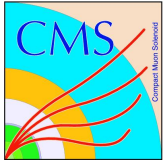
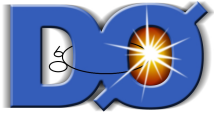
Results on soft QCD at LHC and Tevatron

Leszek Adamczyk

AGH - UST Cracow





Large Hadron Collider Physics 2021

Soft QCD

Soft QCD :

- Processes involving strong interaction characterized by low momentum transfer (soft)
- Low transverse momenta phenomena $\rightarrow$ effective α_s large $\rightarrow$ perturbative calculations not applicable $\rightarrow$ predictions based on phenomenological assumptions

Selected results on soft QCD:

- Elastic scattering
- Soft rapidity gap survival probability
- Underlying events (UE)
- Hadronization (soft particle production and correlations)
- Soft hadron-hadron interactions (via correlations)

Elastic scattering: Observation of Odderon

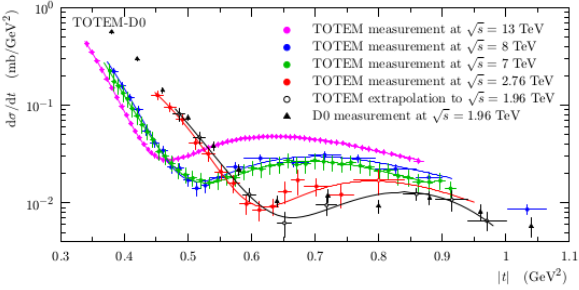
At high energy pp and $p\bar{p}$ elastic collisions dominated by colorless multi-gluon exchanges:

- C-even exchange amplitudes identical for pp and $p\bar{p}$.
- C-odd exchange amplitudes different sign for pp and $p\bar{p}$.
- Odderon : C-odd gluon compound.
  In leading order QCD confirmed as C-odd 3 gluon exchange.
- Odderon exchange predicts differences in elastic $d\sigma/dt$ for pp and $p\bar{p}$ manifesting i.a. by filling in the dip.

D0 and TOTEM elastic scattering data:

- D0 measured elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV.
- TOTEM measured elastic pp $d\sigma/dt$ at: 2.76, 7, 8 and 13 TeV.
- pp elastic $d\sigma/dt$ characterized by a diffractive minimum and a secondary maximum.

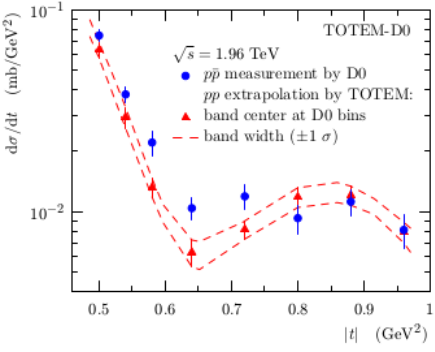
- Extrapolate "characteristic" points of TOTEM $d\sigma/dt$ to predict pp $d\sigma/dt$ at D0 energy.



 D0 and TOTEM: ArXiv:2012.03981 details: F.J. Nemes, Monday, 7 June, 18:30

Elastic scattering Observation of Odderon

Comparison of extrapolated pp $d\sigma/dt$ with $p\bar{p}$ D0 data:



- χ^2-test of difference: 3.4 σ significance for Odderon exchange
- Significance confirmed by a combined Kolmogorov-Smirnov and normalization test

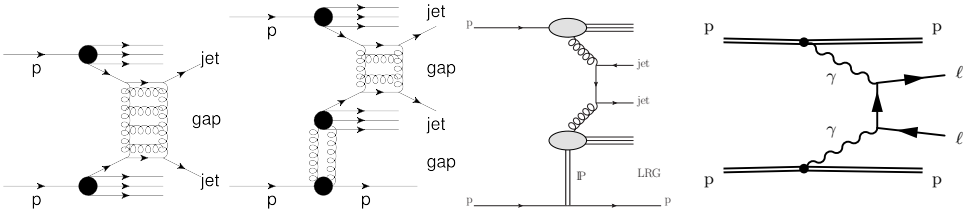
Previous evidence from TOTEM (EPJC (2019) 785):

- Using very low $|t|$ data at 13 TeV TOTEM measured σ_{tot} and ρ (ratio of real to imaginary part of elastic amplitude at $t = 0$).
- Combination of the measured ρ and σ_{tot} values not compatible with any set of models without Odderon exchange at 4.6 σ significance.

Combination of independent evidences of Odderon exchange fromTOTEM ρ and σ_{tot} with pp and $p\bar{p}$ comparison excludes avaiable models without Odderon at 5.2-5.7 σ leading to observation of Odderon

D0 and TOTEM: ArXiv:2012.03981 details: F.J. Nemes, Monday, 7 June, 18:30

Soft gap(proton) survival probability

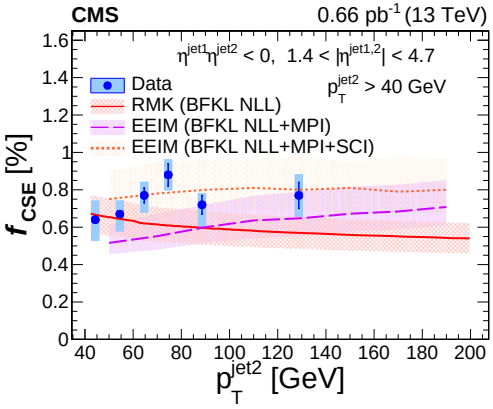


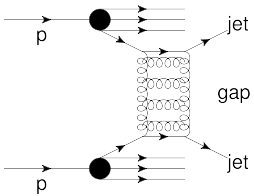
Observed rate of large rapidity gaps = $\langle |S|^2 \rangle$ theoretically calculated rate

- gap can separate two final state objects (like jets)
- gap can separate central state from beam particle (photoproduction, single diffraction)
- gap can separate central exclusive state (dilepton) from beam particle on each side of the system
- in $\gamma - \gamma$ fusion proton survival probability can be also interpreted as absorption effect due to the finite-size of the γ sources

$\langle |S|^2 \rangle$ is the probability of a given gap not to be filled by debris originating from the soft re-scattering of the spectator partons or absorption probability which suppress the rate of intact protons.
At LHC $\langle |S|^2 \rangle$ can be even $< 1\%$

Soft gap survival probability: jet-gap-jet





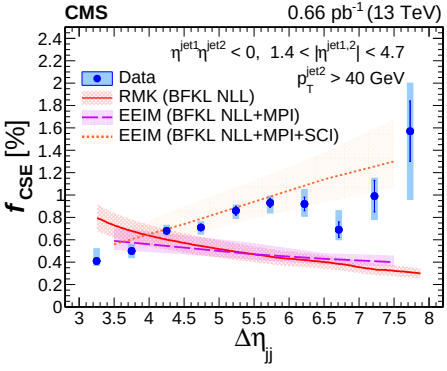
- Central gap due to the color-singlet exchange (CSE)
- f_{CSE} - fraction of CSE events to inclusive
- RMK: constant $|S|^2 = 10\%$ to fit data
- EEIM: constant $|S|^2 = 1.2\%$ to fit data
- EEIM: dynamical modeling of $|S|^2$ (Soft Color Interaction - SCI) tuned to fit 7 TeV data
- Data and SCI support weak $|S|^2$ dependence on p_T^{jet}

RMK: Phys. Rev. D 83, 034036
EEIM: PLB 524 (2002) 273

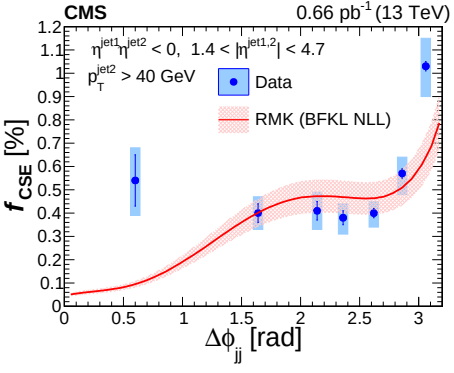
- different treatment of next-to-leading logarithmic corrections in the BFKL evolution

CMS and TOTEM: CMS-SMP-19-006 ; CERN-EP-2020-229 details: R. Gupta, Monday, 7 June, 17:18

Soft gap survival probability: jet-gap-jet



- RMK and EEIM (without SCI) yield a decreasing f_{CSE} with increasing $\Delta\eta_{jj}$ in contrast to data.
- EEIM (with SCI) correctly describe $f_{CSE}(\Delta\eta_{jj})$.



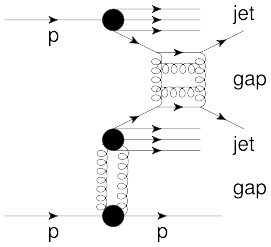
- RMK is consistent with the data at $1 < \Delta\Phi_{jj} < 3$ but underestimate the the data by near $\Delta\Phi_{jj} = \pi$ and at $\Delta\Phi_{jj} < 1$.
- $|S|^2$ larger for well separated jets in rapidity
- Interesting to study $|S|^2$ in $\Delta\eta_{jj} - \Delta\Phi_{jj}$ space.

CMS and TOTEM: CMS-SMP-19-006 ; CERN-EP-2020-229 details: R. Gupta, Monday, 7 June, 17:18

Soft gap survival probability: jet-gap-jet

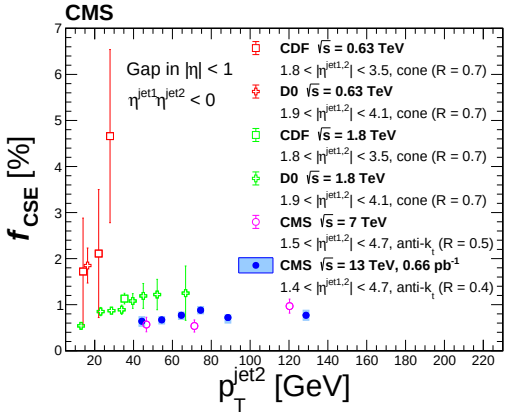
proton-gap-jet-gap-jet

- $|S|^2$ should be larger in the presence of second gap.
- measure f_{CSE} events with intact protons in TOTEM.



- f_{CSE} in events with an intact proton is 2.91 ± 0.70 (stat)+1.02-0.94(syst) times larger compared to inclusive dijet
- suggest that a gap is more likely to form or survive in the presence of another gap

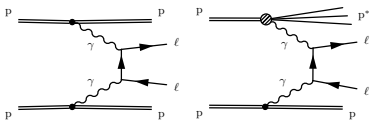
f_{CSE} vs. energy

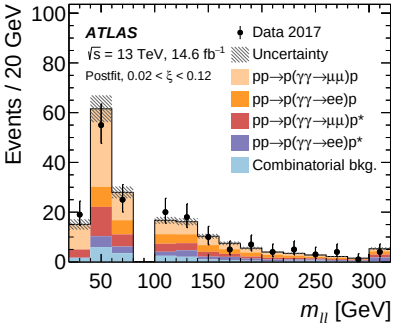


- a larger number of soft interactions with increasing $\sqrt{s}$
- but no further decrease of the f_{CSE} values starting from the 7 TeV

CMS and TOTEM: CMS-SMP-19-006 ; CERN-EP-2020-229 details: R. Gupta, Monday, 7 June, 17:18

Soft gap(proton) survival probability: photon-photon fusion





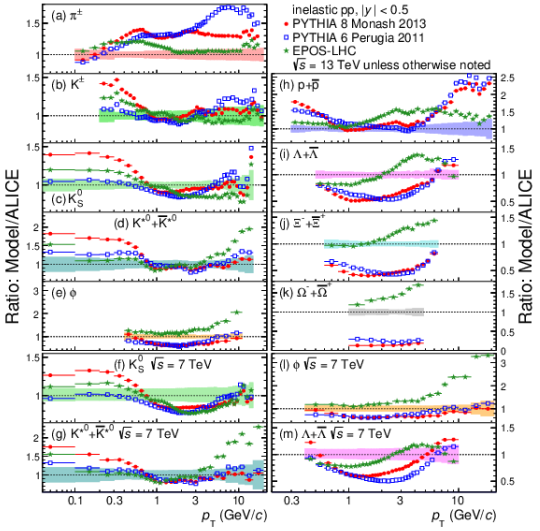
- Exclusive dilepton production $pp \to p(\gamma\gamma \to l^+l^-)p/p^*$ with forward proton measured in proton spectrometer
- Survival factor related to finite size effects of colliding protons DS (Phys. Lett. B741, 66 (2015)) or soft proton–proton interactions SuperChic 4 (Eur.Phys.J.C 80 (2020) 10, 925)

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [31,30]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [94]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

- HERWIG: elastic $pp \to p(\gamma\gamma \to l^+l^-)p$ scaled by $\langle |S|^2(m_{ll}) \rangle = 0.75$(DS).
- LPAIR: single dissociative $pp \to p(\gamma\gamma \to l^+l^-)p^*$ additionally scaled by 0.85 (Eur. Phys. J. C76(2016) 255)
- SuperChic 4 includes full kinematic dependence on $|S|^2$
- Forward proton detectors important for future measurements to better separate elastic, single and double dissociative contributions.

ATLAS: Phys. Rev. Lett. 125 (2020) details: A. Sopczak Monday, 7 June, 17:36

Soft particle production: Production of light-flavor hadrons

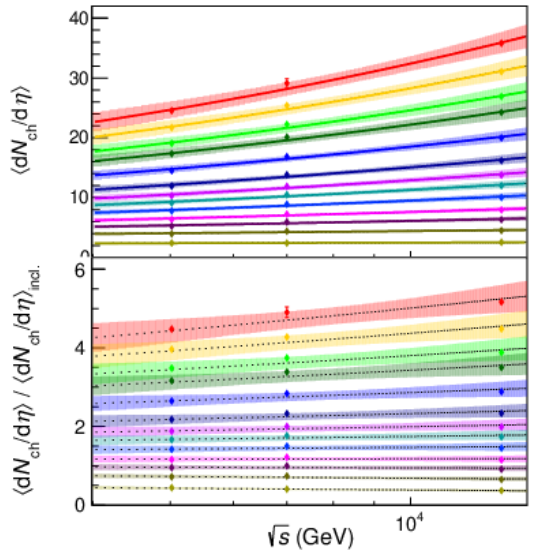


The high-precision measurements of the identified p_T spectra: crucial inputs for tuning of Monte Carlo generators and to improve the understanding of particle production mechanisms.

- PYTHIA 8, PYTHIA 6, and EPOS-LHC give similar descriptions of the data at both 7 and 13 TeV.
- PYTHIA 8 generally give softer p_T spectra than observed at low p_T attributed to difficulties at describing diffractive processes.
- PYTHIA 6 and EPOS-LHC better describe soft particle production.

 ALICE: Eur. Phys. J. C 81, 256 (2021)

Soft particle production: Charge particle densities



ALICE
pp collisions

Forward Multiplicity Class ($\sigma/\sigma_{MB_{AND>0}}$, %)

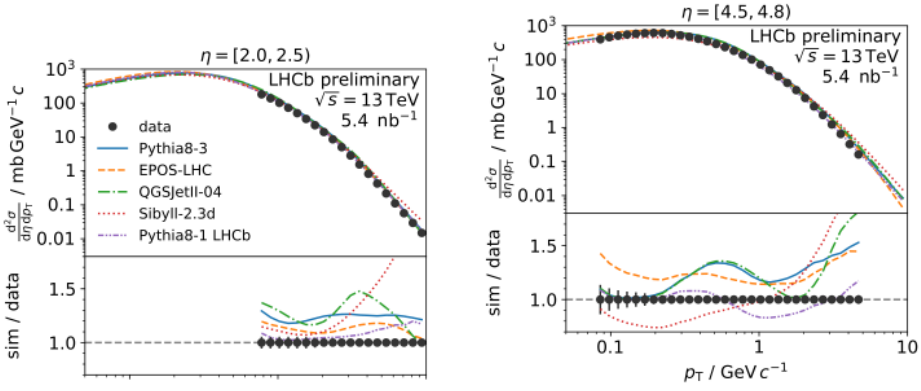
- 0 - 0.01 $\propto s^{0.196(10)}$
- 0.01 - 0.1 $\propto s^{0.186(10)}$
- 0.1 - 0.5 $\propto s^{0.179(10)}$
- 0.5 - 1 $\propto s^{0.176(10)}$
- 1 - 5 $\propto s^{0.163(9)}$
- 5 - 10 $\propto s^{0.156(9)}$
- 10 - 15 $\propto s^{0.147(10)}$
- 15 - 20 $\propto s^{0.140(10)}$
- 20 - 30 $\propto s^{0.131(10)}$
- 30 - 40 $\propto s^{0.110(10)}$
- 40 - 50 $\propto s^{0.095(10)}$
- 50 - 70 $\propto s^{0.063(9)}$
- 70 - 100 $\propto s^{0.030(12)}$

The energy and multiplicity dependence of the charged-particle pseudorapidity density can be used as an input for improving understanding of Multiple Parton Interactions.

- The yields of charged particles in the highest multiplicity classes for are up to about a factor of 5 higher with respect to the inclusive measurements
- Phenomenological power law fit describes the energy evolution.
- The average pseudorapidity density at midrapidity as a function of the energy increases for the highest multiplicity classes.
- It may arise from the increase of the MPI cross sections with the centre-of-mass energy

ALICE: ArXiv:2009.09434 [nucl-ex]

Soft particle production: Forward charged particle production

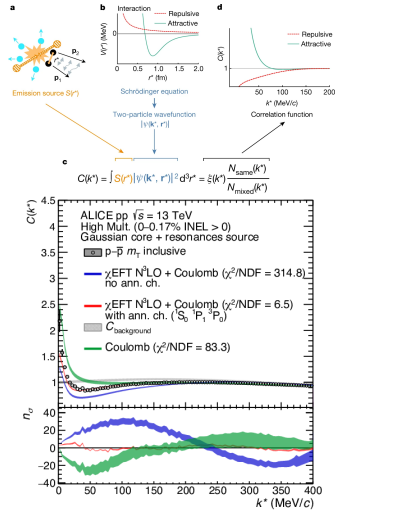


Fundamental measurement for (soft-)QCD, generator tuning, and astroparticle physics

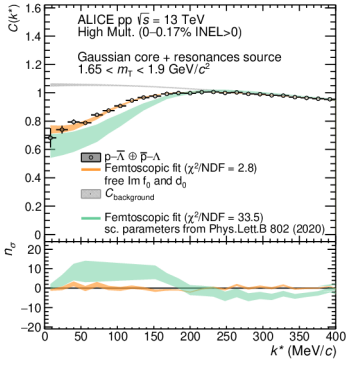
- Generators mostly overestimate forward density.
- Best agreement with EPOS-LHC

 LHCb: LHCb-PAPER-2021-010-001 details: A. Oblakowska-Mucha, Monday, 7 June, 17:54

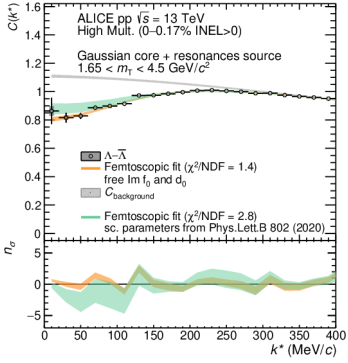
Strong interaction of hadrons : Correlation function



- Significant presence of the annihilation term down to zero momentum in $p - \bar{p}$.



- Scattering parameters obtained from HI collisions(mainly sensitive to elastic processes) describes $\Lambda - \bar{\Lambda}$ but underestimates $p - \bar{\Lambda}$ below 200 MeV/c.



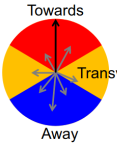
- Data indicates a different contribution of annihilation channels to the two systems containing strange hadrons.

ALICE: ArXiv:2105.05190 [nucl-ex]

Underlying event : Transverse plane activity

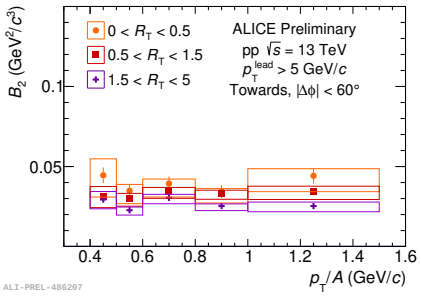
- UE activity quantified by the self-normalized charged particle multiplicity R_T.
- First measurements of (anti)deuteron production in several R_T classes.
- Flat B_2 vs. p_T/A suggests simple coalescence picture, both in towards and transverse regions.
- Similar B_2 in towards and transverse regions, contrary to expectation of large B_2 for small distances

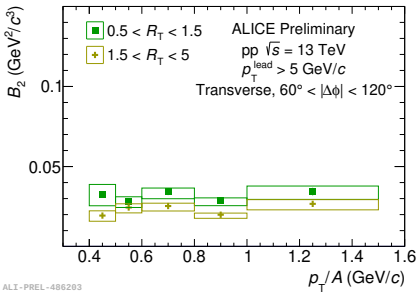
- R_T: self-normalized charged particle mult. in transverse region w.r.t trigger particle



$$R_T = \frac{N_{\text{transverse}}}{\langle N_{\text{transverse}} \rangle}$$

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_A/A}$$





 ALICE: Preliminary details: S. Tripathy, Monday, 7 June, 18:12

Summary

- Soft-QCD processes must be measured to help constrain phenomenological models and to tune Monte Carlos
- Precise models and well tuned Monte Carlos necessary to extract process of interest from large pile-up proton-proton interactions
- Many recent results including:
  - Odderon observation
  - Measurements sensitive to gap survival probability
  - Underlying events
  - Soft particle production and correlations
- Many more new measurements not covered in this presentation.