Strangeness and correlations: Lessons from recent ALICE measurements

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Thanks to Peter Christiansen and Gösta Gustafson for discussion and helpful comments

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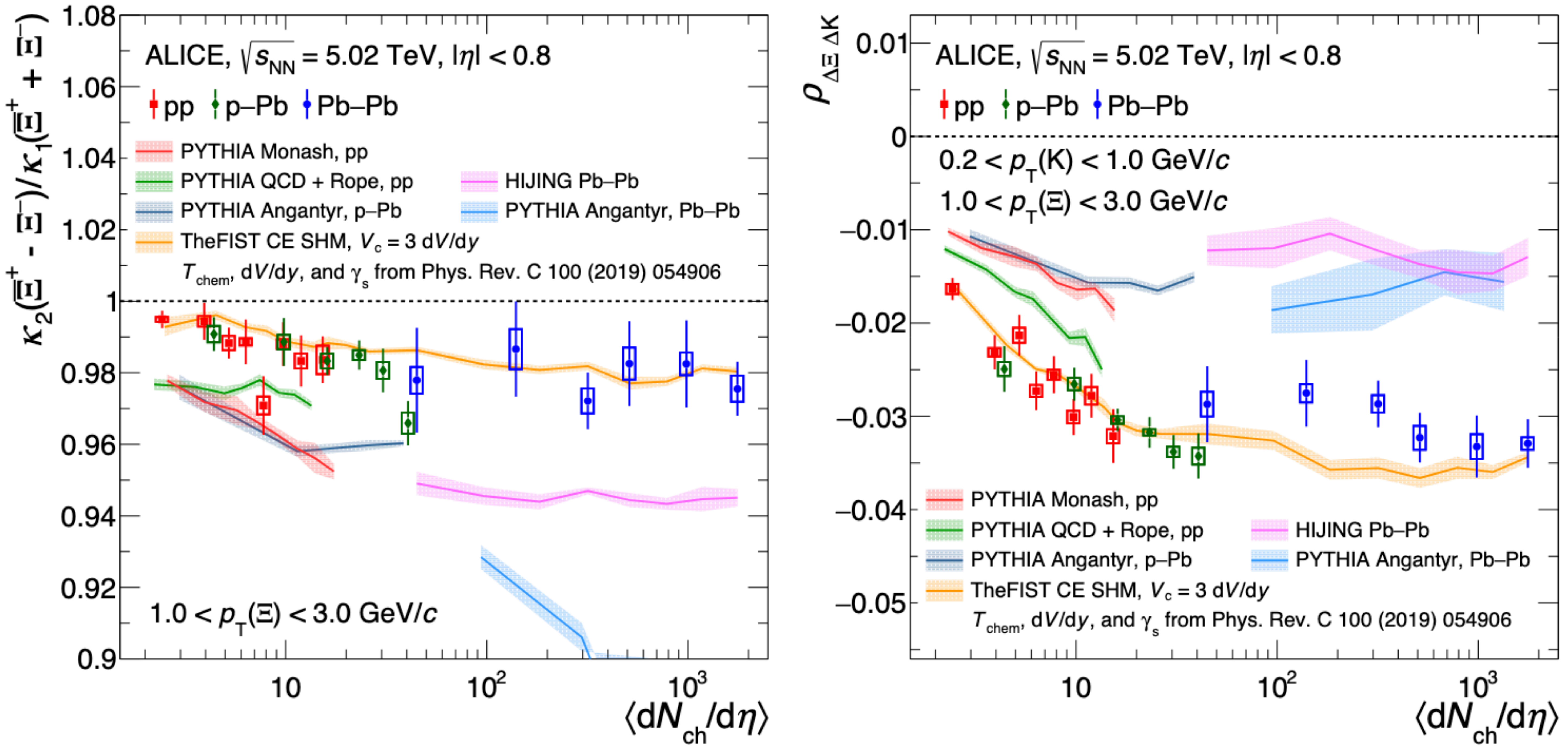
Vetenskapsrådet

Goals of this contribution

- Primary focus: **E-by-E fluctuation measurements in context of PYTHIA models** (ALICE: 2405.19890).
- Strong statement of paper: **significant combined deviation of 7.2σ between the data in pp collisions and the string fragmentation**.
- Main point: **How do we rule out models?** is a good and timely one!
  - Are string ruled out down to low multiplicity? How general is the statement? Where does string models have serious problems and where do they not? **What can we learn about microscopic behavior from these measurements?**



Main points of this contribution

1 **Pearson coefficient ρ in pp too dependent on rare production of Ξ.**
Gives little relevant information about correlations in pp.

2 **Normalized second order Ξ-cumulant informs about $\Xi^+\Xi^-$ correlation length.**
Information is relevant, but well known.

3 **A good discriminating observable must be based on understood, qualitative physics differences in models**

Lund strings at a glance

Many parameters:

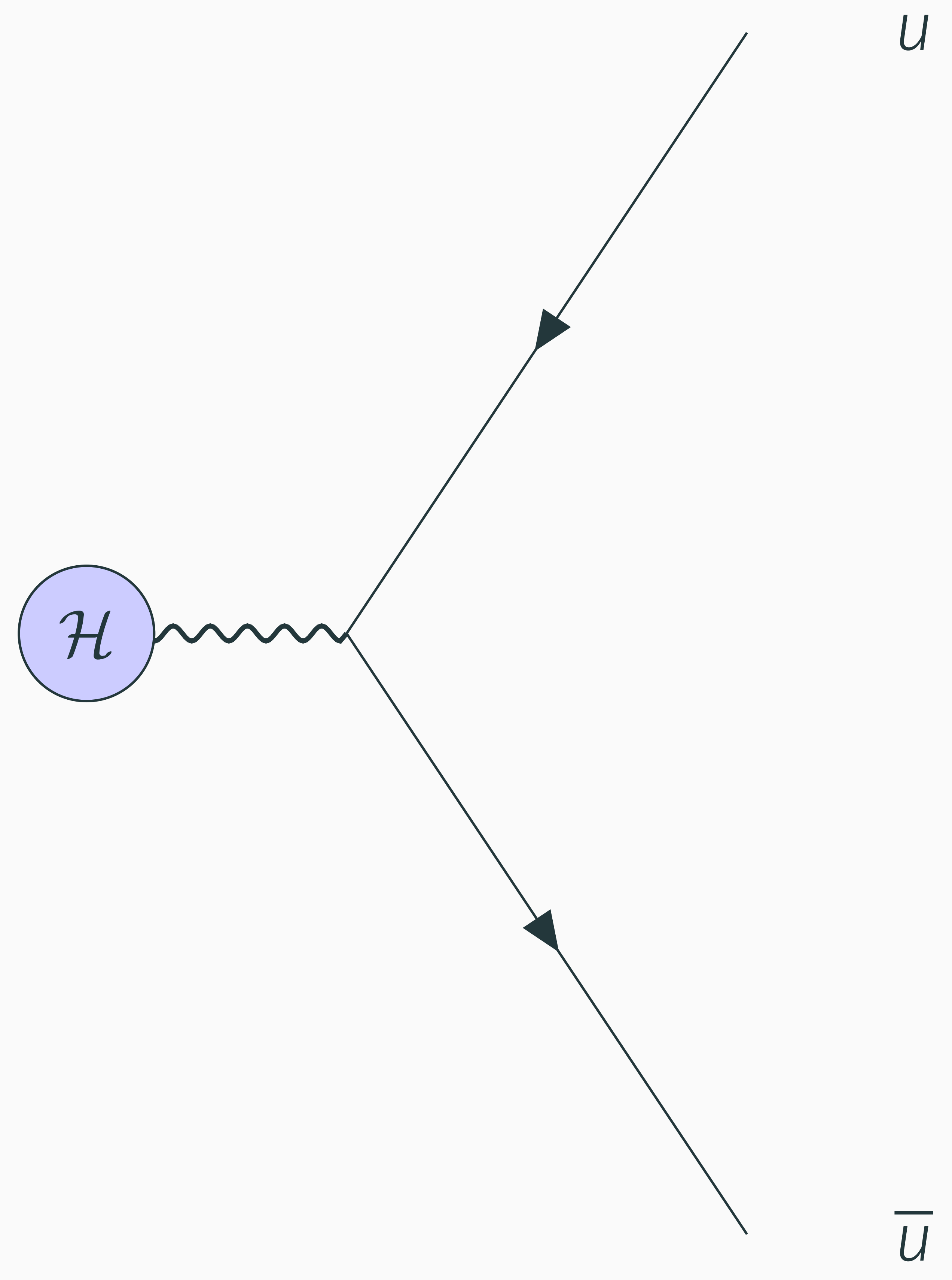
- Kinematics: a, b, $\sigma_{p_\perp}$.
- Quark/diquark flavour selection: ρ, ξ, x, y.
- Hadron spin + η, η' suppression.
- Specialized models (baryons...).
- More for excited states, usually disabled.

Governing equations

Longitudinal kinematics: $f(z) \propto \frac{(1-z)^a}{z} \exp\left(-\frac{bm_\perp^2}{z}\right)$

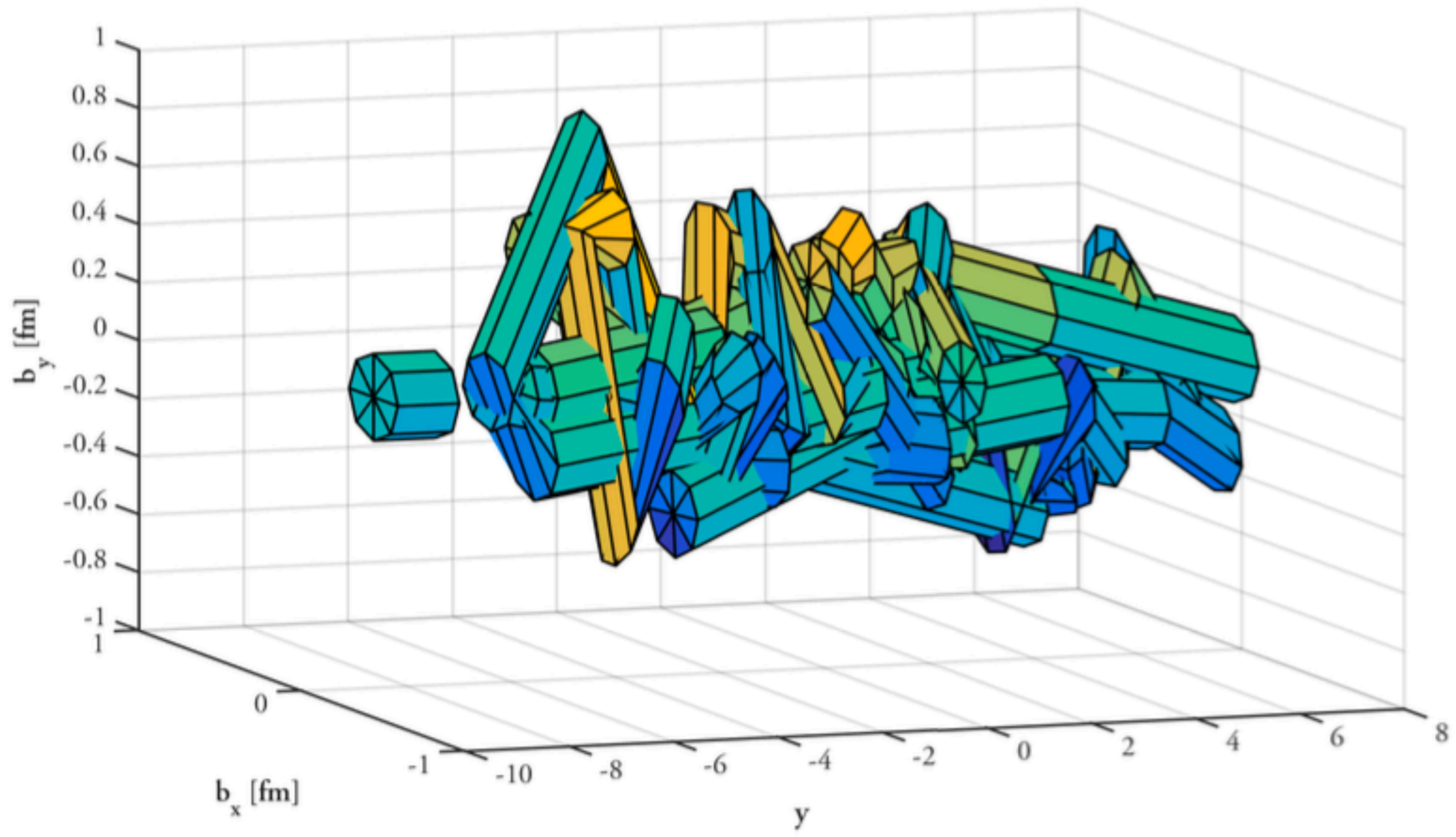
Flavour and $p_\perp$: $\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}^2 p_\perp} \propto \exp\left(-\pi m_{\perp,q}^2/\kappa\right)$

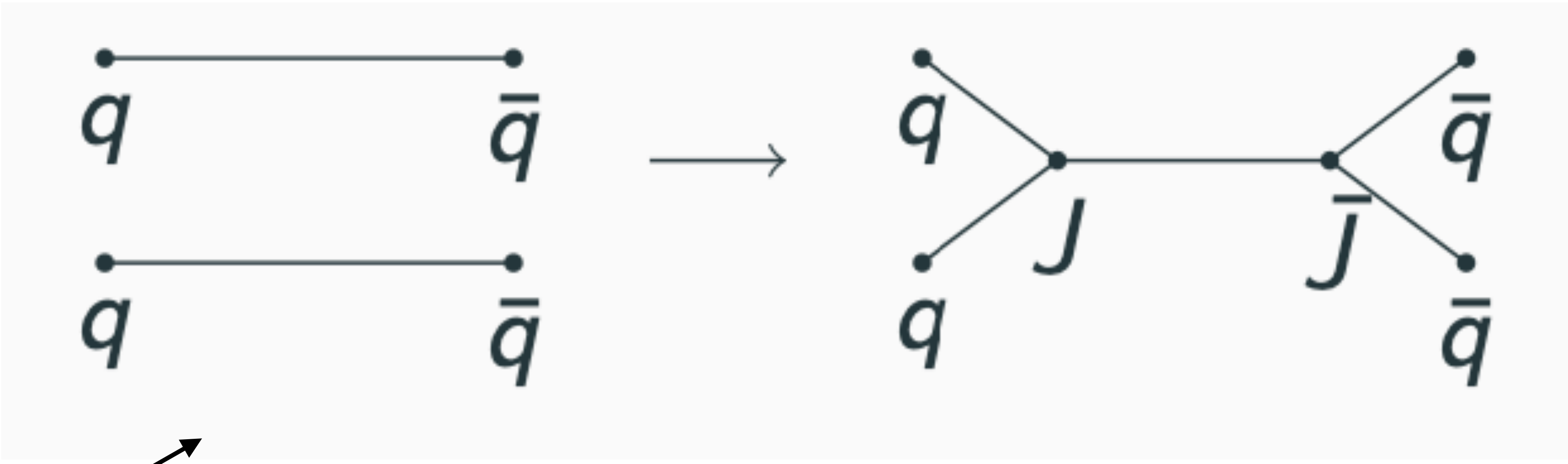
Microscopic correlations!



Simple system, eg. Z-boson to quark-anti-quark

Rope and QCD-CR, basic ideas





Effective string tension from the lattice

$$\kappa \propto C_2 \Rightarrow \frac{\tilde{\kappa}}{\kappa_0} = \frac{C_2(\text{multiplet})}{C_2(\text{singlet})}.$$

Strangeness enhanced by:

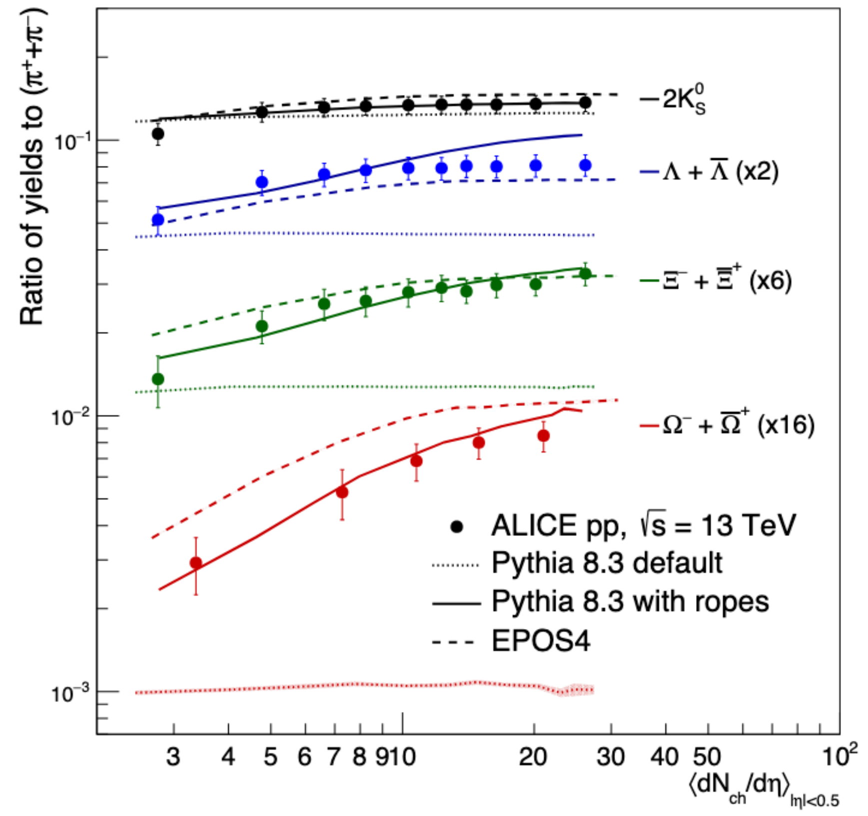
$$\rho_{LEP} = \exp\left(-\frac{\pi(m_s^2 - m_u^2)}{\kappa}\right) \rightarrow \tilde{\rho} = \rho_{LEP}^{\kappa_0/\kappa}$$

- Lund strings overlap: complex color structures giving more multi strange baryons

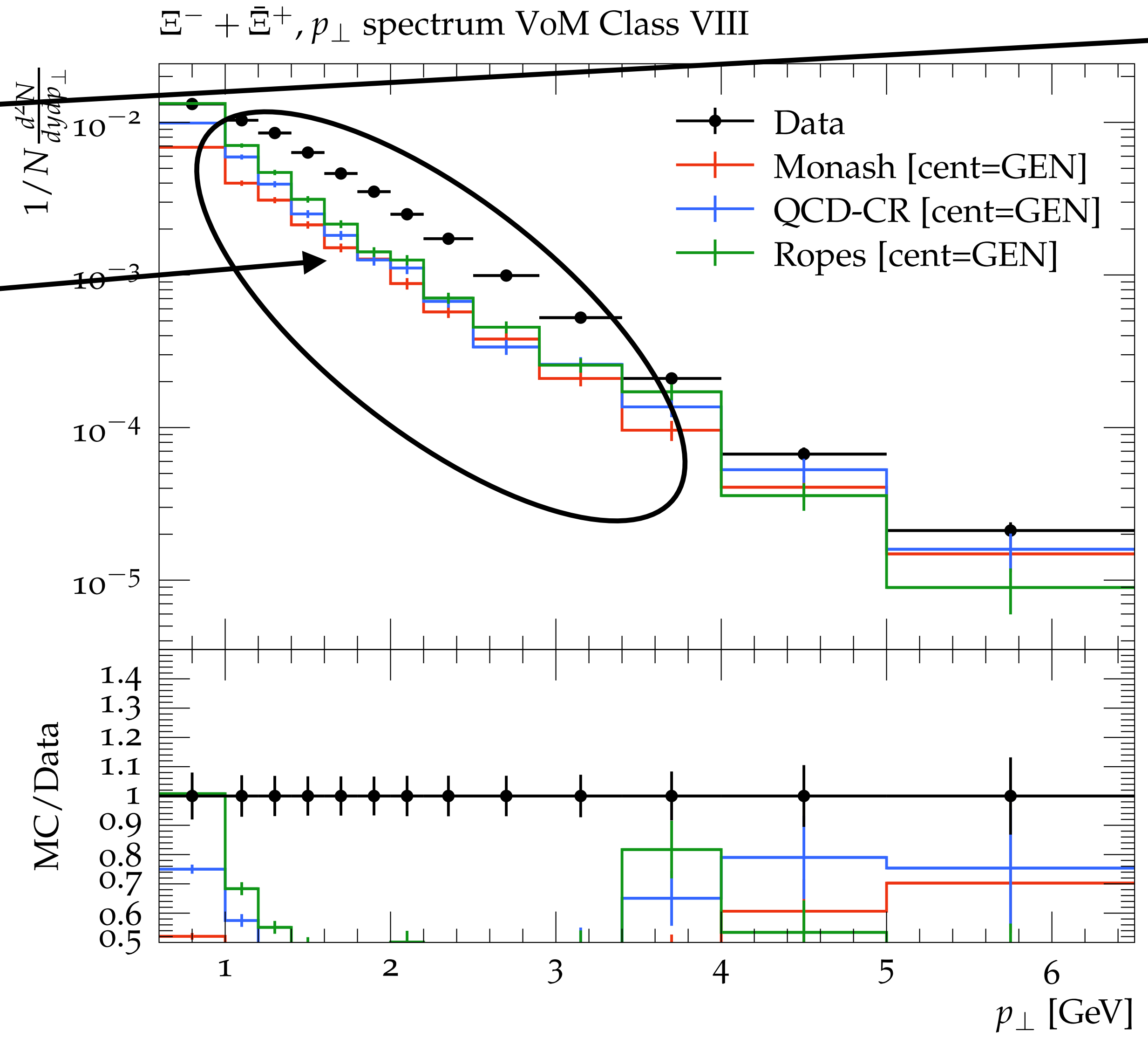
Known phenomenological properties

- 👍 Good description of integrated yield ratios.

CB, Cannito, Zaccolo: 2403.00511

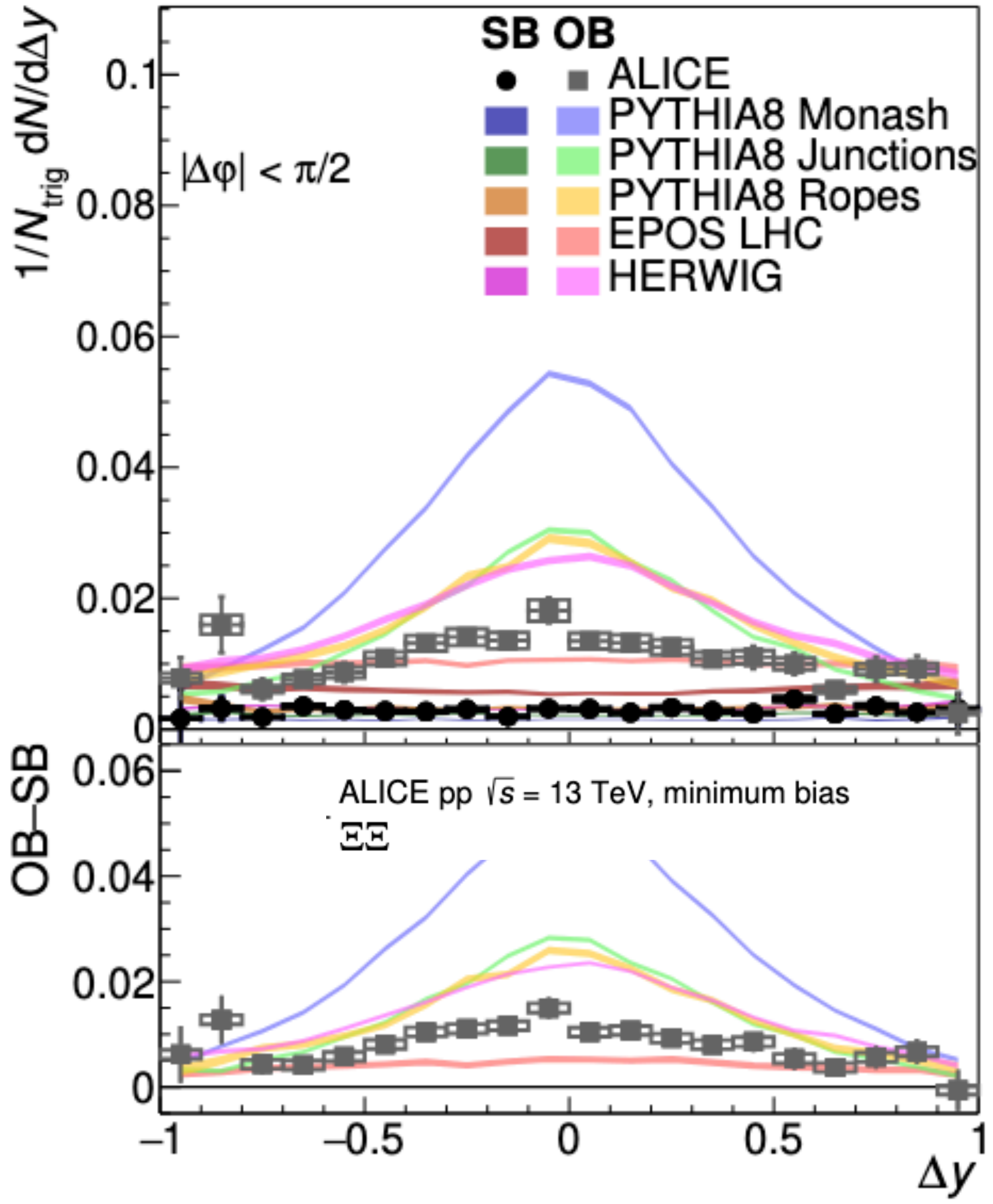


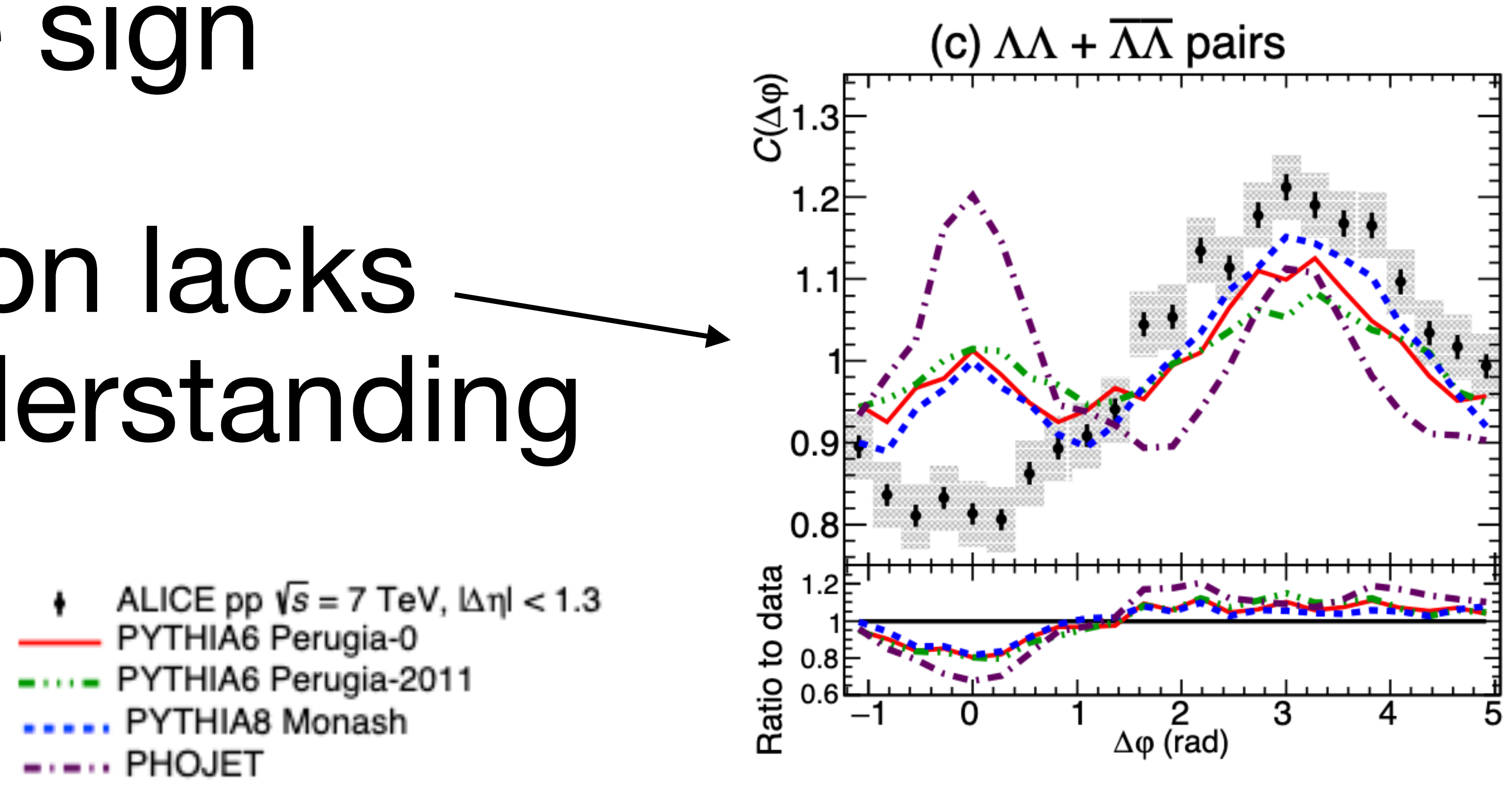
- 👎 Spectral shape $p_\perp$ poorly described
  - lack of flow, no $p_\perp(m_h)$ dependence



- 👎 Baryon correlations generally off, worse for opposite sign
  - baryon production lacks microscopic understanding

ALICE: 2308.16706





ALICE: 1612.08975

Correlation observables in pp: approximations

Building some intuition for the two observables in pp

Ξ production is rare in pp. Either 0 or 1 per event. Probability ε.

$$\langle n_{\Xi^\pm} \rangle \approx \varepsilon, \langle n^2_{\Xi^\pm} \rangle \approx \varepsilon, \text{ and } \langle n_{\Xi^+} n_{\Xi^-} \rangle \approx \langle n_{\Xi^+} \rangle \langle n_{\Xi^-} \rangle \approx 0,$$

Error only of order $1 \cdot \varepsilon$

Crude approximation. Removes microscopic correlations

$$\Rightarrow \qquad \kappa_2(\Delta\Xi) \approx 2\langle n_{\Xi^+} \rangle = 2\langle n_{\Xi^-} \rangle,$$

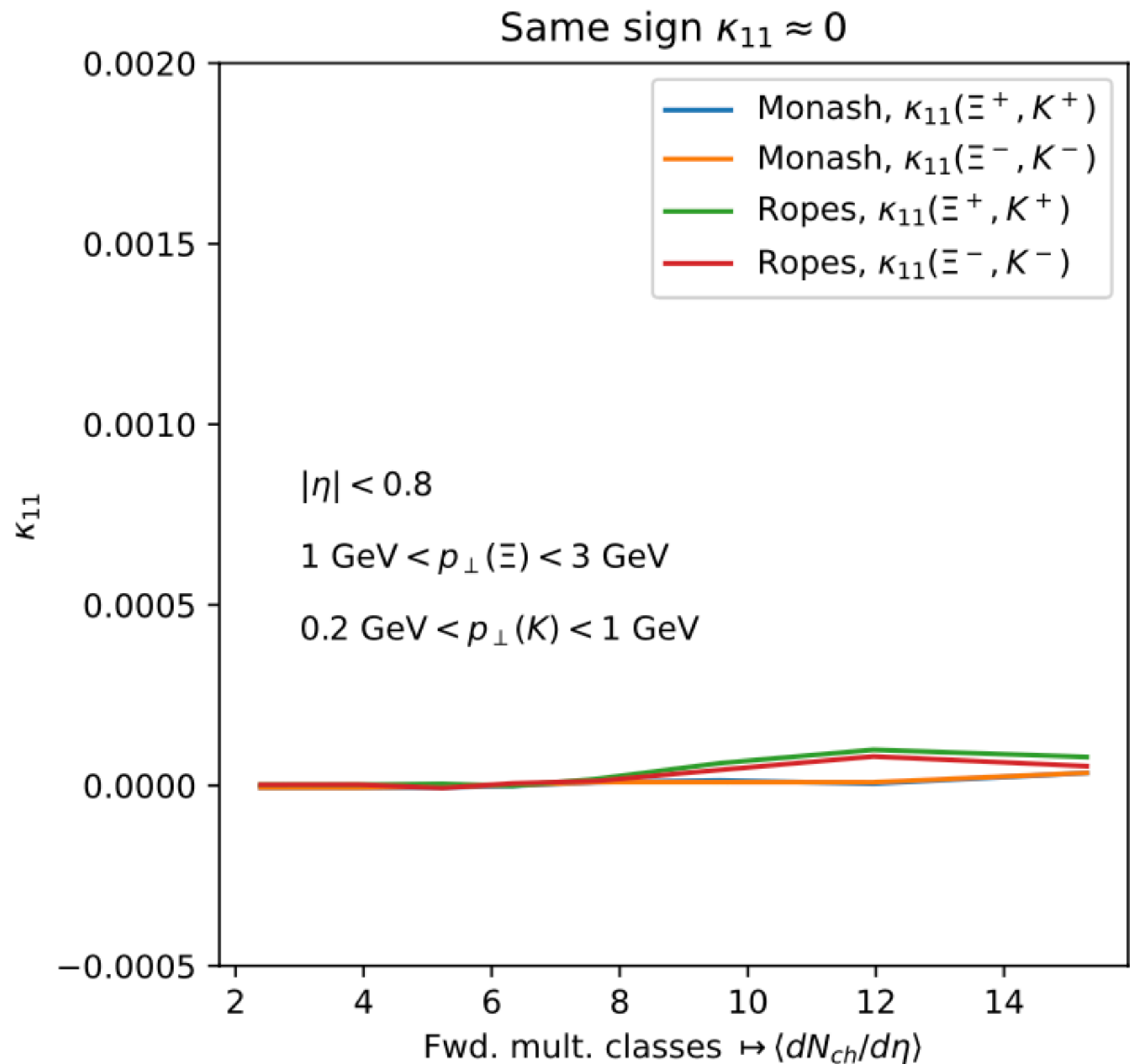
$$\kappa_{11}(n,m) = \langle nm \rangle - \langle n \rangle \langle m \rangle \approx \varepsilon_n(\varepsilon_{m|n} - \varepsilon_m)$$

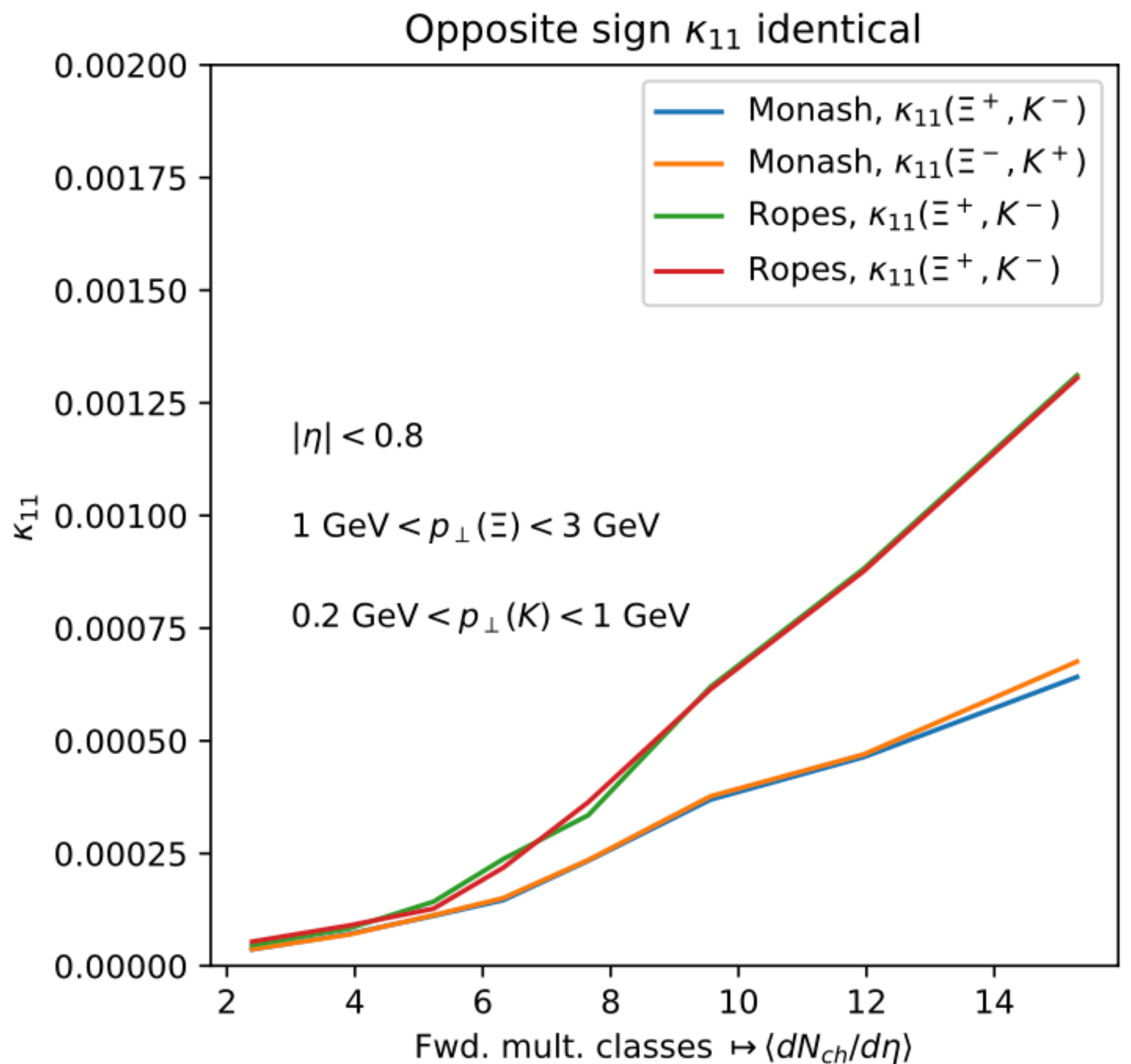
$\Rightarrow$

$\kappa_{11}(\text{same sign}) \approx 0$

$\kappa_{11}(\Xi^+, K^-) = \kappa_{11}(\Xi^-, K^+)$

(Baye's theorem)





Pearson coefficient

- This gives first approximation below. Consider further:

Postulate

$$\frac{\kappa_{11}(\Xi^-, K^+)}{\langle n_{\Xi^-} \rangle} \approx \frac{\varepsilon_{\Xi^-}(\varepsilon_{K^+|\Xi^-} - \varepsilon_{K^+})}{\varepsilon_{\Xi^-}} = \varepsilon_{K^+|\Xi^-} - \varepsilon_{K^+} \equiv a.$$

- Resonable postulate in string model
- Multiplicity dependence of two terms similar
  - Kaons are abundant, they are **not much more likely** because I produced Ξ

$$\rho(\Delta\Xi, \Delta K) = \frac{\kappa_{11}(\Delta\Xi, \Delta K)}{\sqrt{\kappa_2(\Delta\Xi)\kappa_2(\Delta K)}} \approx -\frac{\kappa_{11}(\Xi^+, K^-)}{\sqrt{\langle n_{\Xi^+} \rangle \langle n_{K^+} \rangle}} \approx -\frac{a \langle n_{\Xi^+} \rangle}{\sqrt{\langle n_{\Xi^+} \rangle \langle n_{K^+} \rangle}} = -a\sqrt{\frac{\langle n_{\Xi^+} \rangle}{\langle n_{K^+} \rangle}}$$

Second order moment

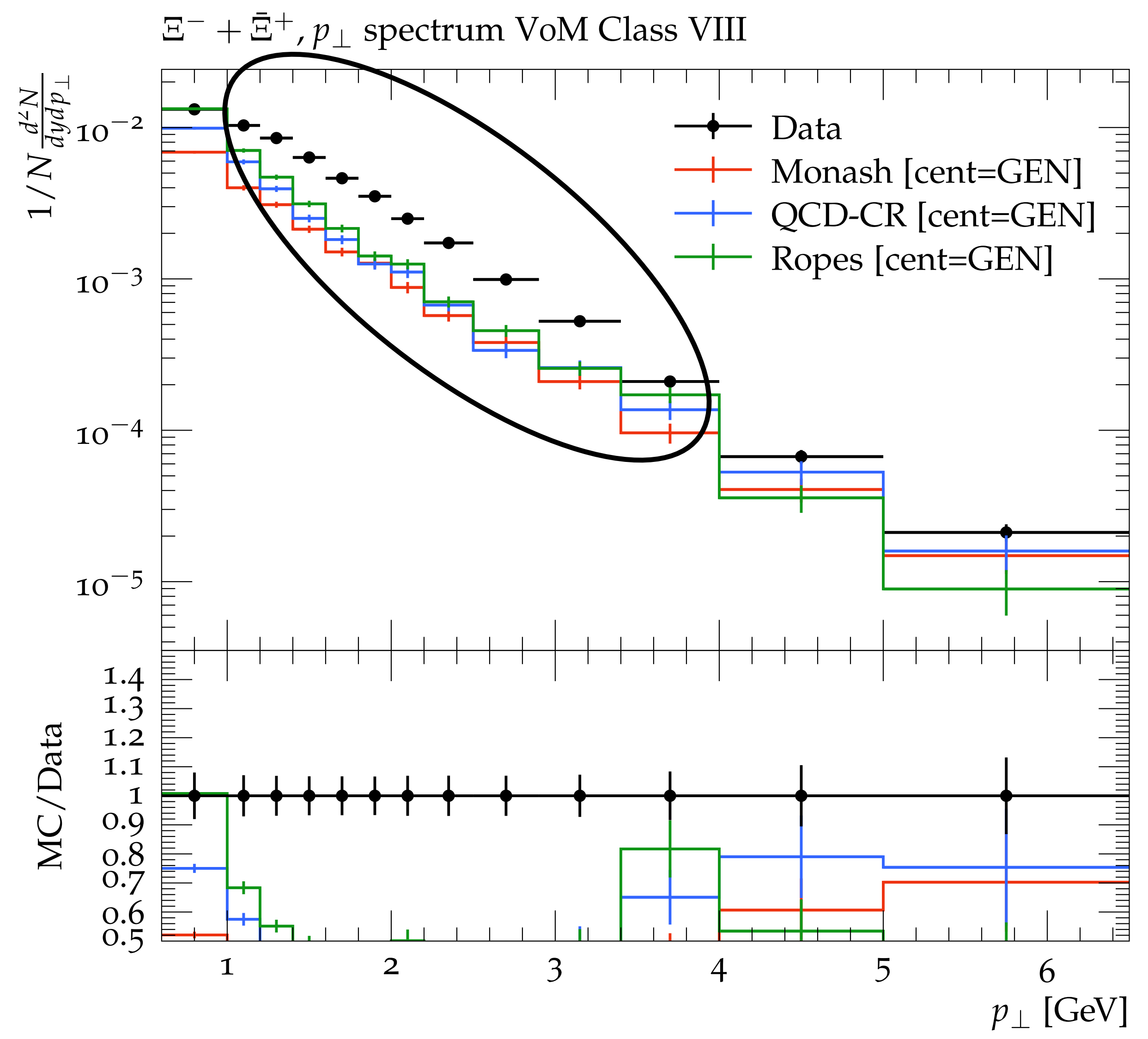
- We can no longer approximate Ξ^+, Ξ^--correlations away.
- Instead, simplify with $\langle n_{\Xi^+} \rangle = \langle n_{\Xi^-} \rangle$
- Note that simplest correlation is pair-production with $\Delta y_{\Xi^+\Xi^-}$ (string model)
- If **only** possibility, then $\langle n_{\Xi^+} n_{\Xi^-} \rangle \propto \varepsilon_{\Xi^+} \varepsilon_{\Xi^-|\Xi^+} \frac{\Delta y_{\text{acc}}}{\Delta y_{\Xi^+\Xi^-}} \equiv \langle n_{\Xi^+} \rangle b$
- In string model *b* is constant up to junction formation

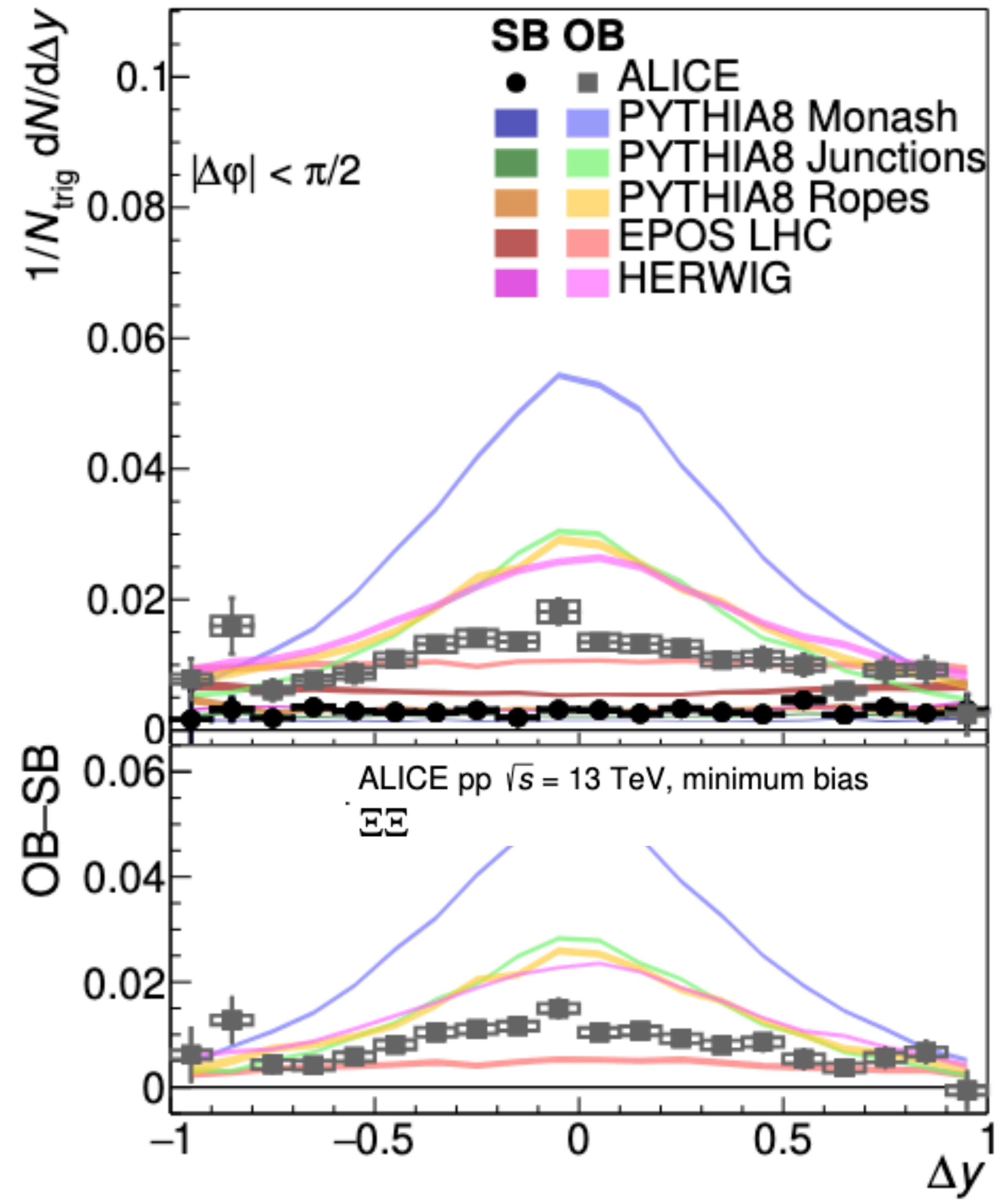
$\langle n_{\Xi^+} \rangle = \langle n_{\Xi^-} \rangle$

$$\sigma(\Delta\Xi) = \frac{\kappa_2(\Delta\Xi)}{\langle \Xi^+ + \Xi^- \rangle} = \frac{\langle n^2_{\Xi^+} \rangle - \langle n_{\Xi^+} n_{\Xi^-} \rangle}{\langle n_{\Xi^+} \rangle} \approx 1 - b$$

Qualitative lessons

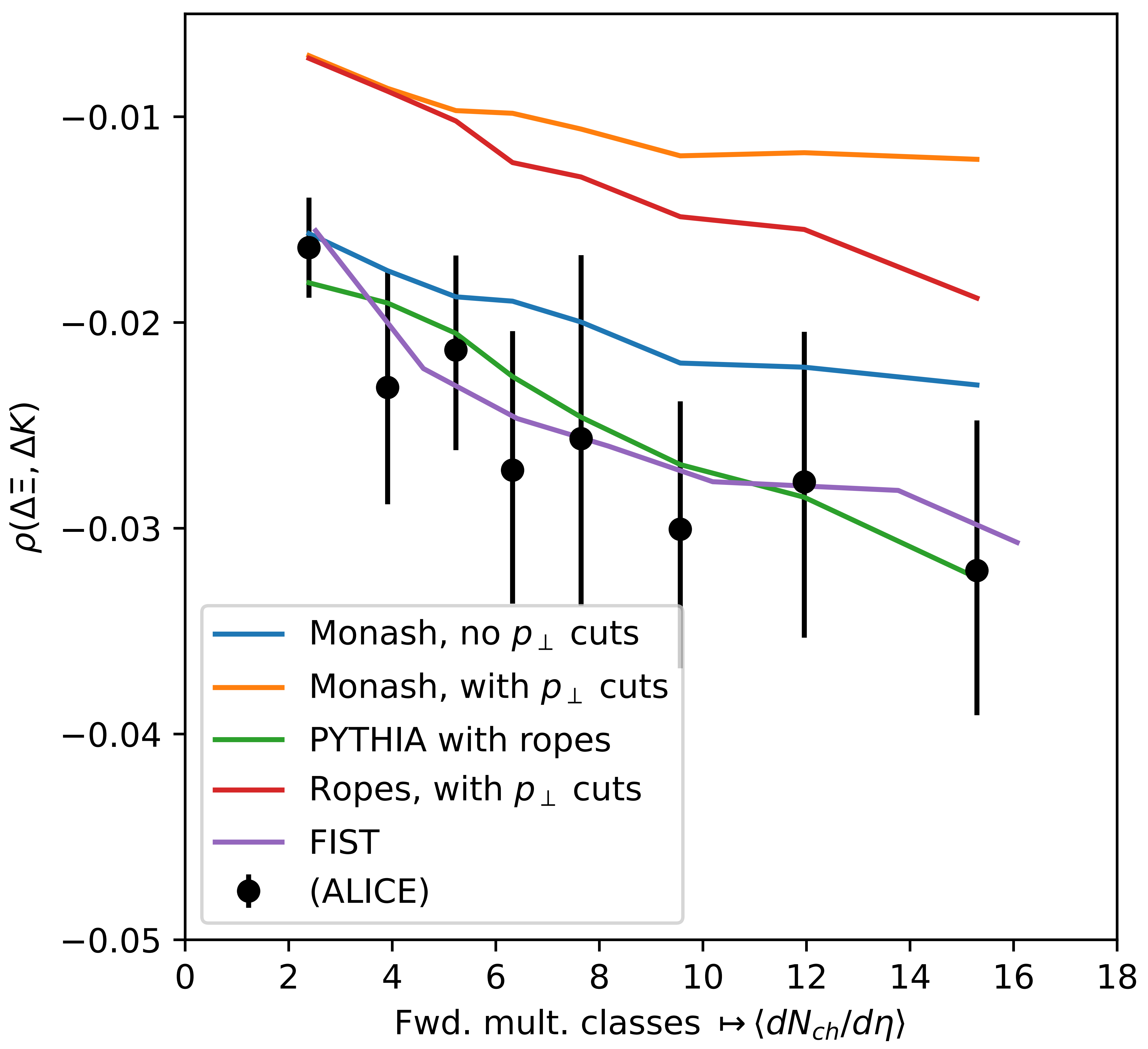
- Usual HI interpretation questionable in pp.
- Pearson strongly affected by Ξ yield.
  - What is the $p_\perp$ dependence? No other clear model dependence.
- Cumulant depends mainly on correlation length vs acceptance.
  - Pythia is slightly too “narrow”.
  - Known from previous measurements.
  - Should be sensitive to parameter choices.





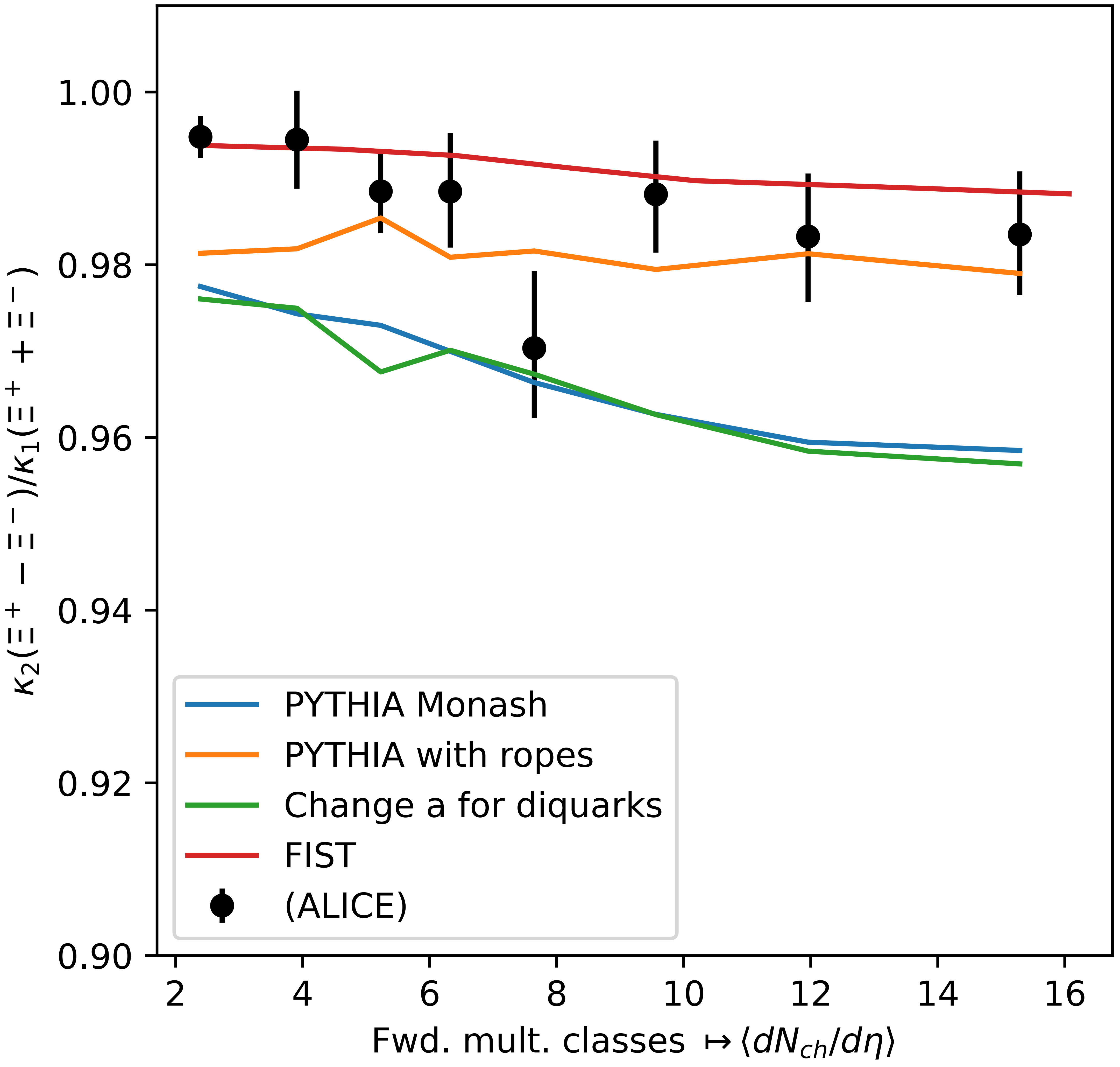
Re-simulation: Pearson

- Observable should be $p_\perp$ insensitive, except for yield dependence.
- Re-simulate, but leave out $p_\perp$ -cuts from PYTHIA?
- If all else equal, the result should be the same.
- (MC truth, data points from paper, own analysis, parameters in backup)



Re-simulation: Cumulant

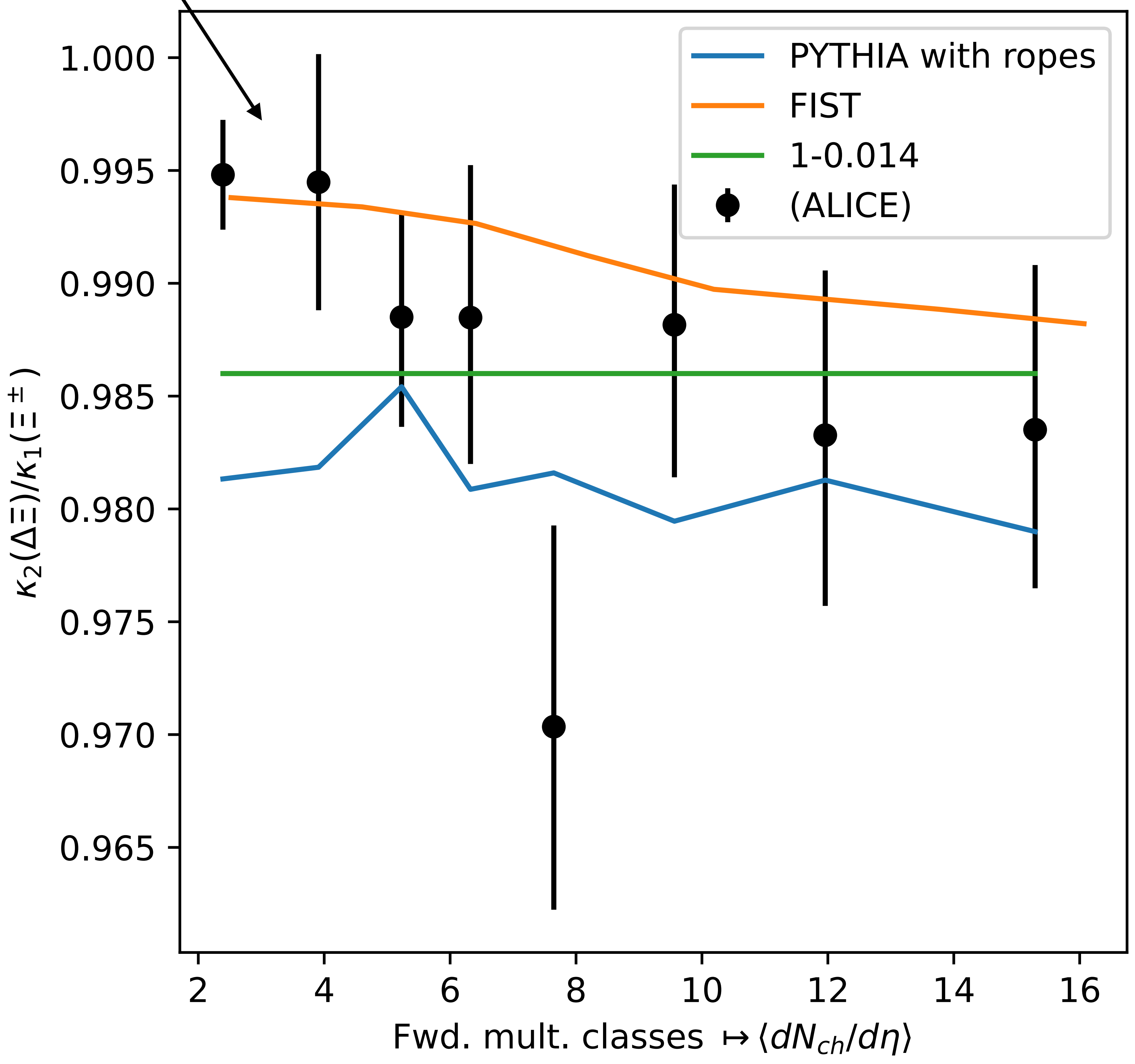
- Observable is $p_{\perp}$ sensitive, larger $p_{\perp}$ typically means mid-rapidity.
- …but quite sensitive to CR and hadronization parameters.
- Re-simulate with correct parameter choice.
- Bonus: Insensitive to change in a-parameter - a lesson to be learned?
- (MC truth, data points from paper, own analysis, parameters in backup)

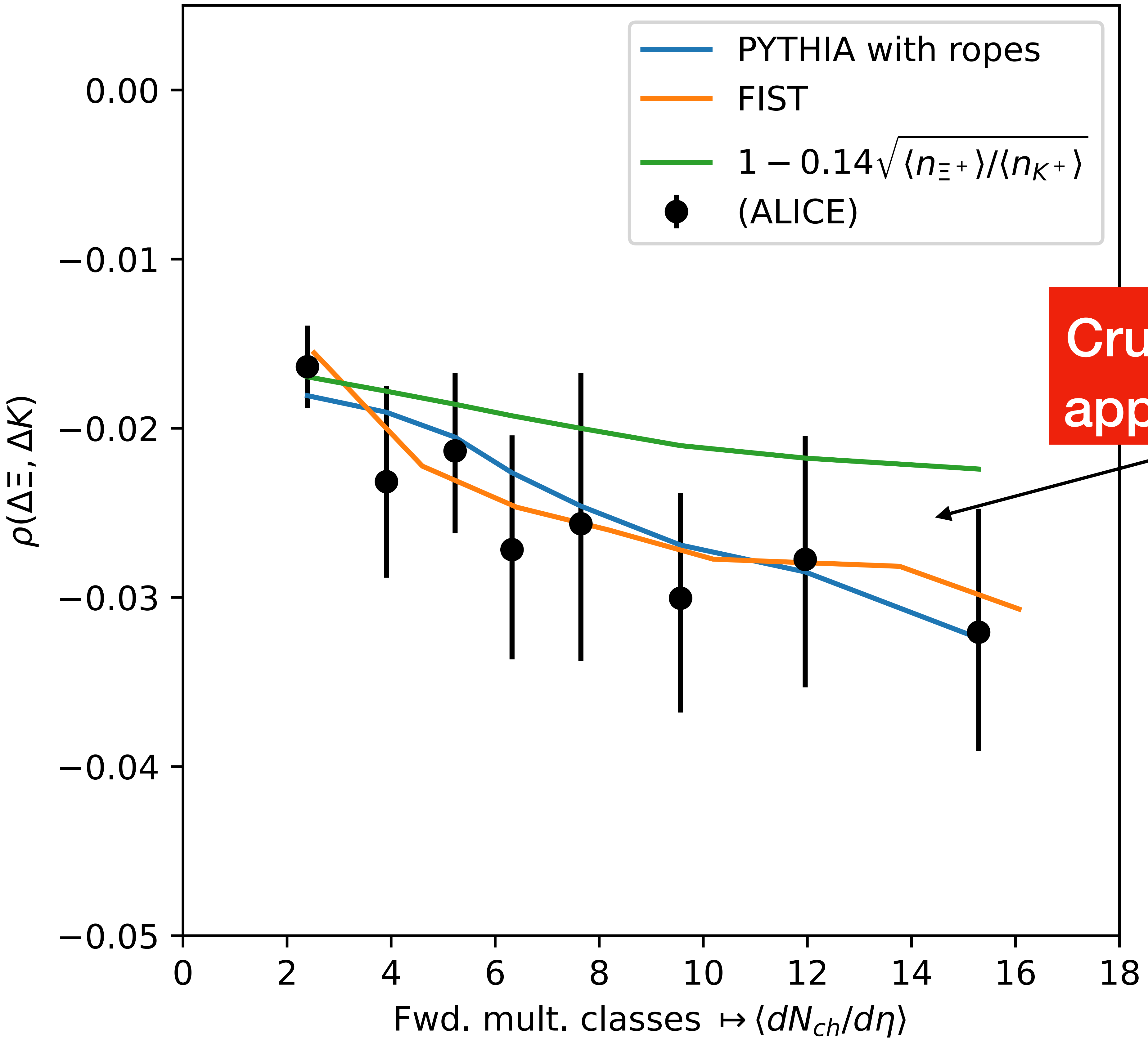


What about the poor approximations?

- Both observables reasonably described by pp statistical toy.

Single-string region?





Crude $\langle n_{\Xi^+} n_{\Xi^-} \rangle$ approximation?

Conclusions

- Correlation measurements reproduced by PYTHIA with altered phase-space and/or correct parameters.
- Toy description of observables almost as good as real MC.
- Correlation measurements **can** provide insights to particle production mechanisms!
- Clear microscopic understanding of observables necessary.
- **Looking forward to discussing new observable proposals which can clearly distinguish between models in pp.**

Backup: Pythia parameters

- For completeness: Parameter recommendation for rope model (from PYTHIA gitlab documentation)

```
# Parameter of the MPI model to keep total multiplicity reasonable
MultiPartonInteractions:pT0Ref = 2.15
# Parameters related to Junction formation/QCD based CR
BeamRemnants:remnantMode = 1
BeamRemnants:saturation = 5
ColourReconnection:mode = 1
ColourReconnection:allowDoubleJunRem = off
ColourReconnection:m0 = 0.3
ColourReconnection:allowJunctions = on
ColourReconnection:junctionCorrection = 1.2
ColourReconnection:timeDilationMode = 2
ColourReconnection:timeDilationPar = 0.18
# Enable rope hadronization
Ropewalk:RopeHadronization = on
# Also enable string shoving, but don't actually do anything.
# This is just to allow strings to free stream until hadronization
# where the overlaps between strings are calculated.
Ropewalk:doShoving = on
Ropewalk:tInit = 1.5 # Propagation time
Ropewalk:deltat = 0.05
Ropewalk:tShove = 0.1
Ropewalk:gAmplitude = 0. # Set shoving strength to 0 explicitly
```

```
# Do the ropes.
Ropewalk:doFlavour = on

# Parameters of the rope model
Ropewalk:r0 = 0.5 # in units of fm
Ropewalk:m0 = 0.2 # in units of GeV
Ropewalk:beta = 0.1

# Enabling setting of vertex information is necessary
# to calculate string overlaps.
PartonVertex:setVertex = on
PartonVertex:protonRadius = 0.7
PartonVertex:emissionWidth = 0.1
```

- Careful drawing general conclusions based on specific settings