Angular correlations of particle yield ratios

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Intro: observables for heavy-ion collision studies

In central Pb-Pb collisions at LHC energies, ~2000 particles within $|\eta|<0.5$.

Many "event-averaged" observables can be studied: particle yields, spectra, flow harmonics…

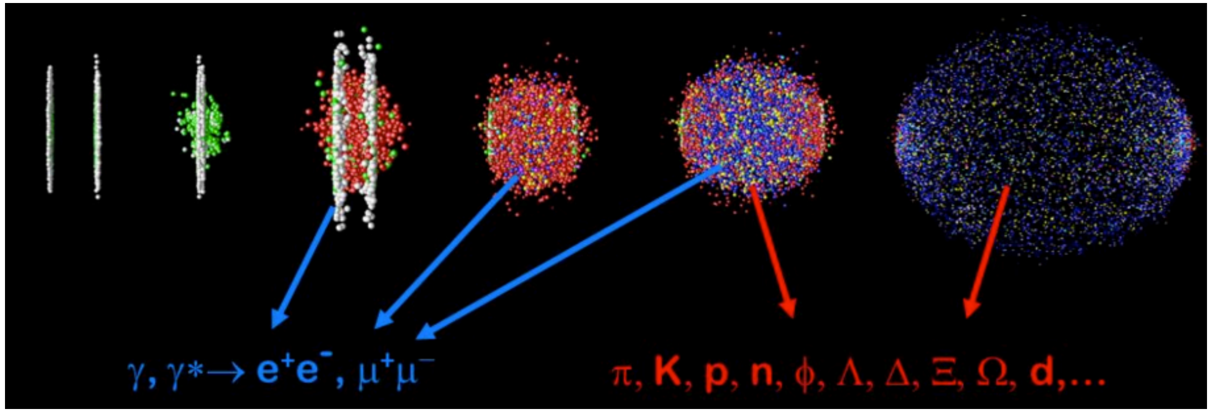
More differentially, one can study correlations, e.g. in emission angles

Event-by-event measurements:
the fluctuations are studied over the ensemble of the events.

- fluctuating net-charge, number of protons, mean p_T, forward-backward yields, etc.

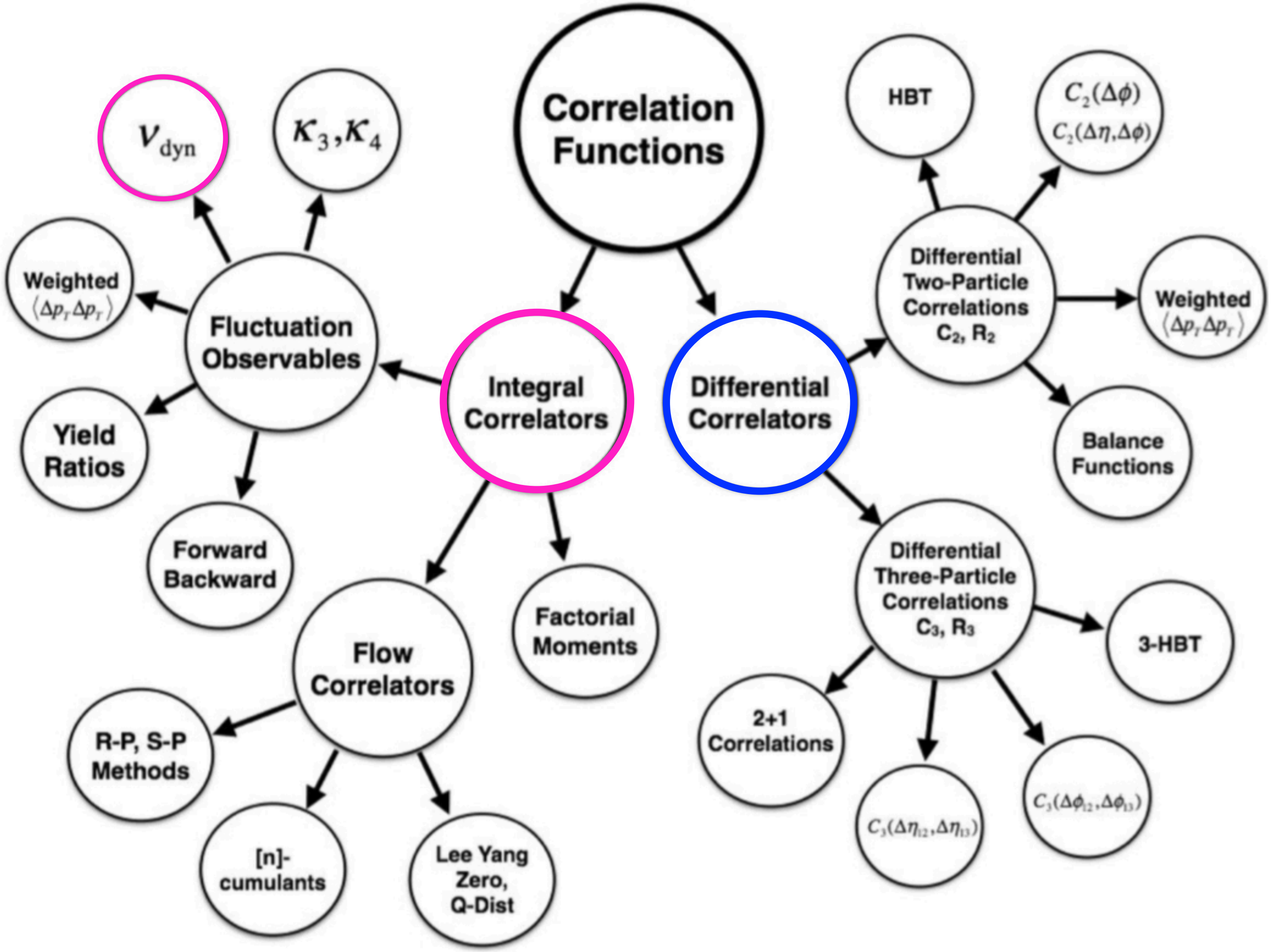
Why e-by-e fluctuations:

- they help to characterize the **properties of the "bulk" of the system**
- fluctuations also are closely related to **dynamics of the phase transitions**



1 Landscape of **integral** and **differential** observables

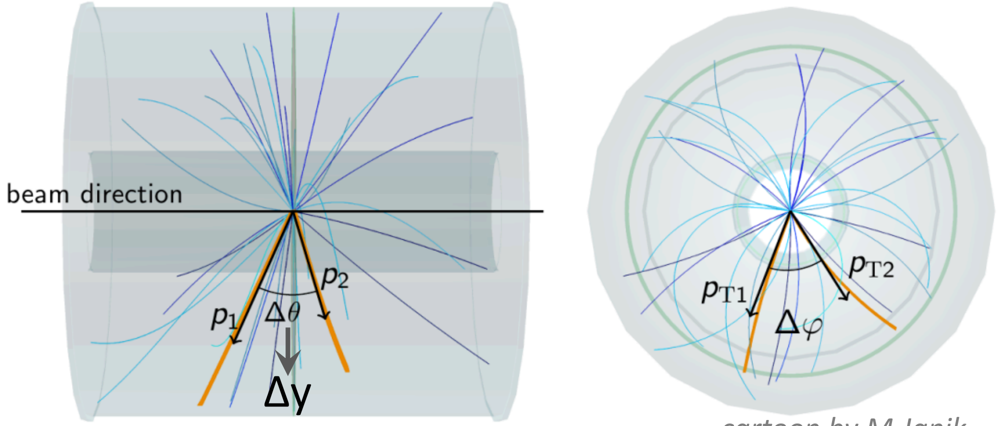
C. A. Pruneau, "*Data Analysis Techniques for Physical Scientists*" (2017)



Differential correlations between + – charges (Balance Functions)

$$B(\Delta\eta) = \frac{1}{2}\left(\frac{\rho_2^{(+,-)} - \rho_2^{(+,+)}}{\rho_1^{(+)}} + \frac{\rho_2^{(-,+)} - \rho_2^{(-,-)}}{\rho_1^{(-)}}\right)$$

Bass et al., Phys. Rev. Lett. 85 (2000) 2689

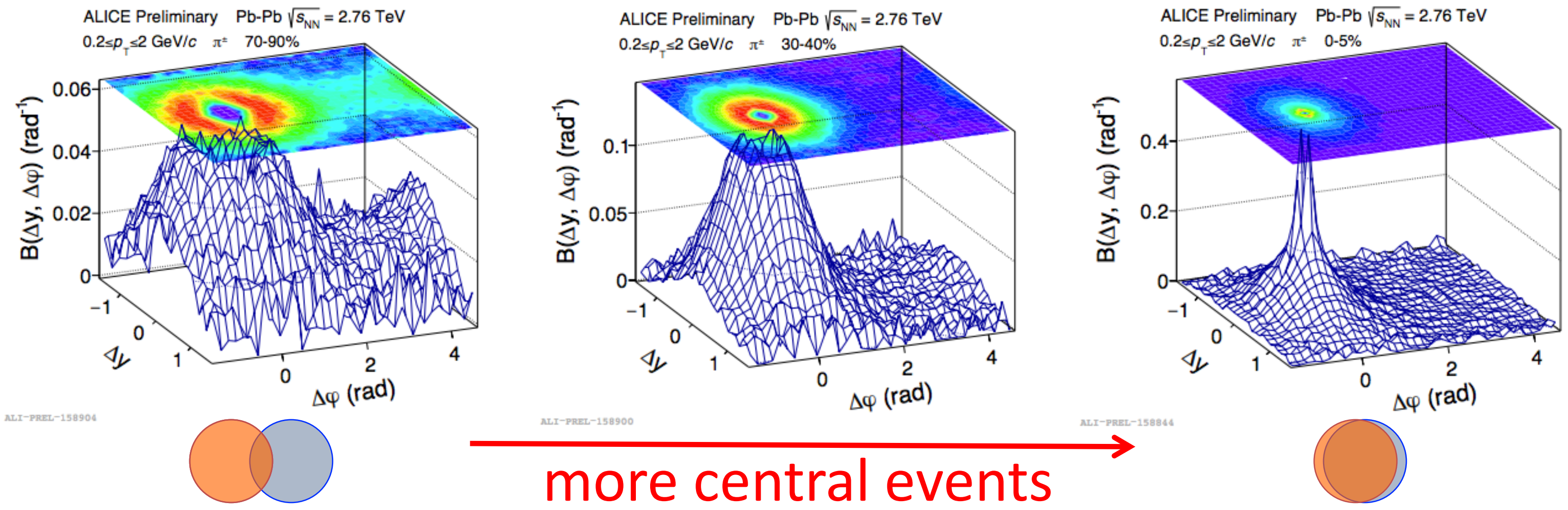


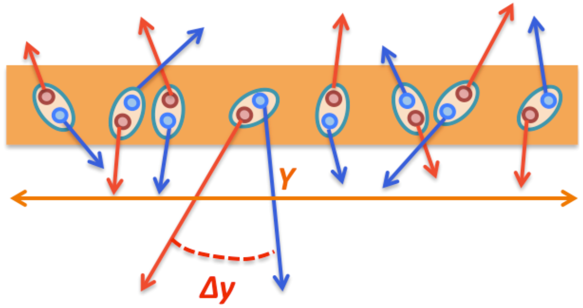
cartoon by M.Janik

Physics picture: charge diffusion in the medium
Affected by: radial flow, resonance decays, HBT, Coulomb effects

→ STAR and ALICE reveal narrowing of BF with centrality:

J. Pan, QM2018, arxiv:1807.10377





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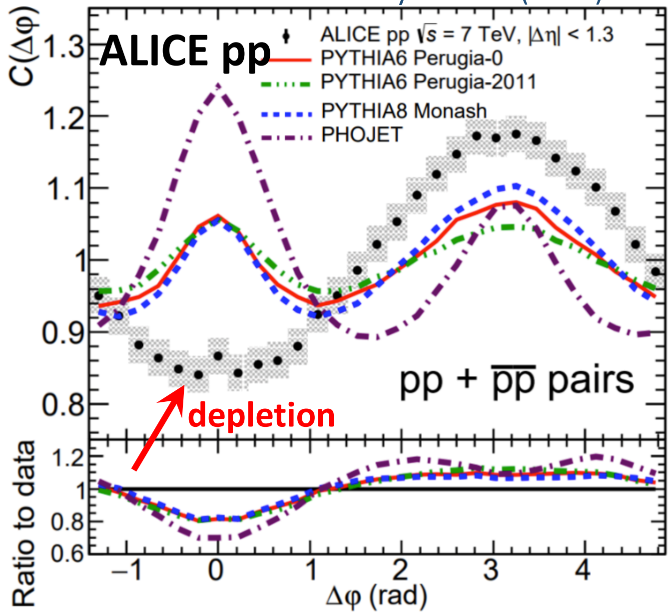
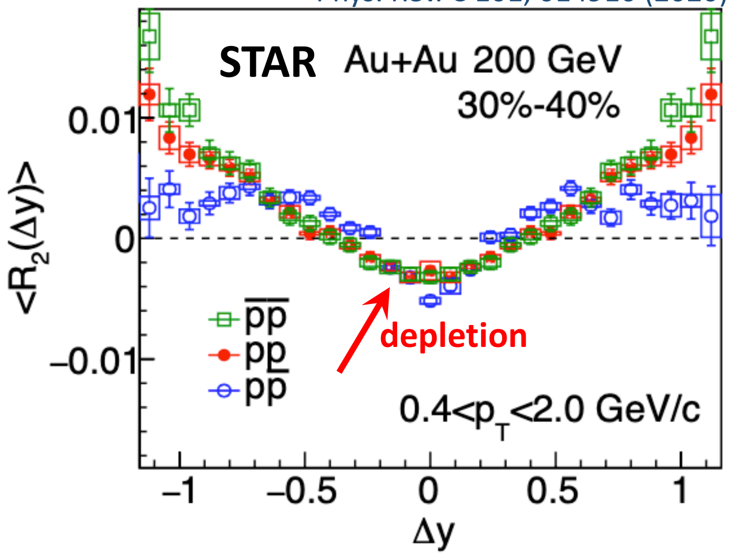
Differential angular correlations: typical definitions

Eur. Phys. J. C77 (2017) 569



Phys. Rev. C 101, 014916 (2020)



ALICE:

$$C(\Delta\eta,\Delta\varphi) = \frac{N^{mixed}_{pairs}}{N^{signal}_{pairs}} \frac{d^2N^{signal}_{pairs}}{d\Delta\eta d\Delta\varphi} \Big/ \frac{d^2N^{mixed}_{pairs}}{d\Delta\eta d\Delta\varphi}$$

STAR:

$$R_2(\Delta y,\Delta\varphi) = \frac{\langle n\rangle^2}{\langle n(n-1)\rangle} \frac{\rho_2(\Delta y,\Delta\varphi)}{\rho_1(y_1,\varphi_1)\rho_1(y_2,\varphi_2)} - 1$$

"angular" part

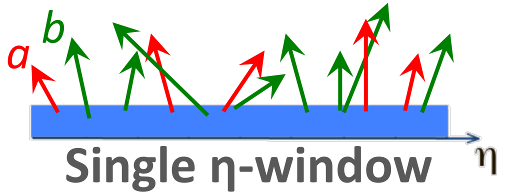
This normalization removes sensitivity to E-by-E fluctuations

→ R_2 is **identically zero** in the absence of any two-particle correlations

Figures: note anti-correlation of same-sign baryons at small angular separations

Integrated observable: particle number fluctuations

$r = n_a / n_b$ – ratio of yields



Variance of the ratio (norm.):

$$\nu \equiv \frac{\langle \Delta r^2 \rangle}{\langle r \rangle^2}$$

Integrated observable (approximation):

$$\nu_{dyn} \equiv \nu - \nu_{stat} = \frac{\langle n_a(n_a-1)\rangle}{\langle n_a\rangle^2} + \frac{\langle n_b(n_b-1)\rangle}{\langle n_b\rangle^2} - 2\frac{\langle n_a n_b\rangle}{\langle n_a\rangle\langle n_b\rangle}$$

Pruneau, Voloshin, Gavin, Phys.Rev. C66 (2002) 044904

- measures deviations from Poissonian behaviour
- robust against volume fluctuations, efficiency losses
- sensitive to correlations between species *a, b*
- affected by resonance decays

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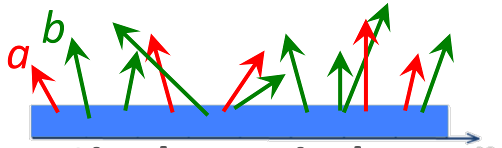

Single η-window

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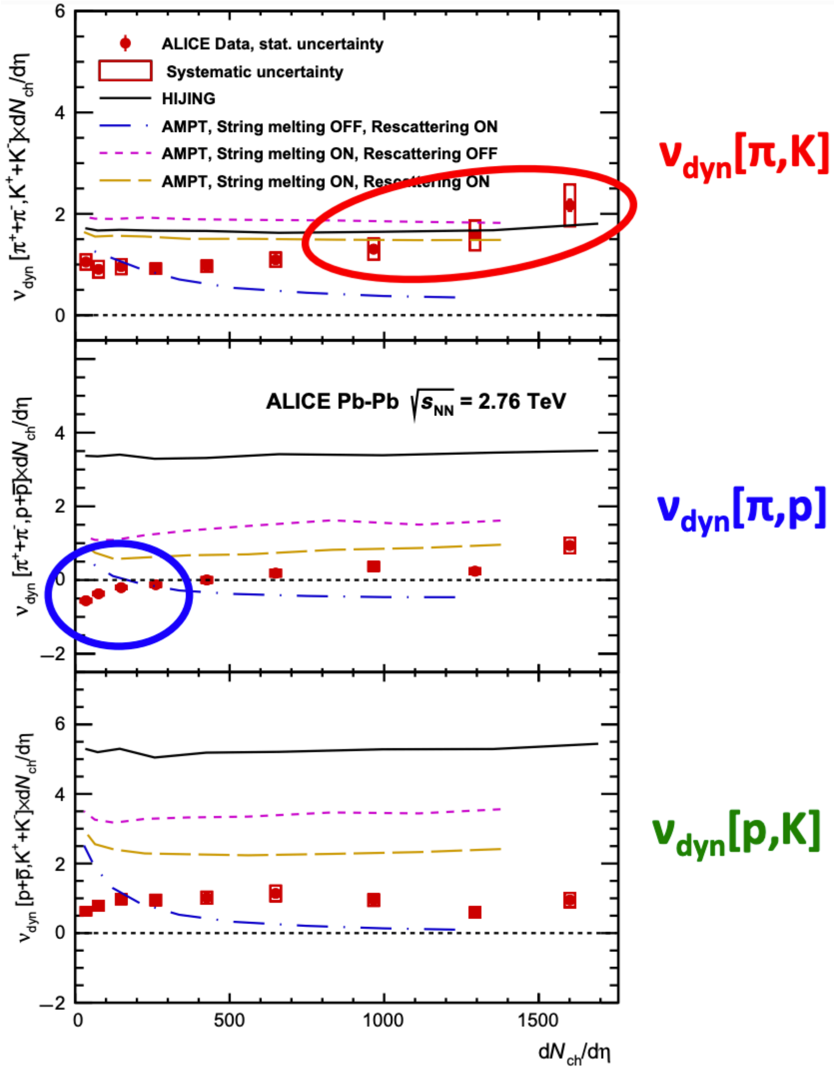
ALICE, EPJ C79 (2019) 236

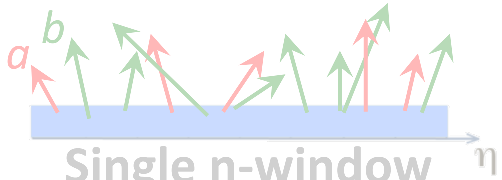


Observations:

- $\nu_{dyn}[\pi,p]$: increasing correlation with decreasing centrality
- $\nu_{dyn}[\pi,K]$: increasing anti-correlation between π and K *or* increasing dynamical fluctuations with increasing centrality
- Models fail to describe data

Differential correlations between ratios of particle yields

$r = n_a / n_b$ – ratio of yields



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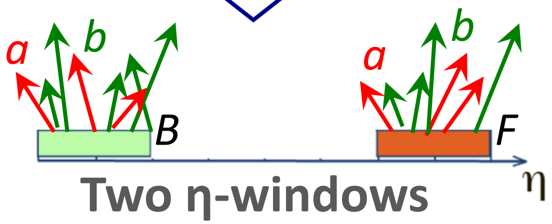


Two η-windows

Correlation strength:

$$\nu_{FB} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

I.A., EPJ Web of Conf. 204, 2019
arXiv:1901.01635

Differential observable (approximation):

$$\nu_{FB} \approx \frac{\langle n_a^F n_a^B \rangle}{\langle n_a^F\rangle\langle n_a^B\rangle} + \frac{\langle n_b^F n_b^B \rangle}{\langle n_b^F\rangle\langle n_b^B\rangle} - \frac{\langle n_a^F n_b^B \rangle}{\langle n_a^F\rangle\langle n_b^B\rangle} - \frac{\langle n_b^F n_a^B \rangle}{\langle n_b^F\rangle\langle n_a^B\rangle}$$

"same-species" terms — "cross-species" terms

- keeps good properties of ν_{dyn}
- if independent particle production → $\nu_{FB} = 0$
- if only short-range effects (decays, jets)
  → at large η_{gap} $\nu_{FB} = 0$
  – not the case for the "classical" ν_{dyn}

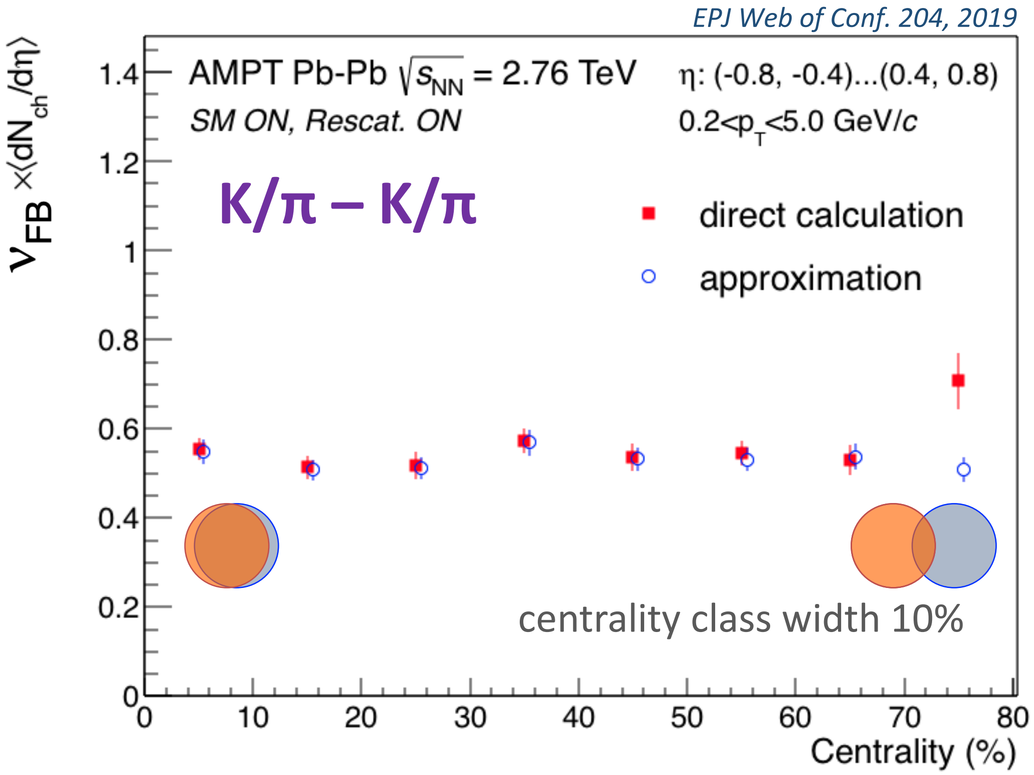
Examples:

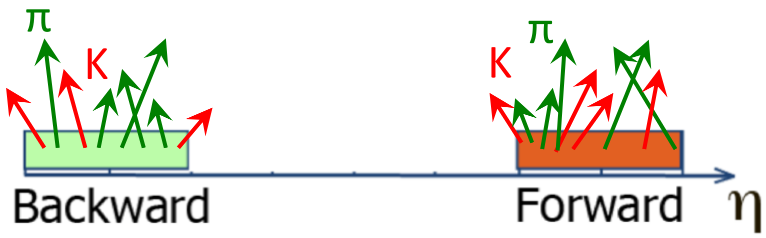
- kaon-to-pion ratio $r = n_K / n_\pi$
- baryon-to-pion ratio $r = n_{proton} / n_\pi$

Physics cases of interest:

- correlations between strangeness or baryon production *at large η gaps* (string interactions, thermal models, ...)

Angular correlations between yield ratios: check approximation



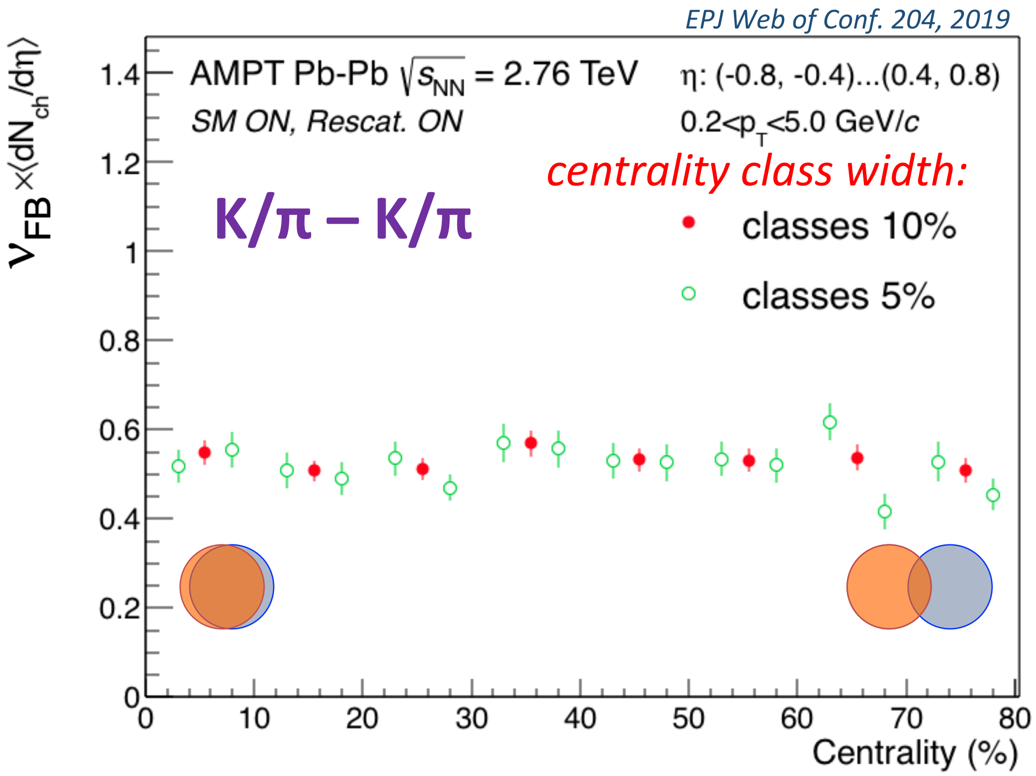


$$\nu_{FB} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

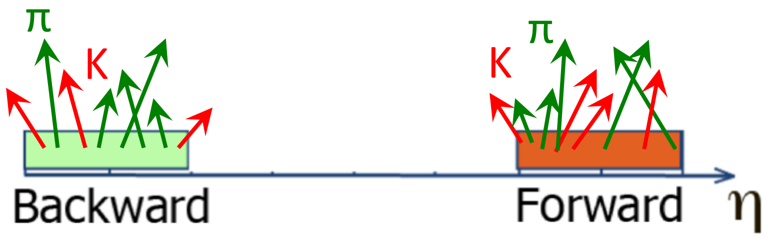
$$\nu_{FB} \approx \frac{\langle n_K^F n_K^B \rangle}{\langle n_K^F \rangle \langle n_K^B \rangle} + \frac{\langle n_\pi^F n_\pi^B \rangle}{\langle n_\pi^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_K^F n_\pi^B \rangle}{\langle n_K^F \rangle \langle n_\pi^B \rangle} - \frac{\langle n_\pi^F n_K^B \rangle}{\langle n_\pi^F \rangle \langle n_K^B \rangle}$$

- Good agreement between direct calculations and the approximation

4 Angular correlations between yield ratios: check robustness to VF



Observables of this type are robust to Volume and Volume Fluctuations



Volume Fluctuations: when system size changes E-by-E
(e.g. due impact parameter fluctuations)

It can be shown that in an independent sources model:

$$\nu_{FB} = \frac{1}{\langle N_{sources} \rangle} \nu_{FB}^{source}$$

A convenient to rescale:

$$\nu_{FB} \cdot \langle N_{sources} \rangle \sim \nu_{FB} \cdot \langle dN/d\eta \rangle$$

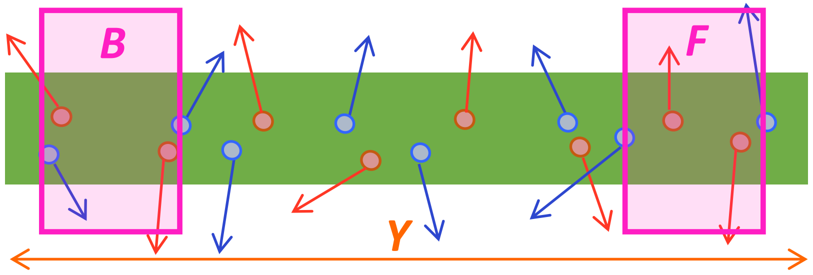
(as for ν_{dyn})

5 **Toy model** for yield ratio correlations

Assumptions:

- number of *positive* particles in each event is from Gauss, <*N*>=80, σ=4
- particles are distributed within |η|<2
- for each positive particle there is one *negative* (charge conservation)

$$\nu_{FB} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$



Then particle ID is assigned, and we can simulate

- a binomial distribution of K^+ (others are pions) → **GCE**
- … or assign a strictly fixed fraction of K^+ → **CE**

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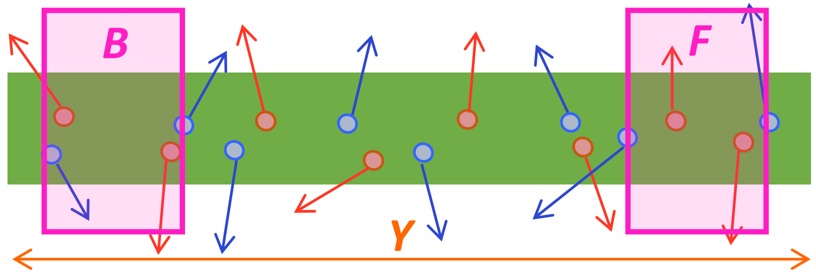

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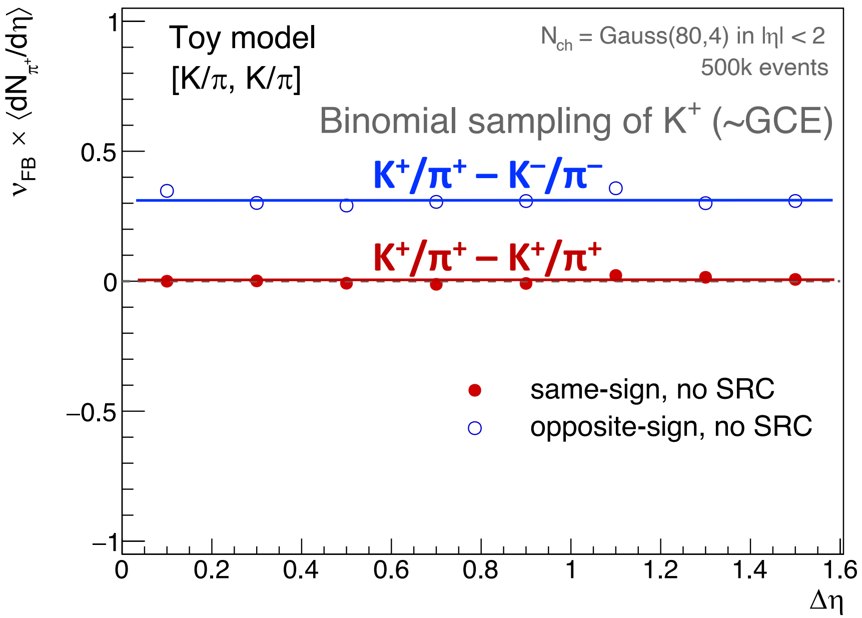
Grand Canonical ensemble for K^+:



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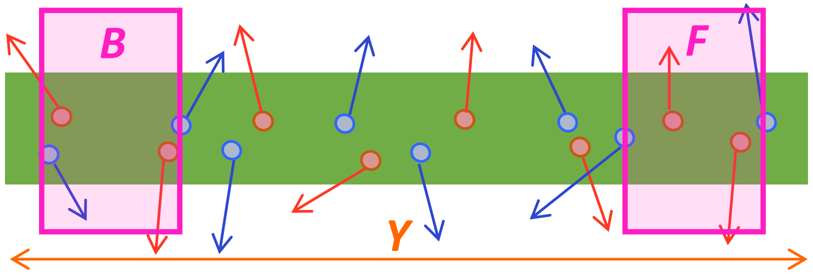

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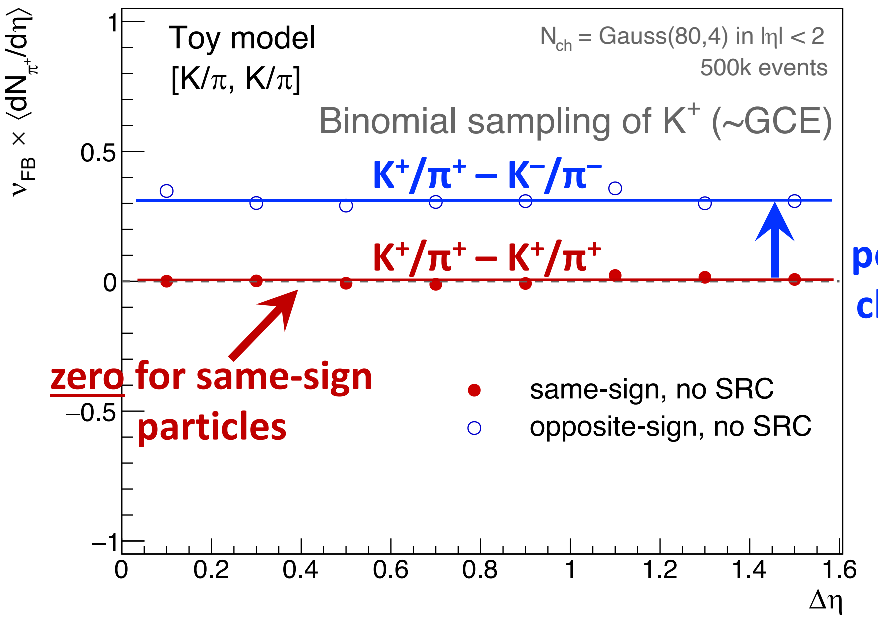

positive impact from charge conservation

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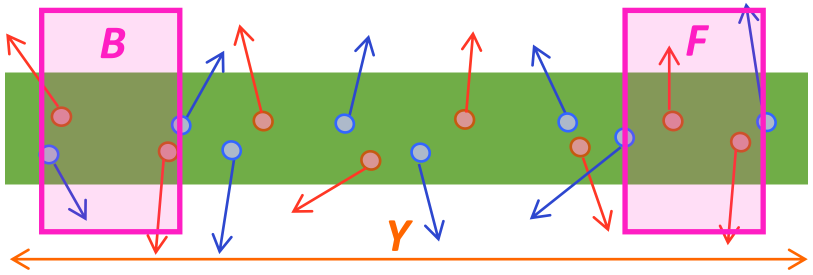

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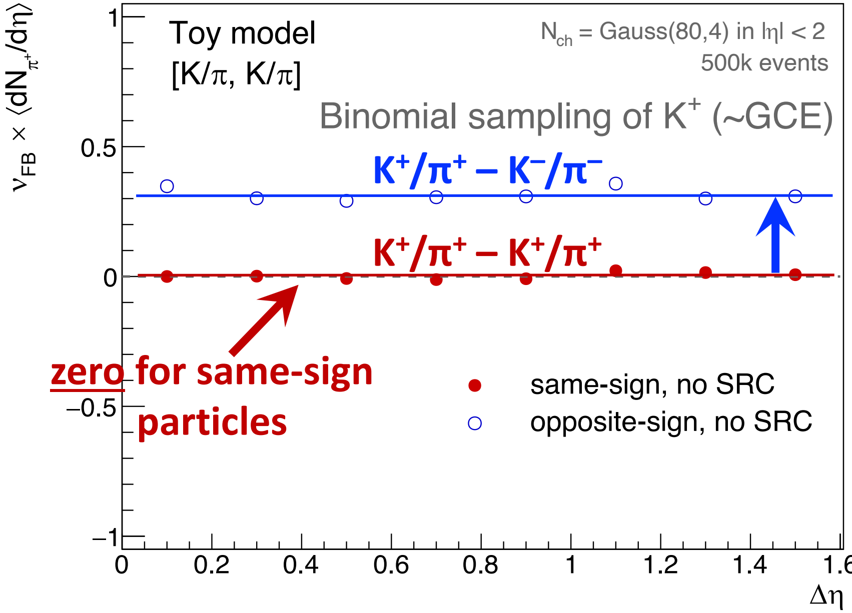

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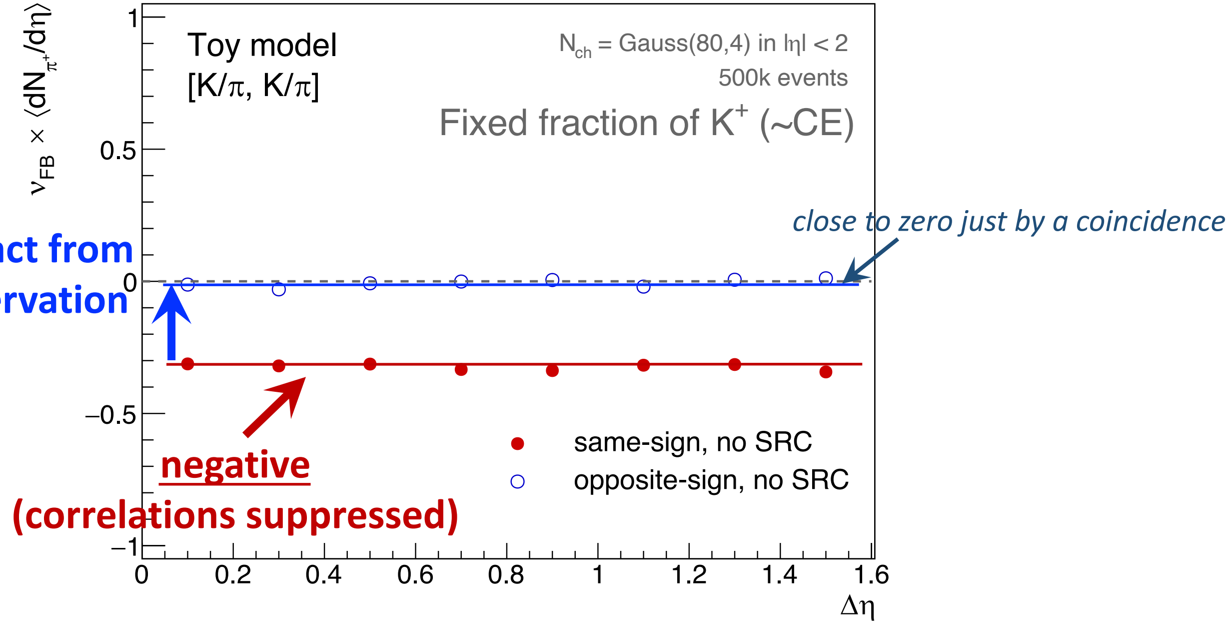

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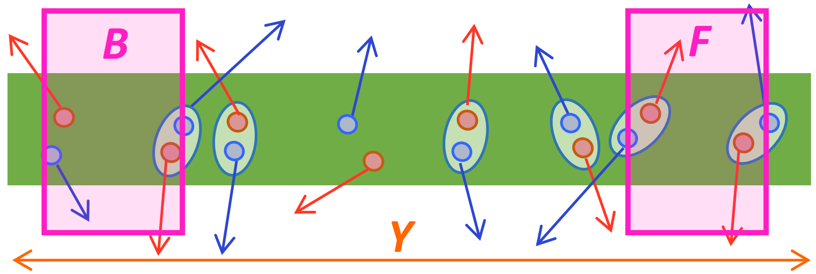

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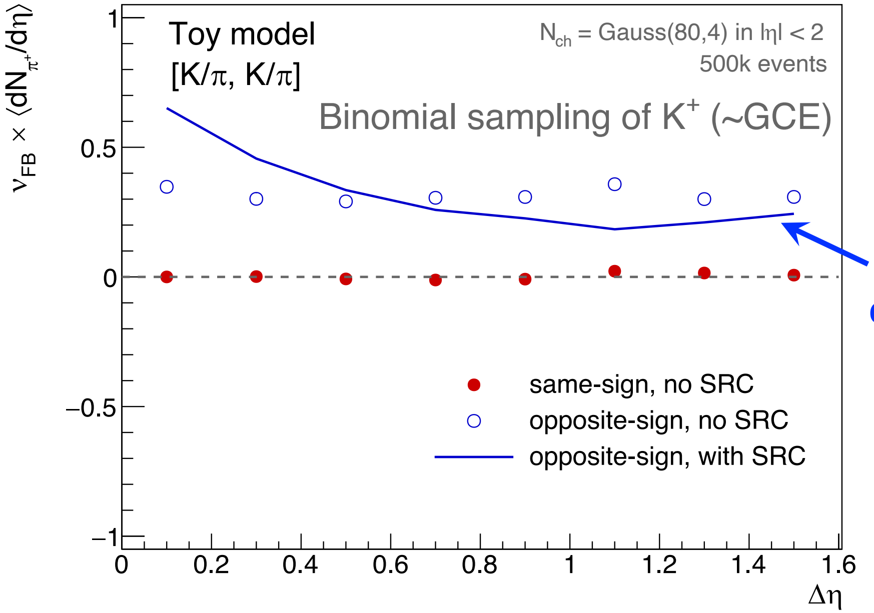

short-range (+,–) correlations added

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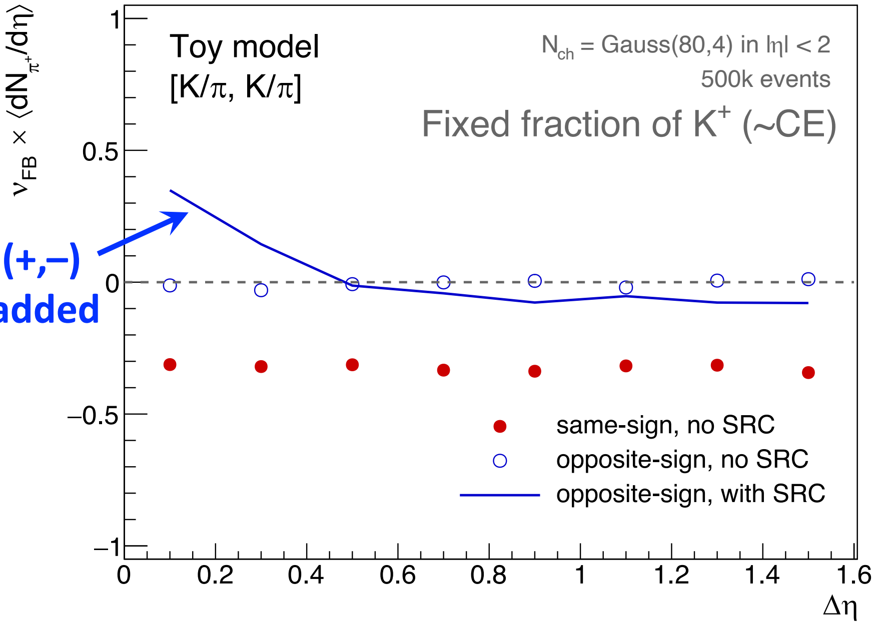

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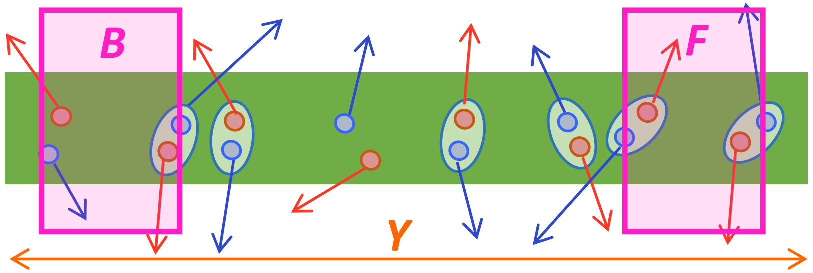

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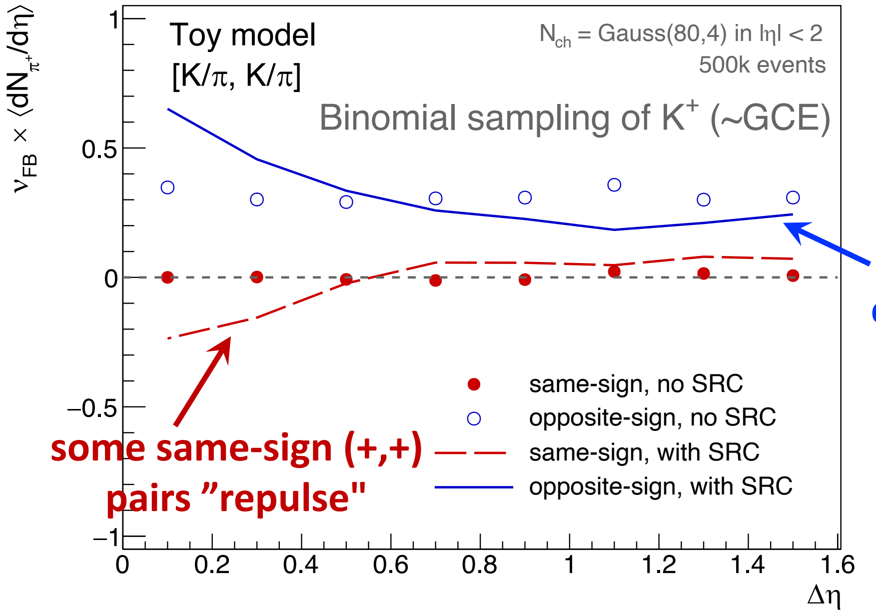

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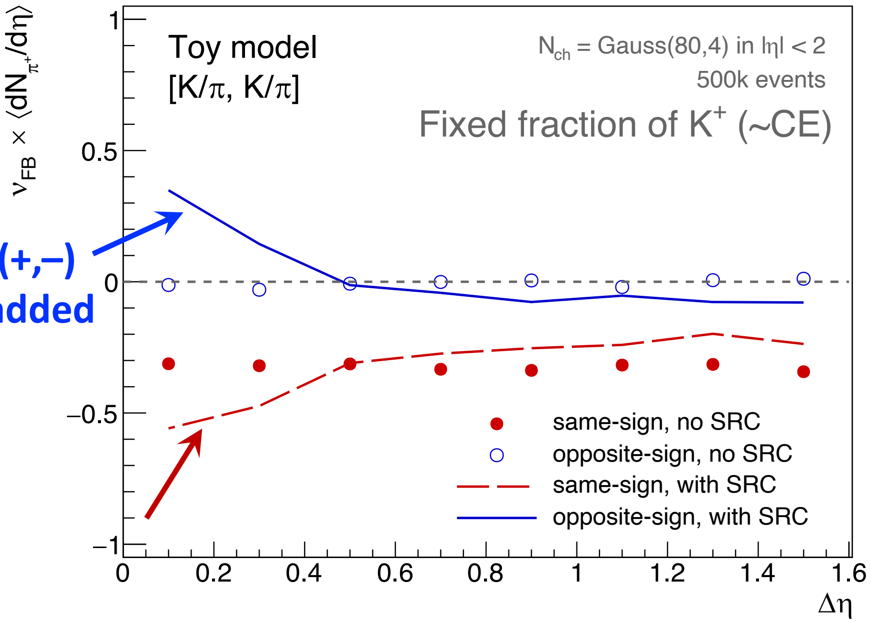

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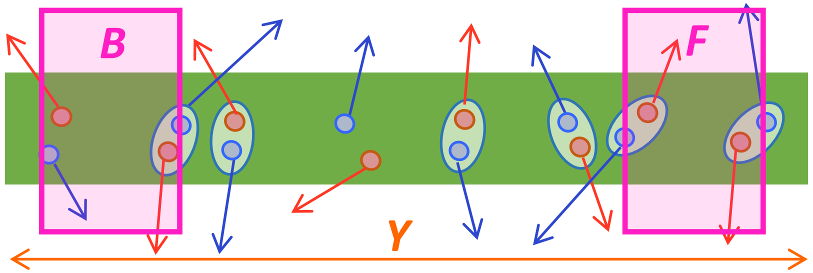

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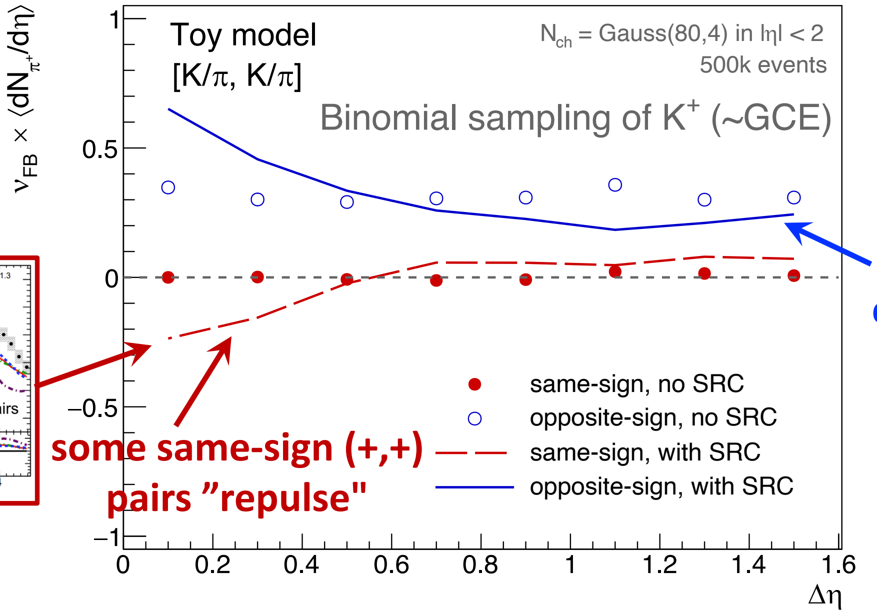
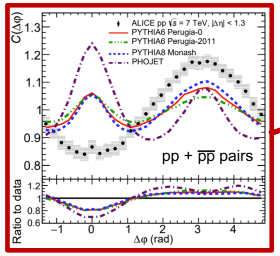


recall:



some same-sign (+,+) pairs "repulse"

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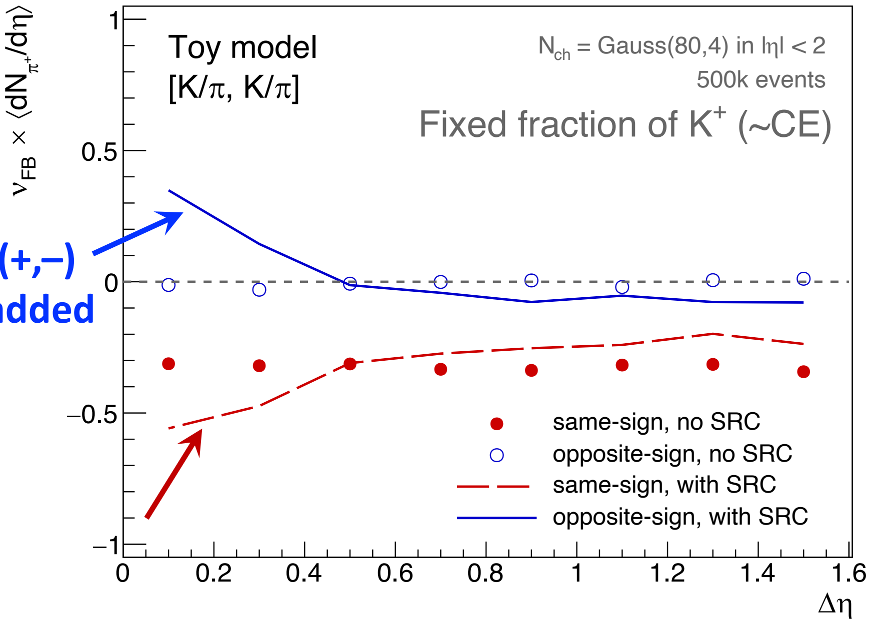

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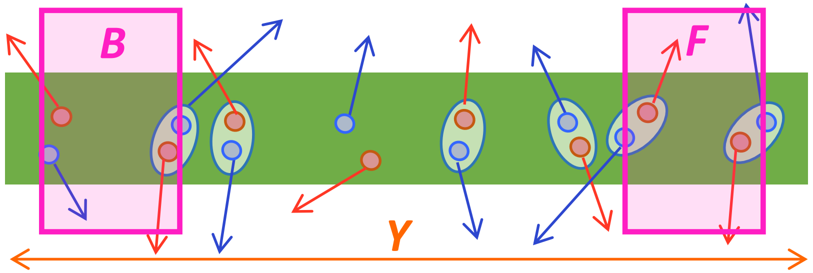
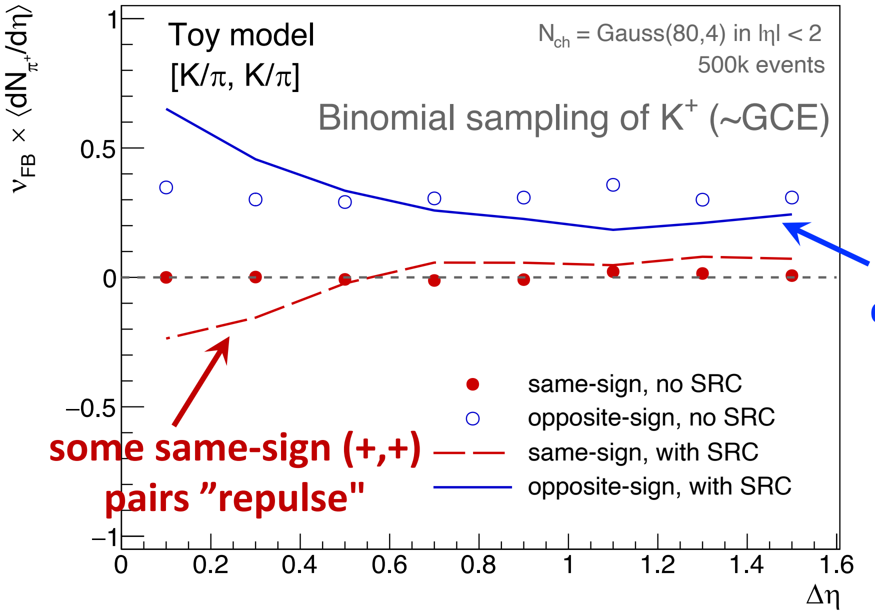


→ ν_{FB} allows one to separate short-range effects from "global" fluctuations

Grand Canonical ensemble for K^+:



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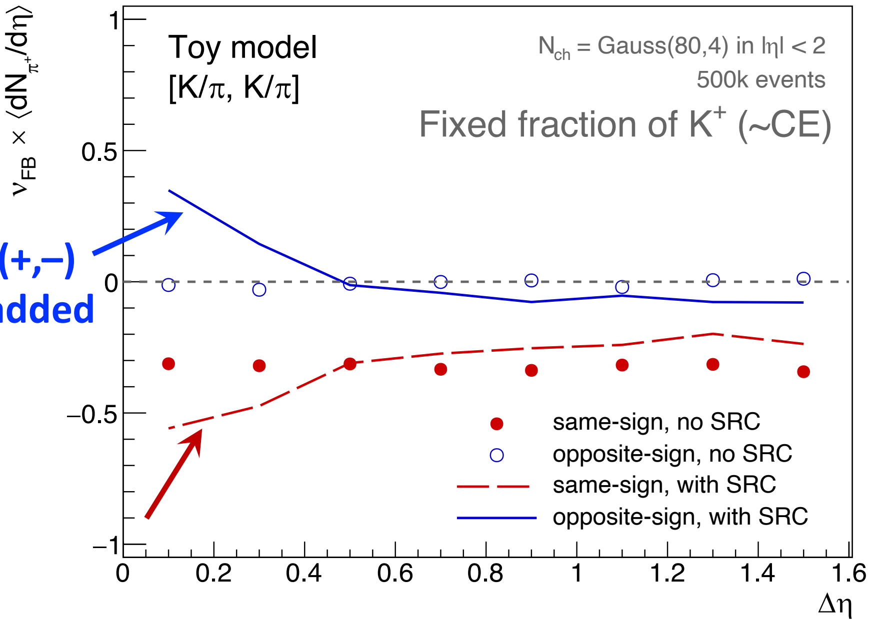

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some same-sign (+,+) pairs "repulse"

Yield ratio correlations as a measure of fluctuations

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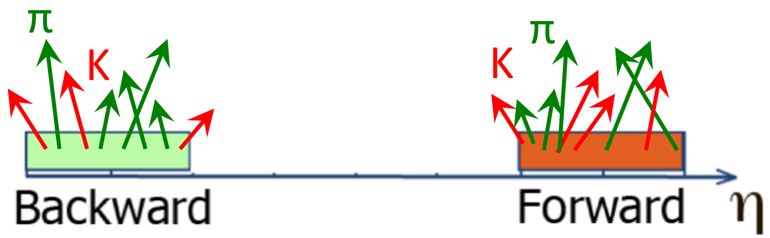
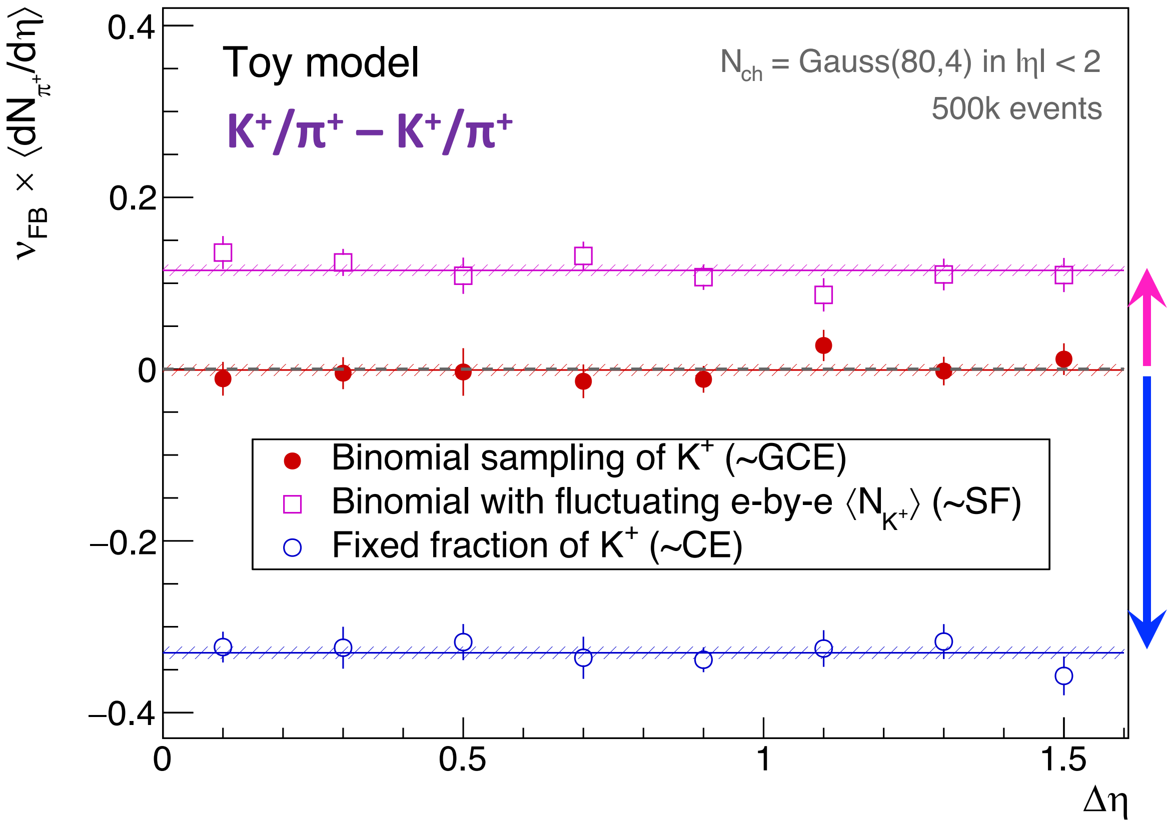
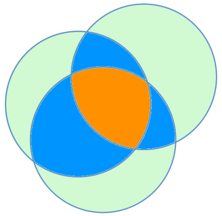


- Remove short-range effects, leave only "global" scenarios:



raise in String Fusion-like models
(when strange particle yield depends on source density fluctuates e-by-e)



Nucl. Phys. B 390 542–558 (1993)

suppression for Canonical Ensemble

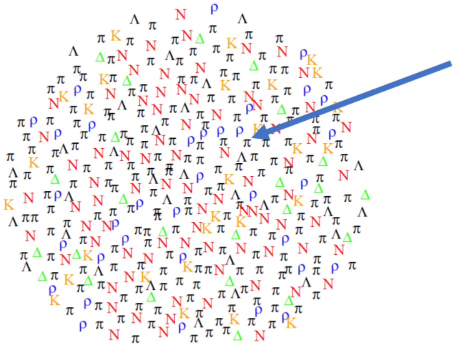
→ ν_{FB} allows one to separate short-range effects from "global" fluctuations

Yield ratio correlations in Hadron Resonance Gas models

Thermal-FIST package

Vovchenko, Stoecker, Comput. Phys. Commun. 244, 295 (2019)

Source code



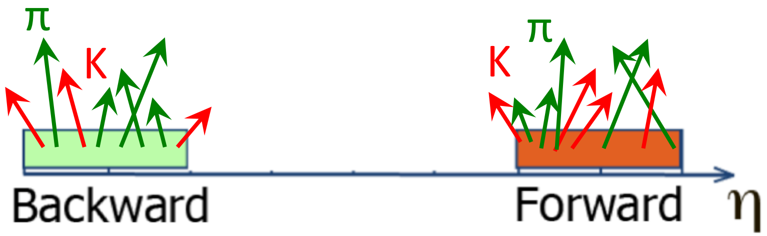
Thermal model:
equilibrated Hadron Resonance Gas at the chemical freeze-out stage

Parameters:

T – temperature

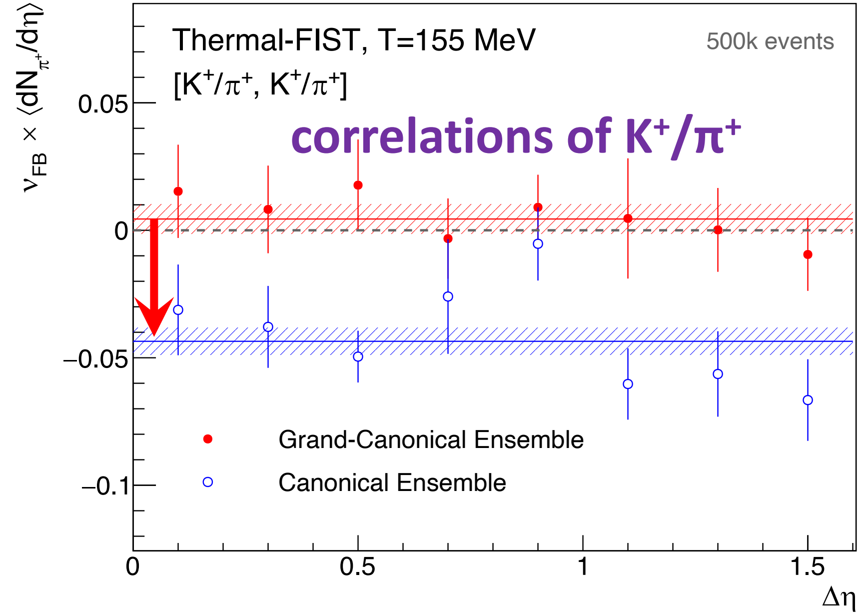
μ_B, μ_Q, μ_S – chemical potentials

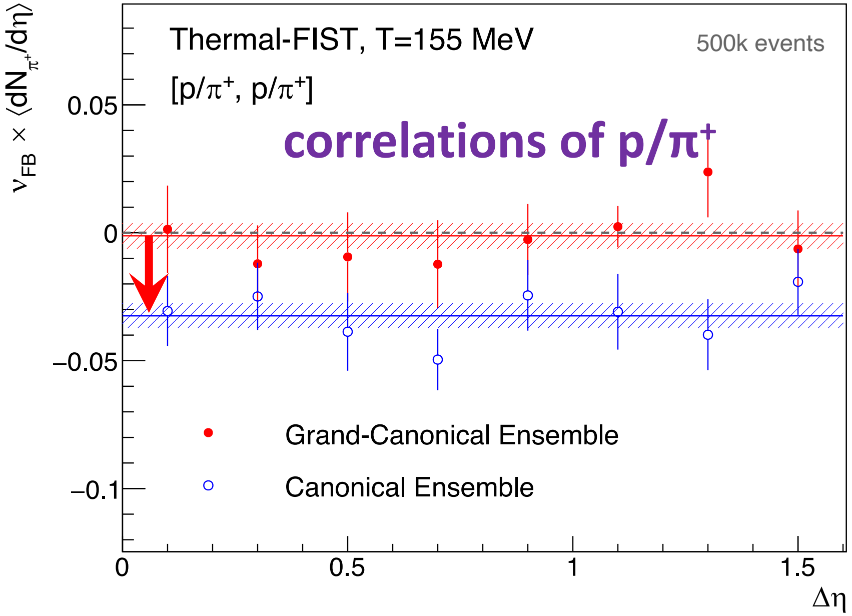
V – system volume



$$\nu_{FB} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

→ Run in Monte Carlo mode (HRG + radial flow + decays) for *Canonical* and *Grand-Canonical* Ensembles:



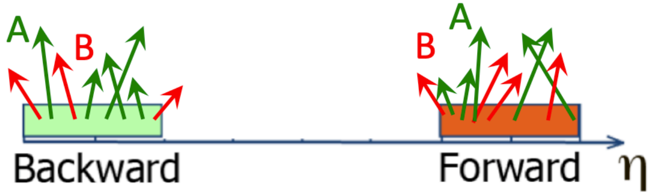


→ The pattern of suppression of ν_{FB} for the Canonical Ensemble

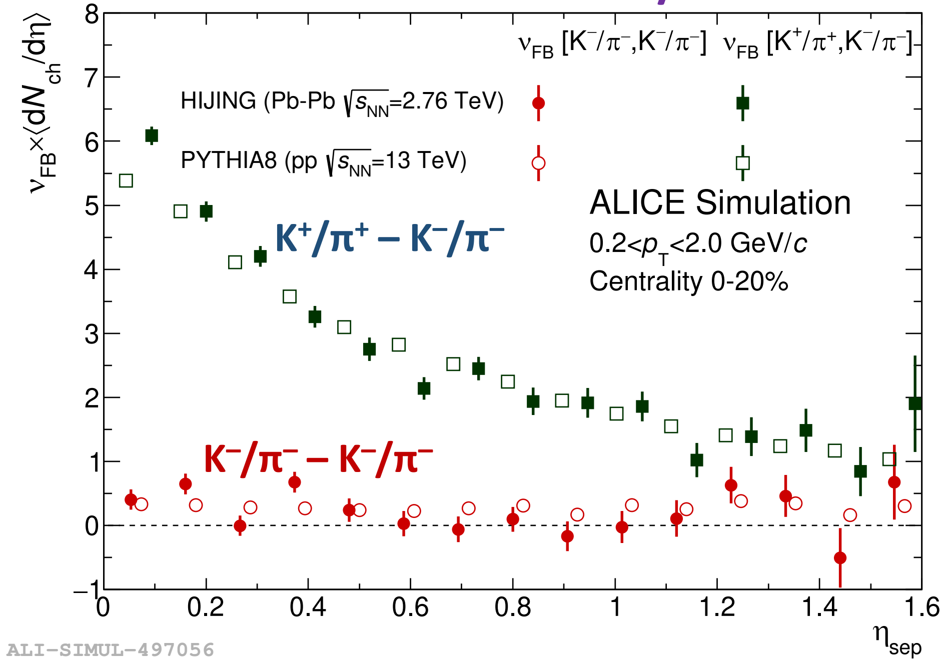
What with realistic models of pp and A-A collisions?

$$\nu_{FB} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

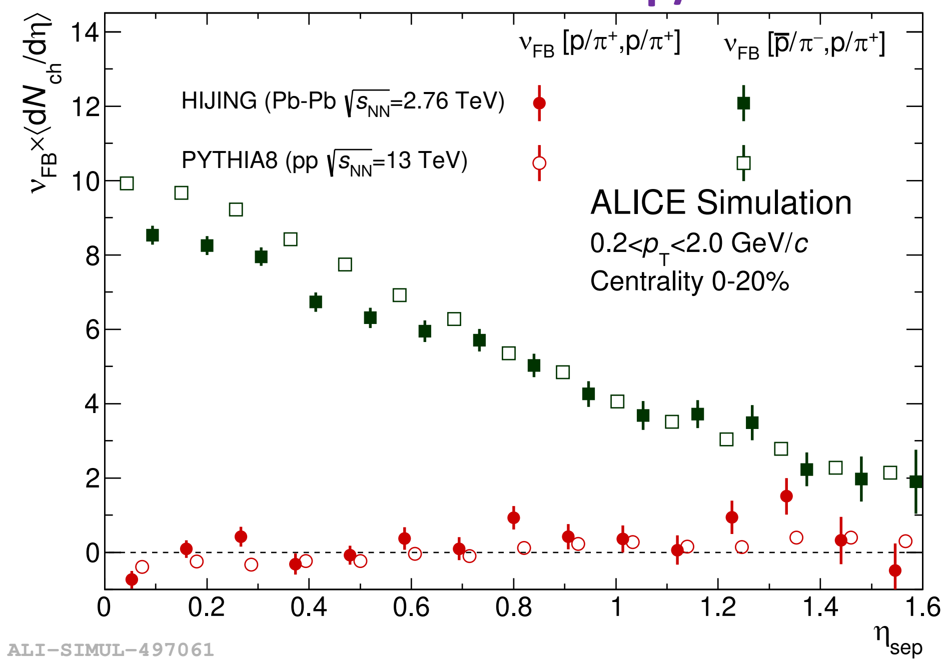
Calculations are done in HIJING (Pb-Pb) and PYTHIA (pp) collisions at LHC energies.



correlations of K/π



correlations of p/π



**plots by V. Petrov*

- Near-side peak for opposite-sign, while nearly zero for same-sign correlations
- Consistent results between HIJING and PYTHIA (thanks to stability to Vol.Fluct.!)
- Both generators are based on Lund string fragmentation → binomial sampling along *η*, ~GCE

7

What with realistic models of pp and A-A collisions?

$$\nu_{FB} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

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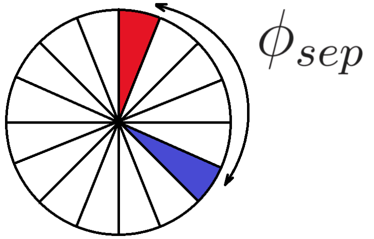
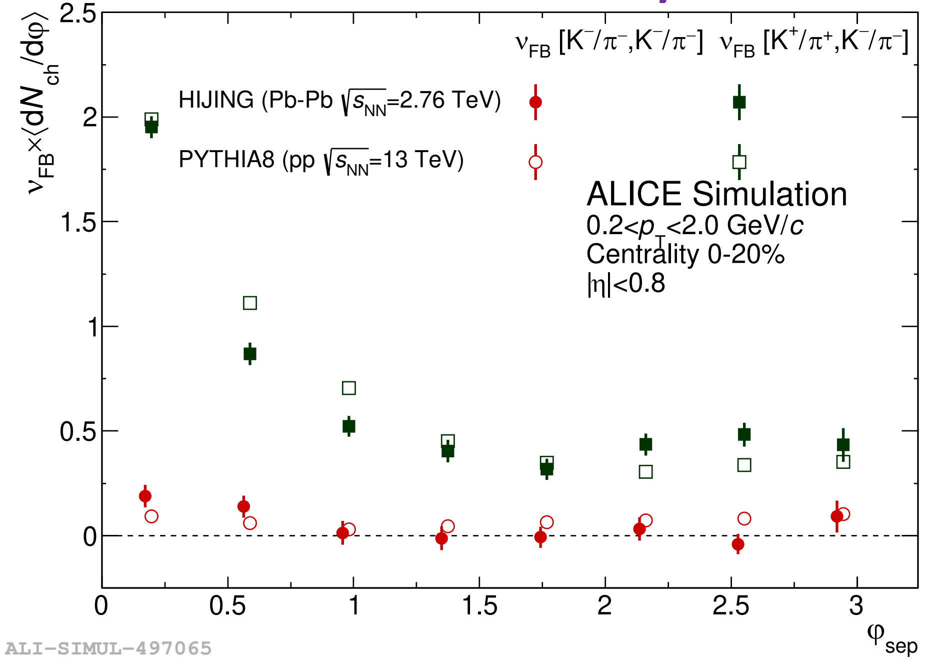
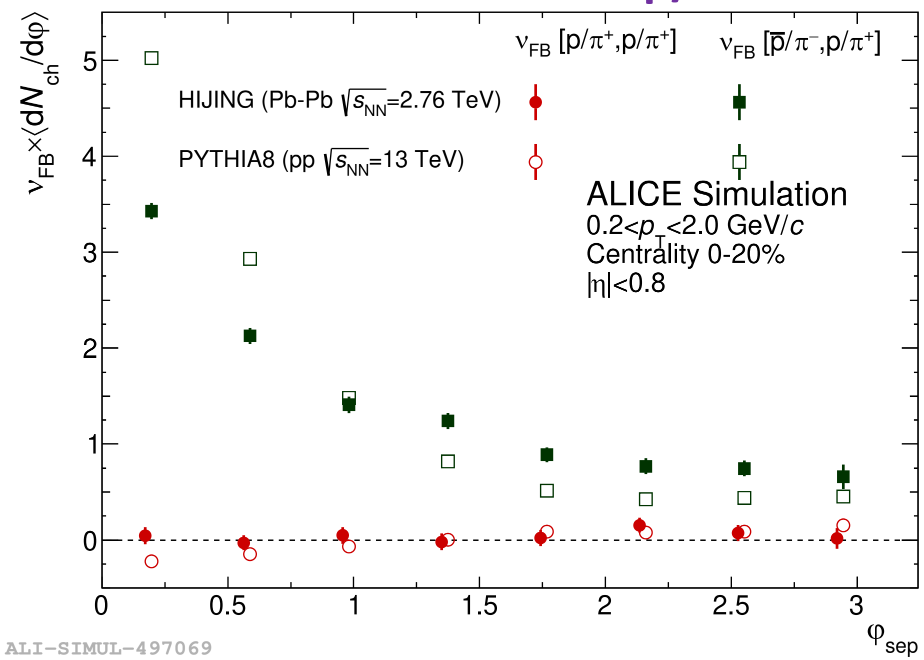


correlations of K/π



correlations of p/π



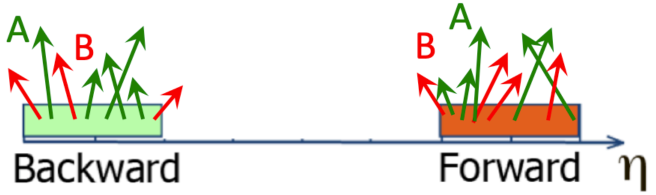
**plots by V. Petrov*

- Similar results for azimuthal intervals

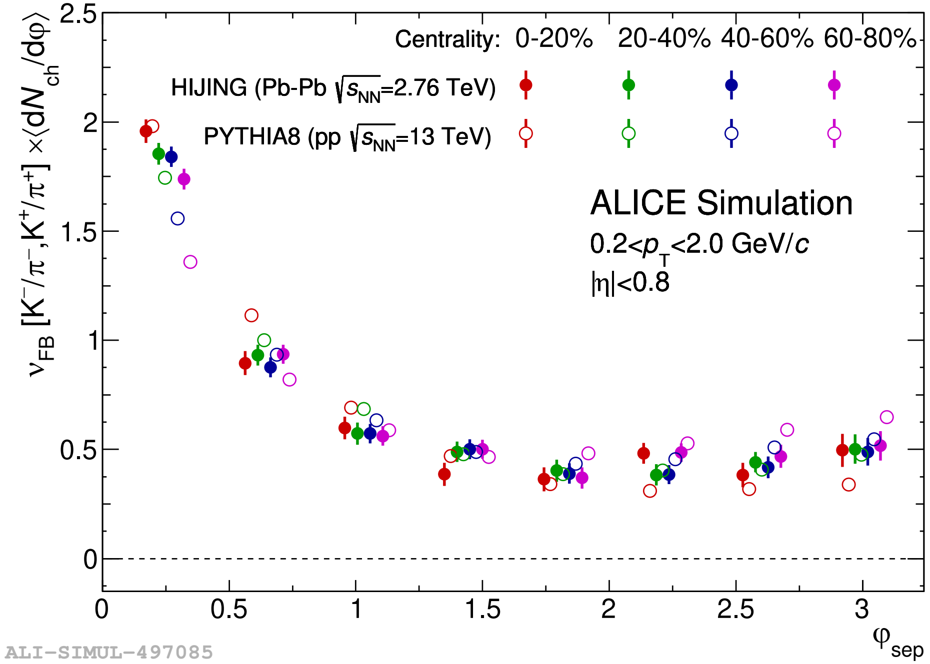
What with realistic models of pp and A-A collisions?

$$\nu_{FB} = \frac{\langle r^F \cdot r^B \rangle}{\langle r^F \rangle \langle r^B \rangle} - 1$$

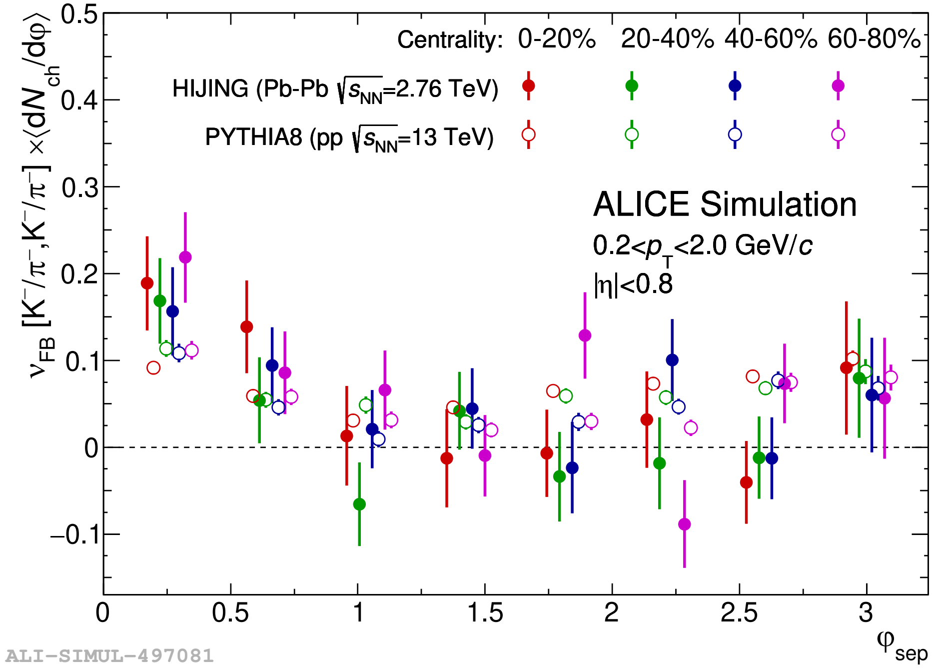
Calculations are done in HIJING (Pb-Pb) and PYTHIA (pp) collisions at LHC energies.



opposite-sign $K^+/\pi^+ - K^-/\pi^-$



same-sign $K^-/\pi^- - K^-/\pi^-$



**plots by V. Petrov*

- ***Centrality (multiplicity) dependence:***
  - HIJING: similar values in all classes due to absence of collective effects
  - PYTHIA: slight dependence, probably due to Color Reconnection

Summary

- **Event-by-event measurements** help to characterize the properties of the "bulk" of the system, they also are closely related to dynamics of the phase transitions.

- **Challenges from the experimental point of view:**
  - fluctuations of the volume of the created system
  - corrections on efficiency and contamination, limited acceptance
  - difficult to interpret the data due to resonance decays, conservation laws

- **Angular correlations between ratios of identified particle yields in two windows** were discussed
  - robust observable, allows to suppress contributions from SRC
  - ν_{FB} allows one to separate short-range effects from global fluctuation patterns caused by canonical suppression, etc.
  - experimental studies – to be done

Thank you for your attention!

This work is supported by the Russian Science Foundation, grant 17-72-20045.