Flavour physics in the LHC era

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Why do we care about flavour physics now that the high p_T LHC programme is finally underway ?

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Flavour Physics is Important

Many of open questions in Standard Model (SM) found in flavour sector:

- Why are there 3 generations ? (and is it only 3 ?)
- What determines the extreme hierarchy of fermion masses?
- What determines the elements of the CKM matrix?
- What is the origin of CP violation (CPV)?

Progress in flavour physics may help understand open questions in cosmology - SM CPV insufficient to explain matter/antimatter asymmetry

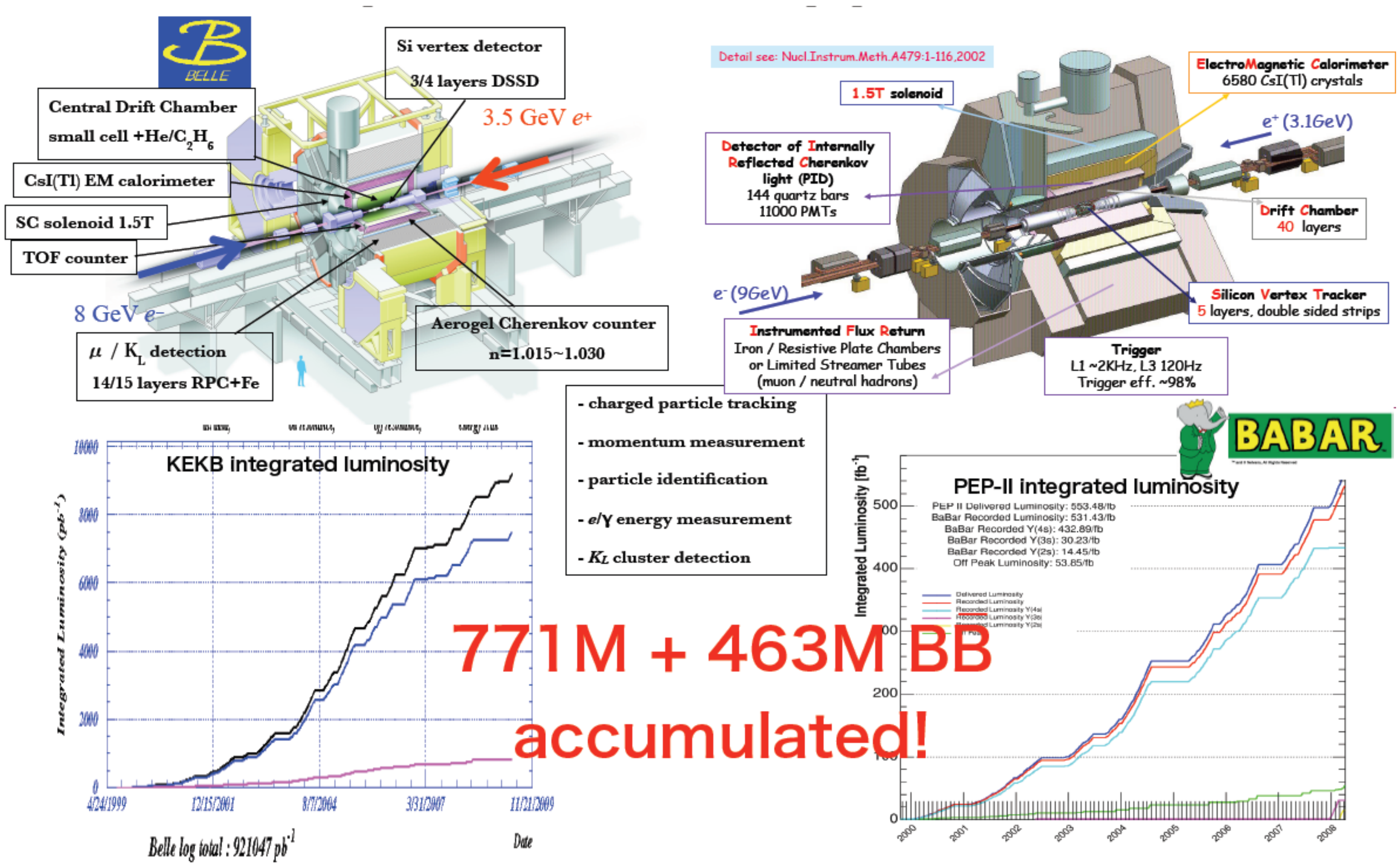
Flavour physics is a proven tool of discovery:

- Kaon mixing, BR($K^0_L \to \mu\mu$) & GIM → prediction of charm
- CP violation → need for a third generation
- B mixing → mass of top is very heavy
- SUSY parameter space already severely constrained by e.g. $b \to s\gamma$

Lesson from history: precise measurements of processes suppressed in existing theories have high sensitivity to new physics (NP) contributions. Excellent way to look for the NP expected at the TeV scale, complementary to high p_T searches.

Cast of characters

B-factories



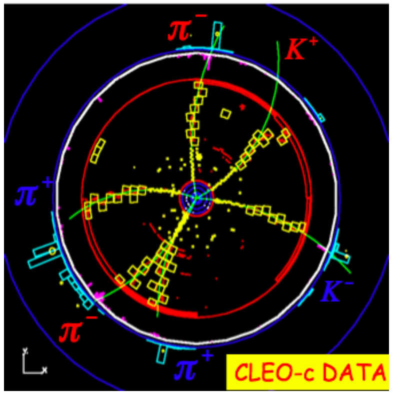
Truly *astounding* achievement ! Bulk of data analysed in bulk of analyses.
Still much vital work to be done. But low likelihood of real surprises (?)

Threshold charm facilities

$e^+e^- \to \Psi(3770) \to D\bar{D}$ has several attractive features:

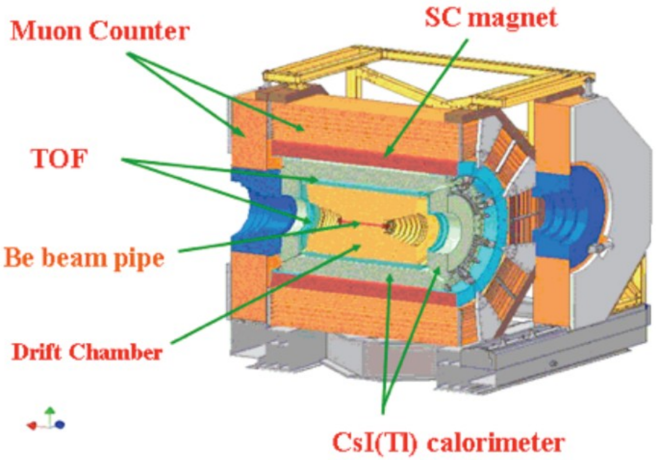
- quantum correlated $D\bar{D}$ system → strong phase measurements and CP violation searches
- no fragmentation particles – very clean environment, plus opportunity to infer unseen particles (e.g. ν and K_L) through kinematics of rest of event

CLEO-c collected 818 pb^{-1} at $\Psi(3770)$



$\psi(3770) \to D^+(K^-\pi^+\pi^+)D^-(K^+\pi^-\pi^-)$

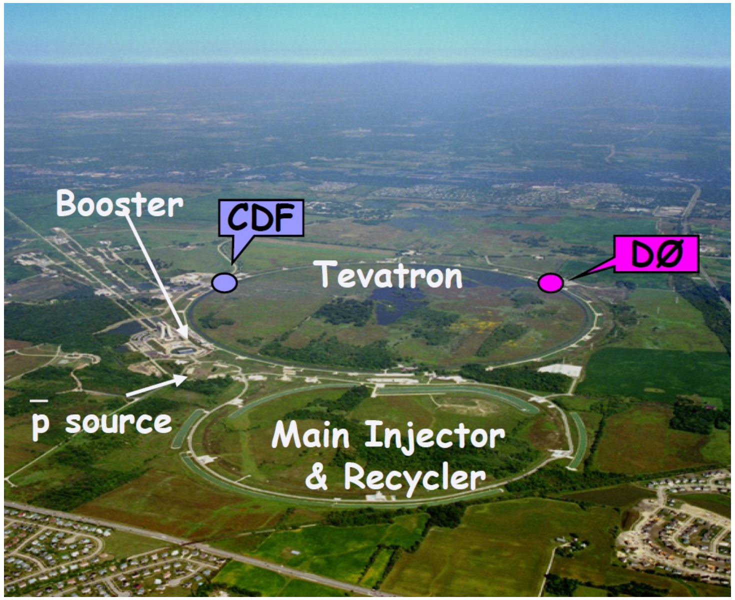
BES-III at BEPCII

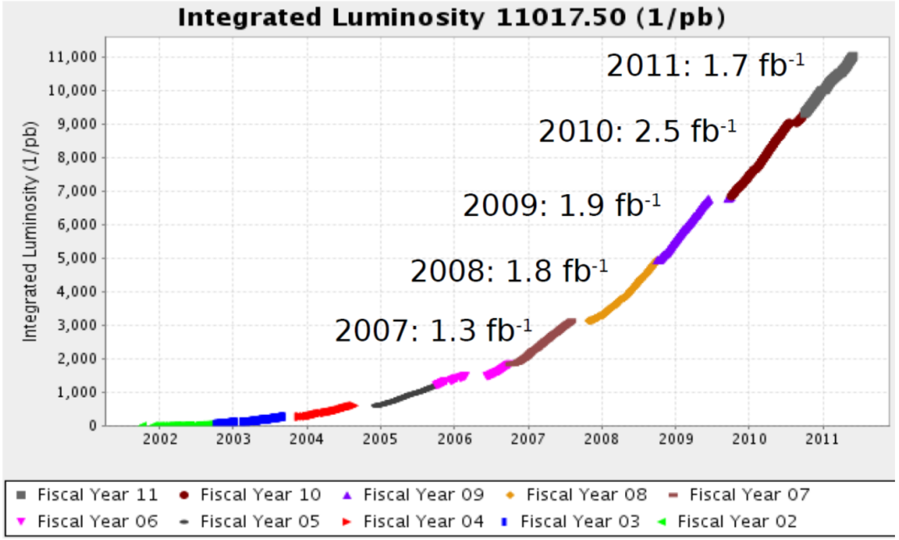


Already collected 2.5 fb^{-1} at $\Psi(3770)$

Intention to collect very big $\Psi(3770)$ sample features in plans of Super-B

State of play at the Tevatron





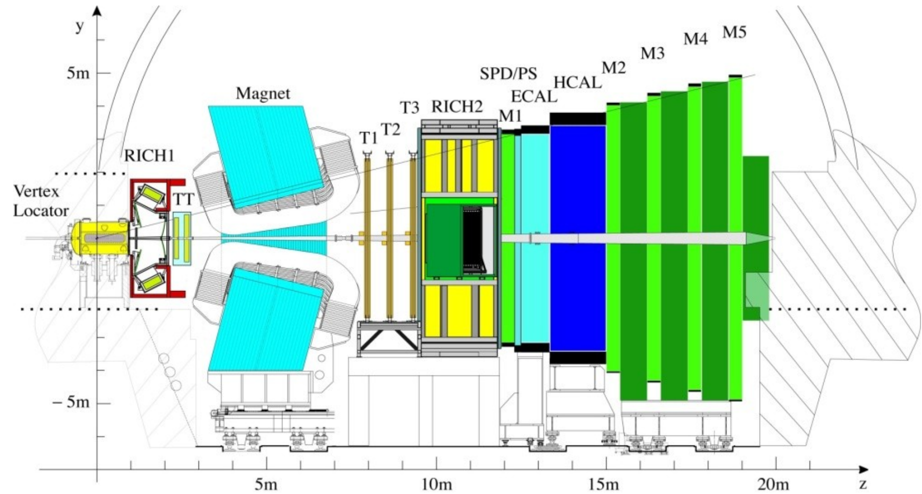
Over 11 fb^{-1} delivered to each experiment, and ~1 fb^{-1} more still to be collected

For many flavour physics analyses, only half of total dataset has been analysed

Still lots of physics to come!

LHCb Essentials

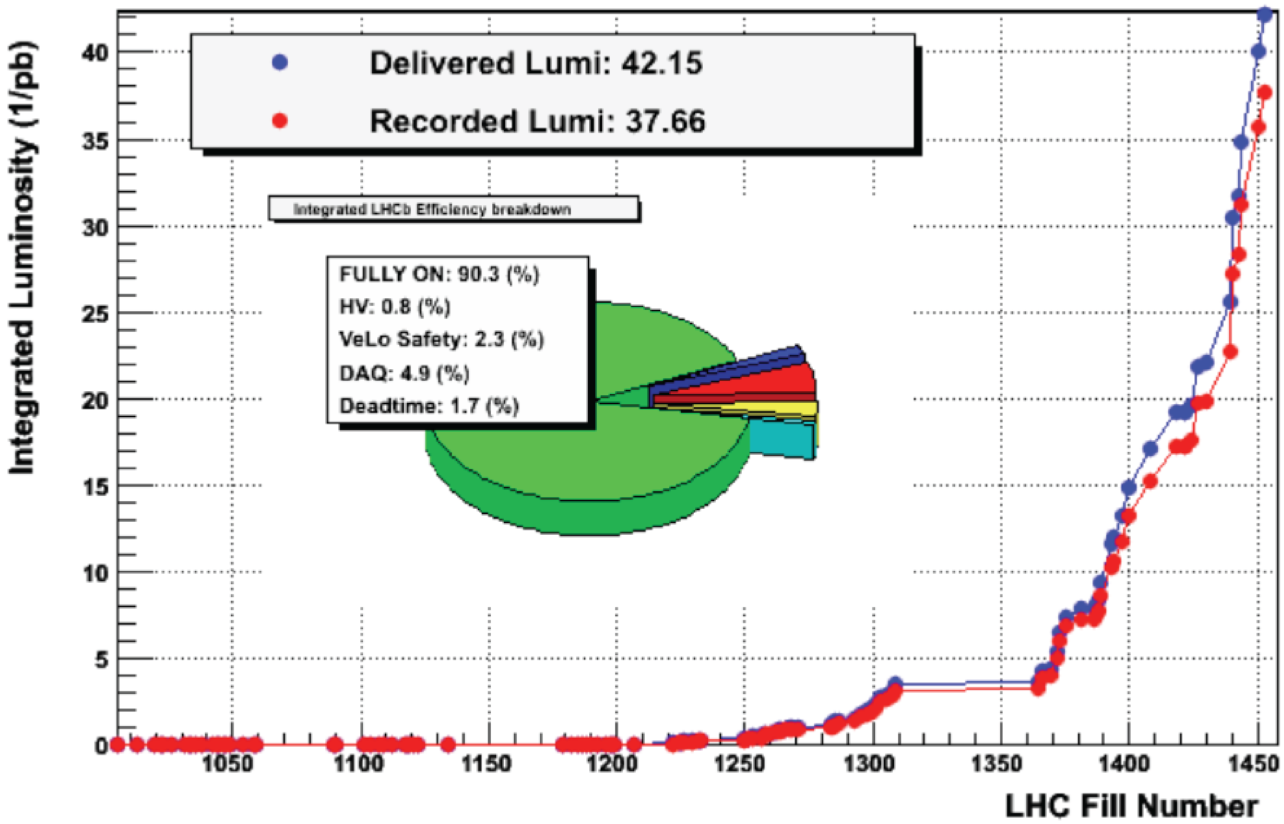
LHCb optimised for flavour physics.
Various attributes distinguish it from Tevatron detectors + ATLAS/CMS:



- Dedicated heavy flavour trigger
  - L0: hardware trigger firing on high p_t hadrons and muons
  - HLT: software trigger exploiting, in particular, tracking and vertexing. Outputs at 3 kHz

    → Efficient for hadronic B and D decays, as well as leptonic channels
- Very precise vertexing
  - VELO (planes of forward silicon) approach to within 8mm of beam
- Hadron identification
  - Two RICHes provide good π/K separation over $2 < p < 100$ GeV/c
- LHCb design luminosity << maximum design luminosity of machine
  - LHCb already operating at (even above!) design luminosity (2×10^{32} cm^{-2} s^{-1})

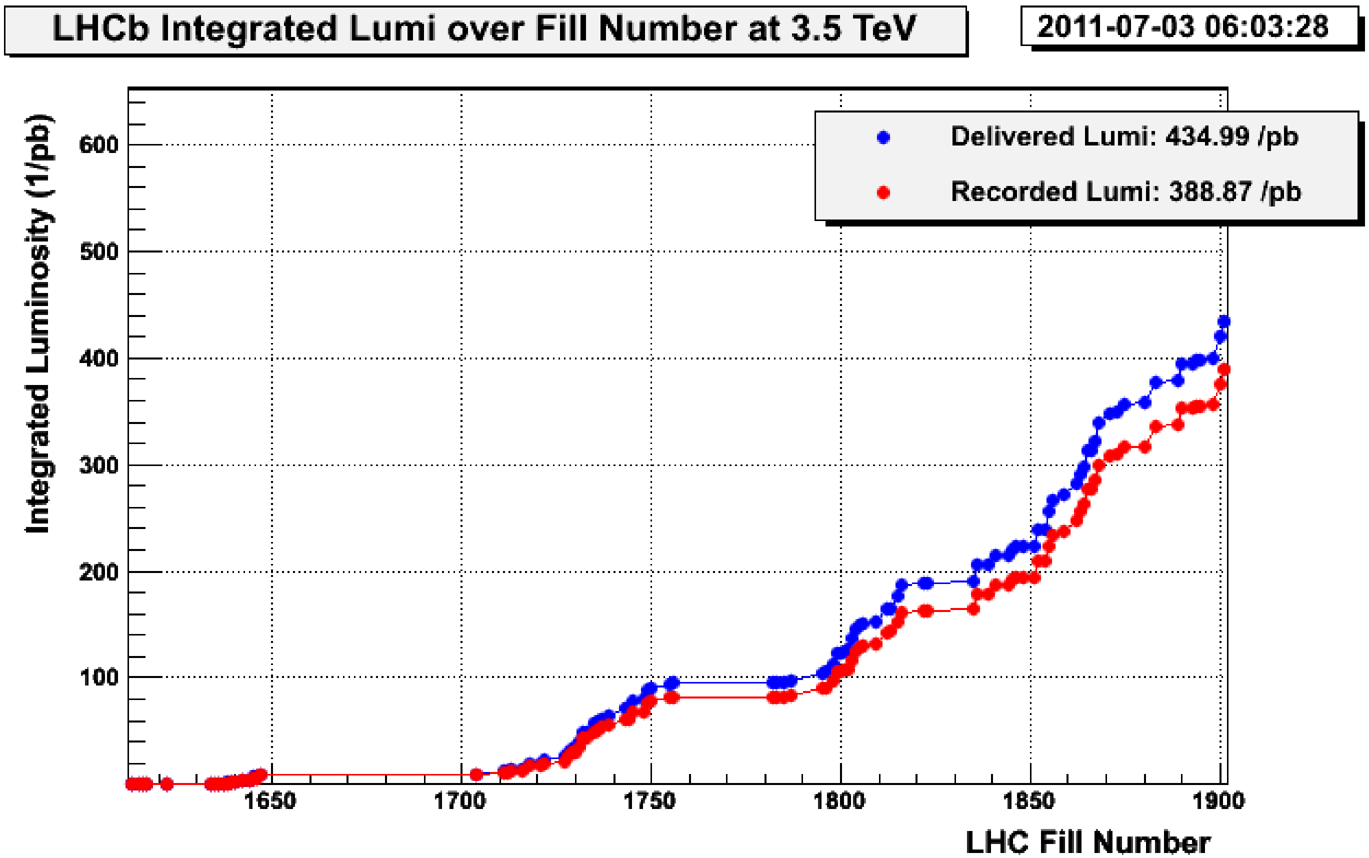
LHCb integrated luminosity in 2010



Design luminosity 2 x 10^{32} cm^{-2} s^{-1}. Almost there at end of run!

Similar amount (~40 pb^{-1}) accumulated by ATLAS and CMS

Integrated luminosity (so far) in 2011

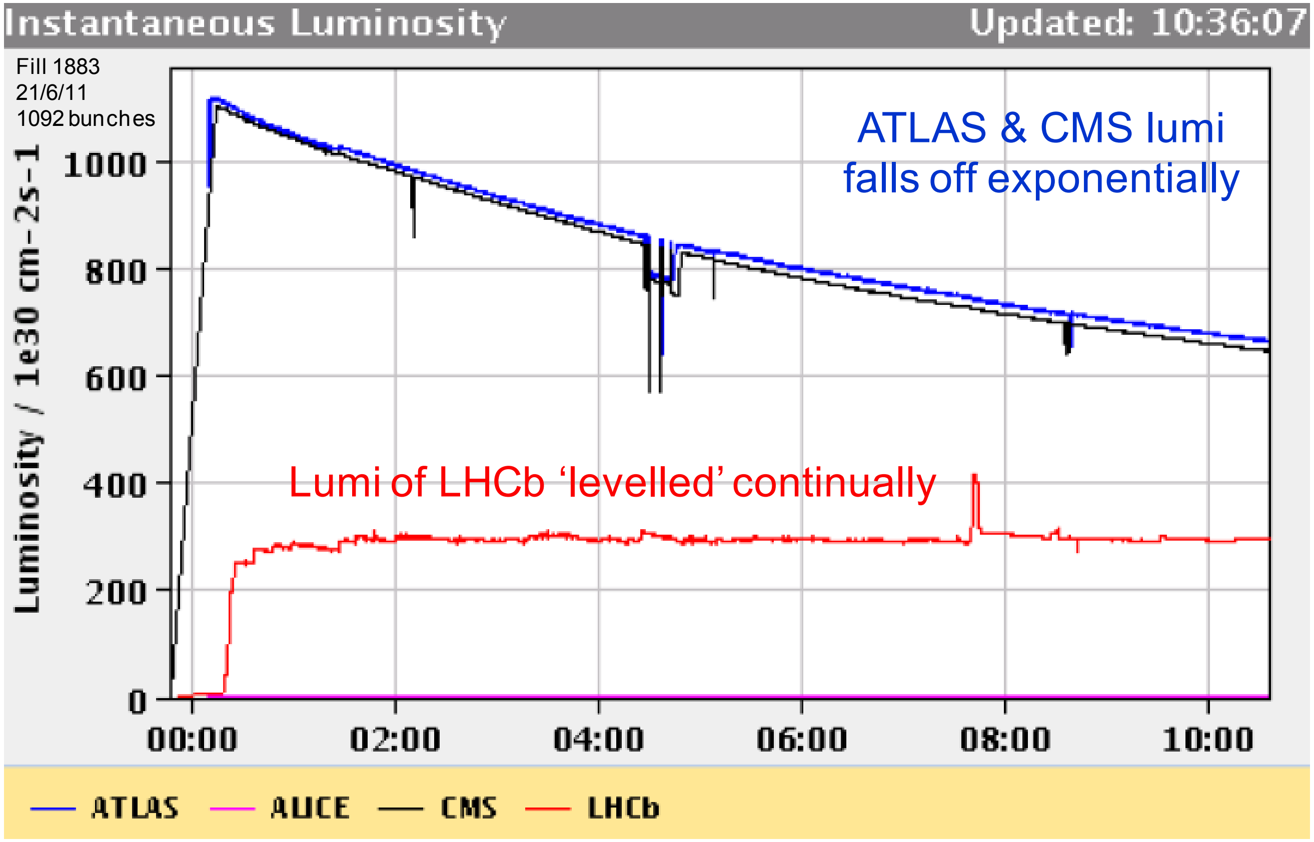


~390 pb^{-1} recorded. On target to accumulate >1 fb^{-1} by end of year.

ATLAS and CMS have collected around 3 times this amount

Running strategy in 2011

Beams at LHCb displaced from head-on, with displacement reduced throughout fill



LHCb lumi choice dictated by event size & complexity, trigger & detector stability

Looking forward...

There exist three approved projects which will bring further step-up in precision...

Belle II: datataking begins 2015 ?

SuperB: datataking begins 2017 ?

datataking begins 2019 ?

...but will not consider these further today, as shall focus on the immediate future

Five potential game-changers – good bets to lead us to NP in the LHC era

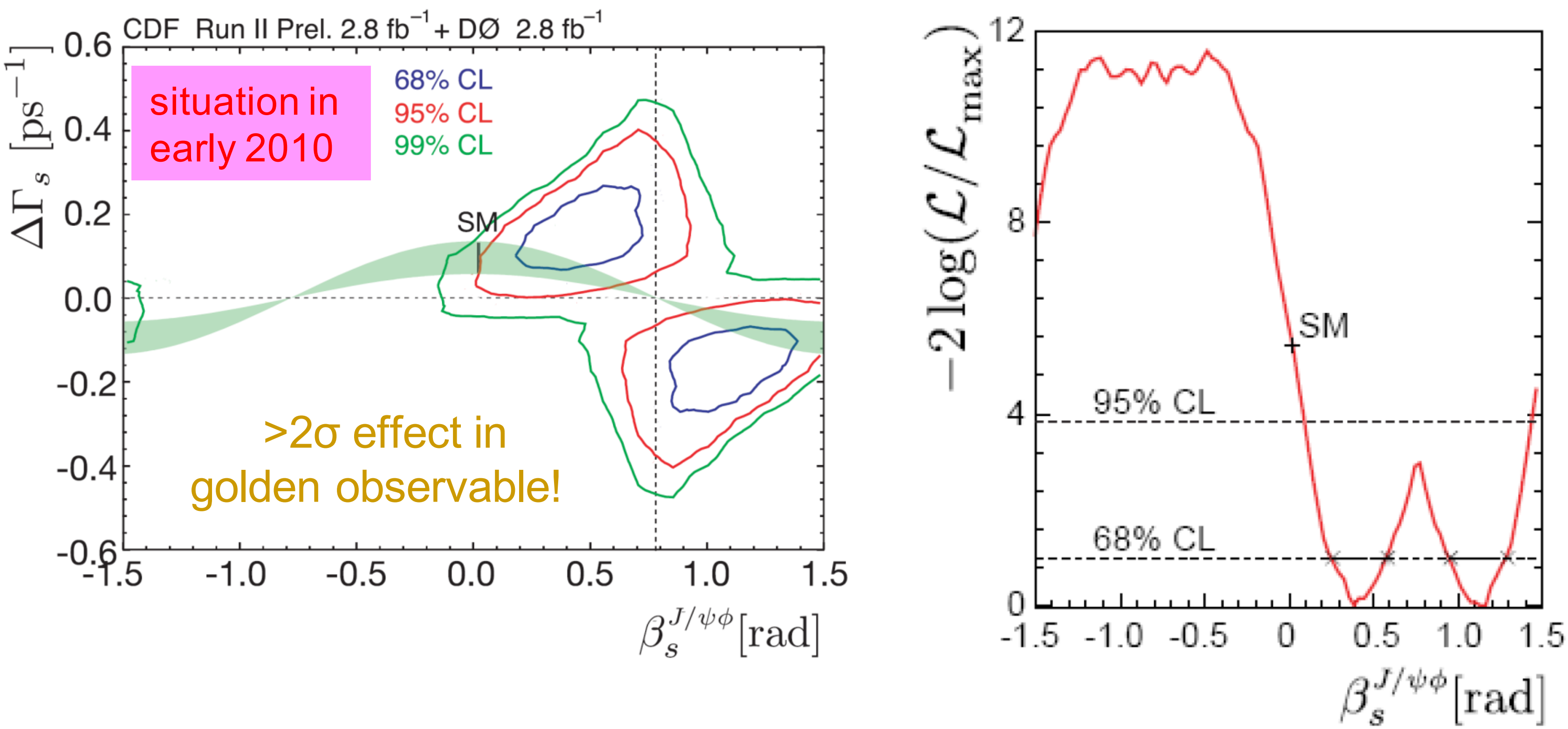
- CPV in B_s mixing: the great hope
- $B_s \rightarrow \mu^+\mu^-$: the SUSY slayer (or finder) ?
- $B^0 \rightarrow K^{*0}\mu^+\mu^-$: the wonder mode
- CPV in charm: the dark horse
- Precise CKM metrology: the slow-burner

Search for CPV in B_s mixing

Mixing induced CPV in $B_s \rightarrow J/\psi\Phi$ ($\varphi_s = -2\beta_s$) is golden mode at hadron machines:

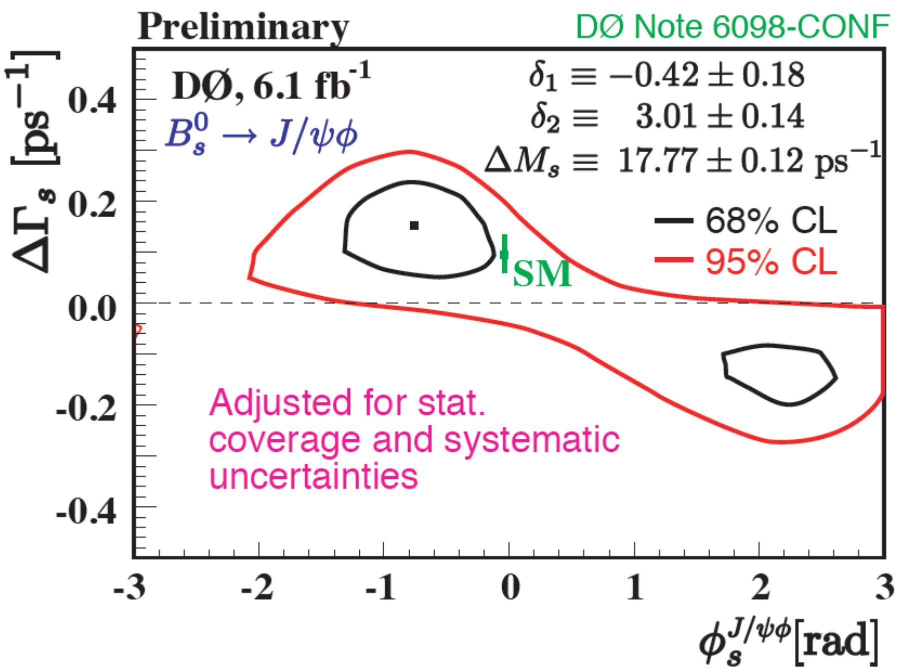
- precisely predicted in SM
- very small in SM – any signal at present sensitivity is very exciting
- a priori sensitive to NP (box diagram) in ways not explored at B-factories

Hence the first results from Tevatron understandably caused a stir..

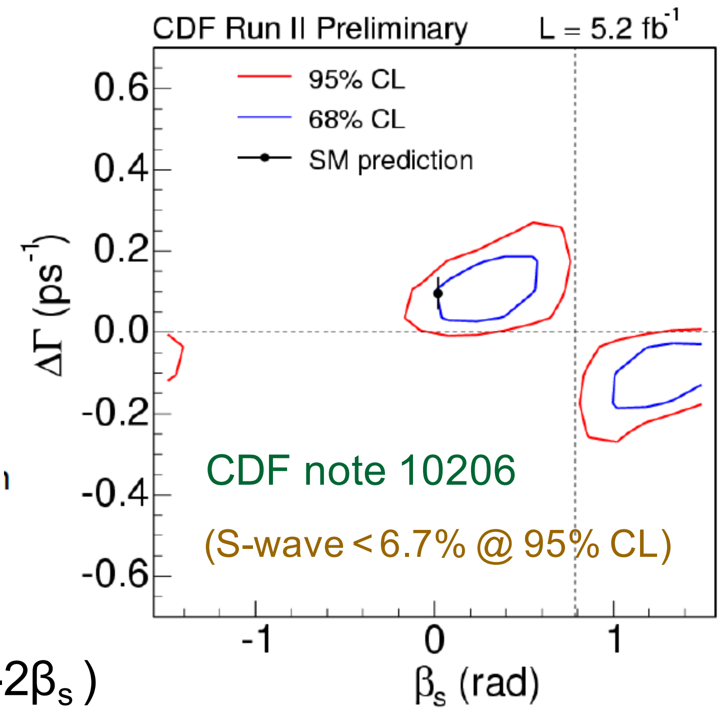


$B_s \to J/\psi\Phi$ after summer 2010 updates

Recent updates to the Tevatron $B_s \to J/\Psi\Phi$ analyses have increased the data sample (6.1 fb^{-1} D0, 5.2 fb^{-1} CDF) and some refinements to the analyses.
e.g. S-wave under Φ: D0 have checked this is small, and CDF include it in the fit



(= $-2\beta_s$)

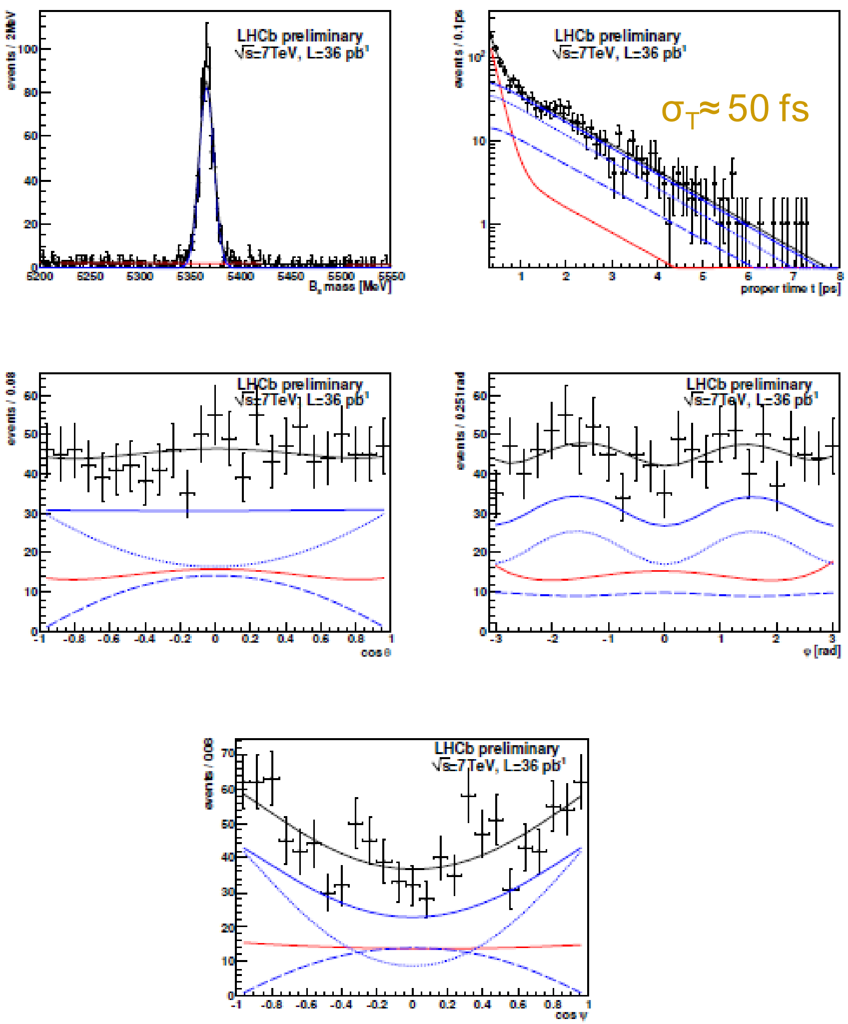


Consistent results, & both are 1σ away from SM. But discrepancy has diminished.
Still, this remains an a priori excellent place to look for physics beyond the SM !

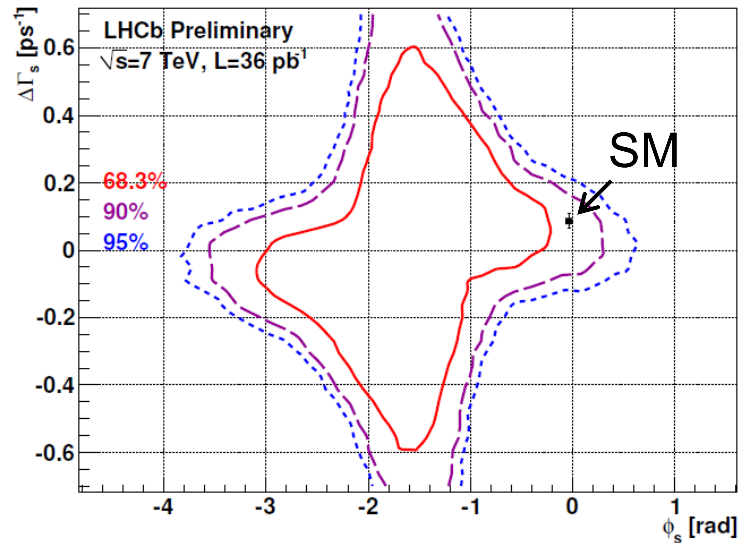
Φ_s at LHCb with 2010 data

LHCb-CONF-2011-006

Fit made to ~760 events with t > 0.3 ps



Lower precision than Tevatron, but same tendency observed. Wait...



$$\phi_s \in [-2.7, -0.5] \text{ rad at } 68\% \text{ CL}$$

...but not for very long! *Much* higher sensitivity expected with 2011 data:

- -Larger sample (> x 20)
- -Improvement in 'opposite side tagging' (present $\varepsilon D^2 = 2.2 \pm 0.5\%$)
- -Inclusion of 'same side' kaon tagger

New physics in a^s_{sl} (&/or a^d_{sl}) ?

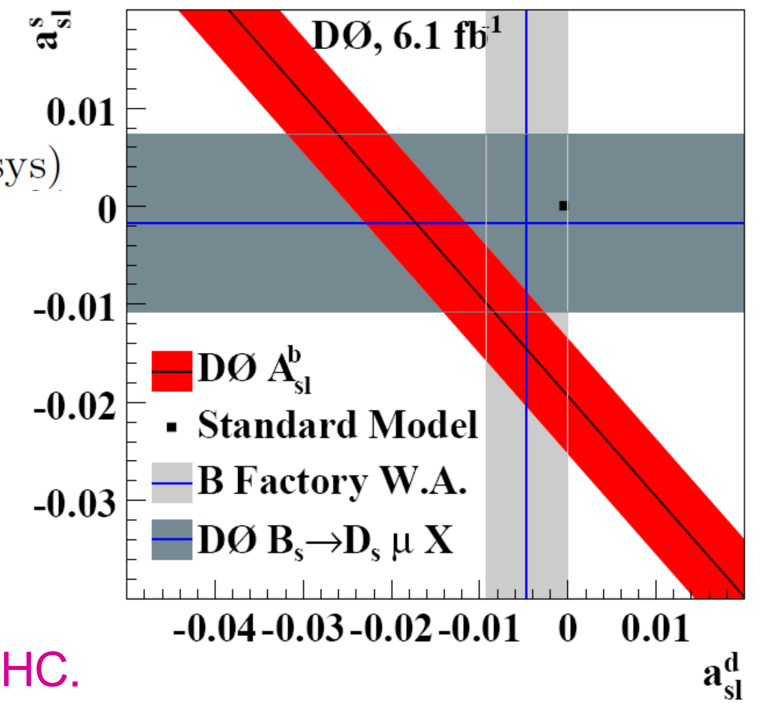
If New Physics enhances CP-violation in $B^0_s \to J/\psi\Phi$, it will likely also dominate over the (negligible) SM CP-violation predicted in the like-sign lepton asymmetry.

D0 collaboration [PRL 105 (2010) 081801, PRD 82 (2010) 032001]:

$$A^b_{sl} = \beta_d a^d_{sl} + \beta_s a^s_{sl}\,, \quad \beta_d \approx \beta_s \approx 0.5$$

$$A^b_{sl}(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

$$A^b_{sl} = -0.00957 \pm 0.00251\,(\mathrm{stat}) \pm 0.00146\,(\mathrm{sys})$$



3σ tension with SM – central value is large (too large?) and in same sense as, & not inconsistent with, $B^0_s \to J/\psi\Phi$ results

Very challenging systematics ! D0 'trick' is to exploit correlation in background between single lepton & dilepton samples

Eagerly await updates, & results from CDF/LHC.
If effect is genuine it will very likely soon manifest itself in $B^0_s \to J/\psi\Phi$ analysis.

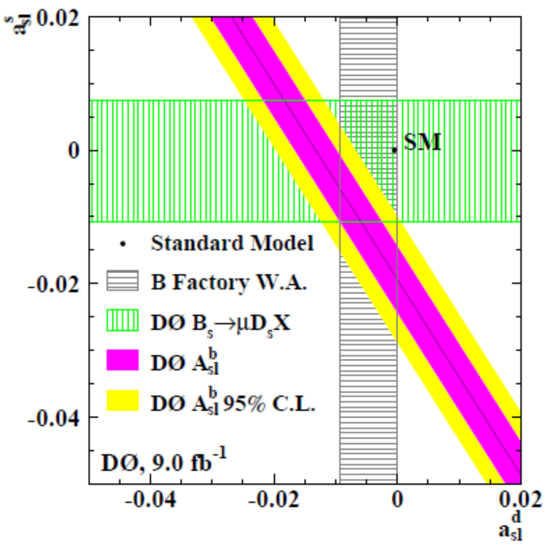
Breaking news on a^s_{sl} !

Previous slide prepared before last Friday, when a D0 update was announced !

Main features in updated analysis:

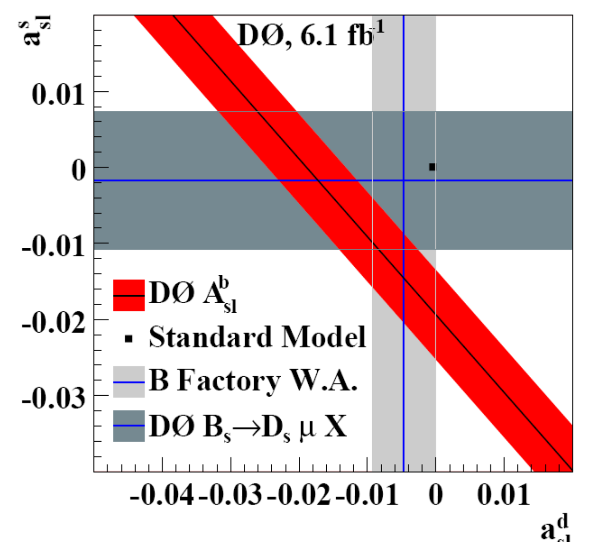
- data 6.1→9.0 fb^{-1}
- analysis refinements
- important cross-checks exploiting μ impact parameter

Update [arXiv:1106.6308]



$A^b_{sl} = (-0.787 \pm 0.172\ (\text{stat}) \pm 0.093\ (\text{syst}))\%$

PRL 105 (2010) 081801



$A^b_{sl} = -0.00957 \pm 0.00251\ (\text{stat}) \pm 0.00146\ (\text{syst}).$

Central value decreased (in magnitude), but disagreement with SM 3.2→3.9 σ

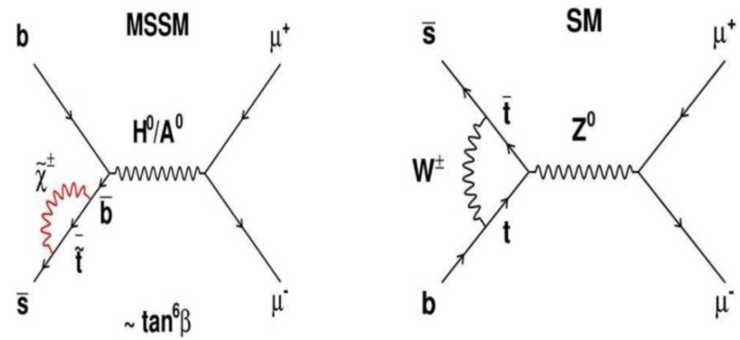
The golden mode: $B_s \to \mu\mu$

B physics rare decay par excellence:

$BR(B_s \to \mu\mu)_{SM} = (3.35 \pm 0.32) \times 10^{-9}$

(Blanke et al., JHEP 0610:003,2006)

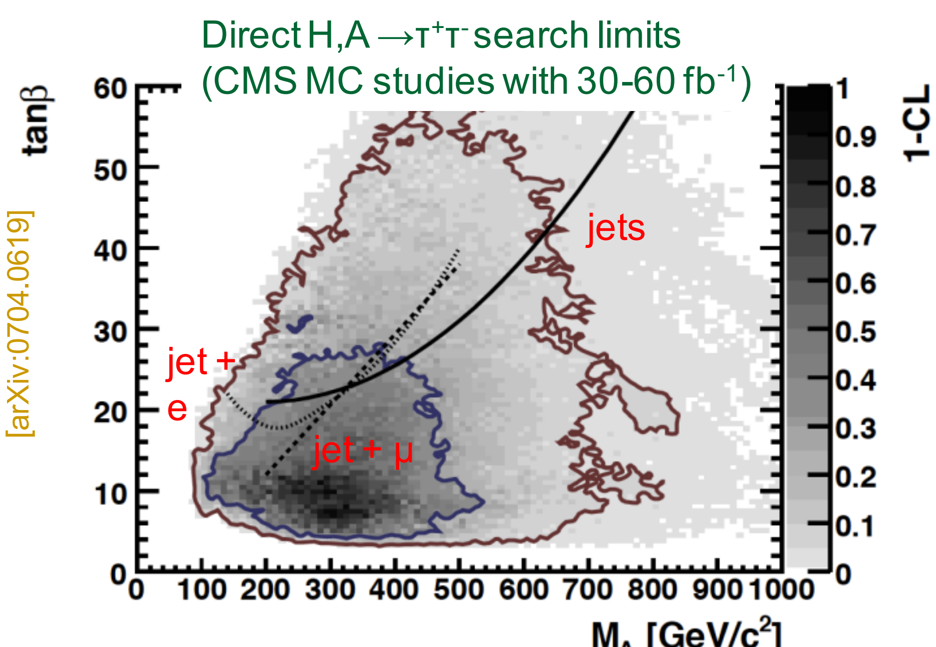
Precise prediction (which will improve) !

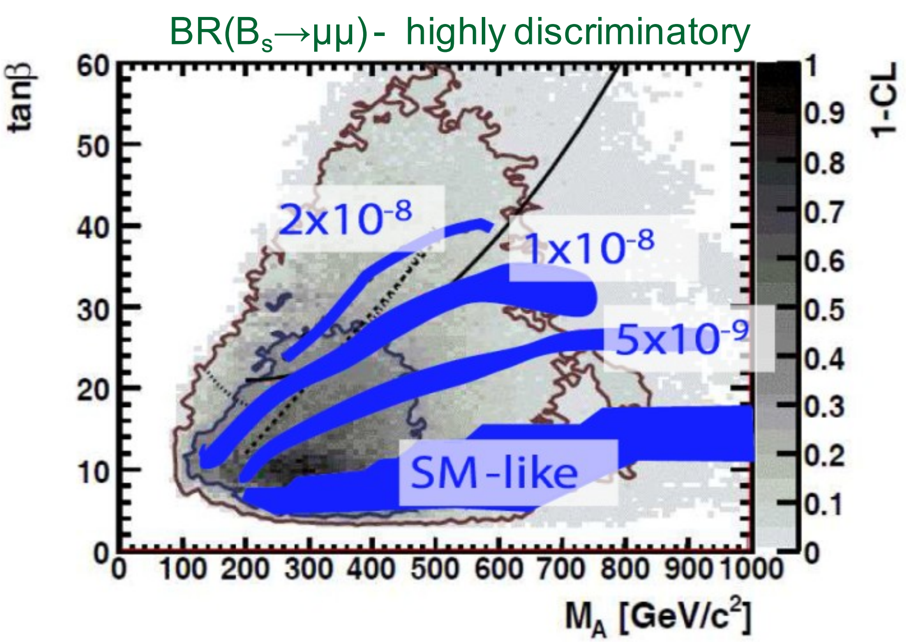


$$Br^{MSSM}(Bq \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$

Very high sensitivity to NP, eg. MSSM:

One example [O. Buchmuller et al, arXiv:0907.5568] : NUHM (= generalised version of CMSSM)

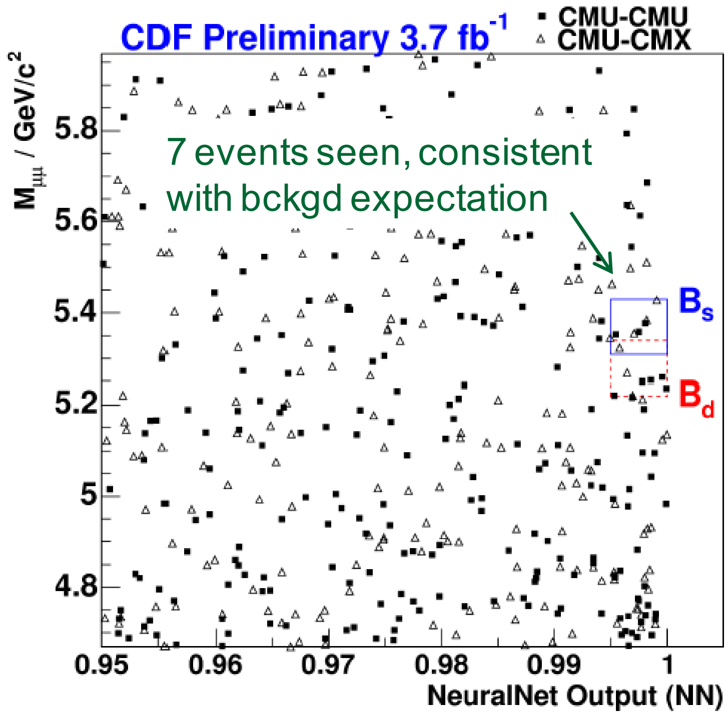




$B_s \rightarrow \mu\mu$ search at Tevatron

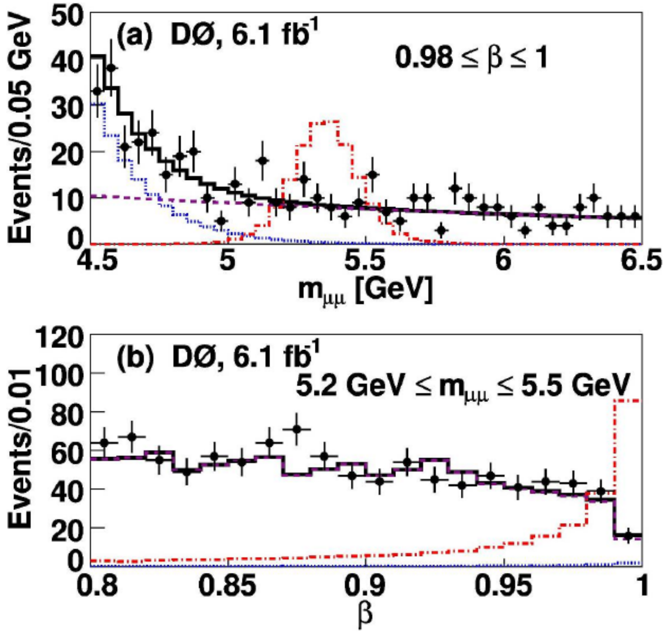
Impressive limits from CDF & D0. After preselection, both form multivariate variable with topological & kinematic info. Study event distributions in this variable vs $m_{\mu\mu}$

CDF note 9892



BR < 4.3 x 10^{-8} @ 95% CL

55 events in most sensitive region, consistent with bckgd expectation



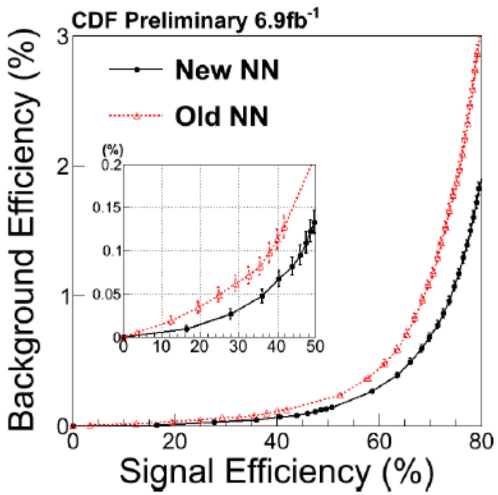
PLB 693 (2010) 539

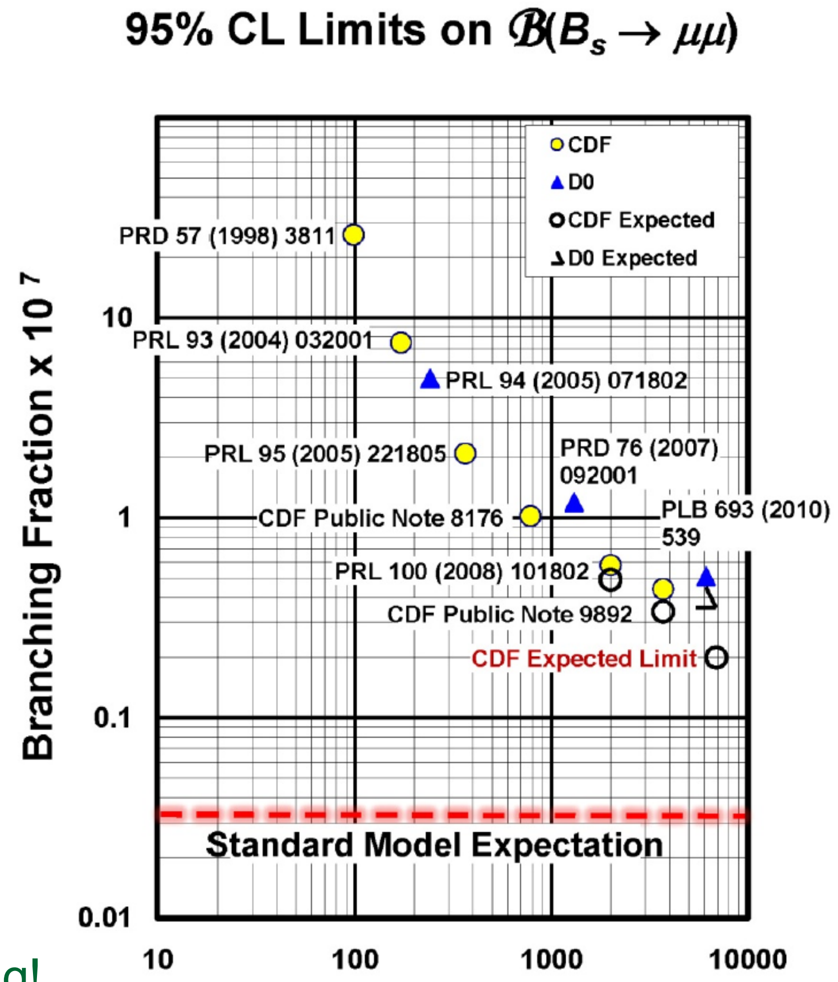
BR < 5.1 x 10^{-8} @ 95% CL

$B_s \rightarrow \mu\mu$ at Tevatron: getting interesting...

New CDF result expected soon, with:

- ~7 fb^{-1}, i.e. 2x more data
- increased muon acceptance
- improved neural net



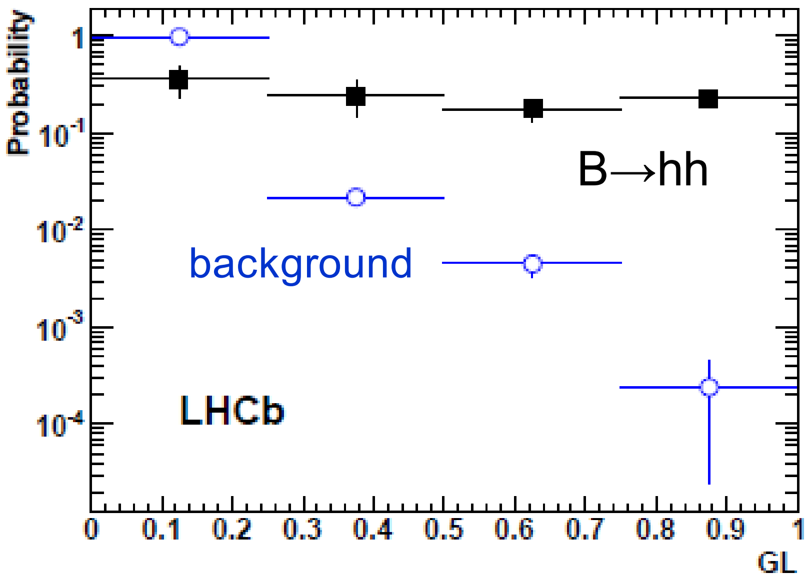


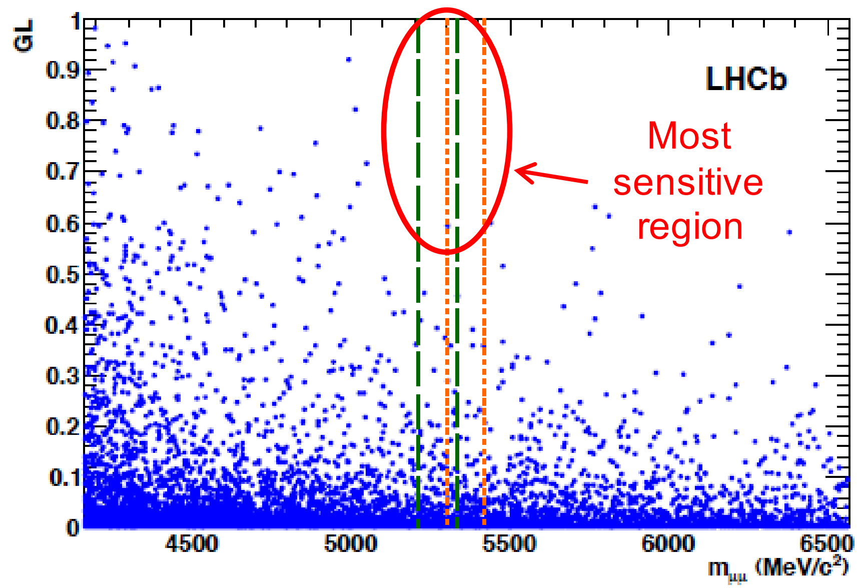
Expected limit of 2 x 10^{-8} – getting interesting!

$B_s \to \mu\mu$ at LHCb

Phys. Lett. B 699 (2011) 330

Form geometrical likelihood (GL) out of discriminant variables and look for enhancement in GL vs $m_{\mu\mu}$ space. Data driven analysis; LHCb $B \to hh$ sample particularly valuable given its identical topology to signal mode.





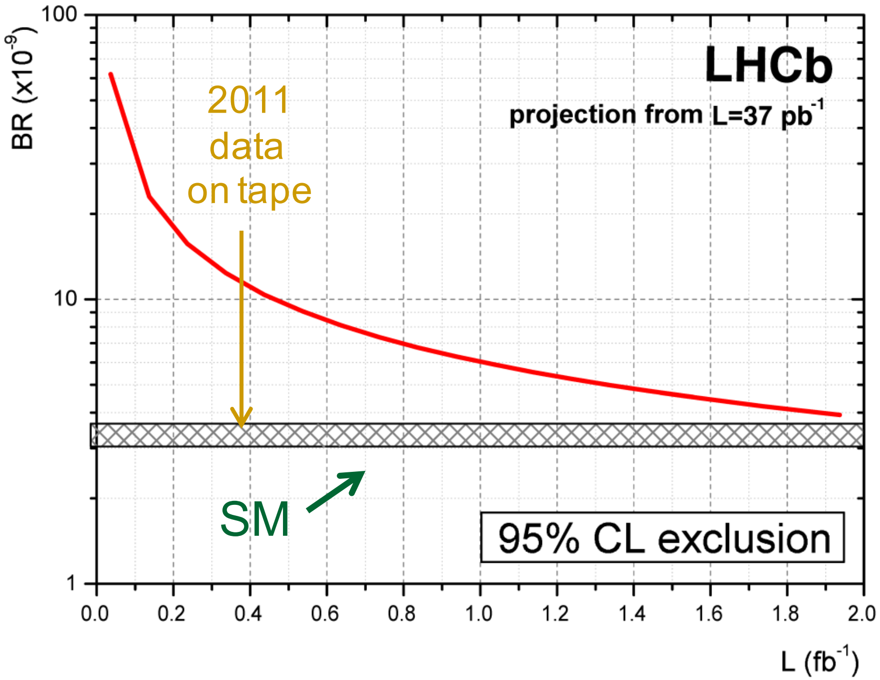
LHCb $BR(B_s \to \mu\mu) < 5.6 \times 10^{-8}$ at 95% CL with 37 pb^{-1}

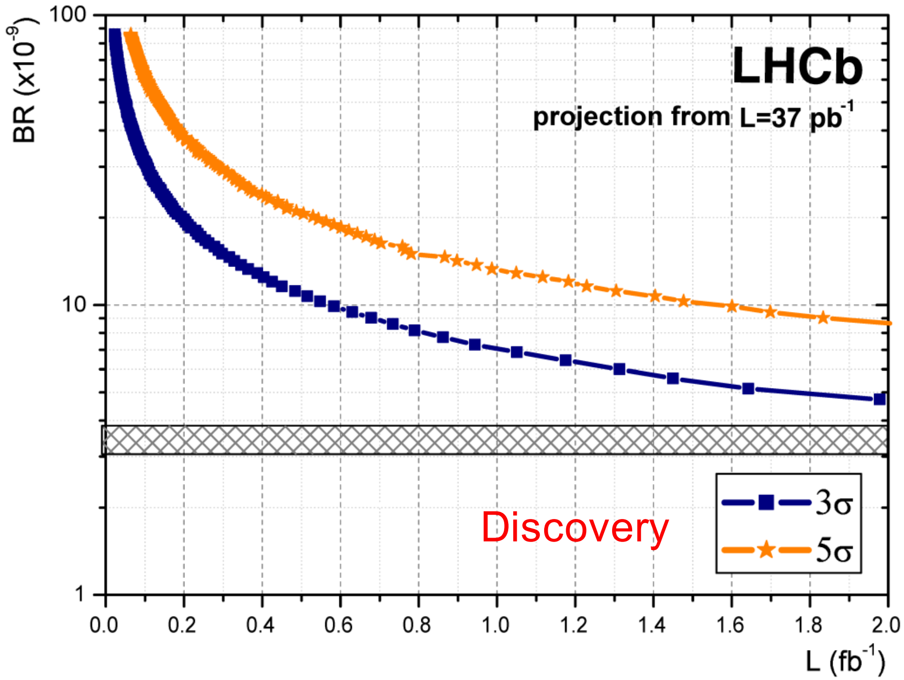
CDF $BR(B_s \to \mu\mu) < 4.3 \times 10^{-8}$ at 95% CL, with 3.7 fb^{-1}

D0 $BR(B_s \to \mu\mu) < 5.1 \times 10^{-8}$ at 95% CL, with 6.1 fb^{-1}

$B_s \rightarrow \mu\mu$: breaking the 10^{-8} barrier

Extrapolating from present result, and not allowing for any analysis improvements:

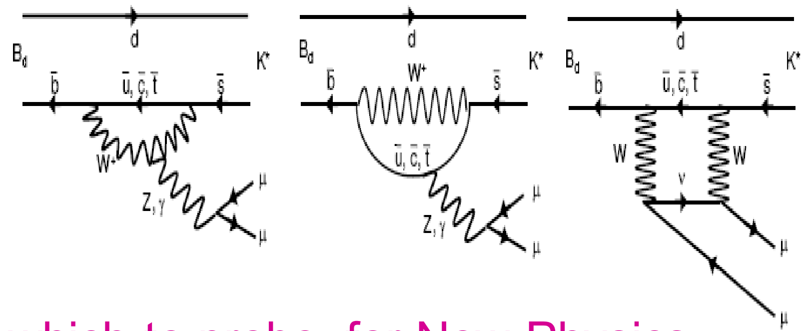




Will be getting close to the <10^{-8} regime already at the summer conferences

Note that GPDs have very interesting potential in this analysis, especially CMS (best GPD mass resolution) – should be able to do (at least?) as well as LHCb!

$B^0 \to K^* l^+ l^-$: the wonder mode



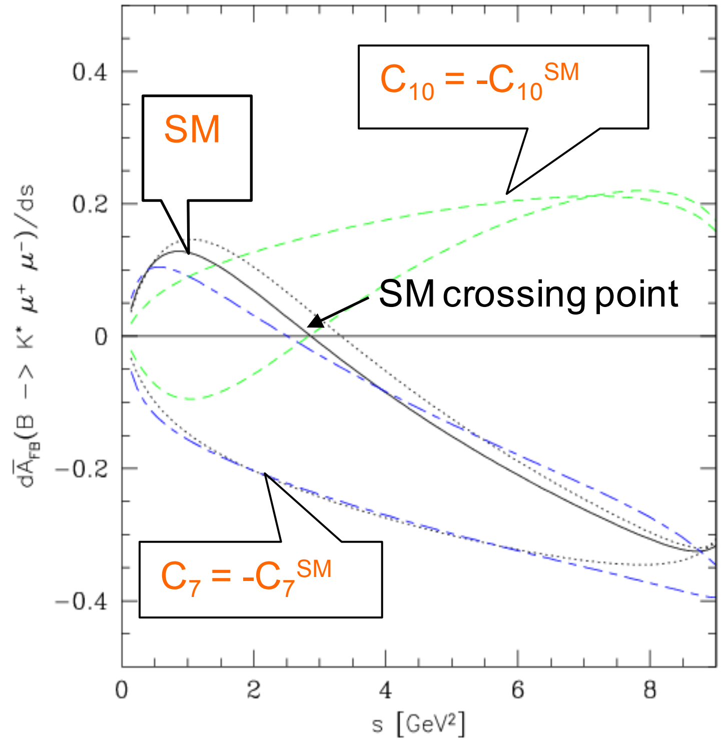
One of the most powerful laboratories in which to probe for New Physics effects in B decays is $B \to K^{(*)} l^+ l^-$.

Host of interesting observables

Most promising in $K^* l^+ l^-$ are angular distributions, eg. forward-backward asymmetry of the angle between lepton and B in the dilepton rest frame

sensitive to effective Wilson coefficients C_7, C_9 and C_{10}

Position of zero-asymmetry 'crossing-point' rather cleanly predicted in SM, but also sensitive to new physics effects

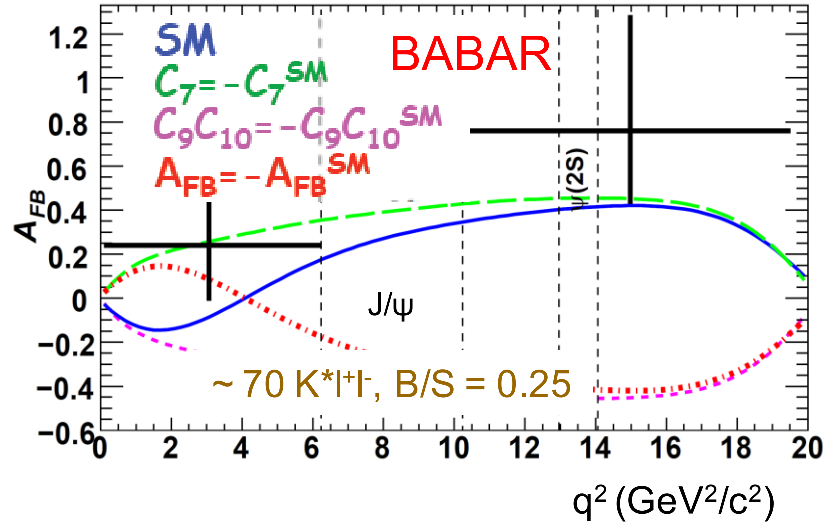


Ali *et al.* PR D61 (2000) 074024

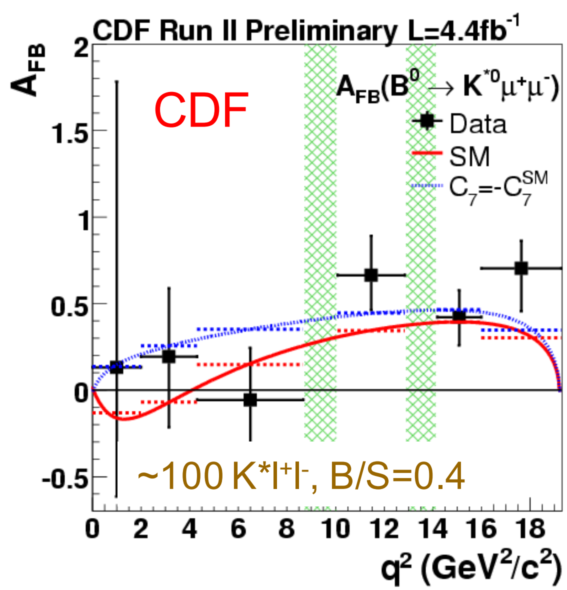
Intriguing hints from $B^0 \to K^* l^+ l^-$

Samples of 100 events or so collected and analysed at B-factories and CDF

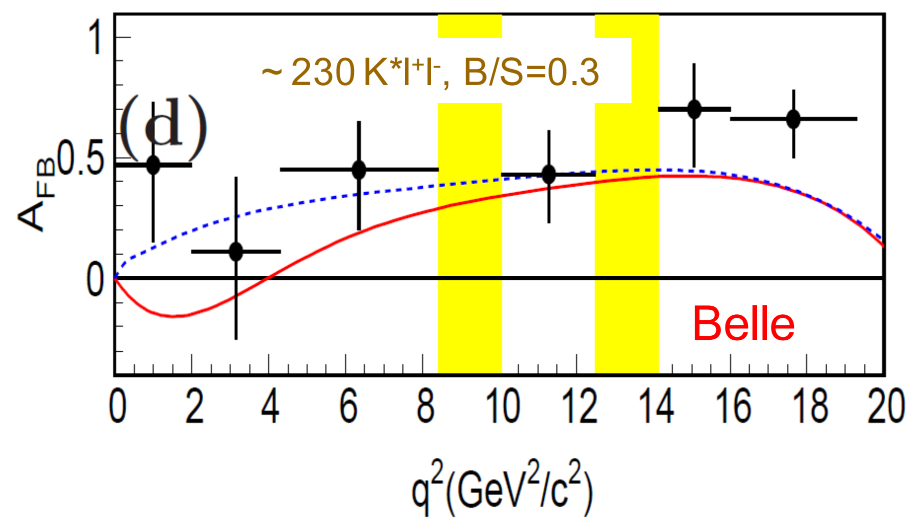
Early results are showing intriguing hints. Not yet an ‘anomaly’, but any deviation where one is hoped for has special interest....



PRD 79 (2009) 031102

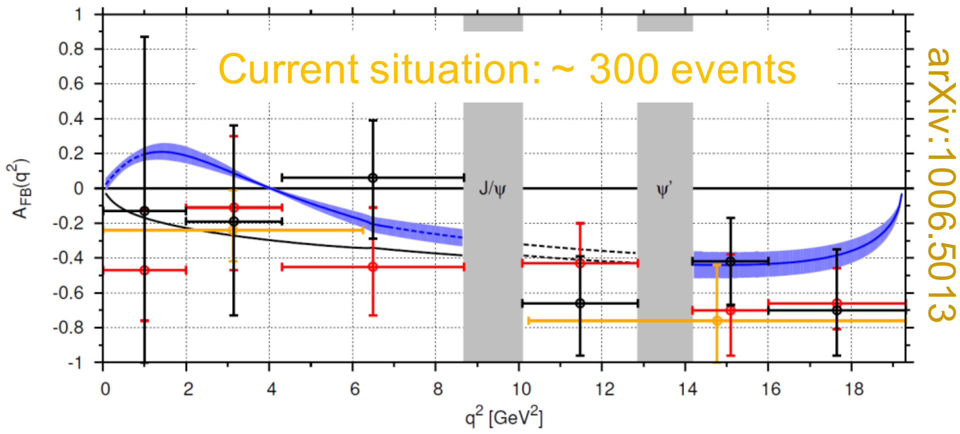


CDF note 10047



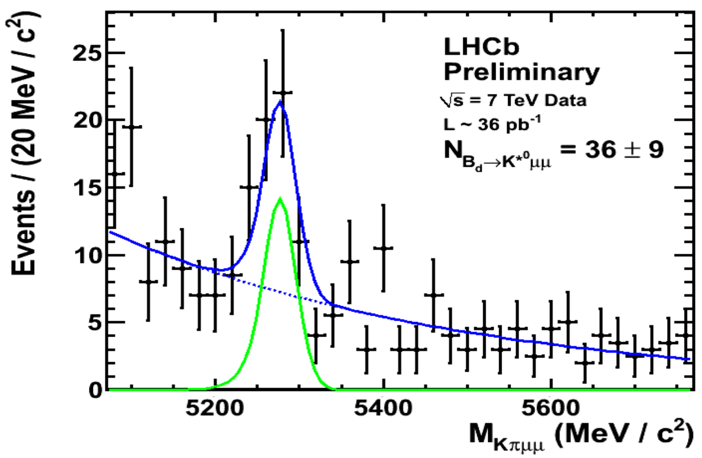
PRL 103 (2009) 171801

$B^0 \to K^* l^+ l^-$ at LHCb

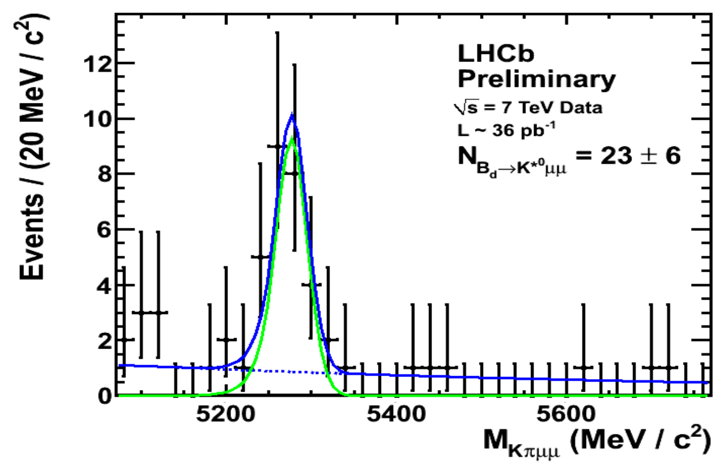


Experiences with 37 pb^{-1} in 2010

Loose selection: 1 event / pb^{-1}, B/S~1



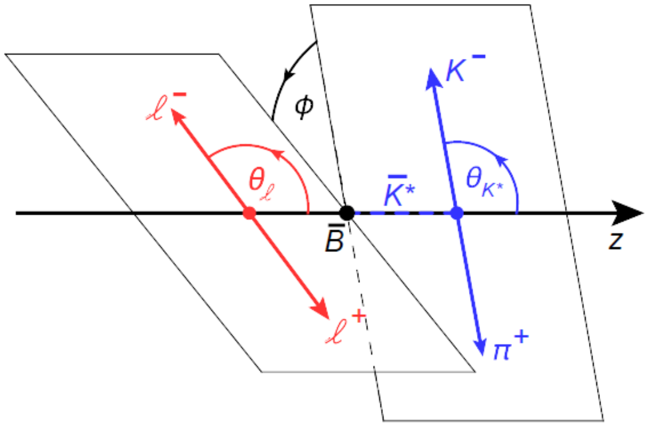
Tight BDT cut : 0.6 event / pb^{-1}, B/S~0.25



Should be around 300-400 events on tape already in 2011 (390 pb^{-1})

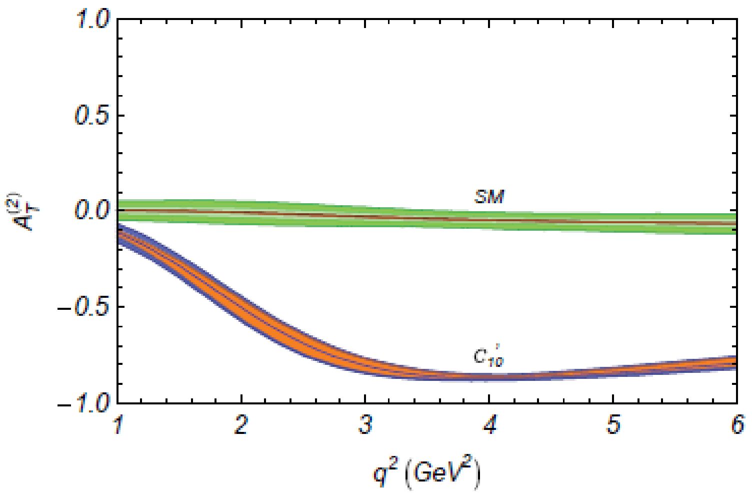
Already chance to say something interesting at EPS/LP? Beyond, a rather precise measurement of A_{FB} crossing point (if it exists!) will be possible with 2011-12 data

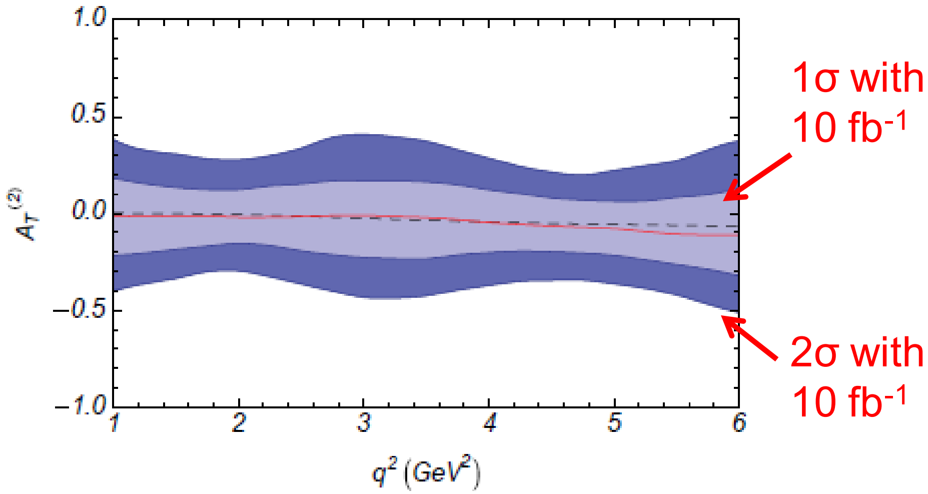
$B^0 \rightarrow K^*\mu\mu$: beyond A_{FB}



With a few 1000 events it will be possible to attempt a full angular analysis of $B^0 \rightarrow K^{*0}\mu\mu$ decays

From this study other, important observables can be constructed, e.g. transversity asymmetry, $A_T^{(2)}$ – highly sensitive to RH currents





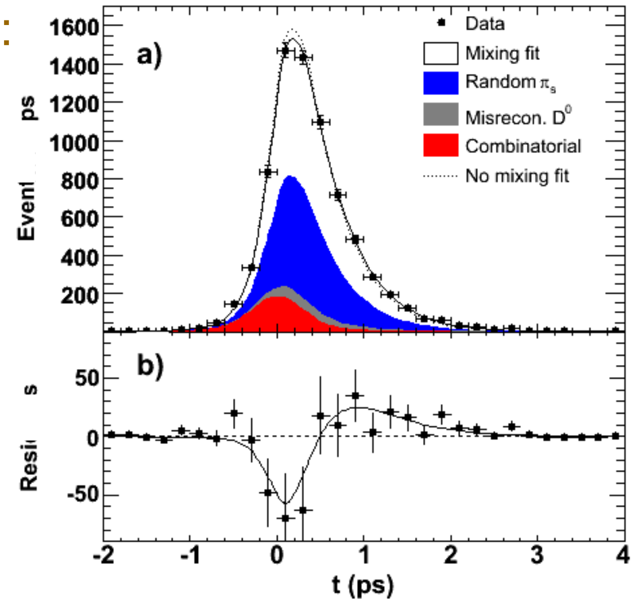
With higher statistics other, related modes also become available:
$B^0 \rightarrow K_2^{*0}\mu\mu$, $B_s \rightarrow \Phi\mu\mu$, $B_s \rightarrow K^*\mu\mu$, $\Lambda_b \rightarrow \Lambda^{(*)}\mu\mu$

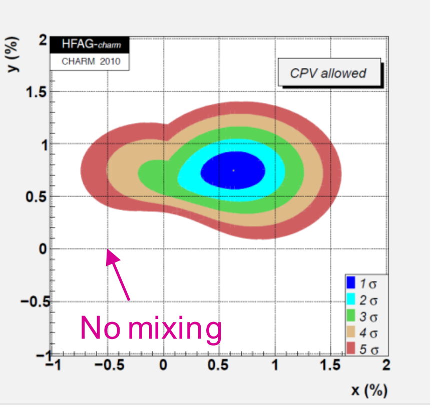
D^0-$\overline{D}^0$ Mixing: Observation

Numerous recent, exciting results on charm mixing:

The most interesting…

- 'Wrong sign' $K\pi$ (x'^2, y')
  - Belle, PRL 96 (2006) 151801
  - BABAR, PRL 98 (2007) 211802
  - CDF, PRL 100 (2008) 121802
- Eigenstate lifetime analyses: y_{CP}
  - BABAR, PRD 80 (2009) 071103
  - Belle, PRL 98 (2007) 211803
- $K_S\pi^+\pi^-$ Dalitz analyses: x,y
  - Belle, PRL 99 (2007) 131803
  - BABAR, PRL 105 (2010) 081803





A whole armada of complementary analyses
Taken *together*, no doubt now that mixing exists…

$x = 0.63\pm^{0.19}_{0.20}$ %

$y = 0.75\pm 0.12$ %

(HFAG, Oct 10, CPV allowed)

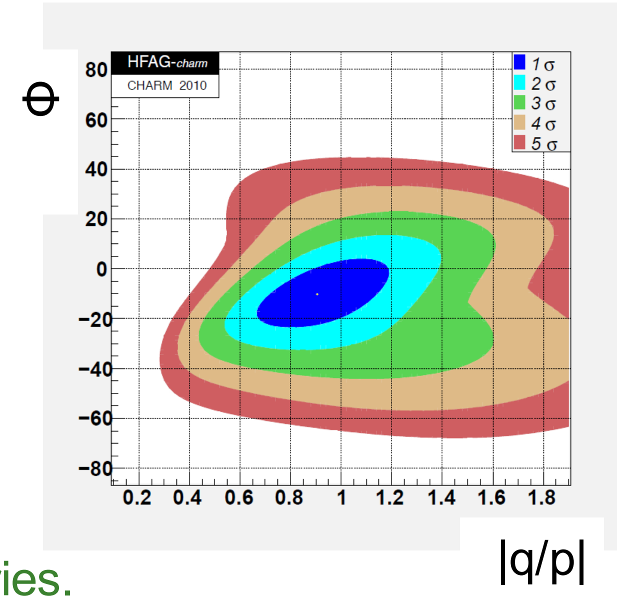
…but what does it mean?

The next step: CPV in charm

Values of x & y at top end of SM expectation – but *not* inconsistent. Use results to constrain many NP models. See, for example, Golowich et al. PRL 98 (2007) 181801.

'High' values of x & y encourage us to follow lessons of B sector - look for CPV !

In SM Φ=0 and |q/p|=1 is an almost perfect approximation. Looking for deviations from this a powerful NP probe, and one complementary to B / K-sector searches.



$$|q/p| = 0.91 \pm^{0.18}_{0.16}$$

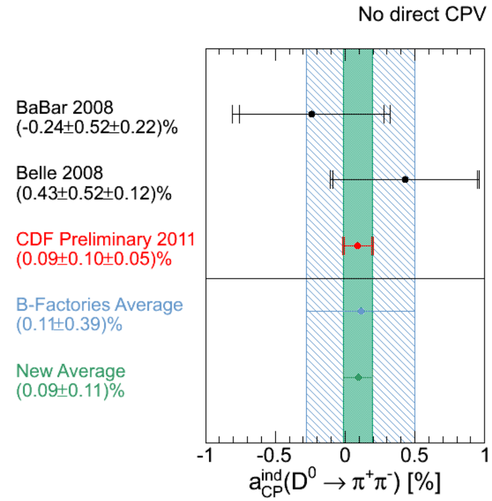
$$\phi = -10.2 \pm^{9.4}_{8.9} \text{ degrees}$$

Further updates possible from CDF and B-factories.
With these, and LHCb order of magnitude improvement possible? Going still further is a strong argument for LHCb upgrade / superflavour factory

For similar reasons, we must intensify the hunt for direct CPV in charm

Grounds for optimisim

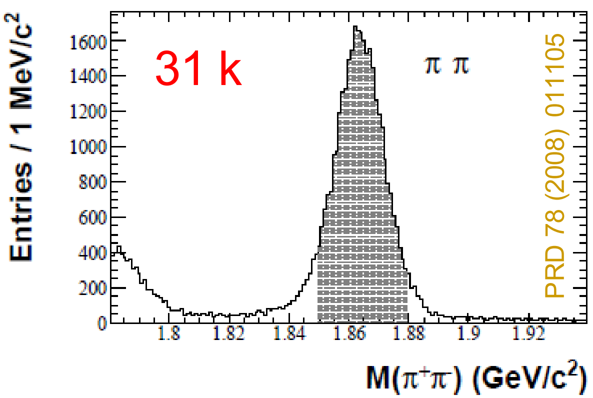
Very large samples of $D^0 \to hh$ events at Tevatron have recently been exploited to give significantly improved constraints beyond (already precise) B-factory results



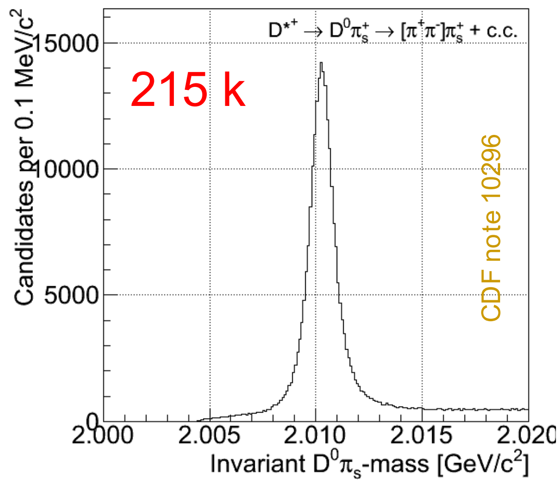
CDF note 10296

e.g. $D^* \to D^0(\pi\pi)\pi$

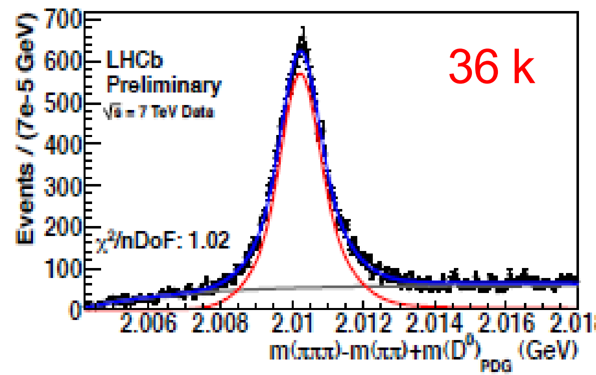
BABAR, 384 fb^{-1}



CDF, 5.94 fb^{-1}



LHCb, 37 pb^{-1}

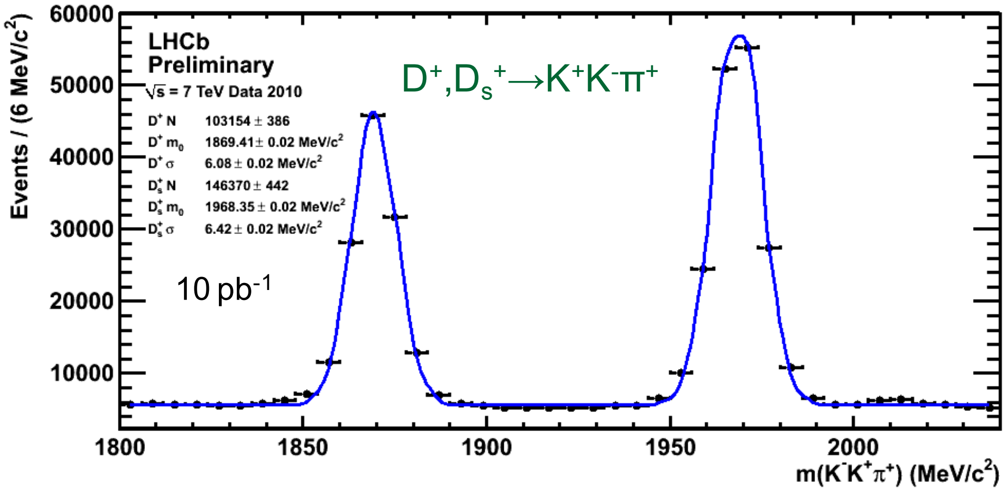


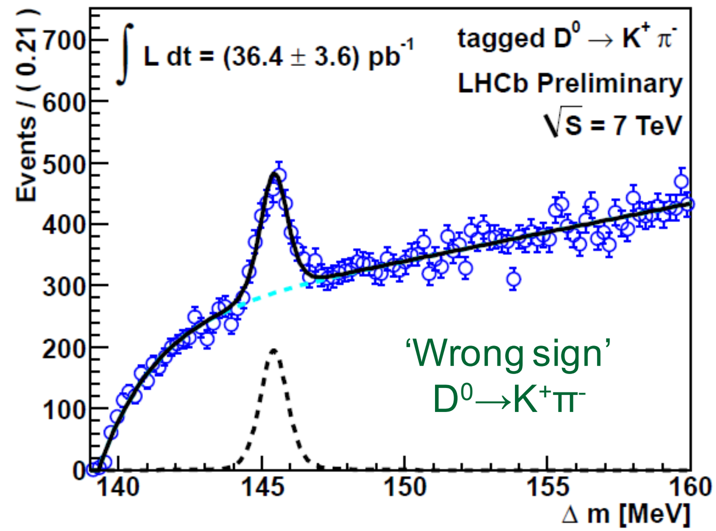
10 x more decays now on tape

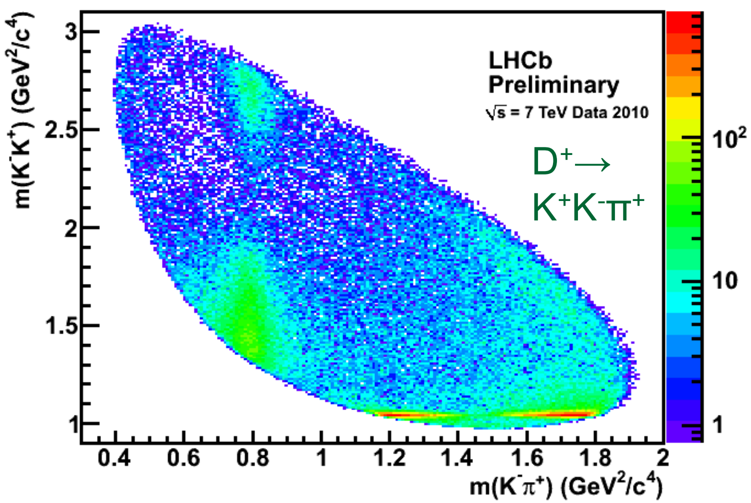
This work will be continue at LHCb, where cross-section is even higher (~6 mb !*) & large fraction of trigger output (~1 kHz) devoted to charm physics

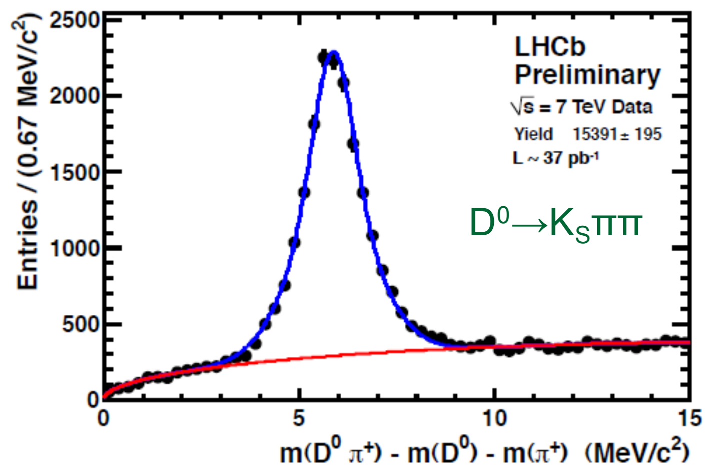
+ LHCb-CONF-2011-023

Promising signals from 2010 LHCb run





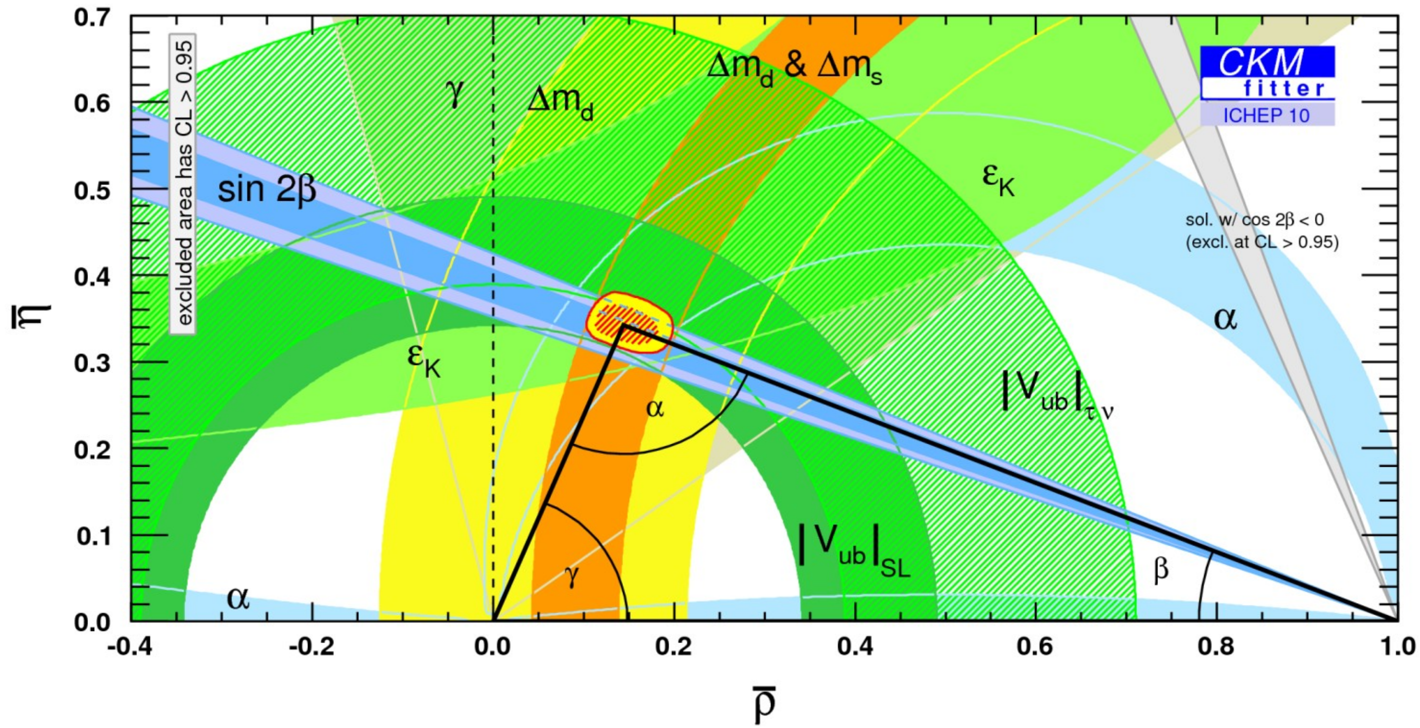




Clear scope for very high precision measurements in 2011 and beyond

The need for more precise CKM-metrology

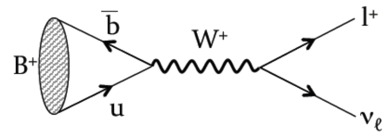
Amazing job by the B-factories (plus kaon experiments [ε_K], plus Tevatron [Δm_s]).
Clear that CKM mechanism is dominant mechanism of CP-violation (in B_d system).



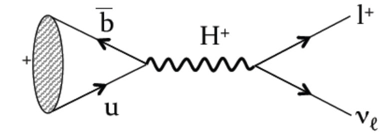
Still possible for NP to be present at ~10% level. And consistency is *not* perfect...
Where are current 'tensions', & where are improved measurements needed?

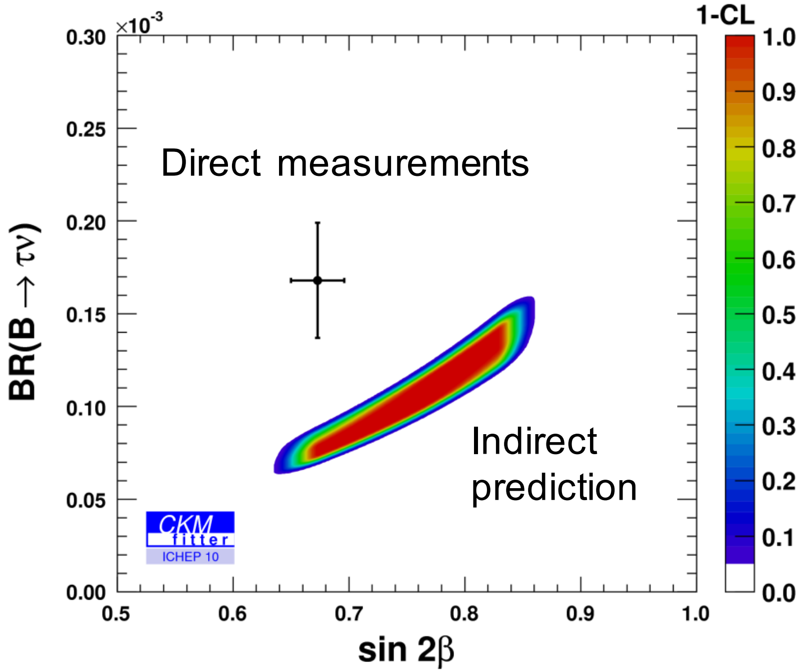
One example of 'tension': B→τν & sin2β

$$\mathcal{B}(B \to \tau\nu) = \frac{G_F^2 m_{B^+} m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 |V_{ub}|^2 f_B^2 \tau_{B^+}$$



+
?





If genuine, this could point to NP in B→τν or sin2β (although sin2β is very well known, it is still *likely* to carry NP at *some* level)

Determination of BR(B→τν) requires full or partial reconstruction of 'other' B.

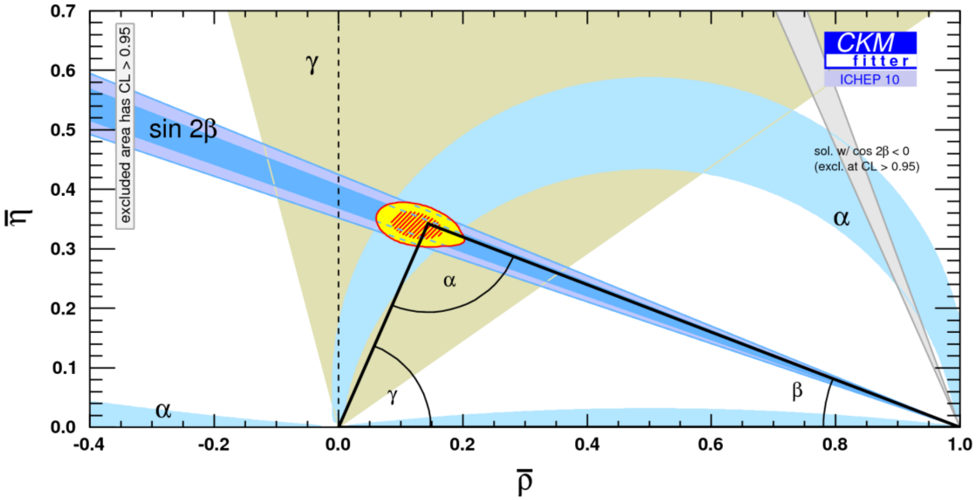
Presently known to ~20% precision. Need Super-B/Belle-II for significant progress.

	0.670 ± 0.023	Summer 2010
New Belle results improve precision on sin2β:	⬇	
	0.678 ± 0.020	Now

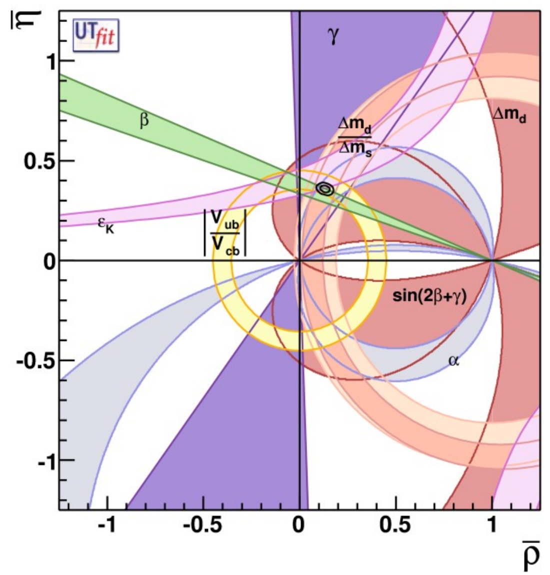
Further progress on sin2β will come from LHCb, but will take time...

The least well known angle: γ / Φ_3

But how badly known is badly known ? Frequentists (CKMfitter) and Bayesians (UTfit) cannot agree, which is surely an indication that our knowledge is too fuzzy.



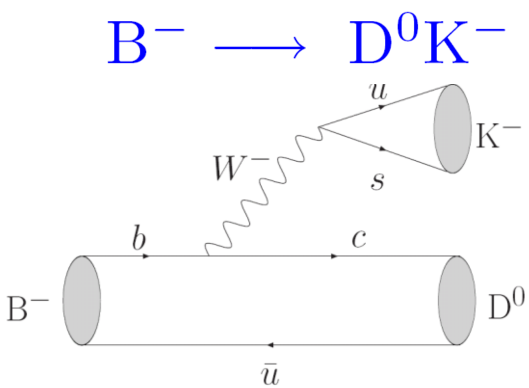
$\gamma = (71\ ^{+21}_{-25})^o$

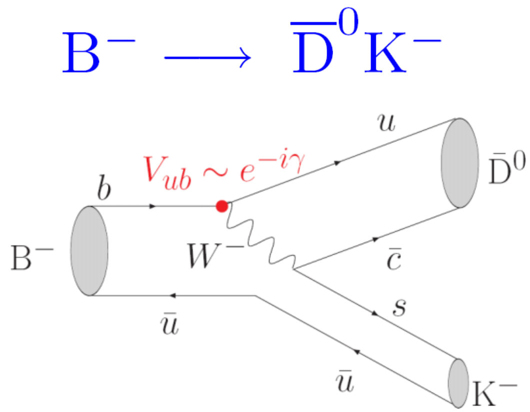


$\gamma = (74 \pm 11)^o$

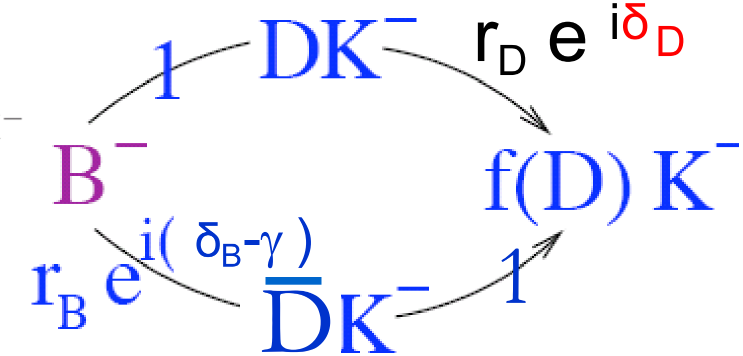
Furthermore γ is the only CP-violating observable that can be measured at tree level – a benchmark quantity to be measured as well as we possibly can.

γ from $B^\pm \to DK^\pm$





$$\frac{< B^- \longrightarrow \overline{D}^0K^- >}{< B^- \longrightarrow D^0K^- >} = r_B e^{i(\delta_B - \gamma)}$$



- Extraction through interference between $b \to u$ and $b \to c$ transitions

- Require D^0 and $\overline{D^0}$ decay to a common final state, f(D). Some examples:

  KK ; $K^0_S hh$; $K\pi$; $K\pi\pi^0$ ...

r_D & δ_D analogous to B-decay quantities. For 3, 4-… body decays, these parameters vary over Dalitz space

- Comparison of B^- and B^+ rates allow γ to be extracted. But other parameters in game. In particular strong phase differences in B and in D system (δ_D)

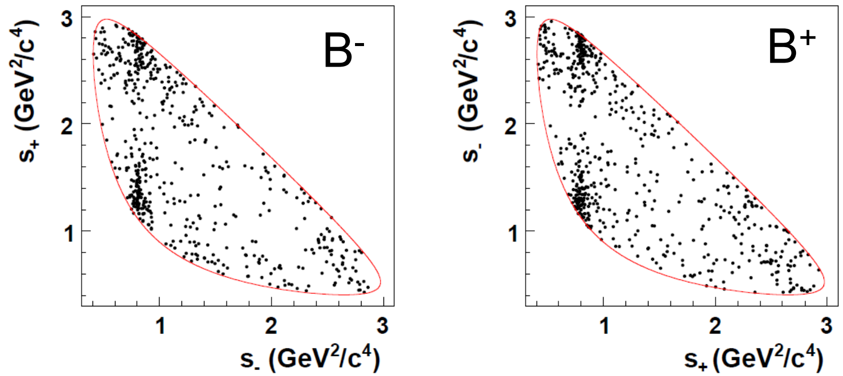
- At LHCb, B_s decays allow for additional strategies to be used e.g. $B_s \to D_s K$

$B^{\pm} \to D(K^0_S\pi\pi)K^{\pm}$:a synergy of facilities

Most statistically sensitive method at B-factories is to use $K_S\pi\pi$ as D-final state.

CPV leads to differences in Dalitz plot distributions

Extraction of γ requires we understand variation of strong phase difference between D^0 and $\bar{D}^0$ across Dalitz space

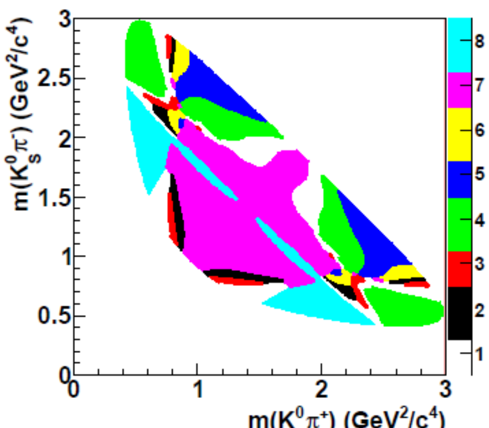


BABAR, PRL 105 (2010) 121801

Either take from amplitude model → incur model error – undesirable

Or use measurements of these phases performed in bins coming from Ψ(3770) decays at CLEO-c [PRD 82 (2010) 112006] Nice demonstration of synergy of facilities!

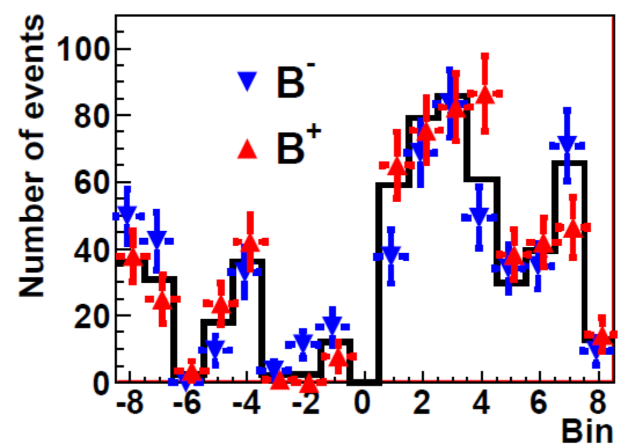
Odd looking bins Chosen to optimise stat precision



Recently applied by Belle

Precision ~ 16°

No model error !

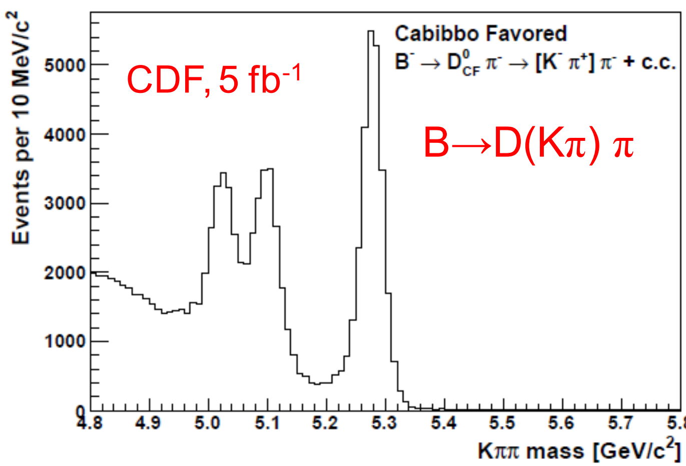


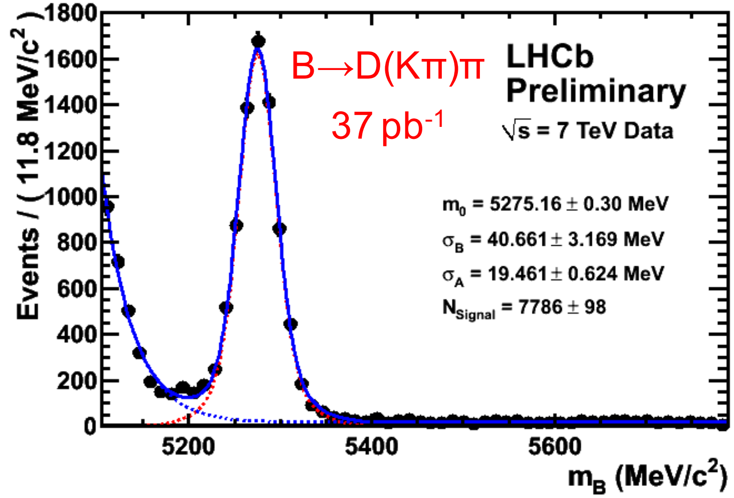
Belle, arXiv:1104.4046

Measuring γ at hadron colliders

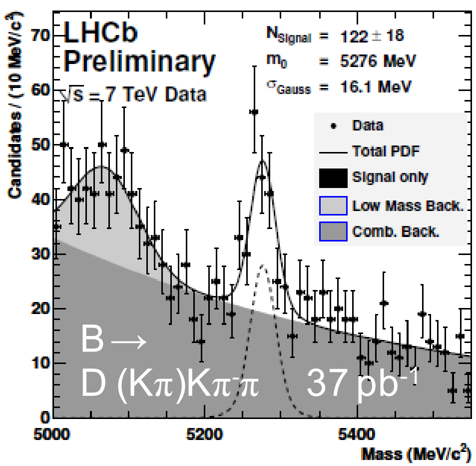
Responsibility for reducing γ uncertainty now rests with LHCb. CDF has led the way and showed these measurements to be feasible at a hadron collider

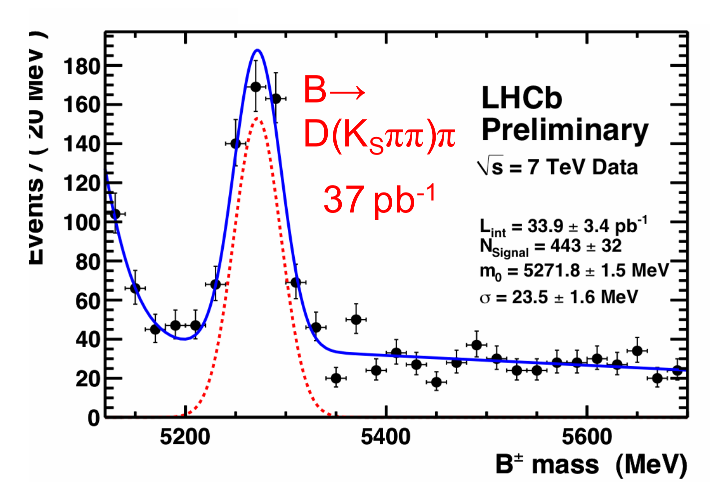
CDF note 10309





First observation
LHCb-CONF-2011-024





LHCb should be able to attain precision of a 'few degrees' on γ with 2010-11 data

Summary and outlook

Even though we are, for sure, at the start of the long-awaited high p_T renaissance, we should not forget that flavour physics still has a role to play

Indeed, some of the results from the Tevatron and B-factories provide tantalising hints that New Physics discovery is not far distant

The studies highlighted here are just examples, to my mind the most promising, but there are many others (e.g. gluonic and radiative Penguins)

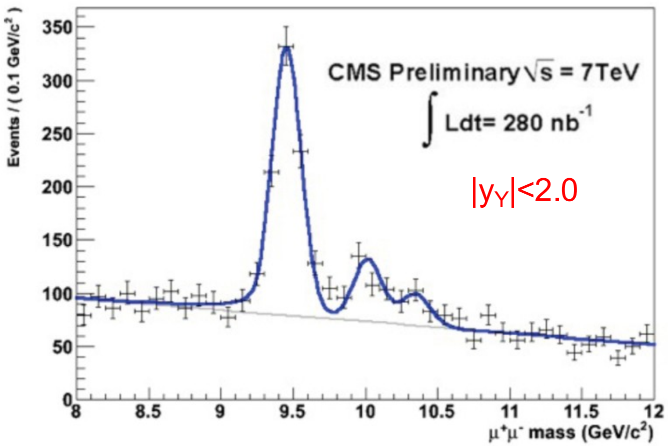
The LHC is a frontier machine not only in terms of energy, but also in heavy flavour production. We may be pushing on an open door...

...& if it opens, there will be plenty inside for the future experiments to explore

Backups

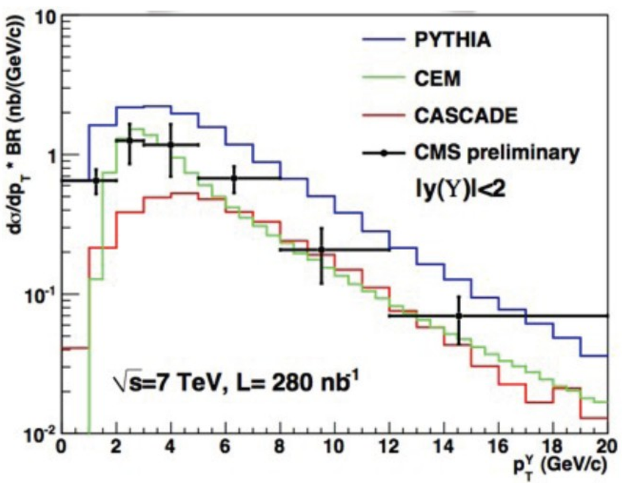
LHC upsilons

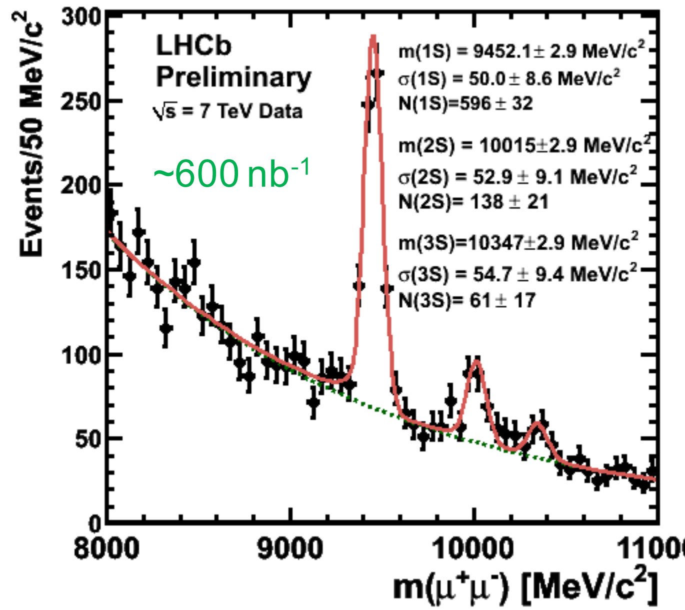
CMS upsilon spectrum...

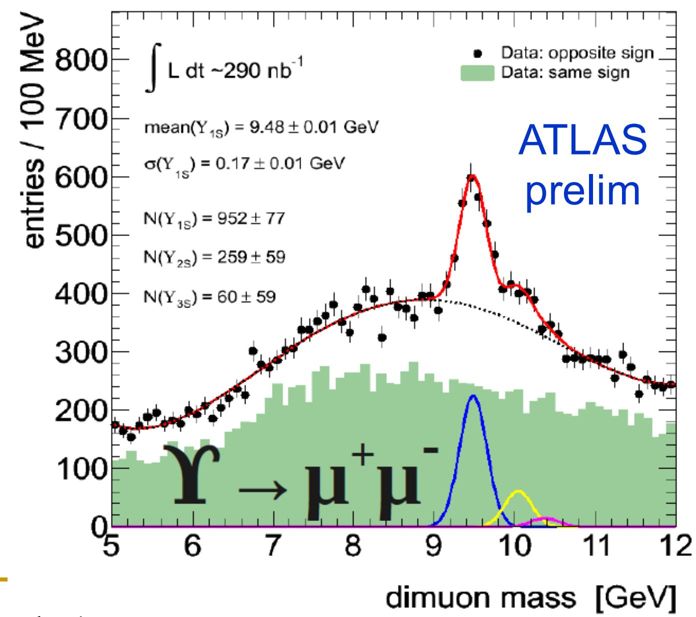


...and preliminary differential cross-section measurements

[CMS PAS BPH-10-003]

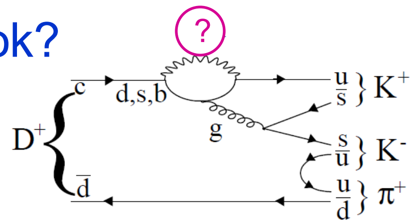






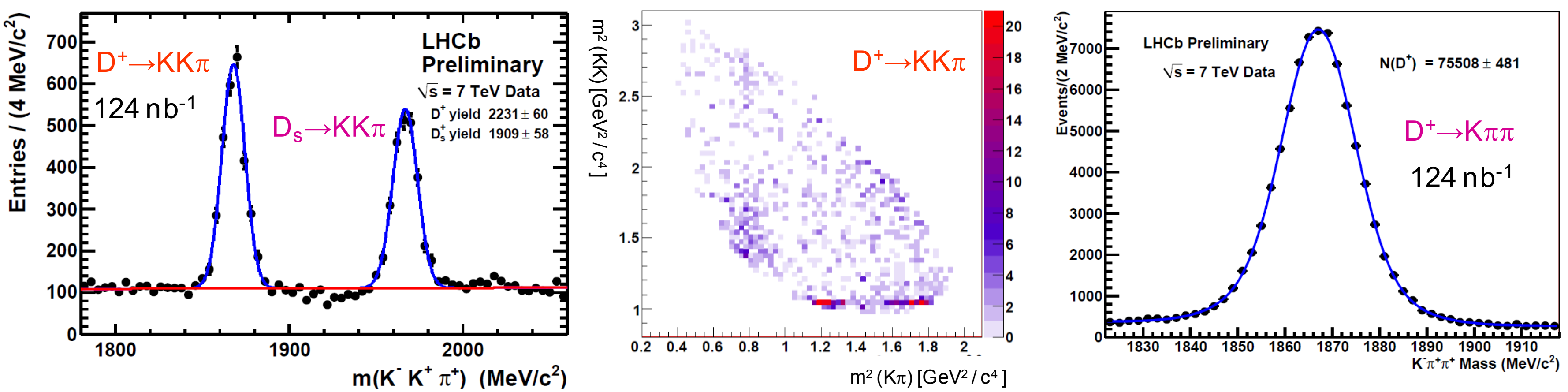
Search for direct CPV in charm at LHCb

Of equal interest is search for direct CPV in charm. Where to look?



- Singly Cabibbo Suppressed decays – significant contribution of gluonic Penguins gives clear 'entry point' for New Physics
- 3-body decays: analysis of Dalitz plane allows for many interference effects to be probed & is more robust against systematics than two-body rate analysis

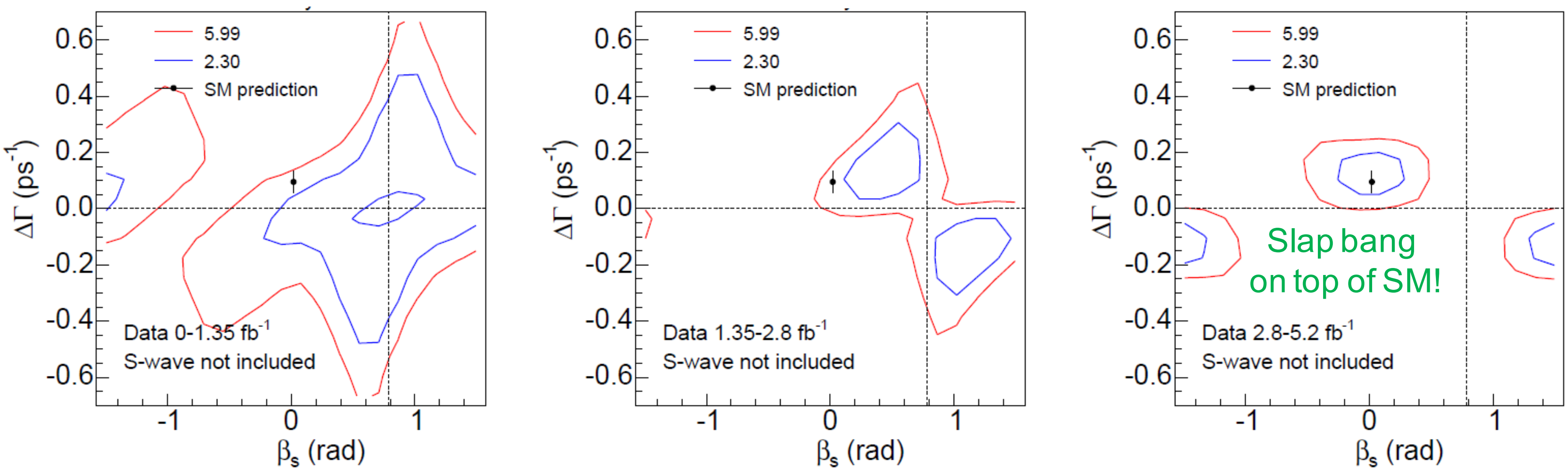
Excellent candidate: $D^+ \to K^+K^-\pi^+$ with $D_s^+ \to K^+K^-\pi^+$ & $D^+ \to K^-\pi^+\pi^+$ as control channels



Can be confident of acquiring signal sample of several million events in 100 pb^{-1}

Time dependent CPV measurements

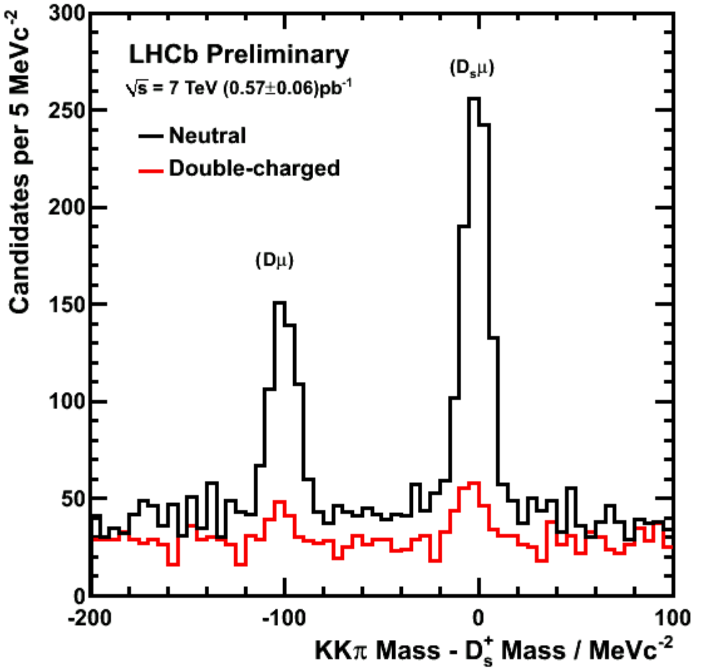
Dividing the CDF dataset into 3 parts yields a result which evolves in time (albeit in a manner which has internal statistical consistency)

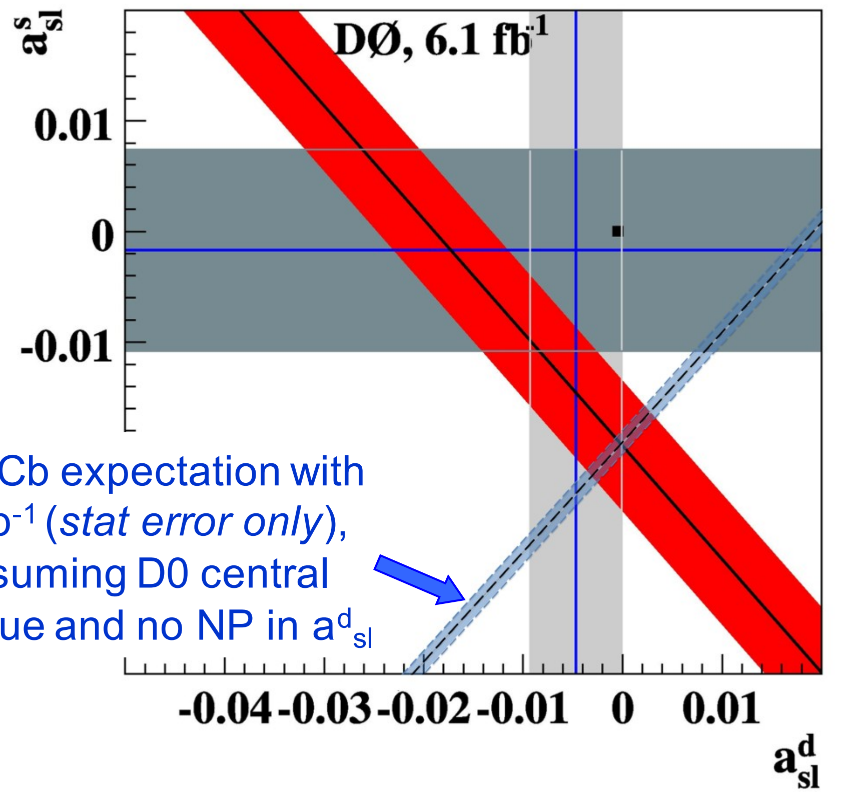


Let's hope it will oscillate back with the next 5 fb^{-1} ...

a^s_{sl} & a^d_{sl} at LHCb

LHCb proposes to measure $a^s_{sl} - a^d_{sl}$, by determining the difference in the asymmetry measured in $B_s \rightarrow D_s(KK\pi)\mu\nu$ & $B^0 \rightarrow D^+(KK\pi)\mu\nu$ - same final state suppresses detector biases. Provides orthogonal constraint to D0 dileptons.





LHCb expectation with 1 fb^{-1} (*stat error only*), assuming D0 central value and no NP in a^d_{sl}

Events already being accumulated

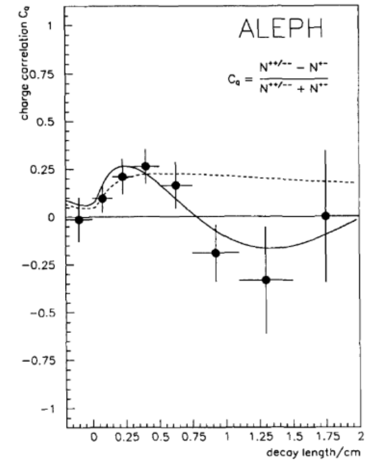
The Long and Wiggling Road to CP Violation

Observation of mixing in (B^0+B_s) and B^0 system

UA1, PLB 186 (1987) 247

Argus, PLB 192 (1987) 245

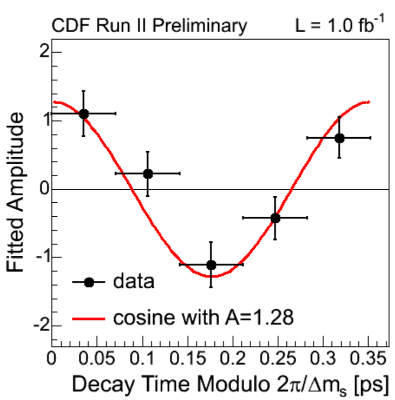
Resolution of B^0 oscillations



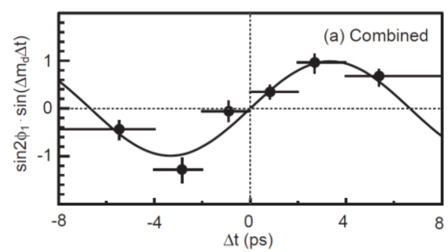
ALEPH, PLB 313 (1993) 498

Resolution of B_s oscillations

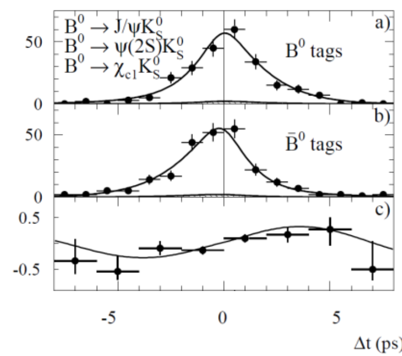
CDF, PRL 97 (2006) 242003



Observation of CPV in interference between B^0 mixing and decay



BELLE, PRL 87 (2001) 091802



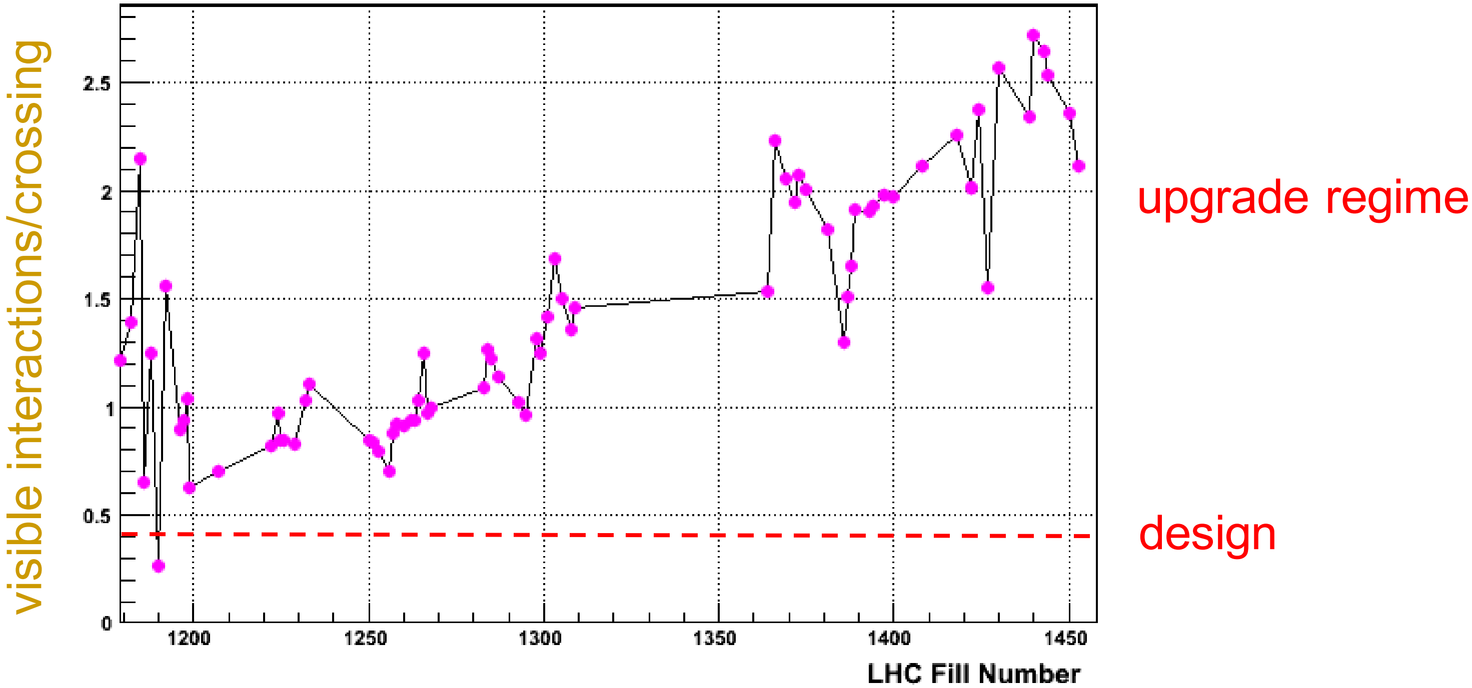
BaBar, PRL 87 (2001) 091801

Which in turn has led to…

2010 running conditions

LHCb designed for luminosity of ~2 x 10^{32} cm^{-2} s^{-1} and ~0.4 interaction/crossing

In 2010 machine quickly went to (above) nominal in emittance and bunch charge, whilst still having only a few hundred bunches. It was therefore necessary to run at > 2 interactions/crossing in order to obtain acceptable luminosity.



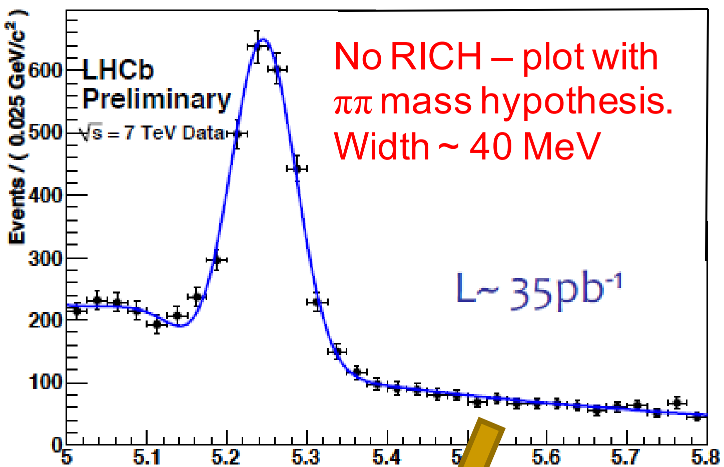
These are the conditions foreseen for upgrade – the experiment performed well!

Two body charmless B-decays

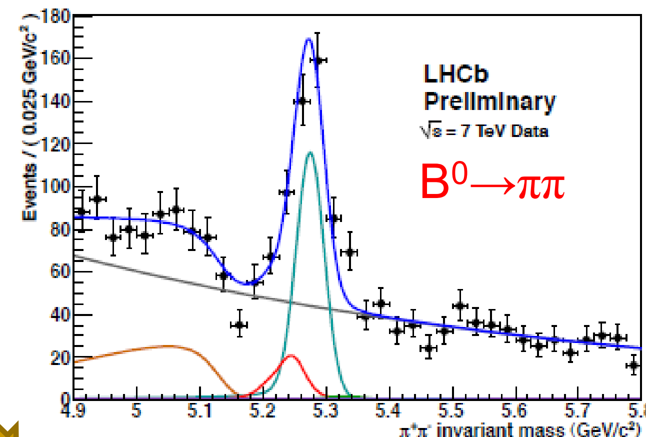
LHCb-CONF-2011-011

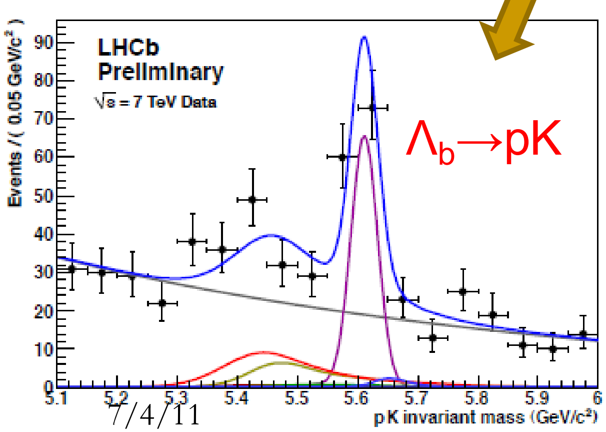
Two-body charmless B-decays central to LHCb physics. The significant contribution of Penguin diagrams provide entry points for new physics.

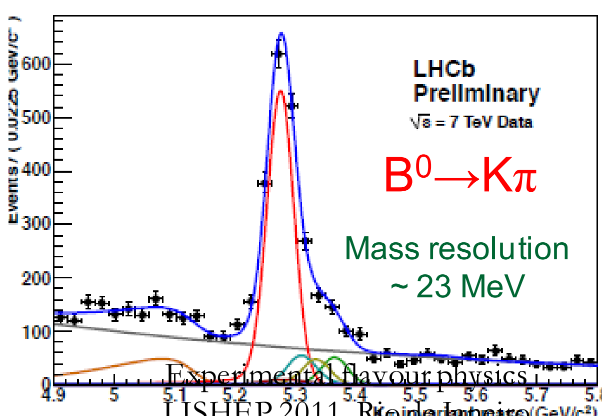
Experimentally, rely on good performance of hadron trigger and RICH system

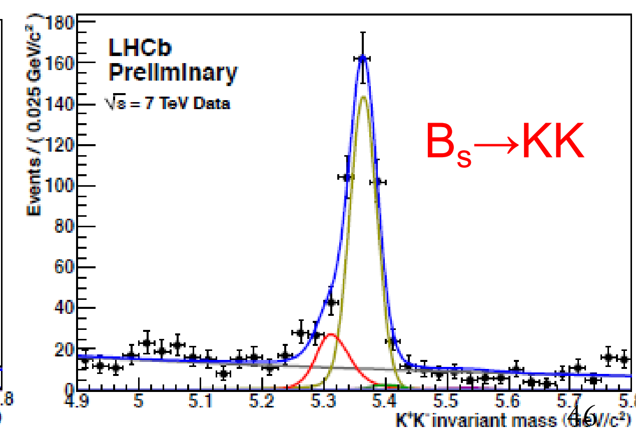


Deploy RICH to isolate each mode



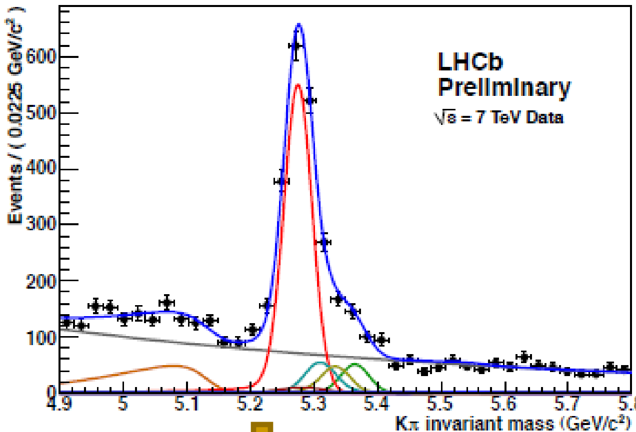




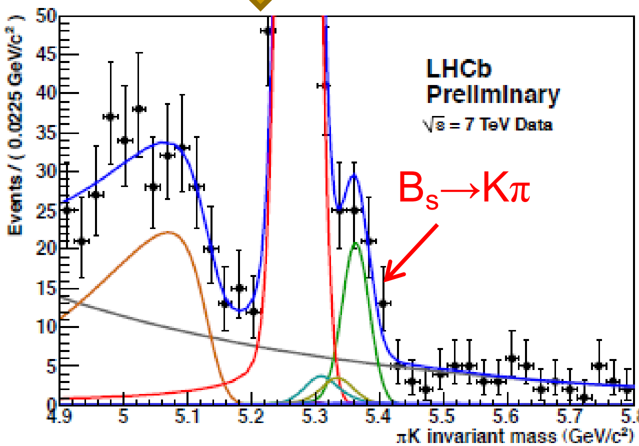


A closer look at B→Kπ

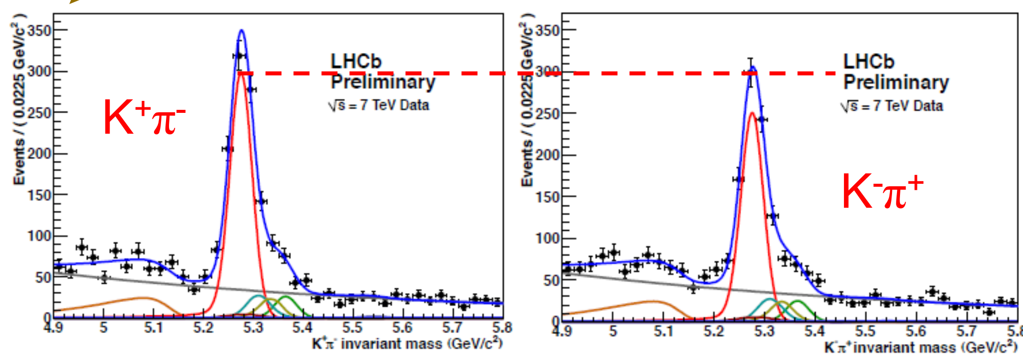
LHCb-CONF-2011-011



Tighter selection



Divide into B^0 and B^0-bar



CP-violation observed at >2σ with central value consistent with world-average:

$$A_{CP}(B^0 \to K^+\pi^-) = -0.074 \pm 0.033 \pm 0.008$$

(uncertainty presently 3x world average),

and a corresponding result for $B_s \to K\pi$:

$$A_{CP}(B^0_s \to \pi^+ K^-) = 0.15 \pm 0.19 \pm 0.02$$

Precision very similar to CDF 1 fb^{-1} result !