The Dirty Picture
Low Energy QCD at the LHC

Manas Maity
Visva-Bharati

Outline

QCD LHC

Large Hadron Collider –
Quantum ChromoDynamics in its full glory & gory details
from hard scattering, ISR, FSR to fragmentation, hadronization
from perturbative/analytical calculations to phenomenological models

Devil is in the detail

- strong coupling
- fragmentation models,
- color reconnection,
- multi-parton interaction (MPI) ...

Good agreement between theory and experiment for the hard scattering part over many orders of magnitudes - jet cross-section, PDF, ... (BM, SG, SSG, ... review talks).

QCD Thali

The limited menu on offer:

- Event Shape Variables
- Heavy Quark Fragmentation
- Jet Charge
- Charged particles - multiplicity, p_T and η,

Why the ESVs

ESV variables are sensitive to various aspects of QCD –

- hard scattering part – analytically calculable with good accuracy
  - Complement of Transverse Thrust $\tau_\perp$, Thrust Minor $T_{m,\perp}$
  - Third-Jet Resolution Parameter Y_{23}
  - Sphericity S, Transverse Sphericity $S_\perp$, Aplanarity A
- hadronization part – described by phenomenological models
  - jet broadening B_T
  - total jet mass ρ_{Tot}, total transverse jet mass $\rho^{\mathrm{T}}_{\text{Tot}}$
  - particle multiplicity and p_T in event, jets

Event Shape Variables have been calculated using

- jets - clustered charged and neutral particles in an event
- unclustered charged particles in an event

Definitions

Complement of Transverse Thrust:

$$\tau_{\perp} \equiv 1 - T_{\perp} = 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \vec{n}_T|}{\sum_i p_{T,i}}, \quad 0 \leq \tau_{\perp} \leq 1 - 2/\pi$$

It is sensitive to the hard scattering process -

Thrust Minor: A measure of the total $\mathrm{p_{T,i}}$ out of the event plane:

$$T_{m,\perp} = \frac{\sum_i |\vec{p}_{T,i} \times \vec{n}_T|}{\sum_i p_{T,i}}, \quad 0 \leq T_{m,\perp} < 2/3$$

Third-Jet Resolution Parameter:

$$\begin{aligned} Y_{23} &= \frac{min(p^2_{T,3}, [min(p_{T,i}, p_{T,j})^2 \times (\Delta R_{ij})^2/R^2])}{P^2_{12}} \quad (CMS) \\ &= \frac{p^2_{T,3}}{H^2_{T,2}} \quad (ATLAS) \end{aligned}$$

Definitions

Sphericity, Transverse Sphericity, Aplanarity:

$$M_{xyz} = \sum_i \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix}, \quad \lambda_1 > \lambda_2 > \lambda_3, \ \sum_i \lambda_i = 1$$

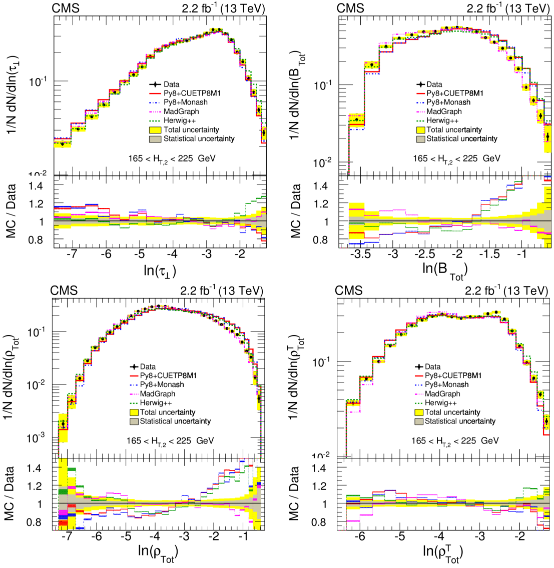
$$S = \frac{3}{2}(\lambda_2 + \lambda_3), \quad S_\perp = \frac{2\lambda_2}{\lambda_1 + \lambda_2}, \quad A = \frac{3}{2}\lambda_3$$

Jet Broadening:

$$\eta_X \equiv \frac{\sum_{i \in X} p_{T,i}\eta_i}{\sum_{i \in X} p_{T,i}}, \quad \phi_X \equiv \frac{\sum_{i \in X} p_{T,i}\phi_i}{\sum_{i \in X} p_{T,i}}$$

$$B_X \equiv \frac{1}{2\,P_T} \sum_{i \in X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}\,, \ B_T = B_U + B_L$$

CMS ESV with Jets $\sqrt{s} = 13\,TeV$



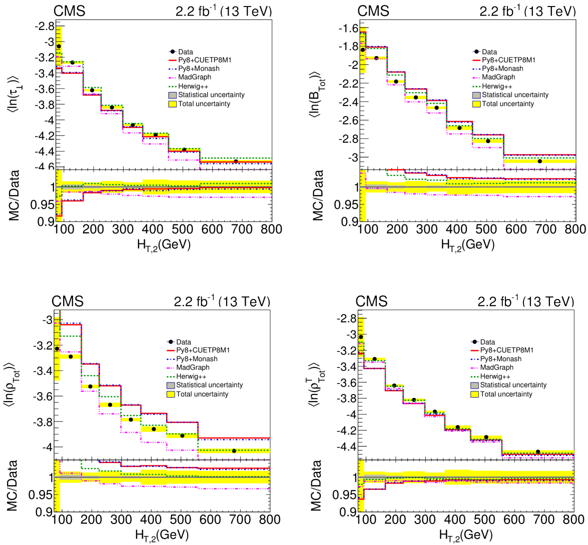
PF jets used $|\eta^{jet}| < 2.4$, $p_T^{jet} > 30$ GeV, $N_{jet} \geq 3$

Events divided into 8 ranges of $H_{T,2} = (p_{T,jet1} + p_{T,jet2})/2$

Unfolded data distributions compared with Pythia 8 (CUETP8M1, Monash), Herwig, Madgraph.

JHEP12(2018)117

CMS ESV with Jets $\sqrt{s} = 13\,TeV$



Agreement improves with $H_{T,2}$

Agreement good for $\tau_\perp$, ρ^{T}_{Tot}

Herwig - better agreement for B_T, ρ_{Tot}

For higher $H_{T,2}$, events become less spherical.

JHEP12(2018)117

CMS ESV with Tracks in MB Events

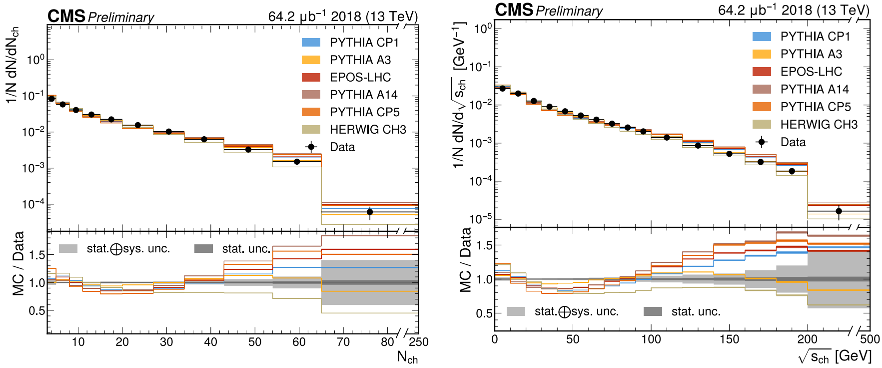
Low pileup data collected in 2018, $\langle N_{PV} \rangle \sim 1$

Tracks $pT > 0.5$ GeV, and $|\eta| < 2.4$, $N_{trk} \geq 2$
No clustering is done.
The unfolded observables are computed using tracks (detector level), or charged particles (particle level)

Results compared with PYTHIA (CP1, A3, A14, CP5), Herwig (CH3), EPOS (LHC), and HERWIG (CH3) tune.

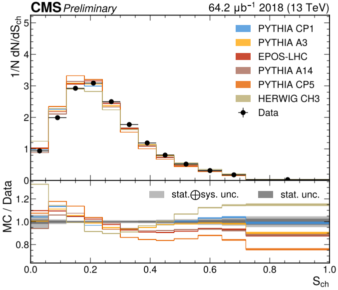
CMS-SMP-23-008-PAS

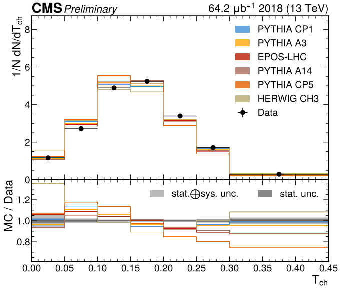
CMS ESV with Tracks in MB Events

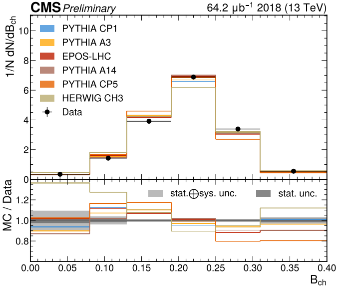


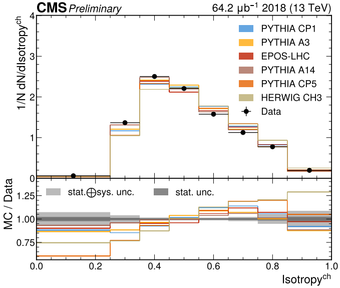
CMS-SMP-23-008-PAS

CMS ESV with Tracks in MB Events

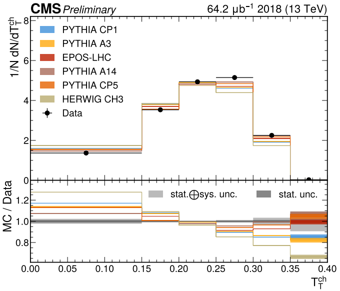


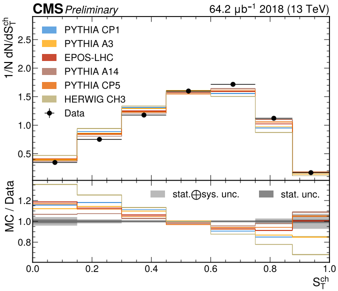






CMS ESV with Tracks in MB Events



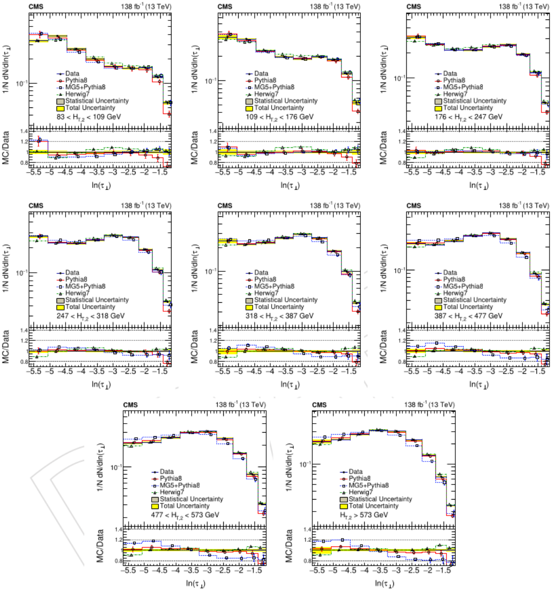


CMS ESV with Tracks in MB Events

No MC generator shows good agreement.

- For $N_{ch} \lesssim 10$ and low $\sqrt{s_{ch}}$ all generators overestimate the fraction of events.
- For high N_{ch} and high $\sqrt{s_{ch}}$, the predictions of the MC generators diverge.
- For the
- Pythia 8 A3 tune (ATL-PHYS-PUB-2016-017) matches much better for all the ESVs.

CMS ESV with Tracks New Result



New CMS study of ESVs using charged particles in jets has been approved.

(Suman Kumar Kundu)

String Fragmentation

Lund Model

$$f(z) = N\frac{(1-z)^a}{z}e^{-(bm^2/z)}$$

For heavy quarks $m \to m_T$

Lund-Bowler Model

$$f(z) = N\frac{(1-z)^a}{z^{1+r_q bm_q^2}}e^{-(bm_T^2/z)}$$

Z. Phys. C 11 (1981) 169

z fraction of the string momentum taken by the hadron,
N normalization constant,
$m_T = \sqrt{m^2 + p_T^2}$, m mass of the hadron
a, b parameters of the model
m_q mass of the quark, r_q shape parameter for the quark

String Fragmentation

- b-jets important for many analyses – top quark, Higgs, new particle searches
- heaviest quark that hadronizes – large m_b is important in the fragmentation
- MC event generator tuned using e^+e^- data from LEP and SLC – no QCD ISR/ UE – less complex
- LHC is a b-factory –
  - high statistics data for understanding fragmentation of b-quarks
  - high luminosity pp data is complex – PU, MPI,

CMS: b Jets in $t\bar{t}$ Events

CMS, $\sqrt{s} = 13$ TeV, 35.9 fb^{-1} data

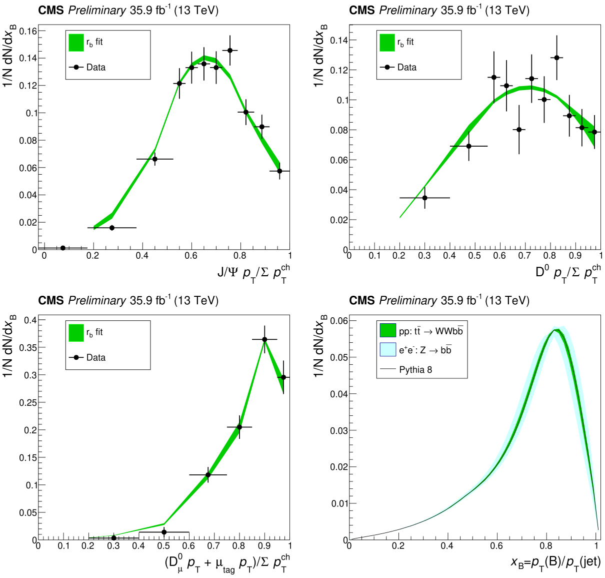
- $t\bar{t}$ events in single lepton (e/μ + jets), opposite sign dilepton ($\ell^+\ell^-$ + jets) channels (isolated high p_T e/μ).
- Charm meson candidates are identified with
  $J/\psi \to \mu^+\mu^-$ (both muons are non-isolated)
  $D^0 \to K^\pm\pi^\mp$ - opposite sign charged tracks
- Events with candiate D^0 are divided into two sub-samples - with soft μ tag and without.
- proxy x_b is calculated for each charm meson,

$$x_b = \frac{p_T(J/\psi,\ D^0)}{\sum_{jet} p_T^{ch}}$$

  the sum includes all tracks with $p_T > 0.5$ GeV in the same jet.
- $t\bar{t}$ event simulation – NLO (POWHEG V2), $m_t = 172.5$ GeV + PYTHIA 8 (CUETP8M2T4), Lund-Bowler fragmentation

CMS PAS TOP-18-012

CMS: b Jets in $t\bar{t}$ Events



CMS: b Jets in $t\bar{t}$ Events

- template fit to x_b distributions for each of the meson samples – $r_b = 0.858 \pm 0.037\ (st) \pm 0.031\ (sys)$
- $f(z)$ does not show any environment dependence e^+e^-, pp.

LHC can compete with LEP in precision measurements.

ATLAS: b Jets in $t\bar{t}$ Events

$t\bar{t} \to e\mu\nu\nu b\bar{b}$ events:

- reconstructed jets = 2, b-tagged jet ≥ 1
- exactly two leptons with opposite sign $e^{\pm}\mu^{\mp}$
- relatively low contamination from light-flavor jets.
- $e\mu$ channel particularly small contributions from non-$t\bar{t}$ processes.

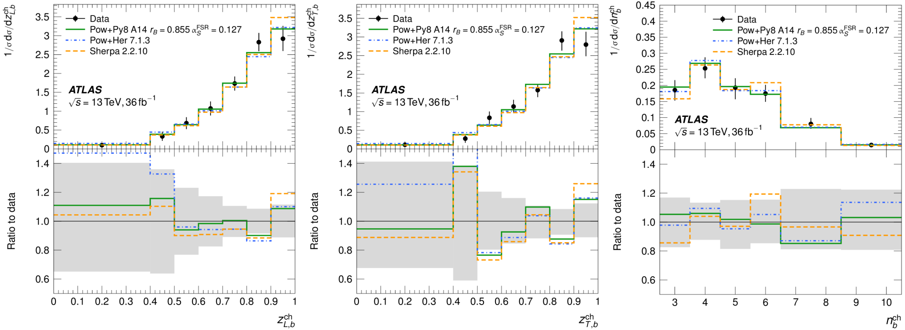
Charged particles with $p_T > 500$ MeV are used to form
$\vec{p}_b^{ch} = \sum_{b-hadron} \vec{p}^{ch}, \ \ \vec{p}_{jet}^{ch} = \sum_{jet} \vec{p}^{ch}$

Four variables are studied

$$z_{T,b}^{ch} = \frac{p_{T,b}^{ch}}{p_{T,jet}^{ch}}, \ \ z_{L,b}^{ch} = \frac{\vec{p}_b^{ch} \cdot \vec{p}_{jet}^{ch}}{|\vec{p}_{jet}^{ch}|^2}, \ \ \rho = \frac{p_{T,b}^{ch}}{p_T^e + p_T^\mu}, \ \ n_b^{ch}$$

PRD 106, 032008 (2022)

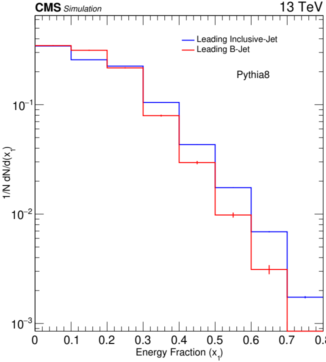
ATLAS: b Jets in $t\bar{t}$ Events



Predictions of MC generators tuned to a combination of lepton and hadron collider measurements show improved agreement with the observed LHC data.

PRD 106, 032008 (2022)

Energy fraction in b Jets



Energy fraction $x_1 = p_{T,1}/p_T^{jet}$ in the leading jet (b-jet) of an event.

Jet Charge Observables

Three jet charge observables are studied – Default, longitudinal and transverse

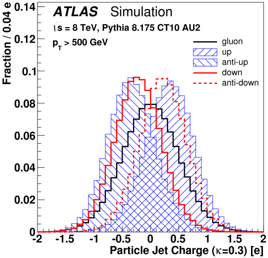
$$
\begin{aligned}
Q_J^\kappa &= \frac{1}{\left(p_T^{jet}\right)^\kappa} \sum_i q_i \left(p_T^i\right)^\kappa \\
Q_{J,L}^\kappa &= \frac{\sum_i q_i \left(p_\parallel^i\right)^\kappa}{\sum_i \left(p_\parallel^i\right)^\kappa}, \;\; p_\parallel^i = \frac{\vec{p}^i \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|} \\
Q_{J,T}^\kappa &= \frac{\sum_i q_i \left(p_\perp^i\right)^\kappa}{\sum_i \left(p_\perp^i\right)^\kappa}, \;\; p_\perp^i = \frac{\vec{p}^i \times \vec{p}_{jet}}{\vec{p}_{jet}|}
\end{aligned}
$$

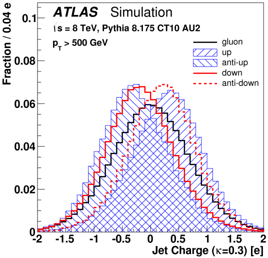
The parameter κ controls the relative weightage given to the low energy particles.

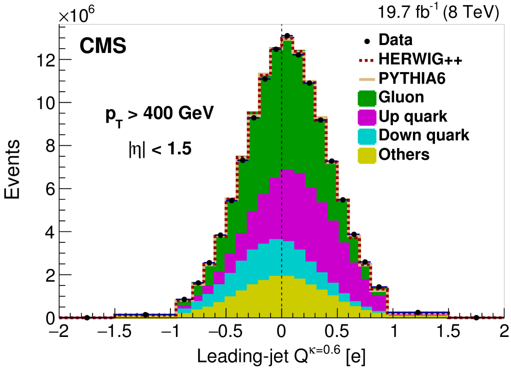
JCO Measurements

- Distributions of the JCOs are broad, overlapping
  $\Rightarrow$ discriminating partonic origin ($q/\ \bar{q}/\ g$) of a jet is not possible.
- D0 used $Q_J^{0.6}$ and later CDF used $Q_{J,L}^{0.5}$ to confirm q_t and exclude exotic quarks. PRL 98 (2007) 041801, PRD 88 (2013) 032003
- ATLAS studied $Q_{J,L}^{0.5}$ for b-jets in $t\bar{t}$ events to estimate q_t. CMS also studied $Q_{J,L}^{0.7}$ JHEP 11 (2013) 031, CMS-PAS-TOP-11-031
- JCOs not affected by PU $\Rightarrow$ suitable for the HL-LHC.

JCO Measurements

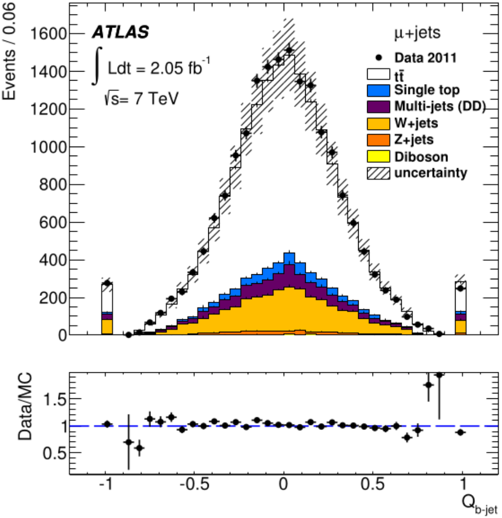


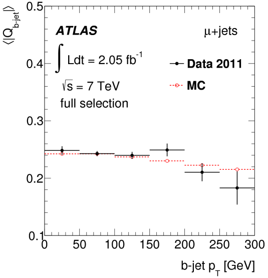


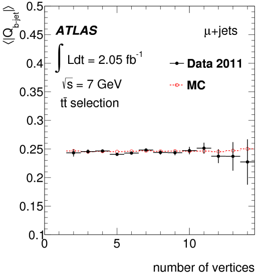


Phys. Rev. D 93 (2016), JHEP 10(2017) 131

ATLAS: JCO Measurements

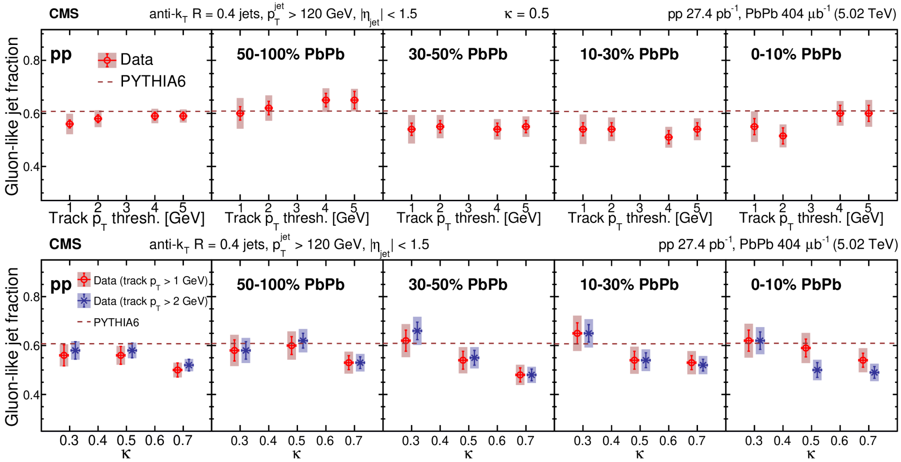






JHEP 11 (2013)

CMS: JCO Measurements



JHEP 07 (2020) 115

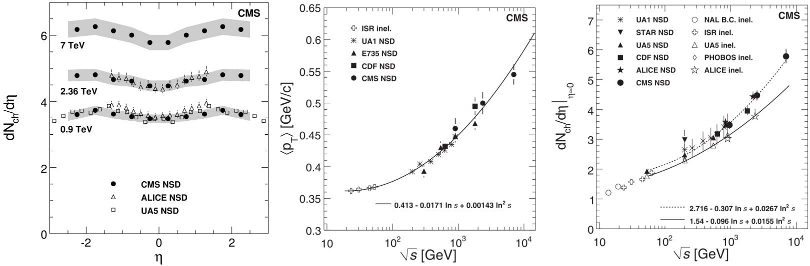
CMS: JCO Measurements

A new CMS study of JCOs is ready for approval process.

Charged Particle Production

- color reconnection
- Power law behaviour - negative binomial distribution (NBD) - double NBD
- KNO scaling $\Psi(z) = \langle n \rangle P_n, \;\; z = n/\langle n \rangle$

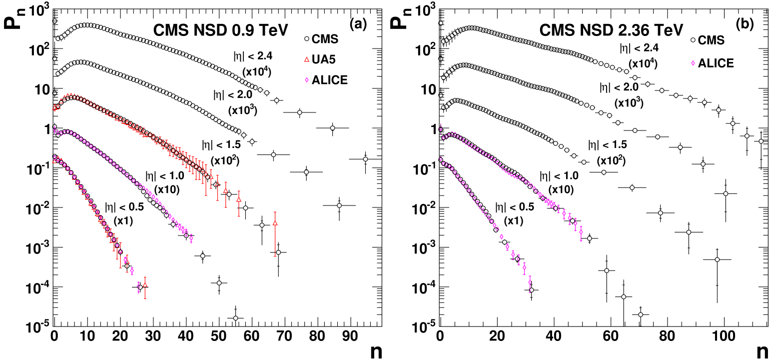
Charged Particles



$$\langle p_T \rangle = 0.545 \pm 0.005 \pm 0.15 \text{ GeV/c}$$

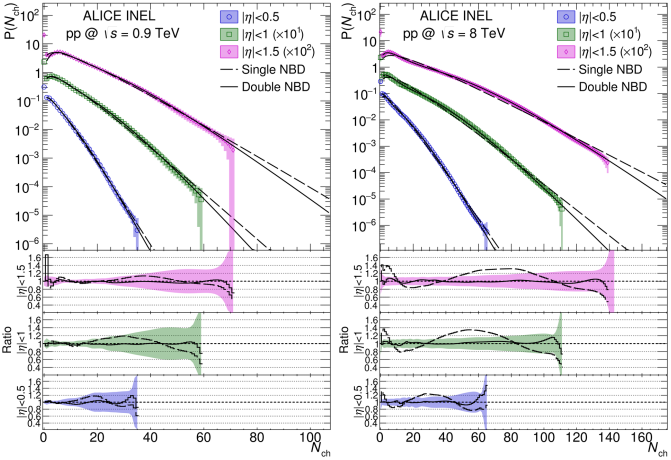
CMS, PRL 105, 022002 (2010)

Charged Particle Production



JHEP 01 (2011) 079

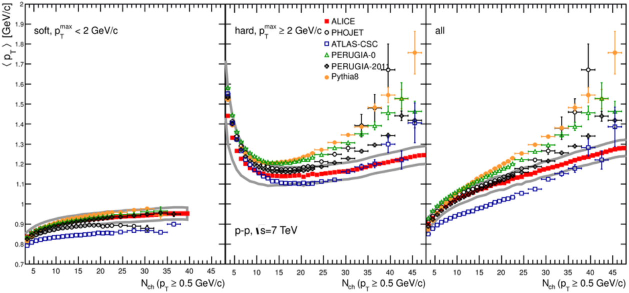
Charged Particle Production

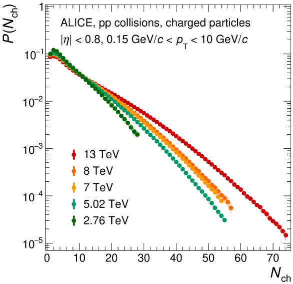


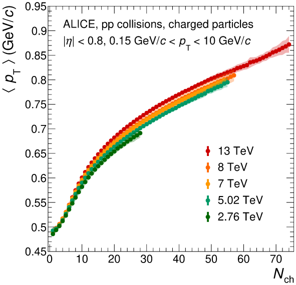
Single NBD fails to describe data at higher multiplicities.

New J. Phys. 13:053033, 2011; arXiv:2211.15326

Charged Particle Production







Outlook

- Many measurements have been done to understand QCD at low energies - event and jet shapes, charged particle production, ...
- The measurements focus on different aspects of particle production in hadron (and nuclear) collisions
- A huge jigsaw puzzle with many pieces
- A combined and exhaustive picture of the process of particle production is yet to emerge ...

... and we keep colliding, particles and ideas