Soft QCD Measurements at LHC

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On behalf of the LHC experiments
(ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM)

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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

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

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 $\rightarrow$ $0.0006 < |t| < 2$ GeV$^2$

13 TeV: $\beta^* = 2500$ m, $0.0006 < |t| < 0.2$ GeV$^2$
- Coulomb-Nuclear Interference region $\rightarrow \rho$ can be measured
- $\rho = $ 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)

\[ \sqrt{s} = 0.9, 2.36, 2.76, 7, 8 \text{ TeV} \]
\[ |\eta| < 2, p_T > 0.1 \text{ GeV} \]

\( \text{INEL} = \text{all (MB) events} \)
\( \text{NSD} = \text{Non Single Diffraction} \)

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

ALICE, EPJC77 (2017) 33

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)

\[ C_q = \frac{<N_{ch}>}{<N_{ch}^q>} \]

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 \( \sqrt{s} \)

In general: all models need to be retuned for every energy

KNO scaling violation

11/08/2017

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Very forward energy flow

CASTOR (-6.6 < η < -5.2) with EM and HAD calorimeters
- Inclusively EM particles (e⁺, e⁻, γ)
- Inclusively hadrons (mainly π⁺, π⁻)  CMS, CERN-EP-2016-313

Measurements suitable to tune:

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

2) MC generators modeling HE cosmic ray air showers

√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

- Xmax (shower maximum position) modeling: σ_p-air & 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,π⁰,γ) particles
- 140m from ATLAS, |η| > 8.4
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

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

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

Ratio of particle yields $K/\pi$ & $p/\pi$ 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
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

- Balance between two soft QCD properties
- Affected by color reconnection

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

More collision energy → more UE activity.
Typical plateau observed

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

High sensitivity to MPI
2-Particle azimuthal correlations

Long-range (|Δη|>2) ridge in 2-PC on near side (Δφ~0) observed in large systems (central AA coll.) - described by Fourier decomposition ~ \( 1 + 2ν_n \cos(nΔφ) \), \( ν_n \) = 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: $v_2\{2\}(pPb) \ll v_2\{2\}(PbPb)$

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PbPb 5 TeV:
LHCb, PLB 762 (2016) 473
(ALICE, CERN-EP-2016-228)

ATLAS, EPJC77 (2017), 428
CMS, PRL 116 (2016), 172302

$\langle N_{ch}(p_T > 0.4 \text{ GeV}) \rangle$

$\langle \text{associated yield} \rangle (\text{GeV}^2)$
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
Angular correlations of identified particles

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

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.

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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

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

$\lambda =$ correlation strength

$R =$ 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)
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)
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
$\beta^* = 11\text{m}, 0.08 < |t| < 0.4 \text{GeV}^2$

New ATLAS 8 TeV results
$\beta^* = 90\text{m}, 0.014 < |t| < 0.1 \text{GeV}^2$
ATLAS, PLB 761 (2016) 158

New ATLAS result for 13 TeV
- Central detector only
ATLAS, PRL 117 (2016) 182002

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

$\sigma_{tot}$ input to model
- amount of pile-up at LHC
- interactions in cosmic rays
8 TeV, $\beta^* = 90$m, $0.027 < |t| < 0.2$ GeV$^2$
- Coulomb effects negligible

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 7.2σ 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-Nuclear Interference region

13 TeV point to come
2018 plan: 900 GeV

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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)

$EPOS$ gives best overall description

Multiplicity distribution again not described perfectly

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

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Energy measured in CASTOR calorimeter (-6.6 < η < -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

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

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

\[ \eta > 10.94 \]

\[ 8.81 < \eta < 8.99 \]

\[ \text{LHCf: soft neutral particles at very forward direction} \rightarrow \text{constrains models for cosmic rays:} \]

- \( X_{\text{max}} \) (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**

**ALICE, EPJC77 (2017) 33**

(PbPb: PRL 116 (2016) 222302)

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

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 \(\sqrt{s}\)

**KNO scaling violation**

|\[ 11/08/2017 \]

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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

EPOS gives best overall description (specialized soft QCD model)

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

CMS-PAS-FSQ-16-008

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Strangeness enhancement in PbPb (5 TeV)

New results from 5 TeV PbPb collisions:
√s closer to pPb and pp energies → PbPb points approach better the trend from pp and pPb points.
**J/Ψ production in jets**

- J/Ψ production occurs in transition between perturbative and non-perturbative QCD
- Measure \( z(\text{J/Ψ}) = \frac{p_T(\text{J/Ψ})}{p_T(\text{jet})} \) for prompt J/Ψ and those from b-hadron decays in jets
  - J/Ψ→μ⁺μ⁻, \( 2 < \eta(\text{J/Ψ}, \mu) < 4.5 \), \( p_T(\mu) > 0.5 \) GeV
  - Jets: anti-kt, \( R=0.5 \), \( p_T > 20 \) GeV, \( 2 < \eta < 4.0 \)

The 1st ever measurement of \( z(\text{J/Ψ}) \) for prompt J/Ψ!

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

- \( z(\text{J/Ψ}) \) of J/Ψ 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

**2-PC ($C_2$) of identical particles:** SS/OS double ratio Data/MC

$$C_2 = C_0 [1 + \Omega(\lambda, R)] (1 + \varepsilon) \quad \lambda = \text{correlation strength} \quad R = \text{correlation source size}$$

- 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)

**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 (2\textsuperscript{nd} order) event plane:
Same sign (SS) and opposite sign (OS) particle pairs and 3\textsuperscript{rd} 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)

CMS, PRL 118 (2017) 122301

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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 (κR, ΔΦ):

  - Hadron spectra follow a simple quantized pattern: \( m_T = n \kappa R \Delta \Phi \)
  - Predicts momentum difference Q for pairs of ground-state hadrons

<table>
<thead>
<tr>
<th>Pair rank difference r</th>
<th>Q expected [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>266 ± 8</td>
</tr>
<tr>
<td>2</td>
<td>91 ± 3</td>
</tr>
<tr>
<td>3</td>
<td>236 ± 7</td>
</tr>
<tr>
<td>4</td>
<td>171 ± 5</td>
</tr>
<tr>
<td>5</td>
<td>178 ± 5</td>
</tr>
</tbody>
</table>

- Adjacent pions produced with \( p_T \) difference ~266 MeV. Low-Q region populated by SS pairs (r=2)

κR, ΔΦ fixed using masses of pseudoscalar mesons:

<table>
<thead>
<tr>
<th>meson</th>
<th>κR [MeV]</th>
<th>ΔΦ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>π</td>
<td>135 - 140</td>
<td>137</td>
</tr>
<tr>
<td>η</td>
<td>548</td>
<td>565</td>
</tr>
<tr>
<td>η'</td>
<td>958</td>
<td>958</td>
</tr>
</tbody>
</table>


Enhanced production of identical pairs

Bose-Einstein correlations (incoherent particle production)

Helical string fragmentation (coherent emission of chains of ground state pions)

- \( \Delta(Q) = \frac{[N(OS)-N(SS)]}{N_{ch}} \)
- Describes the low-Q region
- Source of correlations: 3-hadron chains

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