LHCb FIRST RESULTS AND PROSPECTS

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New Data from the Energy Frontier, Aspen 2011

Outline

- Introduction
- Detector and 2010 operations
- Selected first results
- Prospects
- Conclusions

Many thanks to G.Wilkinson and many others for (un)knowingly helping me!

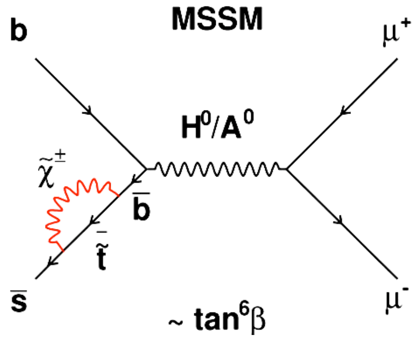
The LHCb Experiment

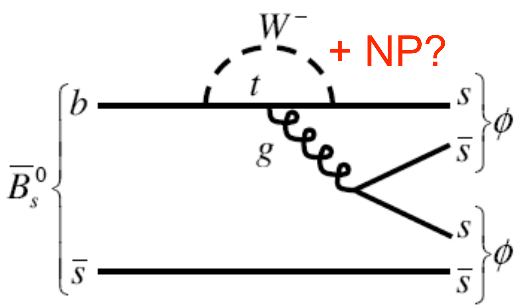
- **LHCb**: dedicated b-physics experiment at LHC searching for NP beyond the SM through the study of very rare decays of b-flavoured (and c) hadrons and precision measurements of CP-violating observables

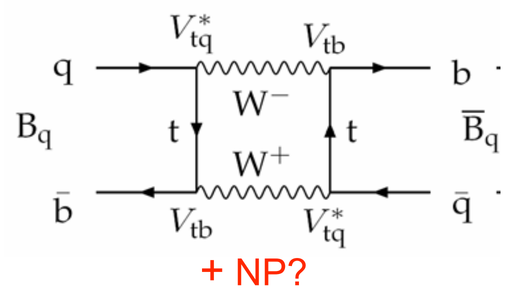
- Enormous progress in recent years from the B factories and Tevatron, far beyond expectations: clear demonstration of the SM CKM mechanism as dominant source of CP violation in the quark sector.

The LHCb roadmap

- Focus has shifted: from seeking to verify the CKM picture to searching for signs of New Physics beyond the Standard Model in the flavour sector
  - Measure processes that are strongly suppressed in the SM and poorly constrained by existing data, but that have sensitivity to new particles at high mass scales via their virtual effects in loop diagrams (complementary approach to direct searches):







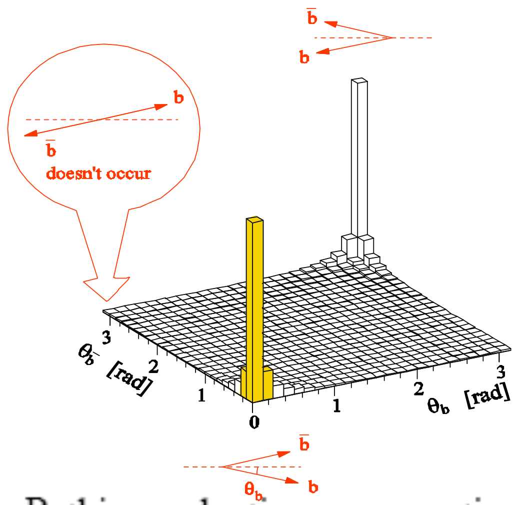
  - Search for possible inconsistencies in measurements of angles and sides of unitarity triangles: compare results from decays dominated by tree-level diagrams with those that start at loop level to probe validity of SM

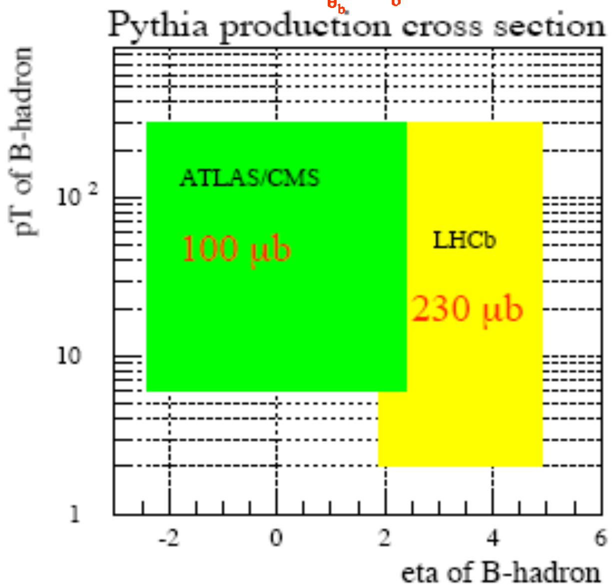
b production at LHC

- Advantages of beauty physics at hadron colliders:
  - High value of beauty cross-section at LHC:
    - σ_{bb} ~0.3 – 0.5 mb @$\sqrt{s}$=7-14 TeV (e⁺e⁻ cross section at Y(4s) is 1 nb)
    - σ_{cc} ~ 6 mb
  - 1fb^{-1} expected in 2011
    - ~ 10^{11} bb pairs produced (10^9 at B-factories in their lifetime!)
  - Access to all b-hadrons: $B^{\pm}$, B^0, B_s, B_c, b-baryons
    - In particular can study the B_s (bs) system, not studied at the B factories, but measured by CDF/D0
- The challenges
  - Rate of background events: σ_{inel}~ 60 mb @$\sqrt{s}$=7 TeV
    - → Trigger is essential!
  - Multiplicity of tracks (~30 tracks per rapidity unit)

LHCb acceptance

- Detector designed to maximize b acceptance (against cosθ)
- Forward spectrometer 1.9<η<4.9
  - b-hadrons produced at low angle
  - Single arm OK as b quarks are produced in same forward or backward cone
- Rely on much softer, lower p_T triggers, efficient also for purely hadronic decays
  - ATLAS/CMS: |η|<2.5
    - Will do B-physics using high P_T μ triggers mostly with modes involving di-μ
    - Purely hadronic modes triggered by tagging μ.





LHCb 2010 running conditions

- Recorded 37.7pb^{-1} at $\sqrt{s}$=7 TeV
  - Data taking efficiency > 90%
  - The B and D physics program does not suffer much from running at half the nominal energy, given the enormous cross-sections
- L design limited to ~2-5 10^{32} cm^{-2} s^{-1}
  - Average of ~0.4 interactions per bunch crossing, maximizing fraction of single-interaction bunch crossings.
- Almost at design L at the end of run! But…
  - Machine quickly went 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.

LHCb originally foreseen running conditions

Geometrical factor

Number of colliding bunches per beam
2622

Bunch revolution frequency:
11.245 kHz

Colliding bunches populations:
~6.5*10^{10} ppb

e.g. LHCb Crossing angle
-673 μrad

$$L = \sum_{i=1}^{N_{bb}} \frac{f_{rev} * N_i^1 * N_i^2 * S}{4\pi * \varepsilon * \beta^*}$$

Instantaneous Luminosity
~2*10^{32}cm^{-2}/s

Bunch transverse emittance
$\varepsilon_N = \varepsilon * \gamma$ = 3.75 μm normalized emittance
for beam energy E = 7 TeV

"beta star" = 10m
after beam squeezing

- Defocus the beams →

~0.4 visible pp interactions per bunch crossing

LHCb 2010 running conditions

Geometrical factor

Number of colliding bunches per beam
344

Bunch revolution frequency:
11.245 kHz

Colliding bunches populations:
~1.15*10^11 ppb

e.g. LHCb Crossing angle
-673 µrad

$$L = \sum_{i=1}^{N_{bb}} \frac{f_{rev} * N_i^1 * N_i^2 * S}{4\pi * \varepsilon * \beta^*}$$

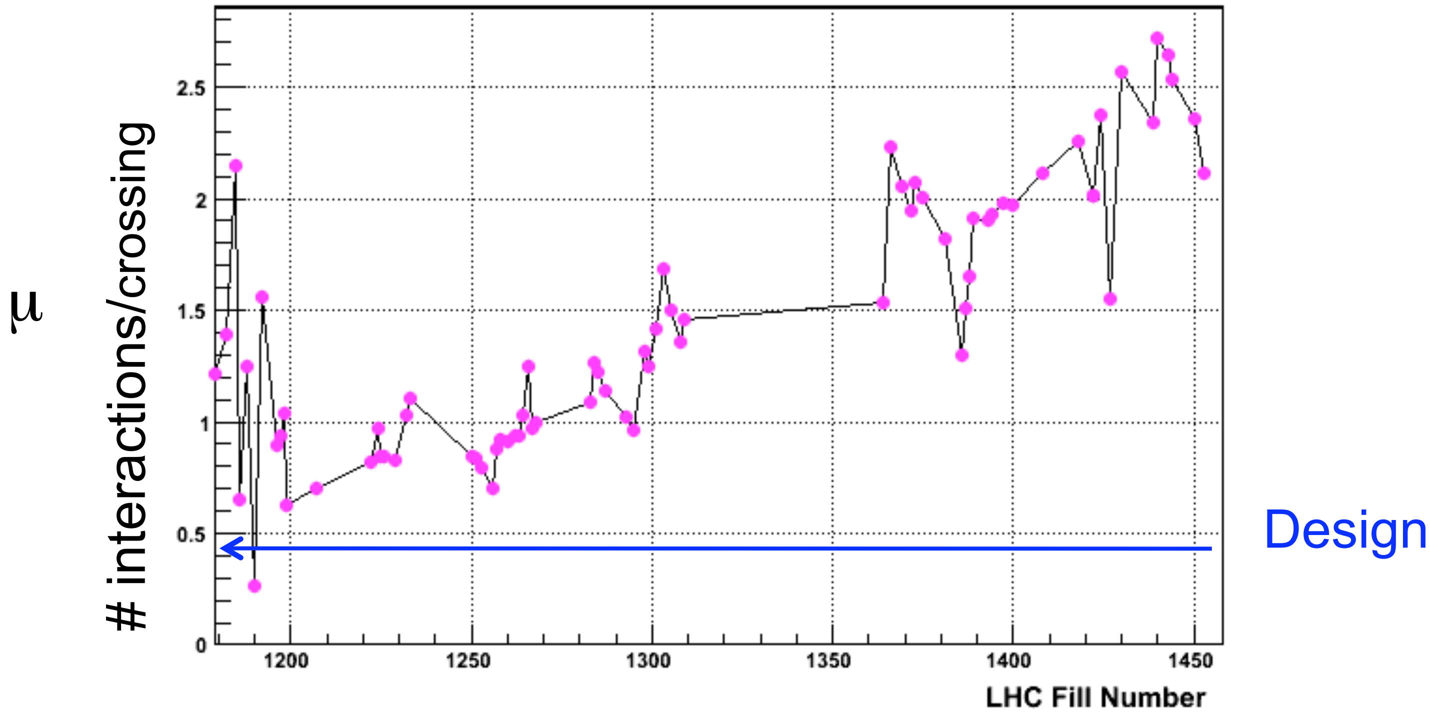
Instantaneous Luminosity
$\sim 1.7*10^{32} cm^{-2}/s$

Bunch transverse emittance
$\varepsilon_N = \varepsilon * \gamma$ = 2.4 µm normalized emittance
for beam energy E = 7 TeV

"beta star" = 3.5m
after beam squeezing

- Reached ~80% of design LHCb instantaneous luminosity with 8 times less colliding bunches!

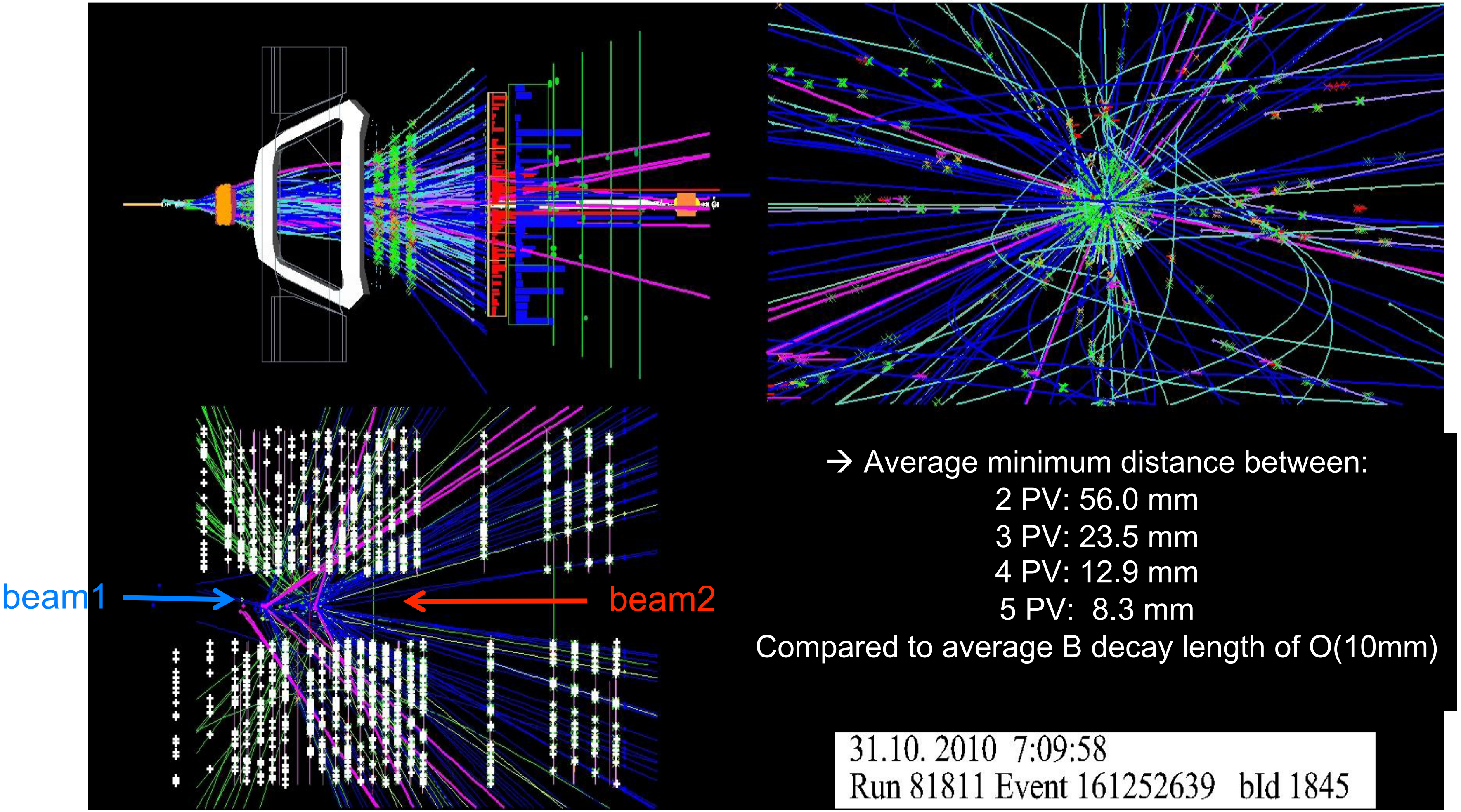
LHCb 2010 running conditions



- Very challenging for trigger, offline reconstruction and processing!
  - More interactions/crossing
  - Bigger event size
  - More vertices/collision
- Initial conditions in 2011 run may be similar but number of bunches will increase
- We will not follow the GPDs to high luminosity → Luminosity levelling

Running in 2010 with high μ

LHCb Event Display



→ Average minimum distance between:
2 PV: 56.0 mm
3 PV: 23.5 mm
4 PV: 12.9 mm
5 PV: 8.3 mm
Compared to average B decay length of O(10mm)

The LHCb Detector

VELO: 21 (R+φ) silicon stations

- Movable:7mm when stable beams

RICH1: C_4F_{10} + AEROGEL

- π/K separation for 2<p<60 GeV

Tracking: Si + straw tubes + 4Tm

- δp/p=0.45%

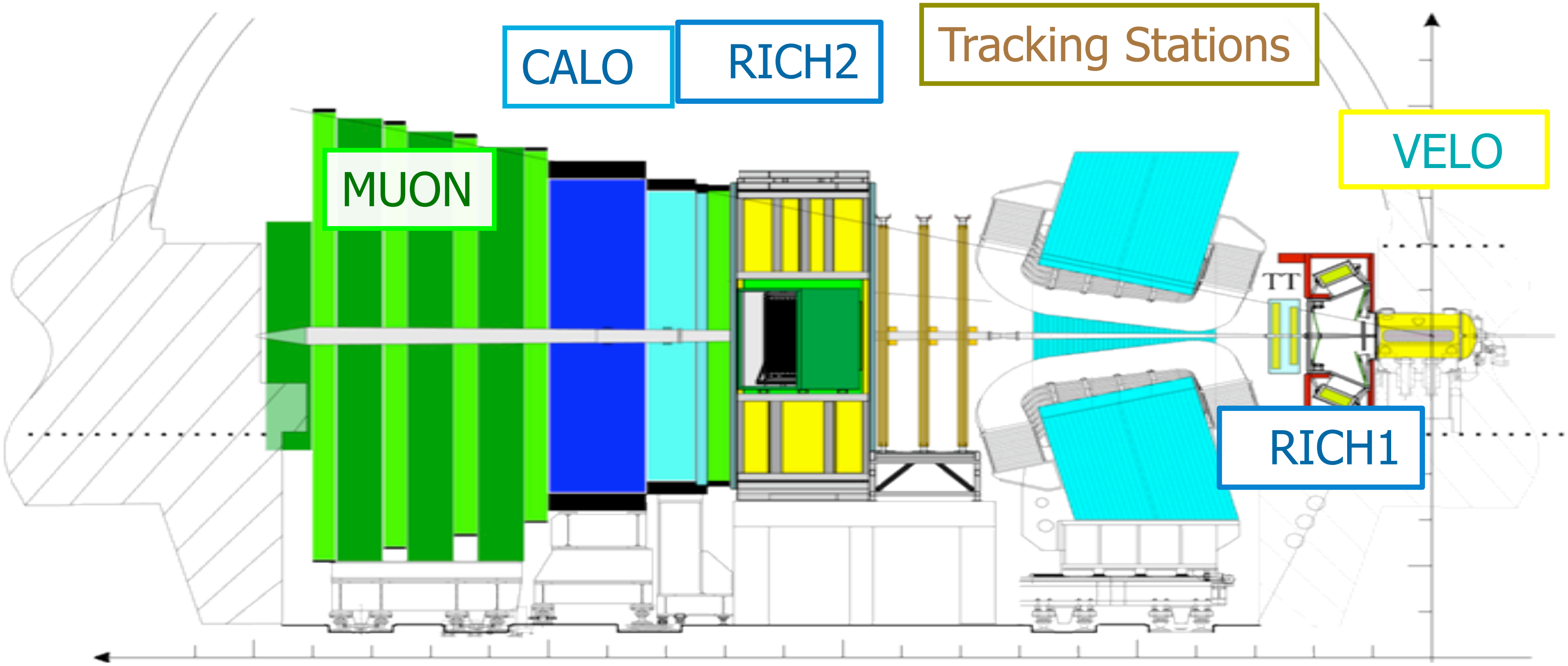
RICH2: CF_4

- π/K separation for 20<p<100 GeV

CALO:

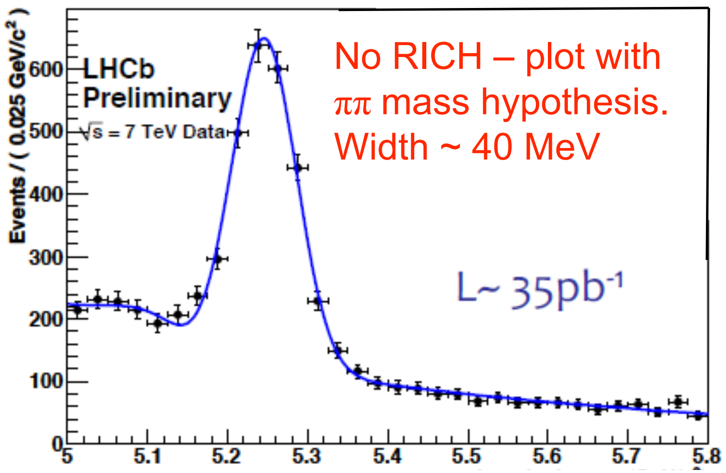
- ECAL: lead+scintillating tiles
- HCAL: iron+scintillation tiles

MUON



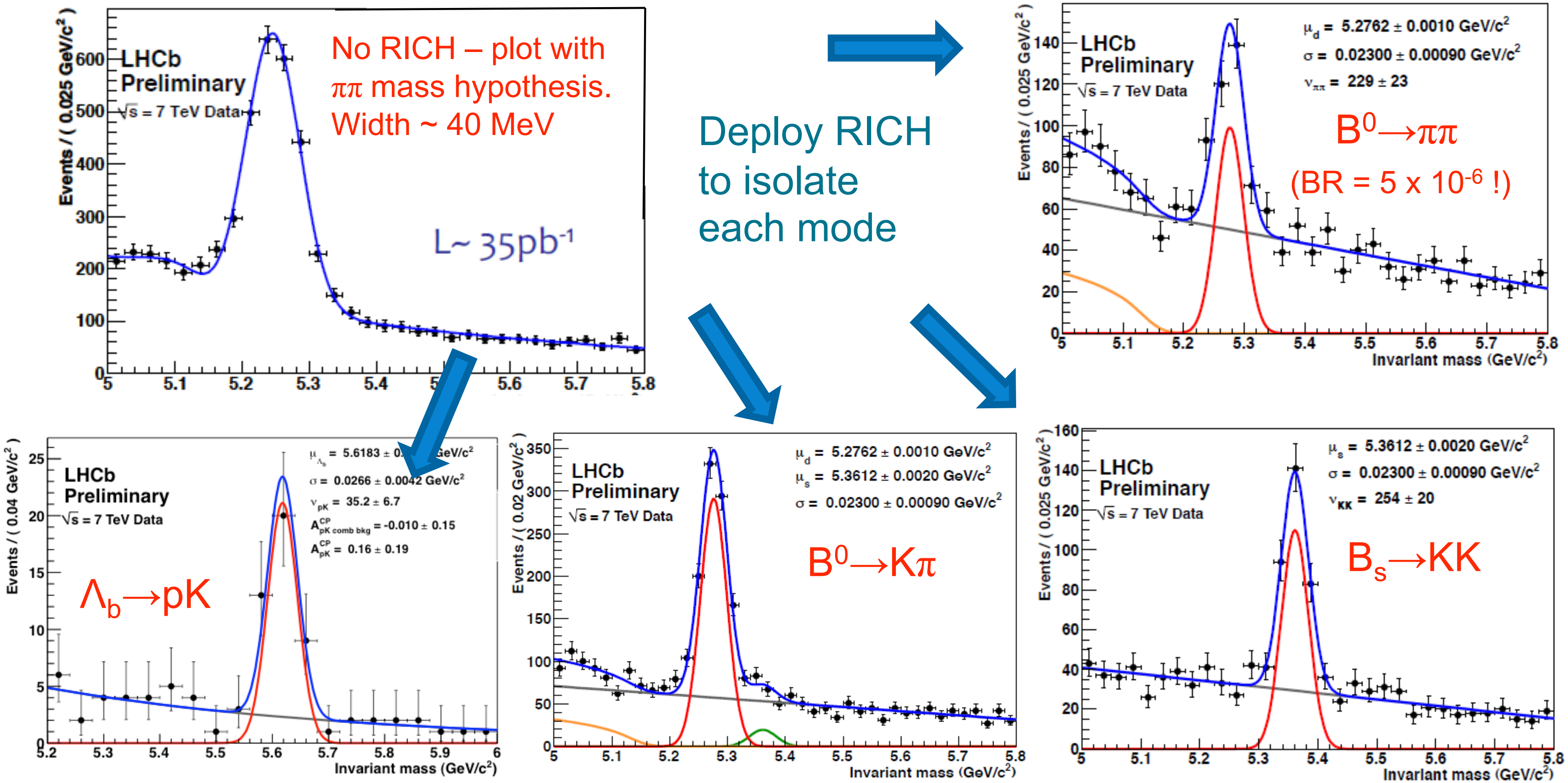
RICH PID performance: B→$h^+h'^-$ with h=p,k,π

- Charmless B decays → Sensitive probes of CKM matrix with potential to reveal NP through penguins



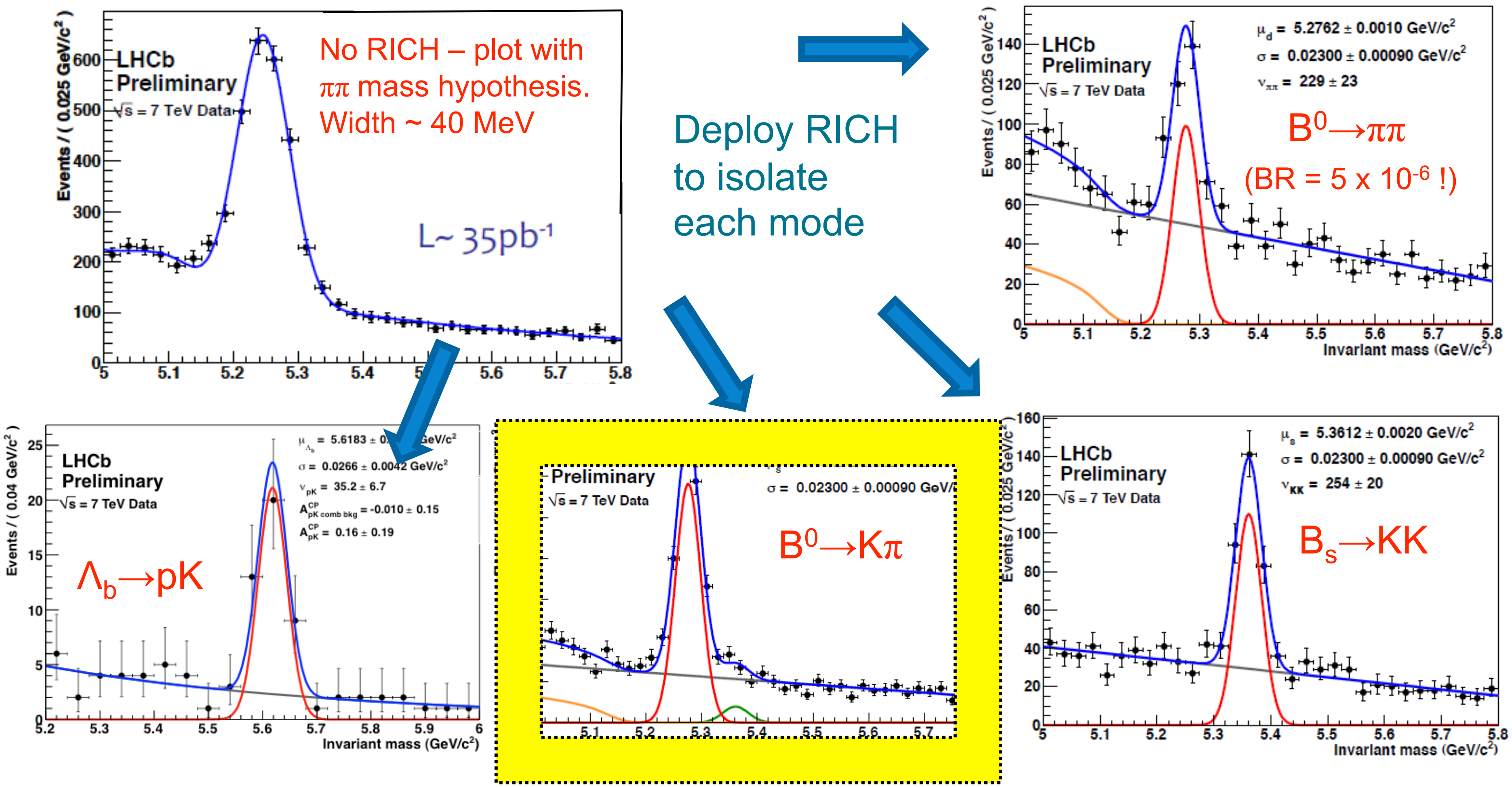
RICH PID performance: B→h⁺h'⁻ with h=p,k,π

- Charmless B decays → Sensitive probes of CKM matrix with potential to reveal NP through penguins



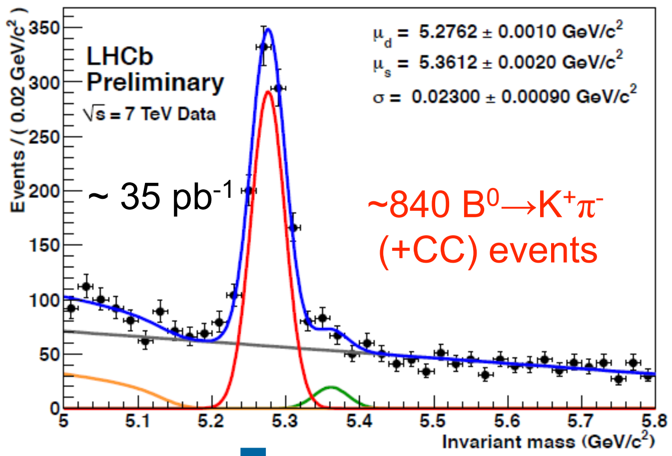
RICH PID performance: $B \rightarrow h^{+}h'^{-}$ with $h=p,k,\pi$

- Charmless B decays → Sensitive probes of CKM matrix with potential to reveal NP through penguins

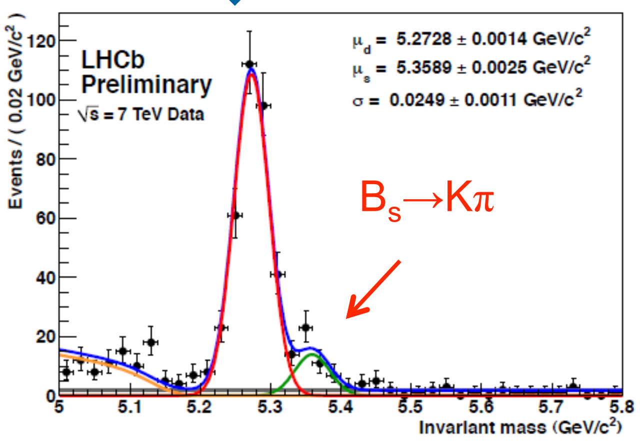


B→Kπ

- Look in more detail…

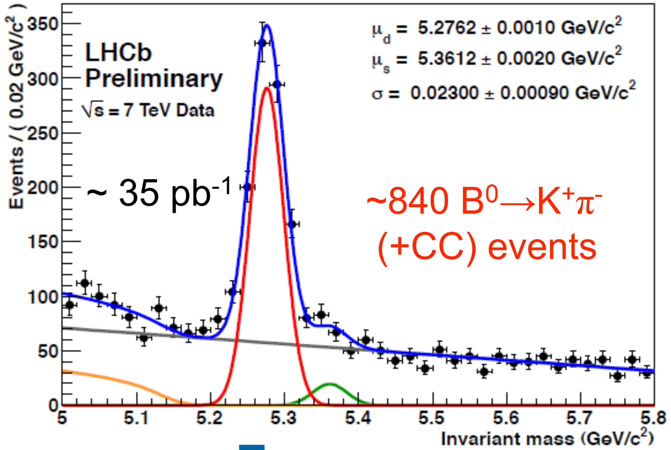


Tighter selection

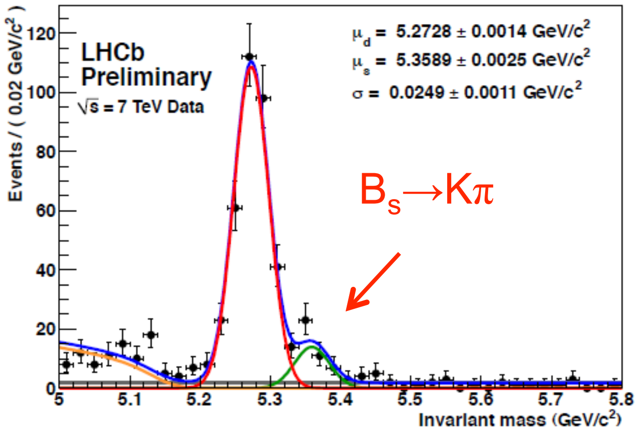


B→Kπ

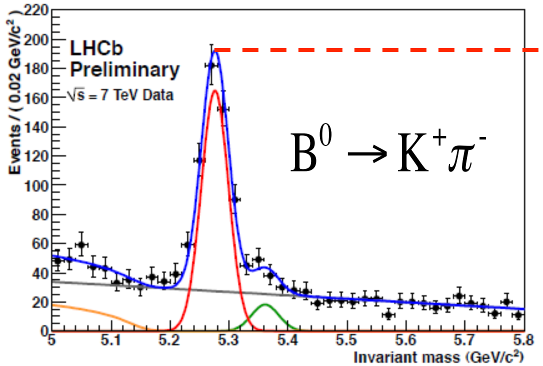
- Look in more detail…

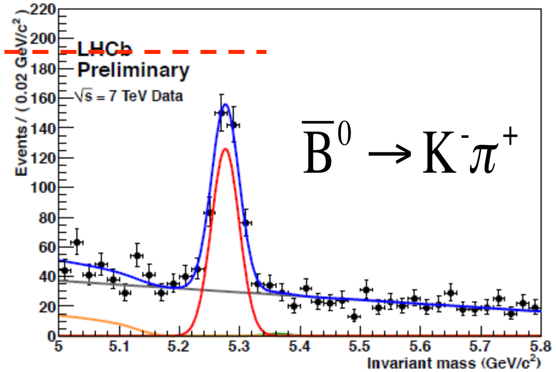


Tighter selection



Divide into B^0 and B^0-bar





Raw result shows CP-violation at > 3 σ!

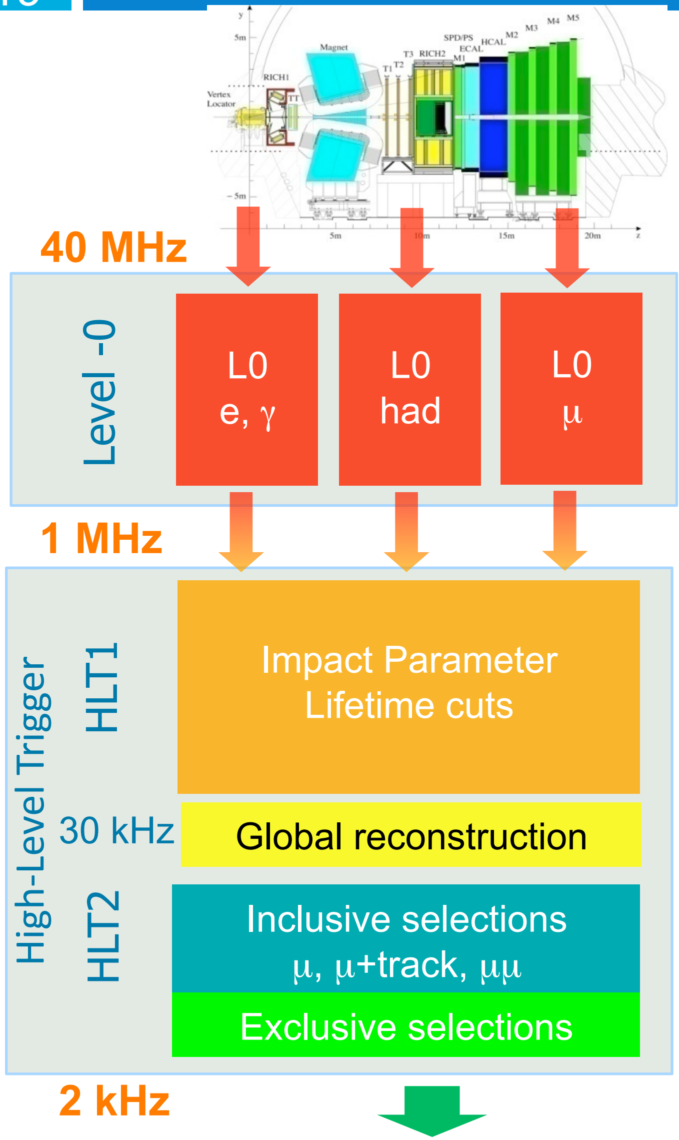
Analysis being optimised & account being taken of (small) production and detector asymmetries

LHCb Trigger

- Trigger is crucial as σ_{bb} is less than 1% of total inelastic cross section and B decays of interest typically have BR < 10^{-5}

- b hadrons are long-lived →
  - Well separated primary and secondary vertices
- Have a ~large mass→
  - Decay products with large p_T

LHCb Trigger



- L0 Hardware Trigger 40 MHz → 1 MHz
  - Search for high p_T , μ, e, γ, hadron candidates
- High Level Software Trigger Farm
  - HLT1: Add Impact parameter cuts
  - HLT2: Global event reconstruction
  - Physics output rate 2 kHz – 2.5 kHz
  - Fully operational. Last batch of CPUs installed
- HLT needs operational flexibility
  - Trigger Configuration Key (TCK) to distribute the configuration to 1000 nodes simultaneously when optimizing parameters during LHC fill
  - Luminosity following also in extreme conditions during 2010 run
  - Global Even Cuts applied to reduce event complexity at high μ
  - High priority to μ triggers (Bs→μμ)

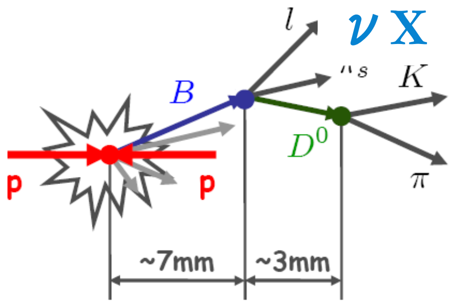
First results

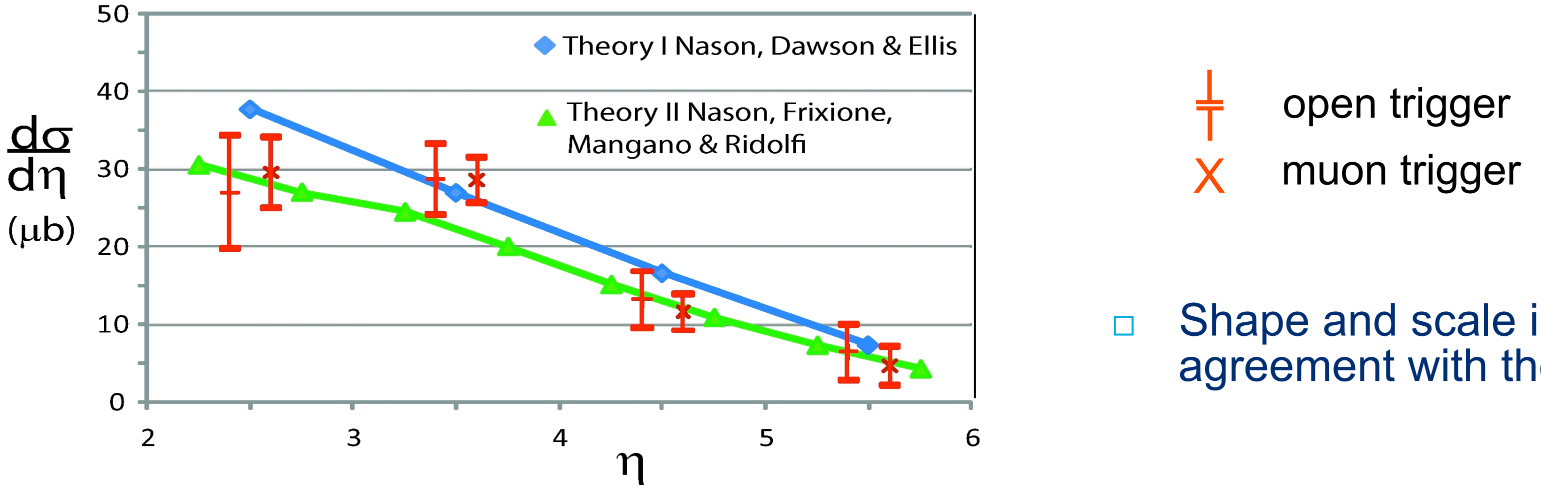
- Selected items from a rich physics programme:

  - Semileptonic B decays
  - Onia
  - CP-violation in $B_s \rightarrow J/\psi\Phi$
  - $B_s \rightarrow \mu\mu$
  - Charm

b production cross-section from $B \to D^0 \mu \nu X$ events ($15 nb^{-1}$)

- Take clean $D^0 \to K\pi$ sample
- Use Impact Parameter of D^0 direction wrt primary vertex to separate prompt and from B decays
- Look for μ with correct charge correlation to suppress background (sign of μ charge same as K charge)





- Shape and scale in good agreement with theories

- $\sigma(pp \to HbX; 2<\eta<6) = (75.33 \pm 5.4 \pm 13.0)\ \mu b$
- Extrapolates to $(284 \pm 20 \pm 49)\ \mu b$ over 4π

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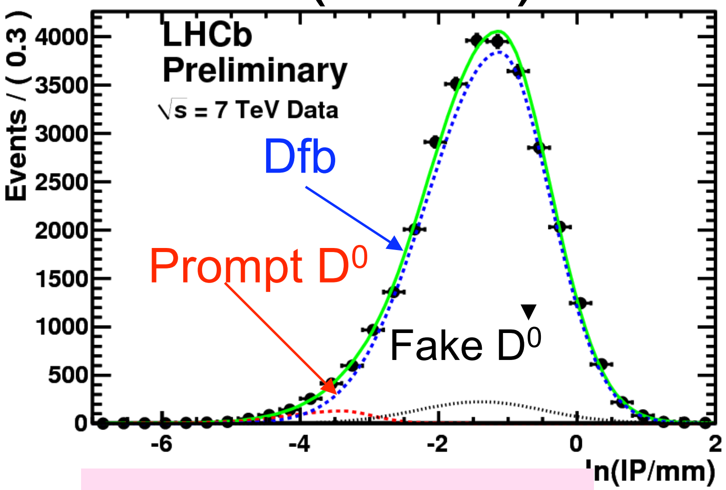
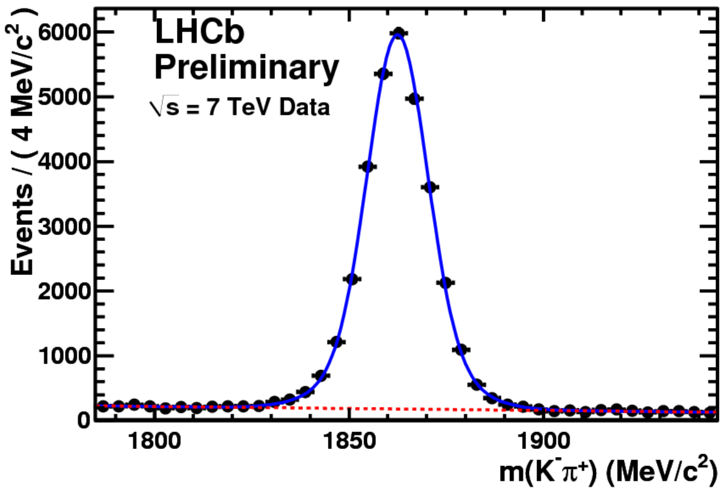
$b \rightarrow D^0 \mu \nu X$ ($3pb^{-1}$)

ln(IP D0) | D0 mass

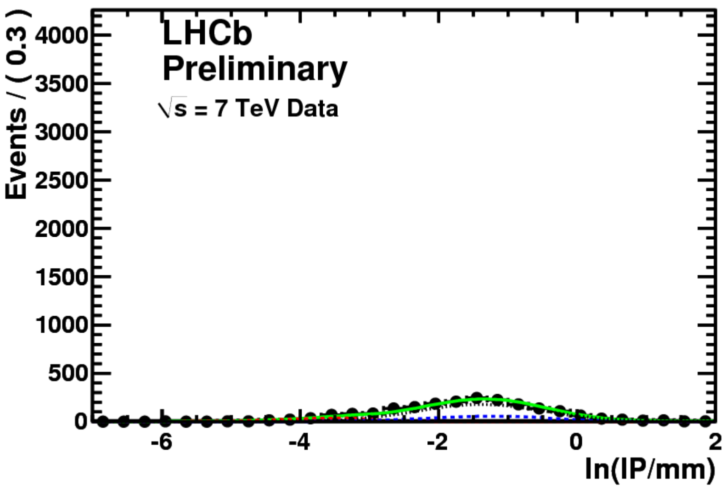
- RS

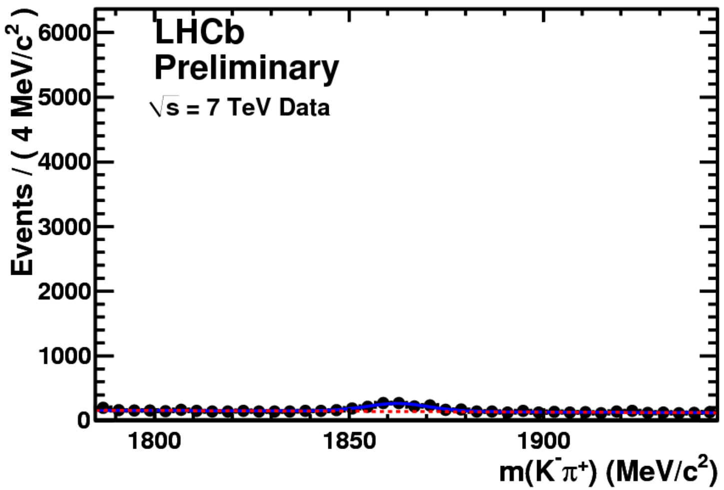




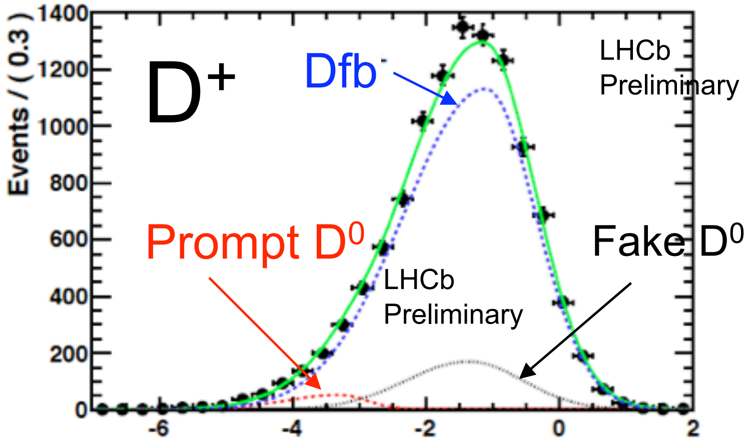
RS Dfb = 28531±193

- WS

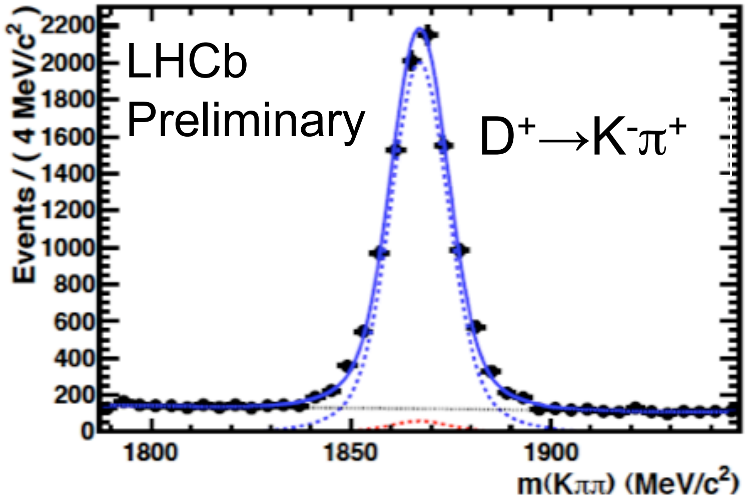


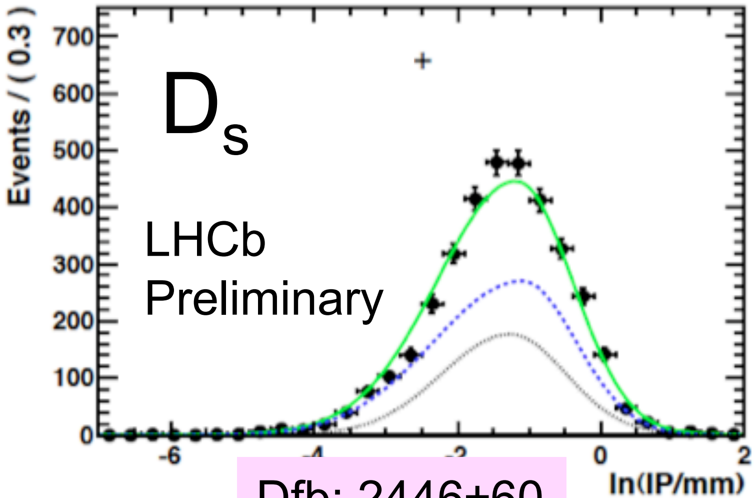


Also D^+, D_s, Λ_b

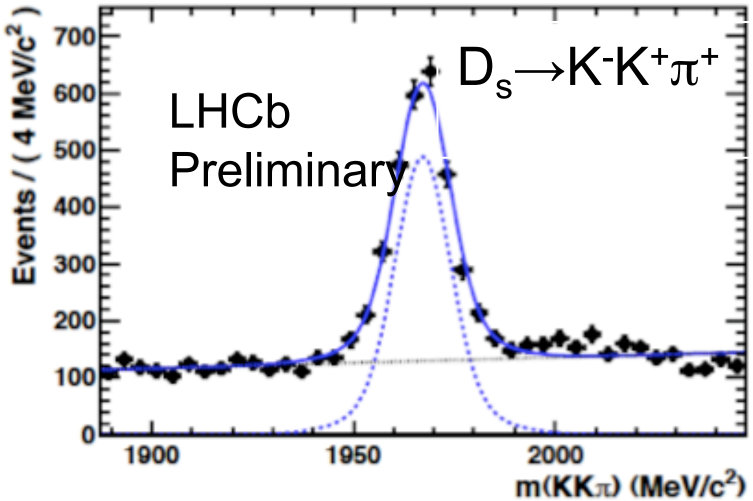


Dfb: 9406±110





Dfb: 2446±60



Extract B_s fractions from $B \rightarrow D \mu \nu X$

- Take yield in various charm channels and correct for cross-feed from $B_s \rightarrow D^0 K^+ X \mu \nu$ and $\Lambda_b \rightarrow D^0 p X \mu \nu$

- Measure ratio of B_s (or Λ_b) to B^-, B^0 (absolute BRs well measured at e^+e^-)

- Knowledge of production rates essential to normalise BRs

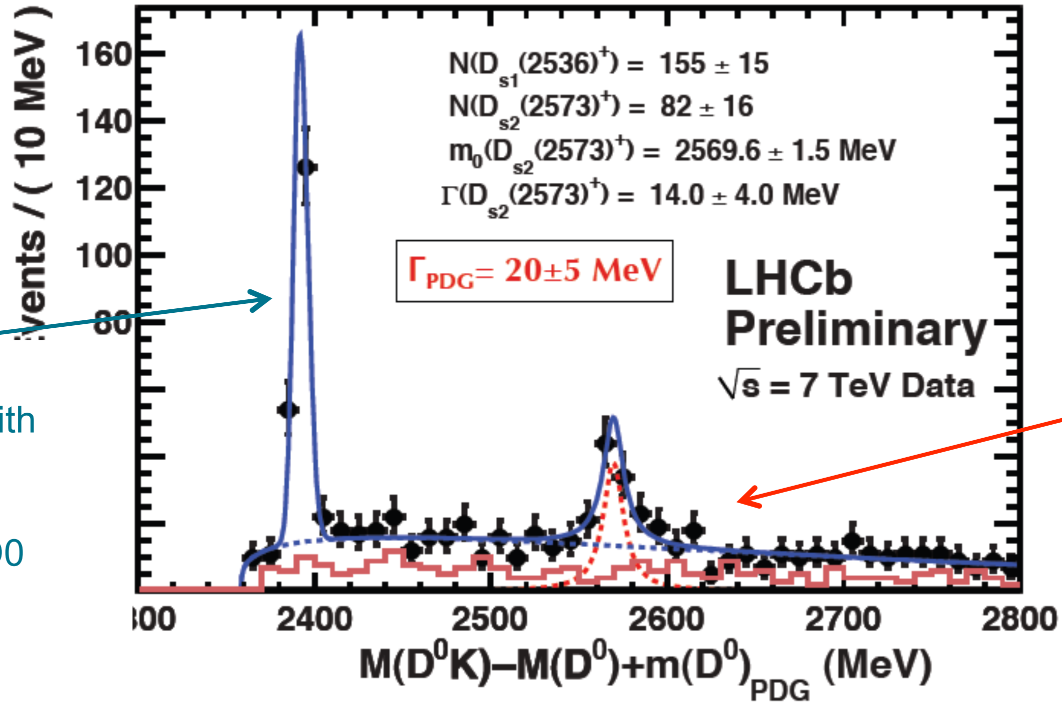
$f_s/(f_u + f_d) = 0.130 \pm 0.004\ (stat) \pm 0.013\ (sys)$ preliminary

- $f_s/(f_u + f_d) = 0.13 \pm 0.01$ LEP
- $f_s/(f_u + f_d) = 0.18 \pm 0.03$ TEVATRON

Better understanding of B_s decays

- $B_s \rightarrow D^0 K^+ X \mu \nu$ with $20 pb^{-1}$

D^0K^+ invariant mass spectrum



$D_{s1}(2536) \rightarrow D^*(2007)^0K^+$ with missed π^0 or γ

Decay seen by D0 [PRL102 051801]

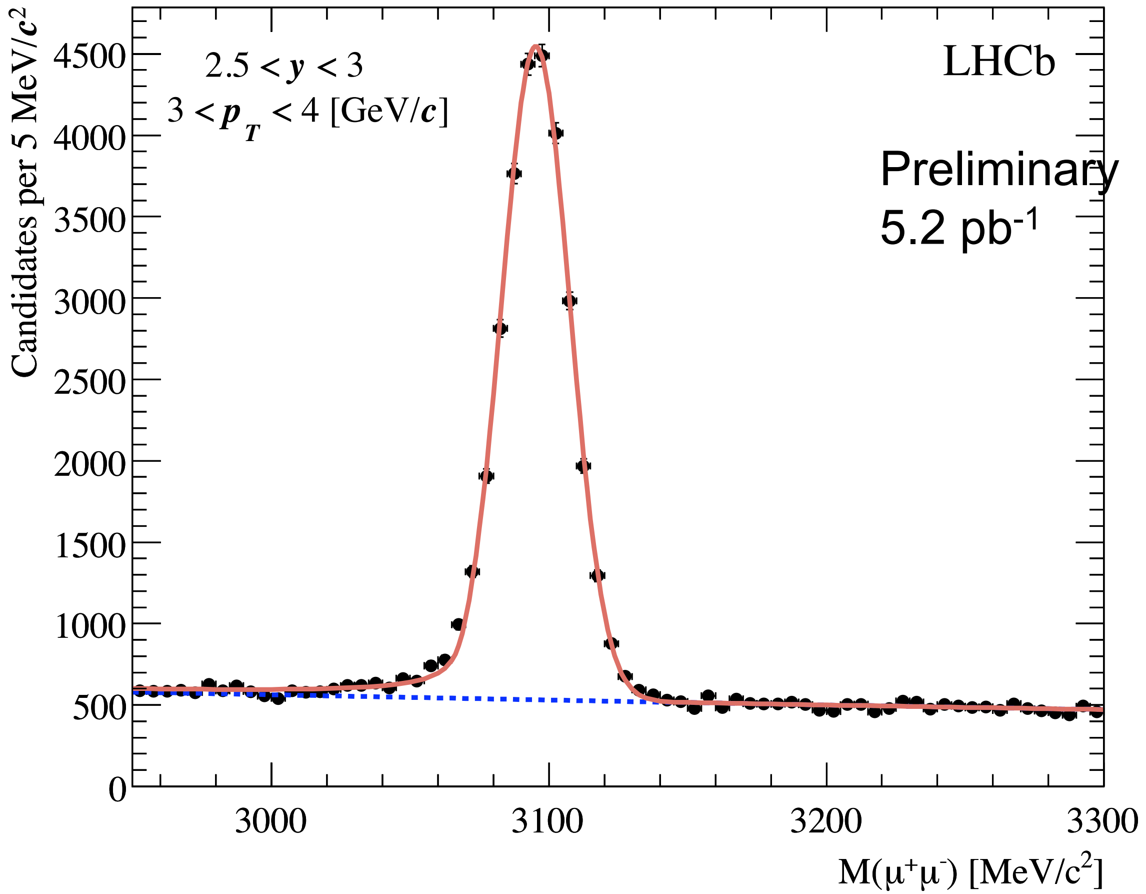
$D_{s2}^*(2573) \rightarrow D^0K^+$

arXiv:1102.0348v1

- D^{*+}_{s2} (2573, 2+?) never observed in B_s decays !
- BR relative to total B_s semileptonic rate

$$\frac{\mathcal{B}(\overline{B}_s^0 \rightarrow D_{s2}^{*+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}_s^0 \rightarrow X \mu^- \overline{\nu})} = (3.3 \pm 1.0 \pm 0.4)\%$$

J/ψ production studies



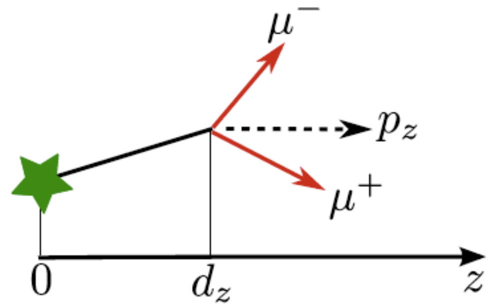
Analysis performed in 70 bins: 14 bins in p_T (p_T<14 GeV) and 5 in y (2.5<y<4.5)

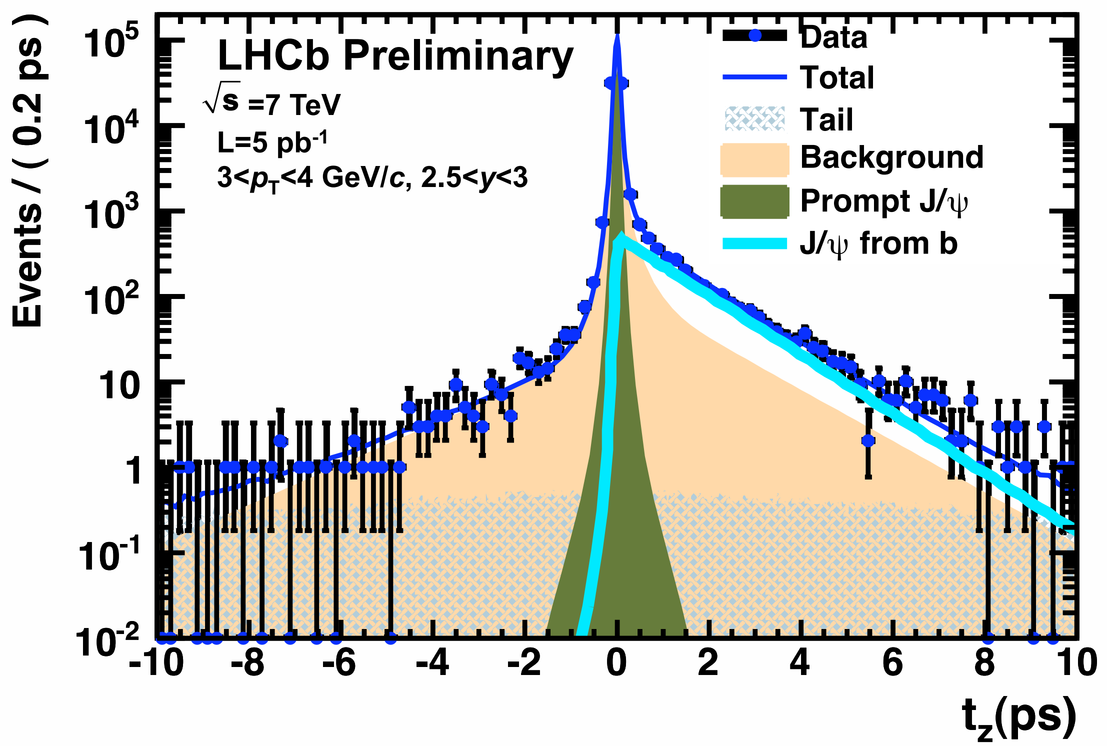
Total signal yield ~560,000 J/ψ

J/ψ from b

- Fraction of J/ψ from b given by t_z fit

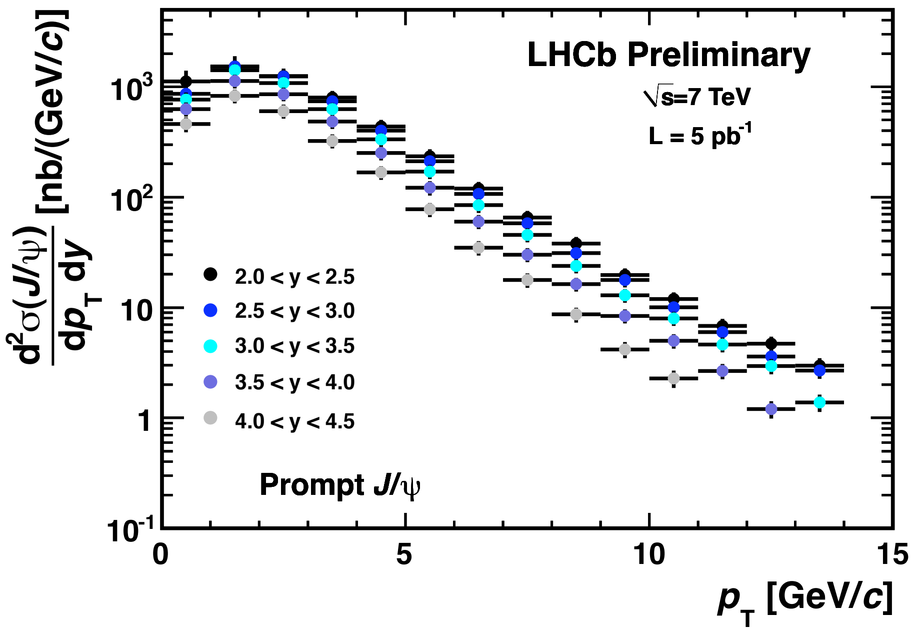
$$t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}$$



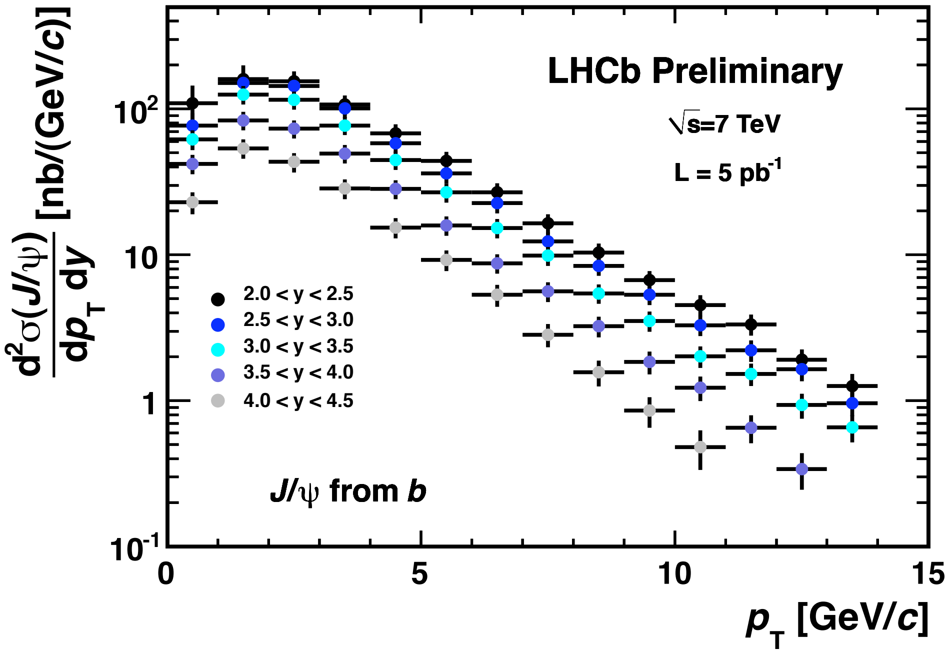


J/ψ production cross-sections

- Prompt J/ψ



- J/ψ from b

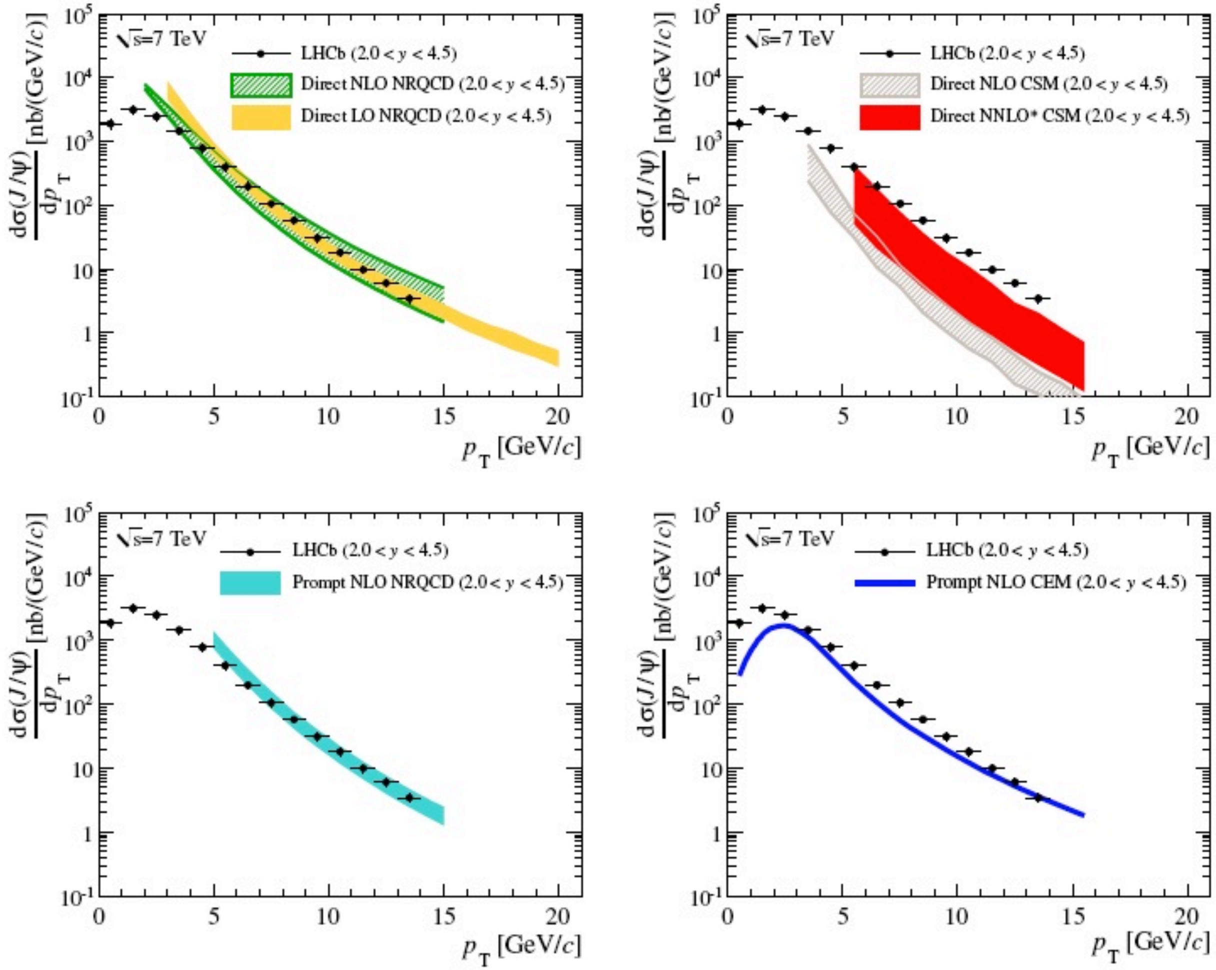


$$\sigma\,(\text{prompt}\,J/\psi\,,\,p_{\mathrm{T}} < 14\,\mathrm{GeV}/c,\,2.0 < y < 4.5) = 10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}\,\mu\mathrm{b}$$

$$\sigma\,(J/\psi\ \text{from}\ b,\,p_{\mathrm{T}} < 14\,\mathrm{GeV}/c,\,2.0 < y < 4.5) = 1.14 \pm 0.01 \pm 0.16\,\mu\mathrm{b}$$

Extrapolating to the total bb cross section $\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\,\mu\mathrm{b}$

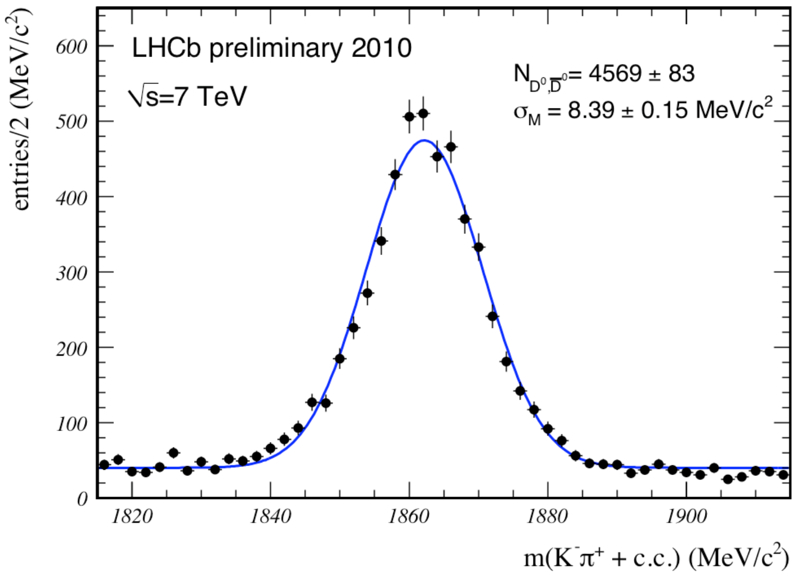
J/ψ production cross-sections

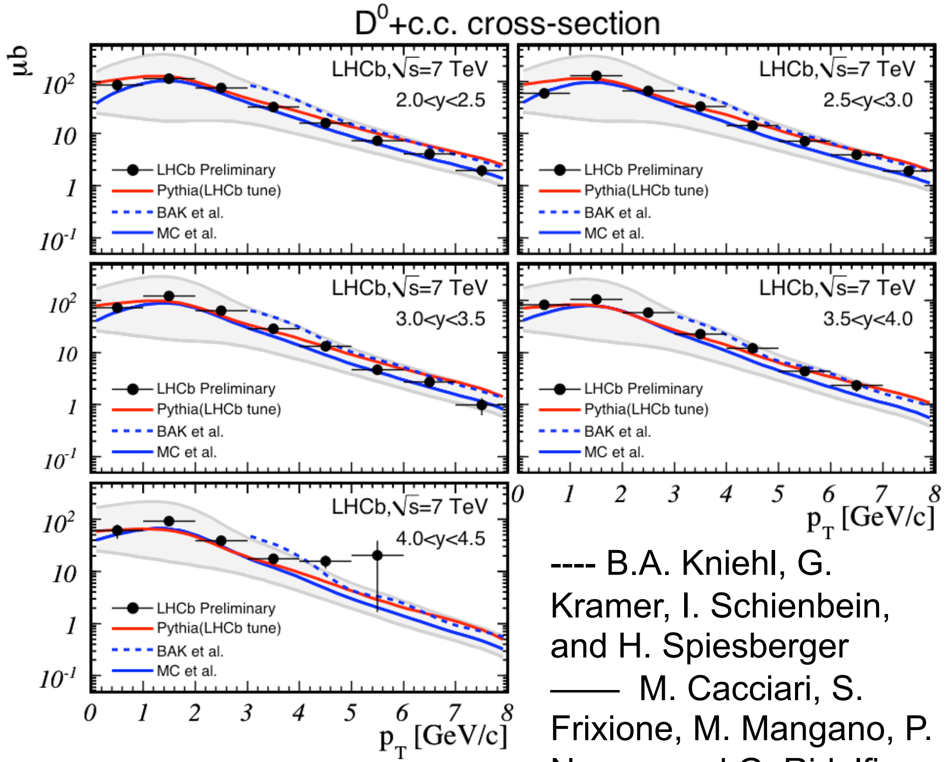


Good general agreement with measured prompt J/ψ cross-section in LHCb acceptance at high p_T

Open charm cross-sections

- Current preliminary results on cross-sections for D^0, D^{*+}, D_s^+ and D^+ with ~$2nb^{-1}$ (fully efficient trigger)
  - Remove secondary charm





---- B.A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger

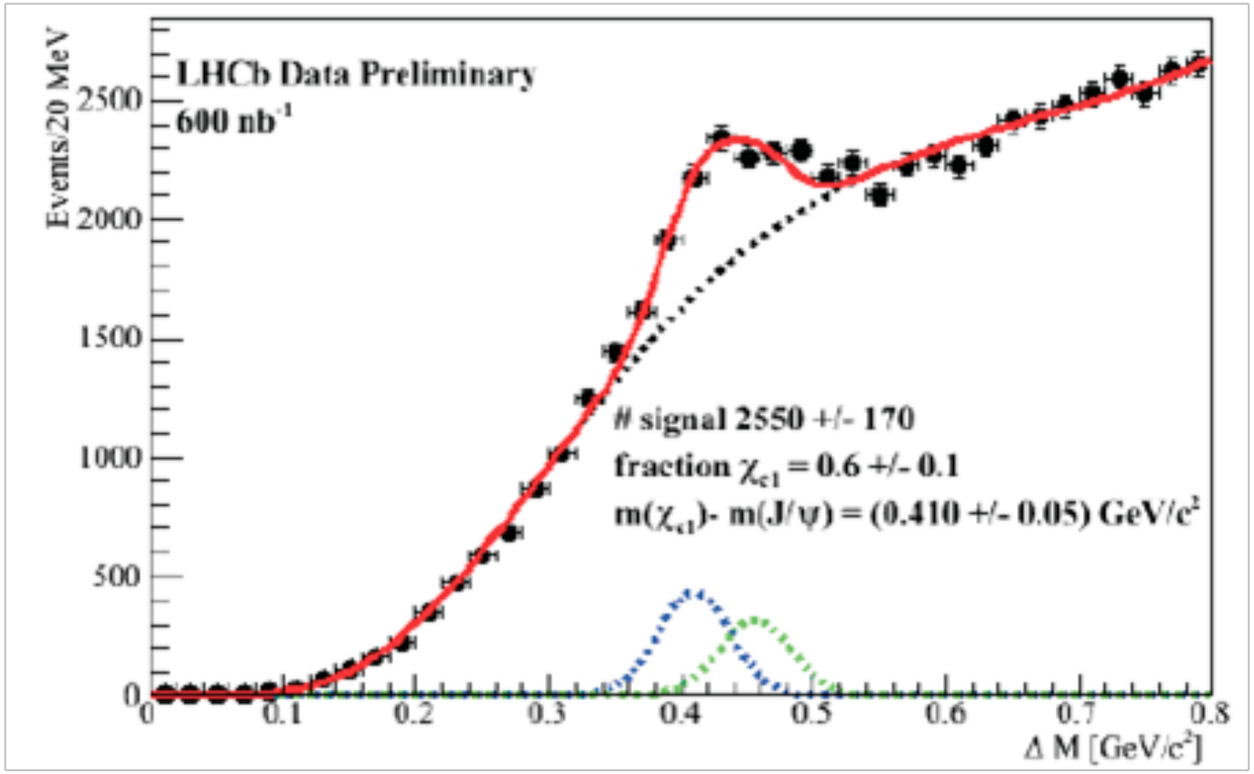
—— M. Cacciari, S. Frixione, M. Mangano, P. Nason, and G. Ridolfi

- (Preliminary) total open charm cross-section:
  - $\sigma(pp\to cc) = 6.10\pm0.93\text{mb} \approx 20\times\sigma(pp\to bb)$
  - Being updated with larger statistics and Λ_c^+

Good agreement with theory

$\chi_c \rightarrow \gamma\ J/\psi$

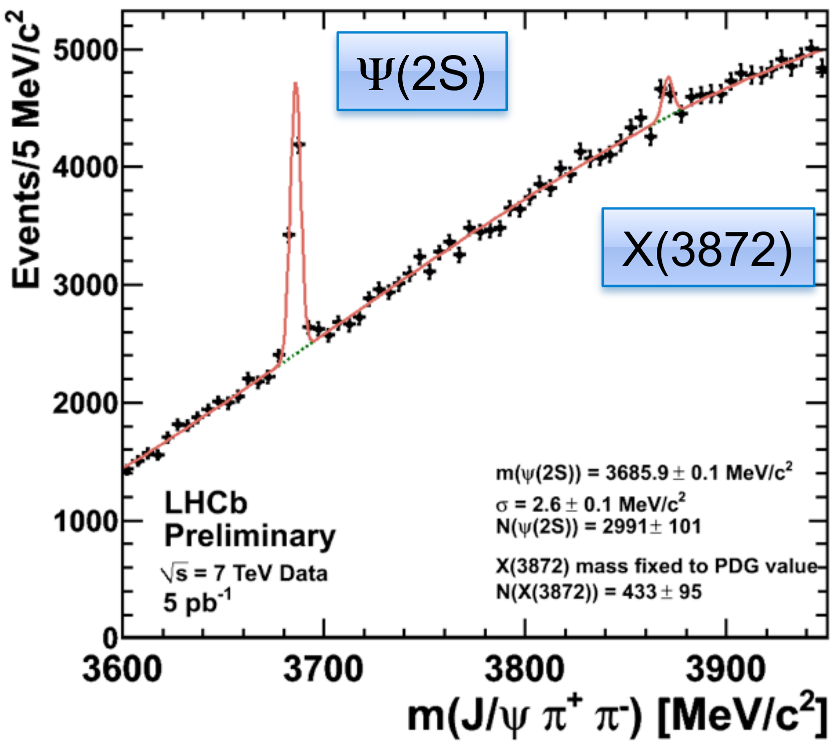
- Will measure χ_c cross-section and proportion of J/ψ from feed-down



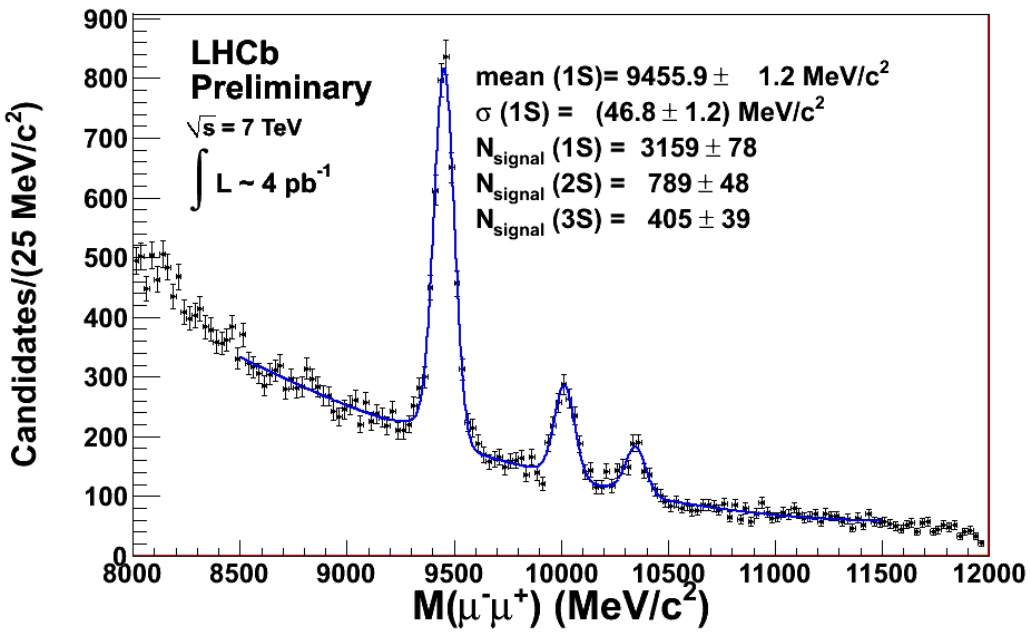
$M(\chi_c)-(J/\psi)$

Other quarkonium states…

- $J/\psi\pi^+\pi^-$



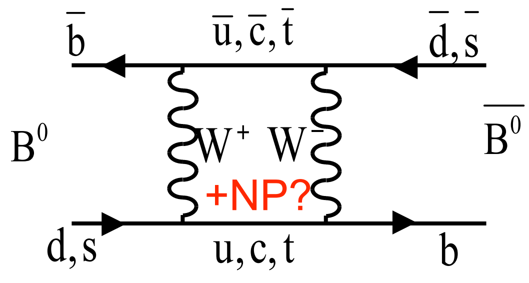
- Upsilons too..

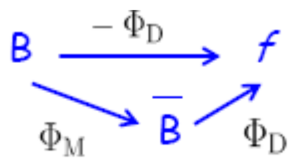


Y(1S), Y(2S), Y(3S)

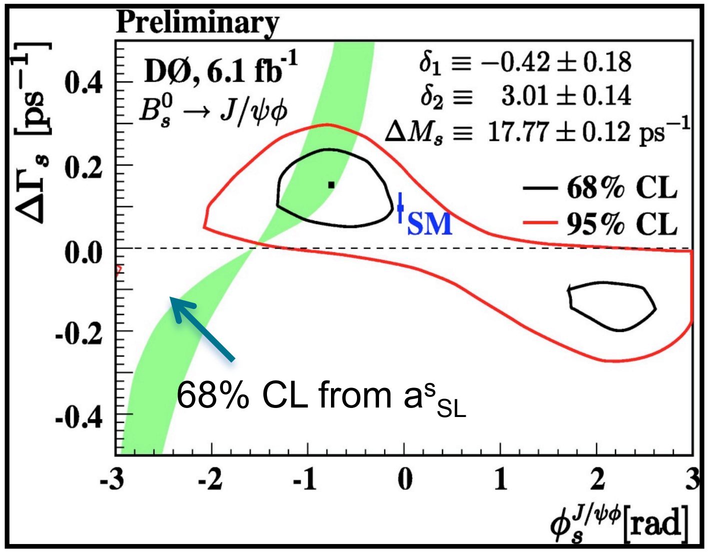
$\phi(J/\psi\phi)$ measurements from $B_s \rightarrow J/\psi\phi$

- Measure of B_s-B_s mixing phase $\phi(J/\psi\phi)$ in $B_s \rightarrow J/\psi(\mu\mu)\phi$ sensitive to NP effects in mixing
  - The phase arises from interference between B decays with and without mixing
  - $\phi SM(J/\psi\phi) = -2\beta s = -2\lambda 2\eta \sim -0.036 \pm 0.002$ rad
  - $\phi(J/\psi\phi) = -2\beta s + \phi^{NP}$

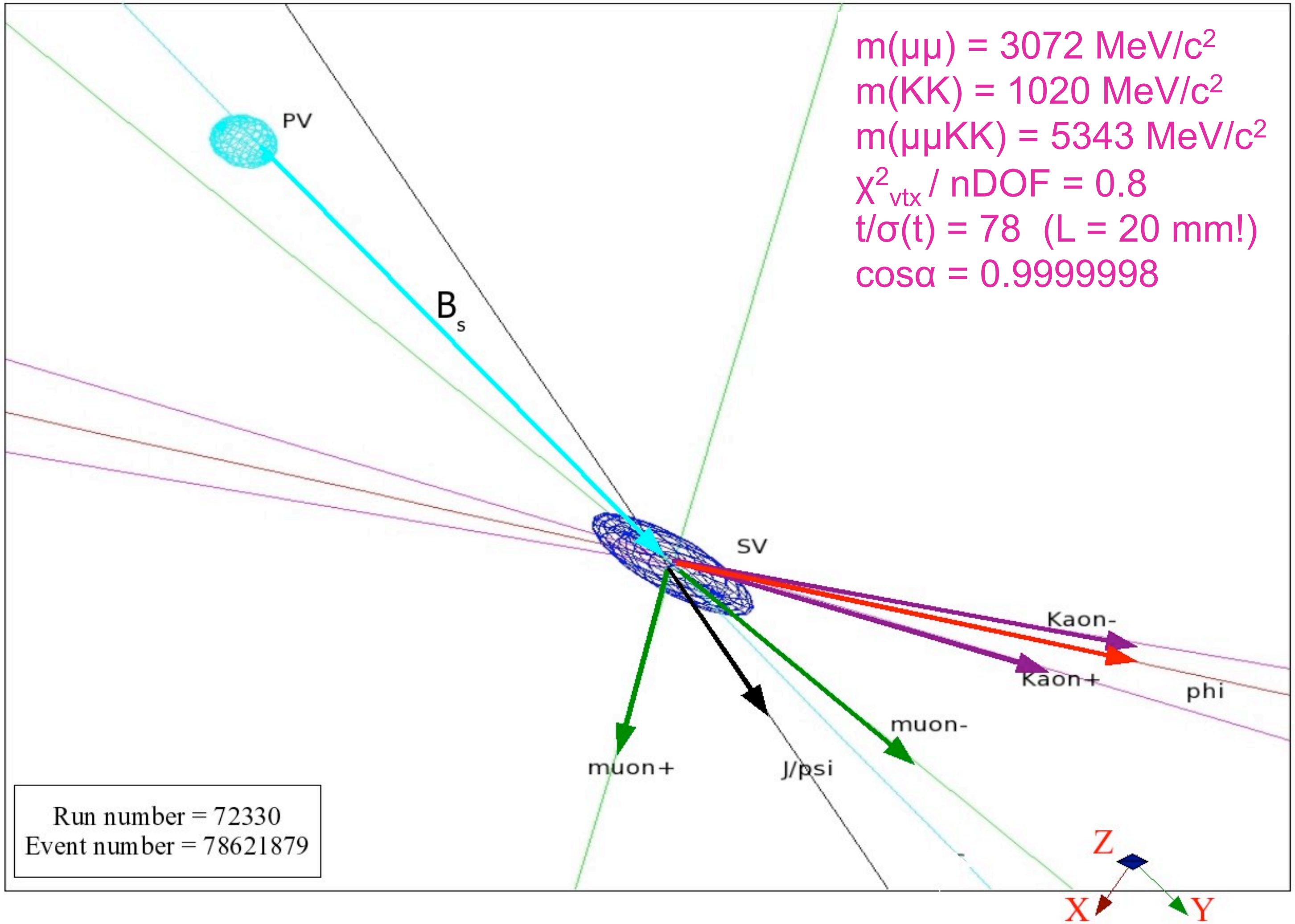




- First measurements from CDF/D0 show some interesting hints
- Recent D0 measurement of an anomalous di-muon charge asymmetry points in the same direction
- The probability that SM is consistent with all these observations at few percent level.

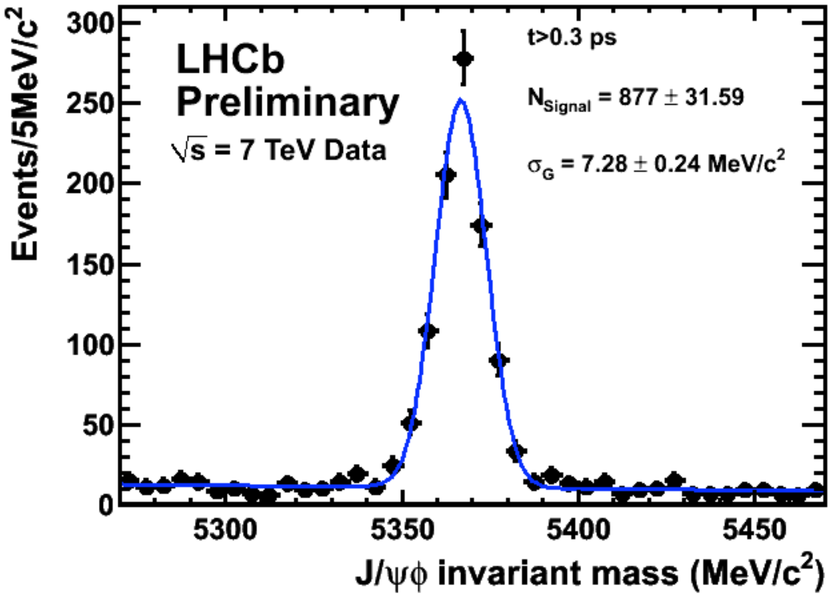


Early $B_s \rightarrow J/\psi\ \phi$ event

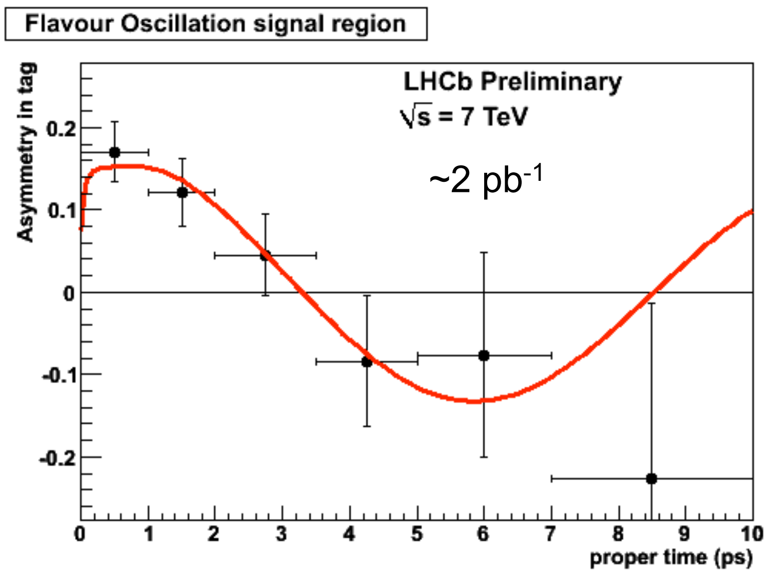


ϕ(J/ψφ) measurements from $B_s \rightarrow J/\psi\ \phi$

- Challenging measurement
  - P→VV decay – need angular analysis to separate CP-even and CP-odd
- Reality check-list:
  - Rate of signal events → consistent with expectations
  - Proper time resolution ~60fs, << B_s oscillation period of ~350 fsec
  - Tagging performance being optimised

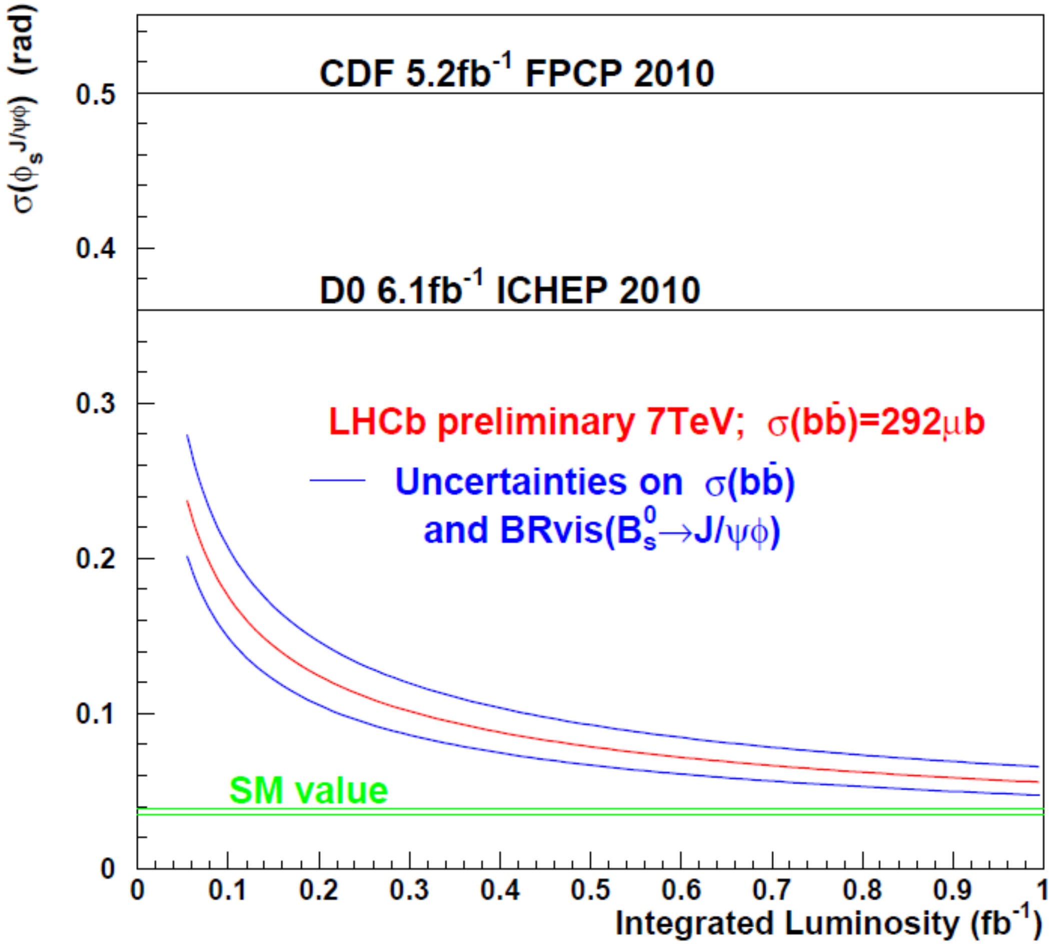


~900 events so far, ~20 times more in 2011
CDF+D0~10,000 events



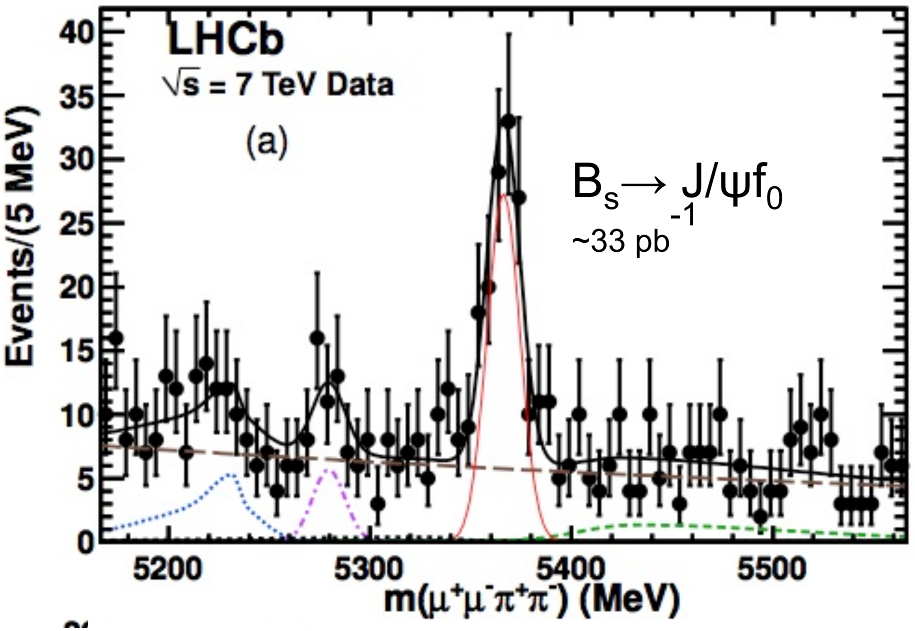
←B^0_d oscillations already seen early in run

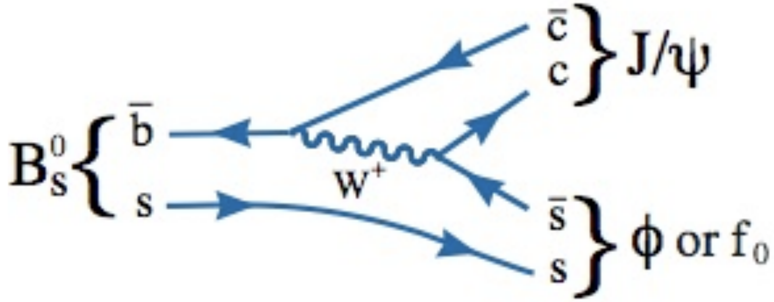
Prospects for $\phi(J/\psi\phi)$ measurements



$B_s \to J/\Psi f_0(980)$

- First Observation of $B_s \to J/\psi f_0(980)$ decays





arXiv:1102.0206

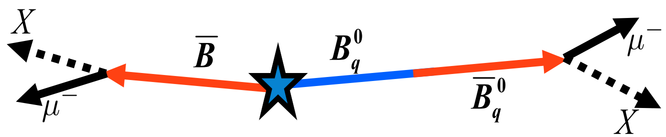
$$R_{f_0/\phi} \equiv \frac{\Gamma(B_s^0 \to J/\psi f_0,\ f_0 \to \pi^+\pi^-)}{\Gamma(B_s^0 \to J/\psi \phi,\ \phi \to K^+K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033}$$

- Can use this decay to improve precision on B_s mixing phase
- CP eigenstate, so simpler analysis

New Physics in di-muon charge asymmetry?

- If NP enhances CPV in $B^0_S \to J/\psi\Phi$, it will likely also enter in semi-leptonic asymmetry
- D^0 measures: $$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

N_b^{++} (N_b^{--}) – number of same-sign $\mu^+\mu^+$ ($\mu^-\mu^-$) events from $B \to \mu X$ decay



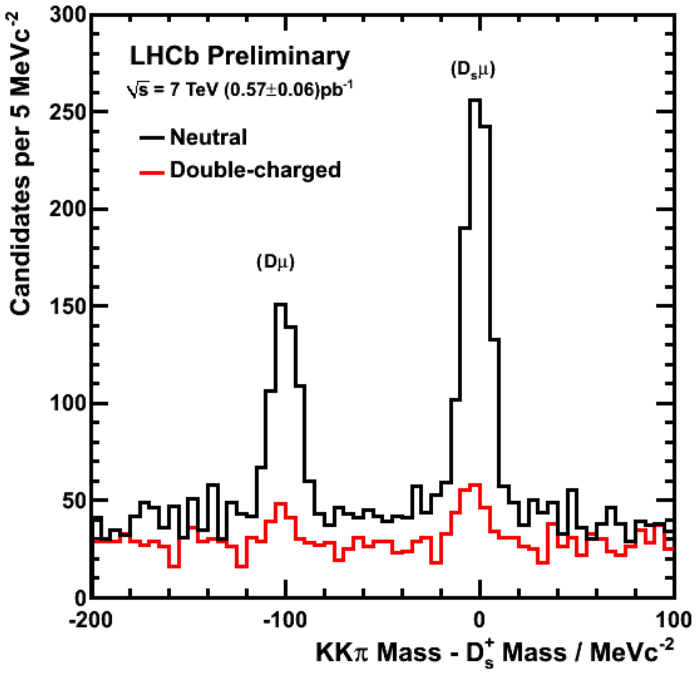
  - Both B_d and B_s contribute to A^b_{sl}
  - $A^b_{sl} = (0.506 \pm 0.043)a^d_{sl} + (0.494 \pm 0.043)a^s_{sl}$

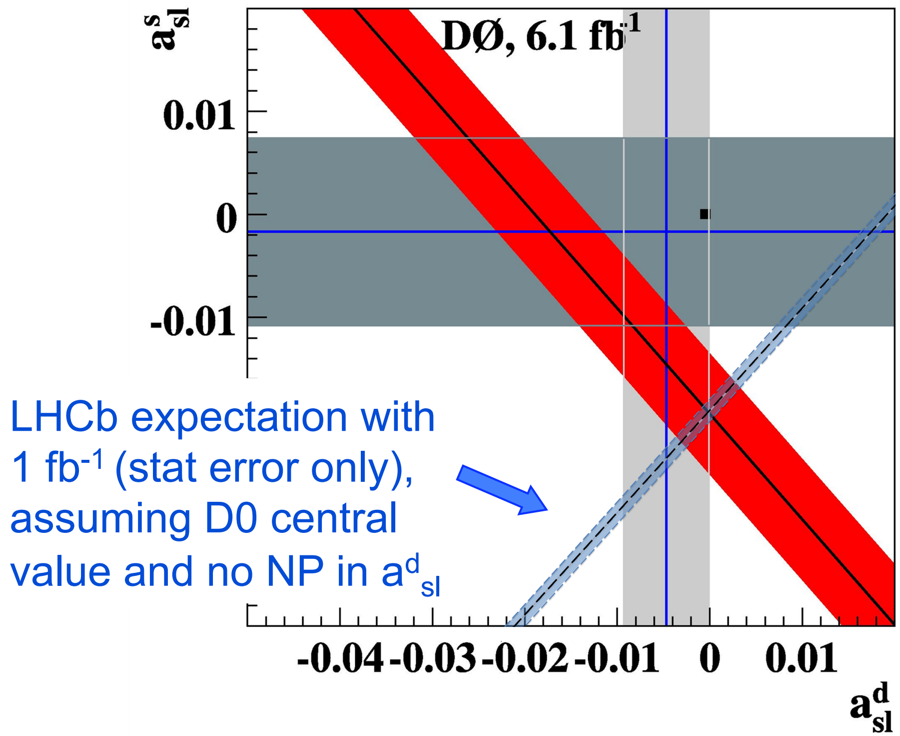
$$a^q_{sl} \equiv \frac{\Gamma(\overline{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\overline{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)}; \quad q = d, s$$

- D0 result ~3.2 σ away from SM (arXiv:1007.0395)

New Physics in di-muon charge asymmetry?

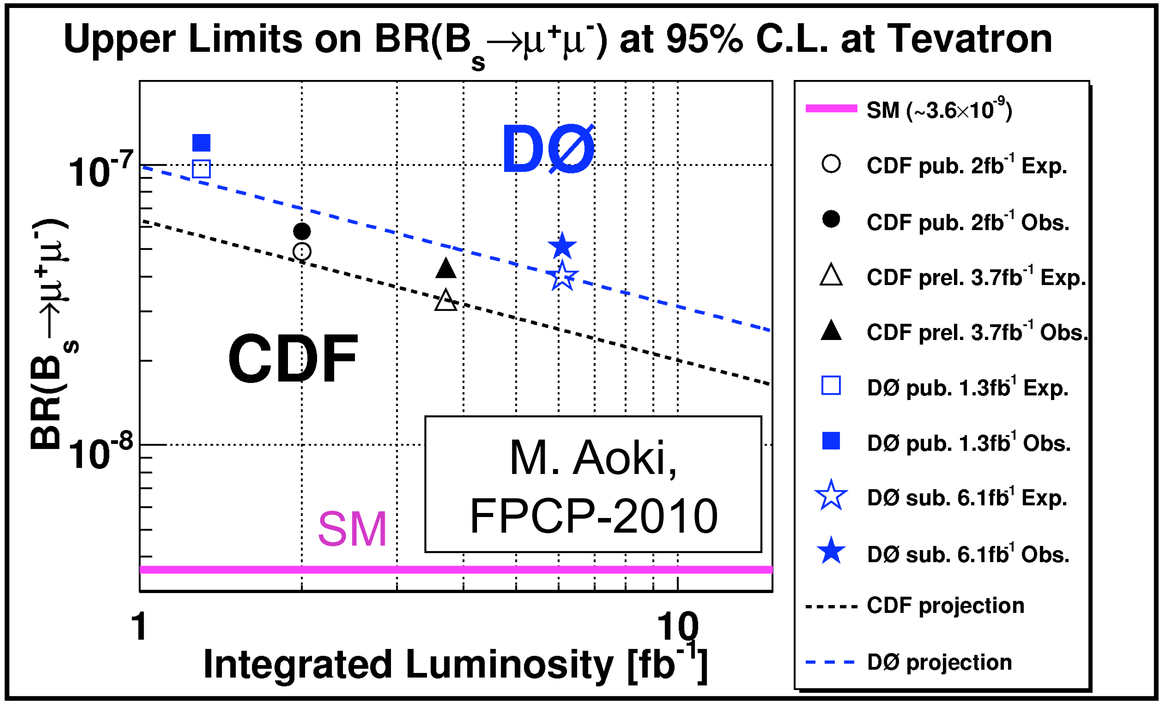
- @LHCb measure $\mathbf{a^s_{sl} - a^d_{sl}}$ from difference in asymmetry in $B_s \rightarrow D_s(KK\pi)\mu\nu$ & $B^0 \rightarrow D^+(KK\pi)\mu\nu$
  - Same final state suppresses detection asymmetry
  - Provides orthogonal constraint to D0 di-leptons

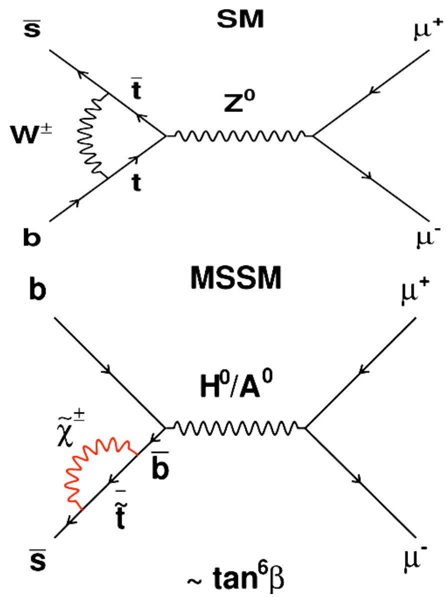




New Physics in $B_s \to \mu^+\mu^-$

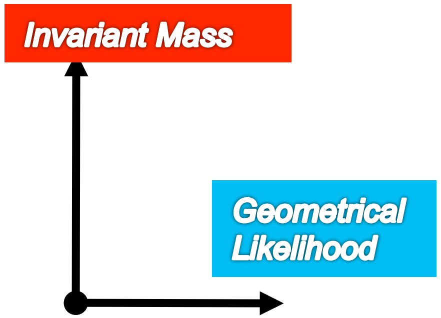
- Small BR in SM: $(3.6 \pm 0.3) \times 10^{-9}$ (Buras arXiv:0904.4917v1)
- Sensitive to NP
  - Could be strongly enhanced in SUSY
  - In MSSM scales like $\sim\tan^6\beta$
- Also $B_d \to \mu^+\mu^-$ BR: $(1.0 \pm 0.1) \times 10^{-10}$





$B_s \to \mu^+\mu^-$: LHCb key features

- High stat. & high trigger efficiency for signal
- Main issue is background rejection dominated by
  $B \to \mu^+ X$, $B \to \mu^- X$ decays
- Events in ±60 MeV mass window classified in 2D plane
  - geometrical likelihood
  - invariant mass (26 MeV mass resolution)



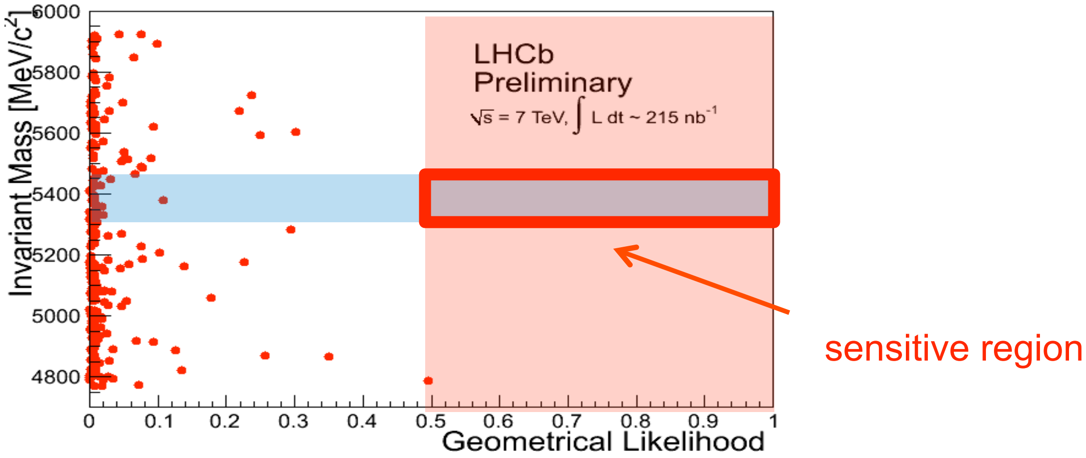
- Use of control channels to minimize dependence on MC simulation
- Convert number of observed events into limit by normalising with channels of known BR and calculating weighted average:
  - $B \to J/\psi K^+$
  - $B^0 \to K^+\pi$
  - $B_s \to J/\psi\varphi$

→ need to know B_s/B production ratio at LHC, already preliminary number from LHCb semileptonic analysis.

$$BR(B_s \to \mu^+\mu^-) = BR(B_q \to X) \frac{f_q}{f_s} \left(\frac{\varepsilon^{TRIG|SEL}_{B_q \to X} \varepsilon^{SEL|REC}_{B_q \to X} \varepsilon^{REC}_{B_q \to X}}{\varepsilon^{TRIG|SEL}_{B_s \to \mu\mu} \varepsilon^{SEL|REC}_{B_s \to \mu\mu} \varepsilon^{REC}_{B_s \to \mu\mu}} \right) \frac{N_{B_s \to \mu\mu}}{N_{B_q \to X}}$$

$B_s \rightarrow \mu^+\mu^-$: first results

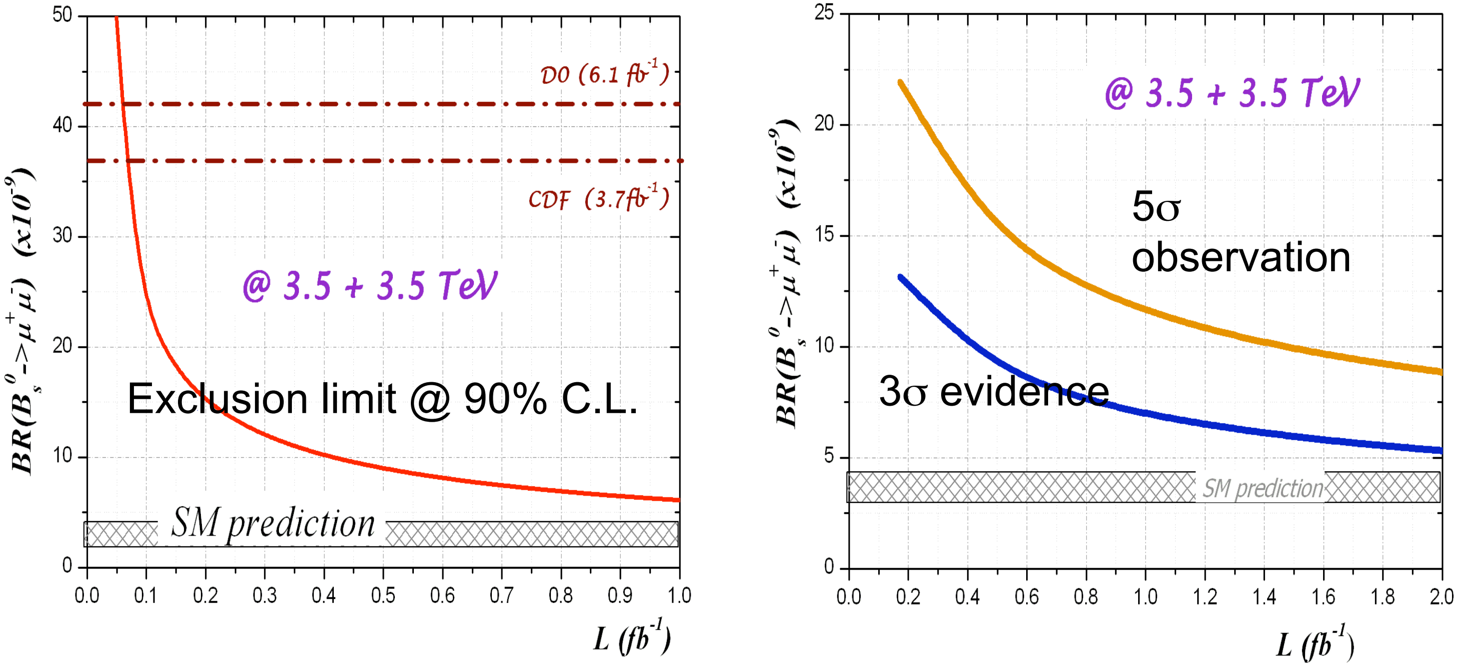
- Muon id, trigger & misidentification performing as expected from MC
- Geometrical likelihood vs invariant mass for 0.2 pb^{-1}



- Expected events reconstructed and selected if BR=SM (with ~36^{-1}pb) :
  - $B_s \rightarrow \mu\mu$: 0.4
  - $B_d \rightarrow \mu\mu$: 0.05
- Blinded analysis - It's almost time to open the box!

Physics reach for BR($B_s^0 \rightarrow \mu^+\mu^-$) as function of integrated luminosity

- Expected sensitivity @LHCb assuming measured bb cross-section (284 μb)



- LHCb results from 2010 data will be presented in la Thuile
- Competitive with Tevatron with our first 36 pb^{-1}

Charm at LHCb

- Study of charm is essential component of flavour physics programme
- Extremely small level of CPV expected in charm mixing and in decays offers the opportunity for very sensitive null tests of the CKM picture
  - First analysis of charm mixing
    → measurement of

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1 = y\cos\varphi - \frac{1}{2}A_M x \sin\varphi$$

A_M=½(|q/p|–|p/q|)
$y_{CP}=y$ if no CPV
φ≡Arg(q/p)

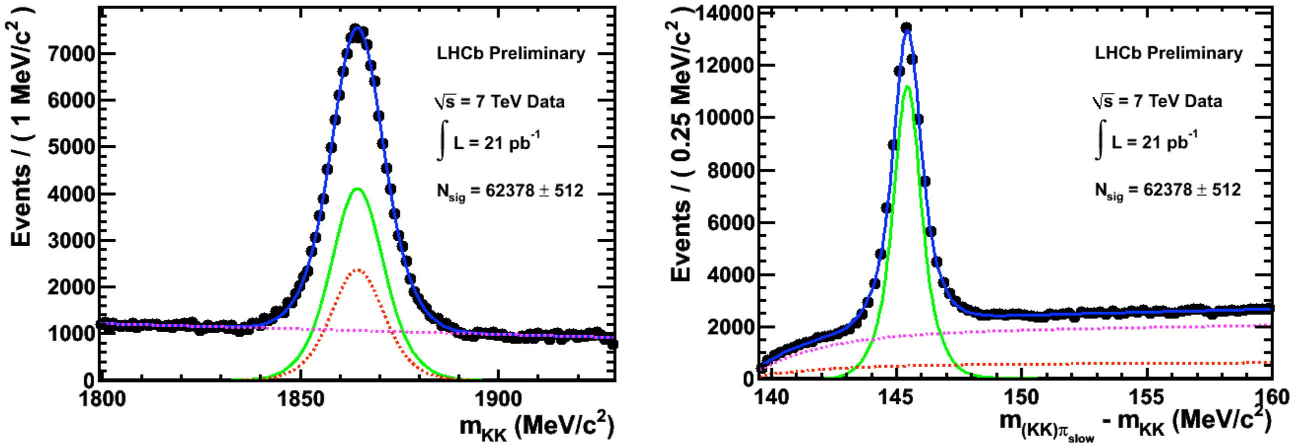
  - CPV via flavour tagged lifetime asymmetry

$$A_\Gamma \equiv \frac{\tau(\overline{D}^0 \longrightarrow K^+K^-) - \tau(D^0 \longrightarrow K^+K^-)}{\tau(\overline{D}^0 \longrightarrow K^+K^-) + \tau(D^0 \longrightarrow K^+K^-)} = \frac{1}{2}A_M y\cos\varphi - x\sin\varphi$$

    - Require that the D^0 comes from a D^{*+} in order to tag the flavour of the neutral D

Charm at LHCb

- Already with 2010 data, LHCb has collected large samples of $D^0 \rightarrow h^+h^-$ decays from D*
- $D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow KK$
  - Fitted signal yield in $22pb^{-1}$ = (62.3±0.5)k
  - Yield comparable to that used in BaBar's A_Γ measurement with <60% of full 2010 statistics
  - Use this sample to measure time-dependent CP observable A_Γ



- Enough statistics for competitive measurement of y_{CP} and A_Γ in 2010!

Conclusions

- Lots of beautiful data from LHCb
- The 2010 integrated luminosity already gives LHCb the statistical precision for many competitive measurements
- First cross-section measurements and first observations
- $B_s \to \mu\mu$ and $B_s \to J/\psi\varphi$ will reach new sensitivity regime with ~ 100 pb^{-1}
- Exciting prospects and rich physics programme for 2011-2012!

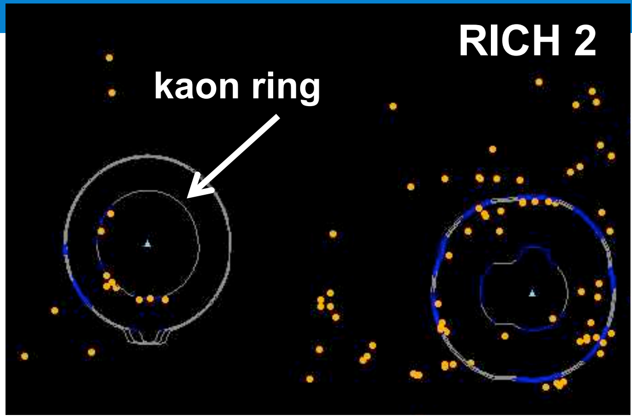
Backup

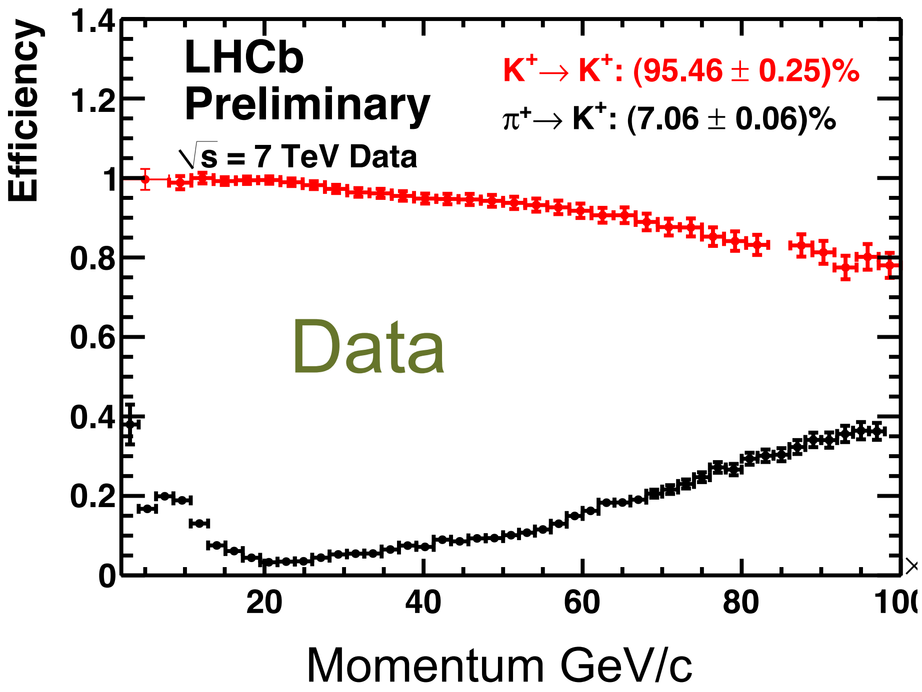
$\phi(J/\psi\phi)$ measurements from $B_s \to J/\psi\ \phi$

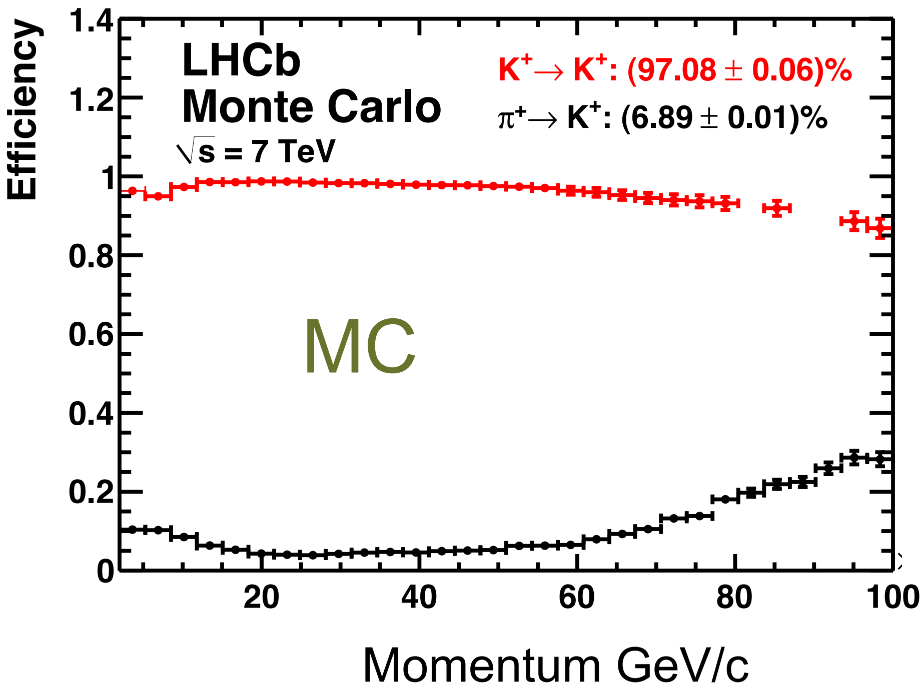
- P→VV decay:
  - B_s pseudoscalar (spin=0), J/ψ and Φ vectors mesons ($J^{PC}=1^{--}$)
  - Total angular momentum conservation implies $\ell=0,1,2$
- $CP|J/\psi\ \phi\rangle = (-1)^{\ell}\ |J/\psi\ \phi\rangle$ →
  - Mixture of CP-even ($\ell=0,2$) and CP odd ($\ell=1$) final states
  - Need to fit angular distributions of decay final states as function of proper time
- Analysis strategy
  - Trigger and select $B_s \to J/\psi\phi$
  - Measure proper time and 3 ‘transversity angles’
  - Tag initial B_s flavour
  - Likelihood fit of proper time and angular B decay rates
    - 6 observables: proper time, 3 angles, q (=0,-1,+1 for untagged, B_s, B_s) and mass
    - 8 physics parameters: Φ, $\Delta\Gamma_s$, Γ_s, Δm_s, $R_\perp$, R_0, δ_1, δ_2
    - many detector parameters (resolutions, acceptances, tagging, …)

RICH PID performance

- PID performing close to MC performance

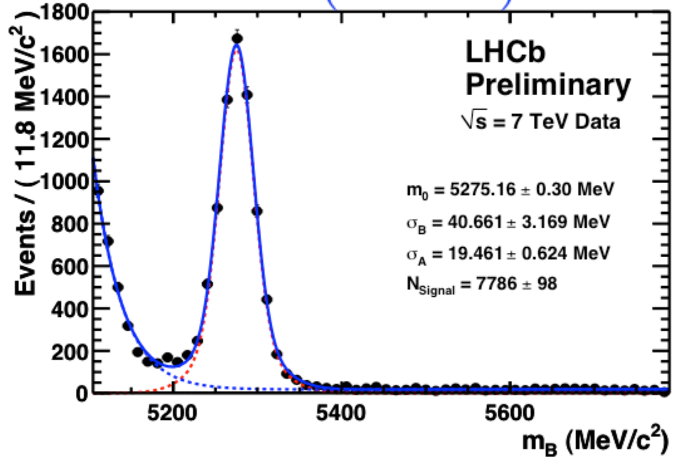




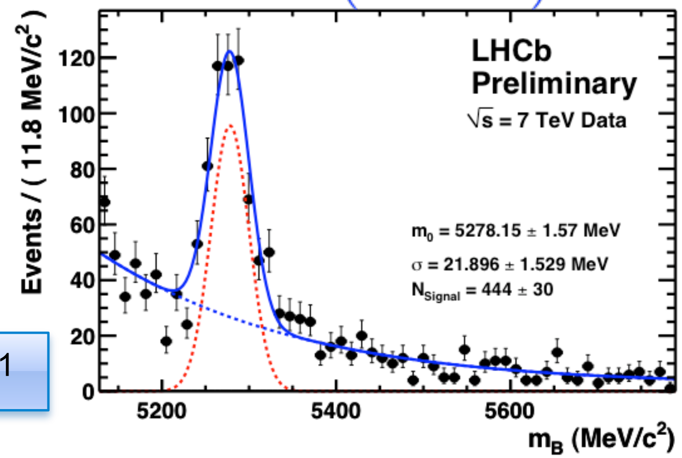


Fully reconstructed hadronic B decays $B^{\pm} \to D\pi^{\pm}$ and $B^{\pm} \to DK^{\pm}$

$B^{\pm} \to D(K^{\pm}\pi^{\mp})\pi^{\pm}$

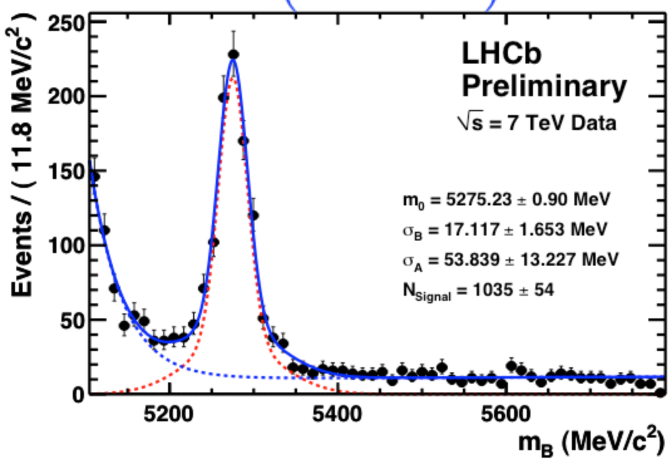


$B^{\pm} \to D(K^{\pm}\pi^{\mp})K^{\pm}$

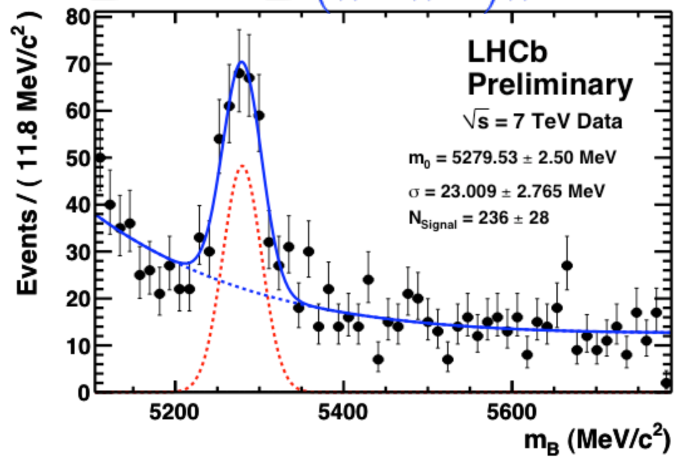


~34 pb^{-1}

$B^{\pm} \to D(K^{+}K^{-})\pi^{\pm}$



$B^{\pm} \to D(\pi^{+}\pi^{-})\pi^{\pm}$



Fully reconstructed hadronic B decays $B \rightarrow J/\psi\ X$

~15 pb^{-1}