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

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MB & UE Working Group

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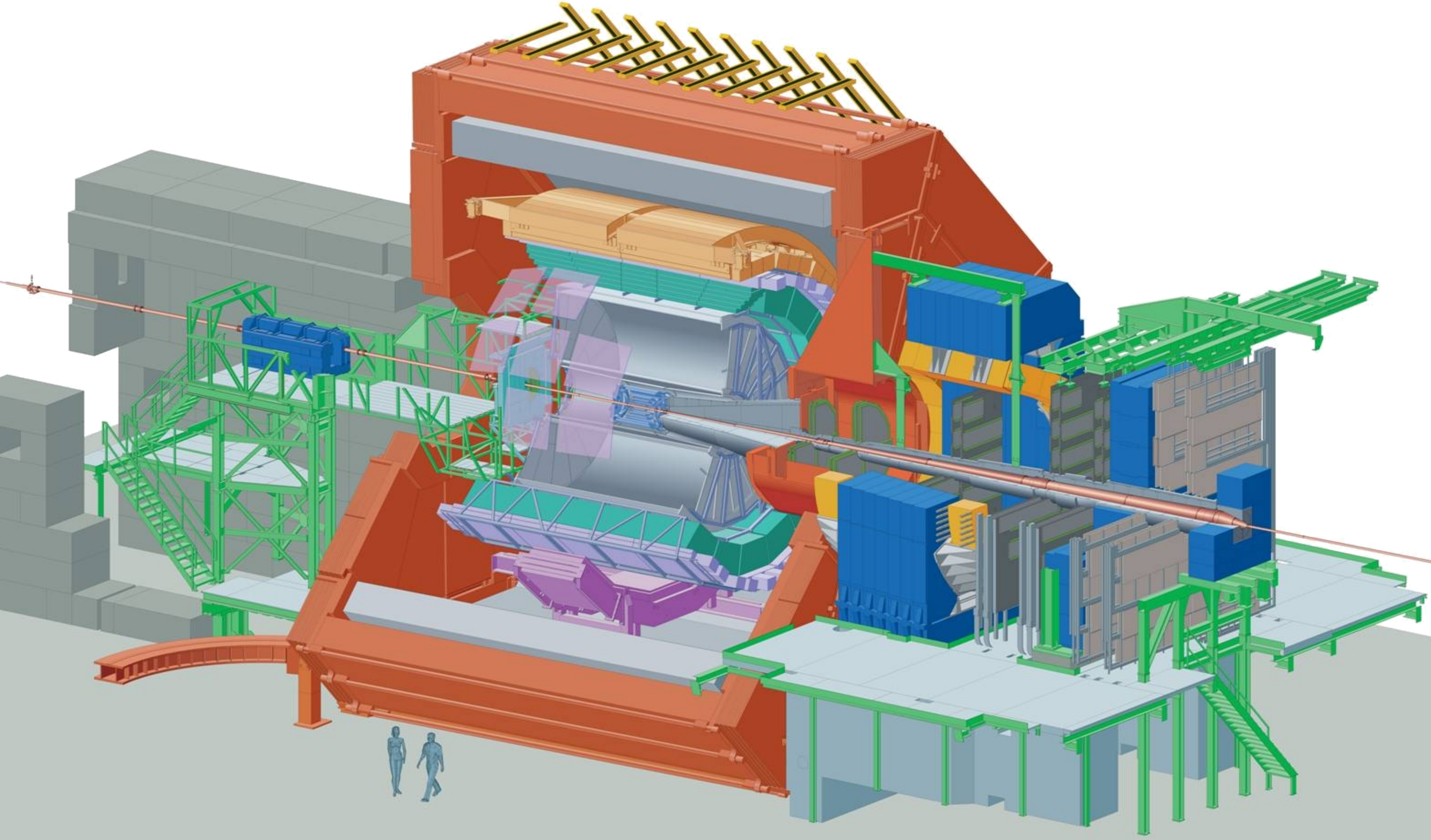
A Large Ion Collider Experiment

- 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



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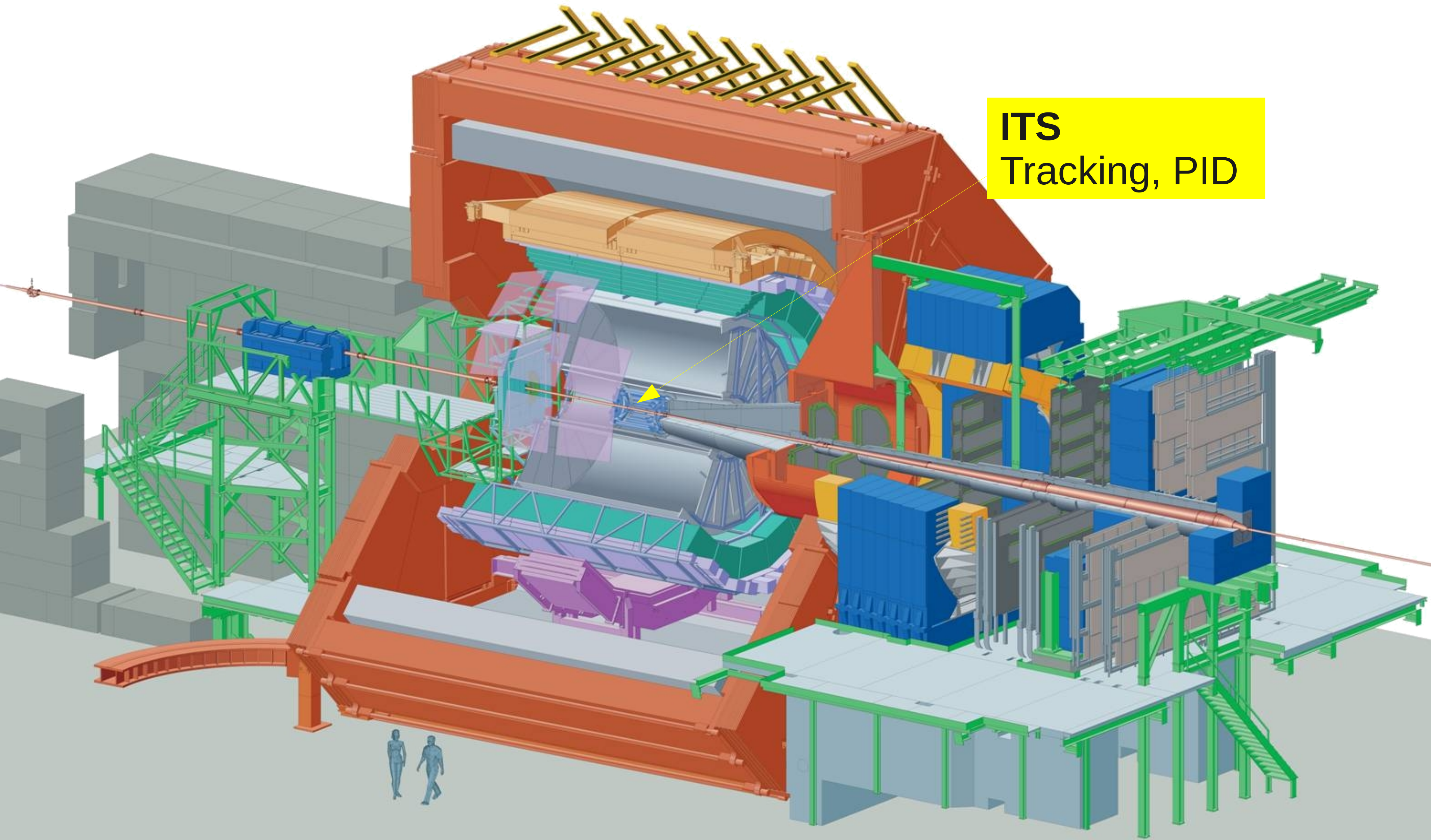

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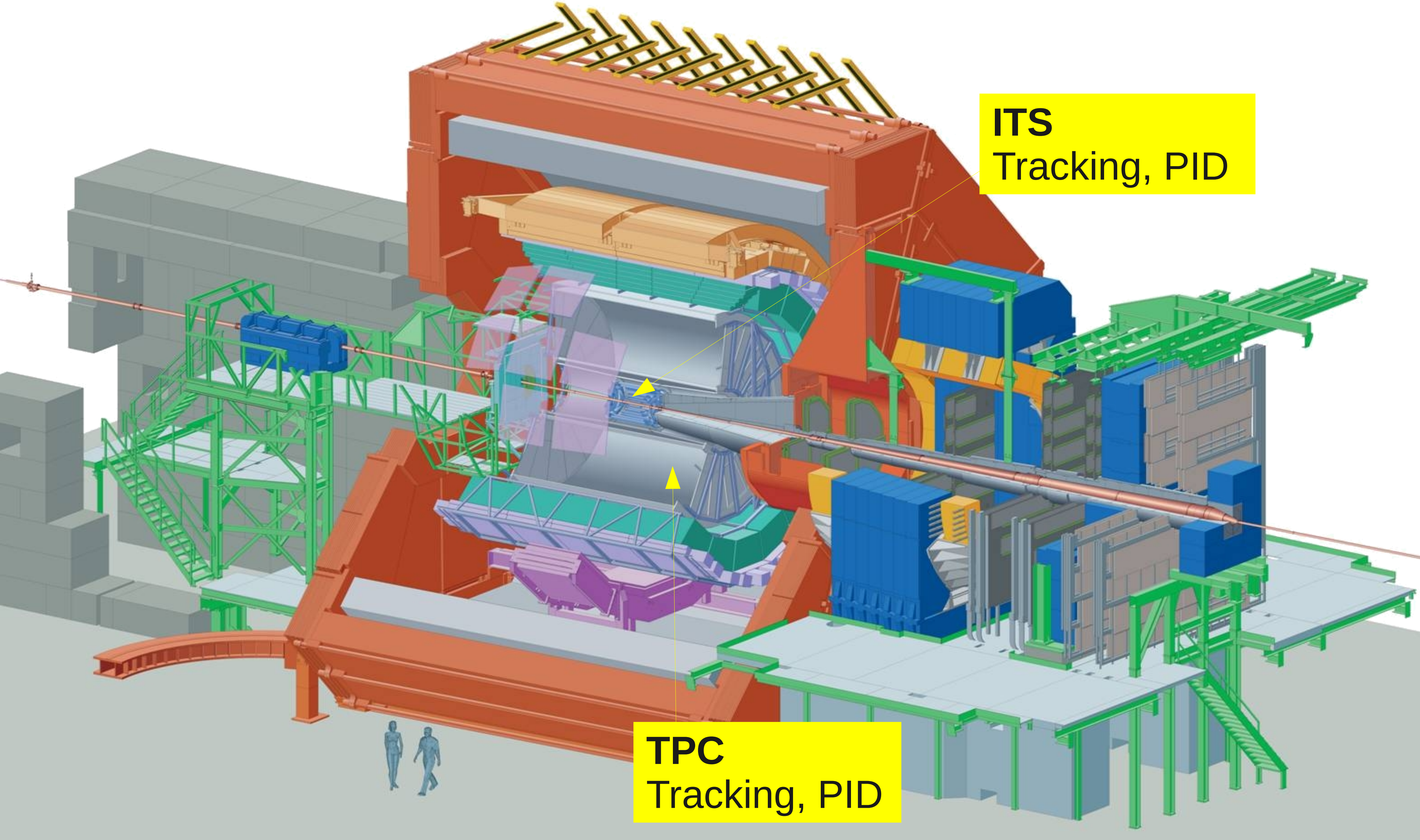

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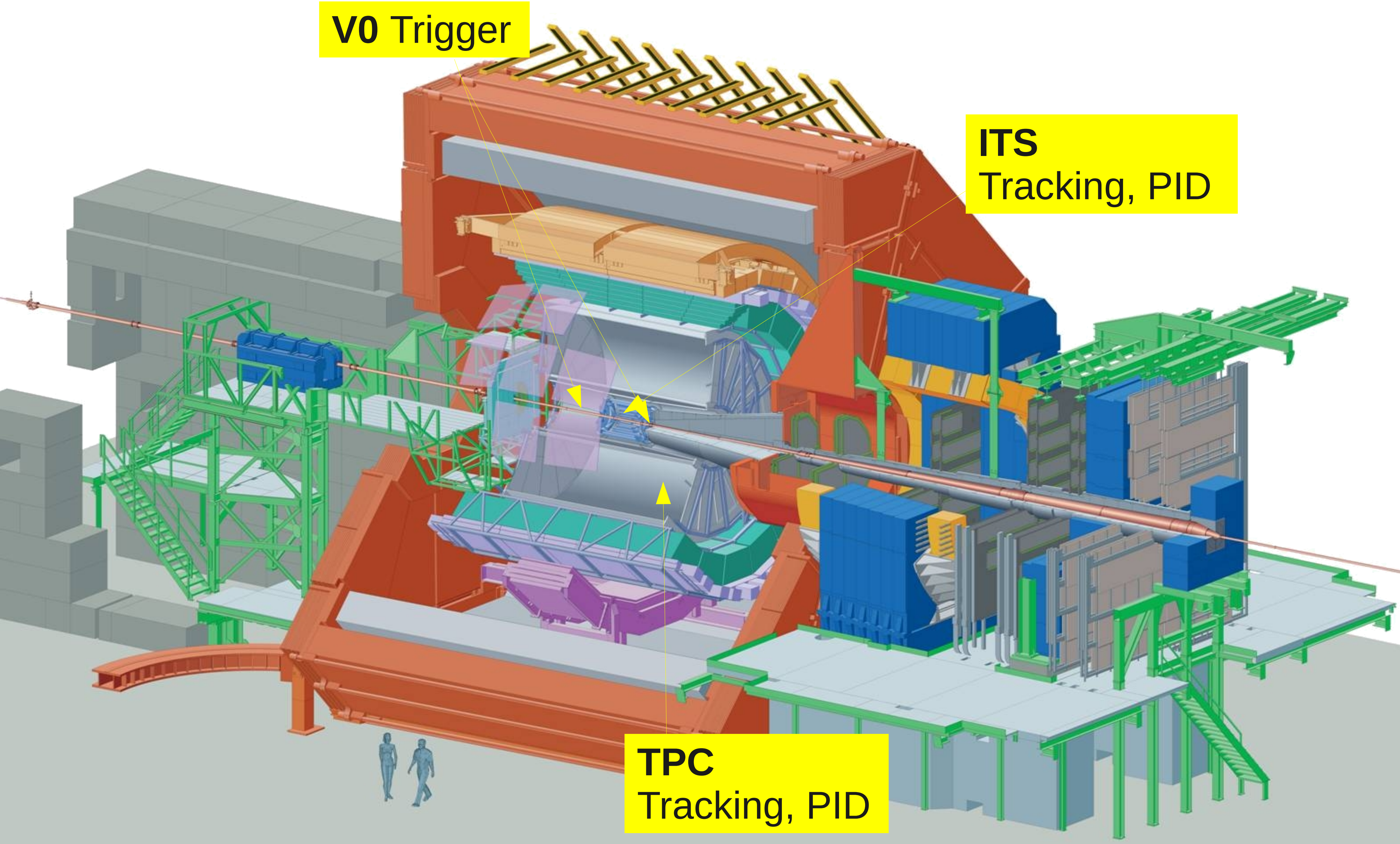

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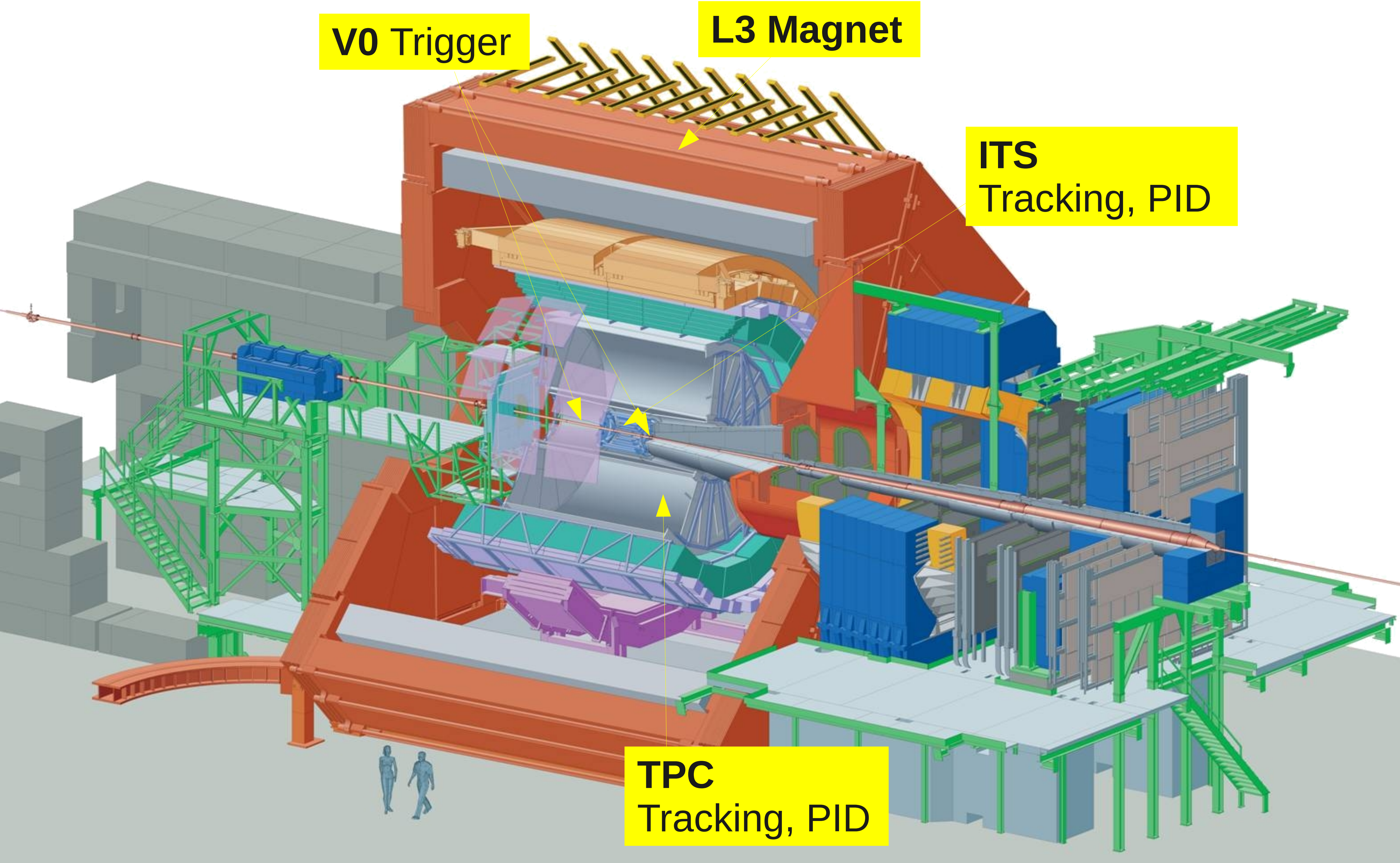

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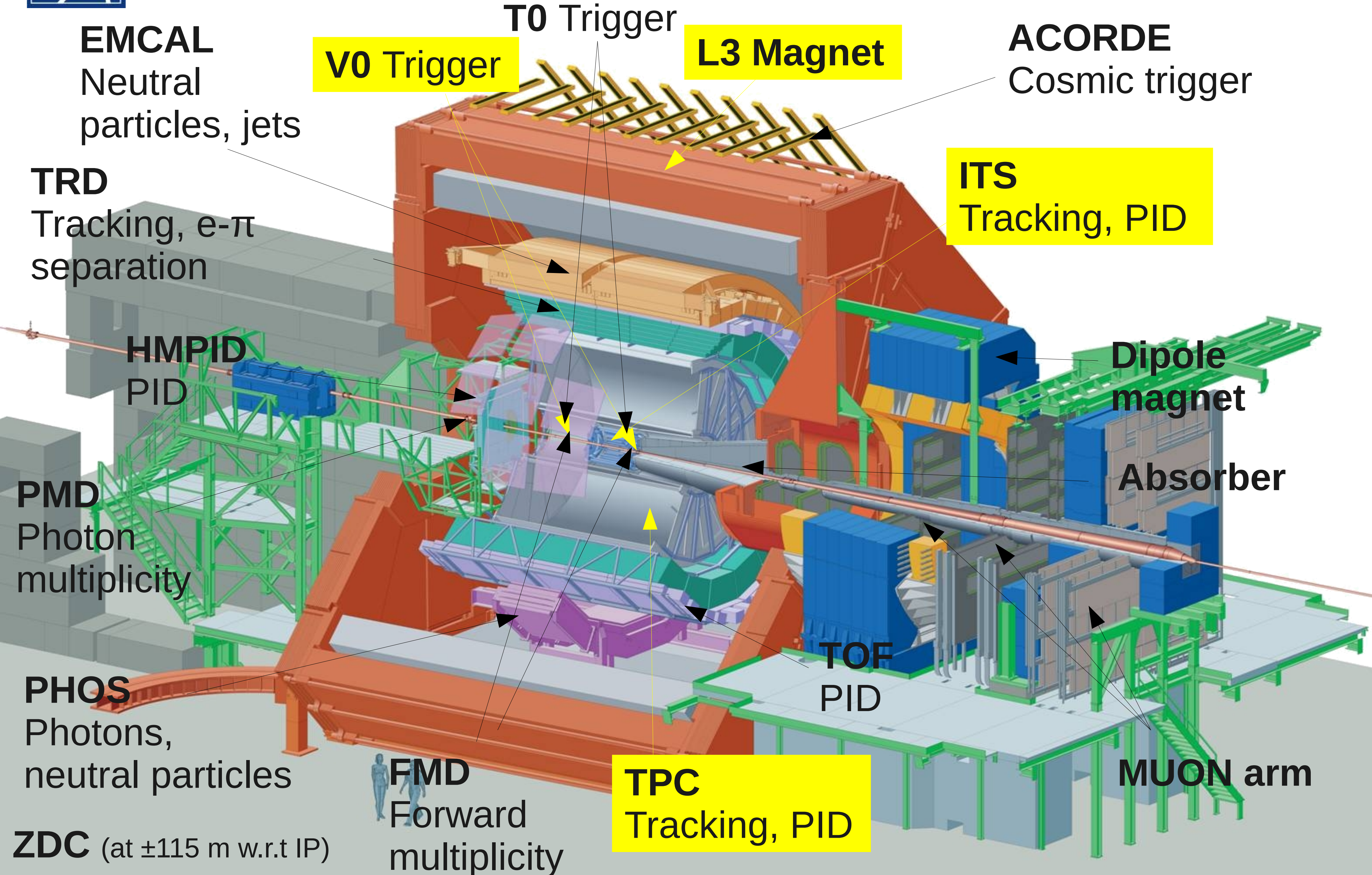
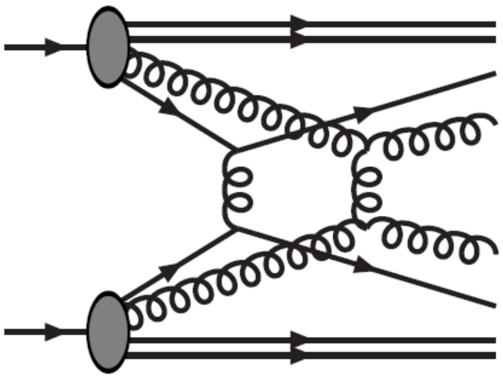


Analysis Motivation

- 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 measurement of di-jets

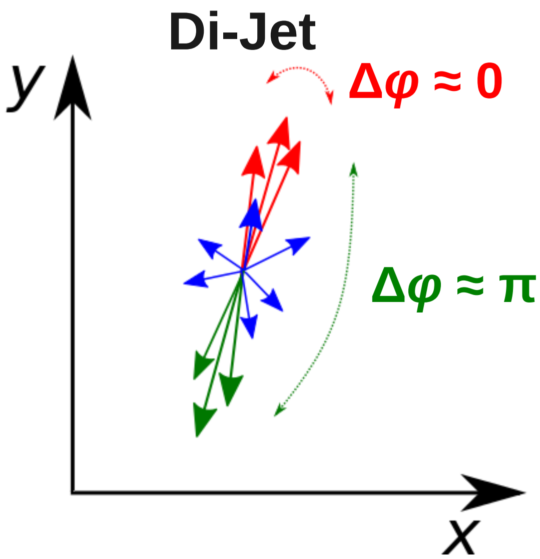
Motivation of Analysis Procedure

- 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
  - → Bias to hard momentum scale (growth of $p_{T,max}$ with N_{ch})
  - → Attention: possible bias due to unwanted combinatorics of correlated trigger particles

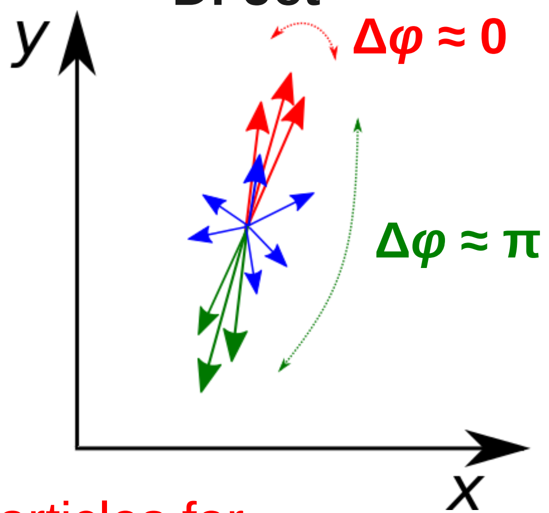
Two-Particle Angular Correlations



- Measure distances between particle pairs of trigger particles ($p_T > p_{T,\,trig}$ with $p_{T,\,trig} >> \Lambda_{QCD}$) and associated particles ($p_T > p_{T,\,assoc}$)
- Distance in terms of azimuthal angle φ and pseudorapidity η

Two-Particle Angular Correlations

Di-Jet



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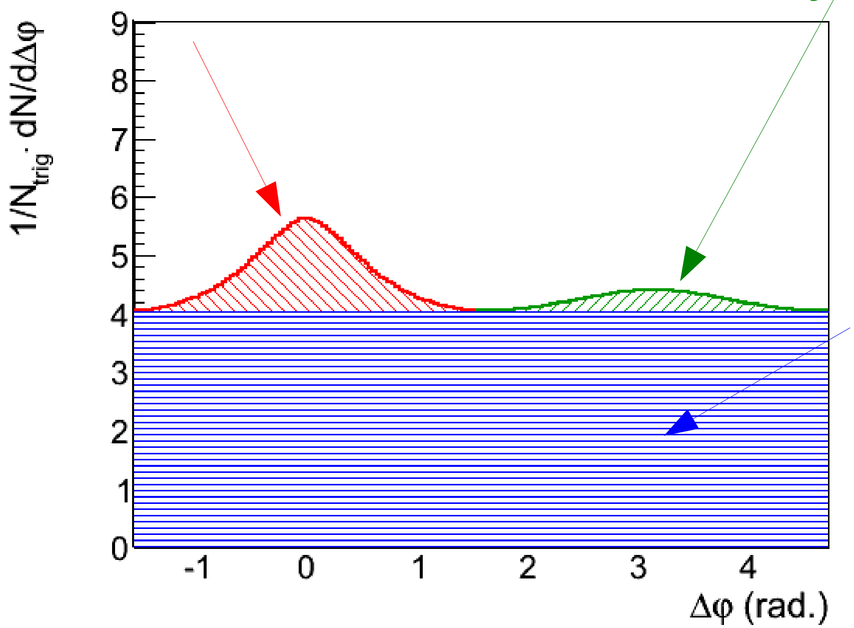
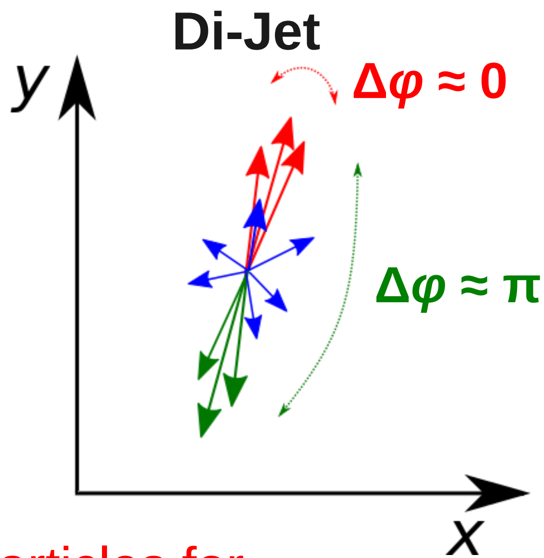
Particles for same jet

Particles from away side jet



Particles from processes uncorrelated to trigger particle

Two-Particle Angular Correlations



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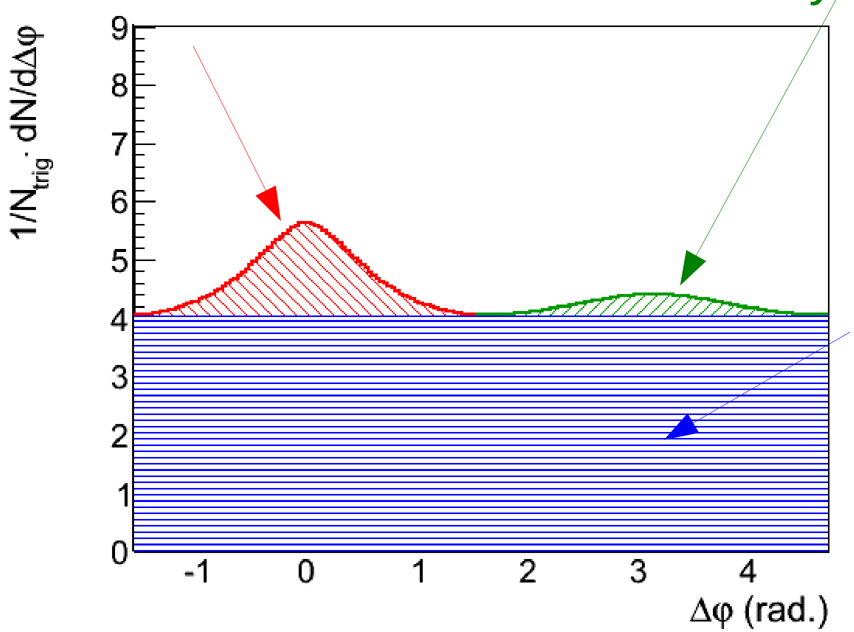
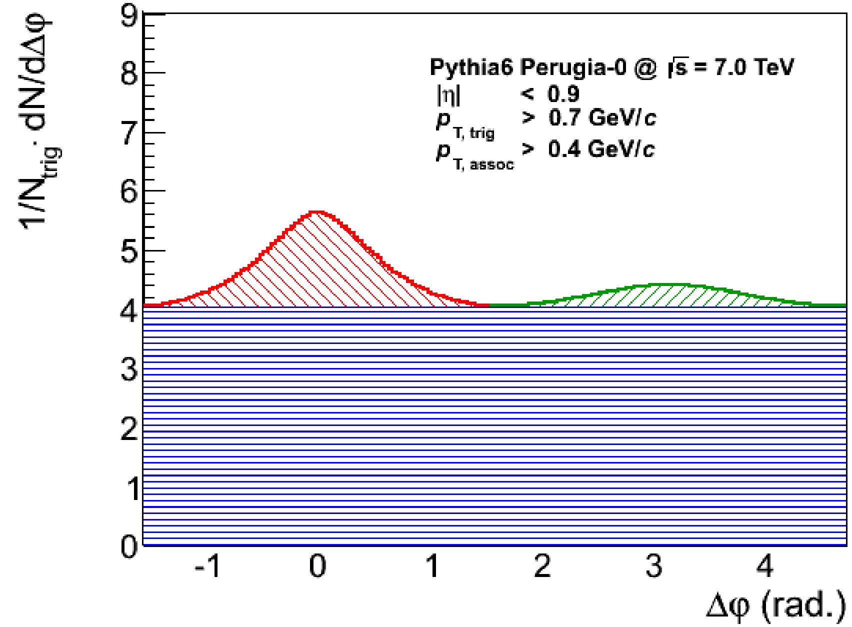


- Further possible contributions can be neglected when choosing $p_{T,trig}^{max} > 0.7$ GeV/c
  - Particle decay (<10%)
  - Photon conversion
  - Hanbury Brown and Twiss effect (HBT)

Yield Extraction of Azimuthal Correlation

- Azimuthal correlation can be divided into three contributions: background and two peaks



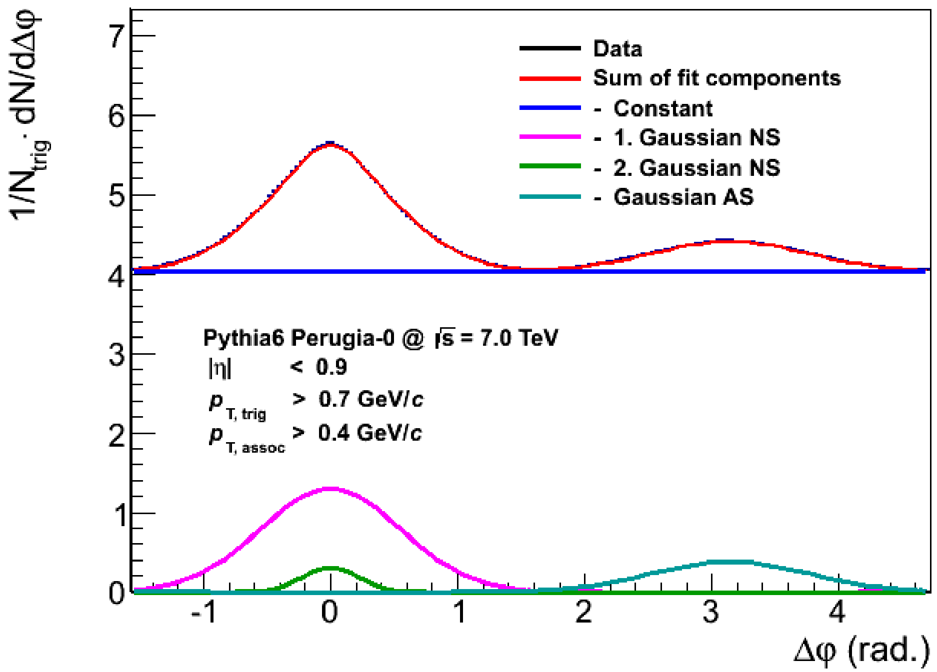
Yield Extraction of Azimuthal Correlation

- Azimuthal correlation can be divided into three contributions: background and two peaks
- Fit function: Combination of constant and Gaussian functions

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

$$+ A_2 e^{\frac{-\Delta\varphi^2}{2\sigma_2^2}} + A_2 e^{\frac{-(\Delta\varphi-2\pi)^2}{2\sigma_2^2}}$$

$$+ A_3 e^{\frac{-(\Delta\varphi-\pi)^2}{2\sigma_3^2}} + A_3 e^{\frac{-(\Delta\varphi+\pi)^2}{2\sigma_3^2}}$$



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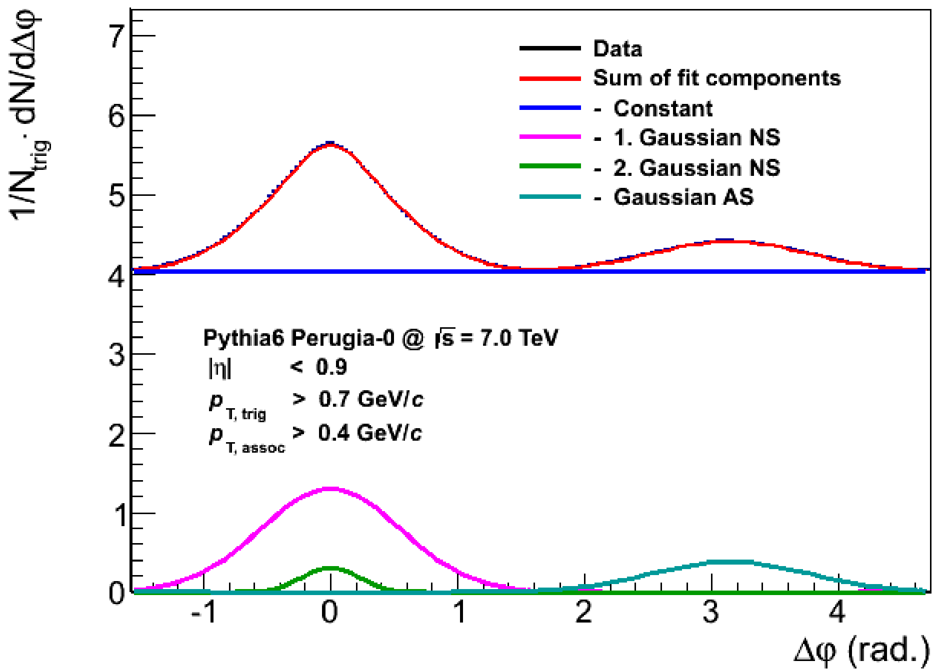

- Data and fit are in excellent agreement, fit is stable

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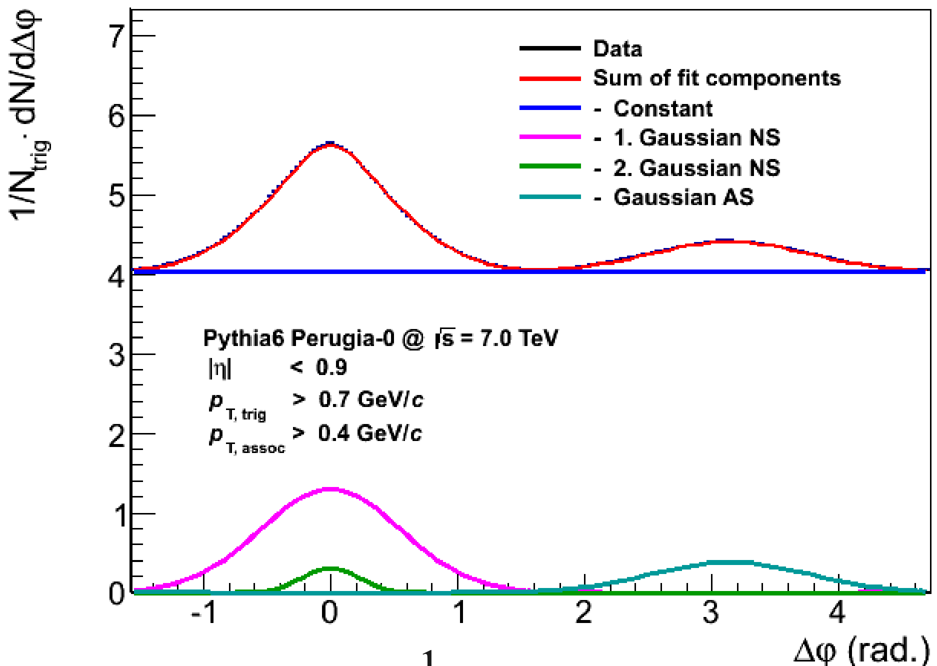

$$\langle N_{isotrop} \rangle = \frac{1}{N_{trig}} \cdot C$$

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

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

$$\langle N_{trigger} \rangle = \frac{N_{trigger}}{N_{event}}$$

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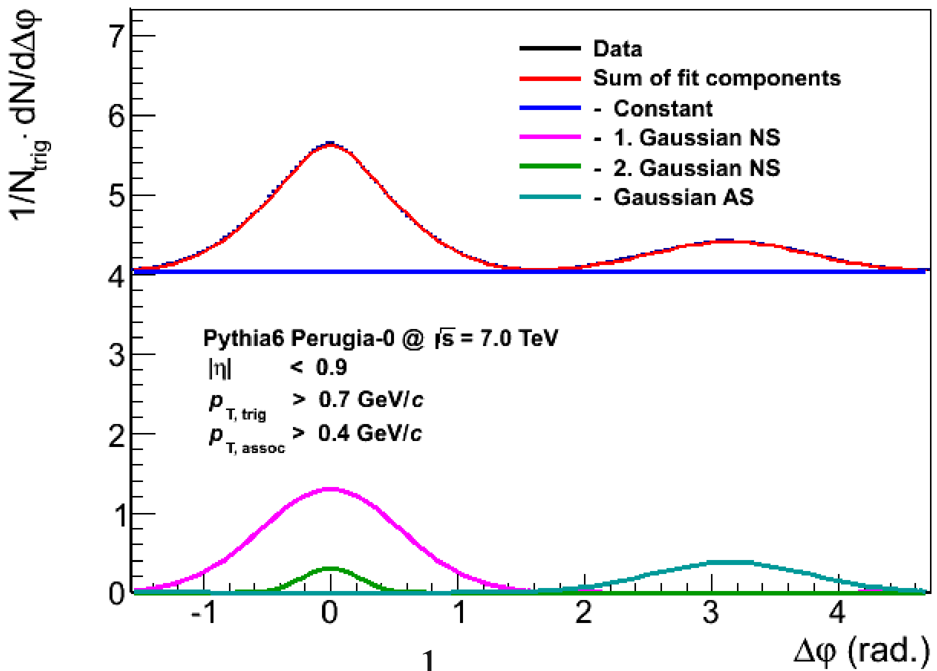

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$$\langle N_{trigger} \rangle = \frac{N_{trigger}}{N_{event}}$$

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

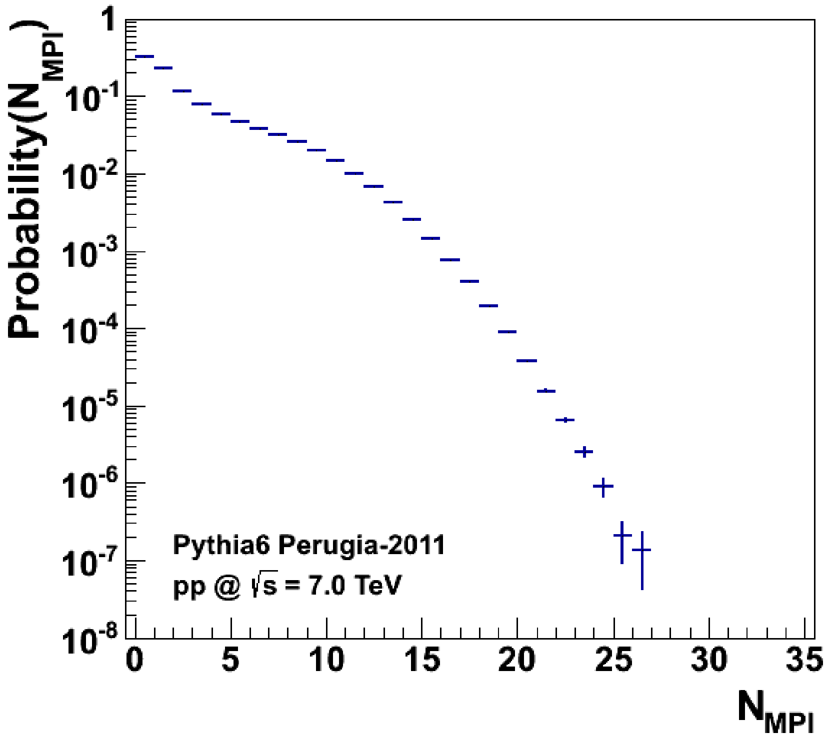
- Data and fit are in excellent agreement, fit is stable
- Compute number of sources of particle production → possibility to access information about MPI

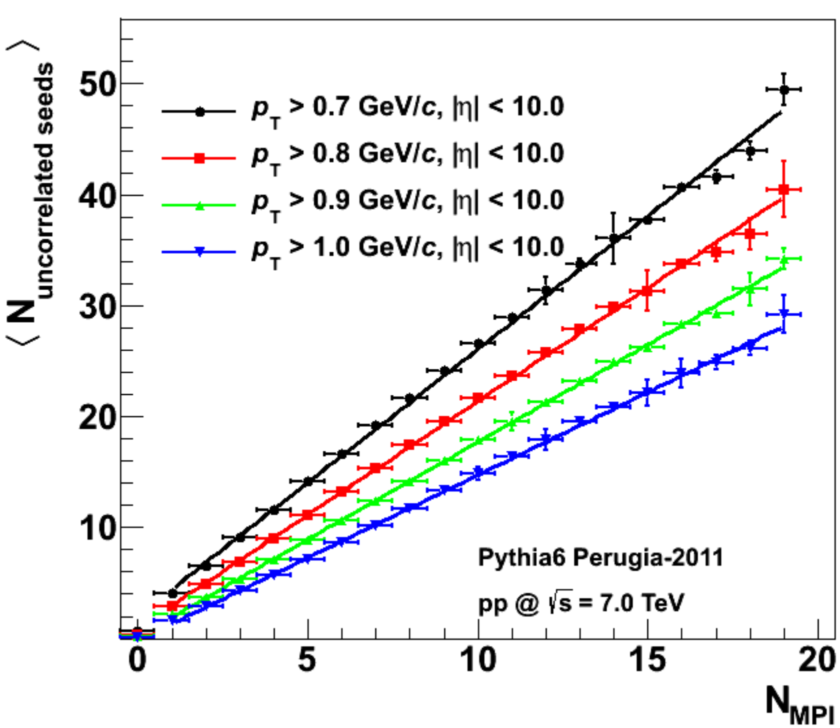
Number of Multiple Parton Interactions

- Pythia has a phenomenological model of multiple parton interactions (MPI)

$$N_{MPI}(p_{T,\,min}) = \frac{\sigma_{interaction}(p_{T,\,min})}{\sigma_{non-diffractive}}$$

- Within the Pythia model, N_{MPI} is proportional to the number of uncorrelated seeds $N_{\text{uncorrelated seeds}}$
- Possibility to access N_{MPI} using presented analysis method

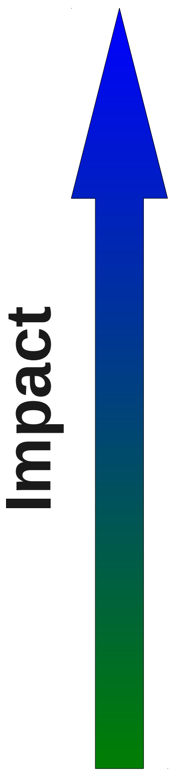




Analysis Details

- Data (including ITS and TPC)
  - pp @ $\sqrt{s}$ = 0.9 TeV:
    - 7 million events
  - pp @ $\sqrt{s}$ = 2.76 TeV:
    - 27 million events
  - pp @ $\sqrt{s}$ = 7.0 TeV:
    - 204 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

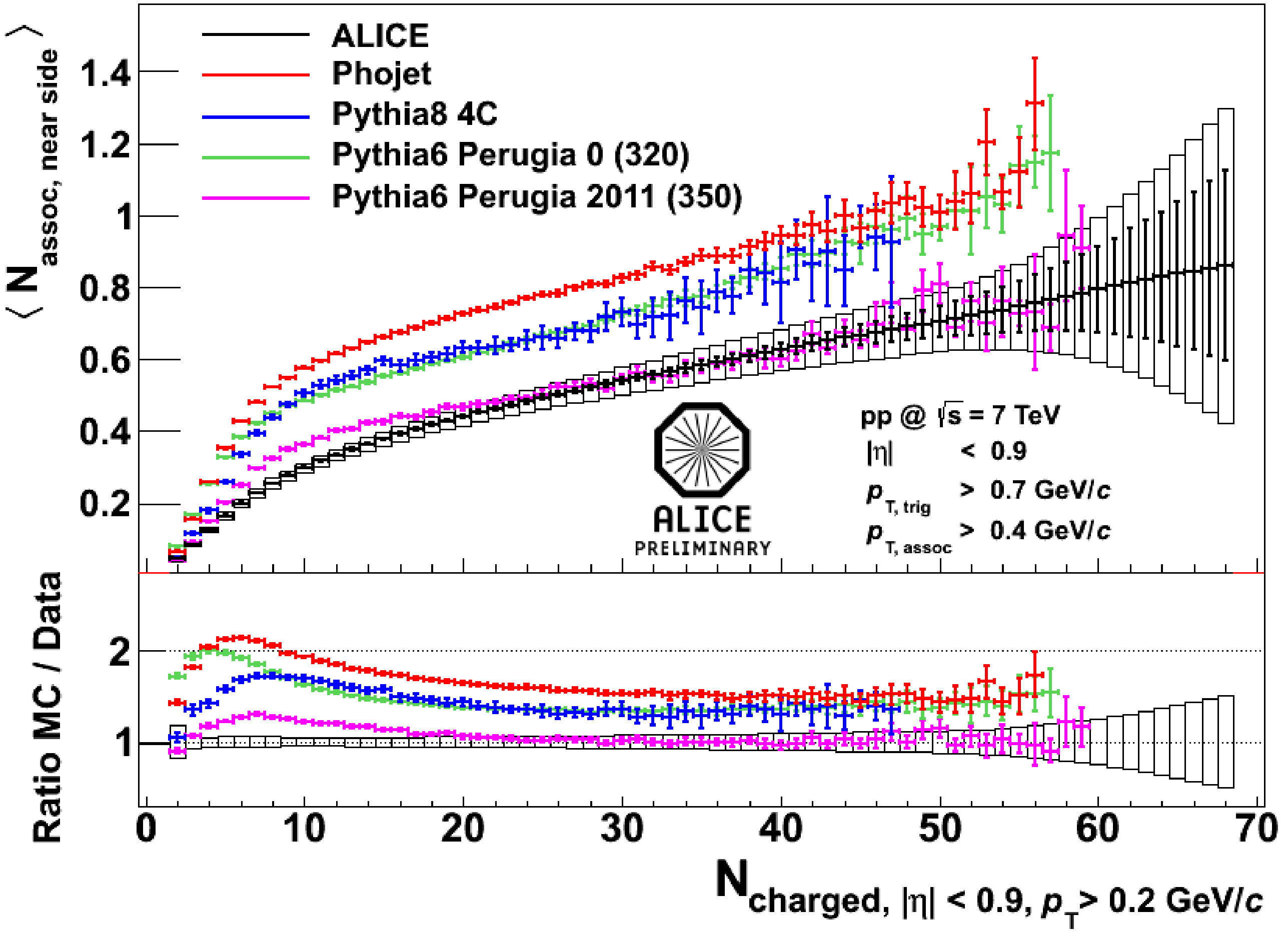
Corrections and Systematic Uncertainties



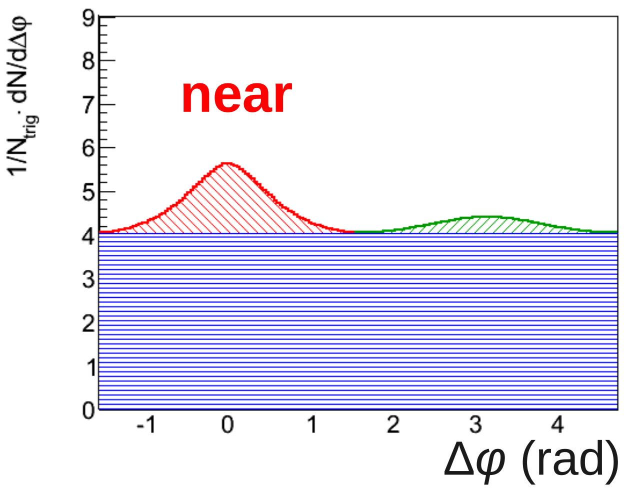
- Correction chain
  - Reconstruction efficiency
  - Contamination with tracks from secondary particles
  - Two-track and detector effects
  - Multiplicity correction
  - Contamination from strange particles
  - Vertex reconstruction efficiency
  - Trigger efficiency

- 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 Near Side Pair Yield

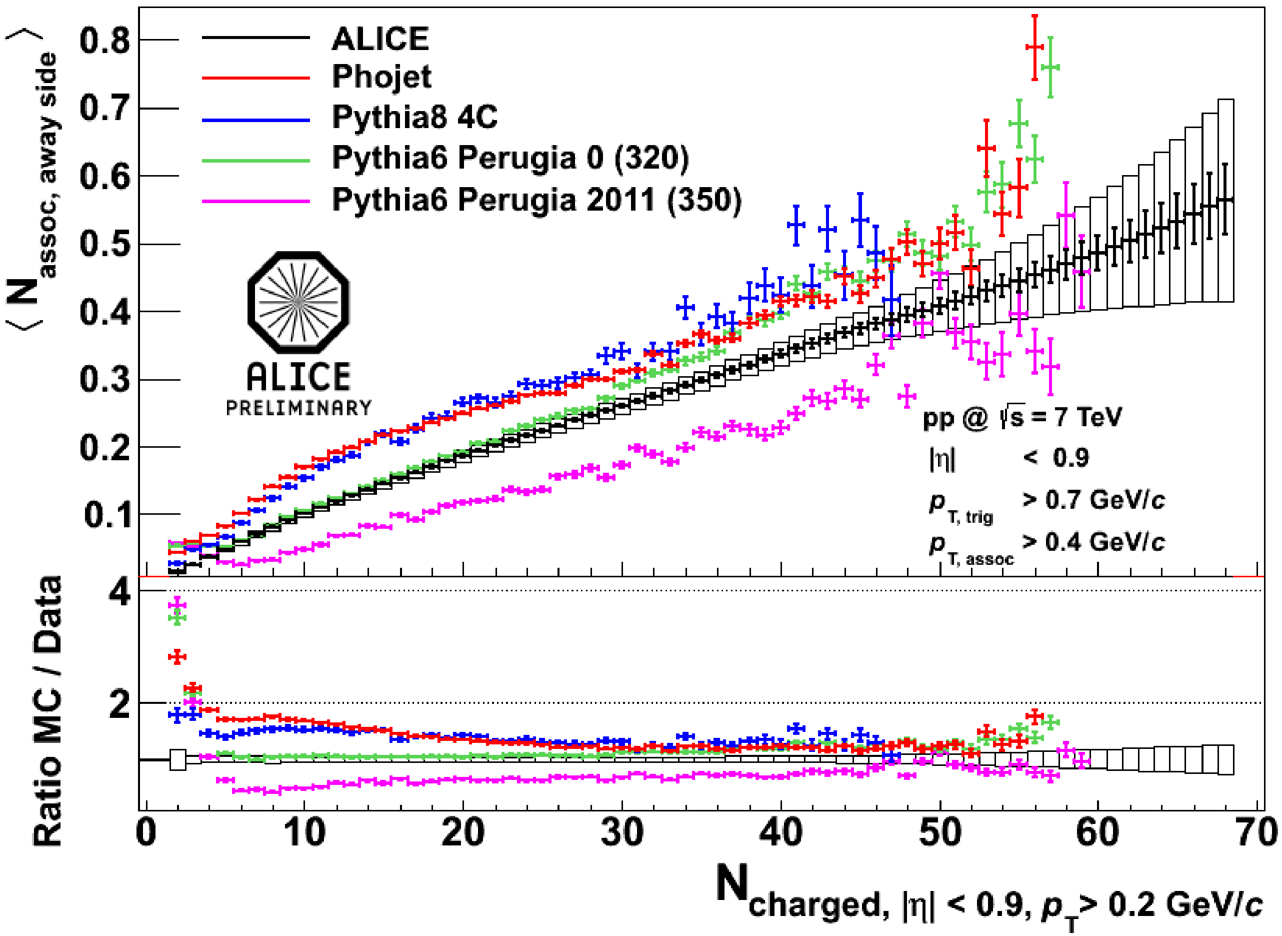


- Particle production in near side peak is dominated by jet fragmentation

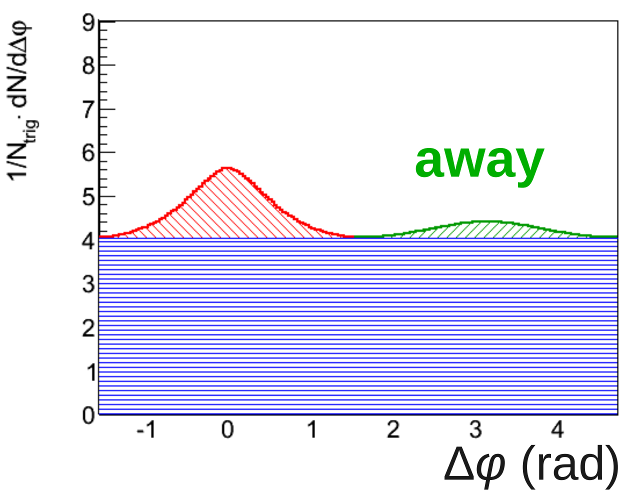


- Per-trigger near side pair yield grows with N_{ch}
- Near side is overestimated by Phojet, Pythia8, and Pythia6 Perugia-0 by up to 100%, Pythia6 Perugia-2011 gives best agreement with only small deviations

Per-Trigger Away Side Pair Yield

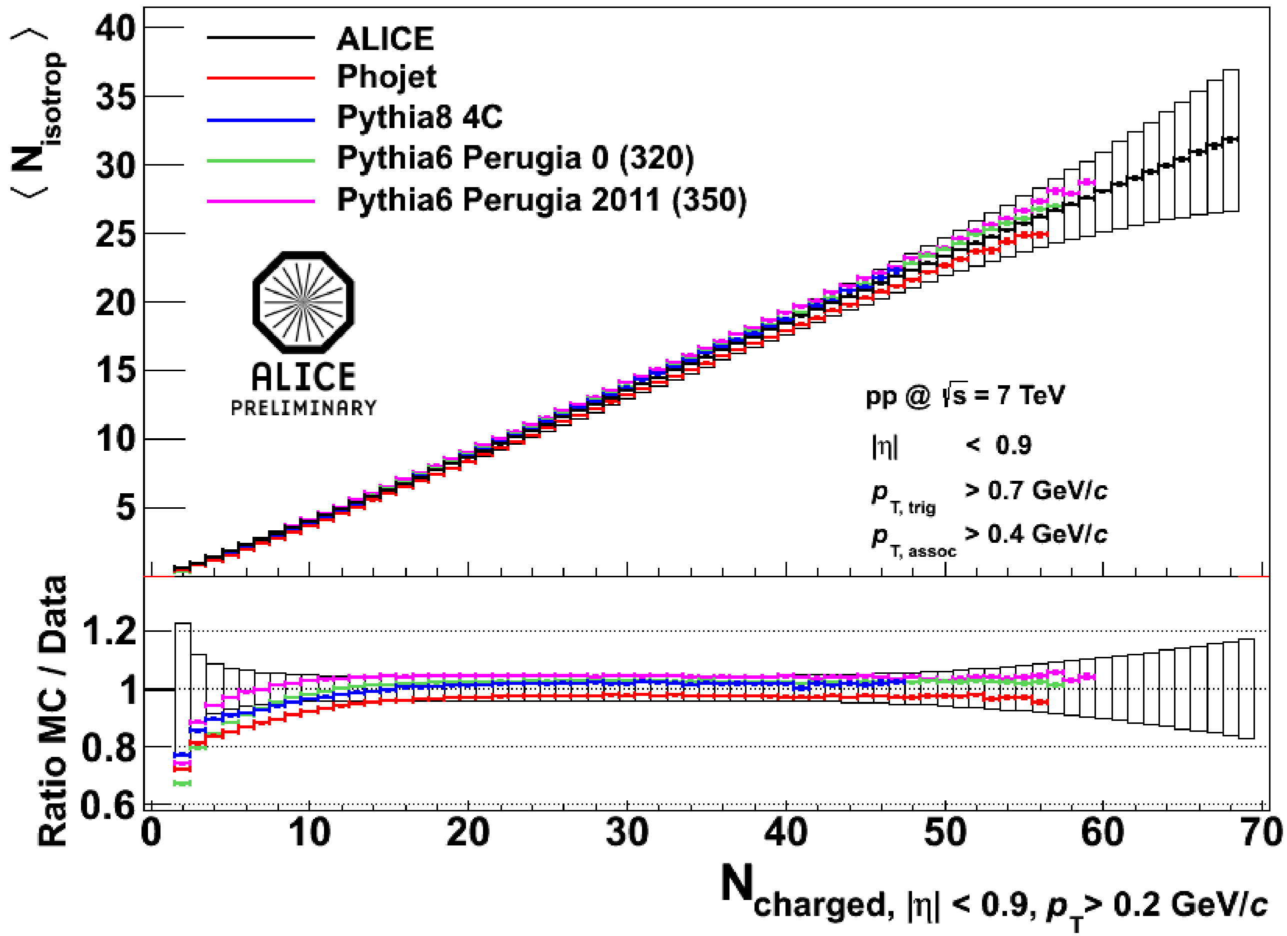


- Particles in away side peak are produced in recoiling jets

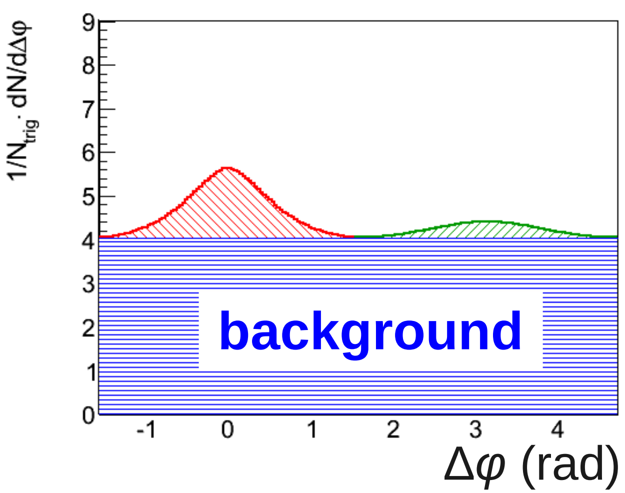


- Per-trigger away side pair yield grows with N_{ch}
- Pythia6-Perugia-0 gives best agreement with ALICE results

Pair Yield in Combinatorial Background

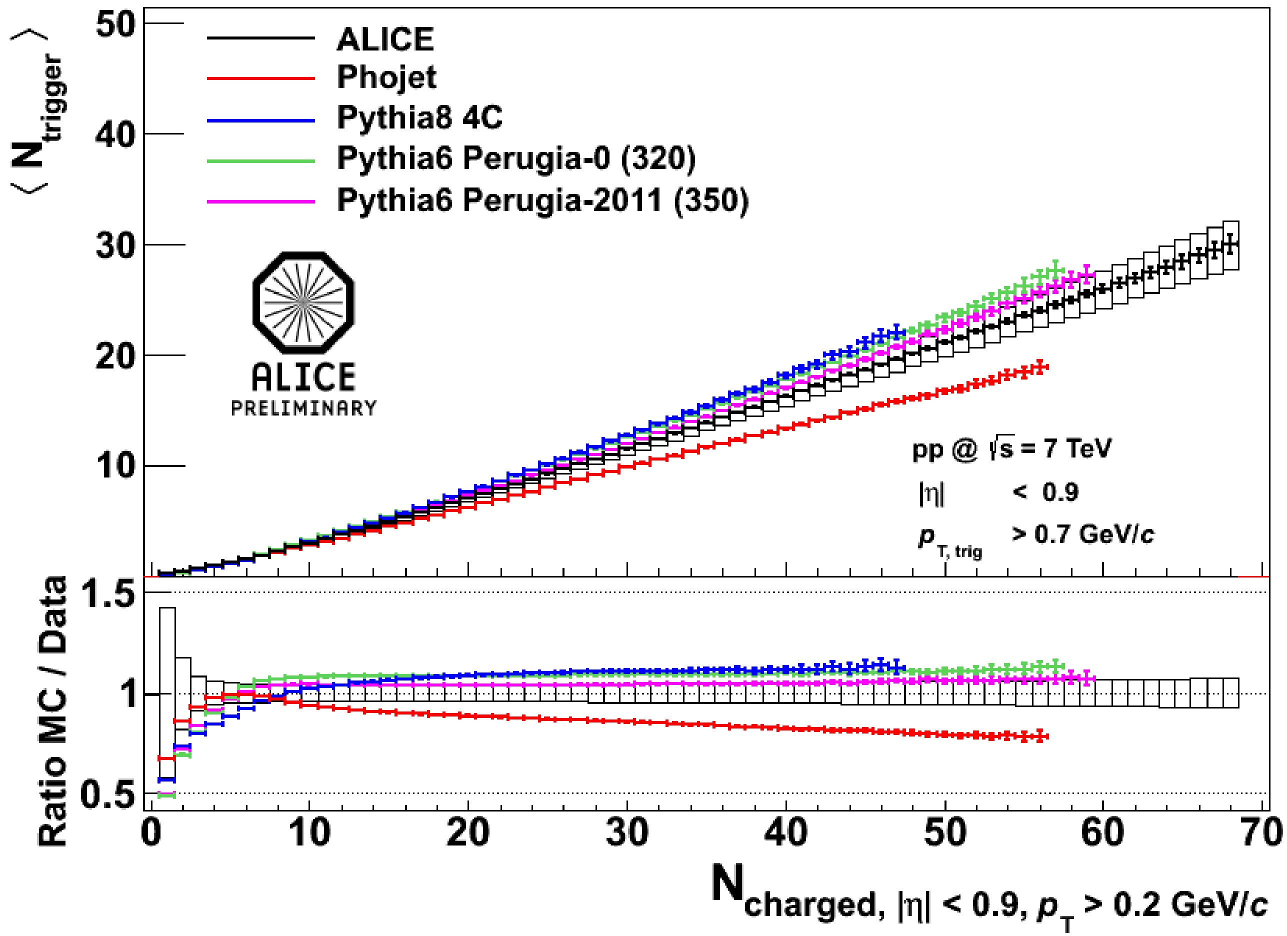


- Particles from processes which are uncorrelated to production process of trigger particle



- Pair yield in uncorrelated background is well reproduced by all models within the systematic uncertainties

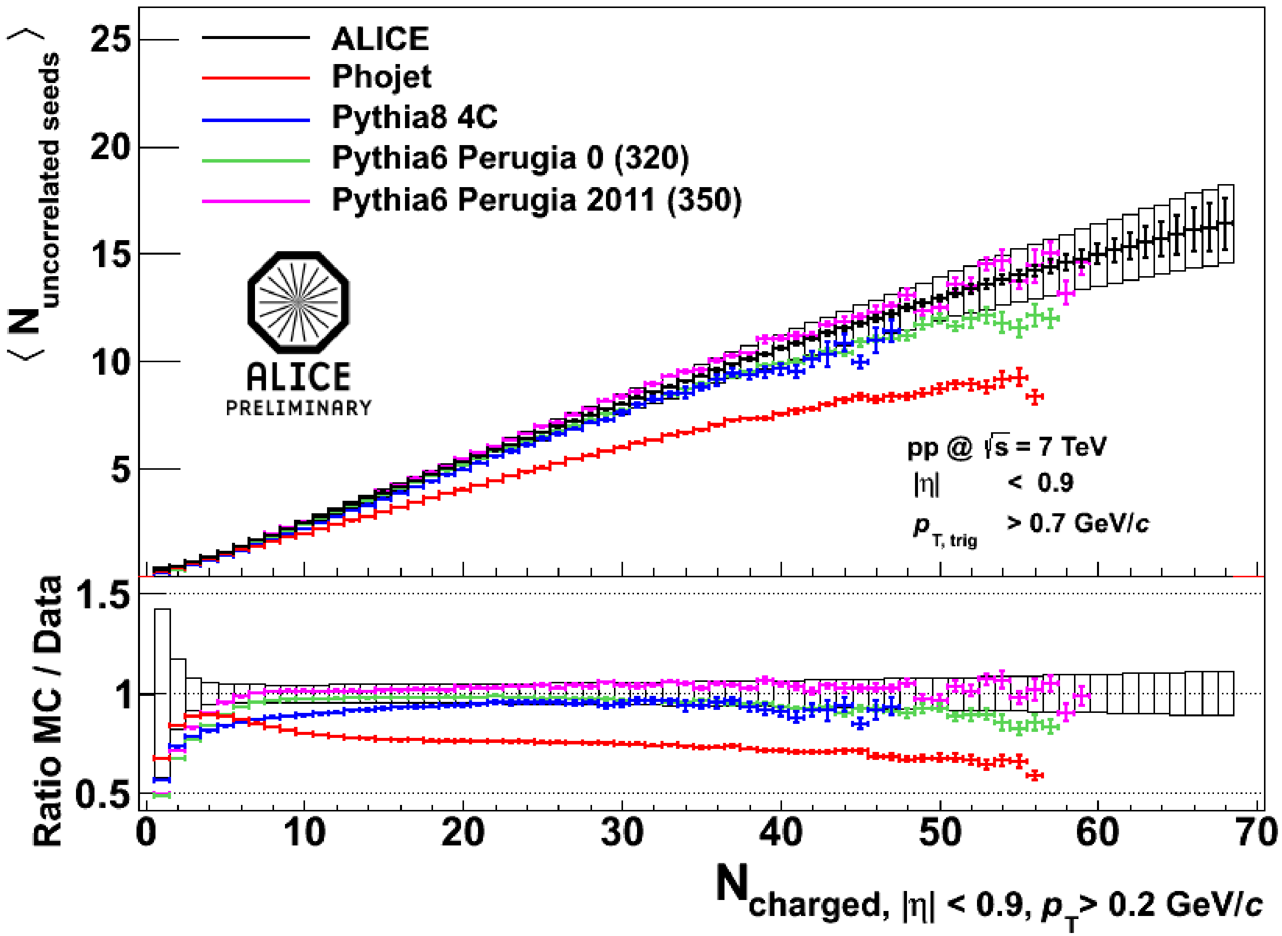
Average Number of Trigger Particles



- Average number of trigger particle contains information about MPI and fragmentation
- $N_{trigger}$ grows slightly faster than linear, growth of mean-p_T with N_{ch}

- All Pythia tunes slightly overestimate the ALICE results
- Phojet underestimated the ALICE results

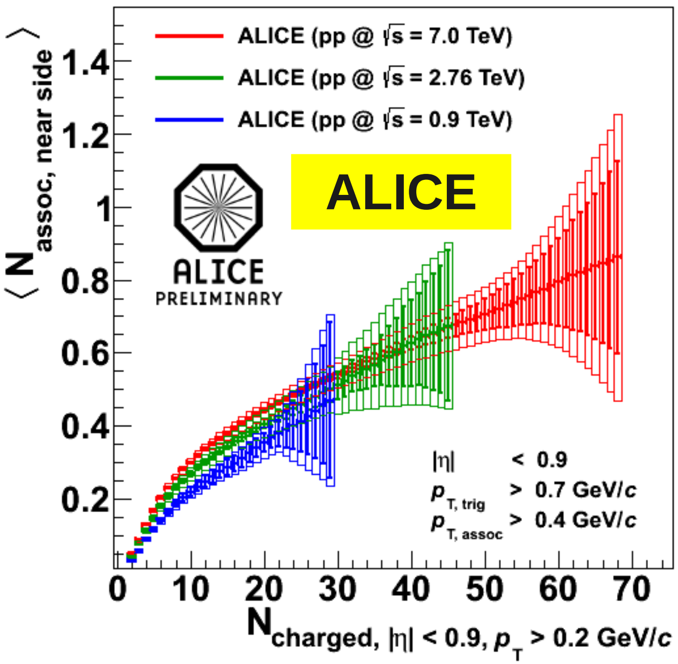
Number of Uncorrelated Seeds

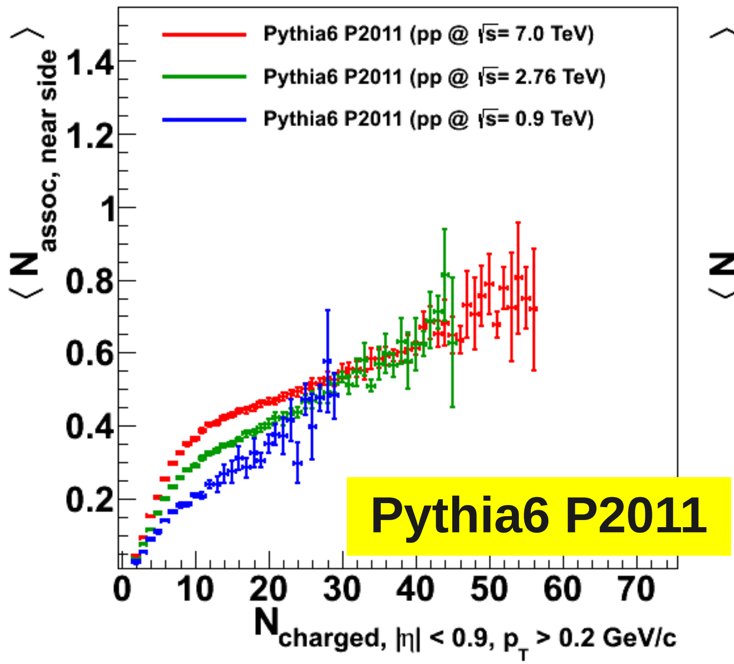


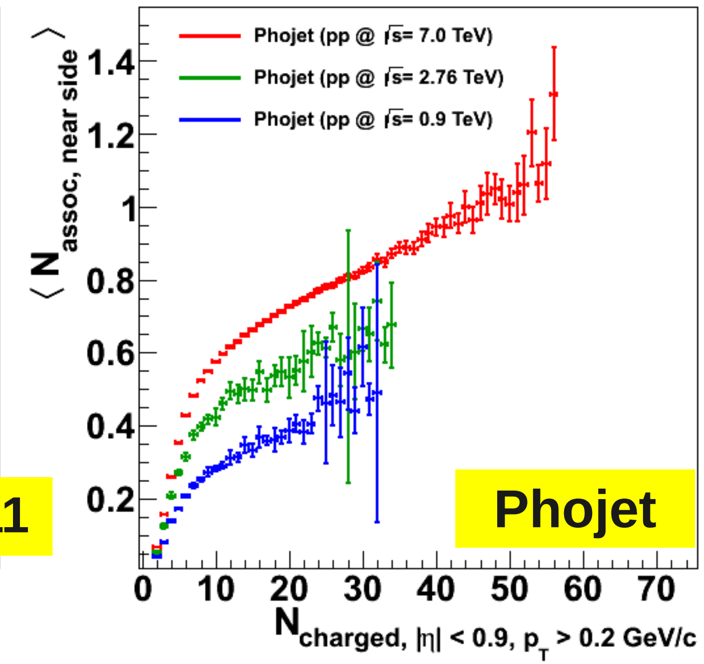
- The number of uncorrelated seeds contains information about MPI: In Pythia N_{MPI} and $N_{\text{uncorrelated seeds}}$ are proportional
- All Pythia tunes reproduced the ALICE results fairly well
- Phojet underestimates the ALICE results

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

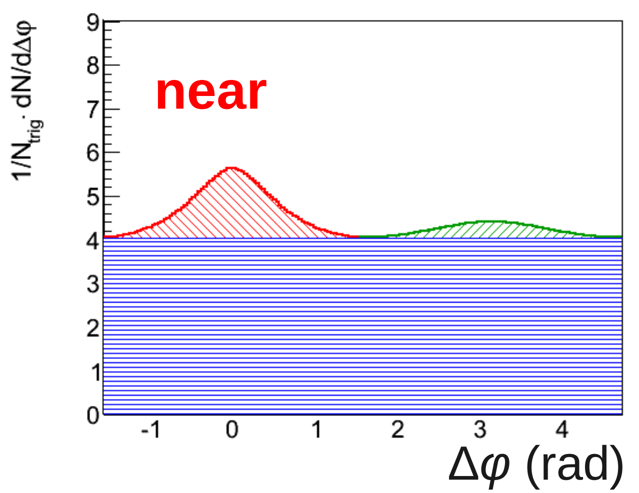
Per-Trigger Near Side Pair Yield



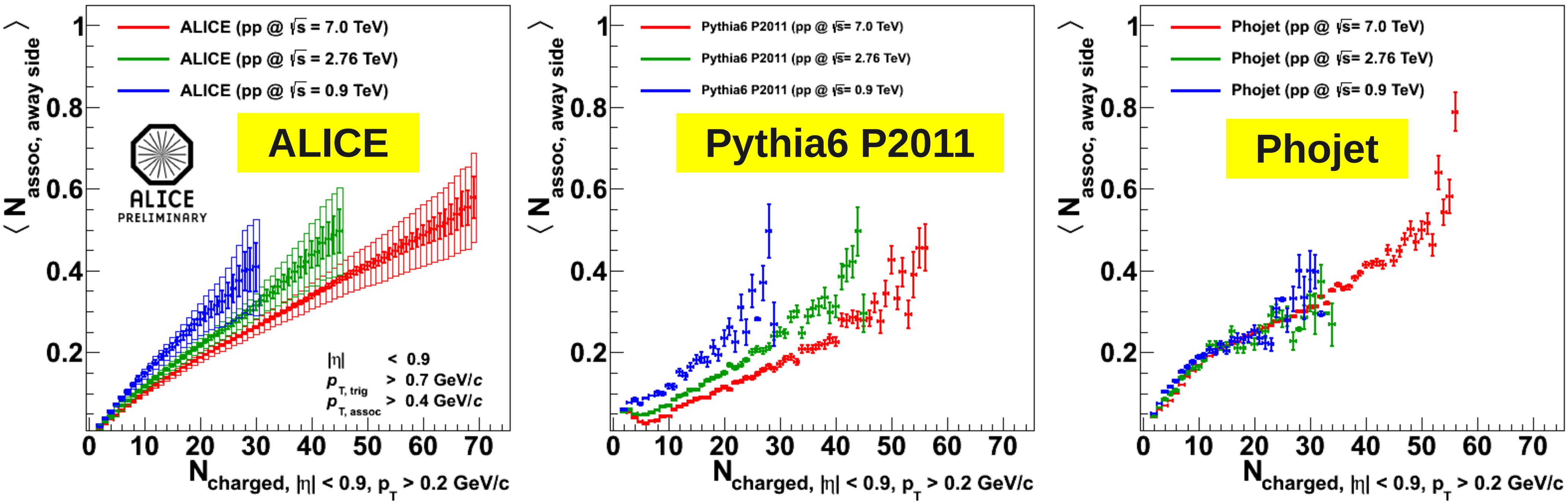




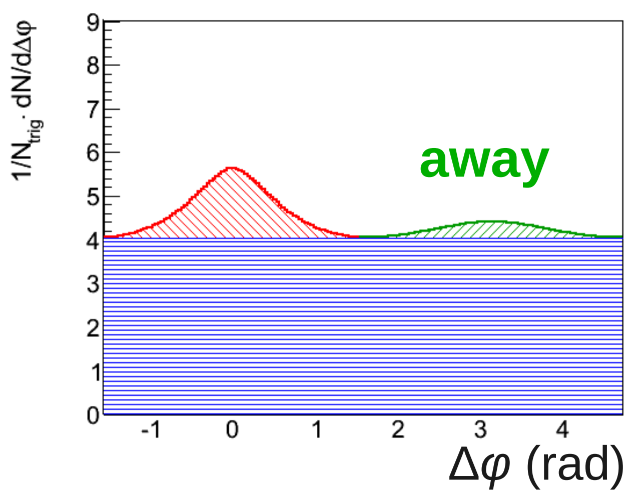
- Center-of-mass energy √s = **0.9**, **2.76**, **7.0** TeV
- Near side pair yield at same multiplicity bin grows with increasing center-of-mass energy
- Splitting between slopes for different √s is largest for Phojet



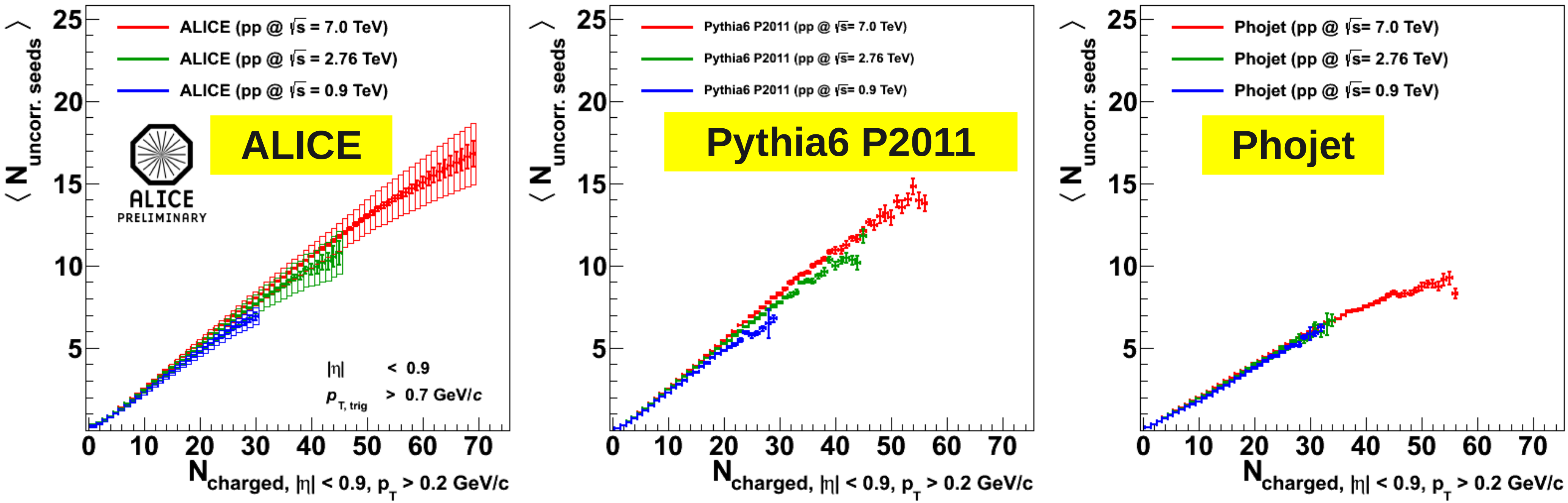
Per-Trigger Away Side Pair Yield



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



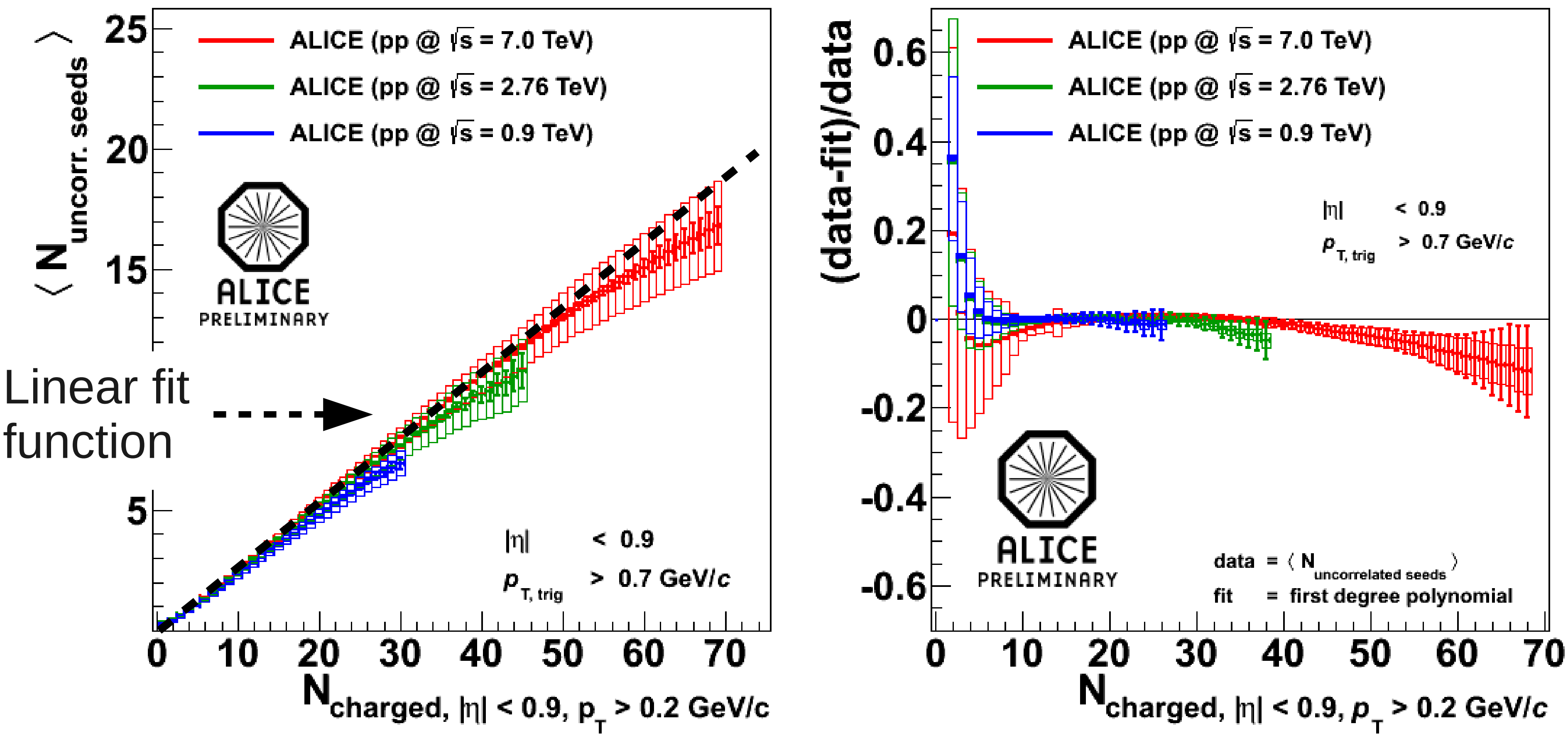
Average Number of Uncorrelated Seeds



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

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

$\langle N_{uncorrelated\ seeds} \rangle$ and Linear Fit



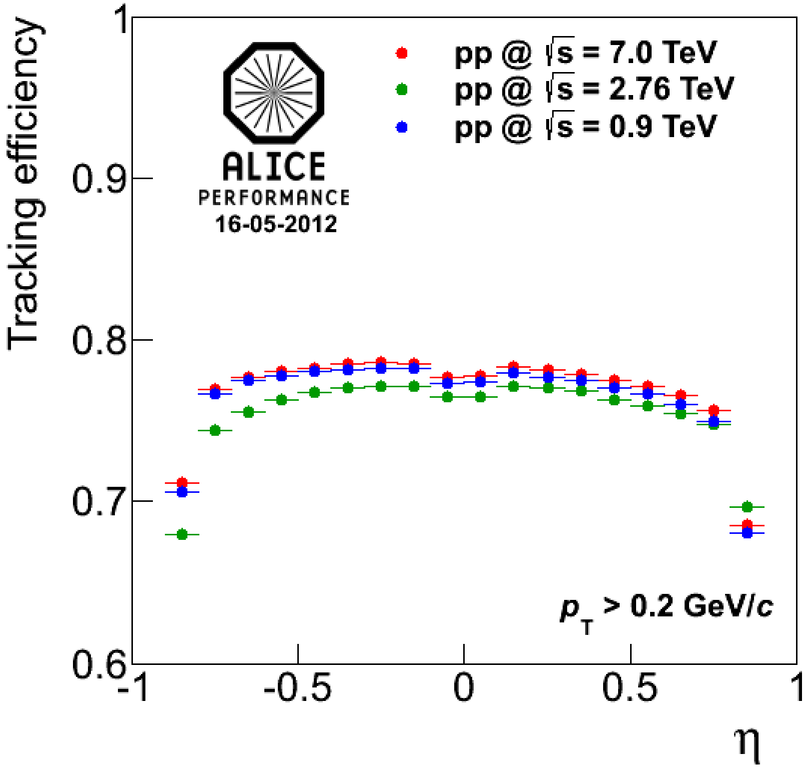
- Compare distribution with linear fit in intermediate N_{ch} range
- At high multiplicities, hint of deviation from linear dependence - this would indicate a limit in MPI

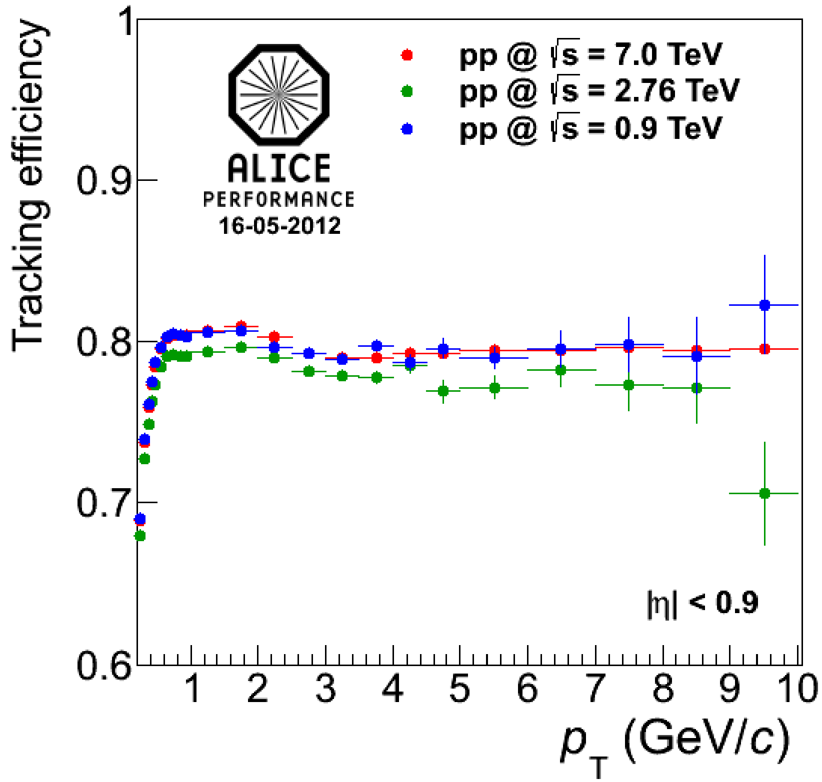
Summary

- Study of the per-trigger pair yield at the near side and the away side as well as the number of uncorrelated seeds using a two-particle correlation analysis
  - Information about jet fragmentation and MPI
- Analysis of ALICE data at $\sqrt{s}$ = 0.9, 2.76, and 7.0 TeV
- At high multiplicities, the number of uncorrelated seeds show a hint of a deviation from linear dependence with multiplicity - 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_{ch}, 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 Monte Carlos by 100% at low and intermediated N_{ch}

Backup

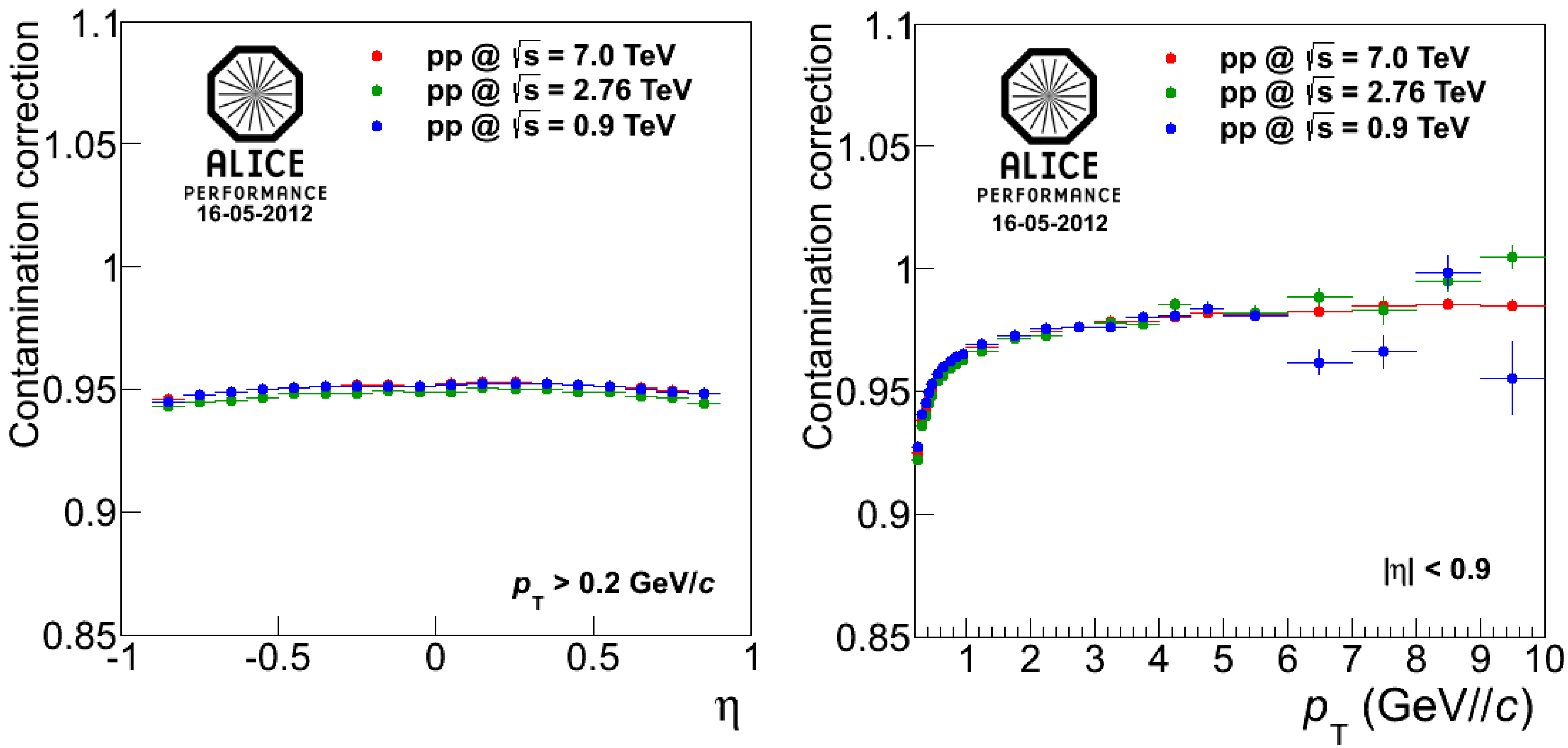
Correction: Reconstruction Efficiency





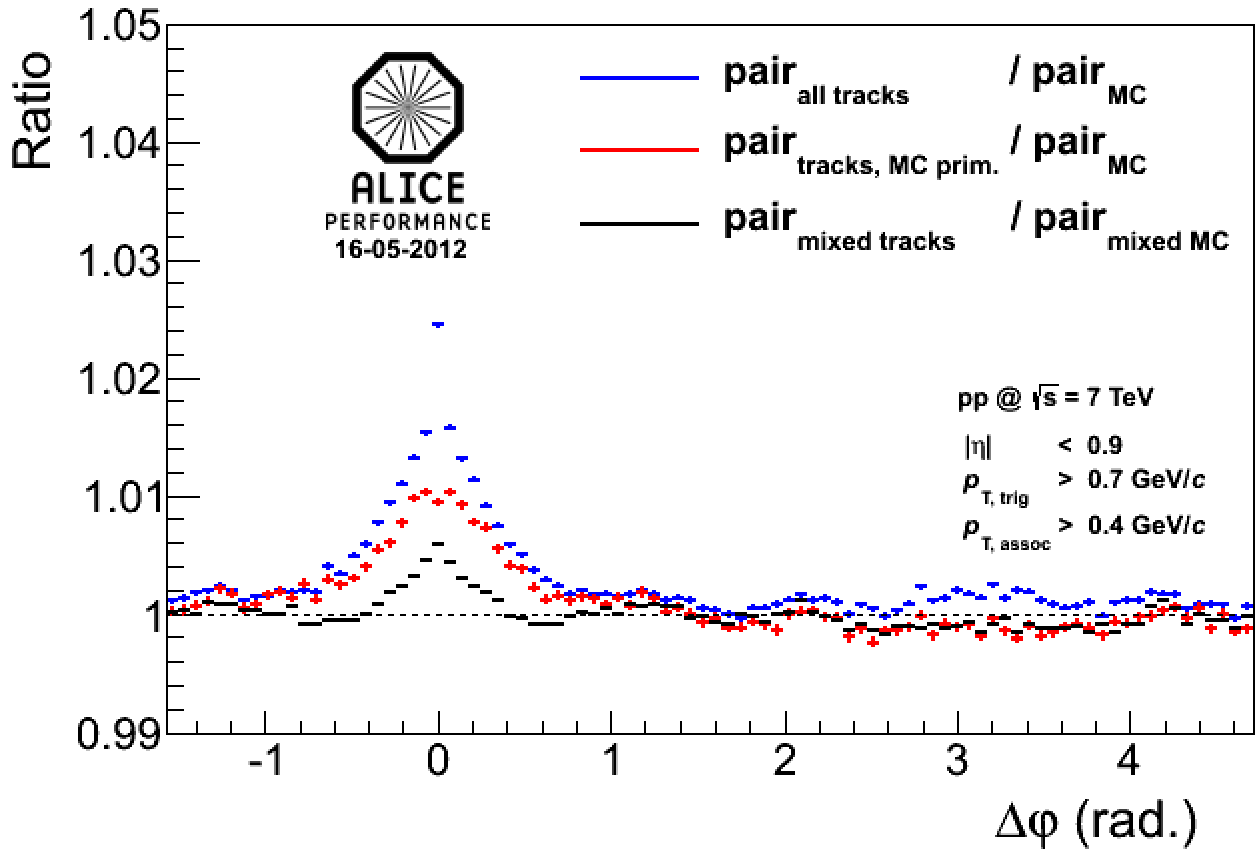
- *Reconstruction efficiency*: Ratio of the number reconstructed and accepted particles tracks of primary particles to number of primary particles
- 78% of all primary particles (at p_T > 0.2 GeV/c, $|\eta|$ < 0.9) are found in the reconstruction → Loss of 22%

Correction: Contamination



- *Contamination*: Ratio of number of all reconstructed tracks to number of reconstructed tracks of primary particles →
  Contamination from decay produces of strange particles, photon conversion, hadronic interaction with the detector material
- Contamination of 6% (at p_T > 0.2 GeV/c, $|\eta|$ < 0.9)

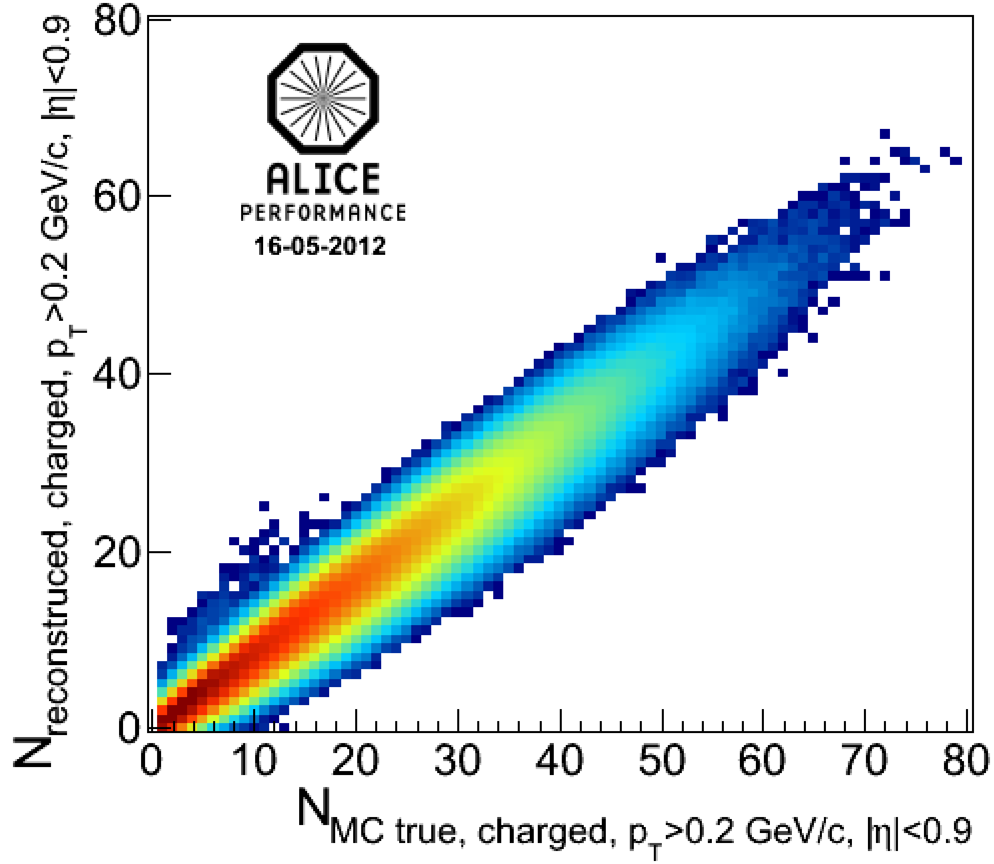
Correction: Two Track and Detector Effects



- 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:

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

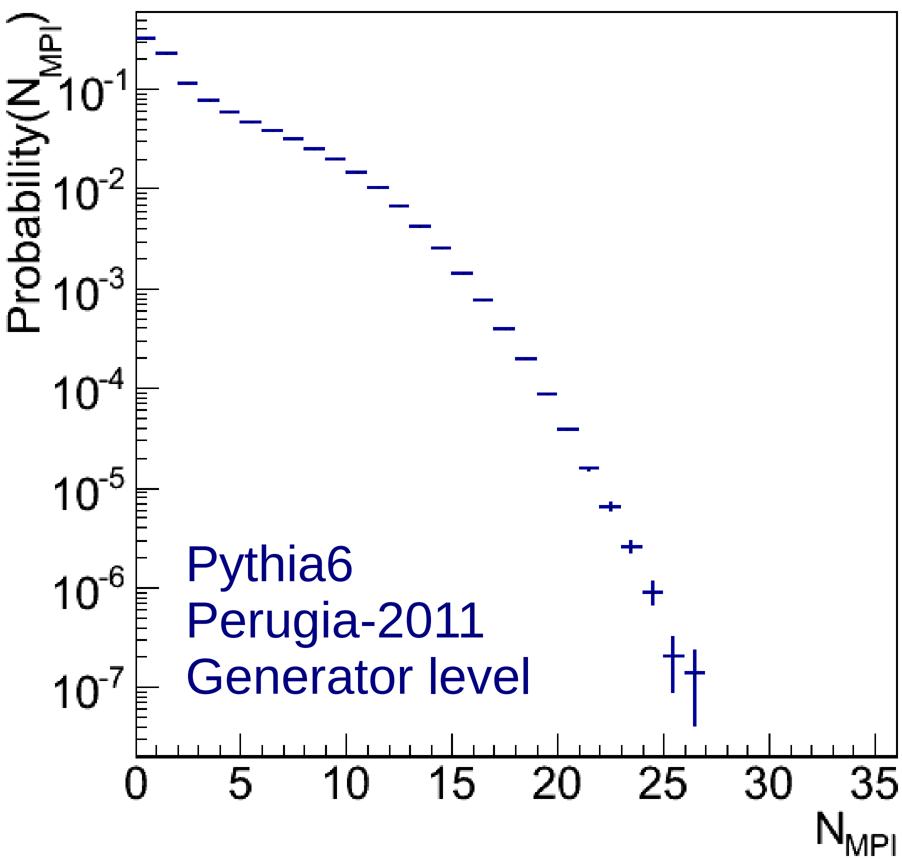
Assumption: $N_{\text{uncorrelated seeds}} \rightarrow N_{\text{MPI}}$

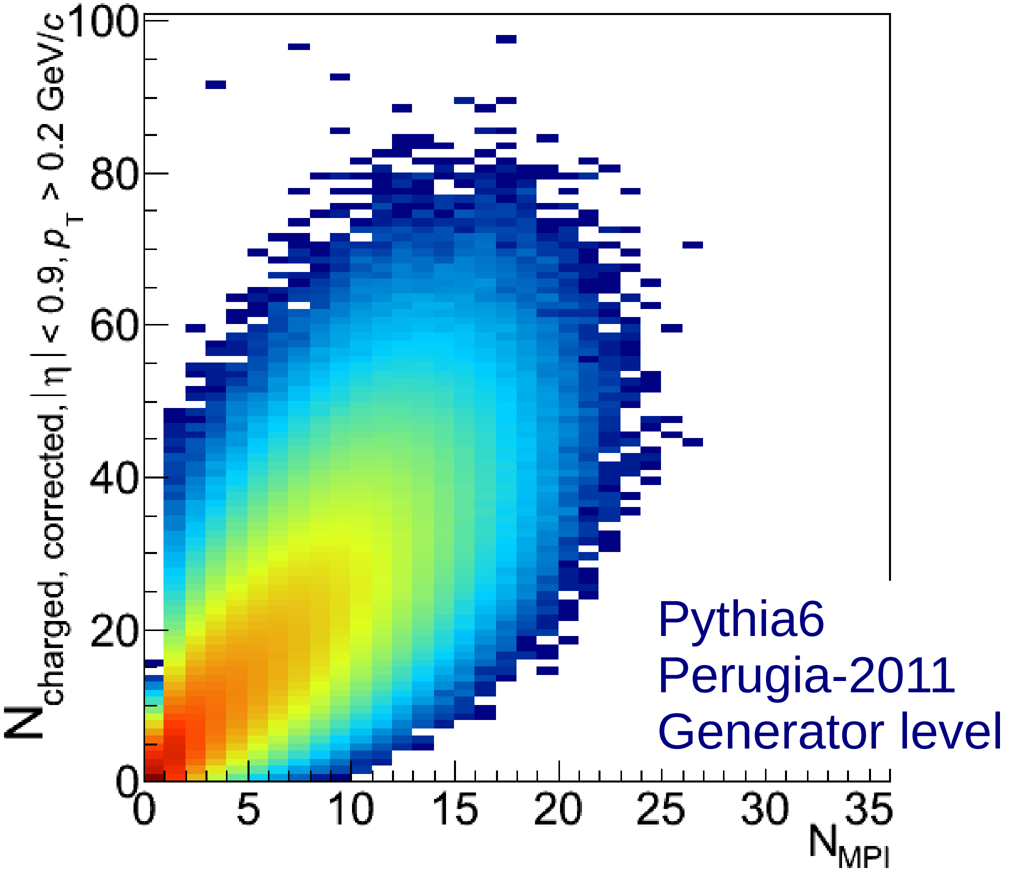
- We measure $N_{\text{uncorrelated seeds}}$

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

- We assume that $N_{\text{uncorrelated seeds}}$ 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

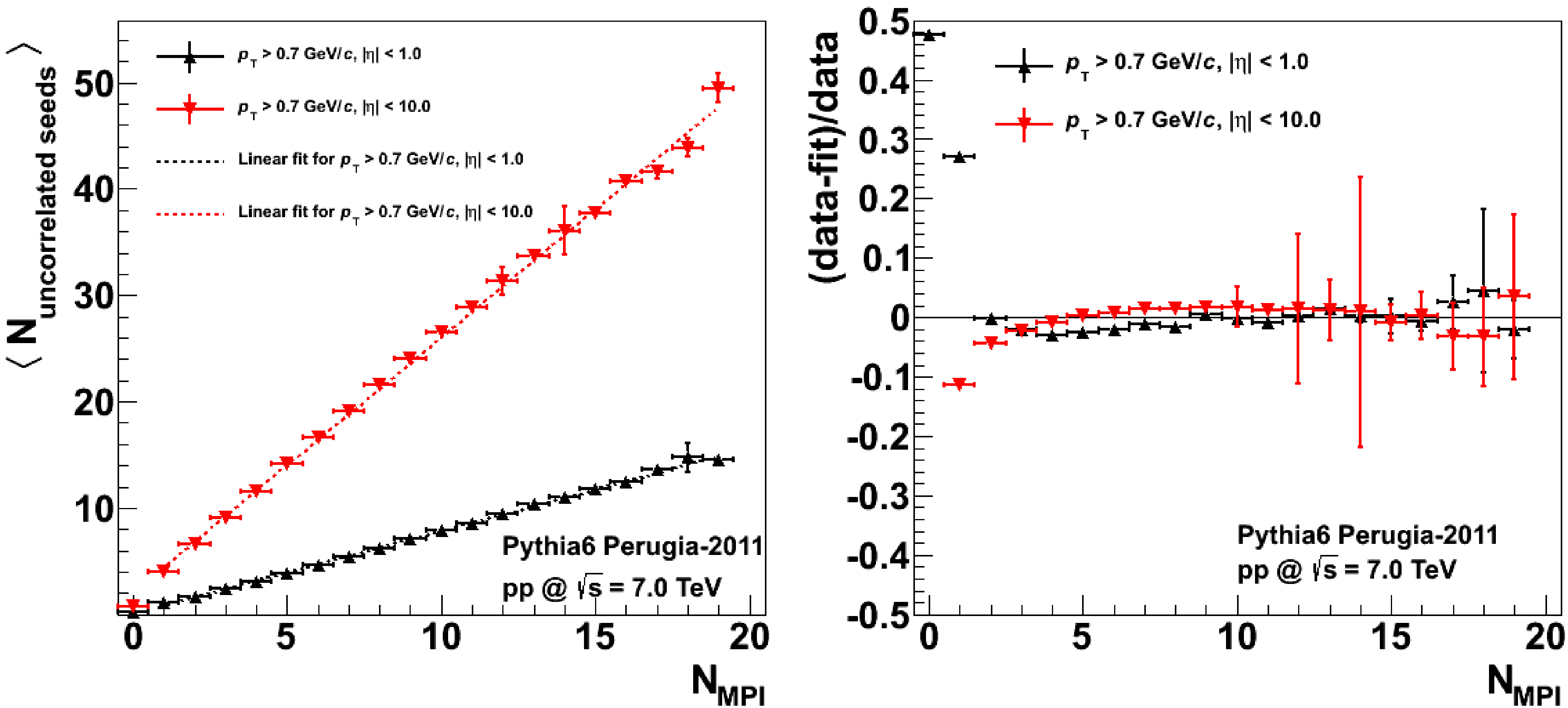
MPI in Pythia6 Perugia2011





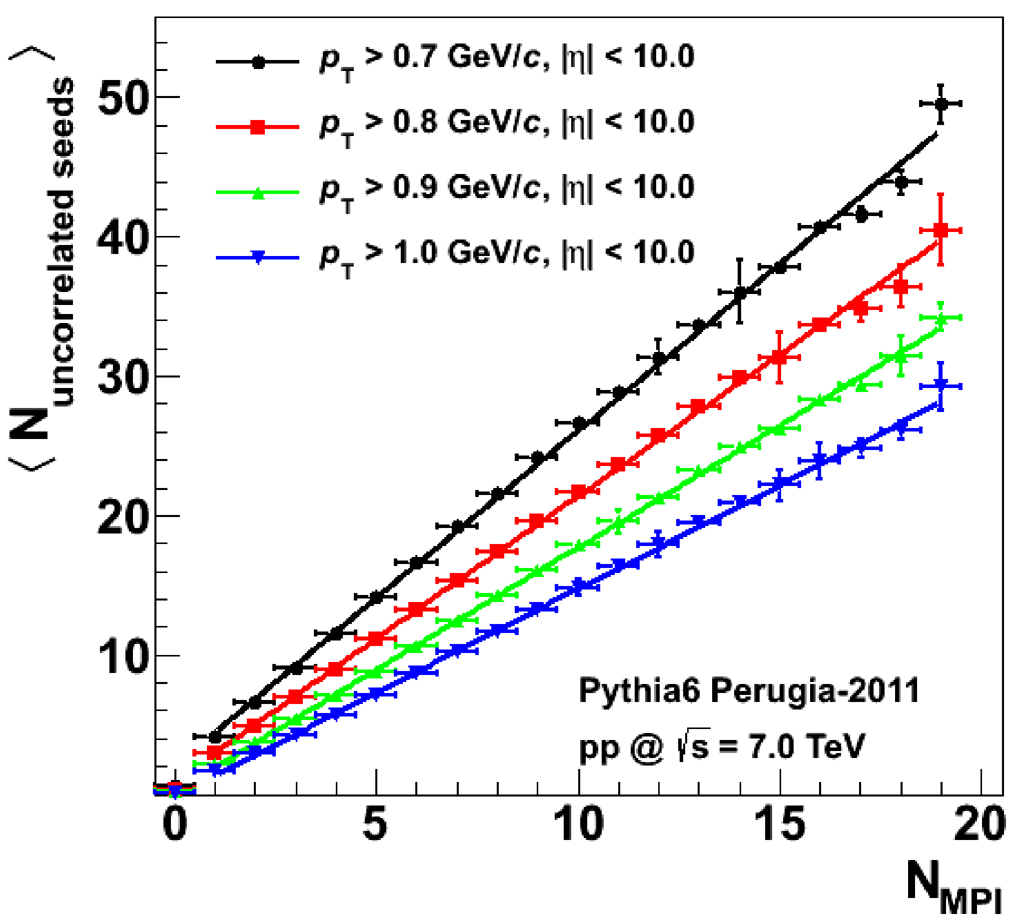
- Spectrum of multiple parton interactions in Pythia6 Perugia-2011
- Correlation of measured multiplicity to number of multiple parton interactions

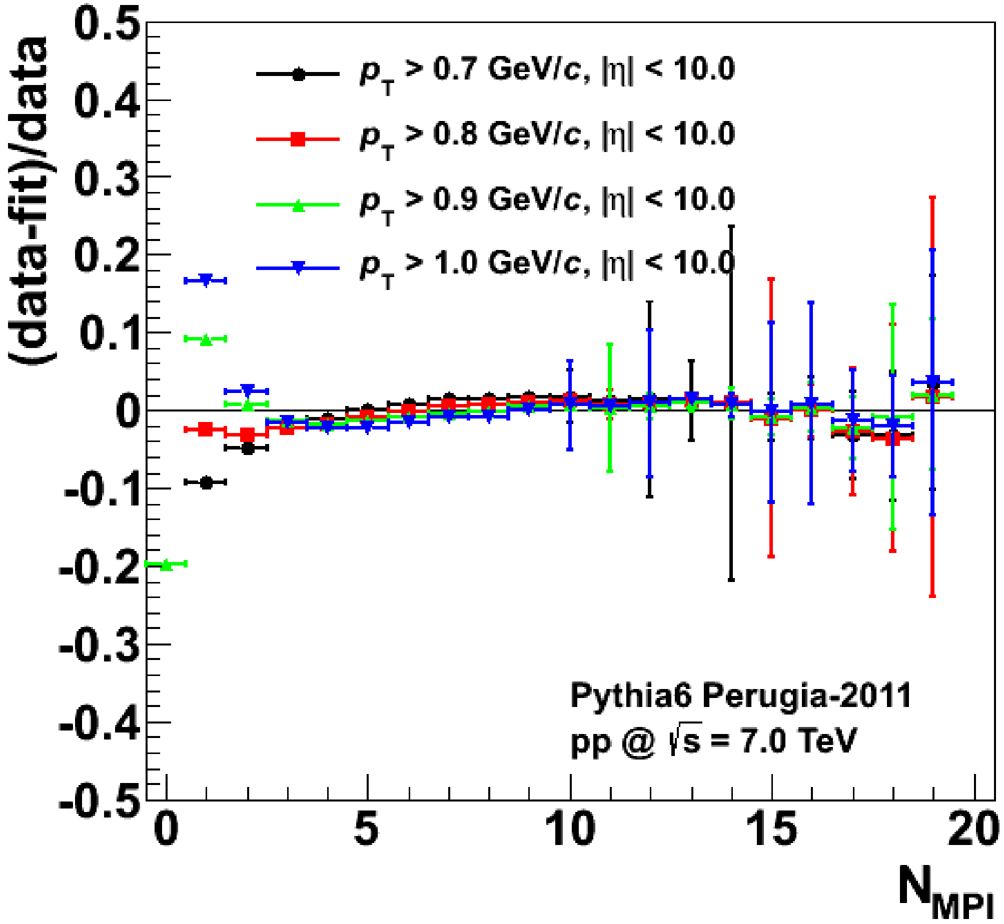
$N_{uncorrelated\ seeds} \sim N_{MPI}$



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

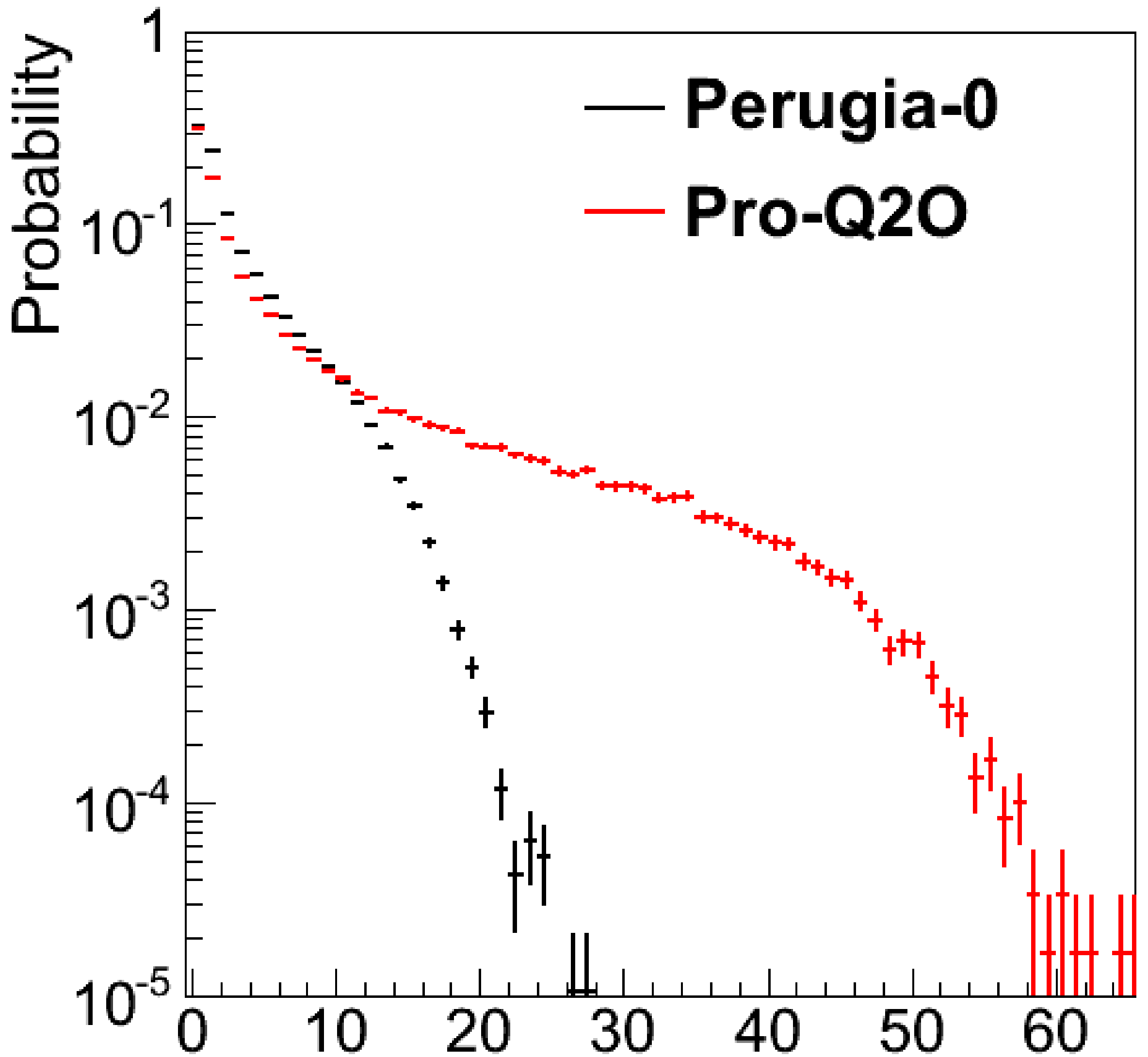
$N_{\text{uncorrelated seeds}} \sim N_{MPI}$





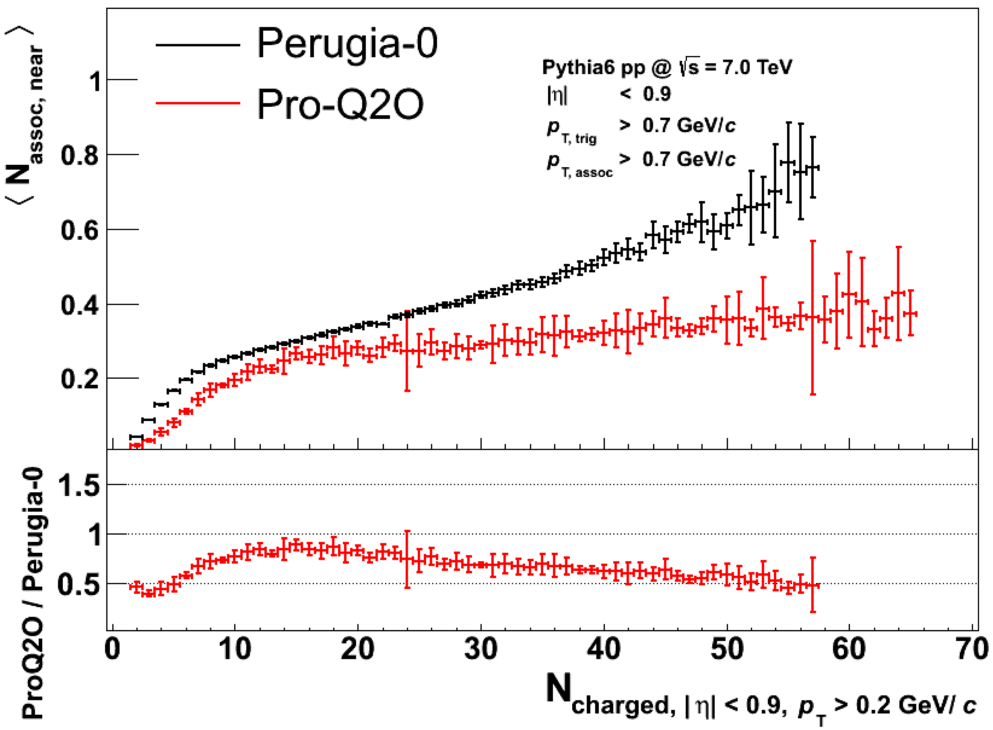
- Linear dependence is given for several p_T thresholds

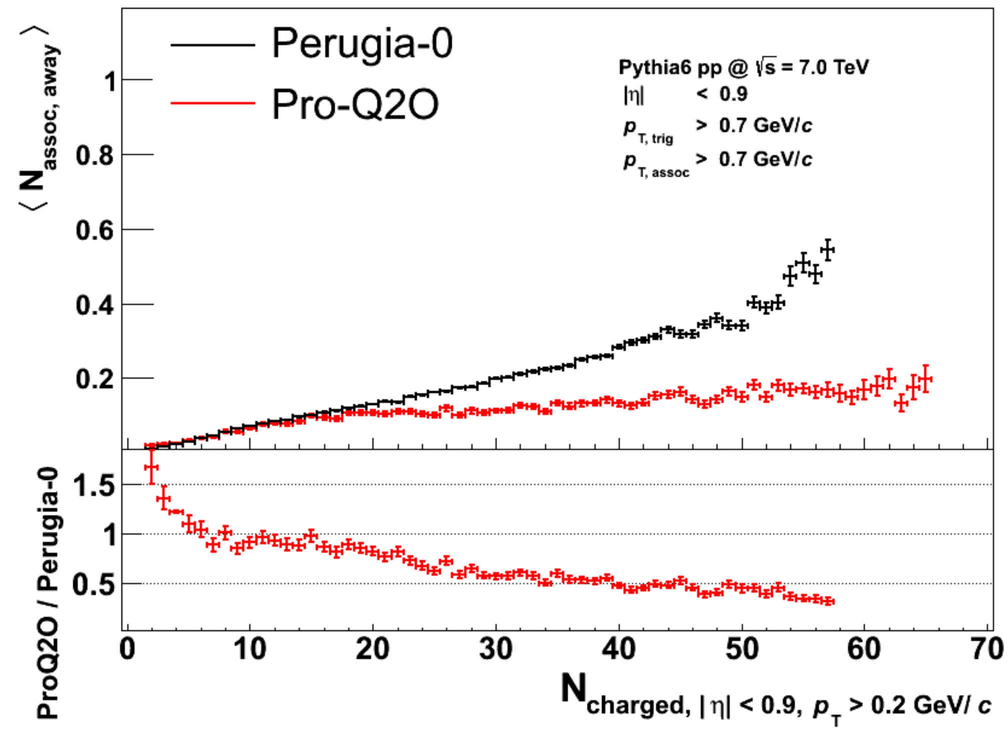
Multiple Parton Interactions in Pythia6



N_{MPI} = MSTI(31)$_{Pythia}$

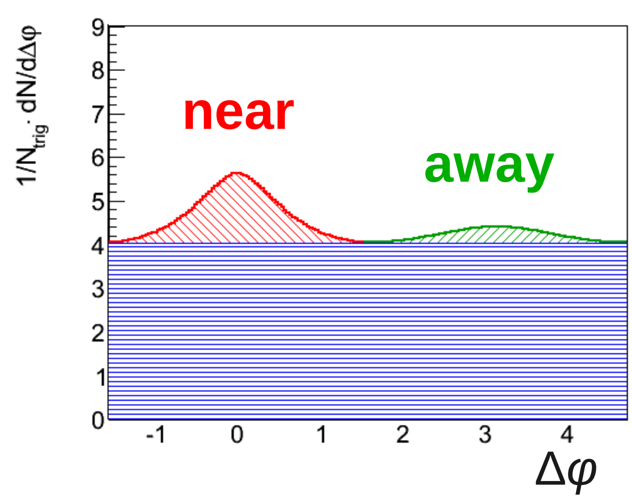
Per-Trigger Near/Away Side Pair Yield



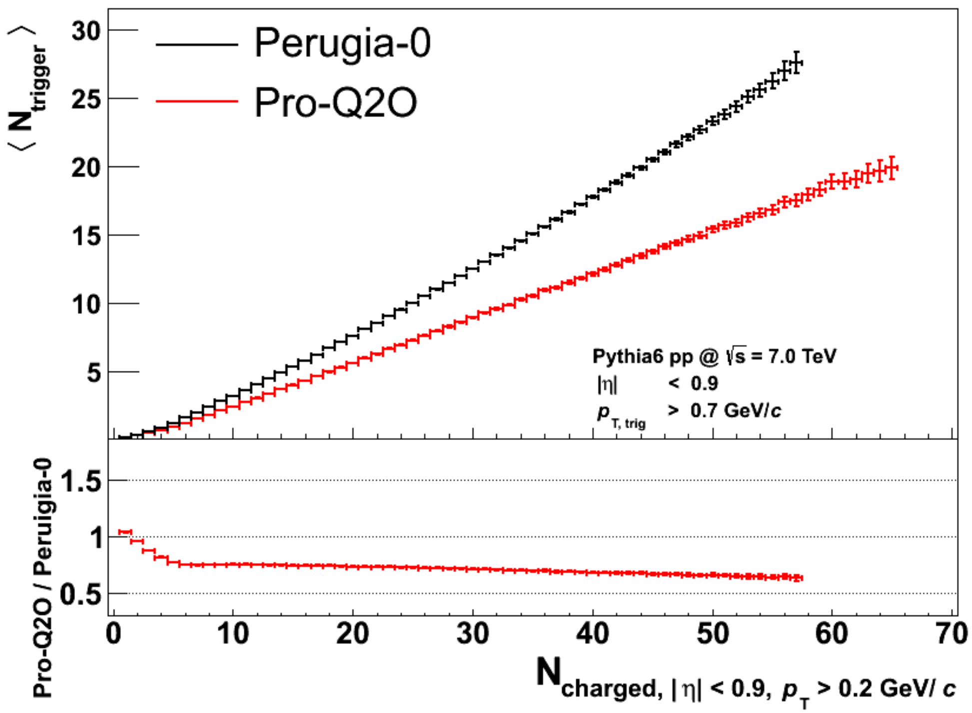


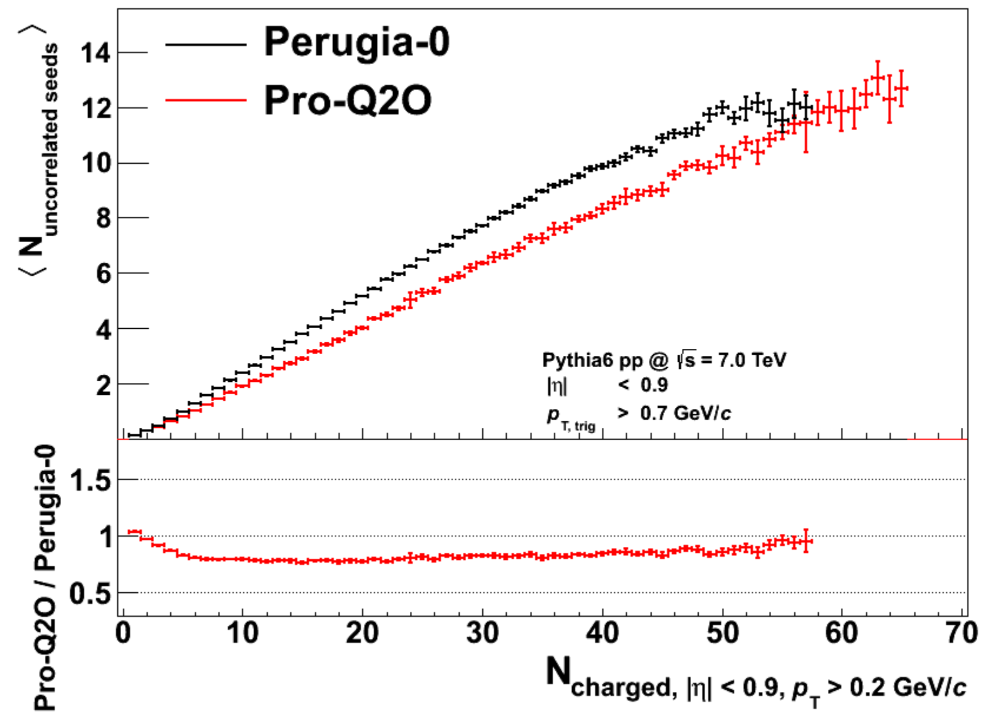
Near side

Away side



Trigger and Uncorrelated Seeds





$\langle N_{trigger} \rangle$

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

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

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):
$P(n)=(1-q)q^n$	$P(n)=\frac{\mu^n e^{-\mu}}{n!}$	$P(n)=\frac{-1}{\ln(1-p)}\frac{p^n}{n}$
$\langle n\rangle=\frac{q}{1-q}$	$\langle n\rangle=\mu$	$\langle n\rangle=\frac{-1}{\ln(1-p)}\frac{p}{(1-p)}$
$\langle n^2\rangle=2\langle n\rangle^2$	$\langle n^2\rangle=\mu^2+\mu$	$\langle n^2\rangle=\frac{\langle n\rangle}{(1-p)}$
$\frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right)=\langle n\rangle$	$\frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right)=\frac{\mu}{2}$	$\frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right)=\frac{p}{2(1-p)}$
$\frac{\langle n\rangle}{1-P(0)}-1=\langle n\rangle$	$\frac{\langle n\rangle}{1-P(0)}-1=\frac{\mu}{1-e^{-\mu}}-1=\frac{\mu}{2}+\frac{\mu^2}{12}+\ldots$	$\frac{\langle n\rangle}{1-P(0)}-1=\frac{p}{2(1-p)}+\frac{p^2}{12(1-p)}+p^3\ldots$
Relation is exact !		

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