Small system physics from CMS: energy and multiplicity dependence of particle correlations

Arthur M. Moraes
Centro Brasileiro de Pesquisas Físicas - CBPF
(on behalf of the CMS Collaboration)

10th International Workshop on Multiple Partonic Interactions at the LHC

Outline:

- *Introduction: QCD at the LHC*
- *Charged particle densities: pp, pA*
- *$\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$*
- *Two-particle and multi-particle angular correlations*
- *Summary*

Disclaimer: obviously there are many results we will not be able to show in this talk! This talk is an attempt to present some of the "latest" results on QCD measurements from CMS. For a complete list of results, please check:

http://cms-results.web.cern.ch/cms-results/public-results/publications/

The Large Hadron Collider

QCD measurements at the LHC:

- test predictions of QCD phenomena at high(est) energies with large statistical samples of rare processes;
- detector allow measurements with unprecedented precision and fiducial coverage (wide x-coverage; unprecedented high-Q^2 interactions)

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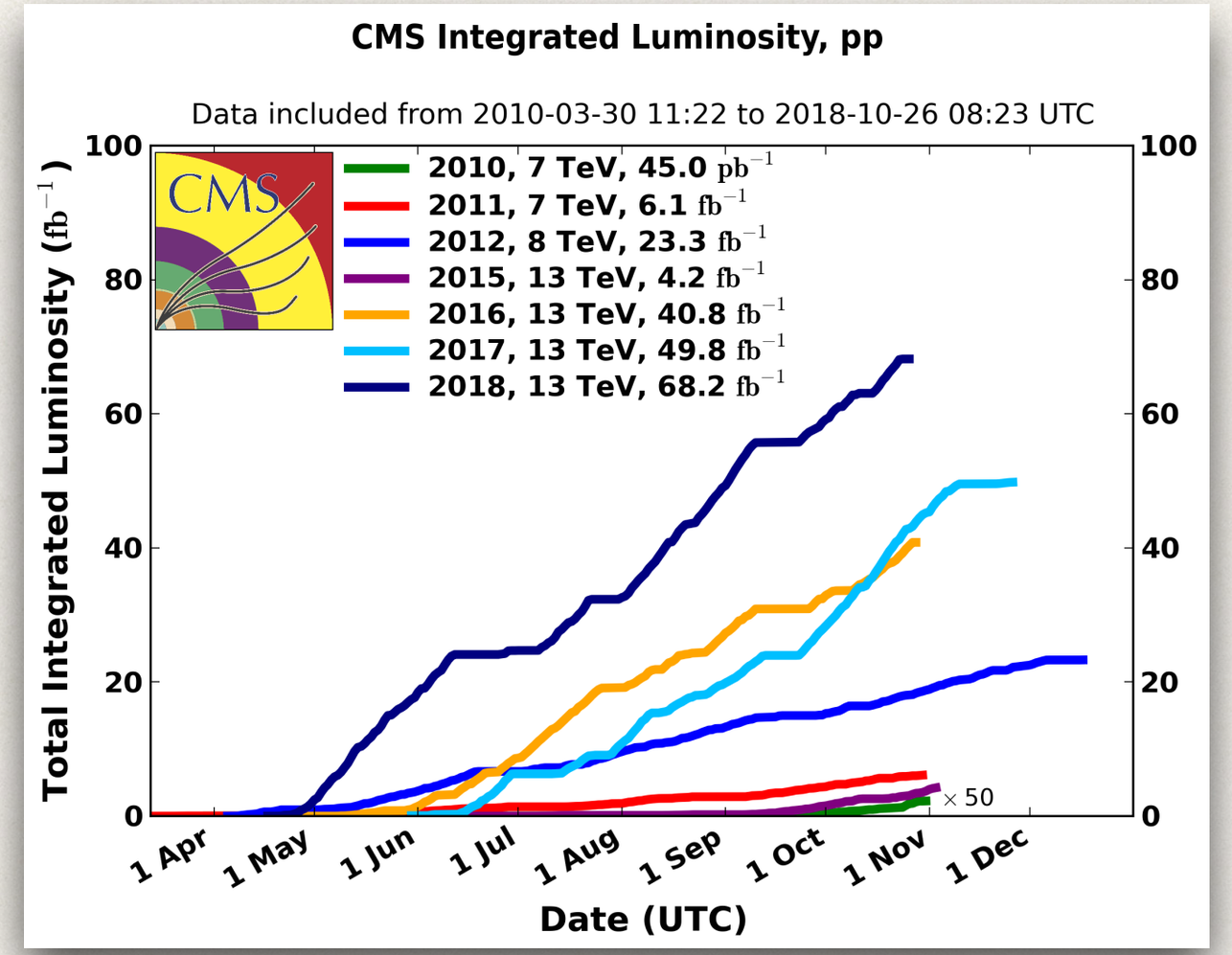
The Large Hadron Collider: pp collisions collected by CMS



The LHC has also delivered several runs on pA and AA collisions.

https://lpc.web.cern.ch

√s=0.9 TeV

√s=7 TeV & 8 TeV

"Long Shutdown 1"

√s=13 TeV

"Long Shutdown 2"

2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

Run 1

Run 2

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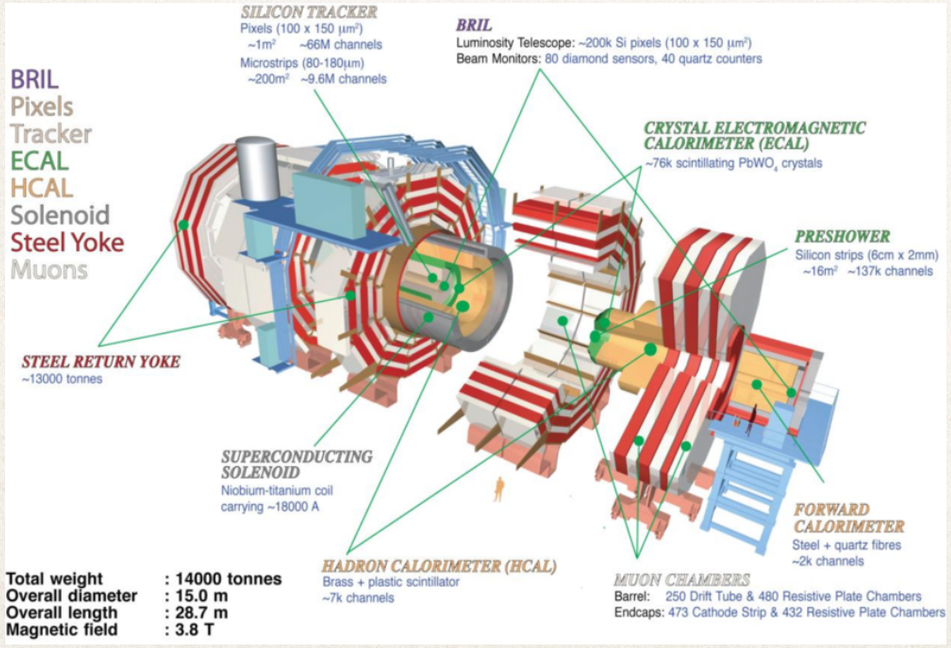
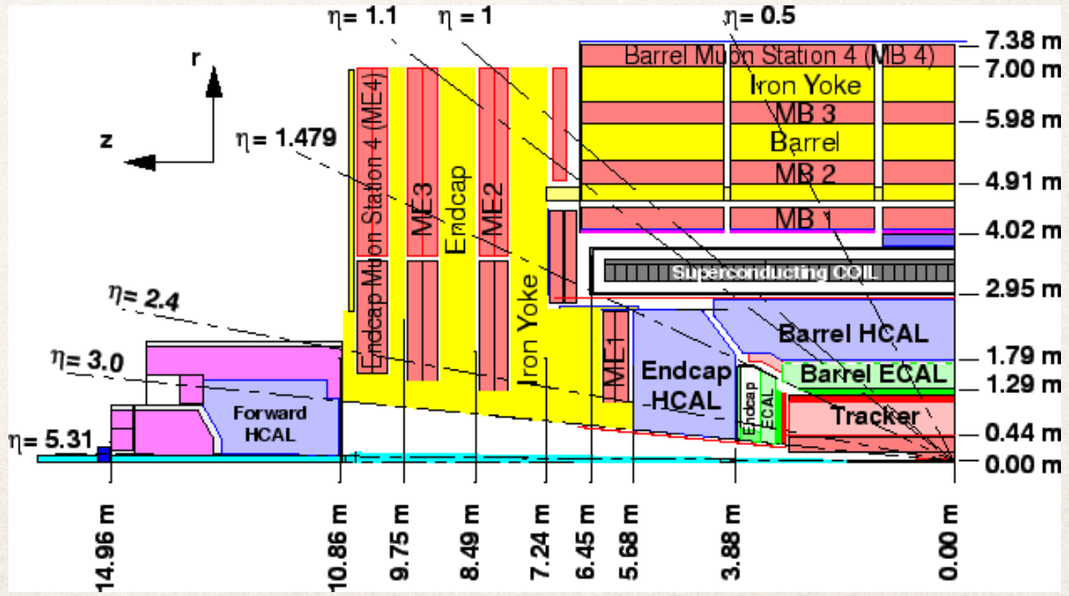
Charged Particle Density: pp

- Measurement of charged particle spectra in minimum-bias events from proton–proton collisions at $\sqrt{s}$ = 13 TeV
  - Pseudorapidity (η), transverse momentum (p_T), and multiplicity distributions are measured in the pseudorapidity range $|\eta| < 2.4$ for charged particles with transverse momenta satisfying $p_T > 0.5$ GeV in pp collisions at $\sqrt{s}$ = 13 TeV.
  - In order to minimize the effect of pileup, the data considered in the analysis were collected in a **special run** in summer 2015 with an average number of pp interactions per bunch crossing of **1.3**.
  - Different event classes are defined based on activity in the HF calorimeters by requiring the presence of at least one tower with an energy above the threshold value of 5 GeV in the fiducial acceptance region, $3 < |\eta| < 5$.





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Charged Particle Density: pp

- Measurements are presented in three different event categories:

a) **Inelastic**: the most inclusive of the categories corresponds to an inelastic pp data set,
b) **NSD**: subsets of the inelastic sample that is depleted in single diffractive dissociation events.
c) **SD**: subsets of the inelastic sample that is enhanced in single diffractive dissociation events.

- An **inelastic sample** consists of events with activity on at least one side of the calorimeters, whereas an **NSD-enhanced sample** contains those with calorimeter activity on both sides. An **SD-enhanced sample** is defined by requiring activity on only one side of the calorimeters, with a veto condition being applied to the other side.

- The measurements are compared to predictions from Monte Carlo (MC) event generators used to describe high-energy hadronic interactions in collider and cosmic-ray physics.

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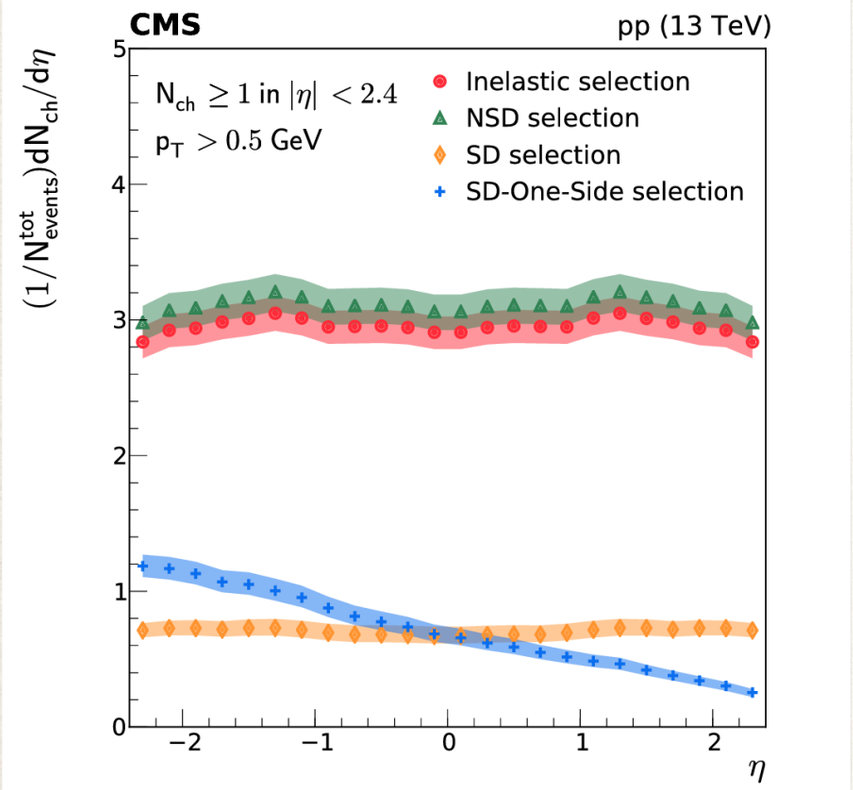
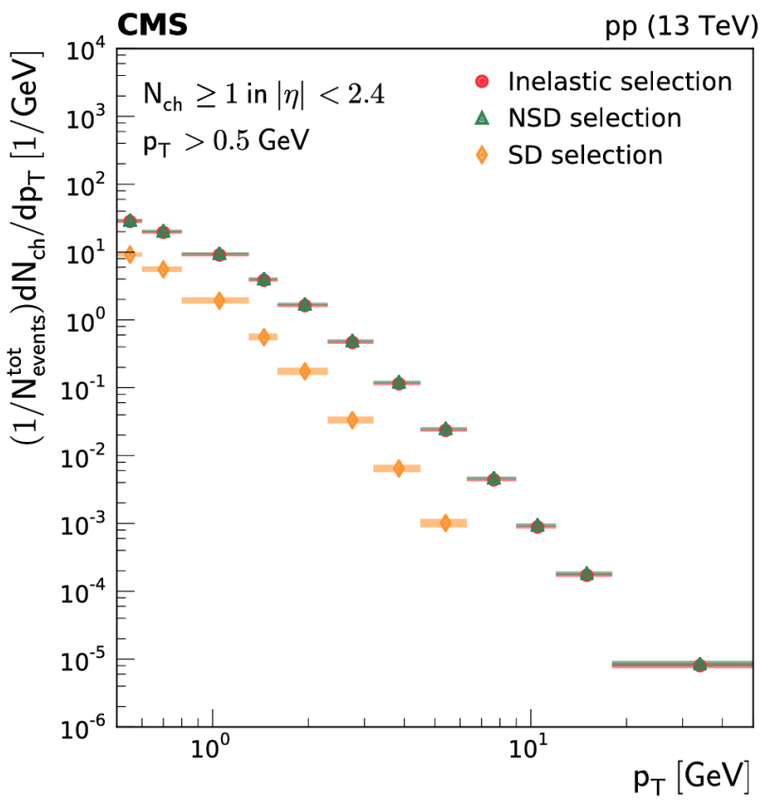
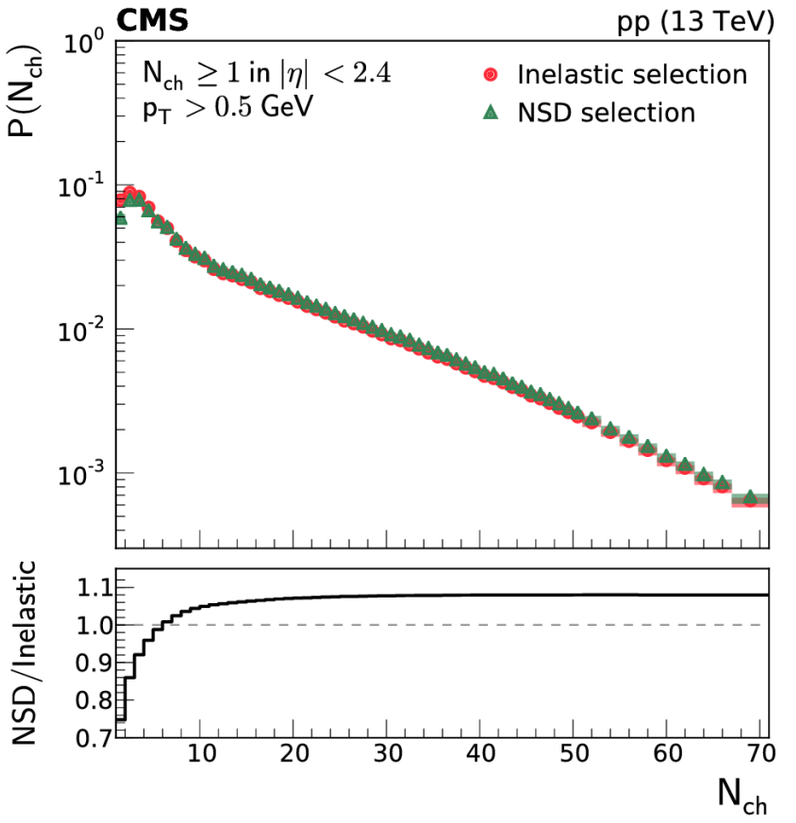
Charged Particle Density: pp







Pseudorapidity (η), p_T and multiplicity of charged particles per event for the inelastic (circles), NSD-enhanced (triangles), SD-enhanced (diamonds), and SD-One-Side enhanced (crosses) event samples. The band encompassing the data points represent the total systematic uncertainty, while the statistical uncertainty is included as a vertical bar for each data point.

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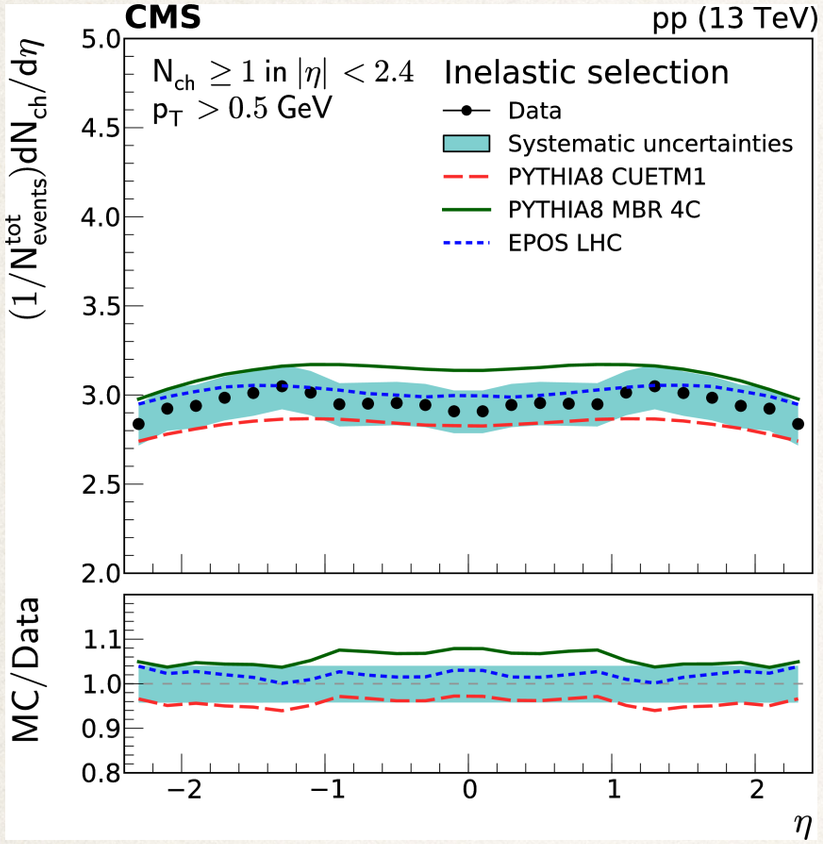
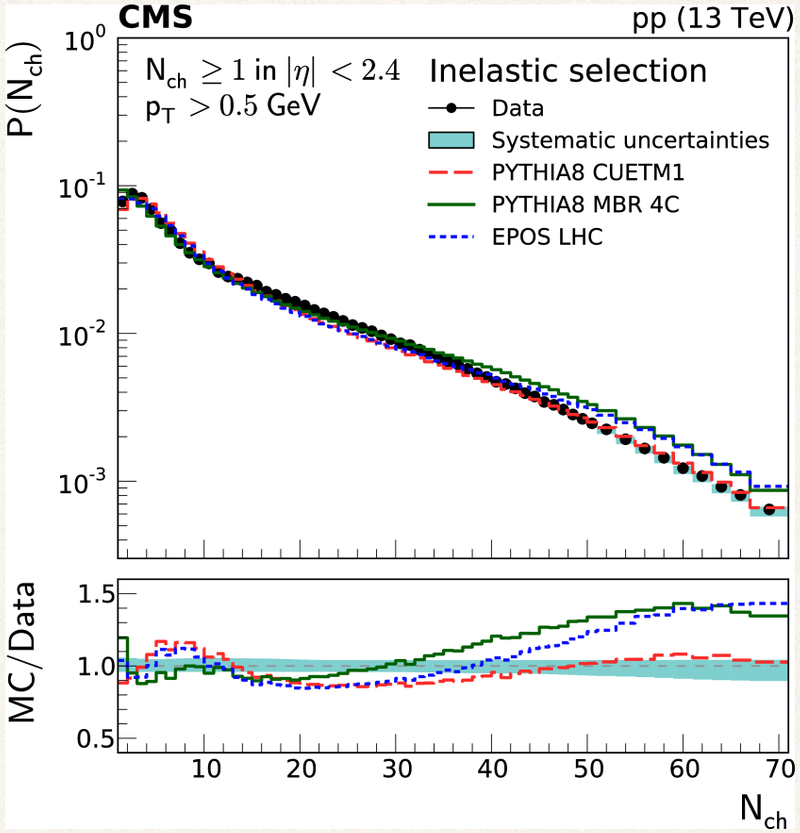
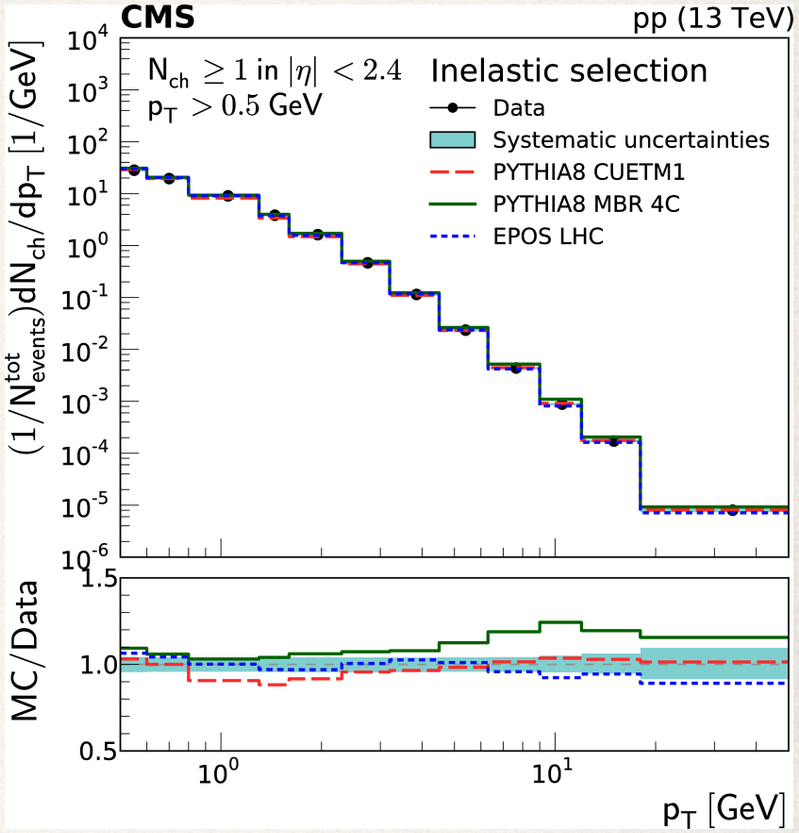
Charged Particle Density: pp







Pseudorapidity (η), p_T and multiplicity of charged particles per event for the inelastic event samples. The measurements are compared to the predictions of the PYTHIA8 CUETM1 (long dashes), PYTHIA8 MBR4C (continuous line), and EPOS LHC (short dashes) event generators.

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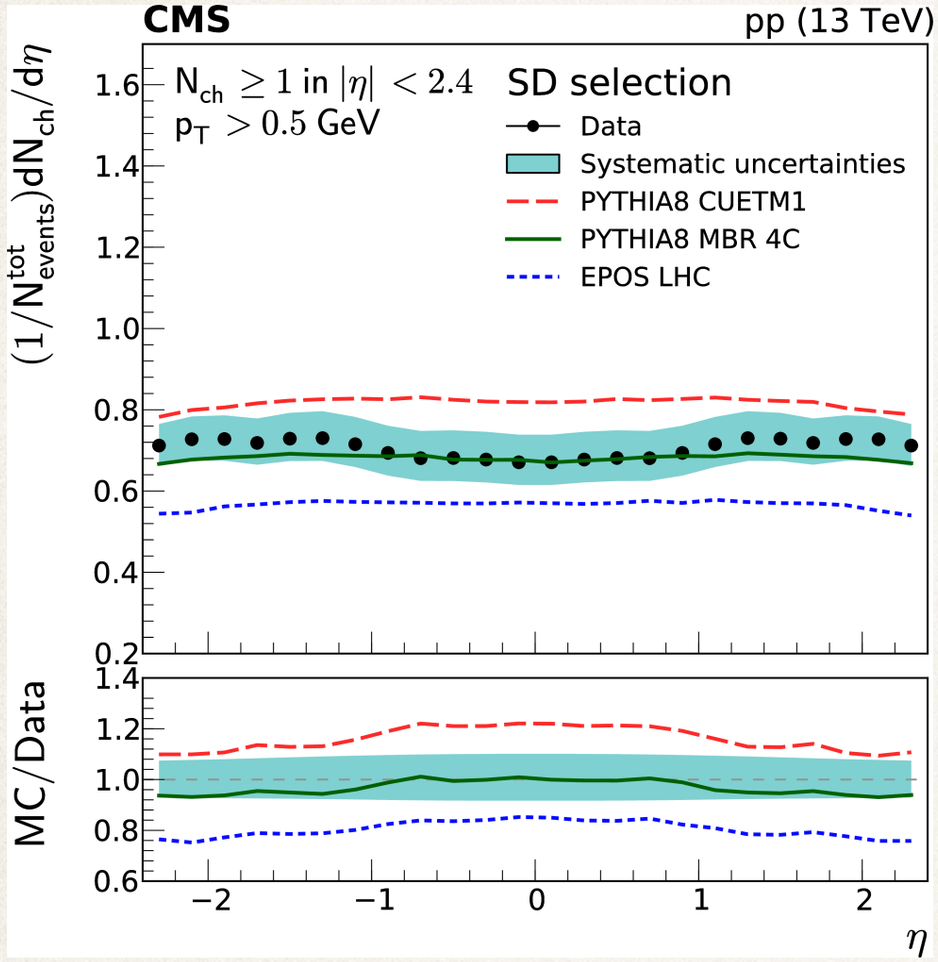
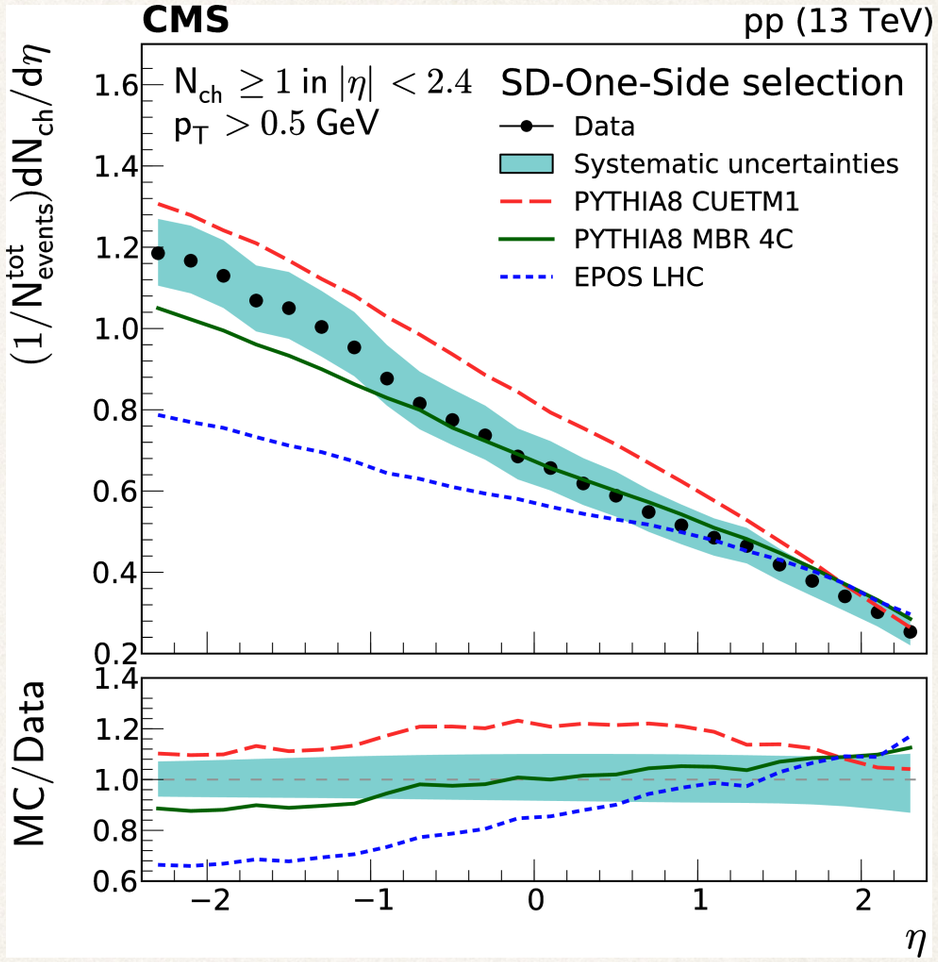
Charged Particle Density: pp





Pseudorapidity (η) of charged particles per event for the SD-enhanced event sample. The measurements are compared to the predictions of the PYTHIA8 CUETM1 (long dashes), PYTHIA8 MBR4C (continuous line), and EPOS LHC (short dashes) event generators.

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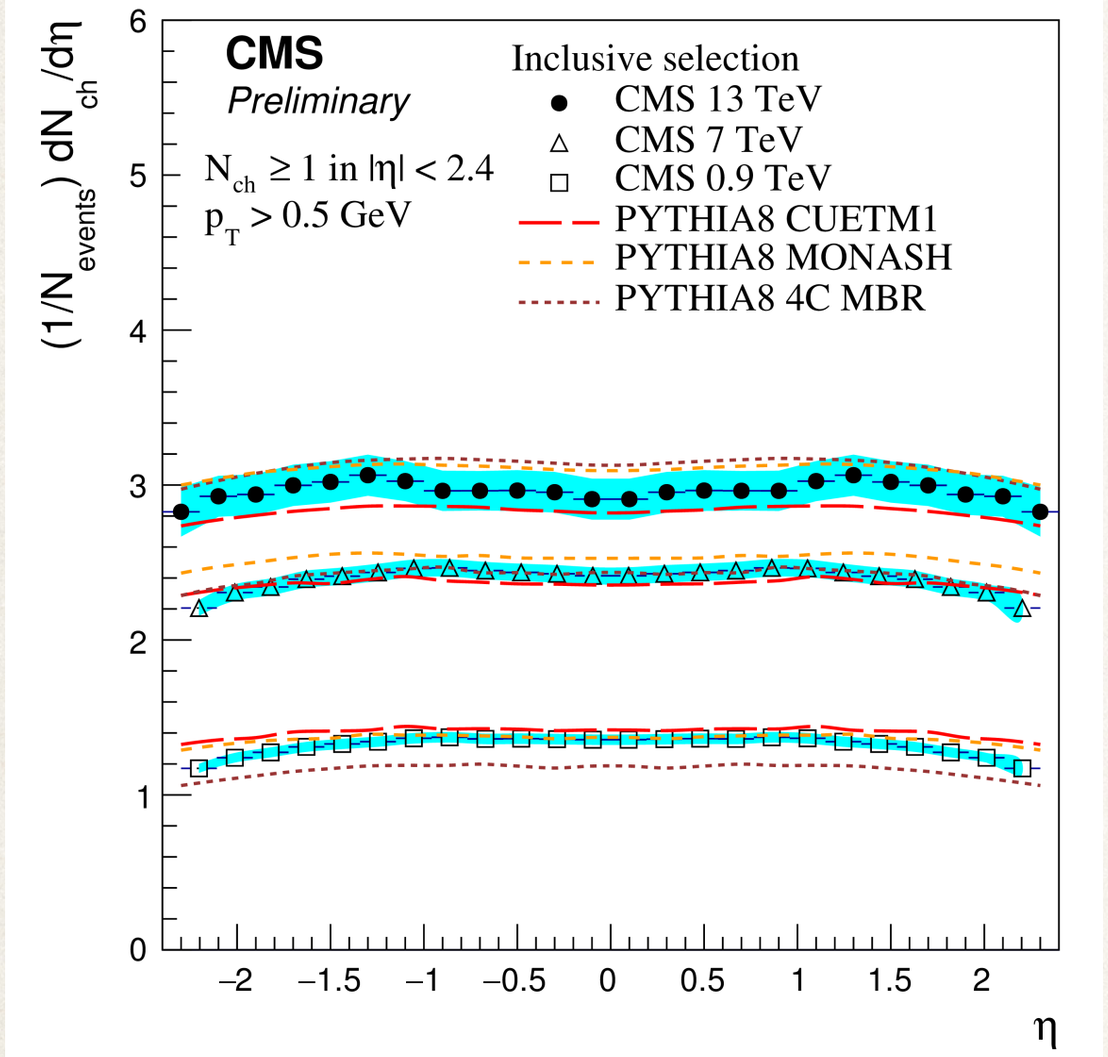
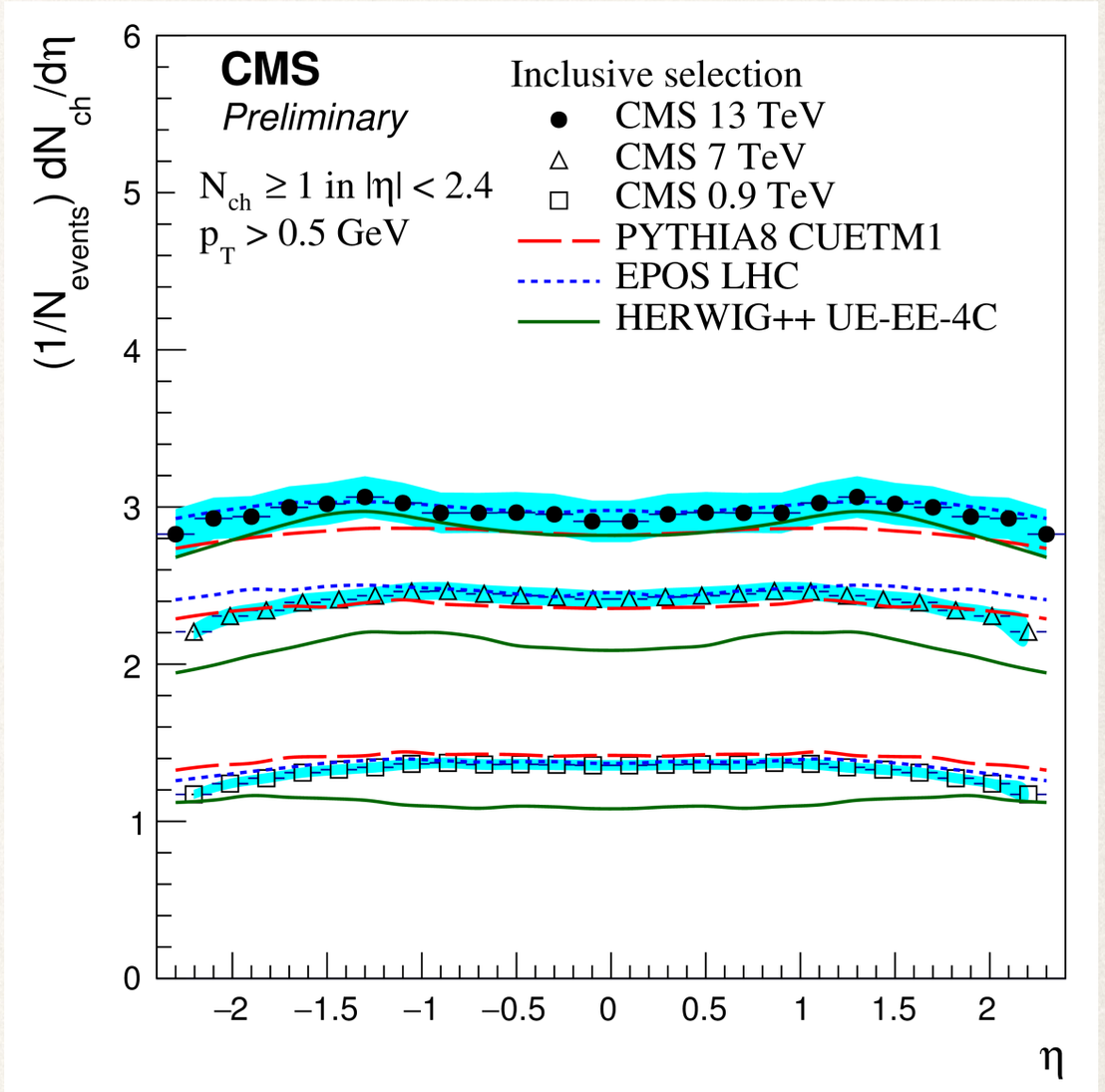
Charged Particle Density: pp

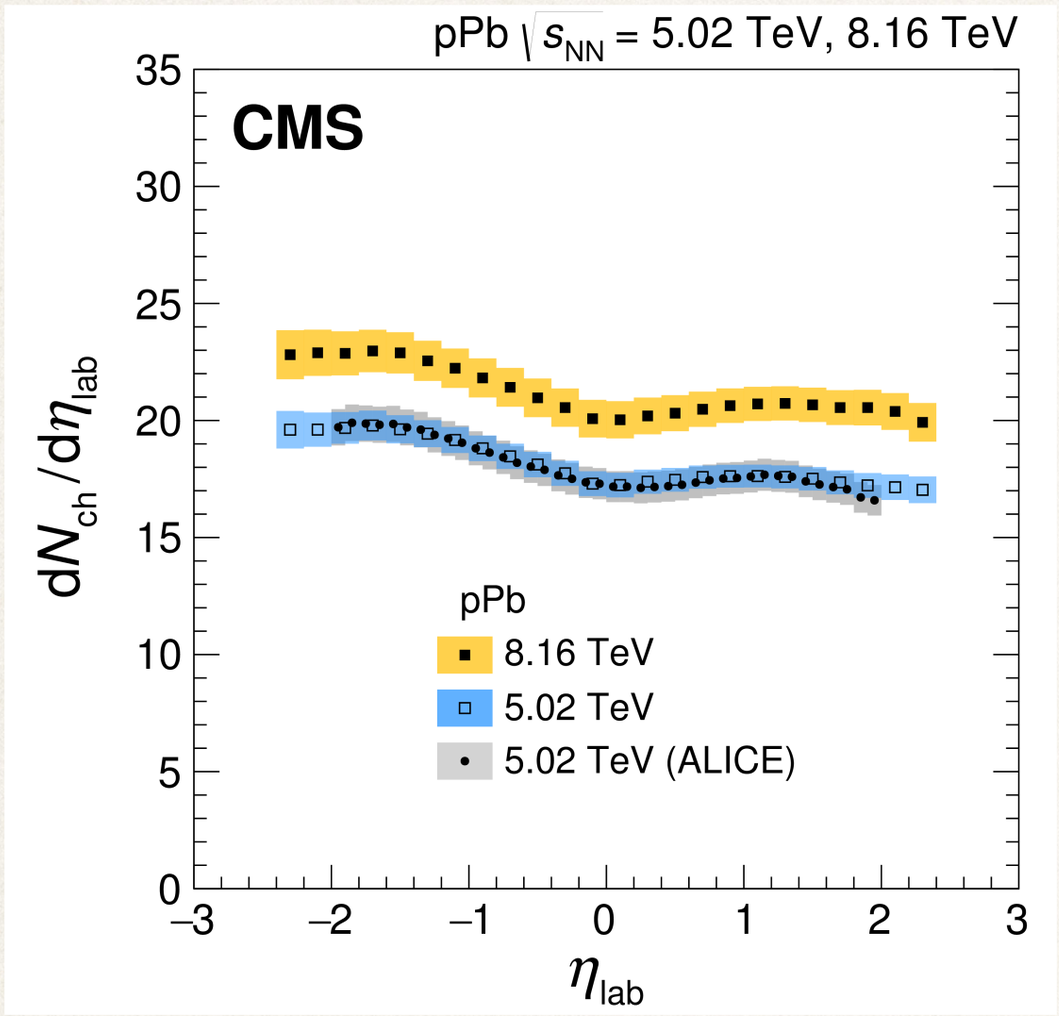
CMS-PAS-FSQ-15-008



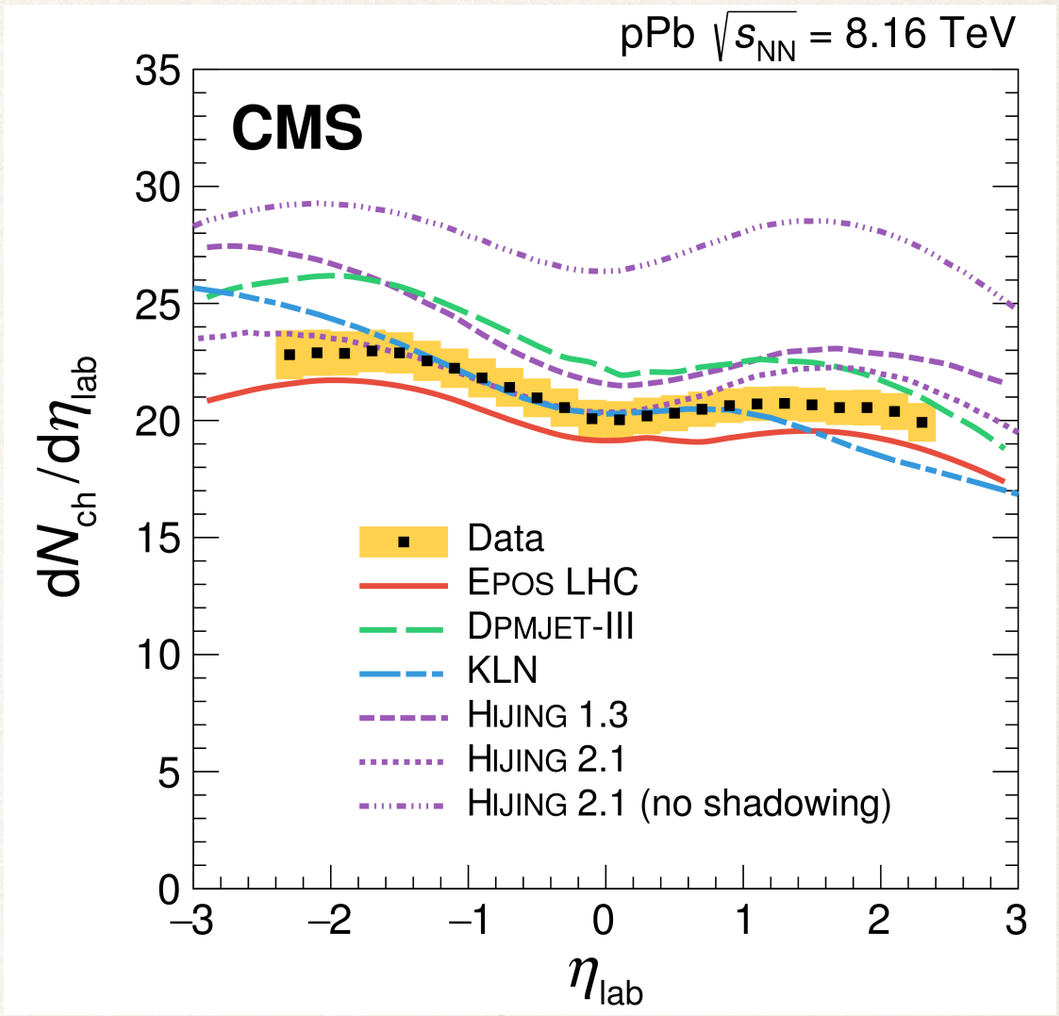


Charged particle densities at different c.m. energies (same phase space selections): Important input to generator tuning!

Charged Particle Density: pA



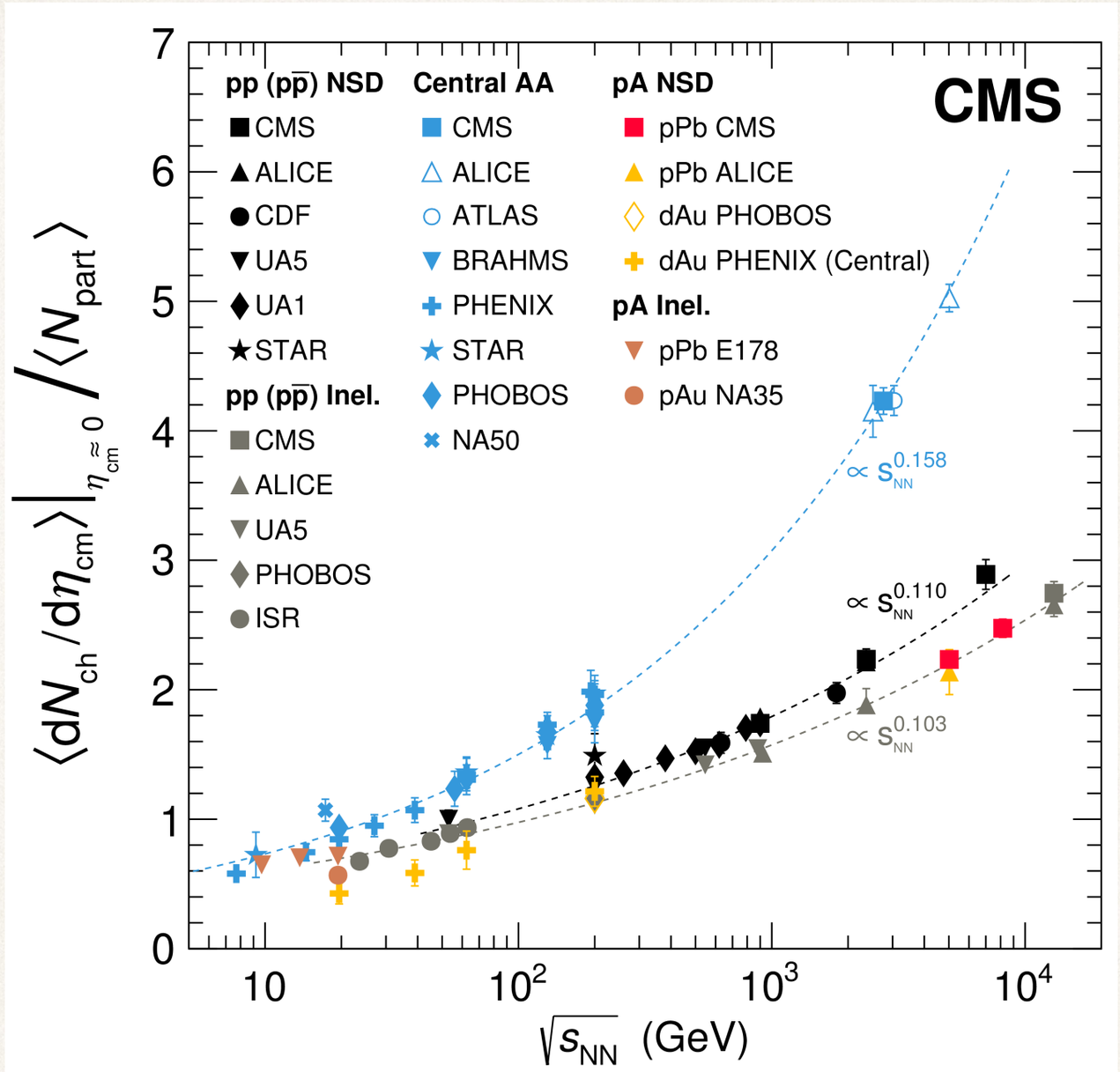
Distributions of the pseudorapidity density of charged hadrons in the region $|\eta_{lab}| < 2.4$ in NSD pPb collisions at $\sqrt{s}NN$= 5.02 (open squares) and 8.16TeV (full squares). The measurement at 5.02 TeV by the ALICE Collaboration is shown as filled circles. **The proton beam goes in the positive η_{lab} direction.**



Distributions of the pseudorapidity density of charged hadrons in the region $|\eta_{lab}| < 2.4$ for NSD pPb collisions at 8.16 TeV (squares) compared to predictions from the MC event generators EPOS LHC (v3400), HIJING (versions 1.3 and 2.1), and DPMJET- III, as well as from the KLN model. **The proton beam goes in the positive η_{lab} direction.**

JHEP 01 (2018) 045

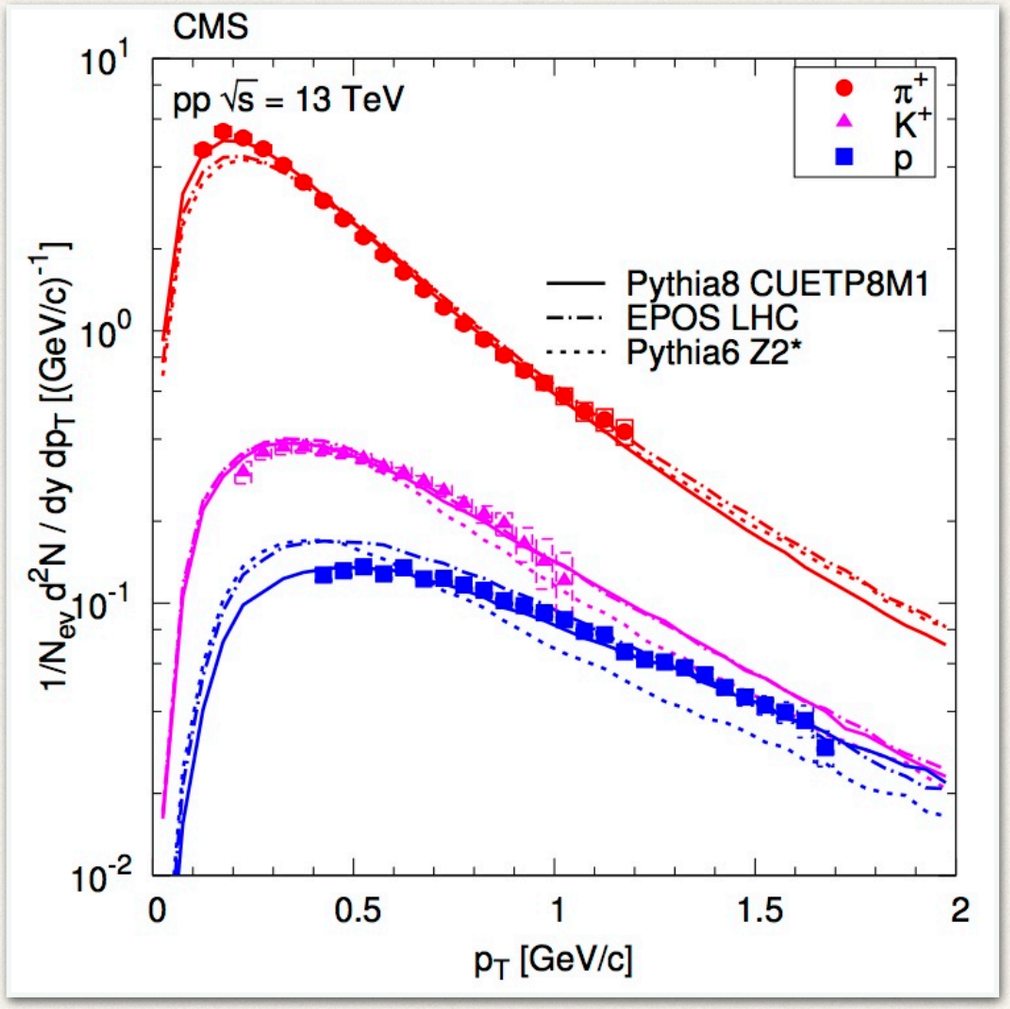
Charged Particle Density: pA



Comparison of the measured $dN_{ch}/d\eta_{cm}$ at midrapidity, scaled by the number of participating nucleons (N_{part}) in pPb, pAu, dAu and central heavy ion collisions, as well as NSD and inelastic pp collisions. The dashed curves, included to guide the eye, correspond to a fit to the data points.

JHEP 01 (2018) 045

Measurement of charged pion, kaon, and proton production in proton-proton collisions at $\sqrt{s}$ = 13 TeV



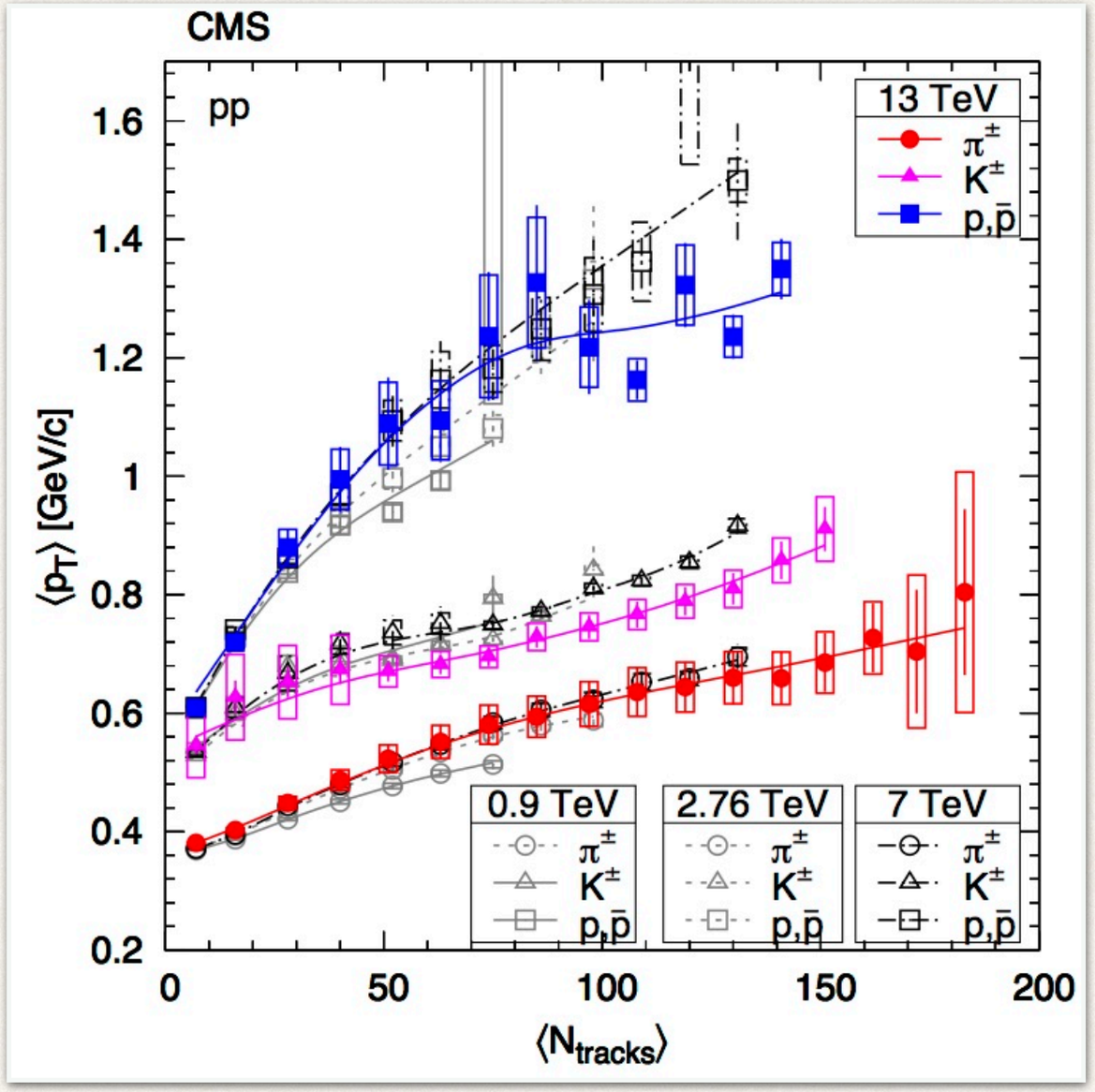
Transverse momentum spectra have been measured for different charged hadron species produced in inelastic pp collisions at $\sqrt{s}$=13 TeV.

Charged pions, kaons, and protons are identified from the energy deposited in the silicon tracker and the reconstructed particle trajectory.

The yields of such hadrons at rapidities $|y|<1$ are studied as a function of the event charged particle multiplicity measured in the pseudorapidity range $|\eta|<2.4$.

PRD 96 (2017) 112003

Measurement of charged pion, kaon, and proton production in proton-proton collisions at $\sqrt{s}$ = 13 TeV

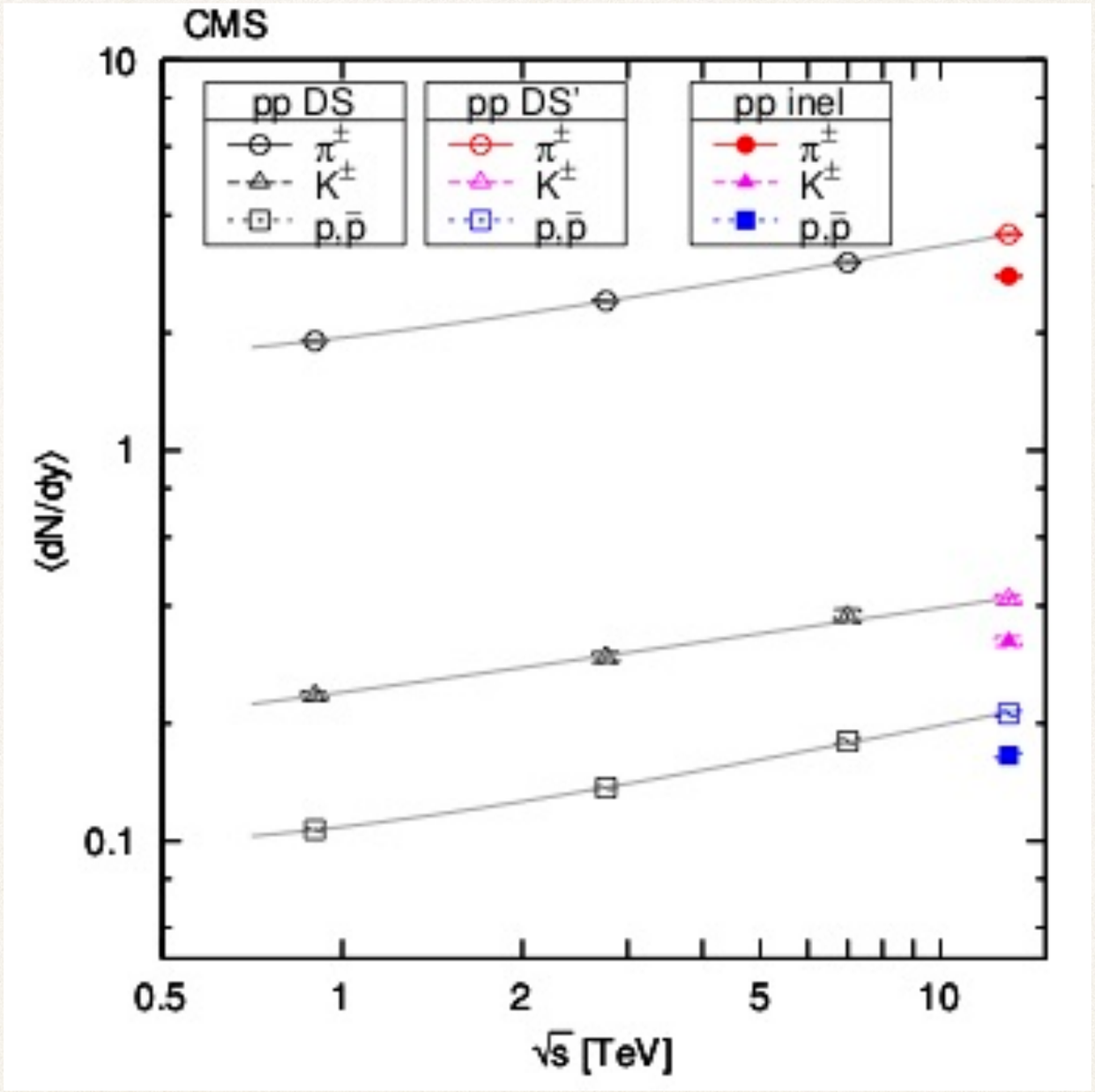


As observed in lower-energy data, the <pT> and the ratios of particle yields are strongly correlated with event particle multiplicity.

No significant dependence with the c.m. energy is observed.

PRD 96 (2017) 112003

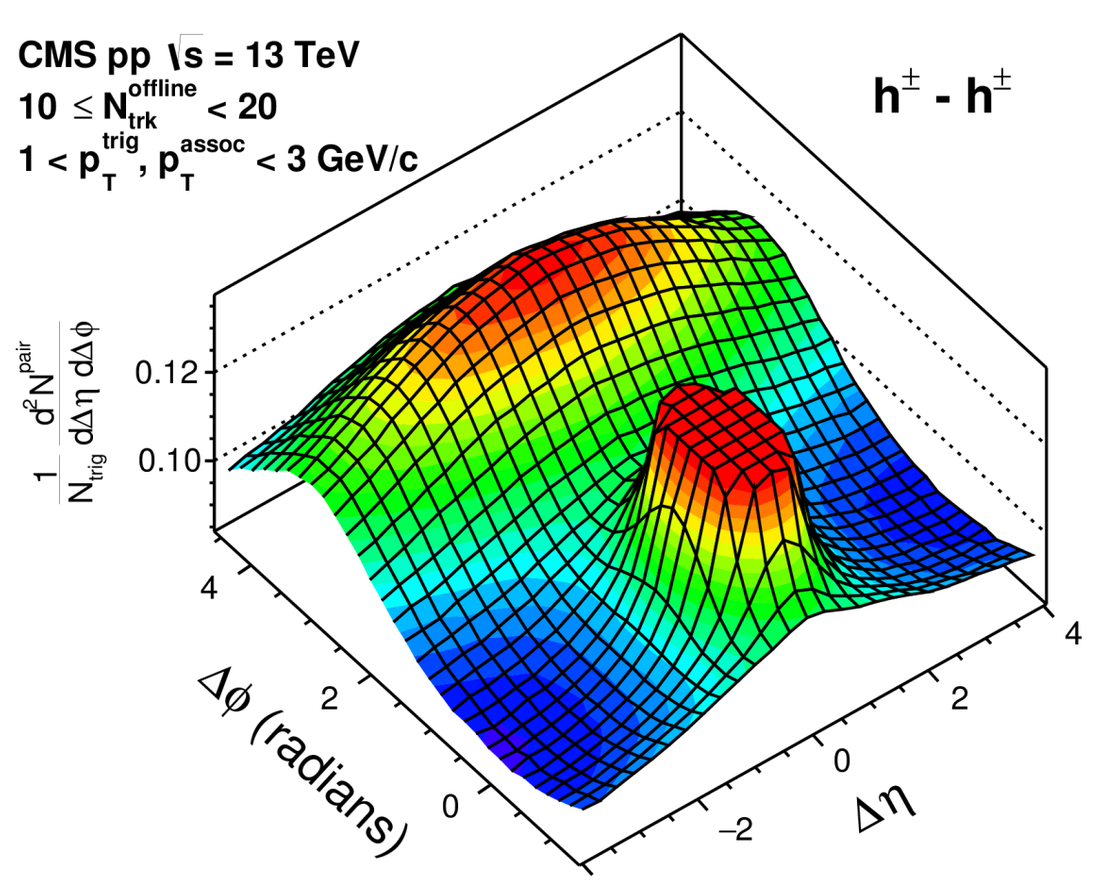
Measurement of charged pion, kaon, and proton production in proton-proton collisions at $\sqrt{s}$ = 13 TeV

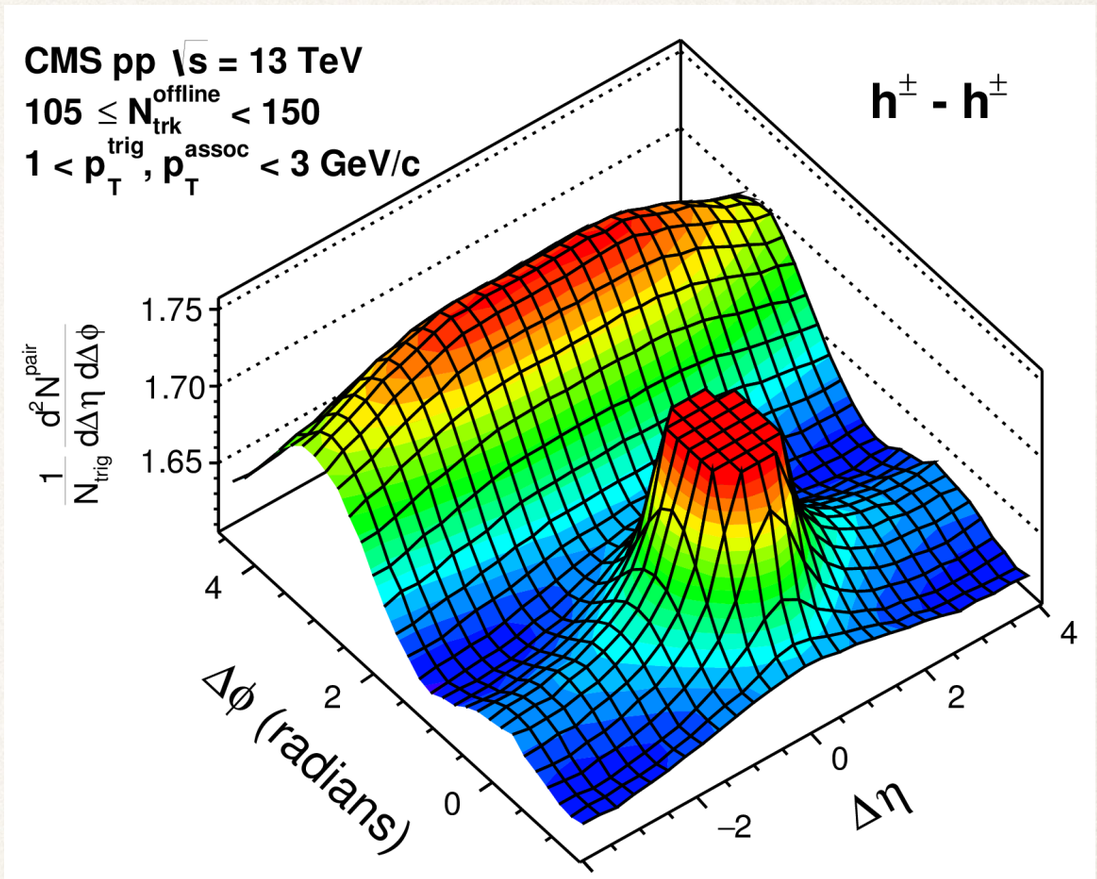


Average rapidity densities <dN/dy> for |y| < 1 as functions of center-of-mass energy for pp collisions (with data at 0.9, 2.76, and 7 TeV), for charge-averaged pions, kaons, and protons. The pp DS' results at 13 TeV have been extrapolated from the inelastic values using simulation.

PRD 96 (2017) 112003

Measurements of two-particle and multi-particle angular correlations in pp collisions

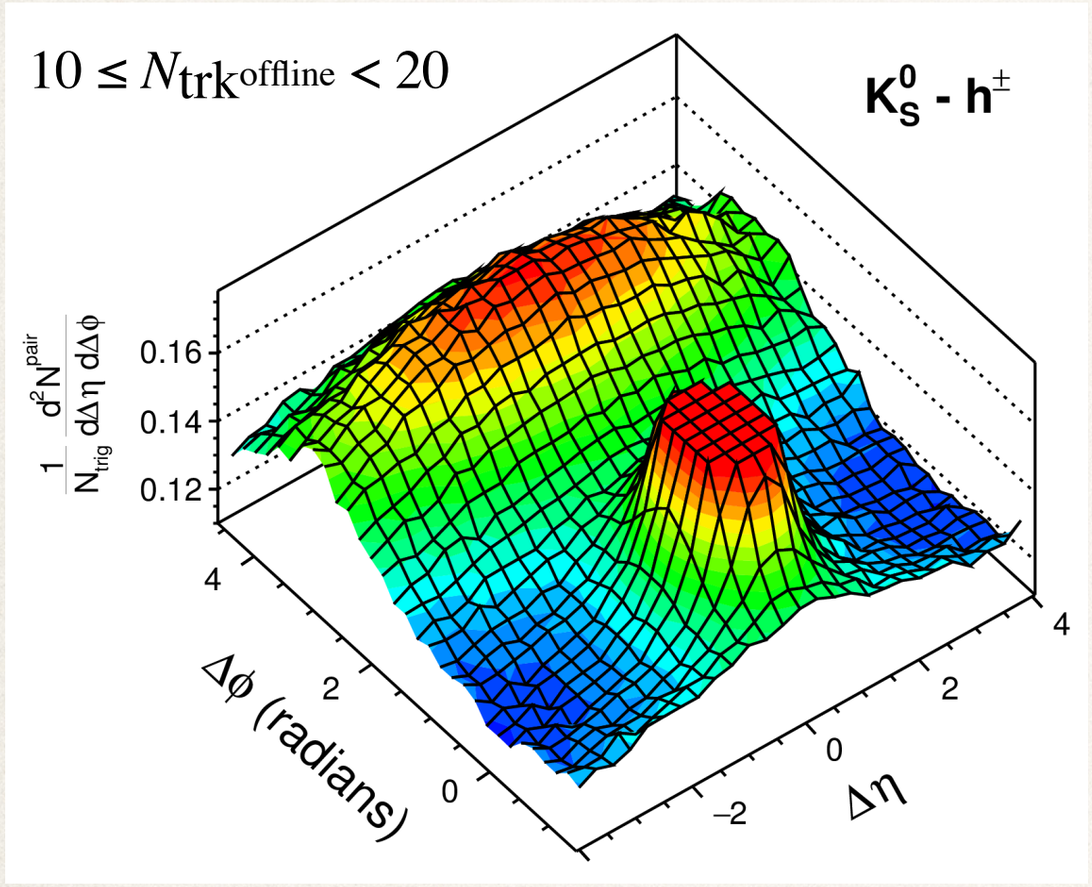


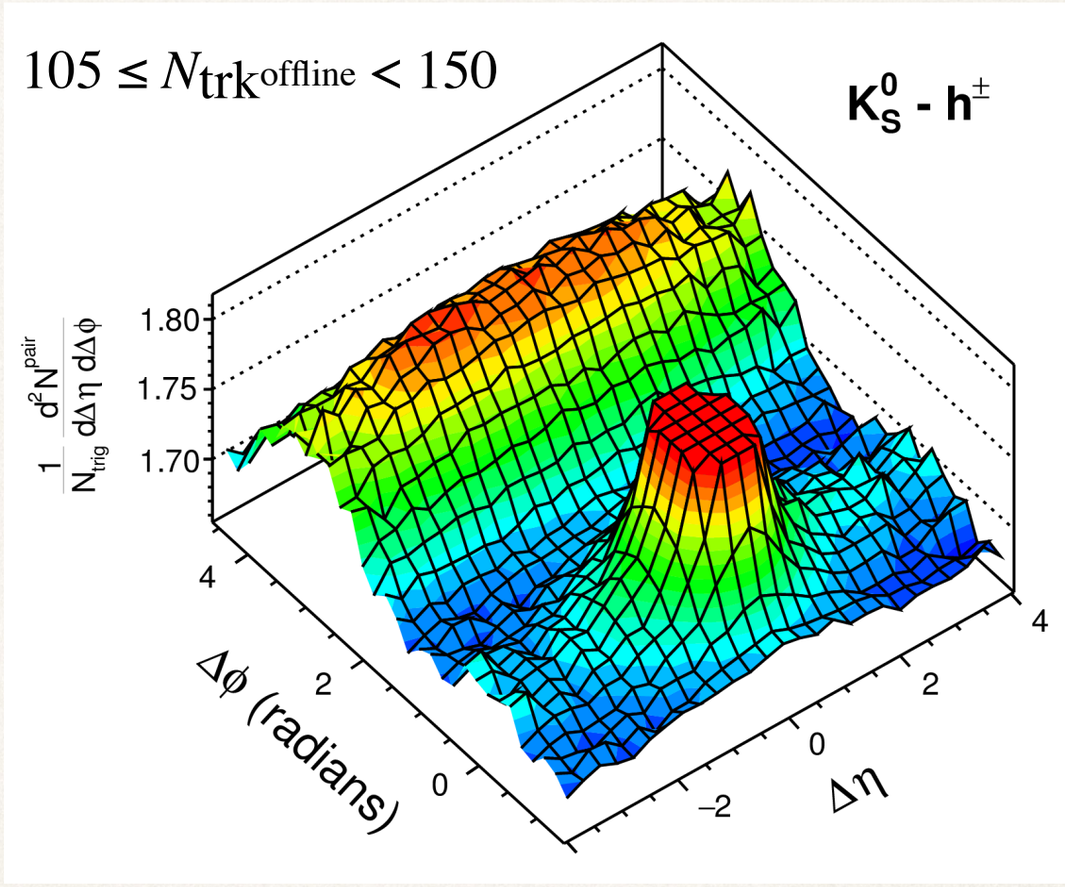


The 2D two-particle correlation functions for inclusive charged particles, with $1 < p^{trig} < 3$ GeV/c and associated charged particles with $1 < p_T^{assoc} < 3$ GeV/c, in low-multiplicity ($10 \leq N_{trk}^{offline} < 20$, left) and high-multiplicity ($105 \leq N_{trk}^{offline} < 150$, right) pp collisions at $\sqrt{s} = 13$ TeV.

Phys. Lett. B 765 (2017) 193

Measurements of two-particle and multi-particle angular correlations in pp collisions

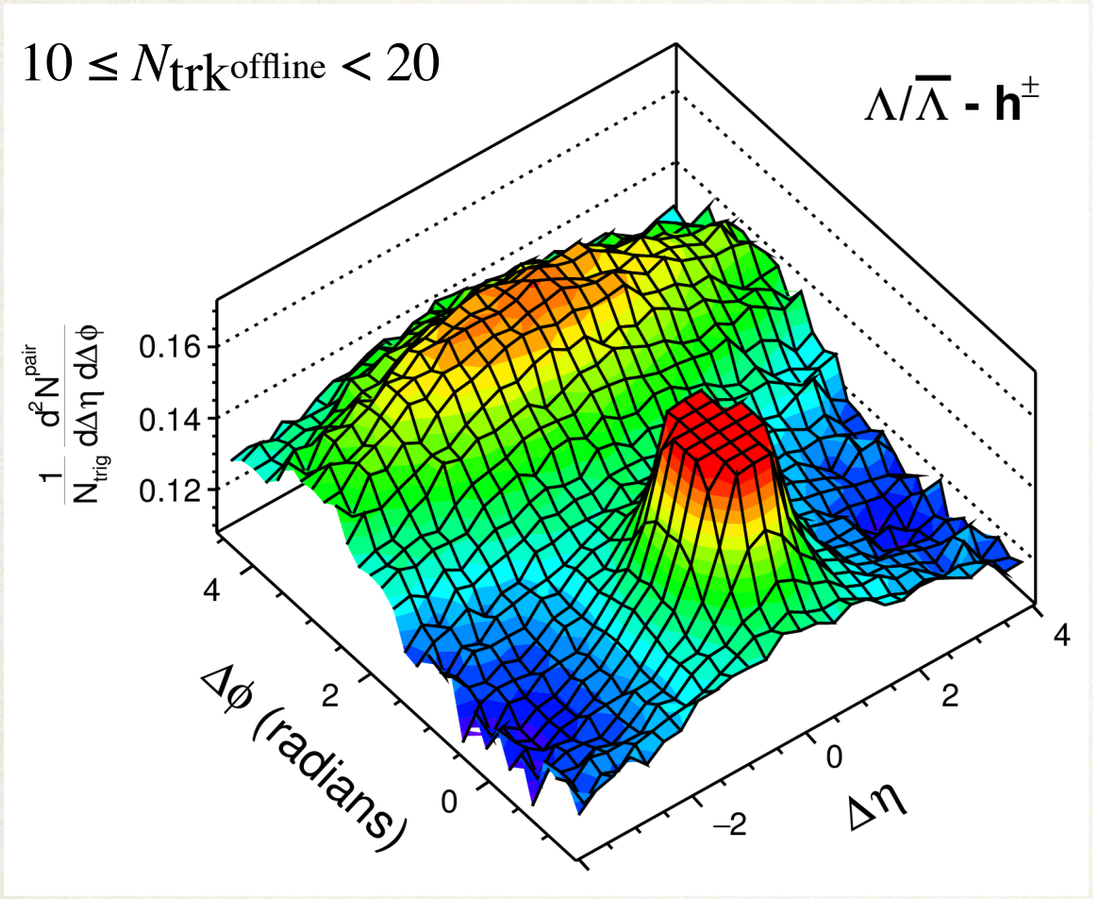


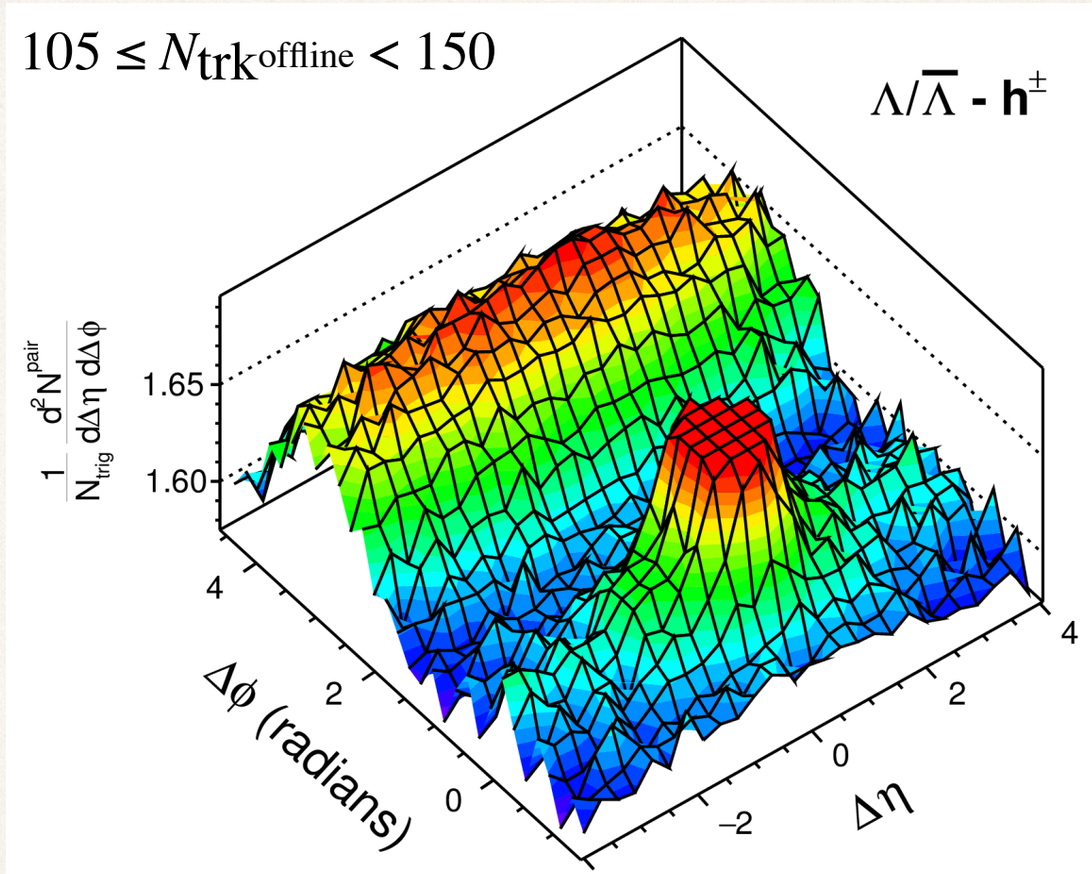


The 2D two-particle correlation functions for K^0 particles with $1 < p^{trig} < 3$ GeV/c and associated charged particles with $1 < p_T^{assoc} < 3$ GeV/c, in low-multiplicity ($10 \leq N_{trk}^{offline} < 20$, left) and high-multiplicity ($105 \leq N_{trk}^{offline} < 150$, right) pp collisions at $\sqrt{s} = 13$ TeV.

Phys. Lett. B 765 (2017) 193

Measurements of two-particle and multi-particle angular correlations in pp collisions

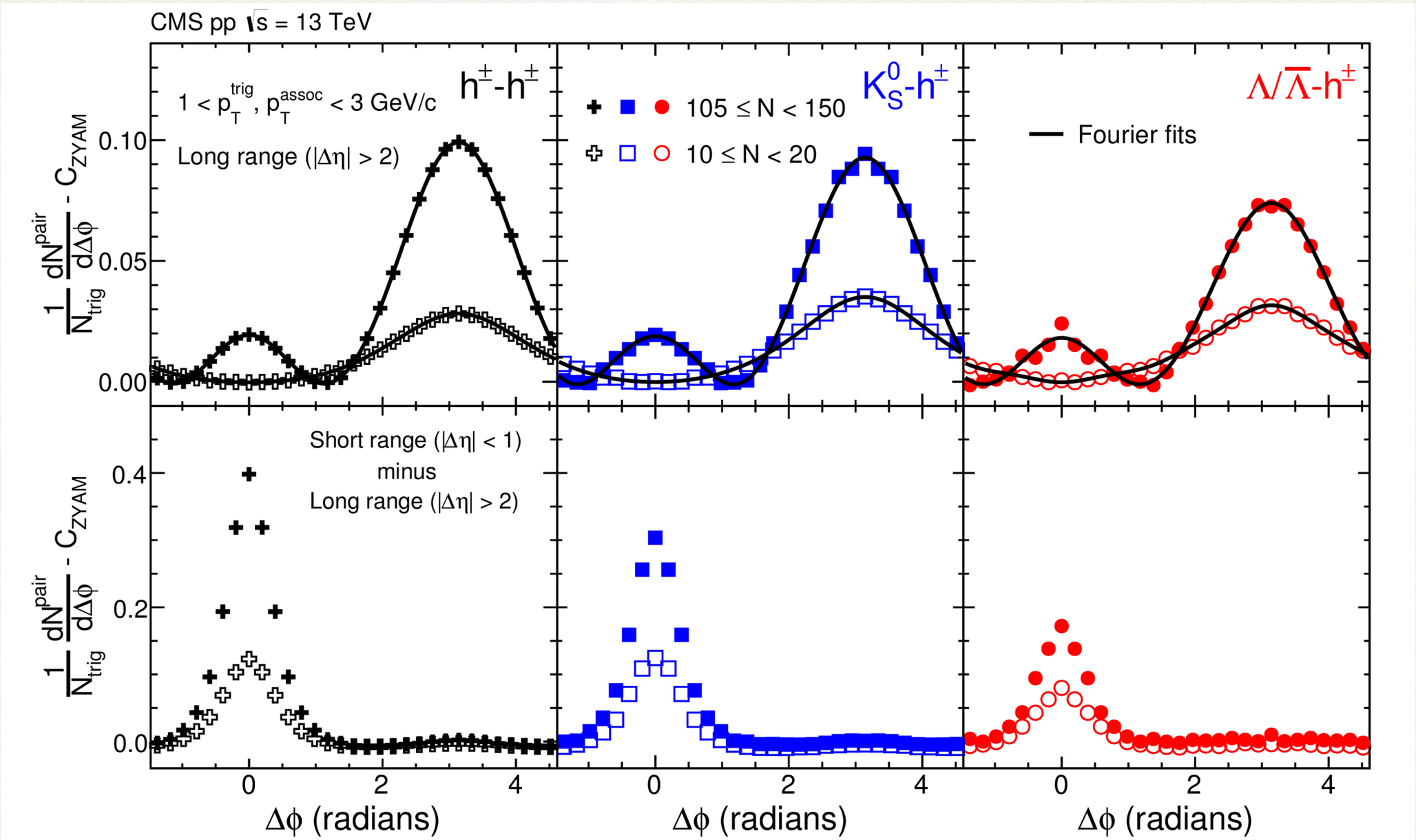




The 2D two-particle correlation functions for $\Lambda/\overline{\Lambda}$ particles, with $1 < p^{trig} < 3$ GeV/c and associated charged particles with $1 < p_T^{assoc} < 3$ GeV/c, in low-multiplicity ($10 \le N_{trk}^{offline} < 20$, left) and high-multiplicity ($105 \le N_{trk}^{offline} < 150$, right) pp collisions at $\sqrt{s} = 13$ TeV.

Phys. Lett. B 765 (2017) 193

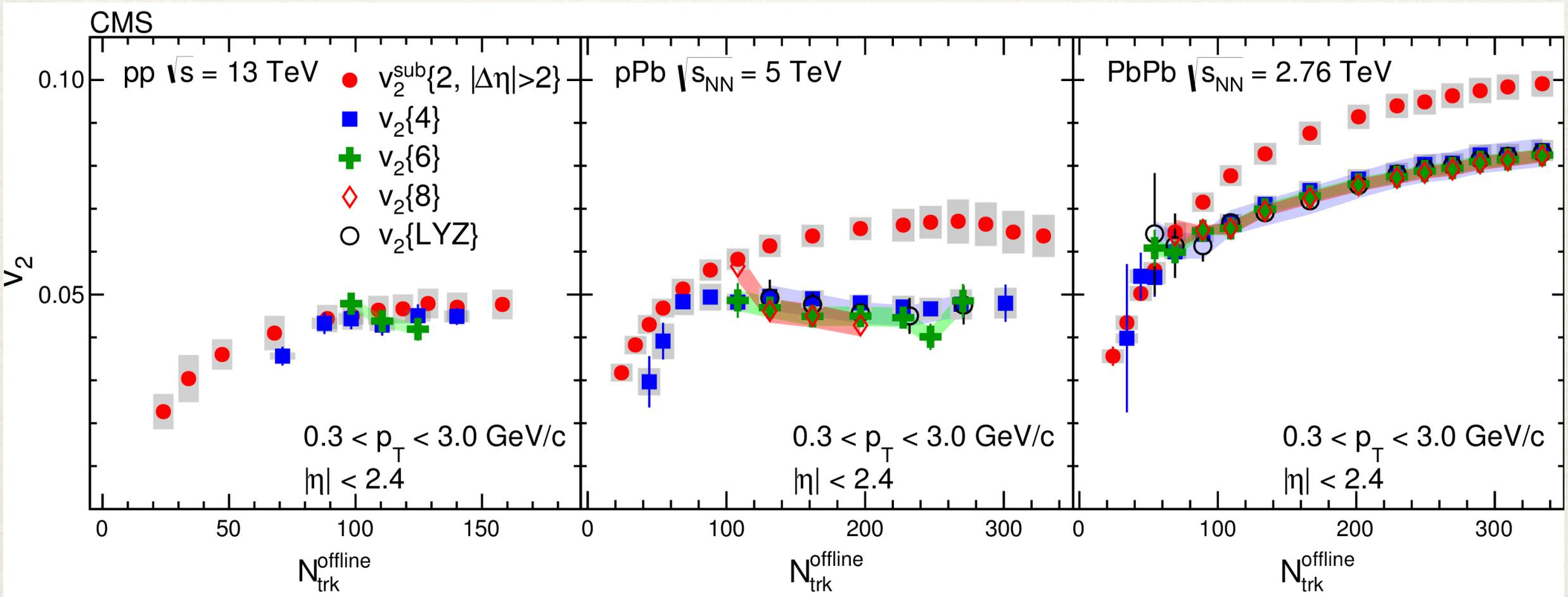
Measurements of two- and multi-particle angular correlations in pp collisions



The 1D ϕ correlation functions for the long-range (top) and short- minus long-range (bottom) regions after applying the ZYAM procedure in the multiplicity range $10 \leq N^{\text{offline}} < 20$ (open symbols) and $105 \leq N^{\text{offline}} < 150$ (filled symbols) of pp collisions at $\sqrt{s} = 13$ TeV, for trigger particles composed of inclusive charged particles (left, crosses), K^0 particles (middle, squares), and / particles (right, circles). A selection of 1–3GeV/c for both p^{trig} and p^{assoc} is used in all cases.

Phys. Lett. B 765 (2017) 193

Measurements of two- and multi-particle angular correlations in pp collisions



Left: the $v^{\mathrm{sub}}\{2,|\eta|>2\}$, $v2\{4\}$ and $v2\{6\}$ values as a function of N^{offline} for charged particles, averaged over $0.3 < p\mathrm{T} < 3.0\mathrm{GeV}/c$ and $|\eta| < 2.4$, in pp collisions at $\sqrt{s} = 13\mathrm{TeV}$.

Middle: the $v^{\mathrm{sub}}\{2,|\eta|>2\}$, $v2\{4\}$, $v2\{6\}$, $v2\{8\}$, and $v2\{\mathrm{LYZ}\}$ values in pPb collisions at $\sqrt{s}\mathrm{NN} = 5\mathrm{TeV}$.

Right: the $v^{\mathrm{sub}}\{2,|\eta|>2\}$, $v2\{4\}$, $v2\{6\}$, $2\sqrt{2}$ $v2\{8\}$, and $v2\{\mathrm{LYZ}\}$ values in PbPb collisions at $\sqrt{s}\mathrm{NN}=2.76\mathrm{TeV}$

Phys. Lett. B 765 (2017) 193

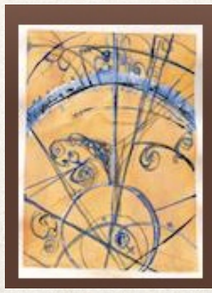
Summary

Data from the LHC provides a unique and rich environment to perform QCD studies.

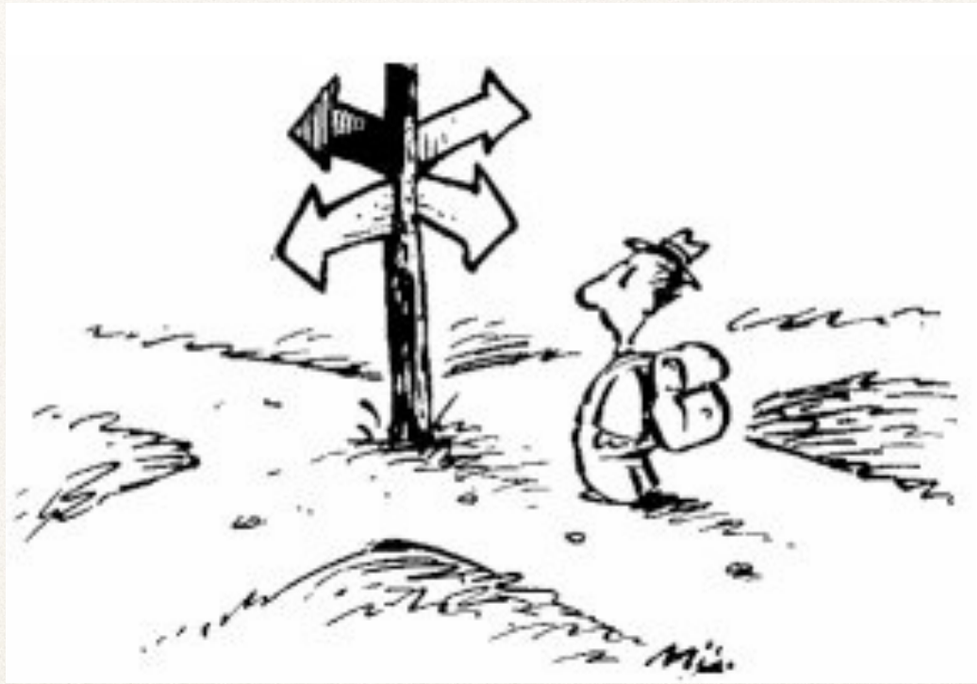
From soft-QCD to very-high p_T jets, LHC detectors are testing QCD as never before!

This talk covered a small sample of results published recently:

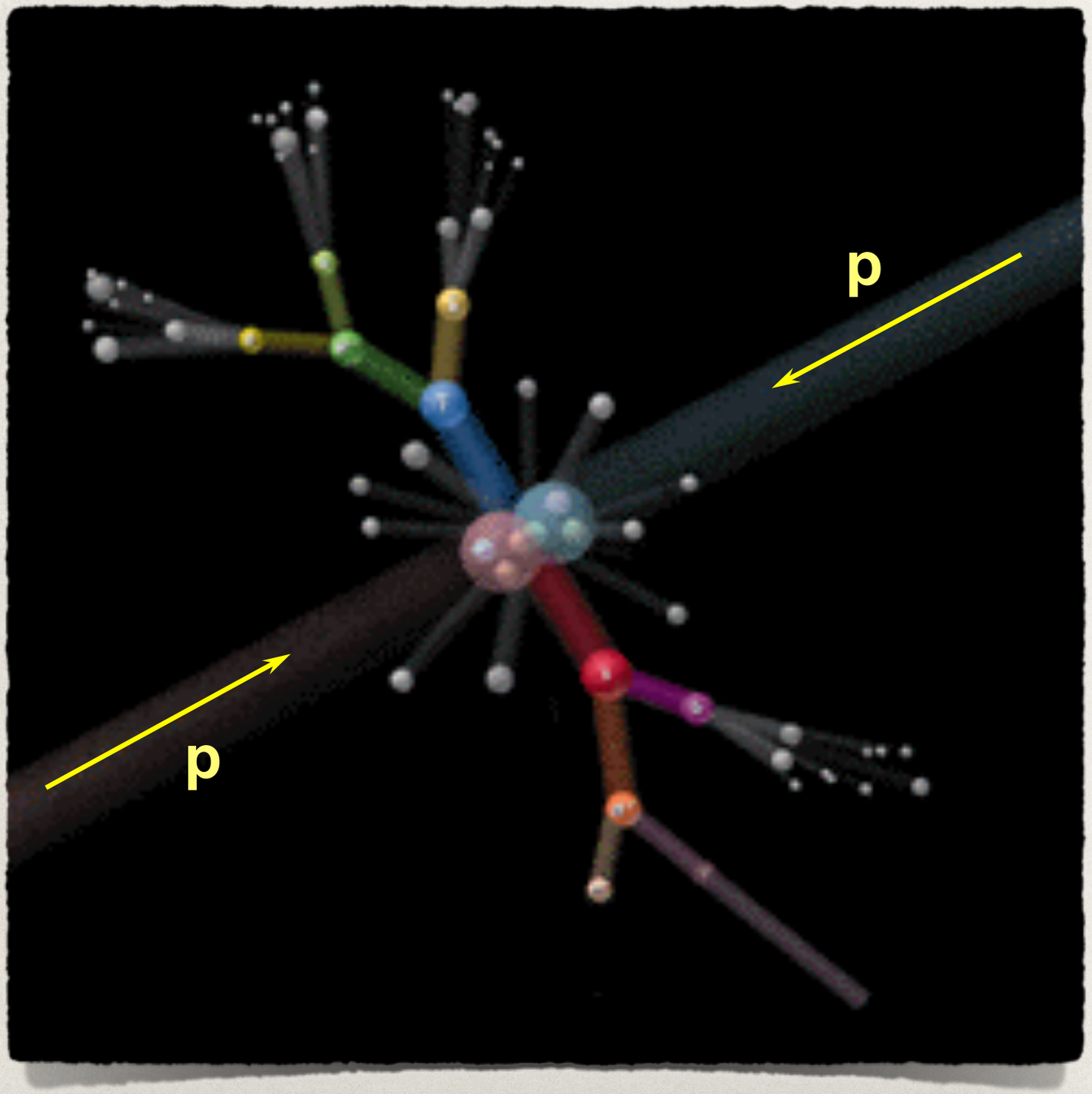
- Charged particle densities: pp, pA — *Eur. Phys. J. C (2018) 78:697*
- $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ — *JHEP 01 (2018) 045*
- Two-particle and multi-particle angular correlations — *PRD 96 (2017) 112003*; *Phys. Lett. B 765 (2017) 193*



Extras...



QCD at the LHC



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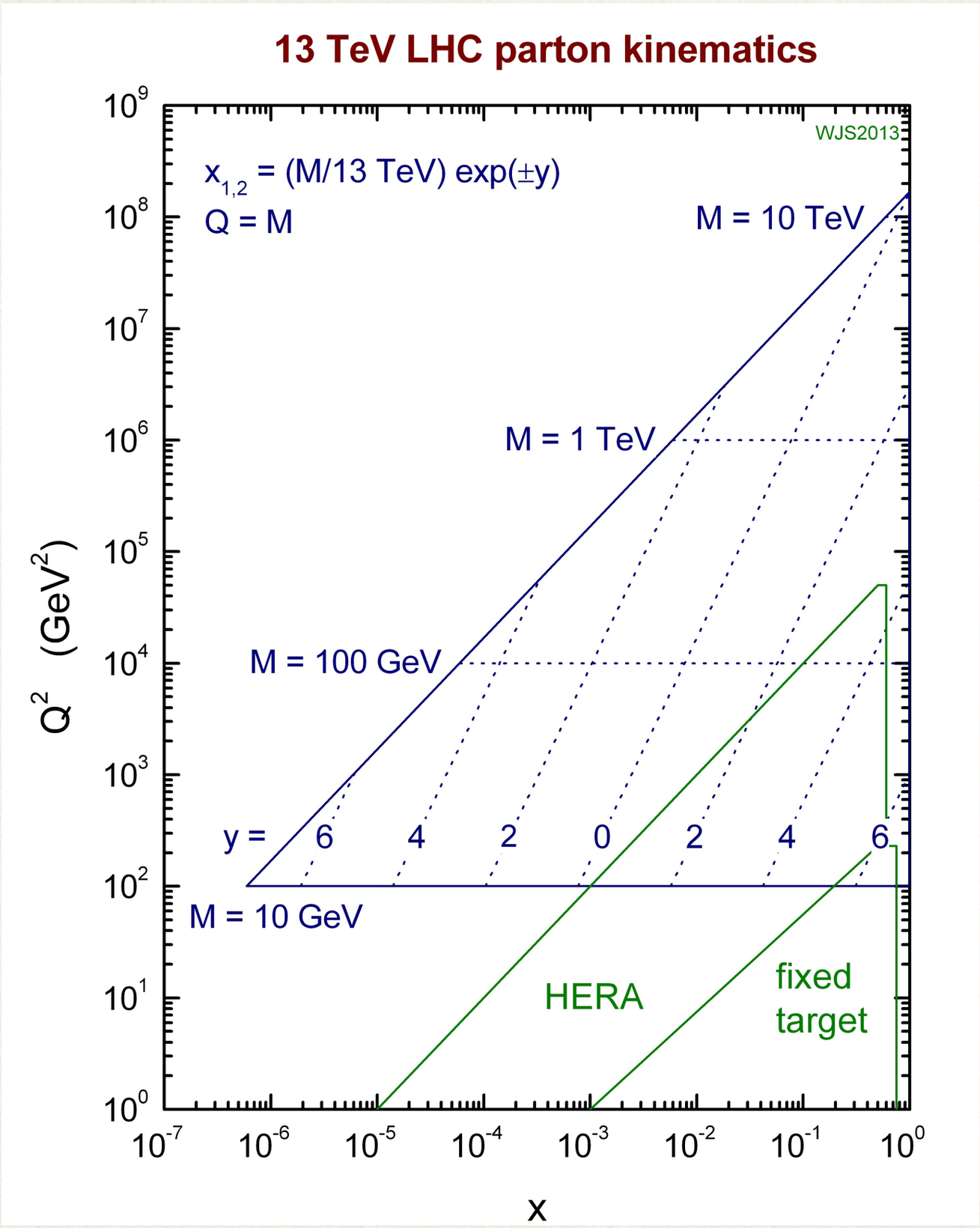
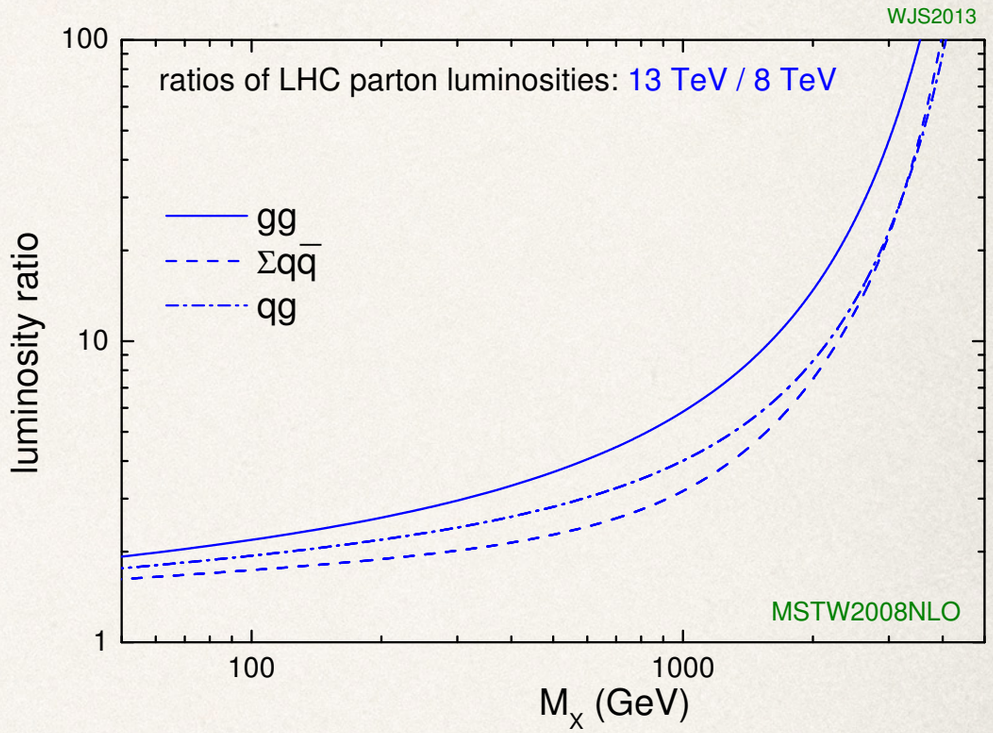
- Essentially all physics at high-energy hadron colliders are connected to the interactions of quarks and gluons (small & large transferred momentum).
  - Hard processes (high-p_T): well described by perturbative QCD
  - Soft interactions (low-p_T): require non-perturbative phenomenological models

- Soft Interactions: Problems with strong coupling constant, $\alpha_s(Q^2)$, saturation effects,…

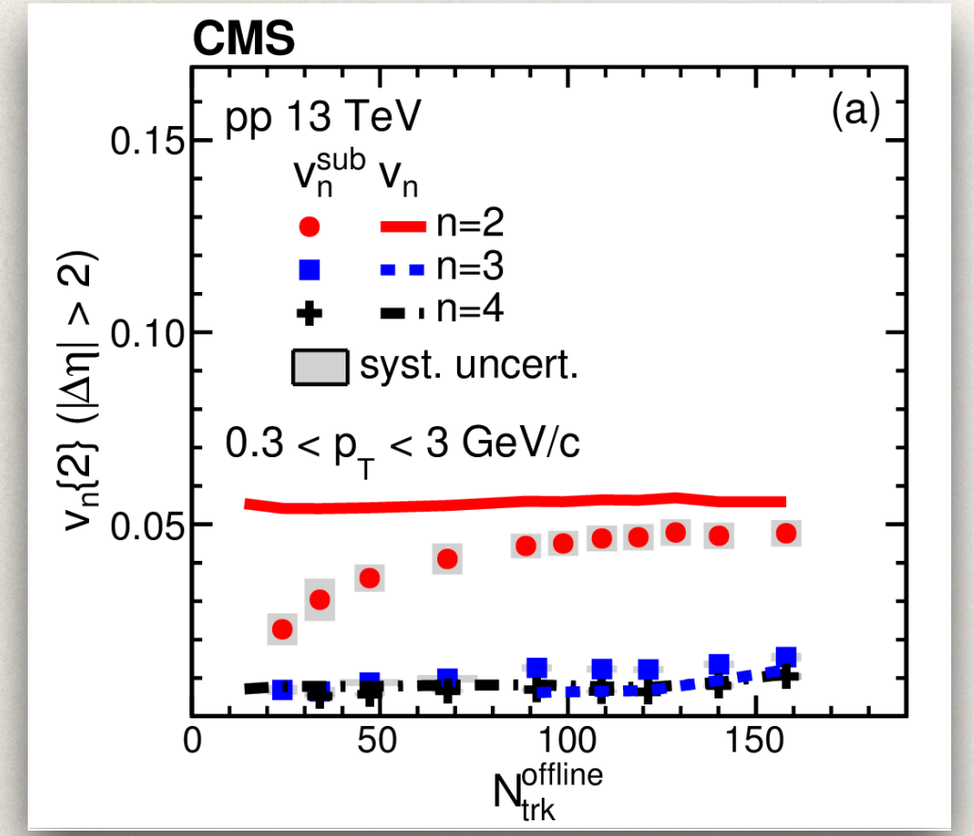
- On average, inelastic hadron-hadron collisions have low transverse energy, low multiplicity.

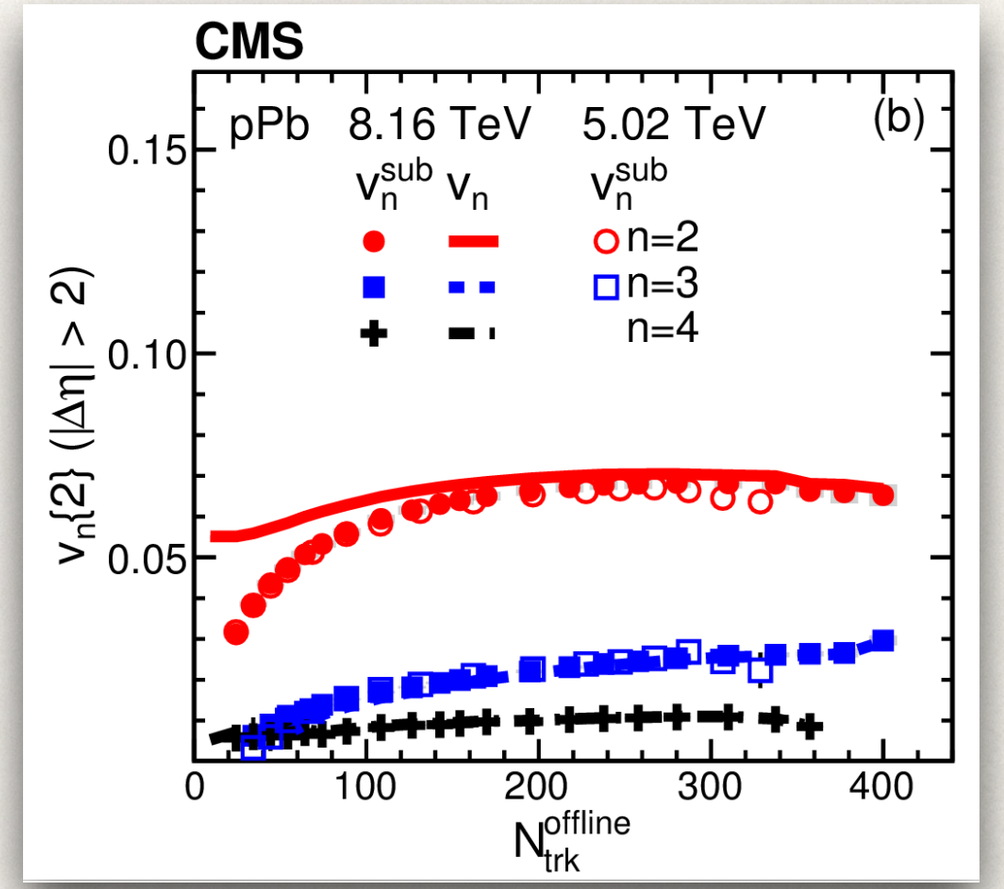
QCD at the LHC





Measurement of multi-particle azimuthal correlations in pp, p + Pb collisions

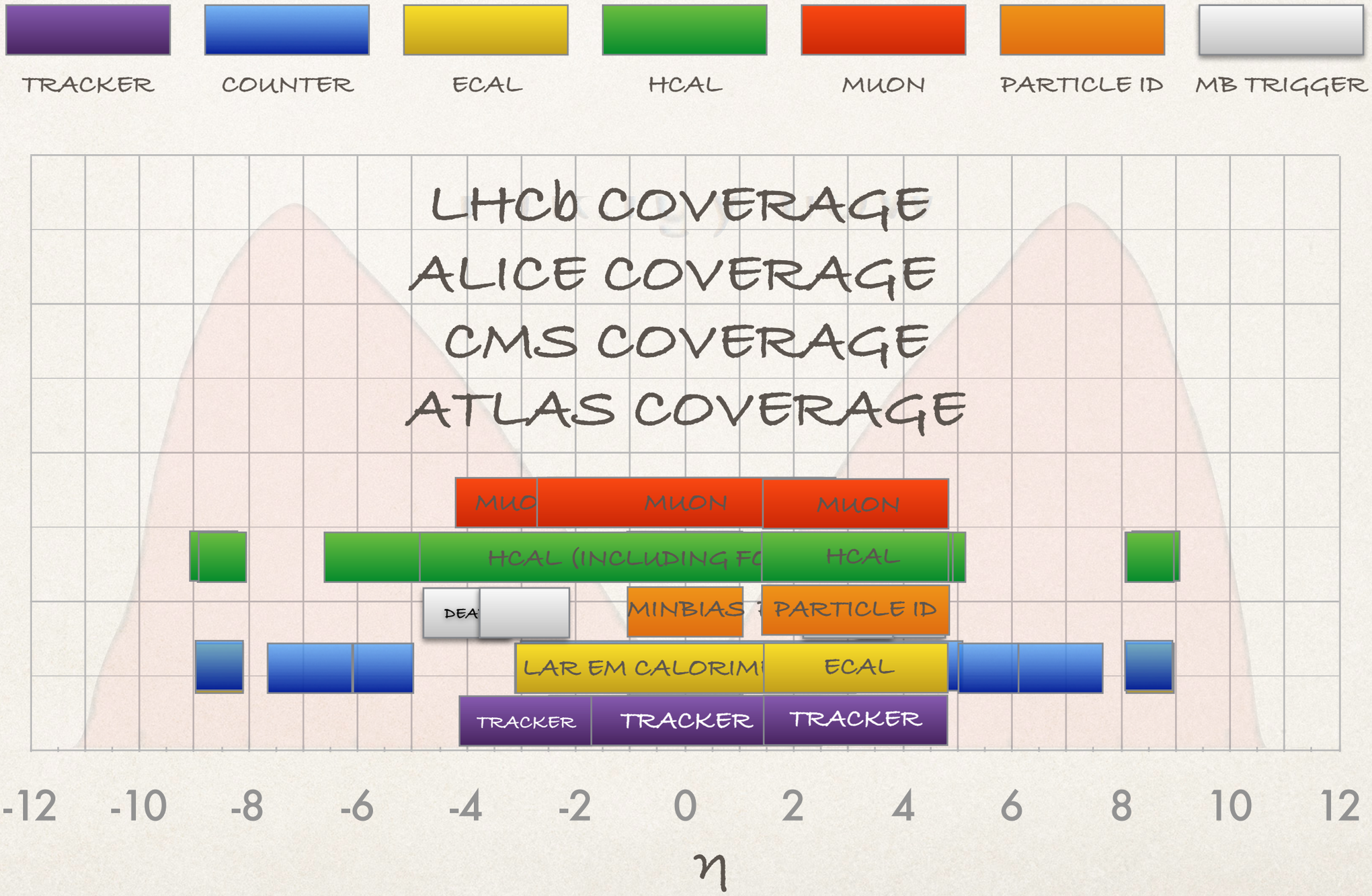




The v2, v3, and v4 coefficients from long-range two-particle correlations as a function of $N^{offline}_{trk}$ in 13 TeV pp (a), 5.02 and 8.16 TeV p+Pb (b).
The results corrected by low-multiplicity subtraction are denoted as
v^{sub}_n . *The lines show the* v_n *results before the subtraction of low-multiplicity correlations.*

Phys. Rev. Lett. 120, 092301 (2018)

Detector Coverage



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