First measurement of the J/ψ v_2 at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX experiment

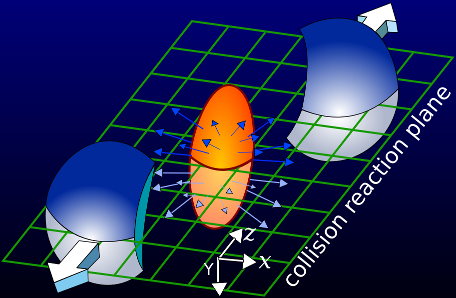
Catherine Silvestre
Saclay, France
for the PHENIX collaboration

PHENIX

Hard Probes 2008 - Illa da Toxa, Galiza

What is the elliptic flow ?

- Azimuthal anisotropy emission of particles with respect to the collision reaction plane.
- Origin: pressure gradient anisotropy in the overlapping zone of the two nuclei in non-central collisions.
- A positive elliptic flow indicates a rapid thermalization of the probe with the system.



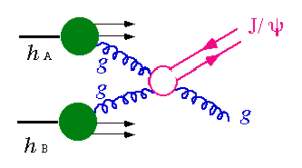
v_2

- Quantified by the second Fourier coefficient of the azimuthal distribution of particles with respect to the reaction plane:

$$\frac{dN}{d(\phi-\psi)} = A[1+2.\mathbf{v_2}.cos2(\phi-\psi)]$$

Why are we interested in the J/ψ elliptic flow ?

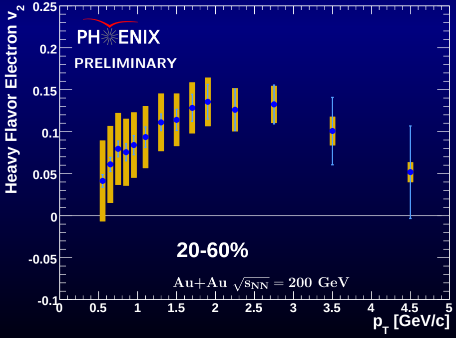
- $c\bar{c}$ production proceeds through gluon fusion in the first instants of the collision. Some of them will form direct J/ψ.



- During the collisions, various mechanisms can dissociate J/ψs or disfavor their formation: comovers, melting, shadowing.
- On the other hand, the large density of uncorrelated charm quarks in the medium may lead to J/ψ regeneration.

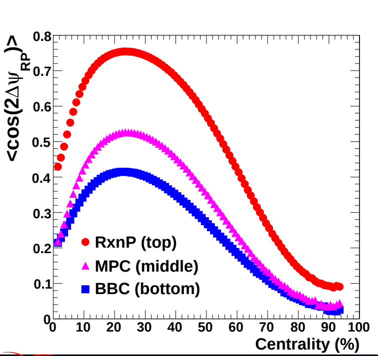
The J/ψ elliptic flow: test of regeneration

- Electrons from open *c* and *b* semi-leptonic decays show positive flow.
- Secondary J/ψs produced by recombination mechanism should inherit *c* quarks' flow.



Measuring the elliptic flow

- Need to know the collision reaction plane. It is measured using the azimuthal distribution of a subset of the particles produced during the collision.
- Run-7 added a new RxnP detector which allows twice more precision on the reaction plane measurement.



- The detector resolution is used as a correction on the measurement

$$\psi_{meas} = \psi_{true} + \delta\psi$$

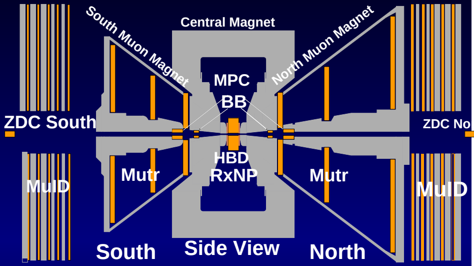
$$v_2^{true} = v_2^{meas} / \langle \cos 2(\psi_{meas} - \psi_{true}) \rangle = v_2^{meas} / \sigma_{RxnP}$$

$\Rightarrow$ Gaining $\times 2$ in this resolution leads to a more precise measurement.

At forward rapidity

$J/\psi \rightarrow \mu^+\mu^- \quad |y| \in [1.2, 2.2]$

- Muon identification: matching between track momentum and penetration depth in Iarroci tubes (MuID) + absorbers
- Selection with front absorber
- Momentum measured with cathode strip chambers (Mutr)



Which RxnP detector ?

- The muon arms and the RxnP acceptances overlap (RxnP: $|\eta| \in [1, 2.8]$, MuTr: $|y| \in [1.2, 2.2]$)
- Might bias the measurement if the muons and possible produced particles by radiative gluons go through the RxnP detector used to estimate the reaction plane angle.
  $\Rightarrow$ The RxnP detector opposite to the arm where the muons go is used in order to minimize the bias

Method

- Estimate the ratio between the number of J/ψ going in-plane, N^{in}, and the number of J/ψ going out-plane, N^{out}:

$$v_2^{\text{meas}} = \frac{\pi}{4} \cdot \frac{(N^{\text{in}} - N^{\text{out}})}{(N^{\text{in}} + N^{\text{out}})}$$

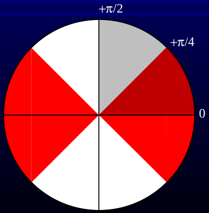
$$\sigma_{v_2^{\text{meas}}} = \frac{\pi/2}{(N^{\text{in}} + N^{\text{out}})^2} \cdot \sqrt{(N^{\text{out}}\sigma^{\text{in}})^2 + (N^{\text{in}}\sigma^{\text{out}})^2}$$

with σ^{in} the error on N^{in} and σ^{out} the error on N^{out}.

- v_2^{meas} is then corrected by the reaction plane resolution.

The following bins have bin used:

- in ϕ-ψ $[0, \pi/4]$ and $[\pi/4, \pi/2]$



Data taking conditions

Equivalent number of minimum bias events:

South arm: 3.41×10^9 events
North arm: 3.88×10^9 events
$\Rightarrow$ almost four times more than published Au+Au results (Run-4).

Level-2 triggered data

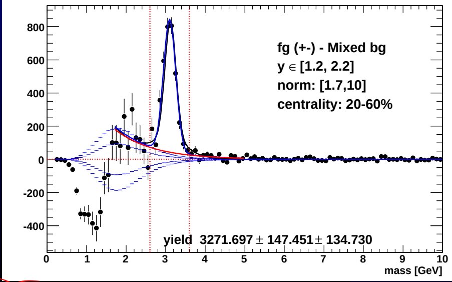
Online filtering based on fast tracking in the MuID

Signal counts

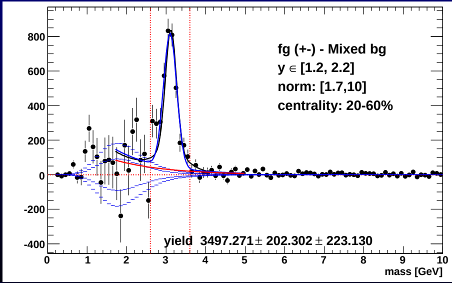
Combined background subtraction

- Combining mixed-event and like-sign distributions
- Purpose: $FG_{+-} - FG_{like} \cdot \frac{Mixed_{+-}}{Mixed_{like}}$
  - mixed event distributions account for the acceptance bias
  - like-sign distributions account for the bias introduced by the online filtering

Mixed-event subtraction



Combined subtraction



Errors on v_2

Bars: statistical and point to point uncorrelated errors

From the J/ψ signal extraction:

- statistical uncertainty on the number of counts;
- systematic uncertainty on the signal + background line-shape.

Boxes: point to point correlated errors

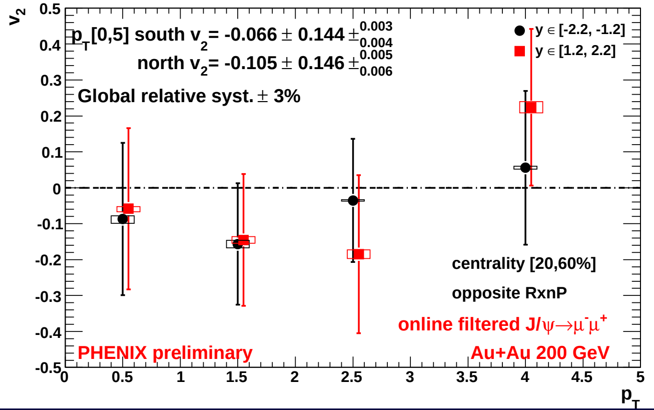
- Error on the average RxnP detector resolution
- Error on the J/ψ ϕ angle measurement that is less accurate at $p_T < 1$

Written: global relative systematics

- Error on the technique used to determine the reaction plane angle and resolution.

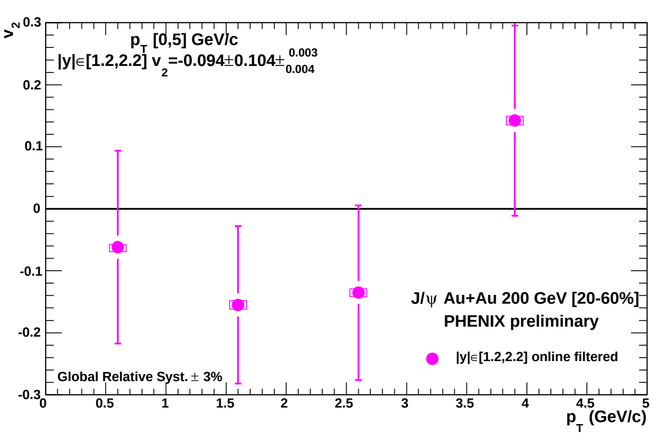
Relative error that allows points to move coherently by 3% of their value

J/ψ v_2 at forward rapidity (each arm)



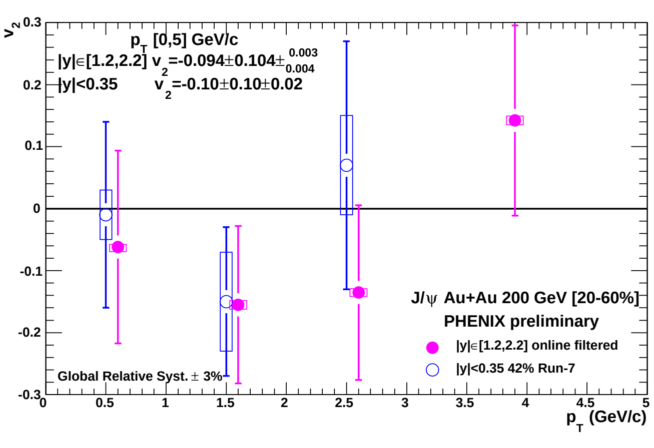
bars: uncorrelated point to point + statistics from signal extraction
boxes: systematics, correlated point to point
global error : relative, applied to each point

J/ψ v_2 at forward (averaged over the 2 arms)



bars: uncorrelated point to point + statistics from signal extraction
boxes: systematics, correlated point to point
global error : relative, applied to each point

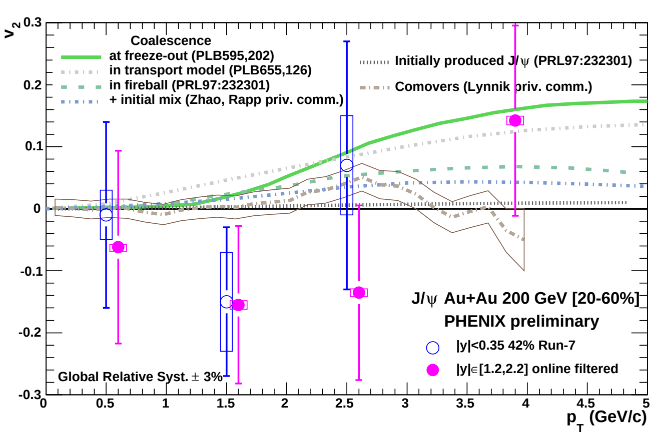
J/ψ v_2 measured by PHENIX



Mid and forward rapidity results use different detectors, triggers, methods...
They are fully independent measurements.

Details on mid-rapidity v_2 method in arXiv:0806.0475

J/ψ v_2 measured by PHENIX

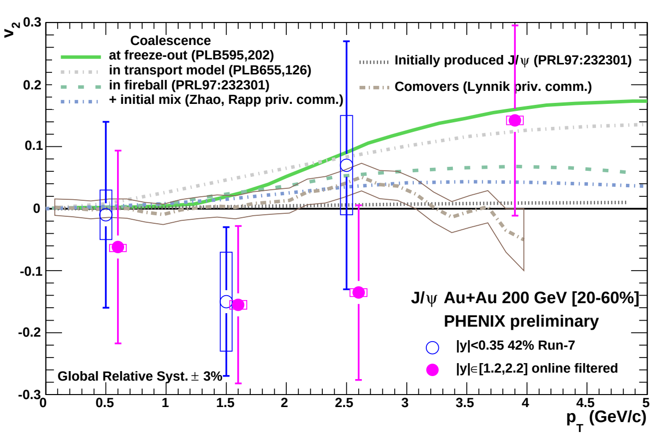


Predictions are for mid-rapidity and most of the time for centrality [0,100%].

$$p_T\ [0,5] \quad |y| \in [1.2, 2.2] \quad v_2 = -0.094 \pm 0.104 \pm^{0.004}_{0.004}$$

$$|y| < 0.35 \quad v_2 = -0.10 \pm 0.10 \pm 0.02$$

J/ψ v_2 measured by PHENIX

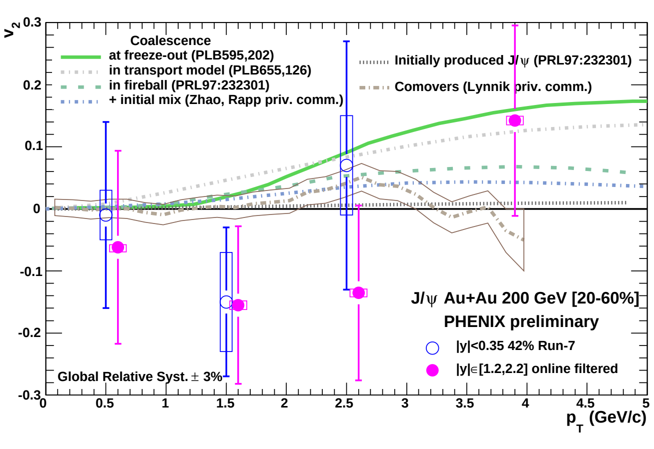


The statistical compatibility of combined results with $v_2 > 0$ is 10%

Predictions are for mid-rapidity and most of the time for centrality [0,100%].

$$p_T \; [0,5] \quad |y| \in [1.2, 2.2] \quad v_2 = -0.094 \pm 0.104 \pm^{0.004}_{0.004}$$
$$|y| < 0.35 \quad v_2 = -0.10 \pm 0.10 \pm 0.02$$

J/ψ v_2 measured by PHENIX



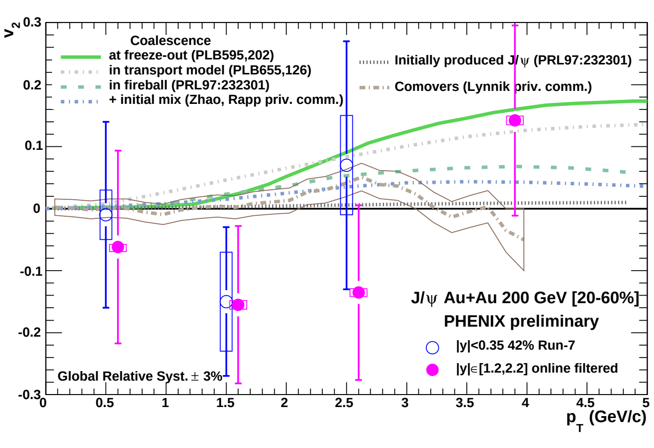
The statistical compatibility of combined results with $v_2 > 0$ is 10%

But low p_T (expected to have less flow) weights more than high p_T (that could have some flow)

Predictions are for mid-rapidity and most of the time for centrality [0,100%].

$$p_T\ [0,5] \quad |y| \in [1.2, 2.2] \quad v_2 = -0.094 \pm 0.104 \pm^{0.004}_{0.004}$$
$$|y| < 0.35 \quad v_2 = -0.10 \pm 0.10 \pm 0.02$$

J/ψ v_2 measured by PHENIX



The statistical compatibility of combined results with $v_2 > 0$ is 10%

But low p_T (expected to have less flow) weights more than high p_T (that could have some flow)

Combining points at p_T [1,2]GeV, $v_2 > 0$ at 6.3%

Predictions are for mid-rapidity and most of the time for centrality [0,100%].

p_T [0,5] $|y| \in [1.2, 2.2]$ $v_2 = -0.094 \pm 0.104 \pm^{0.004}_{0.004}$

$|y| < 0.35$ $v_2 = -0.10 \pm 0.10 \pm 0.02$

Summary / perspective

First measurement at forward rapidity

$$p_T \in [0, 5] \text{ GeV/c}, v_2 = -0.094 \pm 0.104 \pm^{0.003}_{0.004}$$

- Current precision does not allow to draw any conclusion.
- Data points are compatible with zero to maximum flow predictions within errors

What to expect for final results ?

- Minimum bias sample $\Rightarrow$ slight improvement to expect: +10% stat and no more bias from the online filtering $\sqrt{2}$ smaller statistical errors on the v_2
- However, will probably still not permit to discriminate between models. Much larger data sample is needed.

Next data at RHIC (2009, 2010) should give more statistics.

Backups

Signal fit

- Gaussian with variable width and amplitude centered on the J/ψ mass + exponantial to account for the physical residual background
- Double gaussian fit with fixed width (estimated from p+p data) and variable amplitude centered on the J/ψ mass + exponential
- Exponential fit to the residual background outside the J/ψ mass region + counting the number of entries above its extrapolation to the J/ψ range

Statistical errors

- Mean value of the 3 fits

Systematics are estimated

- using the 3 canonical fit functions to the signal;
- varying the fits mass range (starting from 1.5, 1.7, and 2 GeV);
- changing of the normalisation using a correction factor of 1 ± 0.02 to the second term of the signal equation.
- The systematic error is the RMS of the resulting 27 values.

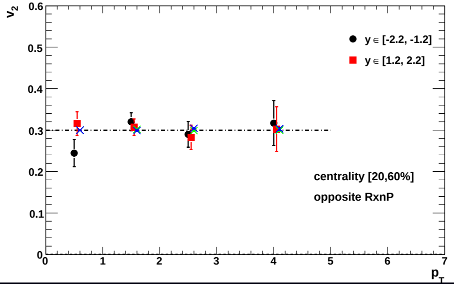
v_2 simulations

Chain:

- Retreive the reaction plane ψ angle from real data (RD)
- Generate randomly distributed J/ψ along $f(x) = [0](1 + 2 \times 0.3 \times cos(2x))$ to get a $v_2 = 0.3$ with respect to the RD reaction plane angle, starting from J/psi's generated by PYTHIA.
- Full GEANT Simulation + Embedding in the same RD + Reconstruction (including online-filtering algorithm)
- Run same v_2 extraction macro

We retrieve the input v_2: here for about the same amount of statistics used in real data

This validates the chain and the method.



Summing centrality bins

Issue

- Efficiency varies vs. centrality inside the bins that are considered
- If we further divide the bins, the signal gets too small

Method

- Weight the unlike-sign mass distributions (foreground and background) in 5% centrality bins by $1/\epsilon$ and sum over larger centrality bins before fitting the signal

$$N = \frac{\sum_i N_i/\varepsilon_i}{\sum_i 1/\varepsilon_i} \quad (1)$$

This maximizes the signal to be fitted

Averaging over North (y>0) and South (y<0) arms

$$dN^{ave}_{J/\psi}/dy = \frac{w_S dN^S_{J/\psi}/dy + w_N dN^N_{J/\psi}/dy}{w_S + w_N} \quad (2)$$

where $dN^{S}_{J/\psi}/dy$ ($dN^{N}_{J/\psi}/dy$) is the J/ψ invariant yield measured in south (north) muon arm

w_S (w_N) the corresponding weight:

$$w = 1/\sigma^2_{arm,uncor} \quad (3)$$

The weight accounts for arm uncorrelated errors.
Here, these errors are the statistical and systematic errors on the signal fit.
This allows to reduce the statistical and systematic errors on the yields by $\sqrt{2}$.

Note: The correlated errors used to calculate the acc$\times$eff do not enter the weight factors. For the v_2 analysis, acc$\times$eff cancels out since it always appear at the nominator and the denominator when used.

Use of the RxnP detector

Resolution

- Use of Ollitrault function (arXiv:nucl-ex/9711003v2)
- The resolution of the North and the South RxnP is found using MPC or BBC as third detectors.

Averaging over centrality

- Weight the RxnP resolution by the J/ψ counts corrected by the efficiency

Calculating the reaction plane resolution

Measurement methods see Ollitrault (arXiv:nucl-ex/9711003v2) and Voloshin & Poskanzer (arXiv:nucl-ex/9805001v2)

If we wish to measure v_2 with respect to the reaction plane we calculate:

$$\begin{aligned} v_2^{meas} &= \langle \cos 2(\phi - \psi_{meas}) \rangle \\ &= \langle \cos 2(\phi - \psi_{true} - \delta\psi) \rangle \\ &= \langle \cos 2(\phi - \psi_{true}) \cos 2(\delta\psi) - \sin 2(\phi - \psi_{true}) \sin 2(\delta\psi) \rangle \\ &= \langle \cos 2(\phi - \psi_{true}) \rangle \langle \cos 2(\psi_{meas} - \psi_{true}) \rangle \\ &= v_2^{true} \langle \cos 2(\psi_{meas} - \psi_{true}) \rangle \end{aligned}$$

Resolution

$$\langle \cos 2(\psi_a - \psi_b) \rangle = \langle \cos 2(\psi_a - \psi_{true}) \rangle \langle \cos 2(\psi_b - \psi_{true}) \rangle$$

where ψ is measured separately by detectors *a* and *b*.

For any 3 detectors one can write:

$$\sigma_a = \langle \cos 2(\psi_a - \psi_{true}) \rangle = \sqrt{\frac{\langle \cos 2(\psi_a - \psi_b) \rangle \langle \cos 2(\psi_a - \psi_c) \rangle}{\langle \cos 2(\psi_b - \psi_c) \rangle}}$$

$\Rightarrow$Measurement of σ_{RxnP} for the RxnP North and South detectors, both separately and combined, using the BBC North/South and MPC North/South as detectors *b* and *c*.

Check on statistical errors

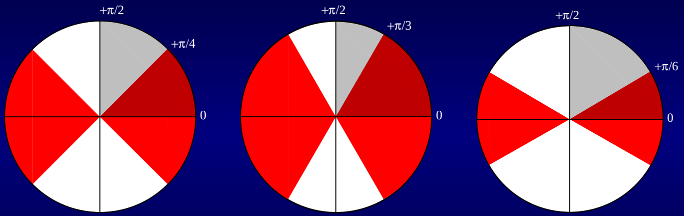
The absolute error on the J/ψ v_2 can be derived from the relative error on the $\phi - \psi$ J/ψ counts for each bins in p_t and centrality. The formula is scaled to match our reaction plane resolution:

$$\sigma_N/N = (0,704/\sigma_{RP})\frac{\sqrt{\sigma_N^{stat} + \sigma_N^{syst}}}{N} \quad (4)$$

This allows to cross-check the point-to-point uncorrelated error on v_2 derived independently from our v_2 measurement macro

Results using different angles

The number of J/ψs going in-plane and out-plane can be calculated with different angle separation:



When changing this angle, the north and arm v_2 agreement of the first 2 p_T bins varies.

J/ψ ϕ resolution

Equation 5 illustrates how this resolution enters the v_2 measurement:

$$\begin{aligned} v_2^{\text{true}} &= \langle \cos 2(\phi_{J/\psi}^{true} - \phi_{\text{RP}}^{\text{true}}) \rangle \\ &= \langle \cos 2(\phi_{J/\psi}^{meas} - \phi_{\text{RP}}^{\text{meas}}) \rangle / \left[\langle \cos 2(\phi_{\text{RP}}^{\text{meas}} - \phi_{\text{RP}}^{\text{true}}) \rangle \langle \cos 2(\phi_{J/\psi}^{\text{meas}} - \phi_{J/\psi}^{\text{true}}) \rangle \right] \\ &= v_2^{\text{meas}} / \left[\langle \cos 2\Delta\phi_{RP} \rangle \langle \cos 2\Delta\phi_{J}/\psi \rangle \right] \end{aligned} \tag{5}$$

$\langle \cos 2\Delta\phi_{RP} \rangle$ is a correction factor due to the finite resolution of the reaction plane measurement. $\langle \cos 2\Delta\phi_{J/\psi} \rangle$ is a similar correction, added to account for the finite resolution of the J/ψ ϕ angle measurement. For most of the v_2 measurements so far, this second term has been assumed to be close enough to 1 especially when compared to the reaction-plane correction factor.

In principle, the correction that accounts for the finite resolution of the J/ψ ϕ angle measurement should also be applied to the real-data v_2 measurement, together with the reaction-plane correction. However, it is not possible to measure this resolution directly, nor check that it would match the value obtained with the simulations. It was therefore decided to account for this correction with an additional source of systematic error to the v_2 measurement: only the first p_T point is affected by this additional uncertainty.

Measuring v_2 at mid-rapidity

arXiv:0806.0475

Using the "background fit method" Borghini, Ollitrault, PRC70, 064905 (2004)

v_2 is additive: $v_2^{\mathrm{S}} N^{\mathrm{S}} = v_2^{\mathrm{FG}} N^{\mathrm{FG}} - v_2^{\mathrm{BG}} N^{\mathrm{comb}}$

$$\Rightarrow v_2^{\mathrm{S}}(M_{\mathrm{J}/\psi}) = v_2^{\mathrm{FG}}(M_{\mathrm{J}/\psi}) \cdot \frac{N^{\mathrm{FG}}(M_{\mathrm{J}/\psi})}{N^{\mathrm{S}}(M_{\mathrm{J}/\psi})} - f^{\mathrm{BG}}(M_{\mathrm{J}/\psi}) \cdot \frac{N^{\mathrm{comb}}(M_{\mathrm{J}/\psi})}{N^{\mathrm{S}}(M_{\mathrm{J}/\psi})}$$

1. $v_2^S = \langle cos(2 \cdot (\phi - \psi_{\mathrm{RP}}))\rangle$ of unlike sign pairs in J/ψ mass window
2. $v_2^{FG}(M_{\mathrm{J}/\psi})$ is the v_2 of the foreground, from same event unlike sign pairs, in [2.9, 3.3] GeV/c^2.
3. $N^{FG}(M_{\mathrm{J}/\psi})$ is the number of counts in the J/ψ mass range from mixed event pairs.
4. $N^S(M_{\mathrm{J}/\psi})$ is the number of measured J/ψ, $N^S = N^{FG} - (N^{comb} + N^{rem})$, with N^{comb} the contribution from the combinatorial background, and N^{rem} the remaining contribution of the background (physical processes or uncertainty on the mixed background normalization) fitted with an exponential.
5. $f^{BG}(M)$ is fitted outside the J/ψ mass to $v_2^{FG}(M) \cdot \frac{N^{FG}(M)}{N^{comb}(M)}$, and extrapolated to [2.9, 3.3] GeV/c^2.