Forward Physics at the HL-LHC

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LHC Working Group on Forward Physics and Diffraction

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Outline/Context


Standard Model Physics at the HL-LHC and HE-LHC

Report from Working Group 1 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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• As part of this chapter on forward physics.

Mario’s talk

• Here - summarise physics prospects discussed here + beyond.
Central Exclusive Production at HL-LHC

\[ pp \rightarrow p + X + p \]

- Two production mechanisms of interest*

- Sensitive to rather different physics/areas of phase space. Play different roles @ HL-LHC.

*In addition- photoproduction
Photon-induced production

• Exclusive photon-initiated production of particular interest for BSM.

★ Theoretical framework well understood. Cross section given in terms of well known equivalent photon approximation:

\[
\frac{d\sigma^{pp\rightarrow pX}}{dM_X^2 dy_X} \sim \frac{d\mathcal{L}^{EPA}}{dM_X^2 dy_X} \hat{\sigma}(\gamma\gamma \rightarrow X)
\]

\[
\frac{d\mathcal{L}^{EPA}_{\gamma\gamma}}{dM_X^2 dy_X} = \frac{1}{s} n(x_1) n(x_2) \quad \text{with} \quad n(x_i) = \frac{1}{x_i \pi^2} \int \frac{d^2 q_{i\perp}}{q_{i\perp}^2 + x_i^2 m_p^2} \left( \frac{q_{i\perp}^2}{q_{i\perp}^2 + x_i^2 m_p^2} (1 - x_i) F_E(Q_i^2) + \frac{x_i^2}{2} F_M(Q_i^2) \right)
\]

• Photon flux depends on well measured EM form factors.

• Impact of QCD, via additional hadron-hadron interactions very low.

\[
S_{\text{soft}}^2 \sim 0.7 - 0.9
\]
- As mass of central system $M_X$ increases, QCD-initiated production cross section suppressed by no radiation probability $\Rightarrow$ BG often low.*

- Example of $\gamma\gamma$ production:

- CEP: unique possibility to observe photon-initiated production of states with EM coupling in clean/well understood environment.

- However typically considering high mass region (RPs) and relatively low cross sections (EM couplings). *Statistics limited.*

$\rightarrow$ Increased statistics from HL-LHC running offer *clear advantage* here, in particular in terms of pushing to higher mass.

*Precise level depends on particular process.
Example 1 - Anomalous Couplings

- Discussed in detail in Cristian’s talk:

\[
\text{Sensitivity on couplings at } 95\% \text{ CL could improve roughly one order of magnitude down to,}
\]

\[
r_{\gamma} \rightarrow \text{hadrons } + \gamma \text{ benefits the most from the use of timing.}
\]

- Expected **improvements** from HL-LHC impressive ~ an **order of magnitude** (~ 5 orders of magnitude better than current best inclusive limits).
Example 2 - Compressed SUSY

- Searches for compressed SUSY scenarios - potential to increase reach in regions of parameter space (EW couplings, low mass difference) where inclusive searches struggle.
- Signal cross section low - gain from HL-LHC.
- In addition - detector upgrades can help reduce BGs:
  - Increased tracker coverage.
  - Timing in forward detectors at IP.
  - Radiation-hard ZDC with timing?
- However higher pile will clearly lead to more challenging environment - further studies needed.
- Note: here and elsewhere ~420m RPs could also greatly improve things, increasing acceptance towards lower mass region.
Further Possibilities

What if?

What if New Physics ...

- Doesn’t couple to quarks?
- Is invisible to detector?
- Decays to a cascade of particles?
- Produces soft decay products?
- Is a broad resonance?
- Long-lived particles?

See also - $t\bar{t}$, ALPs, dileptons, VB pairs - all clearly benefit from increased statistics.

**General motivation**: accessing regions that are challenging/impossible for conventional HL-LHC searches.
**QCD-initiated Production**

- QCD-initiated production more challenging at HL-LHC, but:
  - ★ Possibility to extend to ~ 420m RP positions (revive FP420) ⇒ push to lower mass, and open up possibility of e.g. exclusive Higgs observation.
  - ★ Dedicated ALICE studies in their low pile-up environment planned, making use of larger future dataset.
Physics with tagged protons - QCD

- QCD-induced baseline high mass channels - exclusive jets and Higgs.
  
  ★ Exclusive jets:
  
  ‣ Exclusive jets: CEP theory: dominantly $gg$ colour singlet dijets. Novel features (radiation patterns/zeros) in trijets - a gluon factory!
  
  ‣ New QCD regime - data from Tevatron but not from LHC (yet).
  
  ‣ Challenging measurement, but cross section high.

<table>
<thead>
<tr>
<th>$M_{jj}$ [GeV]</th>
<th>$\sigma(gg)$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>300</td>
<td>0.14</td>
</tr>
<tr>
<td>400</td>
<td>0.024</td>
</tr>
<tr>
<td>500</td>
<td>0.0053</td>
</tr>
<tr>
<td>600</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

$p_{\perp}^j > 25$ GeV
$|\eta_j| < 3$
$q = u, d, s, c$
Physics with tagged protons - QCD

★ Exclusive Higgs:

- Completely novel (and so far unseen) production channel. Complementarity with inclusive modes.
- $H \rightarrow b\bar{b}$: QCD $gg \rightarrow b\bar{b}$ background dynamically suppressed.
- Combined with proton tagging: handle on $CP$/spin-parity analyser.
- Cross section $O(fb) \Rightarrow$ clear benefit from higher lumi.
- Other BSM Higgs scenarios?

• Comprehensive Higgs measurement programme major factor of HL-LHC programme. This would add completely new ingredient.

• Lower mass acceptance highly desirable for jets and essential for Higgs $\Rightarrow$ detectors at $\gtrsim 300$m needed.

Lower luminosity running - ALICE

• **ALICE** - luminosity estimate of 200 pb$^{-1}$ in $pp$ by end of run 4, potential to increase in run 5.

• All low pile-up ⇒ broad programme of lower mass QCD studies and spectroscopy anticipated. Benefits from excellent PID, low thresholds and larger rapidity coverage of ALICE detector.

• Benchmark analyses -

★ Precision scalar and tensor meson **spectroscopy**:

  ‣ Many decay channels (ππ, KK, pp...), partial wave analyses.

  ‣ Probe of soft QCD dynamics.

  ‣ Expand knowledge of still poorly understood sector of QCD.
Lower luminosity running - ALICE

★ **Glueball** searches:

› As yet no clear evidence of states that QCD tells us should be there.
› Gluon rich CEP environment ideal channel to look.
› Data on decays clear indication of glueball nature

★ Exclusive charmonia: probe of gluon PDFs, $gg \rightarrow \chi_c$ modelling. Many decay channels analysed. Realistic possibilities for $\chi_c(0,2)$.

★ **Other benchmarks**: exclusive jets, magnetic monopole searches.

★ **LHCb**? High luminosity + moderate pile-up + good hadron PID - studies of e.g. quarkonia. Not clear will be possible.
Heavy Ion Collisions

• Future possibilities not just limited to pp collisions - heavy ions can also play a role. Runs approved for Runs 3 + 4, possibilities being considered beyond that.

• Variety of applications to BSM physics focus of recent (first) workshop + ESPP document. Motivation for HIs beyond Run 4.

New physics searches with heavy-ion collisions at the LHC


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Abstract

This document summarizes proposed searches for new physics accessible in the heavy-ion mode at the LHC, both through hadronic and ultraperipheral γγ interactions, and that have a competitive or,
Heavy Ion Collisions

- **Photon-initiated** CEP equally possible in heavy ion collisions. Indeed in some cases has significant **advantages**:

  - Significant $\sim Z^4$ enhancement in rate. After accounting for differing luminosities, still $\sim 2$ relative to $pp$, but with no pile-up.
  - QCD-initiated production essentially absent - clear interpretation.
  - Low pile-up - can go to low $M_{\gamma\gamma}$.
  - Conversely, steep fall off at high mass - $pp$ essential here $\Rightarrow$ complementary.
Processes of interest

- Many processes of interest in the lower mass region. Main channel of interest - $\gamma\gamma$ final-state.

  ★ Light-by-light SM signal, but also e.g. Born-Infeld extensions.
  ★ Axion-like particle production.
  ★ Magnetic monopoles.
  ★ Other possibilities? Gravitons, radions, unparticles, SUSY?

- A principle drawback of heavy ions for these studies is the low luminosity $\Rightarrow$ benefit from increased datasets can be significant.
- Input from wider forward physics community could be crucial in supporting this.

<table>
<thead>
<tr>
<th>Production mode</th>
<th>BSM particle/interaction</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrapерipheral</td>
<td>Axion-like particles</td>
<td>$\gamma\gamma \rightarrow \alpha$, $m_\alpha \approx 0.5-100$ GeV</td>
</tr>
<tr>
<td></td>
<td>Radion</td>
<td>$\gamma\gamma \rightarrow \phi$, $m_\phi \approx 0.5-100$ GeV</td>
</tr>
<tr>
<td>Schwinger process</td>
<td>Magnetic monopole</td>
<td>Only viable in HI collisions</td>
</tr>
<tr>
<td>Hard scattering</td>
<td>Dark photon</td>
<td>$m_{A^*} \leq 1$ GeV, advanced particle ID</td>
</tr>
<tr>
<td></td>
<td>Long-lived particles (heavy $\nu$)</td>
<td>$m_{\nu_{LLP}} \leq 10$ GeV, improved vertexing</td>
</tr>
<tr>
<td>Thermal QCD</td>
<td>Sexaquarks</td>
<td>DM candidate</td>
</tr>
</tbody>
</table>

Table 1: Examples of new-physics particles and interactions accessible in searches with HI collisions at the LHC, listed by production mechanism. Indicative competitive mass ranges and/or the associated measurement advantages compared to the pp running mode are given.
We present results of the updated SuperChic 3 Monte Carlo event generator for central exclusive production. This extends the previous treatment of proton–proton collisions to include heavy ion (pA and AA) beams, for both photon and QCD–initiated production, the first time such a unified treatment of exclusive processes has been presented in a single generator. To achieve this we have developed a theory of the gap survival factor in heavy ion collisions, which allows us to derive some straightforward results about the A scaling of the corresponding cross sections. We compare against the recent ATLAS and CMS measurements of light–by–light scattering at the LHC, in lead–lead collisions. We find that the background from QCD–initiated production is expected to be very small, in contrast to some earlier estimates. We also present results from new photon–initiated processes that can now be generated, namely the production of axion–like particles, monopole pairs and monopolium, top quark pair production, and the inclusion of W loops in light–by–light scattering.
SuperChic MC - processes generated

★ $W^+ W^-$, $l^+ l^-$, LbyL, SM Higgs, ALPs, monopoles, monopolium.

★ SM Higgs, dijets, trijets, light meson pairs, heavy quarkonia (single and double), $\gamma\gamma$.

★ Light to heavy vector meson production.

• In all cases in $pp$, $pA$ and $AA$ collisions.
SuperChic MC - Recent Developments


- Extension to heavy ion collisions- first ever treatment of QCD-initiated production.
- Requires detailed treatment of survival factor of no additional particle production in ion-ion QCD interactions.
- Relatively straightforward in photon-initiated case (~ no overlap), but great care needed in QCD-initiated case.

![Graph showing e^{-\Omega_{A_1A_2}(b_\perp)} for Pb-Pb collisions.]

![Diagram illustrating QCD and QED processes.]

\[ e^{-\Omega_{A_1A_2}(b_\perp)} \]
• Application of this - possible QCD-initiated BG to LbyL scattering.
• Previously no MC available for this - in ATLAS/CMS analyses scale superchic prediction for $pp$ by:

$$\sigma^{PbPb} = \sigma^{pp} \cdot A^2 \cdot R^4$$

Scale by Nuclear
nucleon pairs shadowing $\sim (0.7)^4$

• Full calculation - not the case. Not all nucleons can participate in short-range QCD interaction while leaving ions intact. Find:

$$\sigma^{PbPb} \sim \sigma^{pp} \cdot A^{1/3}$$

→ Find that QCD-initiated BG expected to be negligible.

ATLAS Collab., Nature Phys. 13 (2017) no.9, 852-858
LbyL - Predictions

- Predictions for ATLAS/CMS LbyL event selection:

<table>
<thead>
<tr>
<th></th>
<th>LbyL</th>
<th>QCD (coh.)</th>
<th>QCD (incoh.)</th>
<th>$A^2R^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>50</td>
<td>0.008</td>
<td>0.05</td>
<td>50</td>
</tr>
<tr>
<td>ATLAS (aco &lt; 0.01, $p_{\gamma\gamma}^T &lt; 2$ GeV)</td>
<td>50</td>
<td>0.007</td>
<td>0.01</td>
<td>10</td>
</tr>
<tr>
<td>CMS</td>
<td>103</td>
<td>0.03</td>
<td>0.2</td>
<td>180</td>
</tr>
<tr>
<td>CMS (aco &lt; 0.01, $p_{\gamma\gamma}^T &lt; 1$ GeV)</td>
<td>102</td>
<td>0.02</td>
<td>0.03</td>
<td>30</td>
</tr>
</tbody>
</table>

$\sigma$ [nb]

$\rightarrow$ QCD-initiated BG negligible!

- In addition: suppress further with acoplanarity cuts.
SuperChic MC - Recent Developments

• See Valery’s talk - prospects for compressed SUSY searches in photon-initiated CEP.

• Signal for this study:

\[
\gamma\gamma \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow l^+l^-\tilde{\chi}_0\tilde{\chi}_0
\]

implemented in SuperChic, as well as more challenging case:

\[
\gamma\gamma \rightarrow \tilde{\chi}^+\tilde{\chi}^- \quad \text{(hadron/leptonic decays)}
\]

• To be included in official version early in new year.

• In addition, contribution from proton dissociation included in effective way, interfaced to SuperChic.

• Future work: include (more) complete treatment of dissociation. Stay tuned!

LHL et al., arXiv:1812.04886
Summary/Points for Discussion/Wishlist

★ **Clear physics case** for forward physics @ HL-LHC: access regions that are highly challenging in conventional channels, open completely new Higgs observation channel with RPs@420m, sensitive to novel QCD observables…

• Experiment: Detector improvements we need for HL-LHC running: improved timing in RPs (O(few ps) ideally), timing in central detectors, radiation hard ZDCs + timing. What is feasible?

• Theory: complete account of proton dissociation (in progress)…

• 420m RPs- clear/new/distinct physics case vs. ~220m. Push for this?

• Expanding physics case. Identify **further** challenging areas for conventional channels.

Thank you for listening!