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ALICE

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

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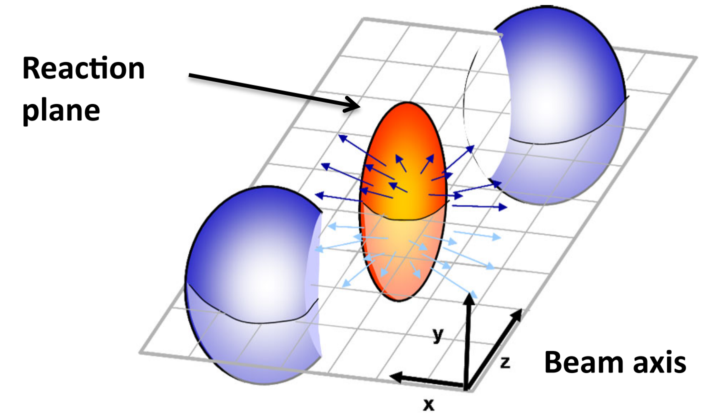
QM12 QuarkMatter

# Outline

- **Physics motivation**
  - Color screening suppression versus J/ψ (re)generation
  - Does J/ψ flow or not flow

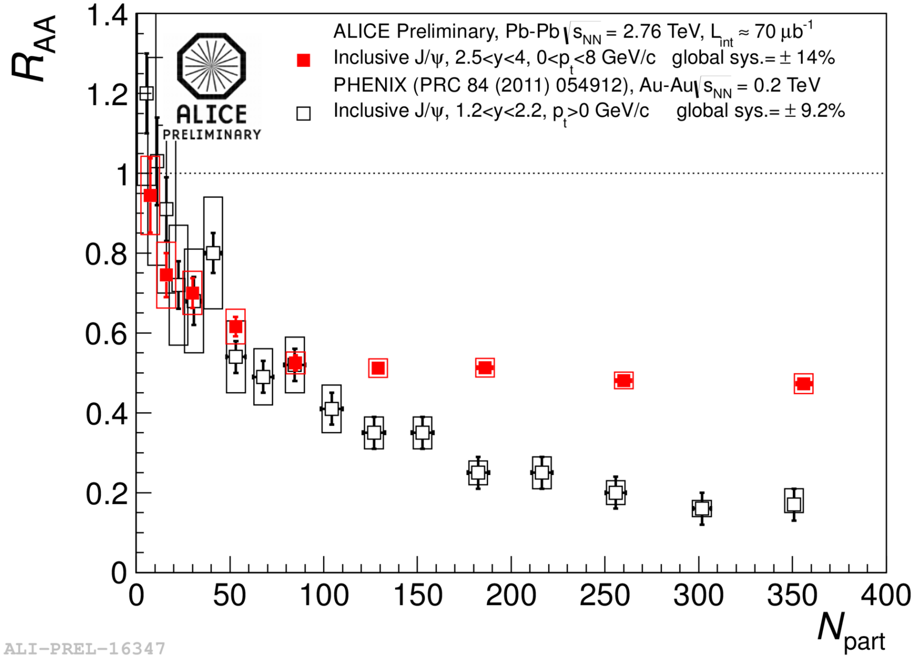
    ⇒ **J/ψ production mechanism in heavy-ion collisions**

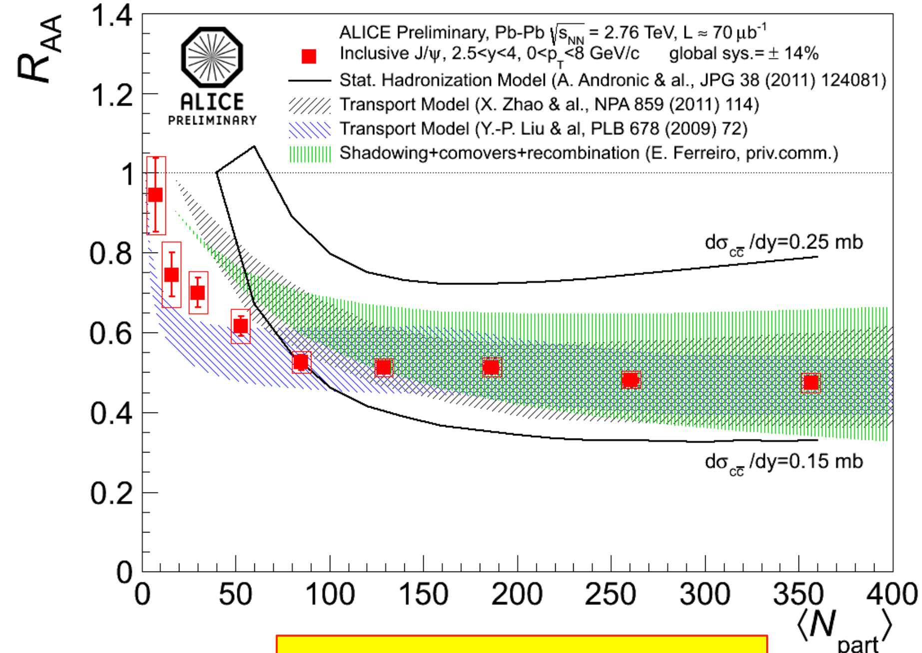



- **ALICE setup**
- **Data analysis**
  - J/ψ signal and elliptic flow extraction
- **Results and discussion**
  - Differential J/ψ $v_2$ in 20%-60%
    - Comparison with STAR results and theory calculations
  - Differential J/ψ $v_2$: centrality scan
  - Centrality dependence of J/ψ $v_2$ with $p_T \geq 1.5$ GeV/$c$
- **Summary and conclusions**

Results from 2010 data soon appear on PRL: arXiv:1202.1383v1 [hep-ex]

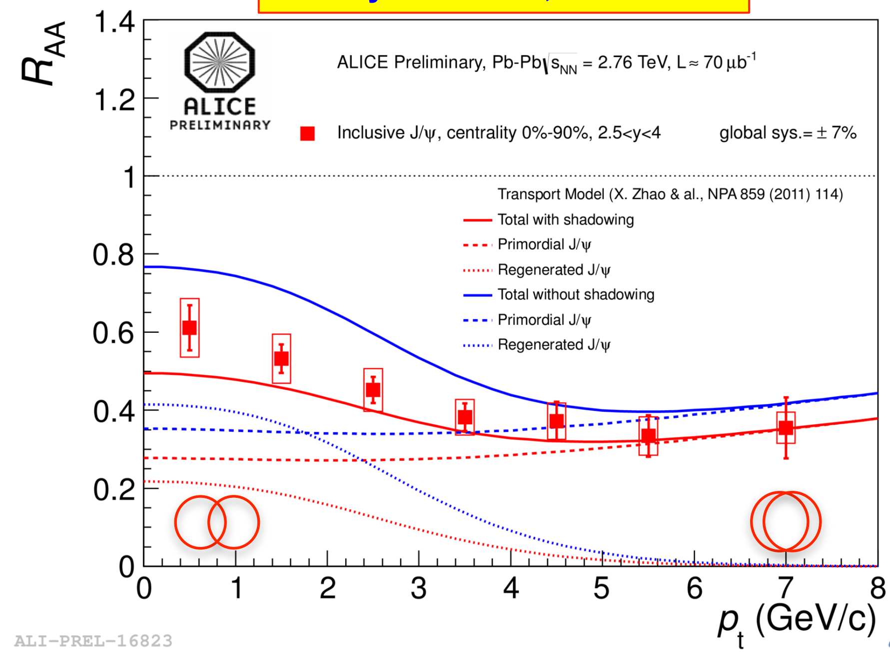
# J/ψ $R_{AA}$ down to $p_T$ = 0 at LHC (2011 data)




**Talk by R. Arnaldi, Parallel 1D**

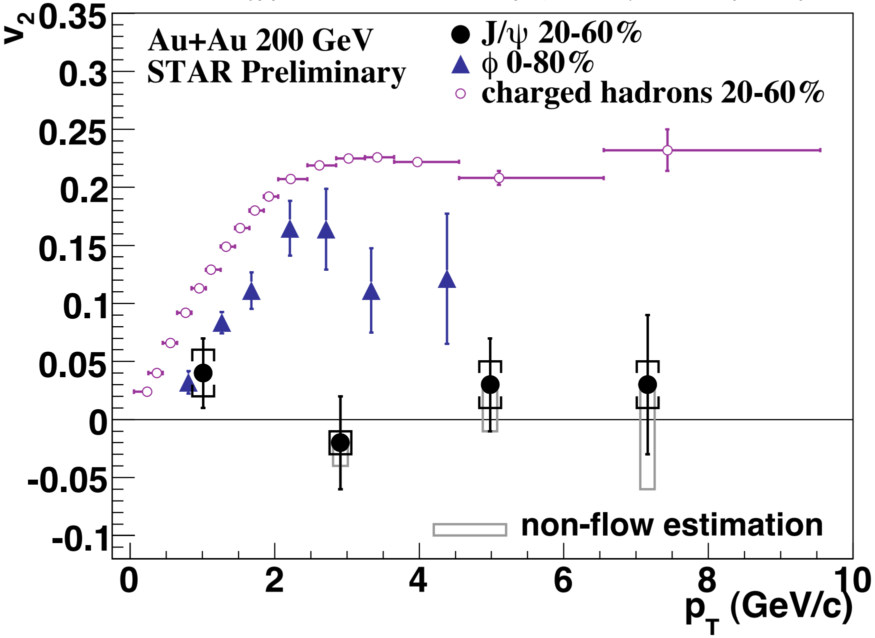
- In Pb-Pb collisions at LHC energy
  - Less suppression at LHC than at RHIC
    - No strong centrality dependence in most central collisions
    - Less suppression at low $p_T$
  - Described by various models including a large fraction of regenerated J/ψ from charm quarks in the QGP



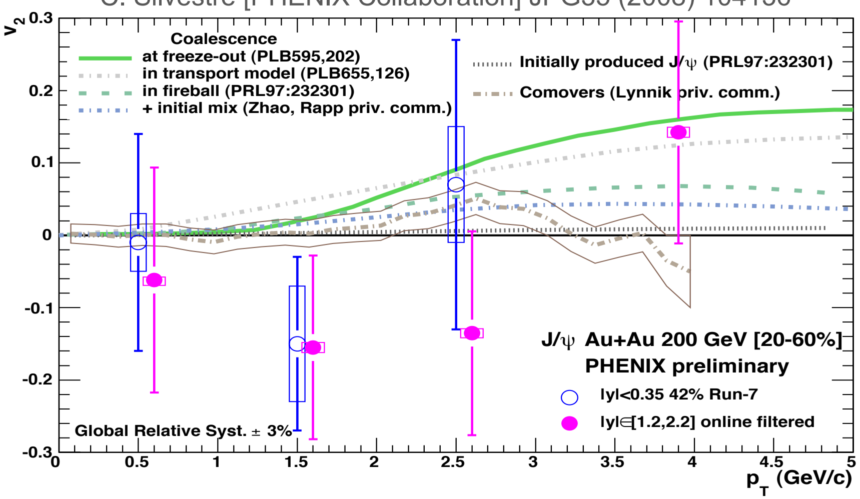
# J/ψ elliptic flow at RHIC

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

Z. Tang [STAR Collaboration] QM2011, JPG38 (2011)

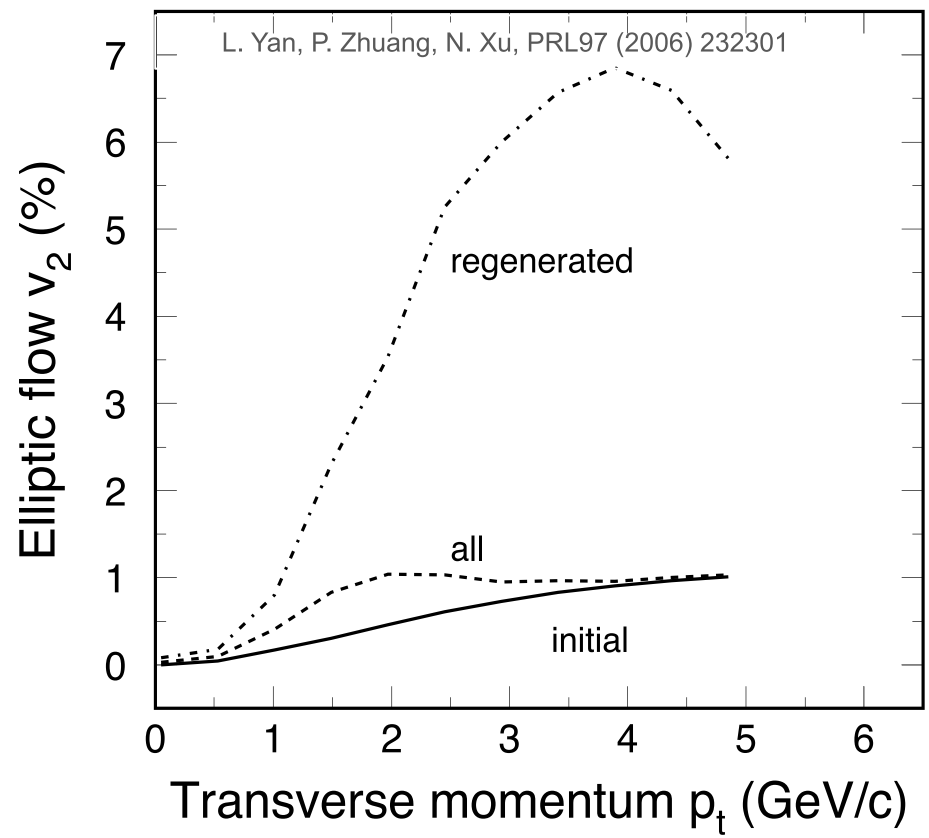



C. Silvestre [PHENIX Collaboration] JPG35 (2008) 104136




**$v_2^{J/\psi}$ in Au-Au collisions at 200 GeV at b = 7.8 fm**

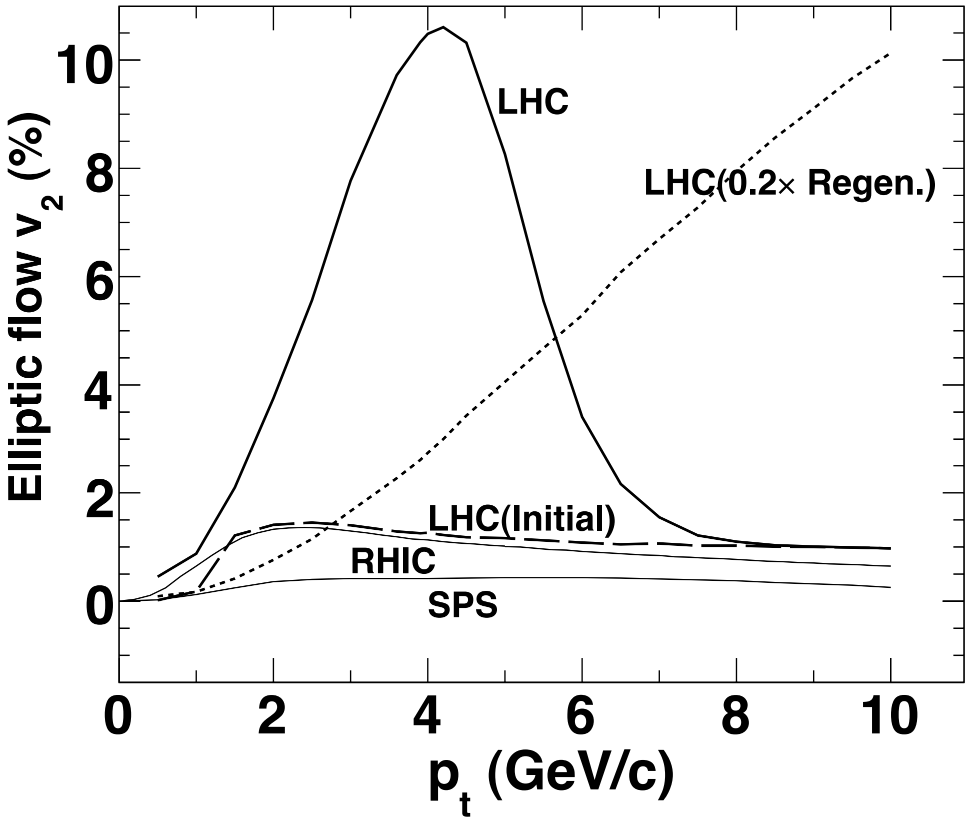
pQCD and thermal scenarios ➔ small $v_2$ at RHIC




If charm quark participates in collective motion of QGP, its $v_2$ will be transferred to J/ψ when charm quarks recombine

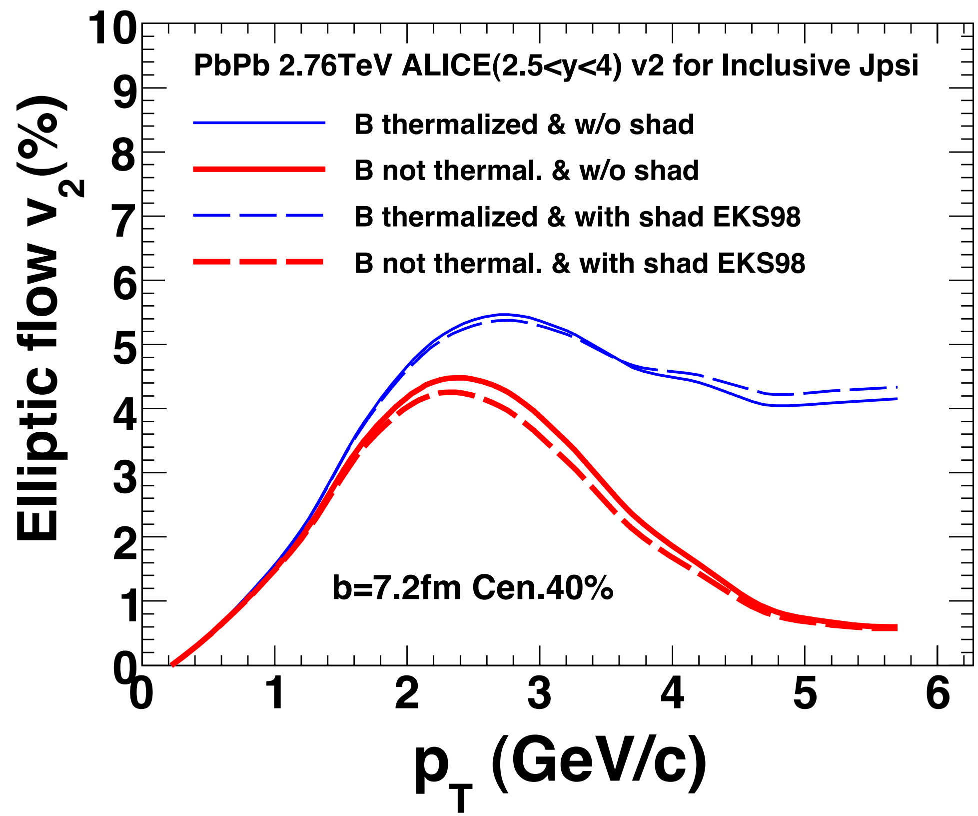
# J/ψ elliptic flow at the LHC energies

**LHC Pb-Pb @ 5.5 TeV, mid-rapidity**
**$d\sigma_{cc\text{-}bar}/dy$ = 0.7 mb, no B feed-down J/ψ**




Y. Liu, N. Xu, P. Zhuang, Nucl.Phys.A834 (2010) 317c

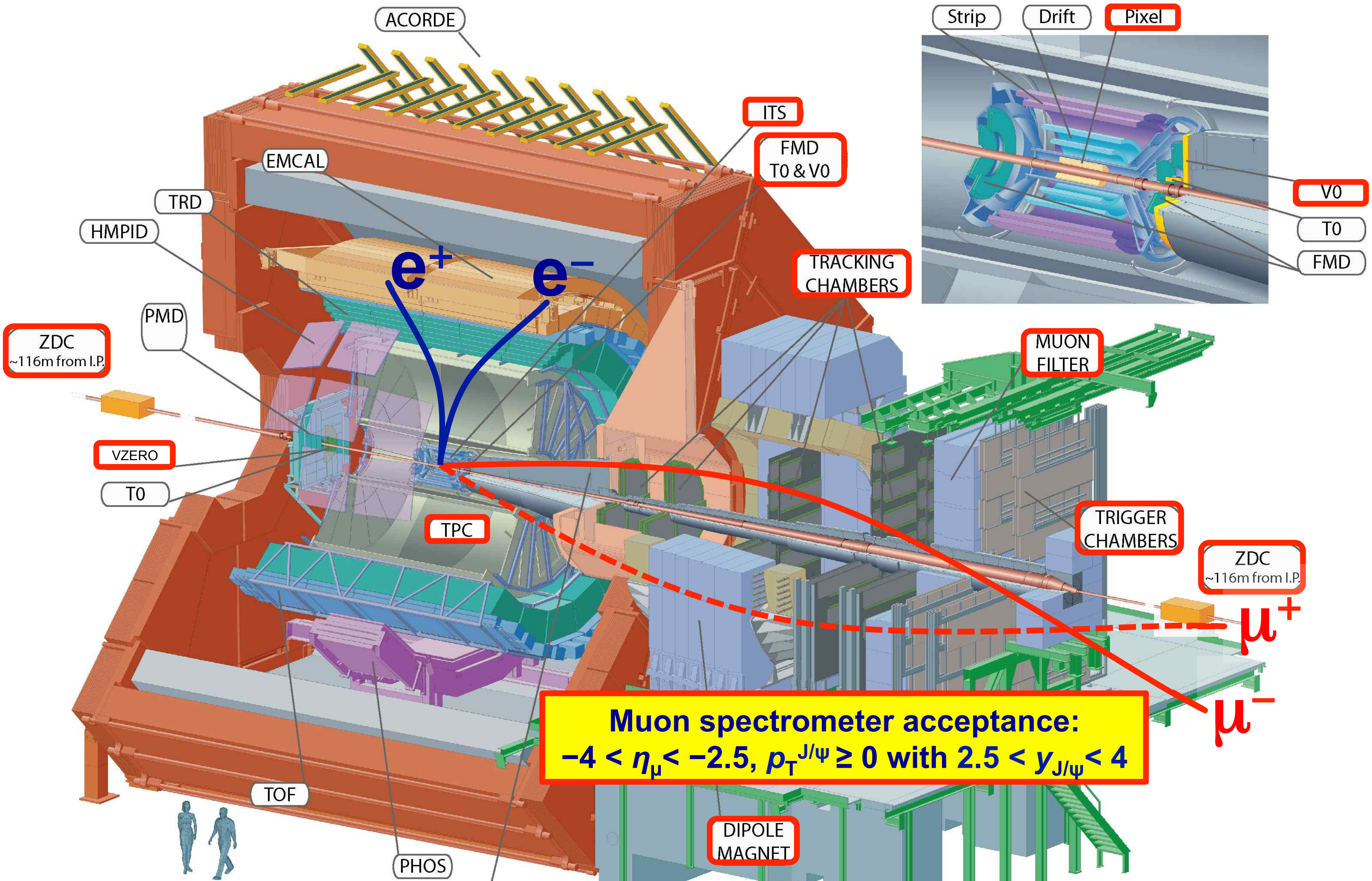
**LHC Pb-Pb @ 2.76 TeV, forward rapidity**
**$d\sigma_{cc\text{-}bar}/dy$ = 0.38 mb, B feed-down J/ψ**




Same authors: P. Zhuang and co., 2012 prediction (priv. comm.)

**a significant elliptic flow may be expected at LHC energies due to the significant contribution of (re)generated J/ψ**

# ALICE experimental setup

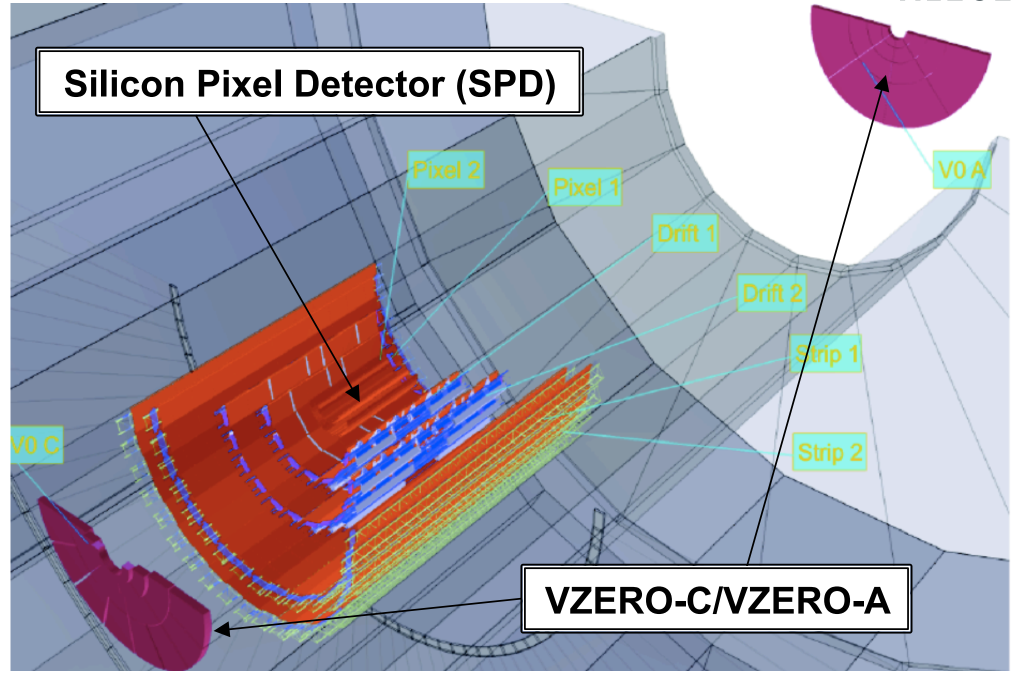



**Muon spectrometer acceptance:**
**$-4 < \eta_\mu < -2.5$, $p_T^{J/\psi} \geq 0$ with $2.5 < y_{J/\psi} < 4$**

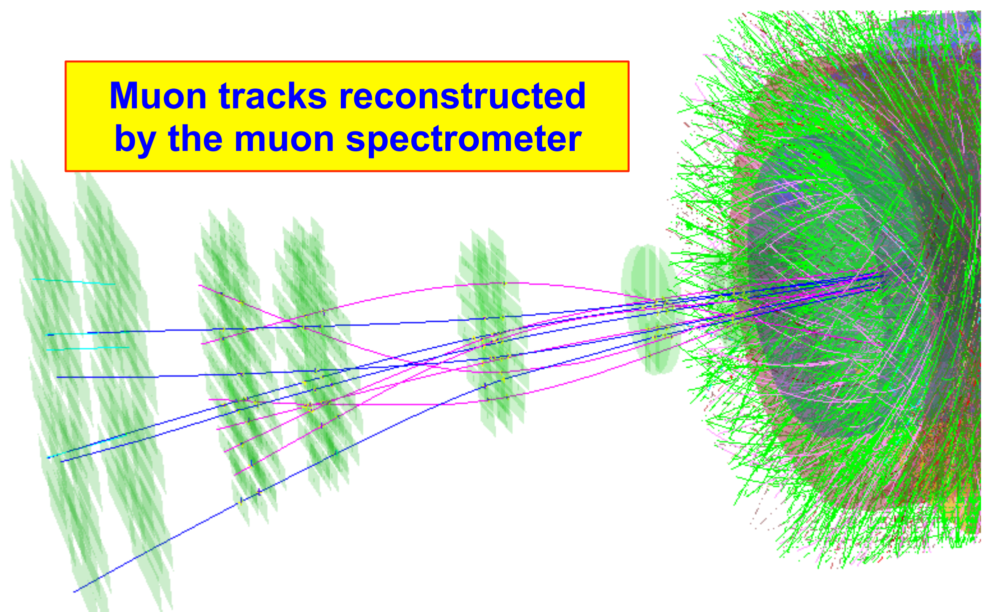
**J/ψ from e⁺e⁻ channel at mid-rapidity**
**I. Arsene, parallel 2D**

# 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→ $\mu^+\mu^-$ 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$^{rd}$ 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 (nΔφ 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:* $v_2^{\mu^+\mu^-} = \langle \cos 2(\Delta\varphi) \rangle$
    - $v_2^{\mu^+\mu^-} = (S \times v_2^{sig} + B \times v_2^{bkg})/(S + B)$

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

$$v_2 = v_2^{obs} / \sigma_{EP}$$

- **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 $v_2^{sig}$
    - Largely limited by statistical uncertainties

N Borghini, P M Dinh, J-Y Ollitrault: PRC63 (2001) 054906, PRC64(2001)054901

# Event plane determination from VZERO

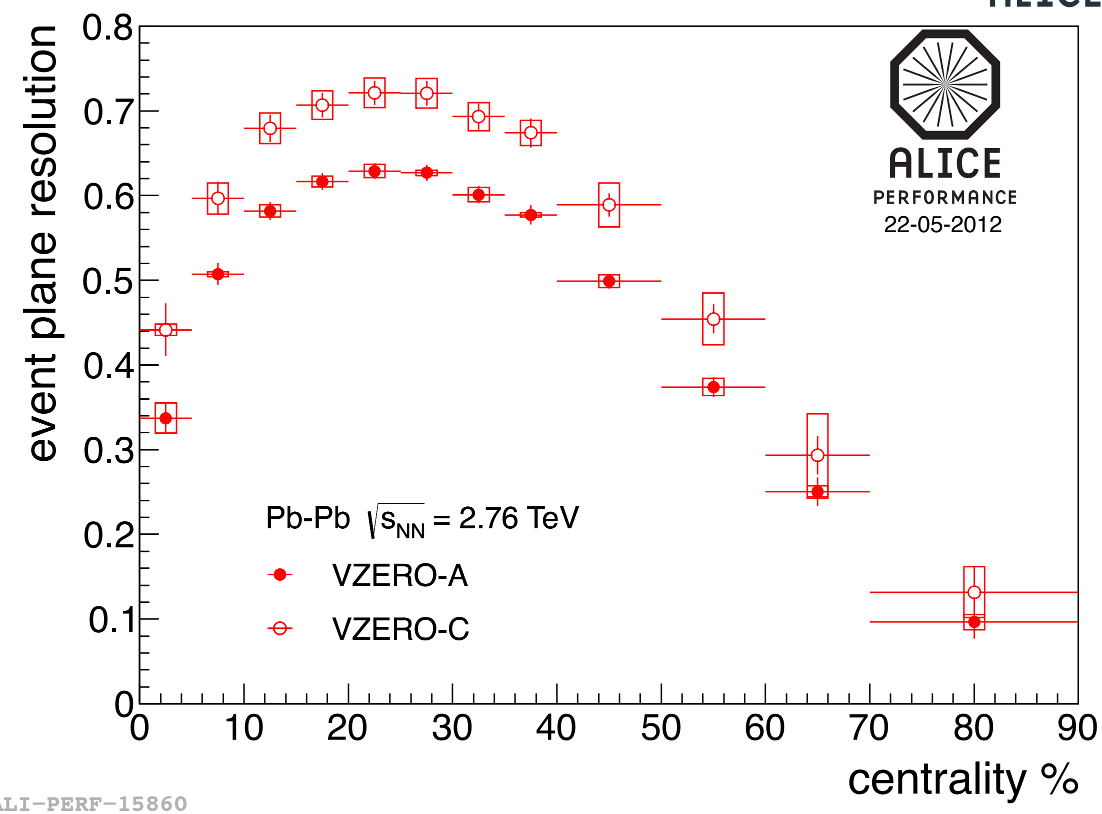
- VZERO detectors
  - 2 arrays of 32 scintillators on both side of IP:
    VZERO-A: $2.8 < \eta < 5.1$
    VZERO-C: $-3.7 < \eta < -1.8$

- Event plane from VZERO-A[1] **second harmonics**

$$Q_{n,x} = \frac{\Sigma_{i=0}^{31} S_i \cos(n\phi_i)}{\Sigma_{i=0}^{31} S_i}$$

$$Q_{n,y} = \frac{\Sigma_{i=0}^{31} S_i \sin(n\phi_i)}{\Sigma_{i=0}^{31} S_i}$$

$$\Psi_{EP,2} = \frac{arctan2(Q_{2,x}, Q_{2,y})}{2}$$




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

$$\langle \cos[n(\Psi_2^a - \Psi_r)] \rangle = \sqrt{\frac{\langle \cos[n(\Psi_2^a - \Psi_2^b)] \rangle \langle \cos[n(\Psi_2^a - \Psi_2^c)] \rangle}{\langle \cos[n(\Psi_2^b - \Psi_2^c)] \rangle}}$$

A. M. Poskanzer and S. A. Voloshin, Phys Rev. C58, 1671

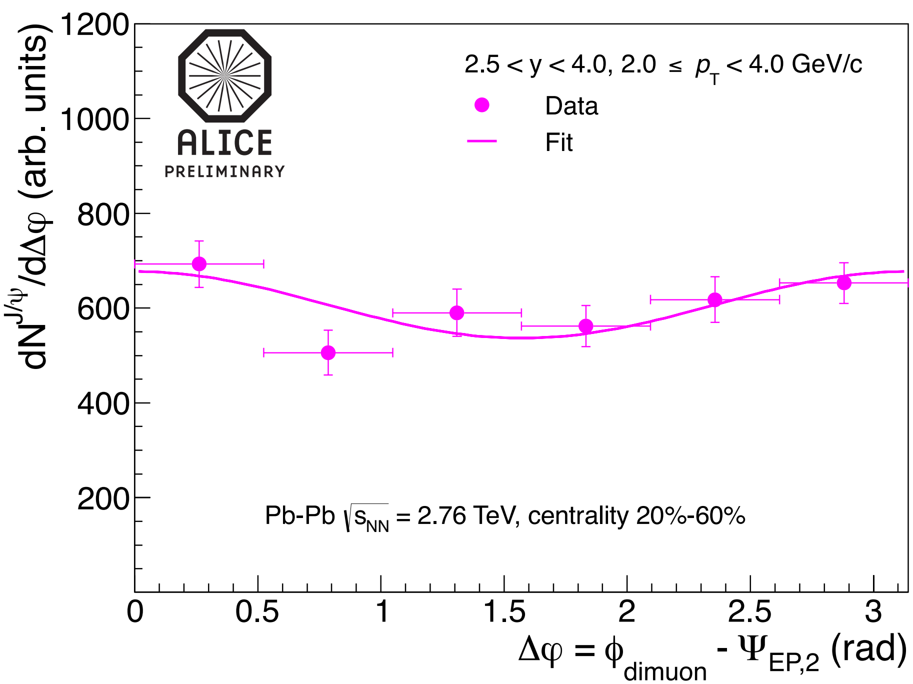
- Event plane resolution in a large centrality bin
  - Estimated by a weighted sum of event plane resolutions using J/ψ yields as weights in its sub-centrality bins

[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

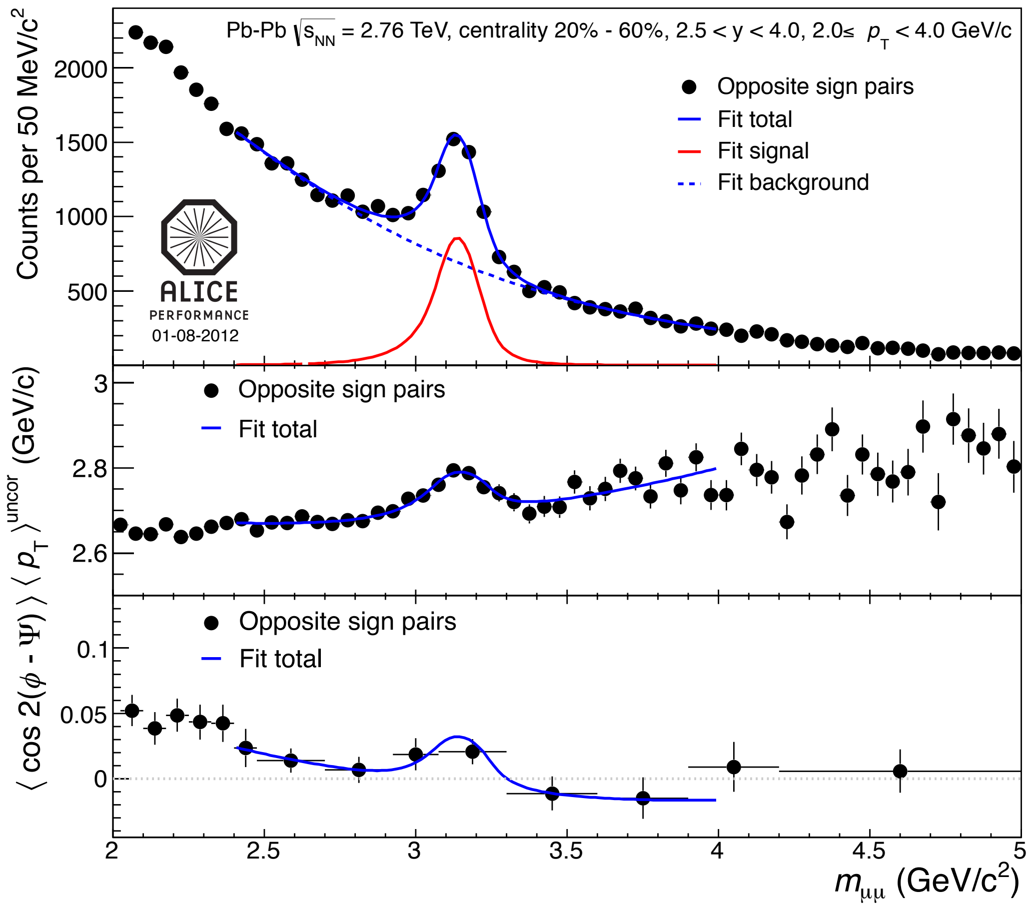
## 6-Δφ method




$$\frac{dN^{J/\psi}}{d\Delta\varphi} = A \times [1 + 2v_2^{obs} cos(2\Delta\varphi)]$$

$$v_2 = v_2^{obs} / \sigma_{EP}$$

## invariant mass fit technique

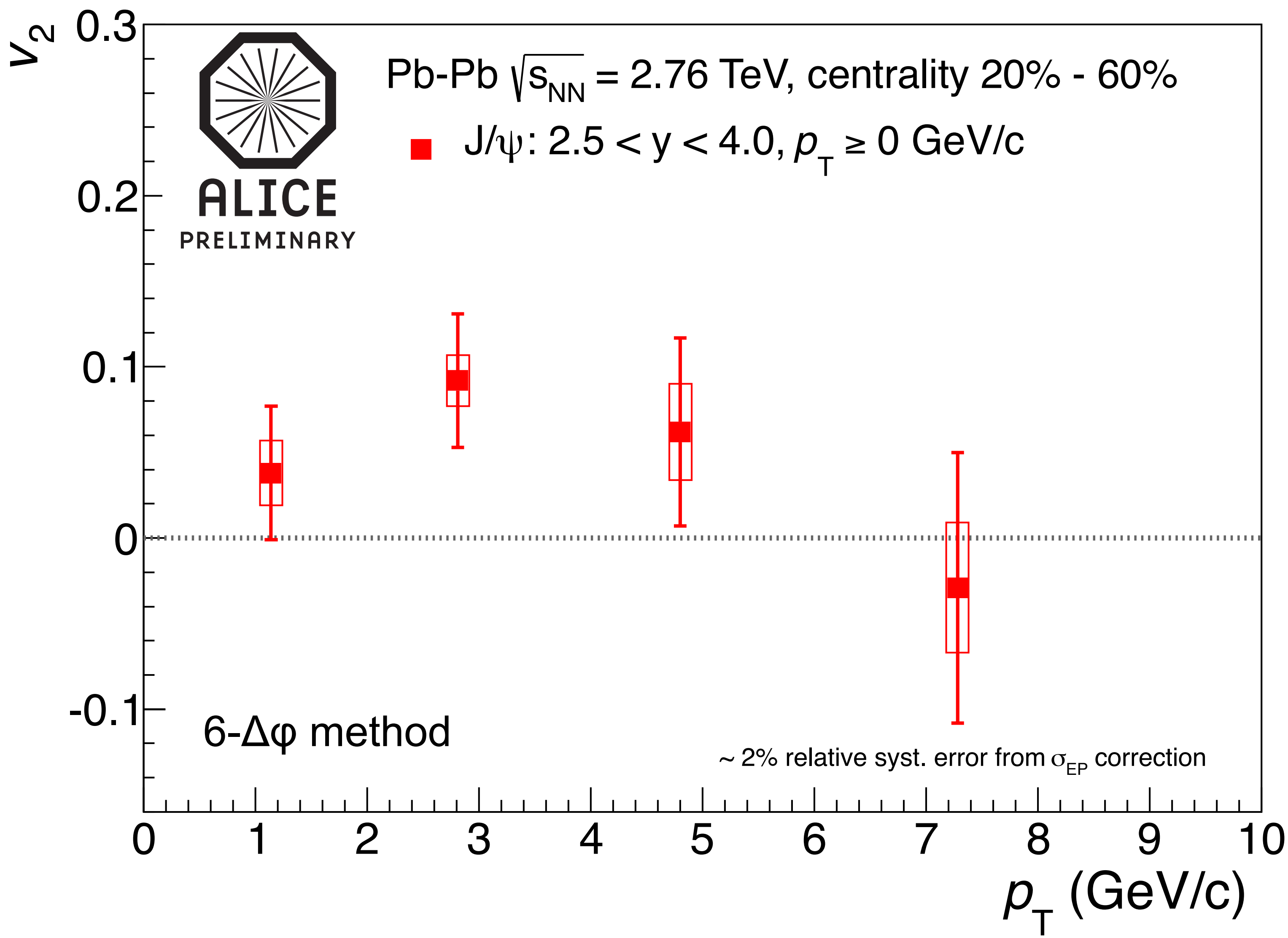



2nd order polynomial function used to describe $\langle p_T \rangle$ and $v_2$ of the background

$$v_2^{\mu^+\mu^-} = (S \times v_2^{sig} + B \times v_2^{bkg})/(S+B)$$

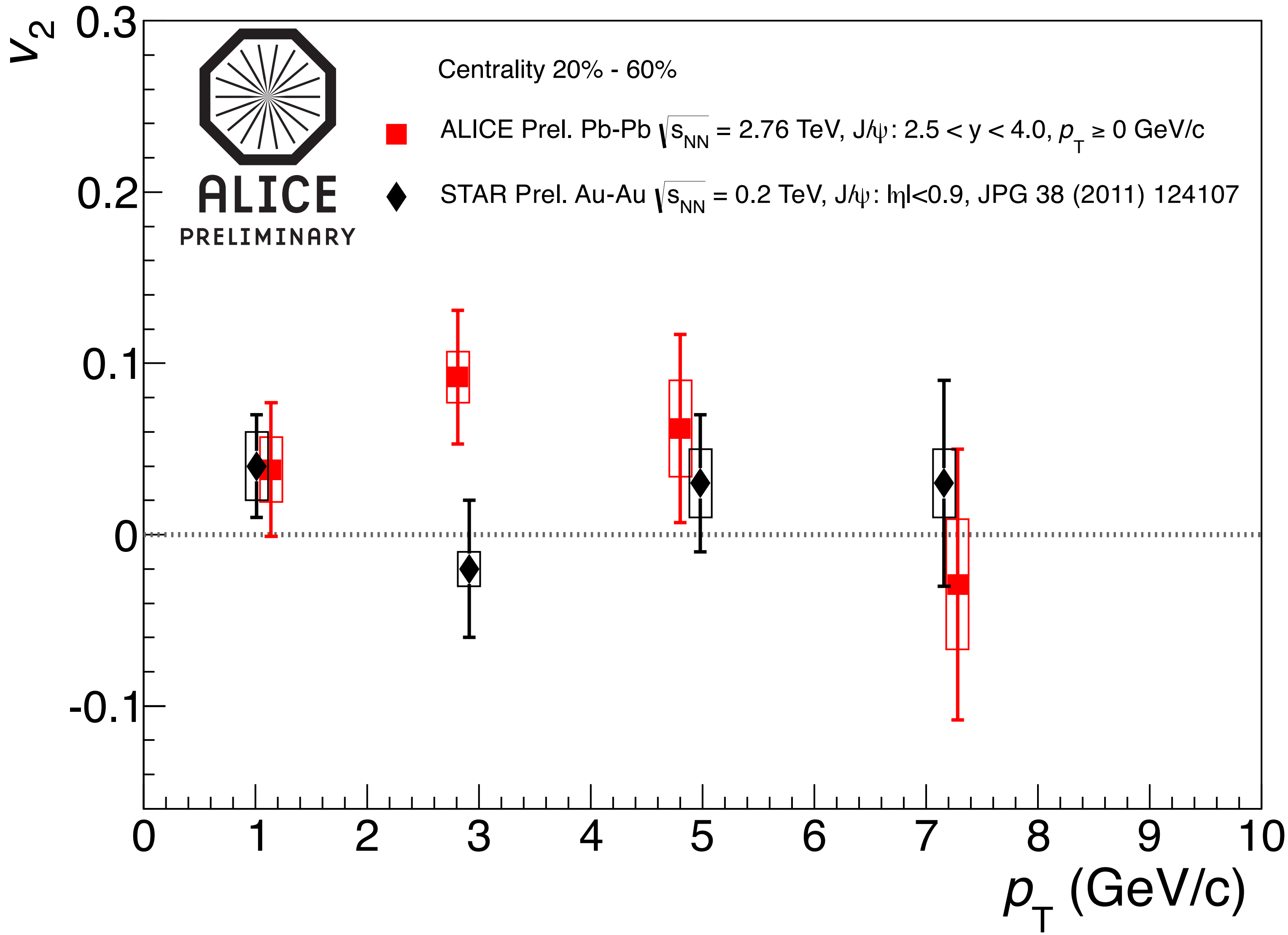
# J/ψ $v_2$ in centrality 20%-60%

- **2 ≤ $p_T$ < 4 GeV/c**
  **hint of non-zero $v_2$ with significance ~ 2.2 sigma**



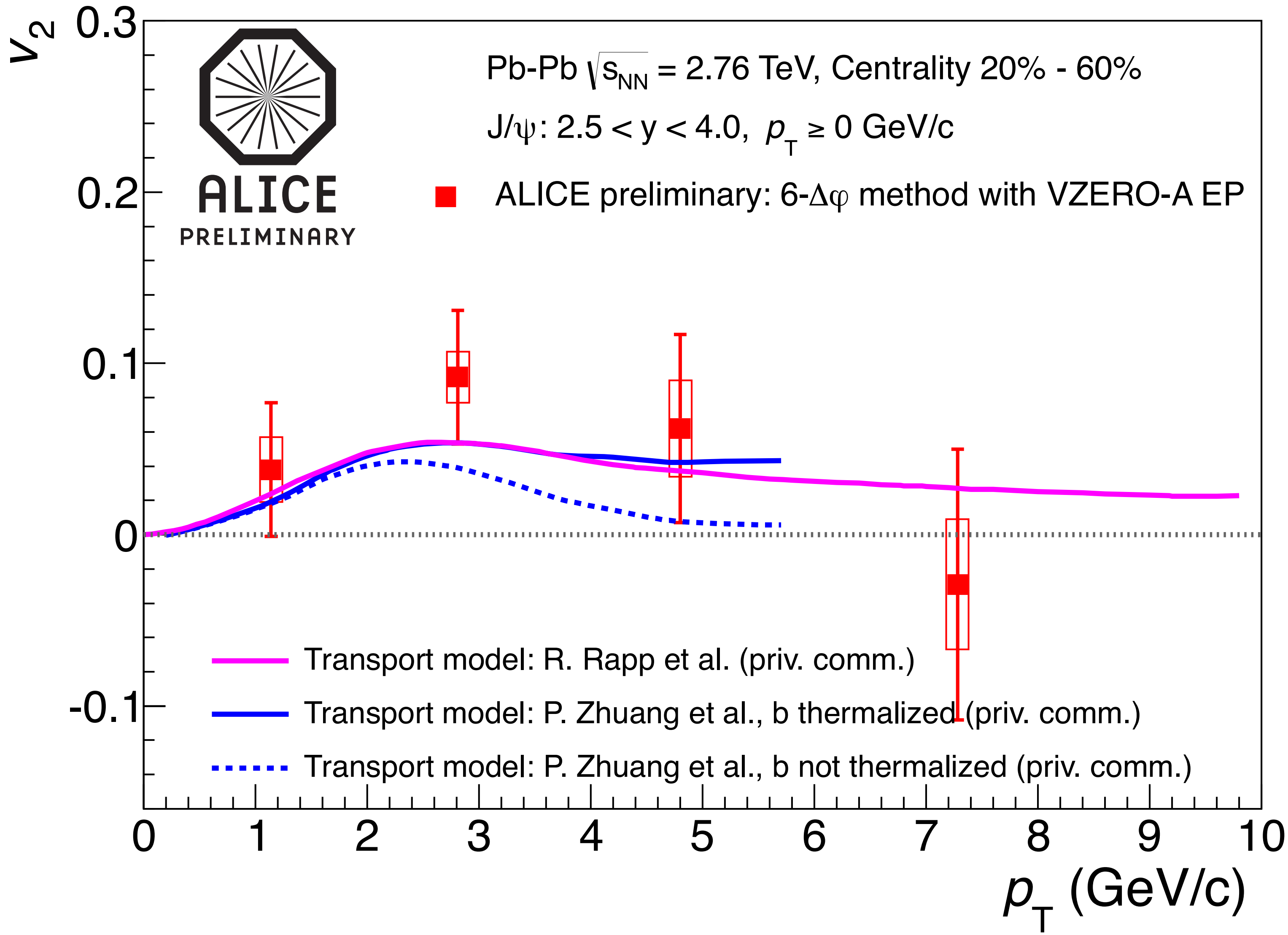
# J/ψ $v_2$ in centrality 20%-60%

- **2 ≤ $p_T$ < 4 GeV/*c*:** contrary to STAR measurement **hint of non-zero $v_2$ with significance ~ 2.2 sigma**



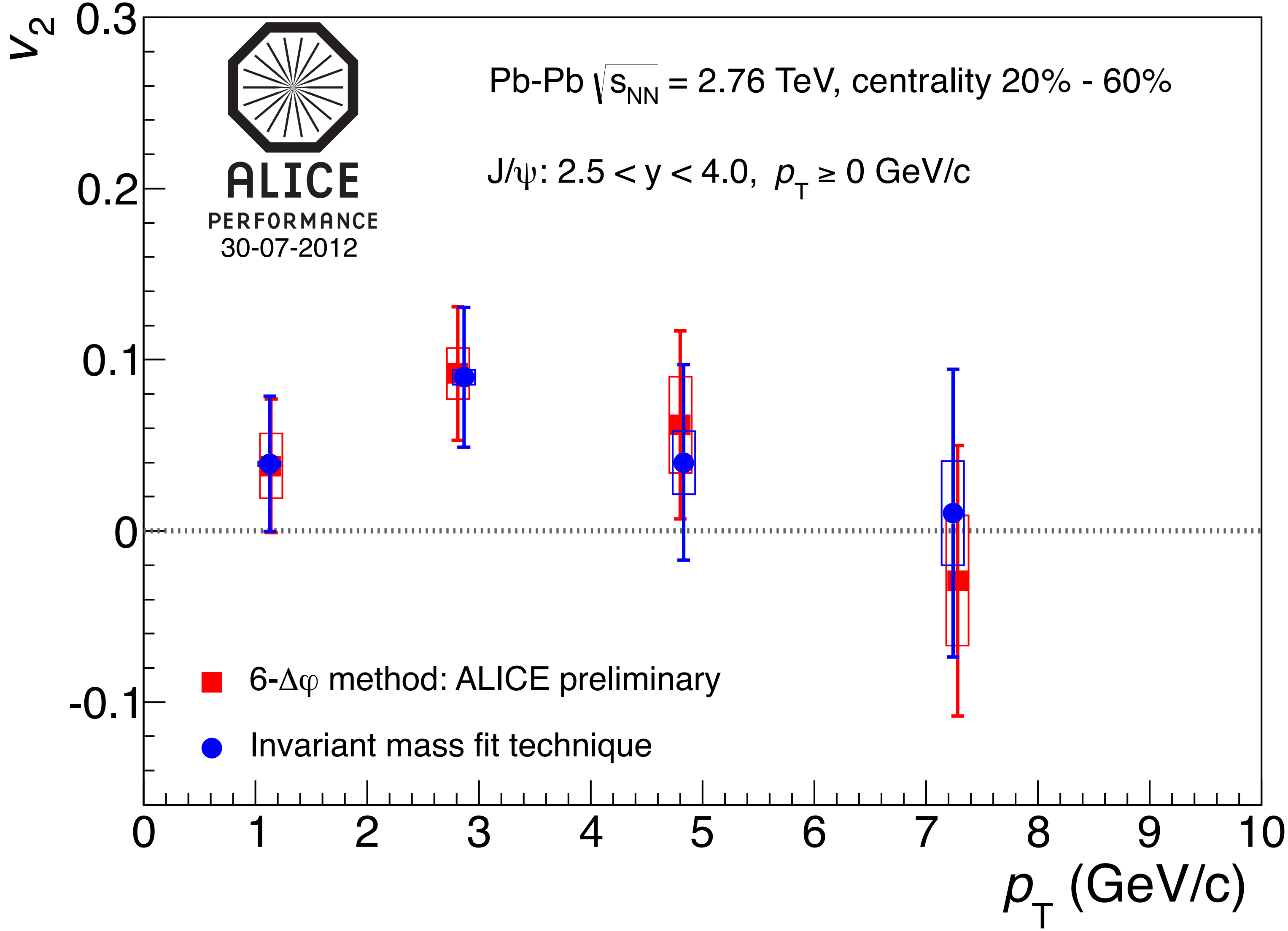
# J/ψ $v_2$ in centrality 20%-60%

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

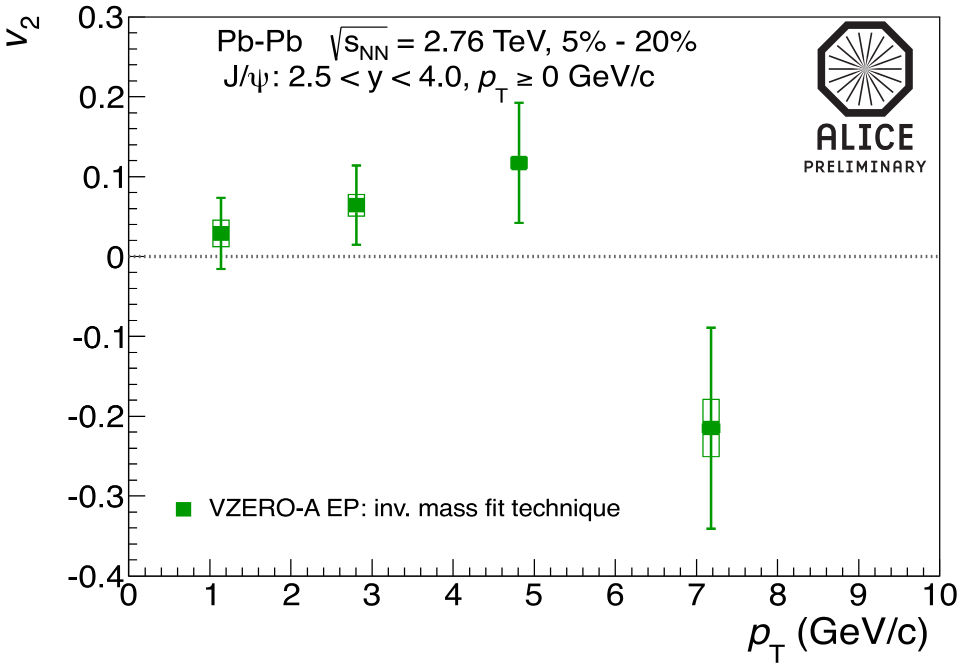


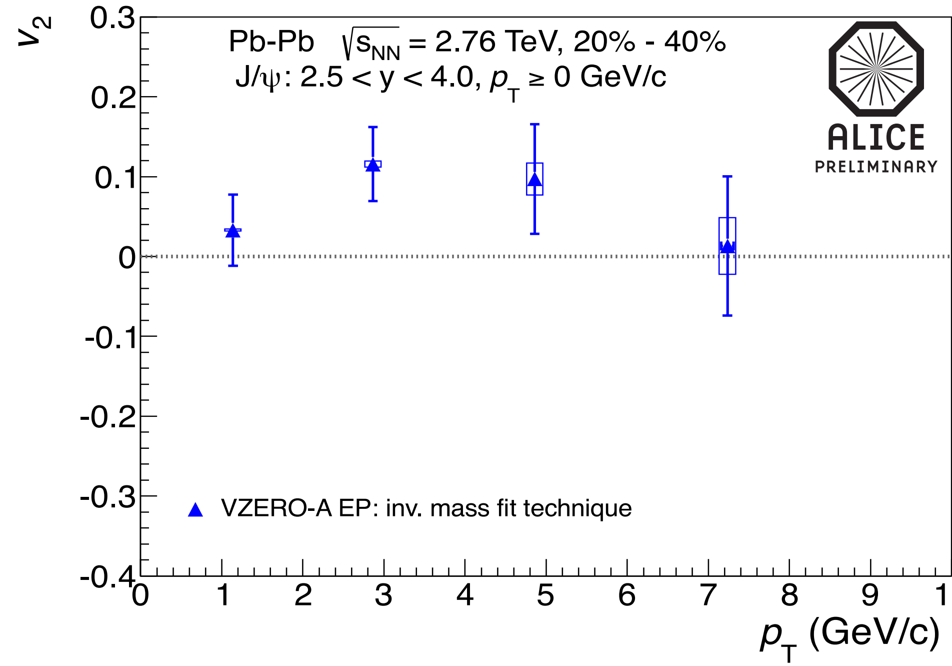
# 6-Δφ method vs. inv. mass fit technique

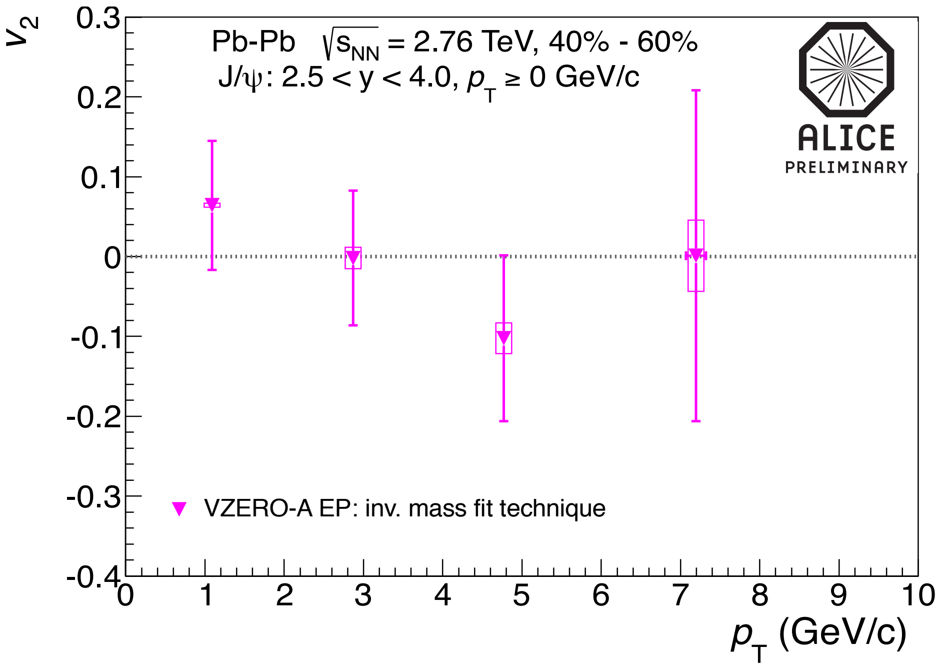
- Agreement achieved between two methods
  - *Invariant mass fit technique* is used for J/ψ $v_2$ in finer centrality bins (5%-20%, 20%-40%, 40%-60% and 60%-90%)



# J/ψ $v_2$ in smaller centrality bins



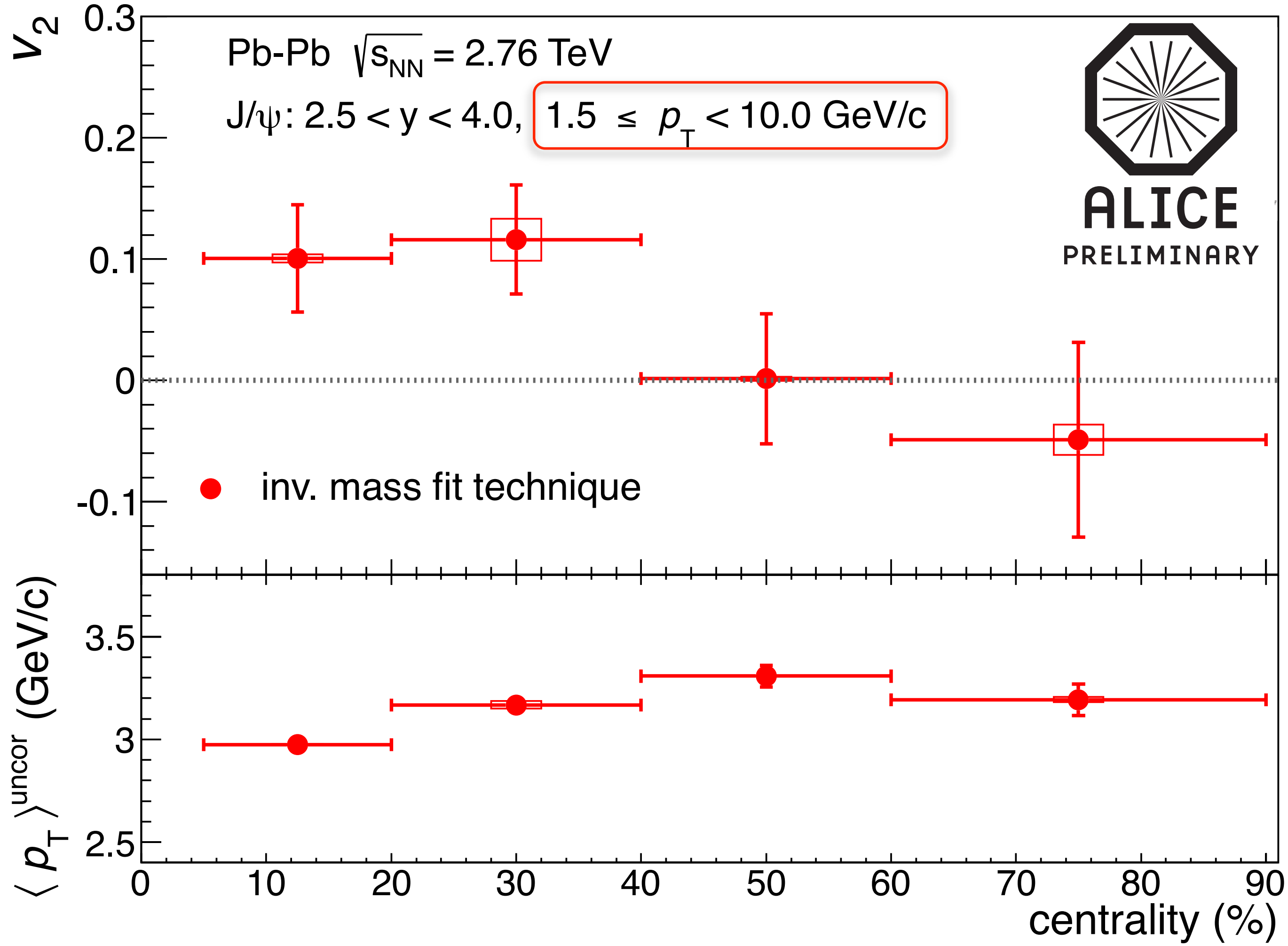




## At intermediate $p_T$: 2 ≤ $p_T$ < 6 GeV/*c*

- **5%-20%: hint of non-zero $v_2$ with significance ~ 2.2 sigma**
- **20%-40%: indication of non-zero $v_2$ with significance ~ 3.0 sigma**
- **40%-60%: statistical errors too large**

# Centrality dependence of J/ψ $v_2$

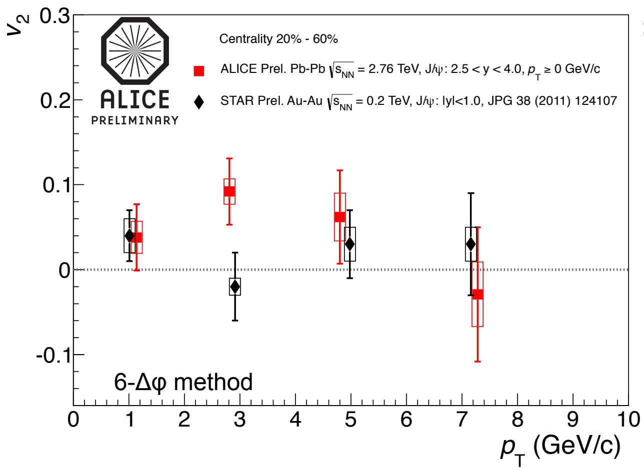
- Non-zero $v_2$ in central and semi-central collisions

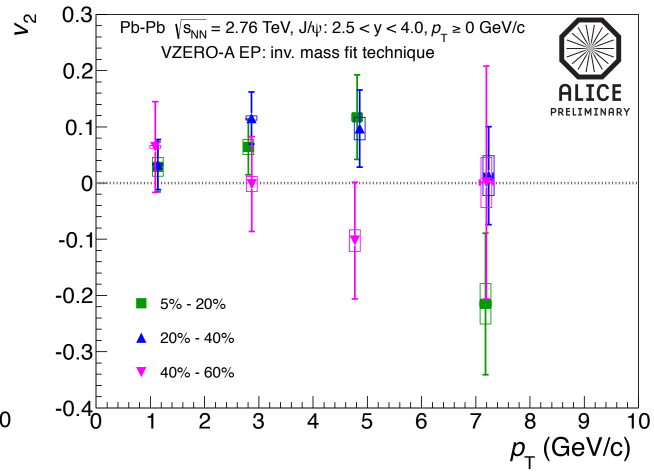


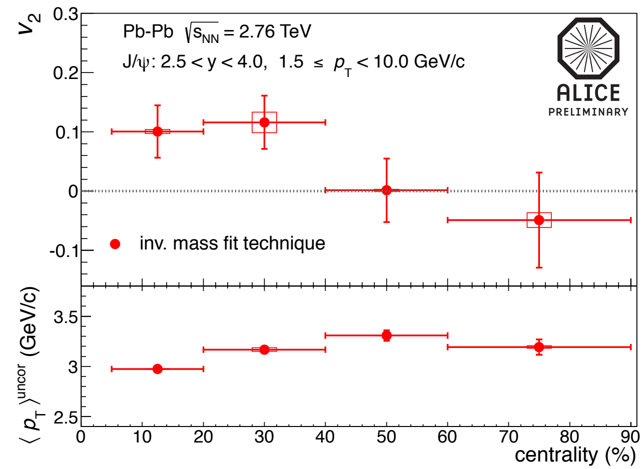

- Low $p_T$ J/ψ has almost $v_2 \approx 0$: apply a cut at $p_T$ = 1.5 GeV/$c$ to remove most of the J/ψ that contribute with very small $v_2$ and leave the bulk of the J/ψ where the $v_2$ is maximum

# Summary

## J/ψ $v_2$ at forward rapidity in Pb-Pb collisions at 2.76 TeV by ALICE



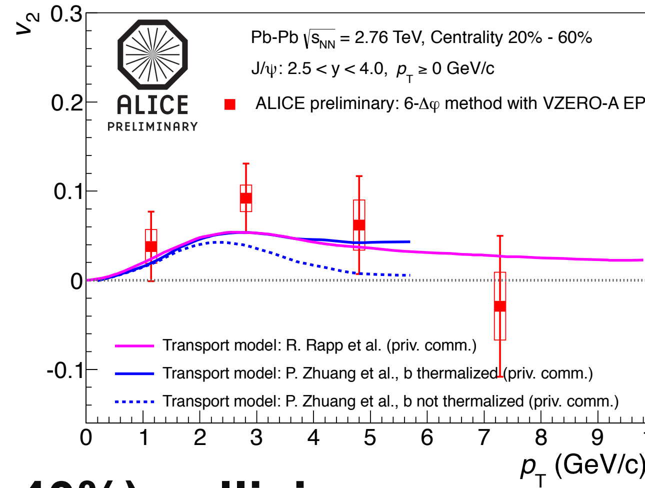

- **Hint of non-zero $v_2$** in **(20%-60%)** collisions at intermediate $p_T$:
  **$2 \leq p_T < 4$ GeV/*c***
  ➢ **contrary to zero or small $v_2$ observed at RHIC**

- **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/ψ $v_2$: in qualitative agreement with transport models with 50% regeneration
  - At high $p_T$: the flow of B feed-down J/ψ 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/ψ in more central Pb-Pb collisions at LHC energy

- **Complement to J/ψ $R_{AA}$ results:**
  - **The non-zero J/ψ $v_2$ 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!

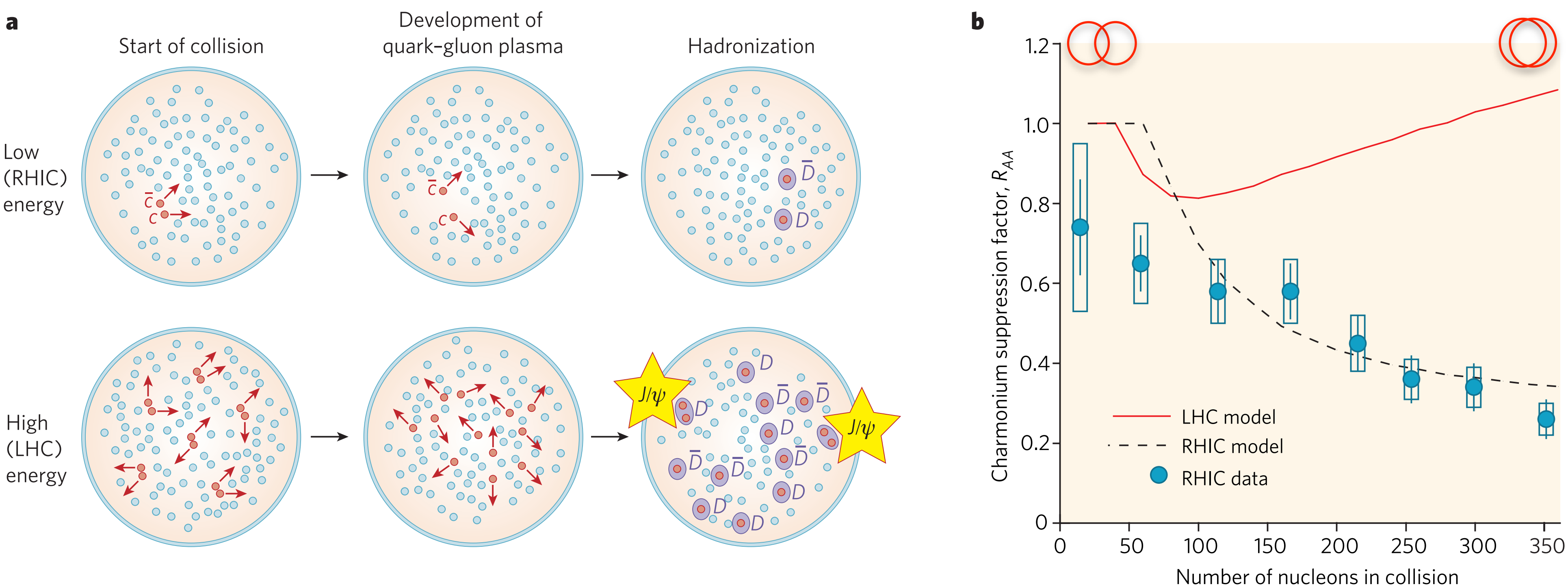
# Backup slides

# 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-$\Delta\varphi$ method in centrality 20% - 60% vs. other methods
  - 2-$\Delta\varphi$ method: anisotropy in/out-of-plane
  - Cumulant (2-particle correlation) method
    - Signal extraction and result
- Centrality dependence of J/ψ $v_2$ without $p_T$ cut
- Differential J/ψ $v_2$ in various centrality bins

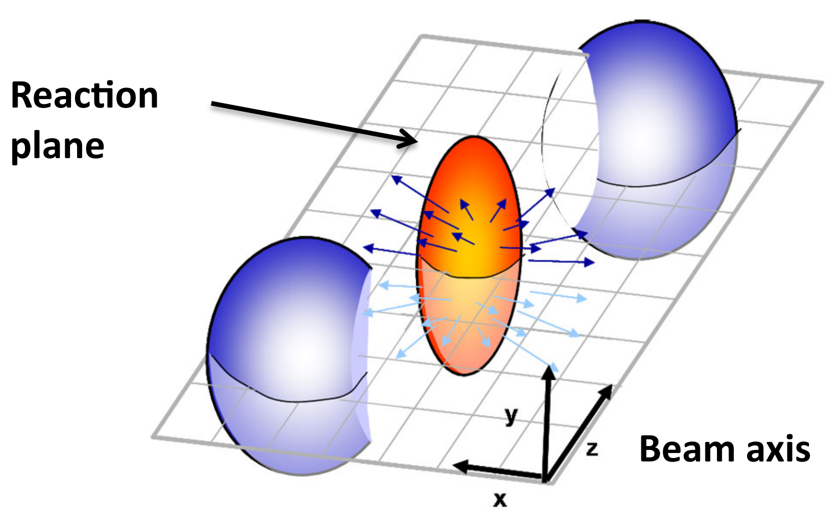
# J/ψ suppression at RHIC and LHC

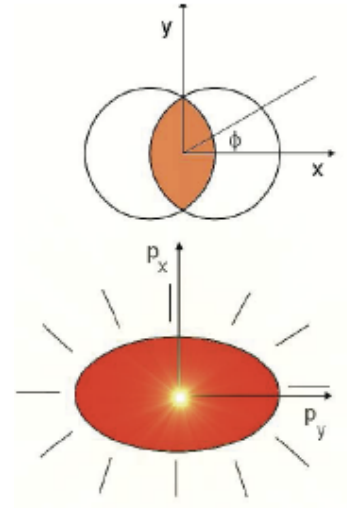
- By statistical hadronization model
  - More (re)generated J/ψ at LHC energy comparing to RHIC energy in the hadronization phase
    → **leads to less suppression**




Braun-Munzinger & Stachel, Nature Vol. 448 (2007)

# 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:

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

$$v_2 = \langle\cos[2(\phi - \Psi_{RP,2})]\rangle$$

# Event plane flattening from VZERO

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

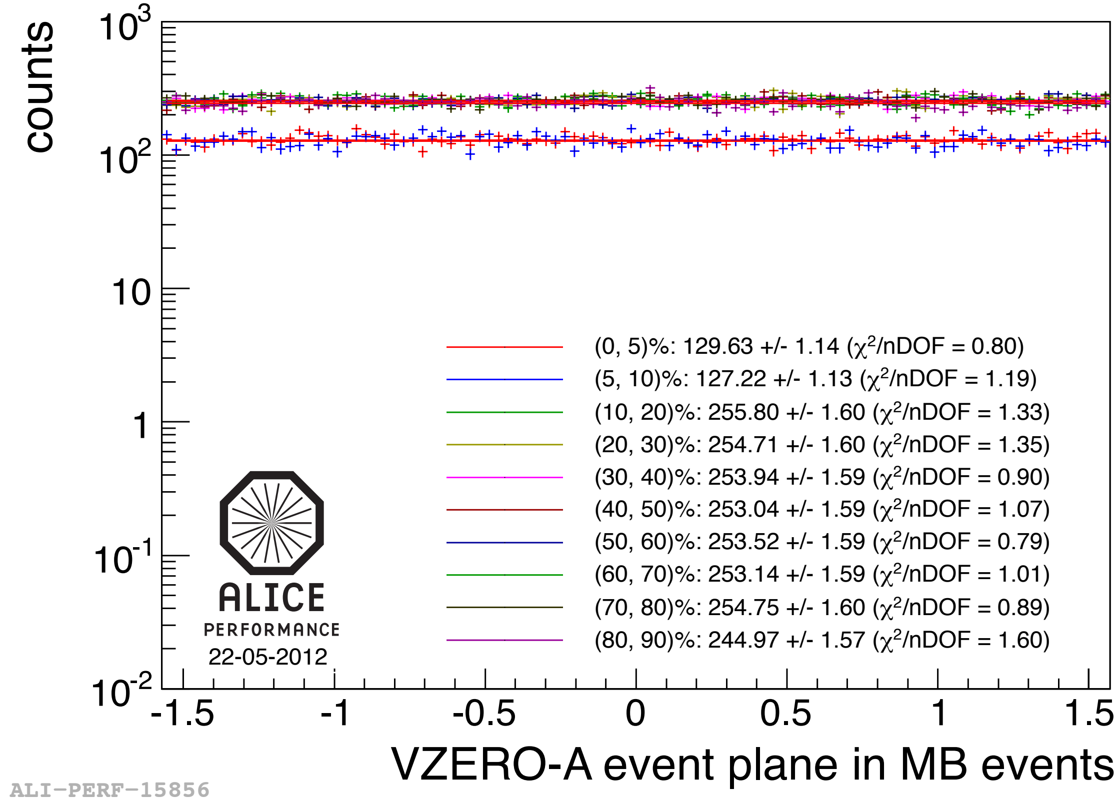
$$Q_{2,x} = \langle Q_{2,x} \rangle + A^{+}[\cos 2\Psi_2 + \Lambda^{+} \sin 2\Psi_2]$$
$$Q_{2,y} = \langle Q_{2,y} \rangle + A^{-}[\cos 2\Psi_2 + \Lambda^{-} \sin 2\Psi_2]$$

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 8th 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

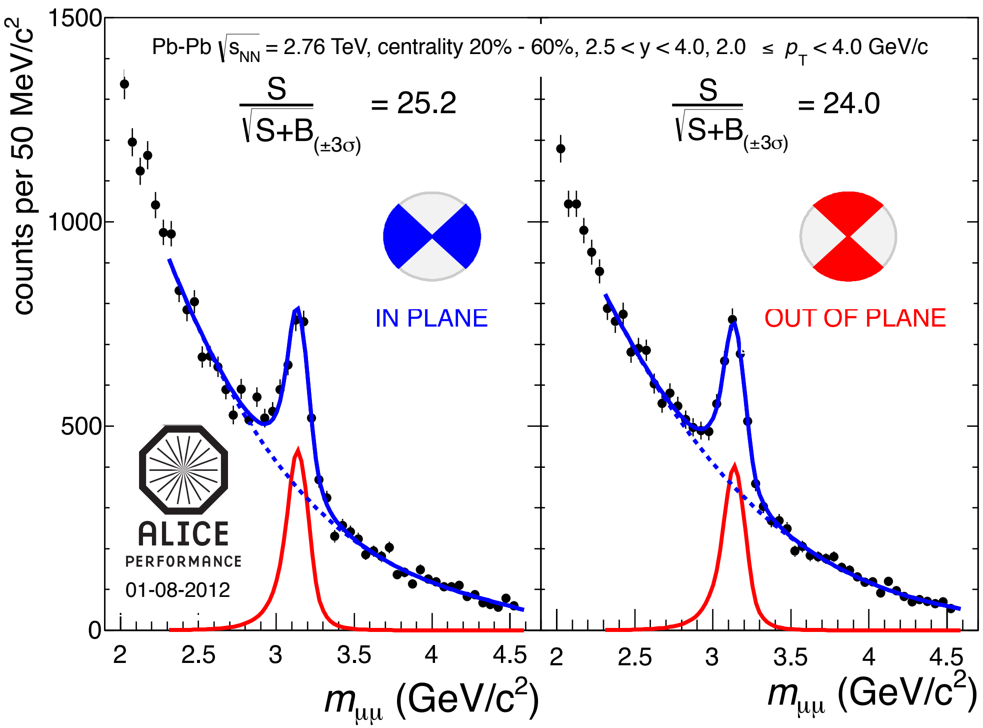
- Event plane resolution within large centrality bins
  - Resolution weighted by the number of J/ψ in smaller centrality bins

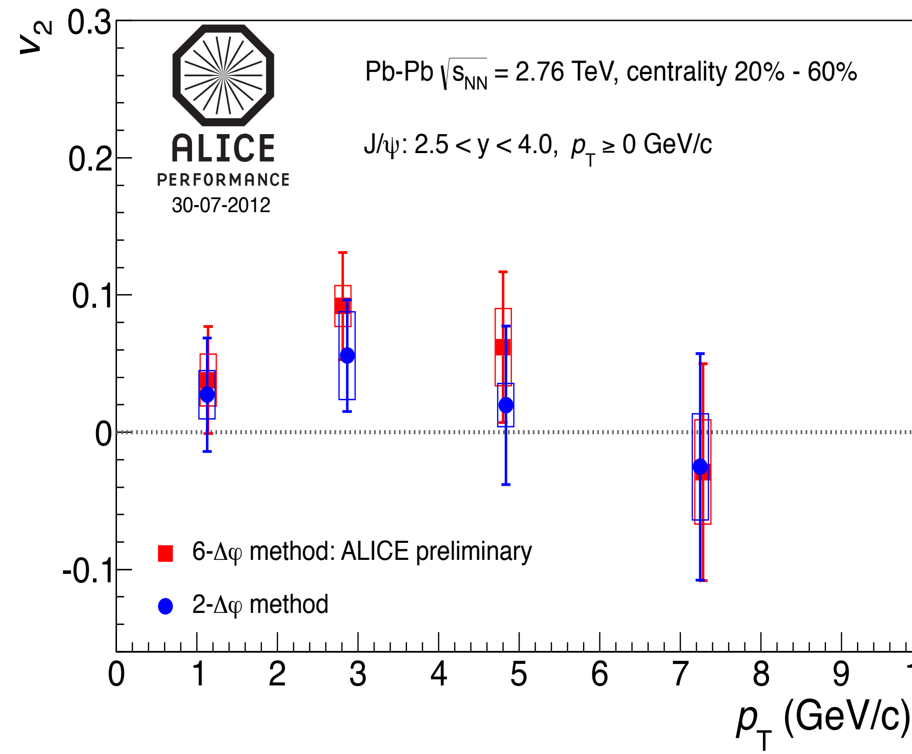
| Centrality | Correction factor |
|---|---|
| 5%–20% | 0.548±0.003 (stat)±0.009 (syst) |
| 20%–40% | 0.610±0.002 (stat)±0.008 (syst) |
| 40%–60% | 0.451±0.003 (stat)±0.008 (syst) |
| 60%–90% | 0.185±0.005 (stat)±0.013 (syst) |
| 20%–60% | 0.576±0.002 (stat)±0.008 (syst) |

# 2-Δφ method: anisotropy in/out-of-plane

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

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



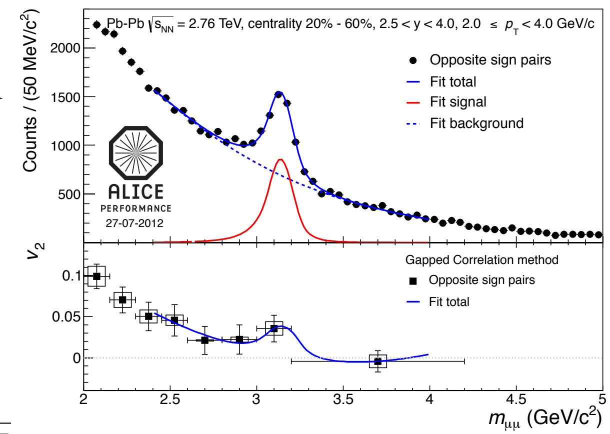
# Cumulant (2-particle correlation) method

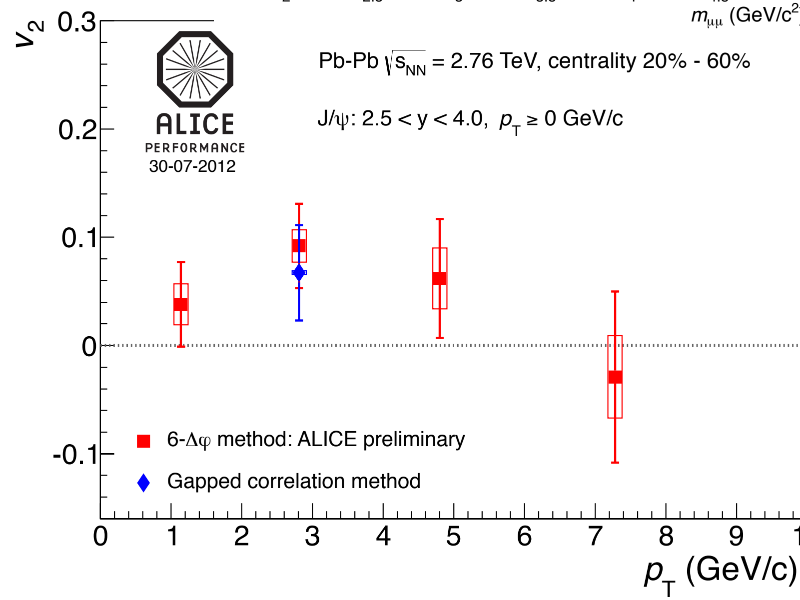
- J/ψ $v_2$ study without event plane determination

$$V_{n,AB} \equiv \frac{\langle Q_{n,A} Q^*_{n,B} \rangle}{\langle N_A N_B \rangle} - \frac{\langle Q_{n,A} \rangle}{\langle N_A \rangle} \frac{\langle Q^*_{n,B} \rangle}{\langle N_B \rangle} = v_{n,A} v_{n,B}$$

$$v_{n,B+C} = \frac{\langle N_B \rangle v_{n,B} + \langle N_C \rangle v_{n,C}}{\langle N_B \rangle + \langle N_C \rangle} \qquad v^2_{n,B} = \frac{V_{n,AB} V_{n,BC}}{V_{n,AC}}$$

  - Advantages
    - Large η gap yield non-flow suppression
    - No requirement on full azimuthal coverage
    - no event plane correction needed
      → avoid systematical uncertainties from $\sigma_{EP}$ correction
    - direct correlation of dimuon, SPD tracklets and V0A
  - Disadvantages
    - need high statistics in each centrality/invariant mass/$p_T$ bin
    - Study dimuon $v_2$ in $p_T$ bins (20%-60%): 0-2, 2-4, 4-6, 6-10 GeV/$c$
      - $v_2$ 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.)




**References:** N Borghini, P M Dinh, J-Y Ollitrault:
PRC63 (2001) 054906, PRC64(2001)054901
**Experimental implementation:** PHENIX Collab PRL94 (2005) 232302

# Centrality scan: differential J/ψ $v_2$