# First LHCb Results

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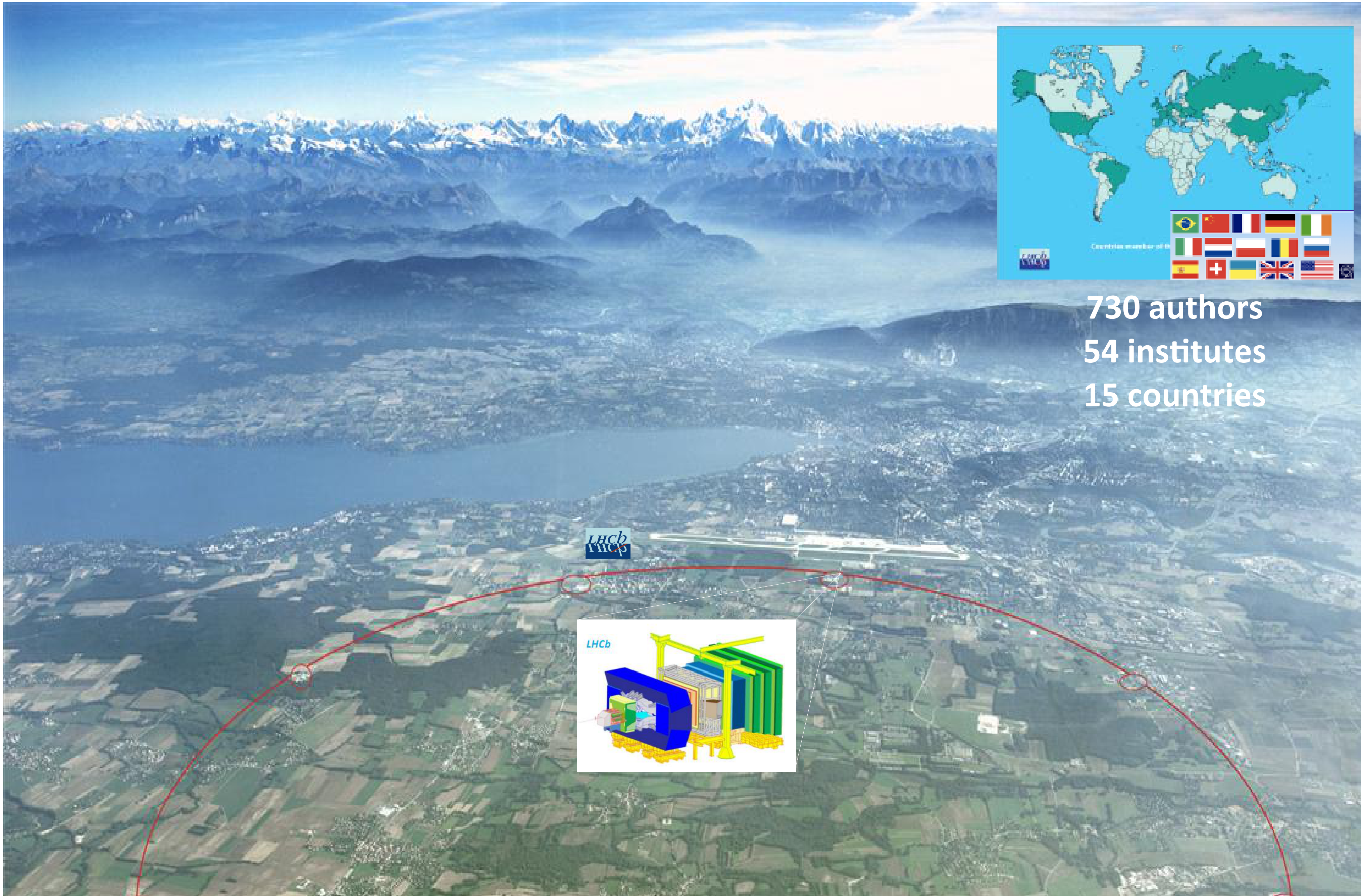
# Overview

- LHCb: What is it, what makes it special and different from ATLAS/CMS?
- Status: Running experience from the first months of LHC operation
- First physics: Results from the 2010 data, published and preliminary
- Discovery potential: Plans for 2011 and beyond


LHCb

# Overview

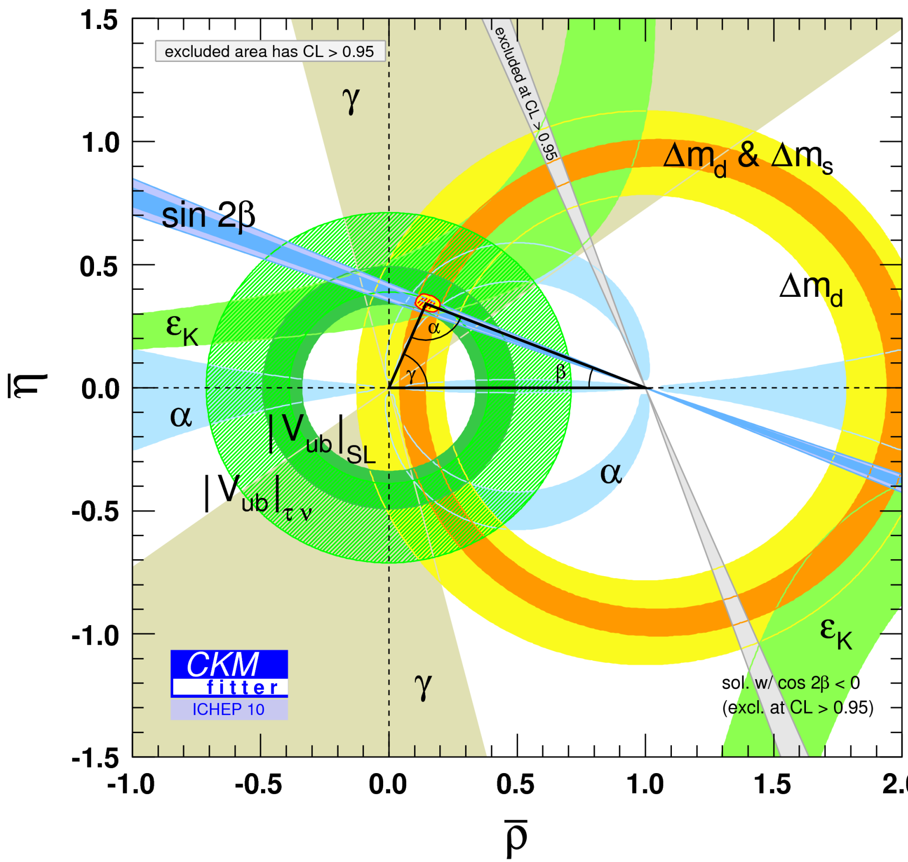


# "Indirect" Search for NP

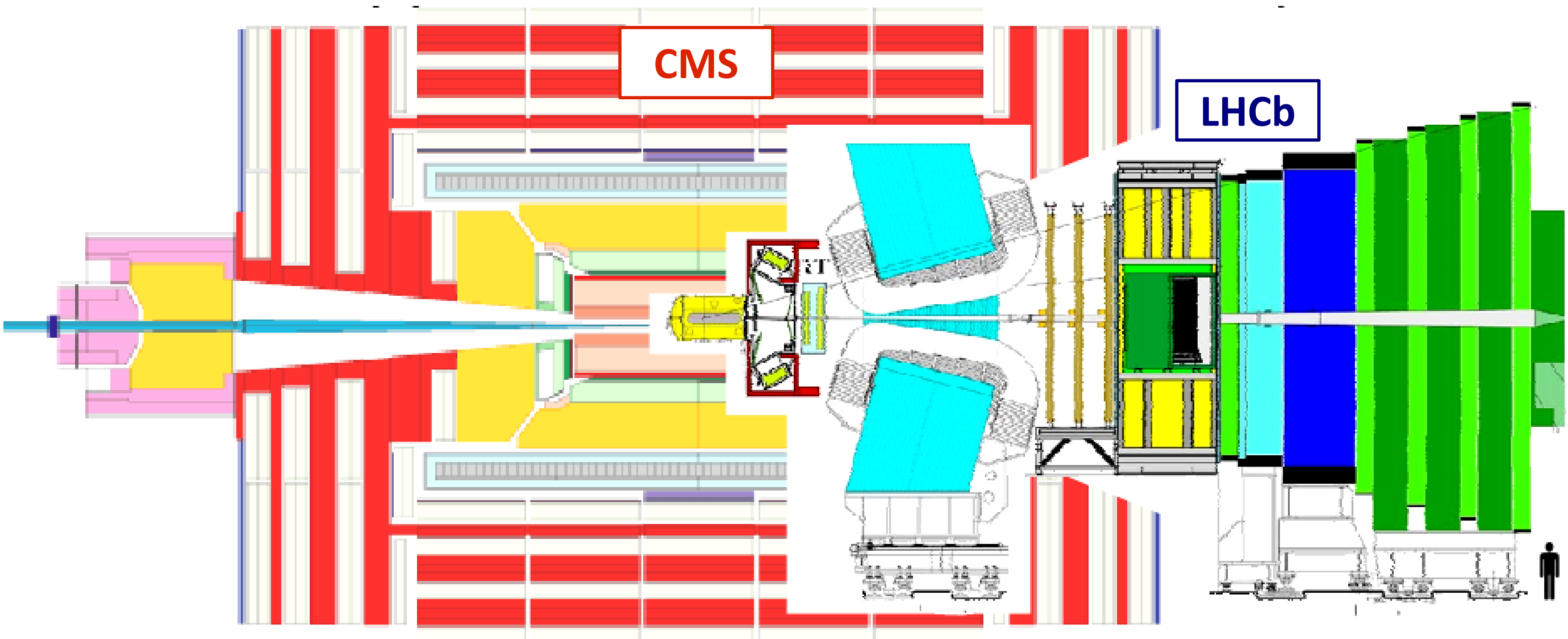
- LHCb performs precision measurements of CP violating phases and rare heavy-quark hadron decays
- New Physics enters through contributions from virtual heavy particles in loop-mediated processes
- sensitivity to New Physics is highest in processes that are strongly suppressed in the Standard Model
- discovery potential for New Physics extends to mass scales far in excess of the LHC centre-of-mass energy
- pattern of observed deviations from Standard Model predictions will hint at the nature of the New Physics
- in continuation of long history of "indirect discoveries"
  - suppression of FCNC → prediction of 2nd quark family
  - CP violation → prediction of 3rd quark family
  - strong BB mixing → prediction of large top-quark mass

# New Physics in B decays

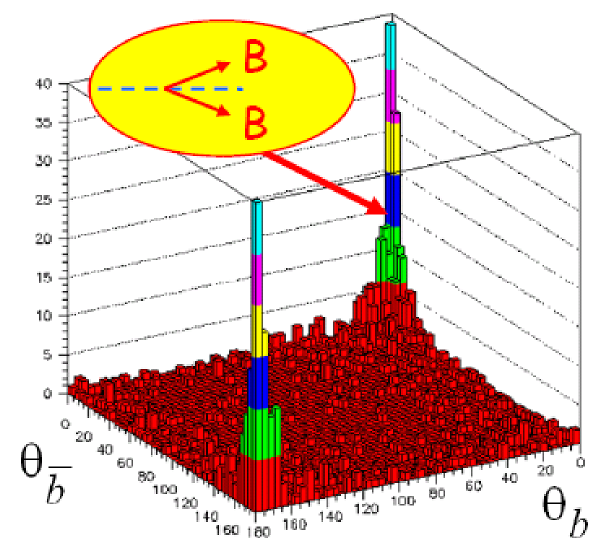
- explore FCNC processes with large sensitivity to New Physics, in particular b→s transitions
- improve measurements on CKM elements and challenge the Standard Model by over-constraining the unitarity triangles
- LHCb roadmap document: [arXiv:0912.4179v2 [hep-ex]]
  - tree-level determination of CKM angle $\gamma$
  - charmless charged two-body B decays
  - $B_s$ mixing phase $\phi_s$ from $B_s \to J/\psi\ \phi$
  - branching fraction of $B_s \to \mu^+\mu^-$
  - angular distributions in $B^0 \to K^*\mu^+\mu^-$
  - $B_s \to \phi\gamma$ and other radiative decays



# LHCb = Forward Spectrometer



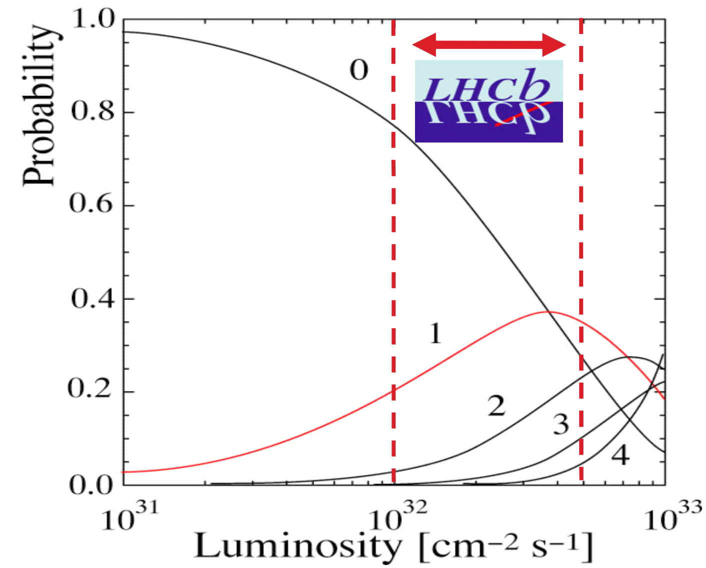

- LHCb covers forward region: $1.9 < \eta < 4.9$
- optimized for the strongly forward peaked heavy quark production at the LHC
- covers only ~4% of solid angle but captures ~40% of heavy-quark production cross section

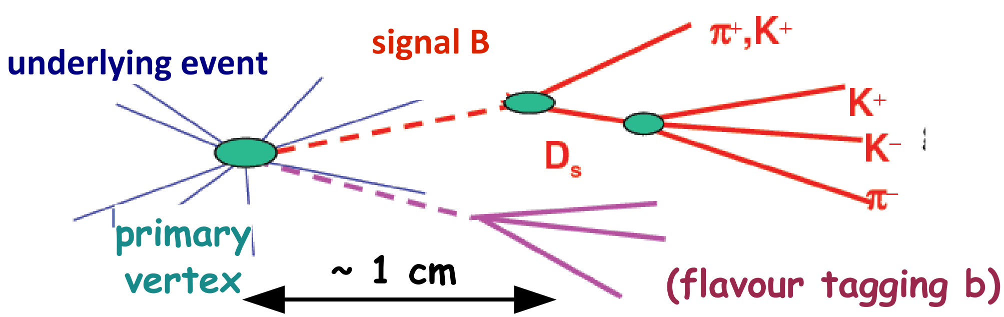


# LHCb = "Day-1 Experiment"

- LHCb designed to operate at an instantaneous luminosity of $2 \times 10^{32} cm^{-2} s^{-1}$
- corresponds to an average of 0.4 visible interactions per bunch crossing, maximizes fraction of single-interaction bunch crossings (for nominal operation with 2622 colliding bunches)
- single primary vertex: no ambiguity associating B decay vertex to its production vertex (required e.g. for time-dependent CP asymmetries)

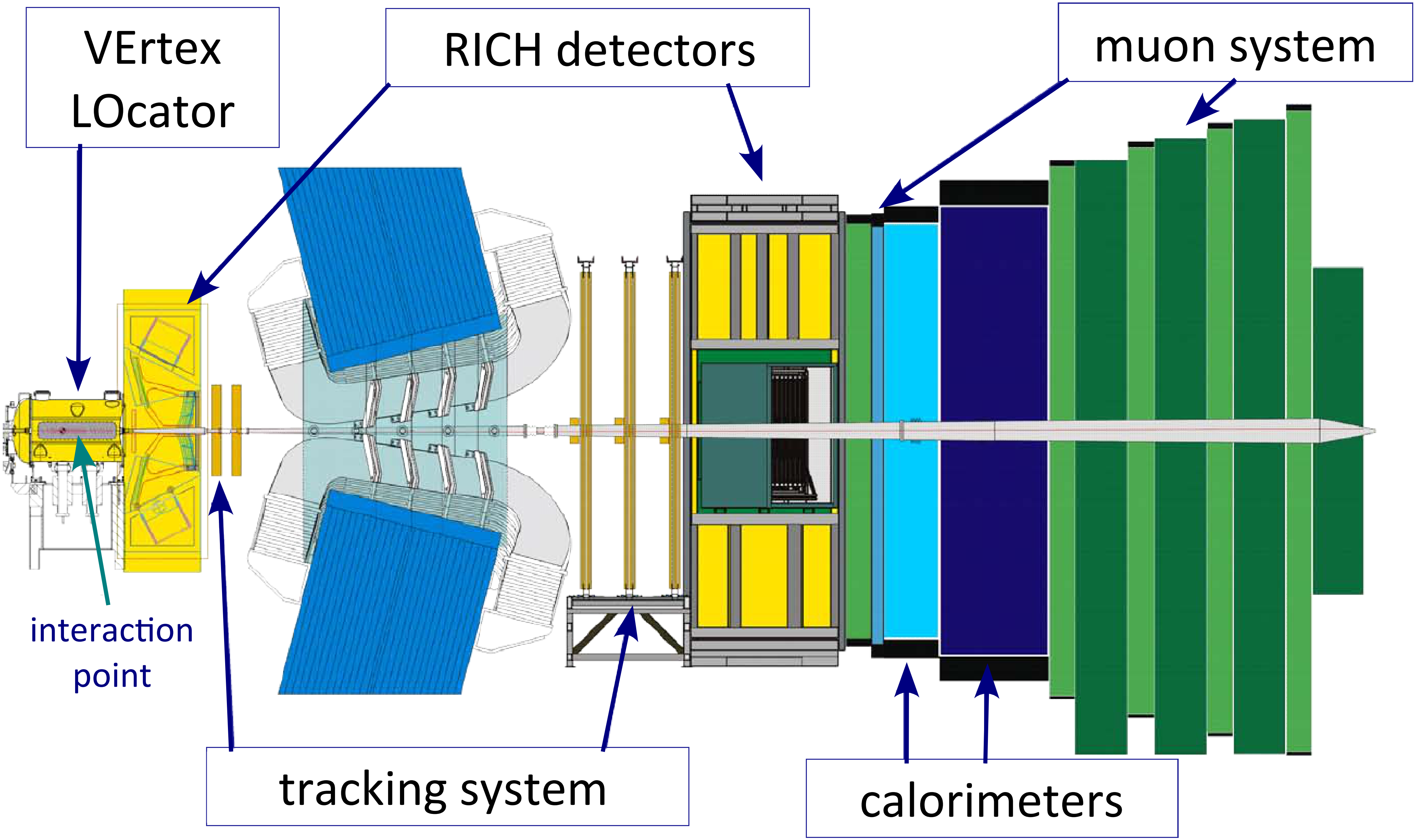
number of visible pp interactions



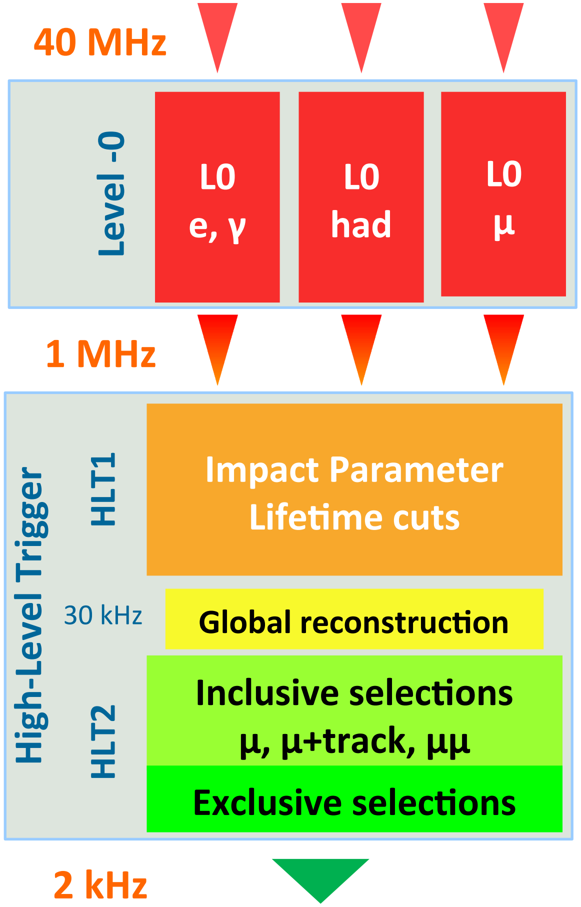

- for several of LHCb's core measurements expect first significant results from 2010/2011 LHC run

# LHCb Detector



# LHCb = Optimized Trigger

- $b\bar{b}$ cross section is less than 1 % of the total inelastic cross section
- interesting B decay channels have typical branching fractions of $10^{-5}$
- exploit generic B decay signature: decay products with large $p_T$ ("large" = few GeV) and high impact-parameter, well separated B decay vertex




Hardware level (L0):

- high-$p_T$ μ, e, γ, or hadron candidates in muon system and calorimeters

Software level (HLT):

- multi-processor farm (14000 CPU cores)
- access to full detector data
- HLT1: cuts on impact parameter and lifetime
- HLT2: global event reconstruction + selections for specific channels

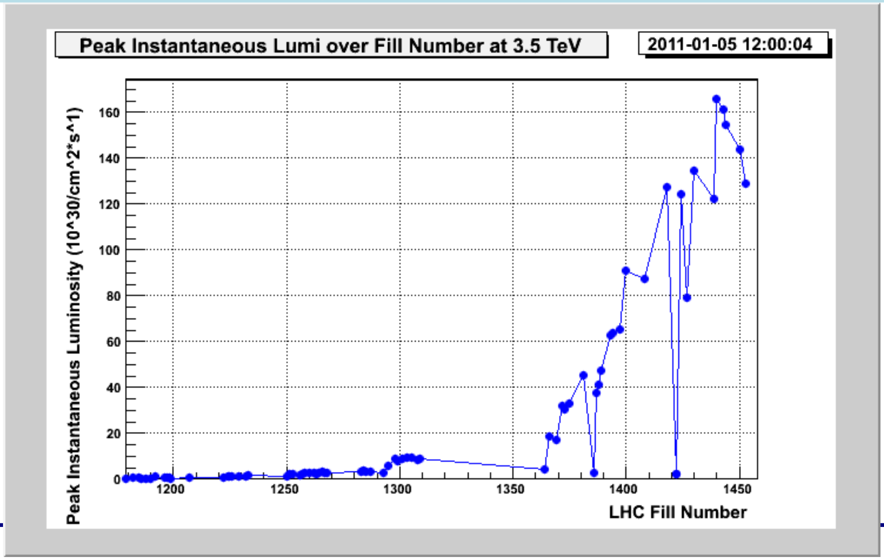
software trigger: flexible → adjust to running conditions

# Running Experience

# LHCb Running in 2010

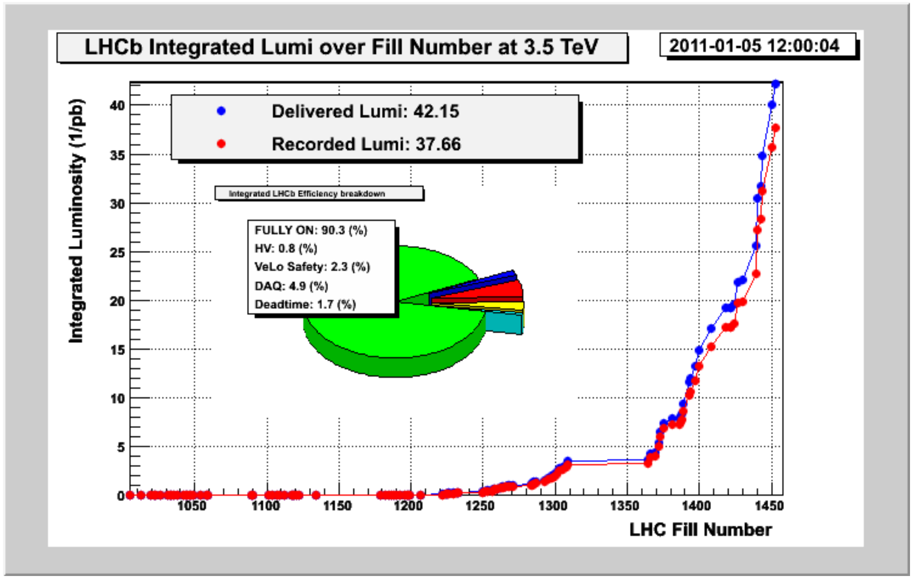
- Extreme conditions compared to design:

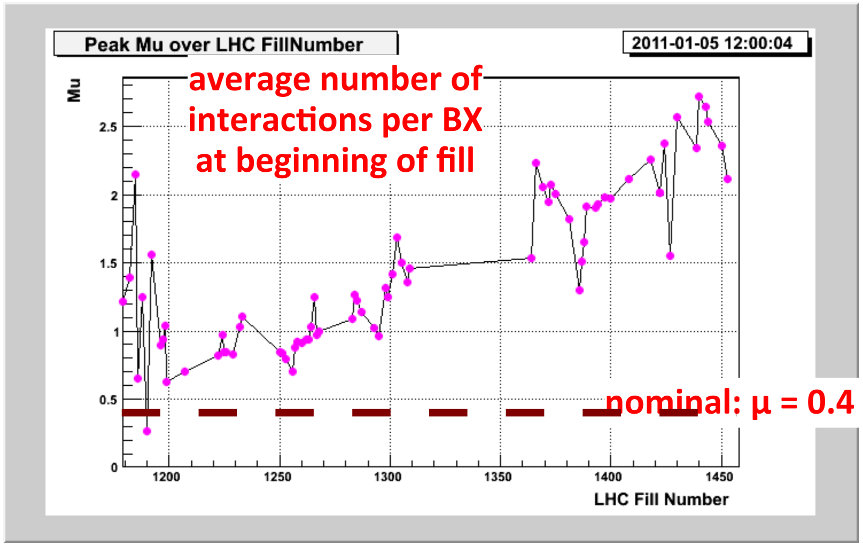
| | Nominal @ LHCb | 2010 |
|---|---|---|
| Number of colliding bunches | 2622 | 344 |
| Instantaneous luminosity | $2 \times 10^{32}$ $cm^{-2}.s^{-1}$ (average) | $1.7 \times 10^{32}$ $cm^{-2}.s^{-1}$ (max) |
| Normalized emittance | 3.75 mm | 2.4 mm |
| $\beta^*$ | 30 m | 3.5 m |
| $\mu$ (number of visible interaction per crossing) | 0.4 | 2.5 |
| pile-up | 1 interaction/bb event | 3.1 interactions/bb event |
| Integrated luminosity | 2 $fb^{-1}$/year | 37.7 $pb^{-1}$ |



# Data Taking & Running Conditions

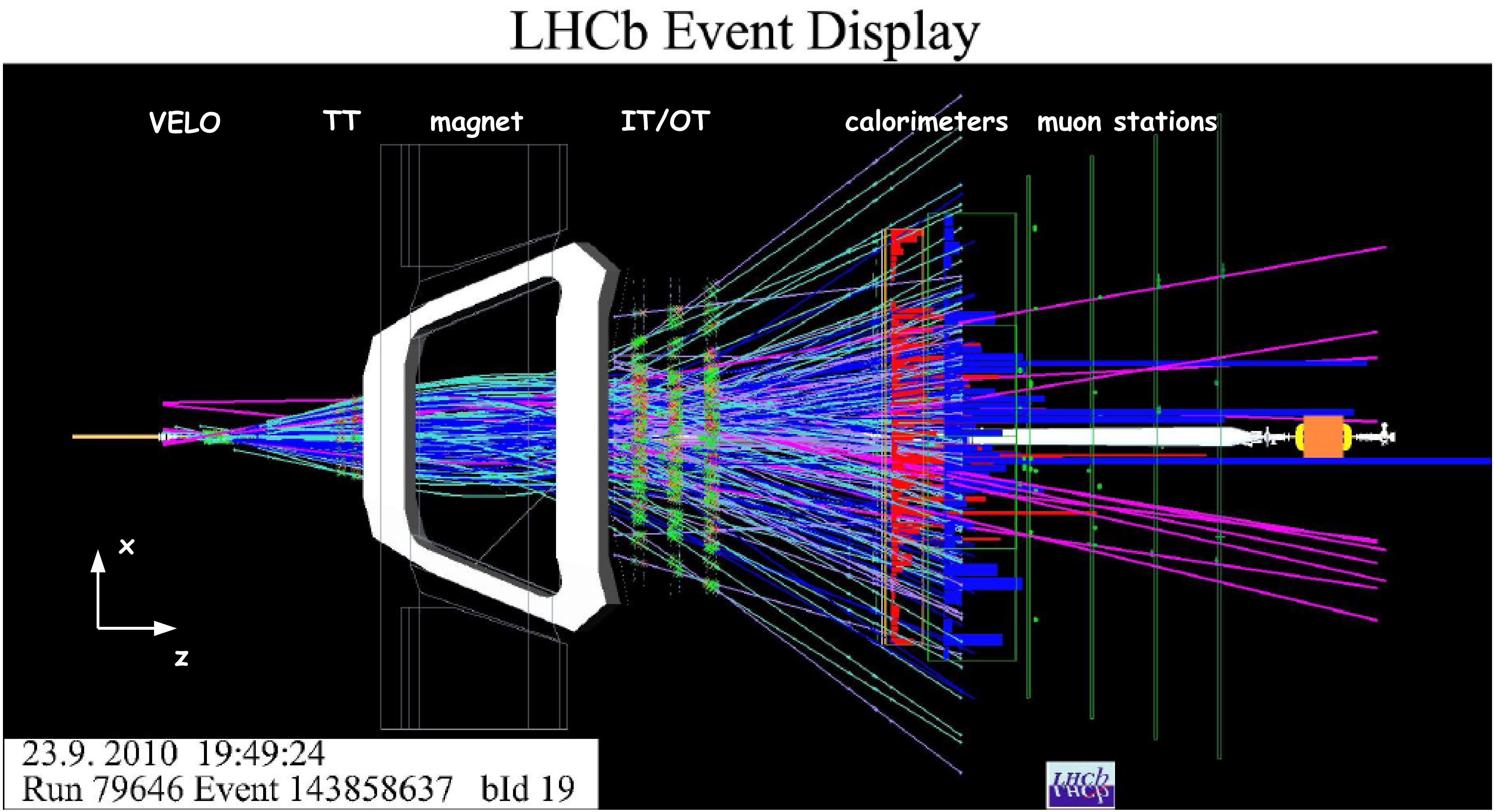
- LHCb fully operational on first day of LHC collisions, running smothly since
- recorded 37.7 $pb^{-1}$ at $\sqrt{s}$ = 7 TeV
- data taking efficiency > 90%



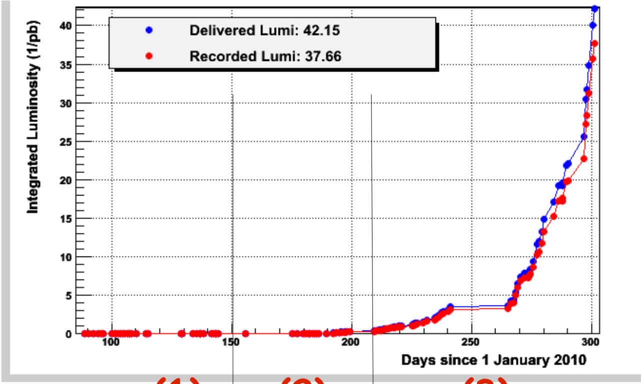

- at beginning of fill: up to more than 2.5 interactions per crossing on average
- significantly harsher conditions than design
  - multiple primary vertices
  - high occupancies, track multiplicities
- detector & reconstruction cope better with these conditions than expected
  - main limitation found: HLT reconstruction time for very busy events

# Typical Event at $\langle\mu\rangle = 2.5$



# Trigger

- trigger settings continuously adapted to rapidly increasing luminosity and changing running conditions.
- <u>early running (1)</u>: low intensity, small number of bunches:
  - *minimum bias trigger, require single track in VELO.*
- <u>with increasing number of bunches and μ (2)</u>:
  - *loose $p_T$ cuts at L0, start to use HLT, adjust settings to fully exploit available bandwidth and CPU.*
- <u>at highest μ (3):</u> give priority to muon triggers, reduce hadron trigger lines when needed:
  - *increase cuts on transverse momentum / energy*
  - *"global event cuts" on hit multiplicities to reject very busy events that require lots of CPU*
- trigger efficiencies determined on data using "tag-and-probe" methods
- results in good agreement with simulation

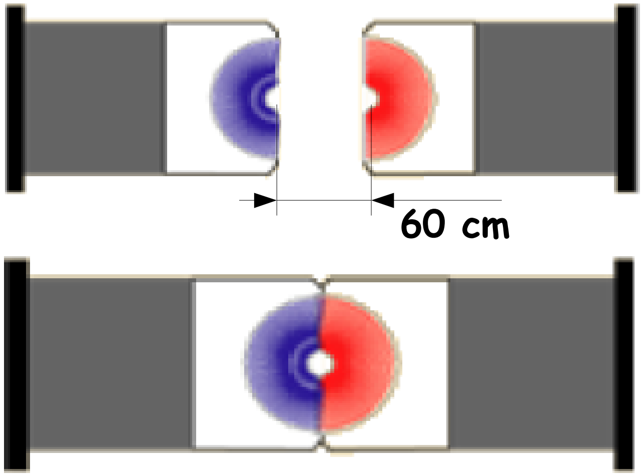



(1) loose L0 cuts, HLT in pass-through
(2) L0 + HLT1
(3) full L0-HLT1-HLT2

| | Muon Trigger ($J/\psi$) | Hadron Trigger ($D^0$, $p_T$>2.6 GeV) |
|---|---|---|
| Data | (94.9 ± 0.2) % | (60 ± 4) % |
| Simulation | (93.3 ± 0.2) % | 66 % |

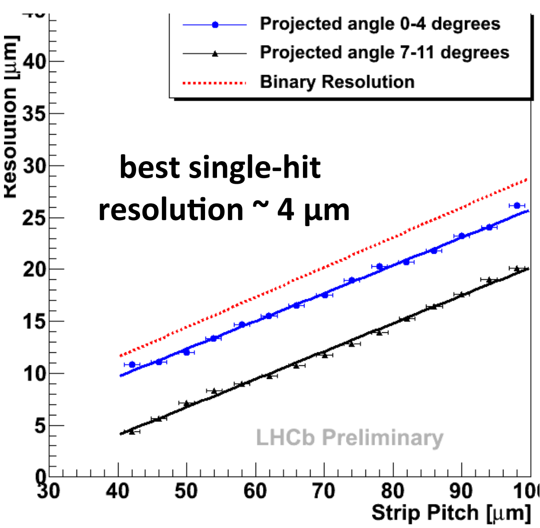
# Vertex Reconstruction

- excellent vertex resolution crucial for high-level triggers and most physics analyses
- VELO detectors inside LHC vacuum pipe
- only 8mm from beam during data taking
- retracted by ±3 cm at end of each fill, re-inserted when stable beams declared

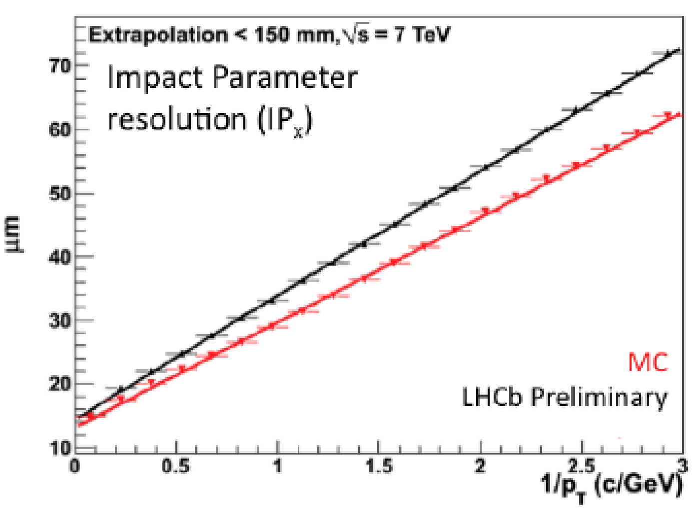



- internal alignment better than 5 μm, fill-to-fill variations also < 5 μm

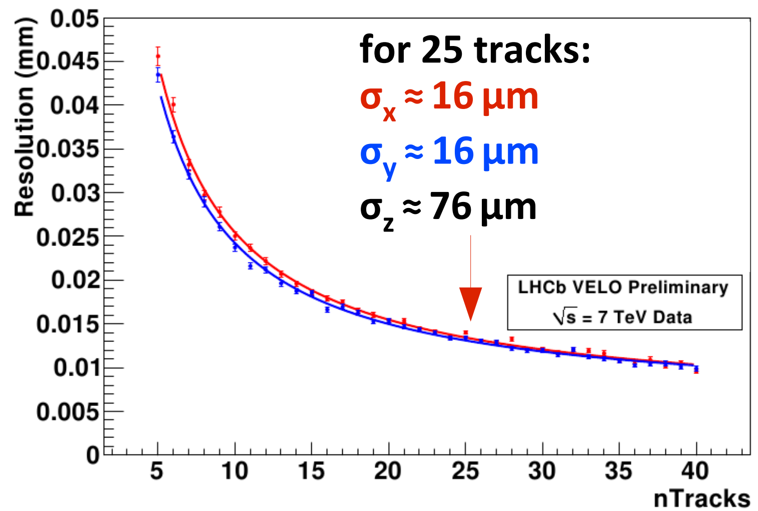
**single-hit resolution**




**impact-parameter resolution**

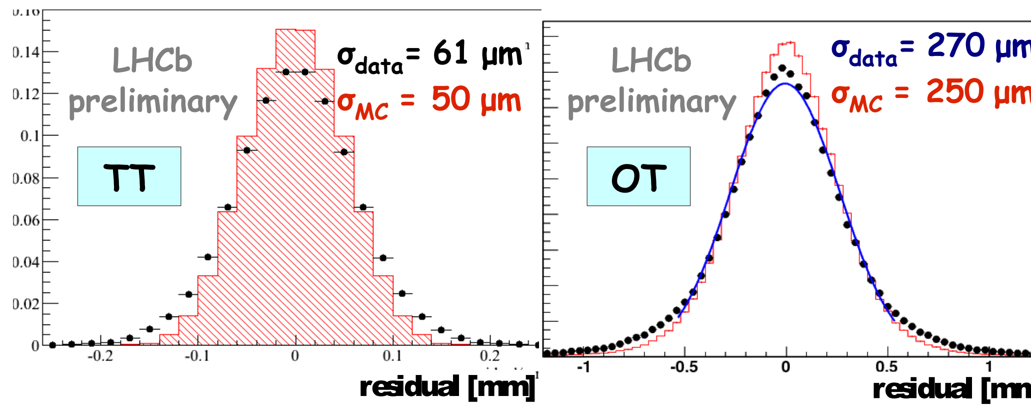



**primary vertex resolution**

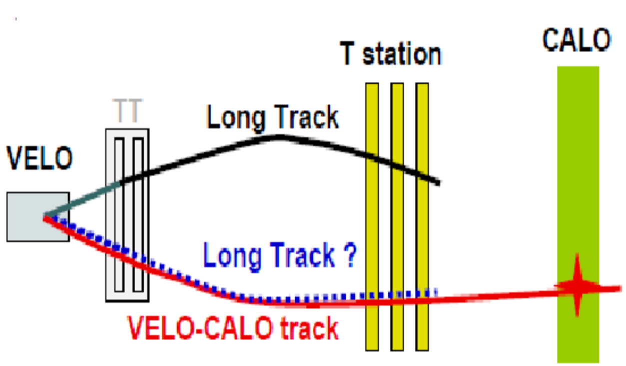


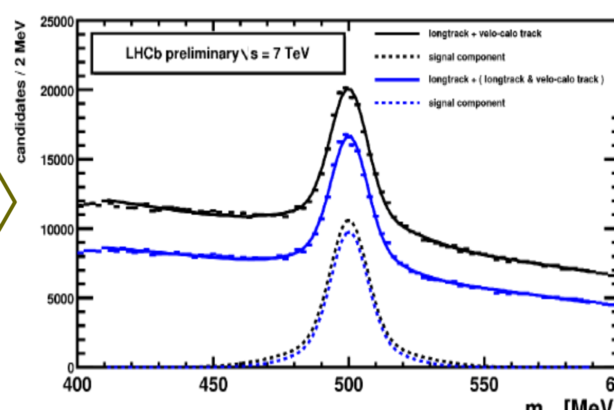
# Tracking

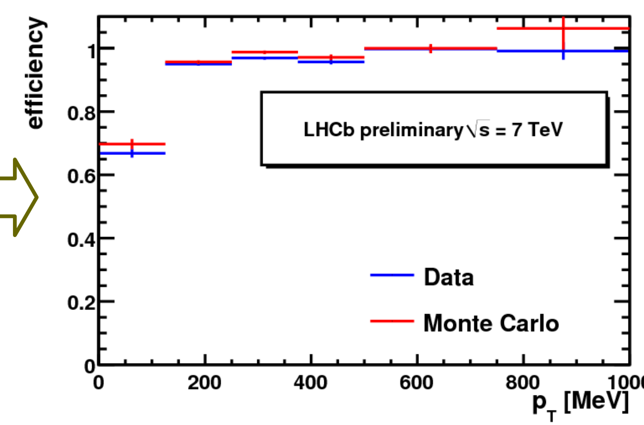
- excellent momentum resolution for invariant mass resolution, rejection of combinatorial backgrounds
- spatial resolutions approaching values expected from simulation




- small differences remaining from residual mis-alignments
- *note: no alignment from cosmics (acceptance too small)*
- reconstruction efficiencies > 90 % for tracks above few GeV
- estimated using "tag-and-probe" methods on $K_S^0 \rightarrow \pi^+\pi^-$

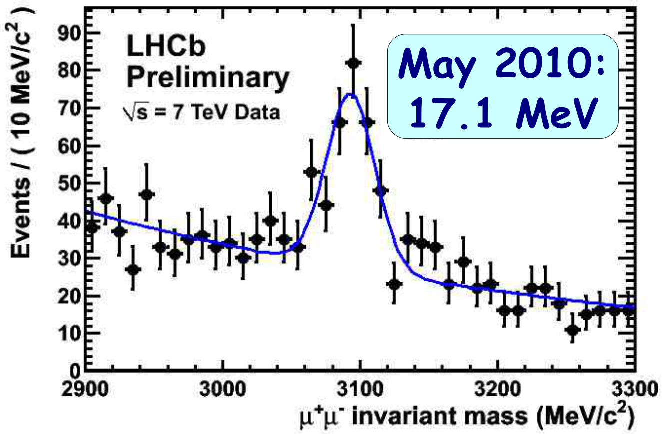


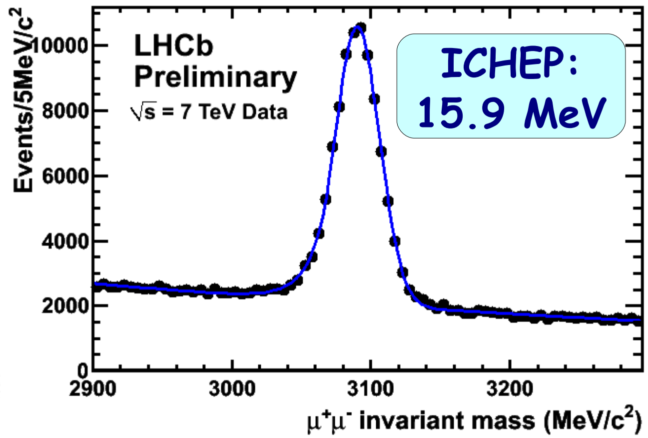



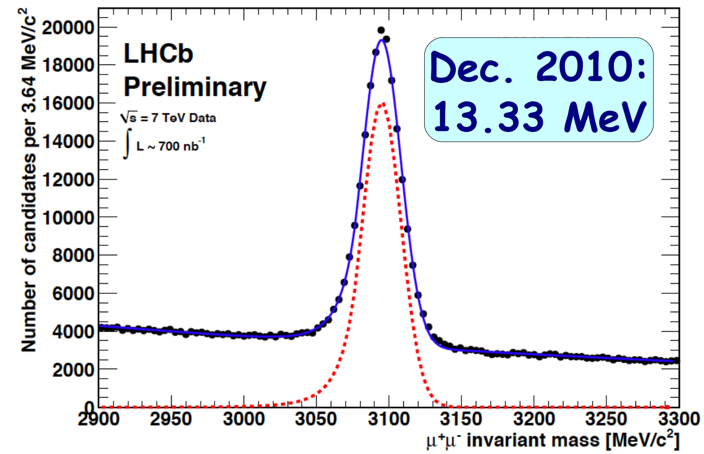



# $\mu^+\mu^-$ Invariant Mass Resolutions

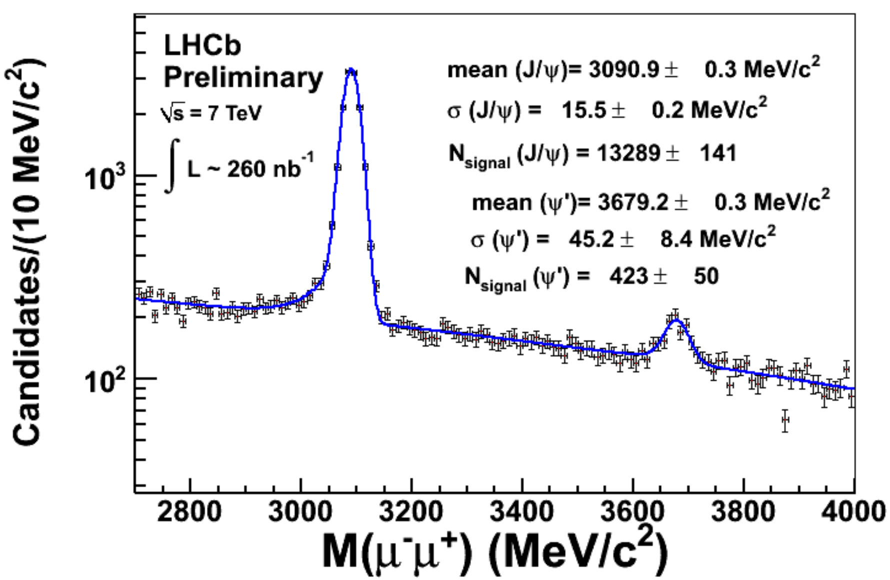
$J/\psi \rightarrow \mu^+\mu^-$ (Monte-Carlo: 12.1 MeV)



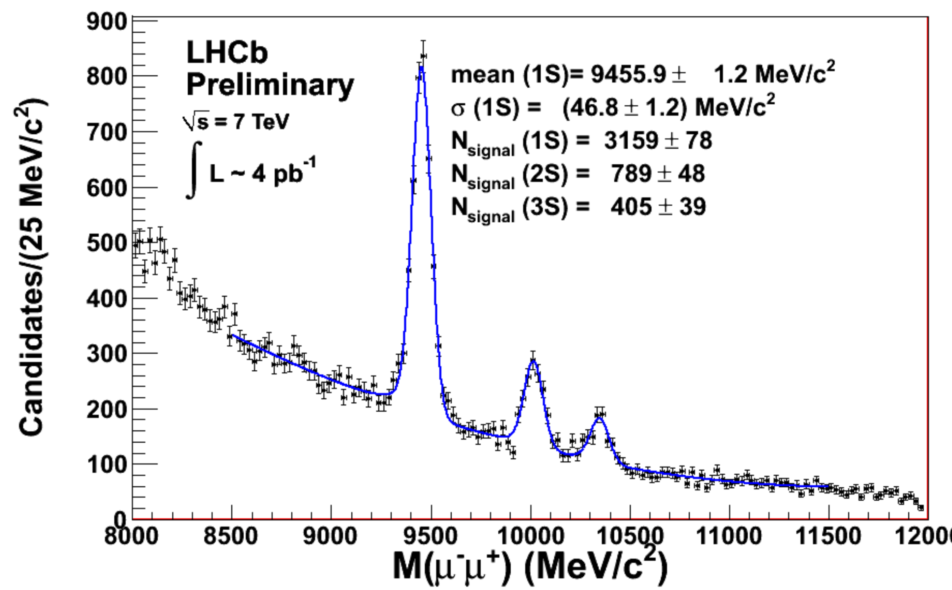




$J/\psi, \psi(2s) \rightarrow \mu^+\mu^-$

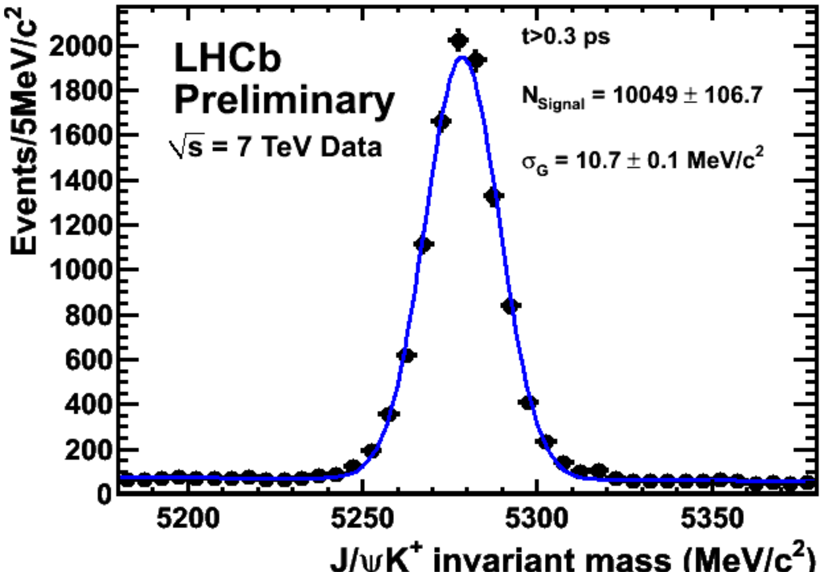



$\Upsilon(1s),(2s),(3s) \rightarrow \mu^+\mu^-$

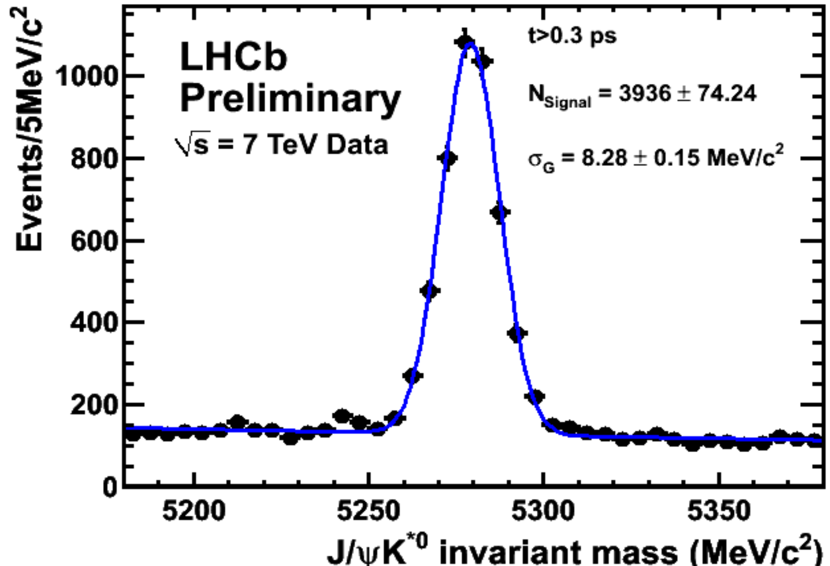


# $b \to J/\psi\, X$ Signals

**$B^+ \to J/\psi K^+$**

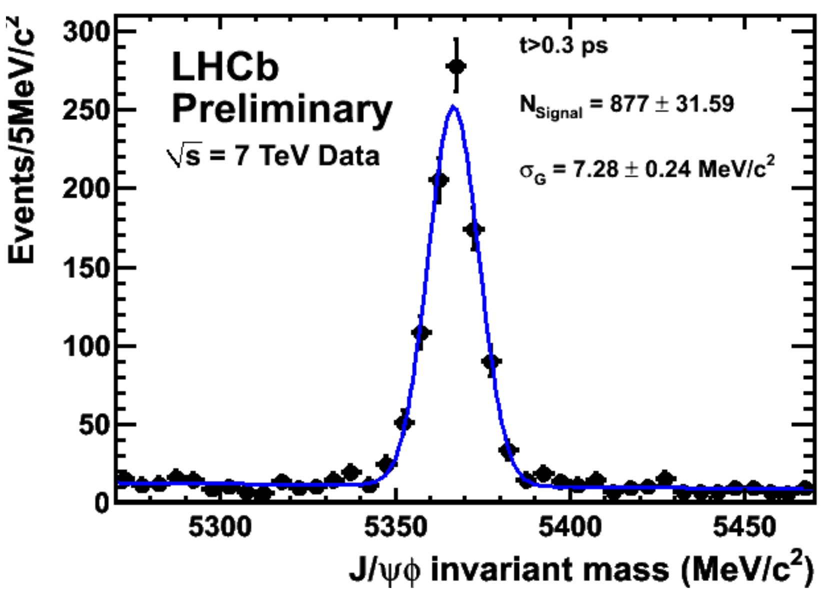



**$B^0 \to J/\psi K^*$**

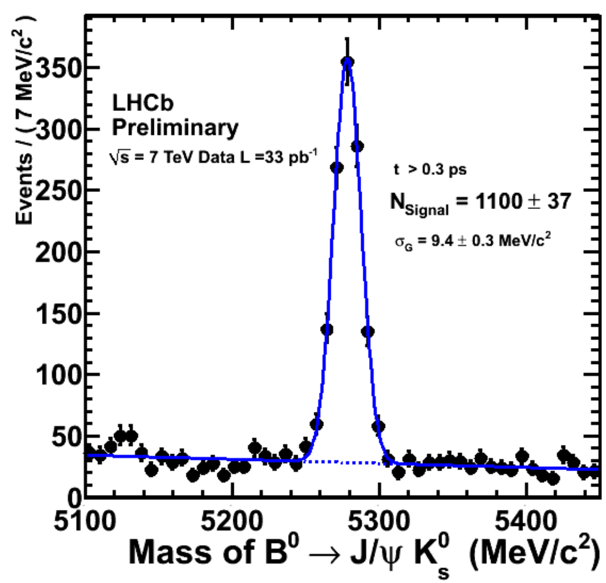



(from 34 $pb^{-1}$)

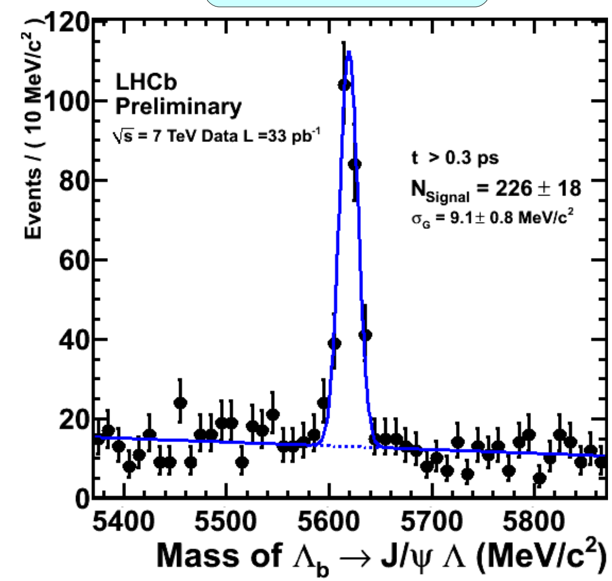
**$B_s^0 \to J/\psi\, \phi$**




**$B^0 \to J/\psi K_S^0$**

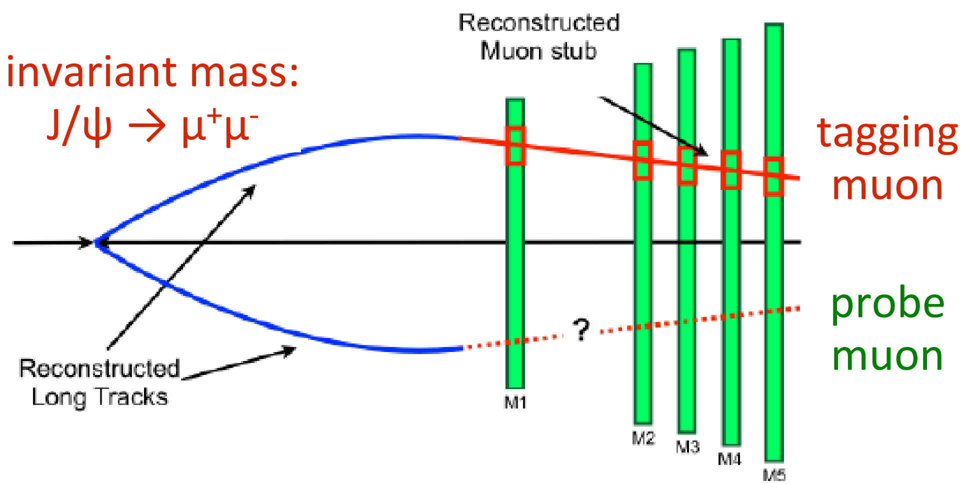


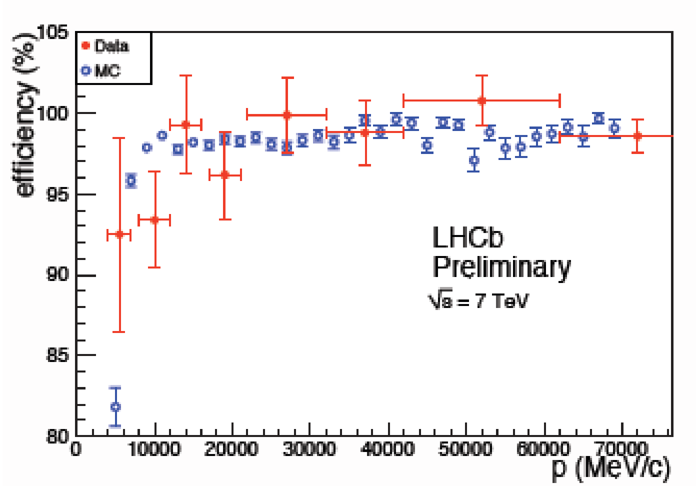

**$\Lambda_b \to J/\psi\, \Lambda$**

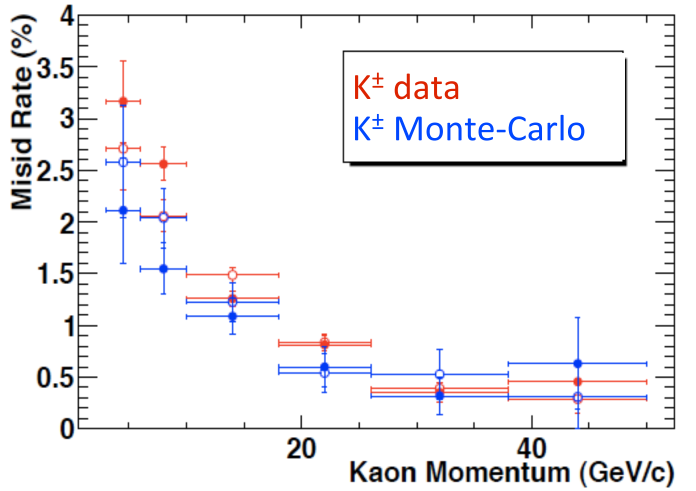


# Muon Identification Performance

- efficiency determined from data using tag-and-probe method on $J/\psi \to \mu^+\mu^-$
- found to be > 90 % for p > 10 GeV
- mis-ID probabilities $K\to\mu$, $\pi\to\mu$, $p\to\mu$ determined from data using tag-and-probe method on $\phi \to KK$, $K_S \to \pi\pi$, $\Lambda \to p\pi$
- all found to be < 2 % for p > 10 GeV
- good agreement between data and simulation

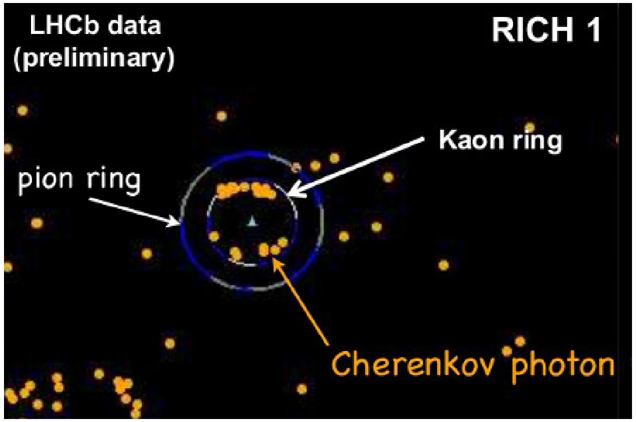


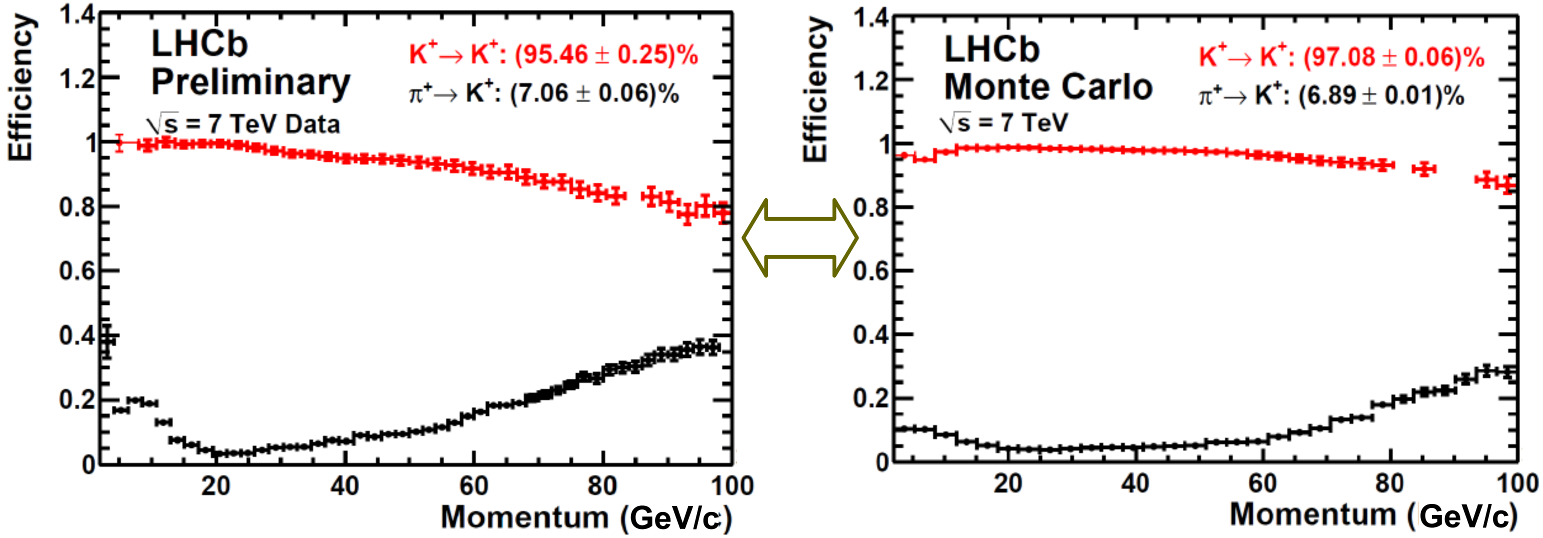



# K/π Identification

- crucial for flavour tagging and for separation of B decays with identical topology, e.g.
  $B^0 \rightarrow \pi^+\pi^- \leftrightarrow B^0 \rightarrow K^\pm\pi^\mp \leftrightarrow B_s \rightarrow K^+K^-$
- two RICH detectors with three radiators
- efficiencies and mis-ID determined from data using tag-and-probe methods on $\phi \rightarrow KK$, $K_S \rightarrow \pi\pi$, $\Lambda \rightarrow p\pi$
- performance found to be close to simulation over full momentum range from few GeV (tagging) to 100 GeV (two-body hadronic decays)

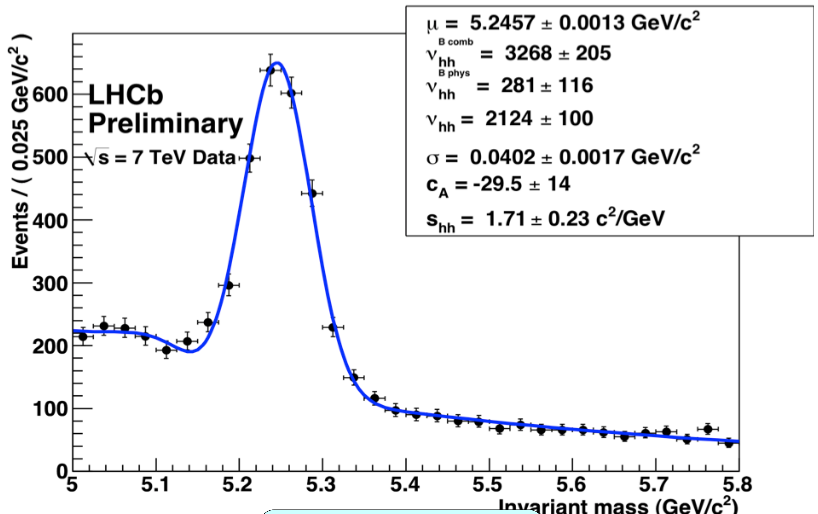


# K/π Identification

(from 34 $pb^{-1}$)

no PID, π mass assumed for both decay particles



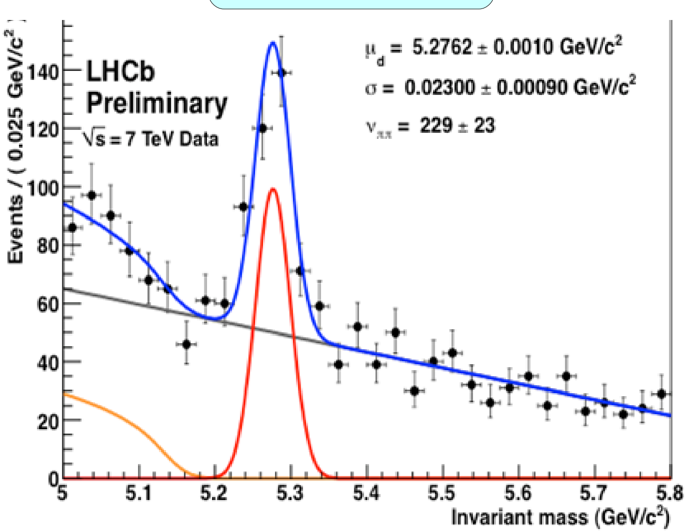

$B \to h^+ h^-$

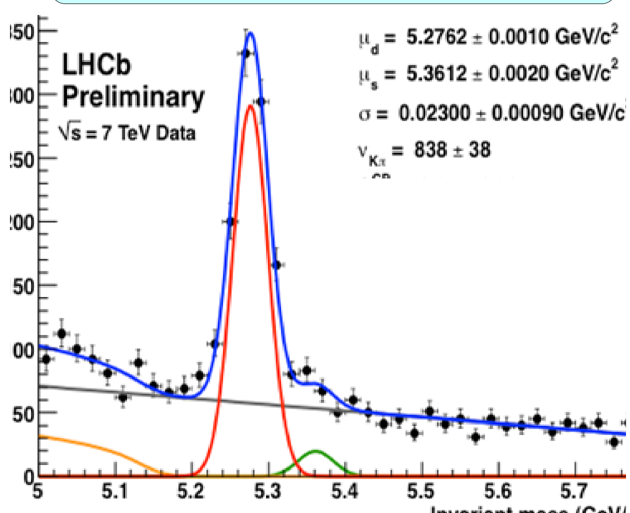
apply PID cuts

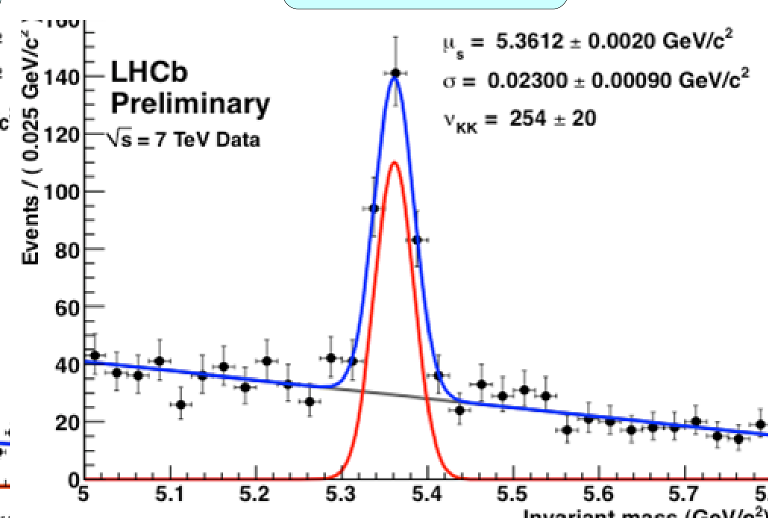
$B^0 \to \pi^+ \pi^-$

$B^0 \to K^\pm \pi^\mp$, $B^0_s \to K^\pm \pi^\mp$

$B^0_s \to K^+ K^-$



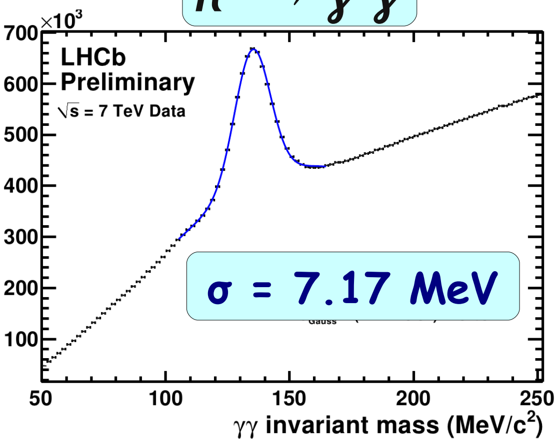



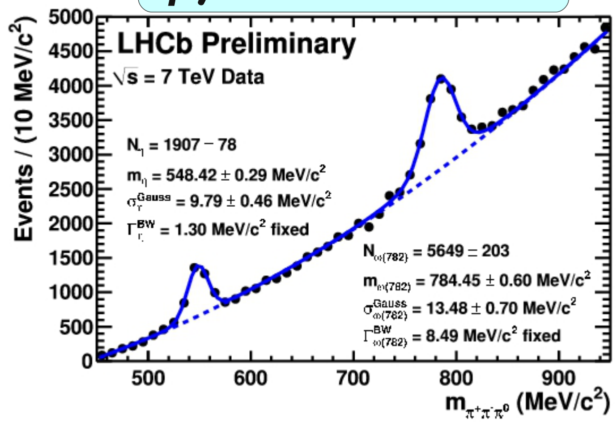
# Calorimeters

- trigger on hadronic decay channels
- reconstruction of final states with e, $\gamma$, $\pi^0$
- $\pi^0$ resolution found in data even better than expected

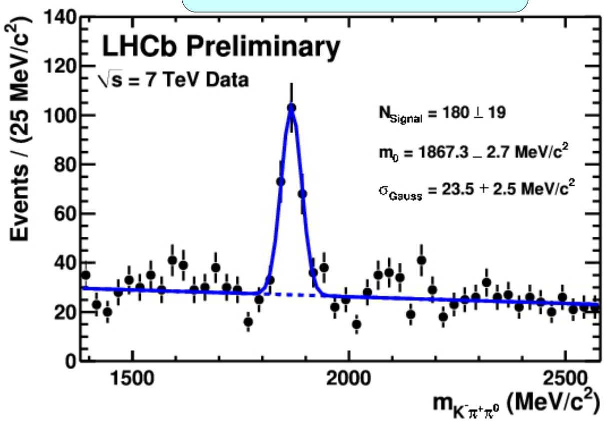
$\pi^0 \rightarrow \gamma\gamma$



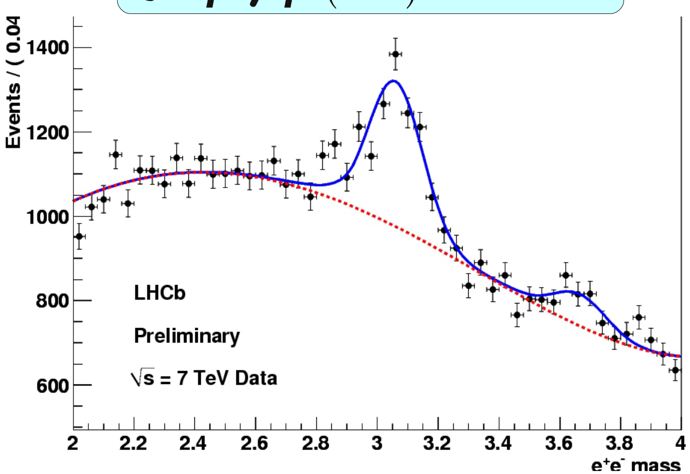

$\eta, \omega \rightarrow \pi^+\pi^-\pi^0$



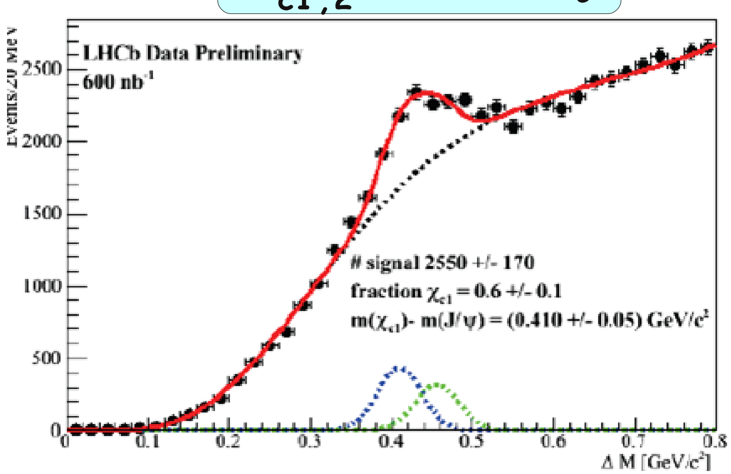

$D^0 \rightarrow K^-\pi^+\pi^0$



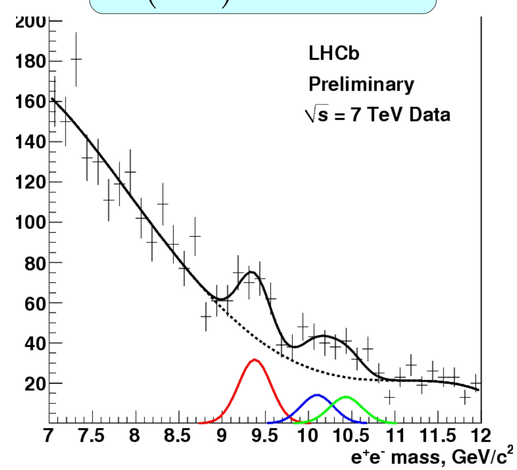

$J/\psi, \psi(2s) \rightarrow e^+e^-$




$\chi_{c1,2} \rightarrow J/\psi, \gamma$



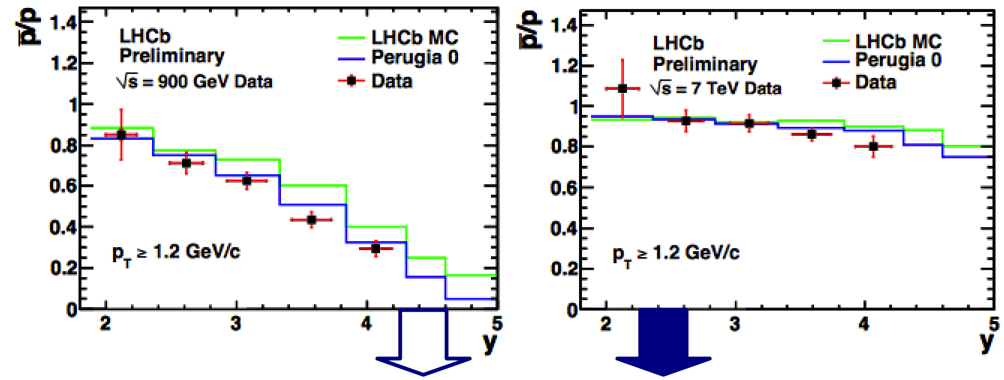

$\Upsilon(ns) \rightarrow e^+e^-$

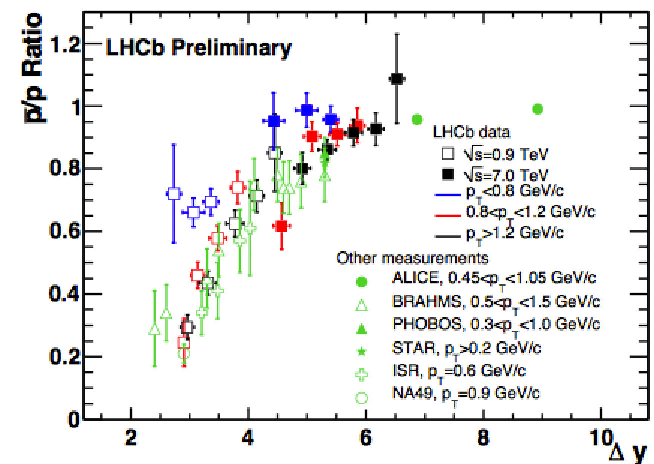


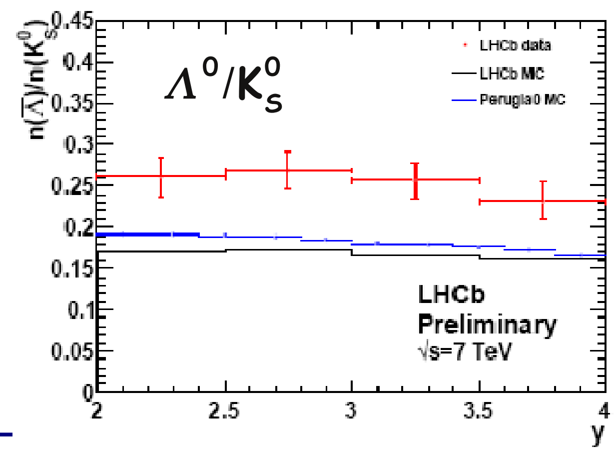
# First Physics

# $p/\bar{p}$, $\Lambda^0/\bar{\Lambda}^0$, $\Lambda^0/K_s^0$ Ratios

- measure Baryon transport from beam particles to final state particles
  - at 900 GeV and at 7 TeV
  - as a function of rapidity y
  - as a function of transverse momentum
- measurements provide important input for Monte-Carlo tuning
- for comparison with previous experiments plot ratios as a function of $\Delta y = y - y_{beam}$
- agreement with previous measurements good
- conclusion for "Perugia 0" Pythia tune
  - describes $p/\bar{p}$ adequately at both energies
  - describes $\Lambda^0/\bar{\Lambda}^0$ poorly at 900 GeV
  - significantly underestimates $\Lambda^0/K_s^0$

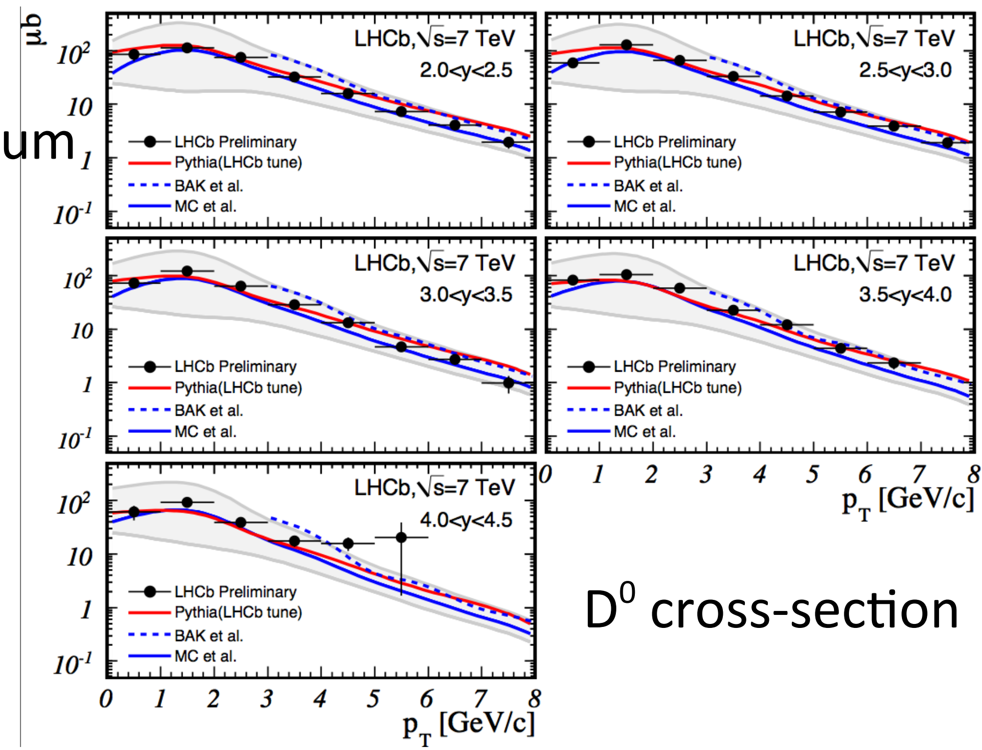


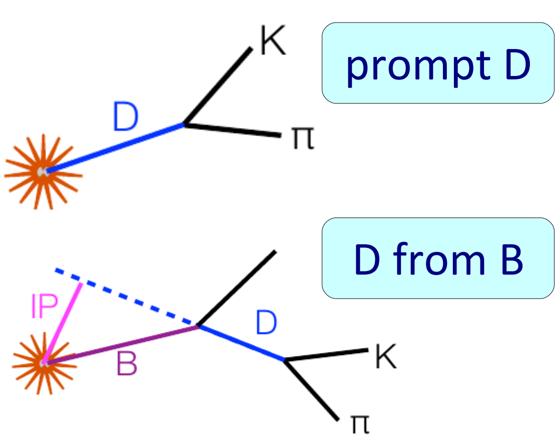



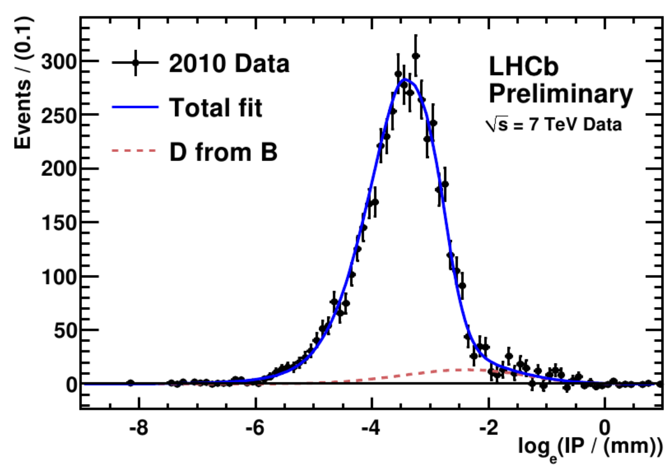
# Open Charm Cross-sections

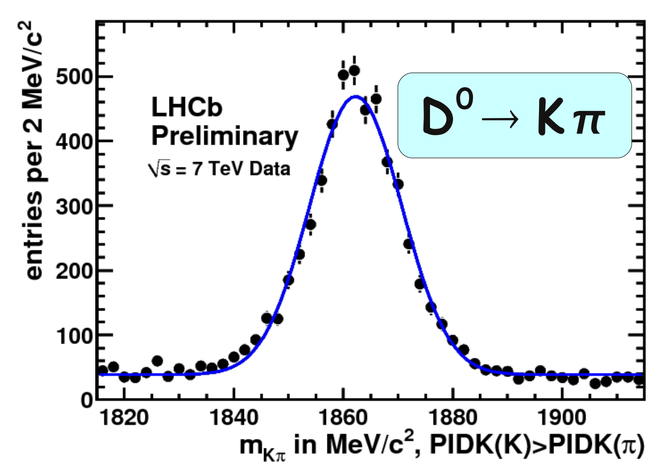
- measure differential cross sections in bins of rapidity up to y = 4.5 and transverse momentum down to $p_T = 0$
- first measurement at $\sqrt{s}$ = 7 TeV
- large uncertainties on theory predictions
- use impact parameter to reject "D from B"
- separate measurements for $D^0$, $D^{*+}$, $D^+$, $D_s^+$
- results agree well with expectation




$D^0$ cross-section

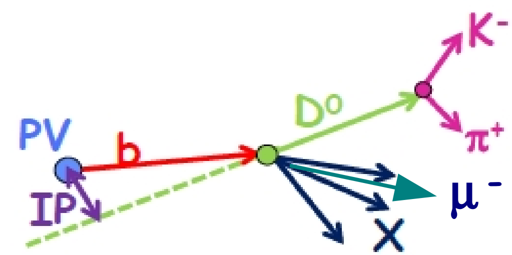


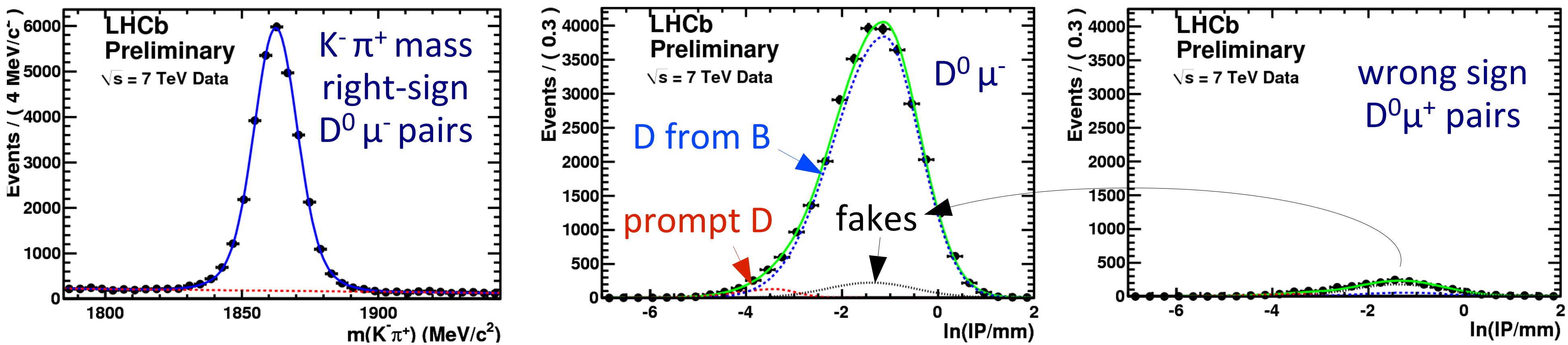



# $b\bar{b}$ Cross Section: $B^0 \to D^0\mu^-\nu X^+$

- reconstruct $D^0$ in $K^-\pi^+$ decay mode
- reconstruct $D^0\mu^-$ pairs from a common vertex
- select “D from B” by large impact parameter
- use wrong-sign $D^0\mu^+$ pairs to estimate backgrounds




- published result based on ~15 $nb^{-1}$ [PLB 694 (2010) 209, arXiv:1009.2731v2 [hep-ex]]

  - within LHCb acceptance $2 < \eta(H_b) < 6$

  **$\sigma(pp \to H_b X) = (75 \pm 5.4 \pm 13)\ \mu b$**

  - using Pythia to extrapolate to full phase space

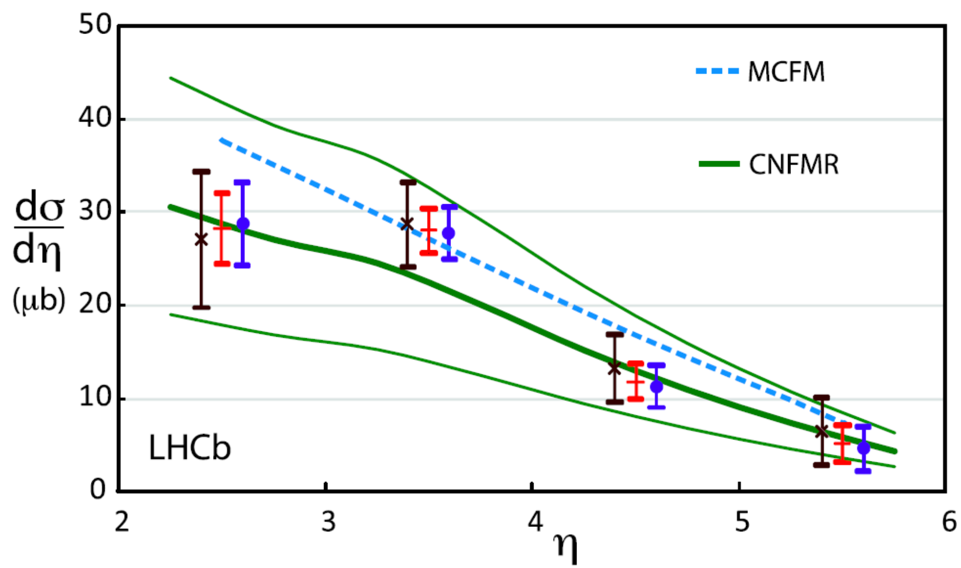
  **$\sigma(pp \to b\bar{b}X) = (284 \pm 20 \pm 49)\ \mu b$**

*good agreement with theory predictions; LHCb performance studies 250 μb*

# $\overline{b}b$ Cross Section: $B^0 \rightarrow D^0\mu^-\nu X^+$

Average cross-section to produce a b or $\overline{b}$ hadron:

$$\sigma(pp \to H_b X) = \frac{\#\text{ of detected } D^0\mu^- \text{ and } \overline{D}^0\mu^+ \text{ events}}{2\mathcal{L} \times \text{efficiency} \times \mathcal{B}(b \to D^0 X \mu^- \overline{\nu}) \mathcal{B}(D^0 \to K^-\pi^+)}$$

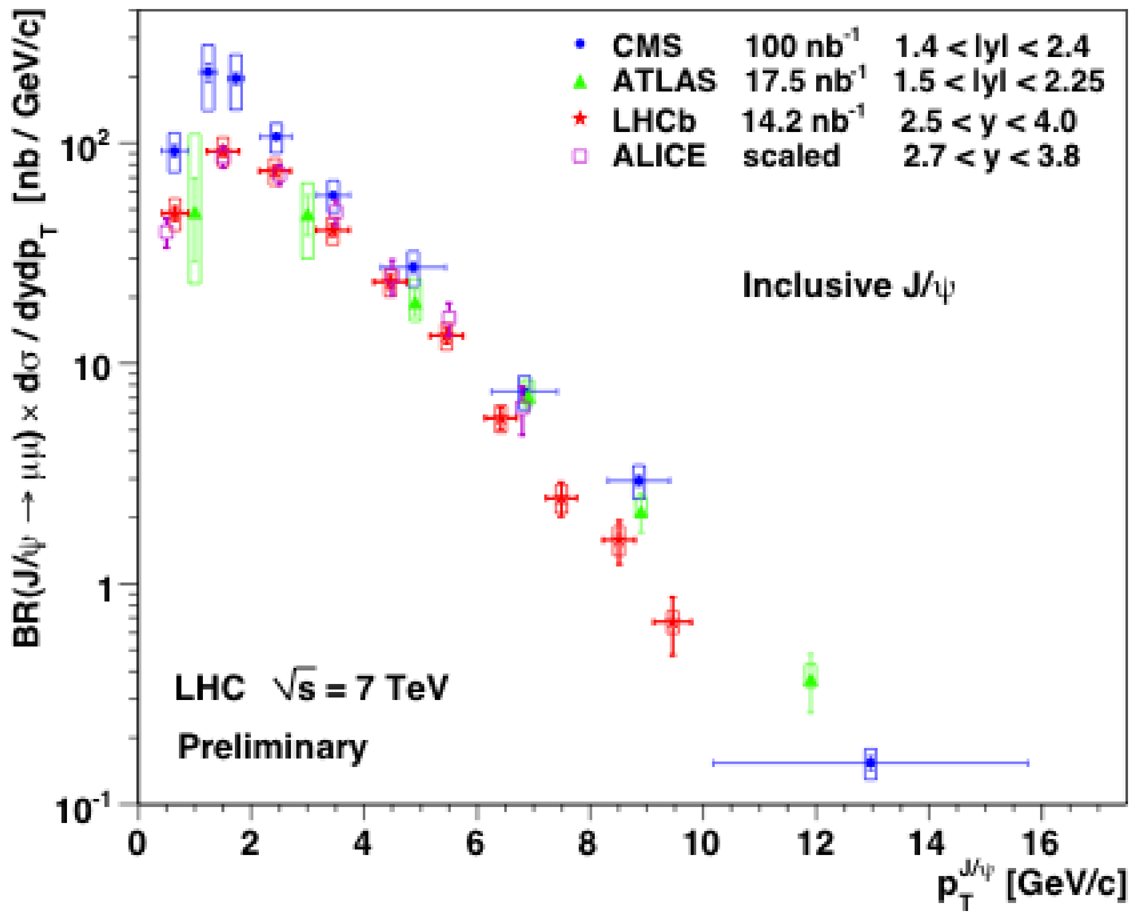



Very good agreement in absolute value and η shape with 2 theories:

- MCFM [Monte Carlo for FeMtobarn processes, Nason, Dawson, Ellis, http://mcfm.fnal.gov], NLO with MSTW8NL PDF.
- CNFMR [Cacciari, Frixione, Mangano, Nason, Ridolfi, JHEP 0407 (2004) 33], FONLL with CTEQ6.5 PDF.

# J/ψ cross-section measurement

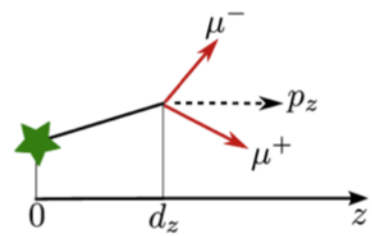
- $J/\psi \rightarrow \mu^+ \mu^-$
- Preliminary results based on early data ($14 nb^{-1}$) shown at ICHEP



# J/ψ cross-section measurement

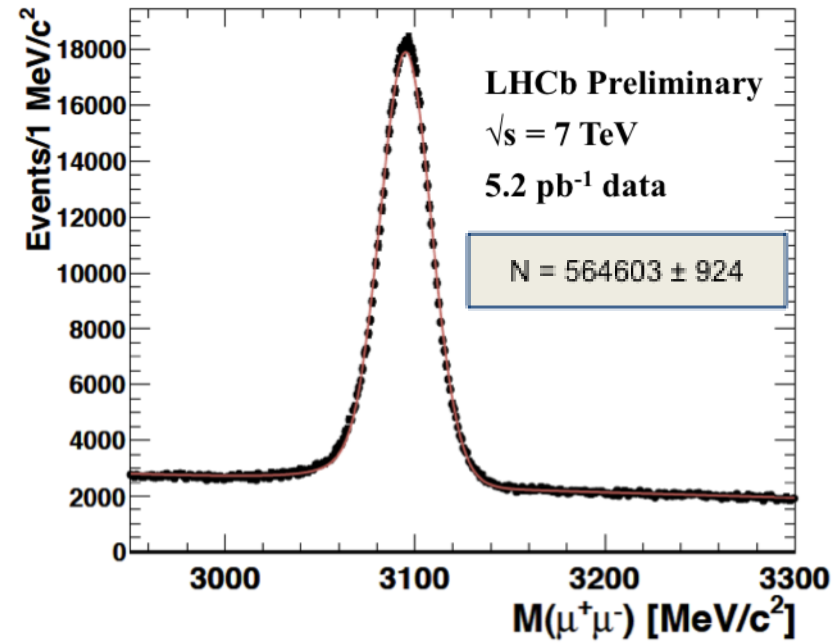
- New measurement released in December, with 5pb$^{-1}$, to be published in January 2011.
- Measure separately:
  - Prompt J/ψ (direct J/ψ + J/ψ from $\chi_c$ feeddown)
  - J/ψ from *b* decays,
- Using to separate them:

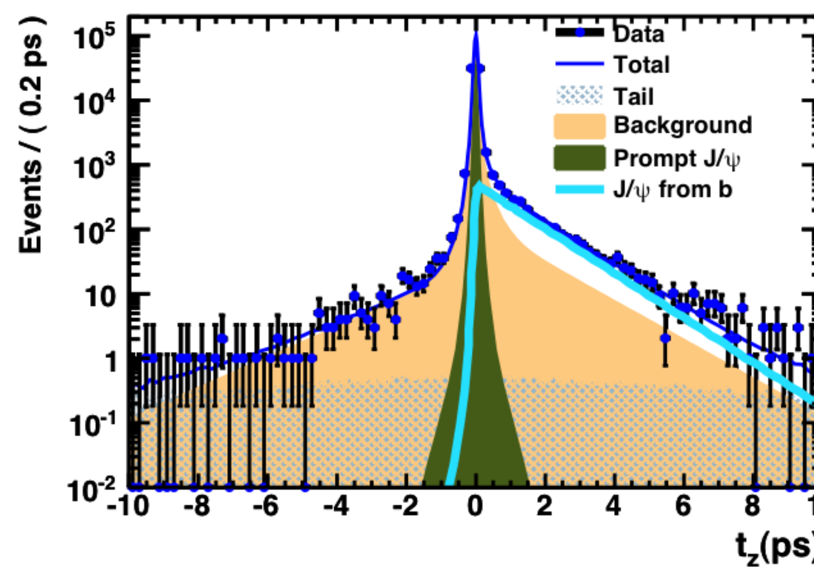
$$t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}$$




- Total bb cross-section:

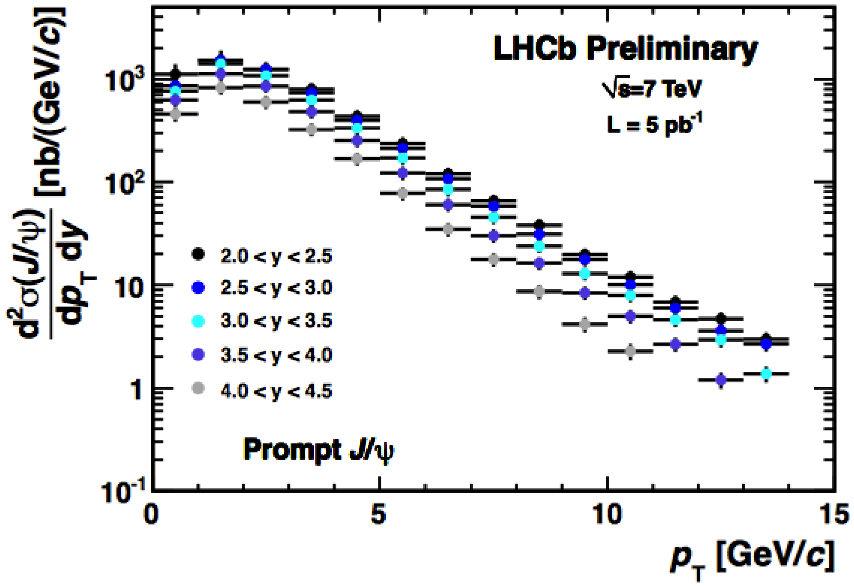
$$\sigma(pp \to b\bar{b}X) = 295 \pm 4 \pm 48\,\mu\mathrm{b}$$

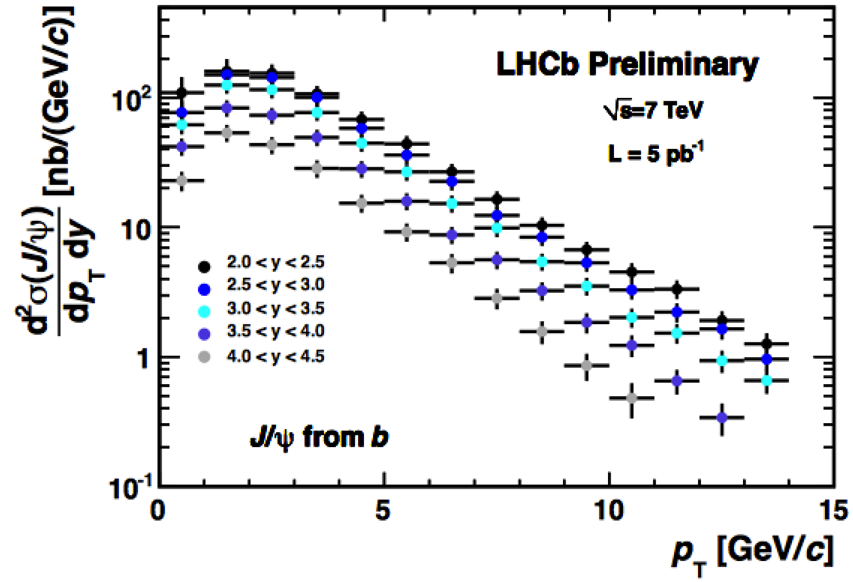


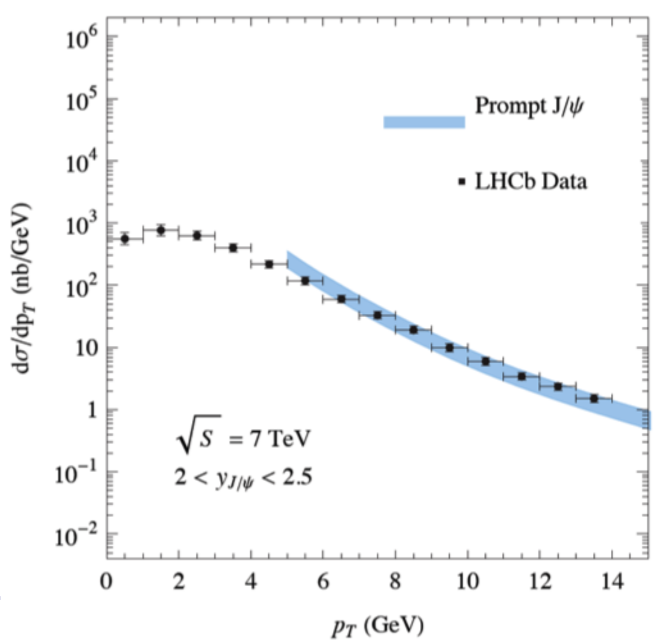



# J/ψ cross-section measurement

- Differential cross-sections in 70 bins ($p_T$ and rapidity, *y*)




Comparison with theory (NLO Color Singlet + Color Octet) [Y.Q. Ma, K. Wang, K.T. Chao, arXiv:1009.3655; Y.Q. Ma, K. Wang, K.T. Chao, arXiv:1012.1030]

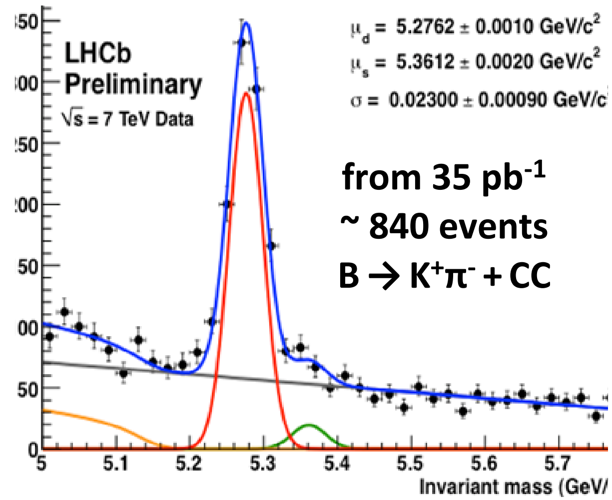
# Prospects for 2011 Physics Results ($1fb^{-1}$)

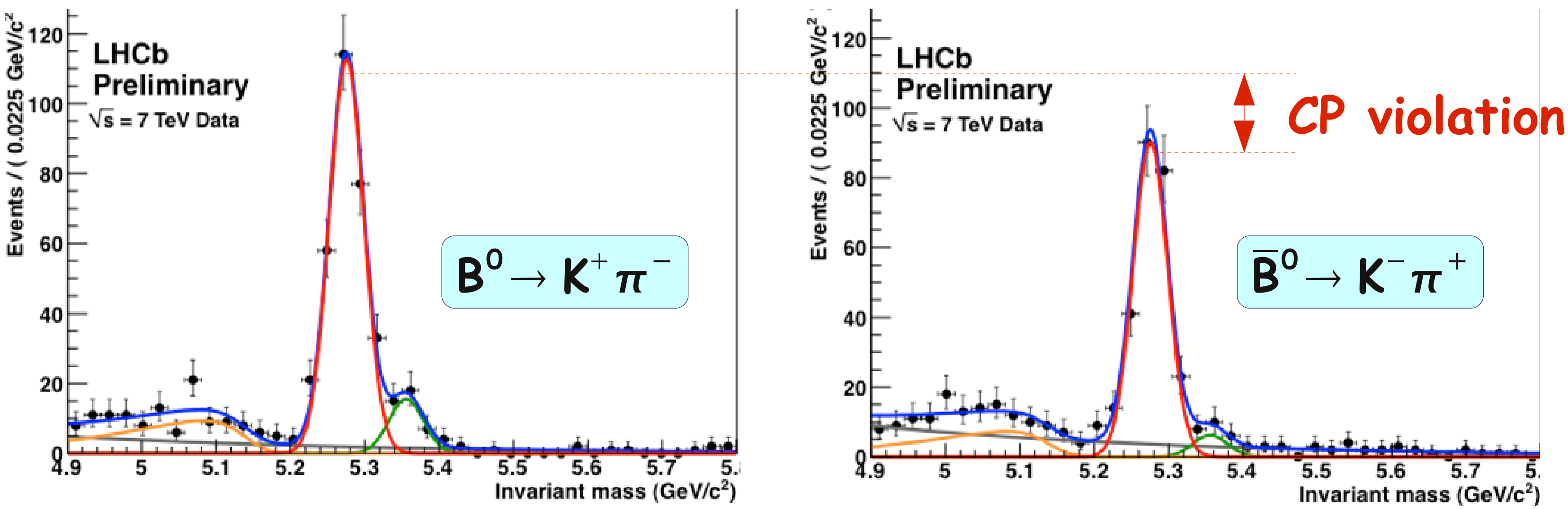
# LHCb running plans for 2011-2012

- <u>From detector point of view</u>:
  - Trigger Computer Farm for HLT will be upgraded to reach 1500 CPU nodes, additional data links will be needed to increase current bandwidth.
  - LHCb has been designed to run for 10 years at 2-5x$10^{32}$ $cm^{-2}.s^{-1}$: limit of the instantaneous luminosity that the detectors can support to have stable operation.
- <u>From trigger point of view</u>:
  - Global event cuts have a large price on luminosity when μ is high.
  - Crucial to improve CPU time consumption per event in the HLT.
- <u>From analysis point of view</u>:
  - No significant gain when μ>2.5.
- <u>LHCb future running strategy</u>:
  - Maximum instantaneous luminosity: 5x$10^{32}$ $cm^{-2}.s^{-1}$
  - Maximum μ of 2.5
  - Propose LHC to displace beams to reduce luminosity at beginning of fill and to readjust them to follow beam lifetime.

# CP Violation in B → Kπ

- separate into $B^0$ and $\overline{B}^0$ using particle ID
- raw asymmetry shows direct CP Violation at 3σ
- central value consistent with world average
- *careful: small corrections from production and detector asymmetry not yet corrected for*

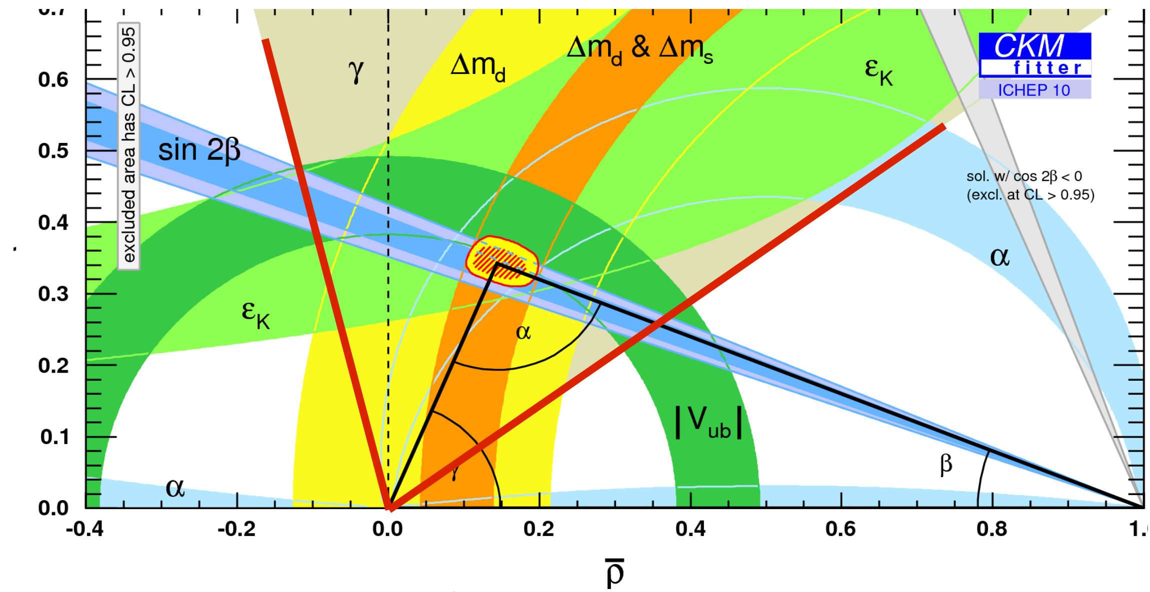


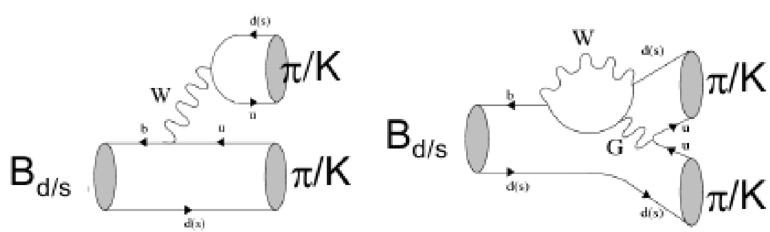

- charmless two-body B-decay modes central to LHCb physics programme
- significant contribution of Penguin diagrams → window to New Physics !

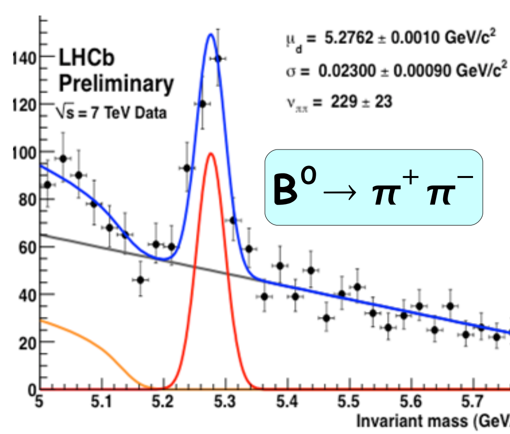
# CKM angle γ

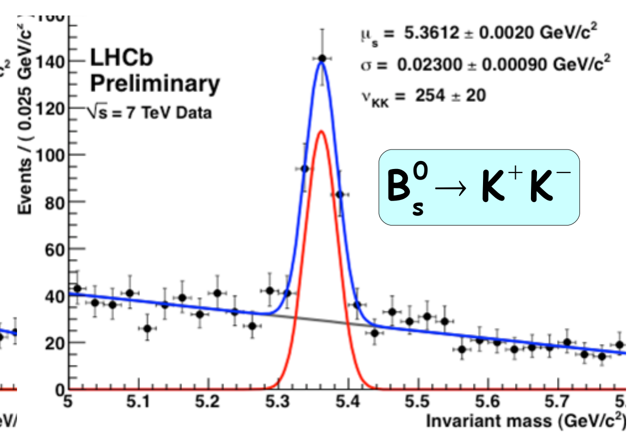
- most difficult to measure and therefore least well constraint by direct measurement
- requires LHCb key features
  - large number of B's
  - trigger on hadronic states
  - excellent π/K separation




- <u>γ from penguins</u>: time-dependent CP asymmetries in $B^0 \to \pi^+ \pi^-$ and $B_s \to K^+K^-$



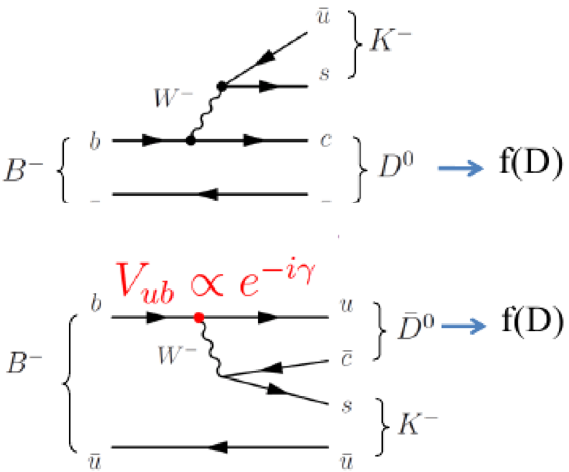



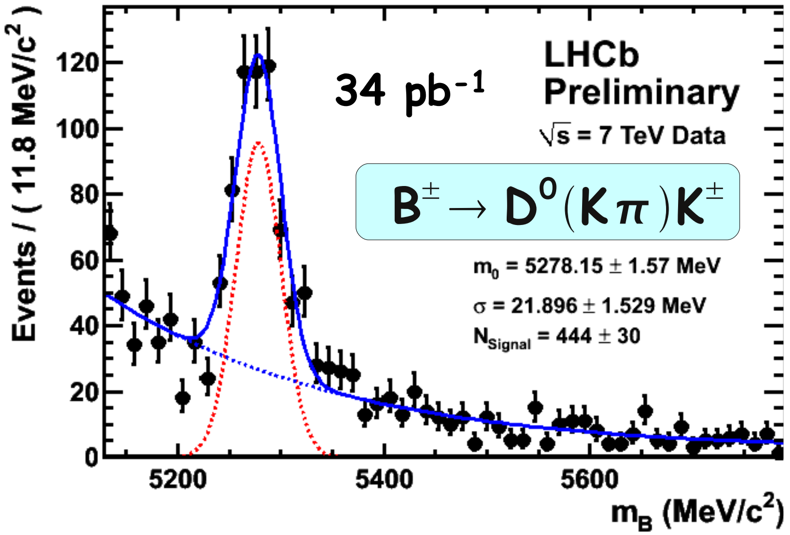




- clear signals from first data
- measured rates match simulation
- expect to reach σ(γ) ≈ 7º from 2 $fb^{-1}$ → beyond 2010/11 run

# γ from Trees

- measure rates $B^\pm \to D^0(\bar{D}^0)\, K^\pm \to f\, K^\pm$
- interference of tree amplitudes if final state f is common to $D^0$ and $\bar{D}^0$:
  - GLW: f = KK, ππ (CP Eigenstates)
  - ADS: f = $K^+\pi^-$ ($D^0$ decay suppressed)
  - GGSZ: f = $K_S\pi\pi$ (Dalitz decays)




- clean signals from first data
- rates match expectation
- expected LHCb event yields for 1 fb$^{-1}$:

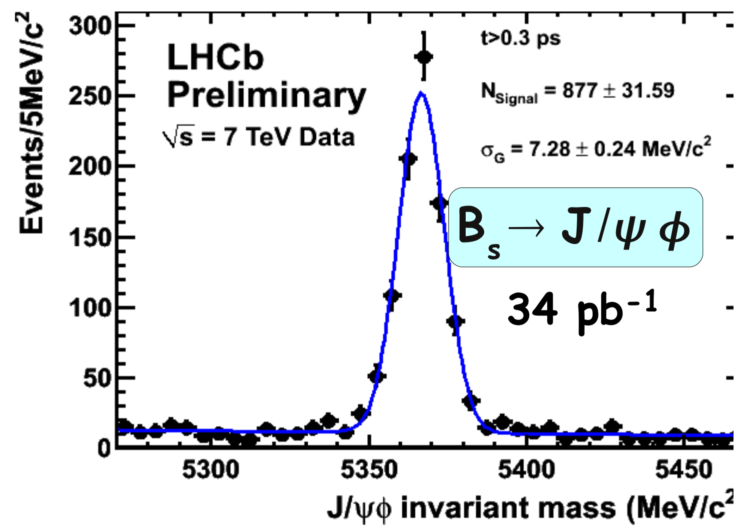
| | |
|---|---|
| $B^- \to D(KK)\, K^-$ | 2000 |
| $B^- \to D(\pi\pi)\, K^-$ | 750 |
| $B^- \to D(K\pi)$ K (favoured) | 20000 |
| $B^- \to D(K\pi)$ K (suppressed) | 400 |

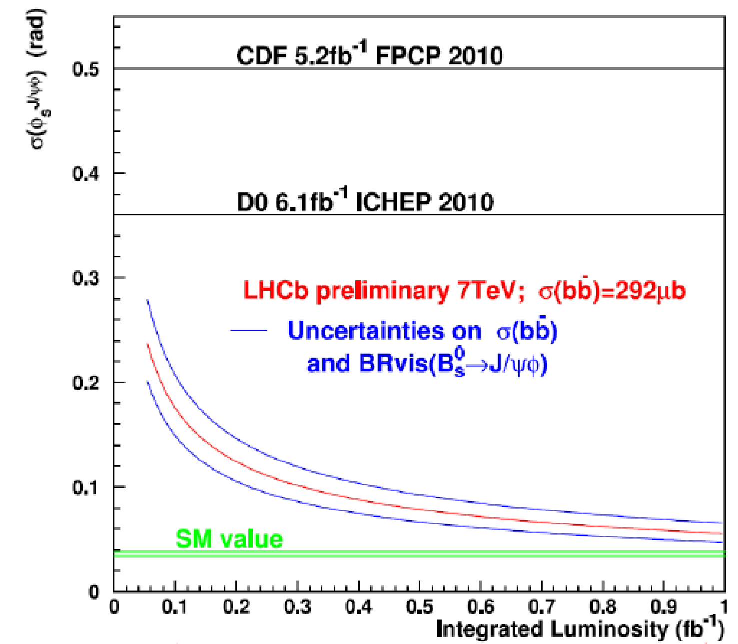
CDF: ~30 events from 5 fb$^{-1}$

- expected reach with 1 fb$^{-1}$: $\sigma(\gamma) \approx 8^\circ$

# $\phi_s$ from $B_s \to J/\psi\ \phi$

- $B_s\bar{B}_s$ mixing phase $\phi_s$: small in the Standard Model, can be enhanced by New Physics
- some hints from CDF/D0 but not significant
- "golden channel" for measurement of $\phi_s$: time-dependent CP asymmetry in $B_s \to J/\psi\ \phi$
- requires large statistics for angular analysis to separate CP even and CP odd final states
  - expect 35000 selected events from 1 $fb^{-1}$
- requires flavour tagging to tag initial $B_s$
- requires excellent proper-time resolution to resolve fast $B_s\bar{B}_s$ oscillation ($\Delta m_s$ = 17.8 $ps^{-1}$)
- currently ~60 fs where 38 fs expected
  - investigation of possible causes ongoing
  - would imply 20 % reduction in sensitivity



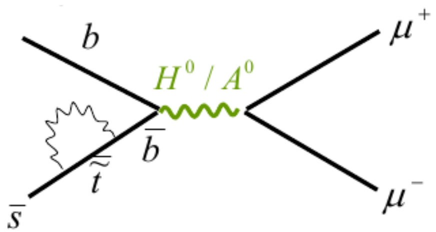



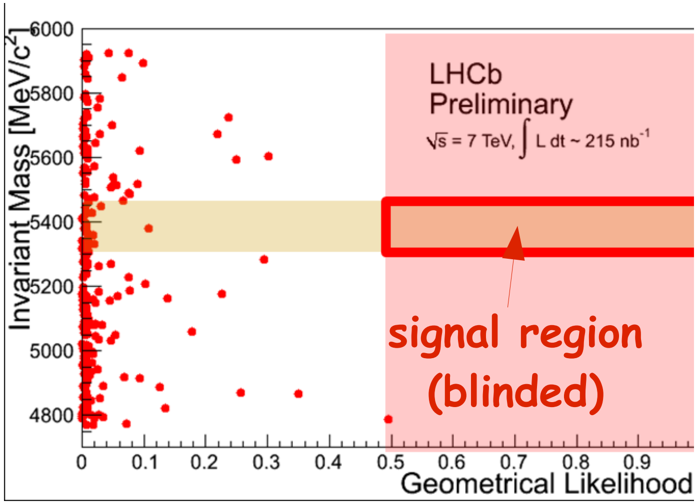
# $B_s \to \mu^+ \mu^-$

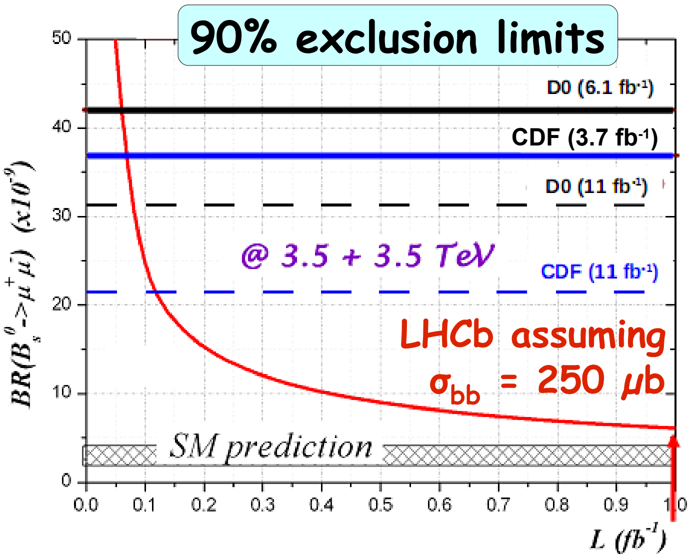
- one of the early benchmark channels
- very rare FCNC decay in Standard Model

$$\mathrm{BR}\,(B_s \to \mu^+\mu^-) = (3.6 \pm 0.4) \times 10^{-9}$$

- can be significantly enhanced by New Physics
- best upper limits from CDF/D0 ~ 10 x SM
- already cutting into New Physics parameter space
- use 3-dim binned likelihood to isolate signal
  - invariant mass of muon pair
  - muon-ID
  - Geometrical Likelihood (lifetime, IP, DOCA…)
- use control channels to calibrate likelihoods from data: $J/\psi \to \mu^+\mu^-$, $B^0 \to K^+\pi^-$, $B_s \to K^+K^-$
- approach current CDF/D0 limits with 2010 data
- with 1 $fb^{-1}$ expect 5σ detection if BR ≈ 5 x $BR_{SM}$



# Conclusions

- LHCb has a unique potential for the

## INDIRECT DISCOVERY

  of New Physics
- the experiment is performing very well, under harsher conditions than it was designed for
- the good agreement between simulation and early measurements indicates that estimated physics reaches seem realistic
- in some areas we are already getting close to being competitive with exisiting results