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

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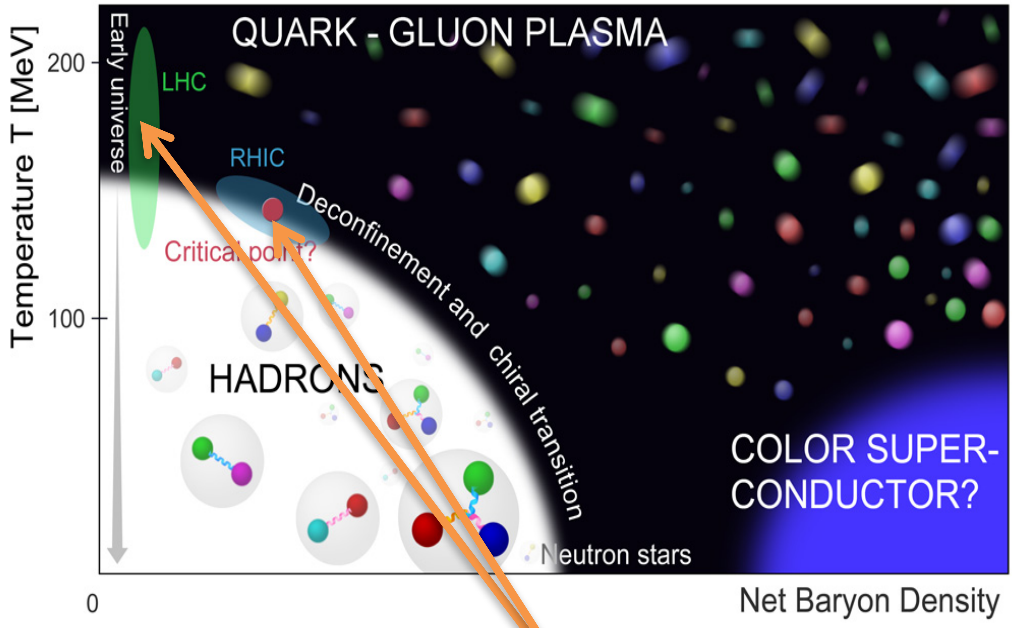
BNL Nuclear Physics Seminar| 02/25/2020

# Just off shift from STAR control room this morning

**Status of STAR:**

- *2 days ago we successfully reached the goal of 11.5 GeV Au-Au (230M good MB events) data taking during my shift*
- *right now STAR is taking 9.2 GeV Au-Au data*

# Why carry out relativistic heavy ion collisions?




***Discovery of QGP:***
***RHIC 2005 Au-Au***
***LHC 2010 Pb-Pb***

**Quark Gluon Plasma (QGP)**

- *hot and dense QCD matter*
- *strongly coupled perfect liquid*
- *deconfined quarks*
- *early universe*

**Open questions:**

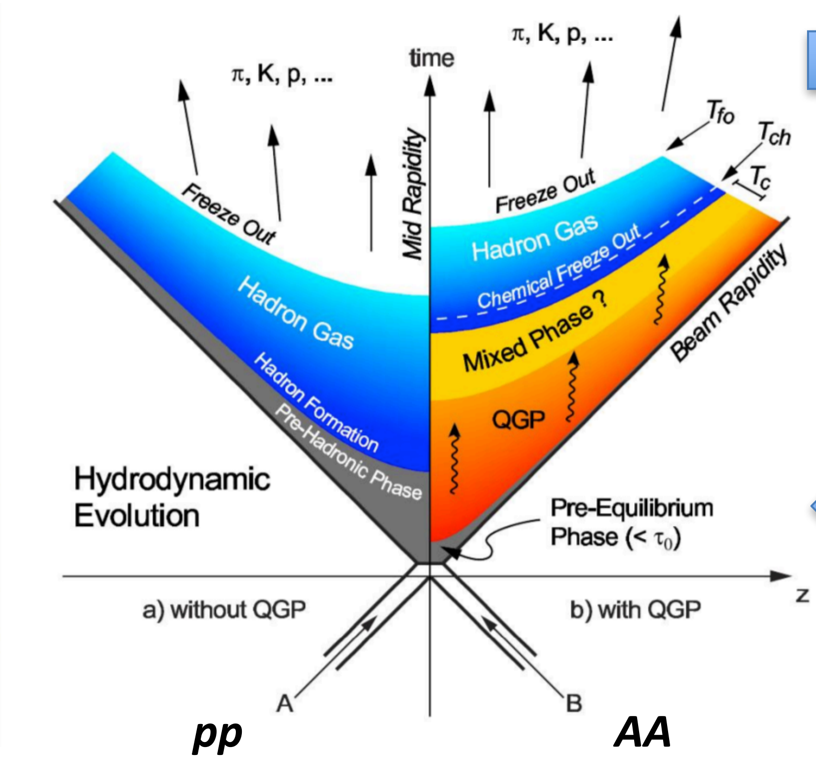
- *QCD phase diagram*
- *critical point*
- *light and strange quark production time*
- *hadronization*
- *transport*

…

# Balance Function – distribution of balancing charges

$B(\vec{p}_1, \vec{p}_1)$

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

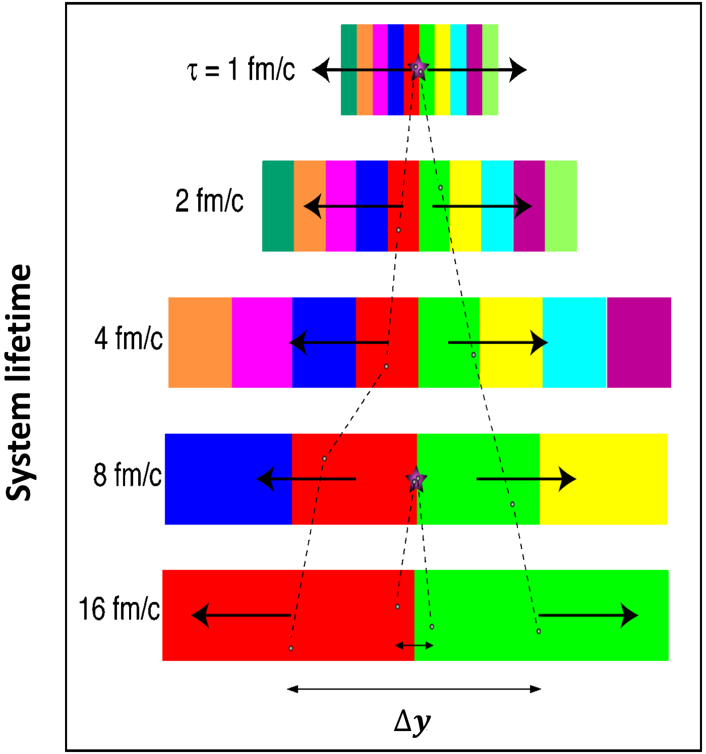



*measure BF of final state identified hadron pairs*

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

*learn about light and strange quark production time*

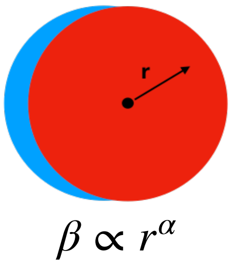
# Balancing charge separation in $\Delta y$




**Balancing charge separation**

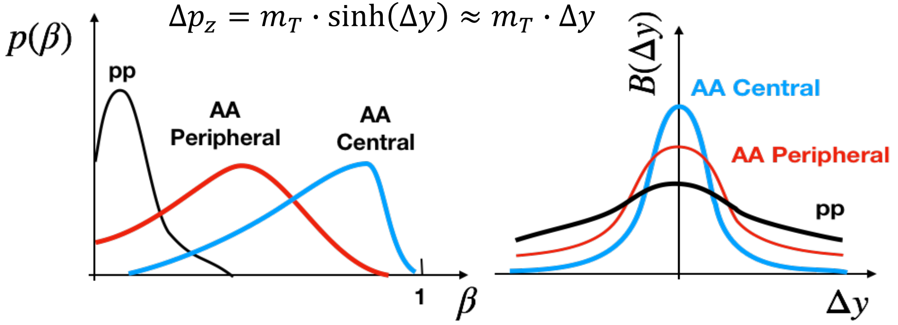
*Bass, Danielewicz, Pratt PRL 85, 2689 (2000)*

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

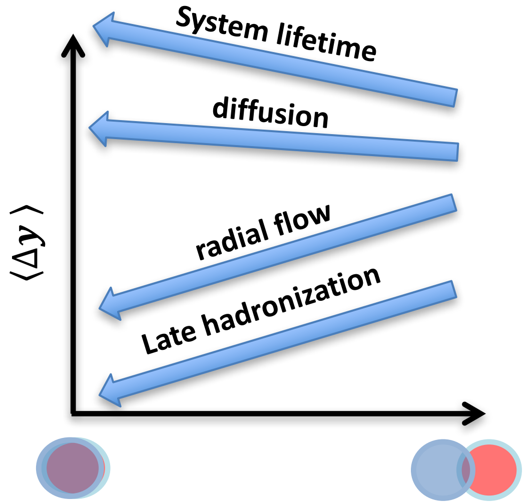



*Voloshin PLB 632 (2006) 490-494*

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




Larger radial flow towards central collisions leads to smaller separation of balancing pairs in $\Delta y$

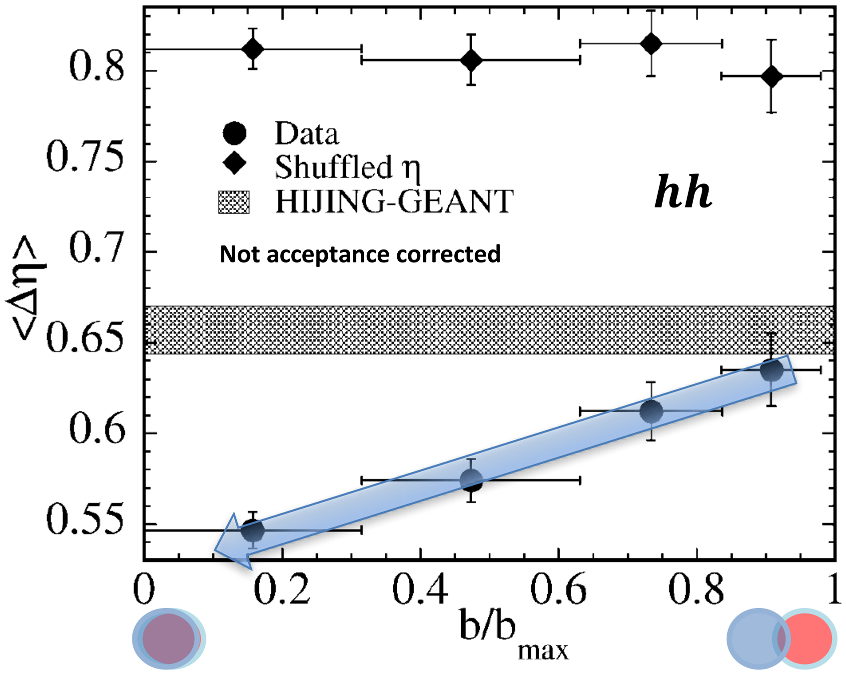


# BF of unidentified hadron pairs $hh$ and $\pi\pi$

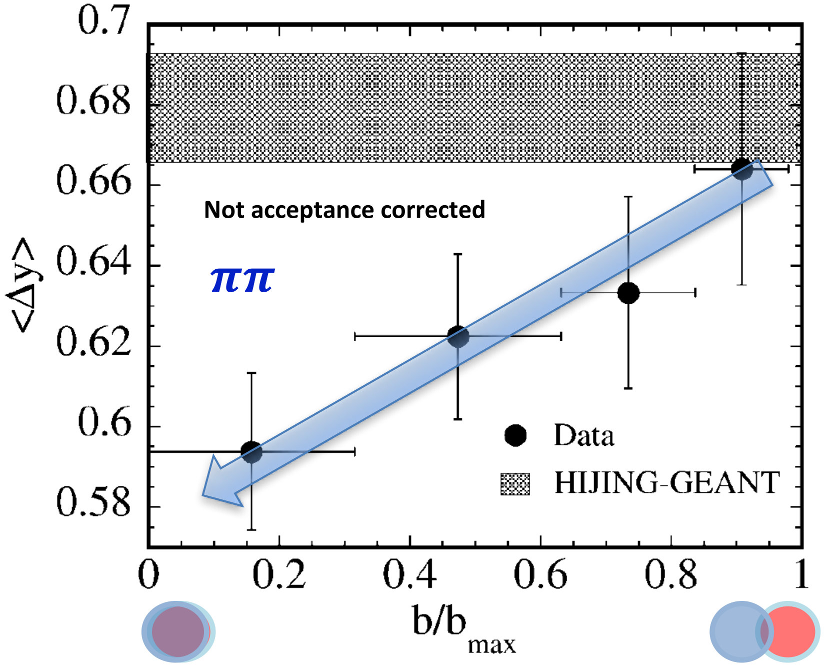
*PRL 90, 172301 (2003)*

**Au-Au @ 130 GeV**

$0.1 < p < 2.0\ GeV/c$




$0.1 < p_T, p < 0.7\ GeV/c$

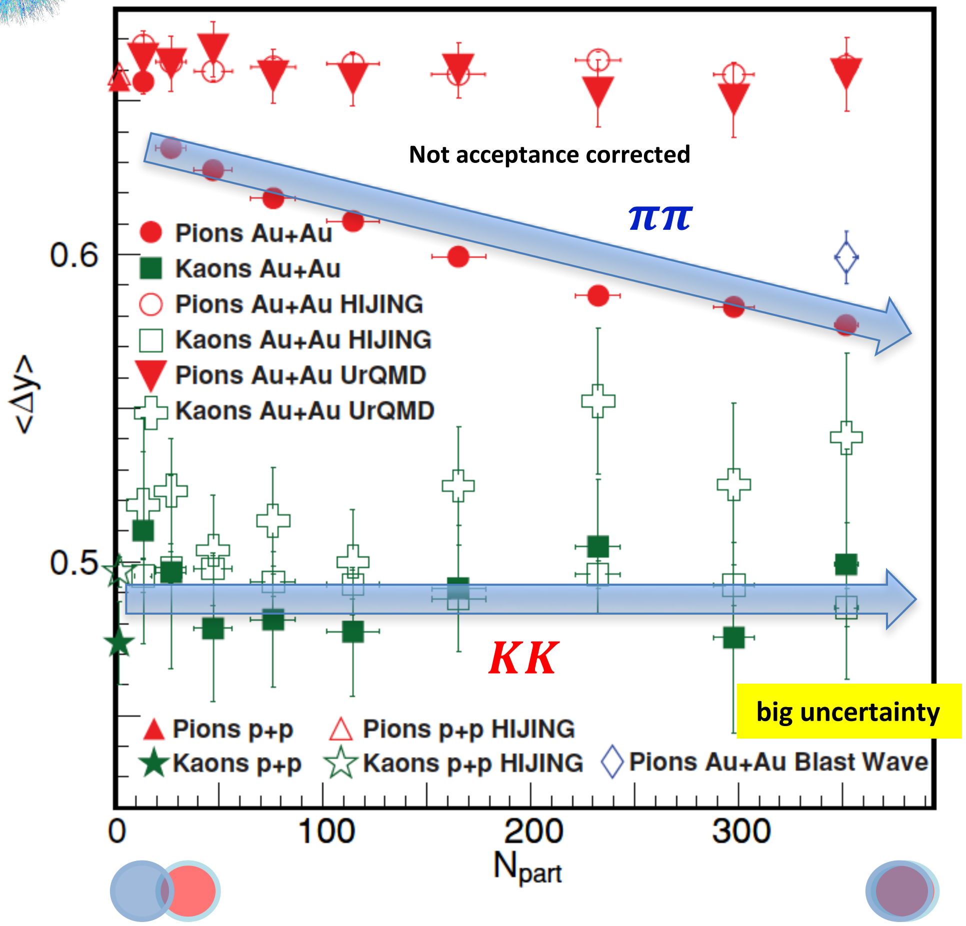



Narrowing of $\boldsymbol{B^{hh}}$ and $\boldsymbol{B^{\pi\pi}}$ towards central Au-Au collisions

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

-> later hadronization towards central collisions leads to narrower BF

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




**Au-Au @ 200 GeV**

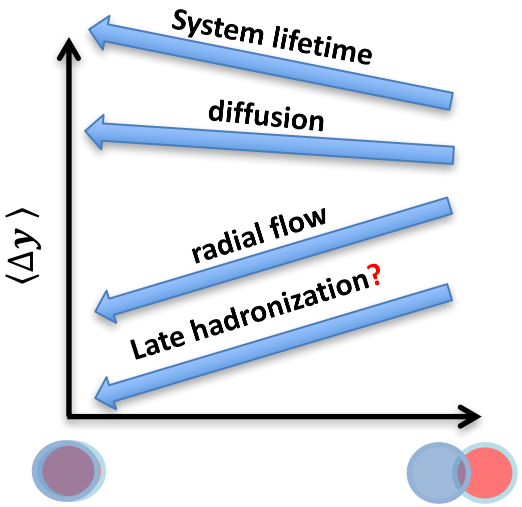
*PRC 82, 024905 (2010)*

$0.2 < p_T < 0.6\ GeV/c$

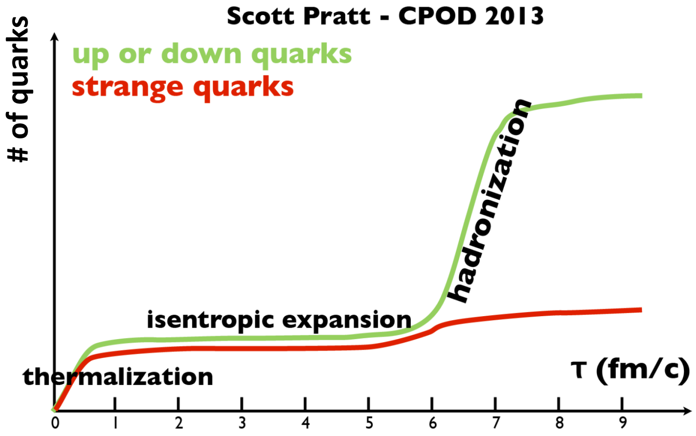
$B^{\pi\pi}(\Delta y)$ narrow towards central collisions, while $B^{KK}(\Delta y)$ no centrality dependence.

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

-> no late hadronization for $KK$?

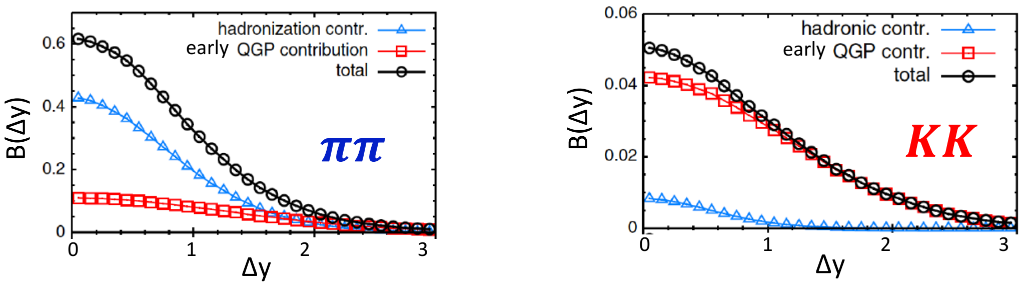


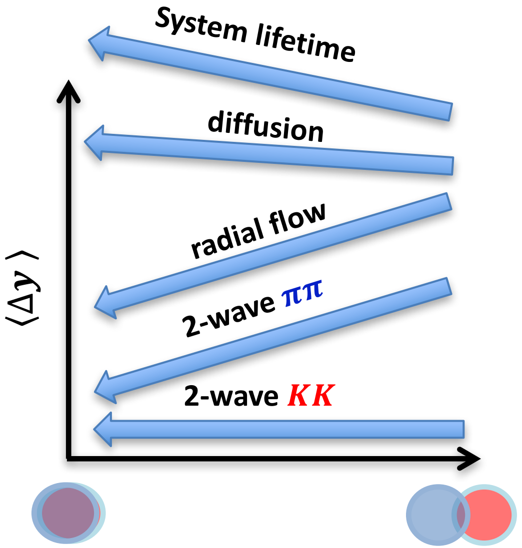
# Two-wave Quark Production




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

Pratt PRL. 108, 212301 (2012)



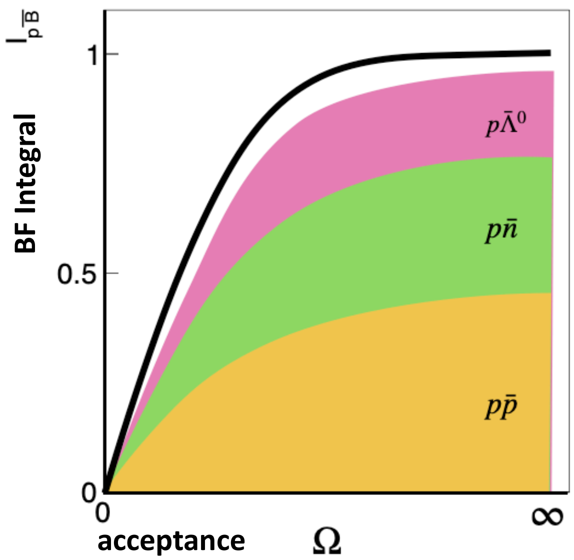



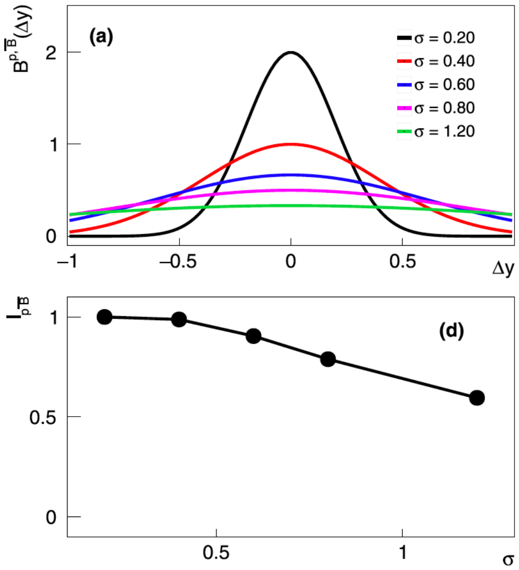

$\pi\pi$: larger 2nd wave up/down quark production -> smaller $\langle \Delta y \rangle$ -> narrow towards central collisions
$KK$: dominant 1st wave strange quark production -> same $\langle \Delta y \rangle$ -> no centrality dependence

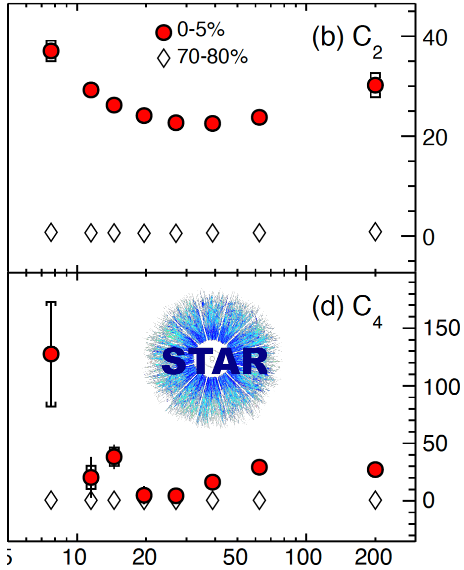
# Baryon number BF & Net-baryon fluctuation

*Pruneau, PRC 100, 034905 (2019)*

*STAR, arXiv:2001.02852*
*submitted to Nature Physics*




**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 $\langle N_p \rangle = \langle N_{\bar{p}} \rangle$

***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 $\boldsymbol{\Xi}$ ...
$\alpha$ – *reference particle*
$\beta$ – *associate particle*
$\rho_1, \rho_2$ – *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**

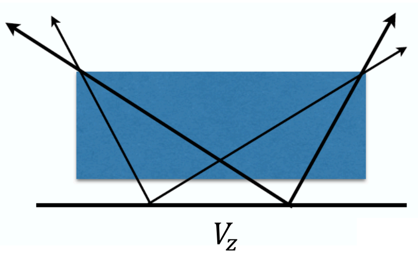
assuming efficiency factorizes
$\varepsilon_2^\alpha(\vec{p}^\alpha, \vec{p}^\beta) \approx \varepsilon_1^\alpha(\vec{p}^\alpha) \cdot \varepsilon_1^\beta(\vec{p}^\beta)$

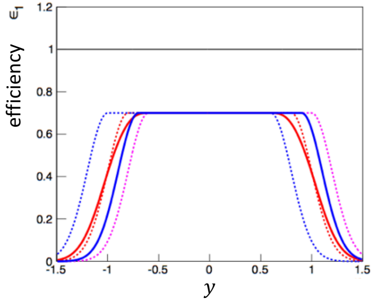
**Normalized 2-Particle Cumulant**

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

**Efficiencies cancel in the ratio -> robust observable**

**Acceptance correction**




*Ravan et al., PRC 89, 024906 (2014)*

weight: $w_\pm(y, \varphi, V_z, p_T) = \frac{\rho^\pm_{avg}(p_T)}{\rho^\pm(y,\varphi,V_z,p_T)}$

small $V_z$ bins

# 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**

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

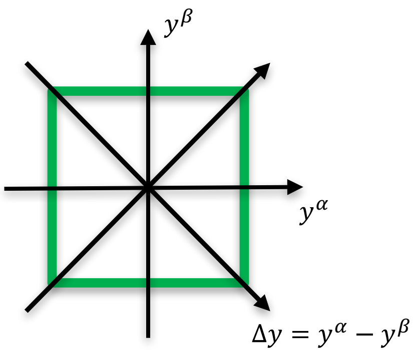
$$= \frac{1}{2}\left[\rho_1^{\beta^-}(\vec{p}^{\beta}) \cdot \boxed{R_2^{\alpha^+\beta^-}(\vec{p}^{\alpha},\vec{p}^{\beta})} - \rho_1^{\beta^+}(\vec{p}^{\beta}) \cdot \boxed{R_2^{\alpha^+\beta^+}(\vec{p}^{\alpha},\vec{p}^{\beta})} + \rho_1^{\beta^+}(\vec{p}^{\beta}) \cdot \boxed{R_2^{\alpha^-\beta^+}(\vec{p}^{\alpha},\vec{p}^{\beta})}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

# Balance Function Measurement

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

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

- 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

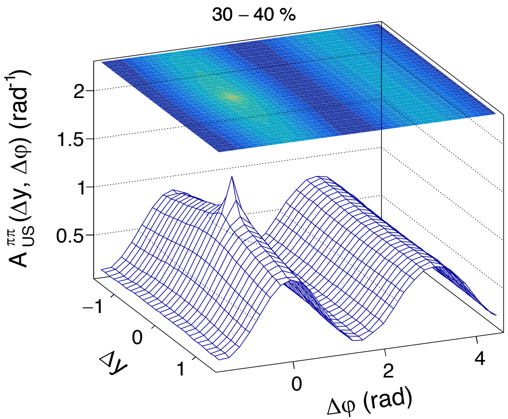



$$\boldsymbol{B^{\alpha\beta}(\Delta y,\Delta\varphi) = \int B^{\alpha\beta}(y^\alpha,\varphi^\alpha,y^\beta,\varphi^\beta)dy^\beta d\varphi^\beta}$$

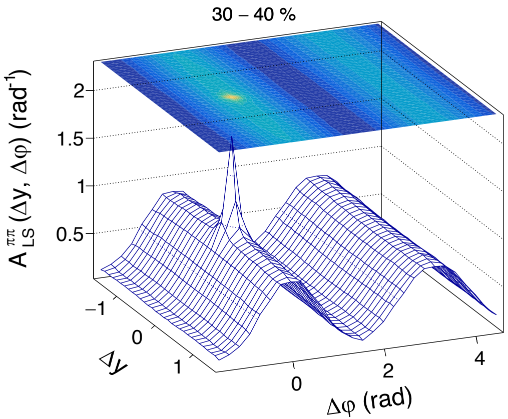
average over $y^\beta$

# BF measures charge-dependent (CD) correlations

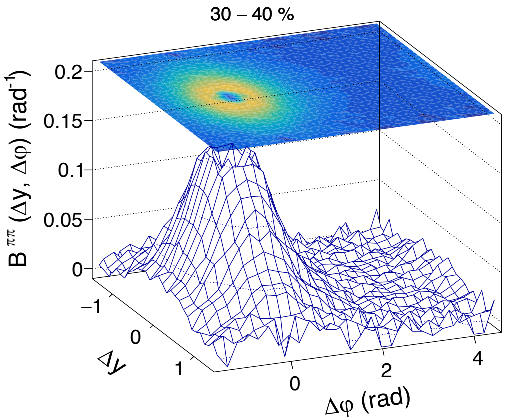
$$A_{US}^{\alpha\beta} = \frac{1}{2}\left(A^{\alpha^+\beta^-} + A^{\alpha^-\beta^+}\right)$$




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



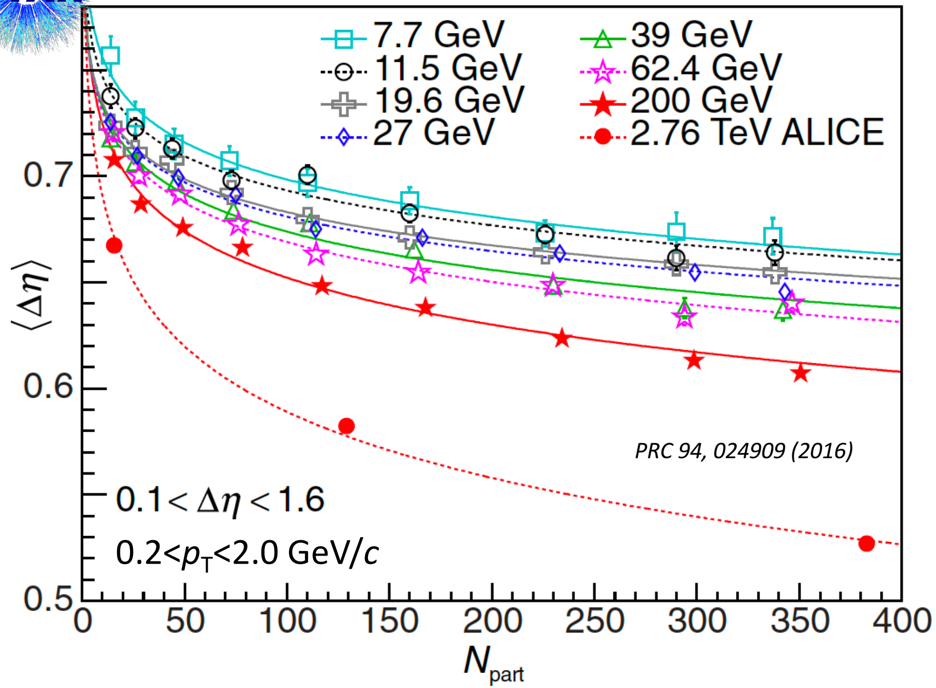

$$B^{\alpha\beta}(\Delta y, \Delta\varphi) = A_{CD}^{\alpha\beta} = A_{US}^{\alpha\beta} - A_{LS}^{\alpha\beta}$$

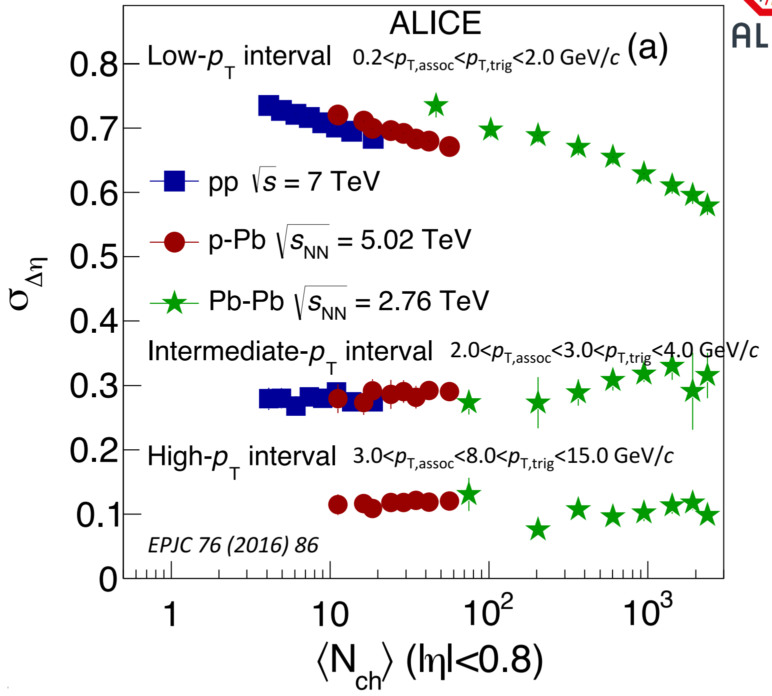



**Remove charge independent effects**

**Keep effects related to balancing pairs**

# BF of unidentified hadrons: STAR BES I & ALICE



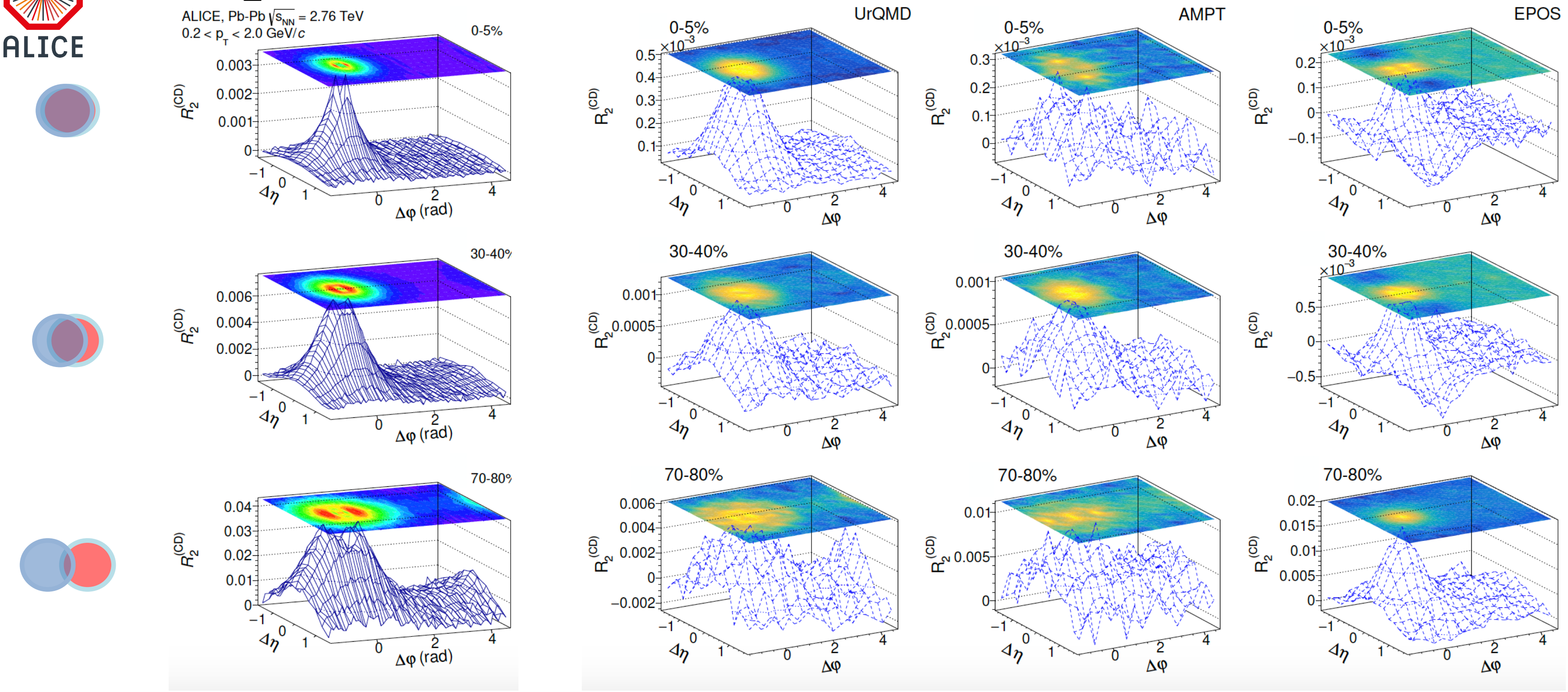




- $B^{hh}(\Delta\eta)$ narrow towards central Au-Au and Pb-Pb collisions
  -> larger radial flow in central leads to smaller $\langle\Delta\eta\rangle$ separation
  -> larger 2nd wave up/down quark production in central -> smaller $\langle\Delta\eta\rangle$
- lower energy (7.7 GeV): narrow towards central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

➢ **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

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



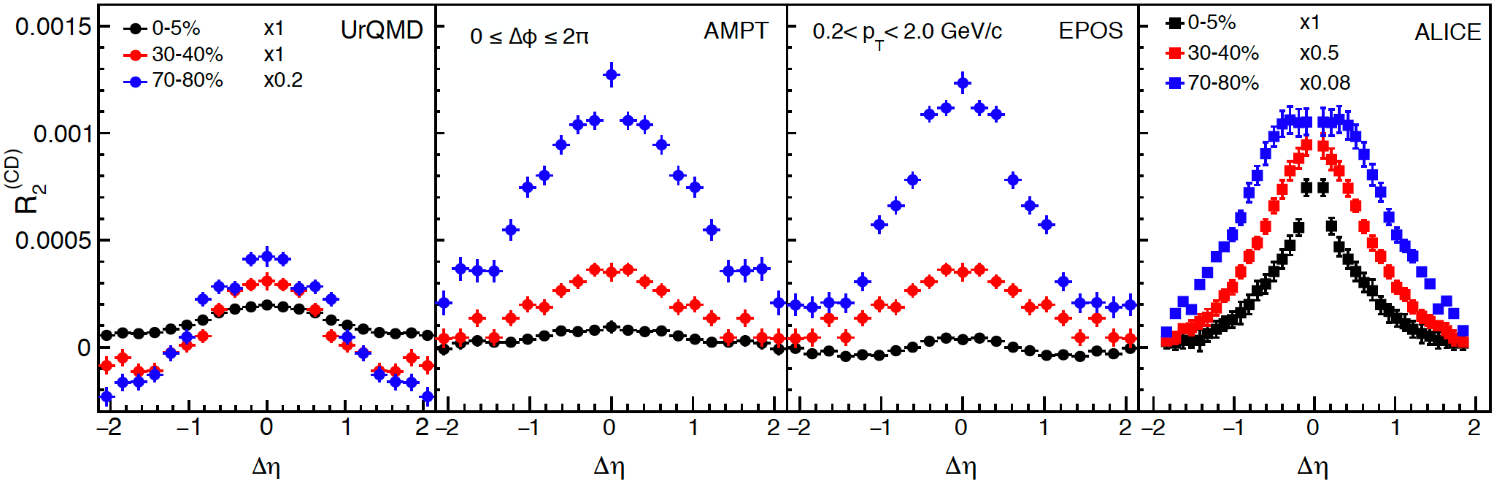

*PRC 100, 044903 (2019)*

*Basu, Gonzalez, JP, et al. arXiv:2001.07167, Submitted to PRC*

- 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. $\rho^0$

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

*ALICE, PRC 100, 044903 (2019)*

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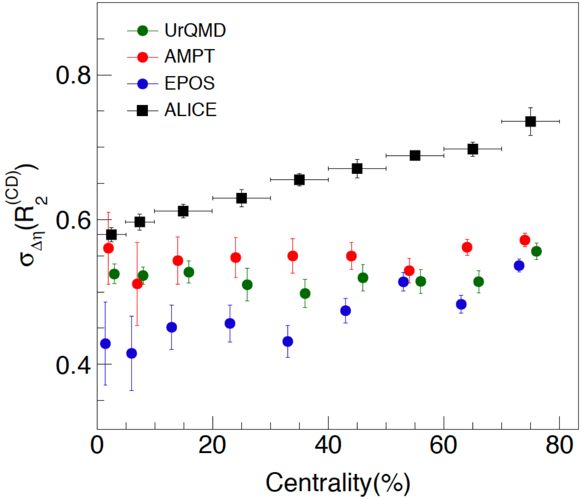



- models **Not** reproduce magnitude and centrality evolution of longitudinal rms
- EPOS: reproduces a narrowing but widths **too narrow** by ~30%
  -> corona particle dominance since **No** event-by-event charge conservation in core
  -> average radial flow imparted to corona ≫ core
- UrQMD: weak amplitude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

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

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

✔: previous works
✔: JP PhD dissertation 2019 (ALICE)

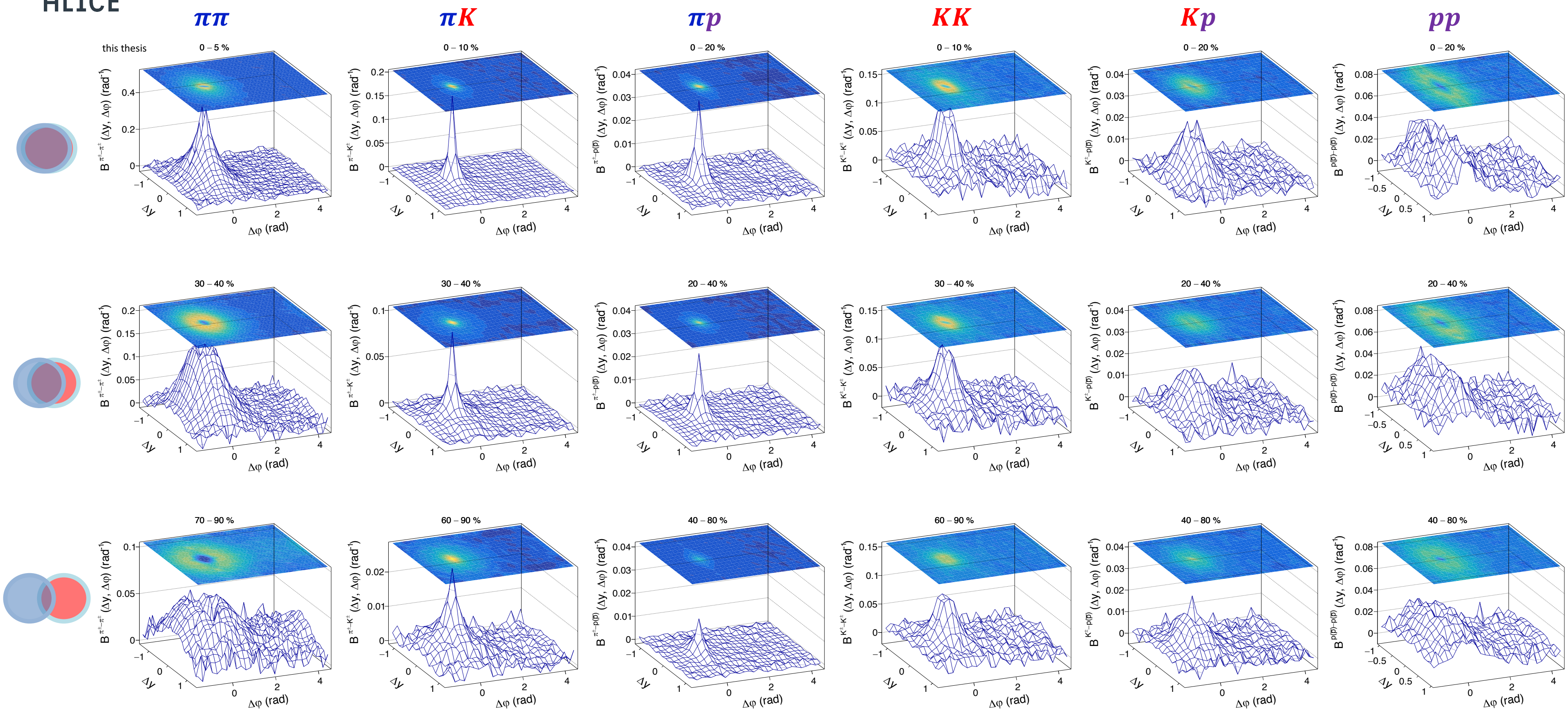
| | $B^{\alpha\beta}(\Delta y, \Delta\varphi)$ | $h^{\pm}$ | $\pi^{\pm}$ | $K^{\pm}$ | $p/\bar{p}$ |
|---|---|---|---|---|---|
| e | $h^{\pm}$ | ✔ | | | |
| e | $\pi^{\pm}$ | | ✔✔ | ✔ | ✔ |
| e S | $K^{\pm}$ | | ✔ | ✔✔ | ✔ |
| e B | $p/\bar{p}$ | | ✔ | ✔ | ✔ |

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

# 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*
*JP (for ALICE), NPA 982 (2019) 315–318*
*JP et al. (ALICE), PRL + PRC In Preparation*



# 1D BF Δy Projections

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

*JP PhD dissertation, arXiv:1911.02234*
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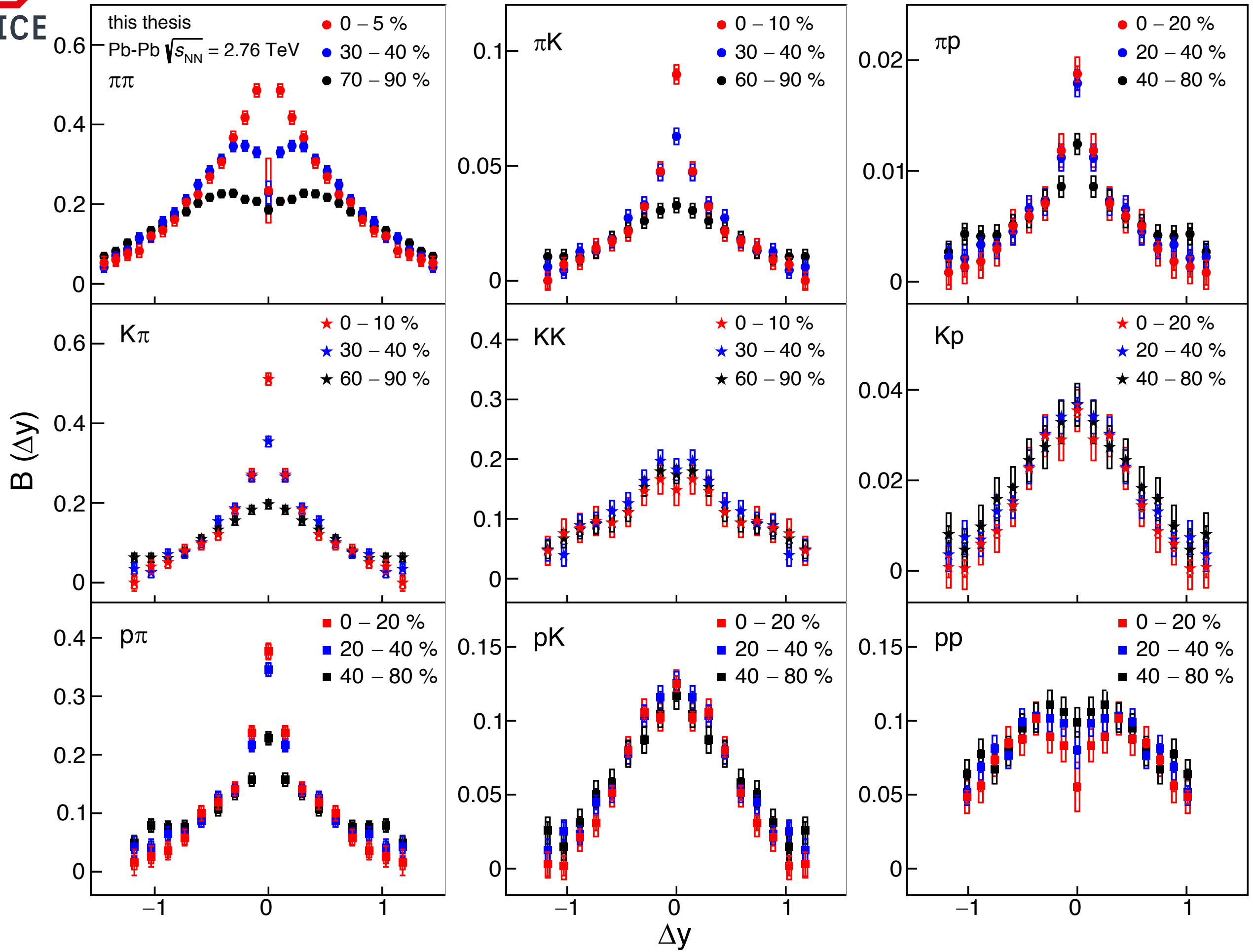


|Δφ|<π

**Note different scale**

***ππ***: 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 $\Delta\varphi$ Projections

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

*JP PhD dissertation, arXiv:1911.02234*
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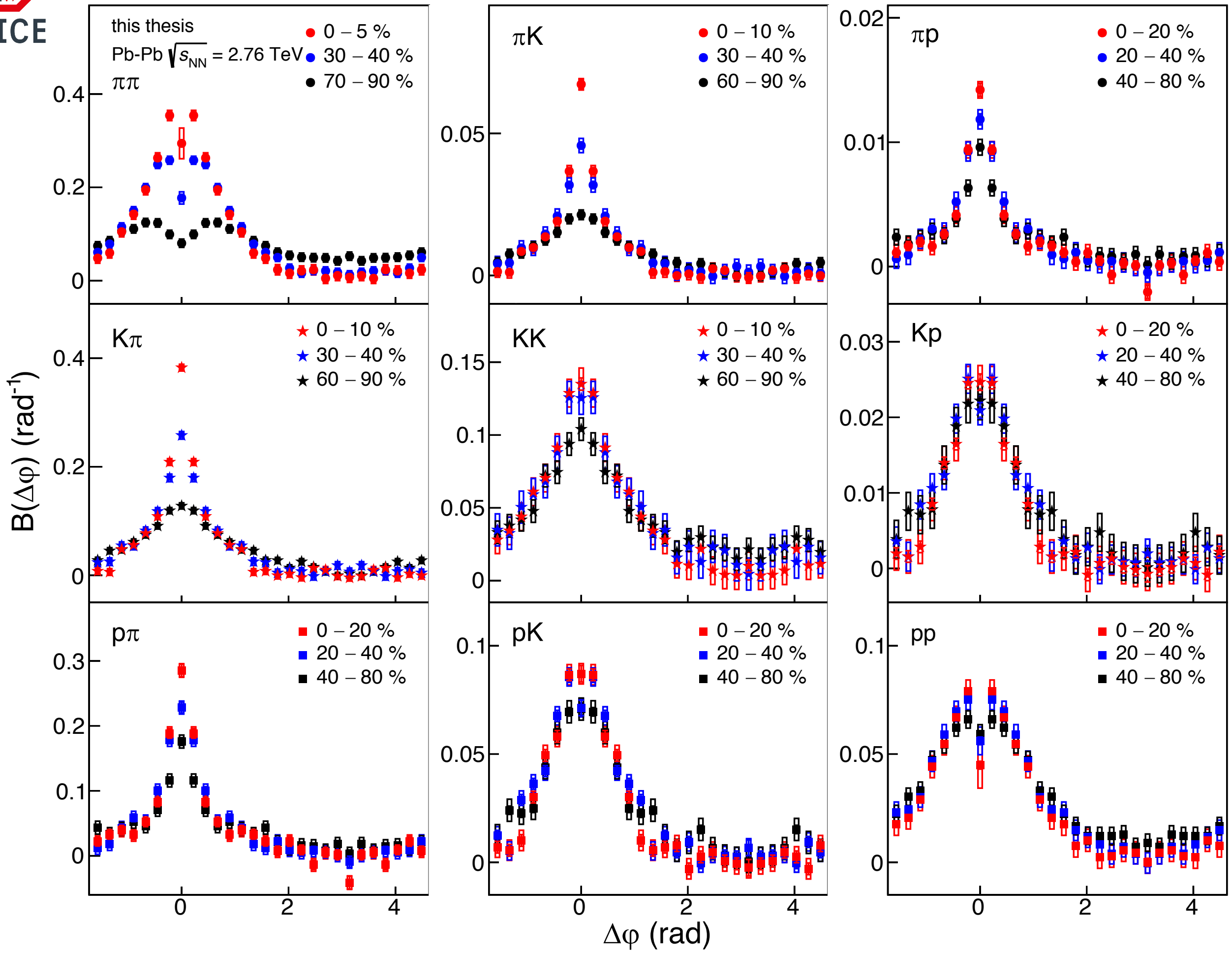


$|\Delta y|<1.4$ $\pi\pi$
$|\Delta y|<1.0$ $pp$
$|\Delta y|<1.2$ other pairs

**Note different scale**

BF including $\pi$:
Clear centrality dependence

BF including $K$, $p$:
no / little centrality dependence

-> different production mechanisms for $\pi$, $K$, $p$

# BF RMS Widths and Integrals

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

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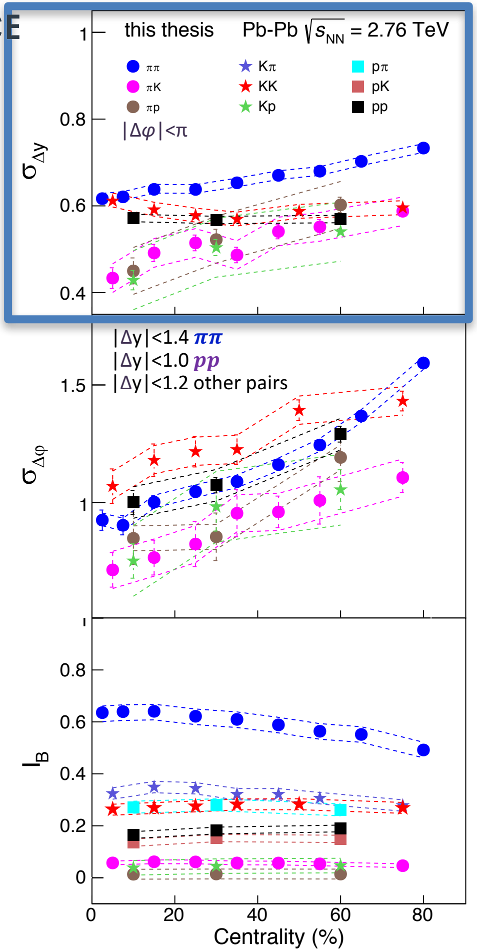
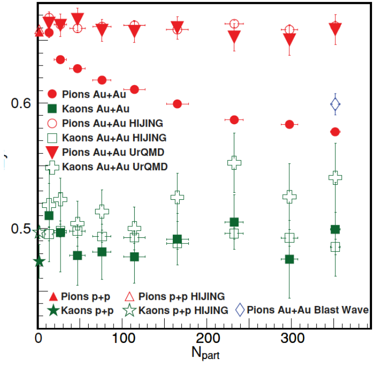


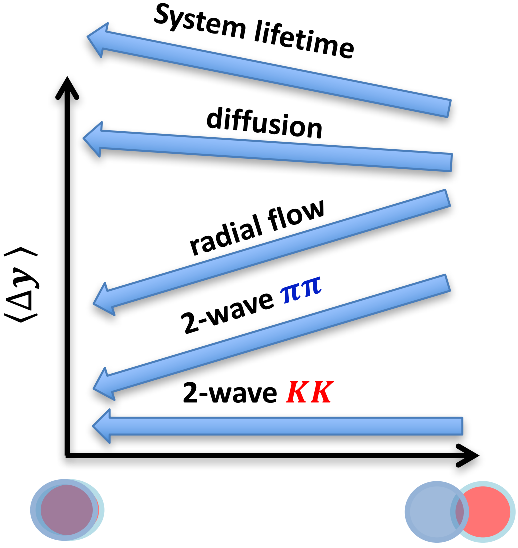

**B(Δy) RMS Widths:**

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




*STAR PRC 82, 024905 (2010)*

Au-Au @ 200 GeV
$0.2 < p_T < 0.6$ GeV/c



# BF RMS Widths and Integrals

$0.2 \le p_T^{\pi,K} \le 2.0$ GeV/c
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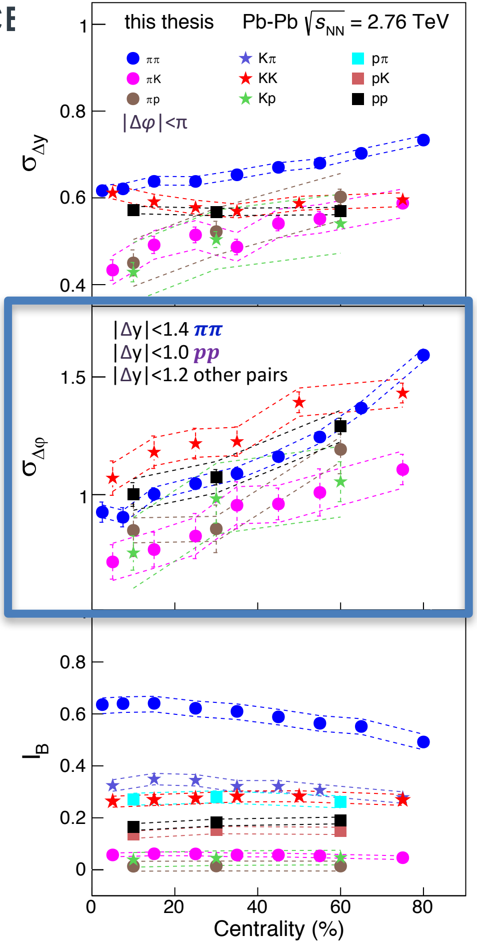
*JP et al. (ALICE), PRL + PRC In Preparation*



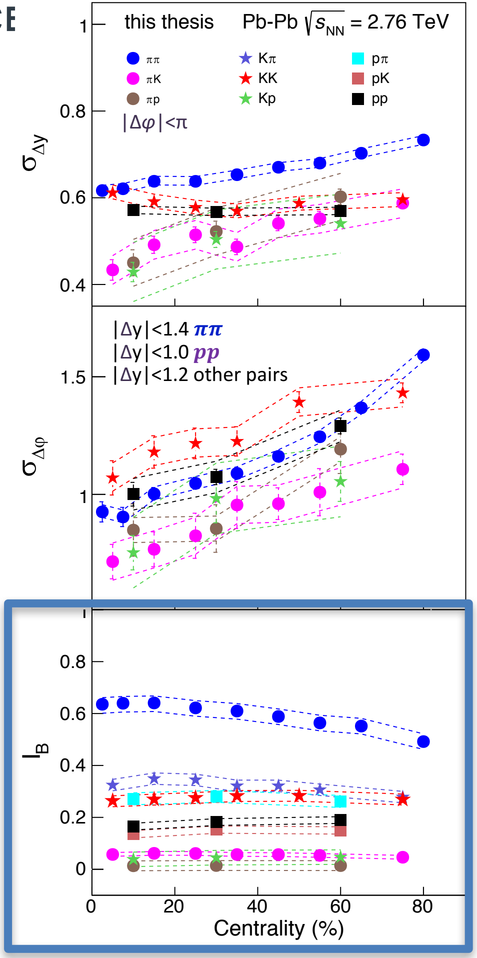

**B(Δ*φ*) RMS Widths:**

- Different values for different species pairs
  -> radial flow affects pairs of different mass differently.
- Widths for ***pp*** is same with ***ππ*** due to different Δ***y*** 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.

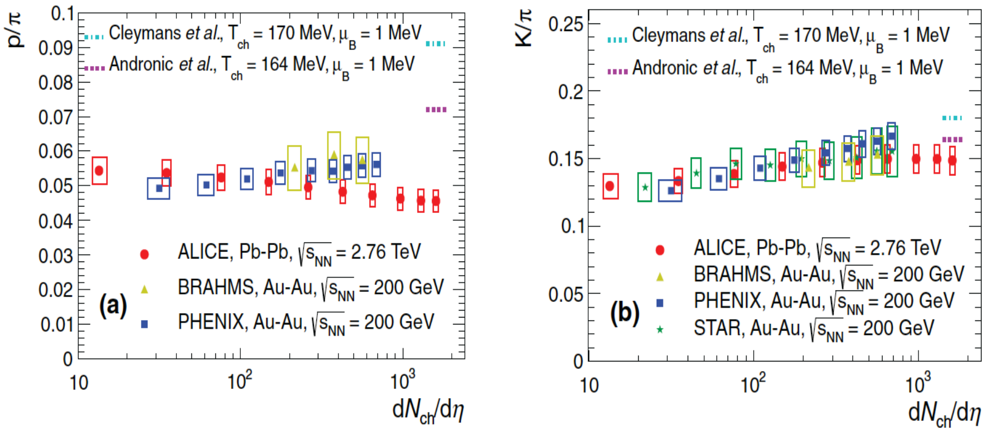
# BF RMS Widths and Integrals

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

*JP PhD dissertation, arXiv:1911.02234*
*JP (for ALICE), NPA 982 (2019) 315–318*
*JP et al. (ALICE), PRL + PRC In Preparation*




*ALICE, PRC 88, 044910 (2013)*




**Balance Function Integrals**

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

# Balance Function experimental outlook

| | | | |
|---|---|---|---|
| $\pi^+$ | $u\,\bar{d}$ | $\pi^-$ | $\bar{u}\,d$ |
| $K^+$ | $u\,\bar{s}$ | $K^-$ | $\bar{u}\,s$ |
| $p$ | $u\,u\,d$ | $\bar{p}$ | $\bar{u}\,\bar{u}\,\bar{d}$ |
| $\Lambda^0$ | $u\,s\,d$ | $\overline{\Lambda^0}$ | $\bar{u}\,\bar{s}\,\bar{d}$ |
| $\Xi^-$ | $d\,s\,s$ | $\overline{\Xi}^+$ | $\bar{d}\,\bar{s}\,\bar{s}$ |

± — **General conserved charges**:

- **e**: electric charge
- **S**: strangeness
- **B**: baryon number

✔ (black): previous works
✔ (green): JP PhD dissertation 2019 (ALICE)
★ : JP et al. (STAR) BES work in progress

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

*uncharted territory* →

- **differential** $B^{\alpha\beta}\left(p_T^\alpha, p_T^\beta\right)$
- $B^{\alpha\beta}$ **w.r.t event plane**
- $B^{\alpha\beta}$ **in jets**

# Summary & Conclusions

- **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):**
  - ***Three 1st***
    - 1st GBF measurement of full species matrix of $\pi^{\pm}, K^{\pm}, p/\overline{p}$.
    - 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.

- **From Model Comparisons**
  - Models need to properly account for balancing charge production & transport mechanisms.

**My contributions in BF research:**

*JP PhD dissertation, arXiv:1911.02234*

*JP (for ALICE), Nuclear Physics A 982 (2019) 315–318*

*JP et al. (ALICE), PRL + PRC In Preparation "BF of $\pi$, $K$, $p$"*

*JP (for ALICE), J. Phys.: Conf. Ser. 832 (2017) 012044*

*Basu, Gonzalez, JP, et al. arXiv:2001.07167, Submitted to PRC*

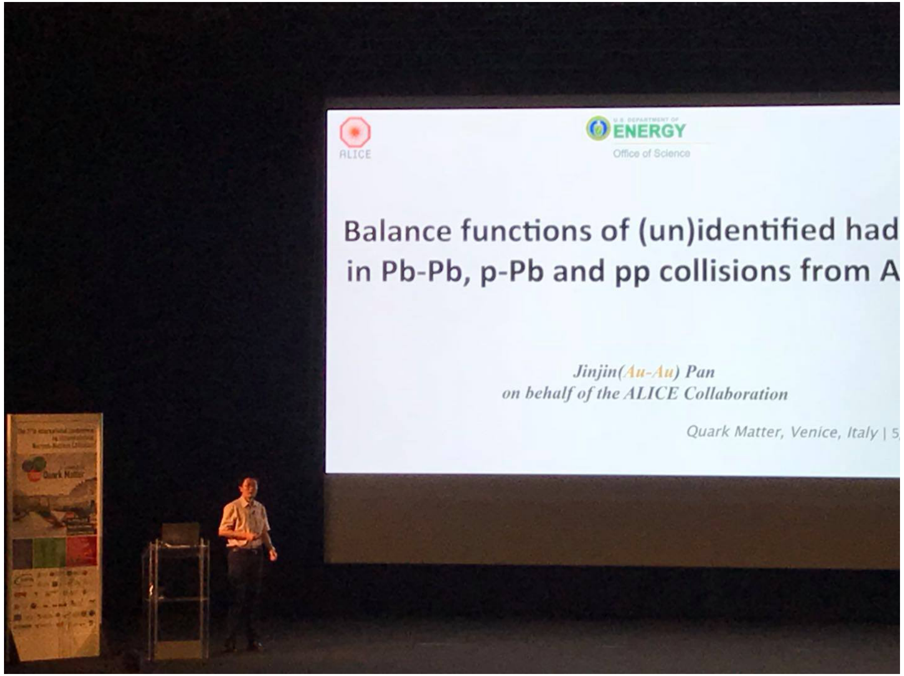
*Gonzalez, Marin, Guevara, JP, et al. PRC 99, 034907 (2019)*

*JP et al. (STAR), PRL In Preparation "BF of $\pi$, $K$, $p$, $\Lambda$ and $\Xi$"*

**More exciting results in STAR BES coming soon!**

# Thank you!

*Quark Matter 2018 Talk*

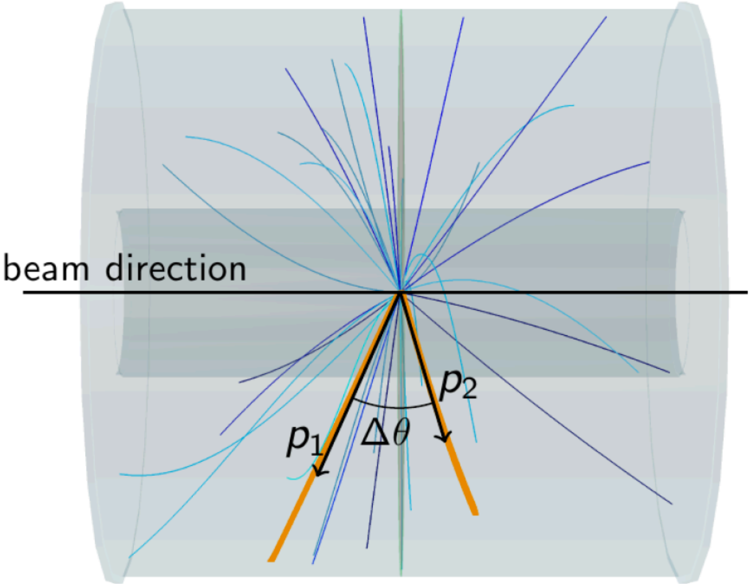



*ALICE Shift Leader (Honor) – Pb-Pb runs 2018*


***Look forward to learning at BNL***

# Back-up

# Momentum Space Variables




Transverse plane

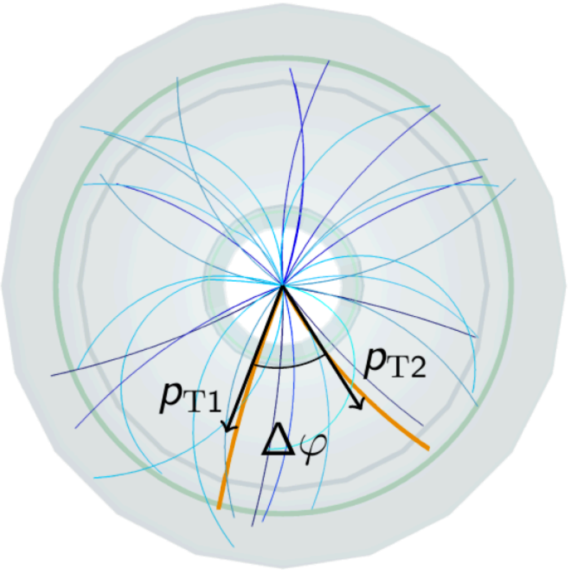



Fig. A. Zaborowska

*p* — particle momentum

$p_T$ — transverse momentum

$\varphi$ — azimuthal angle

θ — polar angle

$\eta$ — pseudorapidity

*y* — rapidity

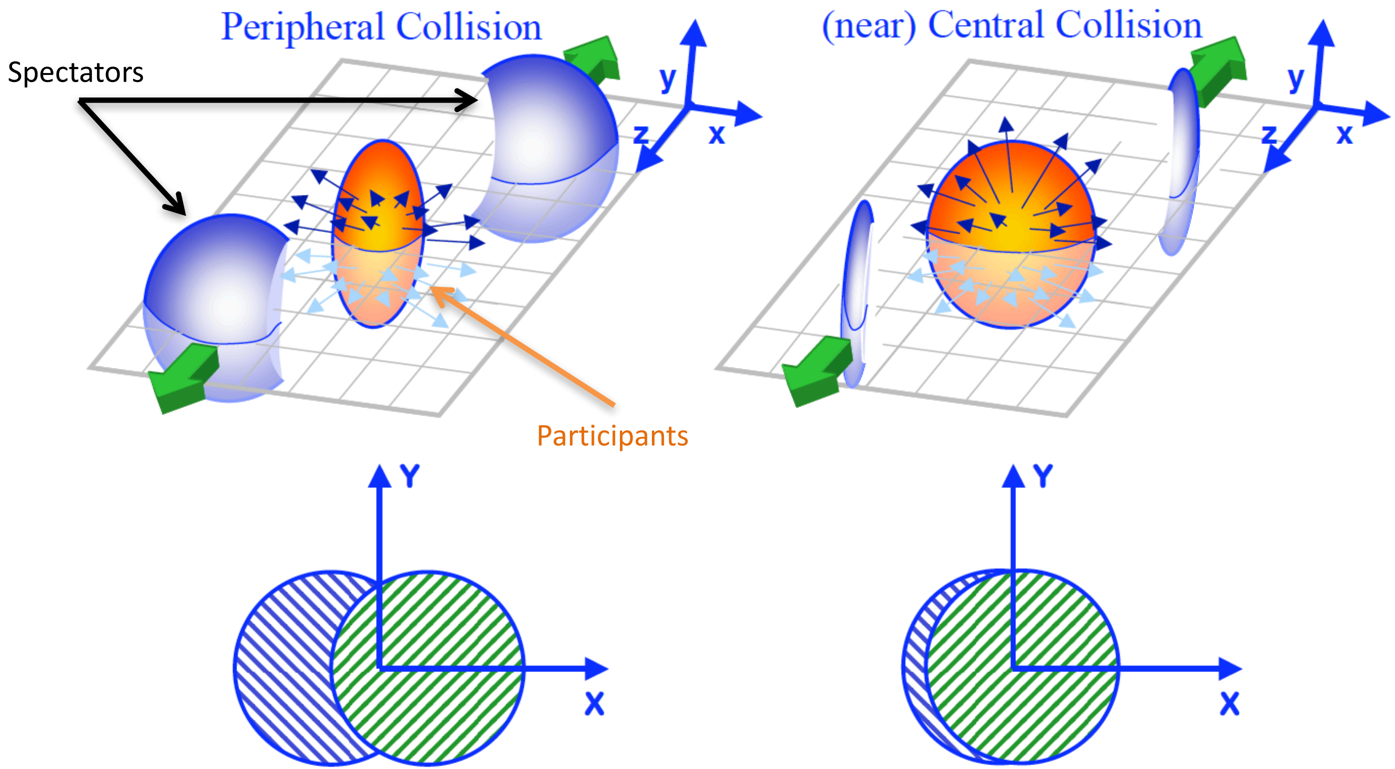
$$p_T^2 = p_x^2 + p_y^2$$

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

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

Lorentz invariant

# Centrality of Relativistic Heavy Ion Collisions



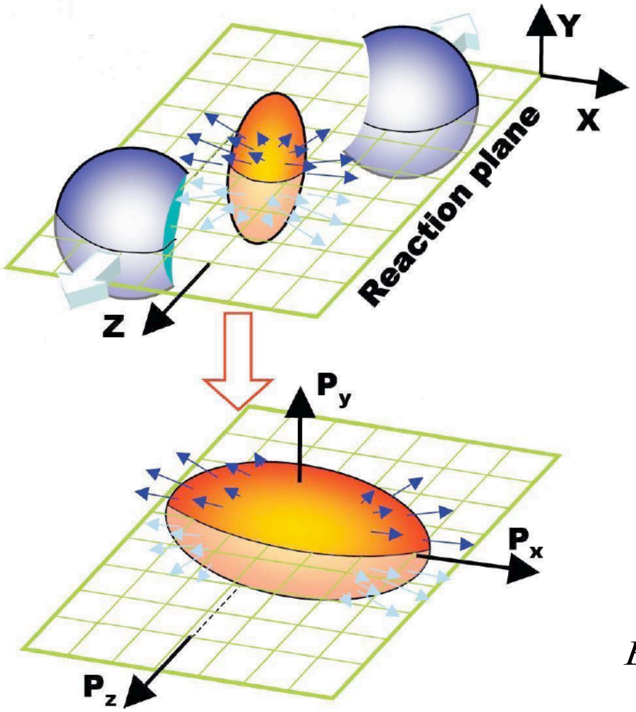

Centrality measured by the multiplicity of charged particles

Masashi Kaneta

# 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.*

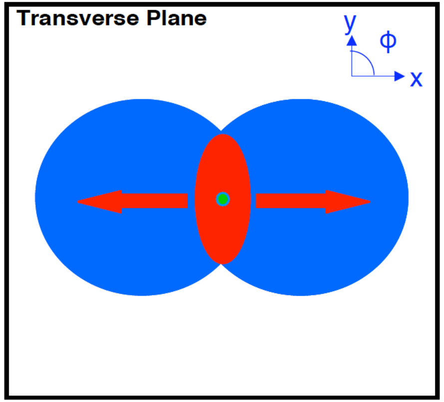



Hiroshi Masui (2008)

**Spatial Anisotropy**

**density gradient -> pressure for anisotropic expansion**

**Momentum Anisotropy**




azimuthal angle around the beam axis

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

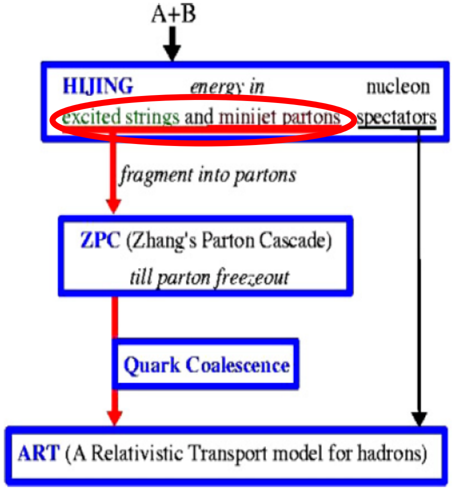
$$v_n = \left\langle \cos\left[n(\phi - \Psi_{RP})\right]\right\rangle$$

**directed flow** ($v_1$) **elliptic flow** ($v_2$) **reaction plane** ($\Psi_{RP}$)

# Models Used In This Work

## AMPT

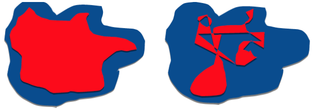
*Structure of AMPT model with string melting*




## EPOS 3.0

CGC – initial condition

Core – Corona approach



Viscous hydrodynamic expansion

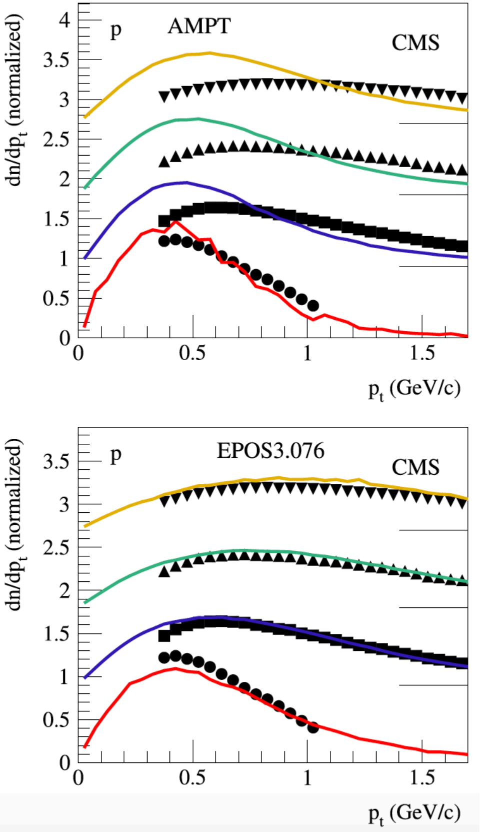
Statistical hadronization (Cooper-Frye)

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

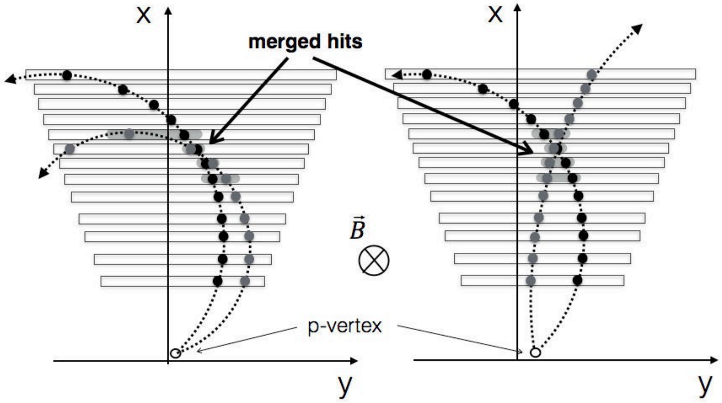
Hadronic relativistic dynamics
*Event Generation: W.J. Llope*

WAYNE STATE UNIVERSITY

# Track Crossing Correction

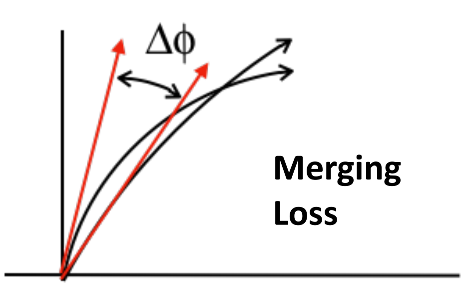
## The cause of track crossing

tracks with Δy ~ 0

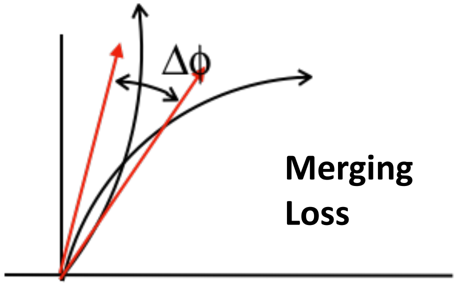



## The solution / correction

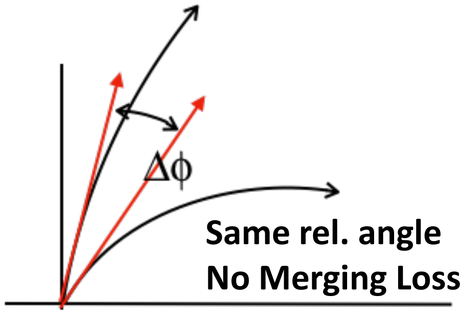
**Like-sign: $p_T$-ordered analysis**

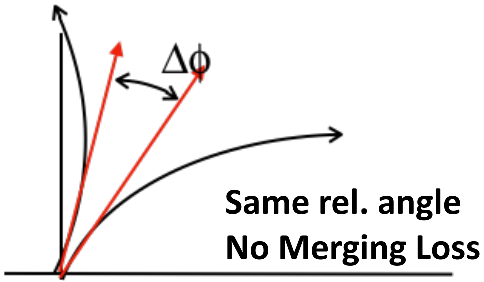



**Unlike-sign: charge-ordered analysis**




At given Δϕ, count un-merged pairs and use count at -Δϕ



# 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**

$$\bar{R}_2^{(k)}(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{1}{Q_k}\sum_{m=m_{\min,k}}^{m_{\max,k}} q(m)R_2(\eta_1,\varphi_1,\eta_2,\varphi_2\,|\,m)$$

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

$$\rho_1(\eta,\varphi\,|\,m) = \langle n\rangle_m \mathrm{P}_1(\eta,\varphi\,|\,m)$$

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

$\mathrm{P}_1$, $\mathrm{P}_2$ — Probability Densities

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

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

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

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

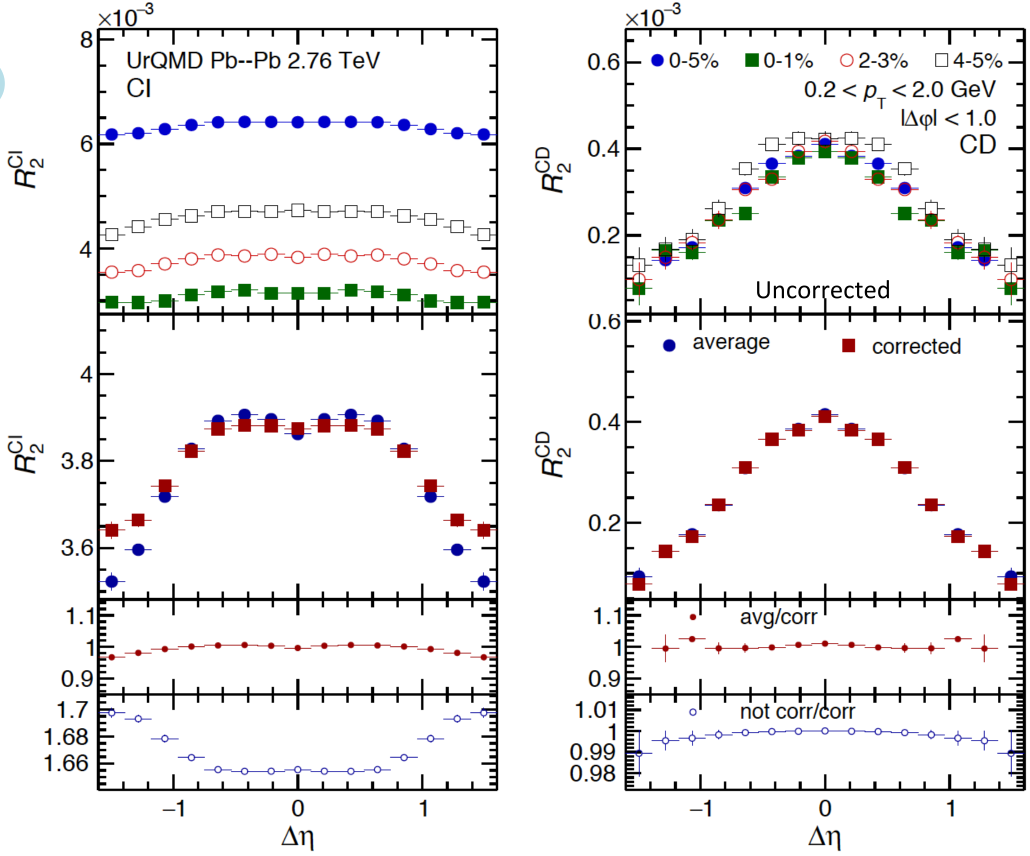
**Correction**

$$\bar{R}_2^{(k)}(\eta_1,\varphi_1,\eta_2,\varphi_2) = \beta\alpha^{-1}\left(R_2^{(Bin,k)}(\eta_1,\varphi_1,\eta_2,\varphi_2) + 1\right) - 1$$

# 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.