LHCB results from proton-ion collisions

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Outline

- The LHCb detector
- The p-Pb and Pb-p data taking
- Physics motivations for proton-nucleus studies
- Results from the pPb and Pbp data taking of 2013
  - J/ψ production
  - ψ(2S) production
  - Y(nS) production
  - Z production
  - Two particle angular correlations
- Conclusions and prospects for heavy ion studies
The LHCb detector

- Single arm spectrometer in the forward region
- Fully instrumented in its angular acceptance
- Pseudorapidity coverage $2 < \eta < 5$
- Designed initially for $b$-physics but general purpose detector (fixed target collisions, heavy ion physics program...)

- Vertex detector
  - IP resolution $\sim 20 \mu m$
  - Decay time resolution $\sim 45$ fs

- Dipole magnet
  - Bending power $4$ Tm

- Tracking system
  - $\Delta p/p = 0.4\% - 0.8\%$ (5 GeV/c – 100 GeV/c)

- Electromagnetic + hadronic calorimeters

- RHIC: $K/\pi/p$ separation
  - $\varepsilon(K \rightarrow K) \sim 95\%$
  - Mis-ID: $\varepsilon(\pi \rightarrow K) \sim 5\%$

- Muon system
  - $\mu$ identification: $\varepsilon(\mu \rightarrow \mu) \sim 97\%$
  - Mis-ID: $\varepsilon(\pi \rightarrow \mu) \sim 1-3\%$

LHCb results from pA collisions – ISMD 2015
The p-Pb and Pb-p data taking

- p-Pb and Pb-p data collected at a nucleon-nucleon center of mass energy $\sqrt{s_{NN}} = 5$ TeV
- Asymmetric beams: nucleon-nucleon center-of-mass system shifted by $\Delta y = 0.47$ in the direction of the p beam

**p + Pb collisions (forward)**
Rapidity coverage: $1.5 < y_{CMS} < 4.5$
2013 data sample: $L_{\text{int}} = 1.1$ nb$^{-1}$
→ Applies to all analyses unless specified

**Pb + p collisions (backward)**
Rapidity coverage: $-5.5 < y_{CMS} < -2.5$
2013 data sample: $L_{\text{int}} = 0.5$ nb$^{-1}$
→ Applies to all analyses unless specified

Rapidity coverage in common to both configurations: $2.5 < |y_{CMS}| < 4.5$
Physics motivation for proton-nucleus studies

Proton-nucleus collisions are interesting by themselves but also provide reference for heavy ion studies.

Heavy flavours and Quarkonia as tools to study cold nuclear matter effect (CNM) → Necessary reference to disentangle QGP effects from CNM effects in AA collisions

Initial state effects
- Nuclear shadowing = gluon shadowing at LHC [1]
- Parton saturation / CGC [2]
- Radiative energy loss [3]
- Cronin effects [4]

Final state effects
- Nuclear absorption [6]: Expected to be small at LHC [7]
- Radiative energy loss [8]
- Comovers [9]

Neither initial nor final
- Coherent energy loss [5]

Physics motivation for proton-nucleus studies

Z boson production to constrain the nuclear parton distribution functions (nPDF)

LHCb in p+Pb and Pb+p probes two different regions in x-Q²
Complementary measurement to ATLAS/CMS

Sensitivity to nuclear PDF at large $x_A (10^{-1})$, and low $x_A (10^{-4})$

Two-particle correlations to probe collective effects in the dense environment of high energy collisions

Highest particle density and multiplicities reached in pp and pA at LHC of similar size to that of non central AA collisions

LHCb can investigate at forward rapidity the long-range correlation on the near side («the ridge») which was observed in pp, pPb (and PbPb) at mid-rapidity $|\eta| < 2.5$
Results from the p-Pb and Pb-p data taking of 2013
**J/ψ production in p-Pb and Pb-p**

- J/ψ are reconstructed from two well identified muons
- Disentangle prompt J/ψ from J/ψ from b using pseudo-proper time:
  \[ t_Z = \frac{(Z_{J/ψ} - Z_{PV}) \times M_{J/ψ}}{p_z} \]
- Yields of prompt J/ψ and J/ψ from b extracted from simultaneous fit of mass and pseudo-proper time

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**Mass distribution:**
- Signal: Crystal-Ball function
- Background: Exponential

**t_z distribution:**
- Signal: \( \delta(t_z) \) for prompts J/ψ (blue curve)
- Exponential for J/ψ from b (black line)
- Background: Empirical function from sideband (green hatched)
$R_{pPb}(y) = (1/A) \times (d\sigma_{pA}/dy)/(d\sigma_{pp}/dy)$ in the common range $2.5 < |y_{CMS}| < 4.0$

**Prompt $J/\psi$:** strong suppression at forward $y$ (strong CNM effect)

$\rightarrow$ Data well described by coherent energy loss models (w and w/o shadowing)

**$J/\psi$ from $b$:** small suppression in the forward region

$\rightarrow$ first indication of suppression of $b$ hadron production


EPS09LNO (shadowing + CEM): IJMP E22 (2013) 1330007

Energy Loss: JHEP 03 (2013) 122; JHEP 05 (2013) 155

nDSg LO: PRC88 (2013) 047901
J/ψ forward to backward ratio ($R_{FB}$)

- $R_{FB}(y) = \frac{(d\sigma_{pA}/dy)}{(d\sigma_{Ap}/dy)}$ in common range $2.5 < |y_{CMS}| < 4.0$

**Rapidity dependence:**
Prompt J/ψ: Clear forward-backward asymmetry

→ More statistics needed to distinguish between models

J/ψ from b: Small forward-backward asymmetry

**$p_T$ dependence:**
Prompt J/ψ: forward backward asymmetry agrees best with eloss + shadowing (except at low $p_T$)

J/ψ from b: $R_{FB}$ close to 1
**ψ(2S) production in p-Pb and Pb-p**

- Similar analysis strategy as for the J/ψ
- Yields of prompt ψ(2S) and ψ(2S) from b extracted from simultaneous fit of mass and pseudo-proper time

### Mass distribution:
- **Signal:** Crystal-Ball function
- **Background:** Exponential

### tz distribution:
- **Signal:** δ(tz) for prompts ψ(2S) (blue curve)
- **Exponential** for ψ(2S) from b (black line)
- **Background:** Empirical function from sideband (green hatched)

LHCb results from pA collisions – ISMD 2015
\[ R_{FB} \] as a function of \( p_T \) and rapidity in common range \( 2.5 < |y_{CMS}| < 4.0 \)

- No need of pp reference cross section, part of experimental and theoretical uncertainties cancel

Large experimental uncertainties \( \rightarrow \) more statistics needed to get a trend (\( R_{FB} \) of inclusive \( \psi(2S) \) compatible both with unity and with suppression of inclusive \( J/\psi \))
Relative suppression is calculated as:

\[
R = \frac{R_{\psi(2S)}^{pPb}}{R_{J/\psi}^{pPb}} = \frac{\sigma_{pPb}^{\psi(2S)}(5 \text{ TeV})}{\sigma_{pPb}^{J/\psi}(5 \text{ TeV})} \frac{\sigma_{pp}^{\psi(2S)}(5 \text{ TeV})}{\sigma_{pp}^{J/\psi}(5 \text{ TeV})} \approx \frac{\sigma_{pPb}^{\psi(2S)}(5 \text{ TeV})}{\sigma_{pPb}^{J/\psi}(5 \text{ TeV})} \frac{\sigma_{pp}^{\psi(2S)}(7 \text{ TeV})}{\sigma_{pp}^{J/\psi}(7 \text{ TeV})}
\]

Intriguing stronger suppression of prompt \( \psi(2S) \) than that of prompt \( J/\psi \)
Similar suppression for \( \psi(2S) \) from \( b \) and \( J/\psi \) from \( b \)
\[ \rightarrow R \text{ compatible with 1 within large uncertainties} \]
Results for inclusive \( \psi(2S) \) compatible with ALICE measurement

**NEW**

LHCb-CONF-2015-005

ALICE: JHEP 12 (2014) 073
Ψ(2S) nuclear modification factor

Ψ(2S) nuclear modification factor is calculated from J/Ψ nuclear modification factor

\[ R_{pPb}^{Ψ(2S)} \approx R_{pPb}^{J/Ψ} \times R \]

Assuming

\[ \frac{\sigma_{pp}^{J/Ψ}(5 \text{ TeV})}{\sigma_{pp}^{Ψ(2S)}(5 \text{ TeV})} \approx \frac{\sigma_{pp}^{J/Ψ}(7 \text{ TeV})}{\sigma_{pp}^{Ψ(2S)}(7 \text{ TeV})} \]

Prompt ψ(2S) more suppressed than prompt J/ψ
Eloss + shadowing don’t explain the ψ(2S) suppression in the backward region (other mechanism at play?)
Suppression of ψ(2S) from b consistent with that of J/ψ from b
Suppresion of inclusive ψ(2S) consistent with ALICE results

ALICE: JHEP 12 (2014) 073
Y(nS) production in p-Pb and Pb-p

- Y states in the dimuon decay channel
- Forward: $1.5 < y_{\text{CMS}} < 4.0$, backward: $-5.0 < y_{\text{CMS}} < -2.5$; $p_T < 15 \text{ GeV/c}$
- Fit performed with 3 Crystal Balls for signal and an exponential for background

Limited statistics do not permit to do a differential measurement

Forward production

Backward production
$\Upsilon(1S) \, R_{pA}$ and $R_{FB}$

- In common range $2.5 < |y_{CMS}| < 4.0$
- Measurement of $\Upsilon(1S) \, R_{pPb}$ and $R_{FB}$ is complementary to the one of $J/\psi$

Probing different $x_A$

$\Upsilon(1S)$ is also sensitive to CNM effects

**$R_{pPb}$ versus rapidity:**
Suppression in forward region is smaller than for $J/\psi$
Central value in forward region close to that of $J/\psi$ from $b \rightarrow$ CNM effects on $b$ hadrons
Indication of enhancement in the backward region → could be attributed to anti-shadowing

**$R_{FB}$ versus rapidity:**
Ratio in agreement with predictions of energy loss + shadowing (EPSO9 NLO)
**Z production in p-Pb and Pb-p**

**Muon selection:** $p_T > 20$ GeV/c, $2.0 < \eta < 4.5$, $60 < M(\mu^+\mu^-) < 120$ GeV/c$^2$

**Backgrounds:** very small, purity $> 99\%$ determined from data

Clean signal: 11 forward candidates, 4 backward candidates

Cross sections in agreement with predictions, although the production of Z in the backward region appears slightly higher than prediction

$R_{FB}$ calculated in the common rapidity range is lower than expectations

$\rightarrow$ deviation of $2.2\sigma$ from $R_{FB} = 1$

Statistical precision of measured cross sections prevents conclusions on the presence of CNM

Looking forward to take more data during run II
Two particle correlations in p-Pb and Pb-p

- Measurement of angular $(\Delta \eta, \Delta \phi)$-correlations of prompt charged particles
- Both beam configurations analyzed separately: $L_{\text{int}} = 0.46 \text{nb}^{-1}$ (p+Pb), $L_{\text{int}} = 0.30 \text{nb}^{-1}$ (Pb-p)
- Rapidity range $1.5 < y_{\text{CMS}} < 4.4$ (forward), $-5.4 < y < -2.5$ (backward)
- Correlation function is described as a per-trigger particle associated yield:

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d \Delta \eta d \Delta \phi} = \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)} \times B(0,0)$$

**p-Pb configuration**
$\Delta \phi = 0$ near-side ridge clearly visible in high event activity class (however not very pronounced)

**Pb-p configuration**
$\Delta \phi = 0$ very pronounced near-side ridge in Pb-p in high activity event class
Two particle correlations in p-Pb and Pb-p

- To study the evolution of the long-range correlations on the near and away sides in more details, correlation function on $\Delta \phi$ are calculated:

$$Y(\Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} = \frac{1}{\Delta \eta_b - \Delta \eta_a} \int_{\Delta \eta_a}^{\Delta \eta_b} \frac{d^2N_{\text{pair}}}{d\Delta \eta d\Delta \phi} d\Delta \eta$$

- 2D-yield averaged in the range $2.0 < \eta < 2.9$ to exclude short range correlations (jet peak)

- Subtraction of the zero yield at minimum (ZYAM)

Correlation yield increases with event activity
Away-side ridge decreases towards higher $p_T$
On the near side the ridge emerges (from 10-30% event activity class in Pb-p, from 0-10% event activity class in p-Pb) with a maximum in $1 < p_T < 2$ GeV/c
Near-side ridge is more pronounce in Pb-p than in p-Pb
Conclusions and prospects for heavy ion studies

- LHCb successfully participated in the proton-Pb data taking in 2013
  - Measurement of $J/\psi$, $\psi(2S)$ and $\Upsilon$ production
    - Cold nuclear matter effects visible in $J/\psi$, $\psi(2S)$ and $\Upsilon(1S)$ production
  - First observation of forward $Z$ production in proton-nucleus collisions
    - Analysis will benefit from larger statistics data sample in Run 2
  - New results on « two-particle» correlations
    - Near side ridge also observed in the forward region

LHCb is more than a pp heavy flavour experiment

- LHCb detector will also collect PbPb data at the end of this year
  - Rich program in heavy flavour physics, EW, (soft) QCD and QGP studied
  - Expected to collect 50-80 $\mu$b$^{-1}$ this year

- In addition LHCb is in the unique position to do fixed target physics
  - Exploit the SMOG system with different noble gases (p-Ne, p-He already collected, p-Ar and Pb-Ar runs to come)
  - Bridge the gap from SPS to LHC physics with a single experiment

LHCb is a truly general purpose detector in the forward region
Back up
J/ψ signal in p-Ne collisions in 2015 with SMOG

- \( \sqrt{s_{NN}} = 110 \text{ GeV} \)
- \(~12\text{h of data taking}~\)
- \(\text{Pressure of the Ne gas} \sim 1.5 \times 10^{-7} \text{mbar}~\)

![Graph showing the J/ψ signal in p-Ne collisions]

- \(\sigma = 19.4 \pm 1.2 \text{ MeV/c}^2\)
- \(\text{mean} = 3094.2 \pm 1.4 \text{ MeV/c}^2\)
- \(N_{\text{signal}} = 274 \pm 17\)
Physics motivation for proton-nucleus studies

Proton-nucleus collisions are interesting by themselves but also provide reference for heavy ion studies.

Heavy flavours and Quarkonia as tools to study cold nuclear matter effect (CNM) → Necessary reference to disentangle QGP effects from CNM effects in AA collisions

Initial state effects

Nuclear shadowing = gluon shadowing at LHC [1]
Gluon distribution functions are modified by the nuclear environment. PDF in nuclei ≠ superposition of the individual nucleon PDFs

Parton saturation / CGC [2]
At small x, density of gluons > density of quarks. Saturation of gluon distributions

Radiative energy loss [3]: incoming partons radiate gluons as it traverses the medium

Cronin effects [4]: increase of $<p_T^2>$ from pp to pA. Broadening of the intrinsic $p_T$ distribution → from multiple scattering experienced by the initial gluon from proton as it goes through the nucleus

Final state effects

Nuclear absorption [6]: break-up of pre-resonant cc pairs due to successives interaction with spectator nucleons

Expected to be small at LHC [7]

Radiative energy loss [8]: outgoing particle radiates energy while traversing the medium

Comovers [9]: interaction of the quarkonium with the produced medium