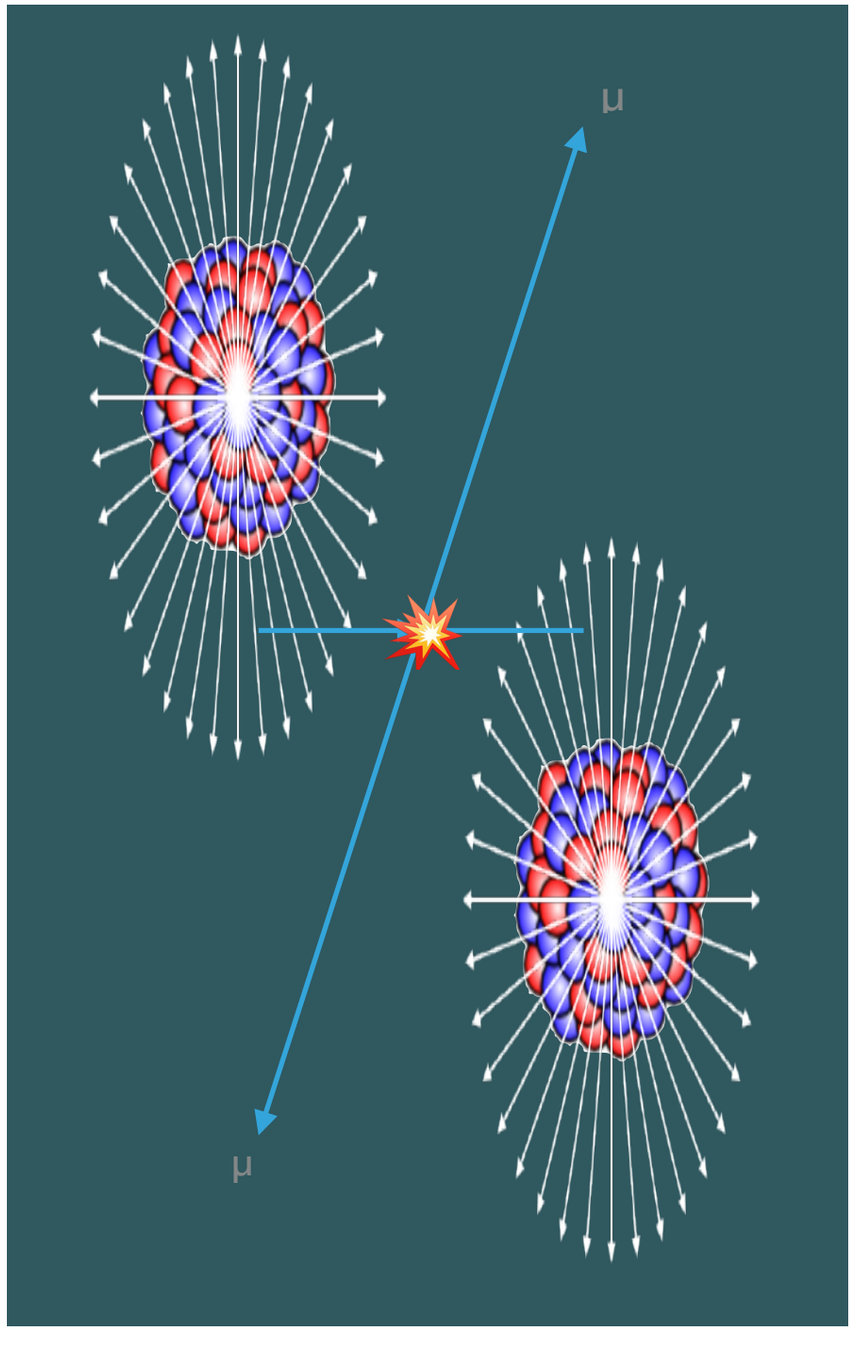
Dimuons from γ+γ fusion in UPC and hadronic Pb+Pb collisions with ATLAS

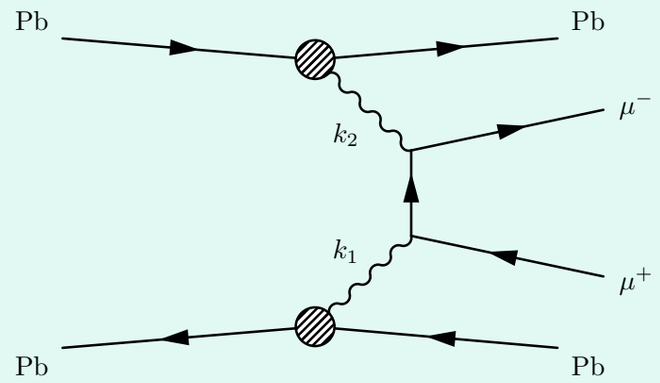
Peter Steinberg, BNL / Initial Stages 2021 / 10-15 January 2021

IS2021

The VI[th] International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR
COLLISIONS

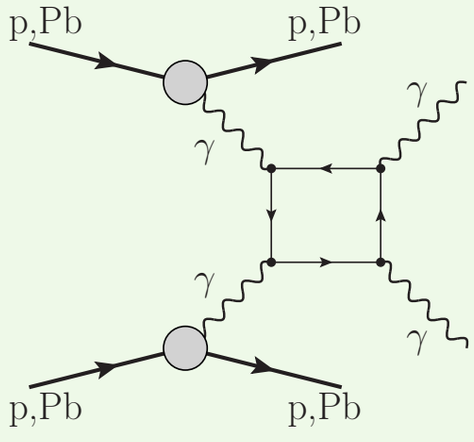
Exclusive γγ processes





lepton pair production
(Breit-Wheeler formula, Brodsky et al 1971)

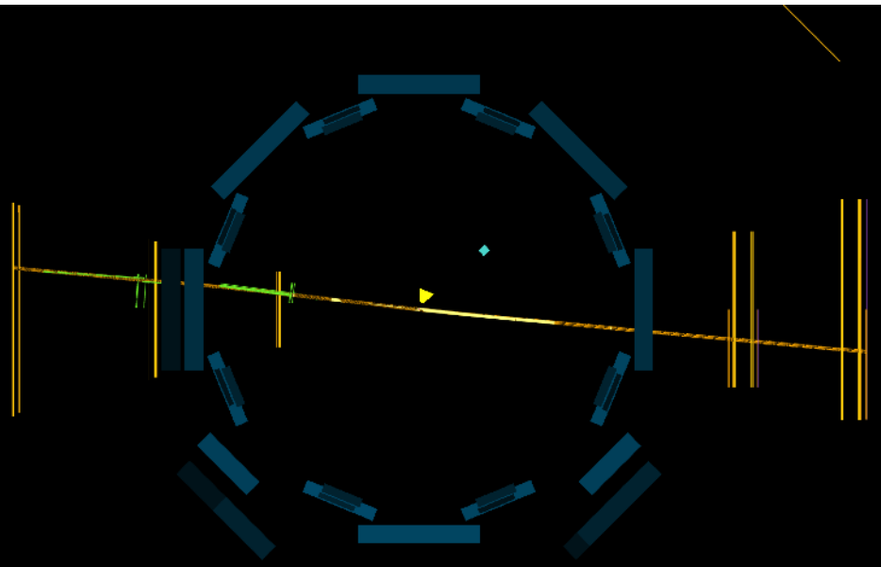
posters by
Ben Gilbert (nonUPC)
PAS (UPC)

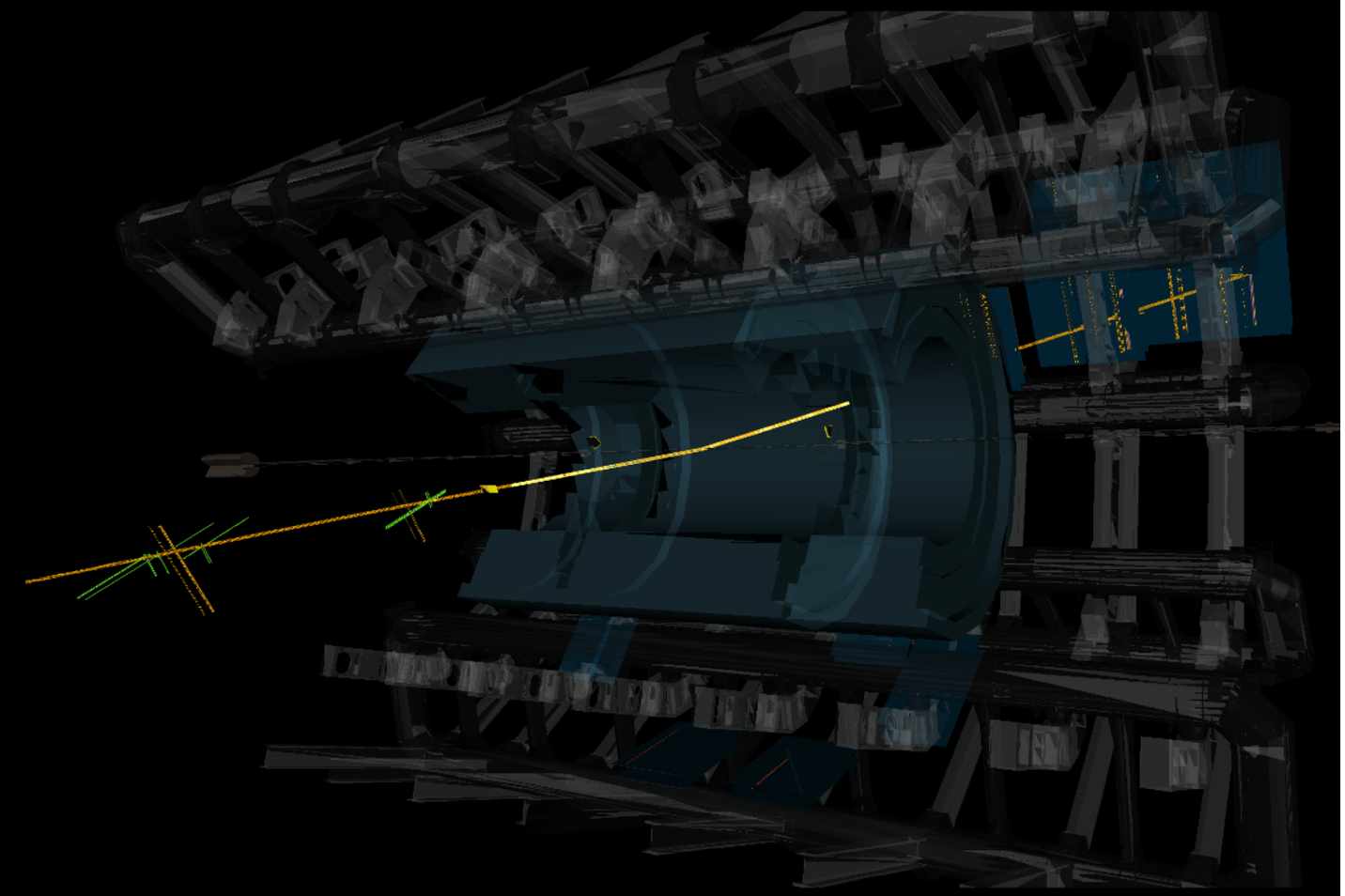


photon pair production
(via quark, lepton, W, BSM? loops)

poster from
Agnieszka Ogrodnik

exclusive μμ production is a pure QED process,
one photon from each nucleus



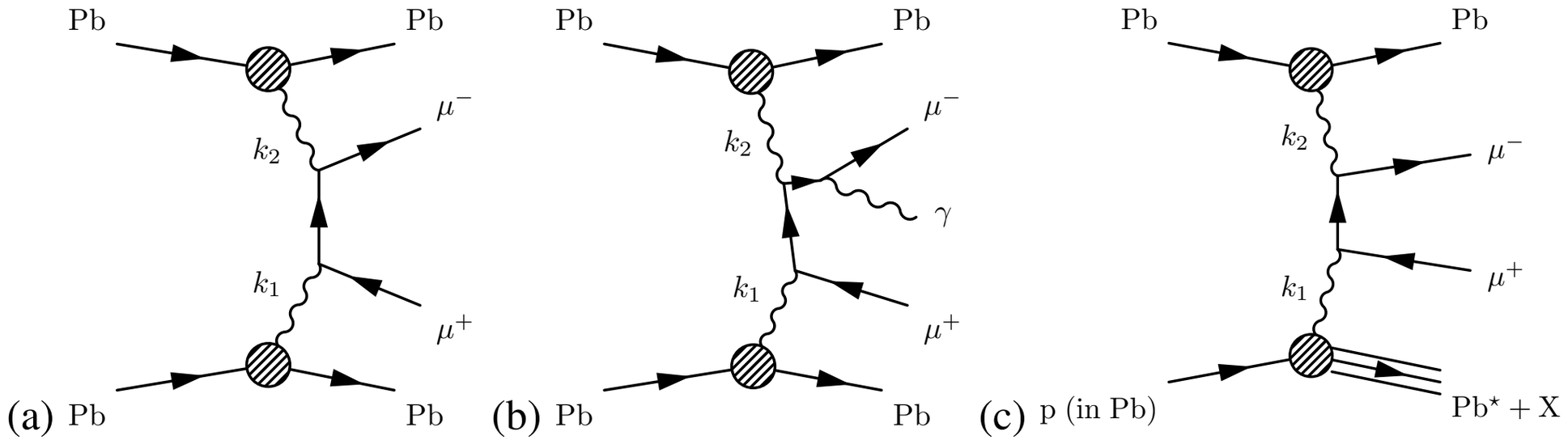


Run: 287038
Event: 71765109
2015-11-30 23:20:10 CEST

Dimuons UPC Pb+Pb 5.02 TeV

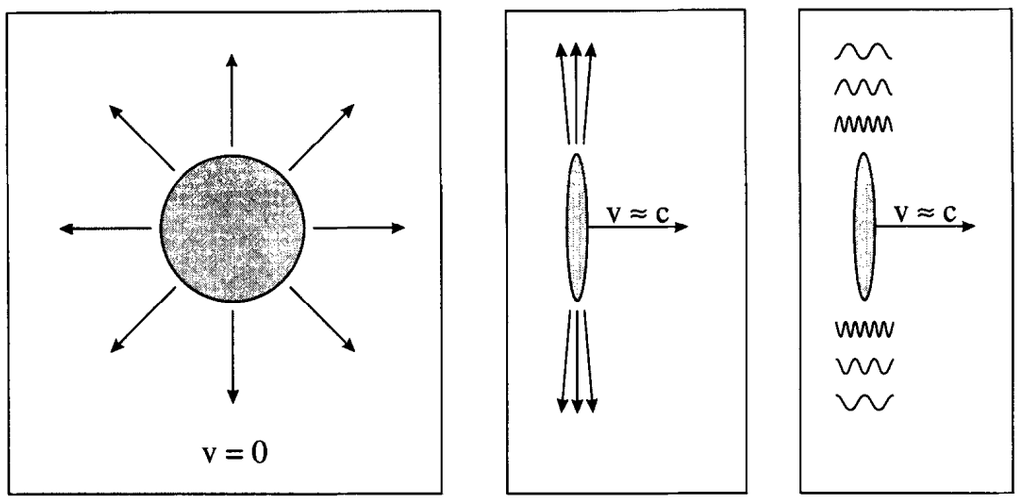
highest mass dimuon event $m_{\mu\mu}$ = 173 GeV

Exclusive processes & dissociation



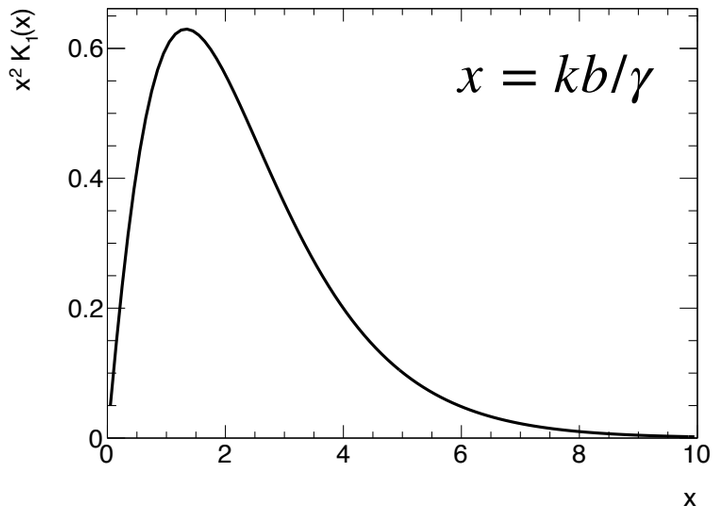
$\mathrm{PbPb}(\gamma\gamma) \to \mu^+\mu^-(\mathrm{Pb}^{(\star)}\mathrm{Pb}^{(\star)})$ is the primary signal Breit-Wheeler process cross section implemented in STARlight, SuperChic, etc.
$\mathrm{PbPb}(\gamma\gamma) \to \mu^+\mu^-\gamma(\mathrm{Pb}^{(\star)}\mathrm{Pb}^{(\star)})$ is a higher order final state, also signal. Not in any existing MC, but now being addressed in calculations, and can be added to final states (e.g. from STARlight) using Pythia8
$\mathrm{Pb} + \mathrm{p/Pb}(\gamma\gamma) \to \mu^+\mu^- X(\mathrm{Pb}^{\star}\mathrm{Pb}^{(\star)})$ is dissociative background (non-EPA) process, including nuclear breakup as well, modeled using LPair.

Two-photon flux



For a point charge:

$$n(k,b) = \frac{d^3N_\gamma}{d^2b\,dk} \propto \frac{\alpha Z^2}{kb^2} f(kb/\gamma)$$



STARlight formalism:

$$\frac{d^2N}{dk_1dk_2} = \int_{b_1>R_1} d^2b_1 \int_{b_2>R_2} d^2b_2\; n(k_1,b_1)n(k_2,b_2)\; P_{\mathrm{fn}}(b)\; (1 - P_{\mathrm{H}}(b))$$

Radial cutoff to nuclear distributions (or use measured form factors)

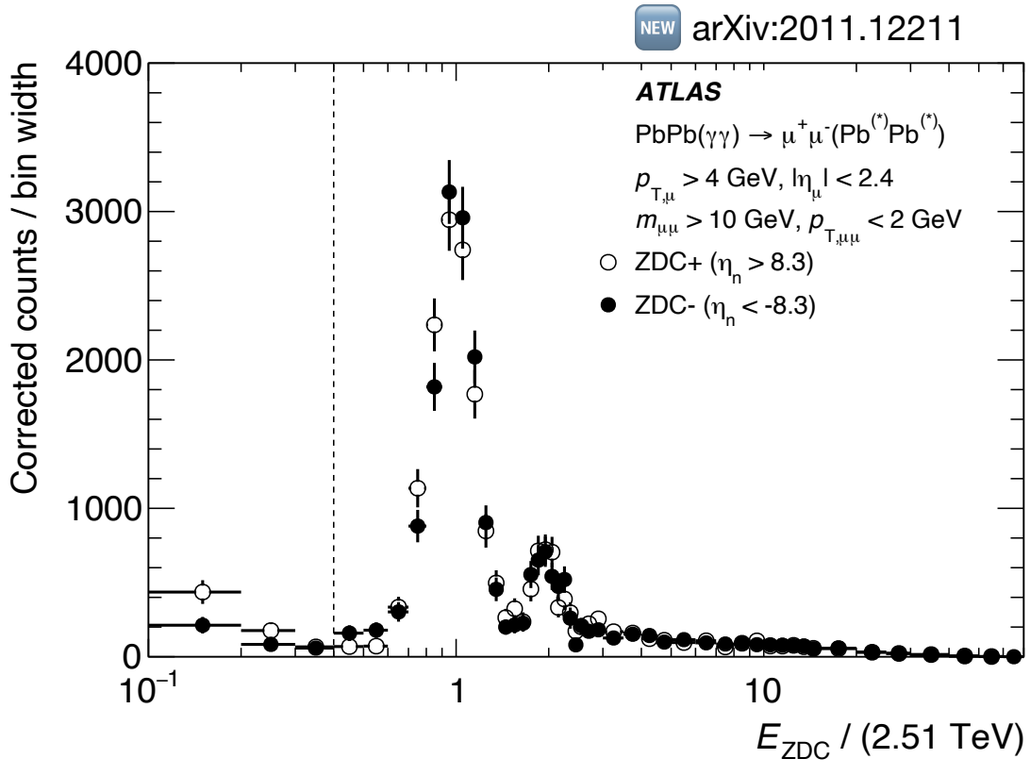
forward neutron topology (from photonuclear processes)

(no) hadronic interaction: Glauber calculation

Two photon flux convolves two separate nuclear photon densities, the probability of a hadronic process (violating exclusivity), and the probability (if required) of a specific forward neutron topology

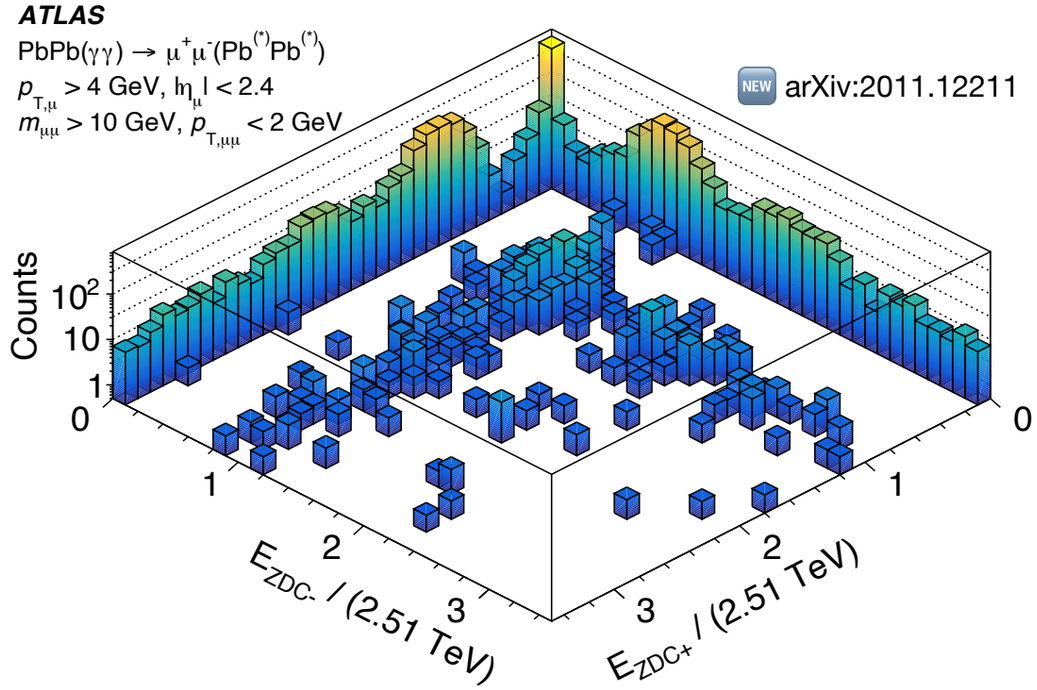
ZDC selections

ZDCs can distinguish 0n from 1n, 2n…

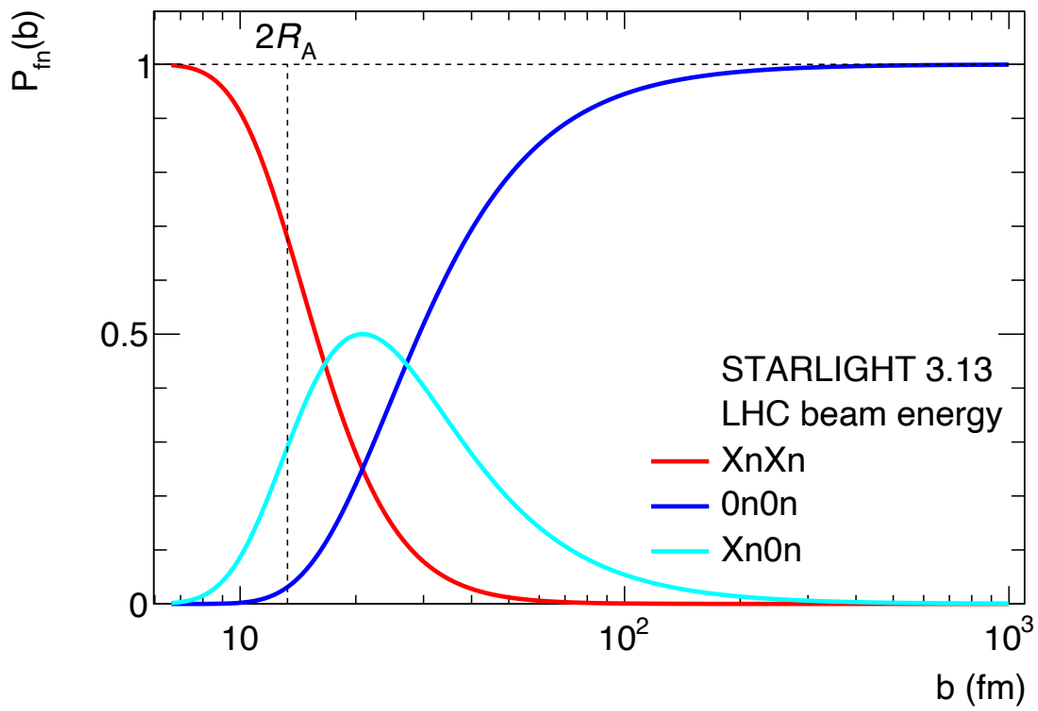


Selection of a specific ZDC topology is also filtering on a range of impact parameters (0-15 fm, 15-40fm, 40+ fm), and so modifies expected incoming photon spectrum

and thus classify events according to 0n0n, Xn0n/0nXn, or XnXn



Klein & PAS, arXiv:2005.08172



Exclusive dimuon dataset & analysis

- **2015 Pb+Pb dataset, L_{int} = 0.48 nb^{-1}**

- **Event trigger**
  - Muon reconstructed at L1 with no p_T selection
  - Maximum total limited to $E_T < 50$ GeV to suppress hadronic events
  - At least one track reconstructed with p_T>200 MeV to suppress empty events
  - No ZDC selection in primary trigger

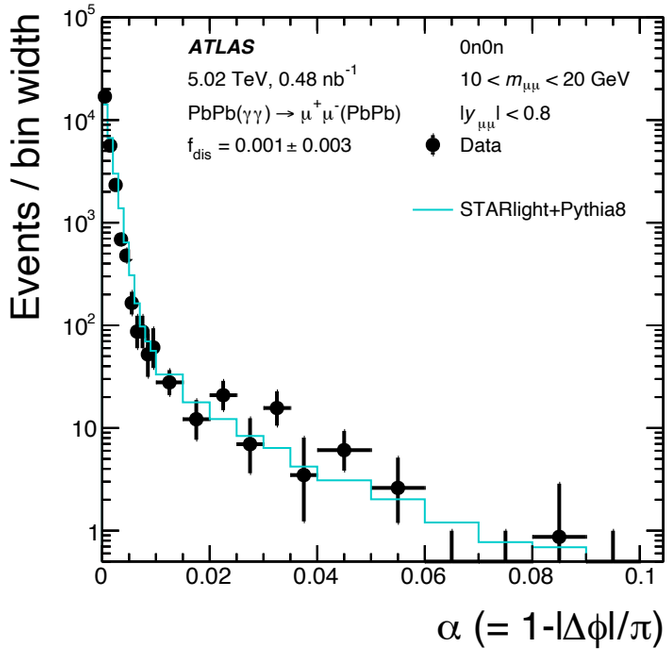
- **Event & fiducial selection**
  - Two good (“tight”) muons and no additional tracks
  - Fiducial selection:
    - $p_{T\mu}$>4 GeV, $|\eta_\mu|$<2.4, $m_{\mu\mu}$ > 10 GeV, $p_{T\mu\mu}$ < 2 GeV
  - (optional) ZDC topology measured using calibrated energies

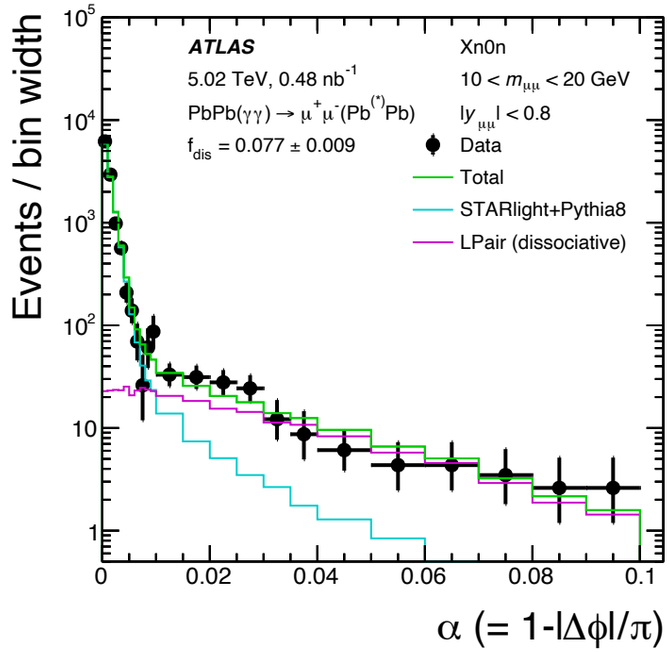
- **Corrections**
  - Trigger efficiency (measured)
  - Reconstruction efficiencies (MC+data corrections)
  - Dissociative background
  - Bin migration (mainly at edges of $p_{T\mu1}, p_{T\mu2}$ = 4 GeV) - 1-3% effect

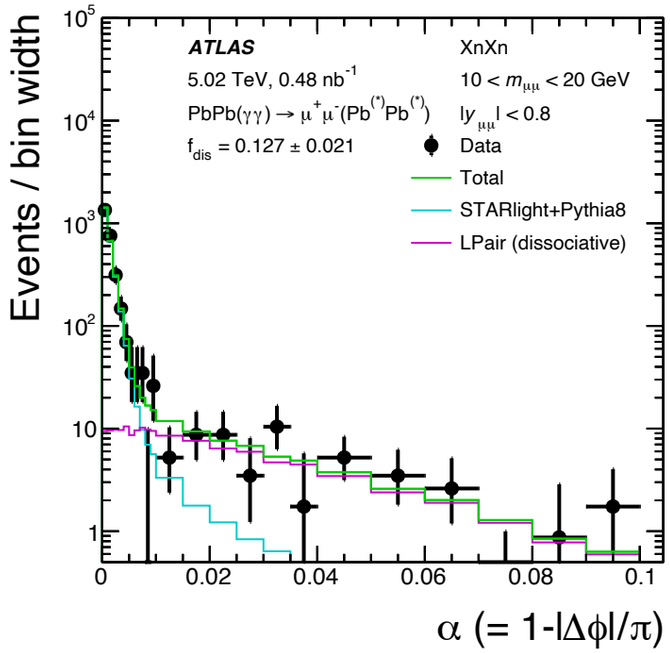
Dissociative contributions

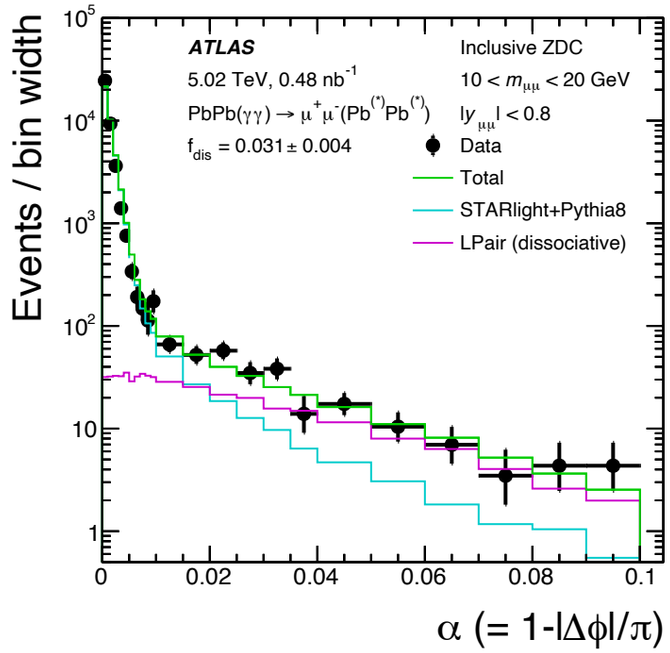
- **Dimuon acoplanarity distributions in coarse $m_{\mu\mu}$ and $y_{\mu\mu}$ bins fit with two templates**
  - STARlight+Pythia8 to include FSR - full description of 0n0n
  - LPair to model dissociative contributions - needed for Xn0n and XnXn
- **Averaged over ZDC topologies, only 3% correction for lower $m_{\mu\mu}$, $y_{\mu\mu}$**

NEW arXiv:2011.12211



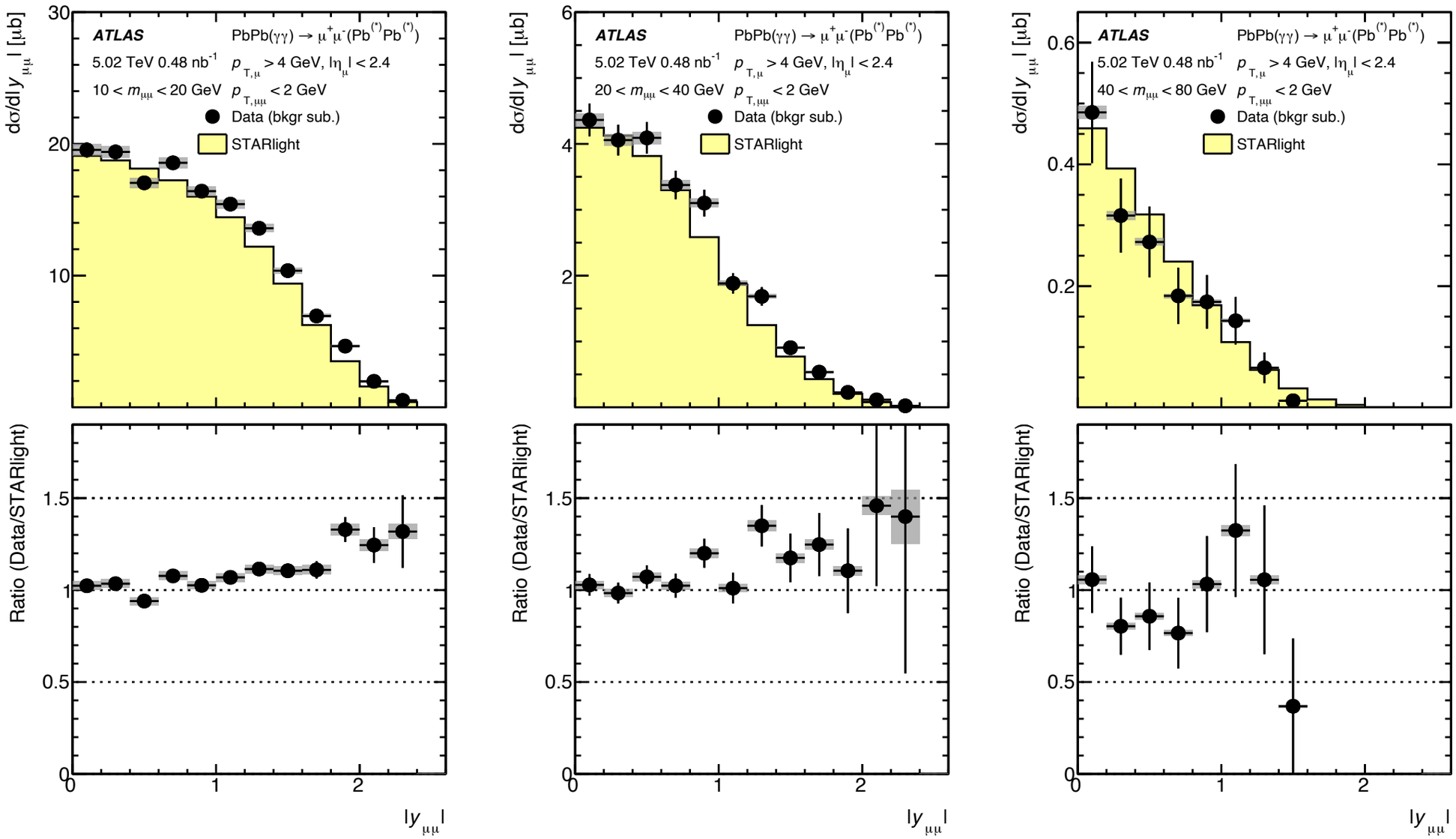






Data compared to STARlight: $y_{\mu\mu}$

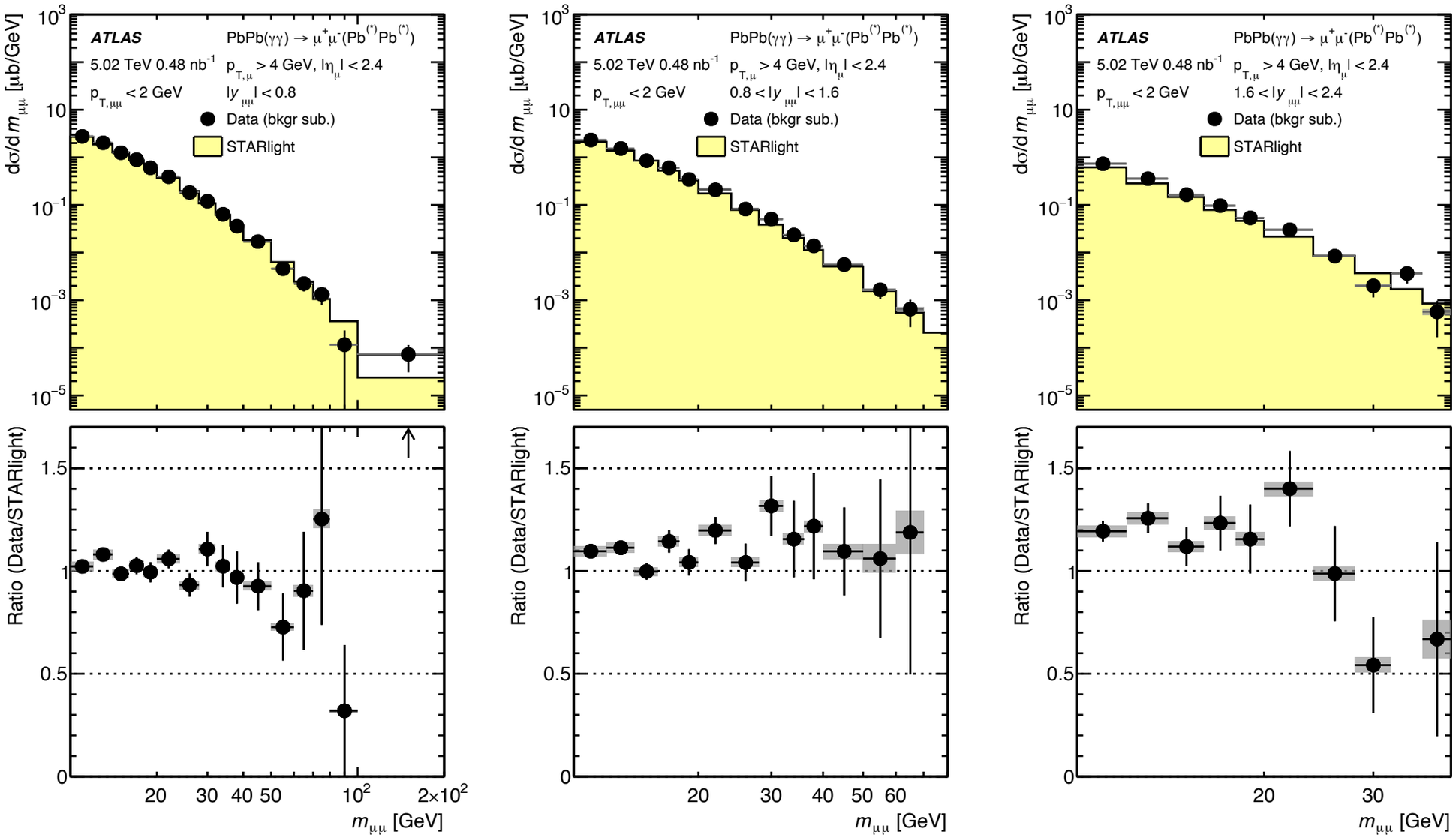
NEW arXiv:2011.12211



Good agreement with STARlight 2.0, but systematic increase observed at higher $y_{\mu\mu}$

Data compared to STARlight: $m_{\mu\mu}$

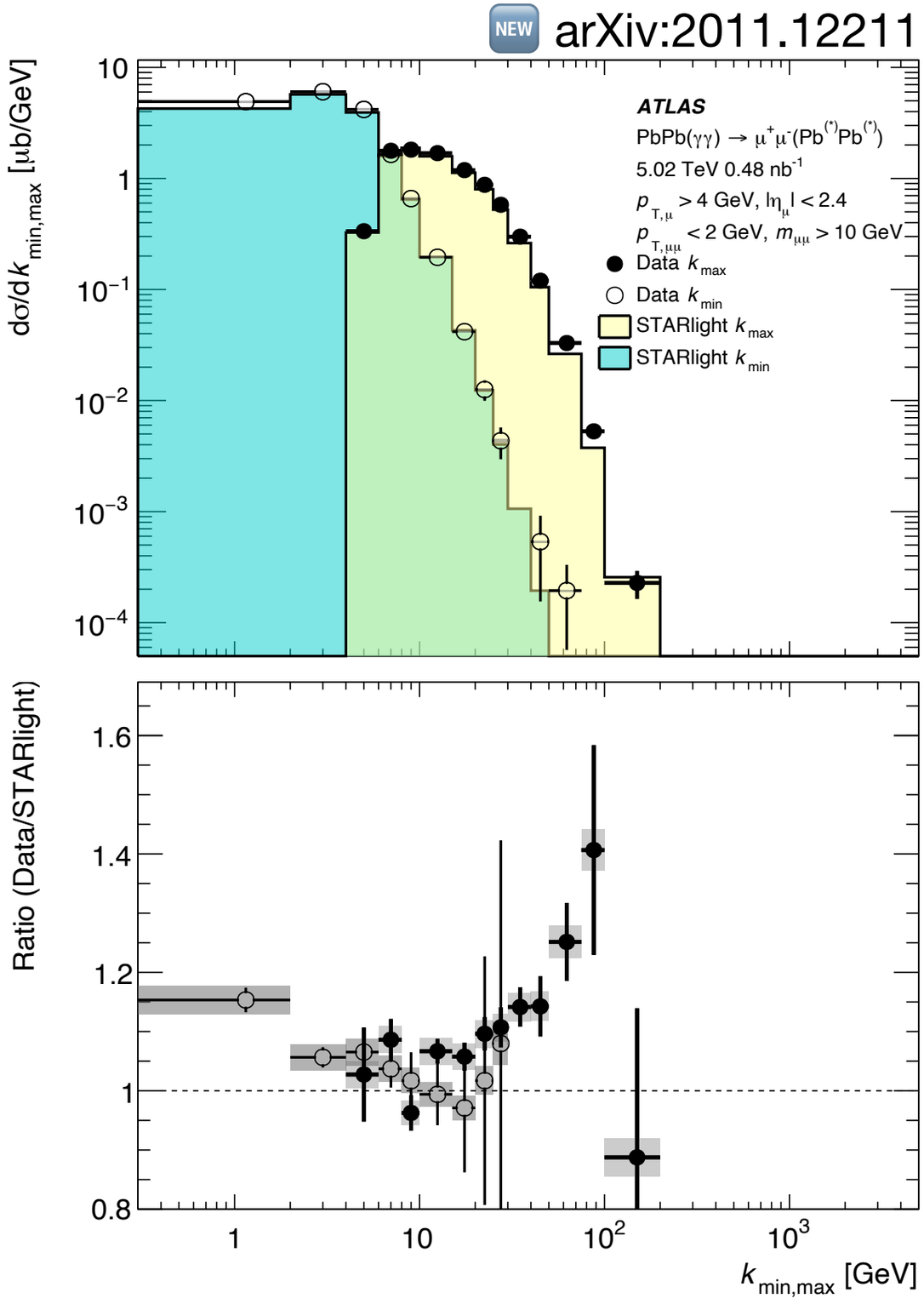
NEW arXiv:2011.12211



Overall increase in mass distribution just reflects increase vs. $y_{\mu\mu}$

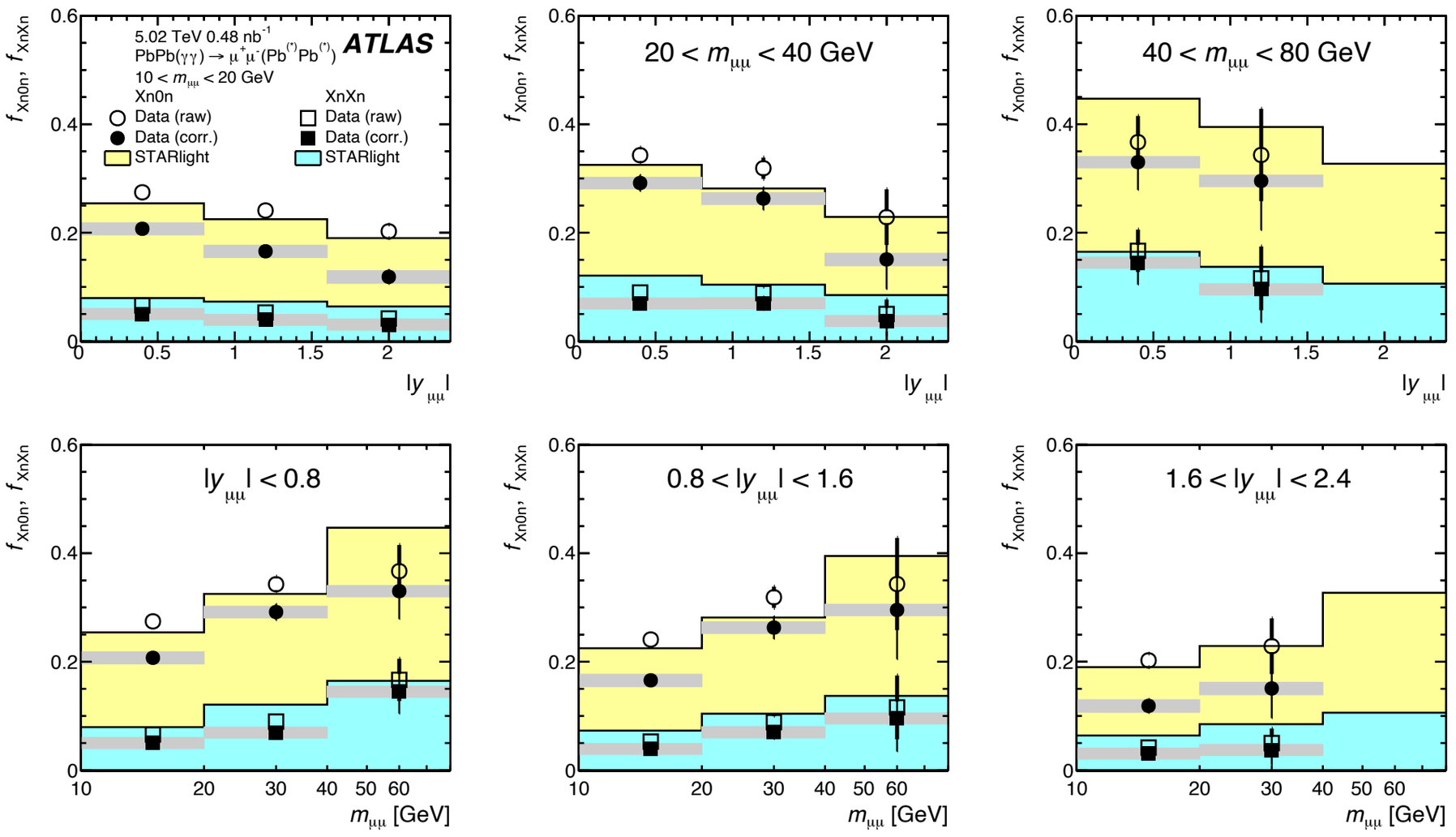
Photon energy distributions

- **Incoming photon energies estimated assuming p_T~0**
  - $k_{1,2} = (m_{\mu\mu}/2)\exp(\pm y_{\mu\mu})$
- **Distributions of maximum and minimum $k_{min,max}$ agree well with STARlight**
  - Systematic differences observed at low and high $k_{1,2}$
- **One obvious issue is requirement of $b>R_{1,2}$ in two-photon flux**
  - Several authors already questioned this, but need to address systematically
  - Ignoring it completely gives 20% increase in predicted cross section



ZDC fraction vs. $m_{\mu\mu}$ and $y_{\mu\mu}$

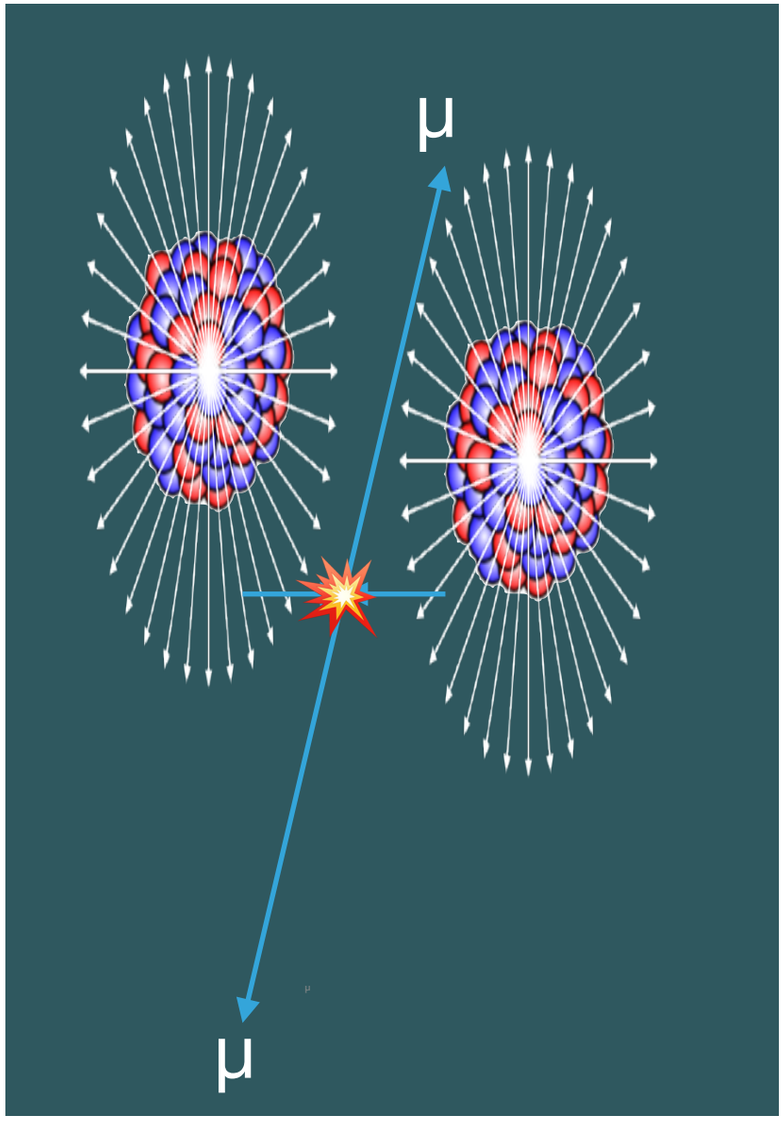
NEW arXiv:2011.12211

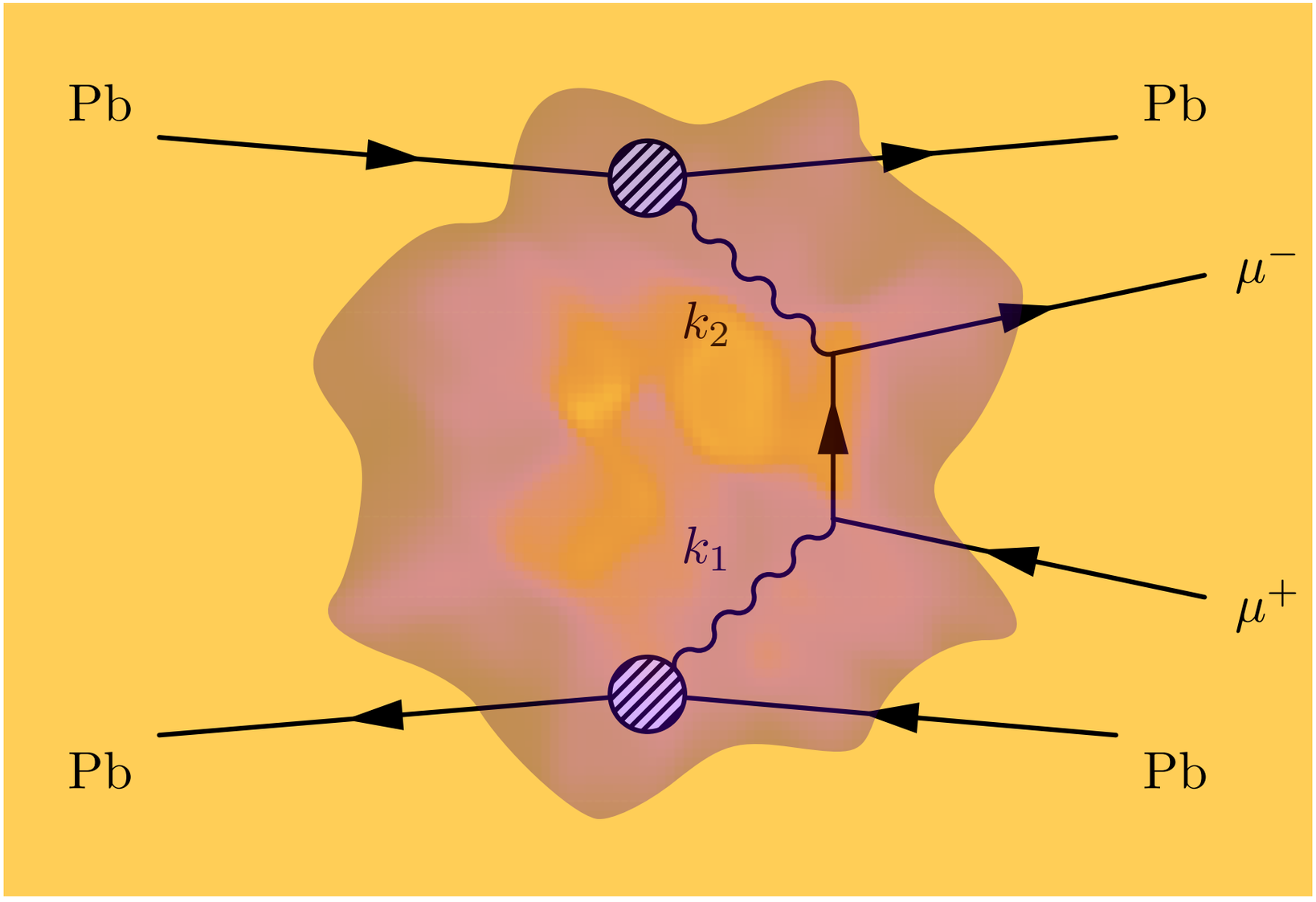


Fractions of events with Xn0n, and XnXn corrected for electromagnetic pileup, assuming Xn cross sections from ALICE, extrapolated to 5.02 TeV

Reasonable agreement with STARlight, but MC slightly overestimates nuclear dissociation.

Non-exclusive μμ from γγ





The same μμ process can occur in non-UPC Pb+Pb collisions,
albeit accompanied by hadronic backgrounds (e.g. HF):
are the outgoing muons sensitive to initial (e.g. B field) or final (QGP) effects?

(initial studies from ATLAS & STAR already in the literature)

Phys. Rev. Lett. 121, 212301 PHYSICAL REVIEW LETTERS **121,** 132301 (2018)

Non-exclusive μμ from γγ

- **Follow-up from pioneering measurements of 2015 Pb+Pb data, showing clear modifications of dimuon angular distributions in 0-10% compared with >80%**

$\alpha \equiv 1 - \lvert\Delta\phi\rvert/\pi$	acoplanarity
$\mathrm{A} \equiv (p_{\mathrm{T}1} - p_{\mathrm{T}2})\,/(p_{\mathrm{T}1} + p_{\mathrm{T}2})$	p_{T} asymmetry
$k_{\perp} \equiv (p_{\mathrm{T}1} + p_{\mathrm{T}2})\,\lvert(\pi - \Delta\phi)\rvert/2 = \pi\alpha\bar{p}_{\mathrm{T}}$	perpendicular p_{T}

- **Background subtraction is the primary problem in making the measurement**
  - Dileptons from heavy flavor have larger displacement
  - Drell-Yan and dissociation are small contributions, but are not included in existing MC (under renewed scrutiny for publication)

- **This measurement uses full 2015+2018 dataset (1.9 nb^{-1})**

Event selection

- **Event level**
  - Single and double muon triggers
  - Reconstructed vertex
- **Muon pair**
  - Two opposite-signed muons, each with p_T>4 GeV and |eta|<2.4
  - $4 < m_{\mu\mu} < 45$ GeV
- **HF rejection by momentum imbalance**
  - $\alpha < 0.012$
  - $A < 0.08$
- **HF rejection (signal selection) by impact parameter selection**

$$d_{0\text{pair}} \equiv \sqrt{d_{0_1}^2 + d_{0_2}^2}$$

$$(z_0 \sin(\theta))_{\text{pair}} \equiv \sqrt{(z_{01} \sin(\theta_1))^2 + (z_{02} \sin(\theta_2))^2}$$

- **"Signal candidates" defined by $d_{0pair} < 0.1$ mm and $z_{0pair} < 0.2$ mm**
  - Removes 50% of HF in more central bins

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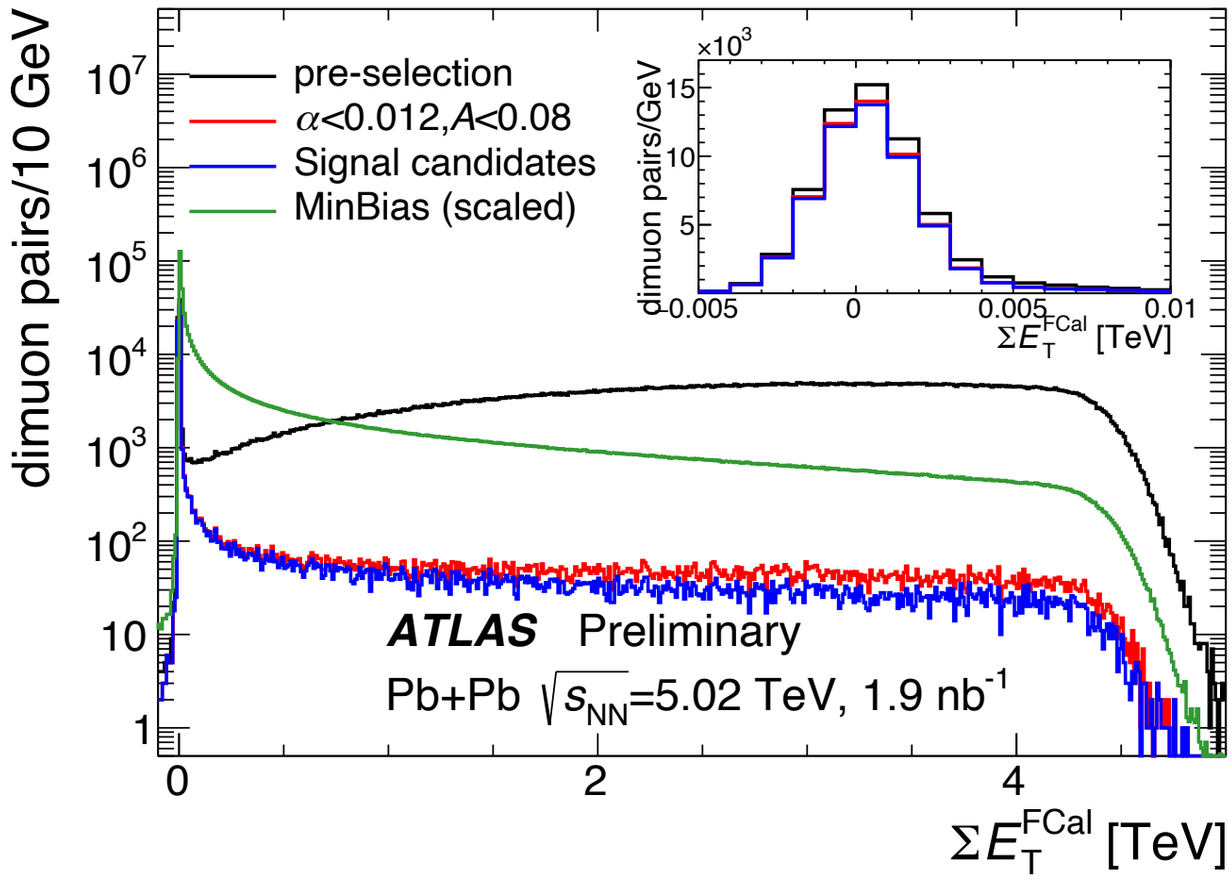
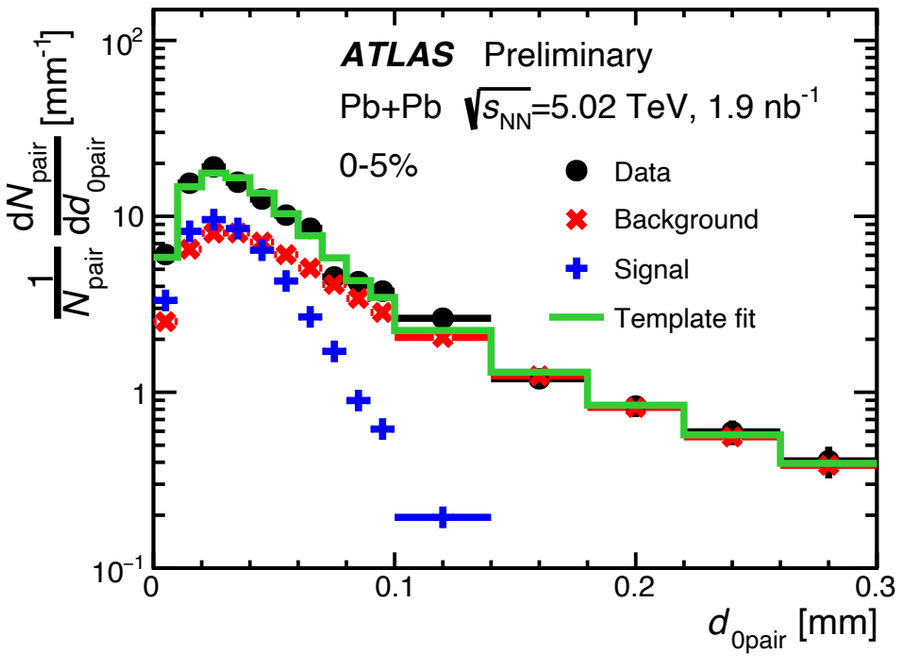


Dimuon selection enhances HF

α,A selections suppresses HF

impact parameter selection removes further residual HF contributions (centrality dep.)

Signal fraction



Fits are performed using a combination of **signal template** (MC + d_0 smearing), and **background template** (data, after anti-selections on A and α)

Fit range is $d_{0pair} < 0.3$ mm but signal fraction is defined for $d_{0pair} < 0.1$ mm

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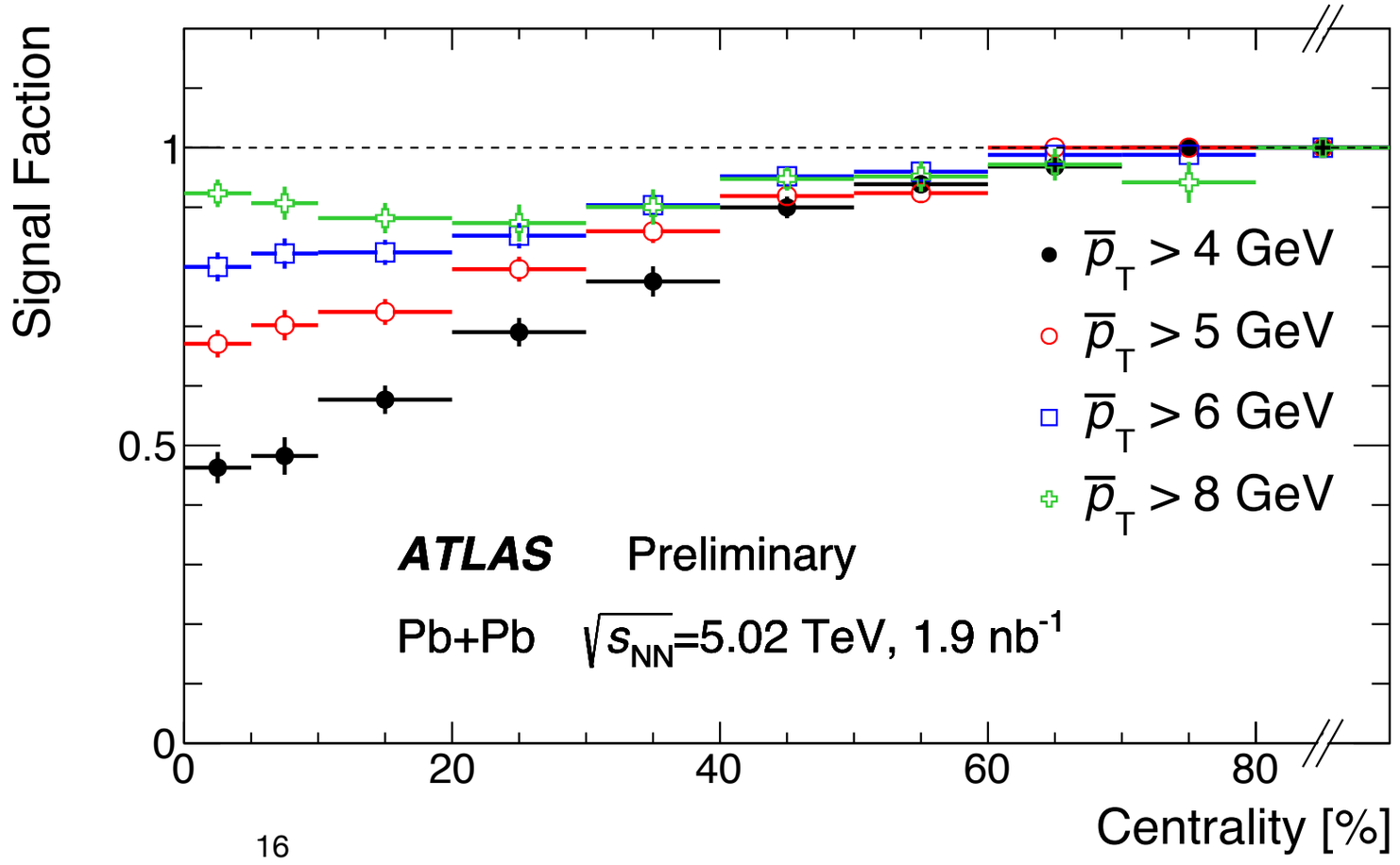
Signal fraction a strong function of centrality

Backgrounds are reduced at higher average p_T



Broadening in α and k_T

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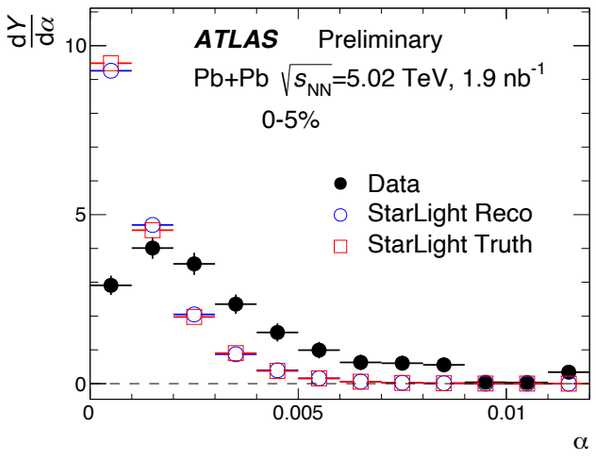
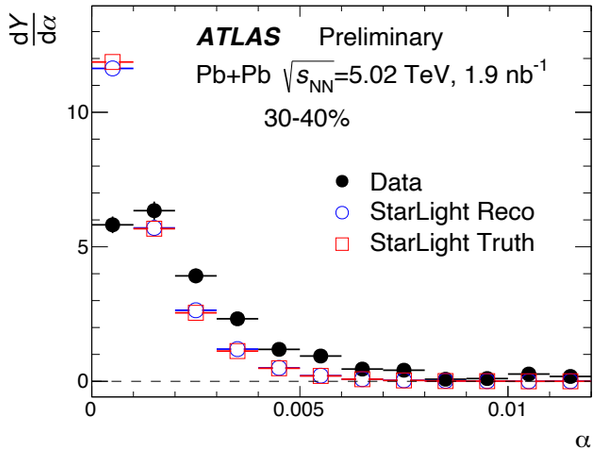
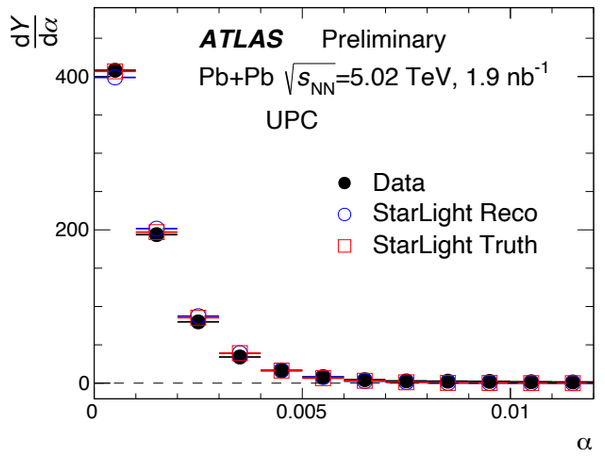
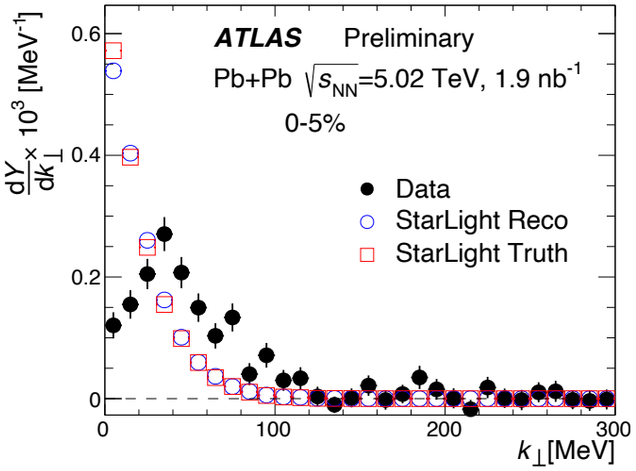
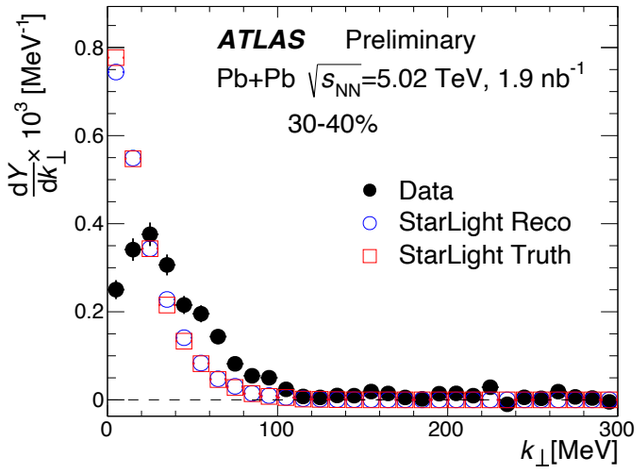


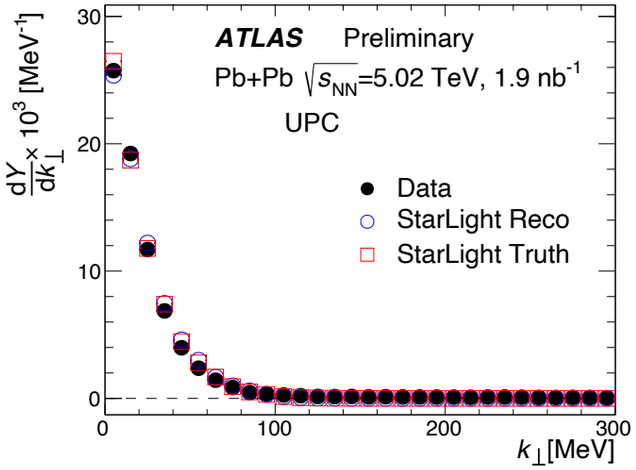




modest peak develops in α as collisions get more central

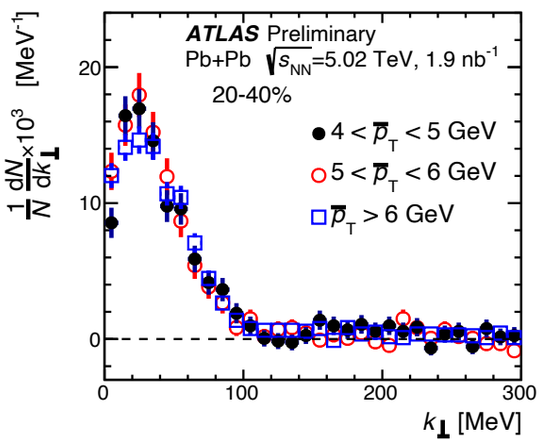




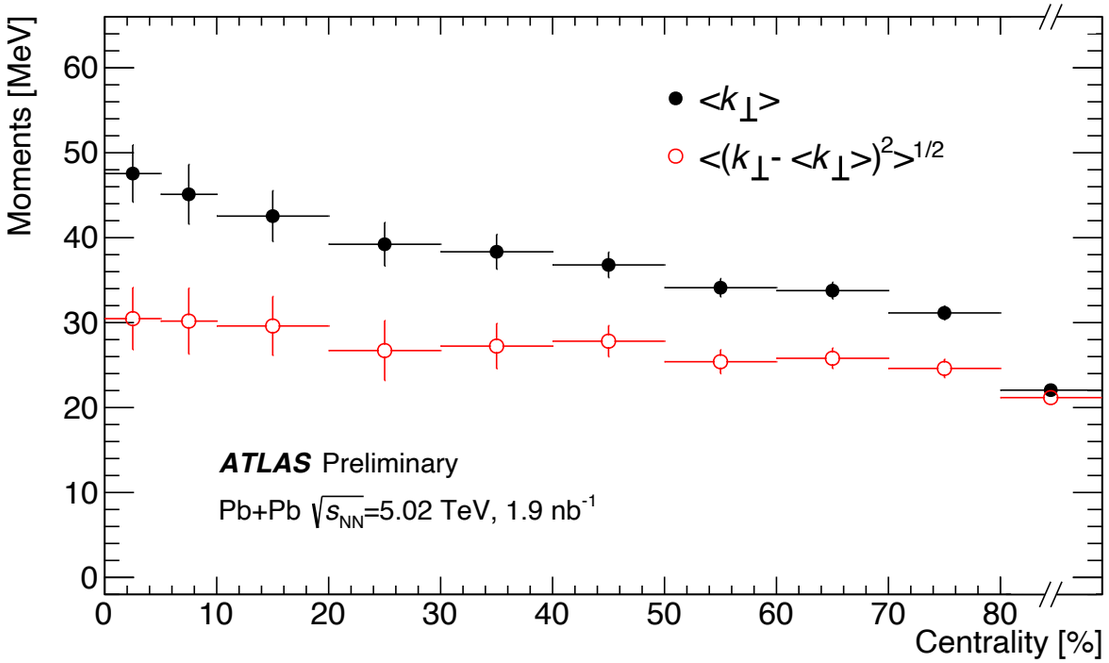


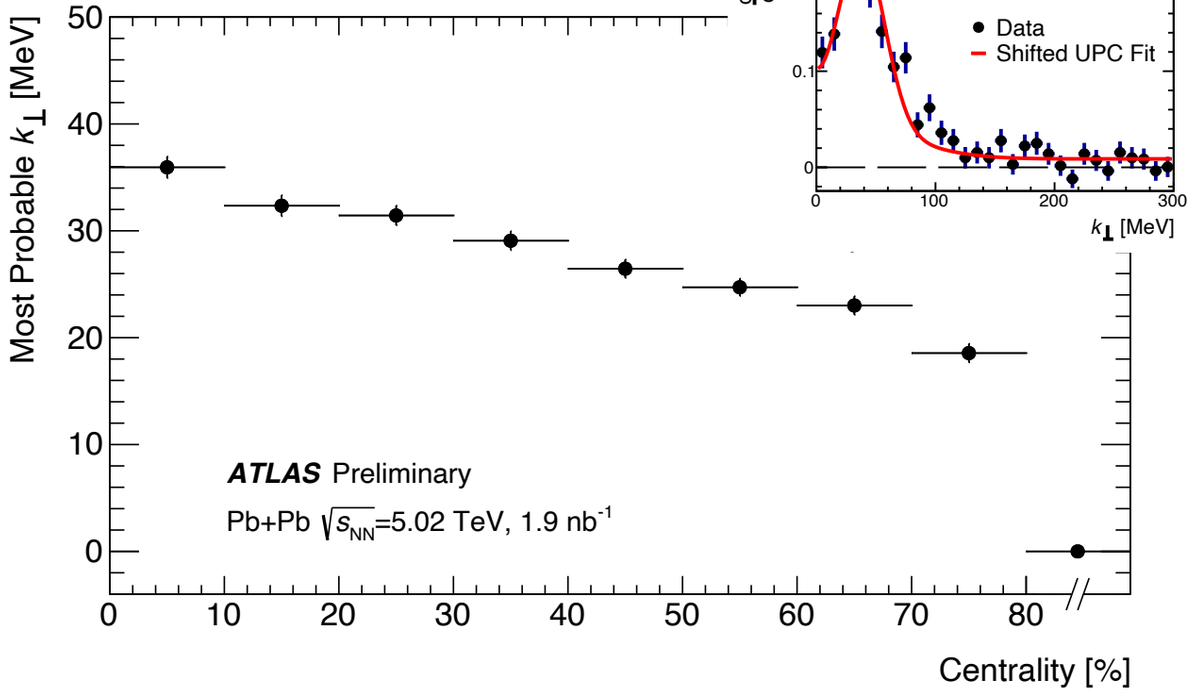
sharper peak observed in k_T

no p_T dependence!



Centrality dependence of k_T





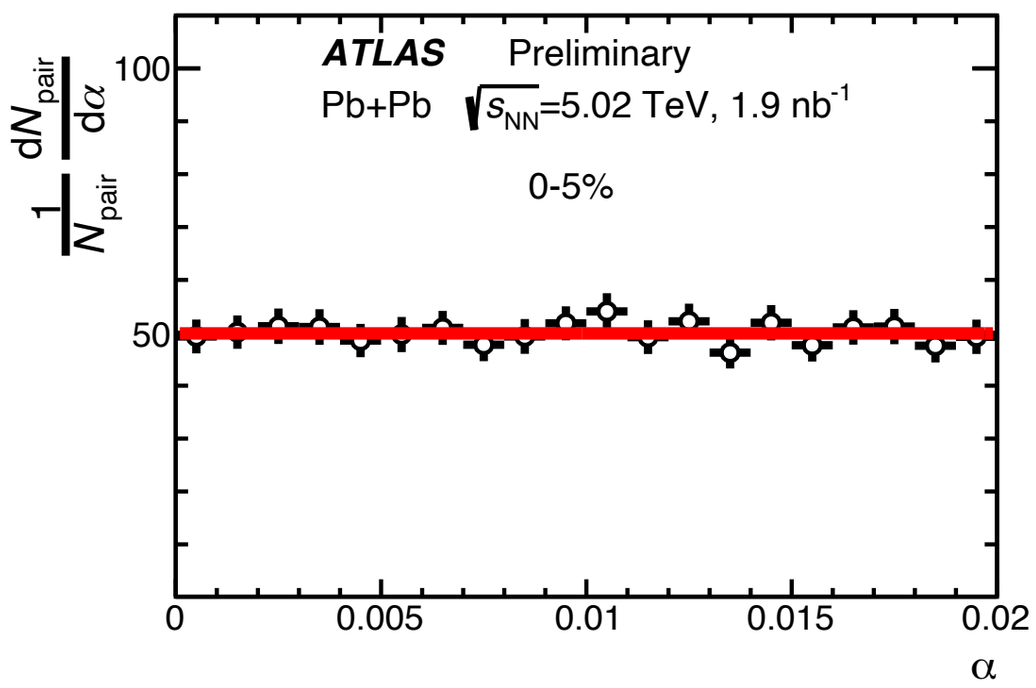
- **Clear increase in <k_T> from peripheral to central events**
  - Weaker dependence of the RMS
- **To capture evolution of peak position, a phenomenological "shifted UPC" fit is performed**
- **QED calculations from Zha et al (PLB 800 (2020) 135089), which include an impact parameter dependence of the initial photon p_T, predicted this feature**

Summary and outlook: μμ from γγ

- **Exclusive dimuons in Pb+Pb (🆕 arXiv:2011.12211)**
  - Measured in 2015 Pb+Pb data
  - Wide range in $m_{\mu\mu}$, $y_{\mu\mu}$
  - Higher order contributions compatible with Pythia FSR
  - Dissociative contribution clearly distinguished and removed, using ZDC selections
  - Good agreement with STARlight, except at higher photon energies: needs closer look at integration boundaries.
    - *New constraints on our understanding of nuclear photon flux*

- **Non-exclusive dimuons (ATLAS-CONF-2019-051)**
  - Now measured with 2015+2018 dataset
  - HF background extracted
  - Clear displaced peak observed in acoplanarity & k_T distributions
  - Use of k_T removes sensitivity to muon p_T
  - Centrality dependence of distributions measured, and awaits detailed comparison to QED calculations

Yield extraction



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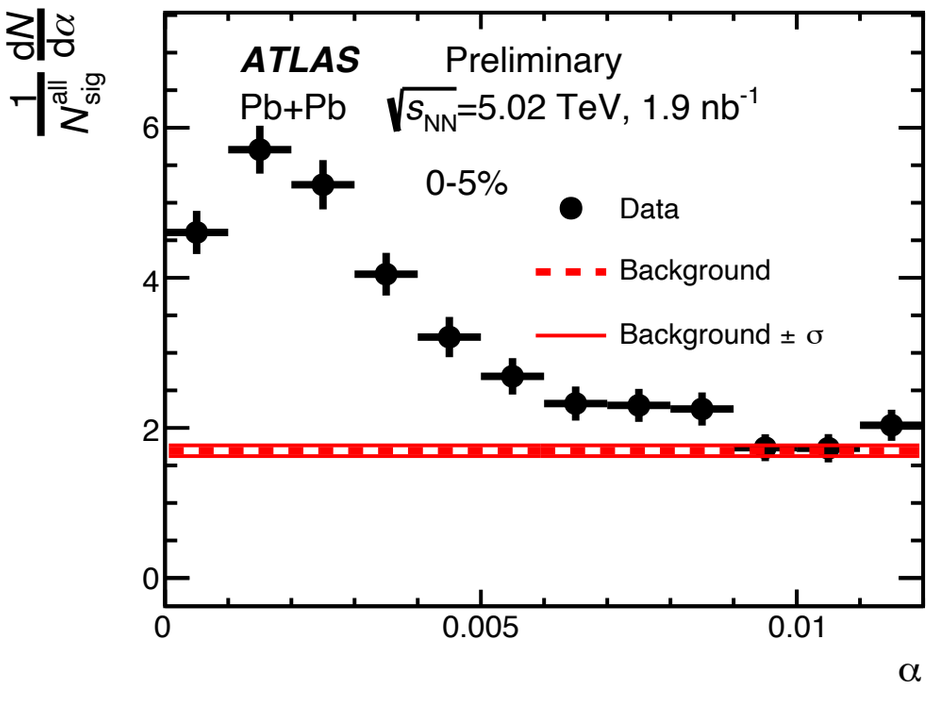


Requiring A>0.08 gives a constant background in α

Normalized by f_{sig}, allows α-dependent extraction of signal yield

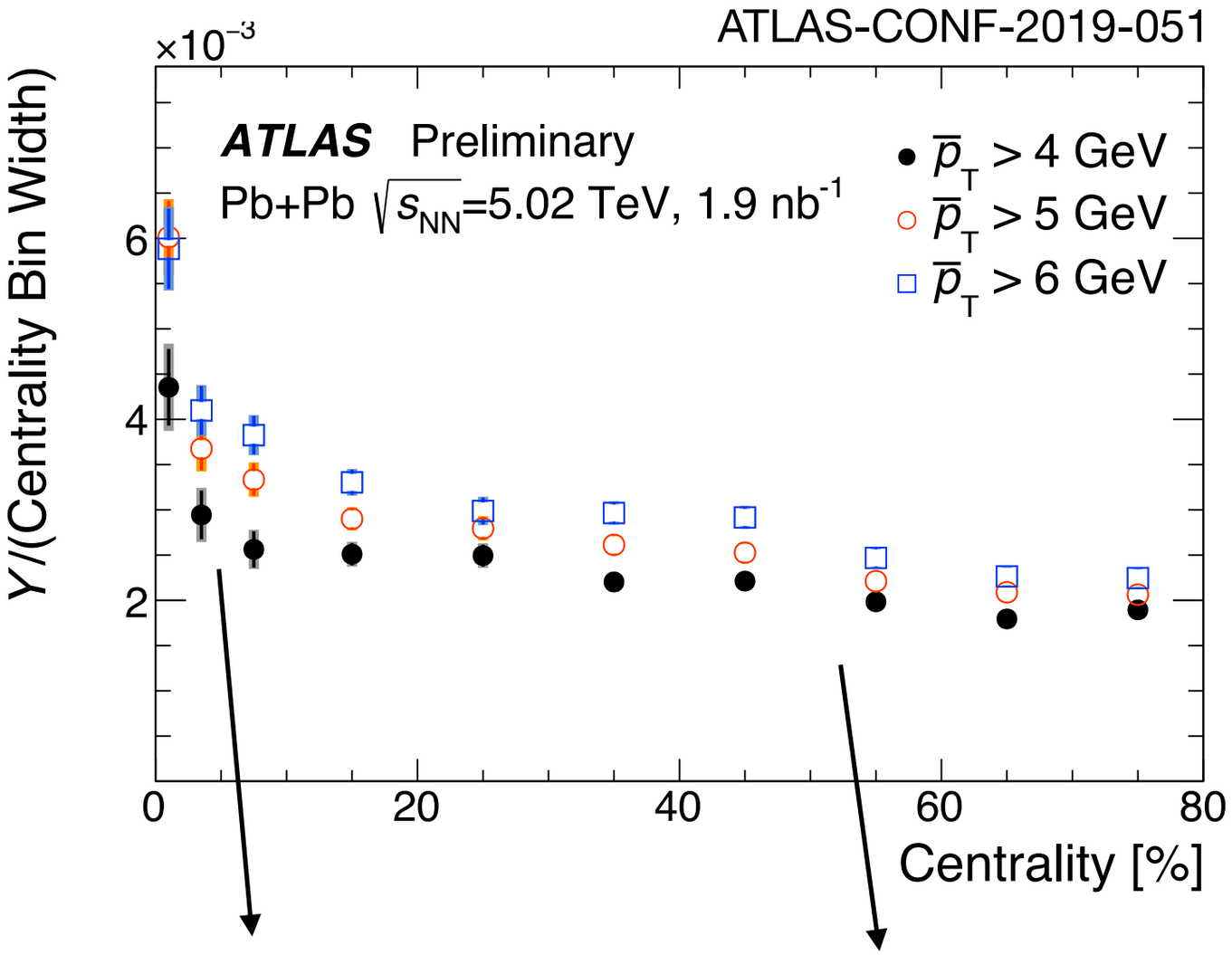
Centrality dependent yield:

$$N_{\mathrm{sig}}^{\mathrm{cent},\bar{p}_{\mathrm{T}}} = f_{\mathrm{sig}}^{\mathrm{cent},\bar{p}_{\mathrm{T}}} \times N^{\mathrm{cent},\bar{p}_{\mathrm{T}}}$$

fractional yield

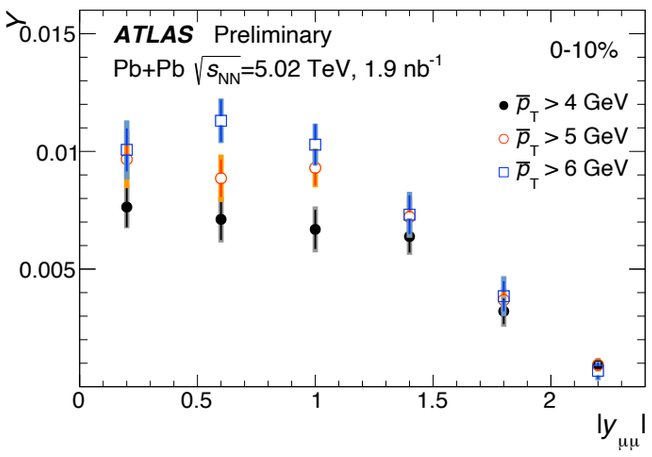
$$Y^{\mathrm{cent},\bar{p}_{\mathrm{T}}} \equiv \frac{N_{\mathrm{sig}}^{\mathrm{cent},\bar{p}_{\mathrm{T}}}}{N_{\mathrm{sig}}^{\mathrm{all},\bar{p}_{\mathrm{T}}}}$$

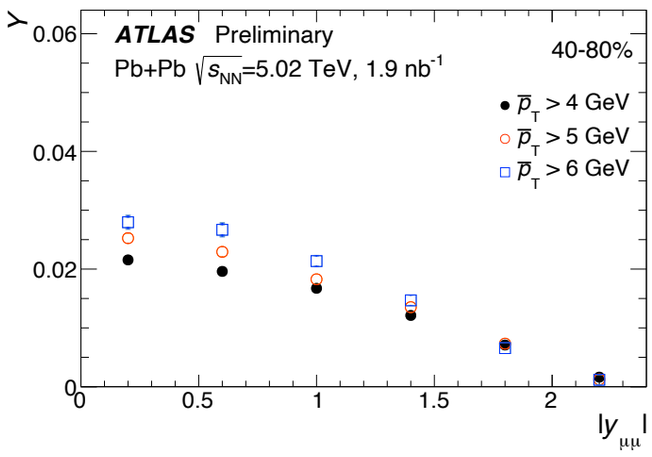
Centrality dependent yields



Weak centrality dependence of fraction yield except in the most central events

Higher fractional yield at larger average p_T in central events.

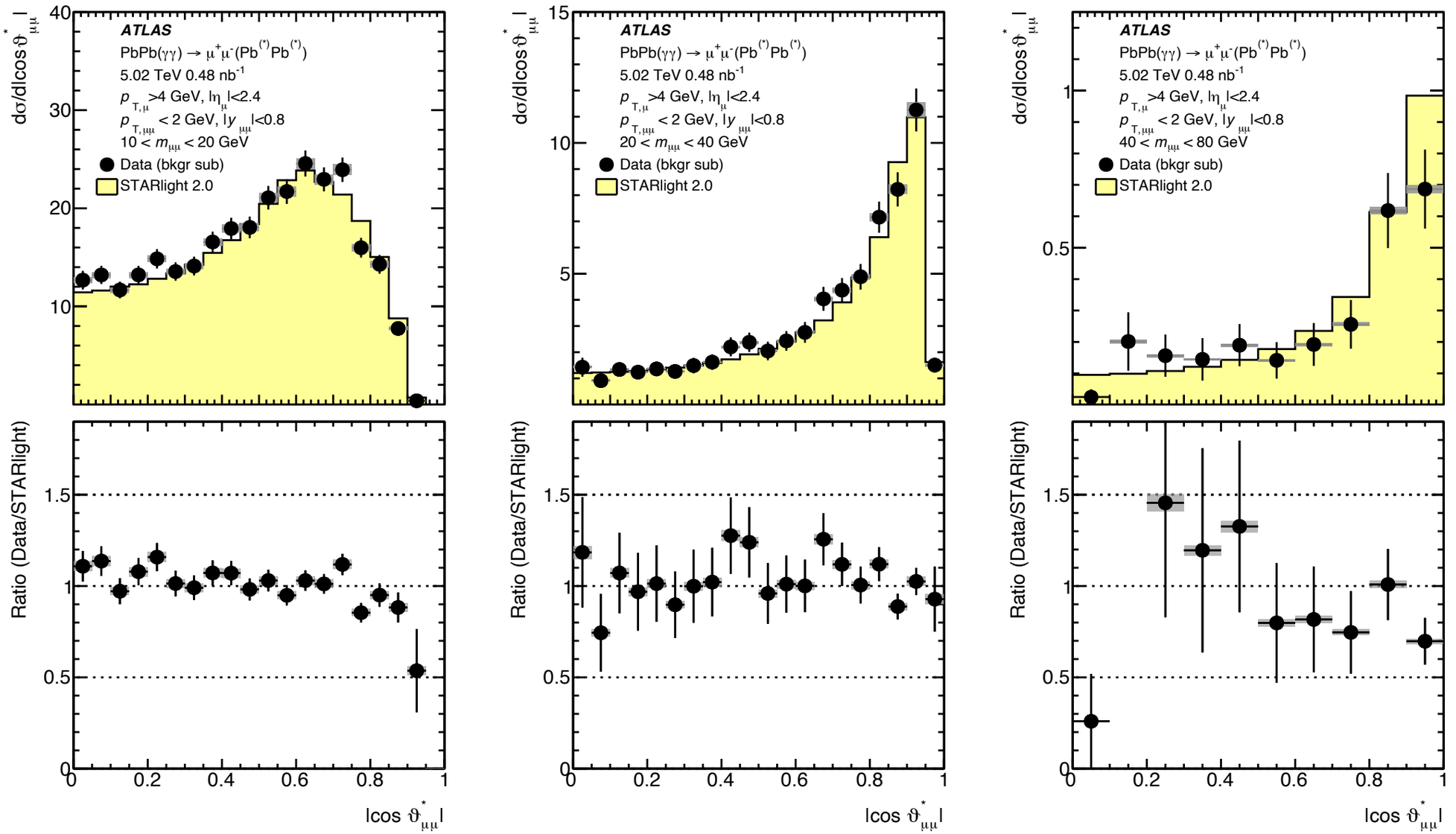




Larger yields at higher p_T in central events do not have strong rapidity dependence

Data compared to STARlight: |cos(θ*)|

NEW arXiv:2011.12211



After restricting comparisons to $|y_{\mu\mu}|<0.8$, to avoid differences at larger $|y_{\mu\mu}|$, good agreement in scattering angle (Breit-Wheeler)