Marek Taševský
Institute of Physics, Academy of sciences, Prague, Czech Republic
On behalf of the LHC experiments
(ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM)
Soft QCD:
- characterized by a soft scale (low $p_T$)
- applied to describe
  - the part of the scattering that dominates at soft scale
  - hadronization
- not uniform description, variability in modeling

Measurements:
- Soft scale $\rightarrow$ processes with large cross sections:
  - Inclusive cross sections
  - Inclusive & Identified particle spectra
  - Underlying event
  - Particle correlations
  - Similarities between pp / pPb / PbPb

Phenomenology:
- Multi-parton interactions (MPI)
- Colour coherence / reconnection
- Hadronization (line, ropes, helix)
- Hydrodynamics / Gluon saturation

Very interesting links between so different fields
Inclusive (total & elastics) pp cross-sections

TOTEM, ALFA(ATLAS): dedicated forward proton detectors (~220-240 m from interaction point)
- very close to beam (~few mm dep. on LHC optics ($\beta^*$))
- the larger $\beta^*$, the lower t
- dedicated runs: various collision energies, negligible pile-up
  $\beta^*$ range: 11m - 2500m → $0.0006 < |t| < 2\text{ GeV}^2$

13 TeV: $\beta^* = 2500\text{m}$, $0.0006 < |t| < 0.2\text{ GeV}^2$
- Coulomb-Nuclear Interference region → $\rho$ can be measured
- $\rho = \text{Real to imaginary part of forward amplitude}$

$\sigma_{tot}$ input to model
- amount of pile-up at LHC
- interactions in cosmic rays
Inclusive charged particles in pp (0.9–13 TeV)

$\sqrt{s} = 0.9$, 2.36, 2.76, 7, 8 TeV

$|\eta| < 2$, $p_T > 0.1$ GeV

**INEL** = all (MB) events

**NSD** = Non Single Diffraction

(ALICE, PbPb: PRL 116 (2016) 222302)

**ATLAS, EPJC76 (2016) 502**

**QGSJET**: no colour coherence

**PYTHIA 8**: colour reconnection

**EPOS**: hydrodynamical evolution

CMS-PAS-FSQ-15-008

Difficulties of all models to describe larger multiplicities

EPOS overall best description (specialized soft QCD model)

ALICE:

- Measurement of $dN_{ch}/d\eta (\eta=0)(\sqrt{s}) \sim s^{\delta}$: $\delta=0.114$(INEL)
  ($\delta=0.15$ for central PbPb)

- Alternatively: normalized q-moments $C_q = \frac{\langle N_{ch}^q \rangle}{\langle N_{ch} \rangle^q}$

For NSD events and three $|\eta|$ intervals:

- $C_2$ constant over $\sqrt{s} = 0.9$-8.0 range

- $C_3$, $C_4$, $C_5$ increase with $\sqrt{s}$ and with increasing $\Delta \eta$ at given $\sqrt{s}$

\[ 11/08/2017 \]

M. Tasevsky, Soft QCD Measurements at LHC, LP2017
CASTOR (-6.6 < \eta < -5.2) with EM and HAD calorimeters
- Inclusively EM particles (e^+, e^-, \gamma)
- Inclusively hadrons (mainly \pi^+, \pi^-)

Measurements suitable to tune:

1) Multi-Parton Interaction models in MC generators for pp collisions

2) MC generators modeling HE cosmic ray air showers

CMS, CERN-EP-2016-313

\sqrt{s} – evolution of model parameters is unknown
Again: MC generators need to be retuned for every energy point

Neutrons at 7 TeV, pp

LHCf, PLB 750 (2015) 360

- X_{max} (shower maximum position) modeling:
  \sigma^{p-air}_{inel} & forward identified particle spectra

- hadronic interaction modeling:
  correlation central-forward particle production
  (ATLAS vs LHCf or CMS vs TOTEM)

LHCf: calorim. measuring soft neutral (n,\pi^0,\gamma) particles
- 140m from ATLAS, |\eta| > 8.4

PRD 94 (2016) 032007, CERN-EP-2017-051
Enhanced strangeness = signature of QGP formation in heavy-ion collisions

- for the 1st time observed in pp
- similar dependence on particle multiplicity in PbPb, pPb, pp

DIPSY closest to data (color ropes)

Strangeness enhancement wrt inclusive sample follows strangeness hierarchy:

- the same for pPb and pp

ALICE, Nat. Phys. 13 (2017) 535

See also talk by A. Kalweit
Identified particle spectra in pp (13 TeV)

- Negligible pile-up
- Identification via dE/dx
- π, K, p: p < 1.2, 1.05, 1.7 GeV
- |y| < 1.0 (2.4 for N_{tracks})

Ratio of particle yields K/π & p/π correctly described by PYTHIA 8

- Low-multiplicity region well described
- High-multiplicity region needs tuning of baryon and/or strangeness prod.

\(<p_T>\) increases with \(m_{particle} & N_{tracks}\)
\(\sqrt{s}\) - evolution connected with saturation scale of gluons in proton

CMS, CERN-EP-2017-091

M. Tasevsky, Soft QCD Measurements at LHC, LP2017
Underlying Event study (13 TeV)

ATLAS, JHEP03 (2017) 157, also CMS tunes for UE/DPS in EPJC76 (2016) 155

Min. Bias events, leading track |

- Min. Bias events, leading track $|\eta| < 2.5, p_T > 0.5$ GeV
- High sensitivity to MPI
- EPOS overall fine but not good for $p_T$ (leading) $> 10$ GeV

- More collision energy $\rightarrow$ more UE activity.
- Typical plateau observed

UE = everything except the hard scattering
- Initial state radiation
- Final state radiation
- Multi-parton interactions
- Color reconnection

Balance between two soft QCD properties
- affected by color reconnection

Drell Yan events, leading $\mu^+ \mu^-$ pair
- $|\eta| < 2, p_T > 0.5$ GeV
- High sensitivity to MPI

CMS-PAS-FSQ-16-008
2-Particle azimuthal correlations

Long-range ($|\Delta \eta|>2$) ridge in 2-PC on near side ($\Delta \phi\sim0$) observed in large systems (central AA coll.)
- described by Fourier decomposition $\sim 1 + 2v_n \cos(n\Delta \phi)$, $v_n$ = single-particle anisotropy harmonics
- result of collective hydrodynamic expansion of hot and dense nuclear matter created in the overlap region

But long-range ridge seen also in pPb (much smaller system) and even in pp at high multiplicity!

- Origin of the ridge in small systems still under debate: hydrodynamics like for QGP? Initial state fluctuations (Color Glass Condensate/gluon saturation) ? Hadronization using ropes? Thin flux tubes?
- Ridge = testing ground to study complementarity between dynamical and hydrodynamical models

See also talk by A. Kalweit
2-Particle azimuthal correlations

- Size of near-side ridge & away-side ridge increases with multiplicity
- Size of near-side ridge maximal for $1 < p_T < 2$ GeV

Ridge separation from non-flow (resonance decays, dijets) using:
- low-multiplicity events (e.g. ATLAS, PRL 116 (2016) 172301)
- three-subevent method (next slide)

$v_2\{2\}(pp) < v_2\{2\}(pPb) < v_2\{2\}(PbPb)$

Expected: $v_2\{2\}(pPb) << v_2\{2\}(PbPb)$

pPb 5 TeV:
LHCb, PLB 762 (2016) 473 (ALICE, CERN-EP-2016-228)
Multi-particle azimuthal correlations

- 2-particle correlations suffer from non-flow. Multi-particle correlations are more robust against non-flow effects. But also more statistically demanding.
- Method: build cumulants $c_n\{2k\}$ and calculate flow harmonics $v_n\{2k\}$
- Extraction of collective flow in pp depends strongly on:
  
  **Event classification**
  
  **Purity of non-flow subtraction**

Three-subevent method: reduces well the non-flow and gives 4-particle cumulant $c_2\{4\} < 0$ in all three collision systems

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$

- $v_2\{4\} < v_2\{2\}$ in pPb and PbPb as expected for a long-range collective effect
- $v_2\{4\} \leq v_2\{2\}$ also in pp ($v_2\{4\}$ smaller for three-subevent method)
- $v_2\{4\} \sim v_2\{6\}$ in all three systems: Collective nature of ridge also in pp!

CMS, PLB 765 (2017) 193

11/08/2017
Angular correlations of identified particles

Study of near-side peak ($\Delta \eta \sim 0, \Delta \phi \sim 0$)

Baryon-(Anti)Baryon correlation

(Anti)Baryon-(Anti)Baryon anticorrelation

Depression not explained by:
- Fermi-Dirac Quant. Stat. (since depression seen also for $p\Lambda + \bar{p}\bar{\Lambda}$)
- Strong final state interactions
- Local baryon nr. conservation

Not reproduced by MC (Pythia 6, Pythia 8, Phojet - conserve local baryon nr., do not include quantum stat. effects).

Something essential missing in string fragmentation.
**Bose-Einstein correlations in pp, pPb, PbPb**

Min.Bias pp events, $|\eta| < 2.5$, $p_T > 0.1$ GeV

2-PC ($C_2$) of identical particles: Same-sign/Opposite-sign double ratio Data/MC

$C_2 = C_0 [1 + \Omega(\lambda, R)](1 + \varepsilon Q)$

$\lambda = \text{correlation strength}$

$R = \text{correlation source size}$

- Decrease of $R$ with $k_T$ measured (as in pPb: ATLAS, CERN-EP-2017-004)

- Saturation of $R$ at high-mult. - observed for the 1st time

Larger sources appear more coherent (pp, LHCb-PAPER-2017-025)

Multi-pion BEC in PbPb: ALICE, PRC 93 (2016) 054908

- Ratio measured multi-$\pi$ / expected multi-$\pi$ from 2-$\pi$:
  - pp, pPb: no suppression observed
  - PbPb: suppression at low $Q_4, Q_3$

- 4-$\pi$: explained by 32% of coherent correlations (but 3-$\pi$: not explained by 32% of coherent correlations)

(PbPb: ALICE, PRL 118 (2017) 222301)

M. Tasevsky, Soft QCD Measurements at LHC, LP2017
SUMMARY

- Soft QCD measurements important in many aspects:
  - $\sigma_{tot}$ as input for modelling pile-up at LHC and extensive air showers caused by cosmic rays
  - Very forward flow (also vs central flow) to model interactions in cosmic rays
  - Underlying event non-negligible in many LHC analyses
  - Particle correlations as a powerful tool to study multihadron production
  - To understand hadronization process

- All collision systems useful for soft QCD studies, complementing each other
- Performant LHC @ experiments provide high-statistics & high-precision data samples → estimate reliably many sources of systematics
- Sophisticated techniques (low $p_T \sim 100$ MeV, efficient background subtraction, unfolding…)
- Precision data help faster understand unexplained phenomena and develop/reject models

- Necessity to retune MC models to describe data at every energy
- Similar phenomena observed in PbPb / pPb / pp (high multiplicity) collisions: strangeness enhancement, collectivity effects. Why in small systems (pPb, pp)? Currently lively discussed
- Near-side ridge as testing ground to study complementarity between hydrodynamics/QGP and dynamics model (CGC/saturation/ropes)
- Intensive works on improving the hadronization models (lines/ropes/helices)
BACKUP SLIDES
Inclusive (total) pp cross-sections

TOTEM, ALFA(ATLAS): dedicated forward proton detectors (~220-240 m from interaction point)
- very close to beam (~few mm dep. on LHC optics ($\beta^*$))
- the larger $\beta^*$, the lower $t$
- dedicated runs (special LHC optics, negligible pile-up)

New TOTEM results for 2.76 TeV
$\beta^* = 11$ m, $0.08 < |t| < 0.4$ GeV$^2$

New ATLAS 8 TeV results
$\beta^* = 90$ m, $0.014 < |t| < 0.1$ GeV$^2$

New ATLAS result for 13 TeV
- Central detector only

$\sigma_{tot}$ input to model
- amount of pile-up at LHC
- interactions in cosmic rays

1) elastic observables only, $\rho=0.145$ from COMPETE, optical theorem

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \frac{1}{L} \frac{dN_{el}}{dt}(0)$$

2) no $\rho$, no optical theorem

$$\sigma_{tot} = \frac{1}{L} (N_{el} + N_{inel})$$

3) no $L$, optical theorem

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \frac{dN_{el}}{dt}(0)$$

11/08/2017
New (preliminary) results at 13 TeV: $\beta^* = 2.5$km, $0.0006 < |t| < 0.2$ GeV$^2$
- Coulomb-Nuclear Interference region

Pure exponential form ($N_b=1$) excluded at 7.2$\sigma$ significance

Non-exponential form observed also at 7 and 13 TeV

8 TeV: $\beta^* = 1.0$km, $0.0006 < |t| < 0.2$ GeV$^2$
Coulomb effects negligible

13 TeV point to come
2018 plan: 900 GeV
Inclusive charged particles in pp (13 TeV)

Min.Bias events: at least two tracks with $|\eta| < 2.5$, $p_T > 0.1$ GeV

very low value: special procedure

$\tau > 300$ ps (exclude strange baryons due to low reconstruction efficiency)

Multiplicity distribution again not described perfectly

$<p_T>(N_{ch})$: QGSJET: no colour coherence
PYTHIA 8: colour reconnection
EPOS: hydrodynamical evolution

EPOS gives best overall description
Inclusive very forward energy flow (13 TeV)

Energy measured in CASTOR calorimeter (-6.6 < \eta < -5.2)

Measurements suitable to tune:

1) MPI models in MC generators for pp collisions

2) MC generators modeling HE cosmic ray air showers

Dashed: tunes based on Tevatron data
Full: Tevatron + LHC (√s = 7 TeV) data
Identified particles at very forward direction

\[ \pi^0 \text{ at } 7 \text{ TeV, pp} \quad \text{LHCf, PRD 94 (2016) 032007} \]

\[ \text{Photons at } 13 \text{ TeV, pp} \quad \text{LHCf, CERN-EP-2017-051} \]

\[ \text{Neutrons at } 7 \text{ TeV, pp} \quad \text{LHCf, PLB 750 (2015) 360} \]

**LHCf:** soft neutral particles at very forward direction → constrains models for cosmic rays:

- \( X_{\text{max}} \) (shower maximum position) modeling needs: \( \sigma_{\text{inel}}^{p-\text{air}} \) & forward identified particle spectra

- hadronic interaction modeling needs: correlation between central and fw particle production (ATLAS vs LHCf or CMS vs TOTEM)
Inclusive charged particles in pp (0.9–8 TeV)

\[ \sqrt{s} = 0.9, 2.36, 2.76, 7, 8 \text{ TeV} \]

\[ |\eta| < 2, p_T > 0.1 \text{ GeV} \]

INEL = all (MB) events
NSD = Non Single Diffraction

- Measurement of \( dN_{ch}/d\eta (\eta=0)(\sqrt{s}) \sim s^\delta \): \( \delta = 0.114 \) (INEL) \( (\delta = 0.15 \text{ for central PbPb}) \)
- Alternatively: normalized q-moments \( C_q = \frac{<N^q_{ch}>}{<N_{ch}>^q} \)

For NSD events and three \( |\eta| \) intervals:

- \( C_2 \) constant over \( \sqrt{s} = 0.9-8.0 \) range
- \( C_3, C_4, C_5 \) increase with \( \sqrt{s} \) and with increasing \( \Delta \eta \) at given \( \sqrt{s} \)

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M. Tasevsky, Soft QCD Measurements at LHC, LP2017
Inclusive charged particles in pp (13 TeV)

Min. Bias events: at least two tracks with $|\eta| < 2.5$, $p_T > 0.1$ GeV

QGSJET: no colour coherence
PYTHIA 8: colour reconnection
EPOS: hydrodynamical evolution

Multiplicity distribution again not described perfectly

CMS-PAS-FSQ-15-008
$|\eta| < 2.4$, $p_T > 0.5$ GeV
SD = Single Diffraction

HERWIG++ deficient
EPOS gives best overall description (specialized soft QCD model)

In general: all models need to be retuned for the 13 TeV energy
Underlying Event study (13 TeV)

ATLAS, JHEP03 (2017) 157, also CMS tunes for UE/DPS in EPJC76 (2016) 155

Min.Bias events, leading track $|\eta| < 2.5, p_T > 0.5$ GeV

Models differ in MPI and color reconnection/coherence model

EPOS overall fine but not good for $p_T$ (leading) $> 10$ GeV

Drell Yan events, leading $\mu^+ \mu^-$ pair $|\eta| < 2, p_T > 0.5$ GeV

High sensitivity to MPI

More collision energy → more UE activity.

Typical plateau observed

M. Tasevsky, Soft QCD Measurements at LHC, LP2017
Strangeness enhancement in PbPb (5 TeV)

New results from 5 TeV PbPb collisions: 
\(\sqrt{s}\) closer to pPb and pp energies \(\rightarrow\) PbPb points approach better the trend from pp and pPb points
$J/\psi$ production in jets

- $J/\psi$ production occurs in transition between perturbative and non-perturbative QCD
- Measure $z(J/\psi) = p_T(J/\psi) / p_T\text{ (jet)}$ for prompt $J/\psi$ and those from $b$-hadron decays in jets

  - $J/\psi \rightarrow \mu^+\mu^-$, $2 < \eta(J/\psi, \mu) < 4.5$, $p_T(\mu) > 0.5$ GeV
  - Jets: anti-kt, $R=0.5$, $p_T > 20$ GeV, $2 < \eta < 4.0$

The 1st ever measurement of $z(J/\psi)$ for prompt $J/\psi$!

- Prompt $J/\psi$ produced in parton showers
- $z(J/\psi)$ not described by LO non-relativistic QCD (includes color-octet+color-singlet mechanisms) as implemented in PYTHIA 8.
- Some soft component missing?

- $z(J/\psi)$ of $J/\psi$ from $b$-hadron decays described by PYTHIA 8.
Bose-Einstein correlations in pp, pPb, PbPb

Min.Bias events, $|\eta| < 2.5$, $p_T > 0.1$ GeV

$\textbf{2-PC ($C_2$) of identical particles:}$ SS/OS double ratio Data/MC

$C_2 = C_0[1 + \Omega(\lambda, R)](1 + \epsilon Q)$

$\lambda$ = correlation strength

$R$ = correlation source size

Saturation of $R$ at high-mult. observed for the 1st time

Decrease of $R$ with $k_T$ observed also in pPb (ATLAS, CERN-EP-2017-004)

Larger sources appear more coherent (pp, LHCb-PAPER-2017-025)

$\textbf{Multi-pion BEC:}$ ALICE, PRC 93 (2016) 054908

- Corrected for Coulomb correlations

- Ratio measured multi-$\pi$ / expected 2-$\pi$:
  - pp, pPb: no suppression observed
  - PbPb: suppression at low $Q_4$, $Q_3$

$4$-$\pi$: explained by $32\%$ of coherent correlations

$3$-$\pi$: not explained by $32\%$ of coherent corr’s

(PbPb: ALICE, PRL 118 (2017) 222301)
Charge-dependent 3-particle azimuthal correlations with respect to (2nd order) event plane:
Same sign (SS) and opposite sign (OS) particle pairs and 3rd particle in forward calorimeter (to probe the long-range correlations).

The (OS-SS) difference interpreted as possible signature of chiral magnetic effect (CME) in AA collisions.

PbPb and pPb data show a similar effect.
BUT: in high-multiplicity pPb collisions a strong CME is not expected
- mag.field smaller than in peripheral PbPb collisions
- angle between mag.field and event plane randomly distrib.

- Slopes for PbPb and pPb different?
- Analogous effect produced by medium vorticity
- (Lambda polarization at STAR)
Hadronization of helical QCD string

- Lund string fragmentation: randomly broken 1D string, no cross-talk between break-up vertices
- Quantized helical (3D) string: causality (cross-talk) → 2 parameters (\(\kappa R, \Delta\Phi\)):
- Hadron spectra follow a simple quantized pattern: \(m_T = n \kappa R \Delta\Phi\)
- Predicts momentum difference \(Q\) for pairs of ground-state hadrons
- Adjacent pions produced with \(p_T\) difference ~266 MeV. Low-\(Q\) region populated by SS pairs (\(r=2\))

![Legend of the diagram](image1)

\[ P_{r=1,2} \geq 100 \text{ MeV, } |\eta| < 2.5, n_{ch} \geq 2 \]

Enhanced production of identical pairs

Identical input data

Bose-Einstein correlations (incoherent particle production)

Helical string fragmentation (coherent emission of chains of ground state pions)
- \(\Delta(Q) = [N(\text{OS})-N(\text{SS})]/N_{ch}\)
- Describes the low-\(Q\) region
- Source of correlations: 3-hadron chains

![Graph of ATLAS data](image2)

ATLAS, CERN-EP-2017-092

PR D89 (2014) 015002

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