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sur les lois fondamentales
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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

Hongyan Yang[1] for the ALICE Collaboration

[1]SPhN/Irfu/CEA, Saclay, France

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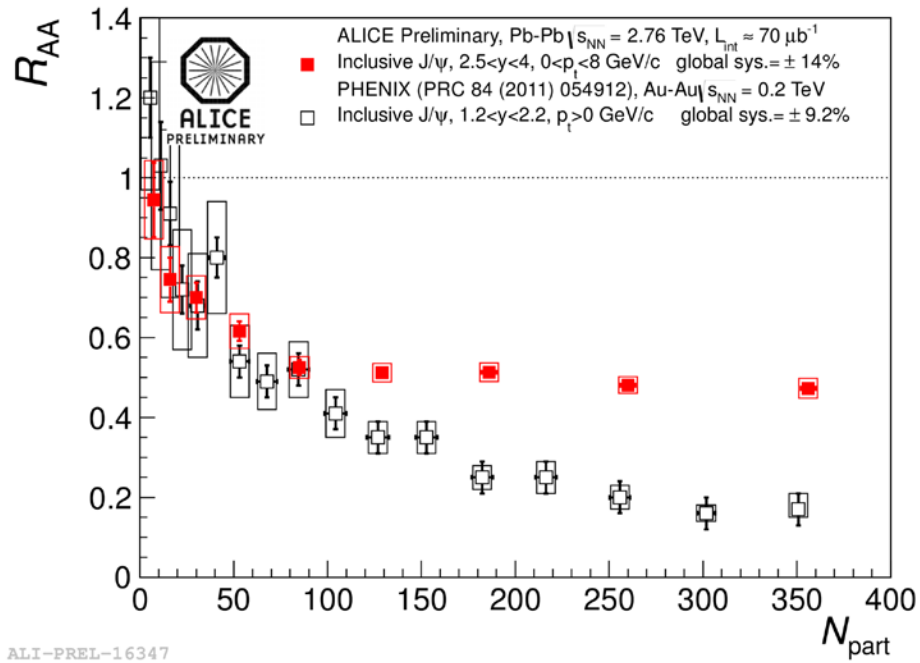
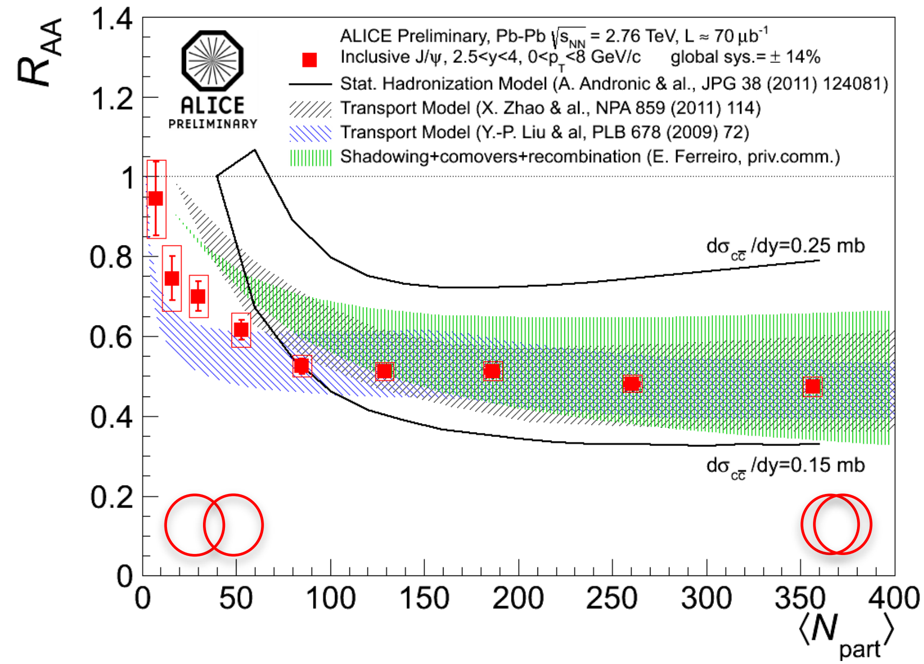
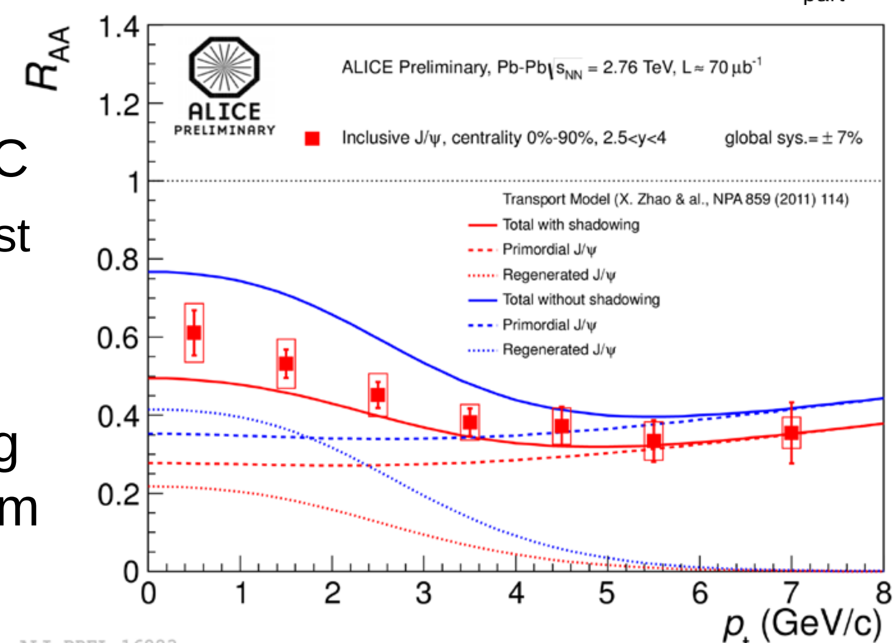
Rencontres QGP-France-2012, Étretat, France

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





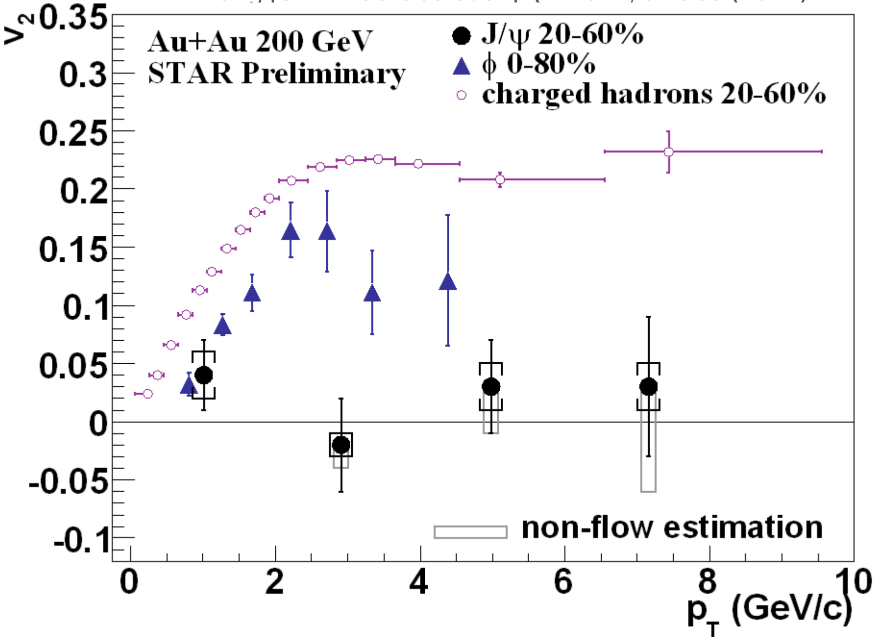
- In Pb-Pb collisions at LHC energy
  - Less suppression at LHC than at RHIC
    - No strong centrality dependence in most central collisions
    - Less suppression at low p_T
  - Described by various models including a large fraction of regenerated J/ψ from charm quarks in the QGP



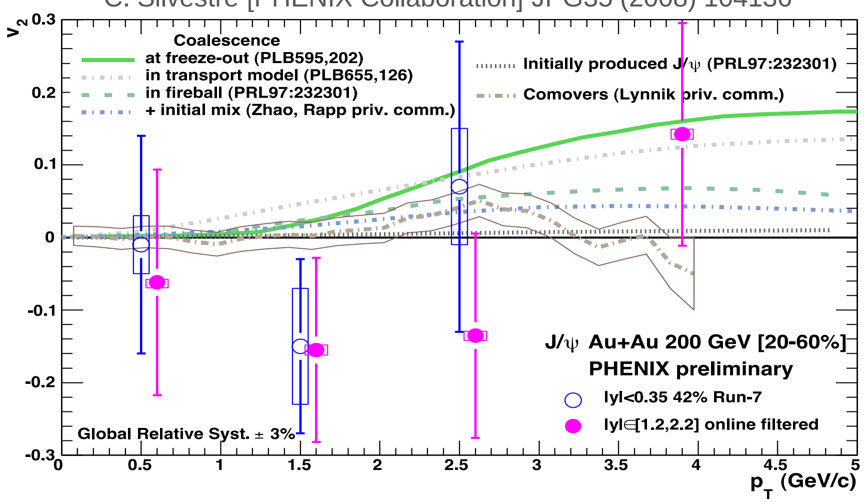
J/ψ elliptic flow at RHIC

At RHIC energy → results favor zero or very small v_2

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

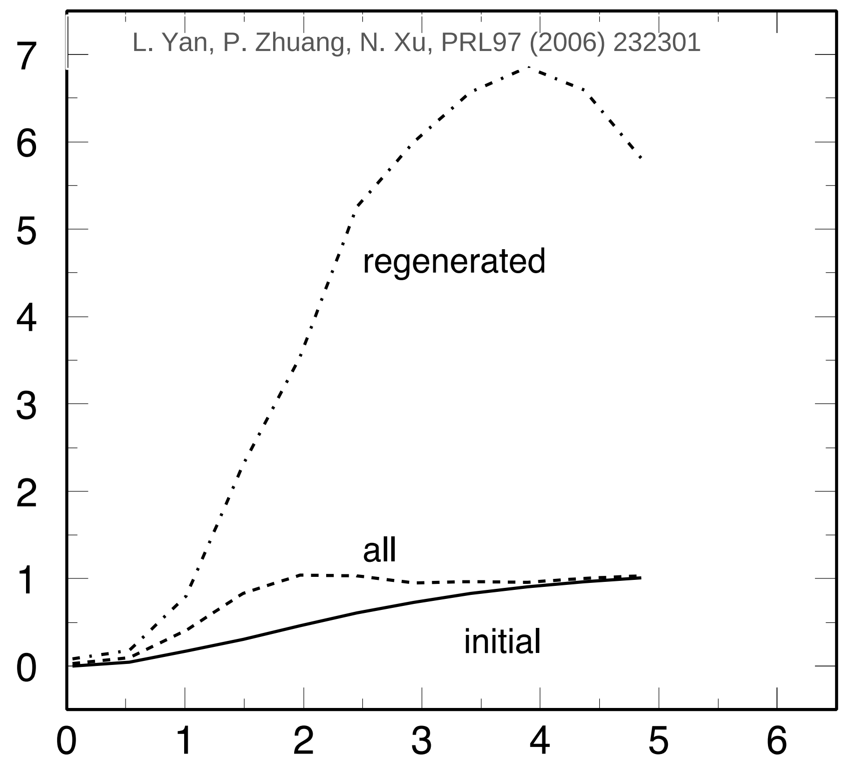


C. Silvestre [PHENIX Collaboration] JPG35 (2008) 104136



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

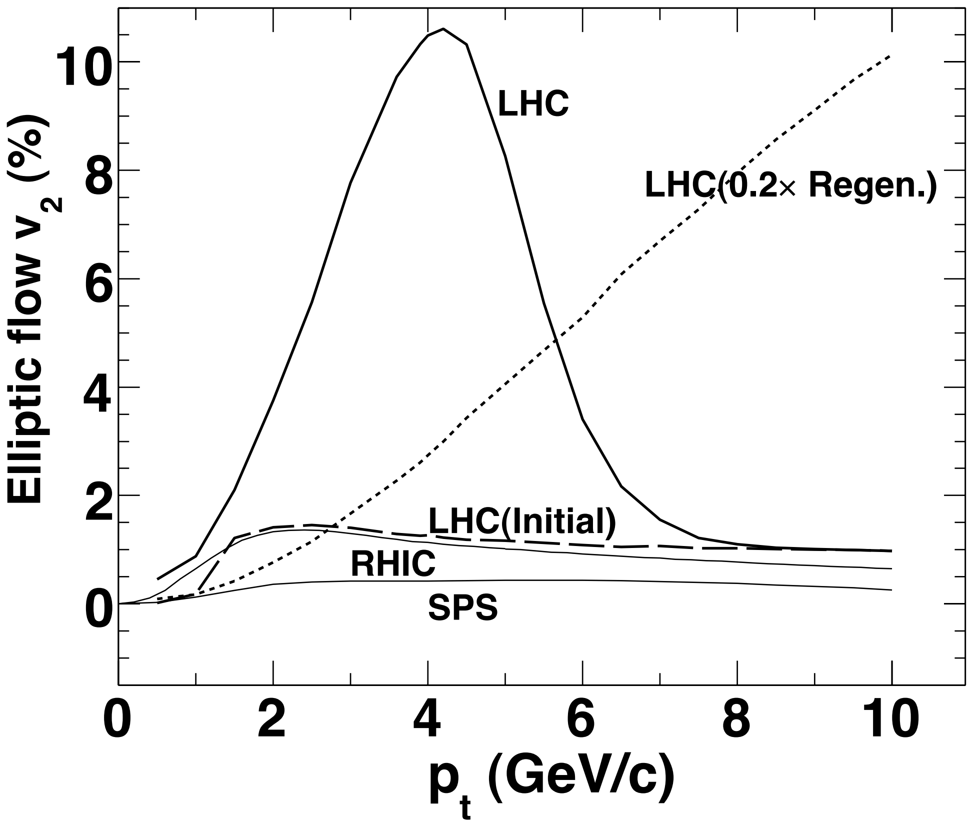
pQCD and thermal scenarios → small v_2 at RHIC



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

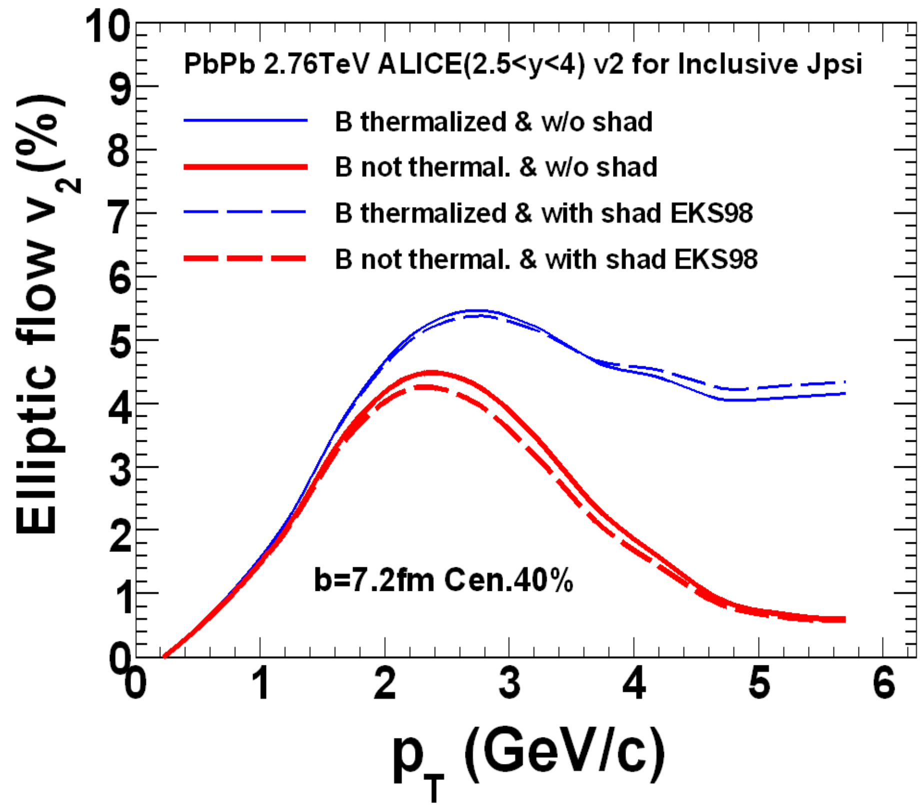
J/ψ elliptic flow at the LHC energies

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

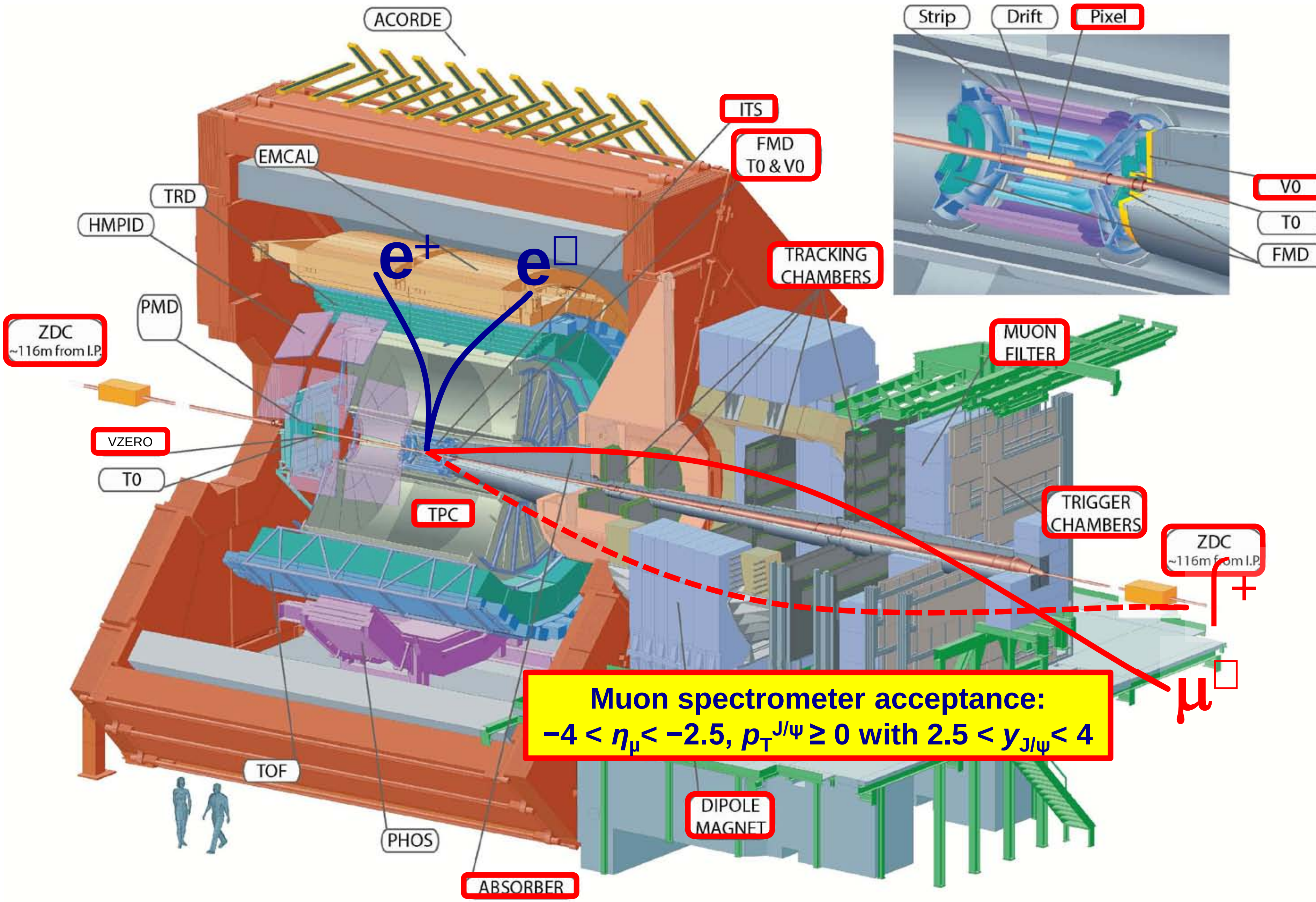
LHC Pb-Pb @ 2.76 TeV, forward rapidity
$d\sigma_{cc\text{-}bar}/dy$ = 0.38 mb, B feed-down J/ψ



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

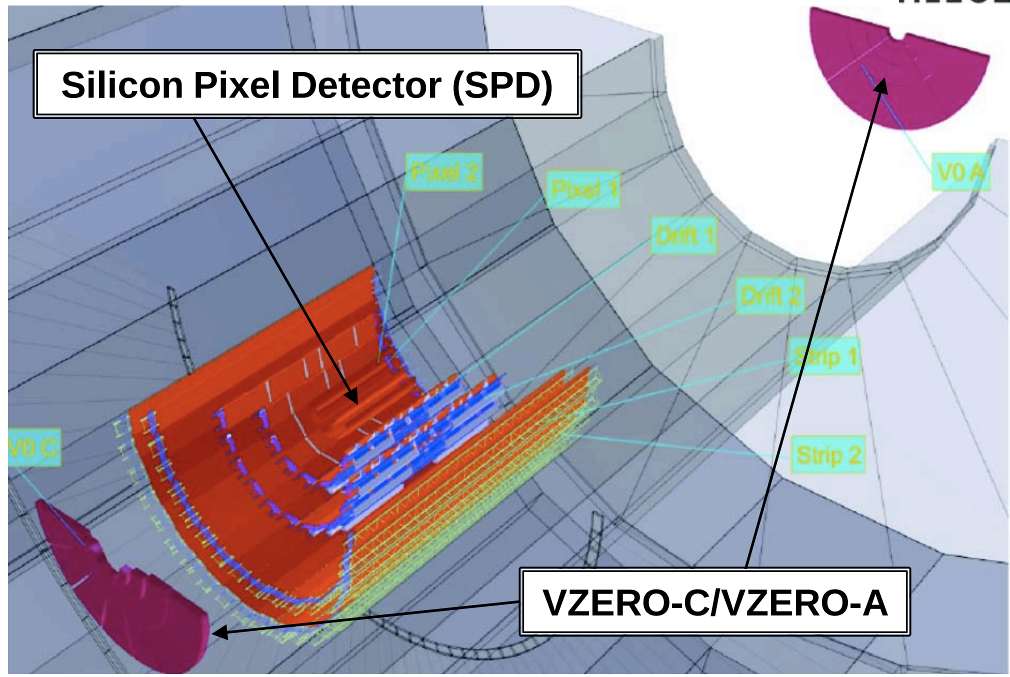
ALICE experimental setup



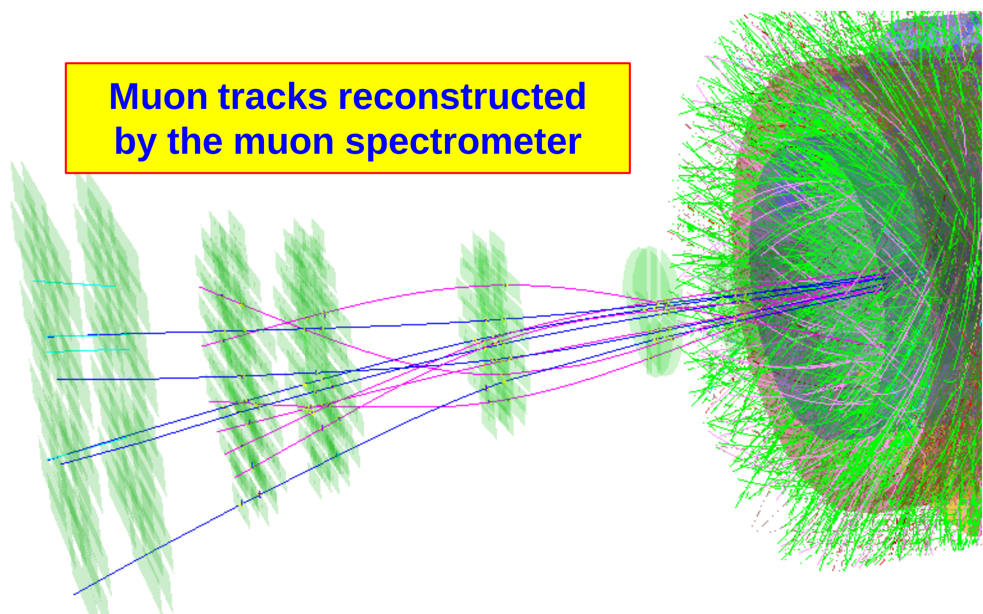
Muon spectrometer acceptance:
$-4 < \eta_{\mu} < -2.5$, $p_{T}^{J/\psi} \geq 0$ with $2.5 < y_{J/\psi} < 4$

J/ψ 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**
  - $J/\psi \rightarrow \mu^{+}\mu^{-}$ 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)
    - 3rd order polynomial (POL3) function
  - Fitting range
    - Varies for systematics study

Next step ➔ J/ψ flow study

Event plane method or not, is a problem

- M Luzum, J-Y Ollitrault, '**The event-plane method is obsolete'**
  http://arxiv.org/abs/1209.2323
  Is it a death sentence of event plane (EP) method?

- Arguments from both sides:
  - Reason to **support the drop** of the EP method:
    - Non-flow effects and flow fluctuation when particle of interest (POI) and reference particles (RP) for EP shares common acceptance
    - When event plane resolution is high, flow fluctuation is larger; higher order harmonics, larger the fluctuation effects
  - Reasons to **against the abandon** of the EP method:
    - One can avoid acceptance overlap between POI and RP to suppress non-flow effects
    - There are detector limitations: when EP resolution is not high, flow fluctuation could become under-control
    - Statistically, large statistical uncertainty with SP and QC methods
    - For elliptic flow, flow fluctuation effects is less than higher order harmonics a few percent difference from EP results & true v_2
    - EP is more suited and might be the only possibility for some specific cases

- For the moment: **NOT YET completely black and white!**

J/ψ elliptic flow analysis methods

- **With event plane** (by VZERO-A, no TPC in the trigger cluster)
  - *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 σ_{EP}**

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

- **Method w/o event plane – a *cumulant method***
  - *2-particle correlation method* with detectors with large η 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: $-3.7 < \eta < -1.8$

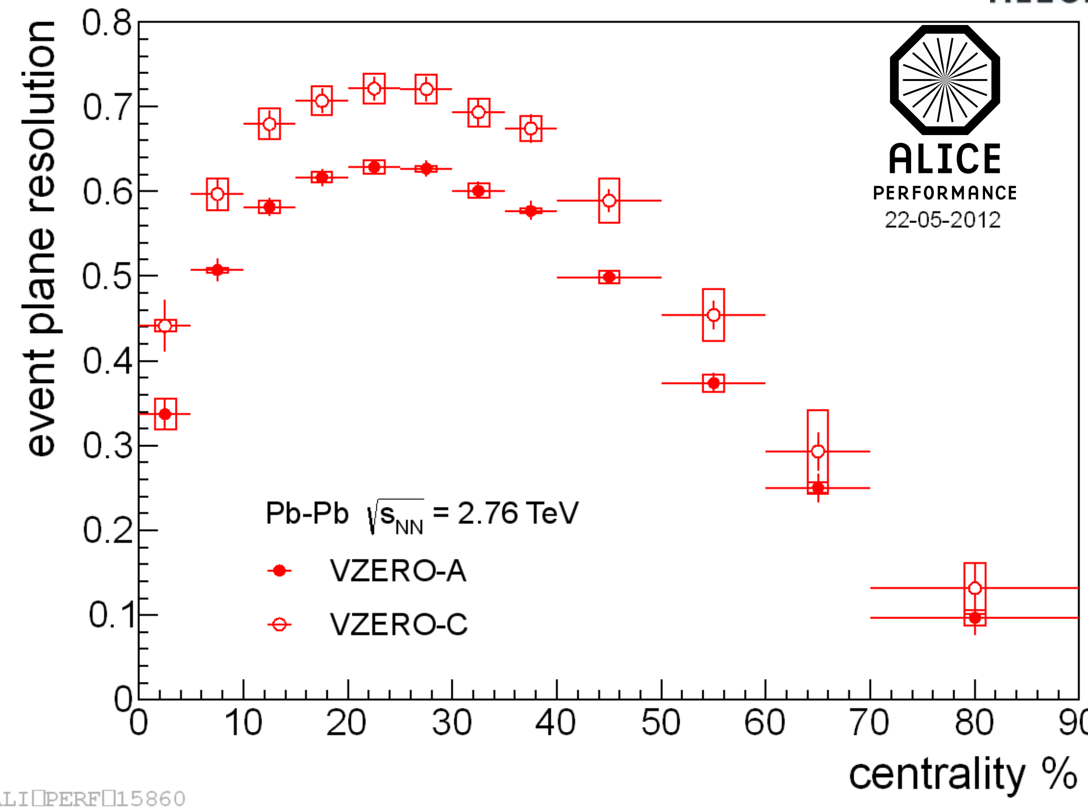
VZERO-A & MUON: η gap ~ 5.3

- 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

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)

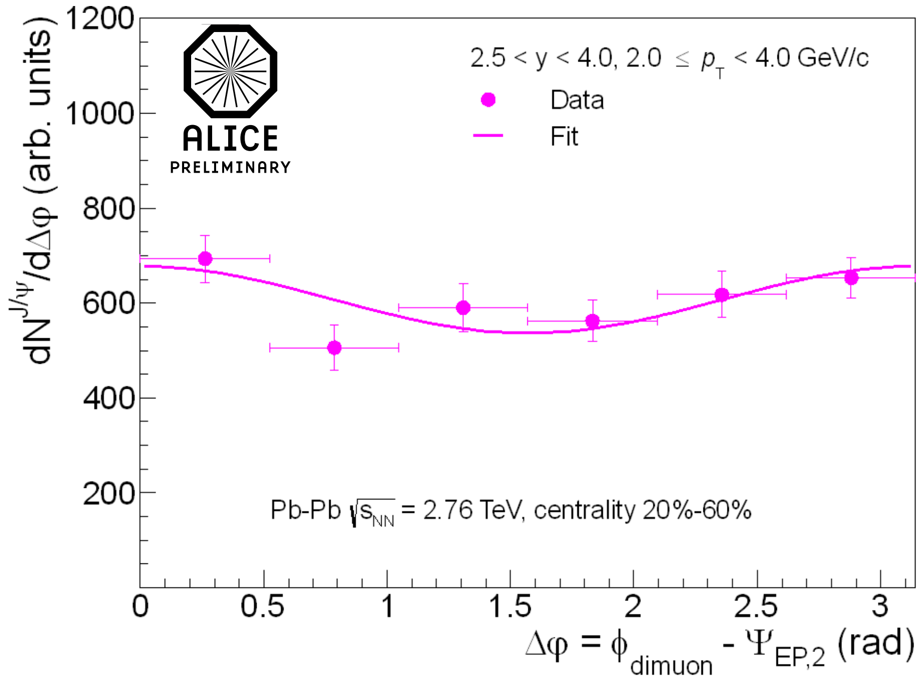
- Event plane resolution in a large centrality bin
  - Estimated by a weighted sum of event plane resolutions using J/ψ yields as weights in its sub-centrality bins

[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

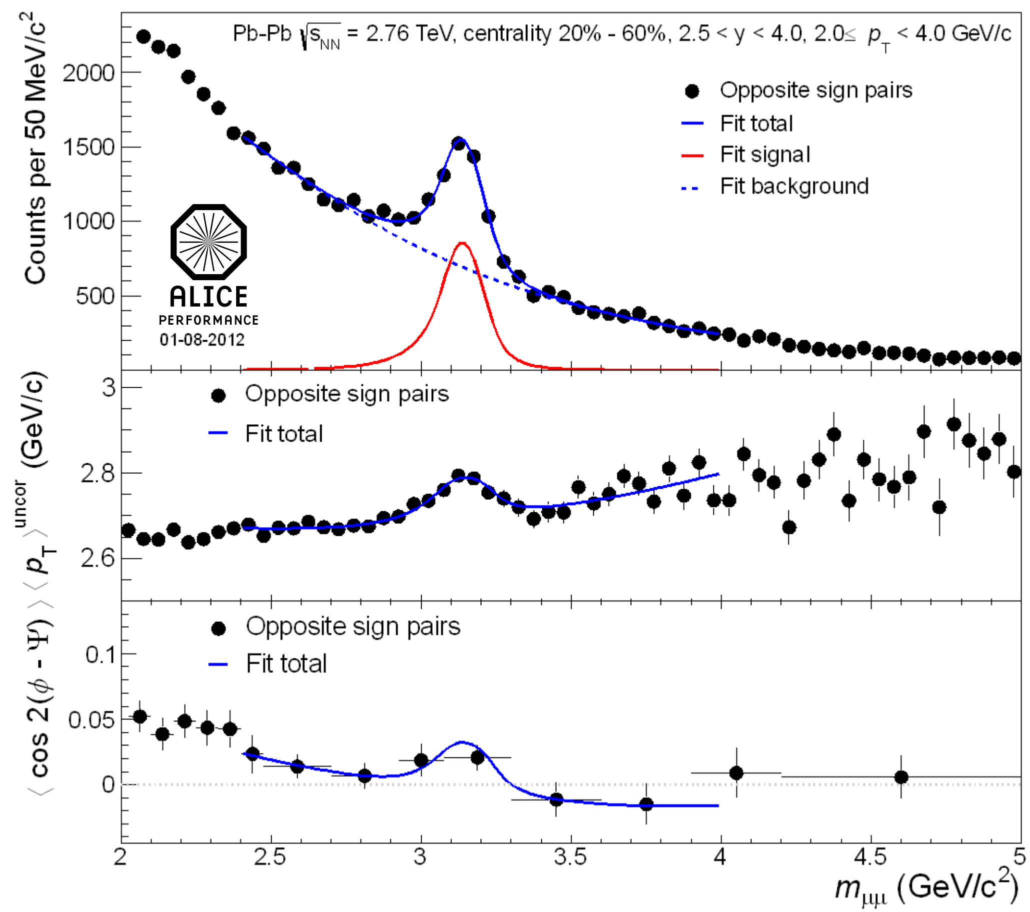
6-Δφ method



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

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

invariant mass fit technique

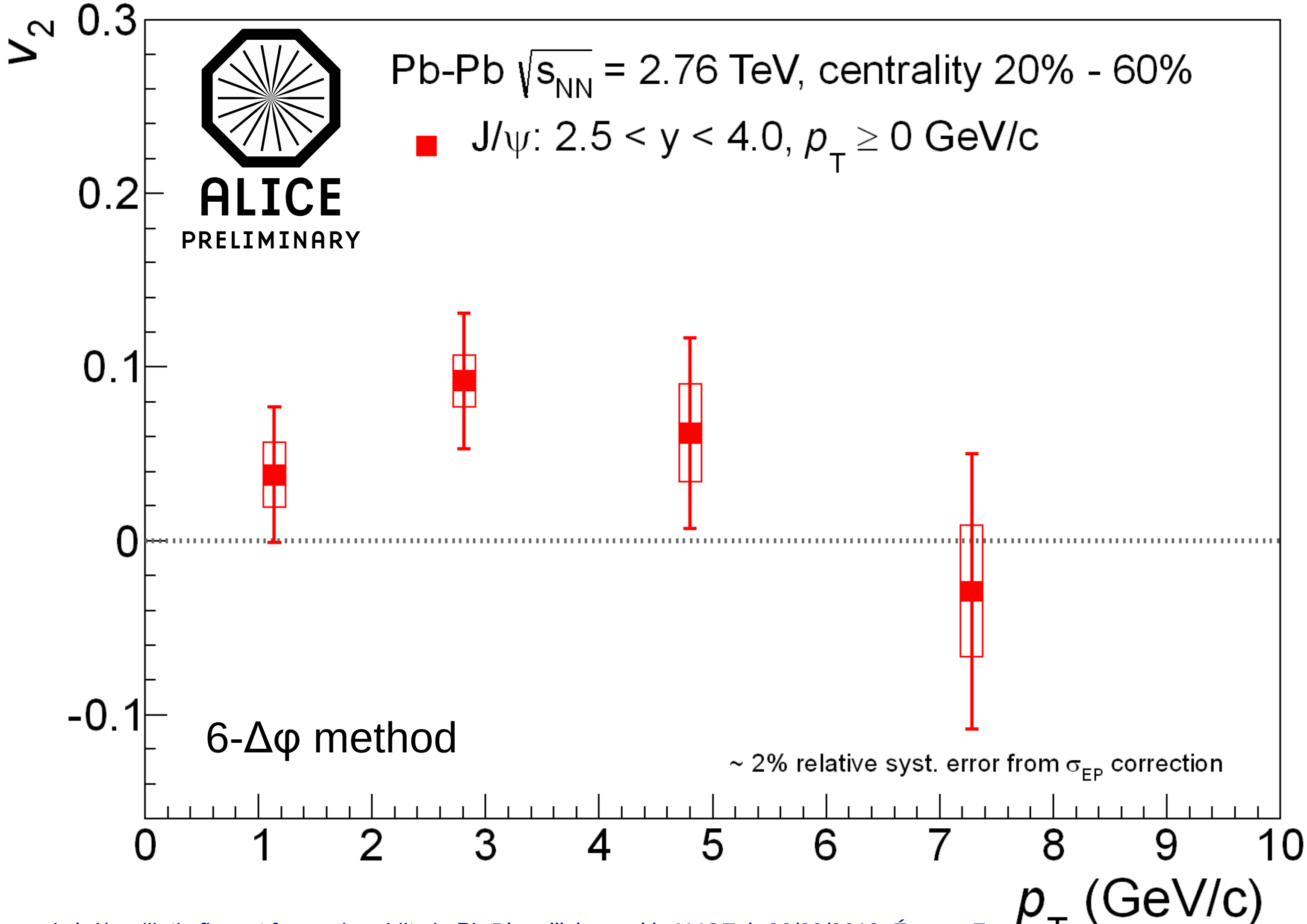


2nd order polynomial function used to describe $\langle p_T \rangle$ and v_2 of the background

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

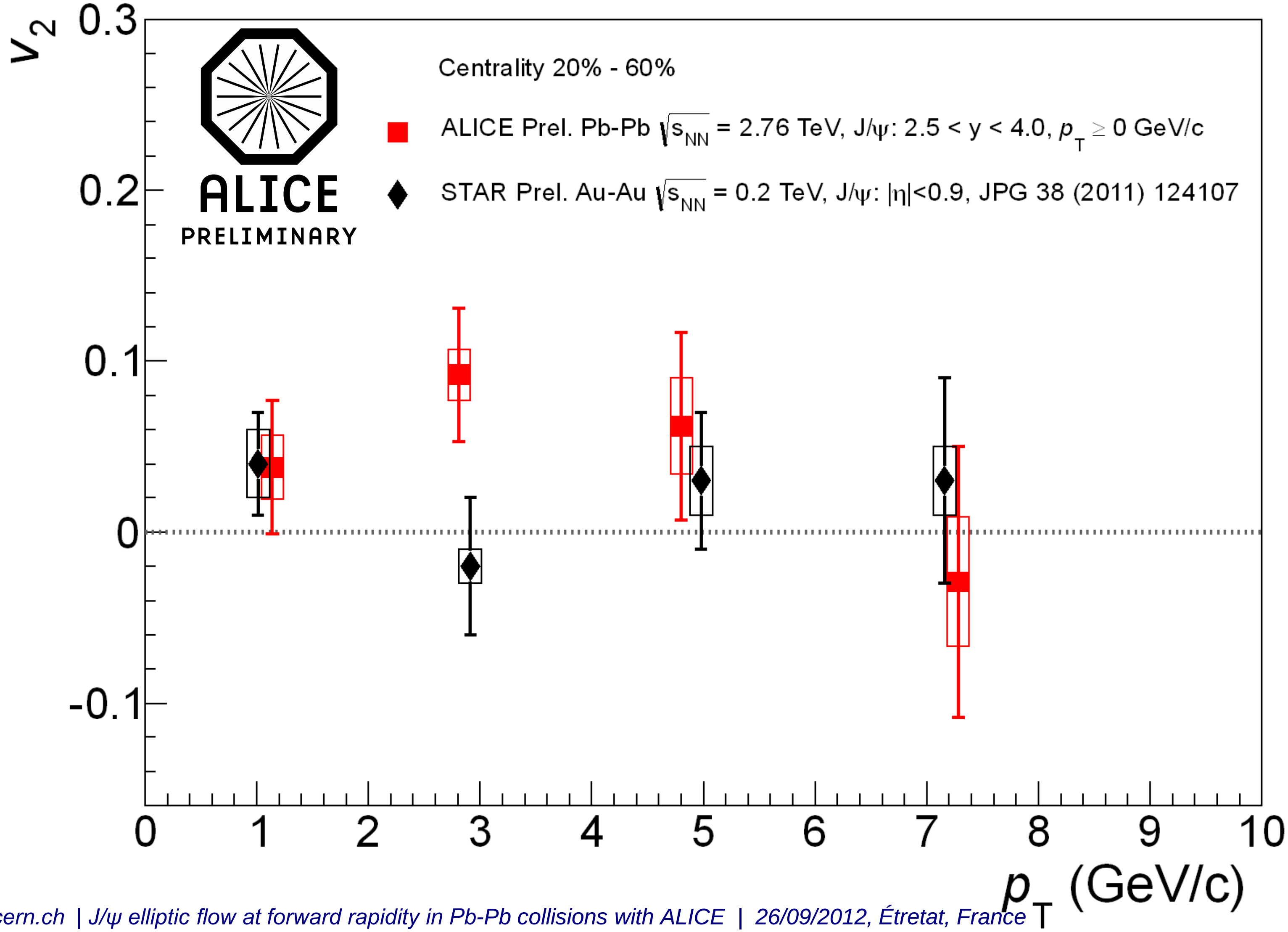
J/ψ v_2 in centrality 20%-60%

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



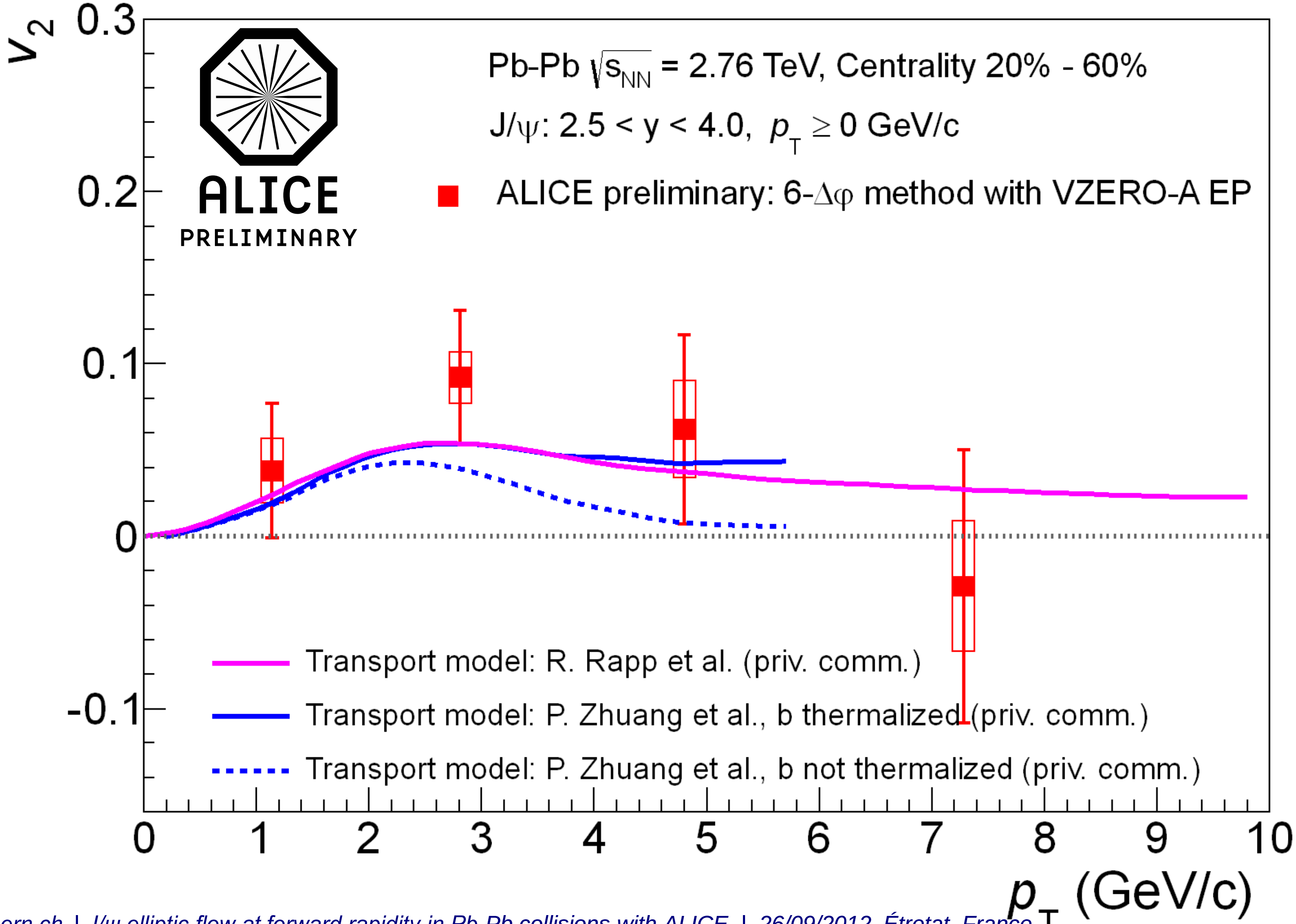
J/ψ v_2 in centrality 20%-60%

- **$2 \leq p_T < 4$ 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



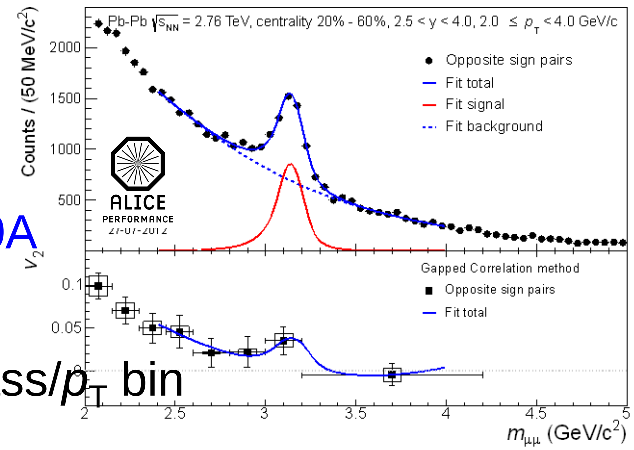
Cumulant (2-particle correlation) method

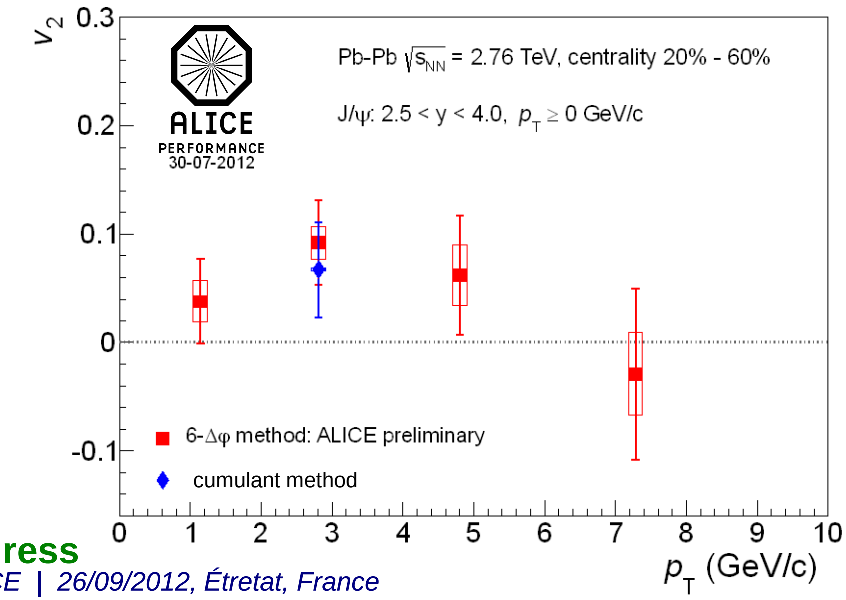
References: N Borghini, P M Dinh, J-Y Ollitrault: PRC63 (2001) 054906, PRC64(2001)054901, **Experimental implementation:** PHENIX Collab PRL94 (2005) 232302

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

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

- J/ψ v_2 study without event plane
  - Advantages
    - Large η gap allows non-flow suppression
    - No requirement on full azimuthal coverage
    - no event plane correction needed
      → avoid systematical uncertainties from σ_{EP} corr.
    - 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.)

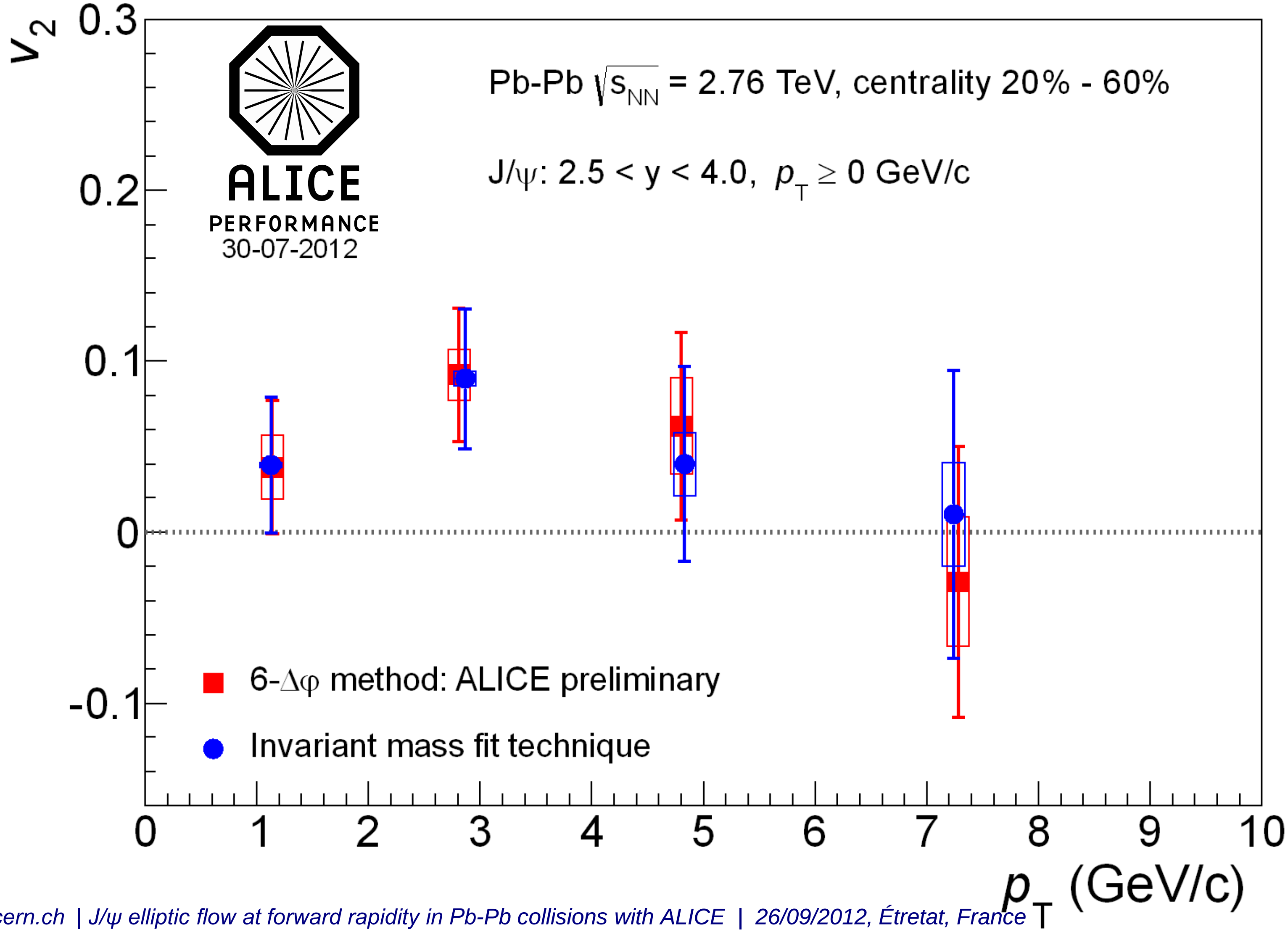




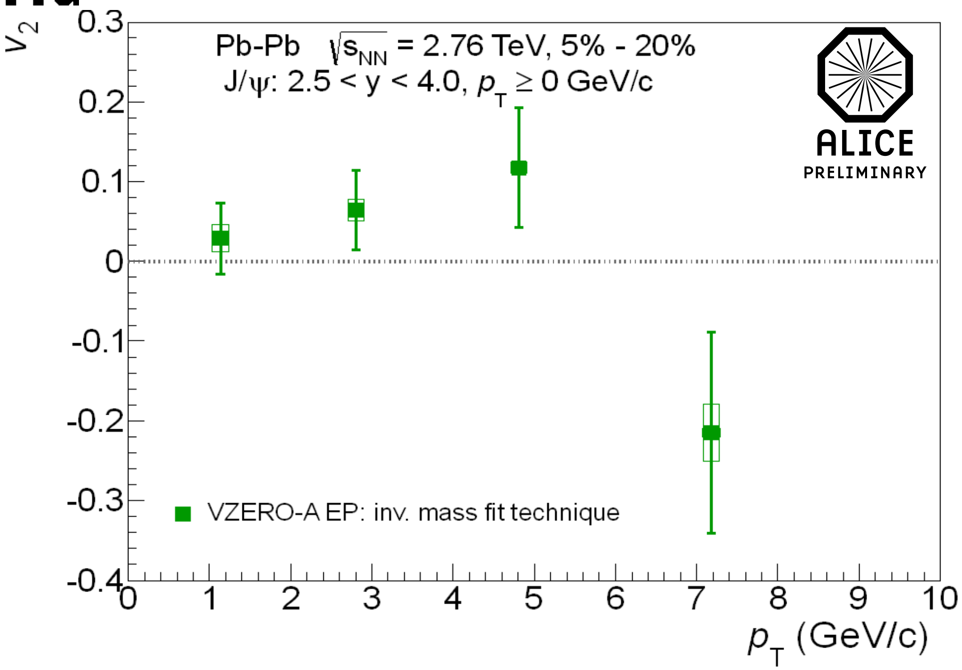
Statistical wise, it's possible for muon v_2 study
→ shows good agreement with EP method – work in progress

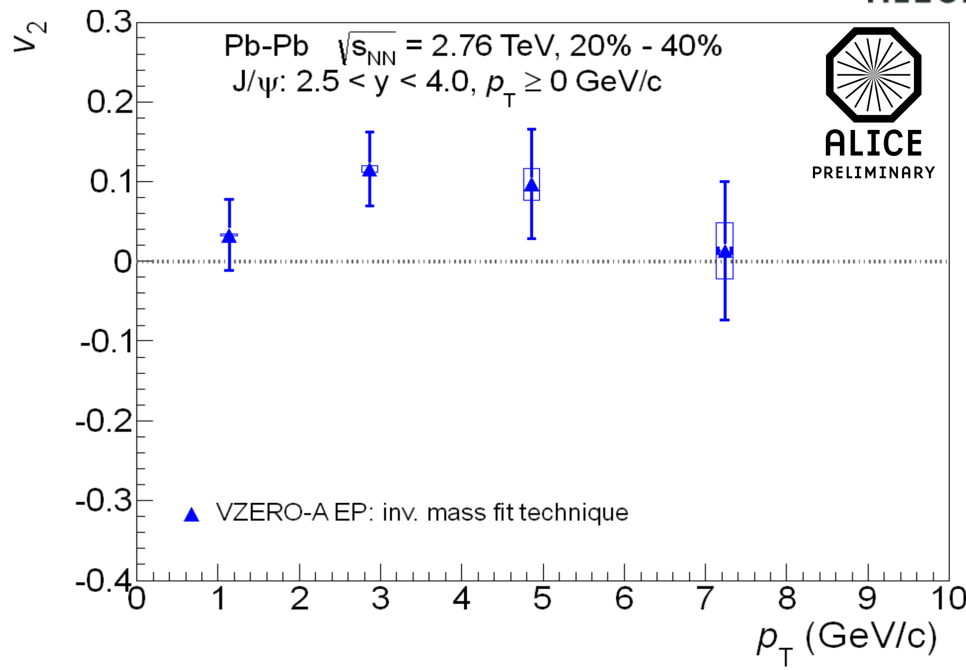
6-Δφ method vs. inv. mass fit technique

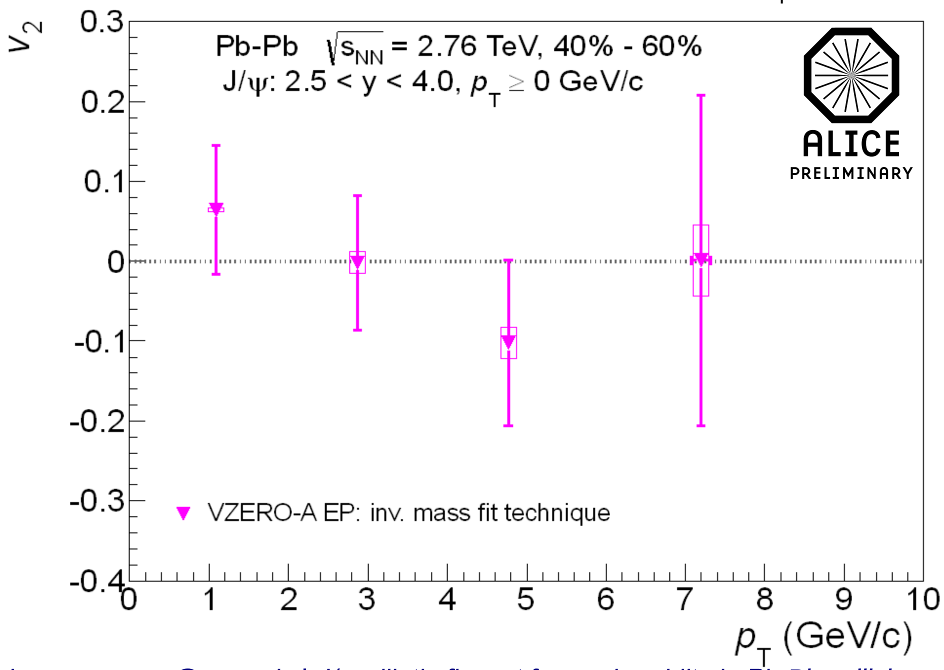
- Agreement achieved between two methods
  - *Invariant mass fit technique* is used for J/ψ v_2 in finer centrality bins (5%-20%, 20%-40%, 40%-60% and 60%-90%)



J/ψ v_2 in smaller centrality bins





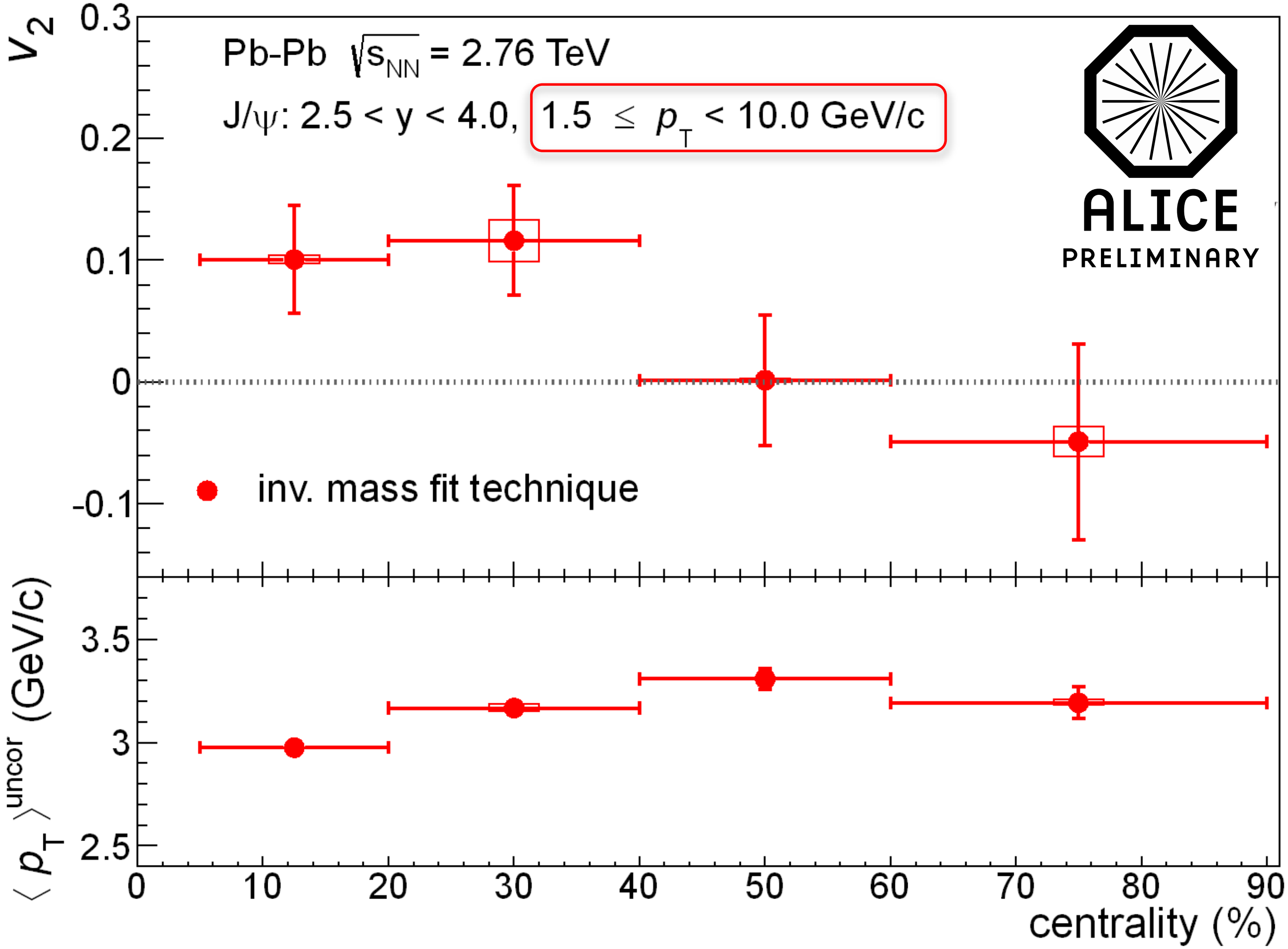


At intermediate p_T: $2 \leq p_T < 6$ GeV/*c*

- **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

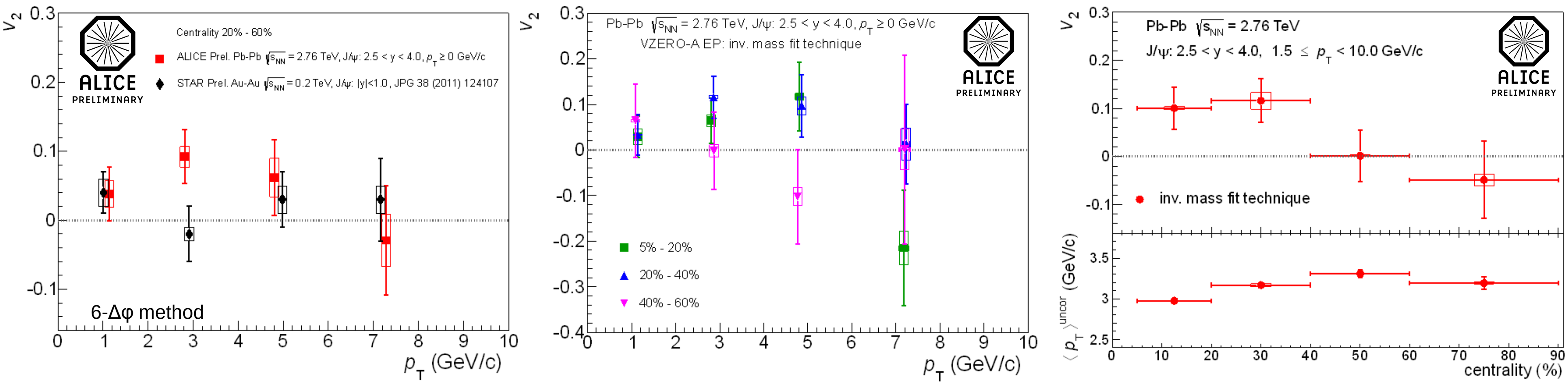
- Non-zero v_2 in central and semi-central collisions



- 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



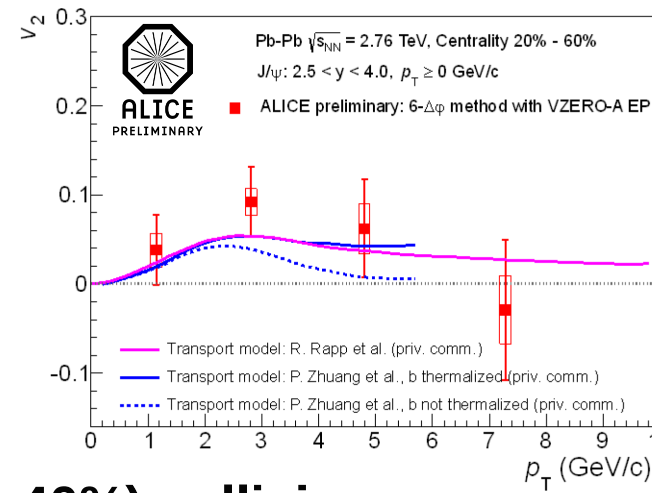
- **Hint of non-zero v_2** in **(20%-60%)** collisions at intermediate p_T:
  $2 \leq p_T < 4$ GeV/*c*
  contrary to zero or small v_2 observed at RHIC

- **Indication of non-zero v_2** in semi-central **(20%-40%)** collisions at 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 non-negligible 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**

Outlook

- The upgrade program of MUON spectrometer
  → allow a more precise measurement of J/ψ v_2

- Higher statistics
  → Lower statistical uncertainty
  → Allow measurements with standard SP and QC methods

Thanks!

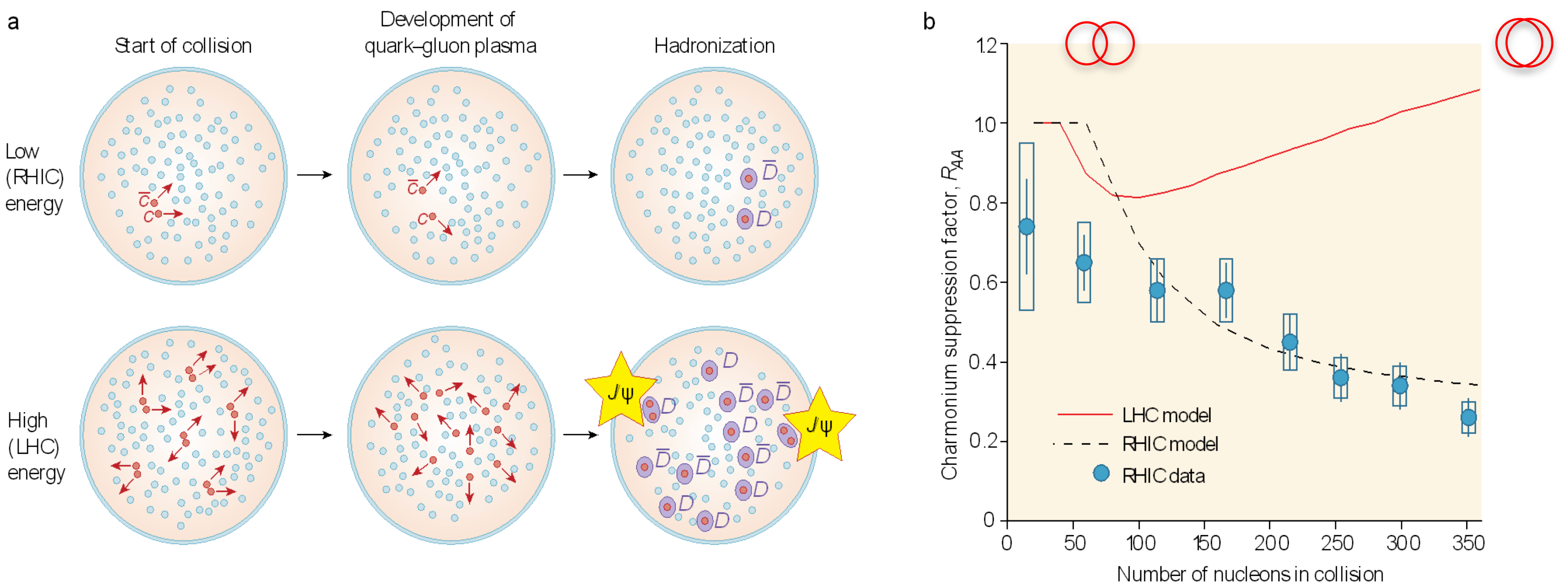
Backup slides

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
- Differential J/ψ v_2 in various centrality bins

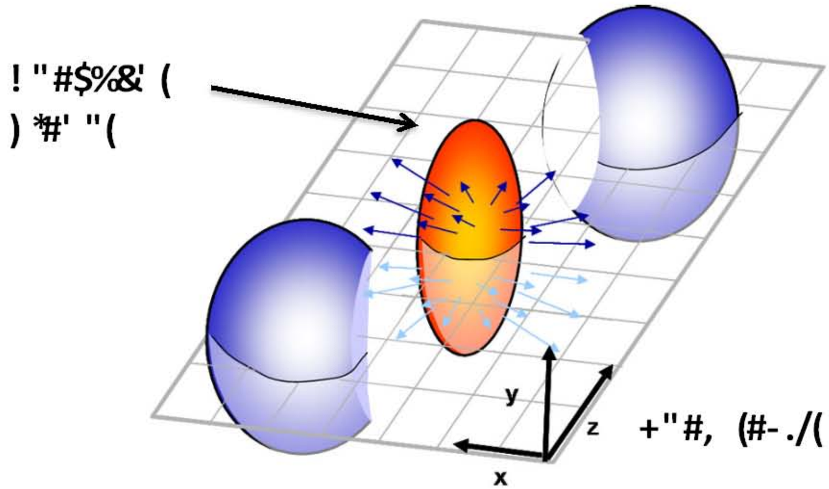
J/ψ suppression at RHIC and LHC

- 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:

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

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

Event plane flattening from VZERO

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

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

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

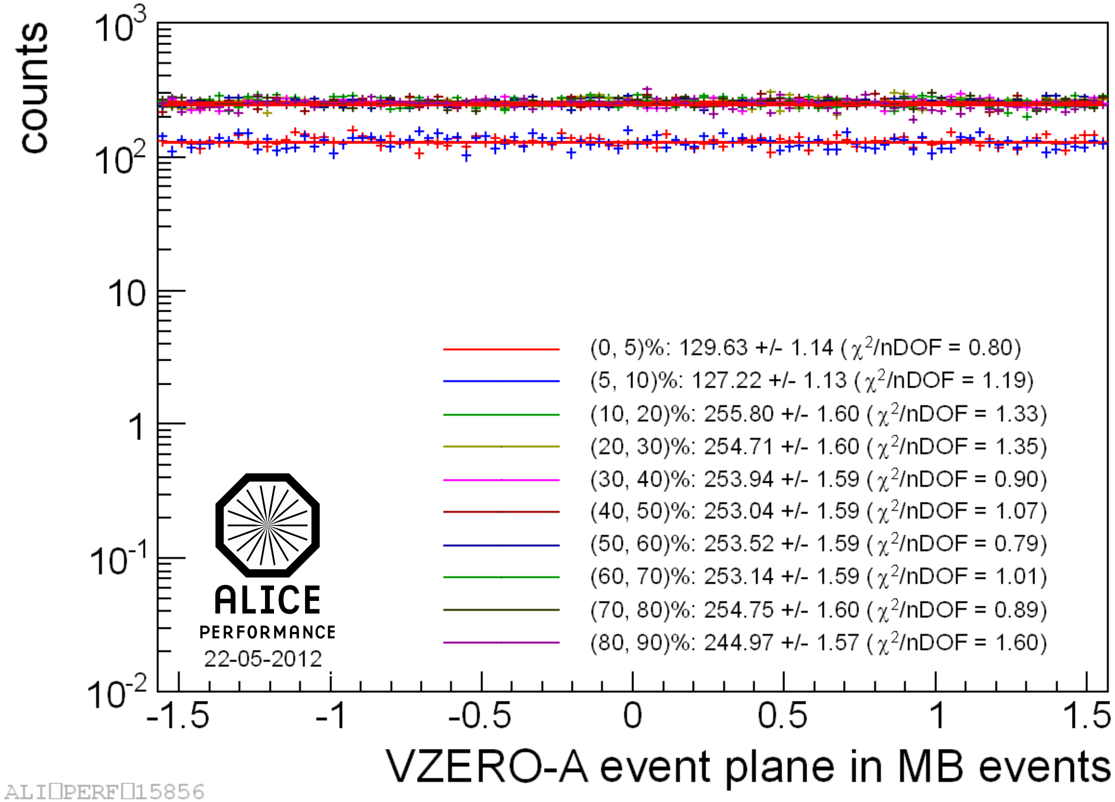
where the parameters $\langle Q_{2,x} \rangle, \langle Q_{2,y} \rangle, A^{+}, A^{-}, \Lambda^{+}$ and Λ^{-} are extracted from the mean and RMS of the $Q_{2,x}, Q_{2,y}$ and $Q_{2,x}Q_{2,y}$ distributions

  - 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

By ALICE-VZERO Lyon group

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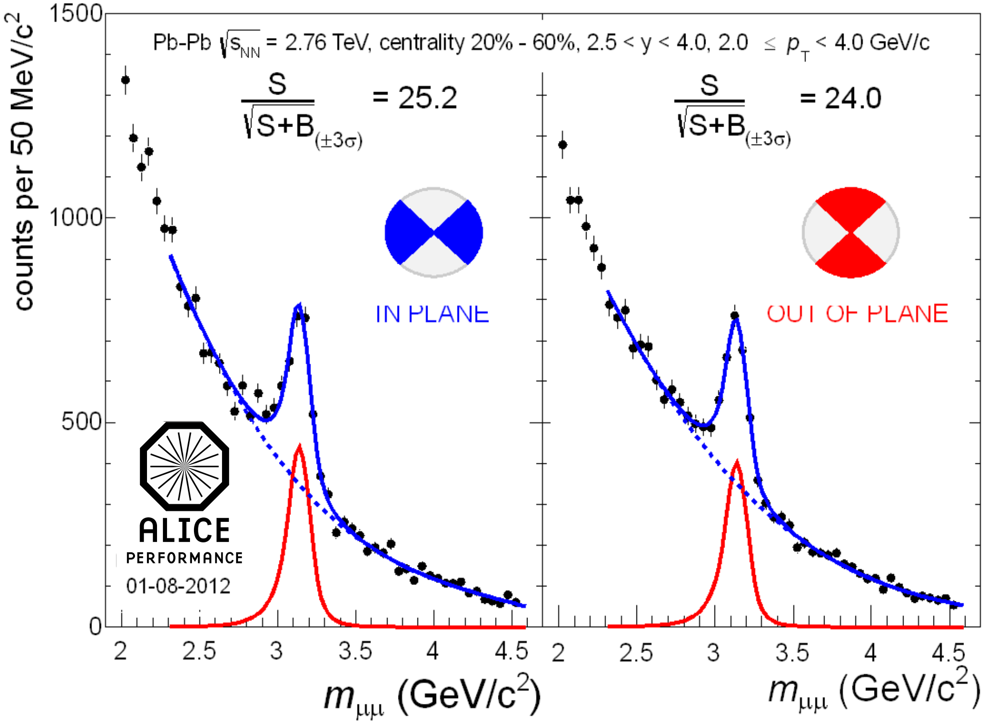
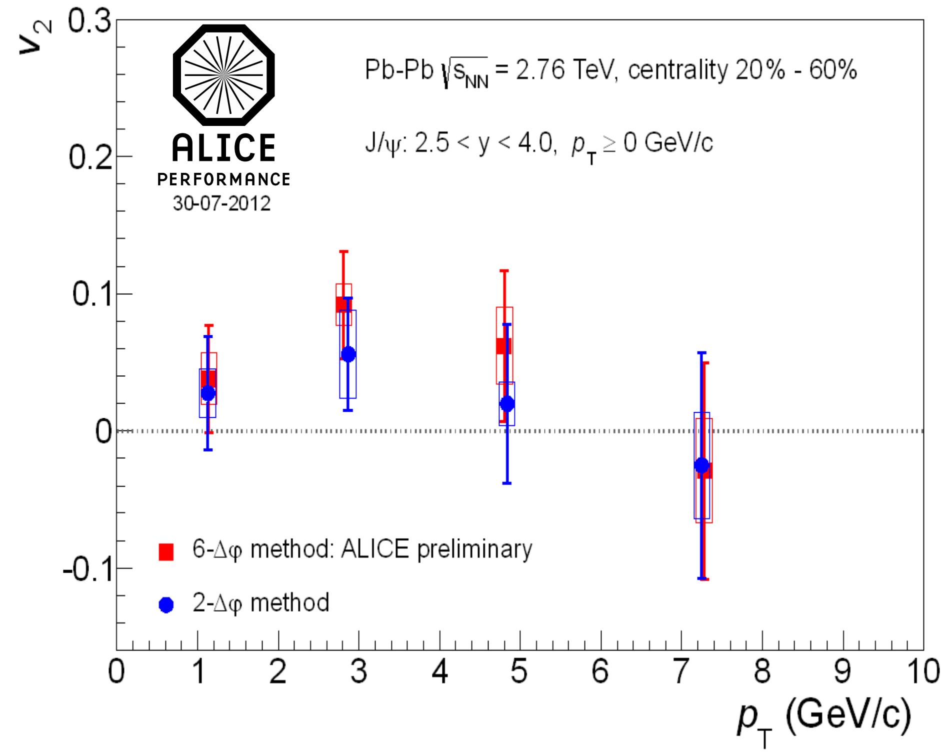
2-Δφ method: anisotropy in/out-of-plane

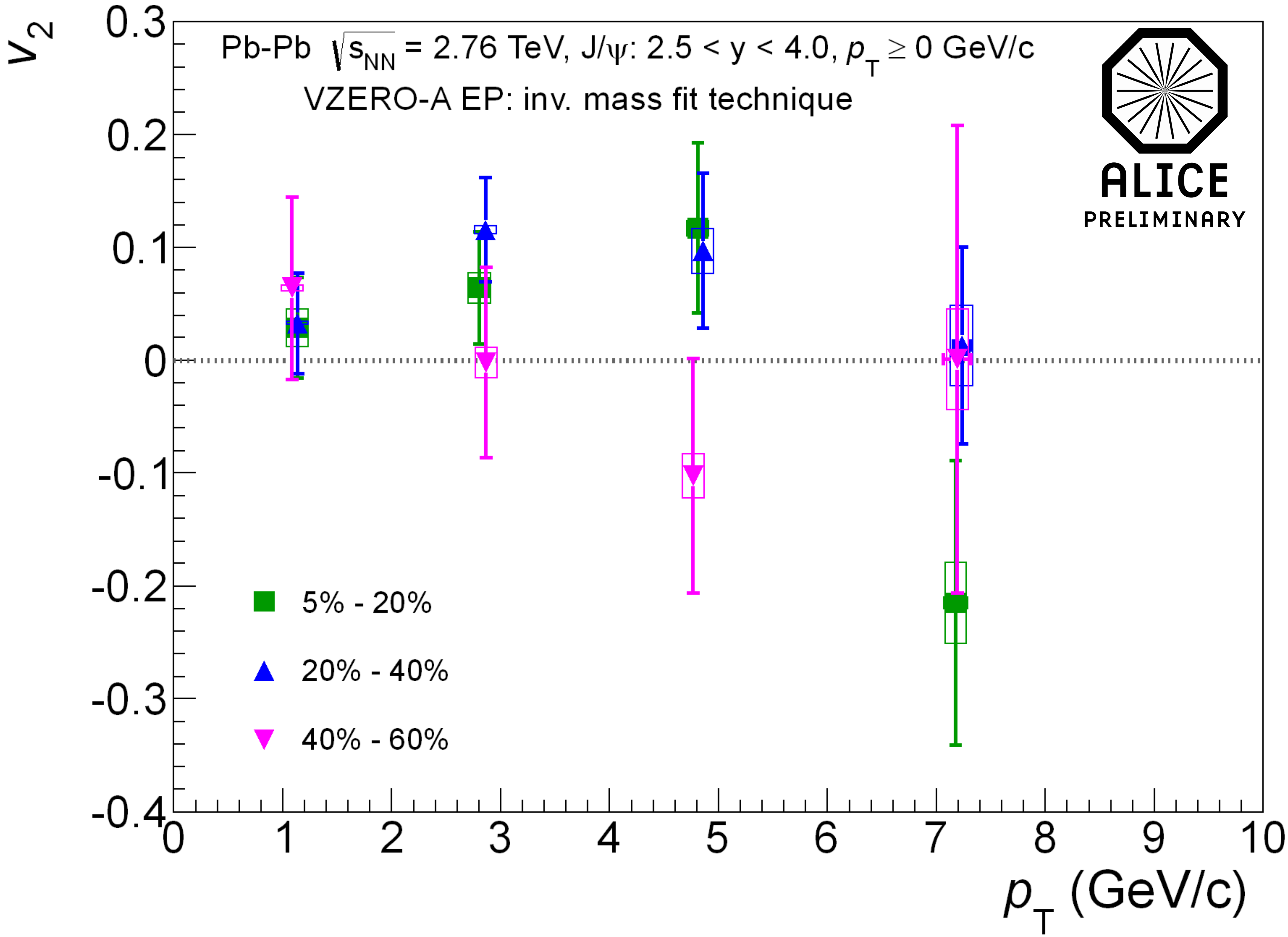
- 2-Δφ method:
  - A direct calculation from J/ψ yield anisotropy in-plane and out-of-plane
  - Correct v_2^{obs} by the event plane resolution σ_{EP}

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





Centrality scan: differential J/ψ v_2



Signal extraction functions

- J/ψ extraction
  - Signal:
    - CB = Crystal Ball function with fixed parameters: $\sigma_{CB}=0.98$, $n_{CB}=5.2$
    - CB2 = extended CB function with fixed parameters - $\alpha = 0.973$, $n = 5.806$, $\alpha_{up} = 1.662$, $n_{up} = 3.645$
  - Background:
    - VWG = Variable Width Gaussian
      sigma = par[2]+par[3]((x[0]-par[1])/par[1])*
      *VWG = par[0]*exp(-(x[0]-par[1])*(x[0]-par[1])/(2.*sigma*sigma))*
    - Pol = 3rd degree polynomial
      *par[0] + par[1]*x[0] + par[2]*x[0]*x[0] + par[3]*x[0]*x[0]*x[0]*