Strong physics at LHCb: probing nuclear matter effects in small systems

Hengne Li
(South China Normal University)
on behalf of the LHCb collaboration
The big picture

STScI-PRC-01-09

This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.
## Fundamental forces

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Current theory</th>
<th>Mediators</th>
<th>Relative strength</th>
<th>Long-distance behavior</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Quantum chromodynamics (QCD)</td>
<td>gluons</td>
<td>$10^{38}$</td>
<td>$\sim r$ (Color confinement)</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Weak</td>
<td>Electroweak Theory (EWT)</td>
<td>W and Z bosons</td>
<td>$10^{25}$</td>
<td>$1/r \cdot e^{-m_{W,Z} \cdot r}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Quantum electrodynamics (QED)</td>
<td>photons</td>
<td>$10^{36}$</td>
<td>$1/r^2$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Gravitation</td>
<td>General relativity (GR)</td>
<td>gravitons (hypothetical)</td>
<td>1</td>
<td>$1/r^2$</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>
The electroweak & Higgs sector

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Current theory</th>
<th>Mediators</th>
<th>Relative strength</th>
<th>Long-distance behavior</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Quantum chromodynamics (QCD)</td>
<td>gluons</td>
<td>$10^{38}$</td>
<td>$\sim r$ (Color confinement)</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Weak</td>
<td>Electroweak Theory (EWT)</td>
<td>W and Z bosons</td>
<td>$10^{25}$</td>
<td>$1/r \cdot e^{-m_{W,Z} \cdot r}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Quantum electrodynamics (QED)</td>
<td>photons</td>
<td>$10^{36}$</td>
<td>$1/r^2$</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

In the Electro-weak sector, the SM shows great predictive power. Two examples: (next slide)
Example 1: prediction of the Higgs boson

\[ V(\phi) = \frac{1}{2} \mu^2 \phi^2 + \frac{1}{4} \lambda (\phi^2)^2 \]

Groundstate at \[ |\phi| = \sqrt{\frac{\mu^2}{\lambda}} = v \]
Example 2: Predictive power of the EW parameters

If we use the measured Higgs mass to constrain the W boson mass assuming SM, we get:

$$M_W = 80356 \text{ MeV} \pm 8 \text{ MeV}$$

Predicted

Comparing with the current world average directly measured value:

$$M_W = 80379 \text{ MeV} \pm 12 \text{ MeV}$$

[PDG 2019, Dec. 6, 2019]

Only ~1.5 sigma difference between the two $M_W$ central values, given a precision of 0.12 per-mil!
### The strong interaction sector

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Current theory</th>
<th>Mediators</th>
<th>Relative strength</th>
<th>Long-distance behavior</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strong</strong></td>
<td>Quantum chromodynamics (QCD)</td>
<td>gluons</td>
<td>$10^{38}$</td>
<td>$\sim r$ (Color confinement)</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td><strong>Weak</strong></td>
<td>Electroweak Theory (EWT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fermions, W and Z bosons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electro-</strong></td>
<td>Quantum electrodynamics (QED)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>magnetic</strong></td>
<td>Quantum electromagnetism (QED)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrons, photons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gravitation</strong></td>
<td>General relativity (GR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gravitons (hypothetical)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the Strong force sector, because of the color confinement (non-perturbative) nature, predictions are more difficult and complicated ...
The Quantum Chromodynamics (QCD)

- Quarks bound together by strong force:
  - Gluons act as strong force mediators

- Color-confinements:
  - Strong force is described by QCD in SM
  - QCD coupling strength diverges at small energy scale, but small at large scale

- No free quarks or gluons at low energy scale, but only colorless objects: hadrons
- Quarks loosely bound at small distance

Figure 9.5: Summary of measurements of $\alpha_s$ as a function of the energy scale $Q$. The respective degree of QCD perturbation theory used in the extraction of $\alpha_s$ is indicated in brackets (NLO: next-to-leading order; NNLO: next-to-next-to-leading order; NNLO+res.: NNLO matched to a resummed calculation; N$^3$LO: next-to-NNLO).

This world average value is in very good agreement with the last version of this Review, which was $\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$, with only a slightly lower central value and decreased overall uncertainty.
The Quantum Chromodynamics (QCD)

- Perturbative QCD can solve part of the problems, not all.
- E.g. Z boson $p_T$ modeling:
  - high $p_T$ part: p-QCD
  - low $p_T$ part: next-to-next-to-leading logarithm resummation of soft gluons e.g. PRD 56, 5558 (1997)

- Lattice-QCD has great predictive power, but need this:

  ![Diagram](image)

  A rich program in the strong force sector!
Today’s main course

❖ **New results from LHCb at Quark Matter 2019:**
  ❖ **Probing the nuclear matter effects:**
    ❖ Study of the prompt D0 meson production in pPb at 8.16 TeV
      ❖ [LHCb-CONF-2019-004]
    ❖ Measurement of the Z production cross-section in proton-lead collisions at 8.16 TeV
      ❖ [LHCb-CONF-2019-003]
  ❖ **Understanding the nature of the X(3872) state:**
    ❖ Multiplicity-dependent modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in pp collisions at 8 TeV
      ❖ [LHCb-CONF-2019-005]

❖ **Let's first have a look at the LHCb detector**
LHCb provides unique datasets for Heavy Ion physics studies.

Event display from the proton-lead collisions in 2016
The LHCb detector is special

- LHCb is the only detector (at LHC) fully instrumented in forward region
- Unique kinematic coverage \(2 < \eta < 5\)
- A high precision device, down to very low-\(p_T\), excellent particle ID, precision vertex reconstruction and tracking.

Hengne Li, LHCb collaboration
Both the collider mode and fixed-target mode running at the same time:

<table>
<thead>
<tr>
<th>Collider Mode</th>
<th>Fixed-target Mode (SMOG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s} = 7, 8, 13 \text{ TeV} )</td>
<td>( \sqrt{s_{NN}} = 8.2 \text{ TeV} )</td>
</tr>
<tr>
<td>( \sqrt{s_{NN}} = 5.0 \text{ TeV} )</td>
<td>( \sqrt{s_{NN}} = 110 \text{ GeV} )</td>
</tr>
<tr>
<td>( \sqrt{s_{NN}} = 69 \text{ GeV} )</td>
<td>( \sqrt{s_{NN}} = 50 \text{ GeV} )</td>
</tr>
</tbody>
</table>

Collider mode:
- Forward and backward coverage

Fixed-target mode:
- Central and backward coverage
- \( \sqrt{s_{NN}}: 69 - 110 \text{ GeV} \), fills the gap between SPS (20 GeV) and RHIC (200 GeV) energy scales

Kinematic Acceptance
Data samples

❖ Colliding beam mode (pPb and PbPb):

<table>
<thead>
<tr>
<th>√s_{NN}</th>
<th>2013</th>
<th>2016</th>
<th>2015</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.02 TeV</td>
<td>8.16 TeV</td>
<td>5.02 TeV</td>
<td>5.02 TeV</td>
<td>5.02 TeV</td>
<td></td>
</tr>
<tr>
<td>pPb</td>
<td>1.1 nb⁻¹</td>
<td>0.5 nb⁻¹</td>
<td>pPb</td>
<td>13.6 nb⁻¹</td>
<td>20.8 nb⁻¹</td>
</tr>
<tr>
<td>10 µb⁻¹</td>
<td>0.4 µb⁻¹</td>
<td>210 µb⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

❖ Fixed Target mode (SMOG):

<table>
<thead>
<tr>
<th>√s_{NN}: 69-110 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>∫ Ldt ~ 5 nb⁻¹</td>
</tr>
<tr>
<td>2 × 10⁻⁷ mbar</td>
</tr>
</tbody>
</table>

Hengne Li, LHCb collaboration
Setups for proton-ion collisions

- **Forward production:**
  - Center of mass rapidity coverage: $1.5 < y^* < 4.0$

- **Backward production:**
  - Center of mass rapidity coverage: $-5.0 < y^* < -2.5$

- Rapidity coverage in center of mass frame considers a rapidity shift of about 0.47 w.r.t. the lab frame coverage $2.0 < y < 4.5$

- Common range for the measurements: $2.5 < |y^*| < 4.0$
Probing the nuclear matter effects
The nuclear matter effects

❖ Ultra-relativistic heavy ion collisions can help us to:

❖ Explore phase diagram of nuclear matter
❖ Large systems (AA):
   ❖ Study QCD matter under extreme conditions (hot nuclear matter effects)
   ❖ E.g. formation of Quark Gluon Plasma (QGP) at high temperature and/or energy density.
❖ Small systems (pp, pA, ..):
   ❖ Nucleon structure, intrinsic charm, reflected in the nuclear modifications (cold nuclear matter effects)
   ❖ also QGP?
❖ Many other things: QED at extreme field strengths, diffractive processes...

Space-time evolution of the collision
Proton-nucleus collisions

- Open Heavy flavors / Quarkonia / WZ boson productions as tools to study cold nuclear matter effect (CNM)
- Necessary reference to disentangle QGP effects from CMT effects in AA collisions

Initial state effects
- Nuclear shadowing, gluon shadowing at LHC [JHEP 0904 (2009) 065]
- Radiative energy loss [PRL 68 (1992) 1834]
- Cronin effects [PRD 11:3105, 1975]

Final state effects
- Nuclear absorption [Nucl. Phys. A700 (2002) 539], expected to be small at LHC [JHEP 0902.014, 2009]
- Radiative energy loss [PRC61 (2000) 035203]
- Comovers [arXiv:1411.0549v2]
- Neither initial nor final
- Coherent energy loss [PRL 109 (2012) 122301]
D0 production

- Heavy quarks produced early in heavy-ion collisions are excellent probes of the cold and hot nuclear matter effects in pPb and PbPb collisions.
- Cold nuclear matter effects, including modification of PDFs in nuclei and other initial/final state effects, might be dominant in pPb collisions.
- The LHCb detector is excellent in pPb collisions for heavy quark production.
- Charm production can be used to probe nuclear modifications at very small $Q^2$ and very small Bjorken-$x$ ($x < 10^{-4}$ and $5 \times 10^{-3} < x < 5 \times 10^{-2}$) in pPb collisions at $\sqrt{s} = 5.02$ TeV were published recently.
- High statistics data of pPb collisions at $\sqrt{s} = 8.16$ TeV are expected to provide high accuracy measurements of prompt open charm hadrons.
Definition of observables

- **Double differential cross-section:**
  \[
  \frac{d^2\sigma}{dp_Tdy^*} = \frac{N}{\mathcal{L} \times \epsilon_{\text{tot}} \times \mathcal{B} \times \Delta p_T \times \Delta y^*}
  \]
  - Prompt signal yields
  - Integrated luminosity
  - Total efficiency
  - Branching ratio

- **Nuclear modification factor:**
  \[
  R_{pPb} (p_T, y^*) = \frac{1}{A} \frac{d^2\sigma_{pPb} (p_T, y^*)/dp_Tdy^*}{d^2\sigma_{pp} (p_T, y^*)/dp_Tdy^*}
  \]

- **Forward-backward production ratio:**
  \[
  R_{FB} (p_T, y^*) = \frac{d^2\sigma_{pPb} (p_T, +|y|^*)/dp_Tdy^*}{d^2\sigma_{pPb} (p_T, -|y|^*)/dp_Tdy^*}
  \]

- **Baryon to meson ratio:**
  \[
  R_{\Lambda^+/D^0} (p_T, y^*) = \frac{d^2\sigma_{\Lambda^+} (p_T, y^*)/dp_Tdy^*}{d^2\sigma_{D^0} (p_T, y^*)/dp_Tdy^*}
  \]

Hengne Li, LHCb collaboration
Cross-section measurement

- $D^0$ yields extracted from $K^\mp \pi^\pm$ mass fits
- Prompt and non-prompt (from b-decay) are separated using fit to the impact parameter (IP) $\chi^2$ spectrum

Total efficiency calculated using simulation and calibration data samples:
- **Forward:** from 0.8% to 14%
- **Backward:** from 0.7% to 13%

Hengne Li, LHCb collaboration
Results from 5.02 TeV pPb collisions

Nuclear modification factor vs. D⁰ pT

JHEP 10 (2017) 090

Nuclear modification factor vs. D⁰ rapidity

- \( R_{pPb} \) suppressed in forward region (~30%), no suppression in backward region, hint of small excess at large backward rapidity (y*<4)
- Baryon-to-meson, forward rapidity: discrepancies at high-\( p_T \) between data and models tuned to pp

Ratio between \( D^0 \) and \( \Lambda_c^+ \)

Hengne Li, LHCb collaboration
Differential cross-section at 8.16 TeV

Double-differential cross-section \(d^2\sigma/dp_Tdy^*\)

- Differential cross-sections (vs. \(p_T\)) and (vs. \(y^*\)) for forward and backward separately

Henghe Li, LHCb collaboration
Forward-backward ratio at 8.16 TeV

- Forward-backward ratio $R_{FB}$

- Improved statistics by factor 20 compared to previous LHCb results.

- Tension between data and nPDFs predictions. Additional effects required.

Electroweak bosons are unmodified by the hot and dense medium created in heavy ion collisions,

Their leptonic decays pass through the medium without being affected by the strong interaction.

Therefore, electroweak boson productions well "conserved" the initial conditions of the collisions, can be:

- used to probe (cold) nuclear effects and constraint nPDFs for Bjorken-x from \(10^{-4}\) to 1 at \(Q^2 \sim 10^4 \text{ GeV}^2\)
- and can be used as a calibration of the nuclear modification of other processes such as heavy quark production
Z boson production in pPb

- Cross-sections measured in fiducial volume for both pPb and PbP:
  \[ \sigma_{Z \rightarrow \mu^+ \mu^-} = \frac{N_{\text{sig.}}}{\mathcal{L} \cdot \epsilon_{\text{tot}}} \]

- Forward-backward ratio measured in fiducial volume + common rapidity coverage:
  \[ R_{FB}^{2.5 < |y^*| < 4.0} = \frac{\sigma_{Z \rightarrow \mu^+ \mu^-, pPb}}{\sigma_{Z \rightarrow \mu^+ \mu^-, PbP}} \text{ with } 2.5 < |y^*| < 4.0 \]

- Fiducial volume:
  \[ 60 < m_{\mu\mu} < 120 \text{ GeV} \]
  \[ 2.0 < \eta^{\mu} < 4.5, \quad p_T^\mu > 20 \text{ GeV} \]
Z boson production in pPb at 5 TeV

- Integrated luminosity: forward (1.099 ± 0.021 nb⁻¹) / backward (0.521 ± 0.011 nb⁻¹)
- Yields: forward (11 events) / backward (4 events)

**Figure 1**

- Invariant dimuon mass distribution of selected candidates in (a) the backward and in (b) the forward, in the laboratory frame, the bottom one the efficiency determination
- Yields: forward (11 events) / backward (4 events)
- Integrated luminosity: forward (1.099 ± 0.021 nb⁻¹) / backward (0.521 ± 0.011 nb⁻¹)

LHCb collaboration

† Hengne Li

LHC Seminar, 10 Dec. 2019, CERN
Z boson production in pPb at 5 TeV

- Fiducial cross-section results:
  - Forward:
    $\sigma_{Z\rightarrow\mu^+\mu^-}(fwd) = 13.5^{+5.4}_{-4.0}\text{(stat.)} \pm 1.2\text{(syst.)}\text{ nb}$
  - Backward:
    $\sigma_{Z\rightarrow\mu^+\mu^-}(bwd) = 10.7^{+8.4}_{-5.1}\text{(stat.)} \pm 1.0\text{(syst.)}\text{ nb}$
  - Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with:
    - MSTW08(PDF) for both p and Pb
    - MSTW08(PDF) for p and EPS09(nPDF) for Pb

Hengne Li, LHCb collaboration
Z boson production in pPb at 8 TeV

- Integrated luminosity: forward (12.2 ± 0.3 nb⁻¹) / backward(18.6 ± 0.5 nb⁻¹)
- Yields: forward (268 events) / backward (167 events)

LHCb Preliminary

\( \sqrt{s_{NN}} = 8.16 \text{ TeV} \)

- Forward
- Backward

Candidates / (3 GeV)

- LHCb Preliminary
- PbPb
- \( m_{\mu^+\mu^-} \) [GeV]
- Z → \( \mu^+\mu^- \)
  - (PbPb data)
  - (MC PYTHIA8)

Figure 1: Control plots of the dimuon system after the offline selection, which includes the dimuon invariant mass (\( m_{\mu^+\mu^-} \)) distributions for pPb (a) and PbPb (b) configurations, the \( p_T \) of the Z candidates (\( p_T(Z) \)) for pPb (c) and PbPb (d) configurations, and the rapidity of the dimuon system in the centre-of-mass frame (\( y^{*}_{Z} \)) for pPb (e) and PbPb (f) configurations. The red line shows the distributions from simulation generated using Pythia 8 with CTEQ6L1 PDF set, normalised to the number of observed candidates.
pPb $Z$ boson production at 8 TeV

- Integrated luminosity:
  - forward $(12.2 \pm 0.3 \text{ nb}^{-1})$
  - backward $(18.6 \pm 0.5 \text{ nb}^{-1})$
- Yields:
  - forward (268 events)
  - backward (167 events)
- MC normalized to data yields

【LHCb-CONF-2019-003】

Hengne Li, LHCb collaboration
pPb Z boson production at 8 TeV

- Fiducial cross-section results:
  \[ \sigma_{Z \rightarrow \mu^+\mu^-}, \text{pPb (forward)} \]
  \[ = 28.5 \pm 1.7 \text{(stat.)} \pm 1.2 \text{(syst.)} \pm 0.7 \text{(lumi.) nb} \]
  \[ \sigma_{Z \rightarrow \mu^+\mu^-}, \text{Pbp (backward)} \]
  \[ = 13.4 \pm 1.0 \text{(stat.)} \pm 1.4 \text{(syst.)} \pm 0.3 \text{(lumi.) nb} \]

- Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with NNPDF3.1(PDF) for p and
  - NNPDF3.1(PDF)
  - EPPS16 (nPDF)
  - nCTEQ15 (nPDF)

Hengne Li, LHCb collaboration
Compare with results at 5 TeV

- Results are compatible with previous 5 TeV results from various experiments
- The 20 times higher statistics bring higher precision in the measurements

* only exp. uncert. shown on data/theory ratio, theo. PDF uncert. shown separately on the line at one.
Forward-backward ratio

\[
\text{Forward-backward ratio is derived based on cross-sections measured in the common rapidity range:}
\]
\[
\sigma_{Z \rightarrow \mu^+ \mu^-}, pPb = 17.1 \pm 1.4(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.4(\text{lumi.}) \text{ nb},
\]
\[
\sigma_{Z \rightarrow \mu^+ \mu^-}, PbPb = 13.3 \pm 1.0(\text{stat.}) \pm 1.4(\text{syst.}) \pm 0.3(\text{lumi.}) \text{ nb},
\]

\text{† Measured forward-backward ratio}
\[
R_{FB}^{2.5<|y^*|<4.0} = 1.28 \pm 0.14(\text{stat.}) \pm 0.14(\text{syst.}) \pm 0.05(\text{lumi.}).
\]

\text{†† Compatible with theoretical predictions:}
\[
R_{FB,\text{NNPDF3.1}}^{2.5<|y^*|<4.0} = 1.59 \pm 0.10(\text{theo.}) \pm 0.01(\text{num.}) \pm 0.05(\text{PDF}),
\]
\[
R_{FB,\text{NNPDF3.1+EPSS16}}^{2.5<|y^*|<4.0} = 1.45 \pm 0.10(\text{theo.}) \pm 0.01(\text{num.}) \pm 0.27(\text{PDF}),
\]
\[
R_{FB,\text{NNPDF3.1+nCTEQ15}}^{2.5<|y^*|<4.0} = 1.44 \pm 0.10(\text{theo.}) \pm 0.01(\text{num.}) \pm 0.20(\text{PDF}).
\]
Understanding the nature of the X(3872)
The story started in 2003

- The first exotic hadron – discovered in $J/\psi \pi^+ \pi^-$ mass spectrum from B decays by Belle in 2003
- Properties do not appear to fit the standard picture of charmonium state
- More than 20 previously unpredicted charmonium- and bottomonium-like states have been discovered, and the understanding of heavy quarkonium physics is undetermined.
X(3872): a puzzle

- The first exotic hadron – discovered in \(J/\psi\pi^+\pi^-\) mass spectrum from B decays by Belle in 2003
- LHCb measured quantum numbers [PRL 110 (2013) 222001]
- \(J^{PC} = 1^{++}\)
- Mass is consistent with sum of \(D^0\) and \(\bar{D}^{*0}\) masses:
  \[
  M_{\chi_{c1}^{(3872)}} - (M_{D^0} + M_{\bar{D}^{*0}}) = 0.01 \pm 0.27 \text{MeV}
  \]
  PDG 2019 has changed the naming X(3872) to \(\chi_{c1}^{(3872)}\)

**Diagram:**
- **Molecule**:
  - \(D^0\bar{D}^{*0}\)
  - Very small binding energy and very large radius, \(\sim 7\) fm
- **Compact tetraquark**:
  - Tightly bound via color exchange between diquark
  - Small radius, \(\sim 1\) fm

Belle Collaboration
PRL 91 262001 (2003)
Effects of binding energy learned from pA collisions

- Strength of the binding energy could be a key point to understand the nature of the exotic state

<table>
<thead>
<tr>
<th>state</th>
<th>$\eta_c$</th>
<th>$J/\psi$</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
<th>$\psi'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass [GeV]</td>
<td>2.98</td>
<td>3.10</td>
<td>3.42</td>
<td>3.51</td>
<td>3.56</td>
<td>3.69</td>
</tr>
<tr>
<td>$\Delta E$ [GeV]</td>
<td>0.75</td>
<td>0.64</td>
<td>0.32</td>
<td>0.22</td>
<td>0.18</td>
<td>0.05</td>
</tr>
</tbody>
</table>


- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
- Ratios of $[\psi(2S)]/[J/\psi]$ and $[\Upsilon(2S,3S)]/[\Upsilon(1S)]$
- Suppression is generally explained with final state effects: regions with high particle multiplicities

LHC Seminar, 10 Dec. 2019, CERN
Apply the binding energy understanding to pp

- Strength of the binding energy could be a key point to understand the nature of the exotic state
- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
- Suppression is generally explained with final state effects: regions with high particle multiplicities
- If X(3872) is a weakly bound hadronic molecule, it may show similar effects:

<table>
<thead>
<tr>
<th>state</th>
<th>$\eta_c$</th>
<th>$J/\psi$</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
<th>$\psi'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass [GeV]</td>
<td>2.98</td>
<td>3.10</td>
<td>3.42</td>
<td>3.51</td>
<td>3.56</td>
<td>3.69</td>
</tr>
<tr>
<td>$\Delta E$ [GeV]</td>
<td>0.75</td>
<td>0.64</td>
<td>0.32</td>
<td>0.22</td>
<td>0.18</td>
<td>0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$D^0\bar{D}^{*0}$ Molecule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very small binding energy and very large radius, ~ 7 fm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compact tetraquark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tightly bound via color exchange between diquark</td>
</tr>
<tr>
<td>Small radius, ~ 1 fm</td>
</tr>
</tbody>
</table>

Probing X(3872) structure in high-multiplicity conditions

❖ **Prompt production (study object):**
❖ X(3872) produced at collision vertex can be subject to further interactions with e.g. co-moving particles produced in the event, potentially subject to breakup effects ==> suppression!

❖ **Production in b-decays (control sample):**
❖ X(3872) is produced outside of the primary collision volume
❖ Hadrons containing b travel down the beampipe and decay away from the primary vertex and decay in vacuum
❖ X(3872) is not subject to interactions with co-moving particles
Selection of X(3872)

- LHCb pp collisions at 8 TeV
- Reconstruct the X(3872) and ψ(2S) from $\mu^+\mu^-\pi^+\pi^-$ final states:
  $X(3872) \rightarrow J/\psi (\rightarrow \mu^+\mu^-) \rho (\rightarrow \pi^+\pi^-)$
  $\psi(2S) \rightarrow J/\psi (\rightarrow \mu^+\mu^-) \pi^+\pi^-$
- Select $J/\psi$ from dimuons, combine with two identified pions. Kinematic fit constraining $J/\psi$ mass to known value and all four tracks to identical vertex.
- Direct comparison between conventional charmonium $\psi(2S)$ and exotic X(3872) via ratio of cross sections:
  $$\frac{\sigma_{Xc1(3872)} \times \mathcal{B}[Xc1(3872) \rightarrow J/\psi\pi^+\pi^-]}{\sigma_{\psi(2S)} \times \mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^+\pi^-]}$$

Hengne Li, LHCb collaboration

LHCb-CONF-2019-005

LHCb Preliminary

pp $\sqrt{s} = 8$ TeV

LHC Seminar, 10 Dec. 2019, CERN
Prompt / b-decay separation

- Simultaneous fit to invariant mass and pseudo proper time spectrum:
  \[ t_z = \frac{z_{\text{decay}} - z_{PV}}{p_z} M \]

- Invariant mass to separate resonance vs. background
- Pseudo proper time to separate prompt and b-decay components
Prompt fraction

- Prompt fraction
  \[ f_{\text{prompt}} = \frac{N_{\text{prompt}}}{N_{\text{prompt}} + N_{b-\text{decay}}} \]

- Significant decrease in prompt fraction of both \( X(3872) \) and \( \psi(2S) \) as event activity increases

- Formation of prompt \( X(3872) \) and \( \psi(2S) \) may be disrupted at the primary vertex, which cannot affect production via \( b \) decays in vacuum.
Ratio of cross-sections

- Ratio of cross-sections:
  \[
  \frac{\sigma_{\chi_c(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_c(3872) \rightarrow J/\psi \pi^+ \pi^-]}{\mathcal{B}[\psi(2S) \rightarrow J/\psi \pi^+ \pi^-]} = \frac{N_{\chi_c(3872)} f_{\chi_c(3872)}^{\text{prompt}}}{N_{\psi(2S)} f_{\psi(2S)}^{\text{prompt}}} \times \frac{\epsilon_{\psi(2S)}}{\epsilon_{\chi_c(3872)}}
  \]

- Prompt Component (study object):
  - Increasing suppression of \(X(3872)\) production relative to \(\psi(2S)\) as event activity increases
  - Syst. uncert. due to eff. is fully correlated bin-by-bin

- \(b\)-decay component (control sample):
  - No significant change in relative production, as expected for decays in vacuum (compatible with a straight line).
  - Ratio is set by decay branching fractions of \(b\) and \(X(3872)\).
  - The average ratio agrees with ATLAS measurement
  - \(R = 0.0395 \pm 0.0032 \pm 0.0008\) (\(p_T > 10\,\text{GeV}\)) [JHEP 2017:117 (2017)]
Outlook

❖ Rich heavy ion program in understanding strong interactions are on going at LHCb.
❖ Results of the following analyses are coming soon!
❖ more plots see: https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlotsQM2019
LHCb fixed-target program evolution

- **SMOG 2 (TDR)**: Standalone gas storage cell covering z position -500 to -300 mm:
  - Up to x100 higher gas density with same gas flow of current SMOG.
  - Gas feed system measures the gas density with few % accuracy.
  - Installation due in December 2019, to be operational from the start of LHC Run 3.
The Standard Model of particle physics has demonstrated its predictive power in the electroweak and Higgs sectors.

Due to the nonperturbative nature of QCD at low energy scales, the predictive power of the SM in the strong sector is more limited. => rich program in the strong force sector is still in front of us!

The LHCb detector has unique capabilities at the LHC, being the only dedicated forward detector.

Capabilities can also be applied to strong interaction physics.

Recent results from LHCb:

- Probing cold nuclear matter effects using D⁰ and Z boson production have been discussed.
- The efforts to understand the nature of the X(3872) resonance has been presented.
- Rich heavy ion program in understanding strong interactions are on going at LHCb.