Isolation in inclusive and exclusive processes

Ronan McNulty
University College Dublin
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Why is isolation important?

- **One definition of diffraction (Alan Martin)**
  “A diffractive process is characterized by a large rapidity gap (LRG), caused by t-channel Pomeron exchange.”

<table>
<thead>
<tr>
<th>Cross-section (13 TeV)</th>
<th>(mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>~40</td>
</tr>
<tr>
<td>Diffractive</td>
<td>~10</td>
</tr>
<tr>
<td>Inelastic</td>
<td>~60</td>
</tr>
</tbody>
</table>

Diffractive can be further divided into single (SD), double (DD) and central exclusive production (CEP) ~ 0.1mb, where the gaps are critical.
Schematic Representation

Elastic

Single Diffractive

Double Diffractive

Central Exclusive Production

Inclusive
Inclusive pp→ZX
Physics of the Vacuum

Elastic scattering

\[ \sigma_{\text{elastic}} \approx 40 \text{mb} \]

\[ \sigma_{\text{diffractive}} \approx 10 \text{mb} \]

\[ \sigma_{\text{inelastic}} \approx 60 \text{mb} \]
Physics of the Vacuum

Elastic scattering

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It’s QCD – but not as we normally see it. It’s colour-free
Physics of the Vacuum

Elastic scattering

At high energy: \[ A(s,t) = s^{\alpha(t)} \]
\[ \alpha_p(t) = \alpha_p(0) + \alpha't \]

\[ \sigma_{\text{elastic}} \approx 40 \text{mb} \]
\[ \sigma_{\text{diffractive}} \approx 10 \text{mb} \]
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Physics of the Vacuum

Single Diffractive

\[ \sigma_{\text{elastic}} \approx 40 \text{mb} \]
\[ \sigma_{\text{diffractive}} \approx 10 \text{mb} \]
\[ \sigma_{\text{inelastic}} \approx 60 \text{mb} \]
Physics of the Vacuum

Central Exclusive Production

Clean way to study QCD:
- structure of projectiles
- nature of colour-free propagators
- structure of what is produced out of vacuum

\[ \sigma_{\text{elastic}} \approx 40 \text{mb} \]
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Physics of the Vacuum

Central Exclusive Production

\[ \sigma_{\text{elastic}} \approx 40 \text{mb} \]
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Physics of the Vacuum

Central Exclusive Production

QED

\( p \) \rightarrow \text{Photon} \rightarrow \text{Photon} \rightarrow \text{Photon} \rightarrow \text{p}

\sigma_{\text{elastic}} \approx 40\text{mb} \quad \sigma_{\text{diffractive}} \approx 10\text{mb} \quad \sigma_{\text{inelastic}} \approx 60\text{mb}

CEP is characterised by a rapidity gap all the way to the proton

Detect as large a gap as possible...

100 \text{pb}
Detectors do not have $4\pi$ coverage.

- How big a gap do you need to know it is diffractive?
- How can we deal with proton dissociation, where the break-up products are emitted at very low angles?
Colour confinement leads to correlations (jets and gaps). But whereas high $p_T$ jets is perturbative, low $p_T$ gaps is not.
Determining isolation....

- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays
Determining isolation...

Final particle distribution depends critically on parton shower and (non-perturbative) hadronisation.
String Fragmentation (Pythia)

String tension, $\kappa=1$ GeV / fm
Cluster Hadronisation (Sherpa/Herwig)

- Force non-perturbative $g \rightarrow qq$
- Follow colour
- Group into colour neutral clusters
- Clusters decay to hadrons according to phass-space
Investigate gaps with simulation

• Very sensitive to details of simulation
  – How partons become hadrons
    • parton shower (parton emissions, radiation)
    • cluster hadronisation / string fragmentation
    • Multiple parton interactions
    • Underlying event
  – Tuning
Given the large inclusive $c_s$, you can easily get a gap and it’s nothing to do with diffraction. Note also the large model dependence (order of magnitude).
Require two rapidity gaps > 2 or 3

Background to CEP DPE:
Massive systems less likely to have two large rapidity gaps.
Light systems often do.
Data exhibits fewer large gaps than models predict.

We are pretty rubbish at describing isolation.

Gaps get filled in nature.....
Regge theory

For $s \gg M_X \gg t$ (where $\xi = M_X^2 / s$)

$$\frac{d^2 \sigma}{d\xi dt} \propto \left( \frac{1}{\xi} \right)^{2\alpha(t)-1} \left( M_X^2 \right)^{\alpha(0)-1} e^{B_0 t}$$

Pomeron flux

Pomeron–p cs

$B_0 = 7.65 \pm 0.34$ GeV$^{-2}$

Good fit to single exponential

$B_0 = 4-12$ GeV$^{-2}$ is typical of diffractive processes at HERA and LHC (J/$\psi$ CEP, DPE $\pi\pi$)
Is it completely isolated?
We see something ‘exclusive’ in our detector. Is it? How can we estimate what we can’t see?
1: CMS-exclusive $\pi\pi$

Extrapolate seen backgrounds to unseen background

Look at additional neutral energy
Assume reasonable shape
Extrapolate below exclusive signal
2: LHCb

Fully instrumented: \( 2 < \eta < 5 \)
Veto region (Run 2): \(-10 < \eta < -5, \ 5 < \eta < 10\)
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2: LHCb

Fully instrumented: $2 < \eta < 5$

Veto region (Run 2): $-10 < \eta < -5$, $5 < \eta < 10$

LHCb simulation

Deposited energy [a. u.]

Pseudorapidity of the parent particle

JINST 13 (2018) no.04, P04017
Calibration exclusive signal

Two muons and nothing else in the LHCb detector
Calibration exclusive signal

Candidates per 0.04 GeV$^2$

$\sqrt{s}=13$ TeV

Total fit

Inelastic background

$JHEP$ 1810 (2018) 167
Discrimination power of Herschel

but what is ‘known’ background with no activity
Extrapolate seen background to unseen background

\[
\tilde{N}_{\text{HRC},i} = \epsilon S_i + b_i B_i \\
\tilde{N}_{\text{NOT},i} = (1 - \epsilon) S_i + (1 - b_i) B_i
\]

\[
\beta_i \equiv \frac{\tilde{N}_{\text{NOT},i} - \frac{1 - \epsilon}{\epsilon} \tilde{N}_{\text{HRC},i}}{\epsilon} = (1 - \frac{b_i}{\epsilon}) B_i
\]

but caution: HRC/NOT has a pT dependence

Almost flat for \( p_T^2 > 1 \text{ GeV}^2 \), so extrapolate this below signal
Assume Signal and Background

\[ \frac{d\sigma}{dt} \sim e^{bt} \]

\[ b_{\text{sig}} = 5.93 \pm 0.08 \text{ GeV}^{-2} \]

\[ b_{\text{bkg}} \sim 1 \text{ GeV}^{-2} \text{ (constrained from exclusivity anti-cut)} \]
3: H1-ep collisions

Forward Muon Chamber $1.9<\eta<3.7$

Plug calorimeter $3.5<\eta<5.5$

Forward Tagging $6<\eta<7.5$

A. Bolz, Thesis. U. Heidelberg
Select proton-dissociation events

Most dissociative products go down beam-pipe.
Not well described in detector simulation, either generator or detector.
DIFVM generator

\[ \frac{d\sigma}{dm_Y^2} \propto \frac{f(m_Y^2)}{(m_Y^2)^{1+\epsilon_Y}} \]

Proton dissociation in DIFVM

\( m_Y^2 < 3.6 \text{ GeV}^2 \): \( f \) taken from proton-deuteron scattering. Includes N* resonances.

\( m_Y^2 > 3.6 \text{ GeV}^2 \): \( f = 1 \). Quark set free and string fragmentation used.

Large \( t \)-dependent reweighting necessary.
Probabilities for signal / dissociation
Very good agreement with simulation, (but required a lot of tuning)
Roughly exponential fall-off again, with steeper fall for elastic than dissociation
$B_{el} = 9.6^{+0.2}_{-0.2} \text{ GeV}^{-2}$, $B_{pd} = 4.8^{+0.4}_{-0.4} \text{ GeV}^{-2}$
Summary

• Isolation is not predictable from first principles: have to use models.
• Less isolation in inclusive SD than in MC
• Proton dissociation not (well) described in simulation.
• Various experimental techniques to correct for what is missed due to $<4\pi$ coverage.
• These techniques can be (too?) simple, assume linearity, or require heavy reweighting of simulation where great care is necessary to avoid a circular argument.
• How can we improve our description of isolation?