“Perfect QCD”- a new Universal approach to soft QCD

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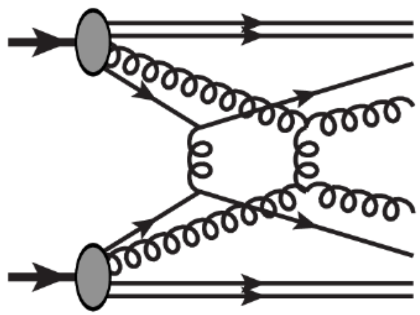
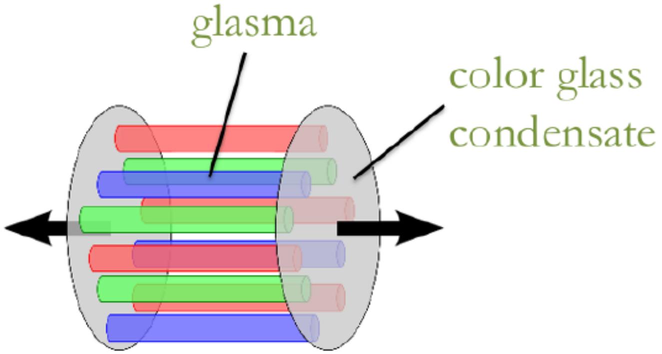
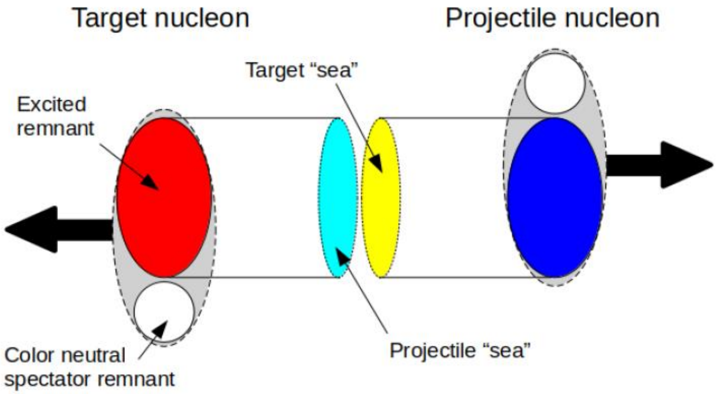
Where I will try to take you

- Maybe these models of MB proton-proton collisions are wrong





- Maybe instead a coherent excitation of the protons occur



- Because maybe the screening in the initial state is so large that soft parton-parton scatterings are heavily suppressed!

Outline

- Motivation
- Perfect liquid and jet quenching tells a similar story
- Perfect QCD
  - Particle production in perfect QCD
  - Easy insights and a strong prediction of perfect QCD
- Conclusions

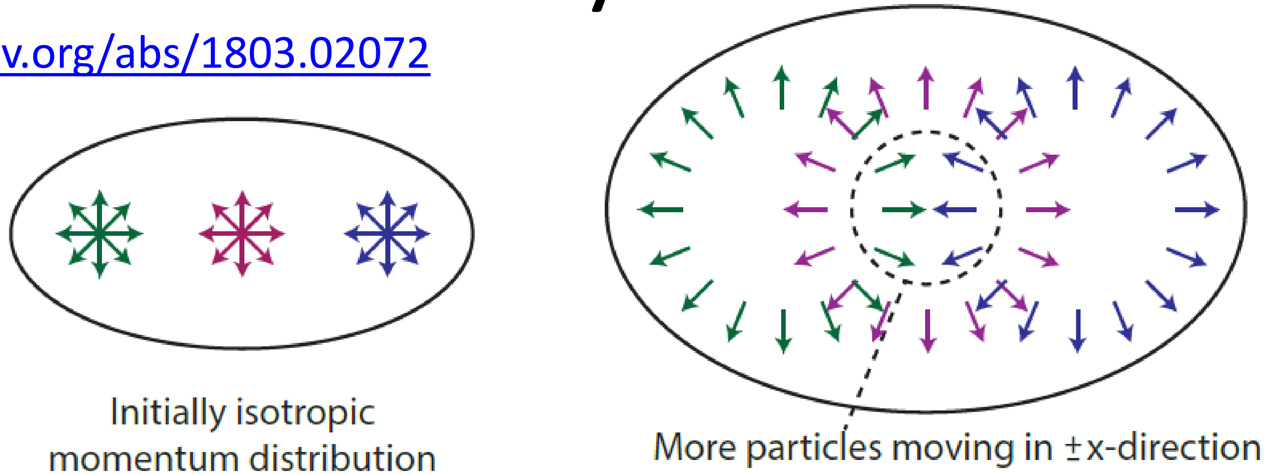
Motivation

The “perfect liquid” is spectacular
Can we generalize this idea?

- Ideal liquid
  - Reversible, no dissipation and no diffusion
- Perfect liquid
  - QGP is as close to ideal as possible
  - Almost reversible (e.g., $\varepsilon_n \rightarrow v_n$), minimal dissipation and diffusion
- The Xover transition (QGP $\rightarrow$ Hadrons) is another aspect of QGP-QCD that is reversible (QGP $\leftrightarrow$ Hadrons)
- Hydrodynamization appears to also be a perfect-liquid-like feature (difficult to thermalize a nearly reversible system)
  - Goes against traditional ideas of Local Charge Conservation $\rightarrow$ GCC
- Question here: Could it be that the perfect liquid is just one feature of an underlying soft QCD description

Kinetic theory: flow in small systems

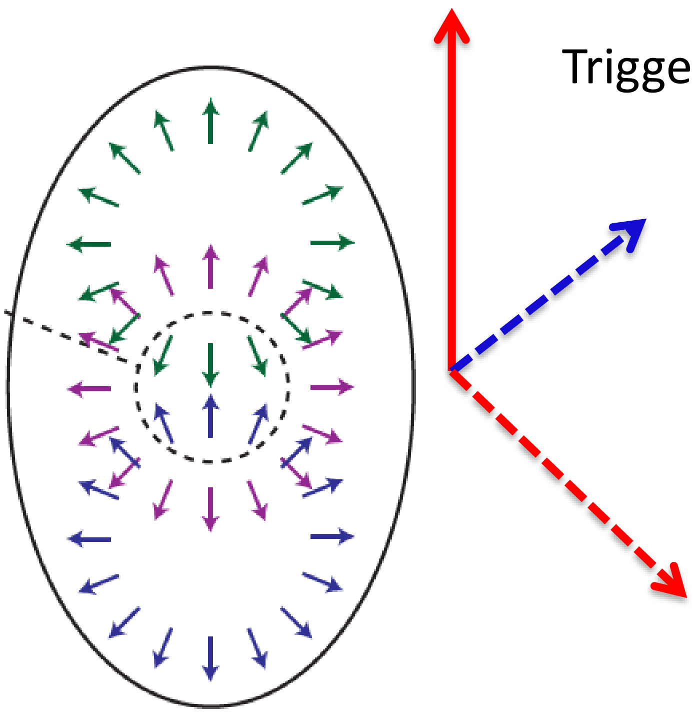
https://arxiv.org/abs/1803.02072



Caption: "Free-streaming particles move along the directions of their momentum vectors leading to local momentum anisotropies. In the central region where most collisions take place, there is an excess of particles moving horizontally compared to vertically moving ones. The interactions in the center region tend to isotropize the distribution function, and thus they reduce the number of horizontal movers and they add vertical movers."

Abstract: "Here, we demonstrate within the framework of transport theory that even the mildest interaction correction to a picture of free-streaming particle distributions, namely the inclusion of one perturbatively weak interaction ("one-hit dynamics"), will generically give rise to all observed linear and non-linear structures. … As a non-vanishing mean free path is indicative of non-minimal dissipation, this challenges the perfect fluid paradigm of ultra-relativistic nucleus-nucleus and hadron-nucleus collisions."

How to measure the dissipation and diffusion?



Trigger on strangeness: $\Xi\ (ssd)$

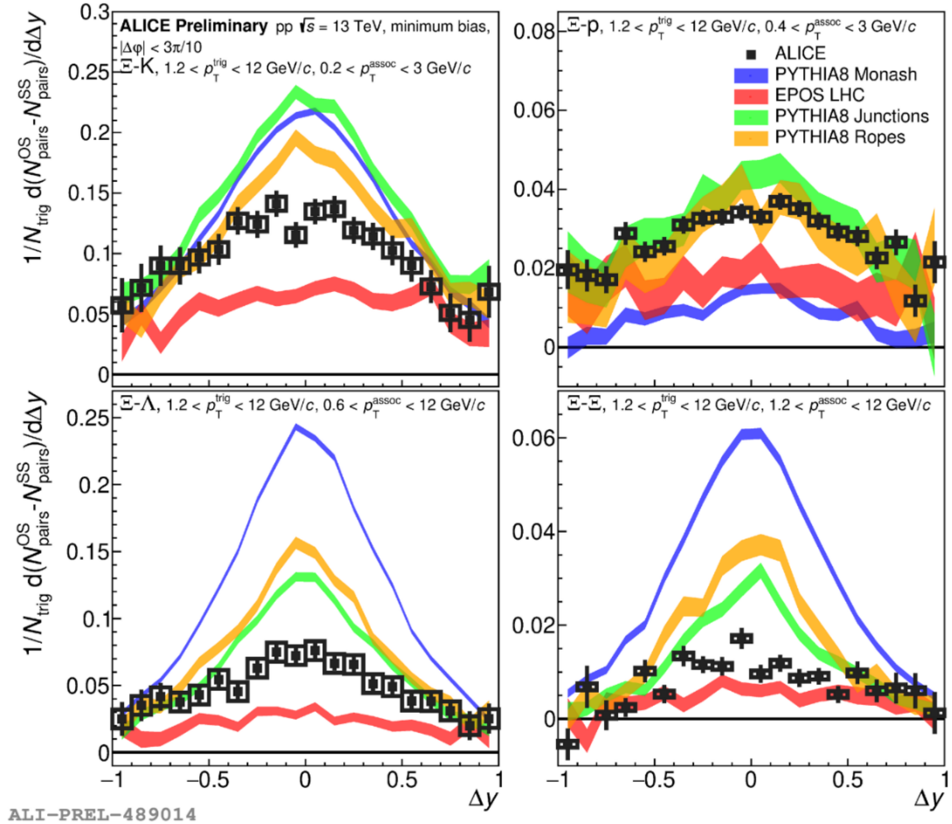
Measure where the anti-strangeness (baryon number, charge) that balances the strangeness ends up:
$K^+\ (u\bar{s}), \bar{p}\ (\bar{u}\bar{u}\bar{d}), \bar{\Lambda}\ (\bar{u}\bar{d}\bar{s}), \bar{\Xi}\ (\bar{s}\bar{s}\bar{d})$

Subtract the uncorrelated production via the same-quantum-number correlations:
$K^-\ (s\bar{u}),\ p\ (uud), \Lambda\ (uds),\ \Xi\ (ssd)$

Results near side (after subtraction of uncorrelated production)

Ξ-K

Ξ-p



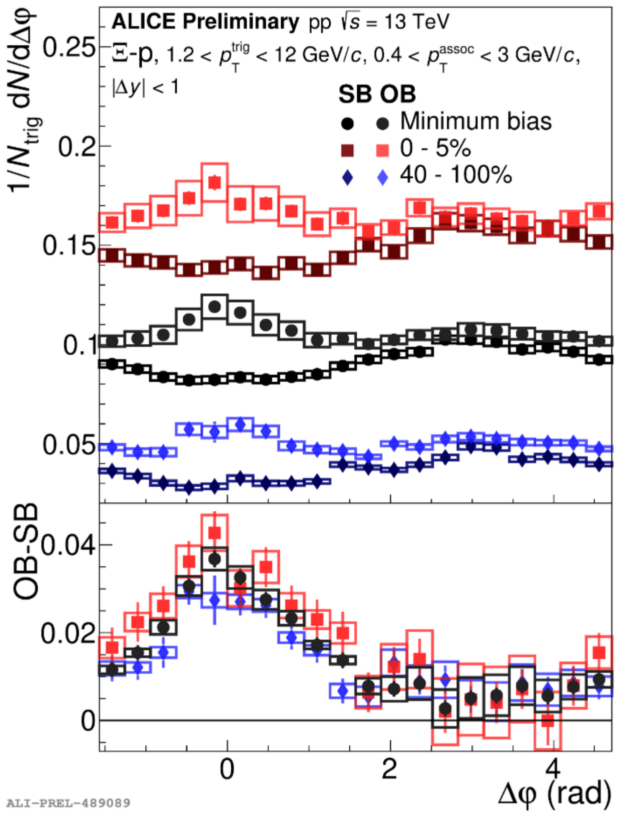
Ξ-Λ

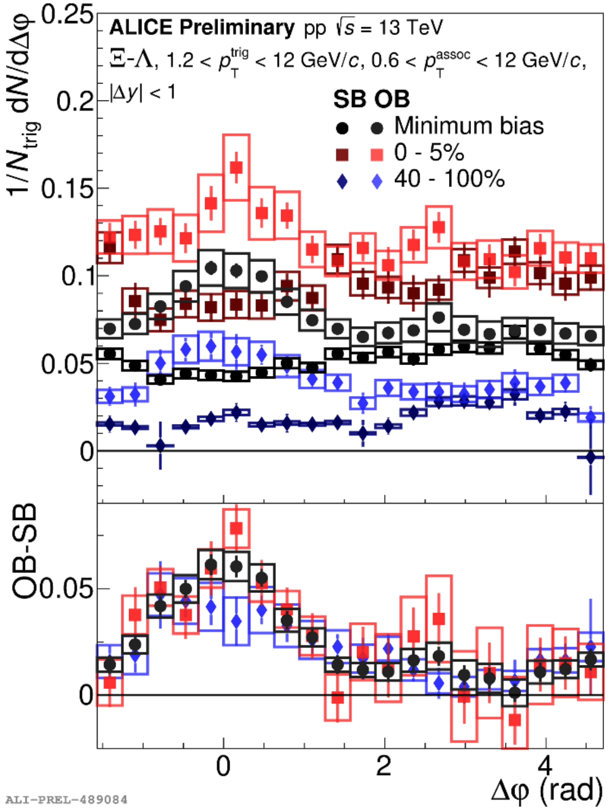
Ξ-Ξ

- EPOS LHC: Ξ are primarily produced by the core
  - no microscopic correlations for production by core
    - A feature (grand canonical limit postulates this – only correlations are from resonance decays)

Little or no multiplicity dependence

Ξ-p





Ξ-Λ

- No strong signals for change in production mechanism (?) or increasing diffusion/dissipation
- Theory challenge: put a QGP curve here

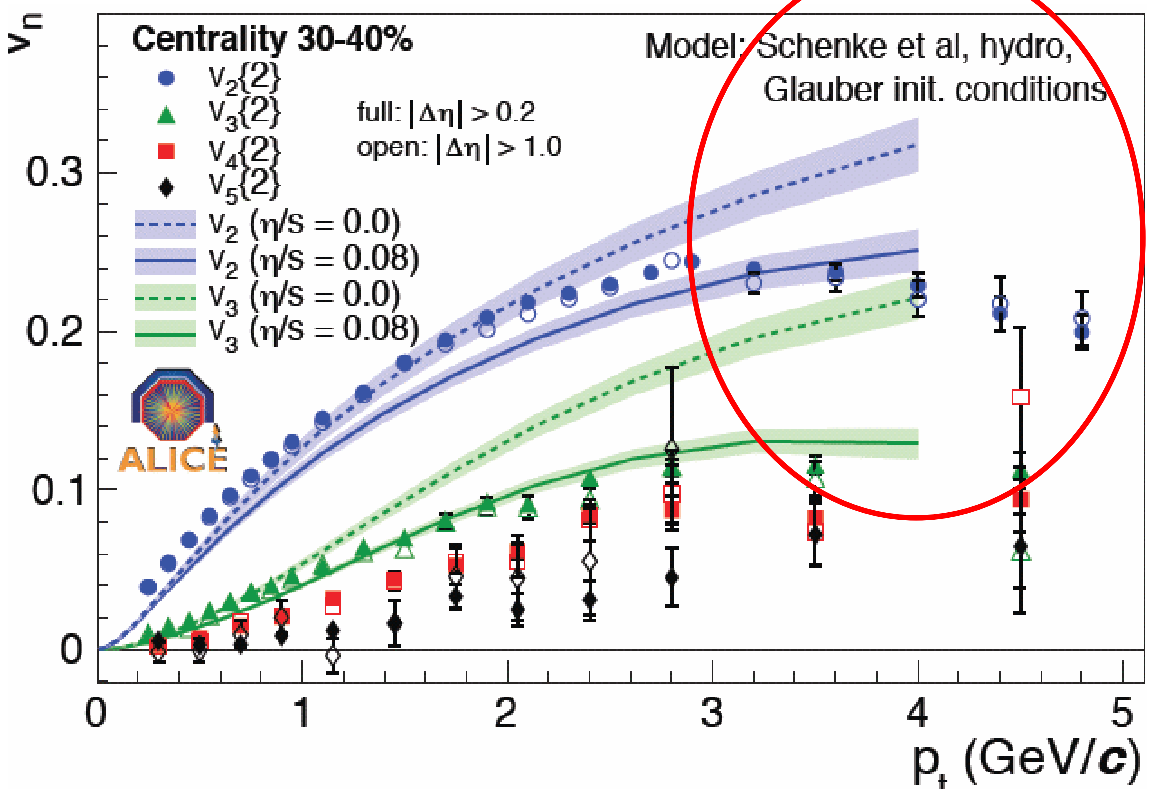
Perfect liquid and jet quenching tells a similar story

Jet quenching main features
Personal view/summary

- Very little information that can tell if a jet is quenched or not
  - Jets loose energy in a coherent way (proportional to hadron fragment p_T)
    - Because jets have self-similar properties, quenched jets appear to be unmodified
  - This is also why PYTHIA is a good reference for jet quenching studies!

- How does it relate to the perfect liquid?
  - Little dissipation and diffusion in the core of the jet
    - Jets thermalize very slowly
      - Could have been very different if the quenching had mainly affected leading p_T particles (mainly “break these up” into smaller fragments, which would generate a lot of entropy)

How is the lack of jet modification similar to perfect liquid flow



High η/s reduces flow at intermediate p_T – the large flow of a few high p_T particles is transferred to many low p_T particles

This could be related to hydrodynamization / thermalization as η/s breaks reversibility.

- The reason that the hydrodynamic v_2 at intermediate p_T is so large in the perfect liquid is that the system is so strongly interacting that there is no dissipation

First key idea (1/2)

- There seems to be a relation between the perfect liquid properties and the experimentally observed lack of strong jet modification
  - Interestingly this seems to go against the idea of thermalization via jet quenching (which is a non-perfect liquid idea!)

- Could also explain why many features of quenched jets are well described by PYTHIA
  - PYTHIA: weakly coupled system $\rightarrow$ little or no final state effects
  - Perfect liquid: so strongly coupled that most initial state correlations are conserved
    - Preserves correlations to 1st order
    - Only visible second order effects like v_2 and strangeness enhancement
  - Used as an argument to "factorize" soft and hard processes (not covered)

First key idea (2/2)

- But if there is a more general version of the perfect liquid (which will be called "perfect QCD" in the following) and it applies to jet quenching which is out of equilibrium physics then it should apply to both initial and final state processes as well

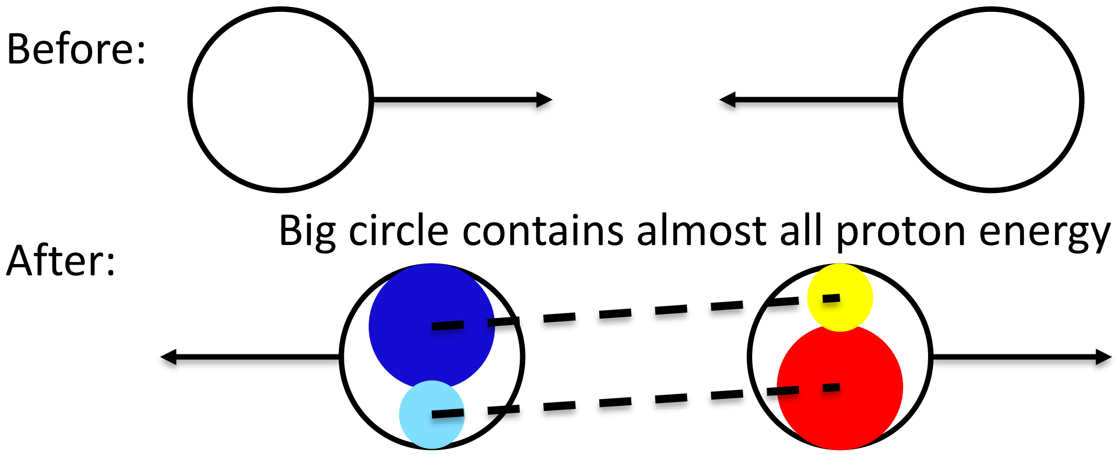
Perfect QCD

- **Only applies to soft QCD**
  - Hard processes are of course described by pQCD
  - Here: focus only on inelastic processes where colour is exchanged
- **Applies in both initial and final state processes**
  - Universal – only one type of soft QCD
- **Postulate:**
  - **Entropy production is as low as possible**
    - Little or no diffusion or dissipation
    - As low as possible $\rightarrow$ still has to obey QCD, e.g., when you "shake" a colour charge it will still radiate
- Goal is to present a fundamentally strongly coupled picture with unique features, not to describe 10-20% effects

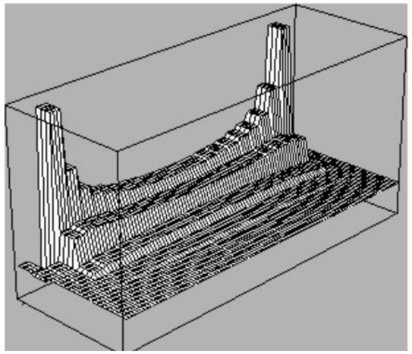
A microscopic picture of minimal particle production

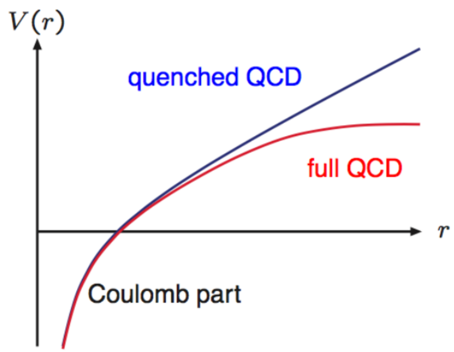
For proton-proton collision

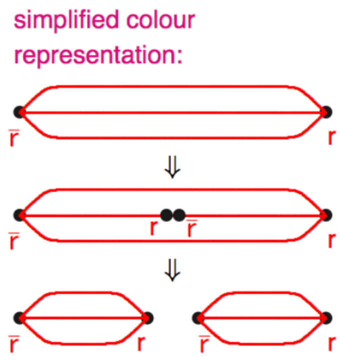
- Perfect QCD tells us that when two protons collide as little as possible should happen!
- Minimal amount of energy and colour that can be exchanged is a single soft gluon (treated as a colour and an anti-colour)
- Idea: collision produces two coherently excited domains in each proton that are coupled to domains in the projectile proton via longitudinal colour fields (Lund like strings)



Lund string-model in one slide



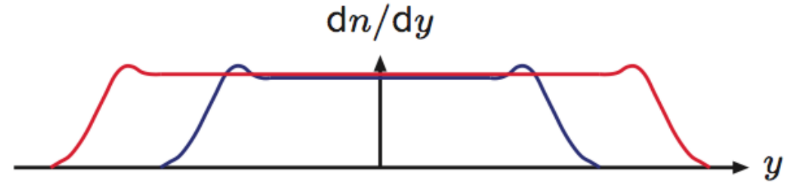




Proper treatment: evenly spaced in rapidity y:

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

Varying z values $\Rightarrow$ varying spacing, but still on the average flat rapidity plateau + some endpoint corrections:



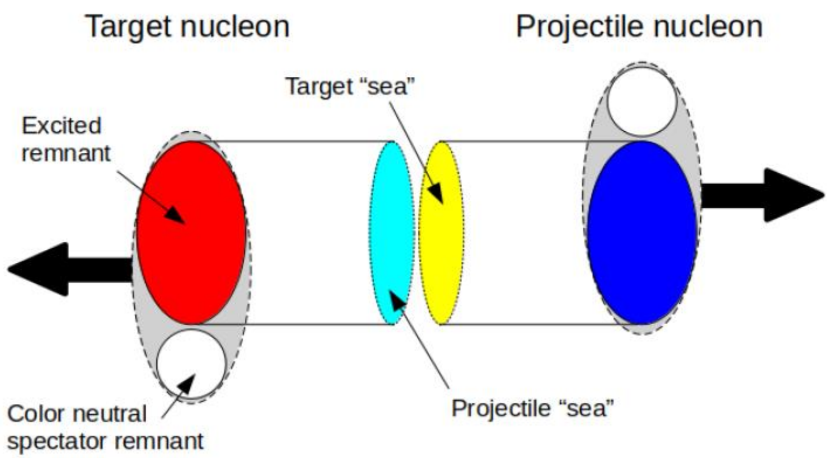
and total multiplicity grows proportional to $\ln(E_{\mathrm{jet}})$.

- Well motivated from LQCD/confinement, simple picture
- Big question is how to assign strings! (e.g., PYTHIA)
- Note that strings are soft non-perturbative QCD objects
  - Should be governed by Perfect QCD and I will assume that they decay into quarks (not hadrons as in the Lund string model)

- More details: https://www.hep.lu.se/staff/christiansen/teaching/spring_2013/lundString.pdf

How do the domains look

- Two extremes:
  - Share energy evenly ($E_{beam}/2$) – total string length ~ 4(y_{beam} – log 2) – or one has all (E_{beam}) and the other none (at rest in CM) – total string length ~ 2 y_{beam} (minimal to connect projectile and target)
- Perfect QCD states that we should take the configuration that produces less particles
  - Lund string model then dictates that it will be the 2nd configuration



- Next: QCD enters, system will radiate!

Building up particle production in pp collisions (1/2)

Z. Phys. C 33 (1986) 1

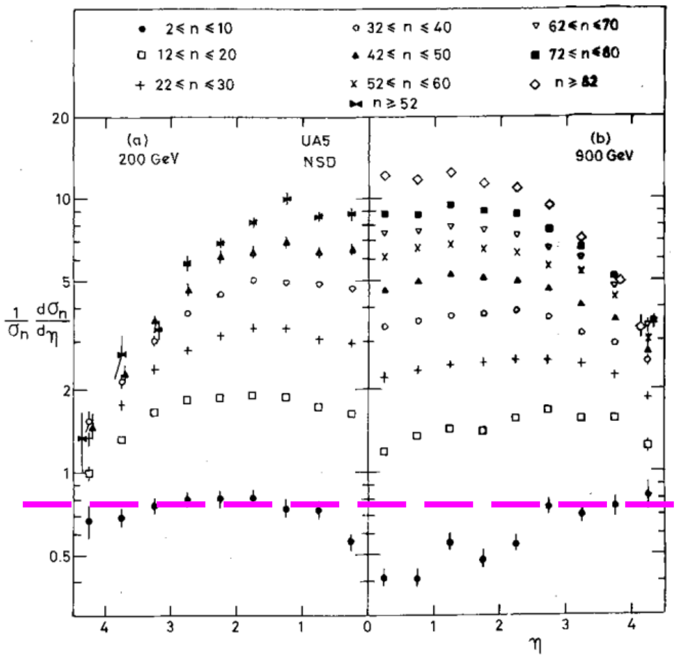
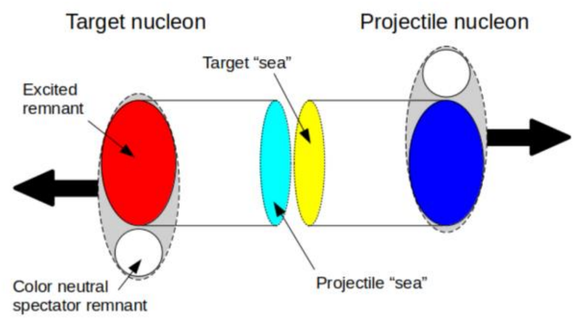


Fig. 3a, b. Pseudorapidity distributions in various intervals of charged multiplicity n for NSD events at **a** 200 GeV and **b** 900 GeV

Idea:
Lowest multiplicity is the simplest configuration:



Effectively we make 1 full Lund string.
(two strings from $\pm y_{beam}$ to y~0).

Building up particle production in pp collisions (2/2)

Z. Phys. C 33 (1986) 1

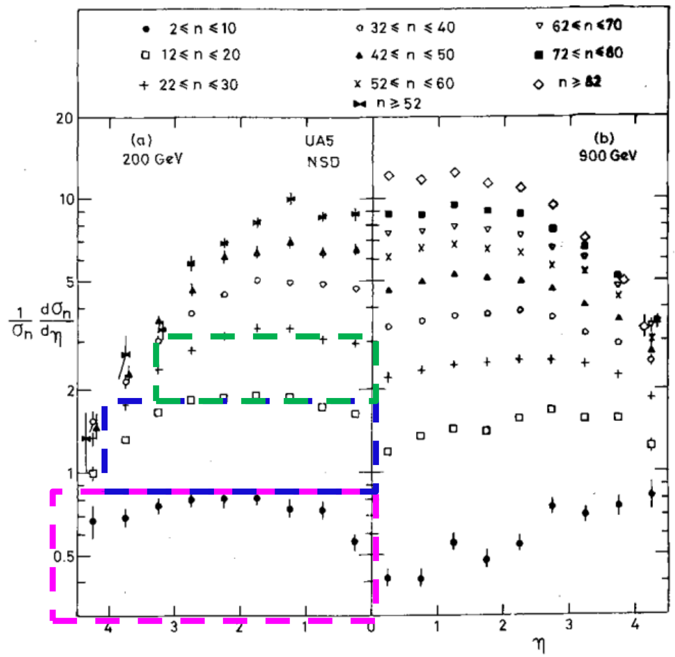
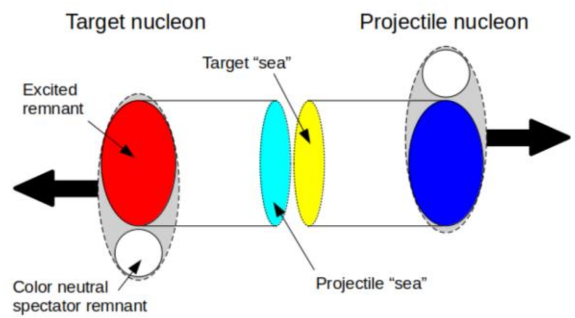


Fig. 3a, b. Pseudorapidity distributions in various intervals of charged multiplicity *n* for NSD events at **a** 200 GeV and **b** 900 GeV

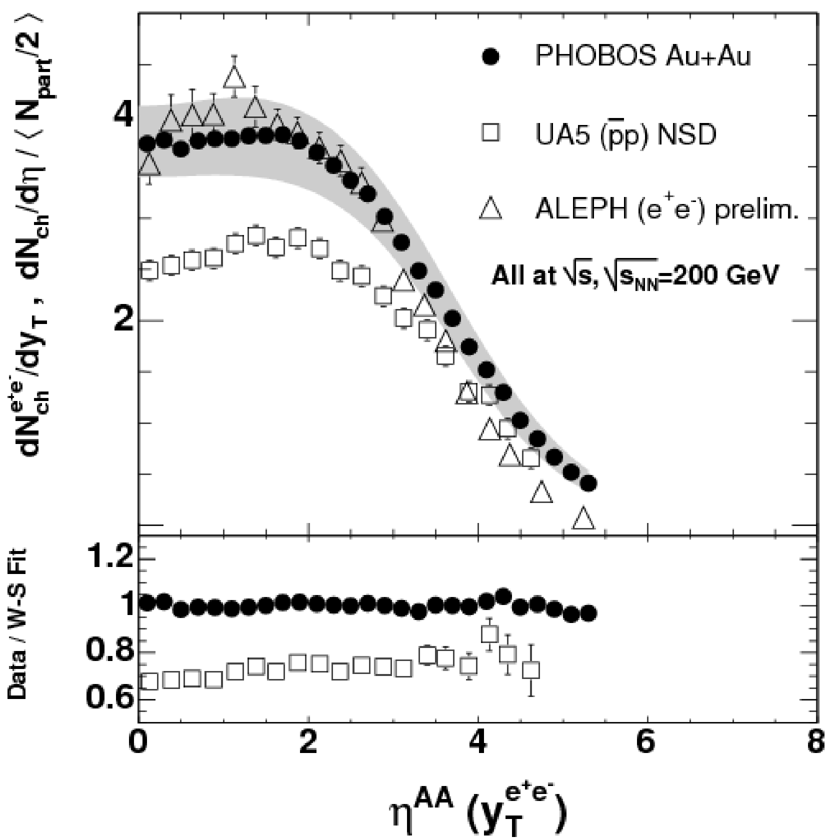
Idea:
Add ration:



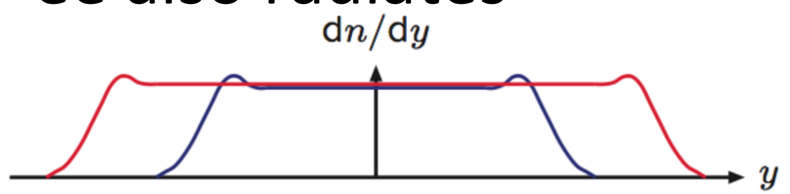
Simplest configuration.
+ 1 gluon radiated
+ 2 gluons radiated
and so forth

How much do they radiate? Use analogy with $e^+e^- \to q\bar{q}$

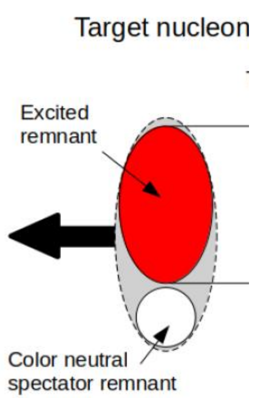
Nucl. Phys. A 757 (2005) 28



- Surprisingly $e^+e^- \to q\bar{q}$ is like AA at the same energy
  - when ee is analyzed along “jet” axis(=“beam” axis)
- ee also radiates

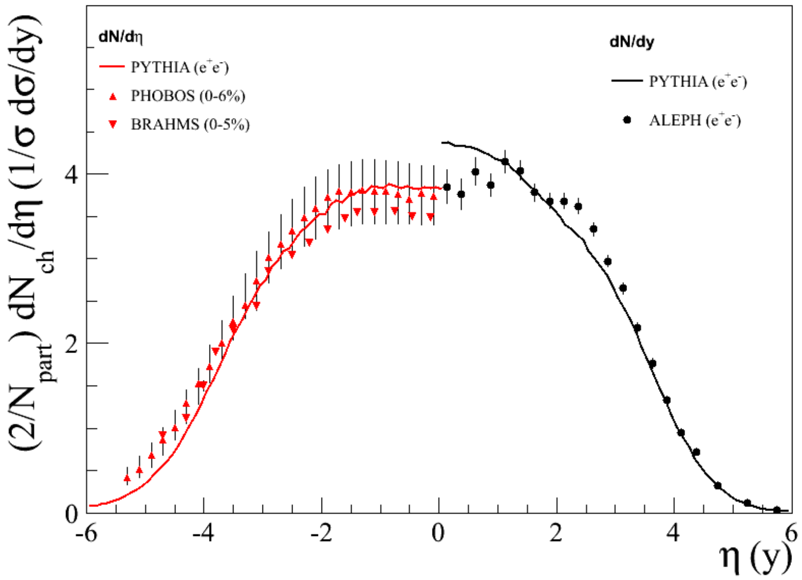


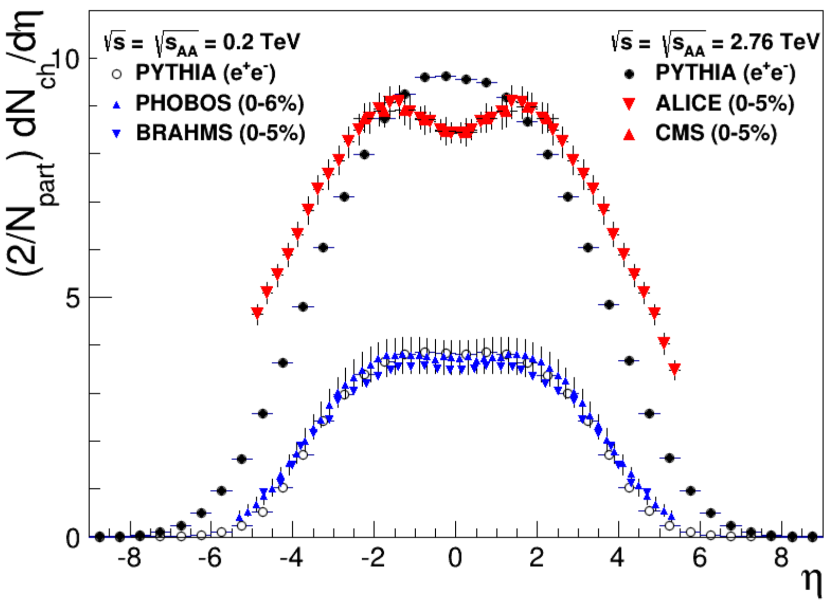
and total multiplicity grows proportional to $\ln(E_{jet})$.



- Difference could be non-iteracting fragments in pp

PYTHIA vs AA at LHC: dN/dη



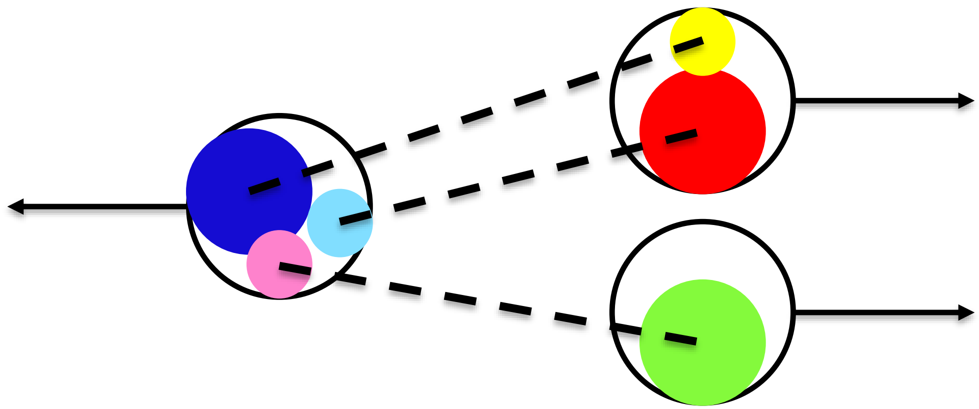


- Left: PYTHIA ee vs experimental data for RHIC energies
- Right: PYTHIA ee vs experimental data for LHC

- Note here that p_T spectra are very different (later) implying maybe that agreement depends on if one uses rapidity or η

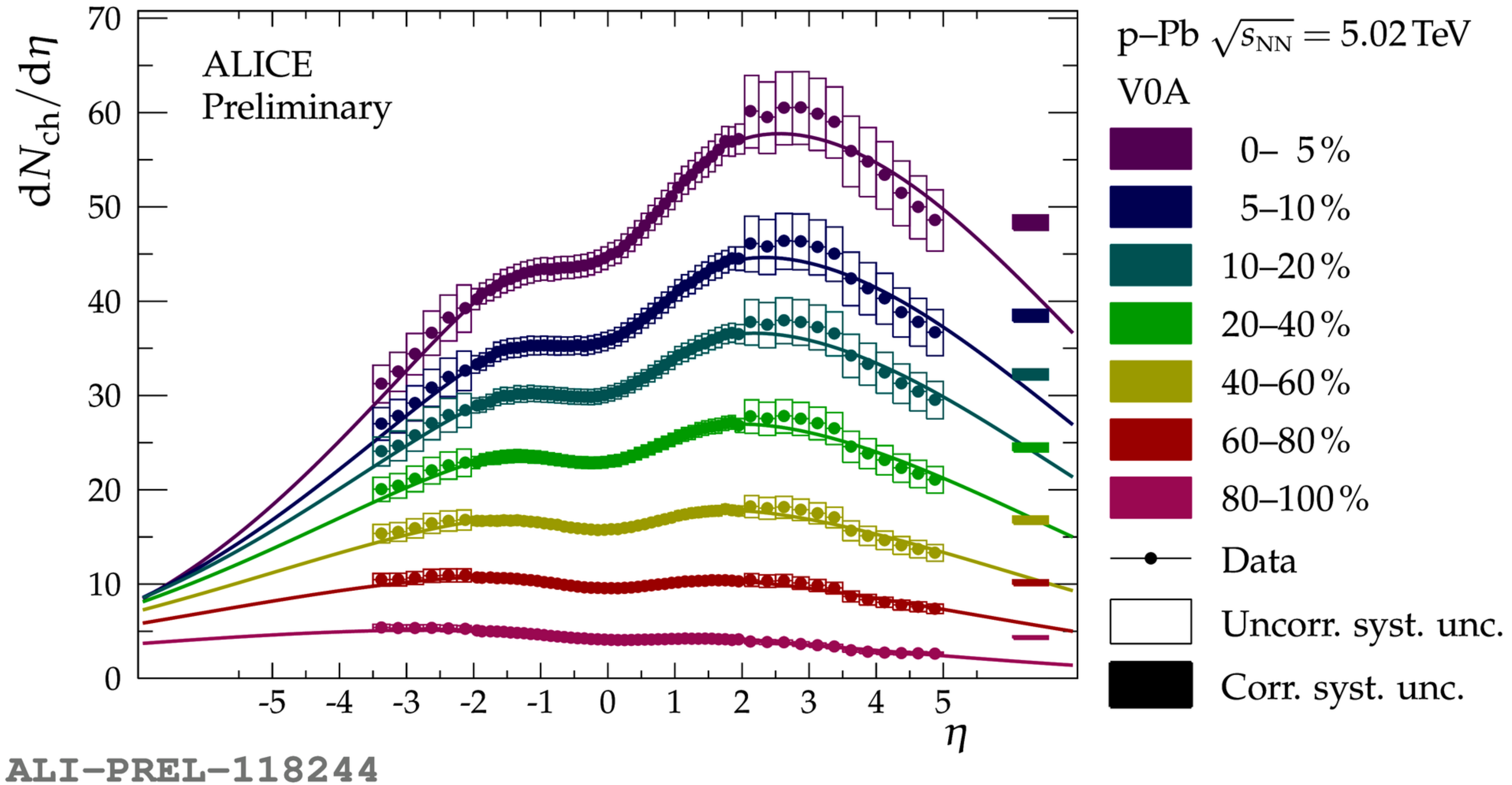
Easy insight 1: N_{part} scaling in pA (and AA collisions)

- The idea is that for the single proton one domain will still take all energy and we just add low energy domains to match each Pb participant
  - For Pb we just ignore the low energy domain (2nd order effect) and couple the high-energy domain to a low energy p domain

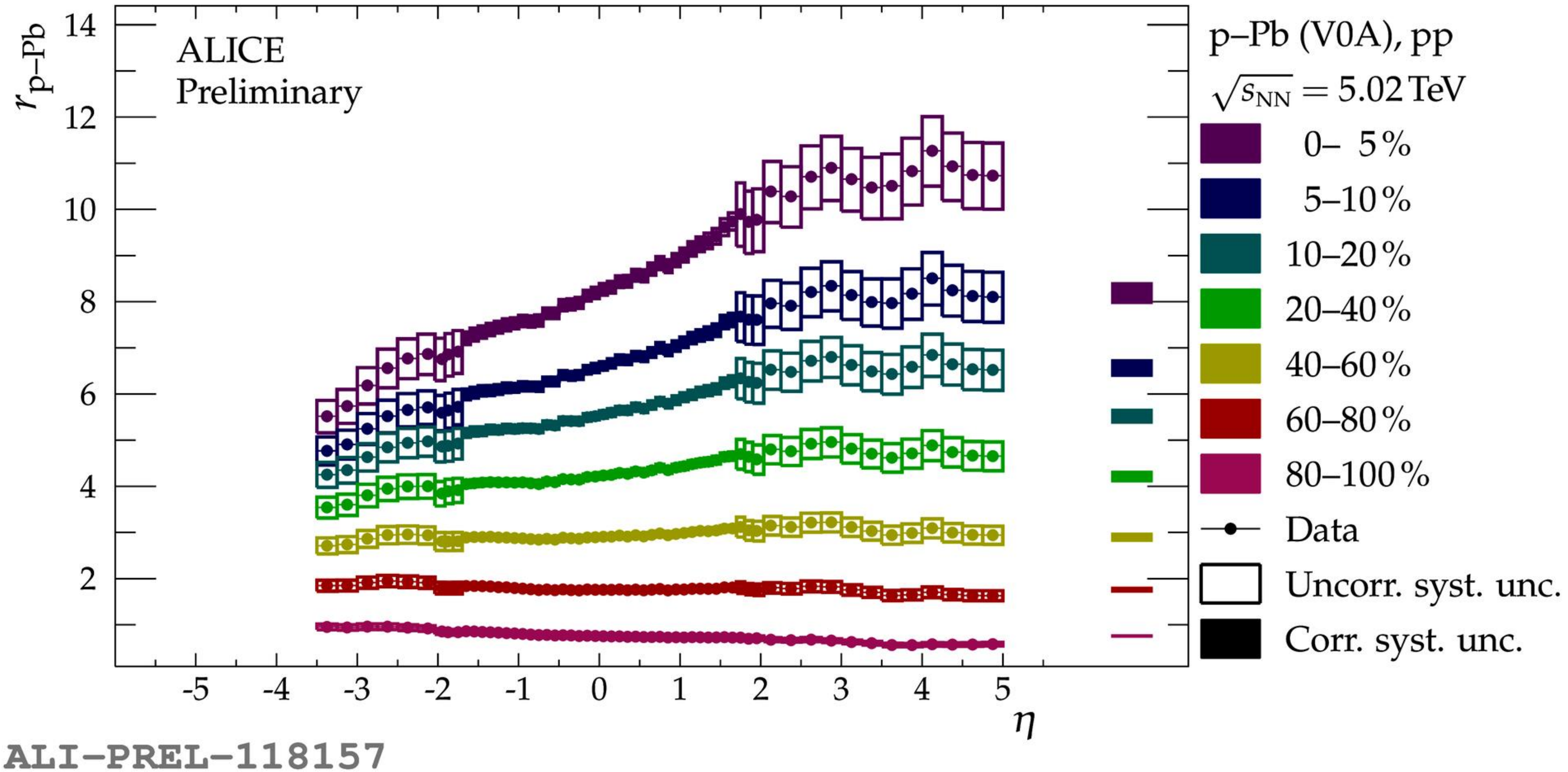


Similar features as expect in BGK picture and Angantyr (see backup slides), but the argument is different.

dN/dη in p-Pb collisions relative to pp collisions



dN/dη in p-Pb collisions relative to pp collisions



Reminiscent of triangles! ("p-Pb ~ pp + Pb-1 triangle")

Easy insight 2: flow in pp >> flow in ee

- As the excited domains in the proton will radiate coherently then the radiation will have:

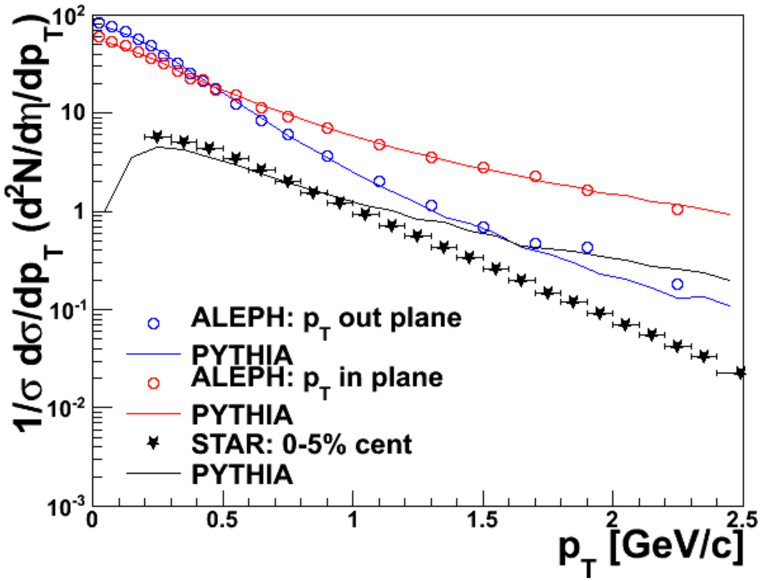
  $p_T < 1/R_{proton} \sim 200$ MeV/c

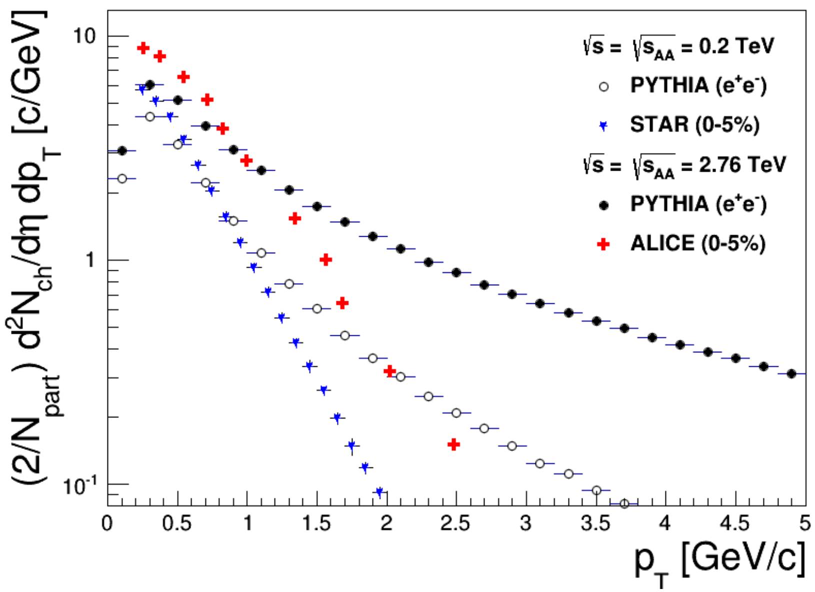
  - Very different from scales in PYTHIA / CGC where:

    p_{T0}, Q_S are of order 2 GeV/c at LHC

  - No need for a complicated thermalization process!
- **pp high-multiplicity systems will be dense and low p_T!**
- Very different from ee where the point-like nature of the electron and proton favours high p_T radiation
- No flow observed when reanalysing ALEPH data: Phys. Rev. Lett. 123 (2019), 212002

PYTHIA vs AA at LHC: dN/dp_T





- Left: PYTHIA ee vs experimental p_T spectra at RHIC
- Right: PYTHIA ee vs p_T spectra at LHC

Easy insight 3: no jet quenching in pp collisions

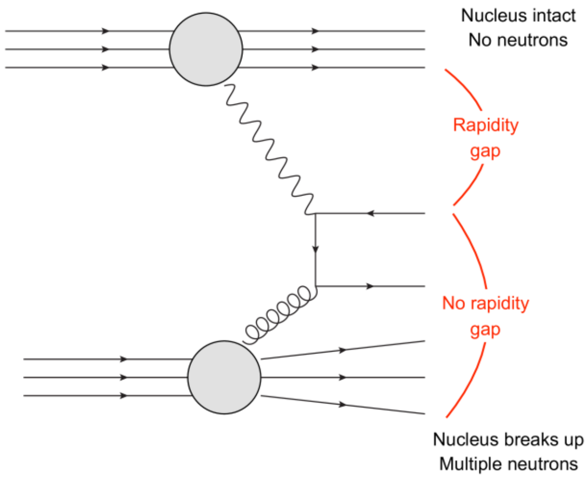
- The time scale associated with the radiation in pp collisions is long:

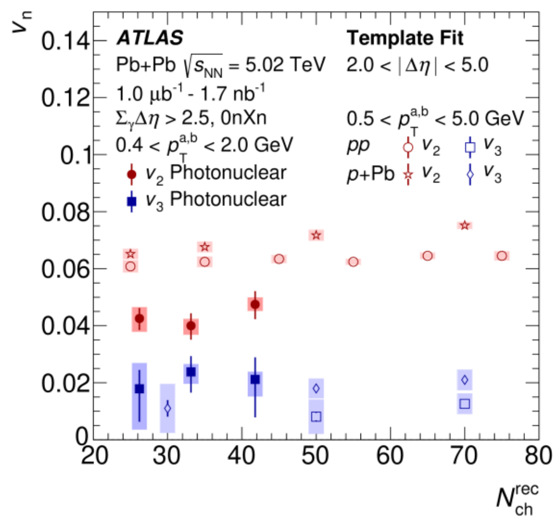
  $$\mathbf{p_{T,radiation} \sim 200\ MeV/c \rightarrow t_{radiation} \sim 1\ fm/c}$$

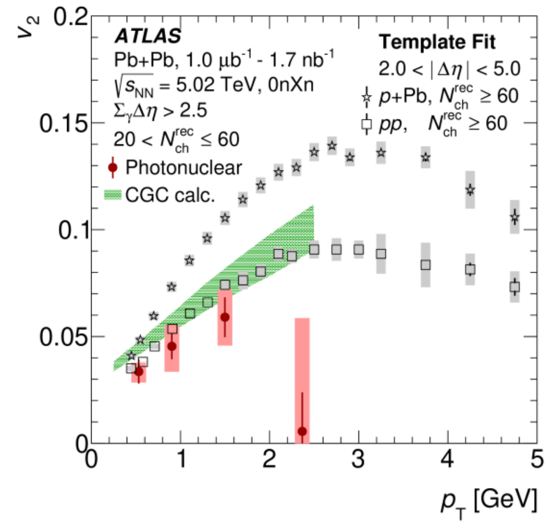
- So the hard scatterings produced at t << 1 fm/c will have time to escape before they are quenched!
  - **We need system sizes >> proton size to observe significant jet quenching**

- Advantage: In such a picture there is no contrast between flow and jet quenching being driven by similar 2 $\leftrightarrow$ 2 processes in AA collisions and the absence of jet quenching in pp collisions!

Easy insight 4: Flow in UPCs







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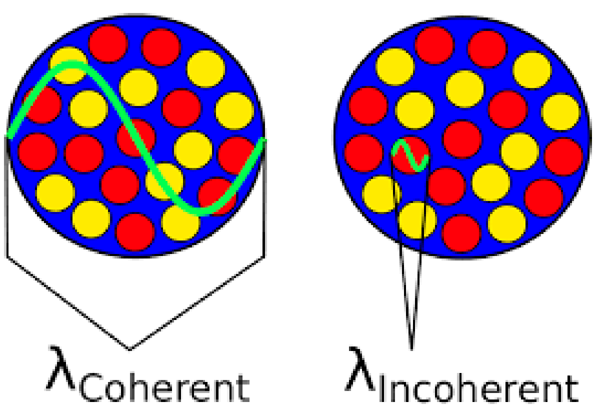
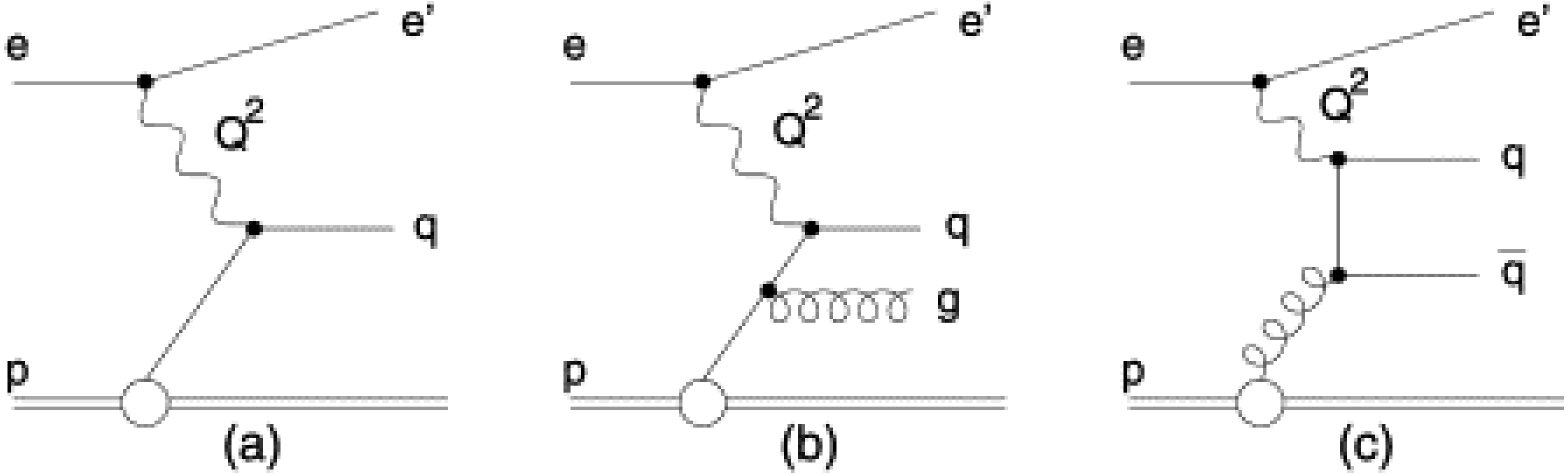


The produced finals state system is as I understand it large and so radiation can again build up a flowing system

Not a unique feature: this you can also get in Angantyr and probably any final state model.

Prediction: switch on and off flow in e-p collisions



- Expand on ideas of others (e.g., Christian Bierlich "Huge opportunity: Control geometry and density at EIC." BNL seminar Sep 2020)
- No flow when Q^2 is large (as published here: ZEUS, JHEP 04 (2020), 070)
- **Prediction: Flow when Q^2 is small (system is large)**

Conclusions

- Spent some time trying to motivate why I think we need a new model/approach to soft QCD (QGP)
- Have outlined a new idea "Perfect QCD" model and tried to show how one can obtain "easy insights" about difficult topics
- Unique (?) prediction for relation between flow in pp, ee, UPCs and ep
  - Would be interesting if one could observe flow in low Q^2 ep collisions
- I would be interesting in collaborating with someone theoretically skilled and for example try to understand better the difference between resolved and unresolved UPCs

Thank You!

Backup

pA BGK triangle

Slide from:

http://indico.cern.ch/event/223909/contribution/11/attachments/367751/511867/MGyulassy-MIT051713v2.

Recalling BGK p+A "Rapidity Triangle"

- Multiple independent wee parton dx/x collisions produce ~uniform in rapidity color charges between valence p and valence wounded A.
- Color neutralizes via pair production between wee and valence partons
-
- Leaves a stack of
- $A^{1/3} \sim 10$ Target beam jets
- For rare Nch~300 maybe 30 Pb nucleons line up
- There is just 1 Proj beam jet
-
- Y *Slope* δ = Ntr / log(s)
- RHIC $\delta \sim 2 \times$ LHC δ

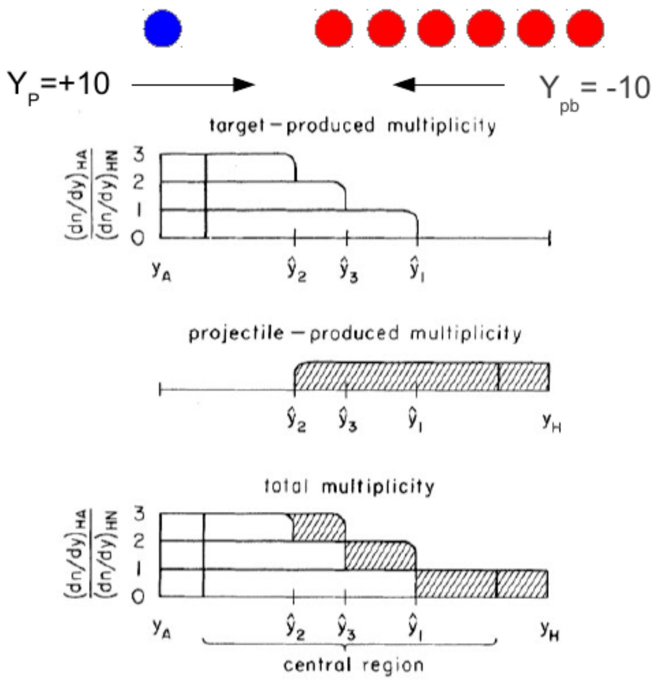


Figure from Brodsky, Gunion, Kuhn 1977

http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.39.1120

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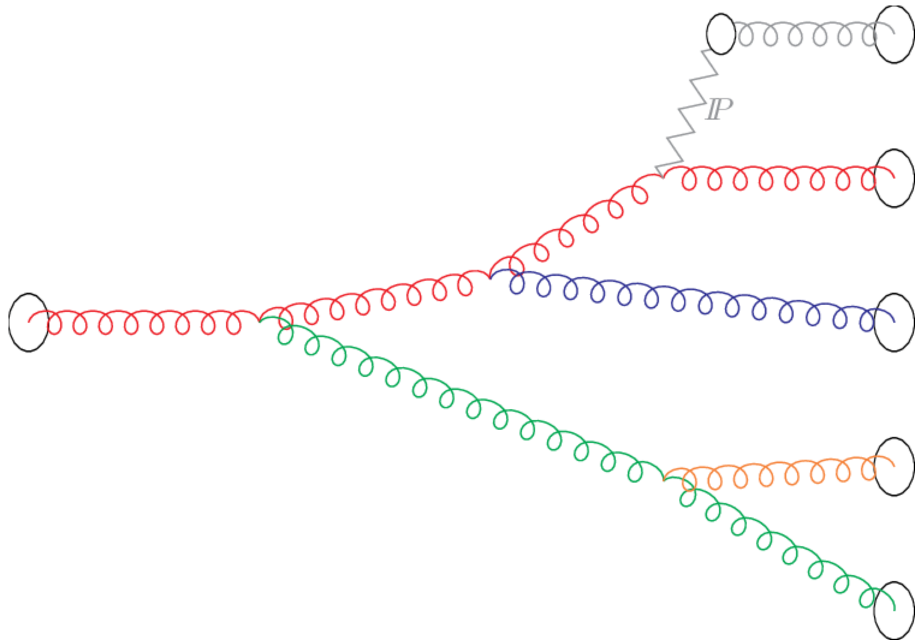
pA in Angantyr



- IMO both models are a bit different from the naïve MPI way one could approach p-Pb based on Pythia
  - Good for soft physics it seems
  - Challenging for hard physics since there is no binary scaling

Other versions of QCD

- The order of the phase transition depends on the quark masses, so it will not in general be reversible
- One can wonder if this would change also something like the perfect liquid nature of the QGP