Forward Physics at LHC

• What is “Forward Physics at LHC”
• The need for coordination: the Yellow Report on “LHC Forward Physics”
• The total proton-proton cross section
• Soft and Hard diffraction
• Central Exclusive production
• New Physics

The Yellow Report community
What is “Forward Physics” at LHC

Forward physics includes a wide range of topics, and different experimental techniques.

The most obvious measurement is the total cross section and its components.

Particle Multiplicity, \( dN/d\eta \), Particle correlations are performed at low luminosity using detectors that covers rapidity < 3.

Soft diffraction, Hard Diffraction, and Exclusive production use higher rapidity detectors, and possibly proton tagging.
Let’s set the scale

The total cross section is dominated by soft processes.

If you were to eliminate every process below the first line (even the Higgs) the value of the total cross section would be the same.

If \( R_1 = R_2 = 10^{-13} \text{ cm} \) (one fermi)

\[ s \sim 10^{-25} \text{ cm}^2 = 100 \text{ mb} \]
A common origin…

The **Elastic**, **Soft diffraction**, **Hard Diffraction**, and **Central Exclusive production** have in common the **exchange of a color neutral object** between the incoming particles:
What is exchanged?

The most obvious configuration is the exchange of a 2-gluon state, but it can get very complicated...

As these gluons are soft, calculations use various parameterizations as pQCD cannot be used.

The exchanged colorless object takes the generic name of **Pomeron**
The word “pomeron” was very fashionable in the seventies, then it almost disappeared due to the lack of people able to do the appropriate calculations.
It had a revival with the HERA data, and it’s still going pretty well.

Number of paper with the word pomeron in the title
Experimental signatures: rapidity gaps

If somebody says “pomeron” you should think “rapidity gap”

In QCD fragmentation, rapidity gaps between two adjacent particles are exponentially suppressed:

\[ p(\Delta \eta) \propto e^{-\Delta \eta} \]

In pomeron exchange, rapidity gaps between two adjacent particles are not exponentially suppressed:

\[ p(\Delta \eta) \propto \text{const} \]
Where is the rapidity gap at LHC?

Total LHC pseudorapidity interval:
\[ \Delta \eta \sim \ln \left( \frac{s}{m_p^2} \right) \sim 20 \]

Assume a diffractive mass \( M_x \sim 500 \text{ GeV} \)
\[ \Delta \eta \sim \ln \left( \frac{M_x^2}{m_p^2} \right) \sim 12 \]

The rapidity gap, \( \Delta \eta \sim 3-4 \), is very forward, outside the CMS-ATLAS acceptance \( \Delta \eta \sim 10 \)

Not really usable!!
Experimental signatures: protons in the final state

If somebody says “pomeron” you should think “proton(s) in the final state”

As the pomeron is a color singlet, the proton does not fragment, and it retains a large fraction of the initial energy. It has high momentum and low pt, so it travels along side of the accelerator beam.
How to catch a forward proton

- Use **the beam magnet as a spectrometer**, to bend away the slightly slower protons
- **Insert your detectors inside the beam pipe**, using a clever device called “roman pot”, at a ~ 2 cm from the beam
- In the pot, **measure position** (pixel detectors) and **timing** (Cherenkov radiators)
CT-PPS (CMS) AFP (ATLAS): High tech detectors

The Upgraded Roman Pot Spectrometer (schematic)

Sector 4-5
(Sector 5-6 analogous)

2 new horizontal pots
(only 1 during LS1)

horizontal pots at 203 m and 214 m
equipped with Faraday cages (RF shields)

Cylindrical RP for timing detectors
CT-PPS (CMS) AFP (ATLAS): High tech detectors

Components installed in the tunnel during LS1
Why do we need timing?

Pileup! At each bunch crossing, there are many interactions (~50)

A precision of ~10 ps is needed in the detection of the leading proton to associate the proton to the correct vertex using “z-by-timing”

2 pots for Tracking

2 pots for Timing
What is the mass coverage of the CT-PPS/AFP?

Central Exclusive Production

\[ pp \rightarrow ppX \]

- \( \xi = p_1 \) momentum lost
- \( t_1 = -p_\perp + p_1 \)
- \( M_x = \sqrt{\xi_1 t_2} \)

Graph showing acceptance percentages for HPS at 22 degrees:
- 100% acceptance
- 50% acceptance

Diagram of mass coverage with:
- Low \( B^+ \)
  - \((\sim 0.6 \text{ m})\)
- High \( B^+ \)
  - \((\sim 90 \text{ m})\)
Detectors coverage

The goal of detector coverage is therefore to detect:

- Leading protons
- Rapidity gaps
- Particle production
- Identification of specific final state

\[ p_T^{max} = \sqrt{s}/2 \exp(-\eta) \]

\[ \frac{dp_T}{d\eta} \text{ (GeV/c)} \]

-10 -8 -6 -4 -2 0 2 4 6 8 10

CT-PPS ALFA RPS TOTEM RPS ZDC, LHCF CASTOR, T2 HFF/Cal, T1 ALICE LHCb CASTOR, T2 ZDC, LHCF TOTEM RPS ALFA RPS CT-PPS ~11 m ~14-17 m ~140m-240m-420m
The Yellow Report

- Large community (>100), dispersed on several experiments.
- Lack of a “Nobel prize” measurement to be used as PR weapon
- Very small weight in the LHC decision process
  ➔ Need coordination into a single voice

**Main problem:** data collected at high luminosity (~ 50 interactions per bunch crossing) cannot be used for forward physics, there are too many overlapping events

**Basic request to LHC:** enough time at reduced beam intensity to collect enough luminosity for forward physics studies.

5-10 days of running at low luminosity are necessary
The Yellow Report - I

Contents

1 Introduction

2 Running conditions and beam induced backgrounds
  2.1 Acceptance of Forward Detectors
  2.2 Background: pp induced background
  2.3 Different running conditions

2 Monte Carlo
  2.1 Introduction
  2.1.1 EPOS LHC
  2.1.2 PHOJET
  2.1.3 POMWIG
  2.1.4 PYTHIA 6 & 8
  2.1.5 QGSJET-II
  2.1.6 SHRIMPS
  2.1.7 Dime
  2.1.8 EXPHI
  2.1.9 FPMP
  2.1.10 STARLIGHT
  2.1.11 SuperCHIC
  2.1.12 HIC forward measurements and MC tuning

3 Soft Diffraction and Total Cross section
  3.1 Introduction
  3.2 Detecting soft diffraction with Forward Detectors
  3.2.1 Per Interaction Probability of Single and Double Tag
  3.2.2 Soft Vertex Reconstruction
  3.2.3 Proton and Vertex Reconstruction Conclusion
  3.3 Physics sources and properties of forward protons from inelastic interactions
  3.3.1 MC versions and tagged proton selection for inelastic studies
  3.3.2 Kinematics of tagged proton samples
  3.4 Soft pseudorapidity gaps
  3.4.1 Previous measurements
  3.4.2 Future soft pseudorapidity gaps studies with a proton tag
  3.4.3 Soft pseudorapidity gap studies with CASTOR
  3.4.4 Extending pseudorapidity gaps with forward shower counters
  3.4.5 Soft rapidity gap conclusion
  3.5 Measurements of the Inelastic Cross-Section
  3.6 Measurements of the Total, Elastic and Inelastic Cross-Section with the TOTEM detectors

4 Inclusive Hard Diffraction
  4.1 Introduction
  4.2 Backgrounds
  4.3 Single Diffractive Jet Production
  4.4 Single Diffractive Z, W and J/\Psi Production
  4.4.1 Motivation
  4.4.2 CMS-TOTEM feasibility studies for \( \sqrt{s} = 13 \text{ TeV} \)
  4.4.3 ATLAS feasibility studies for \( \sqrt{s} = 13 \text{ TeV} \)
  4.4.4 Double Pomeron Exchange Jet Production
  4.4.5 Motivation
  4.5 ATLAS feasibility studies for \( \sqrt{s} = 14 \text{ TeV} \)
  4.5.1 Motivation
  4.5.2 ATLAS feasibility studies for \( \sqrt{s} = 14 \text{ TeV} \)
  4.6 Double Pomeron Exchange Photon-Jet Production
  4.6.1 Motivation
  4.6.2 ATLAS feasibility studies for \( \sqrt{s} = 14 \text{ TeV} \)
  4.7 Double Pomeron Exchange Jet-Gap-Jet Production
  4.7.1 Motivation
  4.7.2 ATLAS feasibility studies for \( \sqrt{s} = 14 \text{ TeV} \)
  4.8 Summary

5 Central Exclusive Production
  5.1 Introduction
  5.2 Analysis techniques and detectors to study exclusive events at the LHC
  5.2.1 Analysis techniques
  5.2.2 CEP at LHCb and ALICE
  5.2.3 CEP at CMS and ATLAS
  5.3 QCD processes
  5.3.1 Introduction
  5.3.2 Forward proton tagging: phenomenological insight and advantages
  5.3.3 Exclusive Quarkonium Production
  5.3.4 'Exotic' Quarkonium
  5.3.5 Exclusive Photon Pair Production
  5.3.6 Exclusive Light Meson Pair Production
  5.3.7 Exclusive production of low mass resonances and glueballs

6.1 Elastic scattering

6.3 Inelastic scattering

6.4 TOTEM Plans at \( \sqrt{s} = 13 \text{ TeV} \)

7 Measurement Total and Elastic cross-section with ALFA

8 ALFA Plans at \( \sqrt{s} = 13 \text{ TeV} \)

9 Conclusions & Running Conditions

10 Elastic scattering

11 Inelastic scattering

12 TOTEM Plans at \( \sqrt{s} = 13 \text{ TeV} \)

13 Measurement Total and Elastic cross-section with ALFA

14 ALFA Plans at \( \sqrt{s} = 13 \text{ TeV} \)

15 Conclusions & Running Conditions
The Yellow Report - II

5.3.8 Exclusive J/ψ Pair Production .................................................. 108
5.3.9 Exclusive jet production ......................................................... 111
5.4 Photon−induced and photoproduction processes ..................... 120
5.4.1 Introduction .............................................................................. 120
5.4.2 Forward proton tagging: phenomenological insight and advantages .................................................... 120
5.4.3 Two-proton collisions .............................................................. 121
5.4.4 Diffractive photoproduction $\gamma p \to V p$ ................................... 123
5.5 Exploratory physics ..................................................................... 133
5.5.1 Introduction .............................................................................. 133
5.5.2 Search for missing mass and momentum candidates ............ 133
5.5.3 Searching for magnetic monopoles with forward proton detectors .......................................................... 134
5.5.4 Exclusive photon induced production of $\gamma \gamma$, WW and ZZ .......................................................... 138
5.5.5 The search for new strong dynamics in exclusive diffraction .......................................................... 150

6 Cosmic Ray Physics, Particle multiplicities, correlations and spectra

6.1 Introduction .............................................................................. 161
6.2 LHC and air showers ................................................................. 163
6.2.1 LHC data and hadronic interaction models ......................... 163
6.2.2 Hadronic interaction models and air showers .................... 165
6.2.3 Need for measuring proton-oxygen interactions ................. 166
6.3 Energy Flow ............................................................................. 168
6.3.1 Past Measurements of Energy Flow ................................. 168
6.3.2 Future Measurements of Energy Flow ............................... 169
6.4 Particle multiplicities ................................................................. 171
6.4.1 Past measurements of charged particle multiplicities ........ 171
6.4.2 Future measurements of charged particle multiplicities .... 173
6.5 Spectra ...................................................................................... 175
6.5.1 Measurement of identified charged particle spectra in pp and p-Pb collisions with ALICE ..................... 175
6.5.2 Neutral particle spectra ......................................................... 181
6.5.3 Heavy flavor particle spectra ................................................. 183
6.6 Beam ....................................................................................... 185
6.6.1 Proton-proton collisions ....................................................... 185
6.6.2 Light ion collisions ............................................................... 187

7 Heavy Ion Physics

7.1 Introduction .............................................................................. 192
7.2 UPC processes at the LHC ........................................................ 192
7.3 The photon flux at the LHC ....................................................... 193
7.4 UPC measurements with lead ions at the LHC during Run1 .......................................................... 195
7.5 UPC measurements with lead ions at the LHC after Run1 .................. 196
7.5.1 Main goals for UPC physics in Run2 ..................................... 196
7.5.2 Experimental challenges ...................................................... 196

8 BFKL and saturation

8.1 Introduction .............................................................................. 203
8.2 Inclusive forward di-jet production in pp ................................ 204
8.2.1 High Energy Factorization .................................................. 205
8.2.2 Dijet production at forward and very-forward rapidities .... 205
8.2.3 Trijet production at forward-central and purely forward rapidities .................................................... 206
8.3 Forward backward jet production in pp and pp ................. 207
8.3.1 Forward backward jet production - theoretical developments I: A window of opportunity to establish the range of applicability of the BFKL resummation program .............................. 208
8.3.2 Forward backward jet production - theoretical developments II .......................................................... 214
8.3.3 Forward backward jet production - theoretical developments III: MPI vs BFKL contribution .................. 216
8.3.4 Forward backward jet production - measurements from D0 .......................................................... 222
8.3.5 Forward backward jet production - measurements from CMS .......................................................... 222
8.3.6 Forward backward jet production - measurements from ATLAS .................................................... 224
8.3.7 RunII expectations ................................................................. 226
8.4 Forward jet production - measurements at very large rapidities .................................................... 226
8.4.1 Forward Drell-Yan production - theoretical developments I .......................................................... 228
8.4.2 Forward Drell-Yan production - theoretical developments II: Low mass DY production at the LHC within the dipole formalism .......................................................... 230
8.4.3 Forward Drell-Yan production - theoretical developments III .......................................................... 236
8.4.4 Forward photon production and gluon saturation - theoretical overview and measurement proposal .......................................................... 239
8.5 Large-x physics in p+p and p+A collisions .......................... 242
8.5.1 Heavy quarks ................................................................. 242

9 Detectors

9.1 ATLAS-ALFA Experiment ...................................................... 257
9.2 TOTEM Experiment ............................................................... 260
9.2.1 Standard TOTEM Detectors Operated during Run-I at High $\beta$ .......................................................... 261
9.2.2 Detector Upgrade for Vertical Roman Pots ......................... 263
9.3 Forward Shower Counters in CMS ........................................... 272
9.4 CMS-TOTEM Proton Spectrometer (CT-PPS) ....................... 274
9.4.1 Development of Low-Impedance Roman Pots ............... 275
9.4.2 Requirements on the Timing Detectors and Strategy ....... 285

Recommendations ........................................................................ 197
Theoretical proposals ................................................................... 197
Tracking fast small color dipoles through strong gluon fields at the LHC .......................................................... 197
Studies of the color fluctuation phenomena ................................ 198
Multiparton interactions in the direct photon kinematics ........... 199
Propagation of partons through nucleons and nuclei at ultrahigh energies .......................................................... 199
Introduction ................................................................................. 199
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4.3</td>
<td>Pixel Tracking System</td>
<td>293</td>
</tr>
<tr>
<td>9.5</td>
<td>The AFP Detector</td>
<td>296</td>
</tr>
<tr>
<td>9.5.1</td>
<td>Beam Interface</td>
<td>297</td>
</tr>
<tr>
<td>9.5.2</td>
<td>Silicon Tracker</td>
<td>297</td>
</tr>
<tr>
<td>9.5.3</td>
<td>Time-of-Flight Detector</td>
<td>299</td>
</tr>
<tr>
<td>9.5.4</td>
<td>Data Acquisition</td>
<td>304</td>
</tr>
<tr>
<td>9.6</td>
<td>LHCb Experiment</td>
<td>304</td>
</tr>
<tr>
<td>9.6.1</td>
<td>HERSCHEL configuration</td>
<td>305</td>
</tr>
<tr>
<td>9.6.2</td>
<td>Detector Design and Installation</td>
<td>306</td>
</tr>
<tr>
<td>9.6.3</td>
<td>Conclusions</td>
<td>308</td>
</tr>
<tr>
<td>9.7</td>
<td>AD: The Alice Diffractive Detector</td>
<td>308</td>
</tr>
<tr>
<td>9.7.1</td>
<td>Design of AD</td>
<td>308</td>
</tr>
<tr>
<td>9.7.2</td>
<td>Commissioning of AD</td>
<td>309</td>
</tr>
<tr>
<td>9.8</td>
<td>LHCf Detectors</td>
<td>310</td>
</tr>
<tr>
<td>10</td>
<td>Summary and Conclusion</td>
<td>316</td>
</tr>
<tr>
<td>A</td>
<td>Title of appendix</td>
<td>316</td>
</tr>
<tr>
<td>A.1</td>
<td>Subsection title in appendix</td>
<td>316</td>
</tr>
</tbody>
</table>
The Total cross section

The cross section between composite particles has a much more complex dependence from the center-of-mass energy, and it’s not calculable.

Let’s consider a proton. It contains:
- valence quarks
- sea quarks
- gluons

These define the particle to be a proton

Mostly SU(3) color symmetric, common to protons and anti-protons (almost true..)

What part is controlling the total cross section?
The pp and ppbar cross section

At low energy $\sigma$ is different: ➔ valence quarks need to be important here

At high energy $s$ is the same: ➔ sea quarks and gluons can contribute
Pre-LHC situation

Three large families of parametrization:

\[ \sigma_{\text{TOT}}(s) = c + a s^{-0.5} + b s^{0.08} \]

\[ \sigma_{\text{TOT}}(s) = c + a s^{-0.5} + g \ln^2(s) \]

(most favorite COMPETE prediction)

\[ \sigma_{\text{TOT}}(s) = c + a s^{-0.5} + b \ln(s) + g \ln^2(s) \]

QCD: exchange of valence quark

QCD: exchange of sea quark and gluons, glueballs...

Pomeron increase

Reggeon decrease

To infinity
Post-LHC situation

Very remarkable precision
The rise of the gluons

As measured at HERA, the gluon PDFs experience a very strong rise as the energy increases.

If the pomeron is related to “gluons”, it’s reasonable to assume a modification of the pomeron term, adding a “hard pomeron”.

the cross section starts rising more rapidly at higher energy.

\[
\sigma_{\text{TOT}}(s) = \alpha s^{-0.5} + \beta s^{0.067} + \gamma s^{0.45}
\]

(2 simple poles)

How much this rise will be at \(s \sim 14\text{TeV}\) is the key question for this year!
Montecarlo Models

- QGSJET 01, QGSJET II
- SIBYLL
- PHOJET
- EPOS

RFT based models

Soft QCD
- $\sigma_{\text{Tot}}$
- $\sigma_{\text{El}}$
- $\sigma_{\text{Inel}}$
- $\sigma_{\text{SD}}$
- $\sigma_{\text{DD}}$

$\sim \Lambda_{\text{QCD}}$

Extended to

Hard QCD

pQCD based models

Extended to

PYTHIA
HERWIG
SHERPA
What is $\sigma_{\text{tot}}$ made of?

**TOTAL cross section means measuring everything...**

We need to measure every kind of events, in the full rapidity range:

**Elastic**: two-particle final state, very low $p_t$, at very high rapidity.

- Very difficult, needs dedicated detectors near the beam

**Diffractive**: Single, Double, Central diffractions, gaps everywhere.

- Quite difficult, some events have very small mass, difficult to distinguish diffraction from standard QCD, needs dedicated detectors near the beam

**Everything else**: jets, multi-particles, Higgs....

- Easy
Diffraction scattering at LHC

Very difficult to tag diffraction using rapidity gaps:

- The gap is outside the detector coverage
- Pile-up events destroy the gap
- Gap-survival probability is low

→ Need to measure the protons in the final state
Case Study: Single Pomeron with Jets, Z, W

Main Goal:
Gluon structure function

Tagging technique: gap + proton
Case Study: Double Pomeron Exchange (DPE)

Main Goal:
Gluon structure function

Tagging technique: proton + proton
Case Study: DPE with Jet-Gap-jet

Main Goal: BFKL evolution between the hard scale set by the two jets

Tagging technique: proton + gap + proton
Central Exclusive Production (CPE)

CPE is a particularly interesting reaction as its kinematics are over constrained.

$M_x$ can be determined either by:
- The central detectors
- The momentum of the two scattered protons

Mass acceptance of the two forward protons

![Diagram showing the reaction process](image-url)
Central Exclusive Production (CPE)

CPE is a particularly interesting reaction as its kinematics are over constrained. \(M_x\) can be determined either by:

- The central detectors
- The momentum of the two scattered protons

Mass acceptance of the two forward protons
Possibility of measuring quartic gauge coupling: $\gamma\gamma WW$

**Standard Model:** $\sigma(\gamma\gamma WW) = 95.6$ fb,

Very good place to look for anomalous coupling!
Possibility of measuring quartic gauge coupling: $\gamma \gamma \gamma \gamma$

Additional diagrams from exotic possibilities

$\gamma \gamma \gamma \gamma$ couplings can be modified in a model independent way by loops of heavy charge particles.

CPE: $\gamma \gamma \rightarrow \gamma \gamma$
Conclusions

The LHC restart opens an exciting period of new physics

The installation of forward detectors will lead to unprecedented possibility in the understanding of forward physics:
- Better understanding the Pomeron structure in terms of quarks and gluon, universality of Pomeron, jet gap jets, search for extra-dimensions in the universe via anomalous couplings between $\gamma$, W, Z, for magnetic monopoles...