A Large Ion Collider Experiment

Measurements of Balance Functions with PID at ALICE

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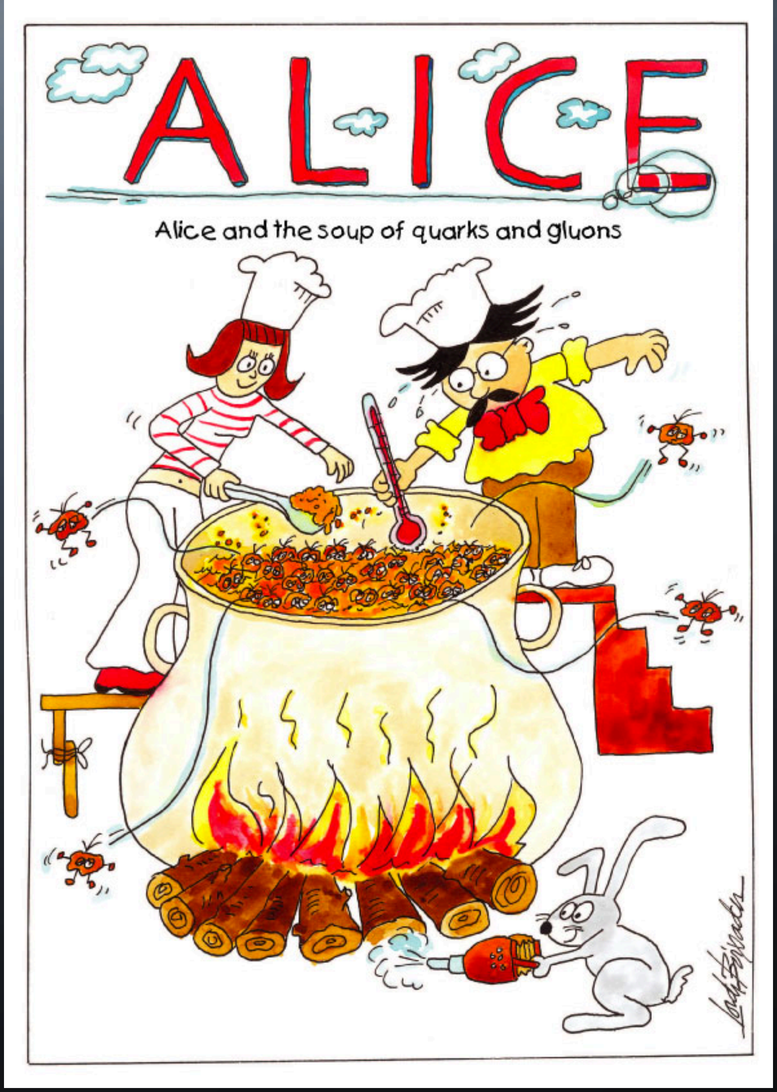
Hot Quarks 2016 | South Padre Island TX | 09/17/2016



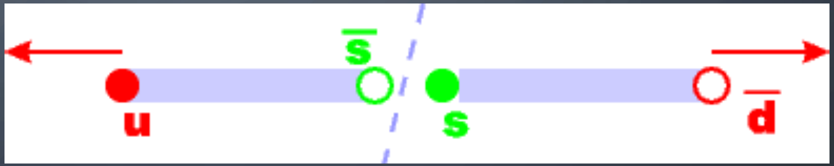
OUTLINE

- **Part I:**
  Balance Functions of Unidentified Charged Particles
- **Part II:**
  Balance Functions with PID
- **Summary**

BALANCE FUNCTIONS
A SIGNAL OF LATE-STAGE HADRONIZATION

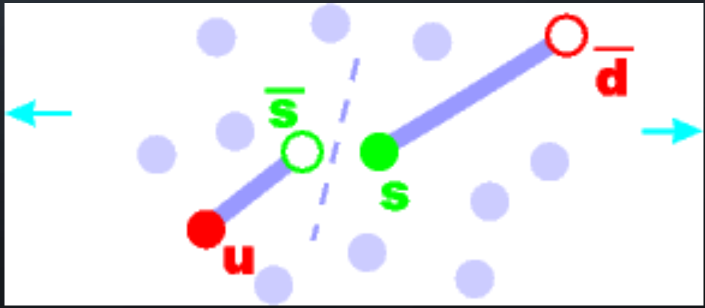
S. Bass, P. Danielewicz and S.P. PRL85, 2689 (2000)

Hadronic Scenario

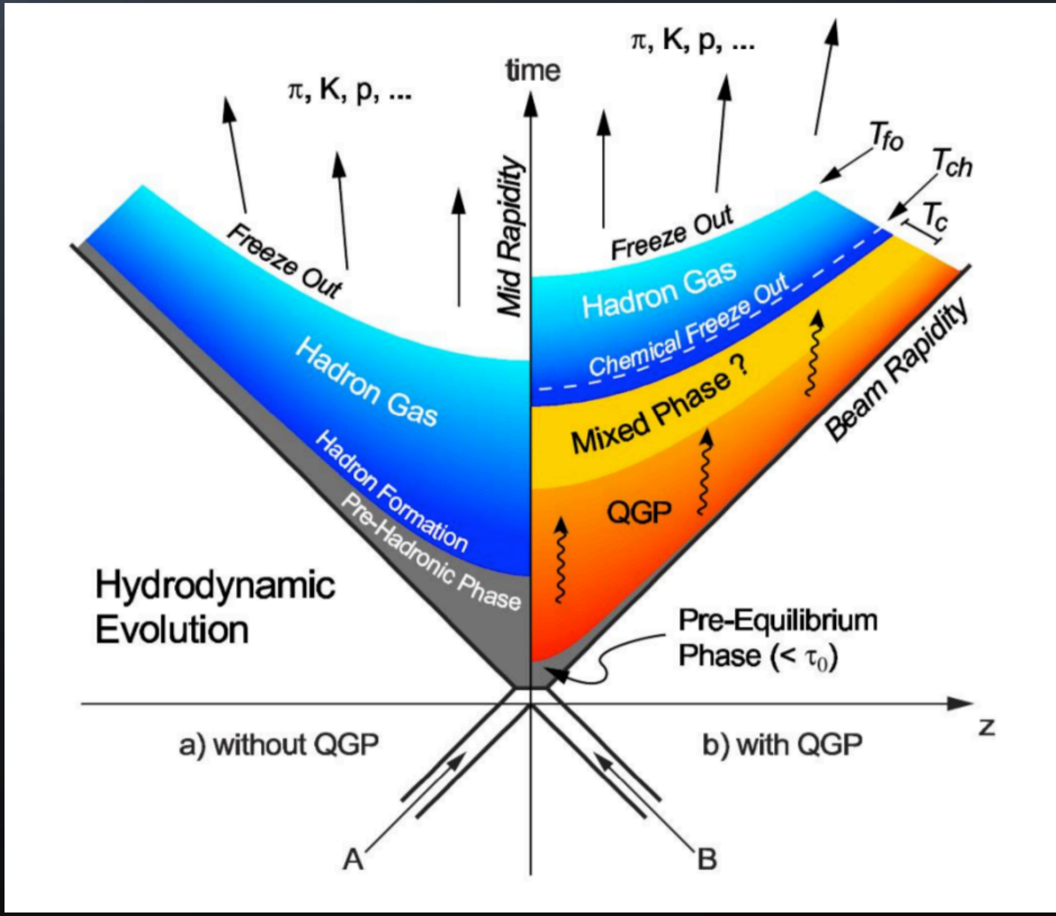


- Hadronization @ 1 fm/c
- Gluon string (or color flux tube) breaks

QGP Scenario



- Delayed Hadronization @ 5-10 fm/c
- Most $q\bar{q}$ pairs created at hadronization



System Longitudinal Expansion

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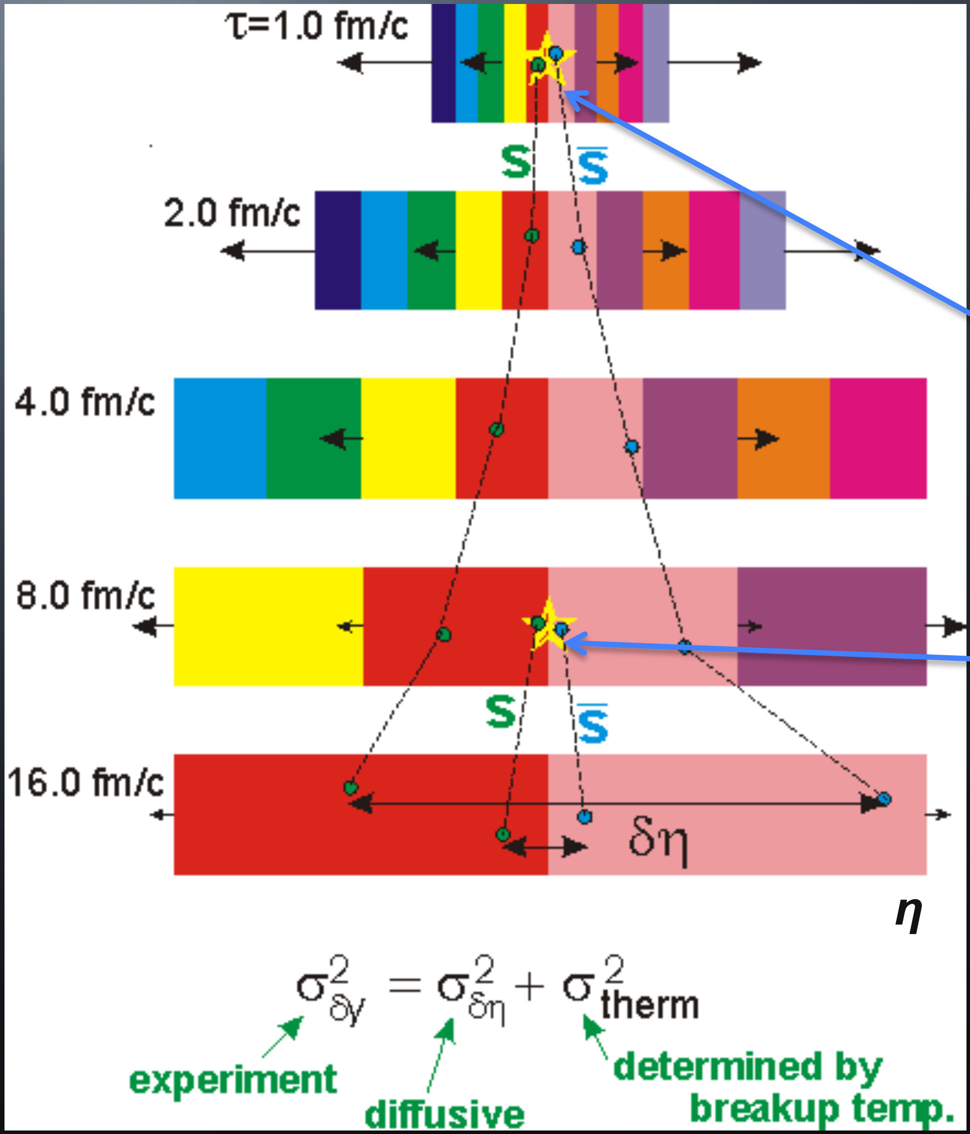

$q\bar{q}$ pair creation in a rapidly expanding system

Early stage creation: larger final separation, wider balance function distributions

Late stage creation: pairs more correlated, narrower balance function distributions

Difficulty:
Identifying balancing partners

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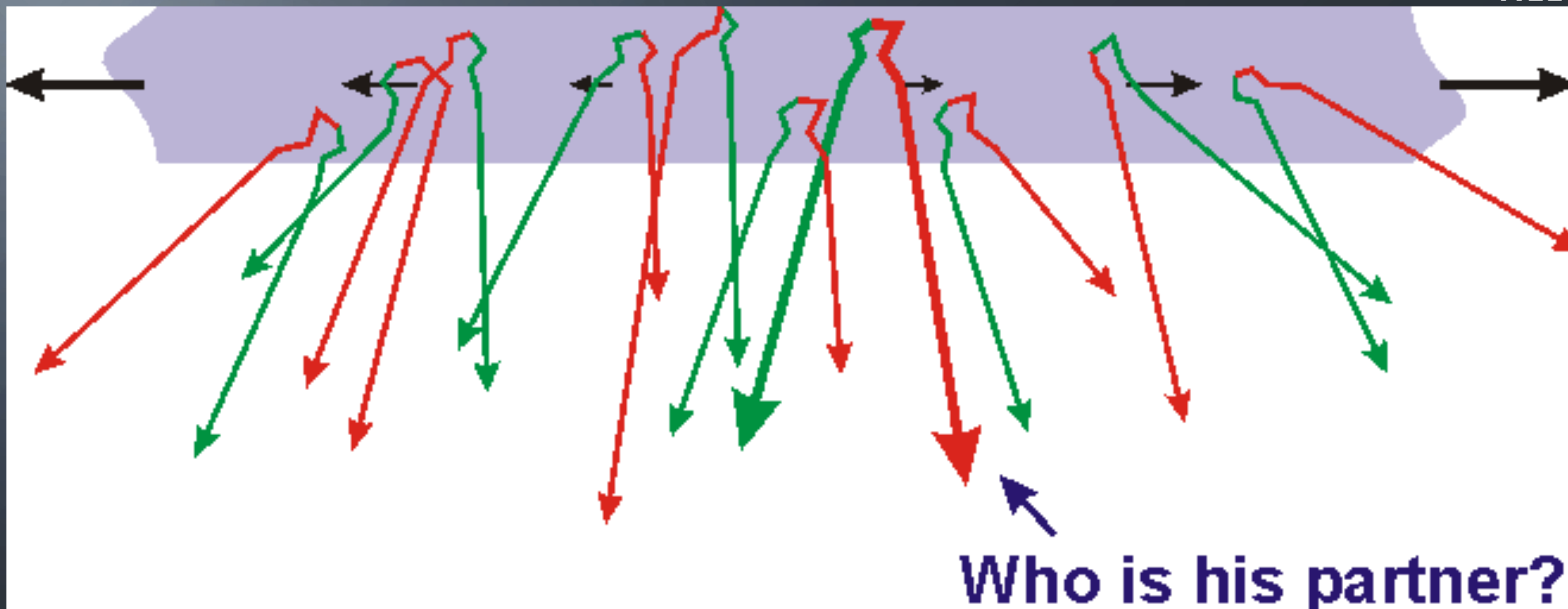
BALANCE FUNCTIONS: HOW THEY WORK



For each charge +Q, there is extra balancing charge -Q produced at the same space time.

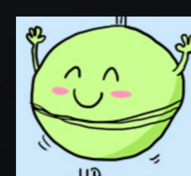
$$B(\Delta\vec{p}) = \frac{1}{2}\left\{ \frac{\langle N_{+-}(\Delta\vec{p})\rangle - \langle N_{++}(\Delta\vec{p})\rangle}{\langle N_{+}\rangle} + \frac{\langle N_{-+}(\Delta\vec{p})\rangle - \langle N_{--}(\Delta\vec{p})\rangle}{\langle N_{-}\rangle} \right\}$$

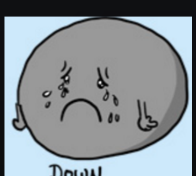
$\Delta\vec{p}$ momentum difference

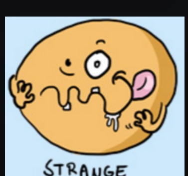
B(Δη,Δϕ)

Balance Functions identify balancing charges on a statistical basis.

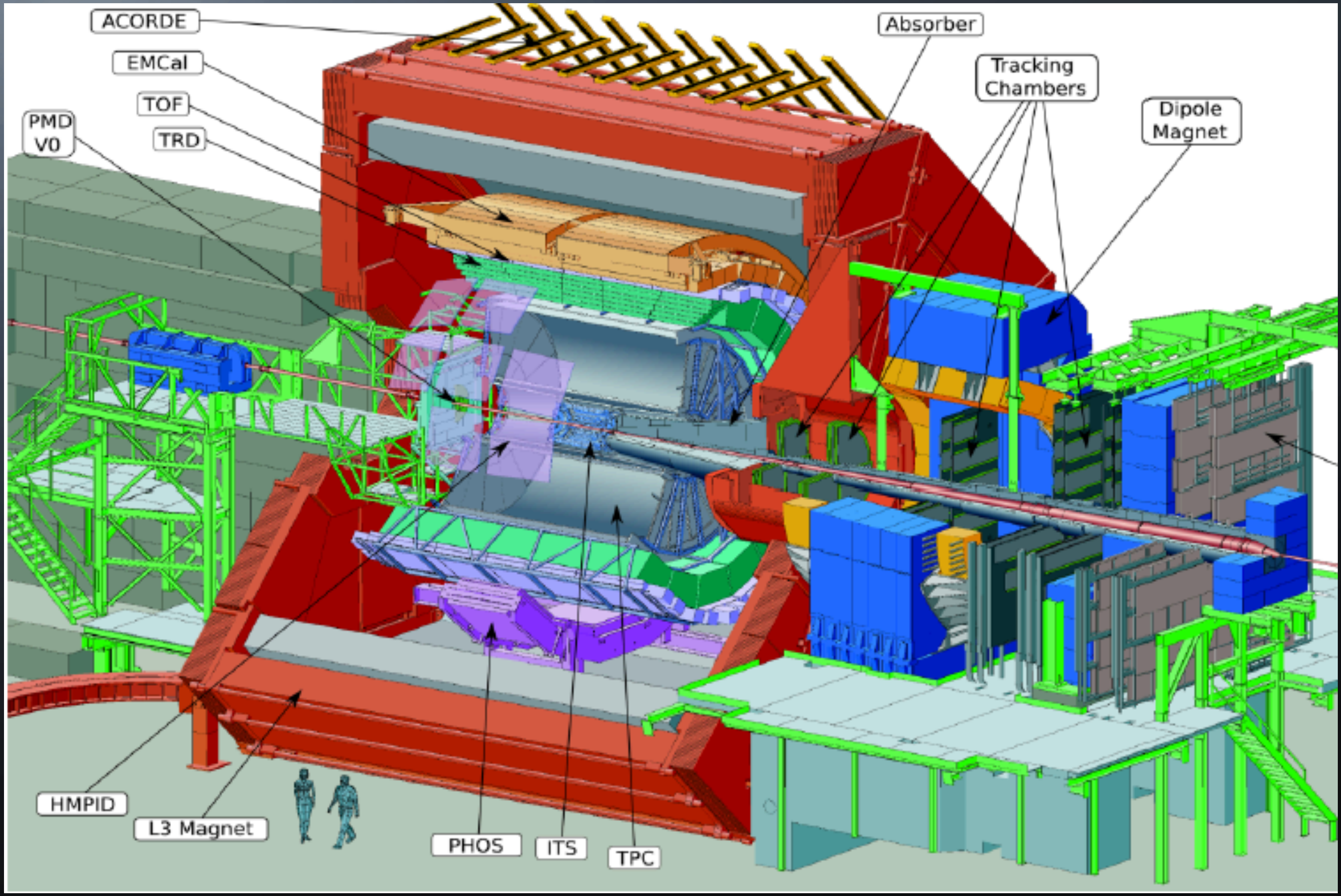
General Charges: up, down, strange quarks (electric charge, baryon number, strangeness)



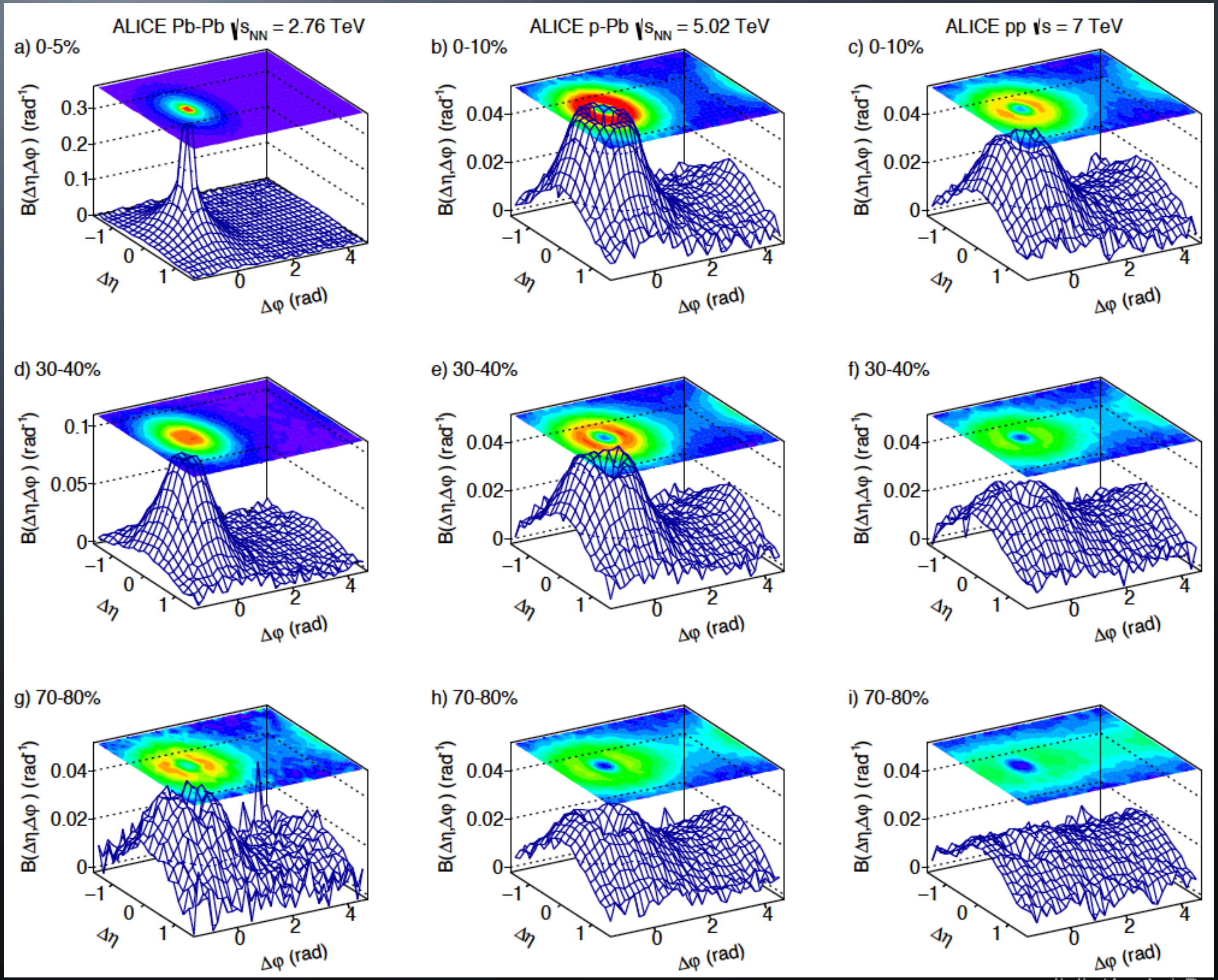




The ALICE Detector



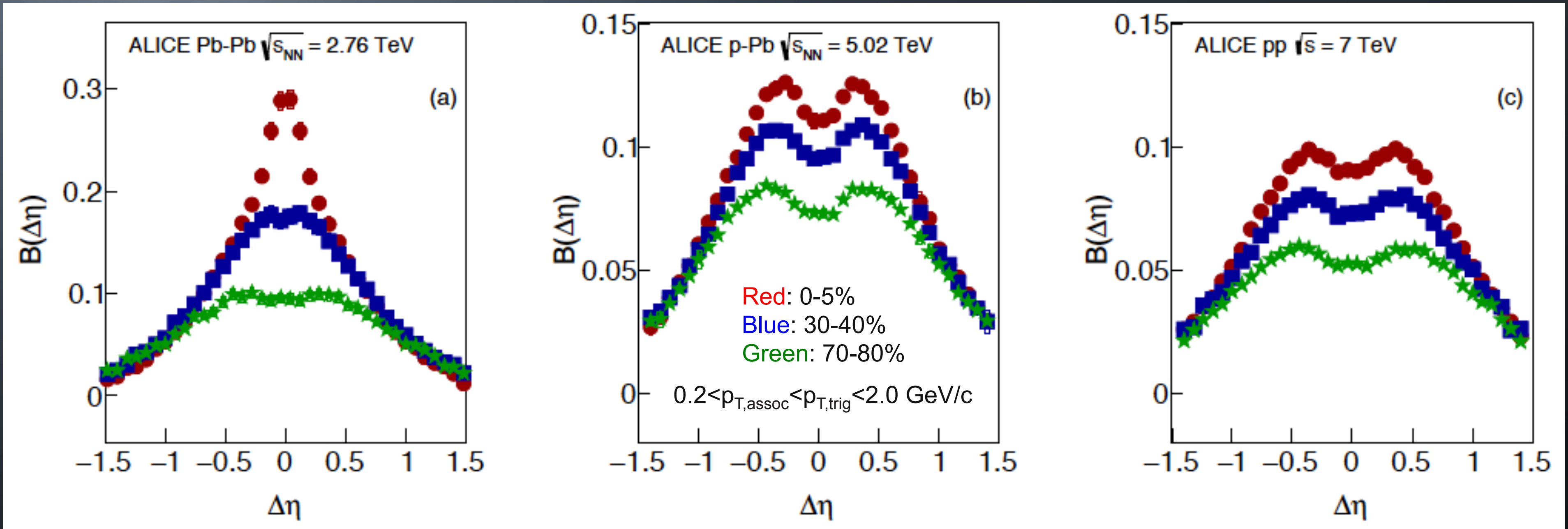
Balance Functions of Unidentified Charged Particles



Eur. Phys. J. C 76 (2016) 86
By the ALICE Collaboration

$0.2 < p_{T,assoc} < p_{T,trig} < 2.0$ GeV/c

Balance Functions of Unidentified Charged Particles



B(Δη) exhibits a strong multiplicity dependence for all collision systems. In particular, the distribution narrows & the amplitude increases with increasing multiplicity.

Balance Functions of Unidentified Charged Particles

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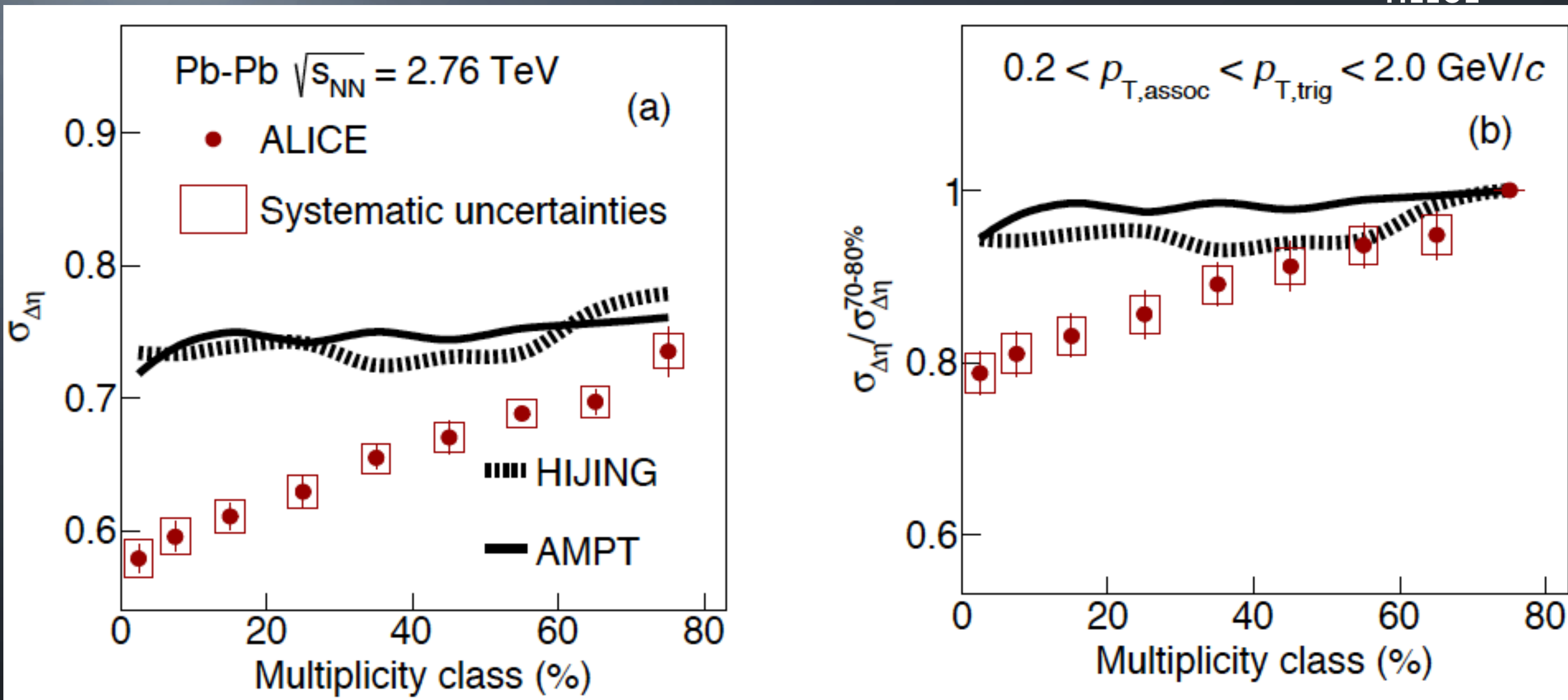

Balance Function widths for Pb-Pb compared with HIJING & AMPT.
In AMPT, the string melting option was used, with parameters tuned to describe the experimental data on anisotropic flow @ LHC energies.

Neither model describes the experimentally observed narrowing of the balance function with increasing multiplicity.

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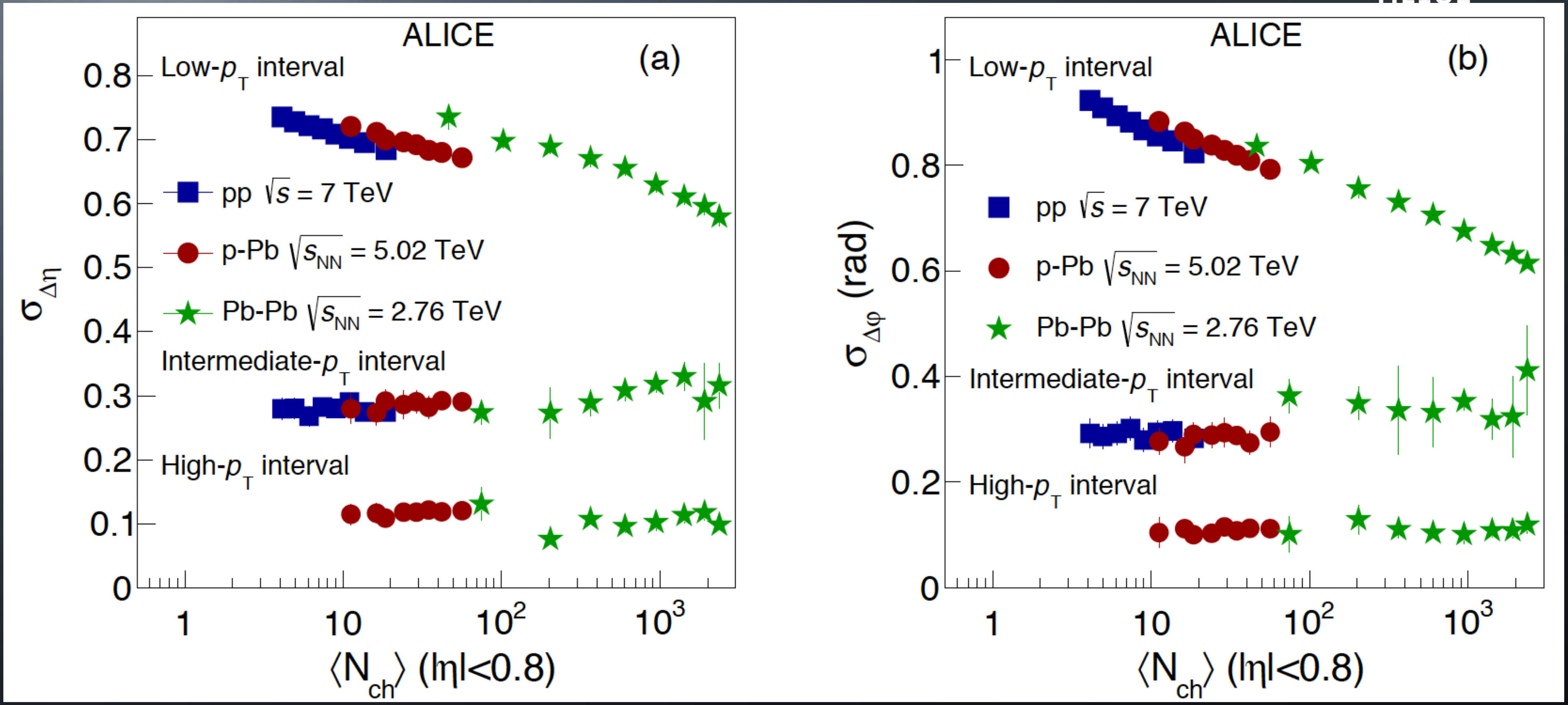
Balance Functions of Unidentified Charged Particles



$0.2<p_{T,assoc}<p_{T,trig}<2$ GeV/c: Δη & Δϕ similar widths between pp & p-Pb for overlapping multiplicities -> similar mechanisms. Origin of charge-dependent correlations probed with BF in Pb-Pb: ***radial flow and/or delayed hadronization***. Differences of Pb-Pb compared w/ pp & p-Pb @ similar multiplicities indicate a different mechanism in smaller systems.

$2<p_{T,assoc}<3<p_{T,trig}<4$ GeV/c & $3<p_{T,assoc}<8<p_{T,trig}<15$ GeV/c : BF narrower & no significant multiplicity dependence for all systems. Correlation origin: ***initial hard parton scattering & subsequent fragmentation***. Indicate the dynamics responsible for the high-pT charge-dependent correlations do not change significantly between pp, p-Pb, & Pb-Pb.

Balance Functions of Unidentified Charged Particles

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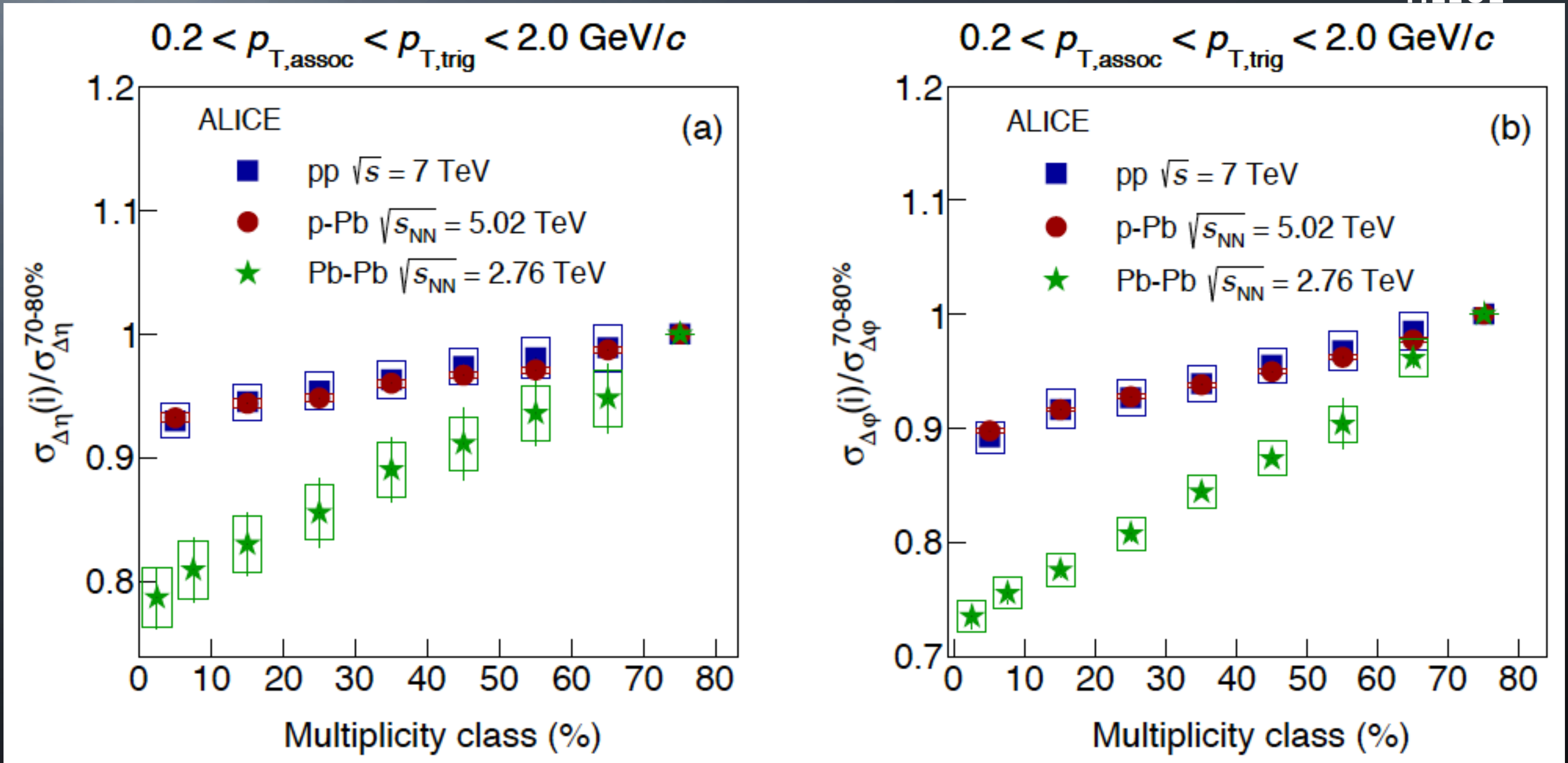

Narrowing of BF in both Δη & Δϕ is a distinct characteristic of low p_T.
Indicate similar mechanism for pp & p-Pb for decrease of width with increasing multiplicity.

Relative decrease similar between 2 small systems (around 7% and 10.5% in Δη & Δϕ).

A significantly larger relative decrease of 21.2 % in Δη (26.5% for Δϕ) for Pb-Pb .

The distinct differences in the relative decrease of $\sigma_{\Delta\eta}$ & $\sigma_{\Delta\phi}$ b/w pp & p-Pb on one side & Pb-Pb on the other, could point to certain differences in the particle-production mechanisms b/w large & smaller systems.

Balance Functions with PID

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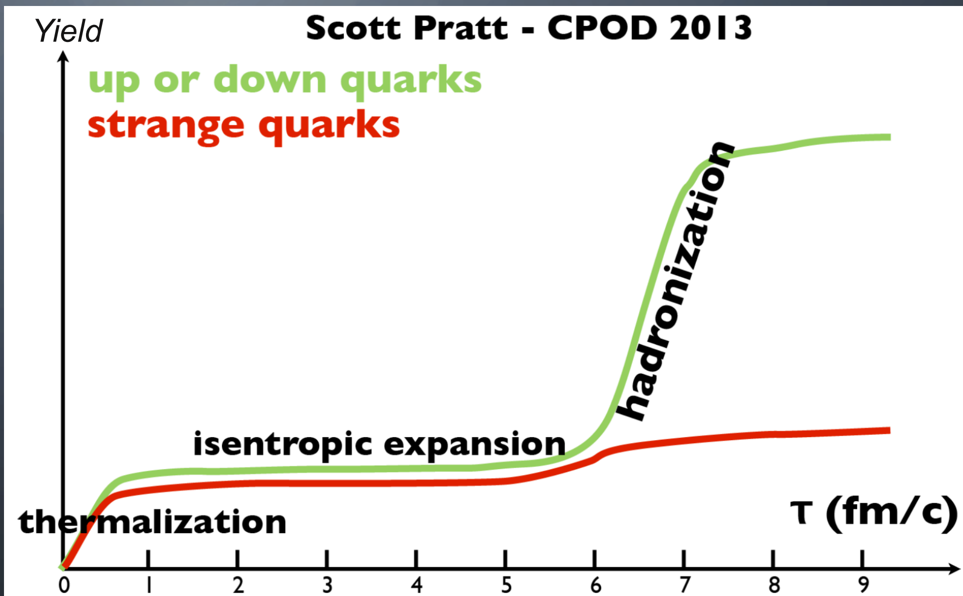


Two-wave scenario of quark production

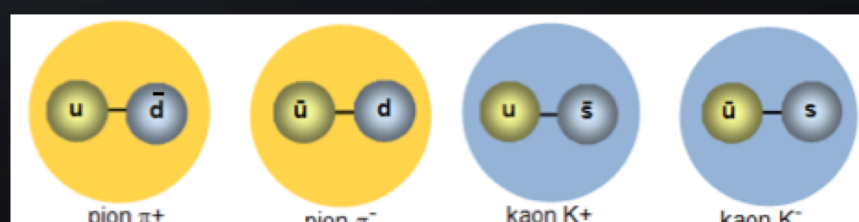
1st wave – flat production rate over time – main source of s-quark

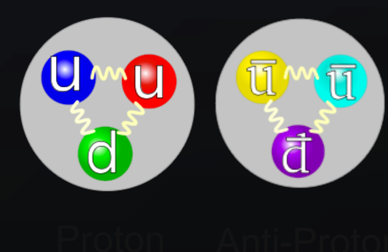
2nd wave – rapid increase around hadronization – main source of u,d-quarks

Scott Pratt PRL. 108, 212301 (2012)

Two-wave quark creation can be studied with balance functions of **identified particle pairs**

- Charged pion pairs
- Charged kaon pairs
- Proton Anti-Proton pairs
- Proton/K⁻ pairs





New Approach of Measuring Balance Functions

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$$x \equiv \{y, \varphi, p_T\}$$

$$\rho(x) = \frac{1}{\sigma}\frac{d\sigma}{dx}$$

Cumulant $$C_2(x_1,x_2) = \rho_2(x_1,x_2) - \rho_1(x_1)\rho_1(x_2)$$

Normalized Cumulant $$R_2(x_1,x_2) = \frac{C_2(x_1,x_2)}{\rho_1(x_1)\rho_1(x_2)}$$

R_2 is a robust observable!
Single track efficiencies cancel out of the ratio

4 different charge combinations for R_2: (+ -), (- +), (+ +), and (- -)

Charge Independent (CI) combinations $$CI = \frac{1}{2}\{LS + US\}$$

Charge Dependent (CD) combinations $$CD = \frac{1}{2}\{US - LS\}$$

$$LS = \frac{1}{2}\{(++) + (--)\}$$

$$US = \frac{1}{2}\{(+-) + (-+)\}$$

R_2^{CD} is proportional to the Balance Function

$$B(\Delta x) \approx \frac{dN_{ch}}{dx} R_2^{CD} = \frac{dN_{ch}}{dx}\frac{1}{2}\left[R_2^{+-} - R_2^{++} + R_2^{-+} - R_2^{--}\right]$$

Method – Efficiency & Robustness

- Correlation function measurement
- Goal: $C_p(\eta_1,\eta_2)=\rho_2(\eta_1,\eta_2)-\rho_1(\eta_1)\rho_1(\eta_2)$ Produced
- "Raw" Measurement

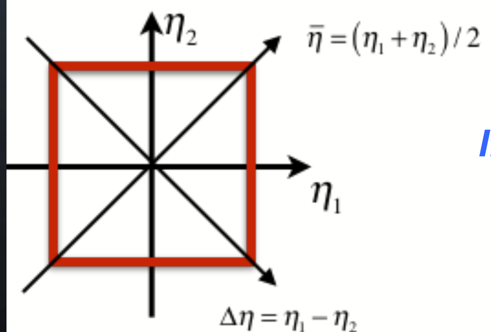
$$C_m(\eta_1,\eta_2)=\langle n_1 n_2(\eta_1,\eta_2)\rangle-\langle n_1(\eta_1)\rangle\langle n_2(\eta_2)\rangle$$ Measured

$$=\varepsilon_1(\eta_1)\varepsilon_2(\eta_2)\left\{\langle N_1 N_2(\eta_1,\eta_2)\rangle-\langle N_1(\eta_1)\rangle\langle N_2(\eta_2)\rangle\right\}$$

- Ratio

$$R_m(\eta_1,\eta_2)=\frac{\langle n_1 n_2(\eta_1,\eta_2)\rangle}{\langle n_1(\eta_1)\rangle\langle n_2(\eta_2)\rangle}-1=\frac{\varepsilon_1(\eta_1)\varepsilon_2(\eta_2)\langle N_1 N_2(\eta_1,\eta_2)\rangle}{\varepsilon_1(\eta_1)\varepsilon_2(\eta_2)\langle N_1(\eta_1)\rangle\langle N_2(\eta_2)\rangle}-1$$

$$=\frac{\langle N_1 N_2(\eta_1,\eta_2)\rangle}{\langle N_1(\eta_1)\rangle\langle N_2(\eta_2)\rangle}-1=R_p(\eta_1,\eta_2)$$



Acceptance Average

If probability of detecting particle pairs @ η_1 & η_2 can be factorized

Efficiencies cancel >>> Robust Observable

Method – Efficiency & Robustness (2)

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- What we actually want: $$R_p(\Delta\eta) = \frac{1}{\Omega}\int_{\bar{\eta}} R_p(\Delta\eta,\bar{\eta})\,d\bar{\eta}$$

- Method 1 $$R_m(\Delta\eta) = \frac{\langle n_1 n_2(\Delta\eta)\rangle_{real}}{\langle n_1 n_2(\Delta\eta)\rangle_{mix}} - 1 = \frac{\int_\Omega \varepsilon_1(\eta_1)\varepsilon_2(\eta_2)\langle N_1 N_2(\eta_1,\eta_2)\rangle_{actual}\,d\bar{\eta}}{\int_\Omega \varepsilon_1(\eta_1)\varepsilon_2(\eta_2)\langle N_1 N_2(\eta_1,\eta_2)\rangle_{mixed}\,d\bar{\eta}} - 1$$

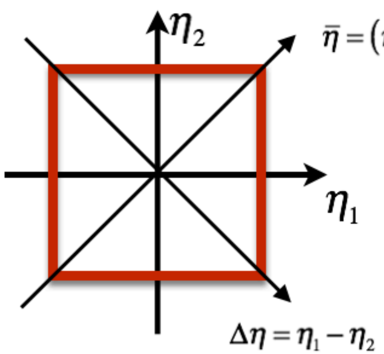
Efficiencies DO NOT cancel >>> Not Robust in general

- Method 2 $$R_m(\Delta\eta) = \frac{1}{\Omega}\int_\Omega \frac{\langle n_1 n_2(\Delta\eta,\bar{\eta})\rangle_{actual}}{\langle n_1 n_2(\Delta\eta,\bar{\eta})\rangle_{mixed}} - 1$$

If pair efficiency factorizes

$$= \frac{1}{\Omega}\int_\Omega \frac{\varepsilon_1(\eta_1)\varepsilon_2(\eta_2)\langle N_1 N_2(\Delta\eta,\bar{\eta})\rangle_{actual}}{\varepsilon_1(\eta_1)\varepsilon_2(\eta_2)\langle N_1 N_2(\Delta\eta,\bar{\eta})\rangle_{mixed}} - 1$$

$$= \frac{1}{\Omega}\int_\Omega \frac{\langle N_1 N_2(\Delta\eta,\bar{\eta})\rangle_{actual}}{\langle N_1 N_2(\Delta\eta,\bar{\eta})\rangle_{mixed}} - 1 = \frac{1}{\Omega}\int_\Omega R_p(\Delta\eta,\bar{\eta}) = R_p(\Delta\eta)$$



Efficiencies DO cancel >>> Robust

i.e. its definition yields a perfect efficiency corrected result

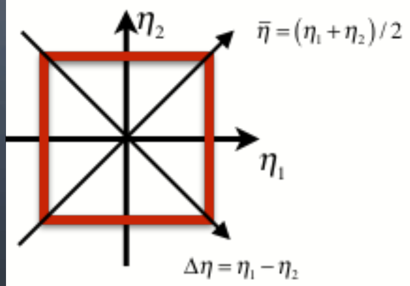
$$R_2(\Delta\eta)^{Method1} = \frac{\int g(\Delta\eta,\bar{\eta})R_2^{true}(\Delta\eta,\bar{\eta})d\bar{\eta}}{\int g(\Delta\eta,\bar{\eta})d\bar{\eta}}$$

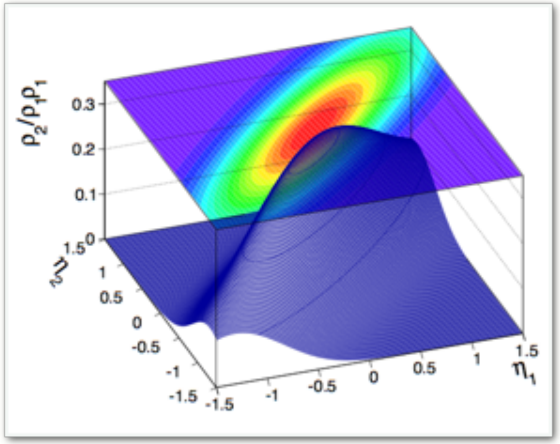
$$g(\Delta\eta,\bar{\eta}) = \epsilon_1 \times \epsilon_1 \times \rho_1 \times \rho_1(\Delta\eta,\bar{\eta})$$

Illustrative Correlation Model

- Particle Production Model

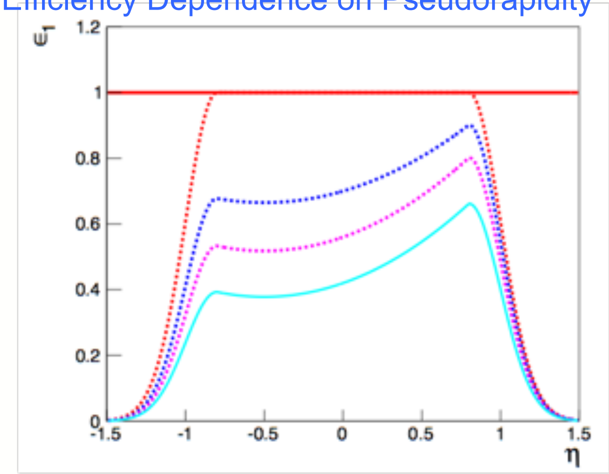
$$C(\Delta\eta,\bar{\eta}) \propto \exp\left(-\frac{\Delta\eta^2}{2\sigma_{\Delta\eta}^2}\right)\exp\left(-\frac{\bar{\eta}^2}{2\sigma_{\bar{\eta}}^2}\right)$$



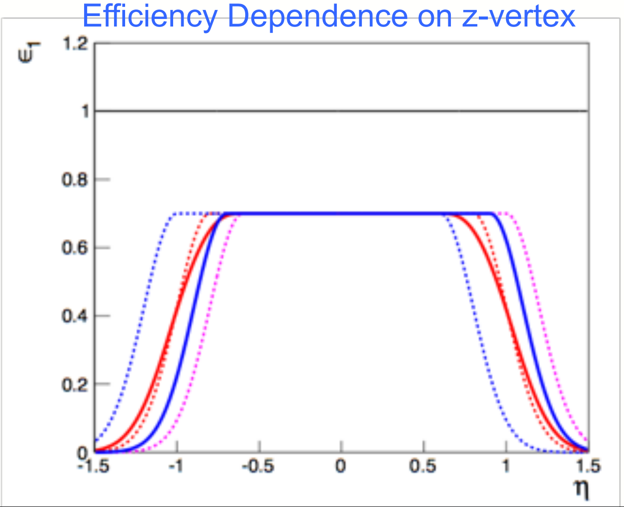


- Efficiency Model

Efficiency Dependence on Pseudorapidity

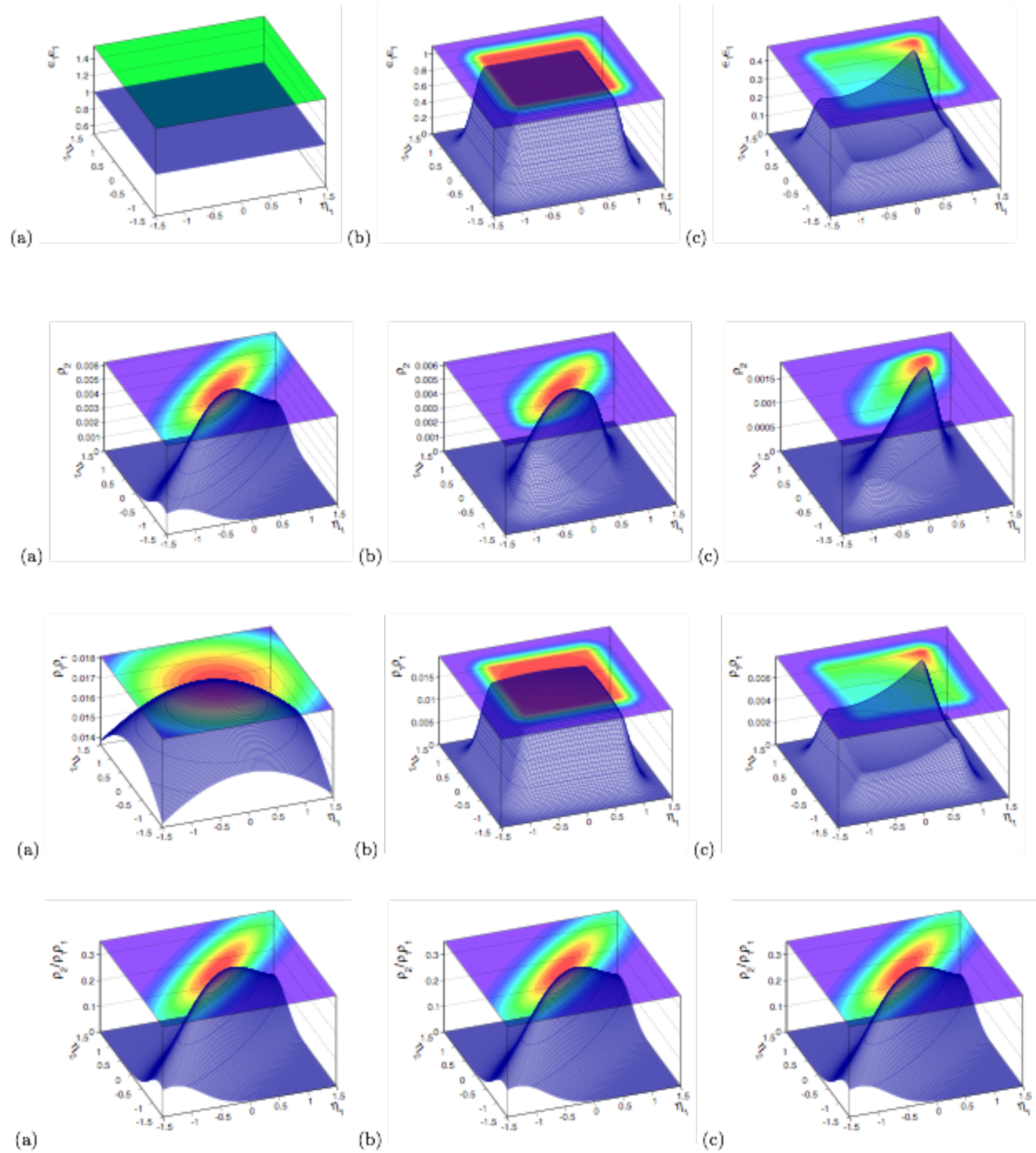


Efficiency Dependence on z-vertex



z: position of z-vertex

Perfect Efficiency | *Flat Response with Smooth Edges* | *Nonlinear Response with edge effects*



Pair Efficiency

Raw Pair Yield

Raw Product of Singles Yield Mixed Events

R2 (Method 2)

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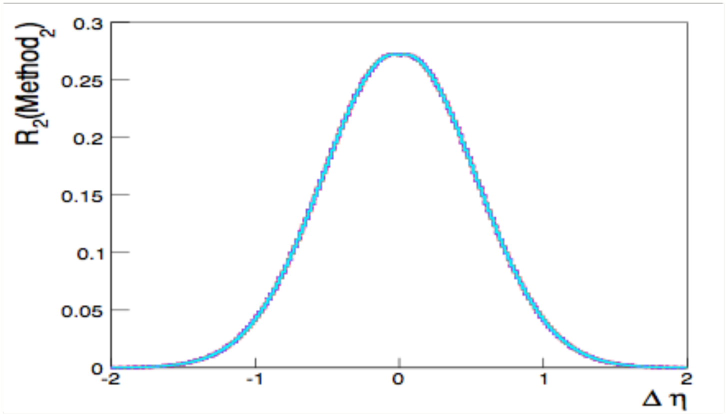
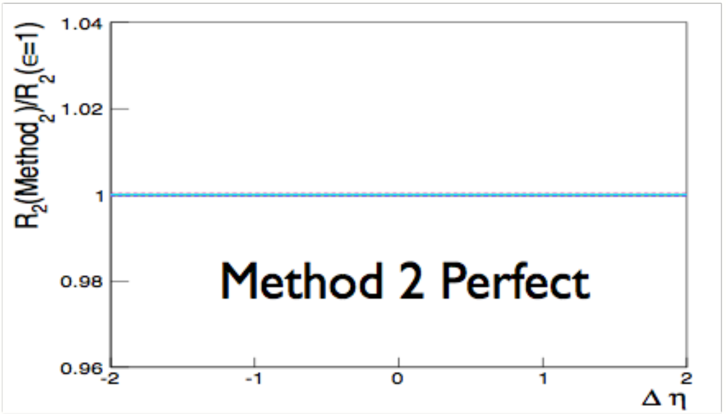
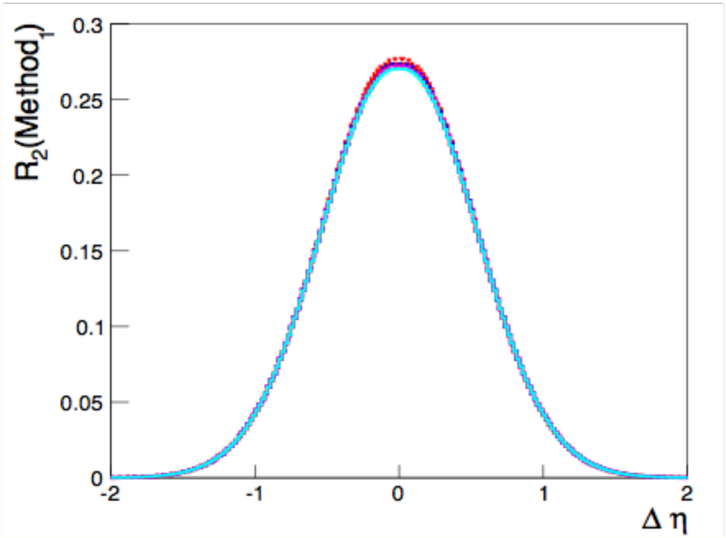
R2(Δη) Method 2

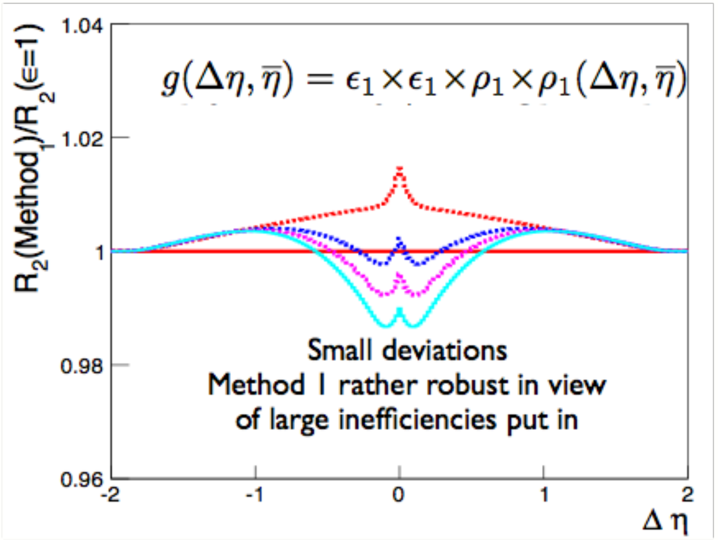




R2(Δη) Method I

$$R_2(\Delta\eta)^{Method1} = \frac{\int g(\Delta\eta,\overline{\eta})R_2^{true}(\Delta\eta,\overline{\eta})d\overline{\eta}}{\int g(\Delta\eta,\overline{\eta})d\overline{\eta}}$$





Efficiency Factorization???

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- Local Factorization:

$$\epsilon_{pair}(\eta_1,\eta_2|z) = \epsilon_1(\eta_1|z) \times \epsilon_1(\eta_2|z)$$

- Loss of "Global" Factorization:

$$f_1(\eta_1) = K\int_{z_{min}}^{z_{max}} P_c(z)\epsilon(\eta_1|z)dz$$

$$f_2(\eta_1,\eta_2) = K\int_{z_{min}}^{z_{max}} P_c(z)\epsilon(\eta_1|z)\times\epsilon(\eta_2|z)dz$$

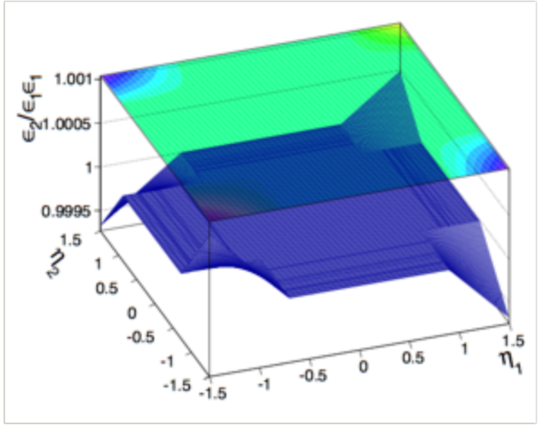
$$\langle n_1(\eta_1)\rangle = K\int_{z_{min}}^{z_{max}} P_c(z)\epsilon(\eta_1|z)\langle N_1(\eta_1)\rangle dz = \langle N_1(\eta_1)\rangle f_1(\eta_1)$$

$$\langle n_2(\eta_1,\eta_2)\rangle = K\int_{z_{min}}^{z_{max}} P_c(z)\epsilon(\eta_1|z)\times\epsilon(\eta_2|z)\langle N_2(\eta_1,\eta_2)\rangle dz = \langle N_2(\eta_1,\eta_2)\rangle f_2(\eta_1,\eta_2)$$

$$K^{-1} = \int_{z_{min}}^{z_{max}} P_c(z)dz$$

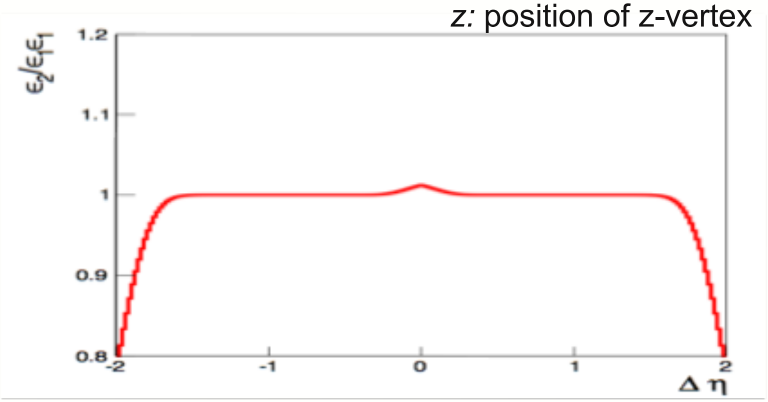
$$R_2(\eta_1,\eta_2) = \frac{f_2(\eta_1,\eta_2)}{f_1(\eta_1)f_1(\eta_2)}\frac{\langle N_2(\eta_1,\eta_2)\rangle}{\langle N_1(\eta_1)\rangle\langle N_1(\eta_2)\rangle}$$

Neither Methods Robust



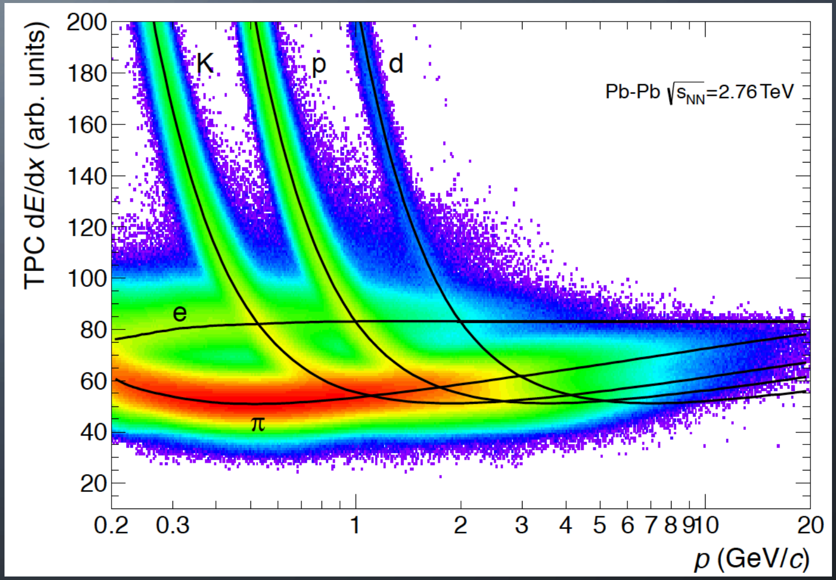
Solution: Small z-bins

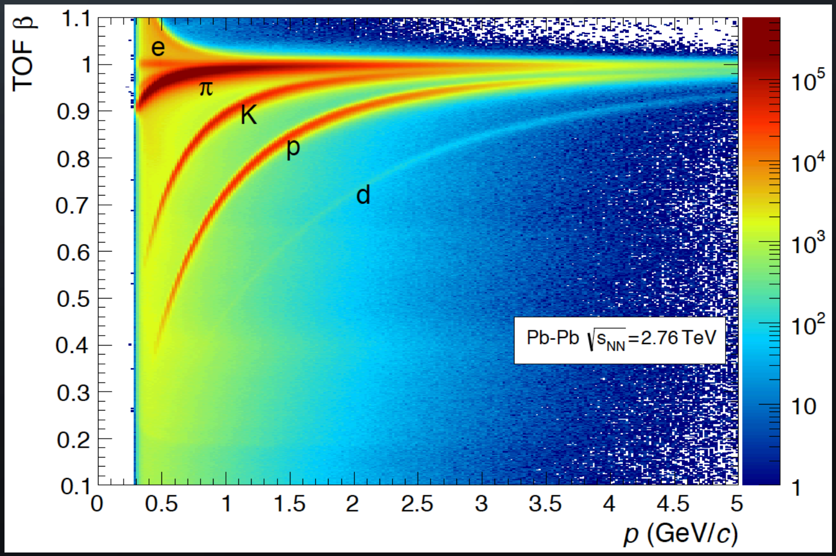
z: position of z-vertex



S. Ravan, P. Pujahari, S. Prasad and CAP, PRC 89, 024906 (2014).

Particle Identification at ALICE





Int. J. Mod. Phys. A 29 (2014) 1430044

Pion as an example:

$0.2<p_T<0.6$ GeV : TPC only

(Since TOF PID efficiency in this regime is low)

$n\sigma_{Pion}<2$

$n\sigma_{Kaon}>2$

$n\sigma_{Proton}>2$

$n\sigma_{Electron}>1$

$0.6<p_T<2.0$ GeV : TPC + TOF

$n\sigma_{Pion}<2$

$n\sigma_{Kaon}>2$

$n\sigma_{Proton}>2$

Purity of identified particles expected 95%-99% with veto cuts

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Summary

➢ ***For Unidentified Charged Particles:***

- BF widths in both Δη & Δϕ were found to decrease with increasing multiplicity for all systems only for low-p_T (for p_T<2 GeV/c). For higher p_T, the multiplicity-class dependence is significantly reduced, if not vanished, & correlations of balancing partners are stronger w.r.t low-p_T.

➢ ***For Identified Particles:***

- BF of identified charged pion pairs, charged kaon pairs, proton/anti-proton pairs, proton/k^- pairs are being measured right now by two separate groups using two different methods at ALICE for RUN I & RUN II data.
- For RUN I Pb-Pb, p-Pb and p-p data, pion BF can be measured without a problem while the statistics (~14M) may not be enough for kaon & protons.
- For RUN II, if the high luminosity Pb-Pb data can come without serious issues, all pion, kaon & proton BF can be measured with 160M events.

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Thank you!

Back-ups

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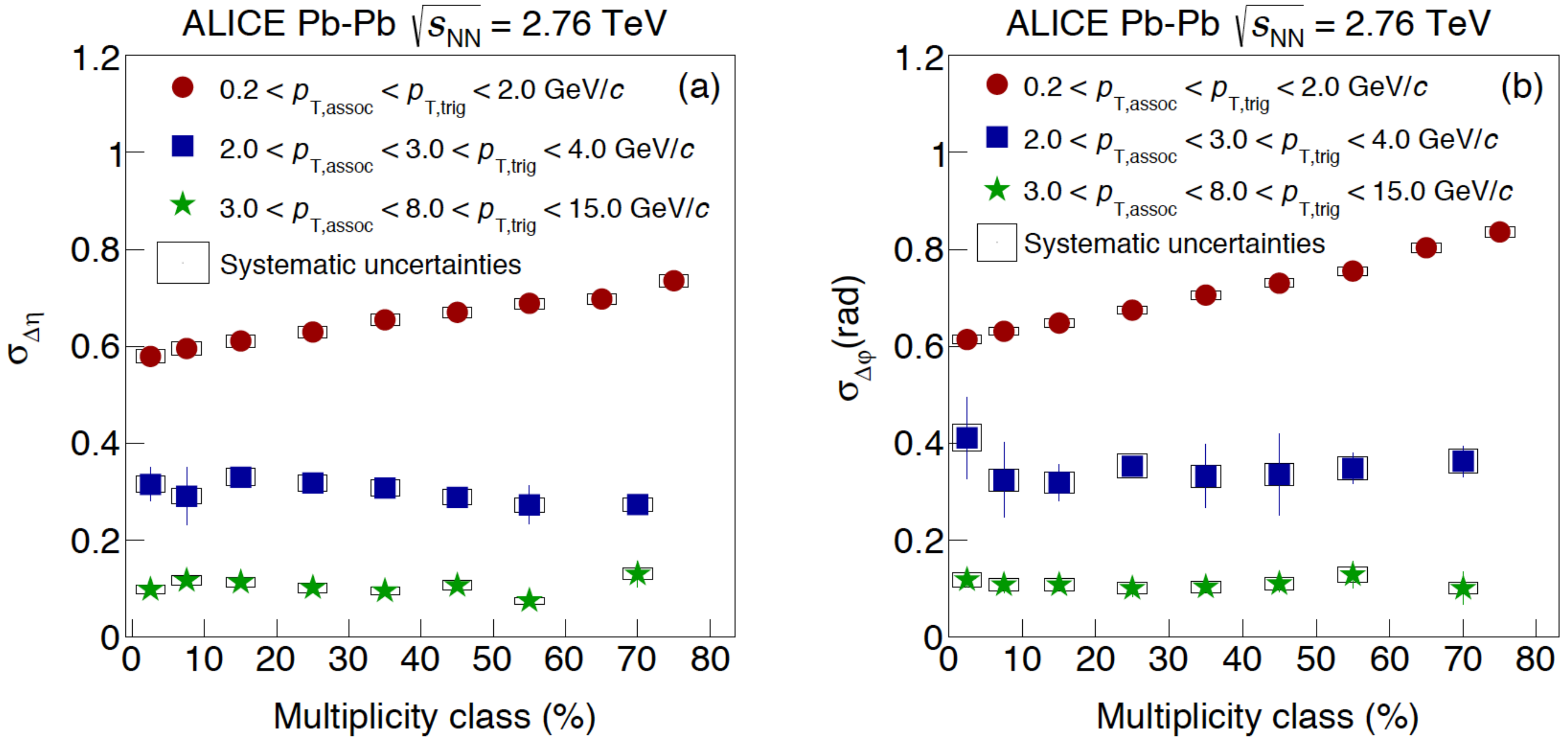
Balance Functions of All-Charged Particles



The observed narrowing of BF w/ increasing multiplicity is restricted to the lower p_T, i.e. where the bulk of particles are produced. For higher p_T, the multiplicity class dependence is significantly reduced, or even vanishes.

$\sigma_{\Delta\eta}$ & $\sigma_{\Delta\phi}$ decrease with increasing p_T for a given multiplicity class. This decrease can be attributed to the transition to a region where initial hard-scattering processes & parton fragmentation become the dominant particle production mechanism. The emerging hadrons are thus correlated within a cone whose angular size decreases w/ increasing p_T.