Quark flavour physics

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- Plan
  - Kaon physics and SM construction (bit of history)
  - Establishing SM experimentally
  - Looking for breakdown of SM
- Hard to cover everything in details in three lectures, some details are offloaded to exercises

Outline – lecture 3

- Why we need new physics
- Where to look for new physics
  - CPV in $B_s \to J/\psi\varphi$
  - $b \to s l^+ l^-$
  - $B_s \to \mu\mu$
  - $B^+ \to \tau\nu$
  - Charm mixing and CPV
- Useful theory oriented reference: A.J.Buras, arXiv:1012.1447

Why new physics?

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- What we saw up to now is extreme success of SM
- So why we are so excited about new physics if we can describe all measurements without it?
- SM does not tell why we have three generations (do we?)
- SM does not tell anything about masses of fermions
- Way SM works needs quite some fine tuning (final result is often difference between two huge numbers)
- Higgs mass in SM is not really stable
- Cosmology argument:
  - No candidate for Dark matter
  - Not possible to generate current matter-antimatter asymmetry in Universe

Sakharov

- In 1967 Andrei Sakharov formulated three necessary conditions to produce baryon-antibaryon asymmetry
  - Baryon number violation
  - CP violation
  - Interactions out of equilibrium
- Surprisingly SM can best cope with baryon number violation – but non-perturbative QCD effect
- CP violation exists in SM, but definitely not large enough
- In SM there is nothing which could drive system out of equilibrium
- Those are in my view strongest needs for new physics

Typical NP scenarios

- SUSY – most popular
  - Each SM particle gets its SUSY partner
  - Squarks can also mix (similar to quarks) and provide additional phases
- Fourth generation
  - Puts in additional fermion generation
  - Not as appealing as SUSY and cannot answer all questions, but can make huge difference on CPV
- Technicolor
  - Gets more popular again as it can dynamically create Higgs like effect without need of Higgs

NP DNA

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	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ε_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	★★

Table 2: "DNA" of flavour physics effects [55] for the most interesting observables in a selection of SUSY and non-SUSY models. ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Buras, arXiv:0910.1032v1

$B_s \to \mu^+\mu^-$

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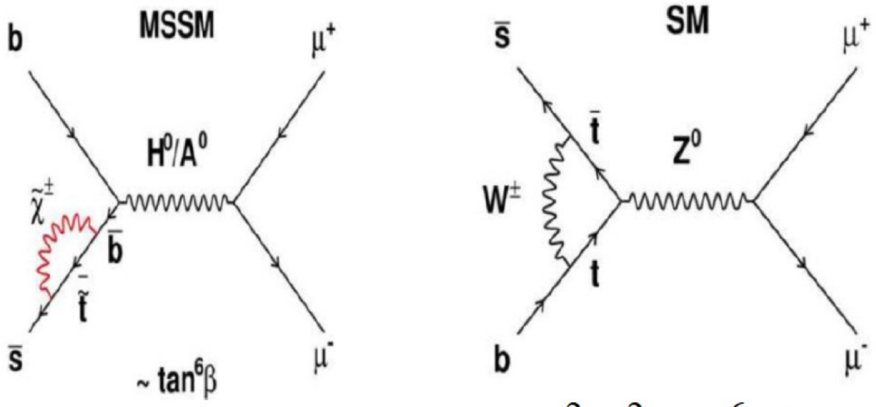
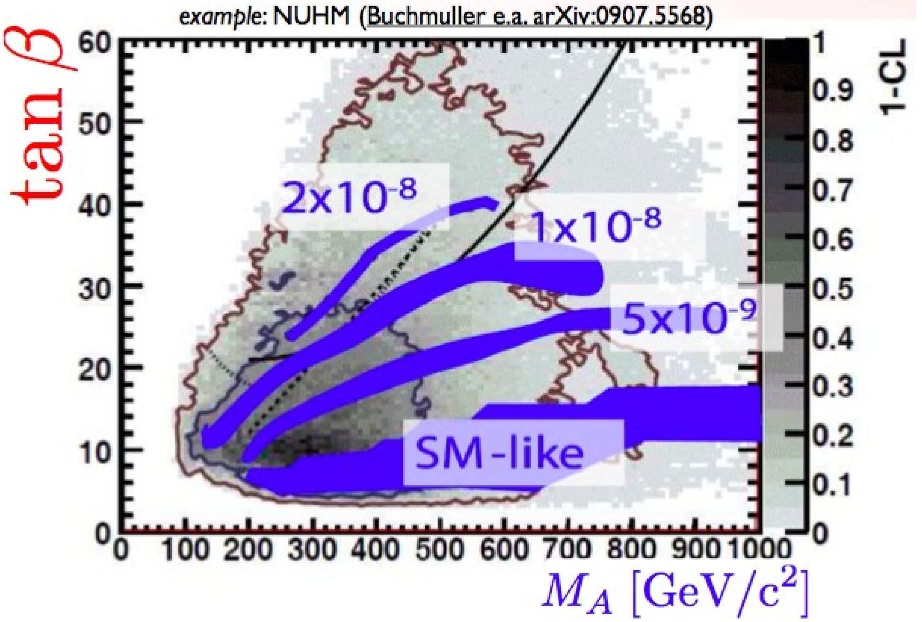


$$Br^{MSSM}(Bq \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$



- SM prediction Br=$(3.2\pm0.2)10^{-9}$
- Extremely sensitive to new physics
- Already with limits 10 times above SM one could severely restrict NP models

Background plot is from
Buchmuller et al arXiv:0907.5568

Blue regions are allowed regions for given measurement.
SuperIso program, (F. Mahmoudi, arXiv: 08083144) and SoftSusy (B.C. Allanach, Comput. Phys. Commun. 143 (2002) 305-331)

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Experiments

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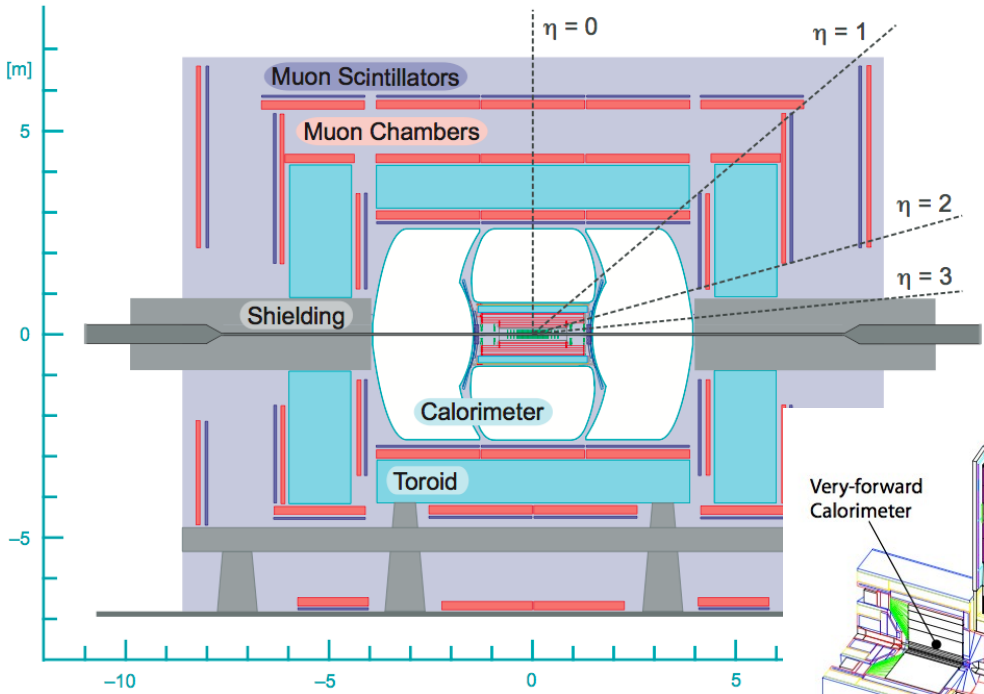
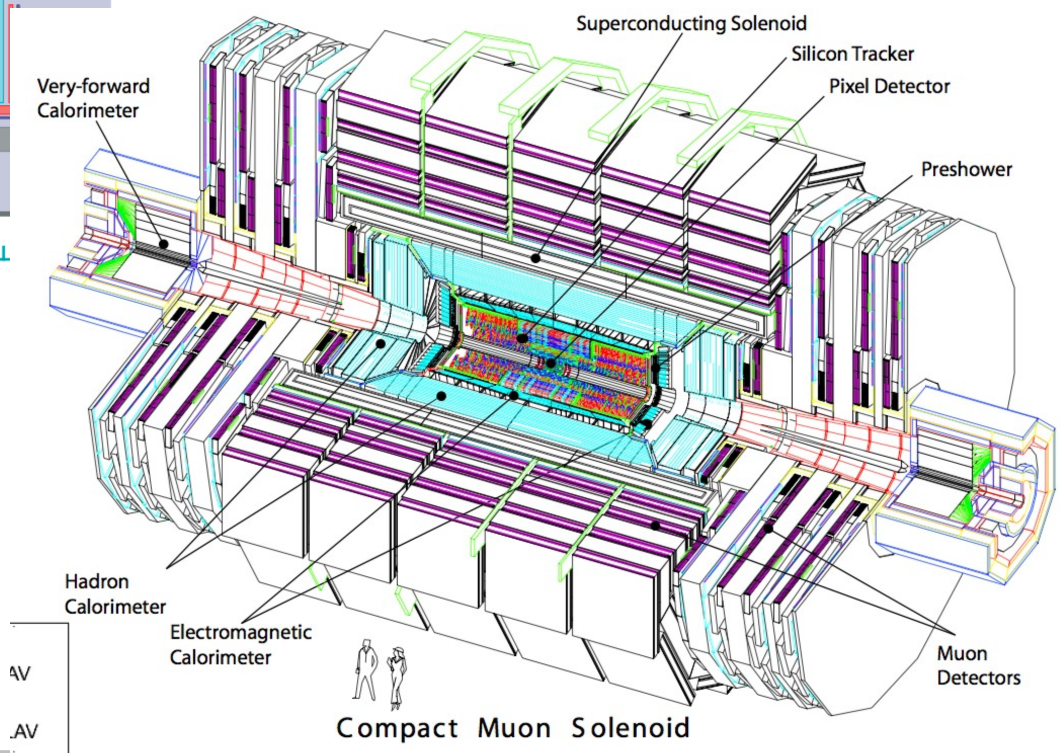
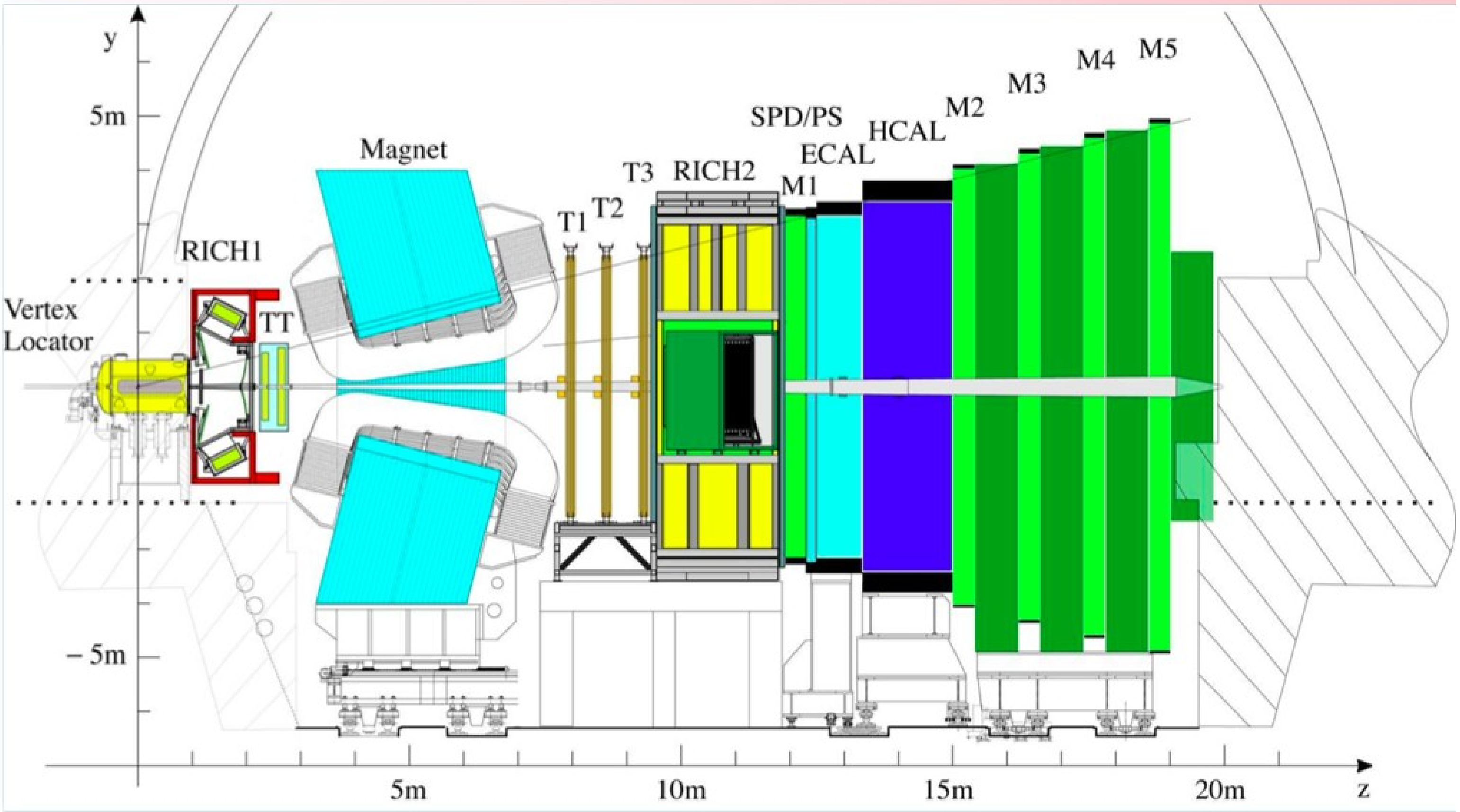
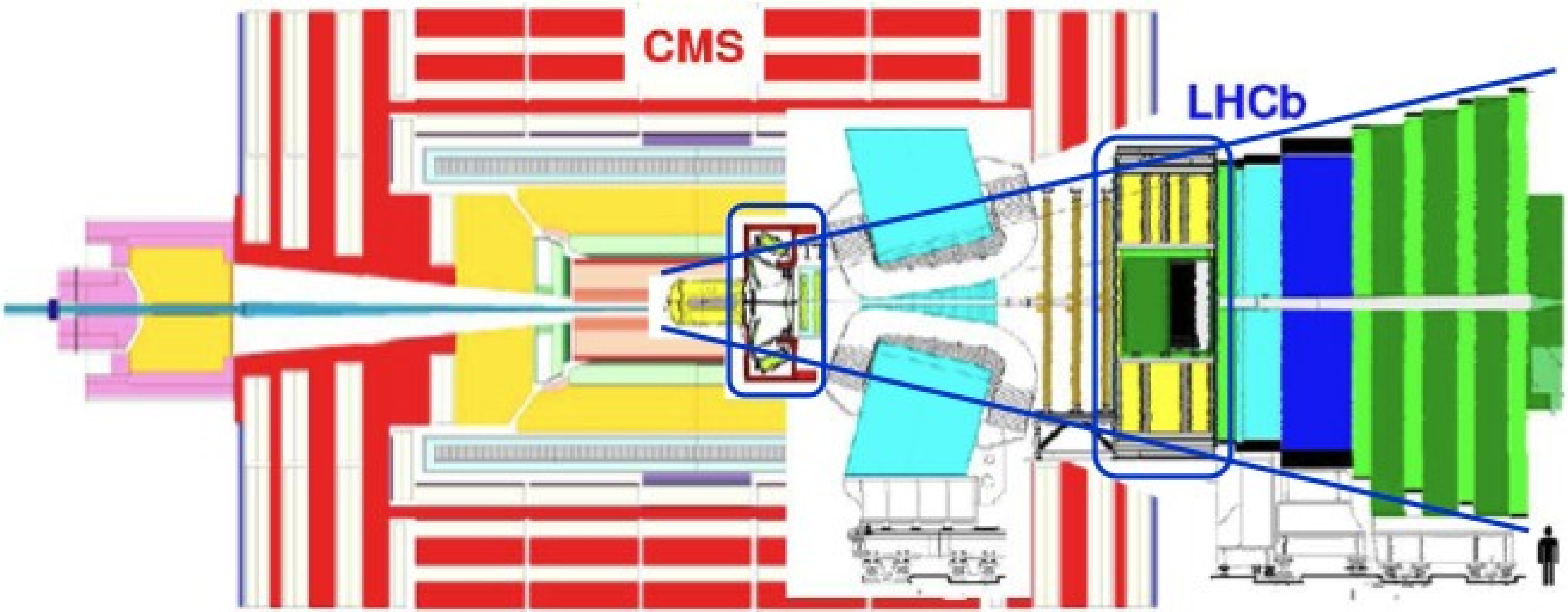




Experiments

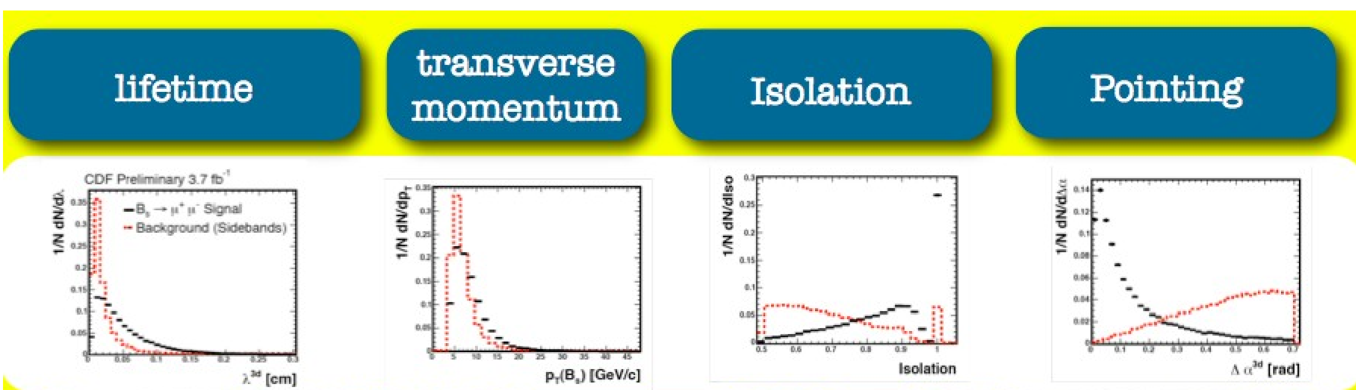


LHCb is not small one

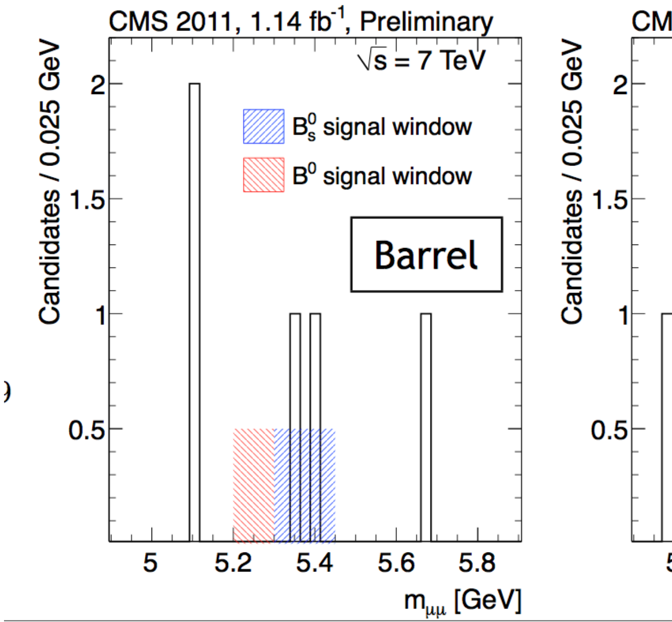


Main experimental issues

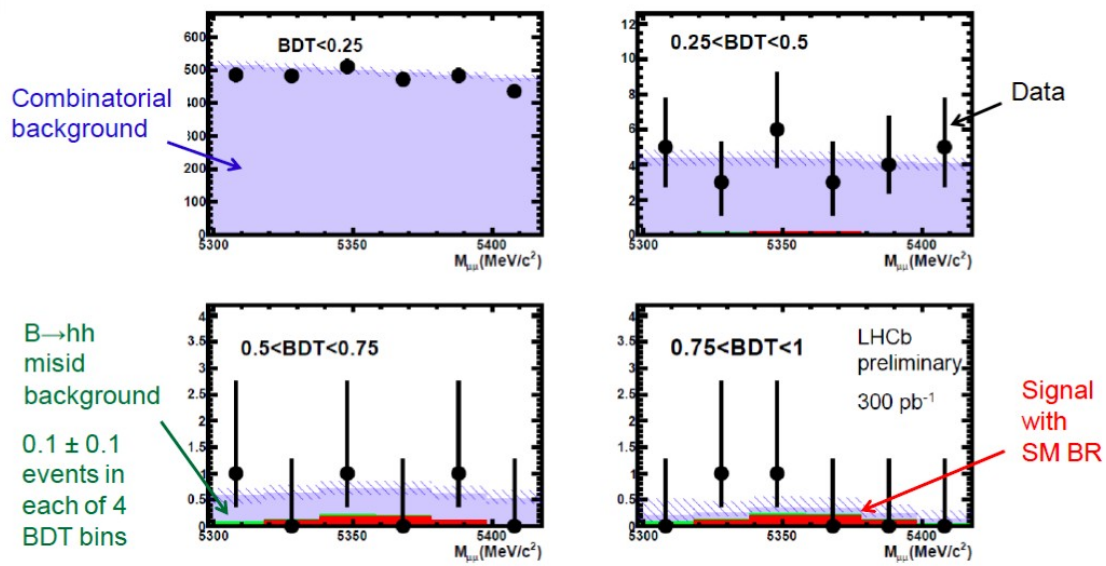
- As decay is rare, main issue is to control background
- Special care is needed for B→hh' decays which peak in same place as signal
- Selection ranges from cut based (CMS) to BDT (LHCb) to NN(CDF, D0)



$B_s \to \mu^+\mu^-$

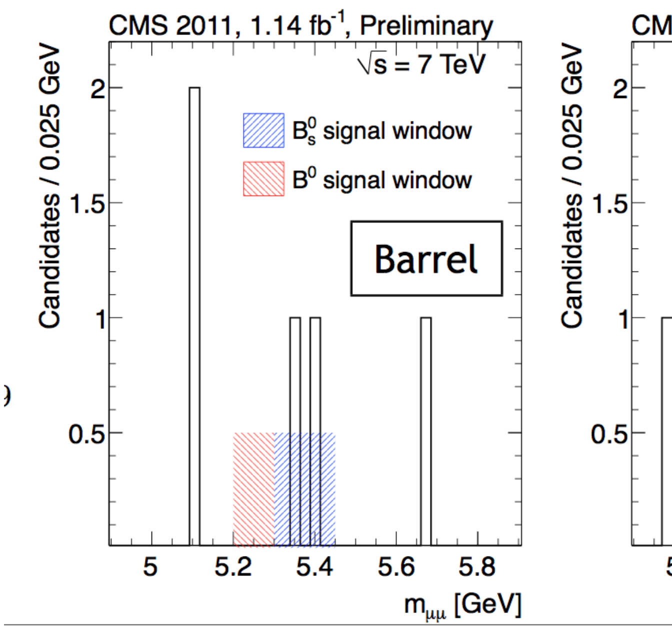


CMS 2011, 1.14 fb-1, Preliminary
√s = 7 TeV
Bs0 signal window
B0 signal window
Barrel
Endcap
Candidates / 0.025 GeV
mμμ [GeV]

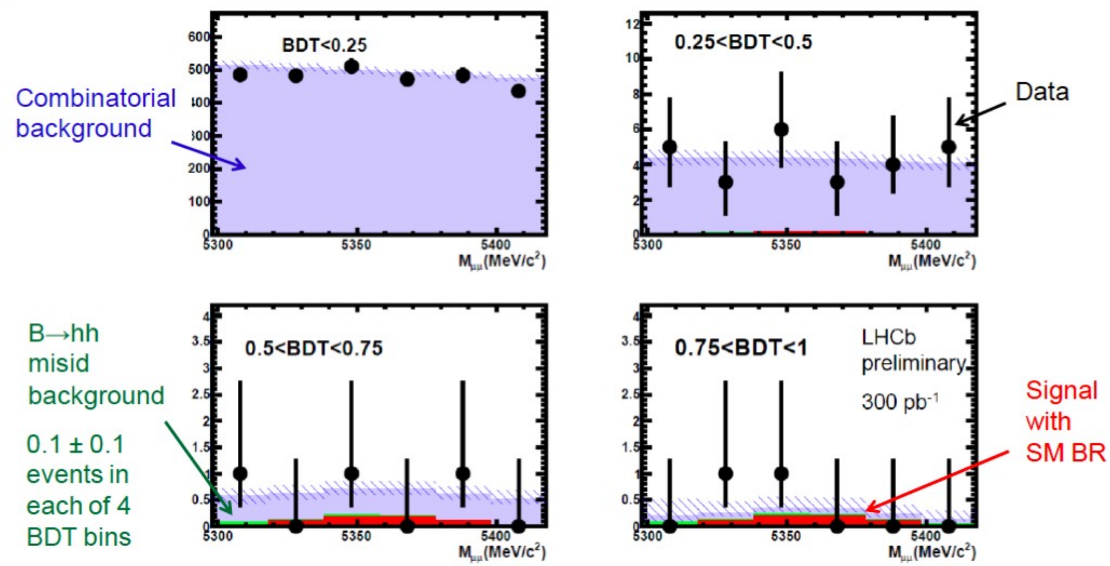


BDT<0.25
0.25<BDT<0.5
0.5<BDT<0.75
0.75<BDT<1
LHCb preliminary
300 pb-1
Combinatorial background
Data
B→hh misid background
0.1 ± 0.1 events in each of 4 BDT bins
Signal with SM BR
Mμμ(MeV/c2)

$B_s \to \mu^+\mu^-$

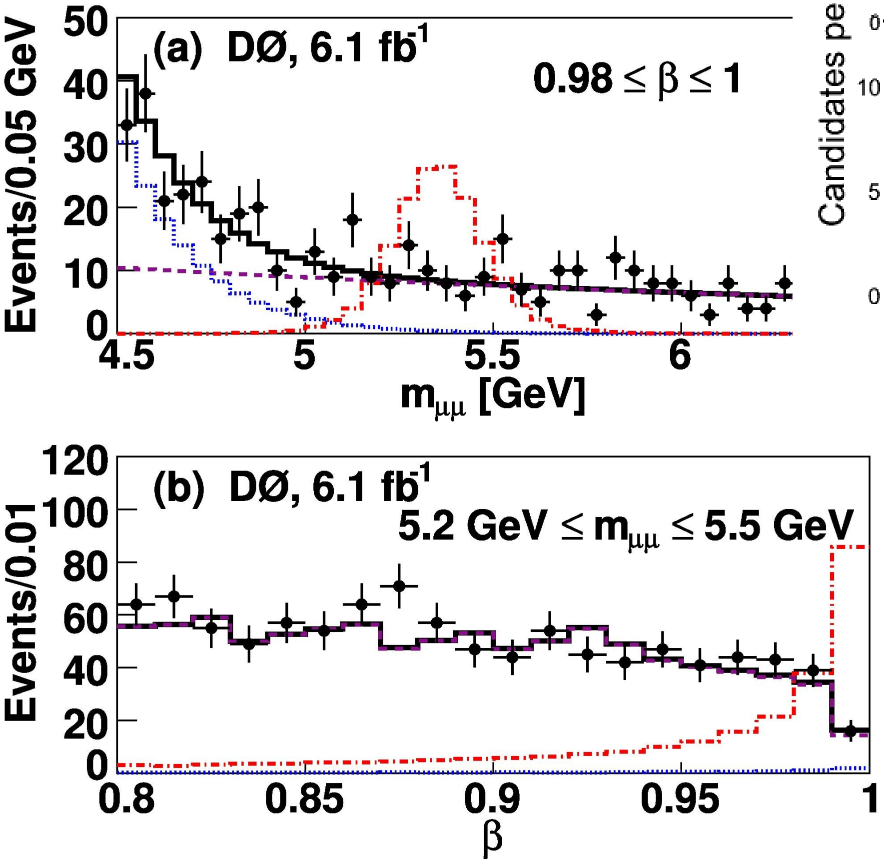


CMS 2011, 1.14 fb^{-1}, Preliminary
$\sqrt{s}$ = 7 TeV
B_s^0 signal window
B^0 signal window
Barrel
Endcap
Candidates / 0.025 GeV
$m_{\mu\mu}$ [GeV]

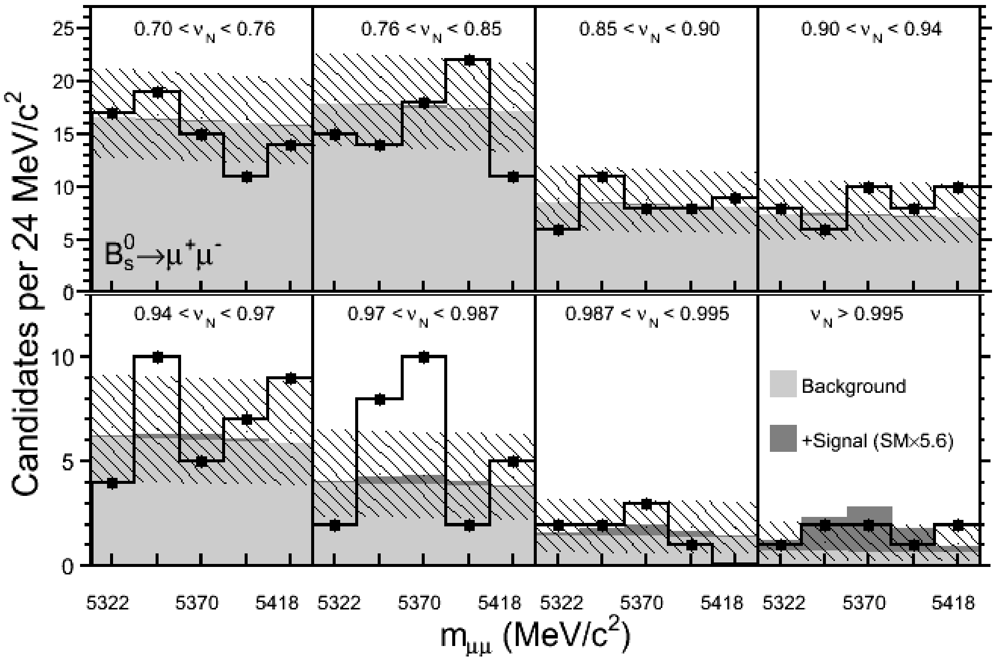


Combinatorial background
BDT<0.25
0.25<BDT<0.5
Data
B→hh misid background
0.1 ± 0.1 events in each of 4 BDT bins
0.5<BDT<0.75
0.75<BDT<1
LHCb preliminary
300 pb^{-1}
Signal with SM BR
$M_{\mu\mu}$(MeV/c^2)

$B_s \to \mu^+\mu^-$



(a) DØ, 6.1 fb-1
0.98 ≤ β ≤ 1
Events/0.05 GeV
m_μμ [GeV]
(b) DØ, 6.1 fb-1
5.2 GeV ≤ m_μμ ≤ 5.5 GeV
Events/0.01
β

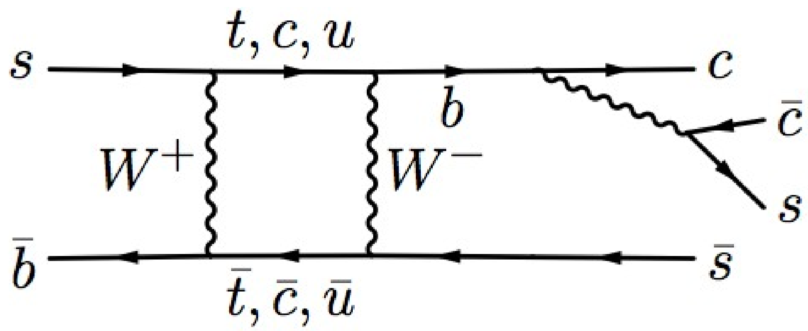


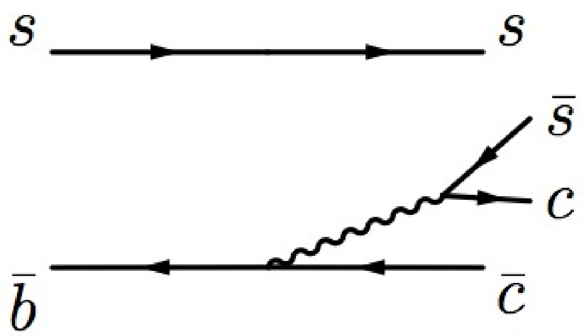
0.70 < ν_N < 0.76
0.76 < ν_N < 0.85
0.85 < ν_N < 0.90
0.90 < ν_N < 0.94
0.94 < ν_N < 0.97
0.97 < ν_N < 0.987
0.987 < ν_N < 0.995
ν_N > 0.995
B0s→μ+μ-
Background
+Signal (SM×5.6)
Candidates per 24 MeV/c2
m_μμ (MeV/c2)

$B_s \to \mu^+ \mu^-$

- D0, LHCb and CMS compatible with pure background (plus tiny SM signal)
- CDF sees excess of events above background
- Results:
  - $B(B_s^0 \quad ^{+} \quad) < 5.1 \times 10^{8}$ @ 95% C.L. (D0)
  - $B(B_s^0 \quad ^{+} \quad) < 1.9 \times 10^{8}$ @ 95% C.L. (CMS)
  - $B(B_s^0 \quad ^{+} \quad) < 1.5 \times 10^{8}$ @ 95% C.L. (LHCb)
  - $B(B_s^0 \quad ^{+} \quad) < 3.9 \times 10^{8}$ @ 95% C.L. (CDF)
  - $B=(1.8^{+1.1}_{-0.9}) \times 10^{-8}$ (CDF interpreting excess as signal)
- About factor 5 above SM
- Expect to come close to SM at latest end of next year

CPV induced by B_s mixing





- CPV stems from interference of decays with and w/o mixing
- In SM it is expected to me tine – Effect of almost real V_{ts}
- Needs some care in interpretation of what is really measured
- Up to now measured with $B_s \to J/\psi\varphi$ and $B_s \to J/\psi f_0(980)$
- Difficult due to large $\Delta m_s \sim 17.8\ ps^{-1}$
- Needs very good time resolution

Master formulas of time evolution

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$$\Gamma(M(t)\to f) = \mathcal{N}_f\,|A_f|^2\,e^{-\Gamma t}\left\{\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma\,t}{2}+\frac{1-|\lambda_f|^2}{2}\cos(\Delta M\,t)\right.$$
$$\left.-\mathrm{Re}\,\lambda_f\,\sinh\frac{\Delta\Gamma\,t}{2}-\mathrm{Im}\,\lambda_f\,\sin(\Delta M\,t)\right\}, \qquad (50)$$

$$\Gamma(\overline{M}(t)\to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1}{1-a}\,e^{-\Gamma t}\left\{\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma\,t}{2}-\frac{1-|\lambda_f|^2}{2}\cos(\Delta M\,t)\right.$$
$$\left.-\mathrm{Re}\,\lambda_f\,\sinh\frac{\Delta\Gamma\,t}{2}+\mathrm{Im}\,\lambda_f\,\sin(\Delta M\,t)\right\}. \qquad (51)$$

$$\Gamma(M(t)\to\overline{f}) = \mathcal{N}_f\left|\overline{A}_{\overline{f}}\right|^2 e^{-\Gamma t}\,(1-a)\left\{\frac{1+|\lambda_{\overline{f}}|^{-2}}{2}\cosh\frac{\Delta\Gamma\,t}{2}-\frac{1-|\lambda_{\overline{f}}|^{-2}}{2}\cos(\Delta M\,t)\right.$$
$$\left.-\mathrm{Re}\,\frac{1}{\lambda_{\overline{f}}}\,\sinh\frac{\Delta\Gamma\,t}{2}+\mathrm{Im}\,\frac{1}{\lambda_{\overline{f}}}\,\sin(\Delta M\,t)\right\}, \qquad (53)$$

$$\Gamma(\overline{M}(t)\to\overline{f}) = \mathcal{N}_f\left|\overline{A}_{\overline{f}}\right|^2 e^{-\Gamma t}\left\{\frac{1+|\lambda_{\overline{f}}|^{-2}}{2}\cosh\frac{\Delta\Gamma\,t}{2}+\frac{1-|\lambda_{\overline{f}}|^{-2}}{2}\cos(\Delta M\,t)\right.$$
$$\left.-\mathrm{Re}\,\frac{1}{\lambda_{\overline{f}}}\,\sinh\frac{\Delta\Gamma\,t}{2}-\mathrm{Im}\,\frac{1}{\lambda_{\overline{f}}}\,\sin(\Delta M\,t)\right\}. \qquad (54)$$

ArXiv:0904.1869

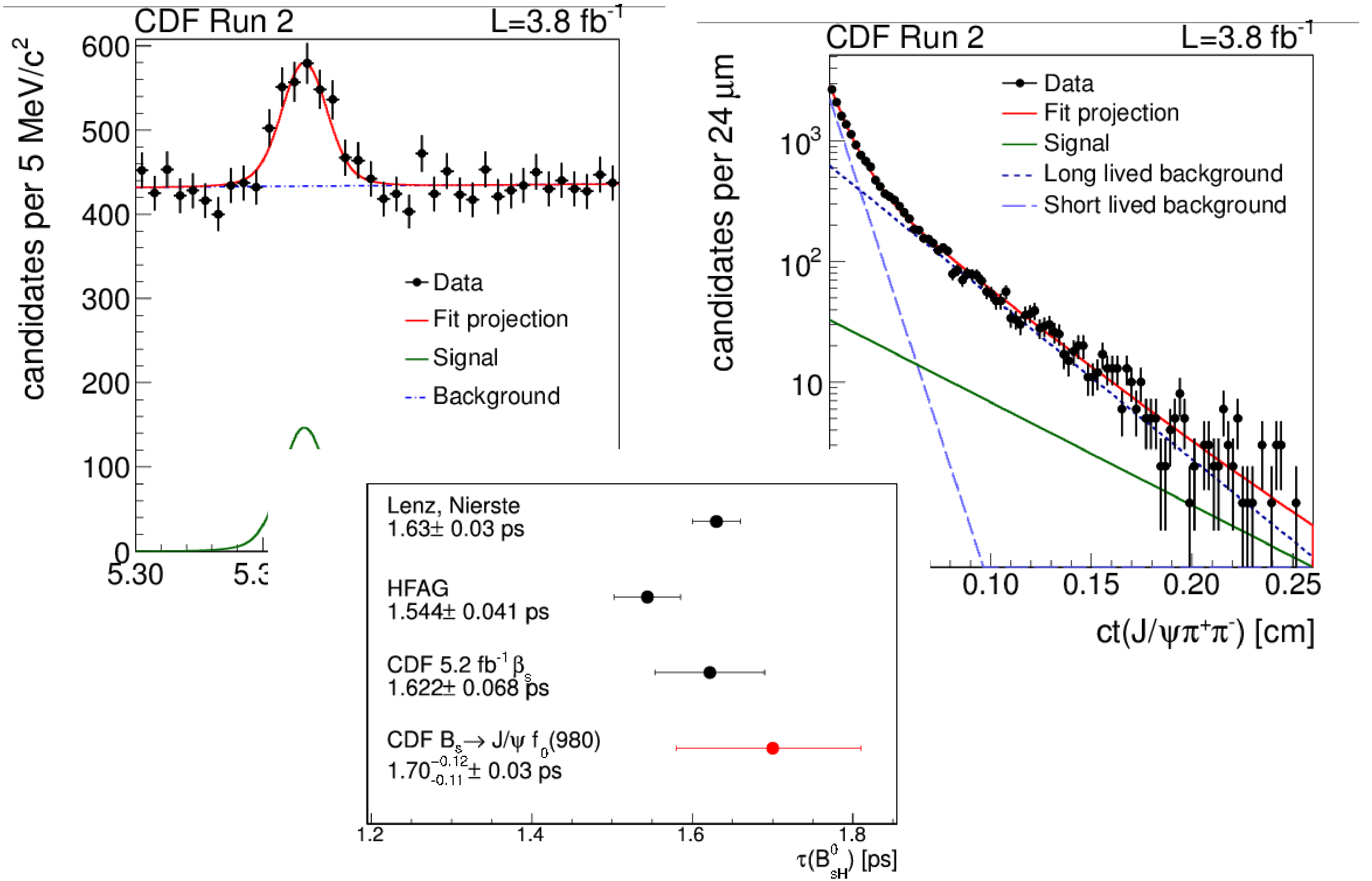
Decay $B_s \to J/\psi f_0$

- This final state is CP-eigenstate
- In master formula this (with some additional assumptions) means $|\lambda_f|=1$
- For B_s the a is at most ~ 1% and $\Delta\Gamma$ is in principle non-zero

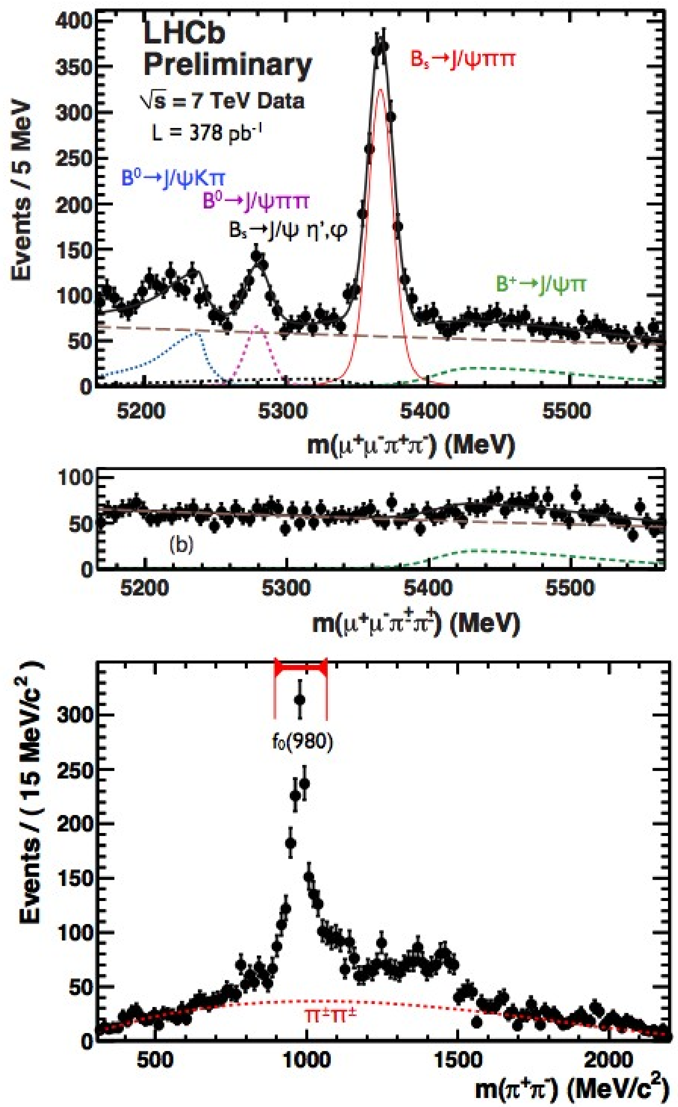
$$\frac{1+\cos(\phi)}{2}e^{-\Gamma_H t} + \frac{1-\cos(\phi)}{2}e^{-\Gamma_L t} - e^{-\Gamma t}\sin(\phi)\sin(\Delta m t)$$

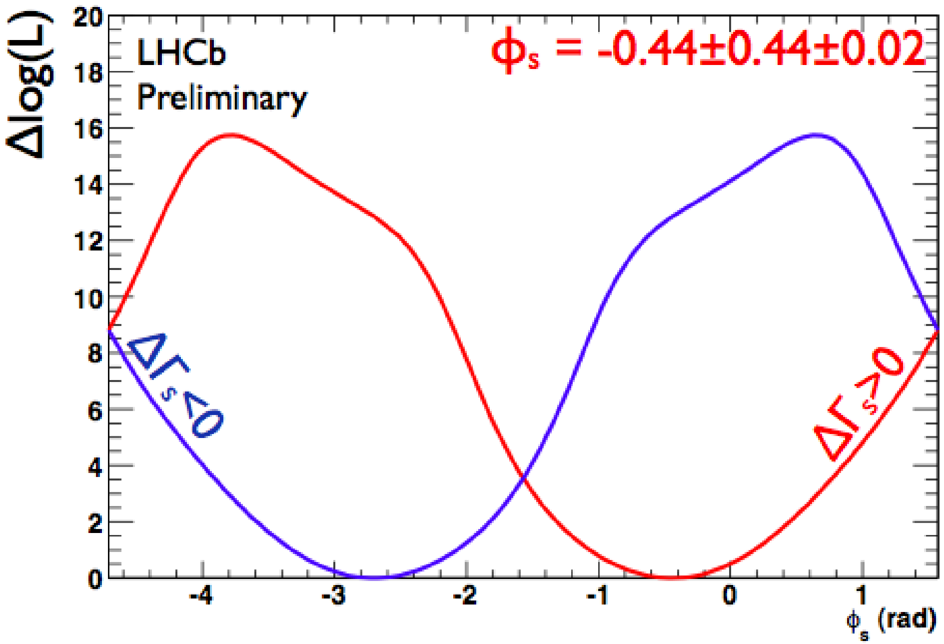
$$\frac{1+\cos(\phi)}{2}e^{-\Gamma_H t} + \frac{1-\cos(\phi)}{2}e^{-\Gamma_L t}$$

Decay $B_s \to J/\psi f_0$ - CDF



Decay $B_s \to J/\psi f_0$ - LHCb



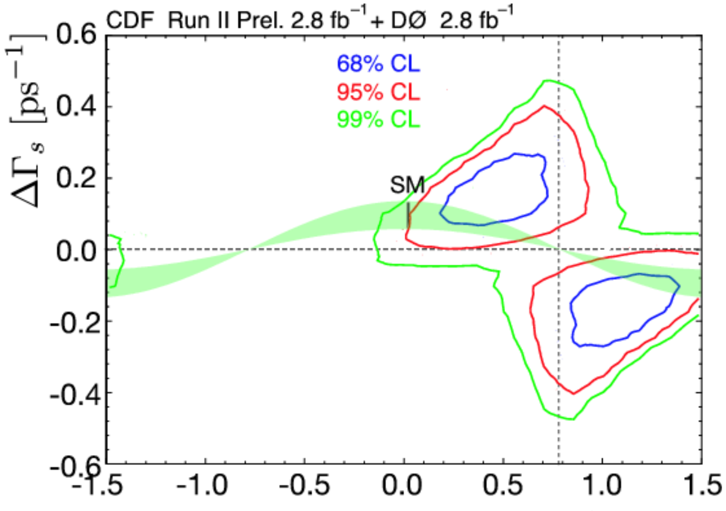


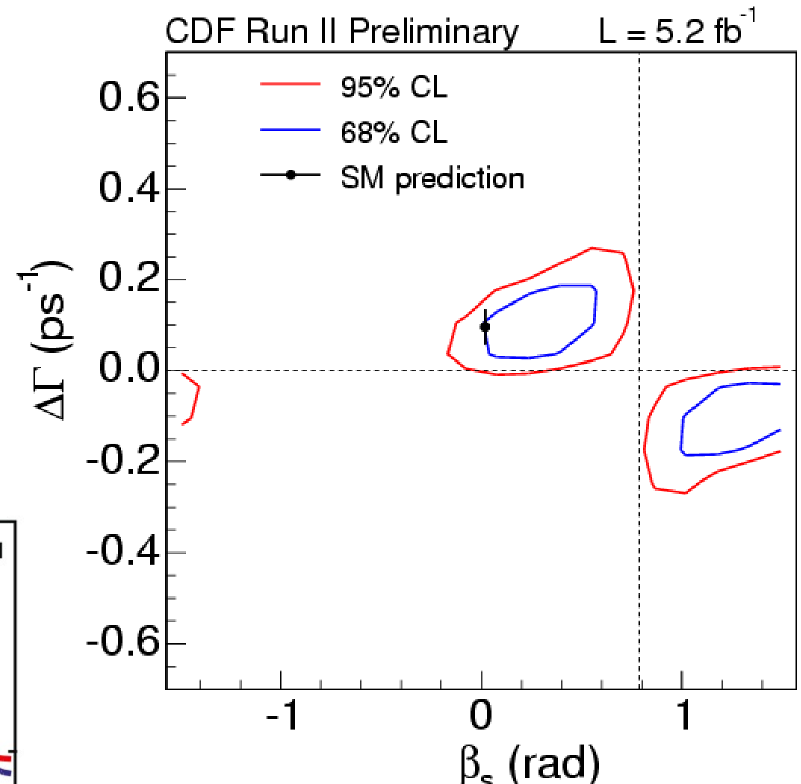
- Takes input of Γ and ΔΓ from LHCb $B_s \to J/\psi\phi$ result
- Consistent with SM

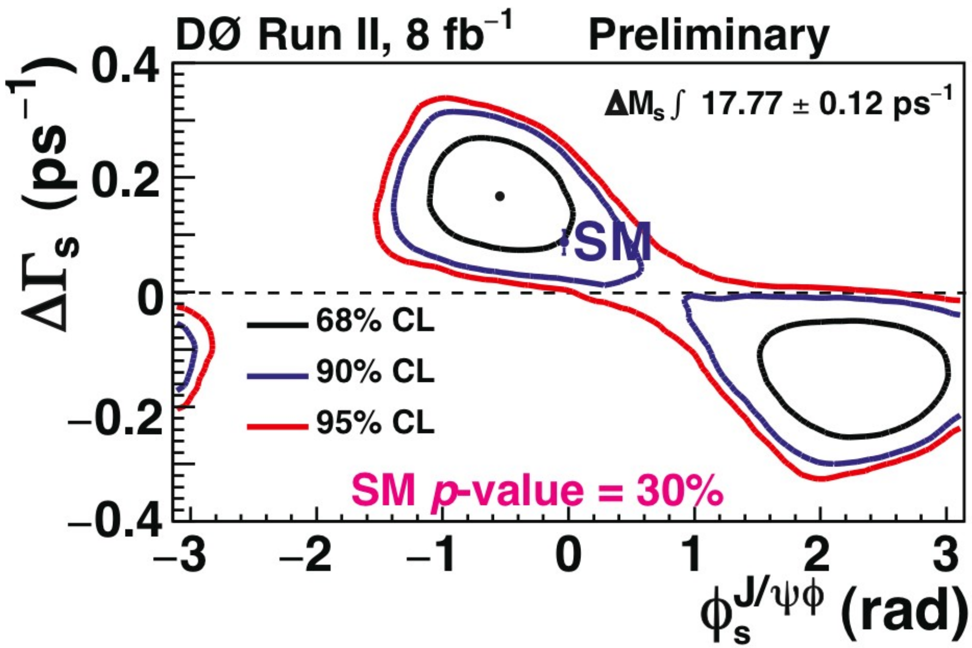
Decay $B_s \to J/\psi\varphi$

- This decay was first to study as it has higher signal yield
- Complication arises from the fact that both J/ψ and φ are have spin 1 => mixture of CP-even and CP-odd
- Need additional work (angular analysis) to statistically distinguish two
- On the other hand it also helps to gain additional sensitivity from interference
- There are many details to care about, much beyond scope of this lecture
- If there is interest, in some free time I can walk you through CDF analysis to full depth

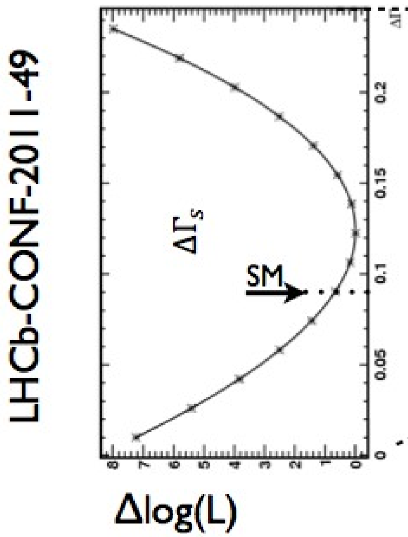
Decay $B_s \to J/\psi\phi$

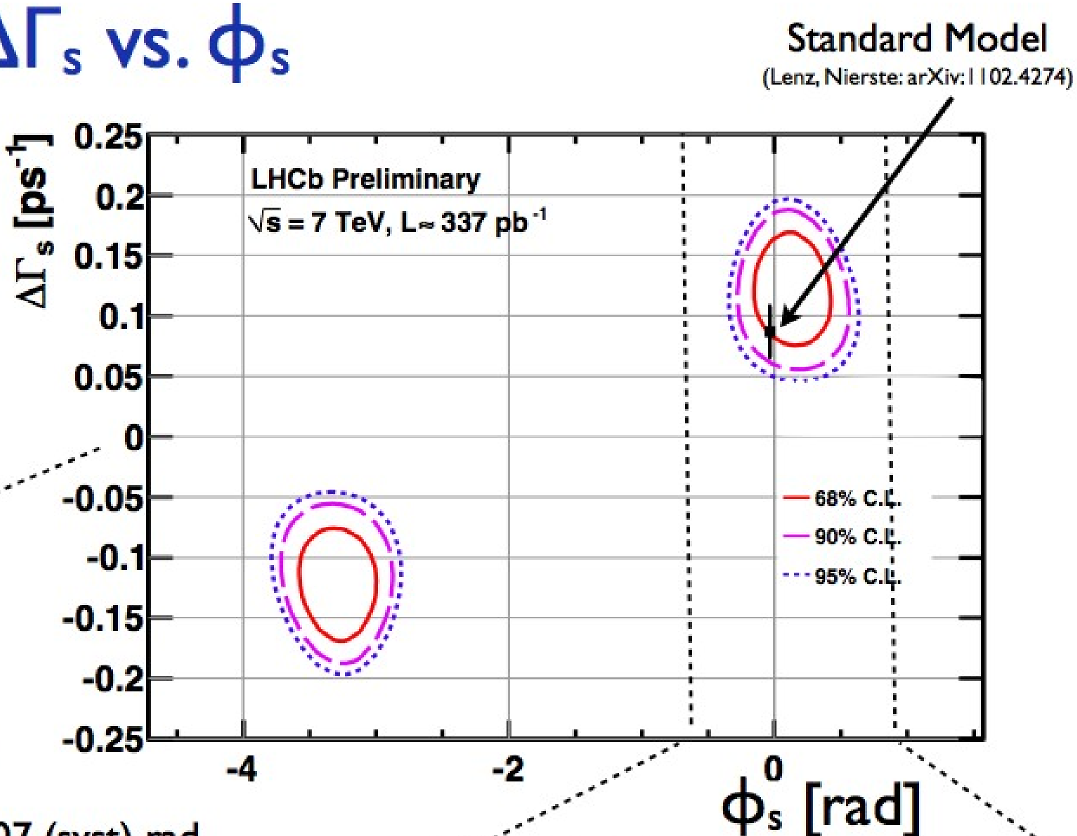






$B_s \rightarrow J/\psi\varphi$: $\Delta\Gamma_s$ vs. ϕ_s



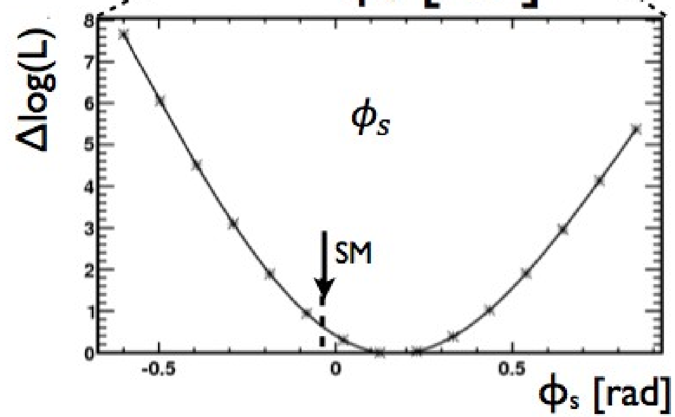


Most precise measurement of ϕ_s

- ϕ_s = 0.13 ± 0.18 (stat) ± 0.07 (syst) rad
- Consistent with SM

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

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



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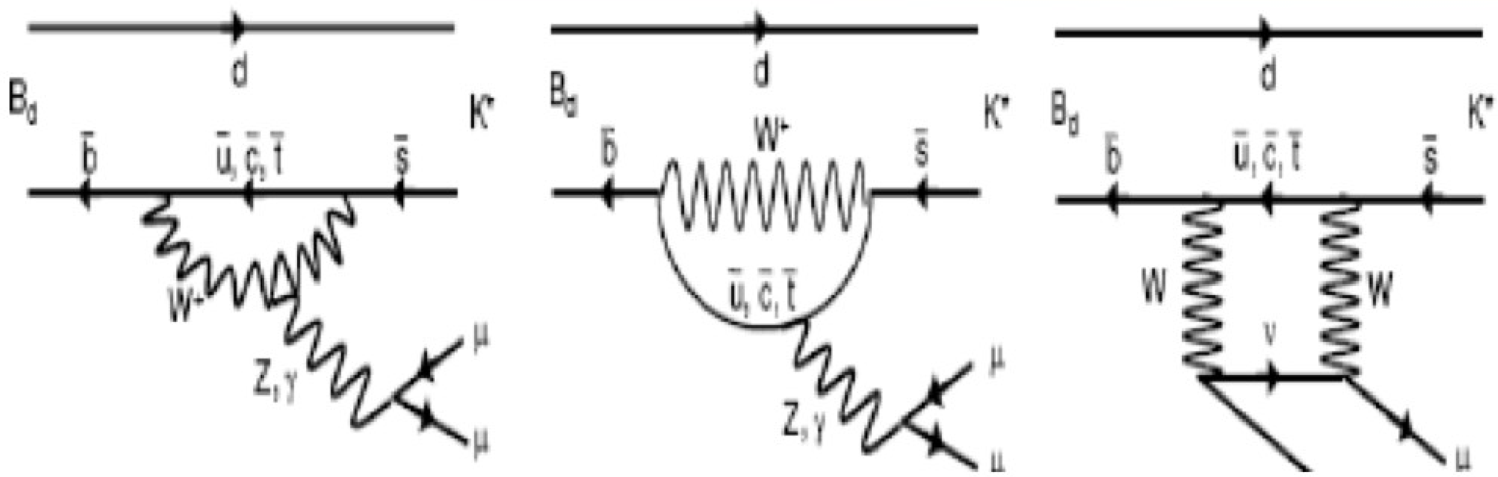
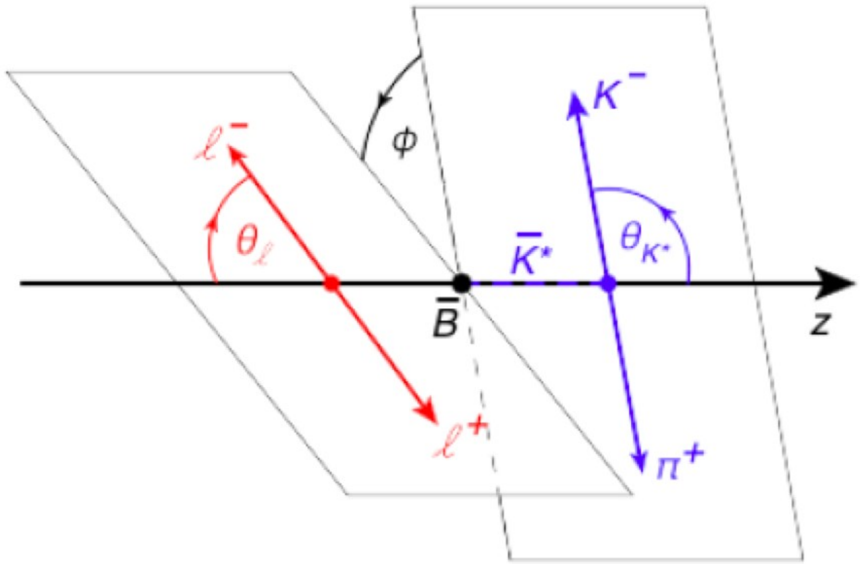
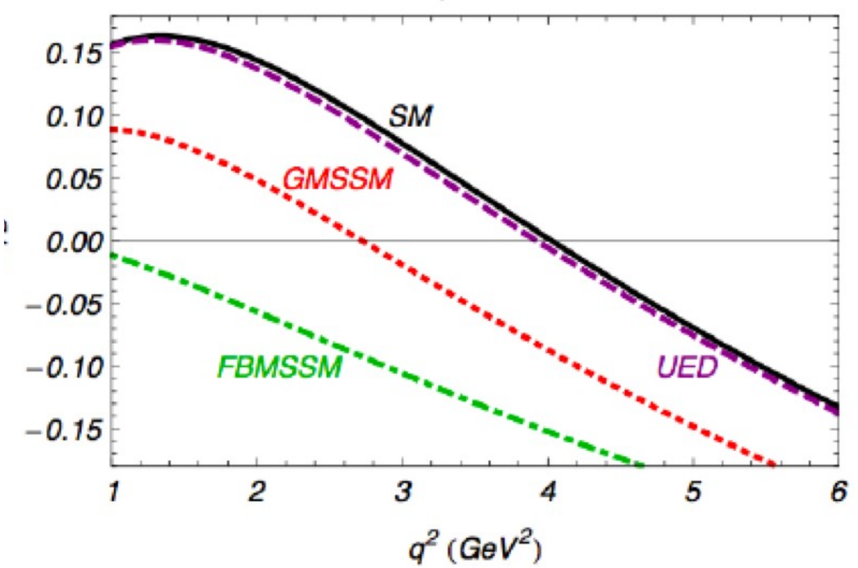
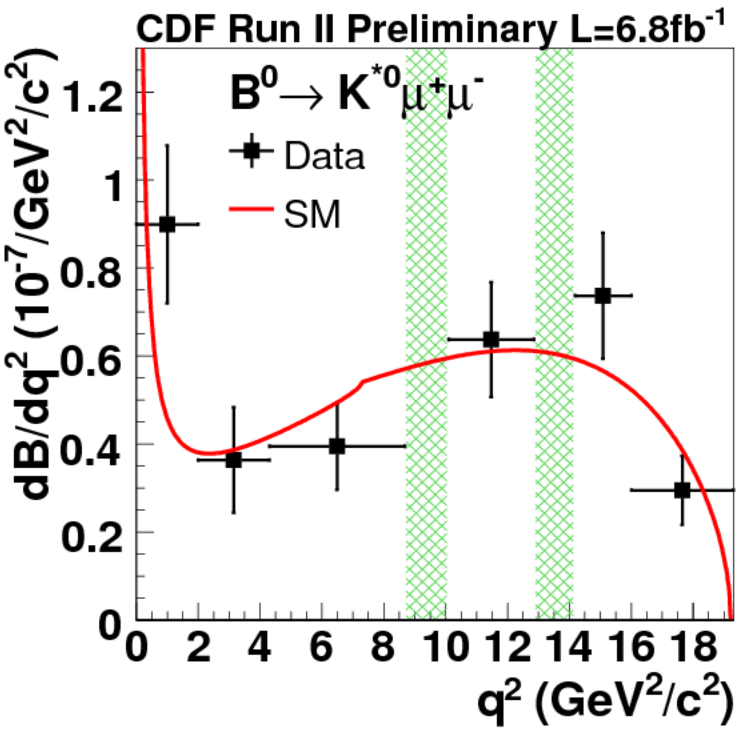
b→sl⁺l⁻


d
B_d
K*
b̄
ū, c̄, t̄
s̄
W+
Z, γ
μ
μ
d
B_d
K*
b̄
W+
s̄
ū, c̄, t̄
Z, γ
μ
μ
d
B_d
K*
b̄
ū, c̄, t̄
s̄
W
W
ν
μ

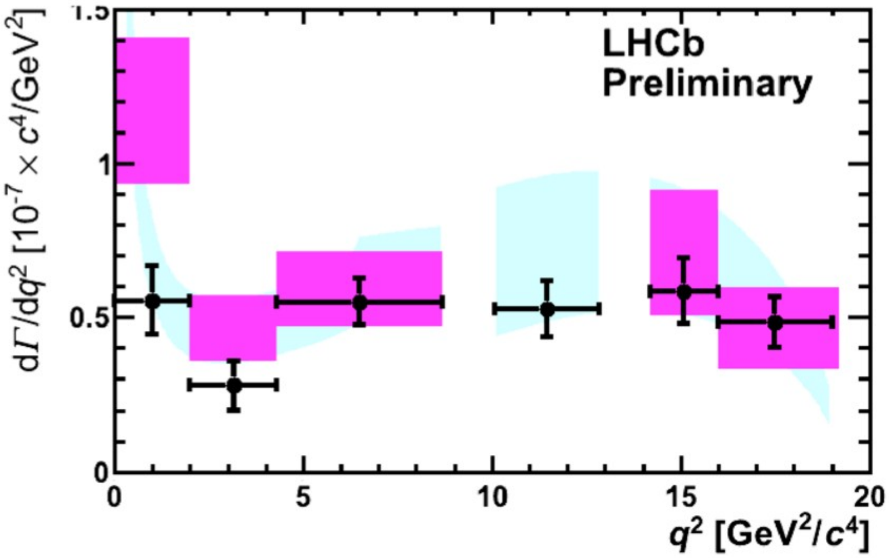

φ
K⁻
ℓ⁻
θ_ℓ
K̄*
θ_K*
B̄
z
ℓ⁺
π⁺


0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
SM
GMSSM
FBMSSM
UED
1
2
3
4
5
6
q² (GeV²)

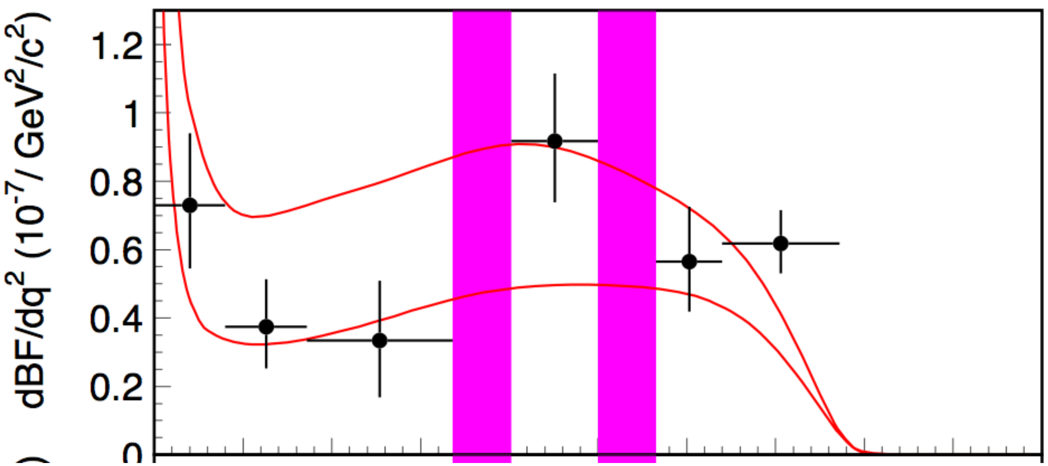
$b \to s l^+ l^-$



CDF Run II Preliminary L=6.8fb-1
B0→ K*0μ+μ-
Data
SM
dB/dq2 (10-7/GeV2/c2)
q2 (GeV2/c2)

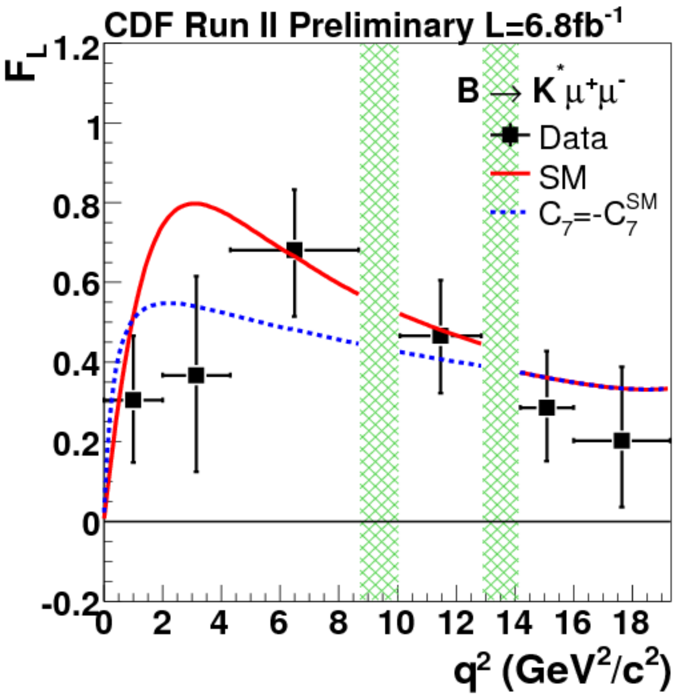


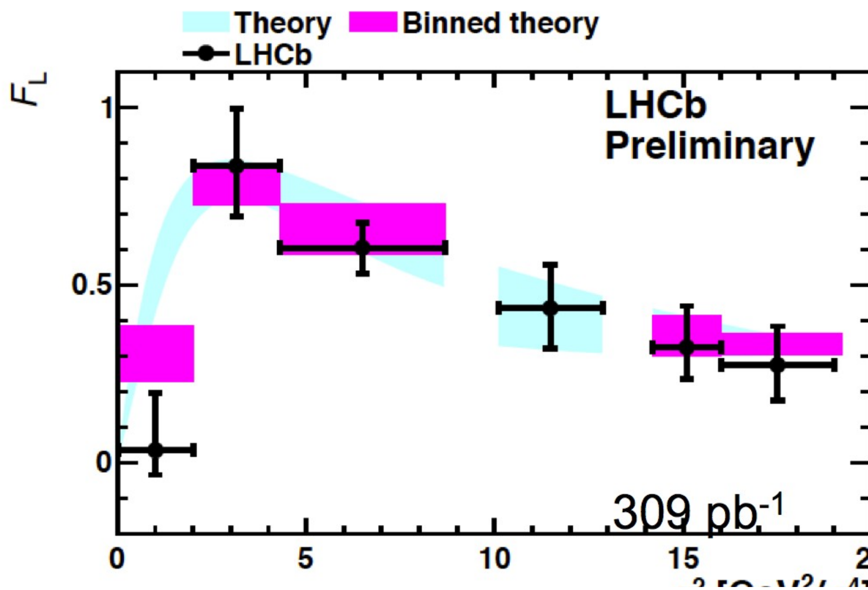
LHCb
Preliminary
dΓ/dq2 [10-7 × c4/GeV2]
q2 [GeV2/c4]

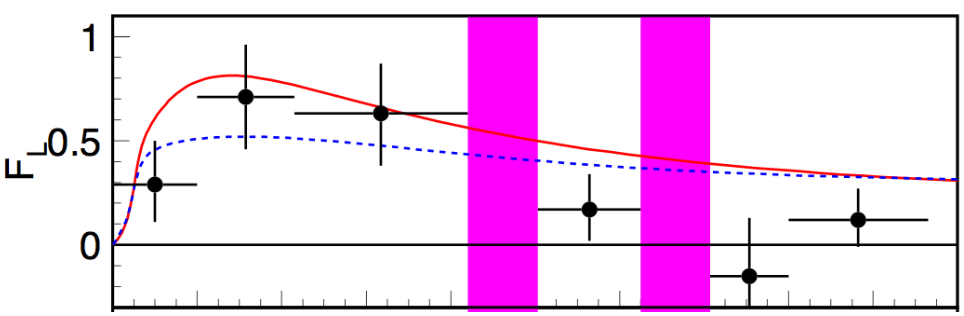


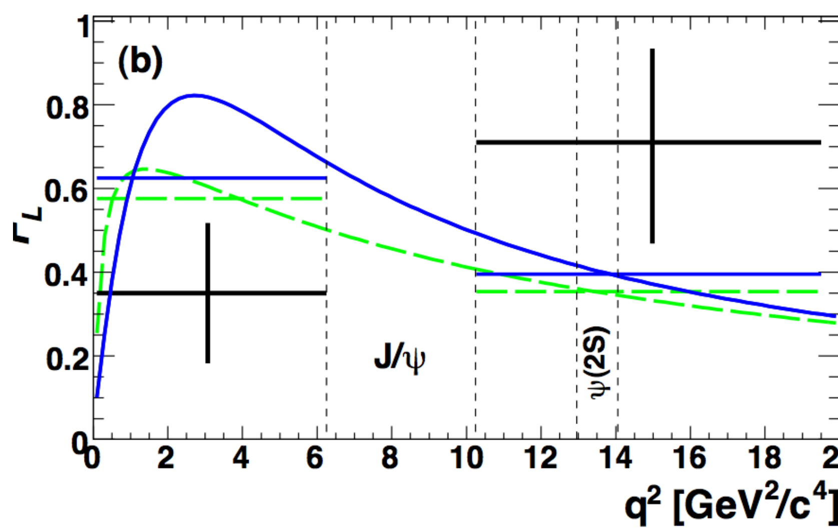
dBF/dq2 (10-7/ GeV2/c2)

$b \to s l^+ l^-$

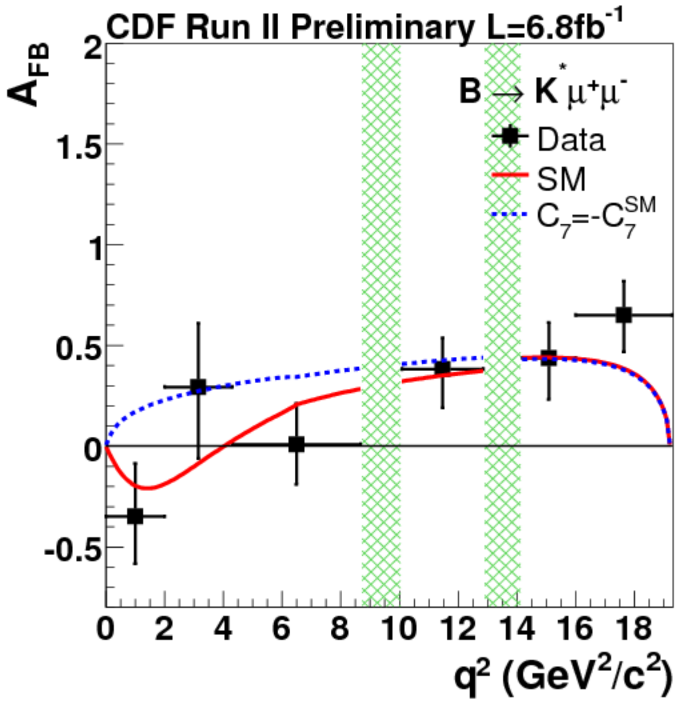

CDF Run II Preliminary L=6.8fb-1
F_L
B → K* μ+μ-
Data
SM
C7=-C7SM
q2 (GeV2/c2)

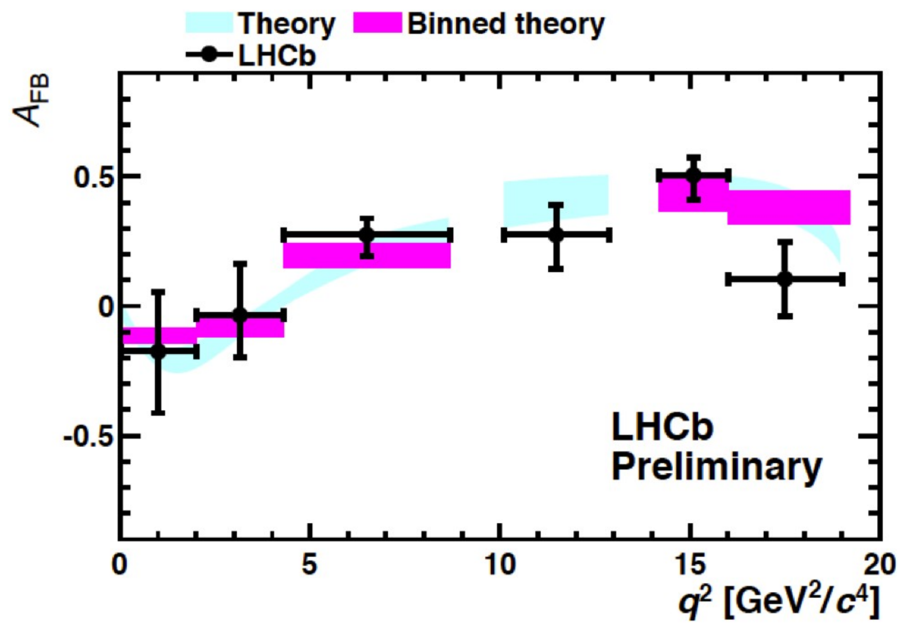

Theory
Binned theory
LHCb
F_L
LHCb
Preliminary
309 pb-1

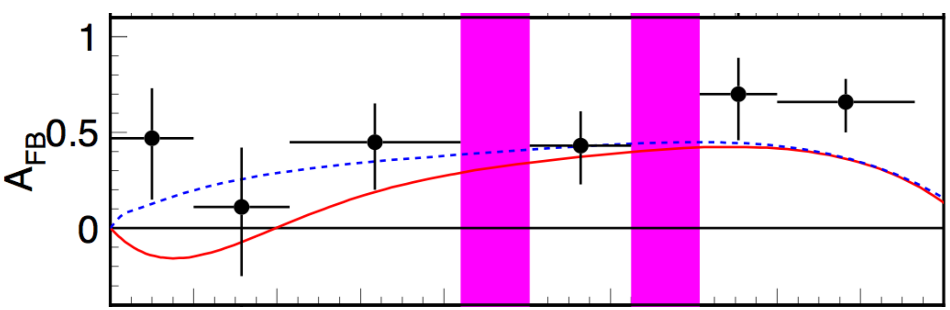

F_L

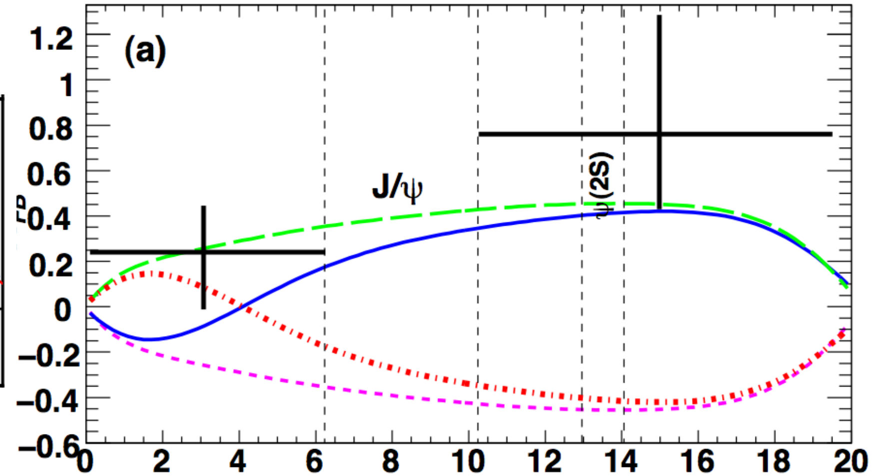

(b)
F_L
J/ψ
ψ(2S)
q2 [GeV2/c4]

$b \to s l^+ l^-$

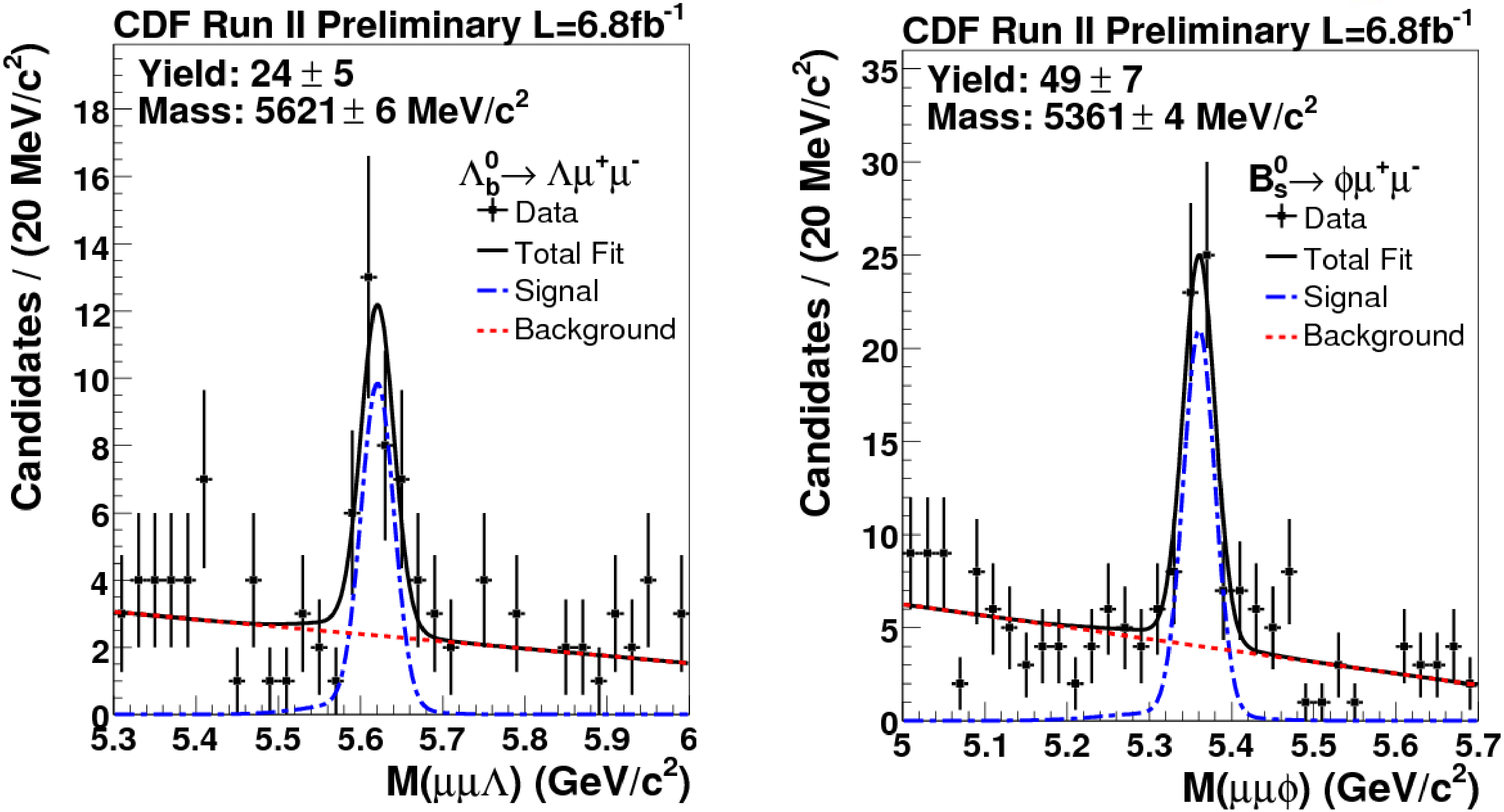

CDF Run II Preliminary L=6.8fb-1
A_FB
B → K* μ+μ-
Data
SM
C_7=-C_7^SM
q² (GeV²/c²)


Theory
Binned theory
LHCb
A_FB
LHCb
Preliminary
q² [GeV²/c⁴]


A_FB


(a)
J/ψ
ψ(2S)

$b \to s l^+ l^-$



$B(\Lambda_b^0 \to \Lambda\mu^+\mu^-) = [1.73 \pm 0.42(stat) \pm 0.55(syst)] \times 10^{-6}$

$B(B_s^0 \to \varphi\mu^+\mu^-) = [1.47 \pm 0.24(stat) \pm 0.46(syst)] \times 10^{-6}$

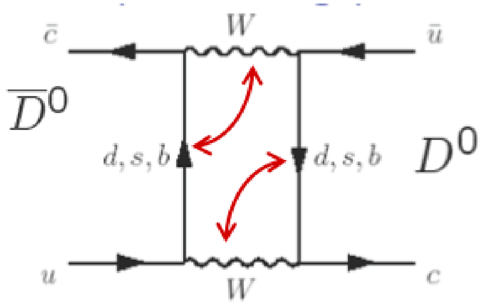
Charm mixing and CPV

- Basic physics is same as in B mixing
- Important because it tests down type quarks in loops
- Complementary to B mixing
- CP violation in SM is very small
  - Mixing in first two generations is real
  - Bottom quark contribution strongly CKM suppressed
- Theory predictions difficult as long distance contributions play important role
- Experiments resolving mixing difficult because of very slow mixing

Mixing in Standard Model is Very Small

- Off-diagonal mass matrix element – two leading terms:

$\Delta C=2$ (short-range)
(contributes mostly to x)



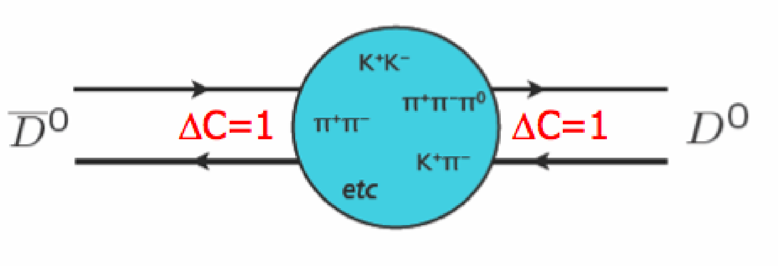
Down-type quarks in loop:

b : CKM-suppressed ($|V_{ub}V_{cb}|^2$)
d, s : GIM-suppressed

$$x \propto (m_s^2 - m_d^2)/m_c^2 \sim 10^{-5}$$

(almost 2 orders of magnitude less than current sensitivity)

Hadronic intermediate states (long-range)



Difficult to compute (need to know all the magnitudes and phases, ...)

Most computations predict x and y in the range 10^{-3}–10^{-2} and $|x|<|y|$

Recent predictions: $|x| \leq 1\%$, $|y| \leq 1\%$

(consistent with current observation)

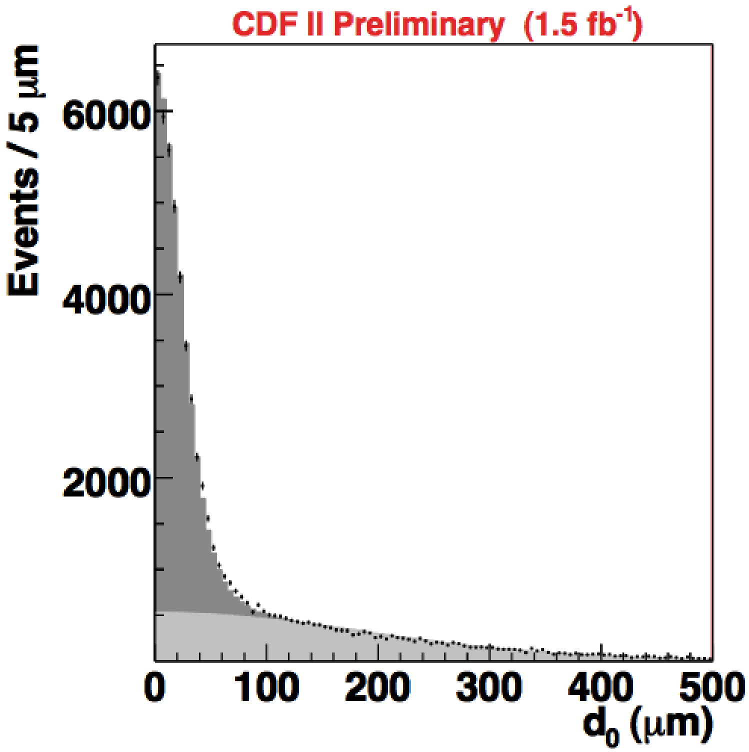
x_D, y_D at 1% consistent with SM, BUT
CPV at 10^{-3} levels would be signal for NP

$x=\Delta m/\Gamma$
$y=\Delta\Gamma/2\Gamma$

CKM 2010, U. Warwick, England, 09/08/2010

Brian Meadows

Charm mixing - technique

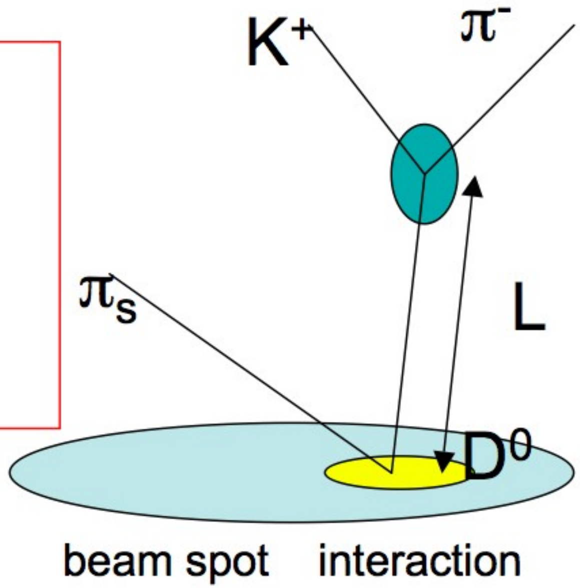


BaBar

3-D flight path

$L \sim 200\ \mu m$

$\sigma_L \sim 100\ \mu m$



Wrong Sign (WS) Decays $D^0 \rightarrow K^+\pi^-$

- The *WS* decay rate R_{WS} is:

$$R_{WS} = e^{-\Gamma t}|\mathcal{A}_{\bar f}|^2 \left[1 \;+\; \lambda_{\bar f} y'_D (\Gamma t) \;+\; \frac{|\lambda_{\bar f}|^2}{4}(x'^2_D + y'^2_D)(\Gamma t)^2 \right]$$

Direct decay — Interference — Decay through Mixing

- Since $|\lambda_{\bar f}| >> 1$, all three terms are comparable

- For "right-sign" (*RS*) decays $D^0 \rightarrow K^-\pi^+$ though, $|\lambda_f| << 1$, so 2nd two terms are negligible and R_{RS} is approximately exponential. $R_{RS} \approx e^{-\Gamma t}|\mathcal{A}_f|^2$

Charm mixing in DCS decays

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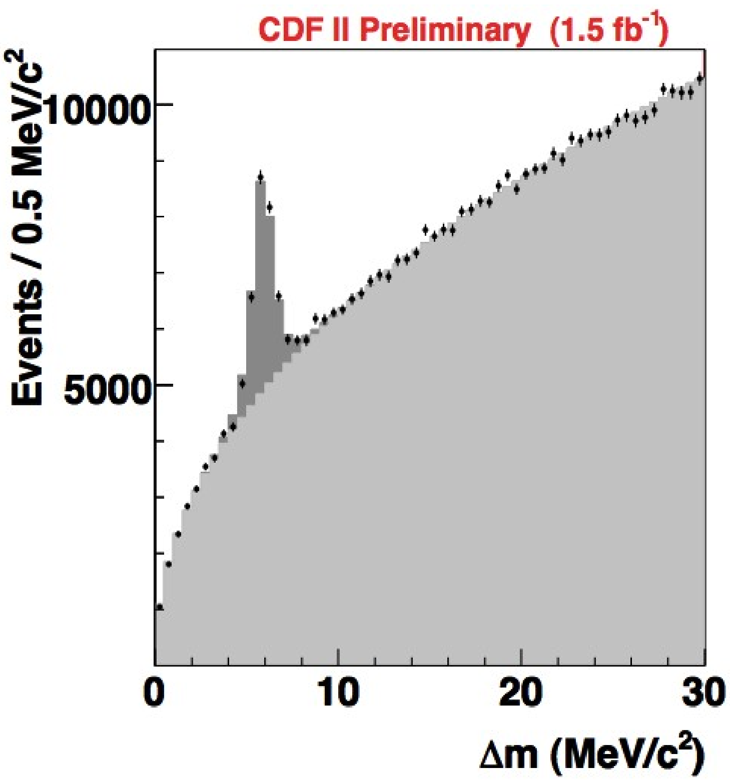
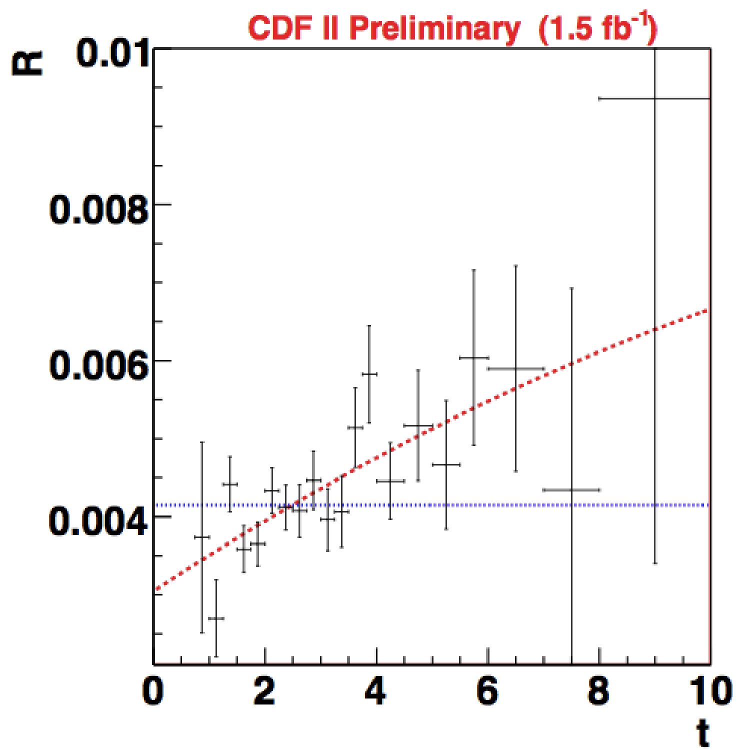
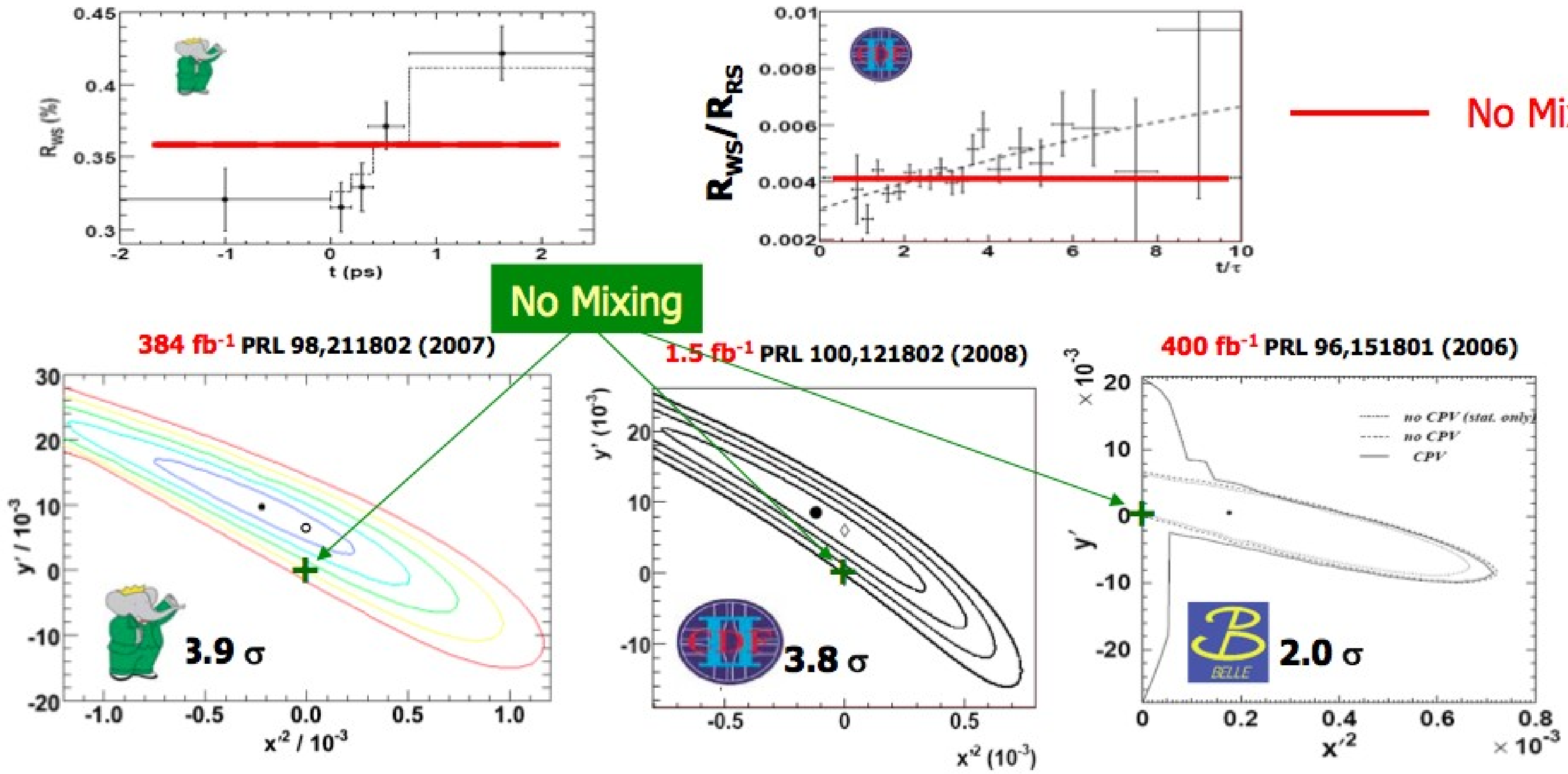




Evidence for Mixing in $D^0 \rightarrow K^+\pi^-$

Mixing seen by Babar and CDF in time-dependence of the R_{WS}/R_{RS} ratio



Belle result was the most sensitive, BUT evidence for mixing not significant !

CKM 2010, U. Warwick, England, 09/08/2010

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Charm mixing - global status

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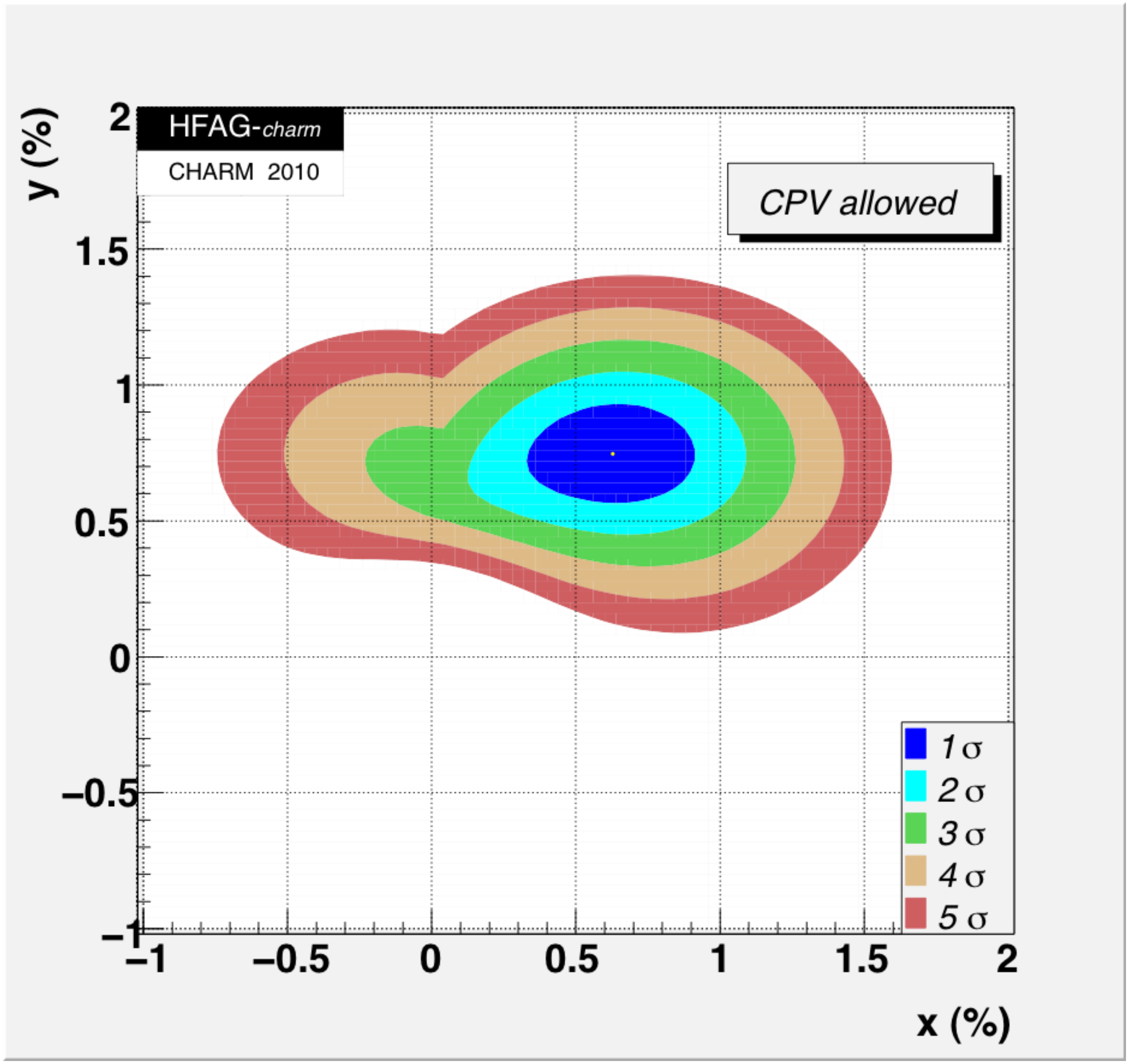

$x = \Delta m / \Gamma$

$y = \Delta\Gamma / 2\Gamma$

Charm CPV

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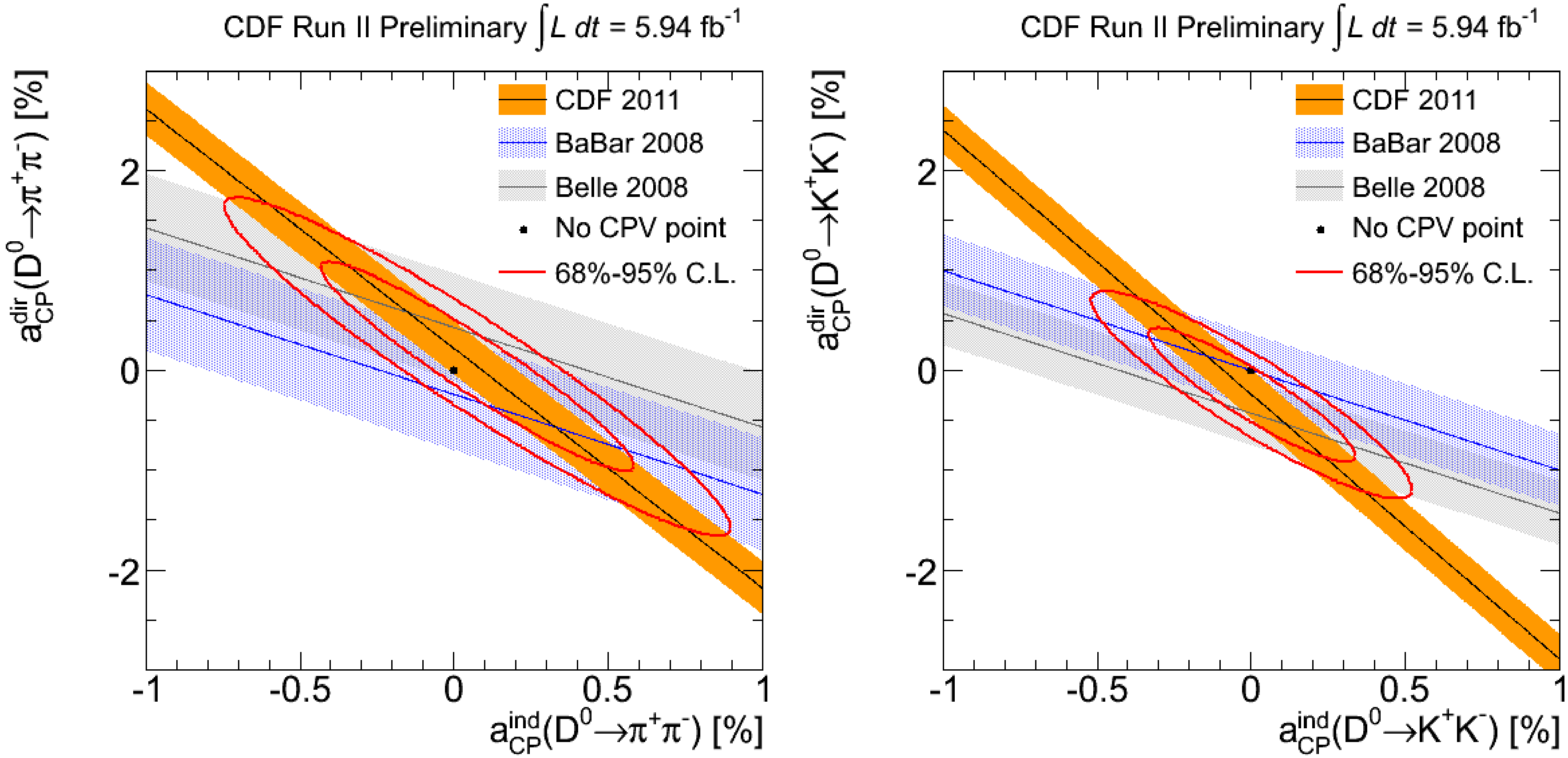
- Concentrate on D^0 here
- What is usually done is time integrated measurement in common final state
  - Tagged by D^*
- Time integrated measurements sensitive also to time-dependent CPV as oscillation is very slow

$$A_{CP}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}.$$

$$A_{CP}(h^+h^-) = a_{CP}^{\mathrm{dir}}(h^+h^-) + \int_0^\infty A_{CP}(t)D(t)dt \approx a_{CP}^{\mathrm{dir}}(h^+h^-) + \frac{\langle t\rangle}{\tau} a_{CP}^{\mathrm{ind}}(h^+h^-).$$

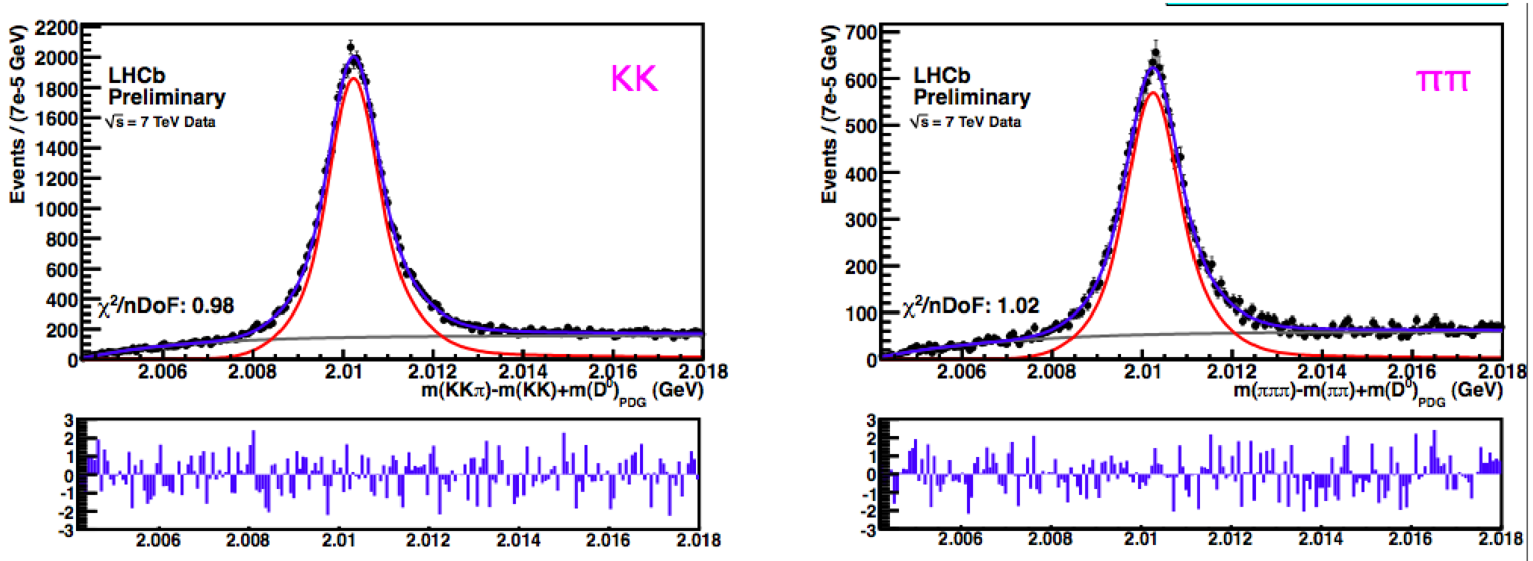
- Method uses also Kπ decays to measure detector asymmetry
- LHCb has additional complication of production asymmetry

CDF result


CDF Run II Preliminary $\int L\,dt$ = 5.94 fb^{-1}
CDF 2011
BaBar 2008
Belle 2008
No CPV point
68%-95% C.L.
$a_{CP}^{dir}(D^0 \to \pi^+\pi^-)$ [%]
$a_{CP}^{ind}(D^0 \to \pi^+\pi^-)$ [%]
CDF Run II Preliminary $\int L\,dt$ = 5.94 fb^{-1}
CDF 2011
BaBar 2008
Belle 2008
No CPV point
68%-95% C.L.
$a_{CP}^{dir}(D^0 \to K^+K^-)$ [%]
$a_{CP}^{ind}(D^0 \to K^+K^-)$ [%]

LHCb charm CPV

- Measure difference A(KK)-A(ππ)
- Detector and production asymmetry cancels in first order
- Mainly sensitive to direct CP violation as indirect is independent of final state



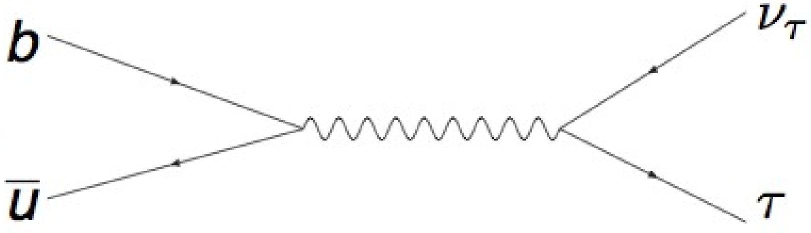
Preliminary: 2010 data, 38 pb^{-1}

$$A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.275 \pm 0.701 \pm 0.25)\%$$

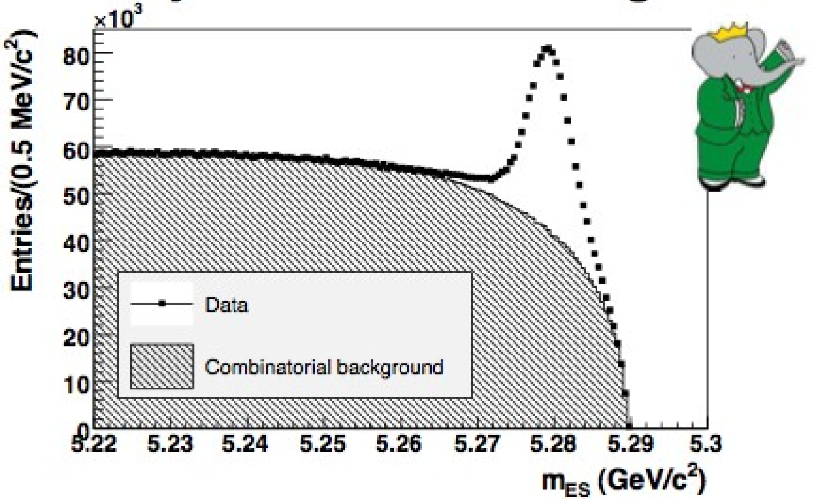
$B \to \tau\nu$

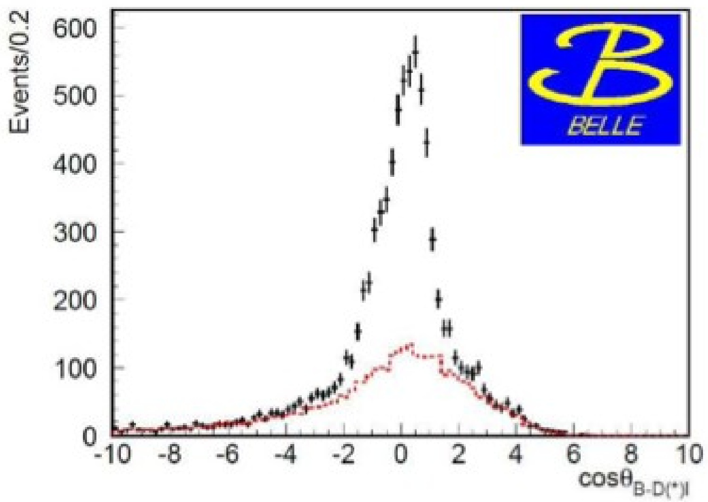
- SM branching fraction given by

  $$BF = \frac{G_F^2 m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$



- One can extract f_B or $|V_{ub}|$
- SM $BF = 1.20 \pm 0.25 \times 10^{-4}$
- Practically only B-factories thanks to clean environment
- After reconstructing tag B and all charged particles from signal B, only neutrinos missing





$B \to \tau\nu$

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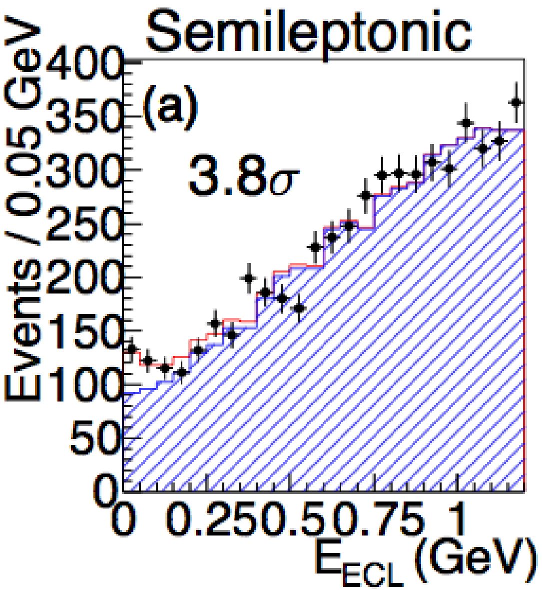
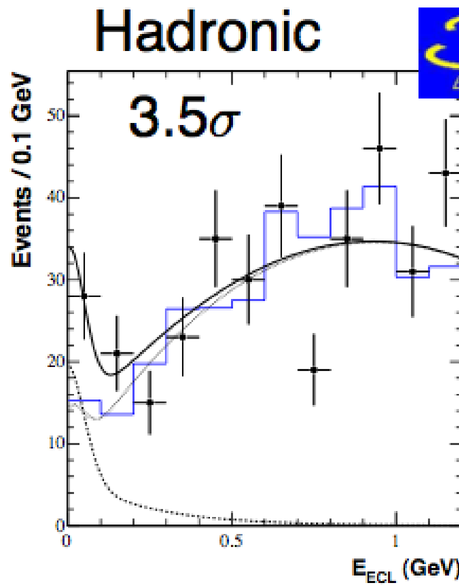




S: $1.65^{+0.38}_{-0.37}\,^{+0.35}_{-0.37} \times 10^{-4}$

H: $1.79^{+0.56}_{-0.49}\,^{+0.46}_{-0.51} \times 10^{-4}$

hep-ex/0809.3834,

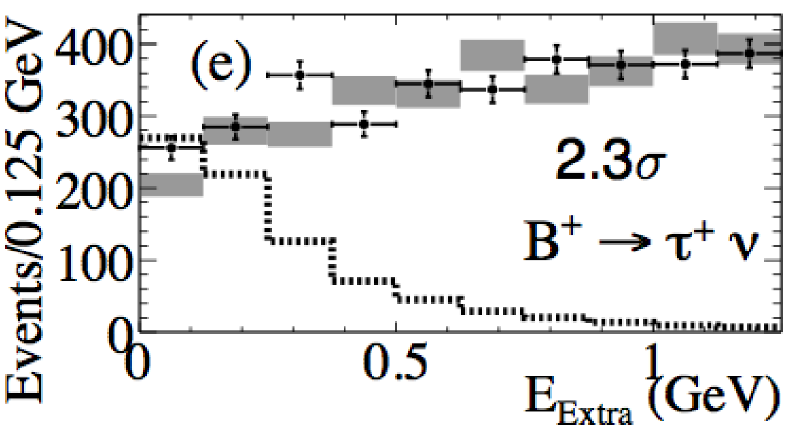
PRL 97, 251802 (2006)

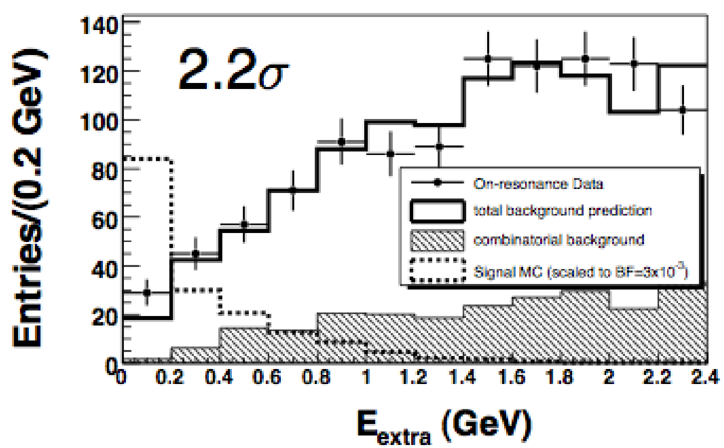
S: $1.7 \pm 0.8 \pm 0.2 \times 10^{-4}$

H: $1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2 \times 10^{-4}$

PRD 81, 051101 (2010)

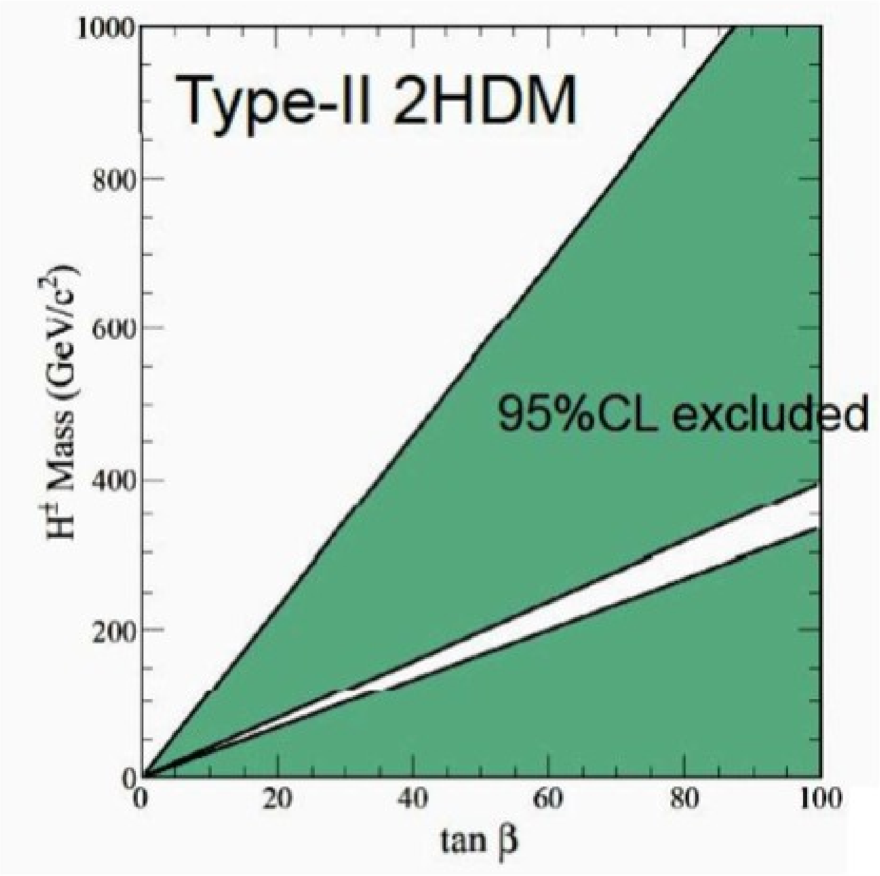
PRD 77, 011107 (2008)





$B \to \tau\nu$

- Naive average of exp. results
  $BF_{exp} = 1.73 \pm 0.35 \times 10^{-4}$
- SM prediction
  $BF_{SM} = 1.20 \pm 0.25 \times 10^{-4}$
- Effect of charged Higgs
  $BF_{exp} = BF_{SM} \times r_H$
  $$r_H = \left(1 - \frac{m_B^2 \tan^2\beta}{m_H^2} \frac{1}{1+\epsilon_0 \tan\beta}\right)^2$$
- For Type-II 2HDM $\epsilon_0 = 0$



Global status of the triangle

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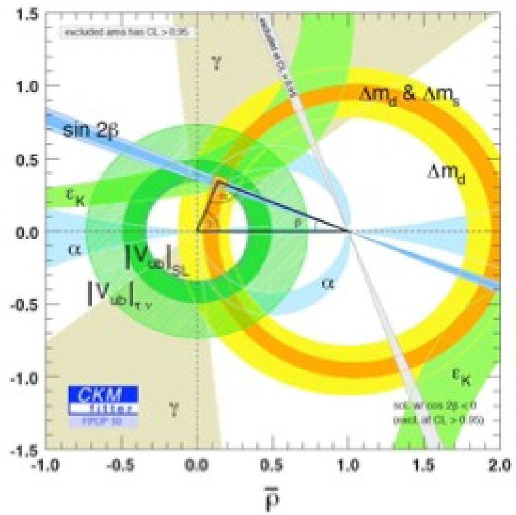
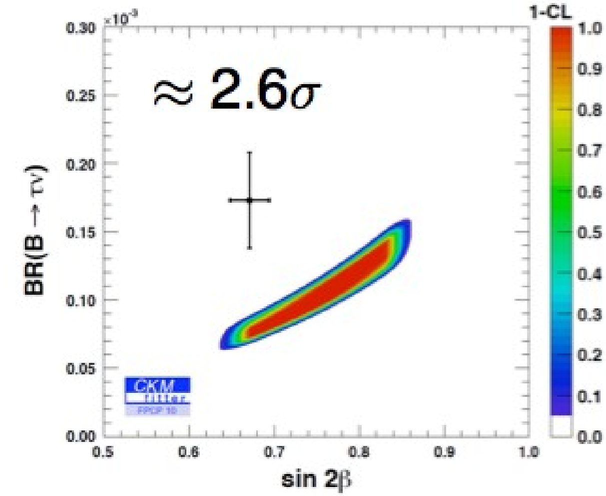
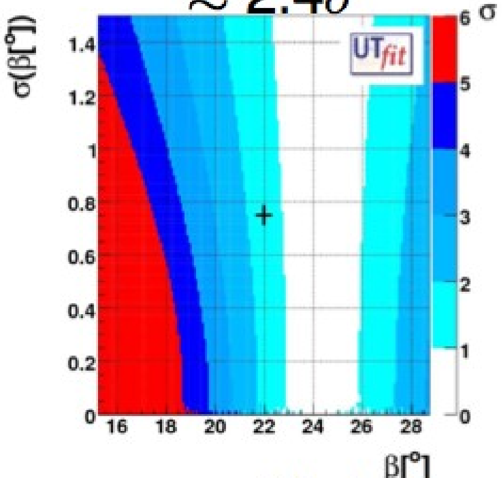


≈ 2.6σ

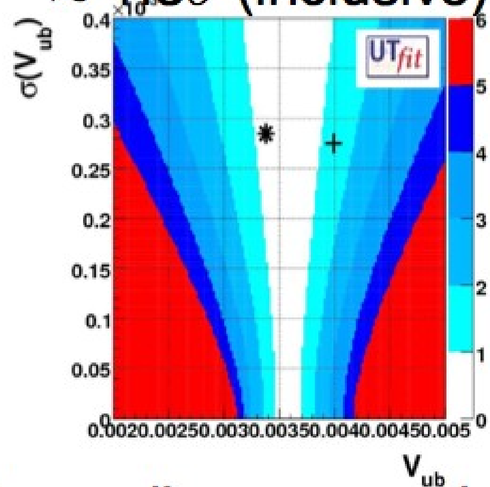


ckmfitter.in2p3.fr

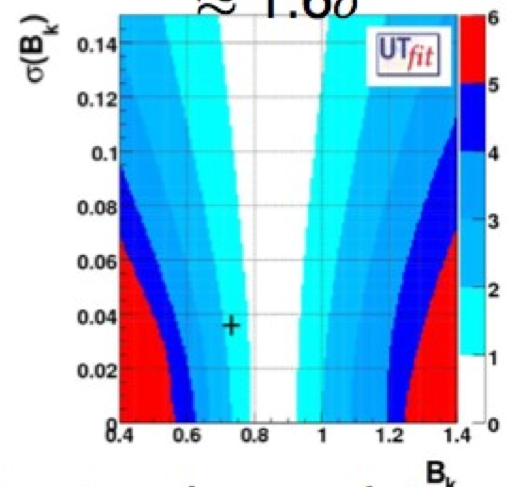
≈ 2.4σ



≈ 1.3σ (inclusive)



≈ 1.6σ



www.utfit.org

Globally no large discrepancy, but few tensions exist

Final remarks

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- Lot of work was done in last few years to discover new physics
- Many places where some tension with SM was observed with small statistics
- Latest results from this summer now agree quite well with SM
- Despite the agreement with SM, there is still quite some room for new physics