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

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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 of nucleus:

\[ \sim \frac{1}{2R} \sim \frac{1}{15} \text{fm} \sim O(10 \text{ MeV}) \]

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

\[
k_\perp \equiv (p_{T1} + p_{T2}) |(\pi - \Delta \phi)|/2 = \pi \alpha \bar{p}_T
\]
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

\[ \gamma\gamma \rightarrow \mu\mu \] 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.


- Measurement more complicated as there are other sources of muons: Heavy-Flavor decays.
Reduce the HF contribution by requiring muons to be closely matched in $p_T$ and be nearly 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 of magnitude in central collisions

HF muons often arise from displaced secondary decay vertices

- Use impact parameter w.r.t. collision vertex in the transverse ($d_0$) plane to remove residual background
- “Pair impact parameter” defined as: $d_{0\text{pair}} = \sqrt{d_{01}^2 + d_{02}^2}$
To estimate the residual background, fit the $d_{\text{0pair}}$ distribution in the data by linear sum of signal and background $d_{\text{0pair}}$-templates

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

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Acoplanarity distributions

\[ \alpha \equiv 1 - \frac{|\Delta \phi|}{\pi} \]

Data compared to STARLIGHT

For UPC collisions the data matches STARLIGHT.

![Graph showing data comparison to STARLIGHT](atlas.png)
Acoplanarity distributions

\[ \alpha \equiv 1 - \left| \Delta \phi \right|/\pi \]

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See distinct change in shape of distribution from:
UPC → mid-central → central collisions
**Aco-planarity distributions**

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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.
- $k_\perp$ is “better” observable for studying centrality dependence.
- 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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- Fits work reasonably well!
- Left plot: Locate most-probable value of $k_{\perp}$ distributions.
- Right plot : Most probable value as function of centrality.
- Most probable value changes from 0 MeV in UPC to 36 MeV in 0-5% central collisions
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

- QED Calculation from W. Zha et al. (Phys. Lett. B 800 (2020) 135089)
  - 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
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 QED calculations accounting for impact parameter dependence qualitatively reproduce the broadening