LHCb: first results

V. Egorychev

on behalf of the LHCb *Collaboration*

The LHCb Experiment

- An experiment dedicated at *b* physics precision measurement
  - CP-violating decays: $B_s \rightarrow J/\psi\ \phi$, $B \rightarrow hh$, …
  - Rare decays: $B_s \rightarrow \mu\ \mu$, $B_d \rightarrow K^*\ \mu\ \mu$, …
  - Flavour physics: open charm sector, soft QCD, quarkonium physics, …
- Look for signs of New Physics:
  - new particle to be produced and observed as real particle at LHC
  - virtual new particles (in loop processes) may alter the decay rate, CP asymmetry and other observable quantities
  - rare B decays, where penguin amplitudes play a dominate role, are excellent places to look for NP

see talk by A.Golutvin, *LHCb: status and perspectives*

b production in LHCb

Advantages of beauty physics at hadron colliders:

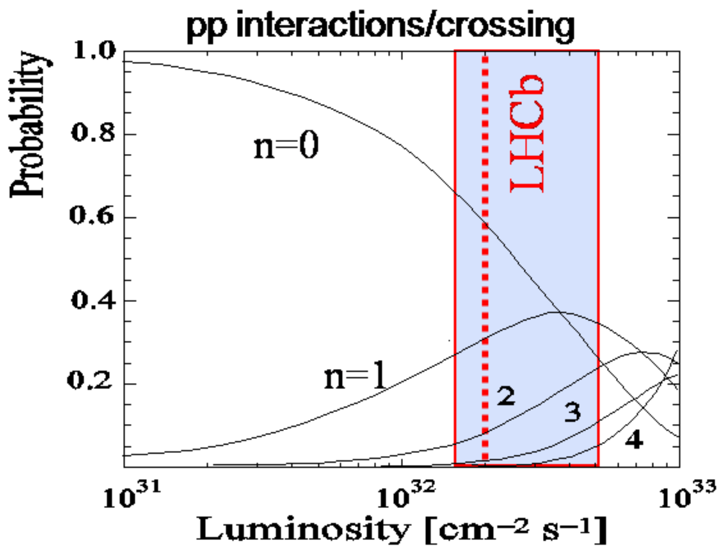
- high value of *bb* cross section at LHC
- access to all quasi-stable *b*-flavoured hadrons

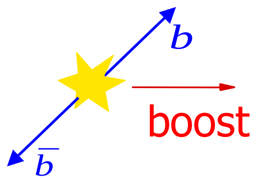
Challenge:

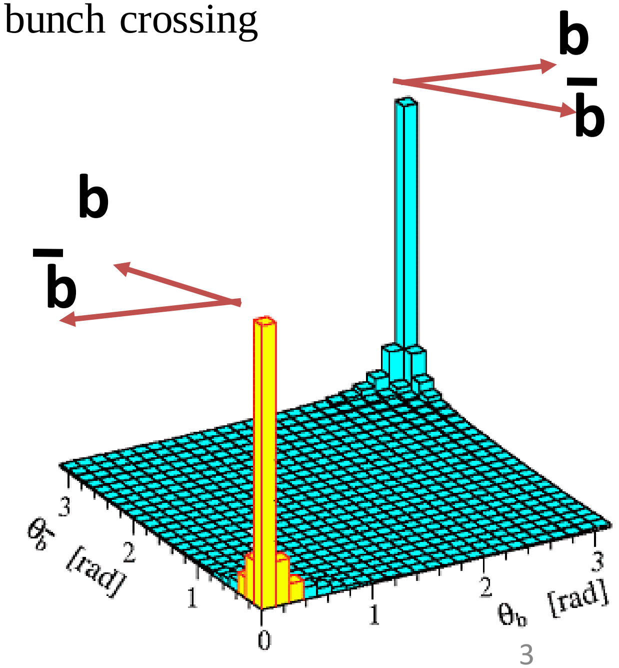
- multiplicity of tracks (~30 tracks per rapidity unit)
- rate of background events: $\sigma_{inel} \sim$ 100 mb

LHCb nominal running conditions:

- luminosity limited to $\sim 2\times10^{32}$ cm^{-2} s^{-1} by not focusing the beam as much as ATLAS and CMS
- maximize the probability of single interaction per bunch crossing

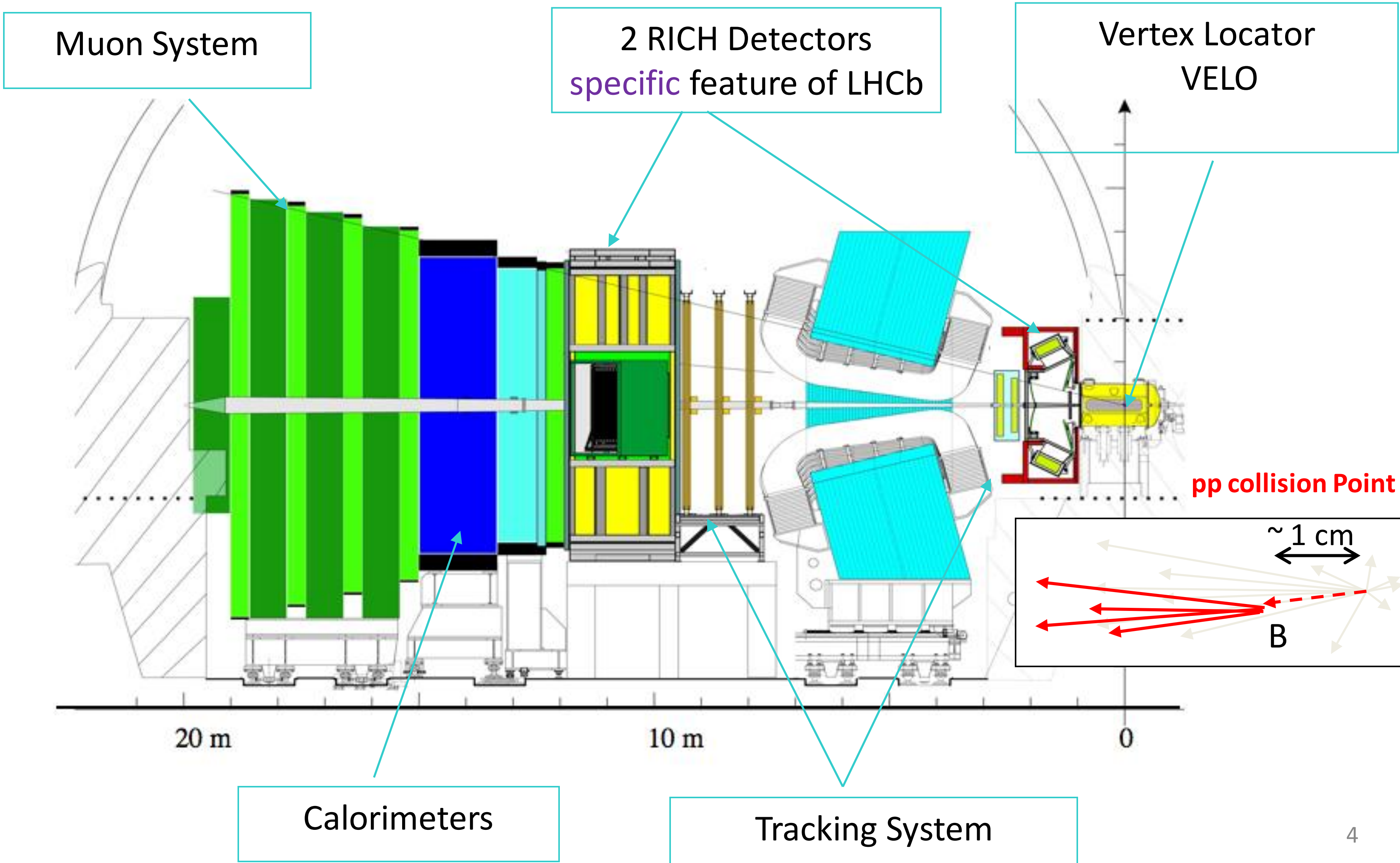




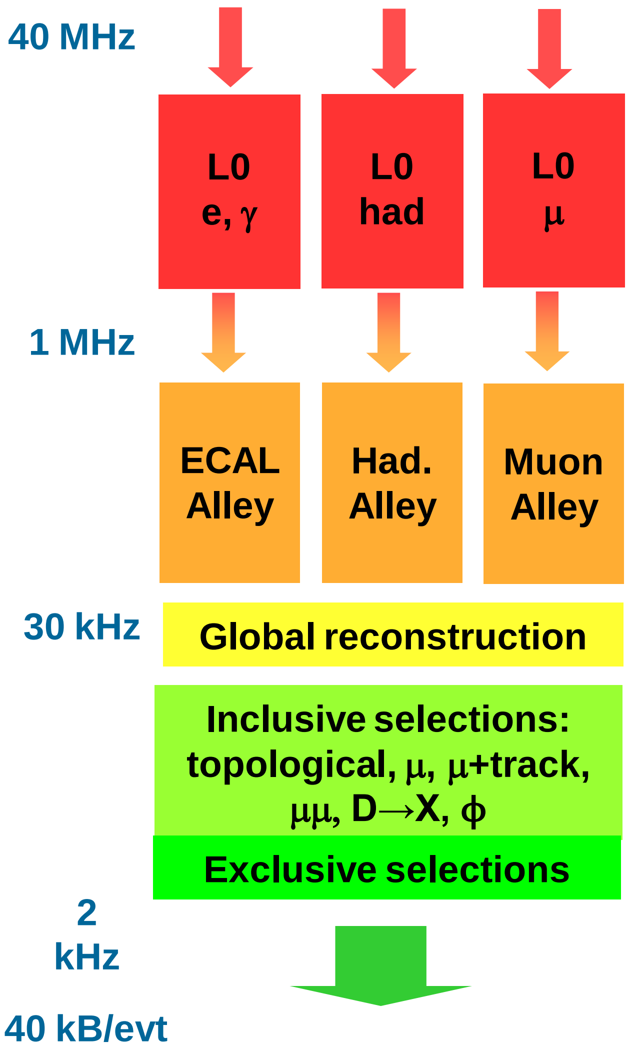


LHCb detector

Angular acceptance $15 < \theta < 300$ mrad that corresponds to $1.9 < \eta < 4.9$



LHCb trigger scheme



Level-0

'High-pt' signals in calorimeter & muon systems

HLT1

tries to confirm the L0 decision by matching the L0 object to tracks

HLT2

Full detector information available for inclusive and exclusive selections

- at design luminosity

  → trigger optimized for B physics

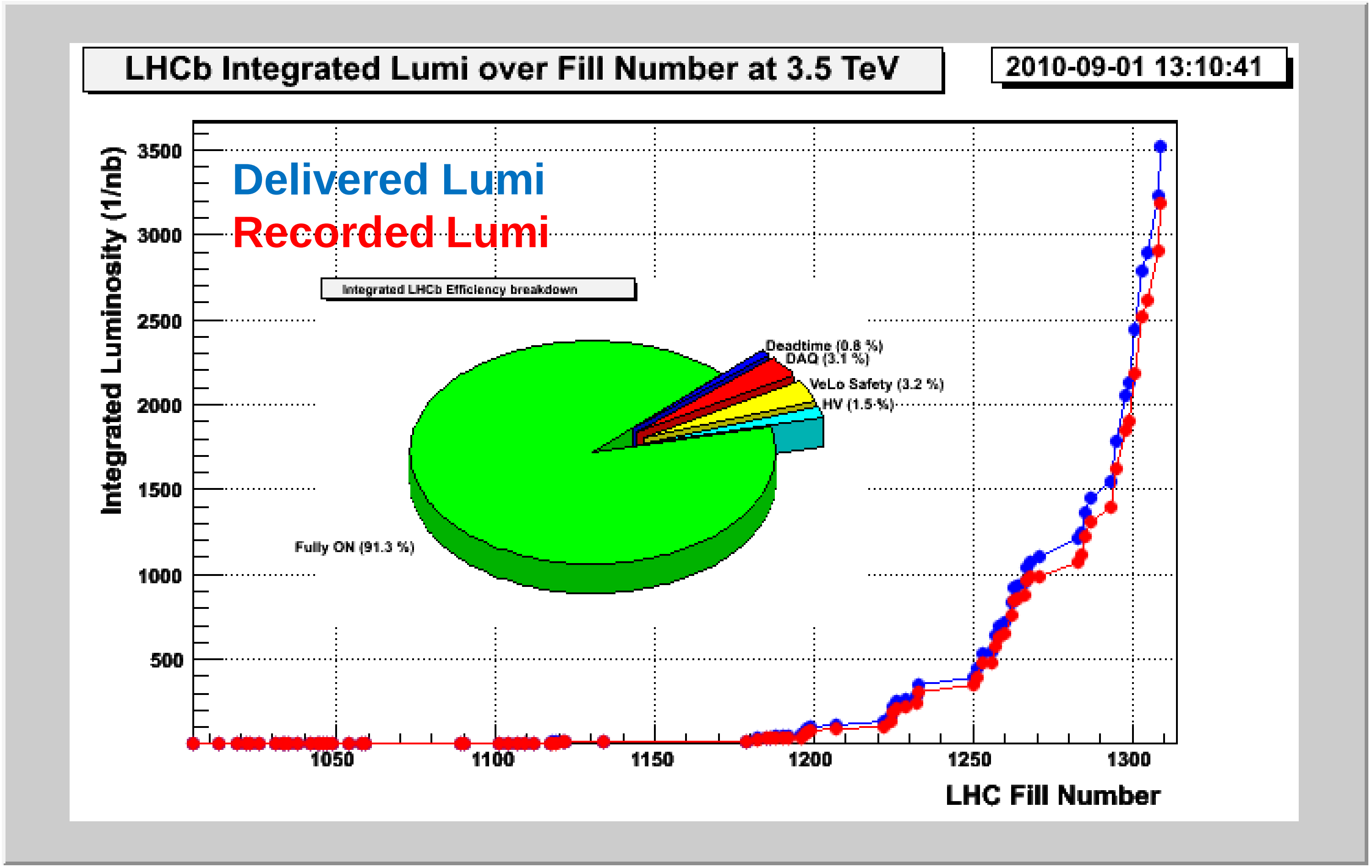
- at low luminosity in Y2010 (up to few 10^{31} $cm^{-2}s^{-1}$)

trigger being re-tuned to cope with the machine parameters of the 2010

high flexibility of the trigger allows us to manage pile-up much higher than nominal !

For details see talk by A.Golutvin, *LHCb: status and perspectives*

LHCb operation



currently taken data: ~ 3.2 pb^{-1}

expect ~20-50 pb^{-1} by end of 2010 and ~1 fb^{-1} by end of 2011

Y2011 – e.g. results on $B_s \rightarrow J/\psi\ \varphi$ and $B_s \rightarrow \mu^+ \mu^-$

Preliminary results

Strange production

Open and hidden charm production

Open and hidden beauty production





K_s analysis (strategy)

final result, arXiv:1008.3105v1 , submitted to Phys. Lett. B

Based on the data collected in Y2009, during the pilot run of the LHC

K_s candidates are selected from all pairs oppositely charged tracks which form a secondary vertex downstream of the interaction point, using only the events triggered by the calorimeter

Measure the K_s production in bins of transverse momentum (p_T)and rapidity (y)

Intervals: $2.5 < y < 4.0$ and $0 < p_T < 1.6$ GeV/c

For each bin, the cross section is:

$$\sigma_i = \frac{N_i^{obs}}{\varepsilon_i^{trig/sel} \times \varepsilon_i^{sel} \times L_{int}}$$

Observed signal decays

Integrated luminosity

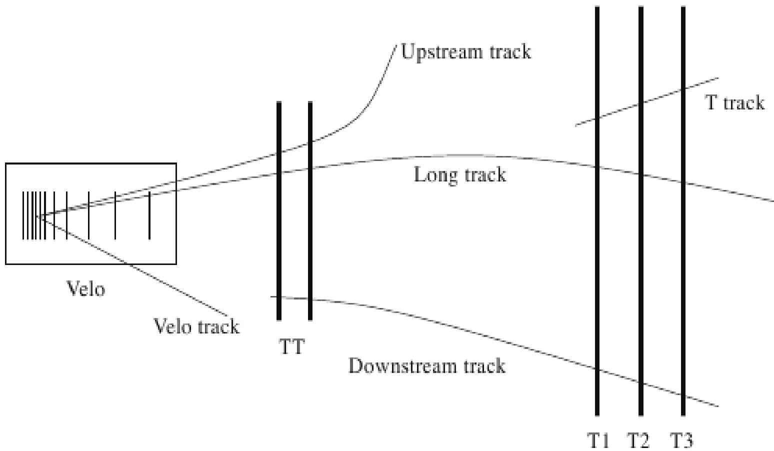
Trigger efficiency

Reconstruction and selection efficiency

K_s analysis (selection)

Two independent, complementary analyses performed:

- Downstream analysis:
  - No VELO hits used in reconstruction
  - High statistics
  - Wider mass resolution, more background



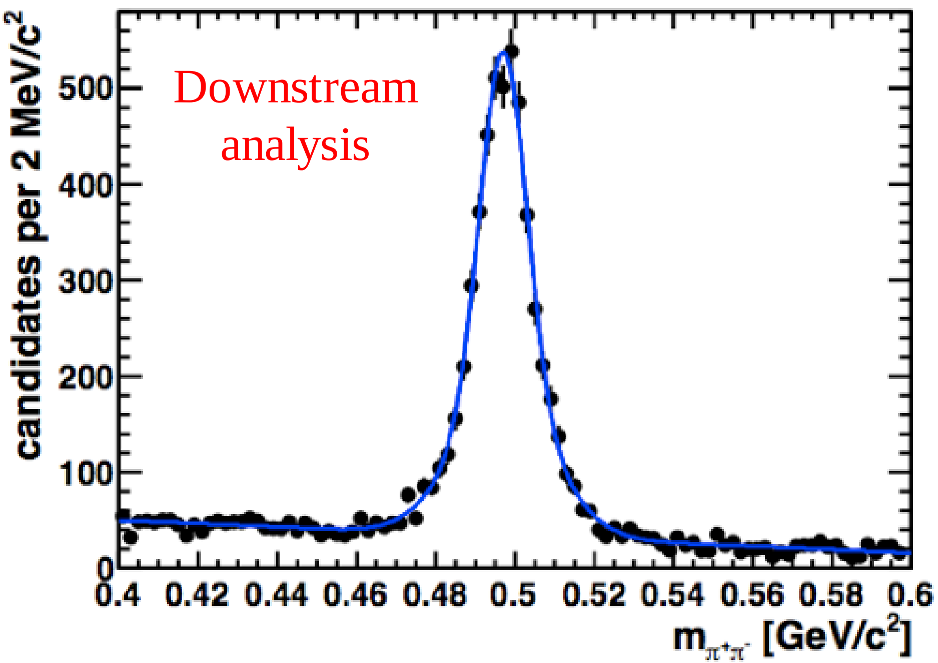
- Long track analysis:
  - Tracks require VELO hits
  - Low statistics due to Ks boost and open VELO
  - Good background rejection, good mass resolution

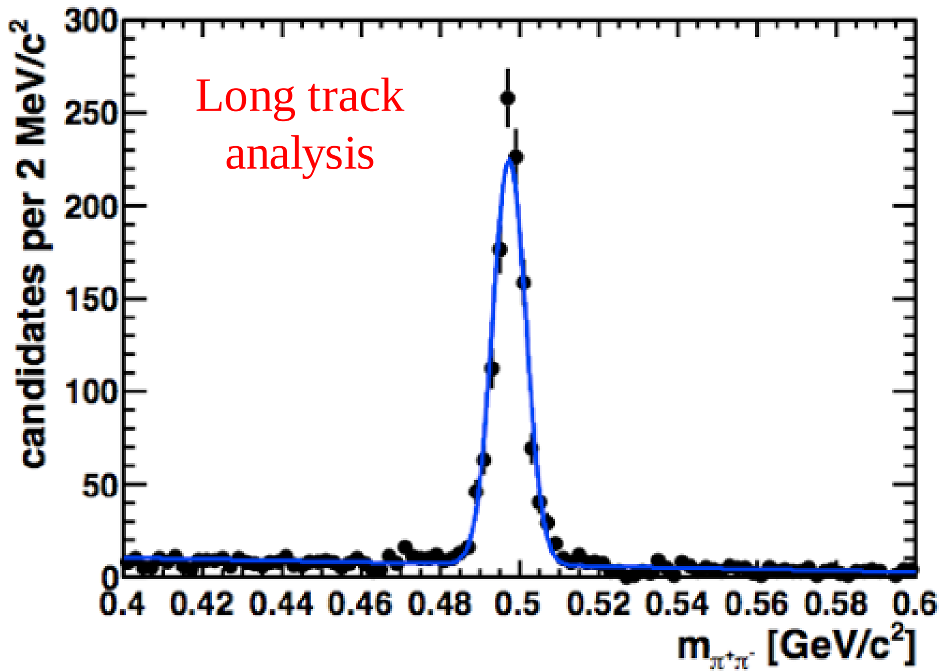
No PID cuts were applied

Used the most precise measurement for each phase-space bin

K_s analysis (signal)

PDG: 497.61 ± 0.02 MeV/c^2





	Downstream	Long
Yield	4801 ± 84	1182 ± 36
Mean mass (MeV/c^2)	497.12 ± 0.14	497.31 ± 0.13
Mass resolution (MeV/c^2)	9.2	4.0

K_s analysis (efficiency)

Efficiencies are estimated per bin of pT and y:

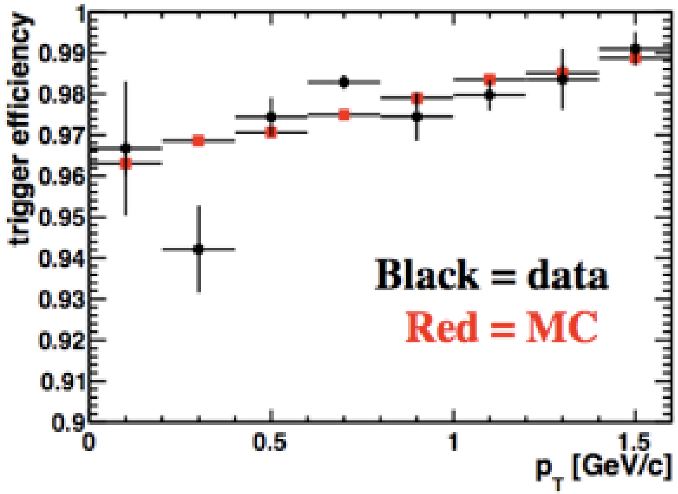
$$\sigma_i = \frac{N_i^{obs}}{\varepsilon_i^{trig/sel} \times \varepsilon_i^{sel} \times L_{int}}$$

reconstruction and selection efficiency ε^{sel}

- Selection efficiency estimated in MC, includes geometric acceptance, reconstruction efficiency
- Tracking efficiency
- Primary vertexing efficiency (for the long analysis only)

Trigger efficiency $\varepsilon^{trig/sel}$

- Calculate ratio of triggered, selected events and selected events in MC



Total efficiency

3-20% depending on bin (geometric acceptance)

	efficiency	syst. uncert.
Tracking	85-100%	6-17%
Primary vertex	91%	1.5%
Trigger	> 95% in every bin	2.5%

very low momenta

K_s analysis (luminosity)

For 2009 runs, luminosity was calculated directly from beam parameters
Luminosity for N pairs of colliding bunches:

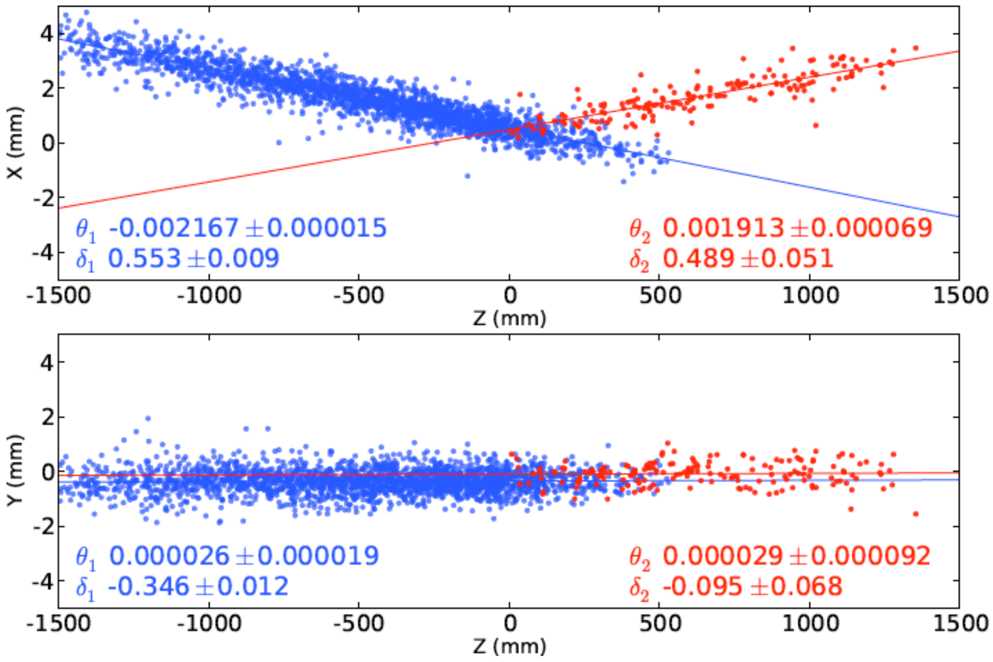
$$L = f \sum_{i=1}^{N} \frac{n_{1i} n_{2i}}{A_{eff\_i}}$$

f = 11.245 kHz is the LHC revolution frequency
n_{1i}, n_{2i} – number of protons in bunch
A_{eff_i} – effective collision area

Get bunch currents from the LHC machine measurements

Use VELO to image beams by reconstructing vertices from beam-gas interactions. Gives the beam sizes, positions and angles for effective area calculation

Distributions in the horizontal and vertical planes of the reconstructed verticies



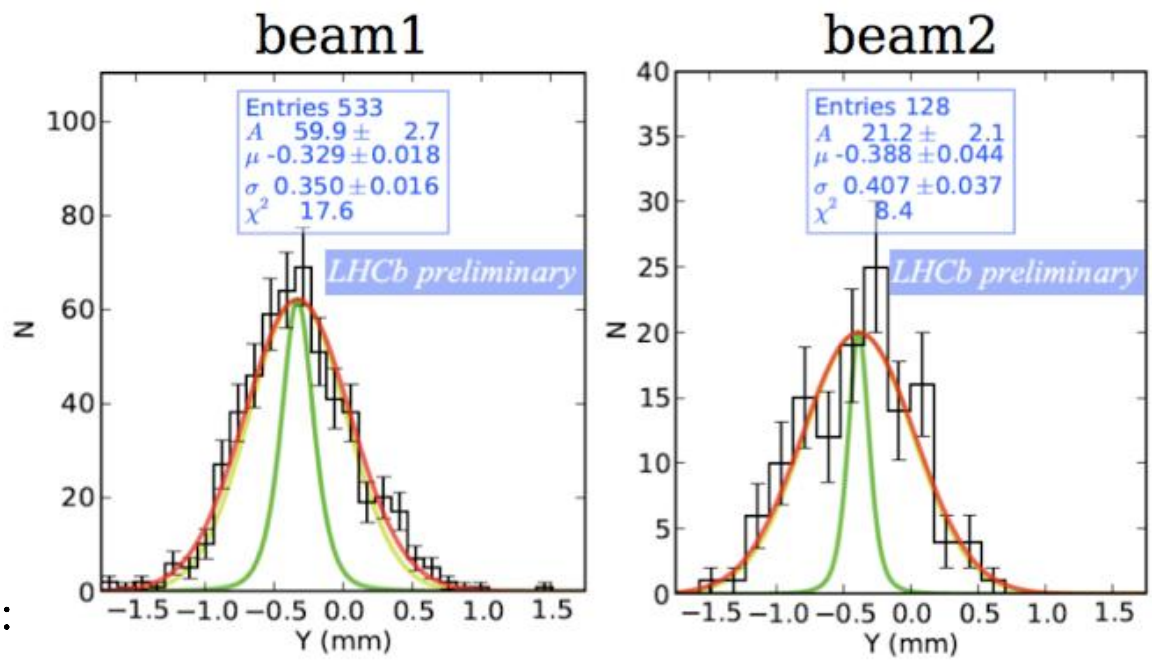
K_s analysis (luminosity)

Vertex resolutions are deconvoluted from the measured beam size

Bare beam sizes then used to calculate the effective crossing-area

example: transverse profiles measured in y for one pair of bunches

- Vertex resolution (red)
- Measured size (yellow)
- Bare beam size, after de-convoluting the resolution (green)

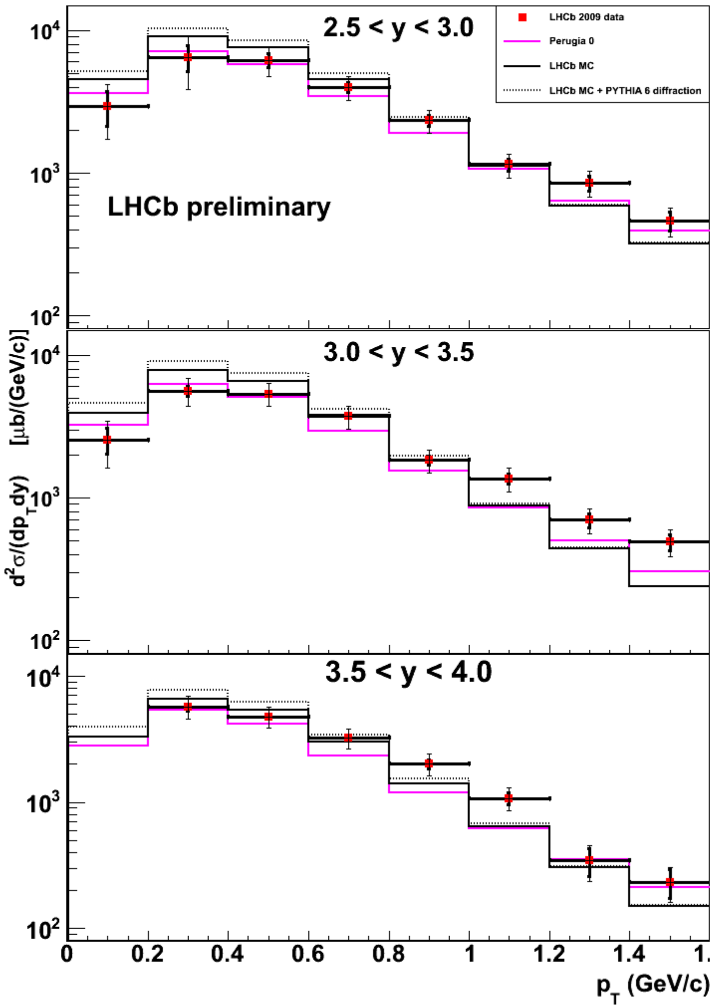


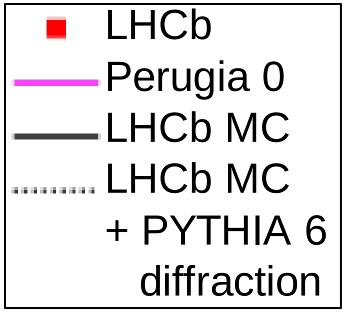
Luminosity delivered during 2009 and used for K_s analysis: $6.8 \pm 1\ \mu b^{-1}$

Dominated by systematic uncertainties:

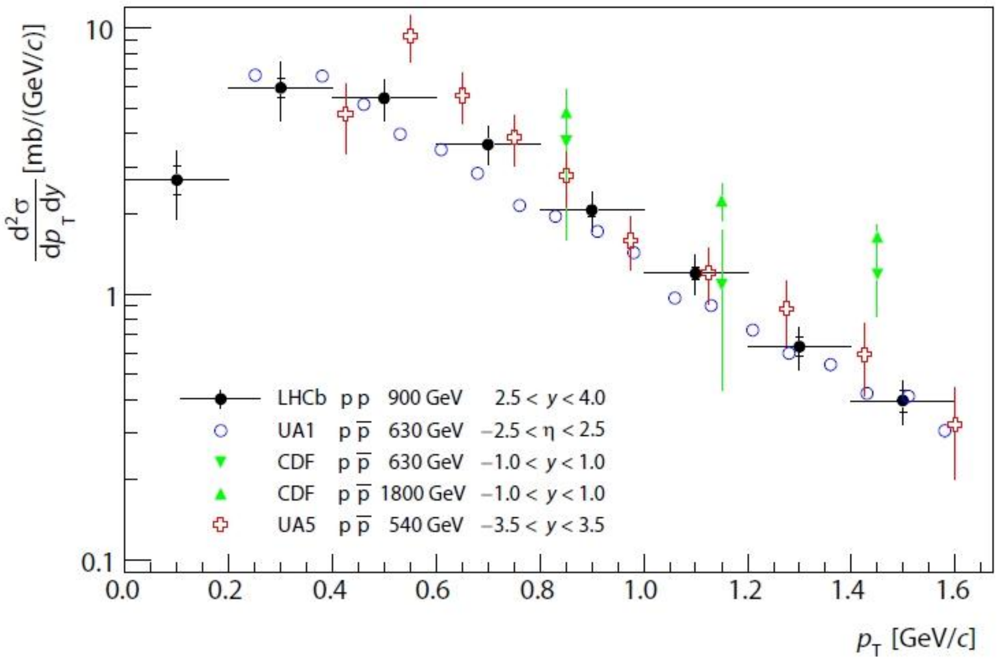
Beam intensities	width	Relative position	Crossing angle
12%	5%	3%	1%

K_s analysis (final results)





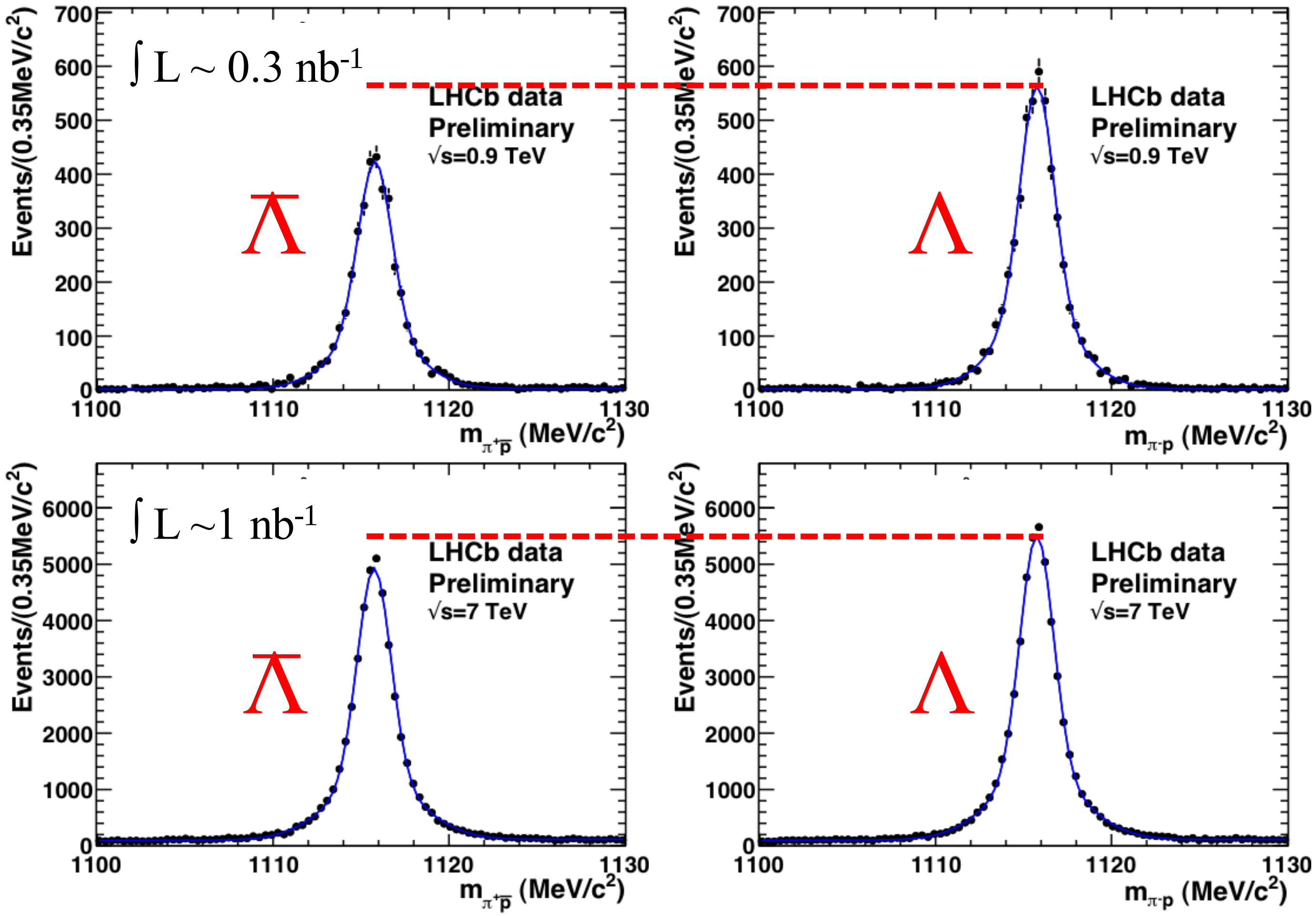
arXiv:1008.3105v1 ,
submitted to Phys. Lett. B



p_T distribution for several rapidity bins
Data tend to be slightly harder than different PYTHIA tuning

First *pp* results at this energy
Extended the kinematic range towards high rapidity and very low p_T

Λ analysis (selection)

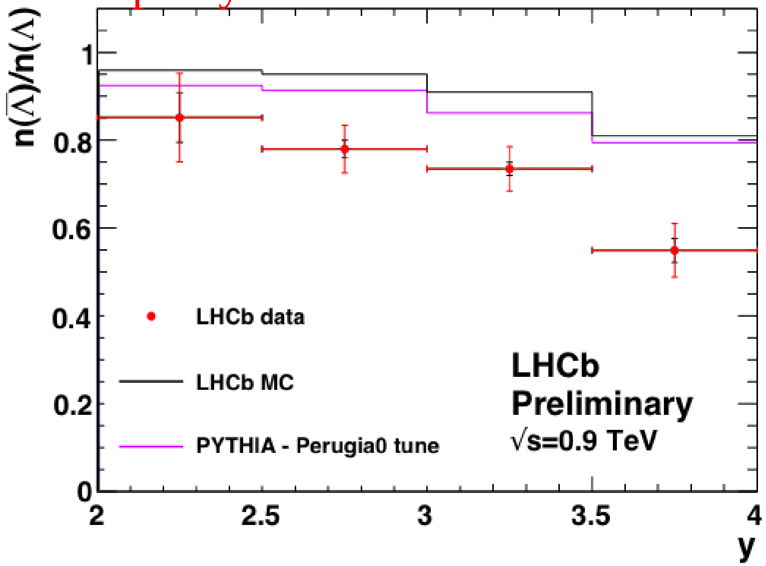


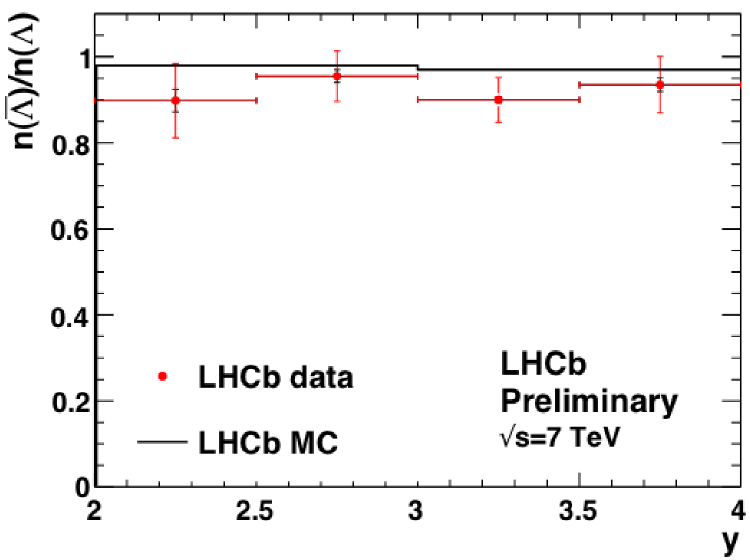
- analysis made with long tracks only
- no particle id. used
- pointing of the Λ to the primary vertex required

Λ analysis (result)

Efficiency corrected ratio,

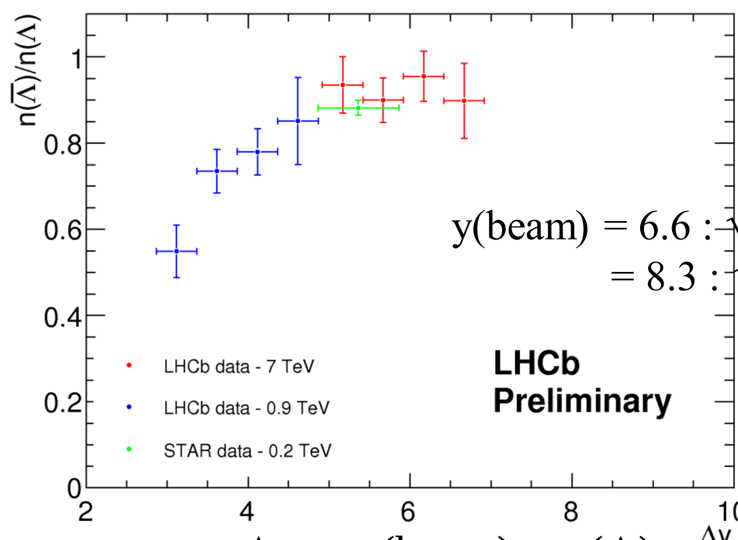
in rapidity bins:





- At 0.9 TeV:
  - Perugia tunes do not include diffraction
  - LHCb tunes include diffraction
  - Tends to be lower than PYTHIA Perugia0 tune and LHCb tune, lower with large y
- At 7 TeV:
  - ratio larger, ~ flat in y
  - prediction in fair agreement

Results at both beam energies compared in *Δy show consistency, also with other experiments*

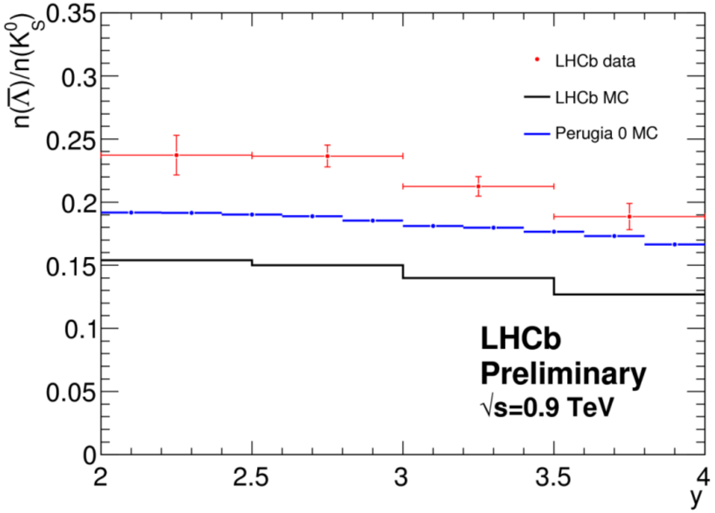


y(beam) = 6.6 : √s = 0.9 TeV

= 8.3 : √s = 7 TeV

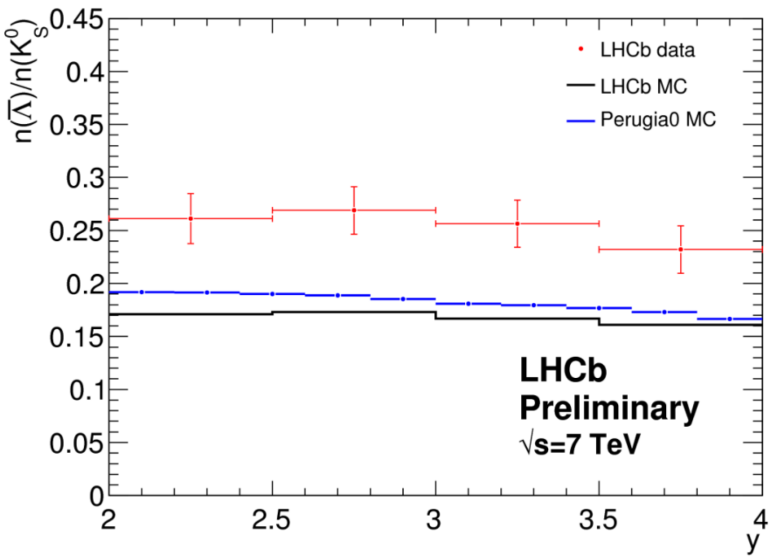
$\Delta y = y(\text{beam}) - y(\Lambda)$

$\bar{\Lambda}/K_s$ and $\bar{p}/p$ (preliminary result)



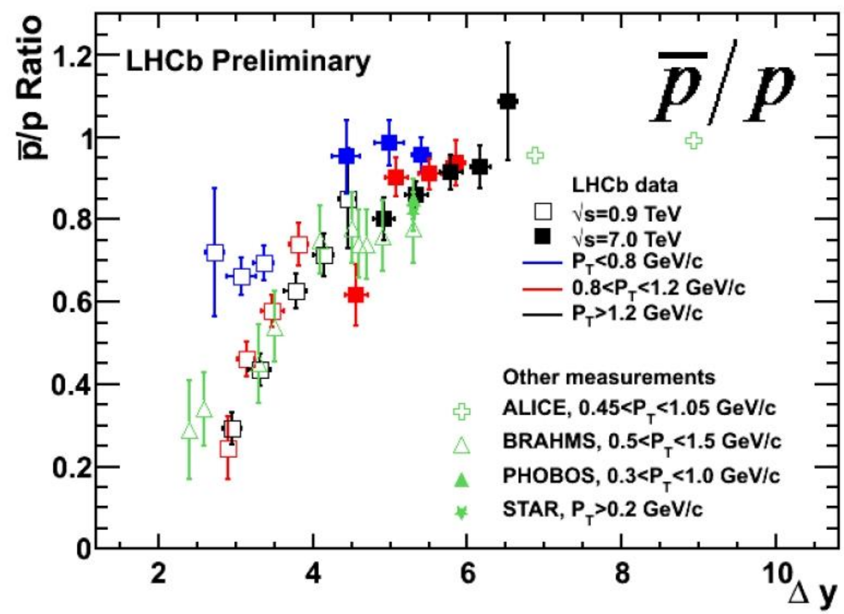
Baryon vs meson production ratio with *pp* collision at $\sqrt{s}$ = 0.9 & 7 TeV

- Baryon suppression in hadronisation significantly lower than predicted



$\bar{p}$/p production ratio with *pp* collision at $\sqrt{s}$ = 0.9 & 7 TeV

Results at both beam energies compared in *Δy show consistency, also with other experiments*



J/ψ analysis (strategy)

Based on a sample collected between April and June 2010

measurement of the production cross section both for prompt J/ψ and for J/ψ from b

Observed signal decays

$$\sigma = \frac{N(J/\psi \to \mu\mu)}{L \times \varepsilon \times Br(J/\psi \to \mu\mu)}$$

Integrated luminosity

branching fraction

J/ψ detection efficiency

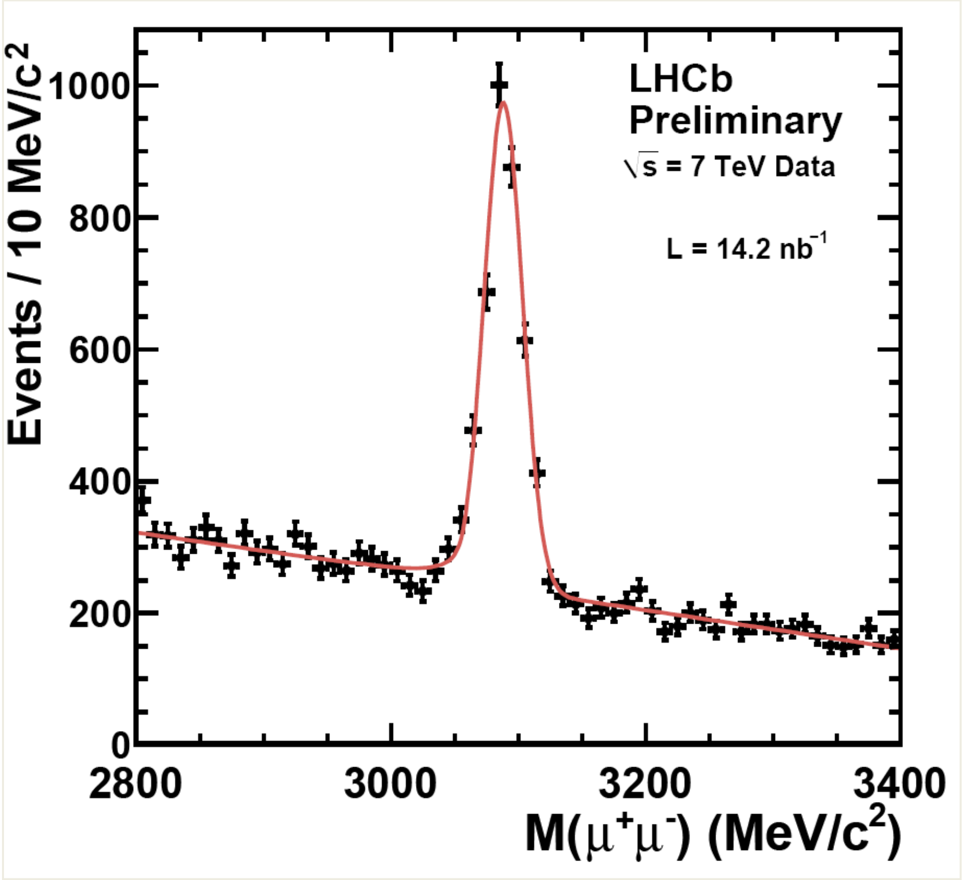
Luminosity used for the cross section measurement : $(14.15 \pm 1.42)\ nb^{-1}$

Measure the J/ψ production in bins of transverse momentum (p_T)and rapidity (y): $2.5 < y < 4.0$ and $0 < p_T < 10$ GeV/c

J/ψ analysis (selection)

Mass fit with Crystal Ball function and 1st order polynomial for background

$$f(x;\mu,\sigma_M,\alpha,n) = \begin{cases} \dfrac{\left(\frac{n}{|\alpha|}\right)^n e^{-\frac{1}{2}\alpha^2}}{\left(\frac{n}{|\alpha|} - |\alpha| - \frac{x-\mu}{\sigma_M}\right)^n} & \dfrac{x-\mu}{\sigma_M} < -|\alpha| \\ \exp\left(-\dfrac{1}{2}\left(\dfrac{x-\mu}{\sigma_M}\right)^2\right) & \dfrac{x-\mu}{\sigma_M} > -|\alpha| \end{cases}$$



Fit results (2.5<y<4, p_T<10 GeV/c):

Signal = **2872 ± 73**

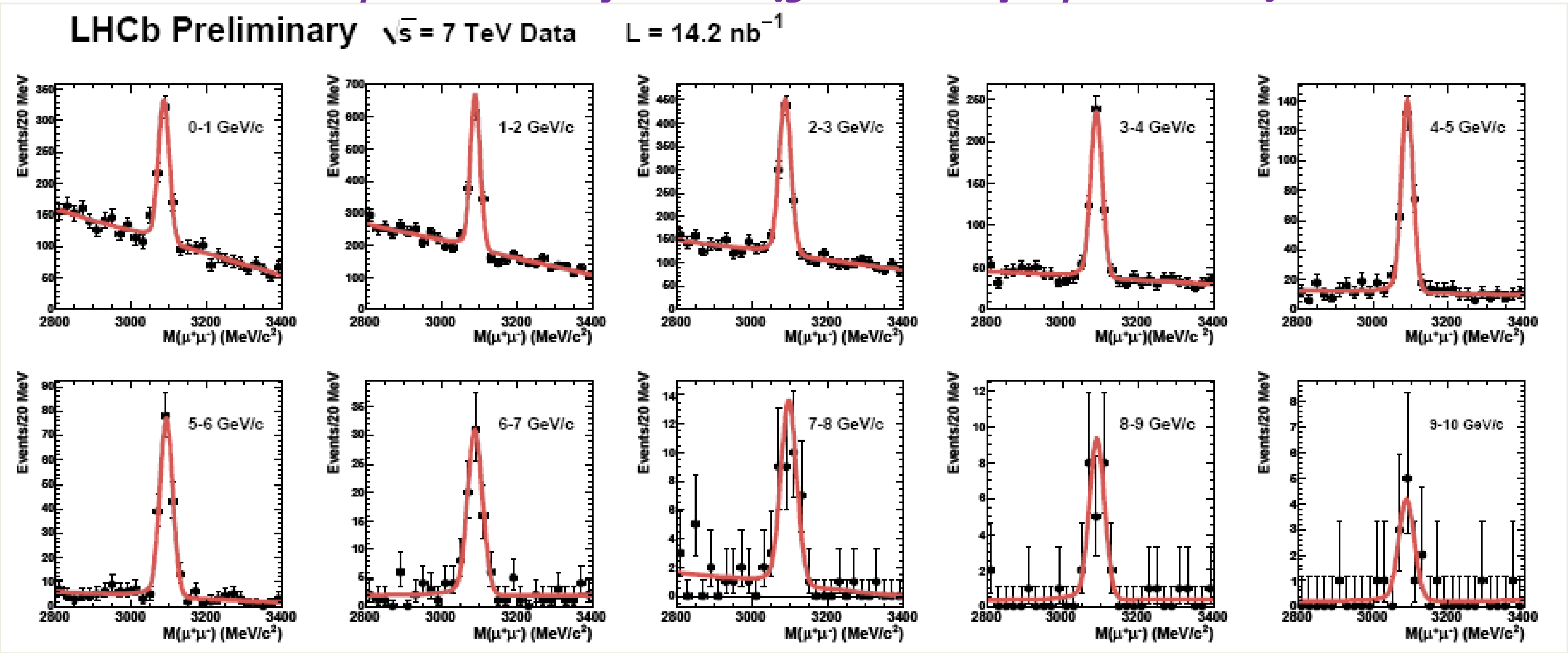
S/B = **1.3**

Mean = **(3088 ± 0.4) MeV/c^2**

σ = **(15.0 ± 0.4) MeV/c^2**

(with preliminary alignment)

J/ψ analysis (fit in p_T bins)



p_T (GeV/c)	total	0 – 1	1 – 2	2 – 3	3 – 4	4 – 5
N	2872 ± 73	427 ± 31	823 ± 40	687 ± 36	398 ± 24	259 ± 18
B	2273 ± 166	520 ± 61	907 ± 79	568 ± 64	182 ± 36	55 ± 20
σ_M (MeV/c^2)	15.0 ± 0.4	14.7 ± 1.2	13.1 ± 0.7	16.0 ± 0.9	15.6 ± 1.0	15.5 ± 1.1
p_T (GeV/c)		5 – 6	6 – 7	7 – 8	8 – 9	9 – 10
N		163 ± 13	74 ± 9	34 ± 6	23 ± 5	10 ± 3
B		18 ± 11	9 ± 8	4 ± 5	1 ± 3	0 ± 2
σ_M (MeV/c^2)		17.2 ± 1.3	19.9 ± 2.5	21.0 ± 1.3	20.0 ± 3.1	21.0 ± 26.2

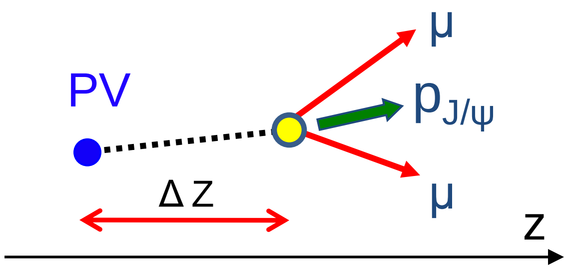
J/ψ analysis (prompt/detached)

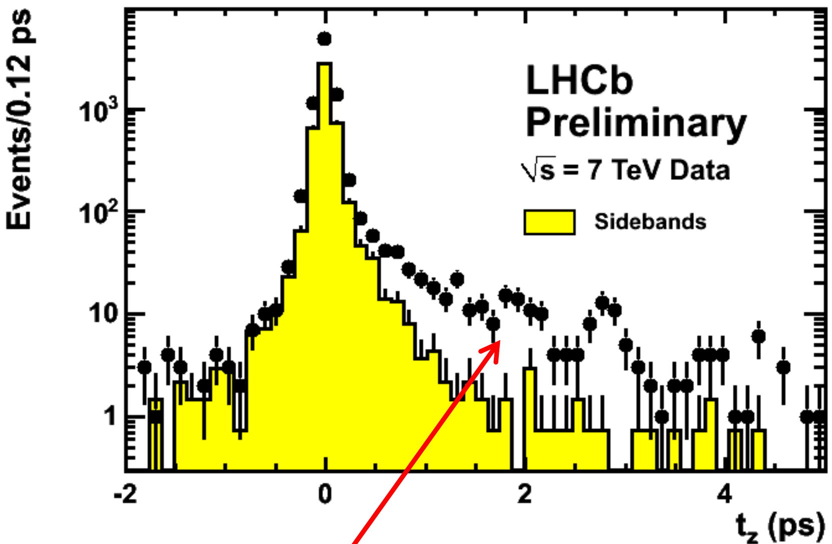
$b\bar{b}$ events identified via detached vertex analysis

t_Z distribution – pseudo-proper time

$$t_z = \left(z_{J/\psi} - z_{PV}\right)\frac{m_{J/\psi}}{p_{z,J/\psi}}$$

combined fit to mass and pseudo proper-time t_z allows separation of prompt J/ψ and $b \rightarrow J/\psi$ components





make measurement of $b \rightarrow J/\psi X$ production:

→ important for initial tuning of b spectrum in LHCb Monte Carlo

Asymmetric distribution with clear long-lived signal from b-hadron decays

Extract f_b = fraction of J/ψ from b decays with an unbinned maximum likelihood fit to t_z

J/ψ analysis (prompt/detached)

- n_p ,n_b ,n_{bkg} : number of prompt J/ψ, J/ψ from b and background events
- μ, σ_1 , σ_2 , β: mean, resolutions and fraction of the 2 gaussians for the resolution
- τ_b : b pseudo-life time
- Background from invariant mass sidebands

Fit results :

n_p = **2527 ± 74**

n_b = **316 ± 24**

n_{bkg} = **28500 ± 180**

μ = **(-8.5±1.5) fs**

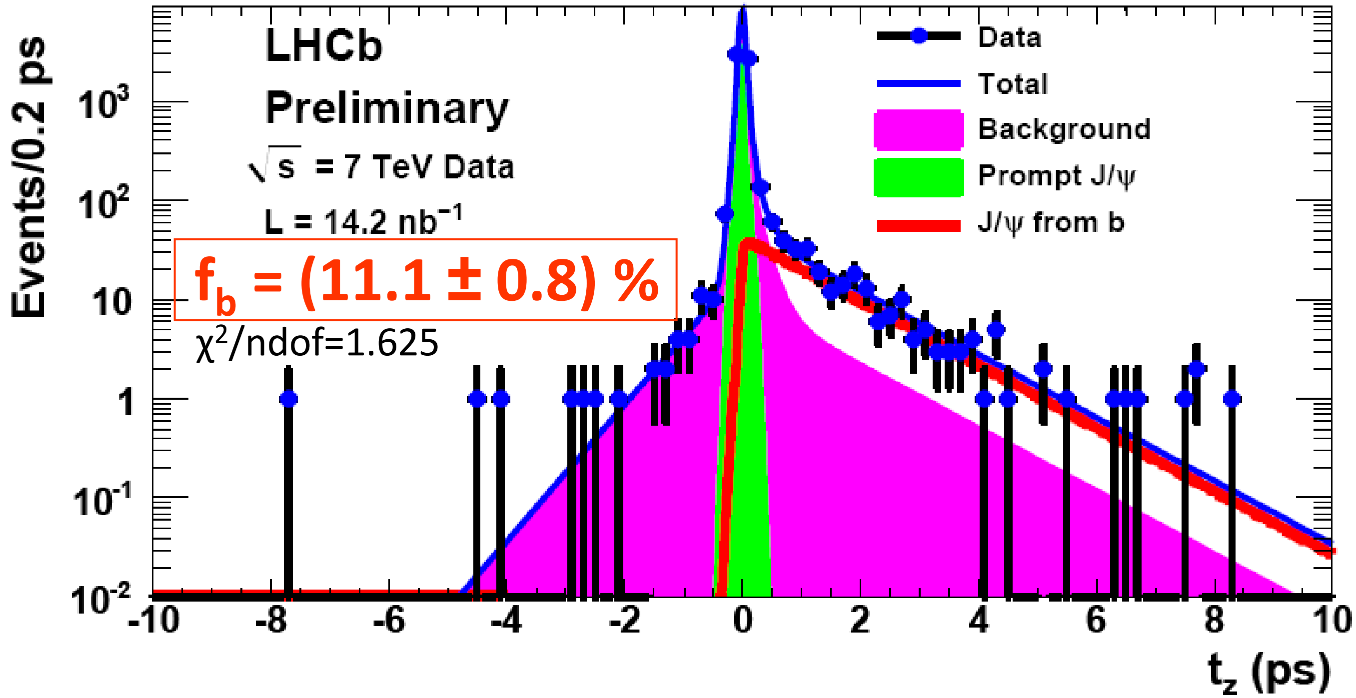
σ_1 = **(111±13) fs**

σ_2 = **(40 ±3) fs**

β = **0.26 ± 0.06**

τ_b = **(1.35 ± 0.10) ps**

$f_b = n_b/(n_p+n_b)$ = (11.1 ± 0.8)%



A crosscheck with a binned fit gives consistent results

Statistical errors only

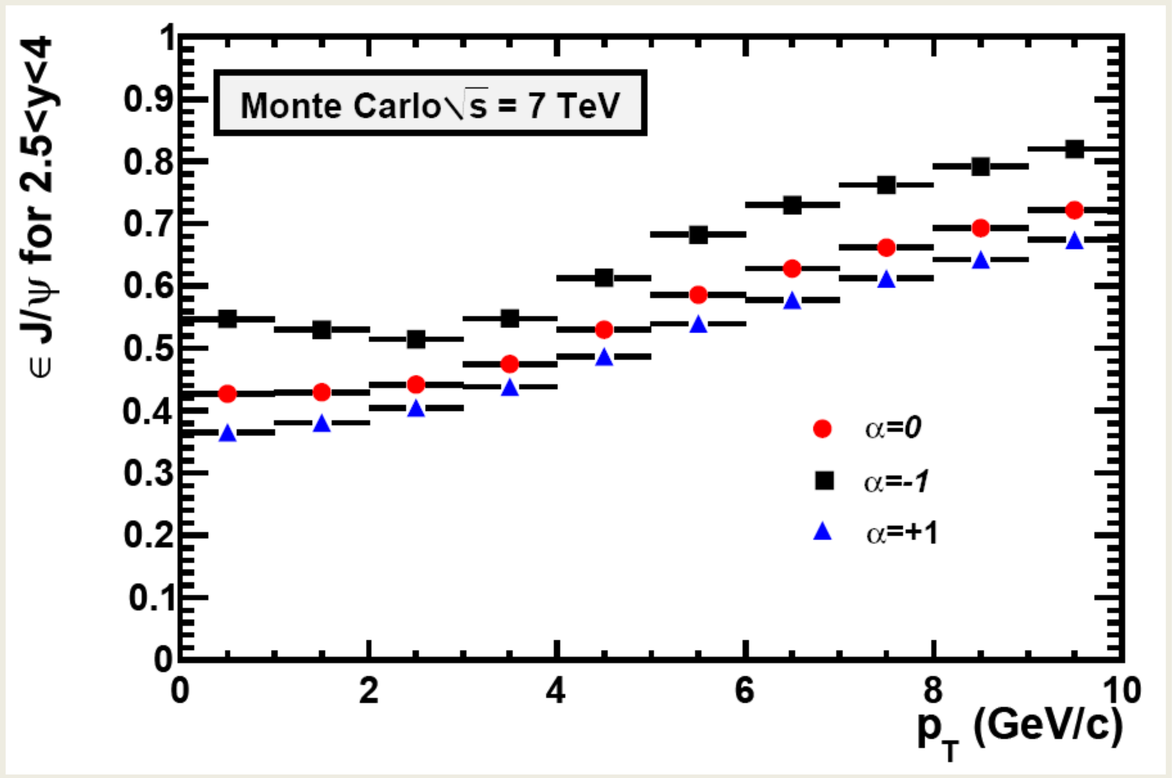
J/ψ analysis (efficiency)

Sample fully simulated inclusive J/ψ is used to estimate the total efficiency ε in each p_T bin integrated over rapidity range ($2.5 < y < 4$)

Efficiency includes the geometrical acceptance, the detection efficiency, the reconstruction efficiency, the selection efficiency and trigger efficiency

ε depends strongly on the polarization ($\alpha = \lambda_\theta = 0, -1, +1$ angular distribution in the helicity frame)

Deviation of σ(α=+1, -1) wrt σ(α= 0) → systematic error



With more statistics, a direct measurement of the polarization with full angular analysis, in different reference frames and in bins of y and p_T is foreseen

J/ψ analysis (systematic uncert.)

- Systematic errors mainly coming from the discrepancy data/MC. Dominant contributions from trigger and tracking efficiencies.
- Large systematic uncertainty from luminosity
- The p_T spectrum of J/ψ from b is not measured (low statistics) $\Rightarrow$ additional systematic errors on σ due to ε dependence on p_T

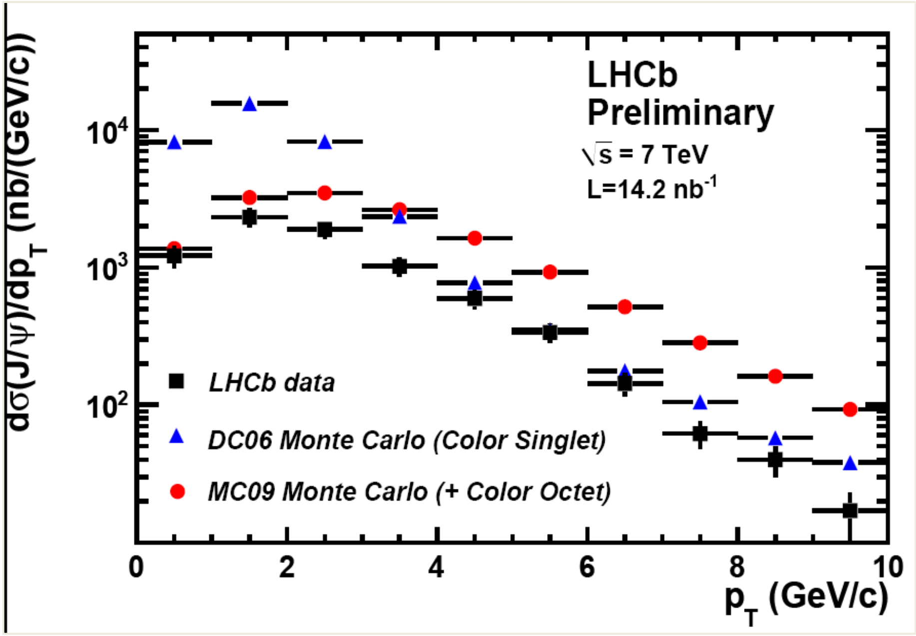
Quantity	Systematic error	Comment
Trigger	2.8 % to 9.4 %	Correlated between bins
Muon identification	2.5%	Correlated between bins
Tracking efficiency	8%	Correlated between bins
Track χ^2	2%	Correlated between bins
Vertexing	1%	Correlated between bins
Bin size	1.3% to 3.9%	Bin dependent
Inter-bin cross-feed	0.5%	Correlated between bins (not applied to the total cross section)
Mass fit procedure	3%	Correlated between bins
Loss of events due to the radiative tail	1%	Correlated between bins
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	1%	Correlated between bins
Luminosity	10%	Correlated between bins
b momentum spectrum	4 %	Applies only to J/ψ from b cross section
b hadronization fractions	2%	Applies only to extrapolation of $b\bar{b}$ cross section
$\mathcal{B}(b \to J/\psi X)$	9%	Applies only to extrapolation of $b\bar{b}$ cross section

J/ψ analysis (preliminary results)

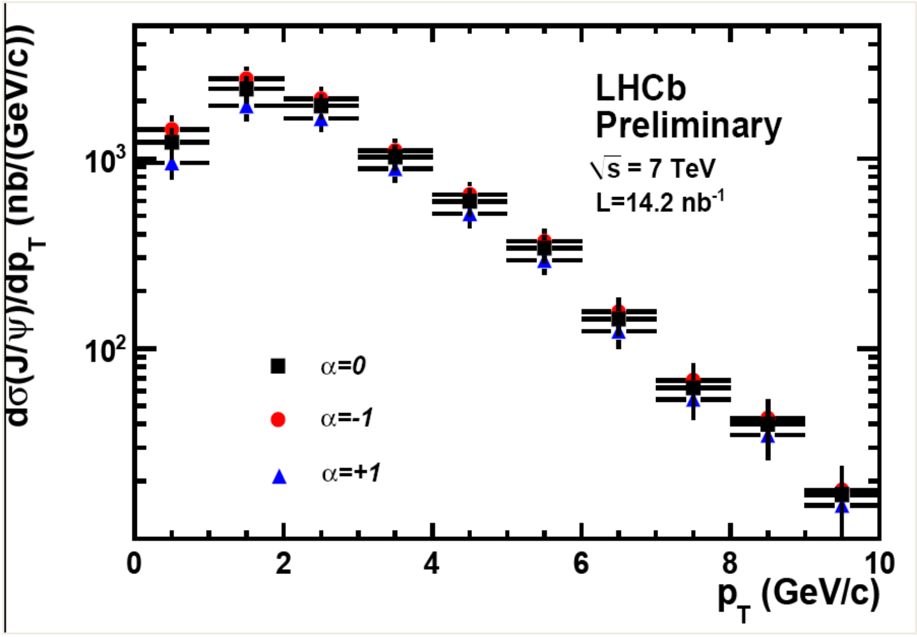
- σ(incl. J/ψ, $p_T^{J/\psi} < 10$ GeV/c, $2.5 < y^{J/\psi} < 4$) = $(7.65 \pm 0.19 \pm 1.10^{+0.87}_{-1.27})$ μb

Uncertainty from polarization

- $d\sigma/dp_T$(incl. J/ψ, $2.5 < y^{J/\psi} < 4$):



Scale and shapes not well described by either CS or CO models as implemented in LHCb Pythia



Different polarization hypotheses

- σ(J/ψ from b, $p_T^{J/\psi} < 10$ GeV/c, $2.5 < y^{J/\psi} < 4$) = $(0.81 \pm 0.06 \pm 0.13)$ μb

J/ψ analysis (extrapolation)

- if one extrapolate

$$\sigma(b \rightarrow J/\psi\ X) \quad \rightarrow \quad \sigma(b \rightarrow H_b\ X)$$

cross section for producing a single b (or bar-b) flavored hadron in the pseudo-rapidity region $2 < \eta < 6$

$$\sigma(b \rightarrow H_b\ X, 2 < \eta(H_b) < 6) = 84.5 \pm 6.3 \pm 15.6\ \mu b$$

Extrapolation with PYTHIA 6.4, EvtGen

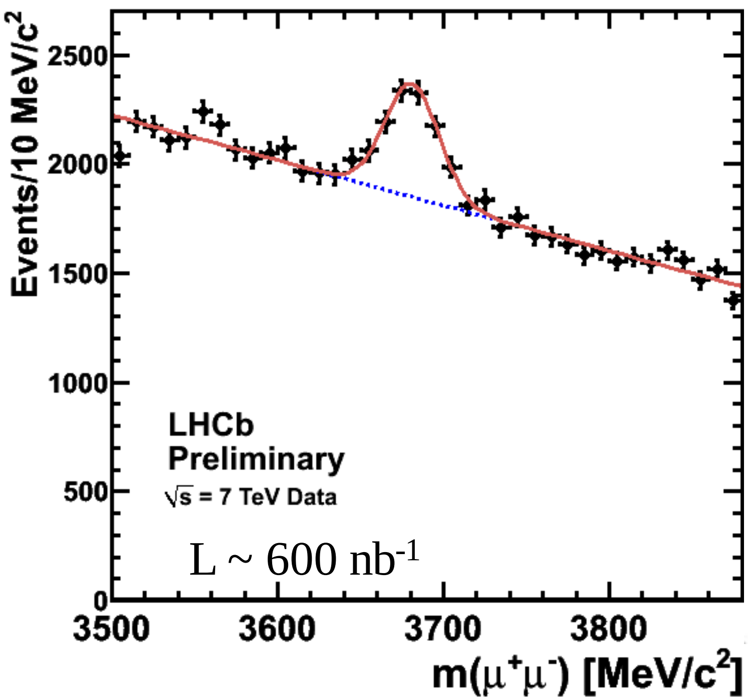
- assume LEP fractions for fragmentation into b-hadrons

- total bb production cross section at $\sqrt{s} = 7$ TeV

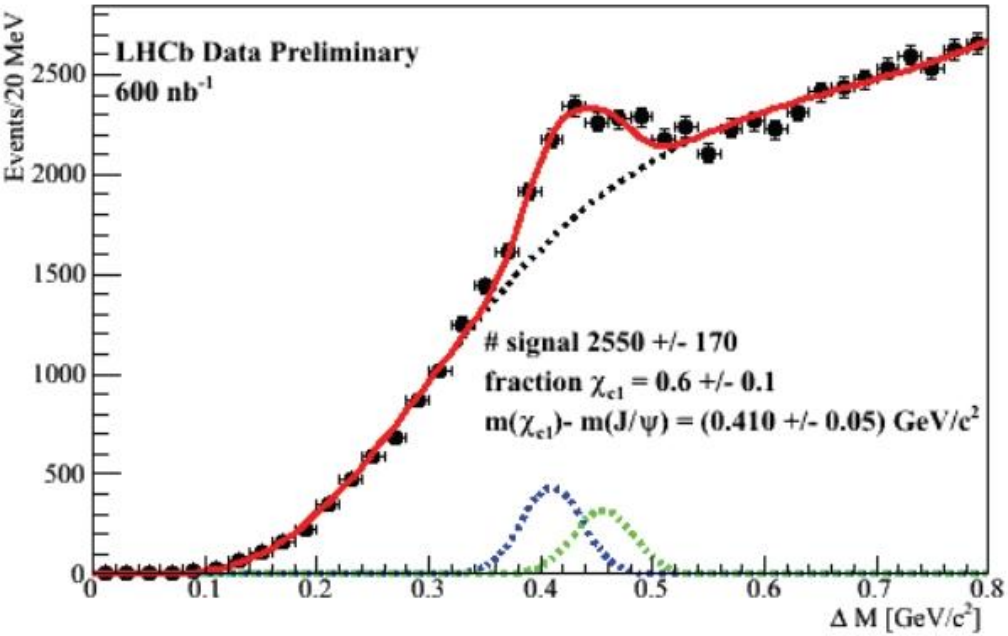
$$\sigma(pp \rightarrow bb\ X) = 319 \pm 24 \pm 59\ \mu b$$

ψ (2S) and χ_c (signal)

M = 3681.1 +- 1.2 MeV/c^2
σ = 16.3 +- 1.3 MeV/c^2
N = 2117 +-153



$\chi_c \to J/\psi\ (\to \mu^+ \mu^-)\ \gamma$
ΔM = 0.41 +- 0.05 GeV/c^2
N = 2550 +- 170



$\Delta M = M(\mu^+ \mu^- \gamma) - M(\mu^+ \mu^-)$

Open charm production (strategy)

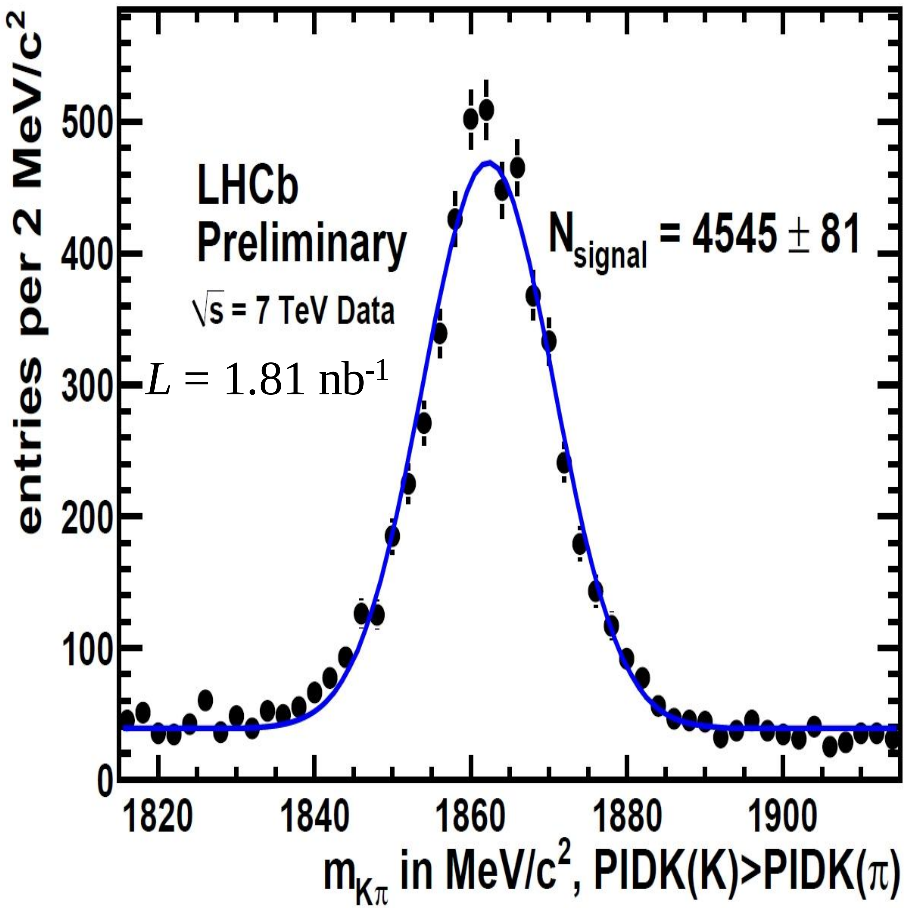
Based on a sample collected using the integrated luminosity of 1.81 nb^{-1}

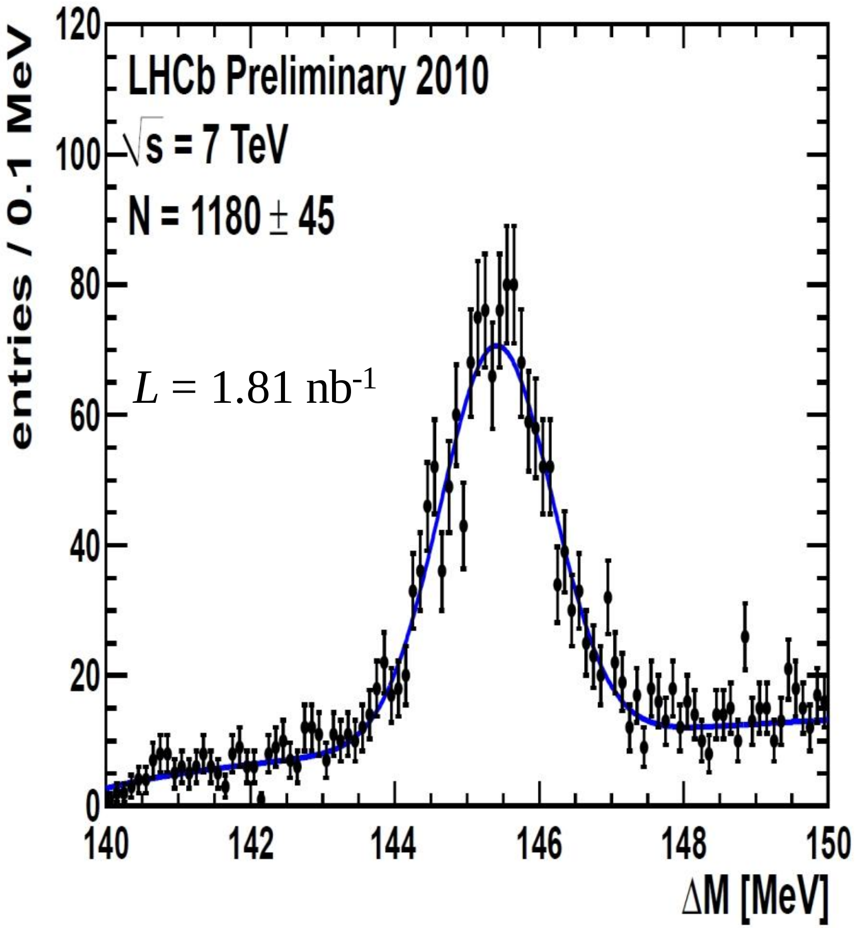
Comparison to QCD predictions of the shapes of production cross-sections of $D^0/\bar{D}^0$, $D^{*\pm}$, $D^{\pm}$ and $D^{\pm}_s$ measured at LHCb in bins of meson transverse momentum (p_T) and rapidity (y)

Signal yields has determined in bins: ($0 < p_T < 8$ GeV/c) and ($2 < y < 5$)

Open charm production (signal)

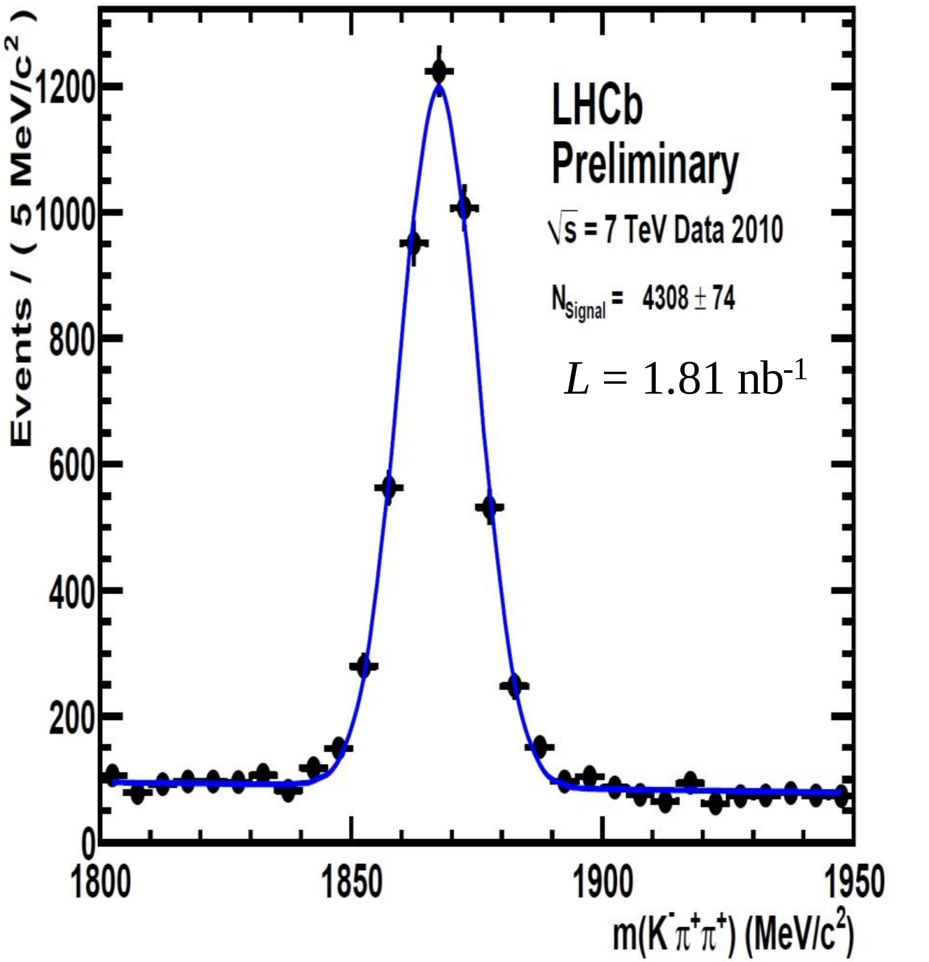
$D^0 \rightarrow K^- \pi^+$ and $D^{*+} \rightarrow (D^0 \rightarrow K^- \pi^+) \pi^+$

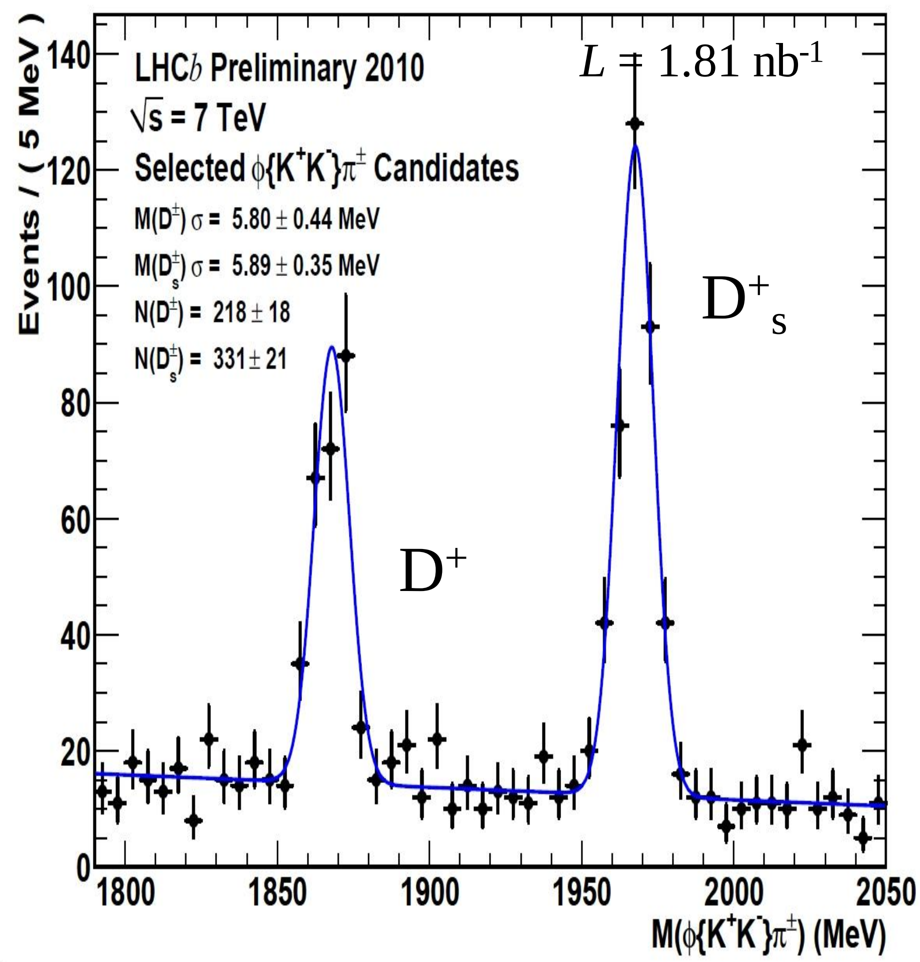




Open charm production (signal)

$D^+ \rightarrow K^- \pi^+ \pi^+$ and $D_s \rightarrow (\varphi \rightarrow K^- K^+) \pi^+$

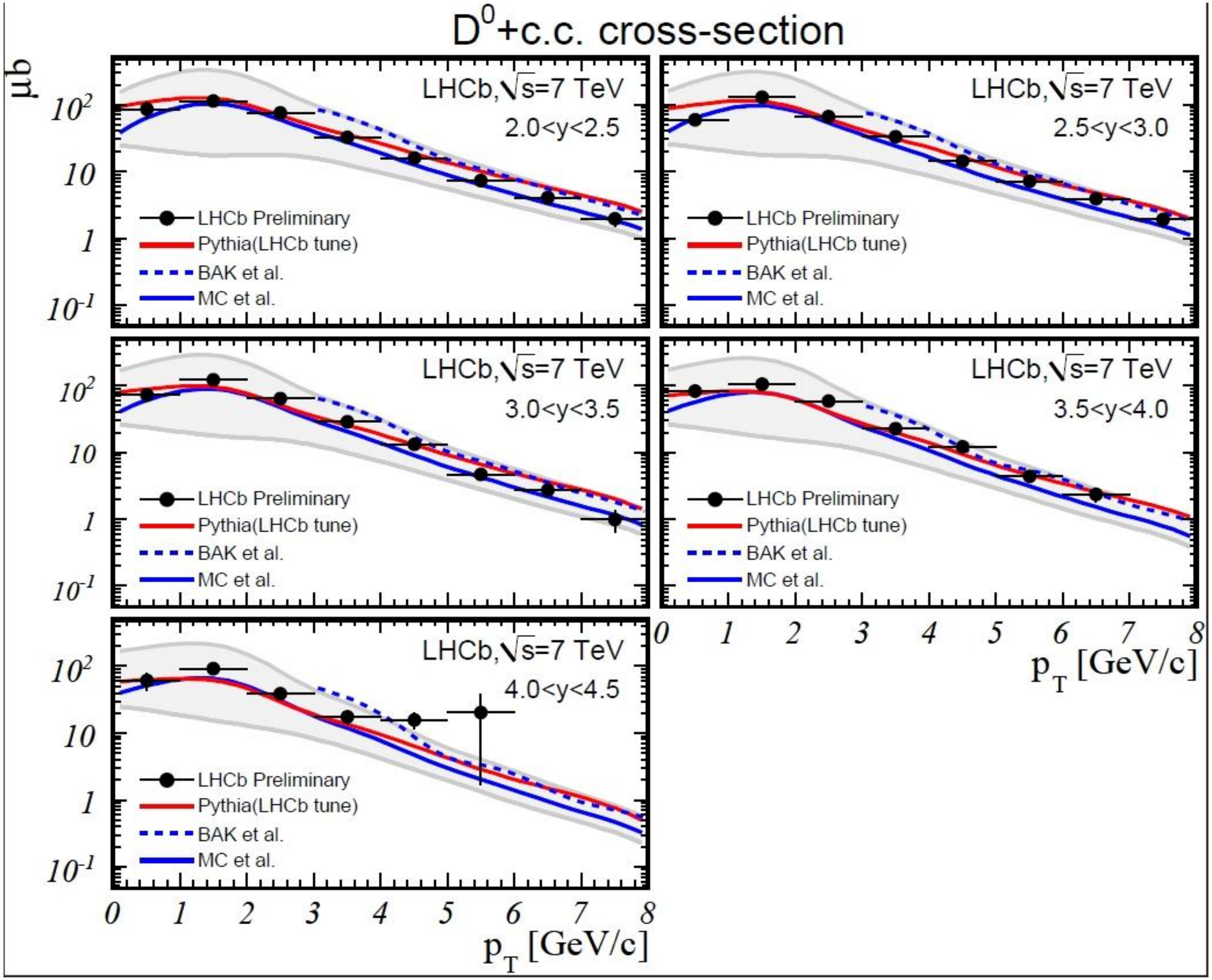




D^0 cross-section shape

Ration between measured and predicted charm cross-section

The errors are the total uncertainties with statistical and uncorrelated systematic errors added



Theory:

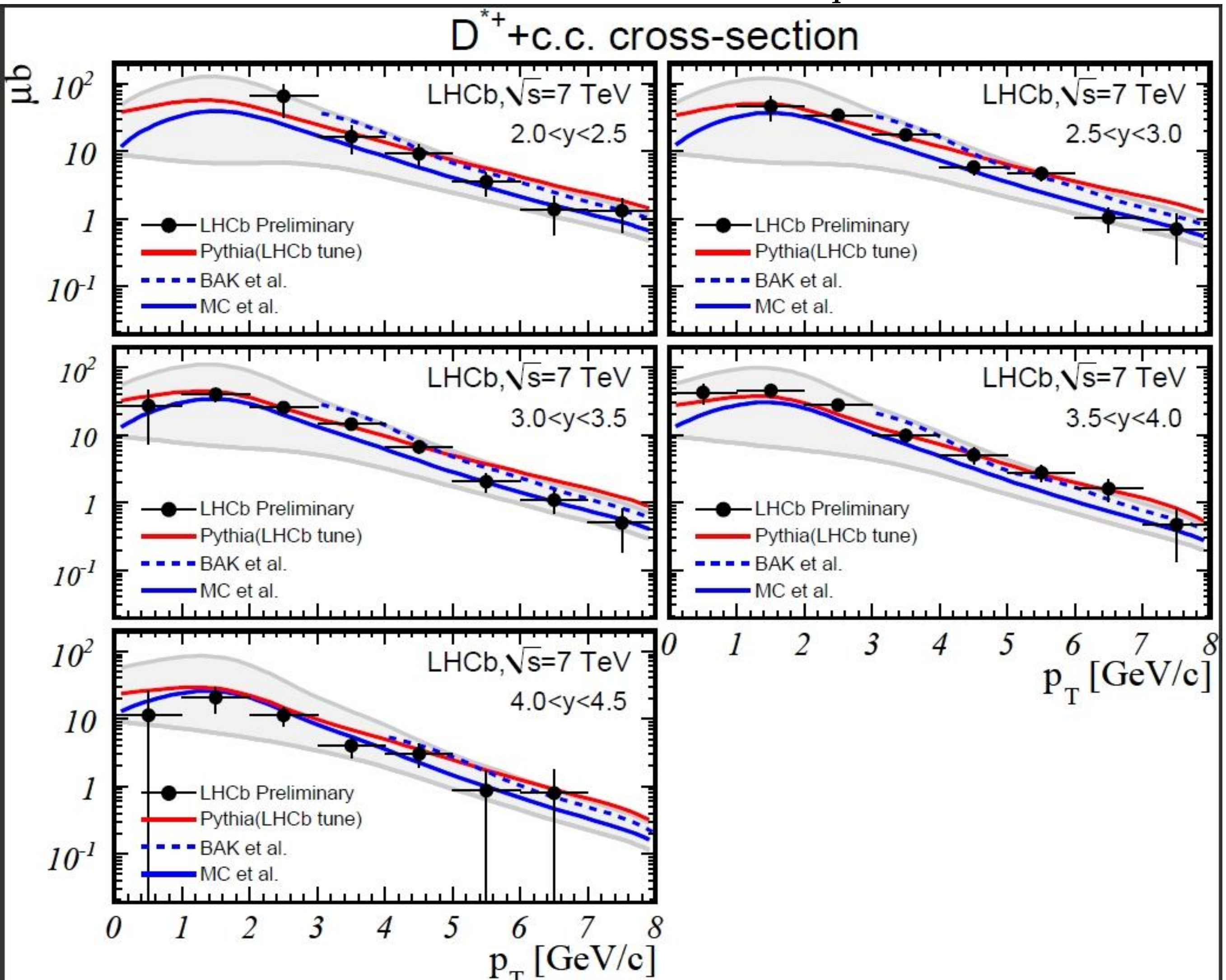
MC - Cacciary M., Frixione, S., Mangano, M., Nason, P. Ridolfi, G.

BAK - B.A.Kneihl, G.Kramer, I.Scheinbein, H.Spiesberger

Acceptable agreement with the theory predictions

$D^{*\pm}$ cross-section shape

Ration between measured and predicted charm cross-section
The errors are the total uncertainties with statistical and uncorrelated systematic errors added in quadrature



Theory:

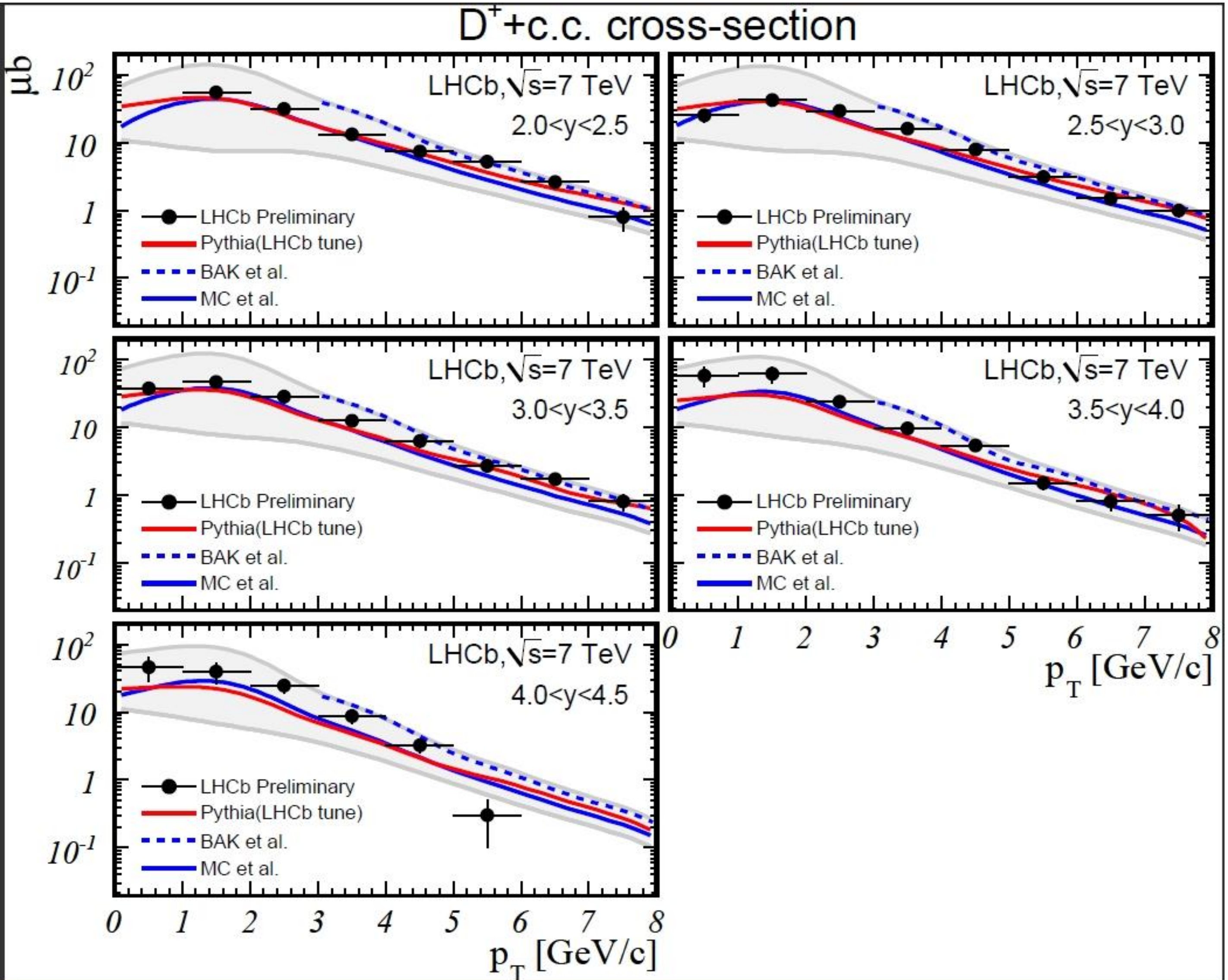
MC - Cacciary M., Frixione, S., Mangano, M., Nason, P. Ridolfi, G.

BAK - B.A.Kneihl, G.Kramer, I.Scheinbein, H.Spiesberger

Acceptable agreement with the theory predictions

D^+ cross-section shape

Ration between measured and predicted charm cross-section



Theory:

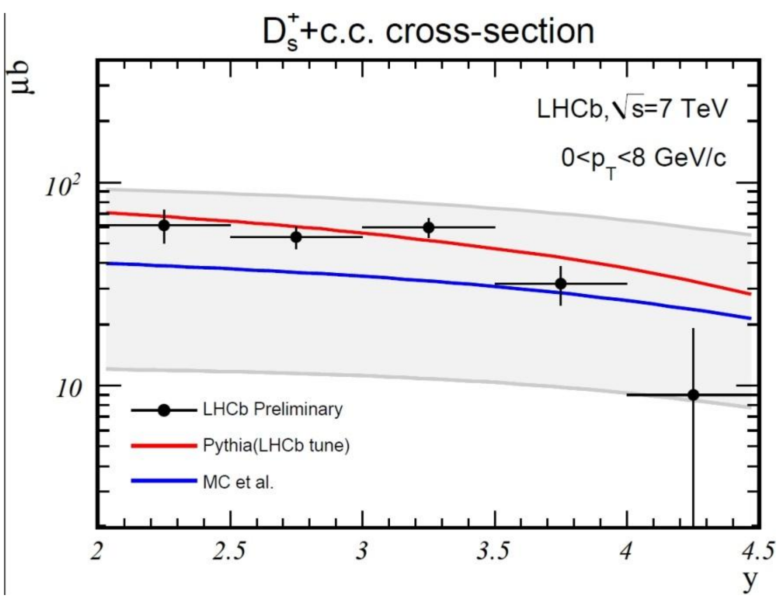
MC - Cacciary M., Frixione, S., Mangano, M., Nason, P. Ridolfi, G.

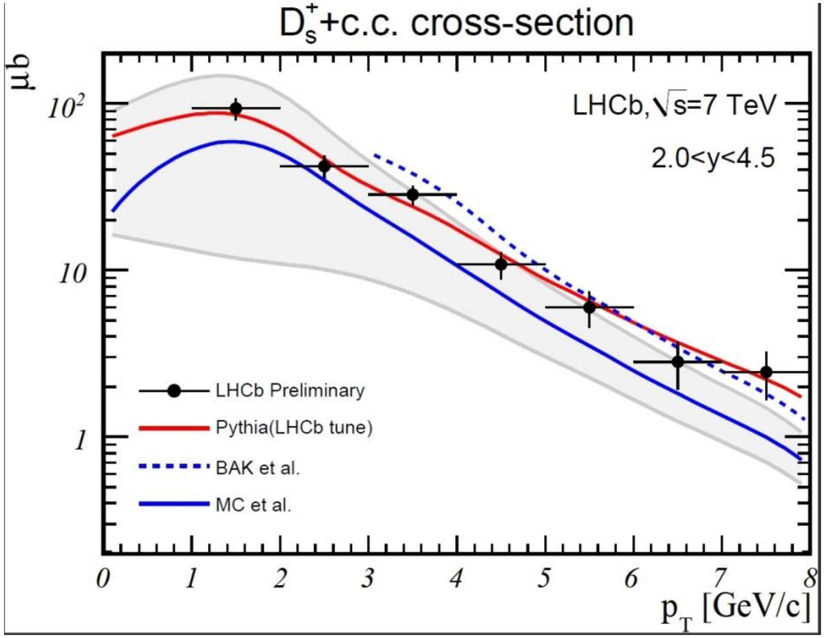
BAK - B.A.Kneihl, G.Kramer, I.Scheinbein, H.Spiesberger

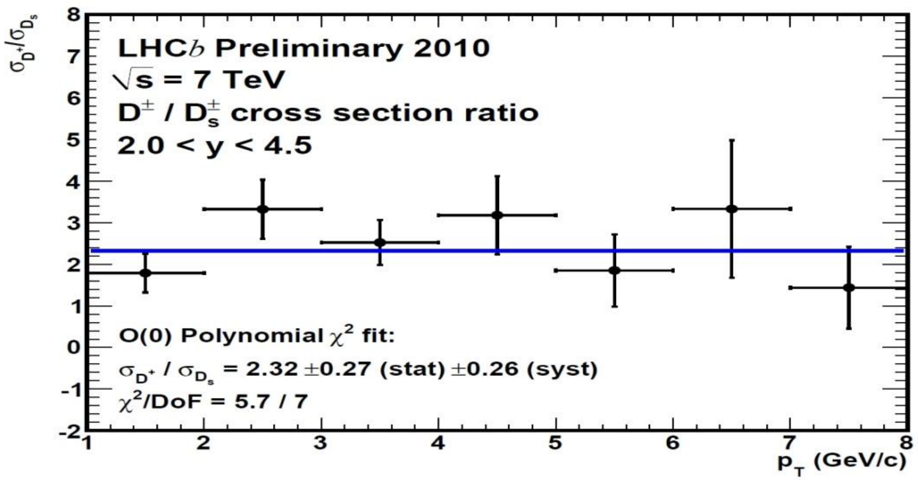
Acceptable agreement with the theory predictions

D_s cross-section

Ration between measured and predicted charm cross-section







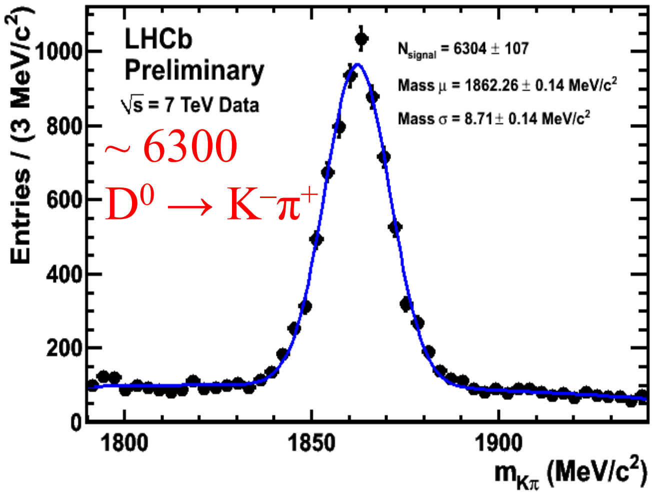
Measured cross-section ratio
(D^+ + c.c. / D^+_s + c.c) .
The measurements are integrated over rapidity in the range $2 < y < 4.5$

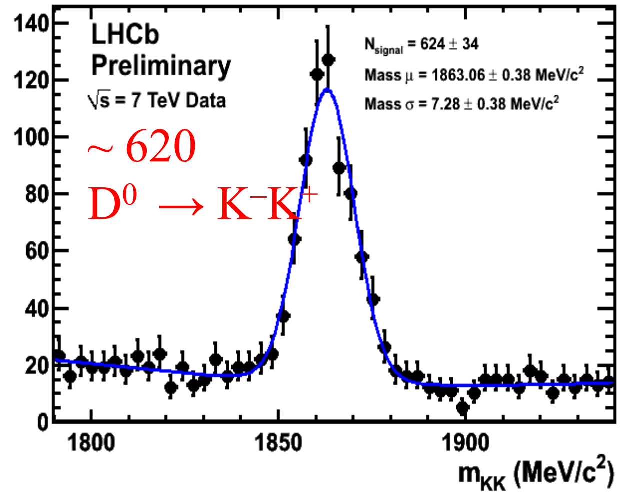
No p_T dependence is observed

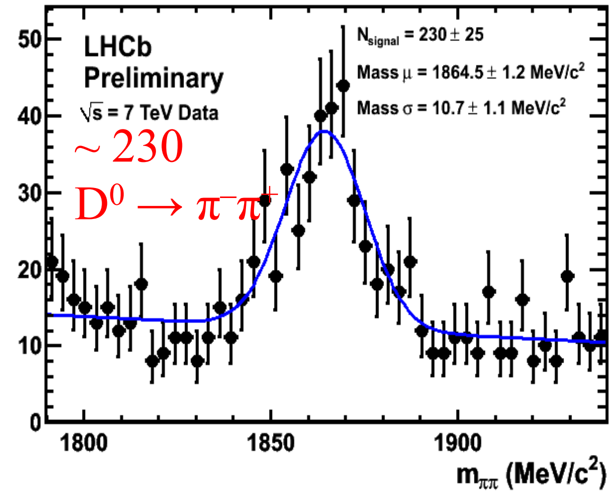
Ratio is consistent with the expectation
3.08 ± 0.70

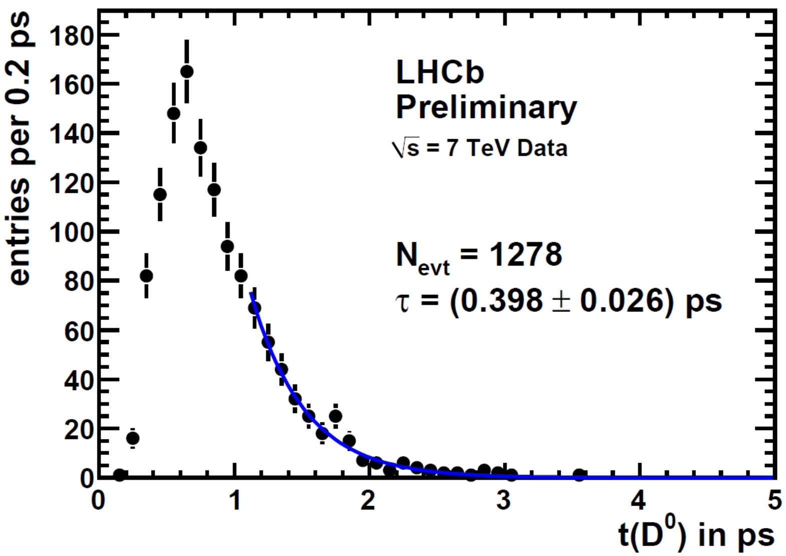
Open charm signals (2 body)

$\int L = 2.7\ nb^{-1}$









Check: measurement of D^0 lifetime

- ✓ use pure $D \to K\,\pi$ selection (S/B ~ 22)
- ✓ proper-time distribution with simple exponential
- ✓ use only tail, where the efficiency is constant

$$\tau(D^0) = 0.398 \pm 0.026\ \text{ps}$$

agrees with the known D^0 lifetime of
$\tau(D^0) = 0.4101 \pm 0.0015$ ps

Expect several million tagged $D^0 \to KK$ in 100 pb^{-1}

$\sigma(pp \rightarrow bbX)$ using $B \rightarrow D^0 X \mu\nu$

- Strategy

measure right-sign D^0 μ^- pairs using tracks not pointing at primary vertex, but which form a common vertex (use $D^0 \rightarrow K^- \pi^+$ decays)

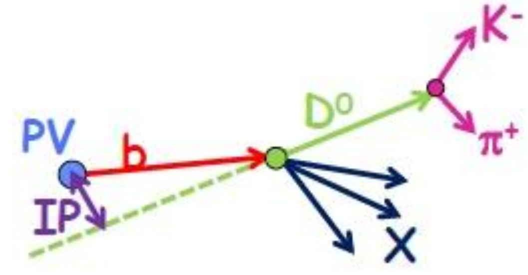
From PDG

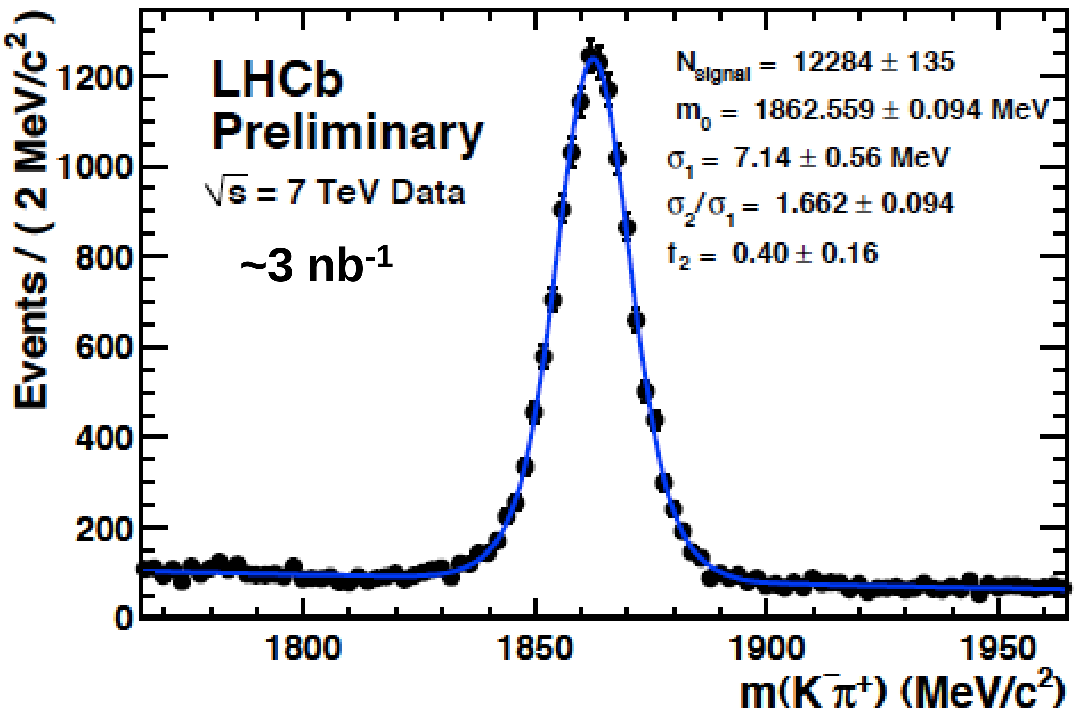
- b in B±/B0/Bs0/b-baryon admixture $\rightarrow D^0\, l\, \nu X$
- BR = 6.82% ±0.35%
- production fractions from Heavy Flavor Averaging Group
- $Br(D^0 \rightarrow K\,\pi) = (3.91 \pm 0.01)\%$

the two types of D^0 produced are “Prompt” (directly in a pp collision or from decay of heavier states) and D^0’s from b-decays. They can be separated statistically by examining the impact parameter (IP) with respect to the primary vertex

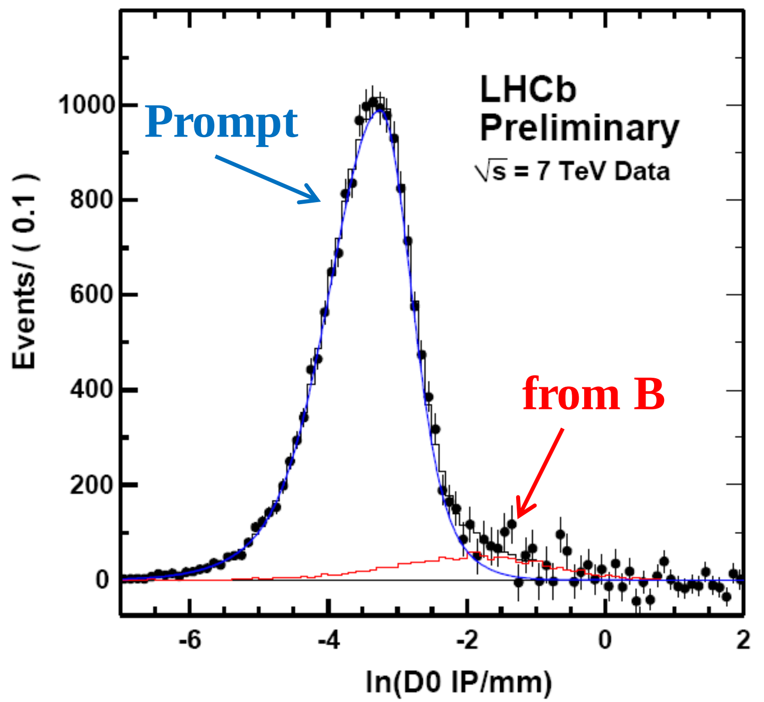
$\sigma(pp \to b\bar{b}X)$ using $B \to D^0 X \mu\nu$

if D^0 comes from a b-decay, then $K^-\pi+$ has a large impact parameter (IP) with respect to the pp vertex





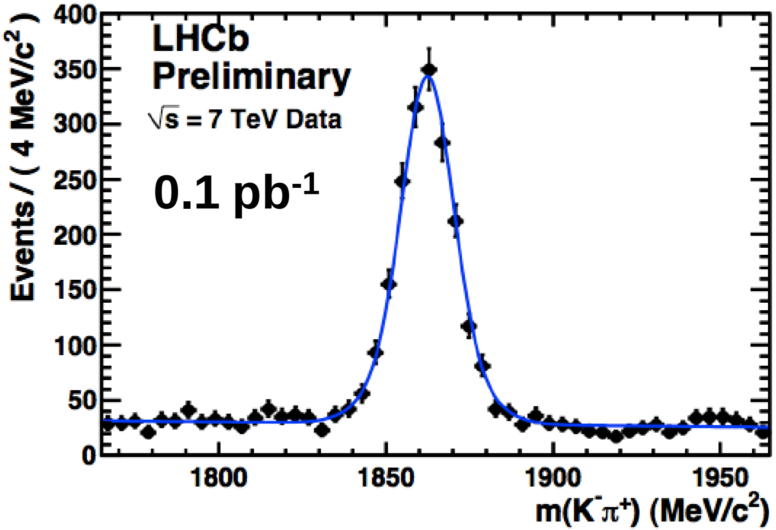
IP distribution used to separate Prompt and D^0's from b-decays

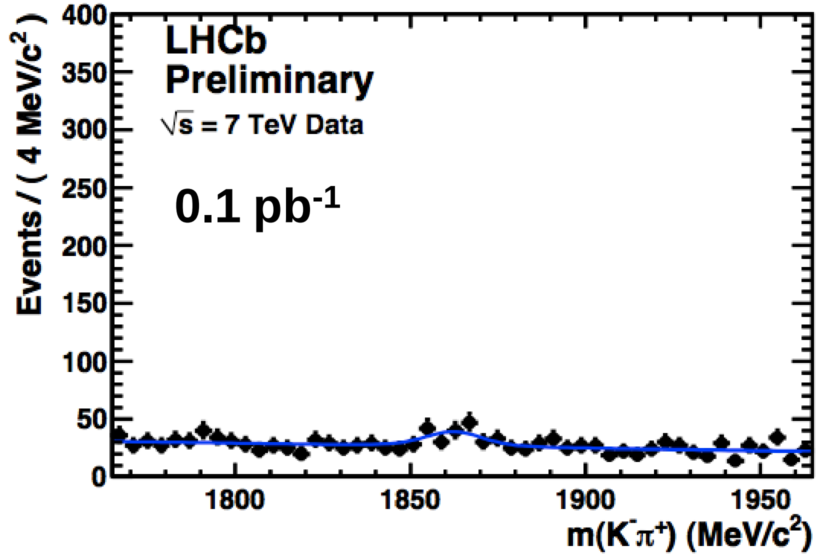


$\sigma(pp \rightarrow b\bar{b}X)$ using $B \rightarrow D^0 X \mu\nu$

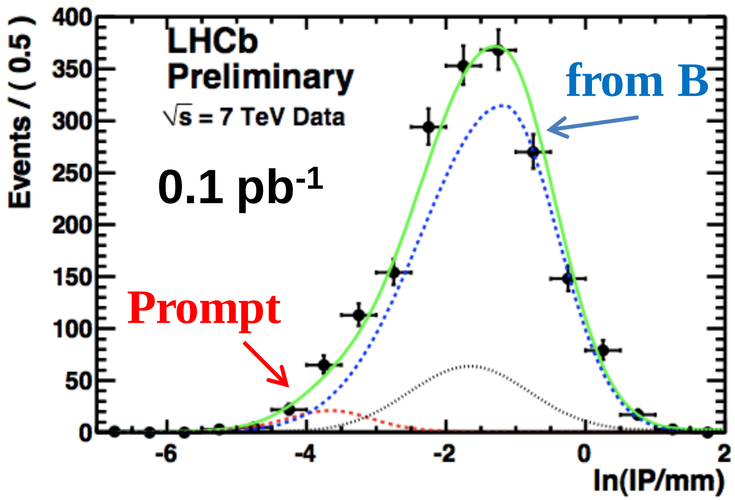
- combine M(Kπ) window with large IP($D^0\mu$) requirement
  - yield from unbinned log-likelihood fit simultaneously to M(Kπ) and ln(IP)

Right sign



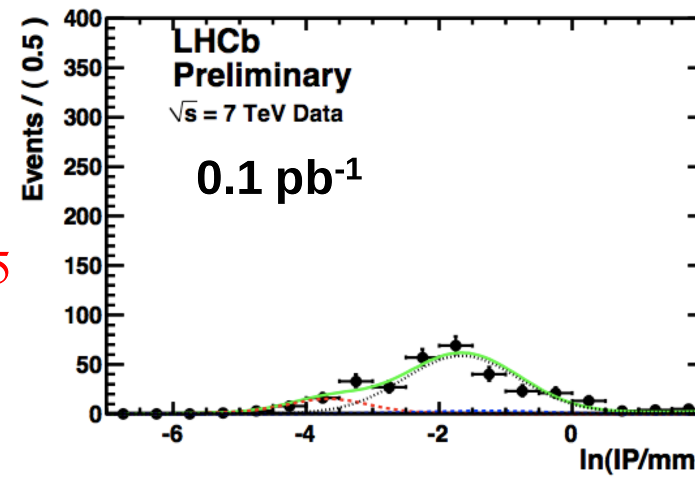


Wrong sign



1540 ↔ 45

D^0 from b

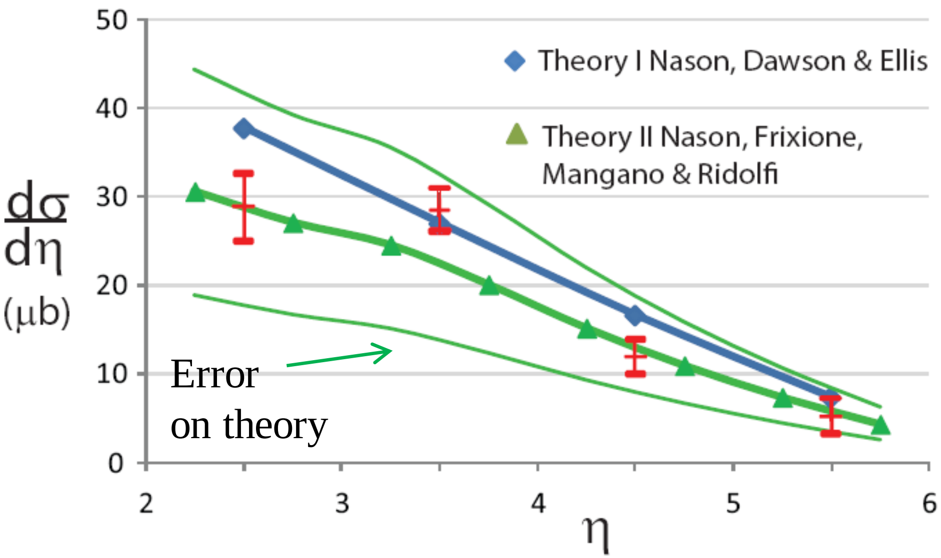


$\sigma(pp \to b\bar{b}X)$ using $B \to D^0 X \mu \nu$

$$\sigma = \frac{N(D^0\mu^- + \bar{D}^0\mu^+)}{L \times \varepsilon(acc, trigger, reco) \times 2}$$

dσ/dη in 4 bins of pseudo-rapidity in the LHCb acceptance 2<η<6

- η= -ln(θ/2), with θ determined from the pp and $D^0\mu$ vertices
- dominating systematic uncertainties from luminosity and tracking
- extrapolate to $\sigma(pp \to H_b X)$ (PYTHIA 6.4, LEP b-hadrons production fractions)



$\sigma(pp \to H_b X, 2 < \eta(H_b) < 6) = 74.9 \pm 5.3 \pm 12.9\ \mu b$

total $b\bar{b}$ production cross section at $\sqrt{s} = 7$ TeV (extrap. to full η)

$\sigma(pp \to b\bar{b}X) = 282 \pm 20 \pm 49\ \mu b$

LHCb: averaging b production results (preliminary)

All measurements of $\sigma(pp \rightarrow H_b X, 2 < \eta(H_b) < 6)$ are compatible:

- determine weighted average of J/ψ and $D^0\mu\nu X$ results
- use MC and Pythia to extrapolate to 4π

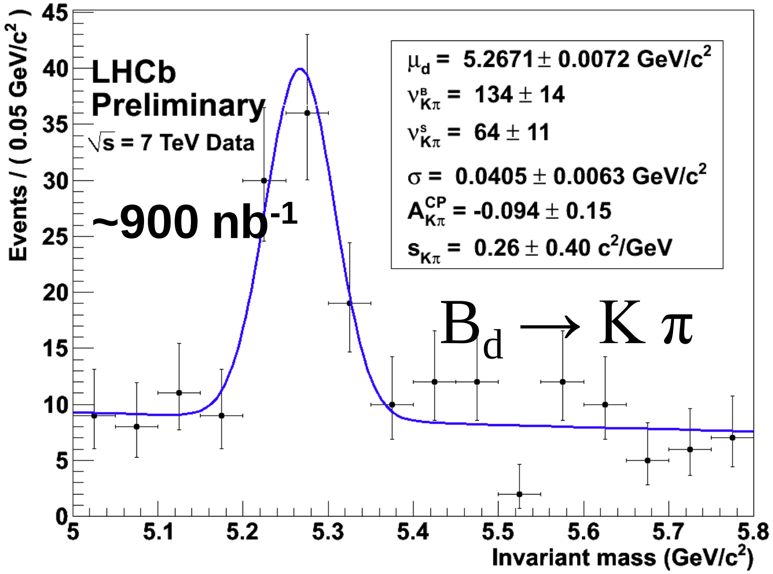
η	LHCb preliminary [μb]	Theory I	Theory II
2-6	$77.4 \pm 4.0 \pm 11.4$	89	70
all	$292 \pm 15 \pm 43$	332	254

Theory I: Nason, Dawson, Ellis
Theory II: Nason, Frixion, Mangano, Ridolfi

B-meson decays

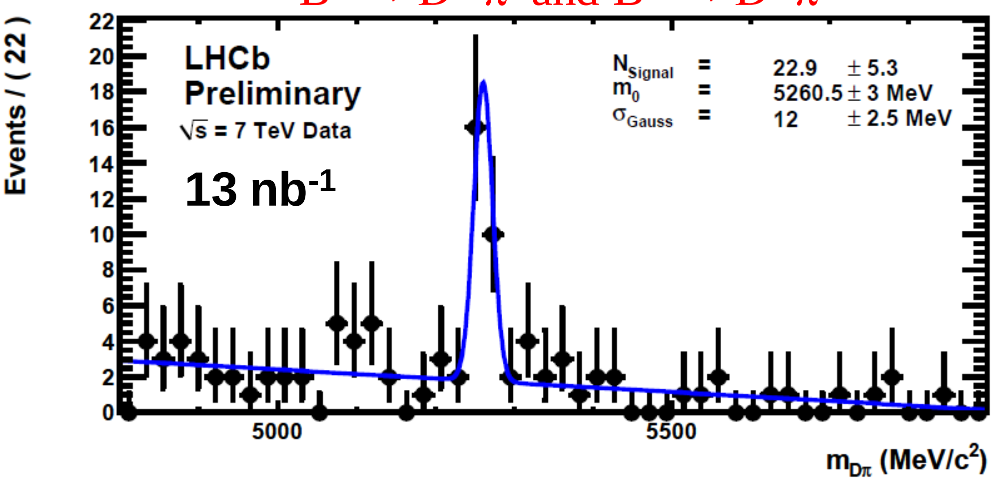
analysis of fully reconstructed B-decays advancing by the day

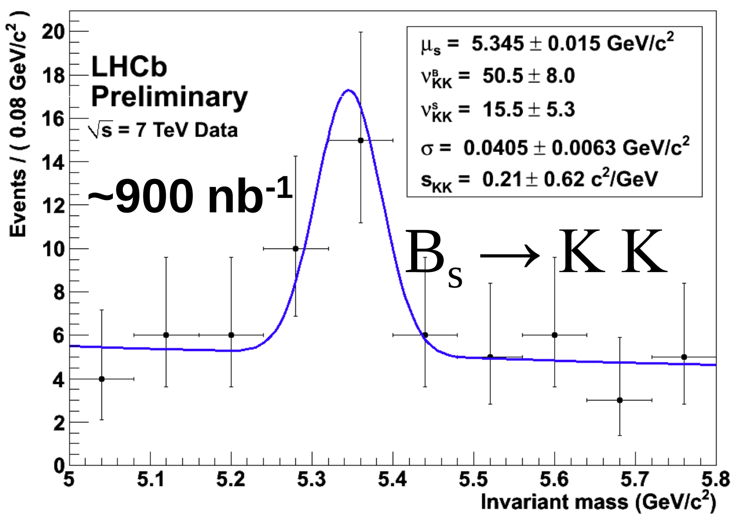
- integrated luminosity growing very fast
- event yields in line with MC expectations
- good mass resolution



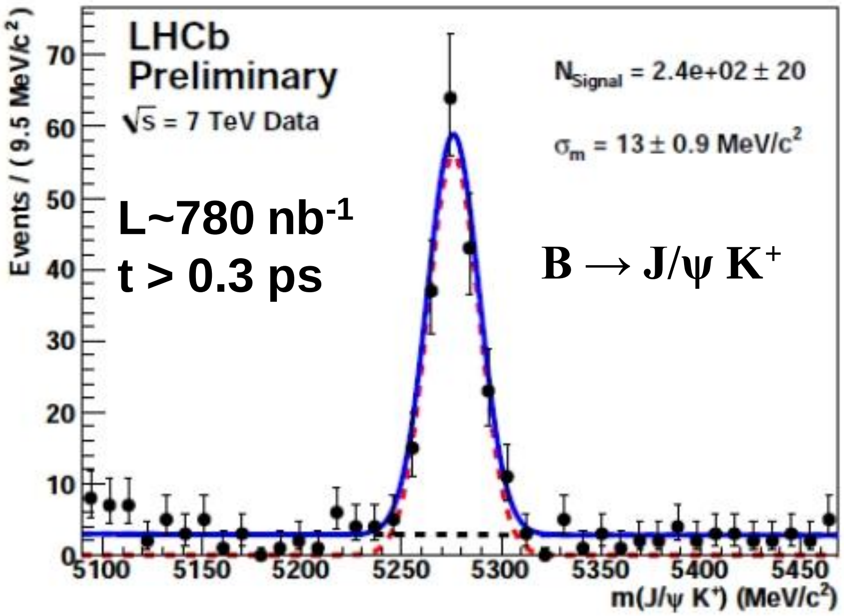
First fully reconstructed B-decays

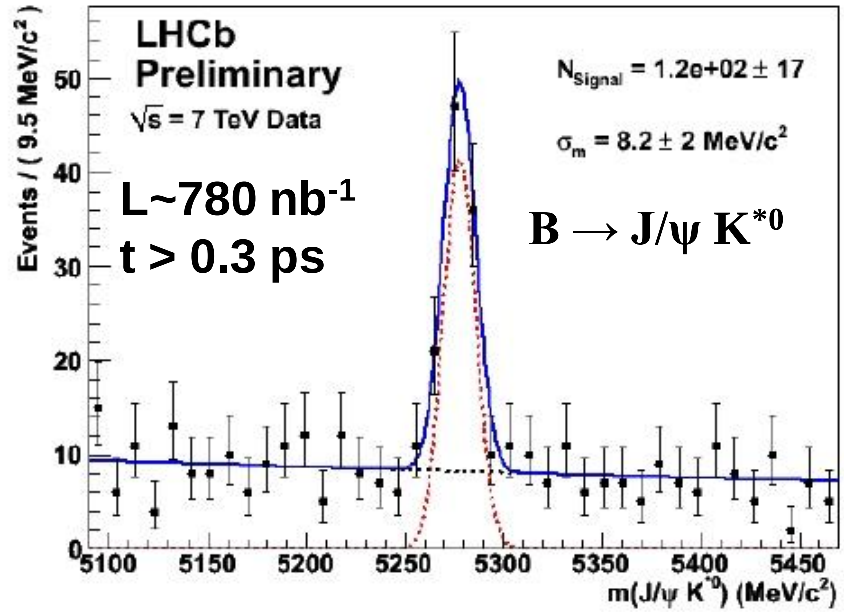
$B^0 \to D^+ \pi^-$ and $B^+ \to D^0 \pi^+$

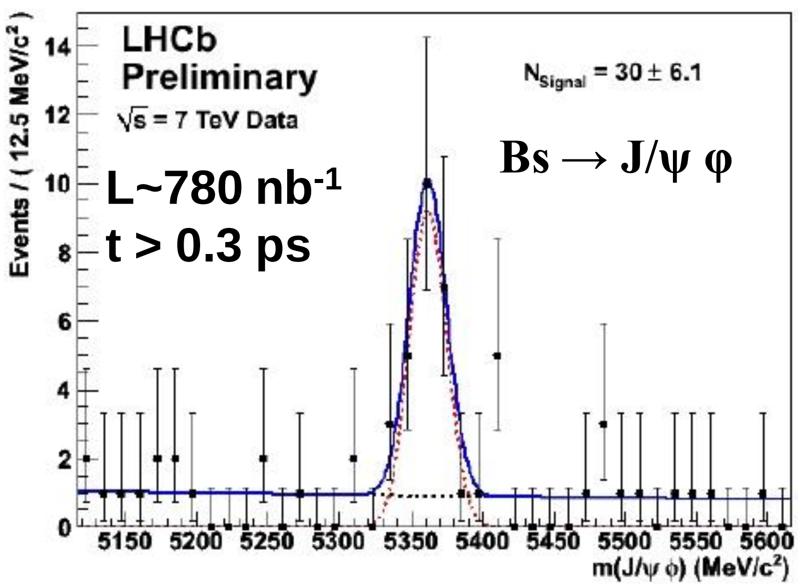




B-meson decays





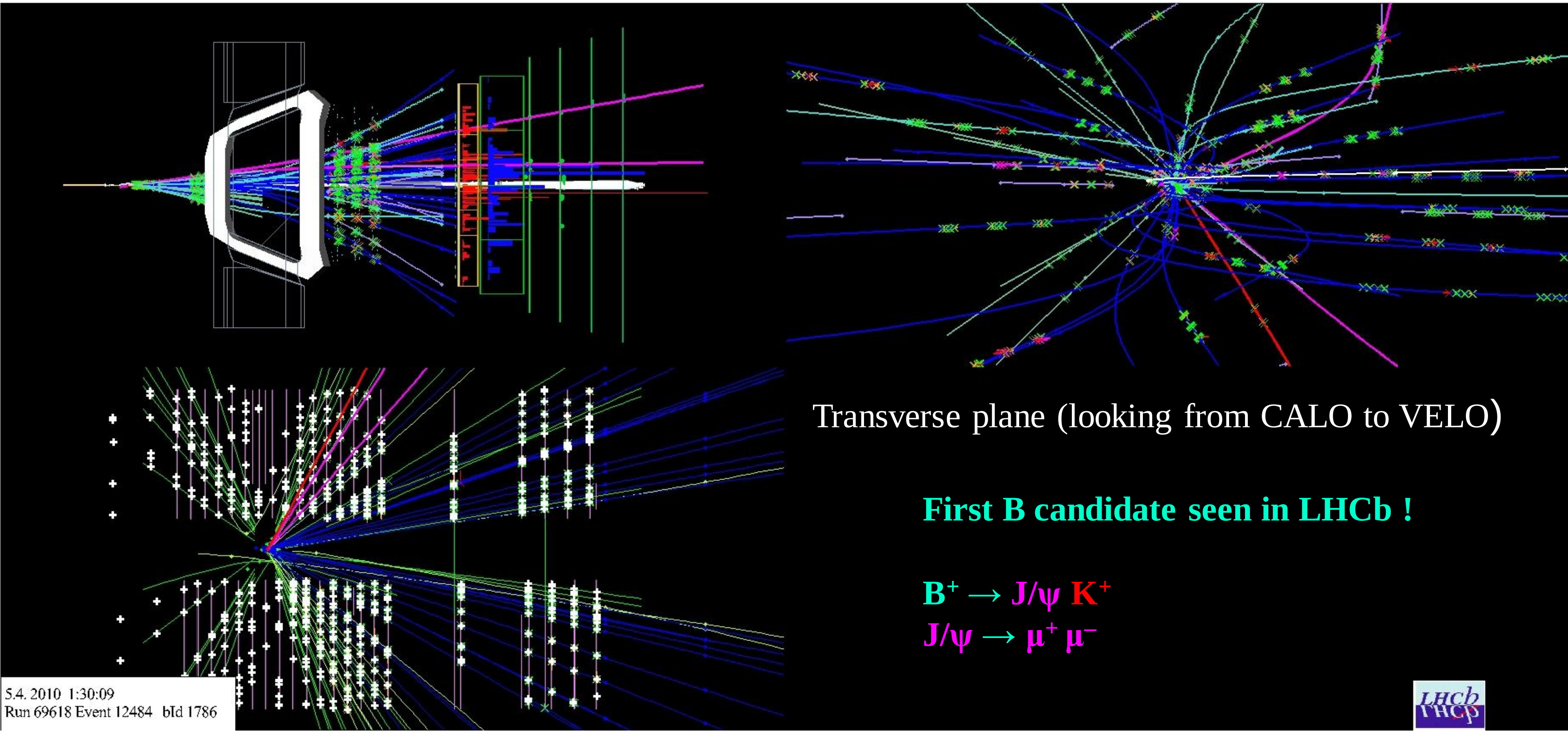


analysis of B→J/ψK+ and B→J/ψK*0 rapidly advancing:

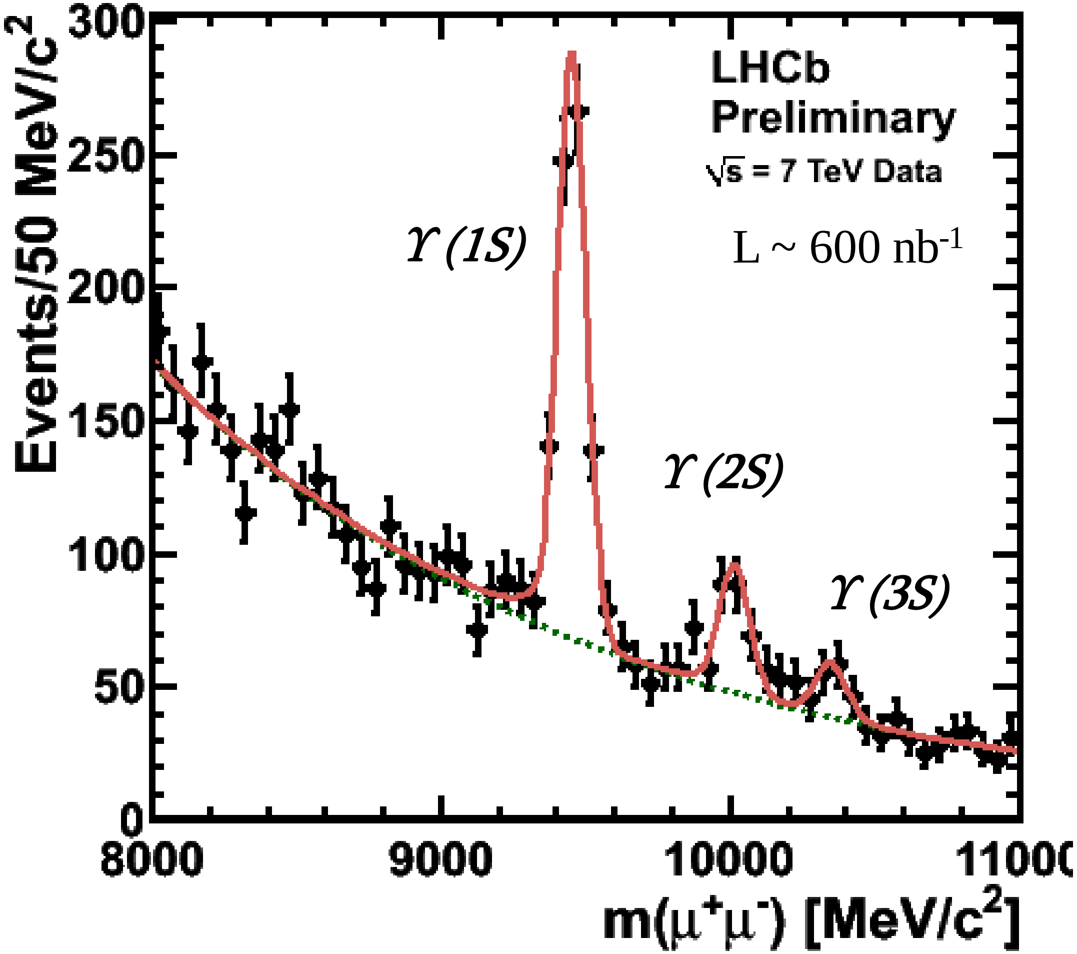
- good momentum resolution
- event yields in line with MC expectations

first Bs → J/ψ φ signal was observed (Bs mixing phase)

Fully reconstructed B



$\Upsilon \rightarrow \mu^+ \mu^-$



M(1S) = 9452.2+- 2.9 MeV/c^2
σ = 50.0 +- 8.6 MeV/c^2
N = 596 +- 32

M(2S) = 10015.1+- 2.9 MeV/c^2
σ = 52.9 +- 9.1 MeV/c^2
N = 138.0 +- 20.6

M(3S) = 10347.4+- 2.9 MeV/c^2
σ = 54.7 +- 9.4 MeV/c^2
N = 61 +- 17

Fixed mass differences

Conclusions

- LHCb experiment is routinely collected data
- First results show the excellent quality of the data collected so far:
  - Charm resonances and B mesons have been reconstructed
  - First measurements of production cross-sections at $\sqrt{s} = 7$ TeV for open charm, J/ψ and *bb*
  - Prompt K_s production in *pp* collisions at $\sqrt{s} = 0.9$ TeV
  - Preliminary results in 2010 for ratios of V0& protons

- Looking forward to analyze full 2010/2011 LHC data set