Event-by-Event $\langle p_T \rangle$ Fluctuations of Identified Particles in pp Collisions at $\sqrt{s}$ = 13.6 TeV in Run-3 Data

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India ALICE-STAR Collaboration Meeting
Variable Energy Cyclotron Center
1-4 July, 2025

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Introduction

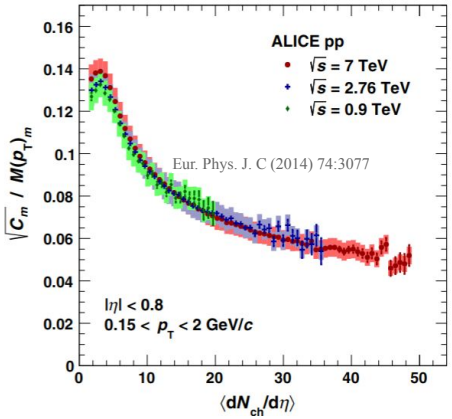
- **Dynamical fluctuations** → system dynamics and responses.
- In **high-energy collisions** (pp, heavy-ion), transverse momentum ($\boldsymbol{p_T}$) reveals system dynamics.
- **Mean transverse momentum ($\langle p_T \rangle$) fluctuations** → sensitive to collective flow, temperature, energy variations.
- **$\langle p_T \rangle$ fluctuations** stem from correlations: **hadronic interactions, resonance decays, jets**, etc.

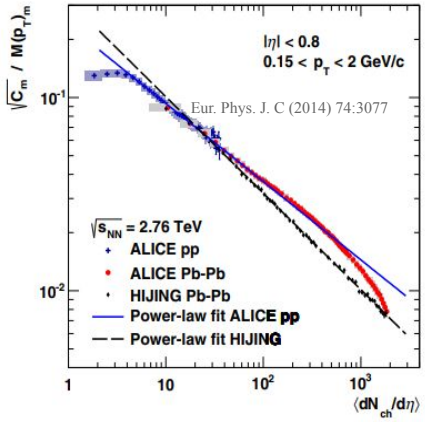
➡ **Why study event-by-event $\langle p_T \rangle$ fluctuations for identified particles?**

- **Probes particle production mechanisms**
  Helps distinguish between fragmentation, recombination, and coalescence processes.
- **Mass and species dependence**
  Different masses (pions, kaons, protons) lead to different $\langle p_T \rangle$ contributions; heavier particles tend to raise the mean $\langle p_T \rangle$.
- **Sensitive to composition fluctuations**
  Event-by-event variation in particle species affects the overall $\langle p_T \rangle$.
- **Energy and multiplicity effects**
  Higher energy or multiplicity enhances strange and baryon production, modifying $\langle p_T \rangle$ and mimicking heavy-ion behavior.

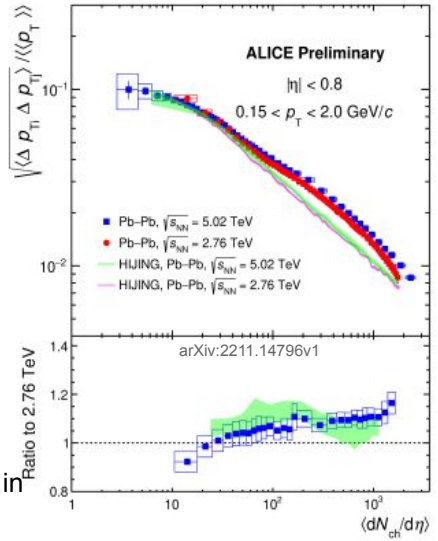
- Provides crucial insights not just for **pp physics** but also for understanding **heavy-ion collisions** .

Previous work





- In **peripheral Pb-Pb** collisions, fluctuations are in **good agreement** with **extrapolation of a power-law fit** to **pp.**
- At **larger multiplicities,** the Pb-Pb results **deviate** from the **pp extrapolation.**



- First multiplicity-dependent analysis of $\langle p_T \rangle$ dynamical fluctuations in pp collisions
- Evidence of **significant non-statistical fluctuations.**
- Observed **dilution with increasing multiplicity.**

- **Power law behavior** in three regions: 3-20, 20-300, >300 $\langle dN_{ch}/d\eta \rangle$.
- **Distinct mechanisms** from peripheral to central collisions.
- **Key factors**: collectivity onset, thermalization, initial energy density.
- **Collision energy dependence** in Pb–Pb as $\langle dN_{ch}/d\eta \rangle$ varies.

Event-by-event mean p_T fluctuations in pp and Pb–Pb collisions at the LHC, Stefan Heckel *et.al.*

Event-by-event fluctuations of mean transverse momentum in Pb–Pb and Xe–Xe collisions with ALICE, Tulika Tripathy, *et.al.*

Observable:

Two-particle correlator

$$\langle \Delta p_{\mathrm{T}i} \Delta p_{\mathrm{T}j} \rangle = \left\langle \frac{1}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)} \sum_{i \neq j} (p_{\mathrm{T}i} - \langle p_{\mathrm{T}} \rangle)(p_{\mathrm{T}j} - \langle p_{\mathrm{T}} \rangle) \right\rangle$$

$$\langle \Delta p_{\mathrm{T}i} \Delta p_{\mathrm{T}j} \rangle = \left\langle \frac{Q_1^2 - Q_2}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)} \right\rangle - \left\langle \frac{Q_1}{N_{\mathrm{ch}}} \right\rangle^2$$

$$\frac{\sqrt{\langle \Delta p_{\mathrm{T}i} \Delta p_{\mathrm{T}j} \rangle}}{\langle \langle p_{\mathrm{T}} \rangle \rangle}$$

→ Dynamical $\langle p_{\mathrm{T}} \rangle$ fluctuation relative to $\langle p_{\mathrm{T}} \rangle$

where,

$$\langle p_{\mathrm{T}} \rangle = \frac{1}{N_{\mathrm{ch}}} \sum_{i=1}^{N_{\mathrm{ch}}} p_{\mathrm{T}i} \quad \& \quad Q_n = \sum_{i=1}^{N_{\mathrm{ch}}} p_{\mathrm{T}i}$$

Robust to efficiency up to first order

- $p_{\mathrm{T}i}$: Transverse momentum of the i^{th} particle
- N_{ch}: Number of particles
- Angular brackets denote an average over events in a multiplicity class

Selection criterion:

System
- pp Collisions
- √s = 13.6 TeV

Data Set
- LHC22o_pass6_small
- # of events: **1.2 B**

MC Data Set
- LHC24f3c_fix
- # of events: **3.5 B**

Event Selection
- $|V_z| < 7$ cm
- sel8()
- kNoSameBunchPileup()
- kIsVertexITSTPC()

Track Selection
- $0.2 < p_T < 2.0$ GeV/c
- $|DCA_z| < 0.15$ cm
- $|\eta| < 0.8$
- isGlobalTrack()

Cuts	globalTrack
min number of crossed rows TPC	70
min ratio of crossed rows over findable clusters TPC	0.8
max chi2 per cluster TPC	4.0
max chi2 per cluster ITS	36.0
require TPC refit	true
require ITS refit	true
max DCA to vertex z	2.0
max DCA to vertex xy	$0.0105 * 0.035 / p_T^{1.1}$
cluster requirement ITS	Run 2 (Run 3): at least one hit in SPD (in 3 innermost ITS layers) [*]

PID selection:

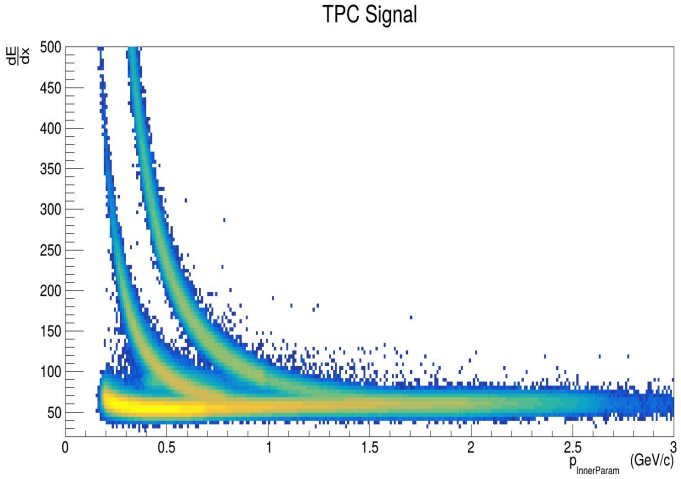
Electron rejection

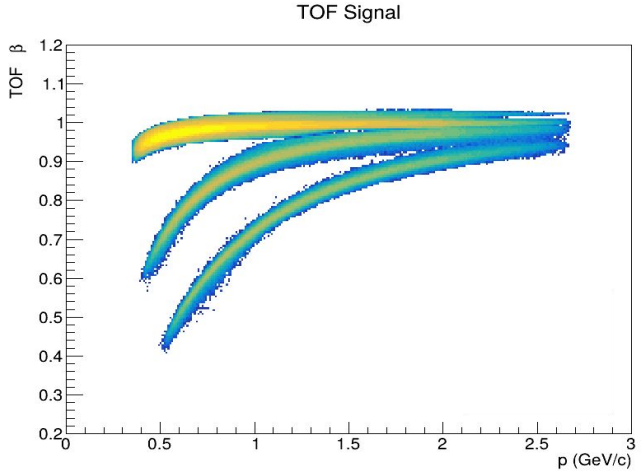
- $-3 < \mathrm{n}\sigma_{TPCe} < 5;\ |\mathrm{n}\sigma_{TPC}|_{\pi,k,p} > 3.0$

π, k , p identification

- Pions: $p_{\mathrm{T}} \geq 0.2$ GeV/c & $p_{\mathrm{Th}} > 0.7$ GeV/c
- Kaons: $p_{\mathrm{T}} \geq 0.3$ GeV/c & $p_{\mathrm{Th}} > 0.8$ GeV/c
- Protons: $p_{\mathrm{T}} \geq 0.4$ GeV/c & $p_{\mathrm{Th}} > 1.0$ GeV/c
- When track is not present in TOF
  - $p < p_{\mathrm{Th}}$
    - $|\mathrm{n}\sigma_{TPC}|_{sp} < 2.0;\ |\mathrm{n}\sigma_{TPC}|_{oth} > |\mathrm{n}\sigma_{TPC}|_{sp}$
- When track is present in TOF
  - $|\mathrm{n}\sigma_{TPC}|_{sp} < 2.0$ & $|\mathrm{n}\sigma_{TOF}|_{sp} < 2.0;\ |\mathrm{n}\sigma_{TOF}|_{oth} > |\mathrm{n}\sigma_{TOF}|_{sp}$

where *sp* represents any of the **π**, **K**, or **p** species, and *oth* represents any of the other two species not being *sp*

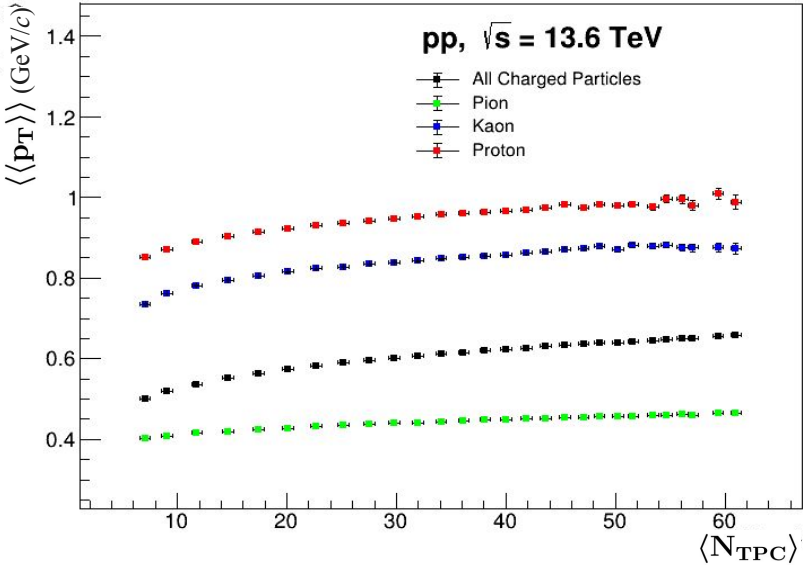




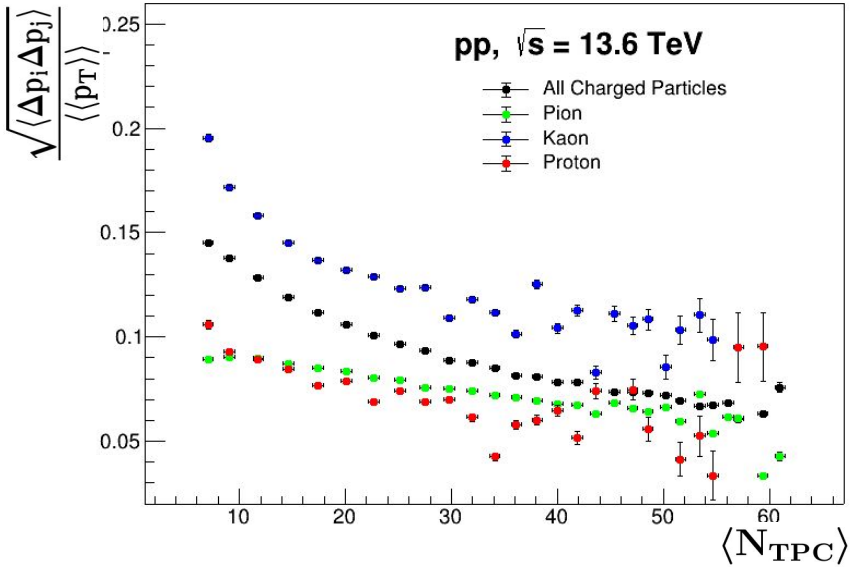
Results:

No efficiency correction

LHC22o_pass6_small



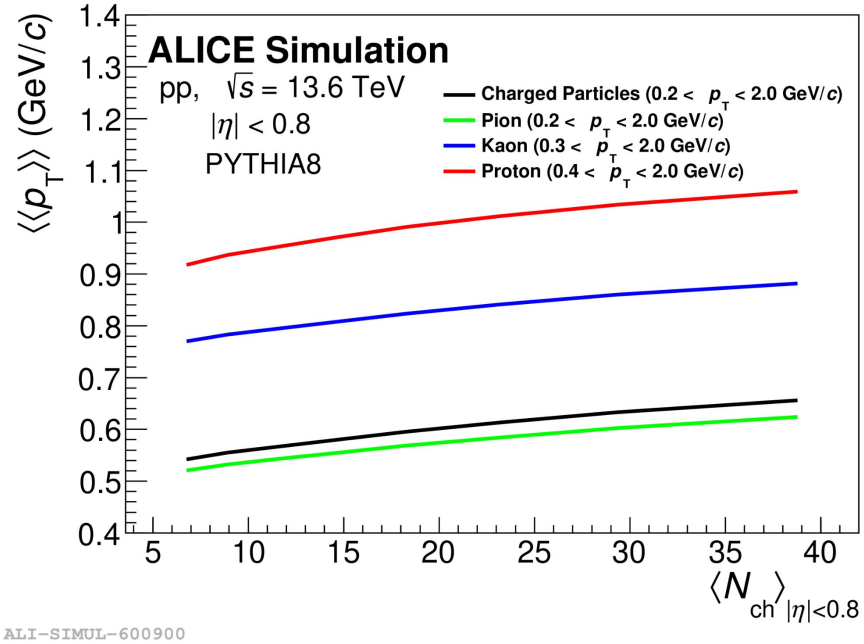
⟨p_T⟩ Distribution



Relative dynamical fluctuation

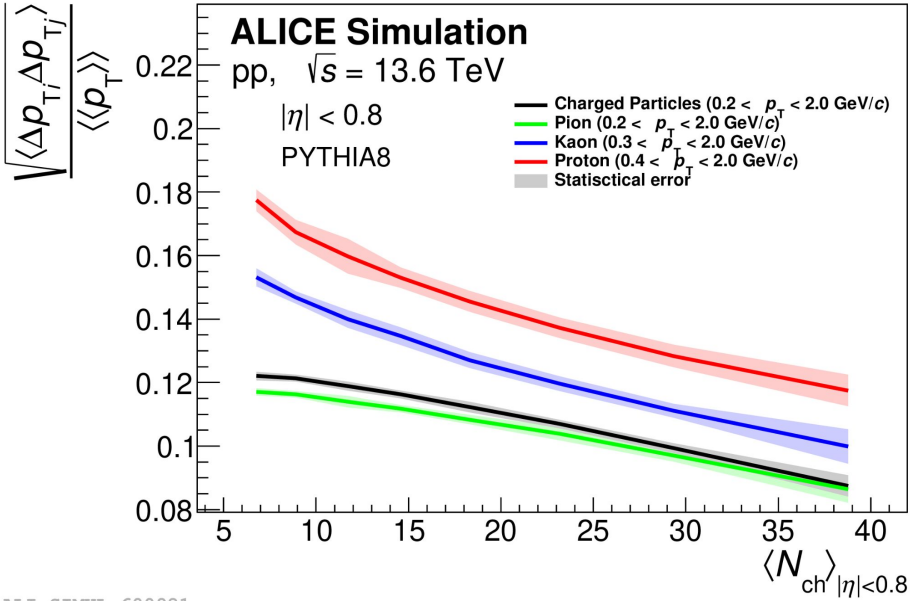
Simulation results:

LHC24f3c



ALI-SIMUL-600900

$\langle p_T \rangle$ Distribution



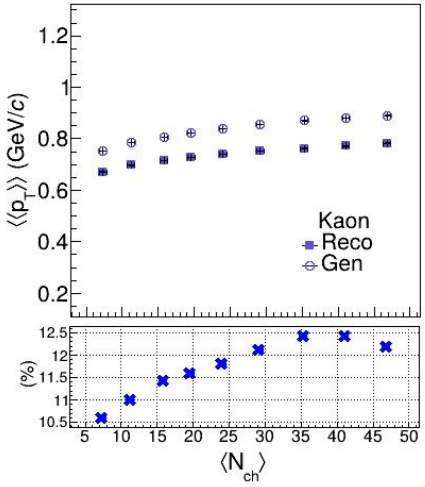
ALI-SIMUL-600921

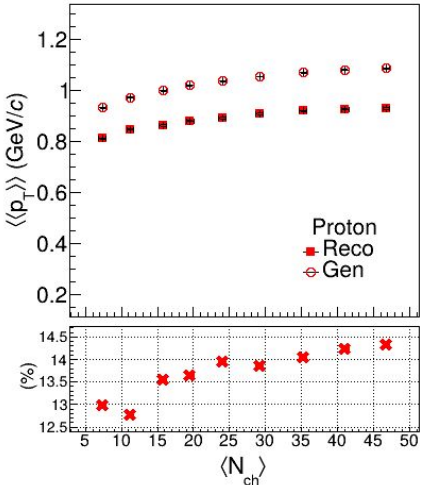
Relative dynamical fluctuation

MC closure test:

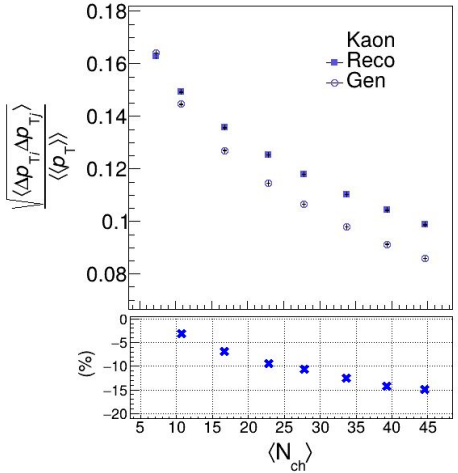
No efficiency correction

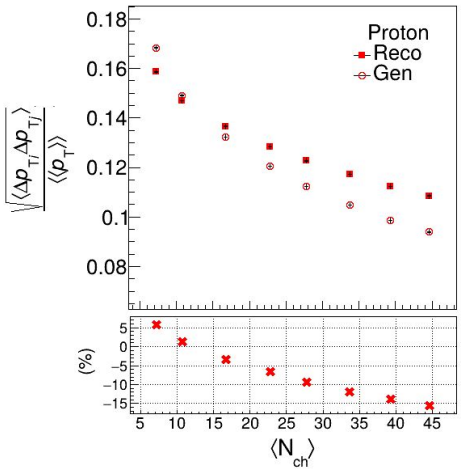
LHC24f3c_fix





$\langle p_T \rangle$ Distribution





Relative dynamical fluctuation

Simulation Summary:

- ⟨⟨p_T⟩⟩ **increases** with multiplicity and mass ordering in ⟨p_T⟩ → due to effects like string fragmentation, color reconnection and harder underlying parton scatterings and **radial flow-like** effects.
- **Correlation strength decreases** with multiplicity.
- **Low multiplicity** → soft processes dominate, leading to larger relative ⟨p_T⟩ fluctuations.
- **Higher multiplicity** → more particles, averaging out fluctuations, reducing correlations.

Current Status

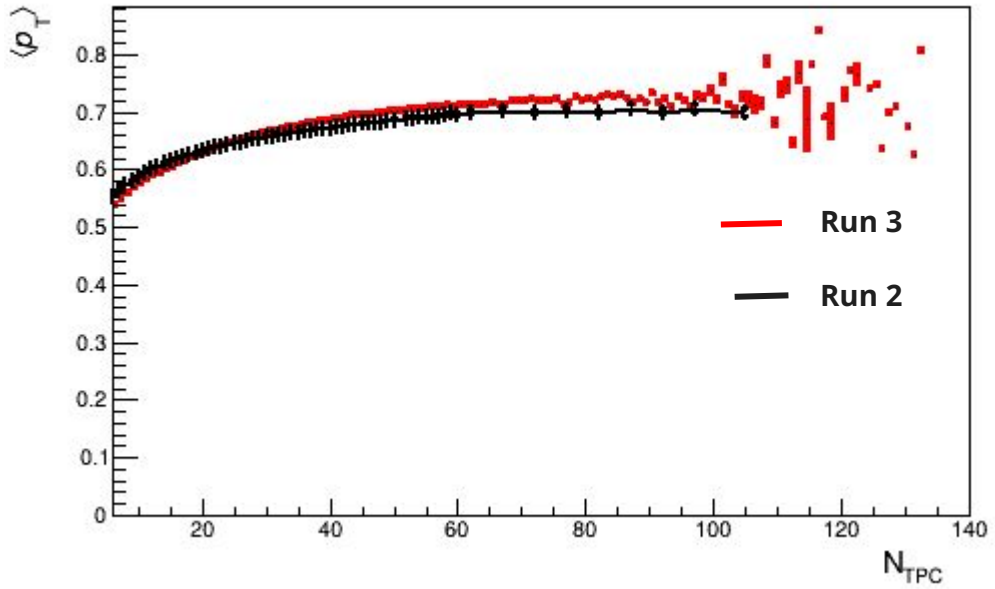
- The Monte Carlo (MC) closure test for two-particle correlator is in progress.

Future Work

- Obtain the efficiency-corrected two-particle correlator after completing the MC closure test.
- Conduct systematic studies.

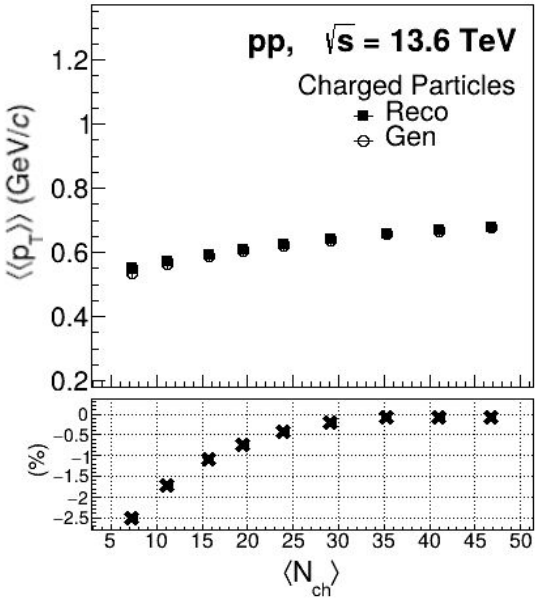
Backup

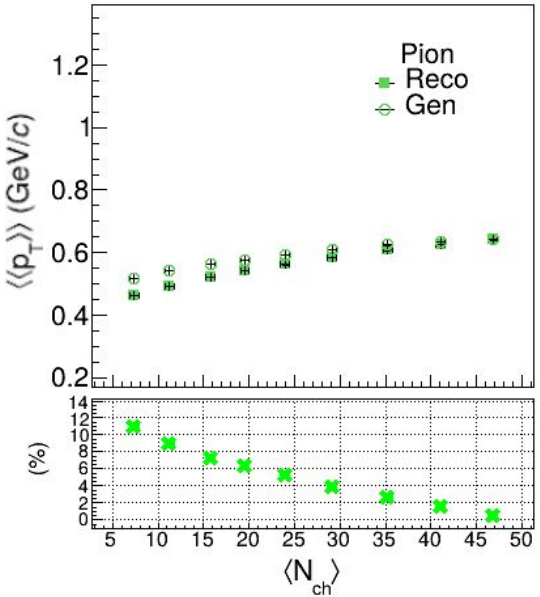
$\langle p_T \rangle$ Distribution



No efficiency correction

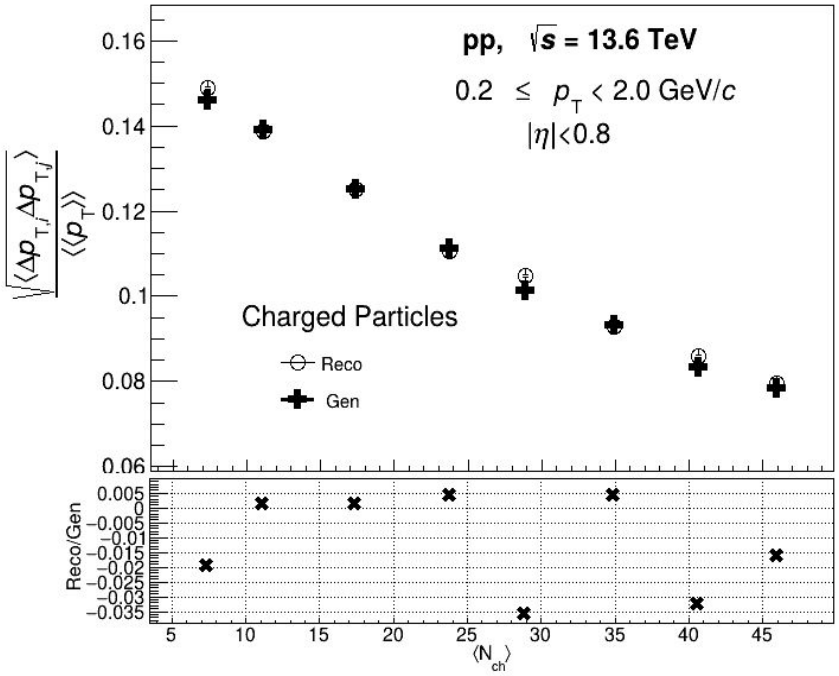
$\langle p_T \rangle$ Distributions (MC Closure test)





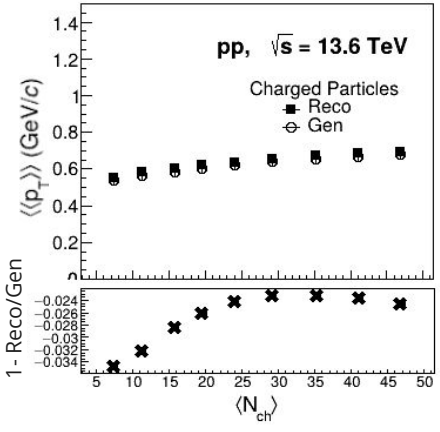
No efficiency correction

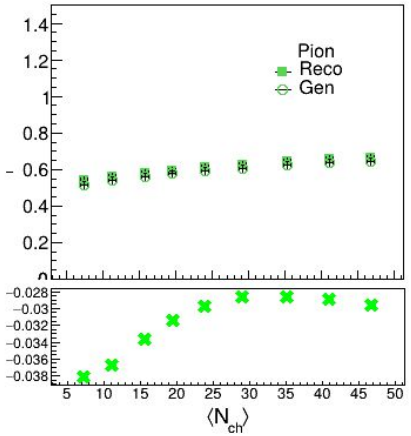
Relative two-particle correlator

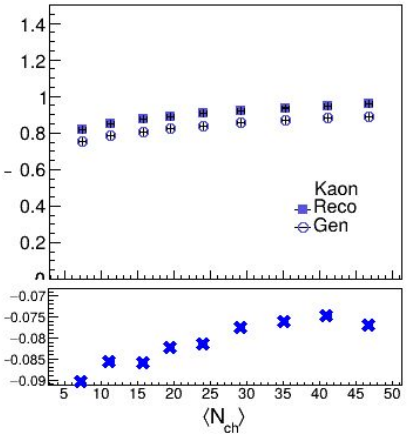


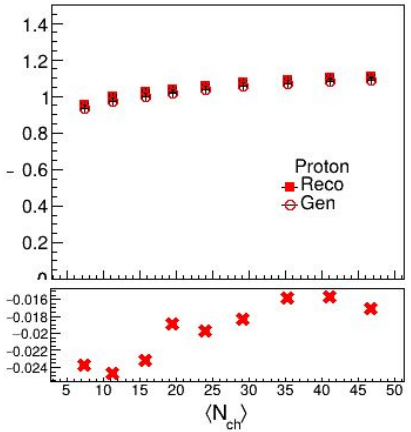
No efficiency correction

<p_T> Distributions (Only PDG)

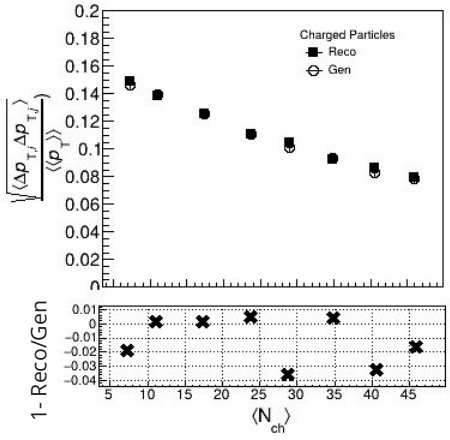


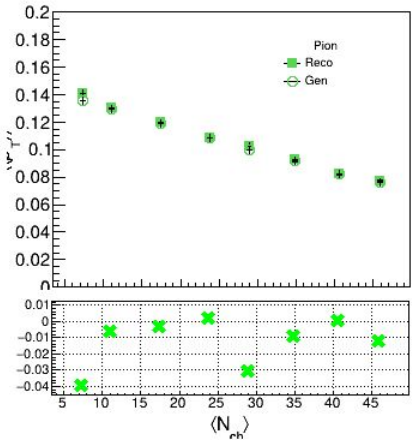


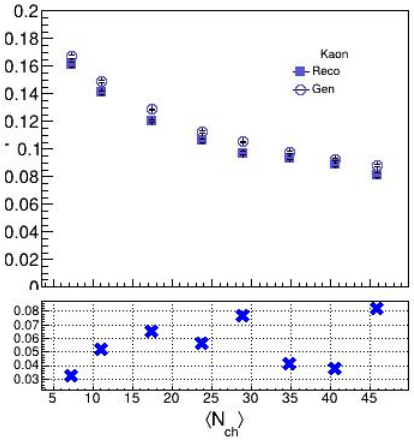


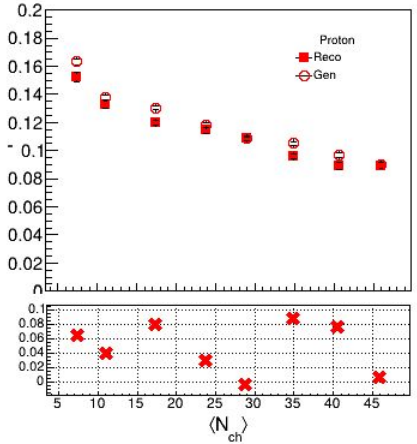


Relative two-particle correlator (Only PDG code)









No efficiency correction