Onia production in pA and Ap collisions at LHCb

- A = Pb -

R. Jacobsson

on behalf of the LHCb Collaboration

Outline

- LHCb objectives and characteristics
- Detector performance
- pA physics motivation – New comers!
- pA cross-section measurement
- Measurement of J/ψ in pA
- Conclusions with future prospects

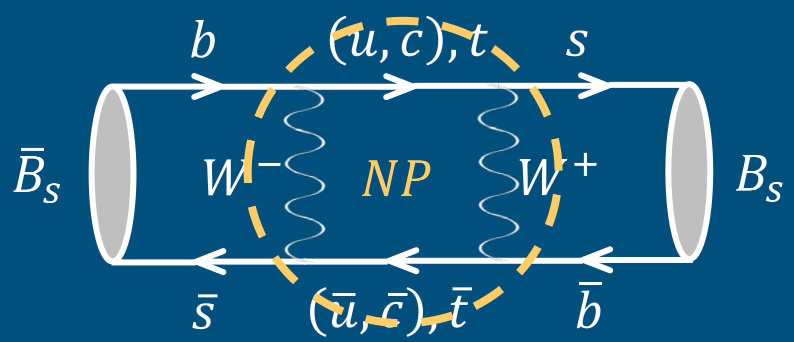
LHCb @ LHC

LHCb Main Objective

- Focus on measuring *indirect* effects of New Physics in CP violation and Rare decays using FCNC processes mediated by loop (box and penguin) diagrams
  - Strongly suppressed processes allow distinguishing NP sources
  - Virtual effects allow probing energies much higher than the E_{cms} of the LHC
  - ➔ Complementary to the direct searches by Atlas and CMS

Ex. B_s oscillations:

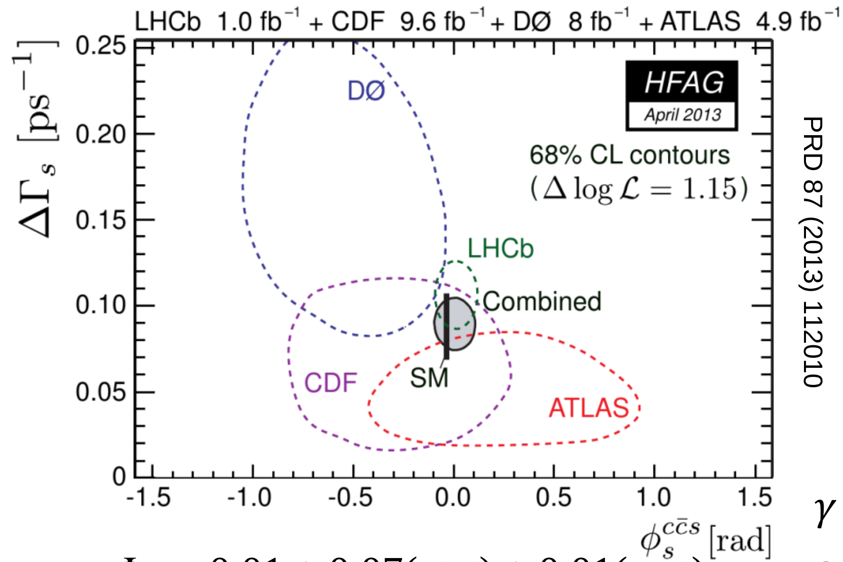
$$\Phi_s^{exp} = \Phi_s^{SM} + \Phi_s^{NP}$$



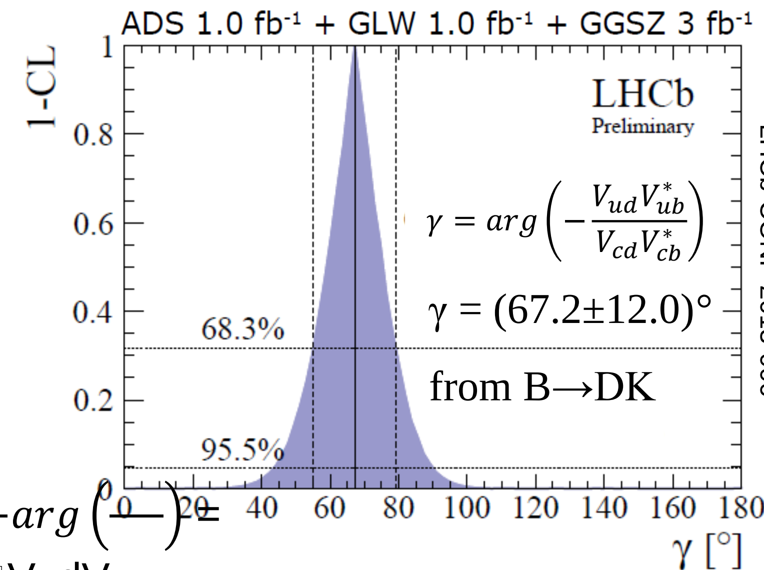
Contribution from New Physics $\Phi_s^{NP} \propto \frac{|\delta|}{\Lambda_{NP}^2}$, Λ_{NP}~mass of new particles

- While initial aim of LHCb was b-physics, has also demonstrated that it can do
  - Charm physics (oscillations, CP violation)
  - QCD physics (PDFs via Z/W production, Central Exclusive Production,...)
  - ➔ In beyond design conditions, LHCb has earned the title of « General Purpose Forward Detector »

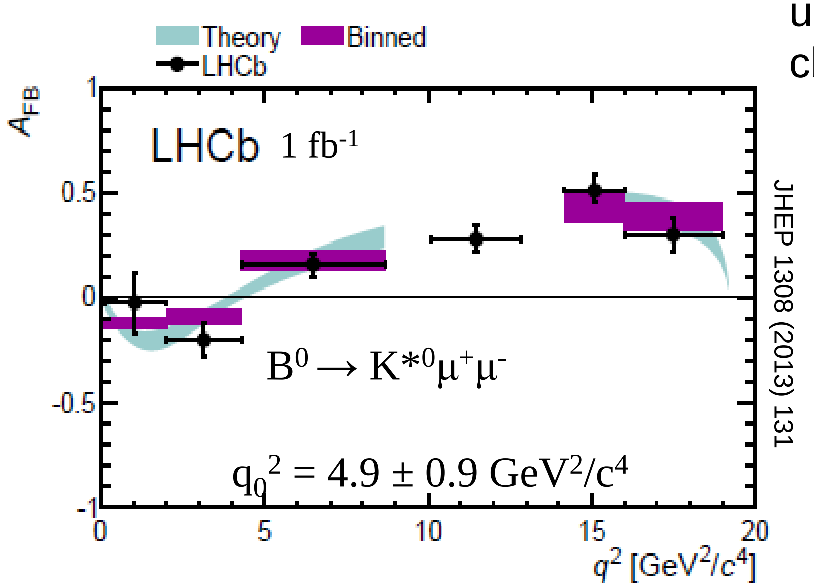
World Class Measurements



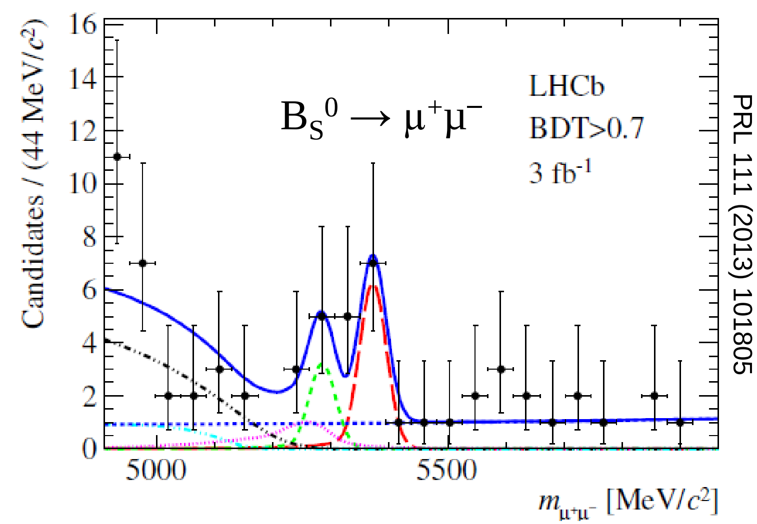
$\Phi_s = 0.01 \pm 0.07(stat) \pm 0.01(syst)$



$\gamma = -arg\left(\frac{}{}\right) =$
arg(□VudV
ub=VcdV
cb)



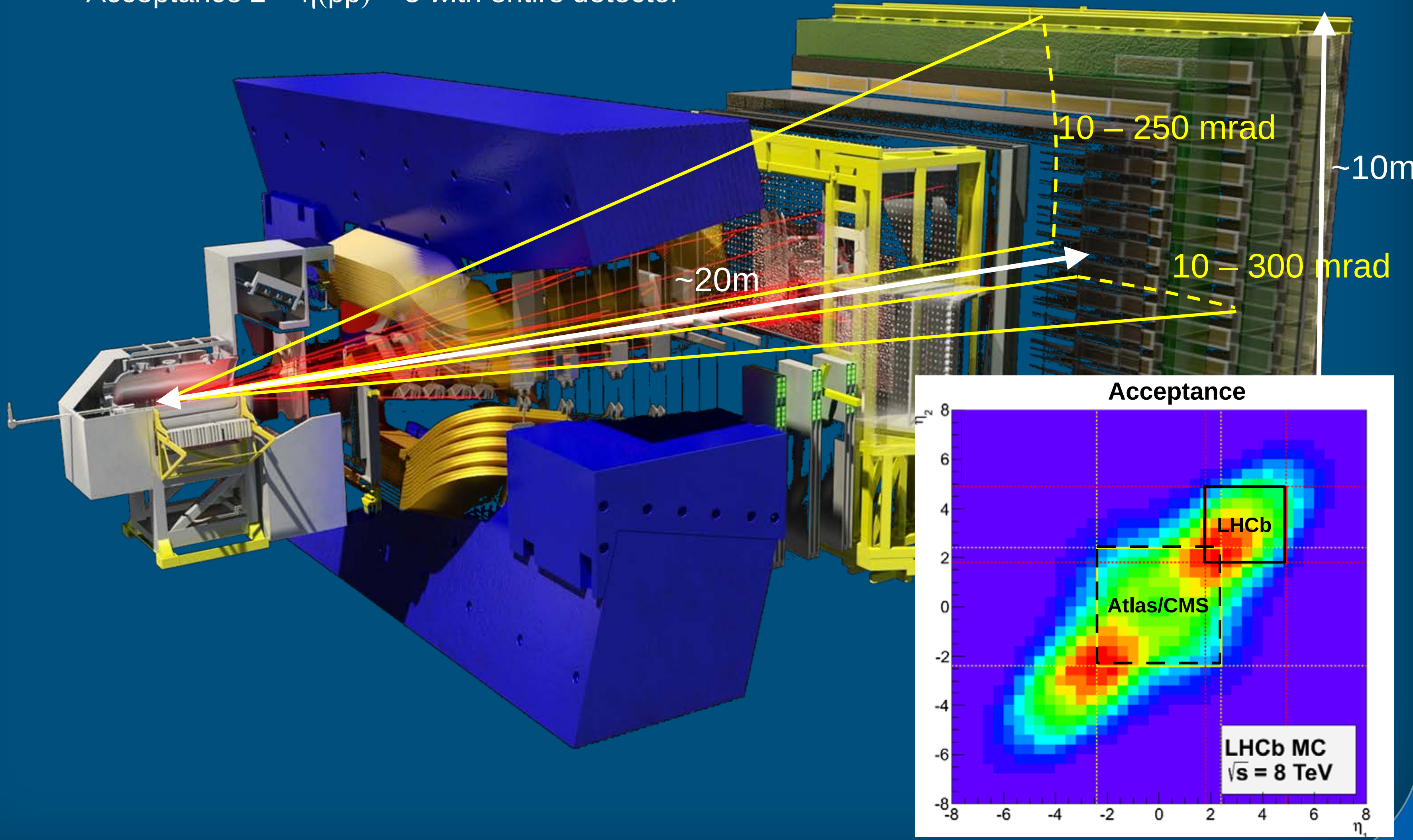
$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$



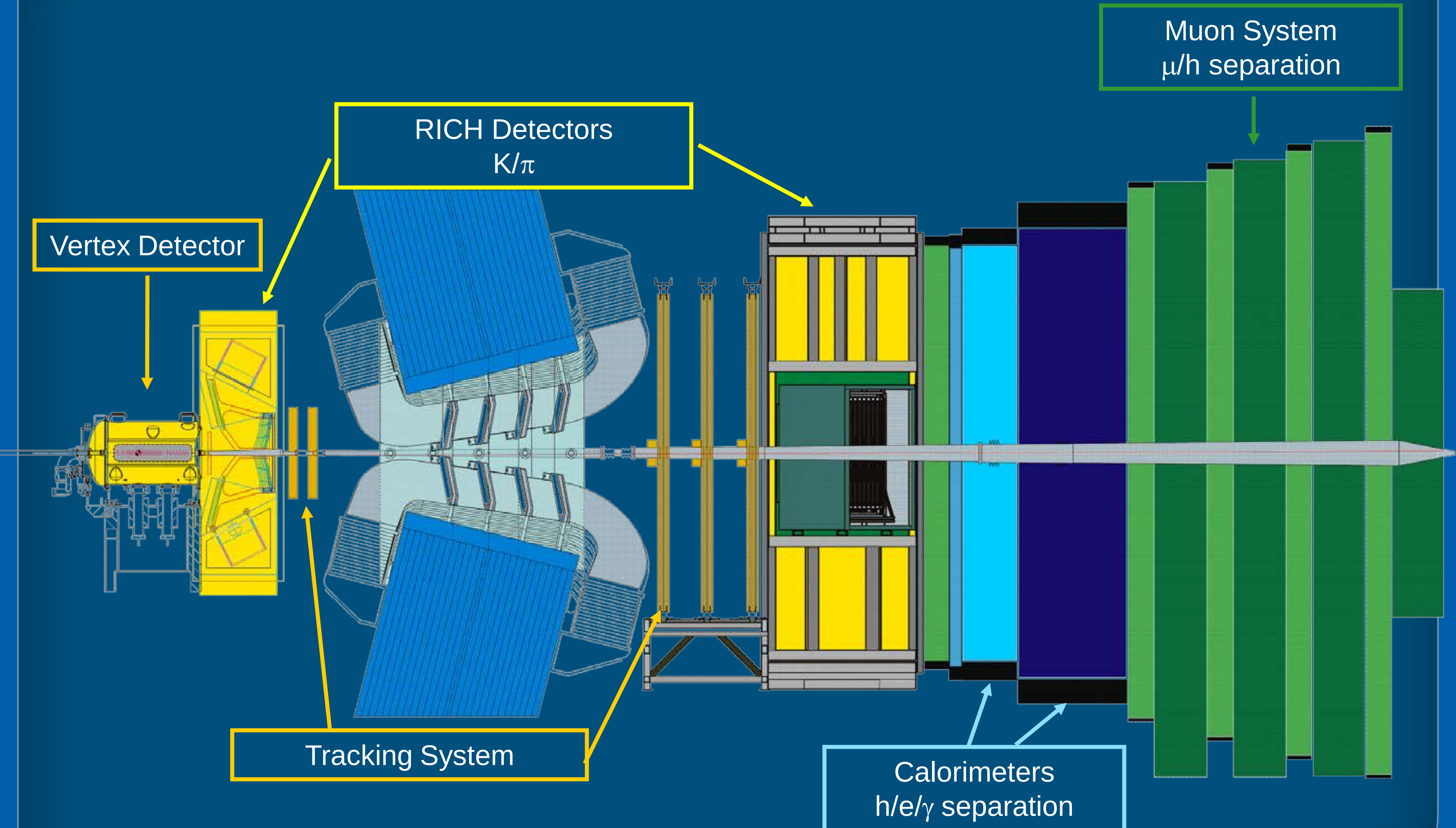
LHCb Detector

Covers ~4% of the solid angle, but captures ~40% of the heavy quark production cross-section in pp collisions

- Acceptance $2 < \eta(pp) < 5$ with entire detector

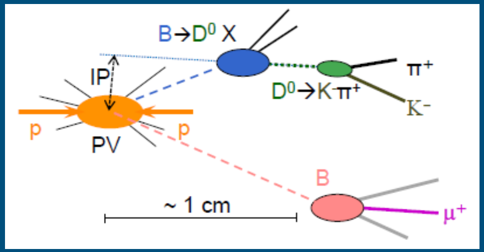


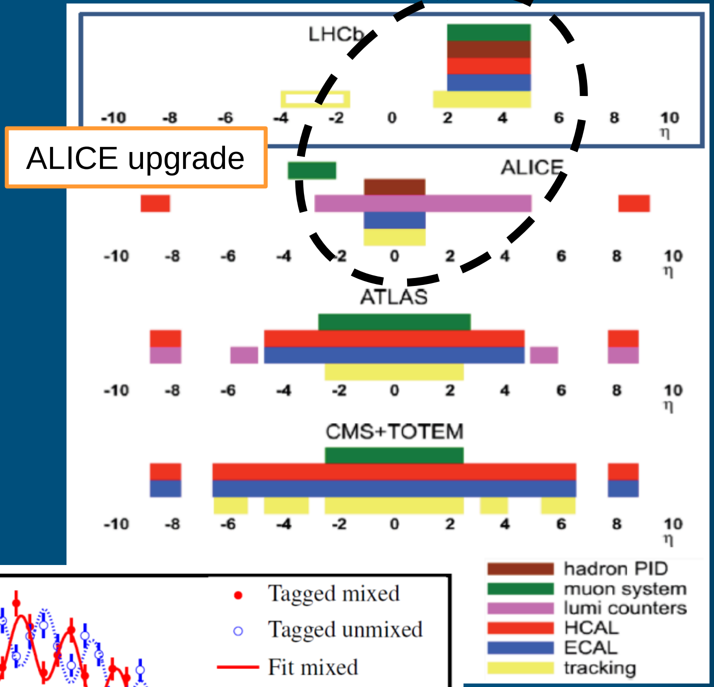
LHCb Detector

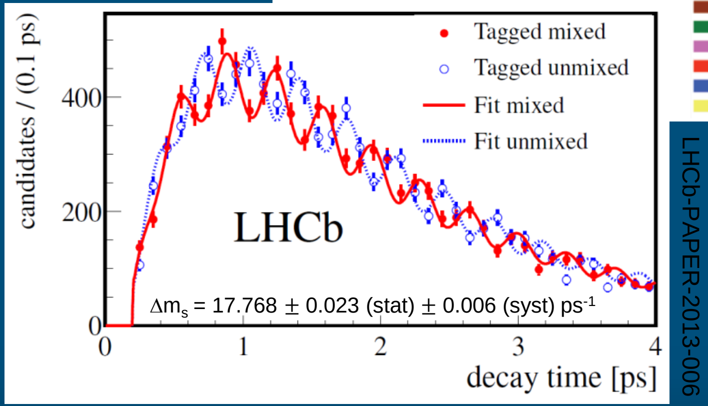


Strengths of LHCb

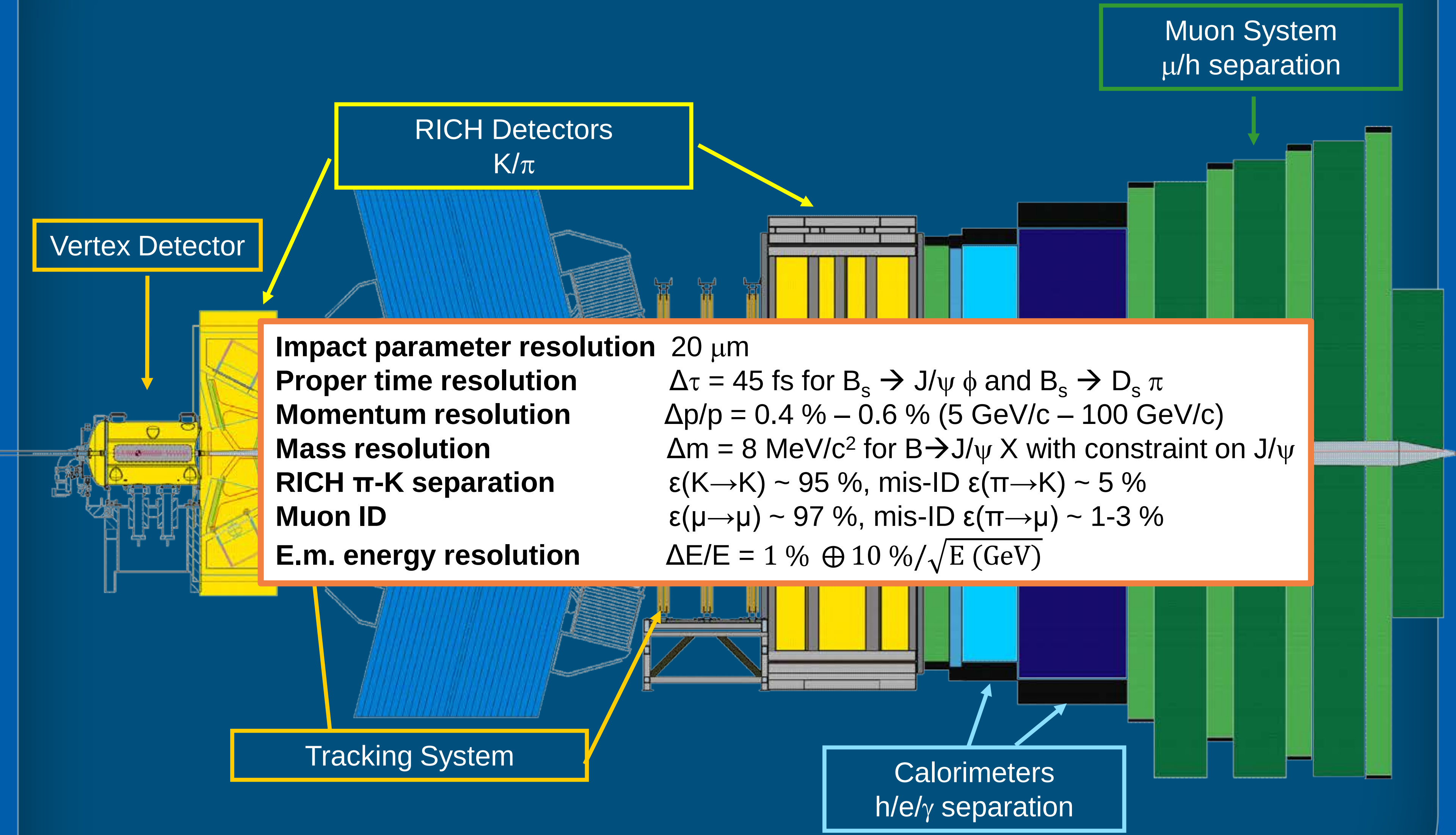
- Collect high statistics of a large variety of B and D final states in an environment with very large background
  - Fast and efficient trigger for both hadronic and leptonic final states
  - Requires reconstruction
- Resolve fast oscillations
  - Vertex resolution
- Background reduction and flavour tagging
  - Very good impact parameter resolution
  - Determination of track parameters
  - Charge determination and momentum resolution
  - Mass resolution
  - K/π separation in a wide momentum range
  - γ / π^0 reconstruction, electron identification
  - Muon identification
- … in the entire acceptance $2 < \eta < 5$







Current LHCb Detector Performance



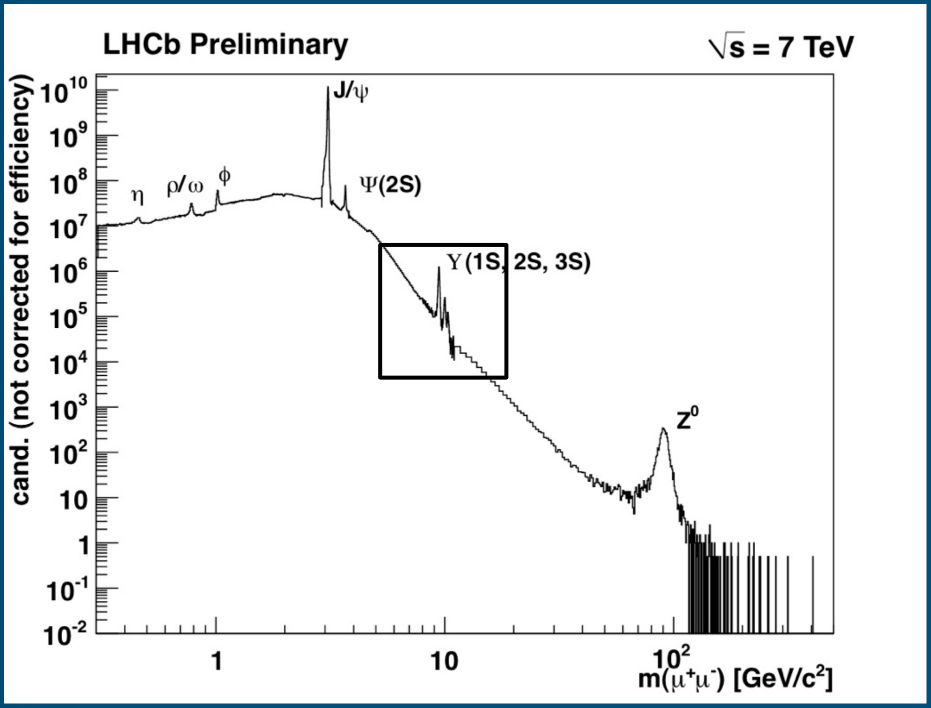
Impact parameter resolution	20 μm
Proper time resolution	$\Delta\tau$ = 45 fs for $B_s \rightarrow J/\psi\ \phi$ and $B_s \rightarrow D_s\ \pi$
Momentum resolution	$\Delta p/p$ = 0.4 % – 0.6 % (5 GeV/c – 100 GeV/c)
Mass resolution	Δm = 8 MeV/c^2 for $B \rightarrow J/\psi$ X with constraint on J/ψ
RICH π-K separation	$\varepsilon(K\rightarrow K)$ ~ 95 %, mis-ID $\varepsilon(\pi\rightarrow K)$ ~ 5 %
Muon ID	$\varepsilon(\mu\rightarrow\mu)$ ~ 97 %, mis-ID $\varepsilon(\pi\rightarrow\mu)$ ~ 1-3 %
E.m. energy resolution	$\Delta E/E = 1\ \% \oplus 10\ \%/\sqrt{E\ (\mathrm{GeV})}$

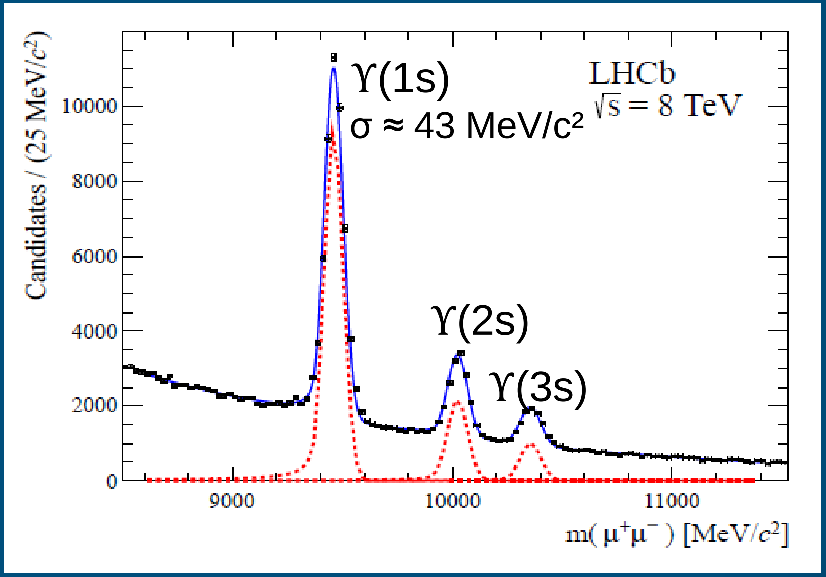
LHCb Detector Performance

- Momentum resolution excellent
  - From **0.4%** at 5 GeV to **0.6 %** at 100 GeV/c
  - Important ingredient to study narrow states
  - Momentum scale checked by comparing the mass of B mesons to the PDG values.

$B_S \rightarrow J/\Psi\Phi$: $\sigma \approx 8$ MeV/c²

$J/\Psi \rightarrow \mu\mu$: $\sigma \approx 15$ MeV/c²

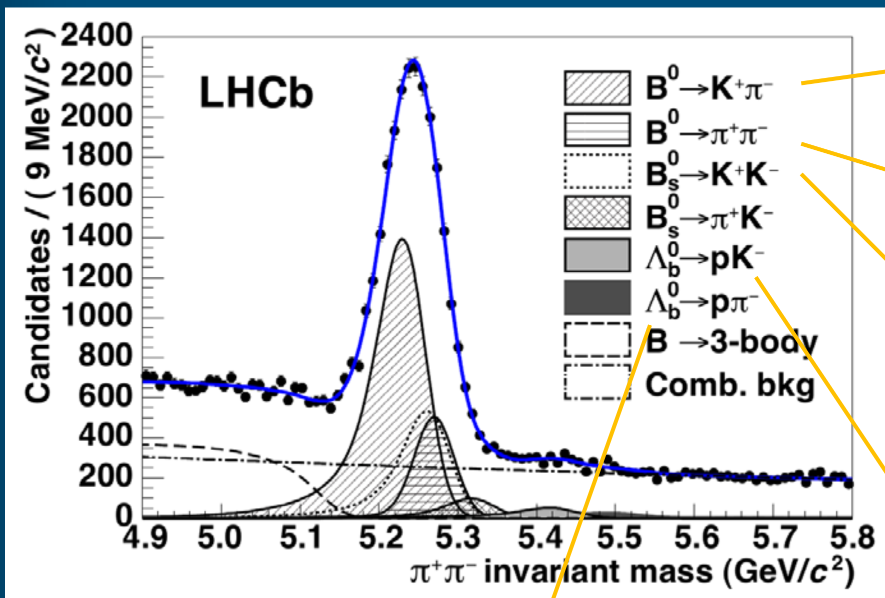


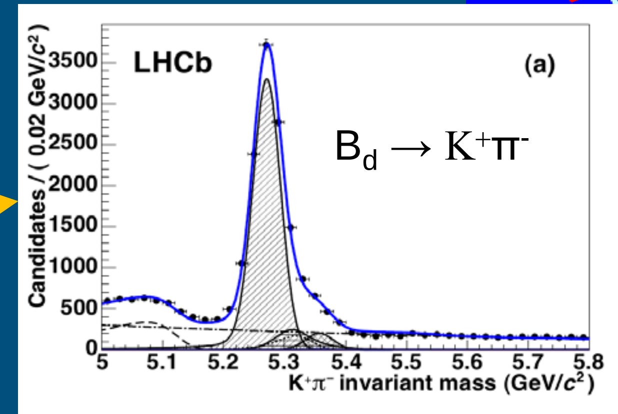


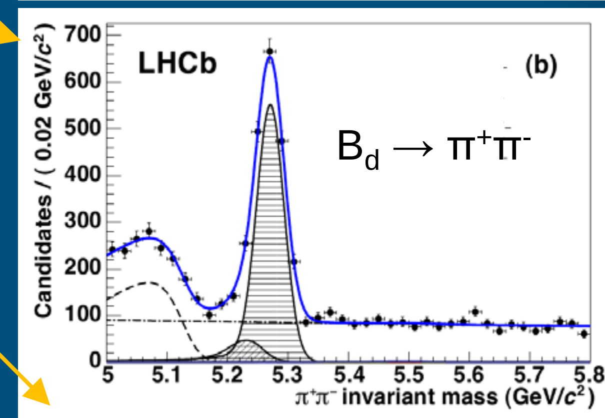
JHEP 06(2013)064

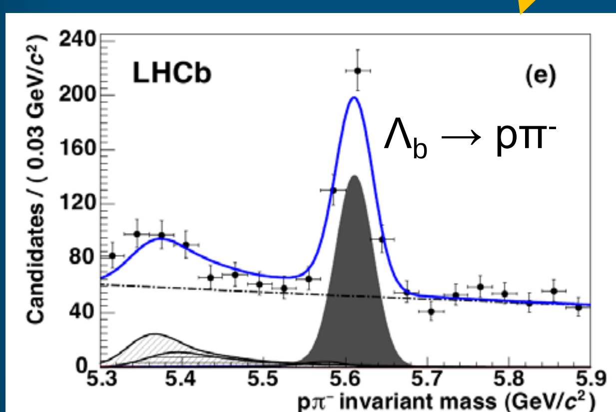
LHCb Detector Performance

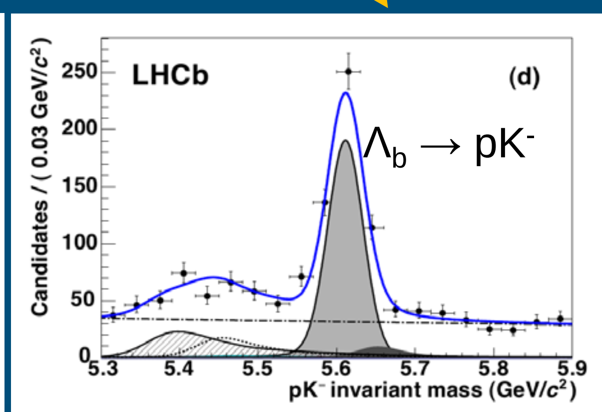
- Excellent particle identification performance
  - Important to disentangle various decays

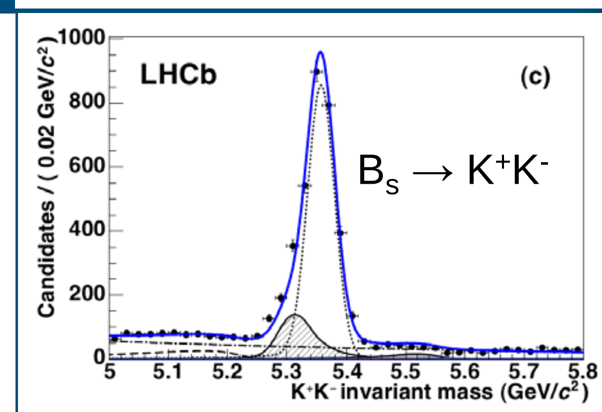












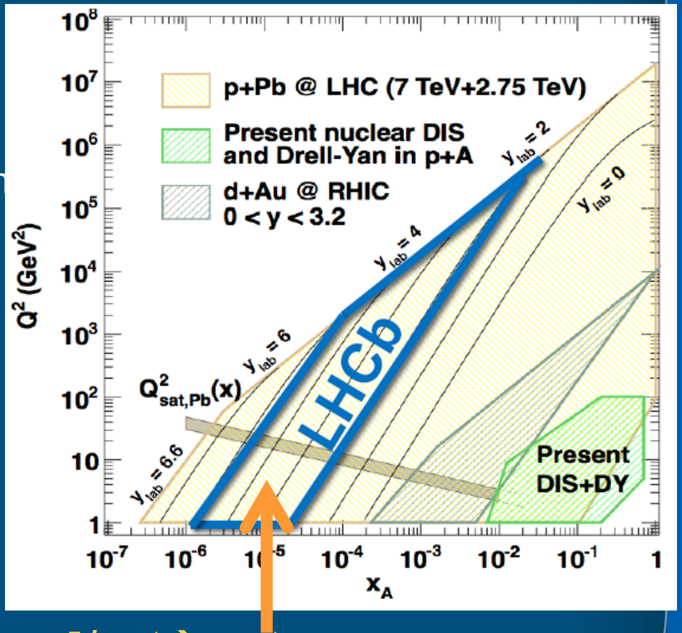
pA Physics Motivation

Natural path to challenge the LHCb performance on ion collisions!

- LHCb can play an important role
  - ➔ Unique rapidity coverage not accessible by other LHC experiments

- pA collision is interesting both in itself and in understanding heavy ion collisions
  - Heavy flavour and quarkonium important probes of the QGP energy loss mechanisms, medium transport properties, quark deconfinement, and temperature
    - ➔ pA data allows factorizing the QGP effects from Cold Nuclear Matter effects

  Also:
  - Study soft QCD, low-x physics
    - ➔ energy-loss vs. gluon density saturation effects
  - Study multi-parton interactions using charged-particle production

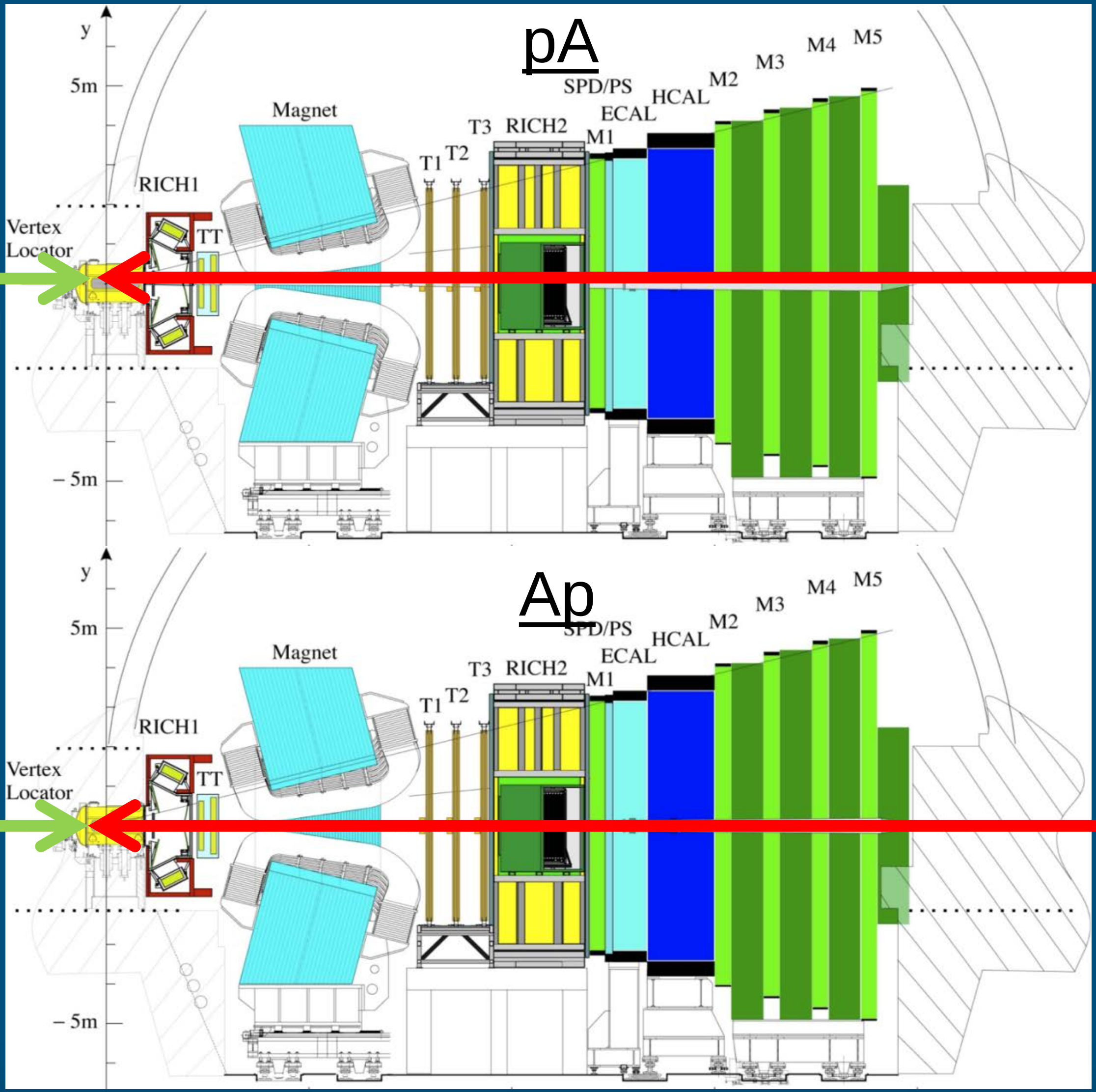


➔ Sensitive probes of properties of nuclear matter with heavy quarkonium production:
- Nuclear attenuation factors
- Nuclear parton distribution function (nPDF)
- ➔ Tests phenomenological models

- LHCb first results with nuclear attenuation factors using J/ψ (➔ μμ)

Rapidity Coverage and Species Configuration

- Forward (-backward) direction defined along the proton (lead) beam



Rapidity coverage in E_{cms}:

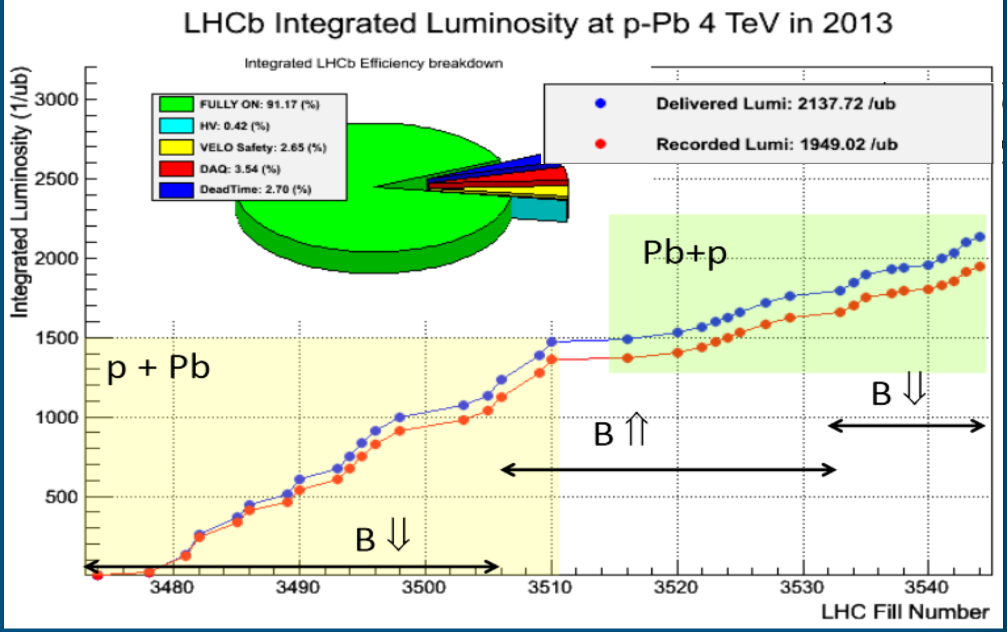
$y = +0.47$
pA: $1.5 < y < 4.5$

$y = -0.47$
Ap: $-5.5 < y < -2.5$

➔ Common range for measurements:
$2.5 < |y| < 4$

Proton-Lead Data Taking 2012-2013

- E_p=4 TeV / E_{Pb}=1.58TeV ➔ E_{cms} (nucleon-nucleon) = 5.02 TeV
- <u>Pilot run Sept. 2012:</u>
  - ➔ $L_{int} \sim 1\ \mu b^{-1}$
    - Multiplicity
    - First look at strange particle production
    - Inelastic cross-section determination
- <u>pA Run Jan 2013:</u>
  - ➔ $\mathcal{L} = 5 * 10^{27}\ cm^{-2}s^{-1}$
  - ➔ Four different configurations:
    - pA : 1.1 nb-1
    - Ap : 0.5 nb-1
    - ➔ After data quality
    - ➔ Both LHCb spectrometer polarities

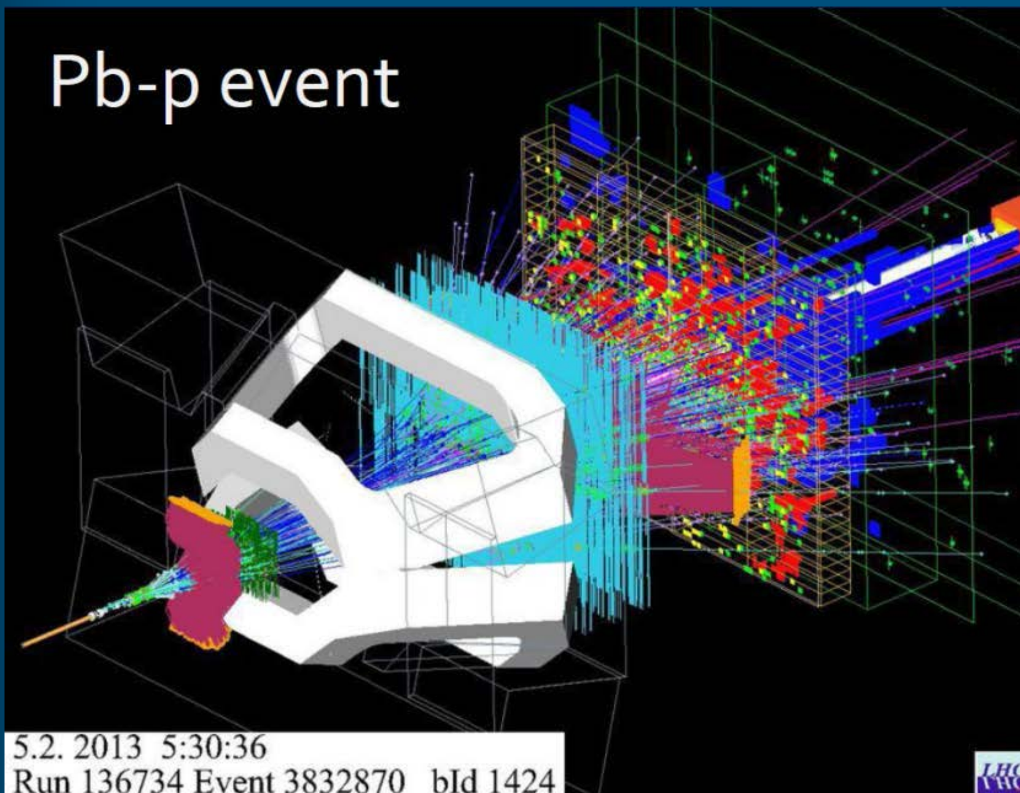


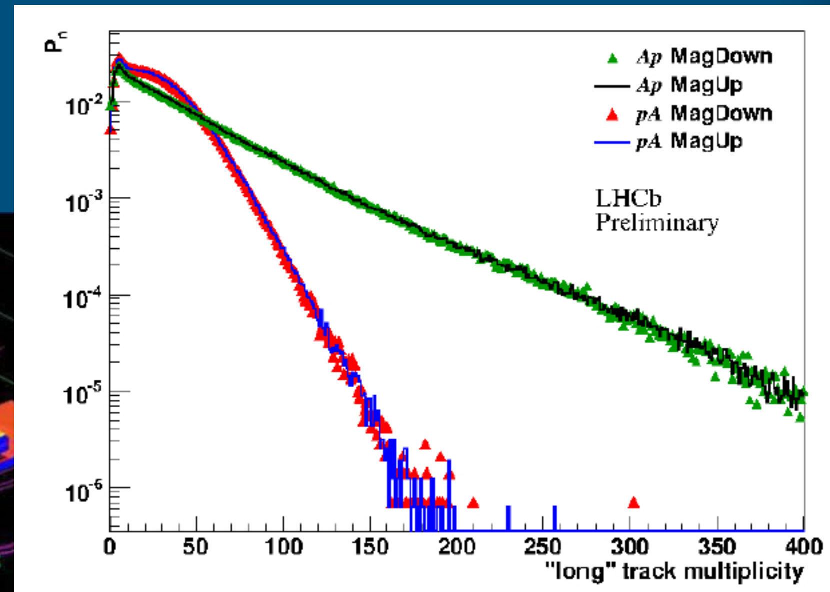
- The results shown here are based on these data sets

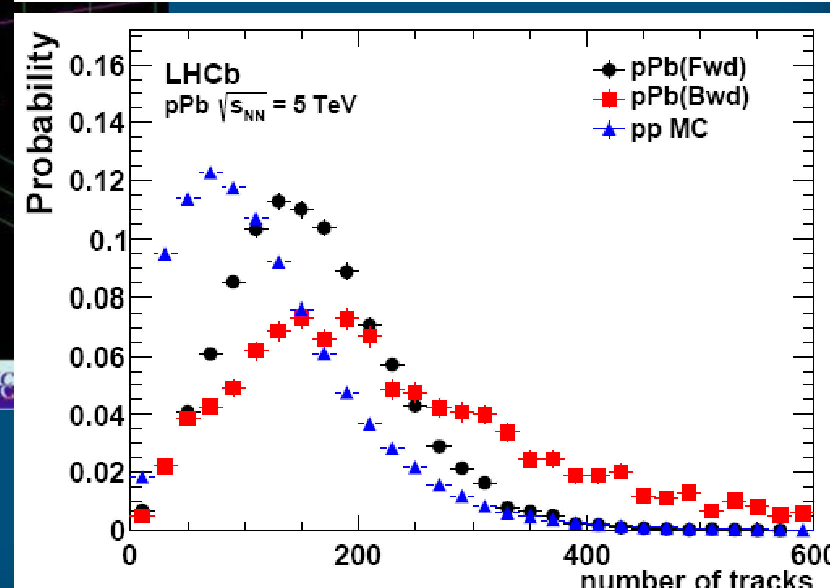
Event Properties

[LHCb-CONF-2012-034]

- Higher track multiplicity in Ap, as expected
  - Both field polarities agree







Inelastic pA cross-section measurement

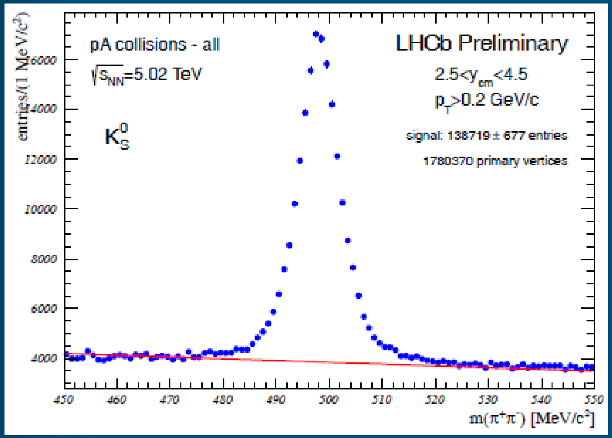
September 2012 pilot run:

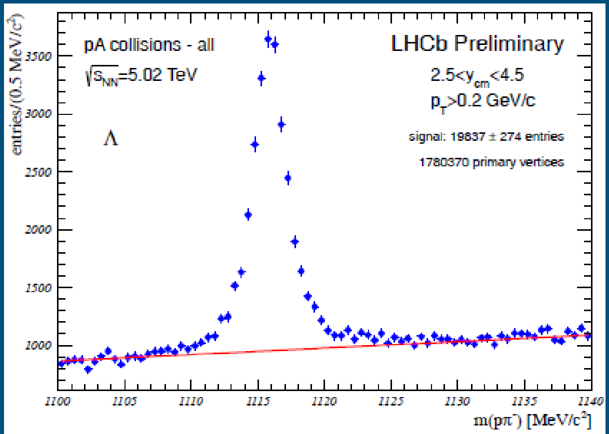
- Luminosity determined by beam-gas imaging with the help of LHCb neon gas injection system (SMOG) and event counting together with beam-gas subtraction:
- Inelastic pA cross section $\sigma_{pA} = \frac{\rho_{pA}}{L*\varepsilon}$
  - Event tag: At least one charged track with 2.5 < y < 4.5 with pT > 0.2GeV/c
  - Trigger efficiency: ~99 ± 1%
  - Event count efficiency: 98 ± 2%
- Measured cross section: σ_{pA} = 2.09 ± 0.12 b
  - Error dominated by statistics together with ~5% uncertainty on luminosity measurement
  - Agree with expected result from geometric behaviour : $\sigma_{pp} \times A^{2/3}$ ~ 2.1 b

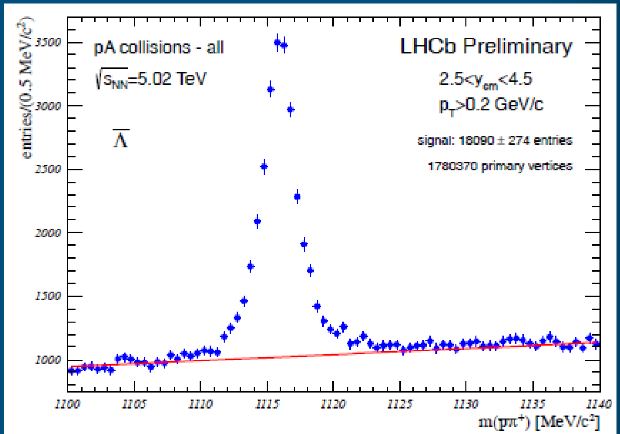
Strange particle production

- The unique angular coverage of LHCb enables study strangeness, charm and also beauty production in regions not accessible to the other experiments.

- Preliminary study of V0 production ratios in p-Pb is promising
  - Pilot run data:







[LHCb-CONF-2012-034]

- First data analysis concentrated on Cold Nuclear Matter effects with J/ψ

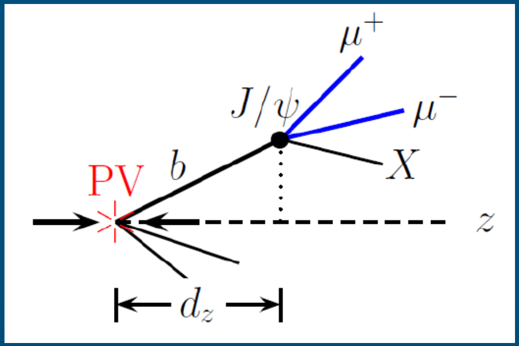
J/ψ Production in pA / Ap collisions

- Three main inclusive sources for J/ψ :
  - Direct production
  - Feed-down from heavier states $\psi(2S)$, χ_c
  - From b-hadron decays

  (Direct production and feed-down: prompt; b-hadron decays: non-prompt)

- Analysis strategy for J/ψ :
  1. Same method as for J/ψ measurements in previous LHCb pp - studies
  2. Measurement of the production cross section both separately for prompt and non-prompt in bins of transverse momentum and rapidity
  3. Pseudo-proper time to separate prompt J/ψ and J/ψ from b

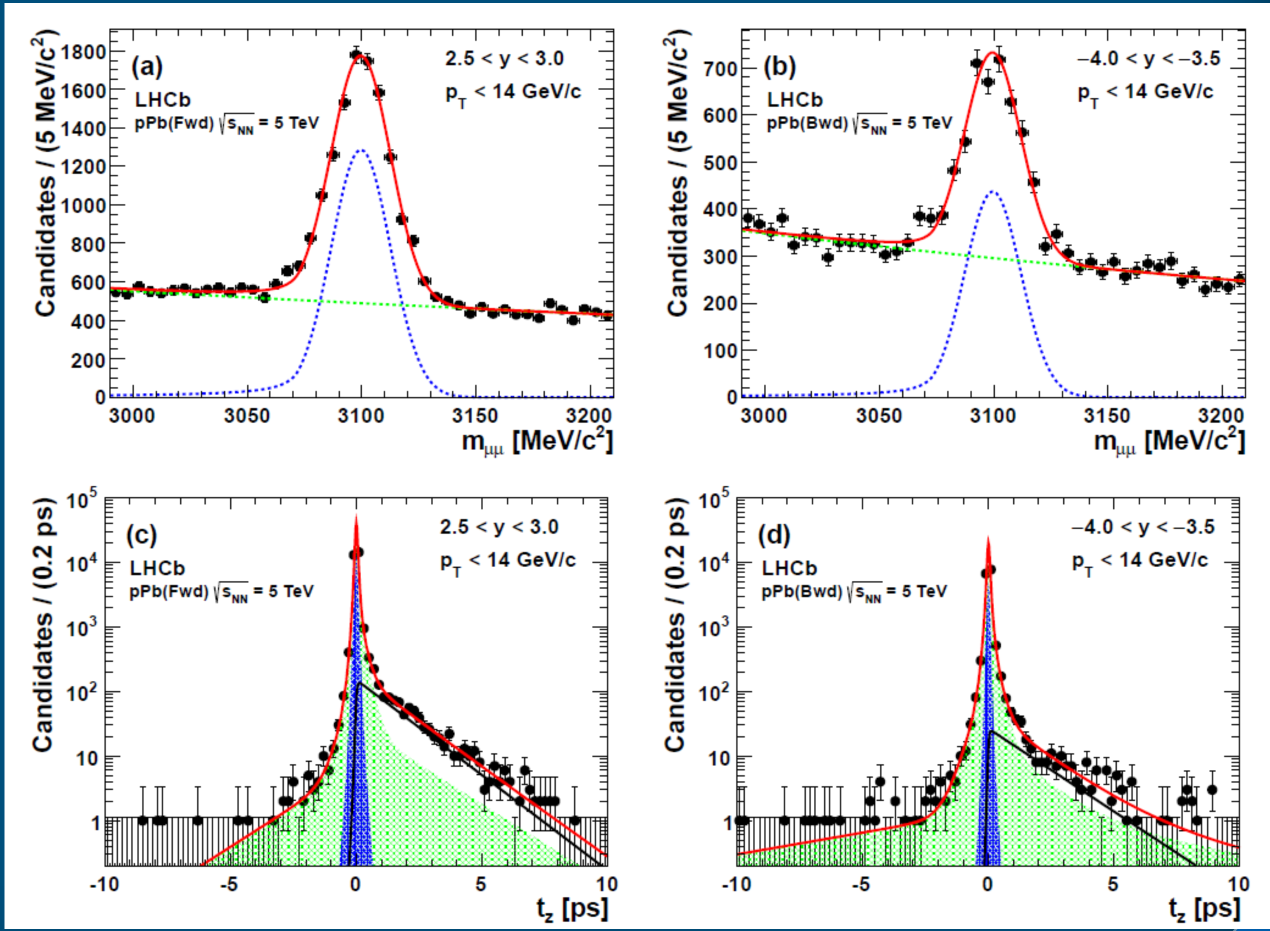
- Yields of prompt and non-prompt J/ψ extracted from simultaneous fit of mass and pseudo-proper time: $t_z = (z_{J/\psi} - z_{PV}) \frac{M_{J/\psi}}{p_z}$



J/ψ Signal Extraction

- Yields of prompt J/ψ and J/ψ from b extracted from simultaneous fit of mass and pseudo-proper time: $t_z = (z_{J/\psi} - z_{PV})\frac{M_{J/\psi}}{p_z}$

pA (forward): Ap (backward):



- Mass fits
  - Signal by Crystal Ball
  - Background by exponential
- Pseudo-proper time fits
  - Prompt signal by δ-function
  - Non-prompt by exponential
  - Background by empirical function from side-bands

arXiv:1308.6729

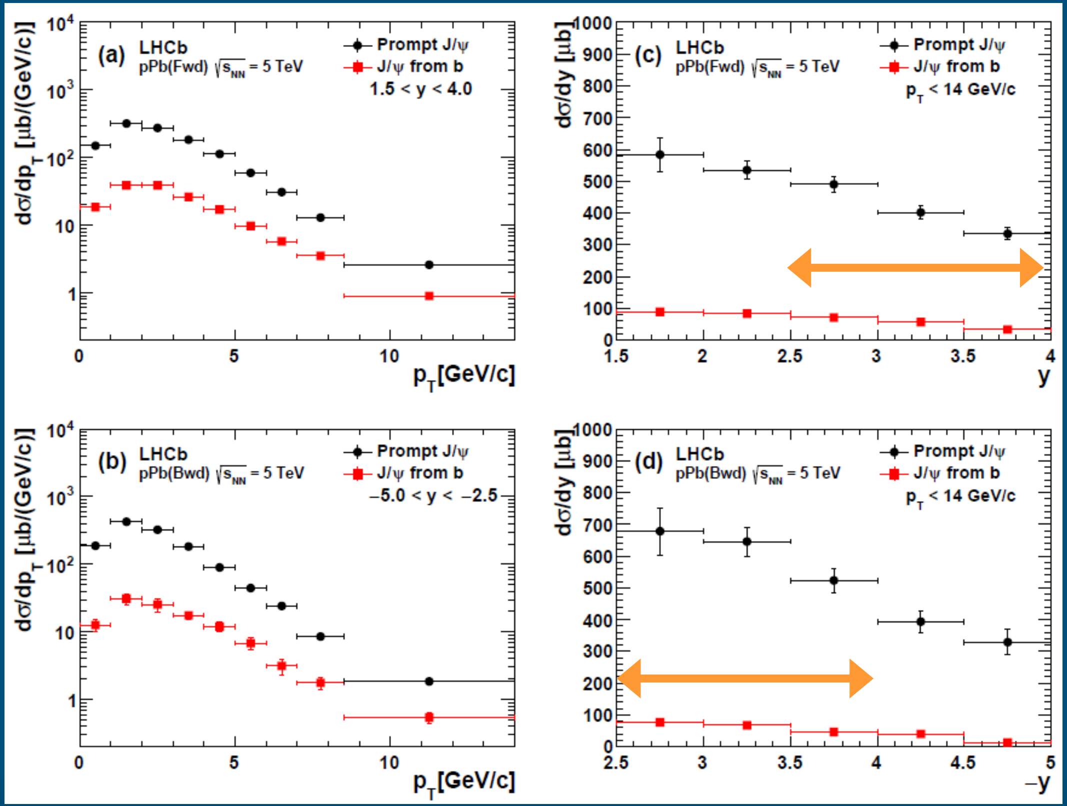
Differential J/ψ Cross-sections

$$\frac{d^2\sigma_{J/\psi}}{dp_T dy} = \frac{N(J/\psi \to \mu^+\mu^-)}{L * \varepsilon * \mathcal{B}(J/\psi \to \mu^+\mu^-) * \Delta p_T * \Delta y}$$

- $\varepsilon_{tot} = \varepsilon_{acc} * \varepsilon_{rec} * \varepsilon_{trg}$ (~ 45%)
  - $\varepsilon_{acc} * \varepsilon_{rec}$ (including detecting, reconstruction and selection) estimated from simulation
  - ε_{trg} obtained directly from the minimum-bias sample collected in the data (~ 95%)
  - N.B.: For efficiency estimation no polarization of J/ψ production is assumed

pA:

Ap:



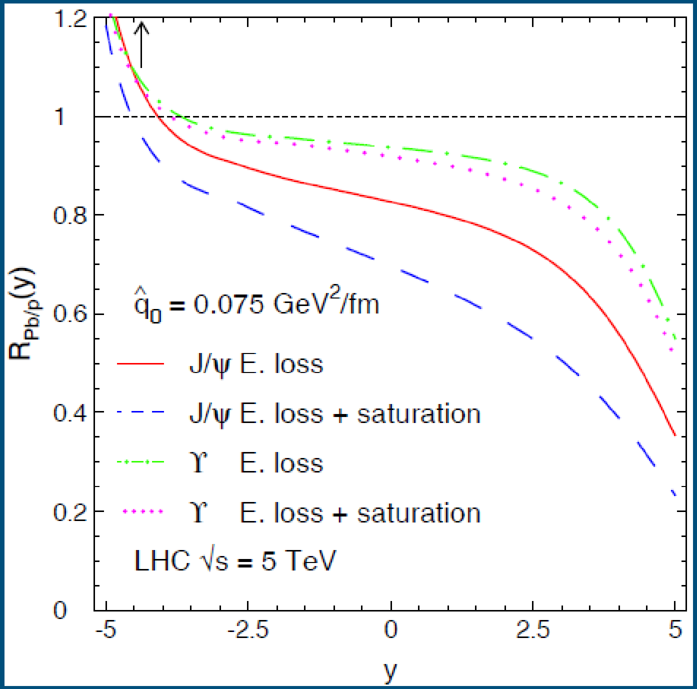
arXiv:1308.6729

pA collisions:
forward hemisphere
1.5 < y < 4.0

Ap collisions:
backward
hemisphere
-5.0 < y < -2.5

J/ψ Transport in pA / Ap collisions

- Cold Nuclear Matter effects
  - Production of heavy quarkonia at large rapidity strongly suppressed in pA collisions



arXiv:1212.0434

- Nuclear Modification Factor
  - N_{coll} = A in pA collisions

$$R_{pA}(y,\sqrt{s_{NN}}) = \frac{1}{N_{coll}} \frac{\frac{d\sigma_{pA}}{dy}(y,\sqrt{s_{NN}})}{\frac{d\sigma_{pp}}{dy}(y,\sqrt{s_{NN}})}$$

- Forward-Back asymmetry
  - pp J/ψ cross-section cancels out

$$R_{FB}(y,\sqrt{s_{NN}}) = \frac{R_{pA}\left(+|y|,\sqrt{s_{NN}}\right)}{R_{pA}\left(-|y|,\sqrt{s_{NN}}\right)}$$

Reference J/ψ proton-proton cross-section

- Input to determination of nuclear modification factor
  - Proton-proton J/ψ cross-section at same E_{cms} = 5.02 TeV and kinematic range
    - ➔ Rapidity re-scaling to 2.5 < y < 4.0 at each energy: ~O(60%) from 2.0 < y < 4.5
    - ➔ Energy interpolation from measurements at 2.76 TeV, 7 TeV, and 8 TeV

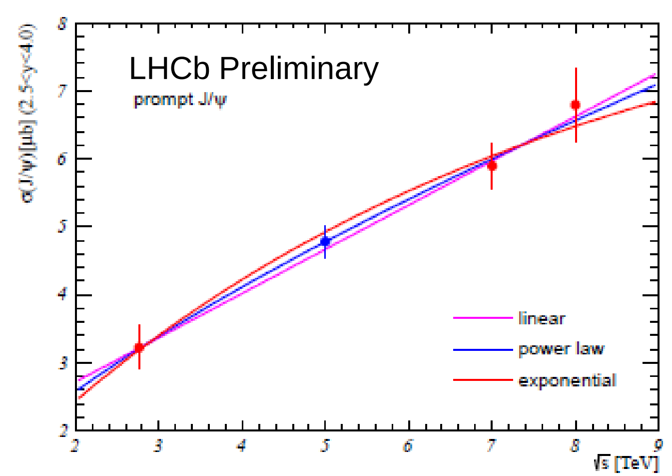
LHCb Preliminary

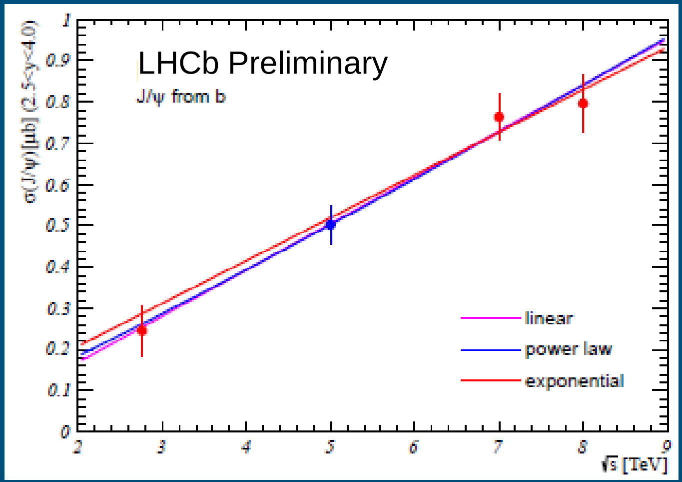
	E_{cms}		σ [μb] stat. sys.
LHCb	2.76	prompt	$3.23 \pm 0.10 \pm 0.30$
LHCb	7	prompt	$5.89 \pm 0.01 \pm 0.33$
LHCb	8	prompt	$6.79 \pm 0.01 \pm 0.54$
LHCb	2.76	J/ψ from b	$0.246 \pm 0.035 \pm 0.049$
LHCb	7	J/ψ from b	$0.763 \pm 0.005 \pm 0.053$
LHCb	8	J/ψ from b	$0.796 \pm 0.002 \pm 0.068$

arXiv:1212.1045 J/ψ @ 2.76 TeV
arXiv:1307.6379 J/ψ @ 7 TeV
arXiv:1304.6977 J/ψ @ 8 TeV
➔ LHCb-CONF-2013- (To appear)

  - Energy interpolation : linear / power law / exponential function
    - ➔ Functions checked against theoretical predictions by LO-CEM and FONLL

$$\sigma(\sqrt{s}) = \begin{cases} p_0 + \sqrt{s}p_1 \\ (\sqrt{s}/p_0)^{p_1} \\ p_0[1 - e^{-(\sqrt{s}/p_1)}] \end{cases}$$





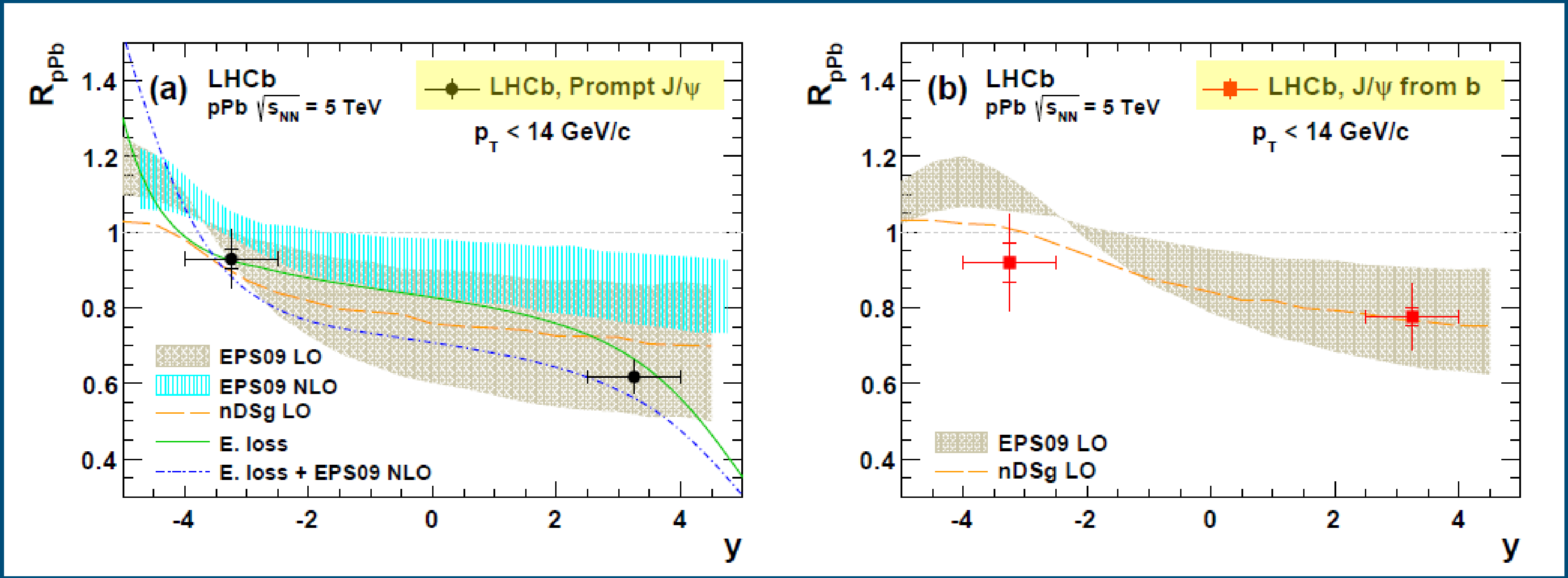
Reference J/ψ proton-proton cross-section

- Proton-proton reference cross-section at 5 TeV from power-law interpolation
  - Preliminary errors: Correlations neglected and error from interpolation model from difference between the fit functions

  ➔ $\sigma_{\text{prompt } J/\psi}$ (5 TeV, $2.5 < y < 4.0$) = $4.78 \pm 0.23_{\text{exp}} \pm 0.15_{\text{model}}$ μb

  ➔ $\sigma_{\text{non-prompt } J/\psi}$(5 TeV, $2.5 < y < 4.0$) = $0.50 \pm 0.05_{\text{exp}} \pm 0.01_{\text{model}}$ μb

Nuclear Modification Factor



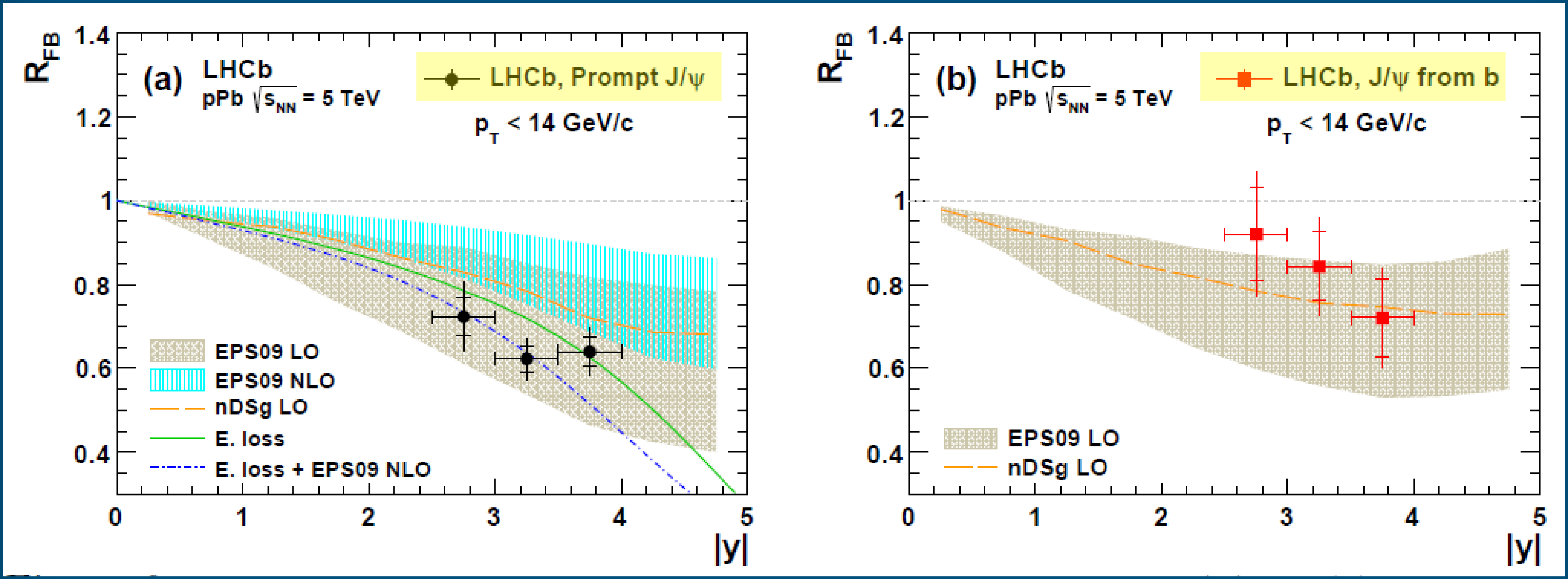
(Inner error bars: statistical, outer error bars: statistical and systematic added in quadrature)

arXiv:1308.6729

- Nuclear Modification Factor depends strongly on rapidity
- B-mesons less affected than prompt J/ψ
  - ➔ B hadrons less affected by cold nuclear effects ➔ mass dependence
  - ➔ Measure for upsilon
- Phenomenological models agree with data but not enough significance to distinguish

Forward-Backward Symmetry

- Cancels out uncertainty from proton-proton reference data
  - Clear difference between suppression of prompt J/ψ and J/ψ from b



arXiv:1308.6729

(Inner error bars: statistical, outer error bars: statistical and systematic added in quadrature)

Systematic Uncertainties

- Source of systematics
  - No uncertainty assigned to the effect of J/ψ polarisation but effect measured to be small

Correlated between bins	**Forward (%)**	**Backward(%)**
• Mass fit from checking dimuon mass with double Crystal Ball	2.3	3.4
• Radiative tail with dimuon mass below signal region (data/MC)	1.0	1.0
• Muon identification from "tag and probe"	1.3	1.3
• Track reconstruction efficiency from pp / pA multiplicity difference	1.5	1.5
• Luminosity calibration	3.0	3.0
• $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ from PDG	1.0	1.0
Uncorrelated between bins		
• $y - p_T$ binning	0.1 – 8.7	0.1 – 6.1
• Reweighting of track multiplicity in simulation cmp to no reweighting	0.1 – 3.0	0.2 – 4.3
• t_Z fit on non-prompt J/ψ by extraction with ${}_s\mathcal{P}lot$	0.2 – 12.0	0.2 – 13.0

Conclusions

LHCb recorded ~2nb^{-1} of pPb/Pbp data

- Nuclear modification factors and forward-backward ratio determined in pPb collisions at 2.5<|y|<4.0

➔ Prompt and non-prompt J/ψ suppression pPb show clear evidence of Cold Nuclear Matter effects
  - Phenomenological models agree well with data
  - Not enough significance to distinguish models yet

  ➔ Important to take into account to interpret signatures of QGP effects in heavy ion collisions

- Systematics dominated by luminosity, fit model and data-MC discrepancy
  - Improve by proper J/ψ cross-section measurement at equivalent energy

- Further analysis planned with the pA data sample
  - Nuclear modification factor with ψ(2S) and $\Upsilon(nS)$ production
  - Charged particle production
  - Central exclusive production

Future

- Potential interest to look into
  - Jet production
  - Open charm production
  - Drell-Yan processes
  - Particle correlations
  - Low-x physics
- Proton-nucleus collisions provide opportunity to study γp interactions (J.Nystrand)
  - Unlike in pp or AA collisions, the photon emitter (nucleus) and photon target (proton) can be separated
  - Exclusive J/ψ photo-production (p+γ → J/ψ + p) at rapidity of 5 : E_{cms}=1900 GeV

LHC Run 2

- Higher collision energy ➔ new species with higher statistics
- LHCb requesting **at least** 10x the integrated luminosity collected in 2013.
- Assuming four weeks pA run
  - Instantaneous luminosity of 5×10^{28} cm^{-2}s^{-1} (2013: ~5×10^{27} cm^{-2}s^{-1})

Thank you!

EXTRA SLIDES

Check of interpolation function against theory

- Cross-section predictions from theory

Model/PDF	factorization scale	σ(2.76 TeV)	σ(5.02 TeV)	σ(7 TeV)
LO-CEM/CTEQ6L	m_c	0.249	0.309	0.339
LO-CEM/CTEQ6L	$2m_c$	1.292	2.025	2.529
LO-CEM/MRST98L	$m_c/2$	0.064	0.079	0.087
LO-CEM/MRST98L	m_c	0.153	0.209	0.244
LO-CEM/MRST98L	$2m_c$	0.743	1.217	1.566
LO-CEM/CTEQ5L	$m_c/2$	0.221	0.301	0.351
LO-CEM/CTEQ5L	m_c	0.495	0.728	0.886
LO-CEM/CTEQ5L	$2m_c$	1.569	2.650	3.464
LO-CEM/MRST01L	$m_c/2$	0.032	0.037	0.039
LO-CEM/MRST01L	m_c	0.116	0.153	0.177
LO-CEM/MRST01L	$2m_c$	0.547	0.855	1.076
LO-CEM/GRV98L	$m_c/2$	0.113	0.162	0.196
LO-CEM/GRV98L	m_c	0.389	0.615	0.785
LO-CEM/GRV98L	$2m_c$	1.058	1.851	2.488
FONLL	(nominal)	3.000	4.773	6.007
FONLL	(min)	1.310	1.793	2.078
FONLL	(max)	7.399	11.49	14.28

$$\sigma(\sqrt{s}) = \begin{cases} p_0 + \sqrt{s}p_1 \\ (\sqrt{s}/p_0)^{p_1} \\ p_0[1 - e^{-(\sqrt{s}/p_1)}] \end{cases}$$