Heavy Ion Results from LHCb

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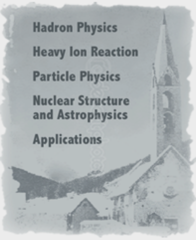
– on behalf of the LHCb collaboration –

Outline

- Introduction
- The LHCb Detector
- LHCb Physis Coverage
- Cold Nuclear Matter Effects
- Fixed Target Physics
- Summary and Outlook



54th International Winter Meeting on Nuclear Physics, Bormio, Italy, January 25–29, 2016

1. INTRODUCTION

➜ *theoretical understanding strong interactions:*

- the QCD Lagrangian is well known and tested
- many open questions in the non-perturbative regime
  - ➜ soft processes and bound states
  - ➜ Quark Gluon Plasma - high densities and temperatures

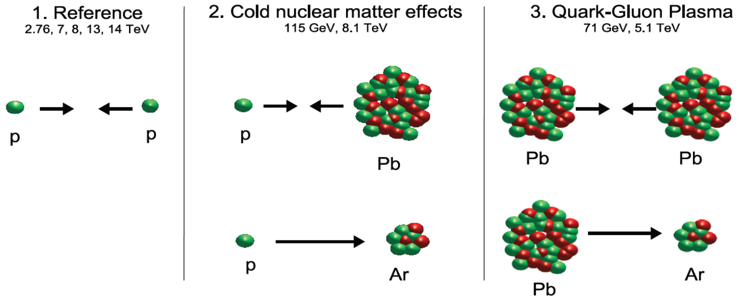
❖ an incomplete list of things to explore...

- ➜ nucleon structure at large x (vital for BSM searches)
- ➜ nuclear effects (EMC effect at large x, cold nuclear matter effects)
- ➜ intrinsic charm in the nucleon
- ➜ spin-structure of the nucleon
- ➜ properties of hadronic matter at high densities and temperatures
- ➜ QED at extreme field strengths
- ➜ dynamics of the hadronization process
- ➜ dynamics of diffractive scattering

Experimental approach

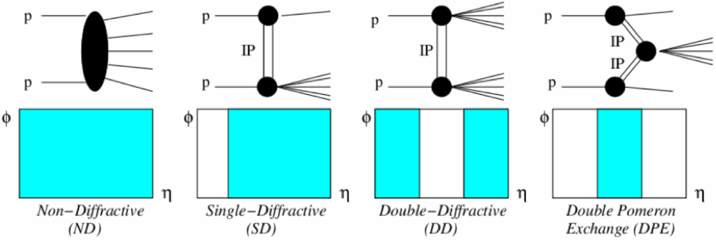
➜ *study hadronic collisions*

- as a function of the centre-of-mass energy
- for different beam-target combinations



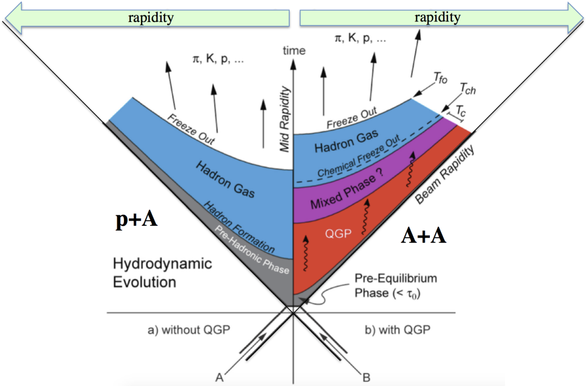
Basic phenomenology

➜ *strong interactions in high energy hadronic collisions, e.g. pp*



- colour exchange processes (dominant contribution in pp)
- scattering without colour exchange – Pomeron and photon exchange
  - ➜ rapidity gap signatures
  - ➜ diffractive scattering
  - ➜ central exclusive production (CEP)
    - ❖ dependence on $\sqrt{s_{NN}}$ and beam-target combinations

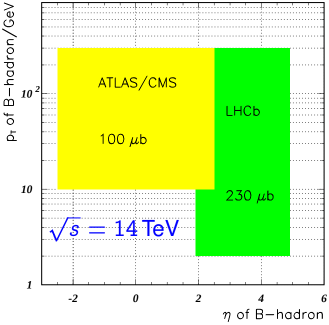
pA and AA: probing the QCD phase diagram

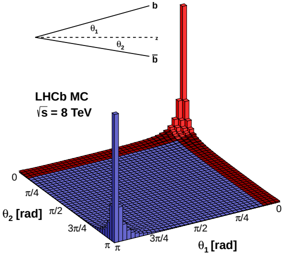


- pA: study of nuclear effects in the initial and final state
- AA: sensitivity to quark-gluon plasma
  - ➜ both in colliding beam and fixed target mode
  - ➜ bridge the gap from SPS to LHC in a single experiment

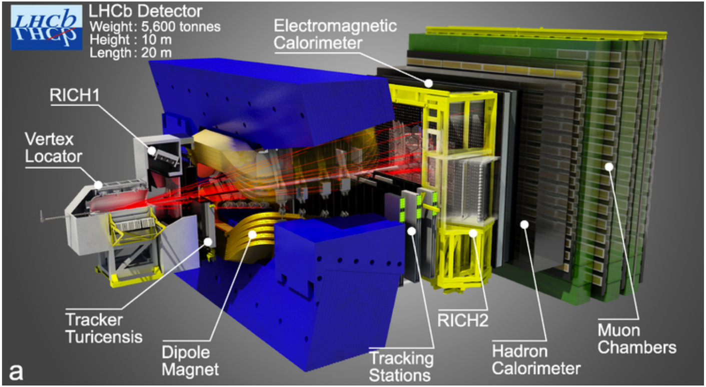
➜ *forward detector for B-Physics – but able to do much more*

- coverage $15 < \Theta < 300\,\text{mrad}$ ➜ large boosts: B decay lengths O(1 cm)
- focus on vertex reconstruction and particle identification
- phase space coverage down to low p_T, small x_{Bj} and large η
- flexible and highly selective trigger





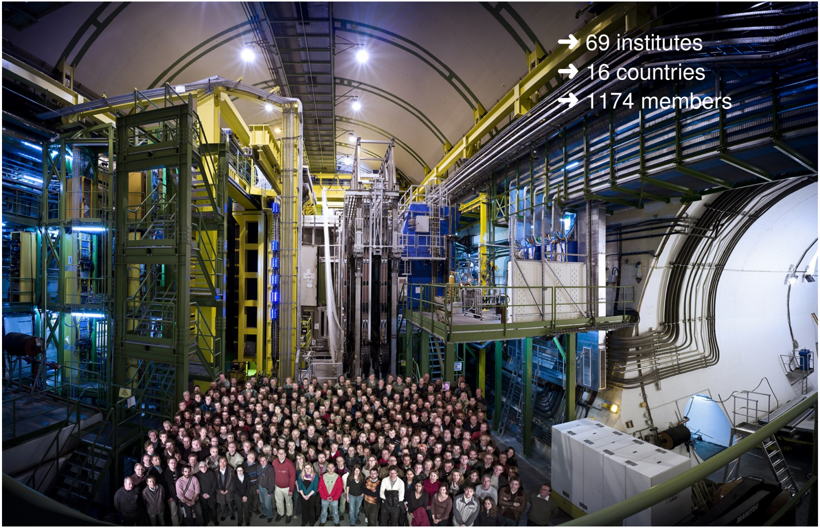
Schematic view



JINST 3 (2008) S08005

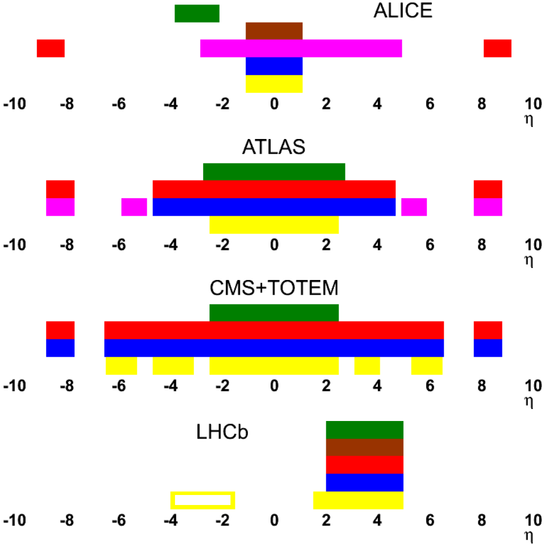
- VELO: silicon strip detector for precise secondary vertex reconstruction
- TT,T1,T2,T2: tracking stations, silicon strip and straws for charged particles
- RICH1, RICH2: ring imaging cherenkov detectors for $\pi / K / p$-separation
- ECAL, HCAL: electromagnetic & hadronic calorimeters for trigger and neutrals
- M1-M5: tracking stations for muon identification

Installation in the cavern



Inside the spectrometer magnet

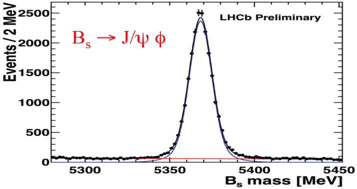
Angular coverage of the LHC experiments



- ALICE
  - ➜ central
  - ➜ forward muon coverage
- ATLAS & CMS
  - ➜ central detectors
- LHCb
  - ➜ forward detector
  - ➜ tracking, particle-ID and calorimetry in full acceptance

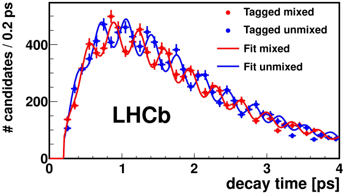
Tracking, vertexing and PID performance

- excellent mass resolution for complex decays



➜ B-mass resolution:
$\sigma(m_B) = 8\,\mathrm{MeV}/c^2$
for $B_s \to J/\psi X$
with J/ψ mass constraint

- excellent vertex- and proper-time resolution

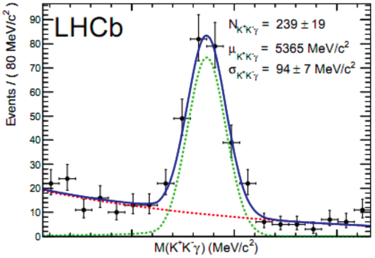


➜ proper time resolution:
$\sigma_t \sim 45$ fs
for B_s-mixing

❖ particle identification essential to reconstruct decay modes
❖ polarity switching of dipole magnet allows to control systematics

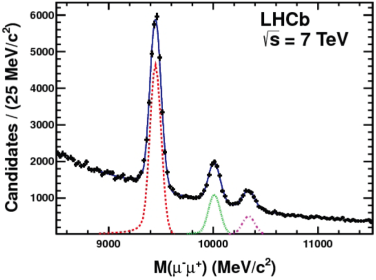
- ECAL: optimized to measure radiative B-decays
- HCAL: for triggering on hadronic final states
- Muon system for quarkonium and semi-leptonic decays

$B_s \rightarrow \phi\, \gamma$



[arXiv:1202.6267]

$\Upsilon \rightarrow \mu^+\mu^-$

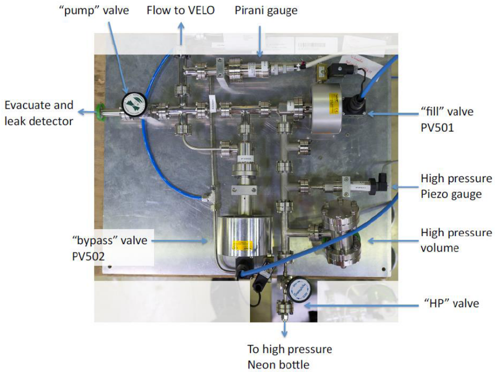


[arXiv: 1202.6579]

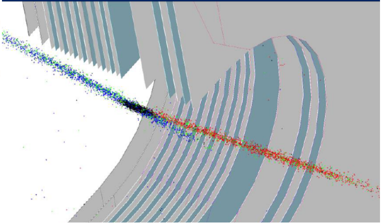
more about the LHCb detector performance: Int.J.Mod.Phys.A 30(2015)1530022

➜ additional extras. . .

➜ SMOG: System for Measuring Overlap with Gas



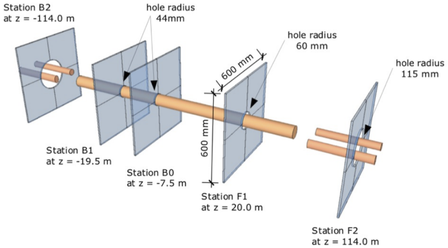
- injection of (Ne) gas into interaction region
- very simple robust system
- used for a precise luminosity determination



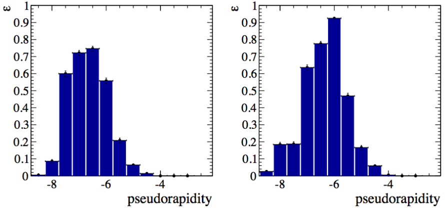
- possibility to inject (noble) gases: He, Ne, Ar (maybe Kr)
- fixed target physics in pA and PbA configuration

Forward extension of the detector

➜ HeRSCheL: High Rapidity Shower Counters for LHCb



- forward scintillators for selecting rapidity gaps
- up to $\pm 114\,\mathrm{m}$ from IP
- central region not covered
- gap size $2 < \eta < 8$
  - ➜ huge gain for diffractive physics and central exclusive production (e.g. J/ψ photoproduction on the proton in pA)



$p_T > 0.5\,\mathrm{GeV}/c$ $p_T > 1.5\,\mathrm{GeV}/c$

LHCb simulation results for the efficiency to see charged pions

3. LHCb Physics Coverage

→ *available/possible LHCb running modes & centre-of-mass energies*

E_{beam}(p)	pp	p-SMOG	p-Pb/Pb-p	Pb-SMOG	Pb-Pb
450 GeV	0.90 TeV				
1.38 TeV	2.76 TeV				
2.5 TeV	5 TeV	69 GeV$^{(1)}$			
3.5 TeV	7 TeV				
4.0 TeV	8 TeV	87 GeV$^{(2)}$	5 TeV	54 GeV$^{(2)}$	
6.5 TeV	13 TeV	110 GeV$^{(3)}$	8.2 TeV	69 GeV$^{(4)}$	5 TeV
7.0 TeV	14 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

(1) SMOG with ^{40}Ar

(2) SMOG with ^{20}Ne

(3) SMOG with ^{2}He, ^{20}Ne, ^{40}Ar

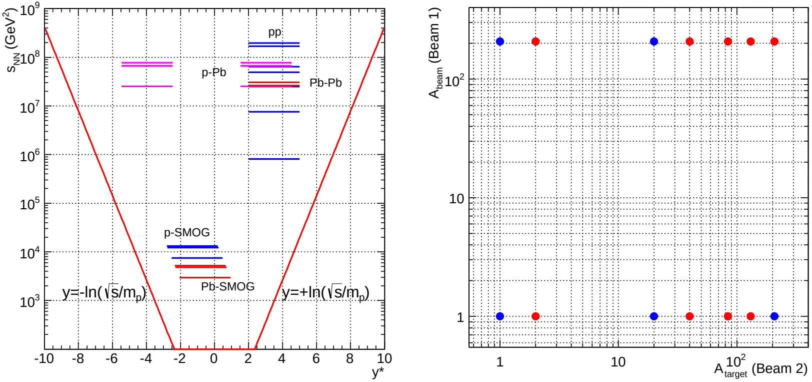
(4) SMOG with ^{40}Ar

→ preferred targets for SMOG operation: noble gases

→ some samples with only small statistics

Phase space coverage of LHCb

➜ *kinematic acceptance & beam-target combinations*



y^*: rapidity in nucleon-nucleon centre-of-mass system, with forward direction (positive values) in direction of the proton/beam

Access to parton densities

➜ *inclusive production of heavy particles:* $Q^2 = M^2$

parton-parton kinematics (ignoring masses and transverse momenta):

$$x_1\, x_2 = \frac{Q^2}{s} \qquad \text{and} \qquad \frac{x_1}{x_2} = e^{2\,y}$$

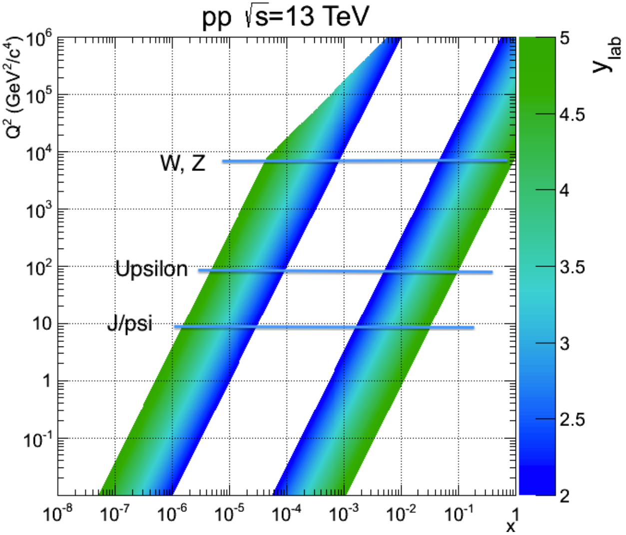
and thus

$$x_1 = e^{y}\,\frac{Q}{\sqrt{s}} \qquad \text{and} \qquad x_2 = e^{-y}\,\frac{Q}{\sqrt{s}}$$

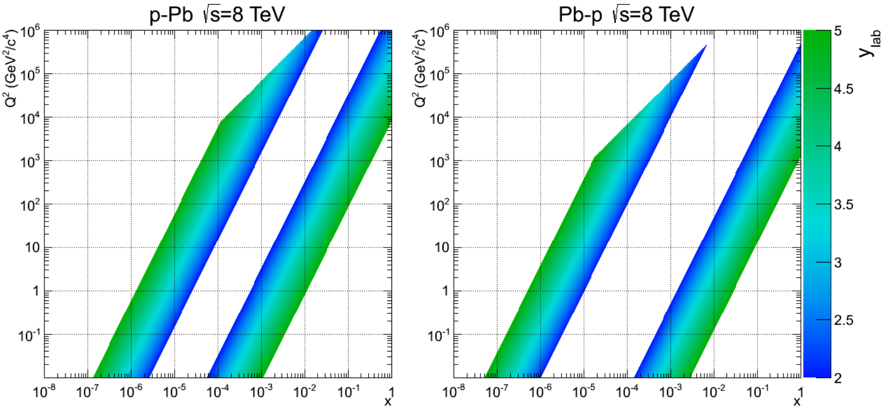
- contribution from two x-regimes for given Q^2 and y
- possibility to probe nucleon and nuclear PDFs

accessible phase space for $E_p = 6.5$ TeV in pp and pPb collisions ➜

Accesible $x - Q^2$ range in pp collisions



Accesible $x - Q^2$ range in pPb collisions



difference between p-Pb and Pb-b due to boost between lab- and nucleon-nucleon centre-of-mass system $\Delta y \approx \pm 0.465$

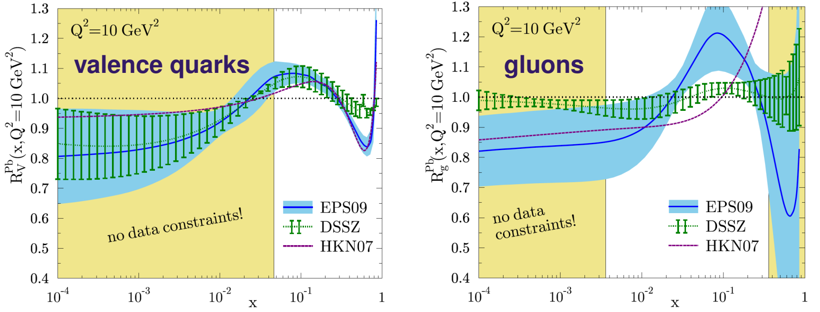
4. Cold Nuclear Matter Effects

➜ *influence of nuclear environment on particle production*

- energy loss - (coherent) superposition of two contributions
  - ➜ energy loss of collision partners in nuclear matter before hard scattering
  - ➜ energy loss of final state particles in nuclear environment
- modification of nucleon PDFs due to binding in the nucleus
  - ➜ compare heavy particle production (hard processes) in pp and pPb
  - ➜ accessible range for LHCb: $x > 10^{-5}$
    - J/ψ: $1 \cdot 10^{-5} < x < 1 \cdot 10^{-4}$ and $7 \cdot 10^{-3} < x < 7 \cdot 10^{-2}$
    - Υ: $3 \cdot 10^{-5} < x < 3 \cdot 10^{-4}$ and $3 \cdot 10^{-2} < x < 3 \cdot 10^{-1}$
    - Z: $2 \cdot 10^{-4} < x < 3 \cdot 10^{-3}$ and $3 \cdot 10^{-1} < x$
    - fixed target: $x \sim 0.1$

❖ collider mode probes small x, fixed target mode probes large x

➜ *ratios of nucleon PDFs: $F_N(\mathrm{Pb})/F_N(\mathrm{free})$*



arXiv:1401.2345

- still large unexplored regions
- regions of suppression ➜ shadowing
- enhancement at large x ➜ EMC effect
- enhancement at small x ➜ anti-shadowing

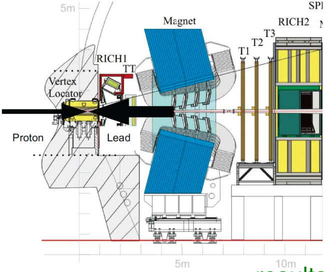
Observables sensitive to nuclear effects

nuclear modification factor: $R_{pA}(y) = \frac{1}{A} \cdot \frac{d\sigma_{pA}/dy}{d\sigma_{pp}/dy}$

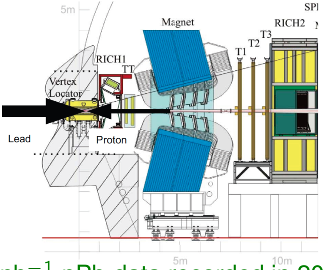
forward-backward asymmetry: $R_{FB}(y) = \frac{\sigma_{pA}(+|y|)}{\sigma_{pA}(-|y|)}$

- positive rapidity in direction of the proton
- pp cross-section cancels in R_{FB}
- exploit asymmetric layout of LHCb to measure forward and backward

p



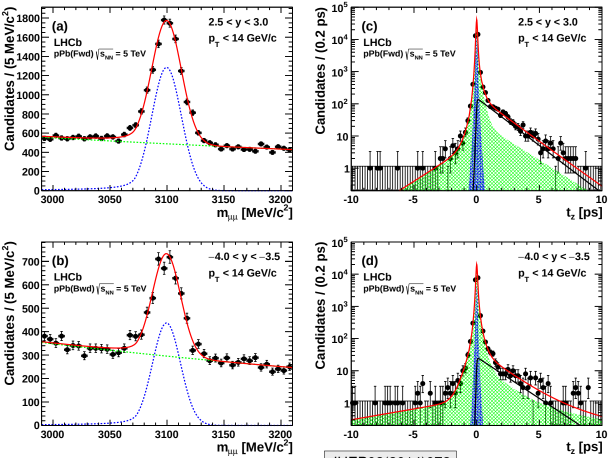
Pb



results from 1.6 nb^{-1} pPb-data recorded in 2013 ➔

J/ψ production in pPb collisions

➜ *separate prompt and delayed components by a simultaneous fit of mass and pseudo-proper-time* $t_z = (z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}/p_z^{J/\psi}$



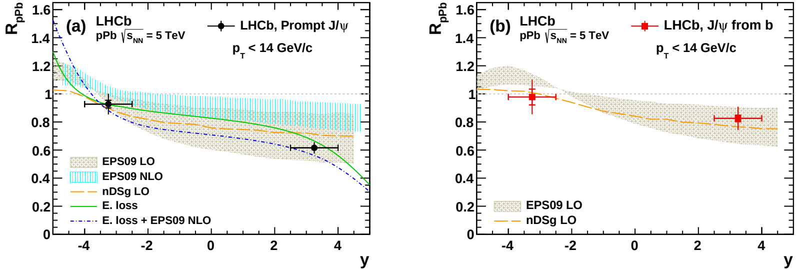
JHEP02(2014)072

pA collisions:
forward hemisphere
$2.5 < y < 3.0$
$p_T < 14\,\mathrm{GeV}/c$

Ap collisions:
backward hemisphere
$-4.0 < y < -3.5$
$p_T < 14\,\mathrm{GeV}/c$

J/ψ results: nuclear modification factors

➜ *common range of forward and backward acceptance:* $2.5 < |y| < 4.0$

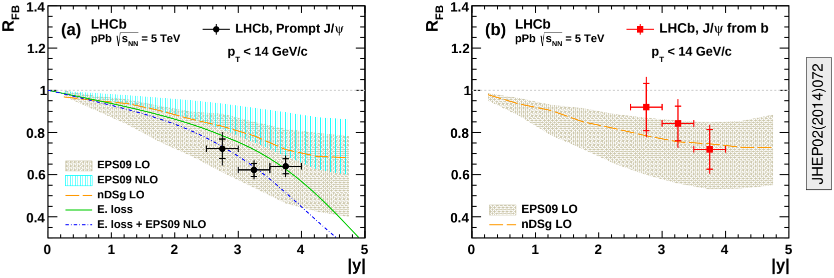


JHEP02(2014)072

- results require interpolation of pp cross-section to $\sqrt{s} = 5\,\text{TeV}$
- $R_{pPb} \neq 1$: the nucleus is not a loose collection of independent nucleons
- tighter bound B-mesons less affected than prompt J/ψ
- energy loss and shadowing are about equally important
- J/ψ data agree with “energy loss + NLO shadowing”

J/ψ results: forward-backward asymmetries

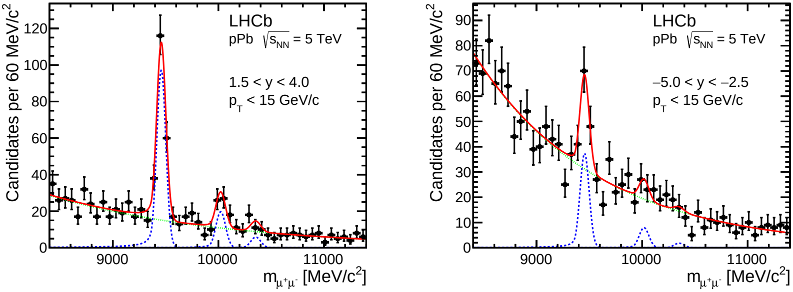
➜ *interpolated pp cross-section not required*



- differential measurement in $|y|$
- same observations/conclusions as for R_{pPb}

➜ study heavier systems

→ *statistics limited measurement*

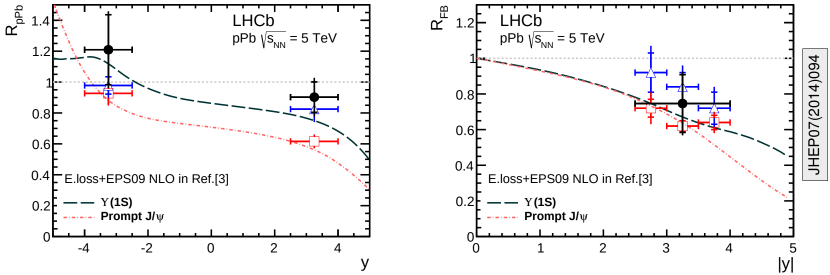


JHEP07(2014)094

- no differential measurements possible
- kinematic range: $p_T < 15\,\mathrm{GeV}/c$, $1.5 < y < 4.0$ and $-5.0 < y < -2.5$
- study nuclear effects in common rapidity range $2.5 < |y| < 4.0$
- evidence for strong suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$

→ focus on $\Upsilon(1S)$

➜ $\Upsilon(1S)$ *nuclear modification factor and forward-backward asymmetry*

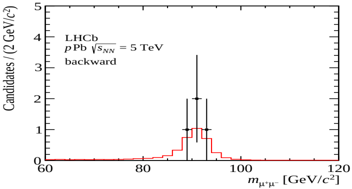


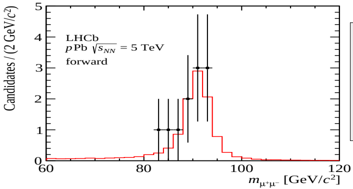
- large uncertainties
- less suppression for Upsilon than for prompt J/ψ production (red symbols)
- backward data consistent with expectations of anti-shadowing
- Upsilon consistent with J/ψ from b (blue symbols)

❖ more data needed for firm conclusions

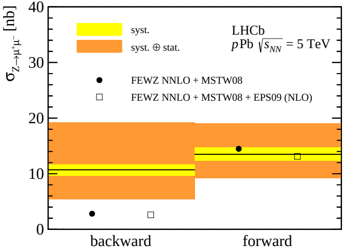
Z production in pPb collisions

➜ *clean signals: 4 backward-candidates, 11 forward-candidates*





arXiv:1406.2885



➜ *muon selection*

- $p_T > 20\,\mathrm{GeV}/c,\ 2.0 < \eta < 4.5$
- $60 < M(\mu^+\mu^-) < 120\,\mathrm{GeV}/c^2$

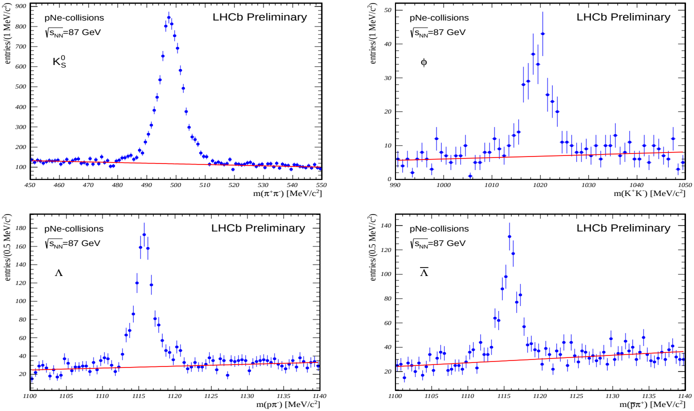
➜ *cross-section results*

$$\sigma_{\mathrm{fwd}} = 13.5\ {}^{+5.4}_{-4.0}\,(\mathrm{stat}) \pm 1.2(\mathrm{syst})\ \mathrm{nb}$$

$$\sigma_{\mathrm{bwd}} = 10.7\ {}^{+8.4}_{-5.1}\,(\mathrm{stat}) \pm 1.0(\mathrm{syst})\ \mathrm{nb}$$

→ *strangeness production in pNe collisions from the pA pilot run*

- $\sqrt{s_{NN}} = 87\,\text{GeV}$, boost to center-of-mass $\Delta y \approx 4.5$
- LHCb: backward direction in the nucleon-nucleon center-of-mass

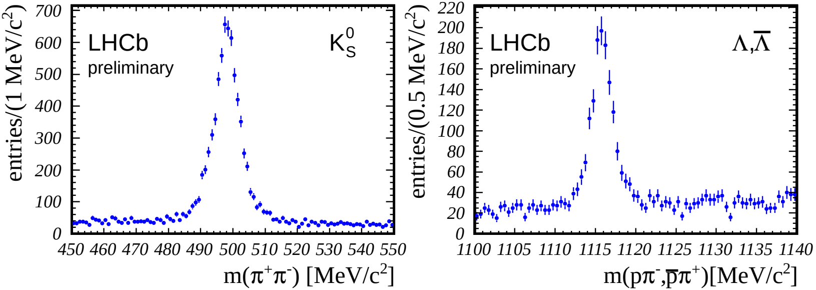


LHCb-CONF-2012-034

Nucleus-nucleus interactions

➜ *a first look at PbNe collisions*

PbNe-interactions - $\sqrt{s_{NN}}$=54.4 GeV

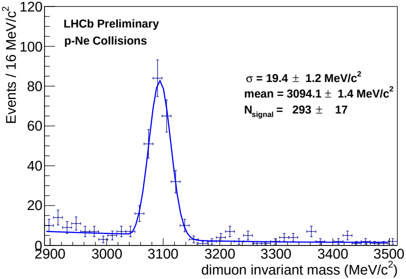


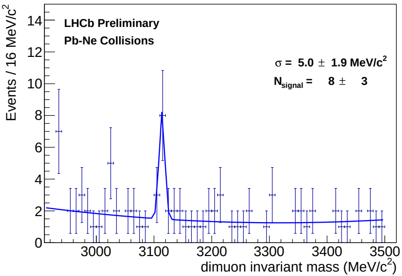
- O(1/2h) very low luminosity data taking with PbNe interactions
- plots based on 1/4 of available statistics

❖ possibility to study nuclear PDFs at large x!

J/ψ production in fixed target collisions

➜ *first look at pNe collisions (2015) and PbNe collisions (2013)*





https://twiki.cern.ch/twiki/bin/view/LHCbPhysics/LHCb2015PublicityPlots#SMOG_plots

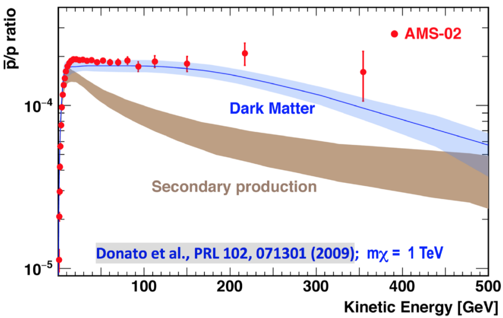
- first (hints) of signal seen, i.e. cross-sections are large
- potential for many interesting measurements

Links to other communities

➜ cosmic ray physics and cosmology

- understanding of extensive air showers ➜ MC tuning
- understanding the AMS antiproton/proton ratio

AMS $\bar{p}/p$ results and modeling



❖ use fixed target measurements to clarify: QCD or Dark Matter annihilation

➜ *LHCb is much more than a pp heavy flavour experiment . . .*

- participation in pp, pPb and, since 2015, PbPb running
- fixed target physics program with (so far) {p,Pb} on {He,Ne,Ar}
- initial measurements, often still statistics limited, from pPb collisions probing cold nuclear matter effects (nuclear PDFs, energy loss) at small x
  - ➜ production of prompt J/ψ and J/ψ from b
  - ➜ studies of Υ and Z production
- first results coming in from fixed target collisions
  - ➜ promising signal for large-x physics
  - ➜ still learning how to deal with the new environment
- analysis of PbPb data starting
  - ➜ physics results expected up to centralities around 50%
- more measurements done, many more in the pipeline. . .

❖ stay tuned to the LHCb ion physics program!