"Perfect QCD"- ideas for a new Universal approach to soft QCD

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https://kraftly.com/product/thoughts-in-progress-a5-notebook-1461826391siv

Outline

- Motivation
- The pp and p-Pb challenge: flow without quenching
- Perfect liquid and jet quenching tells similar story
- "Generalizing" perfect liquid to perfect QCD
  - Particle production in perfect QCD

Motivation

The main issue: no microscopic QGP description

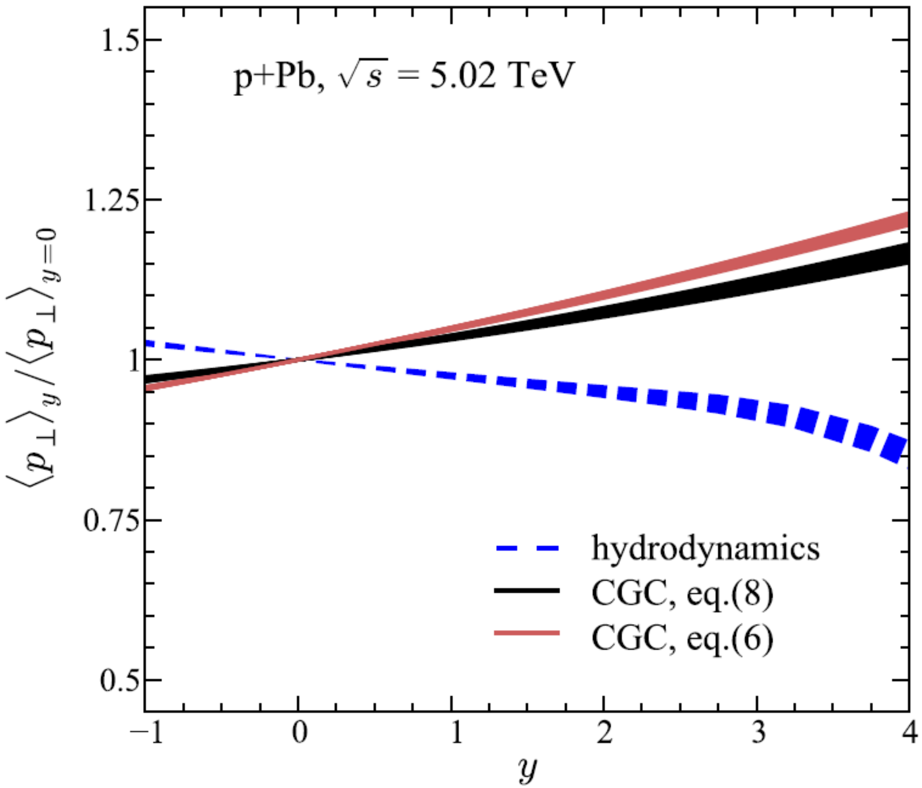
- What I want is someone to develop a new phenomenology based on the QGP paradigm from RHIC and LHC that can also be used to describe soft physics in pp and p-Pb collisions and which uses microscopic degrees of freedom
  = A fully QGP model
  - Microscopic description of flow and particle production
    - Explanations must be simple to understand
      - We cannot have another situation with obscure initial-state ideas that no one understands…
- As the main issue is particle production, this will be the main goal here!
  - The hope is that as experimental results have many systematic features so that a simple picture could be developed to explain them

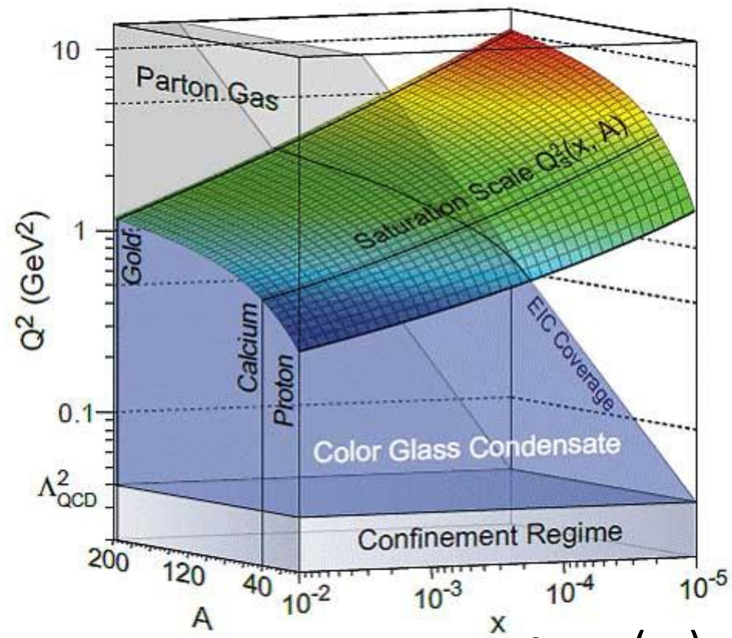
What is wrong with what we have? (my personal view)

- EPOS is a two phase model
  - No microscopic QGP
- AMPT is obscure
  - But it would be interesting if someone would seriously try to scrutinize it
- CGC lacks power to explain
  - Next slides
- Kinetic theory explanations seem to go against what we know about perfect liquid
  - Next slides

CGC early predictions for p-Pb

P. Bozek, A. Bzdak, V. Skokov, Phys. Lett. B 728, 662 (2014)



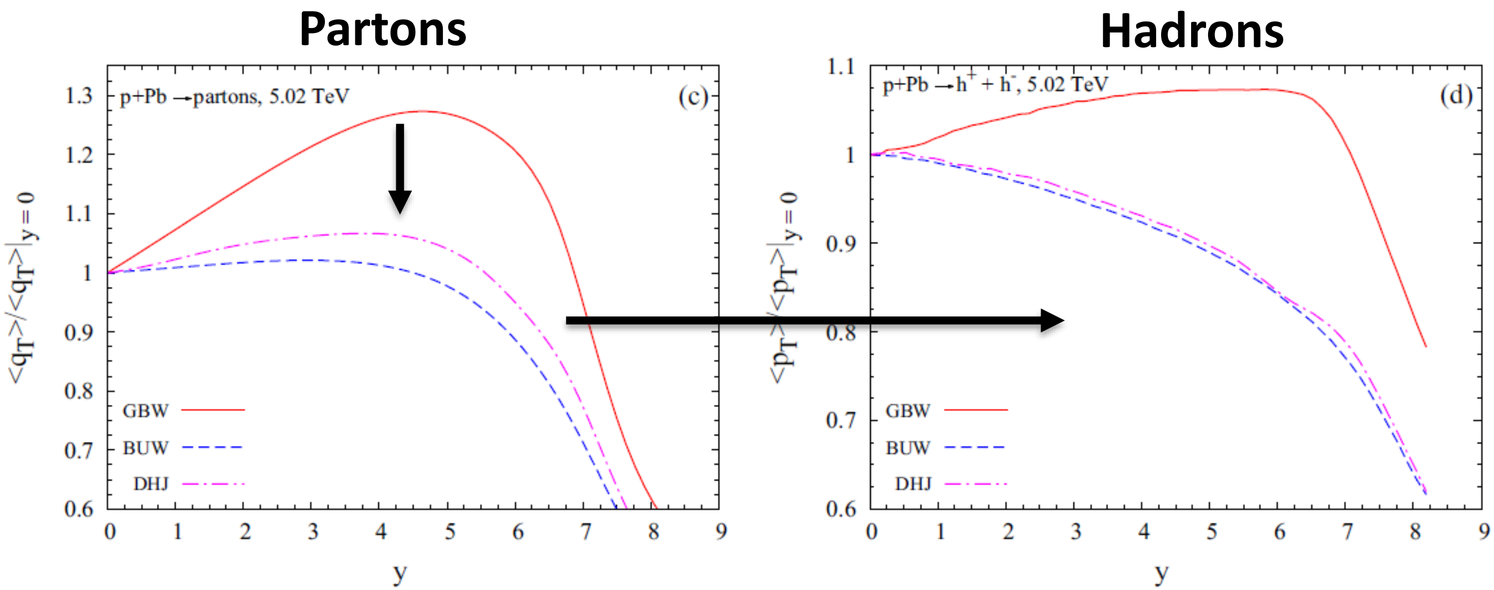


~exp(-y)

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

CGC refined predictions for p-Pb

Phys. Rev. C 94, 024917 (2016)

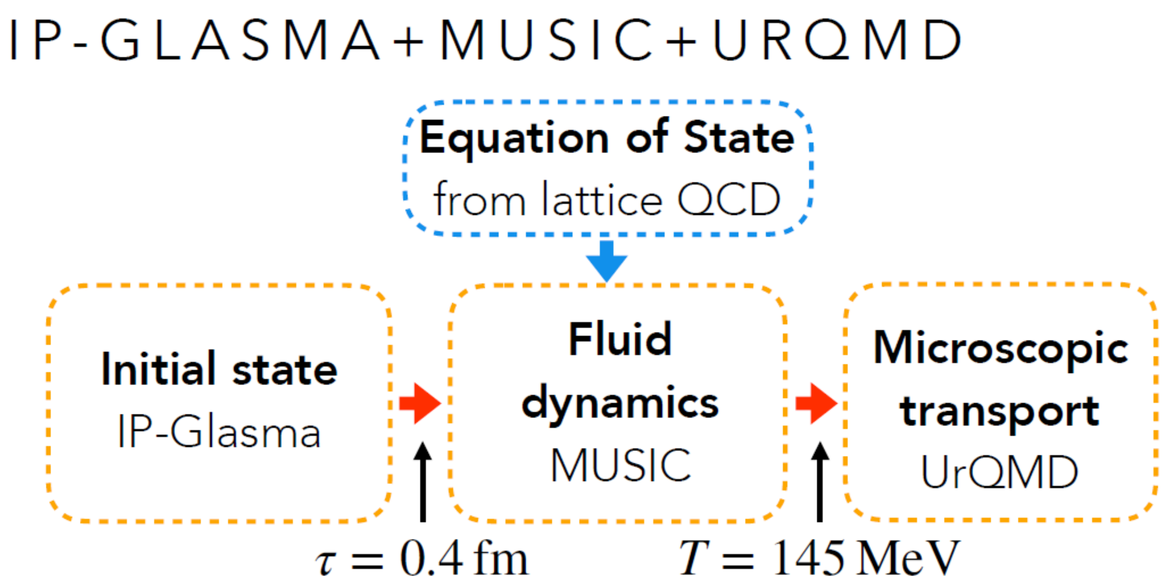


From paper abstract:

"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 behaviour similar to that predicted by hydrodynamical calculations."

But in some sense it is worse…

- … because in most cases CGC has to be post-processed by a model that thermalizes the system and generates “hydrodynamic” flow



From B. Schenke QM19 slides

Very ambitious but also “intransparent” and macroscopic in this case. (Sometimes microscopic when kinetic theory is used to post process)

Maybe we can rephrase the question

- Is there an energy dependent (saturation) scale that characterizes the physics?
  - Or is mainly just colour exchanged by target and projectile and the multiplicity is a proxy for the strength of the final colour field?
- Is there evidence for saturation effects in particle production in p-Pb collisions?

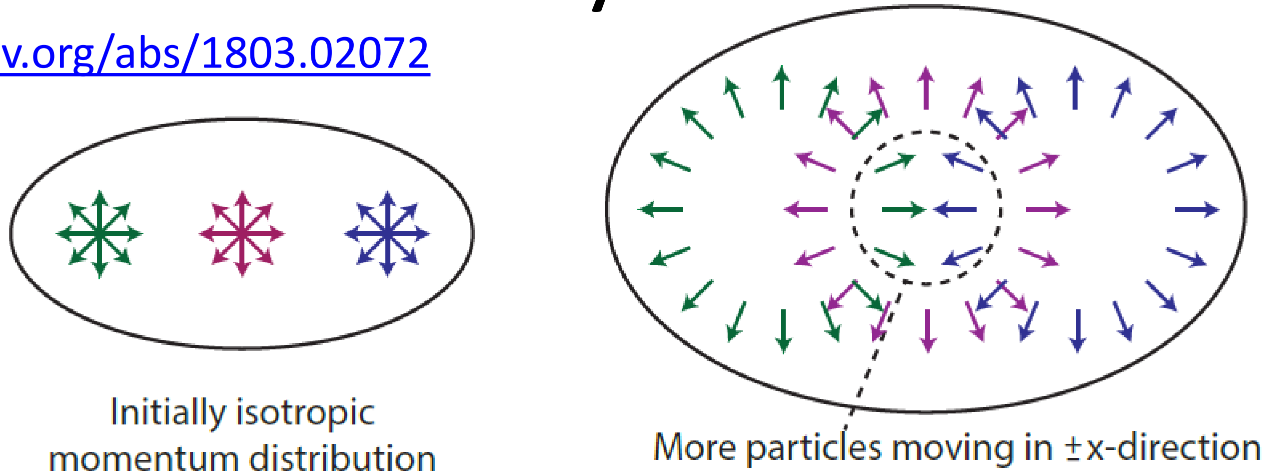
- These are questions that are relevant for the physics and are relevant for the question of the CGC picture
  - If it should be more than an input!

Kinetic theory

- A model where collectivity seems to imply strong jet quenching/modifications
- Kinetic theory primer: (see C. Plumsberg's slides from COST workshop)
  - <u>Weakly coupled!</u>
  - Classical (QM/QFT via cross sections)
  - Partonic (hard modes)
  - Advantage: can be applied out of equilibrium so it can bridge CGC to hydro (thermalization/hydrodynamization)
    - Extremely ambitious goal!

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. <u>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</u>."

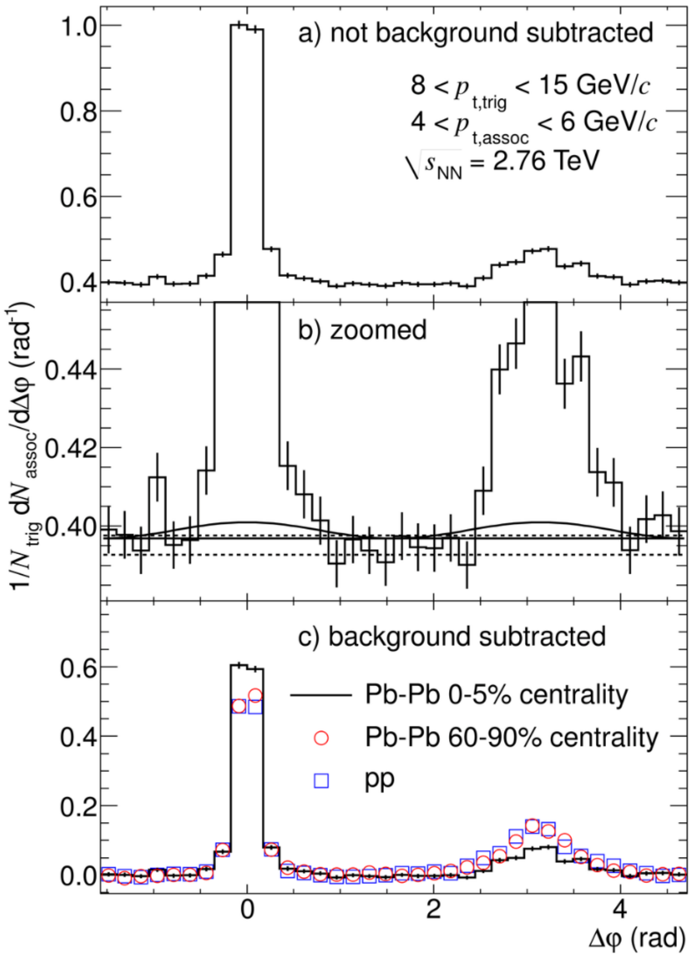
Abstract: "Here, we demonstrate within the framework of transport theory that even the mildest interaction correction to a picture of free-streaming particle distributions, namely the inclusion of one perturbatively weak interaction ("one-hit dynamics"), will generically give rise to all observed linear and non-linear structures. … <u>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</u>."

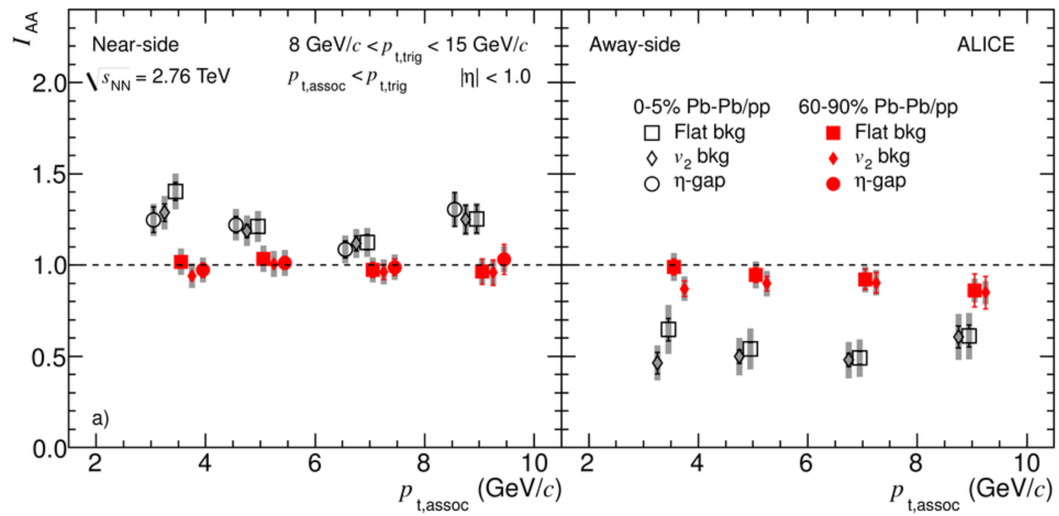
What does this model predict? What are its signatures?

- Difficult because it is not quantitative (only includes collective effects) so these are my guesses!
- Mini jet quenching
  - In particular when comparing near and away side jet!
  - Must be huge effect in larger systems

What do we know? I_{AA}

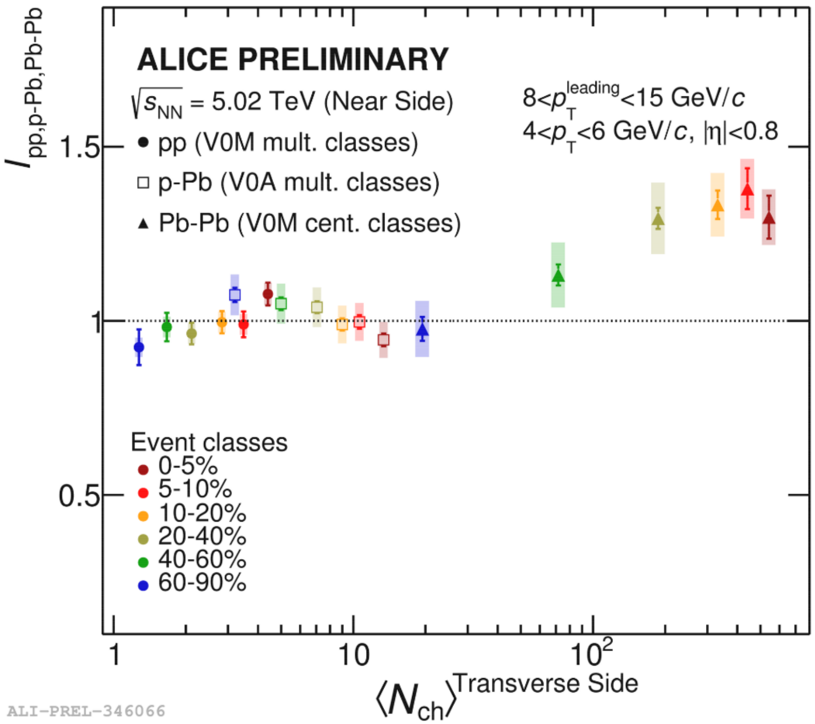
Phys. Rev. Lett. 108 (2012) 092301

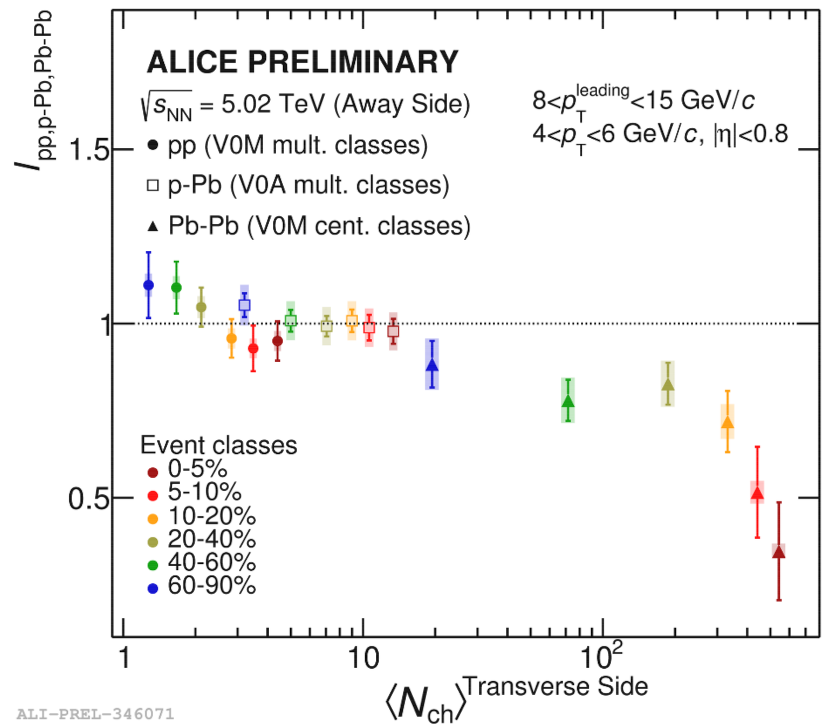




Not any evidence that there are significant jet modifications in peripheral Pb-Pb collisions.
In particular the back-to-back structure is the same!

New ALICE results (fresh for LHCP and Hard Probes)





- Studies the Ipp and Ip-Pb using a traditional UE analysis where we used Nch,Transverse for multiplicity
- In all cases, yields were normalized to yields for MB pp
- No evidence for onset of jet quenching in small systems!

Kinetic theory comments

- Large effect → obvious mechanism
- Small effect → obscure mechanism

- My conclusion: Before kinetic theory can be considered as a serious candidate for non-equilibrium physics, quantitative transparent estimates of (mini-)jet quenching (and ideally more fingerprints) must be done in a way that it can be compared to experimental data

The pp and p-Pb challenge: flow without quenching

The pp and p-Pb challenge: medium but no jet quenching

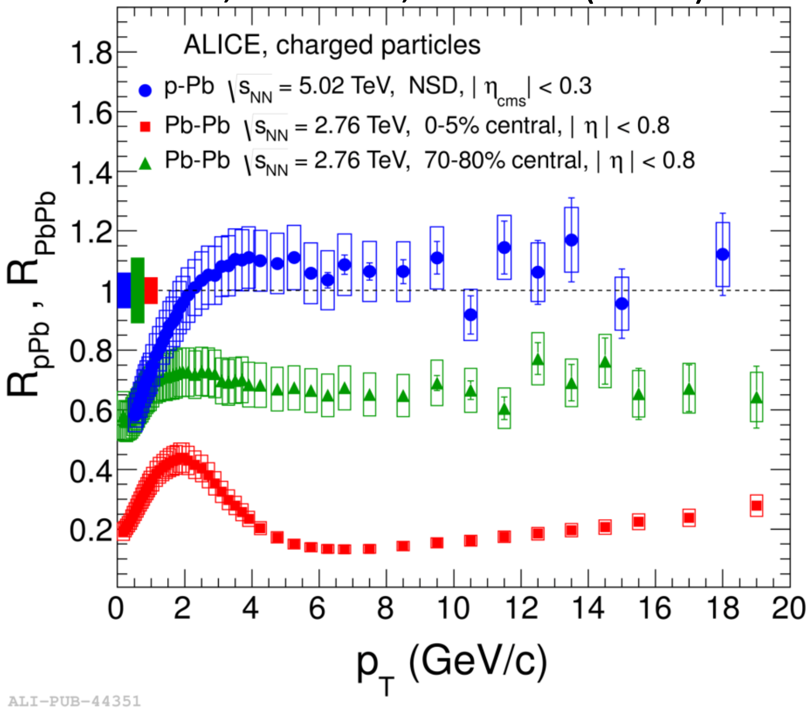
- Interestingly string shoving is one such solution
  - “Medium” like effects but no jet quenching because first we shove and then we hadronize
    - But obviously no thermalization so no “classic” medium
      - This collectivity is a bit like for a nuclei (many short range interactions gives global correlations)

- Here, the idea is to link the perfect liquid properties to the lack of jet quenching in small systems

Jet quenching highlights (1/4)

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}/dp_T d\eta}$$

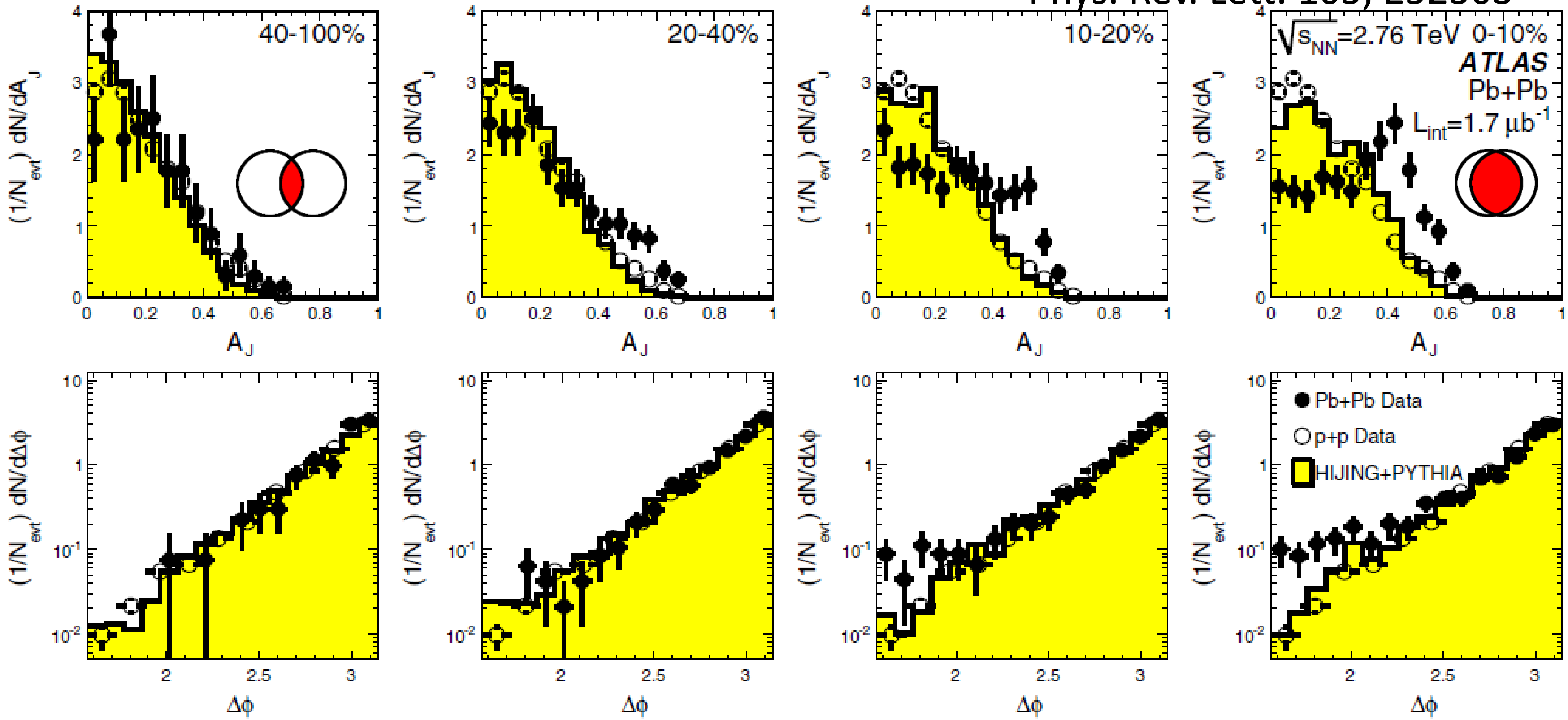
ALICE, PRL 110, 082302 (2013)



Large jet quenching in central AA collisions
Understood as mainly an energy loss (~20-30% for pT=10 GeV/c hadrons)

Jet quenching highlights (2/4)

Phys. Rev. Lett. 105, 252303

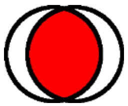


$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

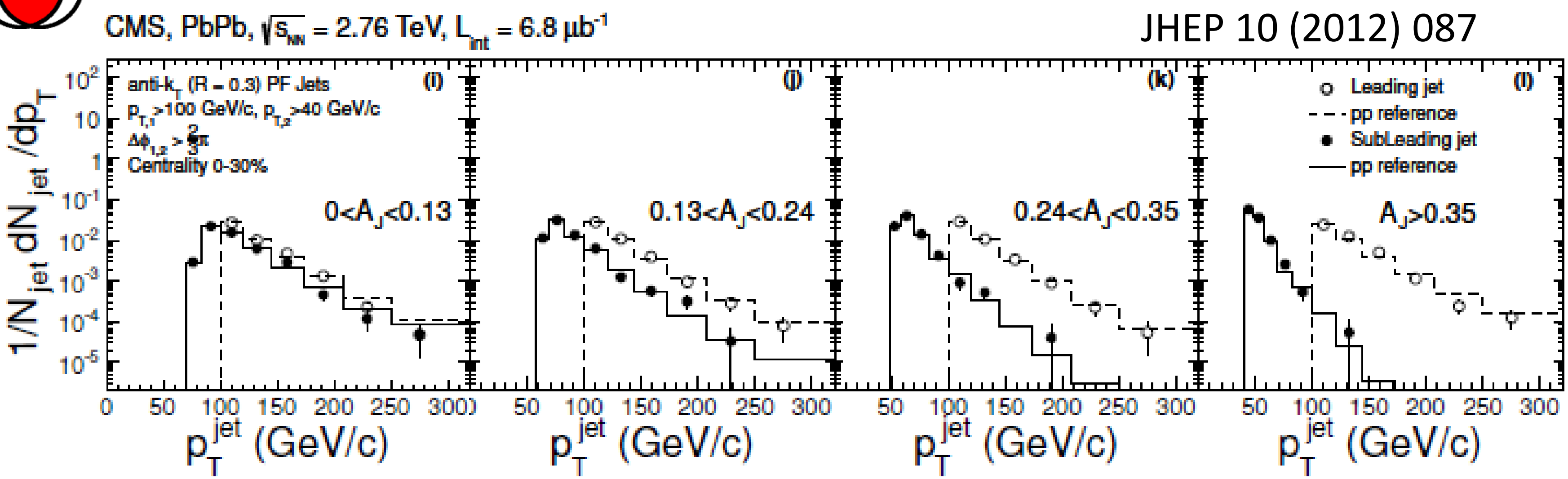
Where E_{T1} (E_{T2}) is the transverse energy of the leading (subleading) jet (E_{T1}>100 GeV and E_{T2}>25 GeV).

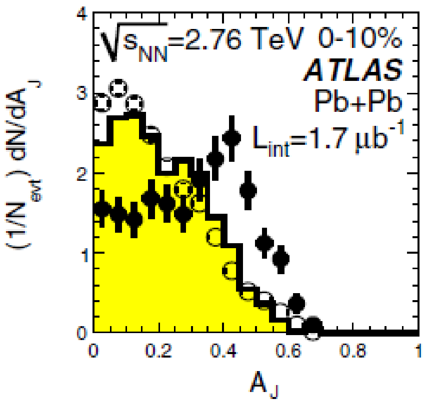
Notice that the jets are still back-to-back!

Jet quenching highlights (3/4)



JHEP 10 (2012) 087





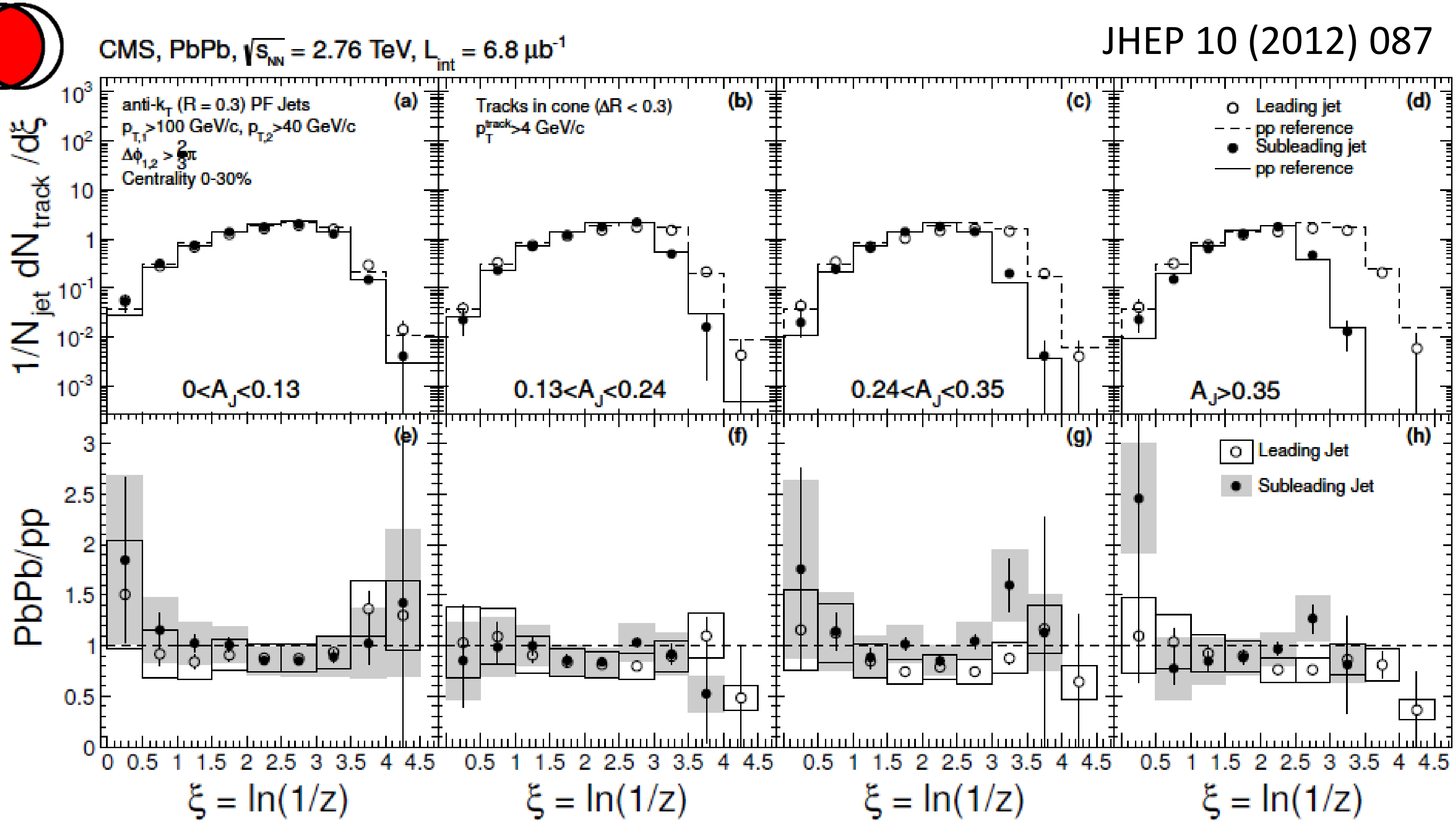
Tracks with p_T>4GeV/c.

The A_J selection introduces the same bias on the dijet samples

Perfect QCD (P. Christiansen, Lund)

Jet quenching highlights (4/4)

JHEP 10 (2012) 087



The result shows that quenched jets looks like pp (vacuum) jets!
Even in the case where A_J is large and for the subleading jet!

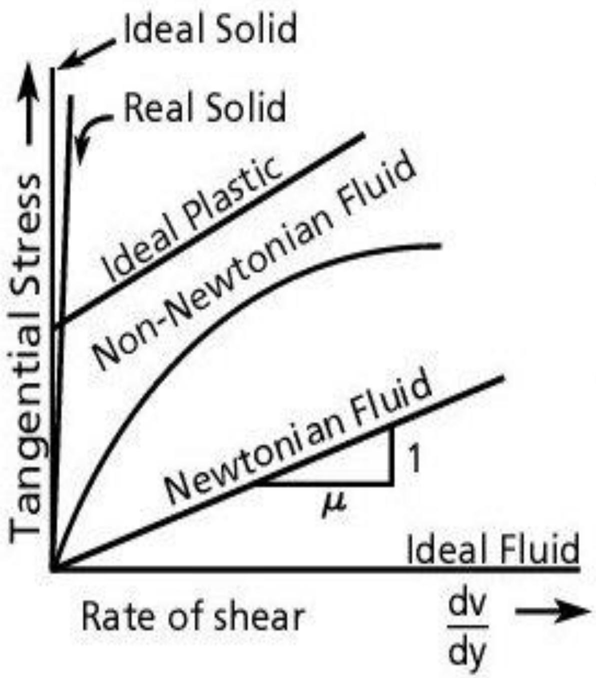
Jet quenching main features
Personal view

- 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 similar properties, quenched jets appear to be unmodified
  - This is also why PYTHIA is a good reference for jet quenching studies!

- This is very different from the main ideas in the kinetic theory description of QGP
  - Because jets do not thermalize from an experimental point of view
  - If the jet mainly would have lost leading p_T then it would have been different…

Perfect liquid and jet quenching tells similar story

“friction” in the perfect liquid is as small as possible



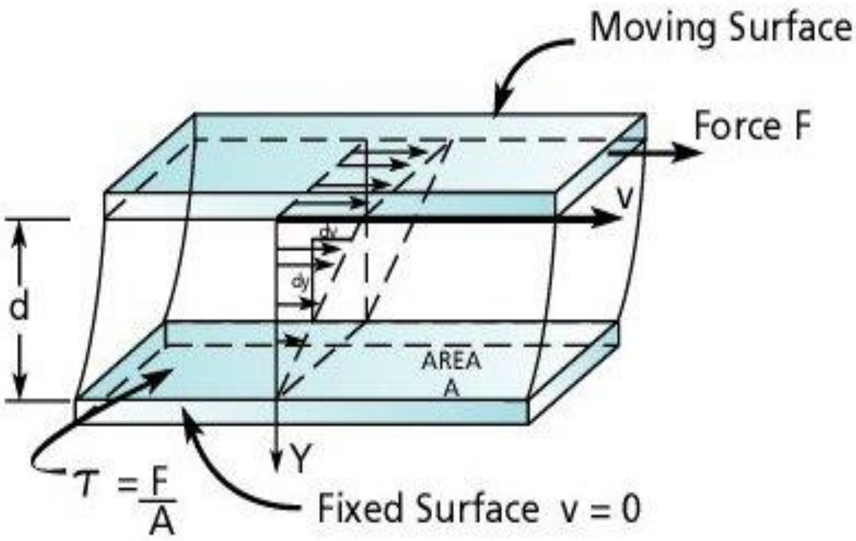


Figure taken from http://www.pumpfundamentals.com/about_fluids.htm

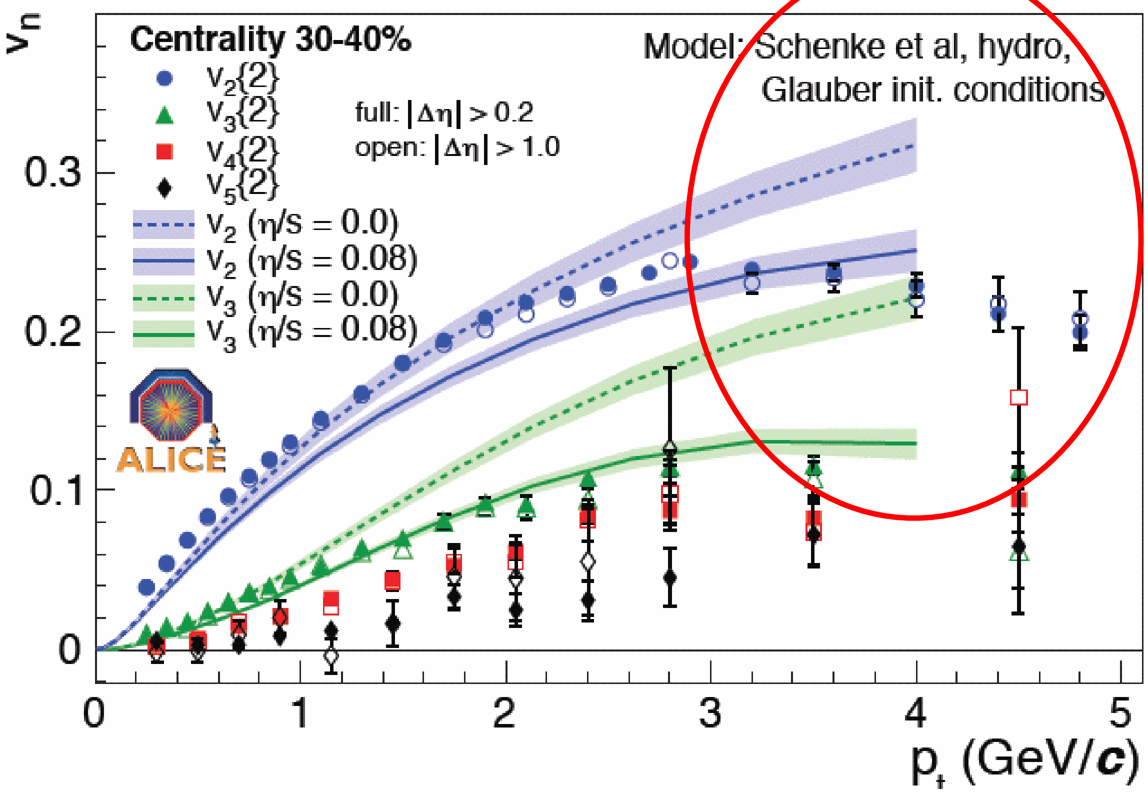
The shear force is given as F=ηAv/d

The shear vicosity-to-entropy density ratio, η/s, is a unitless quantity for characterizing fluids.

For the QGP, η/s is extremely small:

No diffusion and dissipation!

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



High η/s reduces flow at high p_T

The large flow of few particles at high p_T is transferred to many low p_T particles (smells of thermalization)

- It is important to understand that the reason that there is no loss of v_2 at high p_T in the perfect liquid is that it 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 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 most results will be consistent with PYTHIA
  - PYTHIA: weakly coupled system -> little or no final state effects
  - Perfect liquid: so strongly coupled that all initial state correlations are conserved
    - Preserves colour field correlations to 1st order
    - Only visible second order effects like v2 and strangeness enhancement

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

"Generalizing" perfect liquid to perfect QCD

Perfect QCD

- Only applies to soft QCD
  - Hard processes are of course described by pQCD
  - But goal is to eventually explain screening e.g. p_{T0}
- Only applies to inelastic processes where colour is exchanged
- Applies in both initial and final state processes
  - Only one type of QCD
- Entropy production is as low as possible
  - Little or no diffusion or dissipation
- Strongly interacting
- Goal is to explain main features not 5-10% effects

Production of soft particles in perfect QCD (1/2)

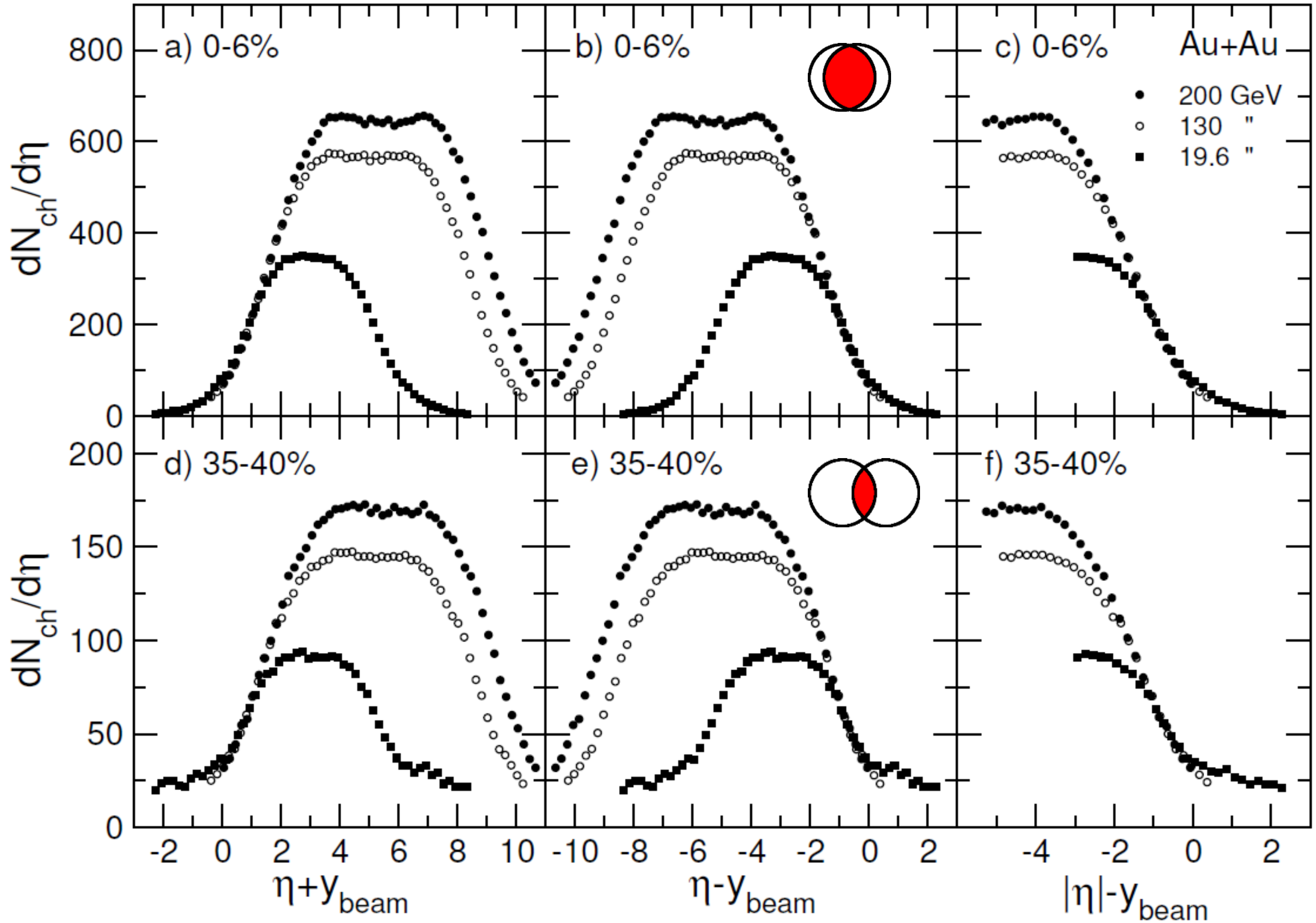
- Inelastic and strongly interacting
  - Exchange of colour and formation of dense colour field between projectile and target
  - 2-2 partonic processes are suppressed by screening (to minimalize entropy)
    - Bulk particle production is dominated by soft component

Production of soft particles in perfect QCD (2/2)

- Minimal entropy production
  - Consider evolution with beam energy
  - If production is as low as possible in the rest frame of projectile and target
    - Colour fields will fill up between them as the systems are colour connected (strongly interacting)
    - This is known as limiting fragmentation
      - Experimental results on next slides

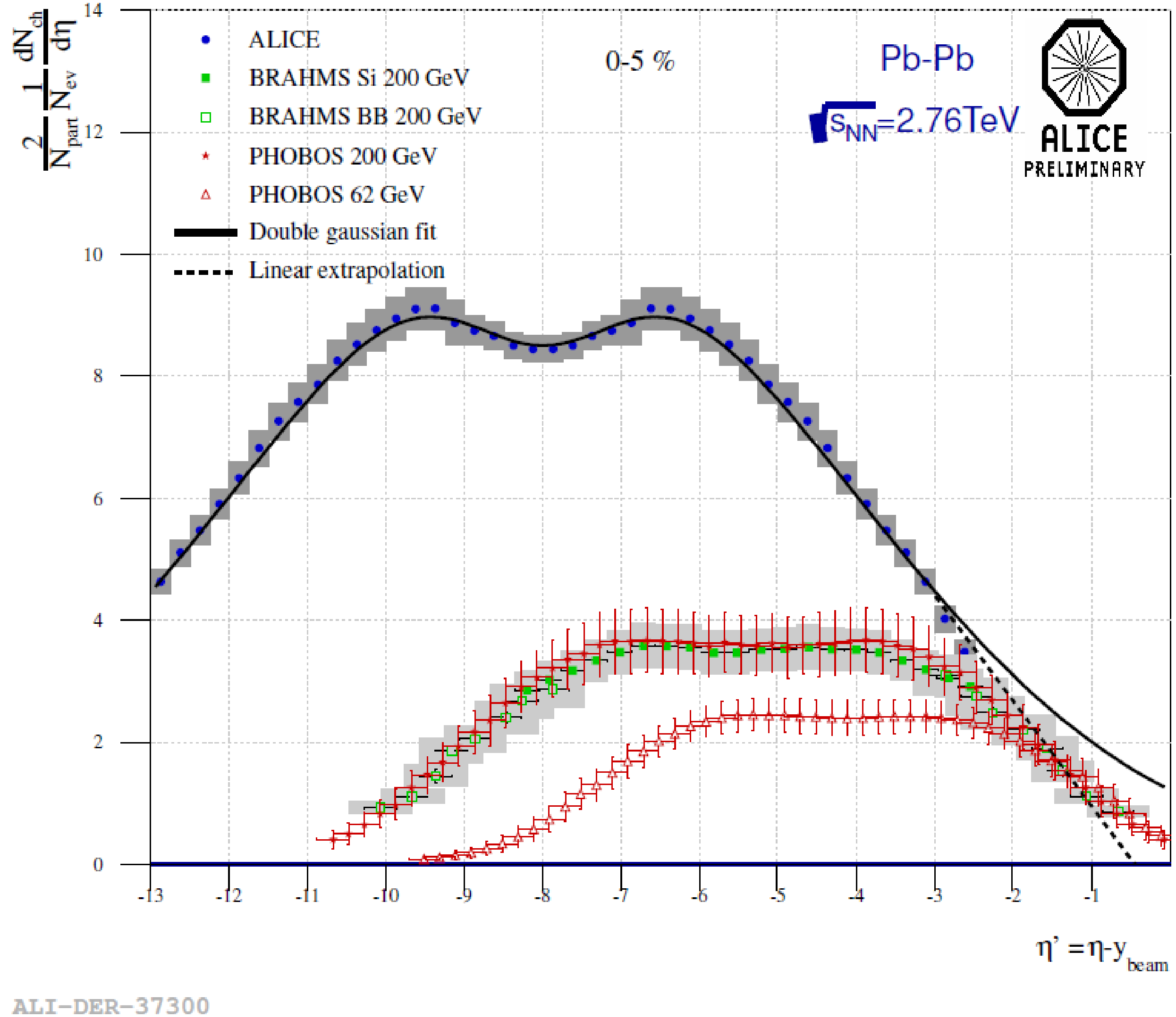
Limiting fragmentation in AA

PHOBOS, Nucl. Phys. A 757, 28



Note that this is not normalized to Npart! Which will be slightly different.

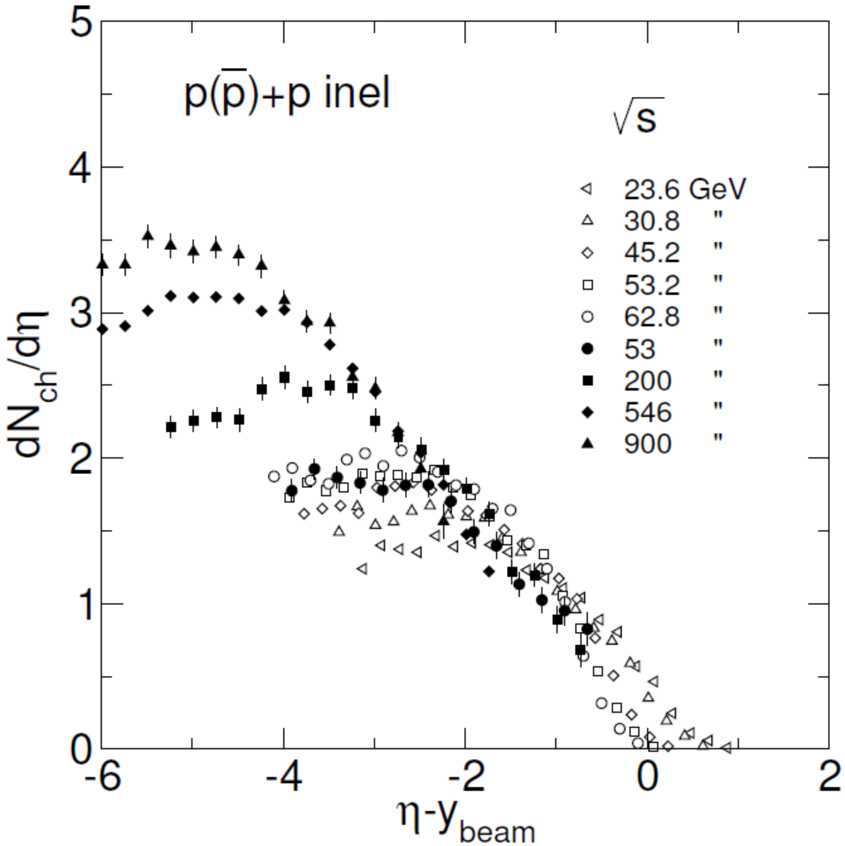
Even at LHC

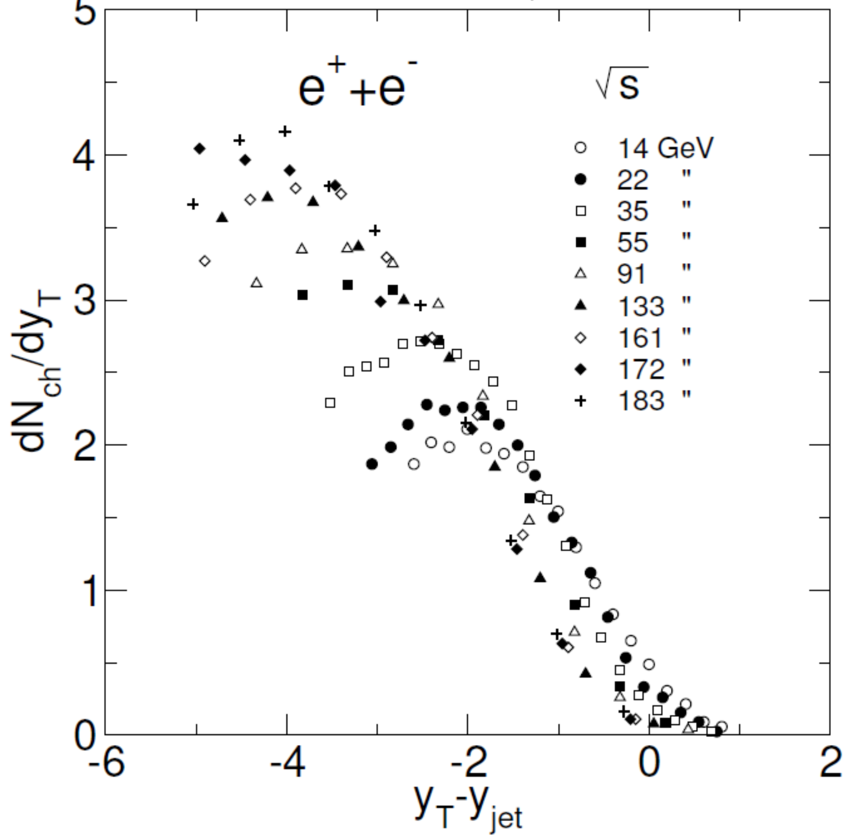


Perfect QCD (P. Christiansen, Lund)

Limiting fragmentation in pp and ee

PHOBOS, Nucl. Phys. A 757, 28

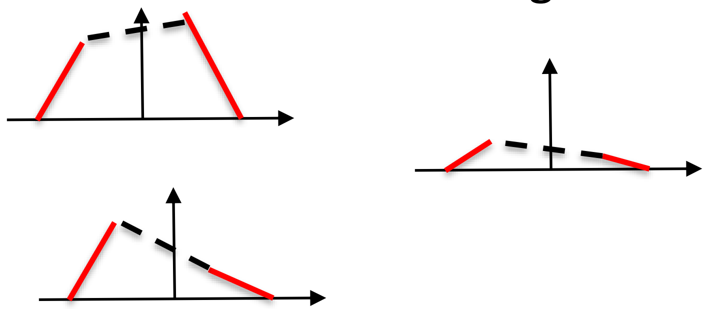




Not so bad even for pp. One has to take into account that this is η and not y and that most measurements were done by different experiments.
For ee it looks significantly worse but the radiation effects are much larger so one does not necessarily expect longitudinal scaling.

KNO scaling in “Perfect QCD”

- Similar to limited fragmentation
  - Each region, projectile and target, will fluctuate the same way independent of energy
  - But as they are colour connected the intermediate region will get similar fluctuations:
    - High and high -> high
    - Low and low -> low
    - High and low -> middle



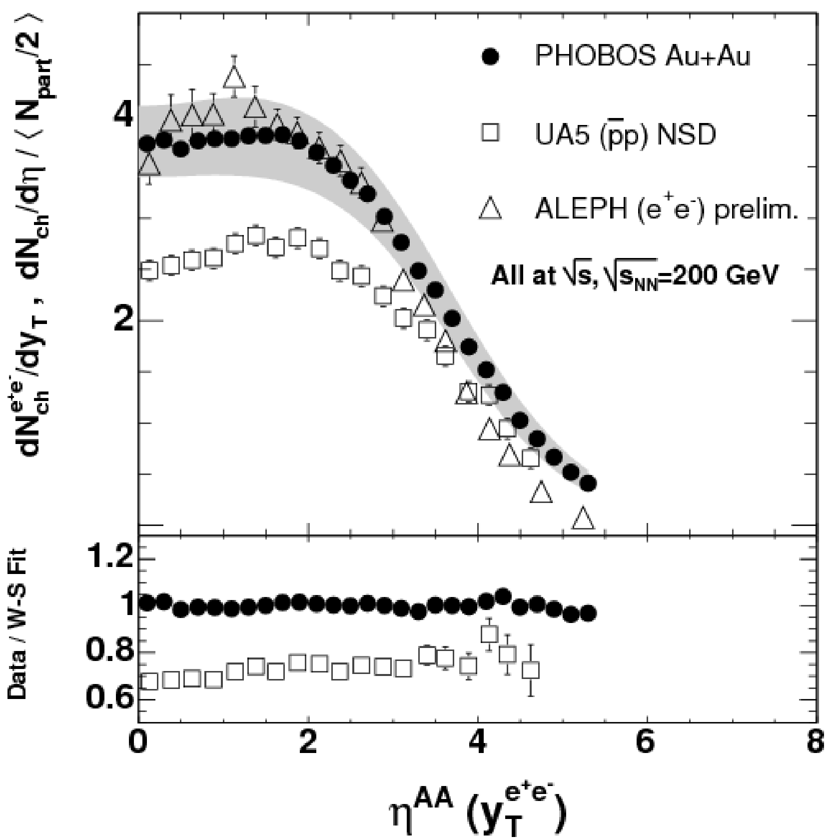
  - So in the picture you have good KNO scaling in similar rapidity regions but not so good in the central region

A microscopic picture of minimal particle production

For proton-proton collision

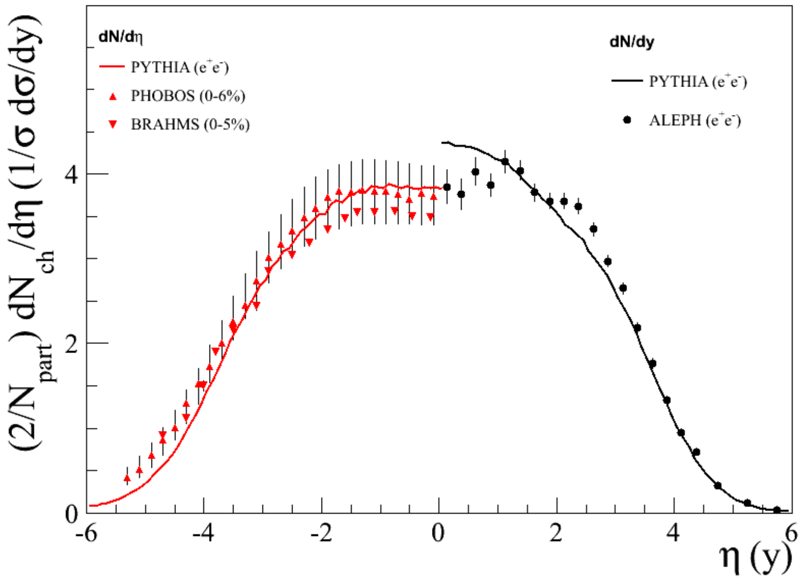
- Minimal amount of energy and colour that can be exchanged is a single soft gluon
  - Will treat this as a colour and an anti-colour
- Idea: collision produces two domains of target proton that
  - share its total momentum
  - are coupled to domains in the projectile proton via longitudinal colour fields (Lund like strings)
- Lund strings produce particles flat in rapidity between rapidity of end points
  - Minimize string length: let one domain have almost all energy (y~yBeam) and the other almost nothing (y~0) -> Effectively we get one long string between the two yBeams
  - But the domains are strongly interacting so they can radiate
    - How much do they radiate?

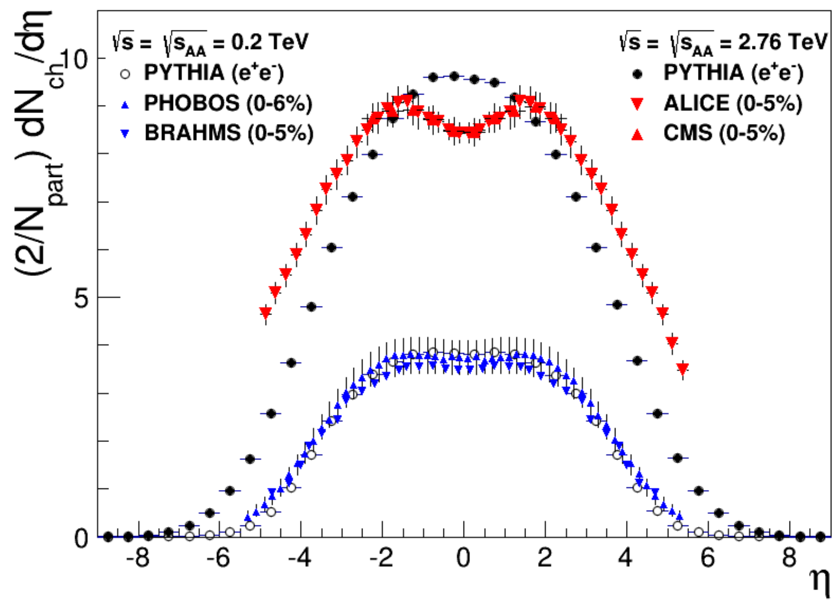
How much do they radiate? Use analogy with $e^+e^- \to q\bar{q}$



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

PYTHIA vs AA at LHC: dN/dη

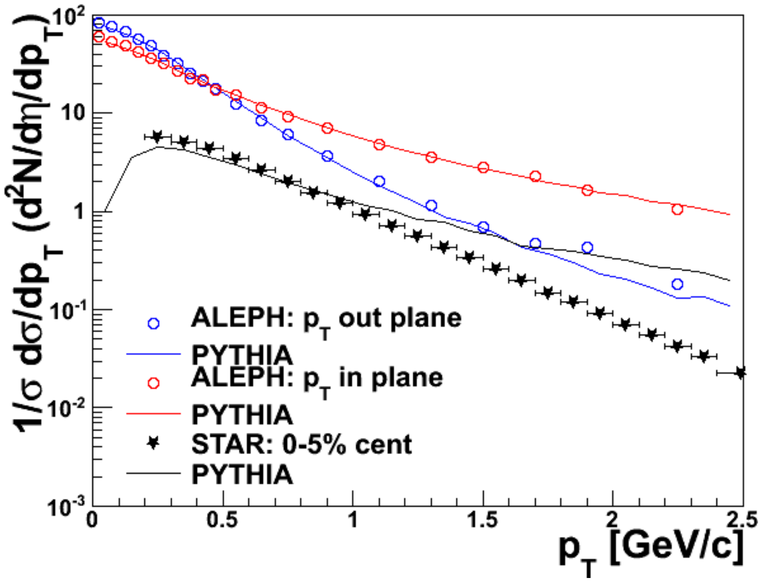


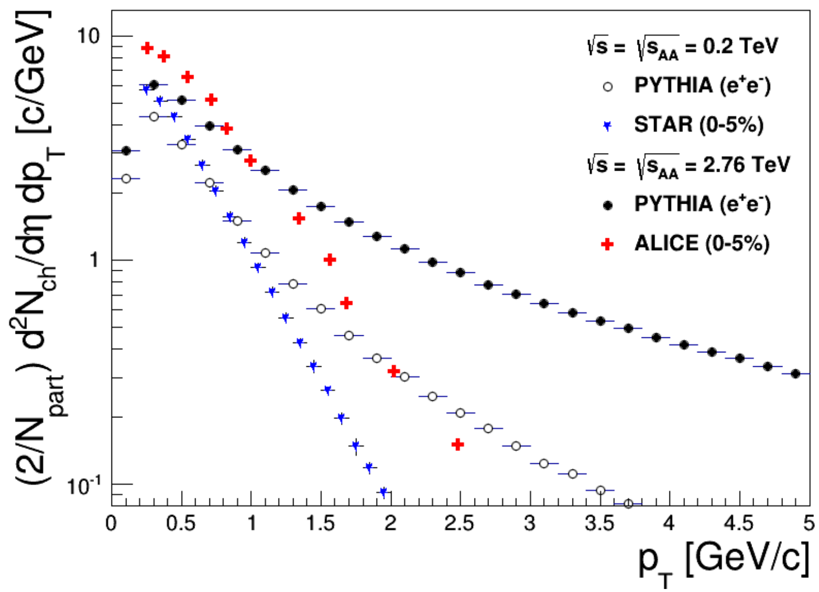


- Left: PYTHIA ee vs experimental data for RHIC energies
- Right: PYTHIA ee vs experimental data for LHC

- Note here that p_T is different (next slide) implying maybe that agreement depends on if one uses rapidity or η

PYTHIA vs AA at LHC: dN/dp_T





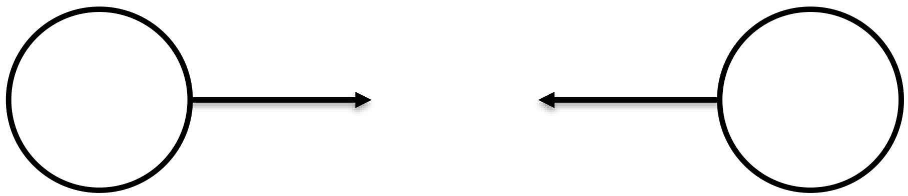
- Left: PYTHIA ee vs experimental p_T spectra at RHIC
- Right: PYTHIA ee vs p_T spectra at LHC
- In both cases the origin of the discrepancy is well understood since for pp/AA the p_T goes via large momentum transfer while for ee it goes via radiation

Is the large p_T radiation a problem here?

- I don't think so
- Because the domain that carries all the proton energy must be large (of order 1 fm) so it can only radiate coherently for p_T up to a few hundred MeV
  - So the radiation will mainly be colinear

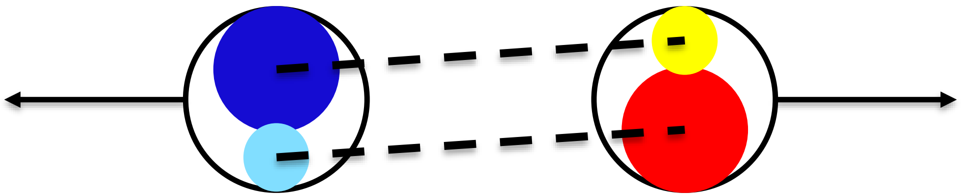
Sketch of pp model

Before:

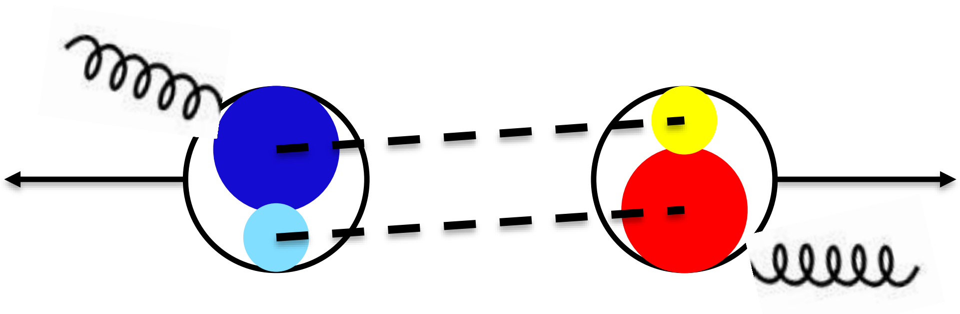


After:

Big circle contains almost all proton energy



Does not have to be “big to small”. Could also be “big to big”.

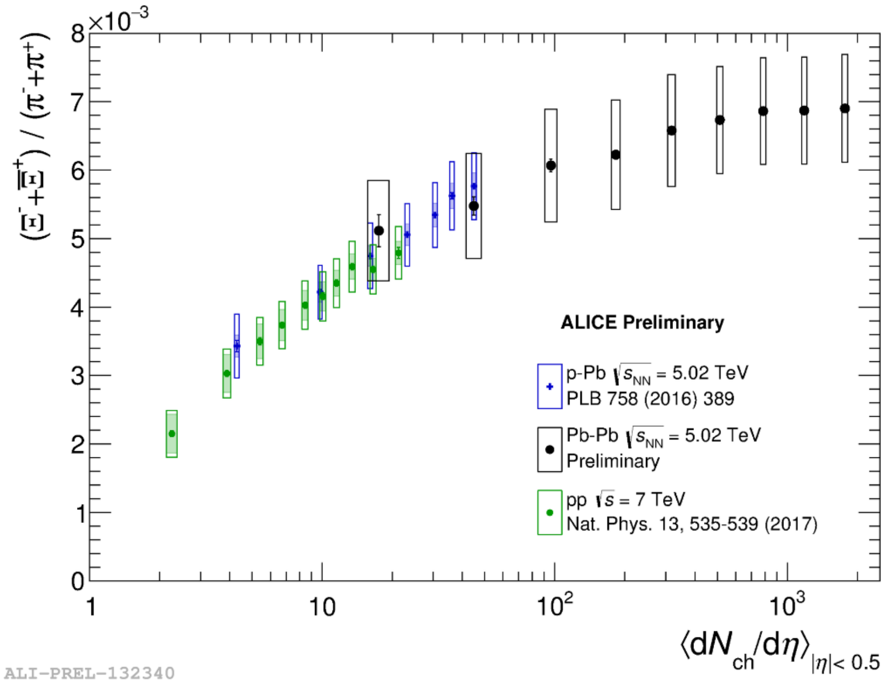


Completely different from CGC picture because here low x gluons are completely uninteresting for bulk production

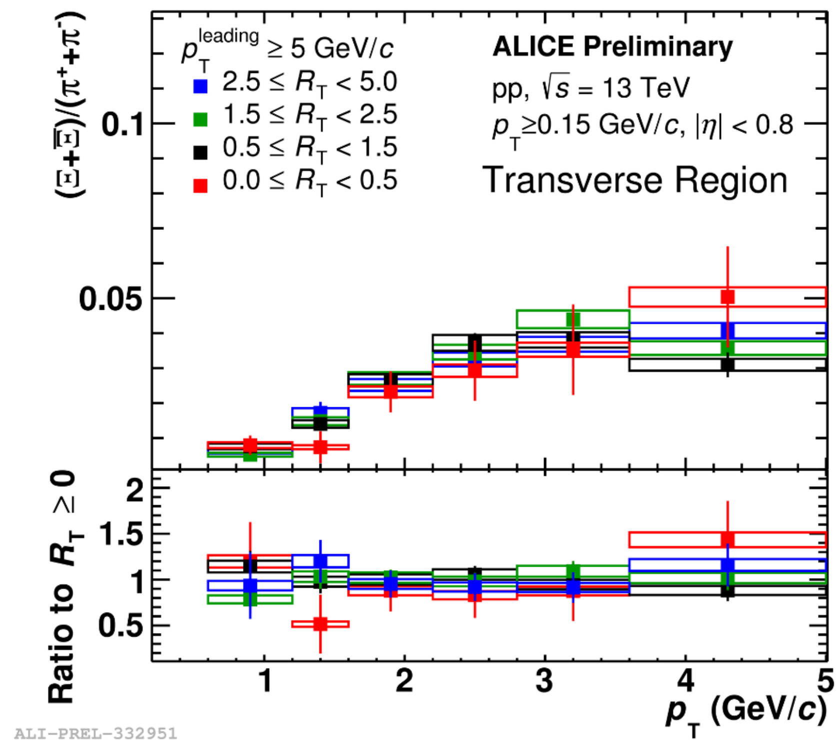
Should be able to falsify by comparing to MPI models. Maybe test factorization?

Evidence that forward multiplicity drives strangeness enhancement

Slicing in forward multiplicity: big effect



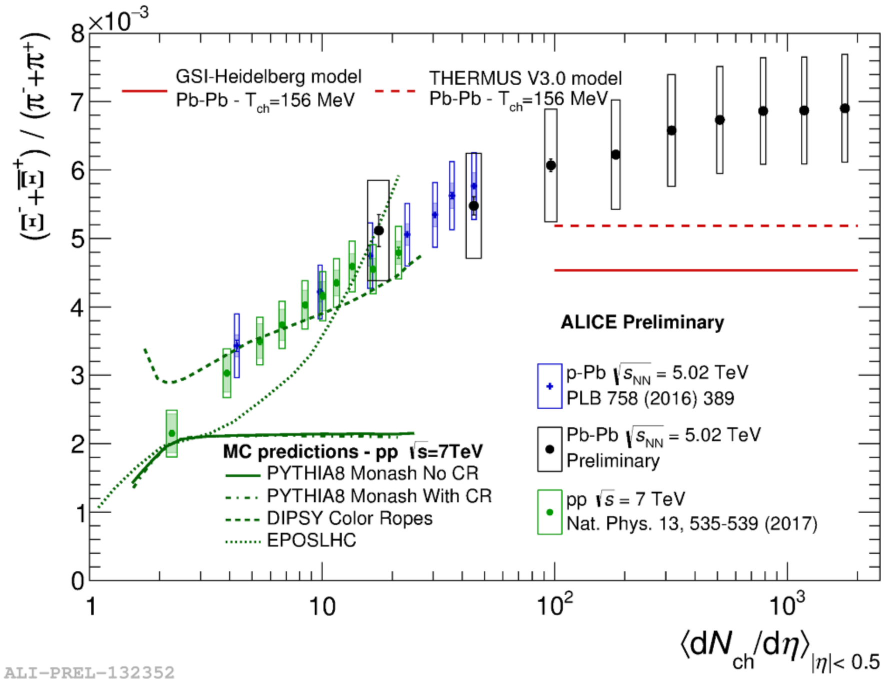
Requiring trigger and slicing in UE activity (mid-rapidity): Little or no effect



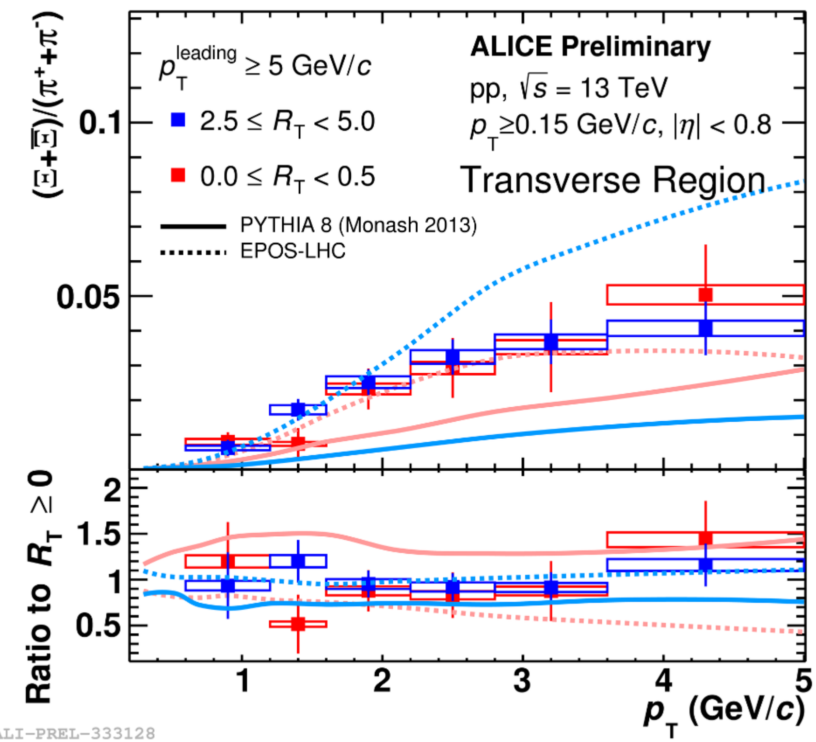
Some evidence that forward multiplicity is driving.

Evidence that forward multiplicity drives strangeness enhancement

Slicing in forward multiplicity: big effect



Requiring trigger and slicing in UE activity (mid-rapidity): Little or no effect



Some evidence that forward multiplicity is driving.

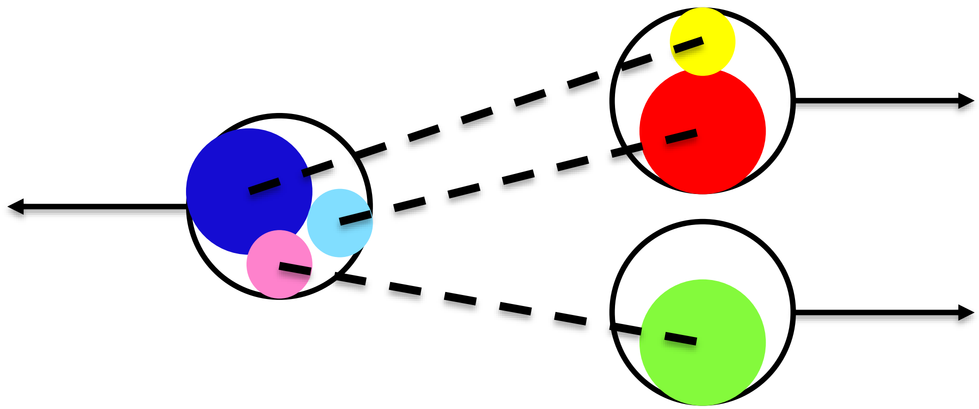
Not expected in models such as EPOS.

We can improve statistics and slice in forward multiplicity also.

Perfect QCD (P. Christiansen, Lund)

What happens when we go to p-Pb

- 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 to BGK triangle

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

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 δ ~ 2 x LHC δ

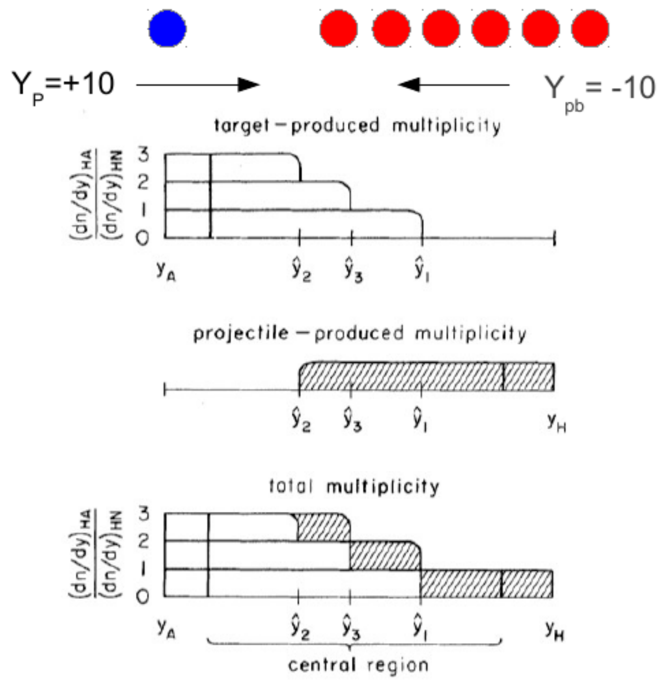
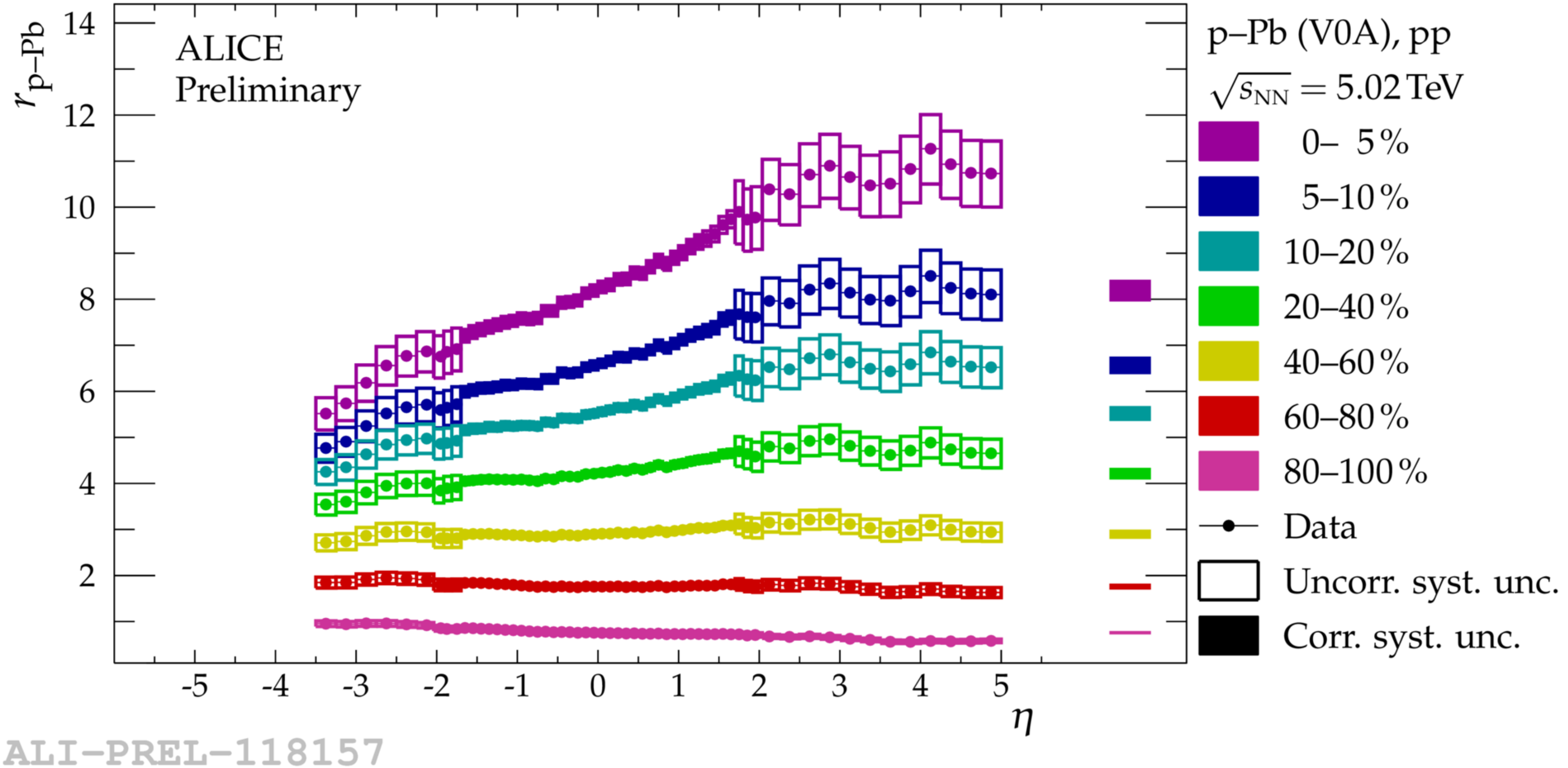


Figure from Brodsky, Gunion, Kuhn 1977

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

M Gyulassy MIT 5/17/13 6

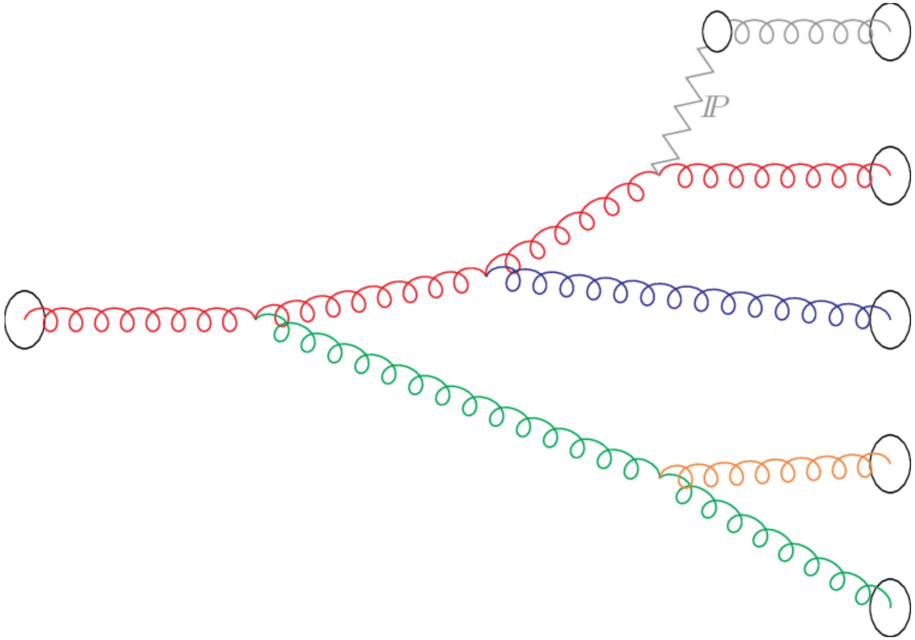
dN/dη in p-Pb collisions relative to pp collisions



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

For more details:
http://indico.cern.ch/event/433345/contributions/2358417/

But in fact also similar to Angantyr



- And 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

Summary and outlook

- Spent a lot of time trying to motivate why I think we need a new model/approach to QGP
- Have outlined a new idea "Perfect QCD" model and tried to show how one can understand experimental results differently in such a picture
  - Have also tried to give a microscopic picture of how a model could
- Did not talk a lot about how to falsify this idea
  - More discussion in the paper I am writing (if interested I can share it)
- Have also some ideas for jet quenching and screening (future)