Event-by-event Hadron Yield Fluctuations in Pb—Pb Collisions at $\sqrt{s} = 2.76$ TeV with ALICE

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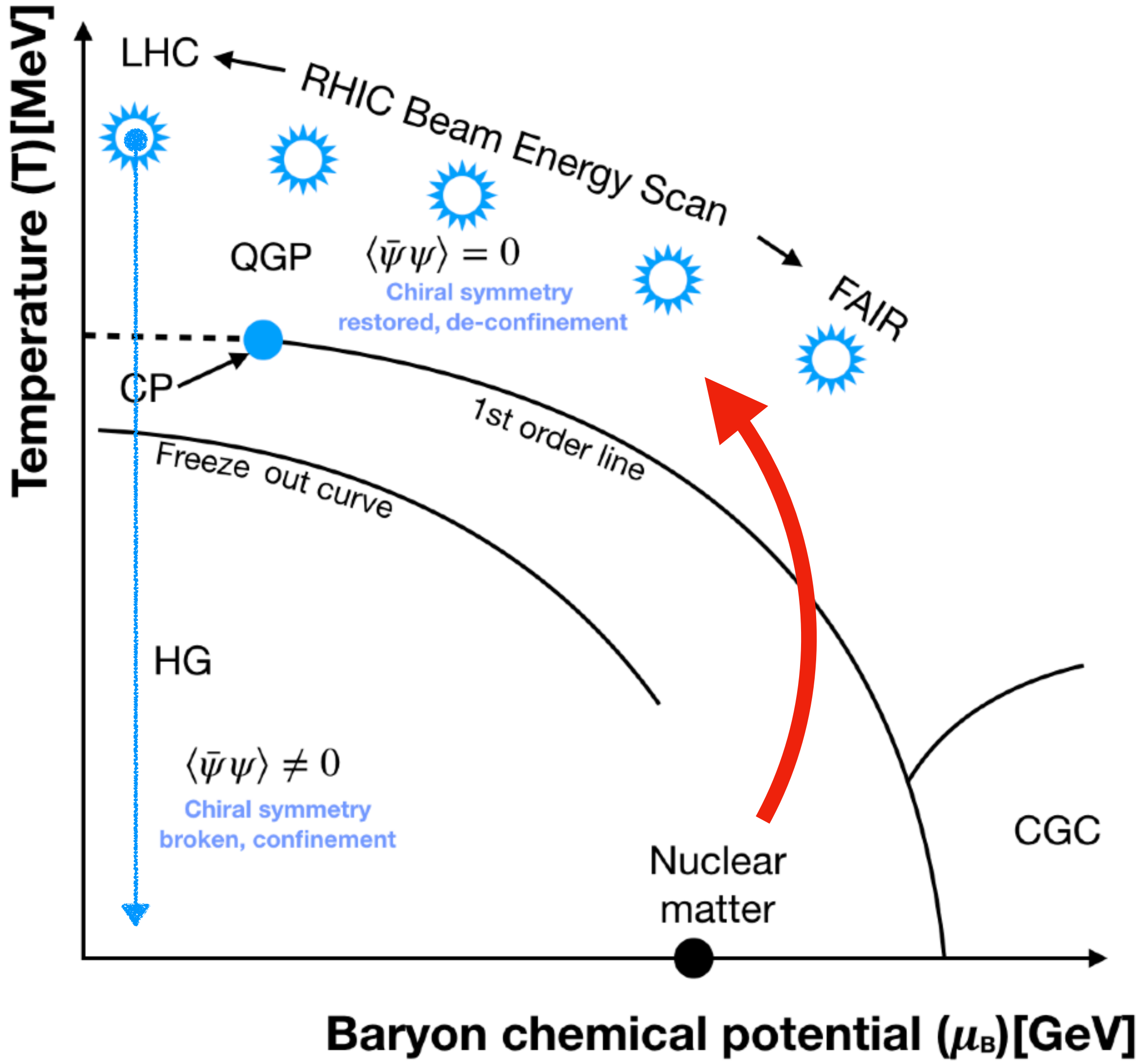
Outline

- Goal:
  - Search for DCCs in Kaon sector w/ scaled $\nu_{\rm dyn}$,
- Methodology + experimental Details,
- ALICE Results,
- DCC, DIC Models,
- Summary

ALICE Papers

- Phys. Rev. Lett. 110 (2013) 15, 152301
- Eur. Phys. J.C 79 (2019) 3, 236
- Phys. Lett. B 832 (2022) 137242, arXiv:2112.09482

Search for (Strange) Disoriented Chiral Condensates



- Two QCD Transitions:
  - **Confinement/Deconfinement**
  - ***Chiral Symmetry***
    - Broken in hadron phase,
    - Partially restored in QGP state (?)
    - Consequence: **Disoriented Chiral Condensates (DCC)**
- Do DCC exist?
  - Nature of chiral phase transition
  - Vacuum structure of strong interaction.

Sigma Model - Pion & Kaon Sectors

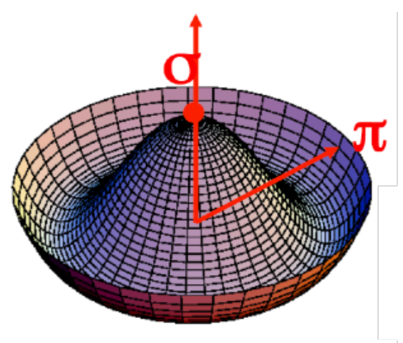
K.L. Kowalski, C.C. Taylor, hep-ph/9211282
K. Rajagopal, F. Wilczek, Nucl.Phys. B399 (1995) 395

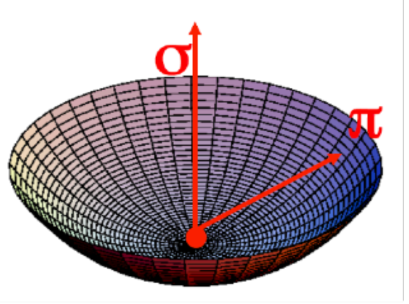
For 2nd order phase transition in QCD:
Landau-Ginzburg free energy w/ 2 massless quarks

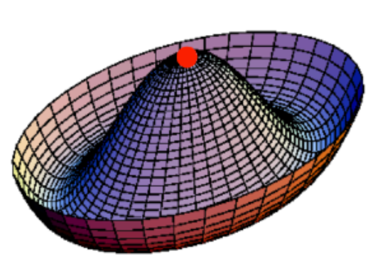
$$F = \int d^3x \left[\frac{1}{2}\partial^i\phi^\alpha\partial_i\phi^\alpha \frac{\mu^2}{2}\phi^\alpha\phi_\alpha \frac{\lambda}{4}\left(\phi^\alpha\phi_\alpha\right)^2 \right]$$

μ : renormalized mass (T)
λ: strength of coupling

Rewritten in terms of σ and $\vec{\pi}$ fields ("Mexican-hat" potential).





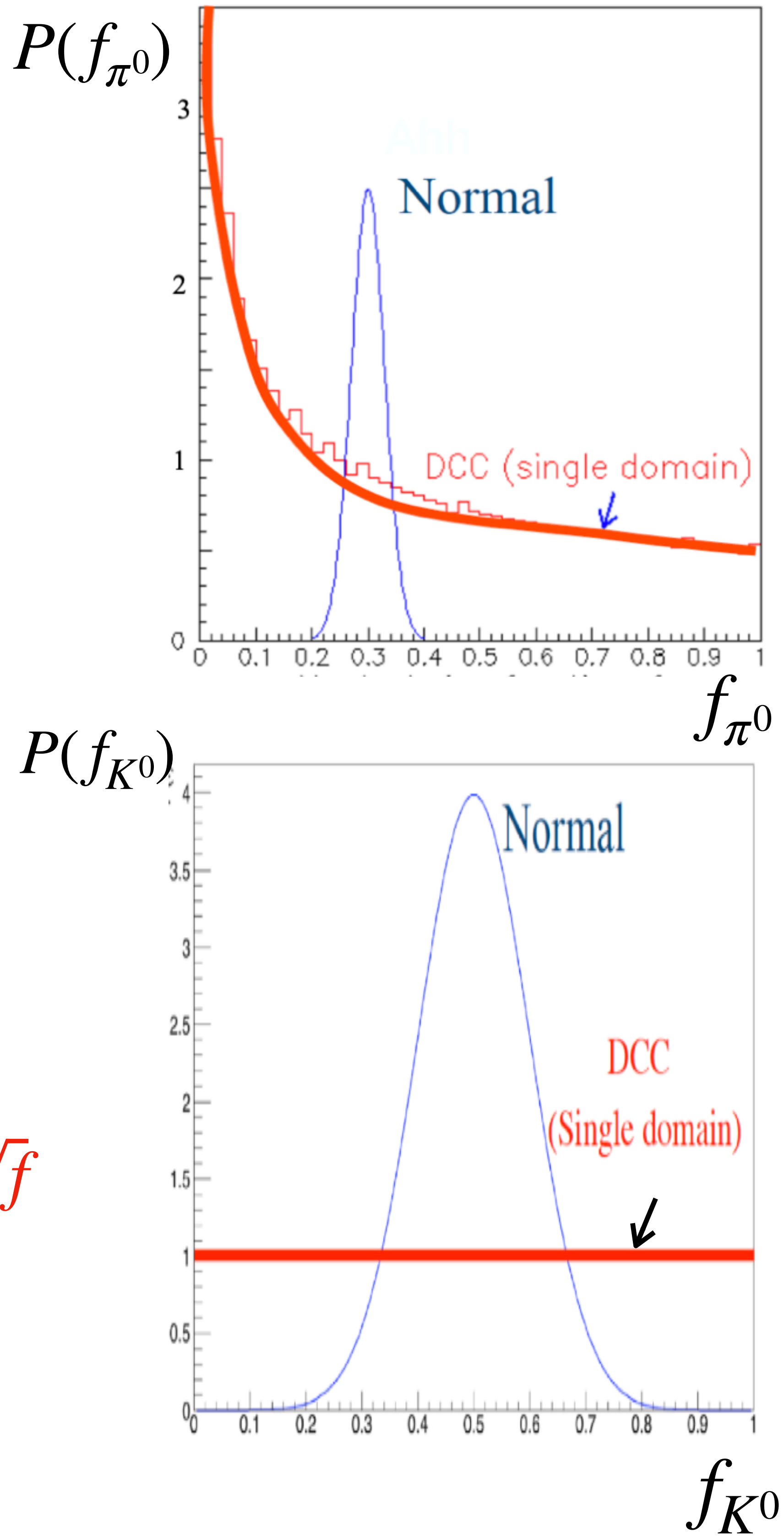


- **Condensates**:
  - 2 flavors: $\sigma \propto \langle \bar{u}u + \bar{d}d \rangle$
  - 3 flavors: $\sigma \propto \cos\theta\langle \bar{u}u + \bar{d}d \rangle + \sin\theta\langle \bar{s}s \rangle$
- **"Normal Vacuum"**:
  - π^+, π^-, π^0 equally probable.
  - $K^+, K^-, K^0, \bar{K}^0$ equally probable
- **Chiral symmetry restored at high-*T***
- **Quenching to low-*T***:
  - **New field "orientation"**
  - **Disoriented Chiral Condensate (DCC)**

K.L. Kowalski, C.C. Taylor, hep-ph/9211282
K. Rajagopal, F. Wilczek, Nucl.Phys. B399 (1995) 395.

DCC: Pions & Kaons Yield Fluctuation

- **“Normal Vacuum”**:
  - **π^+, π^-, π^0 equally probable.**
    - $f_{\pi^0} = \dfrac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^-} + N_{\pi^+}}$;
    - $P(f_{\pi^0}) = B(1/3; N)$
  - **$\mathrm{K}^+, \mathrm{K}^-, \mathrm{K}^0, \bar{\mathrm{K}}^0$ equally probable**
    - $f_{\mathrm{K}^0} = \dfrac{N_{\mathrm{K}^0} + N_{\bar{\mathrm{K}}^0}}{N_{\mathrm{K}^0} + N_{\bar{\mathrm{K}}^0} + N_{\mathrm{K}^-} + N_{\mathrm{K}^+}}$
    - $P(f_{\mathrm{K}^0}) = B(1/2; N)$
- **DCC**:
  - Fluctuations of π^0 vs. π^+, π^-: **Pion DCC**.
    - “Pulse” of low p_{T} pions w/ $P(f_{\pi^0}) = 0.5/\sqrt{f}$
  - Fluctuations of $\mathrm{K}^0, \bar{\mathrm{K}}^0$ vs. $\mathrm{K}^+, \mathrm{K}^-$: **Kaon DCC**.
    - “Pulse” of low p_{T} kaons w/ $P(f_{\mathrm{K}^0}) = 1$



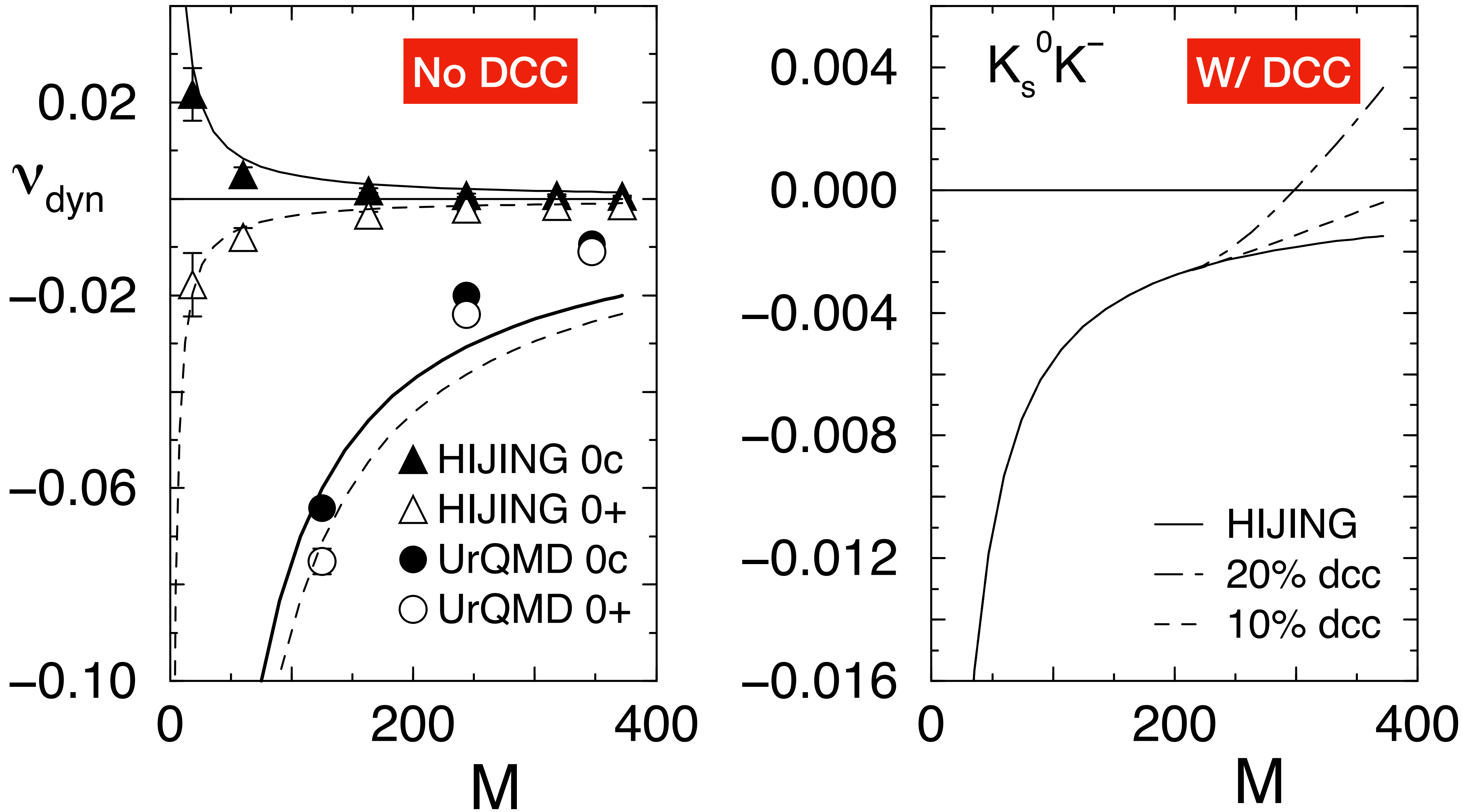
Past theoretical and experimental studies

- **Found 138 publications on DCCs in inspirehep.net**
- Mostly theoretical works on DCCs in the **pion sector**
  - *Evidences for New Type of Cosmic Ray Nuclear Interactions Named CENTAURO*, M. Tamada, Nuovo Cim B41 (1977) 245.
  - *Explosive Quark Matter and the CENTAURO Event*, J.D. Bjorken and L. McLerran, PRD 20 (1979) 2353.
  - ***Baked Alaska*,** J.D. Bjorken et al. SLAC-PUB-6109.
- **Few theoretical works on strange DCCs**
  - *Is anomalous production of Omega and anti-Omega evidence for disoriented chiral condensates?*, J. Kapusta, *et al.*, PRL 86 (2001) 4251.
  - ***Kaon and pion fluctuations from small disoriented chiral condensates***, S.Gavin, J. Kapusta, PRC 65 (2002) 054910.
  - Strange disoriented chiral condensate, S. Gavin, 18th WWND (2002).
- Very few experimental searches — **All with negative or non-conclusive results**:
  - Minimax @ Tevatron: J.D. Bjorken *et al.*, PRD 55 (1997) 5667; T.C. Brooks et al., PRD 61 (2000) 032003.
  - WA98 @ SPS: T. K. Nayak, Nucl.Phys. A 638 (1998) 249c; M.M. Aggarwal, PLB 701 (2001) 300.
  - STAR @ RHIC: S.M. Dogra *et al.*, J. Phys.G 35 (2008) 104094.
  - E864 @ AGS: P. Fachini (Thesis, Wayne State), *et al.,* APS Meeting, (1999).

DCC in Kaon Sector Detectable w/ $\nu_{\text{dyn}}[K_s^0, K^\pm]$

S. Gavin, J. Kapusta PRC 65 (2002) 054910
S. Gavin, et al., Nucl.Phys.A 715 (2003) 657, J.Phys.G 30 (2004) S271

Kaon isospin fluctuations measurable with ν_{dyn} observable.



In this talk…

- **Seek evidence** for DCC-like fluctuations in the **kaon sector**.
  - Measurements with $\nu_{\rm dyn}^{\alpha\beta}$ observable (See next slide).
- **ALICE measurements in Pb—Pb collisions @ 2.76 TeV.**
  - Compare data w/ calculations from various models to establish a reference or “baseline”: **HIJING, AMPT, EPOS**.
- Establish “basic expectations” or “normal evolution” vs. collisions centrality.
- Identify anomalous behaviors if any!

$\nu_{\rm dyn}^{\alpha\beta}$ Observable definition

Definition: C.P., S. Gavin, S. Voloshin, PRC 66 (2002) 044904; Nucl.Phys.A 715 (2003) 661.

Multiplicity of species α, β within acceptance in a given event: N_α, N_β

Ensemble average multiplicity of species α, β: $\langle N_\alpha \rangle, \langle N_\beta \rangle$

Average number of pairs: $\langle N_\alpha (N_\beta - \delta_{\alpha\beta}) \rangle$

Integral correlators:

$$R_{\alpha\beta} = \frac{\langle N_\alpha (N_\beta - \delta_{\alpha\beta}) \rangle}{\langle N_\alpha \rangle \langle N_\beta \rangle}$$

Nu-dyn:

$$\nu_{\rm dyn}^{\alpha\beta} = R_{\alpha\alpha} + R_{\beta\beta} - 2R_{\alpha\beta}$$

Robust observables (approx. independent of efficiencies)

Scaling property
Superposition of n independent sources

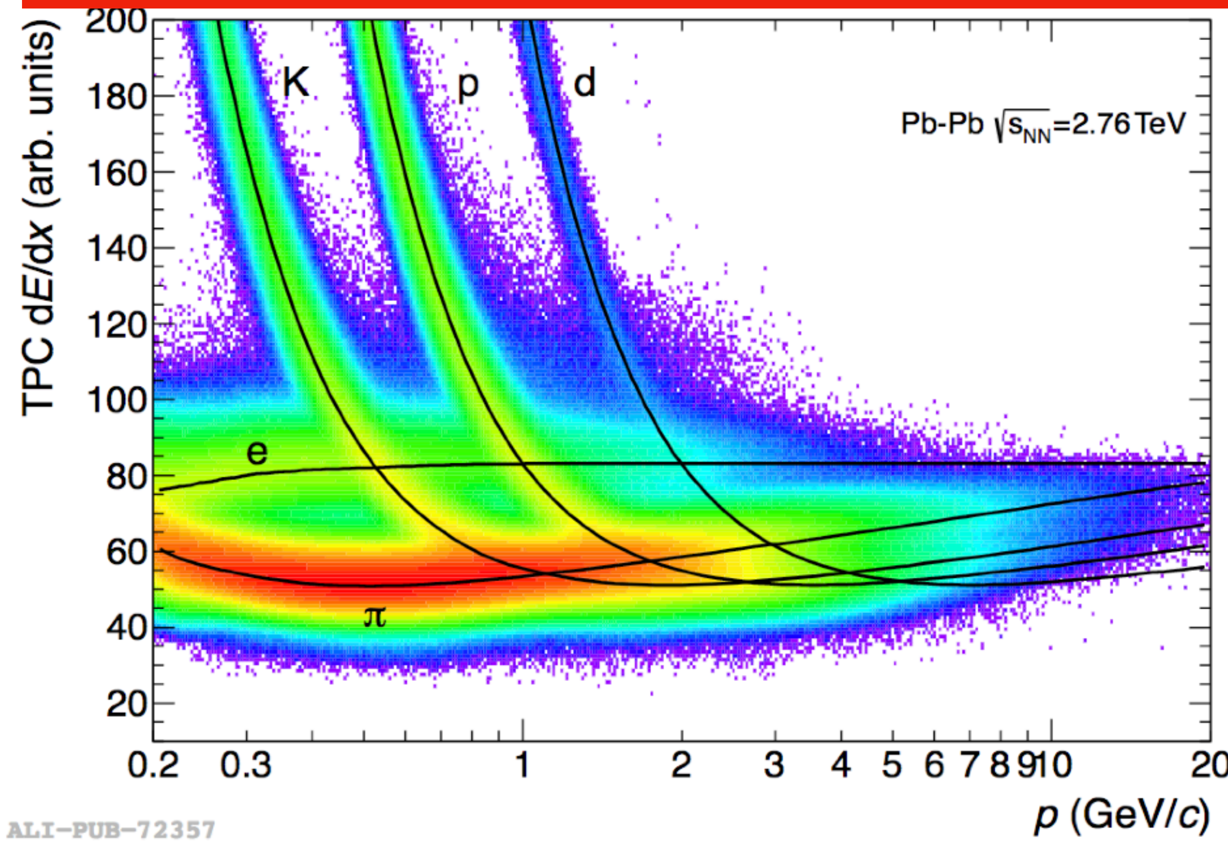
$$R_{\alpha\beta}^{(\rm n)} = \frac{1}{n} R_{\alpha\beta}^{(1)} \Rightarrow \nu_{\rm dyn}^{(\rm n)} = \frac{1}{n} \nu_{\rm dyn}^{(1)}$$

$\nu_{\rm dyn}^{+,-}$ Indicator of deconfinement:
S. Jeon, V. Koch, Phys. Rev. Lett. 85, 2076 (2000).
H. Heiselberg, A.d. Jackson, Phys. Rev. C63 (2001) 064904.

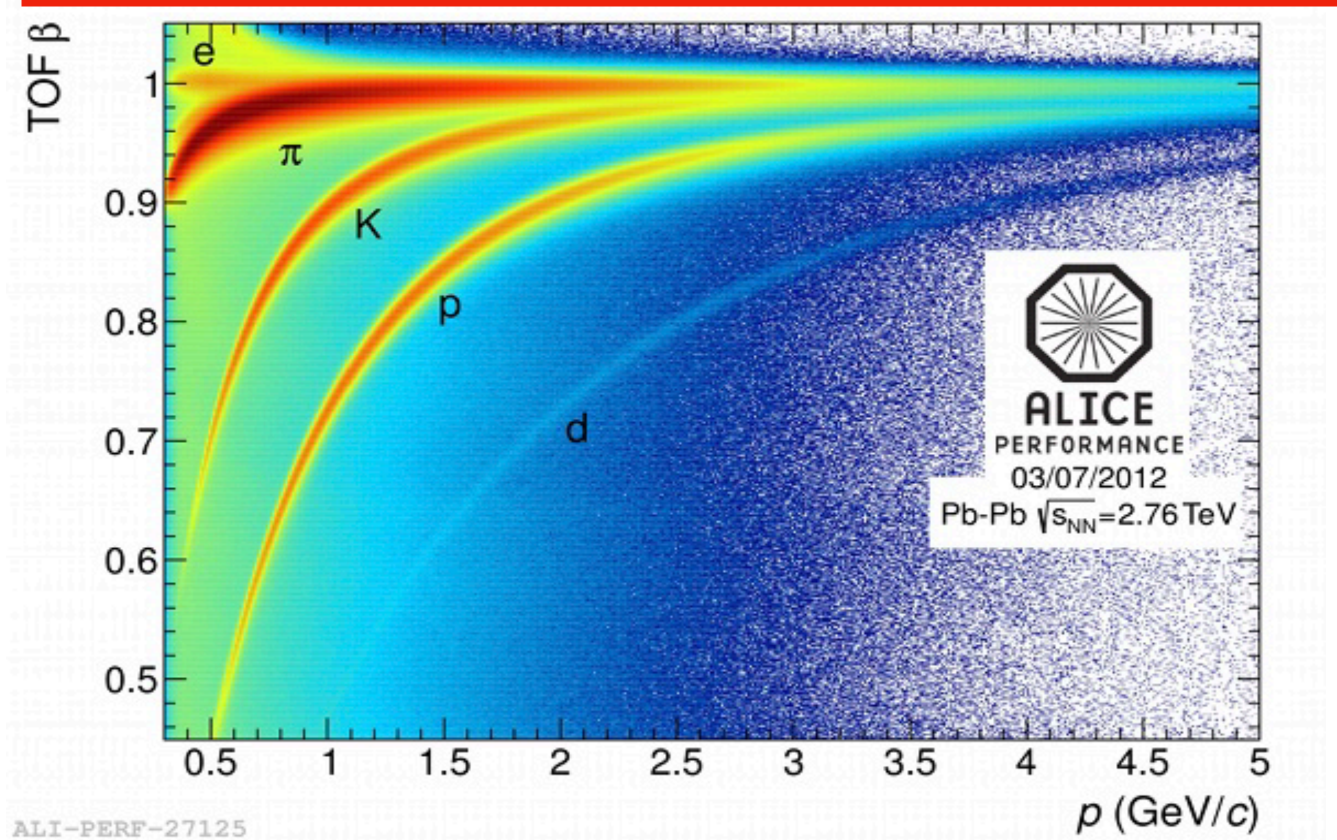
$\nu_{\rm dyn}[{\rm K}^{\pm}, {\rm K}^0]$ Indicator of anomalous kaon isospin fluctuations (DCC):
S. Gavin, J. Kapusta, PRC 65 (2002) 054910.
Feasibility study w/ toy model:
R. Nayak, S. Dash, C.P., PRC 004900 (2020).

$\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$ identification/classification

TPC: dE/dx vs p



TOF velocity vs p



$n\sigma$ method:

- Event-by-event Counting
- Candidates: $n\sigma$ method
- $$n\sigma = \frac{1}{\sigma\left(\frac{dE}{dx}\right)}\left[\left|\frac{dE}{dx}\right|_{\text{measured}} - \left|\frac{dE}{dx}\right|_{\text{particle}}\right]$$
- Similarly w/ TOF signal.
- **Contamination 1-3 %**

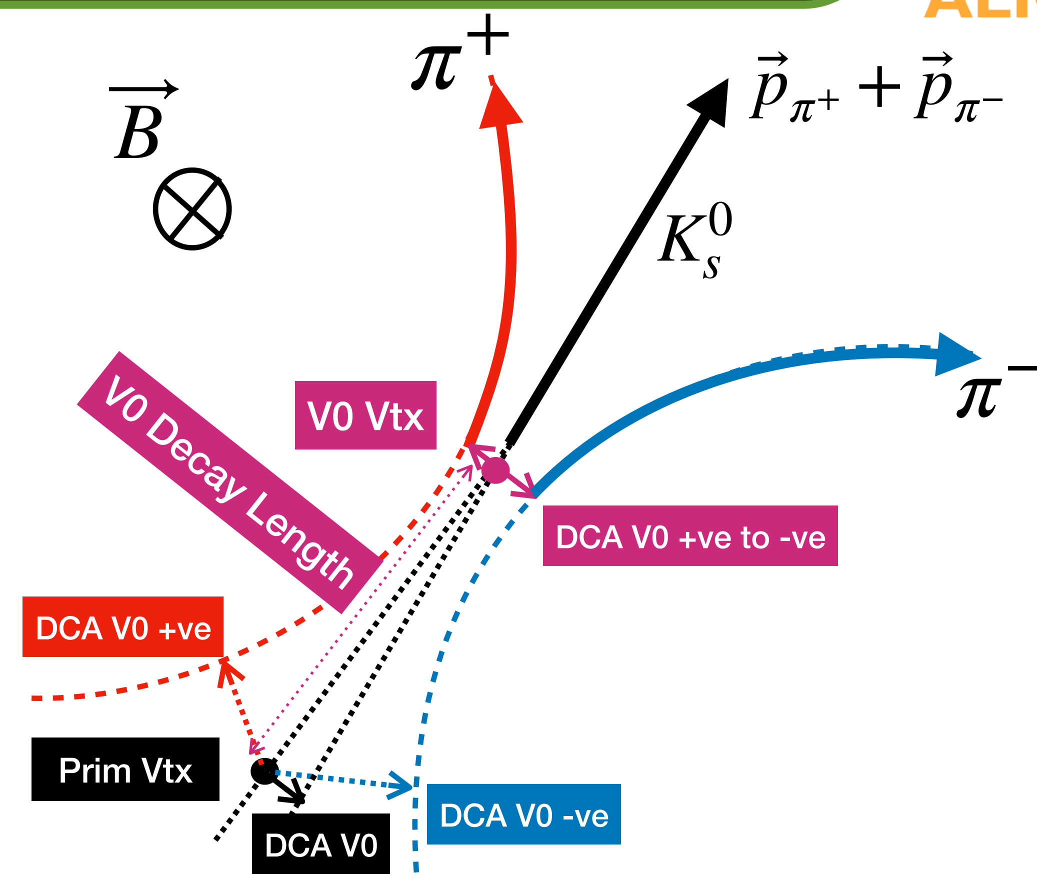
Identity method:

[1] M. Gazdzicki et al., Phys. Rev.C 83 (2011) 054907
[2] M.I. Gorenstein, Phys.Rev.C 84 (2011) 024902
[3] A. Rustamov, Phys.Rev.C 86 (2012) 044906
[4] C. Pruneau, Phys.Rev.C 96 (2017) 5, 054902
[5] C. Pruneau, Alice Ohlson, Phys.Rev.C 98 (2018) 1, 014905

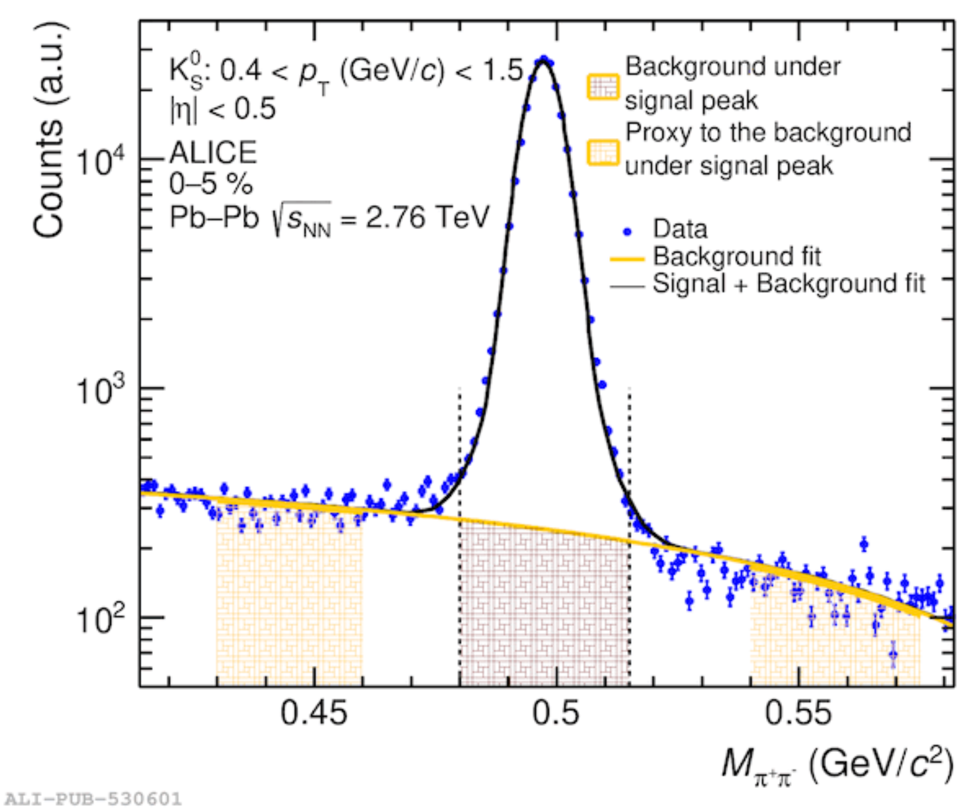
K_s^0 identification & selection

ALICE, Phys. Lett. B 832 (2022) 137242

- Standard ALICE topological (V0) selection criteria,
  - See backup for details.
- Invariant mass selection,
- Kinematic selection:
  - y < 0.5,
  - 0.4 < p_T < 1.5 GeV/*c*.

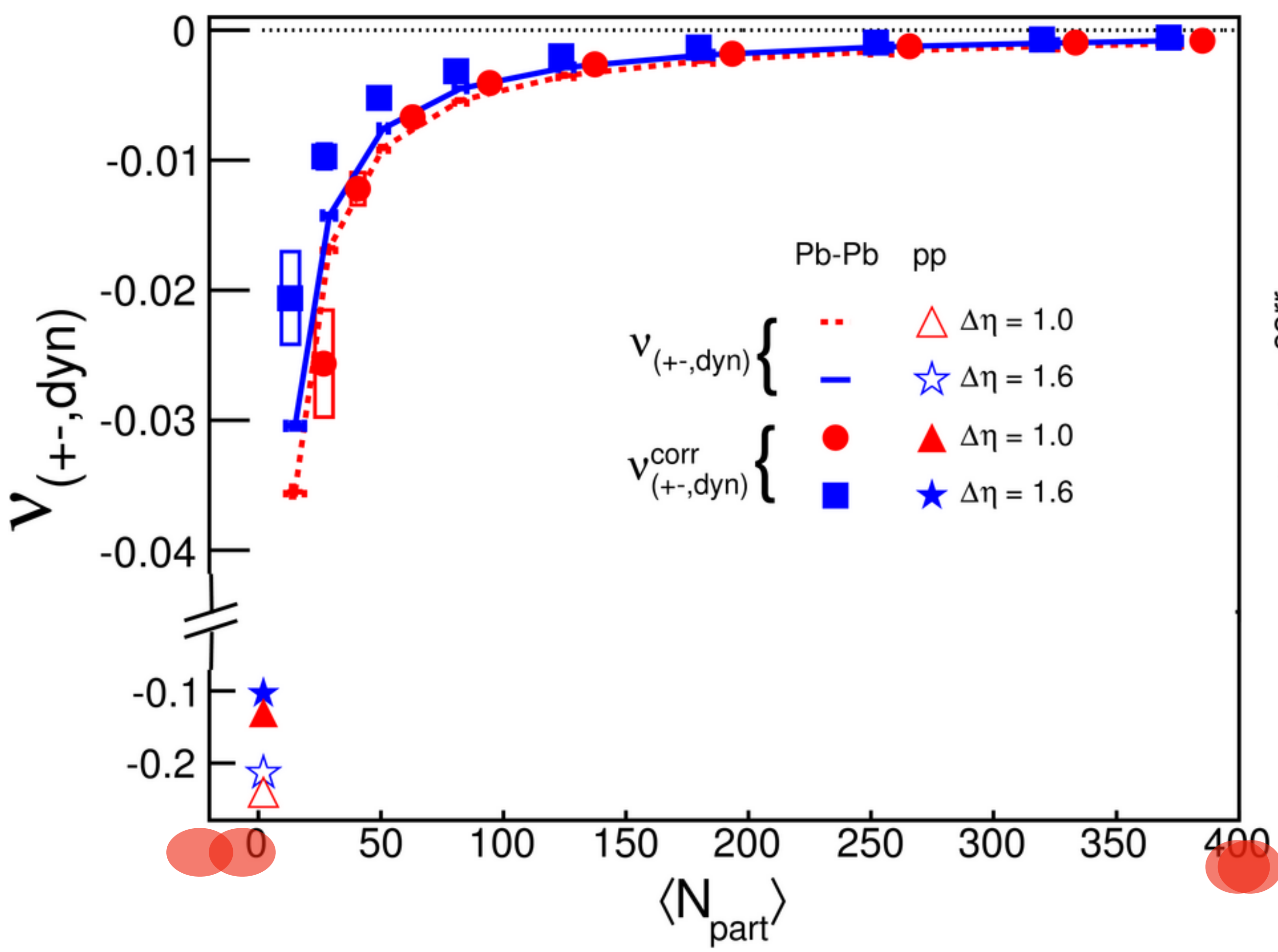


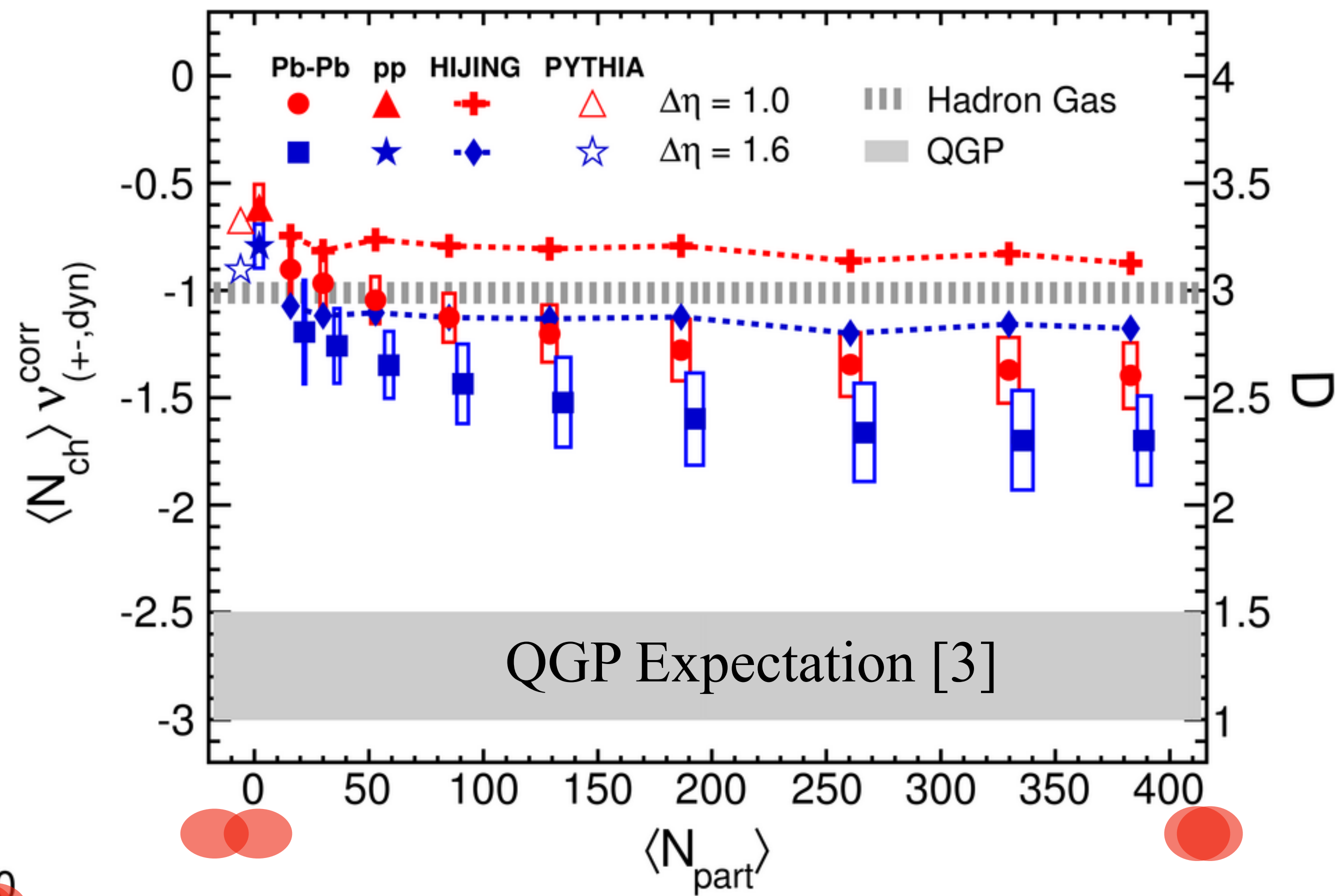
- Event-by-event Counting:
- Candidates:
  - $0.48 < M_{inv}(\pi^+\pi^-) < 0.515$ GeV/c^2
  - **Contamination 1-4 %**
- Background (fluctuations) estimate:
  - From side bands



Net charge fluctuations

ALICE, Phys. Rev. Lett. 110 (2013) 15, 152301





Correction [1]: $\nu^{corr}_{(+-,dyn)} = \nu_{(+-,dyn)} + \frac{4}{\langle N_{total} \rangle}$.

- Magnitude of HIJING prediction "incorrect",
  - **But basic trend OK.**
- *Approximate 1/N scaling observed*.
- Corroborate earlier observations by STAR [2].

Indicator of deconfinement [3]

Q = N+ − N−

$$D = \langle N_{ch} \rangle \langle \delta R^2 \rangle \approx 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle}$$

$$D' = \langle N_{ch} \rangle \nu^{corr}_{(+-,dyn)} + 4.$$

[1] C.P., S. Gavin, S. Voloshin, PRC 66 (2002) 044904
[2] STAR, Phys.Rev.C 79 (2009) 024906
[3] S. Jeon and V. Koch, Phys. Rev. Lett. 85, 2076 (2000)

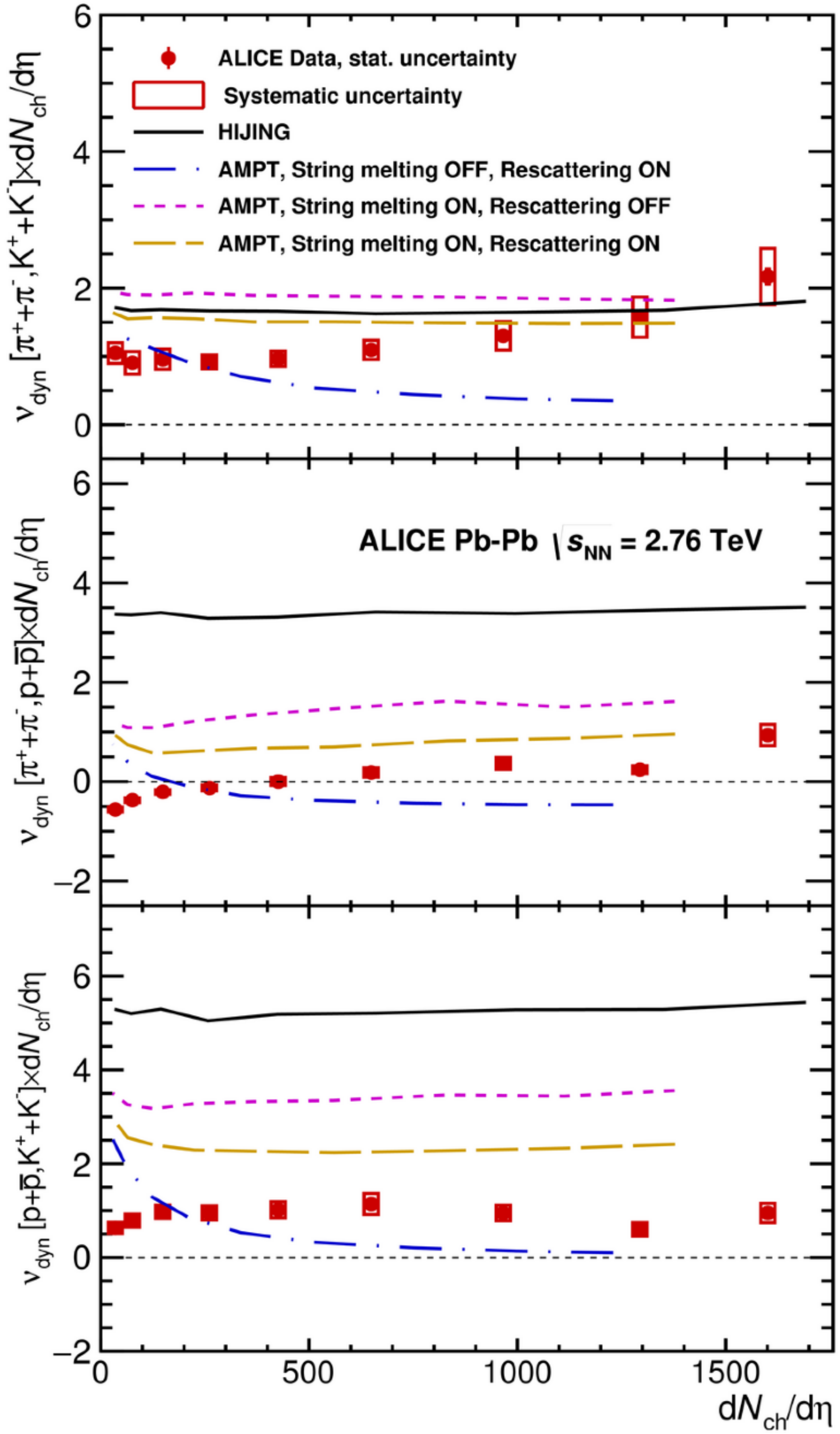
Mixed species yield fluctuations

ALICE, Eur. Phys. J.C 79 (2019) 3, 236

Analysis w/ Identity Method [1-5]

Shown: scaled $\nu_{\mathrm{dyn}}^{\alpha\beta}$

$$\nu_{\mathrm{dyn}}^{\alpha\beta} \times \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}$$



$\pi^{\pm}$ vs. $K^{\pm}$

Approximate 1/N scaling observed

$\pi^{\pm}$ vs. $p, \bar{p}$

Sign change
Scaling violation

$K^{\pm}$ vs. $p, \bar{p}$

Approximate 1/N scaling observed

[1] M. Gazdzicki et al., Phys. Rev.C 83 (2011) 054907
[2] M.I. Gorenstein, Phys.Rev.C 84 (2011) 024902
[3] A. Rustamov, Phys.Rev.C 86 (2012) 044906
[4] C. Pruneau, Phys.Rev.C 96 (2017) 5, 054902
[5] C. Pruneau, Alice Ohlson, Phys.Rev.C 98 (2018) 1, 014905

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Combinatorial background and correction

Single yields:

N_c : Number of $K^{\pm}$

N_s : Number of signal K^0_s

N_b : Number of background pairs

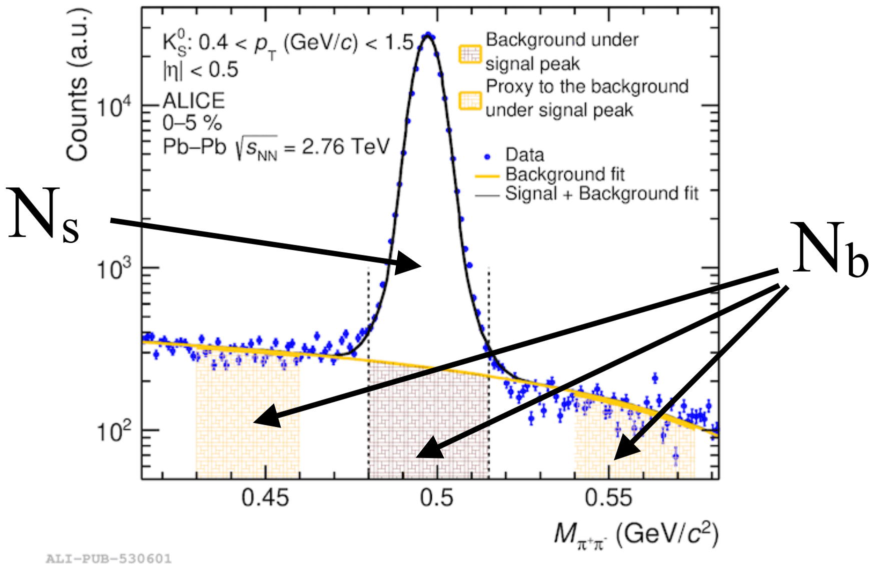
$N_0 = N_s + N_b; \quad f_b = N_b/N_0$

Pair yields

$N_{00} = N_{ss} + N_{bb} + 2N_{sb}$

$N_{ss} = N_{00} - N_{bb} - 2N_{sb}$

$N_{sc} = N_{0c} - N_{bc}$



Use "side windows" to estimate yield of background in the signal region. Example:

$$\frac{\langle N_s(N_s-1)\rangle}{\langle N_s\rangle^2} = \frac{\langle N_0(N_0-1)\rangle}{\langle N_0\rangle^2} - \frac{2f}{(1-f)^2}\frac{\langle N_0 N_b\rangle}{\langle N_0\rangle\langle N_b\rangle} + \frac{f^2}{(1-f)^2}\frac{\langle N_b N_b\rangle}{\langle N_b(N_b-1)\rangle\langle N_b\rangle}$$

Corrected ν_{dyn} based on side mass windows

$$\nu_{dyn}^{corrected} = \frac{\langle N_c(N_c-1)\rangle}{\langle N_c\rangle^2} + \frac{\langle N_s(N_s-1)\rangle}{\langle N_s\rangle^2} - 2\frac{\langle N_c N_s\rangle}{\langle N_c\rangle\langle N_s\rangle}$$

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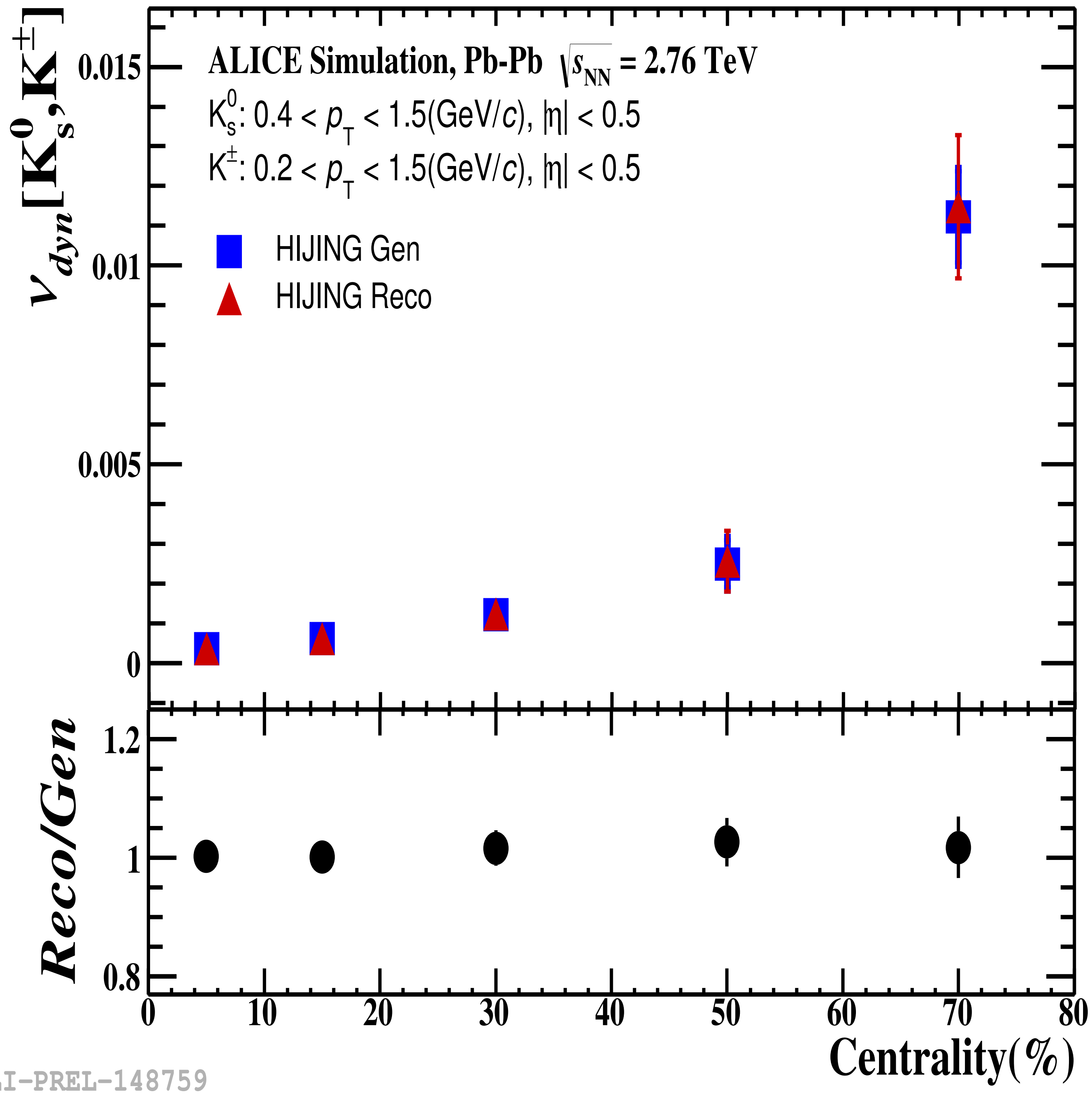
Closure test

- Test performed with HIJING + ALICE/GEANT
- Analysis done at
  - Generator level (Gen)
  - GEANT processed + full reconstruction (Reco)



Seek evidence for DCCs in the strange sector

$K^{\pm}$ vs. K^0 fluctuations

$$\alpha = \left(\langle K_s^0\rangle^{-1} + \langle K^{\pm}\rangle^{-1}\right)$$

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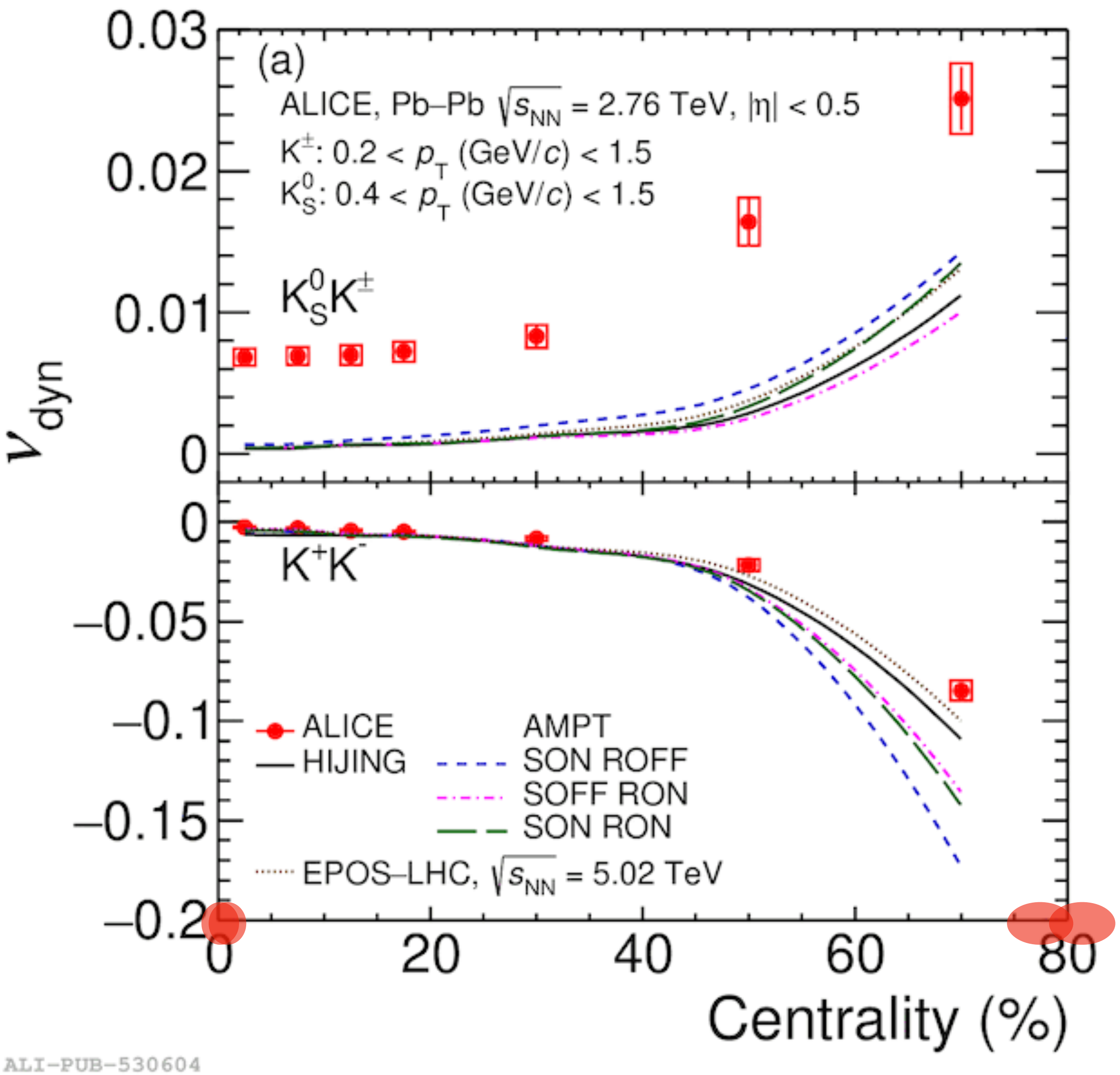

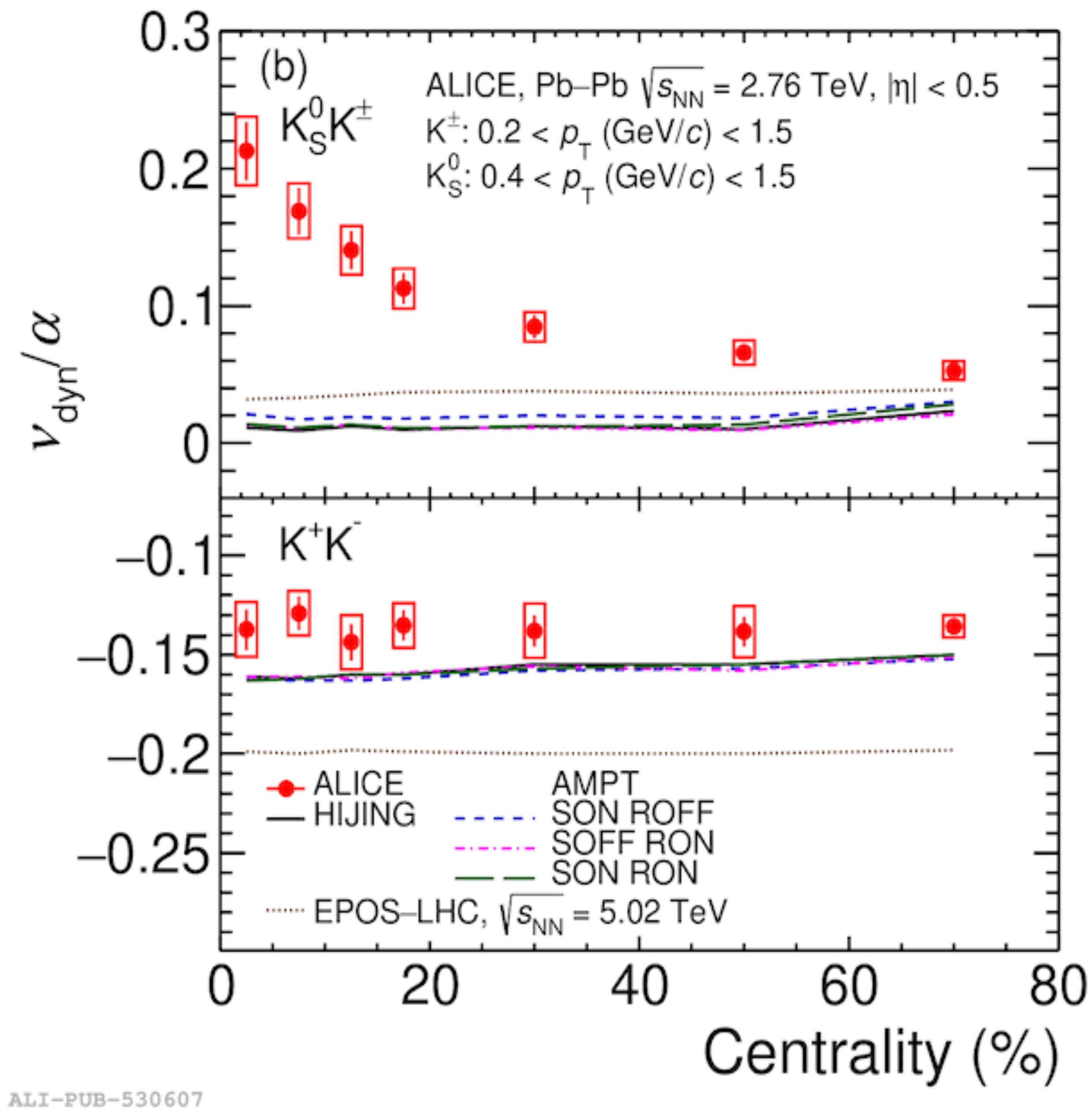

$\nu_{dyn}^{K^+K^-} < 0 \rightarrow K^+K^-$: pair creation dominance;
Data & models feature approx. 1/N scaling;
Models qualitatively reproduce data.

$\nu_{dyn}^{K^{\pm}K^0}$: strong $\alpha \propto 1/N$ scaling vibration;
All models feature α scaling and underpredict data.

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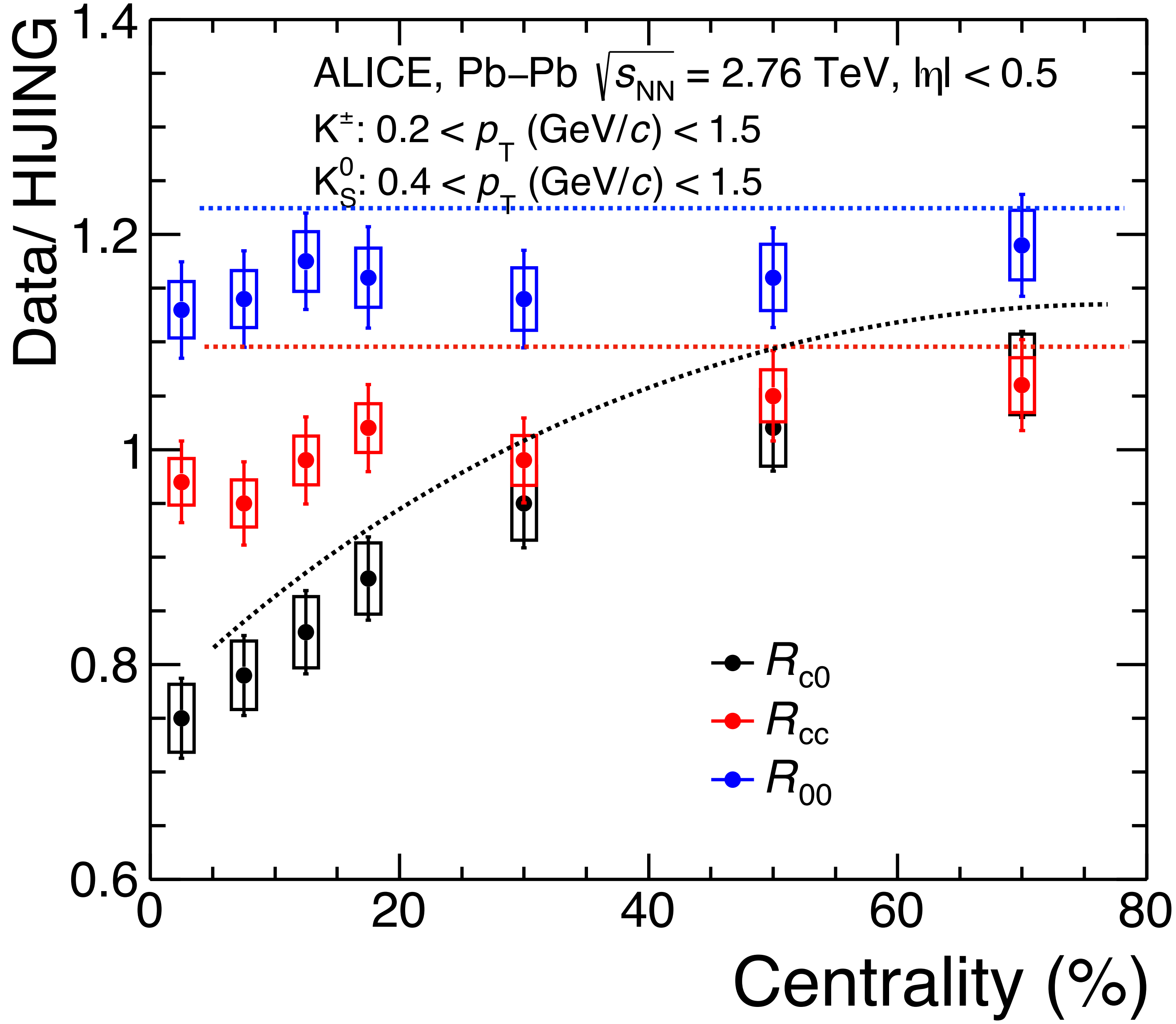
Where is the excess (scaling violation) from?

Exploit HIJING approximate 1/N scaling

Study ratios of data to HIJING for three terms of ν_{dyn}

$$\nu_{dyn}^{K^+K^-} = R_{00} + R_{cc} - 2R_{c0}$$



- Variance terms have little to no centrality dependence.
  - Approx.1/N scaling.
- Covariance term varies by more than 20% with centrality.
- Excess of ν_{dyn} in central collisions from the covariance term.
  - **Expected from fluctuations caused by DCC fluctuations.**

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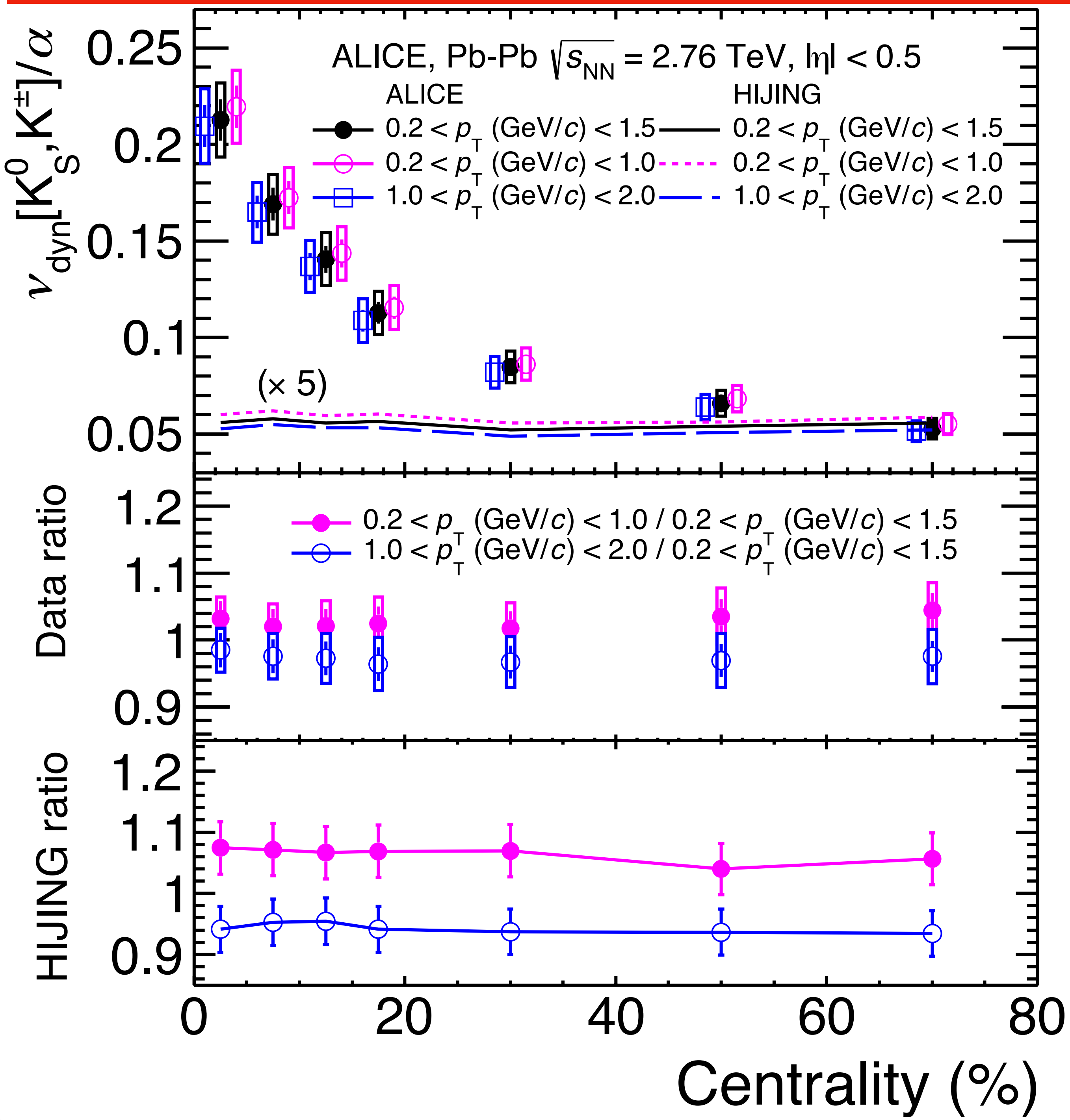
p_T Range Dependence ??

DCC expected to be more prominent at lower p_T

Study p_T dependence of $\nu_{dyn}[K_s^0 K^{\pm}]$



- $\nu_{dyn}[K_s^0 K^{\pm}]$
- Data:
  - Scaling violation in both p_T ranges
  - Marginally weaker at "higher" p_T
  - p_T dependence within systematic errors.
- HIJING:
  - Amplitude exhibits small (finite) dependence on p_T range
- **No evidence for a DCC "surge" at low p_T.**

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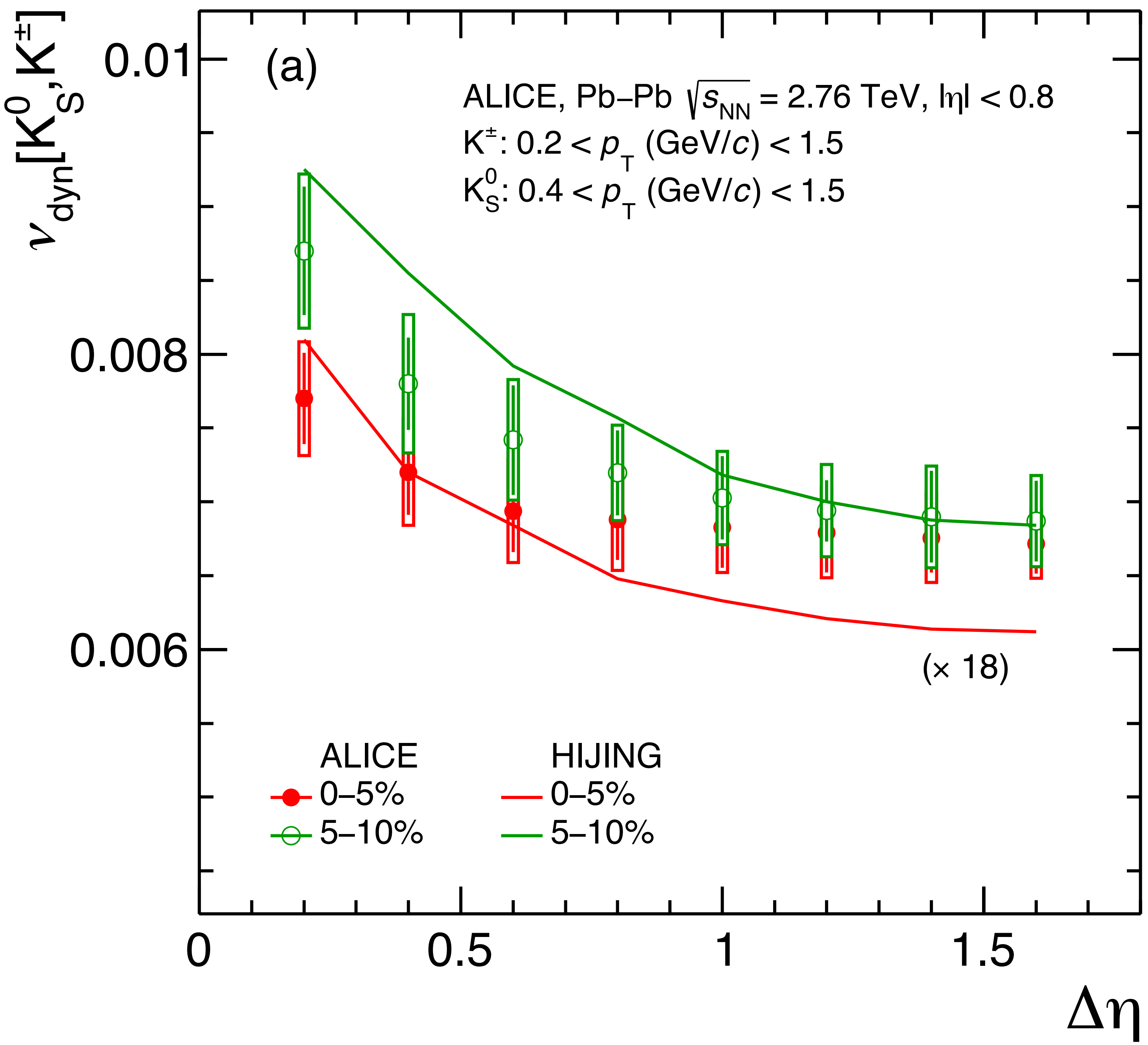
Rapidity Range Dependence



$\Delta\eta$ correlation features "narrow" peak atop broad distribution.
Not readily compatible with DCC production.

DCC & DIC Theoretical Models

J. Kapusta, S. Pratt, M., Singh, Phys.Rev.C 107 (2023) 014913.

- DCC: Disoriented Chiral Condensate Model
- Examined several scenarios of kaon production, e.g., charge conservation effects, Bose symmetrization, resonance decays, degenerate kaons from condensates.
- Concluded condensates provide the only way to explain ALICE results.

J. Kapusta, S. Pratt, M., Singh, 2306.13280 [hep-ph]

- DIC: Disoriented Isospin Condensate Model

- ***"If the scalar condensate, which is typically associated with chiral symmetry, is accompanied by an isospin=1 field, then the combination can produce large fluctuations where $\langle \bar{u}u \rangle \neq \langle \bar{d}d \rangle$.***
- **Hadronizing strange and anti-strange quarks might then strongly fluctuate between charged ($u\bar{s}$, $s\bar{u}$) and neutral ($d\bar{s}$ or $s\bar{d}$) kaons"**

DCC or DIC?

J. Kapusta, S. Pratt, M., Singh, 2306.13280 [hep-ph]

- $I = 0$ iso-singlet: $(\langle \bar{u}u \rangle + \langle \bar{d}d \rangle)/\sqrt{2}$
  - Lowest excitation: $f_0(500)$ or σ meson.
- $I = 1$ iso-triplet: $\langle \bar{d}u \rangle, (\langle \bar{u}u \rangle - \langle \bar{d}d \rangle)/\sqrt{2}, \langle \bar{u}d \rangle$
  - Lowest excitations: a_0^+, a_0^0, a_0^-, i.e, $a_0(980)$

- If only $I = 0$ field were present,
  - It should **couple equally to charged and neutral kaons**.
- If both $I = 1, I_3 = 0$ and $I = 0, I_3 = 0$ contribute in similar amounts,
  - They could combine to form nearly all $\langle \bar{u}u \rangle$ or all $\langle \bar{d}d \rangle$ condensates.
  - Provides seed for the formation of charged and neutral kaons, respectively… leading to isospin kaon fluctuations.
  - Authors given concrete estimates of number of DIC needed to explain measured values given the observed number of kaons.
- ***"Although the DIC mechanism investigated here is speculative, it seems to be the least questionable explanation for the ALICE measurement of*** ν_{dyn} ***thus far".***

Summary.

- Measurements of **yield fluctuations/correlations** with $\nu_{\rm dyn}^{\alpha\beta}$ observable
  - Pb — Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV
- **Approximate 1/N scaling for several species pairs** …
  - h^+ vs. h^- (charged hadrons); $\pi^\pm$ vs. $\rm K^\pm$; $\rm p, \bar{p}$ vs. $\rm K^\pm$; $\rm K^+$ vs. $\rm K^-$
  - Data for h^+ vs. h^- and $\rm K^+$ vs. $\rm K^-$ approximately matched by models
- **Strong 1/N scaling violations in**
  - $\pi^\pm$ **vs.** $\rm p, \bar{p}$
    - Data not described by available MC models; Evolution NOT understood.
  - $\rm K^\pm$ **vs.** $\rm K^0$
    - Data not described by available MC models.
    - But $p_{\rm T}$ **dependence of** $\nu_{\rm dyn}$ **NOT strong/compelling in support of DCC.**
    - **Scaling violation compatible with DCC or DIC production.**
- **Interpretation in terms of DCCs or DICs still highly speculative**…
  - Strong interest in extending measurements to other systems/energies and more differential measurements.

Backup Materials

K_s^0 Identification & Selection

- Standard ALICE Topological (V0) selection criteria
  - Decay length $< 3c\tau$
  - cos(PA) > 0.99
  - Armenteros cut: $p_T^{ARM} > 0.2|\alpha|$
  - $DCA_{pv} > 0.1$cm
  - ν_{dyn} approximately robust
  - Invariant mass selection criterion
    - $0.48 < M_{inv}(\pi^+\pi^-) < 0.515$ GeV/c^2
  - Use p_T dependent efficient correction
- Kinematic selection criterion (acceptance)
  - $|y| < 0.5$
  - $0.4 \leq p_T < 1.5$ GeV/c