Probing the Gluon Plasma with Charm Balance Functions

https://wallpaperaccess.com/lady-justice

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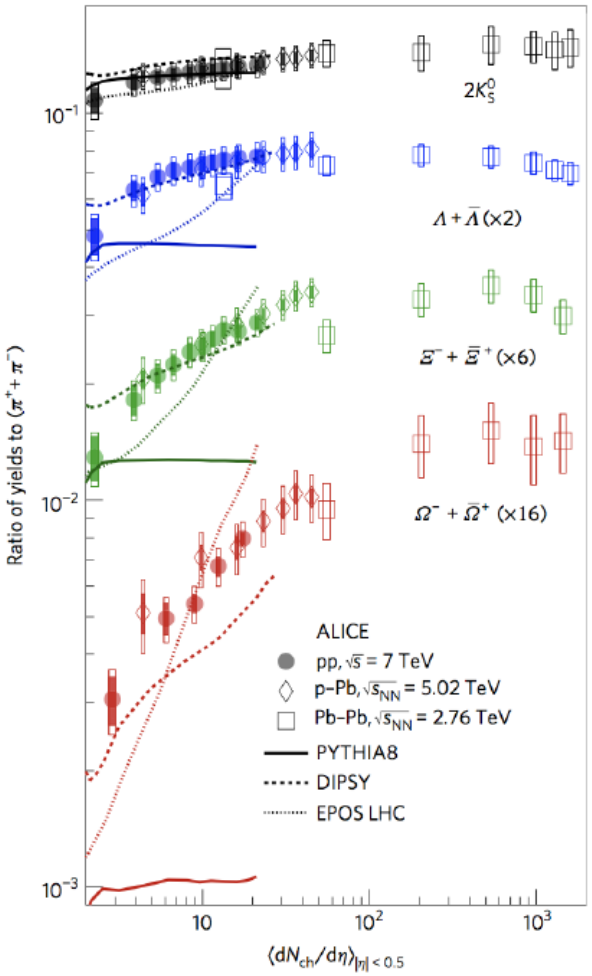
http://www.hep.lu.se/clash/

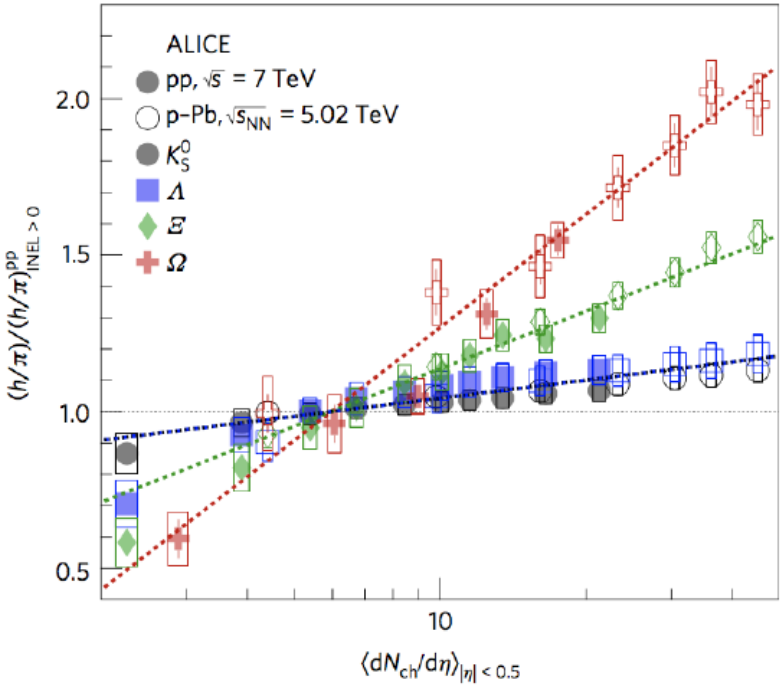
Outline

- Strangeness enhancement in small systems – the ALICE revelation
- CLASH insights: from “microscopic vs macroscopic” to “confinement vs deconfinement”
- A microscopic model of deconfinement?
- The new and old ideas of the Gluon Plasma (GP)
- Probing the GP with charm quarks

- Info: most of the work presented here is a reinterpretation of other people’s work in a new paradigm, e.g.,
  - Gluon plasma is our interpretation of kinetic theory calculations of hydrodynamization (and overlaps with earlier ideas such as hot glue)
  - Charm balance functions have been studied in the literature before

The ALICE revelation: goodbye jet universality!

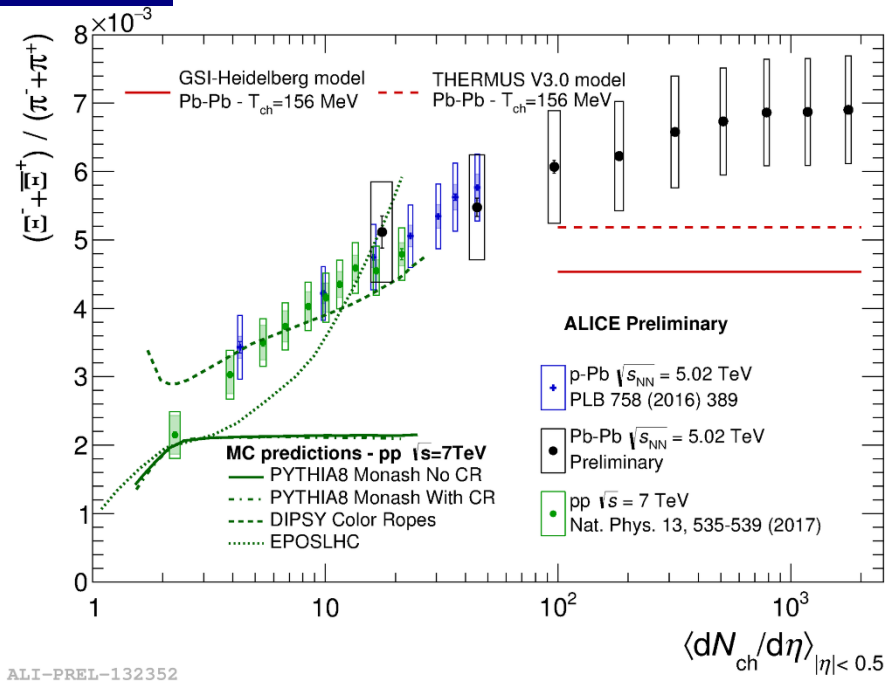




Signs of QGP in high-multiplicity *pp* collisions? If not, what else? A whole new game!

https://indico.cern.ch/event/638344/timetable/#8-pythia-and-extensions

What is the ALICE revelation?



PYTHIA:
pp
~ $\sum_{\mathrm{MPI}}$ parton−parton interactions

predicts “more of the same” as one would expect from jet universality and “asymptotic freedom” (lack of significant final state interactions).

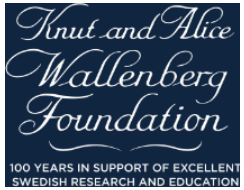
The revelation is that this is wrong!

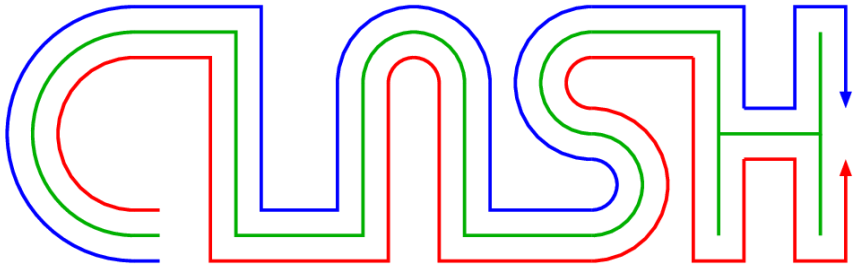
- Irreversible change in understanding of pp collisions

- A new world of physics has been opened by ALICE:
  - DIPSY/Angantyr: “Microscopic extension of PYTHIA”
    - Can IMO even challenge our AA paradigms (Pandora’s box!)
  - QGP in small systems? (One fluid to rule them all?)
  - Something else?

How to pin down the origin of the QGP-like effects in small systems?

- Pythia describes a wide variety of pp measurements
- QGP paradigm describes a variety of AA physics
- Critical to resolve physical understanding of collective effects
  → Collaborate between experimentalists and theorists across pp and AA systems to address this question





CLASH Project: "Pinning down the origin of collective effects in small collision systems" PIs: PC + Leif Lönnblad (LU theory)

Example of output: CLASH workshop write up: J. Adolfsson et al, Eur. Phys. J. A 56 (2020) 11, 288, "QCD challenges from pp to A–A collisions"

Today: extension of some of these ideas!

Insights from CLASH

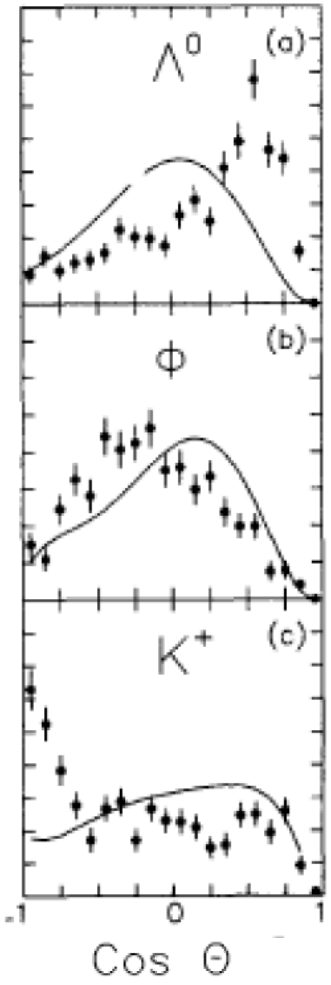
- Original idea: microscopic (PYTHIA++) vs macroscopic (QGP)
- Main insights (PC):
  - We need in the AA community to develop small system QGP generators. Only way we can make comparison between pp and AA descriptions that are apples-to-apples!
  - Microscopic is misleading because strings are macroscopic objects and we need microscopic QGP models to describe small systems
  - Lund string model is “confined” meaning that most soft quarks are created together with the hadrons
    - This is the much bigger difference IMO
- Focus on confinement (PYTHIA) vs deconfinement (QGP) in the rest of the talk

Strangeness correlations / confinement: an old idea

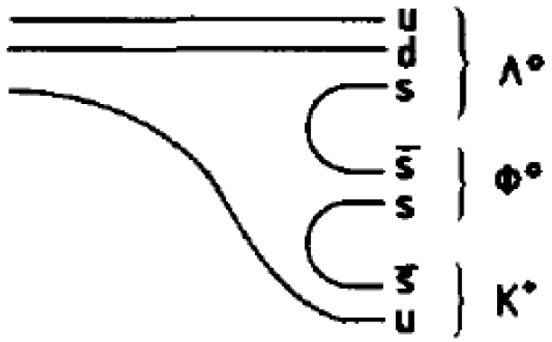
Phys.Lett. 163B (1985), 267

EVIDENCE FOR POMERON SINGLE-QUARK INTERACTIONS IN PROTON DIFFRACTION AT THE ISR

R608 Collaboration



Solid lines are calculations for isotropic phasespace



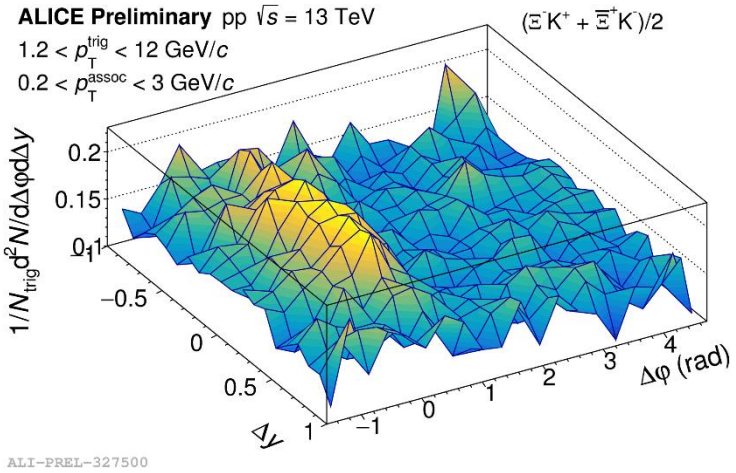
In pp collisions we can ask the question:
Where is the anti-strangeness (strangeness) associated with production of Ξ^-/ssd ($\Xi^+/\bar{s}\bar{s}\bar{d}$) recovered?

PYTHIA/Angantyr: expect strangeness to be recovered locally (as shown to the left).

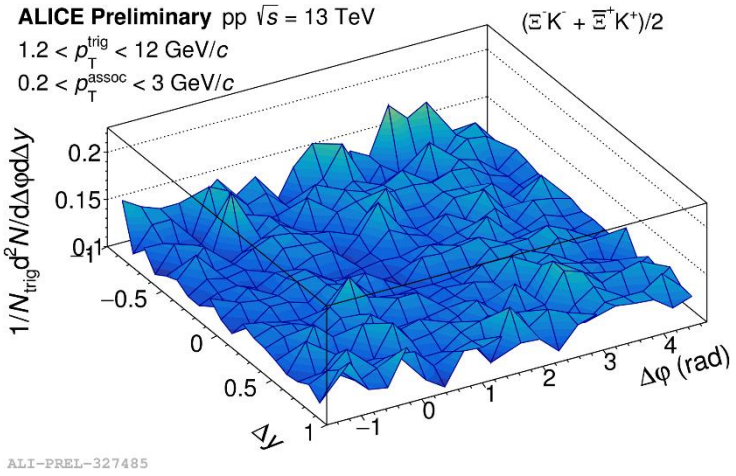
EPOS LHC: expect strangeness enhancement to be associated with a grand canonical (global) reservoir. Microscopic picture?

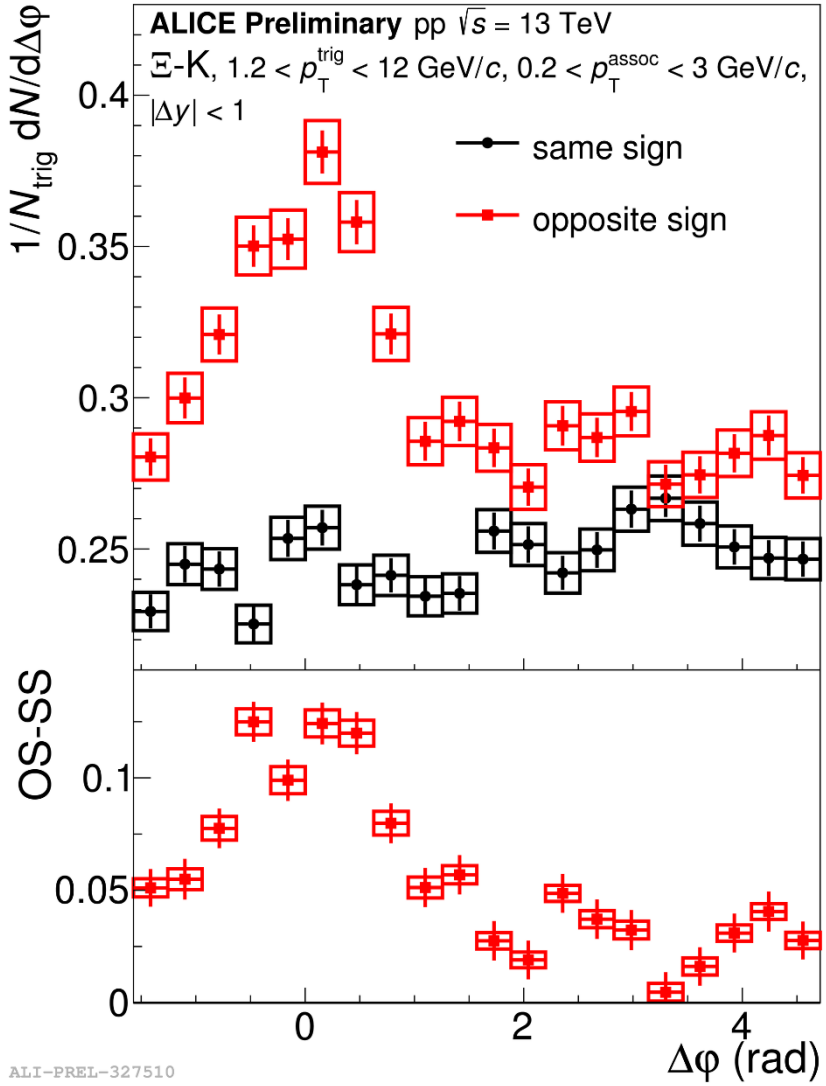
How do we measure that: Ξ-K correlation functions

Opposite sign (OS), e.g., Ξ^-/ssd – $K^+/\bar{s}d$

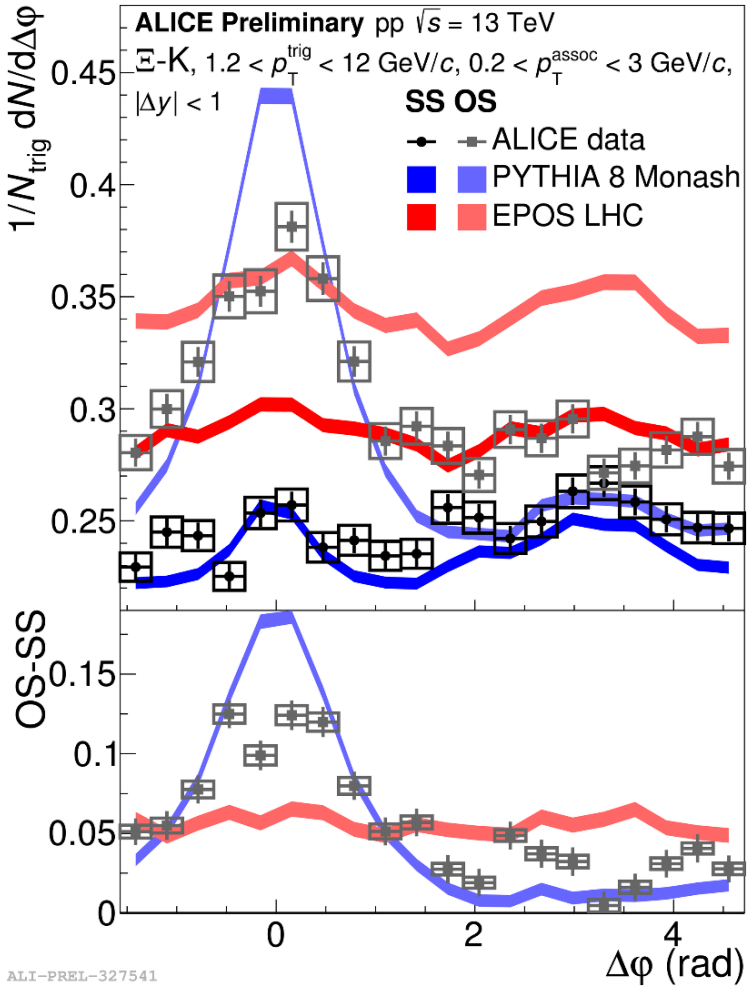


Same sign (SS), e.g., Ξ^-/ssd – $K^-/\bar{d}s$



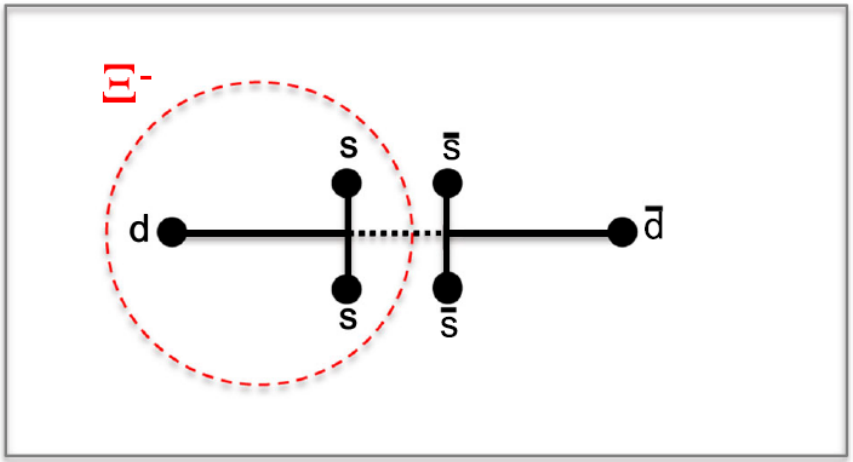


Ξ- K correlation functions

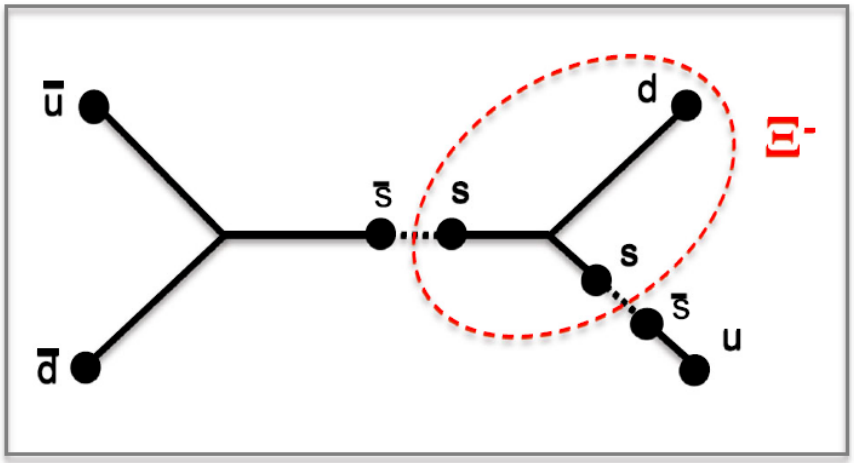


- EPOS LHC (QGP) limit: no microscopic picture of deconfinement.
- This is as I understand it a feature (grand canonical limit postulates this – only correlations are from resonance decays)

“Confinement” of baryon number in Lund strings



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

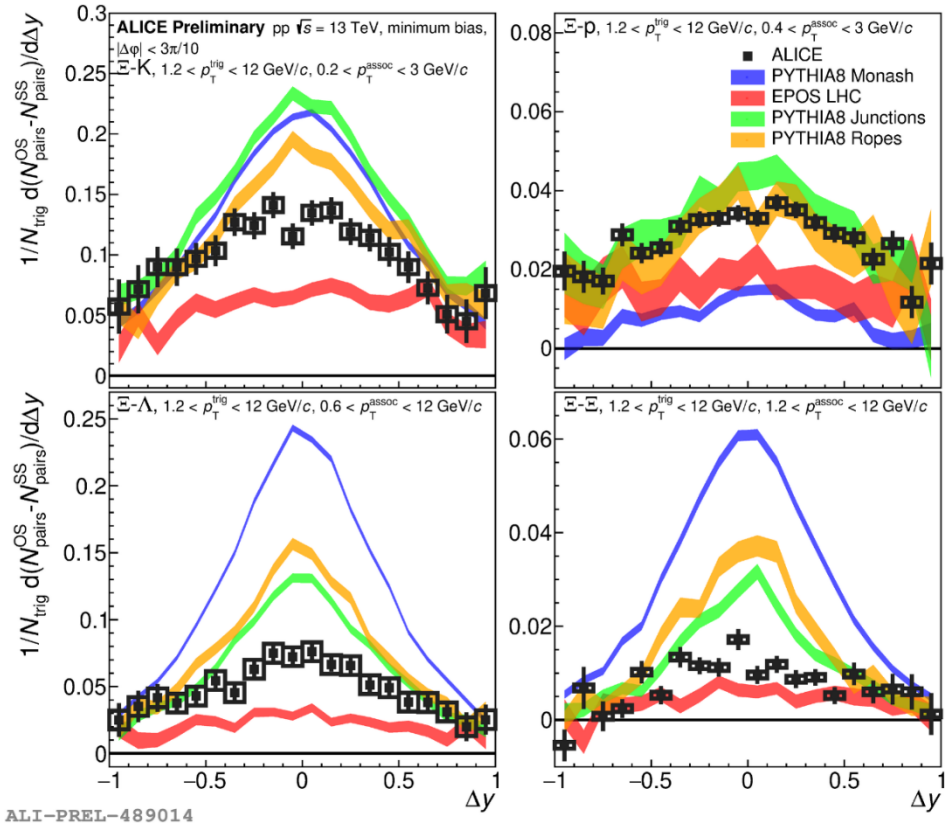


Junction:
Ξ balanced more by kaons and less by antistrange baryons. Broader correlations in rapidity.

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”

Results (near side)

Ξ-K



Ξ-Λ

Ξ-p

ALICE congratulates its PhD thesis award winner

2 JULY, 2021 Jonatan Adolfsson (LU)

ALICE Spokesperson Luciano Musa (left) awards the prize to Jonatan Adolfsson (right) in the virtual presence of Collaboration Board Chair Silvia Masciocchi and the Chairs of the Thesis Award Committee, Giuseppe Bruno and Philippe Crochet (Image: CERN)

https://home.cern/news/news/cern/alice-congratulates-its-phd-thesis-award-winner

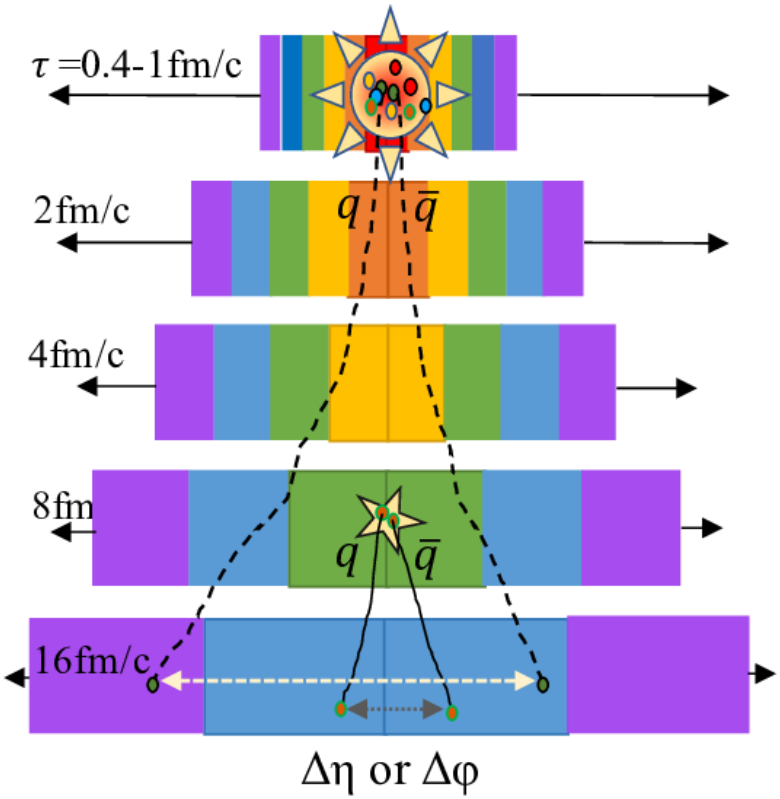
Ξ-Ξ

- Normal strings are disfavoured as main production mechanism
- Junctions describes well protons but not so well Λ and Ξ
- **IF we want to be able to test QGP in small systems directly with data on similar terms as we can test PYTHIA (and other pp generators)**
  - **THEN we need to develop a microscopic model of QGP deconfinement**

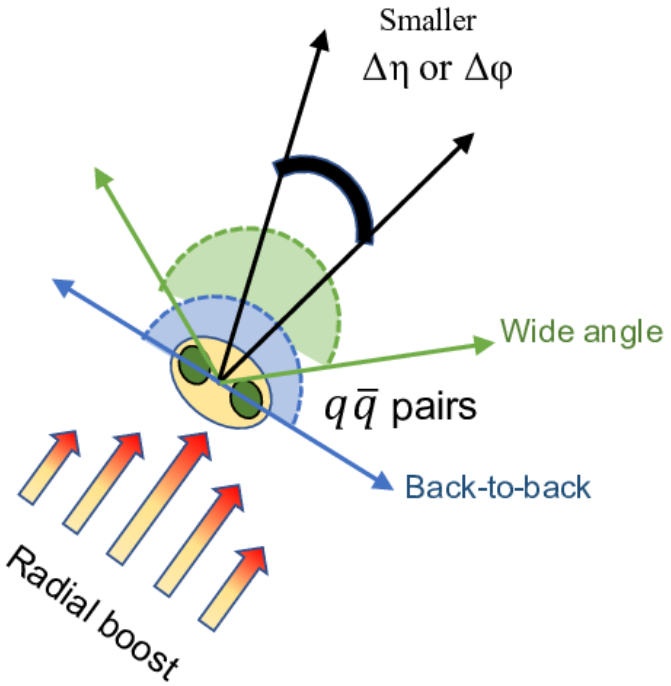
How to do that?

- Idea: try to go to big system where effects are large and see how it behaves there
- Show example of charge balance functions in the following

Q: Which picture is applicable in a large system QGP?

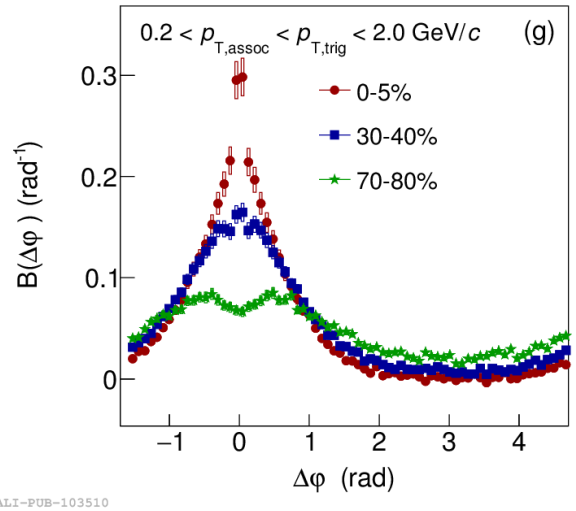


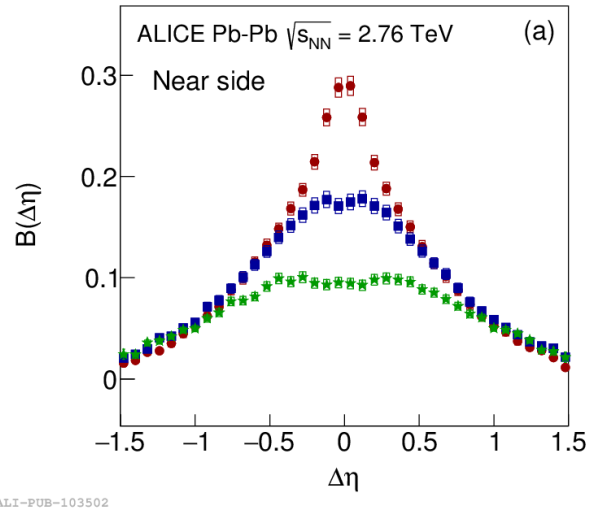
(a) Clocking Hadronization of $q\bar{q}$ pairs



(b) Kinematic Lensing due to radial boost

A: little or no diffusion but significant kinematic lensing



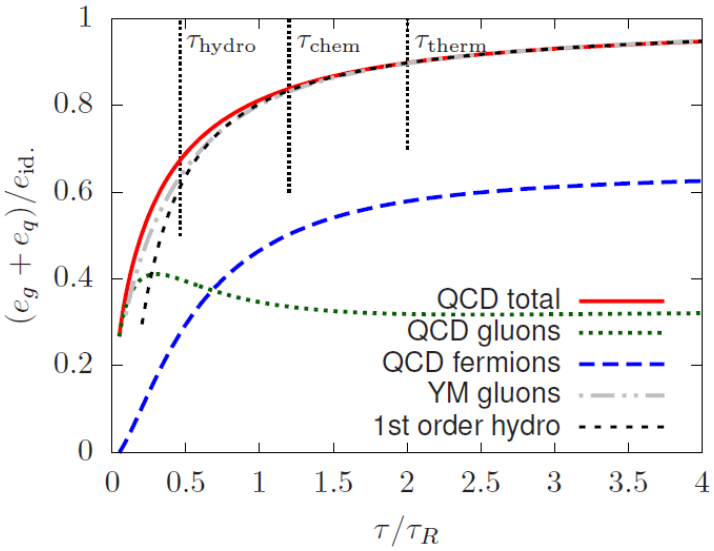


ALICE, EPJ C 76(2), 86 (2016).

- Similar to what one would expect in PYTHIA++!
- There are HI explanations: q-qbar is in thermal equilibrium (in fact this is the original balance function idea!)
  - but THIS STILL GIVES SAME RESULT AS PYTHIA and where is then the grand canonical heat bath?
- Could also be an effect of the perfect liquid (=no diffusion or dissipation)
  - Charge flow is not included in any hydro models yet
- Goal here: try to find alternative QGP explanations where it is clear why it would be so and which can point to QGP deconfinement signals

A microscopic model of hydrodynamization

A. Kurkela, A. Mazeliauskas, Phys.Rev.Lett. 122 (2019) 142301



Kinetic theory calculation (weak)

Start with gluon dominated state: motivated by models such as CGC.

Gluons interact stronger than quarks due to larger charge → build up flow on short time scale.

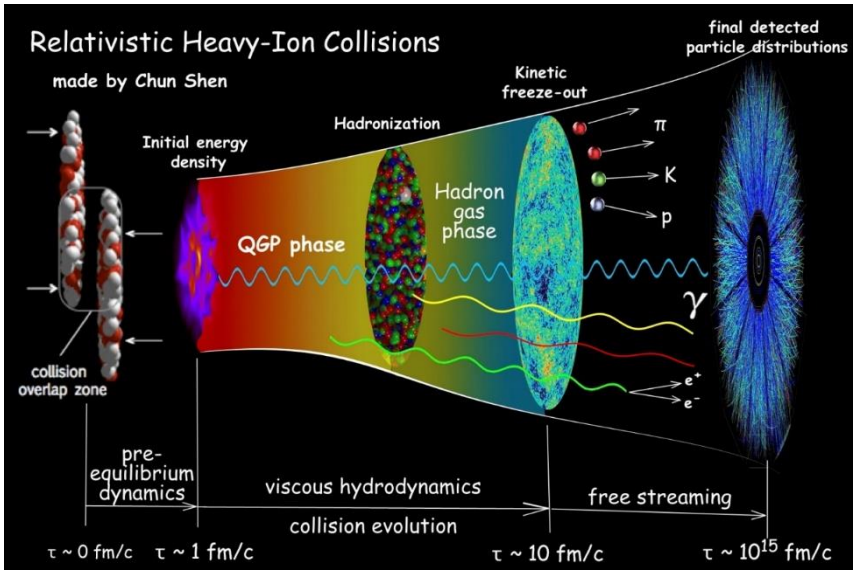
- Caveat: kinetic theory is weakly coupled (see, e.g., Shuryak, arXiv:1901.00178).
  - Dynamics given by LO calculations (“Feynman diagrams”) and imperfect fluid (non-vanishing mean free path).
- If system is strongly coupled (interference effects), gluon dominance can supposedly be extended (shortened).
  - We propose/discuss a scenario in which it is extended!

The gluon plasma: an alternative paradigm (1/2)

- Standard QGP
  - initial → hydrodynamization → QGP (hydro) → hadronization
- (New) GP paradigm
  - initial → hydrodynamization → GP (hydro) → QGP → hadronization
  - Similar to old ideas
    - Hot glue (e.g., Shuryak, PRL 68, 3270, 1992)
    - Undersaturated QGP (e.g., Stöcker et al, Astron. Nachr. 336, 744, 2015)
  - Has been studied in several papers but is not the standard paradigm
- Previous work (hot glue, undersaturated QGP)
  - Most work focused focus on photons and leptons
- We think that the shift in understanding from hydro ↔ thermalization to hydro ↔ hydrodynamization makes these ideas more attractive again because we are already working out of equilibrium

The gluon plasma: an alternative paradigm (2/2)

- We want to explore in the following this new paradigm focusing mainly on deconfinement
  - Something is missing in this picture



- Key ideas:
  - Light flavour quarks (u, d, s) are produced later and flowing
  - Light flavour hadrons cannot probe early-time dynamics / GP

Ideas for signals of the GP

- New: Charge balance is produced late(r) – “by construction”
- Old: Thermal photon flow (quarks are produced flowing)
  - See F.-M. Liu & S.-X. Liu, PRC 89, 034906, 2014 and A. Monnai, PRC 90, 021901, 2014
- New: Little or no Chiral Magnetic Effect (quarks are formed after large magnetic field is gone)
- Old: Thermal dileptons?
- Other?

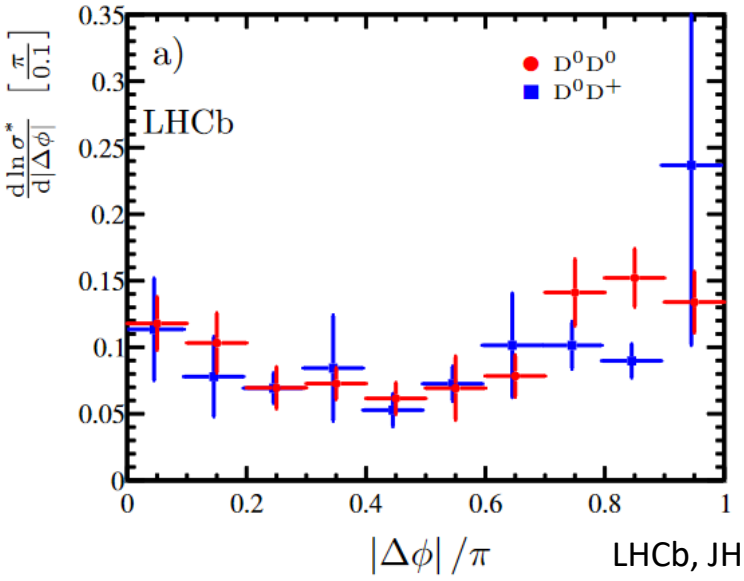
- New: Our worry: deconfined (diffusing) gluons but quarks can appear “confined” (produced late and flowing)
  - Risk that we cannot probe deconfinement with light flavour hadrons

How to measure dynamics of GP formation (hydrodynamization) ?

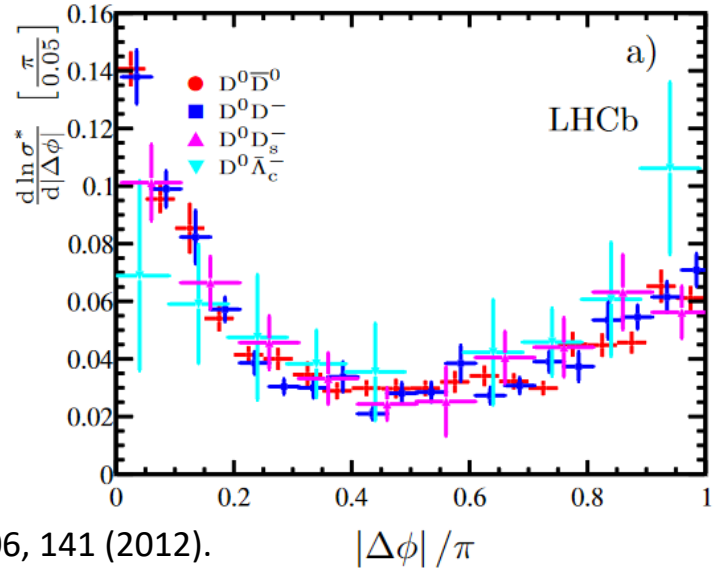
- Cannot use light quarks (first produced when the system is flowing)
- Need early system:
  - Use heavy quarks, in particular charm quarks
    - Produced early in the collision (pQCD rates)
    - Charm is most abundant heavy quark
    - Known to interact with medium (flow)
    - Old: even some estimation of how they are affected by pre-equilibrium physics, S. K. Das et al, J. Phys. G 42, 095108, 2015.
- Need reference:
  - New: Measure how c-cbar balance is affected
    - Reference can be measured in pp (and even calculated in pQCD)

LHCb results for D mesons with same C and opposite C

Same C



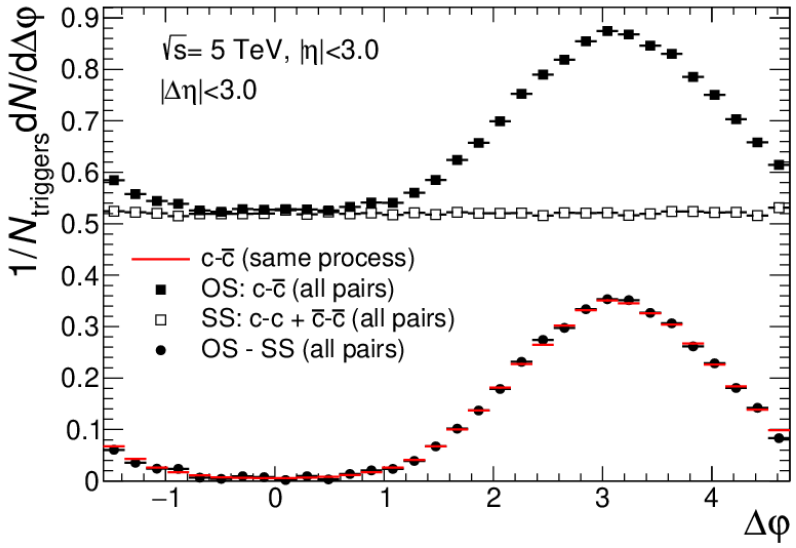
Opposite C

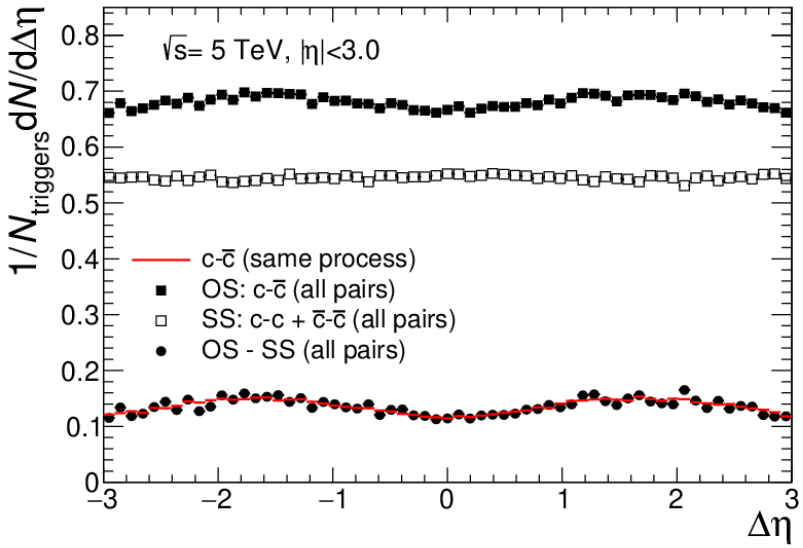


LHCb, JHEP 06, 141 (2012).

- No structure seen for same C correlations (in agreement with PYTHIA simulations)
- Near side (NLO) and away side structure (LO) for opposite C correlations

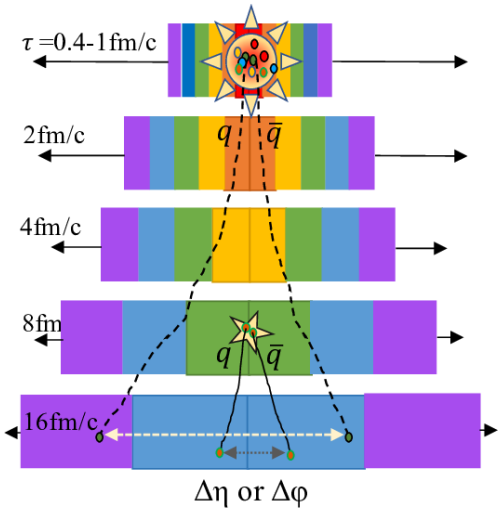
Use same method as for strangeness to measure balance





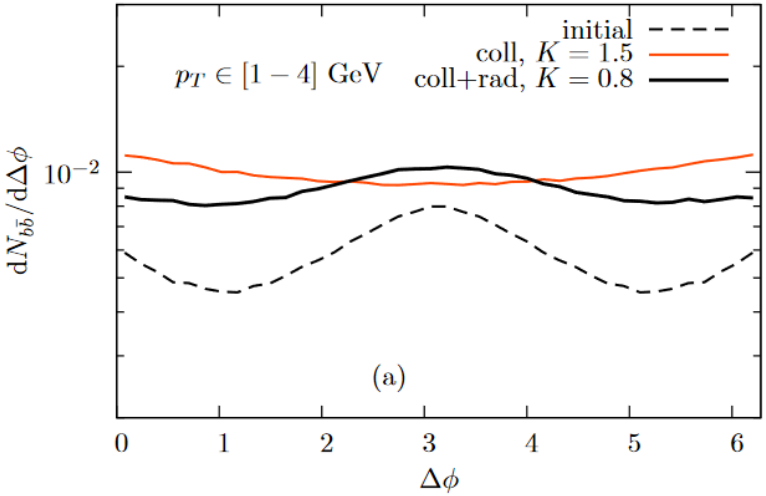
- Used PYTHIA to validate that this in principle also works for charm hadrons
  - Validation of method with mixed events (signal and background)
- Quite different from LHCb results (appears to be due to NLO corrections, see e.g., R. Vogt, PRC 98, 034907, 2018)
  - Does not affect this idea as pp is reference

What to expect?



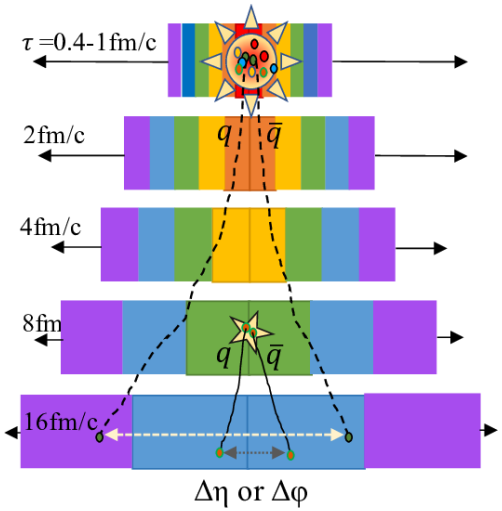
(a) Clocking Hadronization of $q\bar{q}$ pairs

M. Nahrgang, J. Aichelin, P. B. Gossiaux, K. Werner, PRC 90, 024907 (2014)
Done for c-cbar in paper but b-bar figure is nicer.



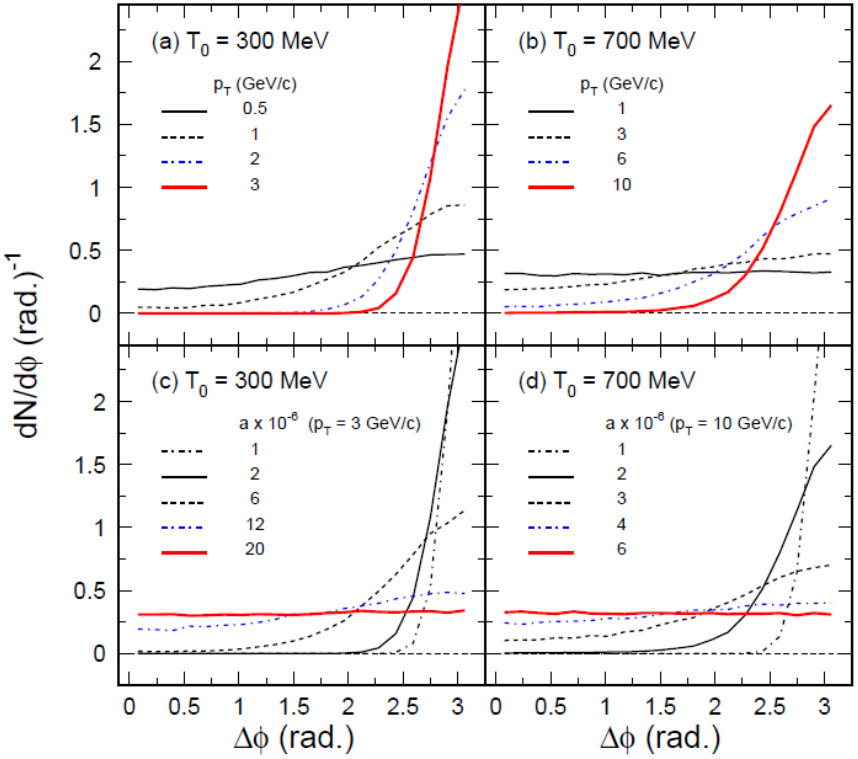
- Want to demonstrate difference to light quarks
  - Correlation widens instead of narrowing
- For now, piggyback on existing calculations

What to expect?
Reuse previous calculations



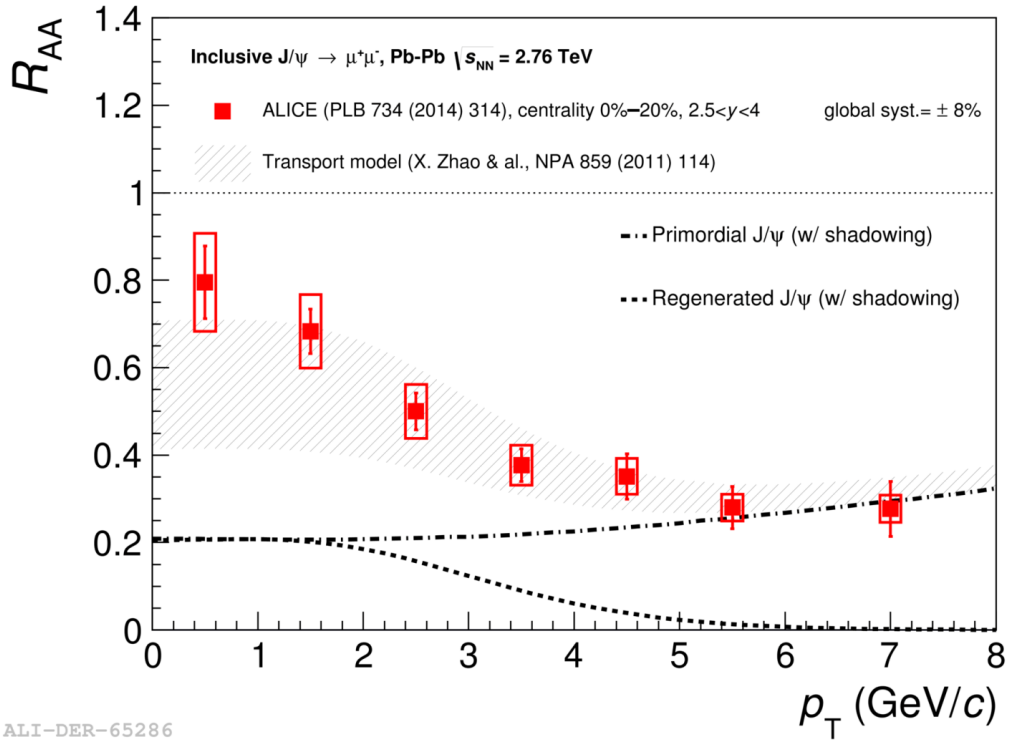
(a) Clocking Hadronization of $q\bar{q}$ pairs

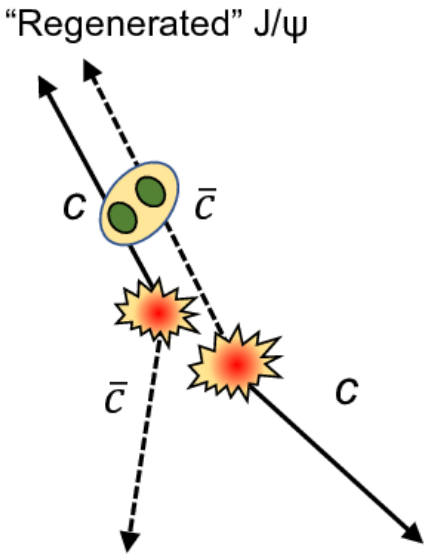
X. Zhu, M. Bleicher, S.L. Huang, K. Schweda, H. Stoecker, N. Xu, P. Zhuang, PLB 647, 366,2007



- As expected one would likely be sensitive to early time effects and one expects a clear broadening unlike for light flavour quarks

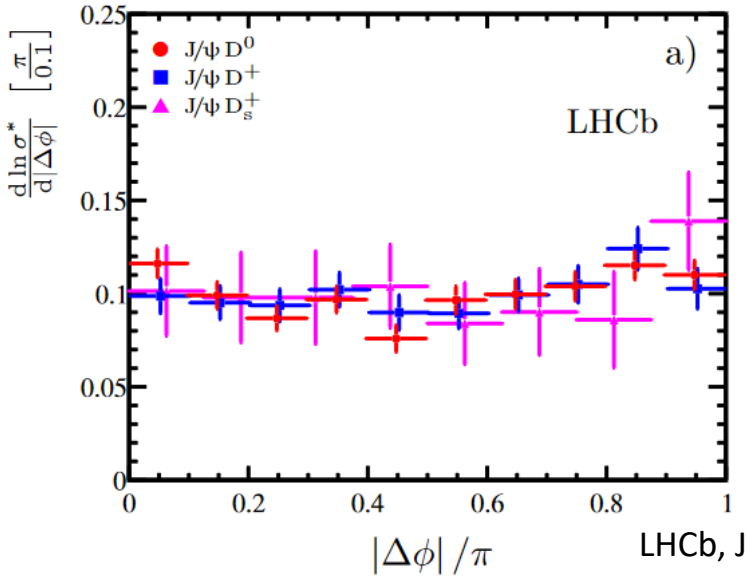
Strengthen signals of deconfinement





- J/ψ regeneration is very important signal of deconfinement
- But R_{AA} is only a relative measure of suppression. Not possible to make absolute comparison between different beam energies due to change in slope.

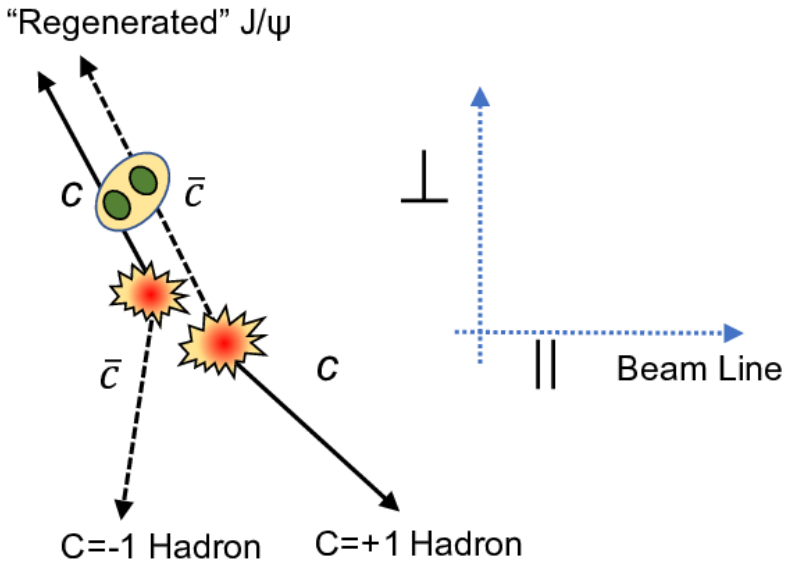
LHCb results for J /ψ-D correlations

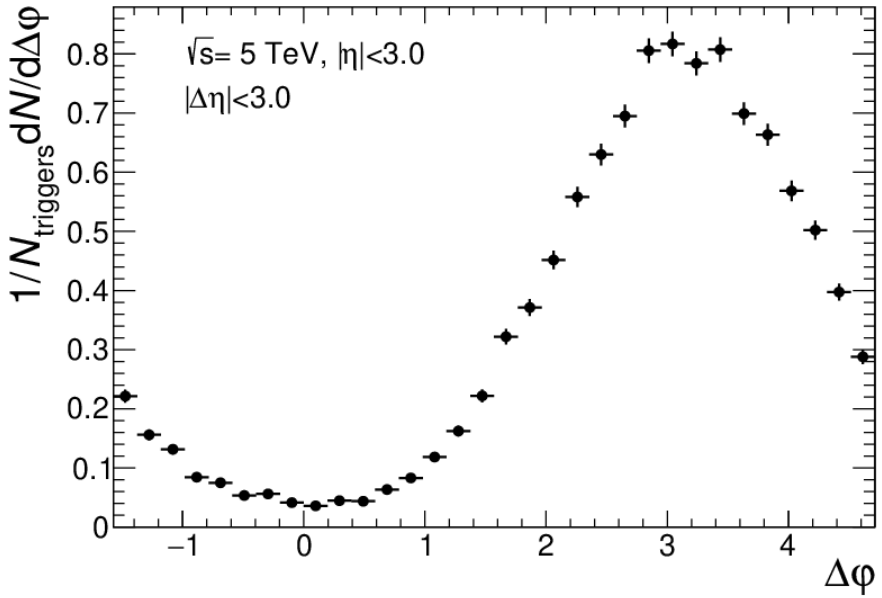


LHCb, JHEP 06, 141 (2012).

- No structure seen

Propose to measure J/ψ balance





- Normal J/ψ is balanced → No structure in correlation
  Regenerated J/ψ needs to be balanced by two charm hadrons (C=-1 and C=+1)
  - One can easily make PYTHIA prediction
- Regenerated J/ψ is balanced on away side
  - Likely wrong due to NLO corrections
    - One can easily derive prediction from experimental charm balance function!

Conclusions

- To answer the question of QGP or not, deconfinement must be a key component
  - We need a microscopic QGP picture/model of what this means
- We propose a paradigm where a Gluon Plasma is produced before the QGP $\rightarrow$ Light flavour quarks are produced late and flowing
  - Heavy quarks could be the primary way to measure hydrodynamization and probe early times physics of the created medium (Nice $\rightarrow$ Need to have)

Thank You!

Backup

Intellectual stimulation?

- There can be differences between SPS, RHIC and LHC due to initial state being dominated more and more by gluons at high energies
  - Same QGP but different mix of GP and QGP
- Standard Lattice QCD will not describe GP phase (is screening accurate? Equation of state?)
  - One can look at calculations for pure glue for ideas (has been done in some cases, e.g., Stöcker et al, Astron. Nachr. 336, 744, 2015)
  - Unclear to me if this is a fair comparison (LQCD pure gluon system is in thermal equilibrium, while GP is not)

p_T spectra of regenerated J/ψ