WORKSHOP ON QUARKONIUM

7th International Workshop on Heavy Quarkonia

Organized by the Quarkonium Working Group

Preparation of analyses of quarkonium states at LHC*b*

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CERN

on behalf of the
LHCb collaboration

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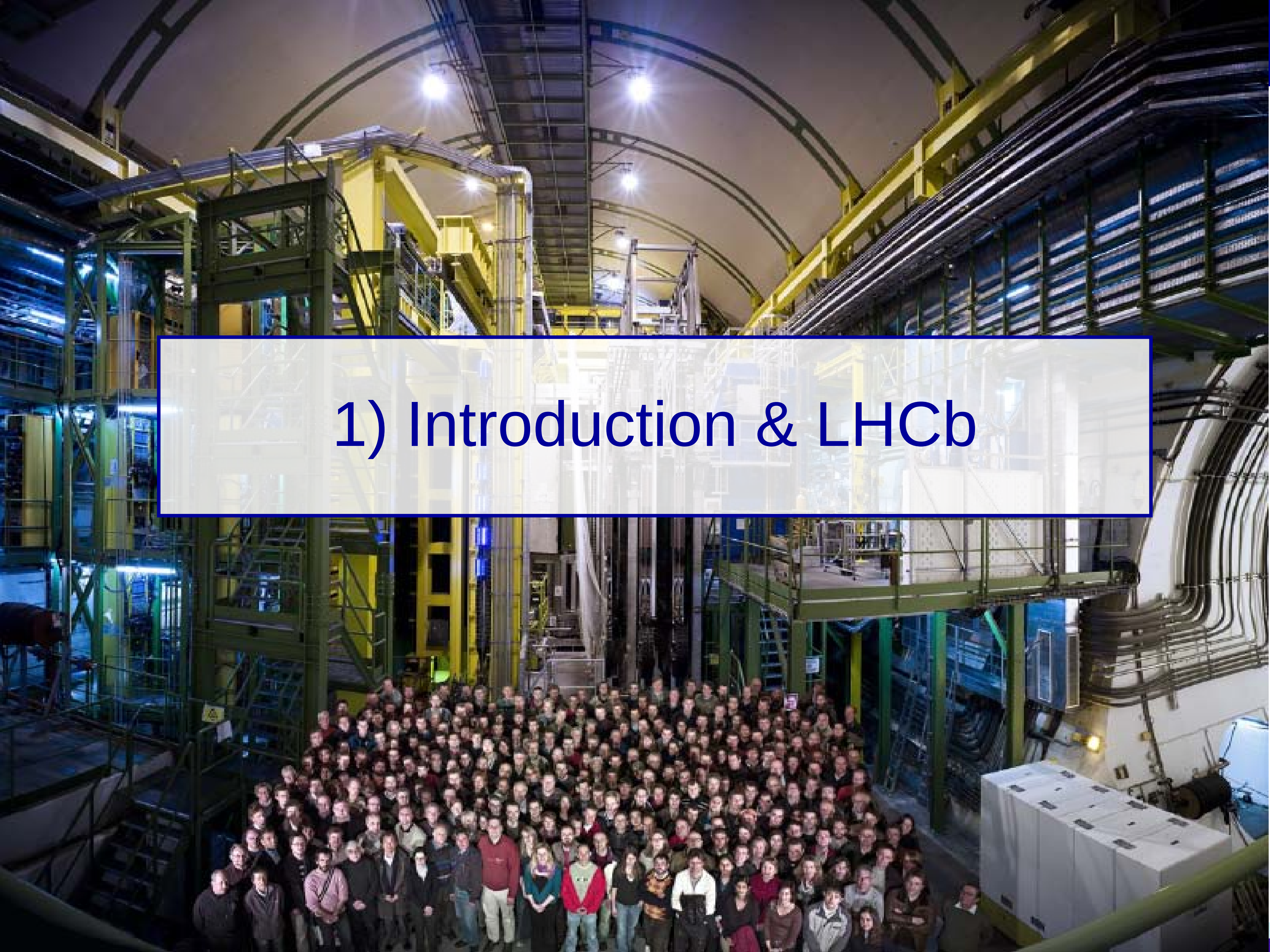
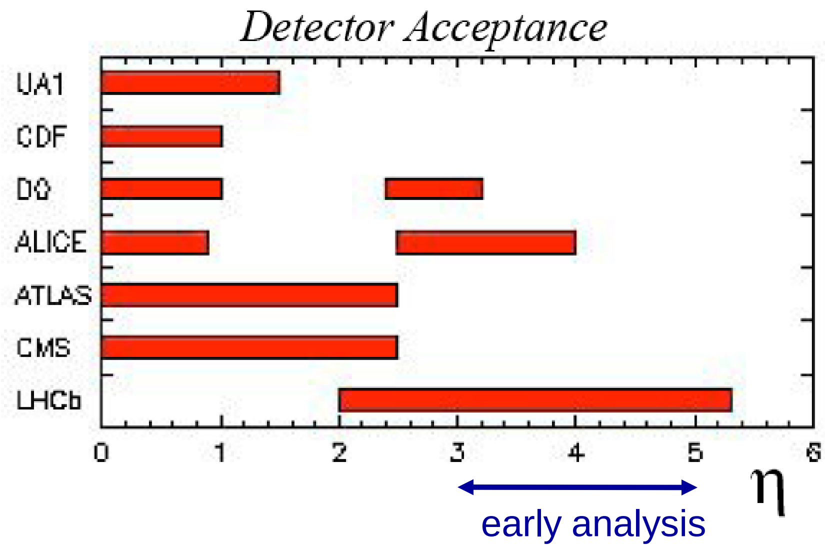
1) Introduction & LHCb



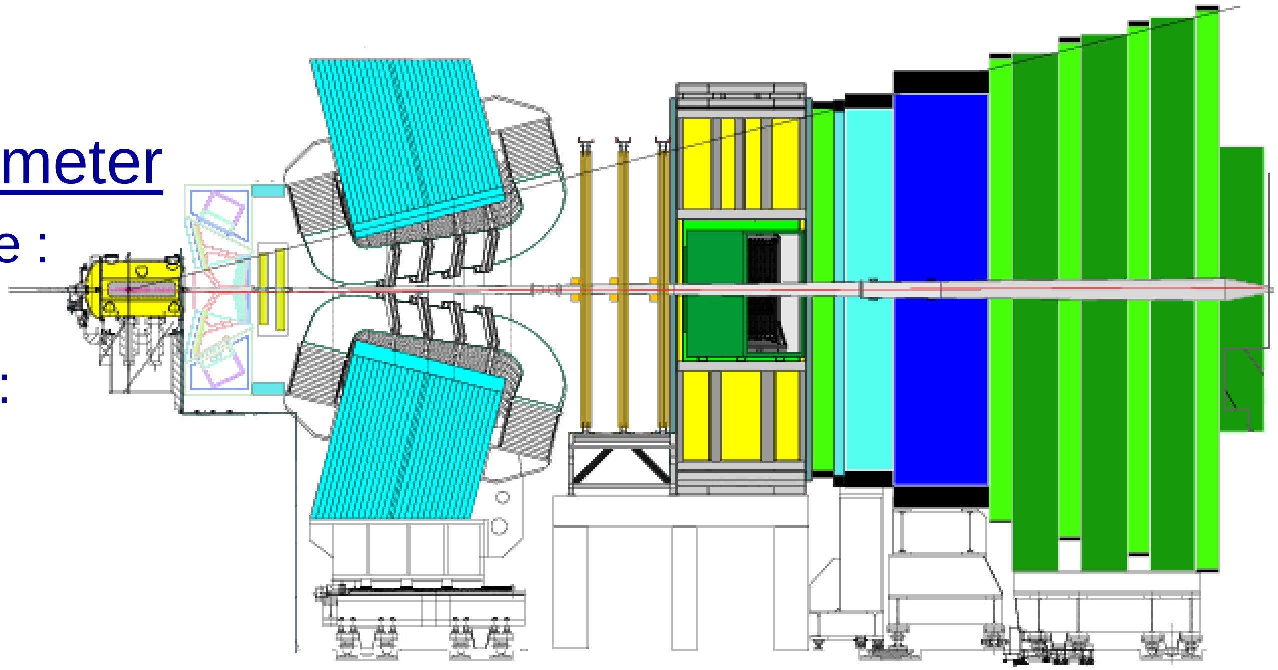
Introduction

- 36 years after the J/ψ discovery, the production mechanism in proton collisions is still unclear
  - Color singlet and color octet mechanisms describe the p_T spectrum and cross section of the J/ψ as measured by Tevatron, **but not the polarization**
  - Other models such as color evaporation model, kt factorization, soft color interaction model **cannot describe the data** either
  - New data from **LHC experiments will help to resolve this issue**

- Cross section measurements of prompt J/ψ and J/ψ from b are important first steps for later LHCb analyses



The LHC*b* Detector



- Forward Spectrometer
  - Angular acceptance : $15<\theta<300$ mrad
  - Nominal luminosity: $L = 2 \times 10^{32}$ $cm^{-2}s^{-1}$

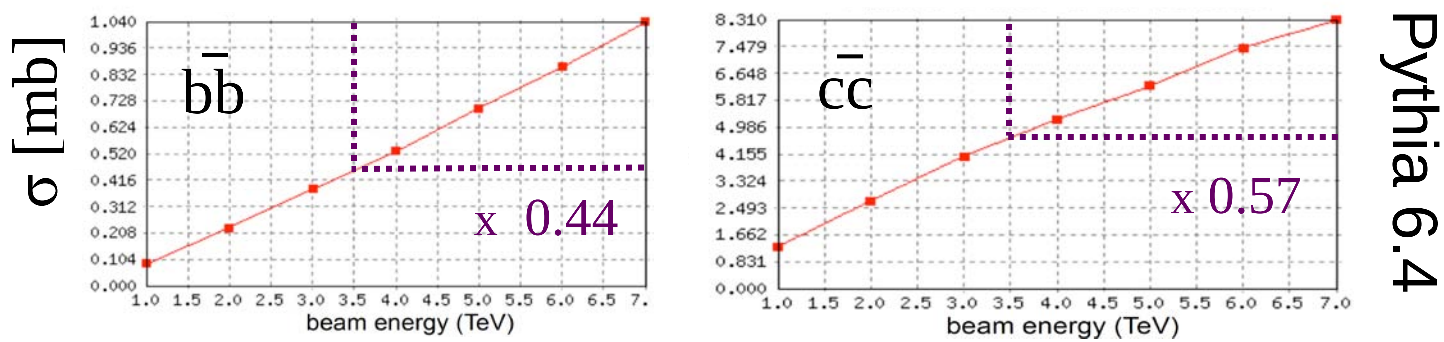
- Performance numbers relevant to quarkonium analyses:
  - Charged tracks $\Delta p/p$ = 0.35 % - 0.55%, $\sigma(m)$=10-25 MeV/c^2
  - ECAL $\sigma(E)/E$= 10% $(E/GeV)^{-1/2} \oplus 1$ %
  - Muon ID: $\varepsilon(\mu\to\mu)$ = 94 %, mis-ID rate $(\pi\to\mu)$ = 1-3 %
  - Vertexing: proper time resolution 30-50 fs
  - Trigger: dominantly software

Reality check: √s and ∫ Ldt in 2010-11

All LHCb simulation studies until recently assumed E_{cm}=14 TeV & annual event yields of 2 fb^{-1}

Beam Energy

Compare expected cross-section at design energy with 3.5 TeV

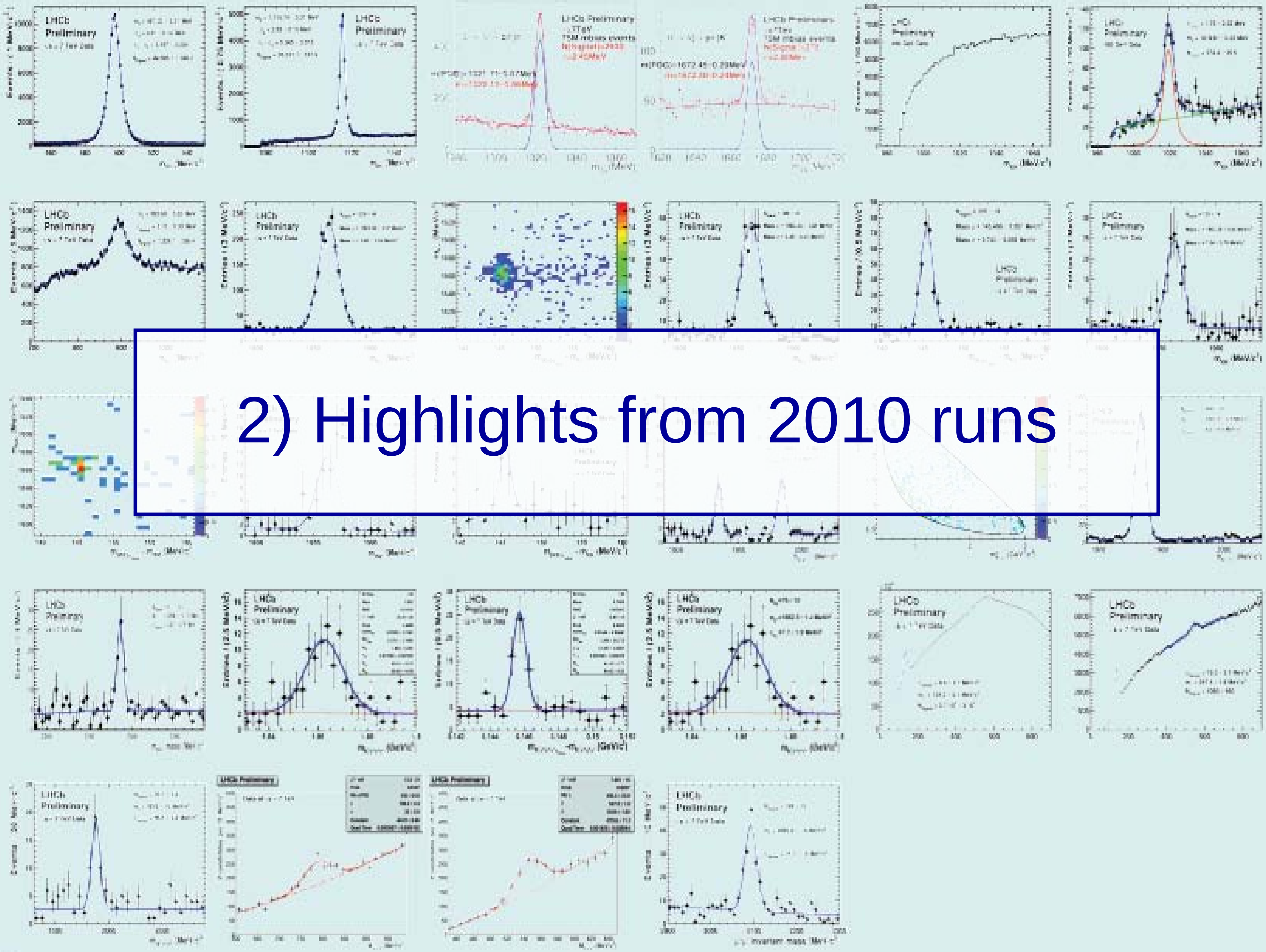


Small penalty in statistical precision
(all MC predictions shown assume bb cross-section of 500 µb at 14 TeV)

Luminosity

LHCb design luminosity is 2 x 10^{32} $cm^{-2}s^{-1}$ – will be in this regime in 2011 !
Lower luminosities of 2010 allows for lower trigger thresholds

LHCb physics prospects in 2010 – 2011 are excellent!

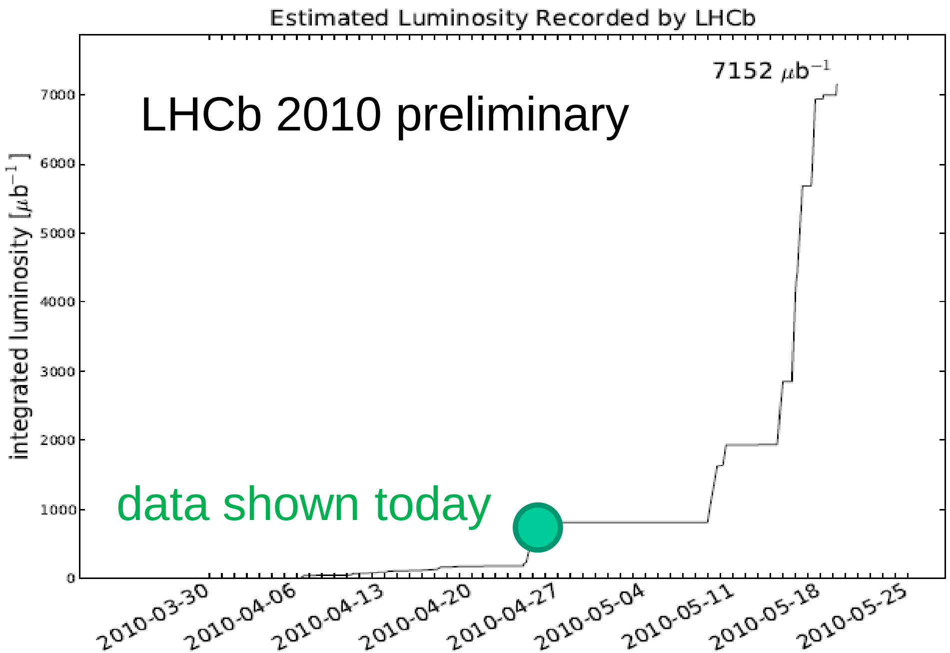


2) Highlights from 2010 runs

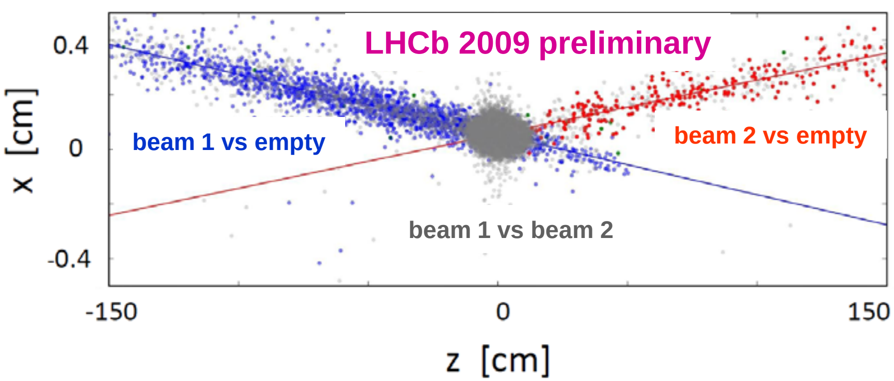
Luminosity

LHCb recorded luminosity:

Online Luminosity determined from #triggers scaled to pythia cross section
→ large uncertainty



Precise Luminosity measurement:

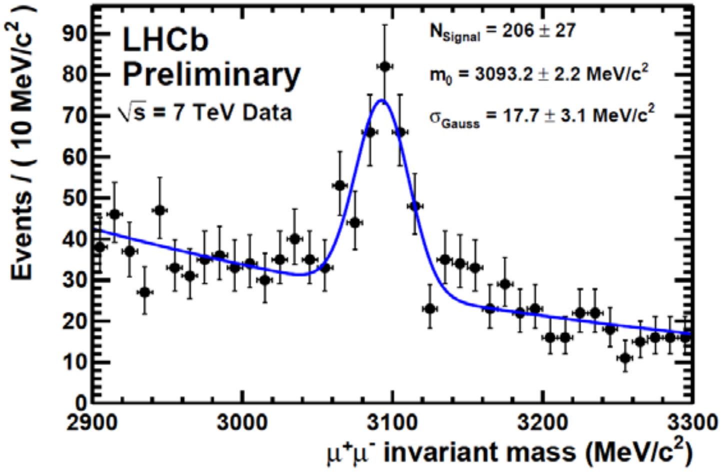


Expected integrated luminosity uncertainty ~5% through measurements of beam profile in beam-gas and beam-beam collisions.

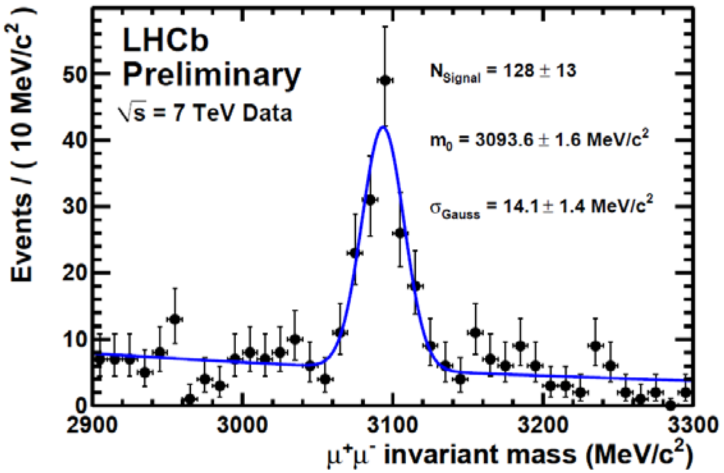
(Already determined to 15% in 2009, with uncertainty limited by knowledge of beam intensities)

First J/ψ data results

Loose selection



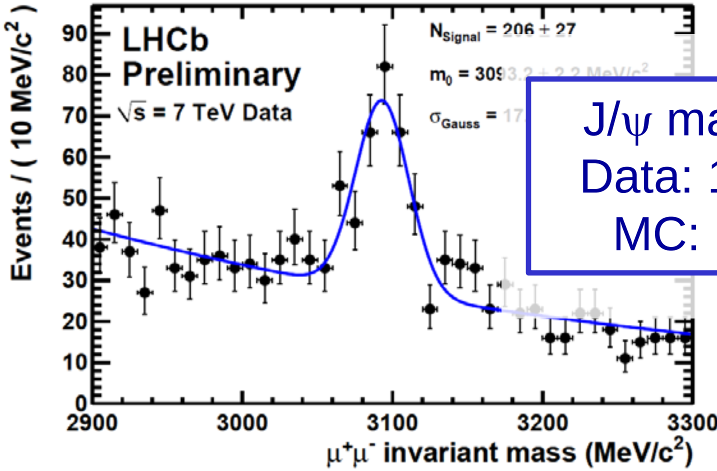
Tight selection



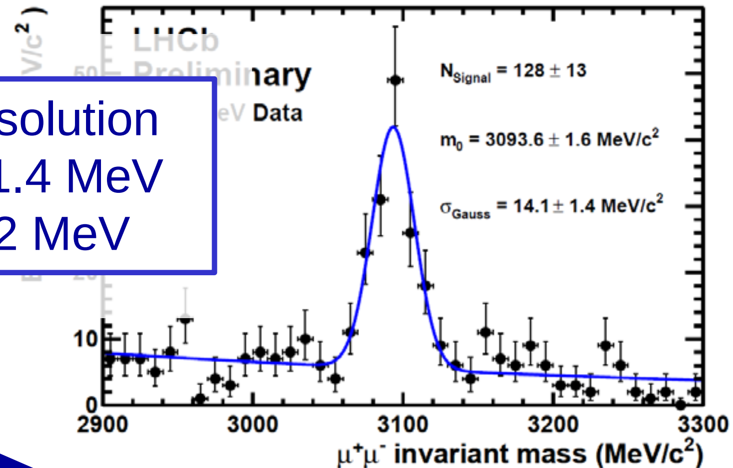
J/ψ mass resolution
Data: 14.1±1.4 MeV
MC: 12.1±2 MeV

First J/ψ data results

Loose selection

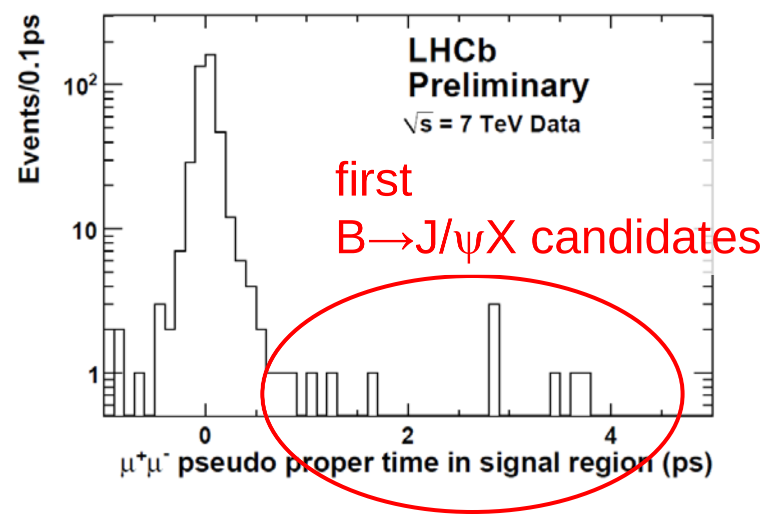


Tight selection



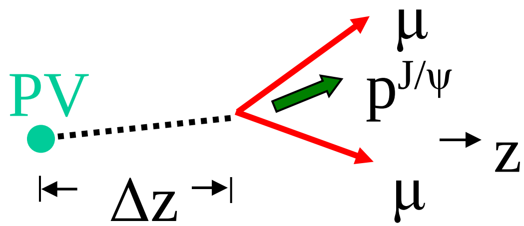
J/ψ mass resolution
Data: 14.1±1.4 MeV
MC: 12.1±2 MeV

Pseudo-proper time in signal peak



pseudo proper-time:

$$t_{J/\psi} = \frac{\Delta z}{p_Z} m_{J/\psi}$$

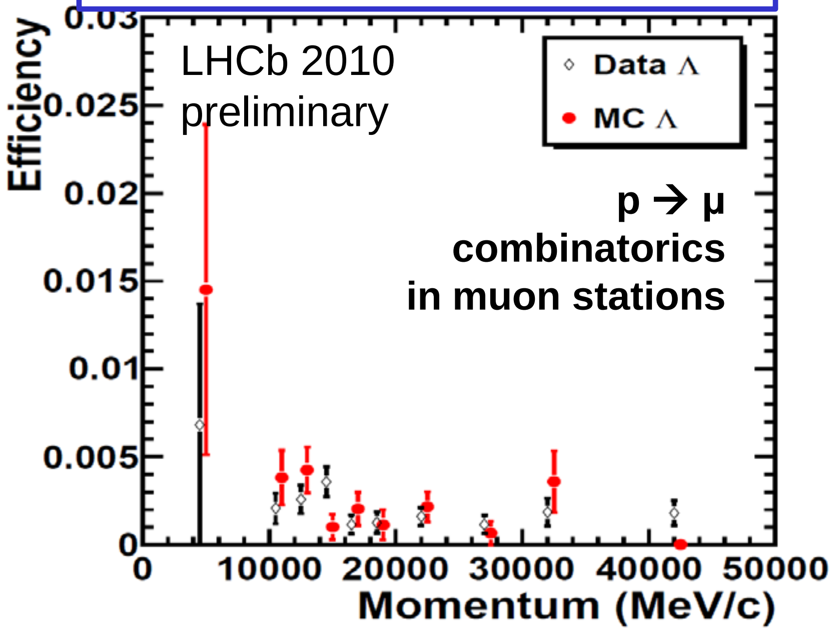


Muon Identification Studies

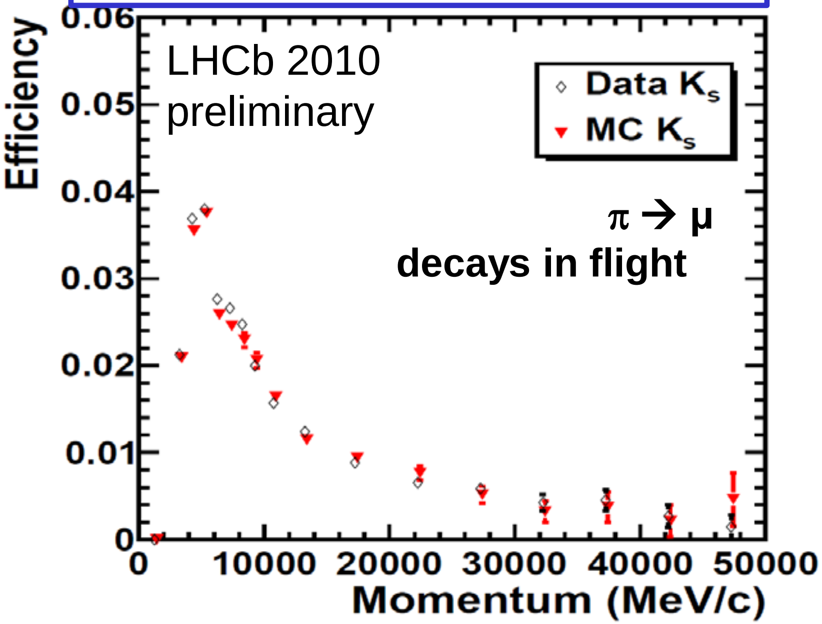
- Not yet enough J/ψ for muon efficiency studies

- Mis-ID: K^0_S and Λ used as clean samples of $\pi^\pm$ and $p^\pm$
  - Proton → Muon mis-ID: (0.18 ± 0.02)%; MC: (0.21 ± 0.04)%
  - Pion → Muon mis-ID: (2.38 ± 0.02)%; MC: (2.34 ± 0.02)%

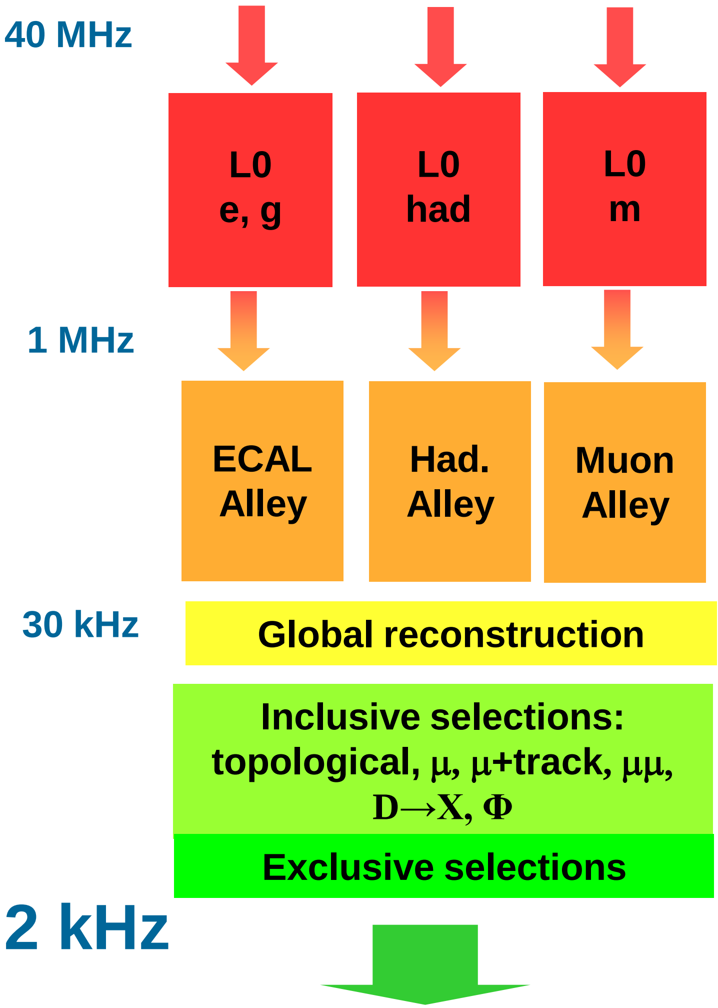
Mis-ID: $p^\pm \rightarrow \mu^\pm$



Mis-ID: $\pi^\pm \rightarrow \mu^\pm$



Trigger



Level-0

'High-pt' signals in calorimeter & muon systems

→ 2010: apply very loose cuts, seed regions of interest

HLT1

Associate L0 signals with tracks, require IP, Pt

→ 2010: reduce requirements w.r.t, initial settings, Initially min. Bias trigger $p_T(\mu) \sim 1\text{GeV}$ or $m(\mu\mu) > 2.5\text{GeV}$

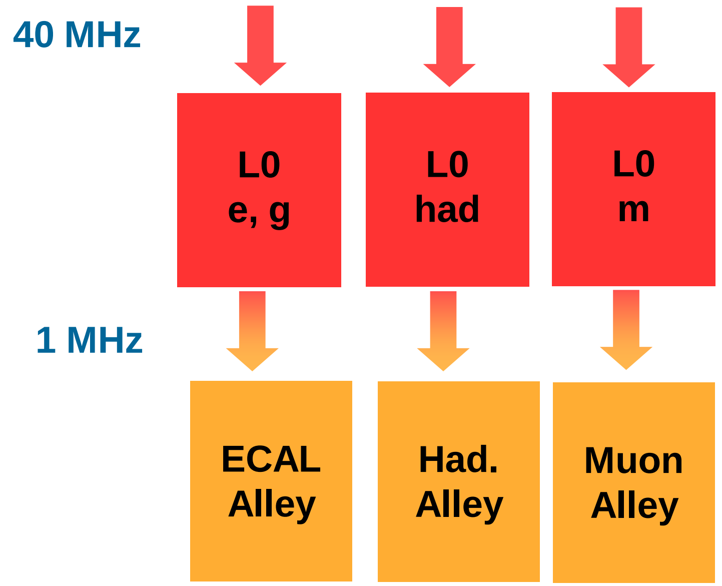
HLT2

Full detector information available.

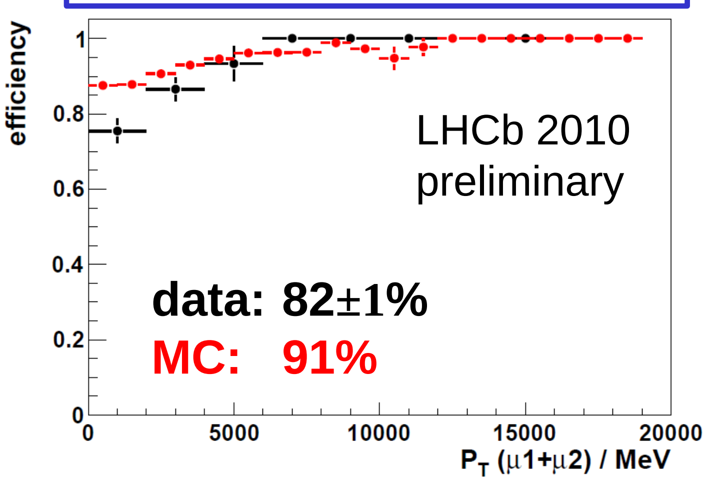
Look for inclusive Signatures, some exclusives

→ 2010: initially not needed, later with very loose suppression

Trigger



J/ψ combined L0xHLT1



Level-0

'High-pt' signals in calorimeter & muon systems
→ 2010: apply very loose cuts, seed regions of interest

HLT1

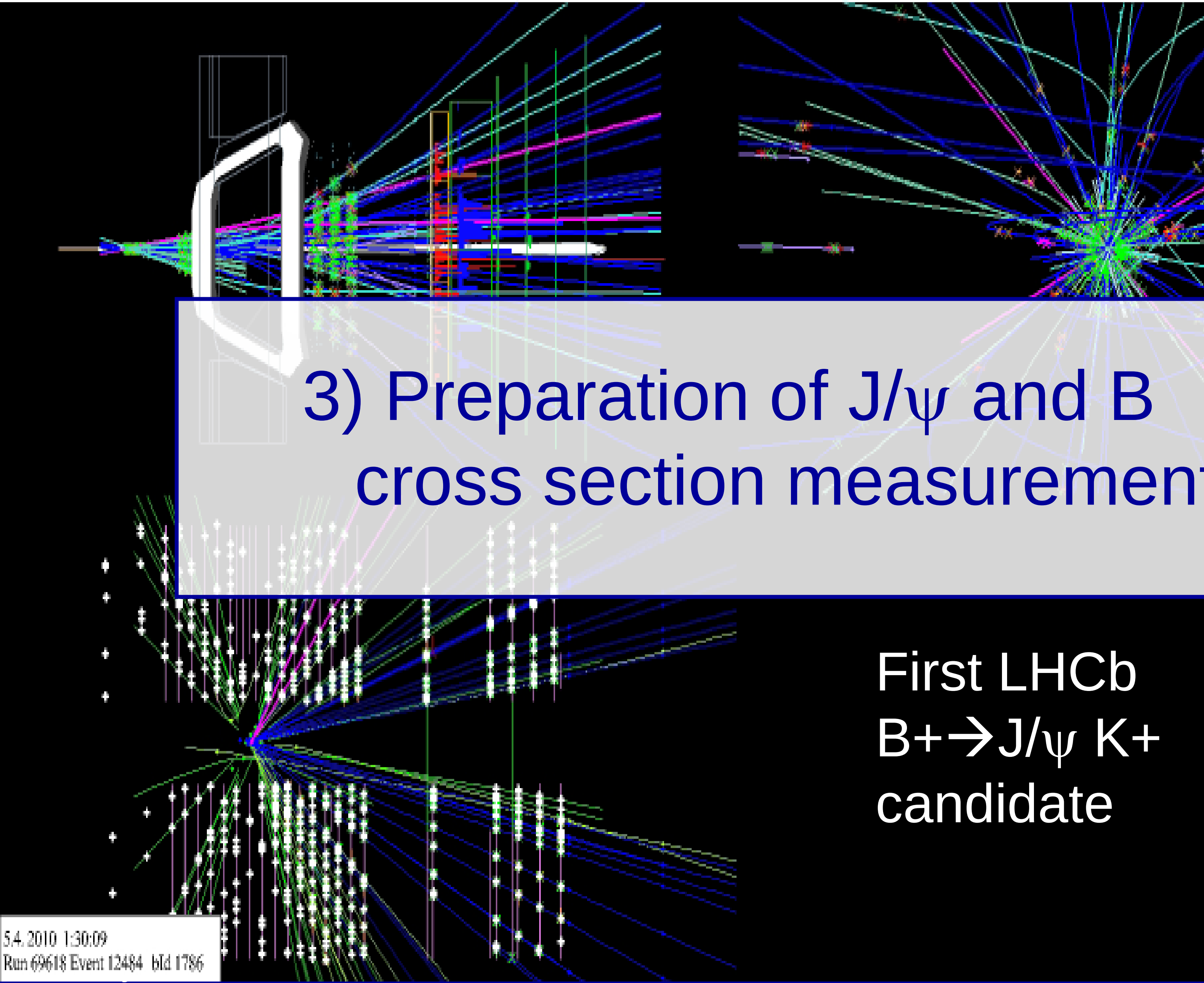
Associate L0 signals with tracks, require IP, Pt
→ 2010: reduce requirements w.r.t, initial settings, Initially min. Bias trigger $p_T(\mu) \sim 1\text{GeV}$ or $m(\mu\mu) > 2.5\text{GeV}$

Evaluation of J/ψ trigger efficiency

Data collected so far in pass through mode
Evaluate which events would have triggered (only unbiased single and dimuon):

data:	82±1%
MC:	91 %

LHCb Event Display



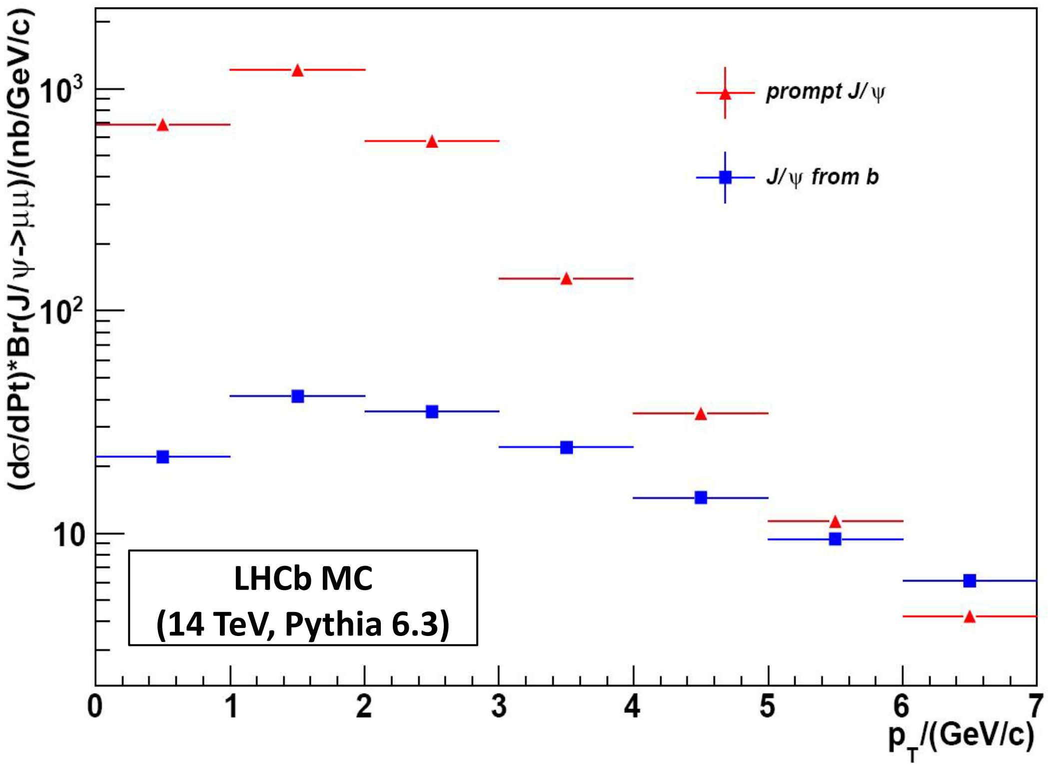
3) Preparation of J/ψ and B cross section measurement

First LHCb
B+→J/ψ K+
candidate

J/ψ Monte Carlo Samples

- Studies presented here (Pythia 6.3, $\sqrt{s}$ = 14TeV)
  - Production of J/ψ through ***Color Singlet Model → unpolarized***
- Current MC productions (Pythia 6.4, $\sqrt{s}$ = 7TeV)
  - Color Octet Model added, tuned to reproduce CDF
  - Produce unpolarized J/ψ

CERN-LHCb-2007-042



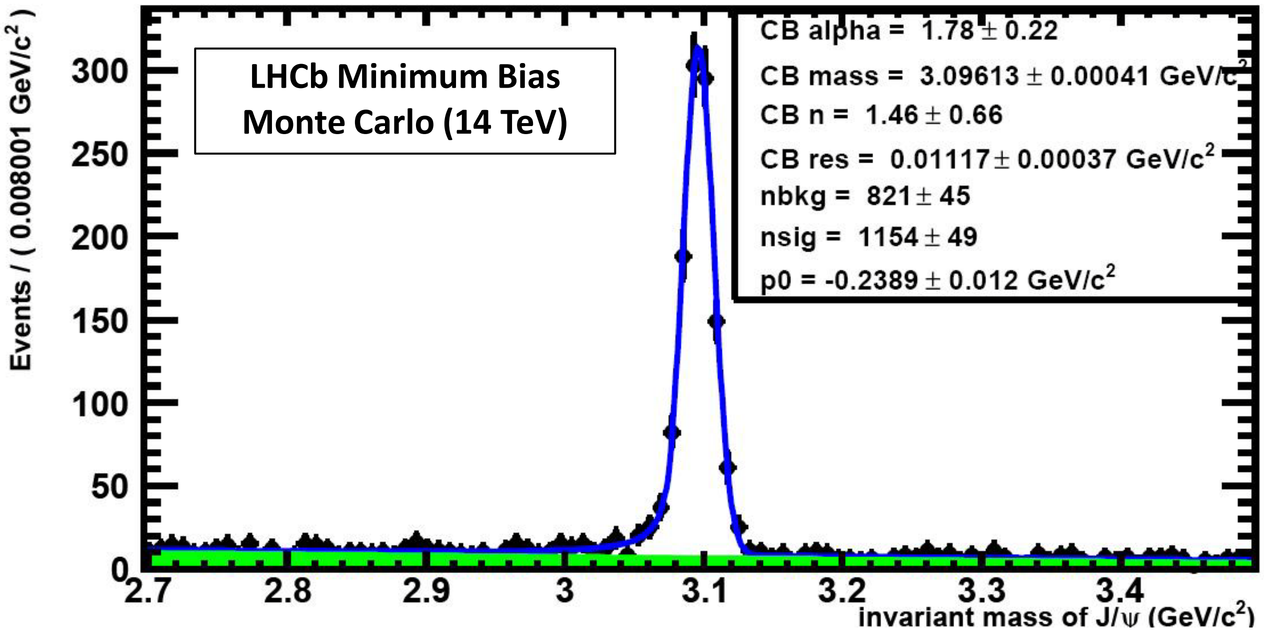
Cross sections in acceptance
(3<η<5, p_T<7 GeV/c, $\sqrt{s}$=14TeV)

- $pp \rightarrow$ prompt $J/\psi(\mu\mu)$ + X
  σ = 2.7 μb
- $pp \rightarrow b \rightarrow J/\psi(\mu\mu)$ + X
  σ = 0.15 μb

$J/\psi \rightarrow \mu^+ \mu^-$ Selection

- Selection based on two identified muons, p_T>0.7GeV
- Analysis example for 3.2M selected J/ψ
  - Invariant mass plot on fully simulated minimum bias events (with all background included):
  - Mass resolution: 11.0 ± 0.4 MeV/c2
  - S/B=17.6 ± 2.3 in ±3σ mass window

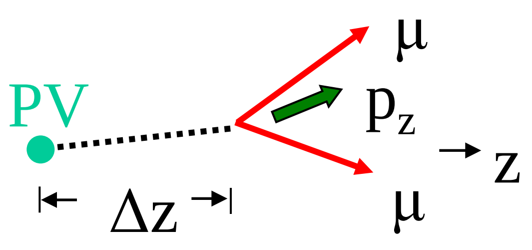
CERN-LHCb-PUB-2010-011

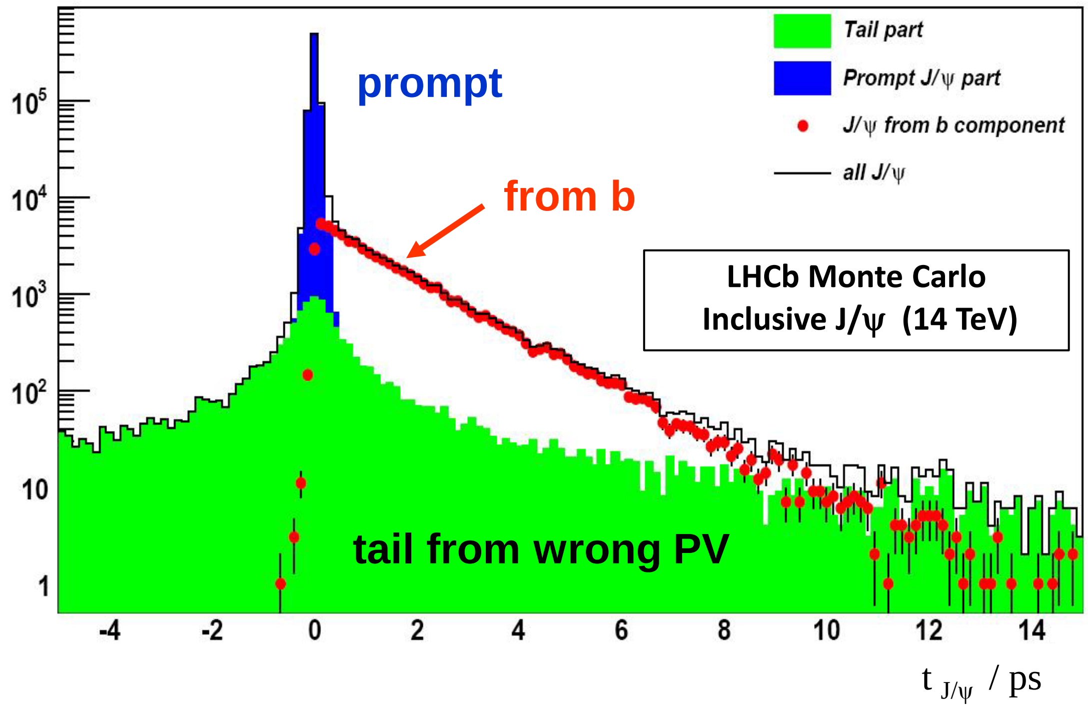


- Combined fit to invariant mass and pseudo proper-time allows for both prompt J/ψ and b production measurement
  - 7 bins of p_t : 0 < pt < 7GeV/c
  - 4 bin of pseudo-rapidity: 3< η <5
    → change to rapidity

pseudo proper-time:

$$t_{J/\psi} = \frac{\Delta z}{p_Z} m_{J/\psi}$$

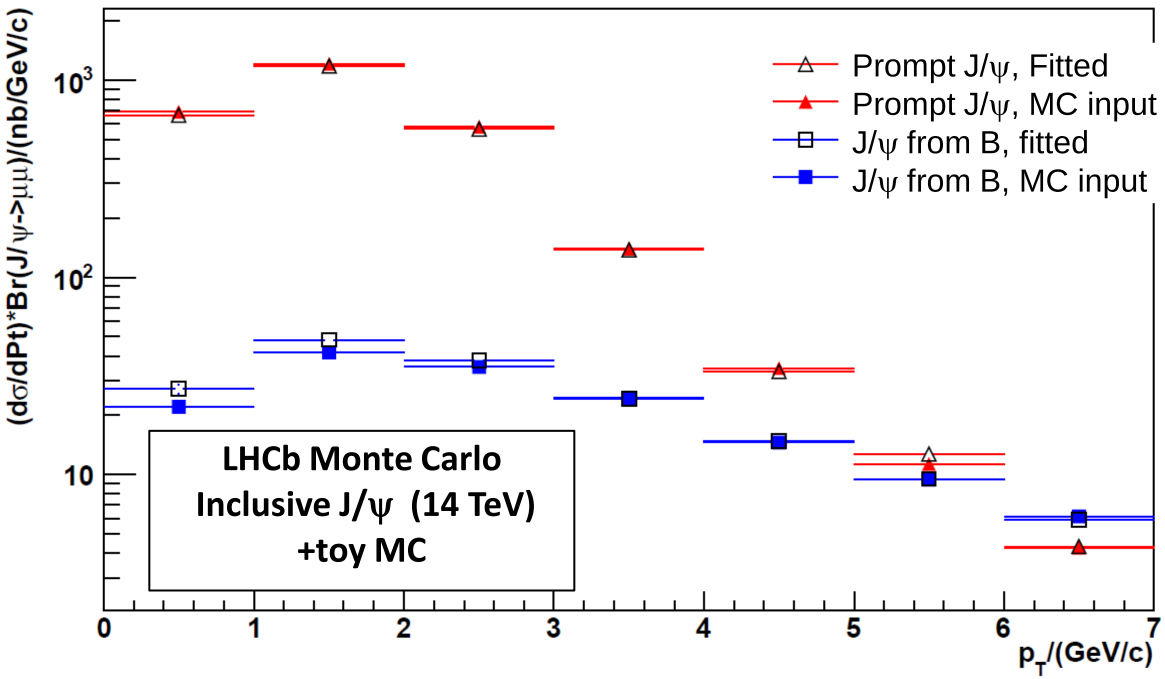




Example: Fit on MC at √s = 14 TeV

- Study fit procedure to determine cross section
  - Signal: Inclusive J/ψ sample
  - Background: toy Monte-Carlo reproducing behaviour (mass and pseudo-lifetime) seen on the Minimum Bias sample
  - Sample corresponding to 0.8 pb^{-1}, $\sqrt{s}$ = 14 TeV
- Good agreement between fit result and MC input

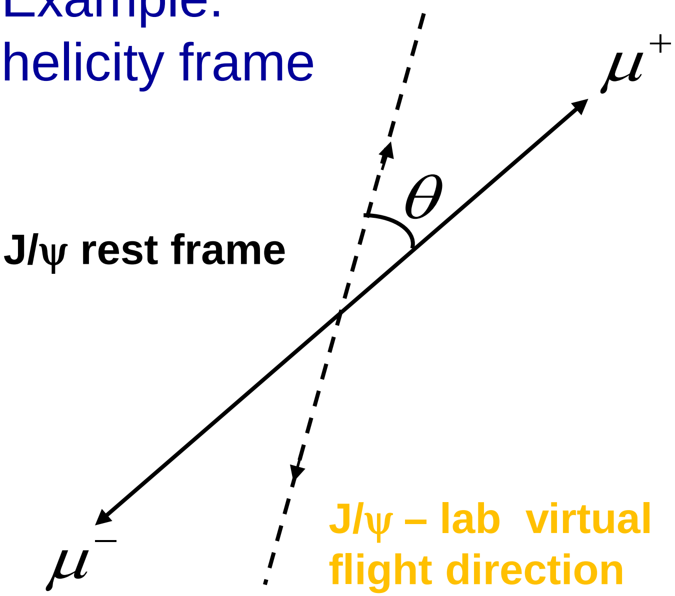
Fit result and MC input

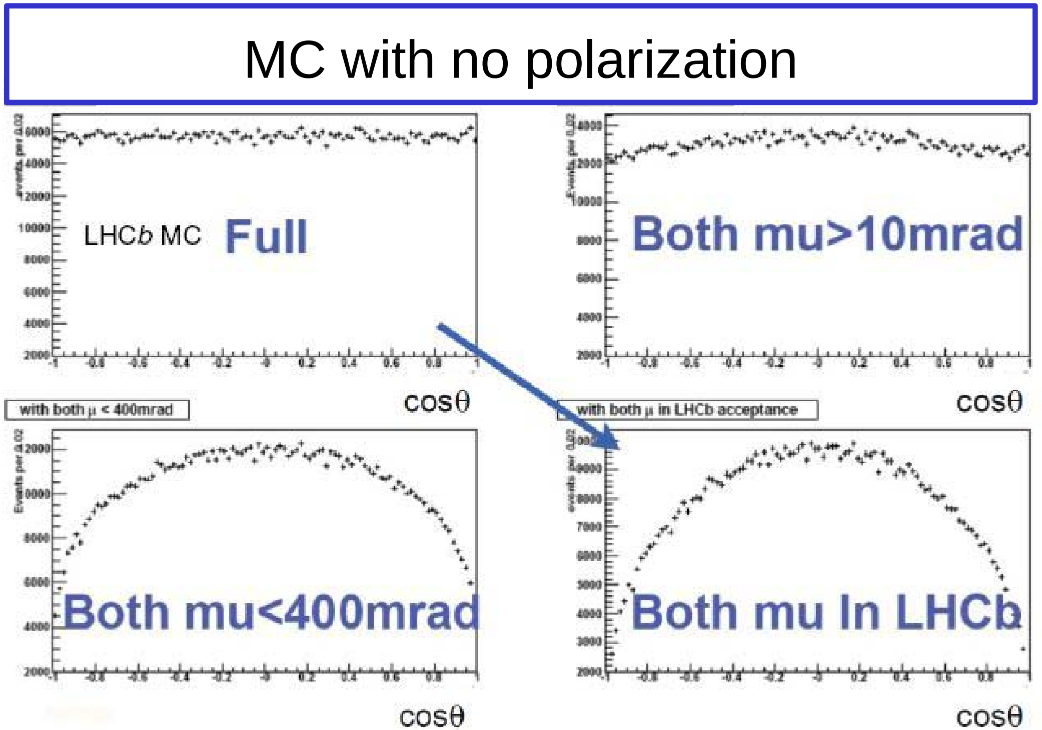


Influence of J/ψ Polarization

- Detector acceptance as a function of helicity angle cosθ

Example:
helicity frame





- LHCb acceptance generates an artificial polarization
  → large influence of polarization on measurement
- First step: Treat polarization as systematic error

Systematics from J/ψ polarization

- Study the effect of ignoring the polarization dependence of the efficiency
  (J/ψ are not polarized in the LHCb Monte Carlo)

$\alpha_{«data»}$	$\sigma_{Measured}$ α=0	Input $\sigma_{«data»}$
0	2758 nb ± 27 nb	2820 nb
+1	2738 nb ± 27 nb	3190 nb
-1	2787 nb ± 28 nb	2286 nb

Systematic
of up to 25 %

- Second step: Measure polarization
  - in bins of η and p_T
  - separating prompt and J/ψ from b
  - with full angular analysis, in different reference frames

4) Other Quarkonium Studies (A Selection)

Term symbol $n^{2S+1}L_J$	$I^G(J^{PC})$	Particle	mass (MeV/c^2) [1]
1^1S_0	$0^+(0^{-+})$	$\eta_c(1S)$	2,980.3 ± 1.2
1^3S_1	$0^-(1^{--})$	$J/\psi(1S)$	3,096.916 ± 0.011
1^1P_1	$0^-(1^{+-})$	$h_c(1P)$	3,525.93 ± 0.27
1^3P_0	$0^+(0^{++})$	$\chi_{c0}(1P)$	3,414.75 ± 0.31
1^3P_1	$0^+(1^{++})$	$\chi_{c1}(1P)$	3,510.66 ± 0.07
1^3P_2	$0^+(2^{++})$	$\chi_{c2}(1P)$	3,556.20 ± 0.09
2^1S_0	$0^+(0^{-+})$	$\eta_c(2S)$, or η'_c	3,637 ± 4
2^3S_1	$0^-(1^{--})$	$\psi(3686)$	3,686.09 ± 0.04
1^1D_2	$0^+(2^{-+})$	$\eta_{c2}(1D)$†	
1^3D_1	$0^-(1^{--})$	$\psi(3770)$	3,772.92 ± 0.35
1^3D_2	$0^-(2^{--})$	$\psi_2(1D)$	
1^3D_3	$0^-(3^{--})$	$\psi_3(1D)$†	
2^1P_1	$0^-(1^{+-})$	$h_c(2P)$†	
2^3P_0	$0^+(0^{++})$	$\chi_{c0}(2P)$†	
2^3P_1	$0^+(1^{++})$	$\chi_{c1}(2P)$†	
2^3P_2	$0^+(2^{++})$	$\chi_{c2}(2P)$†	
$?^??_?$	$0^?(?^?)$†	$X(3872)$	3,872.2 ± 0.8
$?^??_?$	$?^?(1^{--})$	$Y(4260)$	$4{,}260^{+8}_{-9}$

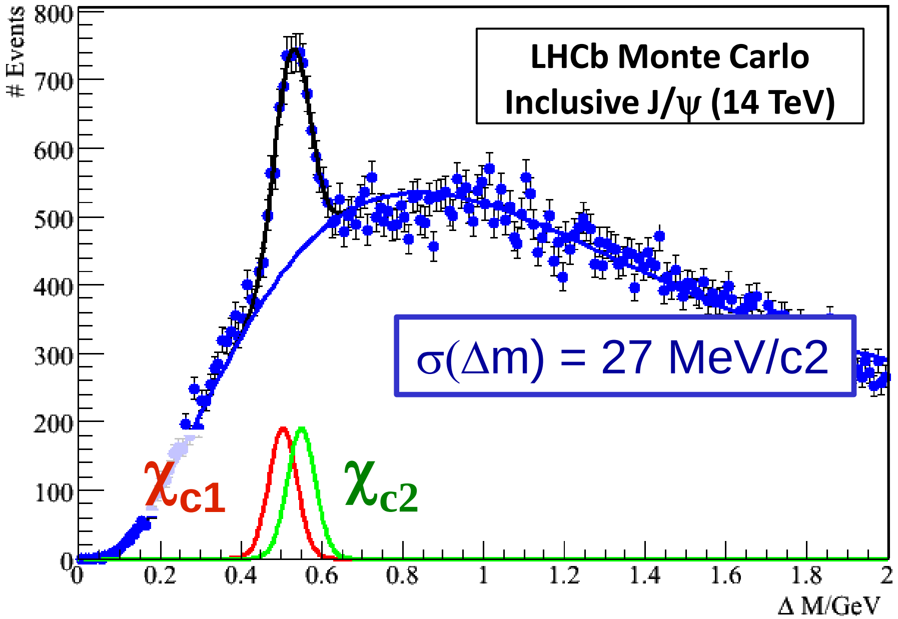
Term symbol $n^{2S+1}L_J$	$I^G(J^{PC})$	Particle	mass (MeV/c^2)[2]
1^1S_0	$0^+(0^{-+})$	$\eta_b(1S)$	$9{,}388.9^{+3.1}_{-2.3} \pm 2.7$
1^3S_1	$0^-(1^{--})$	$\Upsilon(1S)$	9,460.30 ± 0.26
1^1P_1	$0^-(1^{+-})$	$h_b(1P)$	
1^3P_0	$0^+(0^{++})$	$\chi_{b0}(1P)$	9,859.44 ± 0.52
1^3P_1	$0^+(1^{++})$	$\chi_{b1}(1P)$	9,892.76 ± 0.40
1^3P_2	$0^+(2^{++})$	$\chi_{b2}(1P)$	9,912.21 ± 0.40
2^1S_0	$0^+(0^{-+})$	$\eta_b(2S)$	
2^3S_1	$0^-(1^{--})$	$\Upsilon(2S)$	10,023.26 ± 0.31
1^1D_2	$0^+(2^{-+})$	$\eta_{b2}(1D)$	
1^3D_1	$0^-(1^{--})$	$\Upsilon(1D)$	10,161.1 ± 1.7
1^3D_2	$0^-(2^{--})$	$\Upsilon_2(1D)$	
1^3D_3	$0^-(3^{--})$	$\Upsilon_3(1D)$	
2^1P_1	$0^-(1^{+-})$	$h_b(2P)$	
2^3P_0	$0^+(0^{++})$	$\chi_{b0}(2P)$	10,232.5 ± 0.6
2^3P_1	$0^+(1^{++})$	$\chi_{b1}(2P)$	10,255.46 ± 0.55
2^3P_2	$0^+(2^{++})$	$\chi_{b2}(2P)$	10,268.65 ± 0.55
3^3S_1	$0^-(1^{--})$	$\Upsilon(3S)$	10,355.2 ± 0.5
4^3S_1	$0^-(1^{--})$	$\Upsilon(4S)$ or $\Upsilon(10580)$	10,579.4 ± 1.2
5^3S_1	$0^-(1^{--})$	$\Upsilon(10860)$	10,865 ± 8
6^3S_1	$0^-(1^{--})$	$\Upsilon(11020)$	11,019 ± 8

$\chi_c \rightarrow J/\psi\ \gamma$ and $\psi(2S) \rightarrow \mu^+ \mu^-$

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

- A large fraction of prompt J/ψ come from $\chi_{c1,2} \rightarrow J/\psi\ \gamma$
- J/ψ selection, adding a photon with $p_T(\gamma)$>500 MeV/c (from ECal)
- Important observables
  - Fraction of J/ψ from $\chi_{c1,2}$
  - $R_{\chi c} = \sigma(\chi_{c1}) / \sigma(\chi_{c2})$

$\Delta m = m(J/\psi\ \gamma) - m(J/\psi)$



$\psi(2S) \rightarrow \mu^+ \mu^-$

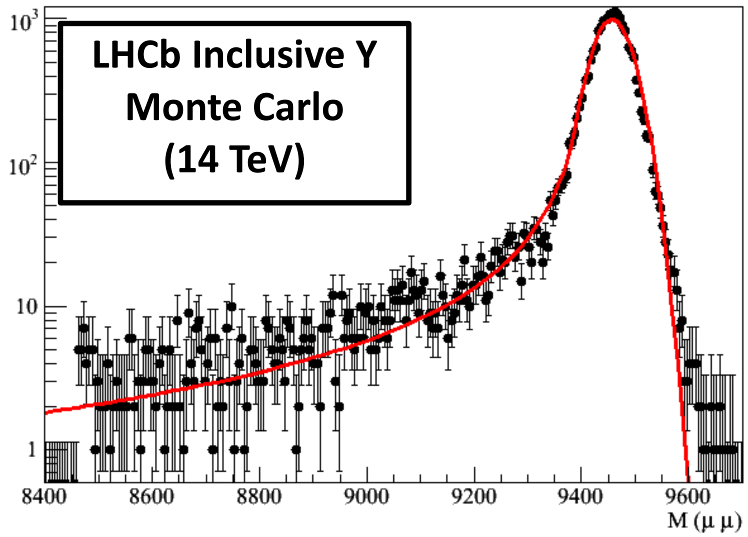
- Measurement of the ratio $\sigma(\psi(2S)) / \sigma(J/\psi)$, as a function of p_T, separating prompt and from b
- Additionally: up to 20% systematic error due to polarization

$$\frac{\varepsilon_{rec\&sel\&trig}(\psi(2S))}{\varepsilon_{rec\&sel\&trig}(J/\psi)} = 1.01 \pm 0.07(stat)$$

$\Upsilon(1S) \rightarrow \mu^+ \mu^-$ and $\chi_{b2}(1P)$

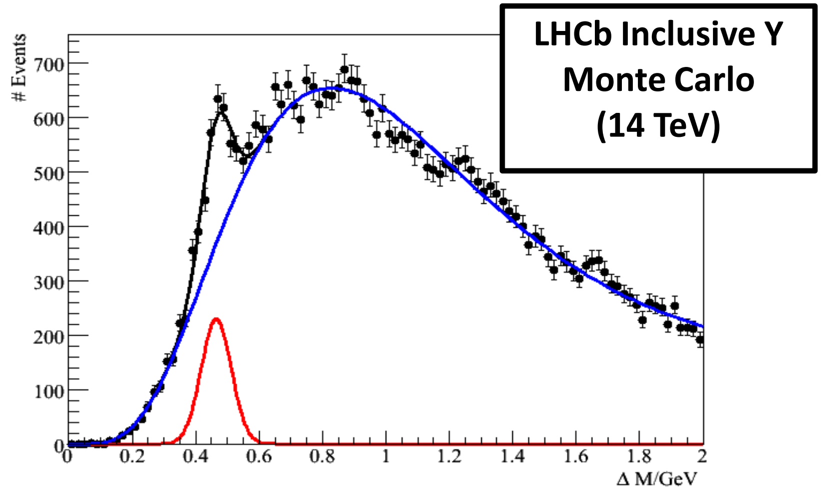
Y(1s):

- Mass resolution: **37 MeV/c²**
- Similar reconstruction and resolutions will be obtained for the Y(2S) and Y(3S) states:
  → separate the 3 Upsilon states



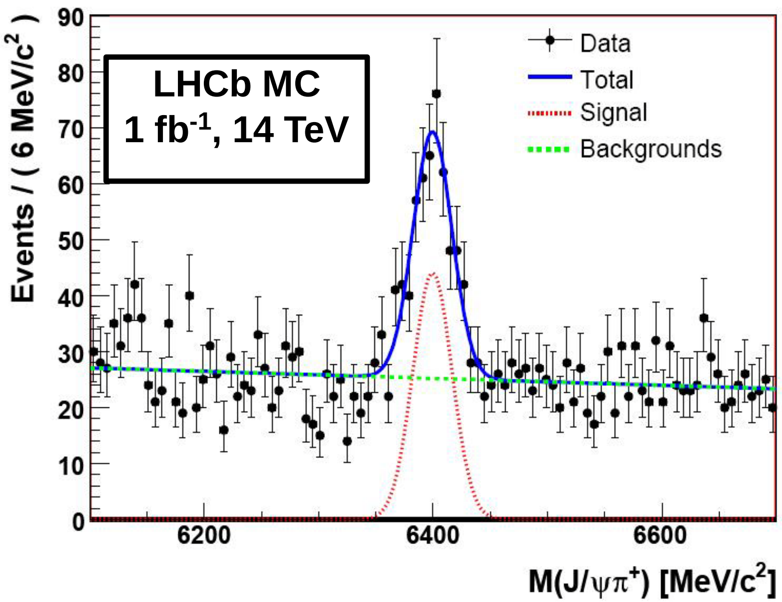
χ_{b2}(1P):

- Reconstruction of $\chi_{b2}(1P) \rightarrow \Upsilon(1S)\ \gamma$
- Photon detected in ECAL, with $p_T(\gamma)$ > 500 MeV/c
- Mass resolution: **47 MeV/c²**



$B_c^{\pm}$

- Measurement of mass, lifetime and production cross section using the decay modes:
  - **$B_c^+ \rightarrow J/\psi\ \pi^+$**: expect **310** signal events for 1 fb^{-1} @ $\sqrt{s}$ = 14 TeV
  - **$B_c^+ \rightarrow J/\psi\ \mu^+\ \nu\ X$**: signal yield one order of magnitude larger, production cross section measurement possible with 2010 data

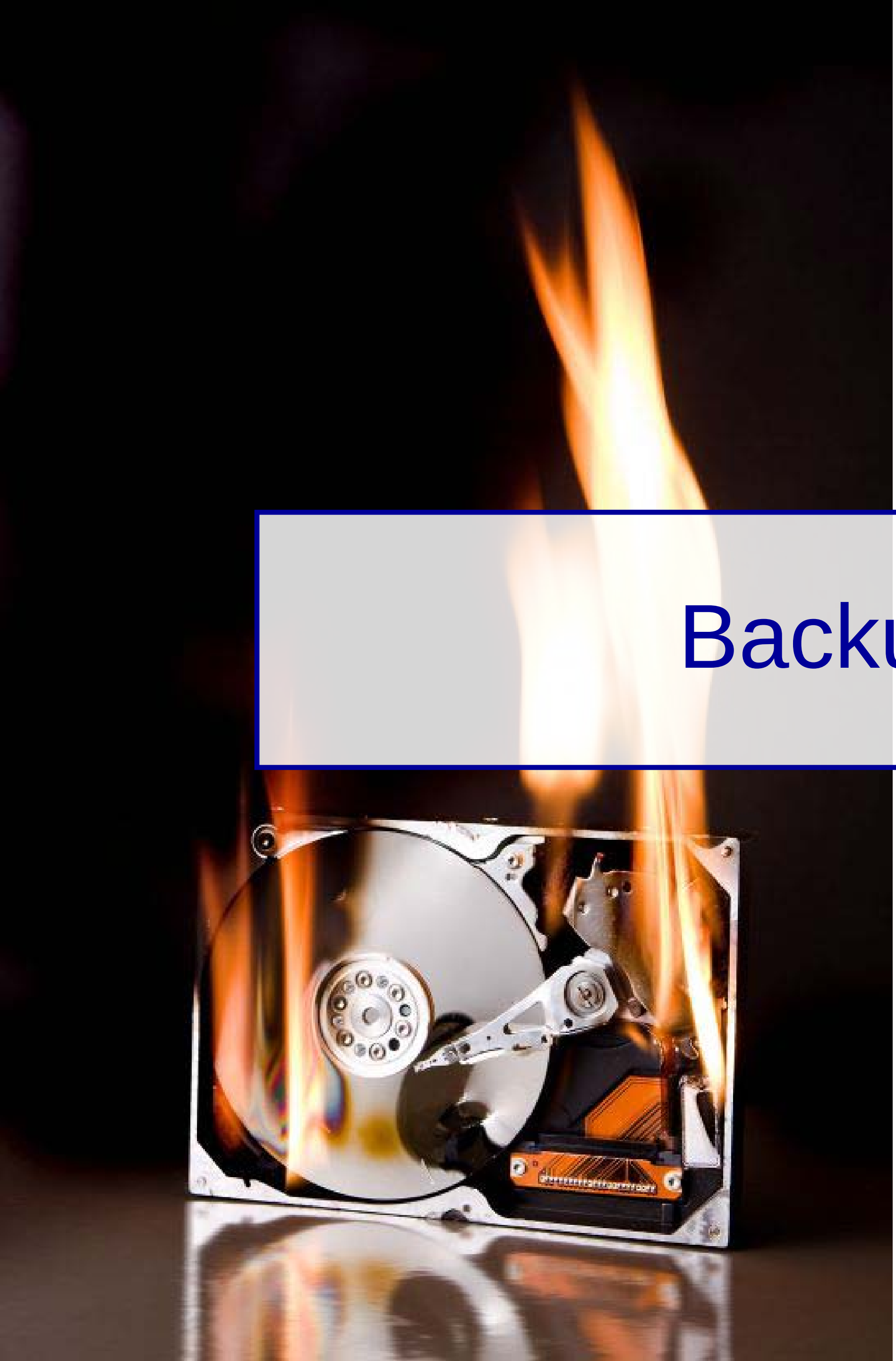


Conclusions

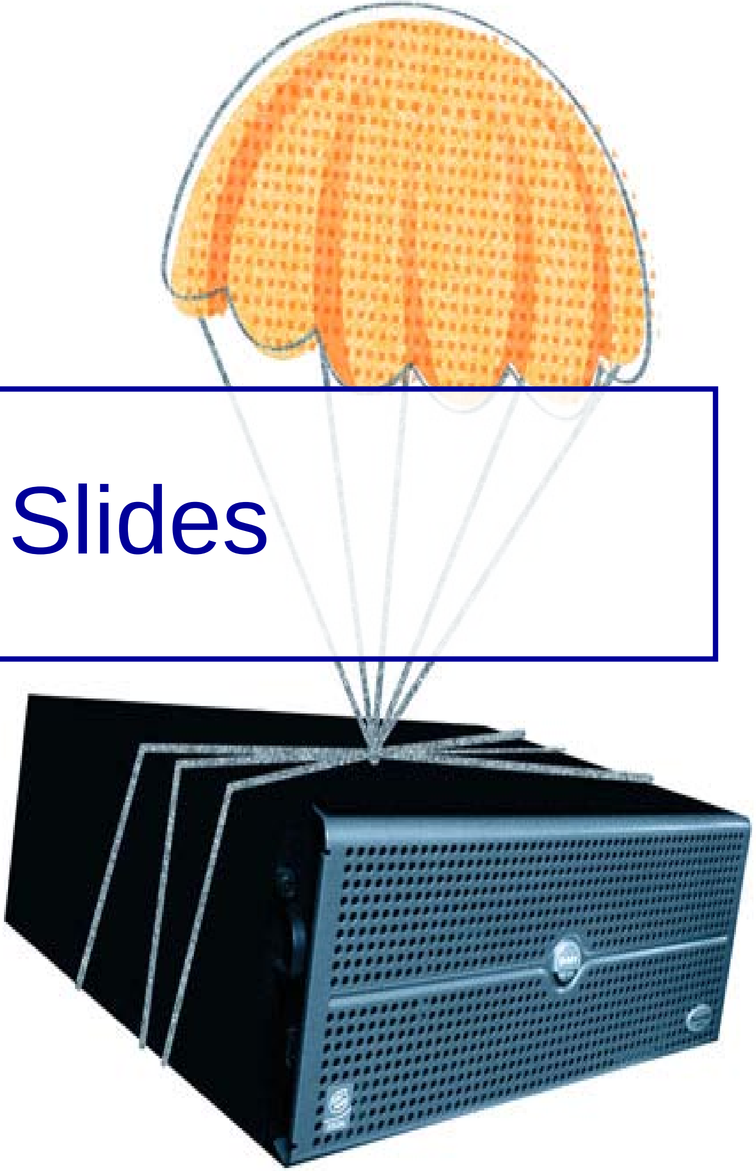
- Plan to measure prompt and non-prompt J/ψ cross section
  - Early analysis: 3 million J/ψ → good statistics in $3<\eta<5$, $0<p_T<7$GeV
  - Second step:
    - measure J/ψ polarization
    - extend rapidity and transverse momentum range

- Other quarkonium states will also be studied:
  - $\chi_{c1,2}$, $\psi(2S)$ production
  - $\Upsilon(1S) \to \mu^+ \mu^-$, $\chi_{b2}(1P)$, $B_c^+ \to J/\psi + X$
  - Not discussed here: h_c, X(3872) and $Z(4430)^{\pm}$

- First studies with $1nb^{-1}$ of 2010 data
  - O(200) prompt and first non-prompt J/ψ candidates reconstructed
  - Invariant mass resolution in agreement with MC (15% stat error)

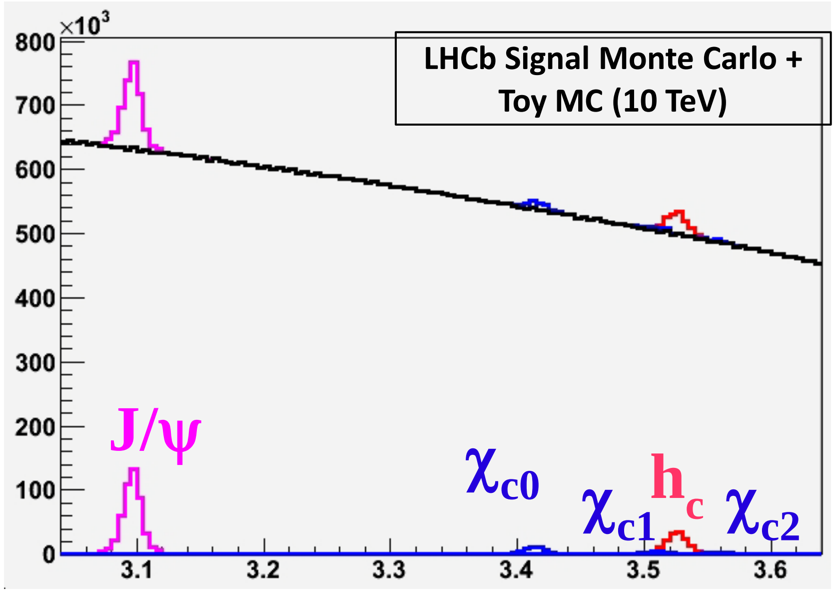


Backup Slides



h_c reconstruction

- Besides di-muon states, LHCb detector performances will allow to study other states though hadronic decay modes
- Reconstruction of $h_c \to \eta_c \gamma$ is difficult ($E(\gamma)$~500 MeV in the h_c rest frame)
- Hadronic decay channels look promising: $h_c \to pp$, $h_c \to \phi K^+ K^-$, $h_c \to \phi \pi^+ \pi^-$
- In particular, $h_c \to$ ppbar probably visible with first year data, which will give access to $\sigma(h_c)$xBr($h_c \to$ ppbar) relative to $\sigma(J/\psi)$xB($J/\psi \to$ ppbar)



m(pp) (GeV/c²)

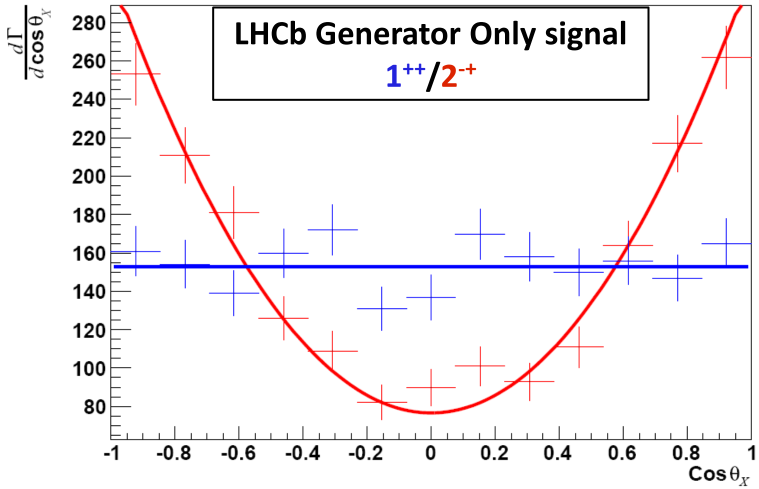
Expected ppbar mass distribution:
- Assuming Br($h_c \to pp$) = 0.12 %,
- Toy Monte Carlo for background, reproducing background seen on fully simulated minimum bias events,
- 100 pb^{-1} at $\sqrt{s}$ = 10 TeV

$$\frac{\sigma(h_c) \times \mathcal{B}(h_c \to p\bar{p})}{\sigma(J/\psi) \times \mathcal{B}(J/\psi \to p\bar{p})}$$

cross check from the measurements of $\frac{\sigma(\chi_{ci}) \times \mathcal{B}(\chi_{ci} \to p\bar{p})}{\sigma(J/\psi) \times \mathcal{B}(J/\psi \to p\bar{p})}$.

X(3872) and $Z(4430)^{\pm}$

- Reconstruction of $X(3872) \rightarrow J/\psi\ \pi^+\ \pi^-$ (and the control channel $\psi(2S) \rightarrow J/\psi\ \pi^+\ \pi^-$), prompt or from b: systematic study of this state.
- Expect 1800 reconstructed $B^{\pm} \rightarrow X(3872)\ K^{\pm}$, with 2 fb^{-1} at $\sqrt{s}$= 14 TeV, allowing to disentangle unknown quantum number J^{PC}: $1^{++}/2^{-+}$.



Expected distributions for 1^{++} and 2^{-+} hypotheses for 2 fb^{-1} of data. Generator level only, no detector simulation, no acceptance corrections yet!

- Similar studies for $\mathbf{B^0 \rightarrow Z(4430)^+(\rightarrow \psi(2S)\pi^+)K^-}$
- About **6200** signal events can be selected from 2 fb^{-1} of data at $\sqrt{s}$ =14 TeV, assuming $B(B^0 \rightarrow Z(4430)^+ K^-)xB(Z(4430)^+ \rightarrow \psi(2S)\pi^+) = 4.1x10^{-5}$
- Possible to confirm the Belle discovery with about 100 pb^{-1} of data at $\sqrt{s} = 7$ TeV.

Monte Carlo Tools

- PYTHIA 6.3 for the studies shown here:
  - Production of J/ψ through ***Color Single Model***.
- PYTHIA 6.4 for the current Monte Carlo productions:
  - With ***Color Octet Model*** added, tuned to reproduce CDF measurements see note CERN-LHCb-2007-042.
- EvtGen for decays:
  - Generator package which allows to have a detailed description of **$b \rightarrow J/\psi\ X$ decays**.
  - Also allows correct **angular correlations** in decays of polarized particles.
- PHOTOS for **radiative corrections**.