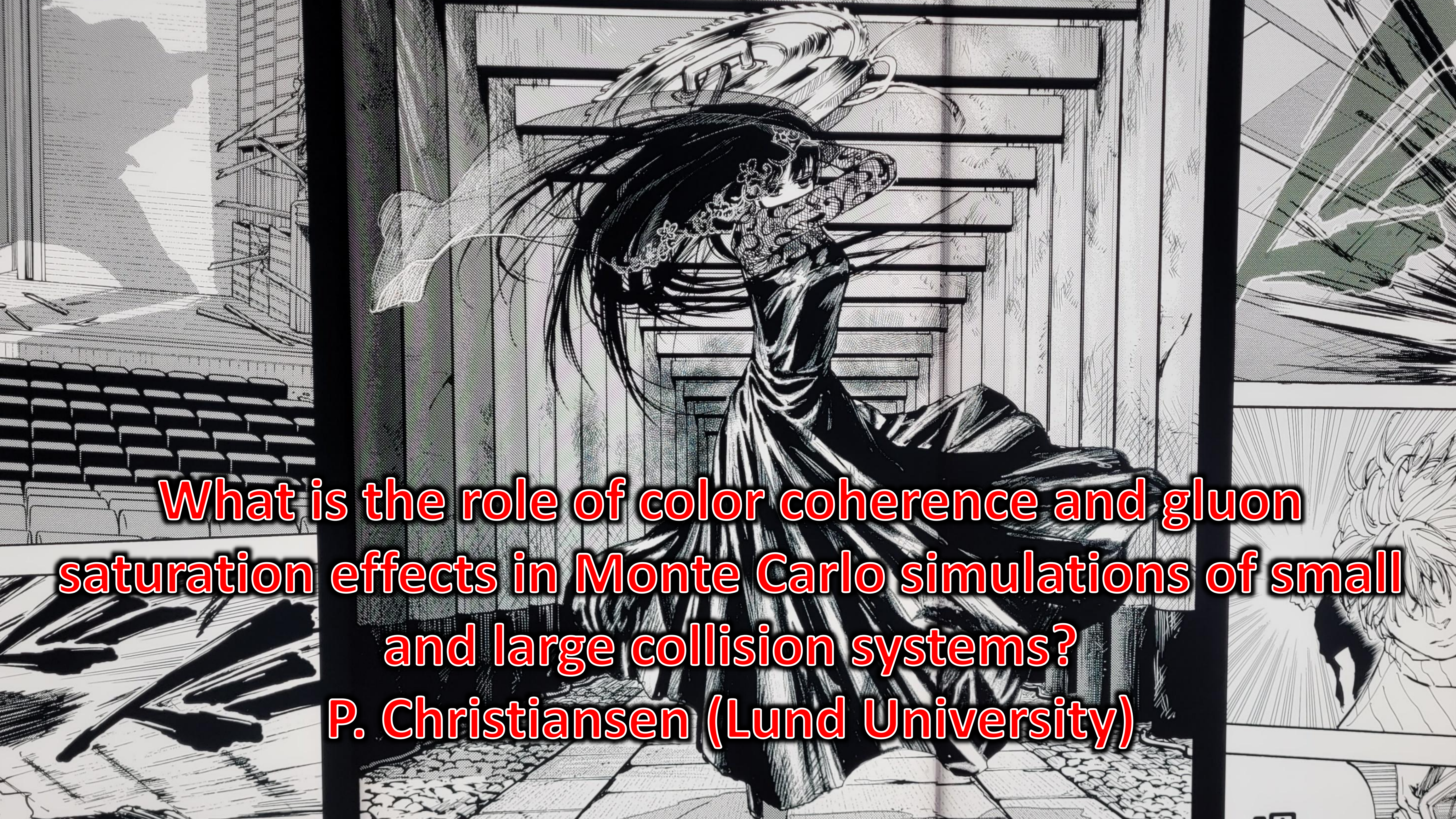
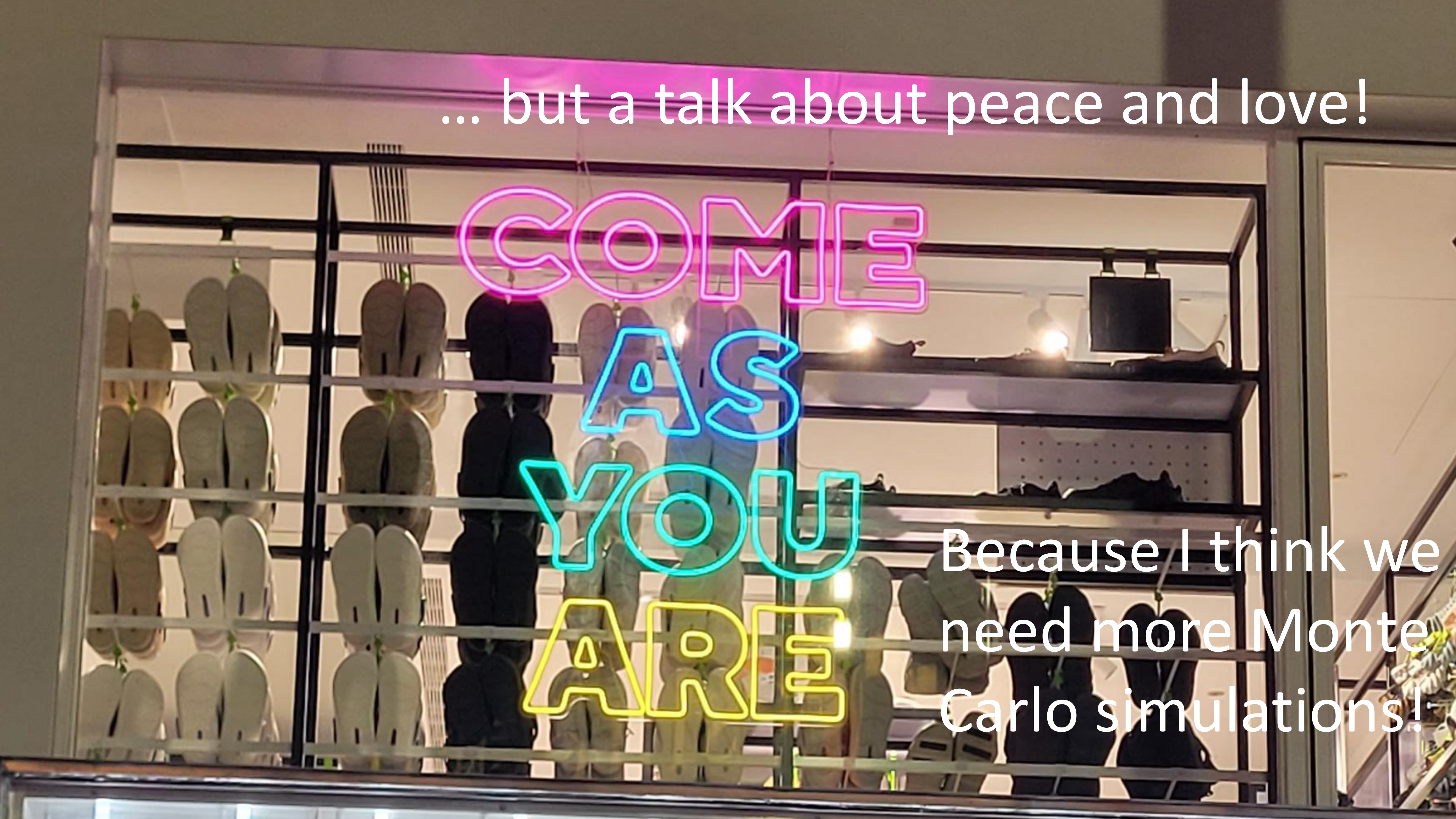


What is the role of color coherence and gluon saturation effects in Monte Carlo simulations of small and large collision systems?

P. Christiansen (Lund University)

Not a talk about “death or glory”…

… but a talk about peace and love!



Because I think we need more Monte Carlo simulations!

Monte Carlo Simulations

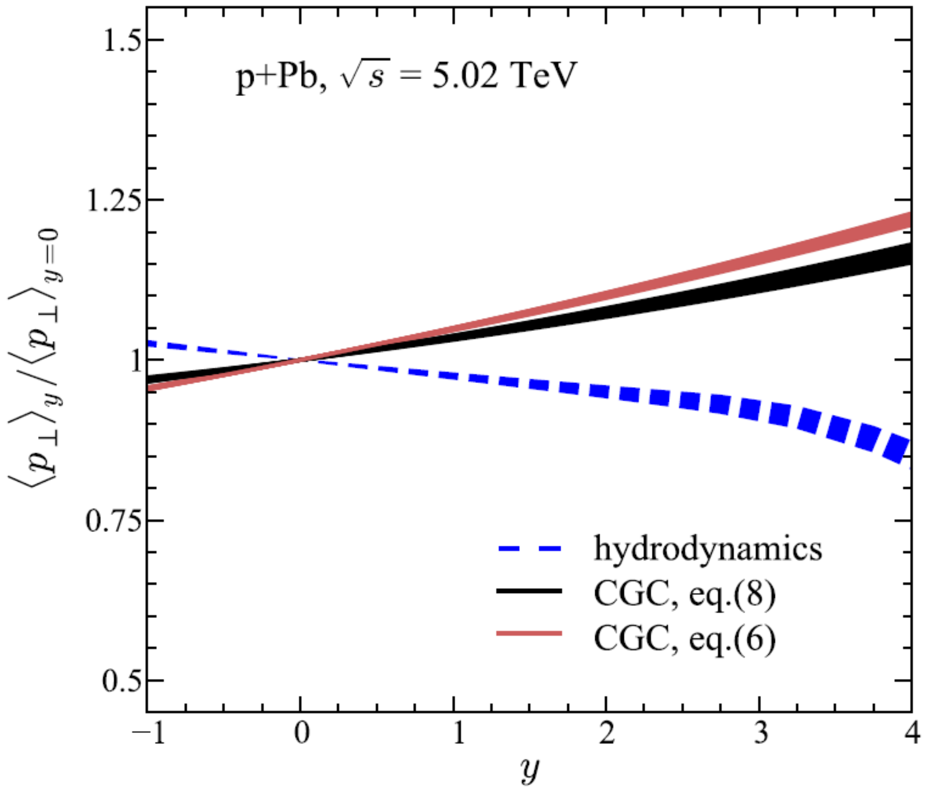
- Can simulate full events (at least in some phase space)
  - Can be compared apples-to-apples with data
  - Same model can be compared with multiple results
- Open
  - Results can be reproduced, and internal machinery examined
  - Can be used by external people to come up with tests of physics
- Peace and love! We have to respect that it is a
  - Huge effort to develop MCs and sometimes there are known issues
  - Best effort that will always be a step behind specialized approaches

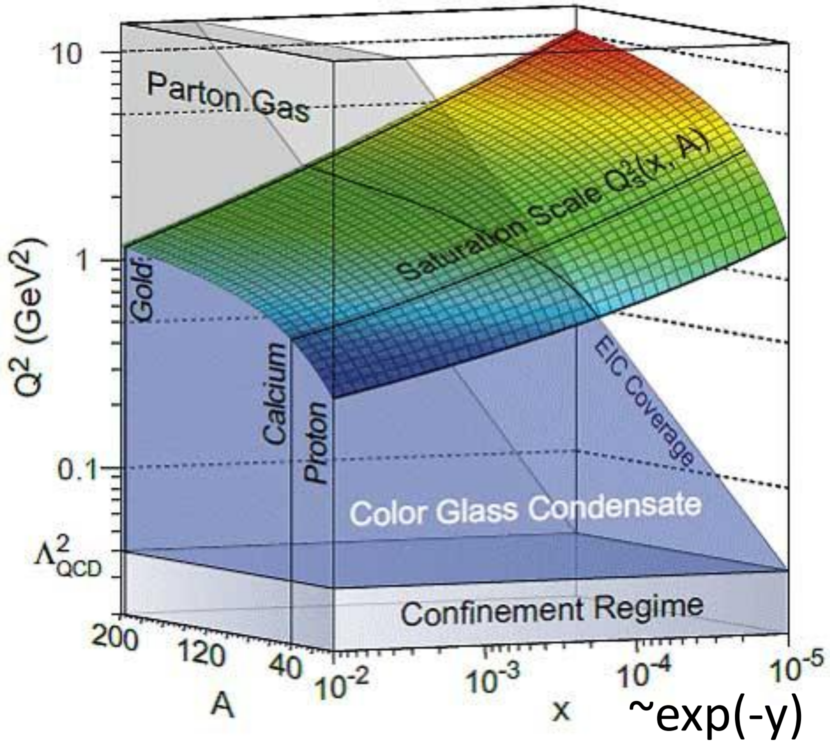
Saturation

- Needed in all Monte Carlo models, e.g.:
  - PYTHIA/Angantyr (arXiv:2203.11601) has p_{T0} that grows with $\sqrt{s}$
  - EPOS4 (arXiv:2301.12517) has a dynamical saturation scale that depends on number of pomerons connected to a nucleon
  - MC-EKRT (arXiv:2406.17592)has final-state EKRT saturation
- Implementations differ and none of the models have CGC-like Q_s
  - CGC is simulated as a mix of codes, e.g., IP-Glasma+MUSIC+URQMD, rather than one open public code
- Can we differentiate between saturation models?
  - Hope to show that it is a difficult question to answer without more work

CGC early predictions for p-Pb

P. Bożek et al, Phys. Lett. B 728, 662 (2014)

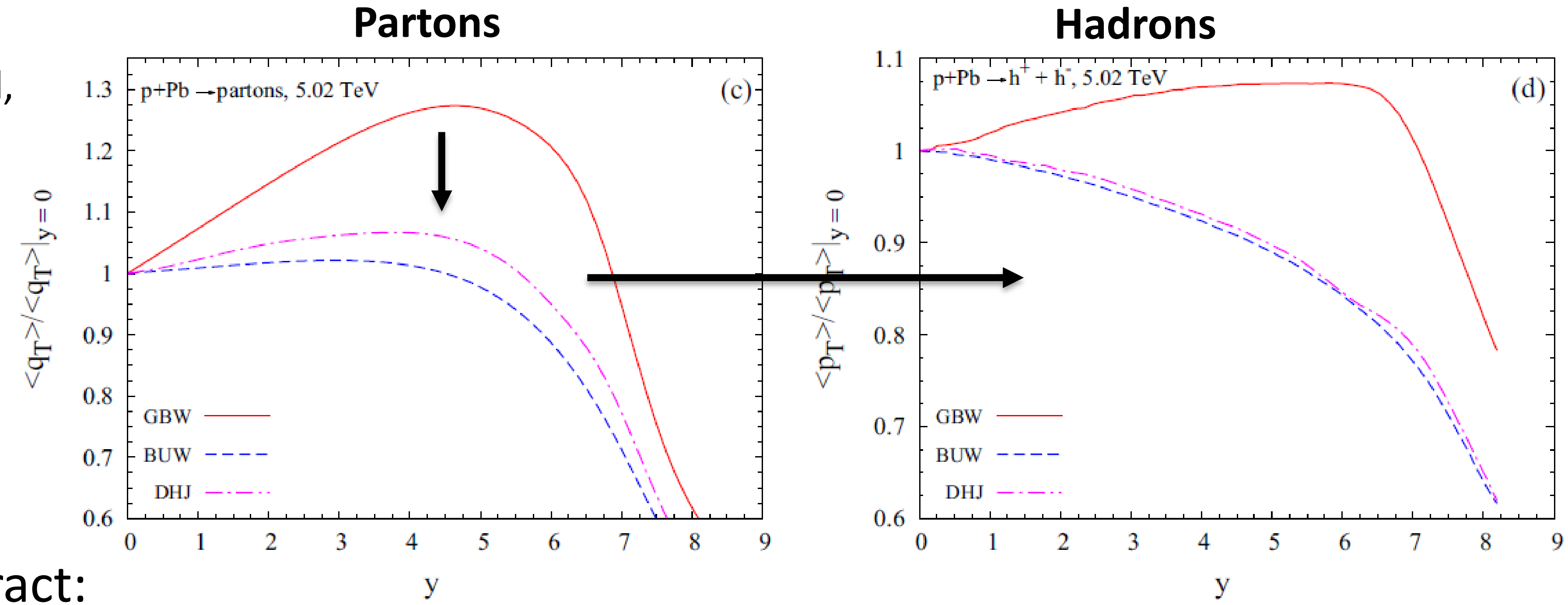




Spectacular prediction:
The proton scatters of the Pb CGC while for hydro <p_T> follows the "energy density".

CGC refined predictions for p-Pb

F. O. Durães et al, PRC 94, 024917 (2016)



From abstract:

"We update previous predictions for the p_T spectra using the hybrid formalism of the CGC approach and two phenomenological models for the dipole-target scattering …. and demonstrate that the ratio $<p_T(y)>/<p_T(y=0)>$ decreases with the rapidity and has a behavior similar to that predicted by hydrodynamical calculations."

Highlights the need for full MC simulations!

The challenge with gluon saturation is that it happens early!

C. Bierlich,
SciPost Phys.Codeb. 2022 (2022) 8

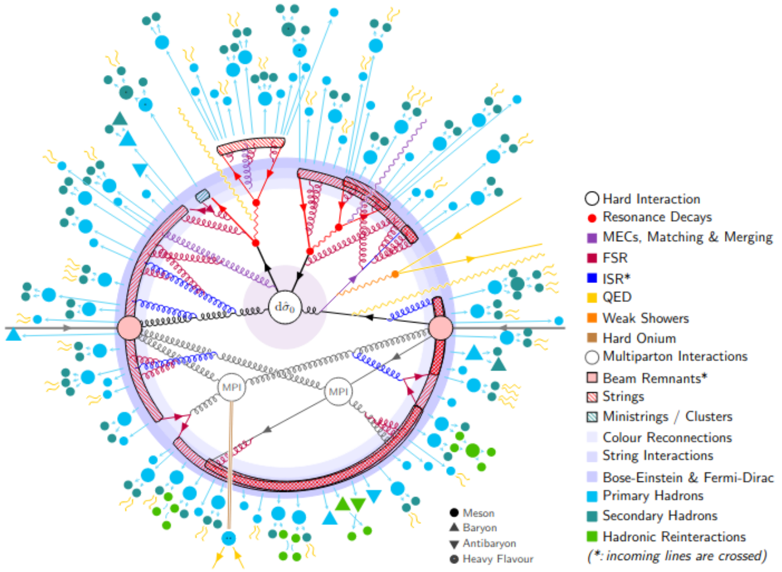
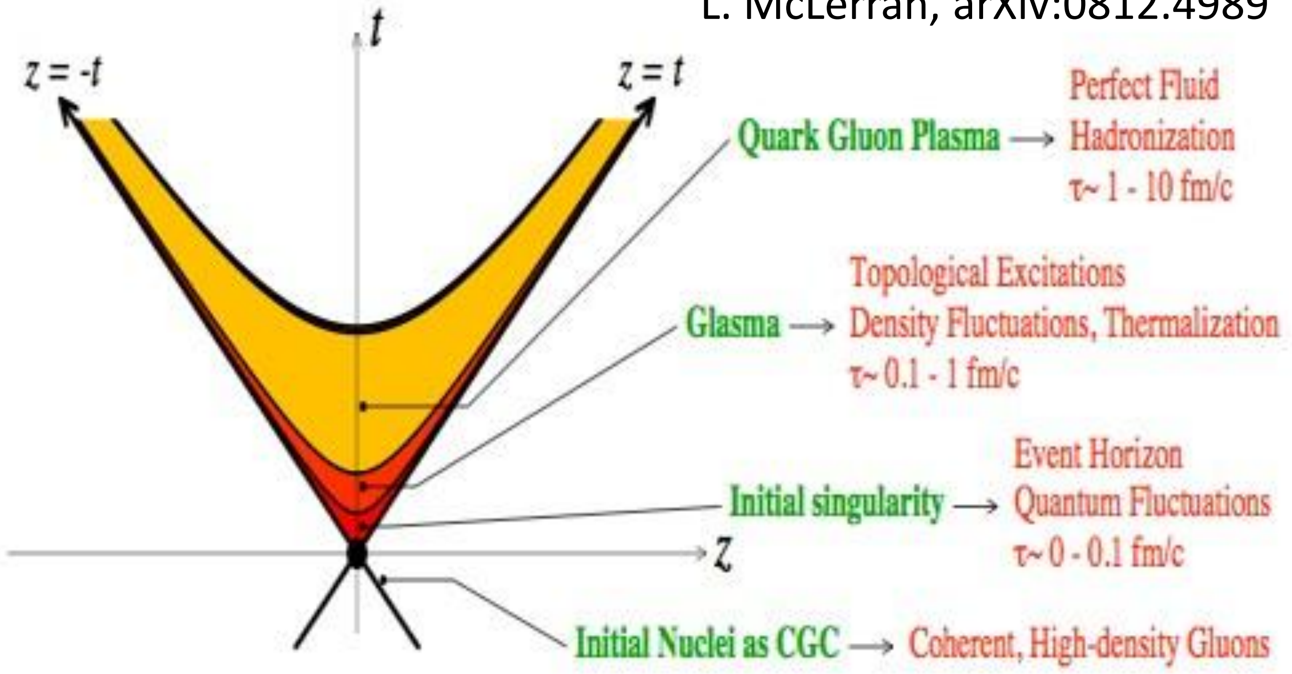


Figure 1: Schematic of the structure of a pp → $t\bar{t}$ event, as modelled by PYTHIA.

L. McLerran, arXiv:0812.4989



- Would be great with an open CGC full generator (baseline) code
- I think we need to try to understand if there are observables – beyond flow ε_n– where different saturation models matter

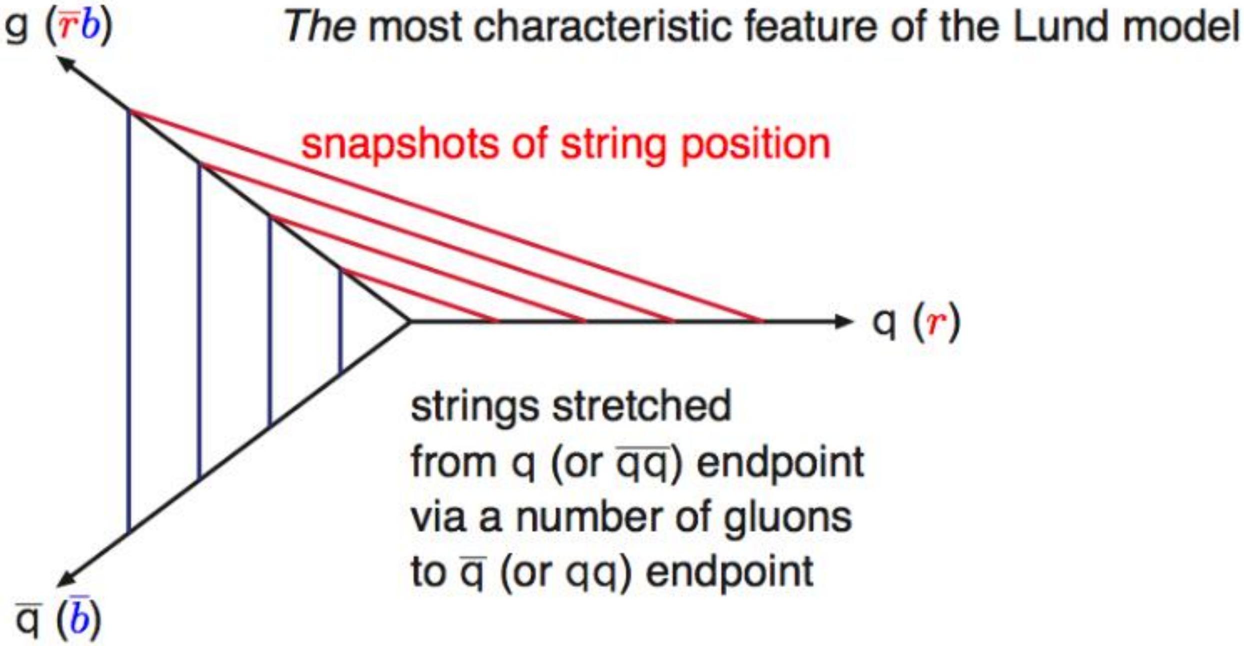
Color coherence

- Use a bit weaker definition than usual: particle production driven mainly by color
  - For example: we scatter quarks and gluons
    $\rightarrow$ the strings between them in the Lund model are in this definition a color coherence effect

Color coherence

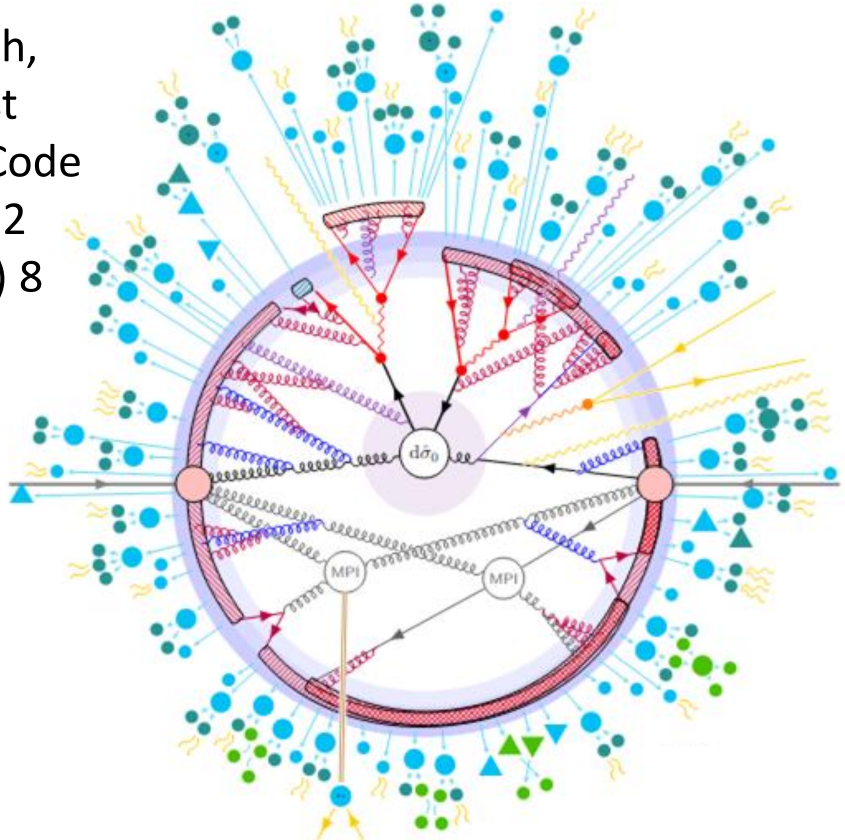
- Use a bit weaker definition than usual: particle production driven mainly by color
  - For example: we scatter quarks and gluons
    $\rightarrow$ the strings between them in the Lund model are in this definition a color coherence effect
    $\rightarrow$ observable effect:

Famous case:
$e^+e^- \rightarrow q\bar{q}g$

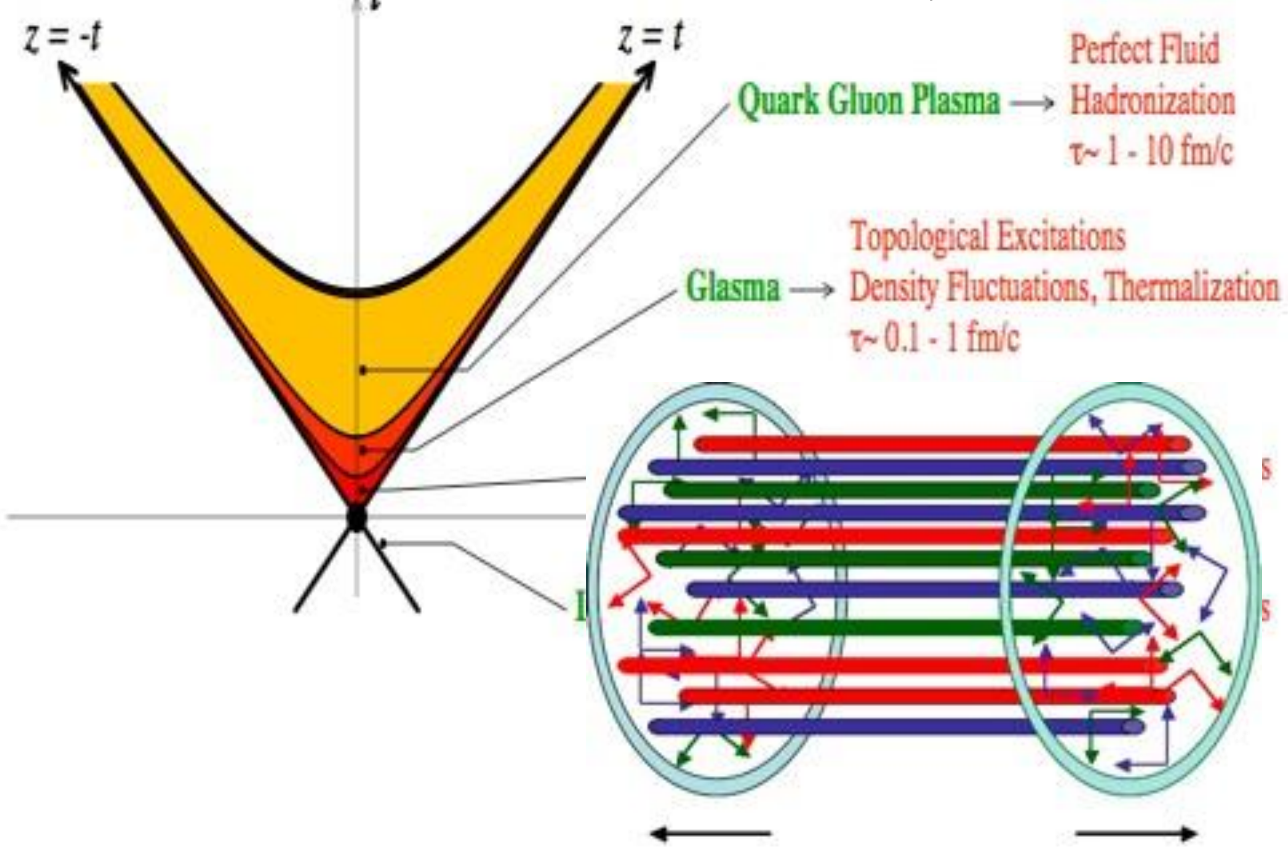


Color coherence is super exciting because it is related to confinement/deconfinement

C. Bierlich, SciPost Phys.Code b. 2022 (2022) 8



L. McLerran, arXiv:0812.4989

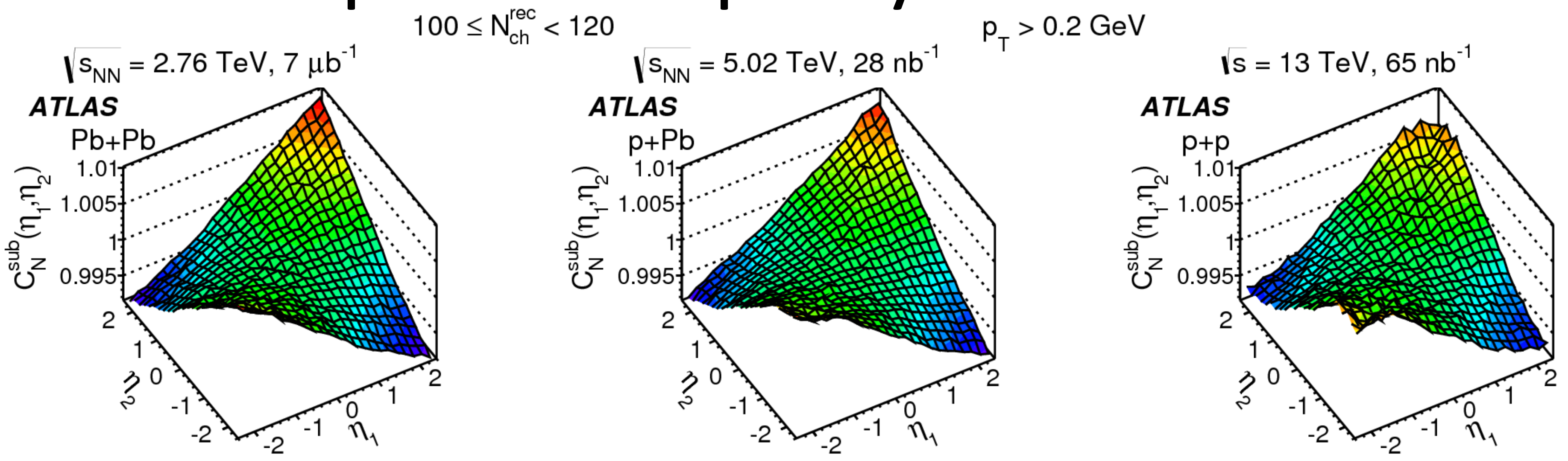


- In PYTHIA the Lund strings are formed late (confined)
- The Glasma is early (deconfined)

We can learn about the longitudinal fields via 2-particle rapidity correlations

ATLAS;
PRC 95 (2017) 6, 064914

Soft long-range part, See paper for details.



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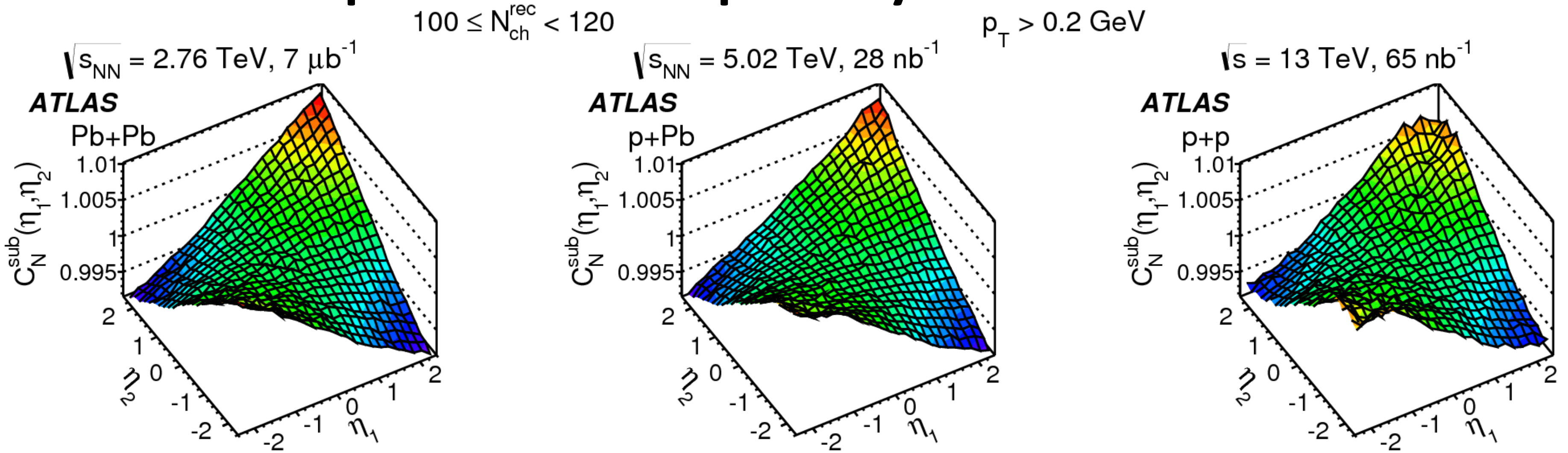
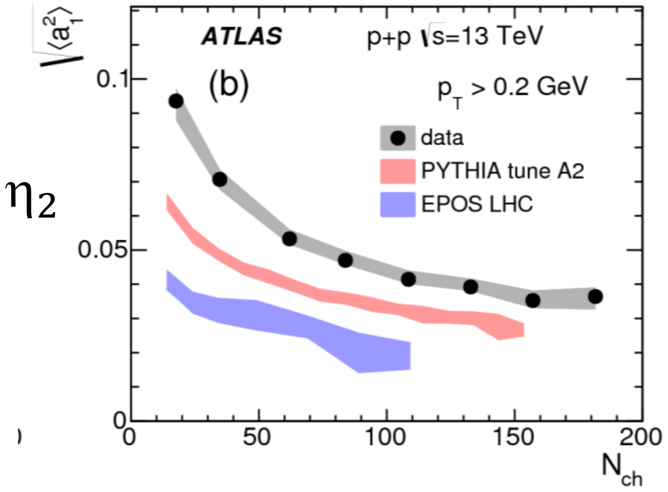


Fit LRC with:

$$C \approx 1 + \langle a_1^2 \rangle \eta_1 \eta_2$$



- I always found these results highly surprising:
  - $\sqrt{\langle a_1^2 \rangle}$ scaling $\rightarrow$ more of the same
    - Same in CGC-like model (A. Bzdak, K. Dusling, PRC 94, 044918 (2016))?

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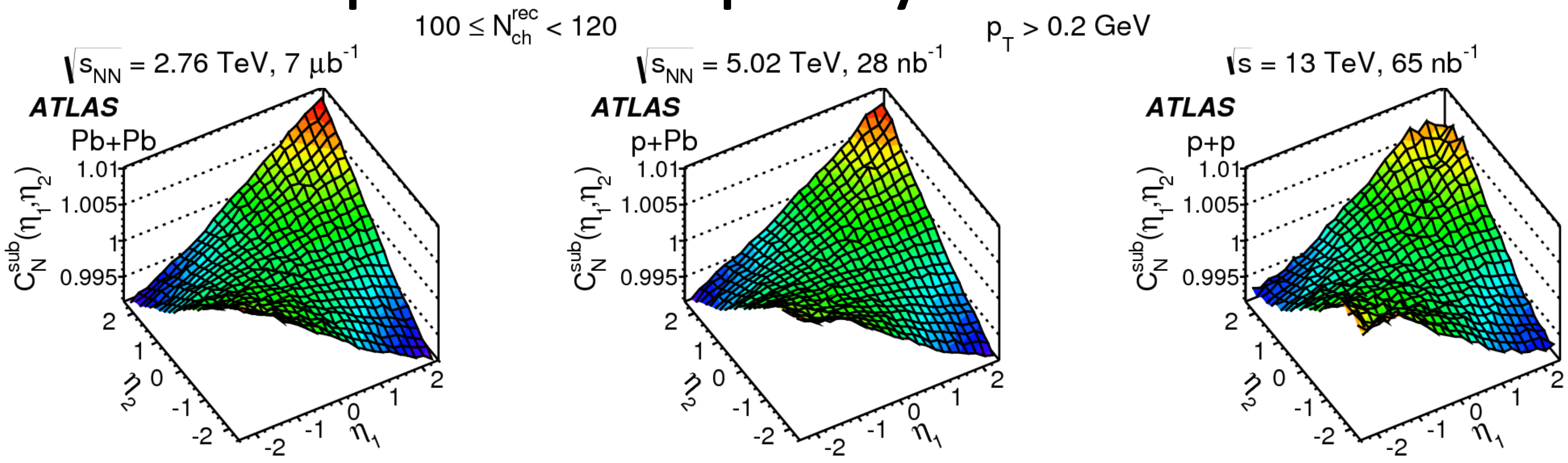

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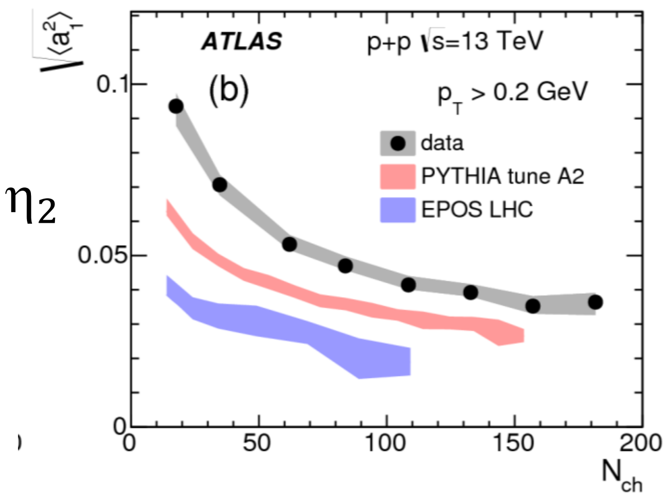

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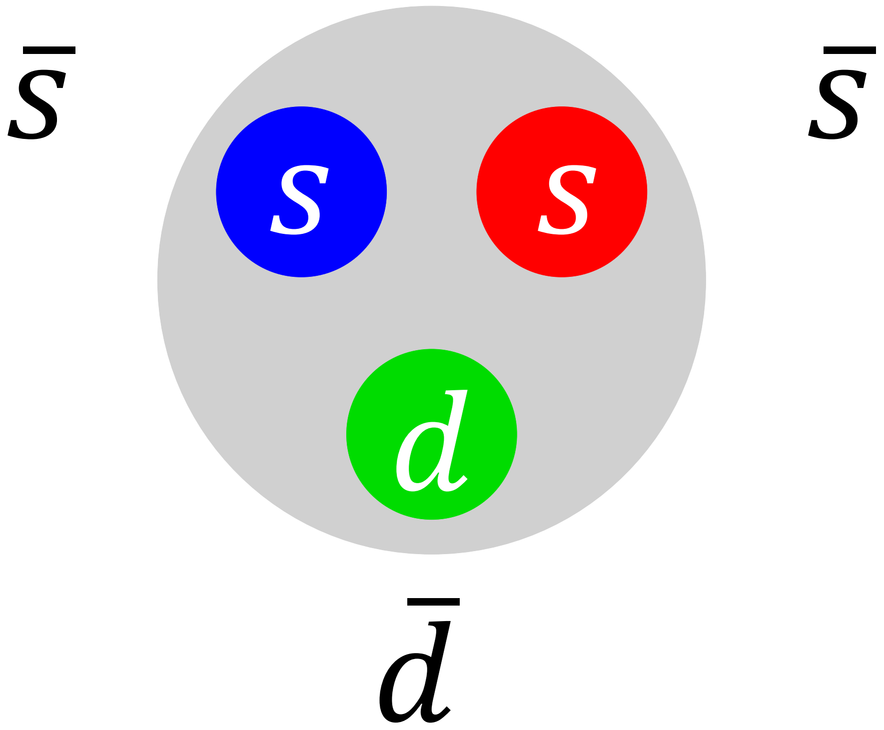
  2-particle corr. mainly intra string/fluxtube
    - Where is the medium contribution?
- "A dog that did not bark"?

Identified particle production string-by-string!

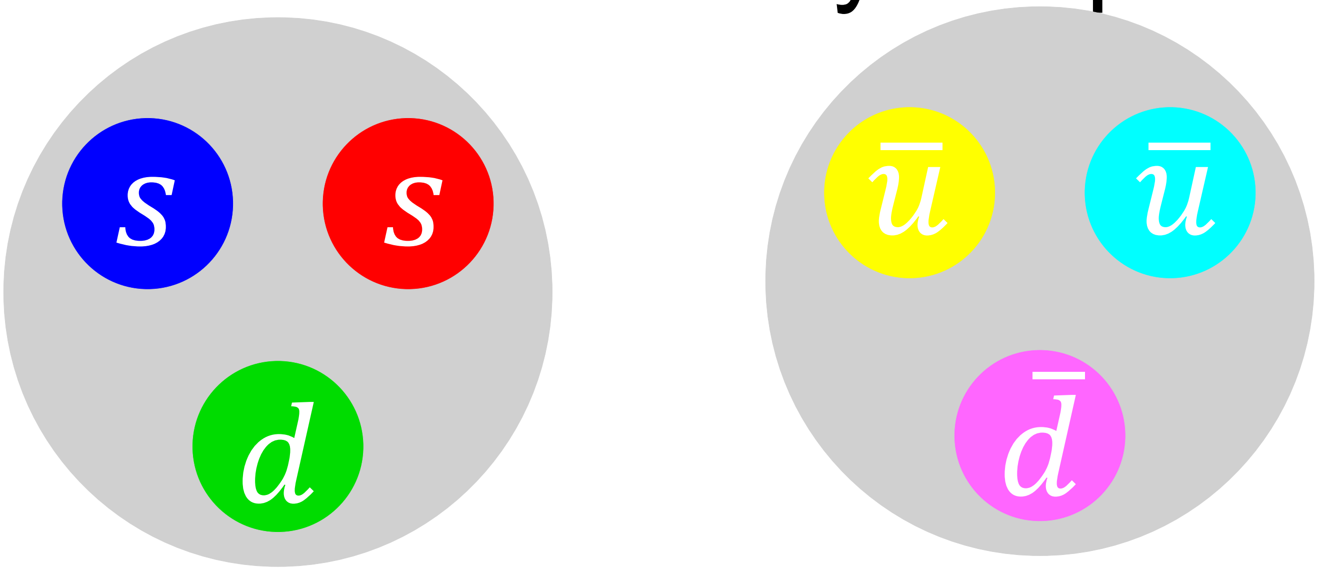
Ξ (Xi) baryon

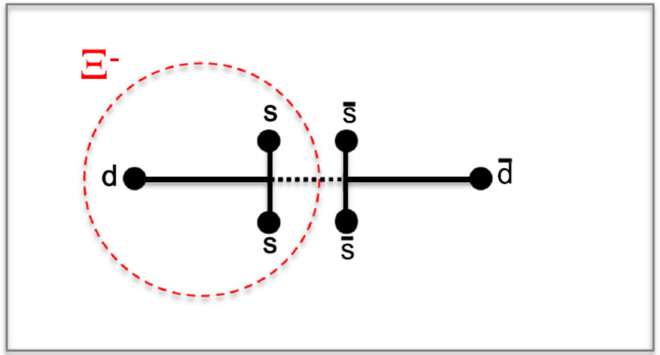


In a Lund string, most correlated particles are produced on the same string. If we require 2 strange quarks at least 1 is produced and balanced on the same string!

We can use balance functions to subtract uncorrelated production!

The easiest case:
Ξ balanced by antiproton





Normal Lund string and ropes:
Ξ almost never balanced by antiproton but instead typically by antistrange baryons and even anti-Ξ!

Idea from CLASH workshop write up: J. Adolfsson et al, Eur. Phys. J. A 56 (2020) 11, 288, “QCD challenges from pp to A–A collisions”

The easiest case:
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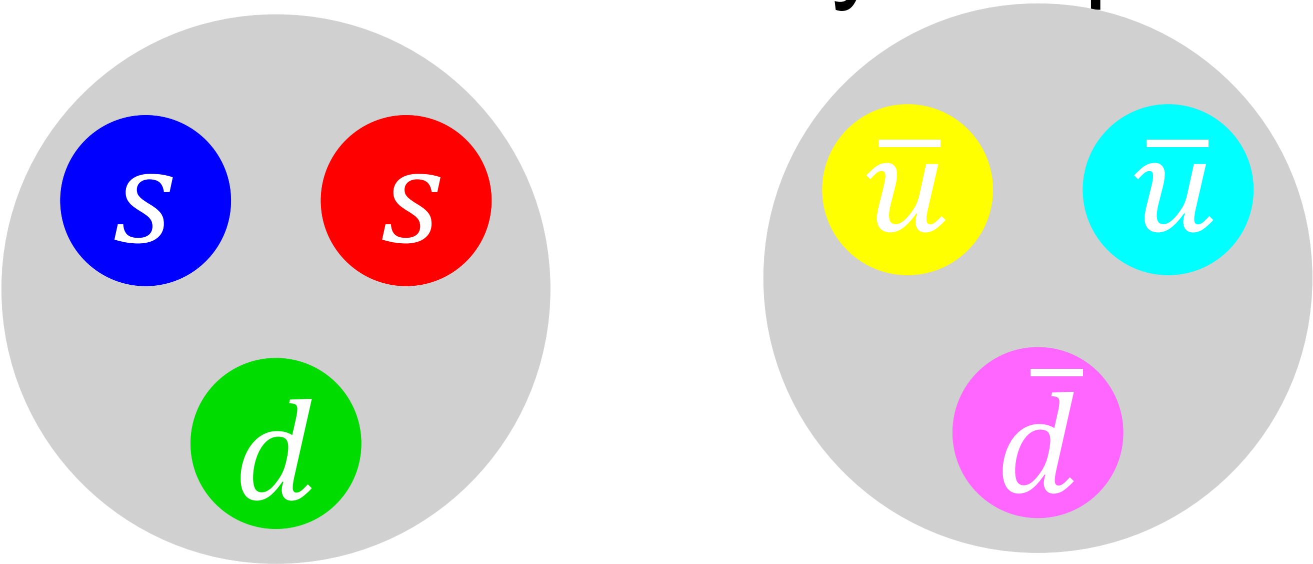

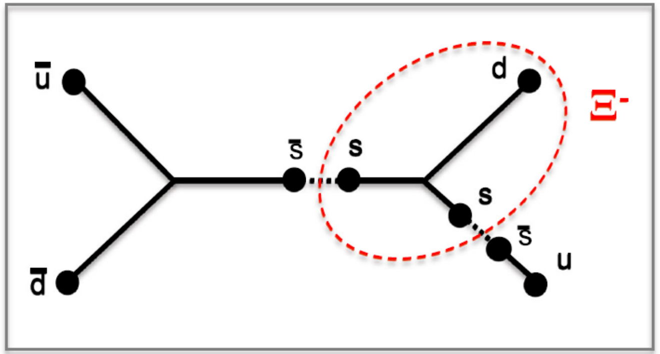

Junction:
Ξ balanced more by kaons and less by antistrange baryons.
Broader correlations in rapidity.

Idea from CLASH workshop write up: J. Adolfsson et al, Eur. Phys. J. A 56 (2020) 11, 288, “QCD challenges from pp to A–A collisions”

The easiest case:
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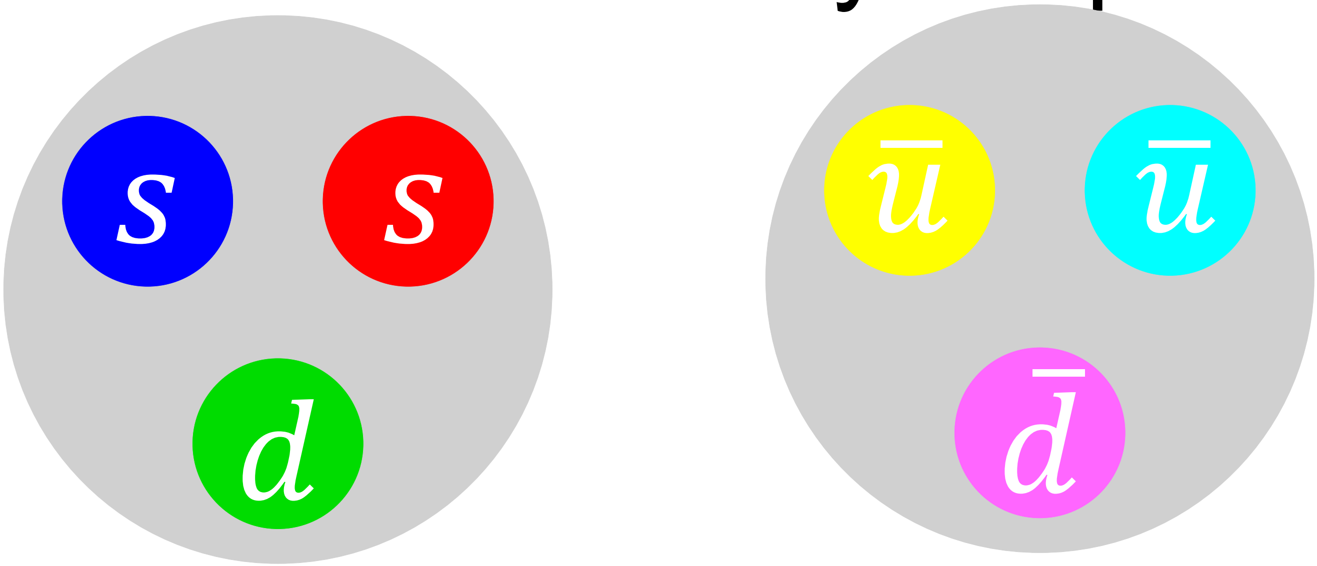
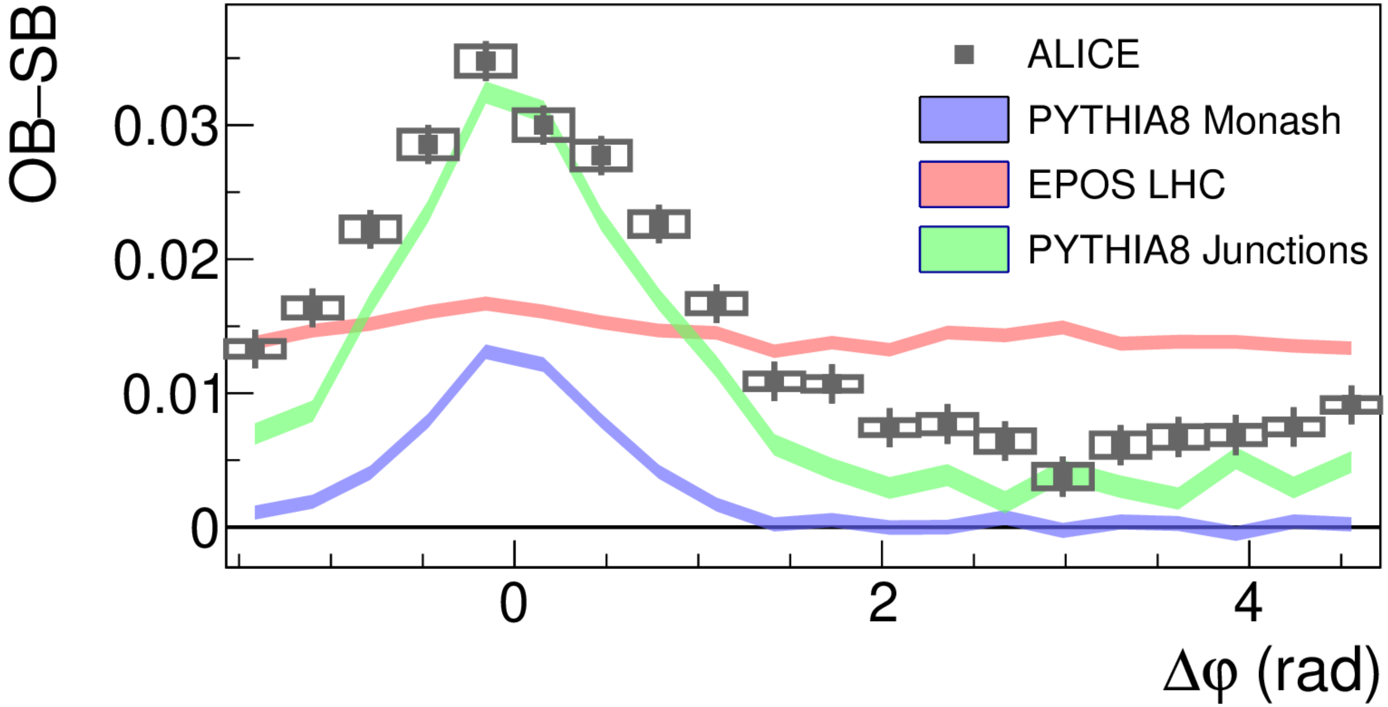


QGP:
We expect that the balancing occurs on a statistical basis so this can happen.
This is also where we hope to see differences to Lund strings: emergence of deconfinement?

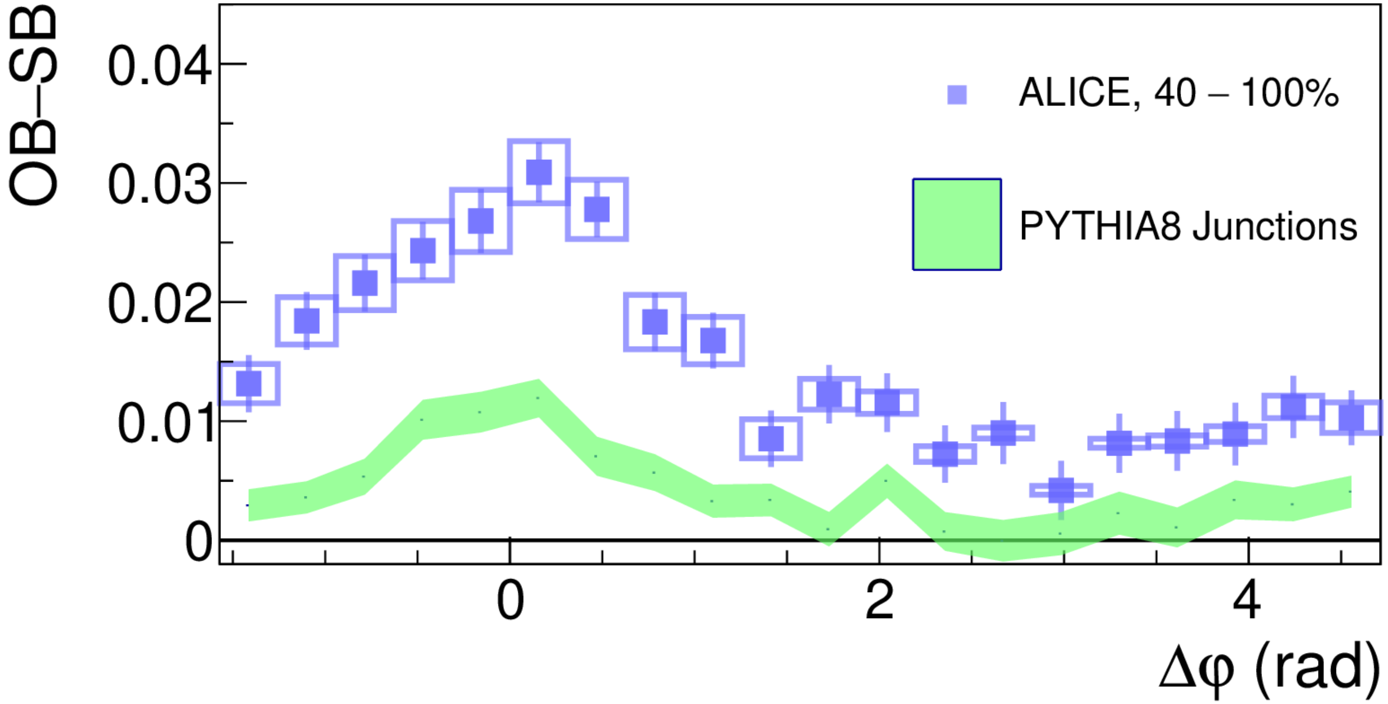
Microscopic balance of Ξ by antiprotons: MB results, pp $\sqrt{s} = 13$ TeV



ALICE, JHEP 09 (2024) 102

- EPOS (QGP) model: no structure due to extreme assumption of grand-canonical ensemble
- Pythia8 Monash: fails since this almost never happens
- Pythia8 Junctions: describes well the data

Microscopic balance of Ξ by antiprotons: low multiplicity results, pp $\sqrt{s} = 13$ TeV

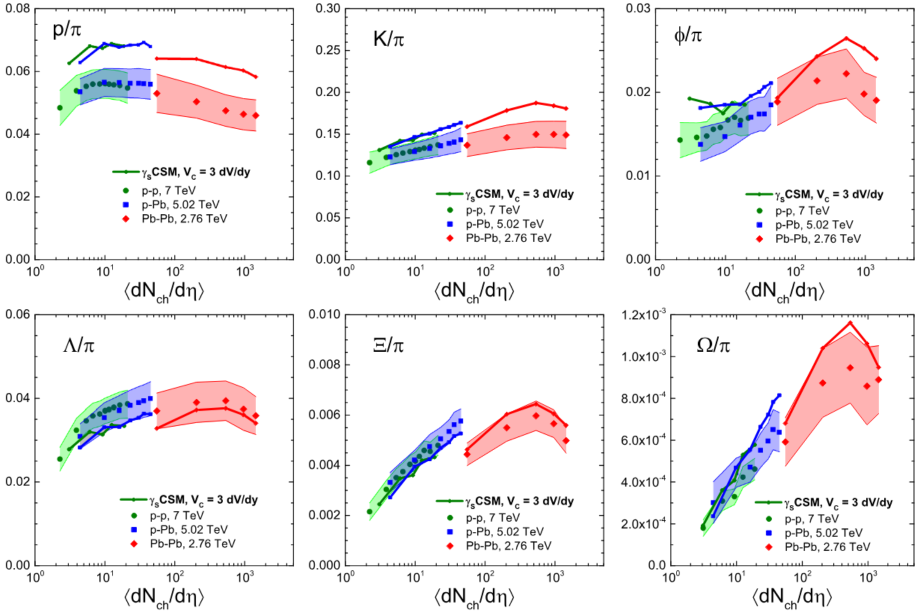


ALICE, JHEP 09 (2024) 102

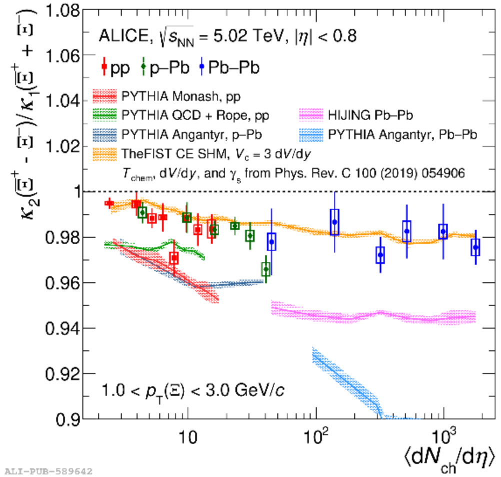
- Pythia8 Junctions: fails to describe the data since in the low multiplicity limit it must agree with Monash (no CR)
- Biggest surprise is that measured BFs are almost independent of multiplicity (not shown in detail) $\rightarrow$ Where is the medium?

Need microscopic correlations: EPOS LHC → Thermal FIST

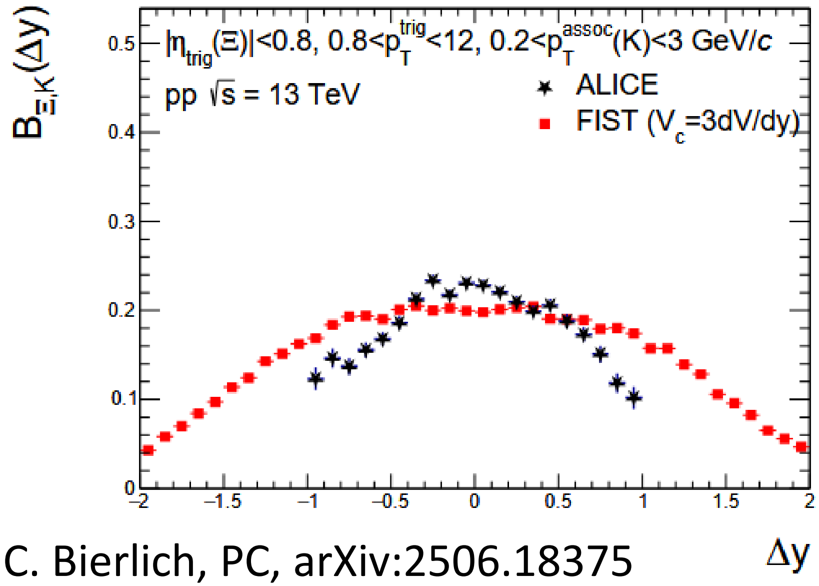
- Thermal FIST is an open Thermal MC (V. Vovchenko, H. Stoecker, Comput.Phys.Commun. 244 (2019) 295)
- Can generate event-by-event hadrons at mid-rapidity for different multiplicities
- No flow but can be boosted with blast-wave model (ALICE, PRL 134 (2025) 2, 022303)
  - Apples-to-apples comparison with data (η/y and p_T cuts, but not φ)
- Predicts similar BFs for all mults!
  - My understanding: given by local volume



V. Vovchenko, B. Dönigus, H. Stoecker, PRC 100, 054906 (2019)



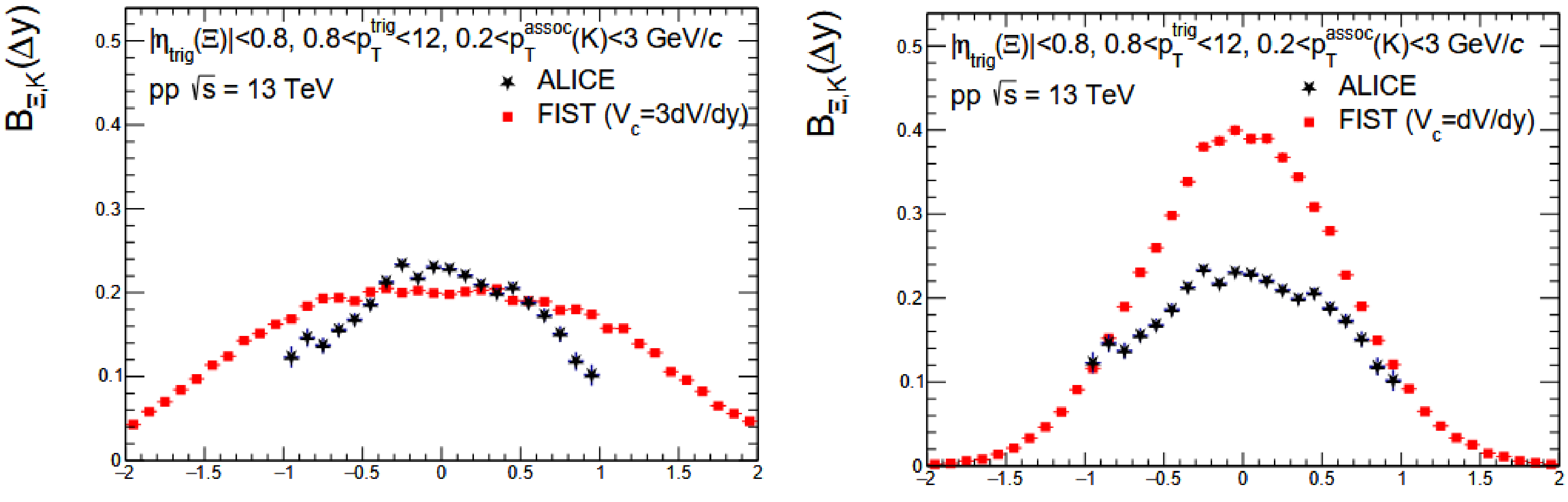
Thermal FIST balance functions for Ξ-K



C. Bierlich, PC, arXiv:2506.18375

- FIST BFs are in general too wide ($V_c = 3dV/dy$)

Thermal FIST balance functions for Ξ-K



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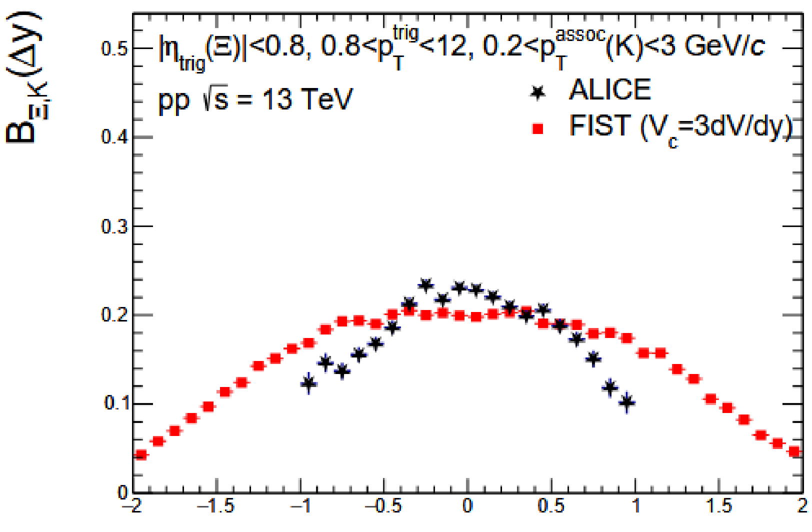
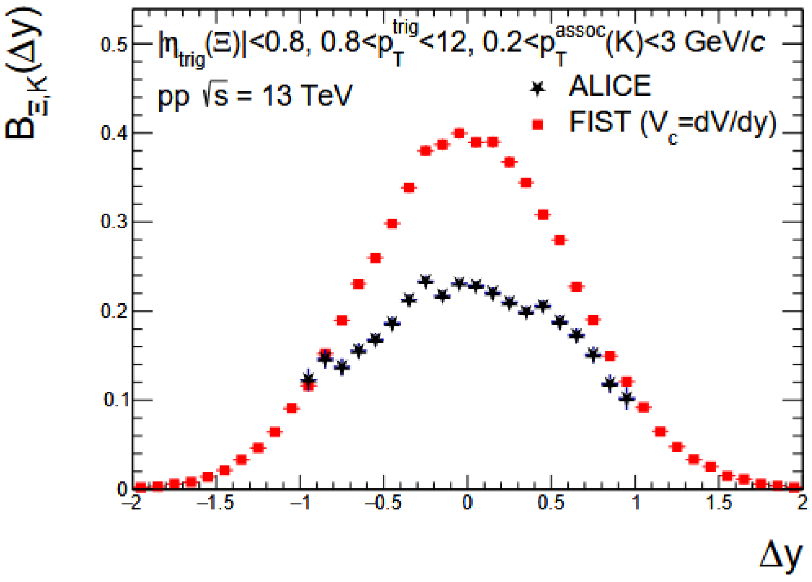
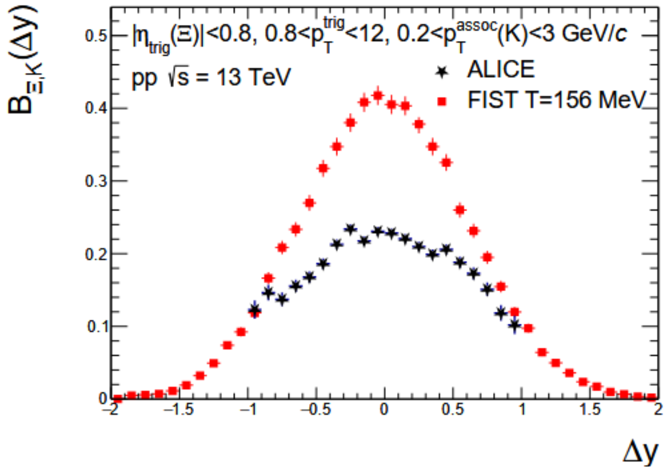
- FIST BFs are in general too wide ($V_c = 3dV/dy$)
- FIST BF is too big for thermal volume

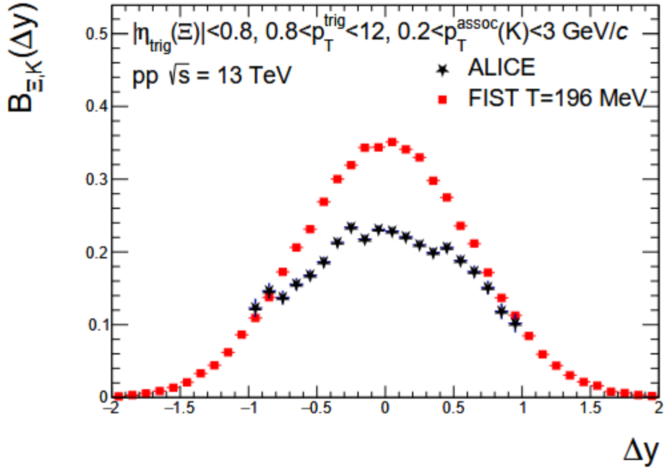
Thermal FIST balance functions for Ξ-K



C. Bierlich, PC, arXiv:2506.18375

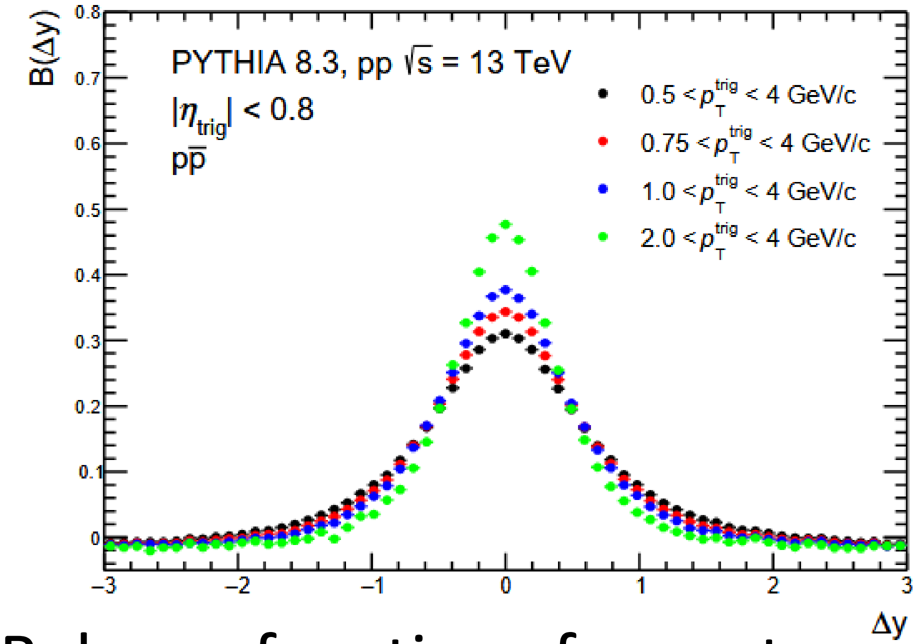


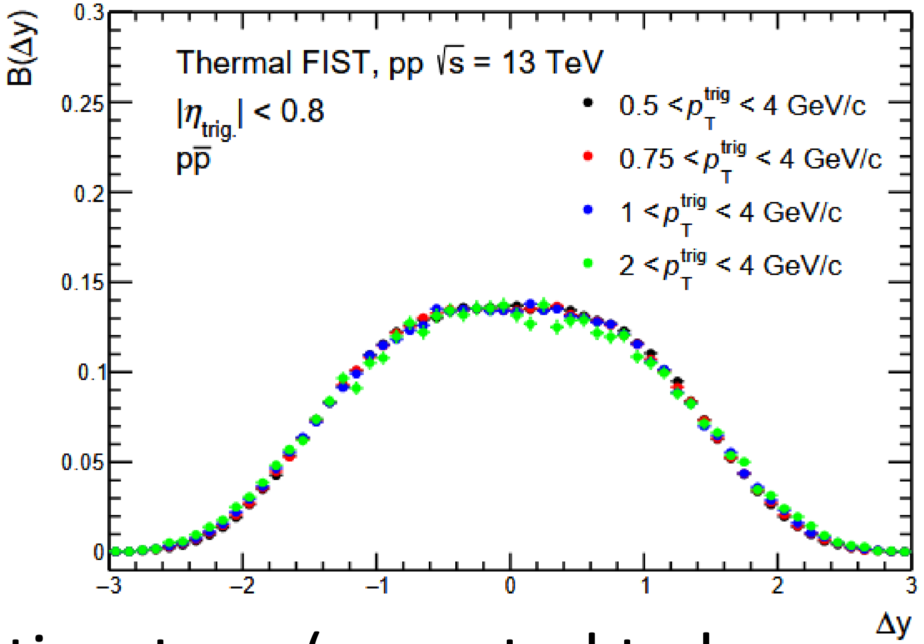




- FIST BFs are in general too wide ($V_c = 3dV/dy$)
- FIST BF is too big for thermal volume
- FIST BFs does not depend a lot on Temperature
- Are Thermal BFs robust? If yes, BFs powerful tests. If no, we should tune.

Balance functions for different trigger p_Ts





PC, S. Tripathy, arXiv:2509.03195

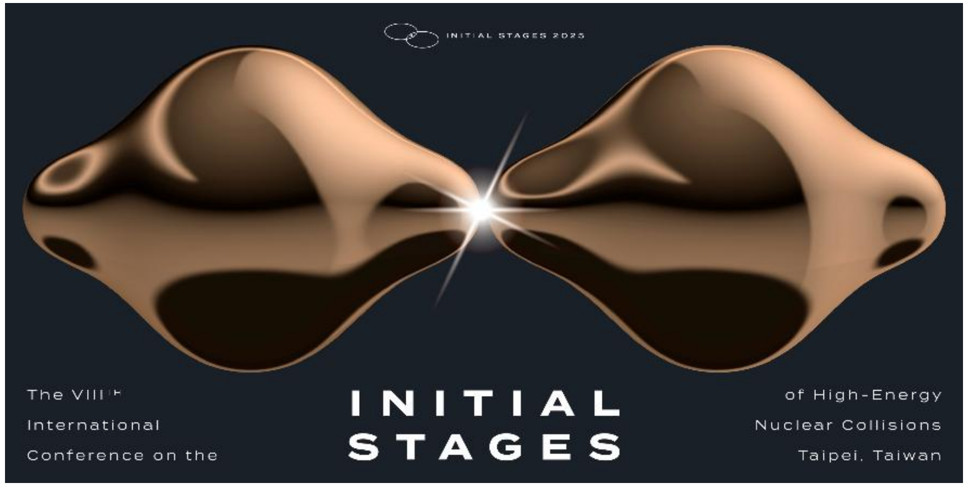
- Balance functions for proton-antiprotons (expected to be general)
  - PYTHIA: A high p_T trigger leads to associated particles being produced narrower in p_T (robust)
  - Thermal FIST: no narrowing (independent production, robust?)
- A way to differentiate? Or do one need to refine thermal models?

Personal conclusion

- I often hear: "PYTHIA + string interactions" = QGP
  - It is in my opinion completely wrong
- PYTHIA produces most quarks and hadrons together (confinement) – no diffusion or dissipation
  - Our challenge is that perfect liquid has minimal diffusion and dissipation $\rightarrow$ QGP models are often unrealistic
- PYTHIA predicts negative v_2 for very small systems
  - Positive v_2 in non-hydro models are often linked to point-like particle dynamics – is this realistic?
- We can learn a lot from comparisons with "PYTHIA + string interactions"
  - "Heavy is the crown" $\rightarrow$ we need more ambitious QGP MC simulations

Conclusion

- Monte Carlo Simulations has a wide range of applications
- Different implementations of saturation – unclear if one is better
  <u>→ Need for new CGC MCs and ideas</u>
- Color coherence appears to play a major role for particle production
  - In traditional pp models it captures many features of experimental data
    <u>→ Need to understand how it is affected by medium formation</u>



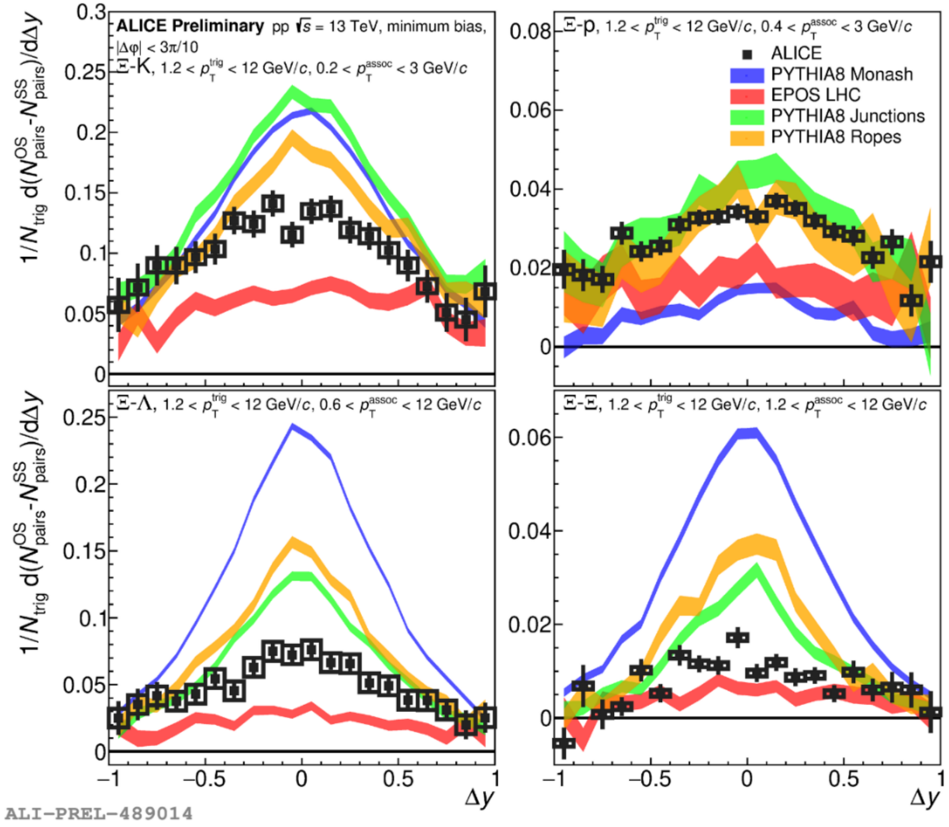
Thank You!

Backup

Many more combinations can be found in JHEP 09 (2024) 102

Ξ-K

Ξ-p



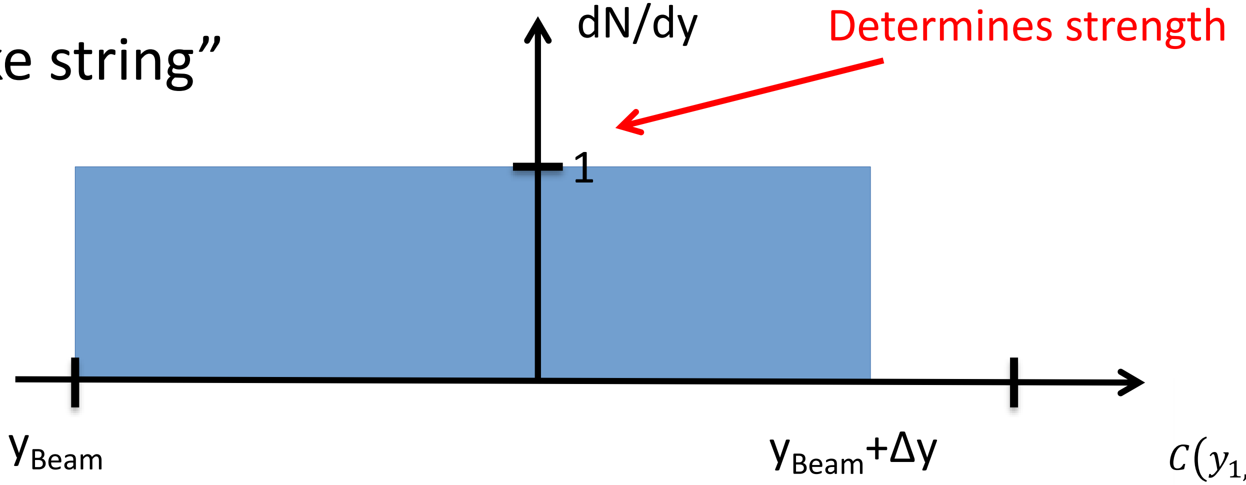
Ξ-Λ

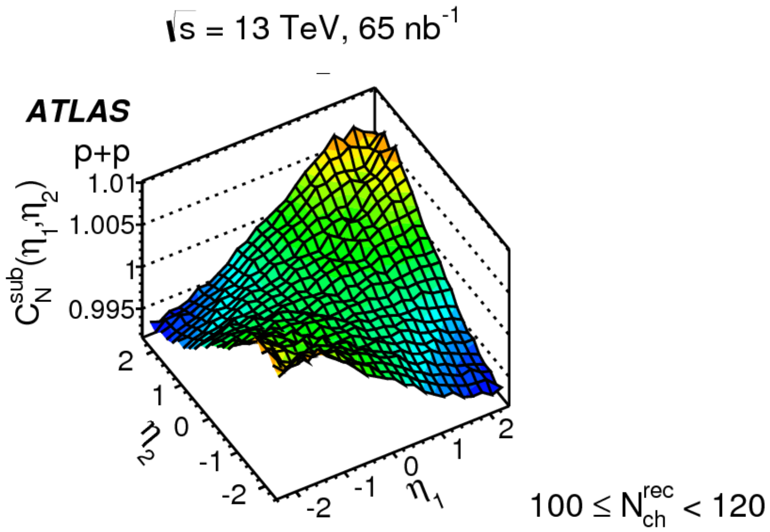
Ξ-Ξ

- + pions (not shown) and multiplicity dependence in pp

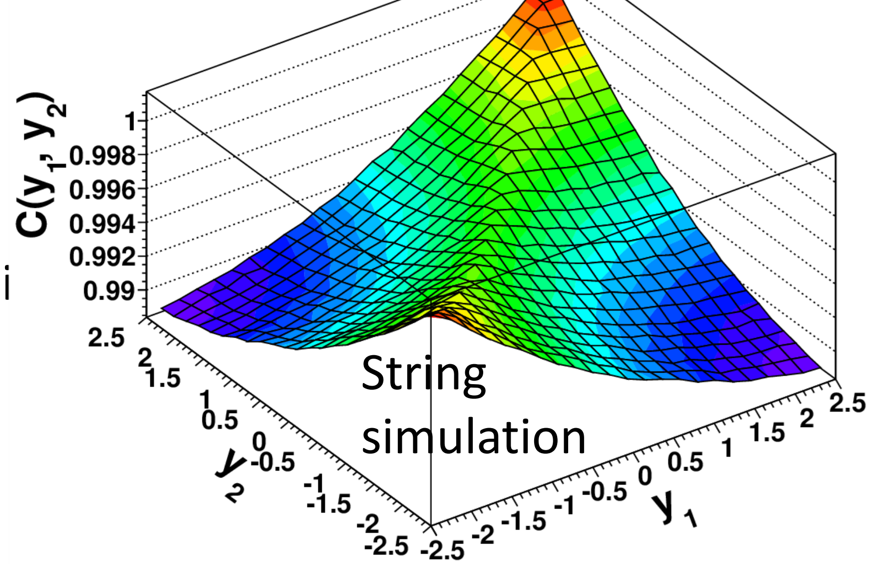
Simple model to explain ATLAS long-range results

"A Lund-like string"





$$C(y_1,y_2) = \frac{N_{pairs}(y_1,y_2)}{N(y_1)N(y_2)}$$



- Simulate strings from target and projectile nucleon independently
- Inspired by Brodsky-Gunion-Kuhn triangle
  - Start: y_{Beam}, Stop: flat in rapidity: $P(\Delta y)=1/(2y_{Beam})$
  - Each string produces on average <Nch>= Δy particles (random i Nch is taken from Poisson distribution
    - Particles are randomly distributed in rapidity
- ~1/2 strings from each side