WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

Multiplicity Dependence of Two-Particle Correlations in Proton-Proton Collisions

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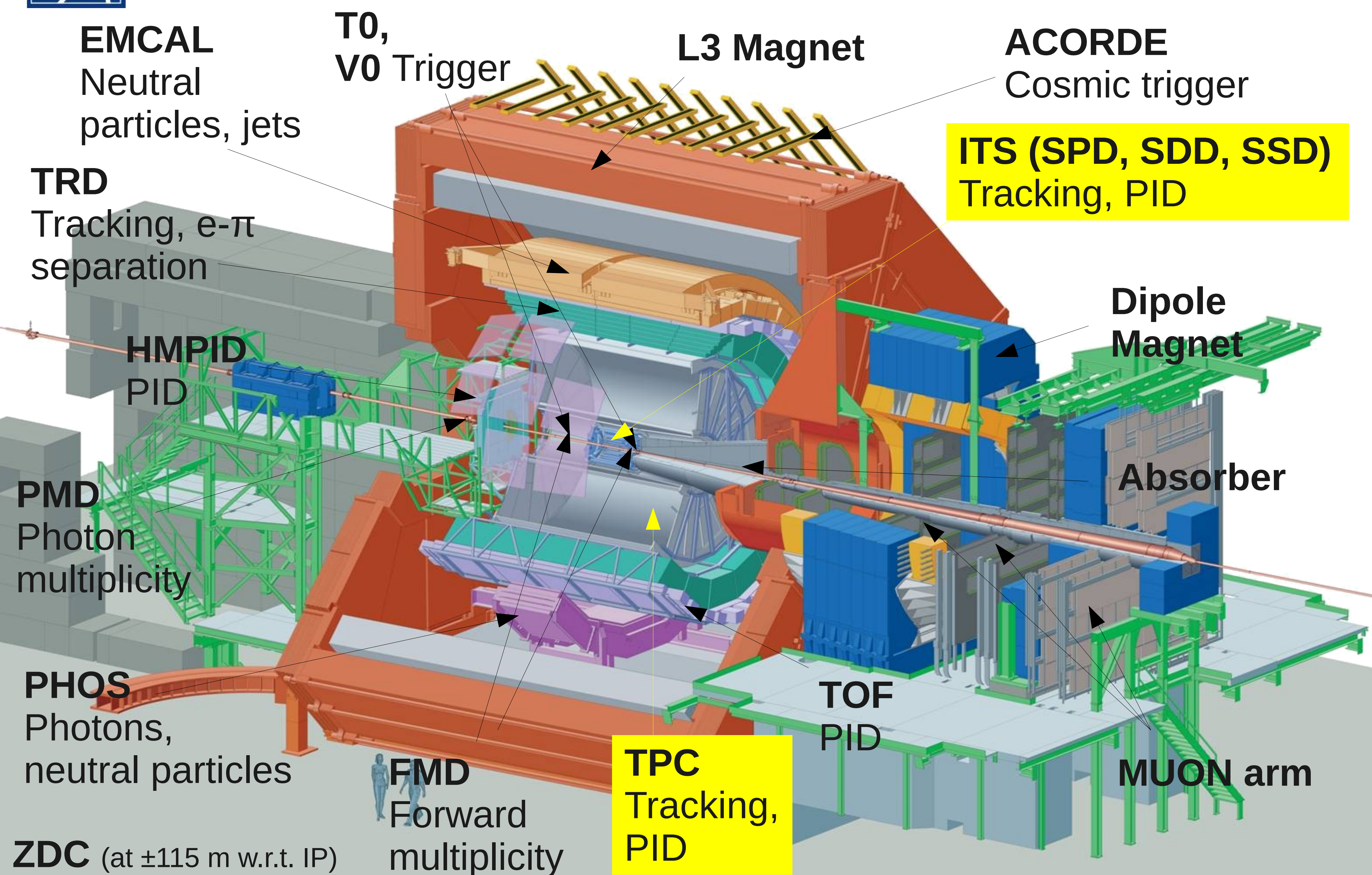
24th Rencontres de Blois, Particle Physics and Cosmology 2012

A Large Ion Collider Experiment

- ALICE is designed to study heavy-ion (Pb-Pb) collisions and also proton-proton (pp) collisions
  - Several signals in heavy-ion collisions are measured relative to pp
  - ALICE also has a rich pp program
- ALICE special features for pp minimum bias physics
  - Low momentum sensitivity due to low material budget and low magnetic field
  - Excellent primary and secondary vertex resolution
  - Excellent Particle Identification (PID) capability
- ALICE can give important input to pp studies
  - Rare signals need good description of soft underlying event
  - Tuning of MC generators in low-p_T region
  - Study of high-multiplicity collisions

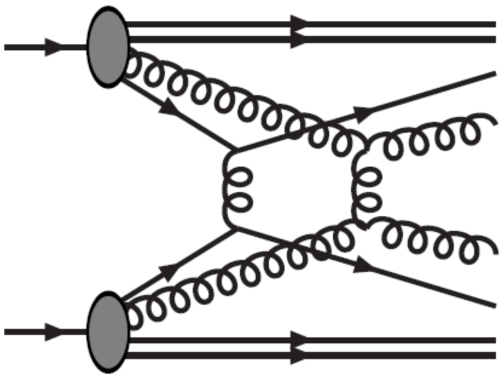
A Large Ion Collider Experiment



Analysis Motivation

- High-energy proton-proton collisions can be interpreted as collisions of two “bunches of partons”
- → when two protons collide, it is possible that multiple distinct pairs of partons collide with each other

→ Multiple parton interactions (MPI)



arXiv:hep-ph/0402078

- MPIs presumably have impact on multiplicity distribution, jets, and the underlying event
- Is it possible to measure multiple parton interactions, e.g. the number and the corresponding particle yield?
  - Possible access to MPI via jets and mini-jets

Motivation of Analysis Approach

- Investigate properties of jets and low energetic "mini-jets" and their contribution to the event multiplicity
  - "Mini-Jets" are particles from "hard scattering", which have too low energy in comparison to the underlying event, and which therefore can not be reconstructed event-by-event
  - But, there is a possibility to access mini-jet properties via two particle correlations averaged over many events

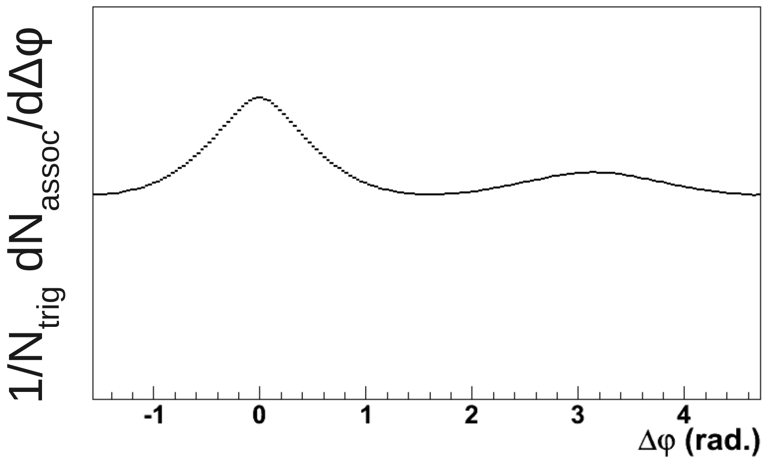
- Different correlation approaches:
  1. Correlation with one leading particle, particles with highest transverse momentum
  2. Triggered, inclusive correlations between all tracks with $p_T > p_{T,trig}$ and $p_T > p_{T,assoc}$ using $p_{T, trig} > p_{T,assoc}$

- Both methods have drawbacks for mini-jet measurements
  1. → Bias to hard momentum scale (increase of $p_{T,max}$ with $N_{charged}$)
  2. → Attention: possible bias due to unwanted combinatorics of correlated trigger particles

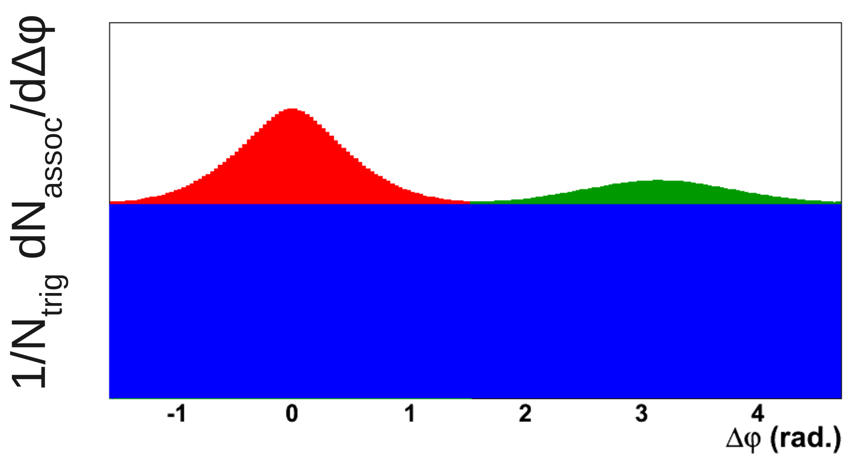
Per-trigger Associated Yield

- Associated per-trigger yield as function of azimuthal angle φ and multiplicity $N_{charged}$
- Several trigger-particle per event
- $p_{T,trig}$ > 0.7 GeV/c or higher
- $p_{T,assoc}$ > 0.4 (0.7) GeV/c or higher

$$\frac{d^2 N}{d\,\Delta\varphi\, dN_{ch}}(\Delta\varphi, N_{ch}) = \frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\,\Delta\varphi\, dN_{ch}}$$

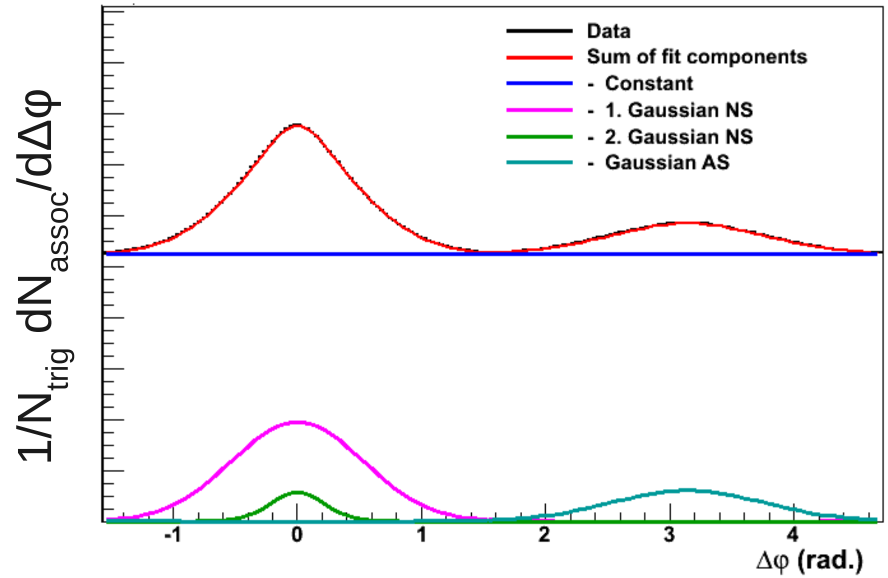


- Associated per-trigger yield can be computed for different
  - N_{ch}, $p_{T,trig}$, $p_{T,assoc}$
- Comparison of single correlation properties instead of comparison of the complete distribution
  - e.g. per-trigger yield in combinatorial background, per-trigger "near side" yield, per-trigger "away side" yield



Signal Extraction via Fit Function

$$f(\Delta\varphi) = C + A_1 e^{\frac{-\Delta\varphi^2}{2\sigma_1^2}} + A_1 e^{\frac{-(\Delta\varphi-2\pi)^2}{2\sigma_1^2}}$$
$$+ A_2 e^{\frac{-\Delta\varphi^2}{2\sigma_2^2}} + A_2 e^{\frac{-(\Delta\varphi-2\pi)^2}{2\sigma_2^2}}$$
$$+ A_3 e^{\frac{-(\Delta\varphi-\pi)^2}{2\sigma_3^2}} + A_3 e^{\frac{-(\Delta\varphi+\pi)^2}{2\sigma_3^2}}$$



- The fit function is a combination of a constant and periodically continuing Gaussian functions
- Data and fit are in good agreement with each other
- Extract correlation observables from fit and derive final observable

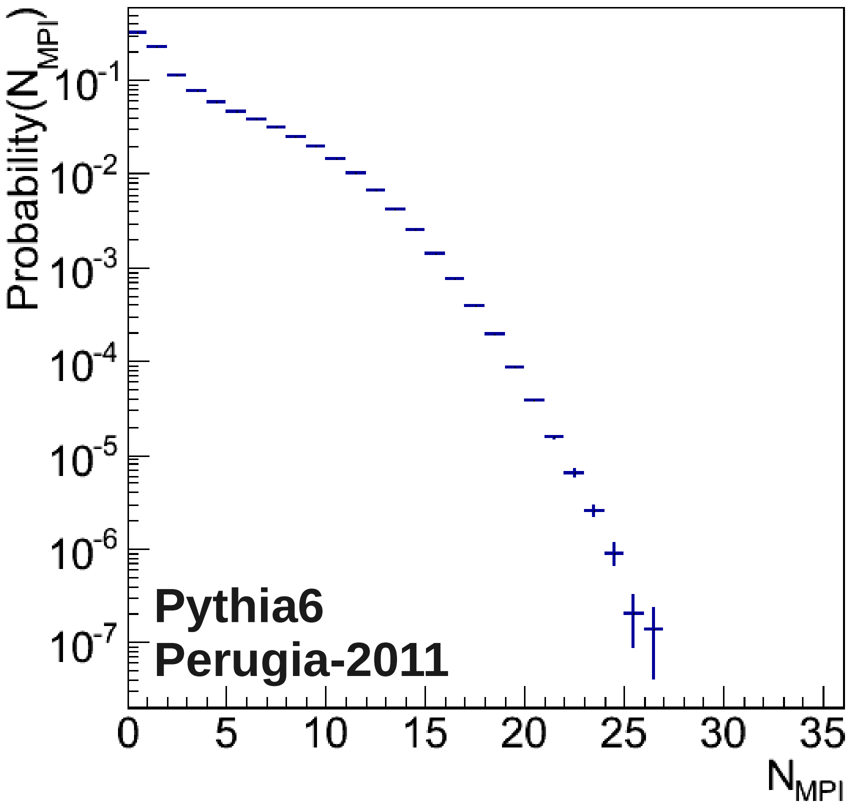
$$\langle N_{const} \rangle = \frac{1}{N_{trig}} Constant$$

$$\langle N_{assoc,\,near\,side} \rangle = \frac{1}{N_{trig}} \sqrt{2\pi}(A_1\sigma_1 + A_2\sigma_2)$$

$$\langle N_{assoc,\,away\,side} \rangle = \frac{1}{N_{trig}} \sqrt{2\pi}(A_3\sigma_3)$$

$$\langle N_{uncorrelated\ seeds} \rangle = \frac{\langle N_{trig} \rangle}{\langle 1 + N_{assoc,\,near}(p_T > p_{T,trig}) + N_{assoc,\,away}(p_T > p_{T,trig}) \rangle}$$

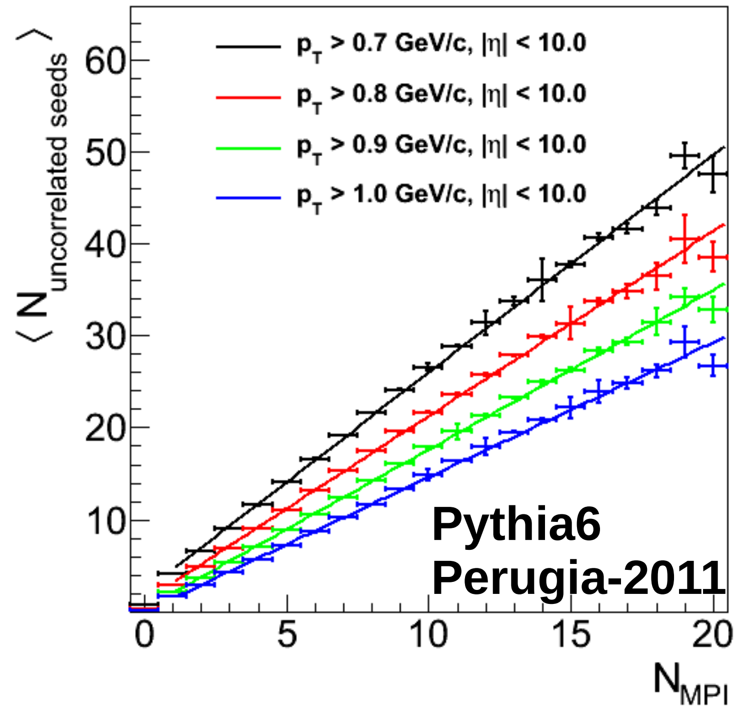
Assumption: Sensitivity on MPI



- Pythia simulations are based on multiple parton interactions (MPI)
- Pythia-MPI = number of (semi-)hard scatterings that occurred in the current event in the multiple interaction scenario

- Check dependency between N_{MPI} and

$$\langle N_{uncorrelated\ seeds} \rangle = \frac{\langle N_{trig} \rangle}{\langle 1 + N_{assoc,\, near+away}(p_T > p_{T,trig}) \rangle}$$



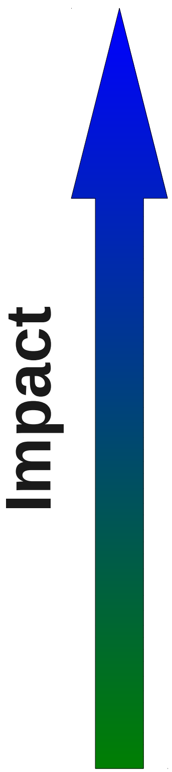
- Dependence is approximately linear → Analysis can probe MPI
- See backup slides for more details

Analysis Details

- Data (including ITS and TPC)
  - pp @ $\sqrt{s}$ = 0.9 TeV:
    - 7 million events
  - pp @ $\sqrt{s}$ = 2.76 TeV:
    - 34 million events
  - pp @ $\sqrt{s}$ = 7.0 TeV:
    - 270 million events
- Event cuts
  - Minimum bias trigger (hit in V0 or SPD)
  - One distinct reconstructed vertex within $|z_{vertex}| < 10$ cm of good quality
  - At least one track in ITS-TPC acceptance ($p_T > 0.2$ GeV/c, $|\eta| < 0.9$)

- Track cuts
  - Full refit procedure during the tracking in ITS and TPC
  - At least 1 hit per track in one of the first 3 ITS layers (first 3 out of 6)
  - At least 70 clusters per track in the TPC drift volume (out of 159)
  - χ^2/TPC cluster < 4
  - Reject tracks with kink topology
  - p_T dependent DCA_{xy} cut corresponding to 7σ of track distribution ($DCA_{xy,max}$ = 0.3 cm)
  - DCA_z < 2 cm

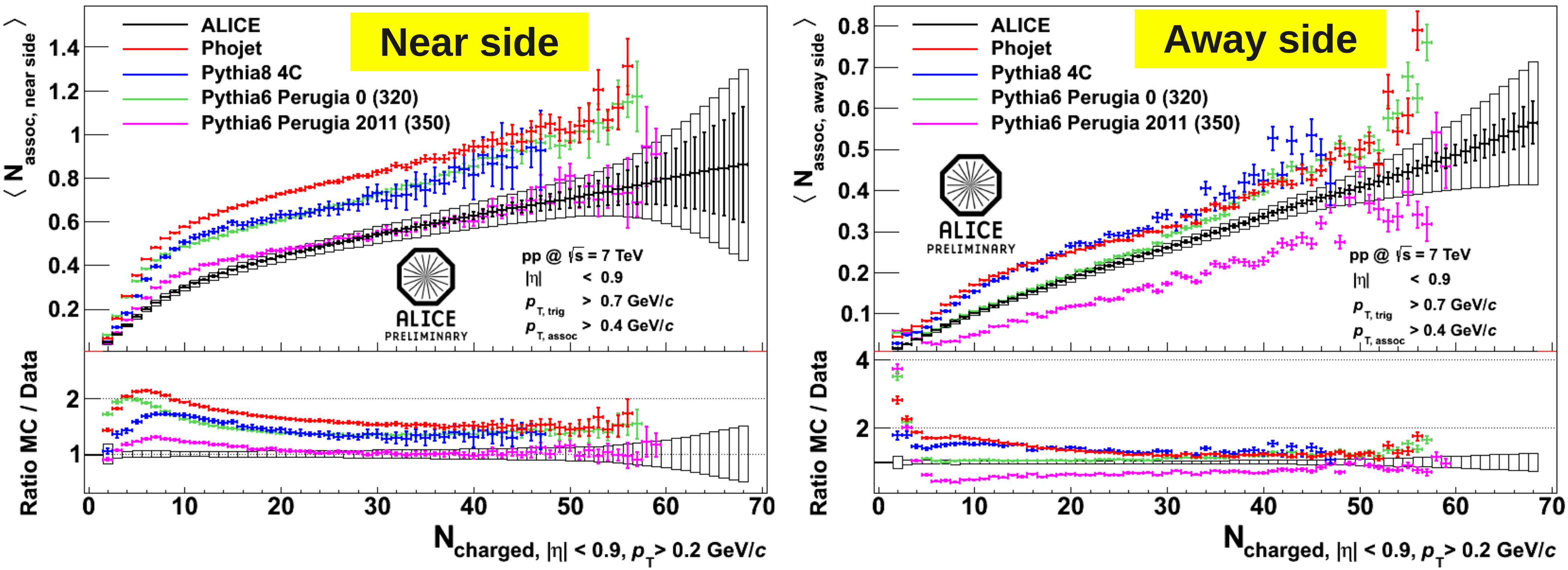
Corrections and Systematic Uncertainties



- Correction chain
  - Reconstruction efficiency
  - Contamination with tracks from secondary particles
  - Two-track and detector effects
  - Multiplicity correction
  - Contamination from strange particles
  - Vertex reconstruction efficiency
  - Trigger efficiency

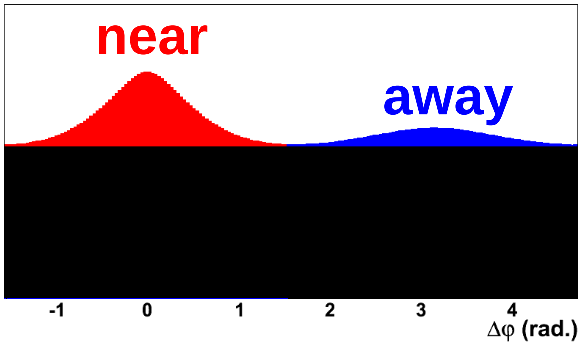
- Sources of systematic uncertainties
  - Uncertainty of ITS-TPC efficiency
  - Particle composition in MC
  - Track cut dependence
  - Correction procedure
  - Event generator dependence
  - Transport MC dependence
  - Signal extraction
  - Vertex quality cut dependence
  - Pileup events
  - Influence of resonances
  - Material budget
  - Strangeness correction

Per-Trigger Yield ($p_{T,assoc}$ > 0.4 GeV/c) @ 7 TeV



- Per-trigger yield at near and away side rises with $N_{charged}$
- Near side yield is overestimated by Phojet, Pythia8, and Pythia6 Perugia-0 by up to 100%, while P2011 agrees well
- Away side is underestimated by Perugia-2011 by up to 50%, best agreement between ALICE data and Perugia-0

$p_{T,trig}$ > 0.7 GeV/c
$p_{T,assoc}$ > 0.4 GeV/c



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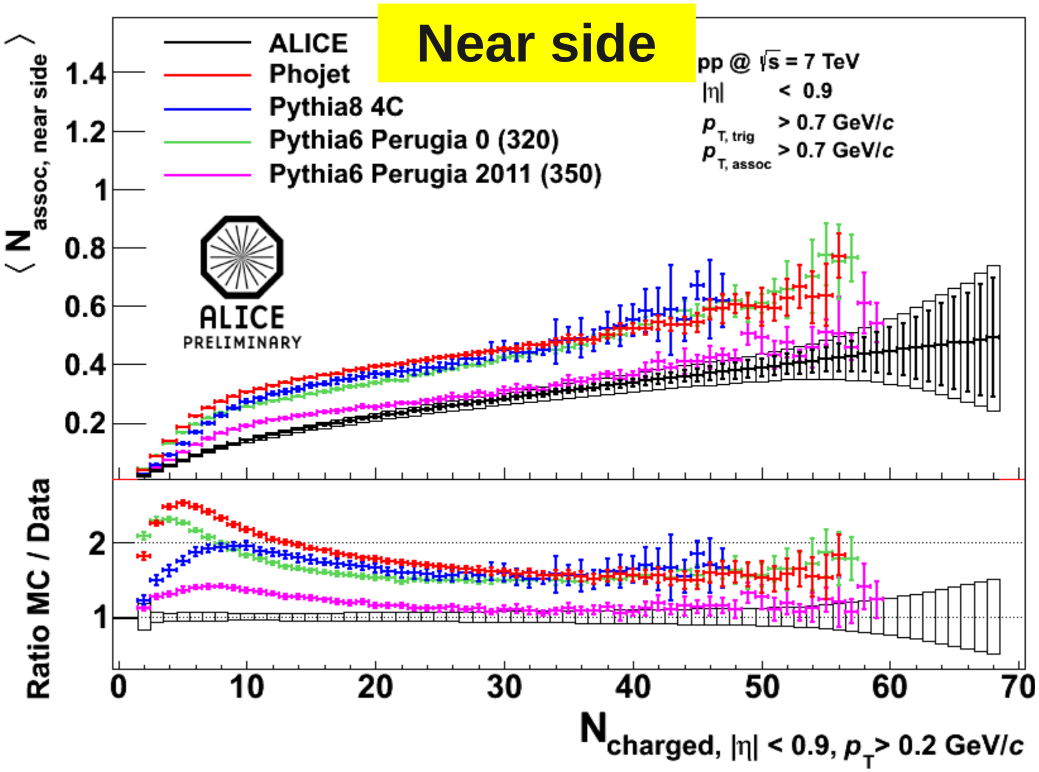

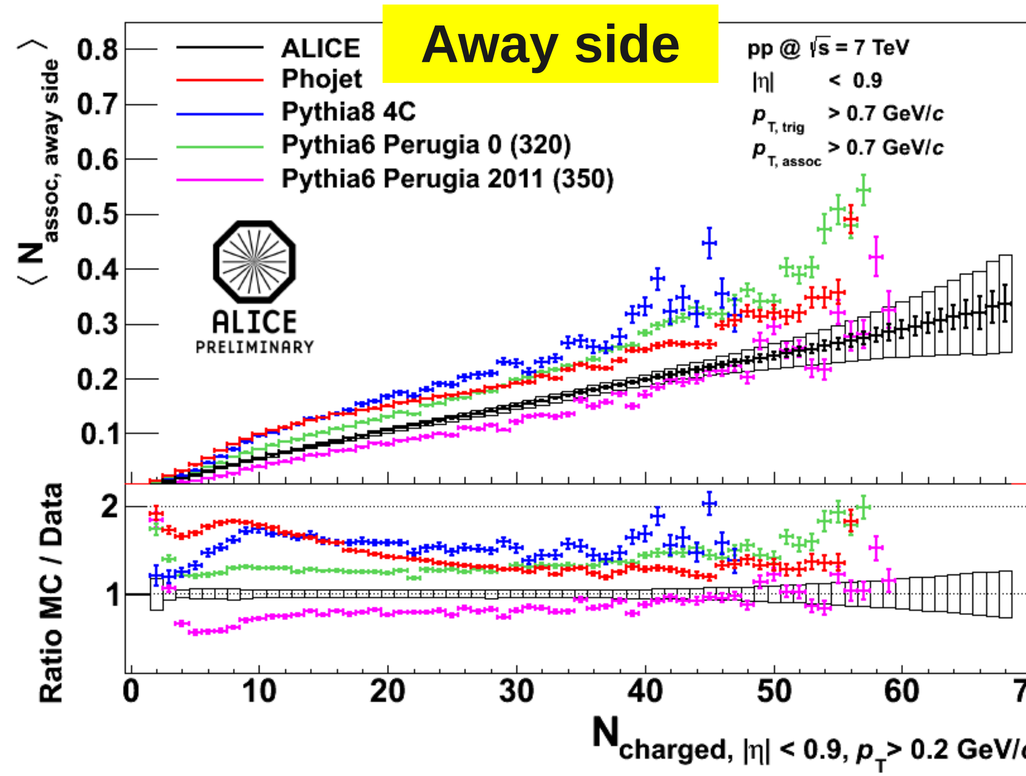

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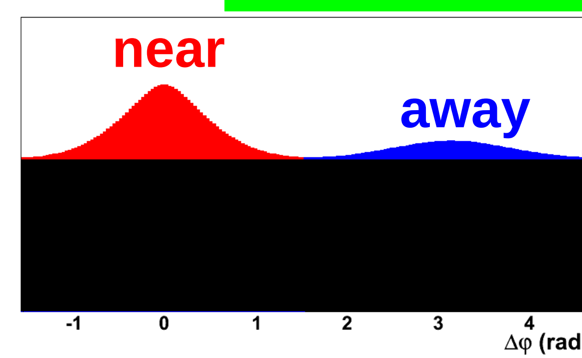
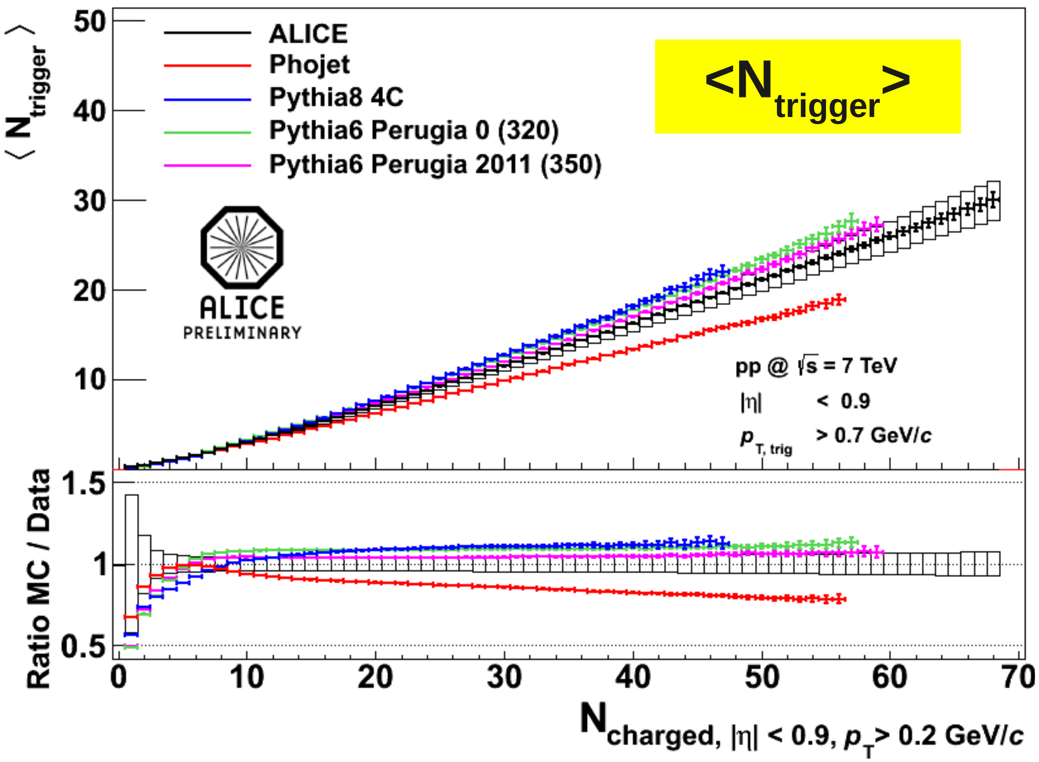
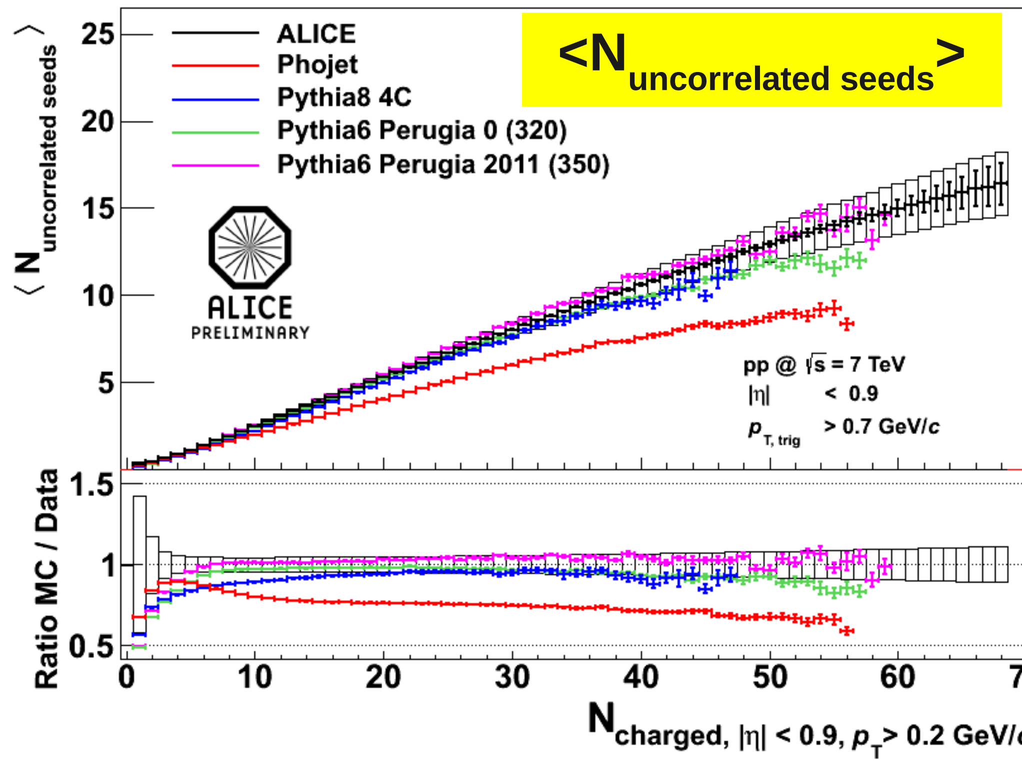


Trigger & Uncorrelated Seeds @ 7 TeV



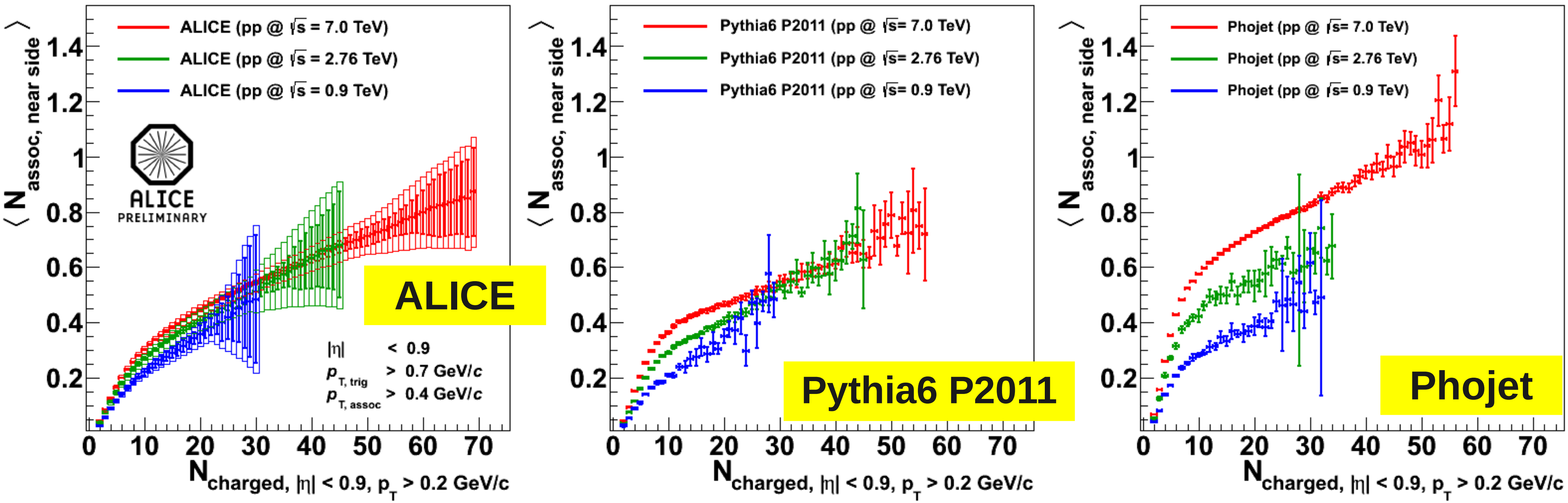


- Number of trigger particles (p_T>0.7GeV/c) rises stronger than linear with $N_{charged}$ → rise of mean-p_T with $N_{charged}$
- Phojet is much softer while Pythia tunes reproduce data fairly well

$$\langle N_{uncorrelated\ seeds} \rangle = \frac{\langle N_{trig} \rangle}{\langle 1 + N_{assoc,\, near+away}(p_T > p_{T,trig}) \rangle}$$

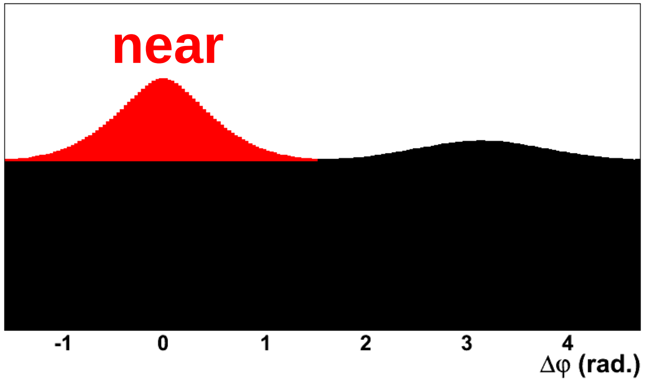
- At low and intermediated multiplicities, $N_{uncorrelated\ seeds}$ rises linearly with multiplicity

Per-Trigger Near Side Yield

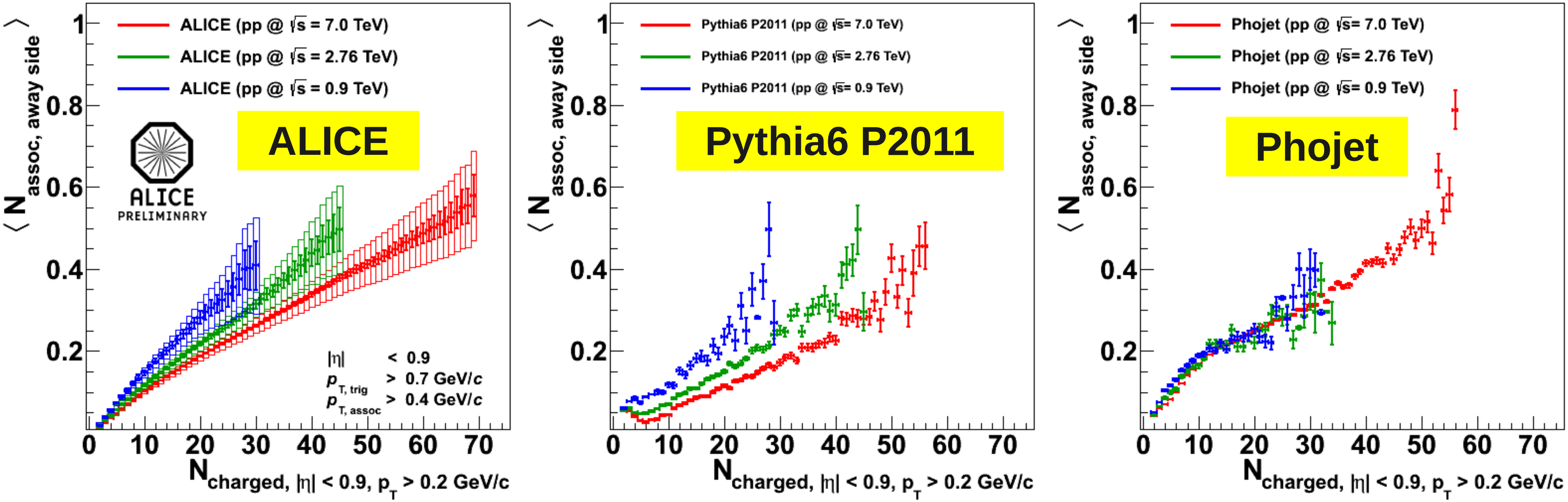


- Near side yield at same multiplicity bin grows with increasing center-of-mass energy
- Splitting between slopes for different √s is largest for Phojet

$p_{T,trig}$ > 0.7 GeV/*c*
$p_{T,assoc}$ > 0.4 GeV/*c*

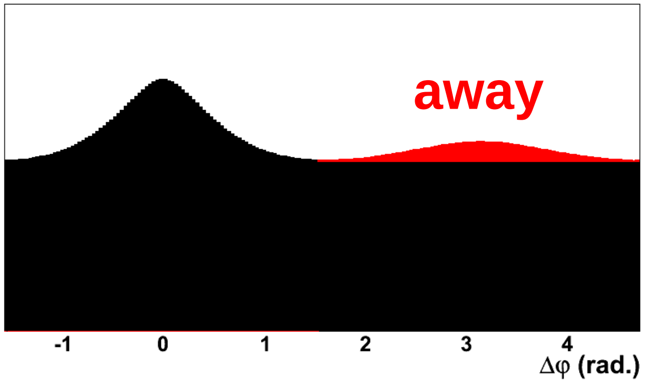


Per-Trigger Away Side Yield

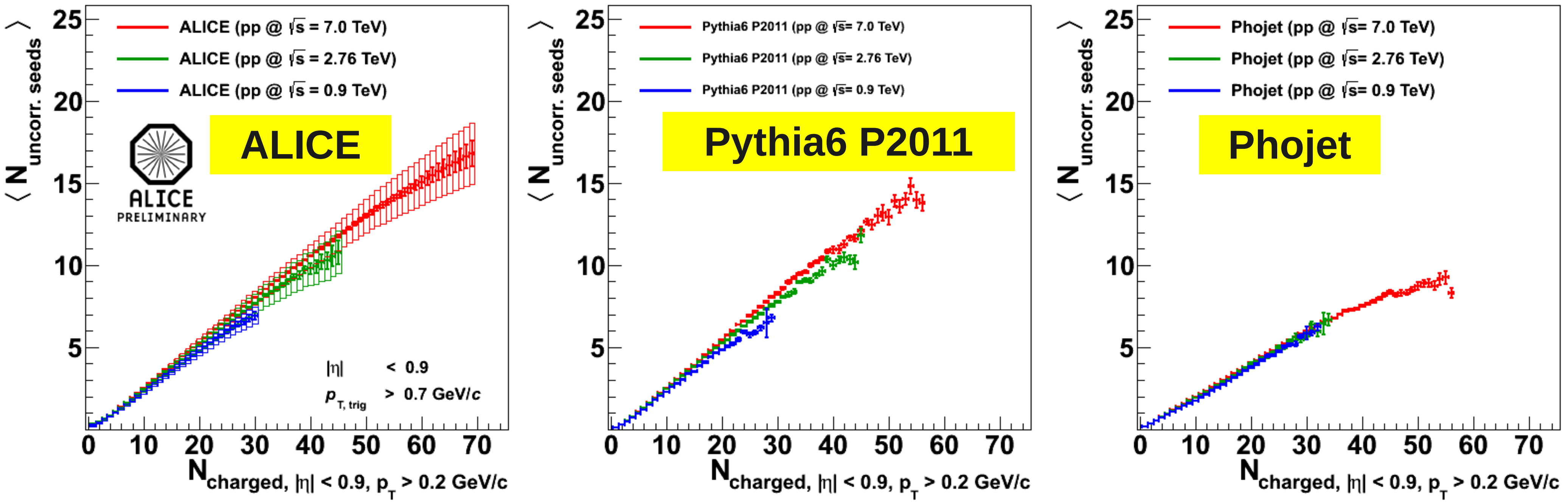


- Away side yield at same multiplicity bin shrinks with increasing √s
- Pythia6 Perugia-2011 underestimates ALICE data
- Phojet shows almost no √s dependence

$p_{T,trig}$ > 0.7 GeV/c
$p_{T,assoc}$ > 0.4 GeV/c



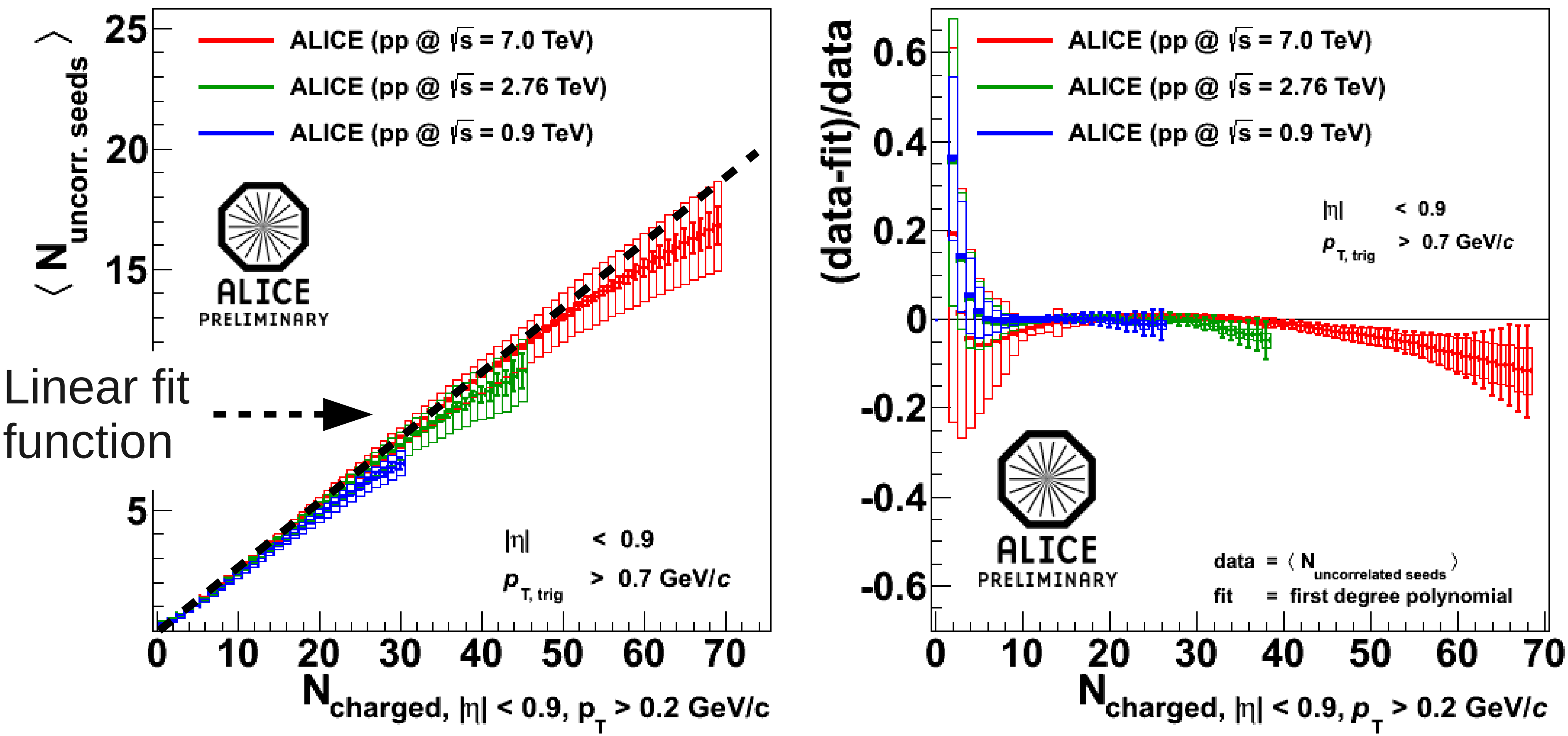
$\langle N_{uncorrelated\ seeds} \rangle$



$$\langle N_{uncorrelated\ seeds} \rangle = \frac{\langle N_{trig} \rangle}{\langle 1 + N_{assoc,\ near+away}(p_T > p_{T,trig}) \rangle}$$

- Only small √s dependence
- In low and intermediate multiplicity region: $N_{uncorr.\ seeds}$ grows linearly with $N_{charged}$
- At high multiplicities, the number of $N_{uncorr.\ seeds}$ stagnates -> Multiplicity increase only by selecting events with highly populated jets, limit in N_{MPI}

$\langle N_{uncorrelated\ seeds} \rangle$ and linear fit



- Compare distribution with linear fit in intermediate $N_{charged}$ range
- At high multiplicities, hint of deviation from linear dependence - this would indicate a limit in MPI

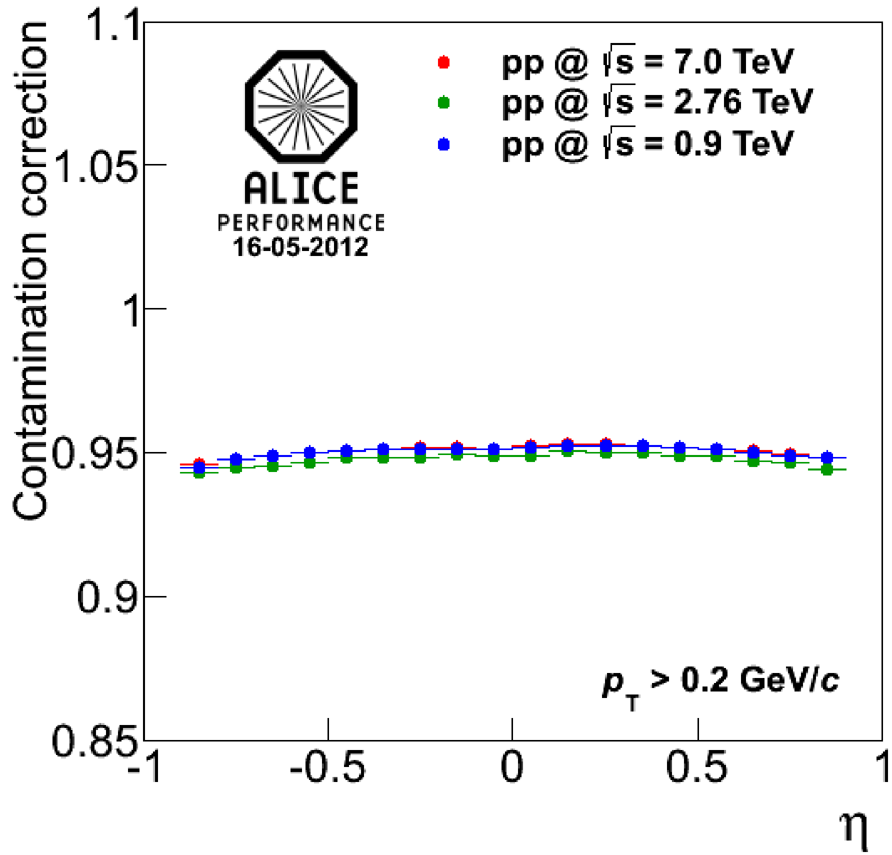
Summary

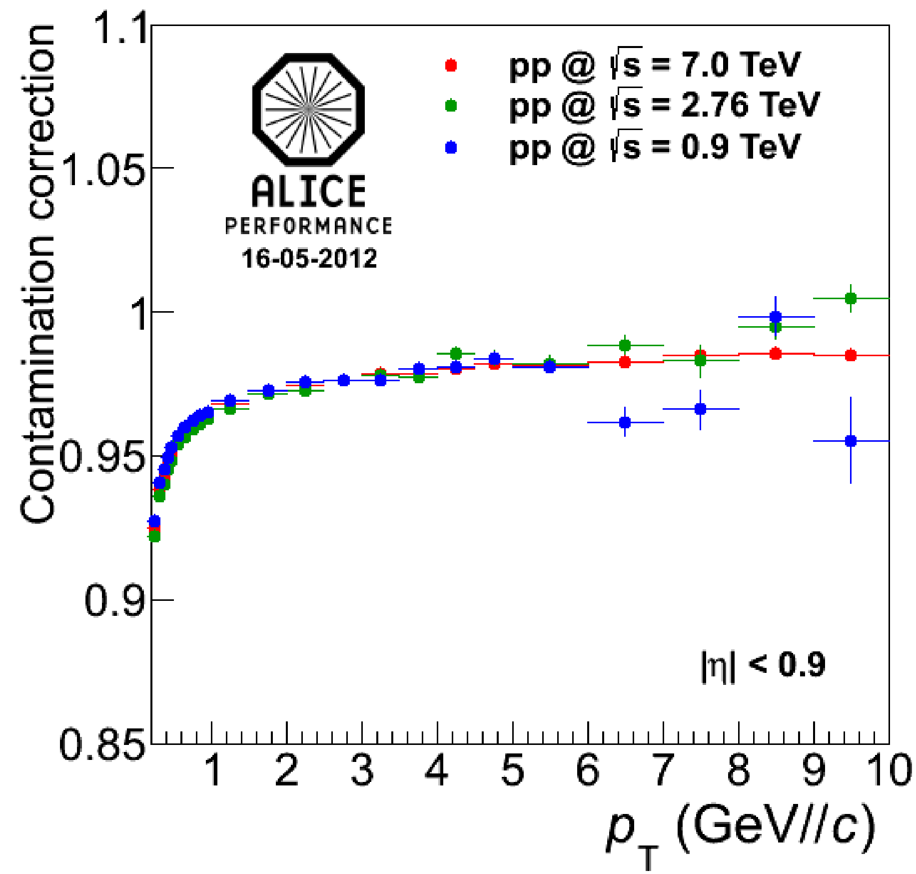
- Study of the per-trigger yield at the near side and the away side as well as the number of uncorrelated seeds using a two-particle correlation analysis
- Analysis of ALICE data at $\sqrt{s}$ = 0.9, 2.76, and 7.0 TeV
- At high multiplicities, hint of deviation from linear dependence - this would indicate a limit in MPI

- Pythia studies show that the analysis approach can probe number of multi parton interactions (MPI)
- Pythia Perugia-2011 gives best description of ALICE results
  - However, at intermediate $N_{charged}$, the away side yield is underestimated by 50%
- Phojet, Pythia6-Perugia-0, and Pythia8 show large discrepancies to ALICE results
  - e.g. per-trigger near side yield is overestimated by all MCs by 100% at low and intermediated $N_{charged}$

Backup

Correction: Contamination

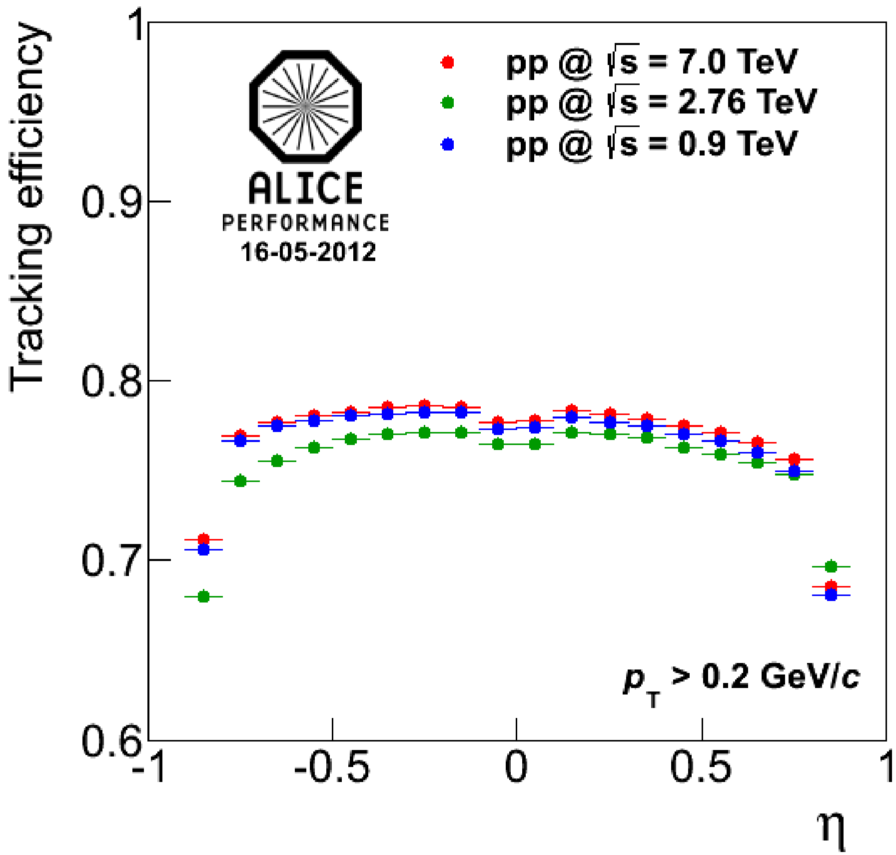


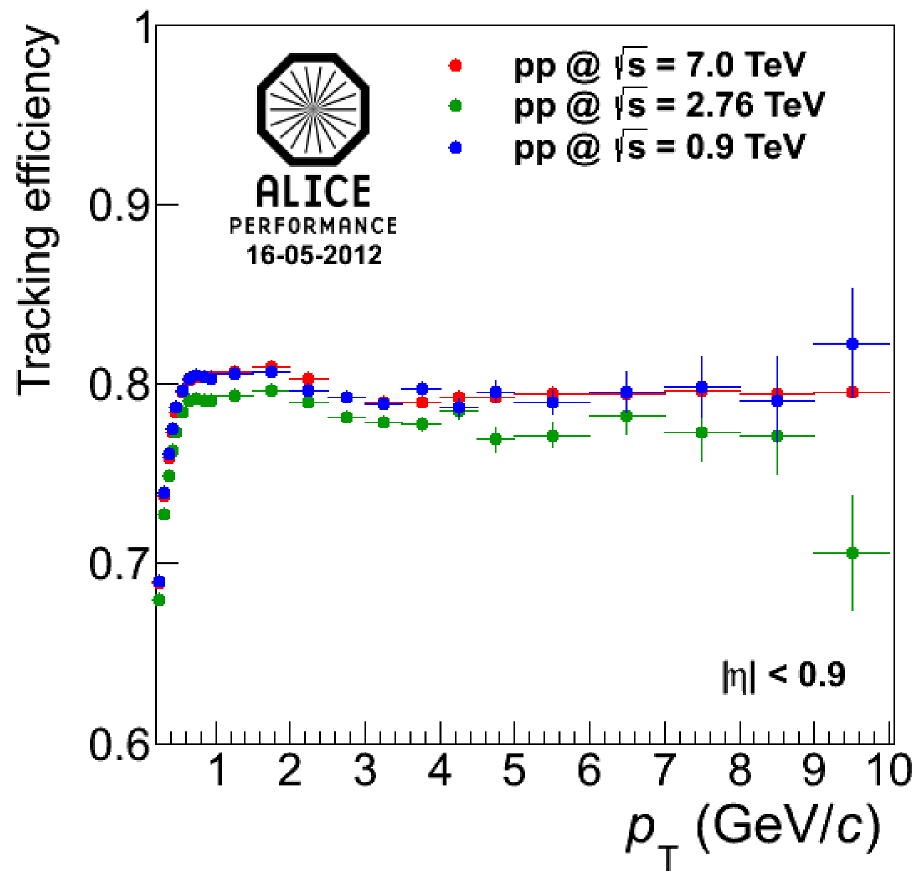


- Contamination of track sample from secondary particles shows p_T dependence, but almost no eta dependence
- Overall contamination ~ 6%

- At high momenta, the statistics is low
- Estimate contamination by extrapolation from intermediate p_T

Correction: Reconstruction Efficiency

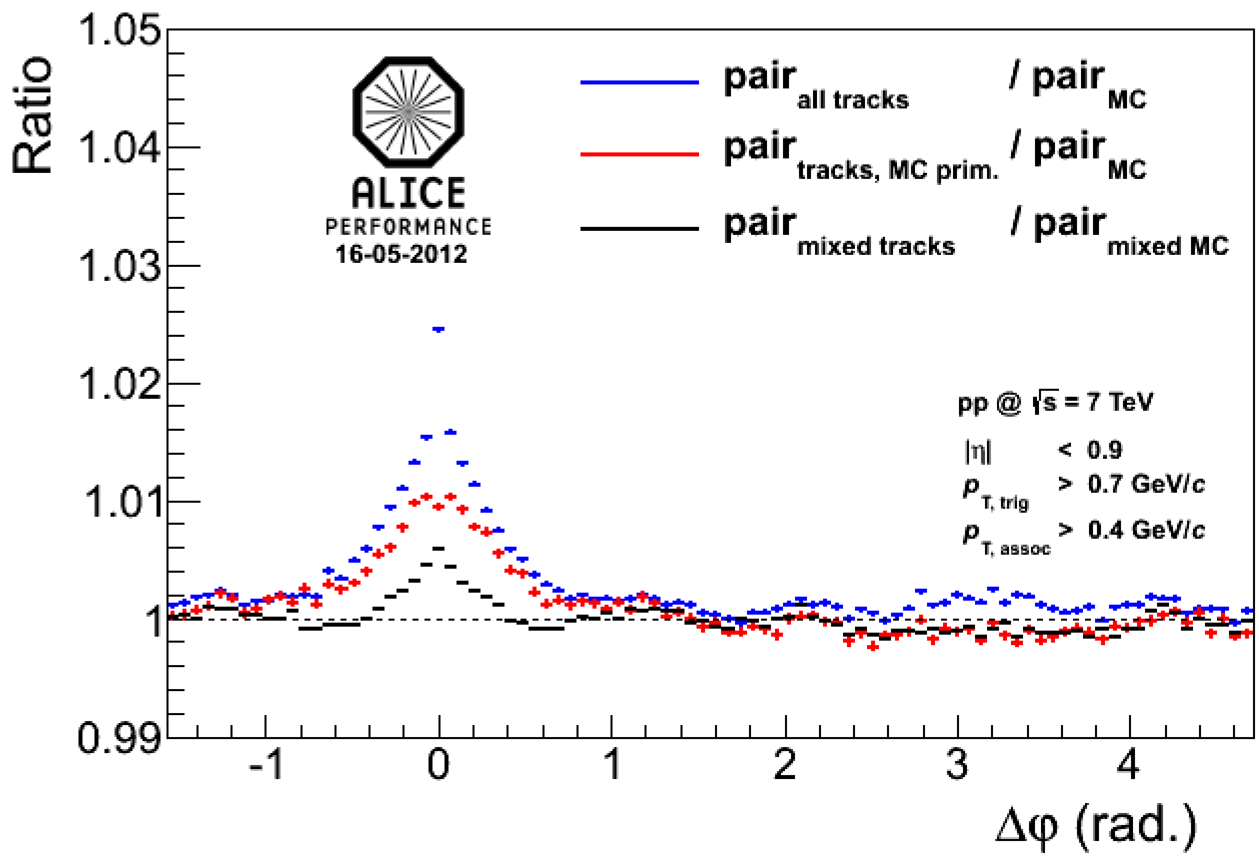




- Reconstruction efficiency shows strong p_T dependence and slight eta dependence
- Overall tracking efficiency is ~80%

- At high momenta, the statistics is low
- Estimate tracking efficiency by extrapolation from intermediate p_T

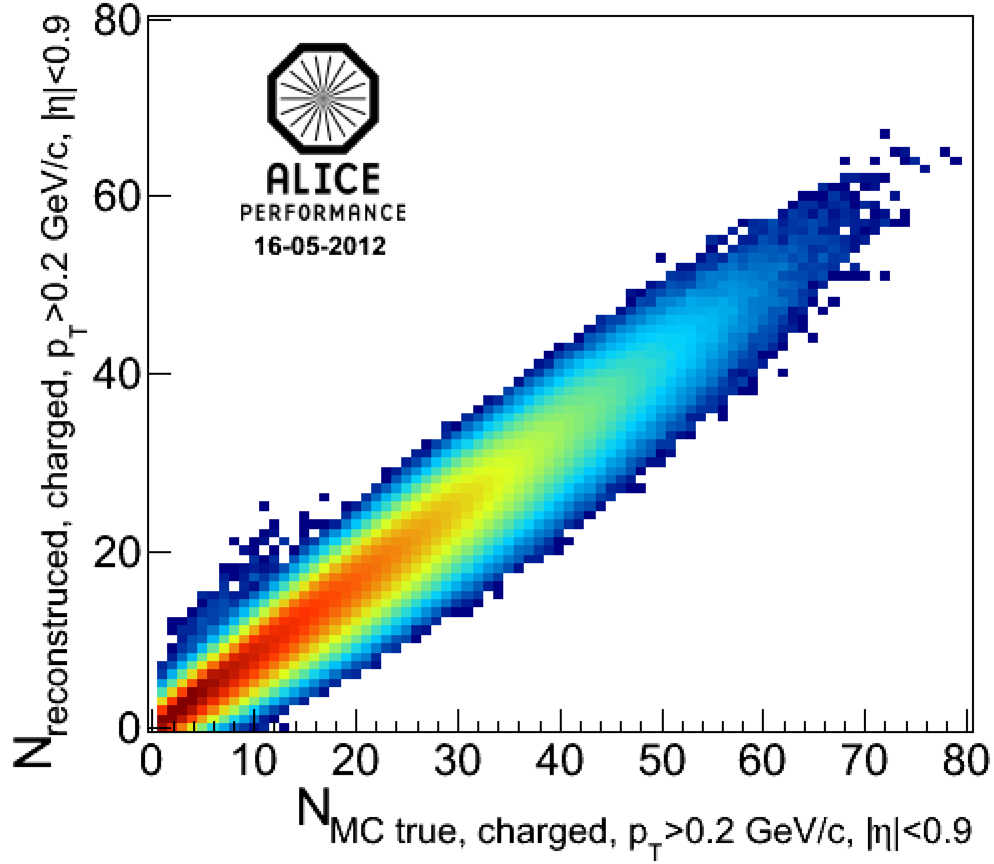
Correction: Two Track and Detector Effects



- A fraction of the near side peak after single track correction is due to detector effects (black) → limited flatness in φ distribution give rise to structures in Δφ
- Remaining peak comes from split tracks, resonances, gamma conversion
- Correction on total yield is very small

Multiplicity Correction

- Multiplicity correction via normalized and extended correlation matrix
- Normalization:
  - $\sum_{N_{rec}} R(N_{mc}, N_{rec}) = 1$
- Extension:
  - Fit slice of correlation matrix with Gaussian function and extract sigma and mean
  - Used extrapolated sigma and mean for extended correlation matrix



- Correction:

$$Observable(N_{mc}) = \sum_{N_{rec}} Observable(N_{rec}) \cdot R_{1,extended}(N_{mc}, N_{rec})$$

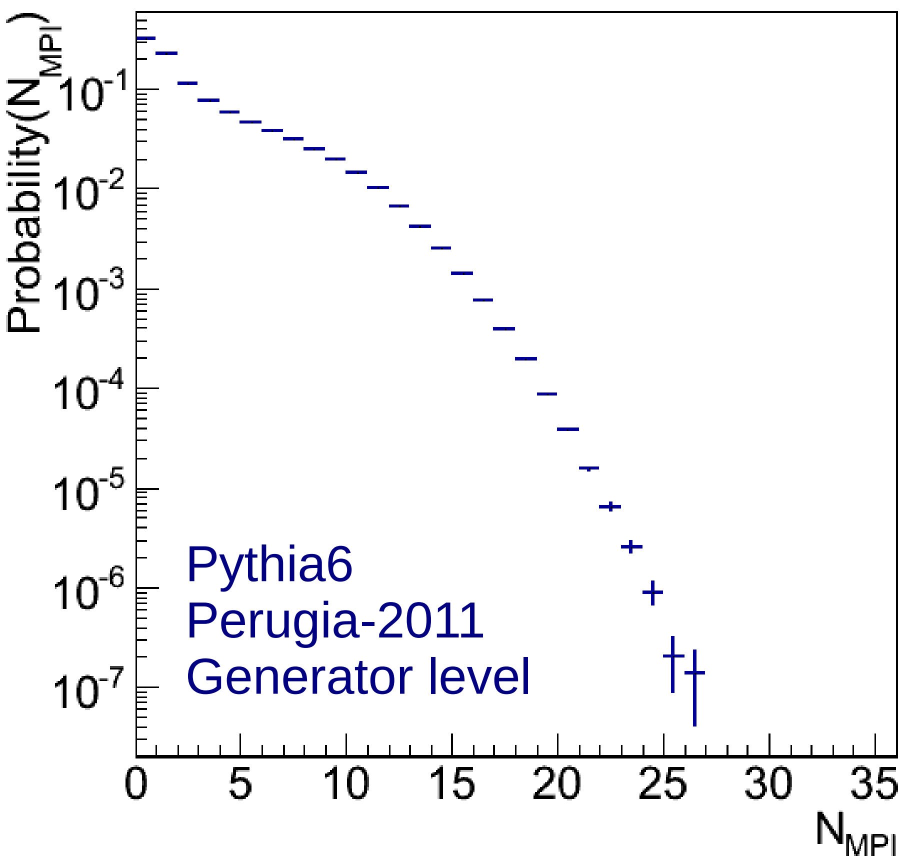
Assumption: $N_{uncorrelated\ seeds} \rightarrow N_{MPI}$

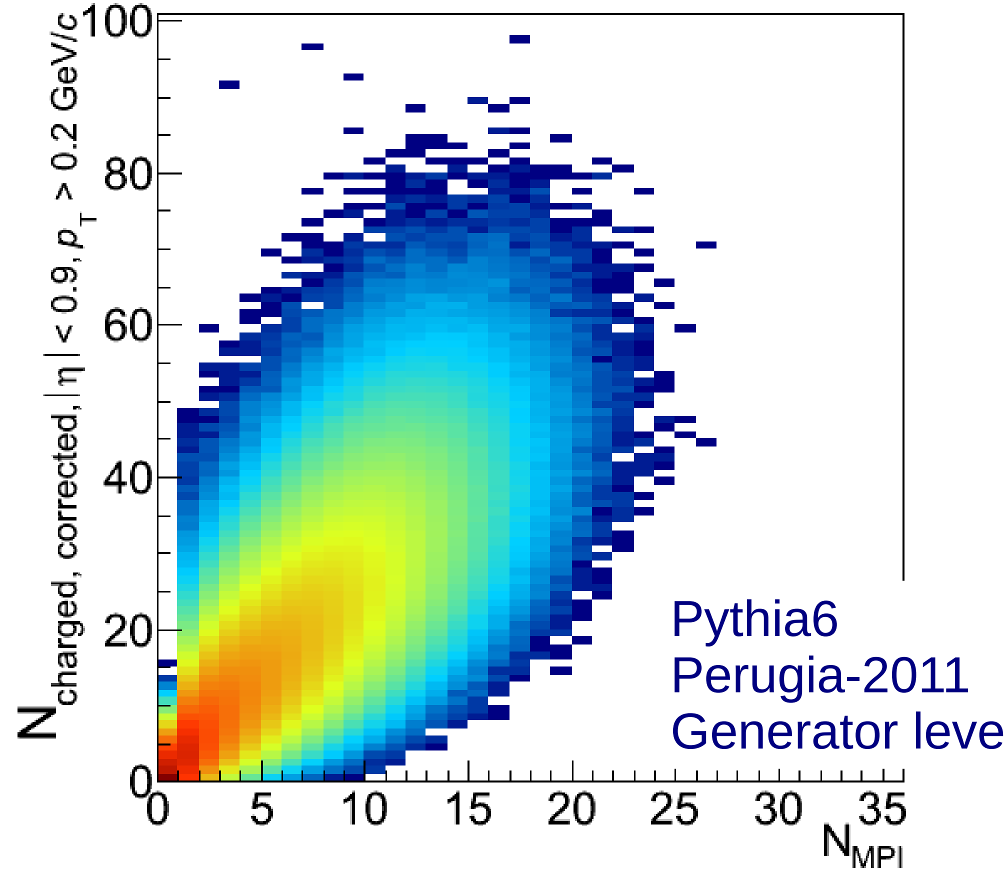
- We measure $N_{uncorrelated\ seeds}$

$$\langle N_{uncorrelated\ seeds} \rangle = \frac{\langle N_{trig,\, p_T > p_{T,trig}} \rangle}{\langle 1 + N_{assoc,\, near,\, p_T > p_{T,trig}} + N_{assoc,\, away,\, p_T > p_{T,trig}} \rangle}$$

- We assume that $N_{uncorrelated\ seeds}$ scales with the number of multiple parton interactions
- Can we demonstrate a direct dependence in Pythia simulations
  - Perform two-particle correlation analysis of Pythia6 simulations as function of N_{MPI} = number of multiple parton interactions
  - N_{MPI} (Pythia definition) = number of hard or semi-hard scatterings that occurred in the current event in the multiple interaction scenario; is 0 for a low-*p*T event

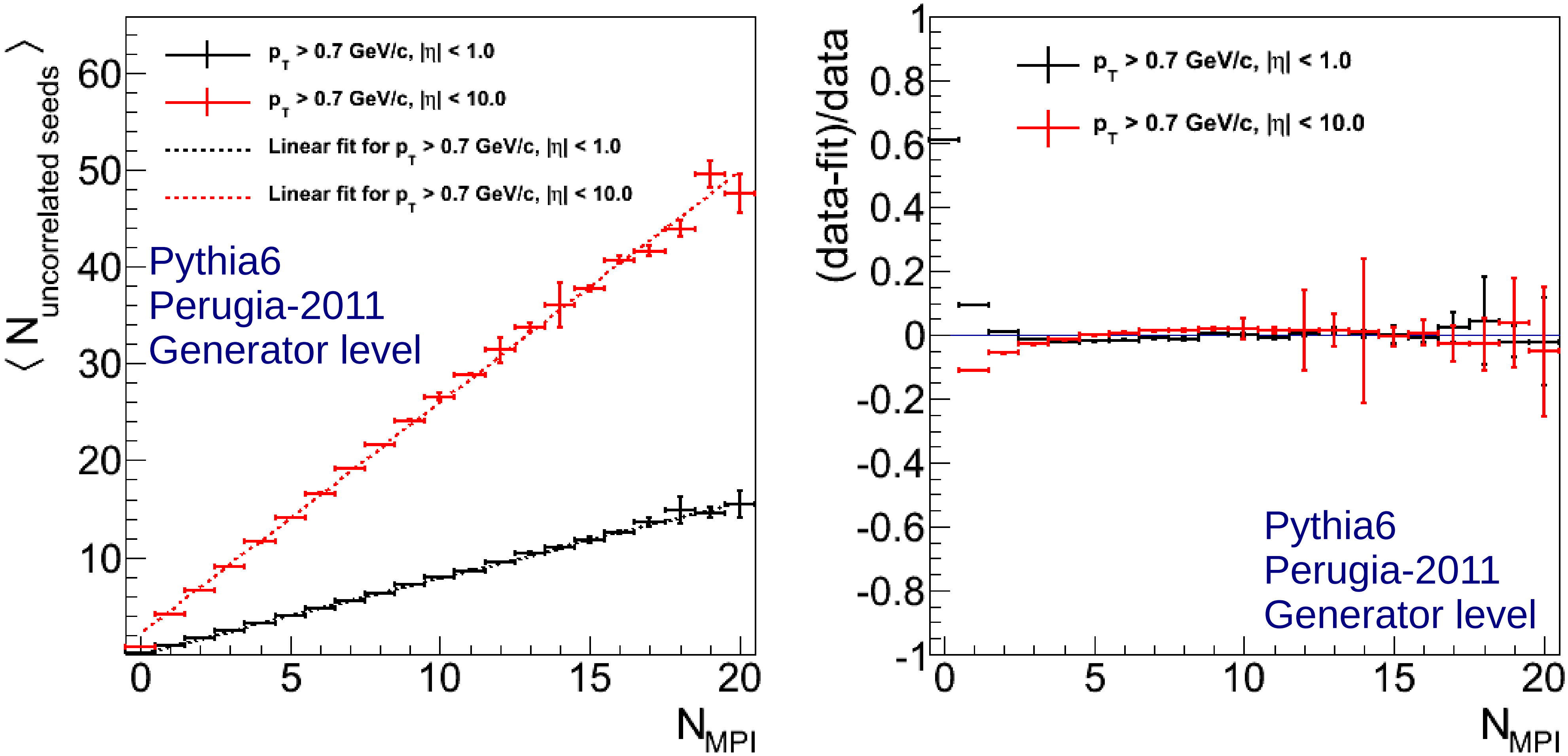
MPI in Pythia6 Perugia2011





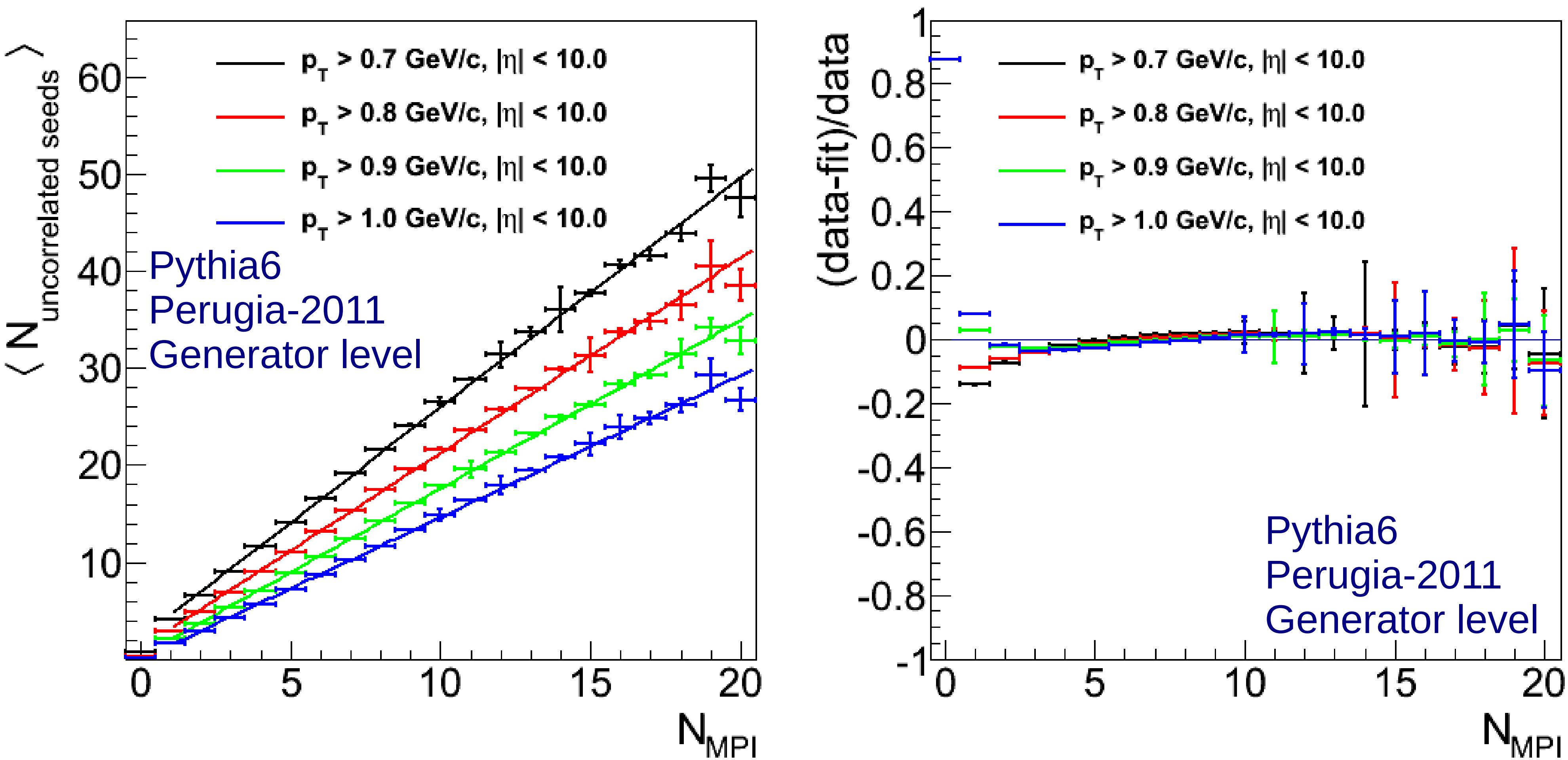
- Spectrum of multiple parton interactions in Pythia6 Perugia-2011
- Correlation of measured multiplicity to number of multiple parton interactions

$N_{uncorrelated\ seeds} \sim N_{MPI}$



- Agreement with linear fit is better when accepting tracks at full η acceptance and not only the tracks in the ALICE acceptance

$N_{\text{uncorrelated seeds}} \sim N_{MPI}$



- Linear dependence is given for several p_T thresholds

Estimation of Combinatorics in Auto Correlations

For an a priori unknown multiplicity distribution *P*(*n*) of the mini-jet, we measure

$$\frac{\langle n(n-1)\rangle}{2\langle n\rangle}=\frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right)$$

For steadily falling *P*(n) and small <*n*> this is in good approximation:

$$\frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right) \quad\rightarrow\quad \frac{\langle n\rangle}{1-P(0)}-1$$

(= <n> with trigger condition - 1)

Which is the mean number of associated particles.

Example 1 (geom. row):	Example 2 (Poisson):	Example 3 (Log Series):
$P(n)=(1-q)q^n$ $\langle n\rangle=\frac{q}{1-q}$ $\langle n^2\rangle=2\langle n\rangle^2$ $\frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right)=\langle n\rangle$ $\frac{\langle n\rangle}{1-P(0)}-1=\langle n\rangle$ Relation is exact !	$P(n)=\frac{\mu^n e^{-\mu}}{n!}$ $\langle n\rangle=\mu$ $\langle n^2\rangle=\mu^2+\mu$ $\frac{1}{2}(\frac{\langle n^2\rangle}{\langle n\rangle}-1)=\frac{\mu}{2}$ $\frac{\langle n\rangle}{1-P(0)}-1=\frac{\mu}{1-e^{-\mu}}-1=\frac{\mu}{2}-\frac{\mu^2}{6}+\ldots$	$P(n)=\frac{-1}{\ln(1-p)}\frac{p^n}{n}$ $\langle n\rangle=\frac{-1}{\ln(1-p)}\frac{p}{(1-p)}$ $\langle n^2\rangle=\frac{\langle n\rangle}{(1-p)}$ $\frac{1}{2}(\frac{\langle n^2\rangle}{\langle n\rangle}-1)=\frac{p}{2(1-p)}$ $\frac{\langle n\rangle}{1-P(0)}-1=\frac{p}{2(1-p)}+\frac{p^2}{3(1-p)}+p^3\ldots$

Expect *P*(n) to be steadily falling, choose $p_{T,trig}$ such that <n> is low