Methods for event plane determination in flow measurements with HADES at SIS18

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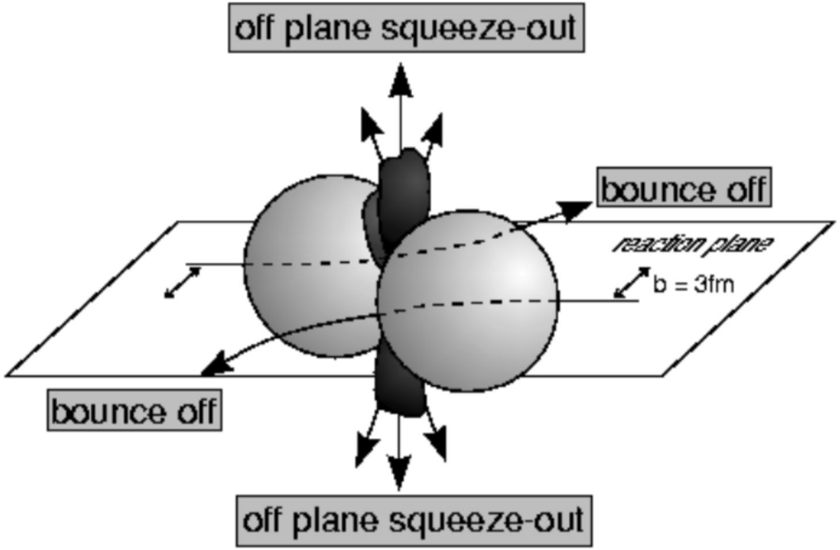
for the HADES Collaboration

Workshop on analysis techniques for centrality determination and flow measurements at FAIR and NICA
27 August 2020

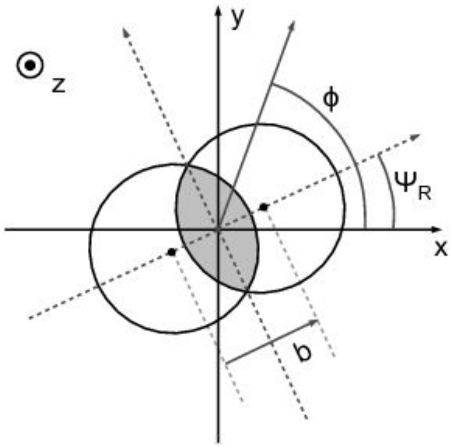
Anisotropic flow & spectators



- Anisotropic flow:
  spatial asymmetry of the initial energy distribution transforms
  via interaction into anisotropic emission of produced particles

- Spectator fragments are bounced off by
  expanding dense matter in the nuclei overlap region
  ⇒ spectator’s deflection can be used to estimate collision symmetry plane

Flow harmonics



The azimuthal angle distribution is decomposed in a Fourier series relative to reaction plane angle:

$$\rho(\varphi - \Psi_{RP}) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_{RP})\right)$$

directed flow:

$$v_1 = \langle \cos\left(\varphi - \Psi_{RP}\right) \rangle$$

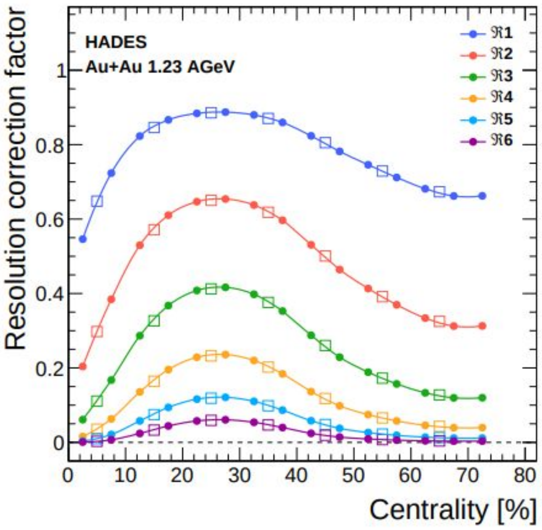
elliptic flow:

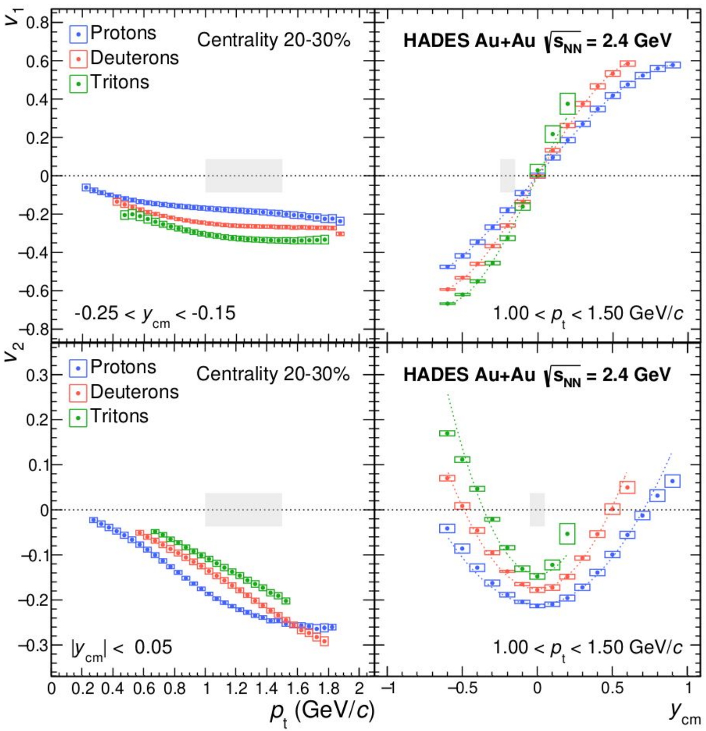
$$v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$$

v_n of protons, deuterons and tritons in Au+Au collisions with HADES

HADES Collaboration, arxiv:2005.12217

Spectator plane resolution correction factor





Details: see talk by B.Kardan (Wed, Aug. 26)

Goal of this presentation

- Test effect of azimuthal non-uniformity corrections on spectator plane resolution and v_n measurement
- Compare different methods of v_n measurements and resolution calculation:
    - Event plane & scalar product
    - Random subevent & extrapolation to full subevent
    - 3 subevents method
- Evaluate systematic uncertainties from spectator plane estimation

Flow vectors

From momentum of each measured particle define a u_n-vector in transverse plane:

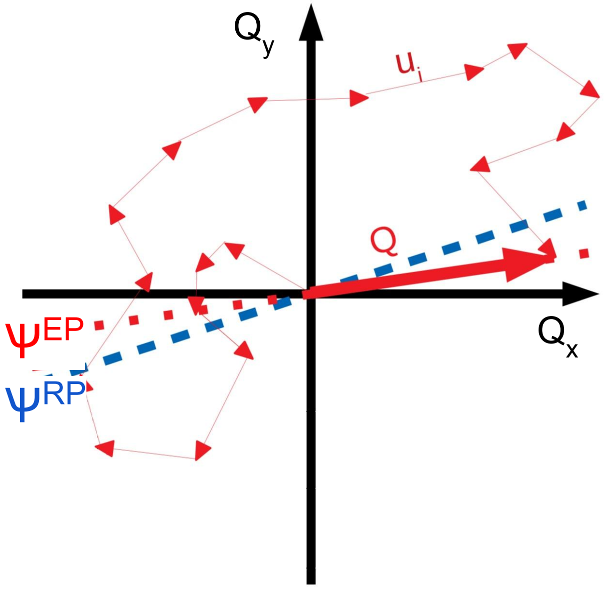
$$u_n = e^{in\phi}$$

where φ is the azimuthal angle

Sum over a group of u_n-vectors in one event forms Q_n-vector:

$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane angle



Flow methods for v_1 calculation

Event plane (EP) method:

$$v_1 = \frac{\langle \cos\left(\phi - \Psi_1^{EP}\right)\rangle}{R_1}$$

Resolution correction from random subevent (RND):

$$R_1^{sub} = \sqrt{\langle \cos(\Psi_n^a - \Psi_n^b)\rangle}$$

Extrapolation to full event plane is implemented following J.Y. Ollitrault [arXiv:nucl-ex/9711003]

$$R_n(\chi) = \frac{\sqrt{\pi}}{2}\chi e^{-\frac{\chi^2}{2}}\left[I_{\frac{n-1}{2}}\left(\frac{\chi^2}{2}\right) + I_{\frac{n+1}{2}}\left(\frac{\chi^2}{2}\right)\right]$$

$\chi = v_n M^{1/2}$,
M is multiplicity in the event
I_k is the modified Bessel function

Scalar product (SP) method:

$$v_1 = \frac{\langle u_1^a Q_1^a \rangle}{R_1}$$

3 subevents (3-sub) resolution correction

$$R_1^a = \frac{\sqrt{\langle Q_1^a Q_1^b\rangle \langle Q_1^a Q_1^c\rangle}}{\sqrt{\langle Q_1^b Q_1^c\rangle}}$$

Flow methods for v_2 calculation

Event plane (EP) method:

$$v_2 = \frac{\langle \cos 2(\phi - \Psi_1^{EP}) \rangle}{R_2(\Psi_1^{EP})}$$

2nd harmonic event plane resolution is extrapolated from 1st harmonic RND-sub resolution following the method from J.Y. Ollitrault [arXiv:nucl-ex/9711003]

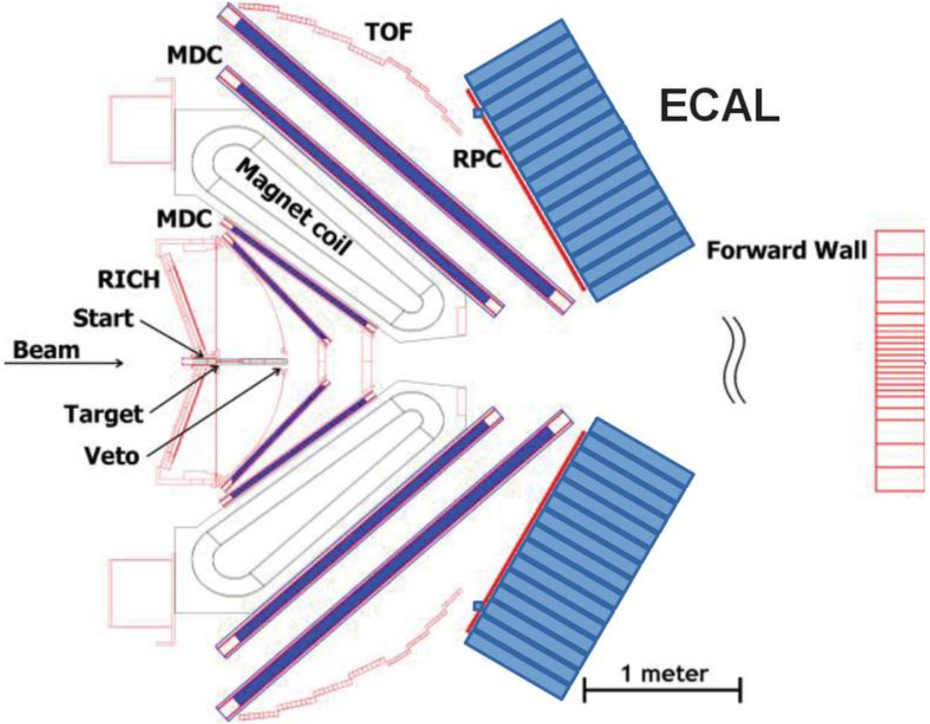
Mixed harmonics method:

$$v_2 = \frac{\langle u_2 Q_1^a Q_1^b \rangle}{R_1^a \times R_1^b}$$

where

$$R_1^{a/b} = \frac{\sqrt{\langle Q_1^a Q_1^b \rangle \langle Q_1^{a/b} Q_1^c \rangle}}{\sqrt{\langle Q_1^{b/a} Q_1^c \rangle}}$$

The HADES experiment



Tracking system

- Multi-wire drift chambers (MDC)
- Magnet coil

Particle identification

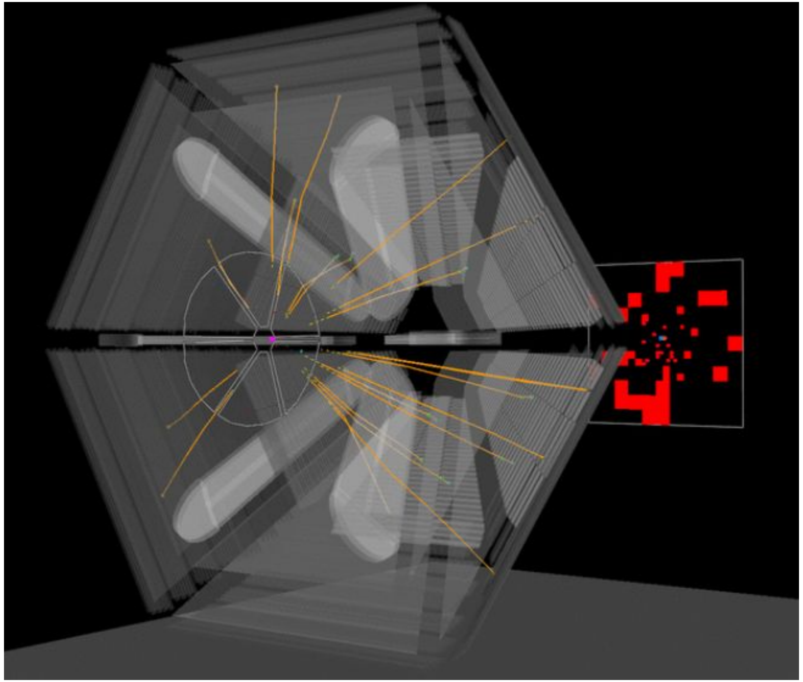
- Time Of Flight (TOF)
- Resistive Plate Chambers (RPC)

Event plane reconstruction

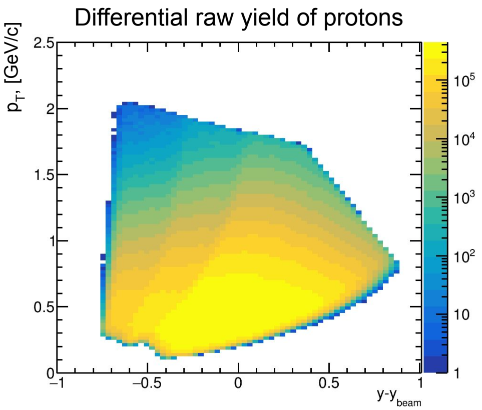
- Forward Wall (FW)

HADES event display & subsystem's acceptance

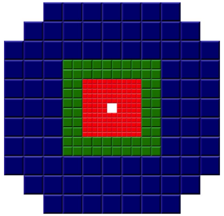
Au+Au collisions at 1.23GeV
(subsample of 10M events)
Minimum bias trigger (PT2), 0-40% centrality



Tracking (MDC) and PID (TOF+RPC)
$0.09 < \eta < 1.84$



Charged fragments (FW)
$2.68 < \eta < 5.38$



Centrality determined from
TOF+RPC hits
see talk by B.Kardan

Q-vectors for protons and charged fragments

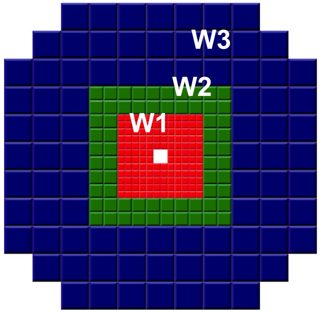
Protons with $p_T < 2$ GeV/*c*

for 2 rapidity regions:

- Mf — y_{cm} [0.35, 0.55]
- Mb — y_{cm} [-0.55, -0.35]

Charged fragments from FW:

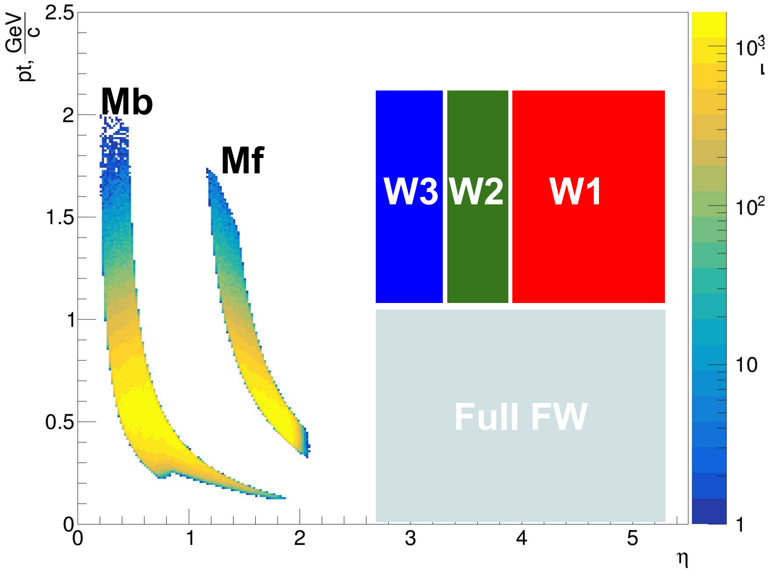
W1: $3.77 < \eta < 5.38$
W2: $3.28 < \eta < 3.88$
W3: $2.68 < \eta < 3.35$



Full FW (sum over all modules) $2.68 < \eta < 5.38$

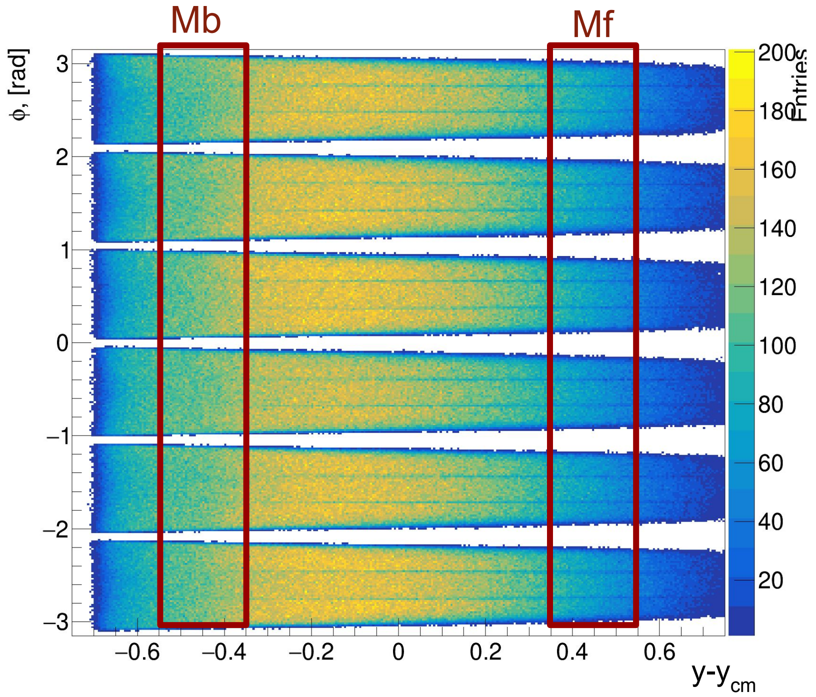
RND-sub: all modules randomly splitted into 2 groups

Rapidity coverage of different subevents

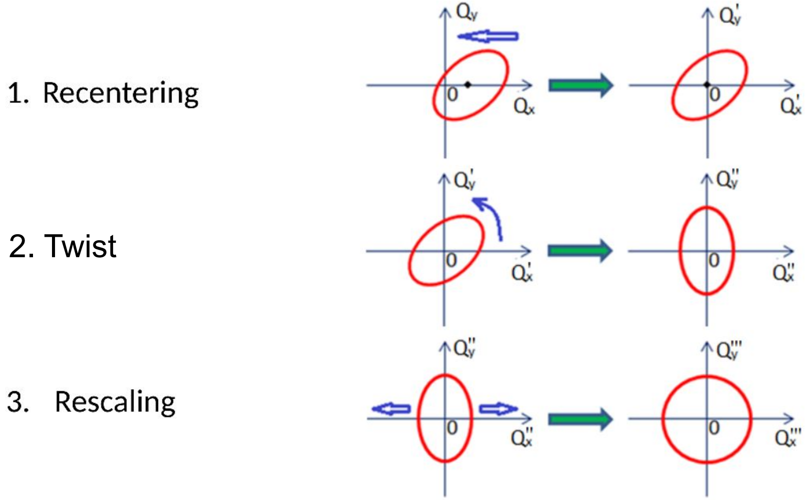


Azimuthal asymmetry of the HADES acceptance

ϕ-Rapidity yield of protons



Required corrections to reduce effects of non-uniform azimuthal acceptance



Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

QnTools framework

Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

Originally implemented as QnCorrections framework for ALICE experiment:
J. Onderwaater, I. Selyuzhenkov, V. Gonzalez

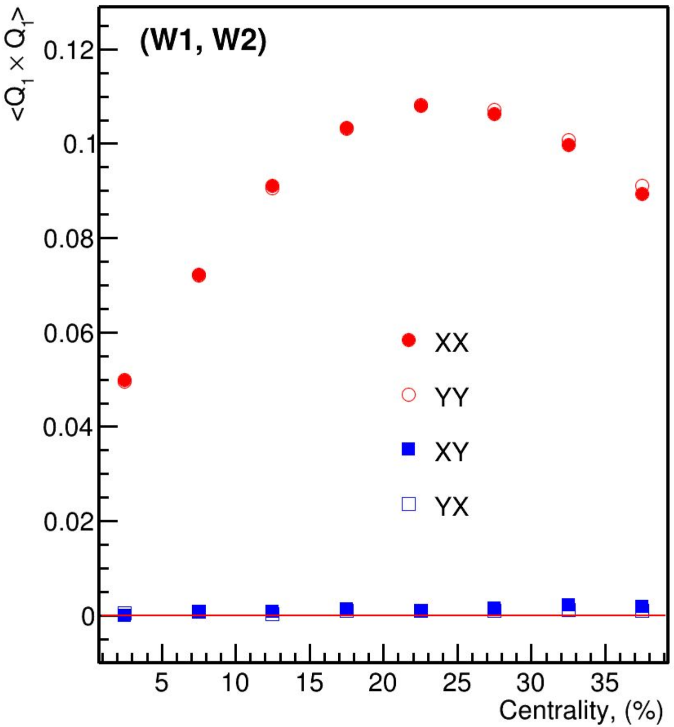
QnTools analysis package:
https://github.com/HeavyIonAnalysis/QnTools

See Lukas Kreis talk
“QnTools framework for flow analyses”
(Heidelberg Uni, ALICE Collaboration)

QnTools configuration

Q-vector	Q_n weight	Correction axes	Correction steps	Error calculation	Q_n Normalization
Protons	1	p_T [0.0, 2.00], 10 bins y_{cm}[-0.75, 0.75], 15 bins Centrality, 8 bins	Recentering Twist Rescaling	Bootstrapping, 100 samples	Sum of Weights
Charged Fragments	Module charge	Centrality, 8 bins	Recentering		

x&y Q_n-vector component correlations



$$\langle Q_n^a Q_n^b \rangle = \langle X_n^a X_n^b \rangle + \langle Y_n^a Y_n^b \rangle$$

Expected for ideal detector:

$$\langle X_n^a X_n^b \rangle = \langle Y_n^a Y_n^b \rangle$$

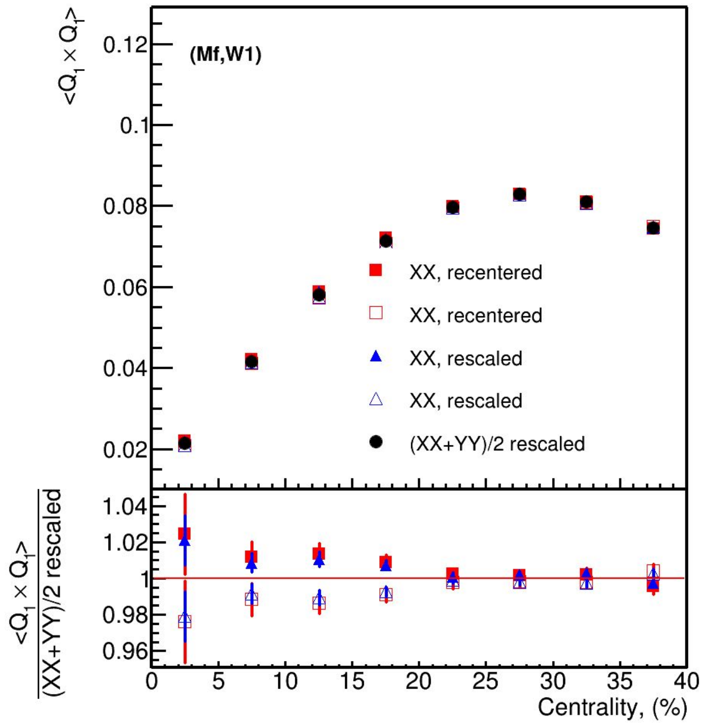
$$\langle X_n^a Y_n^b \rangle = 0$$

$$\langle Y_n^a X_n^b \rangle = 0$$

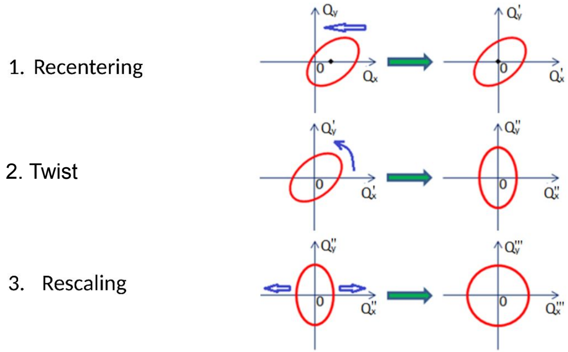
Results for correlations of other Q-vectors pairs from MDC and FW vectors are in the backup

Small differences between x&y components.
Cross correlations are consistent with zero.

Q-vector correlations: azimuthal non-uniformity corrections



Q-vector	Correction steps
Protons	Recentering Twist Rescaling
Charged Fragments	Recentering



Residual effects of detector non-uniformity are below 2%
Average of x&y components is used for the further analysis

Non-flow correlations in the spectator plane resolution

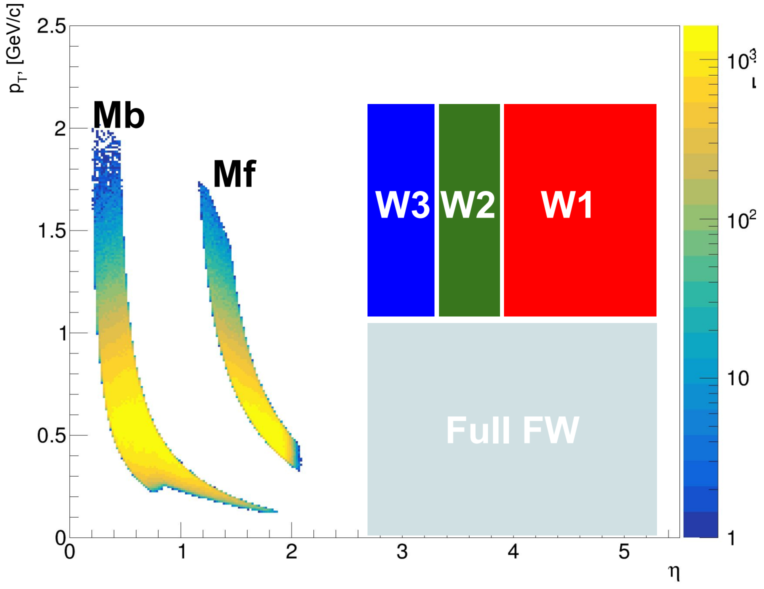
Resolution of each sub-event can be calculated using different combinations of Q-vectors.

$$R_1^a = \frac{\sqrt{\langle Q_1^a Q_1^b \rangle \langle Q_1^a Q_1^c \rangle}}{\sqrt{\langle Q_1^b Q_1^c \rangle}}$$

Ideal case:
without non-flow correlations
different estimates are to be consistent

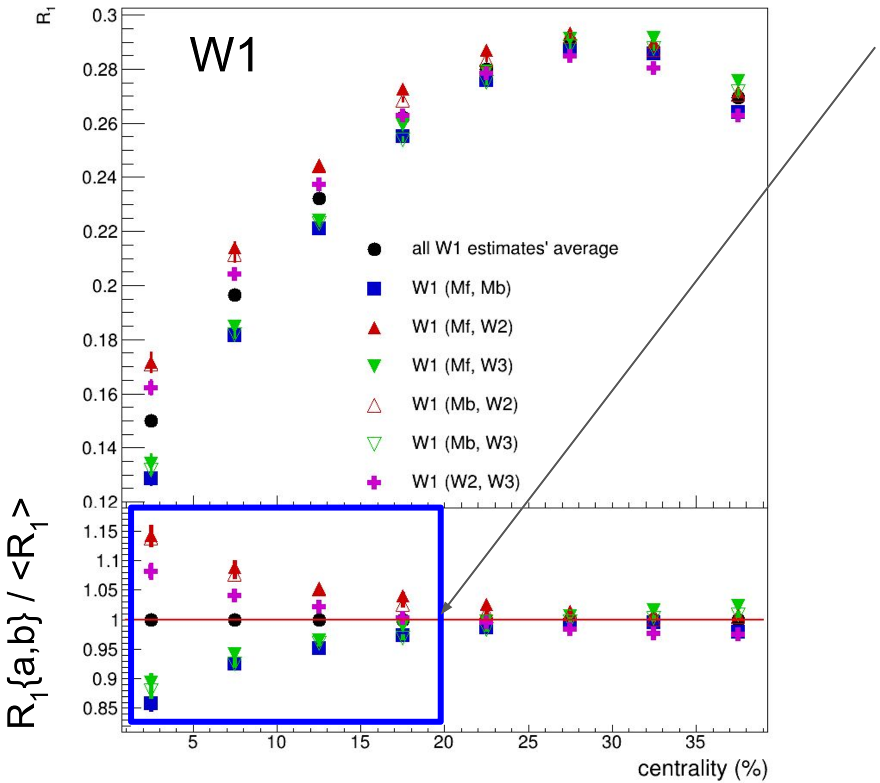
In reality:
Rapidity separation between sub-events reduces “non-flow” (short range) correlations

Rapidity coverage of different subevents



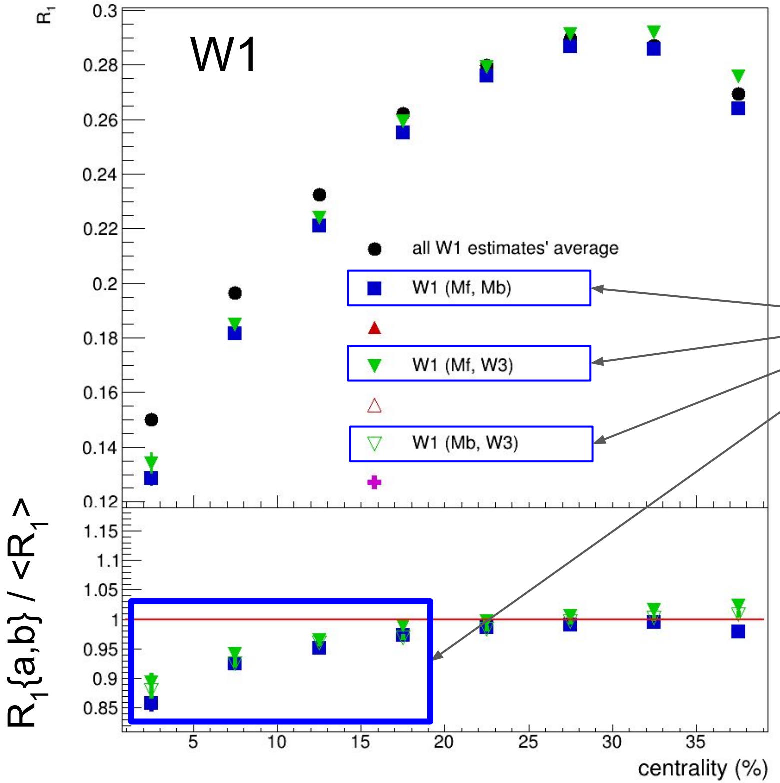
Quantifying non-flow correlations in R_1

1. Rapidity-separated and unseparated combinations split on two branches



Resolution estimates with rapidity-separated subevents are consistent with each other within 3-5%. Other combinations deviate by up to ~30% in central collisions

Quantifying non-flow correlations in R_1



1. Rapidity-separated and unseparated combinations split on two branches

2. Rapidity-separated combinations are consistent with each other

Resolution estimates with rapidity-separated subevents are consistent with each other within 3-5%.
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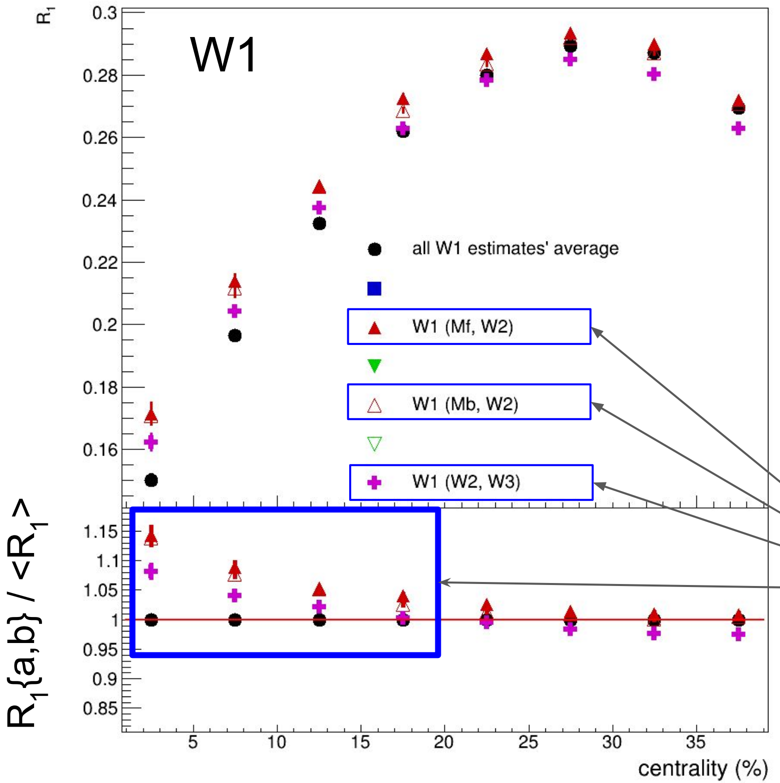
Quantifying non-flow correlations in R_1



1. Rapidity-separated and unseparated combinations split on two branches

2. Rapidity-separated combinations are consistent with each other

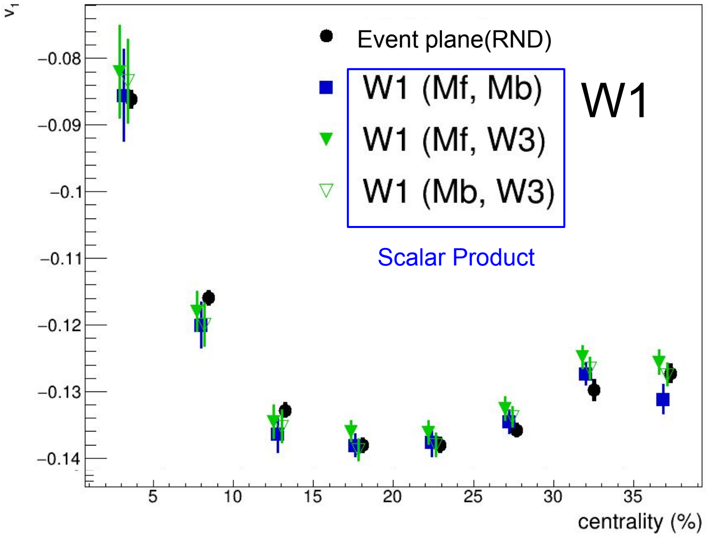
3. Combinations with no rapidity separation deviate from each other

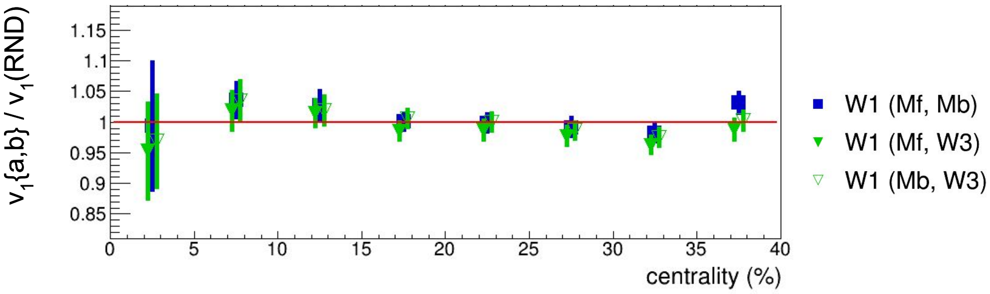
Resolution estimates with rapidity-separated subevents are consistent with each other within 3-5%. Other combinations deviate by up to ~30% in central collisions

Systematic uncertainty of directed flow

proton v_1 vs. centrality
y_{cm} [-0.25; -0.15]
p_T [0.0; 2.0] GeV/c

Rapidity separated only are shown

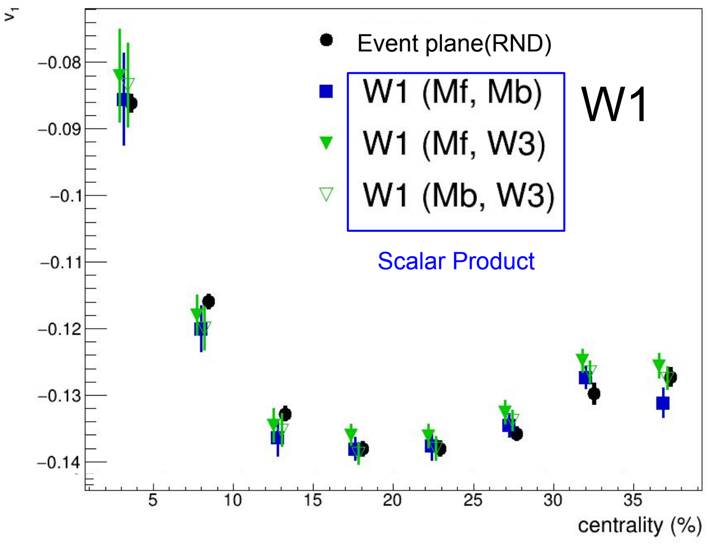




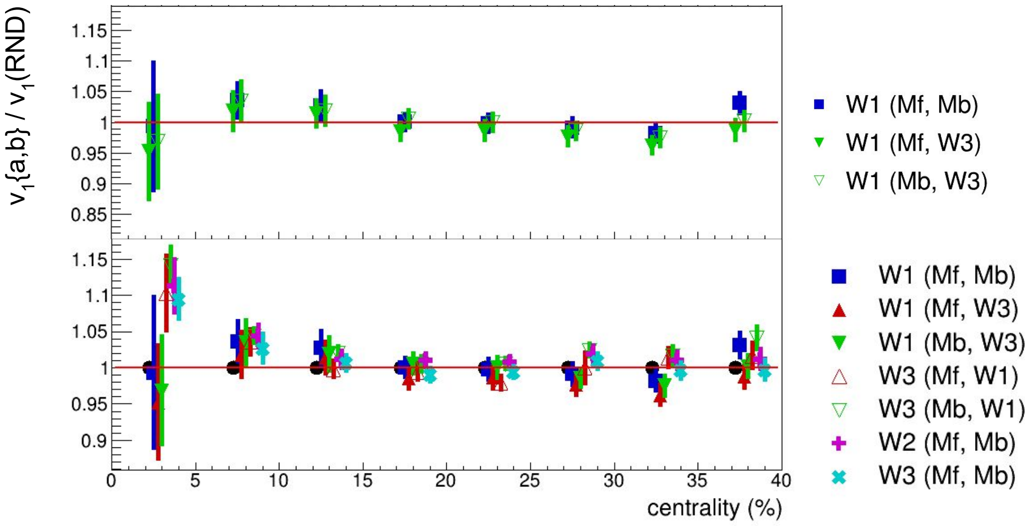
Results for event plane and scalar production
(with rapidity separated subevents)
are consistent within stat. uncertainties.

Systematic uncertainty of directed flow

proton v_1 vs. centrality
y_{cm} [-0.25; -0.15]
p_T [0.0; 2.0] GeV/c



Rapidity separated only are shown

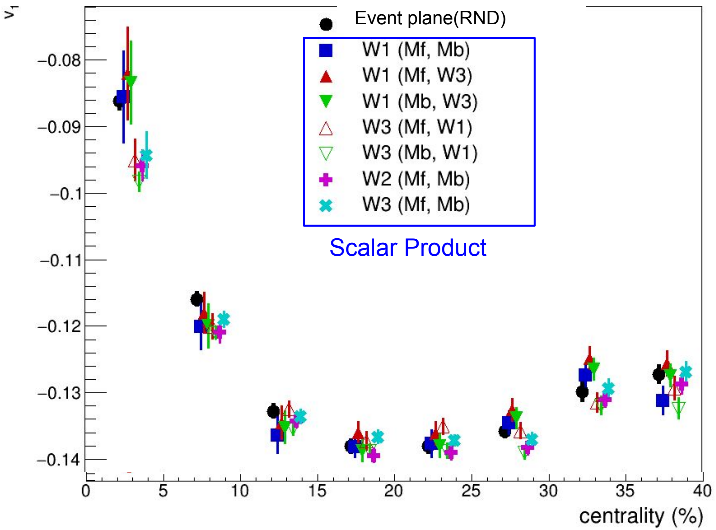


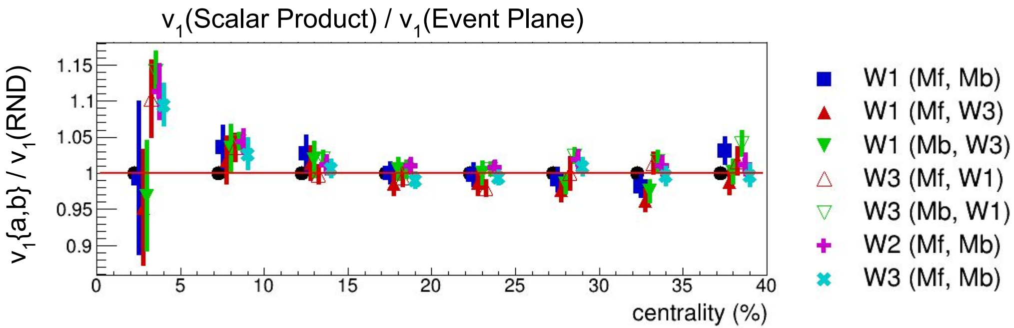
v_1 results with resolution corrections extracted from rapidity separated combinations are consistent for all subevents

Summary of systematic uncertainty for v_1

proton v_1 vs. centrality
y_{cm} [-0.25; -0.15]
p_T [0.0; 2.0] GeV/c

Rapidity separated only are shown





Overall difference between v_1 with event plane (RND-sub) and scalar product (with rapidity separated combinations) is ~10% in central events and below 5% in mid-central

Elliptic flow: mixed harmonics method

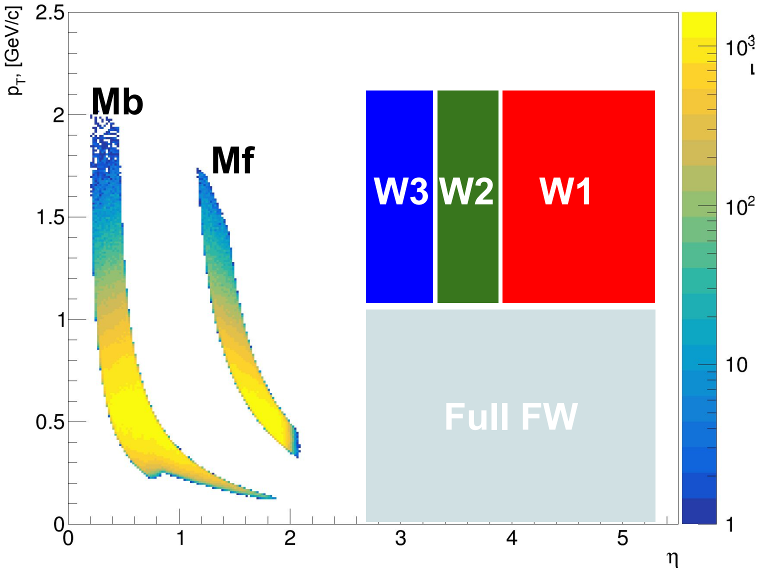
2nd and two 1st harmonic Q-vectors are mixed:

$$v_2 = \frac{\langle u_2 Q_1^a Q_1^b \rangle}{R_1^a \times R_1^b}$$

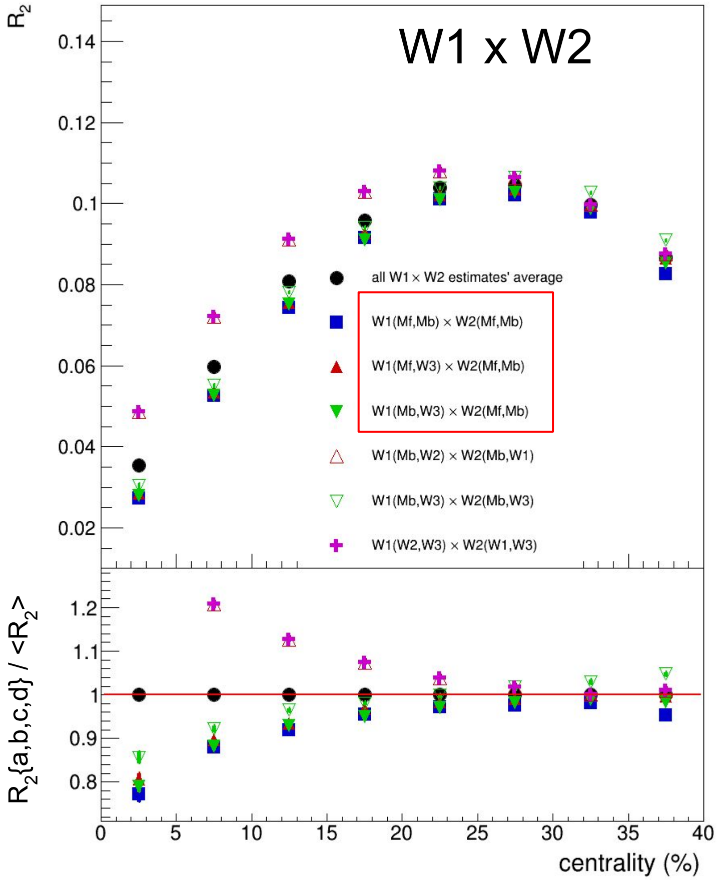
Resolution correction is a product of two 1st harmonic resolutions:

$$R_1^{a/b} = \frac{\sqrt{\langle Q_1^a Q_1^b \rangle \langle Q_1^{a/b} Q_1^c \rangle}}{\sqrt{\langle Q_1^{b/a} Q_1^c \rangle}}$$

Rapidity coverage of different subevents



Quantifying non-flow correlations in R_2



1. Results for combinations with and without rapidity-separation are splitted in two groups

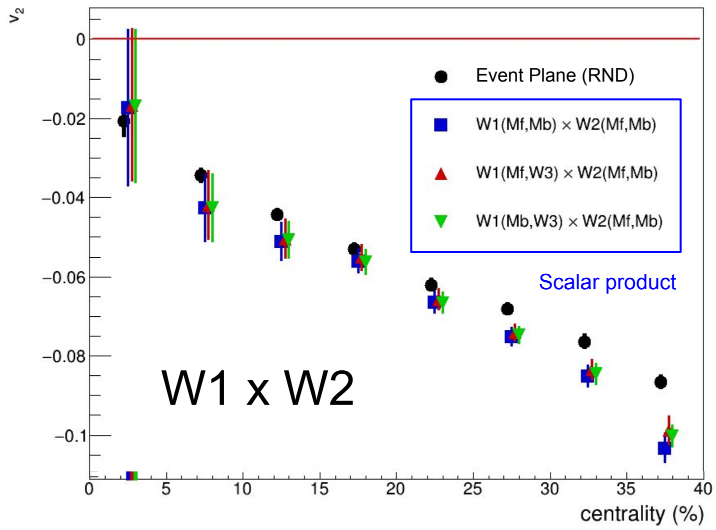
2. Results for rapidity-separated combinations are consistent with each other within 6-10%

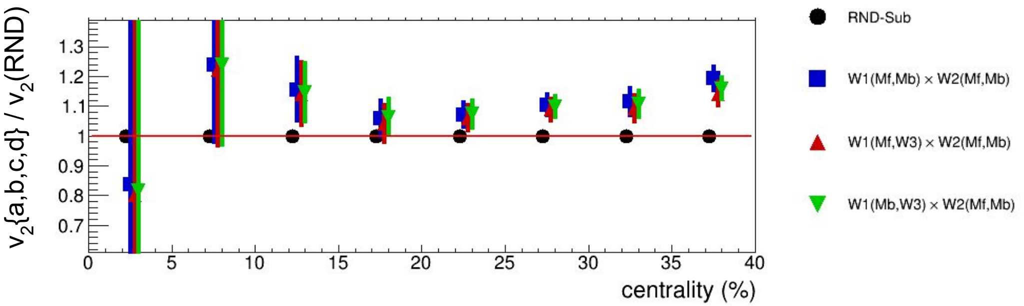
3. Results for combinations without rapidity separation differs from each other by up to 50% in central collisions

Systematic uncertainty of elliptic flow

proton v_1 vs. centrality
y_{cm} [-0.25; -0.15]
p_T [0.0; 2.0] GeV/c

Rapidity separated only are shown



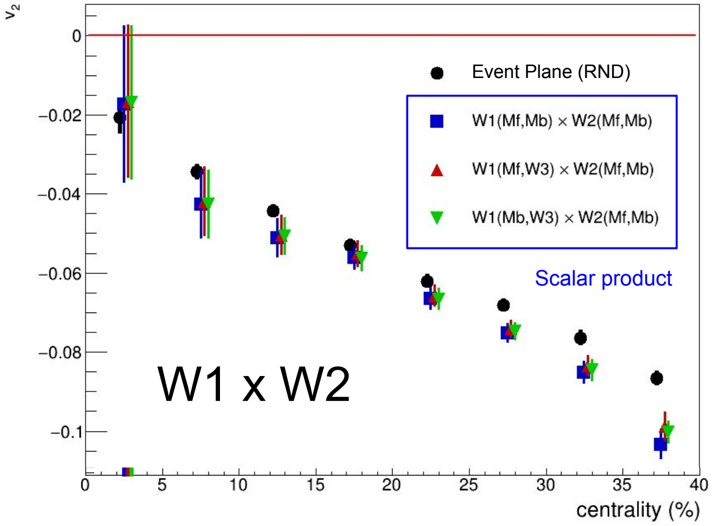


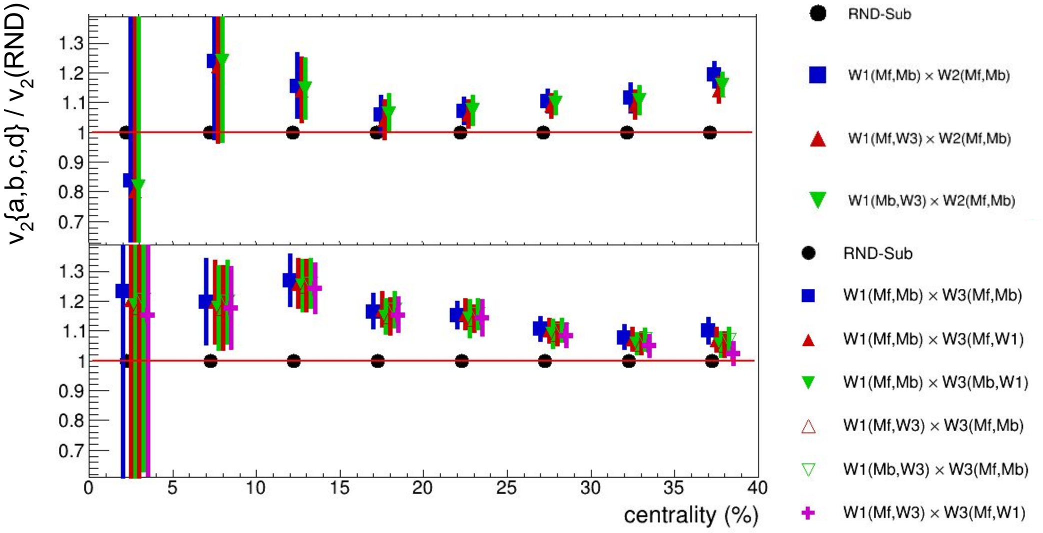
Results for event plane and scalar production (with rapidity separated subevents) in central and mid-central collisions are consistent within stat. uncertainties.

Systematic uncertainty of elliptic flow

proton v_1 vs. centrality
y_{cm} [-0.25; -0.15]
p_T [0.0; 2.0] GeV/c

Rapidity separated only are shown



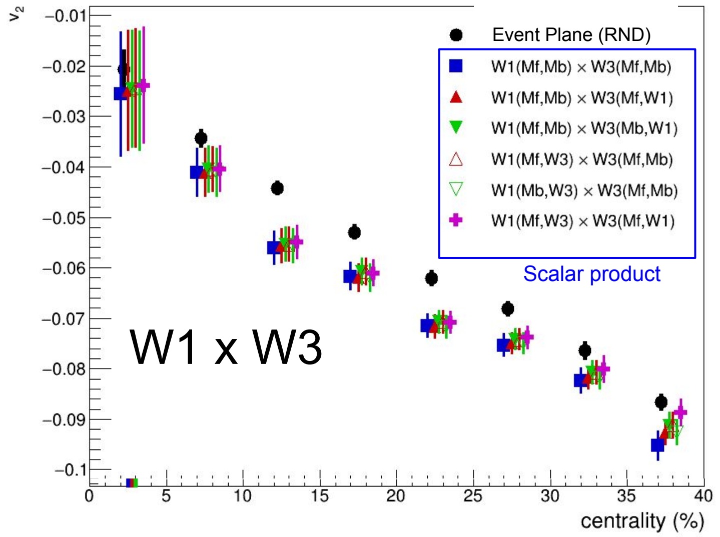


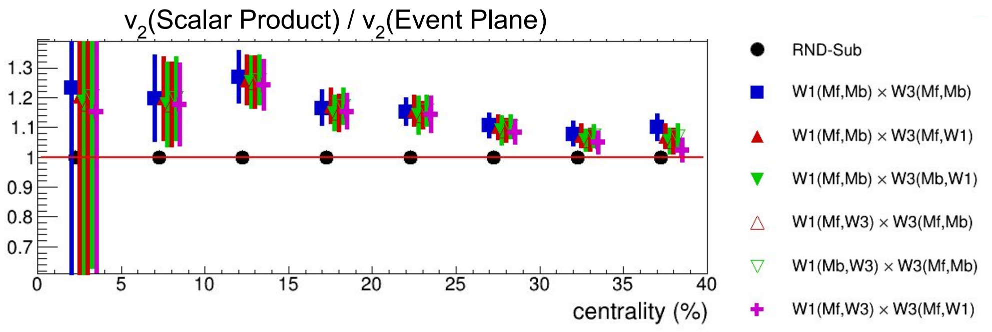
v_2 results with resolution corrections extracted from rapidity separated combinations are consistent for all subevents

Summary of systematic uncertainty for v_2

proton v_1 vs. centrality
y_{cm} [-0.25; -0.15]
p_T [0.0; 2.0] GeV/c

Rapidity separated only are shown





Overall difference between v_2 with event plane (RND-sub) and scalar product (with rapidity separated combinations) is ~20% in central events and below 10% in mid-central

Summary

- Investigated systematic uncertainties in proton's directed and elliptic flow measurement relatively to the spectators symmetry plane
- Implemented scalar product, 3-subevents and mixed harmonics techniques for flow measurement
- After applying corrections for azimuthal acceptance non-uniformity of the detector, the residual effects are found to be below 2%
- From the comparison of event plane (random subevents) and scalar production (three subevents) methods systematic uncertainty of spectator symmetry plane estimation was evaluated:
  - ~ 10% for proton v_1 in most central and < 5% in mid-central collisions
  - ~ 20% for proton v_2 in most central and ~ 10% in mid-central collisions

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- the National Research Nuclear University "MEPhI" in the framework of the Russian Academic Excellence Project (contract no. 02.a03.21.0005, 27.08.2013).

Backup

Data Selection

Data: Au+Au collisions at 1.23GeV (subsample of 10M events)

Event selection:

- Minimum bias trigger
- vertex on Z: [-60;0] mm
- vertex on XY < 3 mm
- Good Vertex Cluster
- Good Vertex Candidate
- Good START
- No Pile Up in START
- Good START VETO
- Good START META
- No VETO

Proton selection

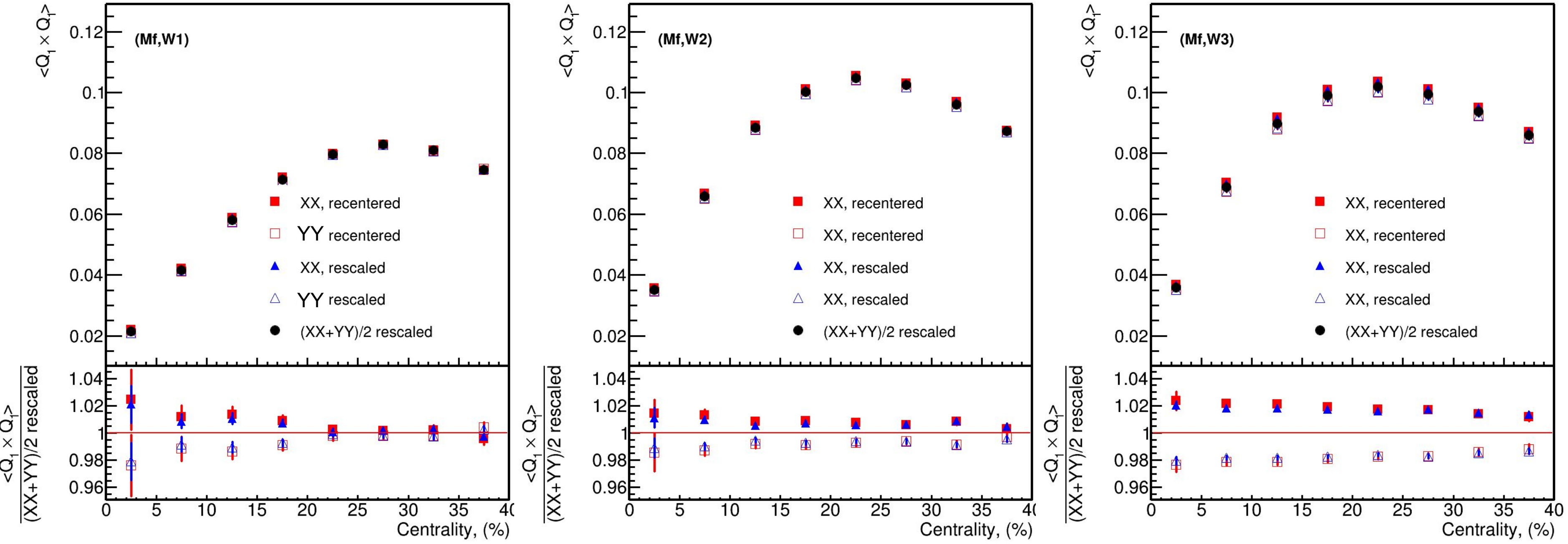
- DCA-z<15mm
- DCA-xy<15mm
- Standard HADES TOF selection

Charged fragment (FW modules) selection

- Wall Ring: 0-4:
  - wallHitCharge > 80
  - wallHitBeta [0.84, 1]
- Wall Ring: 5-6:
  - wallHitCharge > 85
  - wallHitBeta [0.85, 1]
- Wall Ring: 0-4:
  - wallHitCharge > 88
  - wallHitBeta [0.8, 1]

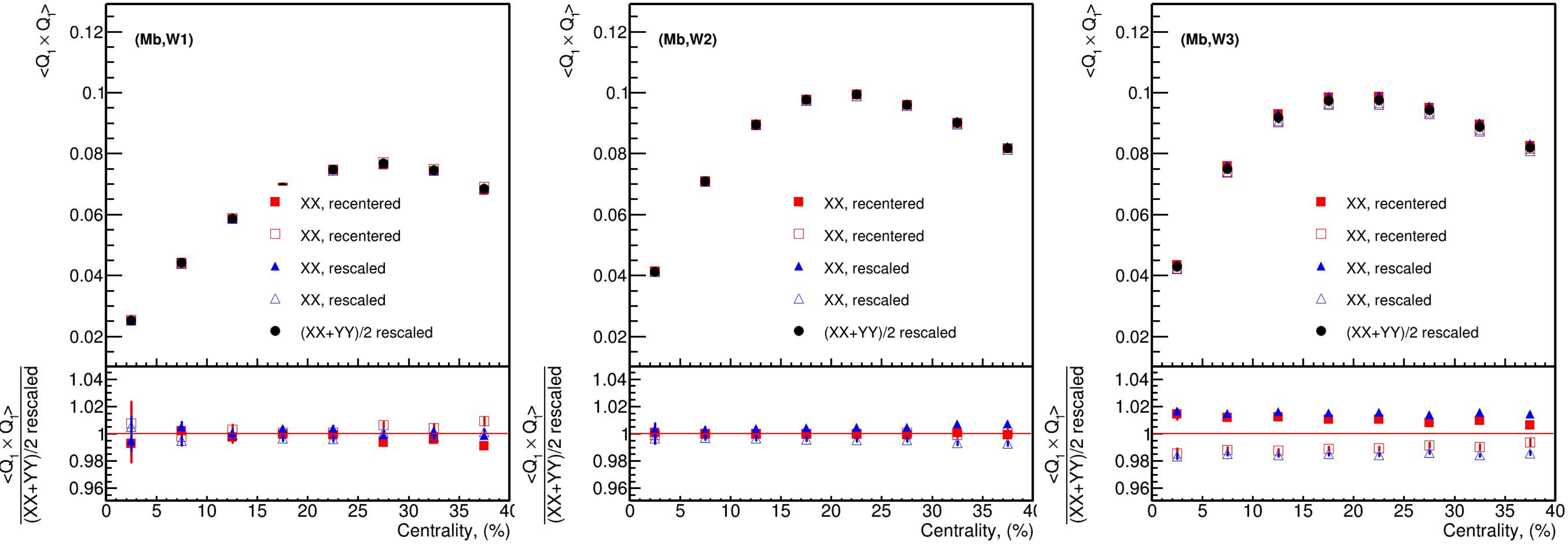
Centrality is determined with selected TOF+RPC hits
Details: see talk by B.Kardan
“Centrality determination in HADES at SIS18: Glauber model approach”

Q-vector correlations (Mf, W): azimuthal non-uniformity corrections



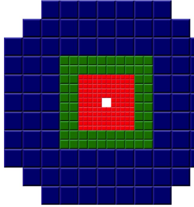
Components are close. Cross-components are zero.

Q-vector correlations (Mb, W): azimuthal non-uniformity corrections

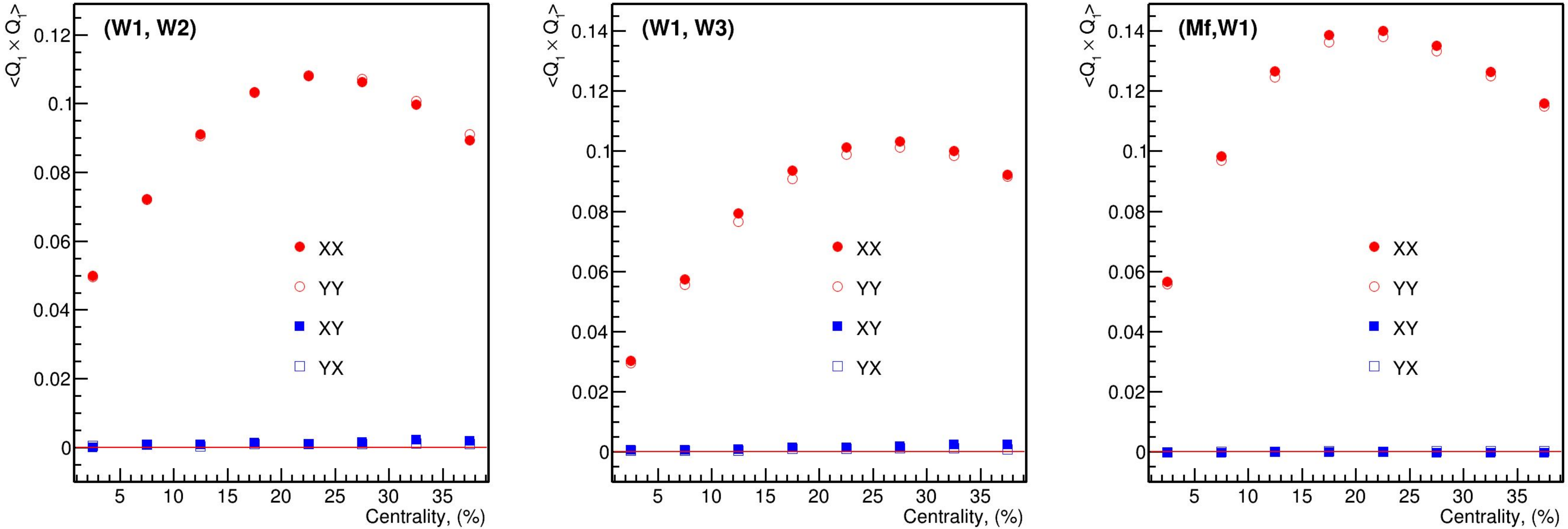


Components are close. Cross-components are zero.

Test of azimuthal non-uniformity corrections



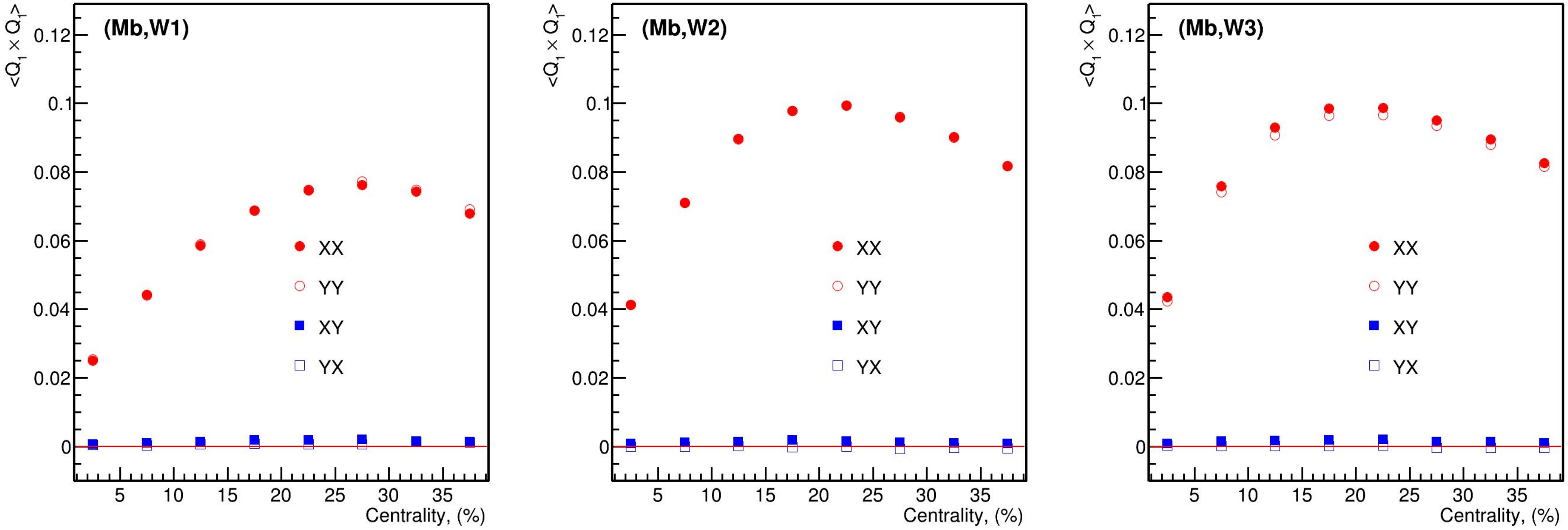
$$\langle Q_n^a Q_n^b \rangle = \langle X_n^a X_n^b \rangle + \langle Y_n^a Y_n^b \rangle$$



Components are close. Cross-components are zero.

(Mb,W) correlations, MDC-vectors recentered only

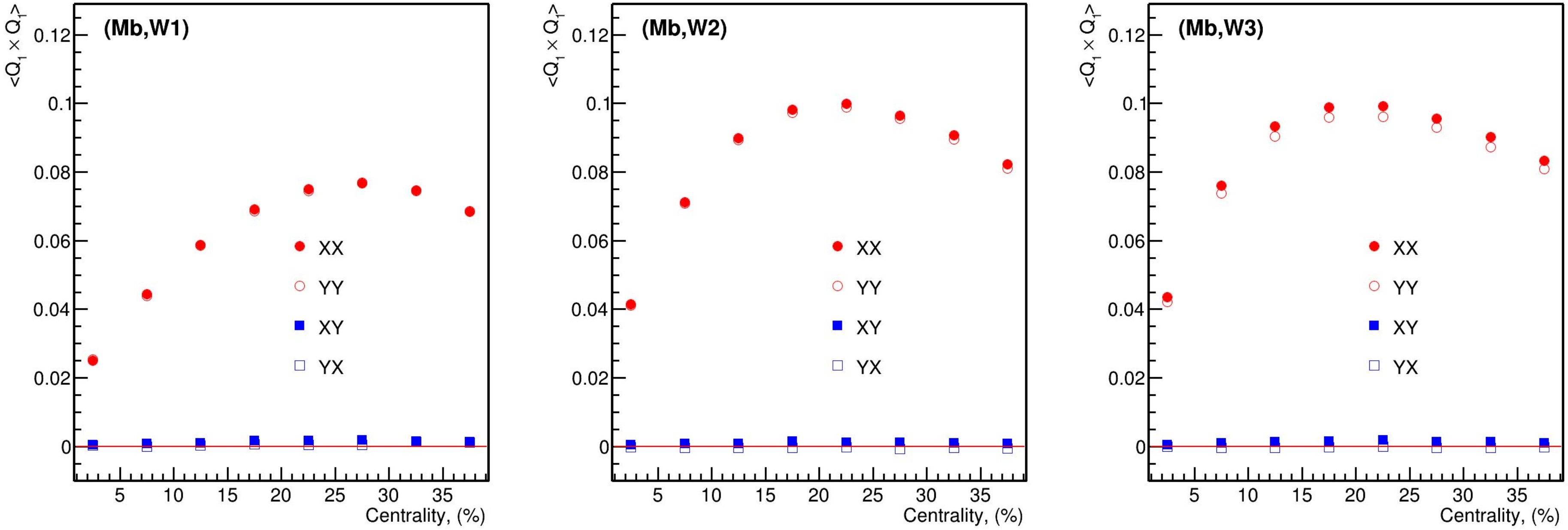
$$\langle Q_n^a Q_n^b \rangle = \langle X_n^a X_n^b \rangle + \langle Y_n^a Y_n^b \rangle$$



Components are not equal except the case of correlations with W3. Cross-components are close to zero, but are not zero

(Mb,W) correlations, MDC-vectors twisted+rescaled

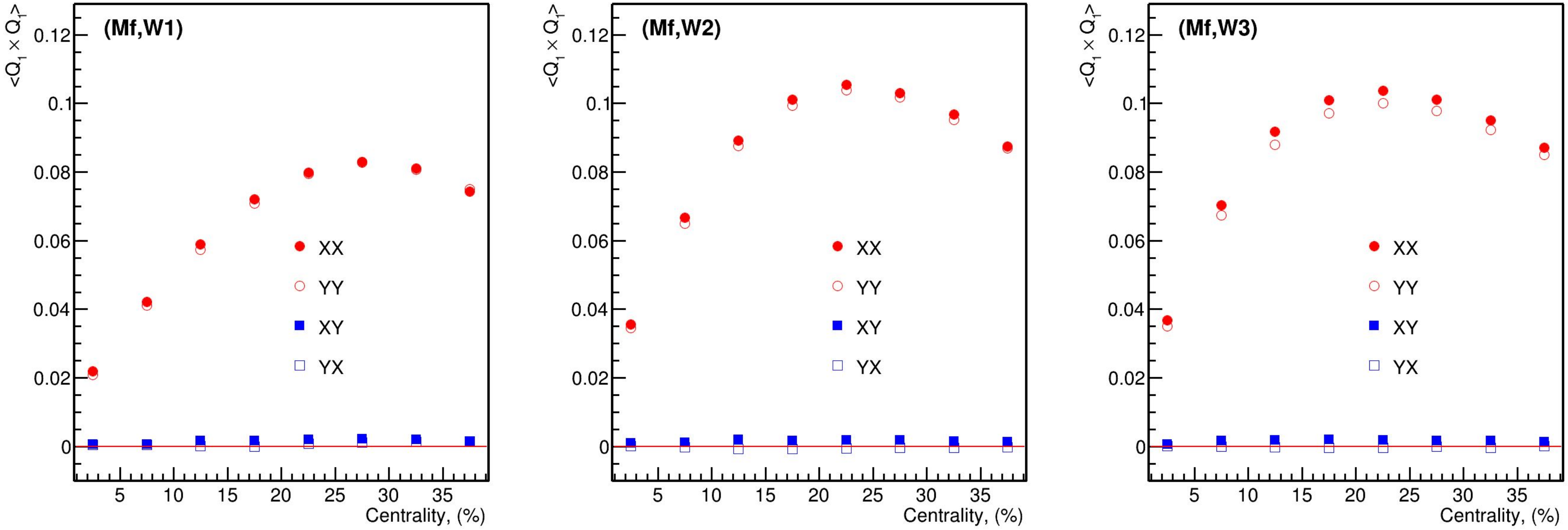
$$\langle Q_n^a Q_n^b \rangle = \langle X_n^a X_n^b \rangle + \langle Y_n^a Y_n^b \rangle$$



Components are not equal except the case of correlations with W3. Cross-components are close to zero, but are not zero

(Mf,W) correlations, MDC-vectors recentered only

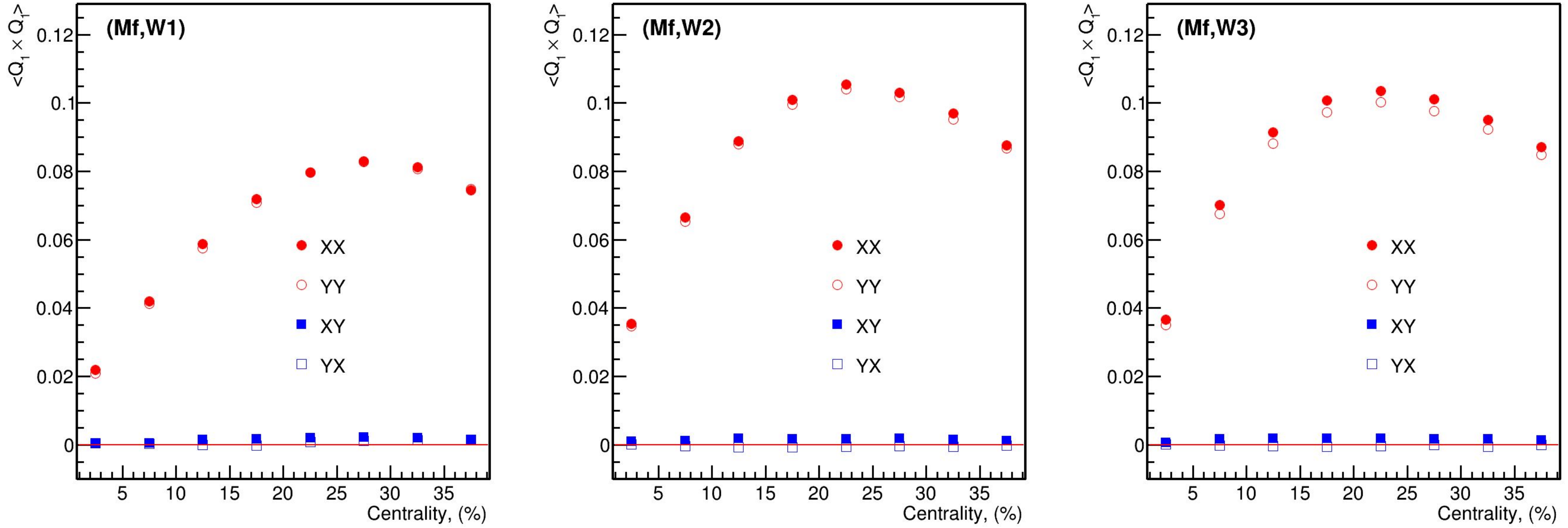
$$\langle Q_n^a Q_n^b \rangle = \langle X_n^a X_n^b \rangle + \langle Y_n^a Y_n^b \rangle$$



Components are not equal except the case of correlations with W3. Cross-components are close to zero, but are not zero

(Mf,W) correlations, MDC-vectors twisted+rescaled

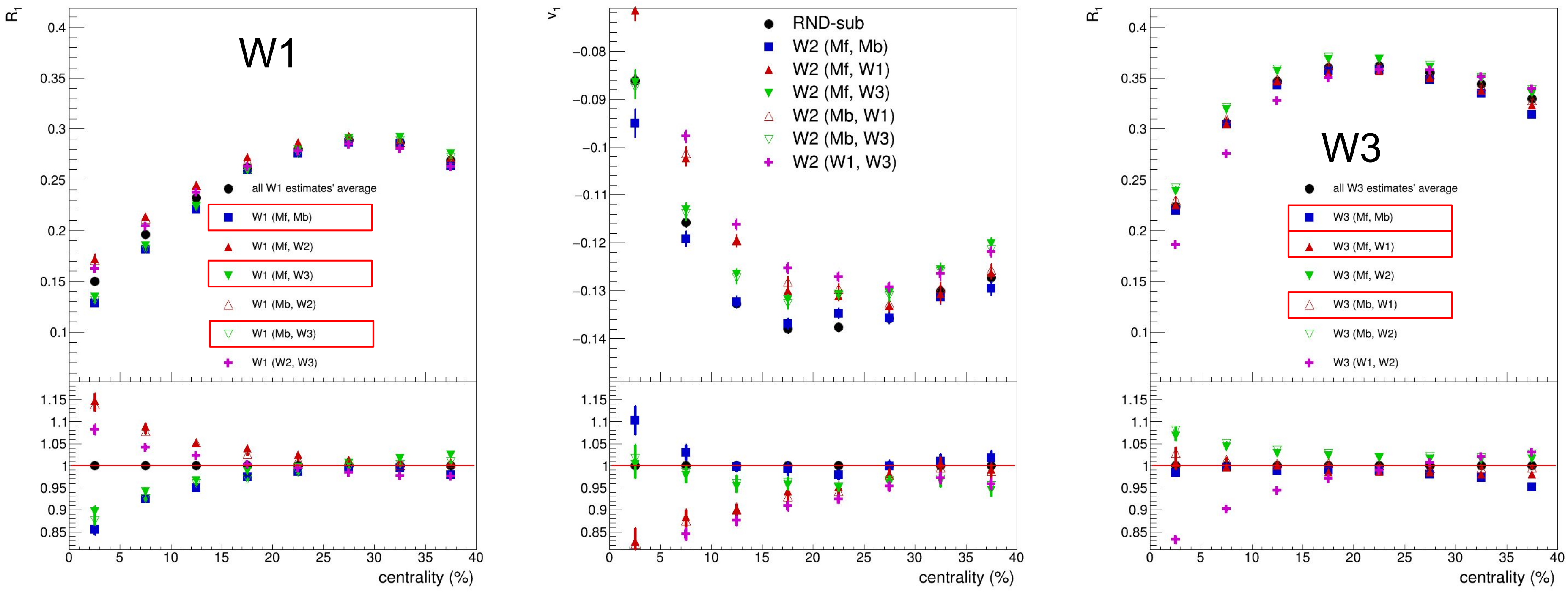
$$\langle Q_n^a Q_n^b \rangle = \langle X_n^a X_n^b \rangle + \langle Y_n^a Y_n^b \rangle$$



Components are not equal except the case of correlations with W3. Cross-components are close to zero, but are not zero

Resolution for W…(Q_1Q_2)

Reference: average of all resolutions on picture

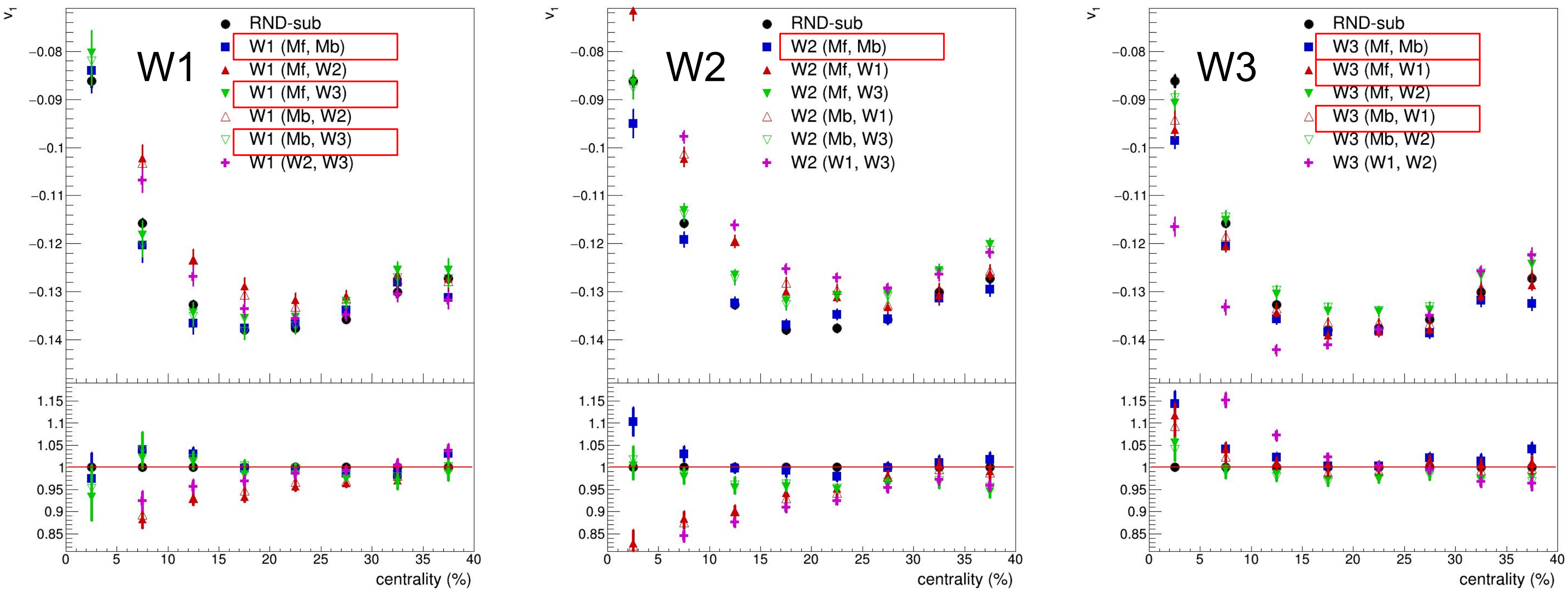


Resolution estimates with rapidity separated (not neighbouring) subevents are consistent with each other

proton v_1 for W…(Q_1Q_2)

Reference: FW-RND sub extrapolation

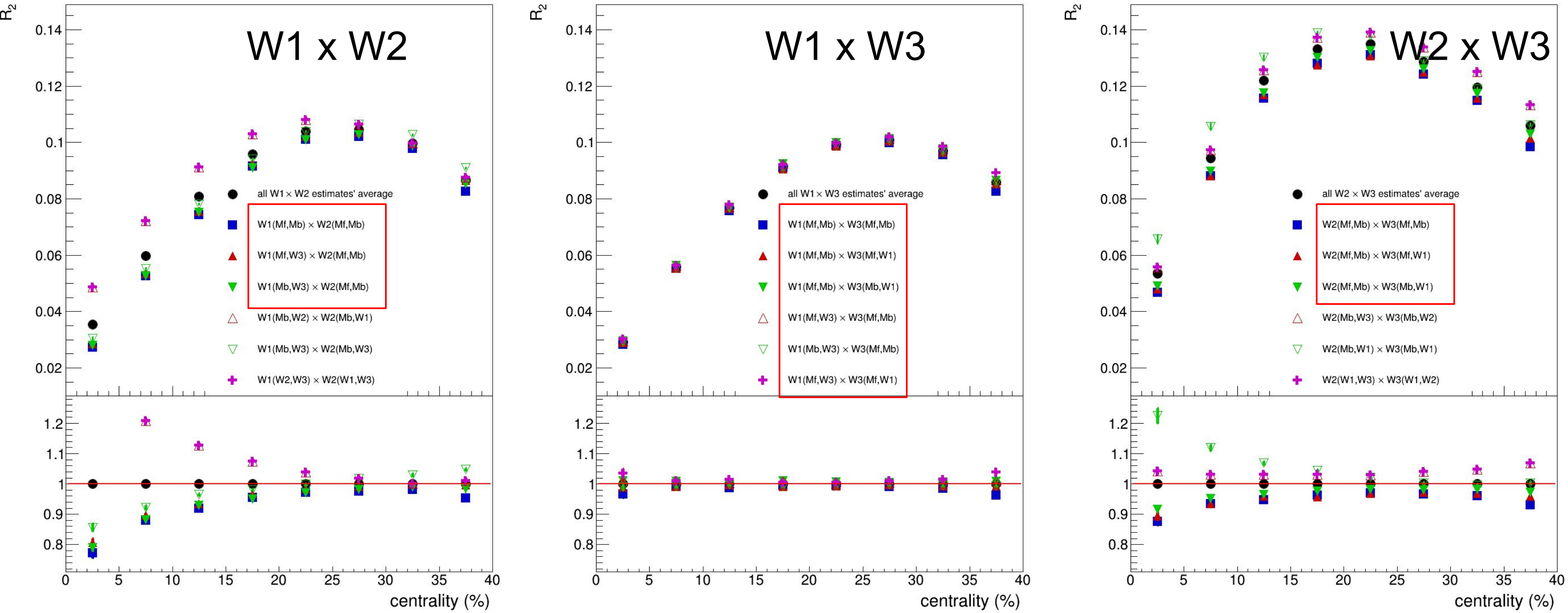
y_{cm}(-0.25, -0.15), p_T(0,2)



v_1 results with rapidity separated (not neighbouring) subevents are consistent with each other

Resolution R_2

$$v_2 = \frac{\langle u_2 Q_1^a Q_1^b \rangle}{R(Q_1^a) R(Q_1^b)}$$



Resolution estimates with rapidity separated (not neighbouring) subevents are consistent with each other

proton v_2

Reference: FW-RND sub extrapolation

$y_{cm}(-0.25, -0.15)$, $p_T(0,2)$