Elliptic flow of J/ψ at forward rapidity in Pb-Pb collisions at 2.76 TeV with the ALICE experiment

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Outline

- **Physics motivation**
  - Color screening suppression versus J/ψ (re)generation
  - Does J/ψ flow or not flow
    ⇒ J/ψ production mechanism in heavy-ion collisions

- **ALICE setup**

- **Data analysis**
  - J/ψ signal and elliptic flow extraction

- **Results and discussion**
  - Differential J/ψ $v_2$ in 20%-60%
    - Comparison with STAR results and theory calculations
  - Differential J/ψ $v_2$: centrality scan
  - Centrality dependence of J/ψ $v_2$ with $p_T \geq 1.5$ GeV/c

- **Summary and conclusions**
In Pb-Pb collisions at LHC energy
- Less suppression at LHC than at RHIC
  - No strong centrality dependence in most central collisions
  - Less suppression at low $p_T$
- Described by various models including a large fraction of regenerated J/ψ from charm quarks in the QGP

J/ψ elliptic flow at RHIC

At RHIC energy → results favor zero or very small $v_2$

$v_2^{J/ψ}$ in Au+Au collisions at 200 GeV at $b = 7.8$ fm

pQCD and thermal scenarios → small $v_2$ at RHIC

If charm quark participates in collective motion of QGP, its $v_2$ will be transferred to J/ψ when charm quarks recombine.
J/ψ elliptic flow at the LHC energies

A significant elliptic flow may be expected at LHC energies due to the significant contribution of (re)generated J/ψ.
ALICE experimental setup

Muon spectrometer acceptance:
$-4 < \eta_\mu < -2.5$, $p_T^{J/\psi} \geq 0$ with $2.5 < y_{J/\psi} < 4$

$J/\psi$ from $e^+e^-$ channel at mid-rapidity
L. Arsene, parallel 2D
J/ψ in Pb-Pb collisions at 2.76 TeV

- **Event selection**
  - Unlike sign muon trigger
  - Require $|Z_{vtx}| < 10$ cm
  - Centrality: from a geometrical Glauber model fit of the VZERO amplitude
    - Centrality bins used for this study
      [5, 20]%, [20, 40]%, [40, 60]%
      [60, 90]%, [20, 60]%

- **J/ψ candidates selection**
  - $J/ψ \rightarrow \mu^+\mu^-$ with muons measured in the muon spectrometer
    - Opposite-sign dimuons rapidity
      $2.5 < y^{\mu^+\mu^-} < 4$
    - Decay daughters:
      1) muon track with low $p_T$ trigger matching ($p_T > 1$ GeV/$c$)
      2) $-4 < \eta^{\mu^+\mu^-} < -2.5$
      3) $170° < \theta_{abs} < 178°$
J/ψ signal (yield) extraction

- Fit the invariant mass spectrum of opposite sign dimuons
  - Signal
    - Crystal Ball (CB) function
      - Signal shape fixed via the J/ψ production in pp simulation
        *i.e. non-Gaussian tail*
    - Extended Crystal Ball (CB2) function
      - Signal shape fixed via the reconstructed J/ψ from a MC sample with embedding 1 simulated J/ψ in each real MB Pb-Pb event
        *i.e. non-Gaussian tails on both sides of the J/ψ peak*
  - Background
    - Variable width Gaussian (VWG)
    - 3\textsuperscript{rd} order polynomial (POL3) function
  - Fitting range
    - Varies for systematics study
J/ψ elliptic flow analysis methods

- With event plane (by VZERO-A)
  - Standard event plane method ($n\Delta\varphi$ method):
    \[ \Delta\varphi = \phi - \Psi_{EP},2 \]
  - $dN_{J/\psi}/d\Delta\varphi = A \times (1 + 2v_2 \cos 2\Delta\varphi)$
  - Invariant mass fit technique:
    \[ v_{2^+}^{\mu^+}\mu^- = \langle \cos 2(\Delta\varphi) \rangle \]
    \[ v_{2^+}^{\mu^+}\mu^- = (S \times v_{2}^{\text{sig}} + B \times v_{2}^{\text{bkg}})/(S + B) \]

  ➔ Finally, correct $v_2^{\text{obs}}$ by the event plane resolution $\sigma_{EP}$

  \[ v_2 = v_2^{\text{obs}} / \sigma_{EP} \]

- Method w/o event plane – a cumulant method
  - 2-particle correlation method with detectors with large $\eta$ gap:
    dimuon + SPD tracklets + VZERO-A for dimuon $v_2$
  - Combine with invariant mass fit technique for extraction of $v_2^{\text{sig}}$
    - Largely limited by statistical uncertainties

Event plane determination from VZERO

- VZERO detectors
  - 2 arrays of 32 scintillators on both side of IP:
    - VZERO-A: $2.8 < \eta < 5.1$
    - VZERO-C: $-3.7 < \eta < -1.8$

- Event plane from VZERO-A\(^1\) second harmonics
  \[
  Q_{n,x} = \frac{\sum_{i=0}^{31} S_i \cos(n\phi_i)}{\sum_{i=0}^{31} S_i} \\
  Q_{n,y} = \frac{\sum_{i=0}^{31} S_i \sin(n\phi_i)}{\sum_{i=0}^{31} S_i} \\
  \Psi_{EP,2} = \frac{\arctan(2(Q_{2,x}, Q_{2,y}))}{2}
  \]

- EP flattened (~1% fluctuation) and resolution obtained from 3 sub-events method

- Event plane resolution in a large centrality bin
  - Estimated by a weighted sum of event plane resolutions using J/$\psi$ yields as weights in its sub-centrality bins

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\(^1\)VZERO-C was not used due to acceptance overlap with the muon spectrometer ($-4.0 < \eta < -2.5$) to avoid autocorrelation effects
J/ψ elliptic flow extraction

- Methods using VZERO-A event plane

6-Δφ method

\[
\frac{dN_{J/\psi}}{d\Delta\phi} = A \times [1 + 2v_{2}^{obsv} \cos(2\Delta\phi)]
\]

\[
v_2 = \frac{v_{2}^{obsv}}{\sigma_{EP}}
\]

2nd order polynomial function used to describe \langle p_T \rangle and \nu_2 of the background

\[
v_2^{\mu^+\mu^-} = \frac{S \times v_{2}^{sig} + B \times v_{2}^{bkg}}{(S + B)}
\]
"J/ψ \( v_2 \) in centrality 20%-60%"

- \( 2 \leq p_T < 4 \text{ GeV/c} \)

hint of non-zero \( v_2 \) with significance \( \sim 2.2 \text{ sigma} \)

\[ \text{Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV, centrality } 20\% - 60\% \]

\[ \text{J/ψ: } 2.5 < y < 4.0, p_T \geq 0 \text{ GeV/c} \]

6-\( \Delta \phi \) method

\( \sim 2\% \) relative syst. error from \( \sigma_{EP} \) correction

~2% relative syst. error from \( \sigma_{EP} \) correction
J/ψ $v_2$ in centrality 20%-60%

- $2 \leq p_T < 4 \text{ GeV}/c$: contrary to STAR measurement
- Hint of non-zero $v_2$ with significance $\sim 2.2$ sigma

![Graph](Image)

- ALICE Prel. Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, J/ψ: $2.5 < y < 4.0$, $p_T \geq 0$ GeV/c
- STAR Prel. Au-Au $\sqrt{s_{NN}} = 0.2$ TeV, J/ψ: $|\eta| < 0.9$, JPG 38 (2011) 124107
**J/ψ ν₂ in centrality 20%-60%**

- **versus** calculations from parton transport models: in agreement within errors

![Graph of J/ψ ν₂ in centrality 20%-60%](image)

- **Pb-Pb √s_{NN} = 2.76 TeV, Centrality 20% - 60%**
- **J/ψ**: 2.5 < y < 4.0, p_T ≥ 0 GeV/c

**ALICE preliminary**: 6-Δφ method with VZERO-A EP

- **Transport model**: R. Rapp et al. (priv. comm.)
- **Transport model**: P. Zhuang et al., b thermalized (priv. comm.)
- **Transport model**: P. Zhuang et al., b not thermalized (priv. comm.)
6-Δφ method vs. inv. mass fit technique

- Agreement achieved between two methods
- *Invariant mass fit technique* is used for $J/\psi$ $v_2$ in finer centrality bins (5%-20%, 20%-40%, 40%-60% and 60%-90%)

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, centrality 20% - 60%

$J/\psi$: $2.5 < y < 4.0$, $p_T \geq 0$ GeV/c

6-Δφ method: ALICE preliminary

Invariant mass fit technique

![Graph showing the comparison between 6-Δφ method and Invariant mass fit technique for $J/\psi$ $v_2$ in Pb-Pb collisions.](image)
J/ψ $v_2$ in smaller centrality bins

At intermediate $p_T$: $2 \leq p_T < 6$ GeV/c

- 5%-20%: hint of non-zero $v_2$ with significance $\sim 2.2$ sigma
- 20%-40%: indication of non-zero $v_2$ with significance $\sim 3.0$ sigma
- 40%-60%: statistical errors too large
Centrality dependence of $J/\psi$ $v_2$

- Non-zero $v_2$ in central and semi-central collisions

- Low $p_T$ $J/\psi$ has almost $v_2 \approx 0$: apply a cut at $p_T = 1.5$ GeV/c to remove most of the $J/\psi$ that contribute with very small $v_2$ and leave the bulk of the $J/\psi$ where the $v_2$ is maximum
J/ψ $v_2$ at forward rapidity in Pb-Pb collisions at 2.76 TeV by ALICE

- **Hint of non-zero $v_2$** in (20%-60%) collisions at intermediate $p_T$: $2 \leq p_T < 4$ GeV/c
  ➢ contrary to zero or small $v_2$ observed at RHIC

- **Non-zero $v_2$** in semi-central (20%-40%) collisions for intermediate $p_T$: $2 \leq p_T < 6$ GeV/c: with significance ~ 3.0 sigma

- **Non-zero $v_2$** for J/ψ with $p_T \geq 1.5$ GeV/c in central (5%-20%) and semi-central (20%-40%) collisions
Conclusions

- In 20%-60% collisions (same as RHIC measurements)
  - ALICE measured $J/\psi$ $v_2$: in qualitative agreement with transport models with 50% regeneration
  - At high $p_T$: the flow of B feed-down $J/\psi$ might have a major impact on the measured inclusive $v_2$

- In central (5%-20%) and semi-central (20%-40%) collisions
  - Indication of non-zero $v_2$ favors regeneration mechanism which may contribute significantly to the production of $J/\psi$ in more central Pb-Pb collisions at LHC energy

- Complement to $J/\psi$ $R_{AA}$ results:
  - The non-zero $J/\psi$ $v_2$ at intermediate $p_T$ and less suppression with respect to RHIC are indications for an observation of regeneration from charm quarks in the QGP phase
Thanks!
Backup slides
Results from other methods

- Hadronization model
- Event plane (EP) method with VZERO-A
  - EP flattening
  - EP resolution in various centralities used in these analyses
- 6-Δφ method in centrality 20% - 60% vs. other methods
  - 2-Δφ method: anisotropy in/out-of-plane
  - Cumulant (2-particle correlation) method
    - Signal extraction and result
- Centrality dependence of J/ψ ν₂ without p_T cut
- Differential J/ψ ν₂ in various centrality bins
J/ψ suppression at RHIC and LHC

- By statistical hadronization model
- More (re)generated J/ψ at LHC energy comparing to RHIC energy in the hadronization phase
  → leads to less suppression

Elliptic flow with event plane method

- Spatial anisotropy is converted via multiple collisions into an anisotropy of momentum distribution.

- The azimuthal dependence of the particle yield can be written in the form of a Fourier series:

\[
E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)] \right)
\]

\[
v_2 = \langle \cos[2(\phi - \Psi_{RP,2})] \rangle
\]
Event plane flattening from VZERO

- Event plane flattening steps:
  - gain equalization ring by ring
  - recentering, twisting and rescaling of VZERO EP cumulant

\[
\begin{align*}
Q_{2,x} &= \langle Q_{2,x} \rangle + A^+ [\cos 2\Psi_2 + \Lambda^+ \sin 2\Psi_2] \\
Q_{2,y} &= \langle Q_{2,y} \rangle + A^- [\cos 2\Psi_2 + \Lambda^- \sin 2\Psi_2]
\end{align*}
\]

where the parameters \( \langle Q_{2,x} \rangle, \langle Q_{2,y} \rangle, A^+, A^-, \Lambda^+ \)
and \( \Lambda^- \) are extracted from the mean and RMS of the \( Q_{2,x}, Q_{2,y} \) and \( Q_{2,x}Q_{2,y} \) distributions

- finally remove residual fluctuations due to azimuthal segmentation of VZERO rings with Fourier flattening technique using one single parameter \( \langle \sin 8\Psi_{EP,2} \rangle \), represents the 8\(^{th}\) Fourier moment of the event-plane distribution
Event plane from VZERO-A

- Event plane flatness
  - Deviation from constant within 1% deviation

- Event plane resolution
  - Two sets of 3 sub-events in MB events in the same runs for systematics
    - TPC + full V0A + full V0C
    - V0A + two rings in V0C

- Event plane resolution within large centrality bins
  - Resolution weighted by the number of J/ψ in smaller centrality bins

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%–20%</td>
<td>0.548±0.003 (stat)±0.009 (syst)</td>
</tr>
<tr>
<td>20%–40%</td>
<td>0.610±0.002 (stat)±0.008 (syst)</td>
</tr>
<tr>
<td>40%–60%</td>
<td>0.451±0.003 (stat)±0.008 (syst)</td>
</tr>
<tr>
<td>60%–90%</td>
<td>0.185±0.005 (stat)±0.013 (syst)</td>
</tr>
<tr>
<td>20%–60%</td>
<td>0.576±0.002 (stat)±0.008 (syst)</td>
</tr>
</tbody>
</table>
2-$\Delta \phi$ method: anisotropy in/out-of-plane

- 2-$\Delta \phi$ method:
  - A direct calculation from J/$\psi$ yield anisotropy in-plane and out-of-plane
  - Correct $v_2^{\text{obs}}$ by the event plane resolution $\sigma_{EP}$

$$v_2^{\text{obs}} = \frac{\pi}{4} \times \frac{N_{in} - N_{out}}{N_{in} + N_{out}}, \quad v_2 = \frac{v_2^{\text{obs}}}{\sigma_{EP}}$$

![Diagram showing $v_2$ for different energy and $p_T$ ranges]
Cumulant (2-particle correlation) method

- J/ψ ν₂ study without event plane determination

  **Advantages**
  - Large η gap yield non-flow suppression
  - No requirement on full azimuthal coverage
  - No event plane correction needed
  → avoid systematical uncertainties from σ_{EP} correction
  - direct correlation of dimuon, SPD tracklets and V0A

- Disadvantages
  - need high statistics in each centrality/invariant mass/p_T bin
  - Study dimuon ν₂ in p_T bins (20%-60%): 0-2, 2-4, 4-6, 6-10 GeV/c
  - ν₂ extraction in 2-4 GeV/c possible
    → possibly due to stronger flow signal and not too low statistics
  - Large fluctuation in lower p_T bin (stat. OK, but weak flow)
  - Large statistical uncertainty in higher p_T bins (too low stat.)


Experimental implementation: PHENIX Collab PRL94 (2005) 232302
Centrality scan: differential $J/\psi \, v_2$

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, $J/\psi: 2.5 < y < 4.0, p_T \geq 0$ GeV/c

VZERO-A EP: inv. mass fit technique

- 5% - 20%
- 20% - 40%
- 40% - 60%

$v_2$ vs. $p_T$ (GeV/c)