Quarkonium production as a function of charged-particle multiplicity in pp collisions measured by ALICE at the LHC

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Outline

• Motivations

• The ALICE detector

• Analysis strategy

• New ALICE results in pp collisions at $\sqrt{s} = 13$ TeV & $\sqrt{s} = 5.02$ TeV

• Summary
Motivations

Quarkonium production as a function of charged-particle multiplicity is an observable developed since 2010 to study:

- Quarkonium production mechanism
- Multiple parton interactions
- Interplay between soft and hard processes

**Observables**

- x axis: relative charged-particle density
- y axis: relative quarkonium yield

**Advantages:**

- Several efficiency factors cancel in relative yields
- Easy to compare results for different energies and systems
The ALICE detector

**ITS:** Inner Tracking System
6 layers (2 drifts, 2 strips, 2 pixels)

**SPD:** Silicon Pixel Detector
2 innermost layers of ITS
Tracking, Vertexing

Charged-particle multiplicity:
Tracklet (=track segments) from SPD within $|\eta| < 1.0$

**ALICE central barrel**

$|\eta| < 0.9$

$J/\psi \rightarrow e^+e^-$

**Muon spectrometer**

$2.5 < y < 4$

$J/\psi, Y \rightarrow \mu^+\mu^-$

y-gap: multiplicity measured at mid-rapidity, quarkonia measured at forward rapidity

w/o y-gap: both multiplicity & quarkonia are measured at mid-rapidity
## Analysis strategy: Event selection & cuts

### Event cuts
- Pile up rejection
- Vertex with good SPD resolution
- At least one primary vertex contributor
- Events within $|Z_{\text{vertex}}|<10$ cm

### Trigger selection
- Minimum Bias (MB)
- Unlike sign di-$\mu$ trigger

### Multiplicity selection
- SPD tracklets within $|\eta|<1$
- INEL>0 selection from MC

**INEL>0 selection:** events with at least one physical primary charged particle within $|\eta|<1$

### $\mu$ event selection
- For single $\mu$:
  - $-4< \eta < -2.5$
  - Matching tracks in tracking & trigger system
  - $17.6$ cm < $R_{\text{abs}}$ < $89.5$ cm ($R_{\text{abs}} = \text{radial position of the track at the end of muon front absorber}$)
  - $p \times \text{DCA} \ (\text{Distance Closest Approach})$, within $6\sigma$ (only for $\Upsilon$)
- For di-$\mu$:
  - Opposite sign $\mu$ pairs
  - $2.5 < y < 4$
Analysis strategy: multiplicity estimation $|\eta|<1$

- Apply SPD inefficiency correction to get corrected tracklet distribution (red points)

- $N_{\text{Tracklets}}$ is approximately proportional to multiplicity estimated from MC simulation

\[
\frac{\langle dN_{\text{ch}}/d\eta \rangle_i}{\langle dN_{\text{ch}}/d\eta \rangle} \propto \frac{\langle N_{\text{corrected tracklet}} \rangle_i}{\langle N_{\text{corrected tracklet}} \rangle}
\]

- $\langle dN_{\text{ch}}/d\eta \rangle_i$, mean number of charged particles in multiplicity interval $i$
- $\langle dN_{\text{ch}}/d\eta \rangle$, mean number of charged particles

- Systematic uncertainties for charged particles are computed from
  - different MC generators (EPOS, PYTHIA)
  - tracklet to charged particle correlation
  - different vertex ranges

- Efficiency factors & systematic uncertainties for event selection
  - trigger selection
  - INEL$>0$ selection
Analysis strategy: relative quarkonia yields 
\(Q = J/\psi \text{ or } \Upsilon\)

\[
\frac{dN_Q/dy}{\langle dN_Q/dy \rangle} = \frac{N_i^Q}{N_i^{tot}} \times \frac{N_{MB}^{tot}}{N_i^{MB}} \times \epsilon
\]

- \(N_i^Q \text{ and } N_i^{tot,Q}\), quarkonia yields in multiplicity interval \(i\) & in total
- \(N_{MB}^{i} \text{ and } N_{MB}^{tot}\), MB events in multiplicity interval \(i\) & in total
- \(\epsilon\), efficiency factors concerning trigger selection, event cuts, pile up rejection & correction factor for INEL>0

Signal extraction by fitting with:
Extended Crystal Ball function (for \(J/\psi\))
One extended crystal ball for each \(\Upsilon\) state

Background:
Variable-width Gaussian fit

- Systematic uncertainty sources: signal extraction using different fit conditions
New ALICE results at forward rapidity
J/ψ production as a function of multiplicity

- pp, \( \sqrt{s} = 13 \) TeV
- Multiplicity measured at mid-rapidity
- J/ψ \( \rightarrow \mu^+\mu^- \) at forward rapidity

- J/ψ yield increases approximately linearly with increasing multiplicity
- Slope compatible with 1, \( x=y \) correlation
J/ψ production as a function of multiplicity

- pp, √s=13 TeV
- pp, √s=5.02 TeV

- Multiplicity measured at mid-rapidity
- J/ψ→μ⁺μ⁻ at forward rapidity

- J/ψ yield increases approximately linearly with increasing multiplicity
- Slope compatible with 1, x=y correlation
- No strong energy dependence between 5.02 and 13 TeV
$\Upsilon$ production as a function of multiplicity

First ALICE measurement of $\Upsilon$ versus multiplicity

- $pp, \sqrt{s}=13$ TeV
- Multiplicity measured at mid-rapidity
- $\Upsilon \rightarrow \mu^+\mu^-$ at forward rapidity

- $\Upsilon(1S)$ yield increases approximately linearly with increasing multiplicity
- Slope compatible with 1, $x=y$ correlation

ALICE Preliminary
$\Upsilon(1S) \rightarrow \mu^+\mu^-, 2.5 < y < 4$

Mult. classes: $|\eta|<1$

$\frac{dN_{\Upsilon(1S)}}{d\eta}$

$\frac{dN_{ch}}{d\eta}$

$\frac{N_{\Upsilon(1S)}}{N_{ch}}$

\text{ALICE-PREL-309508}
**ϒ production as a function of multiplicity**

- pp, $\sqrt{s}=13$ TeV

- Multiplicity measured at mid-rapidity
- $ϒ\rightarrow\mu^+\mu^-$ at forward rapidity

- $ϒ(1S), \,ϒ(2S)$ yields increase approximately linearly with increasing multiplicity
- Slope compatible with 1, $x=y$ correlation

First ALICE measurement of $ϒ$ versus multiplicity
Relative quarkonium yields as a function of multiplicity

- Approximately linear increase for J/ψ, Υ(1S) & Υ(2S) at forward rapidity with slope compatible to 1 (with y-gap)
- Deviation from linearity for J/ψ at mid-rapidity with slope ≠ 1 (w/o y-gap)

▷ No dependence on mass and quark content
▷ Strong rapidity dependence of relative quarkonia versus relative multiplicity
Excited to ground state ratio is compatible with unity within current uncertainties

Deviation from linearity for $\Upsilon$ in the central rapidity (w/o $y$-gap, CMS)

Excited to ground state disappearance in pp at 2.76 TeV & 7 TeV (CMS)

20% decrease in $\Upsilon(2S)/\Upsilon(1S)$ by CMS is still compatible within current uncertainties

Caveats: Not exactly the same observables
J/ψ in pp collisions at √s=13 TeV: comparison with theory

- Theoretical calculations are available only for J/ψ and D mesons at mid-γ
- Theoretical calculations for J/ψ & Y at forward-γ would be very interesting

**PYTHIA:**
Hard processes, MPI, ISR/FSR, color reconnection

**Percolation model:**
PRC86 (2012) 034903
Non linearity caused for a reduction of charged particles due to string percolation

**EPOS3:**
Initial conditions followed by a hydrodynamical evolution

**Kopeliovich et al:**
PRD88 (2013) 116002
Contribution from higher fock states
Summary

- New ALICE results for quarkonia at forward rapidity
  - $J/\psi$, $\Upsilon$ production as a function of multiplicity
  - Approximately linear correlation found for quarkonia with increasing multiplicity
  - No evidence for dependence on colliding energy, mass & quark content
- Strong rapidity dependence on relative quarkonia versus relative multiplicity
- Would be interesting to perform the measurement with multiplicity measured at forward rapidity
- Missing theoretical calculations in the forward rapidity region
Back up
Y production as a function of multiplicity at central rapidity

- Deviation from linearity is observed by CMS for pp 2.76 TeV
- Excited-to-ground state disappearance in central y region for different energies and systems (pp 2.76 & 7 TeV, pPb 5.02 TeV)
- This event activity dependency is confirmed at pp 7 TeV in forward, backward & transverse region
- Global behavior of double ratio has been observed irrespective of the collisions system; pp, pPb
\( \Upsilon \) excited to ground state ratio

- Excited to ground state ratio is compatible with 1 within current uncertainties (with \( y \)-gap)
- Deviation from linearity for \( \Upsilon \) in the central rapidity (w/o \( y \)-gap, CMS)
- Excited to ground state ratio, independent of event activity at least in pp with \( y \)-gap (CMS)
- Caveats: Not exactly the same observables
Hadronization of quarkonium plays a role?

Mid-rapidity

D meson vs. multiplicity

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Multiplicity at mid-\( \eta \)

Multiplicity at forward-\( \eta \) & backward-\( \eta \)
Analysis strategy

Signal extraction

Signal:
Extended Crystal Ball function (for J/ψ)
One extended crystal ball per each states (for Ψ)

Background:
Variable-width Gaussian function
Product of an exponential and a power law
Double exponential

Tail Parameter:
2 sets (MC, Data driven) for Ψ
1 set (MC) for J/ψ

Fitting ranges:
6-13, 5-14, 7-12 GeV/c^2 (for Ψ)
2-5 GeV/c^2 (for Ψ)

Relative Q

\[
\frac{dN_Q/dy}{\langle dN_Q/dy \rangle} = \frac{N_Q}{N_{tot}} \times \frac{N_{MB}^{tot}}{N_{i}^{MB}} \times \frac{\epsilon_Q^{tot}}{\epsilon_i^{MB}} \times \frac{\epsilon_i^{Q}}{\epsilon_{tot}^{MB}}
\]