Quarkonium ellipitc flow v_2 in Pb-Pb collisions at 5.02 TeV

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Outline

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    - Probing the medium with quarkonium
    - The flow in heavy ions collisions
2. Quarkonium v_2 in Pb-Pb collision
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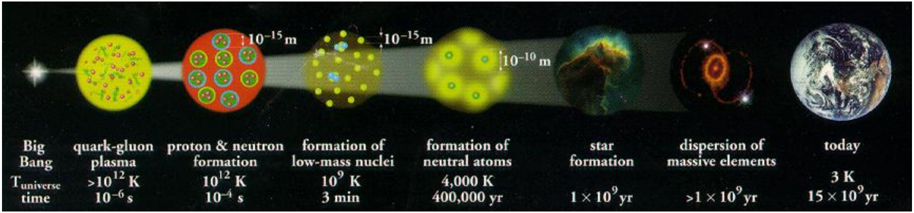
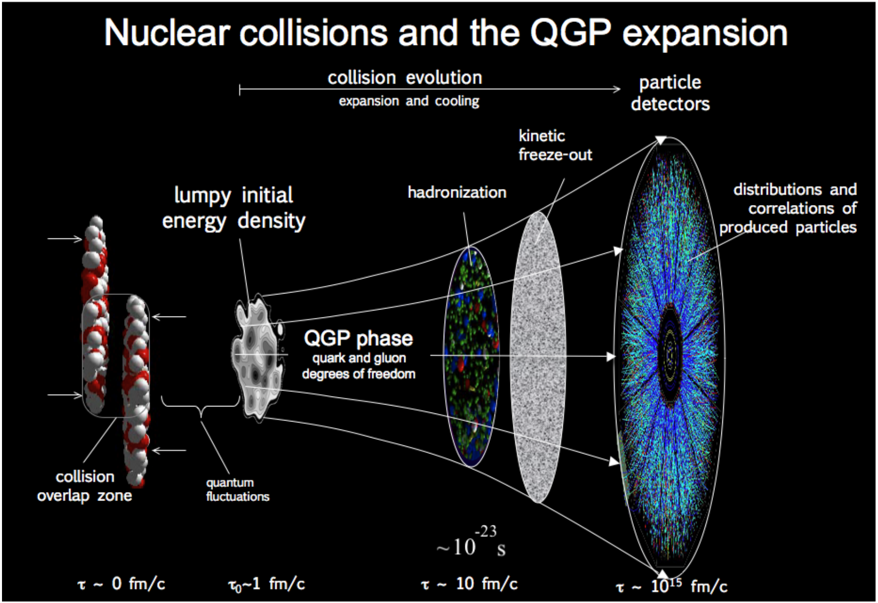
    - Measurement of J/ψ and $\Upsilon(1S)$ v_2 in Pb-Pb collisions
    - Comparison with model predictions
3. Conclusion

The Quark-Gluon Plasma (QGP)

- **Quark and gluons** are ordinarily confined by their color charge to form protons, neutrons ...
- The coupling between quark and gluon become **asymptotically weaker** as the energy scale increases
- This property predicts **a deconfined state** composed of quarks and gluons

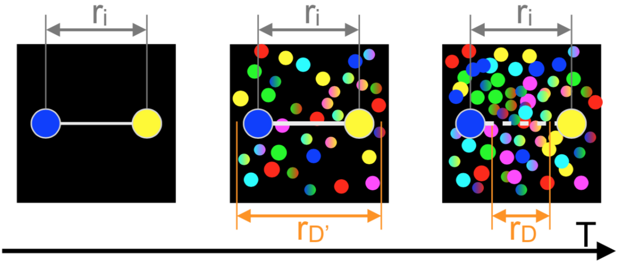


The Quark-Gluon Plasma



Physics motivation

- Heavy quarks are produced by **hard scattering processes prior to the formation of the QGP**
- Measurement of bound states of heavy quarks, is expected to provide **sensitive probes of the strongly interacting medium**



- Quarkonium states used as probes:
  $c\bar{c}$ pair: J/ψ, $\psi(2S)$ and $b\bar{b}$ pair: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

Physics motivation (simple picture)

Sequential suppression used as a ”thermometer” of the QGP

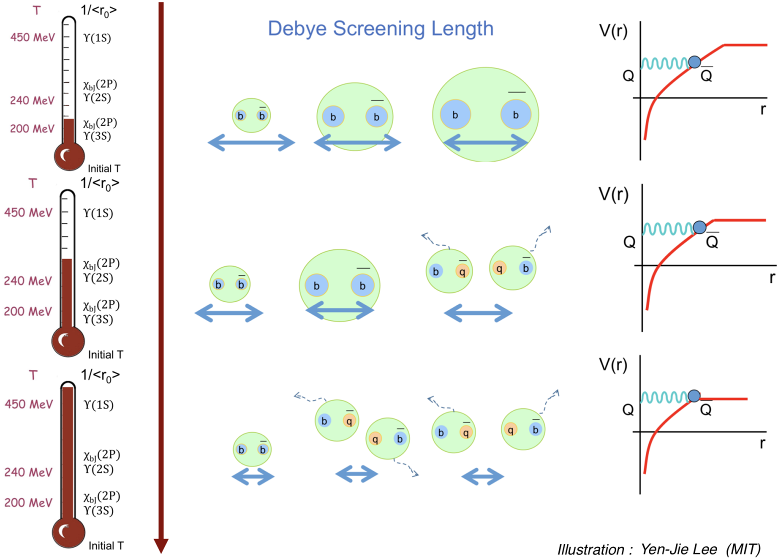
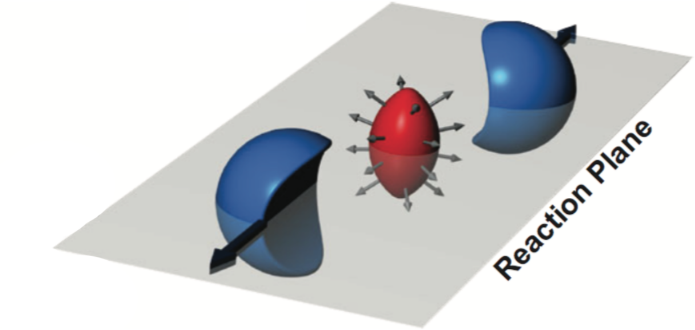


Illustration : Yen-Jie Lee (MIT)

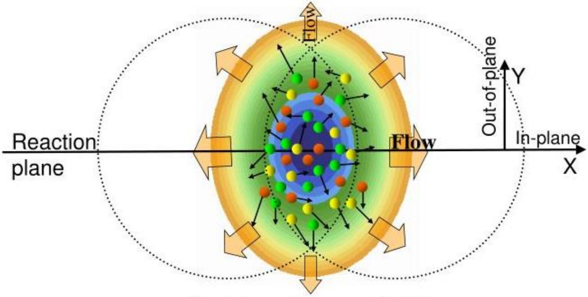
Heavy ions collisions concepts

- **Reaction plane** : define by *beam axis z* and *impact parameter b*



During system expansion, pressure gradients generated by parton interactions, **transform the spatial anisotropy into a momentum space anisotropy** of produced particles.

The flow in heavy ions collisions



- **Azimuthal particles distribution** measured with respect to reaction plane (decomposed by Fourier series where n : harmonic):

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\phi - \Psi_n)\right]\right) \tag{1}$$

Flow concepts

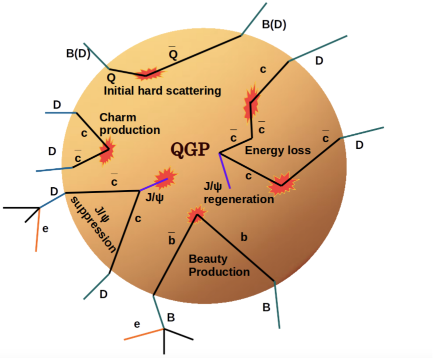
- Estimation of the **reaction plane** (RP) by the $\mathbf{Q_n}$ vector (N : number of charged particles in an event : the multiplicity)

$$\mathbf{Q_n} = \sum_{j=1}^{N} e^{in\phi_j} = |Q_n| e^{in\Psi_n} \tag{2}$$

- Then, to determine the *event plane angle* Ψ_n :

$$\Psi_n = \frac{1}{n} \arctan\left(\frac{Q_{n,y}}{Q_{n,x}}\right) \tag{3}$$

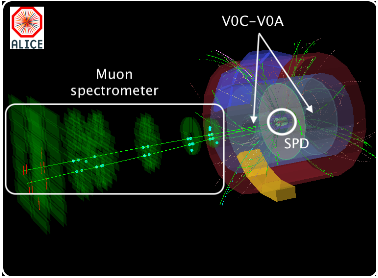
Mechanisms involved in quarkonium v_2 elliptic flow

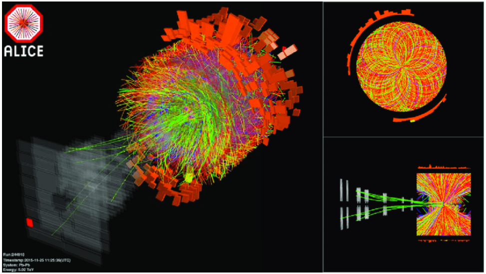


- Models including **suppression** and **regeneration**, predicts a very low v_2 for $\Upsilon(1S)$ and significant v_2 for J/ψ.
- Non-zero v_2 could be an indication for charm (beauty) **collective motion** at low p_T and **path length dependent** at high p_T.

Data set and cuts for analysis

Muon track selection : standard track selection cuts are applied.





- **Event selection** : pass the Physics Selection, trigger for unlike sign tracks
- **Single muon selection** : $-4 < \eta < -2.5$, $17.6 < R_{abs} < 89.5$ cm, matching the tracks, $p_t^{trigger} > 1$ GeV/c on each muon track
- **Dimuon selection** : total charge $= 0$ and $-4 < y < -2.5$

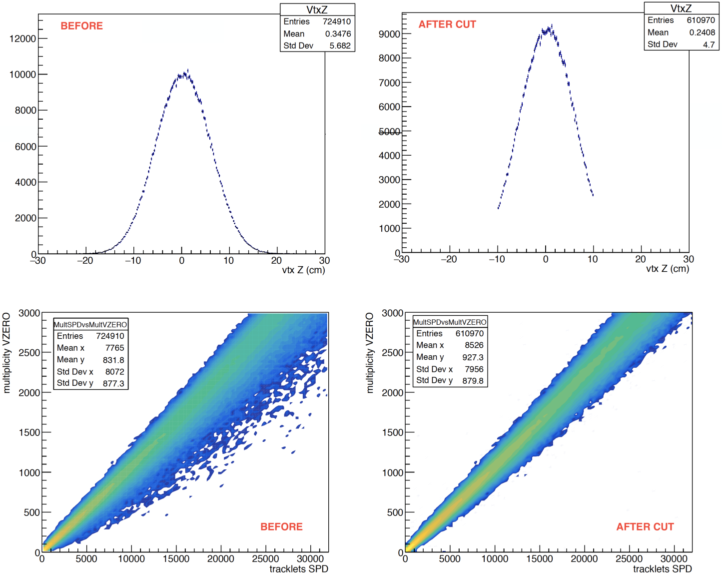
Q_n vector calibration-corrections

FlowVectorCorrections framework	
Event selection	All event with charged particles (MB event) $0 <$ Centrality < 90, $\lvert z_{vertex} \rvert < 10$ cm

Calibration steps (run-by-run basis as function of z_{vertex} and centrality), based on: ***Effect of non-uniform acceptance in anisotropic flow measurement*** arxiv0707.4672

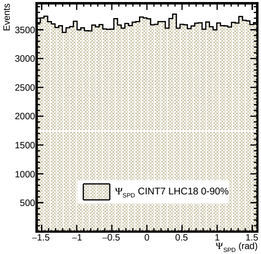
1. **Gain equalization** for channels in V0A, V0C
2. **Re-centering and width equalization** for SPD, V0A, V0C
3. **Alignment** only for V0A, V0C
4. **Twist and re-scale** correction from the non-uniformity of the acceptance for SPD, V0A, V0C

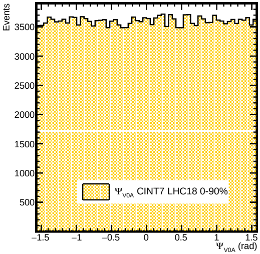
Before and after event selection (run 295586)

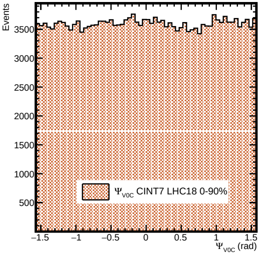


Event plane angle Ψ_2 distribution

All the corrections on $\mathbf{Q_2}$ lead to a flattened Ψ_2 distribution







v_2 extraction

- J/ψ and Υ are reconstructed via their dimuon decay channel $\mu^+\mu^-$
- The invariant mass $m_{\mu\mu}$ are obtained for each dimuon

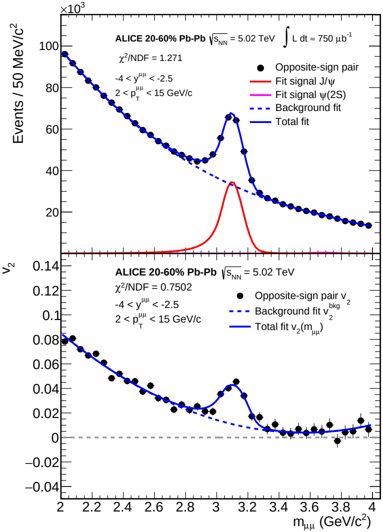
$$v_2 = \frac{v_2^{obs}}{R_2} = \frac{\langle\, \langle\, \cos 2(\phi_{\mu\mu} - \Psi_2)\,\rangle\, \rangle}{R_2} \tag{4}$$

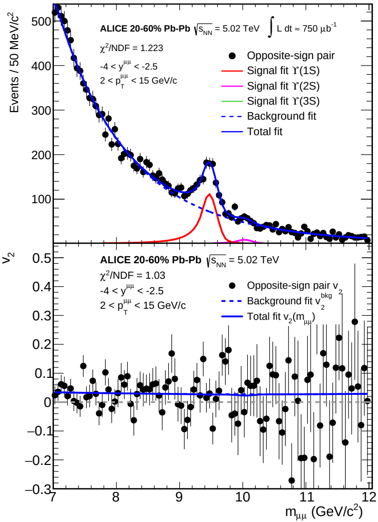
- $\alpha(m_{\mu\mu}) = \frac{S}{S+B}$ is extracted from the invariant mass fit
- v_2^{sig} is extracted by fitting the total v_2 :

$$v_2 = v_2^{bkg}(1-\alpha) + v_2^{sig}\alpha \tag{5}$$

- Background v_2^{bkg} is parametrized by polynomial (order 0,1,2)

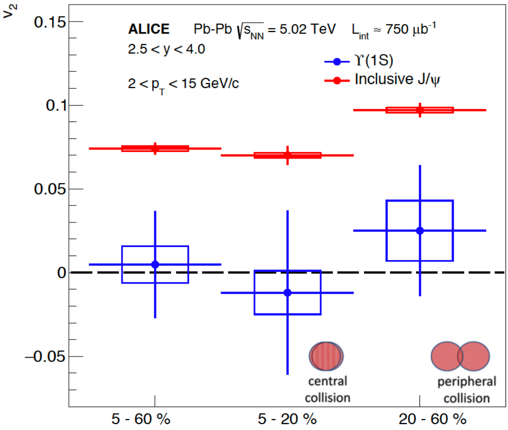
Quarkonium v_2 in Pb-Pb collisions





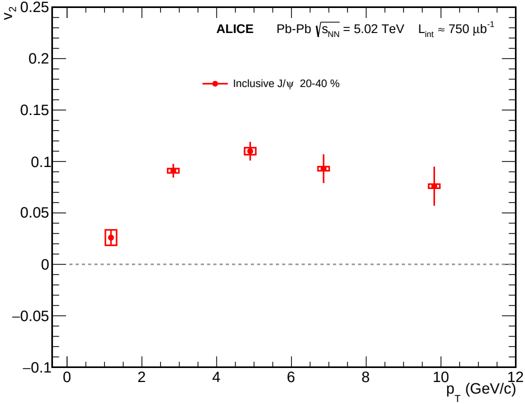
Quarkonium v_2 in Pb-Pb collisions

All $\Upsilon(1S)$ v_2 measurement are compatible with 0 ($2 < p_T < 15$ GeV/c). Comparison with the J/ψ v_2, the $\Upsilon(1S)$ v_2 is lower by 2.4 σ.



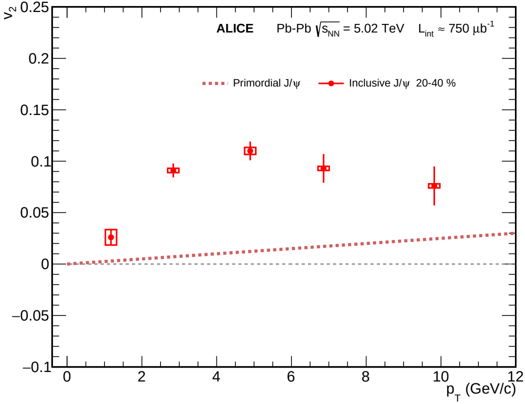
Quarkonium v_2 in Pb-Pb collisions

v_2 of J/ψ as a function of transverse momentum p_T in different p_T bins.



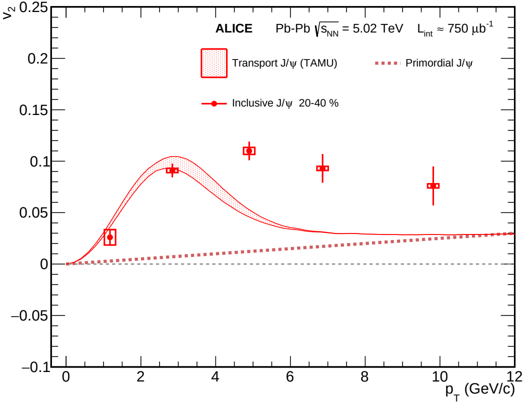
Quarkonium v_2 in Pb-Pb collisions

v_2 from primordial J/ψ (originate from hard scattering $gg \to J/\psi$) do not reproduce the total v_2 in final state



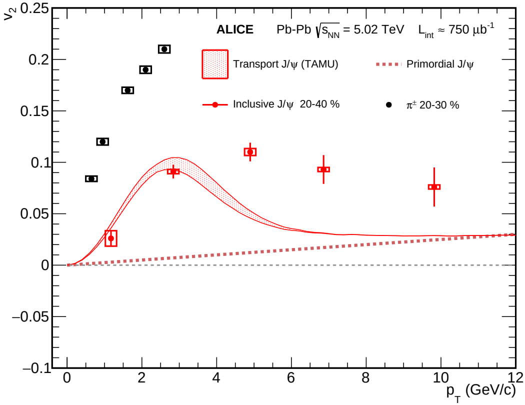
Quarkonium v_2 in Pb-Pb collisions

v_2 of J/ψ at low p_T is mainly explain from the recombination of charm quark in the medium



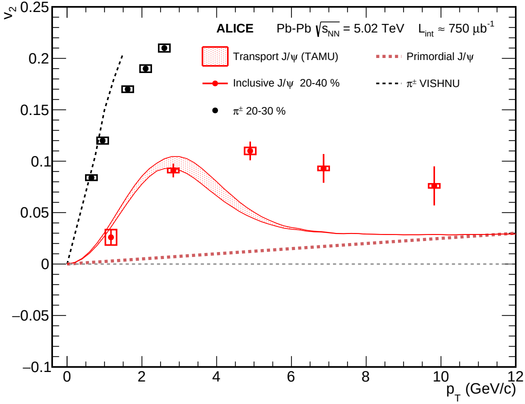
Quarkonium v_2 in Pb-Pb collisions

Comparison with pions $\pi^{\pm}$ which take a higher v_2 from intense interaction with the medium



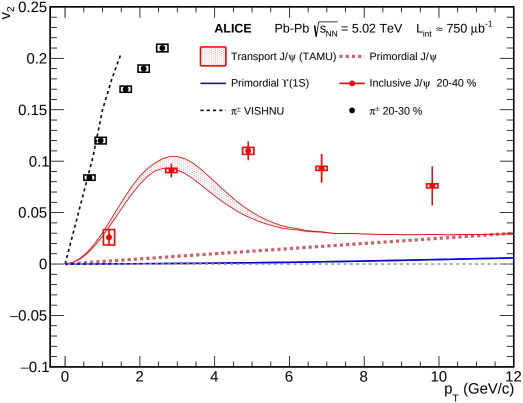
Quarkonium v_2 in Pb-Pb collisions

At low p_T, it can be explain with hydrodynamic models which describe QGP like a nearly perfect fluid



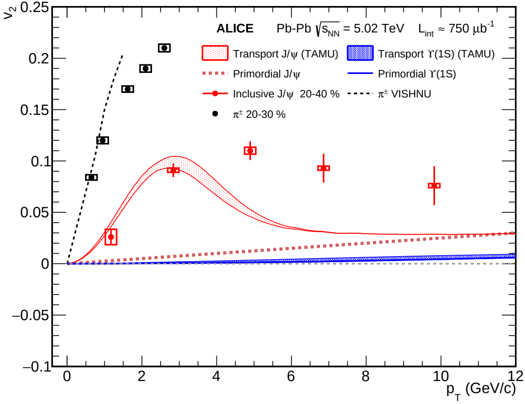
Quarkonium v_2 in Pb-Pb collisions

About beauty quark, the v_2 is expected to be very low from primordial $\Upsilon(1S)$



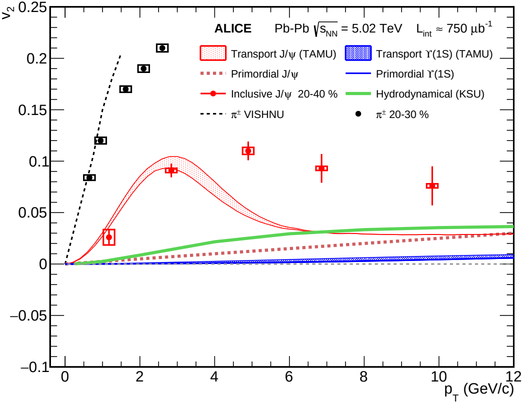
Quarkonium v_2 in Pb-Pb collisions

The regeneration part should have small contribution on the v_2 for $\Upsilon(1S)$



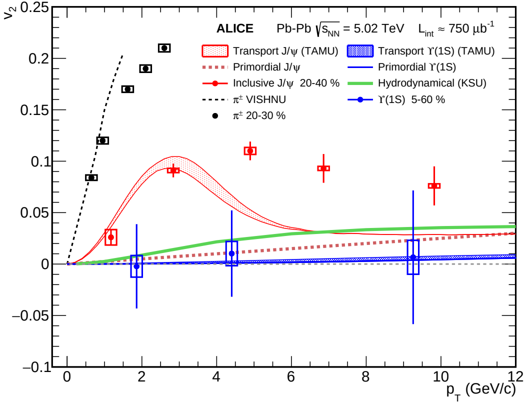
Quarkonium v_2 in Pb-Pb collisions

About hydrodynamics description, the model neglect somes effects (v_2 explain from anisotropic escape mechanism) predict a higher $\Upsilon(1S)$ v_2



Quarkonium v_2 in Pb-Pb collisions

Finally the $\Upsilon(1S)$ v_2 as a function of transverse momentum p_T is compatible with 0



Conclusion

Inclusive J/ψ $\mathbf{v_2}$ in Pb-Pb at 5.02 TeV

- Confirm regeneration mechanisms at low p_T
- Tensions with models beyond 4 GeV/c

Υ(1S) $\mathbf{v_2}$ in Pb-Pb at 5.02 TeV

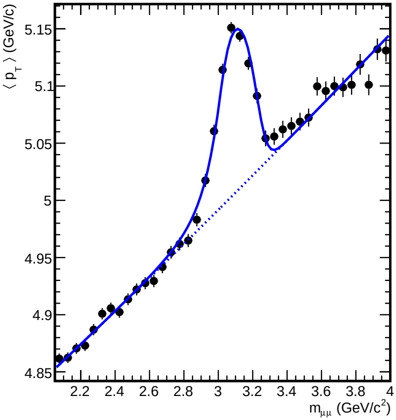
- First measurement of $\Upsilon(1S)$ v_2
- v_2 compatible with 0, lower than J/ψ (2.4 σ)
- v_2 compatible with hydro and transport models

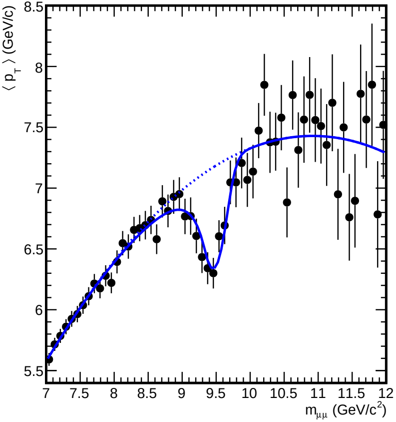
Other effects modify the behavior of quarkonia in the medium and need to be studied in detail : **cold nuclear matter effects, gluon saturation, enery loss, comovers,...**

Thank you for your attention !

For more details about production of quarkonia: arxiv1903.09185
and for quarkonia in QGP: arxiv1302.2180

Quarkonium $\langle p_T \rangle$ determination





Event plane method

- Event plane method :

$$v_n = \frac{v_n^{obs}}{R_n} = \frac{\langle\langle \cos n(\phi - \Psi_n)\rangle\rangle}{R_n} \tag{6}$$

- Resolution (in case of 3 sub-event A, B, and C; this means different η range; for 2 different detectors):

$$R_n = \sqrt{\frac{\langle \cos n(\Psi_n^A - \Psi_n^B)\rangle \langle \cos n(\Psi_n^A - \Psi_n^C)\rangle}{\langle \cos n(\Psi_n^B - \Psi_n^C)\rangle}} \tag{7}$$

The event plane method yields ambiguous v_n measurements which are somewhere between $\langle v_n\rangle$ and $\sqrt{\langle v_n\rangle^2}$. The exact value measured from the event plane method depends on R_n which strongly depends on the experimental setup.

Scalar product method

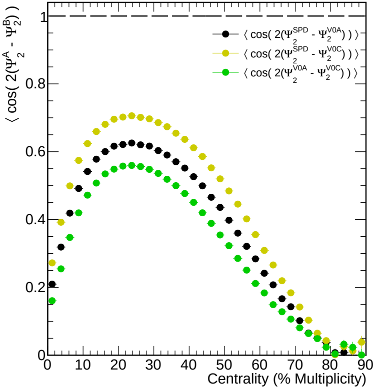
- Scalar product method (for 2 sub-event) independent of the experimental setup :

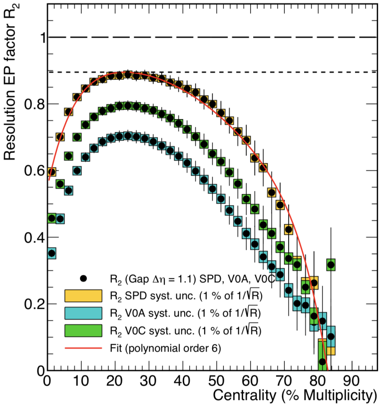
$$v_n = \frac{v_n^{obs}}{R_n} = \frac{\langle\langle \mathbf{u_n Q_n} \rangle\rangle}{\sqrt{\langle \mathbf{Q_n^A Q_n^B} \rangle}} = \sqrt{\langle v_n \rangle^2} \tag{8}$$

- Resolution (in case of 3 sub-event) as function of centrality, correction done event by event :

$$R_n = \sqrt{\frac{\langle \mathbf{Q_n^A Q_n^B} \rangle \langle \mathbf{Q_n^A Q_n^C} \rangle}{\langle \mathbf{Q_n^B Q_n^C} \rangle}} \tag{9}$$

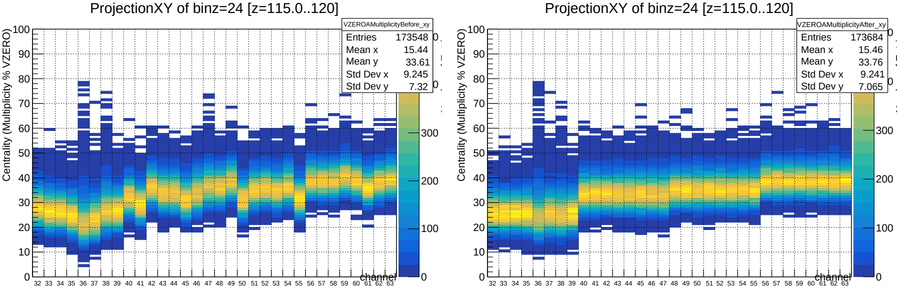
Event plane factor resolution R_2





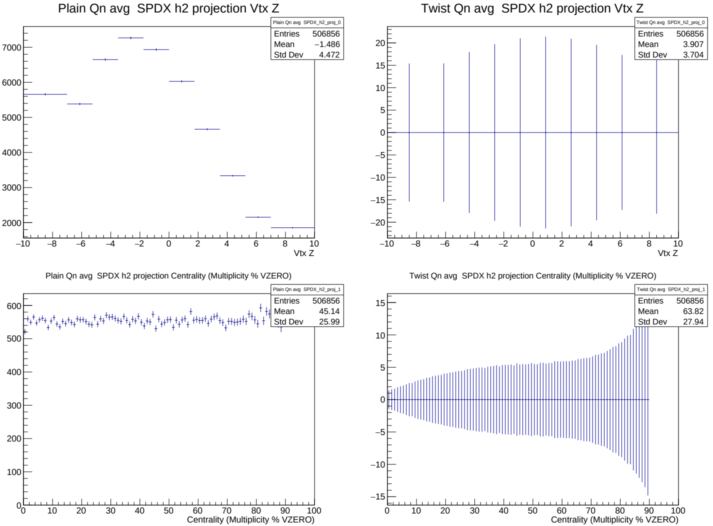
Q_n vector calibration (run 295586)

Before and after gain equalization in 4 rings of V0A channels
(same is done for V0C)



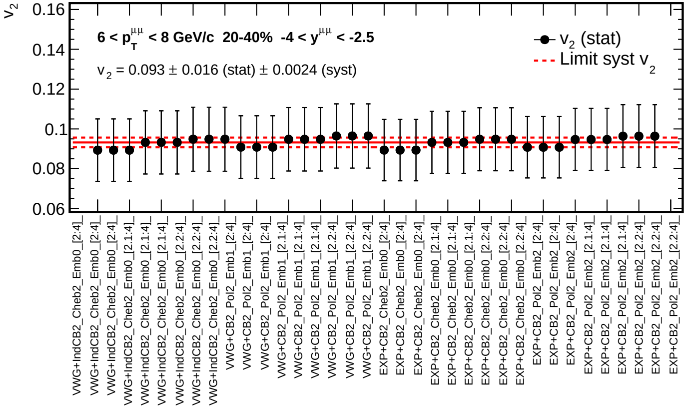
Q_n vector calibration (step1 to step4)

Correction on $\mathbf{Q_2}$ vector as function of z_{vertex} and centrality (re-centering procedure and acceptance correction in SPD)



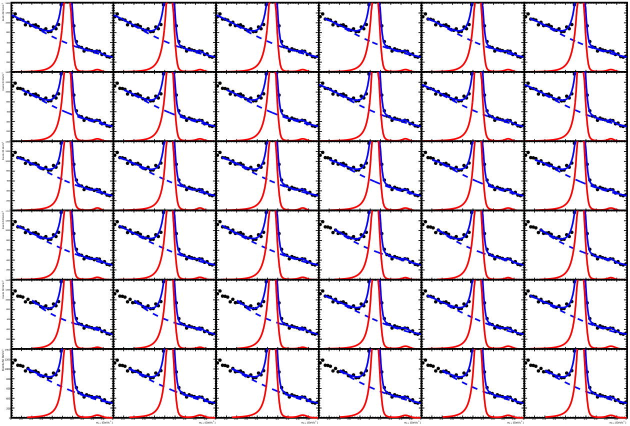
v_2 systematics

- Systematic uncertainty from signal extraction (different fit function, mass range, ...)
- For centrality 20-40% and $6 < p_T < 8$ GeV/c :



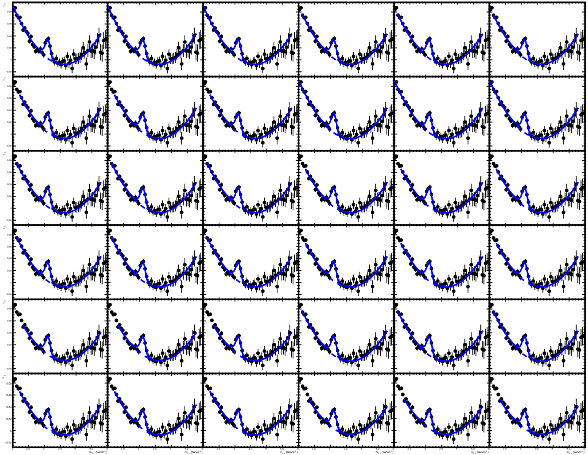
v_2 systematics

- Systematic uncertainty from signal extraction (different fit function, mass range, ...)
- For centrality 40-60% and $4 < p_T < 6$ GeV/c :



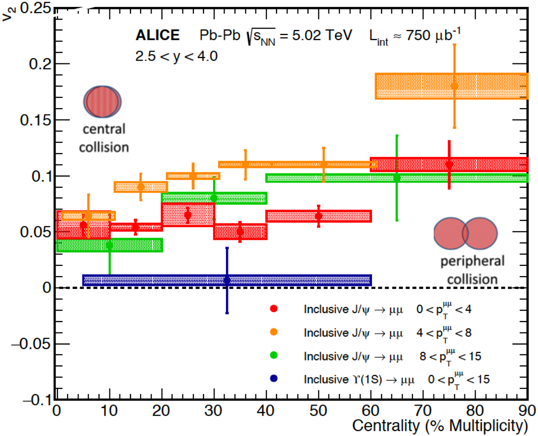
v_2 systematics

- Systematic uncertainty from signal extraction (different fit function, mass range, ...)
- For centrality 20-40% and $2 < p_T < 4$ GeV/c :



Quarkonium v_2 in Pb-Pb collisions

v_2 as a function of centrality for different p_T range in $2.5 < y < 4$



Quarkonium v_2 in Pb-Pb collisions

v_2 as a function of rapidity for $2 < p_T < 15$ GeV/c in 5 - 60 %