Heavy Ion Physics at LHCb

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LHCb

Outline

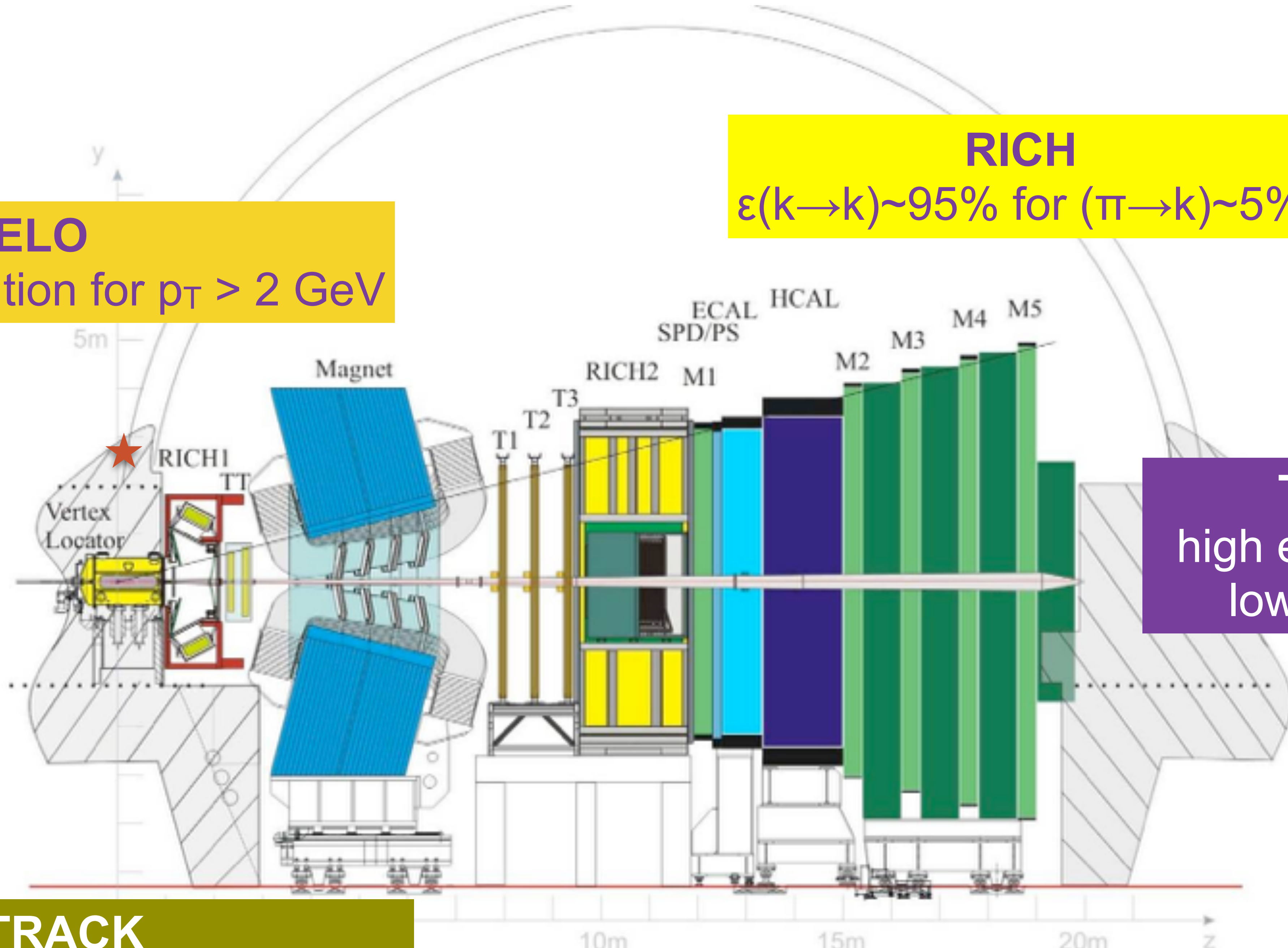
- **LHCb Experiment**
- **Measurements pPb**
  - J/ψ production
  - Υ production
  - Z boson production
  - pNe / PbNe results
- **Summary**

LHCb Experiment

LHCb is a single arm spectrometer fully instrumented in the forward region ($2.0<\eta<5.0$)
Designed for heavy flavour physics ↔ Explored for general purpose physics (low x sensitive)

RICH
$\varepsilon(k\rightarrow k)\sim95\%$ for $(\pi\rightarrow k)\sim5\%$

VELO
$\sim20\mu m$ IP resolution for $p_T > 2$ GeV



Trigger
high efficiency for low p_T muon

TRACK
0.4%-0.6% momentum resolution

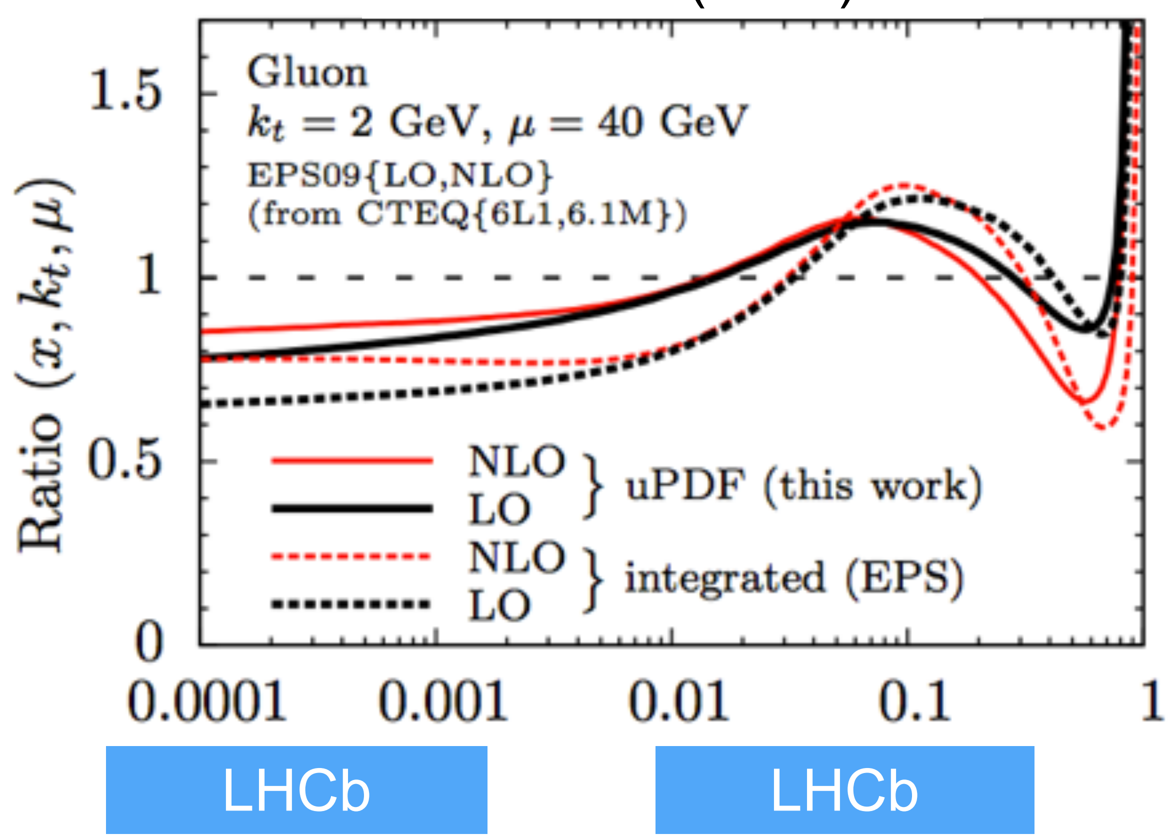
MUON
Muon Identification $\varepsilon\sim97\%$ misID$\sim2\%$

proton-lead (pA) collisions

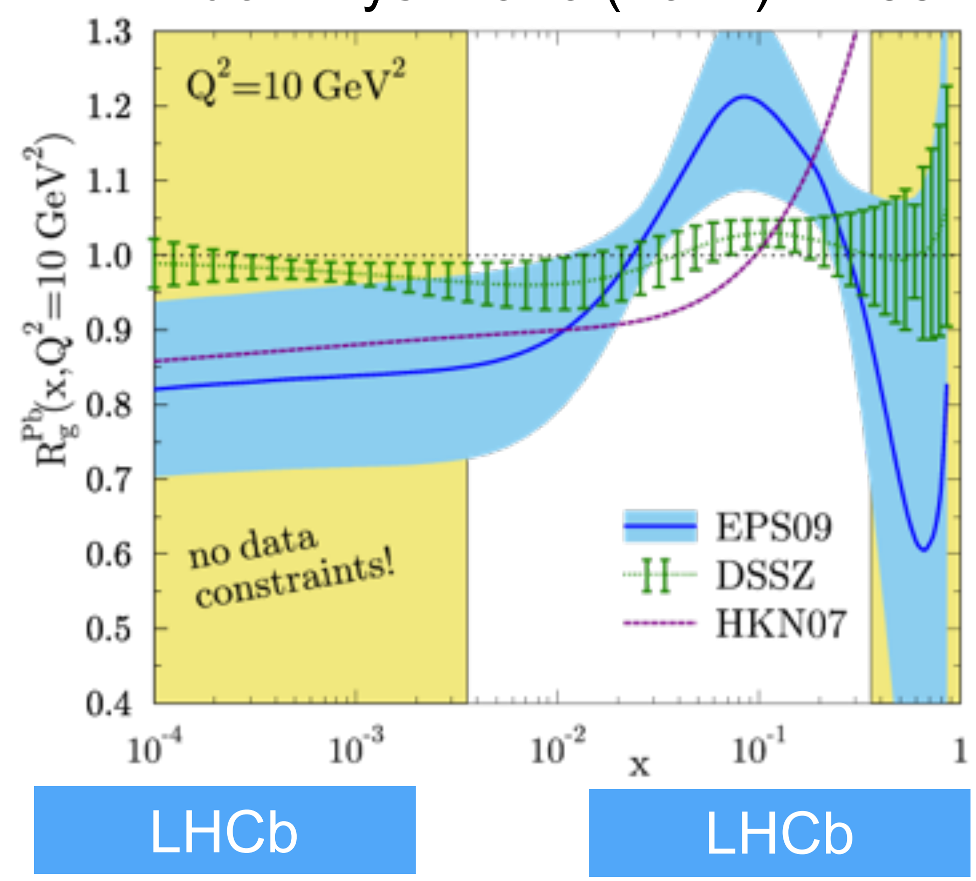
- LHCb is fully instrumented in a unique kinematic region
- factorise effects of Quark Gluon Plasma from Cold Nuclear Matter
- sensitive to nuclear parton distribution function: low and high x

Great laboratory for phenomenological models

JHEP 1309 (2013) 158

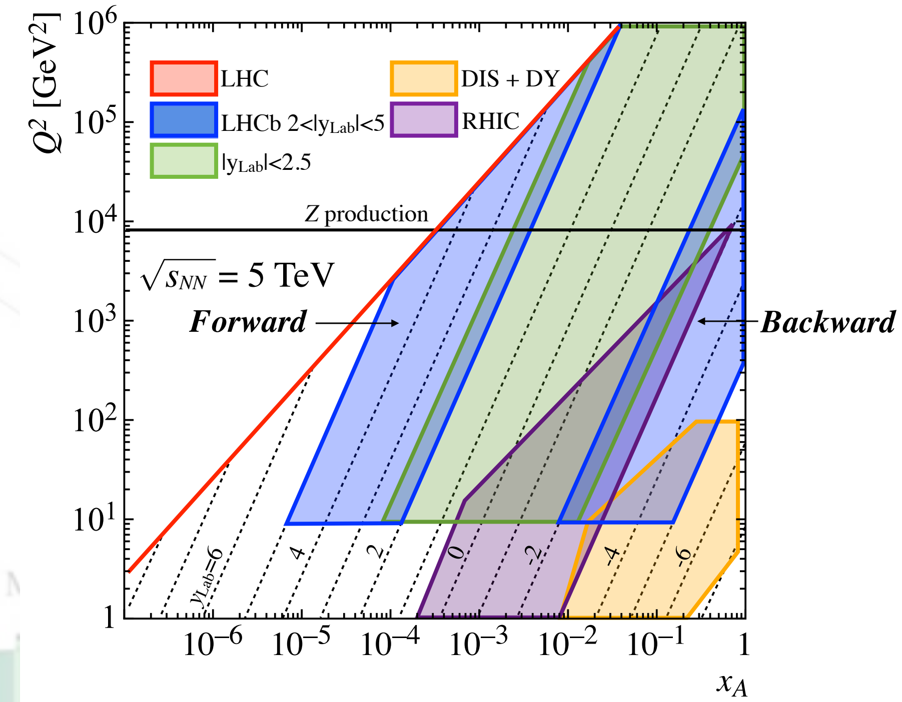


Nucl.Phys. A926 (2014) 24-33

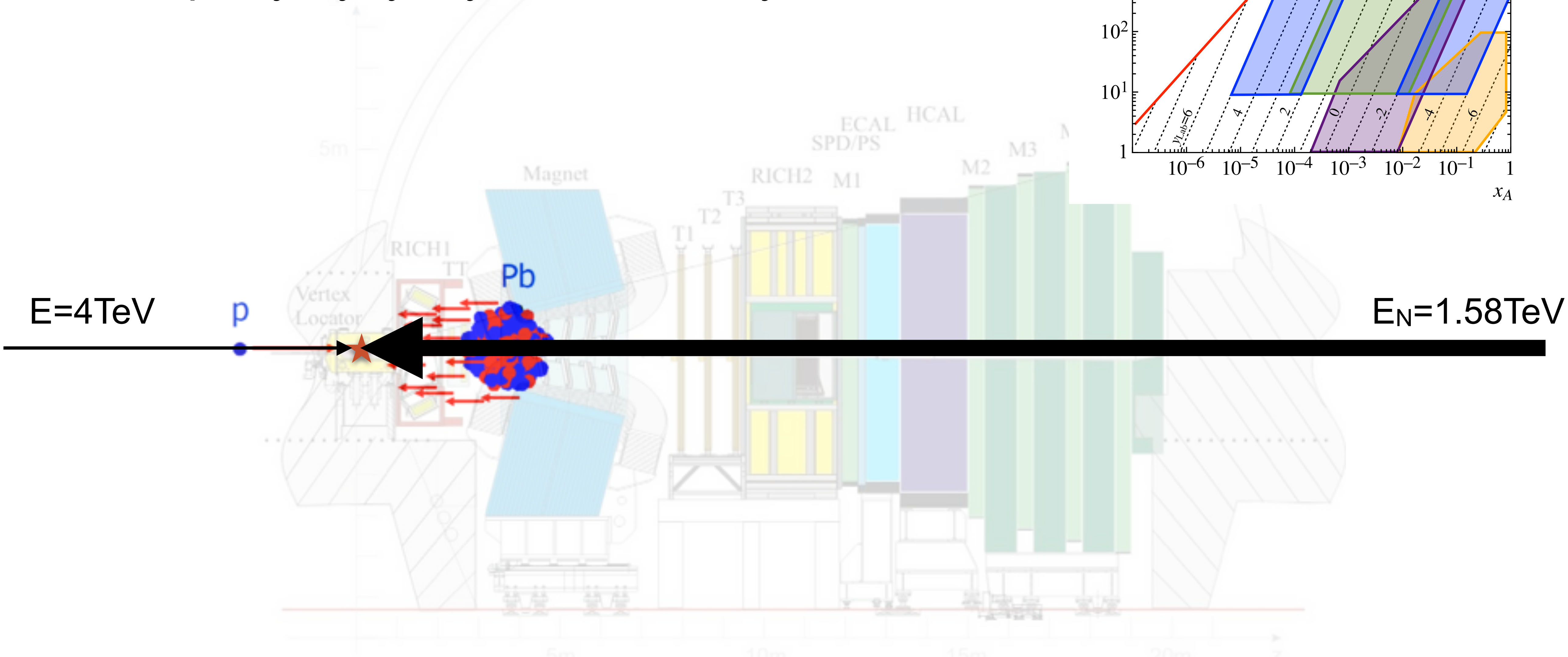


LHCb accessible region for J/ψ, Υ and Z production:
J/ψ: $1\times10^{-5} < x < 1\times10^{-4}$, $7\times10^{-3} < x < 7\times10^{-2}$
Υ : $3\times10^{-5} < x < 3\times10^{-4}$, $3\times10^{-2} < x < 3\times10^{-1}$
Z : $2\times10^{-4} < x < 3\times10^{-3}$, $0.2 < x < 1$

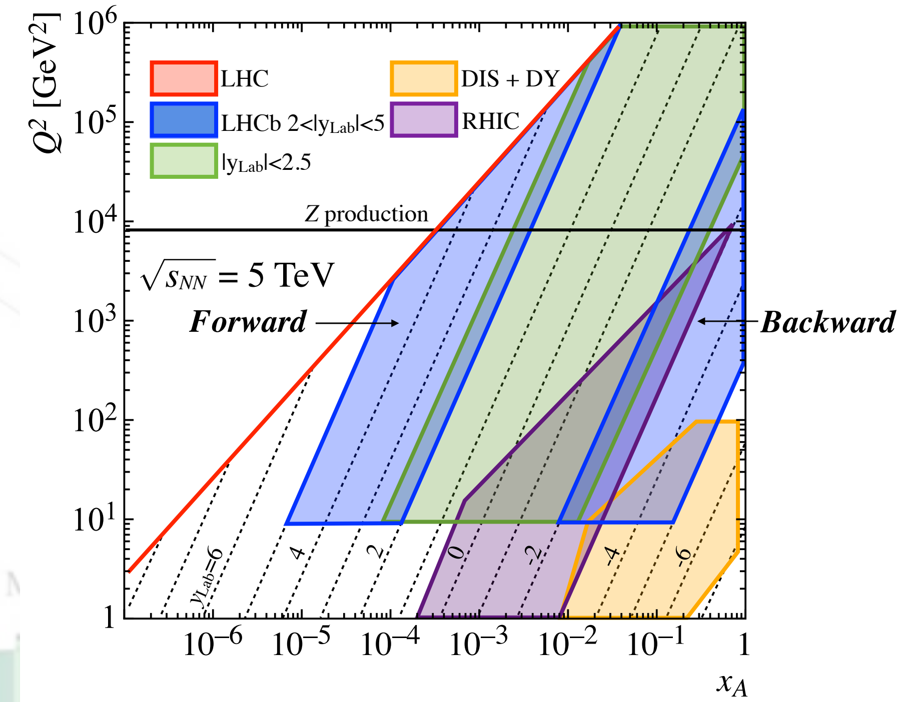
LHCb pA Data

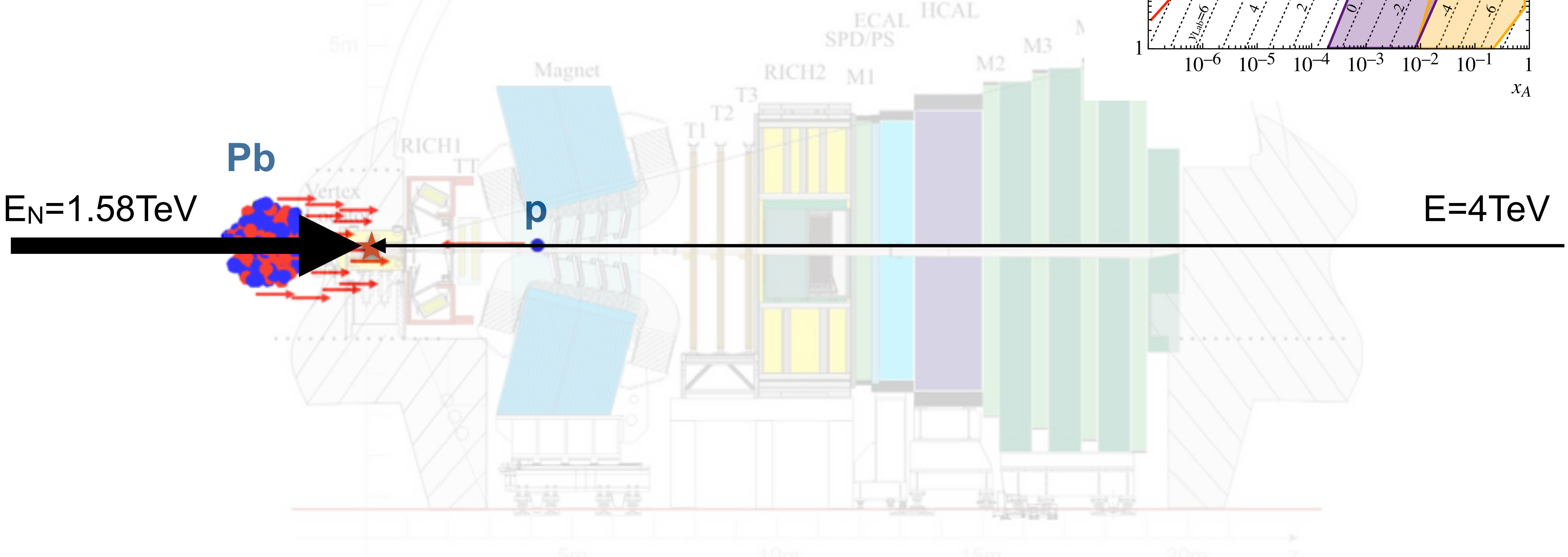


pA (**forward**) at 5 TeV
Integrated Luminosity = 1.1/nb
Shift in rapidity $\Delta y = y_{lab} - y = 0.47 \Rightarrow 1.5 < y < 4.0$



Ap (**backward**) at 5 TeV
Integrated Luminosity = 0.5/nb
Shift in rapidity $\Delta y = y_{lab} - y = 0.47 \Rightarrow -5.0 < y < -2.5$





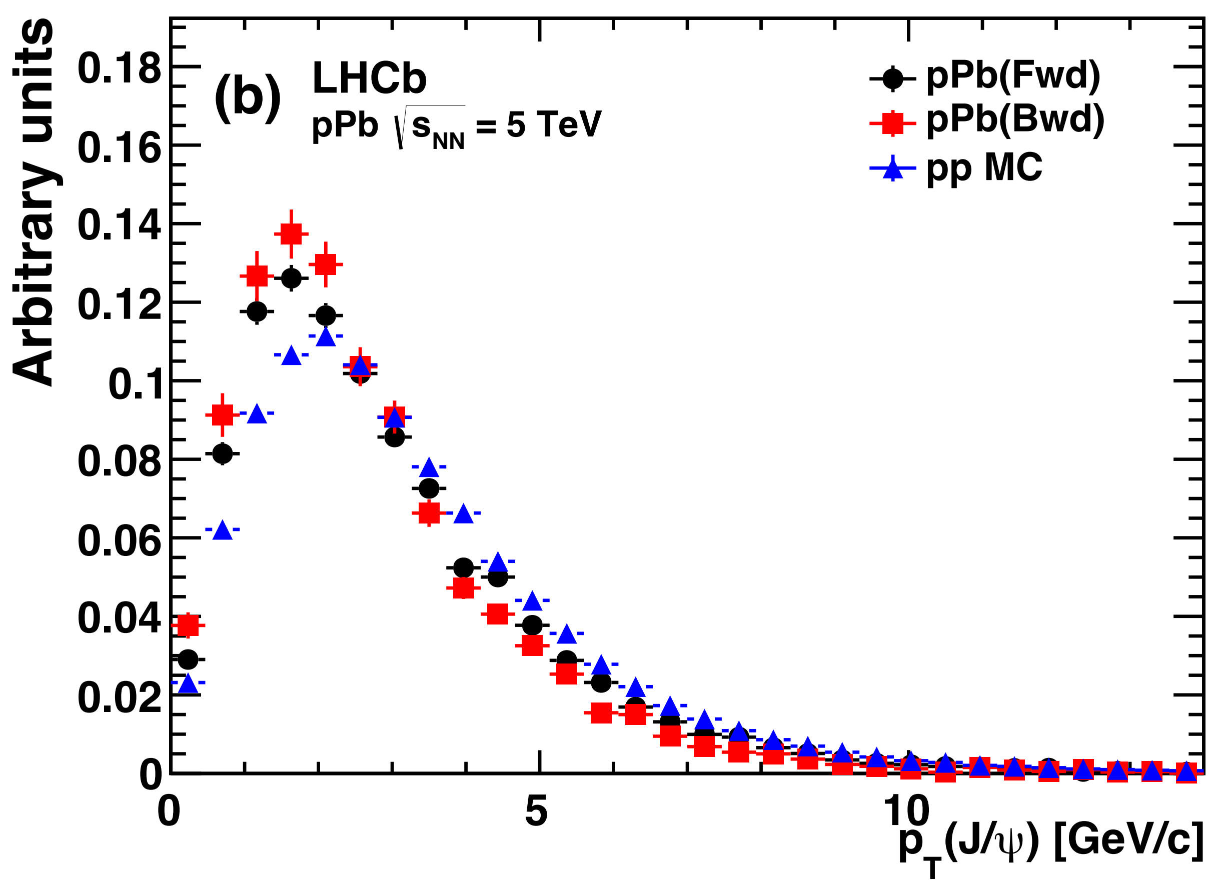
J/ψ Production

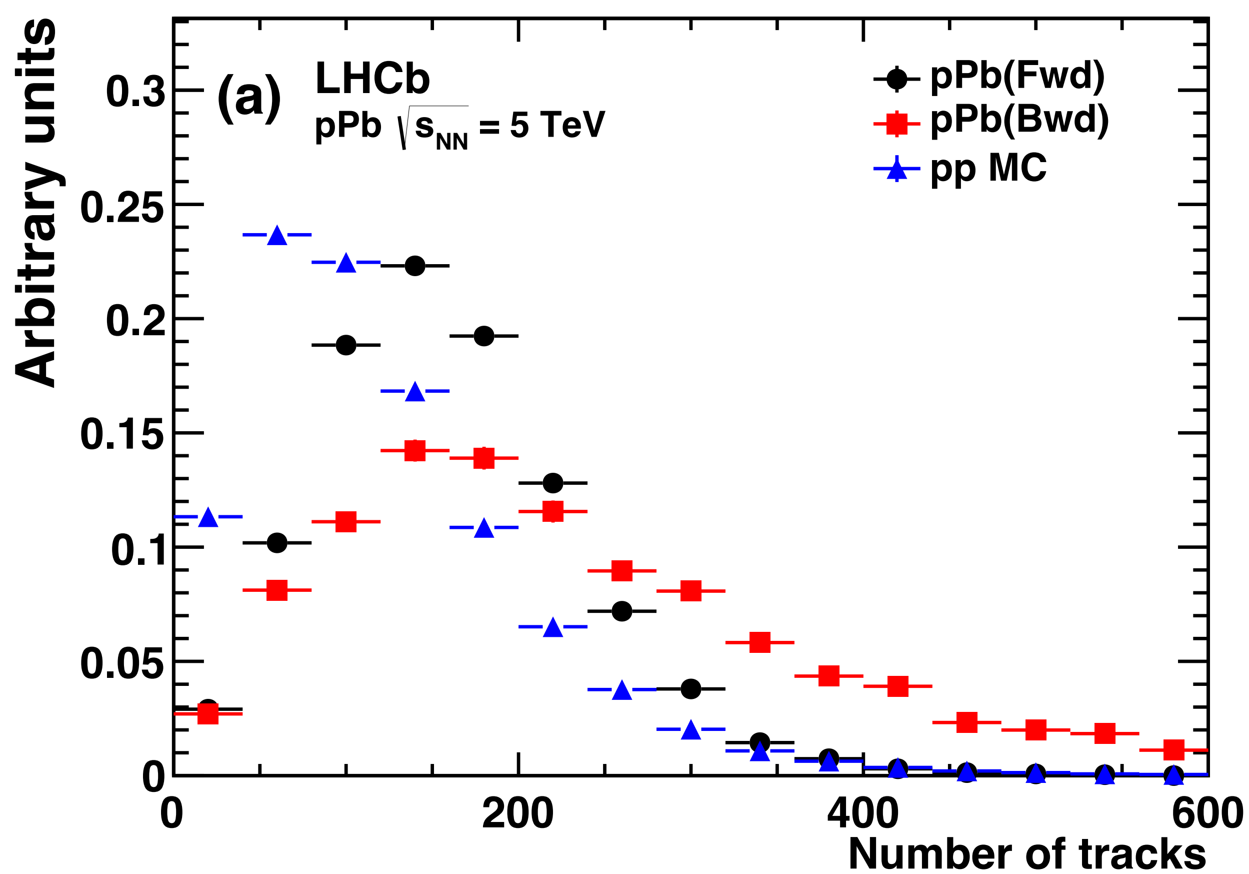
Data and General Strategy

- Trigger:
  - One track with hits in the muon stations with p_T > 600 MeV
- Two Muons with 1.5<y<4.0 (-5.0<y<-2.5) for pA (Ap) and p_T(J/ψ)<14GeV
- Dedicate study for J/ψ from b decays (simultaneous fit to mass and pseudo-proper time)

Backgrounds - combinatorial - exponential distribution

Signal - mass model - crystal-ball function





J/ψ Production

Data and General Strategy

- Trigger:
  - One track with hits in the muon stations with $p_T > 600$ MeV
- Two Muons with 1.5<y<4.0 (-5.0<y<-2.5) for pA (Ap) and $p_T(J/\psi) < 14$GeV
- Dedicate study for J/ψ from b decays (simultaneous fit to mass and pseudo-proper time)

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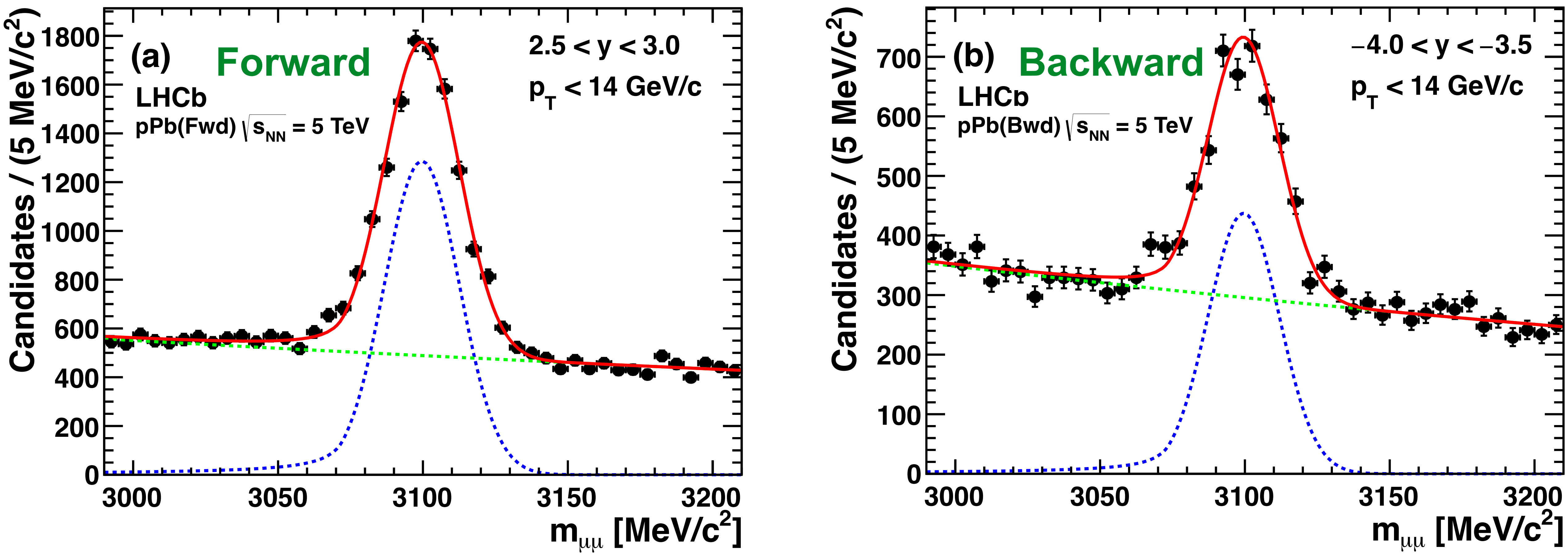
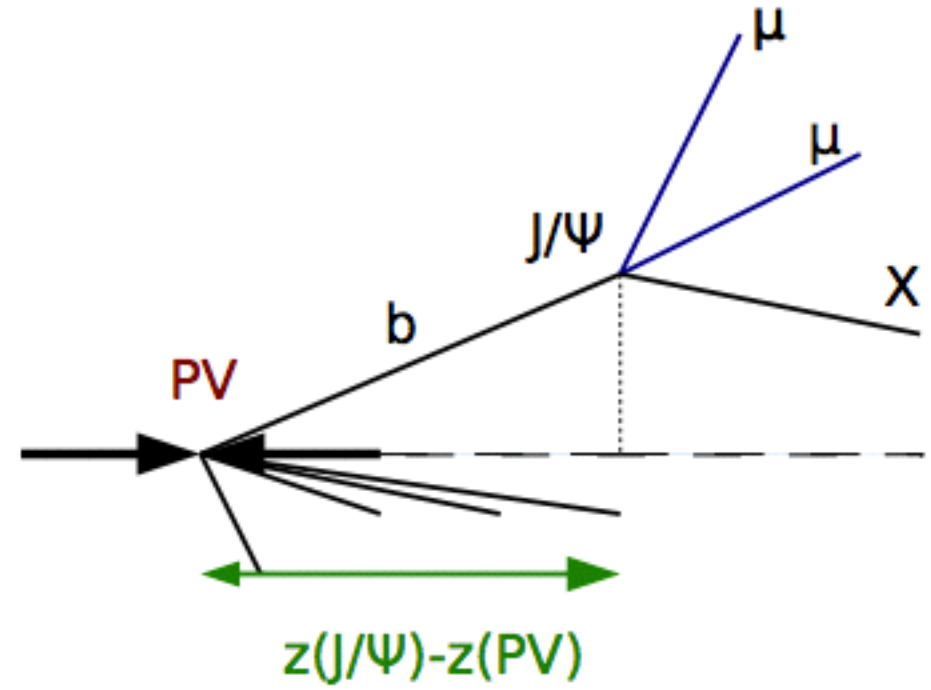
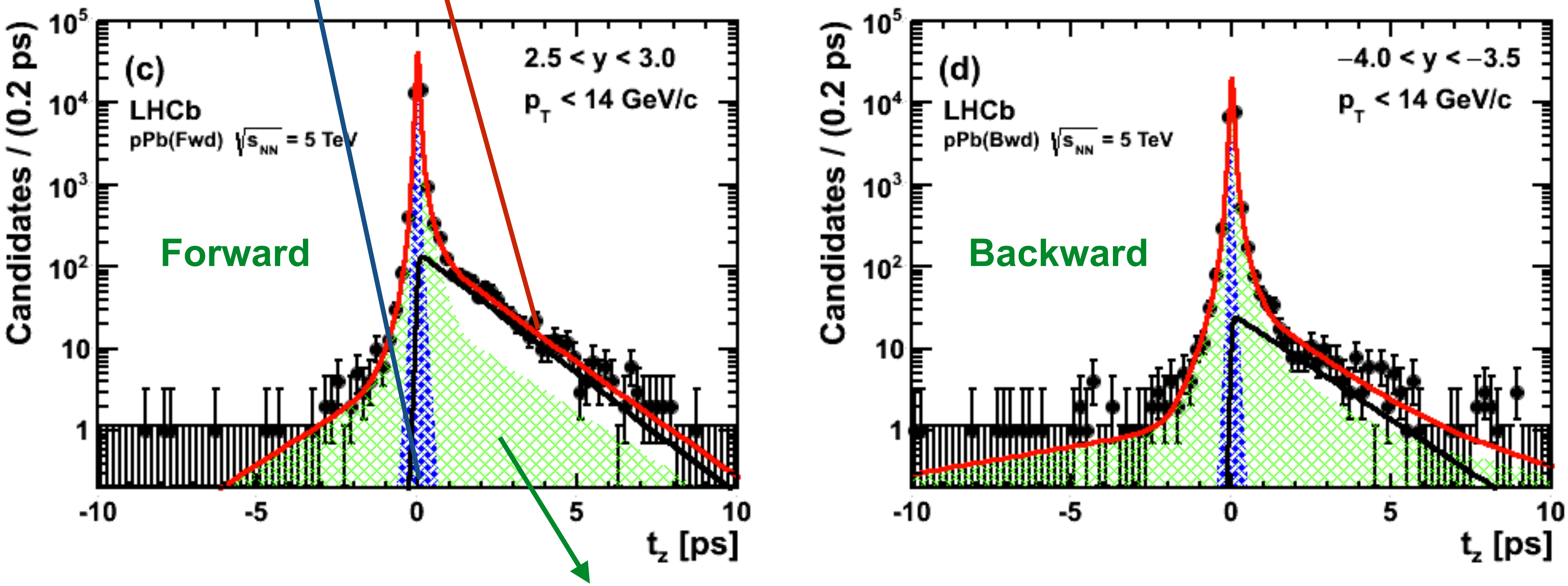


J/ψ Production

$$t_z = \frac{(z_{J/\psi} - z_{\rm PV}) \times M_{J/\psi}}{p_z}$$



Pseudo proper time is used to evaluate prompt vs b hadron decay



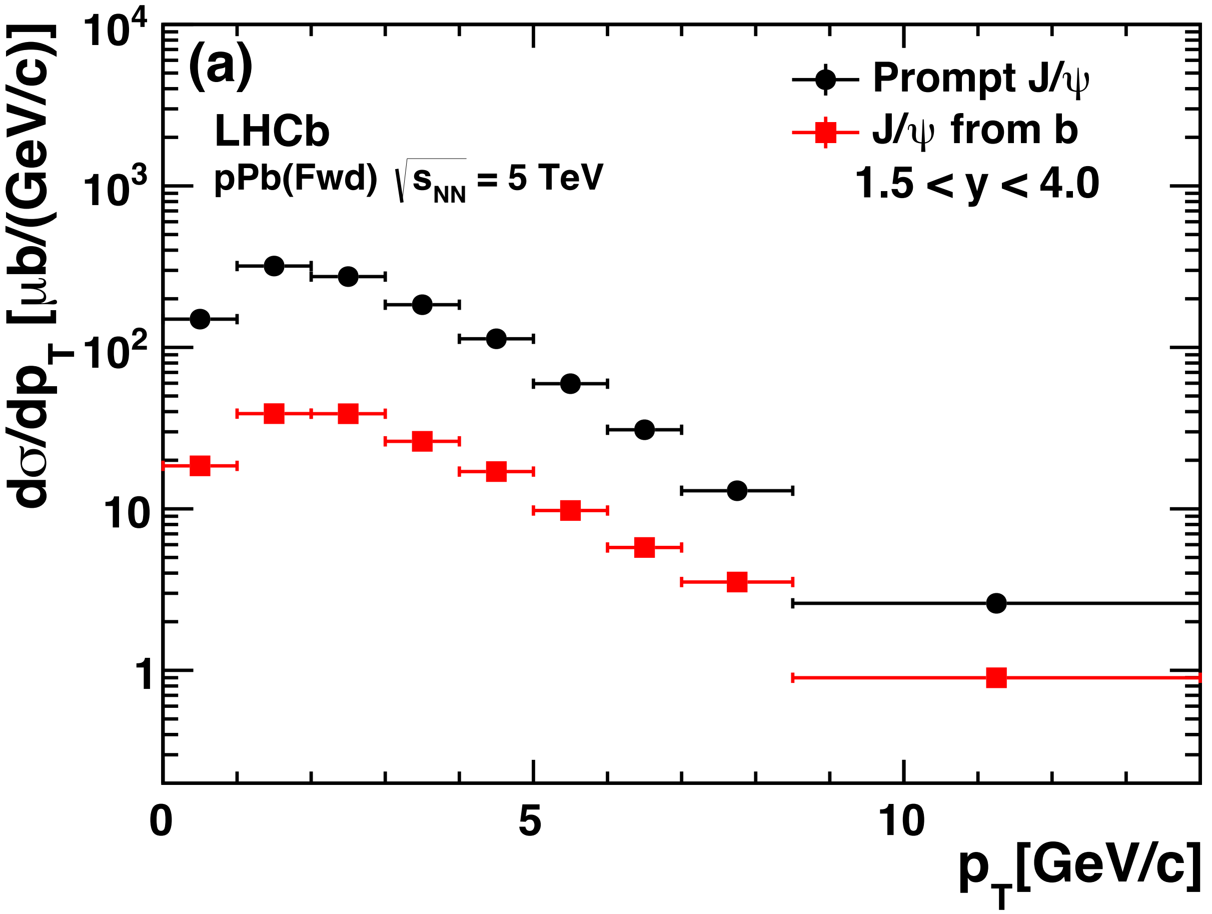
background from sideband

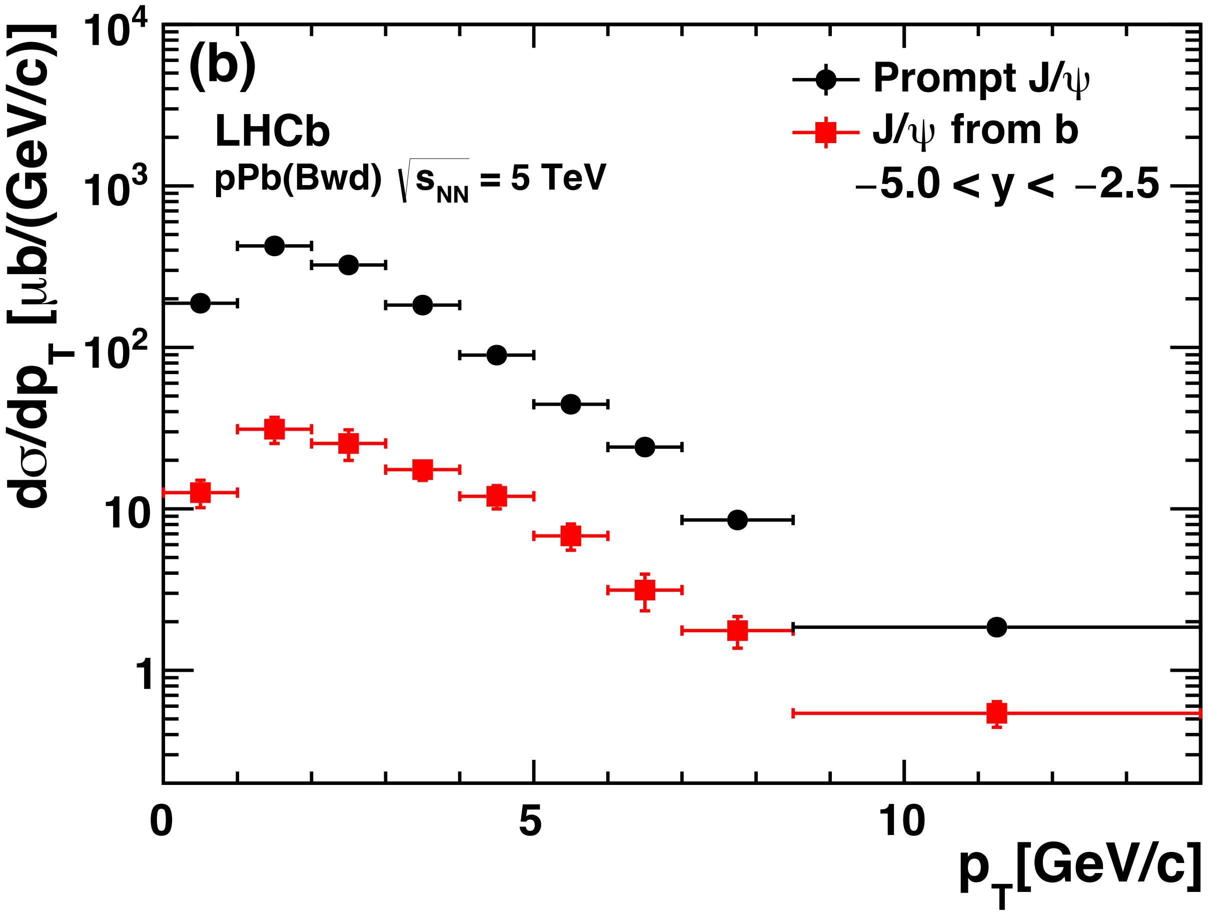
$$\sigma_{\rm F}(\text{prompt } J/\psi,\ +1.5 < y < +4.0) = 1168 \pm 15 \pm 54\ \mu\text{b},$$
$$\sigma_{\rm B}(\text{prompt } J/\psi,\ -2.5 < y < -5.0) = 1293 \pm 42 \pm 75\ \mu\text{b},$$
$$\sigma_{\rm F}(J/\psi \text{ from } b,\ +1.5 < y < +4.0) = 166.0 \pm 4.1 \pm 8.2\ \mu\text{b},$$
$$\sigma_{\rm B}(J/\psi \text{ from } b,\ -2.5 < y < -5.0) = 118.2 \pm 6.8 \pm 11.7\ \mu\text{b},$$

⇒ prompt J/ψ cross section about 10 times higher than J/ψ from b hadron decays

➢ similar to the values observed in pp collisions at 2.76, 7 and 8 TeV

[JHEP 02 (2013) 041], [EPJC (2011) 71 1645], [JHEP 06 (2013) 064]





J/ψ Cross Sections

$$\sigma_F(\text{prompt } J/\psi,\ +1.5 < y < +4.0) = 1168 \pm 15 \pm 54\ \mu b,$$
$$\sigma_B(\text{prompt } J/\psi,\ -2.5 < y < -5.0) = 1293 \pm 42 \pm 75\ \mu b,$$
$$\sigma_F(J/\psi \text{ from } b,\ +1.5 < y < +4.0) = 166.0 \pm 4.1 \pm 8.2\ \mu b,$$
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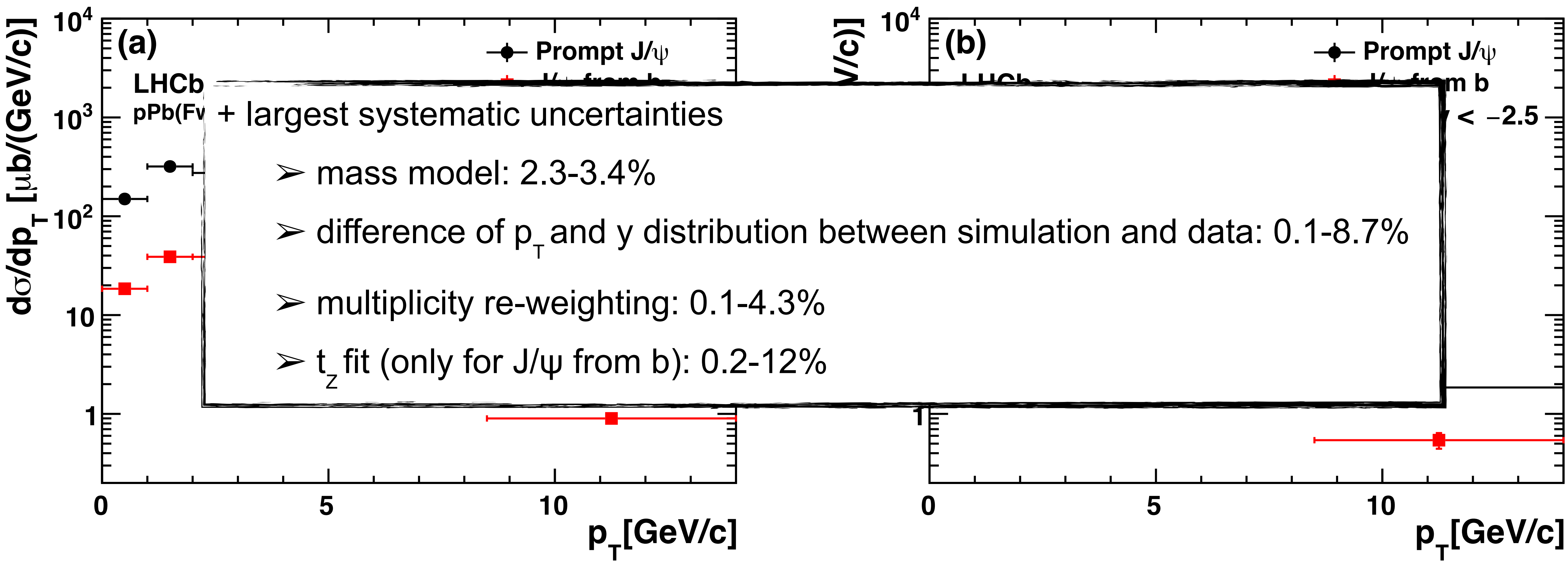


+ largest systematic uncertainties

➢ mass model: 2.3-3.4%

➢ difference of p_T and y distribution between simulation and data: 0.1-8.7%

➢ multiplicity re-weighting: 0.1-4.3%

➢ t_z fit (only for J/ψ from b): 0.2-12%

Cold Nuclear Effects

$$R_{pA}(y, p_T, \sqrt{s_{NN}}) \equiv \frac{1}{A} \frac{d^2\sigma_{pA}(y, p_T, \sqrt{s_{NN}})/dydp_T}{d^2\sigma_{pp}(y, p_T, \sqrt{s_{NN}})/dydp_T}$$

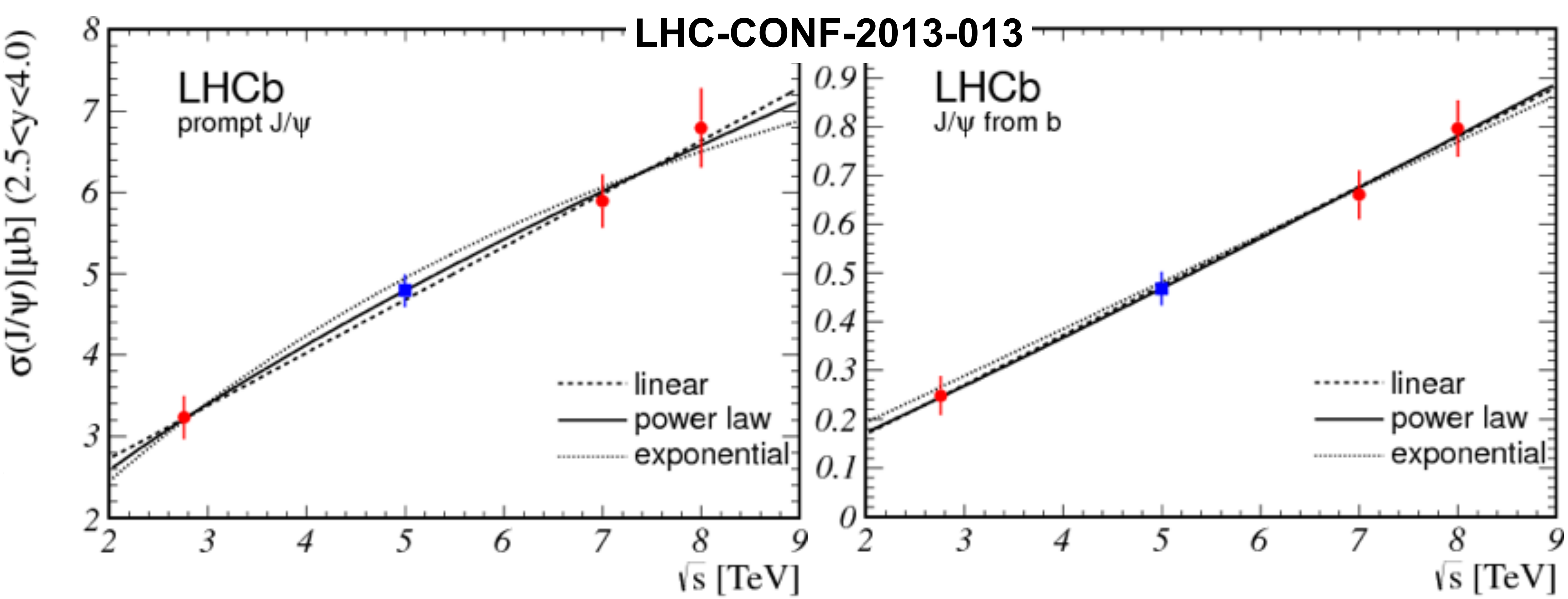
Nuclear modification factor in overlap region 2.5 < |y | < 4.0

- R_{pA}=1 if pA collision is superposition of A pp collisions
- R_{pA}<1 in case of suppression due to medium forward backward production ratio

pp cross section at 5 TeV is needed (LHCb-CONF-2013-013)

→ not measured directly - interpolation 2.76, 7 and 8 TeV rescaled to common rapidity range

→ 3 interpolation functions: linear, exponential, power law (nominal)



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pp cross section at 5 TeV is needed (LHCb-CONF-2013-013)

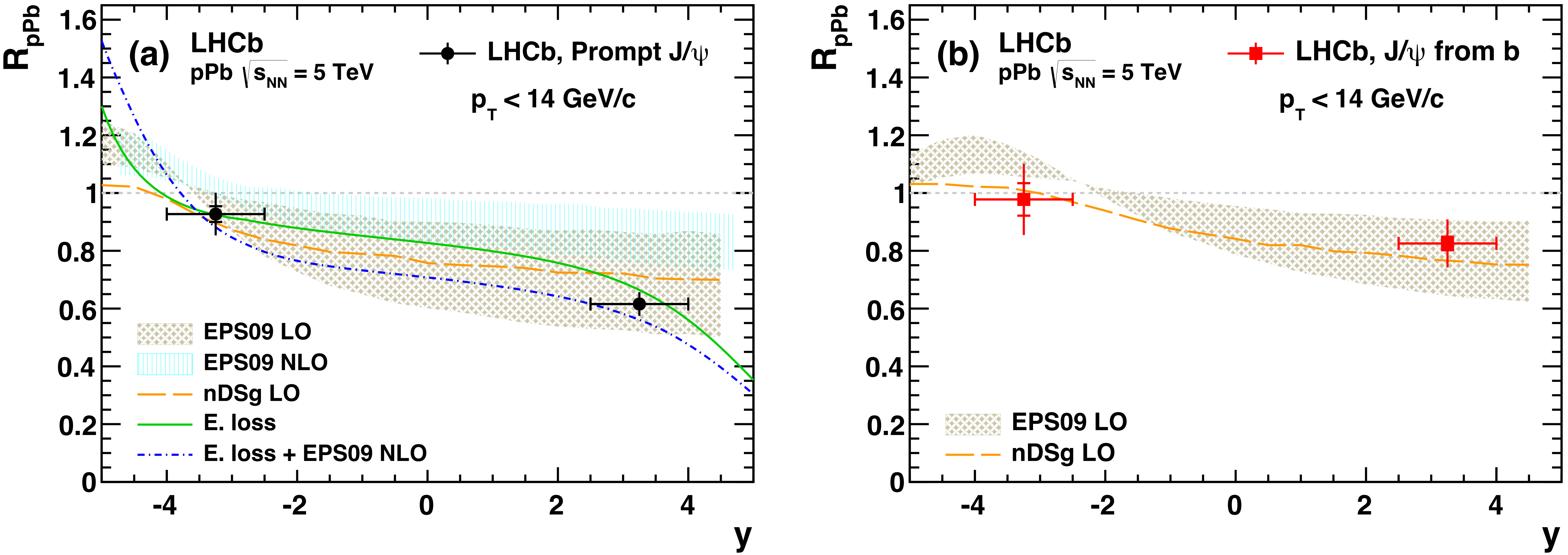
- ➞ not measured directly - interpolation 2.76, 7 and 8 TeV rescaled to common rapidity range
- ➞ 3 interpolation functions: linear, exponential, power law (nominal)

$$R_{FB}(y, p_T, \sqrt{s_{NN}}) \equiv \frac{d^2\sigma_{pPb}(+|y|, p_T, \sqrt{s_{NN}})/dydp_T}{d^2\sigma_{pPb}(-|y|, p_T, \sqrt{s_{NN}})/dydp_T}$$

Forward-Backward production ratio in overlap region 2.5 < |y | < 4.0

- → sensitive to cold nuclear matter effects
- → many uncertainties cancel and no reference cross section needed

JHEP02(2014)072



prompt J/Ψ

+ significant sign of cold nuclear matter effects

+ measurements agree with most of the predictions

J/Ψ from b hadron decays

+ modest suppression with respect to pp

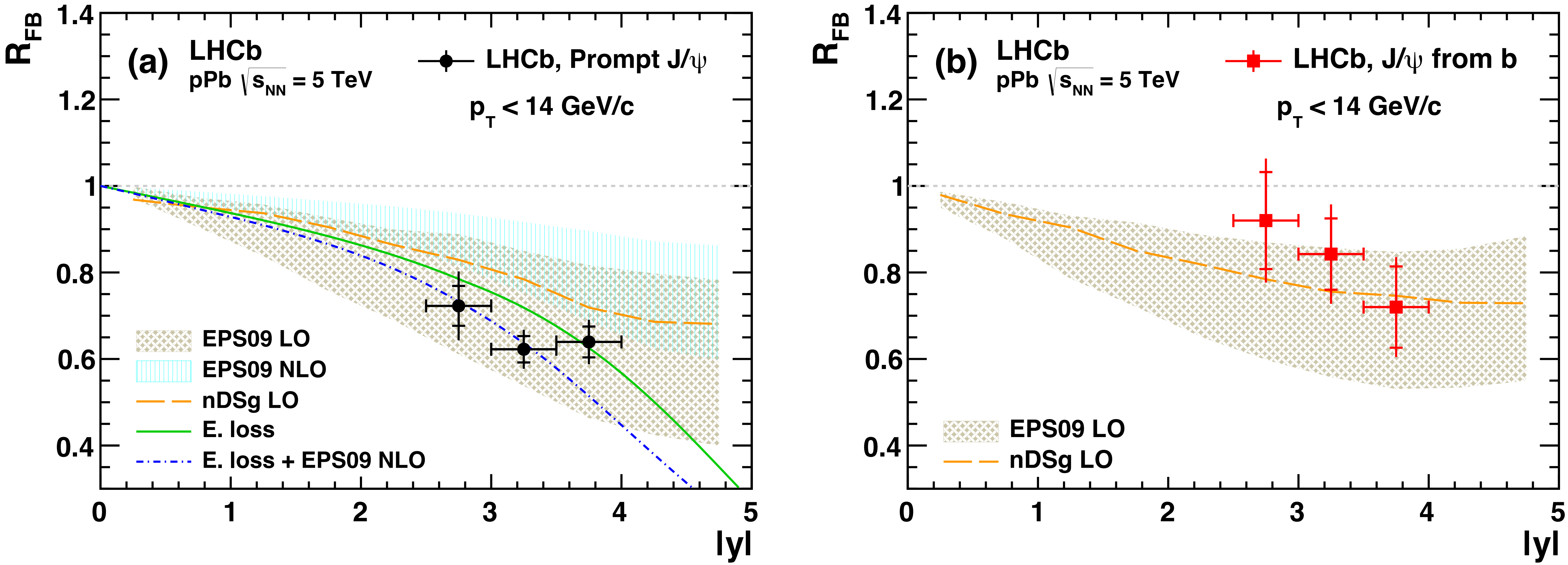
+ first indication of suppression of bottom hadron production in Pb

+ agreement with predictions in forward region

EPS09: JHEP 0904 (2009) 65, nDSG:Phys. Rev.D69(2004) 074028
Energy loss: JHEP 03(2013) 122
NLO: Phys. Rev. D17 (1978) 2324, LO: Nucl. Phys. B127 (1980) 425, Phys. Lett. B102, (1981) 364

J/ψ Production

JHEP02(2014)072



prompt J/Ψ

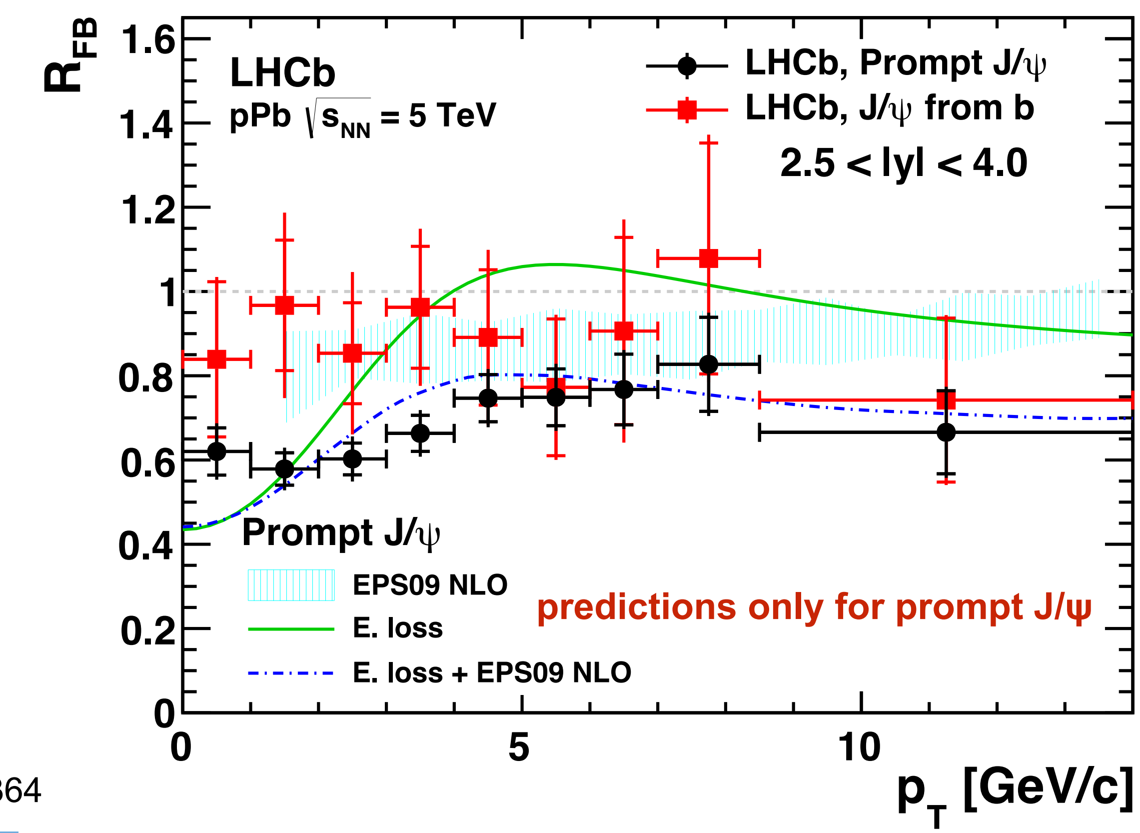
+ significant forward-backward asymmetry

+ better agreement with EPS09+Energy loss

J/Ψ from b hadron decays

+ smaller asymmetry with respect to pp

+ agreement with predictions in forward region



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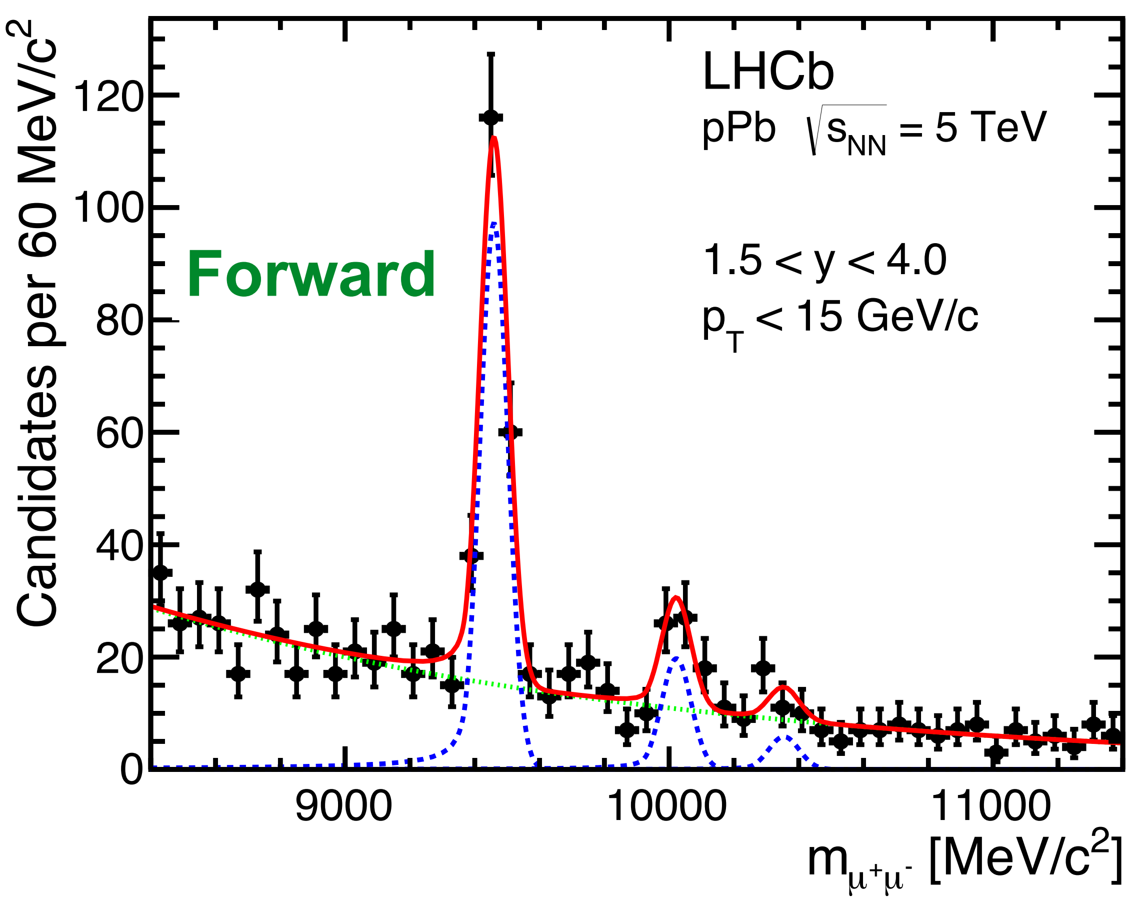
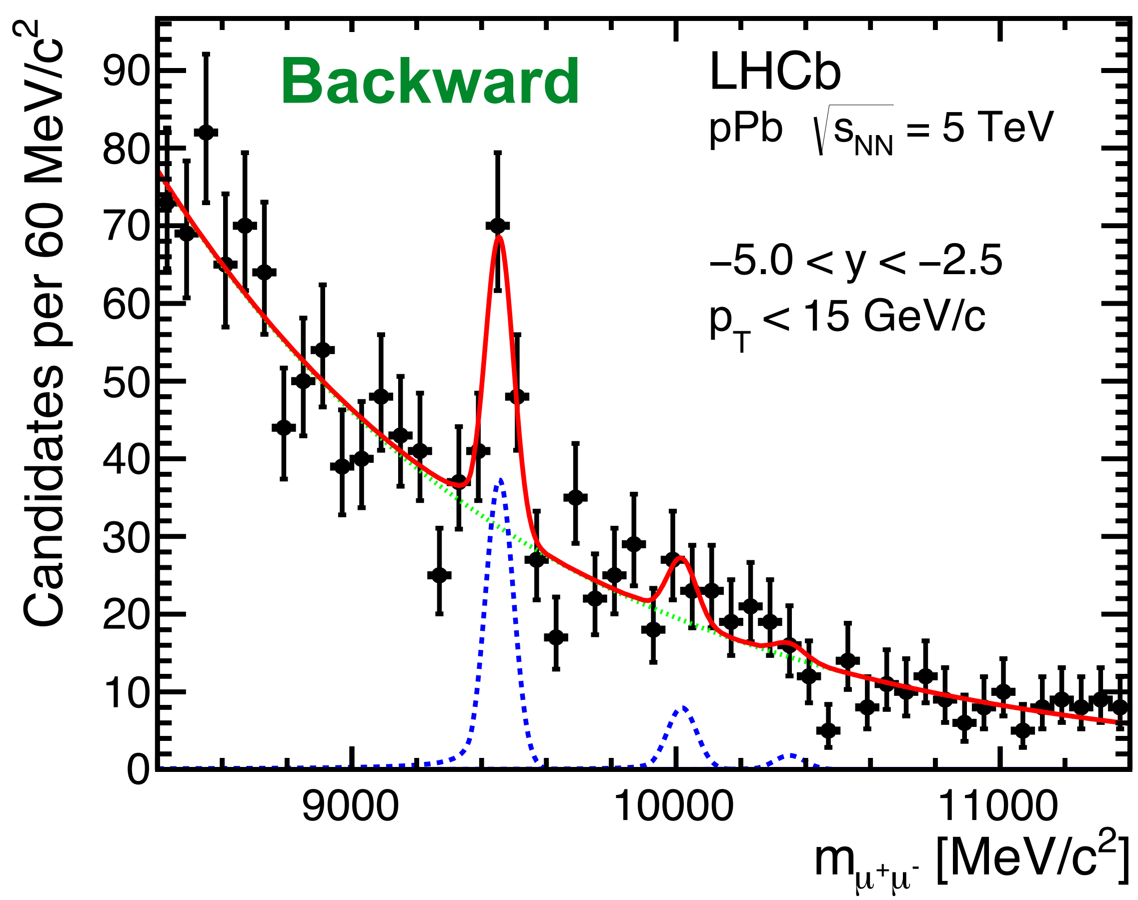
Data and General Strategy

- Trigger:
  - One track with hits in the muon stations with p_T > 600 MeV
- Two Muons with 1.5<y<4.0 (-5.0<y<-2.5) for pA (Ap) and p_T(Υ)<15GeV
- Low statistics

Backgrounds - combinatorial - exponential

Signal - mass model - 3 crystal-balls function

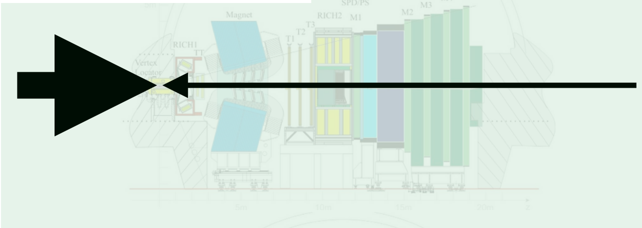




Υ Production

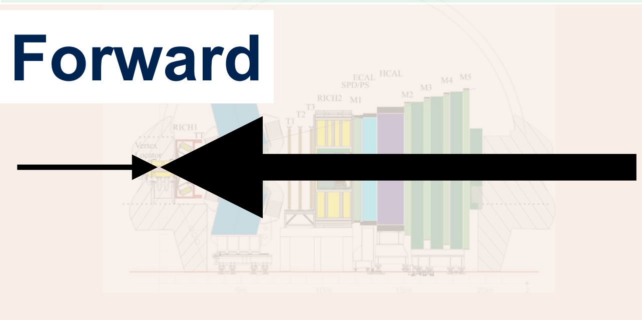
JHEP07(2014)094

Backward



$$\sigma(\Upsilon(1S), -5.0 < y < -2.5) \times \mathcal{B}(1S) = 295 \pm 56 \pm 29 \text{ nb},$$
$$\sigma(\Upsilon(2S), -5.0 < y < -2.5) \times \mathcal{B}(2S) = 81 \pm 39 \pm 18 \text{ nb},$$
$$\sigma(\Upsilon(3S), -5.0 < y < -2.5) \times \mathcal{B}(3S) = 5 \pm 26 \pm 5 \text{ nb},$$

Forward

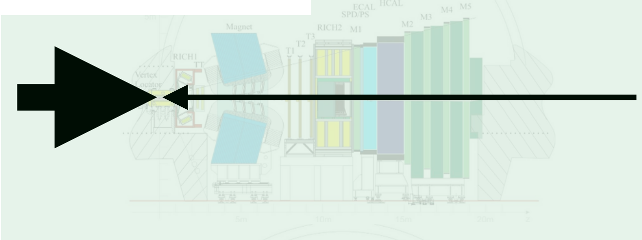


$$\sigma(\Upsilon(1S), 1.5 < y < 4.0) \times \mathcal{B}(1S) = 380 \pm 35 \pm 21 \text{ nb},$$
$$\sigma(\Upsilon(2S), 1.5 < y < 4.0) \times \mathcal{B}(2S) = 75 \pm 19 \pm 5 \text{ nb},$$
$$\sigma(\Upsilon(3S), 1.5 < y < 4.0) \times \mathcal{B}(3S) = 27 \pm 16 \pm 4 \text{ nb},$$

+ statistical uncertainty dominates (concentrate on Υ(1S))
+ dominant systematic uncertainties:
    - → p_T and y dependence of signal: 4%(forward) 7%(backward)
    - → trigger efficiency : 2%(forward) 5%(backward)

JHEP07(2014)094

Backward



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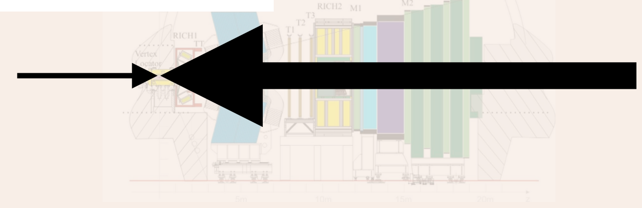
Forward



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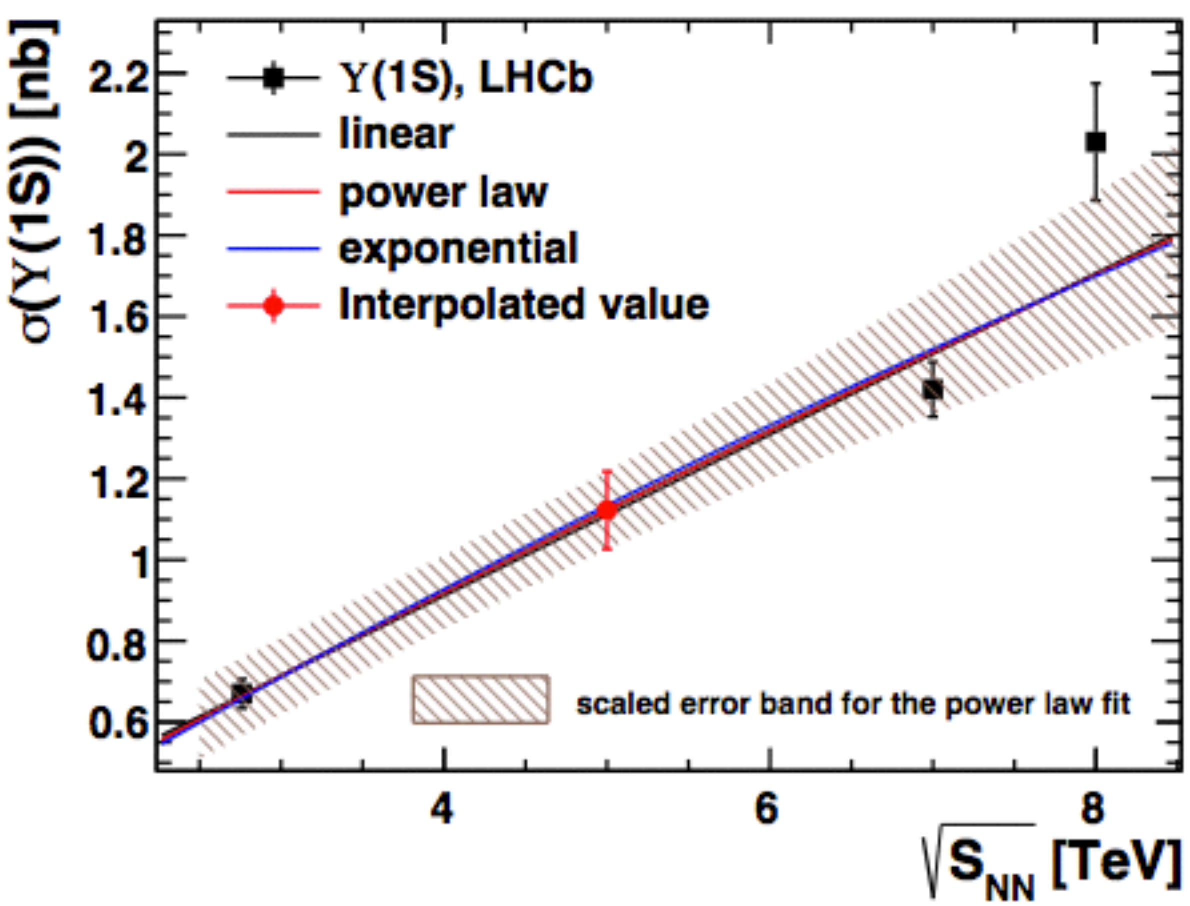
LHCb-CONF-2014-003



pp cross section at 5 TeV

→ not measured directly - interpolation 2.76, 7 and 8 TeV rescaled to common rapidity range

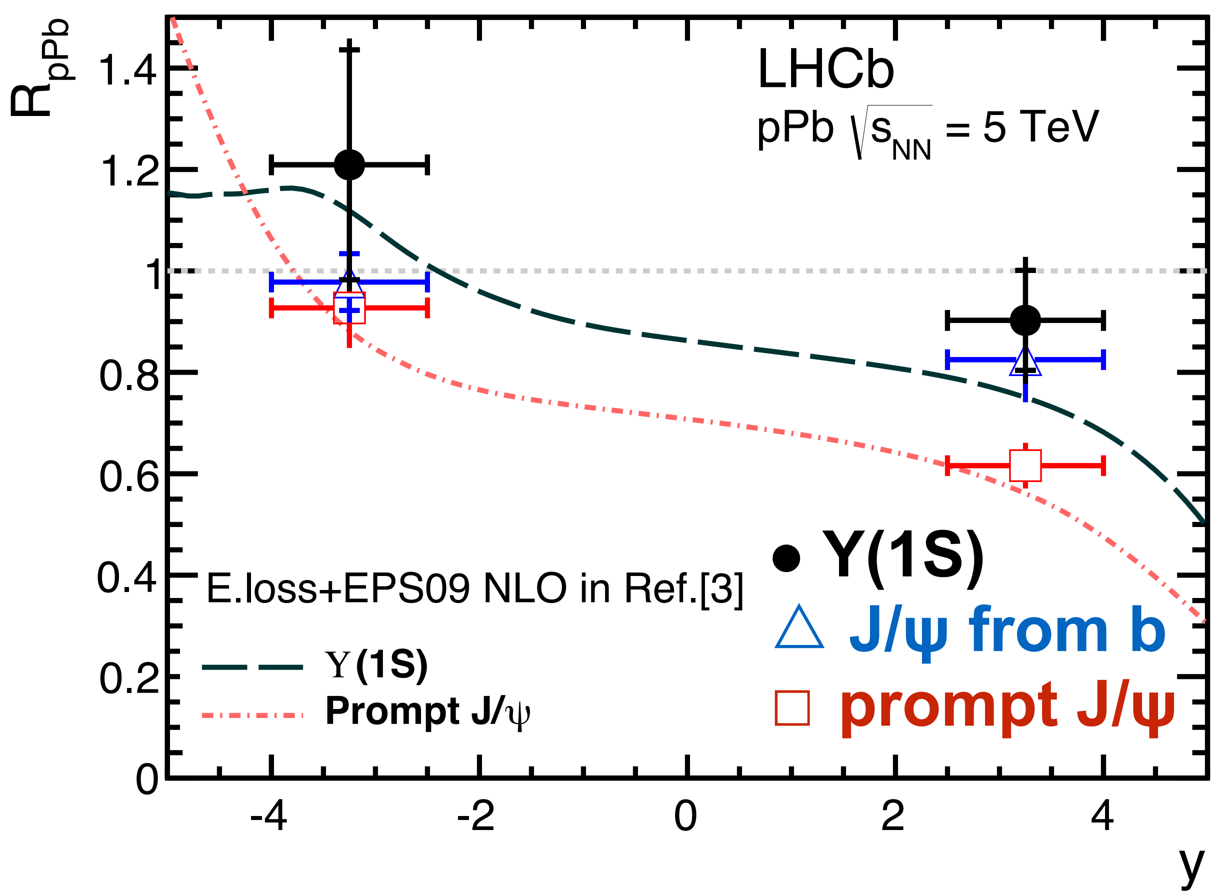
→ 3 interpolation functions: linear, exponential, power law (nominal)

$$\sigma(\sqrt{s}) = \begin{cases} p_0 + \sqrt{s}\, p_1 & \text{linear} \\ (\sqrt{s}/p_0)^{p_1} & \text{power law} \\ p_0(1 - \exp(-\sqrt{s}/p_1)) & \text{exponential} \end{cases}$$

JHEP07(2014)094

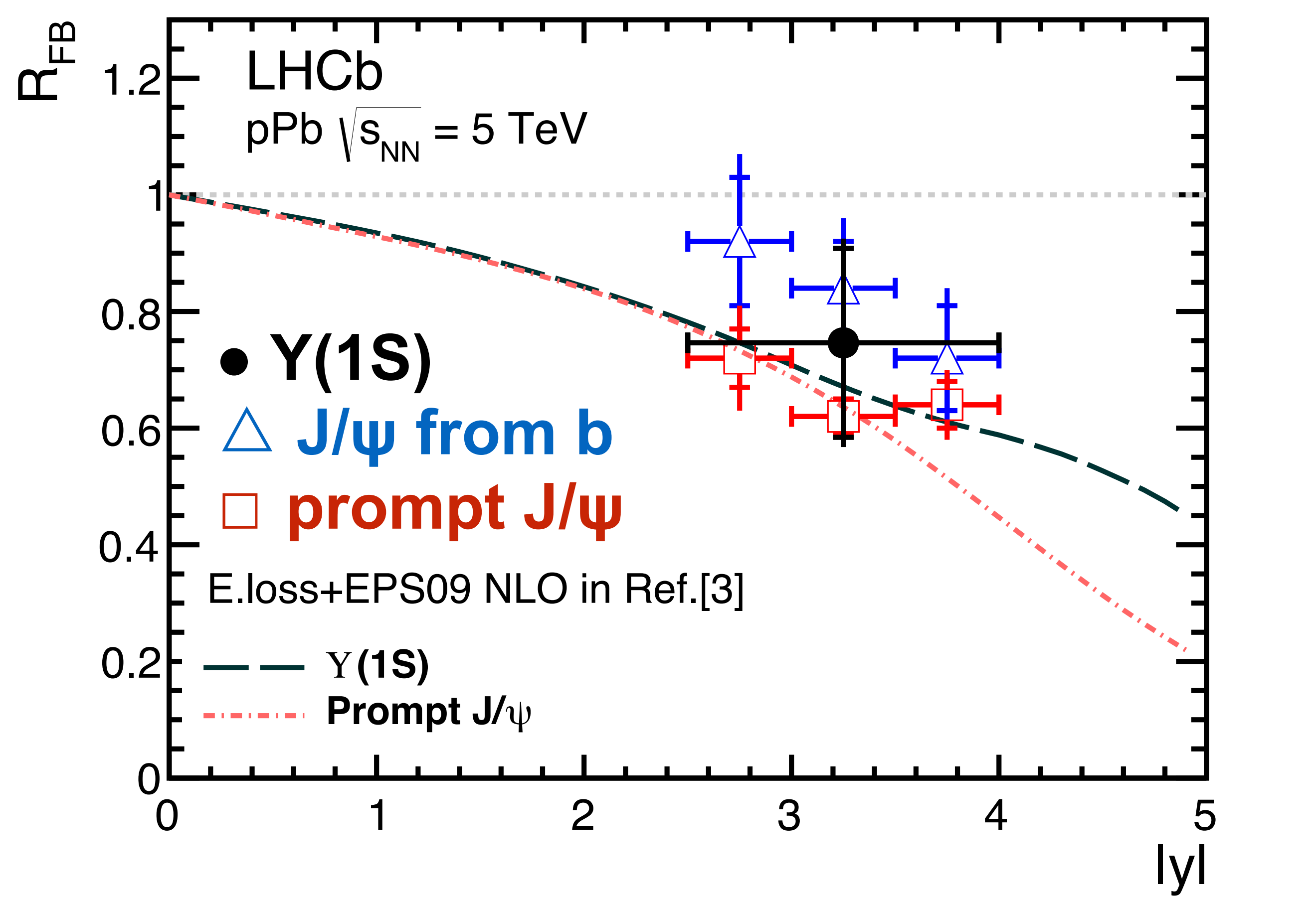
Nuclear modification factor

$$R_{pPb}(\sqrt{s_{NN}}) \equiv \sigma_{pPb}(\sqrt{s_{NN}})/(A \times \sigma_{pp}(\sqrt{s_{NN}}))$$



Forward-Backward ratio

$$R_{FB}(\sqrt{s_{NN}}, |y|) \equiv \sigma(\sqrt{s_{NN}}, +|y|)/\sigma(\sqrt{s_{NN}}, -|y|)$$



+ R_{pPb} measured in the common rapidity region 2.5<y<4.0
+ complementary to J/ψ - different x_A region
+ similar to J/ψ from b hadron decays

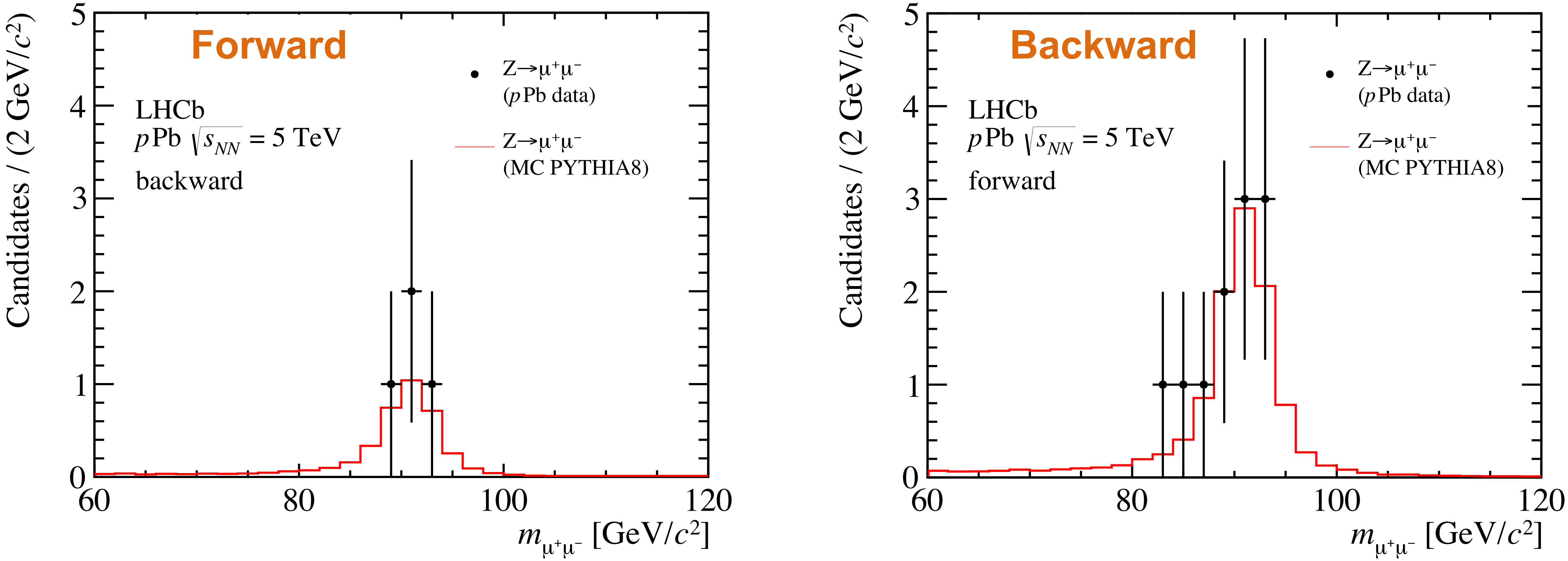
→ visible cold nuclear effect, in agreement with EPS09(NLO) - Ref.[3]

Data and General Strategy

- Trigger:
  - One track with hits in the muon stations with p>8GeV and p_T > 4.8 MeV
- Two Muons with $2.0<y_{lab}<4.5$ and $p_T(\mu)<20$GeV
- Low statistics

Backgrounds - mis-identification+heavy-quark ⟹ purity>99.5%

Signal - shape from simulation / efficiency from pp analysis ⟹ efficiency>72%



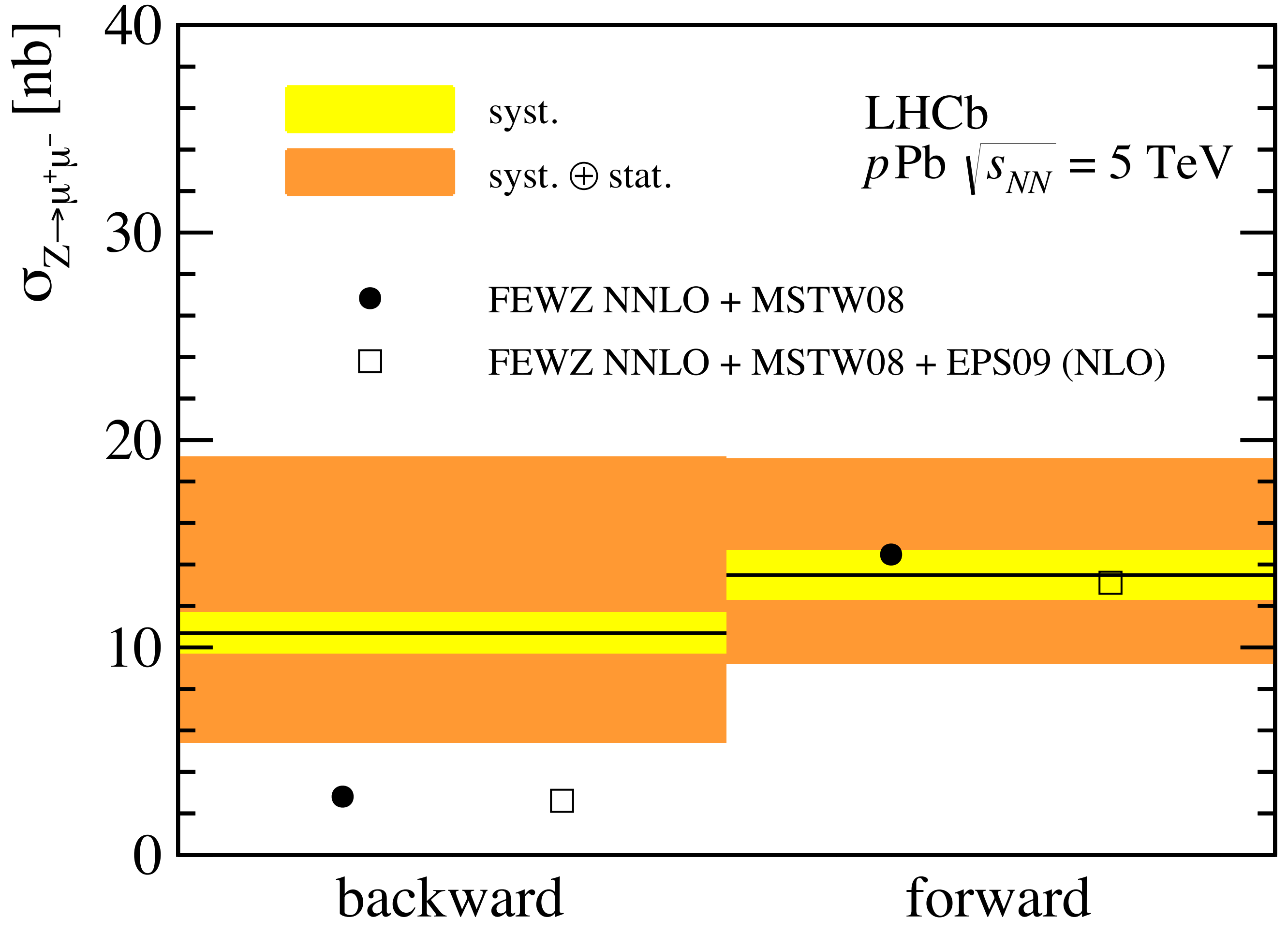
Z Production

+ efficiencies derived in data

+ measurement limited by statistics

+ theoretical predictions in agreement with measurement

+ higher statistics measurements will provide important information on nuclear PDFs



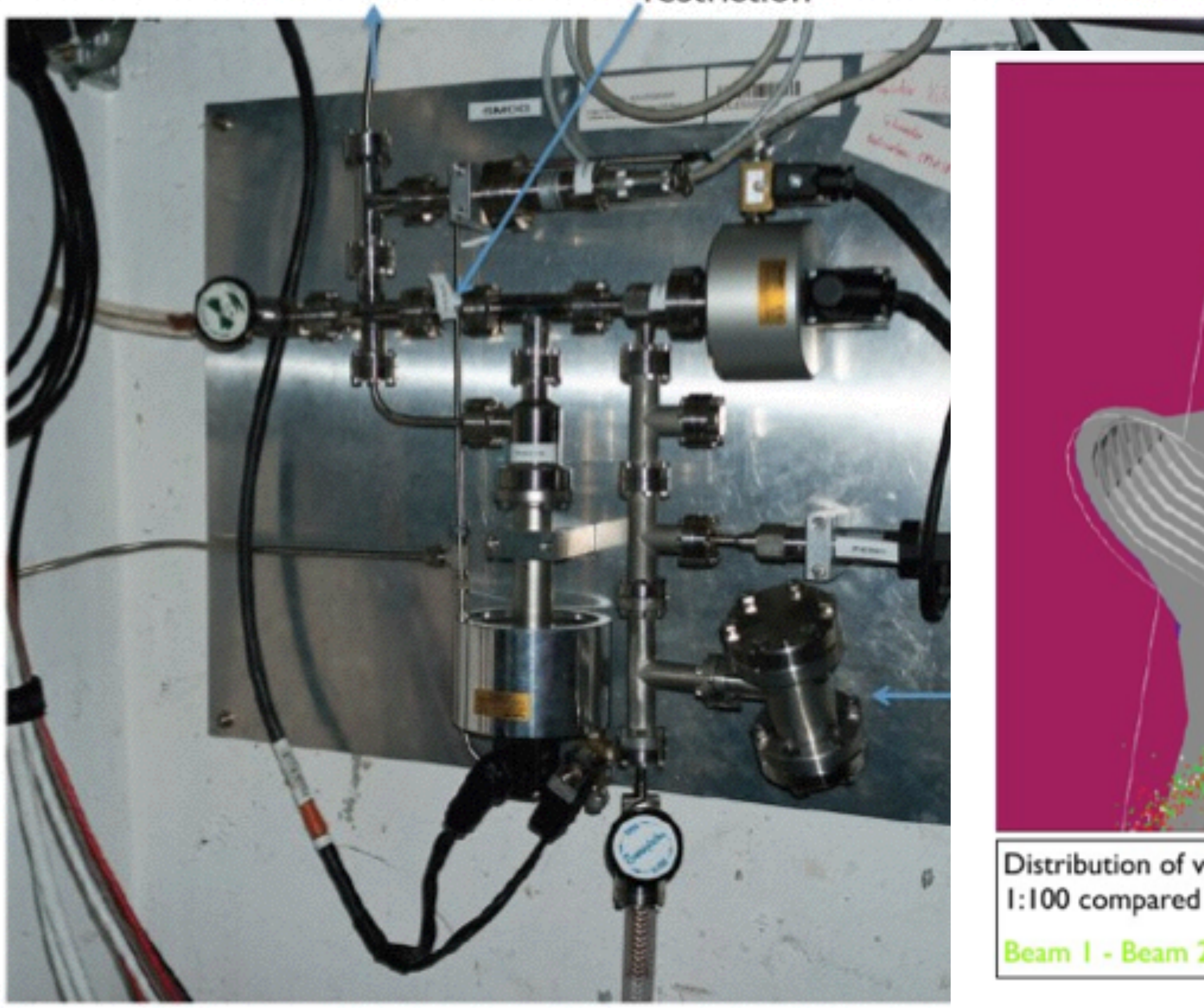
$$\sigma_{Z\to\mu^+\mu^-}(\text{fwd}) = 13.5^{+5.4}_{-4.0}(\text{stat.}) \pm 1.2(\text{syst.})\ \text{nb}$$

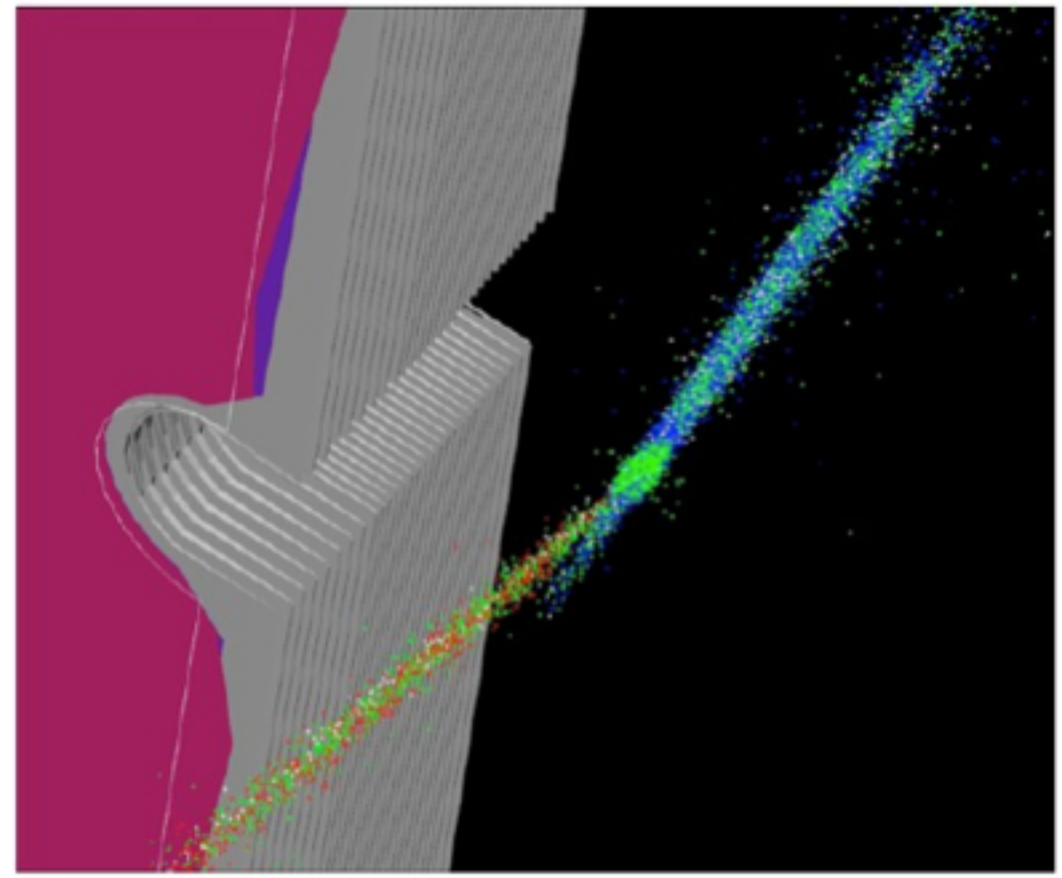
$$\sigma_{Z\to\mu^+\mu^-}(\text{bwd}) = 10.7^{+8.4}_{-5.1}(\text{stat.}) \pm 1.0(\text{syst.})\ \text{nb}$$

FEWZ: Y.LiandF.Petriello,Phys.Rev.D86(2012)094034,arXiv:1208.5967.
MSTW08: A. Martin, W. Stirling, R. Thorne, and G. Watt, Phys. J C63 (2009), no 2 189
EPS09: K. Eskola, H. Paukkunen, and C. Salgado,
JHEP 04 (2009) 065, arXiv:0902.4154.

JINST 9 (2014) 12, P12005
LHCb-CONF-2012-034

SMOG: System for Measuring Overlap with Gas





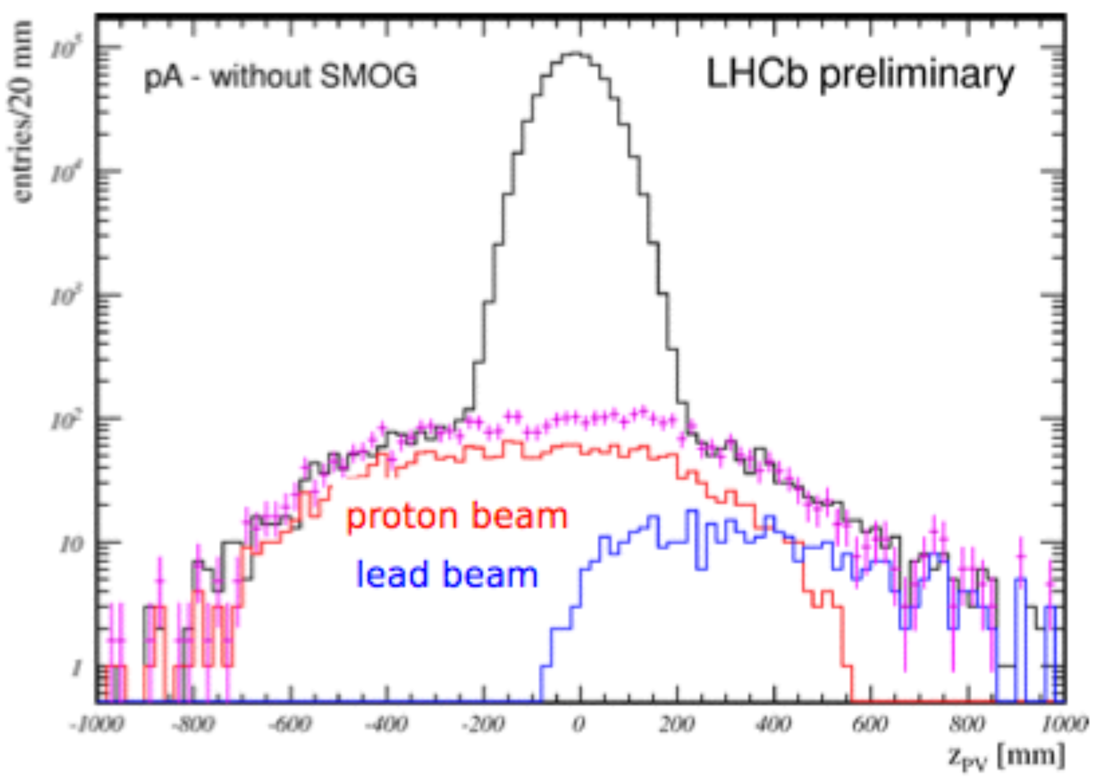
Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

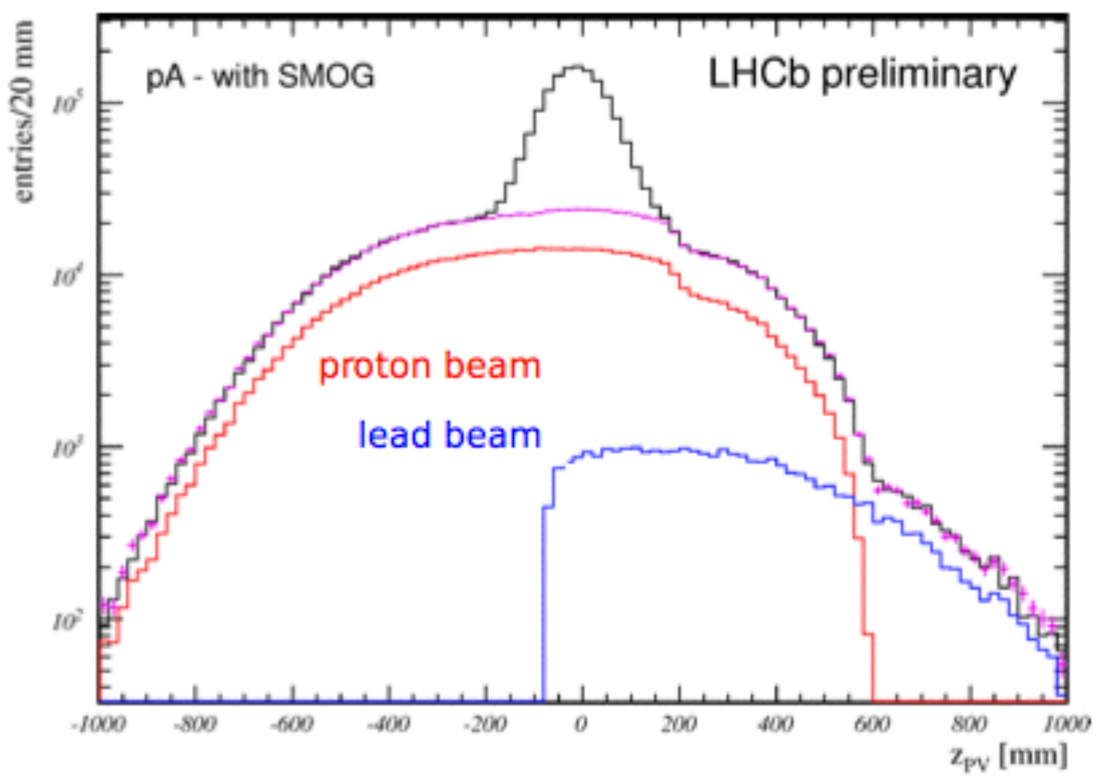
→ injection of Ne gas into interaction region

JINST 9 (2014) 12, P12005
LHCb-CONF-2012-034

no SMOG



with SMOG



Injection of Ne gas into interaction region increases beam-gas interaction rate by 2 orders of magnitude

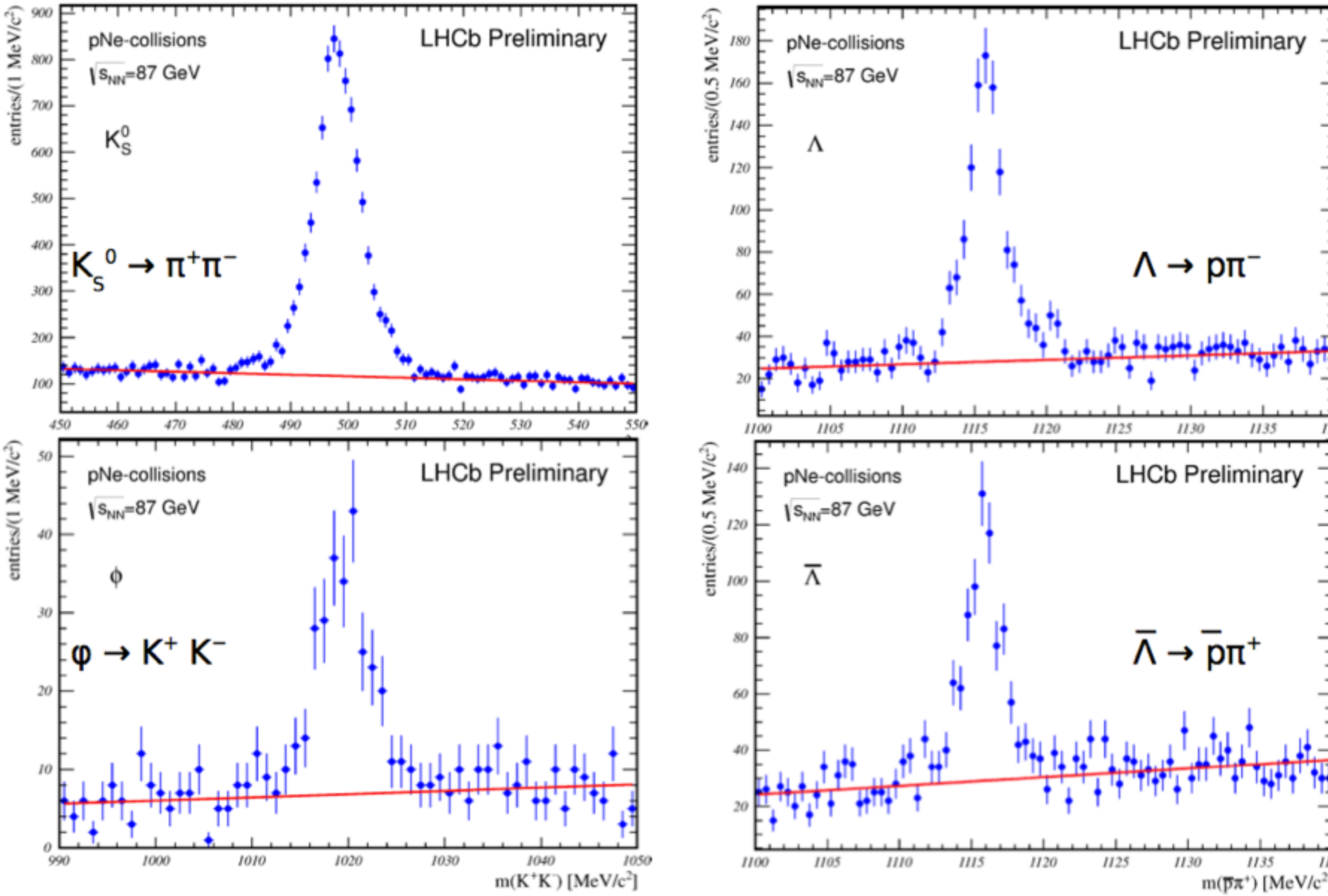
→ accurate measurement of beam profile - precise luminosity determination

→ also allows to study pNe interactions at 87 GeV

++ shift of c.m. system by 4.5 units in rapidity in proton direction

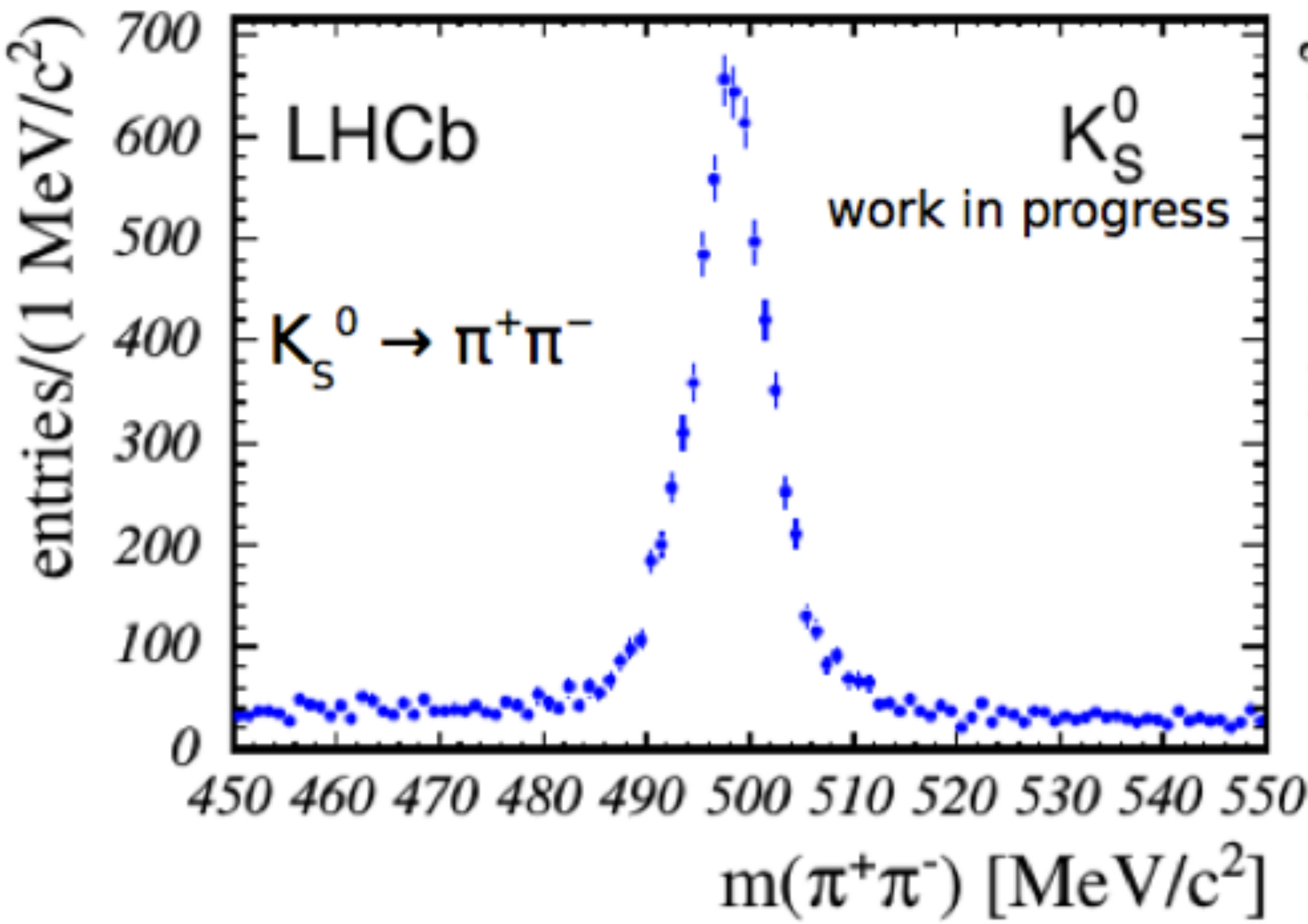
→ LHCb is a central detector for fixed target collisions

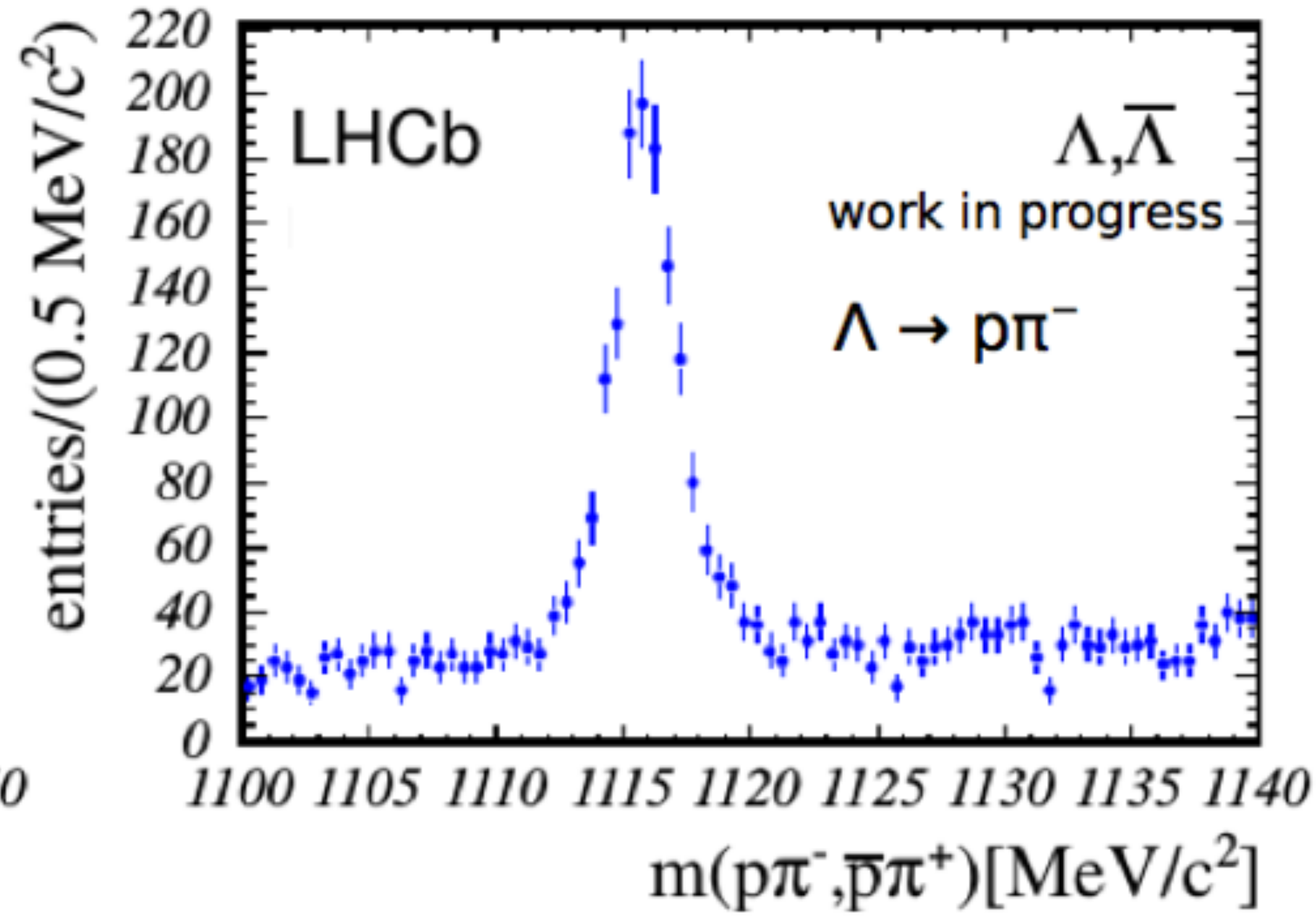
LHCb-CONF-2012-034



Clear observation of signals

LHCb - Fixed Target - PbNe





PbNe interactions at $\sqrt{(s_{NN})}$=54.4 GeV

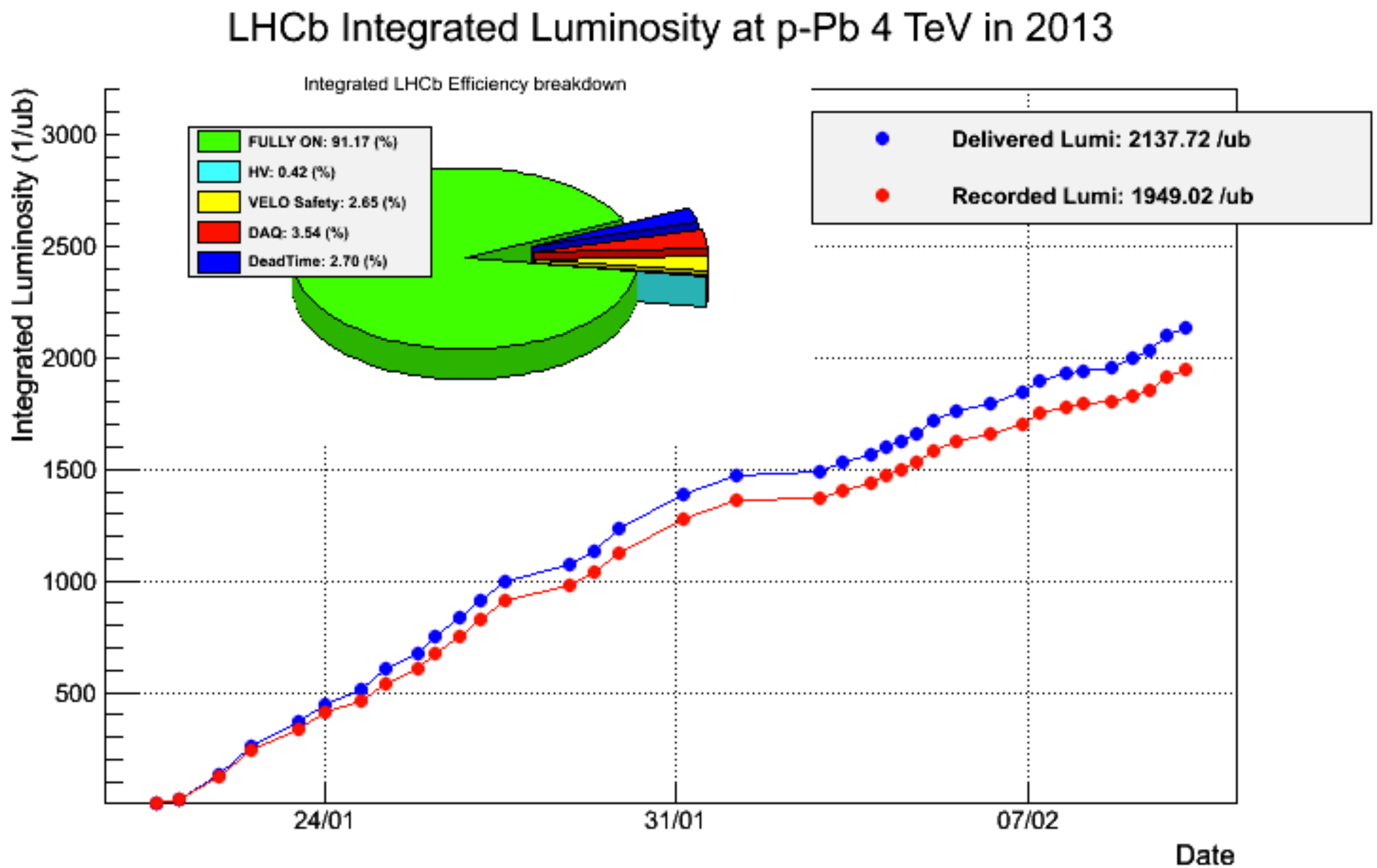
40 minutes data taking with PbNe interactions
plots based on ¼ of available statistics

Summary

- **LHCb has a unique coverage to study Heavy Ion Physics**
- **J/ψ and Υ Production**
  - o Visible cold nuclear effects for prompt J/ψ and Υ
  - o Evidence of cold nuclear effect for bottom production
- **First observation of Z boson Production in proton-nucleus**
- **Measurements are limited by data size**
- **Other studies and samples of pNe and PbNe ongoing**

BACK UP

Data



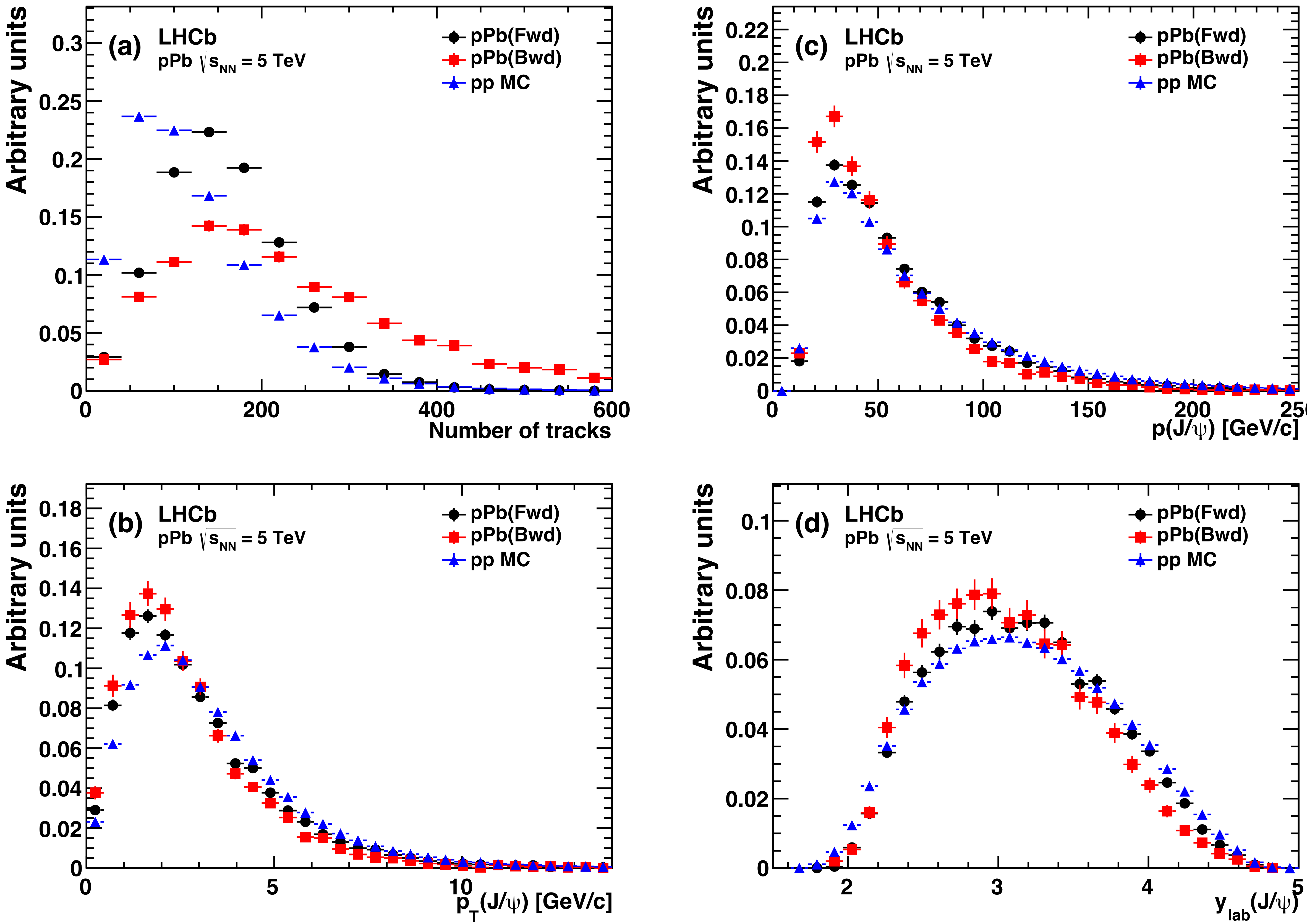
- low pile-up (~ 1 primary vertex per beam crossing)
- data-taking efficiency > 90%.
- results based on 2 beam configurations and 2 magnet configurations.

Ap : $L = 1.1\ nb^{-1}$

pA : $L = 0.5\ nb^{-1}$

J/ψ Production

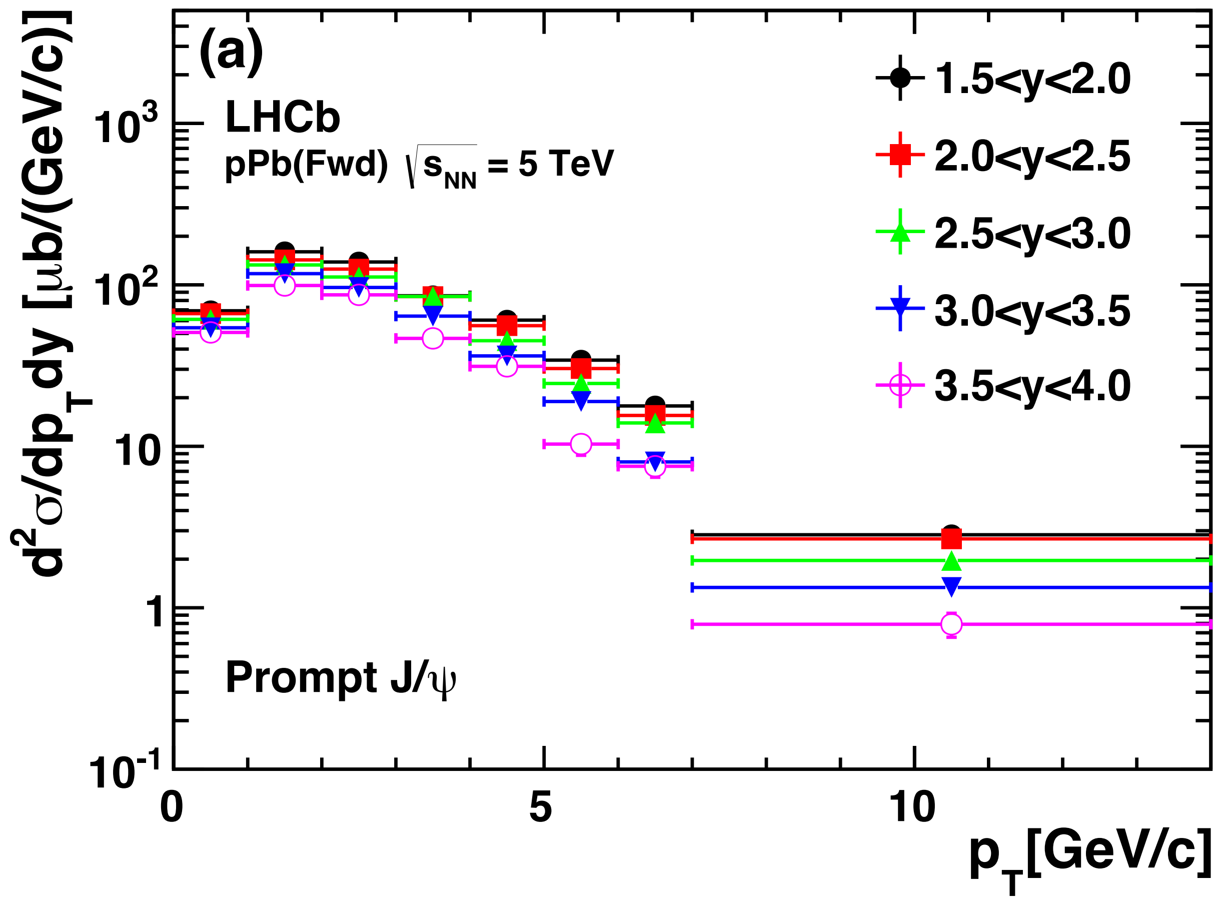
JHEP02(2014)072

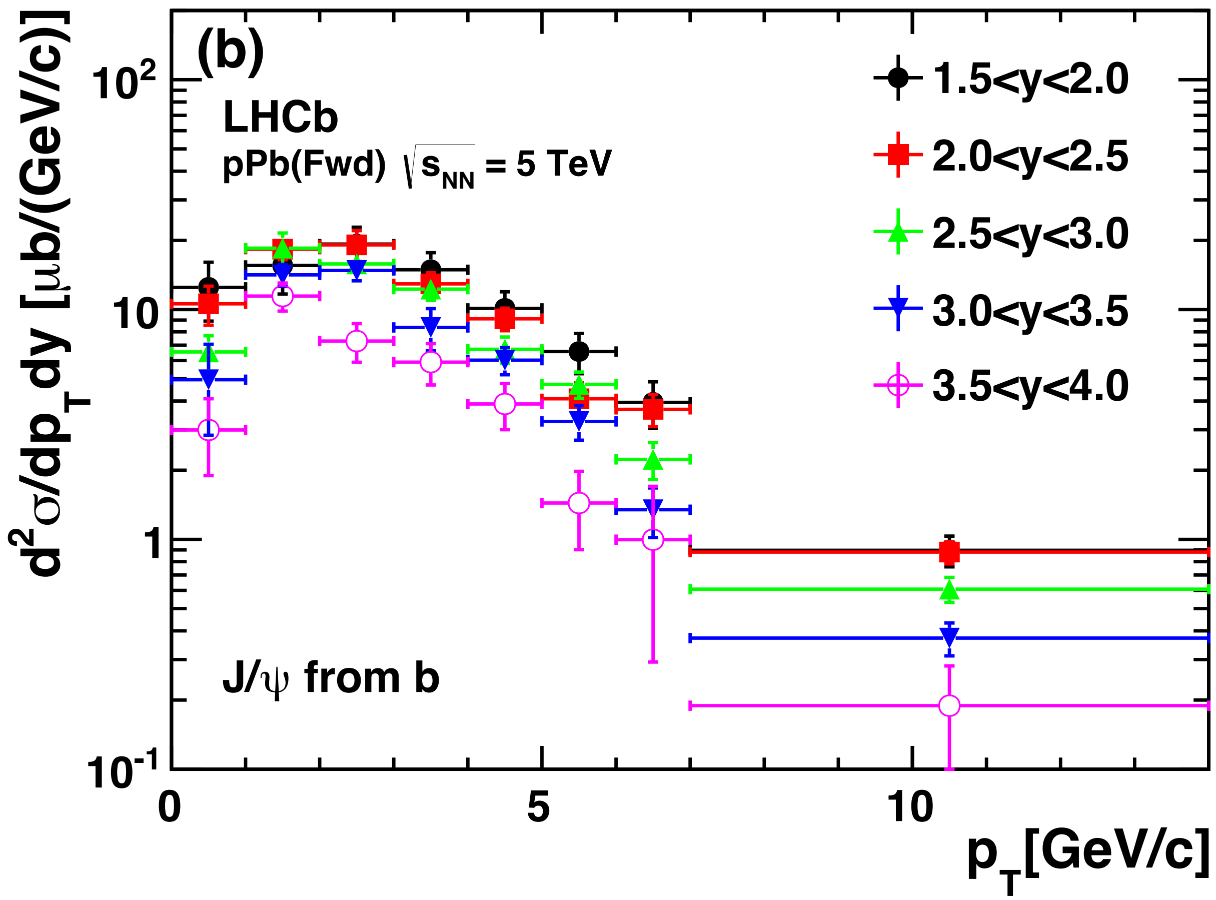


Acceptance and efficiency from pp simulation re-weighted to track multiplicity

 JHEP02(2014)072

$$\sigma_F(\text{prompt } J/\psi, +1.5 < y < +4.0) = 1168 \pm 15 \pm 54\ \mu b,$$
$$\sigma_B(\text{prompt } J/\psi, -2.5 < y < -5.0) = 1293 \pm 42 \pm 75\ \mu b,$$
$$\sigma_F(J/\psi \text{ from } b, +1.5 < y < +4.0) = 166.0 \pm 4.1 \pm 8.2\ \mu b,$$
$$\sigma_B(J/\psi \text{ from } b, -2.5 < y < -5.0) = 118.2 \pm 6.8 \pm 11.7\ \mu b,$$





J/ψ Cross Sections

$$\sigma_{\rm F}(\text{prompt } J/\psi, +1.5 < y < +4.0) = 1168 \pm 15 \pm 54\ \mu\text{b},$$
$$\sigma_{\rm B}(\text{prompt } J/\psi, -2.5 < y < -5.0) = 1293 \pm 42 \pm 75\ \mu\text{b},$$
$$\sigma_{\rm F}(J/\psi \text{ from } b, +1.5 < y < +4.0) = 166.0 \pm 4.1 \pm 8.2\ \mu\text{b},$$
$$\sigma_{\rm B}(J/\psi \text{ from } b, -2.5 < y < -5.0) = 118.2 \pm 6.8 \pm 11.7\ \mu\text{b},$$

+ largest systematic uncertainties
  - ➢ mass model: 2.3-3.4%
  - ➢ difference of p_T and y distribution between simulation and data: 0.1-8.7%
  - ➢ multiplicity reweighting: 0.1-4.3%
  - ➢ t_z fit (only for J/ψ from b): 0.2-12%

⇒ prompt J/ψ cross section about 10 times higher than J/ψ from bottom, similar to the values observed in pp collisions at 2.76, 7 and 8 TeV

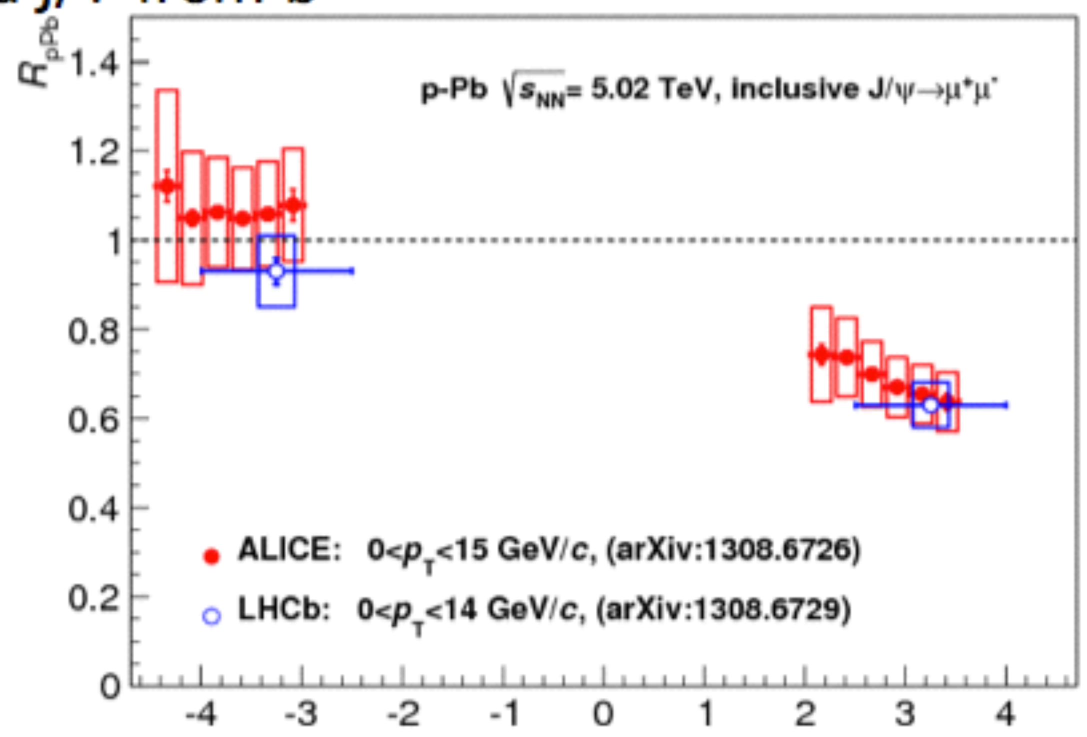
[JHEP 02 (2013) 041], [EPJC (2011) 71 1645], [JHEP 06 (2013) 064]

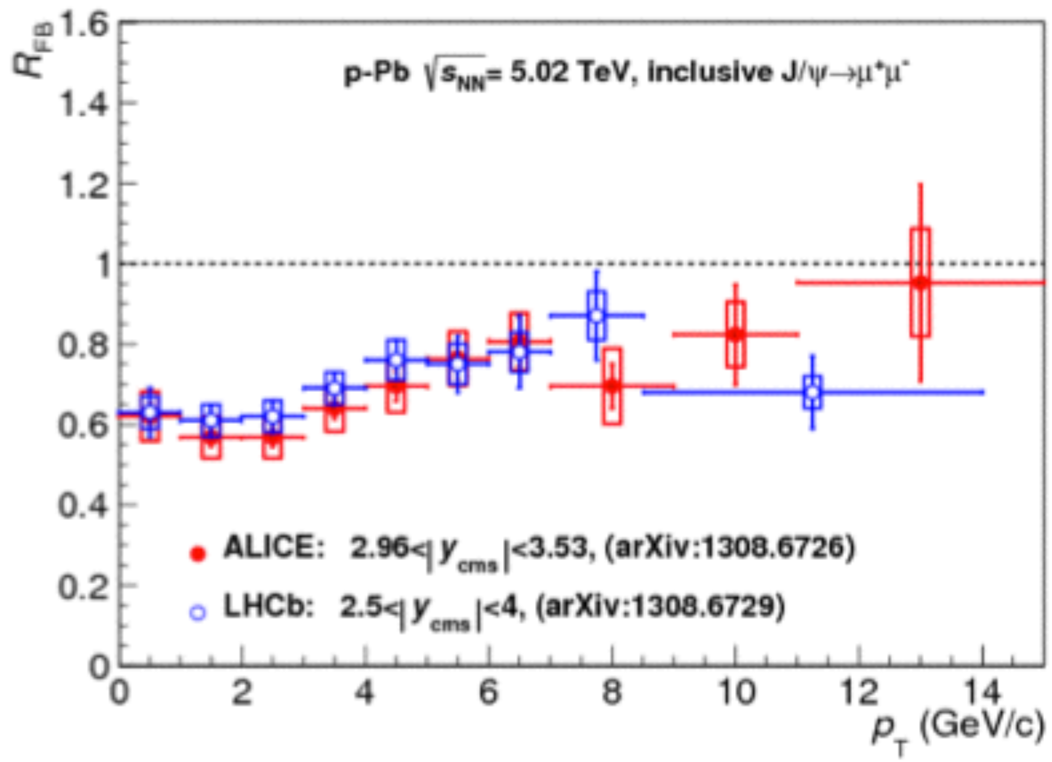
LHCb inclusive J/Ψ: sum of prompt J/Ψ and J/Ψ from b

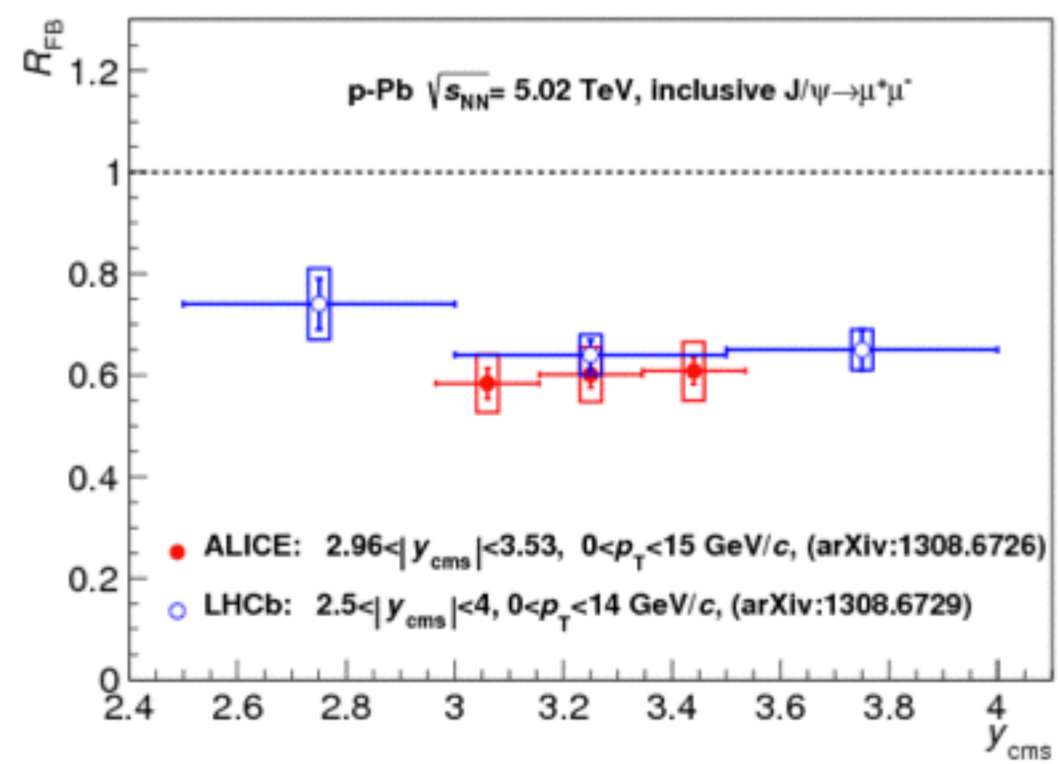
ALICE (JHEP 02(2014) 073)
slightly different phase space:

LHCb |2.5|<y<|4|, p_T<14 GeV
ALICE |2.96|<y<|3.53|, p_T<15 GeV

good agreement within uncertainties



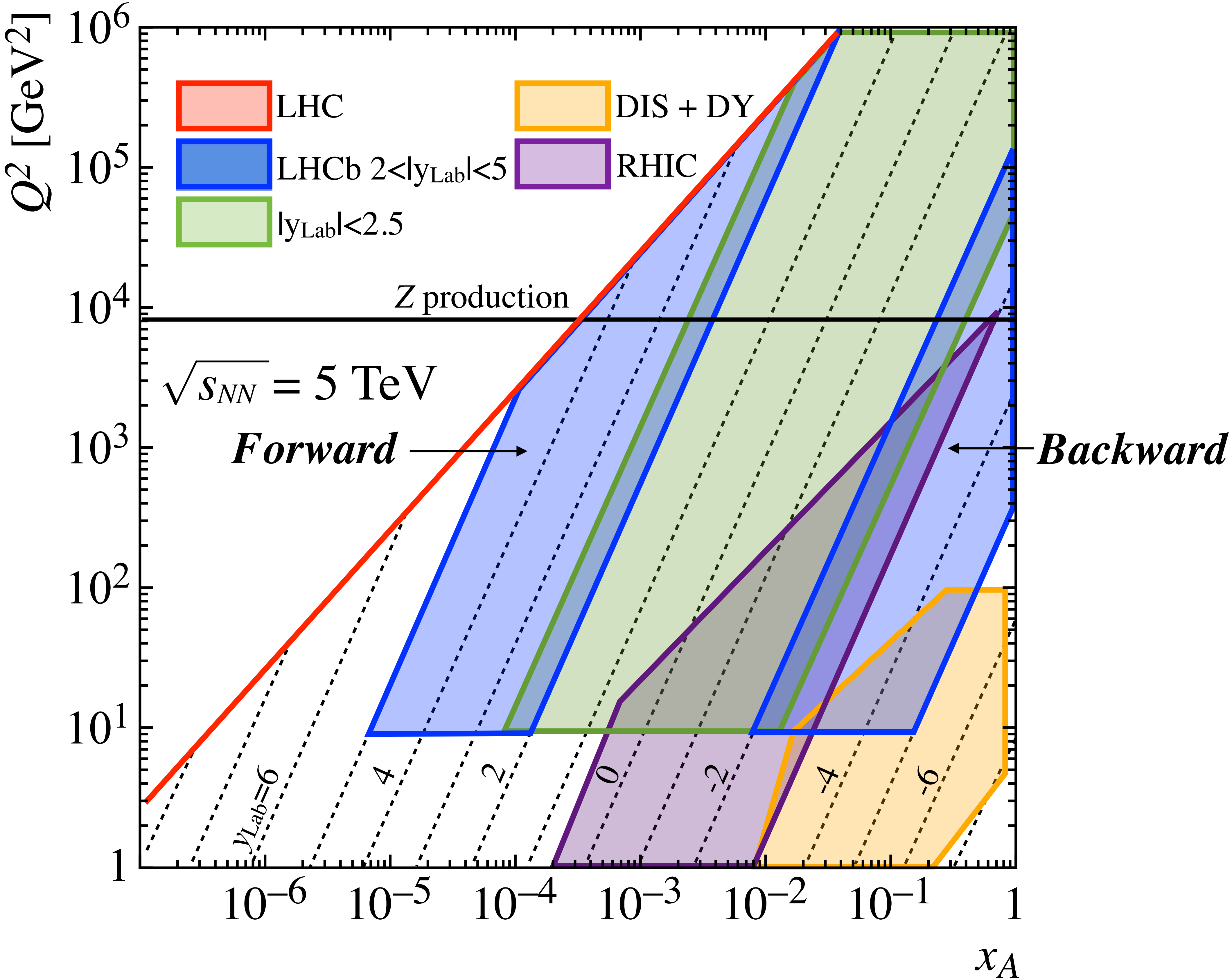




Υ(1S)

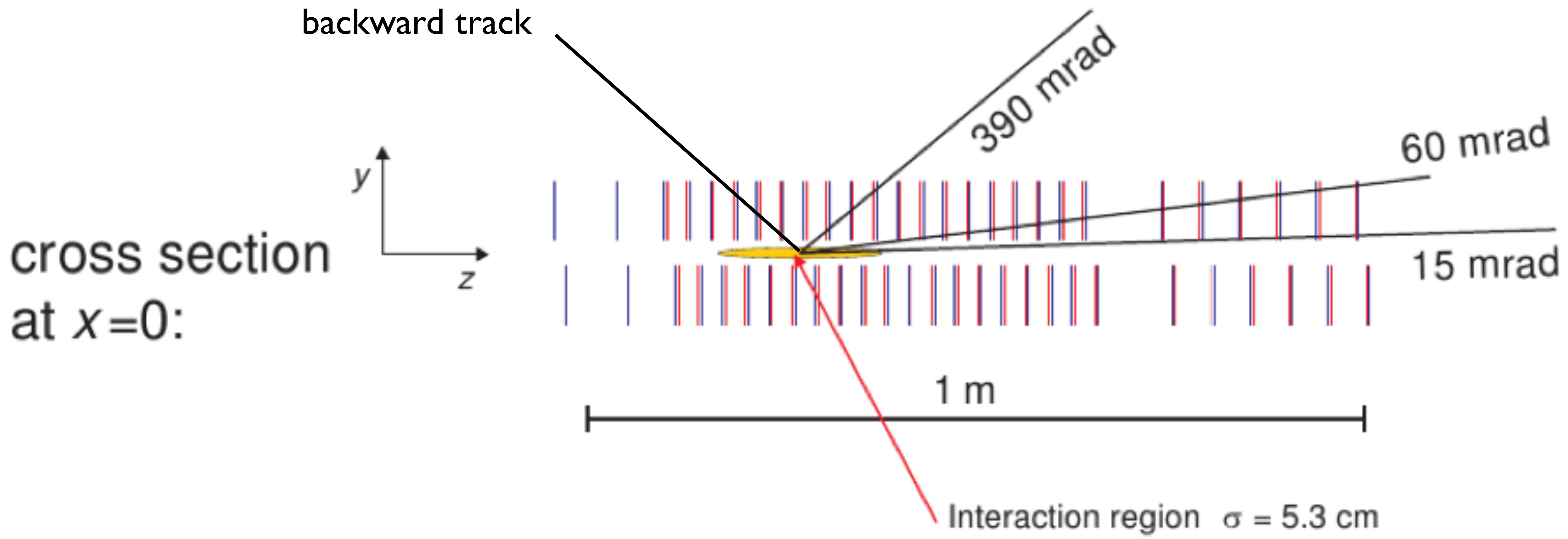
Source	Forward $\Upsilon(1S)$	Forward $\Upsilon(2S)$	Forward $\Upsilon(3S)$	Backward $\Upsilon(1S)$	Backward $\Upsilon(2S)$	Backward $\Upsilon(3S)$
Muon identification	1.3	1.3	1.3	1.3	1.3	1.3
Tracking efficiency	1.5	1.5	1.5	1.5	1.5	1.5
Mass fit model	1.1 (1.0)	4.9	13	1.8 (1.7)	19	90
Luminosity	1.9	1.9	1.9	2.1	2.1	2.1
Trigger	2.1	2.1	2.1	5.0	5.0	5.0
MC generation kinematics	3.9 (3.8)	3.9	3.9	7.6 (6.3)	7.6	7.6
Reconstruction	1.5	1.5	1.5	1.5	1.5	1.5
Total	5.5 (5.4)	7.3	14	9.8 (8.8)	21	91

Table 1. Relative systematic uncertainties on the cross-sections, in percent, in the full rapidity range. The values in parenthesis refer specifically to $\Upsilon(1S)$ measurements when systematic uncertainties in the common rapidity range $2.5 < |y| < 4.0$ are notably different.



Q^2 [GeV^2]
LHC
LHCb 2<|y$_{Lab}$|<5
|y$_{Lab}$|<2.5
DIS + DY
RHIC
Z production
$\sqrt{s_{NN}}$ = 5 TeV
Forward
Backward
y_{Lab}=6
4
2
0
-2
-4
-6
x_A

LHCb VELO



VELO

- surrounds the interaction point
- allows backward tracks (-3.5<η<-1.5)