Diffractive, forward physics and UPC

Workshop on the physics of HL-LHC, and perspectives at HE-LHC
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on behalf of ALICE, ATLAS, CMS, LHCb
10/31/2017
Overview

- **Physics topics**
  - Central diffraction (pp)
  - Light-by-light scattering (pp and ion-ion)
  - Ultra-peripheral collisions (p-ion and ion-ion)
    - photo-production of vector mesons
    - continuum $\gamma\gamma \rightarrow e^+e^-$, $\gamma\gamma \rightarrow q\bar{q}$
    - UPC jets (direct access to nPDF)
- **Detector upgrades**
  - tracker upgrades for LHC run 3 and 4
  - forward detectors, including roman pots
Forward detectors – present situation

CMS:  ZDC, TOTEM
ATLAS:  AFP, ALPHA
LHCb:  HERSCHEL
ALICE:  AD, ZDC

Left: ALFA detectors (vertical RPs, high-β*)
Right: AFP detectors (horizontal RPs, low-β*)
Possible physics cases for HL-LHC

- **Exclusive Higgs**
  - Quantum numbers are constrained to $0^{++}$ or $2^{++}$
  - Produced by gluon fusion, constraints on Hbb

- **New physics searches**
  - Two-photon processes are sensitive to new physics
  - Clean exclusive events, $pp \rightarrow p\gamma\gamma p$

- **Diffraction**
  - High $\beta^*$: pile-up prevents measurements of soft diffraction
  - Low $\beta^*$: study hard diffraction

- **HI collisions:**
  - Provides **centrality** based on spectators and not on participants
  - **Veto** for $\gamma\gamma$ (and $\gamma$-nucleus) processes
First feasibility studies with HL-LHC optics v. 1.3

- Detector size: 22 cm²
- Detector position: 15σ + 500 μm
- Acceptance is studied as a function of proton relative energy loss and proton $p_T$
- HL-LHC has the potential to observe exclusive Higgs production and perform BSM searches with tagged forward protons

Distance from IP1:
- 285 m
- 324 m

Calculated Mass Acceptances 15σ case:

Distances from IP1: 419, 324, 285, 233
Light-by-light scattering

**Pb+Pb collisions**
- softer EPA spectrum ($\omega_{\text{max}} \approx 80$ GeV for $\sqrt{s_{\text{NN}}} = 5$ TeV) $\rightarrow M(\gamma\gamma)_{\text{max}} \approx 160$ GeV
- AA ($\gamma\gamma$) cross-sections scale as $Z^4$
- gluonic cross-sections scale with $A^2$
  (lower QCD background w.r.t. pp)
- low pile-up ($< 1\%$)*
- Short LHC Pb-Pb campaigns (cf. pp)
- Proposed as a good channel to study e.g.
  - Anomalous gauge couplings
  - Contributions from BSM particles in the loops

**pp collisions**
- harder EPA spectrum ($\omega_{\text{max}} \approx 2$ TeV for $\sqrt{s} = 13$ TeV) $\rightarrow M(\gamma\gamma)_{\text{max}} \approx 4$ TeV
- large pile-up (multiple interactions per bunch crossing)
- large datasets available, $O(10 \text{ fb}^{-1})$
- hard to trigger on low-$p_T$ objects

* $O(10\%)$ for EM dissociation will be important effect @ HL-LHC
Light-by-light scattering

Background
- $M(\gamma\gamma) < 200$ GeV: diffractive mechanism dominates
- $M(\gamma\gamma) > 200$ GeV: two-photon production dominates
  - Mainly thanks to $W$ loops
  - Clean channel to study BSM effects at large-mass

Photon pseudorapidity
- Could benefit from the extended tracker range: ($|\eta| < 2.5 \rightarrow |\eta| < 4.0$)
- Increase of $\sigma(\gamma\gamma)$ ($ET > 3$ GeV, $|\eta| < 2.5$)
  - $pp@13$ TeV $\approx 70\%$ (SuperCHIC2)
  - $PbPb@5.02$ TeV $\approx 20\%$
- Difference comes from $Y_{\text{max}} = \ln(2\omega_{\text{max}}/W)$

[PRC 93 (2016) 4, 044907]
Measuring LbyL scattering at (future) LHC

- Trade-off between pp and Pb+Pb configurations
  (e.g. $Z^4$ vs $\omega_{\text{max}}$ vs CEP background)
- Lighter ions as an option? (e.g. Xe-Xe?)

HE-LHC

- moderate increase of cross-sections with $\sqrt{s_{\text{NN}}}$ [ $\approx \ln^3(\sqrt{s_{\text{NN}}})$ ]
- linear increase of $\omega_{\text{max}}$ $\rightarrow M(\gamma\gamma)_{\text{max}} \approx 320\text{GeV}$ for $\sqrt{s_{\text{NN}}} = 10\text{TeV}$ (Pb+Pb)
  $\rightarrow$ possibility to probe W-loop contribution

HL-LHC

- ’EM pileup’ can be an issue in Pb+Pb
- Possible benefits from detector upgrades, e.g., extended tracker acceptance
γA collisions – nPDF measurements

- nPDF could be constrained with high $Q^2$ dijet data, complementary to low-$Q$ data from hadrons.
- Important test for the factorization assumption
- The first dijet data has already been included in EPPS16 which improved gluon nPDF
- Significantly higher statistics pA data in HL-LHC could further reduce the statistical and systematical uncertainties and cover a wider $x$ and $Q$ phase space
- High precision heavy flavor jet (ex: b-dijet 96% from γγ scattering) will become feasible with HL-LHC data
γA collisions – nPDF measurements

- Di-jet production as proof of principle
- Diffractive jet production
  - Diffractive PDFs important input to shadowing models
- Heavy flavour (jets): Is there an EMC effect for gluons?
- γ-jet: Provides access to different flavour distributions

\[ p_{\text{T}}^{\text{lead}} > 20 \text{ GeV} \]
\[ m_{\text{jets}} > 35 \text{ GeV} \]

Data

\[ \text{Pythia+STARlight scaled to data} \]

\[ \text{Not unfolded for detector response} \]
γγ collisions (QCD)

- The process γγ → q̅q̅ is an elementary QCD process
  - Rates can be calibrated with γγ→μ⁺μ⁻
- Can do very clean QCD measurements a la e⁺e⁻
  - α_s, fragmentation functions, etc.
γγ collisions (rare and BSM)

- Improved significance in LbL scattering measurement
  - Currently 4.4 sigma evidence
  - Huge benefit from increased luminosity & increased detector acceptance
- Leads to many exclusive SM processes
  - Exclusive processes non-Abelian gauge couplings, e.g., Diboson production
- Need generators with realistic photon fluxes, calibrated against data.
- Potential for searches
  - BSM, axion-like particles, others?

→ see also Heavy Ions WG: session 4 (Wed 11/1)
Diffractive physics in Run 3 and 4

• Expected integrated luminosities:
  - pp @5.5 TeV: 6 /pb
  - pp @14 TeV
    • pp data taking @14 TeV still to be defined within ALICE
    • For the following estimates we used 200/pb (×10 more than in run 2)

• Benchmark analyses (central diffraction):
  - Precision scalar and tensor meson spectroscopy including strangeonia and charmonia states (ππ, KK, 4π, 2π2K, etc.), partial wave analysis
  - Gluonic jets, two particle correlations and femtoscopy in CEP (→Appendix)
  - Glueball searches (including exotics like 0-- and 0+- at high masses)
  - Magnetic monopole and monopolium searches (→ Appendix)
Hadron spectroscopy

- precision hadron spectroscopy and glueball searches
- see M.Albrow, arXiv:1701.09092 for a short and comprehensive summary of the field

<table>
<thead>
<tr>
<th>Name</th>
<th>M(MeV)</th>
<th>Γ(MeV)</th>
<th>$I^G J^{PC}$</th>
<th>$\pi\pi$</th>
<th>$K\bar{K}$</th>
<th>Other modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(500)/\sigma$</td>
<td>400-550</td>
<td>400-700</td>
<td>0$^{+0++}$</td>
<td>$\sim$100</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>990±20</td>
<td>10-100</td>
<td>0$^{+0++}$</td>
<td>dominant</td>
<td>seen</td>
<td>$\gamma\gamma$ seen</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>1275.5±0.8</td>
<td>186.7$^{+2.2}_{-2.5}$</td>
<td>0$^{+2++}$</td>
<td>84.2$^{+2.9}_{-0.9}$</td>
<td>4.6$^{+0.5}_{-0.4}$</td>
<td>4π $\sim$ 10%</td>
</tr>
<tr>
<td>$f_0(1370)$</td>
<td>1200-1500</td>
<td>200-500</td>
<td>0$^{+0++}$</td>
<td>seen</td>
<td>seen</td>
<td>$\rho\rho$ dominant</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>1504±6</td>
<td>109±7</td>
<td>0$^{+0++}$</td>
<td>34.9$^{+2.3}_{-1.6}$</td>
<td>8.6±1.0</td>
<td>4π 49.5±3.3</td>
</tr>
<tr>
<td>$f_2(1525)$</td>
<td>1525±5</td>
<td>73$^{+6}_{-5}$</td>
<td>0$^{+2++}$</td>
<td>0.8±0.2</td>
<td>88.7±2.2</td>
<td>$\eta\eta$ 10.4±2.2</td>
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<tr>
<td>$f_0(1710)$</td>
<td>1723$^{+6}_{-5}$</td>
<td>139±8</td>
<td>0$^{+0++}$</td>
<td>seen</td>
<td>seen</td>
<td>$\eta\eta$ seen</td>
</tr>
<tr>
<td>$f_2(1950)$</td>
<td>1944±12</td>
<td>472±18</td>
<td>0$^{+2++}$</td>
<td>seen</td>
<td>seen</td>
<td>$\eta\eta$ seen</td>
</tr>
<tr>
<td>$f_2(2010)$</td>
<td>2011$^{+60}_{-80}$</td>
<td>202±60</td>
<td>0$^{+2++}$</td>
<td>-</td>
<td>seen</td>
<td>$\phi\phi$ seen</td>
</tr>
<tr>
<td>$f_2(2050)$</td>
<td>2018±11</td>
<td>237±18</td>
<td>0$^{+4++}$</td>
<td>17%</td>
<td>$\sim$0.7%</td>
<td>$\eta\eta$ 0.2%</td>
</tr>
<tr>
<td>$f_2(2300)$</td>
<td>2297±28</td>
<td>149±40</td>
<td>0$^{+2++}$</td>
<td>-</td>
<td>seen</td>
<td>$\phi\phi$ seen</td>
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<tr>
<td>$f_2(2340)$</td>
<td>2345$^{+50}_{-40}$</td>
<td>322$^{+70}_{-60}$</td>
<td>0$^{+2++}$</td>
<td>-</td>
<td>-</td>
<td>$\phi\phi$, $\eta\eta$ seen</td>
</tr>
</tbody>
</table>

Table I: Light meson states allowed in DIPE. Branching fractions are in %. (PDG 2016)

It is a challenge to measure all these (sometimes overlapping) states with their decay modes, and partial wave analysis to distinguish $J = 0$ and $J = 2$. The most favored states for the lightest glueball, albeit mixed with $q\bar{q}$ states, are the scalar $f_0(1500)$ and $f_0(1710)$.
Glueball searches

- $f_0(1710)$ and $f_2(2300)$ are most promising $0^{++}$, $2^{++}$ glueball candidates
- $0^{++}$, $2^{++}$ glueballs mix with $q\bar{q}$ mesons with similar quantum numbers
  - precise determination of branching ratios needed to determine gluonic content
- Pseudoscalar glueball ($0^{-}$) expected $\sim 2.6$ GeV:
  - $\text{BR}(G \to K K \pi) = 49\%$ according to PRD95 (2017), 014028
  - $K_S K^+ \pi^-$ and $K_S K^- \pi^+$ might be promising in ALICE: $\text{Ax}\varepsilon(|y|<1)$ is about $10\%$
- $K_S K^+ \pi^-$ and $K_S K^- \pi^+$ also promising for $0^{-}$ oddball searches ($2.8$ GeV in JHEP 1510 (2015) 137)
Charm sector in central exclusive production (pp)

<table>
<thead>
<tr>
<th>Channel</th>
<th>BR</th>
<th>$A \times \varepsilon$</th>
<th>$\sigma$(5.5 TeV) pb</th>
<th>$Y$(5.5 TeV) 1/pb</th>
<th>$Y$(5.5 TeV) 6/pb</th>
<th>$\sigma$(14 TeV) pb</th>
<th>$Y$(14 TeV) 1/pb</th>
<th>$Y$(14 TeV) 200/pb</th>
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<tbody>
<tr>
<td>$\chi_{c0} \rightarrow \pi\pi$</td>
<td>0.83%</td>
<td>25.2%</td>
<td>97933</td>
<td>205</td>
<td>1229</td>
<td>118120</td>
<td>247</td>
<td>49412</td>
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<tr>
<td>$\chi_{c0} \rightarrow KK$</td>
<td>0.59%</td>
<td>20.5%</td>
<td>97933</td>
<td>118</td>
<td>711</td>
<td>118120</td>
<td>143</td>
<td>28573</td>
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<td>$\chi_{c0} \rightarrow 4\pi$</td>
<td>2.24%</td>
<td>9.40%</td>
<td>97933</td>
<td>206</td>
<td>1237</td>
<td>118120</td>
<td>249</td>
<td>49743</td>
</tr>
<tr>
<td>$\chi_{c0} \rightarrow 2\pi2K$</td>
<td>1.75%</td>
<td>1.70%</td>
<td>97933</td>
<td>29</td>
<td>175</td>
<td>118120</td>
<td>35</td>
<td>7028</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \pi\pi$</td>
<td>&lt;0.10%</td>
<td>25.2%</td>
<td>968</td>
<td>0</td>
<td>&lt;1</td>
<td>1009</td>
<td>0.3</td>
<td>&lt;51</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow KK$</td>
<td>&lt;0.10%</td>
<td>20.5%</td>
<td>968</td>
<td>0</td>
<td>&lt;1</td>
<td>1009</td>
<td>0.2</td>
<td>&lt;41</td>
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<tr>
<td>$\chi_{c1} \rightarrow 4\pi$</td>
<td>0.76%</td>
<td>9.40%</td>
<td>968</td>
<td>1</td>
<td>4</td>
<td>1009</td>
<td>0.7</td>
<td>144</td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow 2\pi2K$</td>
<td>0.45%</td>
<td>1.70%</td>
<td>968</td>
<td>0</td>
<td>0</td>
<td>1009</td>
<td>0.1</td>
<td>15</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \pi\pi$</td>
<td>0.23%</td>
<td>25.2%</td>
<td>5779</td>
<td>4</td>
<td>22</td>
<td>7634</td>
<td>4.4</td>
<td>885</td>
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<tr>
<td>$\chi_{c2} \rightarrow KK$</td>
<td>0.11%</td>
<td>20.5%</td>
<td>5779</td>
<td>1</td>
<td>9</td>
<td>7634</td>
<td>1.7</td>
<td>344</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow 4\pi$</td>
<td>1.07%</td>
<td>9.40%</td>
<td>5779</td>
<td>6</td>
<td>38</td>
<td>7634</td>
<td>7.7</td>
<td>1536</td>
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<tr>
<td>$\chi_{c2} \rightarrow 2\pi2K$</td>
<td>0.89%</td>
<td>1.70%</td>
<td>5779</td>
<td>1</td>
<td>6</td>
<td>7634</td>
<td>1.2</td>
<td>231</td>
</tr>
</tbody>
</table>

Cross sections were estimated with the SuperChic2 generator

- Using lowest prediction with NNPDF3.0 and model 1 for the gap survival prob.
- Caveat: Superchic2 predicts at least $\times3$ higher cross section w.r.t. LHCb preliminary

Only $\chi_{c0}$ channel is feasible in the baseline plan: $O(10^3)$ expected.
Two-particle correlations in γγ interactions in pp

- Idea is to study the origin of long range correlations (ridges) in photon-photon collisions: https://arxiv.org/abs/1708.07173
- pp CEP is dominated by gluonic jets. Study h-pi, h-K, h-p correlation shapes and pi,K and p associated particle yields in CEP, compare with min bias shapes/yields? Might be more promising then full jet reconstruction analysis.
UPC measurements in Run1 and in Run2

UPC $J/\Psi$ in Pb-Pb
- Impulse approximation (no nuclear effects)
- UPC measurements are being used to constrain nuclear gluon density functions

UPC $J/\Psi$, $\Upsilon$ in p-Pb
- Cross section is proportional to the square of the nuclear gluon distribution
- Higher $W_{\gamma p}$ energies than at HERA can be probed at the LHC
UPC measurements in Run3 and Run4

Physics processes:

• Multi-differential studies for \( J/\psi \) and \( \Psi(2S) \) production
  - b-slope dependence \( \rightarrow \) transverse gluon distributions (1611.05471)
  - ZDC \( \rightarrow \) disentangle low-x and high-x contributions

• High-mass vector mesons:
  - \( \Psi(3S) \rightarrow DD\overline{D} \) (not measured at HERA)
  - \( \Upsilon \) production

• Inclusive photonuclear charm production
  - \( \sigma (\gamma \text{ gluon } \rightarrow c \overline{c}) \approx 1b \)
  - \( \text{Pb+Pb } \rightarrow \text{Pb+c+cbar+X} \)

Expected integrated luminosities:

\[ \begin{align*}
\text{PbPb: 10/nb @0.5T}, & \quad 3/nb @0.2T \\
\text{pPb: 50/nb (ALICE LoI baseline)} &
\end{align*} \]

• \( \gamma\gamma \) processes:
  - \( \eta_c (\chi_{c0}, \chi_{c2}) \) production
  - \( \gamma\gamma \rightarrow 4\mu\): double-VM production, e.g. \( \gamma\gamma \rightarrow J/\psi J/\psi, \rho^0 J/\psi \)
  - \( \gamma\gamma \rightarrow pp\overline{p} (\eta_c \rightarrow pp\overline{p}), \gamma\gamma \rightarrow \gamma\gamma \)

• Jet photoproduction
  - direct access to the gluon distribution (ATLAS-CONF-2017-011)

• coherent UPC \( \Phi \) production
<table>
<thead>
<tr>
<th>process</th>
<th>central barrel</th>
<th>muon arm</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow l^+l^-$</td>
<td>4.1M</td>
<td>620k</td>
<td>STARLIGHT</td>
</tr>
<tr>
<td>$\Psi(2S)$</td>
<td>109k</td>
<td>15k</td>
<td>STARLIGHT</td>
</tr>
<tr>
<td>$\Upsilon$</td>
<td>5,260</td>
<td>430</td>
<td>STARLIGHT</td>
</tr>
<tr>
<td>$\Psi(3S) \rightarrow DDbar$</td>
<td>(acc×eff) × 5,900</td>
<td>---</td>
<td>$\Psi(3S) \rightarrow DDbar \rightarrow K^+\pi^- K\pi^+$ [<a href="https://indico.cern.ch/event/347071/%5C">https://indico.cern.ch/event/347071/\</a>]</td>
</tr>
<tr>
<td>$\eta_c \rightarrow 2\pi 2K$</td>
<td>(acc×eff) × 49k</td>
<td>---</td>
<td>$\sigma = 490 \mu b$ (STARLIGHT), BR($\eta_c \rightarrow 2\pi 2K$) $\approx 0.01$</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow 4\mu$ (VV)</td>
<td>(acc×eff) × 310</td>
<td>---</td>
<td>$p_T &gt; 0.5$ GeV, $</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow ppbar$</td>
<td>(acc×eff) × 350k</td>
<td>---</td>
<td>$p_T &gt; 1$ GeV, $</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow \gamma\gamma$ (E_T &gt;3 GeV,</td>
<td>240</td>
<td>---</td>
<td>ATLAS: 0.45/nb 13 ev $\rightarrow$ 10/nb 240 ev (DOI: 10.1038/NPHYS4208); ALICE/ATLAS acc $\approx 7%$</td>
</tr>
<tr>
<td>UPC jets</td>
<td>(acc×eff) × O(4M)</td>
<td>---</td>
<td>ATLAS-CONF-2017-011: 110k events with 0.3/nb in $</td>
</tr>
</tbody>
</table>
Summary

• Many physics topics
  – Central diffraction (pp)
  – Light-by-light scattering (pp and ion-ion)
  – Ultra Peripheral collisions (p-ion and ion-ion)

• Detector upgrades for LHC run 3 and 4
  – tracker upgrades
  – forward detectors, including roman pots

• More ideas, suggestions?
Appendix
Digression: pA collisions for nPDF measurements

- Asymmetry of pA makes it more sensitive to nPDF effects than AA
- Existing EW boson results show evidence of nuclear modification to PDF
- Results are still statistics limited; more luminosity $\rightarrow$ better constraints on nPDF

\[ \frac{d^2 \sigma}{dy dx} \rightarrow \frac{1}{\sqrt{s}} \]
Quarkonia in PbPb at 5.5 TeV

J/ψ, Ψ(2S), Upsilon:
- Efficiency = tracking efficiency using current AliRoot (no trigger)
- MUON arm: acc(-4.0 < y < -2.5) × eff for μ⁺μ⁻: 22%
- Central barrel: acc(|y|<1) × eff for e⁺e⁻: 25%, μ⁺μ⁻: 27%

<table>
<thead>
<tr>
<th></th>
<th>σ (μb)</th>
<th>Acceptance</th>
<th>BR→μ⁺μ⁻</th>
<th>BR→e⁺e⁻</th>
<th>Yield per 1/ nb</th>
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<tr>
<td></td>
<td>STARLIGHT</td>
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<tr>
<td>Y(1S)</td>
<td>103.74</td>
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<td>40.2%</td>
<td>7.67%</td>
<td>2.48%</td>
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<tr>
<td>Ψ(2S)</td>
<td>8110</td>
<td></td>
<td>32.7%</td>
<td>10.9%</td>
<td>7.9 × 10⁻³</td>
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<tr>
<td>J/ψ</td>
<td>41620</td>
<td></td>
<td>31.5%</td>
<td>11.3%</td>
<td>5.96%</td>
</tr>
</tbody>
</table>

Ψ(3S):
- Cross section ≈ 0.0179 × σ(J/ψ) = 745 μb

BR Ψ(2S) → DDbar → π⁺K⁻π⁻K⁺ = 52.4% × (3.89%)² = 7.93 × 10⁻⁴
- Yield per 1/nb: 590 events (without acc × eff)
Hard central exclusive production

- Light quark production is suppressed
- Clean gluon gets

**Fig. 3** Parton-level distributions for 2- and 3-jet CEP with respect to the system invariant mass $M_X$ at $\sqrt{s} = 13$ TeV, using MMHT14 LO PDFs [54]. The final-state partons are required to lie in the pseudorapidity region $-2.5 < \eta < 2.5$ and have transverse momentum $p_\perp > 20$ GeV (leading to minimum invariant masses, $M_X$, of 40 and 60 GeV in the 2- and 3-jet cases, respectively), while the 3-jet events are defined using the anti-$k_t$ algorithm with $R = 0.6$. Distributions are shown for massless quarks, $q\bar{q}$, as well as for $b\bar{b}$ production. Soft survival effects are included using model 4 of [51]

**Fig. 1** The perturbative mechanism for the QCD-induced exclusive process $pp \to p + X + p$, with the eikonal and enhanced survival factors shown symbolically


Monopolium searches

Monopole searches via monopole pair decays (or monopolium decays) into photons

Monopole pair decays into photons

Monopole mass vs. production cross section

pp - mm

pp - M

CEP (\gamma\gamma) prediction

Drell-Yan prediction

usually no production cross sections given

\Rightarrow no absolute mass limits

CEP and Drell-Yan predictions

\sigma [pb] vs. m [GeV]

\sigma [pb] vs. M [GeV]