Production of muon-pairs from $\gamma \gamma$ scattering in Non-UltraPeripheral Pb+Pb collisions

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Dilepton production in Ultra-Peripheral Collisions (UPC)

In Pb+Pb collisions, the electromagnetic fields of the charged nuclei are enhanced by factors of $Z^2$.

Modelled as quasi-real photon fields, this provides an enhancement of $Z^4$ for the $\gamma\gamma \rightarrow \mu^+\mu^-$ processes. For Pb ions $Z^4 \sim 5 \times 10^7$.

Max $p_z$ of photons in rest frame $\sim 1/2R \sim 1/15\text{fm} \sim O(10 \text{ MeV})$

In Lab frame $|p_z|$ increased by boost: at LHC the $|p_z|$ in lab frame is $\sim 2500 \times 10 \text{MeV} \sim 25 \text{ GeV}$

Maximum $p_T$ of incoming photons $\sim$ same as rest-frame $p_T \sim O(10 \text{ MeV})$.

Outgoing muons will be nearly back-to back in $\phi$ and have nearly identical $p_T$. 

Observables: Asymmetry ($A$), Acoplanarity ($\alpha$), $k_\perp$

$A \equiv \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$

Mismatch in transverse momentum of the two muons
Observables: Asymmetry ($A$), Acoplanarity ($\alpha$), $k_{\perp}$

$$A \equiv \frac{(p_{T1} - p_{T2})}{(p_{T1} + p_{T2})}$$
Mismatch in transverse momentum of the two muons

$$\alpha \equiv 1 - \frac{|\Delta \phi|}{\pi}$$
Deviation from being perfectly back-to-back
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Deviation from being perfectly back-to-back

$$k_\perp \equiv (p_{T1} + p_{T2}) \frac{|\pi - \Delta \phi|}{2} = \pi \alpha \tilde{p}_T$$
Momentum scale corresponding to the angular scale $\alpha$
ATLAS measurements of Acoplanarity distribution of dimuons in UPC Pb+Pb collisions

Measurements well reproduced by STARLIGHT calculations

STARLIGHT uses the equivalent photon approximation + leading order QED cross-sections

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See also CMS-PAS-HIN-19-014
Talk by Shuai Yang, EW Probes-II
\[ \gamma\gamma \rightarrow \mu\mu \text{ in non-UPC collisions: why study it?} \]

- \[ \gamma\gamma \rightarrow \mu\mu \] process also present in inelastic heavy ion collisions.
- Muons produced by photon scattering can in principle interact with the QGP produced in heavy-ion collisions.
- Can also see effects of the magnetic fields of the colliding nuclei (Ye et al. Phys. Rev. C99 (2019) 044901)
- Measurement more complicated as there are other sources of muons, which must be removed.
Reduce the HF contribution by requiring muons to be closely matched in $p_T$ and be back to back in $\phi$.

- Require Asymmetry $< 0.06$, i.e. the $p_T$ of the two muons to be within 6% of the average $p_T$.
- Require Acoplanarity $< 0.012$
- Reduces background by $\sim 2$ orders or magnitude in central collisions

HF muons often arise from displaced secondary decay vertices.

- Use impact parameter in the transverse ($d_0$) plane to remove residual background

$$d_{0\text{pair}} = \sqrt{d_{01}^2 + d_{02}^2}$$
To estimate the residual background, fit the $d_{0 \text{pair}}$ distribution in the data by linear sum of signal and background $d_{0 \text{pair}}$-templates

- $d_{0 \text{pair}}$ template for signal obtained from MC (STARLIGHT)
- $d_{0 \text{pair}}$ template for background obtained from Data:
  - require Acoplanarity $>$ 0.015, Asymmetry $>$ 0.2

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Acoplanarity distributions

$$\alpha \equiv 1 - |\Delta \phi| / \pi$$

Data compared to STARLIGHT

For UPC collisions the data matches STARLIGHT.
**AcoPLANARITY distributions**

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See distinct change in shape of distribution from UPC->mid-central->central collisions
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See distinct change in shape of distribution from UPC->mid-central->central collisions

In particular development of a “dip” at \( \alpha=0 \)
- Strong $p_T$ dependence observed in the shape of the acoplanarity distribution
- Distribution becomes sharper and depletion becomes weaker at higher $p_T$
- Are higher $p_T$ particles affected less?
- Much weaker $p_T$ dependence observed for $k_\perp$ distributions.
- Indicates similar momentum kick at different $p_T$
  - Thus higher $p_T$ particles deflected less.
Can quantify change in shape with moments $k_\perp$ distributions.

- Generally moments increase by 20-25 MeV from UPC to central collisions
  - Indicating a broadening of the $k_\perp$ distributions from UPC to central collisions
Investigation of dip

- See if any systematic modification of the UPC distribution can reproduce centrality dependence.
- Parameterize UPC distribution as sum of two gaussians
- Refit the distributions in other centralities as a smeared+shifted version of the UPC distribution
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- See if any systematic modification of the UPC distribution can reproduce centrality dependence.
- Parameterize UPC distribution as sum of two gaussians
- Refit the distributions in other centralities as a smeared+shifted version of the UPC distribution
- Fits work reasonably well!
Quantifying the shift

- Left plot: Locate most-probable value of $k_\perp$ distributions.
- Right plot: Most probable value as function of centrality
- Prediction from Klein and collaborators (Phys. Rev. Lett. 122, 132301)
- If broadening was caused by deflection from magnetic field, it should increase with rapidity separation between muons
- No clear dependence of shape on rapidity separation between muons observed
Comparison to QED Calculations

  - Qualitatively reproduces dip (compared with prior data from *Phys. Rev. Lett.* 121 (2018) 212301)
- Broadening and depletion entirely reproduced by impact-parameter dependence of EM Fields
Yields of dimuon pairs

- Centrality dependence of Yield fractions
- Increase from peripheral mid-central collisions
- $p_T$ spectra becomes harder with increasing centrality
Summary

- Measured yields and distributions of dimuons from $\gamma\gamma \rightarrow \mu^+\mu^-$ processes in Pb+Pb collisions
  - In UPC and non-UPC collisions
  - Removed background contributions in non-UPC events via a template-fitting method

- Distributions for Acoplanarity and $k_\perp$ show significant centrality dependence
  - Develop a broadening with increasing centrality and a depletion at $k_\perp=0$
  - Most probable value of $k_\perp$ in 0-5% central collisions is at 36 MeV

- Acoplanarity distributions show a $p_T$ dependence while $k_\perp$ distributions do not.
  - Consistent with a process that imparts a momentum kick to the outgoing muons
  - Although calculations accounting for impact parameter dependence of the EM field qualitatively reproduce the broadening

- Yields increase from peripheral to central events
  - Normalized-yields increase with increasing $p_T$.
  - Larger fraction of the higher-$p_T$ pairs are produced in central collisions
FCal (i.e. centrality) distribution of candidate pairs

Black: All pairs passing preselections

Red: Asymmetry<0.06, Asymmetry<0.012

Blue: Cuts on $d_{\text{0pair}}$ and $z_{\text{0pair}}$

Green: min-bias distribution for reference

Inset shows the UPC region
Signal fractions from the $d_{0\text{pair}}$ template fits:
- For different values of the mean-$p_T$ of the pair.
- Typically fractions decrease from peripheral to central collisions
- At higher $p_T$ signal fractions are larger.
Also obtained by applying the anti-cuts to the data:
- Asymmetry $>0.08$ to obtain background shapes for Acoplanarity (or $k_\perp$) distribution
Knowing the background fractions and shape, the backgrounds can be removed.

Shown here for the Acoplanarity (or $\alpha$) distribution for three centrality intervals.
Fractional-Yields of dimuon pairs

- Centrality dependence of Yield fractions
- Increase from peripheral mid-central collisions
- $p_T$ spectra becomes harder with increasing centrality

\[
Y^\text{cent}, \bar{p}_T \equiv \frac{N^{\text{cent}, \bar{p}_T}}{N^{\text{all}, \bar{p}_T}}
\]

\[
= \frac{\text{Yield in given centrality}(p_T)}{\text{Total yield}(p_T)}
\]
- Centrality dependence of Yield fractions
- Increase from peripheral mid-central collisions
- $p_T$ spectra becomes harder with increasing centrality
Compare the Asymmetry distributions in data with the Asymmetry distributions in STARLIGHT MC

STARLIGHT distributions shown for “Truth” i.e. Generated particles

As well as for “Reconstructed” particles: after simulation of detector response

The detector’s $p_T$ resolution washes out any possible modifications in the Asymmetry distribution

\[ A \equiv \frac{(p_{T1} - p_{T2})}{(p_{T1} + p_{T2})} \]