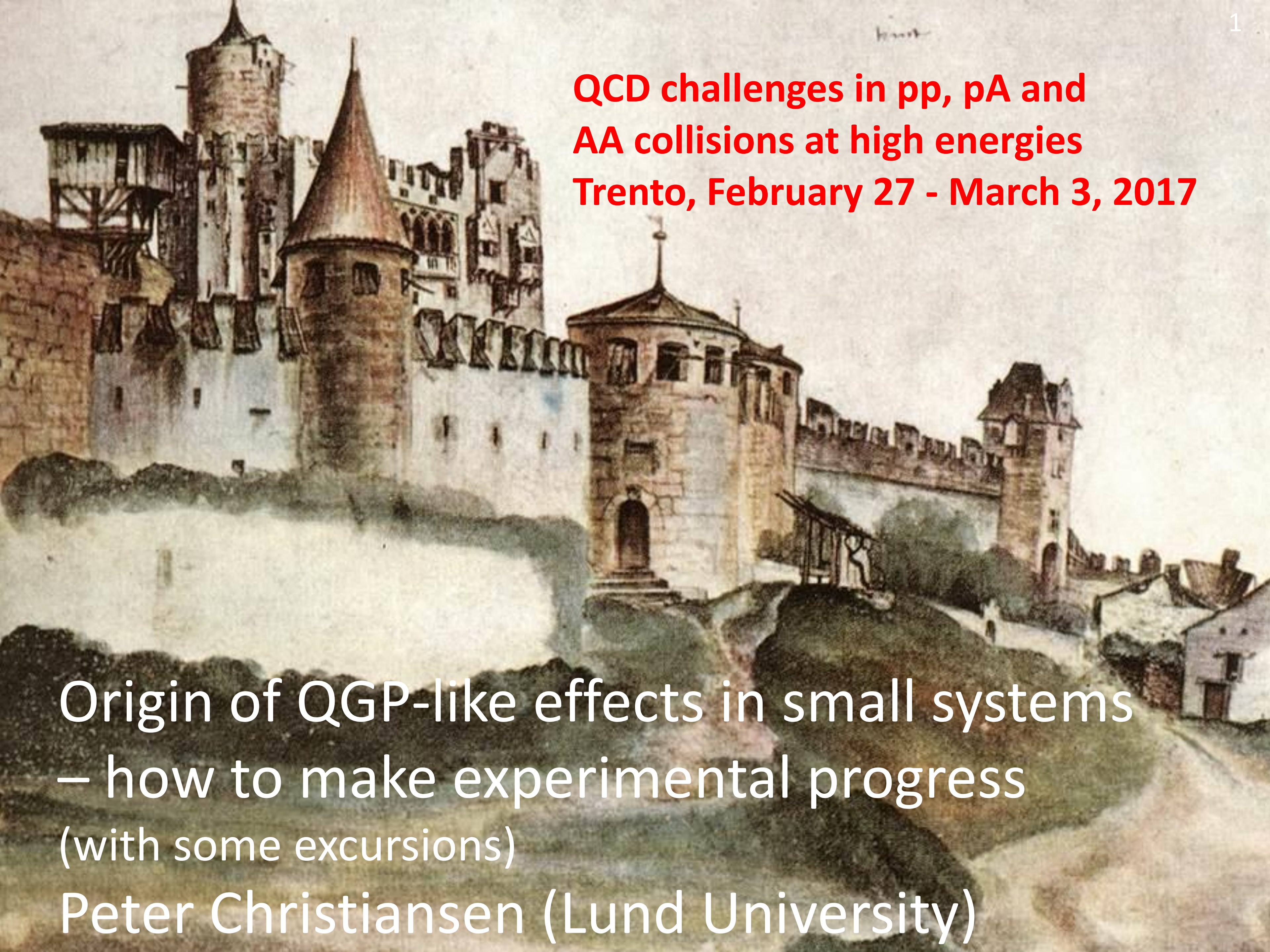


QCD challenges in pp, pA and AA collisions at high energies
Trento, February 27 - March 3, 2017

Origin of QGP-like effects in small systems – how to make experimental progress

(with some excursions)

Peter Christiansen (Lund University)

Outline

- How do we validate or falsify incomplete models
  - CGC model vs CGC picture
- Microscopic vs macroscopic interpretations of small systems
  - The special role of the ϕ meson
  - Separating pp collisions/production into soft and hard components
- Why is QGP in small systems interesting

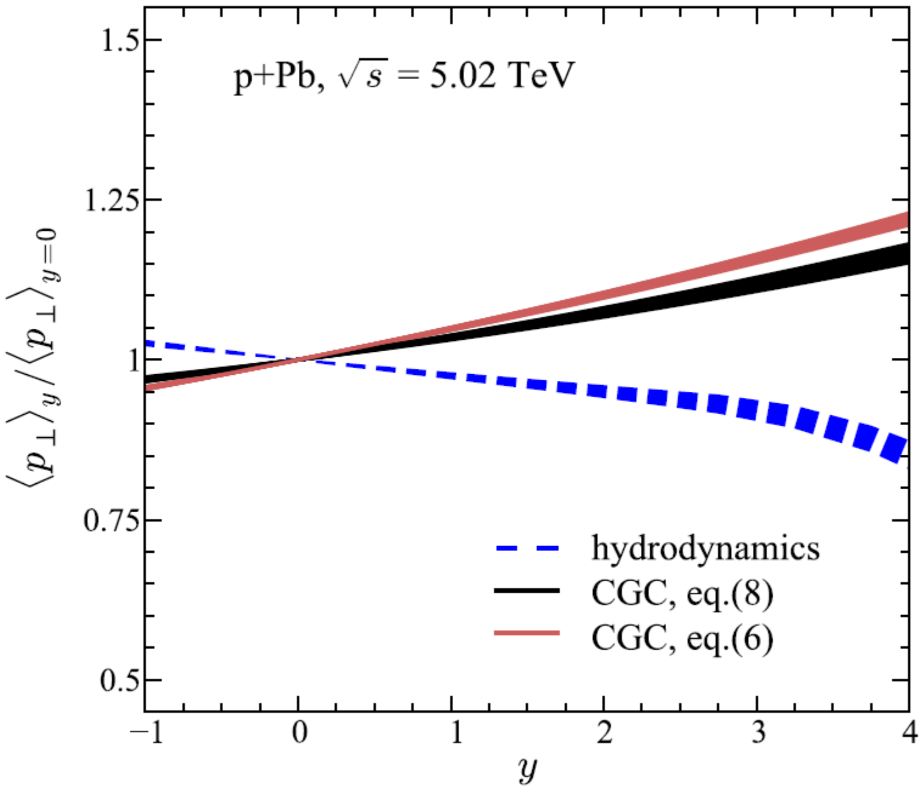
HOW DO WE VALIDATE OR FALSIFY INCOMPLETE MODELS

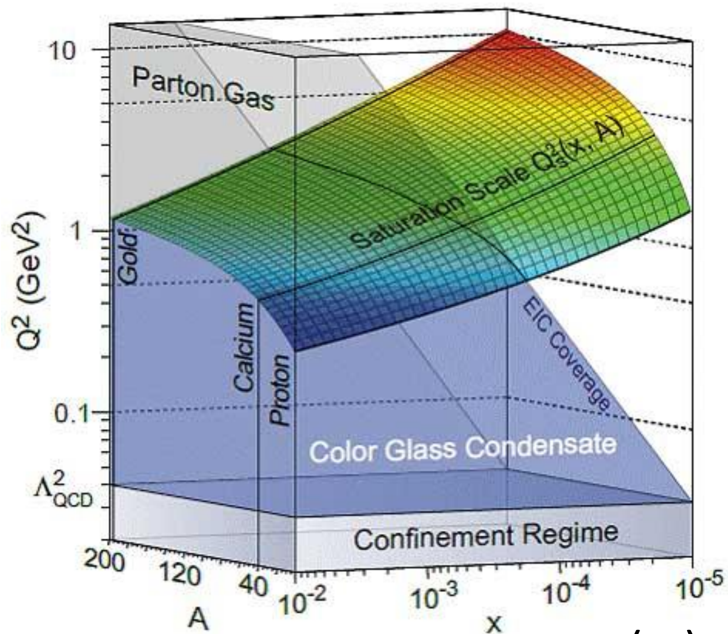
The challenge

- In the end the quest for origin of QGP-like effects in small systems is about validation and falsification of models
- Fundamental caveat: models are incomplete
  - Missing physics, approximations, LO and tuning
- Idea of this talk: to falsify models we need to focus on their principles rather than their predictions (and be lucky)

CGC early predictions for p-Pb

Phys. Lett. B 728, 662 (2014)





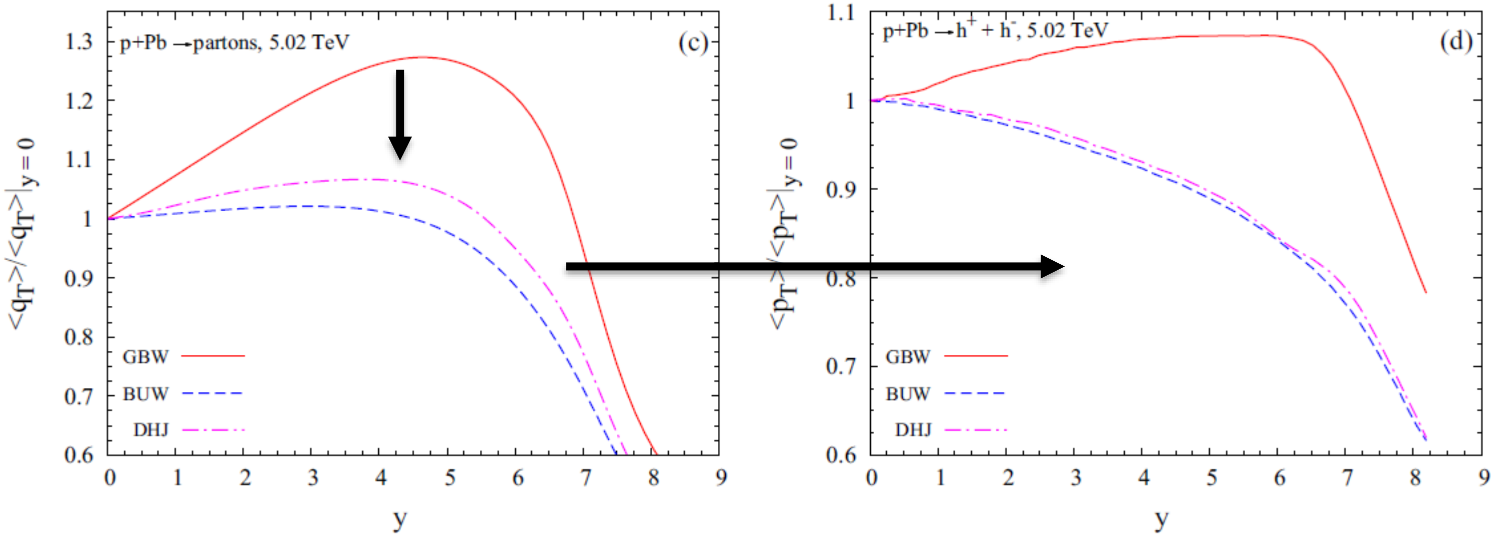
~exp(-y)

Spectacular prediction:
The proton scatters of the Pb CGC while for hydro $\langle p_T \rangle$ follows the "energy density".

CGC refined predictions for p-Pb

Phys. Rev. C 94, 024917 (2016)

Partons **Hadrons**



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 behavior similar to that predicted by hydrodynamical calculations.”

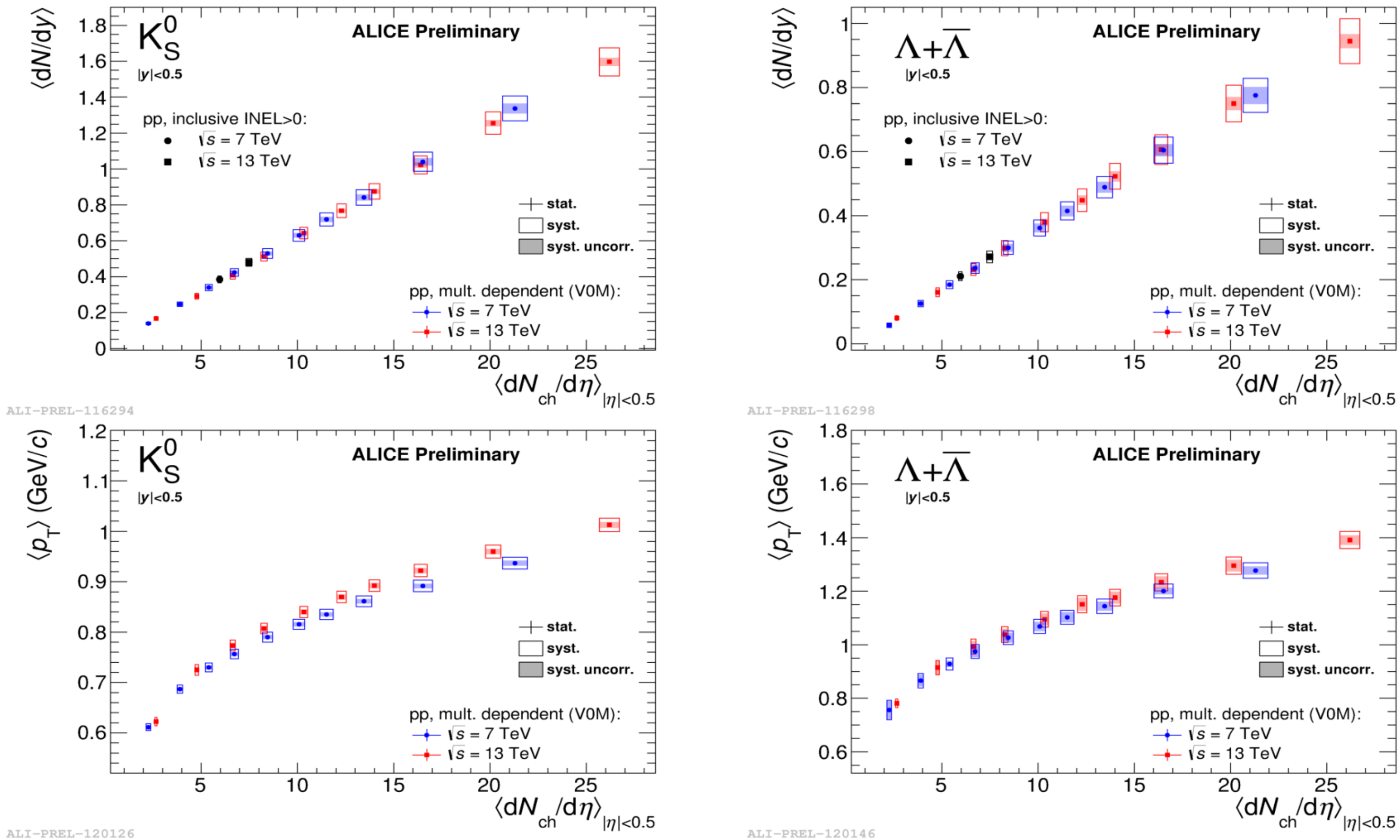
Maybe we can rephrase the question

- 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

Recent results from ALICE

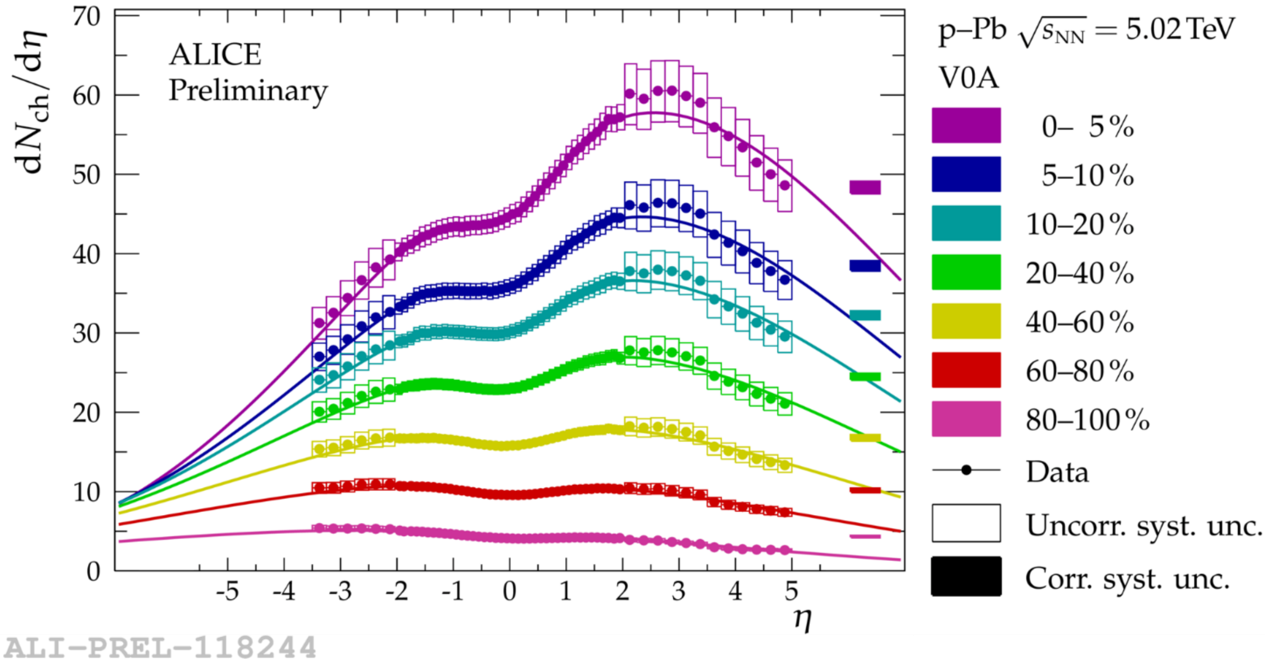
https://indico.cern.ch/event/433345/contributions/2358616/



A new approach to understand the energy dependence of particle production that will benefit from more particle species & energies and predictions.

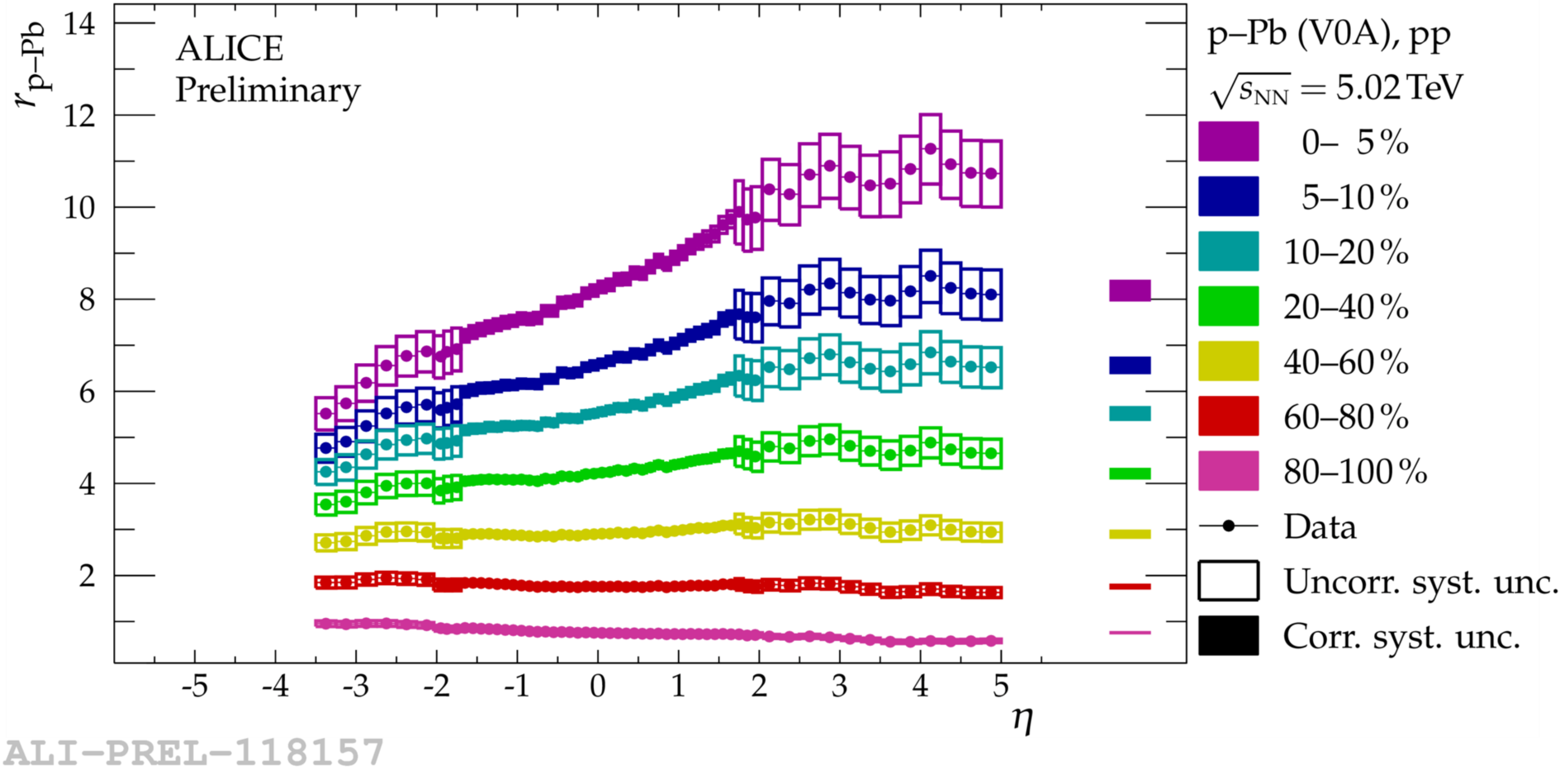
dN/dη in p-Pb collisions

(probing the nuclei at different impact parameters)



- ALICE has pointed out that there is a fundamental caveat in centrality determination in p-Pb collisions due to particle production fluctuations
  - **My interpretation: one needs a full model simulation of the multiplicity selection to compare with experimental results**
- In the following I will show you a very basic model that I have made to test if there are saturation effects.

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



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

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

Origin of the 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

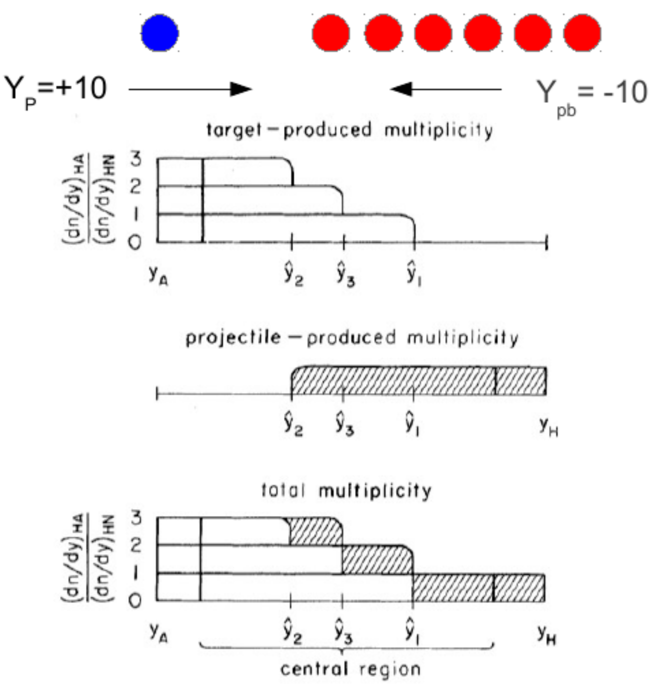


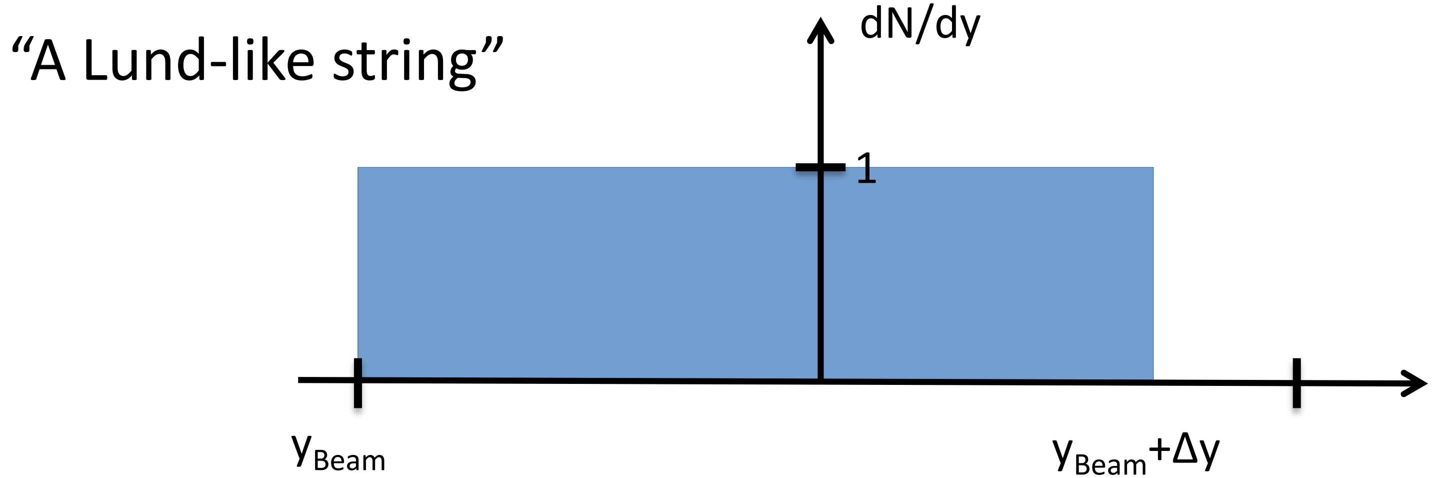
Figure from Brodsky, Gunion, Kuhn 1977

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

M Gyulassy MIT 5/17/13 6

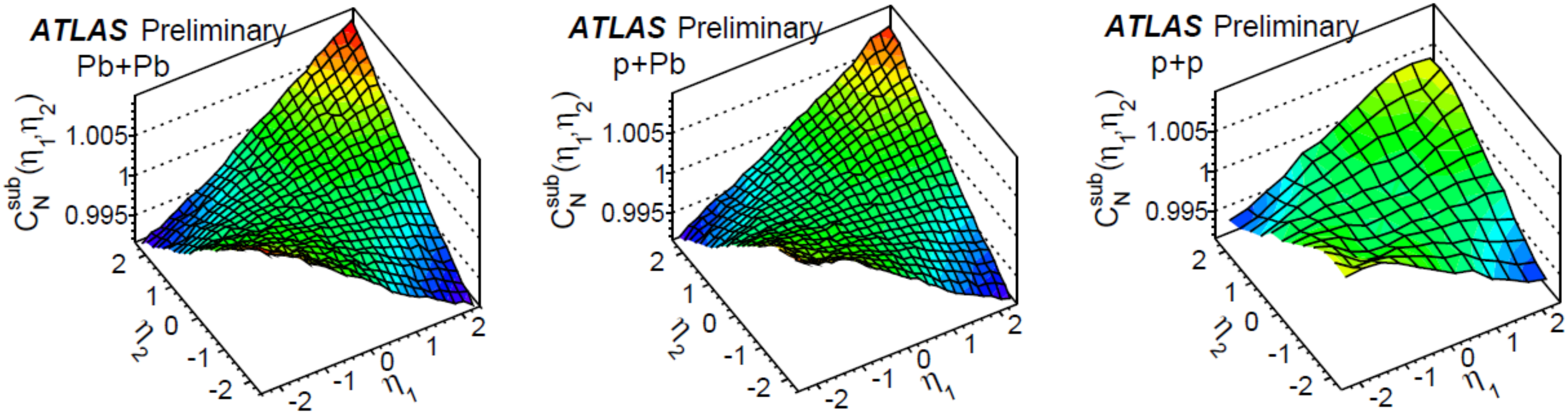
I want to construct simple models based on this idea that particle production factorizes into a sum of "triangles"!

Particle production from a single nucleon (at mid-rapidity)



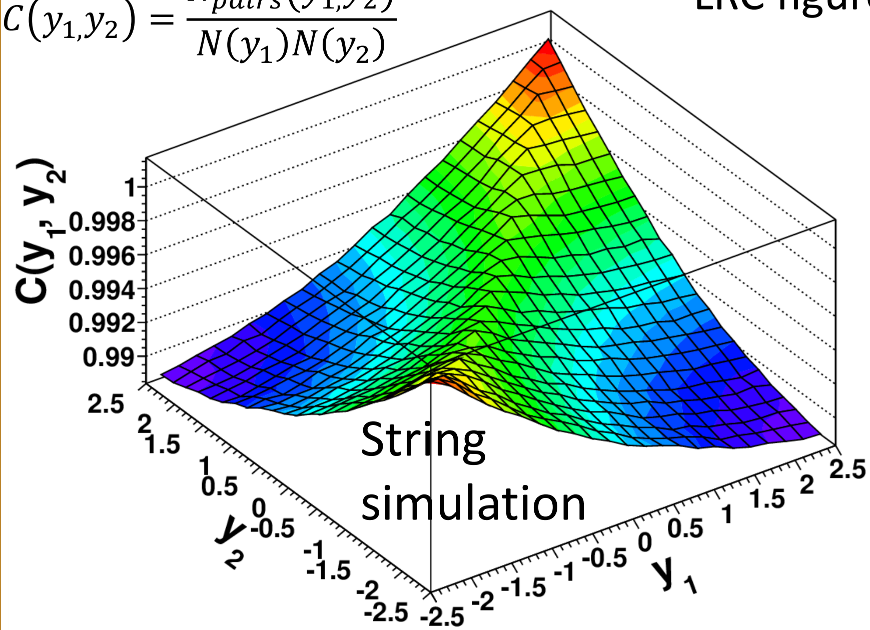
- Inspired by BGK triangle
  - Start: y_{Beam}, Stop: flat in rapidity: $P(\Delta y)=1/(2y_{Beam})$
  - Each string produces on average <Nch>= Δy particles (random in y) – Nch is taken from Poisson distribution
    - Particles are randomly distributed in rapidity

Simulation of long range correlations for $100 \leq N_{ch} < 120$



LRC figures from ATLAS-CONF-2015-051

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



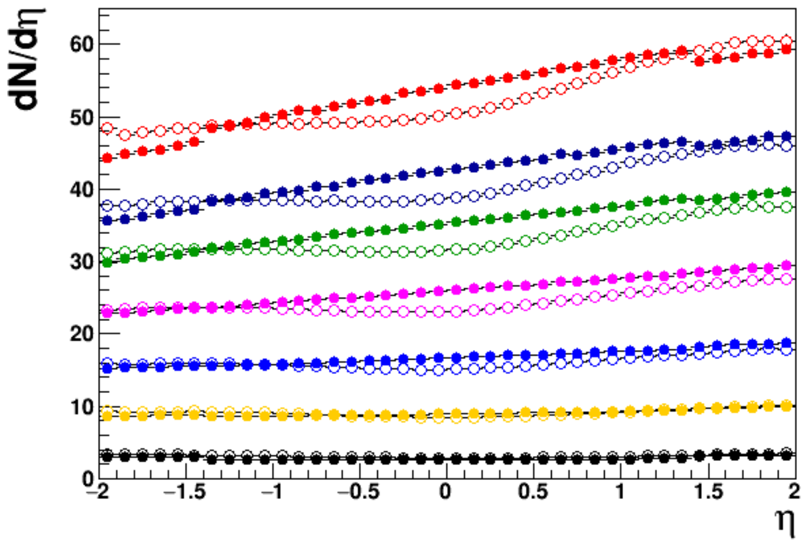
The simple string simulation reproduces both the saddle point shape (via the two “triangles”) and the relative magnitude of the dynamic fluctuations (via the multiplicity per string)

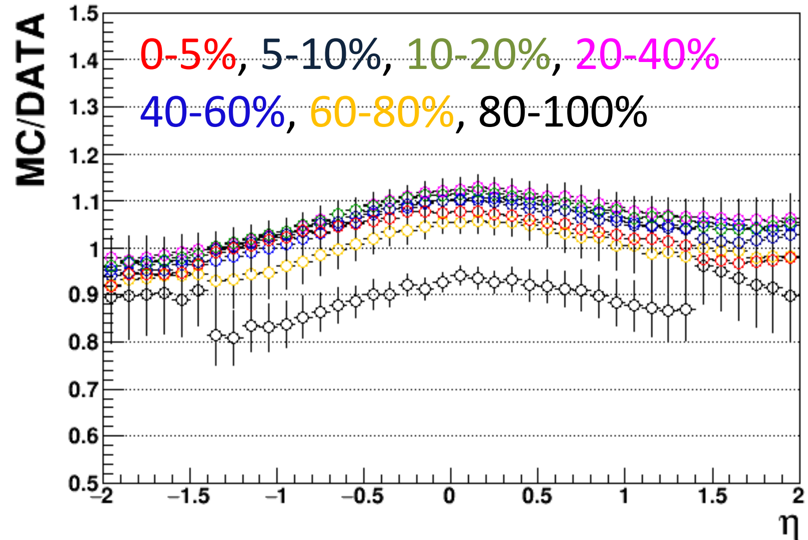
Extend string model to p-Pb collisions

- Select N_{part} from Glauber INEL calculation
  - N_{part} p = 1, N_{part} Pb = $N_{part} - 1$
- <Nstrings> (per N_{part}) is fixed by dN/dη (ALICE)
  - <Nstrings> = 2* dN/dη (MB) / <N_{part}> (MB) = 4.28
- Fluctuations of Nstrings are modelled via NBD matched to pp data
- Each string is boosted from CM to LAB frame
- The goal was to restrict parameters to avoid tuning
  - Essentially only one choice: proton is assigned Nstrings as largest Pb participant (the proton can get more "wounded")

Comparison with dN/dη in p-Pb collisions

Mult estiator: |η|<1.4 Data from ALICE: Phys. Rev C 91 (2015) 064905

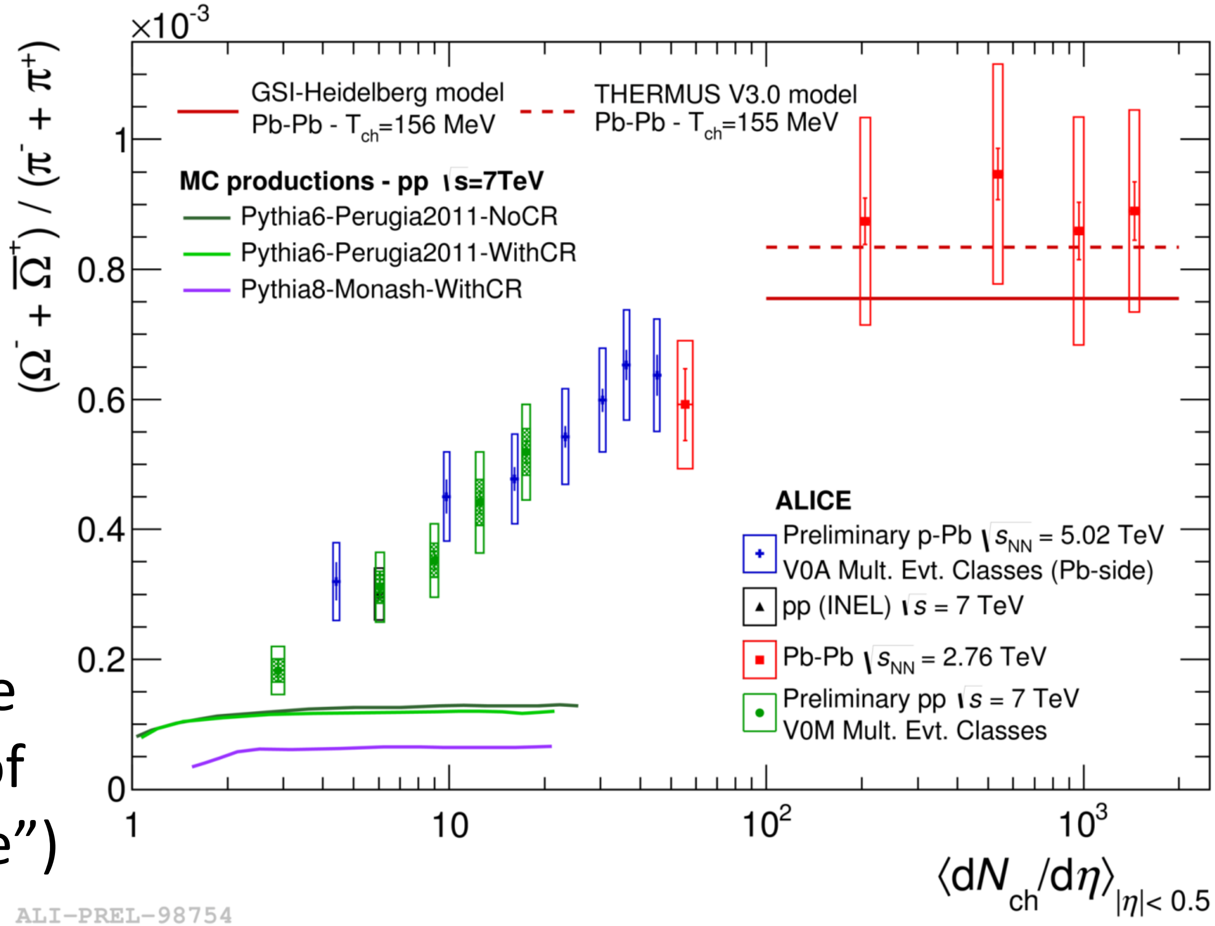




- The string model only works well at mid-rapidity so I use that multiplicity estimator
- It describes the data within ~10% suggesting that saturation effects for dN/dη are small
- For more details, see: https://indico.cern.ch/event/487649/timetable/#18-ideas-for-a-data-driven-mod

MICROSCOPIC VS MACROSCOPIC INTERPRETATIONS OF SMALL SYSTEMS

pp phenomenologists' favorite figure from ICHEP 2016



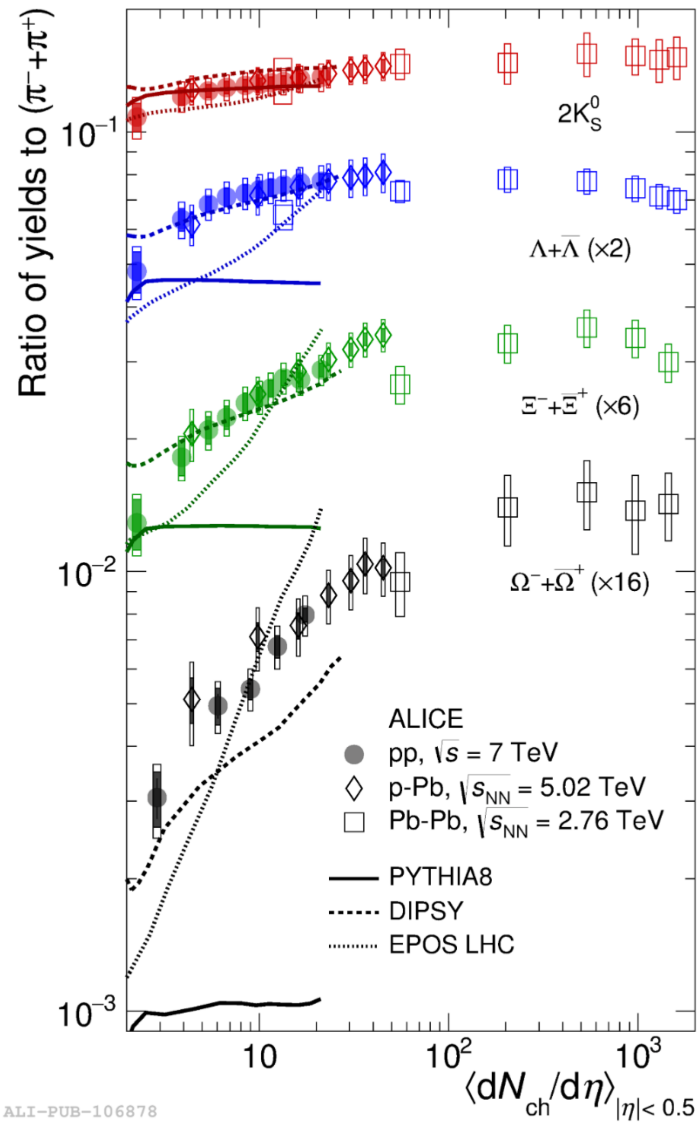
Thermal medium?

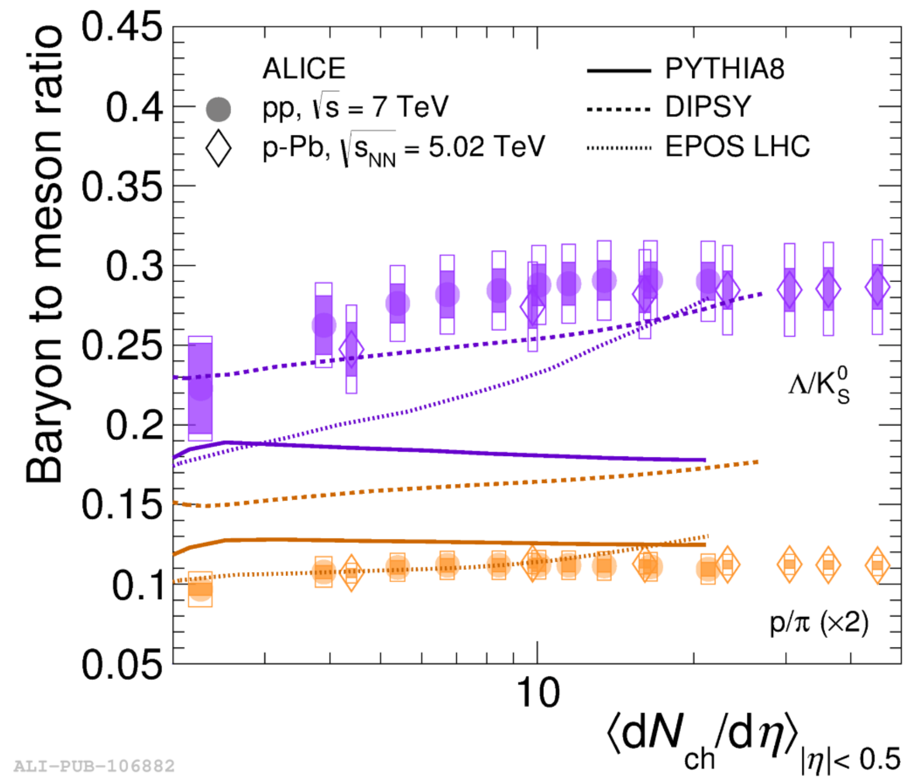
e^{+}+e^{-}like ("more of the same")

Are we observing the onset of thermalization in small systems?
(A mix of jetty and soft effects?)

Integrated particle ratios

arXiv:1606.07424

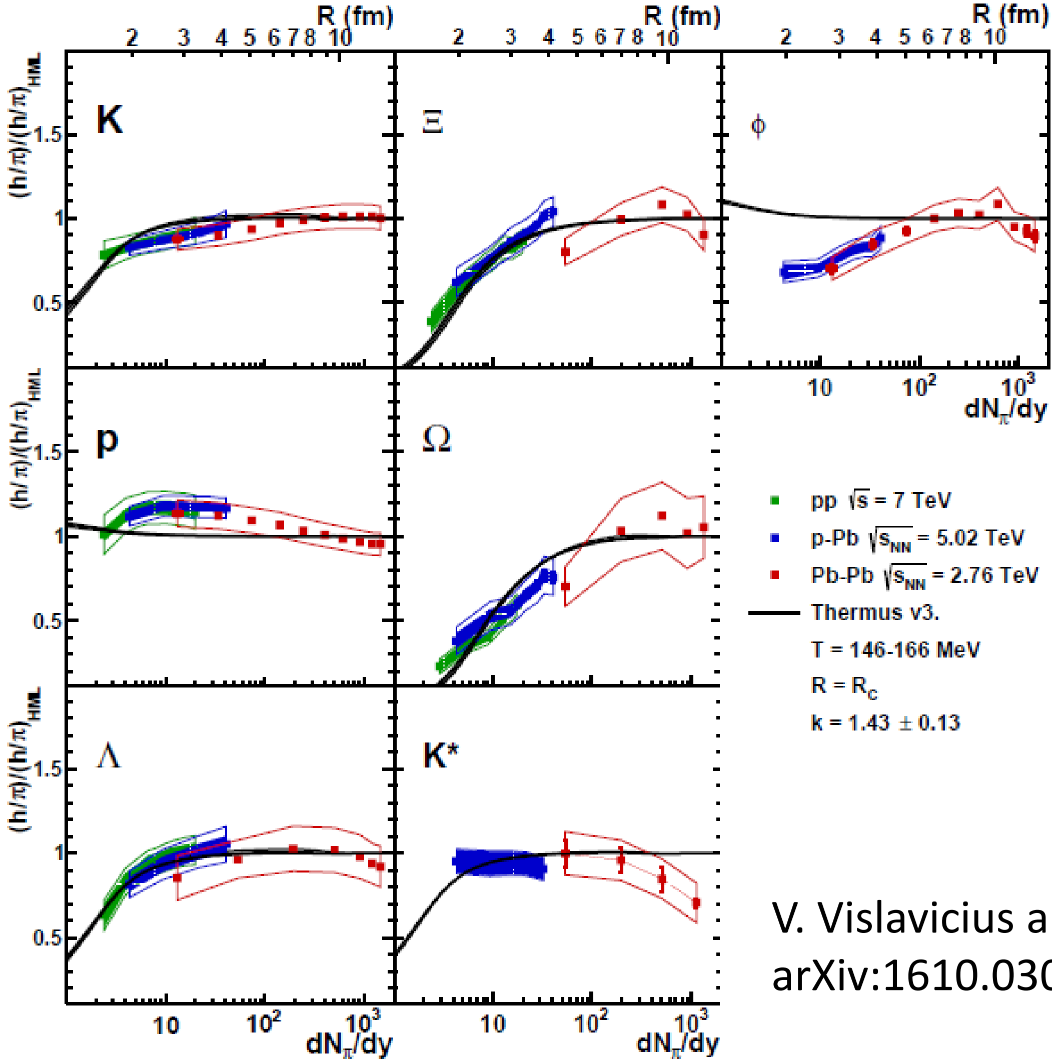




New DIPSY Color Reconnection model:
C. Bierlich, G. Gustafson, L. Lönnblad, A. Tarasov (Jefferson Lab), JHEP 1503 (2015) 148

Nice summary of new CR models: C. Bierlich, J. R. Christiansen, Phys.Rev. D92 (2015), 094010

Statistical thermal models also do well



Multiplicity dependence is well described by the canonical suppression of strangeness in small systems

V. Vislavicius and A. Kalweit arXiv:1610.03001

Dictionary: macro-micro

- Stat. thermal model
  - Canonical
  - Grand-canonical
- Hydrodynamics
  - Radial flow
  - Azimuthal asymmetric

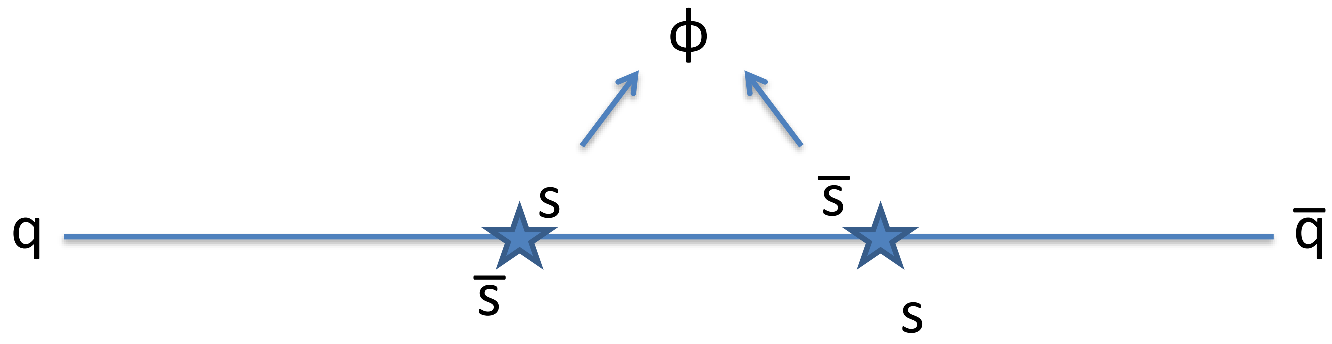
- Tunnelling of $q\bar{q}$-pairs
  - Strings
  - Ropes (Bierlich talk)
- String interactions
  - Colour reconnection
  - Shoving (Bierlich talk)

Macro vs micro: possible outcomes

- Microscopic models can be extended to bridge the gap between small and large systems
  - This is the most likely outcome but also the least interesting....
- Microscopic models cannot reproduce soft effects in pp collisions
  - We need to add new physics to many pp models
- Microscopic models can reproduce effects in pp, p-Pb and Pb-Pb collisions
  - Do we need the QGP then?

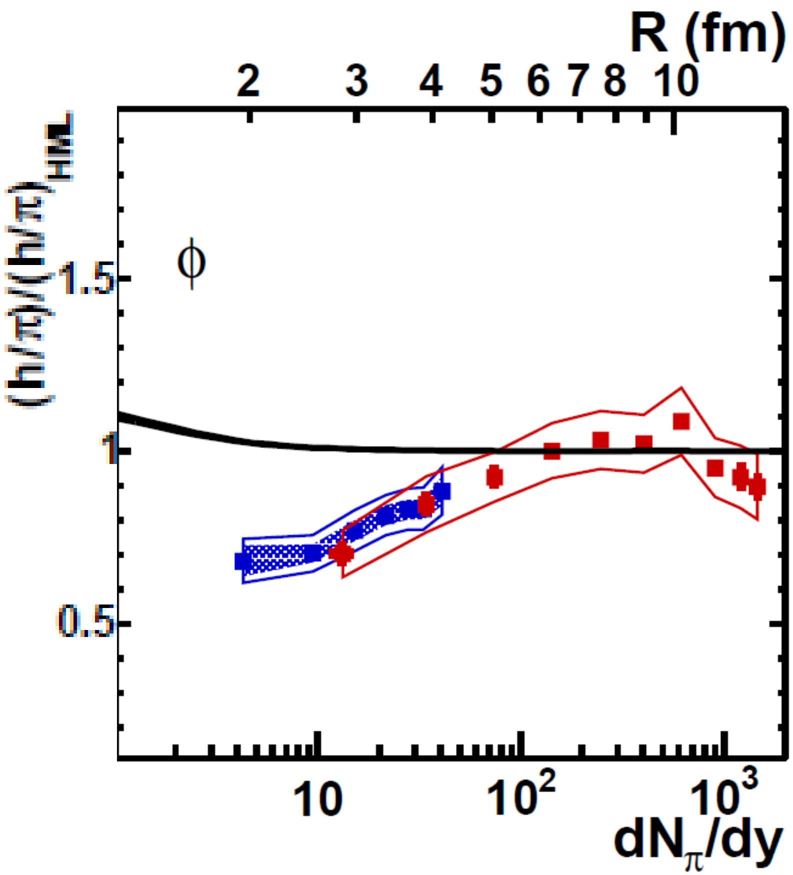
– My point of view: This lack in our understanding of fundamental QCD physics must be addressed

ϕ is doubly suppressed in string models



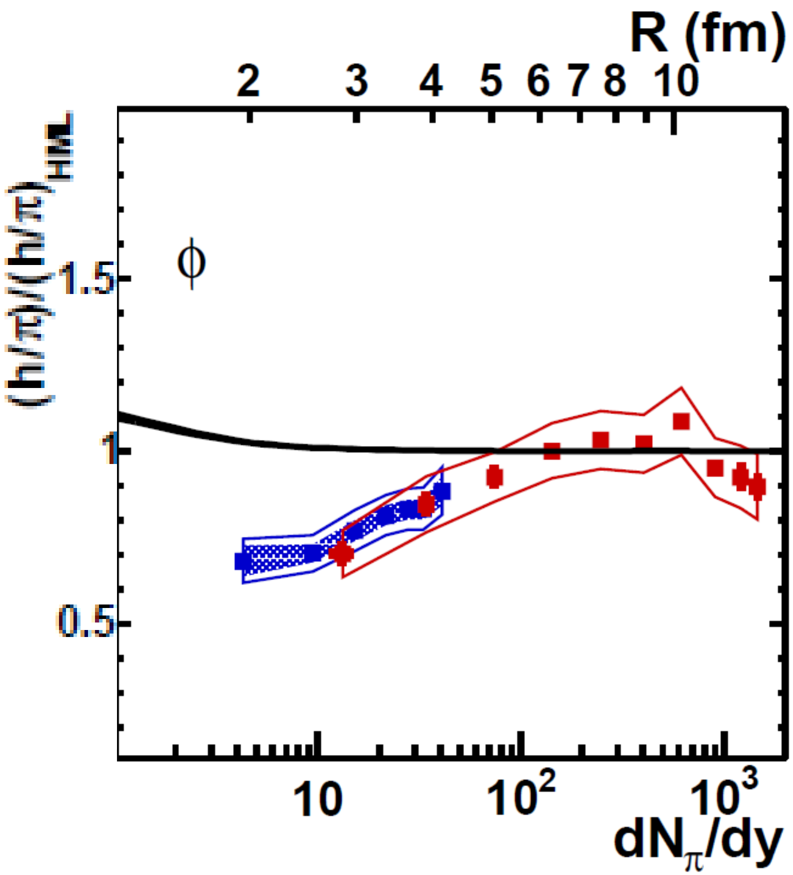
- String model: Requires 2 string breakings to make a ϕ
  - Enhanced with activity in a rope model!
- Statistical thermal model: no open strangeness
  - No canonical suppression (should follow proton)

Naïve behavior is more as expected from stronger color field



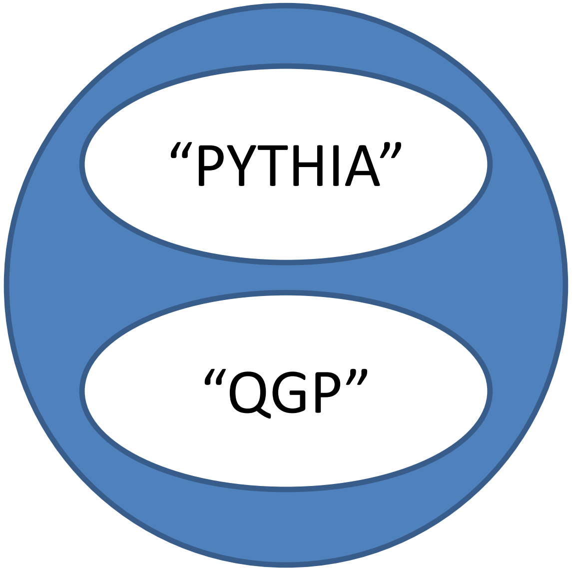
So it seems that these results would favour a model where the ϕ production grows with multiplicity, e.g., strings → ropes

Naïve behavior is more as expected from stronger color field



But there could also be another answer:

pp physics could have 2 components

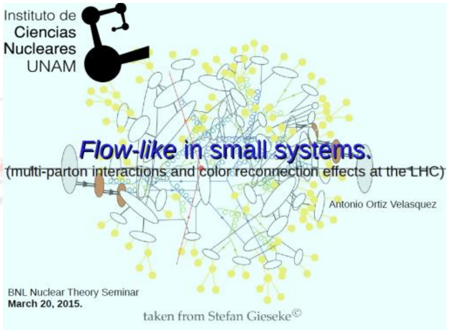


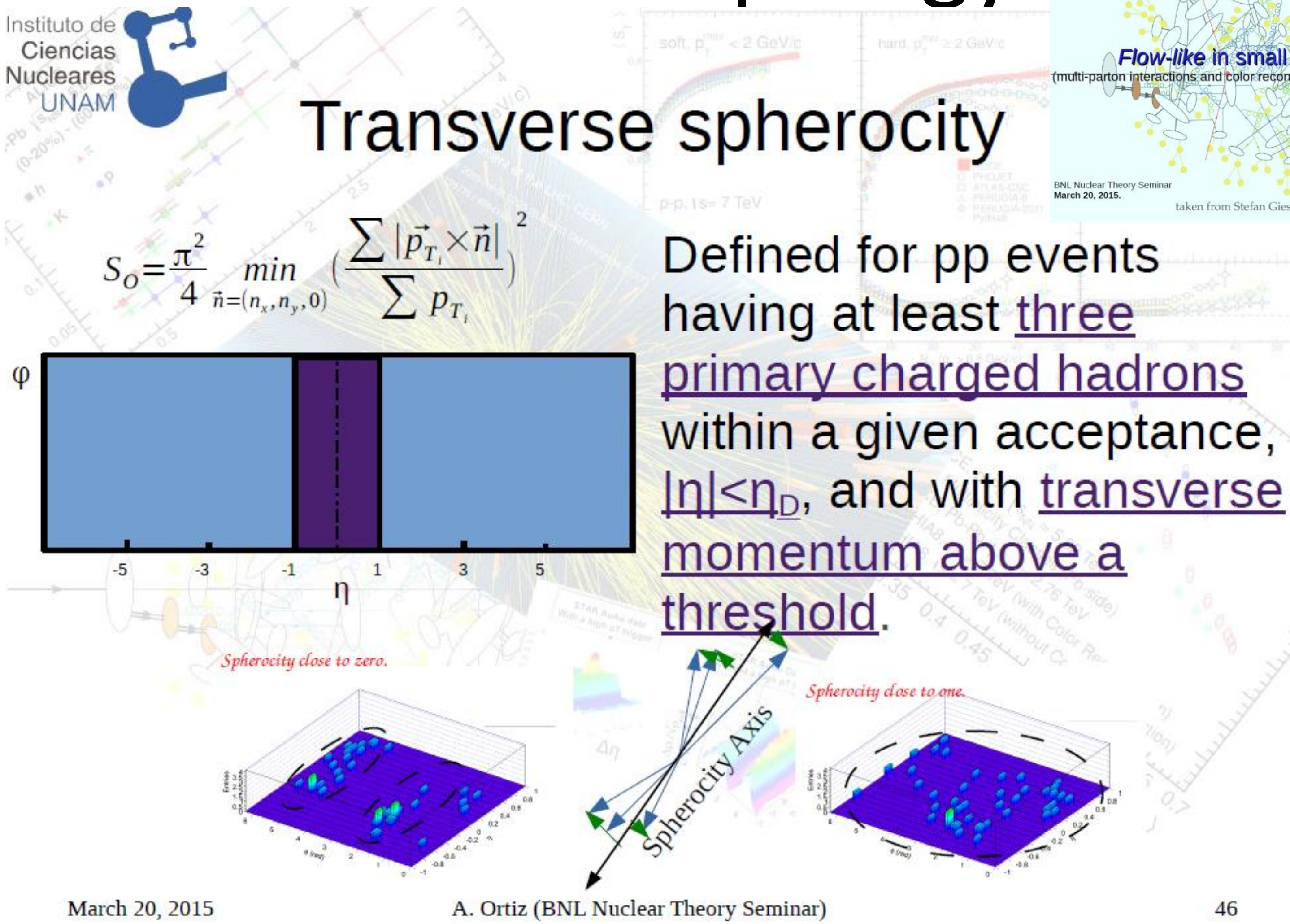
Hard e^+e^- like / jetty

Soft isotropic

Can we separate those?

Event topology

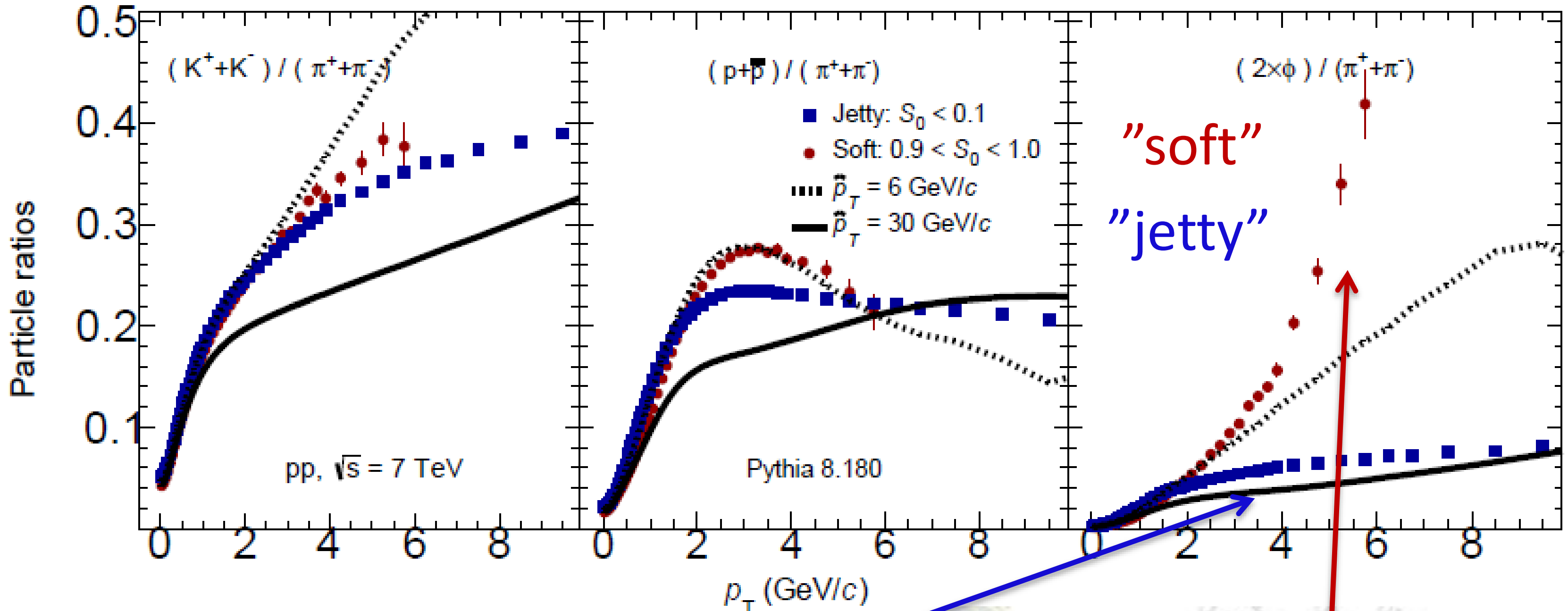


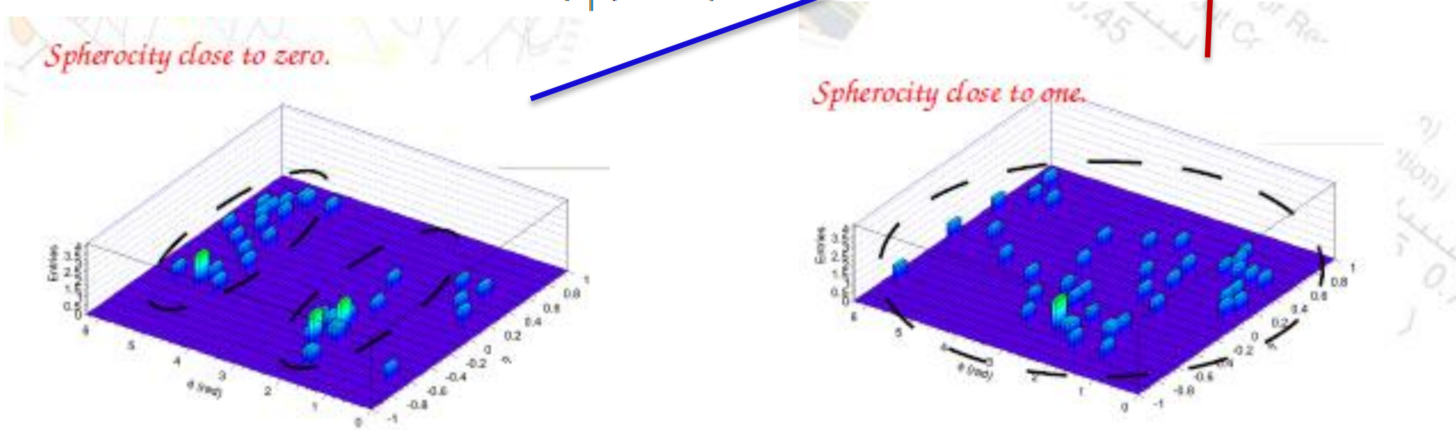


"Disentangling the soft and hard components of the pp collisions using the sphero(i)city approach", E. Cuautle Flores, R. T. Jimenez Bustamante, I. A. Maldonado Cervantes, A. Ortiz Velasquez, G. Paic and E. Perez Lezama, arXiv:1404.2372

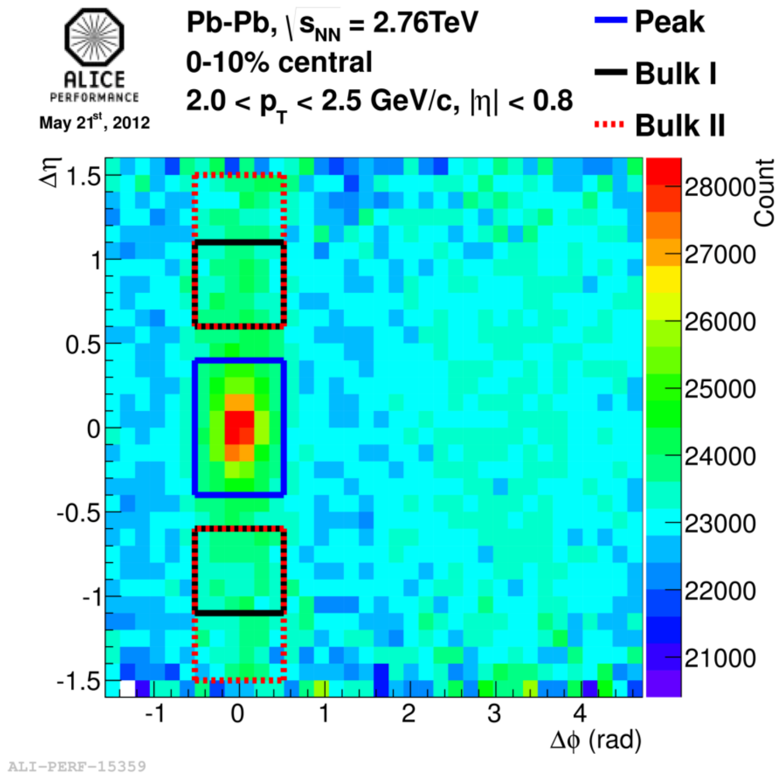
Particle ratios in PYTHIA

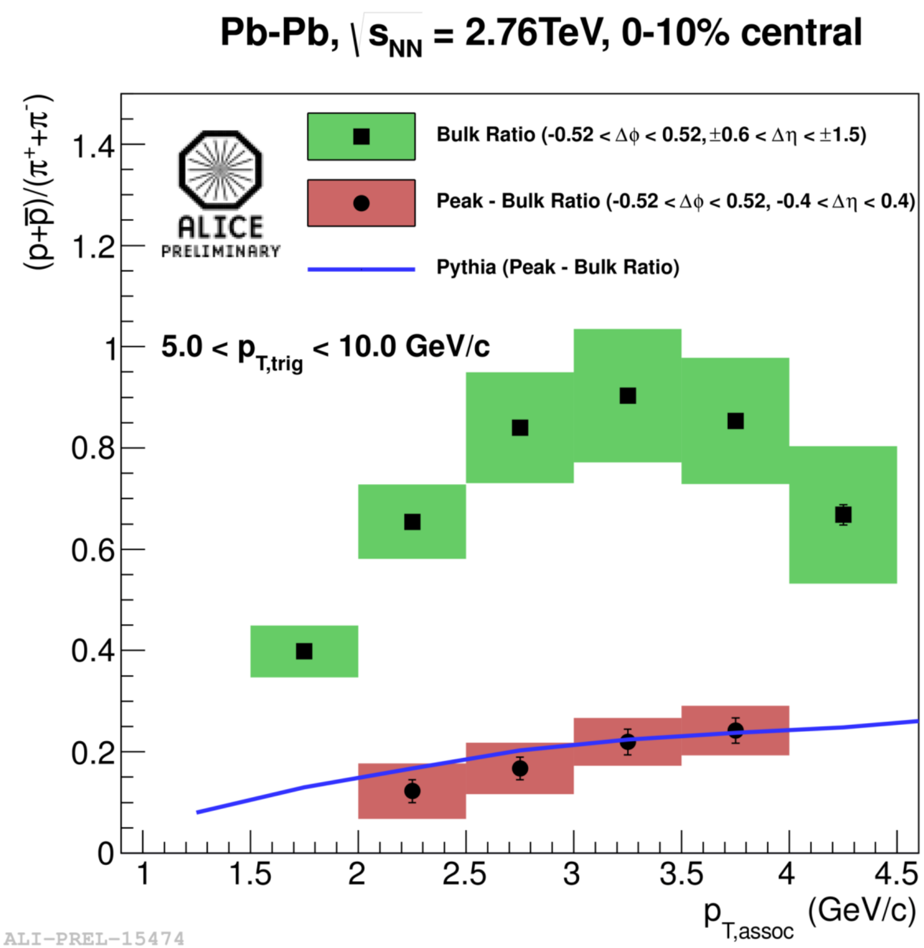
arXiv:1404.2372



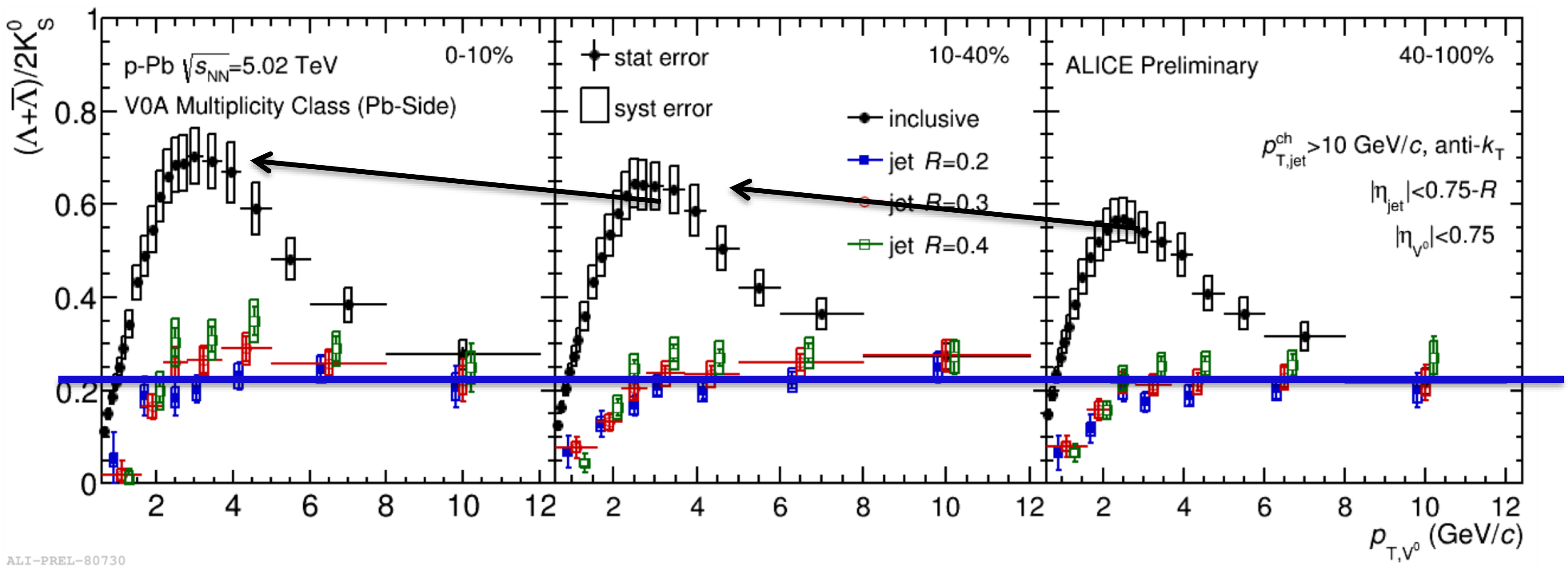


Alternative way to separate soft and hard physics



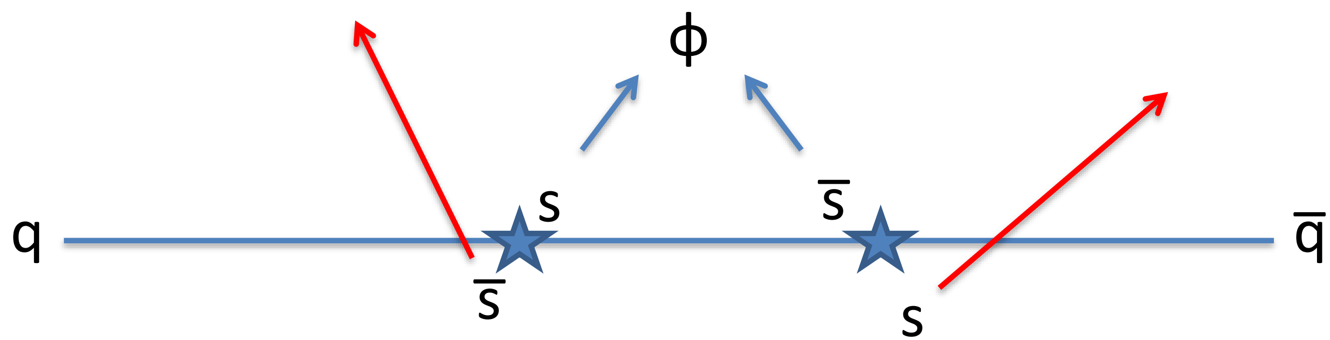


Evolution with mult



- Where the focus so far has been on studying the hard scattering to look for modification in Pb-Pb collisions the "Jet" = "Peak" – "Underlying Event" study could be a tool to study the Underlying Event in pp
  - Especially as a function of mult

Just one last thing about the ϕ



- Correlations most be very different between the two pictures
  - Strings/ropes (jets): strong ϕ-K correlations
  - Stat. thermal model: weak ϕ-K correlations (there can still be, e.g., intra-jet correlations)
  - Recombination: weak ϕ-K correlations ?

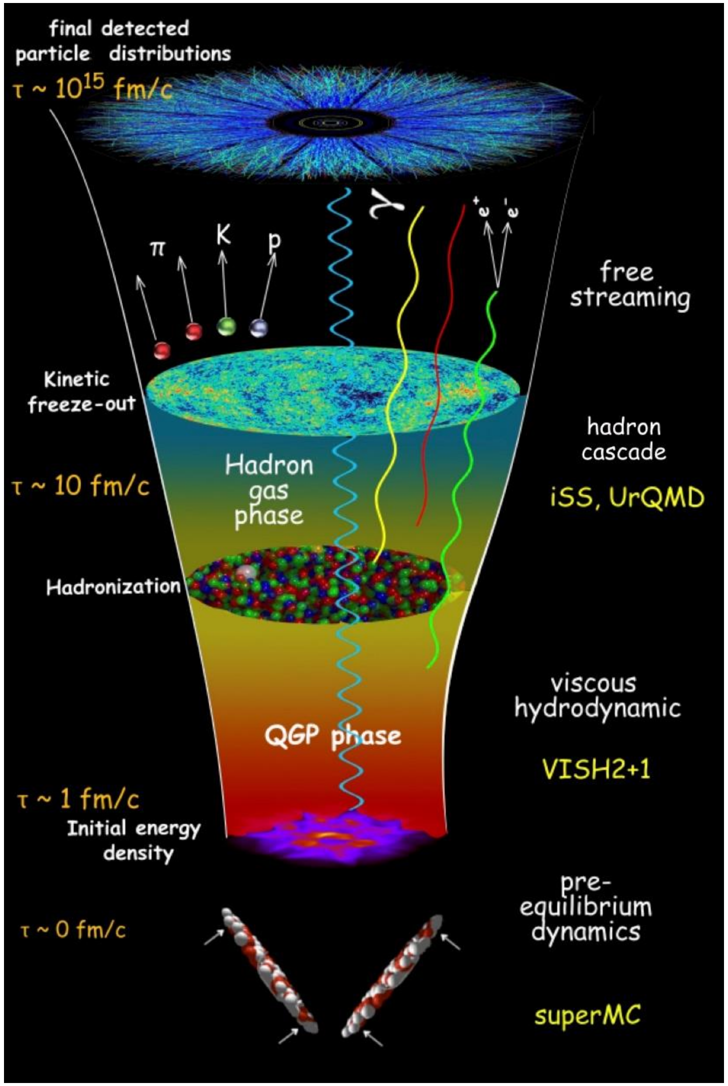
WHY IS QGP IN SMALL SYSTEMS INTERESTING

Can we lift up the result to be of general interest?

- Lesson from perfect liquid in large systems:
  - Interest in field, but did not revolutionize understanding of early Universe
    - I still do not understand why!?

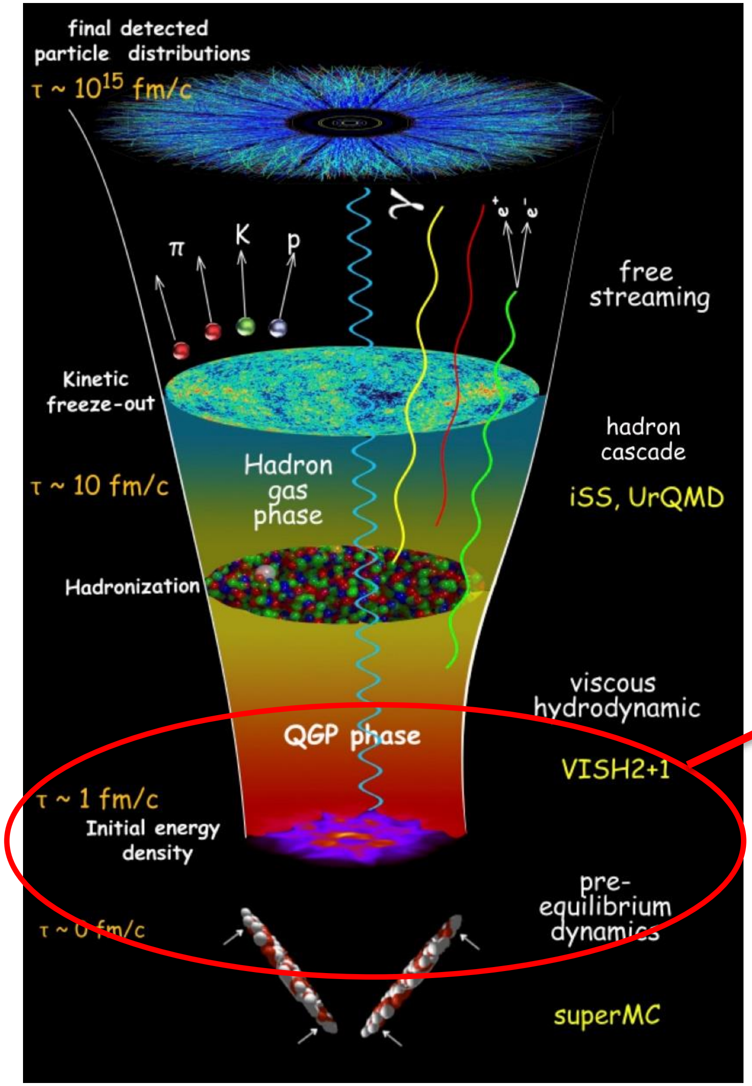
- Solution: we need to start thinking beyond the physics of hadronic collisions

The good thing



- From studies of Pb-Pb collisions we have developed a fantastic understanding and model description of the phases of a collisions
- That I will take over for the dilute pp collision (assuming that a QGP is produced)

The problem

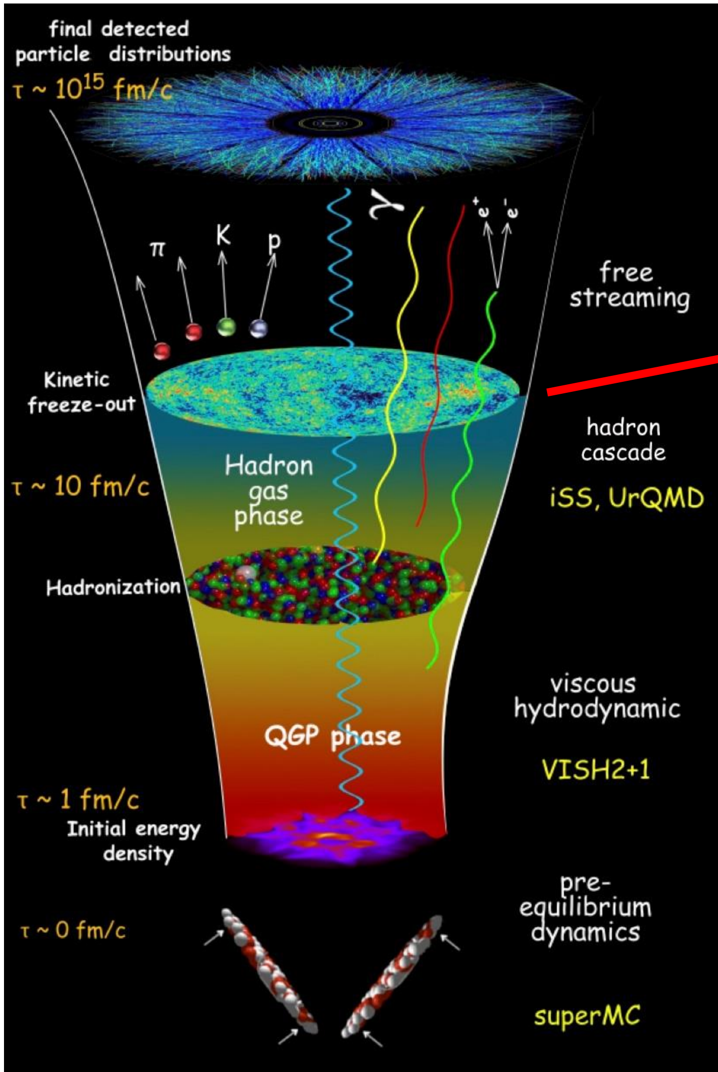


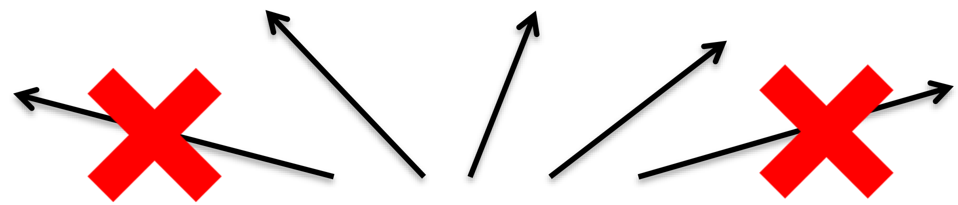
- Physics of initial collisions are not well understood

?

- Proposed solution: start from the back!

Final state particles (at kinetic freezeout)

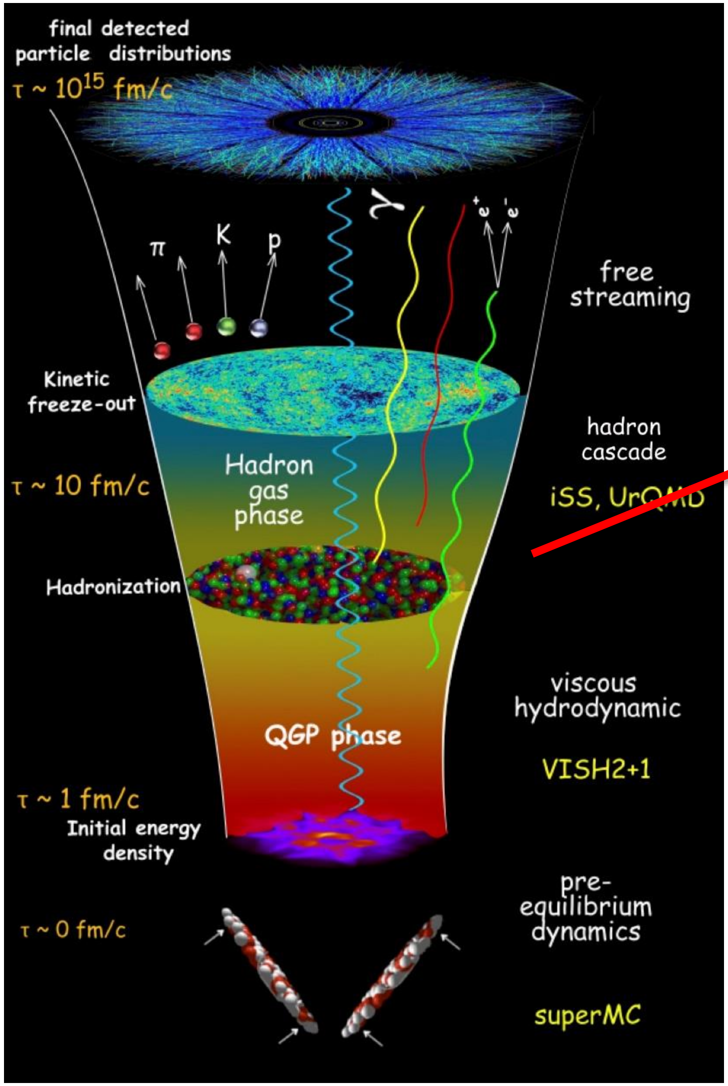


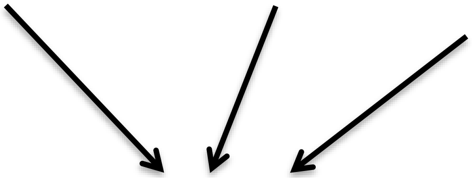


The very forward going particles have most of the energy and are very important for the formation of the QGP, but only for creating it.

After that they decouple.

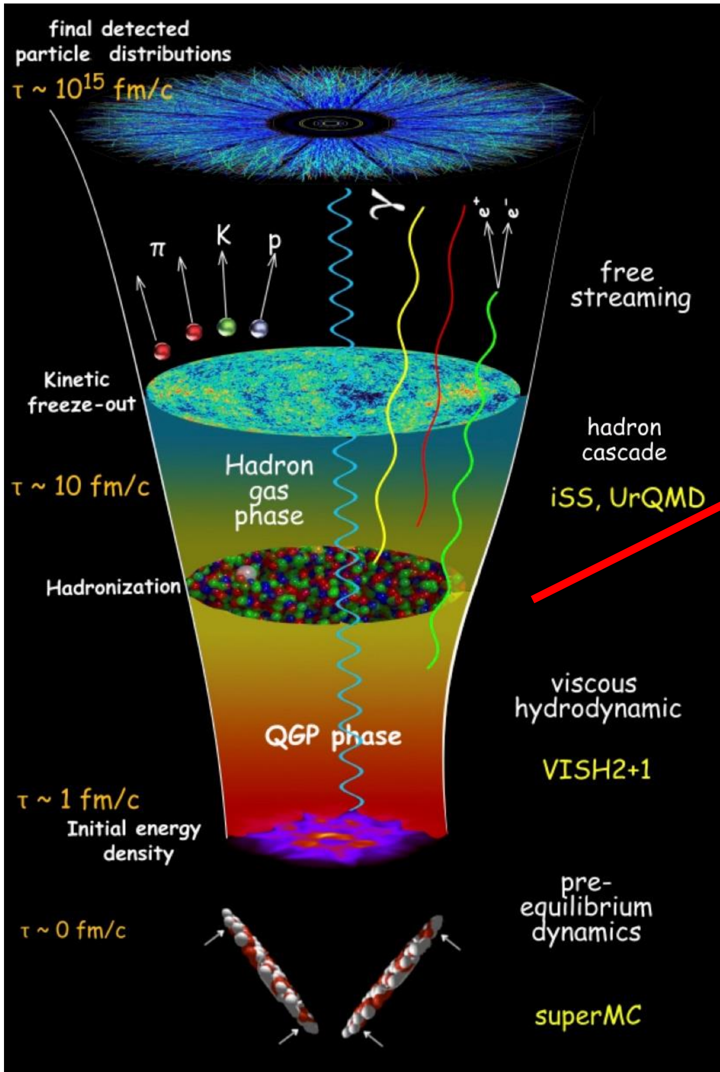
Now we reverse time (to the moment of Hadronization)





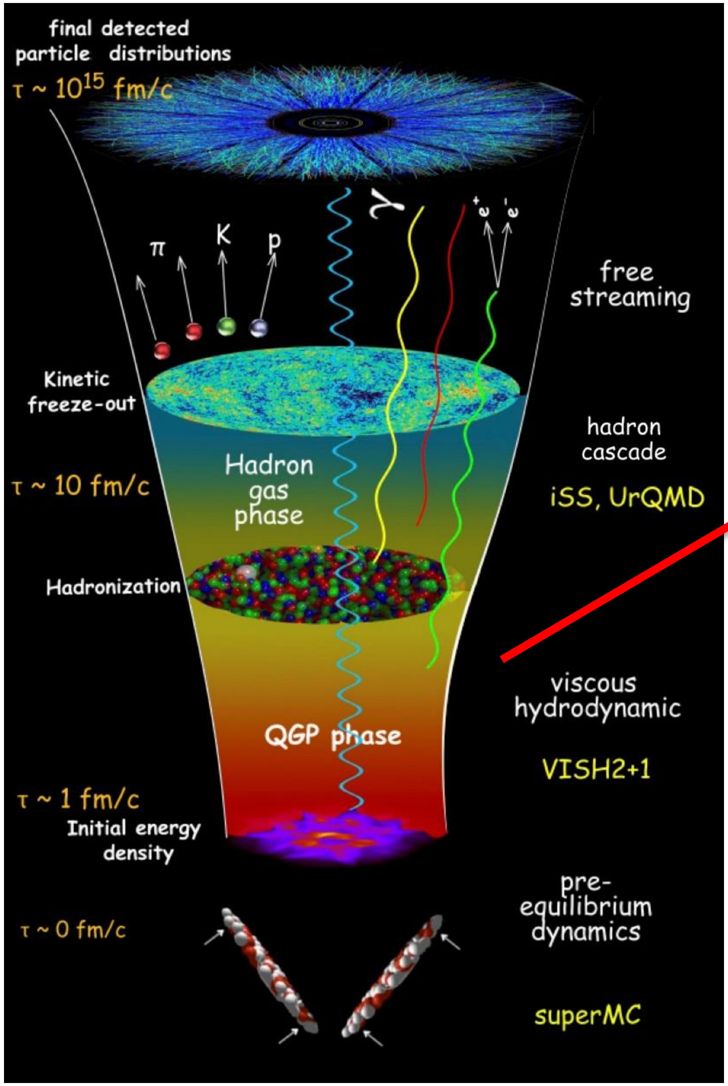
Even in heavy-ion collisions the time between hadronization and chemical and kinetic freeze-out is supposedly short. For these very dilute systems (less than MB pp collisions) the main non-reversible effects is supposedly strong decays. But even that must be a small effect.

Now we reverse time (into the QGP phase)



The phase transition is a Xover so that is reversible!

Now we reverse time (in the QGP phase)



The QGP behaves as a nearly ideal liquid, so it is as reversible as it can be.

This suggests that we create a QGP every time in collisions of evene very few low energy hadrons!? But doesn't this imply that a duality between hadrons and the QGP at Tc?

A duality between QGP and hadrons?

- The proton energy density is similar to that of the QGP at Tc (pion mass is much lighter but driven by Chiral Symmetry Breaking)
  - All hadrons have similar mass as proton within factor 2
- Would explain how QGP can form in small systems
- What does duality mean?
  - Unclear, but must be related to confining field (not valence quarks) and suggests that hadrons are in some sense macroscopic objects

Pushing the envelope

- There are calculations, PRL 111, 202302 (2013), suggesting that the strange quark freezes out at 1.11 times higher temperature than the u and d quark
- This would mean an energy density that is $T^4 = 1.11^4 = 1.52$ times higher
- If one interprets this in a way that the strange quark density in hadrons is similar higher, then the constituent strange quark mass is ~1.5 times the constituent u/d mass
  - 450 MeV instead of 300 MeV

Conclusions

- To make experimental (and theoretical) progress, in addition to comparisons of data with models we need to identify the essential differences between models to be able to test their fundaments
  - The ϕ is very attractive for some of these tests
- To increase the sensitivity of measurements in small systems it is attractive to develop methods to separate soft and hard physics
- We should explore the consequences of our discoveries for QCD, Cosmology and hadronic physics

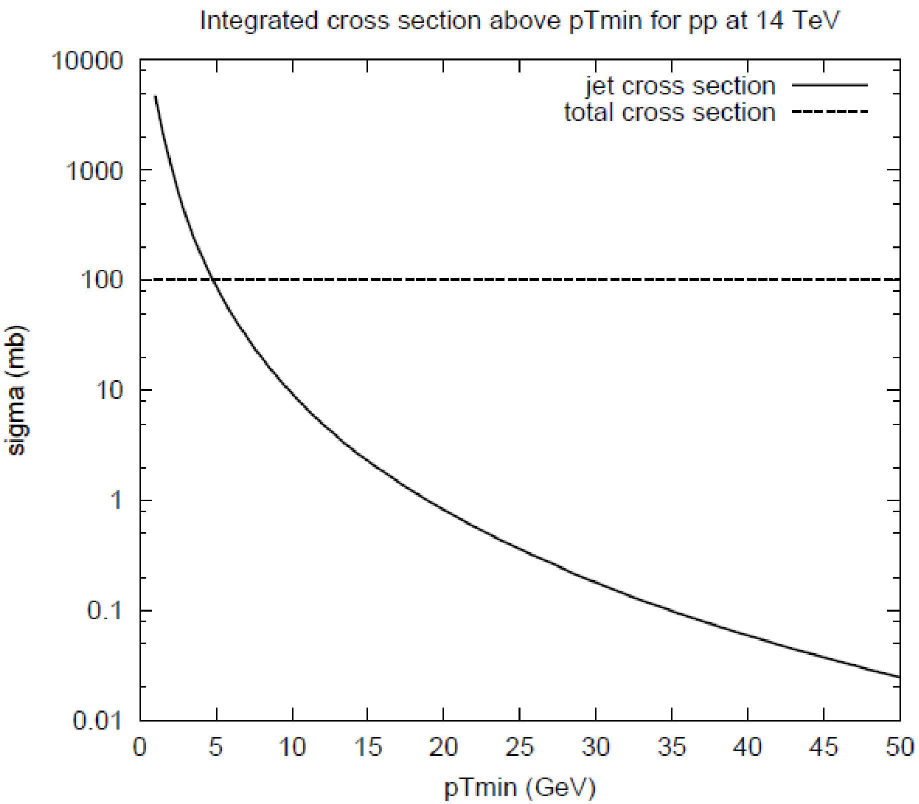
Backup slides

But already the proton has smaller scales

The partonic cross section scales as:

$$\frac{d\hat{\sigma}}{dp_{\perp}^2} \propto \frac{\alpha_s^2(p_{\perp}^2)}{p_{\perp}^4}$$

In PYTHIA it is regularized via a $p_{T,min}$ of order ~2 GeV/c (This plays a big role for MPIs)



The interpretation of this scale is that the proton appears to be color neutral on scales larger than ~0.1 fm (whereas they expected Λ_{QCD} ~ 1 fm)

How to understand this scale

There are random (?) structures in the proton wave function that can be resolved by QED but not by QCD (and vice versa)

d(red) $\bar{\text{u}}$ (anti-red)

Resolved by photon but not by gluon

d(red) $\bar{\text{d}}$ (anti-blue)

Resolved by gluon but not by photon

Toy model study by Johann Dischler and Torbjörn Sjöstrand (Eur. Phys. J. direct C3 (2001) 2) where they evolve a proton (uud + 2g) to a new scale and then, randomly fixing the position of the partons, resolves it with a gluon

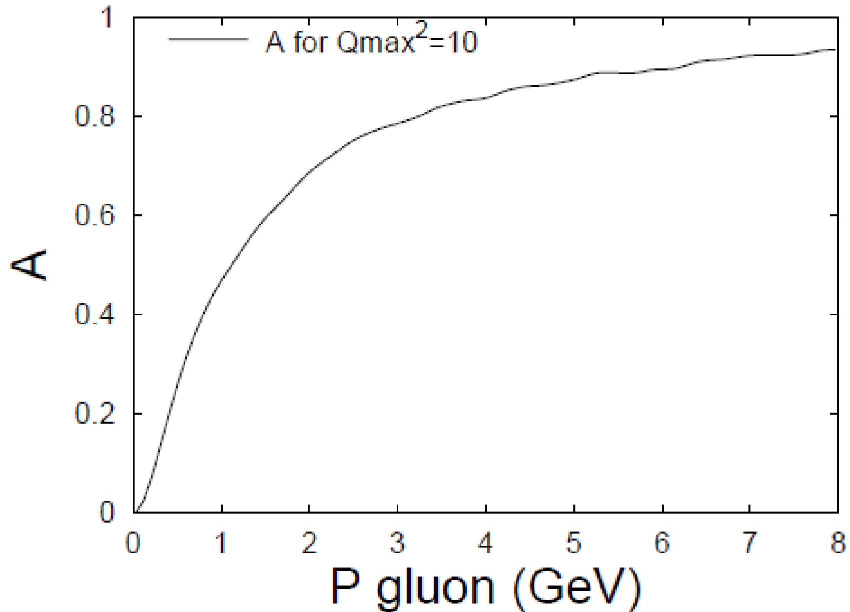
They study the ratio of the coherent to the incoherent cross section

$$A = \frac{|\sum_k q_k e^{i\mathbf{r}_k \mathbf{p}_\perp}|^2}{\sum_k |q_k|^2}$$

Results of toy model study

Coherent / incoherent partonic Xsection

$$A = \frac{|\sum_k q_k e^{i\mathbf{r}_k \mathbf{P}_\perp}|^2}{\sum_k |q_k|^2}$$



- In their model the screening is random (weakly coupled) and has some energy dependence due to the pdfs
- One could ask if the screening is really random or it reflects strong correlations in the proton wave function