Studies of Open Charm and Charmonium Production at LHCb

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On behalf of the LHCb Experiment

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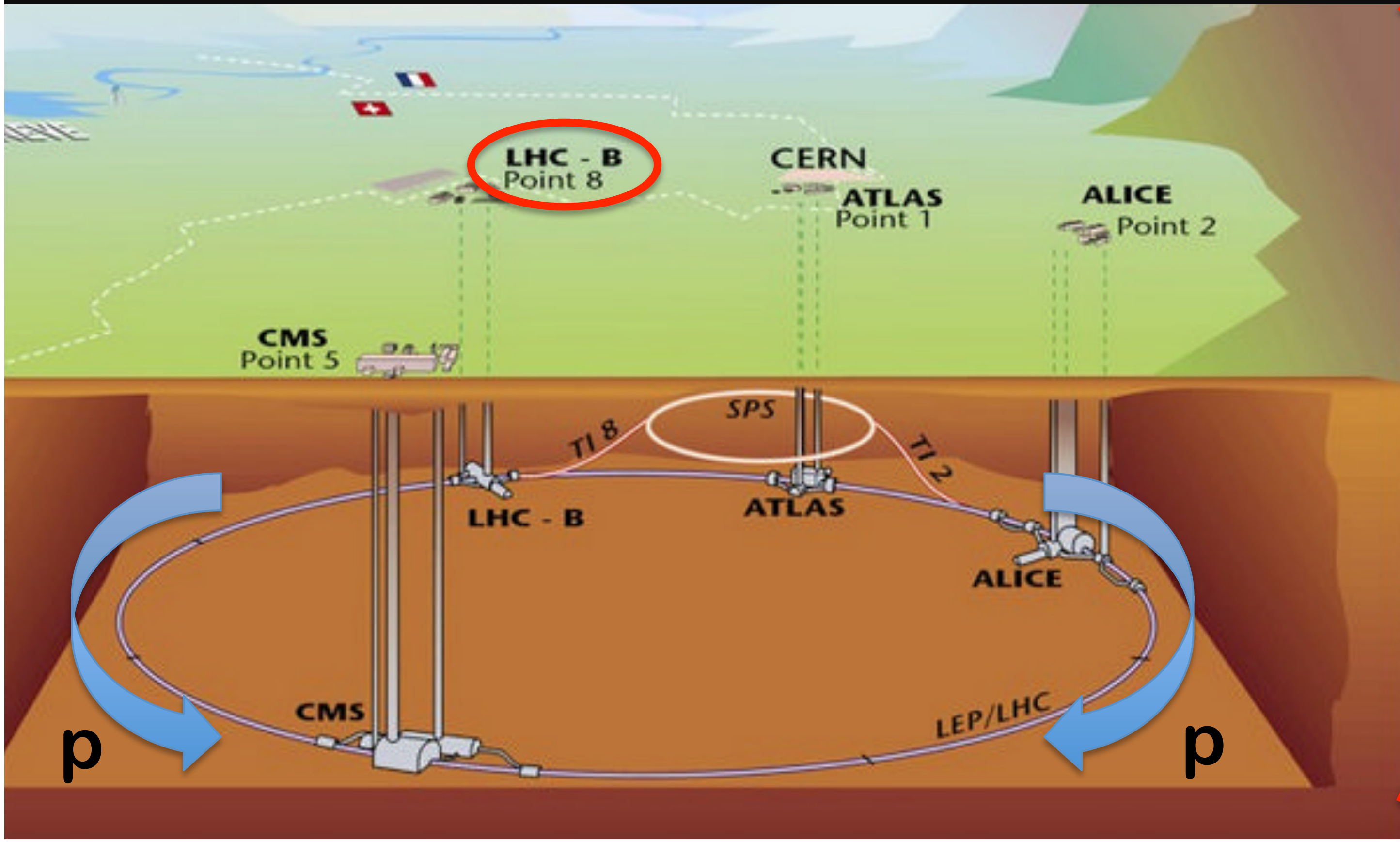
Outline

- ➡Motivation
- ➡Cern and the LHC
- ➡The LHCb experiment
- ➡J/ψ production
- ➡Open charm (few selected results)
- ➡Conclusions and outlook

CERN and the LHC



pp collider : NOW :

➡ @ $\sqrt{s}$ = 7 TeV (highest ever reached!)

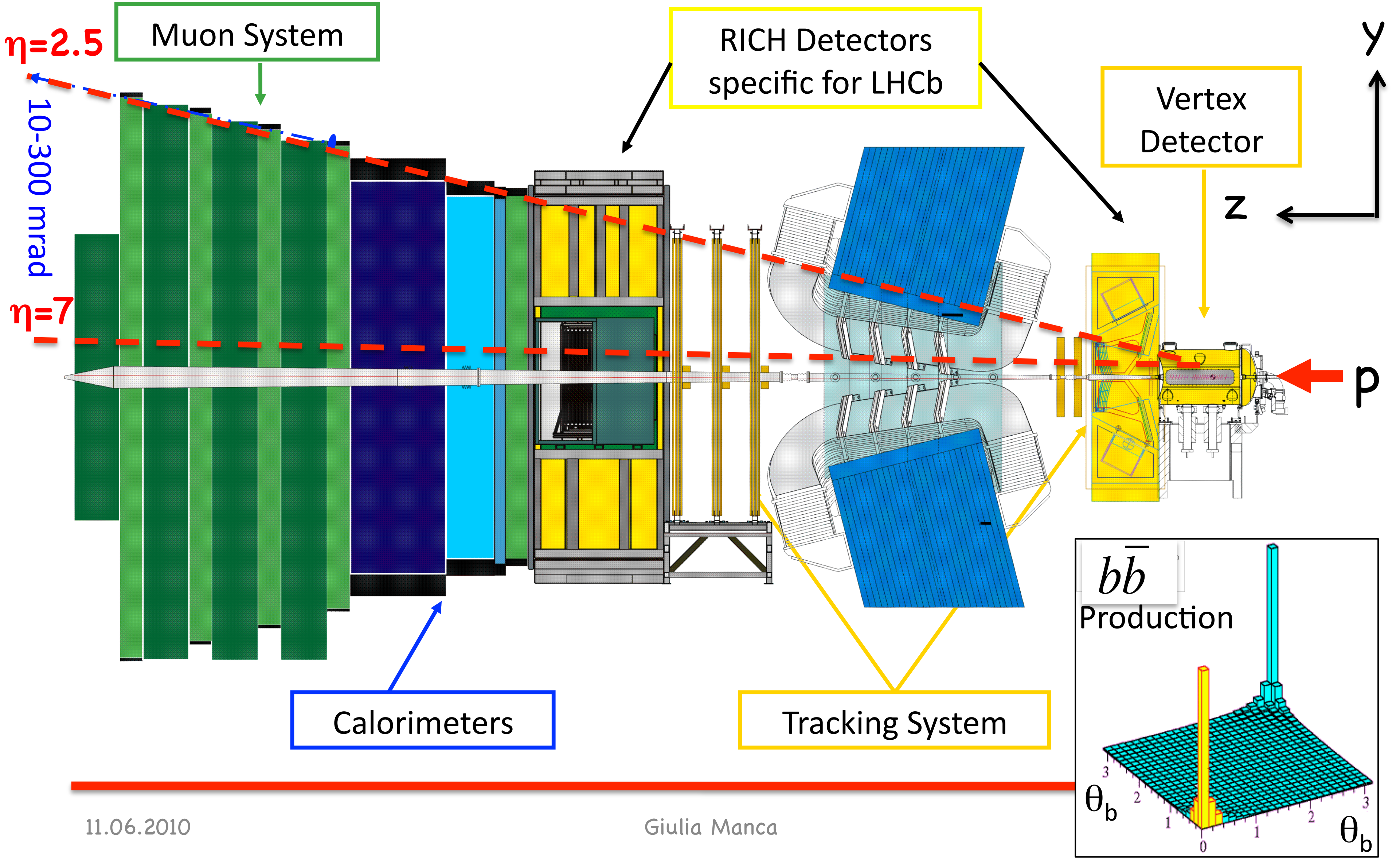
➡ L ≈ 10^{29} cm^{-2}s^{-1} -> up to 1-2·10^{31} cm^{-2} s^{-1}

NOMINAL (2011) :

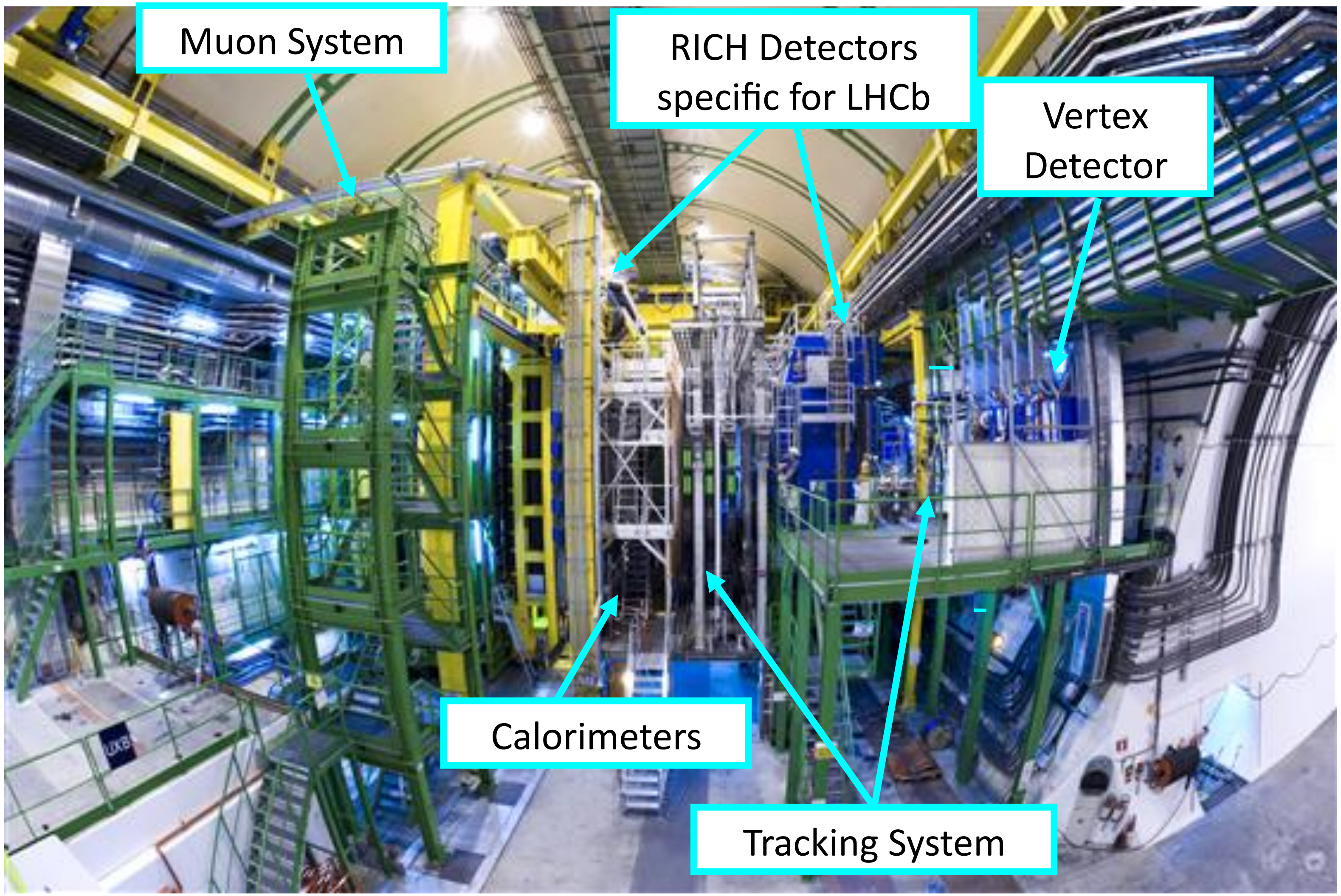
$\sqrt{s}$ =14 TeV

L = 2·10^{32} cm^{-2} s^{-1} (LHCb specific)

The LHCb detector



THE LHCb DETECTOR



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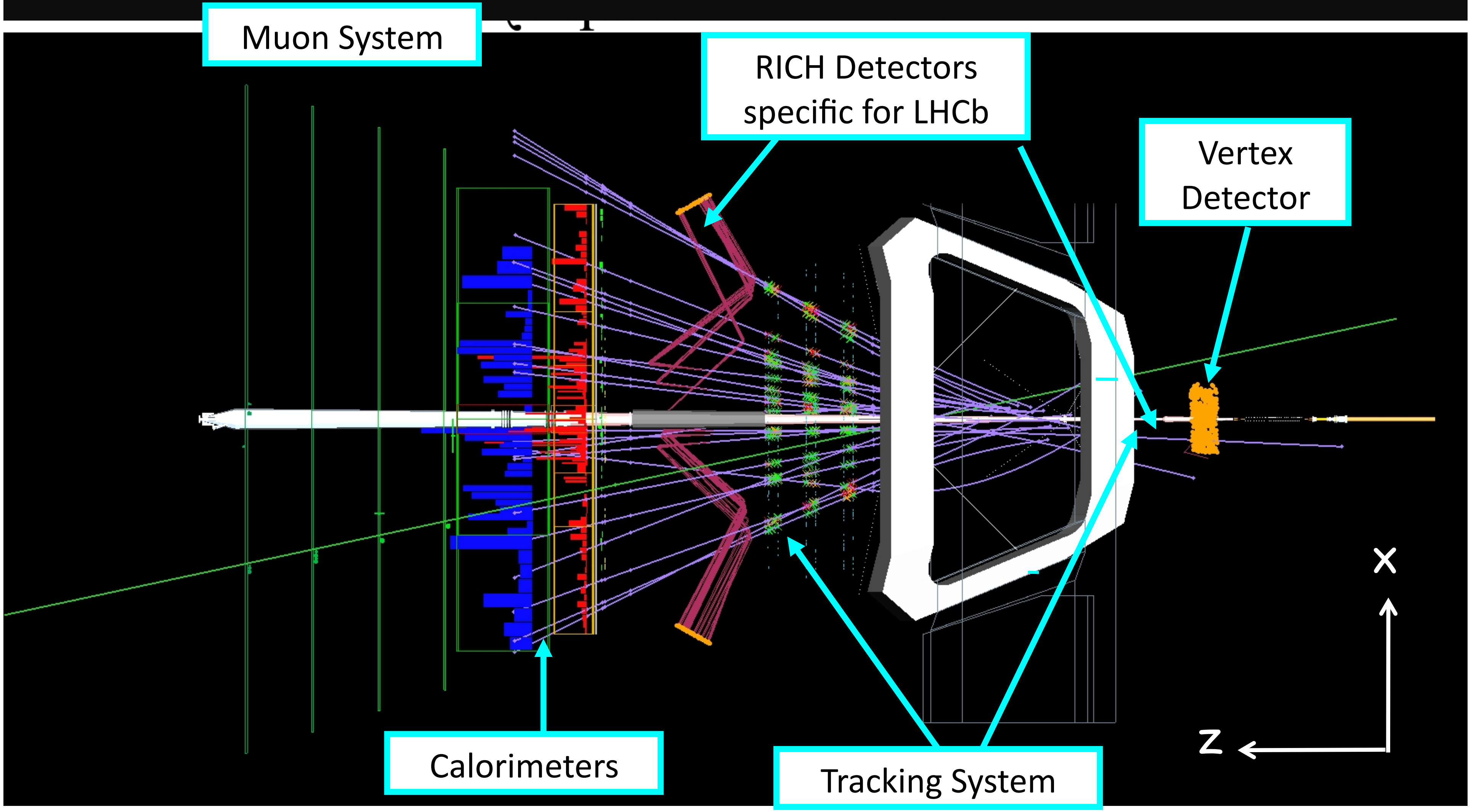
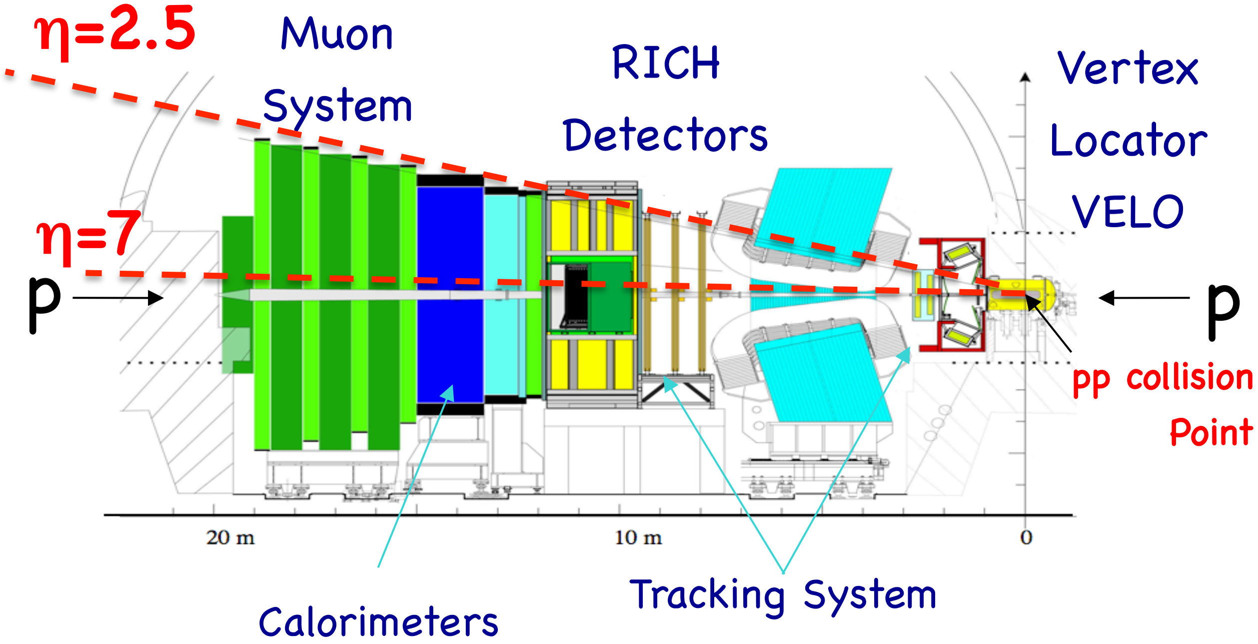


The LHCb detector

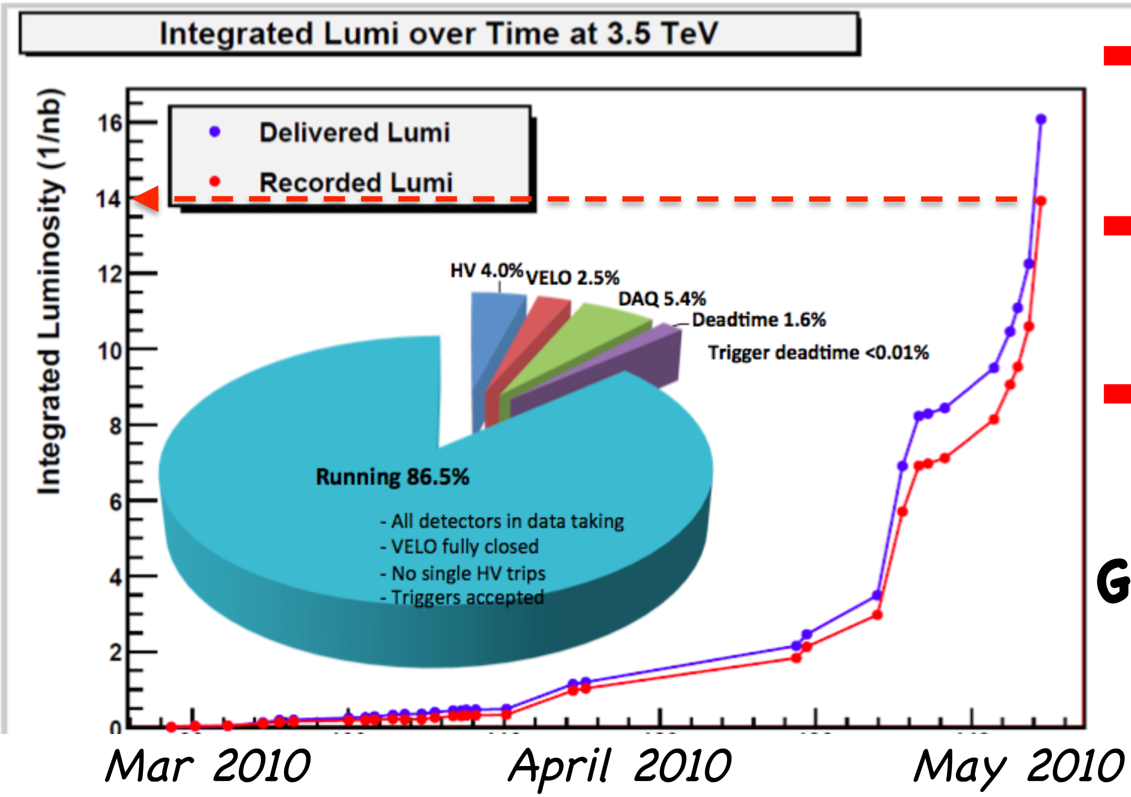
Angular acceptance : $10<\theta<300$ mrad



- 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% $(E/\mathrm{GeV})^{-1/2} \oplus 1$ %
  - Muon ID: $\varepsilon(\mu\to\mu)$ = 97%, mis-ID rate $(\pi\to\mu)$ = 1-3 %
  - Vertexing: proper time resolution 30-50 fs
  - Trigger: dominantly software

possibility to reverse field polarity to check for detector asymmetries

Luminosity



- LHCb running high efficiency ≈90%
- Already L≈16 nb^{-1} on tape
- These analyses ≈3-14 nb^{-1} (±10%)

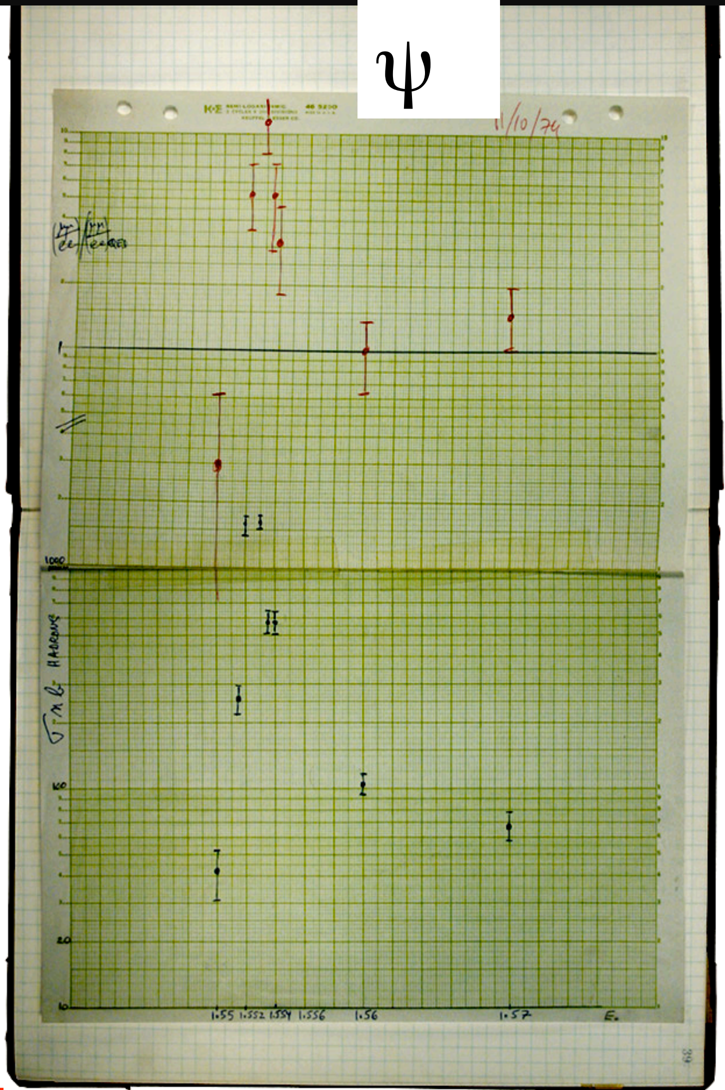
Goals :

- 1 pb^{-1} (August 2010)
- 100 pb^{-1} (end of 2010)
- 1 fb^{-1} (end of 2011)

All plots include the full luminosity L=14 nb^{-1} unless otherwise stated

J/ψ Production

ψ



J

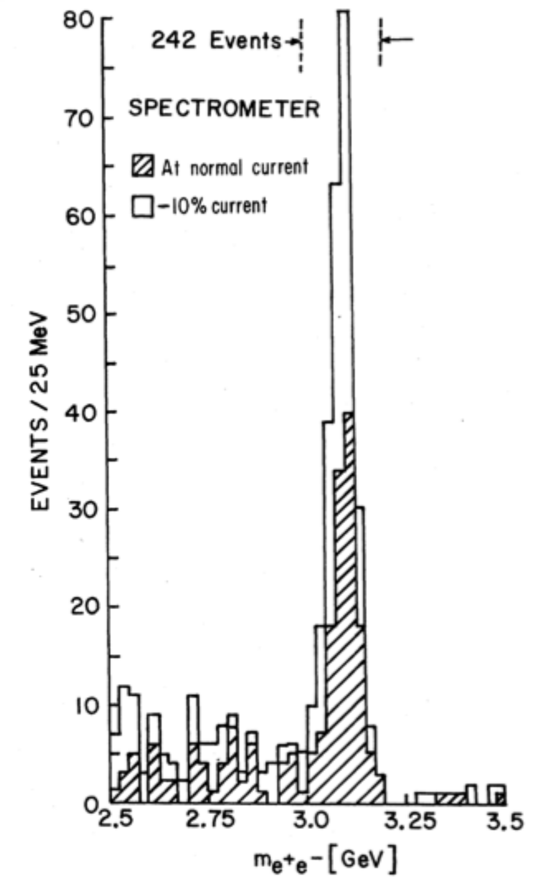


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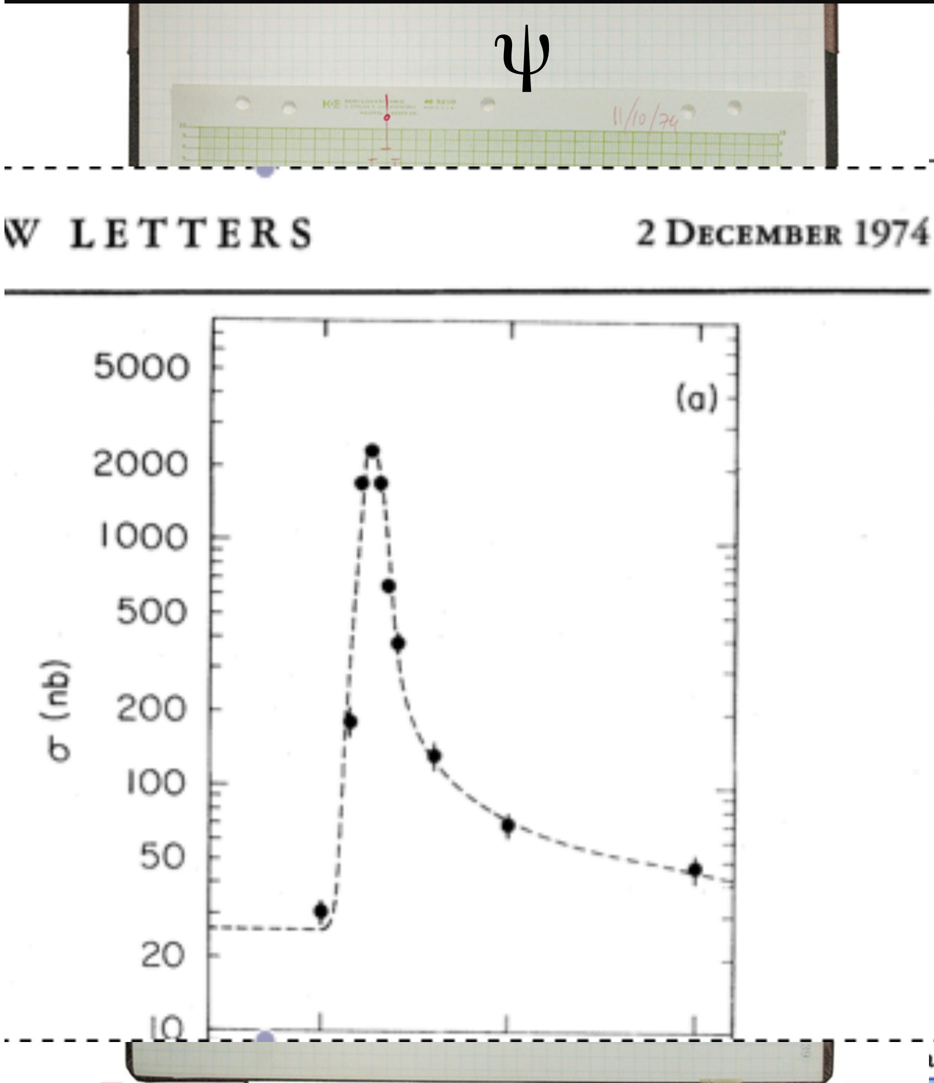
FIG. 2. Mass spectrum showing the existence of J.

J/ψ Production



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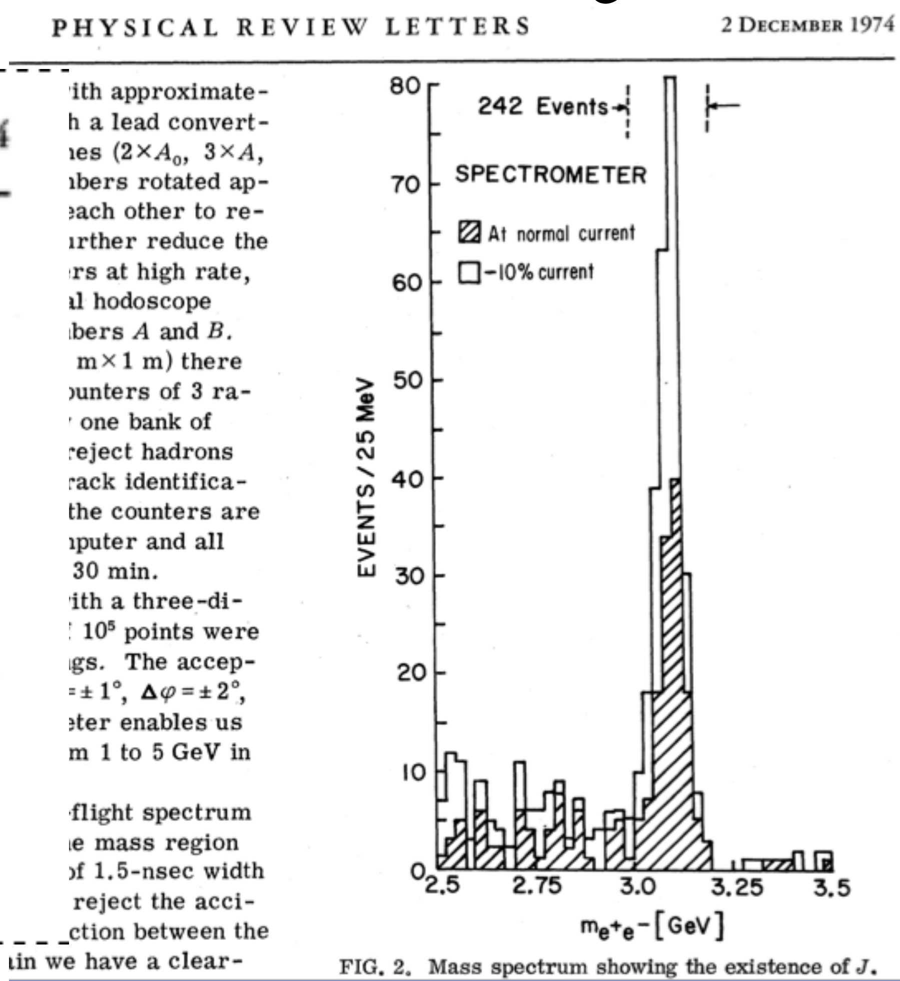
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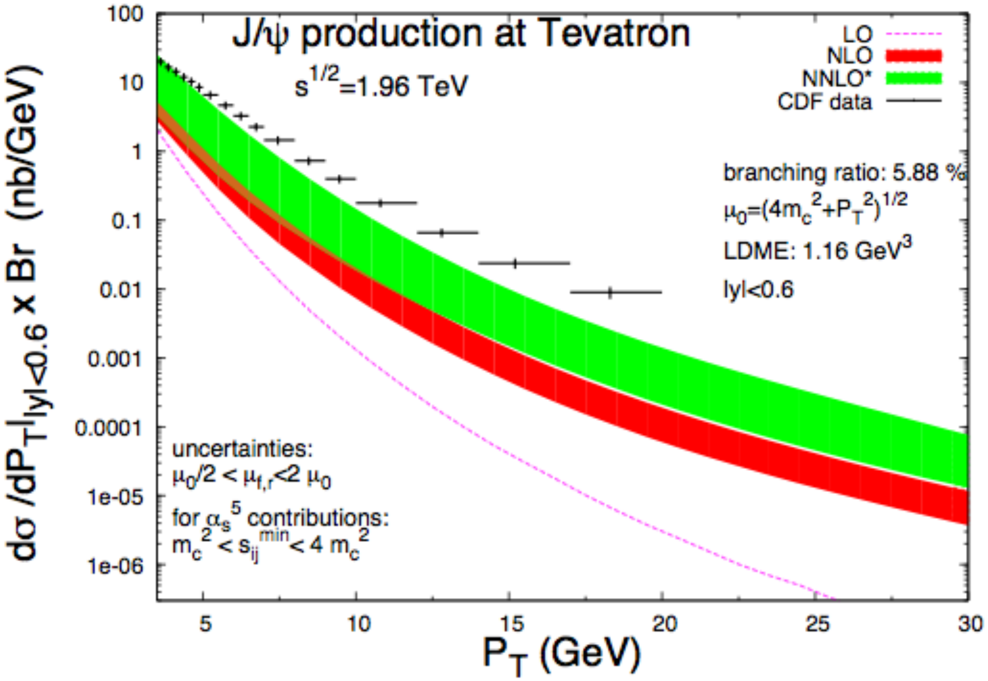
FIG. 2. Mass spectrum showing the existence of J.

Motivations

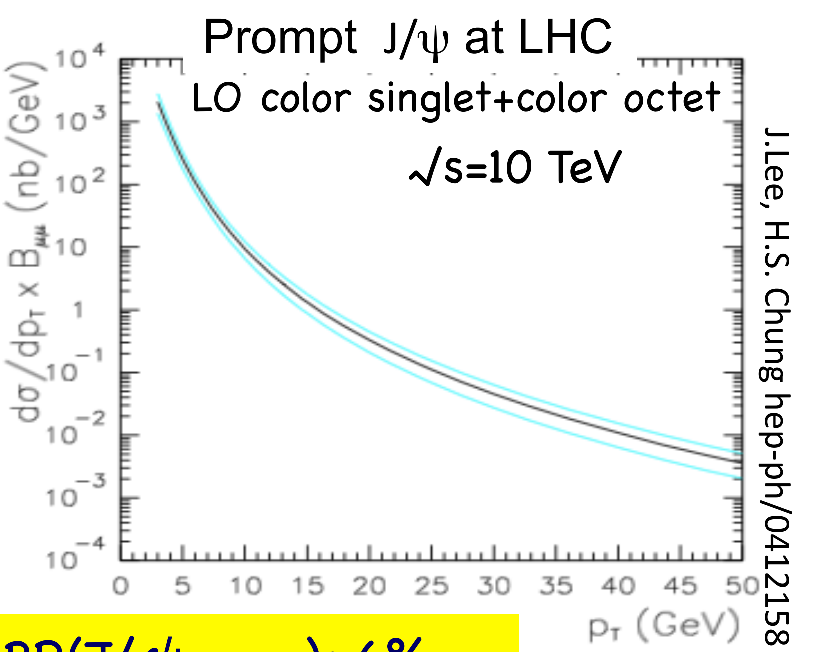
- The production mechanism in pp collisions still unclear
- Several models around :
  - Color singlet and color octet mechanisms (NRQCD) describe the p_T spectrum and cross section of the J/ψ as measured by Tevatron, but not the polarization (and has other failures)
  - Other models such as color evaporation model, kt factorization, soft color interaction model cannot describe the data either
- New data from LHC experiments will help to resolve this issue



J/ψ cross section crucial milestone in understanding detector and first step to B cross section measurement

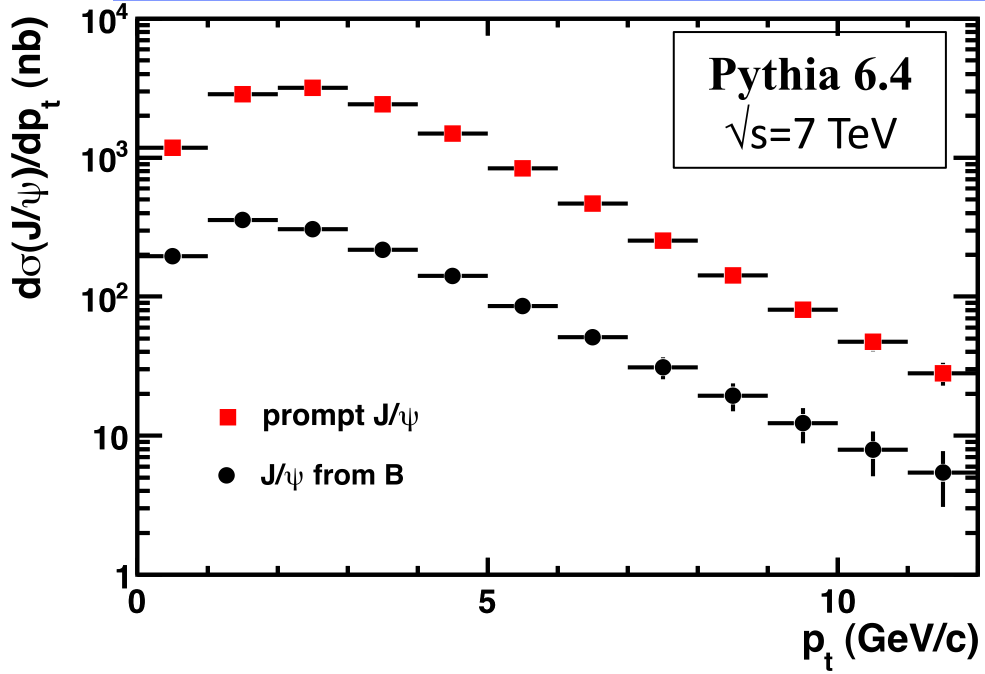
J/ψ Production at pp

1st step	2nd step	3rd step	Production type
$pp \to c\bar{c}, b\bar{b} + X$	$c\bar{c} \to J/\psi + X$		Prompt,direct
	$c\bar{c} \to \chi_{c1}, \chi_{c2} + X$	$\chi_c \to J/\psi + \gamma$	Prompt,indirect
	$b\bar{b} \to B + X$	$B \to J/\psi + X$	Delayed,indirect

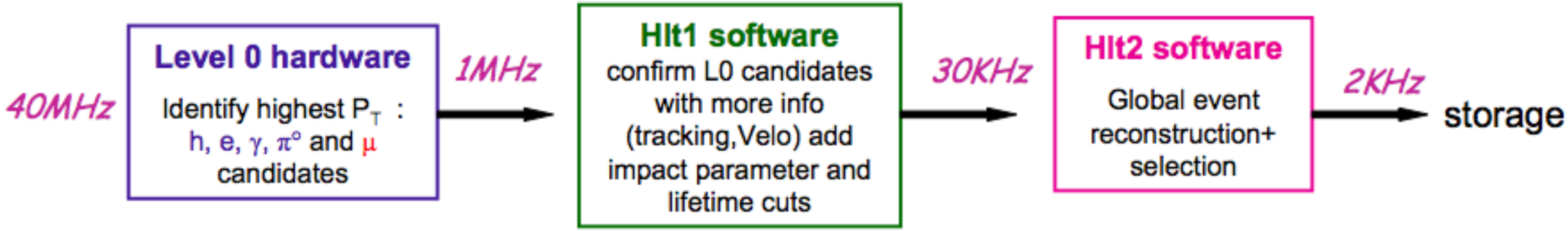


BR(J/ψ →μμ)≈6%

Using our MC samples (unpolarised J/ψ)

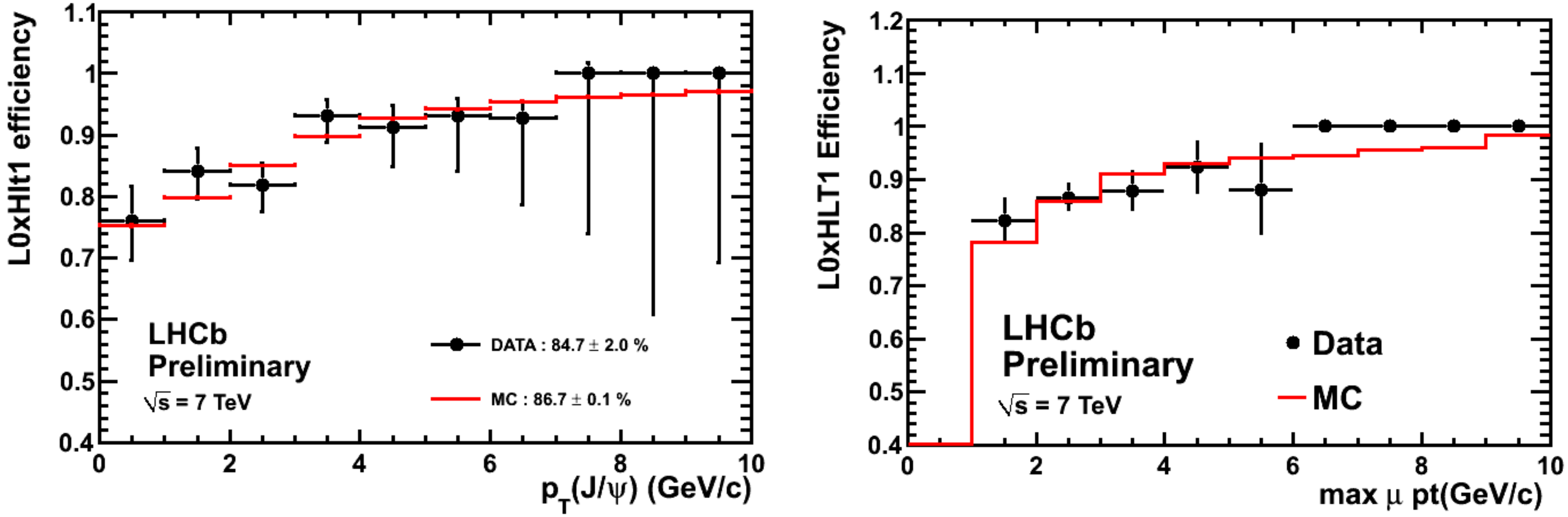


LHCb Trigger

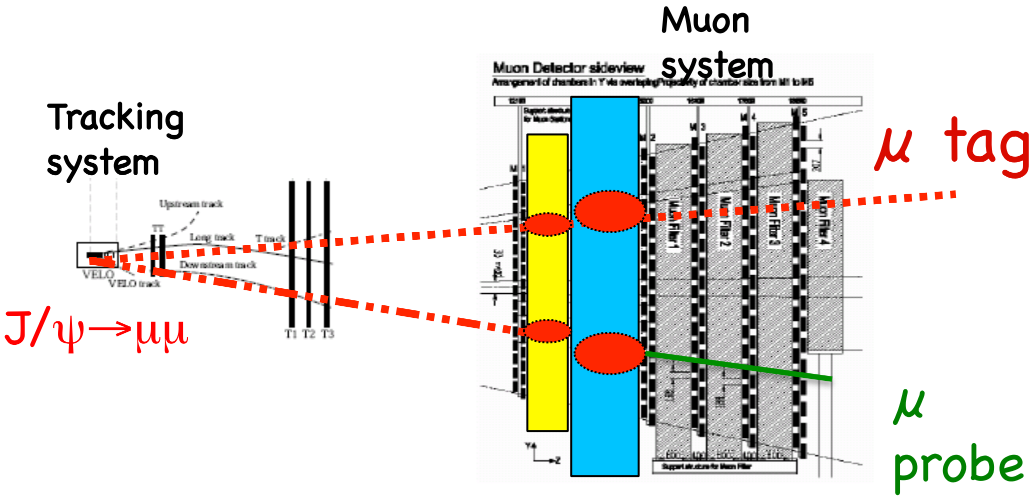


Measure muon trigger efficiencies using trigger lines not involving muons

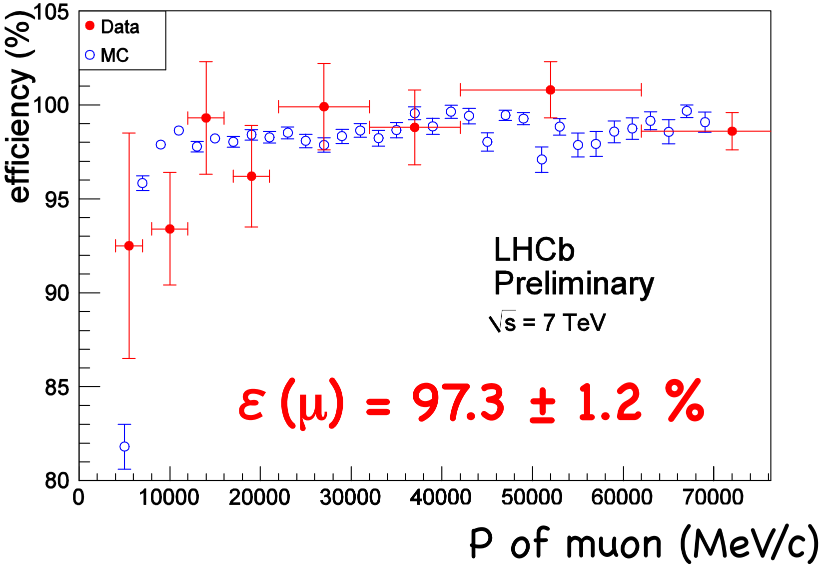
L0 x HLT1 Efficiency J/ψ->μμ

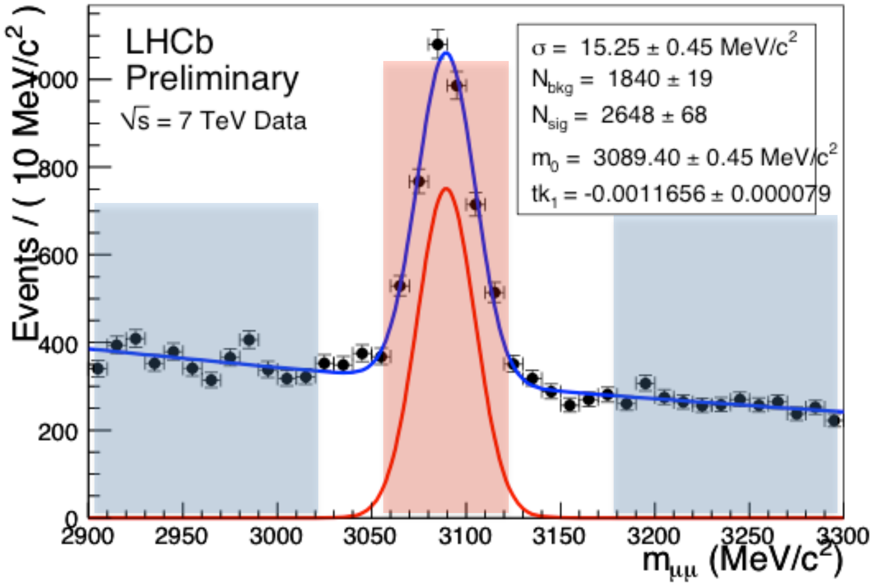


Muon Reconstruction Efficiency



J/ψ used to measure the Muon reconstruction efficiency



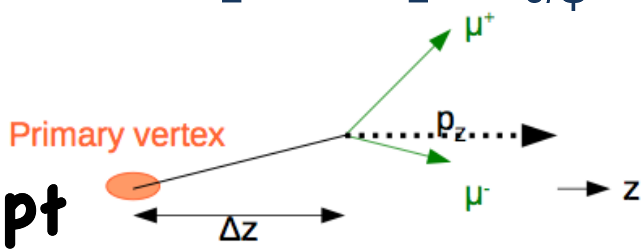


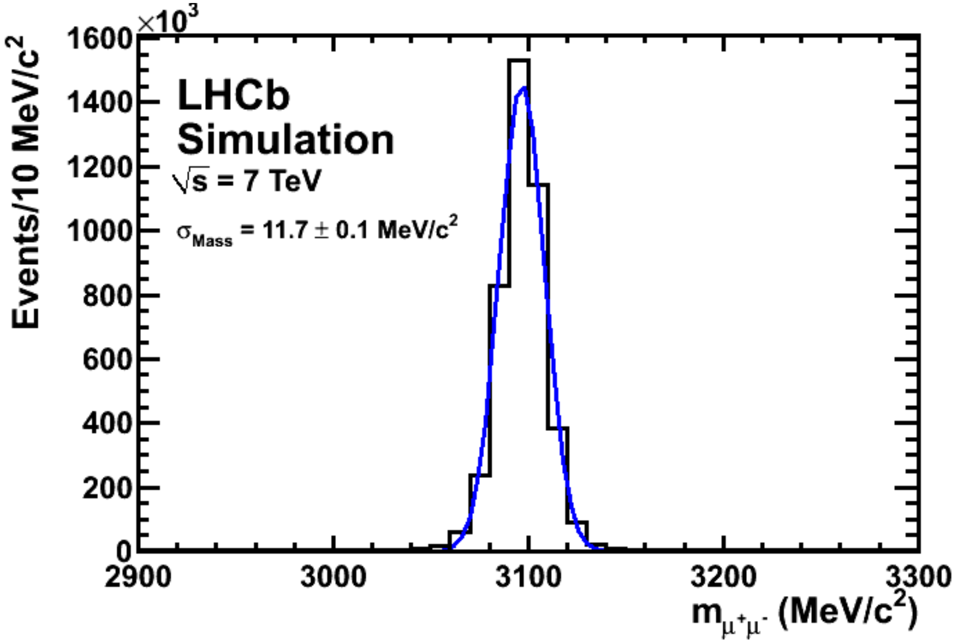
J/ψ

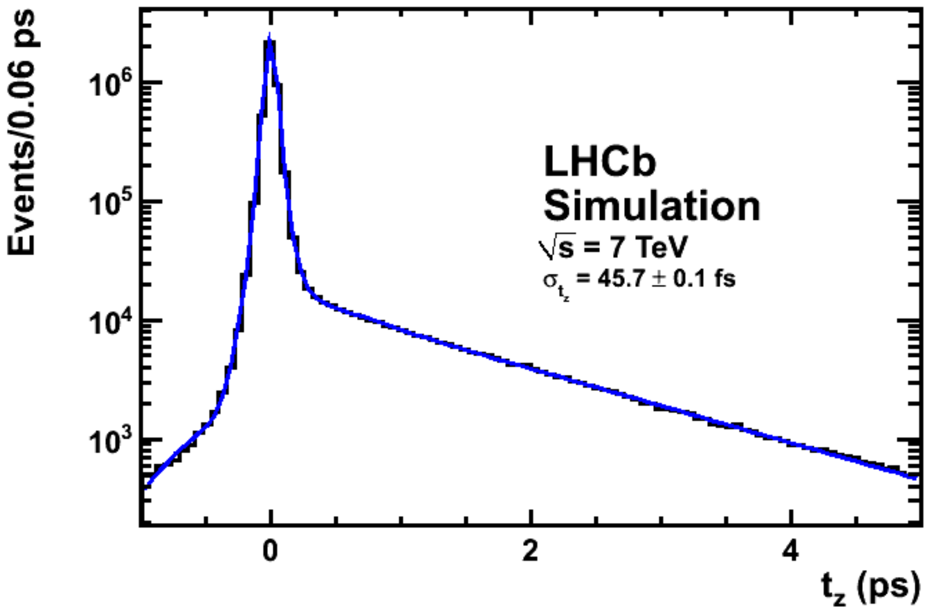
MC expected

- ➡ J/ψ cross sections ≈15 μb
- ➡ Mass resolution ≈11 MeV/c²
- ➡ t_z used to separate J/ψ prompt from J/ψ from B

$t_z = \Delta z / p_z * M_{J/\psi}$







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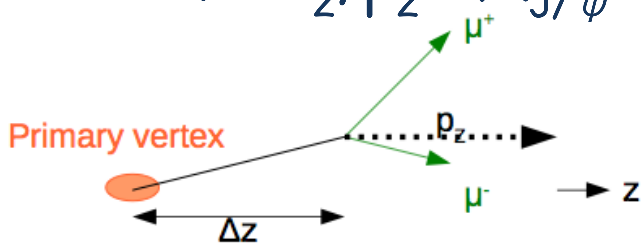
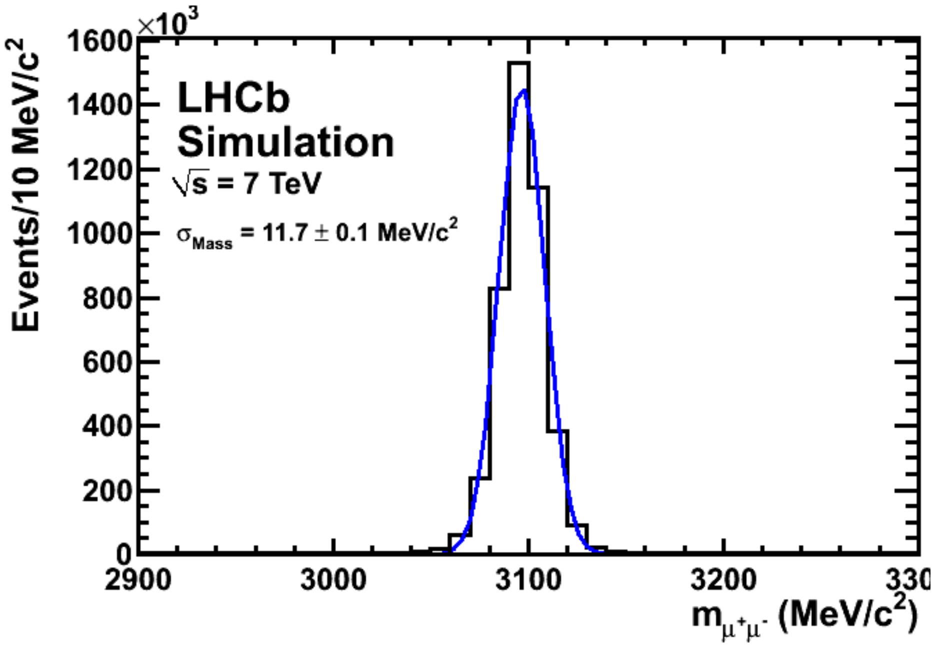
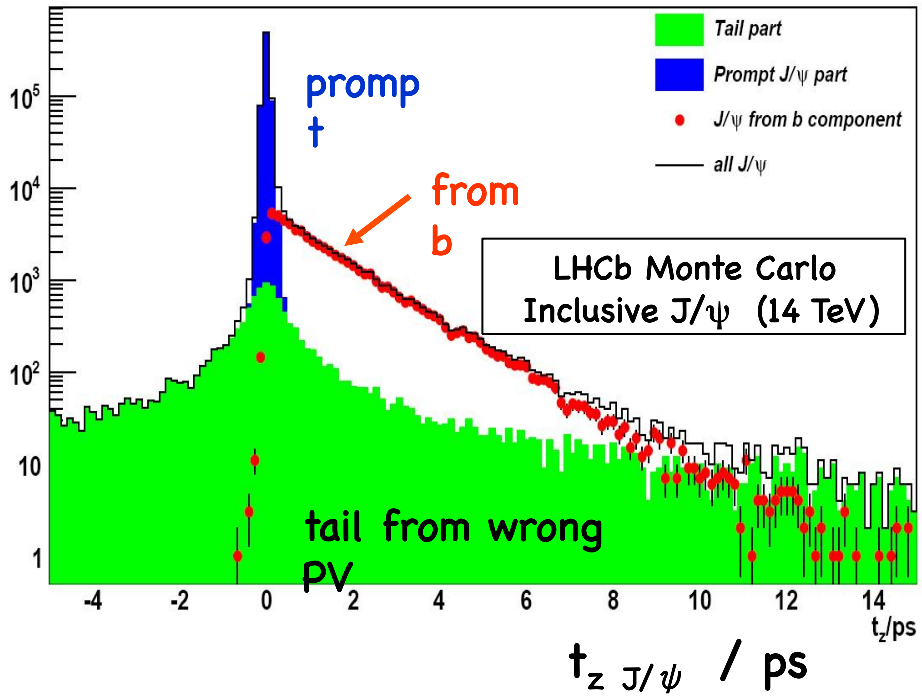


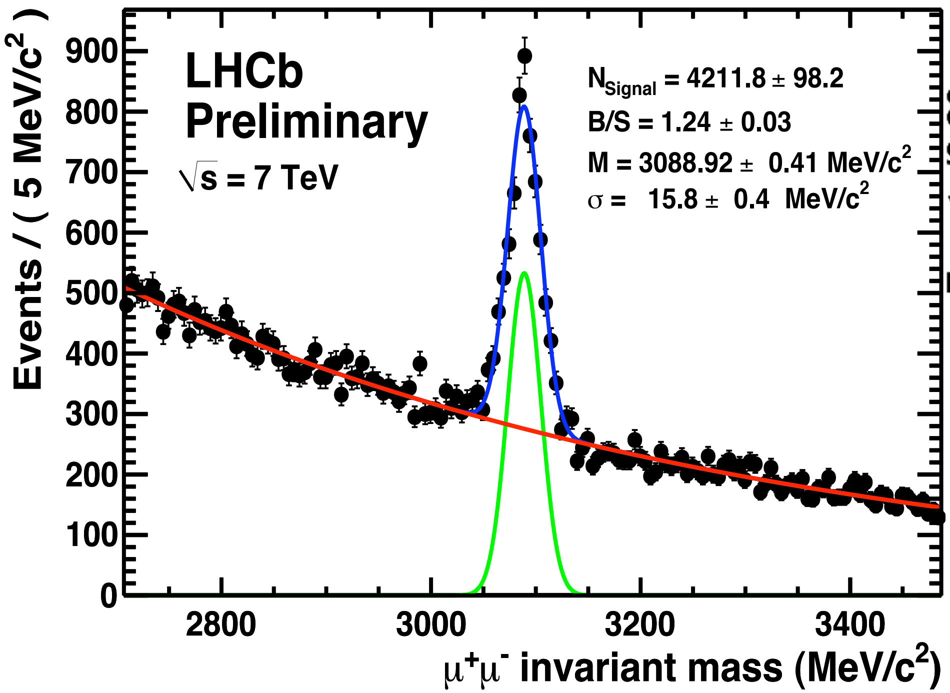


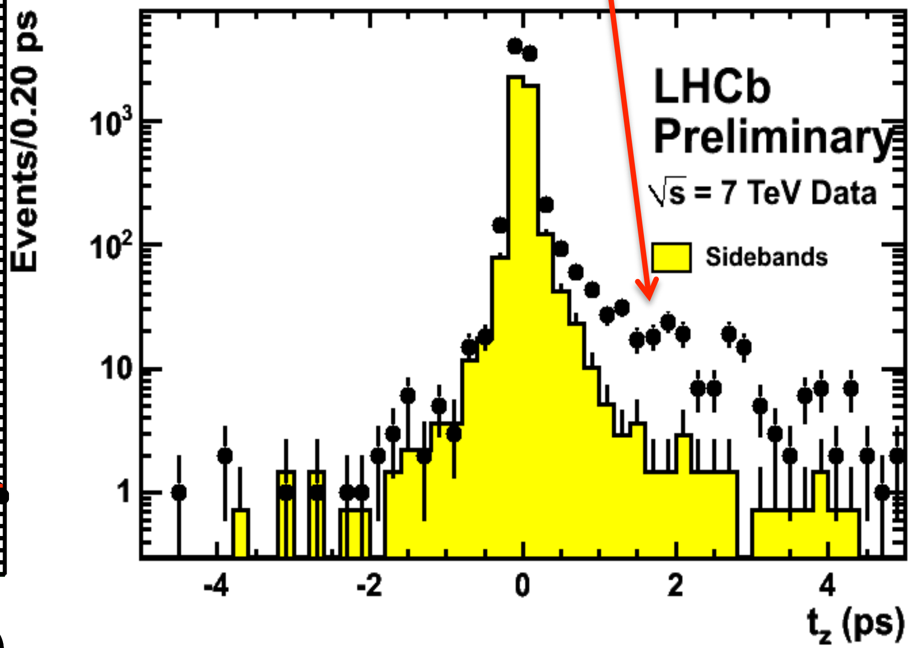


J/ψ

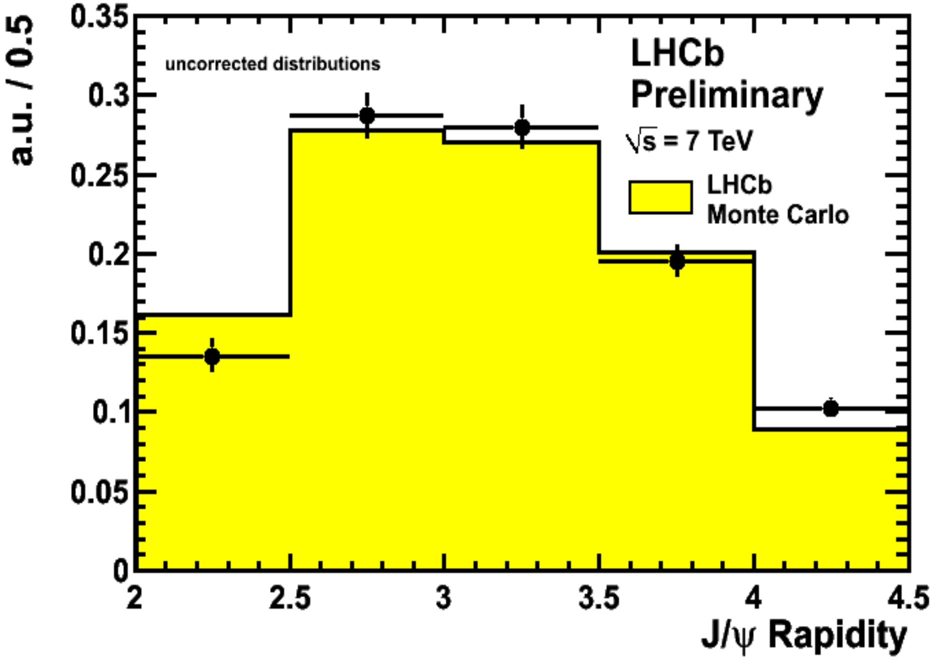
Data Observed

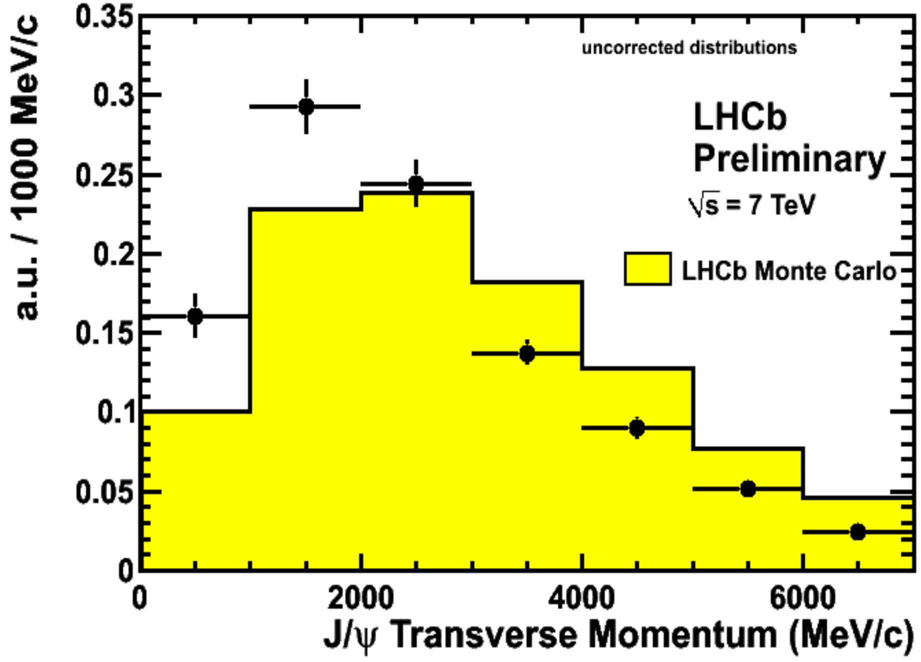
- J/ψ rate ≈300/nb^{-1}
- Mass resolution ≈16 MeV/c^2
- t_z used to separate J/ψ prompt from J/ψ from B





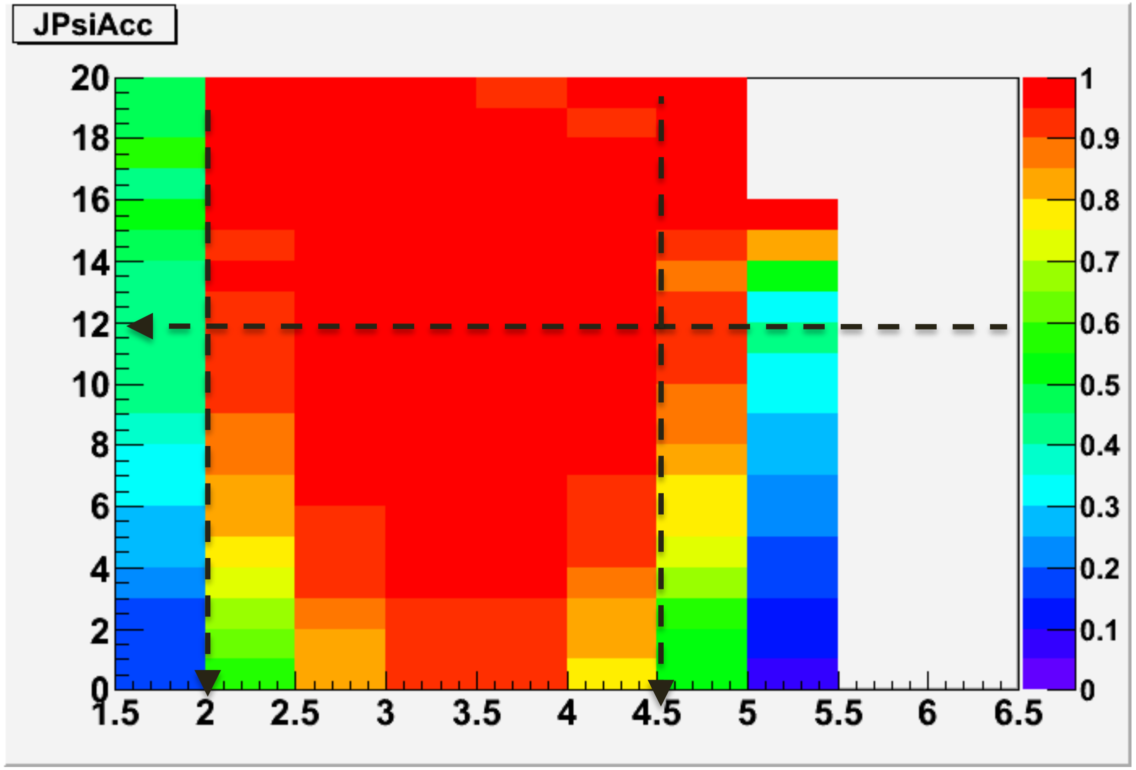
J/ψ p_T and y spectra

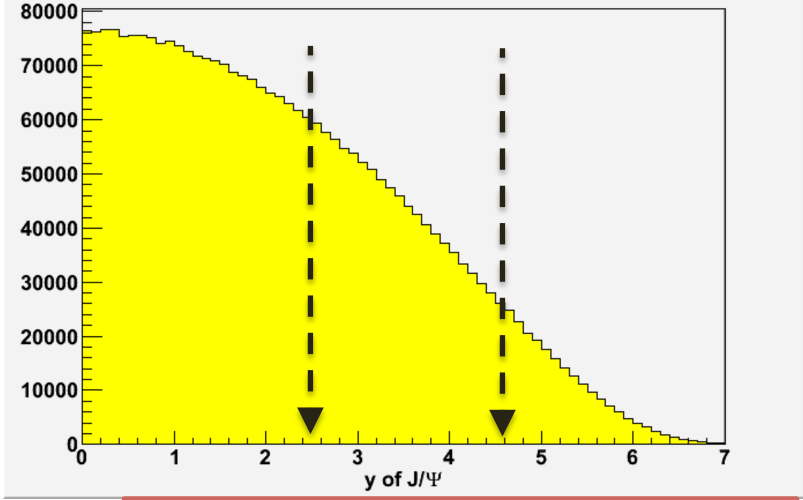




- In each bin, J/ψ yield extracted from mass distribution
  - no correction applied
  - spectrum contains prompt J/ψ and b → J/ψ
- Variables to be used for the cross section calculation in bin of y,pt (expected in late summer);

J/ψ Acceptance





Cross sections in acceptance

($2<y<4.5$, $p_T<12$ GeV/c)

Pythia 6.4, $\sqrt{s}$=7 TeV

- pp → prompt J/ψ + X

  $\sigma = 13.0 \pm 0.1\ \mu b$

- pp → b → J/ψ + X

  $\sigma = 1.4 \pm 0.1\ \mu b$

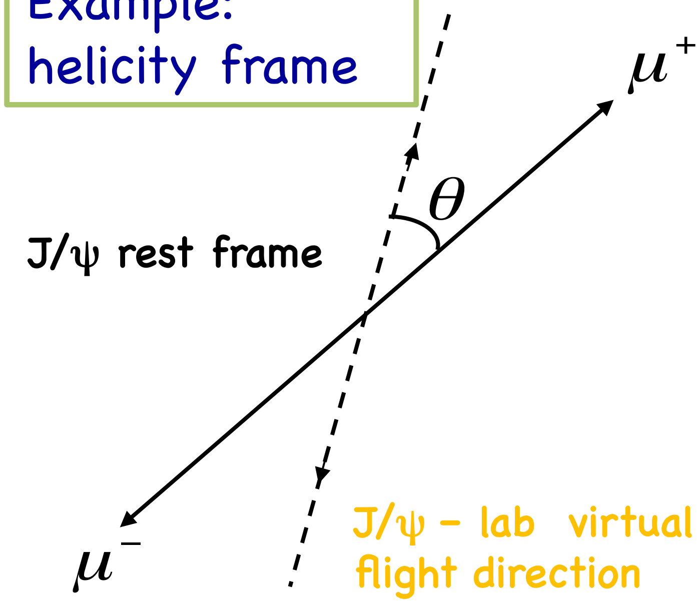
Total Acceptance≈13%

LHCb Acceptance 85%

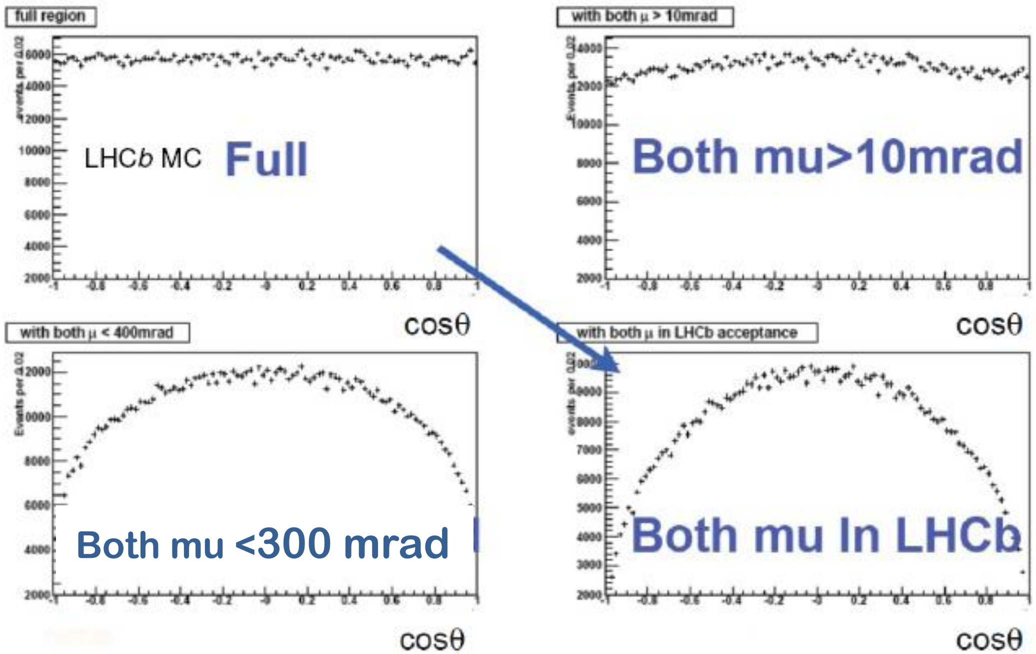
Influence of J/ψ Polarization

- Detector acceptance as a function of helicity angle cosθ

Example:
helicity frame



MC with no polarization



➡ 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 %

➡ *Follow up: <u>Measure polarization</u>*

- ✓ in bins of η and p_T
- ✓ separating prompt and J/ψ from b
- ✓ with full angular analysis, in different reference frames

Example Cross section Measurement @$\sqrt{s}$=14 TeV

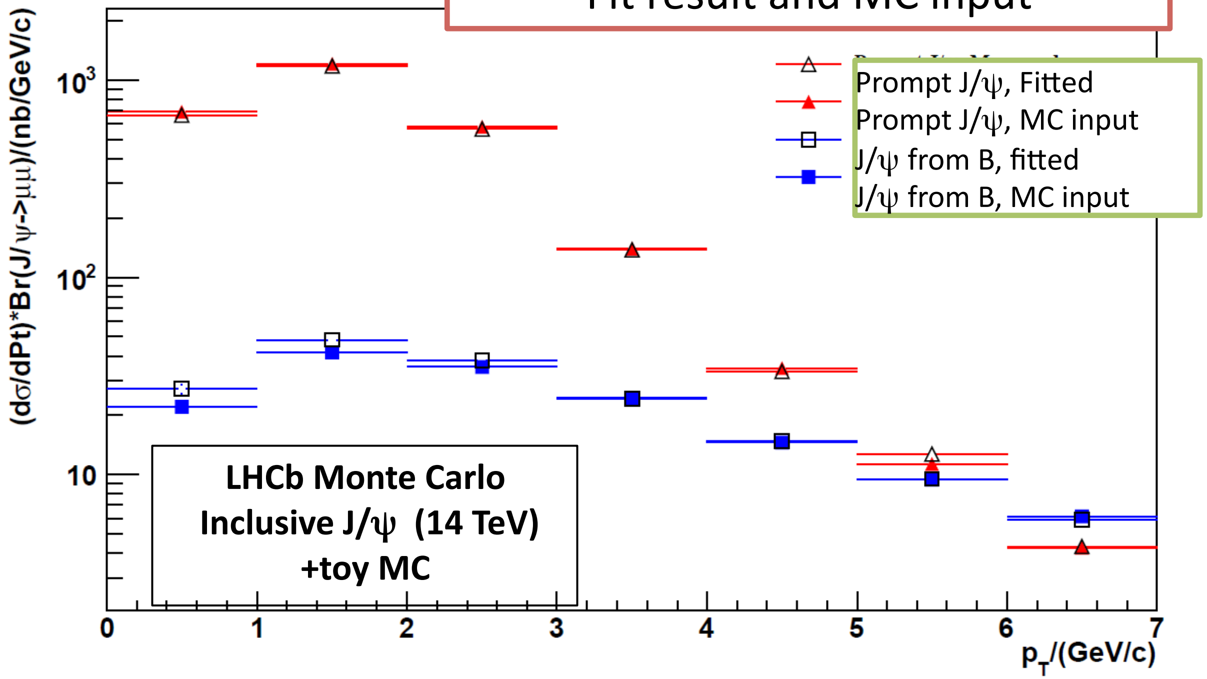
➡ **Study fit procedure to determine cross section**

- **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**

At $\sqrt{s}$=7 TeV we will be able to perform a double differential cross section measurement with O(10) pb^{-1}

Fit result and MC input



Open Charm

Open Charm Production at LHCb

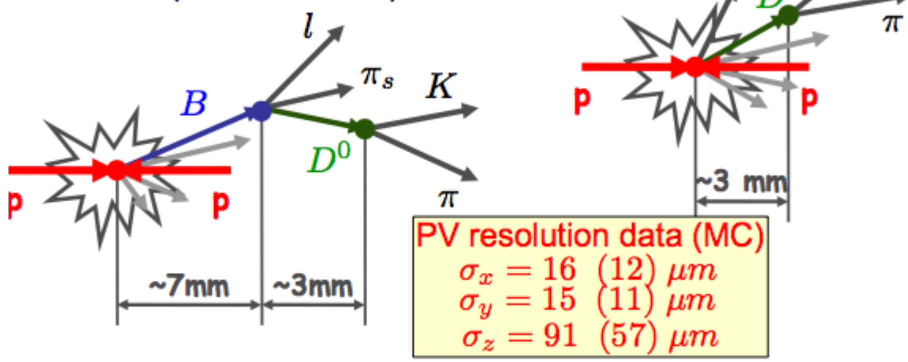
➡ Open charm signals

- probe of new physics
- measurement CP violation
- measurement mixing

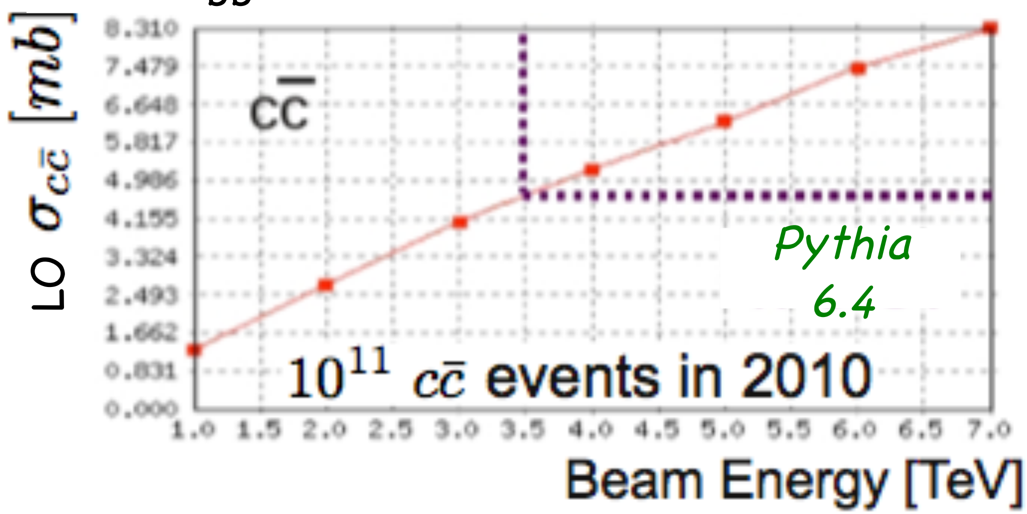
➡ Charm production cross-section large!

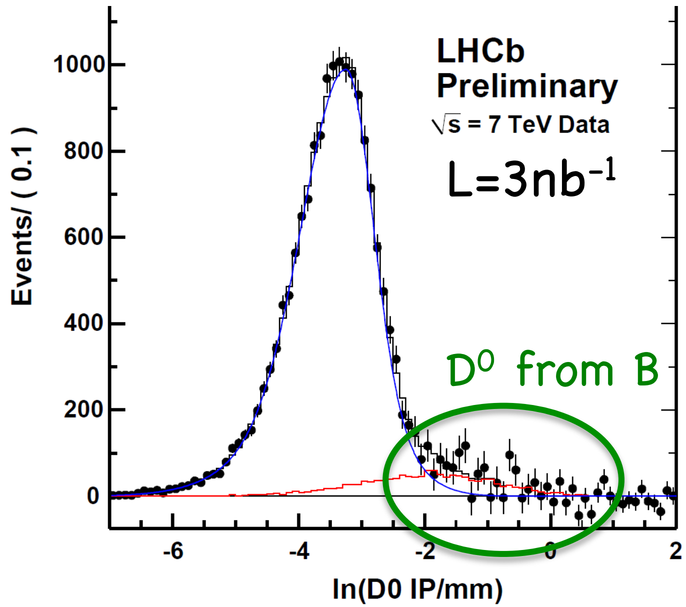
➤ Prompt and secondary charm

$BR(B \to D^{*\pm} X) \approx 0.23$



$\sigma_{bb} \approx 0.3-0.5$ mb @ 10-14 TeV



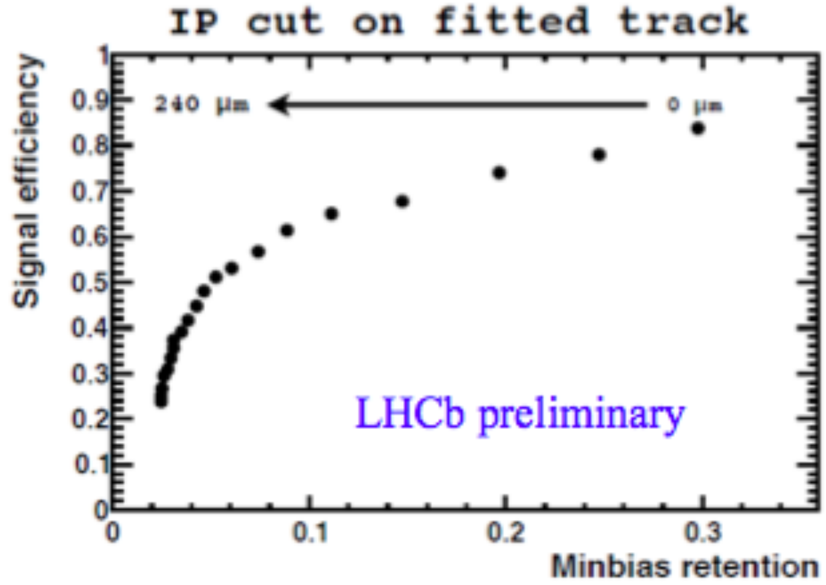


Open Charm Triggers

- **Lower luminosity**
  - trigger thresholds relaxed

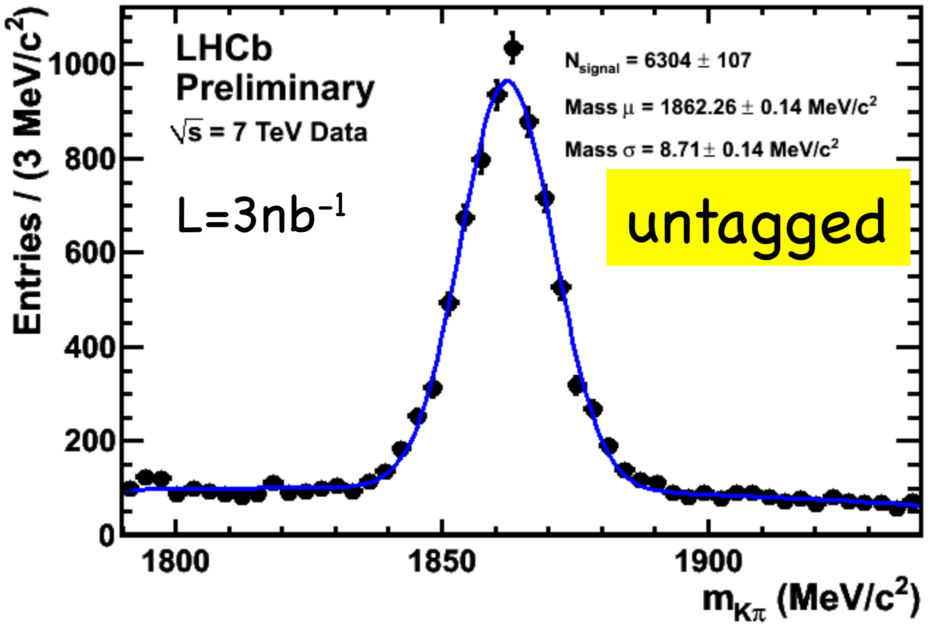
->great opportunity for charm physics!

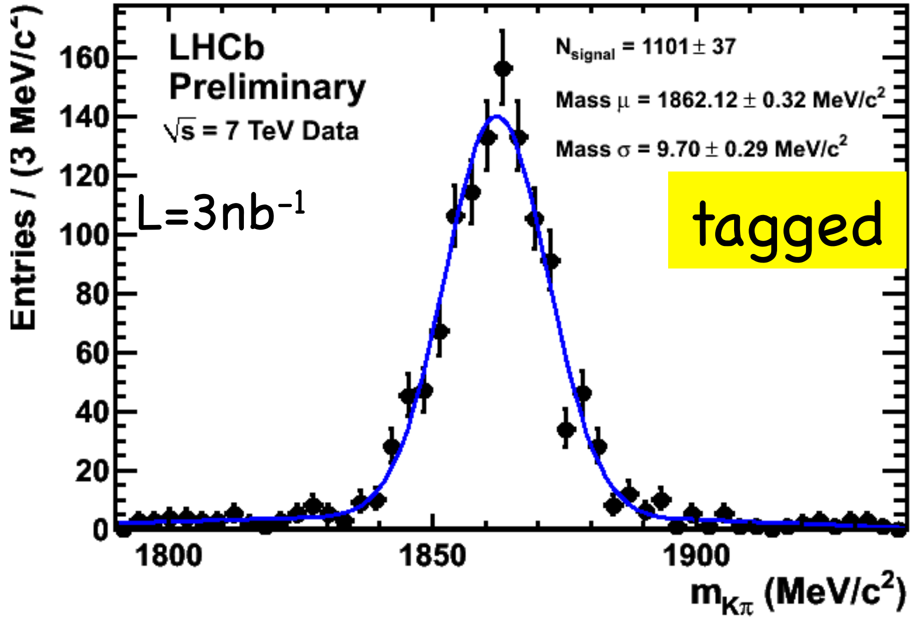
Rate vs. Efficiency $D^+ \to K\pi\pi$



	collision rate	L0	HLT1	HLT2	$\epsilon_{prompt\ D}$	
2010	~~< 2 kHz~~	~~minimum bias trigger~~			~~$> 90\%$~~	
	< 25 kHz	< 25 kHz	2 kHz		40-50%	p_T , IP thresholds
	< 300 kHz	< 300 kHz	10 kHz	2 kHz		
2011	nominal	1 MHz	20 kHz	2 kHz	10%	increasing

D^0->$K\pi$ Decay



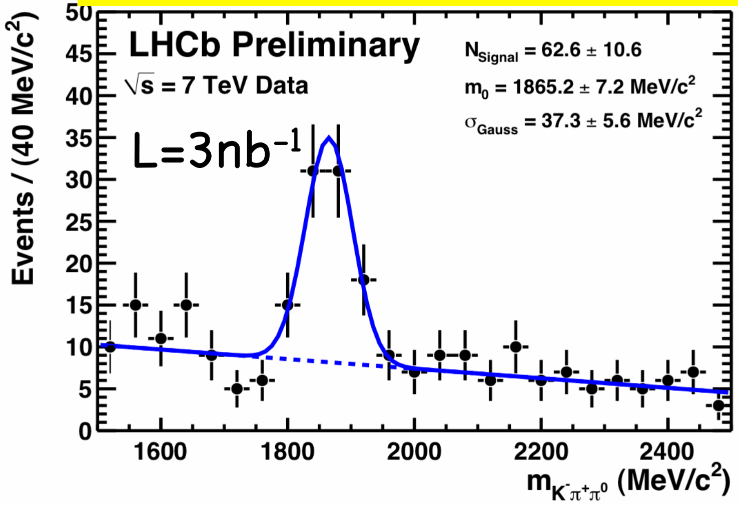


- Untagged and tagged (from D* decay) D^0->$k\pi$ decays
- Uncalibrated masses within few permilles of PDG value
- High yields -> excellent modes for cross section estimate
- Towards the D^0-D^0bar mixing measurement

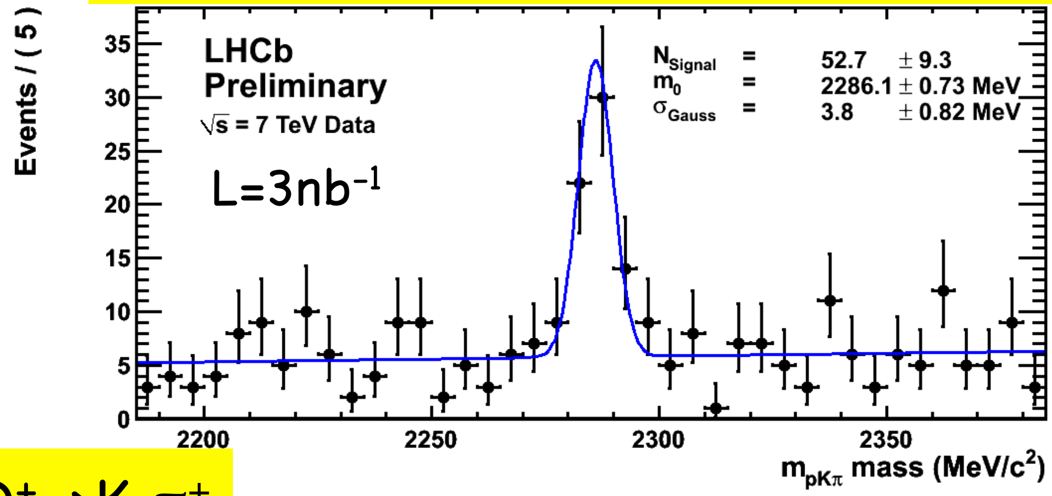
More Charm Signals

➡ Open charm signals from minimum bias 2010 first data

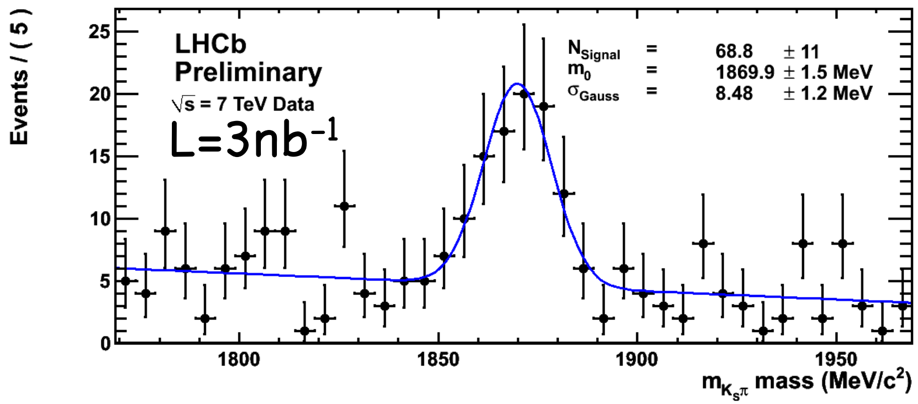
$D^0 \to K^- \pi^+ \pi^0$: neutrals!



$\Lambda_c^+ \to pK^- \pi^+$:good vertex resolution

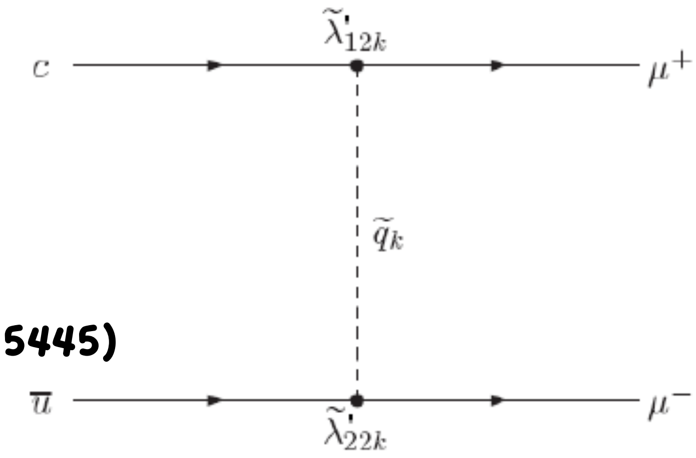


$D^+ \to K_s \pi^+$



New physics in $D^0 \to \mu^+\mu^-$

- Highly suppressed decay in the SM:
  $BR(D^0 \to \mu^+\mu^-) \approx 3.10^{-13}$
- Can be enhanced in MSSM with R-parity violation up to 10^{-7}



- Current best experimental limit by Belle
  $BR(D^0 \to \mu^+\mu^-) < 1.4\ 10^{-7}$ @ 90%CL (arXiv:1005.5445)
- Analysis overview :
  - Use $D^* \to D^0\ \pi$
  - Preselection cuts
  - Multivariate analysis based on impact parameter, pT, difference in ϕ and η between the D^0 and soft π
  - Normalization to $D^0 \to \pi\pi$
  - ⇒ Similar to $B_s \to \mu\mu$ but more difficult due to lower invariant mass and higher background
- **LHCb prospects: Expected limit for 100 pb^{-1}:**
  $BR(D^0 \to \mu^+\mu^-) < 4.10^{-8}$ @ 90% CL

Charm physics prospects

- $1\ pb^{-1}$:
  - cross sections mesurements :
    - Double differential in pt and y ($D^0 \to k^-\pi^+$, $D^+ \to k^-\pi^+\pi^+$, $D_s^+ \to k^-k^+\pi^+$, $D^{*+} \to D^0\pi^+$, $\Lambda_c^+ \to p\ k^-\pi^+$)
- $100\ pb^{-1}$:
  - Rare decays : $D^0 \to \mu\mu$,
  - D^0 mixing:
    - Time dependent : $D^0 \to k^+\pi^+$
    - y_{CP} from time differences ($D^0 \to k^+k^-$, $\pi^+\pi^-$)
  - Direct CP violation in 3 body decays

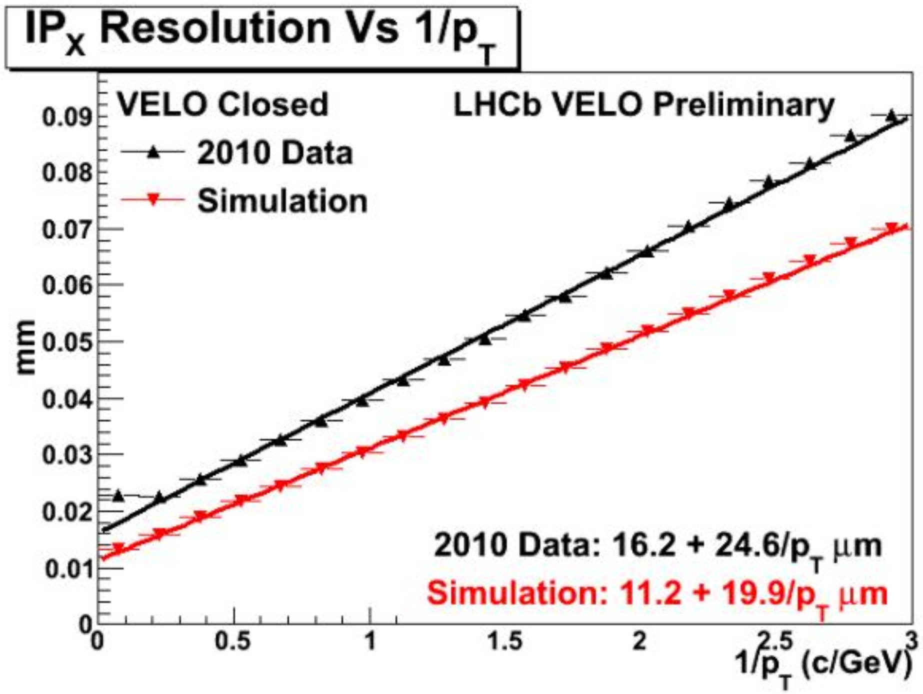
Conclusions and Outlook

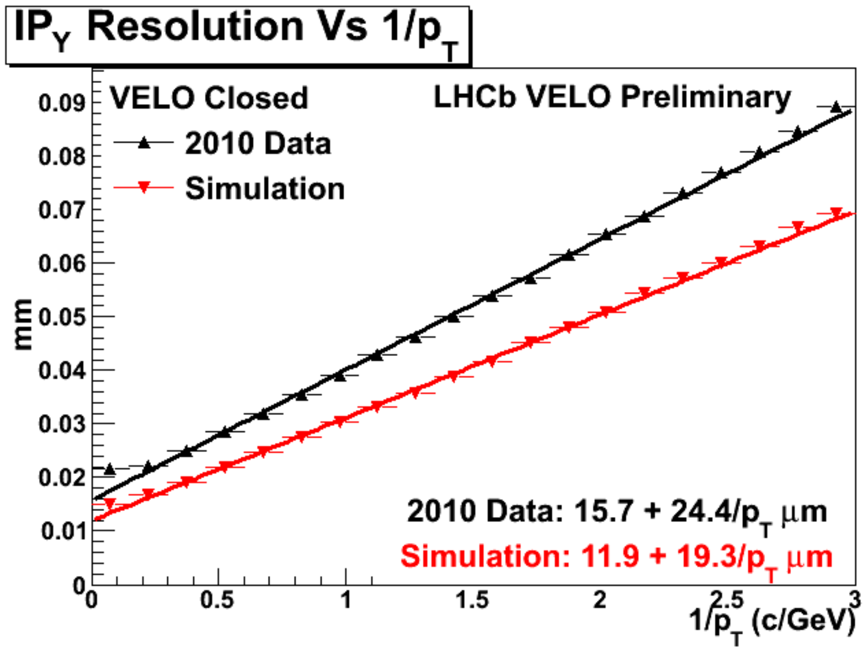
- ➡ LHC and LHCb are in great shape and LHCb is taking data with high efficiency
- ➡ All the analysis tools are in place and start to deliver physics results
- ➡ J/ψ events clearly reconstructed
  - Crucial standard candle for detector understanding as well as cross check of luminosity
  - Cross section measurements probe of non-relativistic QCD theories
- ➡ Open charm peaks well reconstructed, physics program setup and waiting for more statistics

Ready for the first measurements! Stay tuned!

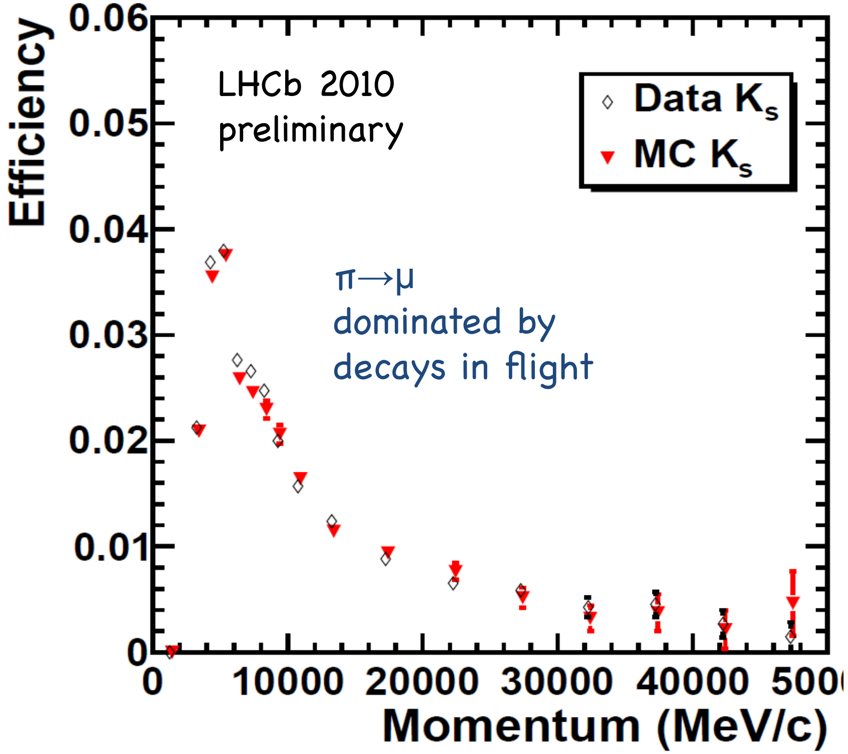
Back-up

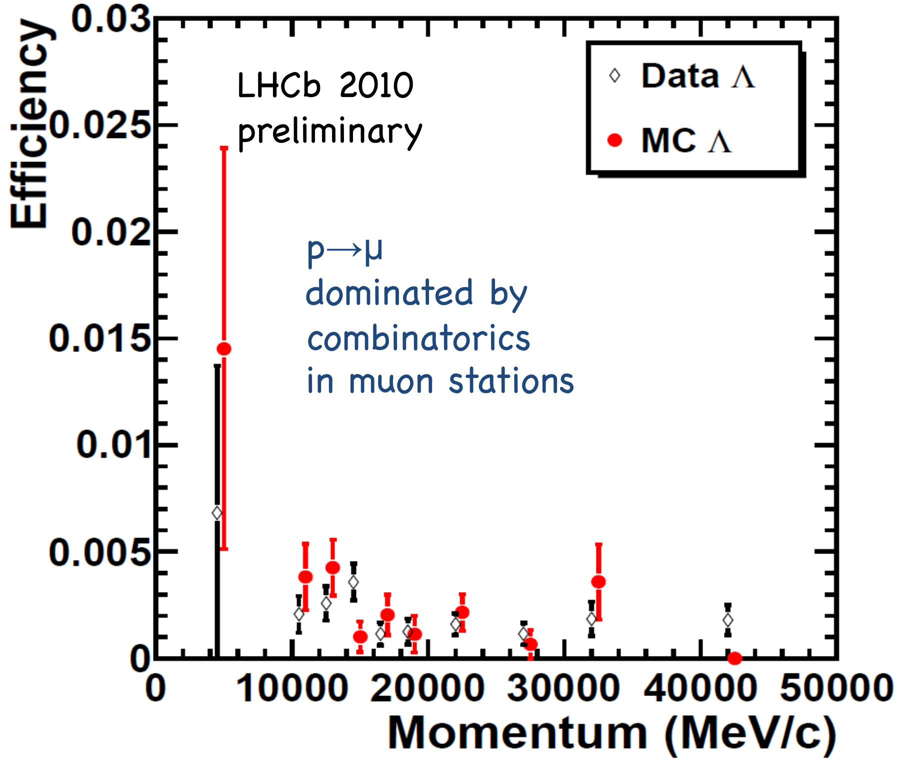
Primary Vertex resolution





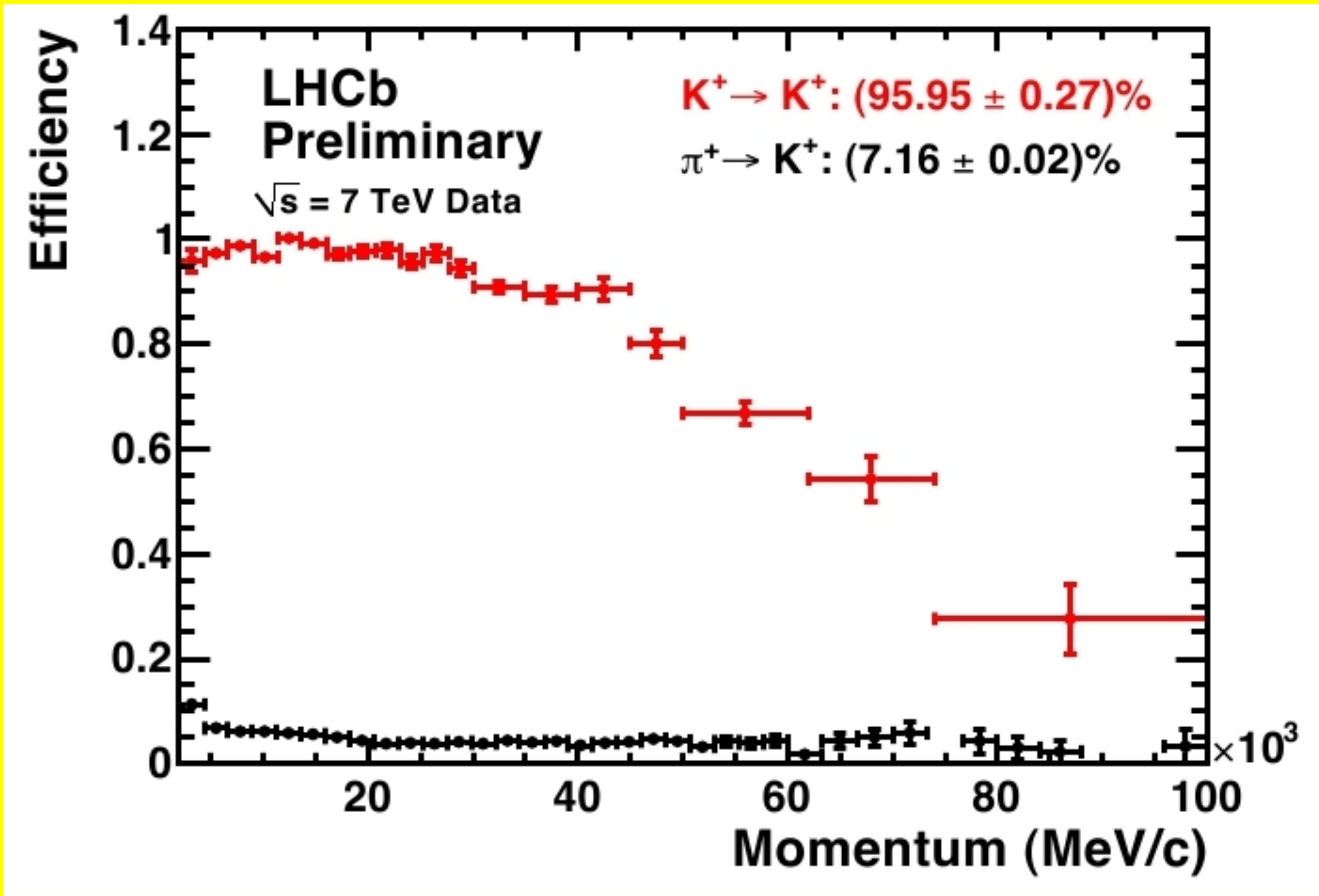
Muon mis-identification



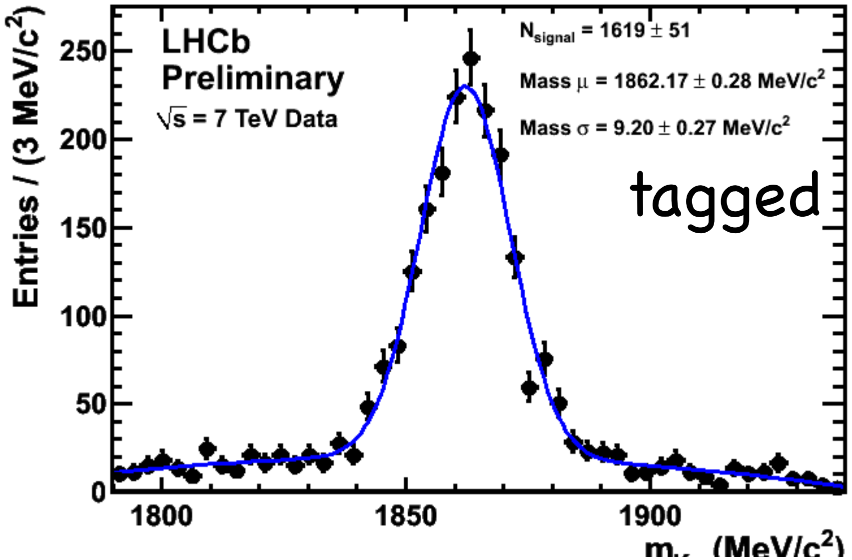


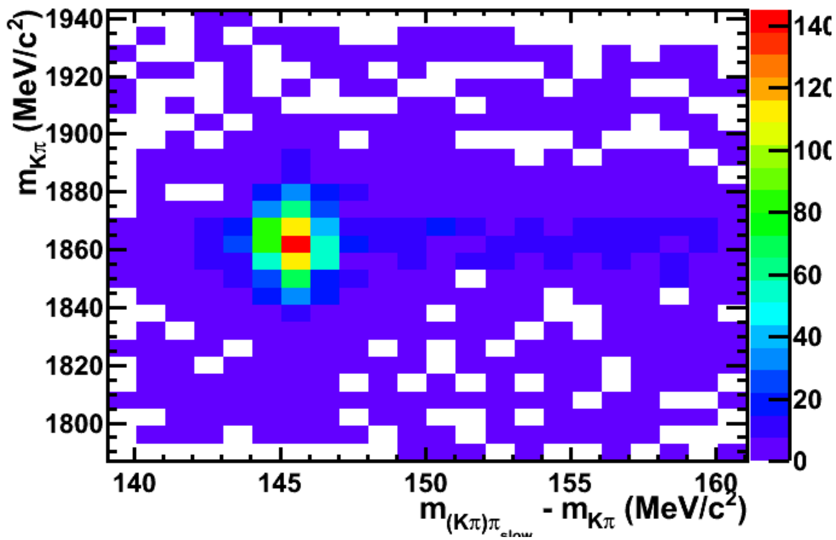
This plots shows the probability to misidentify a pion from Ks and a proton from Lambda as a muon as a function of momentum.

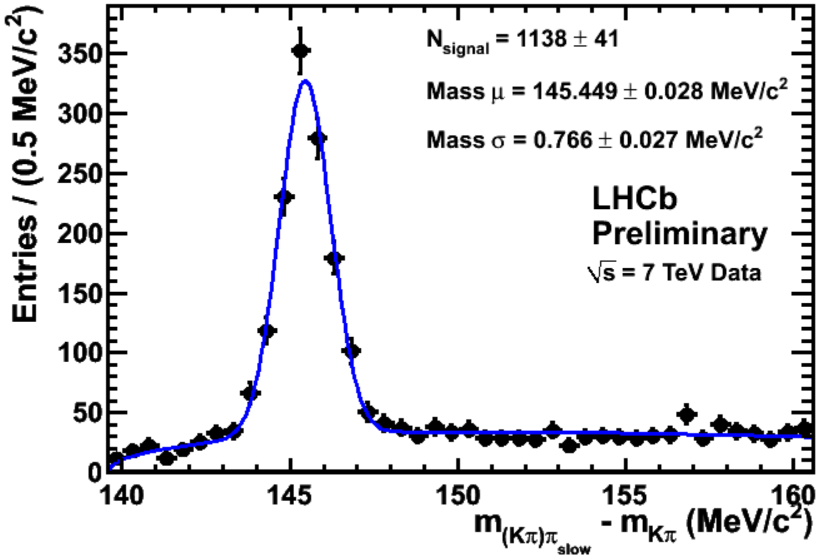
Kaon Efficiency

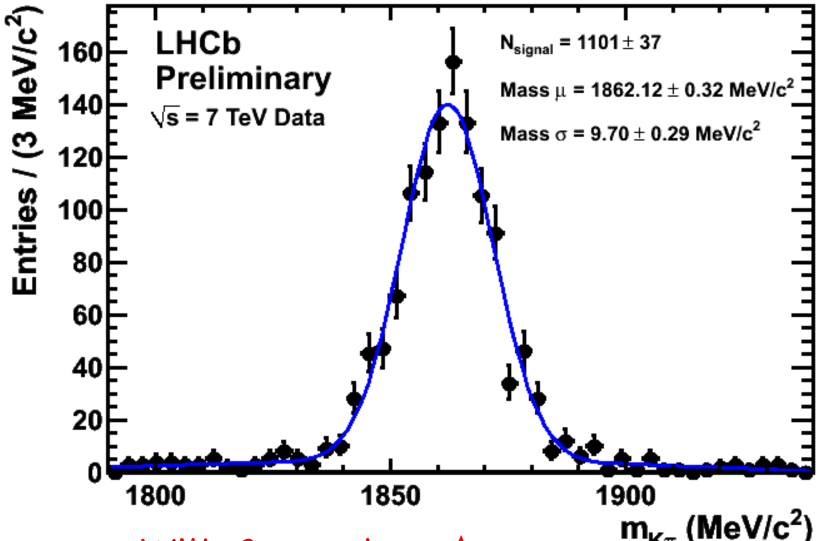


$D^0 \to K\pi$ Decay









With 2 σ cut on Δm

Measurement of y_{CP}

Jorg Marks

- Decay time of D^0's is exponential with modifications due to mixing

$$\tau^{\pm} = \frac{\tau^0}{1 + |q/p|(y\, cos\phi_f \mp x\, sin\phi_f)}$$

$\tau^{\pm}$: lifetime of D^0 ($\bar{D}^0$) → CP+ eigenstates

τ^0: lifetime of D^0 → CP mixed (CF)

- A lifetime difference between CP+ and CP mixed states gives access to mixing

$$y_{CP} = \frac{\tau^0}{\tau} - 1$$

or

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1 = |q/p|(y\ cos\,\phi_f - x\ sin\,\phi_f)$$

$y_{CP} \neq 0 \ \Rightarrow$ D^0-$\bar{D}^0$ mixing

- Test of CP violation

$$\Delta Y = \frac{\tau^0 A_\tau}{\tau}$$

with

$$A_\tau = \frac{\tau^+ - \tau^-}{\tau^+ + \tau^-} = -A_\Gamma$$

$\Delta Y \neq 0 \ \Rightarrow$ CP violation in D^0-$\bar{D}^0$ mixing

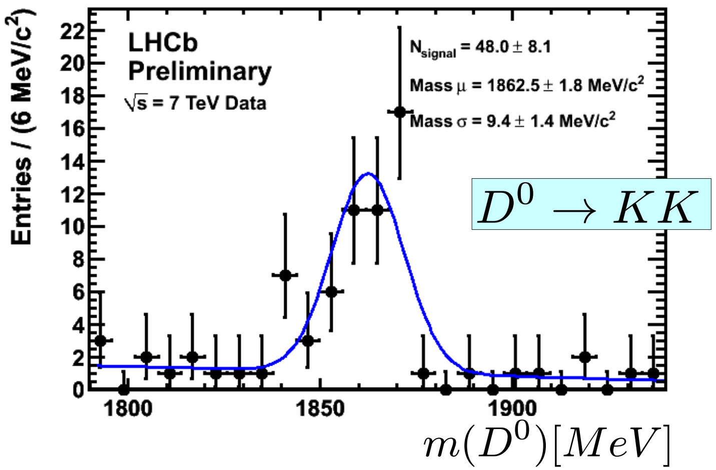
CP violation in interf. between mixing and decay

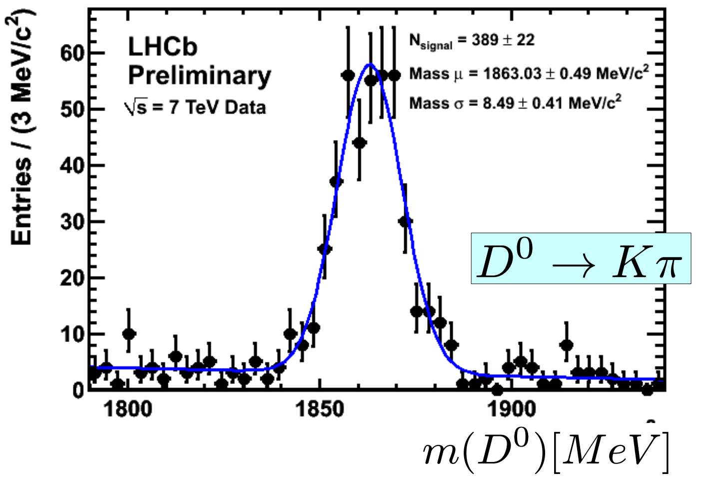
$y_{CP} = y \ \Leftarrow$ CP conservation

LHCb : Towards y_{CP} and A_Γ

Jorg Marks

➢ Compare $D^0 \to KK$, $D^0 \to \pi\pi$ and $D^0 \to K\pi$ to extract y_{CP} and A_Γ





- Analyse the D^0 decay time distributions
  - Determine $\langle\tau_{KK}\rangle_i / \langle\tau_{K\pi}\rangle_i$ in bins i of the lifetime distribution
  - Determine $\tau_{K\pi}$, τ^+_{KK} , τ^-_{KK} from unbinned max. likelihood fits to the lifetime distributions

- Expected events in $\int \mathcal{L} \approx 100\ pb^{-1}$:

$$N_{100\ pb^{-1}}(D^0 \to K\pi) \approx 13 \cdot 10^6$$

$$N_{100\ pb^{-1}}(D^0 \to KK) \approx 7.5 \cdot 10^5$$

factor 10 more data than the *BABAR* analysis

B. Aubert et al., Phys. Rev. D80 071103 (2009)

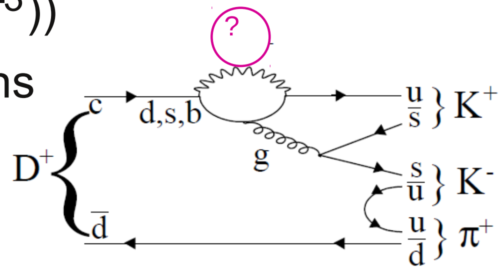
Direct CP Violation Searches in SCS Decays

Jorg Marks

- **Single Cabbibo suppressed decay (SCS)**

Y. Grossman et al.
Phys. Rev. D75 036008 (2007)

- CPV in SM is CKM and loop suppressed (CPV < O (10^{-3}))
- SCS decays are sensitive to CPV in $c \to uq\bar{q}$ transitions
  Contributions due to supersymmetric $\Delta C = 1$ QCD penguins could enter.
  → measurement of large CPV would be a sign of NP



- Search for CPV in SCS tagged $D^0 \to \pi^+\pi^-\pi^0$, $D^0 \to K^+K^-\pi^0$ by *BABAR*
  → results are in accord with SM predictions (few %)

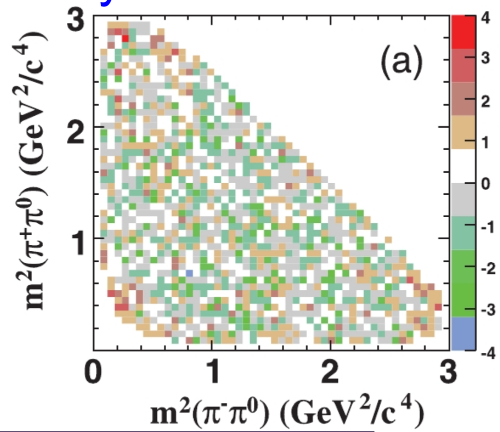
B. Aubert et al.
Phys. Rev. D78 051102 (2008)

- **Model independent Dalitz Plot analysis to look for CP asymmetries**

Miranda procedure arXiv 0905.4233
Consider the significance in the difference between corresponding Dalitz plot bins.

$$^{D_P}S_{CP} = \frac{N(i) - \bar{N}(i)}{\sqrt{N(i) + \bar{N}(i)}}$$

- Provides better filtering between real asymmetries and statistical fluctuations
- Not sensitive to production asymmetries



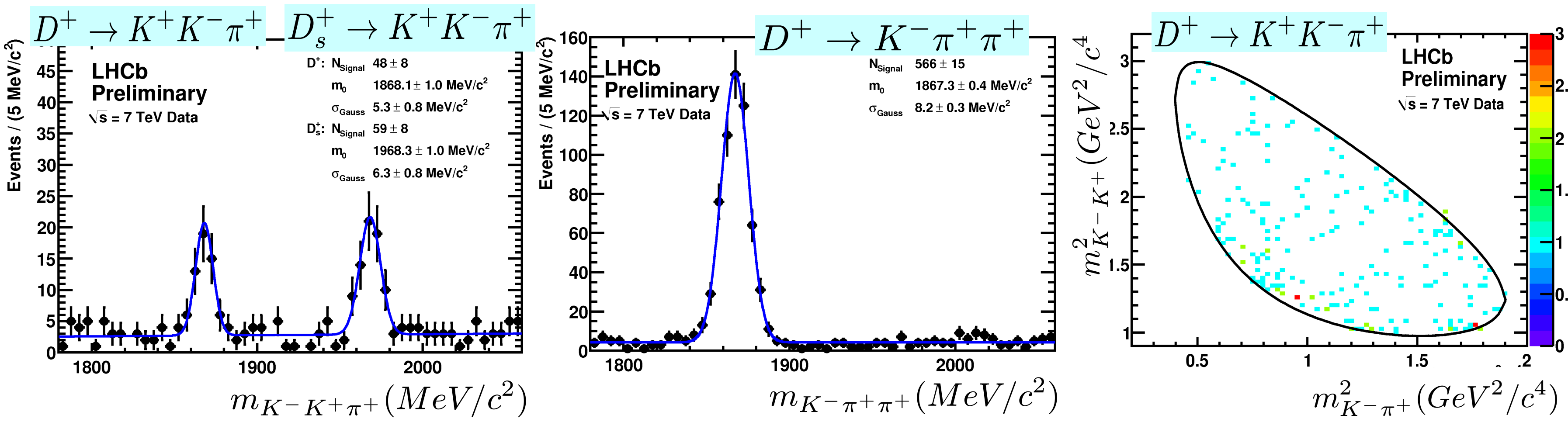
LHCb : Direct CP Violation Search

Jorg Marks

➢ Dalitz analysis of the SCS decay $D^+ \to K^+K^-\pi^+$

Time integrated and model independent search for local CP asymmetries in bins of the Dalitz plane.

- Two suitable control channels: $D_s^+ \to K^+K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$

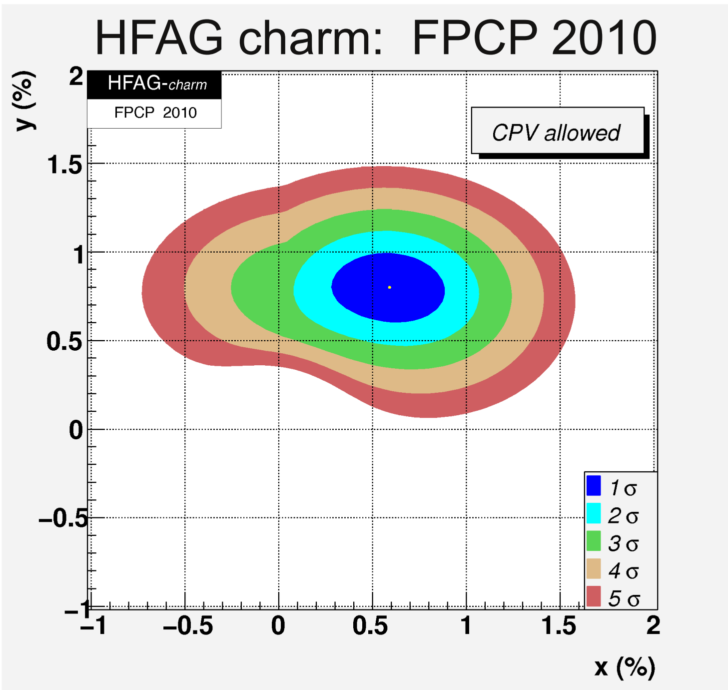


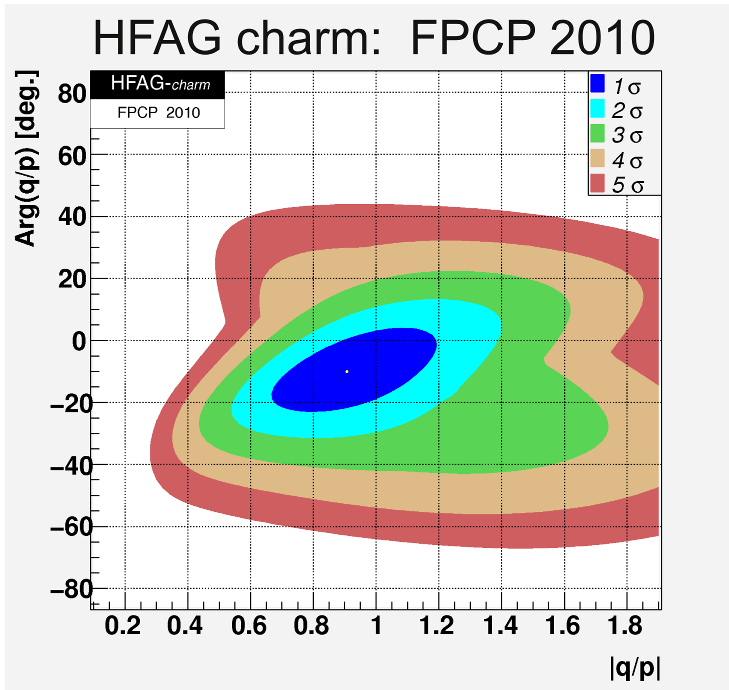
- $\int \mathcal{L} = 0.8\ nb$ $\quad\to$ expect a sample of several million events in 2010

Averaged Mixing Parameters

Jorg Marks

- Mixing parameter as combined by the HFAG charm group





$$y = (0.80 \pm 0.13)\%$$
$$x = (0.59 \pm 0.20)\%$$

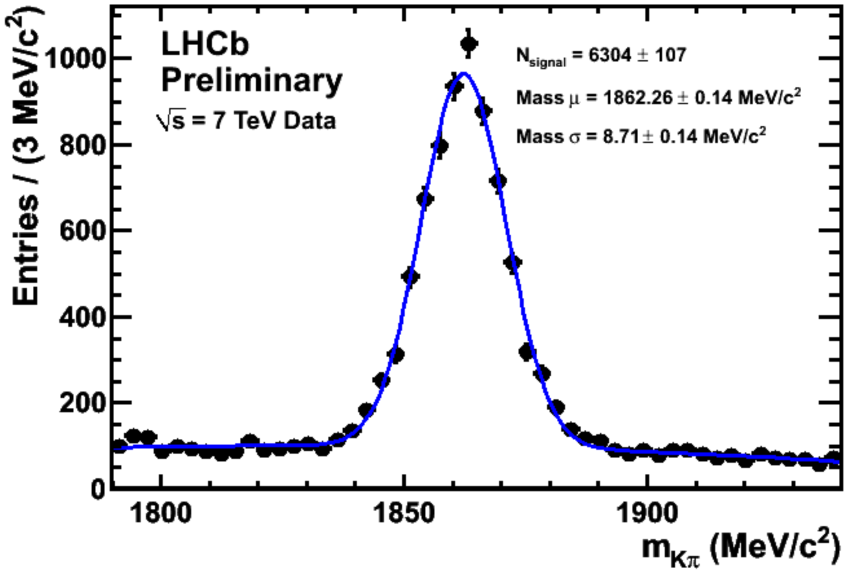
$$|q/p| = (0.91^{+0.19}_{-0.16})\%$$
$$\phi = (-10.0^{+9.3}_{-8.7})^o$$

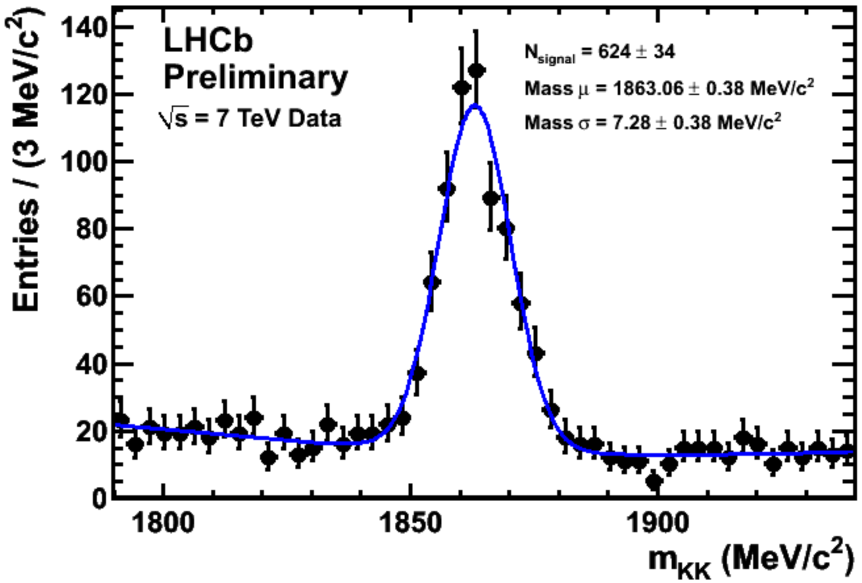
Exclude no mixing case at 10.2 σ

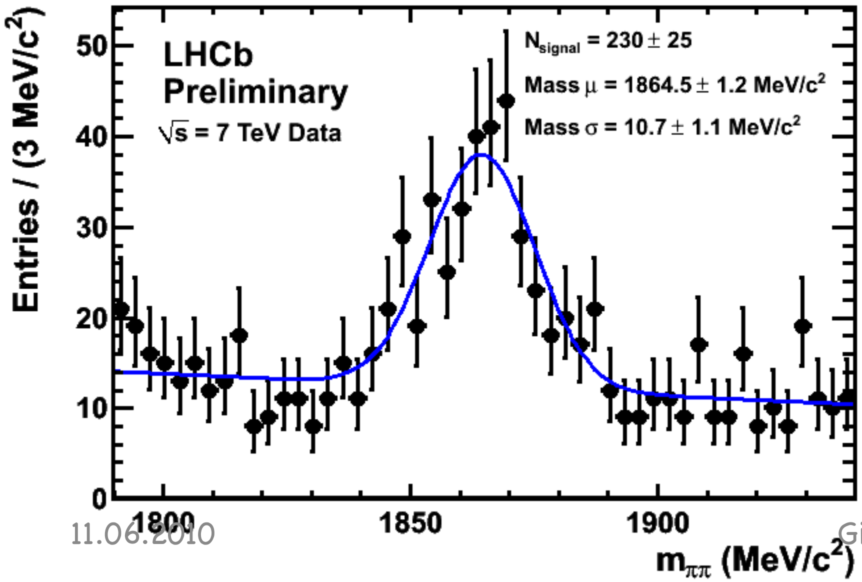
Fully compatible with the CP conservation

Untagged D→Kπ,KK,ππ

≈ 2.7 nb^{-1}
Patrick Spradlin

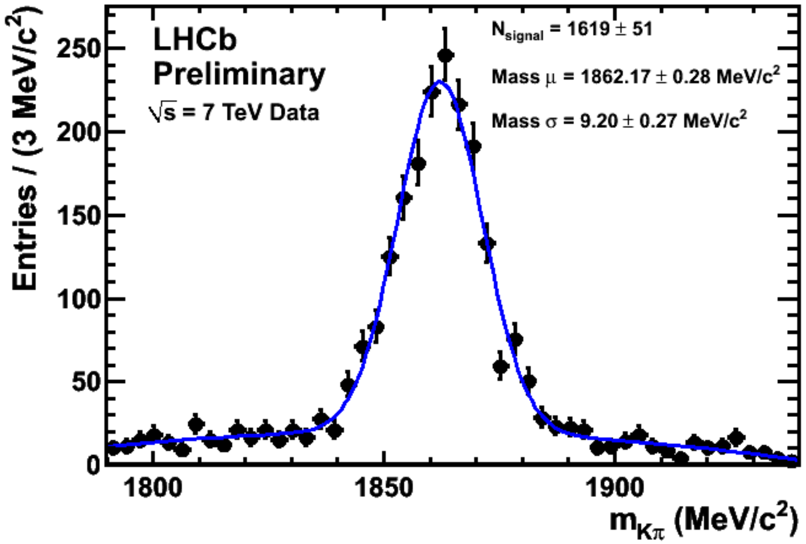


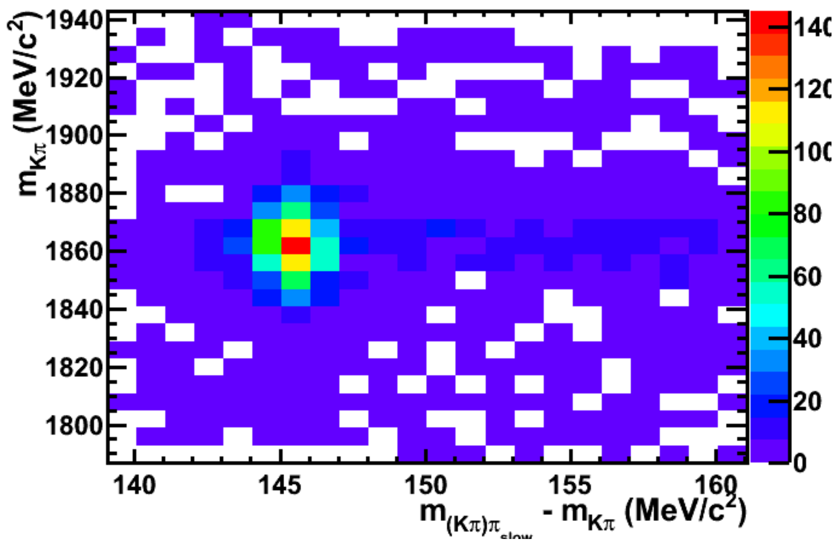


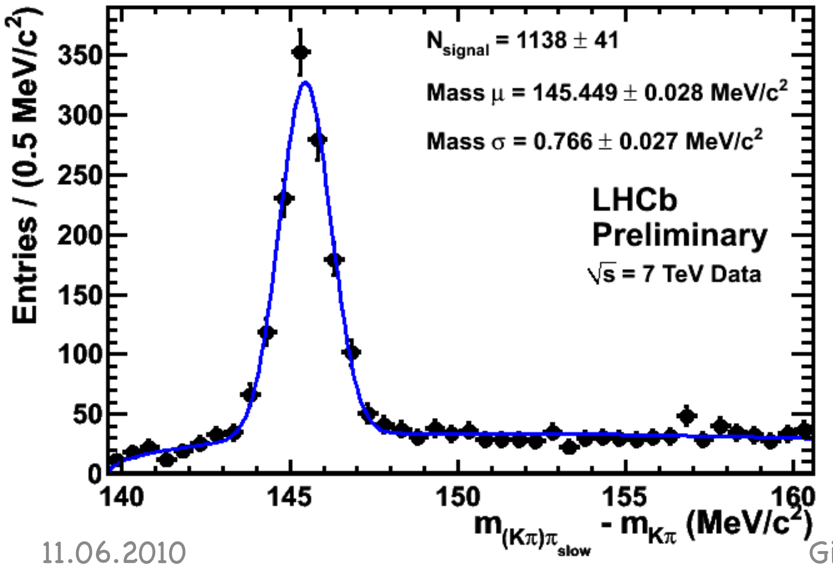


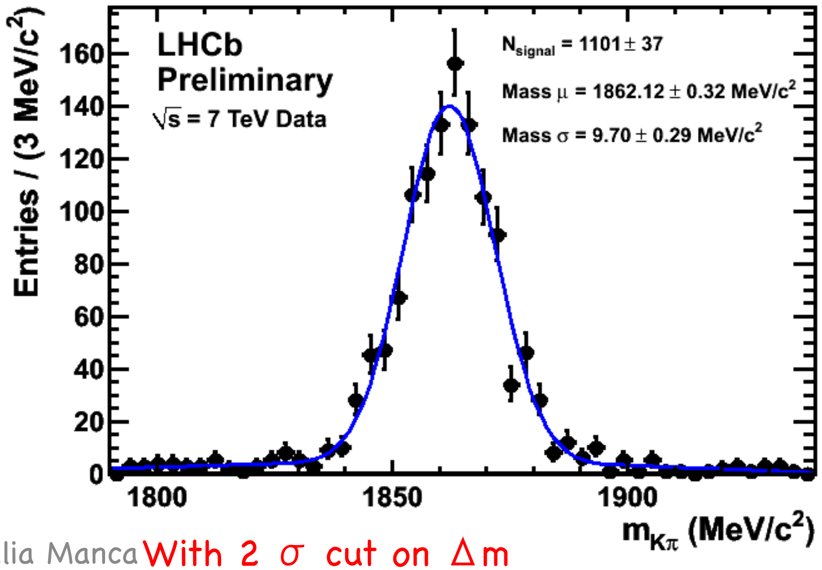
Tagged D→Kπ

≈ 2.7 nb^{-1}
Patrick Spradlin





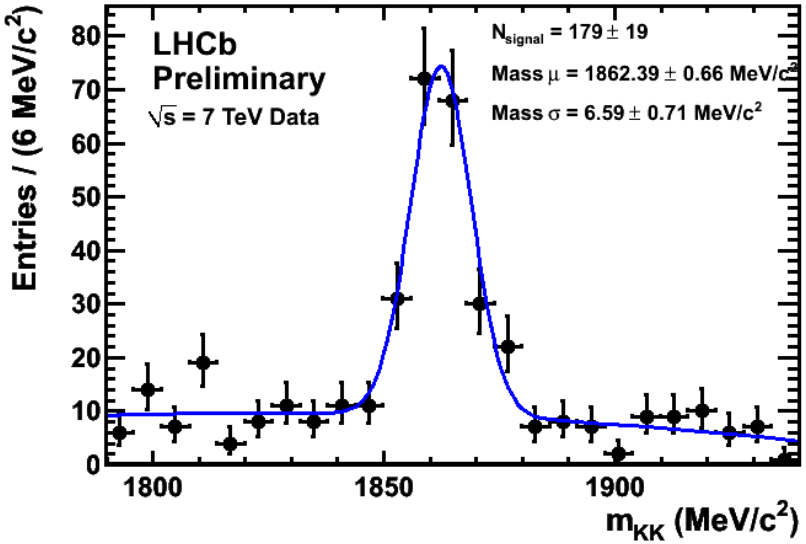


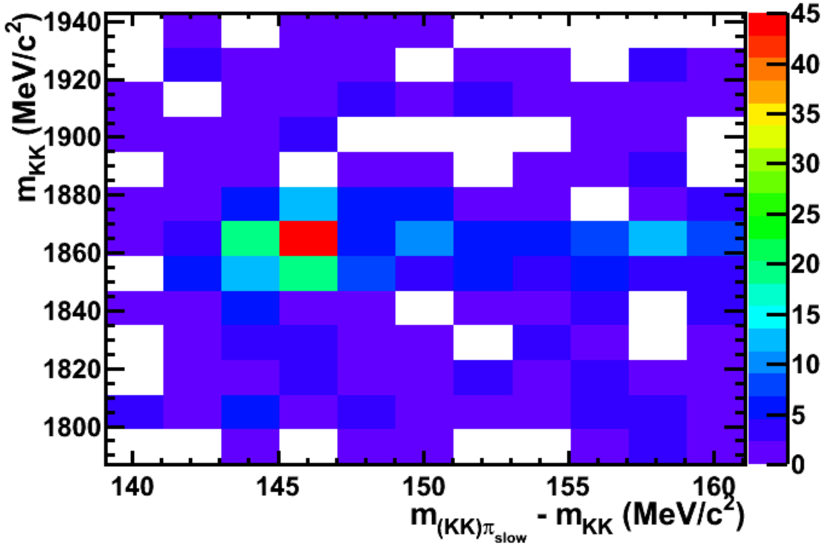


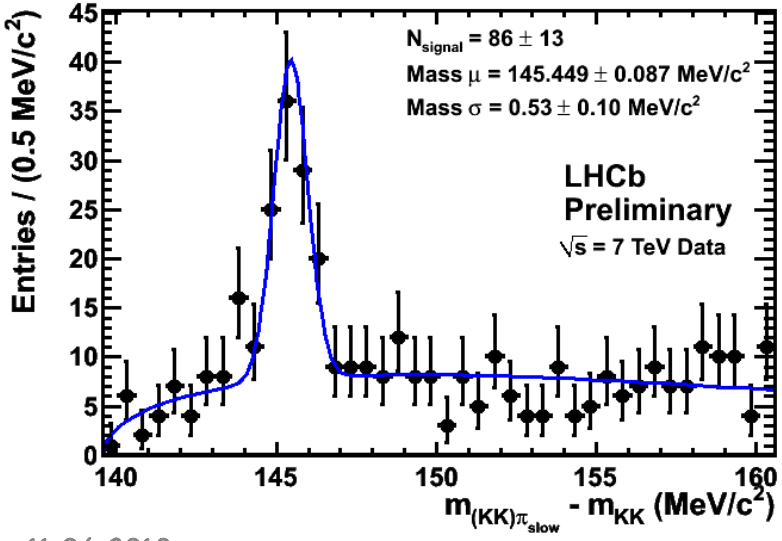
With 2 σ cut on Δm

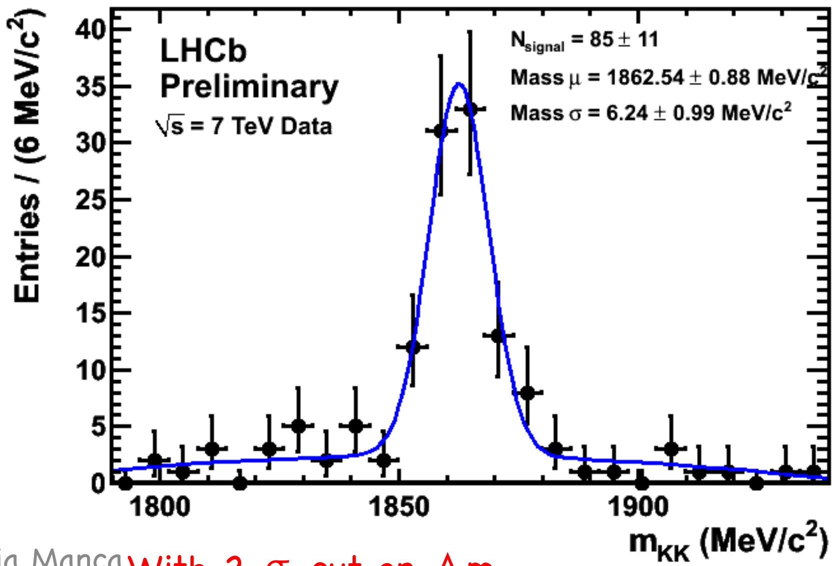
Tagged D→KK

≈ 2.7 nb^{-1}
Patrick Spradlin



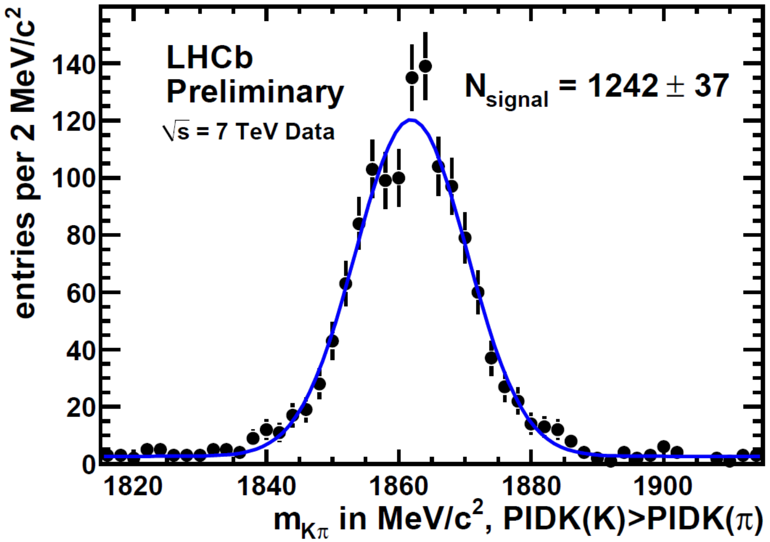


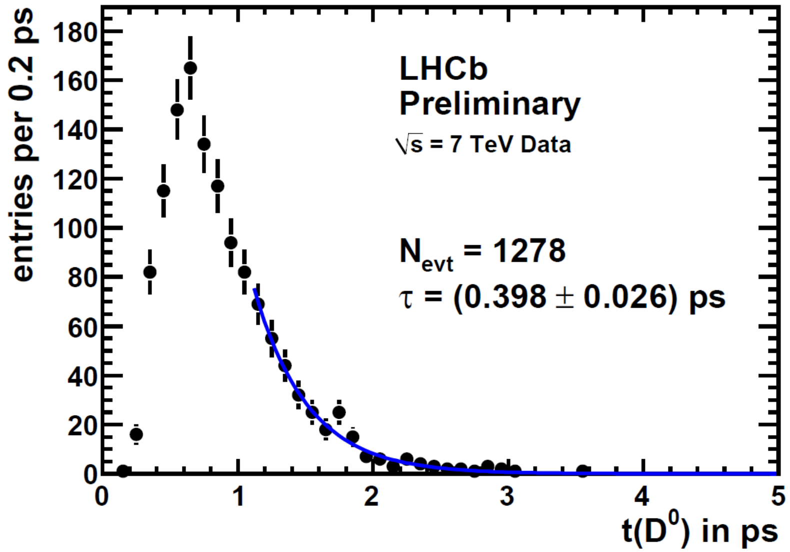




With 2 σ cut on Δm

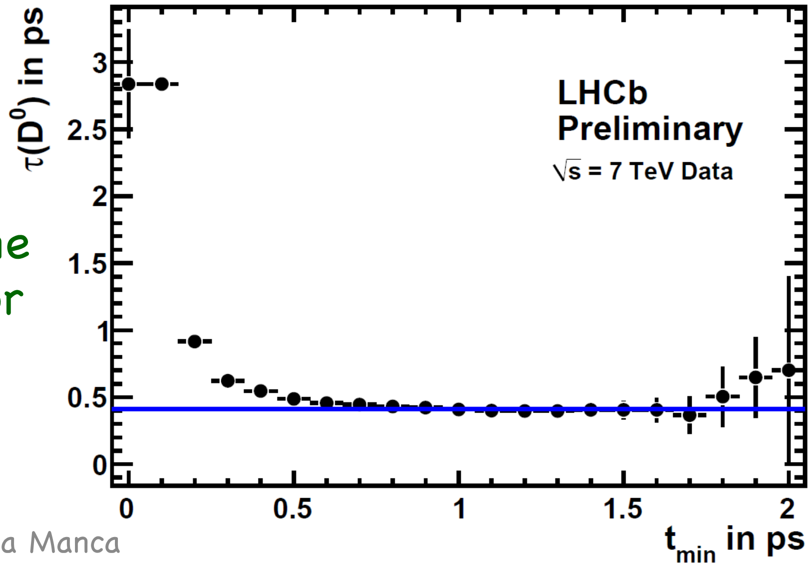
Lifetime fit of untagged $D^0 \to K\pi$



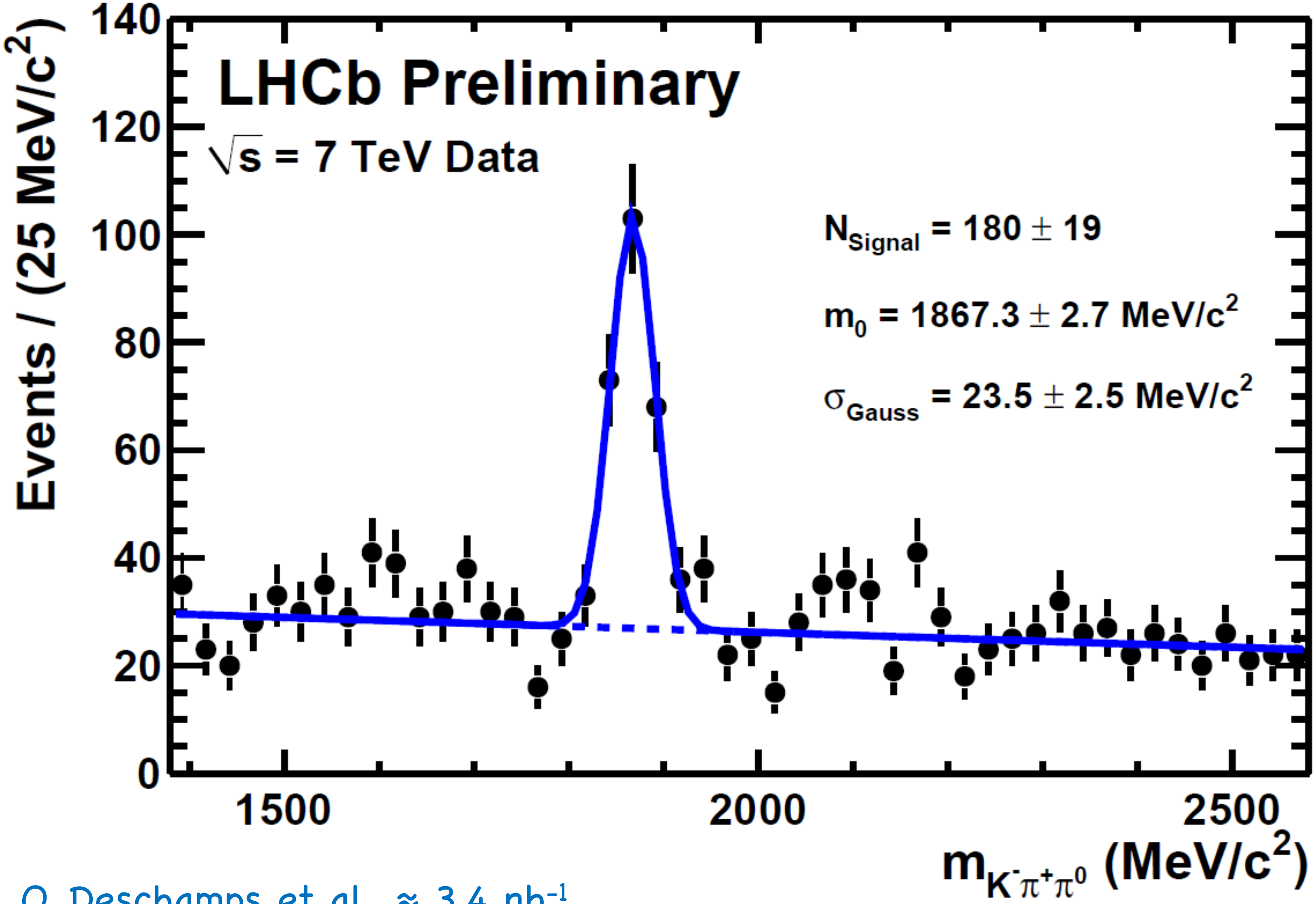


Plots from Marco Gersabeck:

- top: mass peak
- top right: fit of tail of proper lifetime
- bottom right: result of lifetime fit for different lower bound on fit region



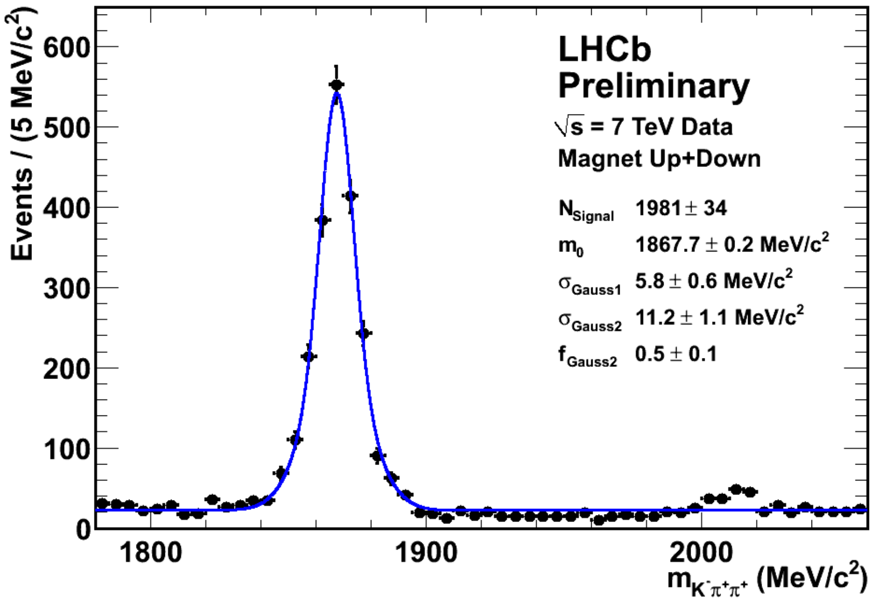
Untagged $D^0 \rightarrow K\pi\pi^0$

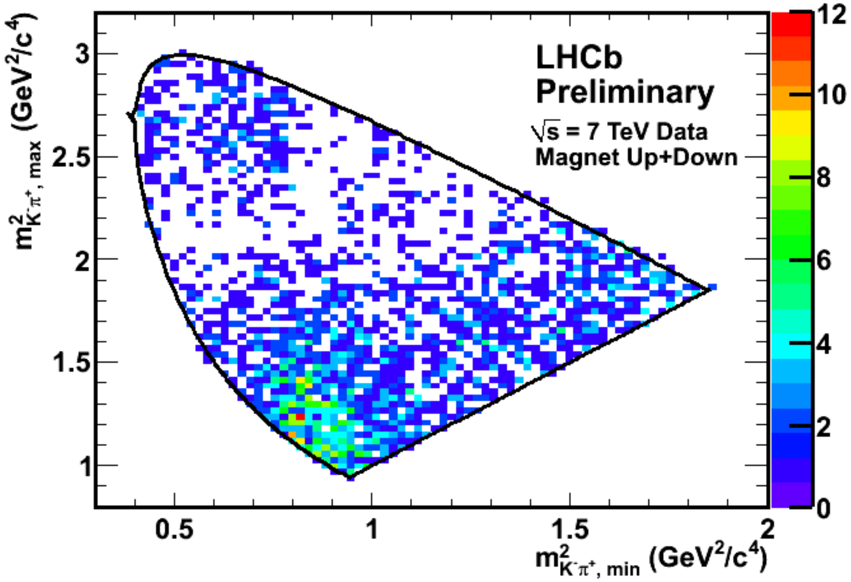


O. Deschamps et al., ≈ 3.4 nb^{-1}

D→Kππ

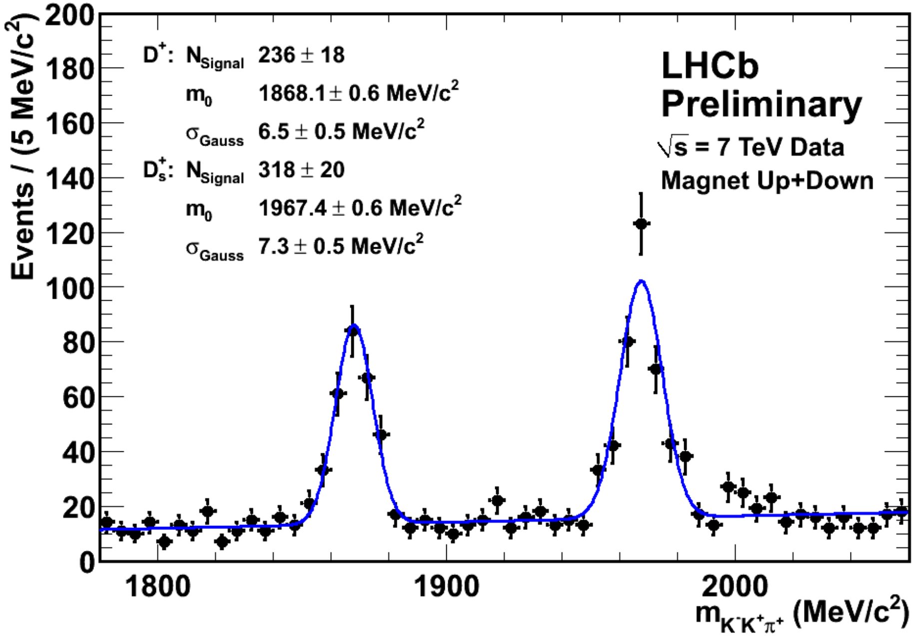
≈ 2.6 nb^{-1}
Hamish Gordon

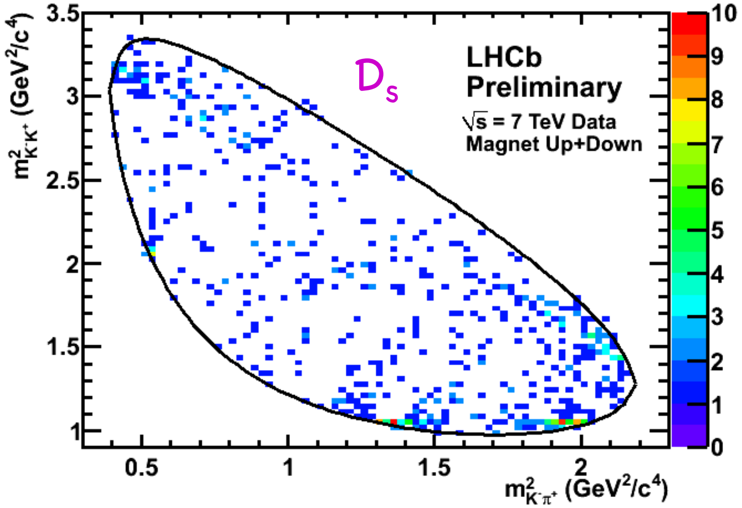


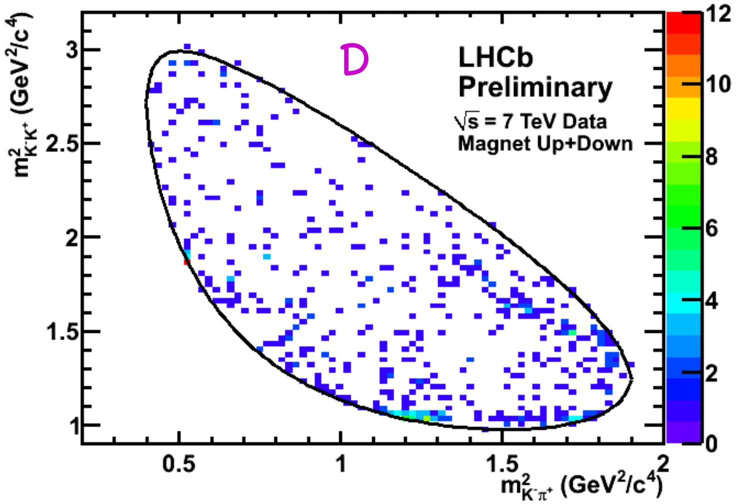


$D_{(s)} \rightarrow KK\pi$

$\approx$ 2.6 nb^{-1}
Hamish Gordon

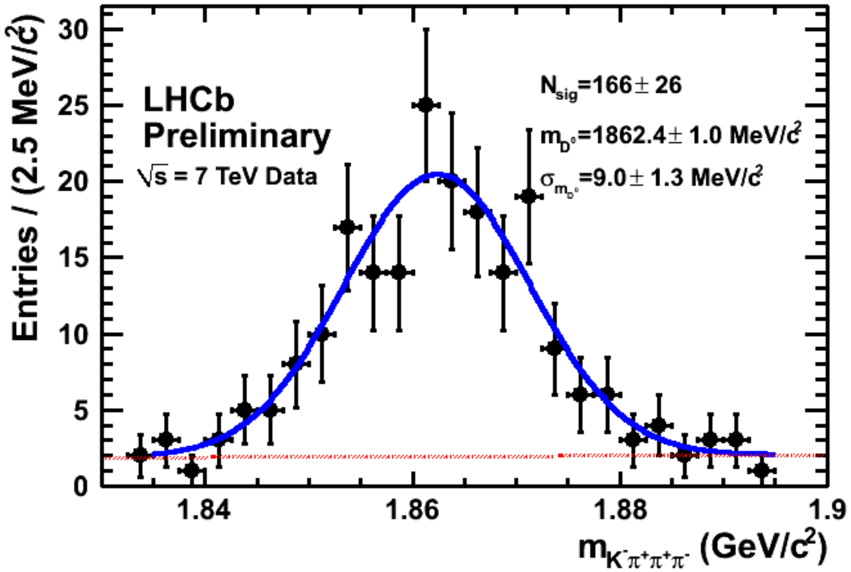


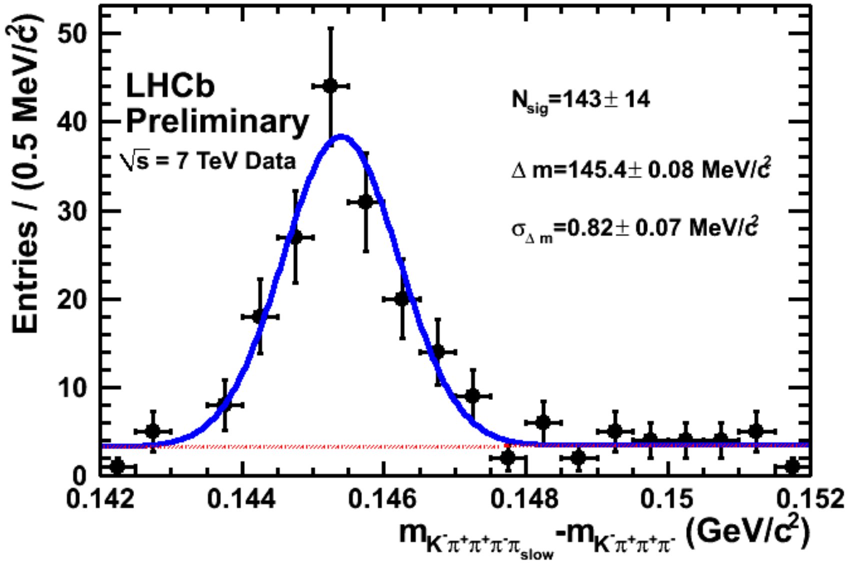




$D^* \to D^0\pi, D^0 \to K\pi\pi\pi$

≈ 1.6 nb^{-1}
Benoit Viaud





Plots tightened w.r.t. LHCC selection – see:

http://www-pnp.physics.ox.ac.uk/≈spradlin/CharmPeaks/D024H/Viaud/index.html