LHCb results in proton-nucleus collisions at the LHC

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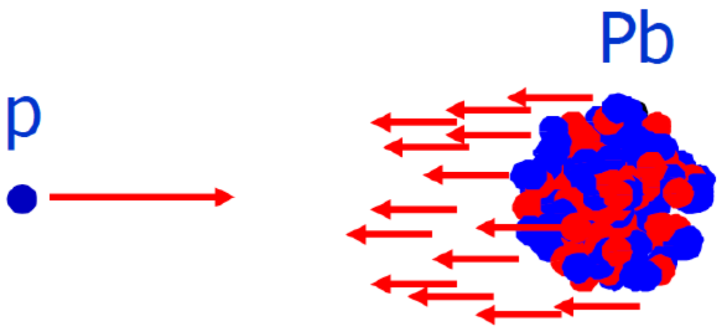
LHCb

Outline

- Motivation
- LHCb Detector
- Beam configurations
- Measurements
  - J/Ψ production
  - Υ production
  - Z boson production
  - Spectroscopy
- Conclusions



Motivation

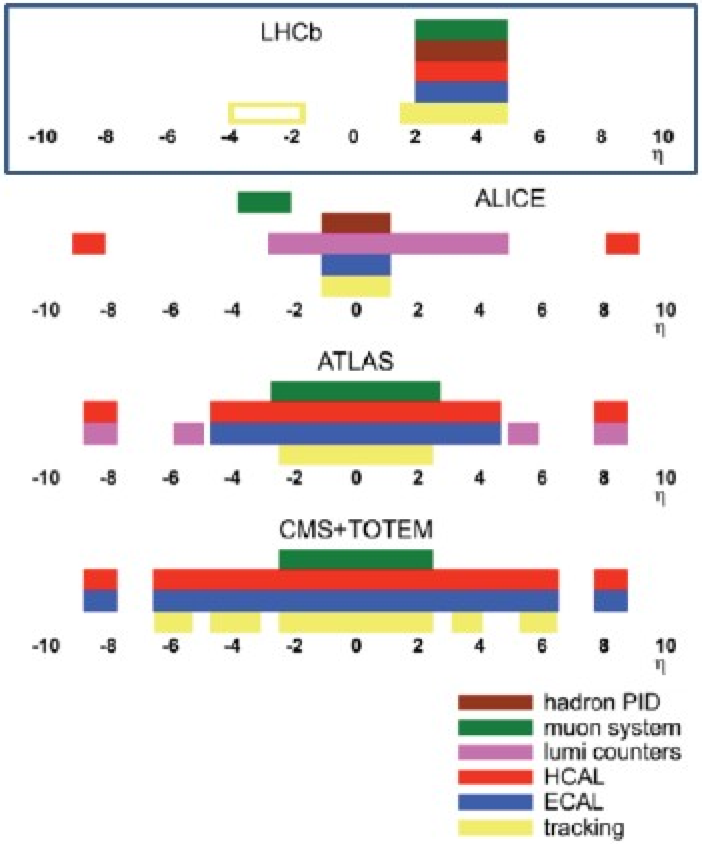
LHCb fully instrumented in the forward region
→ study proton-ion collisions in a unique kinematic region

proton-lead (pA) collisions interesting by itself and as a reference
sample for heavy ion collisions
pA data should allow factorizing the effects of Quark Gluon Plasma from Cold Nuclear Matter

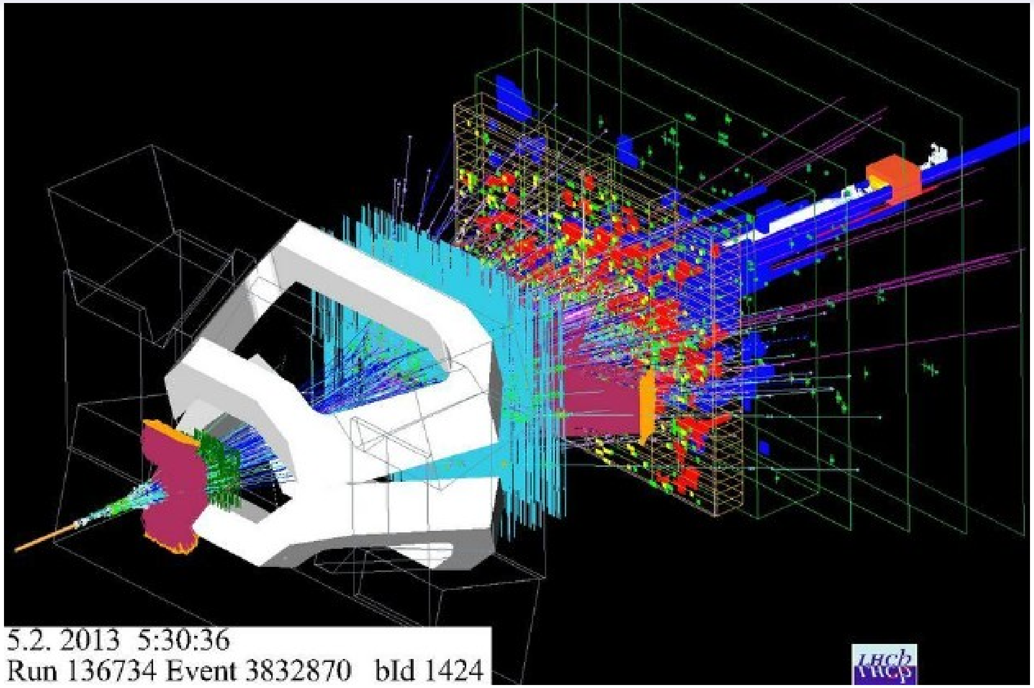
sensitive probes of properties of nuclear matter

- nuclear parton distribution function (nPDF)
- nuclear attenuation factors

→ test phenomenological models



Motivation



- heavy flavour and quarkonium probe
  - energy loss mechanisms
  - medium transport properties
  - quark deconfinement

- electroweak bosons:
  - probe nuclear PDFs which are poorly constraint

  → LHCb sensitive to x_A range $2 \times 10^{-4} – 3 \times 10^{-3}$

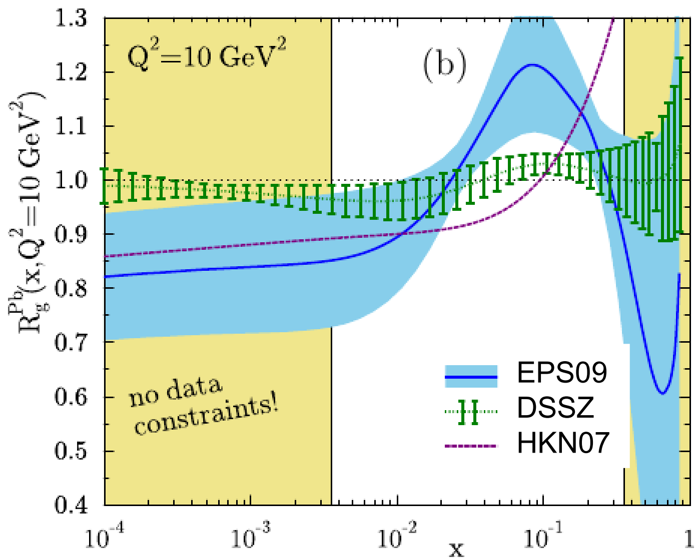
  and 0.2-1 at mass of Z

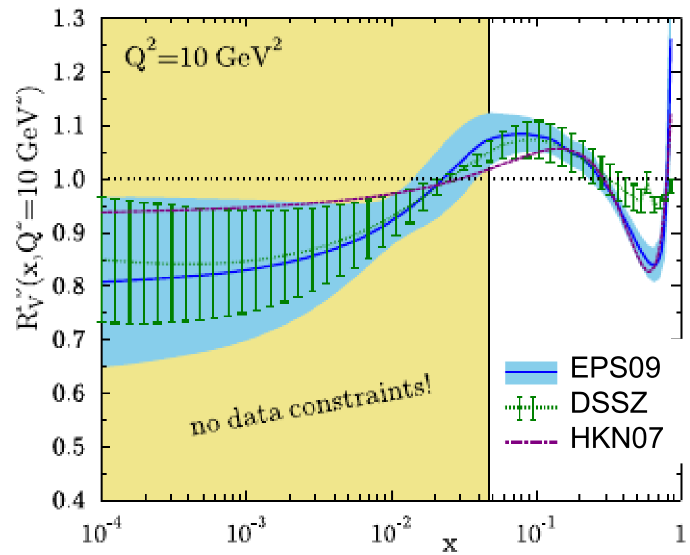
x_A:momentum fraction carried by parton inside the nucleon bound in the lead ion

Current knowledge of nuclear PDFs (nPDF)

ratio: (nuclear PDF for Pb)/ (proton PDF) [Nucl.Phys. A926 (2014) 24-33]

gluon | valence quarks





LHCb | LHCb | LHCb | LHCb

nuclear PDF poorly constrained at high and low x_A, → LHCb has good sensitivity.

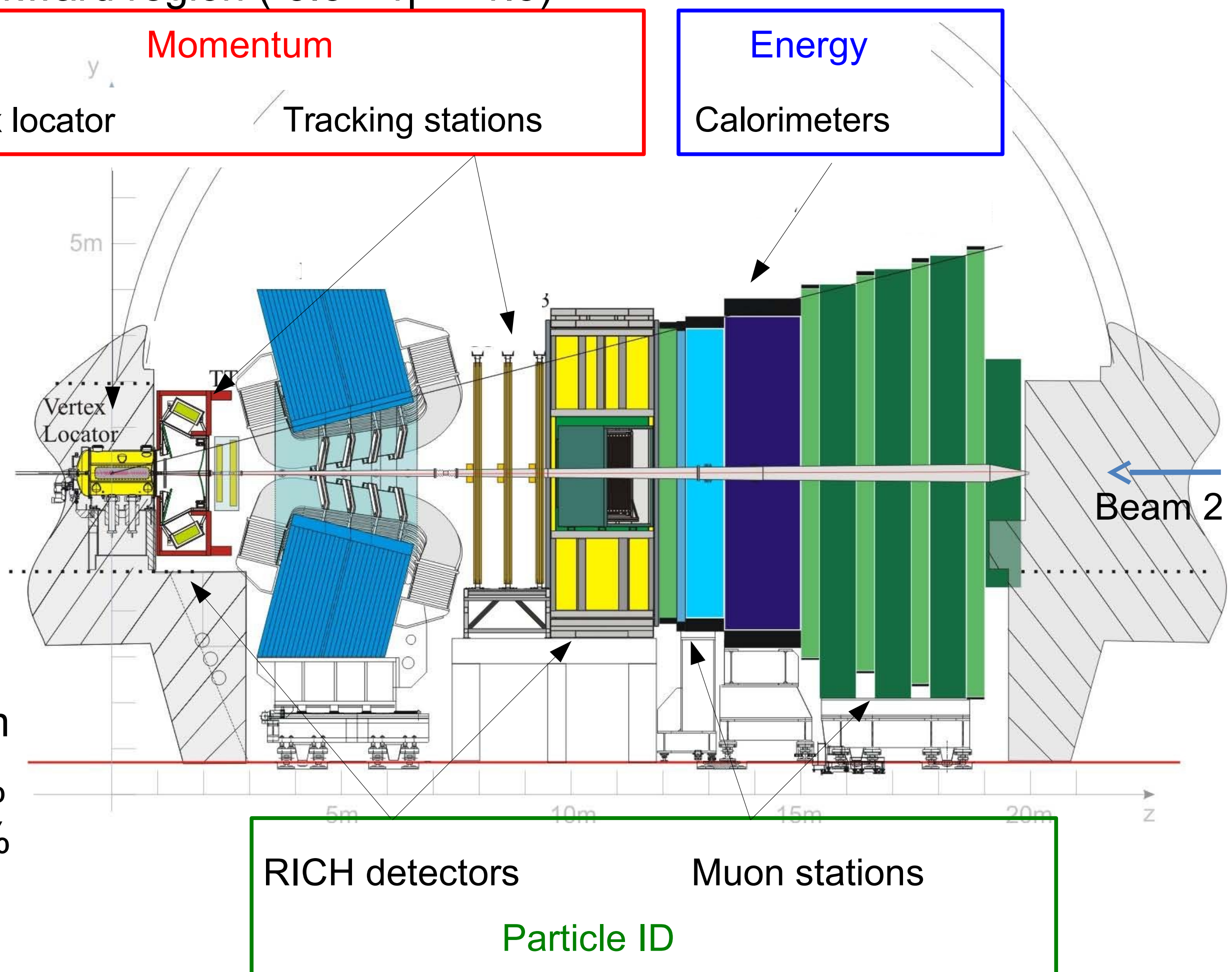
LHCb accessible region for J/ψ, Y and Z production:

J/ψ: $1\times10^{-5} < x < 1\times10^{-4}$, $7\times10^{-3} < x < 7\times10^{-2}$
Y : $3\times10^{-5} < x < 3\times10^{-4}$, $3\times10^{-2} < x < 3\times10^{-1}$
Z : $2\times10^{-4} < x < 3\times10^{-3}$, $0.2 < x < 1$
fixed target physics @ LHCb: x about 0.1

x_A:momentum fraction carried by parton inside the nucleon bound in the lead ion
EPS09: JHEP 04 (2009) 065, DSSZ : Phys. Rev. D 85 (2012),HKN07: Phys. Rev. C 76 (2007) 065207

LHCb Detector

fully instrumented in the forward region (2 < η < 5)
some detection capability in backward region (-3.5 < η < -1.5)



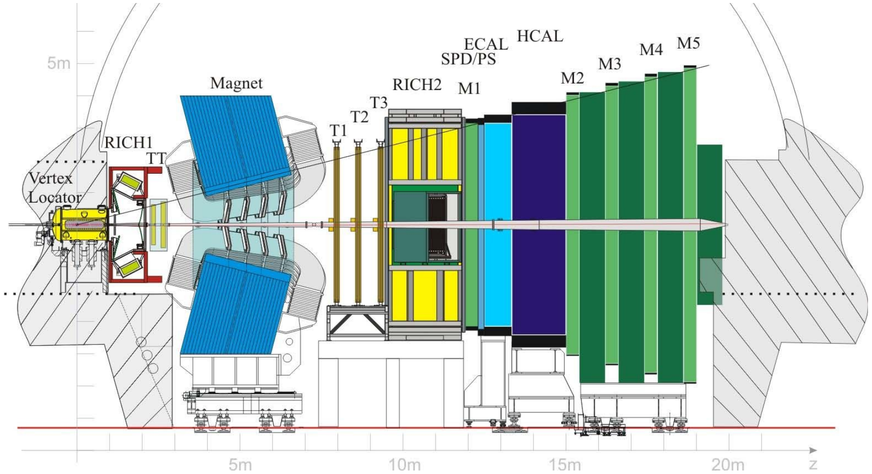
- tracking: σ_p/p ~ 0.4-0.6%
- vertex resolution:
  σ_{xy}~ 15μm, σ_z~ 80μm
- muon ID ε=97%; mis-id 0.7%
- kaon ID ε=90%; π mis-id< 5%

- analyses based on
  - 2013 proton-lead runs @ 5 TeV
  - single arm spectrometer → two different beam configurations
  - preliminary results from pilot run 2012

Beam Configurations

forward:

- proton-lead collisions at 5 TeV
- luminosity: 1.1 nb^{-1} recorded by LHCb
- proton beam in the direction of the LHCb detector
- positive rapidity with respect to the proton
- shift in rapidity: $\Delta y = y_{lab} - y = 0.47$, acceptance $1.5 < y < 4.0$

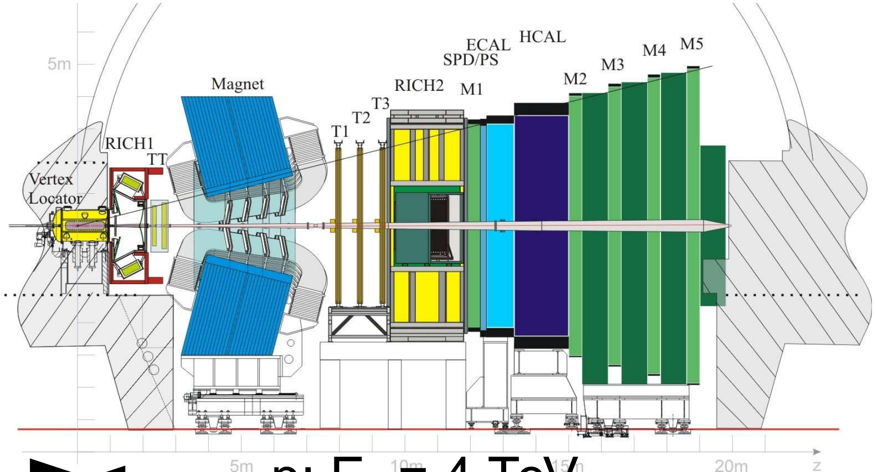


p: E_p=4 TeV → ← Pb: E_N = 1.58 TeV

Beam Configurations

backward:

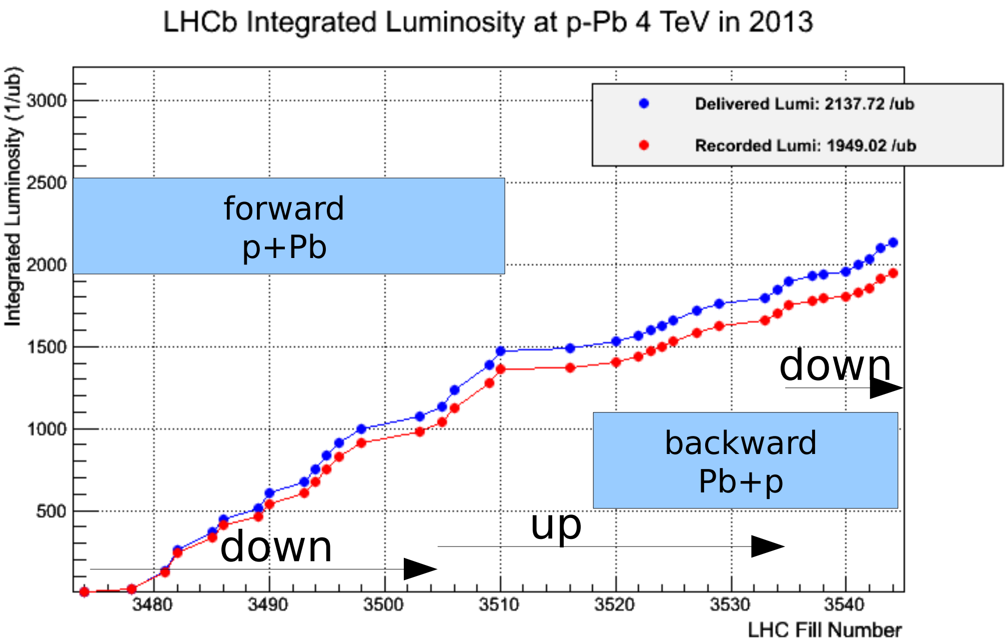
- proton-lead collisions at 5 TeV
- luminosity: 0.5 nb^{-1} recorded by LHCb
- proton beam in the direction of the LHCb detector
- negative rapidity with respect to the proton
- shift in rapidity: $\Delta y = y_{lab} - y = 0.47$, acceptance $-5.0 < y < -2.5$

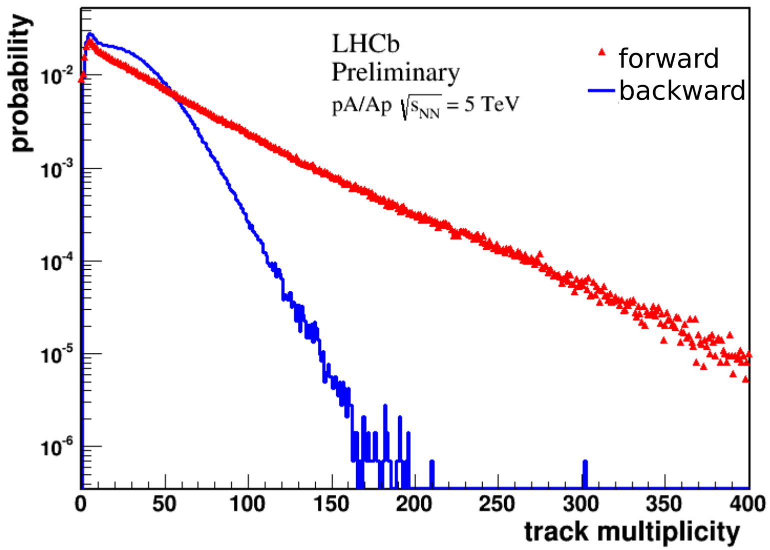


Pb: E_N=1.58 TeV → ← p: E_p = 4 TeV

Luminosity

LHCb-CONF-2013-008



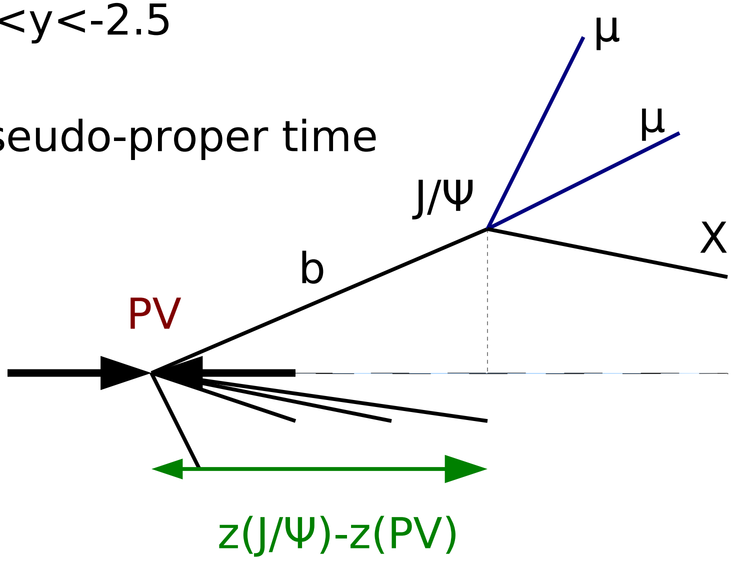


- low instantaneous luminosity: $L \approx 5 \times 10^{27}\ cm^{-2}s^{-1}$
- low pile-up (approx. 1 primary vertex per beam crossing)
- data-taking efficiency better than 91%.
- results based on 2 beam configurations and 2 magnet configurations.
- p+Pb : $L = 1.1\ nb^{-1}$
- Pb+p : $L = 0.5\ nb^{-1}$

J/Ψ production in p-Pb collisions

- reconstruct J/Ψ in di-muon channel
- forward: 1.5<y<4.0 and backward: -5.0<y<-2.5
- p_T < 14 GeV
- separate prompt J/Ψs and J/Ψs from b: pseudo-proper time

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



results:

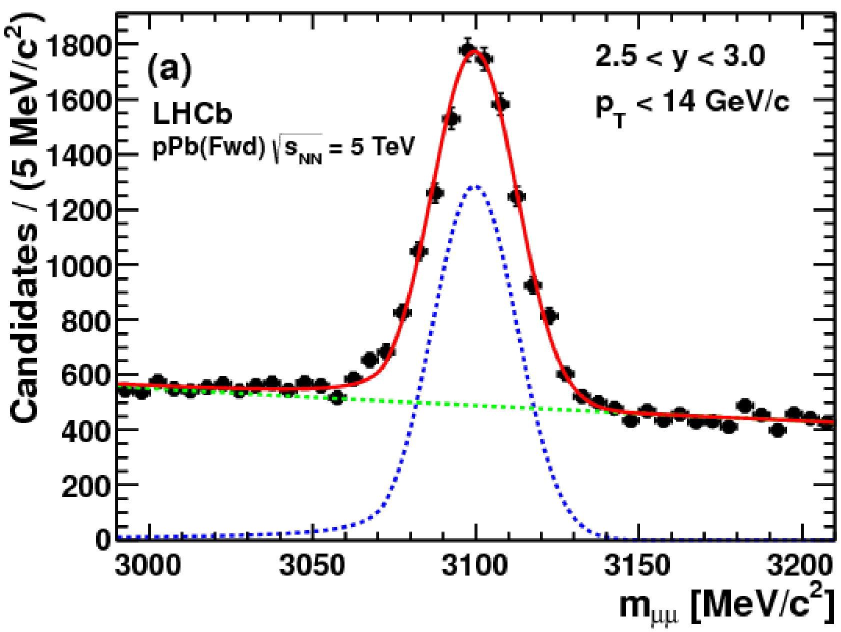
- differential J/Ψ cross sections
- nuclear effects

J/Ψ production in p-Pb collisions

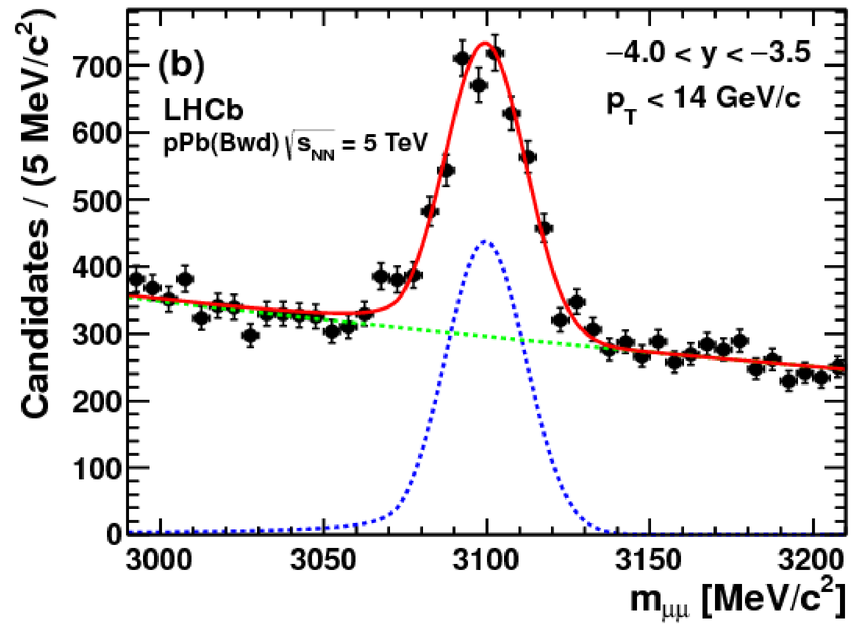
yields: simultaneous fit to mass & pseudo-proper time
mass model: Crystal-Ball signal and exponential background

→ background higher for lead-proton collisions due to higher multiplicities

forward (pA)
$2.5 < y < 3.0$, $p_T < 14$ GeV



backward (Ap)
$-4 < y < -3.5$, $p_T < 14$ GeV

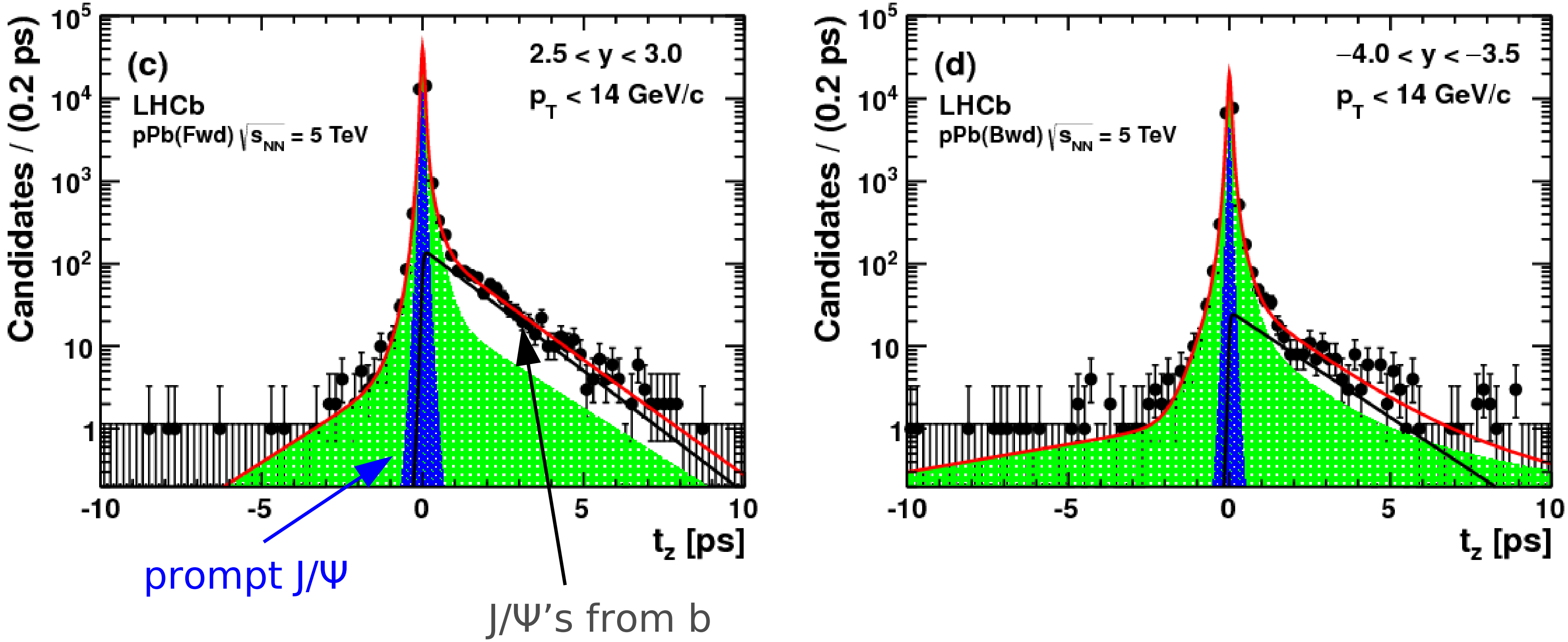


J/Ψ production in p-Pb collisions

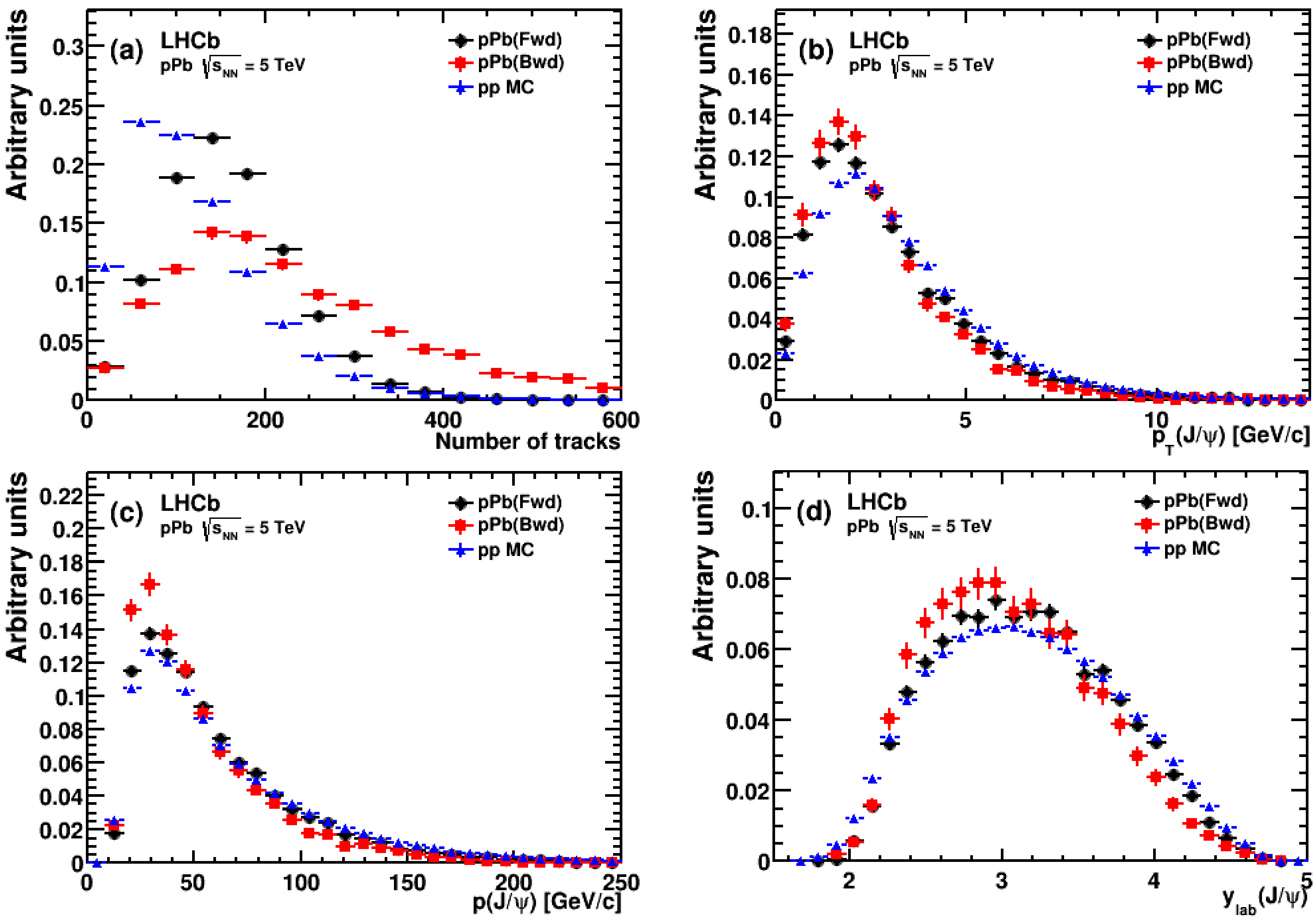
yields: simultaneous fit to mass & pseudo-proper time
mass model: Crystal-Ball signal and exponential background
t_z model: exponential for J/Ψ's from b's convoluted with double Gaussian
δ function for prompt J/Ψ's convoluted with double Gaussian
empirical function (sPlot) from side-band for background

forward (pA)
2.5<y<3.0, p_T<14 GeV

backward (Ap)
-4<y<3.5, p_T<14 GeV



J/Ψ production in p-Pb collisions



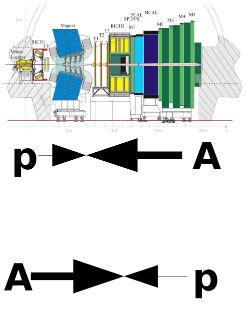
acceptance and efficiency corrections from pp simulation
pp simulation reweighted to describe track multiplicity

forward: $1.5 < y < 4.0$

prompt: $\sigma = 1168 \pm 15\ (stat) \pm 54\ (sys)\ \mu b$
from b's: $\sigma = 166 \pm 4.1\ (stat) \pm 8.2\ (sys)\ \mu b$

backward: $-5.0 < y < -2.5$

prompt: $\sigma = 1293 \pm 42\ (stat) \pm 75\ (sys)\ \mu b$
from b's: $\sigma = 118.2 \pm 6.8\ (stat) \pm 11.7\ (sys)\ \mu b$



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

acceptance and efficiency corrections from pp simulation
pp simulation reweighted to describe track multiplicity

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%

J/Ψ systematic uncertainties

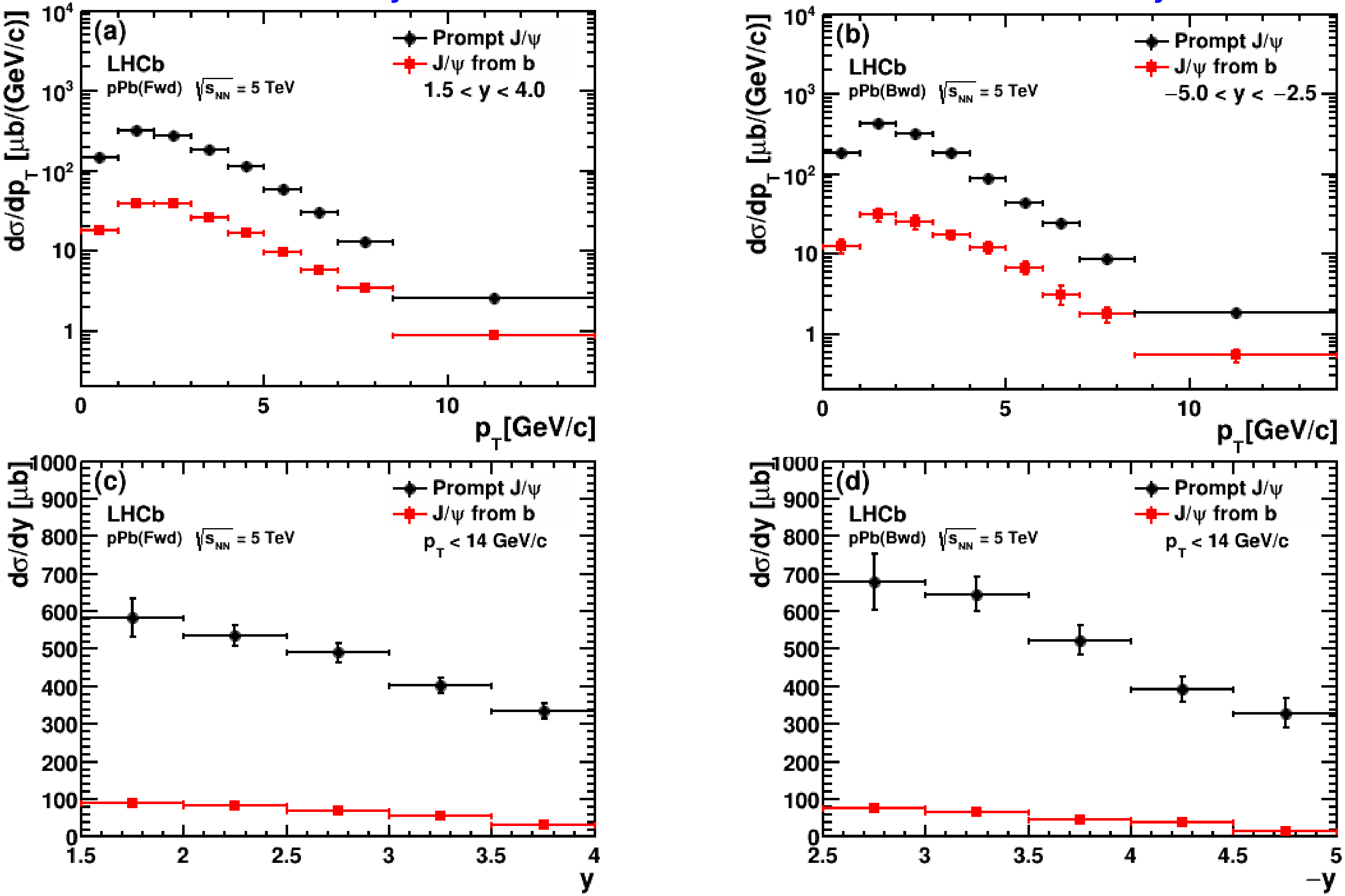
	forward	backward
correlated between bins	%	%
mass fit	2.3	3.4
radiative tail	1.0	1.0
muon identification	1.3	1.3
track reconstruction efficiency	1.5	1.5
luminosity	1.9	2.1
B ($J/\psi \to \mu^+\mu^-$) from PDG	1.0	1.0
uncorrelated between bins		
$y - p_T$ binning	0.1- 8.7	0.1- 6.1
Reweighting of track multiplicity	0.1- 3.0	0.2- 4.3
t_z fit on non-prompt J/ψ	0.2- 12	0.2- 13

systematics are dominated by fit model, luminosity and data-MC agreement

no uncertainty assigned to the effect of J/ψ polarisation, but effect measured to be small

Single differential J/Ψ production cross-sections

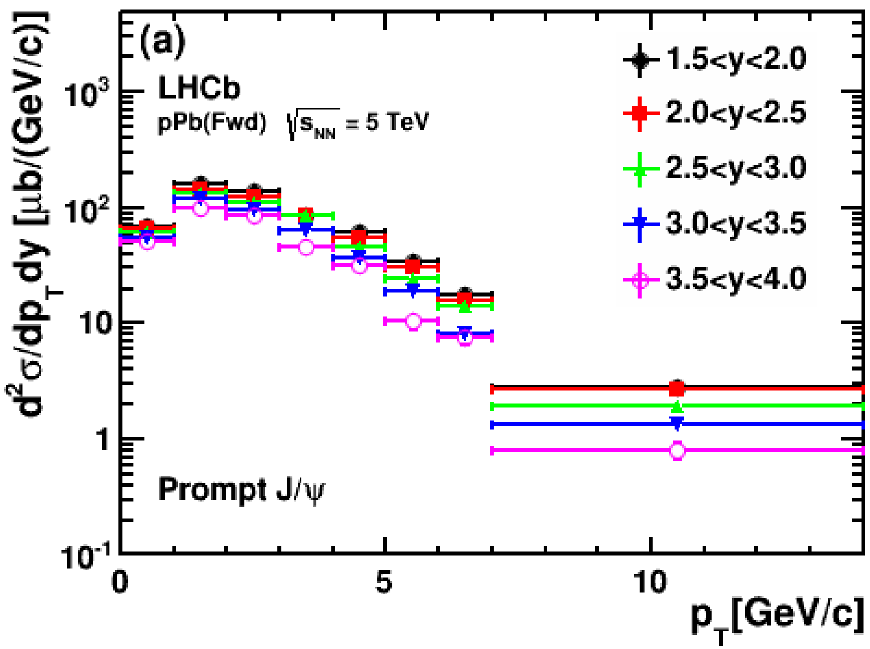
forward 1.5<y<4.0 backward -5.0<y<-2.5



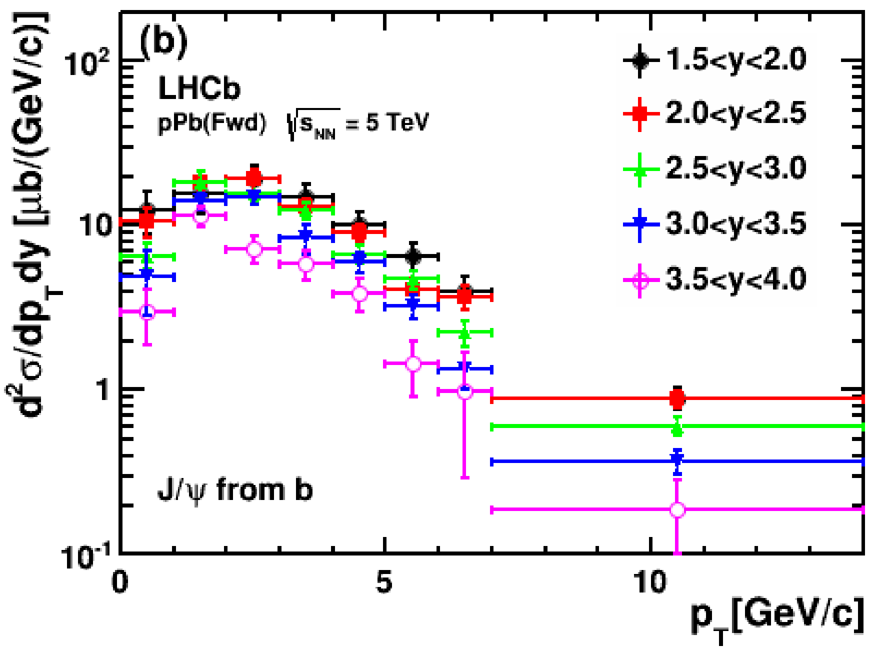
Double differential J/Ψ $d^2\sigma/dp_T dy$ cross-section

forward: double differential cross sections

prompt J/Ψ



J/Ψ from b



Cold nuclear effects

quantified with measurement of

- nuclear modification factor

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

in overlap region 2.5 < |y | < 4.0
=1 if pA collision is superposition of A pp collisions
<1 in case of suppression due to medium

- forward backward production ratio

$$R_{FB}(y,\sqrt{s_{NN}})=\frac{d\sigma_{pA}(+|y|,\sqrt{s_{NN}})/dy}{d\sigma_{Ap}(-|y|,\sqrt{s_{NN}})/dy}$$

in overlap region 2.5 < |y | < 4.0
→ many uncertainties cancel
no reference cross section needed

Reference cross-section

reference pp cross section at 5 TeV not measured directly:
interpolation of σ_{pp} at √s=2.76, 7 and 8 TeV JHEP 02(2013)041, EPJC (2011) 71 1645, JHEP 06 (2013) 064

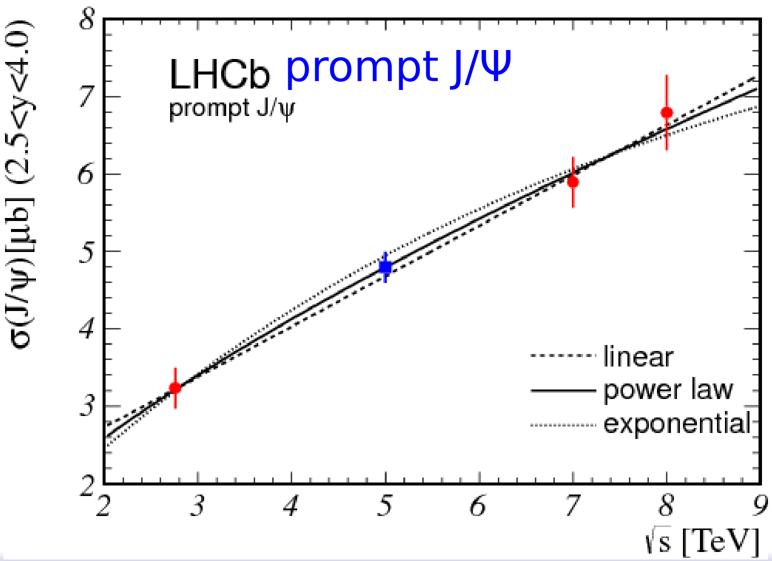
rescaled to common rapidity range 2.5 <y<4.0

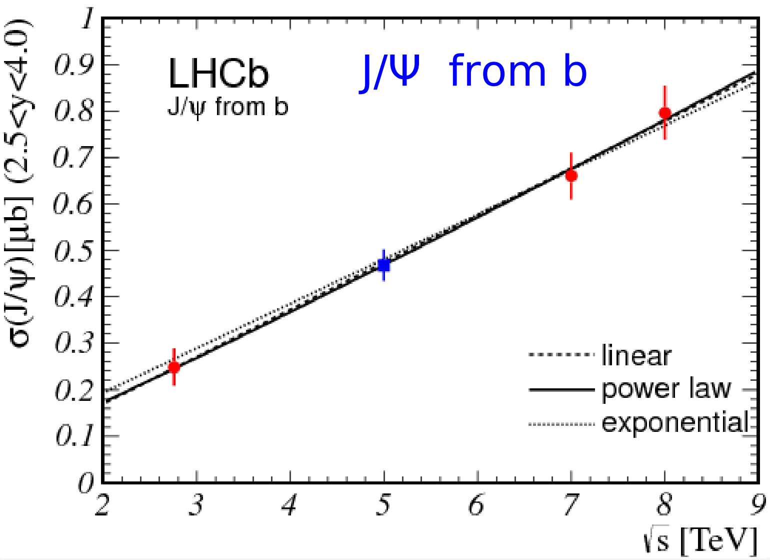
interpolation functions:

- linear $\sigma(\sqrt{s}) = p_0 + \sqrt{s}\, p_1$
- power law $\sigma(\sqrt{s}) = (\sqrt{s}/P_0)^{p_1}$
- exponential $\sigma(\sqrt{s}) = p_0(1 - \exp(-1\sqrt{s}/p_1))$

interpolated cross-section @ 5 TeV [μb]

model	prompt J/Ψ	J/Ψ from b
linear	4.68 ± 0.19	0.473 ± 0.028
power law	4.79 ± 0.20	0.477 ± 0.034
exponential	4.94 ± 0.23	0.481 ± 0.031

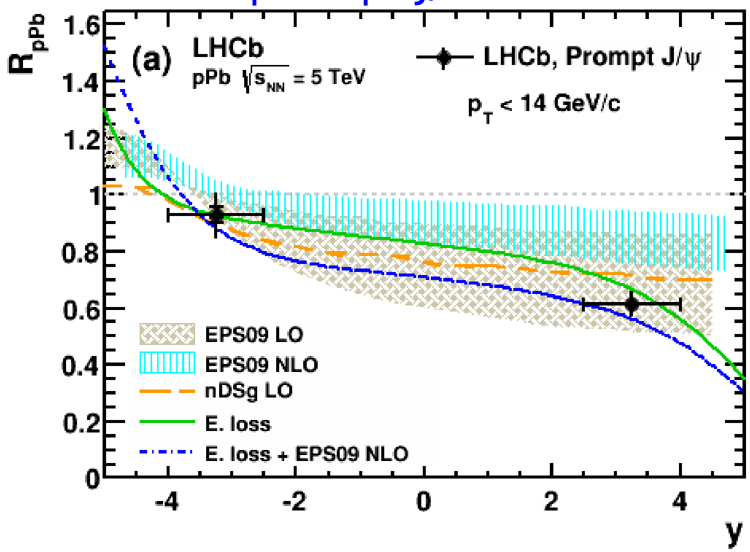




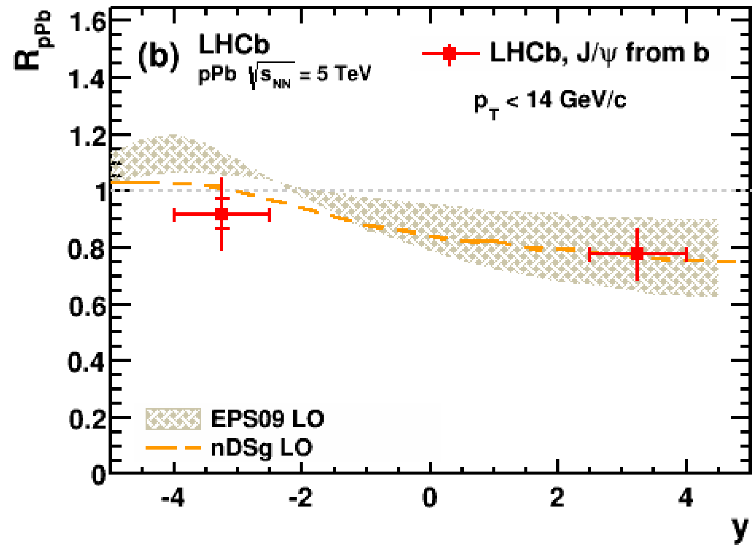
Nuclear modification factor R_{pPb}

$R_{pPb} = 1/A\, (d\sigma_{pA}/dy) / (d\sigma_{pp}/dy)$ in overlap region $2.5 < |y| < 4.0$

prompt J/Ψ



J/Ψ from b



prompt J/Ψ: significant sign of cold nuclear matter effects: 40%
measurements agree with most of the predictions

J/Ψ from b: modest supression wrt pp
first indication of suppression of b hadron production in Pb
agreement with predictions in forward region

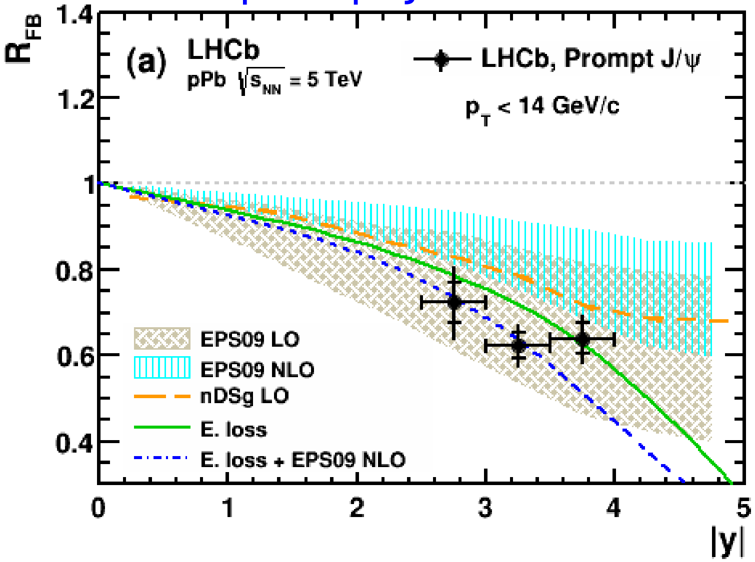
predictions:

- NLO, LO CSM with EPS09 or nDSg parametrisation for modification of PDFs
- energy loss effects of initial and final state partons with or without modification

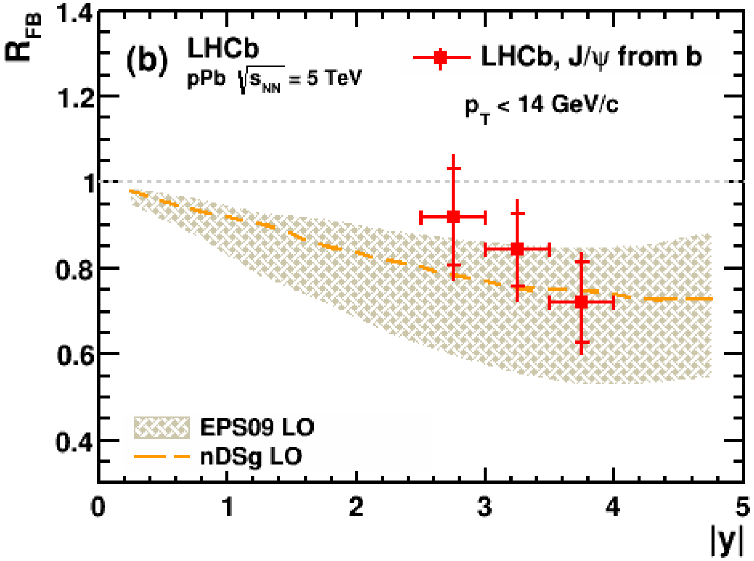
EPS09: JHEP 0904 (2009) 65, nDSG:Phys. Rev.D69(2004) 074028
Energy loss: JHEP 03(2013) 122
NLO: Phys. Rev. D17 (1978) 2324, LO: Nucl. Phys. B127 (1980) 425, Phys. Lett. B102, (1981) 364

$R_{FB} = (d\sigma_{pA}/dy)/(d\sigma_{Ap}/dy)$ in three bins in |y |, does not require reference x-section

prompt J/Ψ



J/Ψ from b



prompt J/Ψ: significant forward-backward asymmetry
J/Ψ from b: R_{FB} closer to one
→ study heavier systems

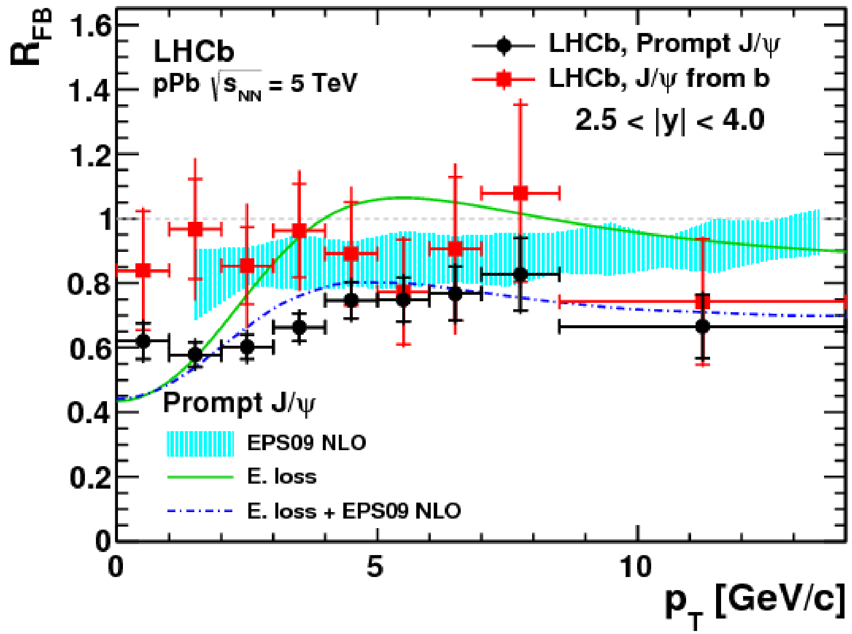
EPS09(NLO) predicts smaller asymmetry for prompt J/Ψ

predictions:

- NLO, LO CSM with EPS09 or nDSg parametrisation for modification of PDFs
- energy loss effects of initial and final state partons with or without modification

R_{FB} vs transverse momentum

R_{FB} in bins of p_T, integrated over y



predictions for prompt J/Ψ only

EPS09(NLO) plus energy loss agrees with data

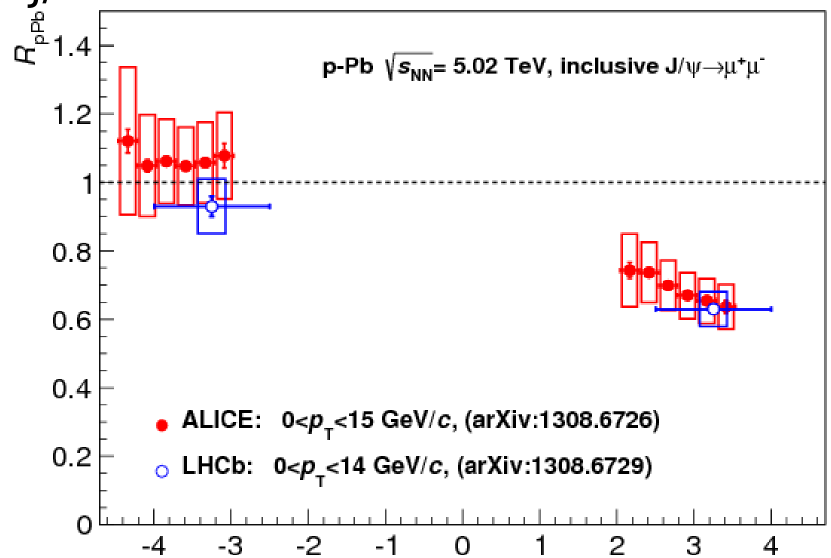
Comparison to ALICE

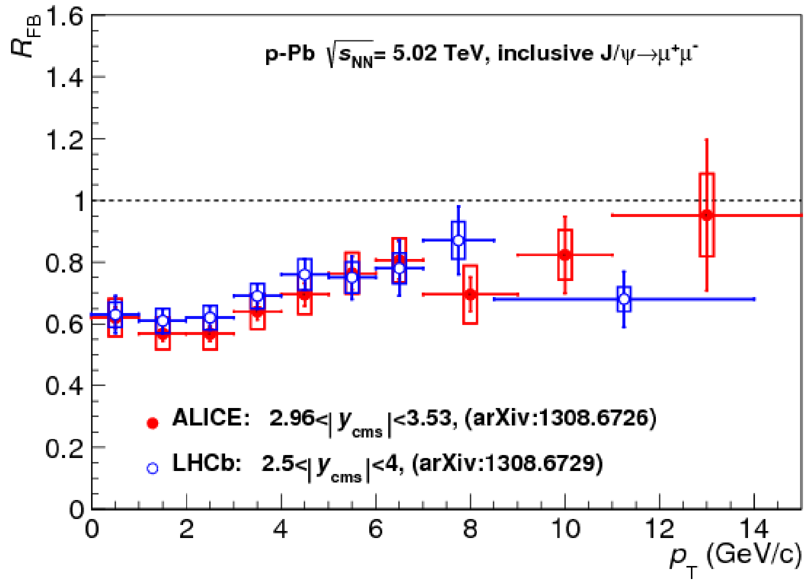
LHCb inclusive J/Ψ: sum of prompt J/Ψ and J/Ψ from b

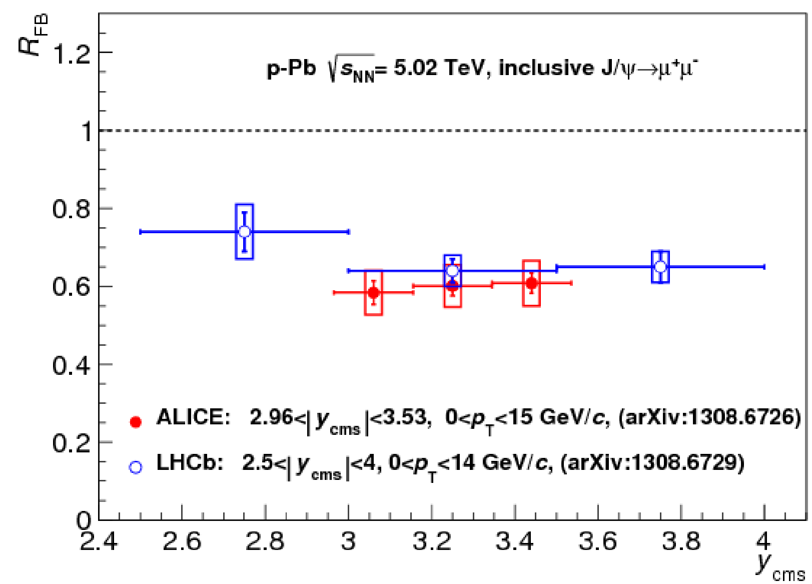
ALICE (JHEP 02(2014) 073)
slightly different phase space:

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

good agreement within uncertainties





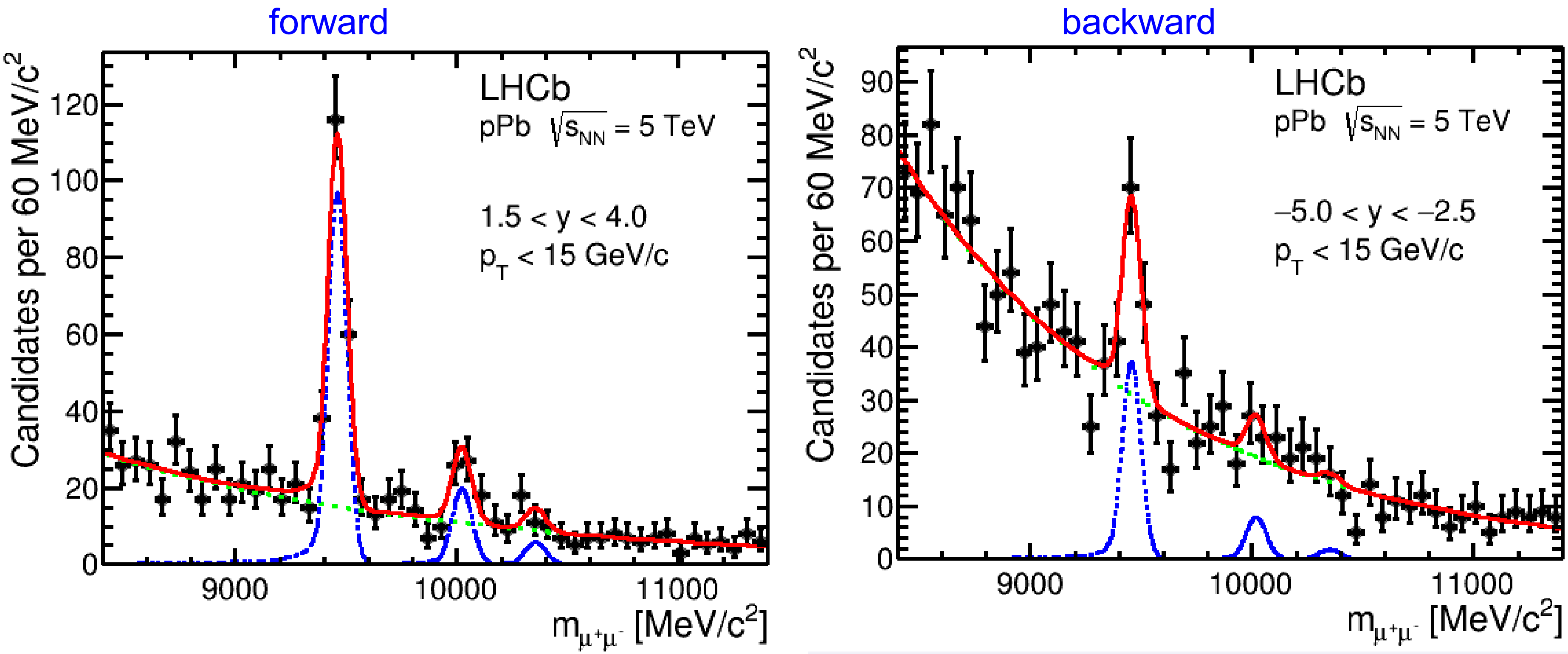


Υ production in p-Pb collisions

- reconstruct Υ in di-muon channel
- forward 1.5<y<4.0 and backward -5.0<y<-2.5
- p_T < 15 GeV

low statistics → no differential measurement

yields: fit to mass
mass model: three Crystal-Balls for signal and exponential background



Υ production in p-Pb collisions

cross-section times branching fraction, integrated over p_T and y

	$\sigma(\Upsilon(nS)) \times B(\Upsilon(nS) \to \mu\mu)$ Forward	Backward
Υ(1S)	$380 \pm 35_{stat} \pm 19_{syst}$ nb	$295 \pm 56_{stat} \pm 27_{syst}$ nb
Υ(2S)	$75 \pm 19_{stat} \pm 5_{syst}$ nb	$81 \pm 39_{stat} \pm 17_{syst}$ nb
Υ(3S)	$27 \pm 16_{stat} \pm 4_{syst}$ nb	< 39 nb @ 90% C.L.

	Relative suppression factor $R^{nS/1S}$ Forward	Backward
$R^{2S/1S}$	$0.20 \pm 0.05_{stat} \pm 0.01_{syst}$	$0.28 \pm 0.14_{stat} \pm 0.05_{syst}$
$R^{3S/1S}$	$0.07 \pm 0.04_{stat} \pm 0.01_{syst}$	<0.13 @ 90% C.L.
	pp at 8 TeV (JHEP 06 (2013) 064)	
$R^{2S/1S}$		$0.256 \pm 0.003_{stat} \pm 0.007_{syst}$
$R^{3S/1S}$		$0.125 \pm 0.002_{stat} \pm 0.004_{syst}$

statistical uncertainty dominates
dominant systematic uncertainties:

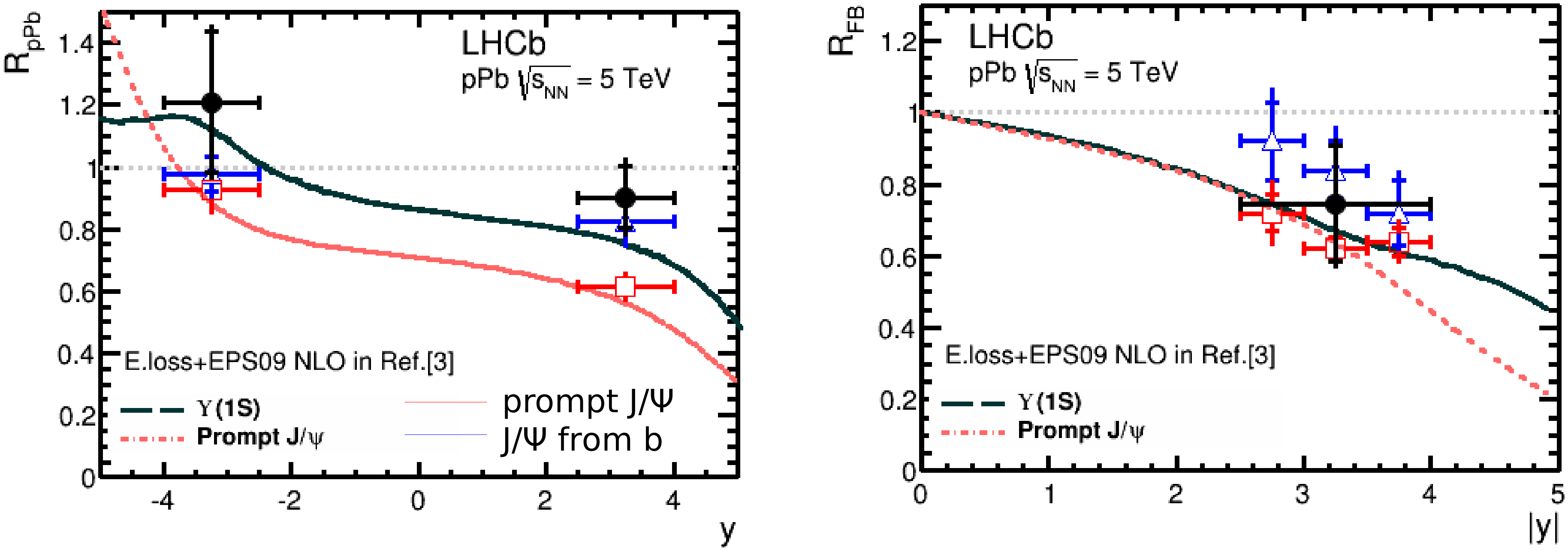
p_T and y dependence of signal 4%(forward) 7%(backward)

or trigger efficiency : 2%(forward) 5%(backward)

→ concentrate on Υ(1S)

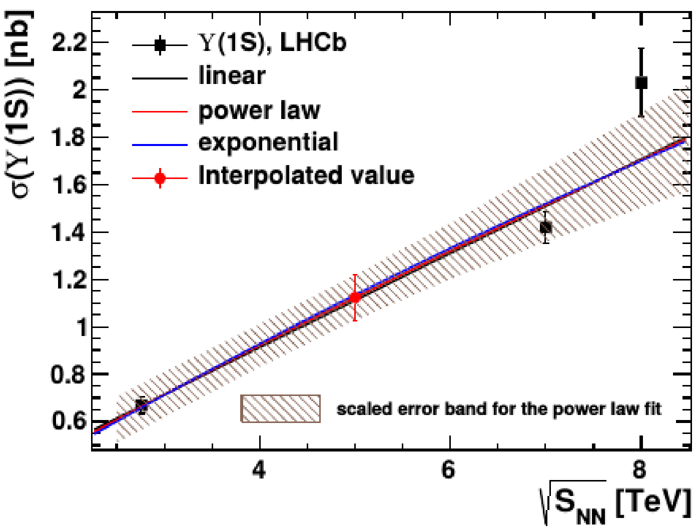
Υ production: cold nuclear effects

measurement of R_{pPb} and R_{FB} with Υ(1S) complementary to J/Ψ (probing different x_A)



- cold nuclear effects are also visible with Υ(1S) production
- suppression in forward region smaller than for J/Ψ
- possible enhancement in backward region due to anti-shadowing
- agreement with prediction EPS09(NLO) for nPDF and with and without energy loss

Υ production

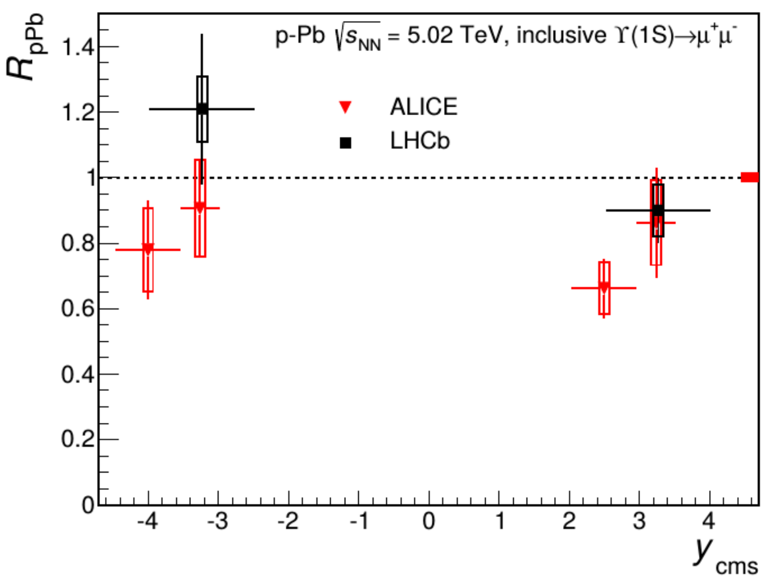


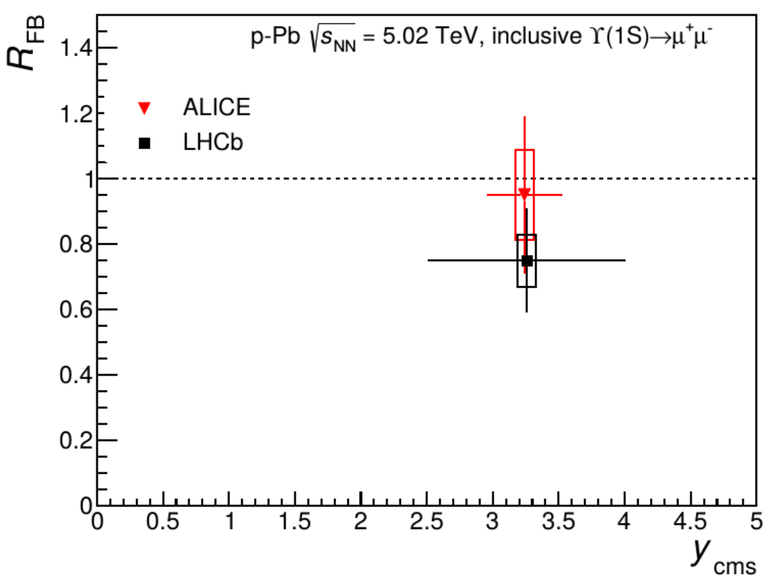
reference cross section @ 5 TeV:
interpolation of measurements at 2.76, 7 and 8 TeV:

linear	1.111±0.036 nb
power law	1.123±0.036 nb
exponential	1.134±0.038 nb

Comparison to ALICE arXiv:1410.2234
slightly different phase space:

LHCb |2.5|<y<|4|
ALICE |2.96|<y<|3.53|
→ reasonable agreement





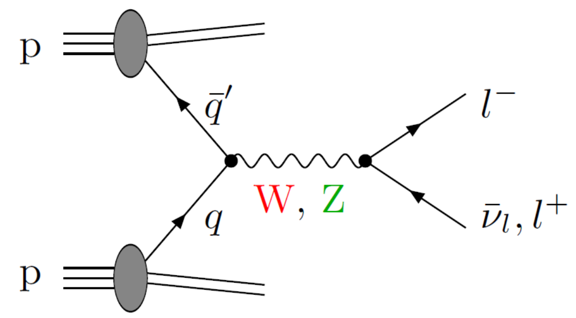
LHCb probes two distinct regions in x-Q^2:

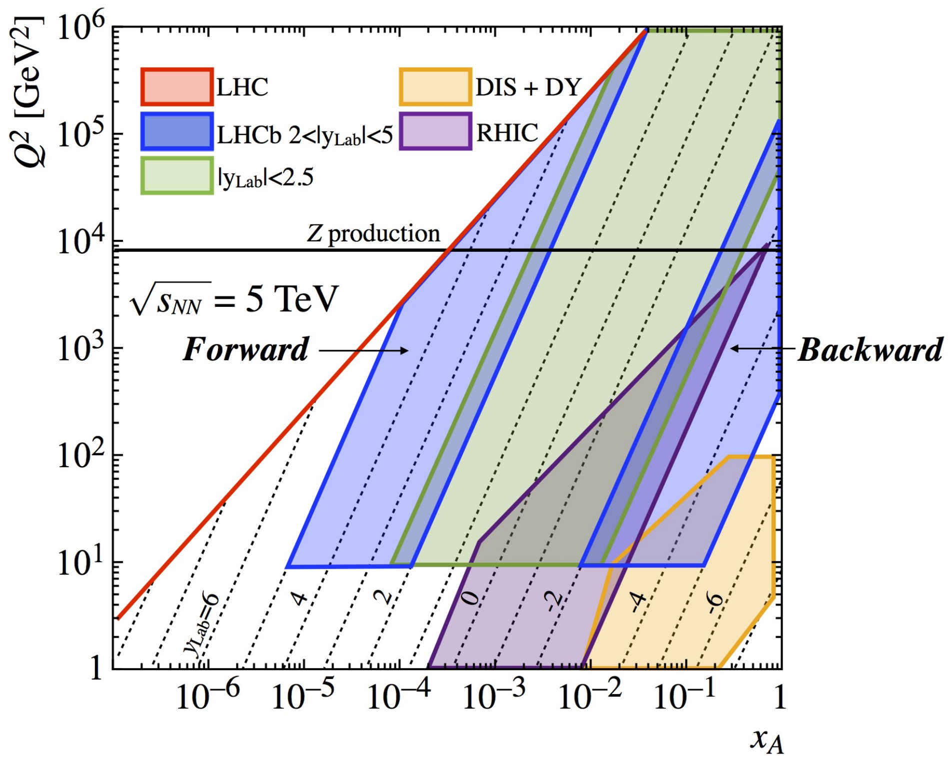
$x_{1,2}=(Q/\sqrt{s})\, e^{\pm y}$

LHCb forward kinematics:
@ first order, collision of a sea and a valence quark

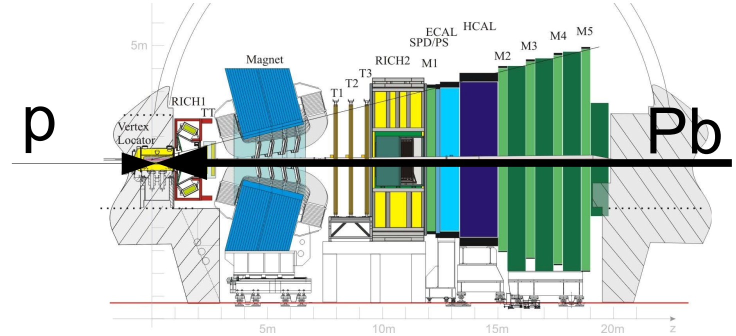
complementary to ATLAS/CMS

LHCb phase space:
→ sensitivity to nuclear PDF at large x_A and low $x_A \approx 2 \cdot 10^{-4}$





Z production in proton-lead



forward: pA collisions

luminosity: 1.099 ± 0.021 nb^{-1}

selection:

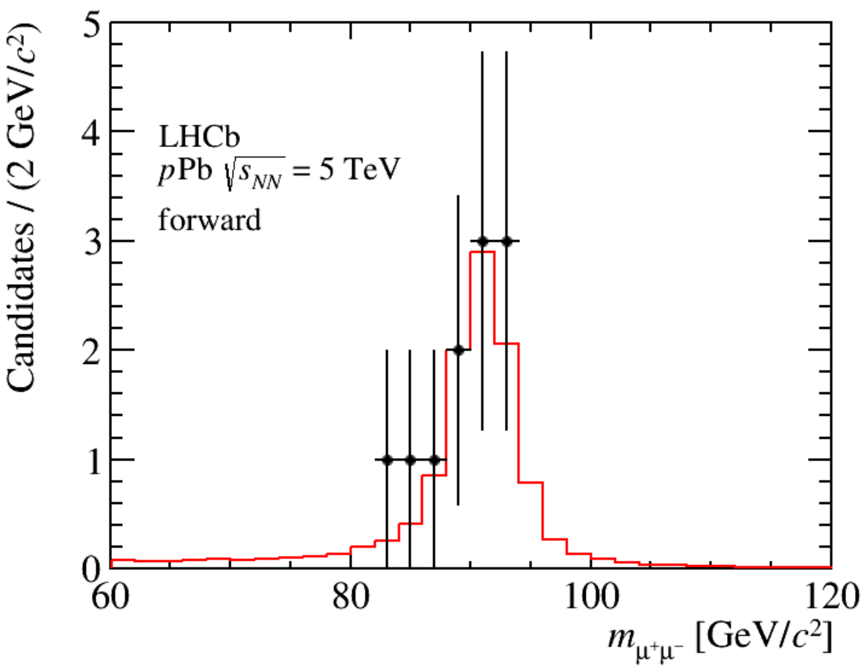
muons: p_T>20 GeV, 2<η<4.5

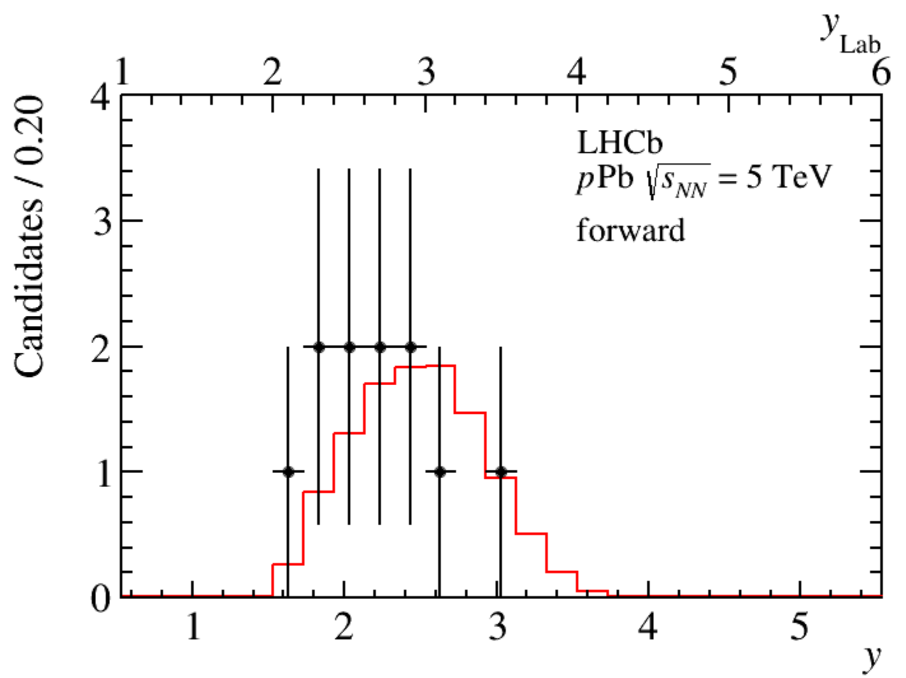
mass: 60<$M_{\mu\mu}$<120 GeV

purity:

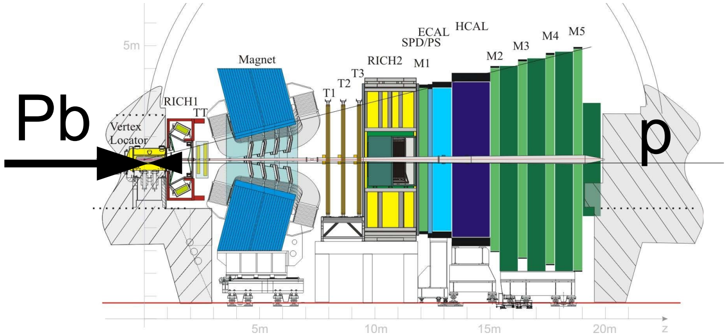
from data: about 99.7%

11 candidates





Z production in proton-lead



backward: Ap collisions

luminosity: 0.521 ± 0.011 nb^{-1}

selection:

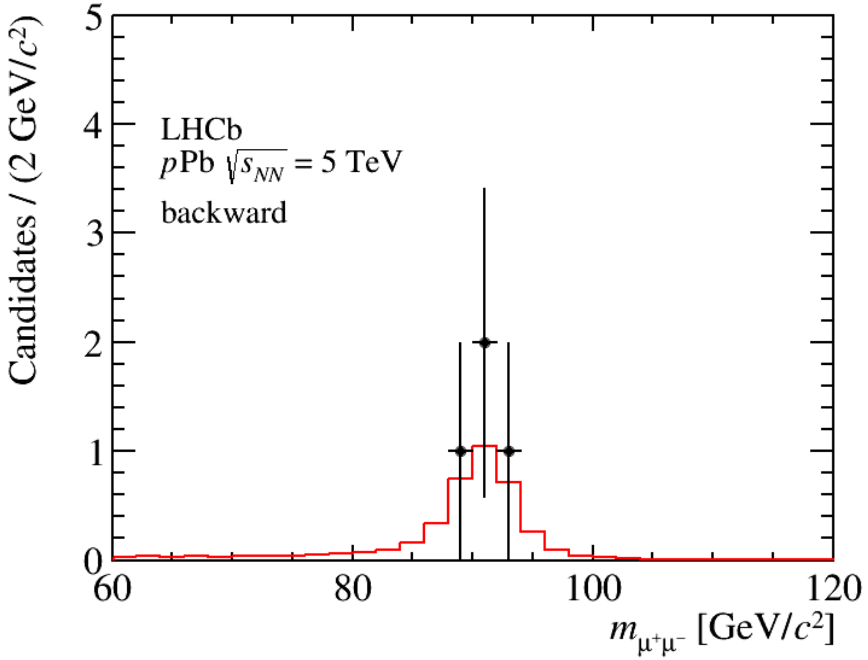
muons: p_T>20 GeV, 2<η<4.5

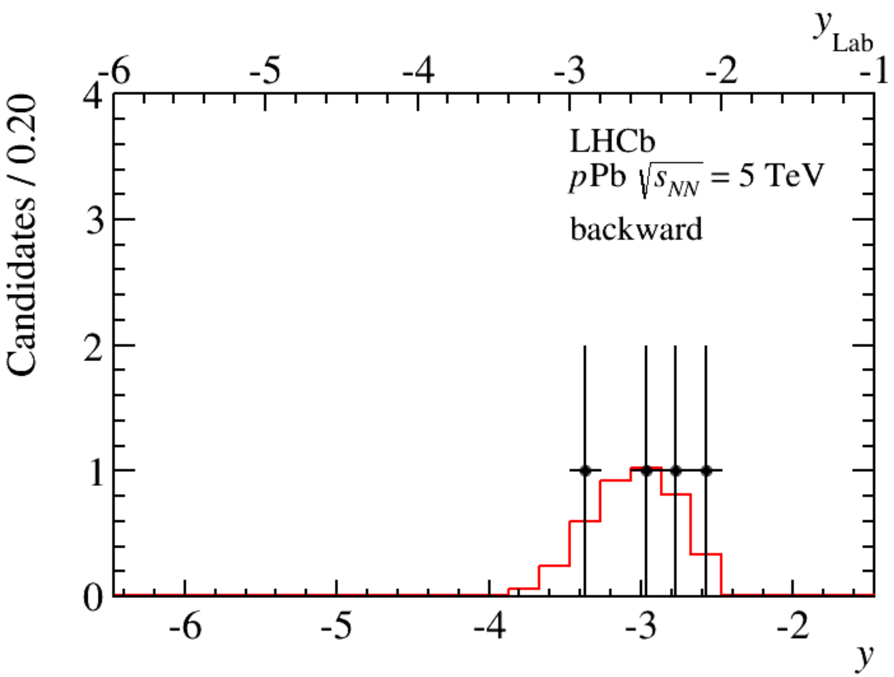
mass: 60<$M_{\mu\mu}$<120 GeV

purity:

from data: about 99.6%

4 candidates





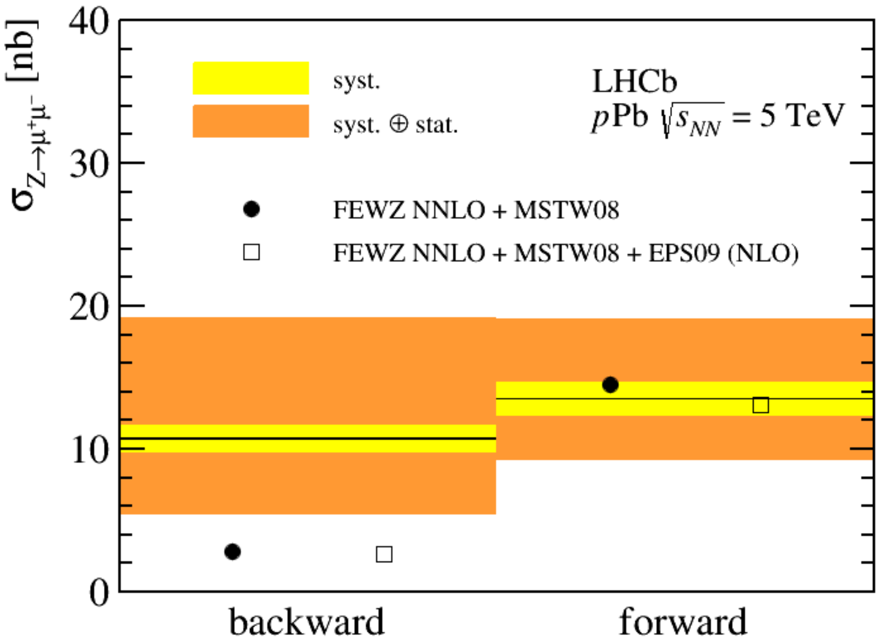
JHEP 1409 (2014) 030

efficiencies, purity from data
cross sections:

forward:
$\sigma_{Z(\to\mu^+\mu^-)} = 13.5^{+5.4}_{-4.0}$ (stat.) ± 1.2(syst.) nb
backward:
$\sigma_{Z(\to\mu^+\mu^-)} = 10.7^{+8.4}_{-5.1}$ (stat.) ± 1.0(syst.) nb

theoretical predictions:
NNLO calculations (FEWZ with MSTW08)
nuclear modification: EPS09(NLO)

future higher statistics measurements
will provide important information
on nuclear PDFs



Fiducial volume
muons: p_T>20 GeV, 2<η<4.5
mass: 60<M(μμ)<120 GeV

FEWZ: Y. Li and F. 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.

Preliminary: Strangeness & Charm production

results from pilot (pA) run

integrated luminosity 0.9 μb^{-1}

look at K_s^0, Λ, Φ, D0 production, kinematic range $2.5<y<4.5$, $p_T>0.2$ GeV
compare pPb collisions to minimum bias pp interactions at $\sqrt{s}=8$ TeV

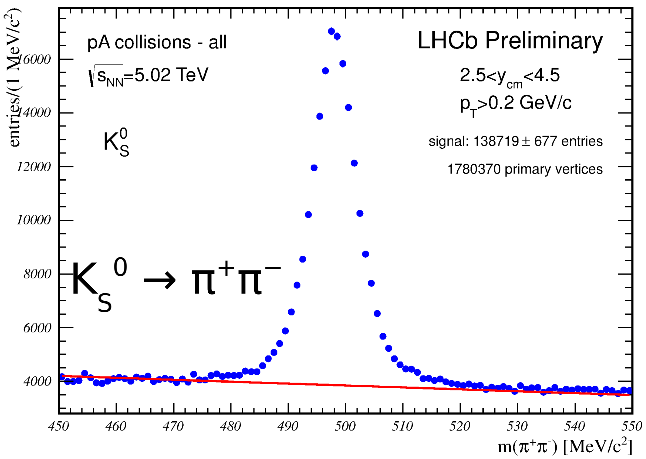
study enhancement of particle production from pp to pA

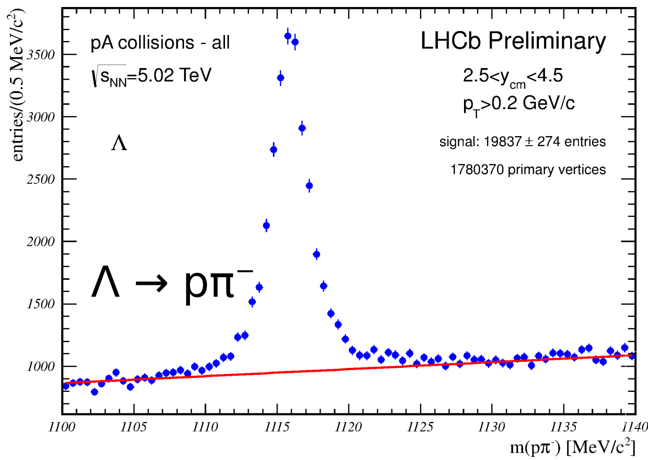
$$R(X)=\frac{N(X)_{pA}\text{ per pA interaction}}{N(X)_{pp}\text{ per pp interaction}}$$

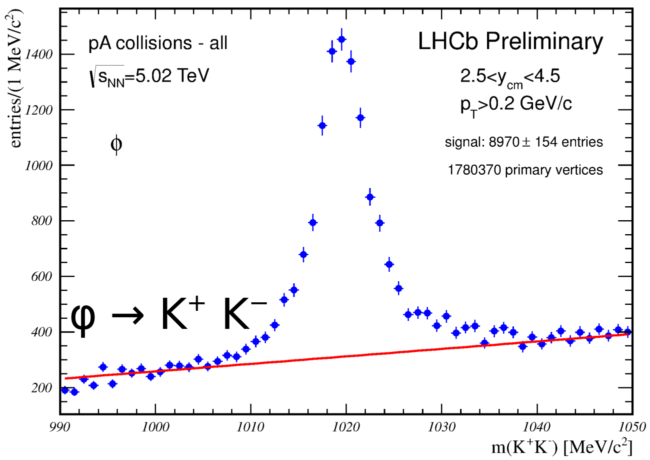
only statistical uncertainties
no corrections for
- spurious or multiply reconstructed tracks
- tracks from decays and secondary vertices
- tracking efficiencies
- different kinematics in lab frame
- different nucleon-nucleon cms energies

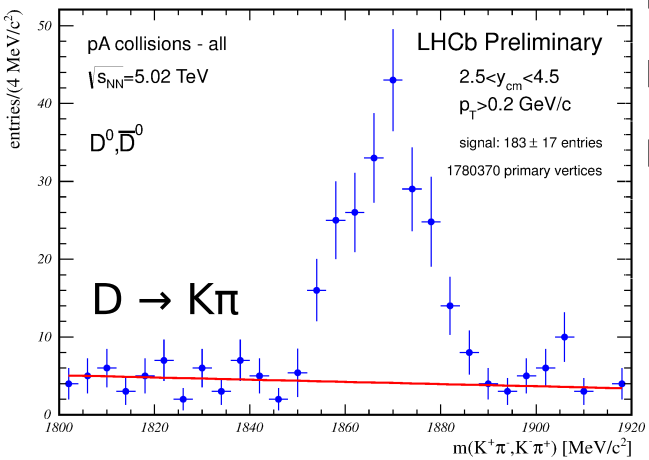
→ expect corrections to increase R(X) by 7 to 16%

Strangeness and Charm production









$R(K_s^0) = 1.745 \pm 0.014$

$R(\Lambda) = 1.818 \pm 0.043$

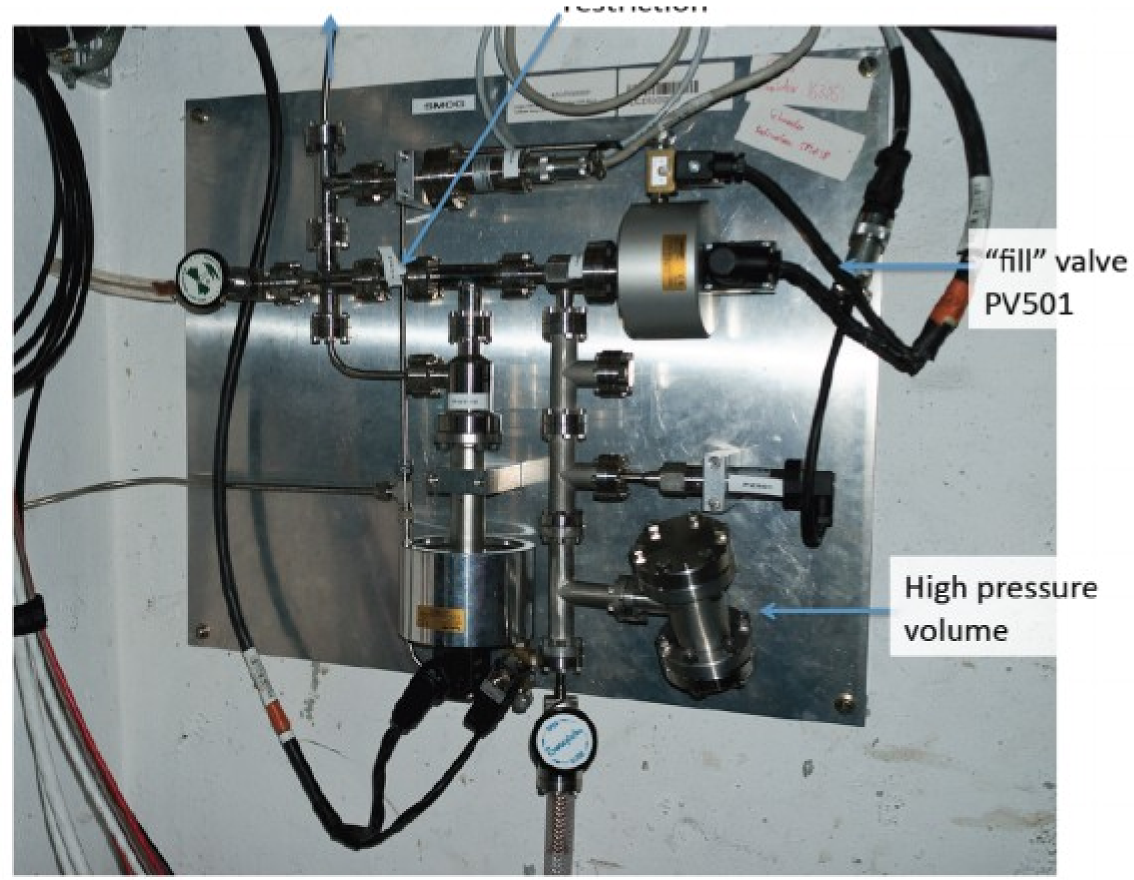
$R(\varphi) = 2.163 \pm 0.071$

$R(D^0) = 1.820 \pm 0.307$

clean signals of strangeness and charm production

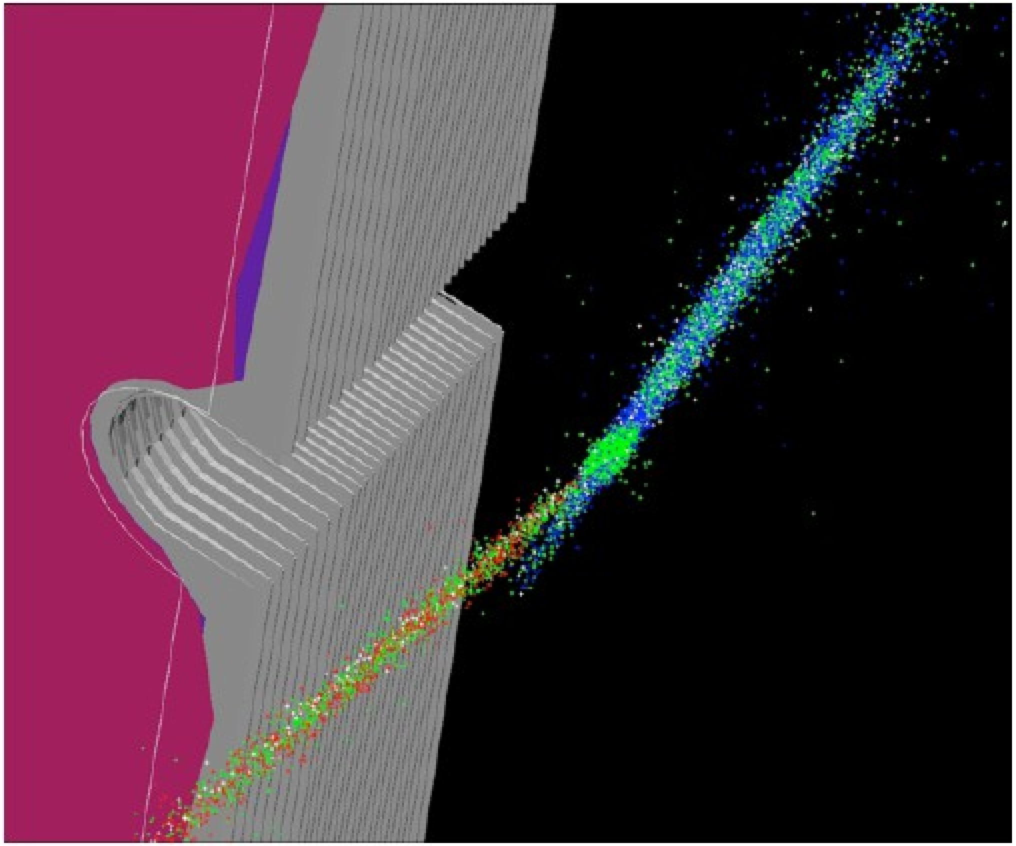
Fixed target physics at LHCb

SMOG: System for Measuring Overlap with Gas



→ injection of Ne gas into interaction region

Fixed target physics at LHCb



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

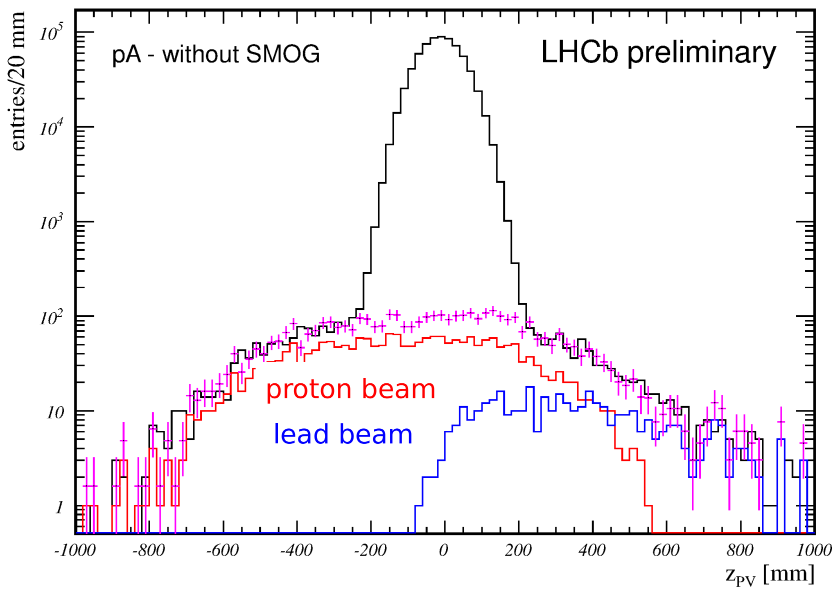
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

→ injection of Ne gas into interaction region

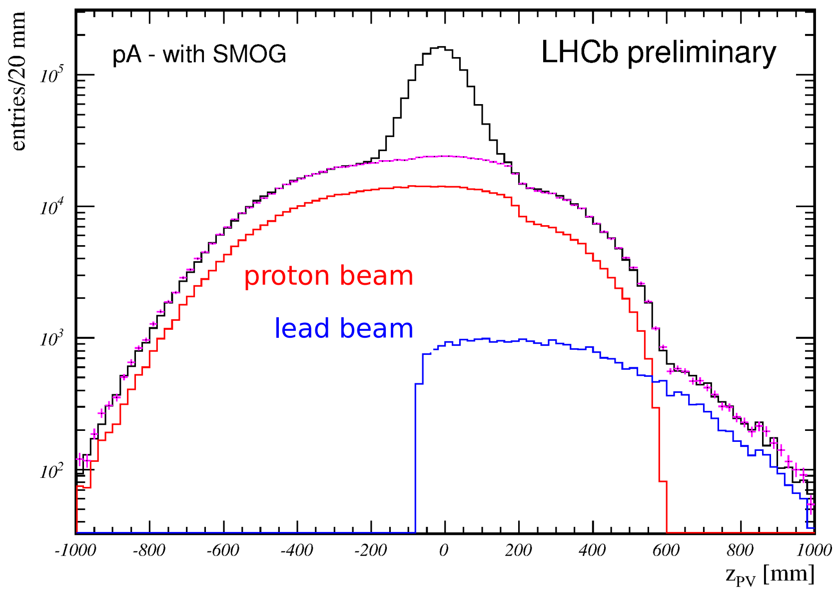
Fixed target physics at LHCb

→ injection of Ne gas into interaction region

no SMOG



with SMOG

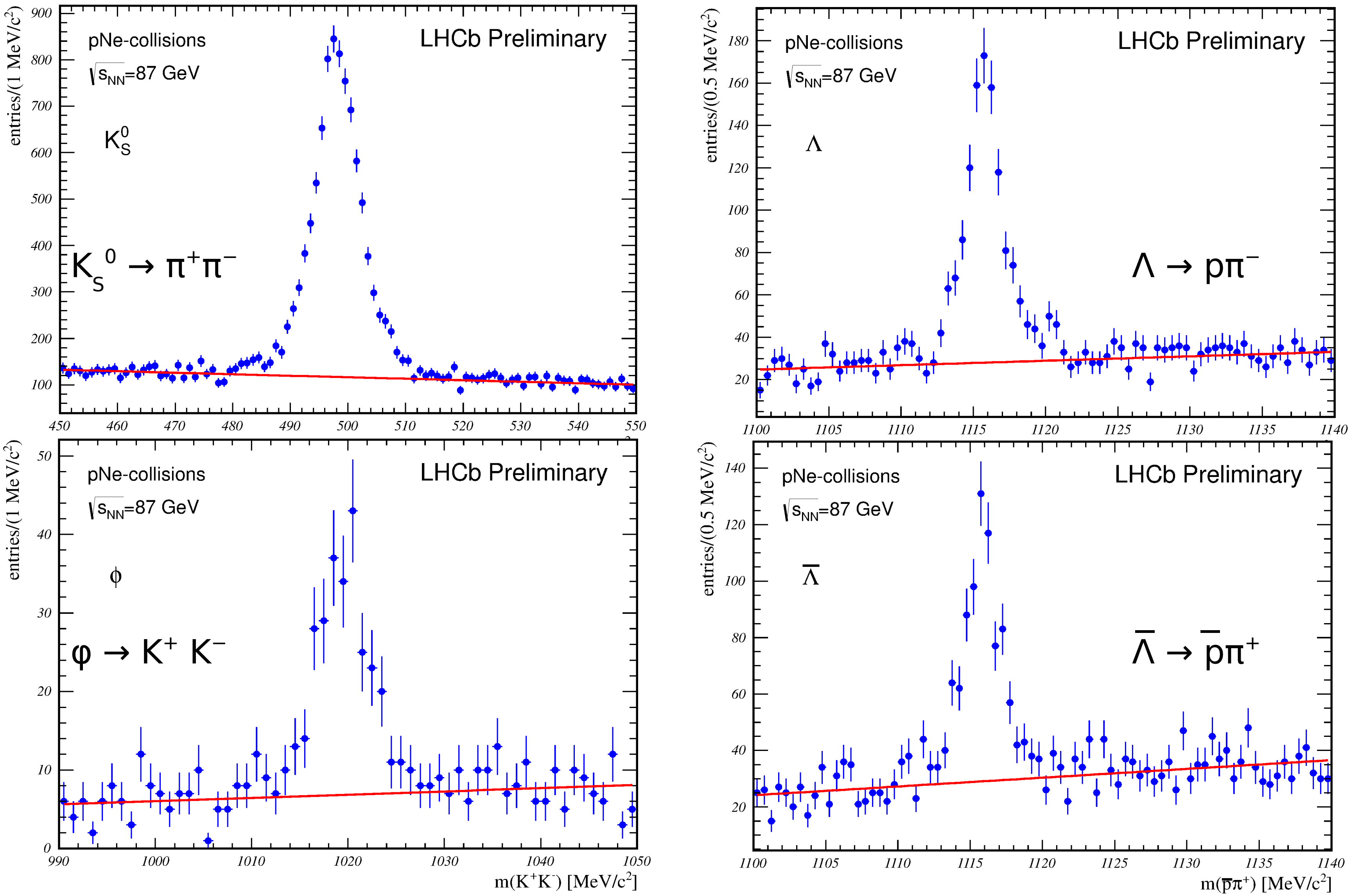


z-distribution of primary vertex

- increase of beam-gas interaction rate by two orders of magnitude
- accurate measurement of beam profile → precise luminosity determination

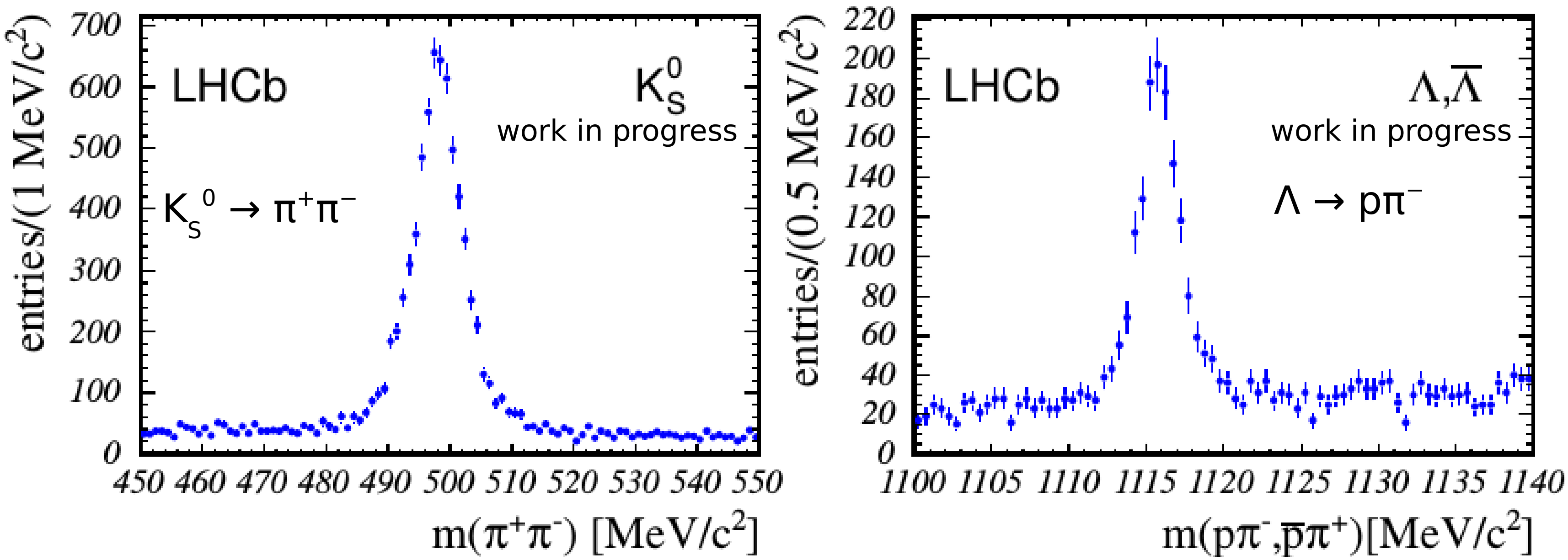
→ also allows to study pNe interactions at $\sqrt{s}$=87 GeV
shift of cm system by 4.5 units in rapidity in proton direction
→ LHCb is a central detector for fixed target collisions

Strangeness production at 87 GeV (pNe)



clear signals observed, can also study PbNe collisions

A first look at PbNe collisions



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

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

Summary and Outlook

- LHCb successfully participated in proton-lead runs
- measurement of J/ψ and Υ production
  → cold nuclear matter effects visible in J/ψ and Υ(1S) production
  → first observation of cold nuclear effects for b hadrons
- first observation of Z production in proton-nucleus collisions
- many more measurements ongoing
- measurements limited by statistics
  → benefit from larger data samples after the restart of LHC
- in addition, we have sample of pNe and PbNe data
- only a small part of LHCbs potential used so far

Backup slides

Check of interpolation method

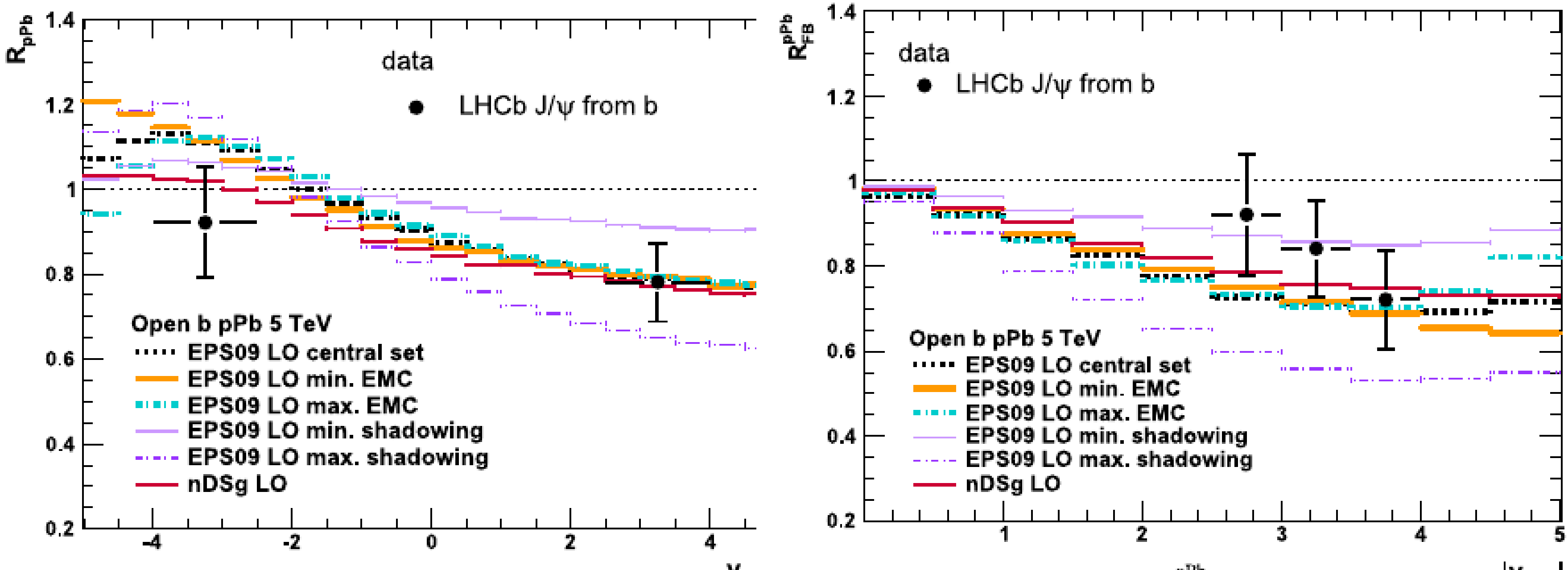
Cross check with theory: FONLL, Leading Order Colour Evaporation Model (LOCEM)

FONLL:
Phys. Rev. D17 (1978) 2324.
LO-CEM
JHEP 9805 (1998) 007

Model/PDF	factorization scale	σ(2.76 TeV)	σ(5.02 TeV)	σ(7 TeV)
LO-CEM/CTEQ6L	$m_c, m_c/2$	4.271	5.300	5.815
LO-CEM/CTEQ6L	$2m_c$	3.382	5.300	6.619
LO-CEM/MRST98L	$m_c/2$	4.294	5.300	5.837
LO-CEM/MRST98L	m_c	3.880	5.300	6.188
LO-CEM/MRST98L	$2m_c$	3.236	5.300	6.820
LO-CEM/CTEQ5L	$m_c/2$	3.891	5.300	6.180
LO-CEM/CTEQ5L	m_c	3.604	5.300	6.450
LO-CEM/CTEQ5L	$2m_c$	3.138	5.300	6.928
LO-CEM/MRST01L	$m_c/2$	4.584	5.300	5.586
LO-CEM/MRST01L	m_c	4.018	5.300	6.131
LO-CEM/MRST01L	$2m_c$	3.391	5.300	6.670
LO-CEM/GRV98L	$m_c/2$	3.697	5.300	6.412
LO-CEM/GRV98L	m_c	3.352	5.300	6.765
LO-CEM/GRV98L	$2m_c$	3.029	5.300	7.124
FONLL	(nominal)	3.331	5.300	6.670
FONLL	(min)	3.872	5.300	6.142
FONLL	(max)	3.413	5.300	6.587

Absolute cross-sections unconstrained → fixed to 5.3μb at 5 TeV
check interpolation methods:
- adjust parameters of the interpolation function to cross-section at 2.76 and 7TeV
- compare interpolated value to fixed reference.

Z. Conesa del Valle , E.G. Ferreiro , F. Fleuret , J.P. Lansberg , A. Rakotozafindrabe
Nuclear Physics A 926 (2014) 236–241

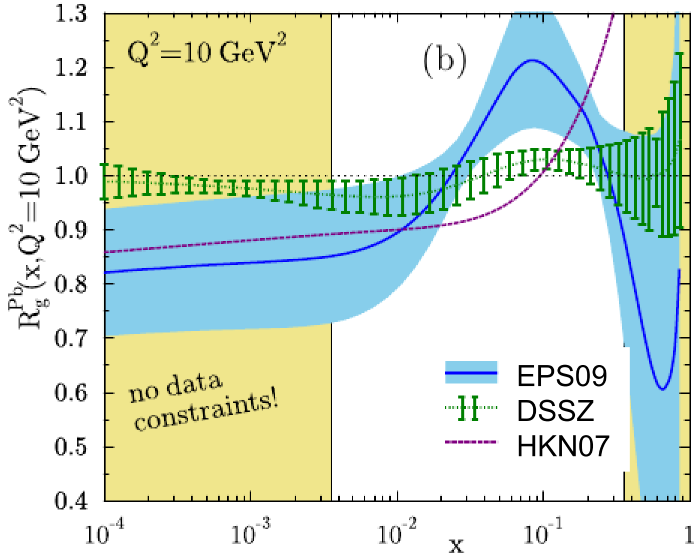


(a) $R_{pPb}(y_{c.m.})$ (b) $R_{FB}^{pPb}(|y_{c.m.}|)$

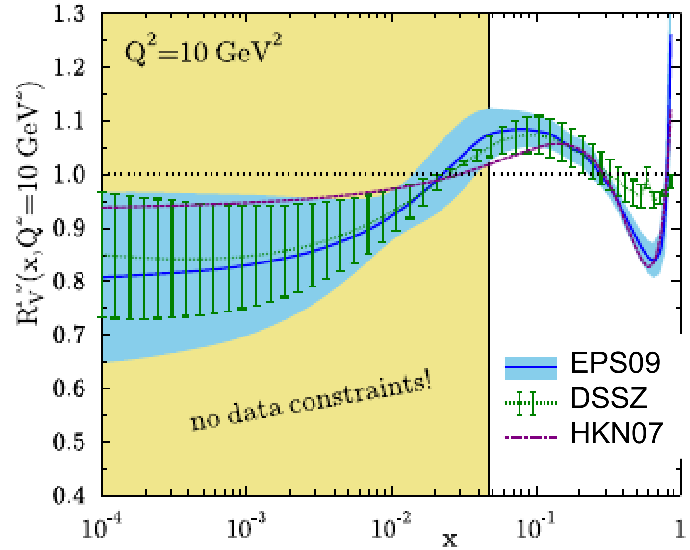
Current knowledge of nuclear PDFs (nPDF)

ratio: (nuclear PDF for Pb)/ (proton PDF) [Nucl.Phys. A926 (2014) 24-33]

gluon



valence quarks



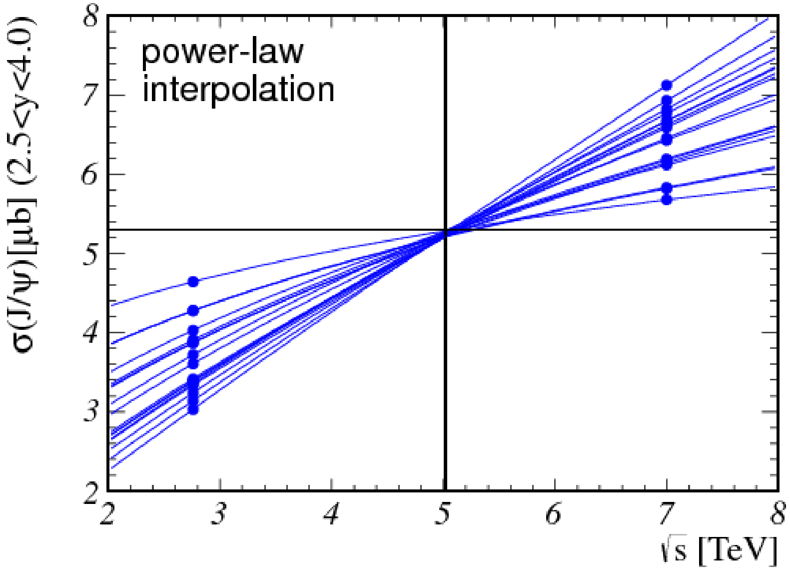
small x: R<1, shadowing, interference of scattering amplitudes
0.4<x<0.8: R<1, EMC effect
$x \to 1$ R>1, Fermi motion of nucleons in nucleus
x around 0.1: R>1 antishadowing (sum rules of PDFs)

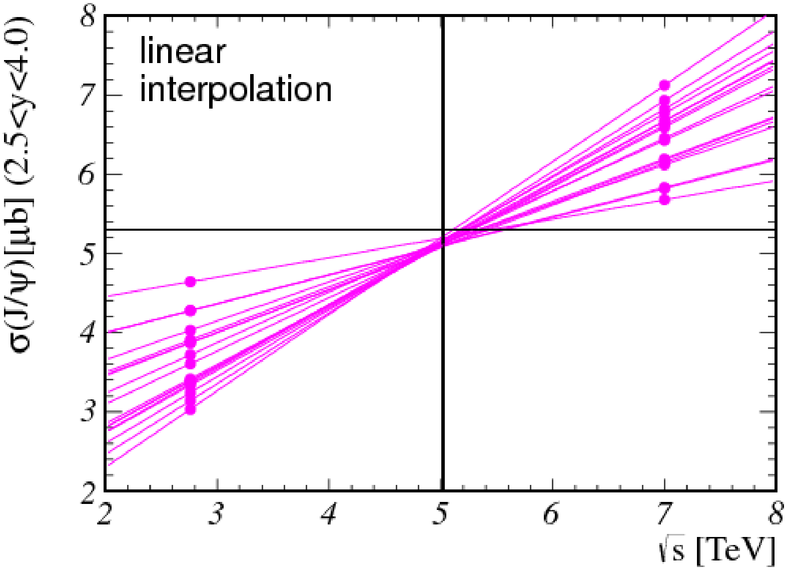
x_A:momentum fraction carried by parton inside the nucleon bound in the lead ion

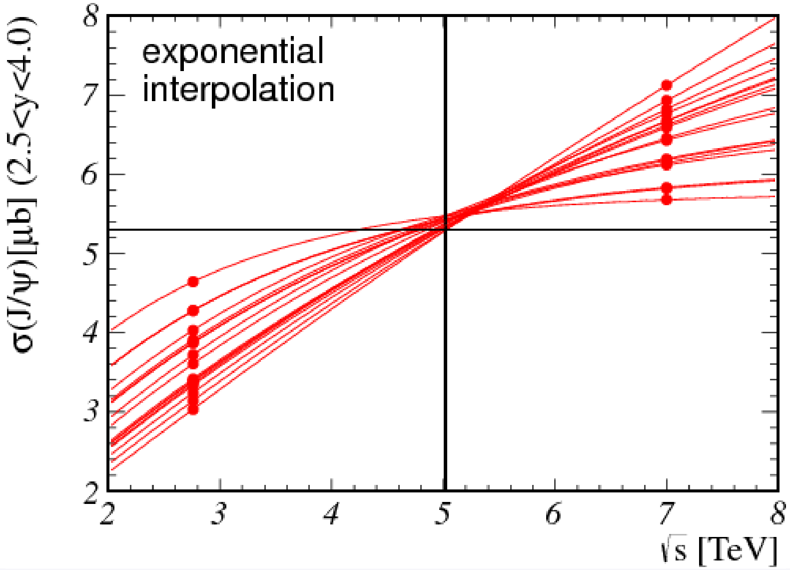
EPS09: JHEP 04 (2009) 065, DSSZ : Phys. Rev. D 85 (2012),HKN07: Phys. Rev. C 76 (2007) 065207

Check of interpolation method

cross check with theory: FONLL, Leading Order Colour Evaporation Model







→ power-law parametrisation gets closest to reference points at 5 TeV