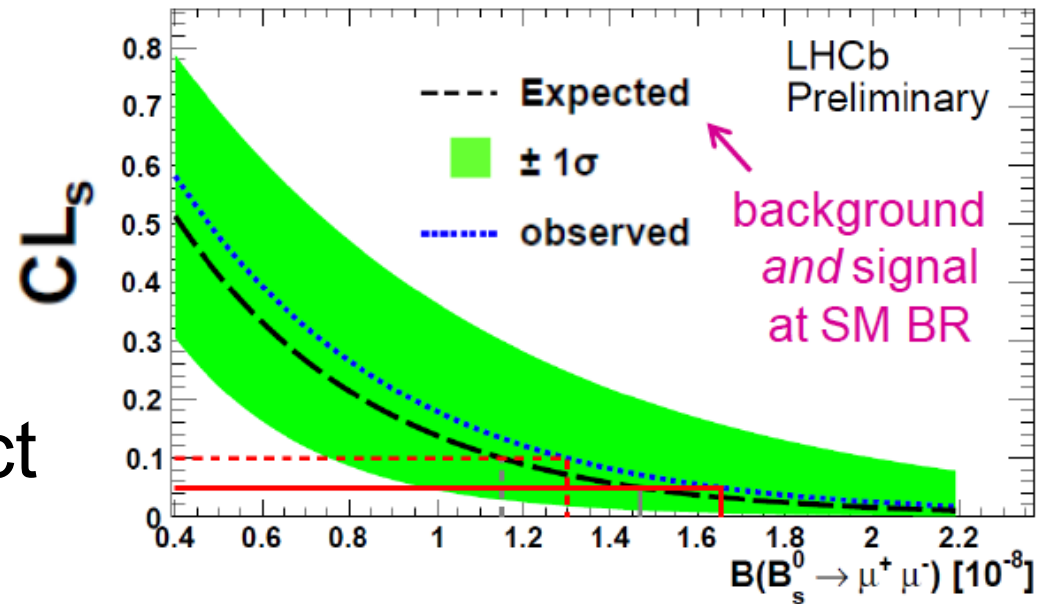
BF

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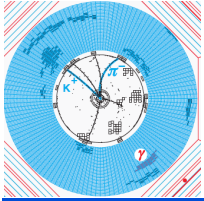
LHCb

- 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



LHCb-CONF-2011-037

- | | |
|-------------------------------------|---------------------------|
| ■ Expected limit @95% (90%) | 1.5(1.2) $\times 10^{-8}$ |
| ■ Observed limit @95% (90%) | 1.6(1.3) $\times 10^{-8}$ |
| ■ p-value of bkgrnd only hypothesis | 14% |
| ■ Observed limit with 2010 data | 1.5(1.2) $\times 10^{-8}$ |

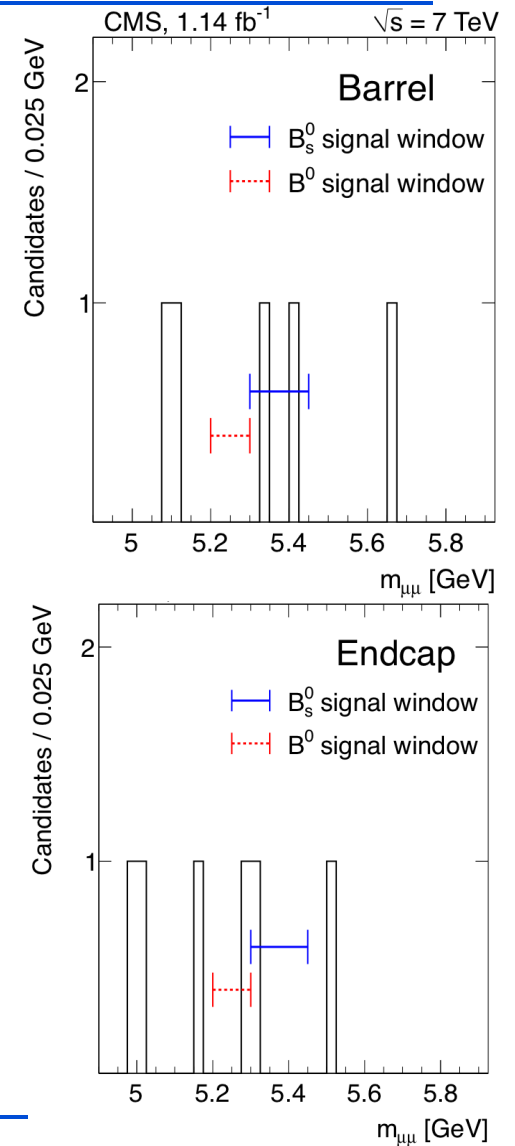


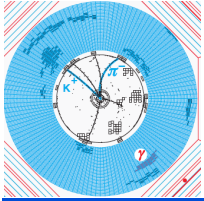
■ Cut based analysis

	Barrel	Endcap
# expected bkgrd	0.60 ± 0.35	0.80 ± 0.40
# bkgrd $B \rightarrow h^+ h^-$	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

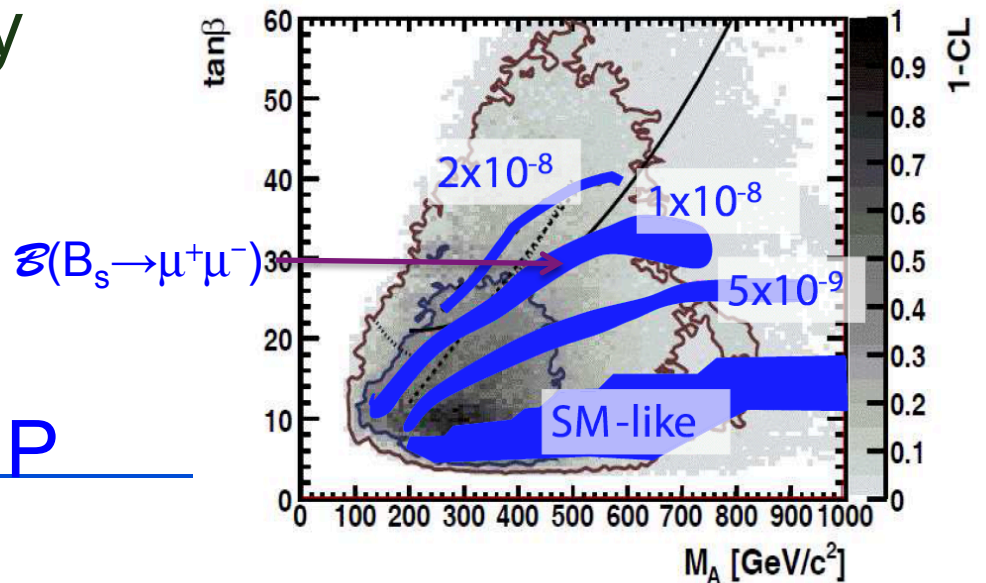
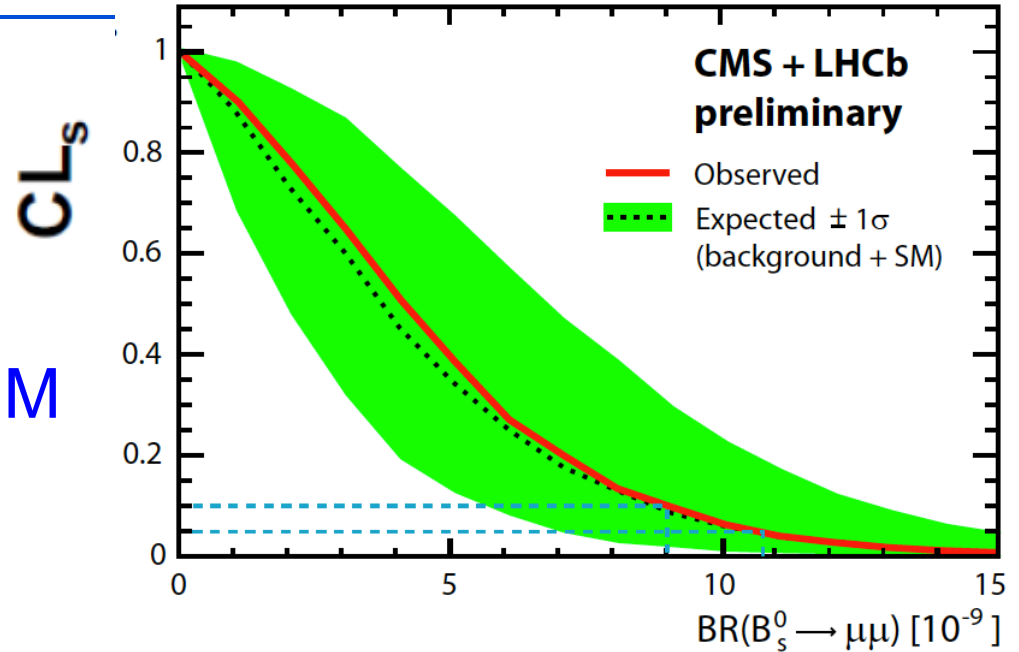


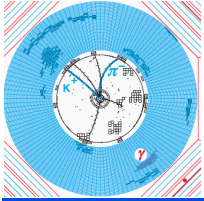


LHC Combined

- 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

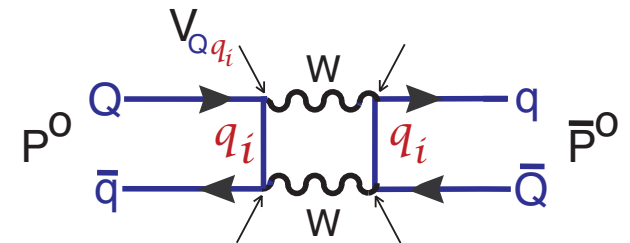
BF11, Oct. 20, 2011





Neutral Meson Mixing

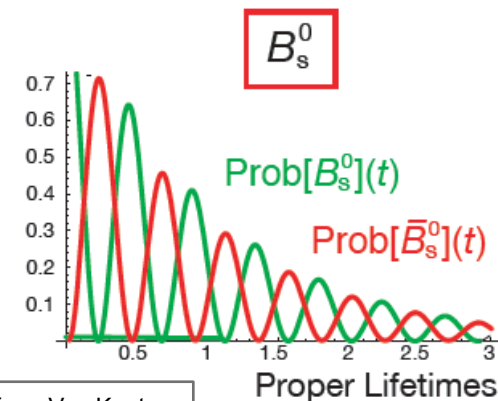
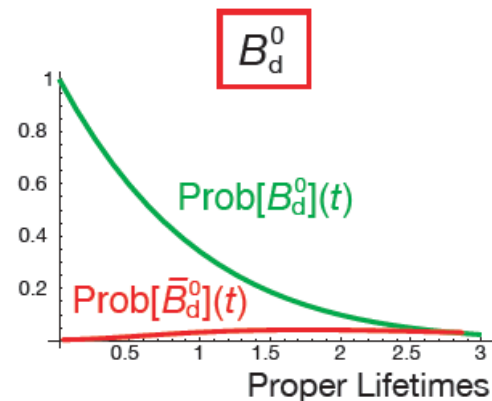
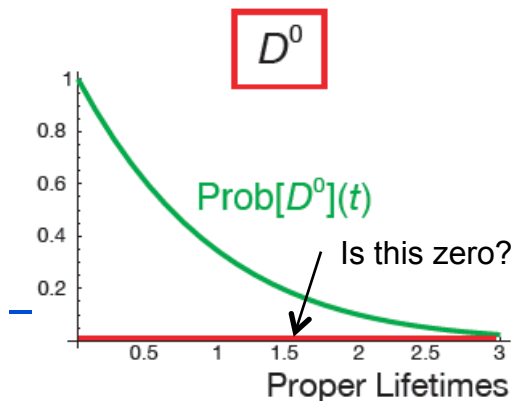
- Neutral mesons can transform into their anti-particles via 2nd order weak interactions
- Short distance transition rate depends on
 - mass of intermediate q_i the heavier the better, favors s & b since t is allowed, while for c, b is the heaviest
 - CKM elements V_{ij}



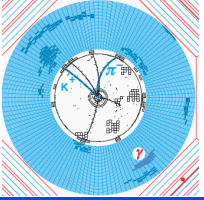
New particles possible in loop

+ “long distance” for D^0

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

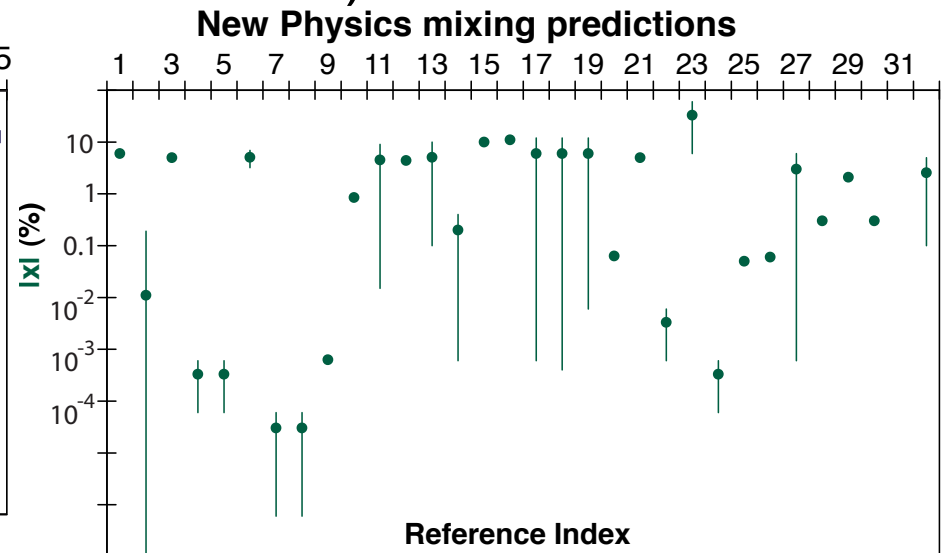
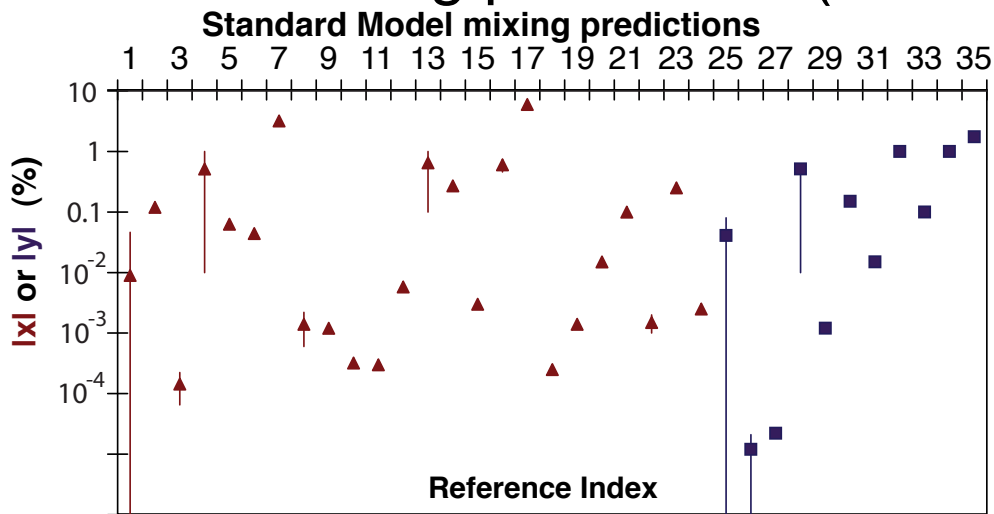


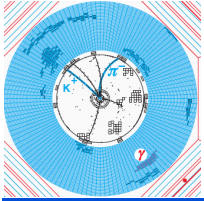
from Van Kooten



Some Definitions

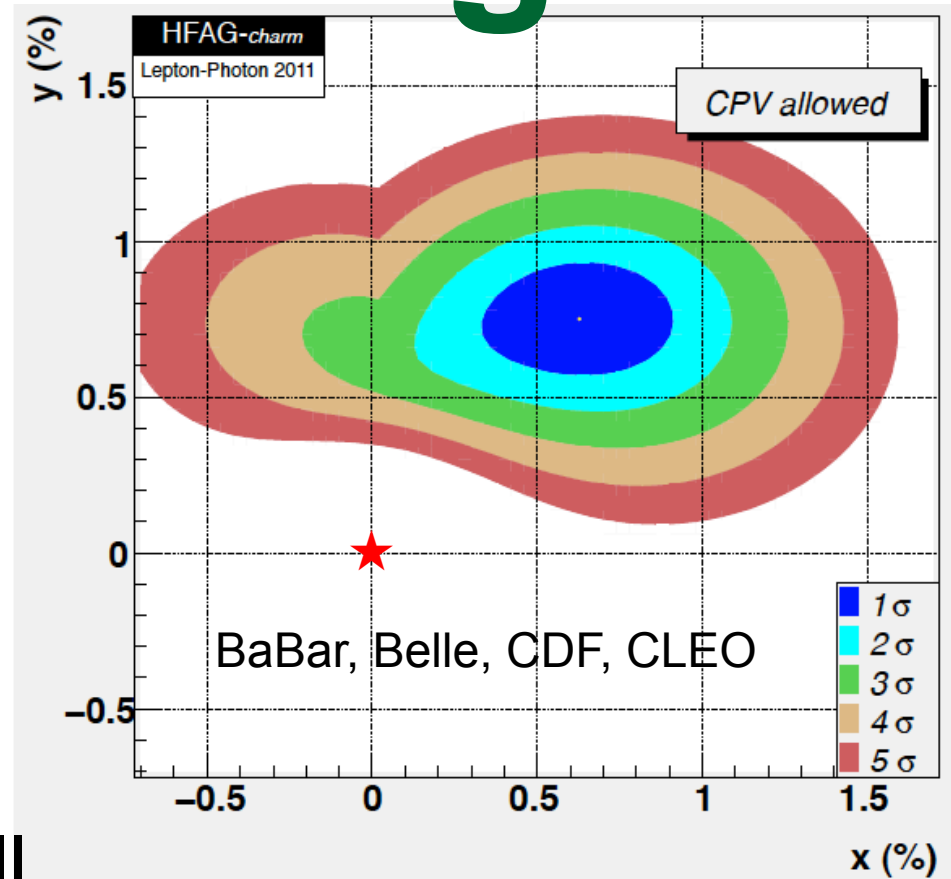
- Weak interaction eigenstates are different that strong interaction eigenstates
- $|M_L\rangle = p|M^0\rangle + q|\bar{M}^0\rangle$, $|M_H\rangle = p|M^0\rangle - q|\bar{M}^0\rangle$,
- Since we observe the mesons via their weak decays,
 $m = (M_H + M_L)/2$, $\Delta M = M_H - M_L$,
 $1/\tau = \Gamma = (\Gamma_H + \Gamma_L)/2$, $\Delta\Gamma = \Gamma_L - \Gamma_H$,
- Useful quantities are $x = \Delta M/\Gamma$, $y = \Delta\Gamma/2\Gamma$
- D^0 mixing predictions (from Petrov 2006):

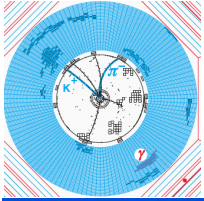




D⁰ Mixing

- 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

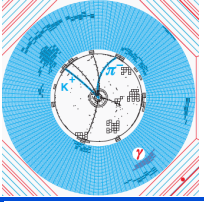




CPV in Charm

- 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 $A(D \rightarrow f) = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}$) if $f = \bar{f}$, CP eigenst
 - Belle $A(D^+ \rightarrow \phi\pi^+) - A(D_s^+ \rightarrow \phi\pi^+) = (-0.51 \pm 0.28 \pm 0.05)\%$ [arXiv: 1110.0694]
 - CDF $A(D^0 \rightarrow \pi^+\pi^-) = (-0.22 \pm 0.24 \pm 0.11)\%$ & $A(D^0 \rightarrow K^+K^-) = (-0.24 \pm 0.22 \pm 0.10)\%$ [CDF Public Note 10269]
 - BaBar using T-odd triple products in $D^+ \rightarrow K^+K_S\pi^+\pi^-$ finds $A_T = (-1.21 \pm 1.00 \pm 0.46)\%$ [arXiv:1105.4410v2]

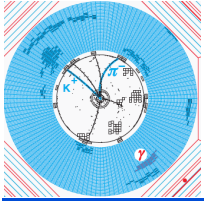




CPV Time Evolution

- Consider
$$a[f(t)] = \frac{\Gamma(\bar{M} \rightarrow f) - \Gamma(M \rightarrow f)}{\Gamma(\bar{M} \rightarrow f) + \Gamma(M \rightarrow f)}$$
- Define
$$A_f \equiv A(M \rightarrow f), \bar{A}_f \equiv A(\bar{M} \rightarrow f), \lambda_f = \frac{p}{q} \frac{\bar{A}_f}{A_f}$$
- Only 1 A_f & $\Delta\Gamma=0$
$$\Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} (1 - \text{Im} \lambda_f \sin(\Delta M t))$$
- Then $a[f(t)] = -\text{Im} \lambda_f$, & λ_f is a function of V_{ij} in SM
- For B^0 , $\Delta\Gamma \approx 0$, but there can be multiple A_f
$$\Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left(\frac{1 - |\lambda_f|^2}{2} \cos(\Delta M t) - \text{Im} \lambda_f \sin(\Delta M t) \right)$$
- If in addition $\Delta\Gamma \neq 0$, eg. B_s
$$\Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left(\frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta\Gamma t}{2} + \frac{1 - |\lambda_f|^2}{2} \cos(\Delta M t) - \text{Re} \lambda_f \sinh \frac{\Delta\Gamma t}{2} - \text{Im} \lambda_f \sin(\Delta M t) \right)$$

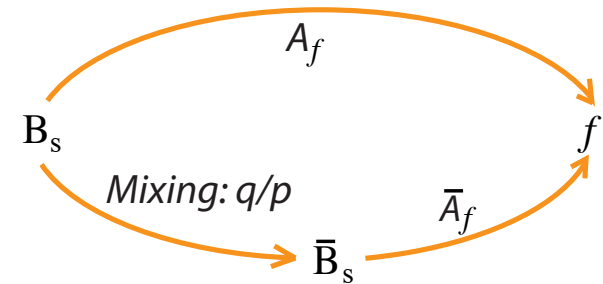
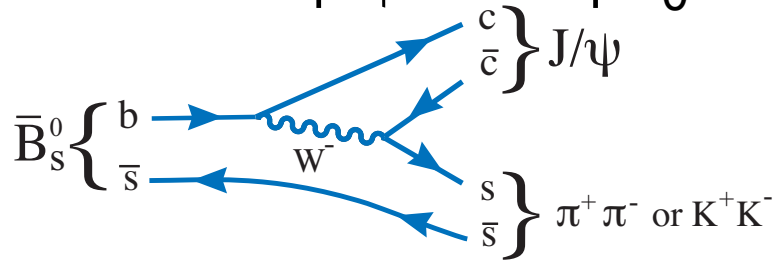
See Nierste
arXiv:0904.1869 [hep-ph]



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

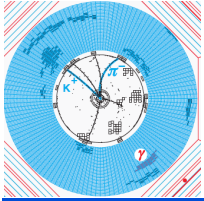
- Interference between mixing & decay

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



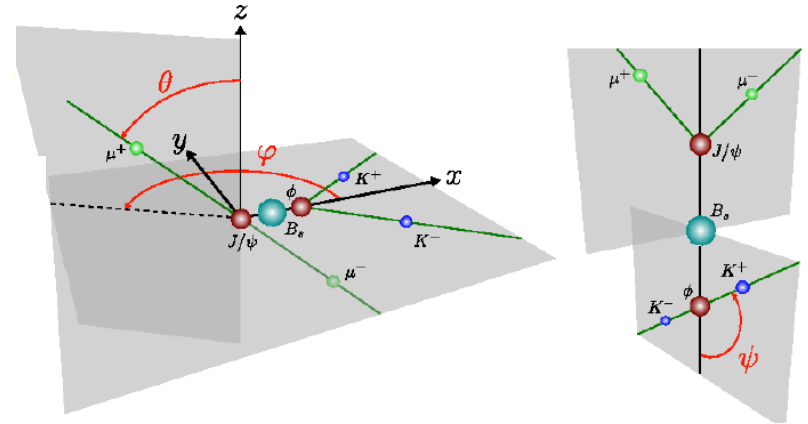
$$\varphi_s^{SM} \equiv -2\beta_s = -2 \arg \left(-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) = -0.04 \text{ rad}$$

- Small CPV expected, good place for NP to appear
- $B_s \rightarrow J/\psi \phi$ 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



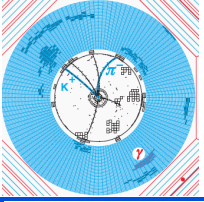
Transversity

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



k	$h_k(t)$	$f_k(\theta, \psi, \varphi)$
1	$ A_0 ^2(t)$	$2 \cos^2 \psi (1 - \sin^2 \theta \cos^2 \phi)$
2	$ A_{\parallel}(t) ^2$	$\sin^2 \psi (1 - \sin^2 \theta \sin^2 \phi)$
3	$ A_{\perp}(t) ^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	$ A_s(t) ^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

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

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

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

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

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

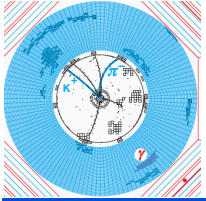
$$\begin{aligned} \Im(A_0^*(t) A_{\perp}(t)) &= |A_0| |A_{\perp}| e^{-\Gamma_s t} \left[-\cos(\delta_{\perp} - \delta_0) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \right. \\ &\quad \left. - \cos(\delta_{\perp} - \delta_0) \cos\phi_s \sin(\Delta mt) + \sin(\delta_{\perp} - \delta_0) \cos(\Delta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

$$|A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t} \left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta mt) \right], \quad \text{only term for } f=f_{cp}$$

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

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

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



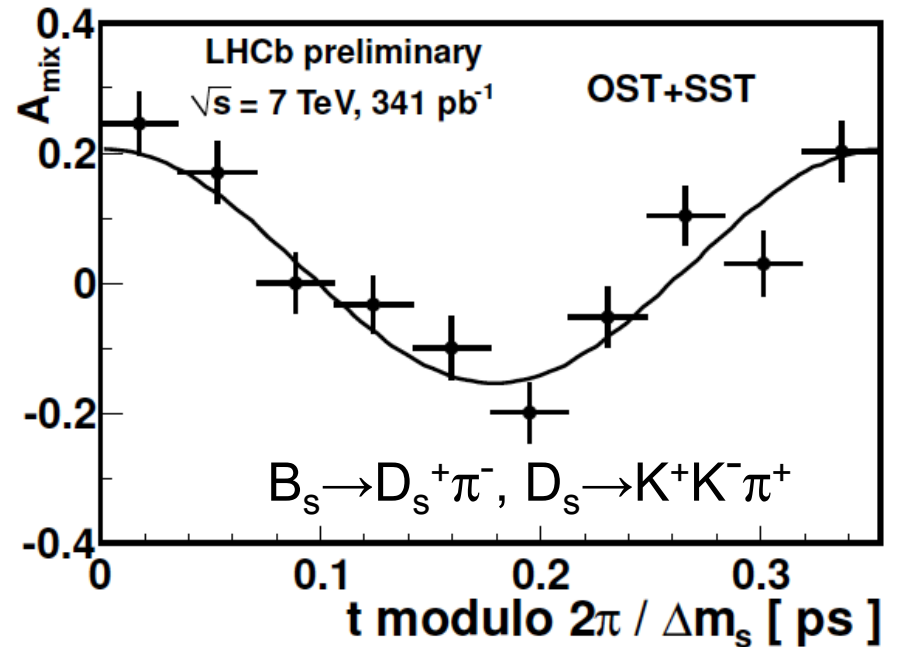
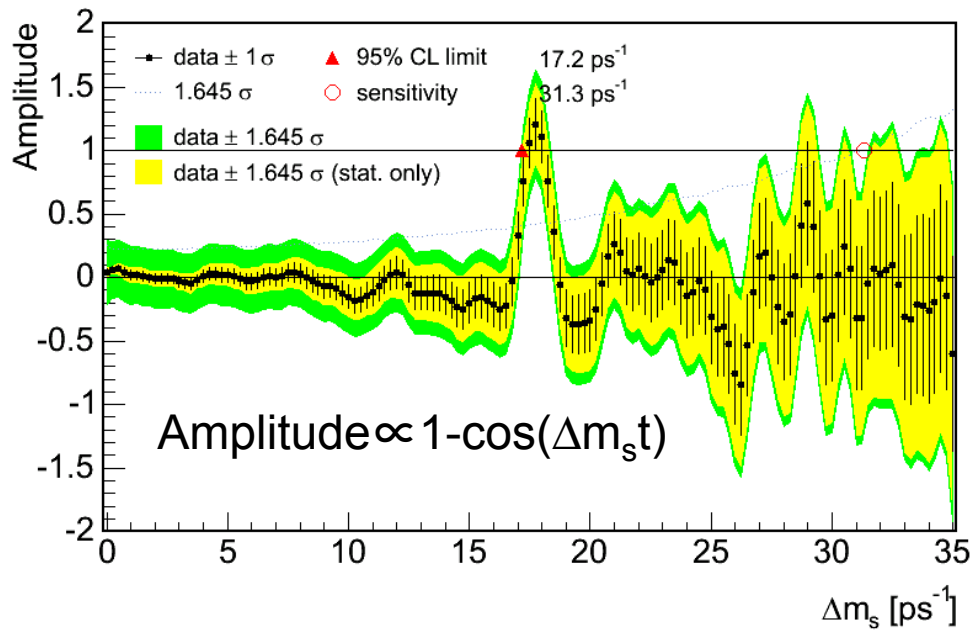
ΔM_s

CDF 1 fb⁻¹ (2006)

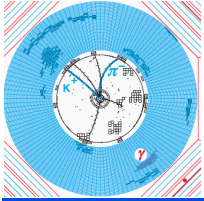
$17.77 \pm 0.10 \pm 0.07$ ps⁻¹

LHCb 0.34 fb⁻¹ (2011)

$17.725 \pm 0.041 \pm 0.026$ ps⁻¹

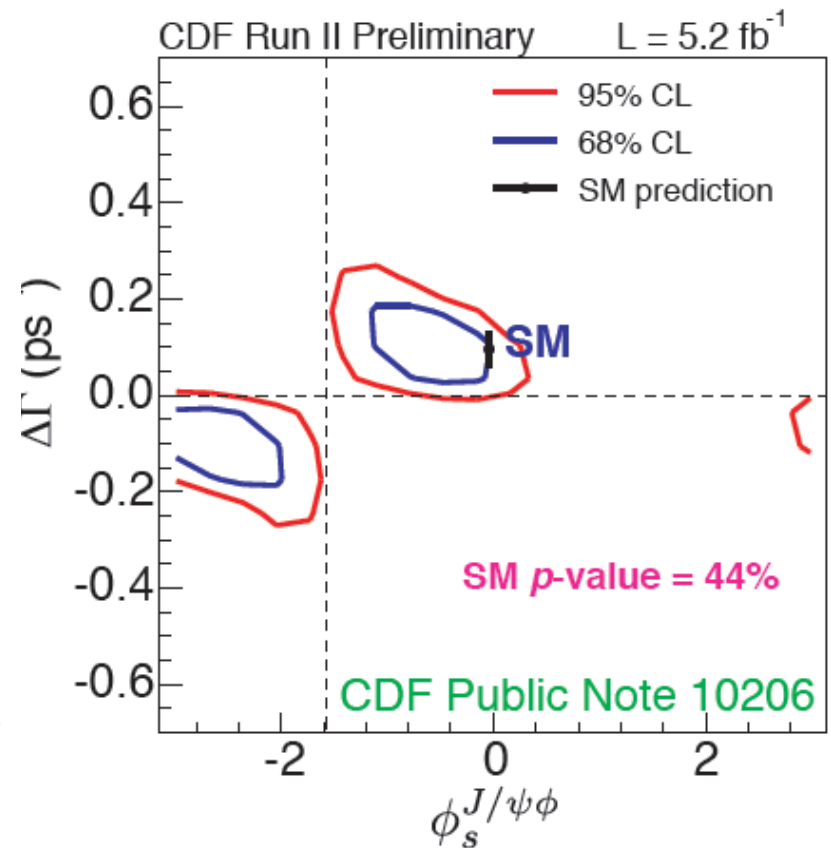
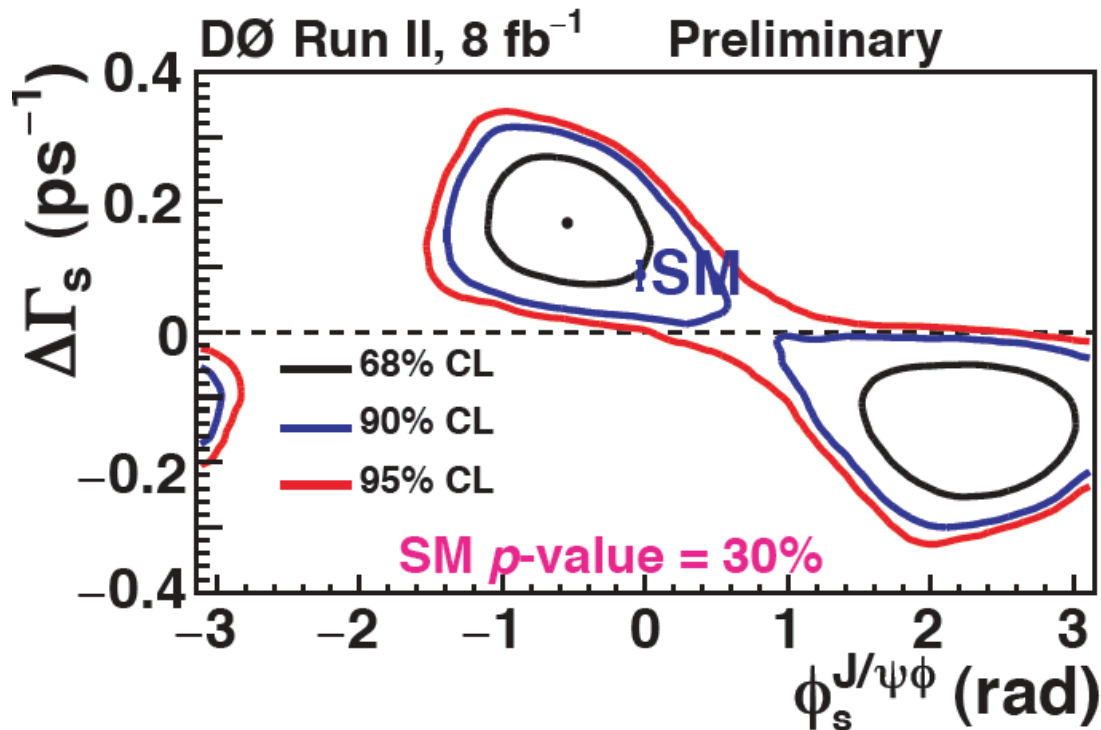


- Used to calibrate the flavor tagging

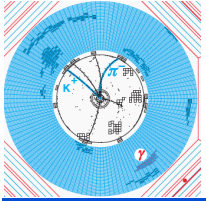


CPV in $B_s \rightarrow J/\psi\phi$

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

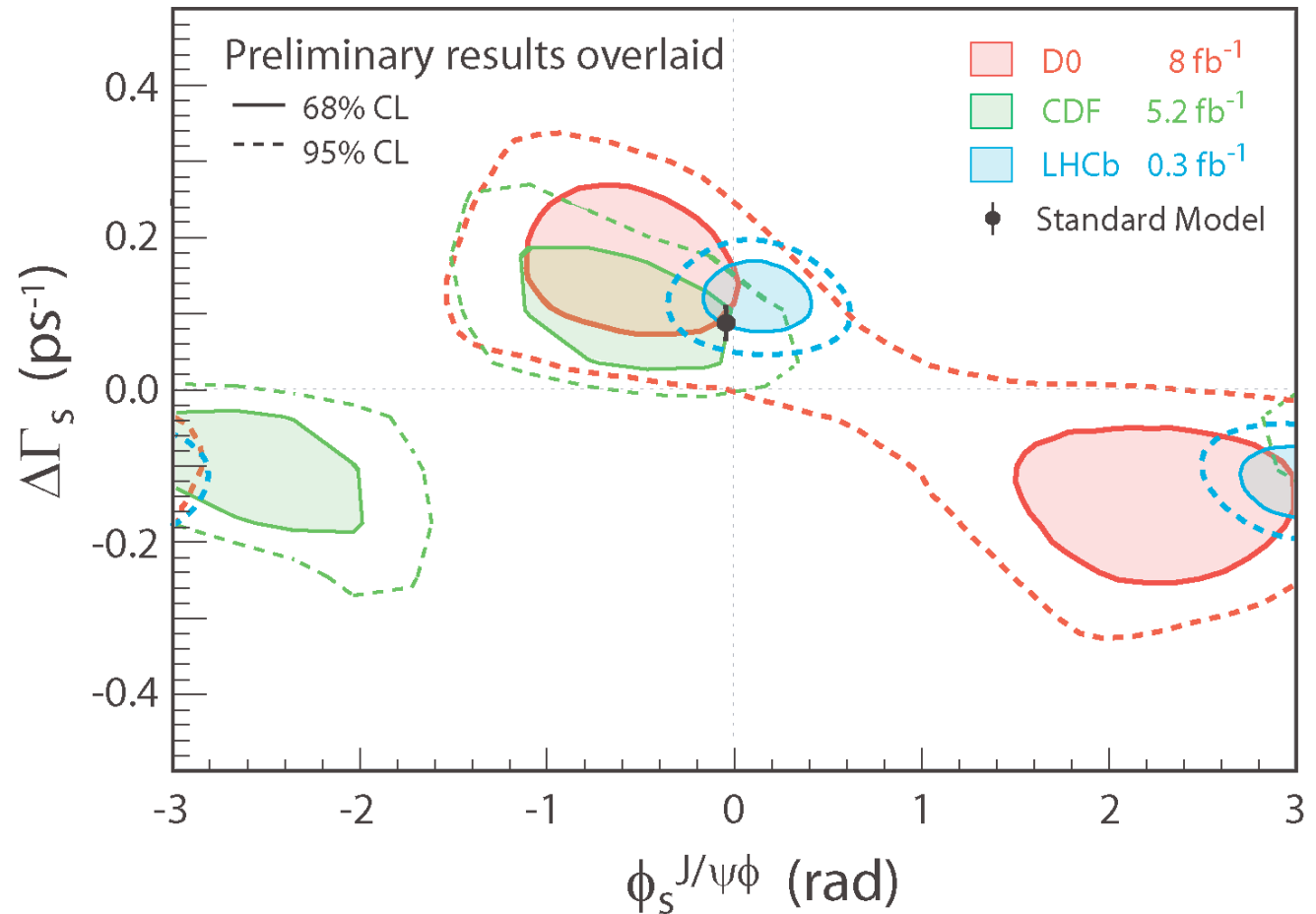


BF11, Oct. 20, 2011

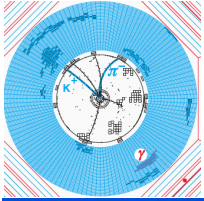


New LHCb ϕ_s result

$$\begin{aligned}\Gamma &= 0.656 \pm 0.009 \\ &\pm 0.008 \text{ (ps}^{-1}\text{)} \\ \Delta\Gamma &= 0.123 \\ &\pm 0.029 \\ &\pm 0.011 \text{ (ps}^{-1}\text{)} \\ \phi_s &= 0.13 \pm 0.18 \\ &\pm 0.07 \text{ (rad)}\end{aligned}$$

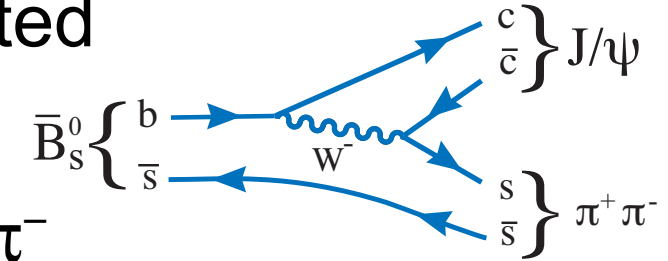


- All measurements consistent with SM value



1st Observation of $B_s \rightarrow J/\psi f_0(980)$

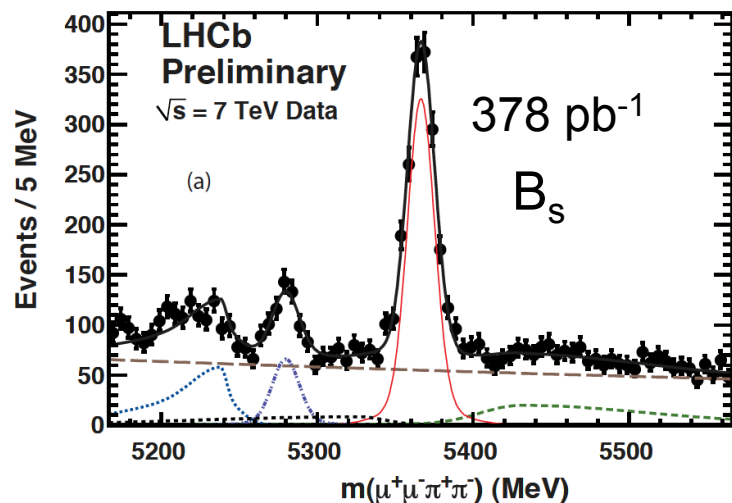
- In $B_s \rightarrow J/\psi \phi$ the S-wave predicted (& now observed) under the ϕ could manifest itself as a $0^+ \pi^+ \pi^-$



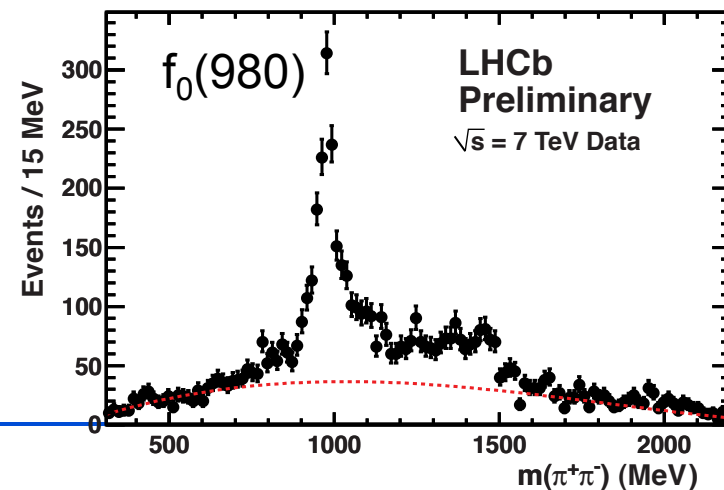
system, the $f_0(980)$ [Stone & Zhang PRD 79, 074024 (2009)]. As a CP eigenstate can be used to measure ϕ_s without angular analysis

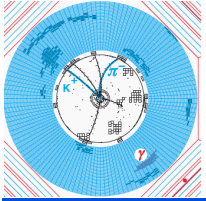
$$\frac{\Gamma(J/\psi f_0; f_0 \rightarrow \pi^+ \pi^-)}{\Gamma(J/\psi \phi; \phi \rightarrow K^+ K^-)} \approx 0.25$$

$m(J/\psi \pi^+ \pi^-)$ within 90 MeV of 980 MeV



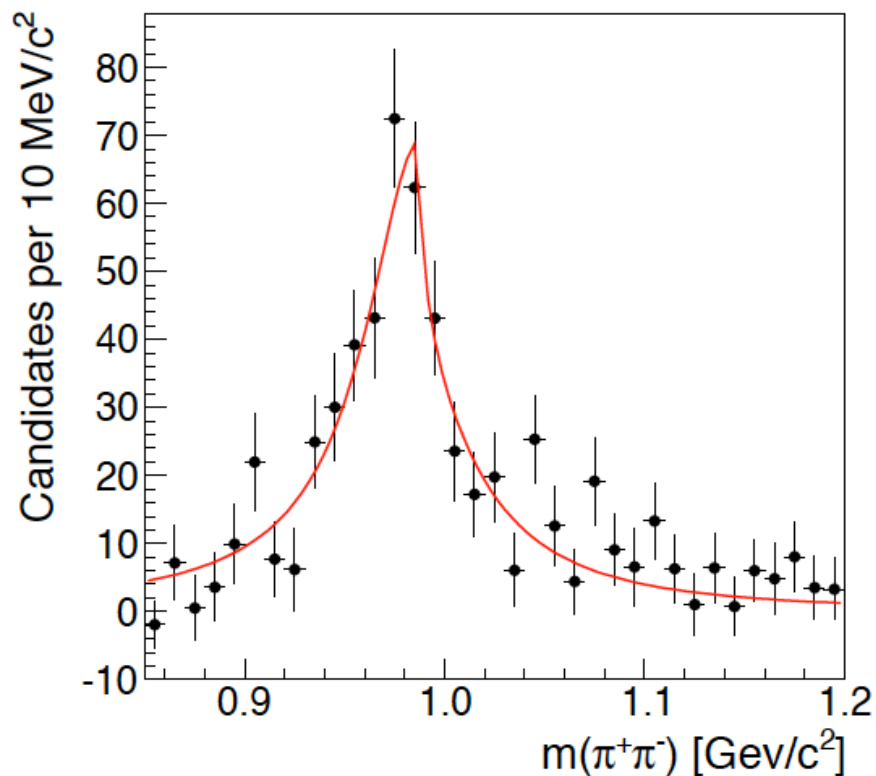
$m(\pi^+ \pi^-)$ within 30 MeV of B_s mass



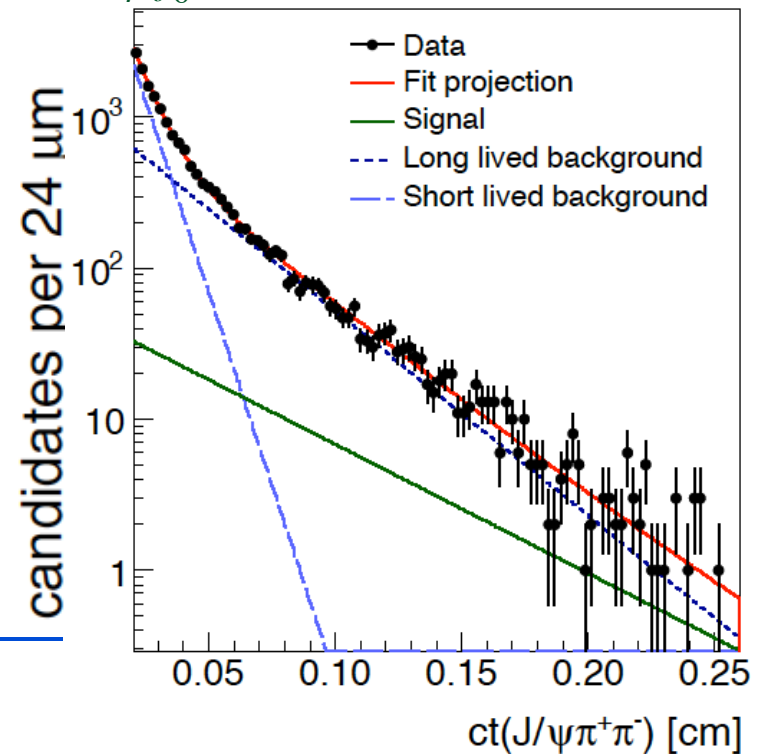


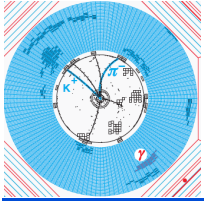
Confirmations

- Belle, CDF & D0
- CDF measures τ also, ignoring CP violation, in this CP odd eigenstate. $\langle\tau_{B_S}\rangle = 1.43 \pm 0.04$ ps (PDG)



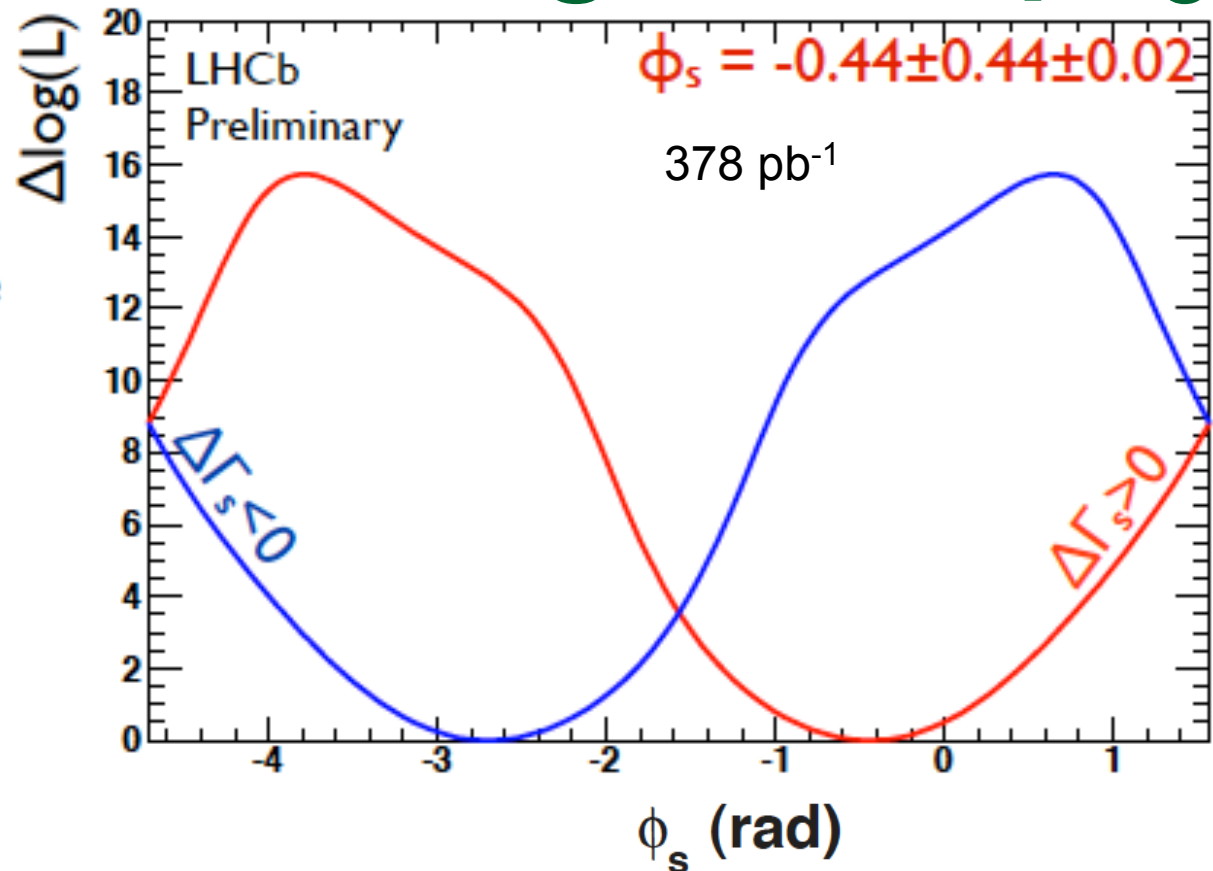
$$\tau_{J/\psi f_0} = 1.70^{+0.12}_{-0.11} \pm 0.03 \text{ ps}$$



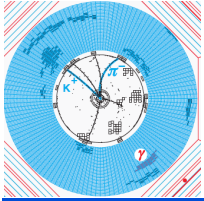


CPV in $B_s \rightarrow J/\psi f_0$

Log-likelihood profile

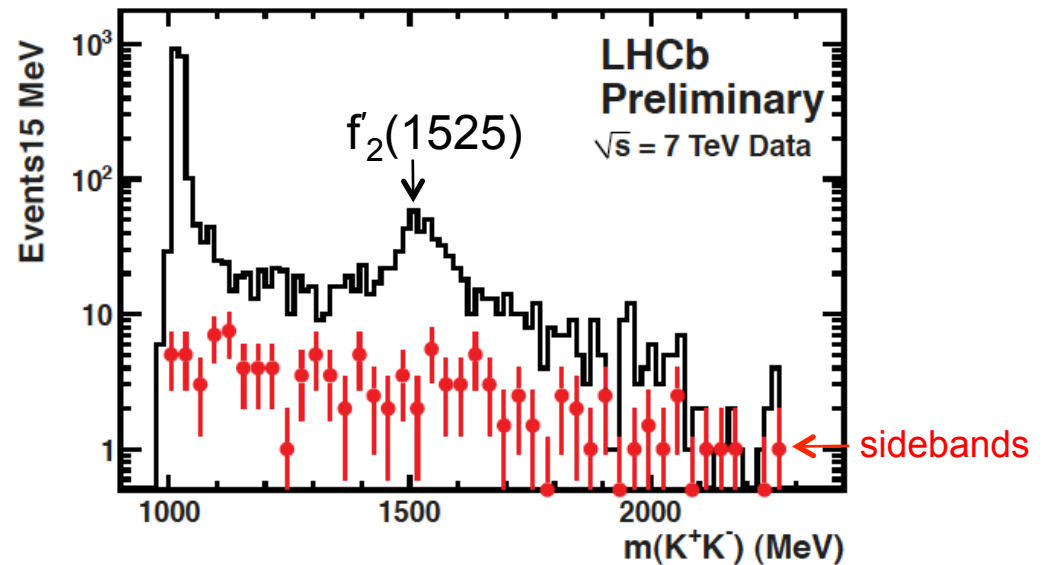
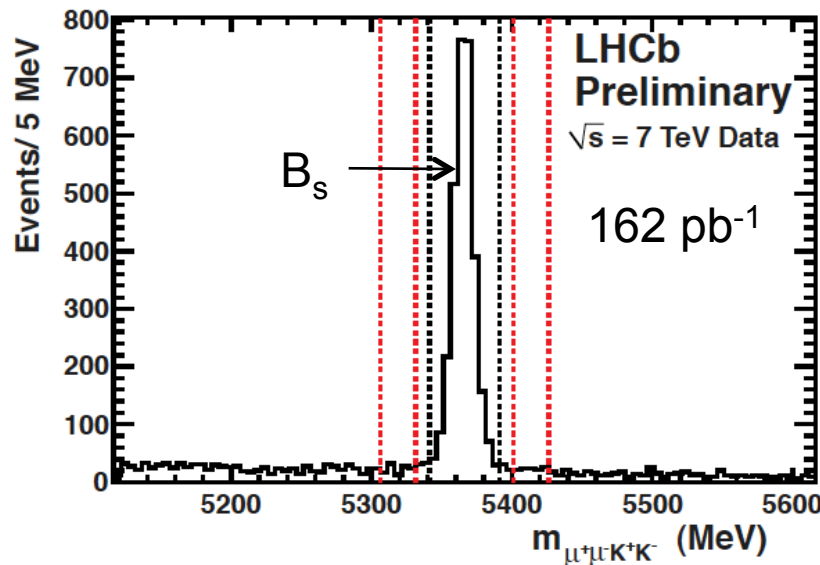


- $\phi_s = -0.44 \pm 0.44 \pm 0.02$ rad
- Combined with $J/\psi \phi$, $\phi_s = 0.03 \pm 0.16 \pm 0.07$ rad



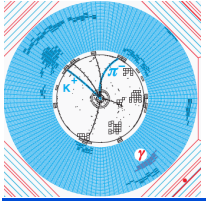
1st Observation of $B_s \rightarrow J/\psi f_2(1525)$

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



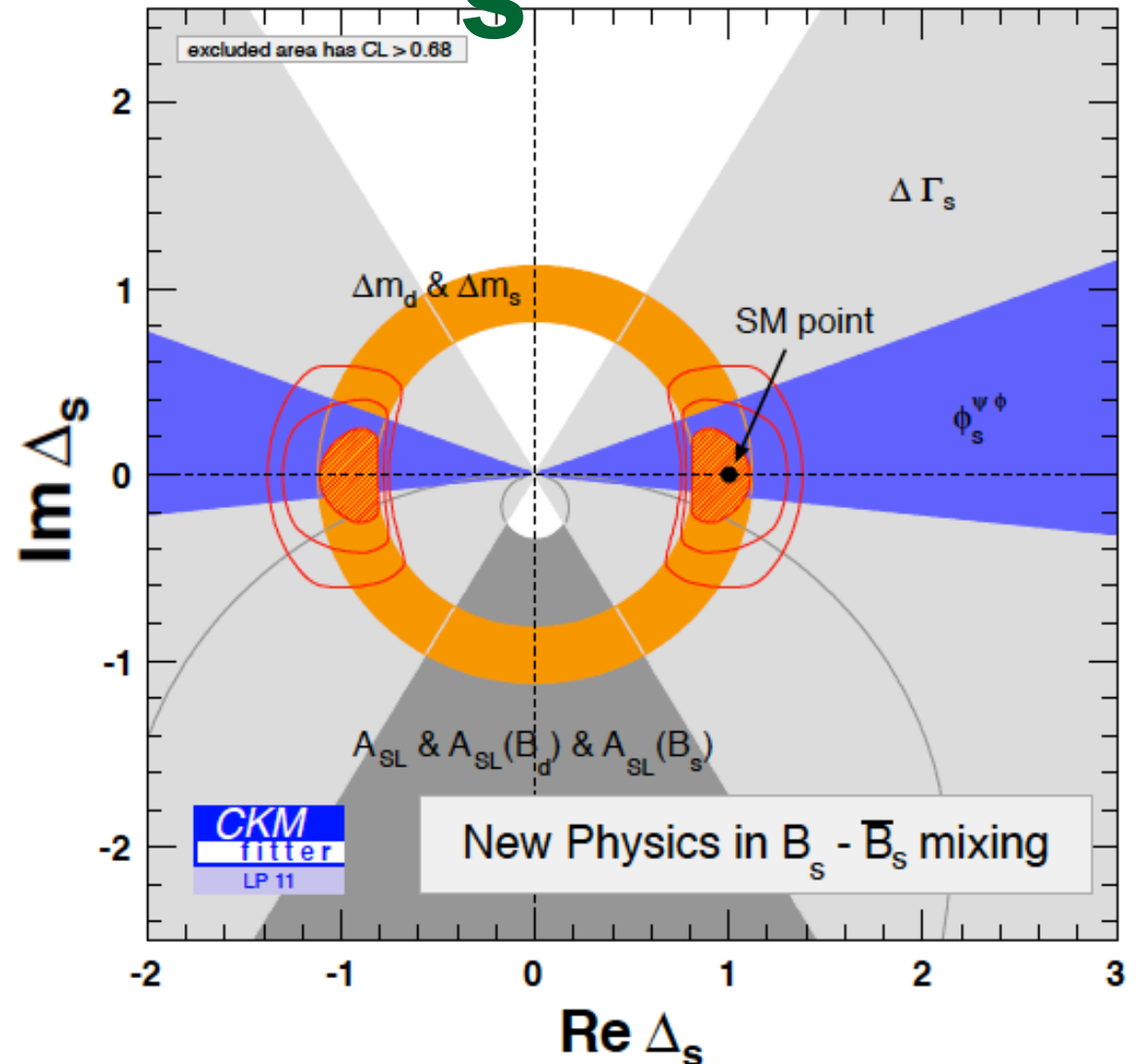
$$R_{\text{effective}}^{f_2'} \equiv \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi f_2'(1525), f_2'(1525) \rightarrow K^+ K^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi, \phi \rightarrow K^+ K^-)} = (19.4 \pm 1.8 \pm 1.1)\%$$

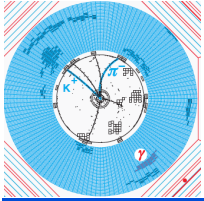
for $|m(K^+ K^-) - 1525 \text{ MeV}| < 125 \text{ MeV}$.



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





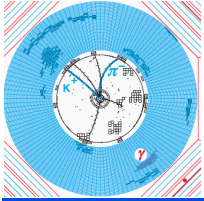
a_{sl}

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

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

- 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^0 -7.6×10^{-4} for B_s $+3.4 \times 10^{-5}$

arXiv:1008.1593 [hep-ph]

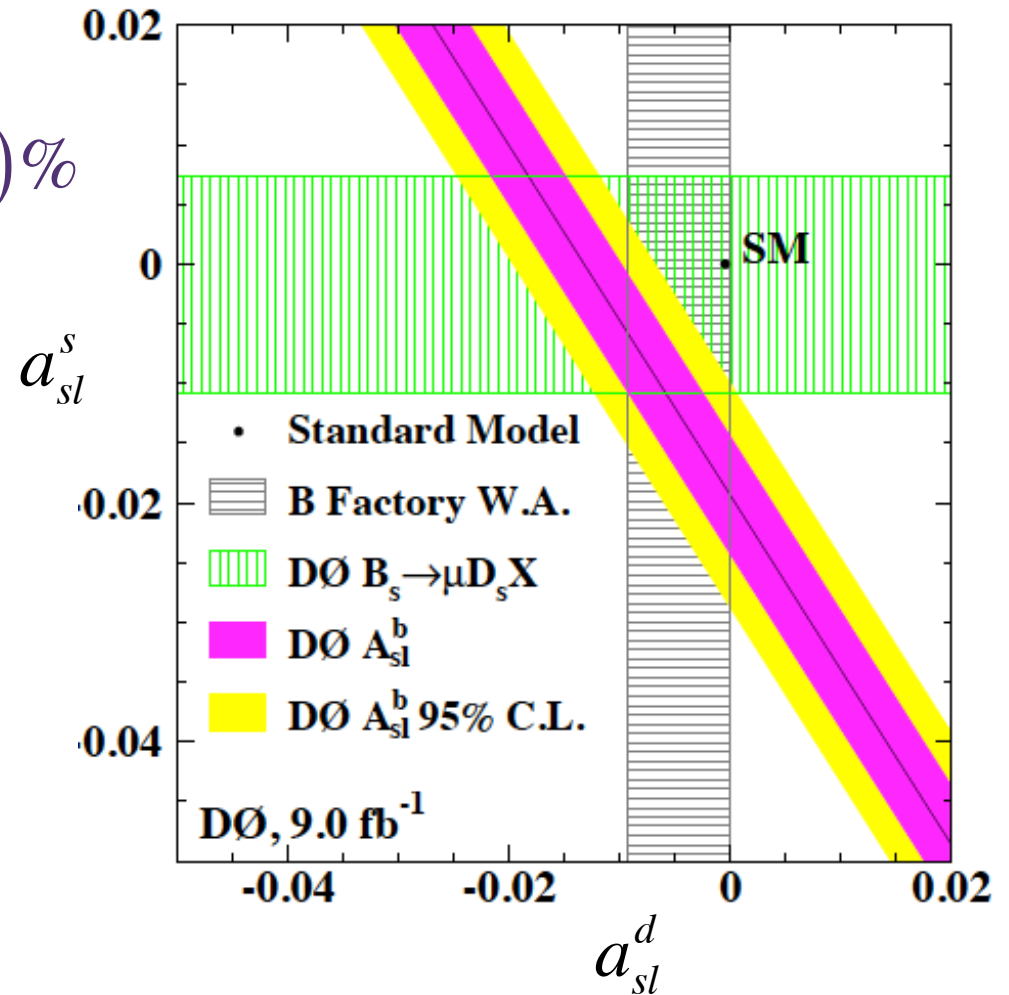


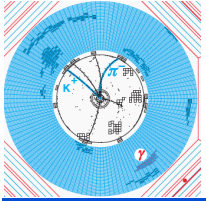
D⁰ result on a_{sl}

■ Using dimuons

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

3.9 σ from zero



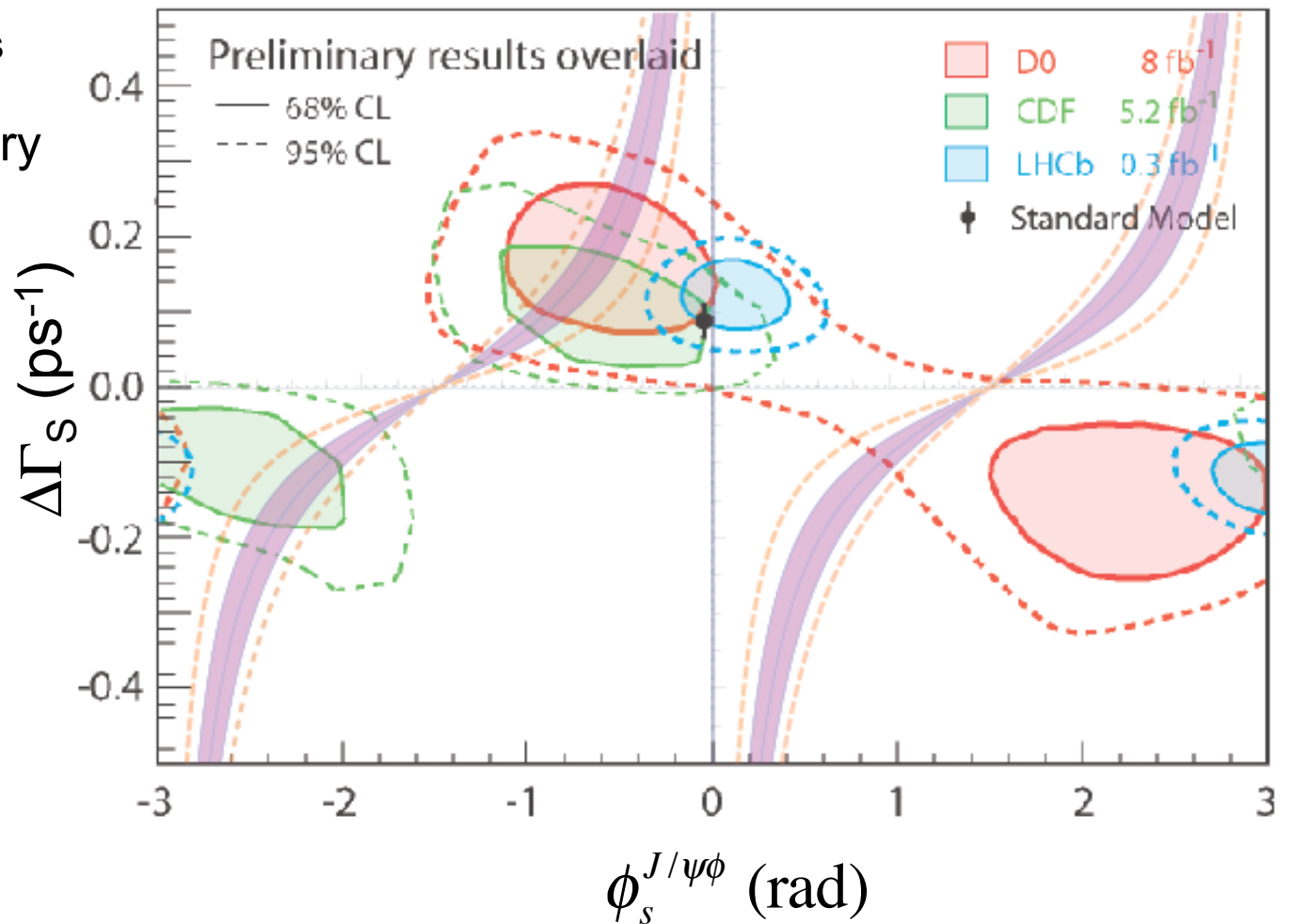


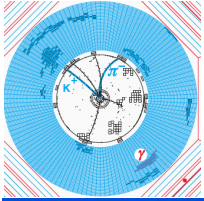
a_{sl} vs ϕ_s

$$a_{sl}^s = (\Delta\Gamma/\Delta M) \tan \phi_s$$

Assume all asymmetry
is due to B_s

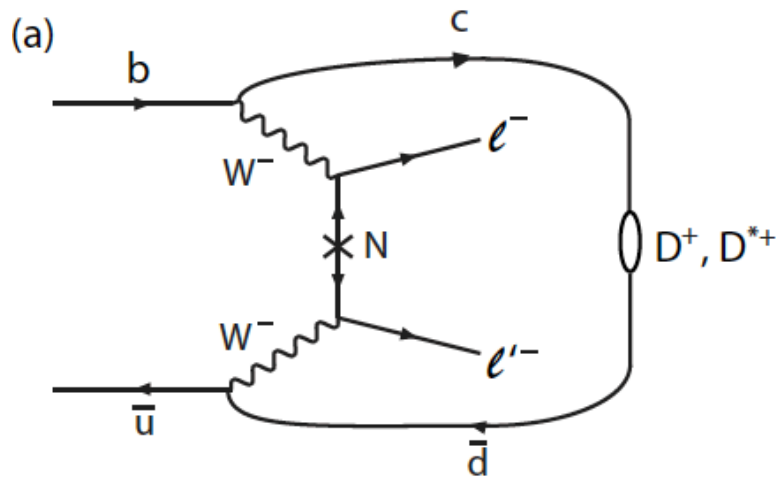
$$a_{sl}^s = (-0.787 \pm 0.196)\%$$



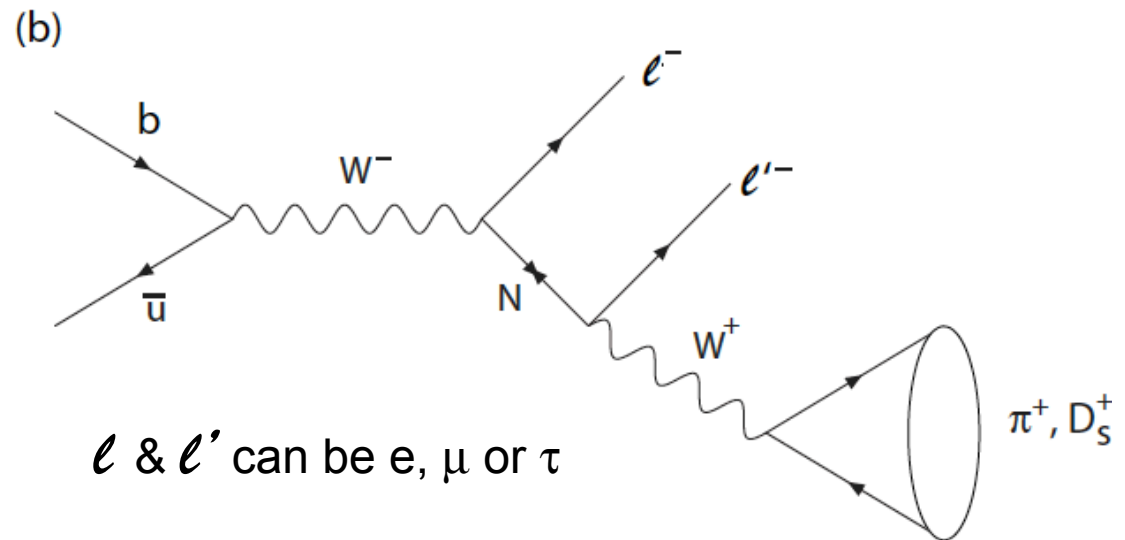


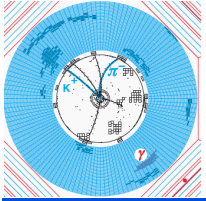
Majorana ν 's

- Several ways of looking for presence of heavy ν 's (N) in heavy quark decays if they are Majorana (their own anti-particles) and couple to "ordinary" ν 's



Analogous to ν -less nuclear β decay





Current Searches

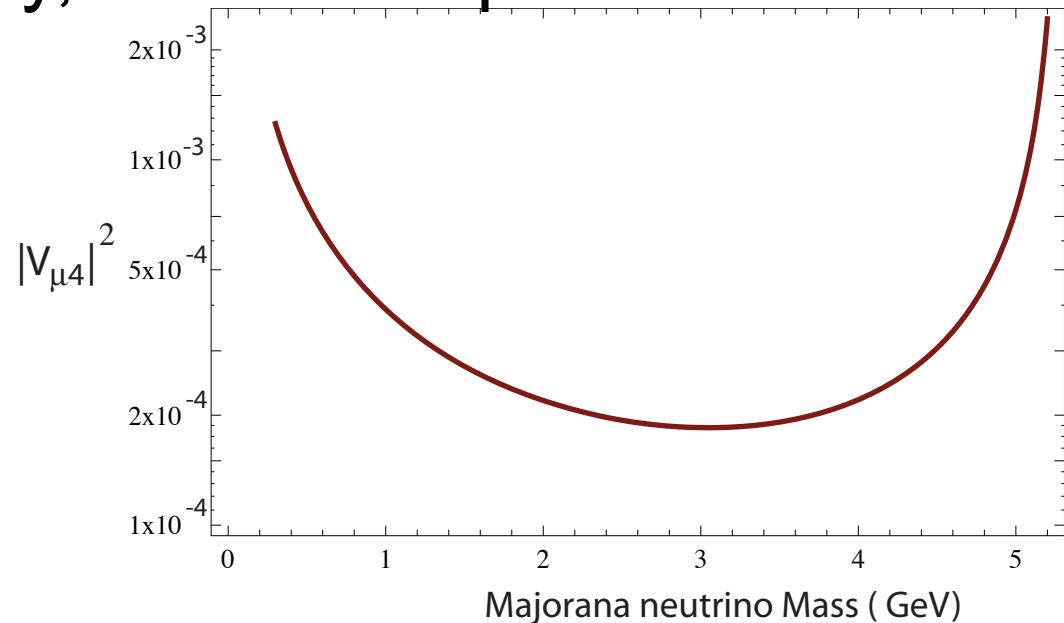
- Belle $B^- \rightarrow D^- \ell \ell'$
- Found upper limits, ee mode not competitive with nuclear β decay, others unique

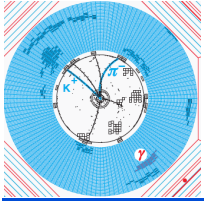
LHCb $B^- \rightarrow \pi^+ \mu^- \mu^-$,
u.l $< 4.5 \times 10^{-8}$

See A. Atre, T. Han,
S. Pascoli, & B. Zhang
[arXiv:0901.3589]

Mode	U.L. [10^{-6}]
$B^+ \rightarrow D^- e^+ e^+$	< 2.6
$B^+ \rightarrow D^- e^+ \mu^+$	< 1.8
$B^+ \rightarrow D^- \mu^+ \mu^+$	< 1.0

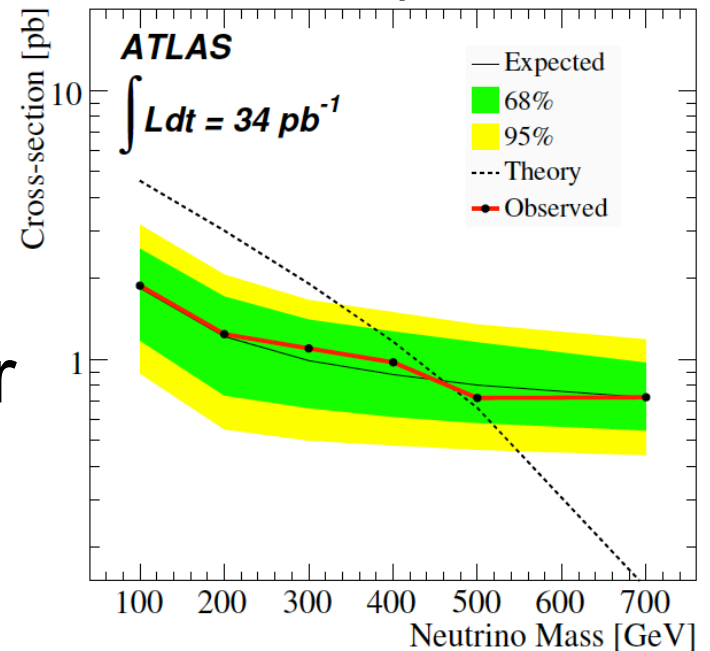
[arXiv:1107.064]

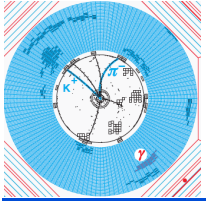




Searches at higher masses

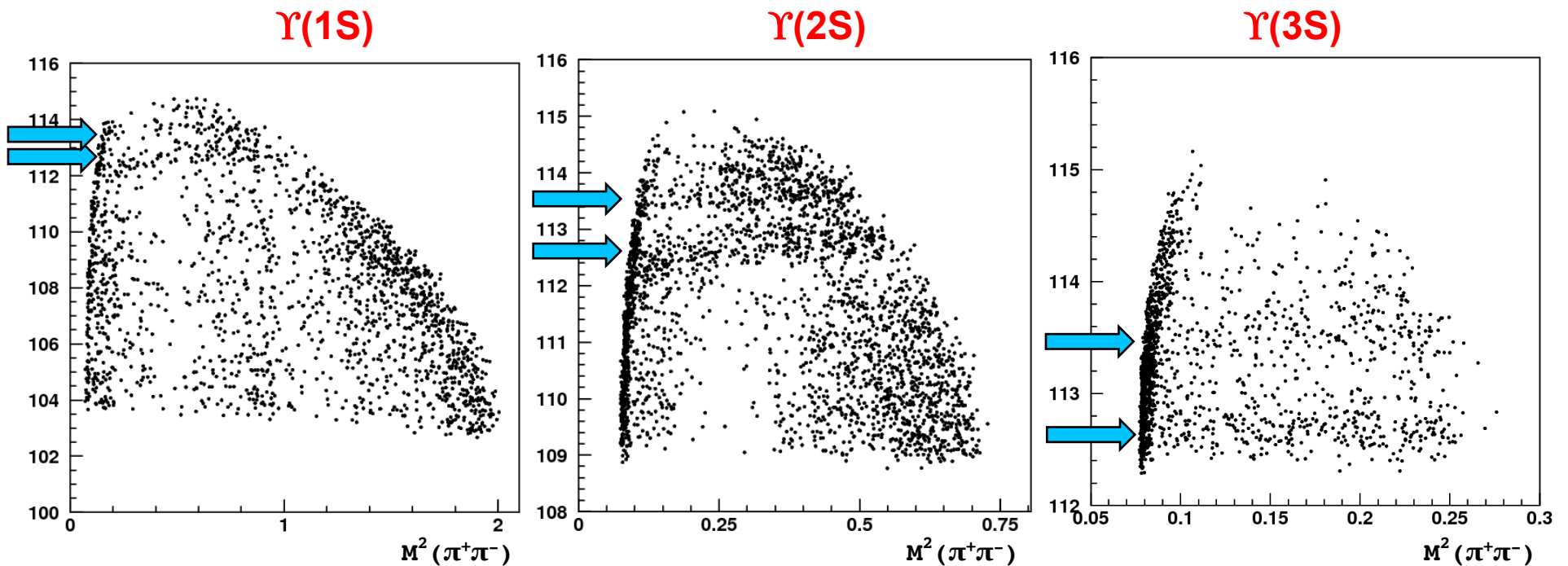
- CDF general search for like-sign dileptons [A. Abulencia et. al, Phys. Rev. Lett. 98, 221803 (2007)]
- CMS search for events with two isolated like-sign leptons, hadronic jets & missing E_T [arXiv:1104.3168]
- ATLAS [arXiv:1108.0366]
- If seen could also be interpreted in terms of other NP, ie. supersymmetry....

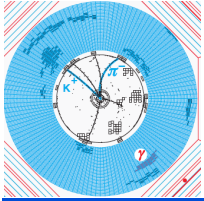




New Exotic States

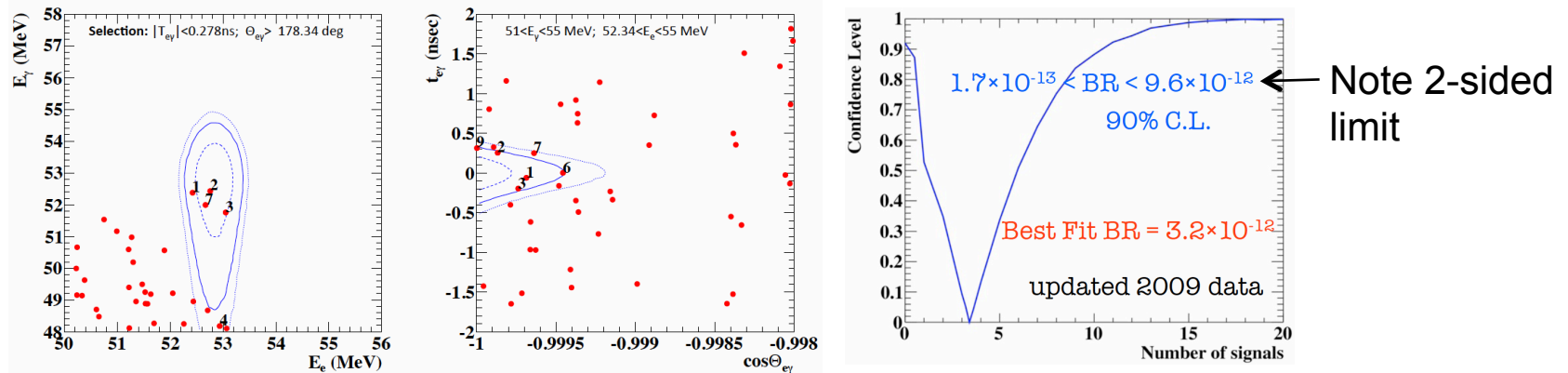
- Belle discovery of $Z_b(10610)$ and $Z_b(10650)$
- $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ Dalitz plots. See $\Upsilon(nS)\pi^\pm$ states
- Also seen in $h_b(1P)\pi^\pm$ & $h_b(2P)\pi^\pm$ decays [arXiv:1105.4583](https://arxiv.org/abs/1105.4583)



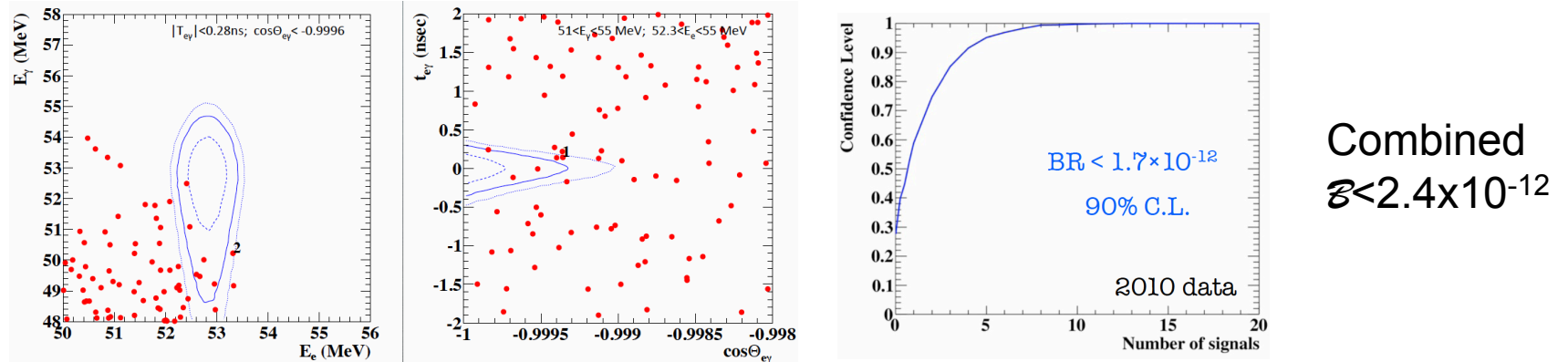


Lepton Flavor Violation

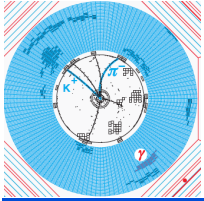
■ $\mu \rightarrow e\gamma$ MEG data 2009 results (Mori EPS2011)



■ Data 2010 Results

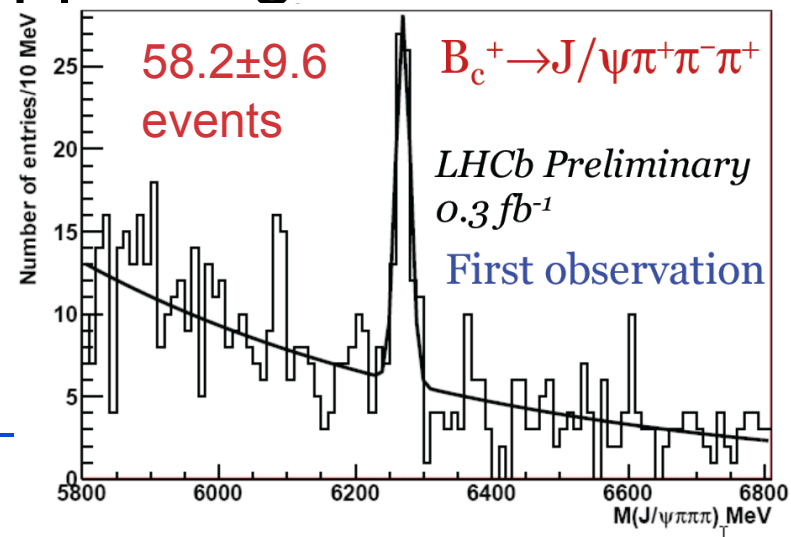
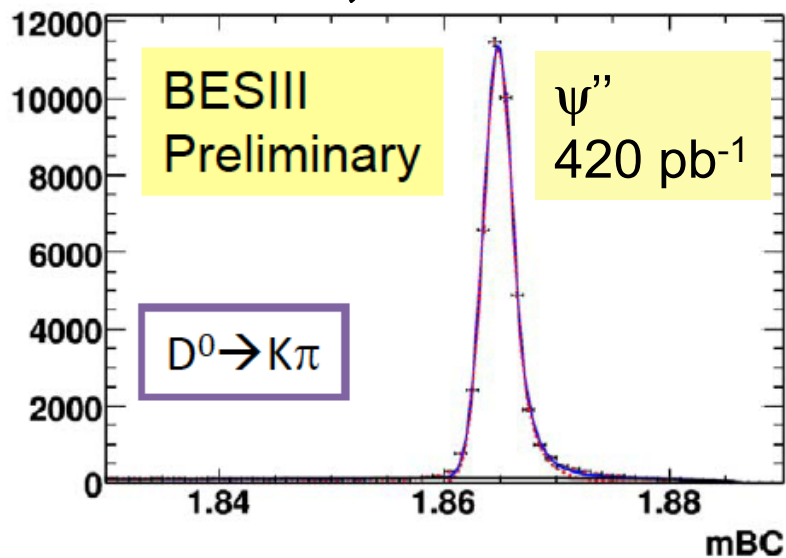


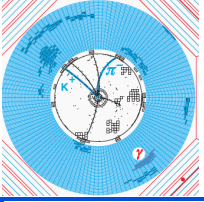
■ Many limits on $\tau \rightarrow \ell h h$, Λh , $\bar{\Lambda} h$, $\mu\gamma$, μh , 3μ , best limits near 10^{-8} (Belle, BaBar)



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

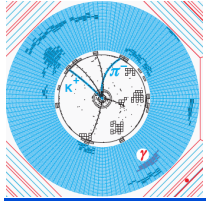




Conclusions

- 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



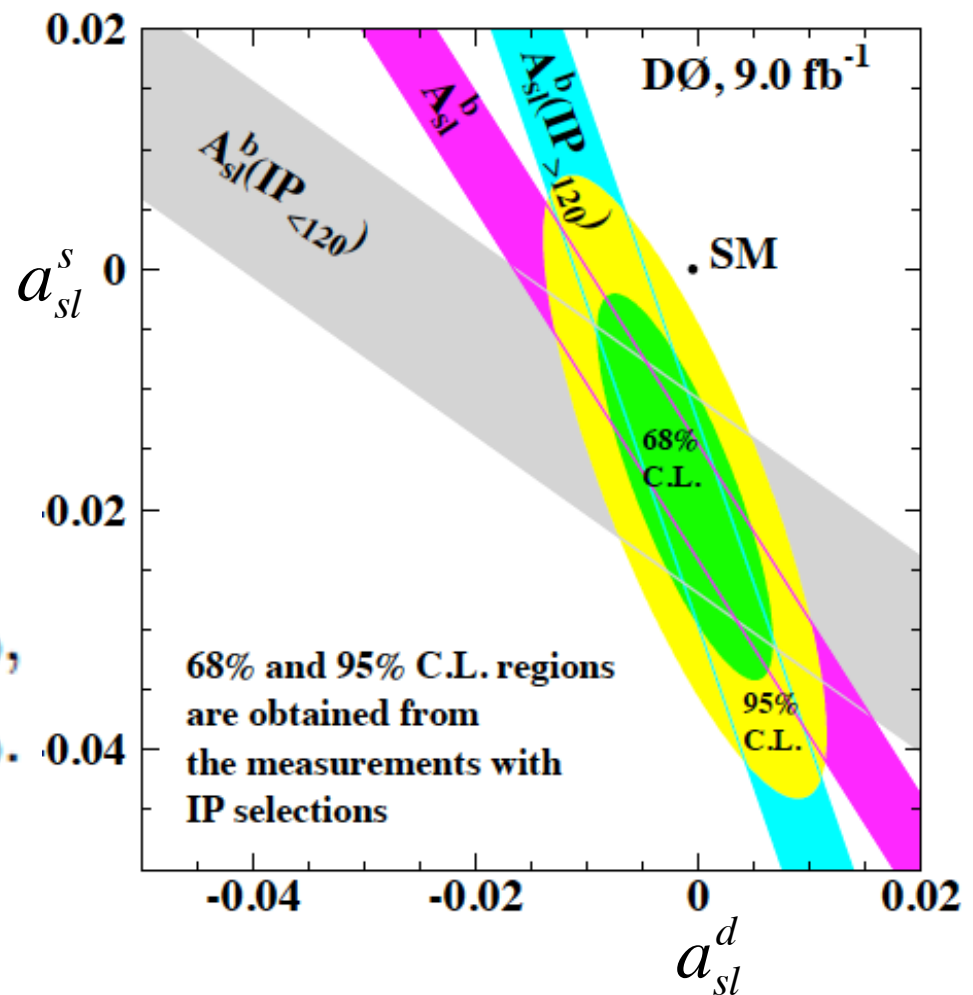
$D^0 a_{sl}$

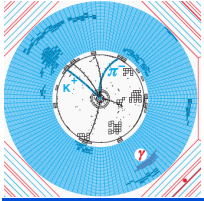
- Separate into B_d and B_s samples using impact parameter of muons

- Find

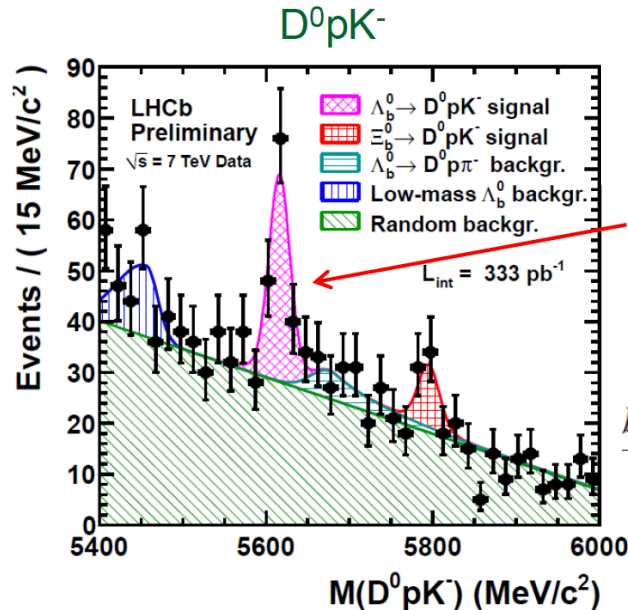
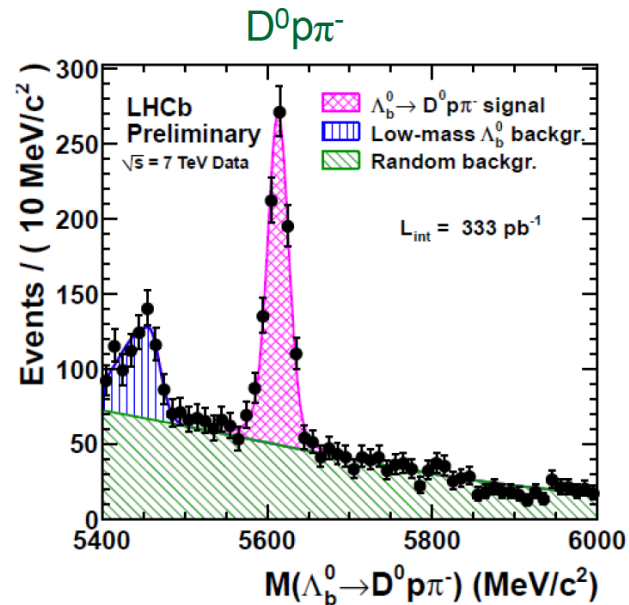
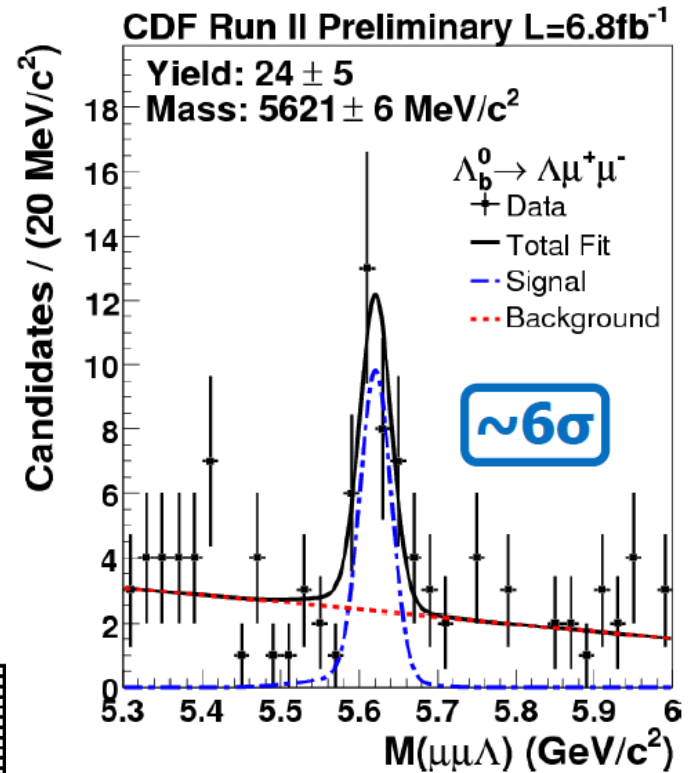
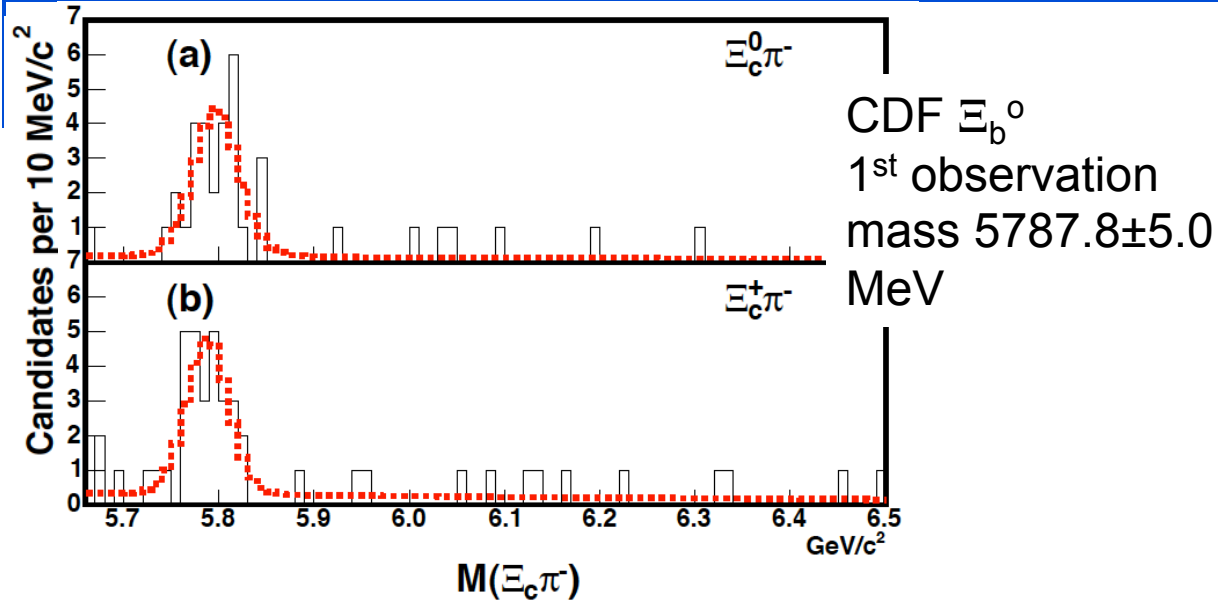
$$a_{sl}^d = (-0.12 \pm 0.52)\%$$

$$a_{sl}^s = (-1.81 \pm 1.06)\%$$



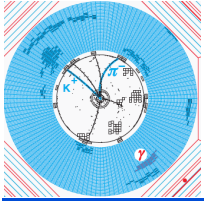


New b-Baryon Decays



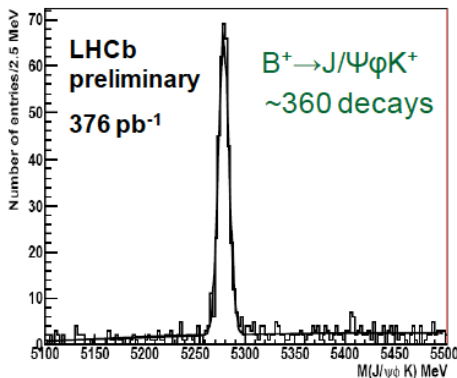
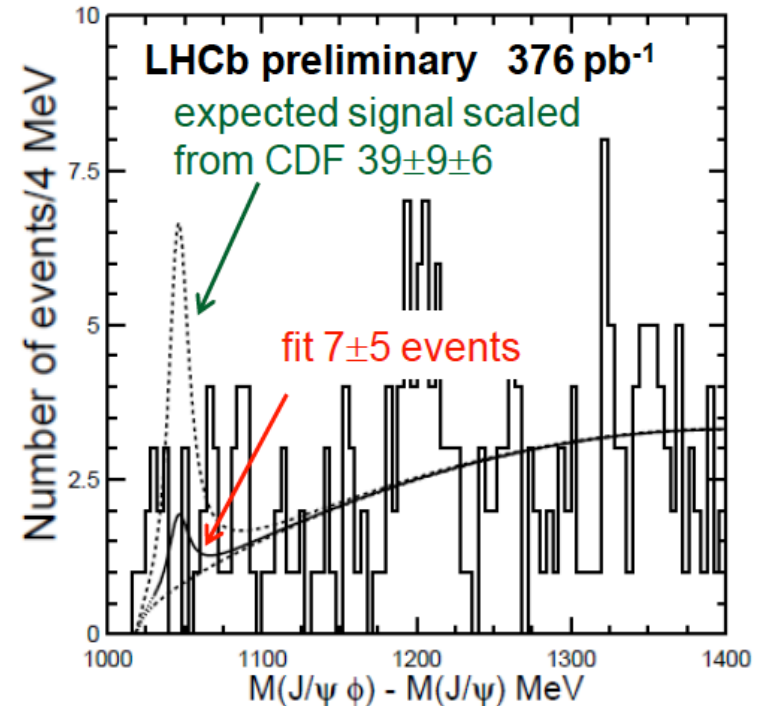
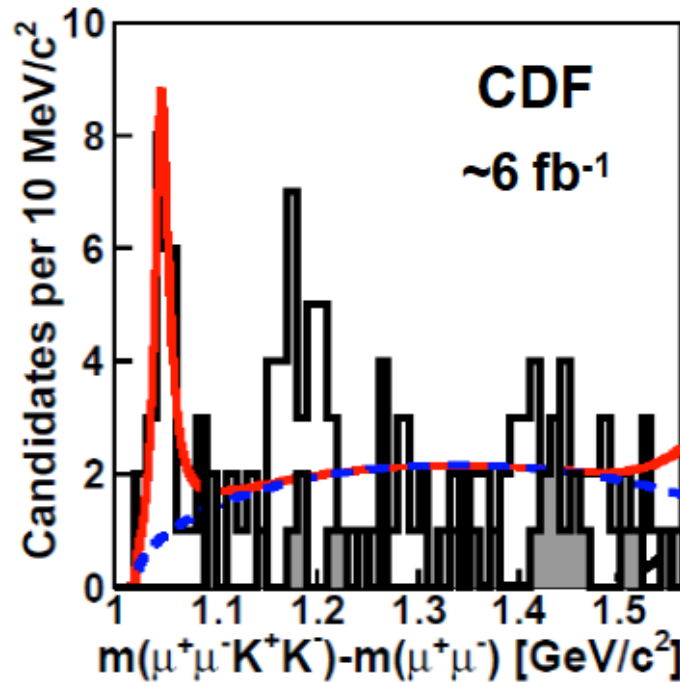
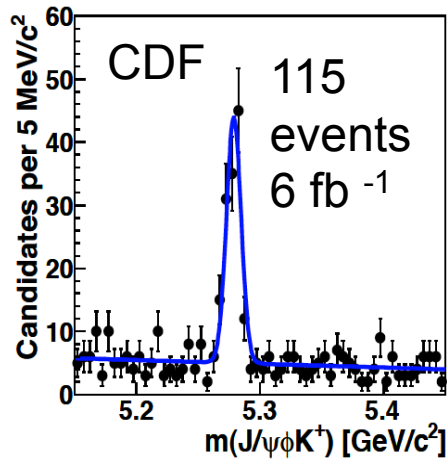
$\Lambda_b^0 \rightarrow D^0 p K^-$
 $\Lambda_b^0 \rightarrow D^0 p K^-$ observed for first time with significance of 6.3σ

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

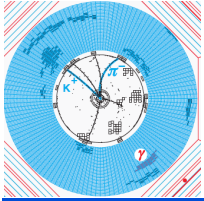


X(4140)?

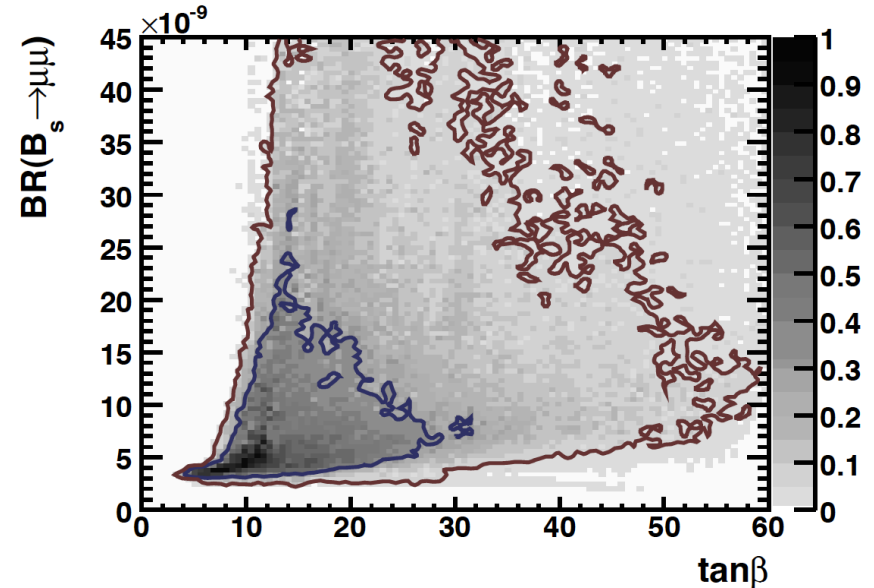
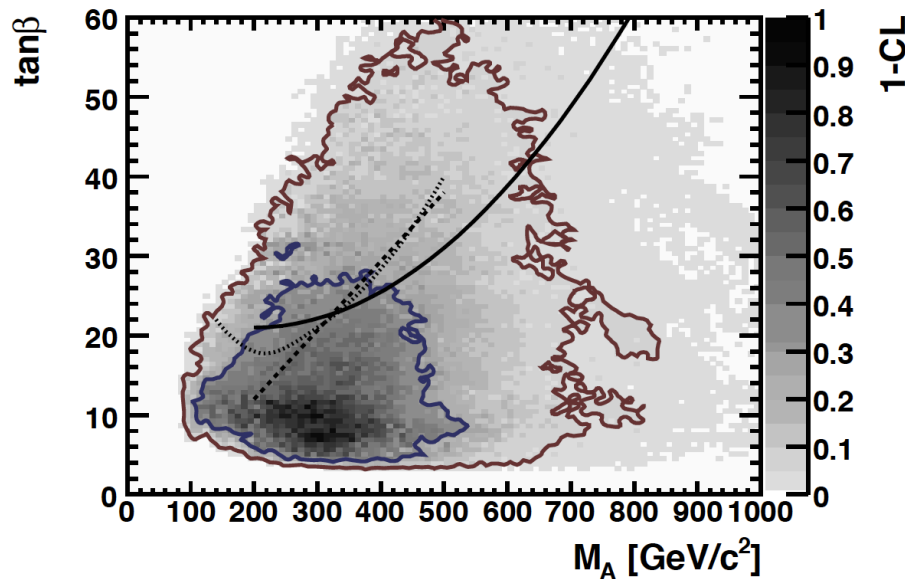
- In $B^- \rightarrow J/\psi \phi K^-$ decays, CDF reported a narrow structure in $m(J/\psi \phi)$ mass [arXiv:1101.6058]



No signal evident in LHCb data



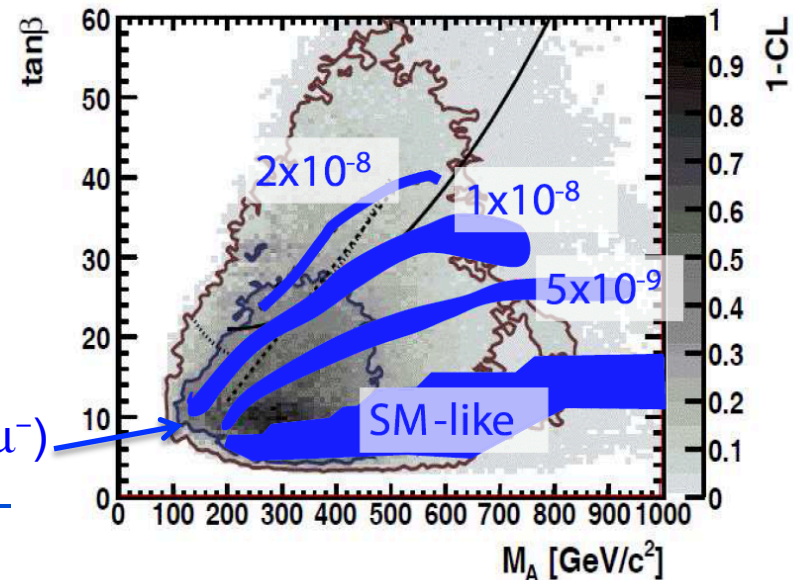
Exp: $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ in NUHM1

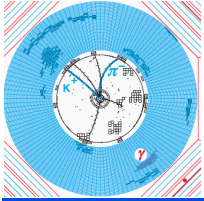


- CMS discovery contours for $H, A \rightarrow \tau^+ \tau^- \rightarrow$ jets (solid line), jet + μ (dashed), jet + e (dotted) using 30-60 fb^{-1}

- (From O. Buchmueller et al., arXiv:0907.5568)

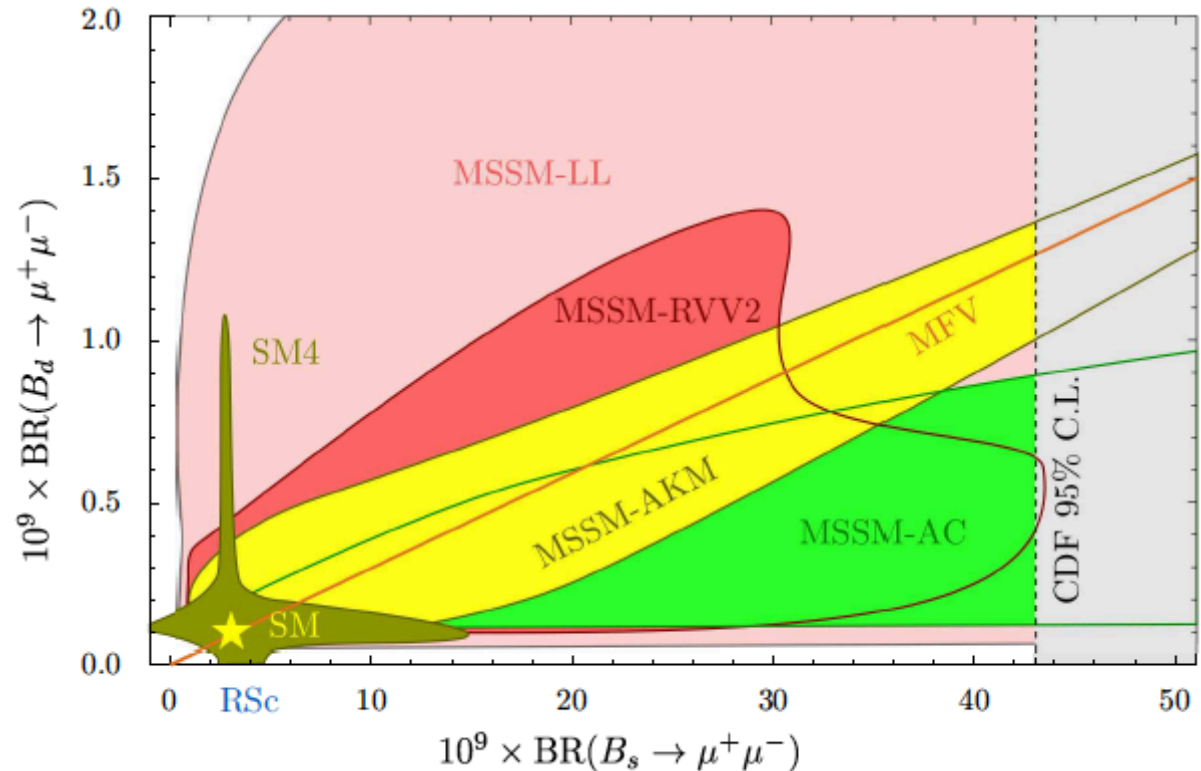
$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$



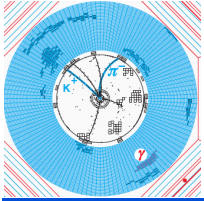


$B^0 \rightarrow \mu^+ \mu^-$

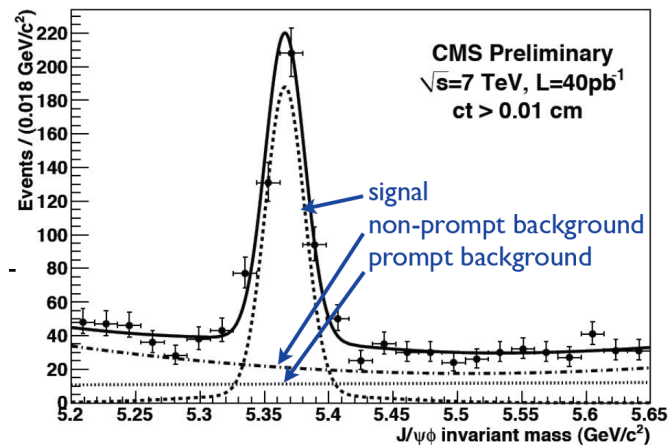
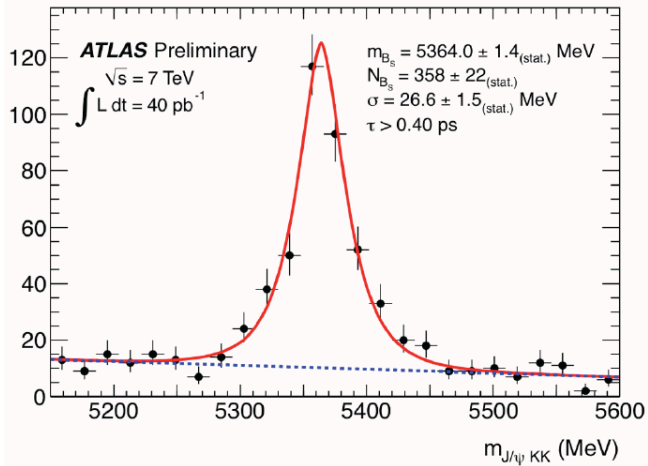
- In fact correlation between B_d & B_s $\mu^+ \mu^-$ could be crucial



- This can only be done with the LHCb Upgrade

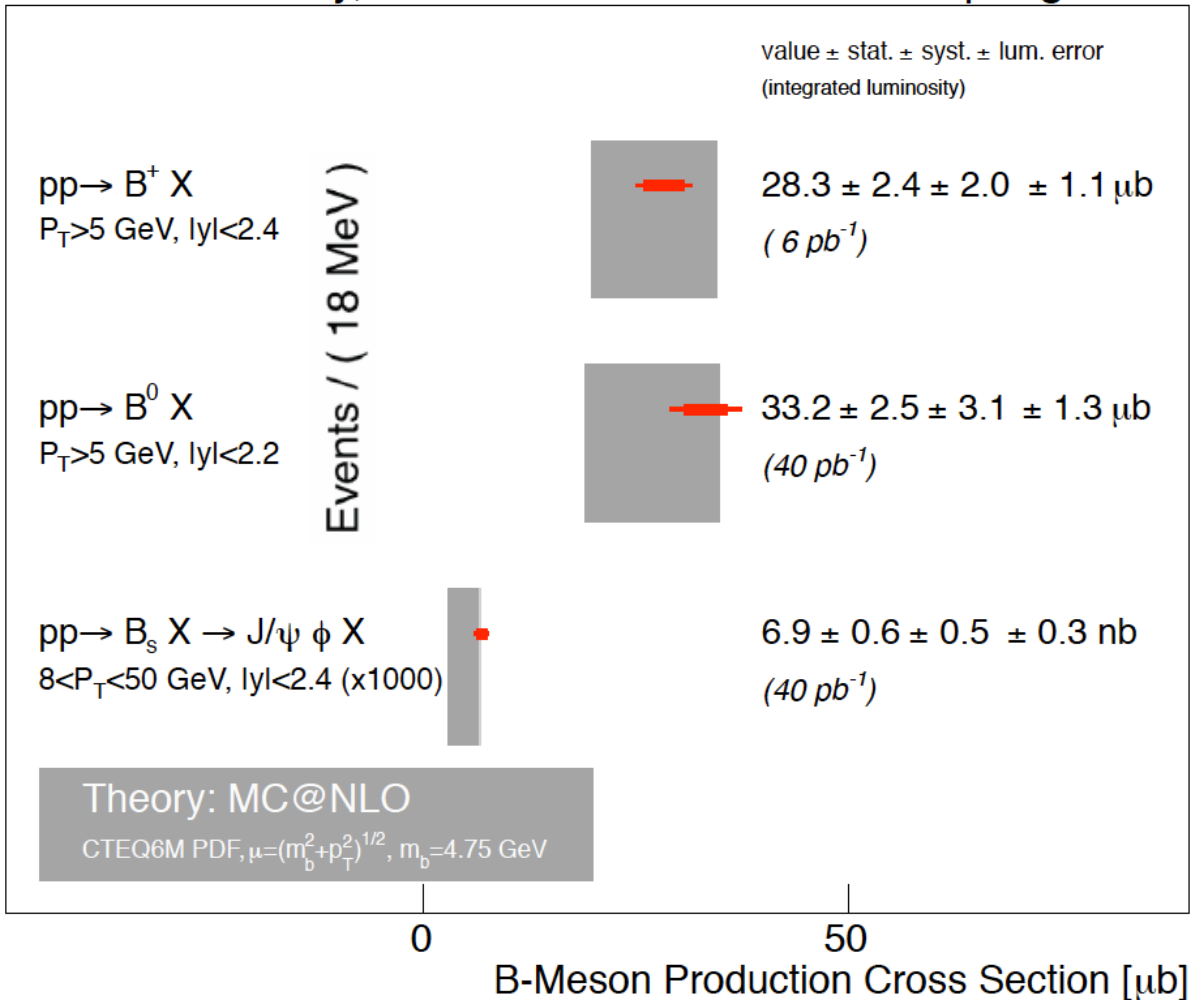


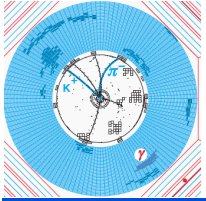
ATLAS B σ 's



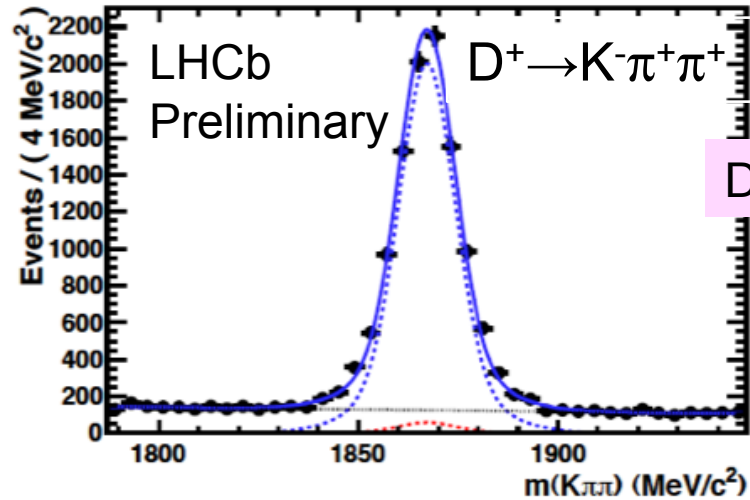
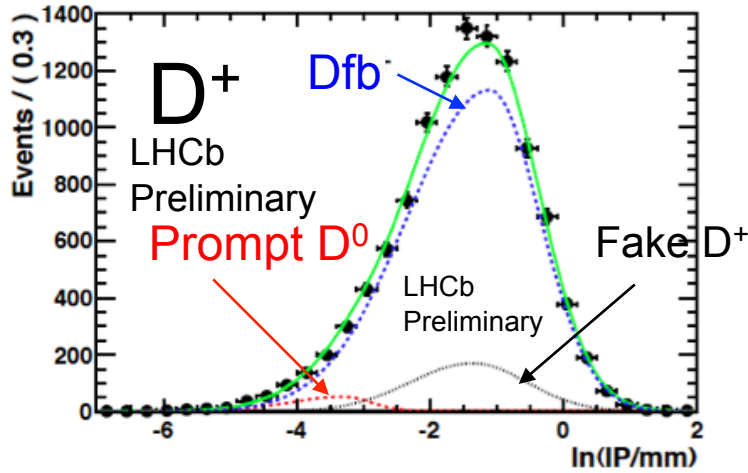
CMS Preliminary, $\sqrt{s}=7$ TeV

Spring 2011

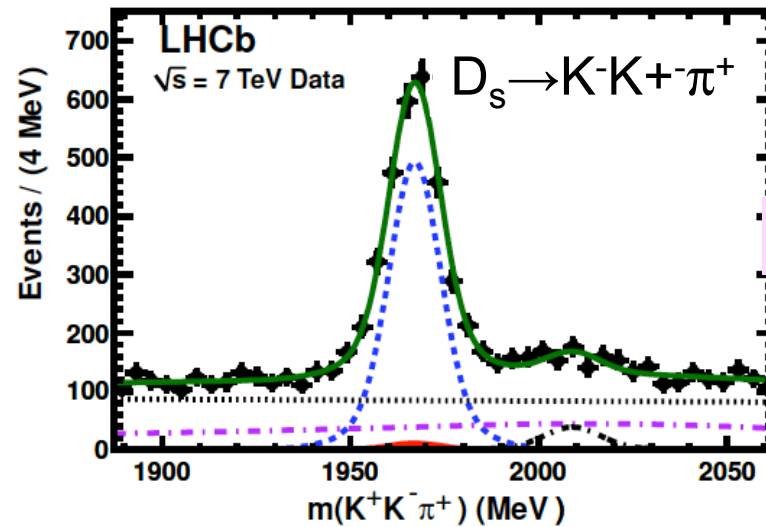
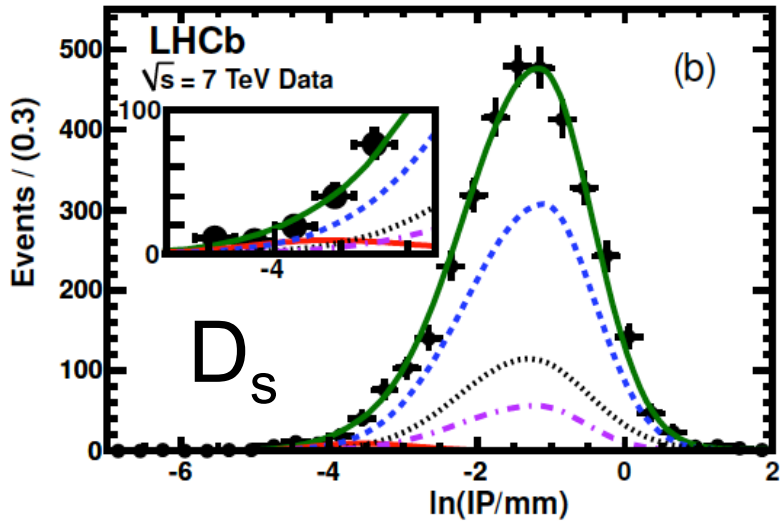




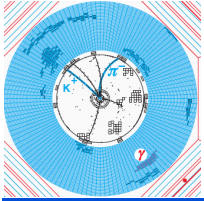
Also D^+ , D_s , Λ_b



D_{fb} : 9406 ± 110



D_{fb} : 2446 ± 60

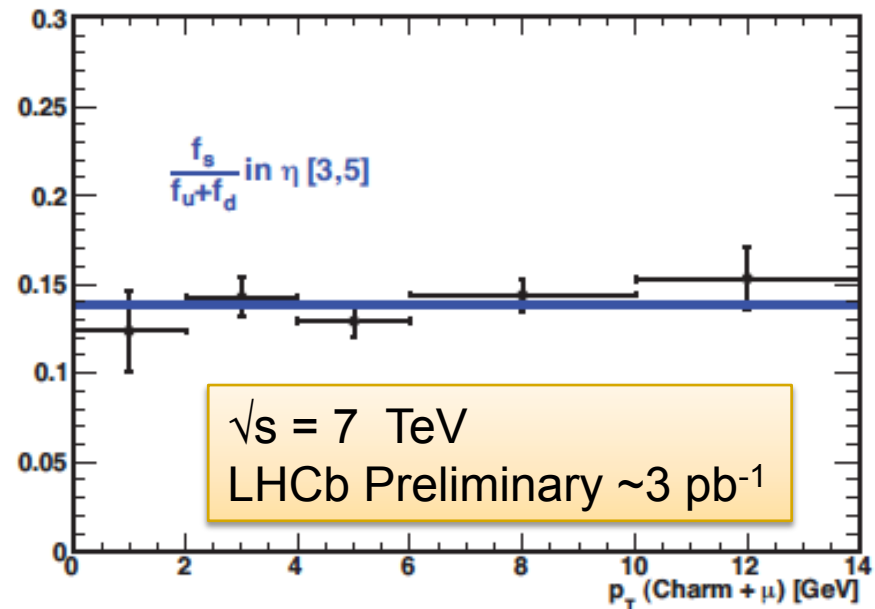
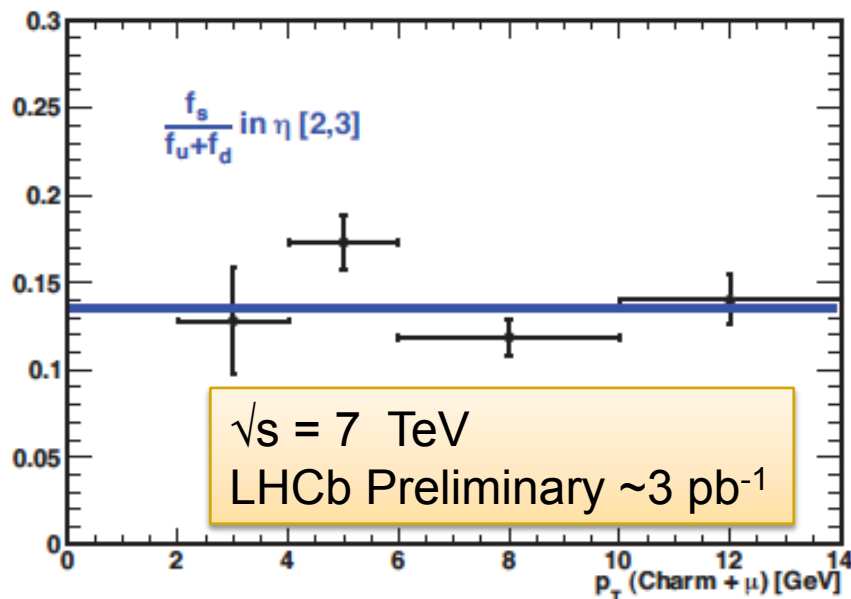


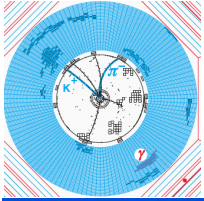
Extract B_s fractions

- Crucial to set absolute scale for B_s rates, since not given by e^+e^- machines.
- Must correct for $B_s \rightarrow D^0 K^+ X_{\mu\nu}$, also

$$\Lambda_b \rightarrow D^0 p X_{\mu\nu}$$

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

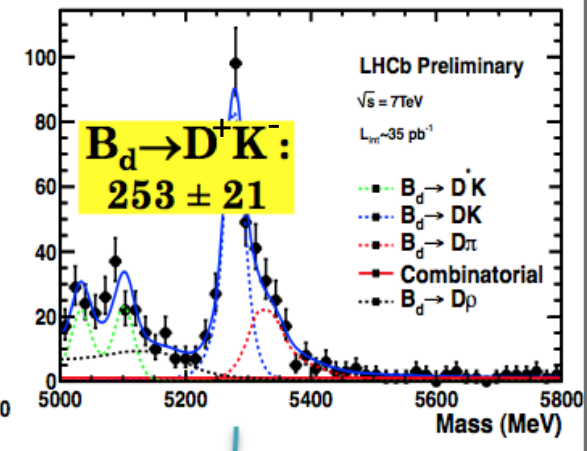
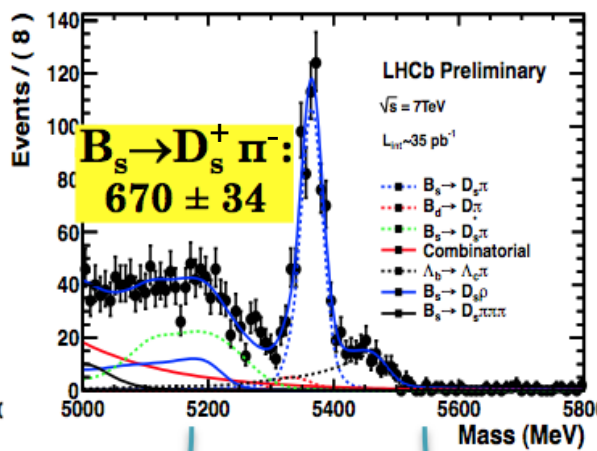
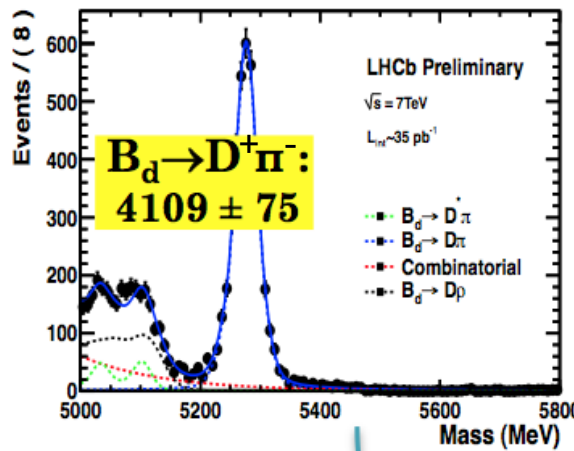




B_s fraction - hadronic

- Also can use hadronic decays + theory $\sim 35 \text{ pb}^{-1}$

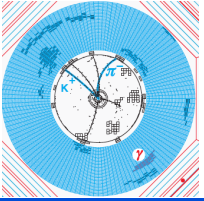
$\sqrt{s} = 7 \text{ TeV}$
LHCb Preliminary



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

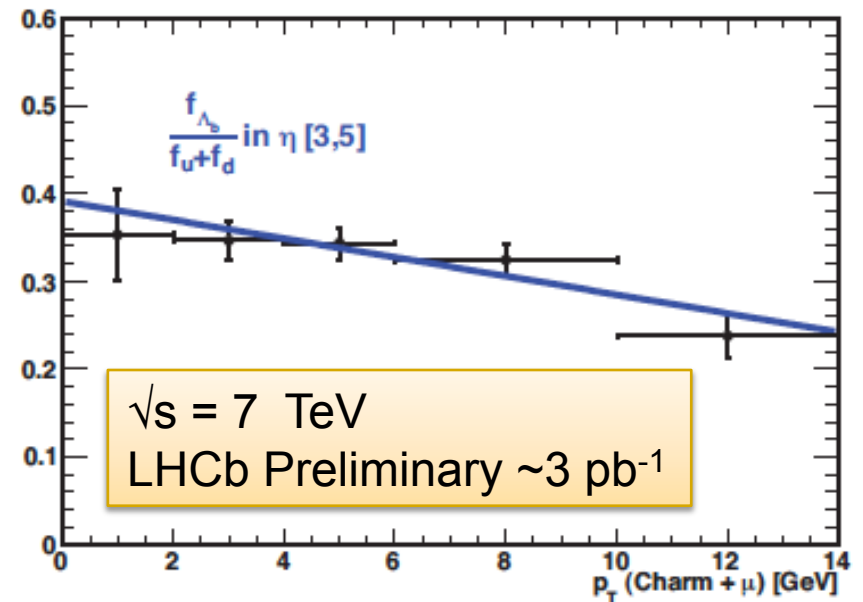
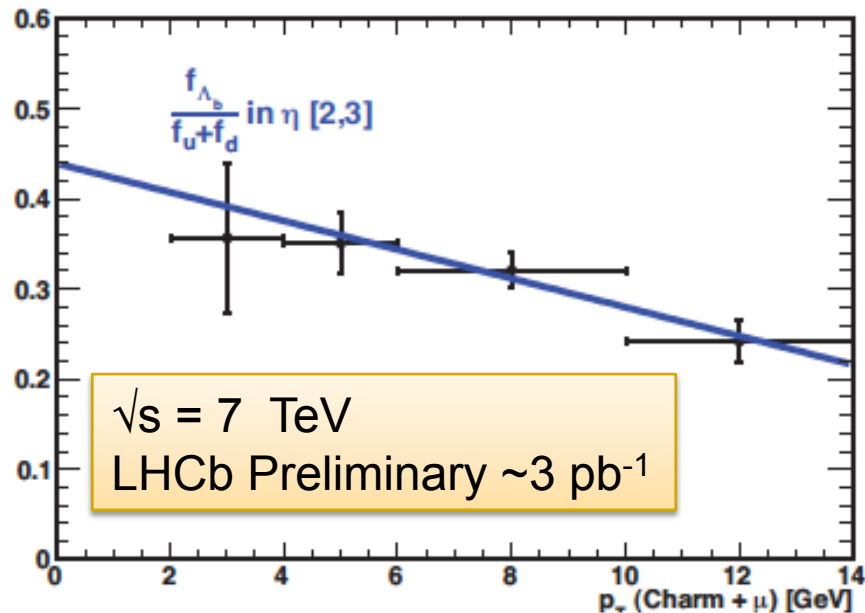
$$\frac{f_s}{f_d} = 0.242 \pm 0.024^{\text{stat}} \pm 0.018^{\text{syst}} \pm 0.016^{\text{theor}}$$

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



Λ_b Fraction

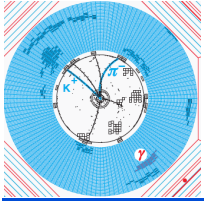
- Significant p_t dependence



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

- In general agreement with CDF measured at

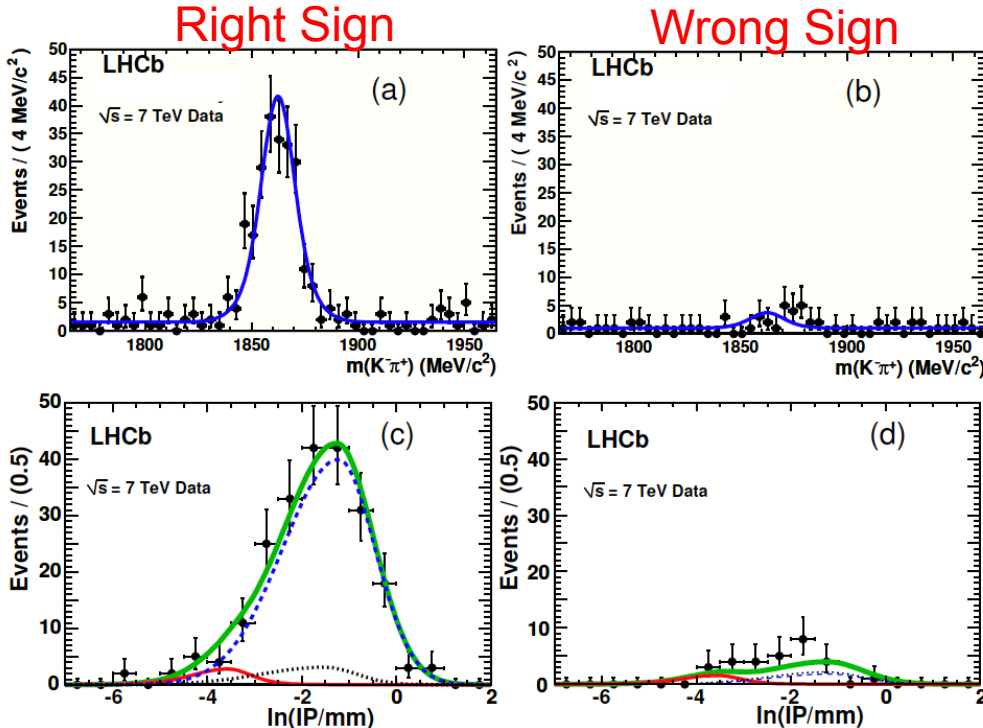
$$\langle p_t \rangle \sim 10 \text{ GeV}/c \quad f_{\Lambda_b}/(f_u + f_d) = 0.281 \pm 0.012^{+0.011+0.128}_{-0.056-0.086}$$



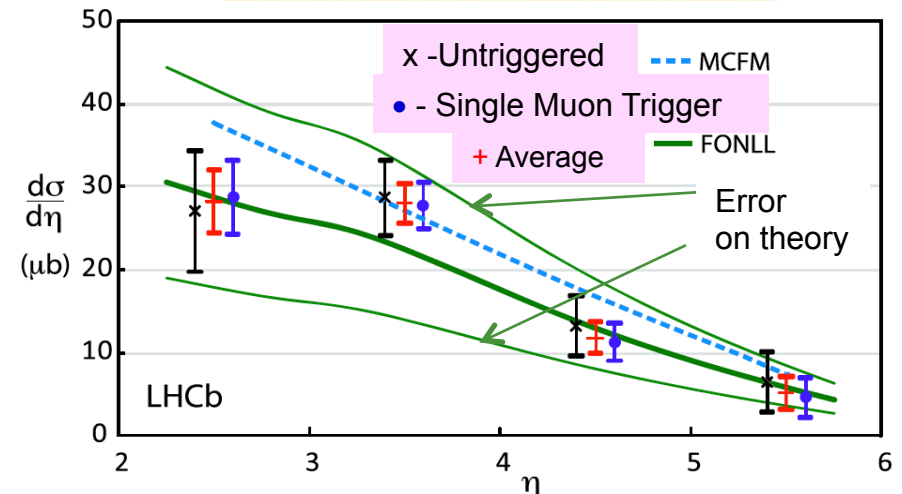
$\sigma(pp \rightarrow b\bar{b}X)$ using 15 nb^{-1}

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

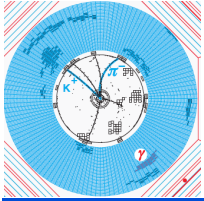
Infancy



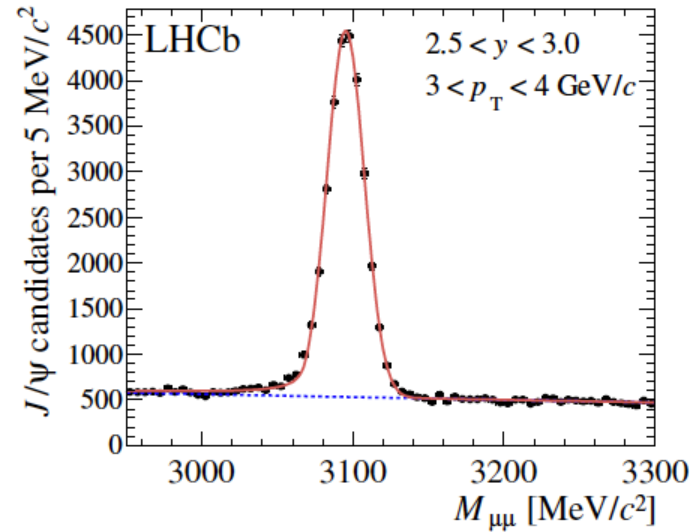
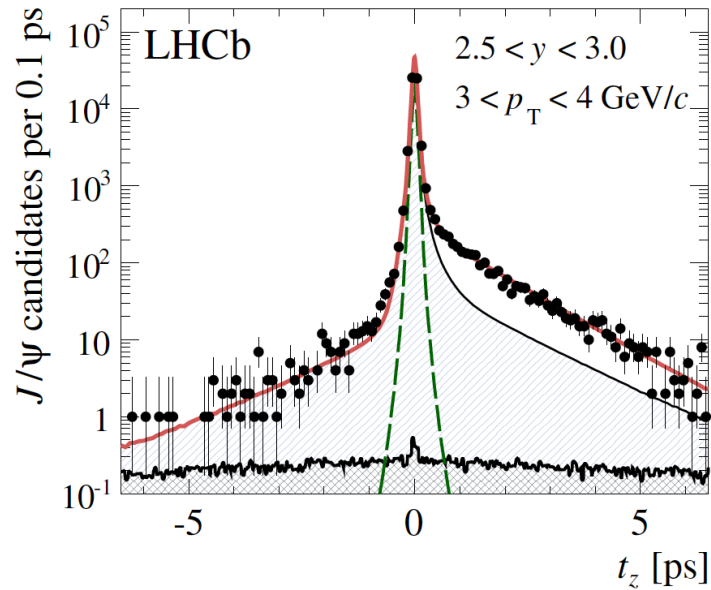
$$\sigma = \frac{\# \text{ of detected } D^0 \mu^- \text{ \& } \bar{D}^0 \mu^+}{L \times \text{efficiency} \times 2}$$



- In $2 < \eta < 6$, $(75.3 \pm 5.4 \pm 13.0) \mu\text{b}$ LEP frag $\Rightarrow 284 \pm 20 \pm 49 \mu\text{b}$
- In $2 < \eta < 6$, $89.6 \mu\text{b}$ Tevatron frag $\Rightarrow 338 \pm 24 \pm 58 \mu\text{b}$
- Also measured charm cross-section, $\sim 20 \times b$

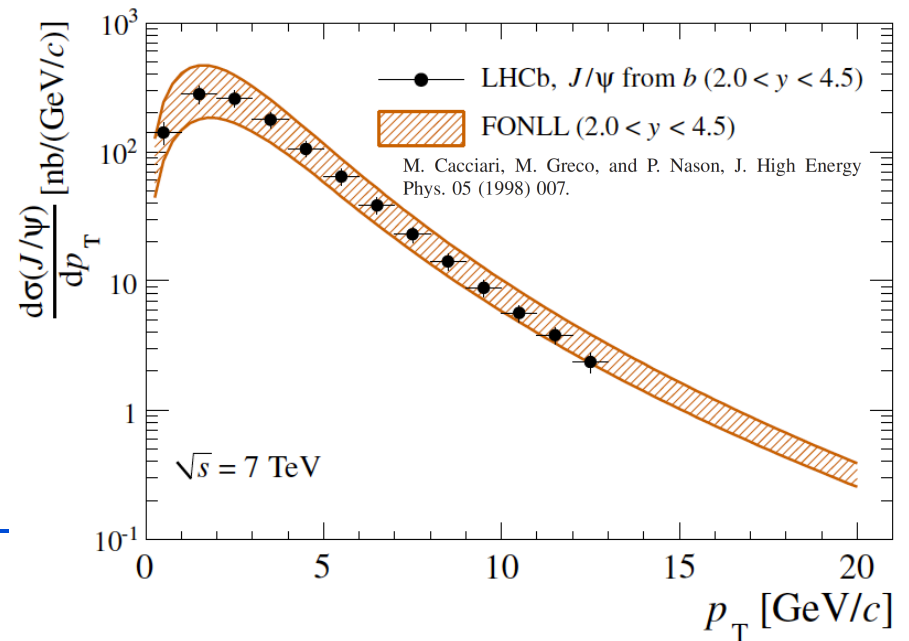


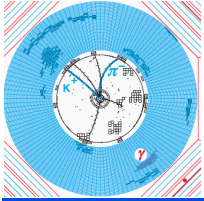
b xsect from $b \rightarrow J/\psi X$



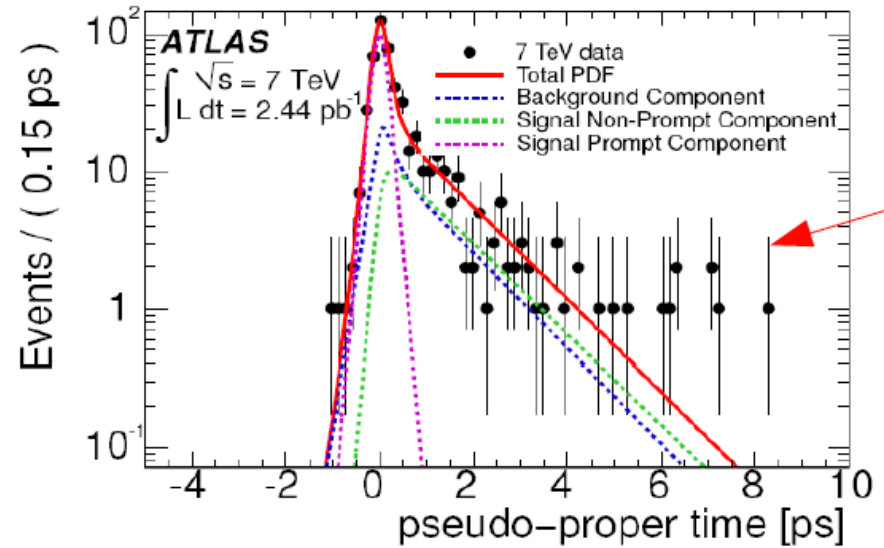
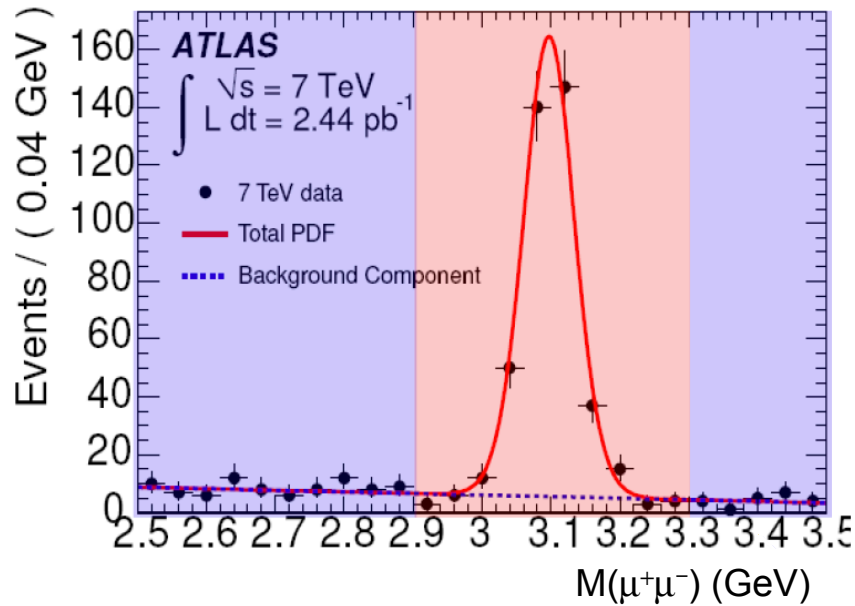
$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$

- Here use 5.2 pb^{-1}
- $\sigma = 288 \pm 4 \pm 48 \text{ } \mu\text{b}$

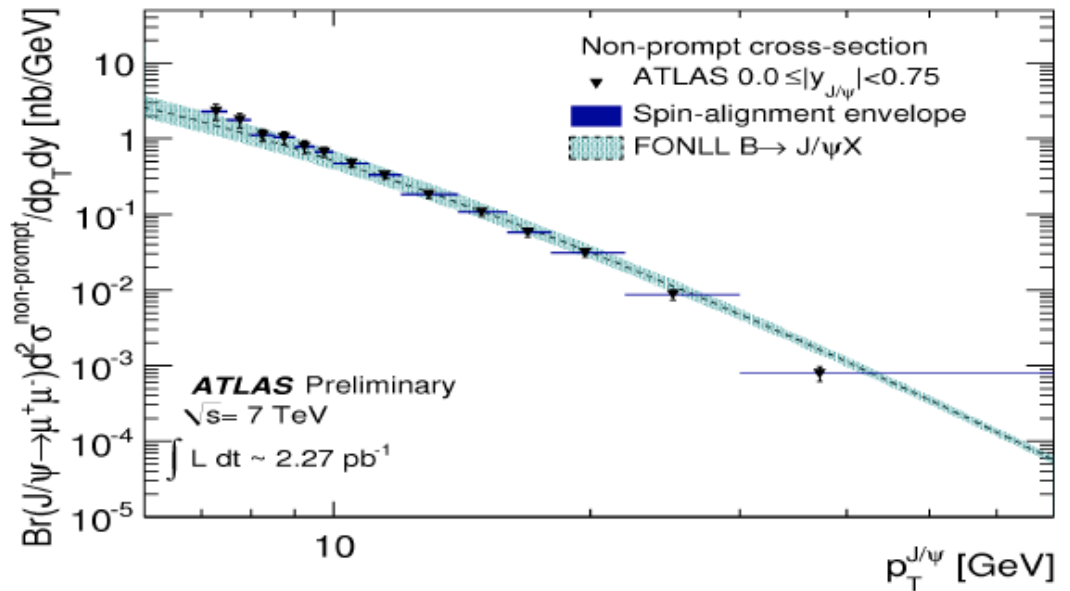


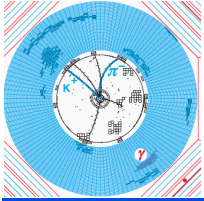


ATLAS σ from $b \rightarrow J/\psi X$

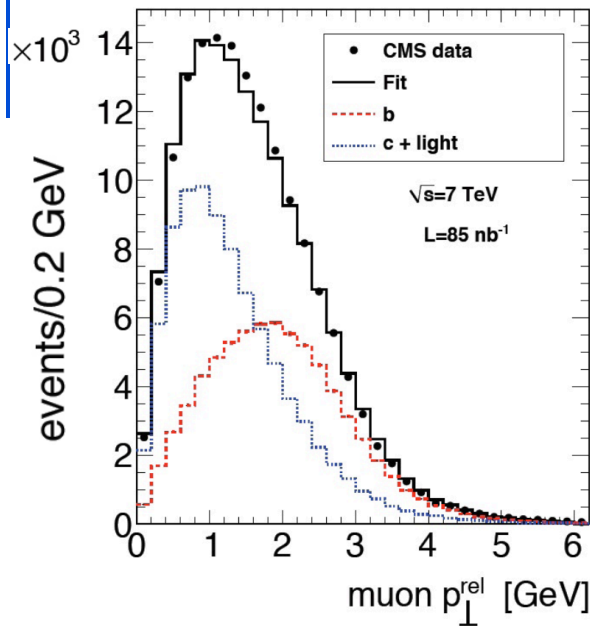


- ATLAS also in agreement with FONLL for $p_t > 5$ GeV/c





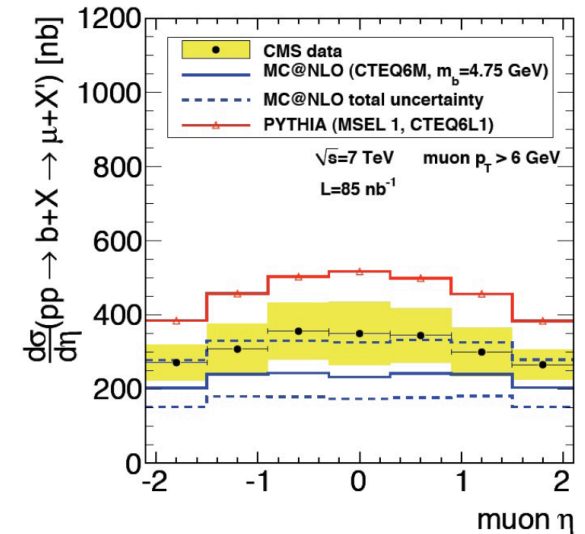
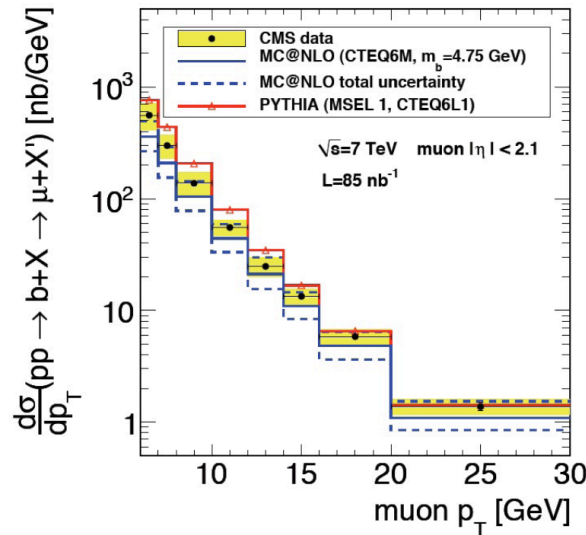
CMS σ from $b \rightarrow X\mu\nu$



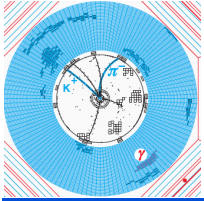
$$\sigma = 1.32 \pm 0.01(\text{stat}) \pm 0.30(\text{syst}) \pm 0.15(\text{lumi}) \mu\text{b}$$

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

$$\sigma_{PYTHIA} = 1.8 \mu\text{b}$$



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



CPV Time Evolution

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

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

See Nierste
arXiv:0904.1869 [hep-ph]

- For B^0 , $\Delta\Gamma \approx 0$

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

- if only 1 A_f $\Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} (1 - \text{Im } \lambda_f \sin(\Delta M t))$

- and a CP eigenstates

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