Light-by-Light Scattering in ATLAS

GRK Seminar Freiburg, 06. Nov. 2019

Kristof Schmieden
• The story starts in the **early 30ies**:

  • Dirac's theory developed and positrons discovered
    • Evident that light could scatter off light via pair-production (Halpern & Heisenberg)

  • Heisenberg, Euler, Kockel
    • Using effective Lagrangian to calculate cross section
      \( E_\gamma \ll m_\ell \)
      • \(~ 10^{-70} \text{cm}^2 \) for visible light, \(~ 10^{-30} \text{cm}^2 \) for \( \gamma \)-radiation

[\text{Naturwissensch. 23, 246, 1935}],[\text{Z. Phys. 98 (1936) 714}]

• Exact calculation: loop calculation needed
  • Box diagram involving charged fermions and W-Boson
• Early experimental approach:
  • Search for scattering of visible photons using focused sunlight

[Hughes and Jauncey, Phys. Rev. (36 1930), 773]

- No light was detected
  • "Calculations show that if the photon has a cross section, its area must be less than $3 \times 10^{-20}$ cm²."

- Cross section for visible light actually is:
  • $10^{-60}$ cm²!

**Figure 3** Apparatus for a light-light scattering experiment:
The two lenses C and D focus sunlight on the same spot O in a light-tight box AB. The dark-adapted eye of an observer at the point P serves as the detector for scattered light.
Outline

- Observing Light-by-Light scattering at the LHC
- The ATLAS measurement

What's next?

- Sensitivity to axion-like particles & other BSM models
- Ideas for measurement anomalous magnetic moment of the tau lepton
Overview of Light-by-Light scattering

- Several names known for Light-by-Light scattering
  - Depending on number of virtual photons
    - Photon - Photon scattering: 4 real photons
    - Pseudo-scalar meson production in S-channel
    - Photons splitting: 1 virtual, 3 real photons
    - Delbrück scattering [1933]: 2 virtual, 2 real photons
    - Lepton g-2: 3 virtual, 1 real photon

- Cross section box-diagram
  - Broken down by particle type in loop
  - Cross section of elementary process: ~10 pb
  - Source of photons?

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Ultra Peripheral Heavy Ion Collisions - LHC as photon collider

• Relativistic nuclei are intense source of (quasi-real) photons

• Equivalent photon flux scales with $Z^4$
  • PbPb beams at LHC are a superb source of high energy photons!

• Maximum photons energy:
  • $E_{\text{max}} \leq \gamma/R \sim 80$ GeV
  • Lorentz factor $\gamma$ up to 2700 @ LHC
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• Maximum photons energy:
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• Various types of photon interactions possible
  • Photon-Pomeron: e.g. exclusive J/Psi production
  • Photons - Gluon: photo production of jets
  • Photon - Photon:
    • Producing fermion pairs (e.g. $e^+e^-$)
  • Light - by - Light scattering
    • QED interaction
    • Mediated via box-diagram
    • Beam particles stay intact

[Fermi, Nuovo Cim. 2 (1925) 143]
The LHC

- Usually operates with proton @ 6.5 TeV beam energy
- ~1 month / per year:
  - Lead ions instead of protons @ 2.76 TeV / nucleon

Proton operation:
- Bunch crossings every 25ns (40 MHz)
- ~60 simultaneous pp collision per bunch crossing
  - ‘Pileup’

Heavy ion operation:
- Bunch crossings every 75ns (13 MHz)
- ~0.004 simultaneous PbPb collision per bunch crossing
  - Essentially no pileup at all
  - Only EM interaction in most bunch crossings! (UPC events)
- Used for photon physics

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How to measure the $\gamma \gamma \rightarrow \gamma \gamma$ process

- **Experimental signature:**
  - 2 exclusive photons in the final state
  - Photons are back-to-back in $\phi$
    - $A_\phi = 1 - |\Delta \phi| / \pi < 0.01$

- Cross section steeply falling with increasing energy
  - Looking for low energy photons: $E_T > 3$ GeV

- Very unusual topology and energy range for a high energy collider experiment

- Interesting challenge :-)
How to measure the $\gamma\gamma \rightarrow \gamma\gamma$ process

- pp collision
- Light-by-Light scattering candidate event
- PbPb collision
How to measure the $\gamma\gamma \rightarrow \gamma\gamma$ process

Triggering

• L1 requirements (OR):
  • $\geq 1$ EM cluster with $E_T(\gamma) > 1$ GeV && 4 GeV < total $E_T < 200$ GeV
  • $\geq 2$ EM clusters with $E_T(\gamma) > 1$ GeV && total $E_T < 50$ GeV

• HLT Requirements (AND):
  • $\Sigma E_T(\text{FCal}) < 3$ GeV on both sides
  • $\leq 15$ hits in pixel detector
    • Tagging of exclusive photon final state

• Support Triggers:
  • Sum $E_T < 50$ GeV & FCal Veto & $< 15$ tracks & $> 2$ tracks
  • HLT_mb_sptrak_exclusiveloose_vetosp1500_L1VTE20
How to measure the $\gamma\gamma \rightarrow \gamma\gamma$ process

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- **Support Triggers:**
  - Sum $E_T < 50$ GeV & FCal Veto & $< 15$ tracks & $> 2$ tracks
  - HLT_mb_sptrk_exclusiveloose_vetosp1500_L1VTE20

• Trigger efficiency determined using $e^+e^-$ final states
  • Triggered by independent support triggers

• Applied to simulated events to correct yield

ATLAS

Pb+Pb $\sqrt{s_{NN}}$=5.02 TeV
• Data 2018, 1.7 nb$^{-1}$

Level-1 trigger efficiency

Fit to data

Stat

Stat $\oplus$ syst

$E_T$\text{cluster}_1 + $E_T$\text{cluster}_2 [GeV]

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Photon reconstruction:

- Using default photon reconstruction algorithm
  - Entries in calorimeter cells are grouped to clusters
  - Track matching performed
    - Electrons / Photons
    - Some overlap allowed

Photon identification:

- Uses neural net (Keras), trained for low $E_T$ photons
- Combination of EM calorimeter shower shape variables
  - Discrimination between photons, pions, electrons, noise
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Photon reconstruction and identification

- **Efficiency measurement:**
  - Using $e^+e^-$ events where a hard bremsstrahlung photon was radiated

- **ee$\gamma$ final state selection:**
  - Exactly 1 electron $p_T > 4$ GeV \& 1 additional track
  - Track $p_T < 1.5$ GeV
    - Photon with $E_T > 2.5$ GeV must be present in Event!

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How to measure the $\gamma\gamma \rightarrow \gamma\gamma$ process

**Event Selection**

- **Trigger**
- Exactly 2 photons with $E_T > 3$ GeV && $|\eta| < 2.37$
  Excluding $1.37 < |\eta| < 1.52$

- Invariant di-photon mass $M_{\gamma\gamma} > 6$ GeV

- Veto any extra particle activity within $|\eta| < 2.5$
  - No reconstructed tracks ($p_T > 100$ MeV)
  - No reconstructed pixel tracks ($p_T > 50$ MeV, $|\Delta\eta (\gamma,\text{track})| < 0.5$)

- Back-to-Back topology
  - $p_T(\gamma\gamma) < 2$ GeV (rejects cosmic muons)
  - Reduced acoplanarity $< 0.01$ ($A_\phi = 1 - |\Delta\phi| / \pi$)
How to measure the $\gamma\gamma \rightarrow \gamma\gamma$ process

**Background processes**

- **What else has a similar signature?**
  - Central Exclusive Production of 2 photons (CEP): $gg \rightarrow \gamma\gamma$
    - Coloured initial state: significant intrinsic transverse momentum!
      - Broader shape of $A_\phi$ distribution
      - Control region defined to study CEP: $aco > 0.01$
  - Shape of $A_\phi$ distribution taken from simulation (SuperChic v3.0)
    - Uncertainty estimated using simulation without secondary particle emission (absorptive effects)
  - Normalisation measured in control region
    - Dominating uncertainty form limited statistics (17%)
  - Overall uncertainty of CEP background in signal region: 20%
  - Expected events in signal region: $5 \pm 1$
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  - **Pb*** dissociates, releasing neutrons detectable in the Zero Degree Calorimeter

  - Cross check of ZDC information for events in CEP control region:
    - Good agreement with expectations :)

- **Background processes**

  - $\pm 140m$ from ATLAS IP
  - $8.3 < |\eta| < \infty$
ZDC cross check on CEP background

- ZDC energy deposits
  - Single neutron peaks clearly visible

- More quantitatively
  - Expected that all CEP events have a signal in ZDC
  - 20% of yy and ee final states
  - Can calculated expected ratio of events with / without ZDC activity

\[
\frac{r_{ZDC/noZDC}^{pred}}{r_{ZDC/noZDC}^{meas}} \approx \frac{CEP + 0.2 \times (\text{signal} + ee)}{0.8 \times (\text{signal} + ee)}
\]

- For \( E_T > 3 \) GeV:
  - \( r(\text{pred.}) = 1.5(0.5) \), \( r(\text{meas}) = 0.8 \)

- To compensate difference:
  - Raise in the ee background yield of 20% needed
  - Well covered by uncertainty of 40%

\[ E_{ZDC,C} / \langle E_{1n} \rangle \]

\[ \text{ATLAS Preliminary} \]
\[ \text{Pb+Pb } \sqrt{s_{NN}}=5.02 \text{ TeV} \]
\[ 0.8 \mu b^{-1} \]
How to measure the $\gamma\gamma \rightarrow \gamma\gamma$ process

- **What else has a similar signature?**

  - Exclusive production of e$^+$e$^-$ electron pairs
    - Both electrons misidentified as photons
  - Electrons bent in magnetic field
    - Broader $A_\phi$ distribution compared to signal
  - Background rate estimated from data
    - 2 control regions:
      - Signal region + requiring 1 or 2 associated pixel tracks
      - Event yield from control regions extrapolated to signal region
      - Needed: probability to miss pixel track if full track is not reconstructed $p^{\text{mistag}}$

    - $p^{\text{mistag}}$ measured requiring 1 full track and exactly 2 signal photons: $(47 \pm 9)\%$

  - Events in signal region: $7 \pm 3$

- **Background processes**

  - Statistics, $p^{\text{mistag}}$, difference in CRs

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**Background processes**

- **Total background + signal:**

**What else has a similar signature?**

- Other potential backgrounds found to be negligible:
  - $\gamma \gamma \rightarrow qq$
  - Exclusive di-meson production (pi0, eta, eta’)
    - Also charged mesons considered
  - Bottomonia: $\gamma \gamma \rightarrow \eta_b \rightarrow \gamma \gamma$ (sigma ~1pb)
  - Fake photons: Cosmic rays, calorimeter noise

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Systematic Uncertainties

- Reco & PID SFs:
  - SFs derived in dependence of eta instead of $p_T$
    - Impact on measured C-factor taken as systematic unc.
    - 4% (Reco) 2% (PID)

- Photon energy scale & resolution
  - Taken from EGamma-group recommendations
    - 2% impact on MC yields, for both scale & resolution

- Angular resolution (in phi)
  - Comparing electron tracks to cluster in $yy\rightarrow ee$ events
  - Additional single cluster smearing in MC: $\sigma_\phi \approx 0.006$
    - Impact on CEP background: 1%
    - Impact on SFs: 2% (taken as systematic)
  \[
  \sigma_{\phi,\text{cluster}} \approx \frac{|\phi^{\text{cluster}1} - \phi^{\text{trk}1}| - |\phi^{\text{cluster}2} - \phi^{\text{trk}2}|}{\sqrt{2}}
  \]

- Trigger
  - Three ee event selection criteria defined: loose, nominal, tight
    - Difference between those taken as systematic unc.
      - Max. Uncertainty: +10% -4% @ $E_T$(cluster sum) 5 GeV
      - Overall: 2%

- Alternative LbyL signal sample
  - Starlight instead of SuperChic
    - 1% impact on C
  - Signal MC stats:
    - 1%

- Total: 7% on the detector correction factor C
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- **Total: 7% on the detector correction factor C**

- **Uncertainty on total background: 21%**

### Table 6: Impact of individual systematic variations on the expected number of background events in the signal region.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEP Aco &gt; 0.01 CR stat uncertainty</td>
<td>±0.06</td>
</tr>
<tr>
<td>CEP Superchic2 vs Superchic3 uncertainty</td>
<td>±0.09</td>
</tr>
<tr>
<td>ee CR stat uncertainty</td>
<td>±0.12</td>
</tr>
<tr>
<td>ee CR variation uncertainty</td>
<td>±0.11</td>
</tr>
<tr>
<td>ee $p_T$ variation uncertainty</td>
<td>±0.07</td>
</tr>
<tr>
<td>EG scale uncertainty</td>
<td>±0.005</td>
</tr>
<tr>
<td>EG resolution uncertainty</td>
<td>±0.01</td>
</tr>
<tr>
<td>Photon angular resolution uncertainty</td>
<td>±0.01</td>
</tr>
<tr>
<td>Trigger uncertainty</td>
<td>±0.004</td>
</tr>
<tr>
<td>photon reco uncertainty</td>
<td>±0.002</td>
</tr>
<tr>
<td>photon PID uncertainty</td>
<td>±0.001</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>±0.21</strong></td>
</tr>
</tbody>
</table>
Results on 2015 data

- Very similar analysis, some optimisations missing
- 480µb⁻¹ of PbPb data recorded in 2015
- **First Evidence of Light-by-Light scattering** released in 2016 by ATLAS
  - Compatible result by CMS
- **13 Events observed**, Background: 2.6 ± 0.7
- Cross section:
  - Measured: 70 ± 20 (stat) ± 17 (sys) nb
  - SM expectations: 49 ± 5 nb
- Significance: **4.4σ** (3.8σ expected)
Results on 2018 data

- **2018 Data**: 1.7 nb\(^{-1}\) of PbPb data analysed

- **59 Events observed**, Background: 12 ± 3

- Cross section:
  - Measured: 78 ± 13 (stat) ± 8 (sys) nb
  - SM expectations: 49 ± 5 nb

- **Significance: 8.2\(\sigma\) (6.2\(\sigma\) expected)**

- Light-by-Light scattering of GeV photons observed

- Compatibility with SM prediction within 1.8 standard deviations
Active field:
- Phenomenological work: arxiv:1607.06083,
Interpretation - Search for new Axion Like Particles: CMS

- 0.39 nb⁻¹, E_T > 2 GeV, m > 5 GeV

- p_T (yy) < 1 GeV, |eta| < 2.4 => similar to ATLAS selection

- 14 events observed, 4 background events expected

- ALP limits statistically limited
- Factor 4 difference in statistics

- Expect ~2 times lower limits from ATLAS soon
Interpretation - Other Models

- Measurement can be transformed into limit on specific models beyond the standard model

- Born - Infeld theory
  - Nonlinear extension to QED
    - Imposing an upper limit of the EM field strength
      [Born and Infeld, Proc. R. Soc. A 144, 425 (1934)]
    - More recently: connection to string theory
      [Fradkin and Tseytlin, Infeld, Phys. Lett. 163B, 123 (1985)]
  - Differential Light-by-Light scattering cross section can be turned into limit on mass scale appearing in B-I theory


\[ m_{\gamma\gamma} > 6 \text{ GeV}, \quad \text{Pb+Pb (\gamma\gamma)\rightarrow Pb^{(*)}+Pb^{(*)} \gamma} \]

\[ \frac{\sigma_{\text{fid}}}{\text{nb}} \]

95% CL exclusion by ATLAS

\[ \sqrt{\beta} \text{ [GeV]} \]

\[ \sigma_{\text{fid}} \text{ [nb]} \]
Tau anomalous magnetic moment: $\gamma\gamma \rightarrow \tau\tau$

- Electromagnetic interaction - $\gamma\tau$

$$\mathcal{L} = \frac{1}{2} \bar{\tau}_L \sigma^{\mu\nu} \left( a_\tau \frac{e}{2m_\tau} - id_\tau \gamma_5 \right) \tau_R F_{\mu\nu}$$

$$a_\tau^{\text{exp}} = -0.018 \ (17)$$

$$a_\tau^{\text{pred, SM}} = 0.001 \ 177 \ 21 \ (5)$$

- $\gamma\gamma \rightarrow \tau\tau$ sensitive to electric & magnetic moments of tau!
  - $a_\tau$: anomalous magnetic moment
  - $d_\tau$: electric diplome moment

- Usage of UPC PbPb collisions suggest in 1991
  

- Sensitivity estimation at LHC brand new (Beresford & Liu)
  - 3x smaller uncertainties compared to LEP measurement

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**Electromagnetic interaction - $\gamma \tau$**

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$$a_\tau^{\text{exp}} = -0.018 (17)$$
$$a_\tau^{\text{SM}} = 0.001 177 21 (5)$$

- $a_e$: Harvard06 (error bar $\times 10^9$)
- $a_\mu$: BNL06 (error bar $\times 10^6$)
- $a_\tau$: DELPHI04
  - $2 \text{ nb}^{-1}$, 10% syst
  - $2 \text{ nb}^{-1}$, 5% syst
  - $20 \text{ nb}^{-1}$, 5% syst
- SM $a_\tau^{\text{pred}}$ (error bar $\times 10^4$)
- SMEFT $a_\tau^{\text{pred}}, C_{\tau B} = -1$

$\alpha = (g - 2)/2$
Tau anomalous magnetic moment: $\gamma\gamma \to \tau\tau$

- **Challenges:**
  - **Trigger:**
    - Similar triggers as used in Light-by-Light scattering analysis
  - **Reconstruction:**
    - Rely on lepton and tracks reconstruction
    - Track reach down to 0.5 GeV is standard
  - **Selection**
    - 2 leptons with different flavour (very clean)
    - 1 lepton + 1 or 3 tracks
    - Difficult to tag photon initial state without requirement on $\Delta\phi$
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- **Why are the tau-EM moments interesting?**
  - $a_\tau$ poorly measured
  - Sensitive to BSM physics:
    - Tests lepton compositeness
    - SUSY at scale $M_S \Rightarrow \delta a_\tau \sim m^2 / M_S^2$
    - $\tau$ way more sensitive than $\mu$

- **Impact of BSM effects modelled in EFT vial 2 dim-6 operators:**

![Graph showing constraints on $\delta a_\tau$](image)

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Ongoing analysis in ATLAS

- Combine 2015 + 2018 data \(\Rightarrow 2.2 \text{ nb}^{-1}\)

- Lower \(E_T\) threshold to 2.5 GeV
  - Expect \(~90\) events

- Unfold measured distributions
- ALP limits
- Limits on EFT operators
## Ongoing analysis in ATLAS

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## Where could we potentially go?

- **Lowering $E_T$ threshold:**
  - Calorimeter cluster noise: 1 GeV
  - Exploit longitudinal boost
    - Cut on $E$ (not $E_T$), $|\eta| < 2.5$
    - $M_{inv} \sim 1$ GeV
  - Trigger?
    - Difficult, even including topological requirements

- **pp collisions (~fb of data):**
  - Challenge: tagging of photon initial state
    - Dedicated low pileup runs
    - Proton tagging

- **Proton tagging**
  - Forward detectors in ATLAS: AFP
  - Different kinematic region:
    - $M_{inv} > 350$ GeV
First direct observation of Light-by-Light scattering at the ATLAS experiment
- Hi collisions from the LHC used as photon collider

Challenging measurement, very different from usual high energy analyses:
- Low energy objects
- Very little activity in detector
- Difficult to trigger

59 Events observed (12 background events expected)
- Measured fid. cross section for $m_{\gamma\gamma} > 6$ GeV: $\sigma = 78 \pm 15$ nb
  - Compatible with SM prediction

Useful to constrain several models beyond the standard model, e.g.
- Axion like particles
- Born-Infeld theory

Lepton final states sensitive to:
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**What’s left to do?**

• Refined measurement of differential distributions
  • Combination of 2015 & 2018 data \(\Rightarrow 2.1 \text{nb}^{-1}\)

• Derivation of improved limits on some BSM models

• Interpretations in the framework of effective couplings
Additional Kinematic Distributions

ATLAS

Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

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Electron studies

**ATLAS**

\[ \text{Pb+Pb} \, \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

**ee selection**

![Graph showing data and MC comparison](image)

Data 2018, 1.7 nb\(^{-1}\)

**Sys. unc.**

\[ 0.6, 0.8, 1.0, 1.2, 1.4 \]

Data / MC

\[ 0, 10, 20, 30, 40, 50, 60, 70, 80 \]

**m_{ee} [GeV]**
Details on peMistag

- Pixel tracks badly modelled in MC
- Chance to miss a pixel track if the track is not reconstructed:
  - Data: 47%, MC: 10%
- Nominal selection + 1 reconstructed track matched to a photon cluster:
  - Selects ee events
- Check how often one or two PIX tracks are reconstructed => $p_{\text{mistag}}$

\[
p_{N_{\text{Pix}}=0}^{\text{event}} = \left(p_{\text{mistag}}^e\right)^2
\]

\[
SR_{\text{expected}} = (N_{\text{events}}^{\text{CR}(N_{\text{PixTrk}}=1)} + N_{\text{events}}^{\text{CR}(N_{\text{PixTrk}}=2)}) \cdot \frac{p_{N_{\text{Pix}}=0}^{\text{event}}}{1 - p_{N_{\text{Pix}}=0}^{\text{event}}}
\]

![Graph showing pixel track multiplicity distribution for events satisfying signal selection except for $\gamma\gamma$ acoplanarity.](Image)

![Graph showing $\gamma\gamma$ acoplanarity distribution for events in control regions.](Image)
masses, angular and at much lower energies \cite{10, 11}. The cross sections, pair intermediate-energy photons, there is a pair-mass dependence only weakly on the pair mass \cite{5}. However, for real photons incident on a heavy atom, these Coulomb Maximon approach \cite{5}, and found that at RHIC, calculations.

Some early coupled-channel calculations predictive calculations of the process are questionable. Many the fine-structure constant), that conventional perturbative result \cite{8}. However, improved all-orders calculation also provides a convenient experimental trigger. In contrast, initial all-orders calculations based on solving the Dirac equation exactly in the ultra-relativistic limit \cite{7} found results that match the lowest-order perturbative result \cite{6}.

The energy of the reaction is the sum of two photons, while the nuclei exchange additional, in \cite{12}, as is shown in Fig. 1. An

Very useful to tag the ultra-peripheral collisions can be selected by choosing events where the nuclei undergo small ion-ion impact parameters, leading -o- order terms \cite{6}. Any higher-order corrections should be the largest seen in Fig. 2, where the mutual Coulomb dissociation is independent of the parameter \( b \) (different order terms \cite{6}).

The Coulomb nuclear breakup requirement selects in \cite{13, 14}, as is shown in Fig. 1. An

\[ E_{ZDC_c} / \langle E_{1n} \rangle \]

ZDC cross check on CEP background

- **CEP control region:** \( A_\phi > 0.01 \)
  - Additionally require energy deposit in ZDC corresponding to at least 1 neutron

- Simulation normalised from control region compatible with data
  - But very limited statistics

- **ZDC energy deposits**
  - Single neutron peaks clearly visible

\[ \gamma \gamma \text{ acoplanarity} \]

\[ \begin{array}{c}
\text{Events / 0.01} \\
0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10
\end{array} \]

\[ \begin{array}{c}
0.02 & 0.04 & 0.06 & 0.08 & 0.1 & 0.12
\end{array} \]

\[ \begin{array}{c}
\text{ATLAS} \\
\text{Data, } n_{ZDC} \geq 1 \\
\text{Pb+Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV}
\end{array} \]

\[ \text{CEP } \gamma \gamma \text{ MC} \]

\[ \text{2015 data set} \]

\[ |< +\infty | \bar{\eta} < 8.3 | \eta | < 8.3 | \bar{\eta} > +\infty | \]

\[ |< +\infty \! +\! 2 \pi | \bar{\eta} < 8.3 \! +\! \pi | \eta | < 8.3 \! +\! \pi | \bar{\eta} > +\infty \! +\! 2 \pi | \]

\[ |< +\infty | \bar{\eta} < 8.3 | \eta | < 8.3 | \bar{\eta} > +\infty | \]

\[ |< +\infty \! +\! 2 \pi | \bar{\eta} < 8.3 \! +\! \pi | \eta | < 8.3 \! +\! \pi | \bar{\eta} > +\infty \! +\! 2 \pi | \]

\[ |< +\infty | \bar{\eta} < 8.3 | \eta | < 8.3 | \bar{\eta} > +\infty | \]

\[ |< +\infty \! +\! 2 \pi | \bar{\eta} < 8.3 \! +\! \pi | \eta | < 8.3 \! +\! \pi | \bar{\eta} > +\infty \! +\! 2 \pi | \]

\[ |< +\infty | \bar{\eta} < 8.3 | \eta | < 8.3 | \bar{\eta} > +\infty | \]
Di-Photon spectrum at low energies => Mesons exchange

Lebiedowicz et al.

Kristof Schmieden
The LHC

- **CERN's accelerator complex**

- **LHC:**
  - Usually operates with **proton @ 6.5 TeV** beam energy
  - ~1 month / per year:
    - **Lead** ions instead of protons

https://cds.cern.ch/record/2197559
The ATLAS Detector

- Size of a 6 story building
- 100M readout channels
- 2 staged trigger system
  - L1: hardware based
    - 40MHz -> 100kHz
  - L2: software based
    - 100kHz -> 1kHz
- 100 kHz readout
- 1 kHz to disk
  (~1.5 MB/event)

Kristof Schmieden
The ATLAS Detector

- ~100M readout channels
- 100kHz readout (~1.5 MB/event)
  - 1 kHz to disk
- ‘Textbook’ like multi purpose detector

- ATLAS coordinate system:
  - \( \eta = -\ln \tan(\theta/2) \), \( \phi \)

\( r, \phi, z \) cylindrical coordinates and \( \Theta \) - visualization