Balance function as a unique probe of the quark gluon plasma: experimental overview and outlook

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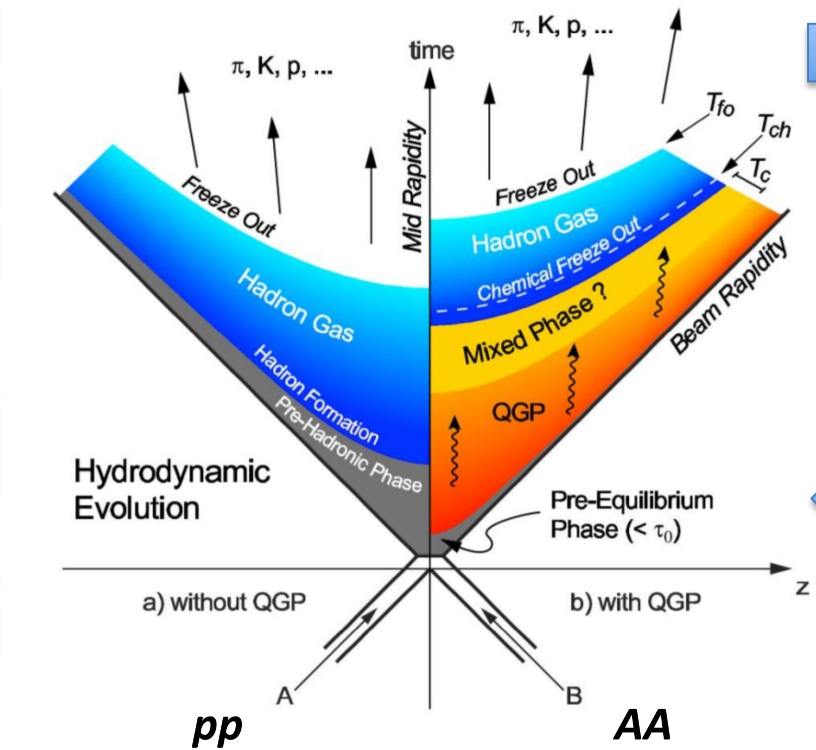
WPCF at FRIB | 07/19/2022

Balance Function – distribution of balancing charges

$$B^{\alpha\beta}(\Delta\vec{p}) = \frac{1}{2}\left[\frac{\rho_2^{\alpha^+\beta^-}(\Delta\vec{p}) - \rho_2^{\alpha^+\beta^+}(\Delta\vec{p})}{\rho_1^{\alpha^+}(\vec{p}^{\alpha})} + \frac{\rho_2^{\alpha^-\beta^+}(\Delta\vec{p}) - \rho_2^{\alpha^-\beta^-}(\Delta\vec{p})}{\rho_1^{\alpha^-}(\vec{p}^{\alpha})}\right]$$

For each charge +Q, BF identifies the probability where its balancing charge -Q is.

Bass, Danielewicz, Pratt PRL 85, 2689 (2000)

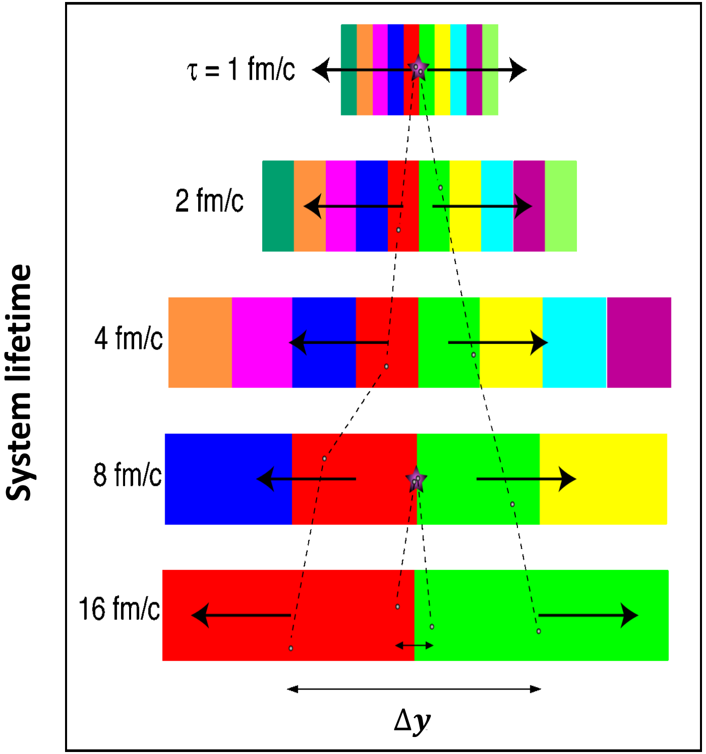


measure BF of final state identified hadron pairs

± — **General conserved charges**:
- e: electric charge
- S: strangeness
- B: baryon number

learn about light and strange quark production

Balancing charge separation in Δy



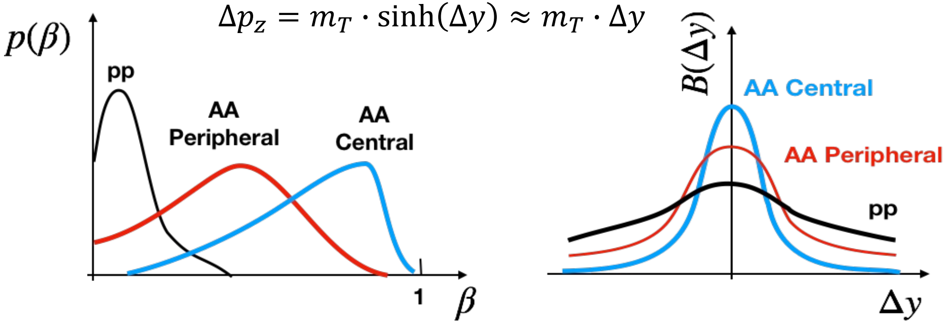
Balancing charge separation

Bass, Danielewicz, Pratt [PRL 85, 2689 (2000)](#)

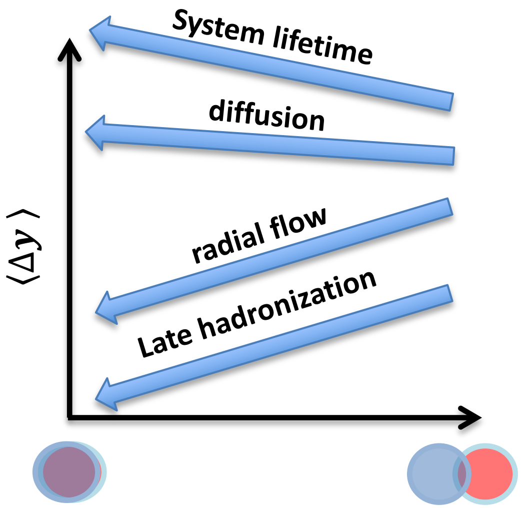
Later hadronization towards central collisions -> narrower BF of $\boldsymbol{\pi\pi}$, $\boldsymbol{KK}$, $\boldsymbol{pp}$

Voloshin [PLB 632 (2006) 490-494](#)

$$\Delta p_z = m_T \cdot \sinh(\Delta y) \approx m_T \cdot \Delta y$$



Larger radial flow towards central collisions leads to smaller separation of balancing pairs in Δy

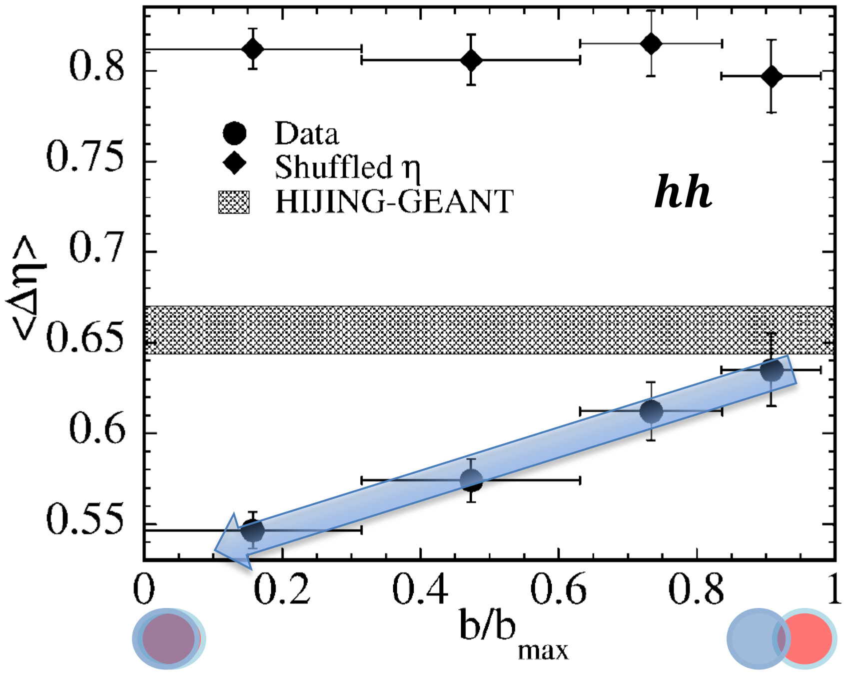


BF of unidentified hadron pairs hh and $\pi\pi$

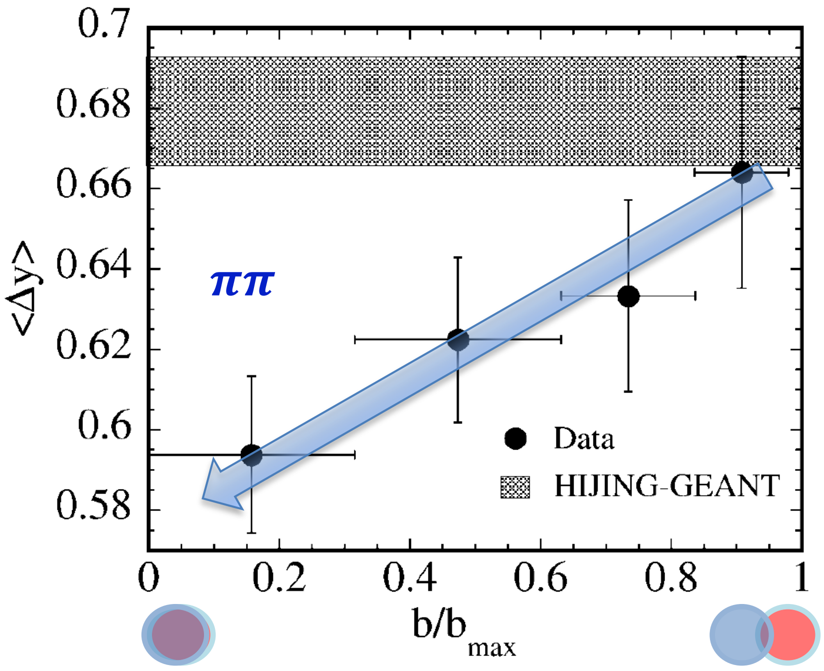
STAR [PRL 90, 172301 (2003)](#)

Au-Au @ 130 GeV

$\mathbf{0.1 < p < 2.0\ GeV/c}$



$\mathbf{0.1 < p_T, p < 0.7\ GeV/c}$

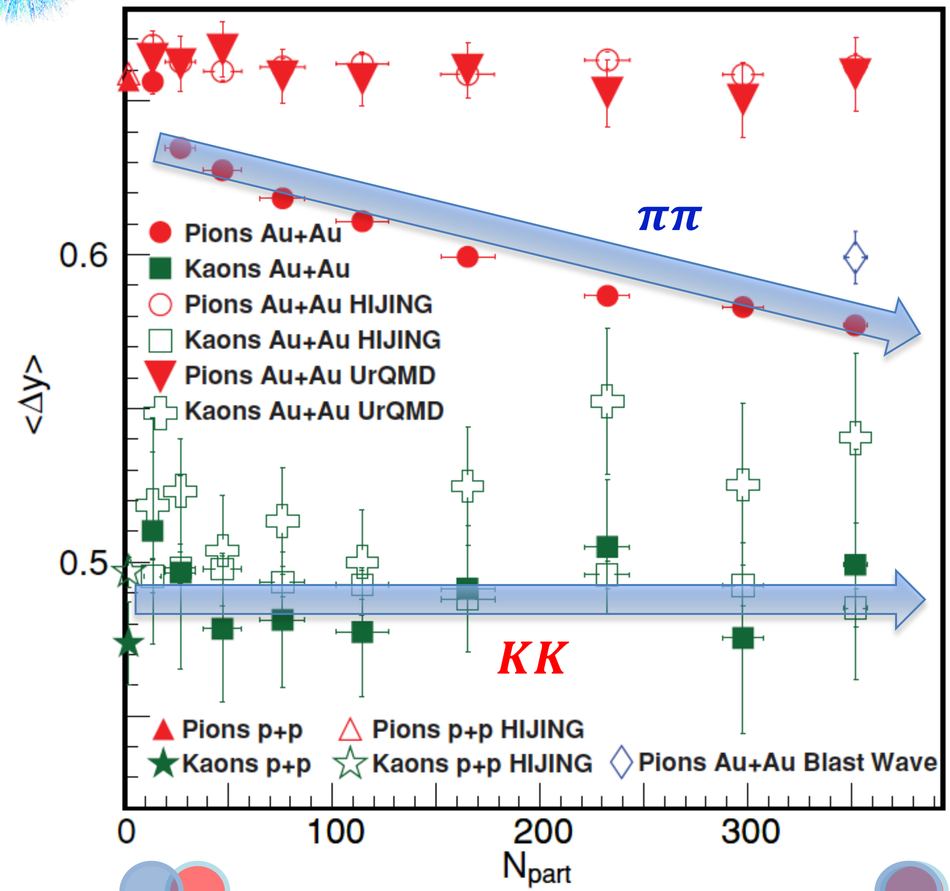


Narrowing of $\boldsymbol{B^{hh}}$ and $\boldsymbol{B^{\pi\pi}}$ towards central Au-Au collisions

-> larger radial flow towards central collisions leads to smaller separation of balancing pairs in $\Delta\eta$ & Δy

-> later hadronization towards central collisions leads to narrower BF

BF of identified hadron pairs $\pi\pi$ and KK



Au-Au @ 200 GeV

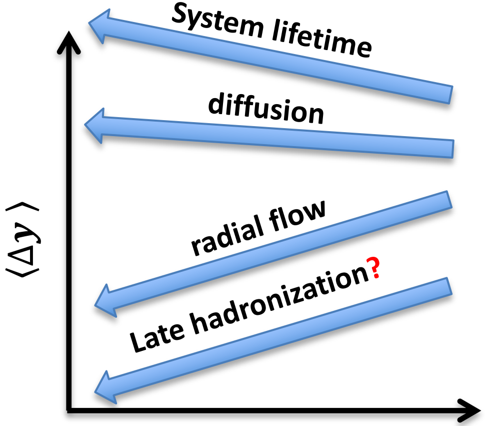
STAR [PRC 82, 024905 (2010)](#)

$\mathbf{0.2 < p_T < 0.6\ GeV/c}$

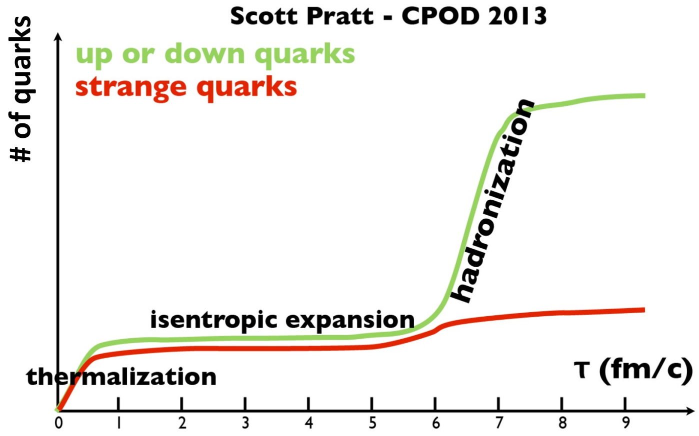
$B^{\pi\pi}(\Delta y)$ narrow towards central collisions, while $B^{KK}(\Delta y)$ no centrality dependence.

-> larger radial flow towards central collisions leads to smaller separation of balancing pairs in Δy for $\pi\pi$ and KK.
-> $\langle \Delta y \rangle$ for KK is smaller than $\pi\pi$ due to ϕ decay.

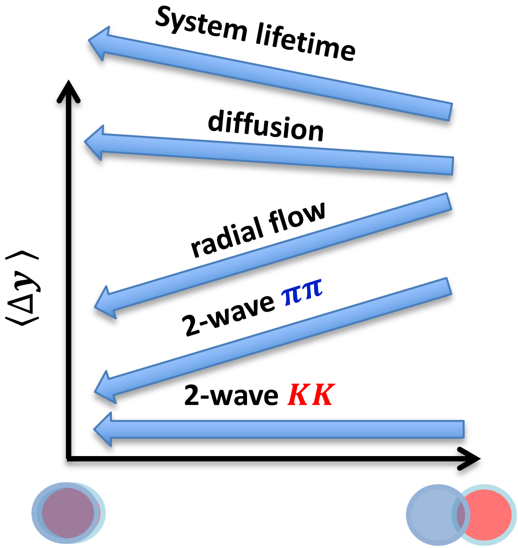
-> no late hadronization for KK?



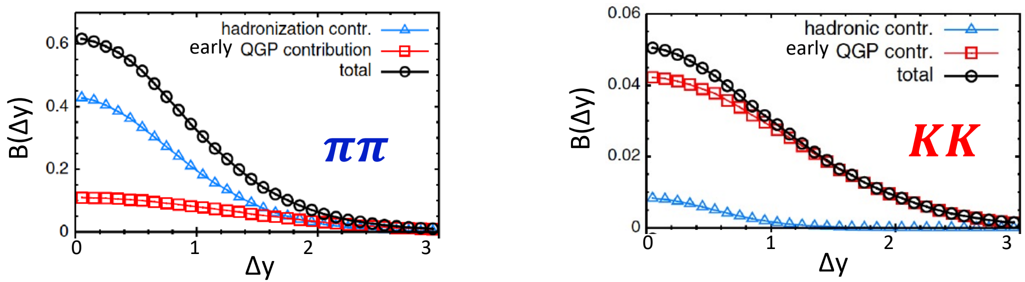
Two-wave Quark Production



Generalized BF (between different particle species)
-> understand balancing between quark species
-> access to light and strange quark production time



Pratt [*PRL. 108, 212301 (2012)*]



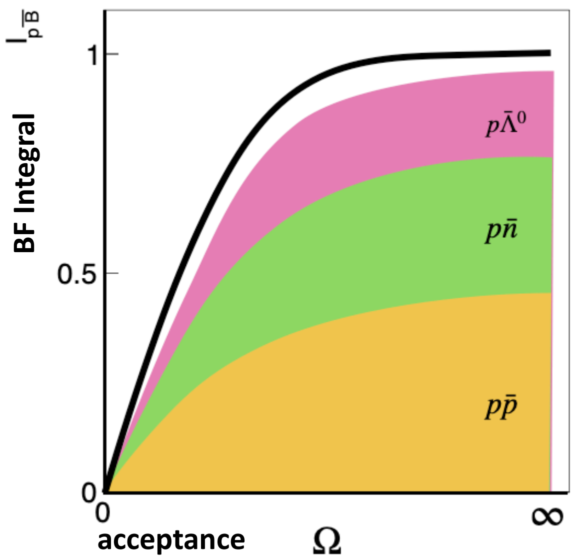
$\pi\pi$: larger 2nd wave up/down quark production -> smaller $\langle \Delta y \rangle$ -> narrow towards central collisions

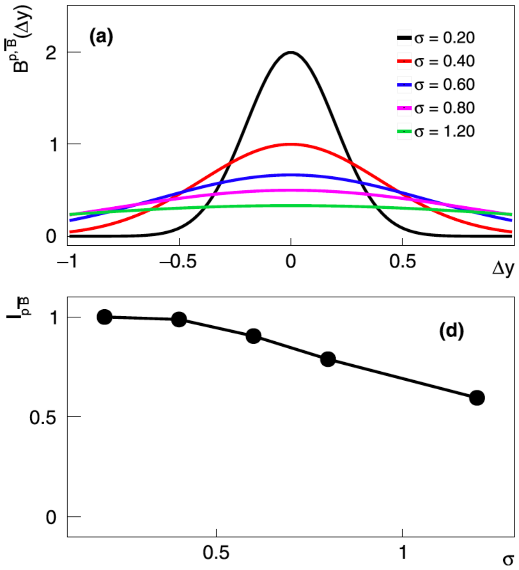
KK: dominant 1st wave strange quark production -> same $\langle \Delta y \rangle$ -> no centrality dependence

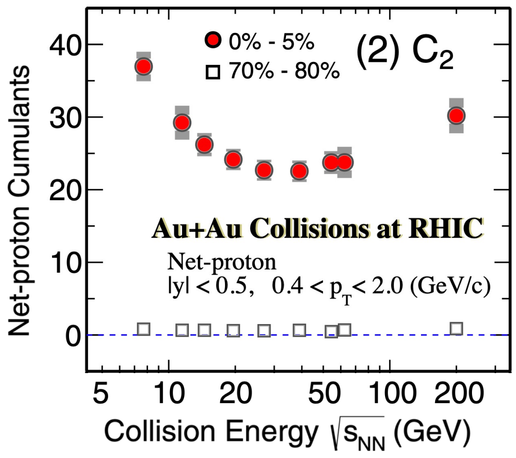
Baryon number BF & Net-baryon fluctuation

Pruneau *PRC 100, 034905 (2019)*

STAR *PRL 126, 092301 (2021)*







BF Integral

- hadron species pairing probability (never measured before)
- interplay of pair production process, acceptance, and BF width

$$1 - \frac{C_2(\Delta N_p)}{C_2^{Skellam}(\Delta N_p)} = I_{BF}(\Omega)$$

high energy A-A collisions in the limit $\langle N_p \rangle = \langle N_p \rangle$

Differential baryon number BF in BES -> critical point search

Two-particle Number Correlation Function

$\alpha, \beta - \boldsymbol{h}, \boldsymbol{\pi}, \boldsymbol{K}, \boldsymbol{p}, \boldsymbol{\Lambda}$ and $\boldsymbol{\Xi}$ ...
α – *reference particle*
β – *associate particle*
ρ_1, ρ_2 – *single particle & pair number density per event*

2-Particle Cumulant

$$C_2^{\alpha\beta}(\vec{p}^{\alpha}, \vec{p}^{\beta}) = \rho_2^{\alpha\beta}(\vec{p}^{\alpha}, \vec{p}^{\beta}) - \rho_1^{\alpha}(\vec{p}^{\alpha}) \cdot \rho_1^{\beta}(\vec{p}^{\beta})$$

Measurement:
M – Measured

$$C_{2,M}^{\alpha\beta}(\vec{p}^{\alpha}, \vec{p}^{\beta}) \approx \boxed{\varepsilon_1^{\alpha}(\vec{p}^{\alpha}) \cdot \varepsilon_1^{\beta}(\vec{p}^{\beta})} \cdot C_2^{\alpha\beta}(\vec{p}^{\alpha}, \vec{p}^{\beta})$$

Require separate efficiency estimation for single particles

assuming efficiency factorizes

$$\varepsilon_2^{\alpha}(\vec{p}^{\alpha}, \vec{p}^{\beta}) \approx \varepsilon_1^{\alpha}(\vec{p}^{\alpha}) \cdot \varepsilon_1^{\beta}(\vec{p}^{\beta})$$

Normalized 2-Particle Cumulant

$$R_2^{\alpha\beta}(\vec{p}^{\alpha}, \vec{p}^{\beta}) = \frac{C_2^{\alpha\beta}(\vec{p}^{\alpha}, \vec{p}^{\beta})}{\rho_1^{\alpha}(\vec{p}^{\alpha}) \cdot \rho_1^{\beta}(\vec{p}^{\beta})} = \frac{\rho_2^{\alpha\beta}(\vec{p}^{\alpha}, \vec{p}^{\beta})}{\rho_1^{\alpha}(\vec{p}^{\alpha}) \cdot \rho_1^{\beta}(\vec{p}^{\beta})} - 1$$

Efficiencies cancel in the ratio -> robust observable

Balance Function (BF) Definition

Associated particle distribution (per trigger yield)

$$A^{\alpha\beta}(\vec{p}^{\alpha},\vec{p}^{\beta}) = \frac{\rho_2^{\alpha\beta}(\vec{p}^{\alpha},\vec{p}^{\beta})}{\rho_1^{\alpha}(\vec{p}^{\alpha})} - \rho_1^{\beta}(\vec{p}^{\beta}) = \rho_1^{\beta}(\vec{p}^{\beta}) \cdot R_2^{\alpha\beta}(\vec{p}^{\alpha},\vec{p}^{\beta})$$

BF of positive reference particle $\boldsymbol{\alpha^{+}}$

$$B^{\alpha^{+}\beta}(\vec{p}^{\alpha},\vec{p}^{\beta}) = A^{\alpha^{+}\beta^{-}} - A^{\alpha^{+}\beta^{+}} = \frac{\rho_2^{\alpha^{+}\beta^{-}}(\vec{p}^{\alpha},\vec{p}^{\beta})}{\rho_1^{\alpha^{+}}(\vec{p}^{\alpha})} - \rho_1^{\beta^{-}}(\vec{p}^{\beta}) - \frac{\rho_2^{\alpha^{+}\beta^{+}}(\vec{p}^{\alpha},\vec{p}^{\beta})}{\rho_1^{\alpha^{+}}(\vec{p}^{\alpha})} + \rho_1^{\beta^{+}}(\vec{p}^{\beta})$$

BF of negative reference particle $\boldsymbol{\alpha^{-}}$

$$B^{\alpha^{-}\beta}(\vec{p}^{\alpha},\vec{p}^{\beta}) = A^{\alpha^{-}\beta^{+}} - A^{\alpha^{-}\beta^{-}} = \frac{\rho_2^{\alpha^{-}\beta^{+}}(\vec{p}^{\alpha},\vec{p}^{\beta})}{\rho_1^{\alpha^{-}}(\vec{p}^{\alpha})} - \rho_1^{\beta^{+}}(\vec{p}^{\beta}) - \frac{\rho_2^{\alpha^{-}\beta^{-}}(\vec{p}^{\alpha},\vec{p}^{\beta})}{\rho_1^{\alpha^{-}}(\vec{p}^{\alpha})} + \rho_1^{\beta^{-}}(\vec{p}^{\beta})$$

Balance function

$$\boldsymbol{B^{\alpha\beta}(\vec{p}^{\alpha},\vec{p}^{\beta})} = \frac{1}{2}\left[B^{\alpha^{+}\beta}(\vec{p}^{\alpha},\vec{p}^{\beta}) + B^{\alpha^{-}\beta}(\vec{p}^{\alpha},\vec{p}^{\beta})\right]$$

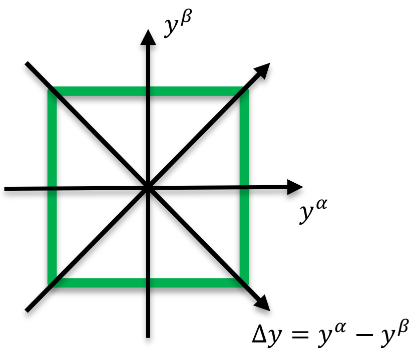
$$= \boldsymbol{\frac{1}{2}\left[\rho_1^{\beta^{-}}(\vec{p}^{\beta}) \cdot \boxed{R_2^{\alpha^{+}\beta^{-}}(\vec{p}^{\alpha},\vec{p}^{\beta})} - \rho_1^{\beta^{+}}(\vec{p}^{\beta}) \cdot \boxed{R_2^{\alpha^{+}\beta^{+}}(\vec{p}^{\alpha},\vec{p}^{\beta})} + \rho_1^{\beta^{+}}(\vec{p}^{\beta}) \cdot \boxed{R_2^{\alpha^{-}\beta^{+}}(\vec{p}^{\alpha},\vec{p}^{\beta})} - \rho_1^{\beta^{-}}(\vec{p}^{\beta}) \cdot \boxed{R_2^{\alpha^{-}\beta^{-}}(\vec{p}^{\alpha},\vec{p}^{\beta})}\right]}$$

Balance Function Measurement

$$B^{\alpha\beta}(y^\alpha,\varphi^\alpha,y^\beta,\varphi^\beta)$$
$$=\frac{1}{2}[\rho_1^{\beta^-}(y^\beta,\varphi^\beta)\cdot\boxed{R_2^{\alpha^+\beta^-}(y^\alpha,\varphi^\alpha,y^\beta,\varphi^\beta)}-\rho_1^{\beta^+}(y^\beta,\varphi^\beta)\cdot\boxed{R_2^{\alpha^+\beta^+}(y^\alpha,\varphi^\alpha,y^\beta,\varphi^\beta)}$$
$$+\rho_1^{\beta^+}(y^\beta,\varphi^\beta)\cdot\boxed{R_2^{\alpha^-\beta^+}(y^\alpha,\varphi^\alpha,y^\beta,\varphi^\beta)}-\rho_1^{\beta^-}(y^\beta,\varphi^\beta)\cdot\boxed{R_2^{\alpha^-\beta^-}(y^\alpha,\varphi^\alpha,y^\beta,\varphi^\beta)}]$$

$0.2 \le p_T^{\pi,K} \le 2.0\ GeV/c$
$0.5 \le p_T^{p} \le 2.5\ GeV/c$

- measure $R_2^{\alpha\beta}(y^\alpha,\varphi^\alpha,y^\beta,\varphi^\beta)$ for interested p_T range
- $\rho_1^{\beta}(y^\beta,\varphi^\beta)$ (assuming constant for mid-rapidity) calculated from previous p_T spectra measurements



$$\boldsymbol{B^{\alpha\beta}(\Delta y,\Delta\varphi)=\int B^{\alpha\beta}(y^\alpha,\varphi^\alpha,y^\beta,\varphi^\beta)dy^\beta d\varphi^\beta}$$

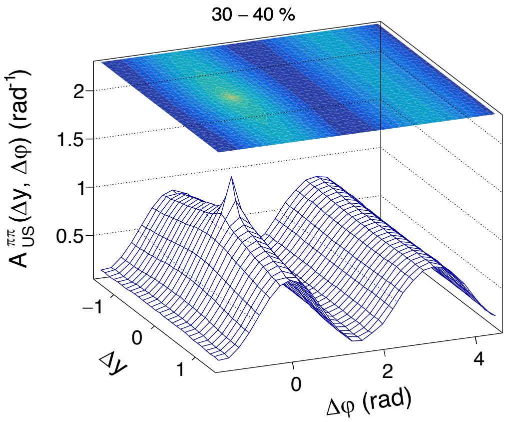
average over y^β

BF measures charge-dependent (CD) correlations

$$A_{US}^{\alpha\beta} = \frac{1}{2}\left(A^{\alpha^+\beta^-} + A^{\alpha^-\beta^+}\right)$$

$$A_{LS}^{\alpha\beta} = \frac{1}{2}\left(A^{\alpha^+\beta^+} + A^{\alpha^-\beta^-}\right)$$

$$B^{\alpha\beta}(\Delta y, \Delta\varphi) = A_{CD}^{\alpha\beta} = A_{US}^{\alpha\beta} - A_{LS}^{\alpha\beta}$$



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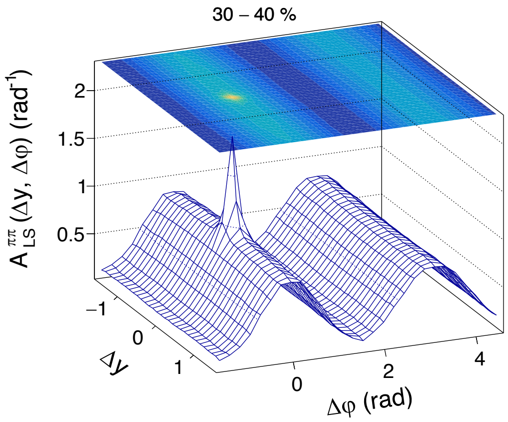

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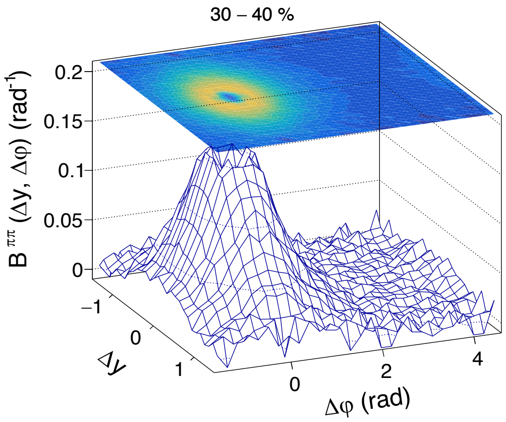
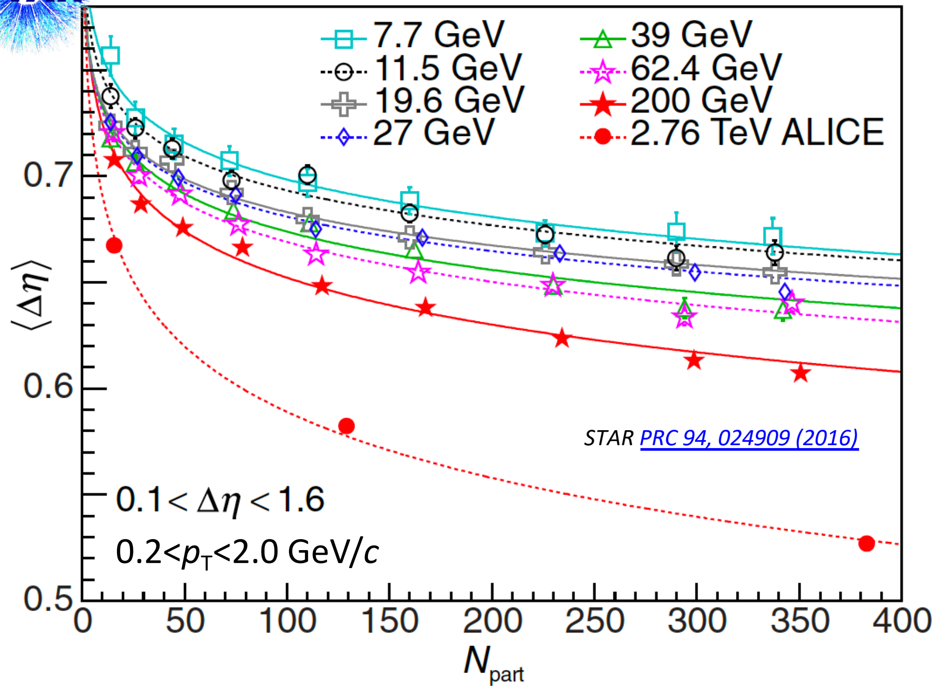
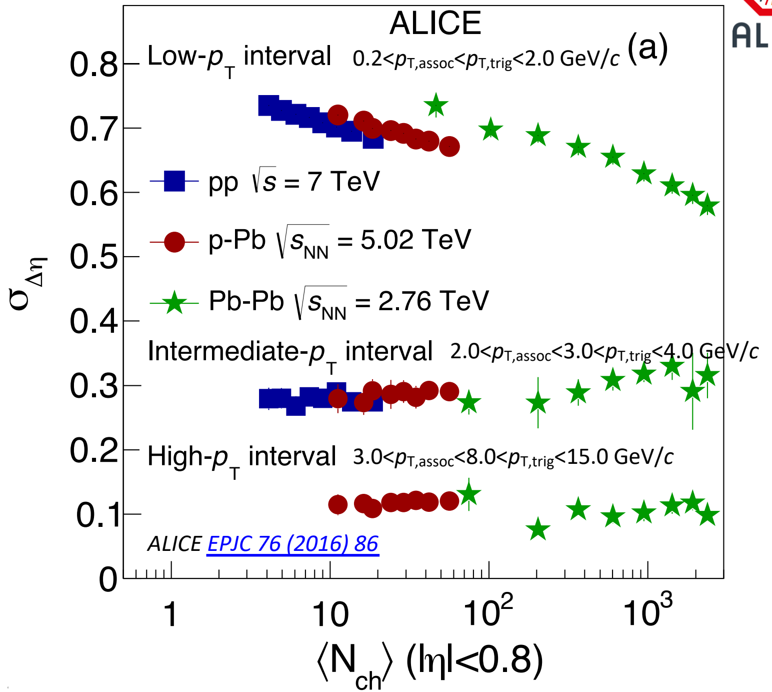


Remove charge independent effects

Keep effects related to balancing pairs

BF of unidentified hadrons: STAR BES I & ALICE





- $B^{hh}(\Delta\eta)$ narrow towards central Au-Au and Pb-Pb collisions
  -> larger radial flow in central leads to smaller $\langle\Delta\eta\rangle$ separation
  -> larger 2nd wave up/down quark production in central -> smaller $\langle\Delta\eta\rangle$
- lower energy (7.7 GeV): narrow towards central collisions -> QGP

➢ **Low p_T:**
- pp, p-Pb: similar widths at overlapping multiplicities -> similar origin in BF
- p-Pb and Pb-Pb: different at overlapping multiplicities -> different origin

➢ **Intermidiate & high p_T:**
- narrower & no multiplicity dependence -> initial hard parton scattering & subsequent fragmentation
- similar values for all multiplicities over all three systems -> similar dynamics

BF of full species matrix $(\pi^{\pm}, K^{\pm}, p/\overline{p})\times(\pi^{\pm}, K^{\pm}, p/\overline{p})$

± — **General conserved charges**:
- **e**: electric charge
- **S**: strangeness
- **B**: baryon number

✔: previous works

✓: *ALICE 2021 arXiv:2110.06566*

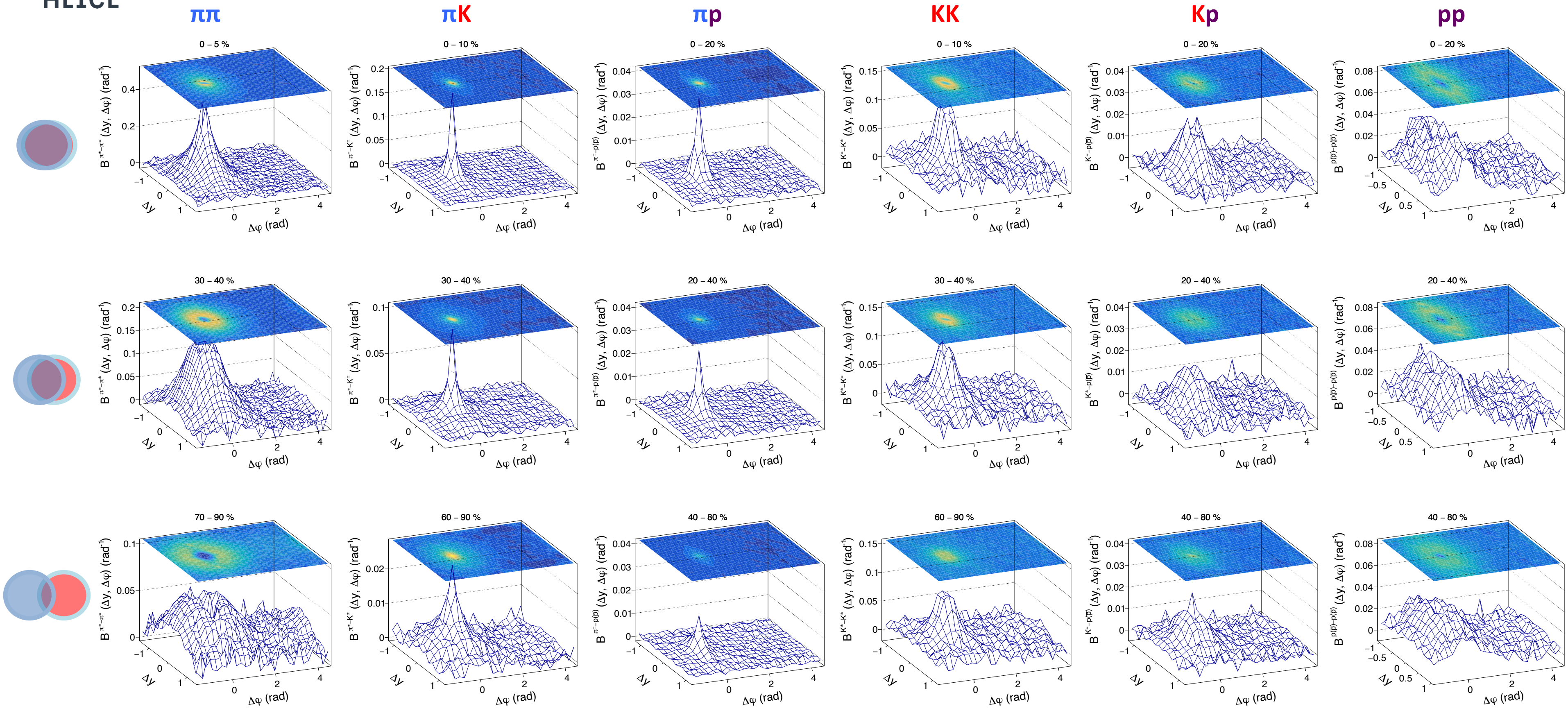
		$B^{\alpha\beta}(\Delta y, \Delta\varphi)$	$h^{\pm}$	$\pi^{\pm}$	$K^{\pm}$	$p/\overline{p}$
e		$h^{\pm}$	✔			
e		$\pi^{\pm}$		✔✓	✓	✓
e	S	$K^{\pm}$		✓	✔✓	✓
e	B	$p/\overline{p}$		✓	✓	✓

1st BF measurement of full species matrix of $(\pi^{\pm}, K^{\pm}, p/\overline{p})\times(\pi^{\pm}, K^{\pm}, p/\overline{p})$.

PID BF – Full Species Matrix

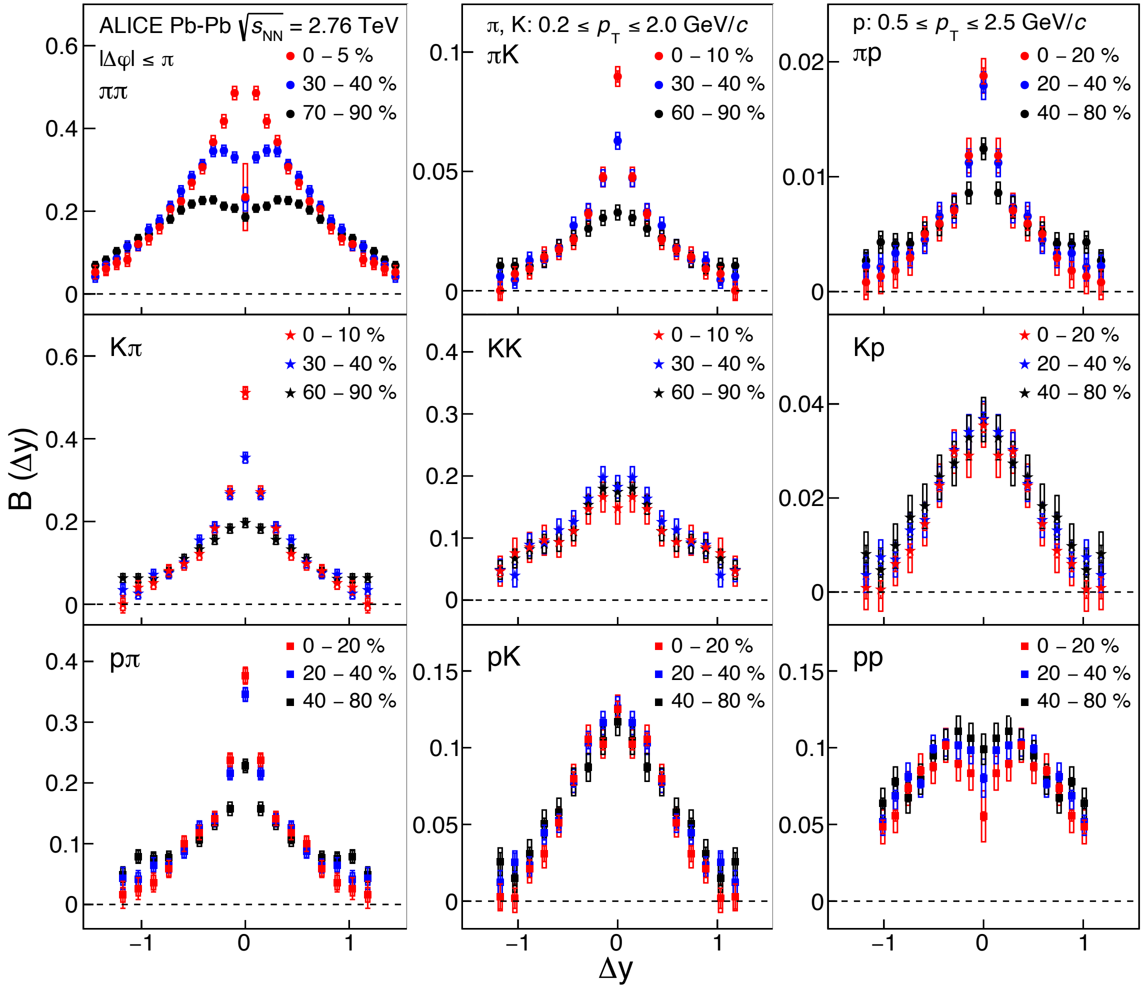
$0.2 \leq p_T^{\pi,K} \leq 2.0\ GeV/c$
$0.5 \leq p_T^{p} \leq 2.5\ GeV/c$

JP PhD dissertation, arXiv:1911.02234
ALICE 2021 arXiv:2110.06566



1D BF Δy Projections

JP PhD dissertation, [arXiv:1911.02234]
ALICE 2021 [arXiv:2110.06566]



Note: different scale

$\pi\pi$: clear centrality dependence
KK: no centrality dependence
-> consistent with radial flow and two wave quark production

BF including π:
Clear centrality dependence

BF including K, p:
no / little centrality dependence

-> different production mechanisms for π, K, p

1D BF Δφ Projections

JP PhD dissertation, arXiv:1911.02234
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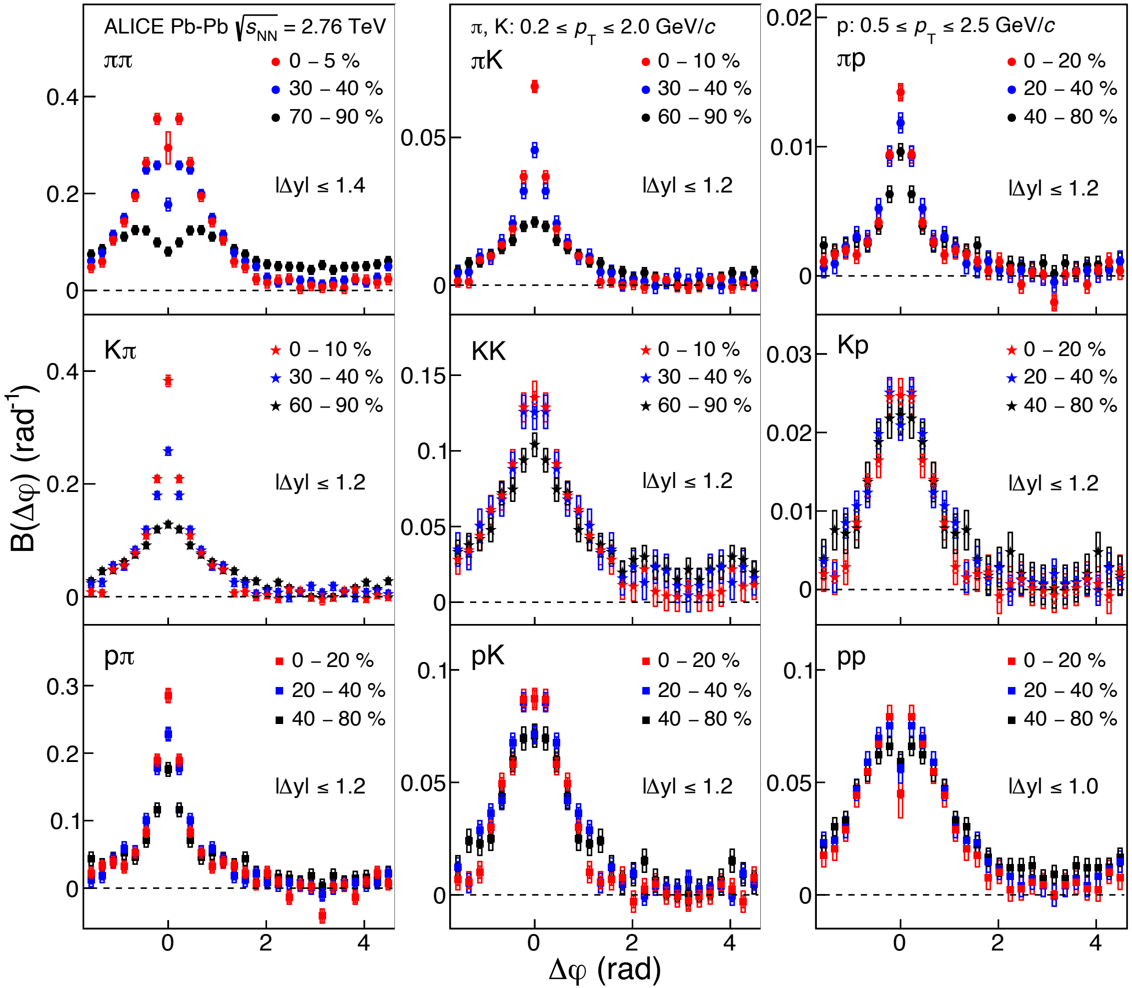

Note: different scale

BF including π:
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BF RMS Widths and Integrals

JP PhD dissertation, arXiv:1911.02234
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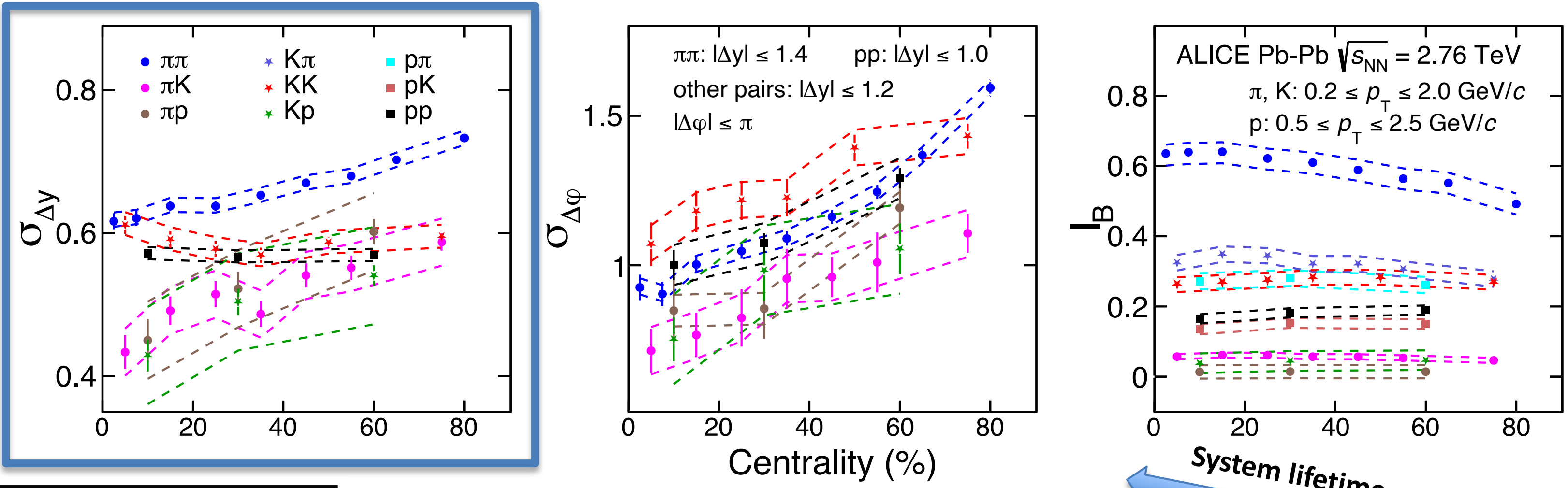
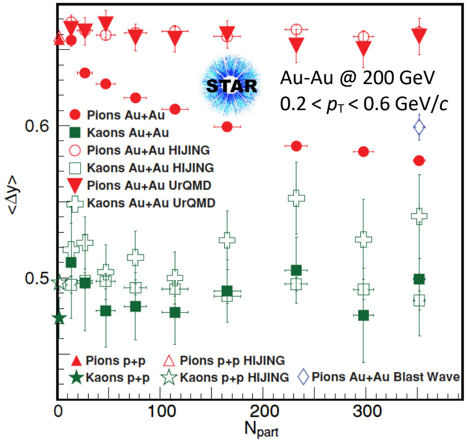
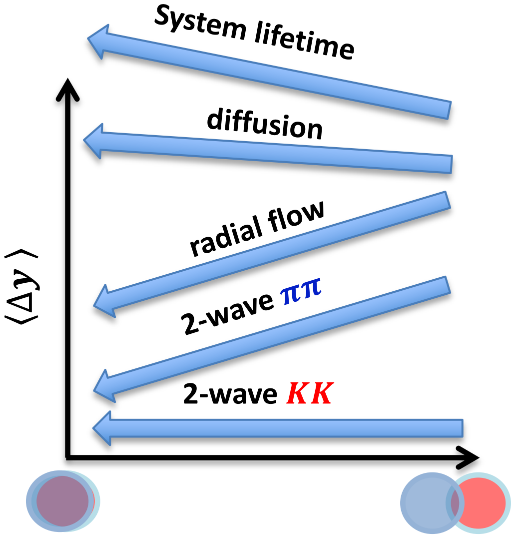




STAR PRC 82, 024905 (2010)

B(Δy) RMS Widths:

- **KK** & **pp** no centrality dependence; **ππ** & cross-species pairs narrow towards central collisions
- Similar values for all cross-species pairs.
- Qualitatively consistent with radial flow & two-wave quark production
  -> detailed modeling required to distinguish them.



BF RMS Widths and Integrals

JP PhD dissertation, arXiv:1911.02234
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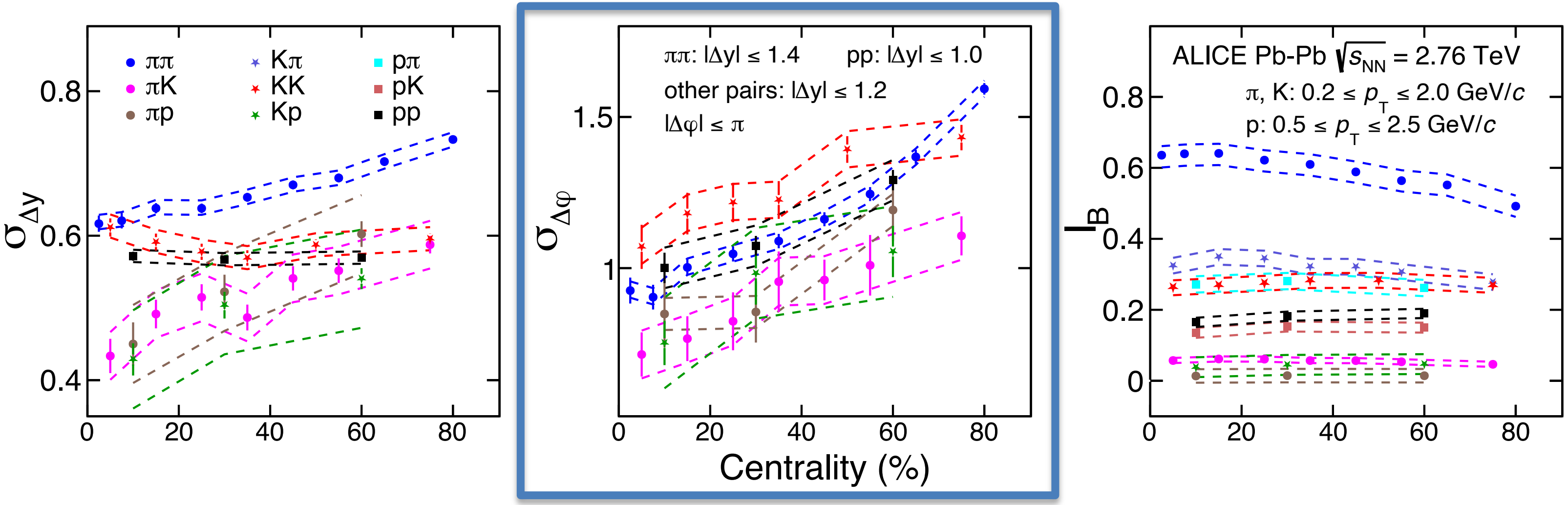
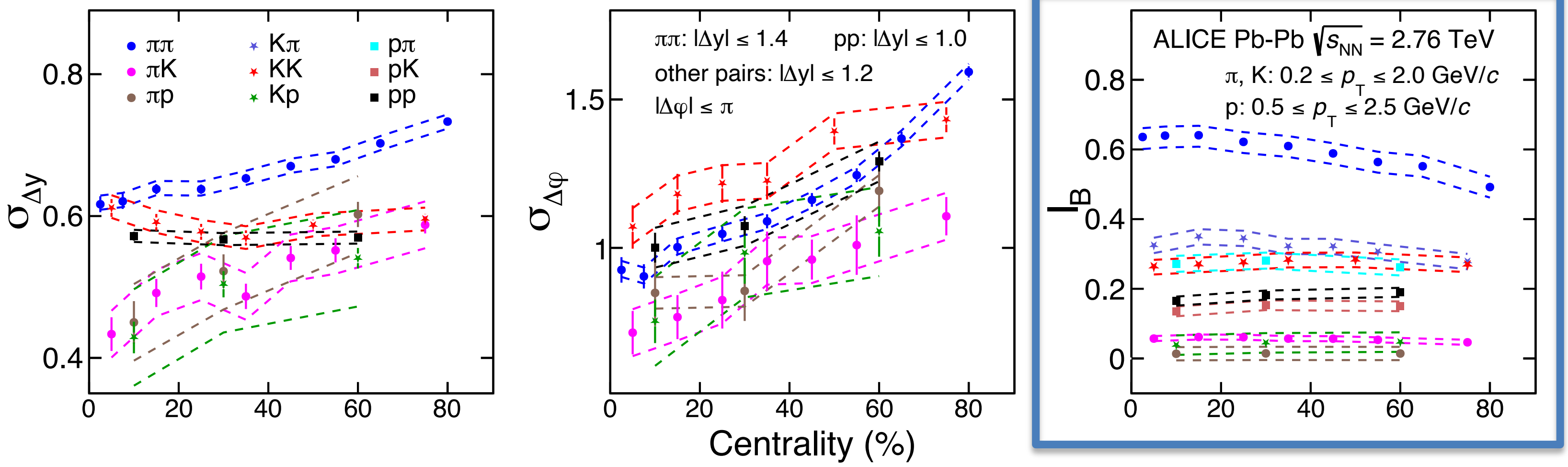


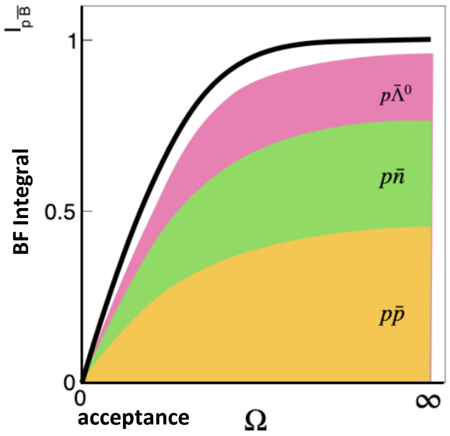
B(Δ*φ*) RMS Widths:

- Different values for different species pairs
  -> radial flow affects pairs of different mass differently.
- Widths for pp is same with $\pi\pi$ due to different Δy range. Other effects?
- All species pairs narrow towards central collision -> qualitatively radial flow > diffusion.
- More detailed information on radial flow profile in context of hadron species pairs.

BF RMS Widths and Integrals

JP PhD dissertation, arXiv:1911.02234
ALICE 2021 arXiv:2110.06566





Balance Function Integrals:

- 1st measurement of hadron species pairing probability.
- Sum of integrals of π trigger, K trigger, p trigger BFs ~0.65.
- Minimal centrality dependence for most pairs, but ππ increasing towards central collisions
  -> B(ππ) losses beyond acceptance more for peripheral than central collisions.

BF RMS Widths and Integrals

JP PhD dissertation, arXiv:1911.02234
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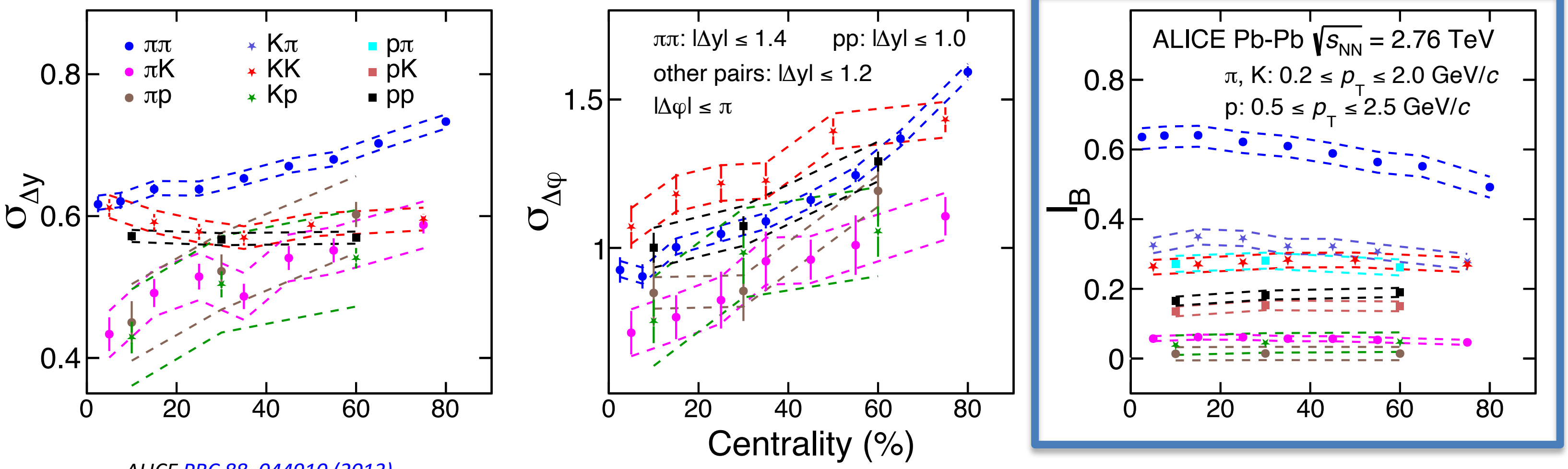
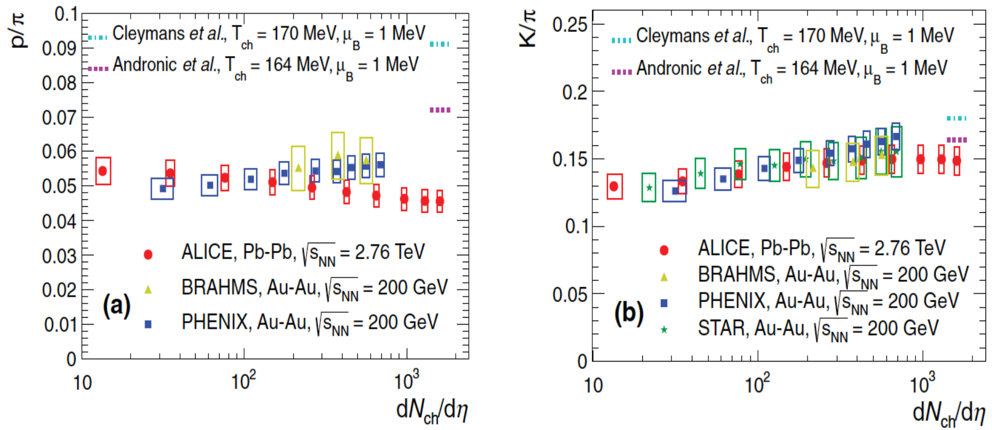


ALICE [PRC 88, 044910 (2013)](PRC 88, 044910 (2013))



Balance Function Integrals:

- 1st measurement of hadron species pairing probability.
- Sum of integrals of **π** trigger, **K** trigger, **p** trigger BFs ~0.65.
- Minimal centrality dependence for most pairs, but ***ππ*** increasing towards central collisions
  -> B(***ππ***) losses beyond acceptance more for peripheral than central collisions.
- Hadron species pairing probabilities very different from single hadron ratios.
  e.g. **Kπ** not larger than **KK** by **π**/**K** ratio; **pp** larger than **pK**.
  -> better constraint for models.

Balance Function experimental outlook

π^+: $u\ \bar{d}$	π^-: $\bar{u}\ d$
K^+: $u\ \bar{s}$	K^-: $\bar{u}\ s$
p: $u\ u\ d$	$\bar{p}$: $\bar{u}\ \bar{u}\ \bar{d}$
Λ^0: $u\ s\ d$	$\overline{\Lambda^0}$: $\bar{u}\ \bar{s}\ \bar{d}$
Ξ^-: $d\ s\ s$	$\overline{\Xi^+}$: $\bar{d}\ \bar{s}\ \bar{s}$

± — **General conserved charges**:
- **e**: electric charge
- **S**: strangeness
- **B**: baryon number

✔: previous works

✓: *ALICE 2021 arXiv:2110.06566*

★: ALICE, STAR work in progress

Charges	$B^{\alpha\beta}(\Delta y, \Delta\varphi)$	$h^\pm$	$\pi^\pm$	$K^{\pm 0}$	$p/\bar{p}$	$\Lambda^0/\overline{\Lambda^0}$	$\Xi^-/\overline{\Xi^+}$
e	$h^\pm$	✔					
e	$\pi^\pm$		✔✓	✓	✓		
e, S	$K^{\pm 0}$		✓	✔✓	✓	★	★
e, B	$p/\bar{p}$		✓	✓	✓	★	★
S, B	$\Lambda^0/\overline{\Lambda^0}$			★	★	★	★
e, S, B	$\Xi^-/\overline{\Xi^+}$			★	★	★	★

uncharted territory →

- **3D $B^{\alpha\beta}(\Delta y, \Delta\varphi, \Delta p_T)$**
- **differential $B^{\alpha\beta}(\Delta p_T)$**
- **$B^{\alpha\beta}$ w.r.t event plane**
- **$B^{\alpha\beta}$ in jets**

Summary & Conclusions

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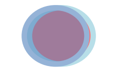
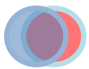
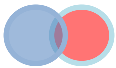
- **Generalized BF (between different particle species) key observable**
  -> understand balancing between quarks
  -> have access to the timing
  -> equivalent to net-baryon C_2 for critical point search

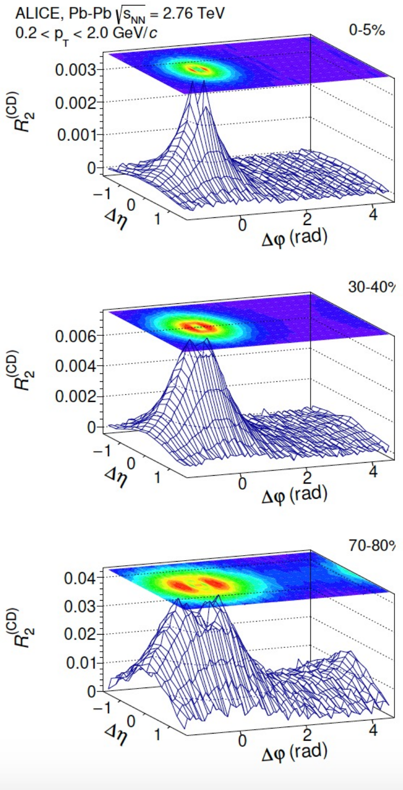
- **GBF (Pb-Pb @ 2.76 TeV) *ALICE 2021* arXiv:2110.06566 :**
  - ***Three 1st*** -> challenge models
    - 1st GBF measurement of full species matrix of $\boldsymbol{\pi^{\pm}}, \boldsymbol{K^{\pm}}, \boldsymbol{p/\bar{p}}$.
    - 1st 2D differential measurement of PID BF.
    - 1st measurement of hadron species pairing probability.
  - ***B(Δy) Widths****:*
    - qualitatively consistent with radial flow and two-wave quark production
      -> a detailed model required to distinguish them.
  - ***B(Δφ) Widths****:*
    - qualitatively radial flow > diffusion.
    - more info on radial flow profile in context of hadron pairs.
  - ***BF Integrals****:*
    - minimal centrality dependence.
    - hadron pairing probabilities different from single hadron ratios.
      -> better constraint for models.

Thanks to DOE for partially funding some of the works shown in this talk.

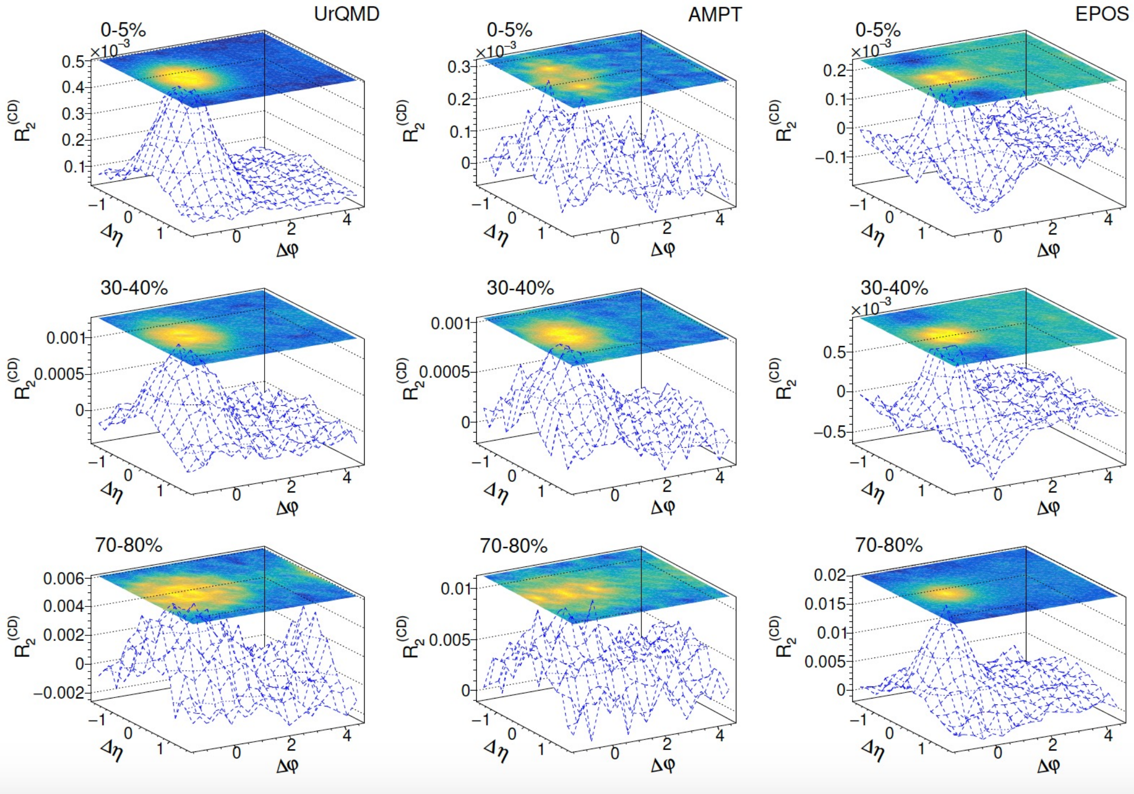
Back-up

$R_2^{(CD)}$ vs. models — unidentified hadrons



PRC 100, 044903 (2019)

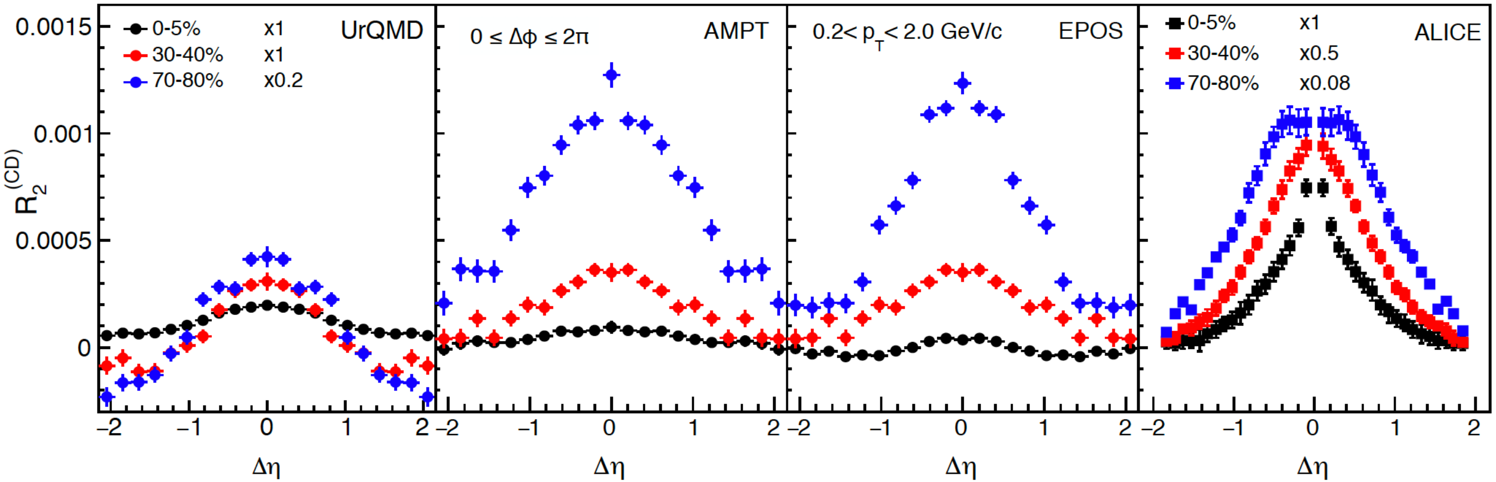


Basu, Gonzalez, JP, et al. [Phys. Rev. C 104, 064902 (2021)]

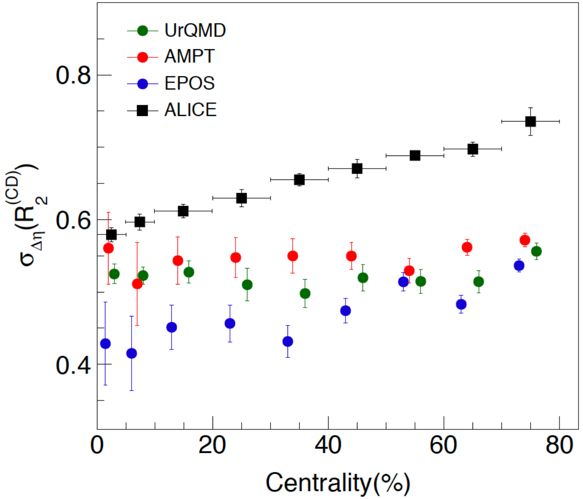
- models qualitatively reproduce near-side peak, but **Not** its amplitude and collision centrality evolution.
- broad dip at $(\Delta y, \Delta\varphi) = (0,0)$ in data due to HBT **Not** reproduced by models -> no HBT afterburner
- models qualitatively reproduce away-side tail in peripheral and its suppression in central collisions -> resonance decays, e.g. ρ^0

$R_2^{(CD)}$ vs. models — unidentified hadrons

ALICE, PRC 100, 044903 (2019)



Basu, Gonzalez, JP, et al. [*Phys. Rev. C 104, 064902 (2021)*]



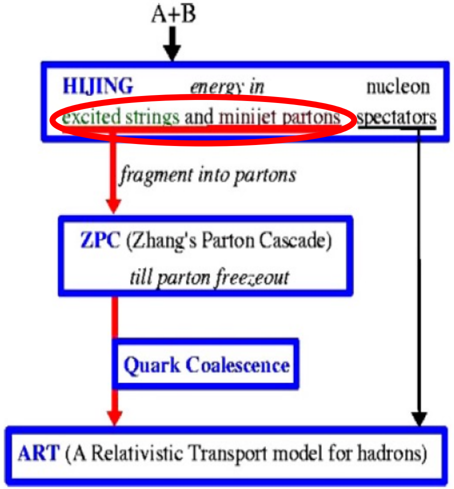
- models **Not** reproduce magnitude and centrality evolution of longitudinal rms
- EPOS: reproduces a narrowing but widths **too narrow** by ~30%
  -> corona particle dominance since **No** event-by-event charge conservation in core
  -> average radial flow imparted to corona ≫ core
- UrQMD: weak amplitude of near-side peak -> insufficient high-mass resonances
- AMPT: weak amplitude of near-side peak -> incomplete handling of charge conservation

Models Used In This Work

STAR

AMPT

Structure of AMPT model with string melting



EPOS 3.0

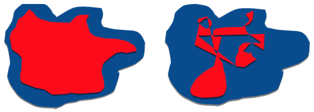
CGC – initial condition

Core – Corona approach

Viscous hydrodynamic expansion

Statistical hadronization (Cooper-Frye)

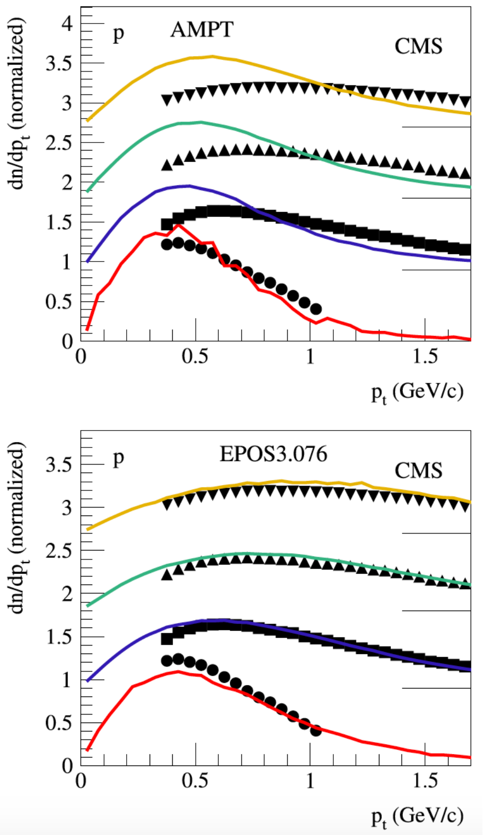
Final state hadronic cascade (UrQMD model)



Event Generation:
A. Knospe, C. Markert

TEXAS
The University of Texas at Austin

Werner et al. NPA 931(2014)83–91



HIJING

- QCD Lund jet fragmentation
- Hard parton scatterings dominate
- Emphasis on mini-jets in pp, pA & AA

UrQMD

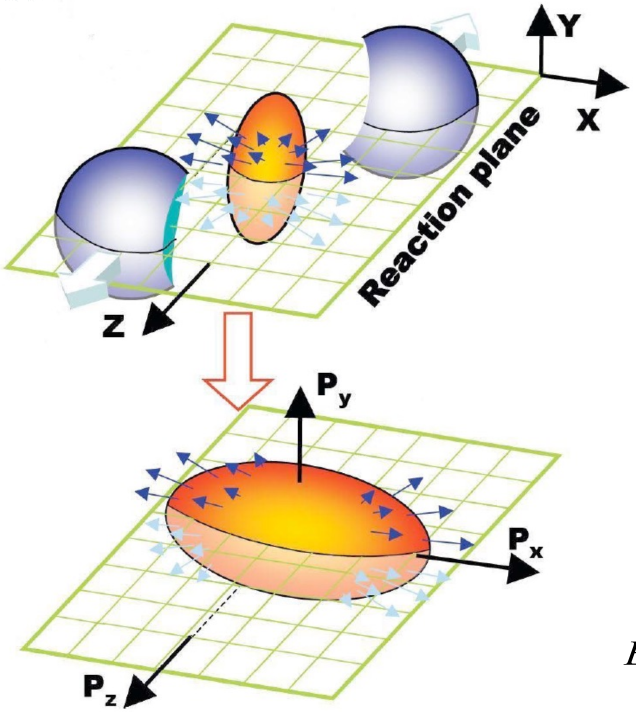
Hadronic relativistic dynamics
Event Generation: W.J. Llope

WAYNE STATE UNIVERSITY

Definition of Anisotropic Flow

- Flow refers to a collective expansion of matter.
- The system follows an anisotropic expansion.
- Anisotropy in the azimuthal particle distribution are studied in terms of the Fourier decomposition.

Voloshin and Zhang. Z.Phys.,C70:665-672,1996.

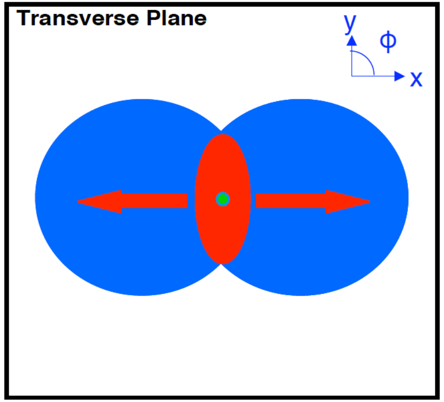


Hiroshi Masui (2008)

Spatial Anisotropy

density gradient -> pressure for anisotropic expansion

Momentum Anisotropy



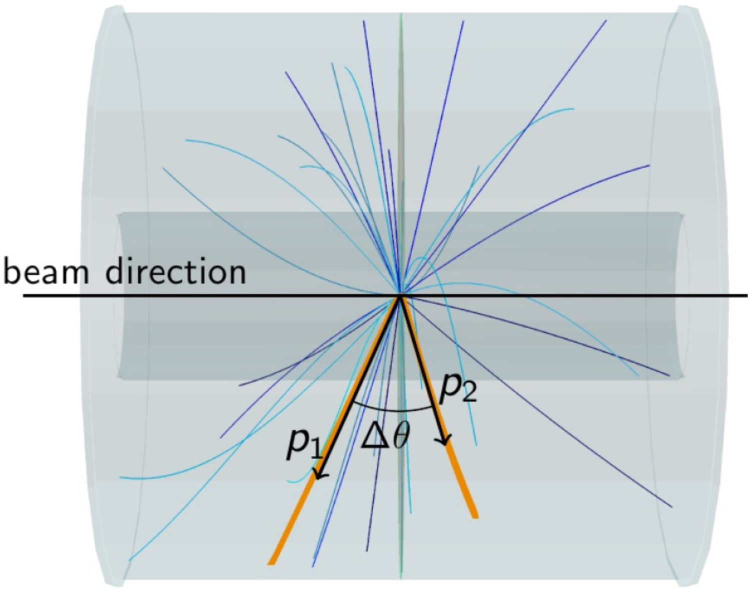
azimuthal angle around the beam axis

$$E\frac{dN^3}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1+2v_1\cos(\phi-\Psi_{RP})+2v_2\cos(2(\phi-\Psi_{RP}))+\ldots)$$

$$v_n=\left\langle\cos\left[n(\phi-\Psi_{RP})\right]\right\rangle$$

directed flow **elliptic flow** **reaction plane**

Momentum Space Variables



Transverse plane

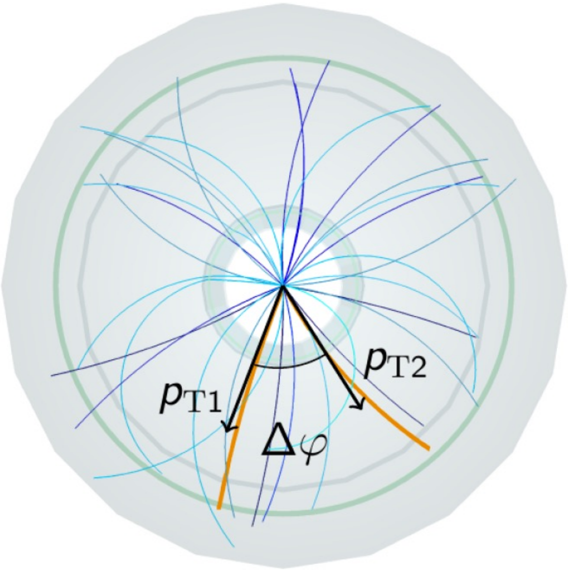


Fig. A. Zaborowska

p — particle momentum

p_T — transverse momentum

φ — azimuthal angle

θ — polar angle

η — pseudorapidity

y — rapidity

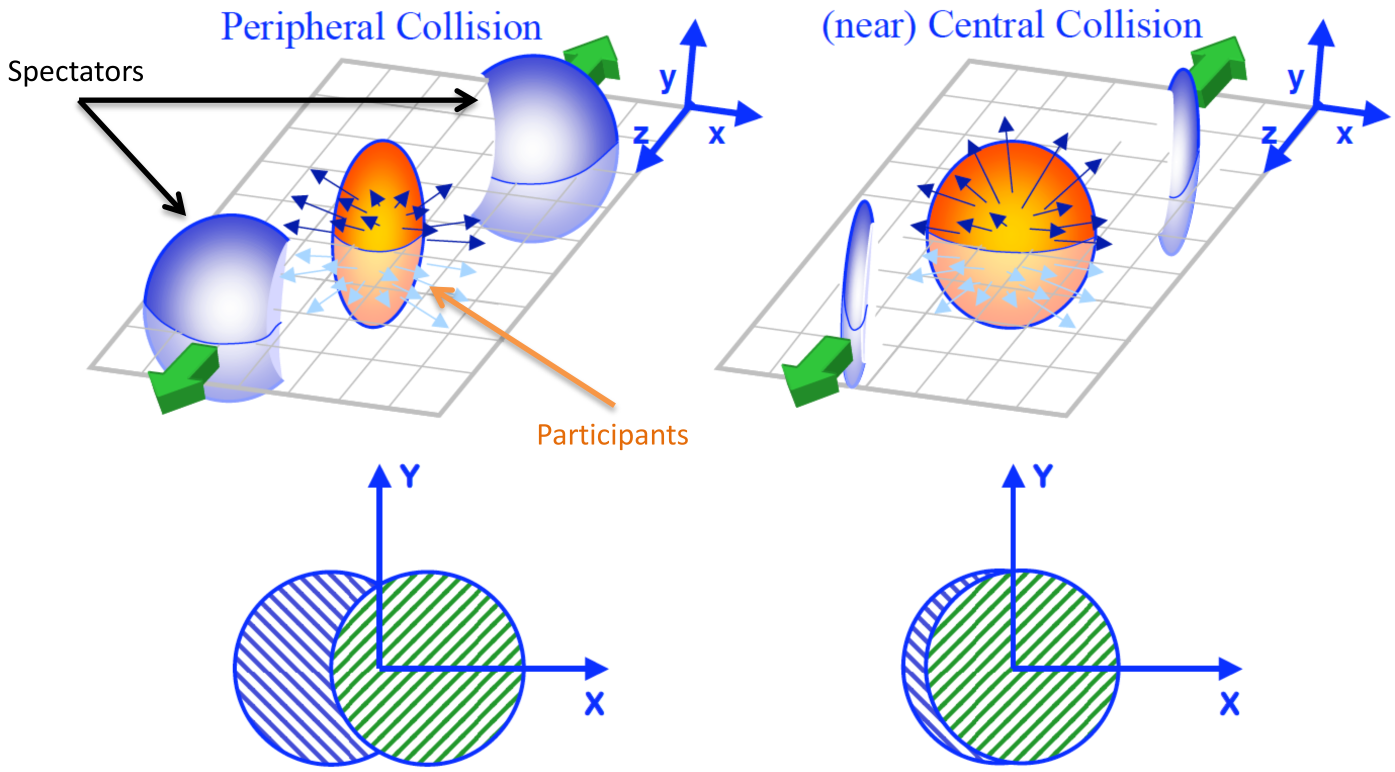
$$p_T^2 = p_x^2 + p_y^2$$

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] = \frac{1}{2}\ln\frac{|p| + p_z}{|p| - p_z}$$

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

Lorentz invariant

Centrality of Relativistic Heavy Ion Collisions

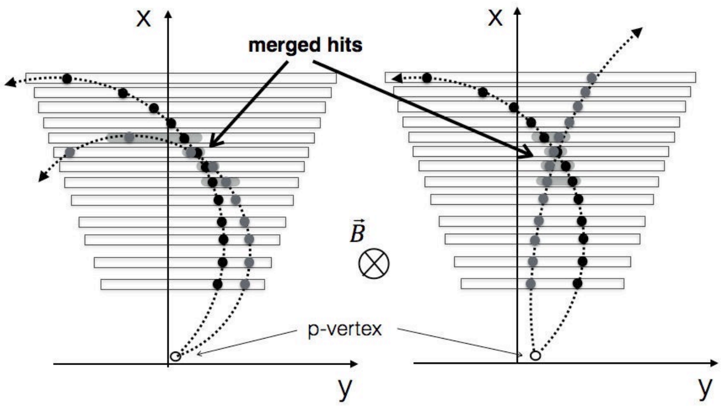


Centrality measured by the multiplicity of charged particles

Track Merging Correction

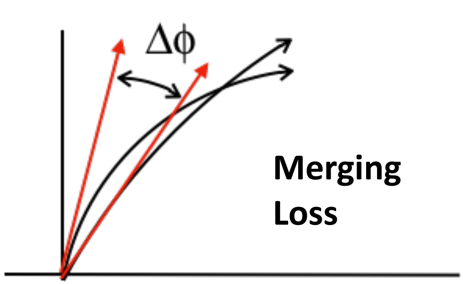
The cause of track merging

tracks with $\Delta y \sim 0$

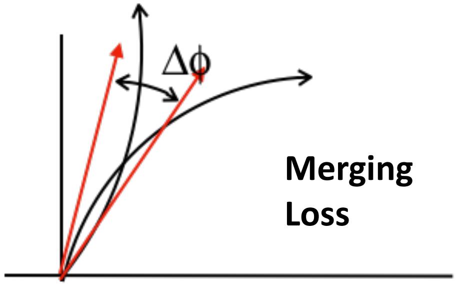


The solution / correction

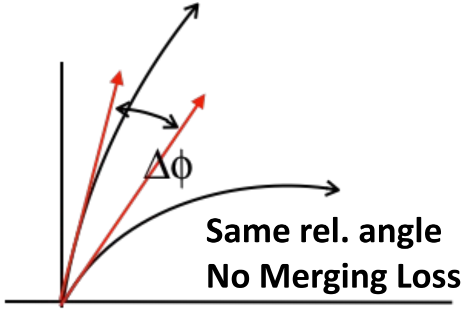
Like-sign: p_T-ordered analysis

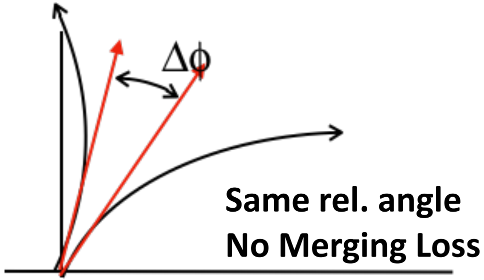


Unlike-sign: charge-ordered analysis



At given $\Delta\phi$, count un-merged pairs and use count at $-\Delta\phi$





Correcting The Collision Centrality Bin Width Effects

Gonzalez, Marin, Guevara, JP, Basu, Pruneau, PRC 99, 034907 (2019)

2-Particle Normalized Cumulant (for multiplicity m)

$$R_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)=\frac{\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)}{\rho_1(\eta_1,\varphi_1\,|\,m)\rho_1(\eta_2,\varphi_2\,|\,m)}-1$$

Weighted Average

$$\rho_1^{(Bin,k)}(\eta_1,\varphi_1)=\bar\rho_1^{(k)}(\eta_1,\varphi_1)=\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)\rho_1(\eta_1,\varphi_1\,|\,m)$$

$$\rho_2^{(Bin,k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)=\bar\rho_2^{(k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)=\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)$$

Uncorrected

$$R_2^{(Bin,k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)=\frac{\rho_2^{(Bin,k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)}{\rho_1^{(Bin,k)}(\eta_1,\varphi_1)\rho_1^{(Bin,k)}(\eta_2,\varphi_2)}-1$$

$$=\frac{\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)}{\left[\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)\rho_1(\eta_1,\varphi_1\,|\,m)\right]\left[\frac{1}{Q_k}\sum_{m'=m_{\min,k}}^{m_{\max,k}}q(m')\rho_1(\eta_2,\varphi_2\,|\,m')\right]}-1$$

Weighted Average

$$\bar R_2^{(k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)=\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)R_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)$$

$$=\left[\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)\frac{\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)}{\rho_1(\eta_1,\varphi_1\,|\,m)\rho_1(\eta_2,\varphi_2\,|\,m)}\right]-1$$

$$\rho_1(\eta,\varphi\,|\,m)=\langle n\rangle_m \mathrm{P}_1(\eta,\varphi\,|\,m)$$
$$\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)=\langle n(n-1)\rangle_m \mathrm{P}_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)$$

P_1, P_2 — Probability Densities

$$R_2^{(Bin,k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)=\alpha\frac{\bar{\mathrm{P}}_2(\eta_1,\varphi_1,\eta_2,\varphi_2)}{\bar{\mathrm{P}}_1(\eta_1,\varphi_1)\bar{\mathrm{P}}_1(\eta_2,\varphi_2)}-1$$

$$\alpha=\frac{\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)\langle n(n-1)\rangle_m}{\left(\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)\langle n\rangle_m\right)^2}$$

$$\bar R_2^{(k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)=\beta\frac{\bar{\mathrm{P}}_2(\eta_1,\varphi_1,\eta_2,\varphi_2)}{\bar{\mathrm{P}}_1(\eta_1,\varphi_1)\bar{\mathrm{P}}_1(\eta_2,\varphi_2)}-1$$

$$\beta=\frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}}q(m)\frac{\langle n(n-1)\rangle_m}{\langle n\rangle_m^2}$$

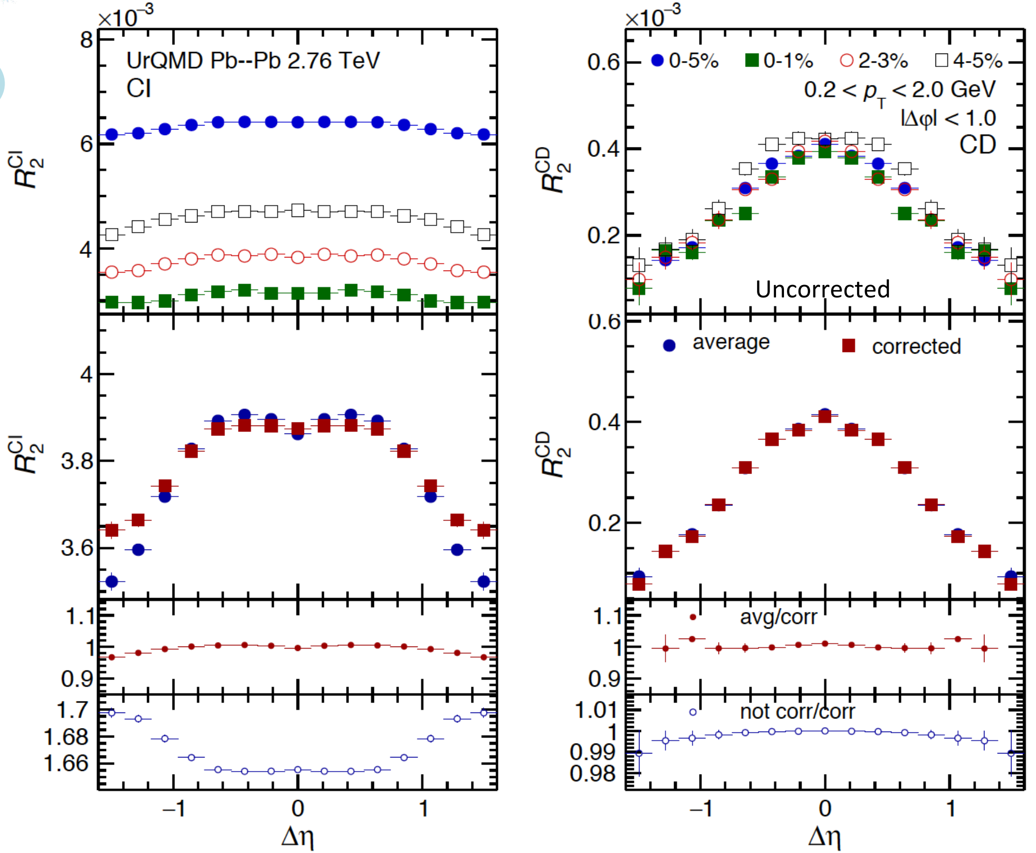
Correction

$$\bar R_2^{(k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)=\beta\alpha^{-1}(R_2^{(Bin,k)}(\eta_1,\varphi_1,\eta_2,\varphi_2)+1)-1$$

Correcting The Collision Centrality Bin Width Effects

UrQMD (100k events) — Unidentified Hadrons

Gonzalez, Marin, Guevara, JP, Basu, Pruneau, PRC 99, 034907 (2019)



$$R_2^{CI} = \frac{1}{4}\left[R_2^{+-} + R_2^{++} + R_2^{-+} + R_2^{--}\right]$$

$$R_2^{CD} = \frac{1}{4}\left[R_2^{+-} - R_2^{++} + R_2^{-+} - R_2^{--}\right]$$

- Results corrected agree with those obtained with the weighted mean within 1% for both R_2^{CI} and R_2^{CD}.
- The correction enables reasonably accurate corrections of the R_2 correlators in the context of HIJING and UrQMD models.
- Given these models provide relatively realistic representations of single and pair particle spectra, the correction method should provide reasonably reliable bin-width corrections of R2 correlation functions measured at any heavy ion collider.