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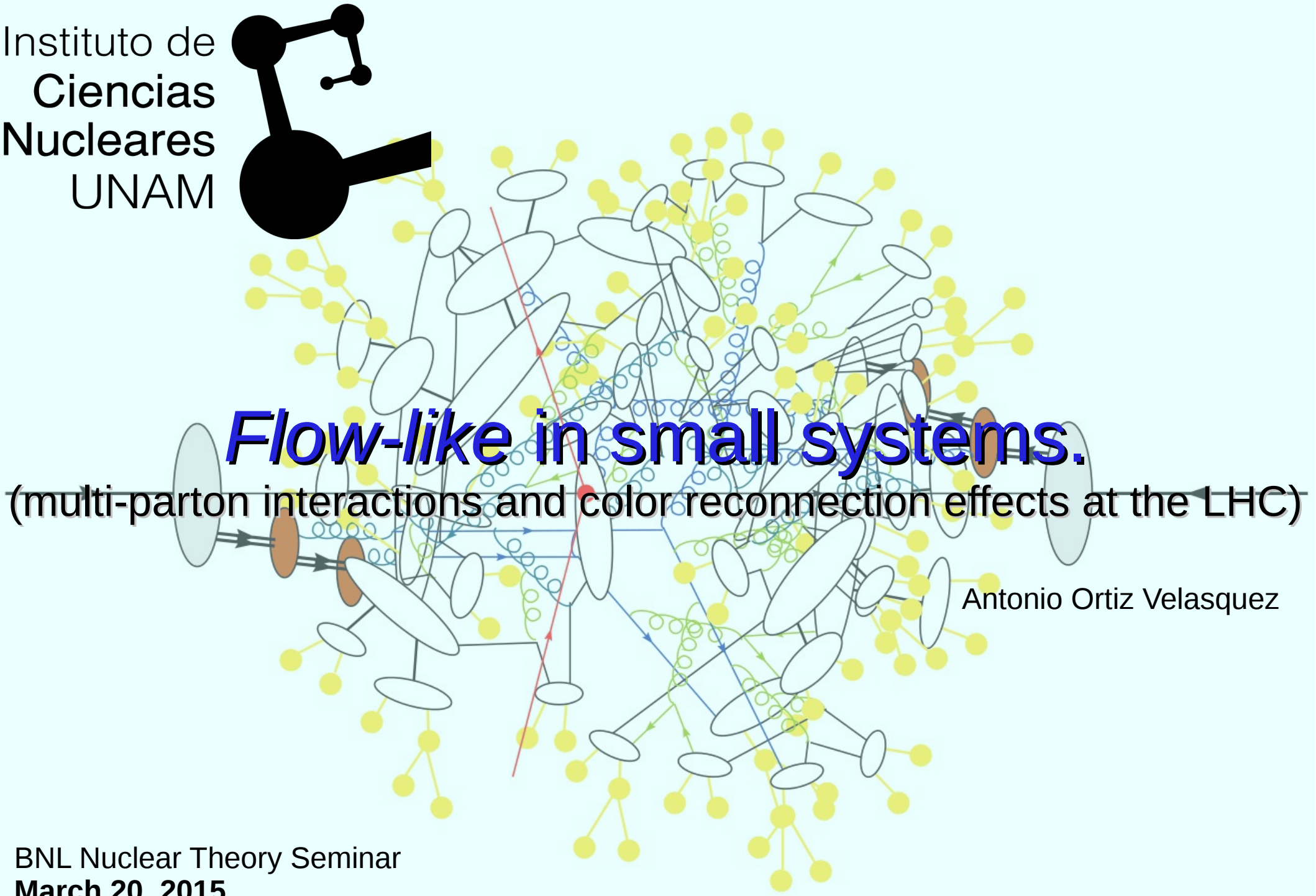

Flow-like in small systems.

(multi-parton interactions and color reconnection effects at the LHC)

Antonio Ortiz Velasquez

BNL Nuclear Theory Seminar
March 20, 2015.

taken from Stefan Gieseke©

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Outline

- pp and p-Pb collisions.
  - Their role in heavy ion collision physics.
  - Results for high multiplicity pp and/or p-Pb collisions: sphericity, ridge and flow patterns.
- *Flow-like* via: multi-parton interactions (MPI) and color reconnection (CR).
- *Flow-like* vs flow (hydro): study using LHC data.
- Can jets also mimic flow? Study using event shapes.
- Summary.

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Goal of pp and p-Pb collisions in heavy ion experiments

- pp and p-Pb runs were thought to provide trivial reference for Pb-Pb physics. The main purpose was to allow the extraction of the genuine properties of the strongly coupled Quark Gluon Plasma (sQGP).
- e.g. jet quenching effects can be quantified through the measurement of the production of hadrons at large transverse momenta (p_T) in vacuum compared to that in the medium.

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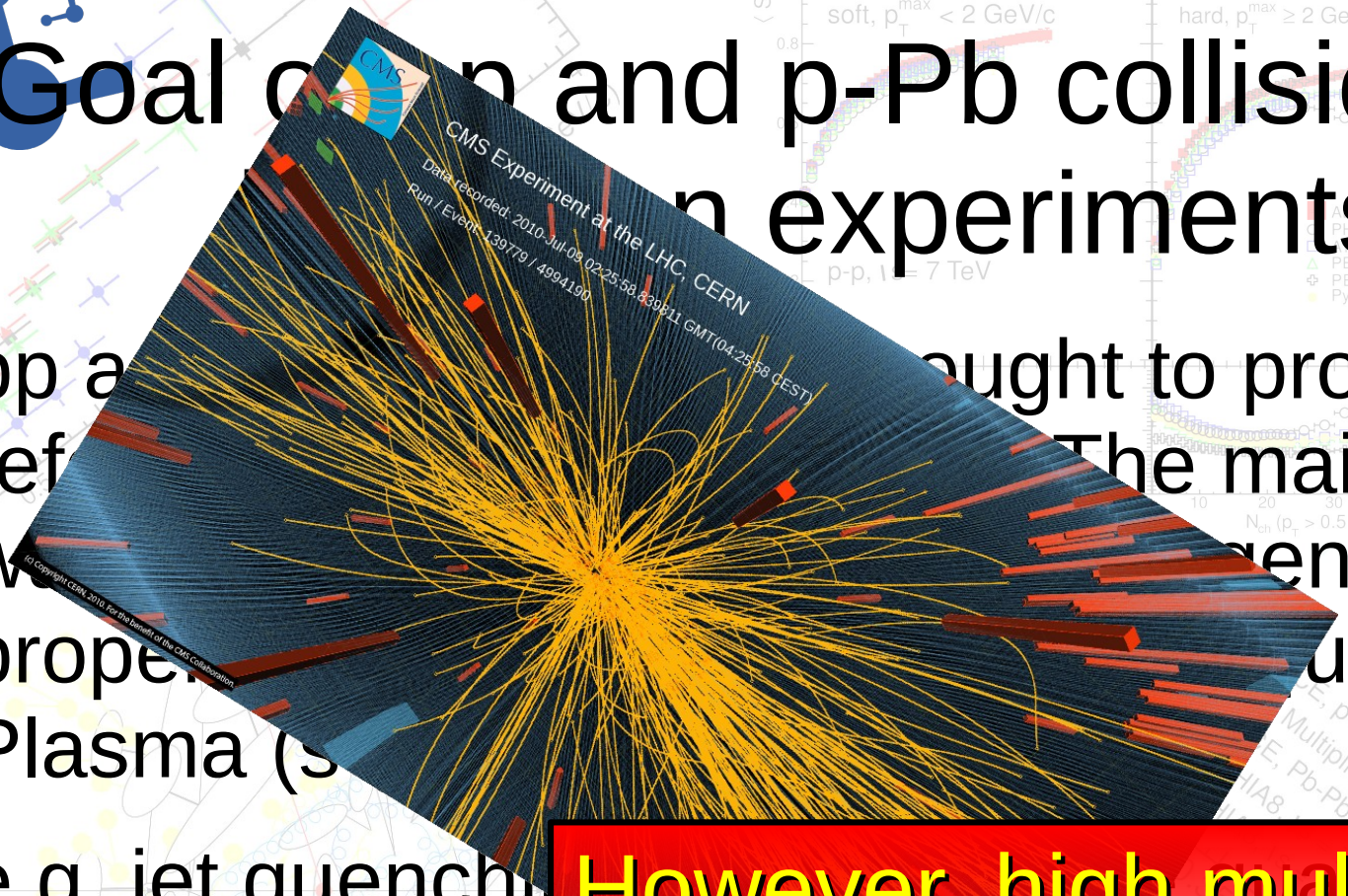
Goal c… n and p-Pb collisions in … n experiments



- pp a… …ught to provide trivial ref… …The main purpose w… …genuine prope… …uark Gluon Plasma (S…
- e.g. jet quenchi… …e production of hadrons at large transv… …momenta (p_T) in vacuum compared to that in the medium.

However, high multiplicity pp and p-Pb events were found to be very interesting!

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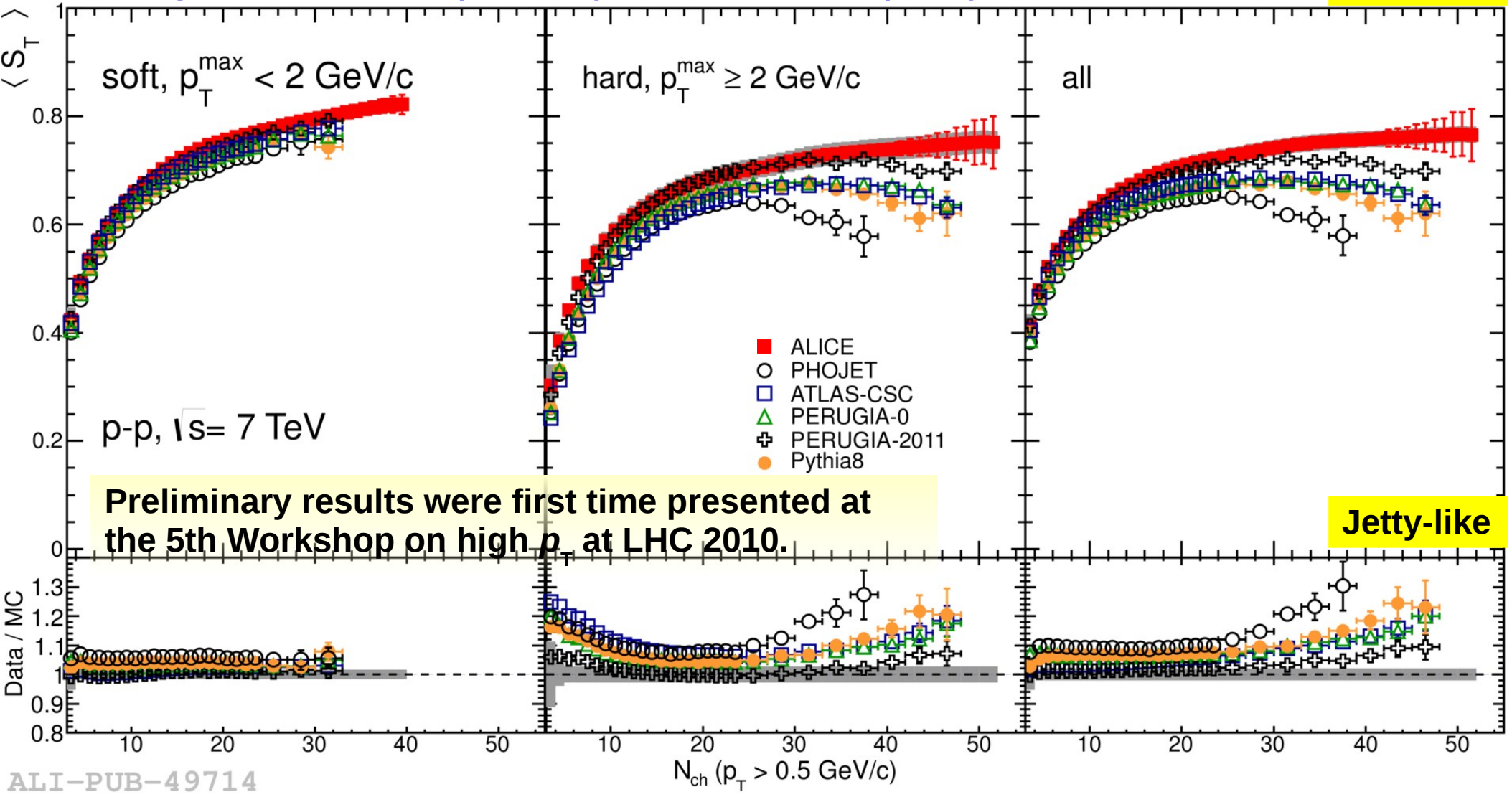
First observations ...

Average transverse sphericity vs event multiplicity.

Isotropic



Jetty-like

Preliminary results were first time presented at the 5th Workshop on high p_T at LHC 2010.

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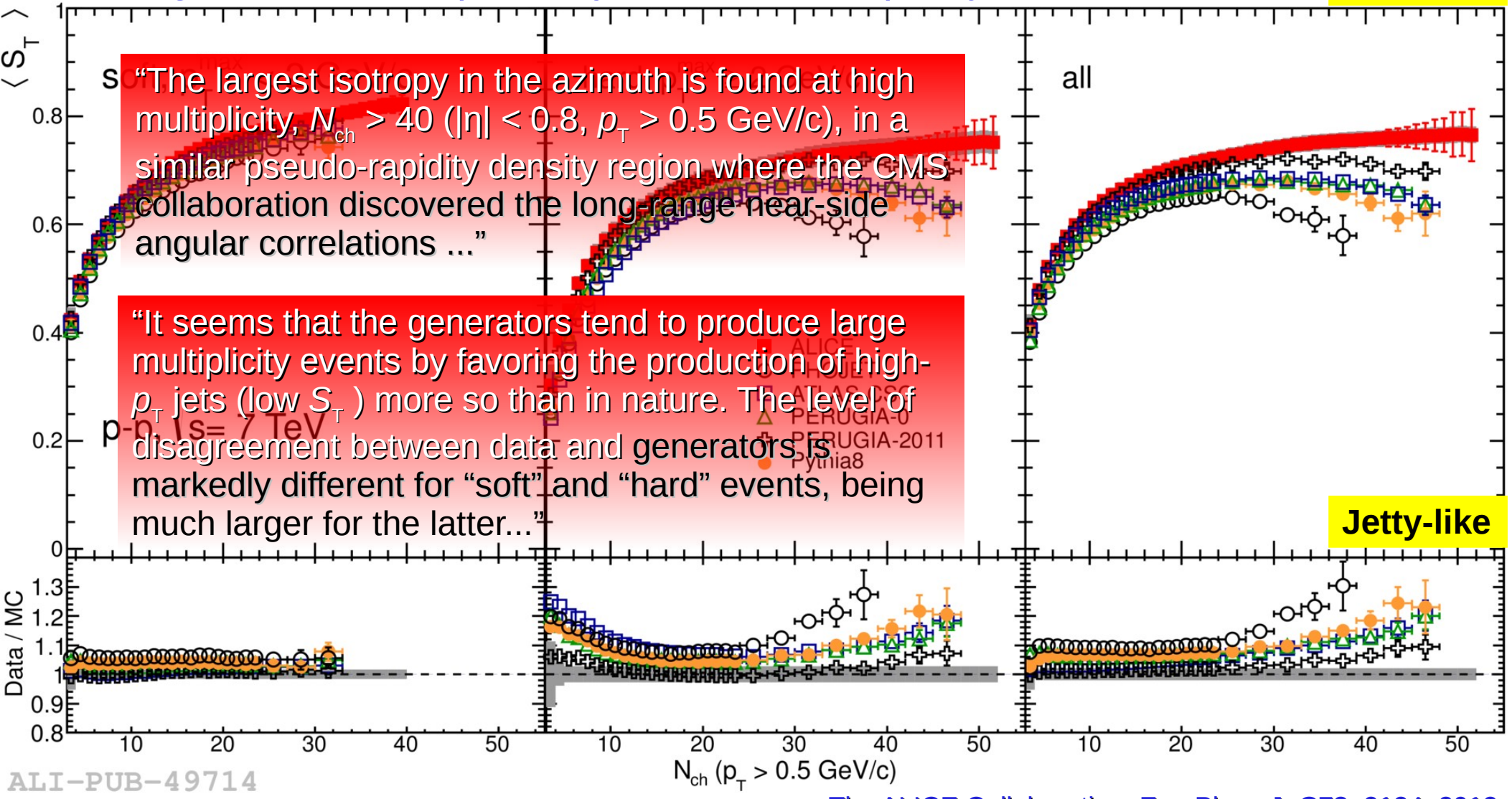
First observations ...

Average transverse sphericity vs event multiplicity.

Isotropic



"The largest isotropy in the azimuth is found at high multiplicity, N_{ch} > 40 (|η| < 0.8, p_T > 0.5 GeV/c), in a similar pseudo-rapidity density region where the CMS collaboration discovered the long-range near-side angular correlations ..."

"It seems that the generators tend to produce large multiplicity events by favoring the production of high-p_T jets (low S_T) more so than in nature. The level of disagreement between data and generators is markedly different for "soft" and "hard" events, being much larger for the latter..."

Jetty-like

The ALICE Collaboration, Eur. Phys. J. **C72**: 2124, 2012.

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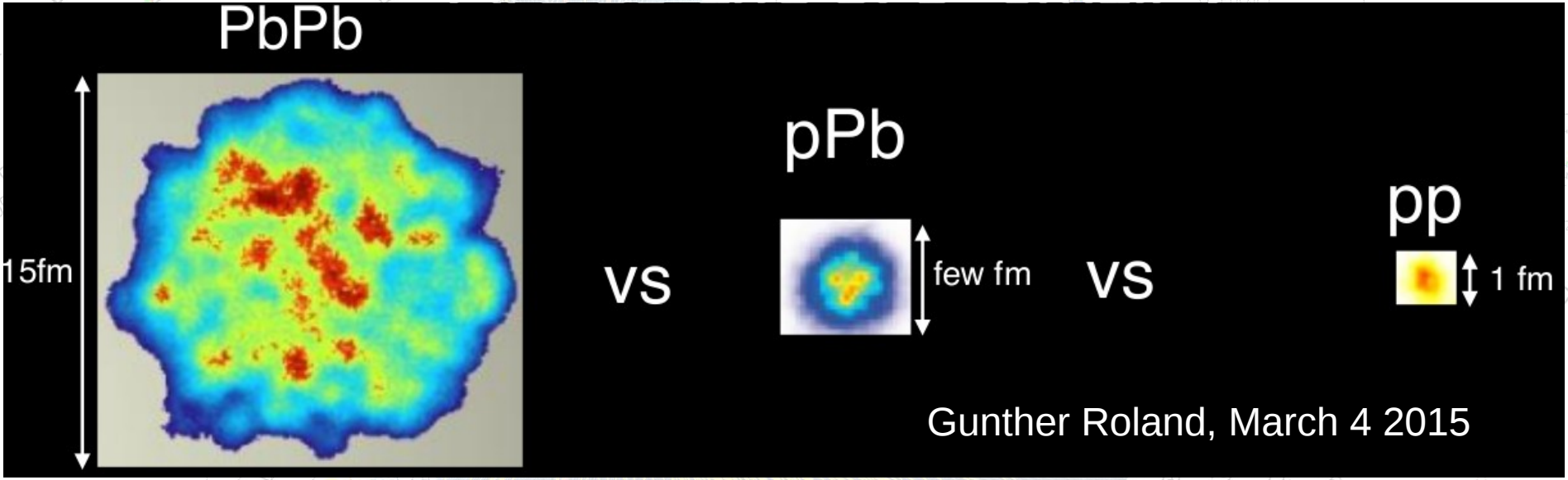
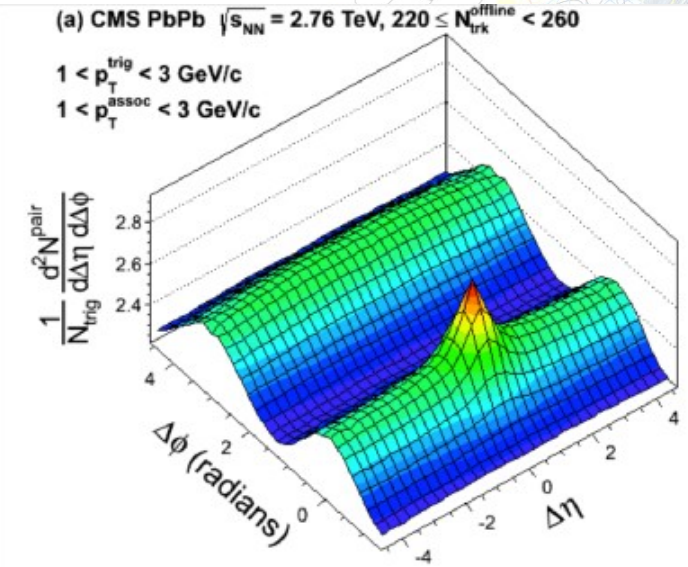
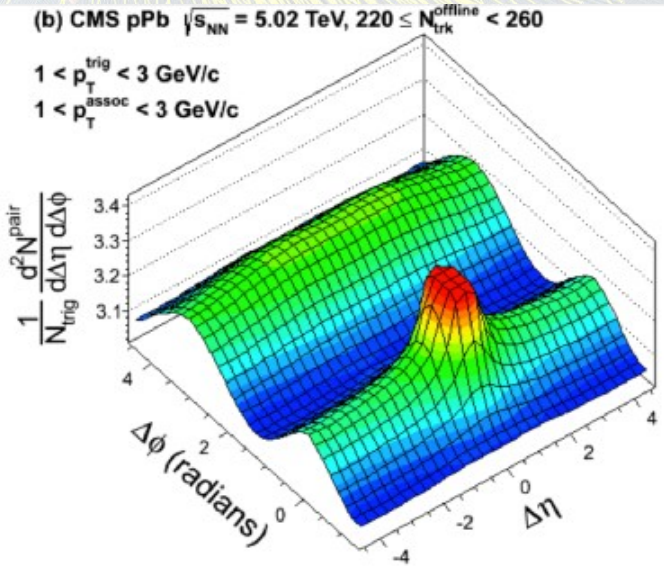
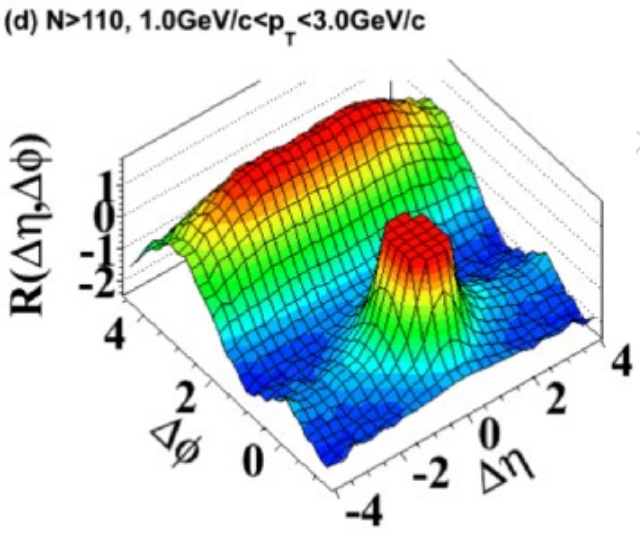
Ridges in small systems









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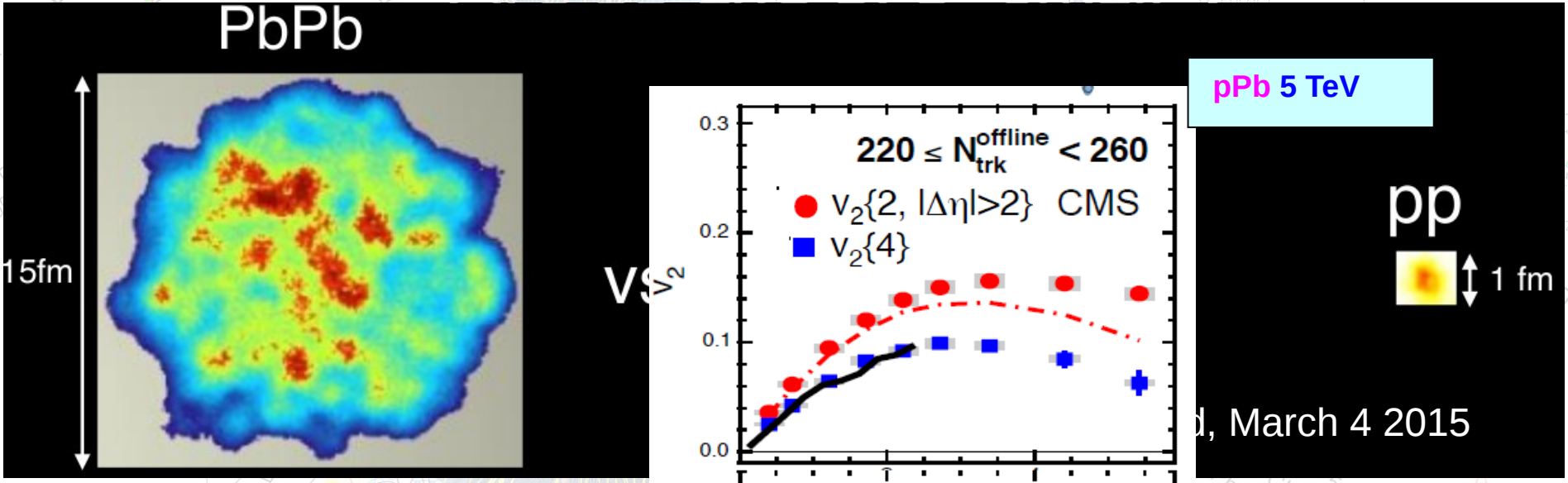
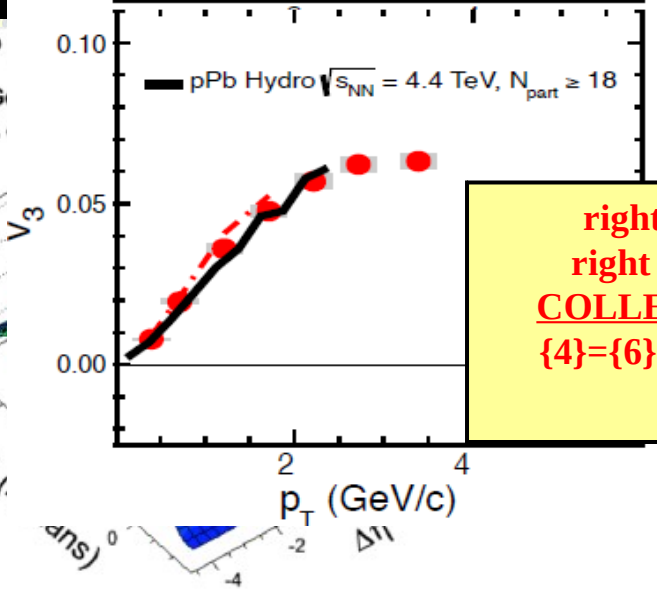
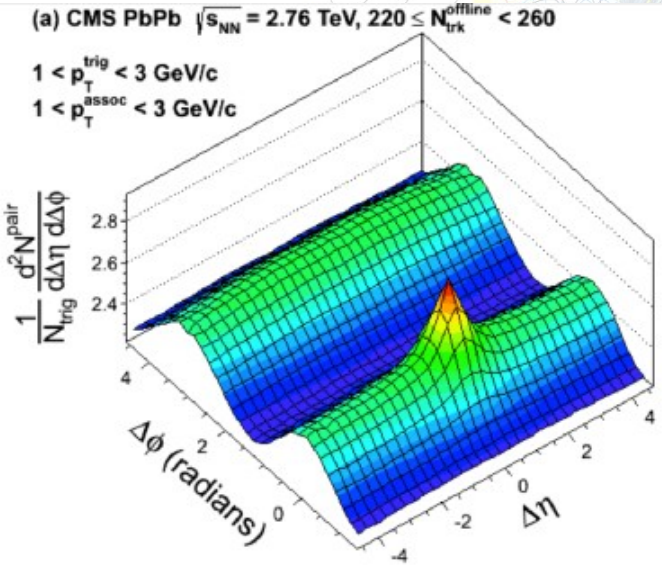
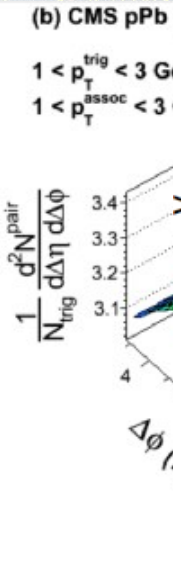
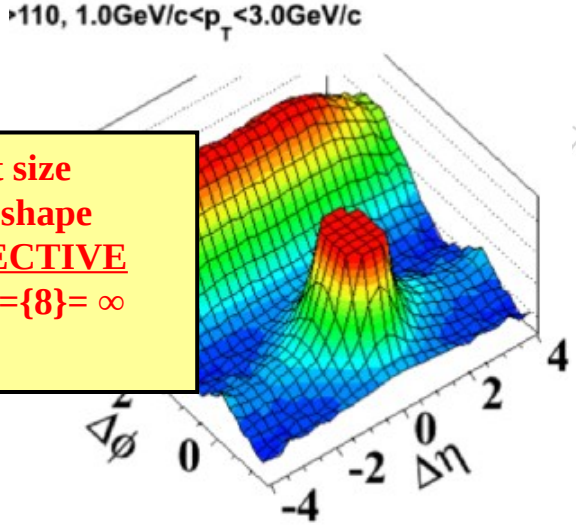
also anisotropic flow











right size
right shape
COLLECTIVE
{4}={6}={8}= ∞

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Hydro calculations gives a qualitatively good description of data:

P. Bozek, Phys. Rev. C85: 014911 (2012).
E. Shuryak and I. Zahed, Phys. Rev. C88:044915 (2013).
P. Bozek and W. Broniowski, Phys. Rev. C88: 014903 (2013).
A. Bzdak et al., Phys. Rev. C87: 064906 (2013).
G.-Y. Qin and B. Mueller, Phys. Rev. C89 044902 (2014).
K. Werner et al., Phys. Rev. C89: 064903 (2014).
P. Bozek et al., Phys. Rev. Lett. 111: 172303 (2013).

But, its applicability in small systems is questionable.

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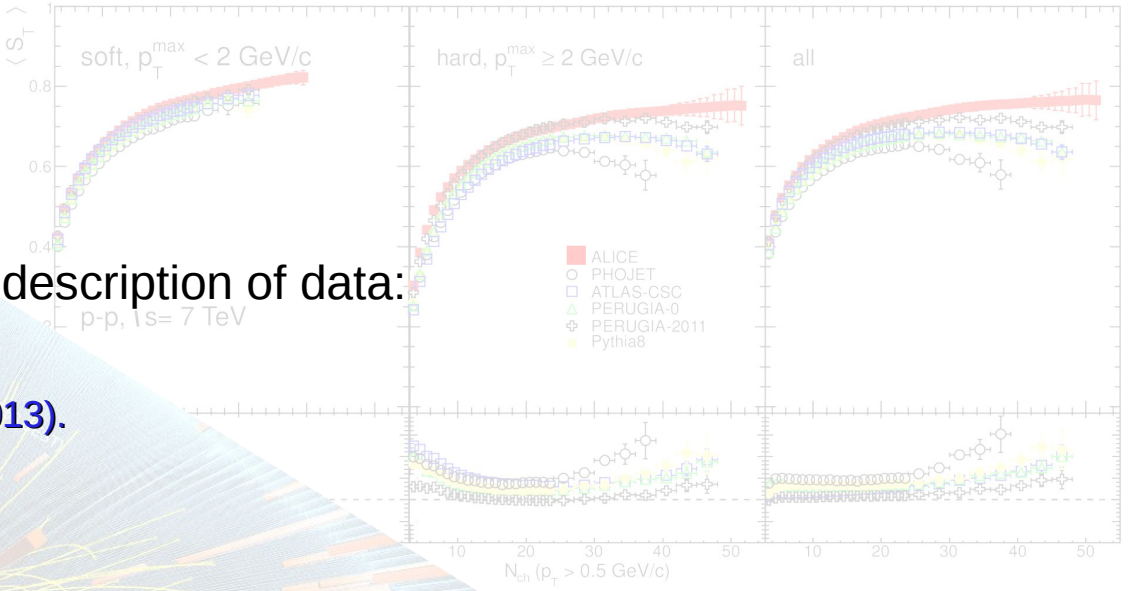

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K. Werner et al., Phys. Rev. C89: 064903 (2014).
P. Bozek et al., Phys. Rev. Lett. 111: 172303 (2013).

But, its applicability in small systems is questionable.

Other approaches which do not invoke final state effects nicely reproduce some features of data.

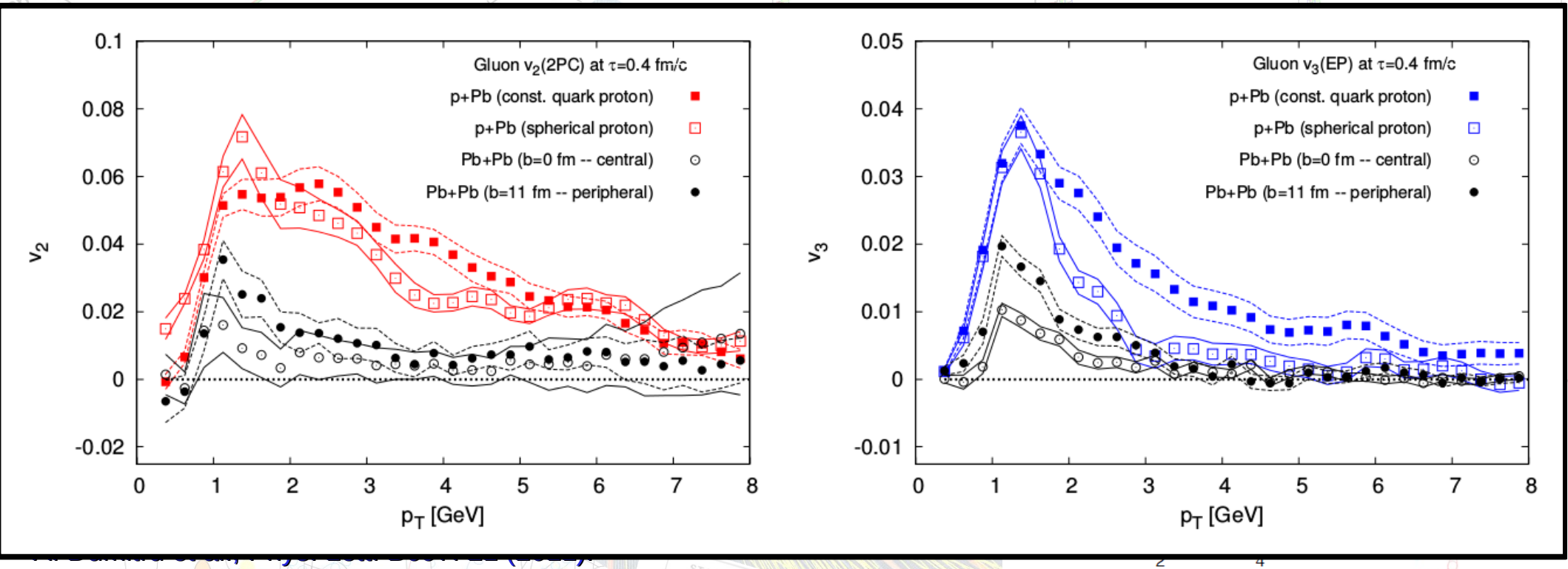
- Color Glass Condensate.

A. Dumitru et al., Phys. Lett. B697: 21 (2011).
K. Dusling and R. Venugoapalan, Phys. Rev. D87: 094034 (2013).
Y. V. Kovchegov and D. E. Werterpny, Nucl. Phys. A906:50 (2013).

- AMPT model (incoherent elastic scattering of partons).

G.-L. Ma and A. Bzdak, Phys. Lett. B739: 209-213 (2014).

taken from Stefan Gieseke©



K. Dusling and R. Venugoapalan, Phys. Rev. D87: 094034 (2013).
Y. V. Kovchegov and D. E. Werterpny, Nucl. Phys. A906:50 (2013).

- AMPT model (incoherent elastic scattering of partons).

G.-L. Ma and A. Bzdak, Phys. Lett. B739: 209-213 (2014).

Recently, it has been demonstrated that calculations of single and double inclusive gluon distributions in classical Yang-Mills simulations of pA collisions give azimuthal anisotropies.

B. Schenke, S. Schlichting and R. Venugopalan arXiv:1502.01331v1

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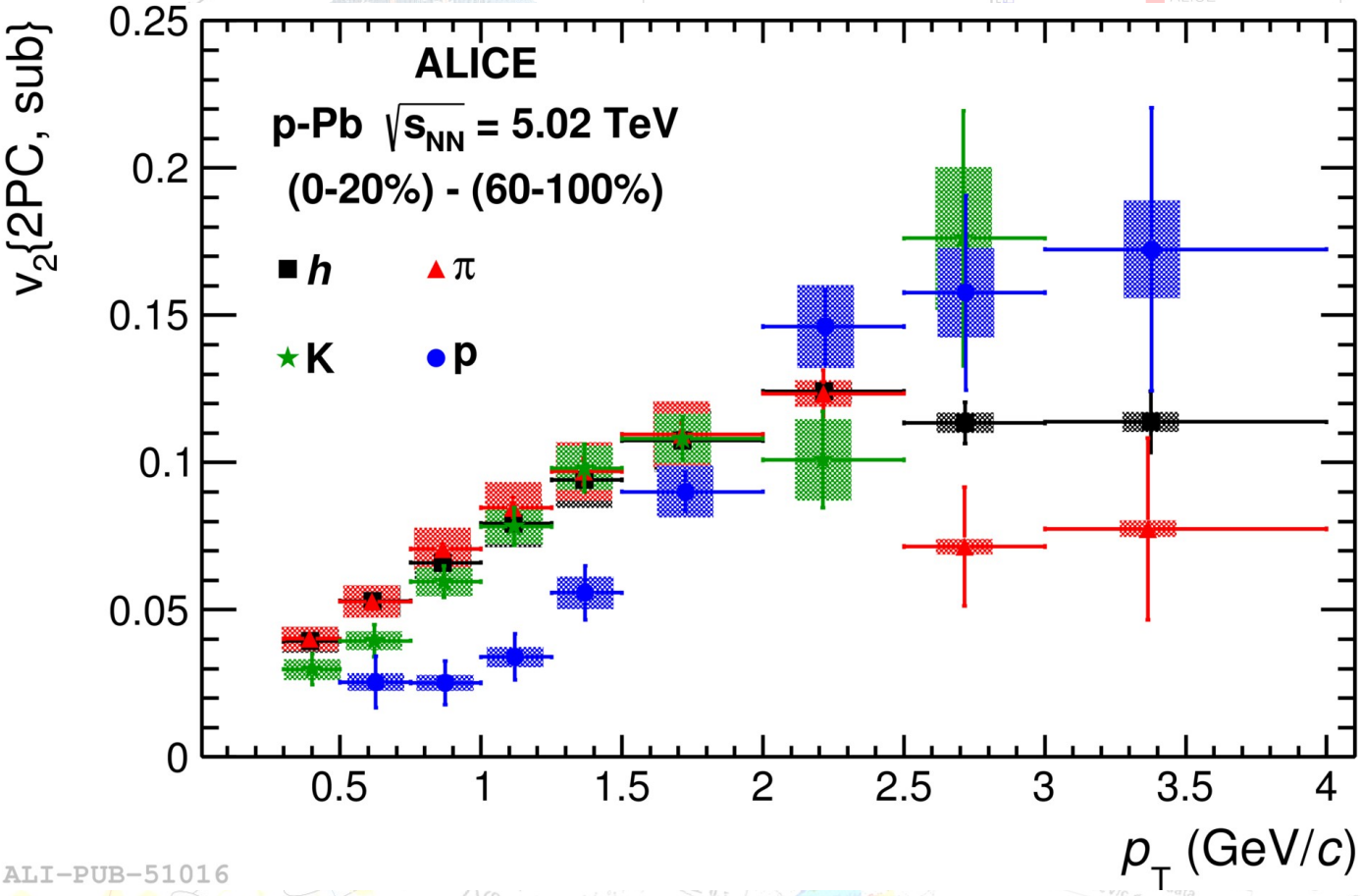
Data also show a mass ordering



The mass ordering could be also explained w/o invoking final state effects, for example multi-parton interactions + color reconnection mimic radial flow.

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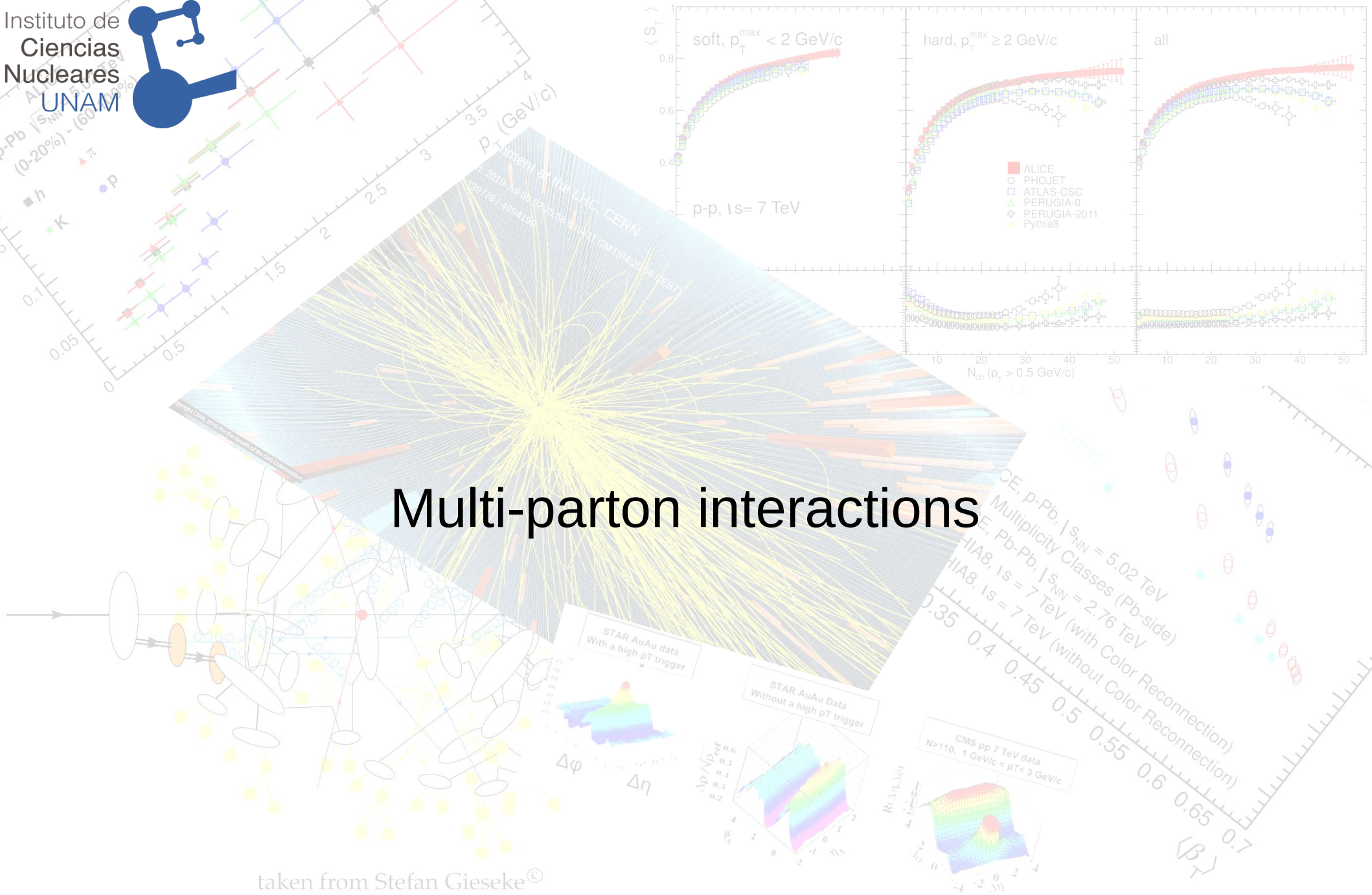
Multi-parton interactions



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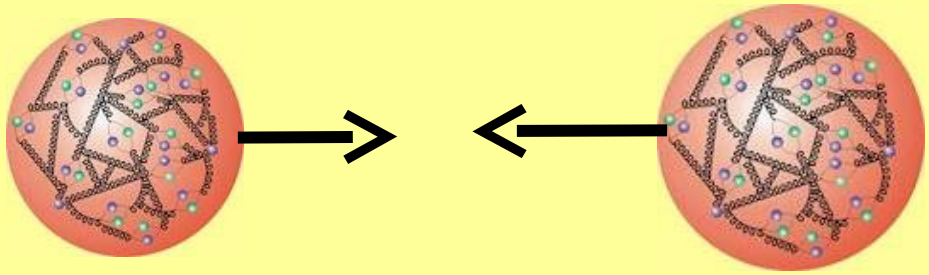
Basis

Due to the simple fact that hadrons have structure, multi-parton interactions (several distinct parton-parton interactions in one and the same hadron-hadron collision) can occur.



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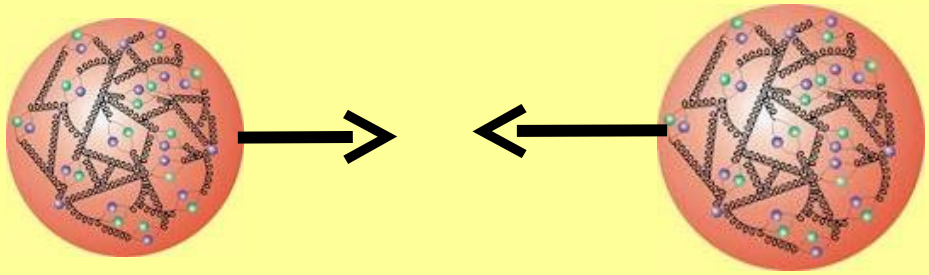

The first crucial observation is that the *t*-channel propagators appearing in perturbative QCD $2 \rightarrow 2$ scattering almost go on shell at low p_T, causing the differential cross sections to become very large, behaving roughly as:

$$d\sigma_{2\rightarrow 2} \propto \frac{dt}{t^2} \sim \frac{dp_T^2}{p_T^4}$$

taken from Stefan Gieseke©

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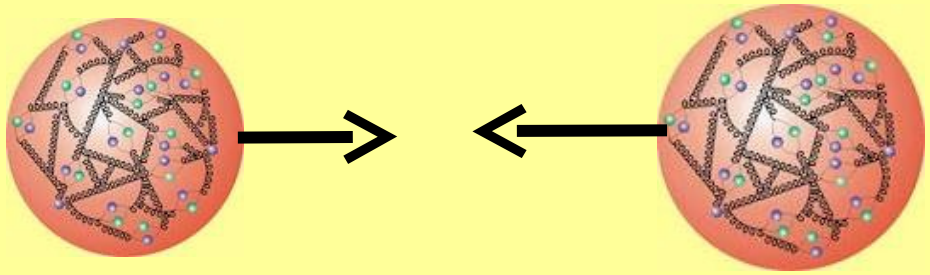
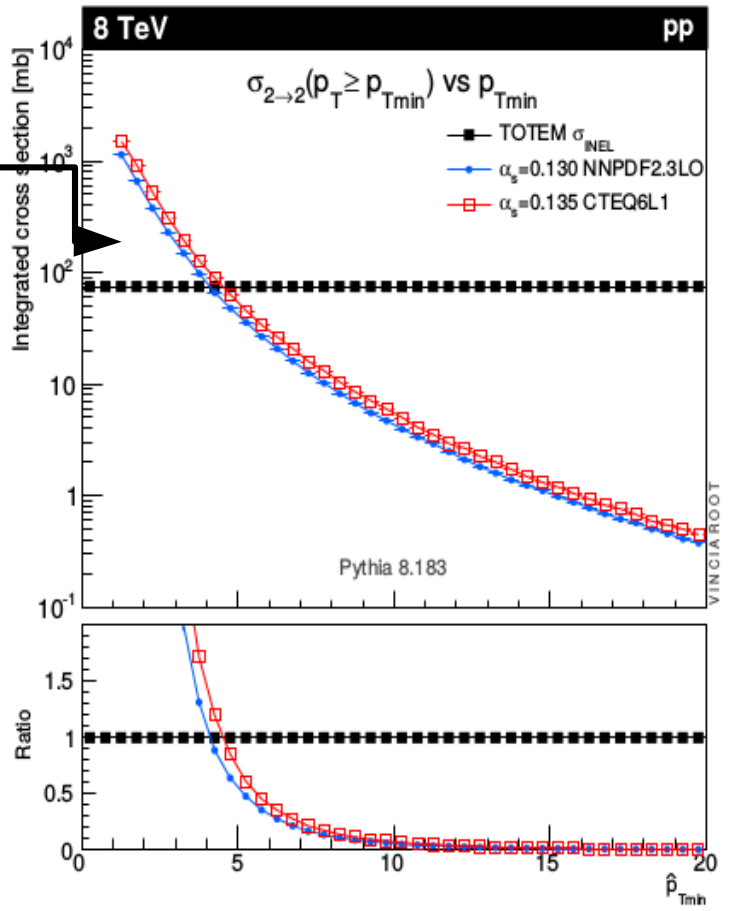


The first crucial observation is that the *t*-channel propagators appearing in perturbative QCD $2 \rightarrow 2$ scattering almost diverge as p_T, causing the differential cross section to become very large, behaving roughly as:

$$d\sigma_{2\rightarrow 2} \propto \frac{dt}{t^2} \sim \frac{dp_T^2}{p_T^4}$$

Each hadron-hadron collision contains several few-GeV parton-parton collisions (MPI)!



At LHC energies, the parton-parton cross section becomes larger than the total hadron-hadron cross section at p_T scales of order 4-5 GeV.

P. Skands, "Introduction to QCD," arXiv:1207.2389v4

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Basis

In the limit that all the partonic interactions are independent and equivalent, one would simply have a Poisson distribution in the number of MPI, with average:

$$\langle n \rangle (p_{Tmin}) = \frac{\sigma_{2\to 2}(p_{Tmin})}{\sigma_{tot}}$$

σ_{tot} is the inelastic hadron-hadron cross section and p_{Tmin} is a lower cutoff scale.

Some considerations:

- The interactions can not use up more momentum than is available in the parent hadron.
- In Pythia-based models, the MPI are ordered in p_T, and the parton densities for each successive interaction are explicitly constructed so that the sum of x fractions can never be greater than one.

taken from Stefan Gieseke©

P. Skands, "Introduction to QCD," arXiv:1207.2389v4

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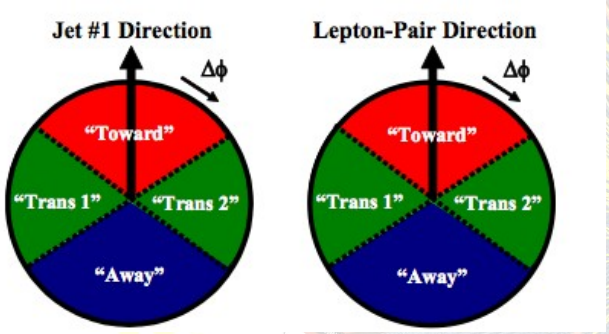
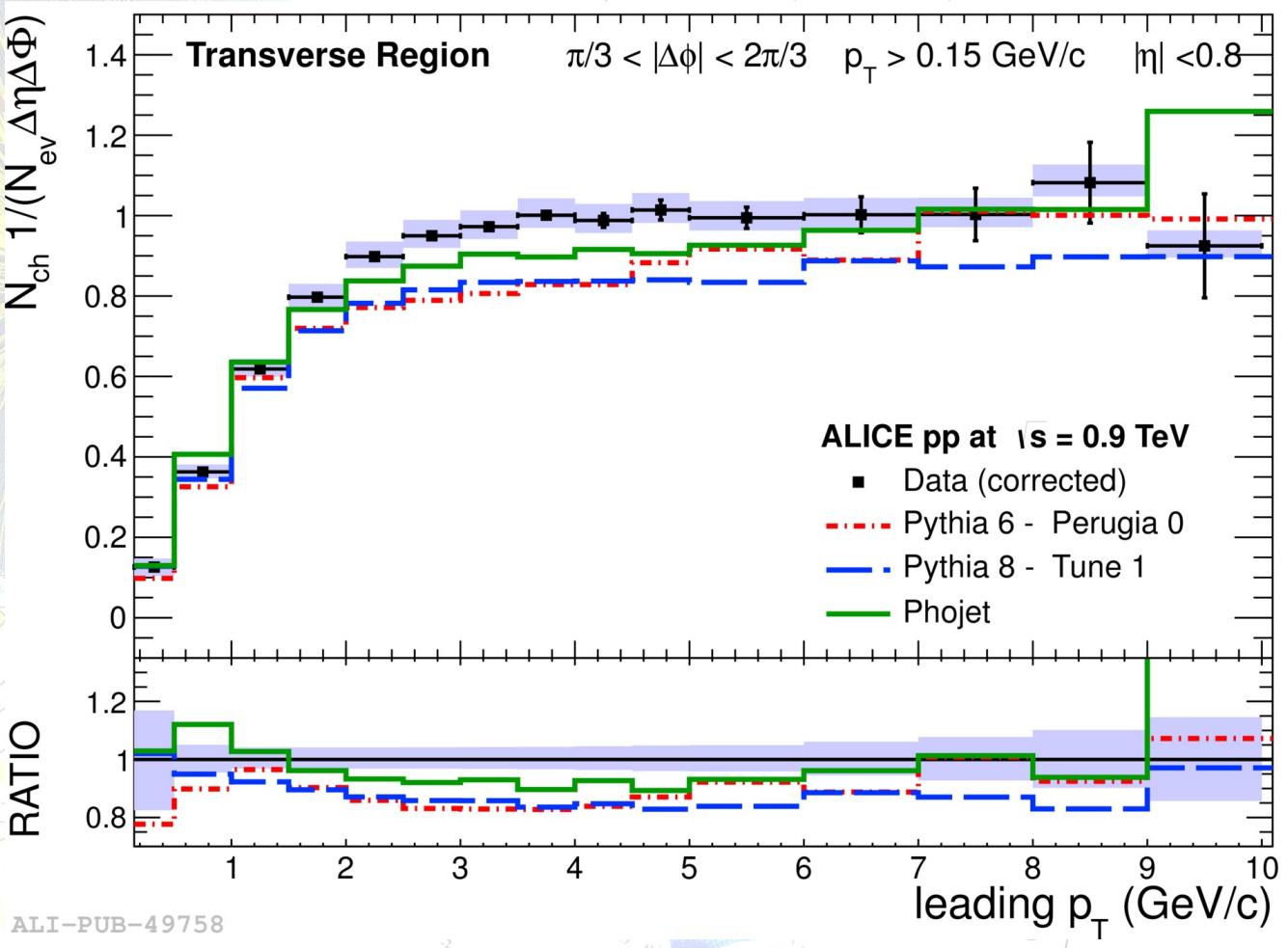
Impact-parameter dependence



- Hard jets appear to sit on top of a higher "pedestal" of underlying activity than events with no hard jets.



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The ALICE Collaboration, JHEP 116, 2012.

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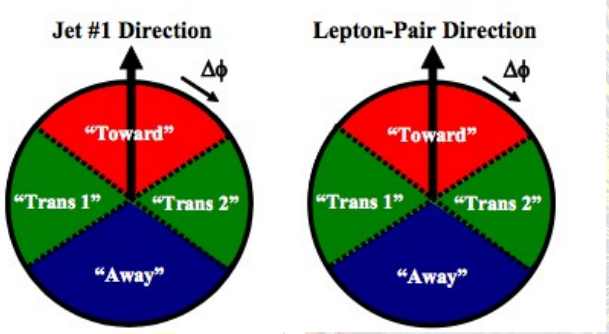
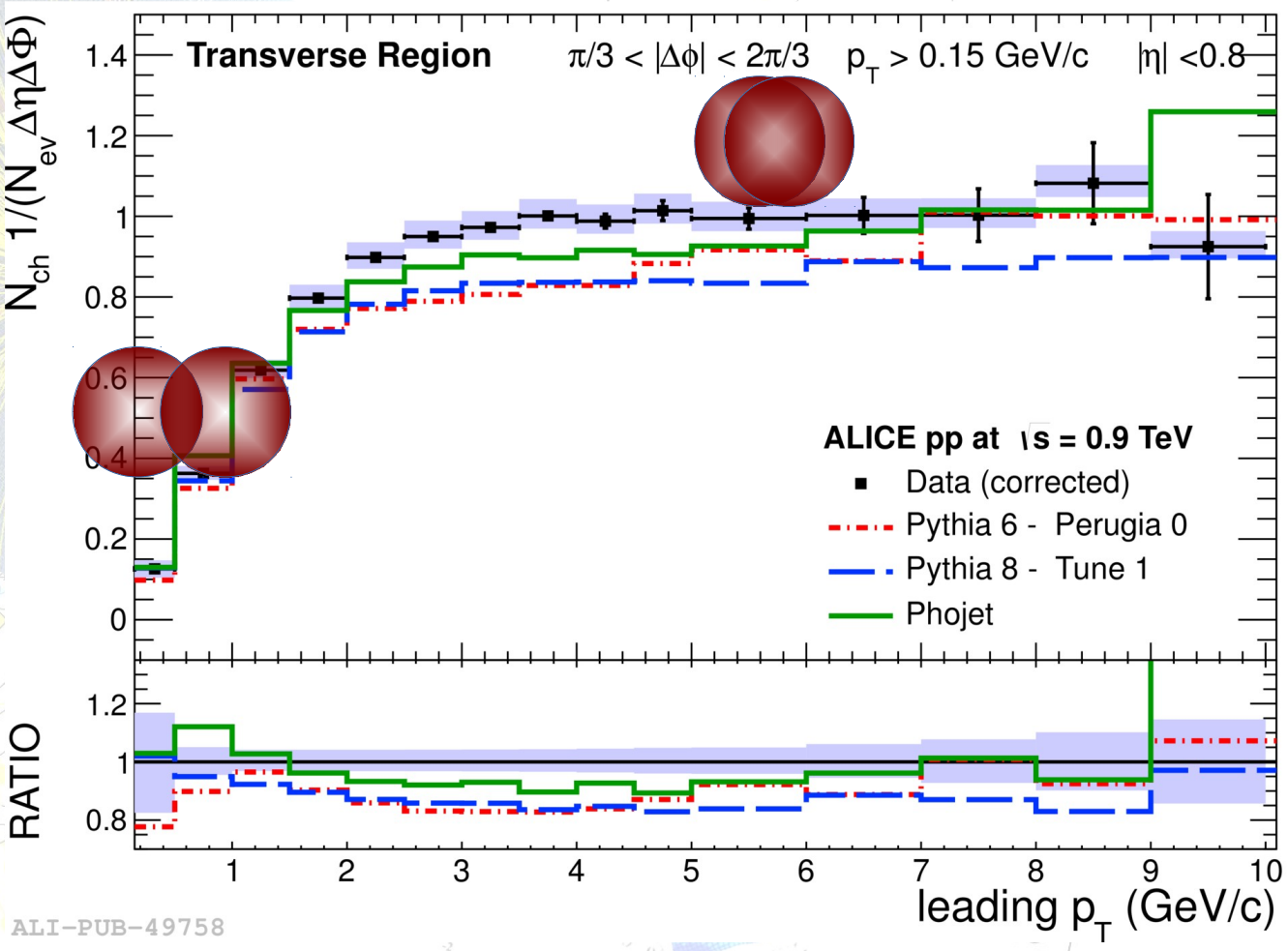
Impact-parameter dependence



- Hard jets appear to sit on top of a higher "pedestal" of underlying activity than events with no hard jets.
  - ➔Centrality bias in pp collisions!



taken from Stefan Gieseke©

The ALICE Collaboration, JHEP 116, 2012.

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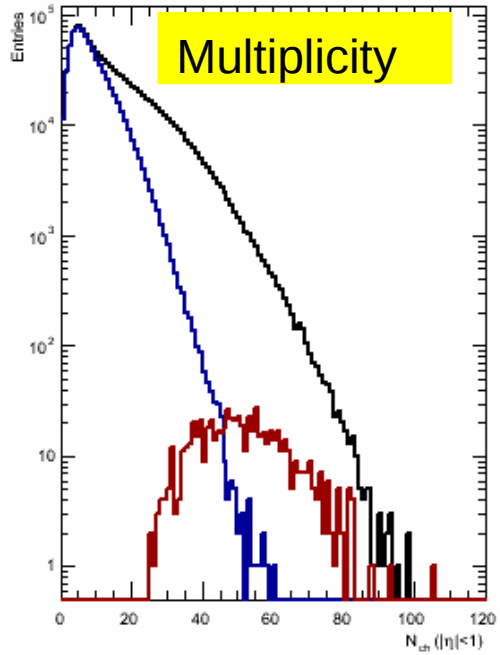
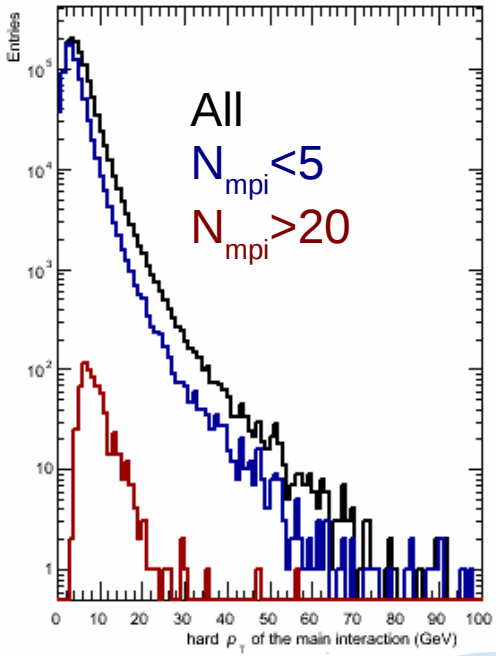
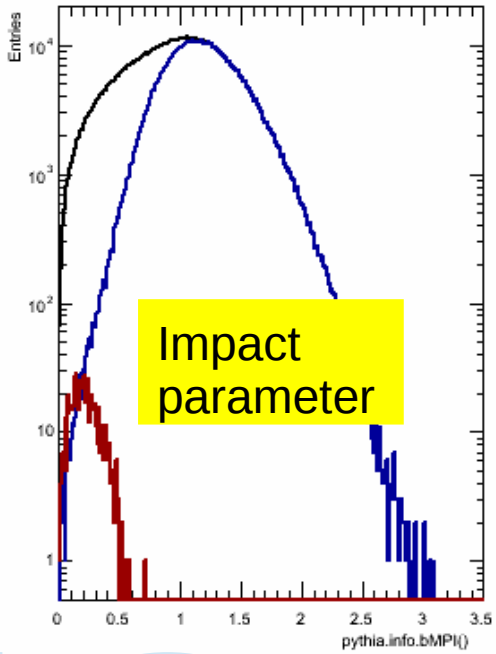
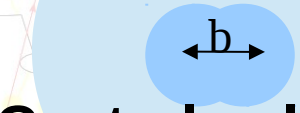
Simulations with Pythia 8

pp $\sqrt{s}$=7 TeV



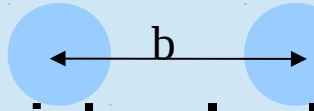






Central collisions:

- Hard p_T scale.
- Many MPI - > High Multiplicity Events



Peripheral collisions:

- Smaller hard p_T scale.
- Few MPI - > Smaller Multiplicity

taken from Stefan Gieseke

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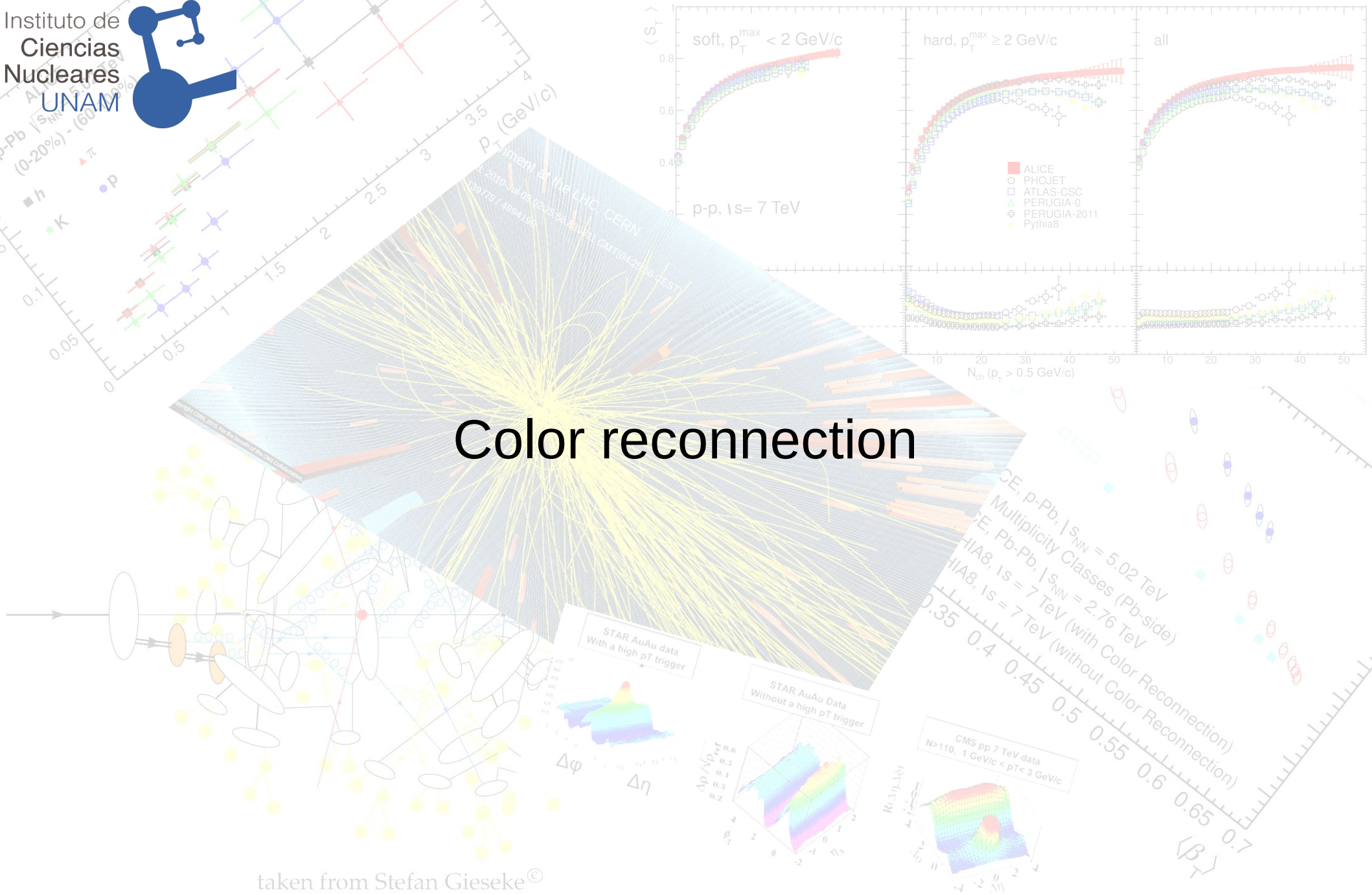
Color reconnection



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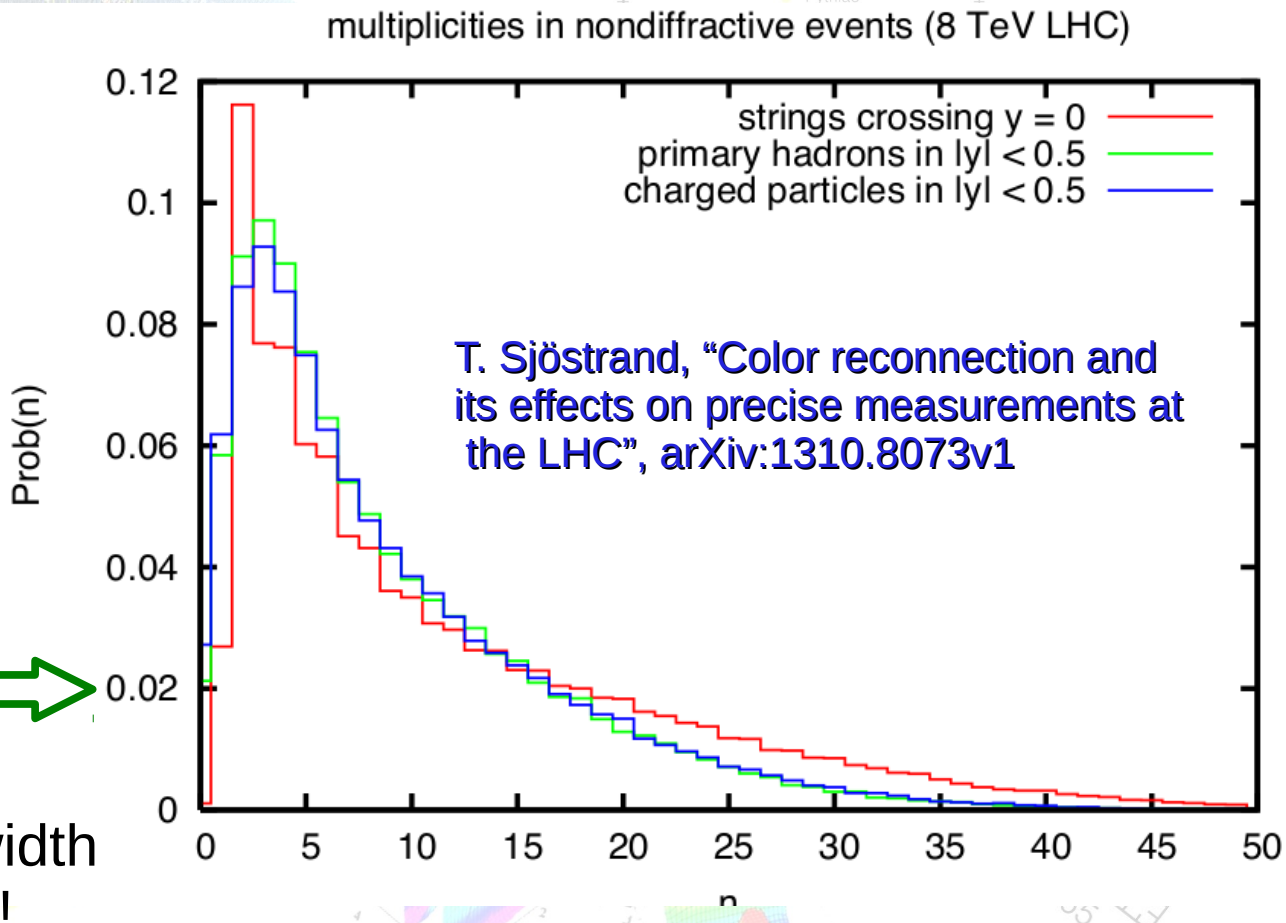
Strings overlap in space and time

LHC events have complicated structure, the different physics components (MPI, ISR, FSR, BR) may produce high density of color charges, that may interact (color reconnection) in a nontrivial nonlinear manner.

To quantify the effect, let us consider MB events.



String width ~ hadronic width
⇒ Overlap factor ~ 10!
Larger for hard collisions
(small impact parameter)

taken from Stefan Gieseke©

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Color reconnection

In Pythia, the final step at parton level before the hadronization is the color **reconnection** CR, its aim is to describe the hadronization of a many parton system in a single event with multiple hard sub collisions.

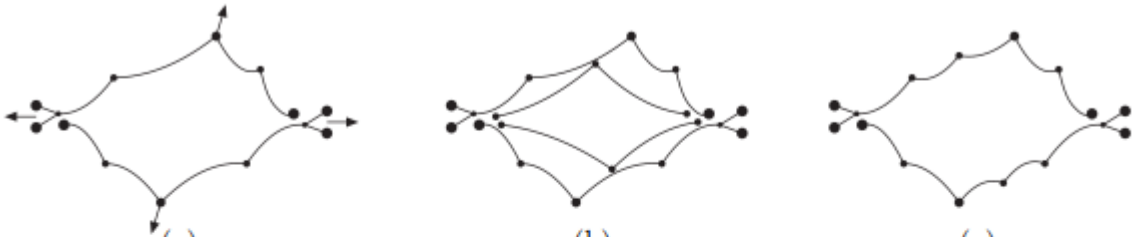

Fig. 2. (a) In a hard gluon-gluon subcollision the outgoing gluons will be colour-connected to the projectile and target remnants. Initial state radiation may give extra gluon kinks, which are ordered in rapidity. (b) A second hard scattering would naively be expected to give two new strings connected to the remnants. (c) In the fits to data the gluons are colour reconnected, so that the total string length becomes as short as possible.

G. Gustafson, Acta Phys.Polon.B40:1981-1996,2009

taken from Stefan Gieseke©

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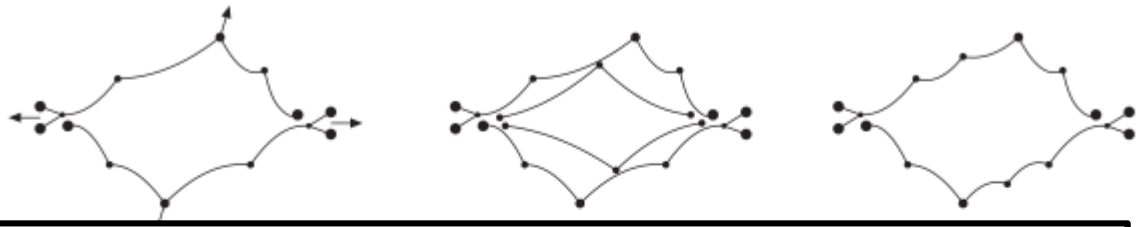

The tune 4C (Pythia 8.1.2), uses a model where either all or none of the final-state partons of a MPI system are attached to the string pieces of a higher-p_T system, in a way so as to keep the total string length minimal.

G. Gustafson, Acta Phys.Polon.B40:1981-1996,2009

taken from Stefan Gieseke©

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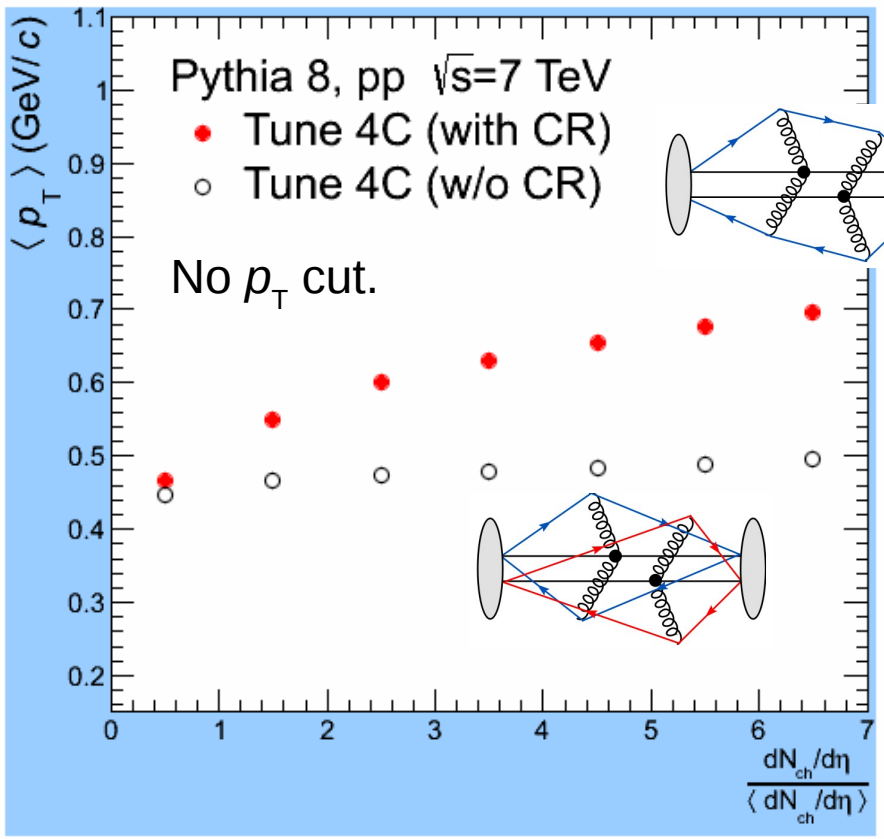
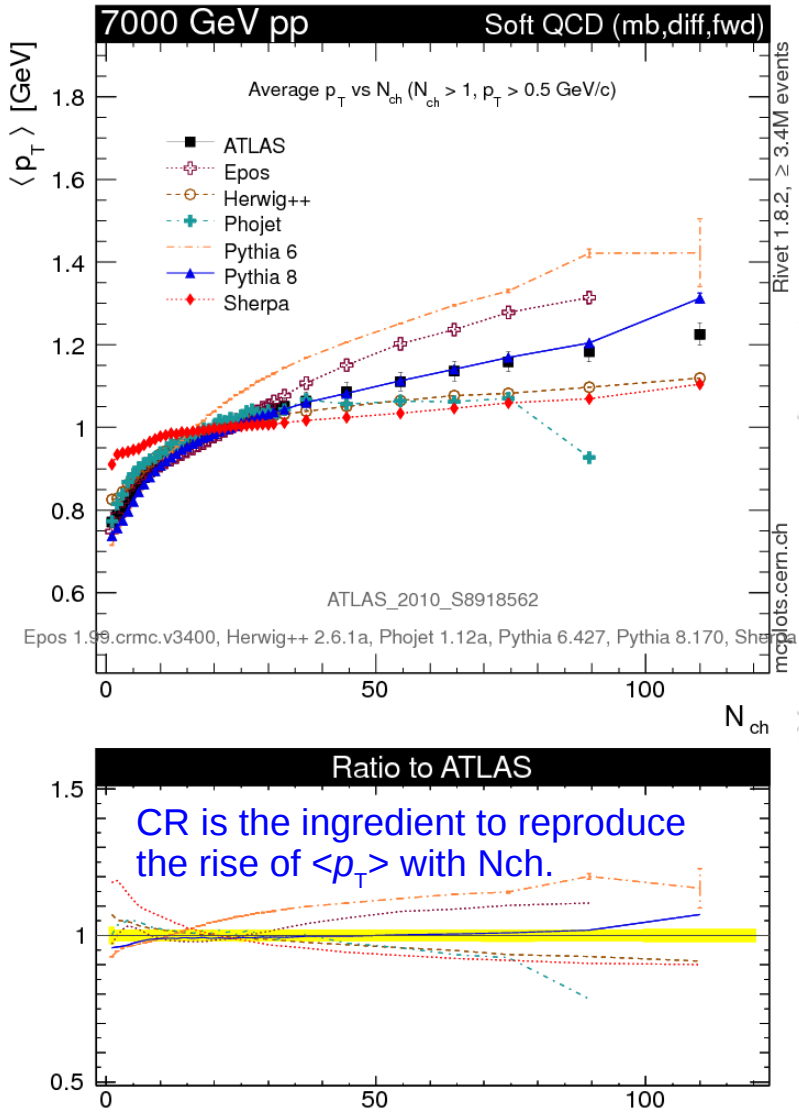
CR is needed to describe data

CR is the mechanism which produces the rise of $\langle p_T \rangle$ with multiplicity





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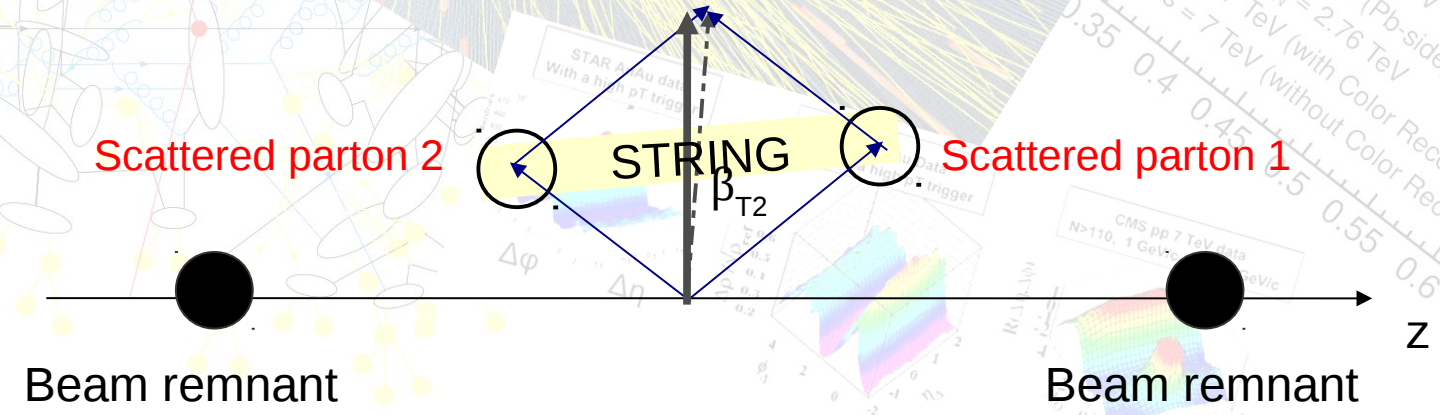
But also we discovered that CR produces *flow-like* effects

- A string piece moving with some transverse velocity tends to transfer that velocity to the particle produced from it, albeit with large fluctuations, thereby giving larger transverse momenta to heavier hadrons.
- A string piece has a larger transverse velocity the closer to each other the two endpoint partons are moving, which is precisely what is favored by CR scenarios intended to reduce the string length.



A. Ortiz et al., Phys. Rev. Lett. 111, 042001, 2013.

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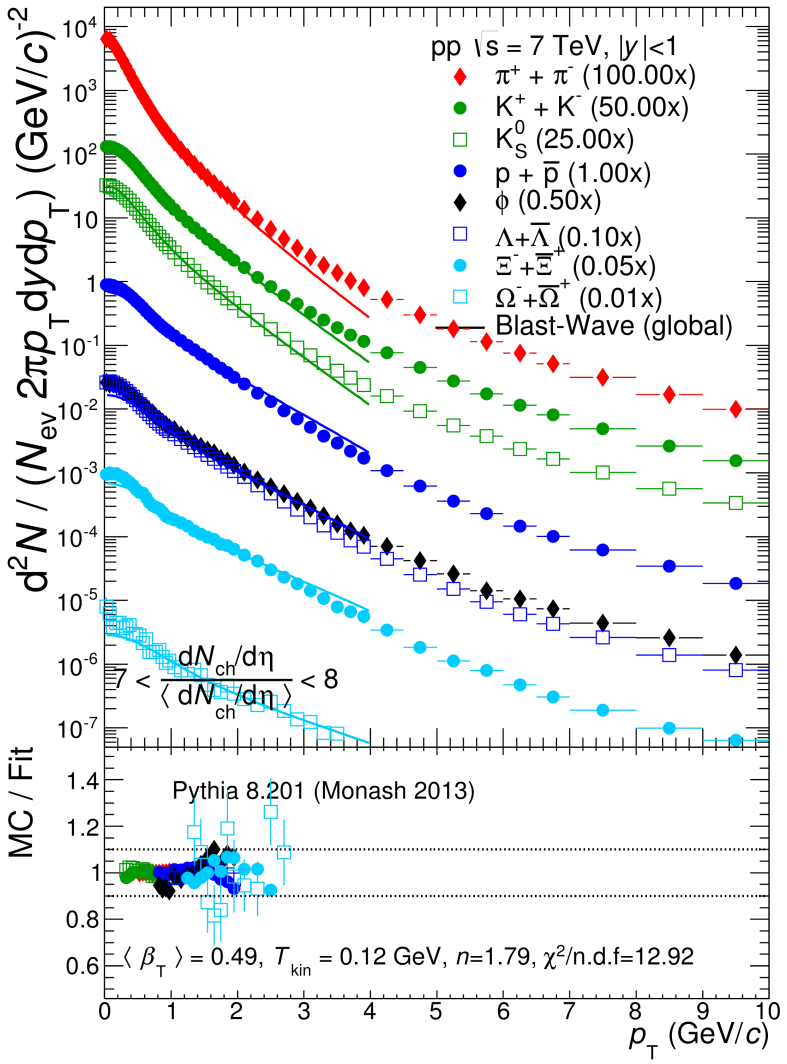
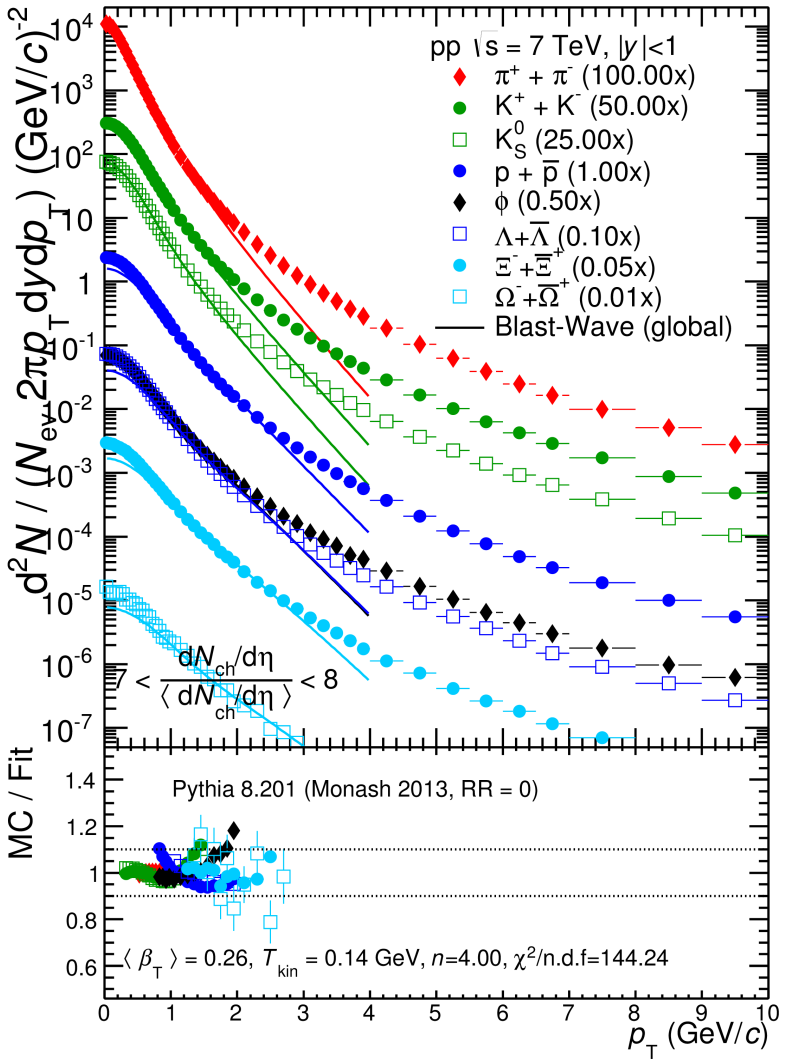
Hydro model fitted to p_T spectra

MC, Pythia CR, pp



MC, Pythia no CR, pp



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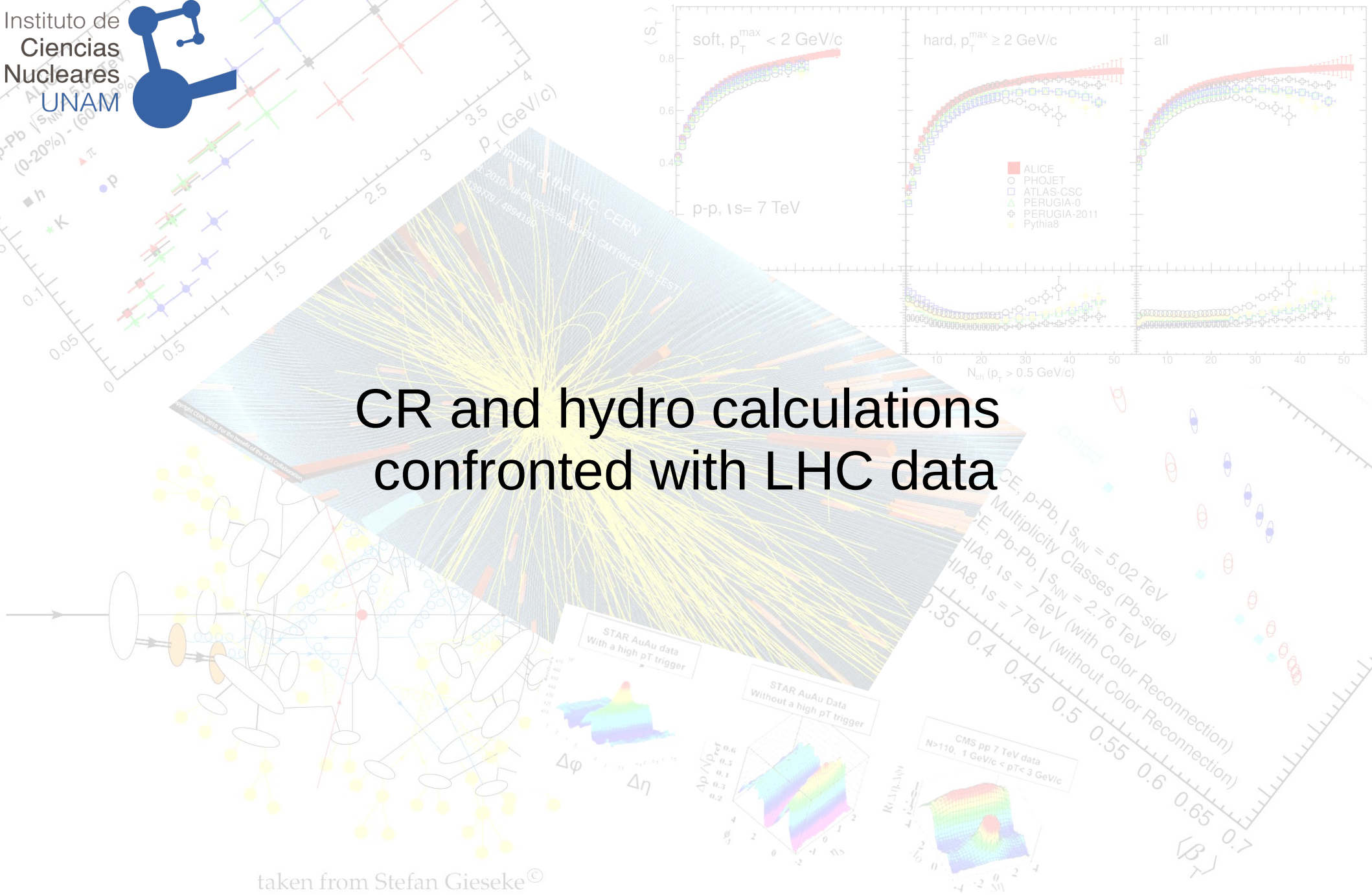
CR and hydro calculations confronted with LHC data



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Average p_T vs m

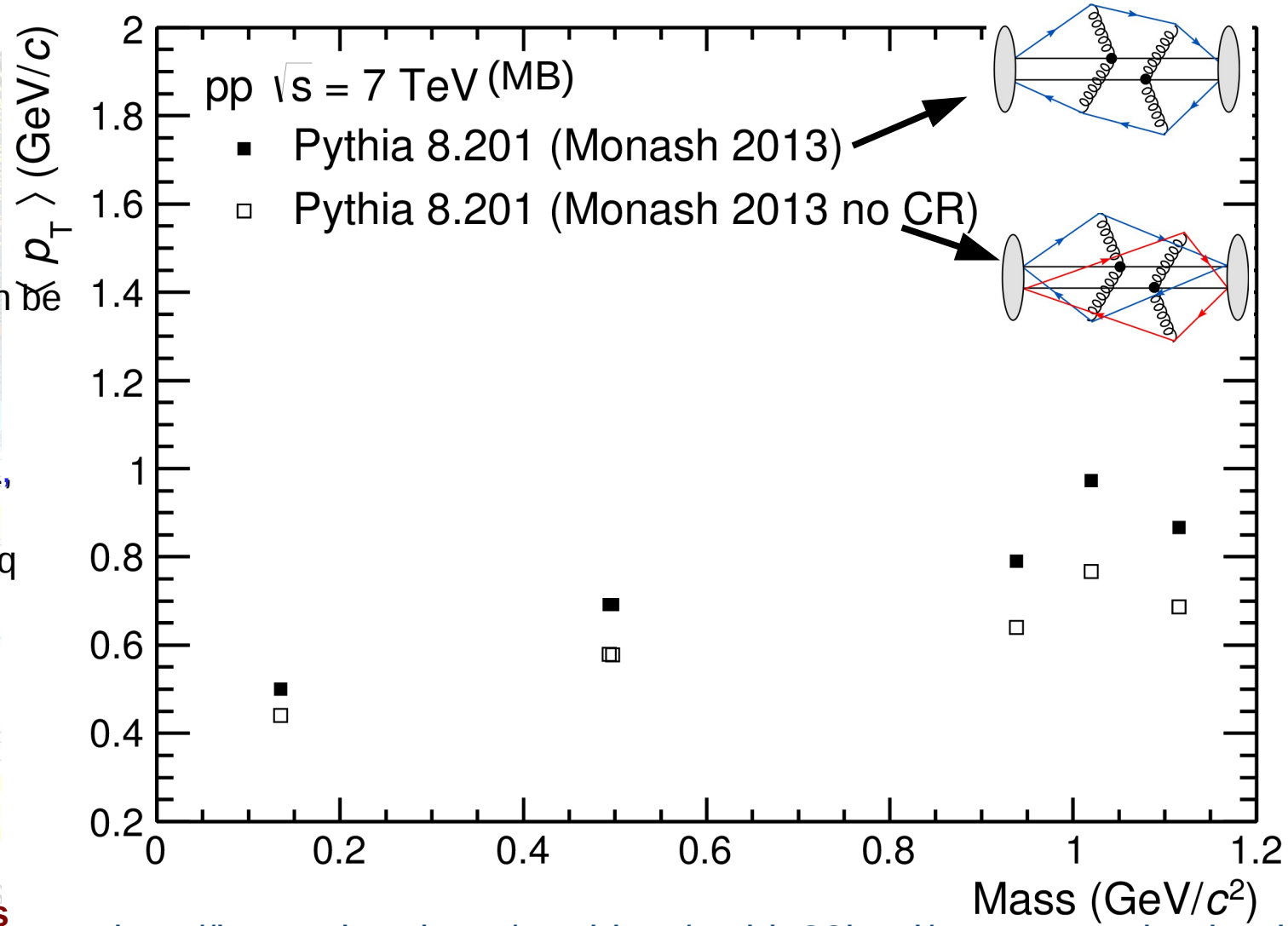
Pythia 8.201:
T. Sjöstrand et al., arXiv:1410.3012

Tune Monash 2013.
P. Skands et al., EPJ C74 (2014) 8, 3024.

In Pythia 8, the average p_T can be affected by:

- Collective *flow-like* due to transversely boosted string pieces ($\langle p_T \rangle \sim k*m$, PRL 11, 042001, 2013).
- At each string breaking the q and qbar are supposed to receive opposite and compensating p_T kicks according to a Gaussian distribution in p_x and p_y separately (Gaussian fragmentation p_T).

Different scaling for baryons and mesons?



http://home.thep.lu.se/~torbjorn/pythia82html/Fragmentation.html

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Scaling with m/n_q

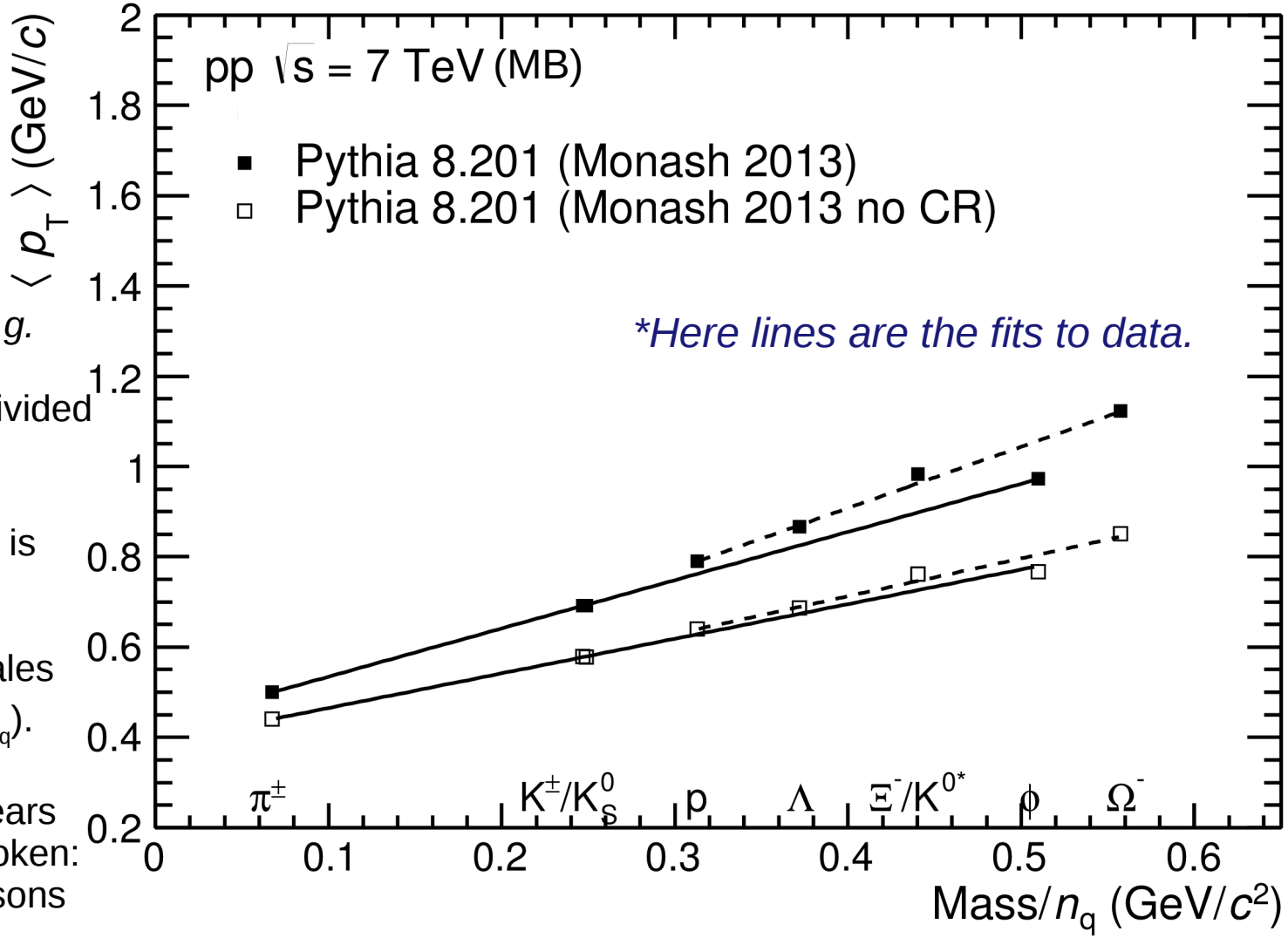
Pythia 8.201:
T. Sjöstrand et al., arXiv:1410.3012

Tune Monash 2013.
P. Skands et al., EPJ C74 (2014) 8, 3024.

To facilitate the comparison (*e.g.* slopes) between bayons and mesons, the hadron mass is divided by the number of quark (n_q).

When color reconnection (CR) is switched off (independent fragmentation of the partonic systems), mean p_T roughly scales with m/n_q, $\langle p_T \rangle \sim$ constant*(m/n_q).

With CR, *flow-like* effects appears and the universal scaling is broken: the $\langle p_T \rangle$s for baryons and mesons scale with m/n_q, independently.



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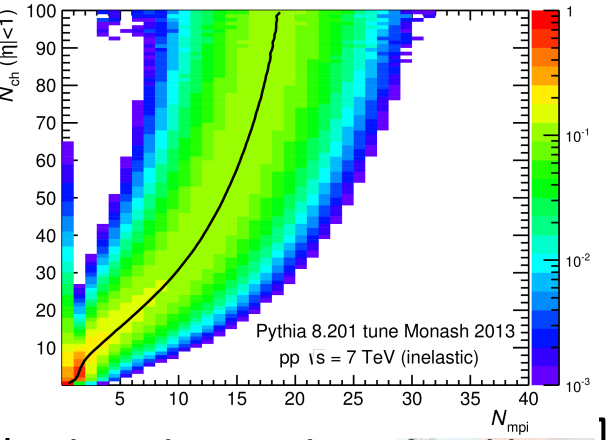
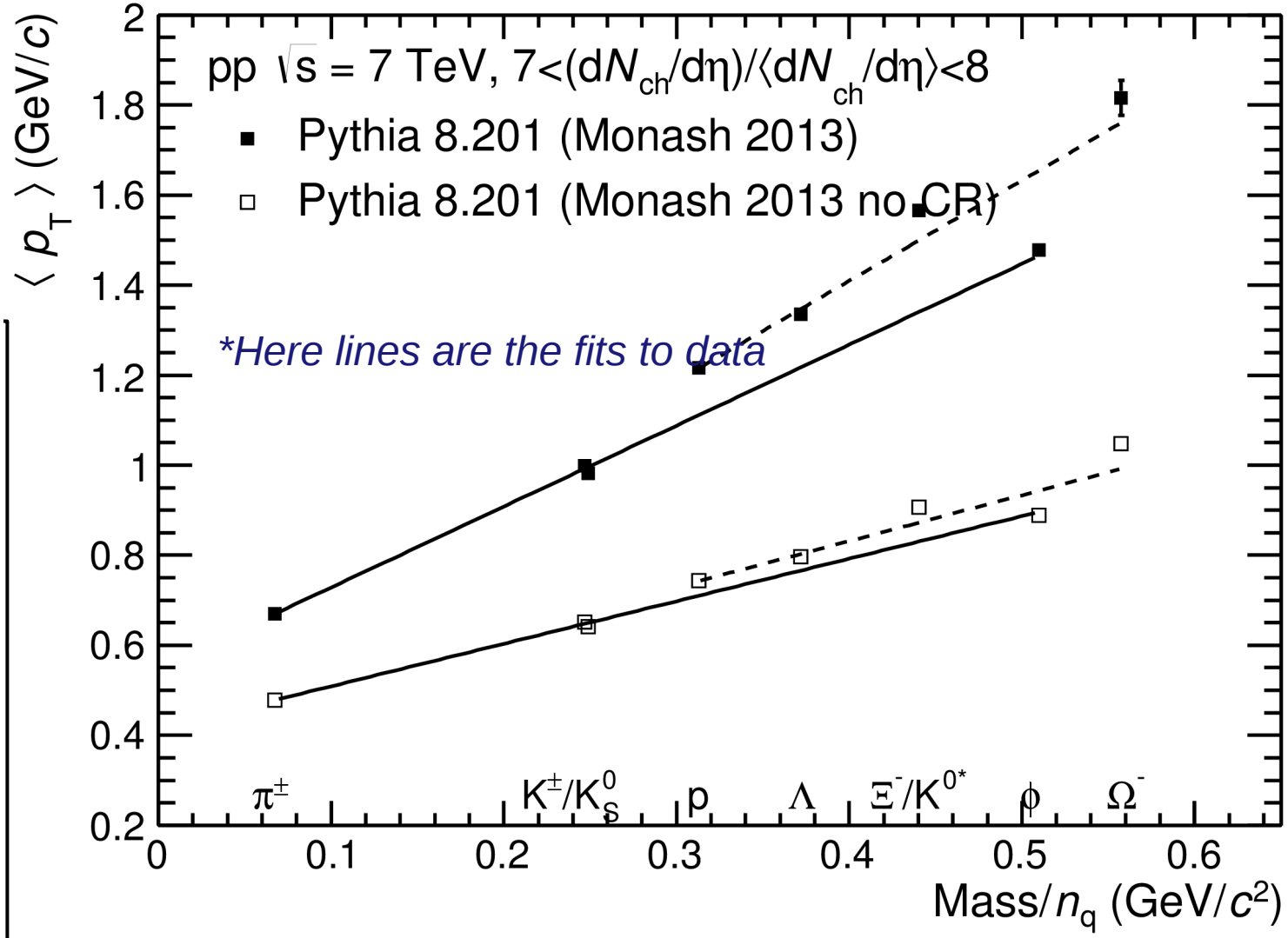
Pythia: high multiplicity



When the number of multi-parton interactions is increased (large multiplicity) we observe an overall increase of the average p_T.

The mean p_T is larger when CR is activated. Baryons have an overall larger mean p_T than mesons.

Without CR, $\langle p_T \rangle$ is still closer to the universal scaling with m/n_q.



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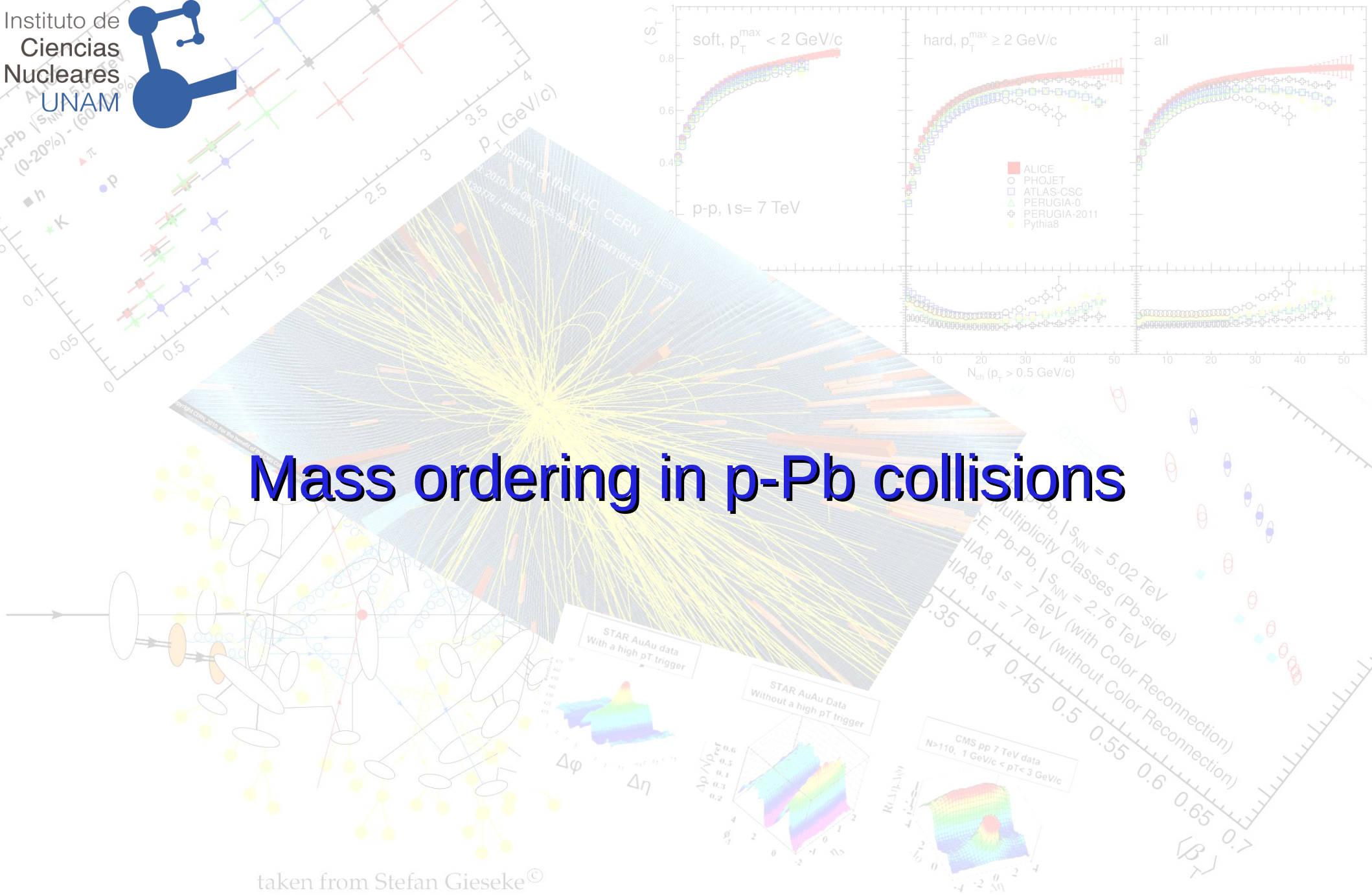
Mass ordering in p-Pb collisions



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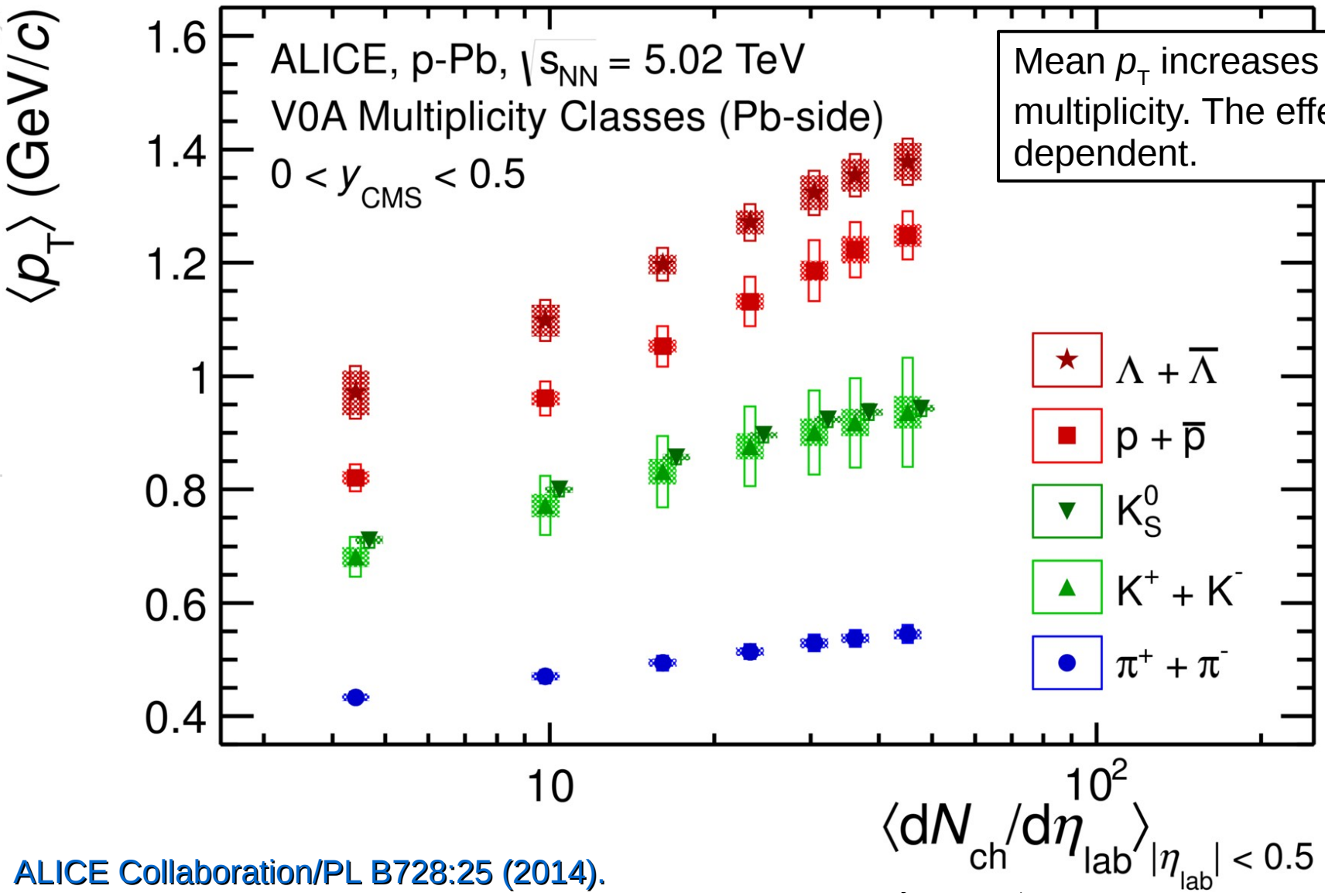
$\langle p_T \rangle$ vs N_{ch} in p-Pb collisions



Mean p_T increases with the event multiplicity. The effect is mass dependent.

ALICE Collaboration/PL B728:25 (2014).

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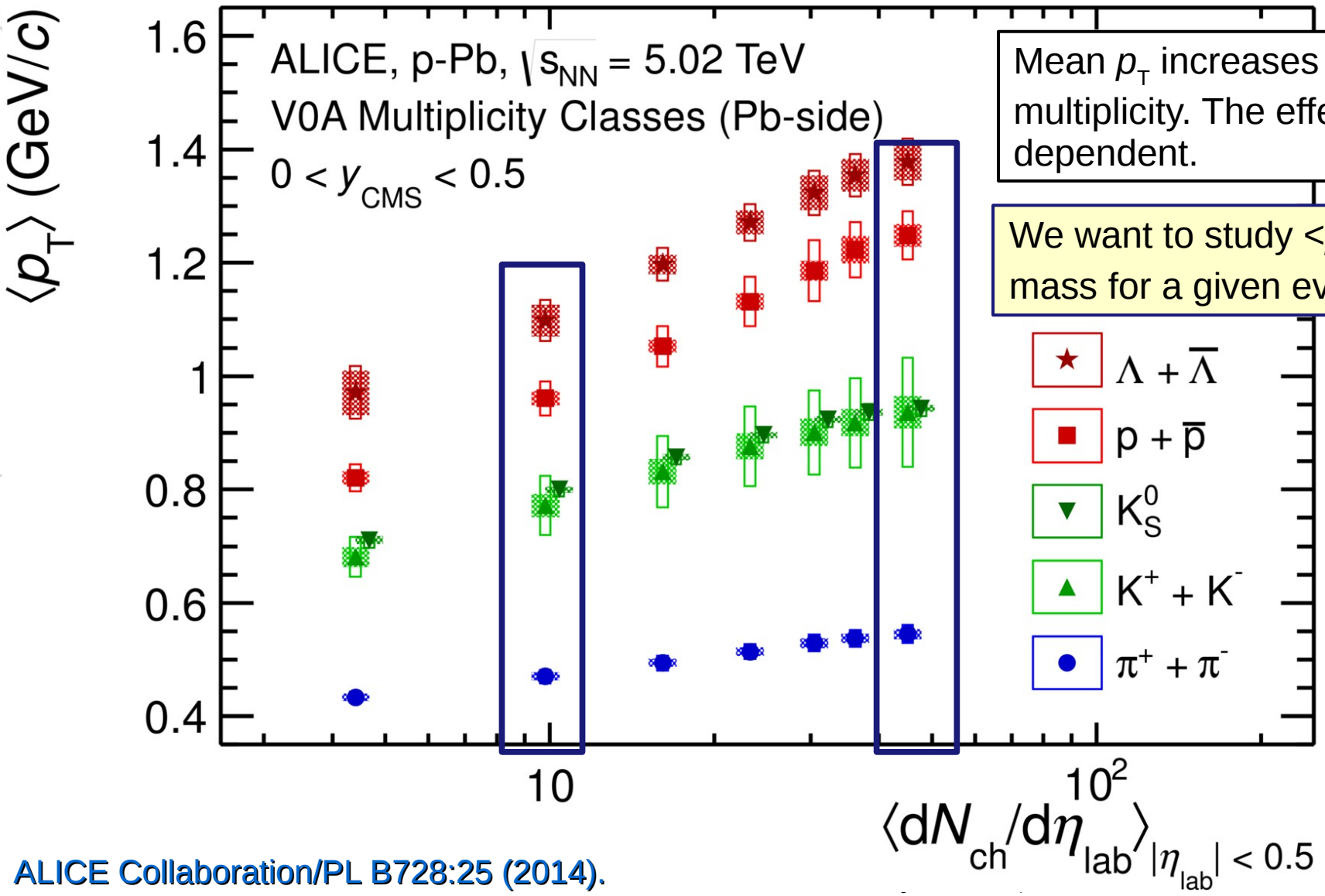
$\langle p_T \rangle$ vs N_{ch} in p-Pb collisions



Mean p_T increases with the event multiplicity. The effect is mass dependent.

We want to study $\langle p_T \rangle$ vs hadron mass for a given event class

ALICE Collaboration/PL B728:25 (2014).

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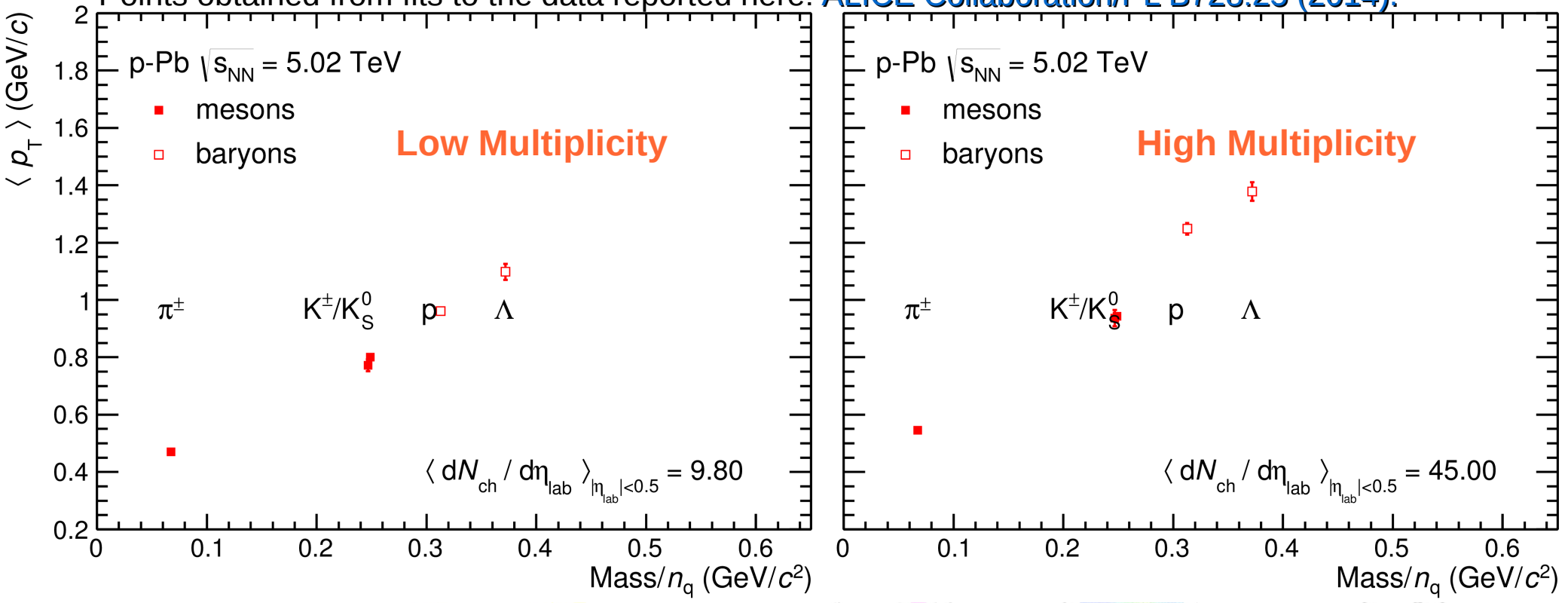
$\langle p_T \rangle$ vs hadron mass

Mass (m) is divided by the number of quarks constituents (n_q).

Points obtained from fits to the data reported here: ALICE Collaboration/PL B728:25 (2014).



Mean p_T seem to scale with m/n_q, $\langle p_T \rangle \sim c(m/n_q)$.

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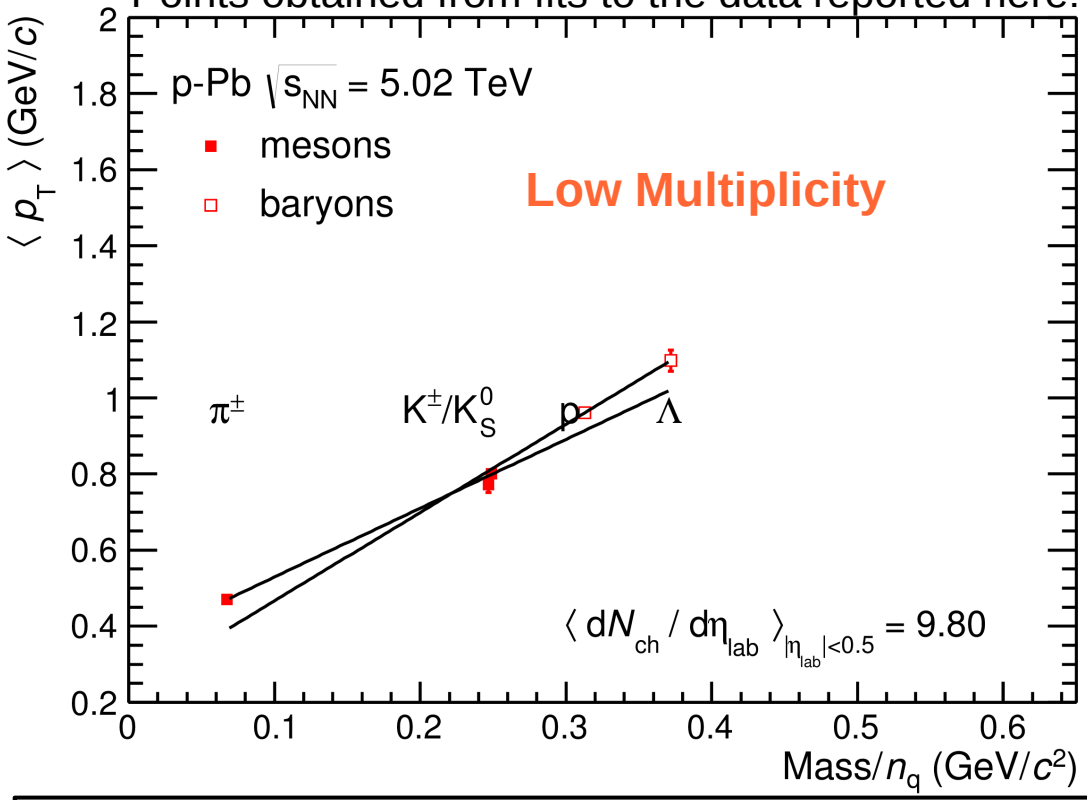
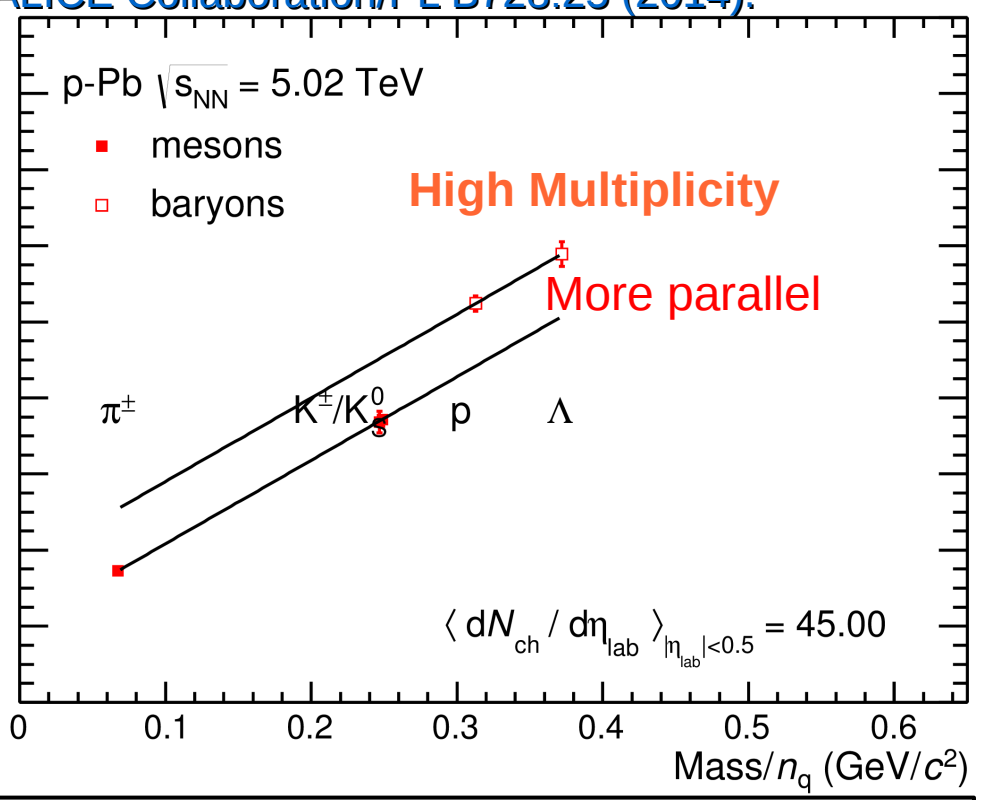
$\langle p_T \rangle$ vs hadron mass

Mass (m) is divided by the number of quarks constituents (n_q).

Points obtained from fits to the data reported here: ALICE Collaboration/PL B728:25 (2014).





Larger *c* is obtained for baryons than for mesons. The data are fitted to linear functions, the parameters as a function of multiplicity are studied in the next slides ...

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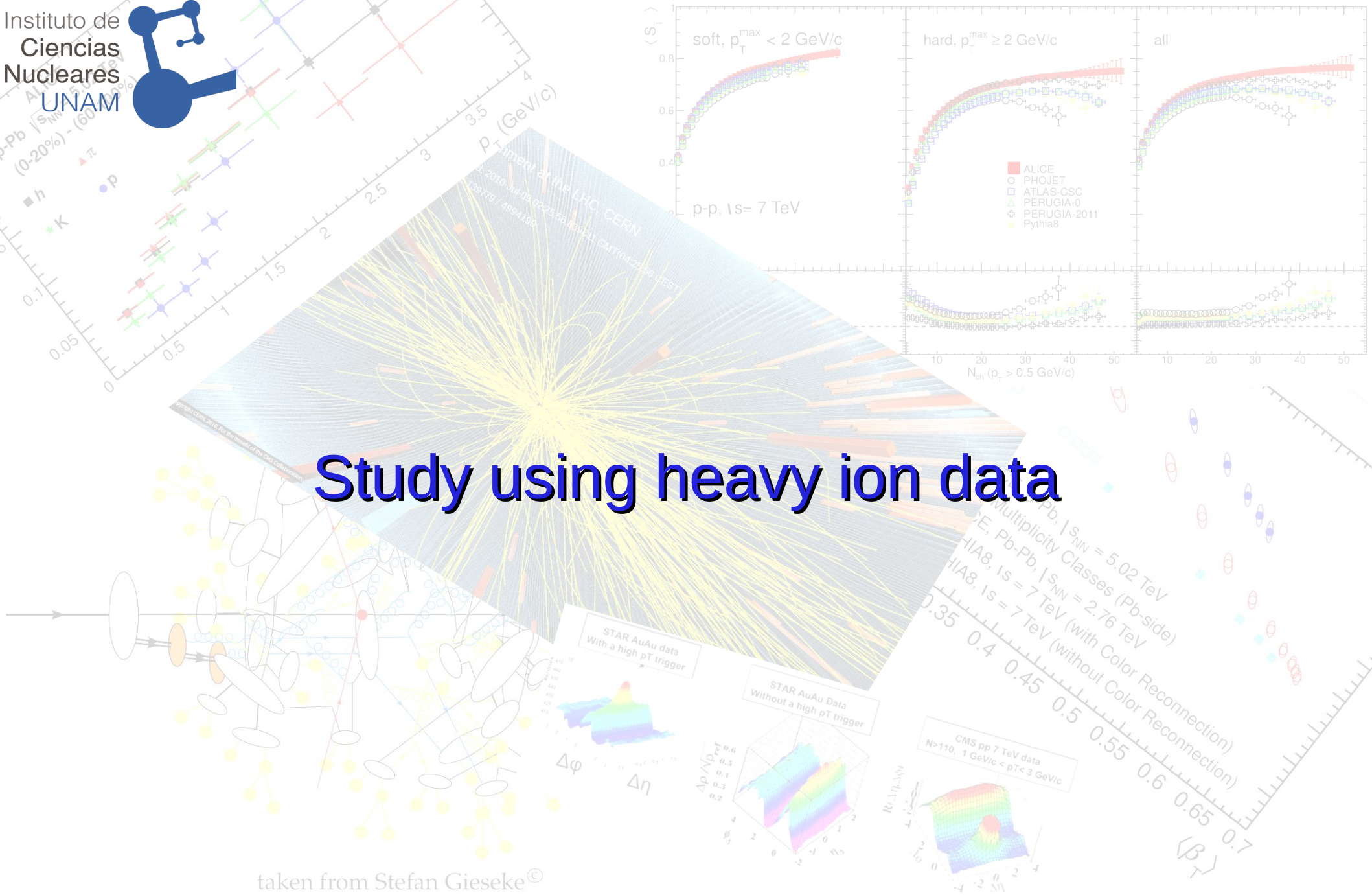
Study using heavy ion data



taken from Stefan Gieseke©

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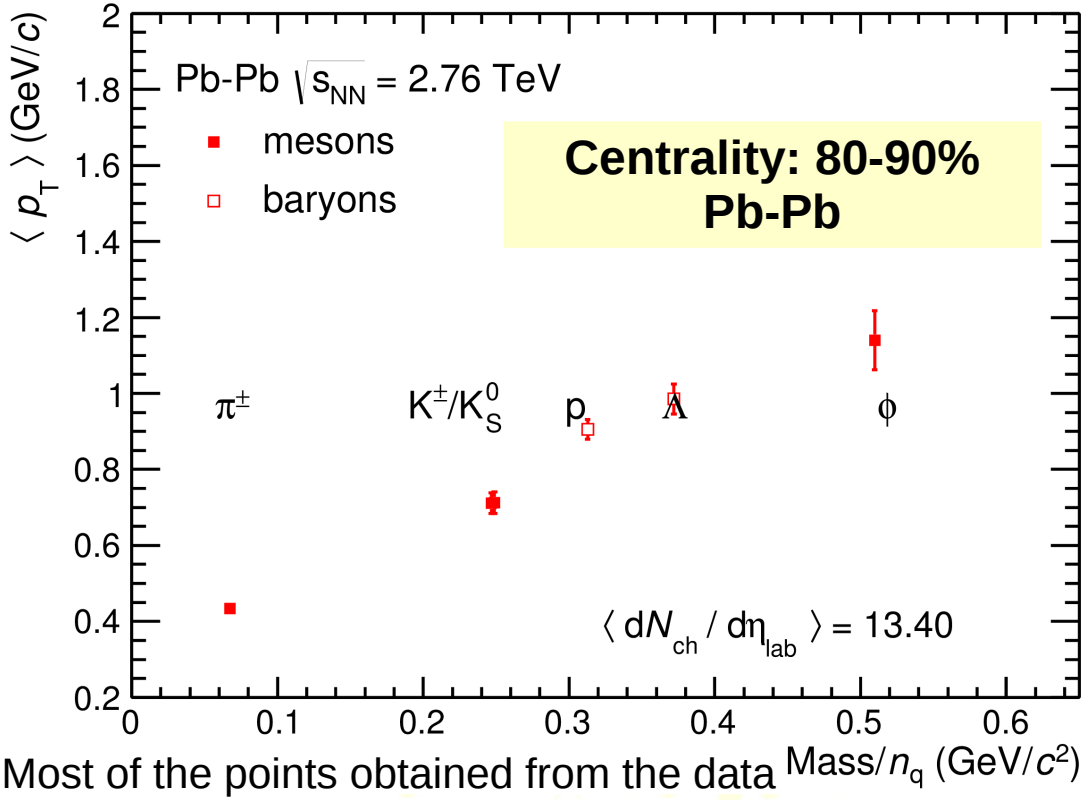
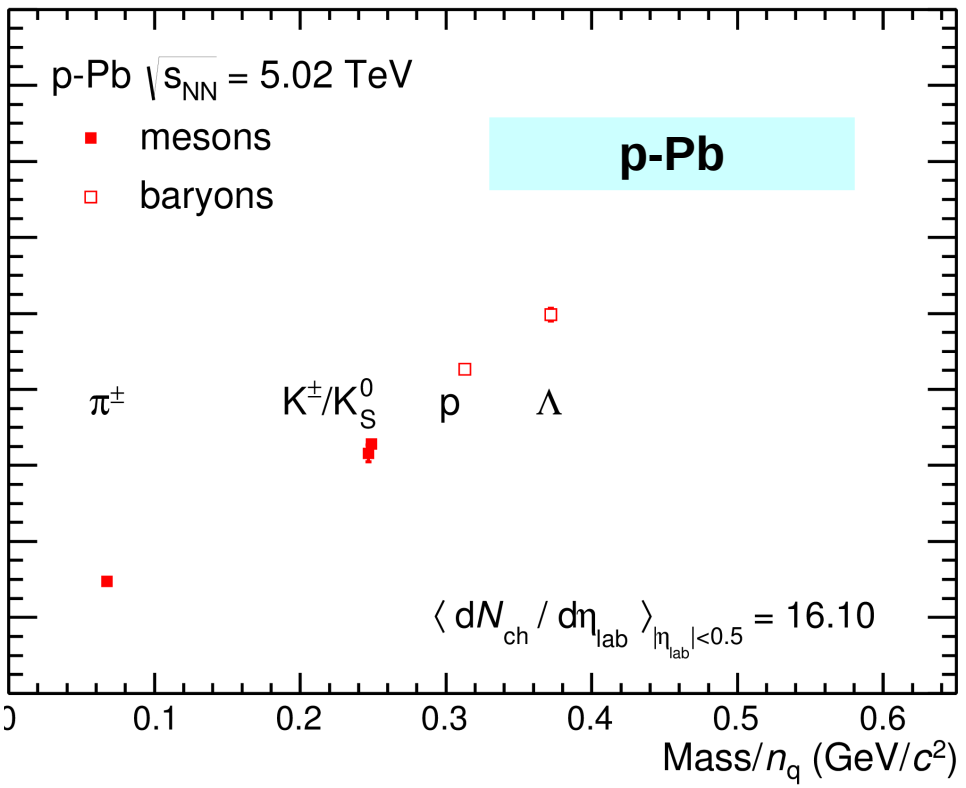
$\langle p_T \rangle$ vs m/n_q, comparison with Pb-Pb

Low multiplicity events





Most of the points obtained from the data reported here:
ALICE Collaboration/PR C88, 044910 (2013).
ALICE Collaboration/PL B728:25 (2014).
ALICE Collaboration/arXiv:1404.0495

Mean p_T for Λ and K^0_s in Pb-Pb collisions are derived from spectra reported here:
ALICE Collaboration/PRL. 111 (2013) 222301.

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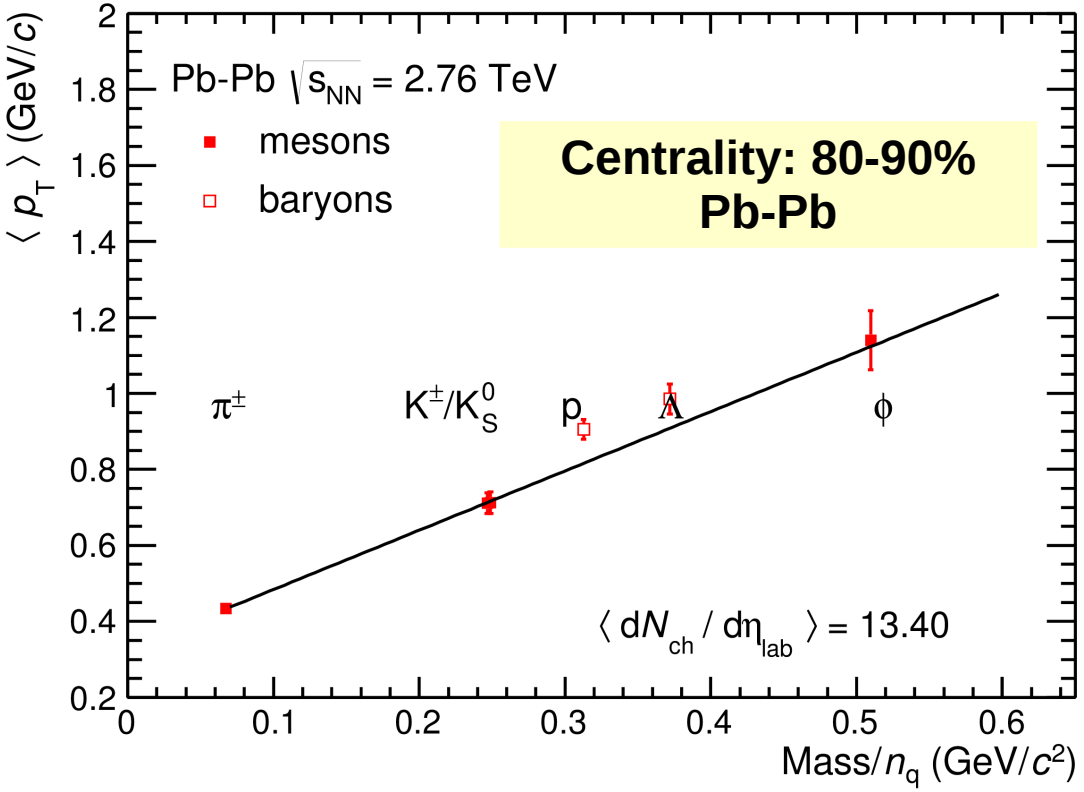
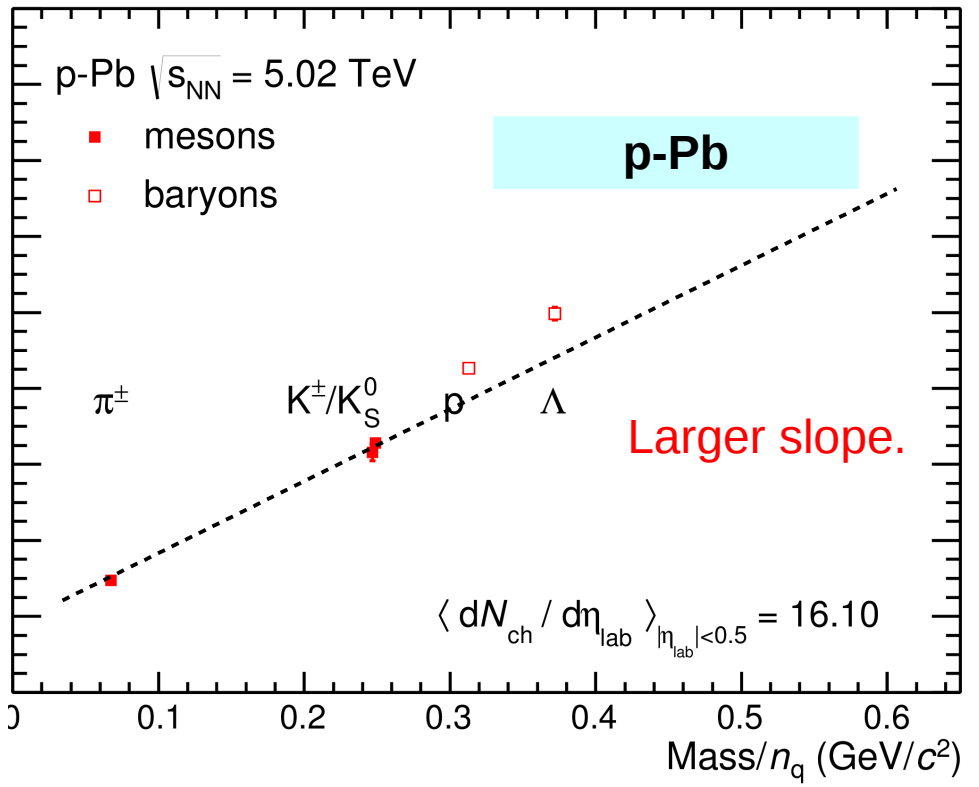
$\langle p_T \rangle$ vs m/n_q, comparison with Pb-Pb

Low multiplicity events





Close to the universal scaling: **$\langle p_T \rangle$ ~ constant*(m/n_q)**

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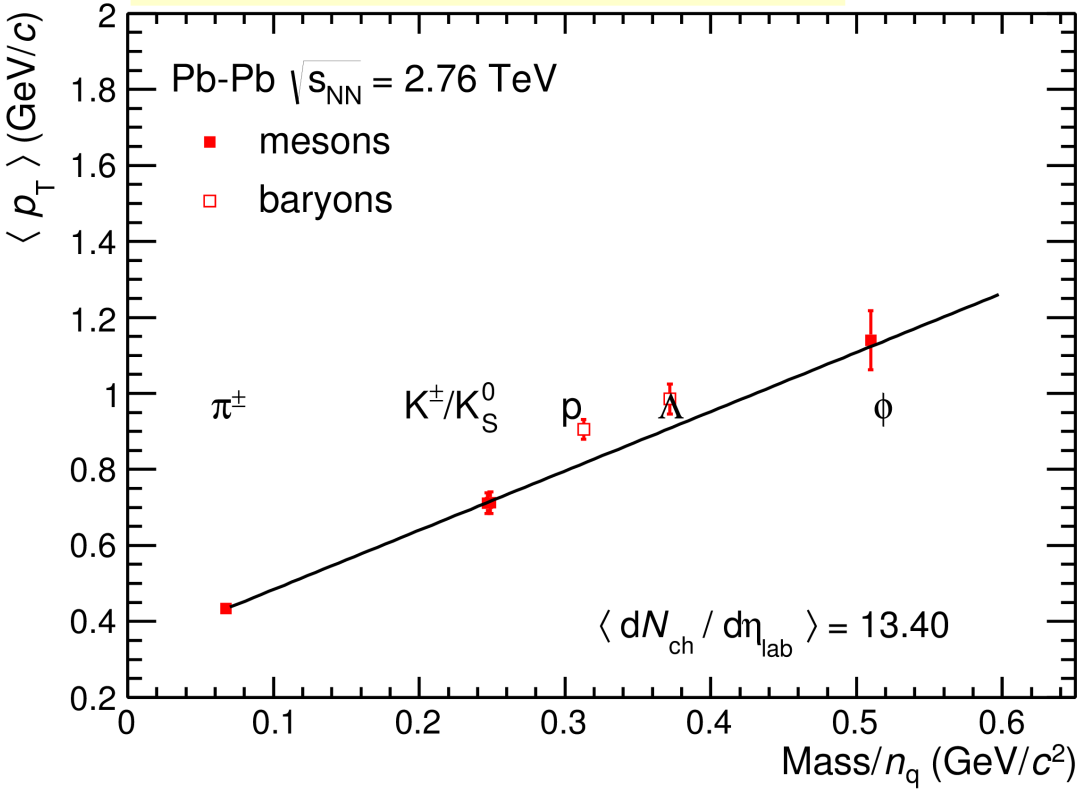
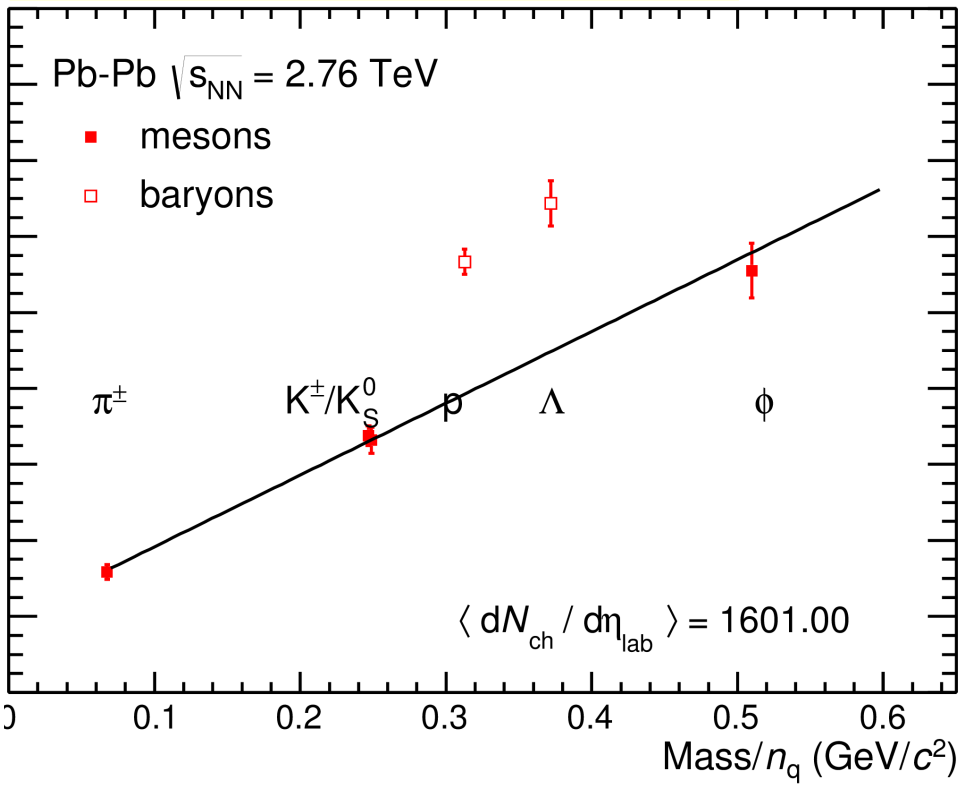
$\langle p_T \rangle$ vs m/n_q, comparison with Pb-Pb

Central vs Peripheral Pb-Pb collisions

Centrality: 80-90% Pb-Pb



Centrality: 0-5% Pb-Pb



In the most central Pb-Pb collisions a deviation from the universal scaling, **$\langle p_T \rangle$ ~ constant*(m/n_q)**, is observed.

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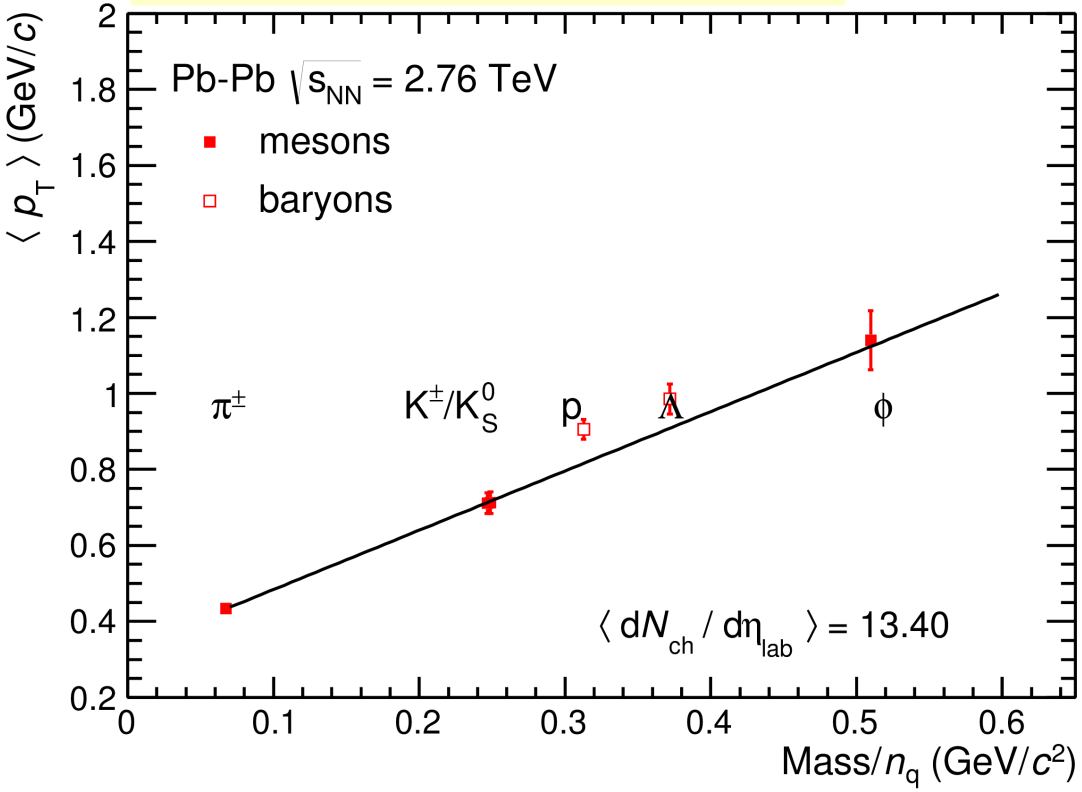
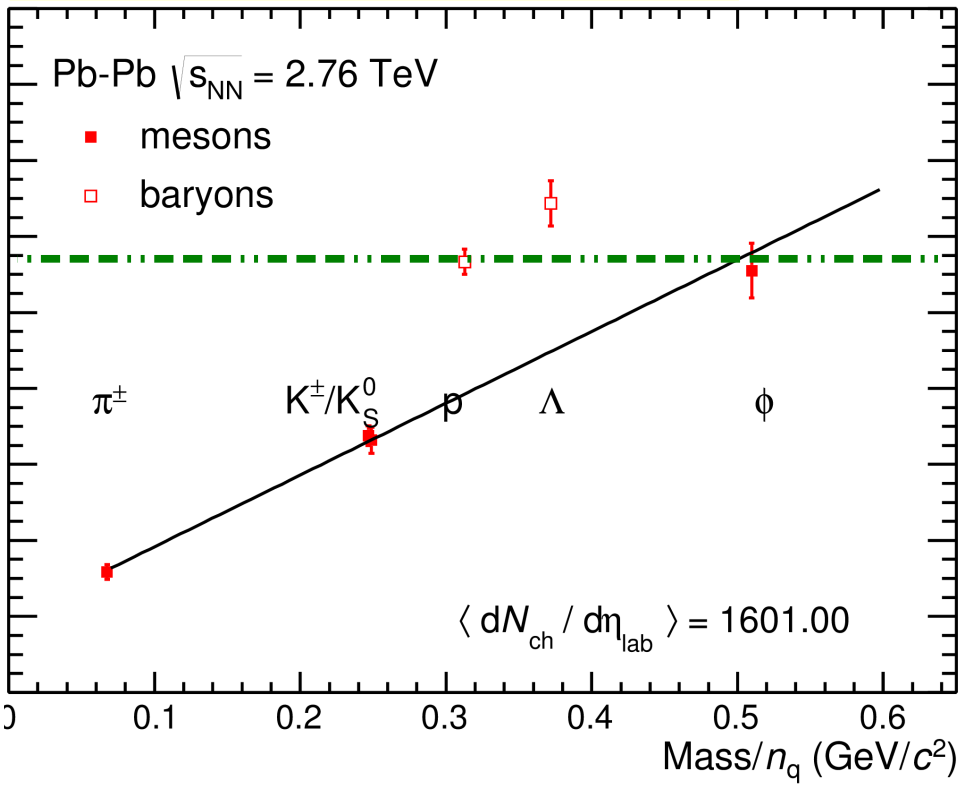
$\langle p_T \rangle$ vs m/n_q, comparison with Pb-Pb

Central vs Peripheral Pb-Pb collisions

Centrality: 80-90% Pb-Pb



Centrality: 0-5% Pb-Pb



In central Pb-Pb collisions, the φ meson $\langle p_T \rangle$ is the same to that for protons.

Is this an universal scaling with hadron mass and not with *m*/*n*$_q$?

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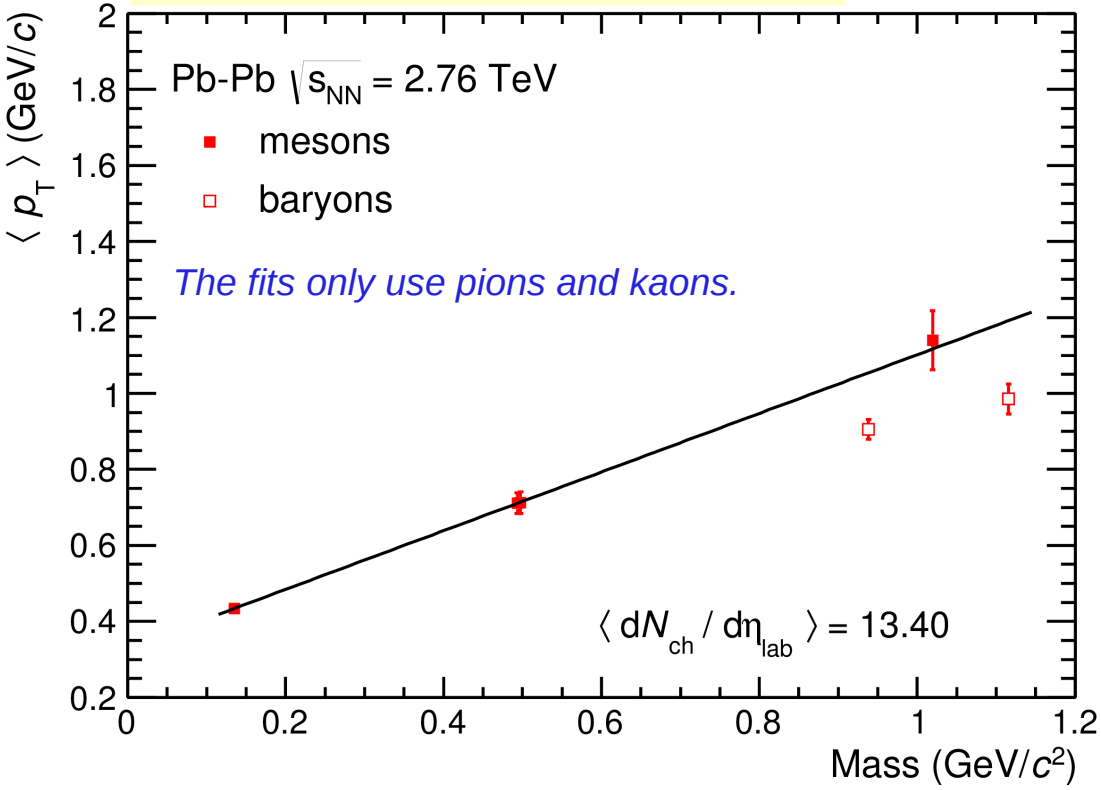
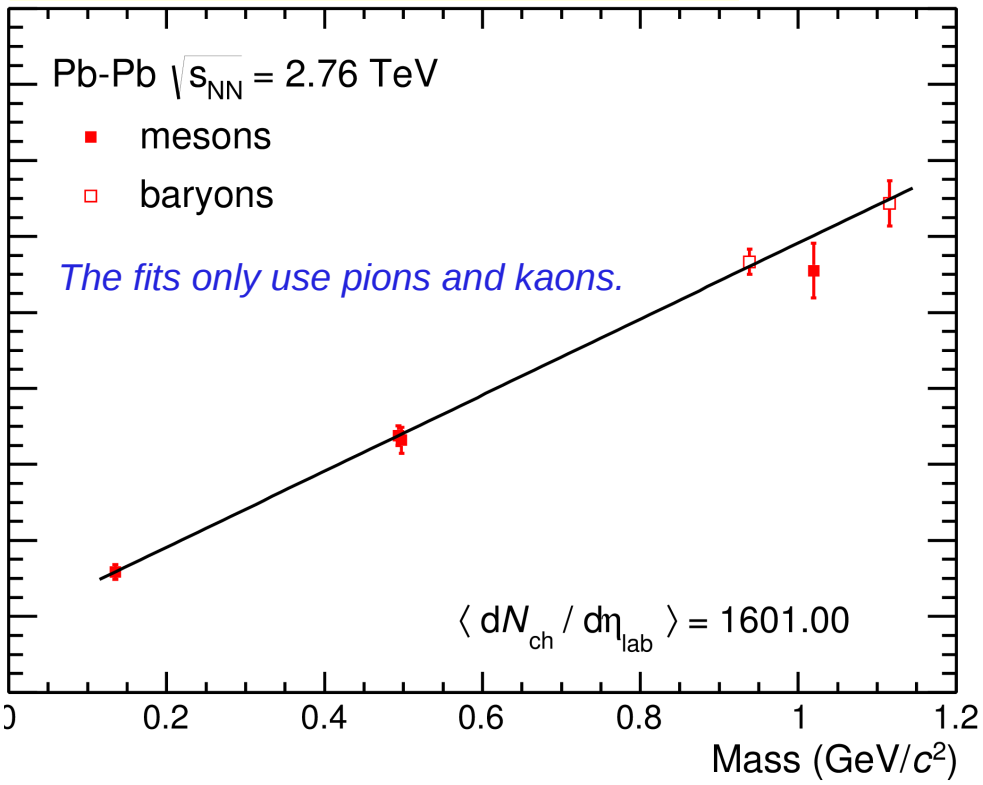
$\langle p_T \rangle$ vs m/n_q, comparison with Pb-Pb

Central vs Peripheral Pb-Pb collisions

Centrality: 80-90% Pb-Pb



Centrality: 0-5% Pb-Pb



Actually, **the answer is YES**, but this scaling is only observed in central (0-40%) Pb-Pb collisions (the effect is not present in p-Pb events).

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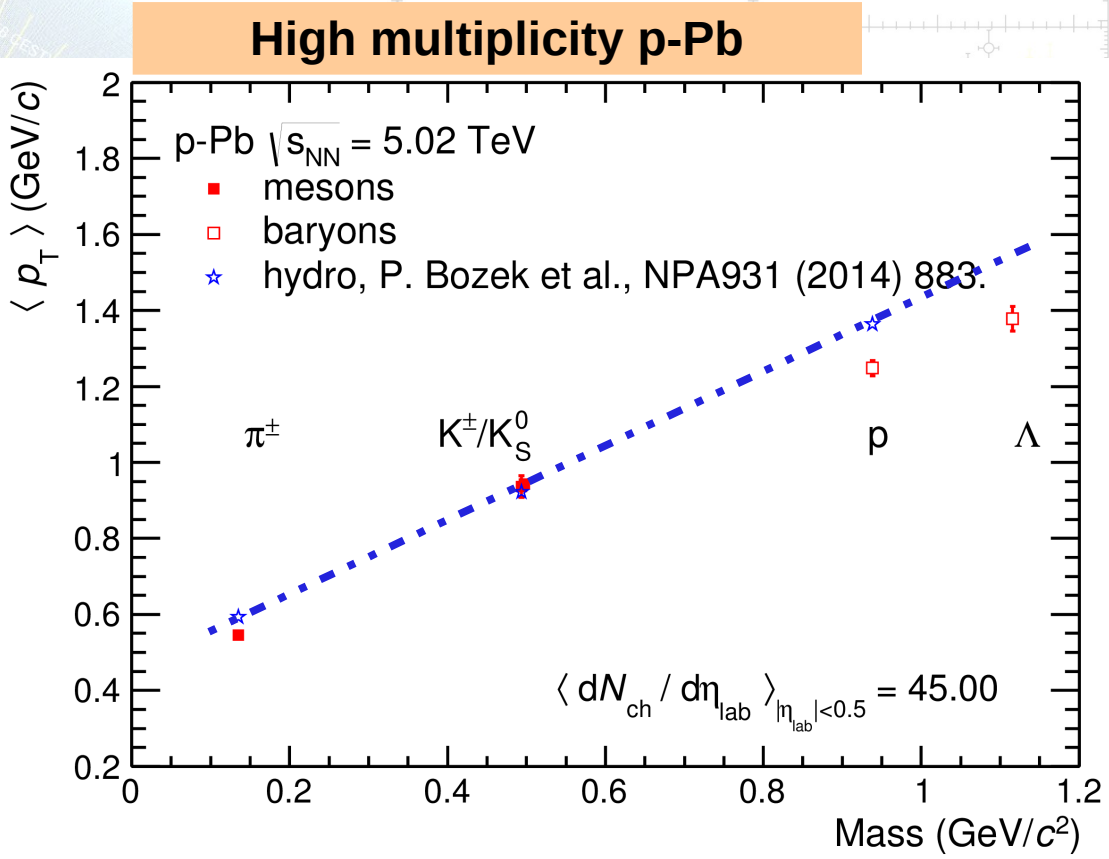
For p-Pb, the scaling with mass is seen in hydro calculations but not in data

Actually, the calculations for p-Pb collisions gives a scaling of $\langle p_T \rangle$ with the hadron mass. Here we do not observe the dependence with the number of quark constituents.

→ p-Pb data behave like Pythia with MPI and color reconnection.



taken from Stefan Gieseke©

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Summary I

From Pythia studies:

- Without color reconnection (independent fragmentation) we observe an universal scaling of $\langle p_T \rangle$ with m/n_q.
- When color reconnection is activated (*flow-like*), baryons and mesons follow different linear trends, $c_B > c_M$, for low to semi-high multiplicity. At high multiplicity, $c_B = c_M$.

From studies with data:

- pp, p-Pb and peripheral Pb-Pb data behave like Pythia with color reconnection. Is this an indication of *flow-like* in small systems?
- The central Pb-Pb collisions indicate an universal scaling of $\langle p_T \rangle$ with m, and not with m/n_q.

taken from Stefan Gieseke©

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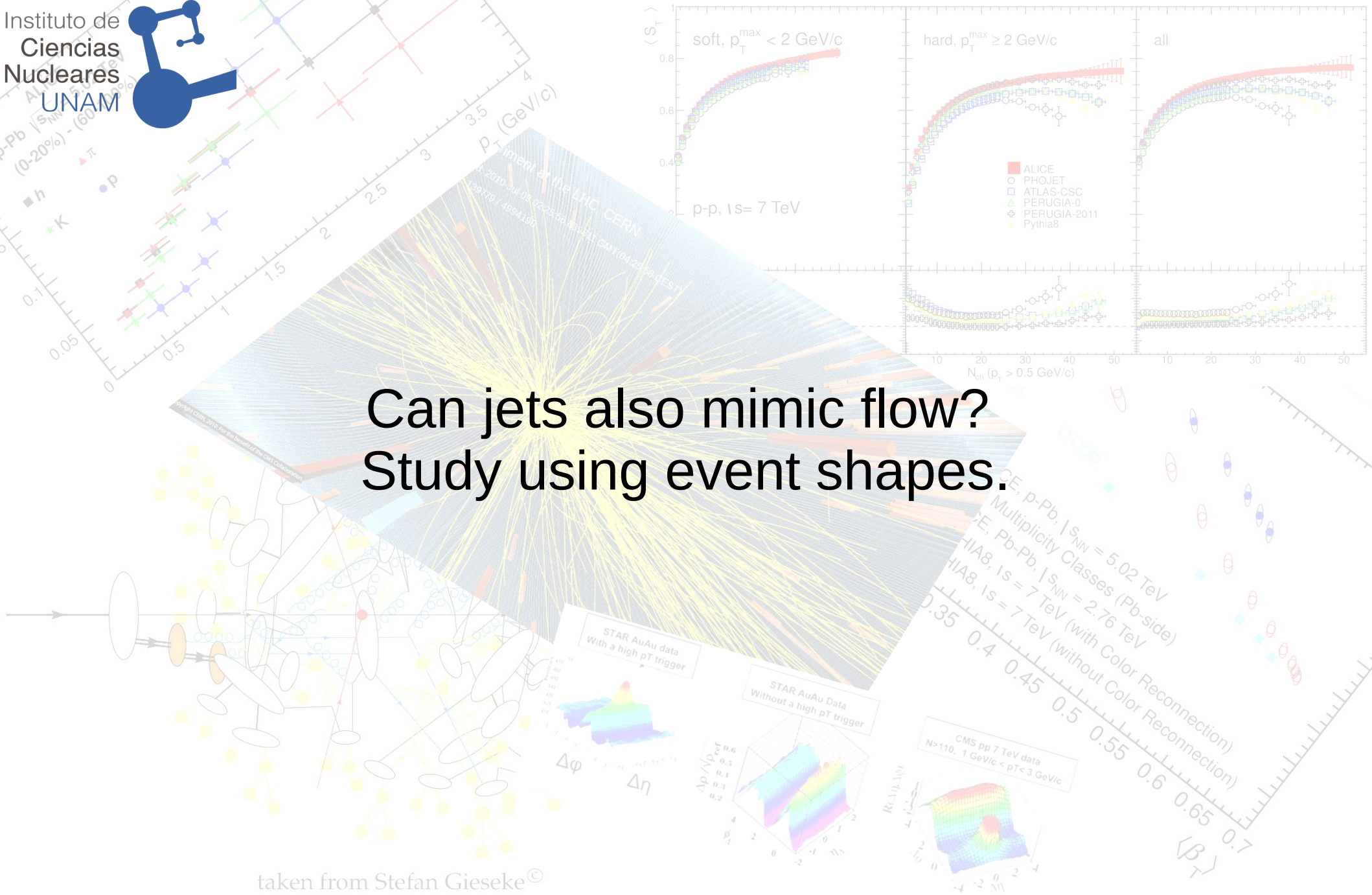

Can jets also mimic flow? Study using event shapes.

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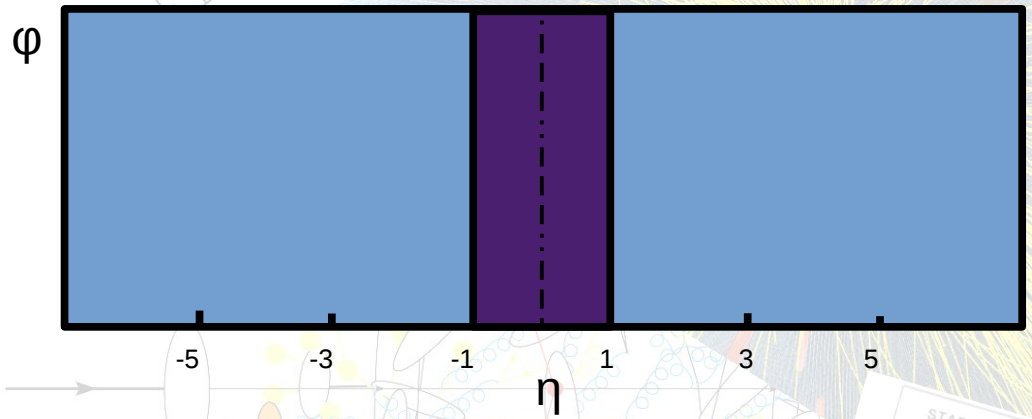
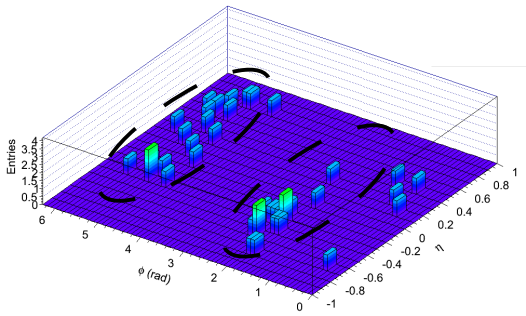
Transverse spherocity

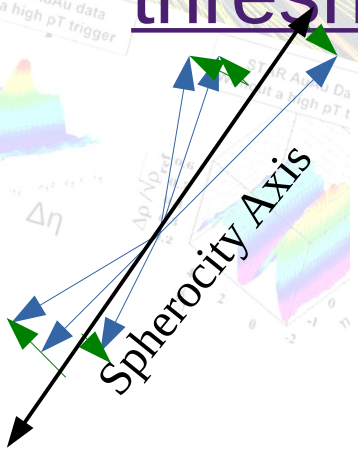
$$S_O = \frac{\pi^2}{4} \min_{\vec{n}=(n_x, n_y, 0)} \left(\frac{\sum |\vec{p}_{T_i} \times \vec{n}|}{\sum p_{T_i}} \right)^2$$



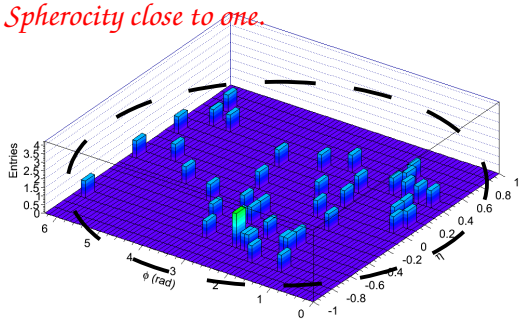
Defined for pp events having at least three primary charged hadrons within a given acceptance, $|\eta| < \eta_D$, and with transverse momentum above a threshold.

Spherocity close to zero.





Spherocity close to one.



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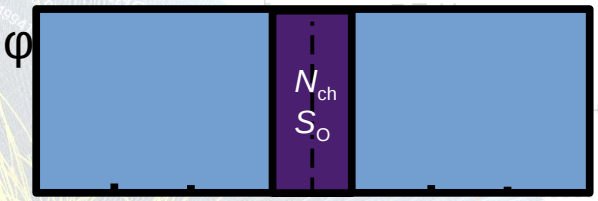
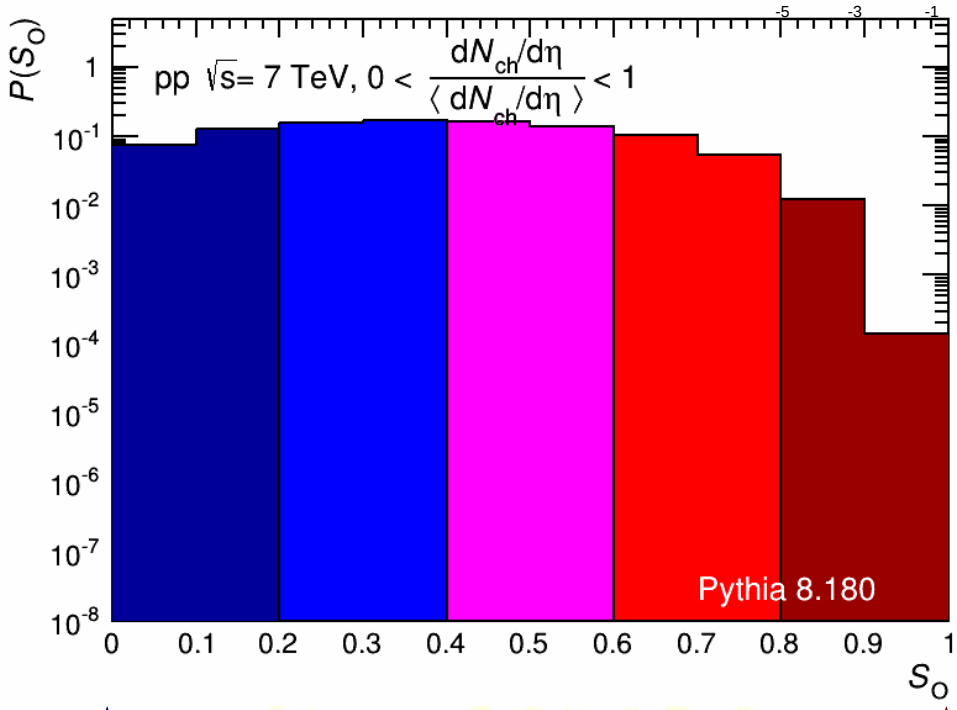
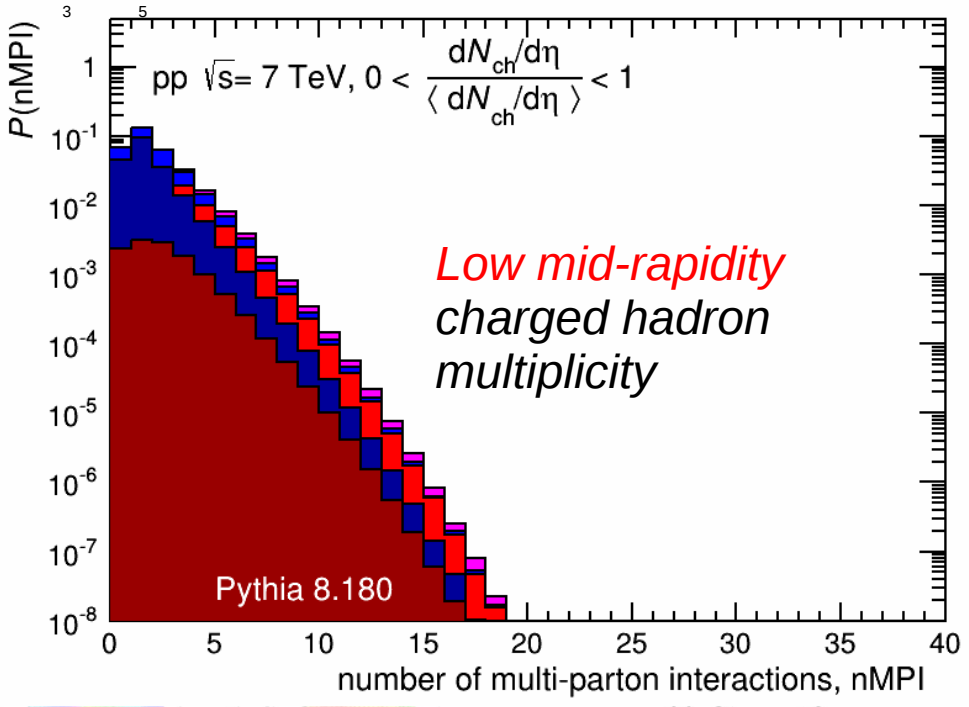
N_{ch}, S_O and MPI







Low mid-rapidity charged hadron multiplicity

Pencil-like limit

Isotropic limit

taken from Stefan Gieseke©

E. Cuautle et. al., arXiv:1404.2372

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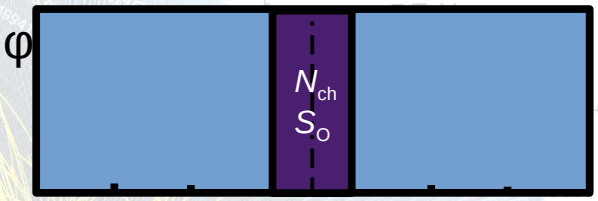
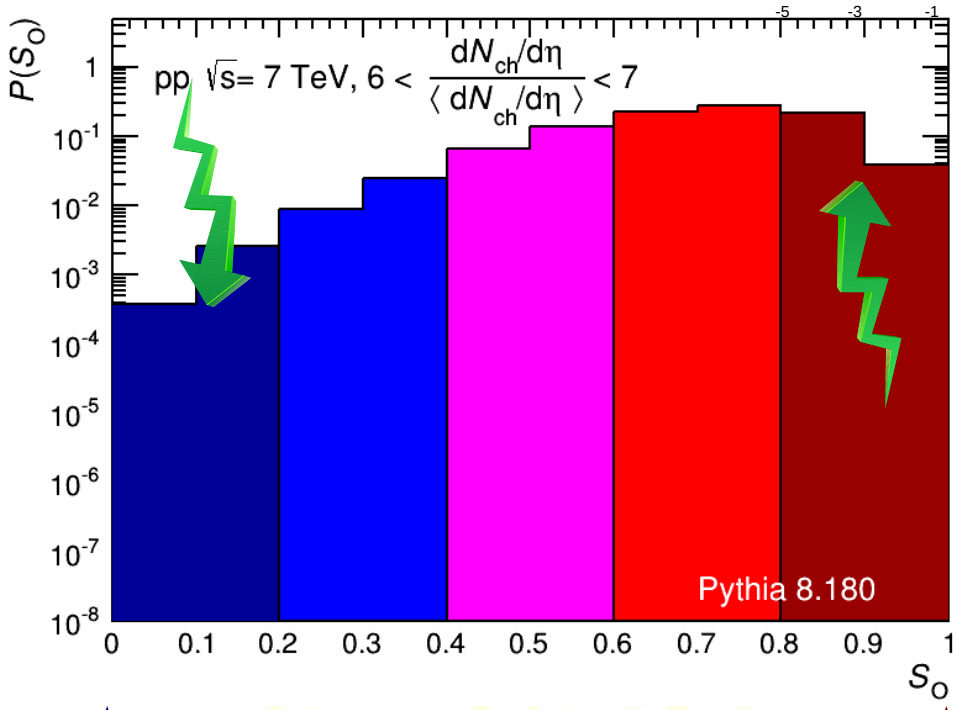
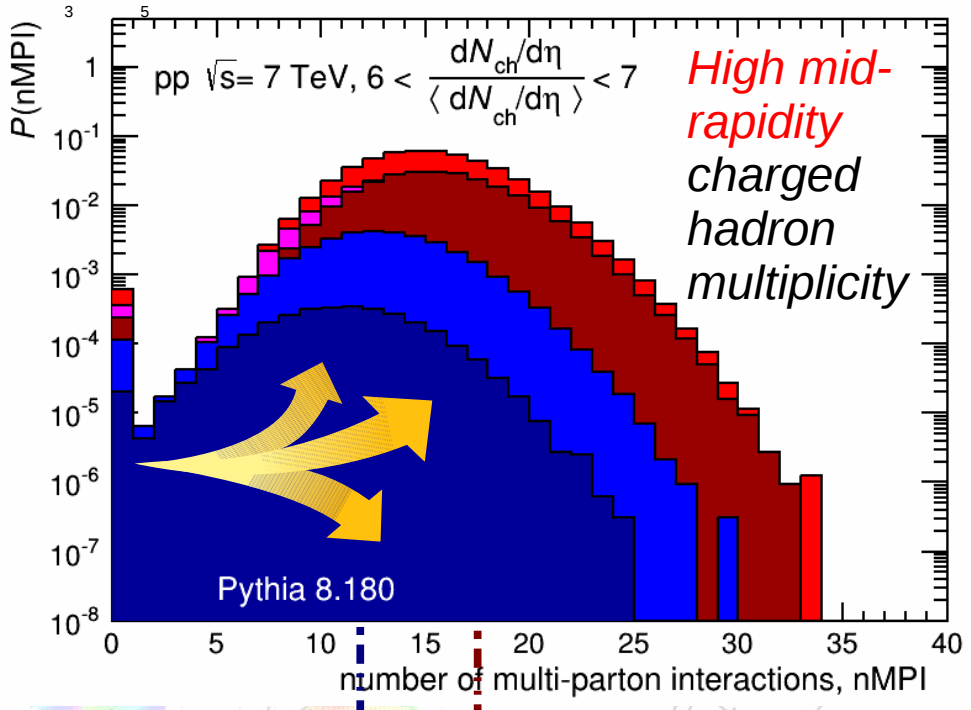
N_{ch}, S_O and MPI







High mid-rapidity charged hadron multiplicity

Pencil-like limit

Isotropic limit

E. Cuautle et. al., arXiv:1404.2372

taken from Stefan Gieseke©

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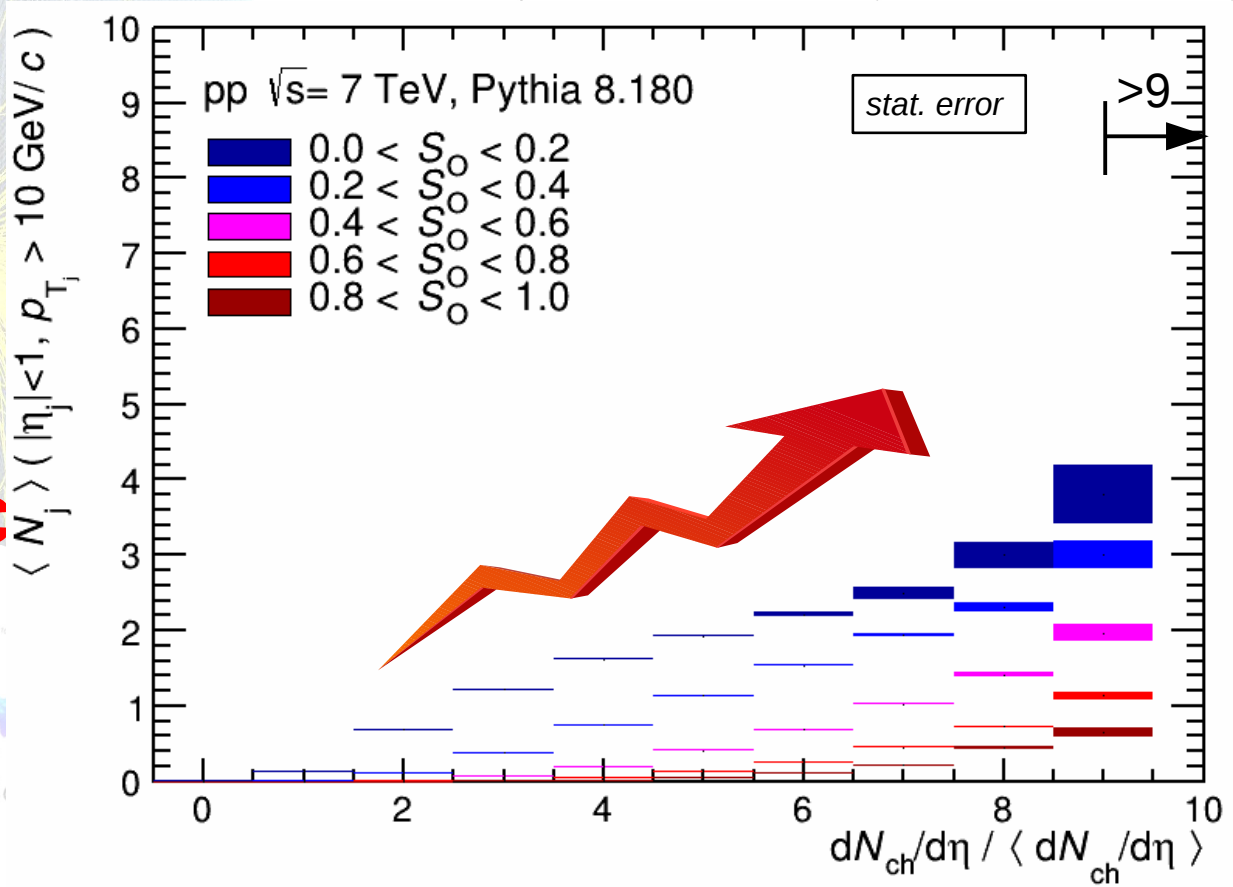
Jet production vs N_{ch} and S_O

Fast jet 3.0.6

M. Cacciari, G.P. Salam and G. Soyez, EPJC72, 1896, 2012.

- Anti-k_T algorithm.
- Jet size, R = 0.4
- **Min p_T jet: 10 GeV/c**
- Only charged constituents.

Average number of jets vs multiplicity



(Jet multiplicity distributions are shown in the backup)

*The inclusive case (w/o any cut on S_O) roughly follows the magenta points

taken from Stefan Gieseke©

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Jet-p_T vs N_{ch} and S_O

Fast jet 3.0.6

M. Cacciari, G.P. Salam and G. Soyez, EPJC72, 1896, 2012.

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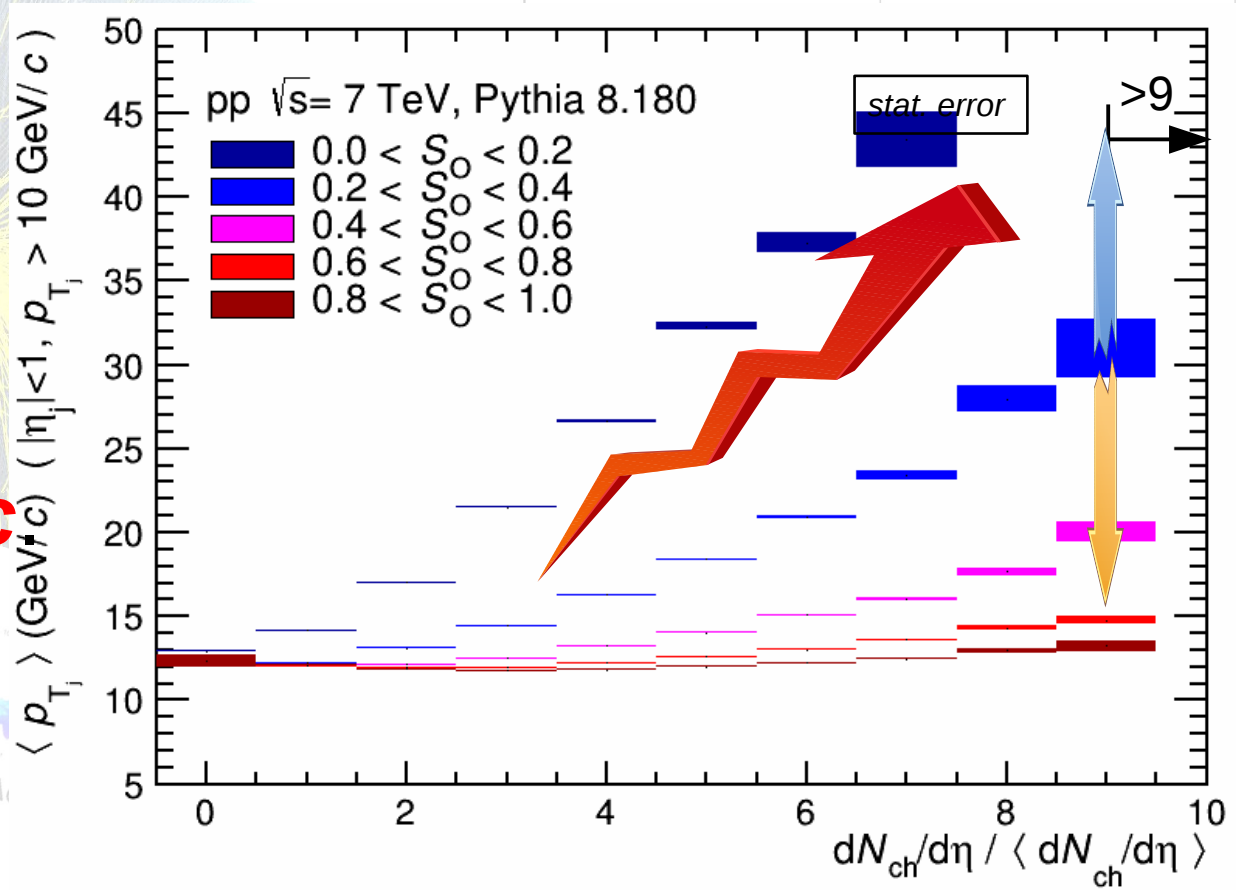
- Jet size, R = 0.4
- **Min p_T jet: 10 GeV/c**
- Only charged constituents.

Average jet p_T vs multiplicity



(Jet transverse momentum distributions are shown in the backup)

*The inclusive case (w/o any cut on S_O) roughly follows the magenta points

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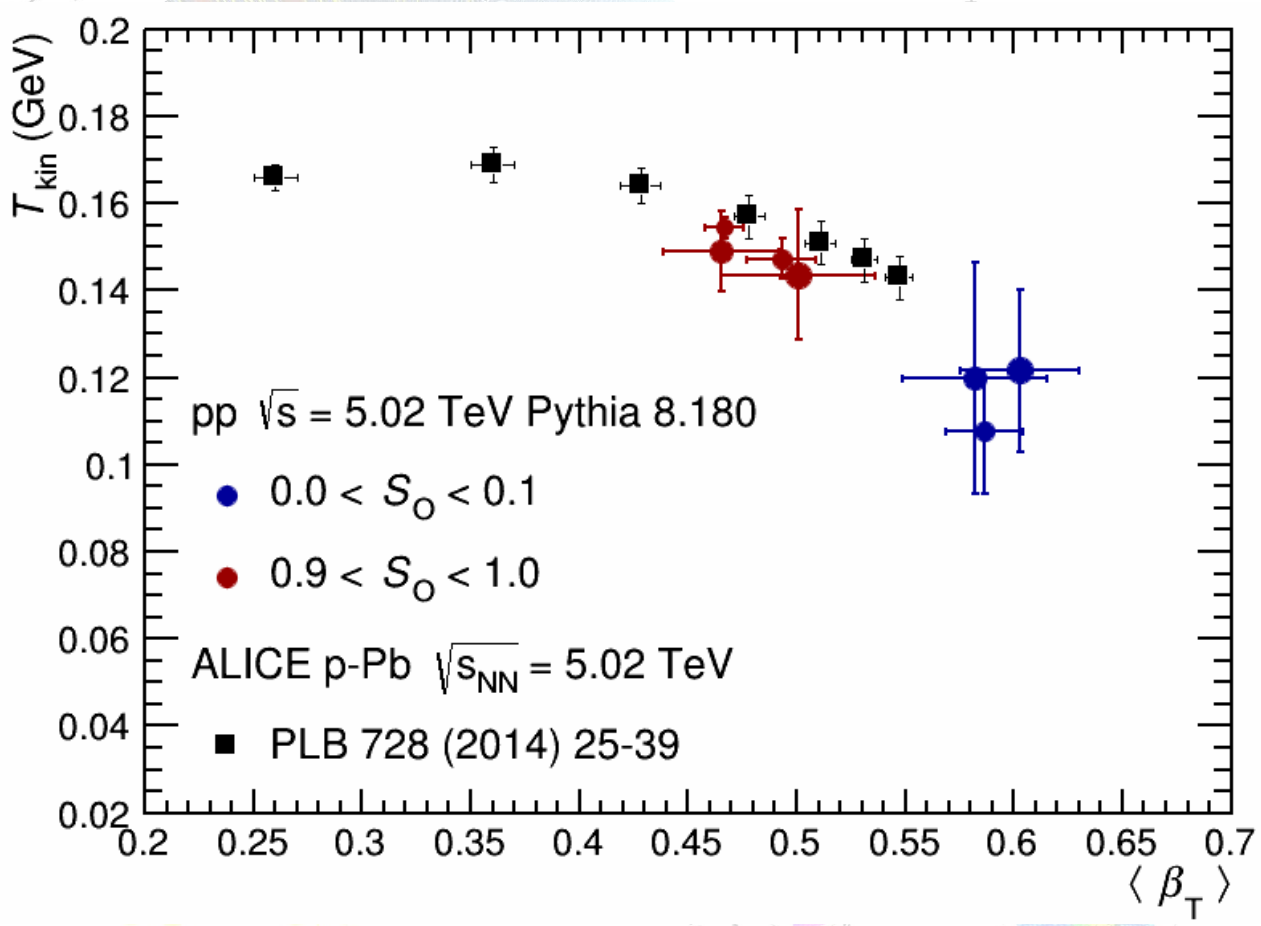
Jets may mimic also flow?



taken from Stefan Gieseke©

E. Cuautle, A. Ortiz and G. Paic, arXiv:1503.03129

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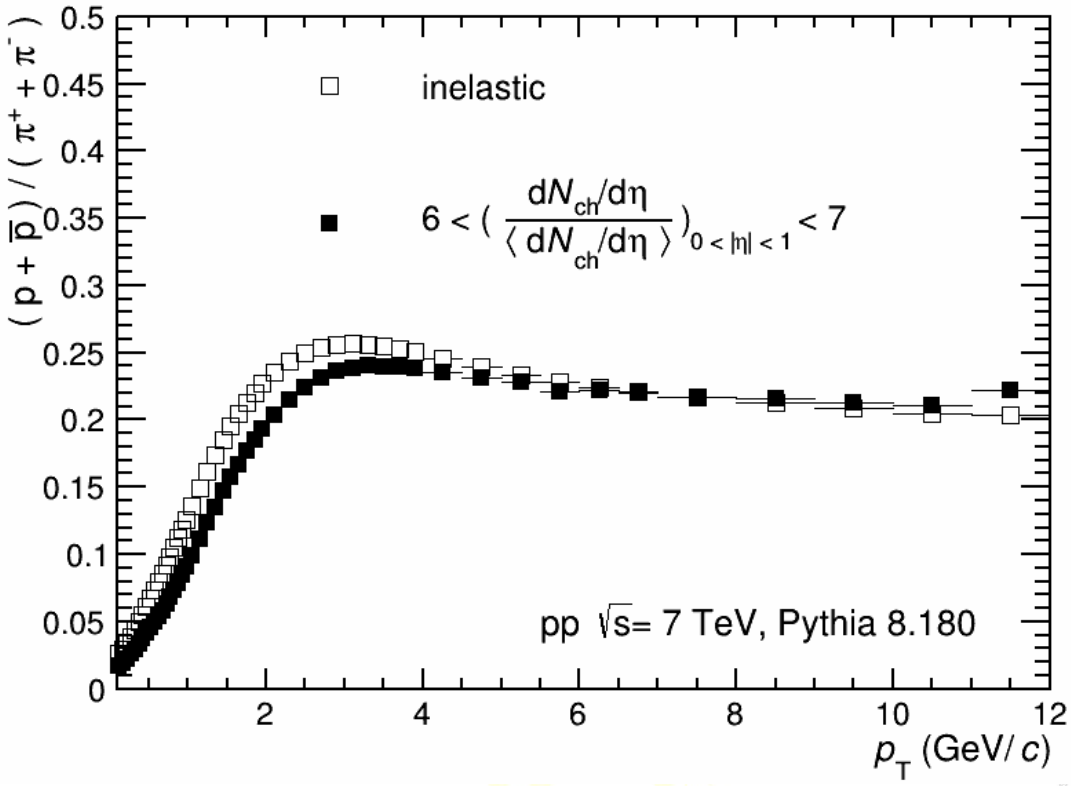
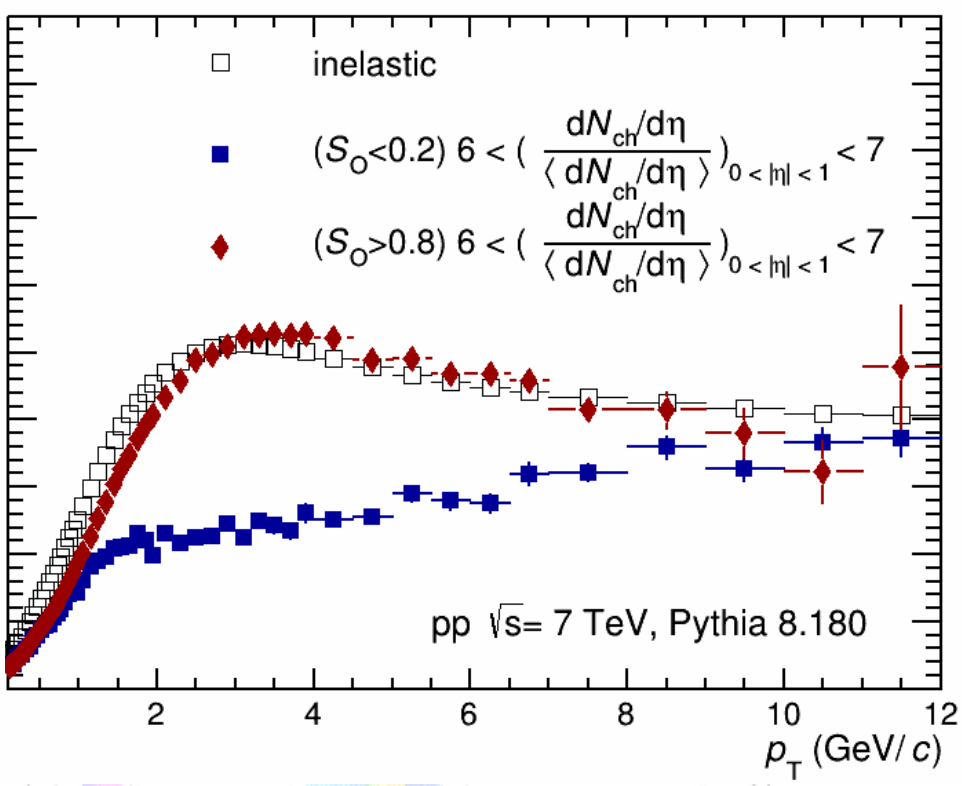
Particle ratios





Like in data!

taken from Stefan Gieseke©

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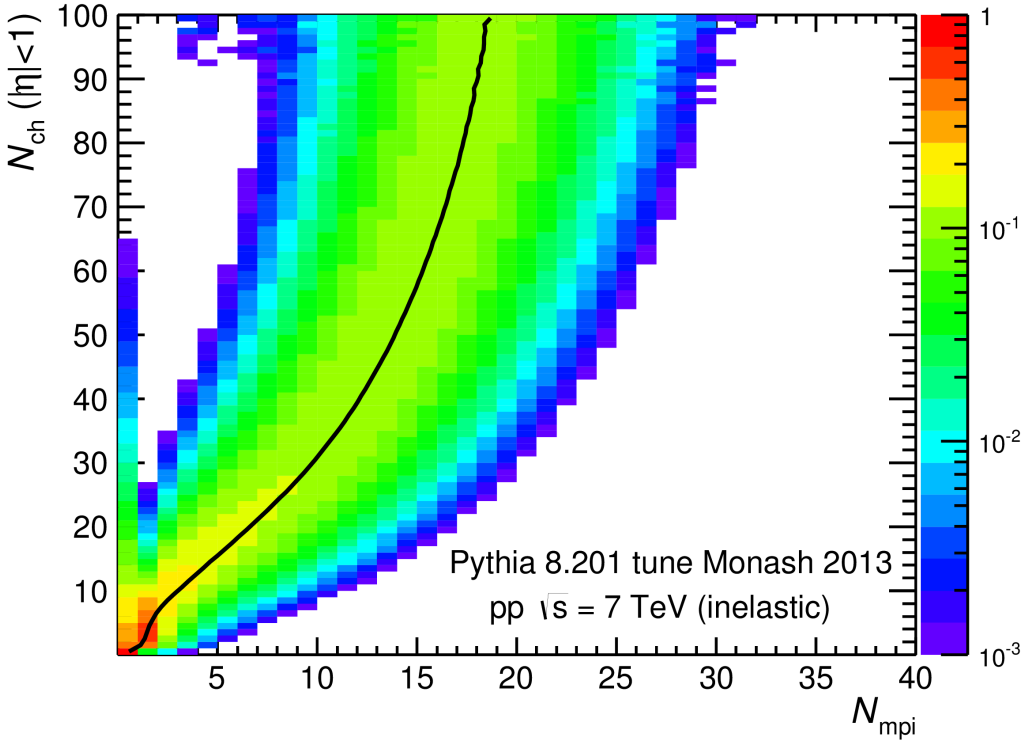
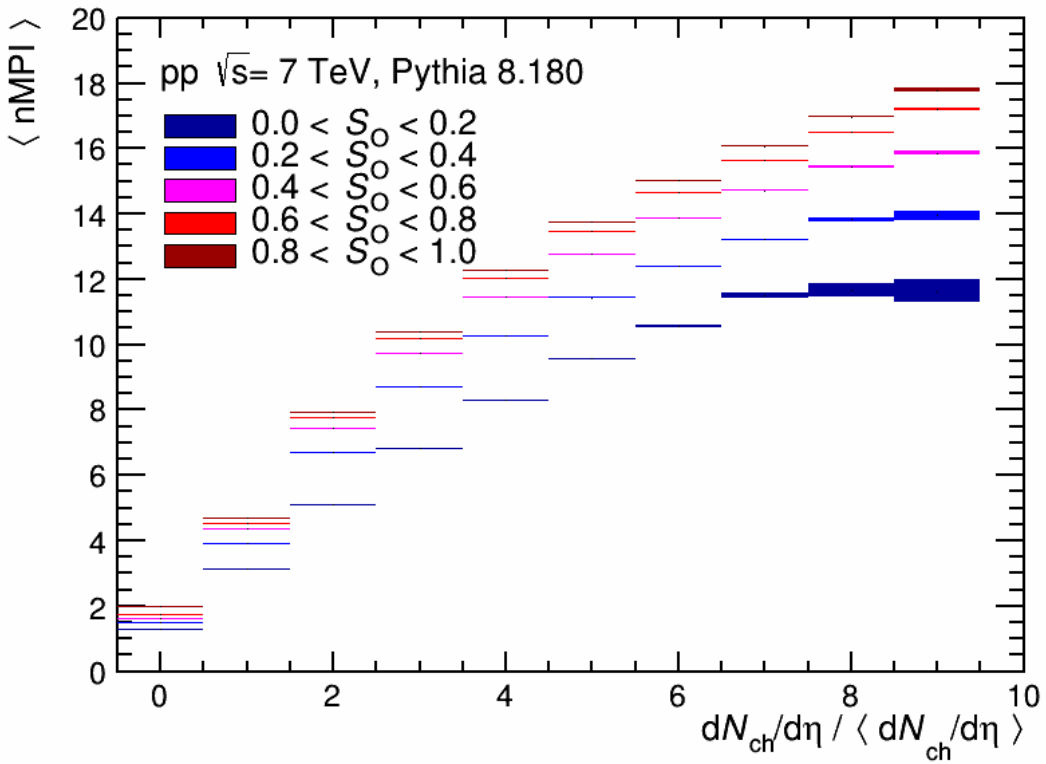
Summary II





- The selection on S_O allows to identify and analyze two extreme cases: the jetty-like and the isotropic events.
- This selection entails a much smaller fluctuations on the number of multi-parton interactions on the selected classes.
- The present work strongly suggests that the selection in multiplicity is much less potent than the one combining multiplicity and transverse spherocity.

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Backup

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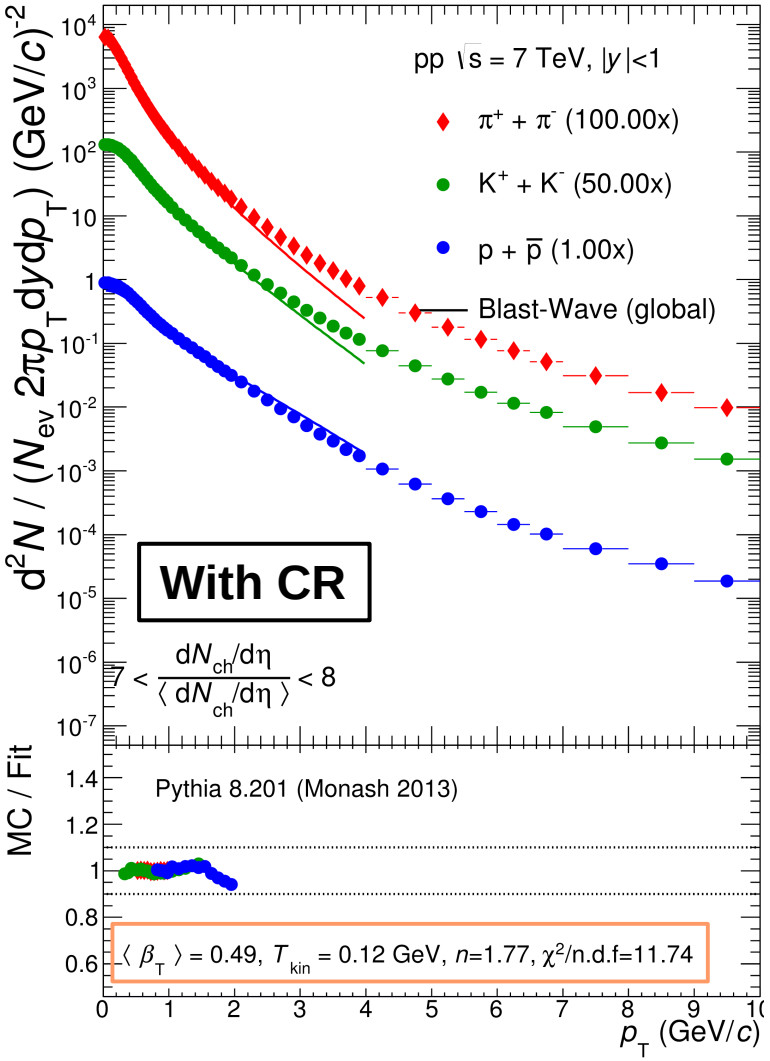
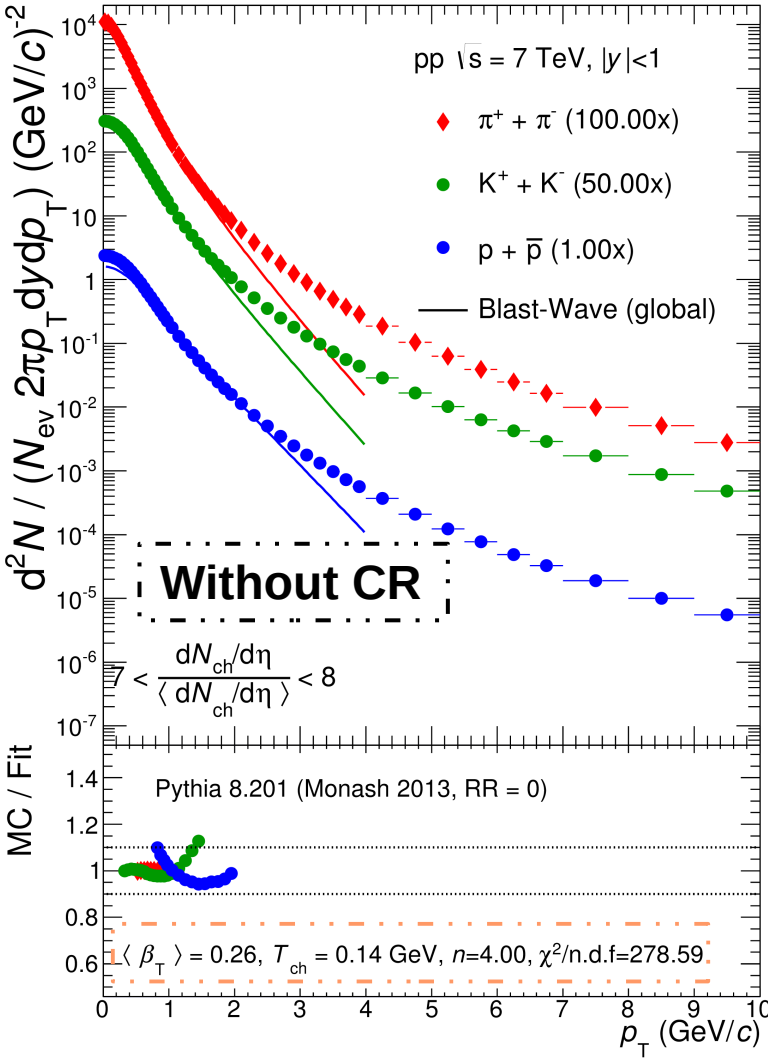
Spectra at high multiplicity





taken from Stefan Gieseke

Simultaneous blast-wave fit to the pion, kaon and proton spectra. Within 10% the spectra are well desribed by the model when color reconnection is on.

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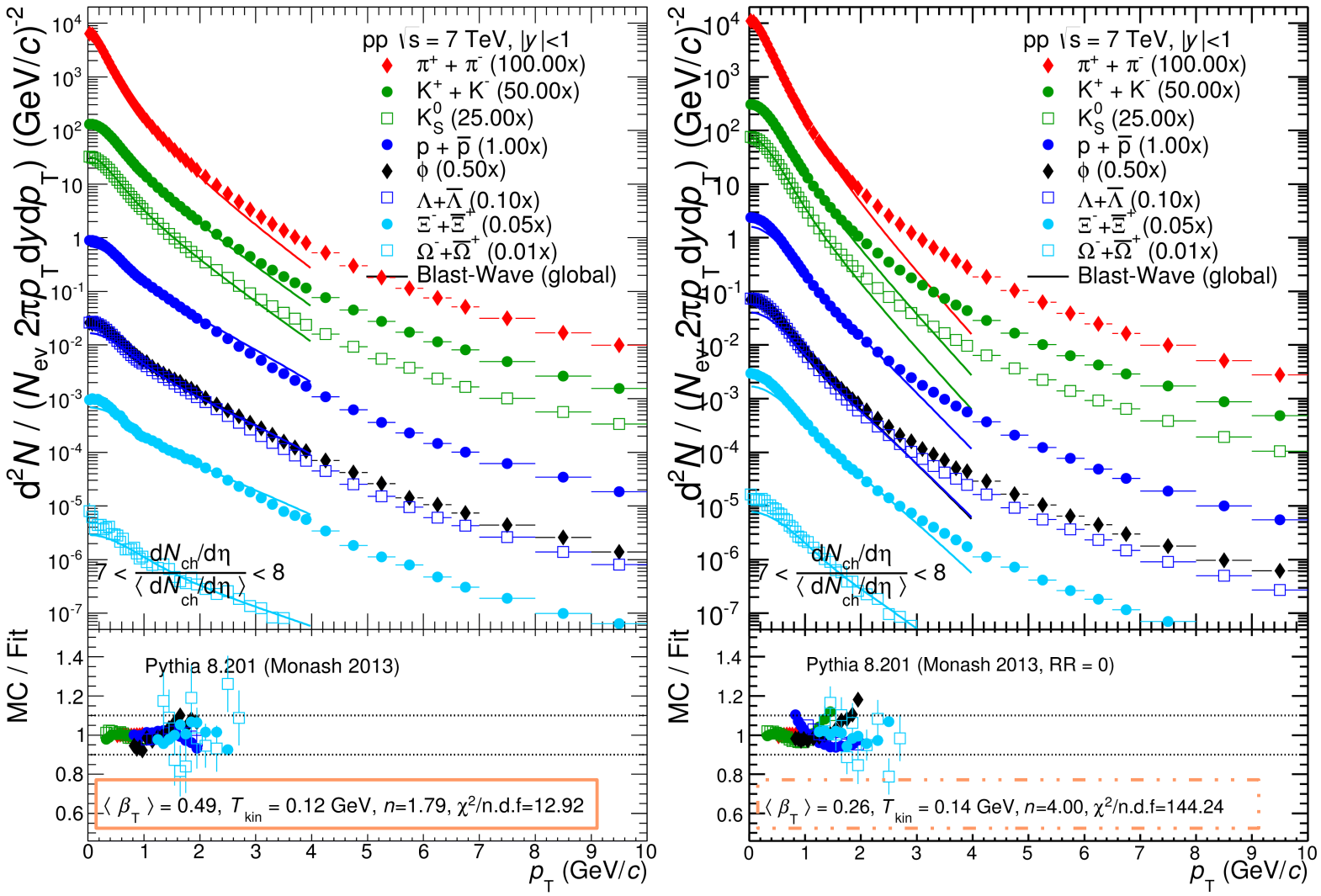
Spectra at high multiplicity



taken from Stefan Gieseke

Same result when heavier hadrons are included.

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Color screening

Used to suppress the number of interactions, at low p_T and x; if the wavelength $\sim 1/p_T$ of an exchanged coloured parton becomes larger than a typical color-anticolor separation distance, it will only see an average colour charge that vanishes in the limit $p_T \rightarrow 0$, hence leading to suppressed interactions. This provides an infrared cutoff for MPI (p_{Tmin}).

$$\frac{dp_T^2}{p_T^4} \rightarrow \frac{dp_T^2}{\left(p_T^2 + p_{Tmin}^2\right)^2}$$

With $p_{Tmin} \approx 1.5\text{-}2.0$ GeV → finite MPI number.

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P. Skands, "Introduction to QCD," arXiv:1207.2389v4

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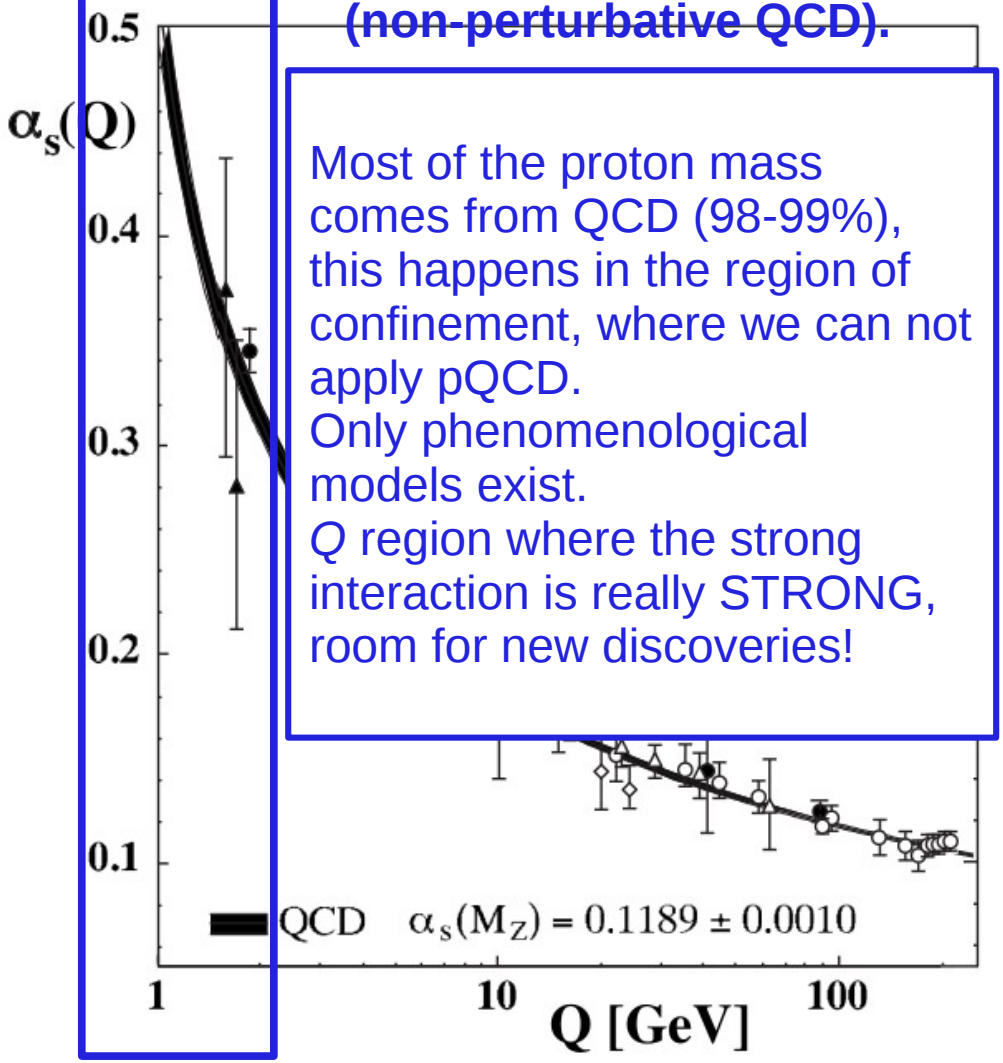
Strenght of QCD interactions

- In QCD, quarks and gluons are the elementary degrees of freedom.
- Quarks and gluons carry “color charge” as an additional quantum number.
- A pronounced variation (“running”) of the strong fine structure constant with (space-time) distance or momentum transfer *Q*.



Confinement (non-perturbative QCD).

Most of the proton mass comes from QCD (98-99%), this happens in the region of confinement, where we can not apply pQCD.
Only phenomenological models exist.
Q region where the strong interaction is really STRONG, room for new discoveries!

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Parametrization of $\langle p_T \rangle$ vs m/n_q (p-Pb data)

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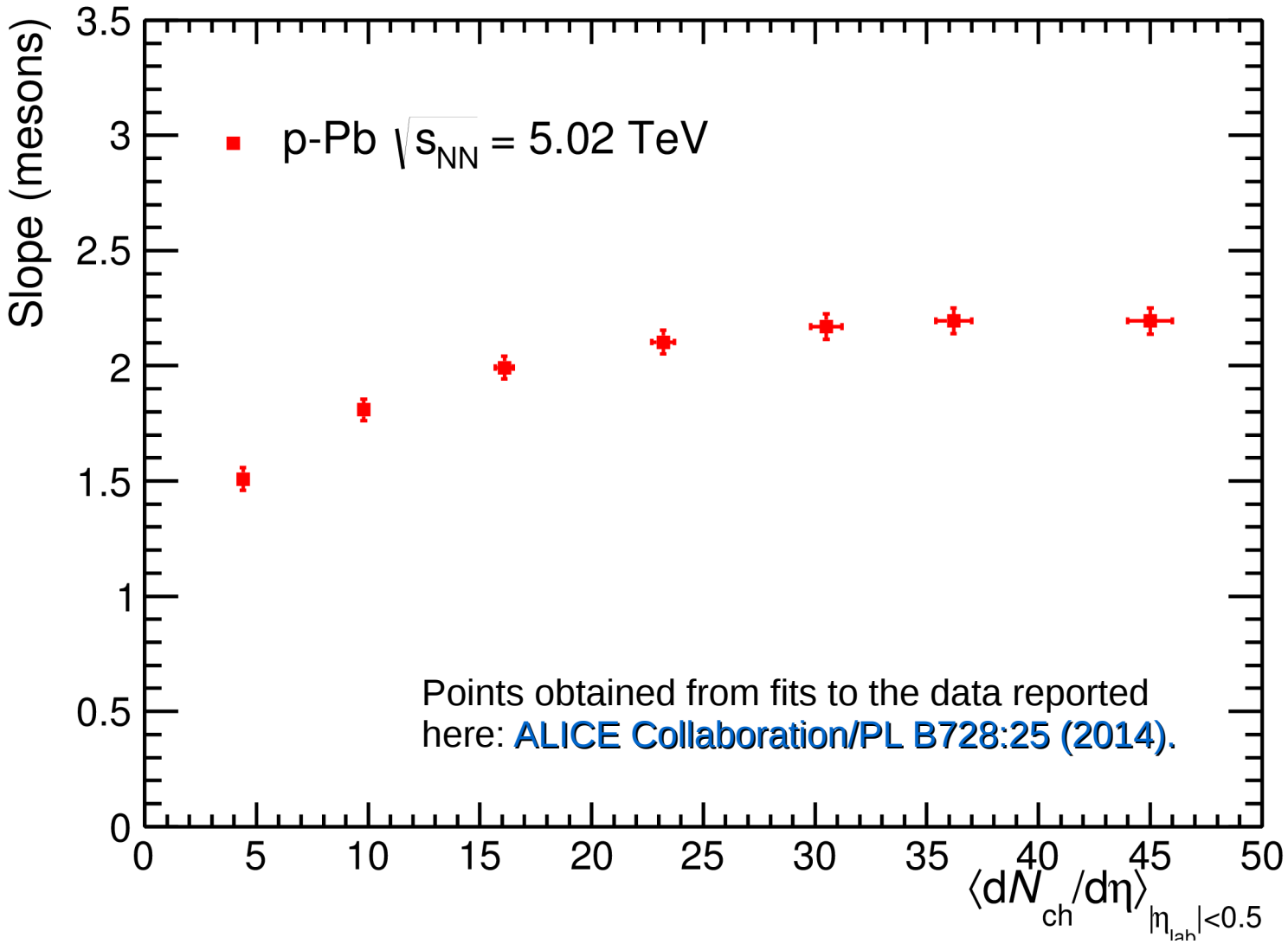
Slope vs N_{ch} (mesons)

The slope increases with the event multiplicity, then it shows a weaker rise.



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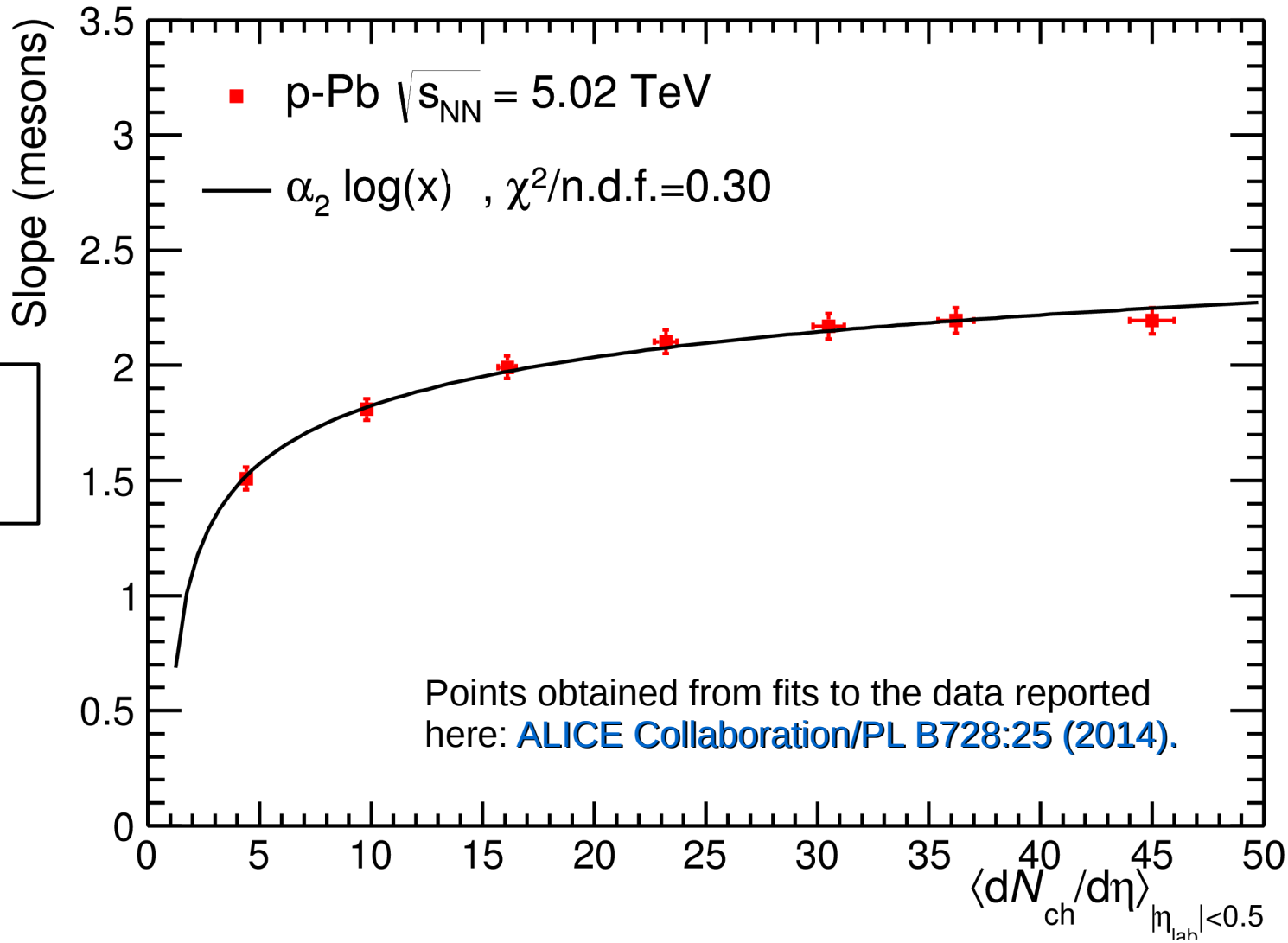
Slope vs N_{ch} (mesons)



Data are well described by a logarithmic function.

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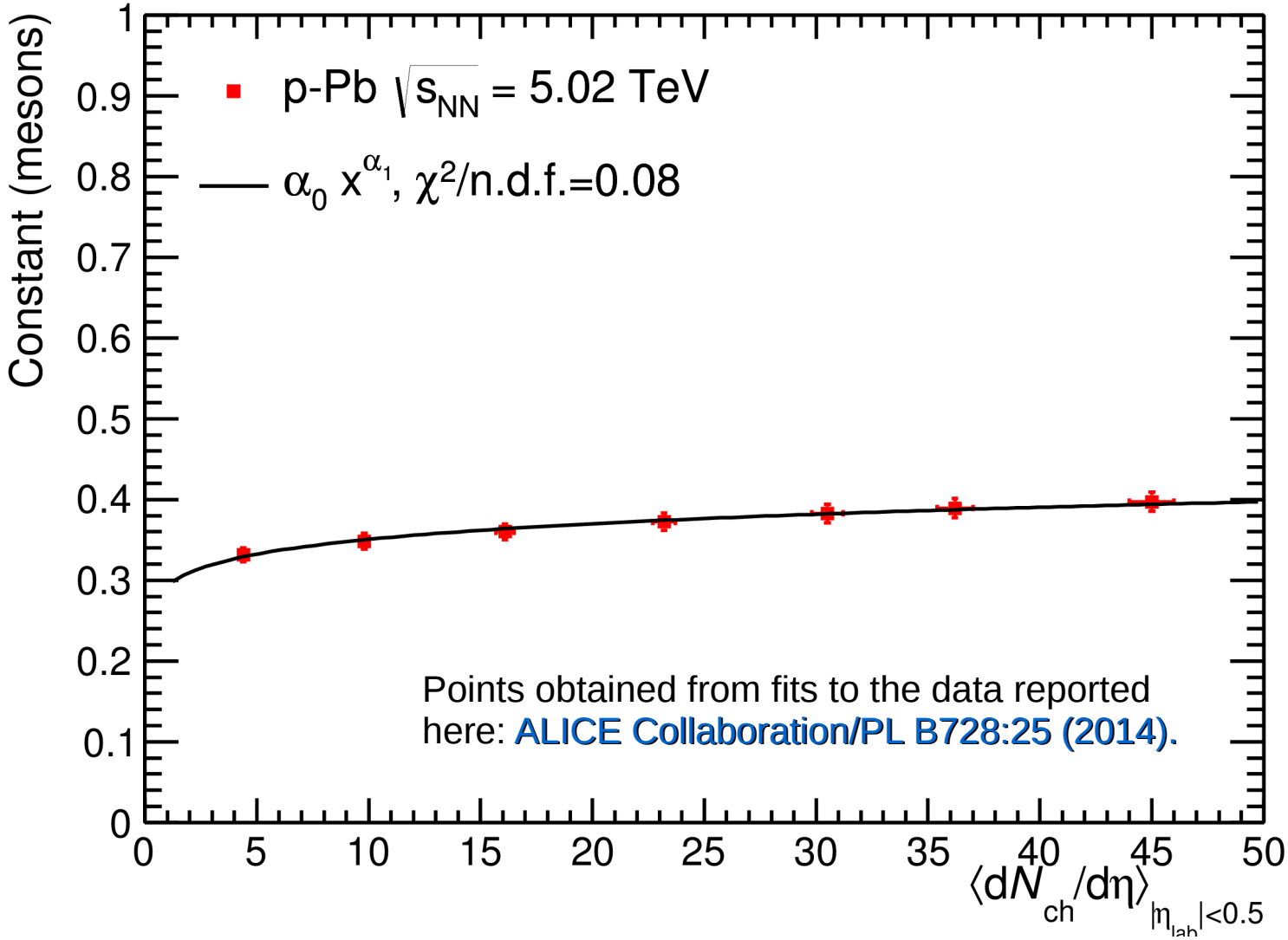
Constant vs N_{ch} (mesons)



The constant vs multiplicity can be described by a power law function.

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Parametrization

$$\langle p_T \rangle = \alpha_0 x^{\alpha_1} + \alpha_2 \log(x) y$$

$$x = \frac{dN_{ch}}{d\eta} \qquad y = \frac{m}{n_q}$$

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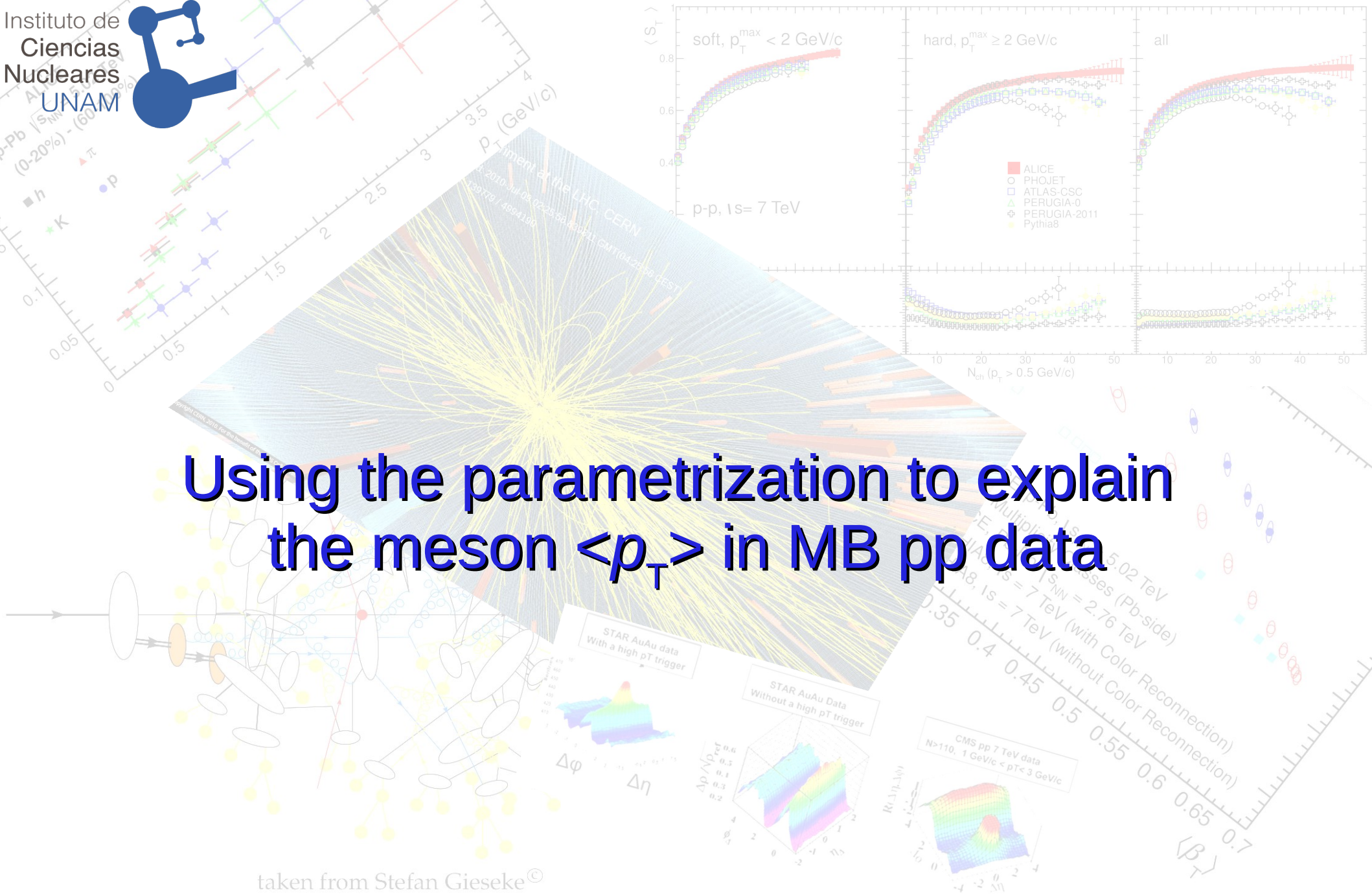
Using the parametrization to explain the meson $\langle p_T \rangle$ in MB pp data



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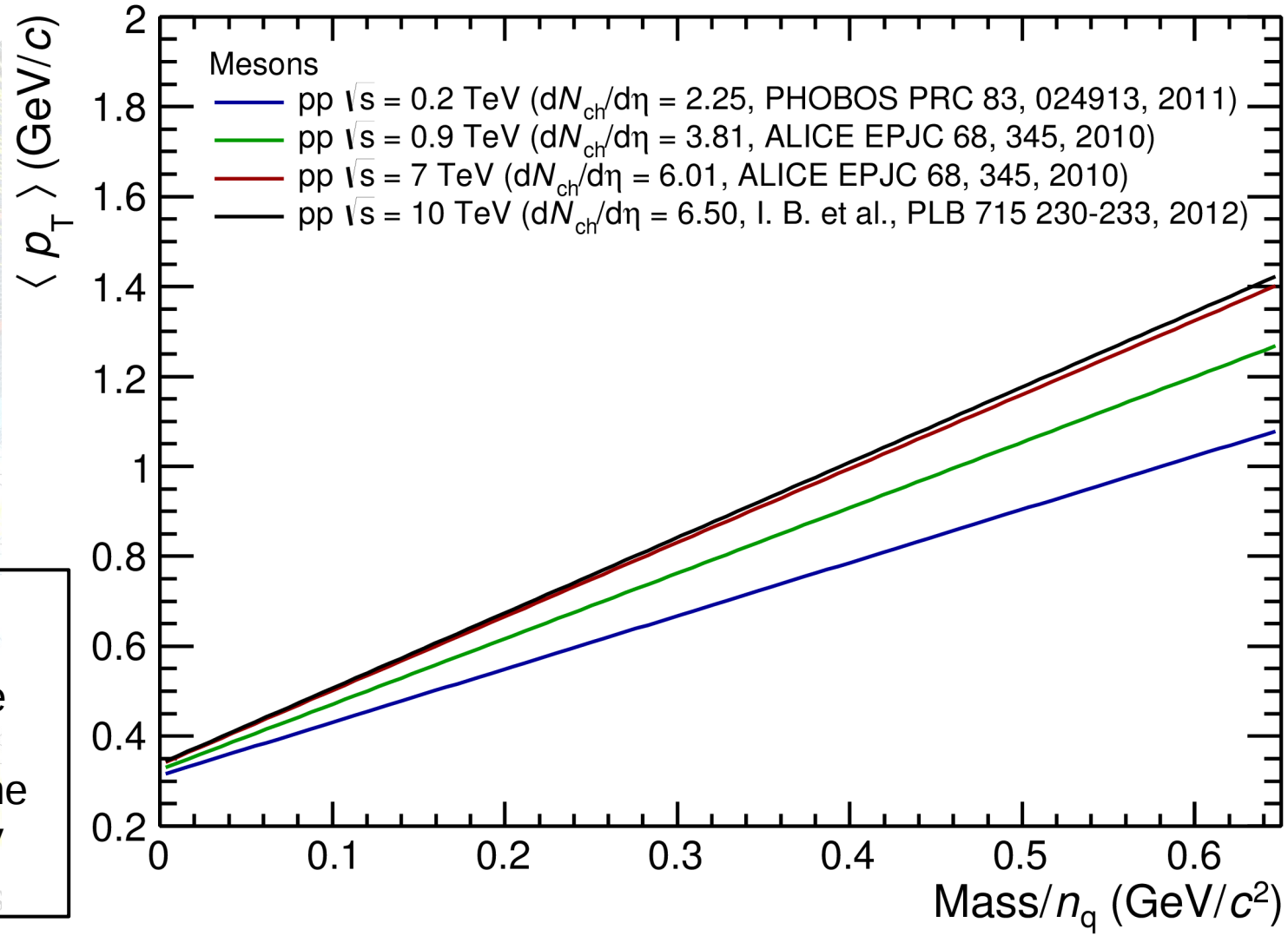
Evaluating $\langle p_T \rangle$ at N_{ch} for MB pp

$$\langle p_T \rangle = \alpha_0 x^{\alpha_1} + \alpha_2 \log(x) y$$

$$x = \frac{dN_{ch}}{d\eta} \qquad y = \frac{m}{n_q}$$

A prediction for higher center-of-mass energy is included. Modest increase for pp at √s = 10 TeV, with respect to 7 TeV, due to the expected small multiplicity increase.



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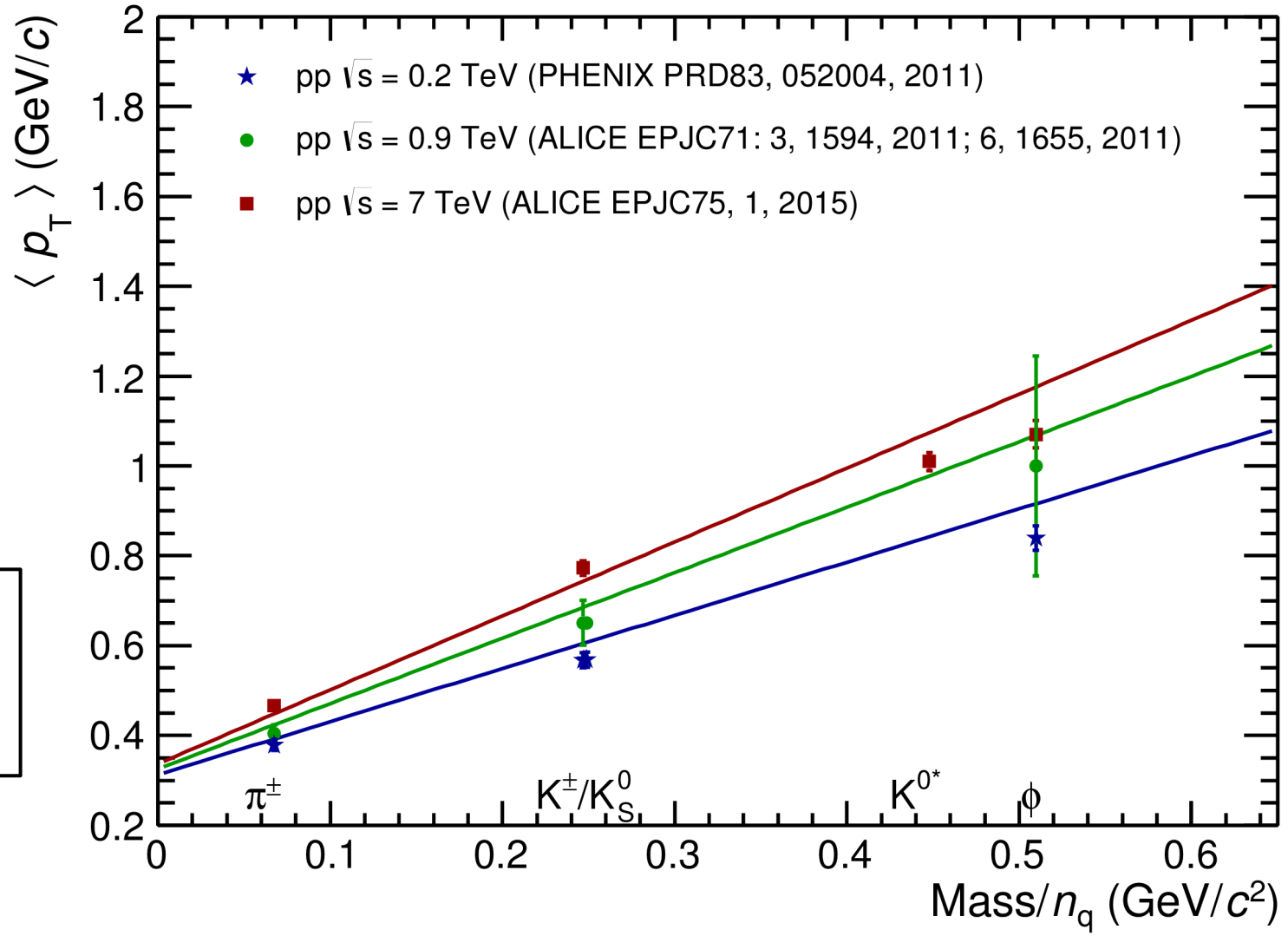
Comparison with data

$$\langle p_T \rangle = \alpha_0 x^{\alpha_1} + \alpha_2 \log(x)\, y$$

$$x = \frac{dN_{ch}}{d\eta} \qquad y = \frac{m}{n_q}$$

The multiplicity-based parametrization describes qualitatively well the behavior of data.



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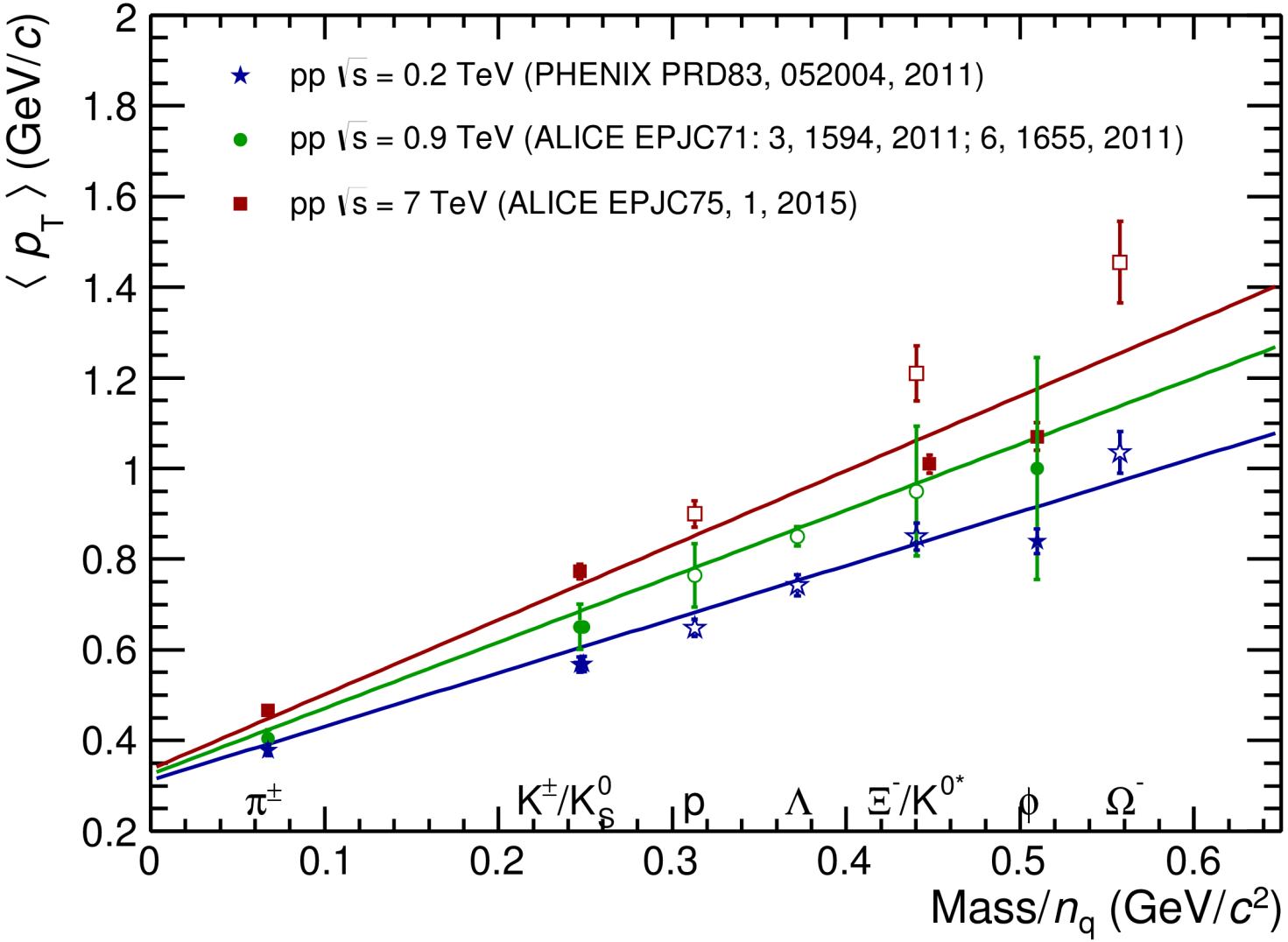
Adding baryons

The large uncertainties on the baryon $\langle p_T \rangle$ measured in p-Pb data do not allow to extract the parametrization. Here we only show the behavior of pp data.



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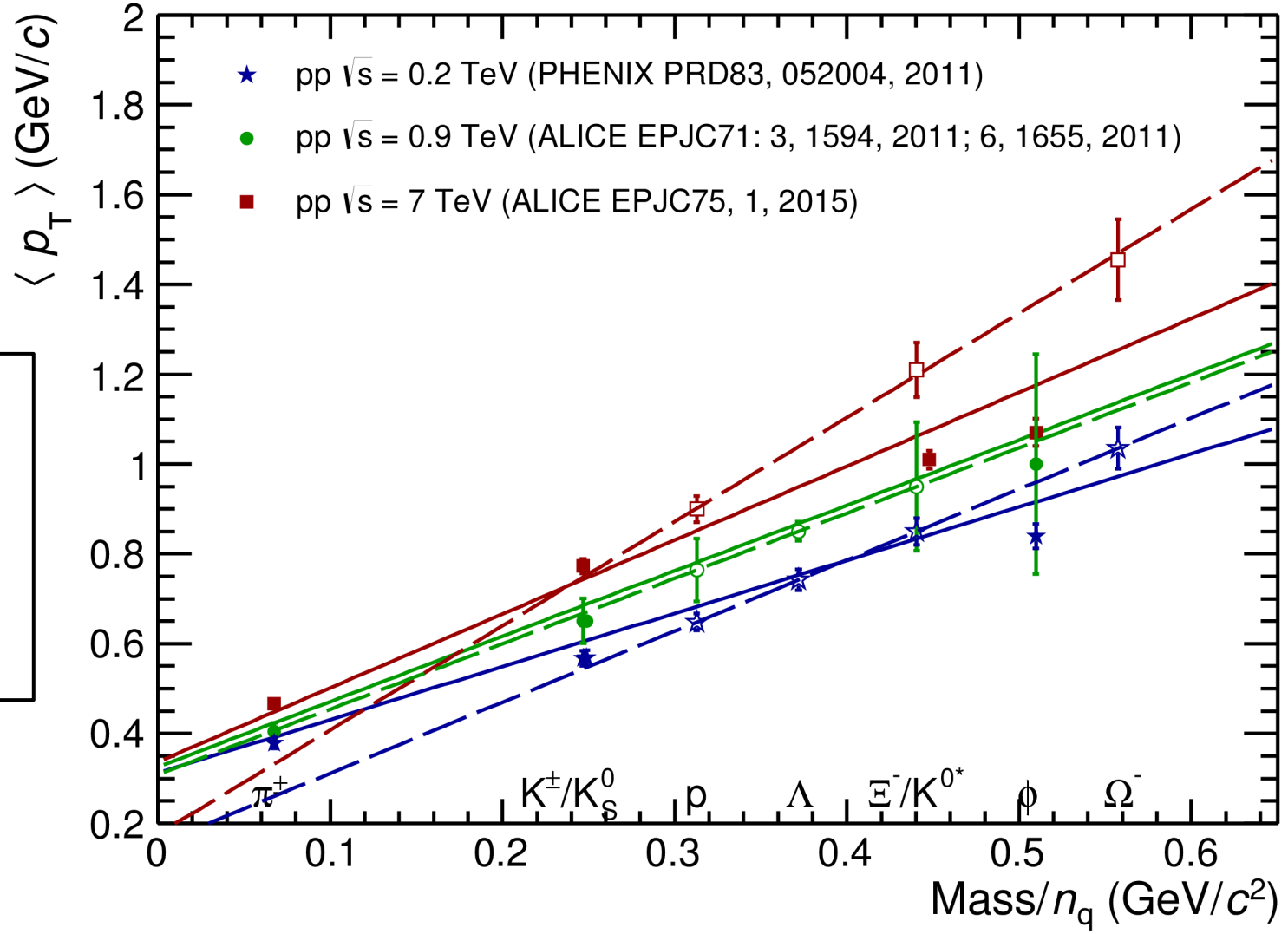
Adding baryons



As seen in low multiplicity p-Pb collisions, baryons are described by a linear function with a larger slope than the one obtained for mesons.

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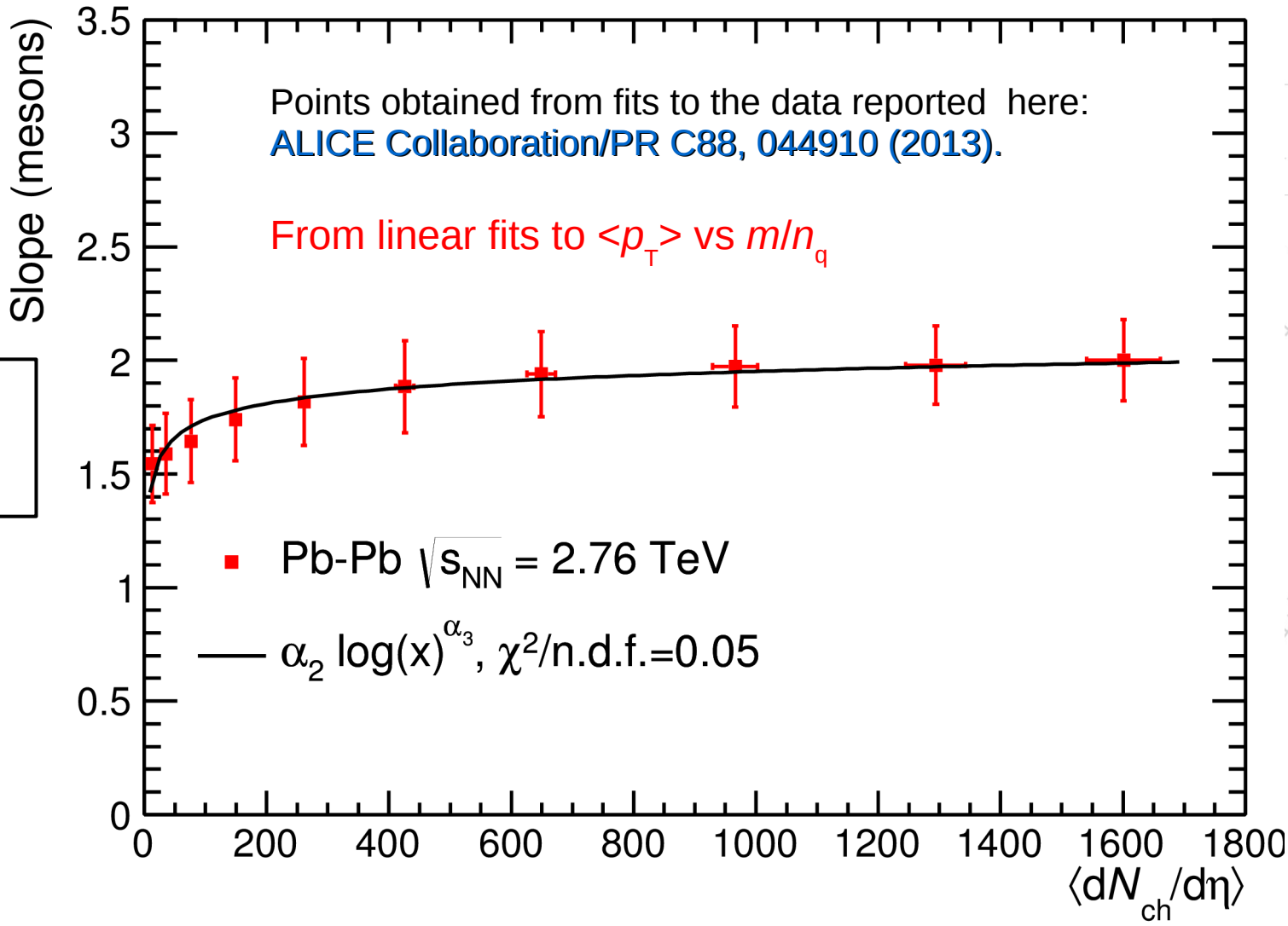
Slope vs N_{ch} (mesons)



Data are well described by a logarithmic function.

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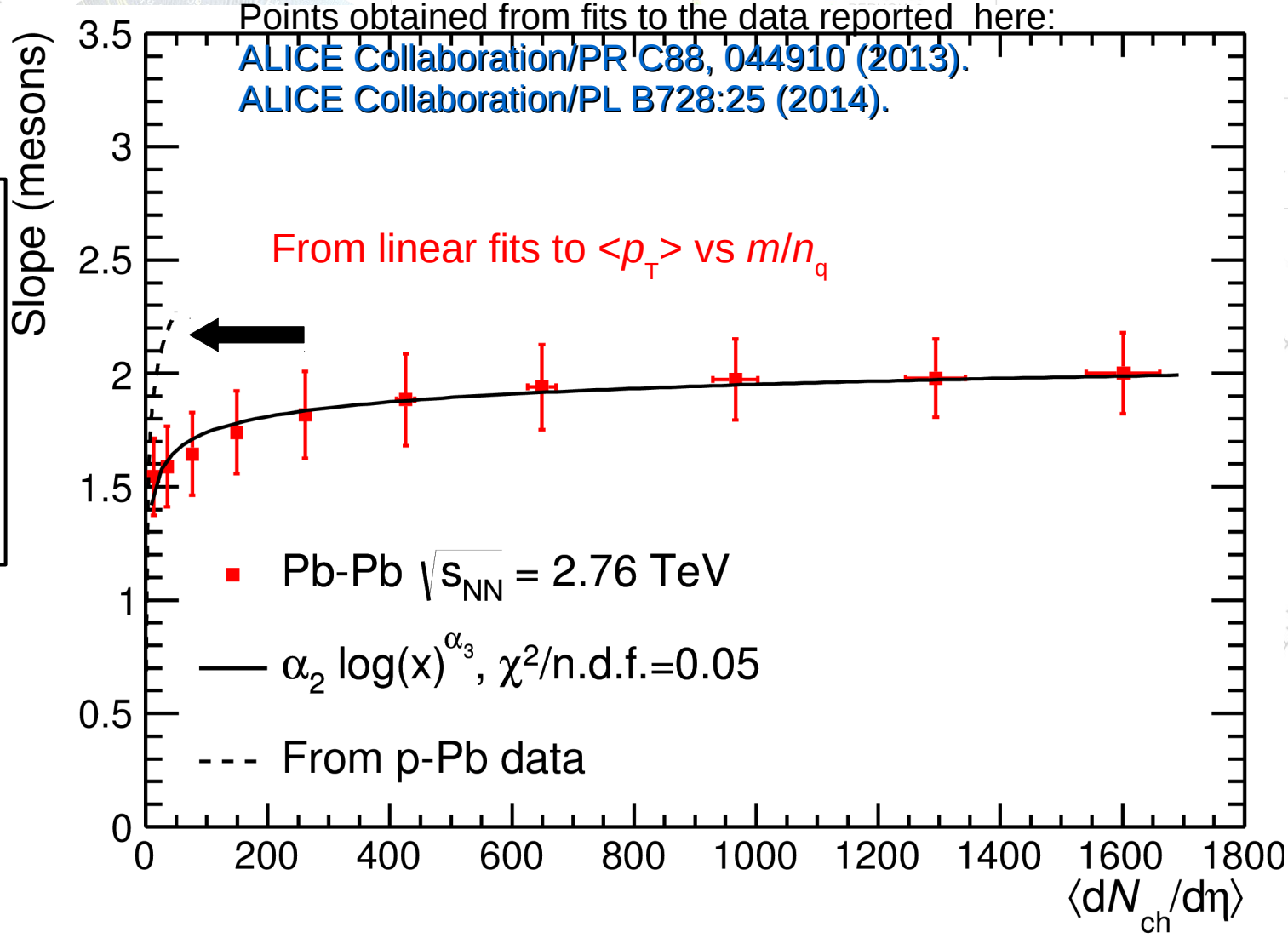
Slope vs N_{ch} (mesons)

A larger slope is obtained for p-Pb data.

The Pb-Pb parametrization fails to reproduce the MB pp results.



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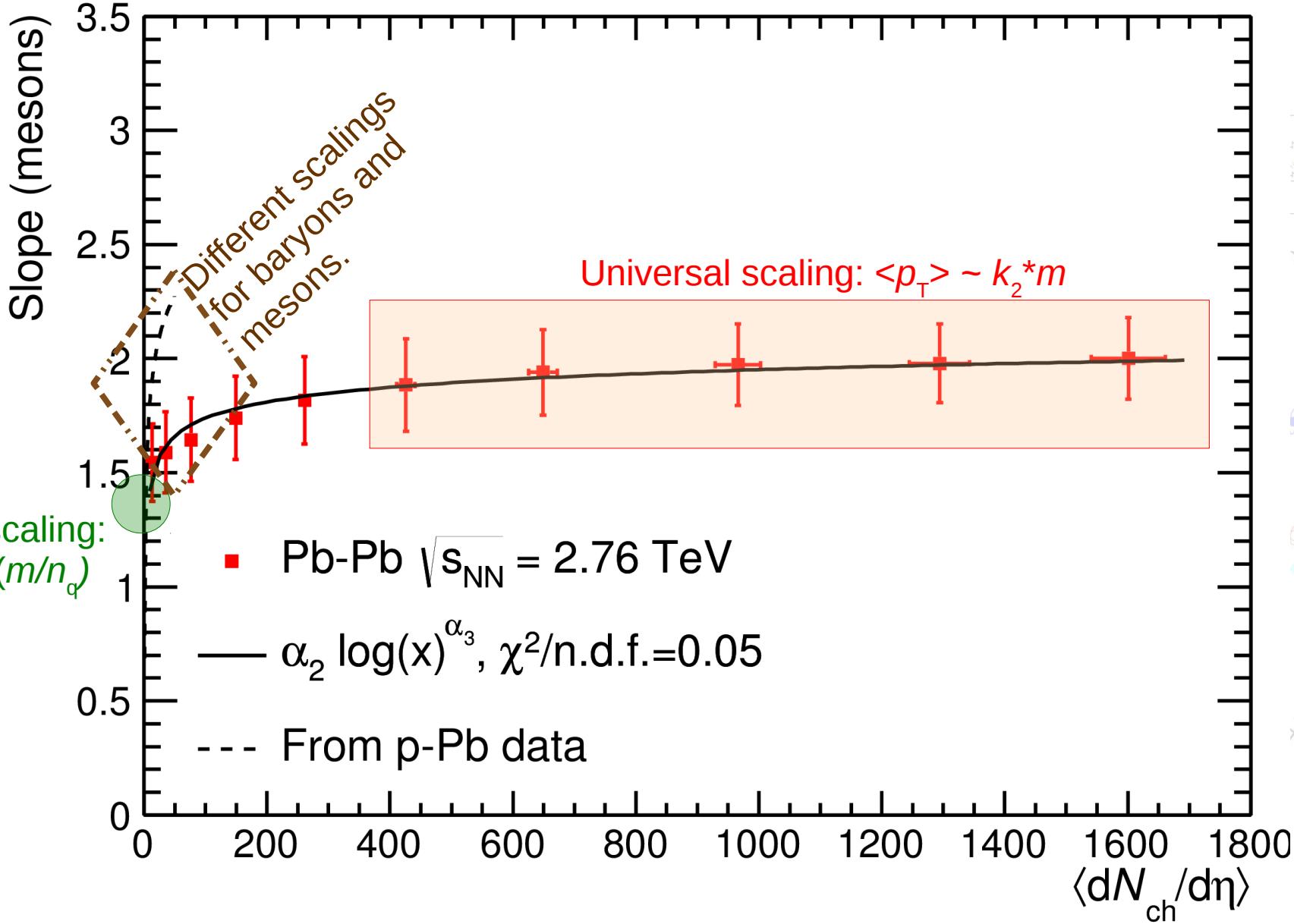
Thanks!



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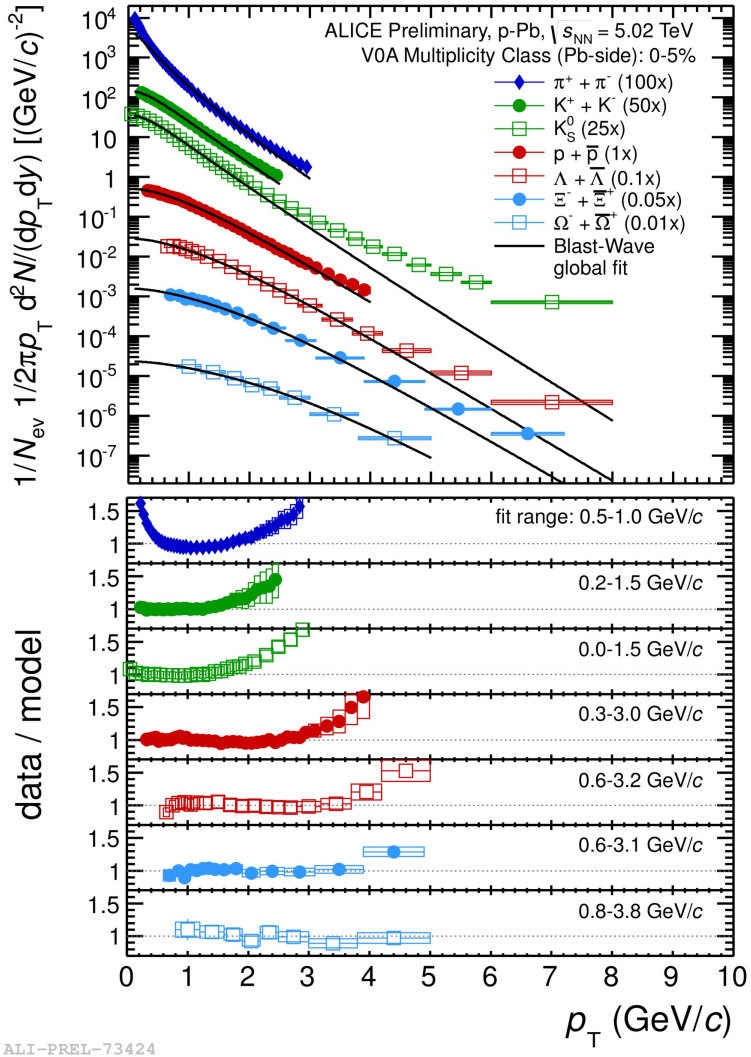
Blast-wave fitted to p_T spectra

ALICE p-Pb data.



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