Experimental overview on proton-nucleus collisions at the LHC

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Outline

• Why proton-nucleus at the LHC?
• Latest p-Pb measurements:
  • Electroweak bosons and Drell-Yan
  • Open heavy flavour
  • Quarkonium
  • Azimuthal angular correlations of charged particles, open and hidden heavy flavour

Selection of new results from ALICE, ATLAS, CMS and LHCb
Why proton-nucleus at the LHC?

Reference to Pb-Pb measurements and Quark Gluon Plasma studies

Cold nuclear matter (CNM) effects
- nuclear modification of the parton distribution functions (PDFs) depending on $x$, the nucleon longitudinal momentum fraction of the struck parton, and the hard scale, $Q^2$
  - EPPS16 constrained by LHC dijet measurements in p-Pb
- gluon density saturation at high energy and low hard scale (low $x$ and low $Q^2$)
- medium-induced radiative parton energy loss in the initial and/or final state
- multiple scatterings of partons (initial state) or produced particle (final state)
- produced particle breakup by interactions with comoving particles/partons
Collective behaviors (QGP-like) have been discovered in high-multiplicity pp and p-Pb collisions

- Multiplicity defined as the number of charged particles per event: $N_{\text{ch}}$
- e.g.: long-range near-side angular correlations in high-multiplicity events for charged particles in p-Pb collisions

**Origin of collectivity in small systems**

- Similar $N_{\text{ch}}$ in high-multiplicity pp and p-Pb collisions w.r.t. peripheral Pb-Pb collisions
- Is a droplet of QGP created in small systems? Or is it an effect from initial-state or from hadronisation in a high-multiplicity environment?

**pp and p-A collisions at high mult.**: search for and study the onset of the QGP formation
Proton-nucleus measurements at the LHC

LHC p-Pb collisions
- $\sqrt{s_{\text{NN}}} = 5.02, 8.16$ TeV
- 2 beam configurations: p-Pb and Pb-p

Shift in rapidity of the nucleon-nucleon center of mass system with respect to the laboratory frame by $\Delta y = 0.465$ in the proton beam direction imposed by the LHC two-in-one magnet design: $y_{\text{cms}} = y_{\text{lab}} - \Delta y$

LHC in fixed target mode (see Daniele Marengotto talk)
- energy range: $\sqrt{s_{\text{NN}}} = 68 - 110$ GeV
- collision systems: pHe, pNe, pAr
Electroweak bosons: W, Z

- W, Z: do not carry colour charges and do not suffer final state effects: they can constrain quark and anti-quark nPDF at large scale $Q^2$

- Precise W measurements at 8.16 TeV
  - W probes $10^{-3} < x_{Pb} < 10^{-1}$
  - Inconsistent with free PDF: W data favor nuclear shadowing at forward rapidity
  - Data uncertainties lower than nPDF uncertainties

- More precise measurements at 8.16 TeV with Z bosons
Drell-Yan ($\gamma^*, Z$)

\[ R_{FB} = \frac{\sigma(y > 0)}{\sigma(y < 0)} \]

**CMS-PAS-HIN-18-003**

First Drell-Yan measurements in p-Pb collisions for $15 < M_{\mu\mu} < 600$ GeV
- Complementary to W boson: different mass probed (different scales Q²)
- Forward to backward rapidity ratio, $R_{FB}$:
  - Partial cancellation of theoretical and experimental uncertainties
  - $R_{FB} < 1$ at large mass and and large $y_{\text{cms}}$ consistent with EPPS16 (mixture of shadowing and anti-shadowing)
**Open heavy-flavour: $R_{pPb}$**

\[ R_{pA} = \frac{1}{A} \frac{\sigma_{PA}}{\sigma_{pp}} \]

**ALICE, JHEP12(2019)092**

- **Open heavy-flavour $R_{pPb}$ vs $p_T$ and $y_{cms}$**
  - Sensitive to gluon distribution
  - Mid-rapidity: compatible with scaled pp yield over full $p_T$ range
  - Backward rapidity (Pb-going): compatible with scaled pp yield except at $y_{cms} < -4$
  - Forward rapidity (p-going): large suppression

**Comparison with models**

- nPDF: strong nuclear shadowing favored at forward rapidity but not at mid-rapidity
- CGC: good description of mid- and forward rapidity data from saturation of gluon density in nucleus
Charmonium: $R_{pPb}$

**ALICE, JHEP07(2018)16**

**$J/\psi$ $R_{pPb}$ vs $y_{\text{cms}}$**
- Backward rapidity (Pb-going): compatible with scaled pp yield
- Forward rapidity (p-going): large suppression concentrated at low $p_T$

**Comparison with models**
- nPDF: strong nuclear shadowing favored at forward rapidity
- CGC: good description of forward rapidity data from gluon density saturation in nucleus
- Coherent energy loss: $y$-dependence well reproduced
- Comovers (nPDF and comoving particles/partons): reproduce the magnitude of the data
- Transport (nPDF and hot fireball in central collisions): underestimates ALICE backward rapidity data
**Bottomonium: $R_{ppb}$**

**$Y(1S)$ $R_{ppb}$ vs $y_{cms}$**
- Different mass than $J/\psi$: different scale
- Backward rapidity: compatible with pp scaled yield at $y_{cms} \sim -4$
- Mid- and forward rapidity: $Y(1S)$ suppressed

**Comparison with models**
- nPDF: strong nuclear shadowing favored at $y_{cms} > 0$ and ALICE $R_{ppb}$ overestimated at $y_{cms} < 0$ and low $p_T$
- Coherent energy loss: $R_{ppb}$ overestimated at $y_{cms} > 0$
Quarkonium excited states

Relative suppression of excited states vs $y_{\text{cms}}$

• At backward rapidity (Pb-going): excited states more suppressed than ground state
• Initial state effect (nPDF, CGC,...) or coherent energy loss models predict similar suppression for ground and excited states
• Excited states less bound: additional final-state effect on heavy quark pair (by comoving particles/partons) can explain the measured relative suppression

<table>
<thead>
<tr>
<th>State</th>
<th>$J/\psi$</th>
<th>$\psi'$</th>
<th>$\Upsilon$(1S)</th>
<th>$\Upsilon$(2S)</th>
<th>$\Upsilon$(3S)</th>
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<tbody>
<tr>
<td>Mass [GeV]</td>
<td>3.10</td>
<td>3.68</td>
<td>9.46</td>
<td>10.02</td>
<td>10.36</td>
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<tr>
<td>$\Delta E$ [GeV]</td>
<td>0.64</td>
<td>0.05</td>
<td>1.10</td>
<td>0.54</td>
<td>0.20</td>
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<tr>
<td>$\Delta M$ [GeV]</td>
<td>0.02</td>
<td>0.03</td>
<td>0.06</td>
<td>-0.06</td>
<td>-0.07</td>
</tr>
<tr>
<td>$r_0$ [fm]</td>
<td>0.50</td>
<td>0.90</td>
<td>0.28</td>
<td>0.56</td>
<td>0.78</td>
</tr>
</tbody>
</table>

*Cynthia Hadjidakis FCP2020 June 2020*
Open vs hidden heavy-flavour

Open and hidden charm and beauty production for $p_T > 0$

- Useful to investigate final-state effects
- No significant difference between D and J/ψ $R_{pPb}$: J/ψ modification dominated by initial state effects
- Y(1S) systematically lower than J/ψ from $b$ in p-Pb w.r.t. pp at forward rapidity: striking since the Y(1S) is more bound than the J/ψ
Relative yield measurements

Self-normalized yield vs self-normalized charged-particle multiplicity

- Useful to link pp, p-Pb and Pb-Pb
- J/ψ yield increases with increasing multiplicity
- p-Pb backward rapidity (Pb-going): stronger than linear increase and compatible with pp@7 TeV and Pb-Pb@5.02 TeV
- p-Pb forward rapidity (p-going): less than backward rapidity increase
Azimuthal anisotropies

Overlap region in non-central heavy-ion collisions is asymmetric, in « almond » shape

Momentum anisotropy of final-state particles
Quantified in terms of Fourier coefficient $v_n$

$\Psi_n$: symmetry planes

Anisotropic flows ($v_n$) sensitive to the initial geometry and properties of the produced medium

$$\frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)].$$
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Charged particles in high-multiplicity pp and p-Pb events

– Significant elliptic ($v_2$) and triangular ($v_3$) flow
– $v_n$ compatible with Pb-Pb at low $N_{ch}$
– Ordering of flow coefficient $v_2 > v_3 > v_4$ as in Pb-Pb and Xe-Xe

Models

– Hydrodynamic model describes well high-multiplicity p-Pb events, mid-central and central Pb-Pb and Xe-Xe collisions
Azimuthal anisotropies at large $p_T$

**High-$p_T$ charged particles**
- Positive elliptic and triangular flow measured for high-$p_T$ charged particles in correlation with another particle or a jet
- $R_{pPb}$ consistent with unity: no nuclear suppression

**Jet quenching model**
- Flows described by jet quenching model (medium modification of the yield from partons losing energy in QGP)
- Can not describe both $v_n$ and $R_{pPb}$: how to reconcile $v_n$ and $R_{pPb}$ at large $p_T$?
Open and hidden heavy-flavour: $v_2$

Open heavy flavour
- First measurement of $b$ flow in p-Pb: no significant flow for $D^0$ from B mesons
- Flavor hierarchy: $v_2$ (D) > $v_2$ (B) at $p_T < 3$ GeV/c similarly to Pb-Pb: common flow velocity?
- Gluon saturation model (CGC) reproduces the flavour hierarchy

$J/\psi$
- $v_2$ found positive with similar magnitude than in Pb-Pb: common mechanism in Pb-Pb and p-Pb at the origin of $v_2$?
- Different theoretical expectations for Y(1S) $v_2$ in p-Pb (Transport model vs CGC model): experimentally challenging!
Conclusion and outlook

• Many new and final results in p-Pb collisions at the LHC! Useful to understand and constrain nuclear effects at low or high multiplicity in p-Pb
  - Electroweak bosons production and first Drell-Yan $R_{FB}$: deviation of the measurements from free-PDF calculations at forward rapidities
  - Open heavy flavour and quarkonium ground states $R_{pPb}$: production largely suppressed at forward rapidity and low $p_T$ (and favour a strong gluon nuclear shadowing), moderate or no suppression at mid- and backward rapidity
  - Quarkonium excited states: relative suppression w.r.t. ground states at backward rapidity where the multiplicity is the largest
  - Azimuthal angular anisotropies: non-zero flows measured for low and high-$p_T$ charged particles, open charm and $J/\psi$ but not for open beauty: common mechanism as in Pb-Pb or initial-state effects?

• What next?
  - High luminosity p-Pb in Run3/4 very useful for rare probes and correlation studies: $L_{pPb} = 1.2$/pb for ATLAS, CMS and $L_{pPb} = 0.6$/pb for ALICE, LHCb
  - Fixed target at LHC: system size scan, lower energy in-between SPS and nominal RHIC

CERN Yellow Report, arXiv:1812.06772
CERN-PBC-REPORT-2019-001
backup slides
J/ψ and ψ(2S) in high-multiplicity pp collisions

Self-normalized yield vs self-normalized charged-particle multiplicity
• Stronger than linear increase
• Various mechanisms (color string reconnection, percolation, gluon saturation) responsible for multiplicity dependent reduction of \( dN_{\text{ch}}/d\eta \)

Double ratio \( \psi(2S) / J/\psi \)
• Hint of a multiplicity dependence of \( \psi(2S) \) relative suppression w.r.t. \( J/\psi \)?
• Comovers model predicts a stronger suppression at high multiplicity while it reproduces well \( \psi(2S) \) relative suppression in p-Pb
• Charm and beauty flow from open heavy flavor muons also measured in high multiplicity events in pp at 13 TeV: flow for muons from charm decays consistent with charged hadrons and flow for muons from beauty decays consistent with zero
Prompt charm pair production in p-Pb

First double charm production in p-Pb at 8.16 TeV
- Like-sign production enhanced by about a factor 3 at $y_{\text{cms}} > 0$ and even more at $y_{\text{cms}} < 0$

Effective cross-section $\sigma_{\text{eff}}$
- Effective transverse overlap area of the partonic correlation that produces DPS: process independent
- Increases with increasing rapidity and different for $D^0-D^0$ and $J/\psi-D^0$

\[ \sigma_{\text{eff}} = \frac{\sigma^A \sigma^B}{(1 + \delta_{AB})\sigma_{\text{DPS}}^{AB}} \]
**$\chi_{c1}(3872)$ production in high-multiplicity pp**

The nature of $\chi_{c1}(3872)$

- Hadronic molecule, tetraquark or charmonium-molecule mix?

$\chi_{c1}(3872)$ production in pp collisions vs multiplicity

- No significant dependence with multiplicity for non-prompt $\chi_{c1}(3872)$ / $\psi(2S)$
- Relative suppression of prompt $\chi_{c1}(3872)$ with increasing event multiplicity
- Comoving interaction model describes the data only by considering a hadronic size of about 1.3 fm for the $\chi_{c1}(3872)$, disfavoring the molecular state hypothesis

A. Esposito et al. Paper in preparation
Strangeness enhancement in small systems

- Strangeness production in AA: first QGP signature proposed *Rafelski PRL48(1982)1066*
- Strange to non-strange particle ratios increase with event multiplicity in Pb-Pb but also in pp and p-Pb: similar values for similar $N_{ch}$
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- **Hierarchy of increase** with strangeness content
- **Models**
  - models with color ropes - interactions between produced strings - (DIPSY) and radial expansion (EPOS) qualitatively reproduce the measured trend with multiplicity
  - PYTHIA8: no evolution with multiplicity