A Large Ion Collider Experiment

ALICE

Measurements of event-by-event mean transverse momentum fluctuations with ALICE at the LHC

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on behalf of the ALICE Collaboration

HIC for FAIR Workshop on Fluctuation and Correlation Measures in Nuclear Collisions 2015

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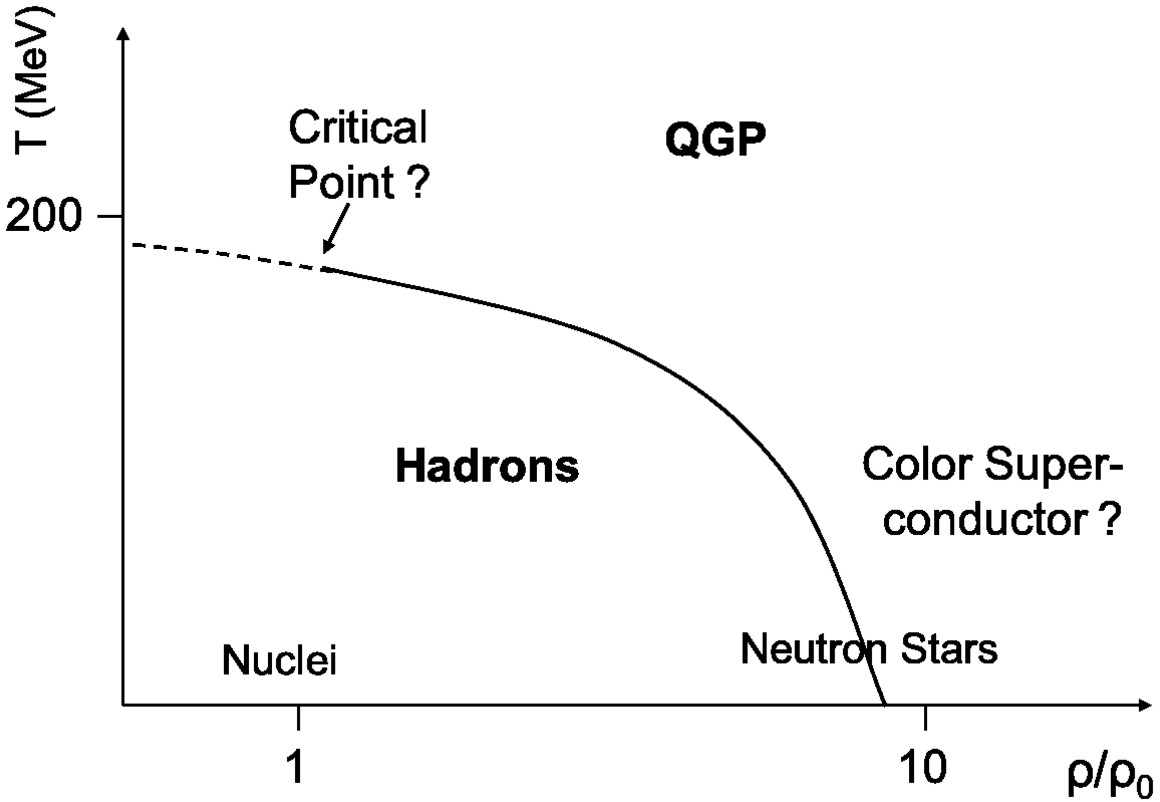
H-QM Helmholtz Research School Quark Matter Studies

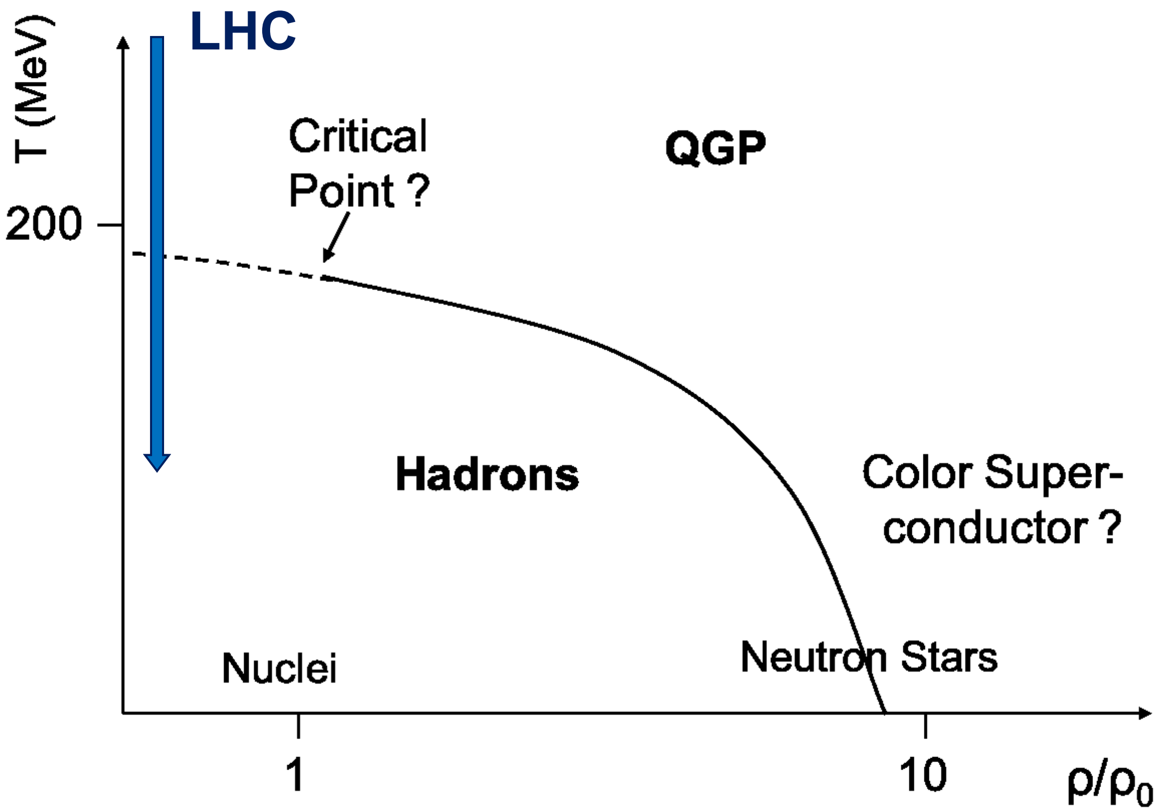
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Motivation



- Fluctuations of thermodynamic quantities suggested as a signal for a phase transition and especially a potential critical endpoint

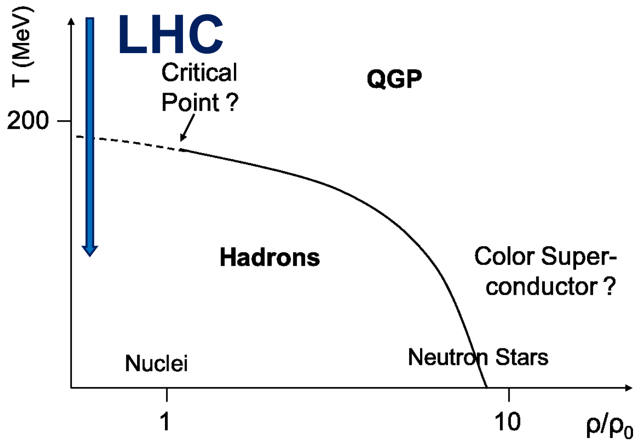
Motivation



- Fluctuations of thermodynamic quantities suggested as a signal for a phase transition and especially a potential critical endpoint
- At the LHC: Main focus on phase transition and QGP properties

Motivation

- One of the observables proposed: event-by-event fluctuations of the mean transverse momentum

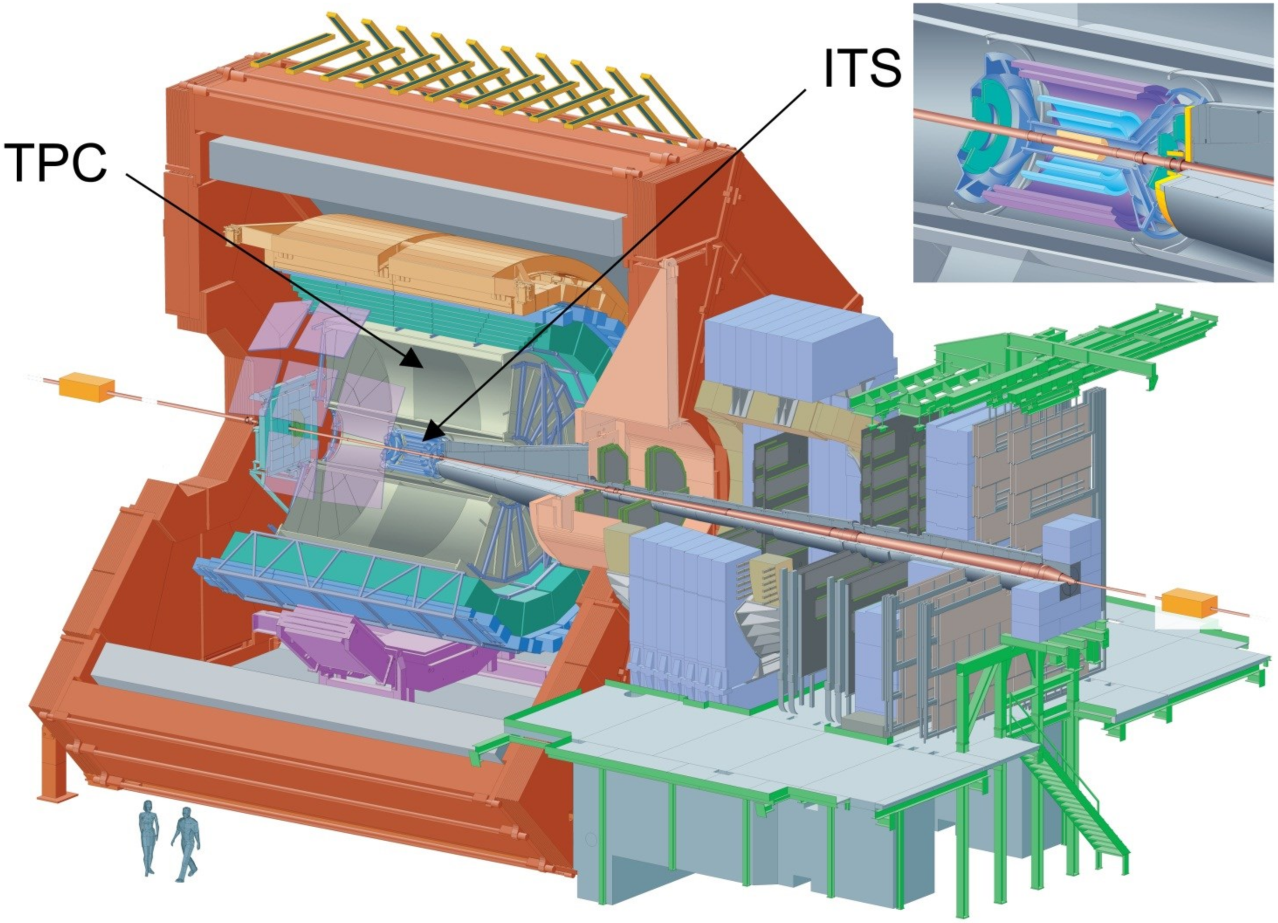


- Heavy-ion collisions (A–A): complex system with potentially many different effects

- Start with a much more simple system: pp collisions

- At first: experiment, data sets, observables …

ALICE detector setup



Main detectors used in this analysis:

Time
Projection
Chamber

(Tracking, Vertex)

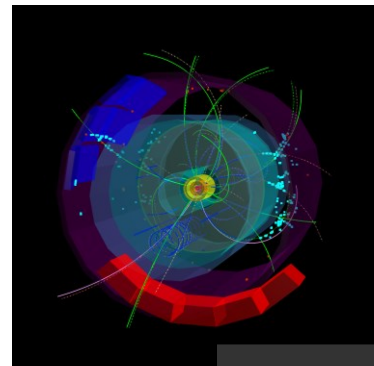
Inner
Tracking
System

(Vertex)

Data sets and acceptance

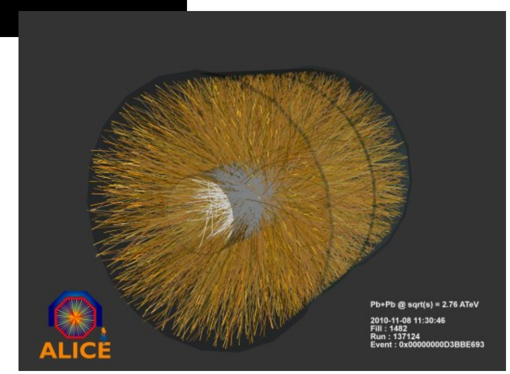
pp collisions:

- $\sqrt{s}$ = 0.9 TeV, 6.9 M events
- $\sqrt{s}$ = 2.76 TeV, 66 M events
- $\sqrt{s}$ = 7 TeV, 290 M events



Pb–Pb collisions:

- $\sqrt{s_{NN}}$ = 2.76 TeV, 19 M events



Acceptance:

Pseudorapidity range: $|\eta| < 0.8$

Transverse momentum range: $0.15 < p_T < 2$ GeV/c

Getting started: The mean transverse momentum

True mean transverse momentum in an event *k*:

$$\langle p_{\mathrm{T}} \rangle_k = \frac{1}{N_{\mathrm{ch},k}} \cdot \sum_{\mathrm{i}=1}^{N_{\mathrm{ch},k}} p_{\mathrm{T},i}$$

Cannot be measured event-by-event, approximated by the measured raw quantity:

$$M(p_{\mathrm{T}})_k = \frac{1}{N_{\mathrm{acc},k}} \cdot \sum_{\mathrm{j}=1}^{N_{\mathrm{acc},k}} p_{\mathrm{T},j}$$

$N_{\mathrm{ch},k}$: True number of particles in event *k*

$N_{\mathrm{acc},k}$: Measured raw number of particles in event *k*

Observables: The dispersion

The dispersion quantifies the total fluctuations:

$$D(M(p_{\mathrm{T}})) = \left[\langle M^2(p_{\mathrm{T}}) \rangle - \langle M(p_{\mathrm{T}}) \rangle^2 \right]^{1/2}$$

Dominated by statistical fluctuations!

Assumption: non-statistical contribution not depending on multiplicity n

⇒ Square of normalized dispersion described by the fit:

$$\left[D_n(M(p_{\mathrm{T}})) / M(p_{\mathrm{T}}) \right]^2 = \frac{\langle M^2(p_{\mathrm{T}}) \rangle_n - \langle M(p_{\mathrm{T}}) \rangle_n^2}{M^2(p_{\mathrm{T}})} = A + \frac{B}{n}$$

Observables: The dispersion

$$\left[D_n\left(M\left(p_\mathrm{T}\right)\right)/M\left(p_\mathrm{T}\right)\right]^2 = \frac{\left\langle M^2\left(p_\mathrm{T}\right)\right\rangle_n - \left\langle M\left(p_\mathrm{T}\right)\right\rangle_n^2}{M^2\left(p_\mathrm{T}\right)} = A + \frac{B}{n}$$

For large multiplicities $\left(\frac{1}{n} \to 0\right)$ the non-statistical contribution *R* yields:

$$R = \left[D_n\left(M\left(p_\mathrm{T}\right)\right)/M\left(p_\mathrm{T}\right)\right]_{n\to\infty} = A^{1/2}$$

Has been measured by SFM at the ISR [1]

Can we do better? ⇒ Two-particle transverse momentum correlator

[1] K. Braune *et al.*, Phys.Lett. **B123** (1983) 467

Observables: Two-particle correlator

The mean of covariances of all particle pairs i and j

$$C = \left\langle \Delta p_{\mathrm{T,i}}, \Delta p_{\mathrm{T,j}} \right\rangle = \frac{1}{\sum_{\mathrm{k=1}}^{n_{\mathrm{ev}}} N_{\mathrm{k}}^{\mathrm{pairs}}} \cdot \sum_{\mathrm{k=1}}^{n_{\mathrm{ev}}} \sum_{\mathrm{i=1}}^{N_{\mathrm{k}}} \sum_{\mathrm{j=i+1}}^{N_{\mathrm{k}}} \left(p_{\mathrm{T,i}} - M(p_{\mathrm{T}})\right) \cdot \left(p_{\mathrm{T,j}} - M(p_{\mathrm{T}})\right)$$

[2] S. Voloshin *et al*., Phys.Rev. **C60** (1999) 024901

[3] D. Adamová *et al*., Nucl.Phys. **A811** (2008) 179

[4] J. Adams *et al*., Phys.Rev. **C72** (2005) 044902

n_{ev}: Number of events

N_{k}: Number of particles in event *k*

$N_{\mathrm{k}}^{\mathrm{pairs}} = 0.5 \cdot N_{\mathrm{k}} \cdot \left(N_{\mathrm{k}} - 1\right)$: Number of pairs in event *k*

$M(p_{\mathrm{T}})$: Mean p_{T} of all tracks in all events

Observables: Two-particle correlator

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$C = 0$ for only statistical fluctuations

Robust quantity!

n_{ev}: Number of events

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$C = 0$ for only statistical fluctuations

$$\frac{\sqrt{C}}{M\left(p_{\mathrm{T}}\right)}$$

n_{ev}: Number of events

N_{k}: Number of particles in event *k*

$N_{\mathrm{k}}^{\mathrm{pairs}} = 0.5 \cdot N_{\mathrm{k}} \cdot \left(N_{\mathrm{k}} - 1\right)$: Number of pairs in event *k*

$M(p_{\mathrm{T}})$: Mean p_{T} of all tracks in all events

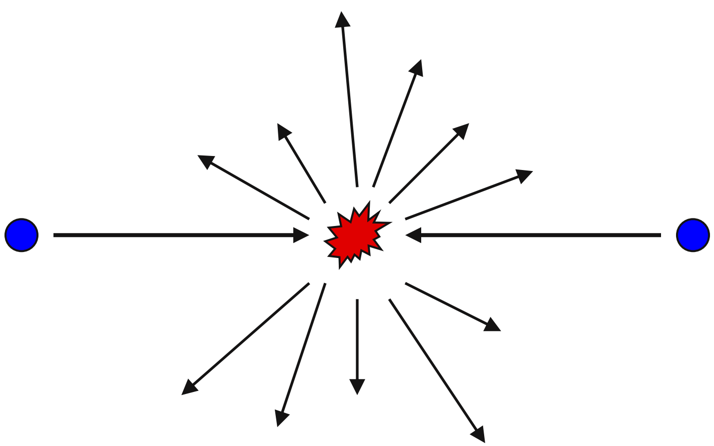
Measure fluctuations relative to $M(p_{\mathrm{T}})$:

- Dimensionless
- Reduced systematic uncertainties

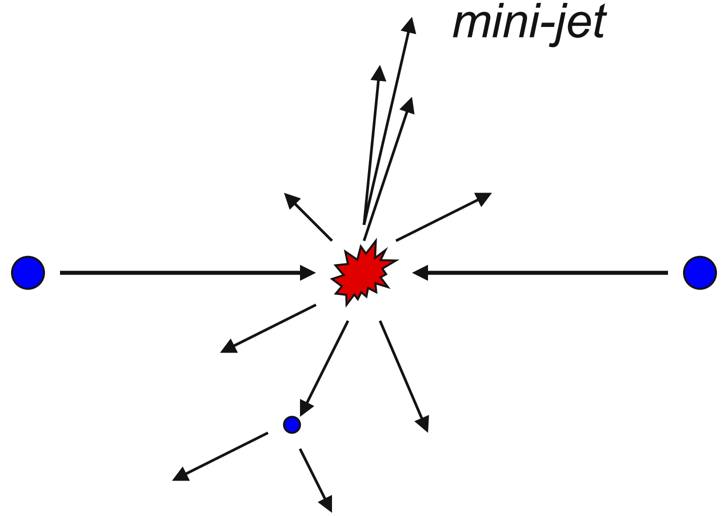
Motivation: pp collisions

On top of statistical fluctuations there are dynamical sources of correlations, e.g. resonance decays, (mini-)jets, quantum correlations

Statistical fluctuations:



Dynamical fluctuations:

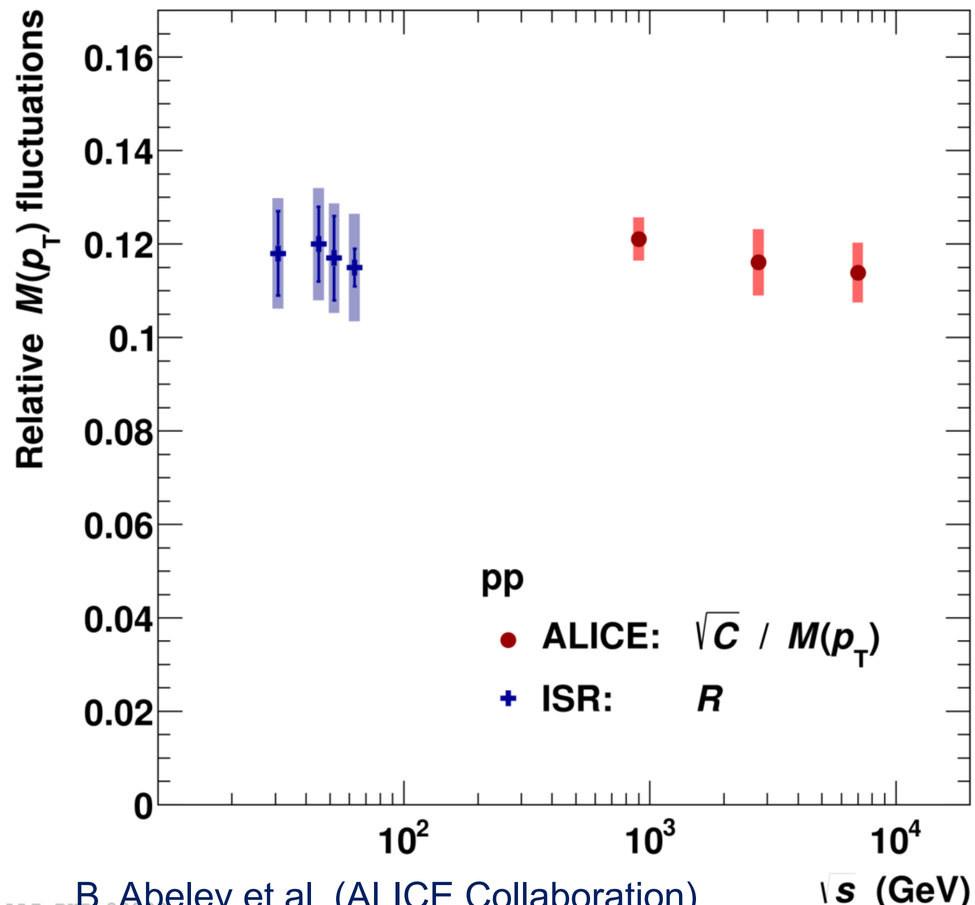


pp also interesting as reference measurement for heavy-ion collisions

Results in pp collisions

Inclusive results as a function of $\sqrt{s}$

- Significant dynamical fluctuations
- ALICE measures no significant dependence on collision energy
- Comparison to *R* measured at ISR [1]
- No significant dependence over a large range of collision energies



B. Abelev et al. (ALICE Collaboration) Eur.Phys.J. **C74** (2014) 3077

[1] K. Braune *et al*., Phys.Lett. **B123** (1983) 467

Two-particle correlator

As a function of multiplicity

- First measurement of non-statistical mean p_T fluctuations as a function of multiplicity in pp collisions!
- Differential studies can bring more insight in the origin of the fluctuations

$$C_m = \left\langle \Delta p_{\mathrm{T,i}}, \Delta p_{\mathrm{T,j}} \right\rangle_m = \frac{1}{\sum_{\mathrm{k}=1}^{n_{\mathrm{ev}}} N_{\mathrm{k}}^{\mathrm{pairs}}} \cdot \sum_{\mathrm{k}=1}^{n_{\mathrm{ev}}} \sum_{\mathrm{i}=1}^{N_{\mathrm{k}}} \sum_{\mathrm{j}=\mathrm{i}+1}^{N_{\mathrm{k}}} \left(p_{\mathrm{T,i}} - M(p_{\mathrm{T}})_m\right) \cdot \left(p_{\mathrm{T,j}} - M(p_{\mathrm{T}})_m\right)$$

$C_m = 0$ for only statistical fluctuations

$$\frac{\sqrt{C_m}}{M(p_{\mathrm{T}})_m}$$

Multiplicity determination

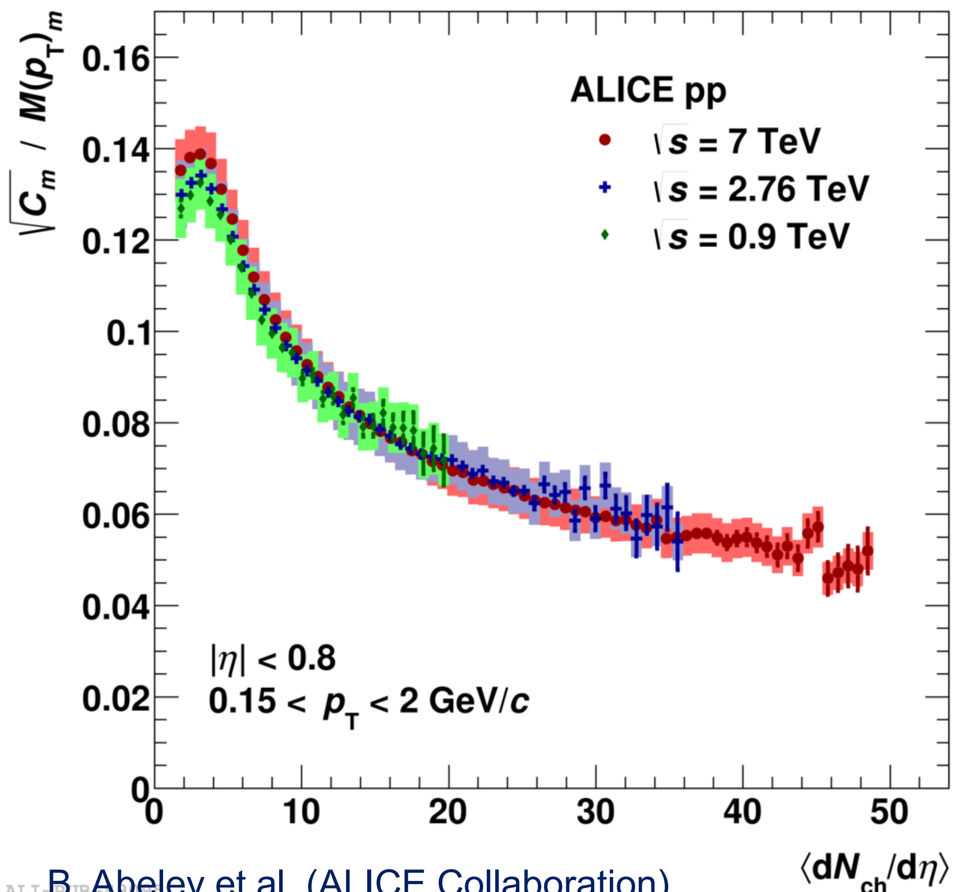
- Measured multiplicity $N_{\mathrm{acc},k}$ = number of tracks in event *k* which survive the track selection criteria

- The two-particle correlator is calculated in intervals of $\langle N_{\mathrm{acc}} \rangle$

- Afterwards, the multiplicity axis is corrected to obtain $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$
  - In Pb–Pb collisions: Linear relation between $\langle N_{\mathrm{acc}} \rangle$ and published ALICE $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$
  - In pp collisions: Detector response matrix from MC simulation + unfolding procedure

Results in pp collisions

As a function of the charged-particle multiplicity density



- Significant dynamical fluctuations
- Strong decrease with multiplicity
- Inclusive value of ≈ 12% has underlying structure
- No significant collision energy dependence

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Eur.Phys.J. **C74** (2014) 3077

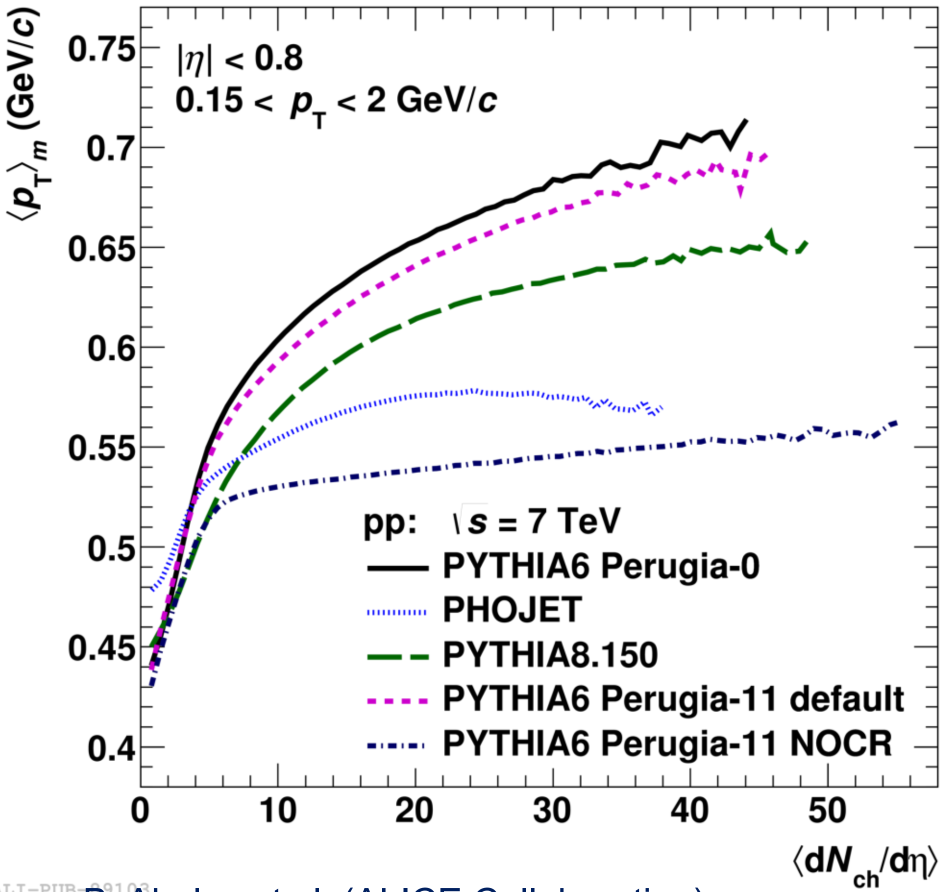
Systematic uncertainties

- Most important contributions:
  - MC generator level versus MC reconstructed – up to 6%
  - Tracking scheme: TPC standalone versus TPC+ITS combined tracking – up to 5%
- Further contributions:
  - Vertex position criteria and vertex calculation – up to 2%
  - Track selection criteria – up to 3%

⇒ **Data can be compared to MC generator level (i.e. theory without detector response) within the systematic uncertainties!**

Monte Carlo event generators

- All Monte Carlo simulations performed on the generator level
- True $\langle p_\mathrm{T} \rangle$ is available!
- Color reconnections (CR) important to describe the increase with multiplicity, PYTHIA6 NOCR almost flat
- PHOJET also differs from the others (and from data)



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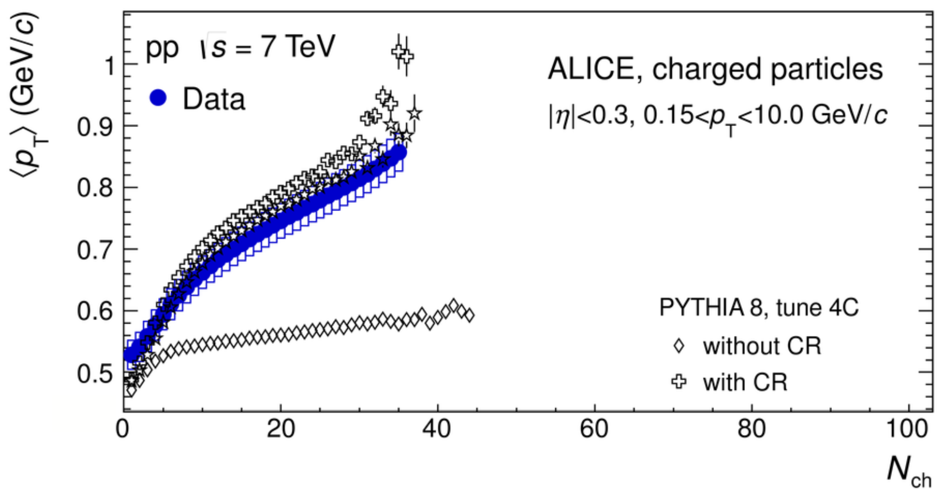
ALICE published $\langle p_{\mathrm{T}} \rangle$



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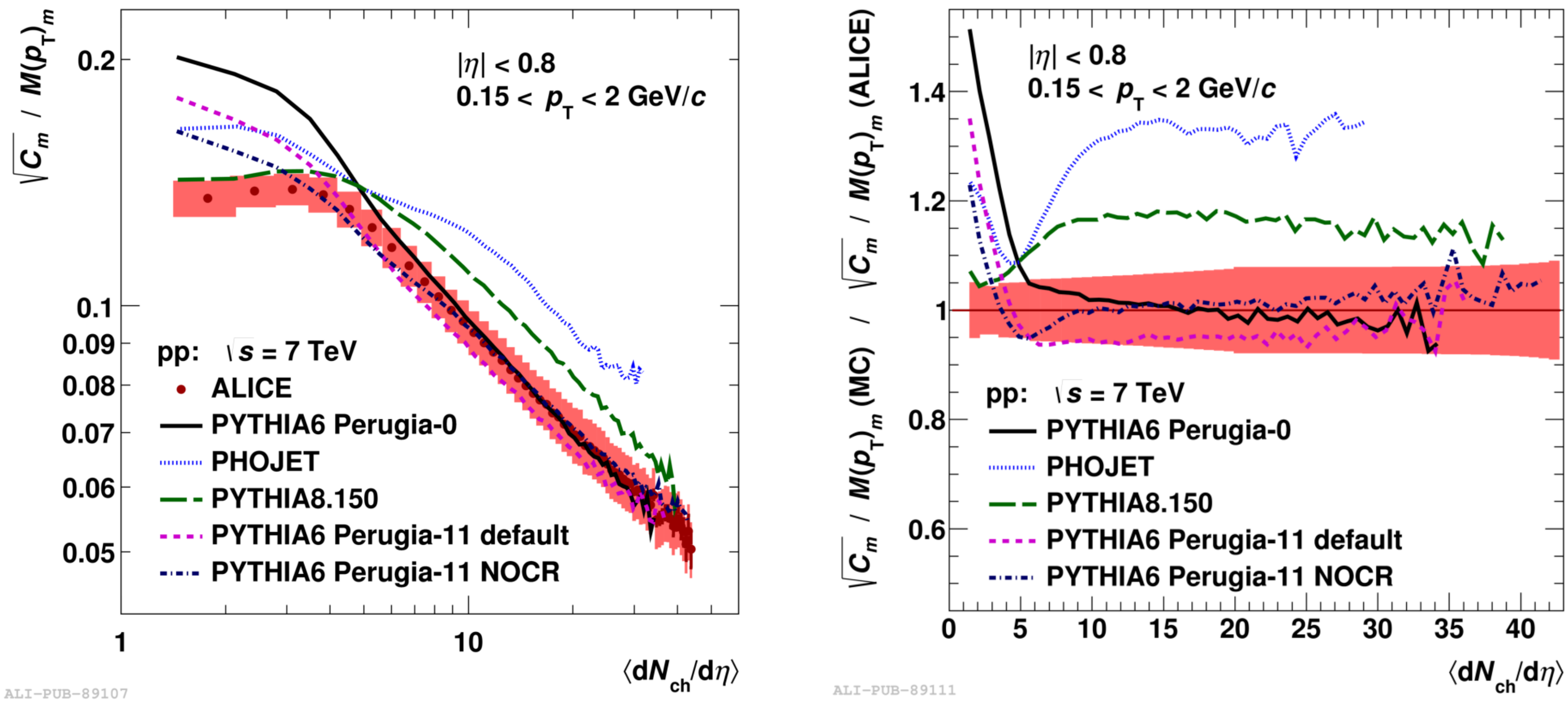
Phys.Lett. **B727** (2013) 371

Results in pp collisions

Comparison to Monte Carlo generators



For $\langle dN_{ch}/d\eta \rangle > 5$:

- Reasonable description by most of the generators
- Color reconnections have no influence on the slope!

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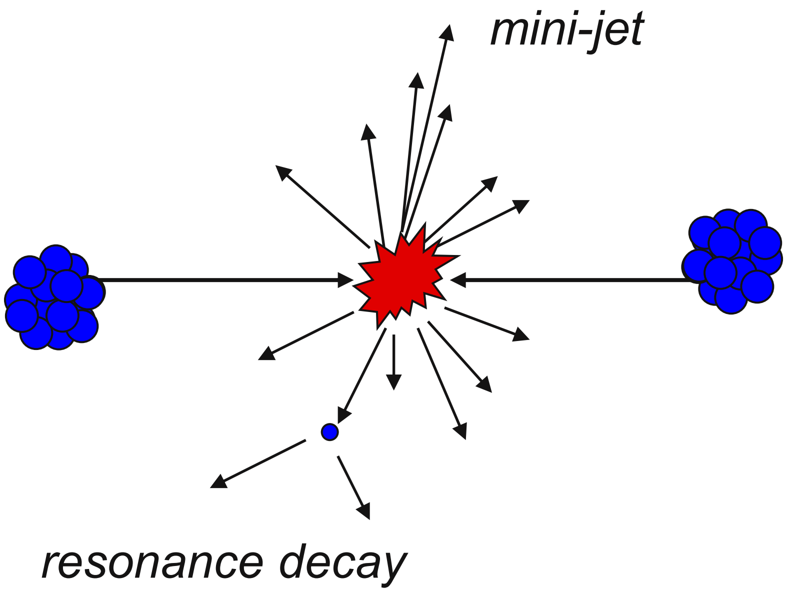
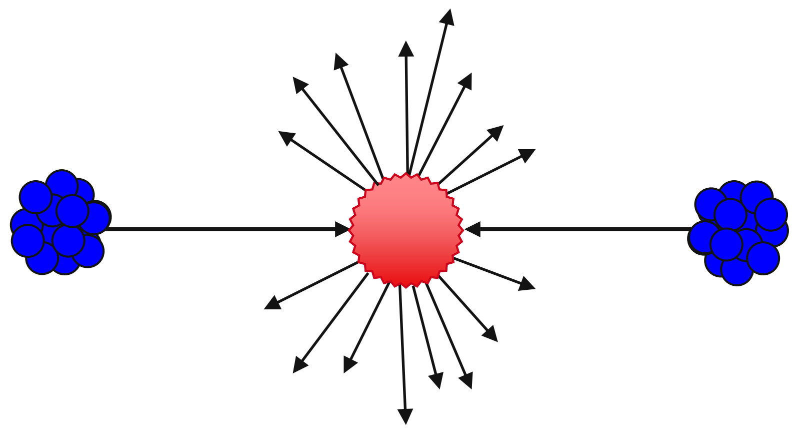
Motivation: From pp to Pb–Pb collisions

Contributions also observed in pp collisions:



pp collisions important as reference measurement!

Contributions unique to heavy-ion collisions:

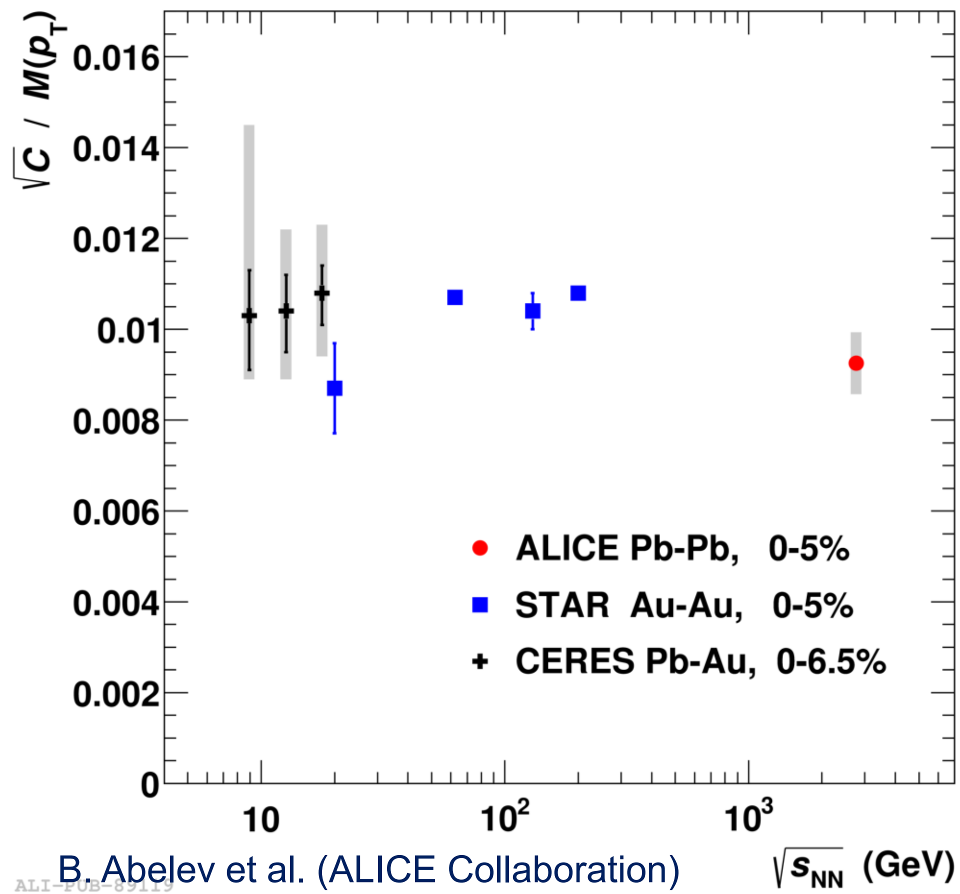


- Thermalization
- Collectivity
- Phase transitions
- Initial state fluctuations
- …

Results in Pb–Pb collisions

Central A–A collisions as a function of √*s*

- Significant dynamical fluctuations
- Much smaller values than in pp
- Comparison to data from CERES [3] and STAR [4]
- No significant collision energy dependence



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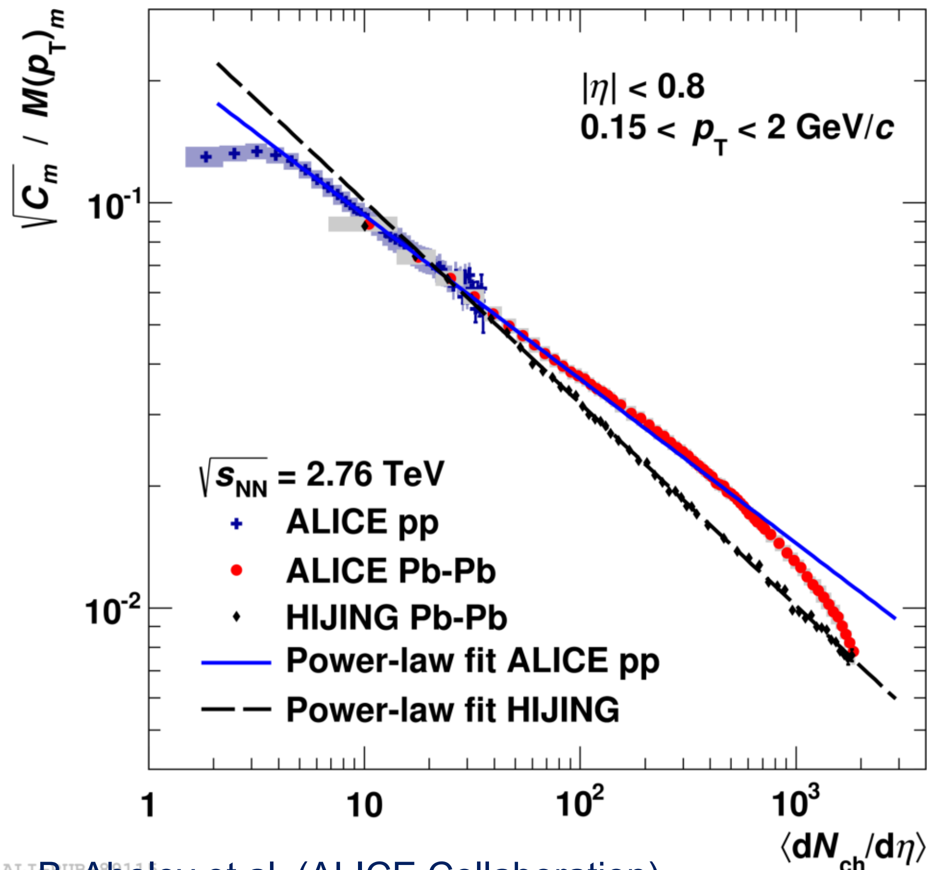
[3] D. Adamová *et al*., Nucl.Phys. **A811** (2008) 179
[4] J. Adams *et al*., Phys.Rev. **C72** (2005) 044902

Results in Pb–Pb collisions

Comparison to pp collisions as a function of the multiplicity



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- Peripheral Pb–Pb in agreement with pp baseline:

$$\propto \langle dN_{ch} / d\eta \rangle^{b}$$

$$b = -0.405 \pm 0.002(\text{stat.}) \pm 0.036(\text{syst.})$$

- Deviation in central Pb–Pb

- Not described by HIJING:

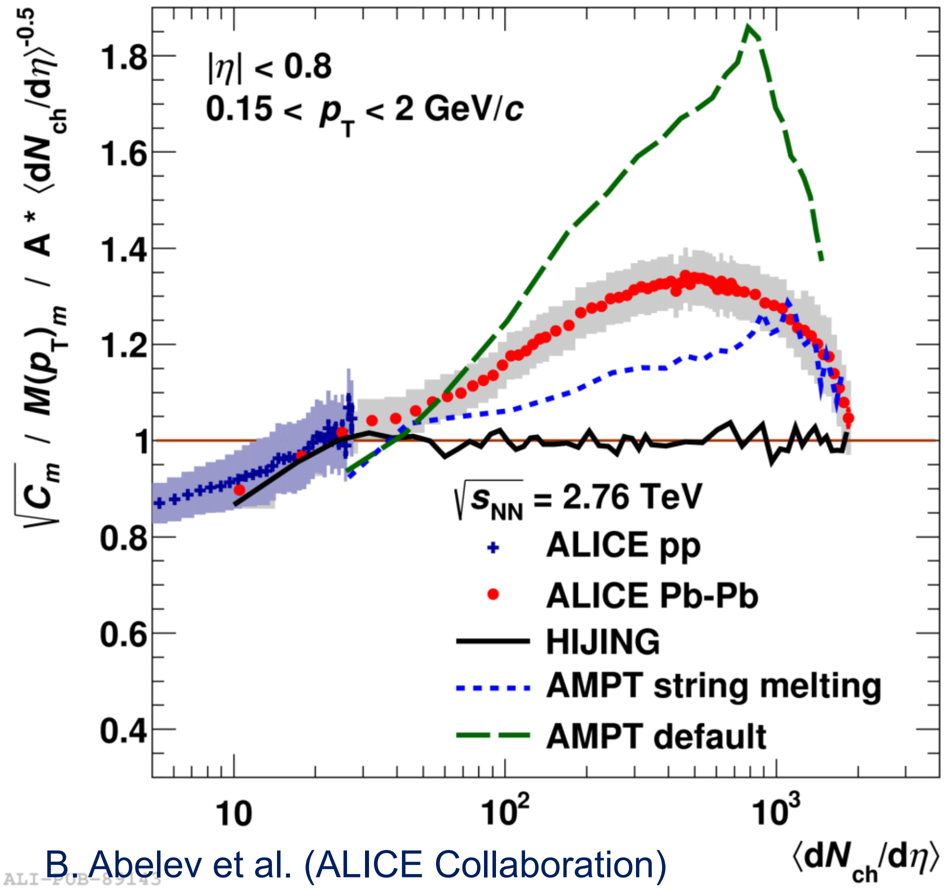
$$b = -0.499 \pm 0.003(\text{stat.}) \pm 0.005(\text{syst.})$$

corresponds to simple superposition expectation

Results in Pb–Pb collisions

Comparison to Monte Carlo generators

- HIJING shows behaviour $\propto \langle dN_{ch} / d\eta \rangle^{-0.5}$ and cannot describe the data
- AMPT (includes collective effects) both versions:
  - Increase above simple superposition expectation
  - Decrease towards central events
  - Fail in terms of absolute values



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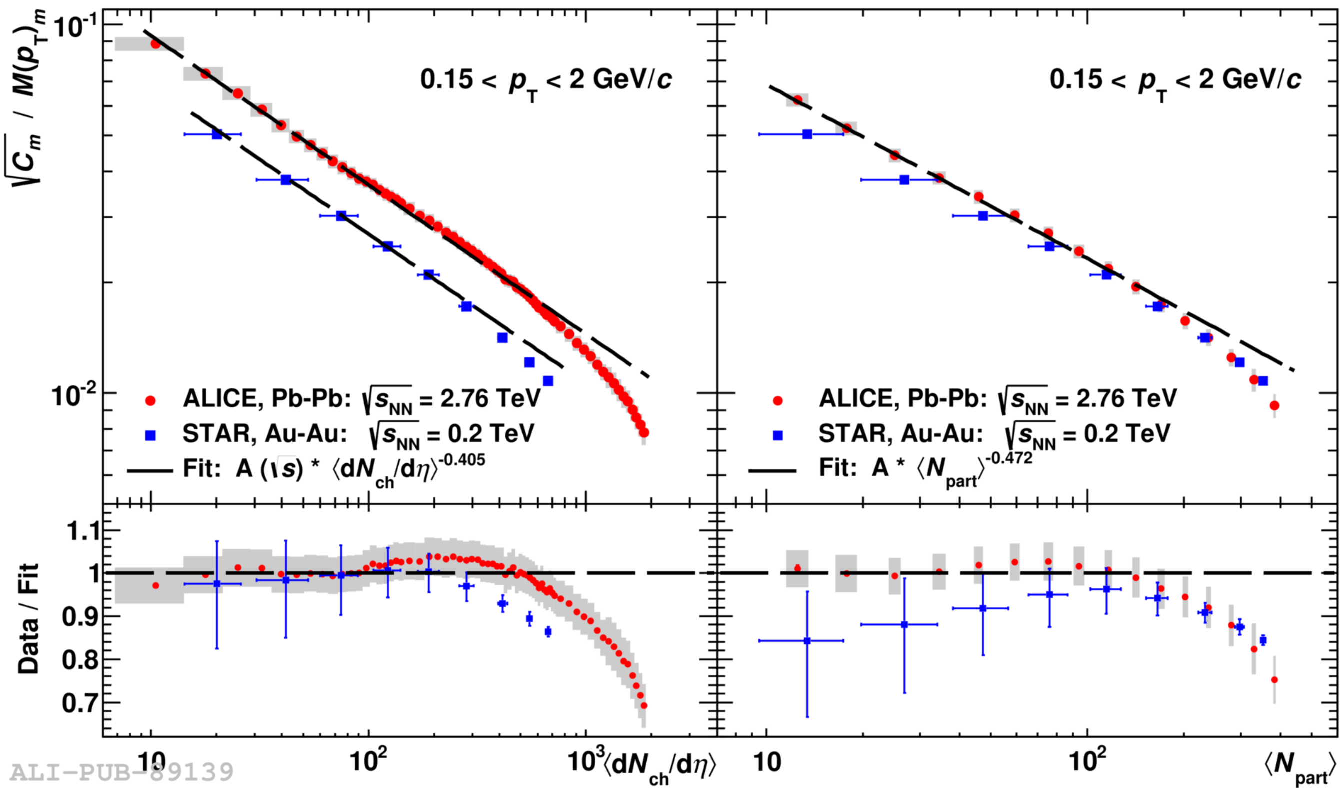
Results in Pb–Pb collisions

Comparison to STAR [4] results in Au–Au collisions



Left:

Power of fits from ALICE pp:

$$\langle dN_{ch} / d\eta \rangle^{-0.405}$$

Right:

In terms of $\langle N_{part} \rangle$

Deviation from fit at same centrality

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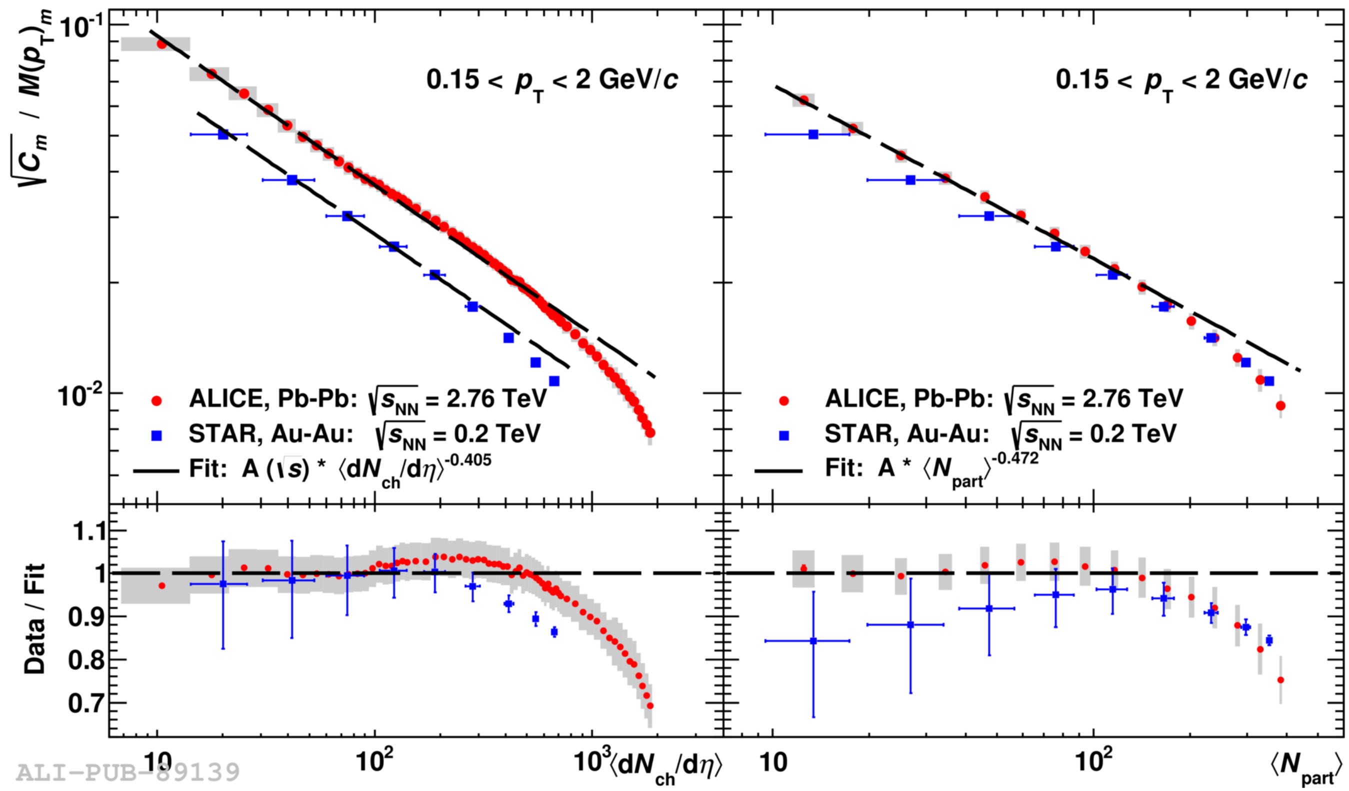
[4] J. Adams *et al*., Phys.Rev. **C72** (2005) 044902

Results in Pb–Pb collisions – going back to pp!



Left:

scaling with multiplicity density

$$\left\langle \mathrm{d}N_{\mathrm{ch}} / \mathrm{d}\eta \right\rangle$$

Right:

scaling with number of participants

$$\left\langle N_{\mathrm{part}} \right\rangle$$

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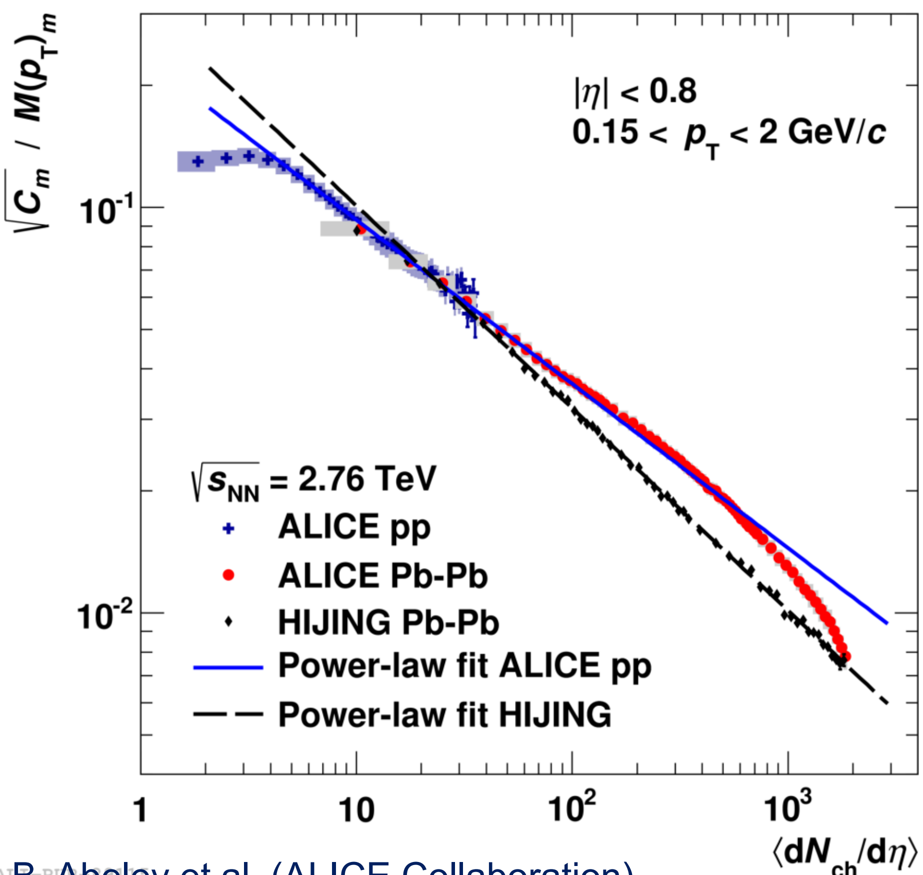
Naive expectation in pp:

Single point at N_{part} = 2

[4] J. Adams *et al.*, Phys.Rev. **C72** (2005) 044902

Recap: Comparison of pp and Pb–Pb



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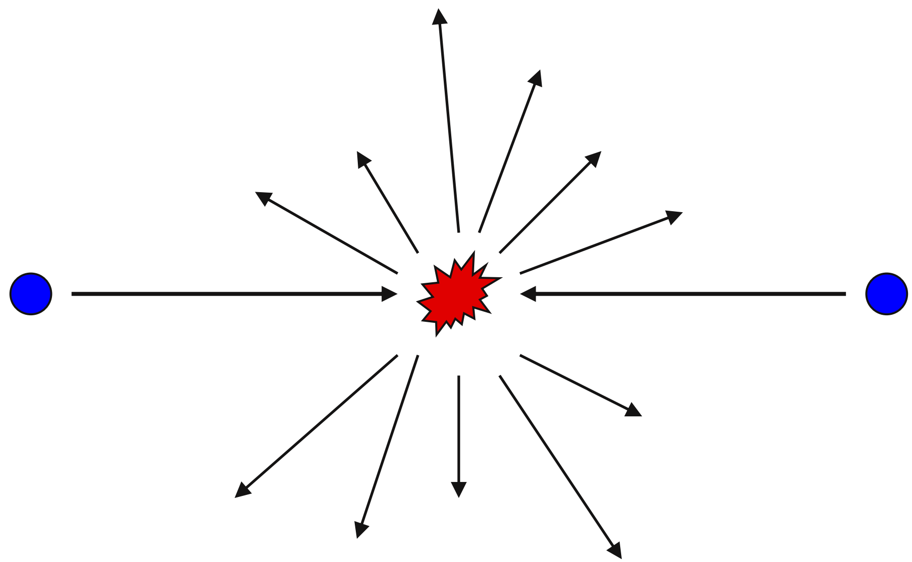
- Results for pp collisions indeed scale with multiplicity
- Good agreement of pp and peripheral Pb–Pb collisions

⇒ If dependence in Pb–Pb is understood as superposition of N_{part}, what is it in pp?

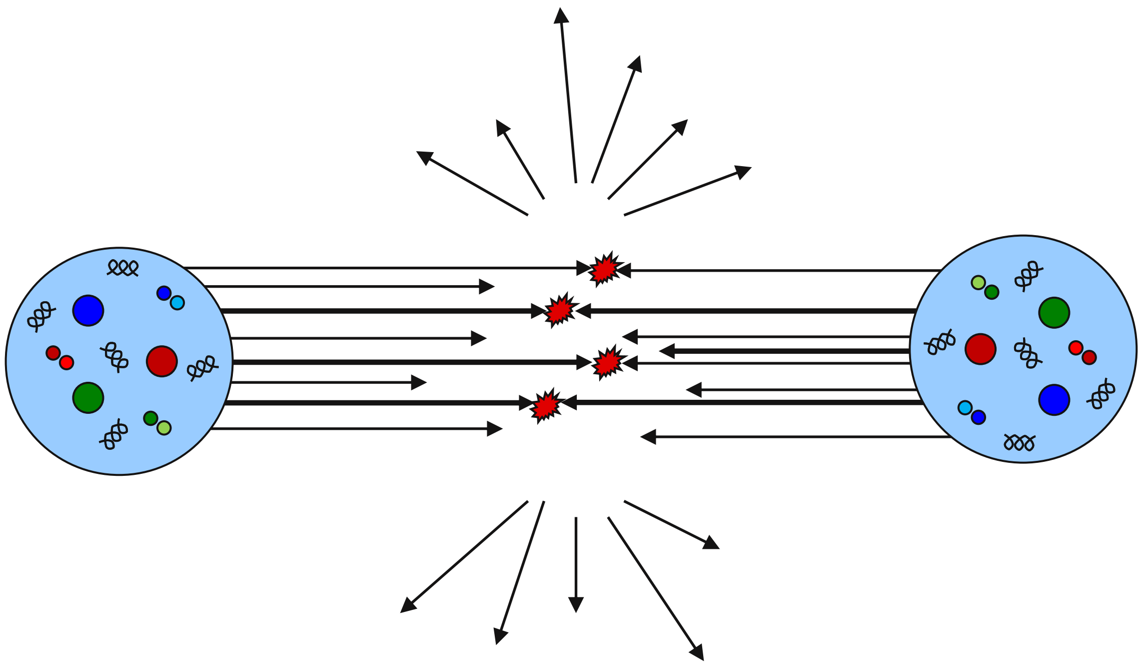
pp in detail: multi-parton interactions



At low collision energies:

proton-proton collision = **1 nucleon-nucleon collision**

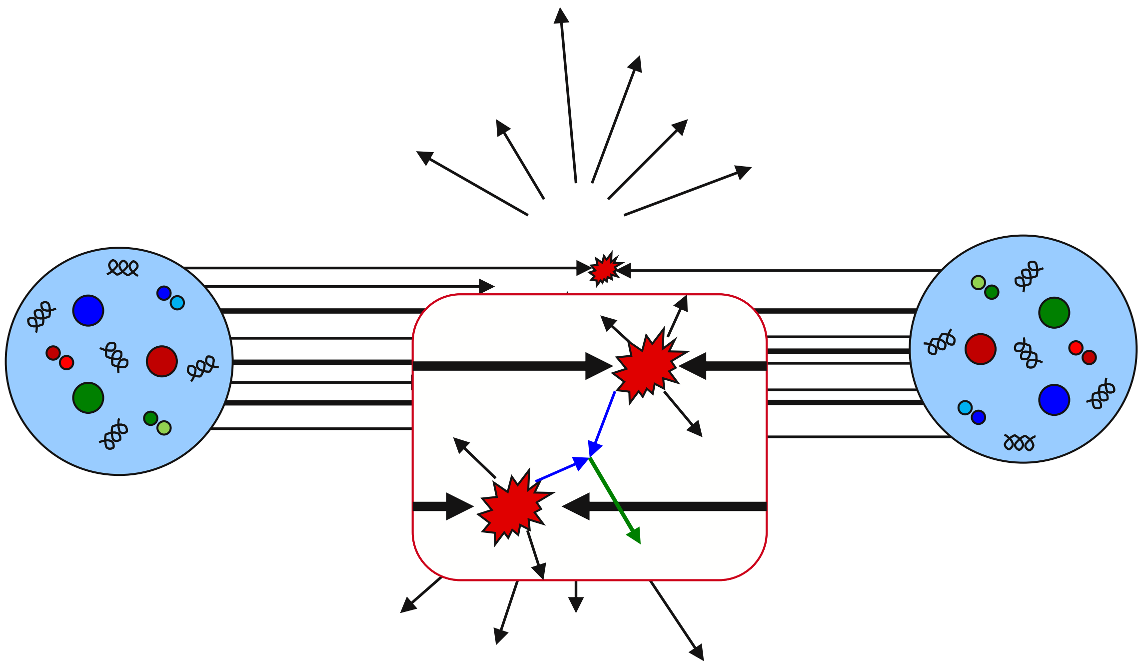
pp in detail: multi-parton interactions



At high collision energies, reached at the LHC:

proton-proton collision = **multiple parton-parton interactions (MPI)**

pp in detail: multi-parton interactions

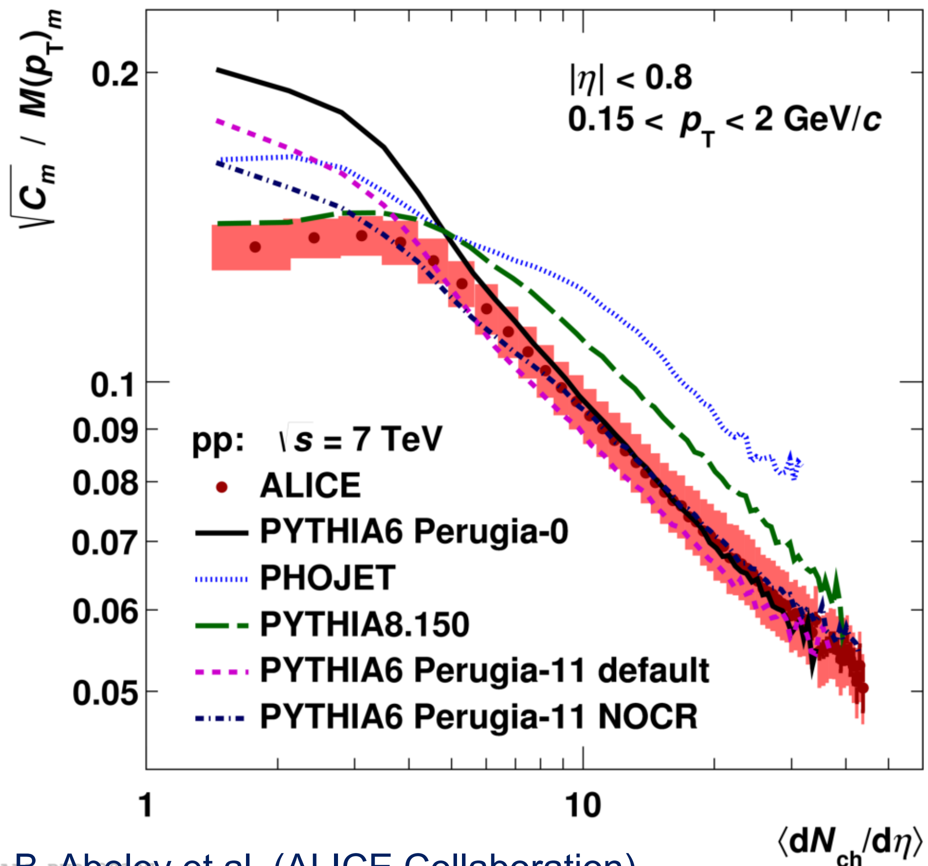


At high collision energies, reached at the LHC:

proton-proton collision = multiple parton-parton interactions (MPI)

→ particles from different scattering centers can recombine via **color reconnections (CR)**

Recap: Comparison to Monte Carlo studies



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- Reasonable description by the PYTHIA generators (all with MPIs)
- Worst description by PHOJET (no MPIs)
- Color reconnections have no influence on the slope!

Monte Carlo simulations

With multi-parton interactions (MPIs)

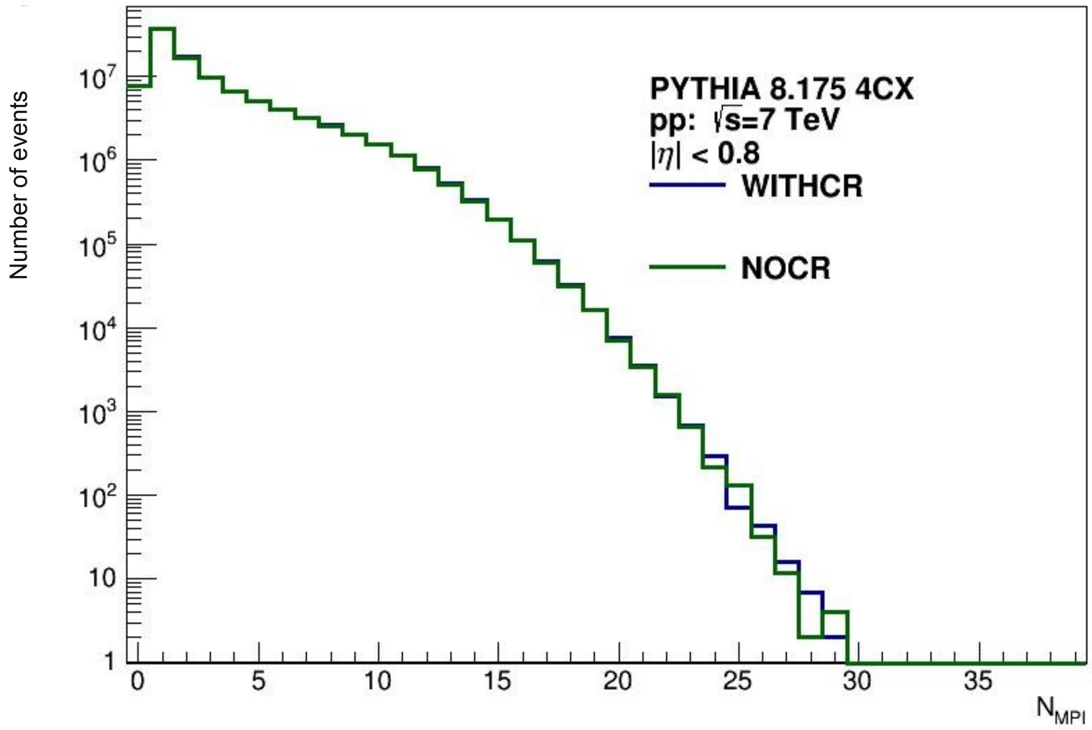
Bachelor Thesis by
Bernhard Schütz

- MC generator: PYTHIA 8.175
- MC tune: 4CX
- Pure MC generator level, no ALICE detector simulation
- Two simulations with 100 M events each:
  - Default tune 4CX including Color Reconnections (WITHCR)
  - Modified version without Color Reconnections (NOCR)*
- MPIs are included in PYTHIA and important for the creation of high multiplicity pp events

*Note: CR has just been switched off, this is not a complete tune.
Results are of qualitative nature only.

Basic distributions I

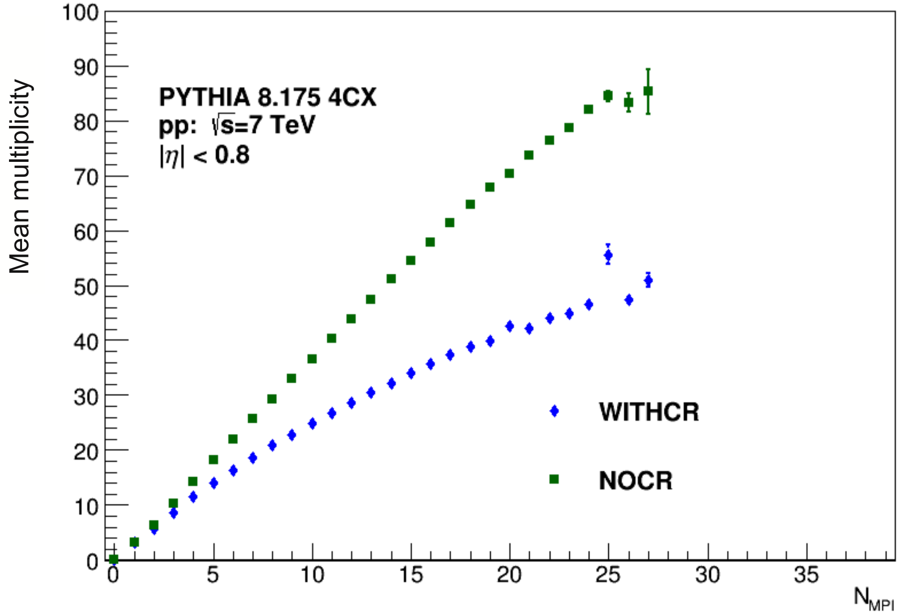
Number of events versus number of parton-parton interactions

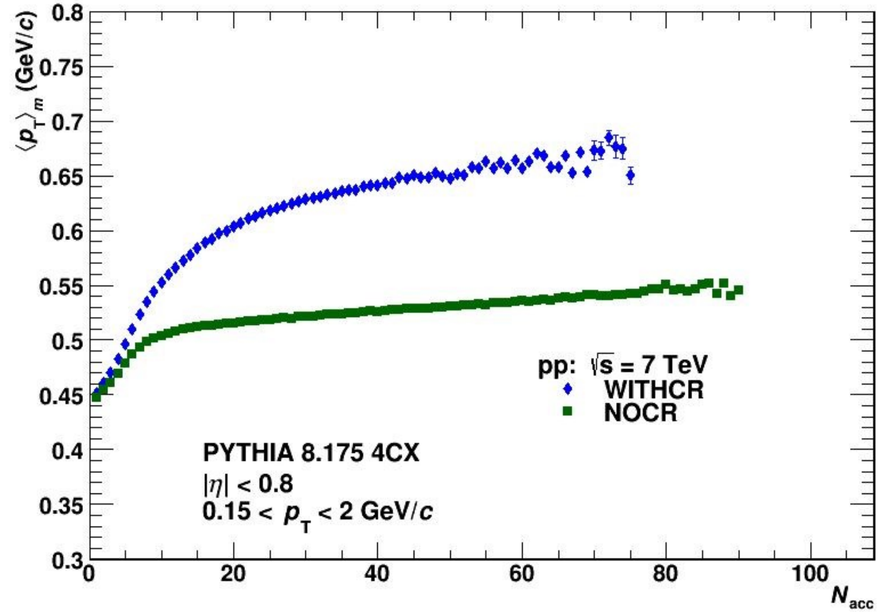


- N_{MPI} = Number of Multi-Parton Interactions
- Peak at N_{MPI} = 1 (about 35%), maximum at $N_{MPI} \approx 30$

Basic distributions II

Mean multiplicity versus N_{MPI} and mean p_T versus multiplicity

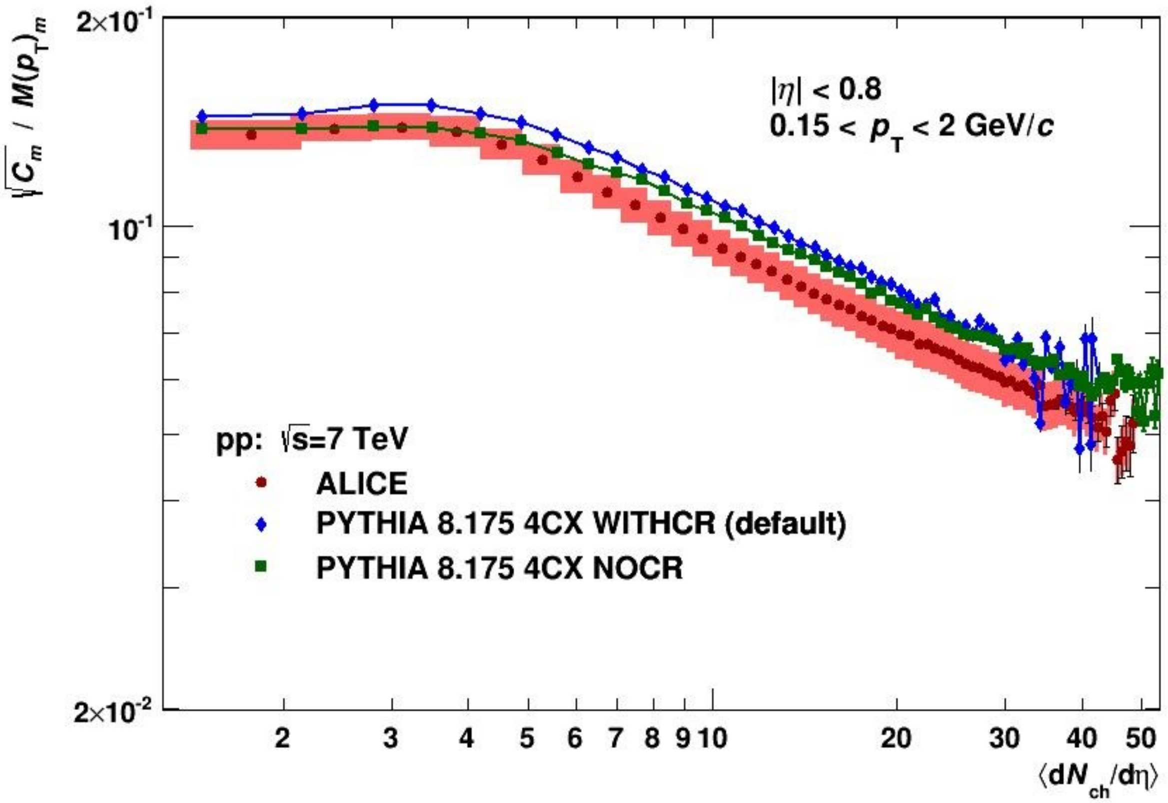




- As expected, the mean multiplicity increases with N_{MPI}
- Multiplicities are larger in the NOCR scenario

- $\langle p_T \rangle$ increases with multiplicity in WITHCR and is almost flat in NOCR
- WITHCR consistent with data

Results for relative dynamical fluctuations

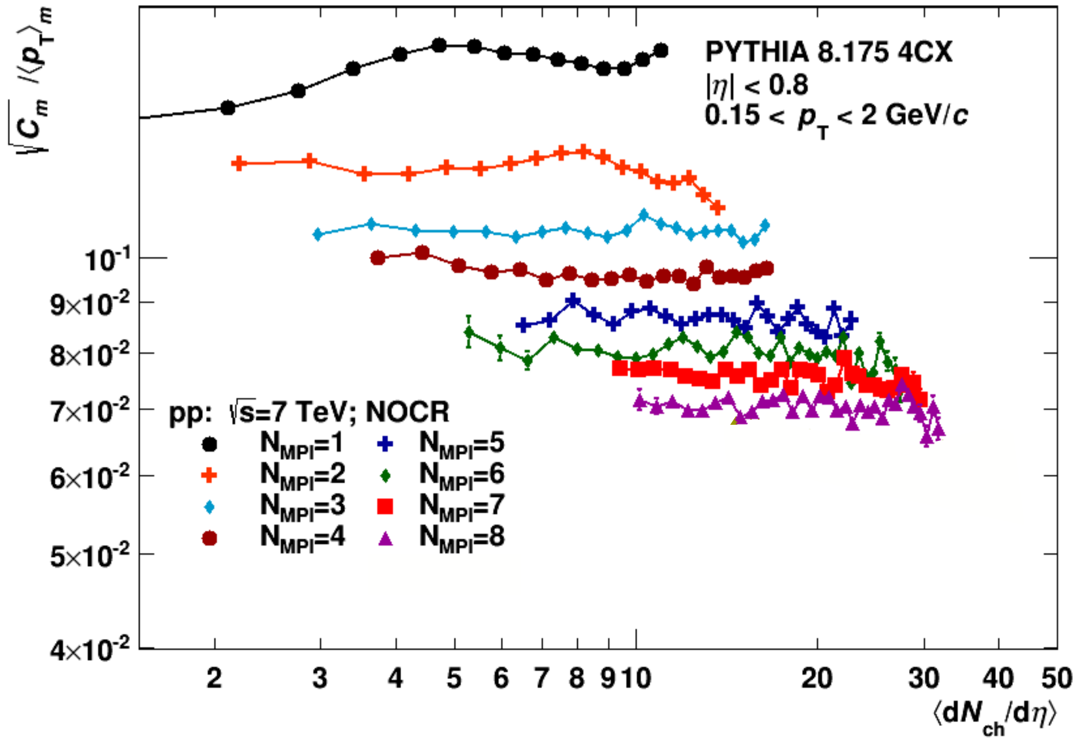


ALICE data from:
B. Abelev et al.
Eur.Phys.J. **C74** (2014) 3077

- Results show similar behavior as ALICE data
- Can we learn more in an N_{MPI}-dependent analysis?

Results for relative dynamical fluctuations

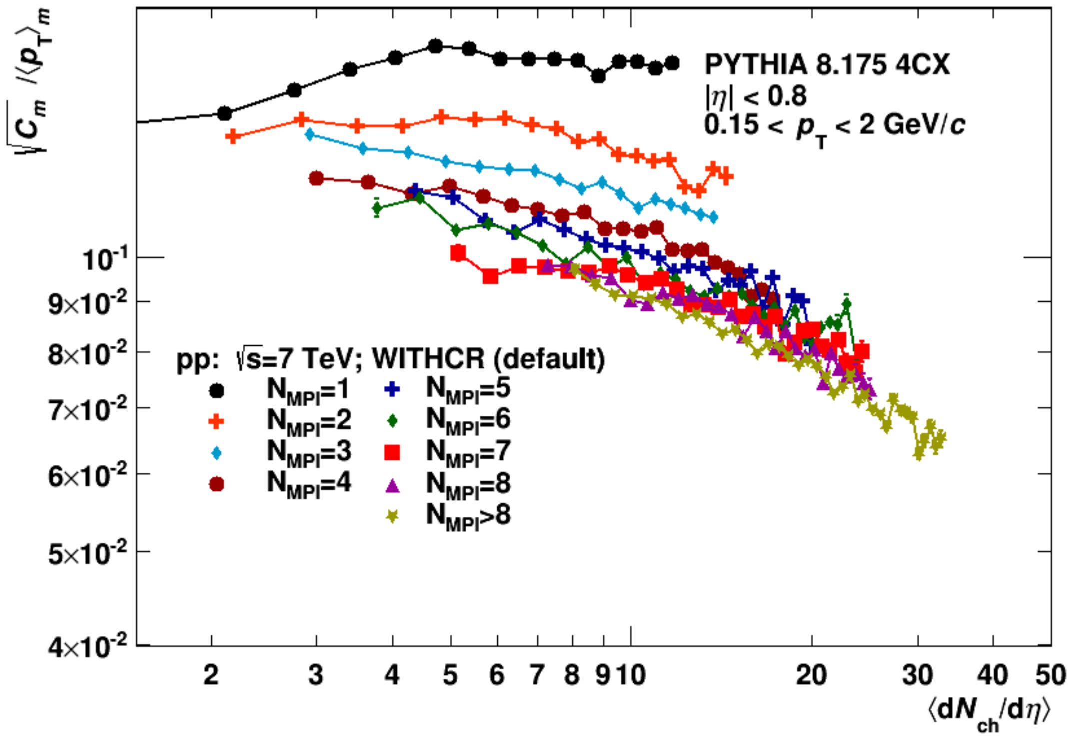
Detailed analysis without color reconnections (NOCR)



- All samples almost flat as a function of multiplicity
- Parton-parton interactions = independent sources of particle production

Results for relative dynamical fluctuations

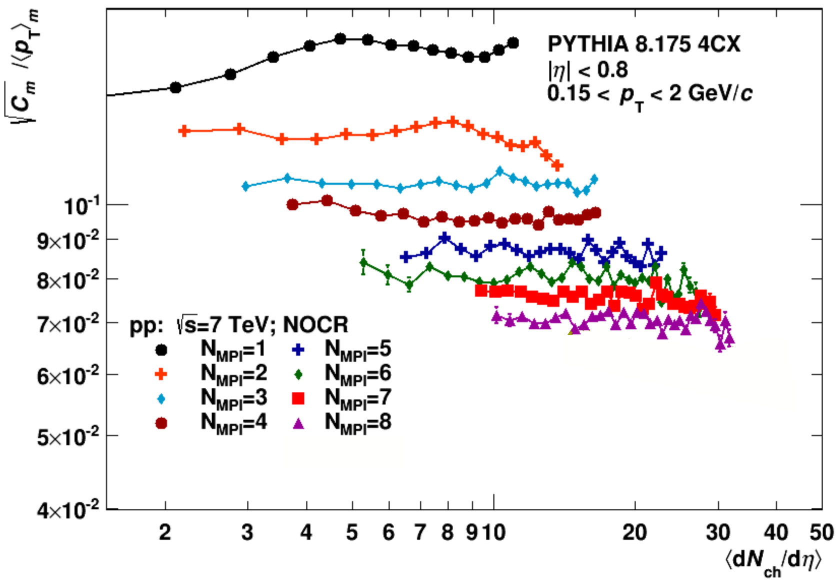
Detailed analysis with color reconnections (WITHCR)

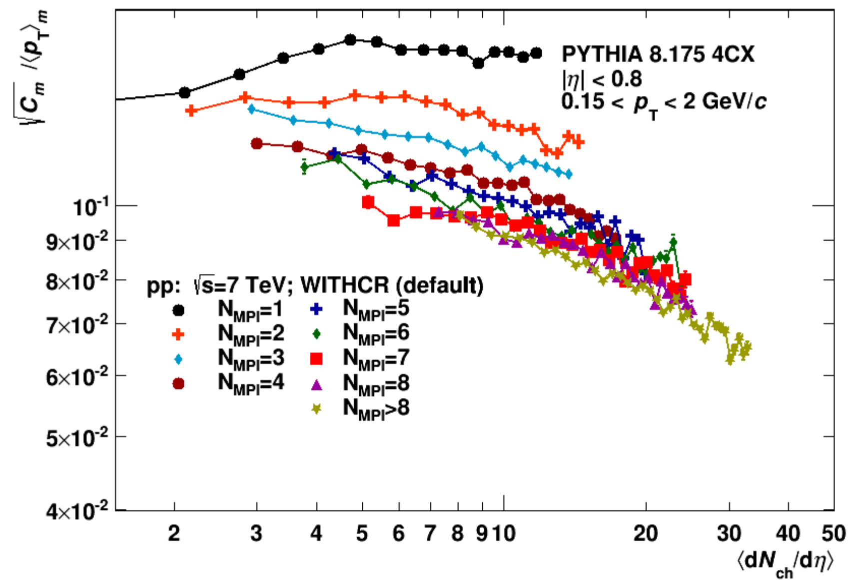


- N_{MPI} = 1: almost flat as a function of multiplicity
- N_{MPI} > 1: decreasing trend with increasing multiplicity, getting more pronounced for higher N_{MPI}, not independent anymore!

Results for relative dynamical fluctuations

Comparison of NOCR and WITHCR





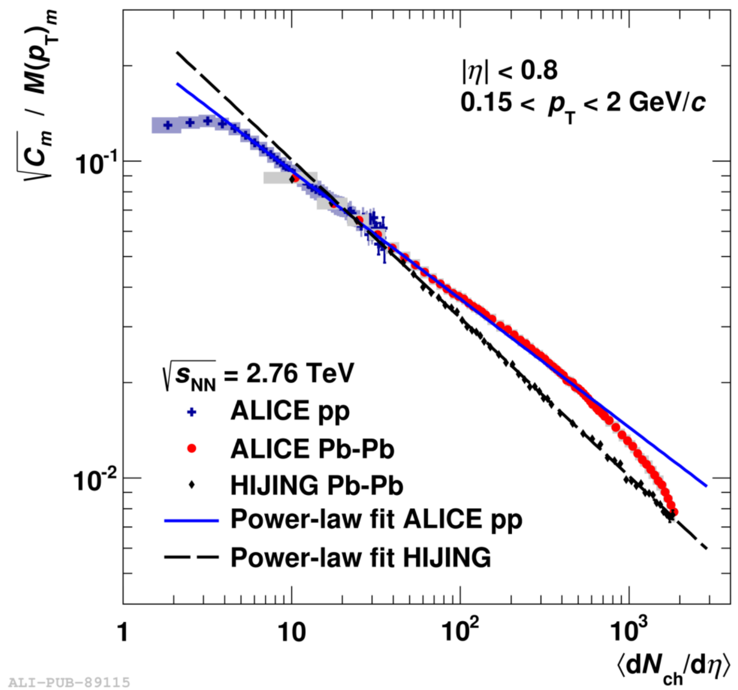
- Independent sources of particle production
- Flat as a function of multiplicity

- Sources of particle production not independent
- Decreasing trend with multiplicity

⇒ Integrated observables comparable, experimentally not distinguishable

Conclusions

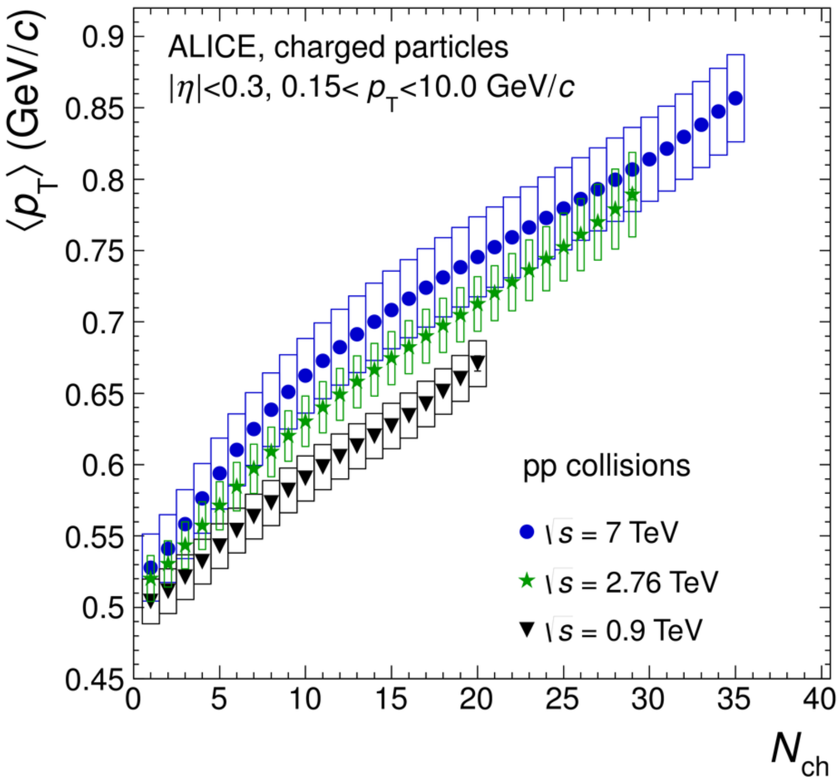
- Event-by-event mean p_{T} fluctuations measured by ALICE
- Observable: Two-particle correlator
- Significant dynamical fluctuations decreasing with multiplicity
- No significant energy dependence
- Peripheral Pb–Pb agrees with a pp extrapolation, central Pb–Pb deviates
- Monte Carlo generators describe pp rather well, Pb–Pb is not described as well
- MC studies with MPIs: Interesting differences with and without color reconnections

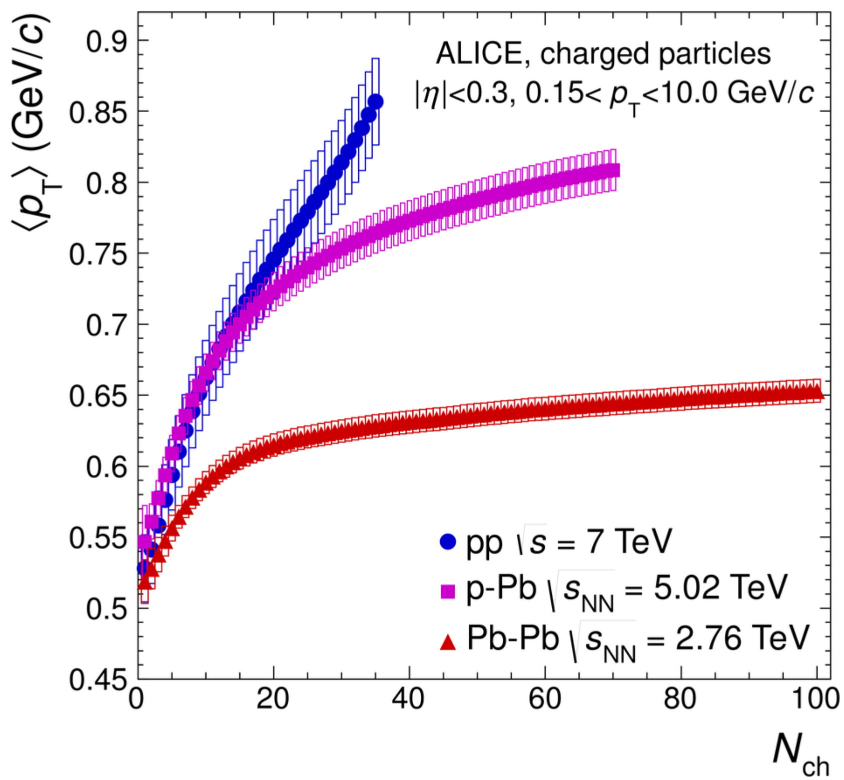


B. Abelev et al. (ALICE Collaboration)
Eur.Phys.J. **C74** (2014) 3077

BACKUP

Mean transverse momentum – ALICE published



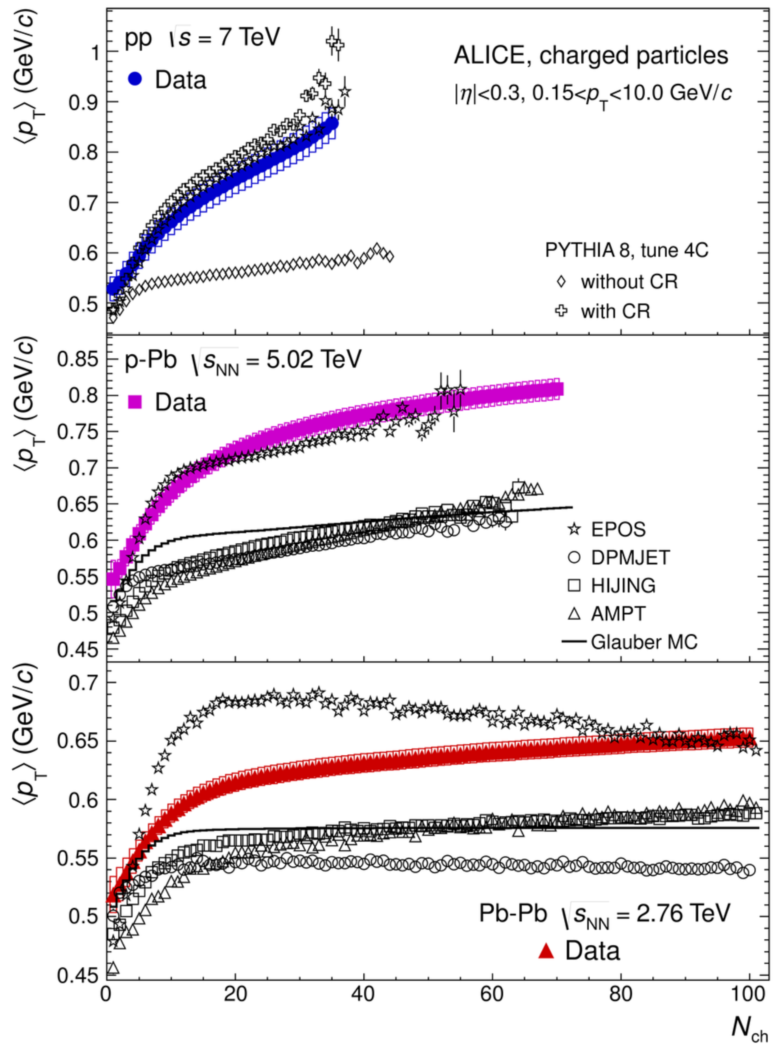


B. Abelev et al. (ALICE Collaboration)
Phys.Lett. **B727** (2013) 371

Mean transverse momentum – ALICE published

- Comparison of pp, p–Pb and Pb–Pb data to several Monte Carlo simulations

- Color reconnections needed to describe the increase of $\langle p_{\mathrm{T}} \rangle$ with multiplicity in pp



B. Abelev et al. (ALICE Collaboration)
Phys.Lett. **B727** (2013) 371

Event and track selection

Event selection:

- Minimum bias trigger
- Maximum distance of the vertex to the nominal position in beam direction
- …

Track selection:

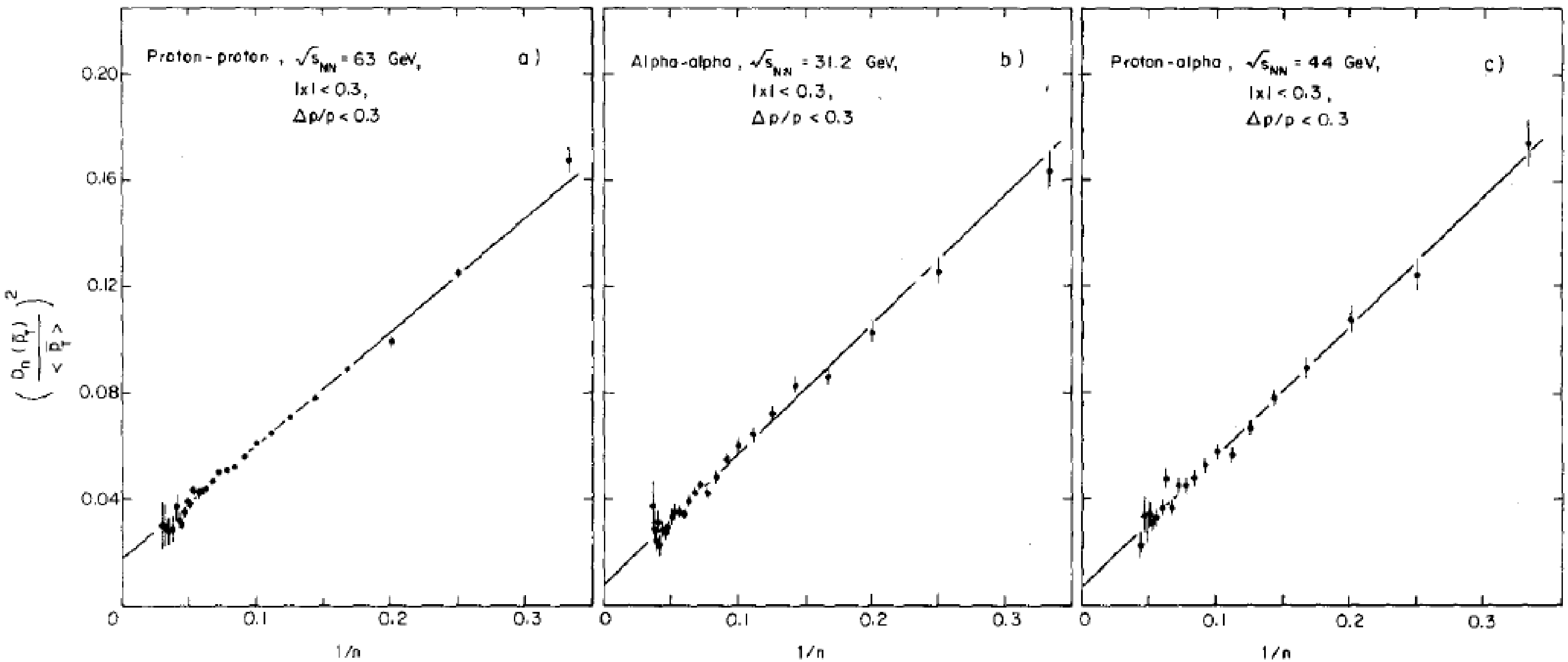
- Minimum number of clusters in the TPC
- Maximum χ^2 per space point in the TPC
- Restriction of the distance to closest approach to the primary vertex along the beam and in the transverse plane
- Pseudorapidity range: $|\eta| < 0.8$
- Transverse momentum range: $0.15 < p_T < 2$ GeV/c
- …

Systematic uncertainties

Complete list of systematic uncertainties:

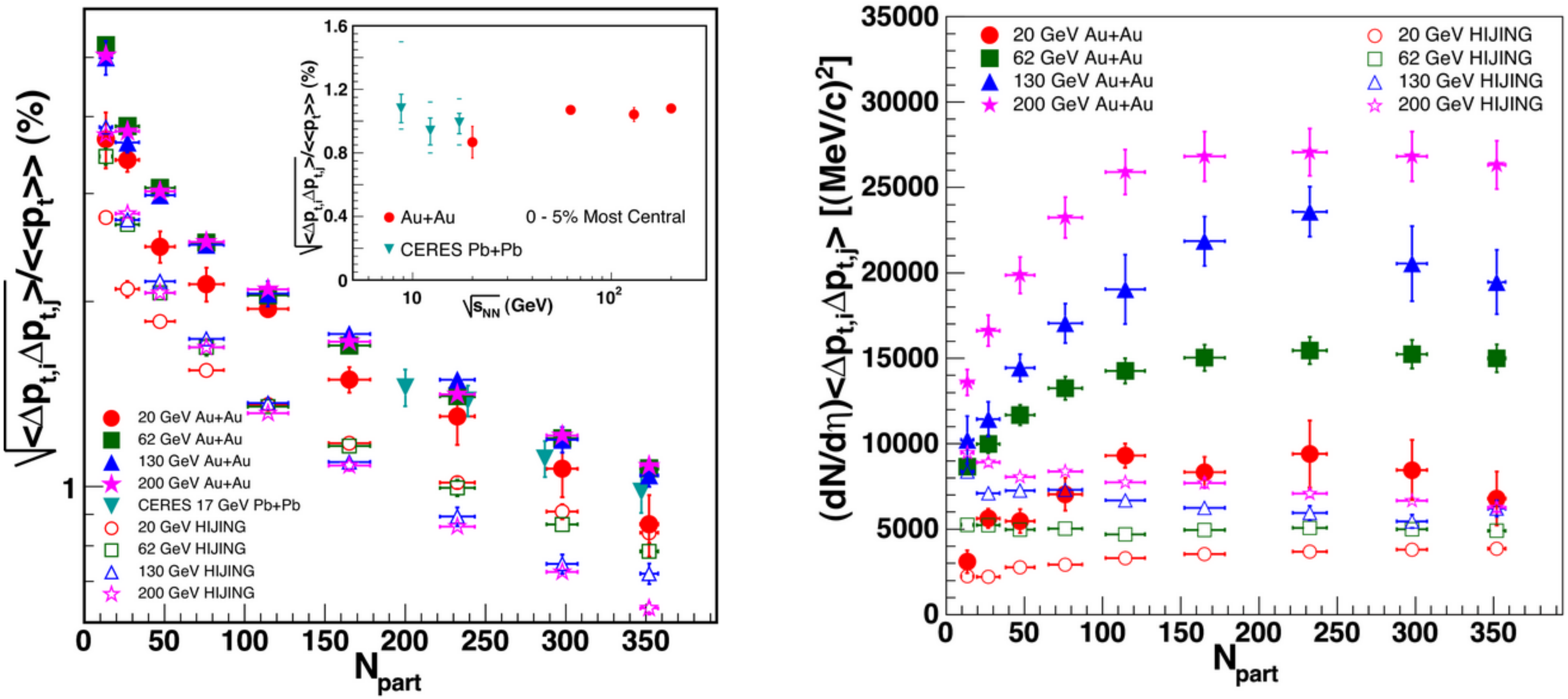
Collision system $\sqrt{s_{NN}}$	pp 0.9 TeV	pp 2.76 TeV	pp 7 TeV	Pb–Pb 2.76 TeV
Vertex z-position cut	0–0.5 %	<0.1 %	<0.1 %	0.5–1 %
Vertex calculation	0–2 %	0.5–2 %	0.5–2 %	<0.1 %
Vertex difference cut	0–1.5 %	0–3 %	0–2 %	0–2 %
Min. TPC space points	1.5–3 %	1–2 %	1–3 %	2–3 %
TPC χ^2 / d.o.f.	<0.1 %	<0.1 %	<0.1 %	<0.1 %
DCA to vertex	1 %	1–1.5 %	0.5–1 %	0.5–1 %
B-field polarity	0.5 %	0.5 %	0.5 %	0.5 %
Centrality intervals	–	–	–	1–3 %
TPC-only vs. hybrid	4 %	4 %	4 %	1–5 %
MC generator vs. full sim.	0–6 %	0–6 %	0–6 %	0–4 %
Total	4.4–7.7 %	4.4–7.6 %	4.4–7.9 %	4.2–7.4 %

The dispersion measured at the ISR



[1] K. Braune *et al.*, Phys.Lett. **B123** (1983) 467

The two-particle correlator measured by STAR



[4] J. Adams *et al.*, Phys.Rev. **C72** (2005) 044902