Diffraction Physics at LHCb

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- The LHCb Experiment
- Energy Flow
- Central Exclusive Production
- New Developments
- Summary
1. The LHCb Experiment

- 69 institutes
- 16 countries
- 1132 members
Detector layout and performance

**RICH1 & RICH2**
- $\epsilon(K \rightarrow K) \sim 95\%$
- $\pi \rightarrow K$ mis-id: $\sim 5\%$

**Calorimeters**
- ECAL: $\sigma_E/E \sim 1\% + 10%/\sqrt{E[GeV]}$

**Tracking System**
- $\Delta p/p = 0.4\%$@5 GeV/c to $0.6\%$@100 GeV/c

**VELO**
- $\sigma_{IP} \sim 20$ $\mu$m for high-$p_T$ tracks
- bwd acc. $-4 < \eta < -1.5$

**Muon System**
- $\epsilon(\mu \rightarrow \mu) \sim 97\%$
- $\pi \rightarrow \mu$ mis-id: $1 \sim 3\%$

**Pseudorapidity acceptance**
- $2 < \eta < 5$
Angular coverage of the LHC experiments

- ALICE
  - central
  - forward muon coverage

- ATLAS & CMS
  - central detectors

- LHCb
  - forward detector
  - tracking, particle-ID and calorimetry in full acceptance

Legend:
- hadron PID
- muon system
- lumi counters
- HCAL
- ECAL
- tracking
- **long and downstream tracks**: used for physics measurements
  - proper momentum measurement (best resolution for long tracks)
- **VELO tracks**: (primary) vertex reconstruction
  - large angular acceptance $-4 < \eta < -1.5$ and $1.5 < \eta < 5$
- **upstream tracks**: subset of VELO tracks with hits in TT
- **T-tracks**: only found in T-stations (partly from secondary interactions)
The VErtex LOcator (VELO)

→ LHCb subsystem with largest angular coverage

- 21 $r\phi$ & 2 $r$-only stations
- outside of magnetic field
- no momentum measurement
- forward and backward coverage
- blind in central region

 RF-foil

 VELO silicon sensors

 1m

 Interaction region $\sigma = 5.3\text{cm}$

 cross section at $y=0$: $x$ $z$

 1 m

 390 mrad

 60 mrad

 15 mrad
Inelastic pp Interactions

→ classification of pp-interactions

Notes:
- differentiation of inelastic cross section according to
  - color exchange (color octet, gluon): non-diffractive processes
  - no color exchange (color singlet, pomeron): elastic & diffractive scattering
- no acceptance for elastic scattering with LHCb
inelastic processes are not truly distinguishable

- example: $pp$-event with single diffractive signature
  - one proton is scattered quasi-elastically, OR
  - both protons are broken up & fragmentation generates a forward proton
- PYTHIA approach: cross sections for different processes
  \[
  \sigma_{inel} = |A_{SD1}|^2 + |A_{SD2}|^2 + |A_{DD}|^2 + |A_{DPE}|^2 + |A_{ND}|^2
  \]
- alternative view: amplitudes for different processes
  \[
  \sigma_{inel} = |A_{SD1} + A_{SD2} + A_{DD} + A_{DPE} + A_{ND}|^2
  \]
- comments:
  - interference terms small in some regions of phase space
  - experimental cuts allow to probe contributions by certain amplitudes
    - leading protons, large rapidity gaps: color singlet amplitudes
    - large multiplicities, large range in $\eta$: color octet amplitudes
  - rigorous separation of diffractive & non-diffractive processes impossible


2. **Energy Flow**

→ **Energy Flow (EF):** average energy per event in a given $\eta$-interval

\[
EF : \quad \frac{1}{N_{int}} \frac{dE}{d\eta} = \frac{1}{\Delta \eta} \left( \frac{1}{N_{int}} \sum_{i=1}^{N_{part,\eta}} E_{i,\eta} \right)
\]

→ part of underlying event
→ sensitive to multi-parton interactions & parton radiation
→ comparison to PYTHIA 6, PYTHIA 8 and cosmic ray models
  (generators used to model cosmic ray induced air showers)

❖ analysis for different event classes:

- **inclusive minimum bias:** $\geq 1$ tracks with $\eta \in [1.9, 4.9]$ and $p > 2$ GeV/$c$
- **hard scattering:** inclusive $\&\& \geq 1$ tracks with $p_T > 3$ GeV/$c$
- **diffractive enriched:** inclusive $\&\&$ 0 tracks with $\eta \in [-3.5, -1.5]$
- **non-diffractive enriched:** inclusive $\&\& \geq 1$ tracks with $\eta \in [-3.5, -1.5]$
Energy Flow: data vs PYTHIA

**(charged+neutral)EF**

- Energy Flow increases with momentum transfer
  \[ EF_{\text{diff}} < EF_{\text{incl}} < EF_{\text{ndiff}} < EF_{\text{hard}} \]
- highest sensitivity at large \( \eta \)
- uncertainties:
  - dominated by systematics
  - smallest at large \( \eta \)

PYTHIA 6: Energy Flow is
- overestimated at small \( \eta \)
- underestimated at large \( \eta \)

PYTHIA 8.135 default:
- except for hard scattering
  - the Energy Flow is well described for all samples
models not tuned to LHC

EPOS & SIBYLL:
- good description of EF for inclusive and non-diffractive events

QGSJET models:
- overestimated EF for inclusive and non-diffractive events; good description of hard scattering
- best description by SIBYLL
- all models underestimate the EF of diffractive events
contributing processes

QED  photo production  double pomeron exchange

- di-muon or di-muon plus photon final states (for $\chi_c$)
- in the following focus on di-muon final states
Experimental aspects

- use VELO to veto non-exclusive processes

- note that some background will remain...
Event displays

→ compare $pp \rightarrow Z(\mu\mu)X$ and CEP $J/\psi$ production

- clean experimental signatures
- very low multiplicities at TeV centre-of-mass energies!
Exclusive di-muon invariant mass spectrum

- clear mass peaks of $J/\psi$ and $\psi(2S)$
- exponentially falling QED background
Transverse momentum spectra

→ disentangle exclusive and non-exclusive components

- superposition of two exponentials - Regge theory inspired \(d\sigma/dt \sim e^{bt}\)
  - soft component: CEP
  - hard component: “normal” QCD
- fitted slopes consistent with expectations extrapolated from HERA
  - \(J/\psi\): \(b_{\text{CEP}} = 5.70 \pm 0.11\,\text{GeV}^{-2}\), \(b_{\text{non-excl}} = 0.97 \pm 0.04\,\text{GeV}^{-2}\)
  - \(\psi(2S)\): \(b_{\text{CEP}} = 5.1 \pm 0.7\,\text{GeV}^{-2}\), \(b_{\text{non-excl}} = 0.8 \pm 0.2\,\text{GeV}^{-2}\)
Rapidity dependence

- compare data to theoretical predictions

- data and predictions agree within uncertainties
- NLO calculations are preferred
Photo-production cross-section

**Theoretical Description**

\[
\frac{d\sigma}{dy_{pp \to pJ/\psi p}} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p \to J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p \to J/\psi p}(W_-)
\]

- Left-hand side measured by LHCb
- Two targets for producing the $J/\psi$
- LHCb cross-sections proportional to
  - Gap survival probability $r$
  - Photon flux $dn/dk$
- Sensitivity to gluon PDF $g(x)^2$

**HERA Measurement:**

\[
\sigma_{\gamma p \to J/\psi p}(W) = 81 \left( \frac{W}{90\text{GeV}} \right)^{0.67} \text{ nb}
\]

- Take $\sigma_{\gamma p \to J/\psi p}(W_{\pm})$ from HERA and solve for $\sigma_{\gamma p \to J/\psi p}(W_{\mp})$
Comparison to HERA results

- LHCb data enter twice
- significant extension of kinematic range
- qualitative description by power law works
- evidence for deviation from simple power law \(\Rightarrow\) NLO contributions (?)
Double $J/\psi$ production

→ surprise discovery

- initially not expected
- a posteriori reasonable well theoretically understood
Double $J/\psi$ mass spectra

- Clean experimental signal
- Di-$J/\psi$ mass spectra similar in CEP and inclusive production
Extraction of the exclusive part

- disentangle components via $p_T$ spectrum

- 42 ± 13% exclusive contribution
- additional large uncertainties from modelling the non-exclusive part
4. New Developments

HeRSChel: High Rapidity Shower Counters for LHCb

- forward scintillators for selecting rapidity gaps
- up to $\pm 114$ m from IP
- central region not covered
- gap size $2 < \eta < 8$

- huge gain for diffractive physics and central exclusive production (e.g. $J/\psi$ photoproduction on the proton in pA)

LHCb simulation results for the efficiency to see charged pions

$p_T > 0.5$ GeV/c  \quad p_T > 1.5$ GeV/c
Fixed target physics with LHCb

**SMOG: System for Measuring Overlap with Gas**

- injection of (Ne) gas into interaction region
- very simple robust system
- used for a precise luminosity determination

- possibility to inject (noble) gases: Ne or He, Ar, Kr (under discussion)
- fixed target physics in pA and PbA configuration
→ first look at PbNe collisions using data from $O(10)$ min running

PbNe-interactions - $\sqrt{s_{NN}}=54.4$ GeV

Physics potential:

- explore nuclear structure at large $x$
- conditions between SPS and RHIC for QGP studies
**cosmic ray physics and cosmology**

- understanding of extensive air showers ➔ MC tuning
- understanding the AMS antiproton/proton ratio

**AMS \( \bar{p}/p \) results and modeling**

- **use fixed target measurements to clarify:** QCD or Dark Matter annihilation
5. SUMMARY

▶ diffraction physics is an integral part of the LHCb physics portfolio

- results from RunI
  - Energy Flow measurements study diffractive particle production
  - results on single and double charmonium production in CEP
  - CEP results from p-Pb collisions in the pipeline

- prospects for LHC RunII
  - improved detector for diffractive physics
  - more data in pp and p-Pb
  - new centre-of-mass energies
  - new developments further enlarge the physics program
    - fixed target physics
    - Pb-Pb collisions