Heavy flavors at the LHC

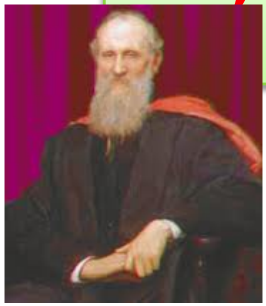
A review

Marina Artuso

Disclaimer

- Approach to this talk illustrative not encyclopedic
- Some topics excluded altogether:
  - ❑Onia
  - ❑Charm mixing and several CPV channels
  - ❑Open charm production
  - ❑Exclusive hadronic decays
- Much more information in parallel section talkand plenary talks by Stone and Jawahery

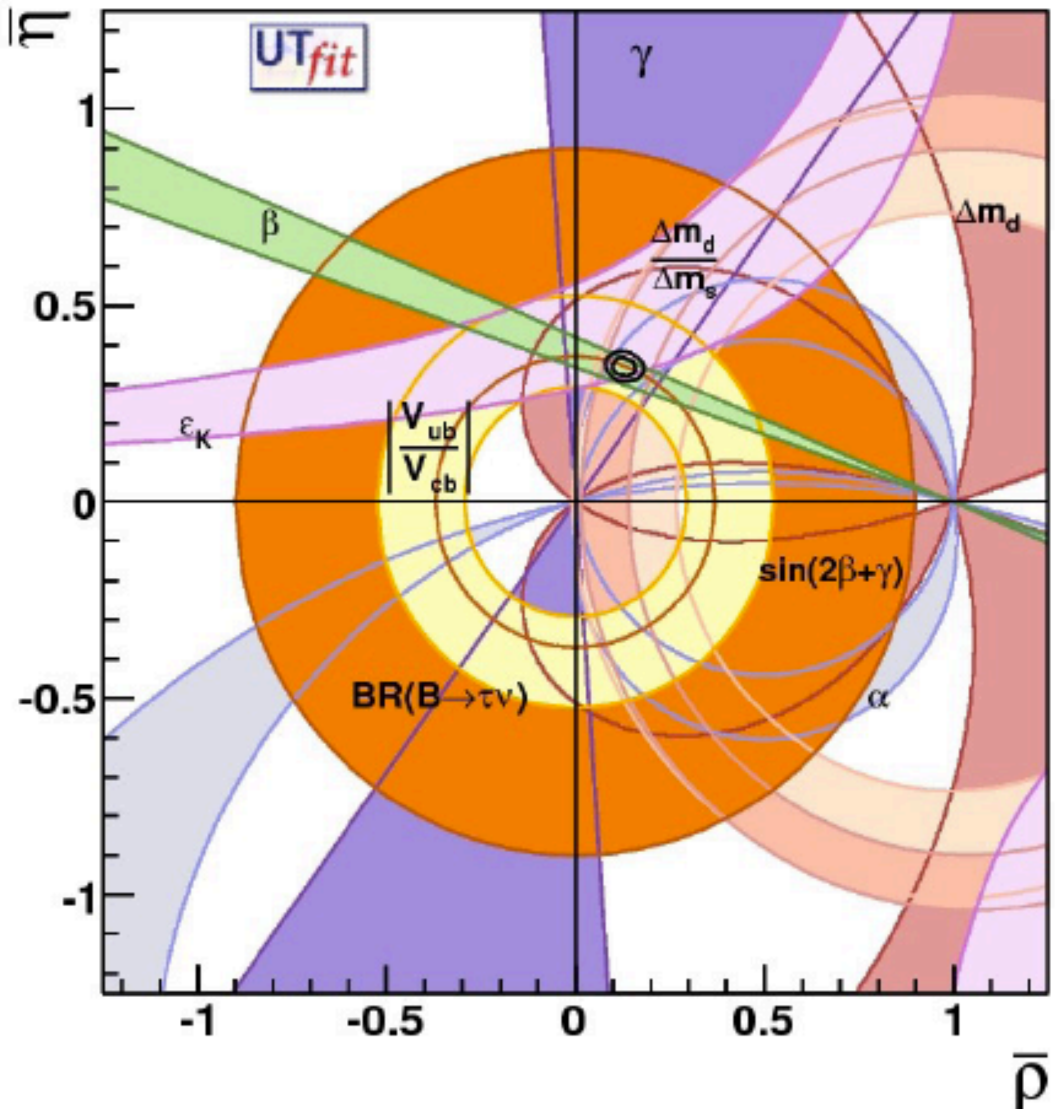
Prologue: a little bit of history



In 1900, Lord Kelvin famously stated, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

Five years later, Albert Einstein published his paper on special relativity, which challenged the very simple set of rules laid down by Newtonian mechanics

A parable for flavor physics? The CKM saga



A triumph for the Standard Model?

levels @ 95% Prob

$\bar{\rho} = 0.129 \pm 0.022$

$\bar{\eta} = 0.346 \pm 0.015$

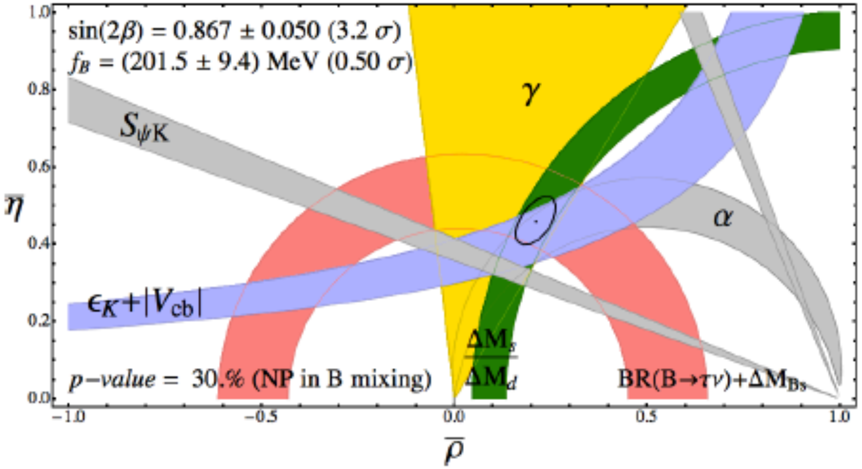
$\beta = (22 \pm 1)°$

$\gamma = (69 \pm 3)°$

$\alpha = (89 \pm 3)°$

But consistency not so clear

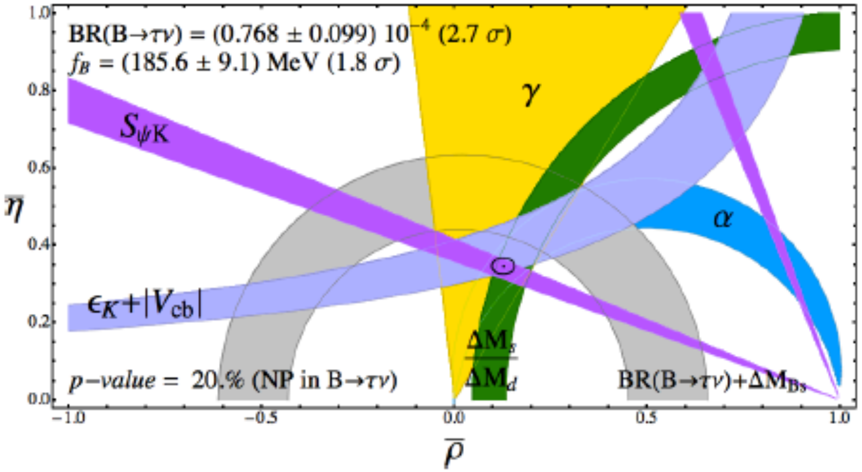
Lunghi-Soni arXiv:1104.2117v3 [hep-ph]



$$\sin(2\beta)^{fit} = 0.867 \pm 0.050$$

EPS 2011 Babar Belle Average

$\sin 2\beta(J/\psi K^0) = 0.667 \pm 0.021$

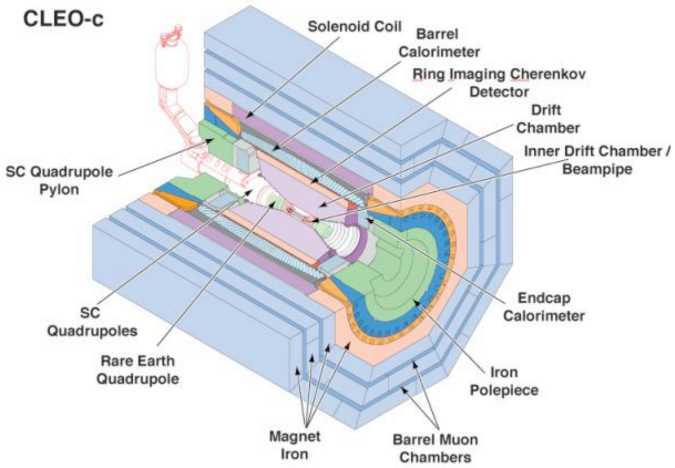


$$BR(B \to \tau\nu)^{fit} = (0.768 \pm 0.099) \times 10^{-4}$$

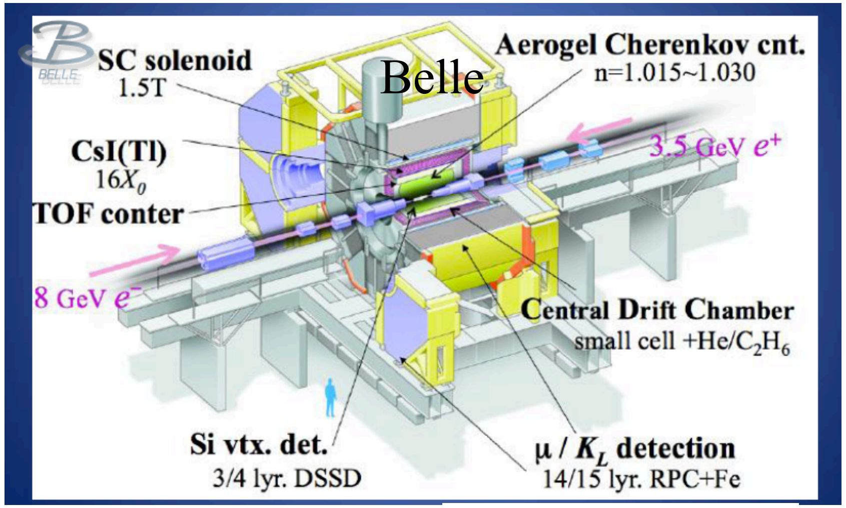
current HFAG world average

$BR(B \to \tau\nu) = (1.64 \pm 0.34)\ 10^{-4}$

A tribute to the e^+e^- b-factories



CLEO/CLEO-c 9.1 fb^{-1}+ 4.4 fb^{-1} at or just below Y (4S), 4.4 fb^{-1} cont , 0.82 fb^{-1} ψ”,0.60 at E_{cm}=4.170 GeV



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

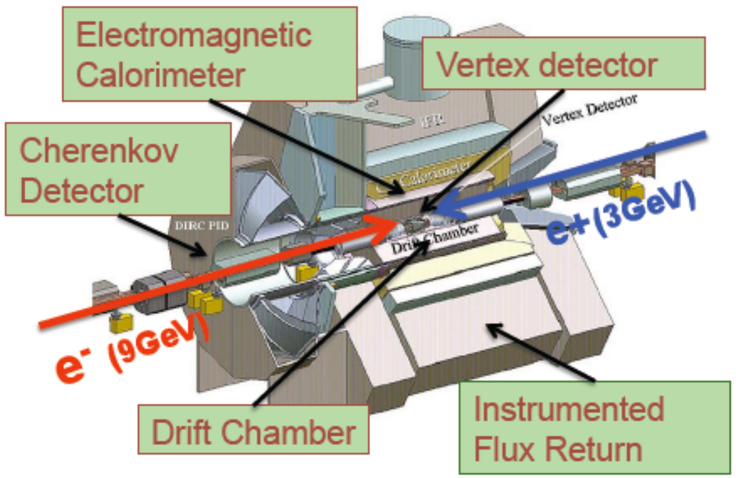
$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}



BaBar

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

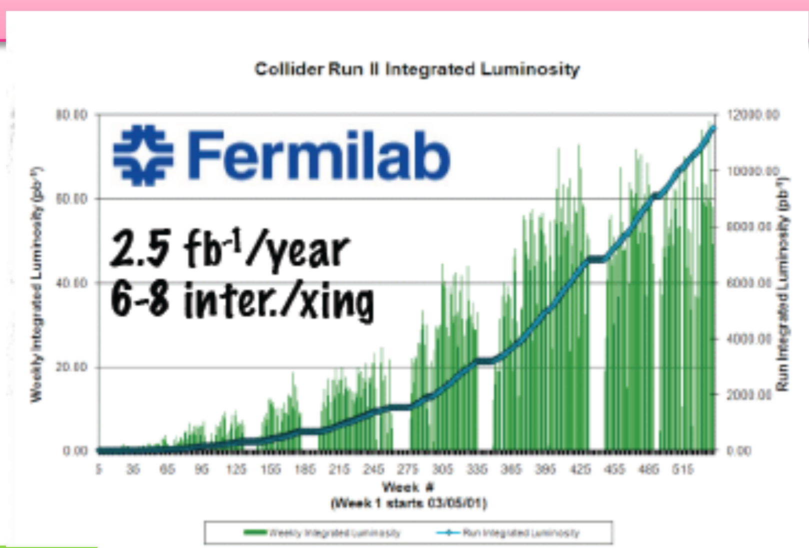
$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

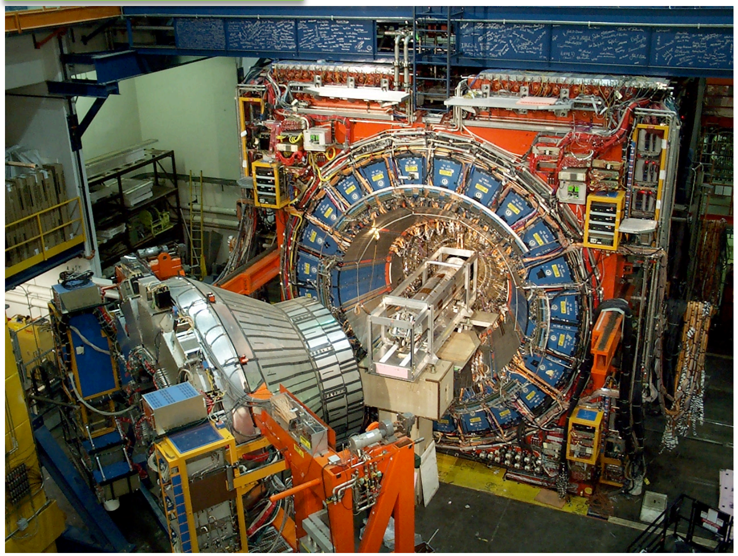
And the Tevatron



12 fb^{-1} at end of operation (September 2011)

D0

CDF

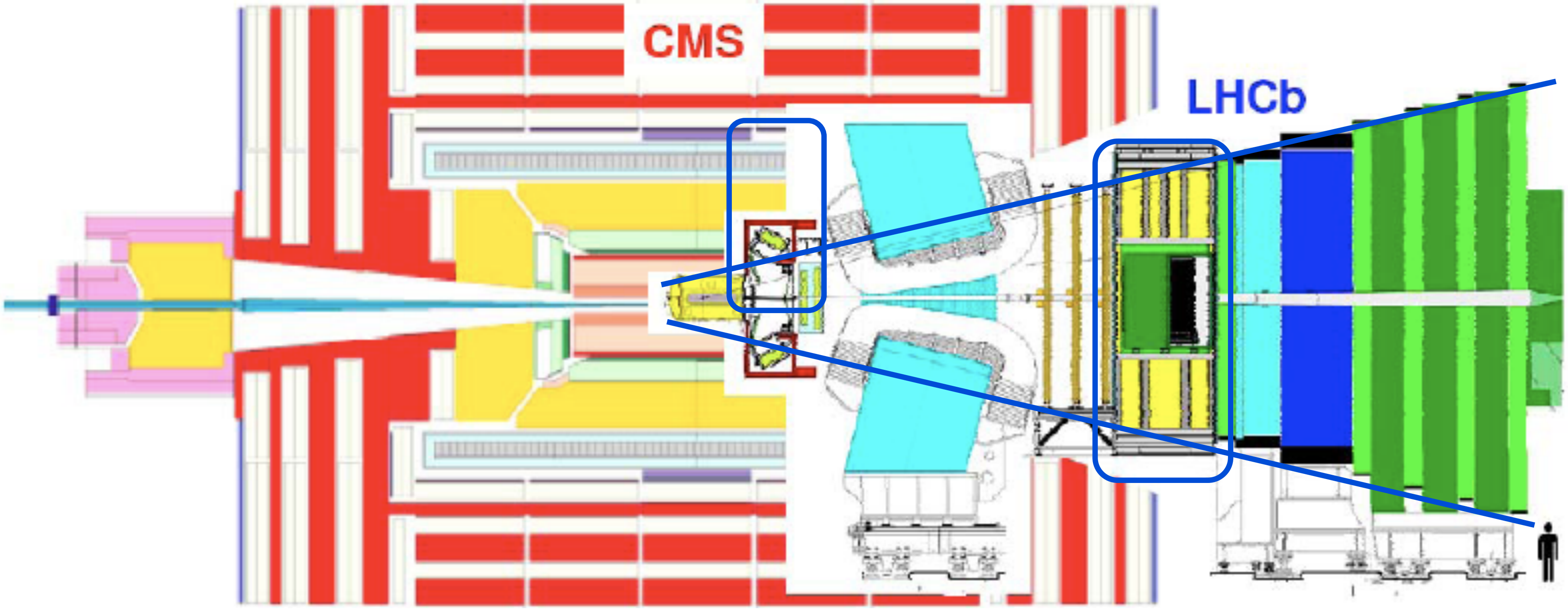


Starting a new era: the dawn of LHC

Atlas and CMS are general purposed detectors, b-physics capabilities based on vertexing and good lepton ID.

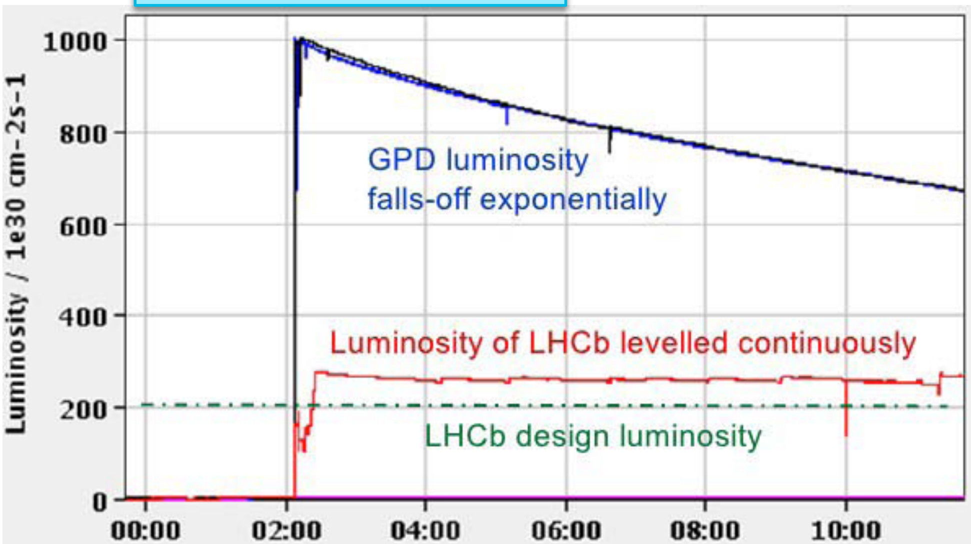
Important new addition: LHCb first dedicated detector to pursue search for new physics in beauty and charm decays. Important LHCb features:

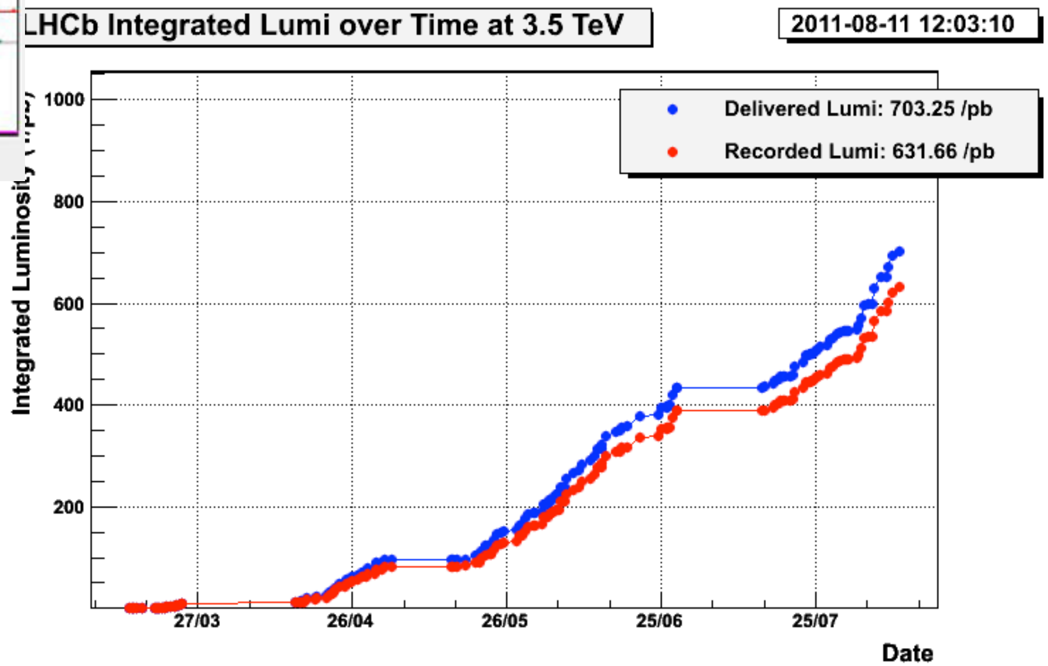
- ✓ particle detection in the forward region (down to beam-pipe)
- ✓ special particle identification capability in particular for hadrons due to RICH detector
- ✓ precise vertexing



LHC operation, a snapshot

Running conditions





The pillars: from quarks to hadrons

QCD at work:

- b-hadron production
- Hadronic decays
- Exotic final states

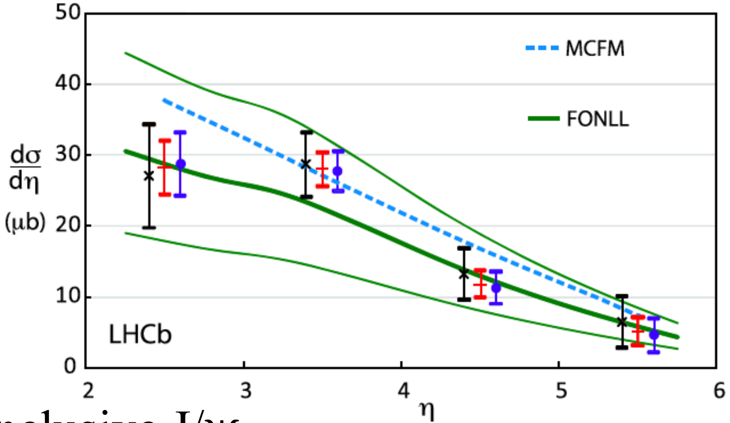
LHCb measurements of the b-hadron cross section

- LHCb measures b-hadron cross section in good agreement with state of the art perturbative QCD calculations (FONNL).

Phys.Lett.B694:209-216,2010

$\sigma(pp \to b\bar{b}X)$

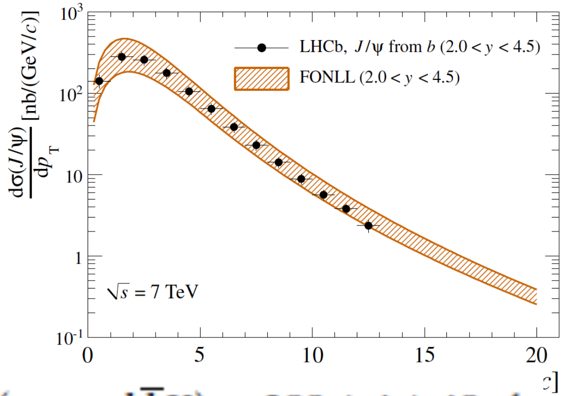
From $D^0\mu\nu X$



η	σ(μb)Theory I	σ(μb)Theory II	Measured σ(μb)
2,6	89.0	70.2	75.3 ± 5.4 ± 13.0
All	332	253	284 ± 20 ± 49

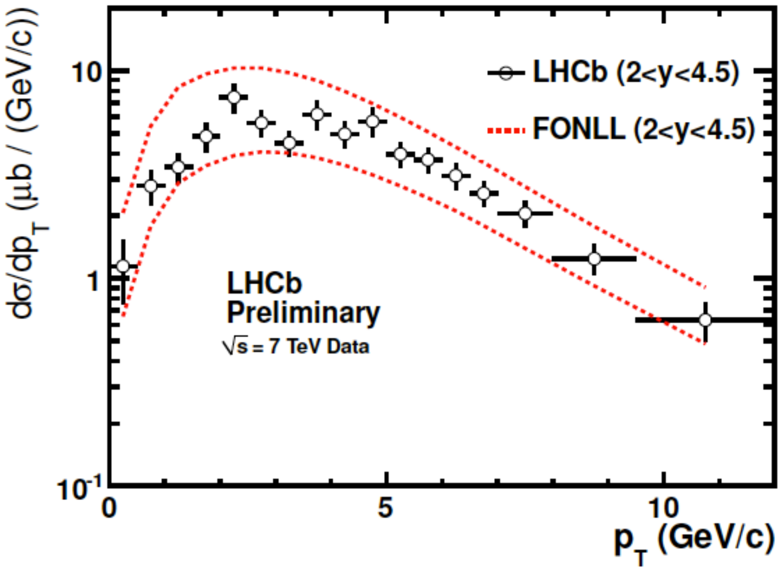
$\sigma(B^+, 2 < y < 4.5) = 37.1 \pm 1.9(\mathrm{stat.}) \pm 5.3(\mathrm{syst.})\,\mu b.$ from $B^{\pm} \to J/\psi K^{\pm}$

Inclusive J/ψ

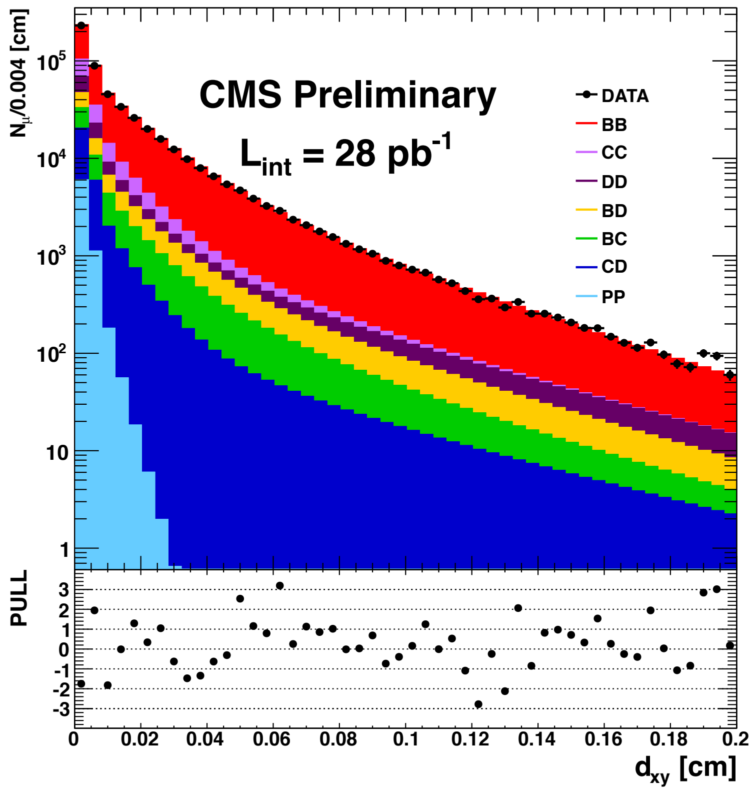


$\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\,\mu b,$

Eur.Phys.J.C71:1645,2011

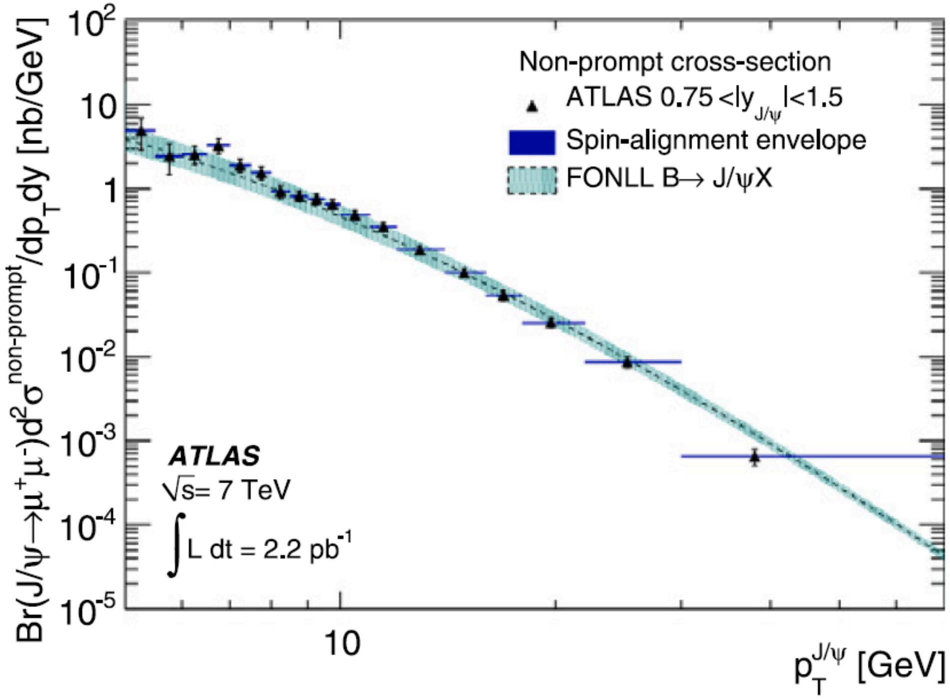


Complementary measurements from ATLAS and CMS



$$\sigma(pp \to b\bar{b}X \to \mu\mu Y) = 26.18 \pm 0.14\,(\mathrm{stat.}) \pm 2.82\,(\mathrm{syst.}) \pm 1.05\,(\mathrm{lumi.})\ \mathrm{nb}$$

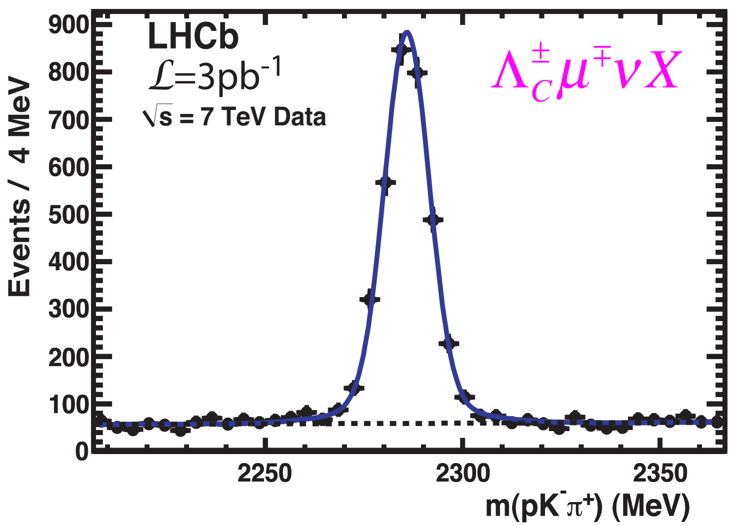
ATLAS

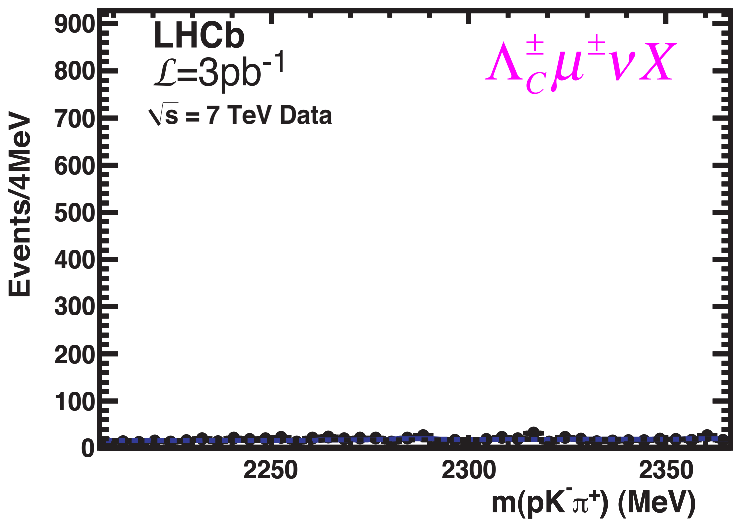


Also in the kinematic region studied by CMS and ATLAS FONNL gives a good description of the data

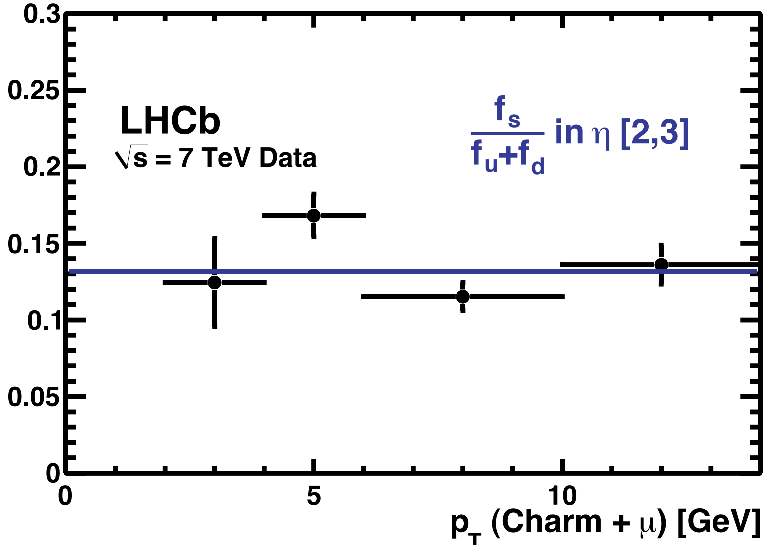
b-hadron production fractions

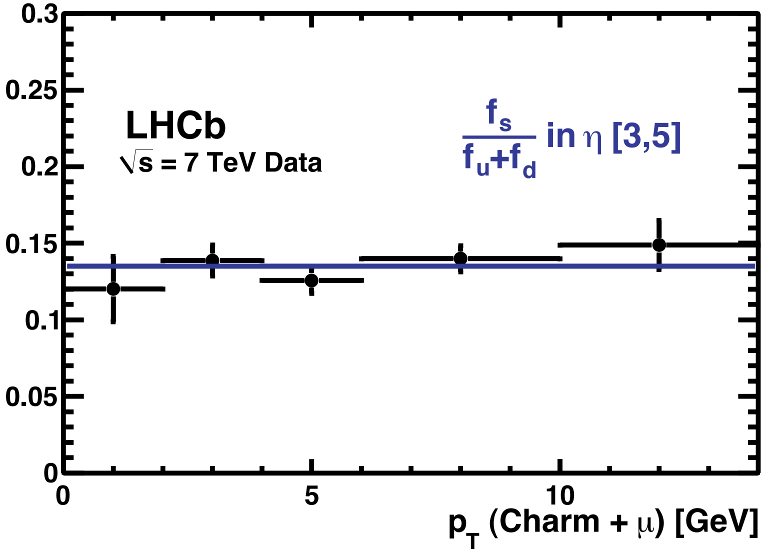
- b-fractions measured from charm-μ final states:
  - ❑ B^0+B^+ mostly $D^0\mu\nu$+$D^+\mu\nu$
  - ❑ B_s mostly $D_s\mu\nu$
  - ❑ Λ_b mostly $\Lambda_c\mu\nu$
- taking into account all the possible cross-feeds:
  - ❑ $D^{0,\pm}K\mu\nu$ (B^0,B^+,B_s)
  - ❑ D_sK (B^0,B^+, B_s)
  - ❑ $D^0p(n)$ (B^0,B^+, Λ_b)





$$f_s/(f_u+f_d)=0.134\pm0.004^{+0.012}_{-0.011}$$





Systematic error breakdown

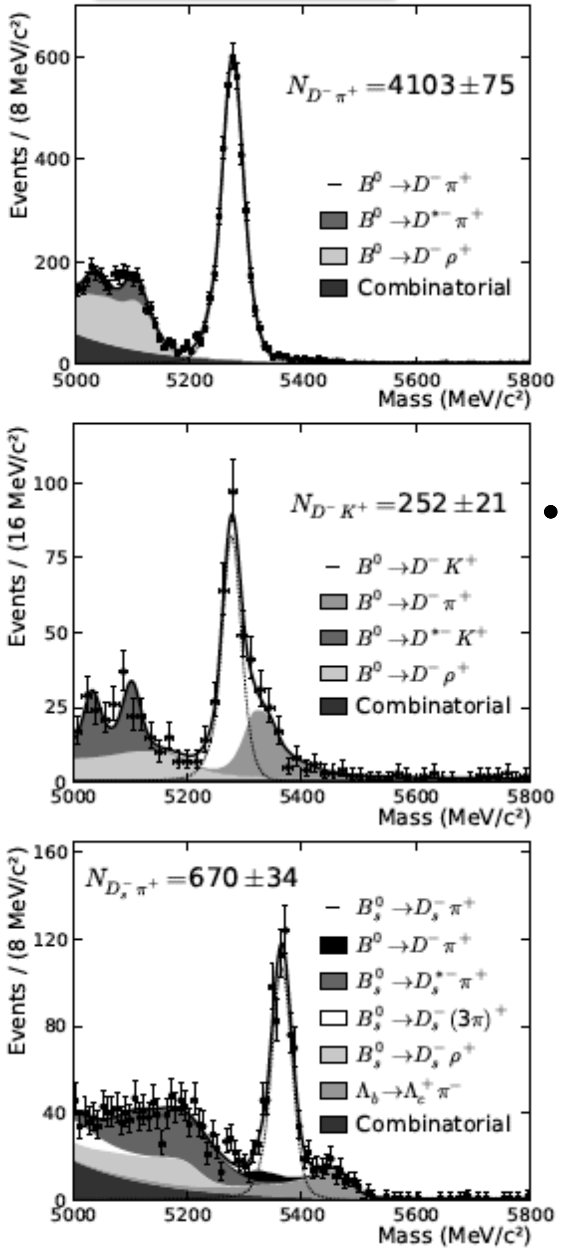
Source	Error (%)
Bin dependent errors	1.0
Charm hadron branching fractions	5.5
B_s semileptonic decay modeling	3.0
Backgrounds	2.0
Tracking efficiency	2.0
Lifetime ratio	1.8
PID efficiency	1.5
$\overline{B}^0_S \to D^0 K^+ X \mu^- \overline{\nu}$	$^{+4.1}_{-1.1}$
$(B^-, \overline{B}^0) \to D_s^+ K X \mu^- \overline{\nu}$	2.0
Total	$^{+8.6}_{-7.7}$

LEP: 0.128 ± 0.012
Tevatron: 0.156 ± 0.026 (HFAG)

***$f_s/(f_u+f_d)$* doesn't depend on η or p_T (charm+μ)**

LHCb determination of f_s/f_d

arXiv:1106.4435.



$$\frac{f_s}{f_d}(D_s\mu\nu X)=0.268\pm0.008^{+0.024}_{-0.022}$$

LHCb has two other measurements:

$$\frac{BF(B_s^0\to D_s^-\pi^+)}{BF(B^0\to D^-K^+)}=0.250\pm0.024(stat)\pm0.017(syst)\pm0.017(theor)$$

$$\frac{BF(B_s^0\to D_s^-\pi^+)}{BF(B^0\to D^-\pi^+)}=0.256\pm0.014(stat)\pm0.019(syst)\pm0.026(theor)$$

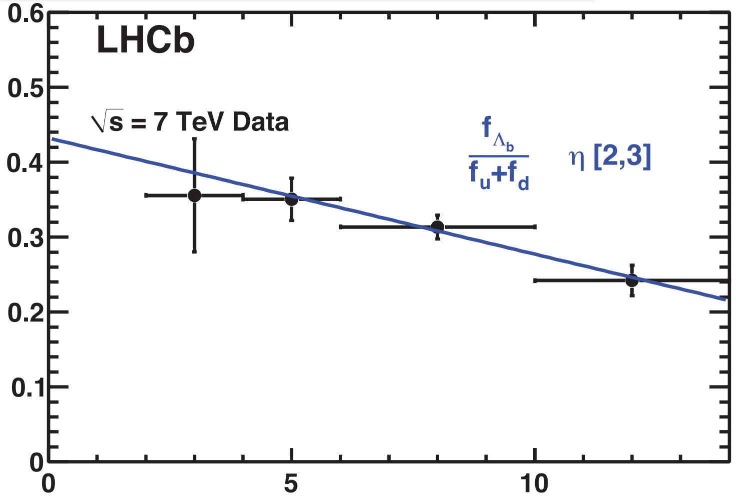
- We average the 3 LHCb measurements to get [LHCb-CONF-2011-34]

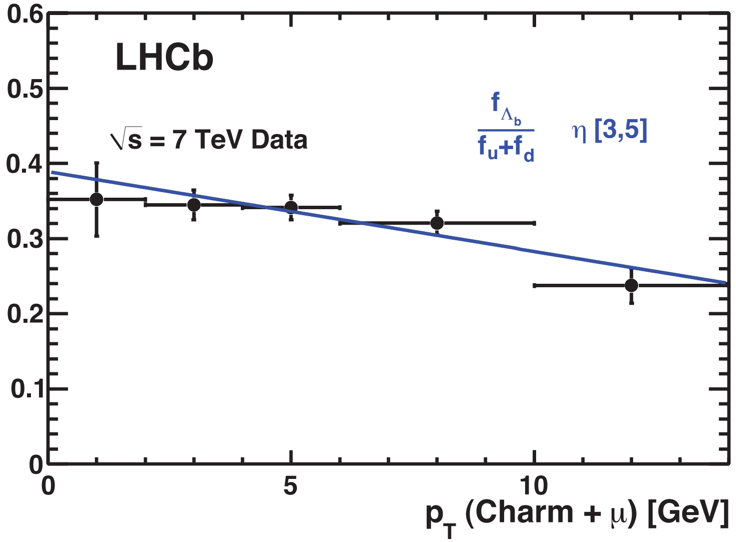
$$\left\langle\frac{f_s}{f_d}\right\rangle=0.267^{+0.021}_{-0.020}$$

Source	Error(%)
Statistical	2.8
Experimental Sys (symme)	3.3
$B_s\to D_sKX\mu\nu$	+3.0 -0.8
$\mathcal{B}(D^+\to K^-\pi^+\pi^-)$	2.2
$\mathcal{B}(D_s\to K^-K^+\pi^-)$	4.9
B lifetimes	1.5
$\mathcal{B}(B^0/B^+\to D_sK^-)$	1.5
Theory	1.9

The fraction $f_{\Lambda_b}/(f_u+f_d)$

LHCb-CONF-2011-028



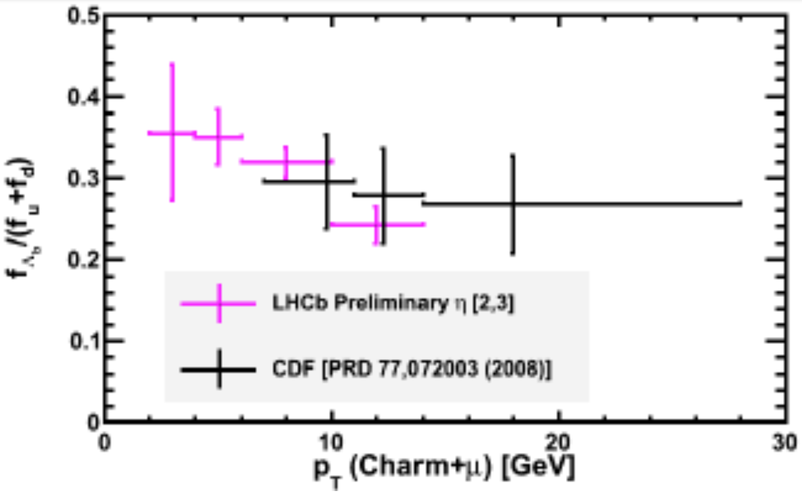


$f_{\Lambda b}/(f_u+f_d)$ not consistent with flat over p_T

If we fit with straight line, we get

$$\frac{f_{\Lambda_b}}{f_u+f_d} = (0.404 \pm 0.017 \pm 0.027 \pm 0.105)\times \left[1-(0.031 \pm 0.004 \pm 0.003)\times p_T\,/\,\mathrm{GeV}\right]$$

Systematic error on the scale 26% from $\mathcal{B}(\Lambda_c \rightarrow pK\pi)$

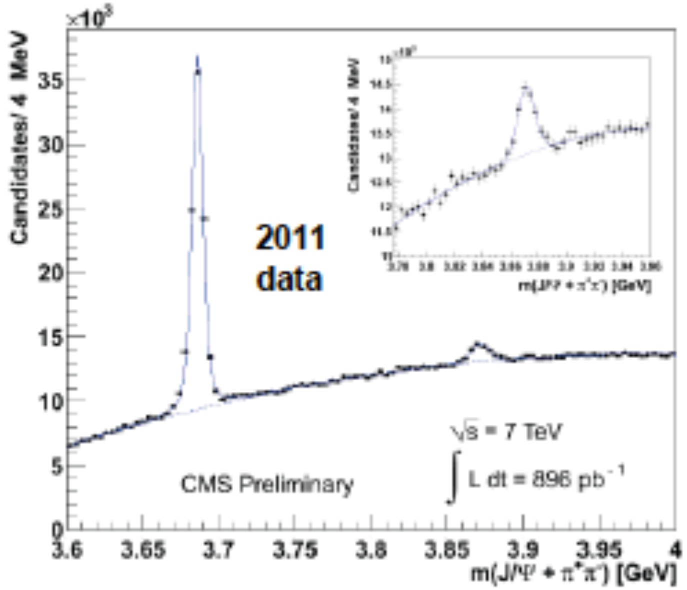


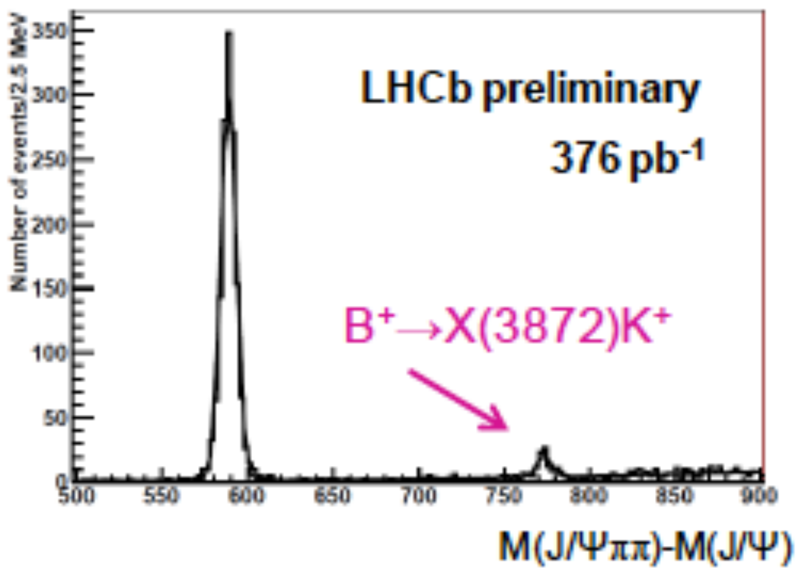
CDF value $(0.281 \pm 0.012^{+0.011}_{-0.056}{}^{+0.128}_{-0.086})$ $\langle p_T \rangle_{\mathrm{CDF}} \approx 14.1\,\mathrm{GeV}$

LEP value 0.110 ± 0.035 $\langle p_T \rangle_{\mathrm{LEP}} \approx 40\,\mathrm{GeV}$

Venturing into exotica: studies of the X(3872)

CMS-DP-2011-009
2010 production analysis:
CMS PAS BPH-10-018





- ❑Discovered by Belle in 2003, confirmed by CDF. D0, BaBar, started "gold rush" of exotic QCD states.
- ❑Its nature still uncertain, 2 possible QN 2^{-+} or 1^{++}.
- ❑CMS measures ratio of inclusive X (3872) to ψ(2S) production in J/ψππ channel
- ❑LHCb studied mass (2010 sample) [LHCb-CONF-2011-021]

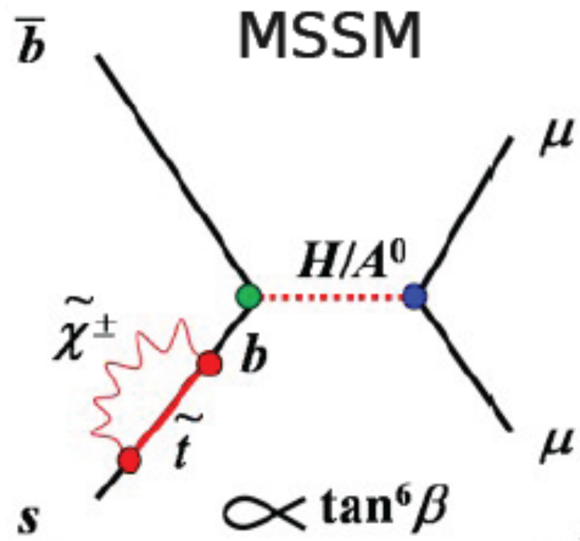
$$M_{X(3872)} = 3871.96 \pm 0.46 \pm 0.10 \text{ MeV}/c^2 \,.$$

- ❑Next use B→X(3872)K to find quantum numbers

Looking deeper: the search for new physics signatures

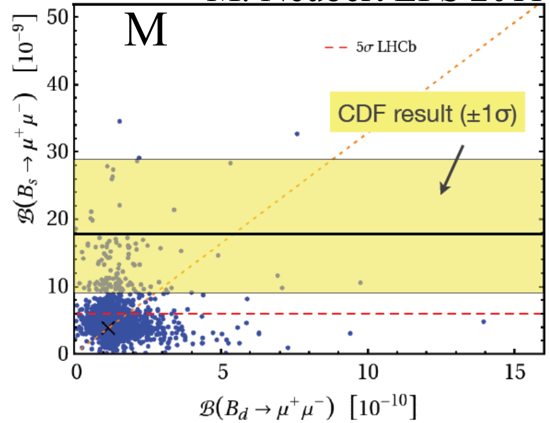
- ❑Flavor changing neutral currents
- ❑Search for new physics in B_d mixing
- ❑Search for new physics in B_s mixing
- ❑CP Violation in charm decays

$B_s \to \mu\mu$ *and* $B_d \to \mu\mu$



- Interesting decays
- Highly suppressed in the Standard Model
- They can be enhanced in models with warped extra-dimension or SUSY at large tanβ

M. Neubert EPS 2011



Recent report from CDF

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \cdot 10^{-8} \qquad \text{SM:} \quad (3.2 \pm 0.2) \cdot 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-) < 6.0 \cdot 10^{-9} \qquad \text{SM:} \quad (1.0 \pm 0.1) \cdot 10^{-10}$$

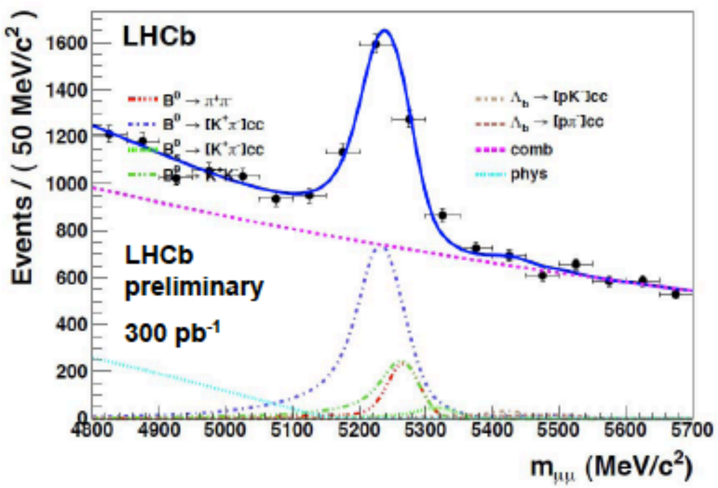
More recent results from LHCb and CMS

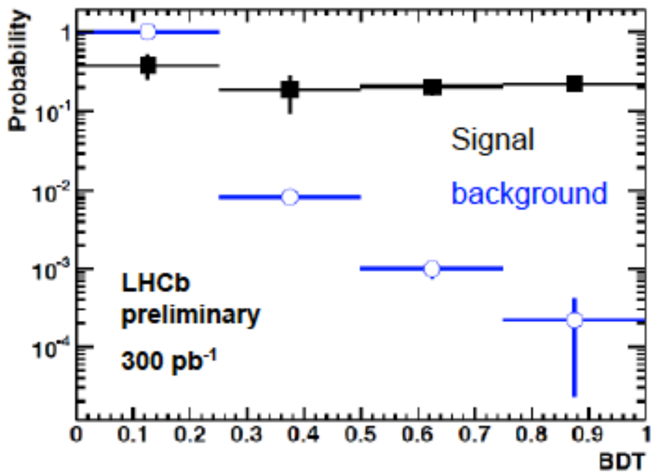
A.J. Buras, arXiv:1012.1447
E. Gamitz et al., Phys. Rev. D 80(2009) 014503

LHCb search for $B_s \rightarrow \mu\mu$

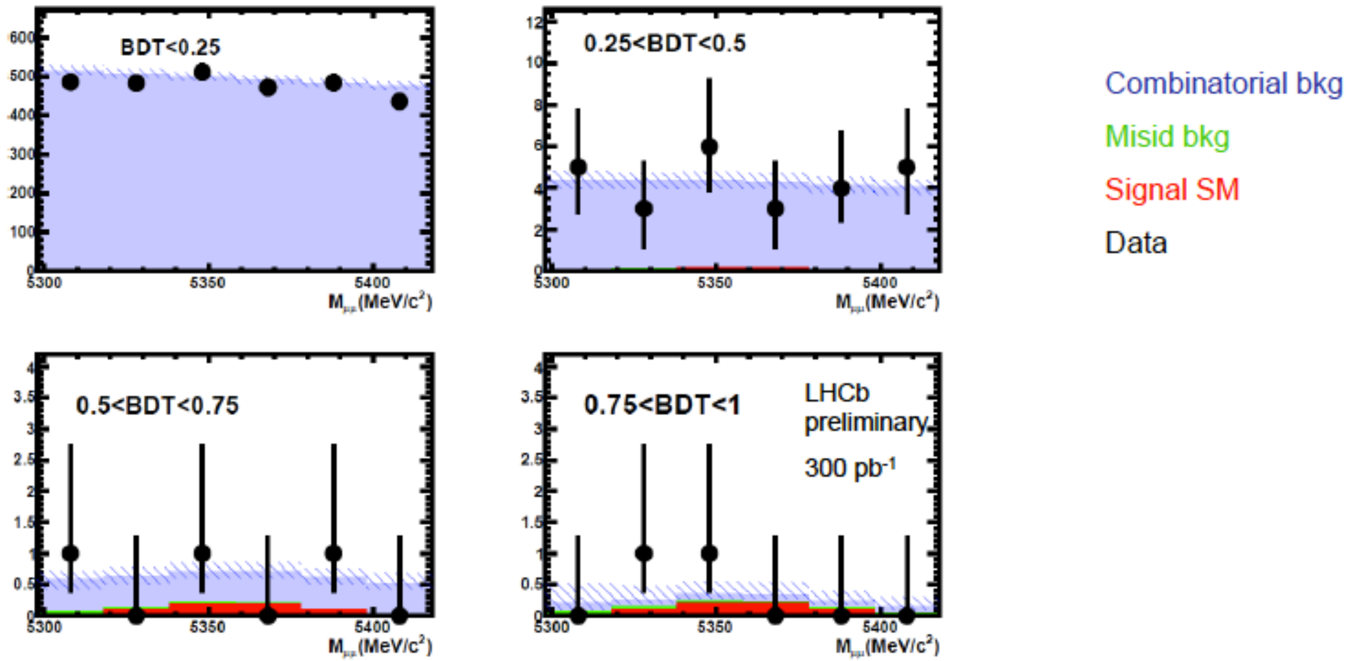
Analysis strategy:

- ❑Muon-based trigger
- ❑Blind signal region ($M(B_d)$-60 MeV to $M(B_s)$ +60 MeV)
- ❑Boosted decision tree using 9 input variables
- ❑Calibration channel $B_{d/s} \rightarrow h^+h^-$





B_s signal region



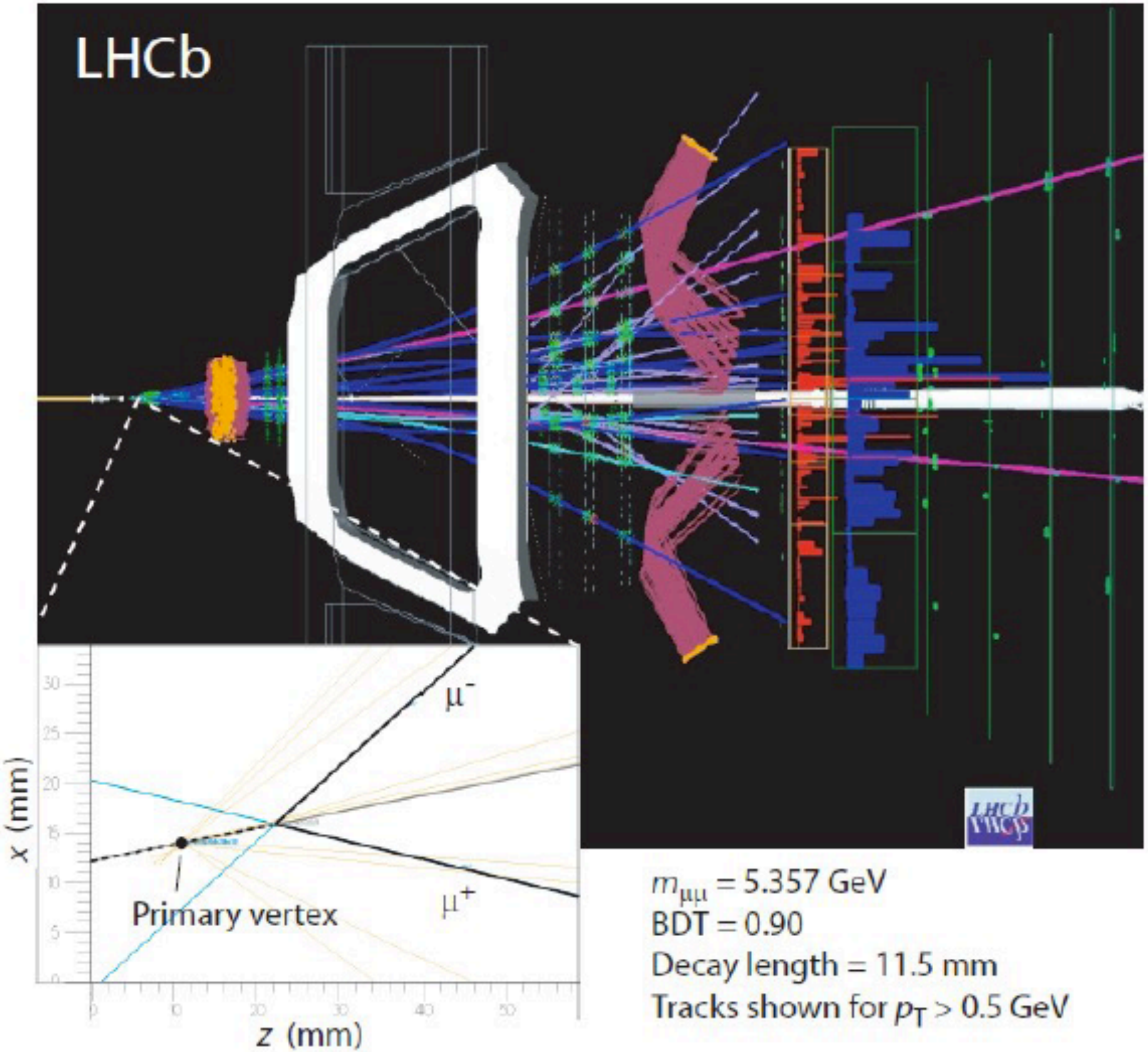
	BDT<1/4	1/4<BDT<1/2	½<BDT<3/4	¾<BDT<1
# expected bkgrd	2968±69	25.0±2.5	2.99±0.89	0.66±0.40
# expected signal	1.26±0.13	0.61±0.06	0.67±0.07	0.72±0.07
Sum expected	2969±69	25.6±2.5	3.66±0.89	1.38±0.41
Observed	2872	26	3	2

$$BR(B_s \to \mu^+\mu^-) < 1.3\times10^{-8}(1.6\times10^{-8})@90(95)\%CL$$

$$BR(B_d \to \mu^+\mu^-) < 4.2\times10^{-9}(5.2\times10^{-9})@90(95)\%CL$$

$$BR(B_s \to \mu^+\mu^-) < 1.2\times10^{-8}(1.5\times10^{-8})@90(95)\%CL$$

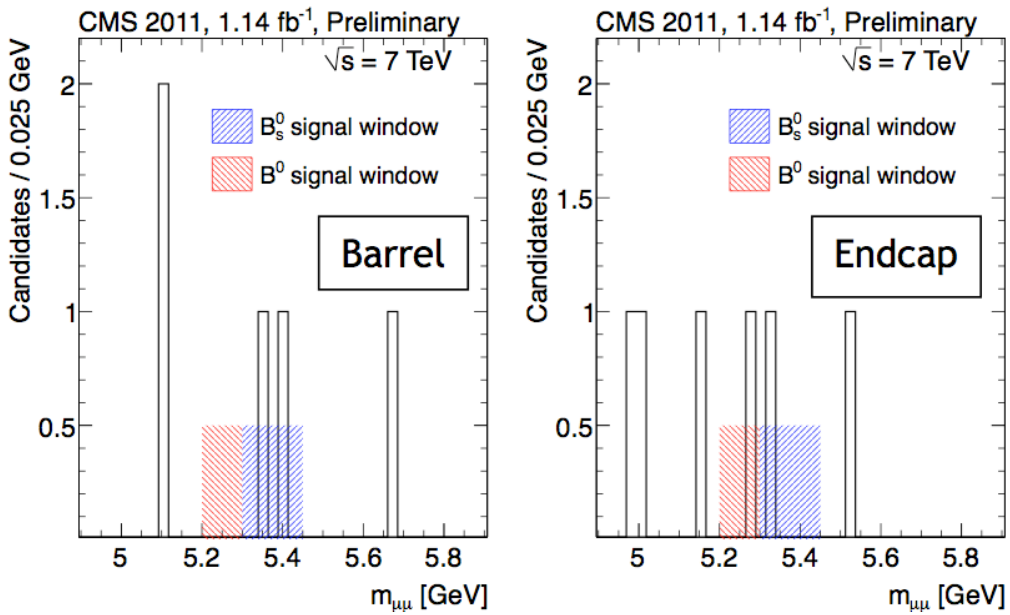
Combined with 2010 data



$m_{\mu\mu} = 5.357$ GeV
BDT = 0.90
Decay length = 11.5 mm
Tracks shown for $p_T > 0.5$ GeV

CMS search for $B_{s,d} \to \mu\mu$

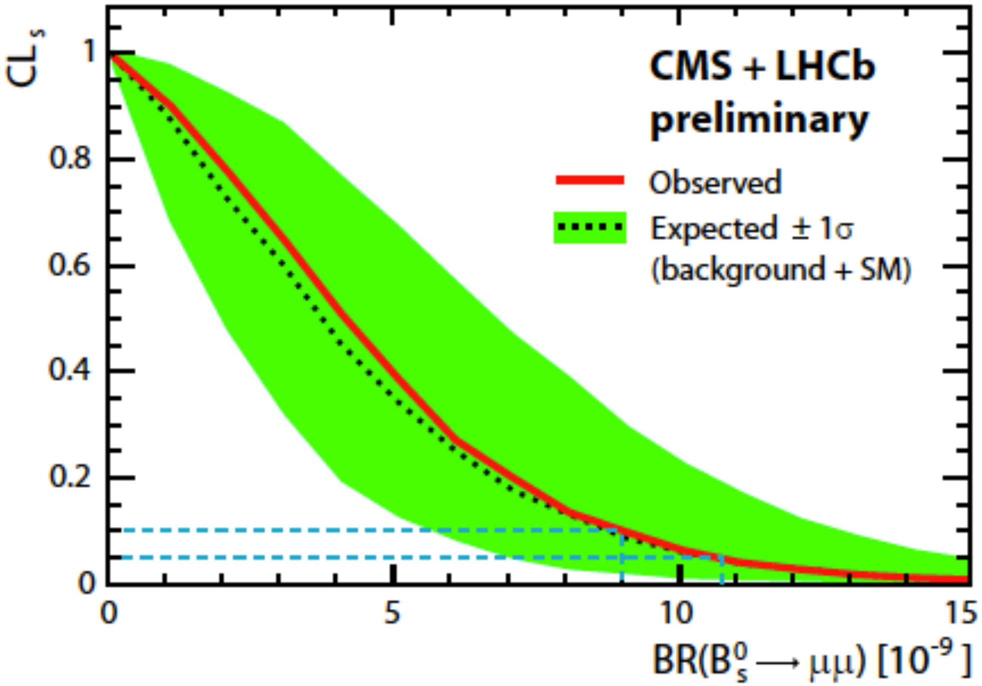
- $\mathcal{L}$=1.14 fb^{-1}
- Cut based analysis, optimized on MC and data sidebands prior to unblinding
- Two geometrical regions: "barrel" [both μ $|\eta|$ <1.4] and "end cap" [at least 1 μ $|\eta|$ >1.4]
- Efficiency of variables potentially sensitive to pile-up checked on data: excellent stability observed



Events observed in the unblinded windows consistent with background plus SM expectations.
$B_s \to \mu^+\mu^- < 1.9\times10^{-8}$ (95% CL)
$B_d \to \mu^+\mu^- < 4.6\times10^{-9}$ (95% CL)

LHC limit for $B_s \rightarrow \mu\mu$

- preliminary CMS-LHCb combination on $BR(B_s \rightarrow \mu\mu)$ using the CLs approach



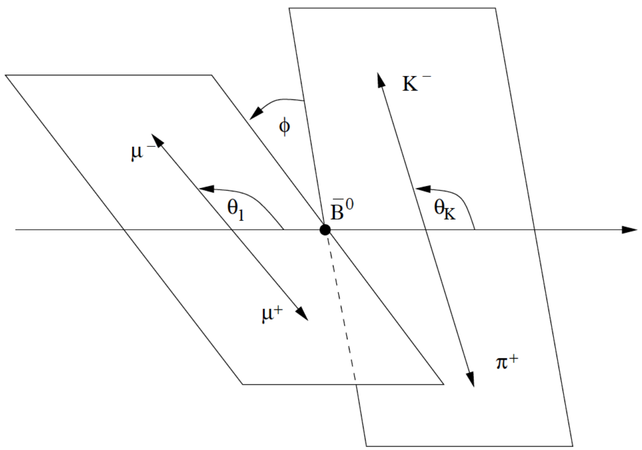
$$BR(B_S \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-8} (95\% CL)$$

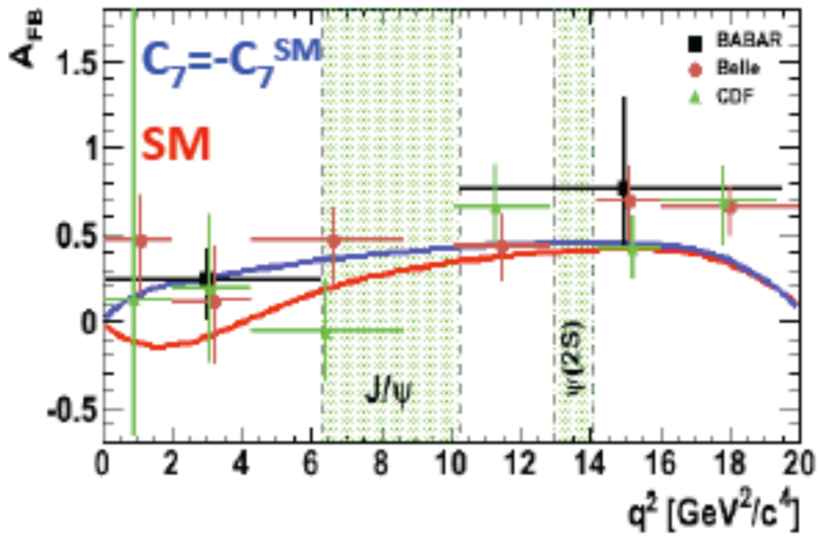
$$BR(B_S \rightarrow \mu^+\mu^-) < 0.9 \times 10^{-8} (90\% CL)$$

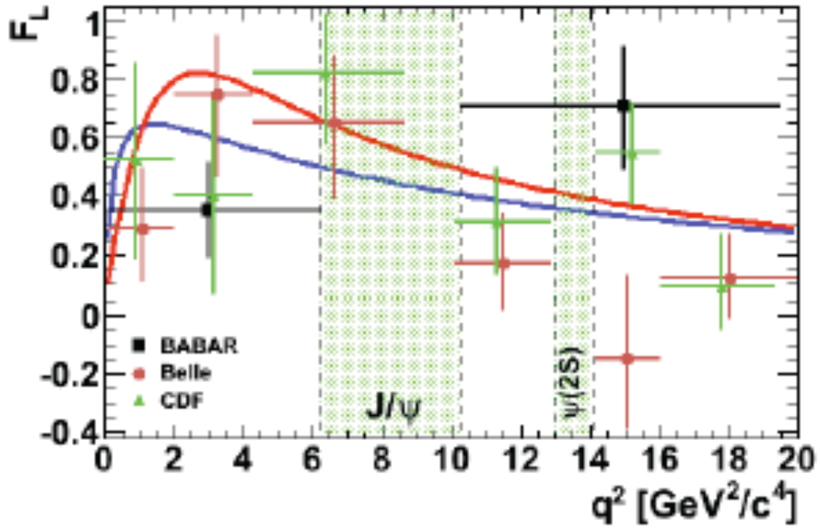
$1.8 \text{x} 10^{-8}$ (central value of the “2 sided upper limit”) reported by CDF excluded with p-value of 0.29%

Angular analysis of $B_d \rightarrow K^*\mu\mu$

- Flavor changing neutral current highly sensitive probe of new physics due to large number of complementary measurements possible from full angular distribution (θ_l, θ_K, ϕ) and di-μ invariant mass q^2

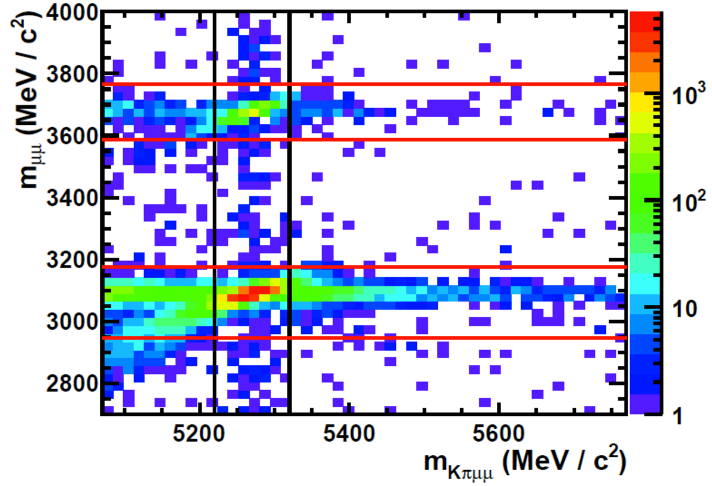


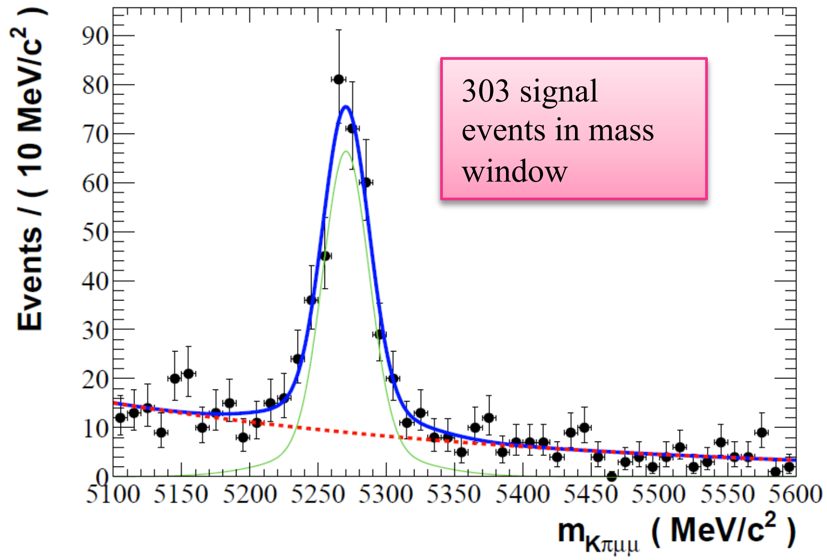




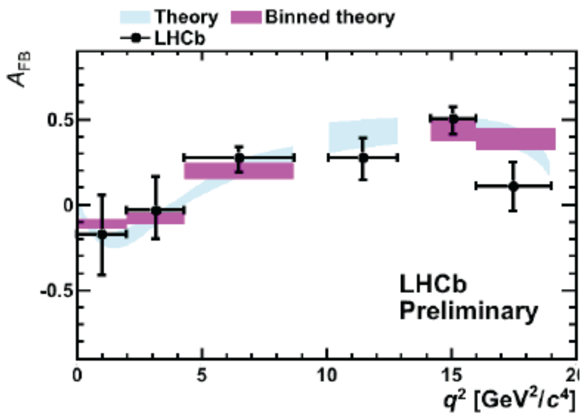
LHCb Studies of $B_d \to K^*\mu\mu$

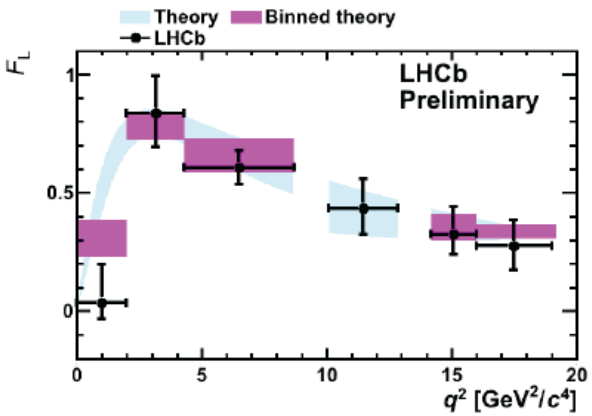
- $\mathcal{L}_{int}$= 309 pb^{-1}
- Remove J/ψ and ψ(2S) resonances
- Select events using Boosted Decision Tree
- Measure $d\Gamma/dq^2$, longitudinal polarization F_L, and A_{FB} in 6 q^2 bins

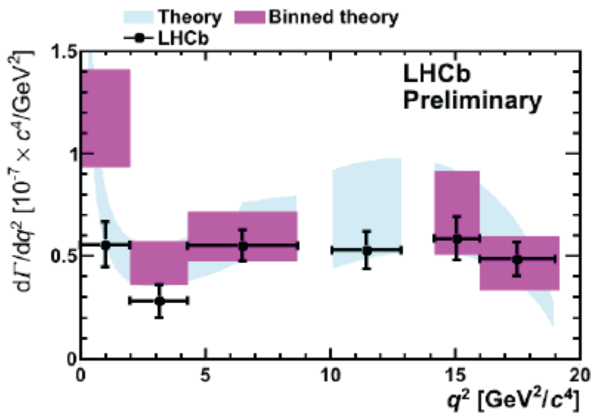


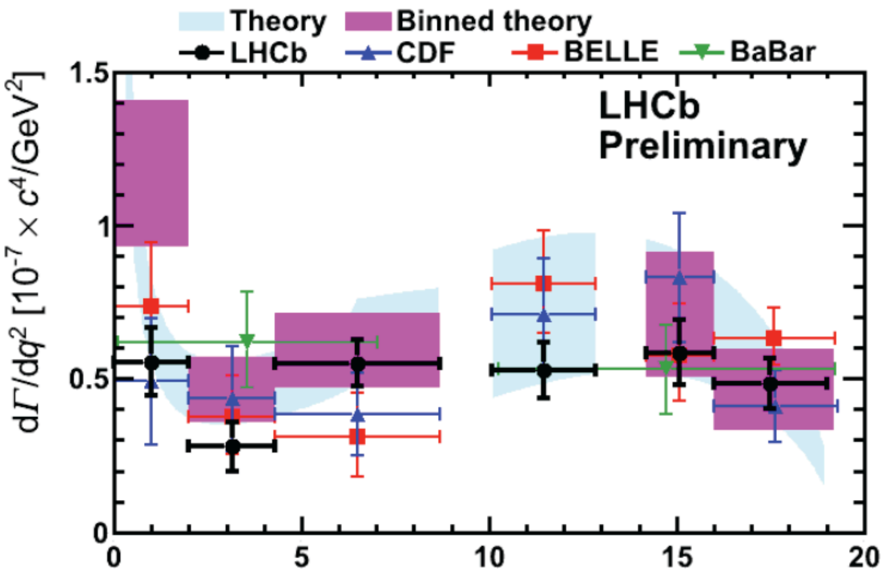


Results







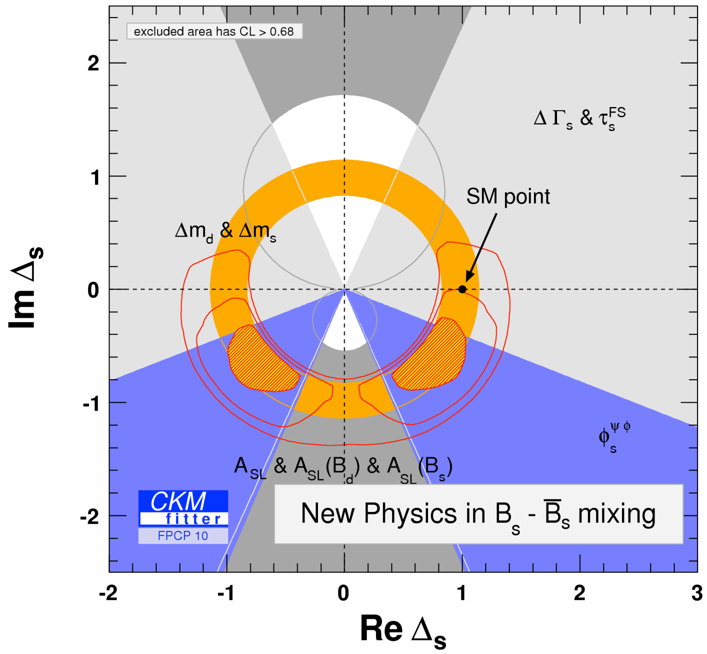


LHCb measurement is more precise than previous measurements, statistical errors dominate.

Data are consistent with SM predictions at this level of sensitivity.

Next: determination of 0 crossing point in AFB & study other observables (e.g. $A_T^{(2)}$ sensitive to RH currents)

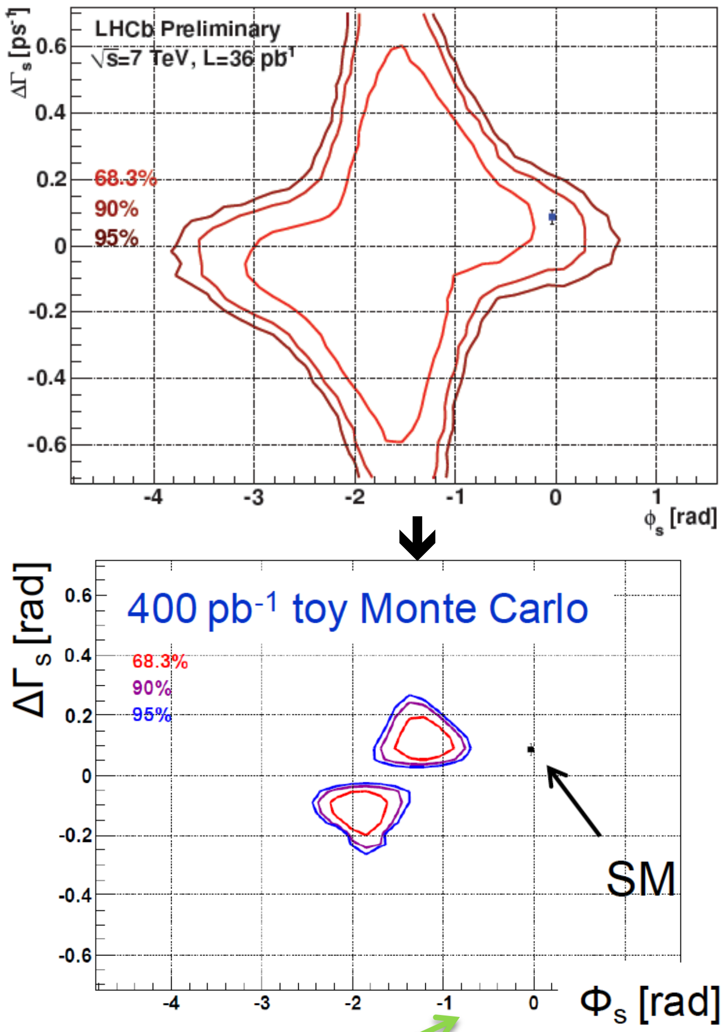
New physics in $B_s^0 - \bar{B}_s^0$ mixing



- Measurements of mixing induced CP violation in B_s^0 decays are of prime importance in probing new physics, most studied channel is $B_s^0 \to J/\psi\phi$
- but other final state may play a major role such as $B_s^0 \to J/\psi f_0$

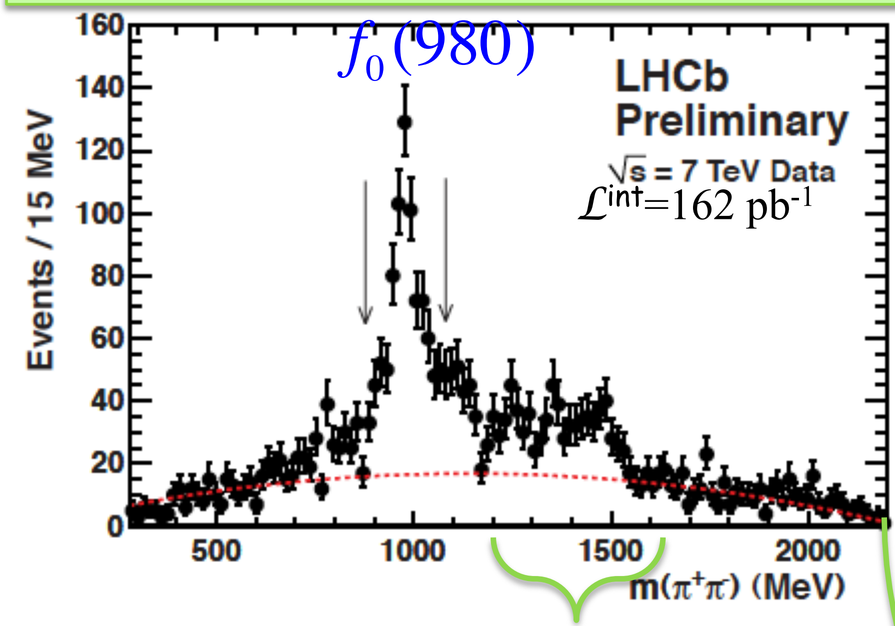
LHCb ϕ_s Measurement

- Confidence Level scan
- 2010 data ($36pb^{-1}$)1.2σ from SM
- Using opposite side flavor tagging only
- Preliminary result less precised than Tevatron, 10 times bigger data set being processed
- Sensitivity can be improved through inclusions of CP-eigenstates modes such as $B_s \to J/\psi f_0$



Assuming identical analysis performance + central values

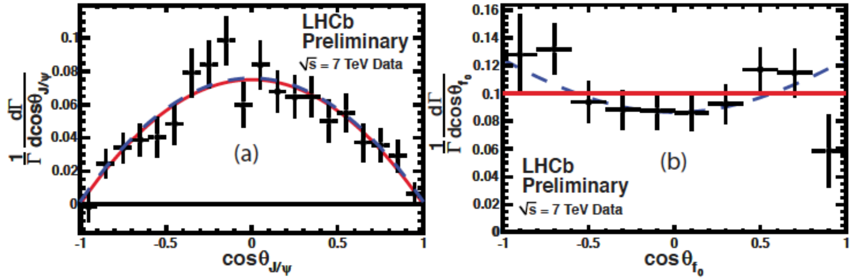
Bs→J/ψf$_0$ at LHCb



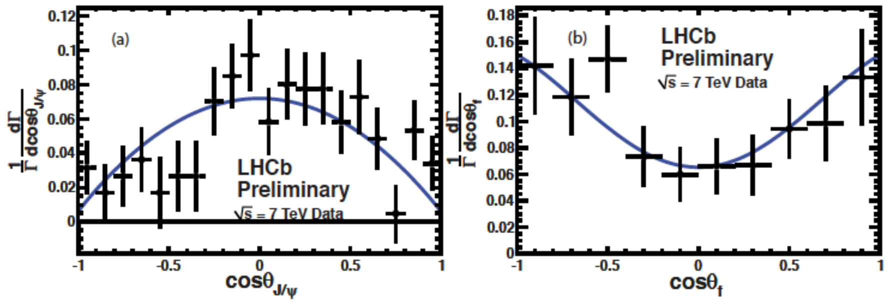
$$R_{eff}^{f_0} \equiv \frac{N_{corr}(J/\psi f_0)}{N_{corr}(J/\psi \phi)} = (21.7 \pm 1.1 \pm 1.0)\%$$

Existence of decay predicted by Stone & Zhang, with $R_{th}^{f_0} \approx 20\%$

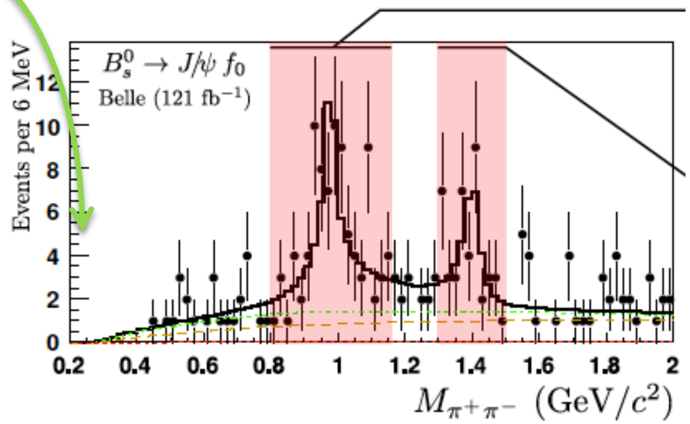
Phys.Rev. D79 (2009) 074024



Cutting on m(π⁺π⁻)= (1200,1600)
significant D-wave component



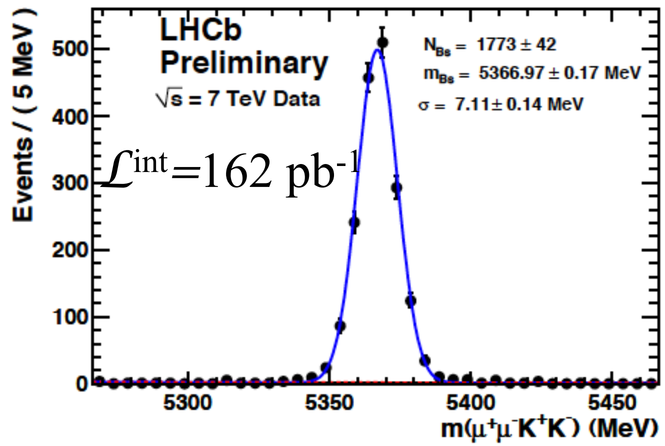
f$_0$ mass region ≈ s-wave

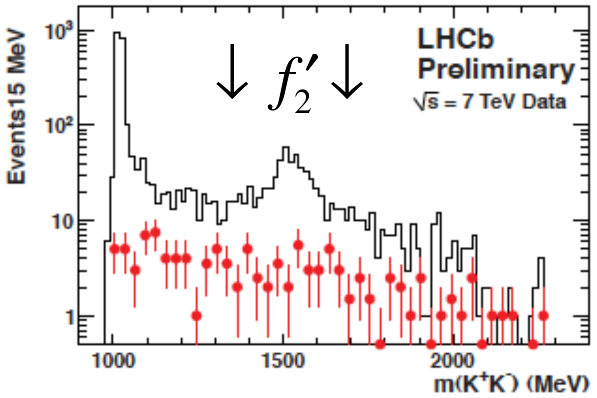


Inconsistent with Belle evidence for f$_0$(1370)

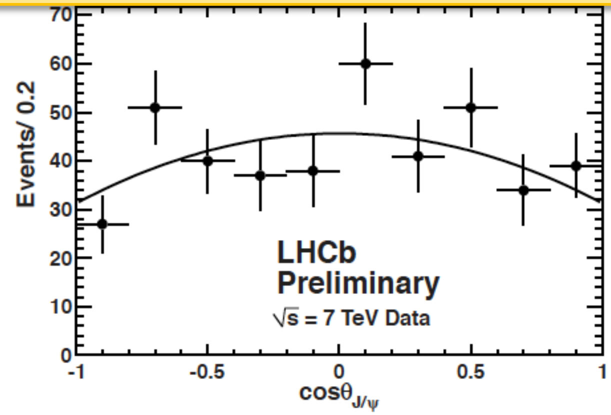
Study of $B_s^0 \to J/\psi K^+K^-$ and first observation of $B_s^0 \to J/\psi f_2'(1525)$

Selecting events with K^+K^- within ±20 MeV of the ϕ mass, we obtain the normalization $J/\psi\phi$ signal





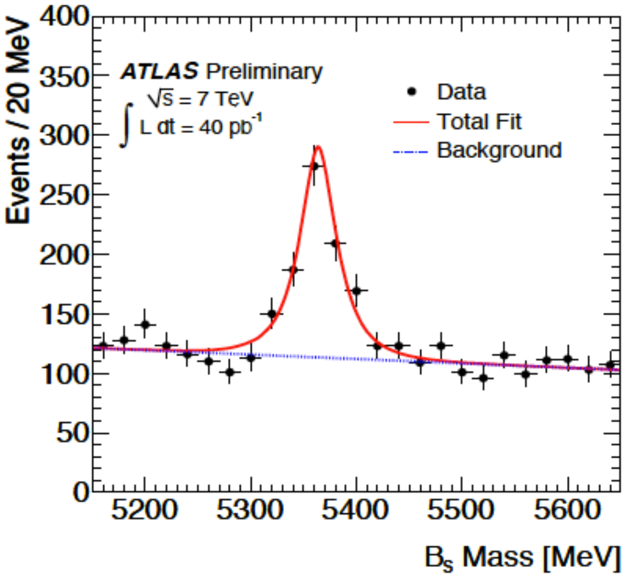
Angular analysis shows consistency with spin 2

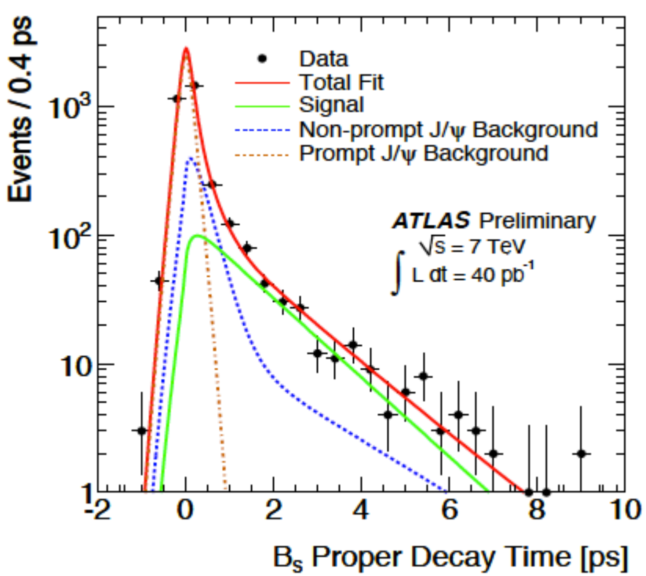


$$R_{eff}^{f_2'} \equiv \frac{N_{corr}(B_s^0 \to J/\psi f_2')}{N_{corr}(B_s^0 \to J/\psi\phi)} = (19.4 \pm 1.8 \pm 1.1)\%$$

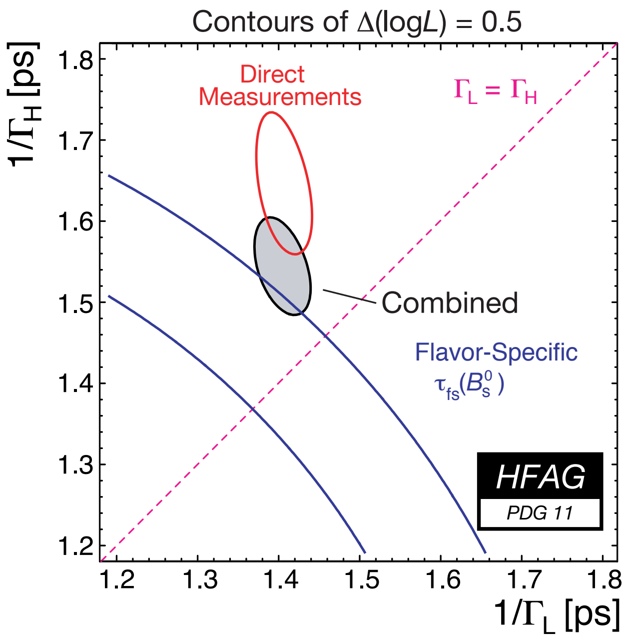
More opportunities for CPV measurements!

From ATLAS: B_s lifetime





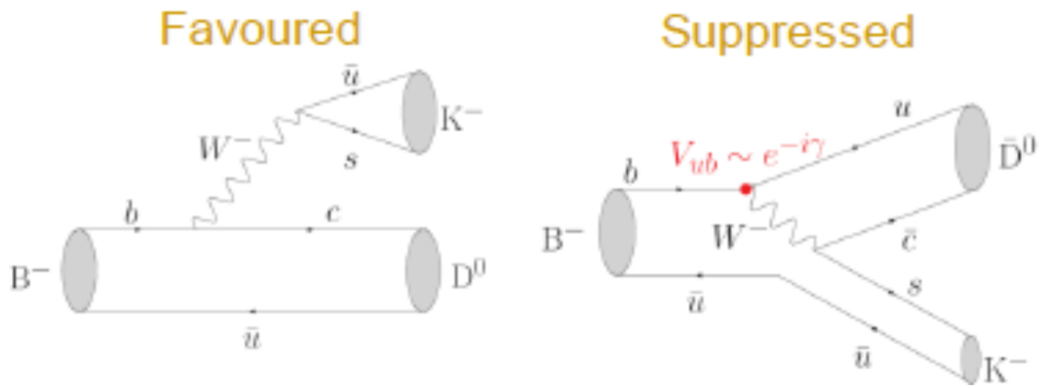
Simultaneous fit of mass and proper time gives τ_{Bs}=(1.41±0.08±0.05) ps



Towards a precise determination of the angle γ

- ❑Important because, together with |Vub|, it determines the “reference unitary triangle” [Goto et al., PRD 53 (1996) 6662] free from penguin pollution.
- ❑Study $B^{\pm} \to DK^{\pm}$ with final states common to D^0 and D^0

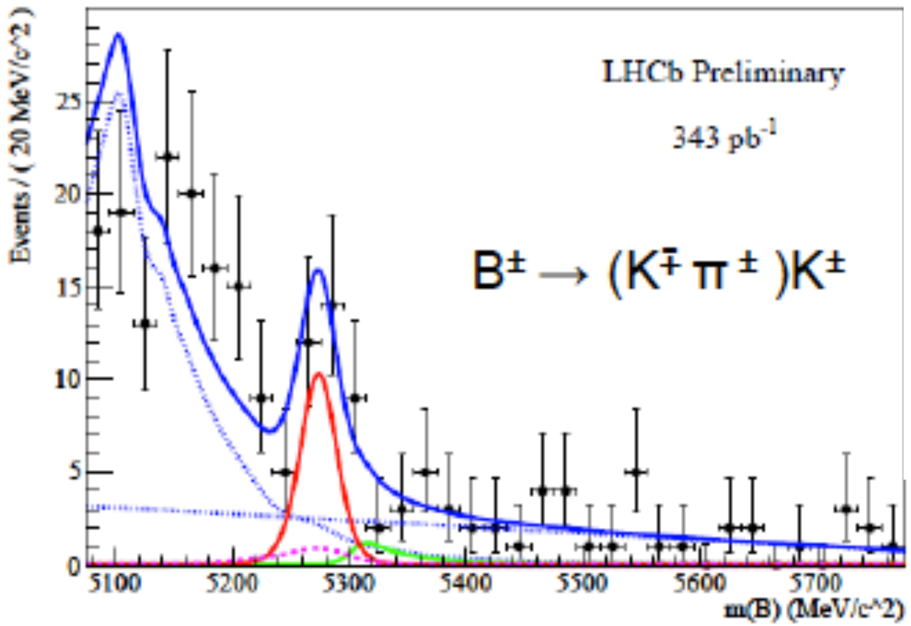
❑Cabibbo favored D0 and Cabibbo suppressed D^0 maximize interference

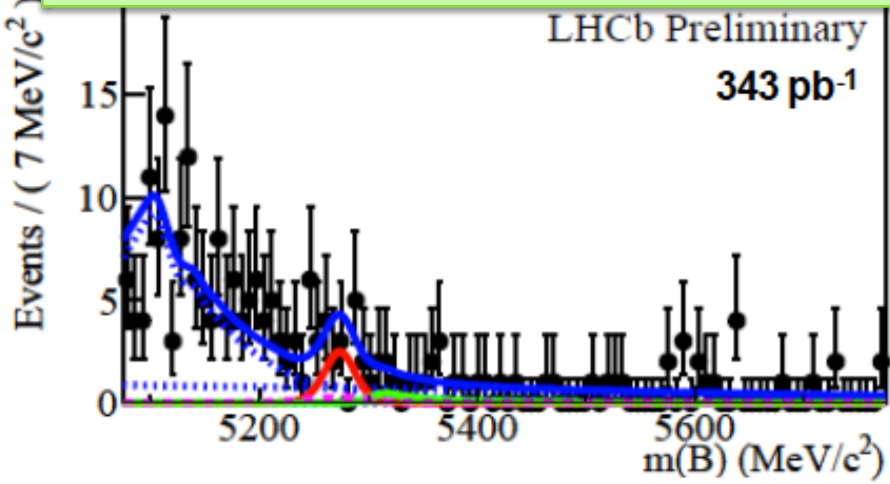


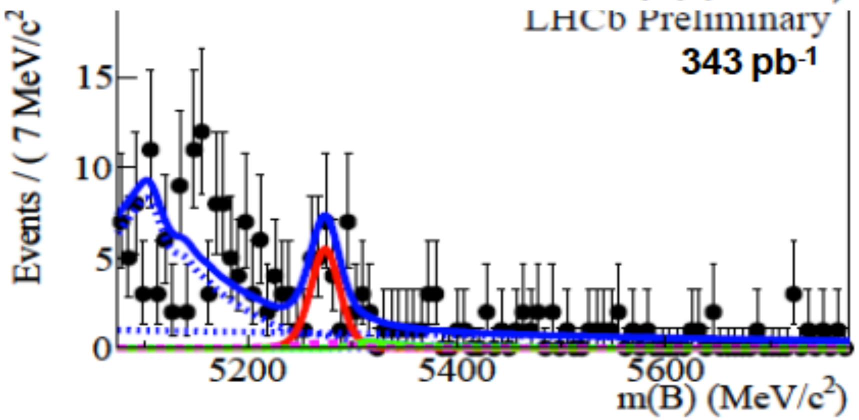
Evidence for $B^{\mp} \rightarrow K^{\pm}\pi^{\mp}K^{\mp}$ *(ADS)*

Atwood, Dunietz, Soni **Phys.Rev. D63 (2001) 036005**

LHCb-CONF-2011-044







Ratio to favored mode:

$$R_{ADS}^{DK}(LHCb) = (1.66 \pm 0.39 \pm 0.24) \times 10^{-2}$$

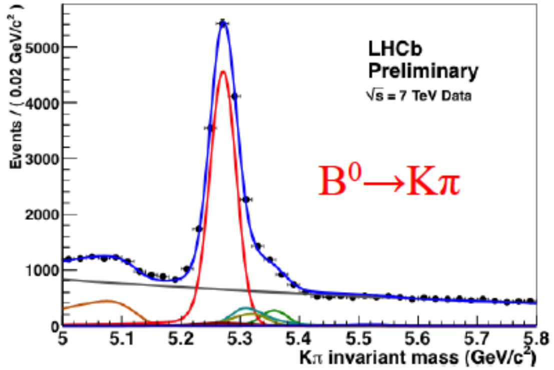
$$R_{ADS}^{DK}(WA - noLHCb) = (1.6 \pm 0.3) \times 10^{-2}$$

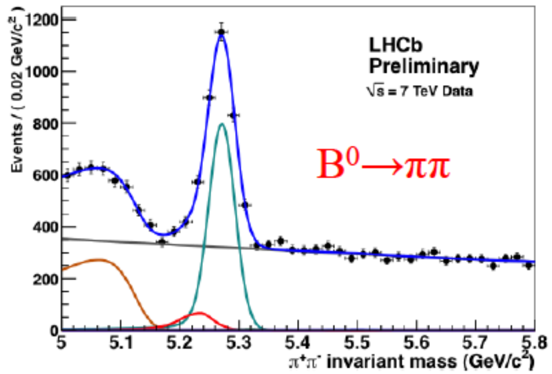
$$A_{ADS}^{DK}(LHCb) = -(0.39 \pm 0.17 \pm 0.02)$$

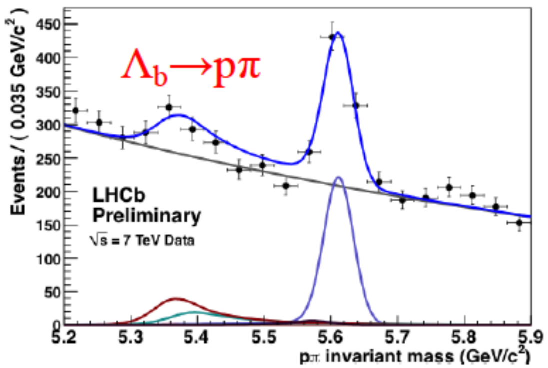
$$A_{ADS}^{DK}(WA - noLHCb) = -(0.58 \pm 0.21)$$

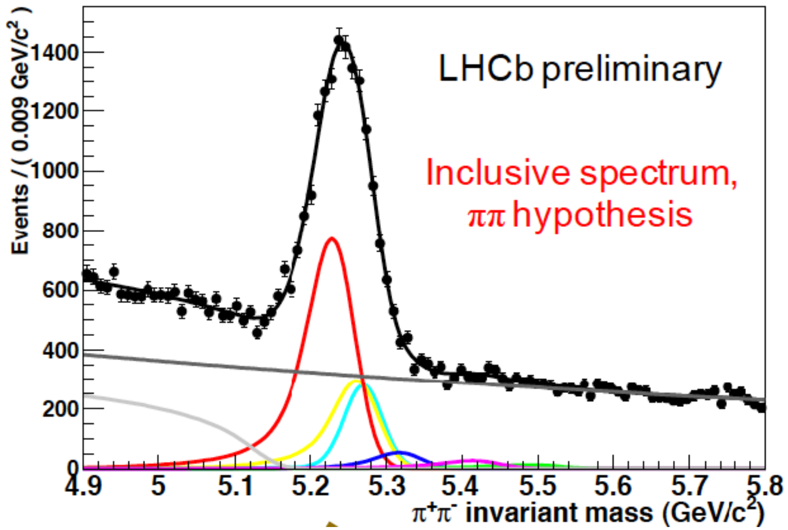
Non leptonic 2 body B decays

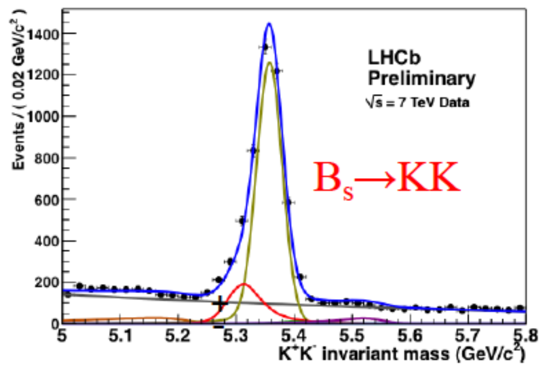
- Important tests of CKM framework & interplay between QCD effects and weak interactions [many theoretical methods proposed to tackle this]
- $B_{(s)} \rightarrow \pi\pi, \pi K, KK$ extensively studied in the last 10 years, great body of experimental knowledge and growing! (new PID power of LHCb RICH)

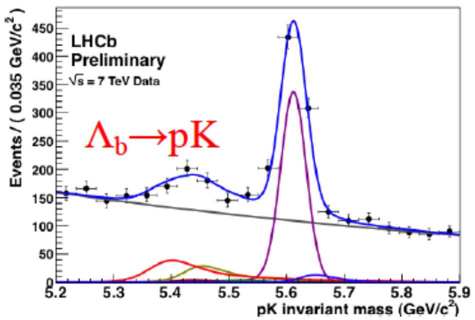








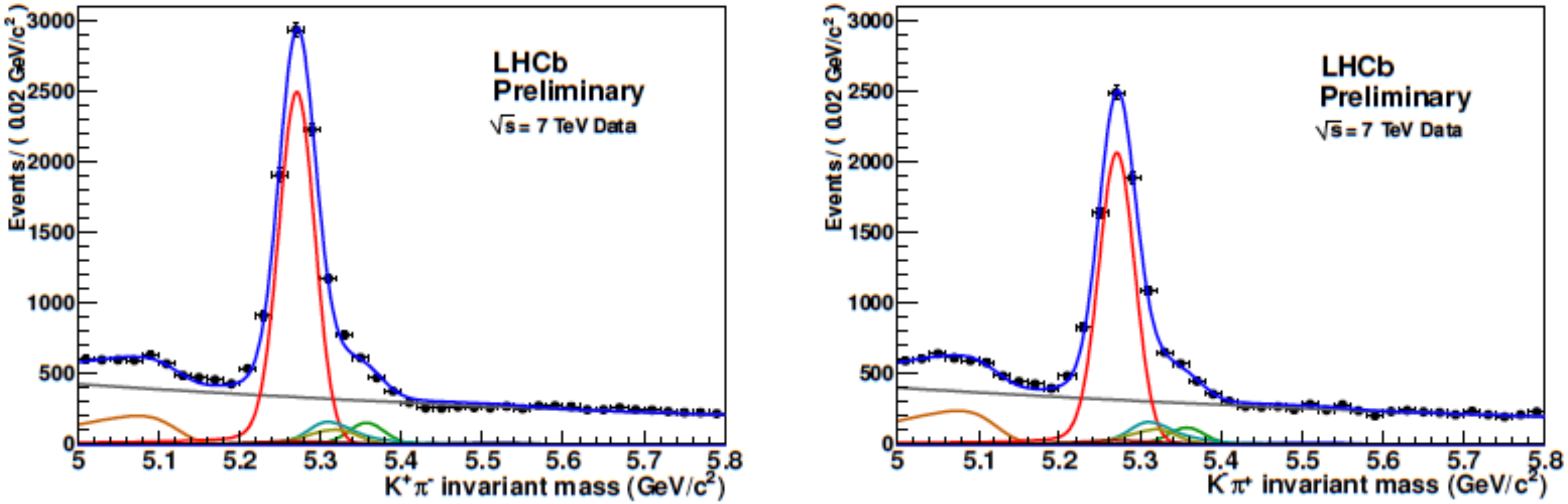




Direct CP Violation

$$A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011 \pm 0.008$$

$$A_{CP}(B^0 \to K\pi) = -0.098^{+0.012}_{-0.011} \quad (HFAG)$$



$$A_{CP}(B_s^0 \to \pi K) = -0.27 \pm 0.08 \pm 0.02$$

First evidence for direct CPV in $B_s \to \pi K$ decays

CP Violation in charm decays

Example CPV in $D^0 \rightarrow K^+K^-$ & $\pi^+\pi^-$ decays

$$A_{RAW}(f)^* = \boxed{A_{CP}(f)} + \boxed{A_D(f)} + \boxed{A_D(\pi_s)} + \boxed{A_P(D^{*+})}$$

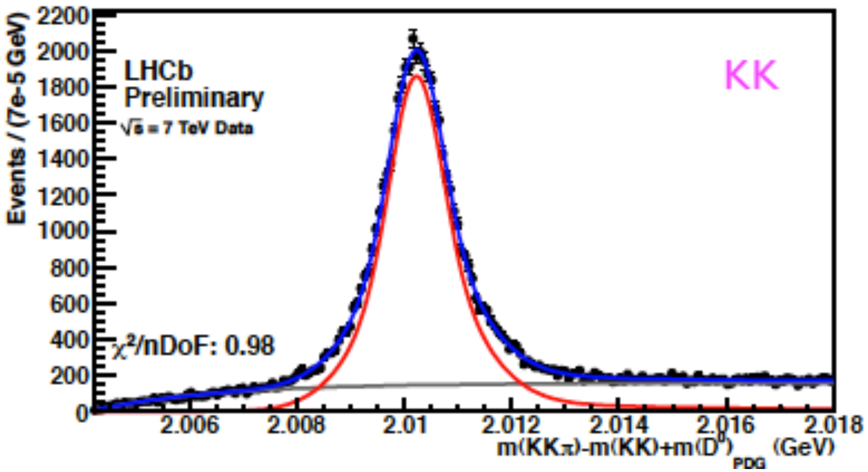
physics CP asymmetry

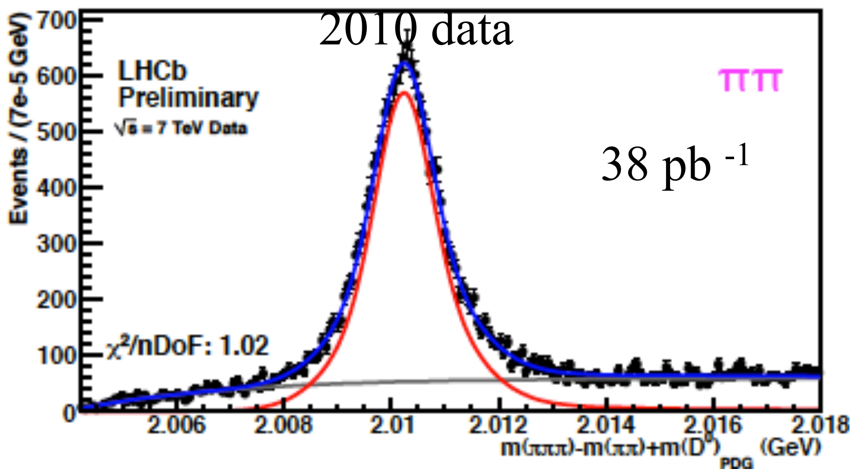
Detection asymmetry of D^0

Detection asymmetry of soft pion

Production asymmetry

LHCb Preliminary
2010 data



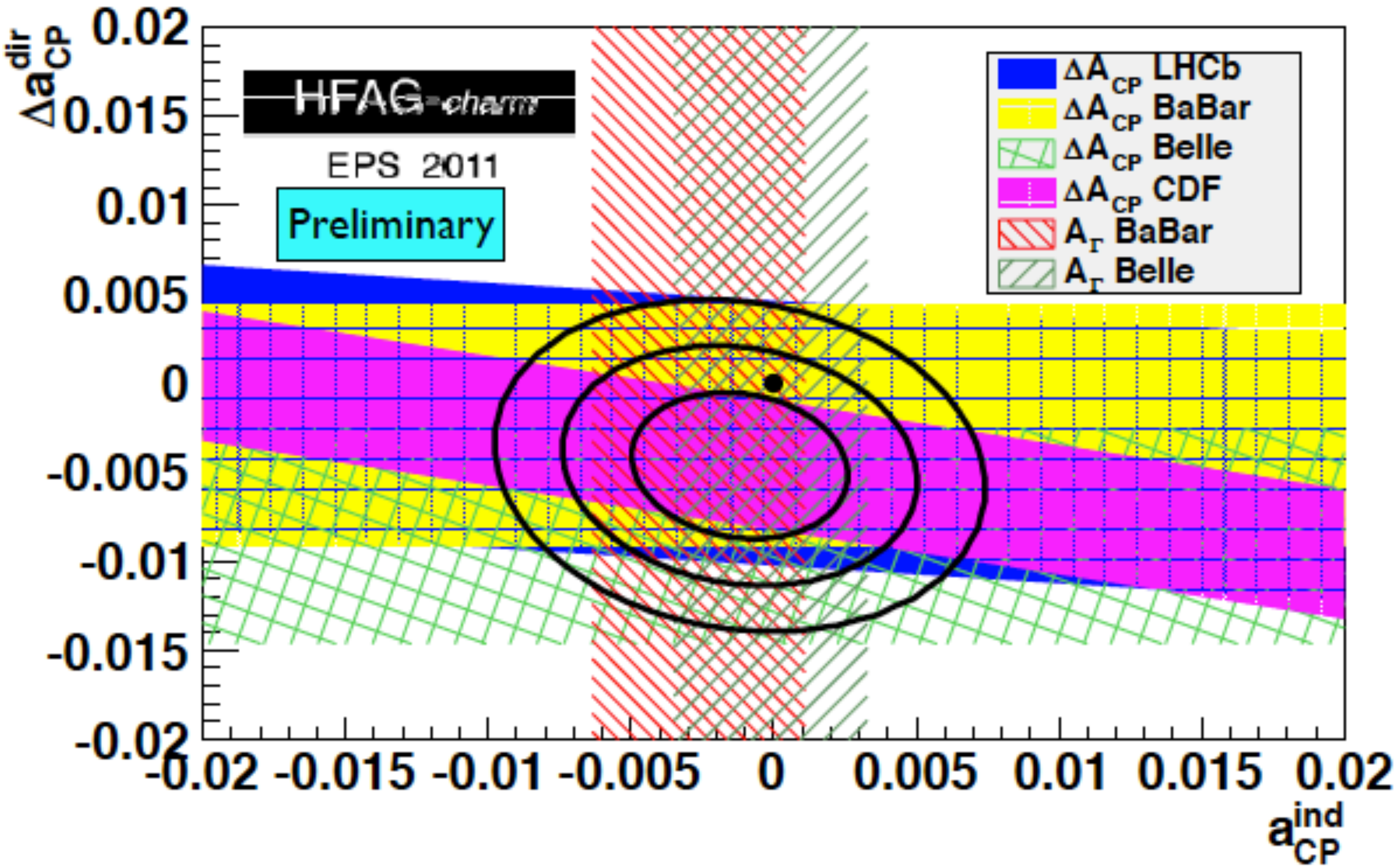


38 pb $^{-1}$

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

Remarks and interpretation

With less than 1/20 of present data sample LHCb already competitive with b-factories



Summary and conclusions

- A new ambitious experimental program to study new physics manifestations in charm and beauty decays has had a very good start.
- Already several "world's best" results from LHCb, the first dedicated heavy flavor experiment at a hadron collider.
- Much more to come!

The end

Decay Angles

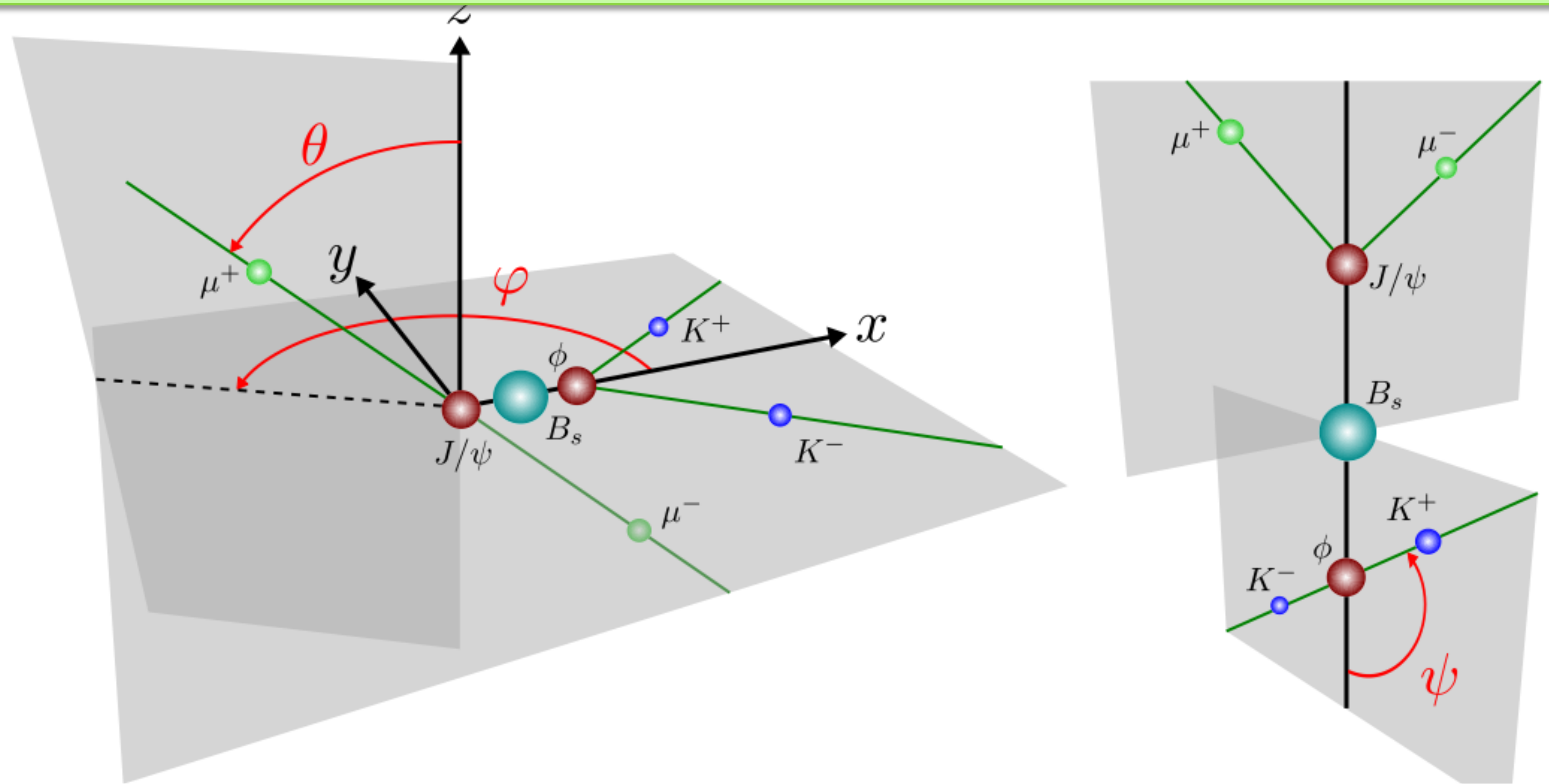
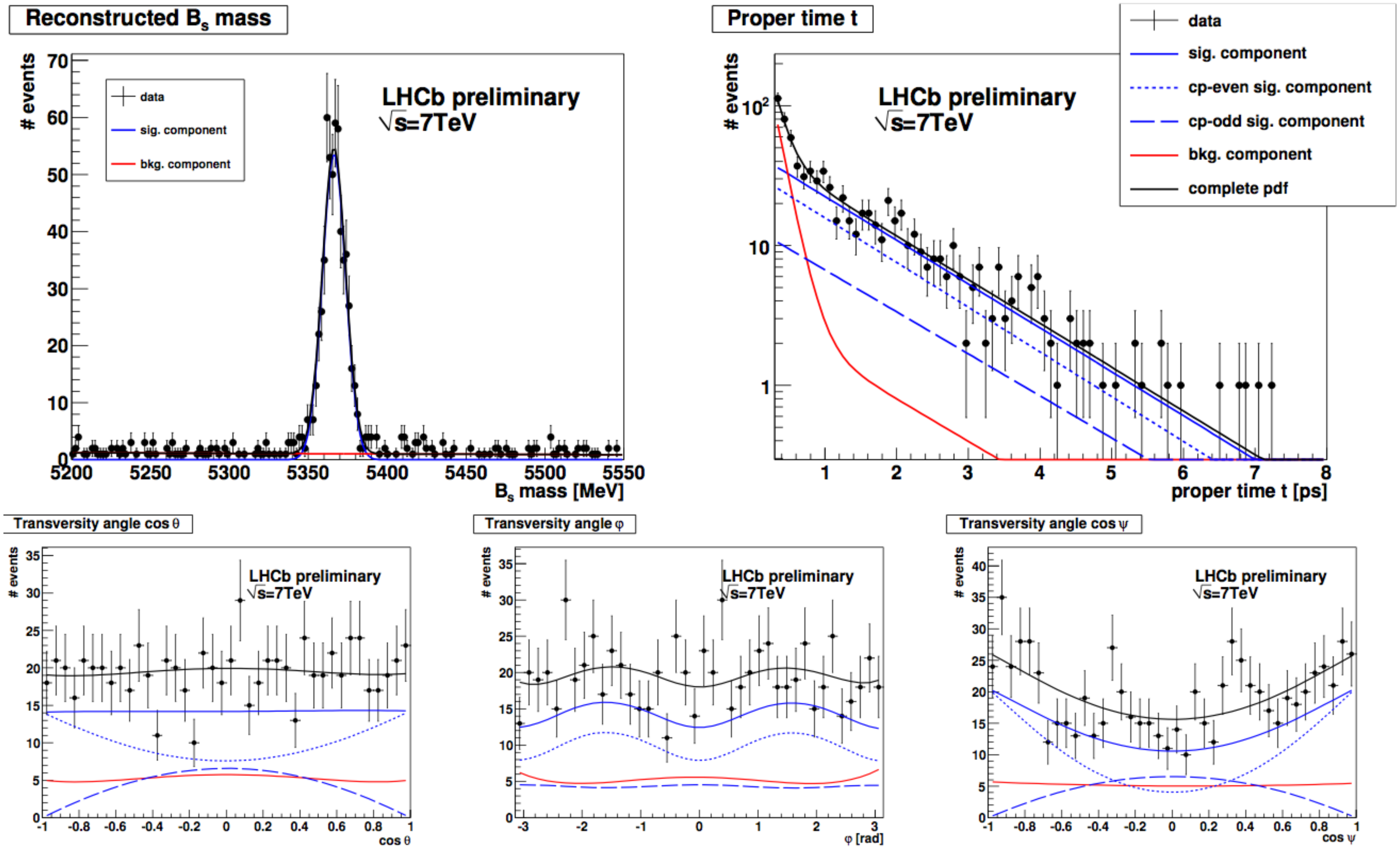


Figure 6: Angle definition: θ is the angle formed by the positive lepton (ℓ^+) and the z axis, in the J/ψ rest frame. The angle φ is the azimuthal angle of ℓ^+ in the same frame. In the ϕ meson rest frame, ψ is the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$. The definition is the same whether a B_s^0 or a $\overline{B}_s^0$ decays.

LHCb data



Reconstructed B_s mass
events
data
sig. component
bkg. component
LHCb preliminary
$\sqrt{s}$=7TeV
B_s mass [MeV]
Proper time t
events
data
sig. component
cp-even sig. component
cp-odd sig. component
bkg. component
complete pdf
LHCb preliminary
$\sqrt{s}$=7TeV
proper time t [ps]
Transversity angle cos θ
events
LHCb preliminary
$\sqrt{s}$=7TeV
cos θ
Transversity angle φ
events
LHCb preliminary
$\sqrt{s}$=7TeV
φ [rad]
Transversity angle cos ψ
events
LHCb preliminary
$\sqrt{s}$=7TeV
cos ψ