Dilepton production from $\gamma\gamma$ fusion in Pb+Pb collisions with ATLAS

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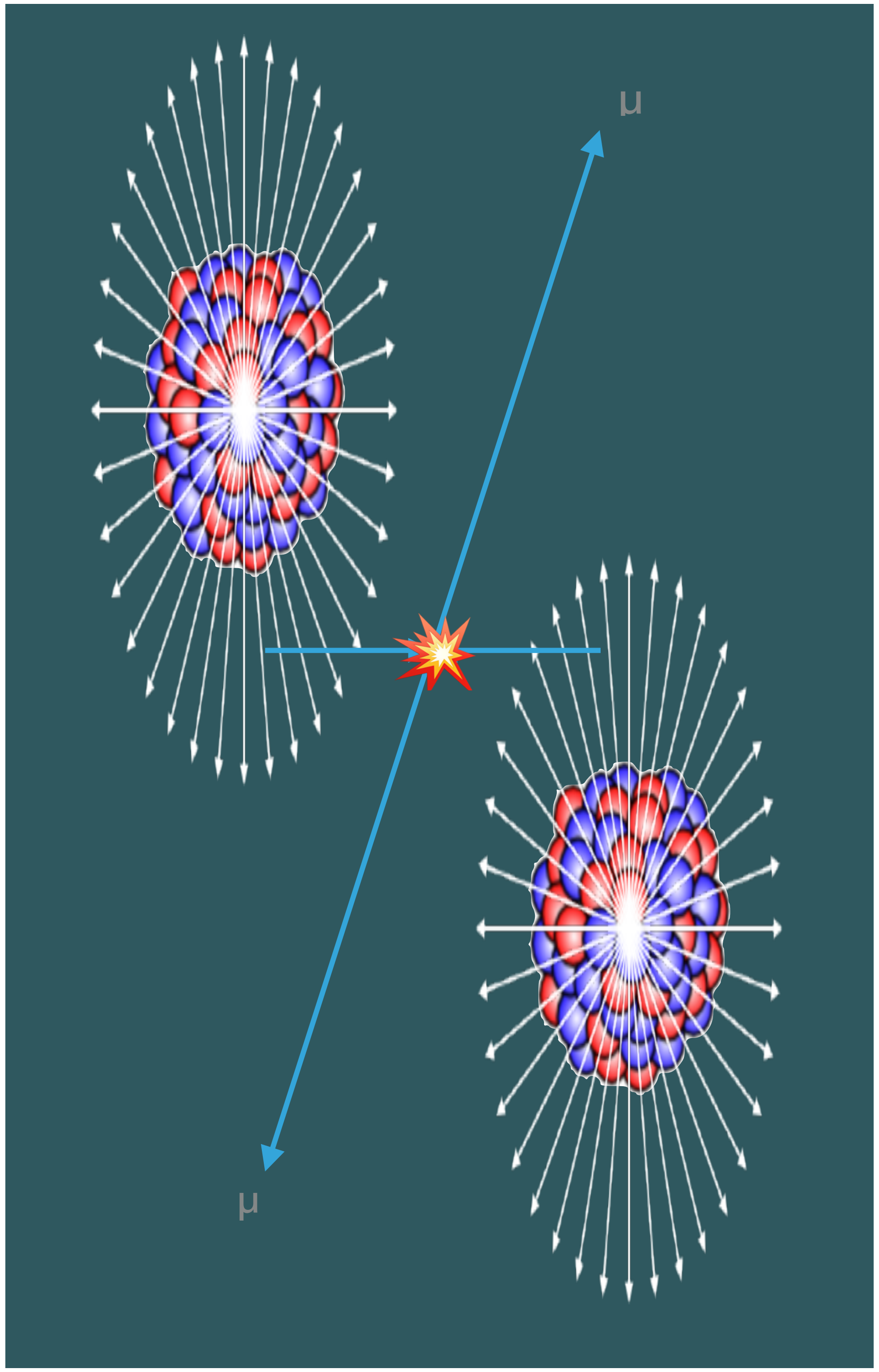
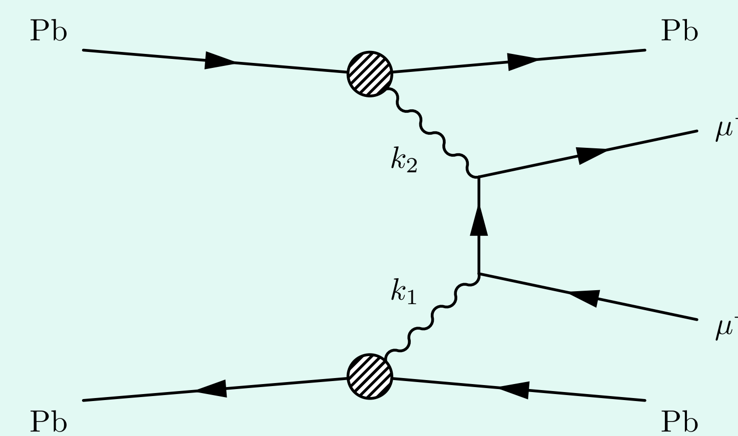
DIS 2023 / 27-31 March 2023

Brookhaven National Laboratory

https://www.symmetrymagazine.org/article/a-collision-of-light

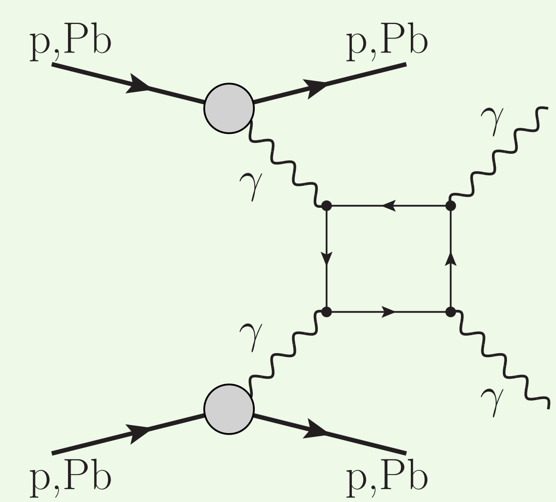
Exclusive γγ processes





lepton pair production

(Breit-Wheeler formula, Brodsky et al 1971)



<u>photon</u> pair production

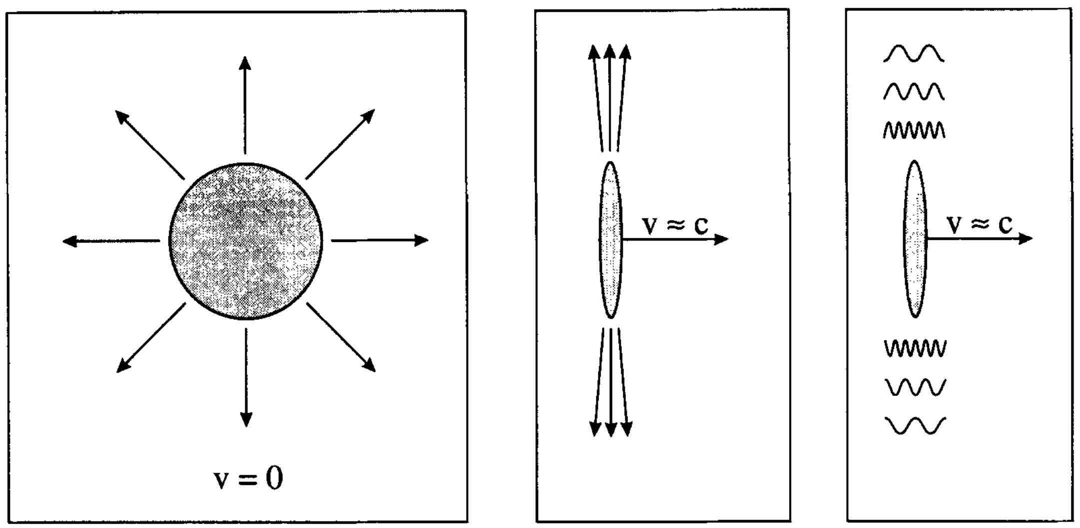
(via quark, lepton, W, BSM? loops)

Heavy ion collisions are excellent QED & BSM laboratories!

see next talk by K. Maj!

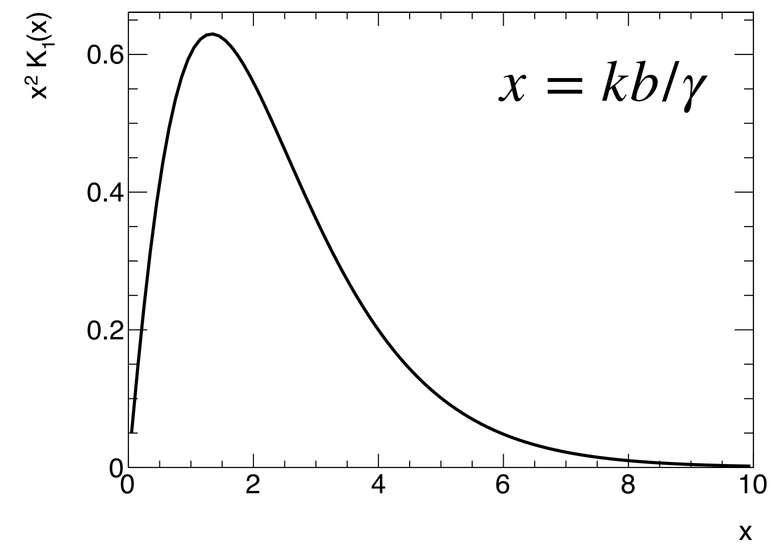
Fermi, Landau, von Weiszacker, Williams

Equivalent Photon Approximation



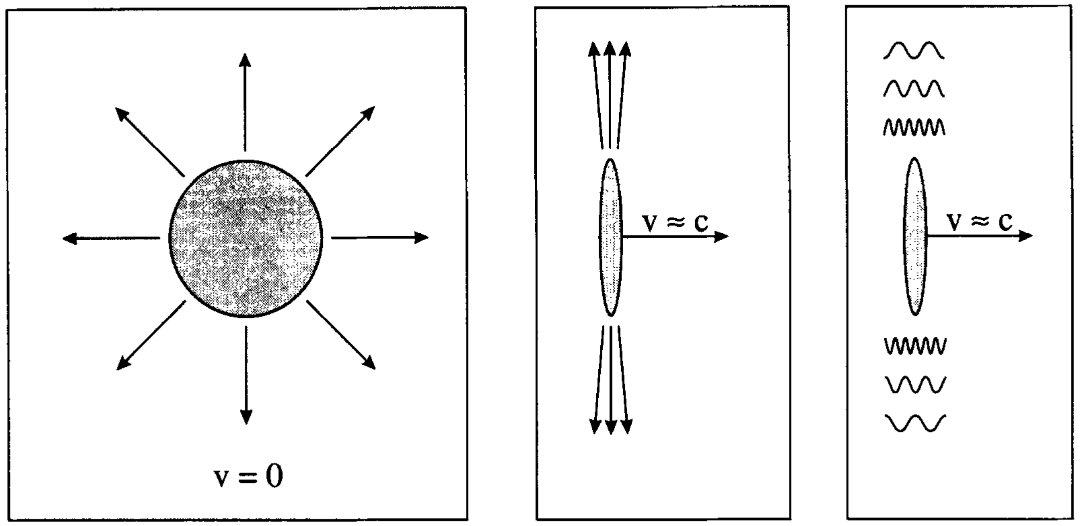
For a point charge:

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



maximum energy **$E_{\gamma,max}$~γ(ℏc/R)**	**80 GeV in Pb+Pb@LHC 3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) **p_{Tmax} ~ ℏc/R**	**O(30) MeV @ RHIC & LHC**
Coherent strengths (rates) scale as **Z^2**: nuclei >> protons	Flux of photons on other nucleus ~ **Z^2**, flux of photons on photons ~ **Z^4 (45M!)**

Two-photon fluxes, two approaches



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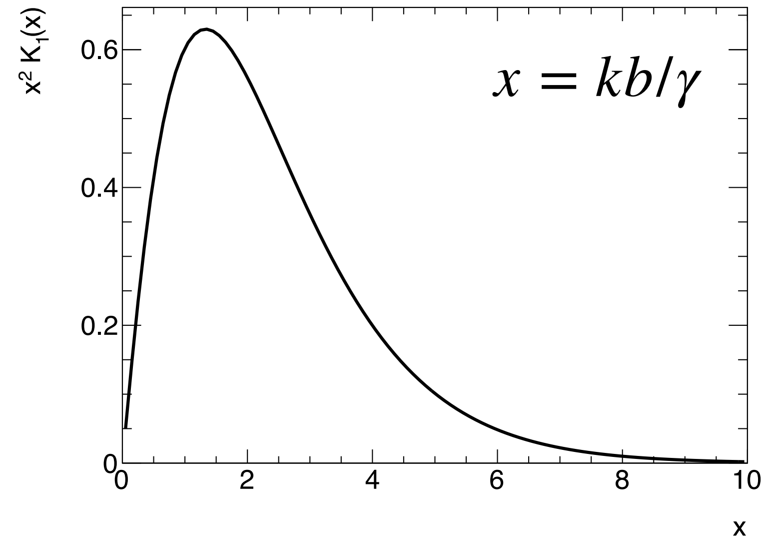


STARlight formalism:

Comput.Phys.Commun. 212 (2017) 258-268

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

Radial cutoff to nuclear distributions

forward neutron topology

(no) hadronic interaction: Glauber calculation

SuperChic formalism:

SciPost Phys. 11, 064 (2021)

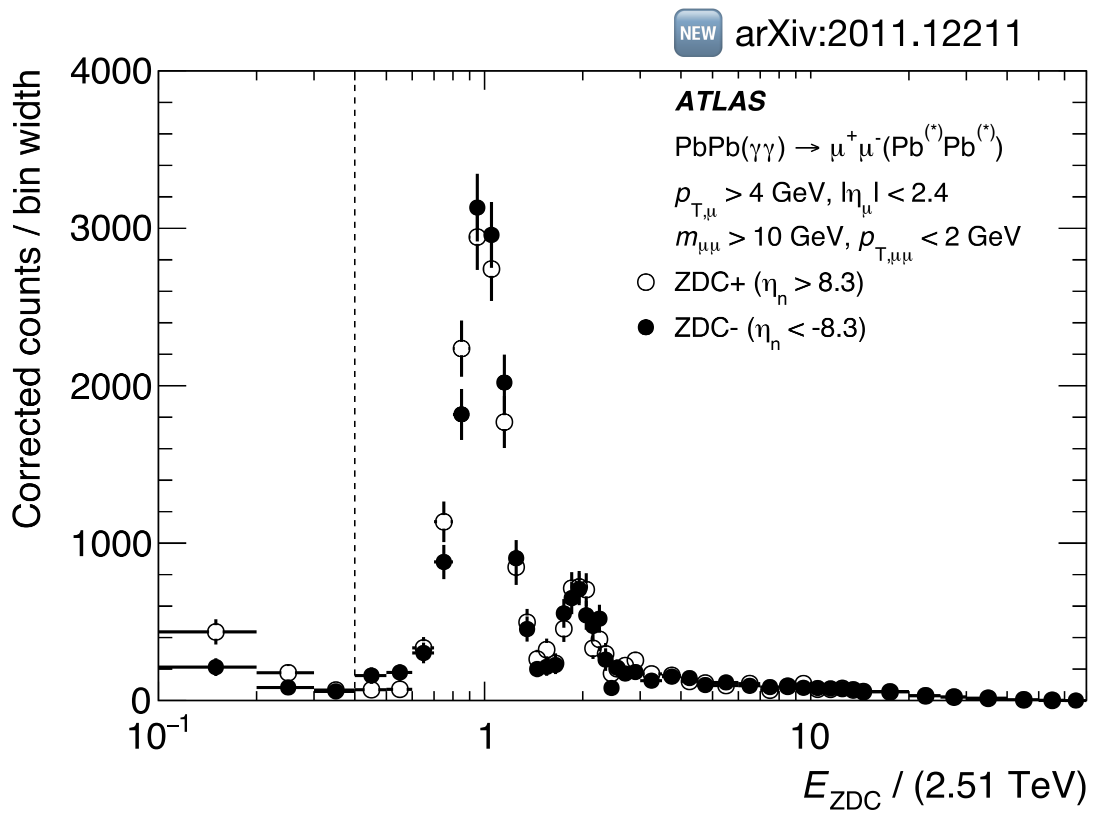
$$\sigma_{N_1N_2\to N_1XN_2} = \int \mathrm{d}x_1\mathrm{d}x_2\, n(x_1)n(x_2)\hat{\sigma}_{\gamma\gamma\to X}$$

$$n(x_i) = \frac{\alpha}{\pi^2 x_i}\int \frac{\mathrm{d}^2q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2}\left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2}(1-x_i)F_E(Q_i^2) + \frac{x_i^2}{2}F_M(Q_i^2)\right)$$

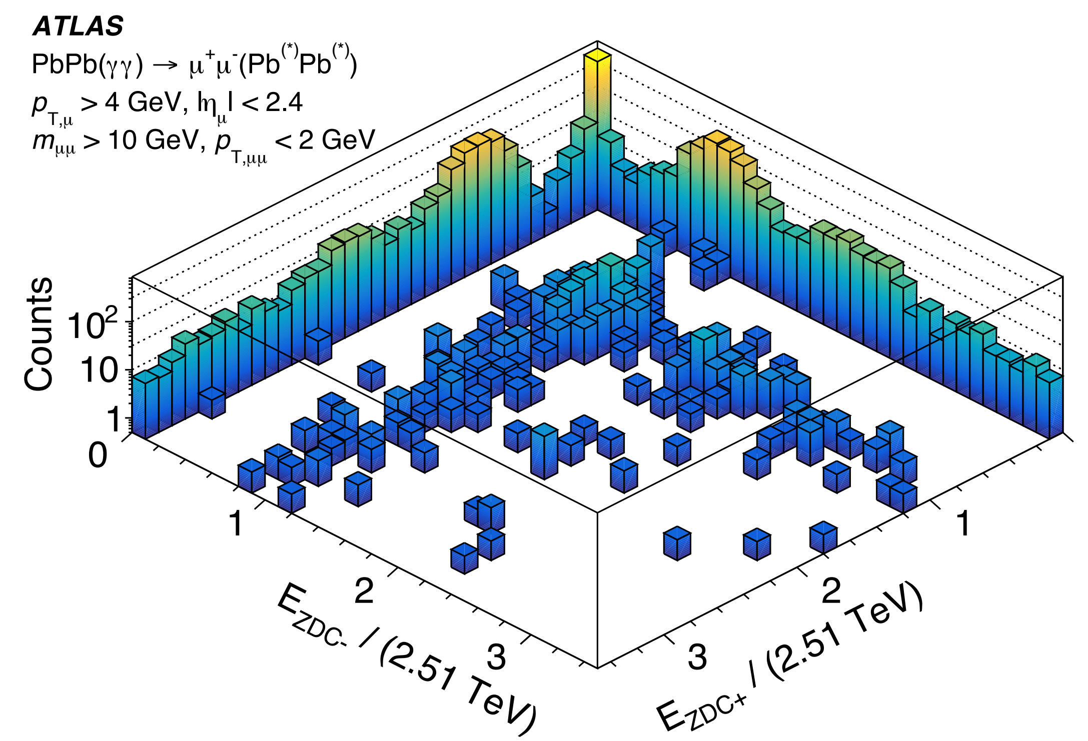
includes survival and polarization effects, forward neutrons now available in SC4.2

ZDC selections

ZDCs can distinguish 0n from 1n, 2n…

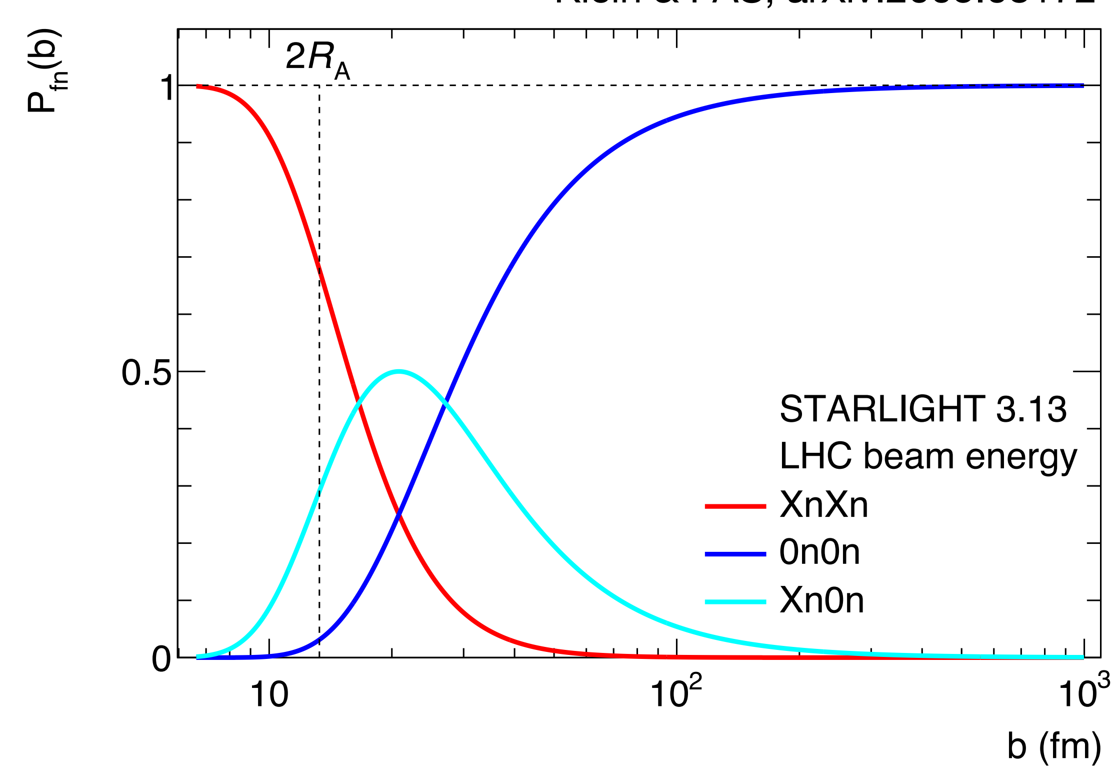


and thus classify events according to 0n0n, Xn0n/0nXn, or XnXn



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

Klein & PAS, arXiv:2005.08172

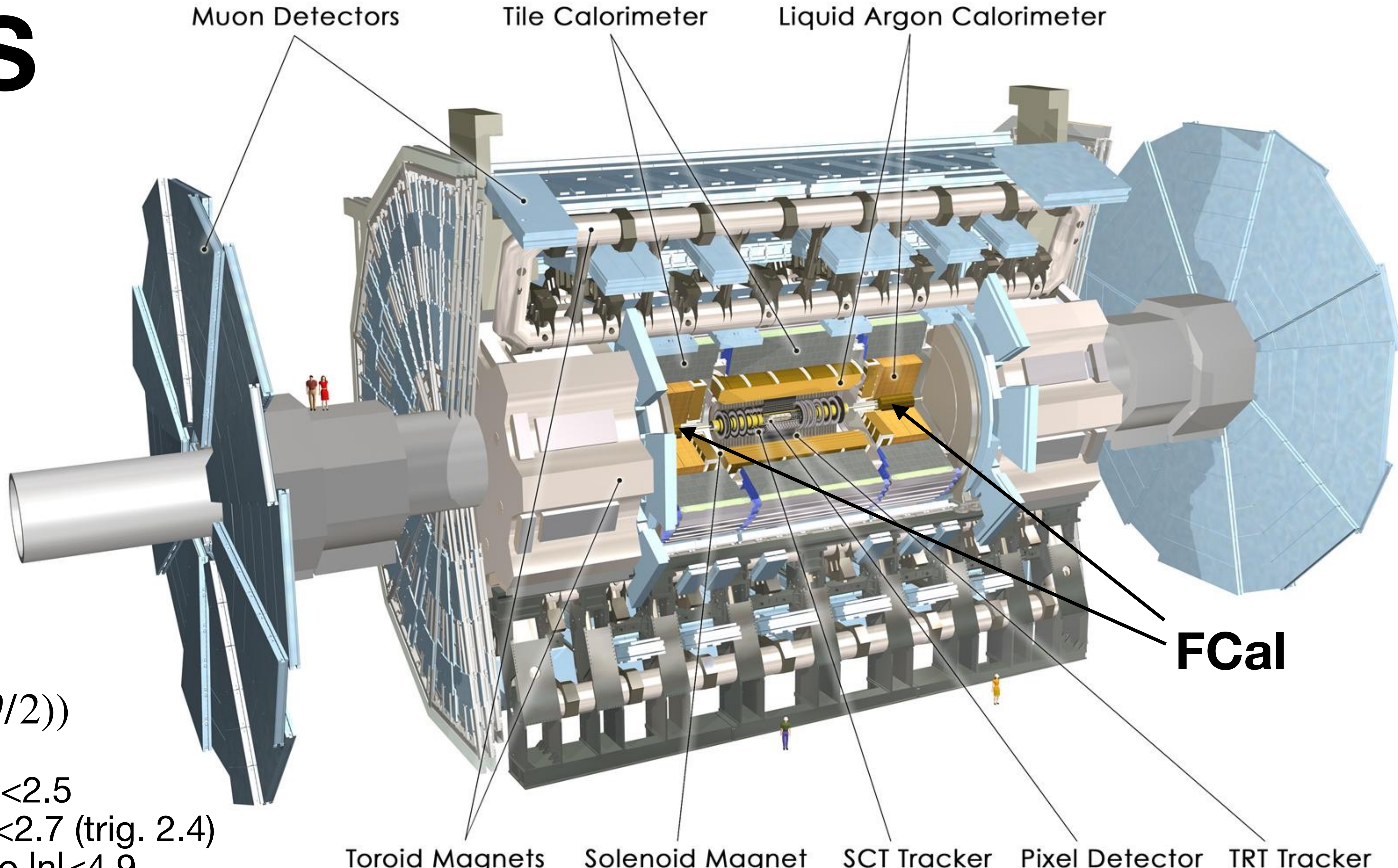


ATLAS

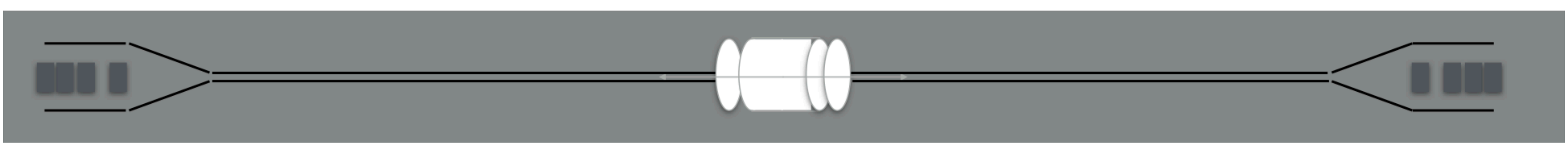
44m long
22m tall

$$\eta = -\log(\tan(\theta/2))$$

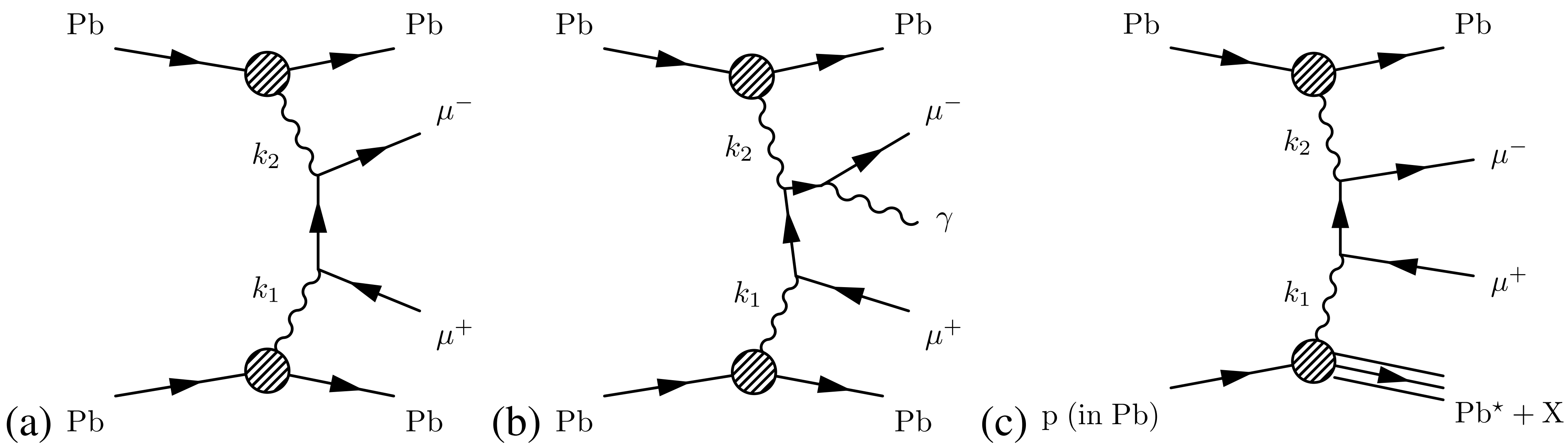
Inner detector |η|<2.5
Muon system |η|<2.7 (trig. 2.4)
Calorimetry out to |η|<4.9



Zero degree calorimeters (ZDC) z=±140m: neutrons & photons |η|>8.3



Exclusive dilepton processes & dissociation

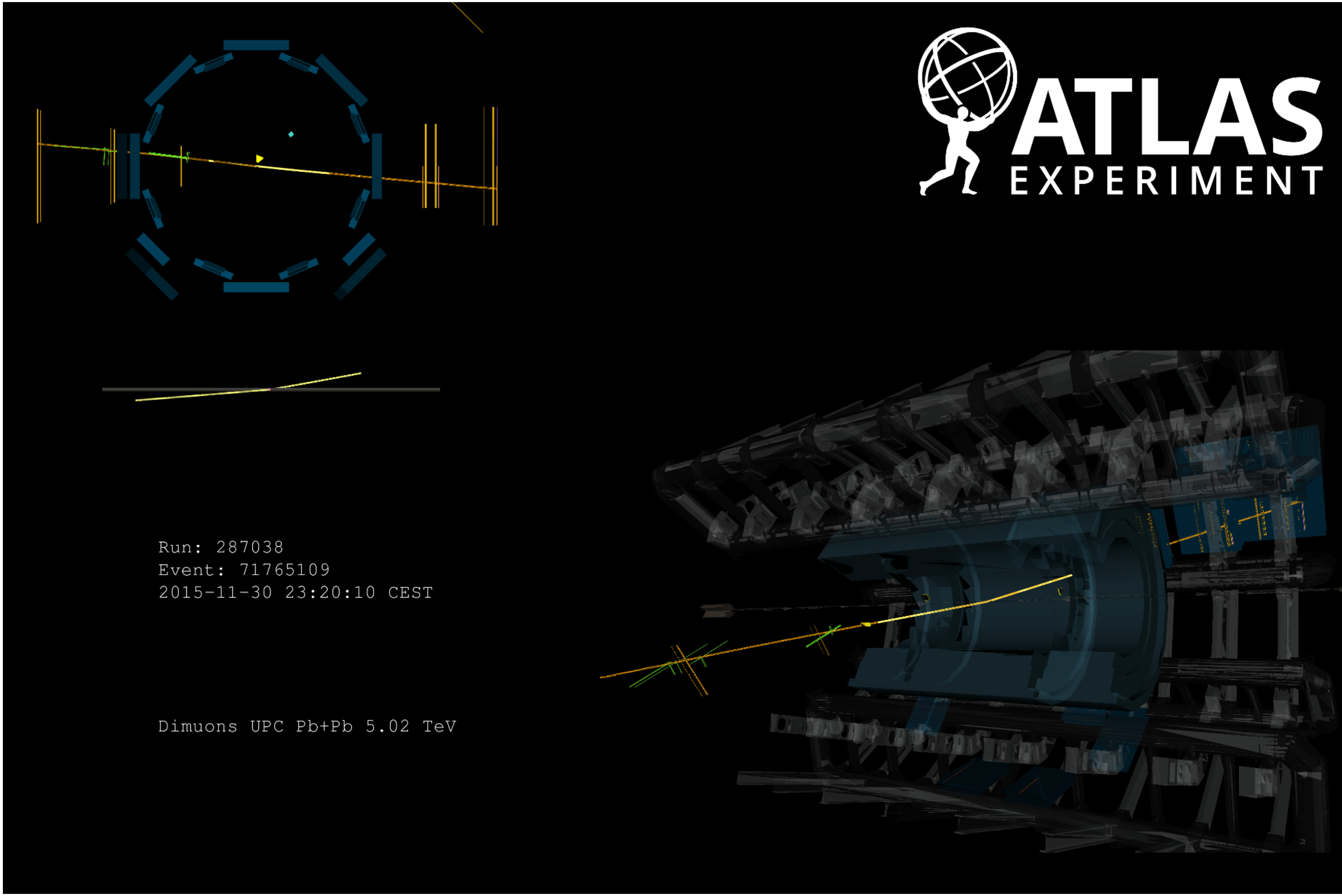


$\mathrm{PbPb}(\gamma\gamma) \rightarrow \mu^+\mu^-(\mathrm{Pb}^{(\star)}\mathrm{Pb}^{(\star)})$ is the primary signal Breit-Wheeler process cross section implemented in STARlight, SuperChic, etc.

$\mathrm{PbPb}(\gamma\gamma) \rightarrow \mu^+\mu^-\gamma(\mathrm{Pb}^{(\star)}\mathrm{Pb}^{(\star)})$ 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

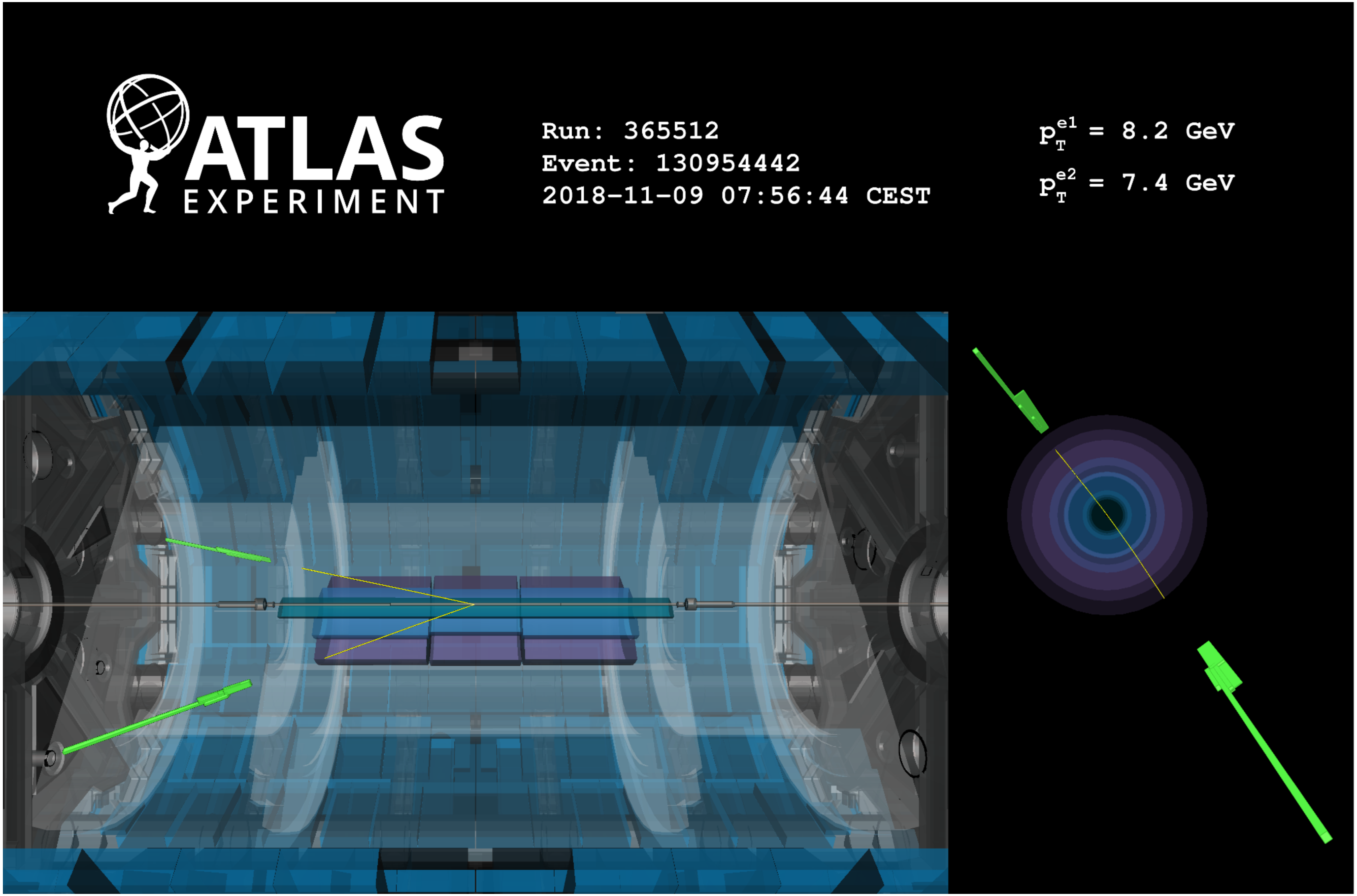
$\mathrm{Pb} + \mathrm{N}/\mathrm{Pb}(\gamma\gamma) \rightarrow \mu^+\mu^-X(\mathrm{Pb}^\star\mathrm{Pb}^{(\star)})$ is dissociative background (non-EPA) process, including nuclear breakup as well, modeled using LPair (μμ) or SuperChic (ee)

an exclusive dimuon event



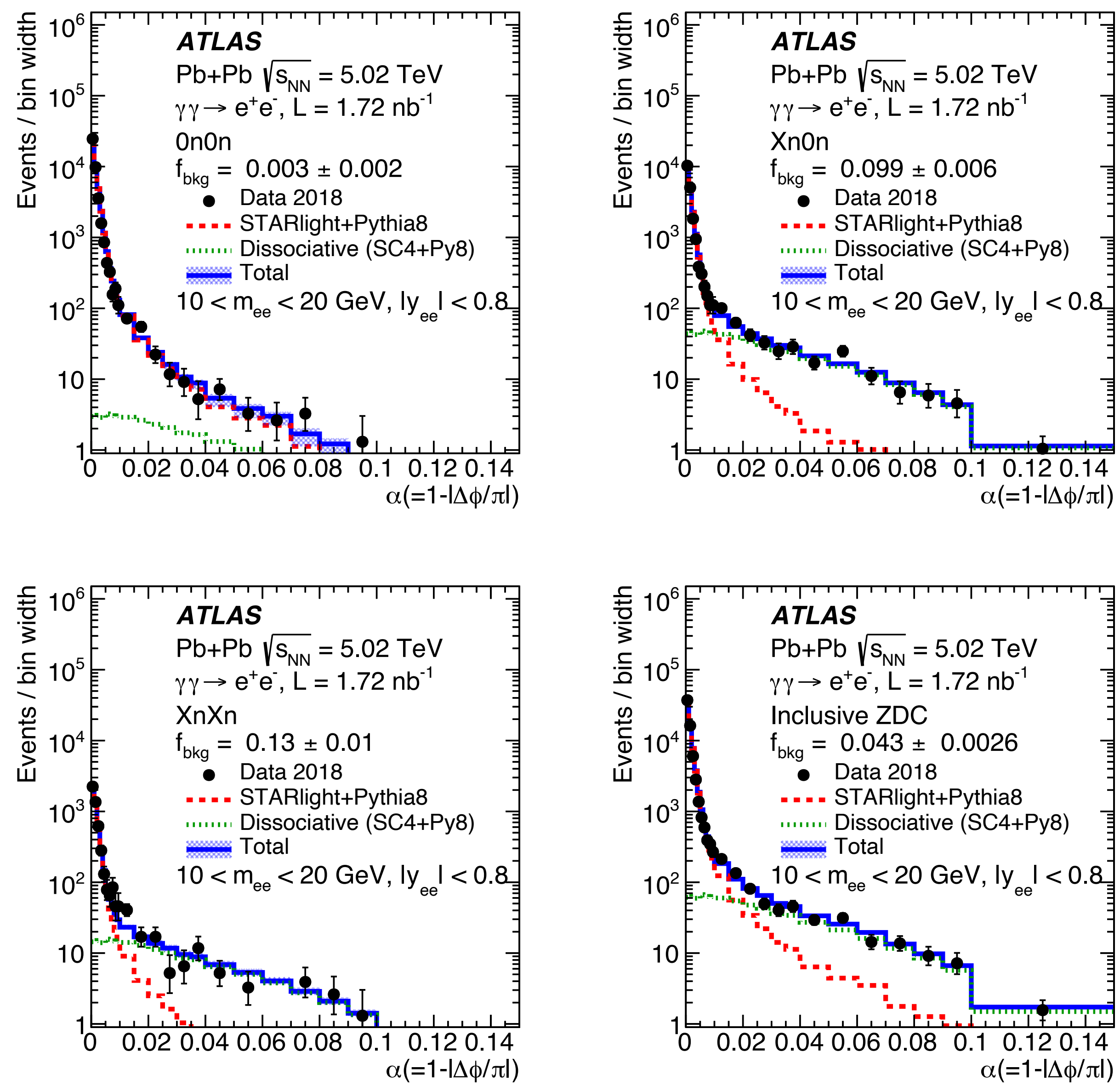
highest mass dimuon event in 2015 dataset - $m_{\mu\mu}$ = 173 GeV

an exclusive dielectron event



ee: dielectron measurement

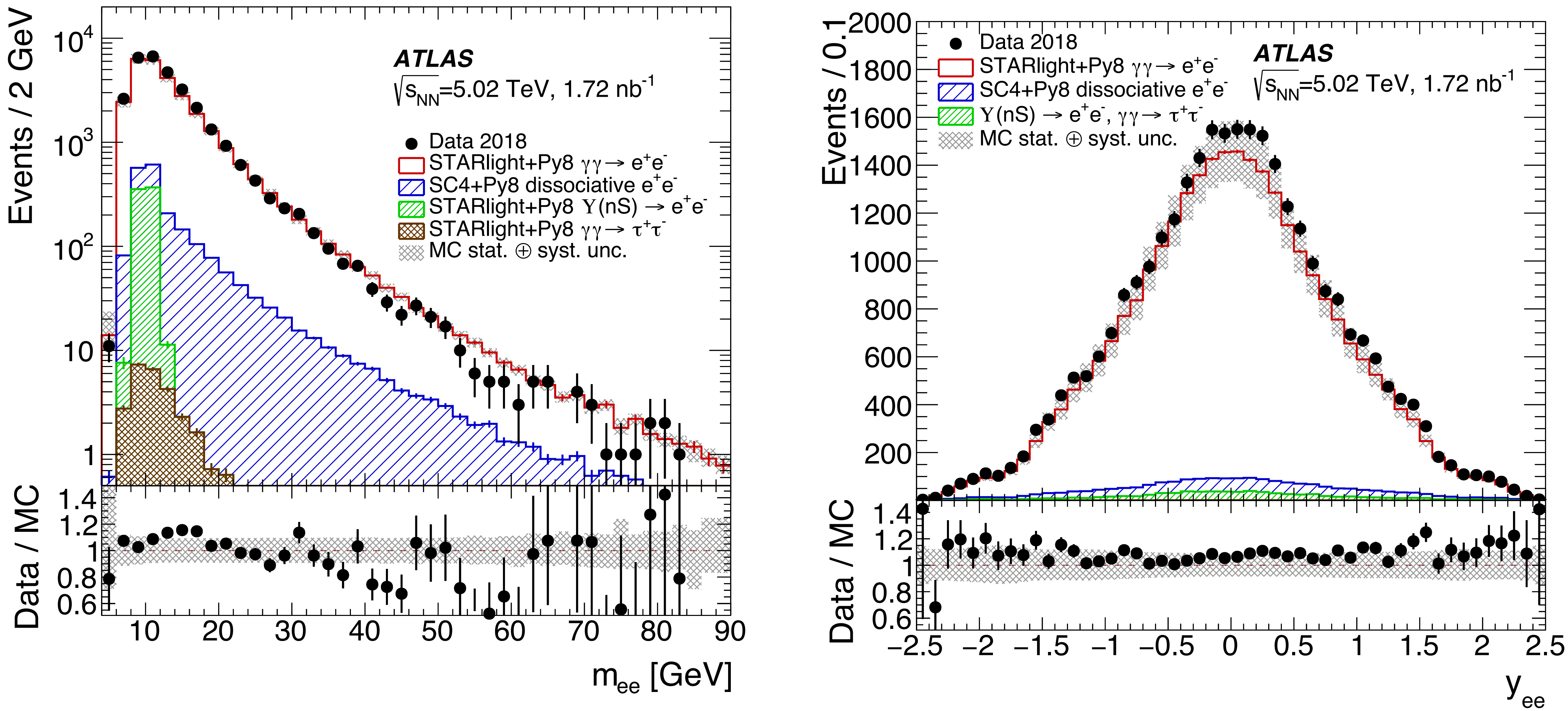
- **Similar techniques as μμ but notable advances**
  - Higher statistics from 2018 data
  - Extended fiducial region
    - p_{Te}>2.5 GeV
  - Unfolding electron response
  - SuperChic 4.0 for dissociative processes



- **Also provides measurement of <p_T> relevant for τ g-2**

ee: Control distributions

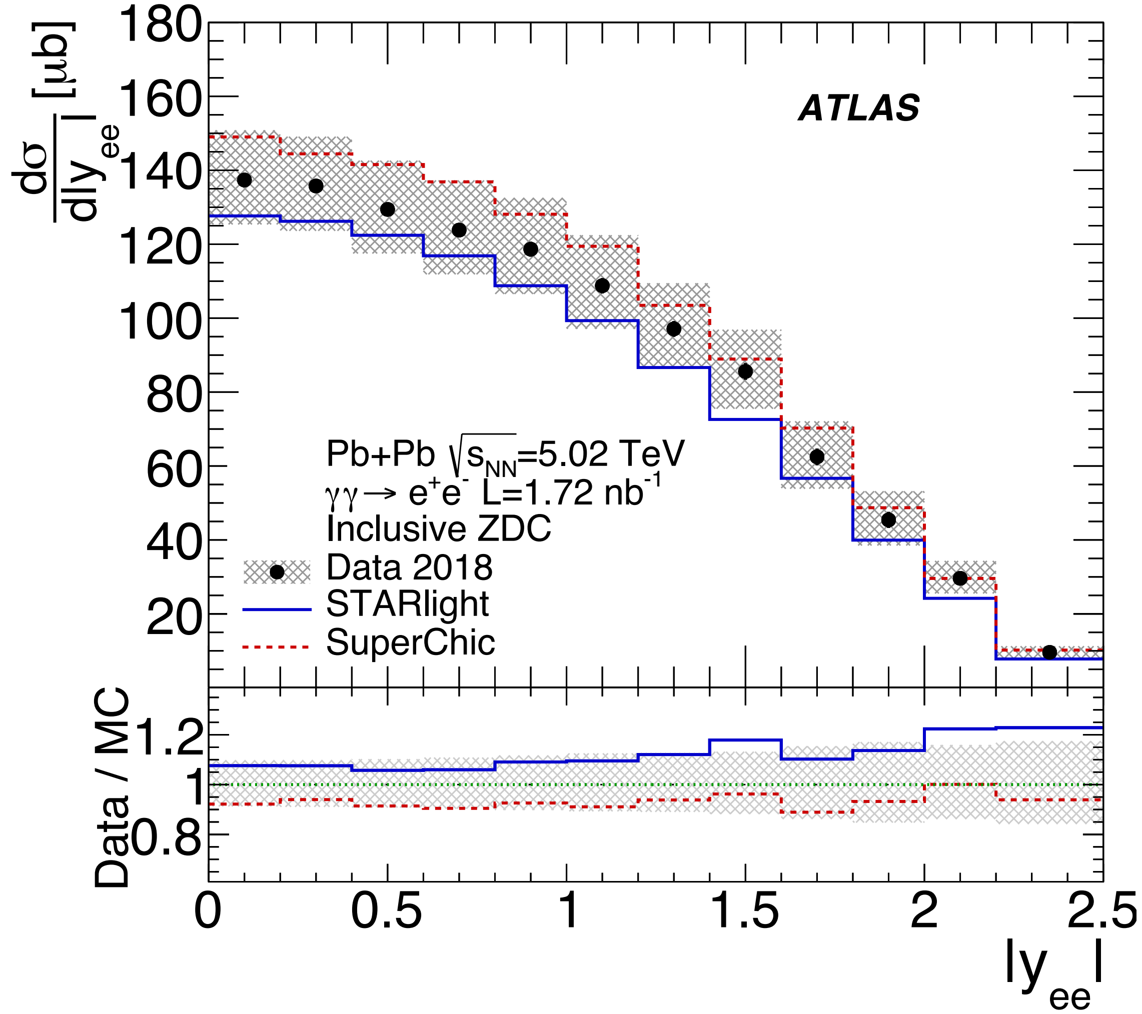
$p_{Te} > 2.5$ GeV, $|\eta_e|<2.47$, $m_{ee} > 5$ GeV, $p_{Tee} < 2$ GeV

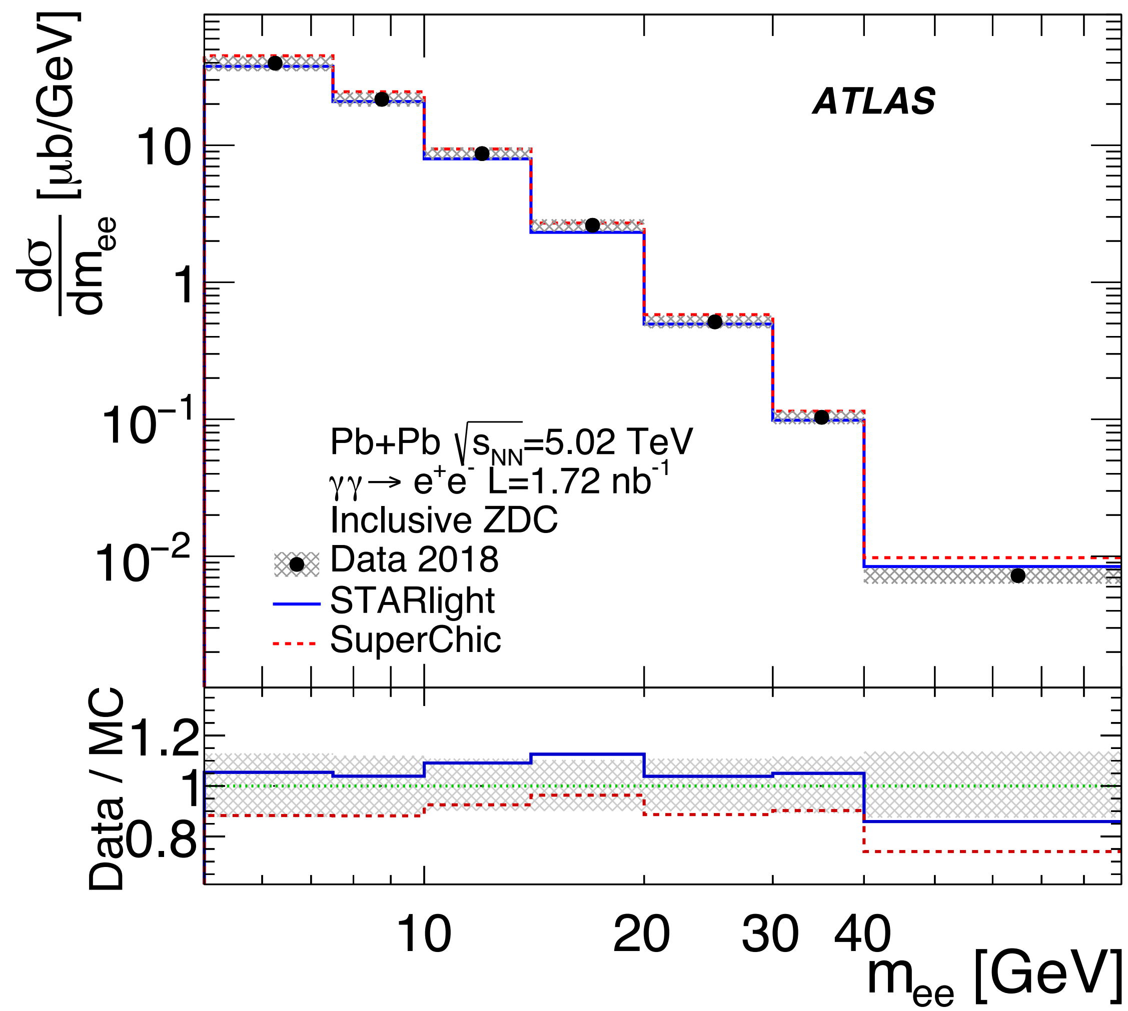


Uncorrected distributions compared to MC expectations after applying measured trigger efficiencies: generally good agreement with some excesses at larger $|y_{ee}|$, similar to μμ measurement

ee: rapidity and mass

p_{Te} > 2.5 GeV, $|\eta_e|$<2.47, m_{ee} > 5 GeV, p_{Tee} < 2 GeV



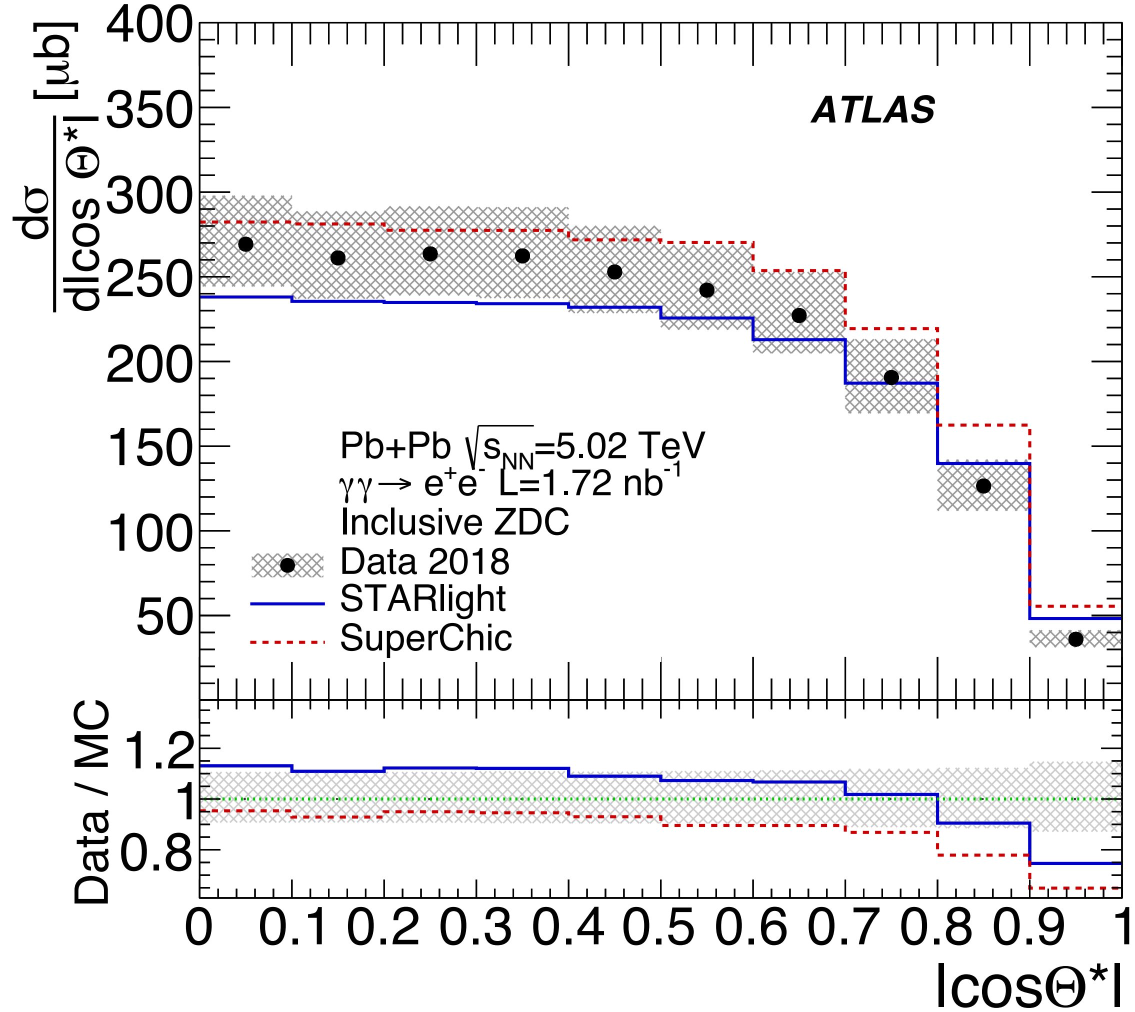


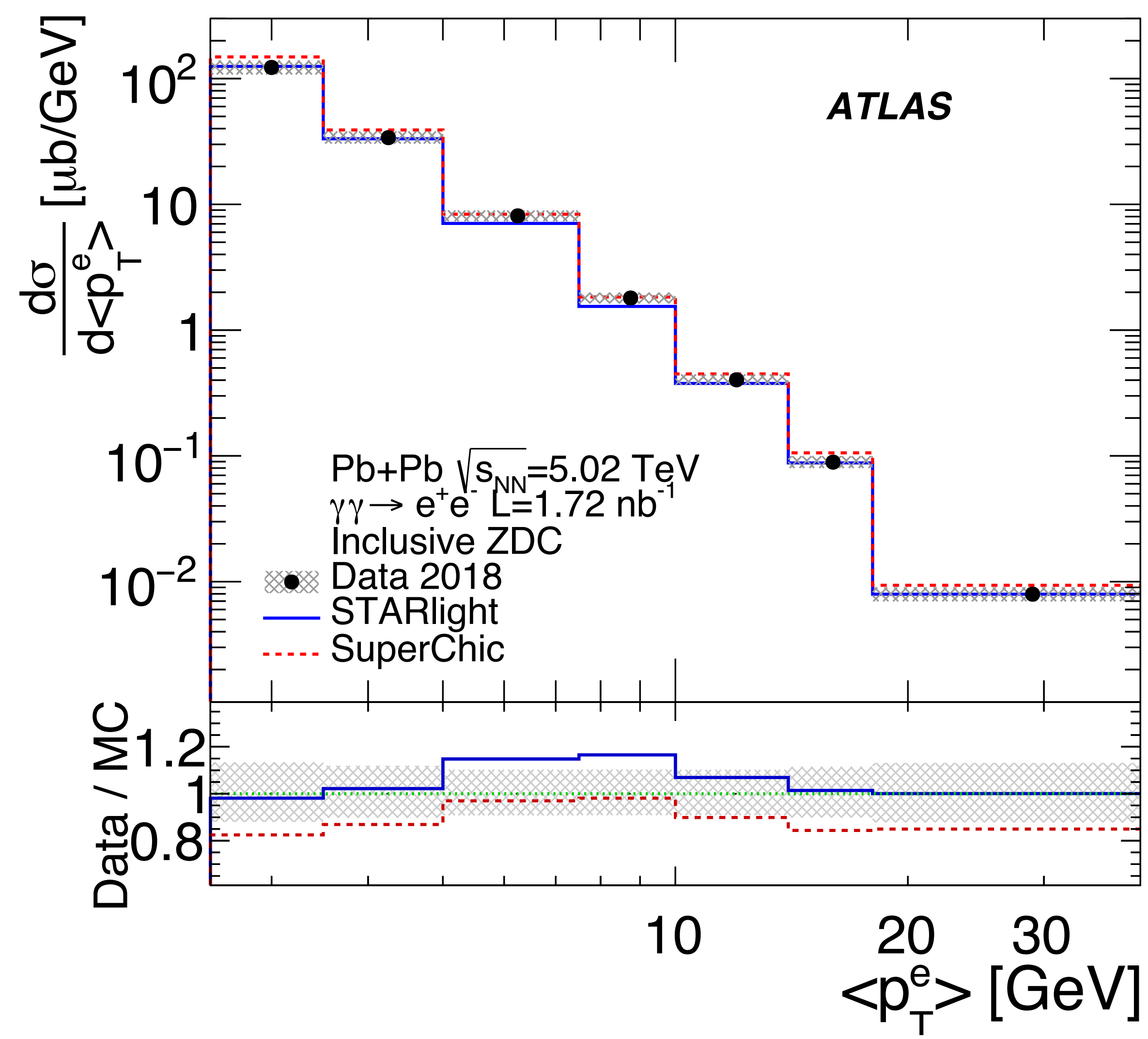
Similar comparison to STARLIGHT as with μμ - steady rise with $|y_{ee}|$ but similar spectral shape in mass.

STARlight tends to underpredict data while, SuperChic has better shape but overpredicts it.

ee: scattering angle and $\langle p_T^e \rangle$

$p_{Te} > 2.5$ GeV, $|\eta_e|<2.47$, $m_{ee} > 5$ GeV, $p_{Tee} < 2$ GeV





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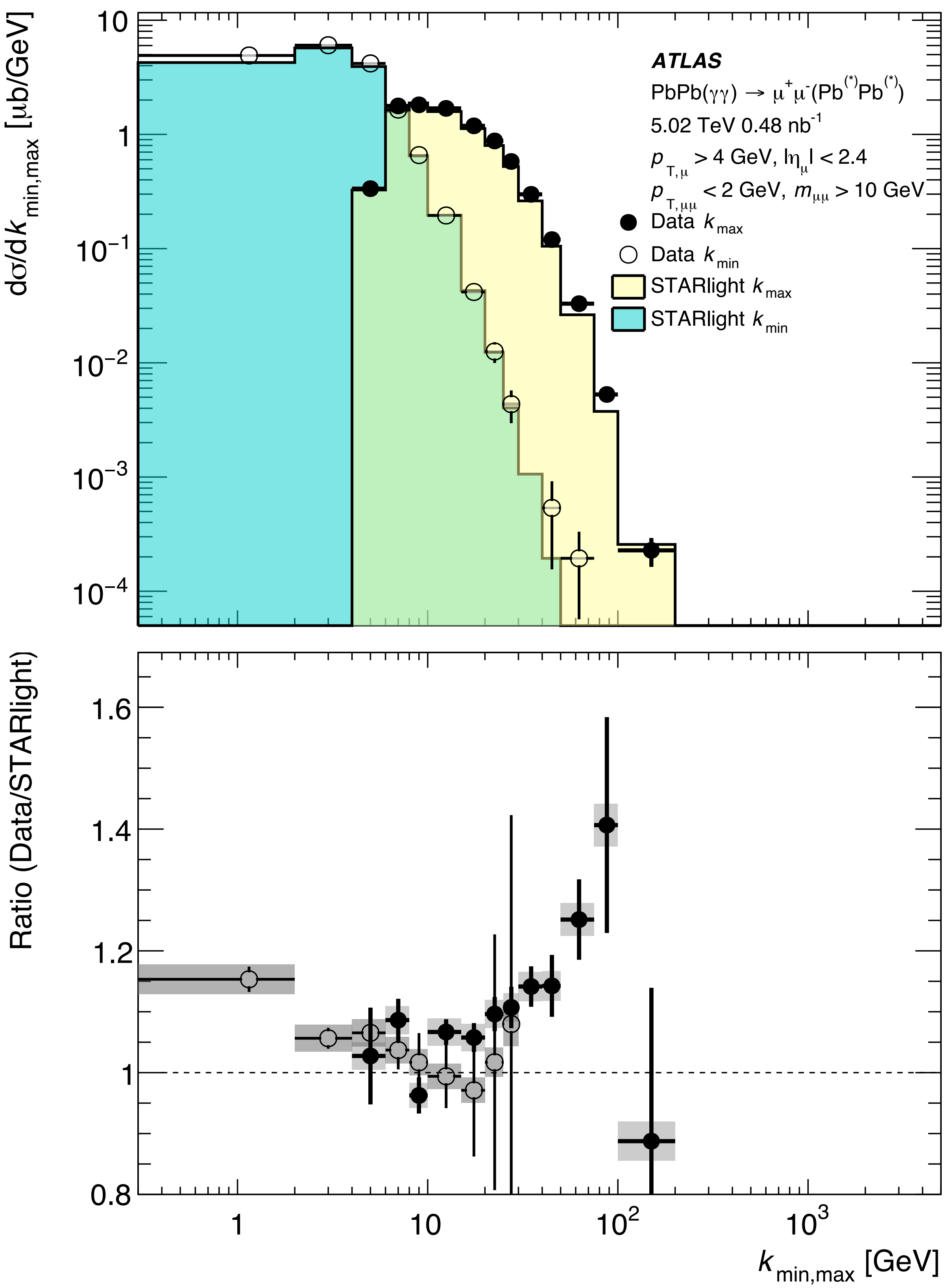
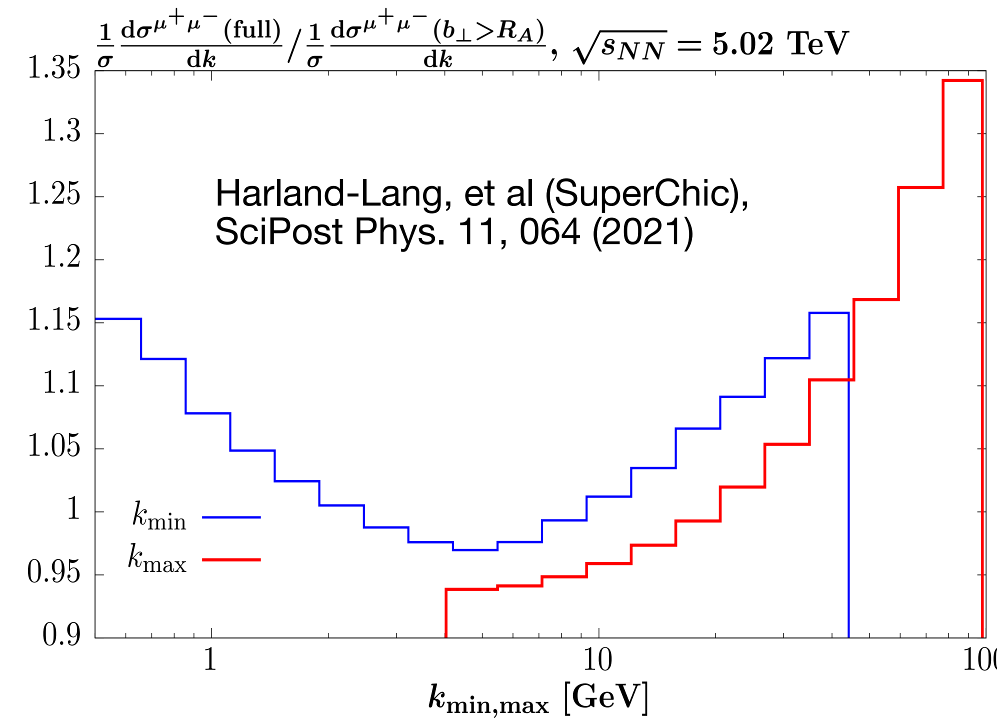
Photon energy distributions



Can combine $m_{\mu\mu}$ and $y_{\mu\mu}$ to estimate photon energies

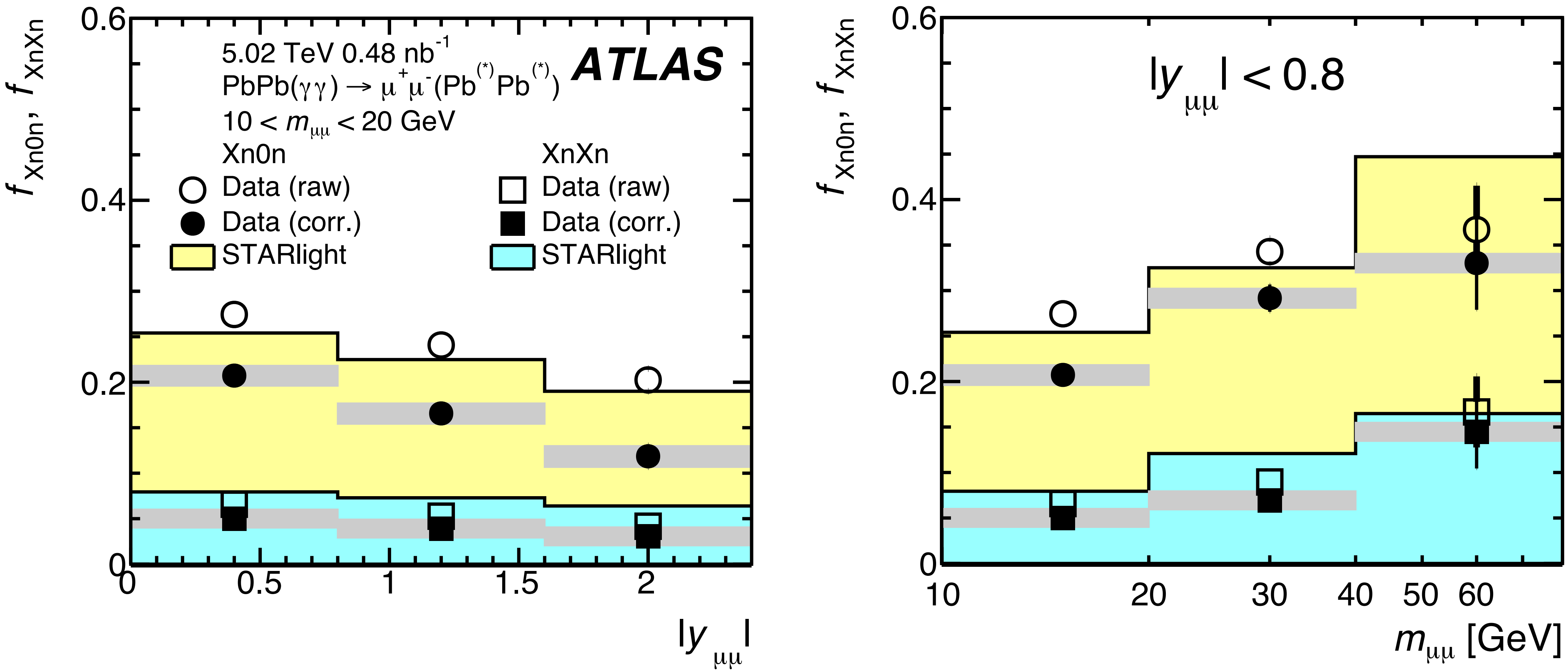
$$k_{1,2} = (m_{\mu\mu}/2)\exp(\pm y_{\mu\mu})$$

Overall good agreement but clear enhancements at low and high k: consistent with relaxing impact parameter cuts in STARlight (Harland-Lang, et al)



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

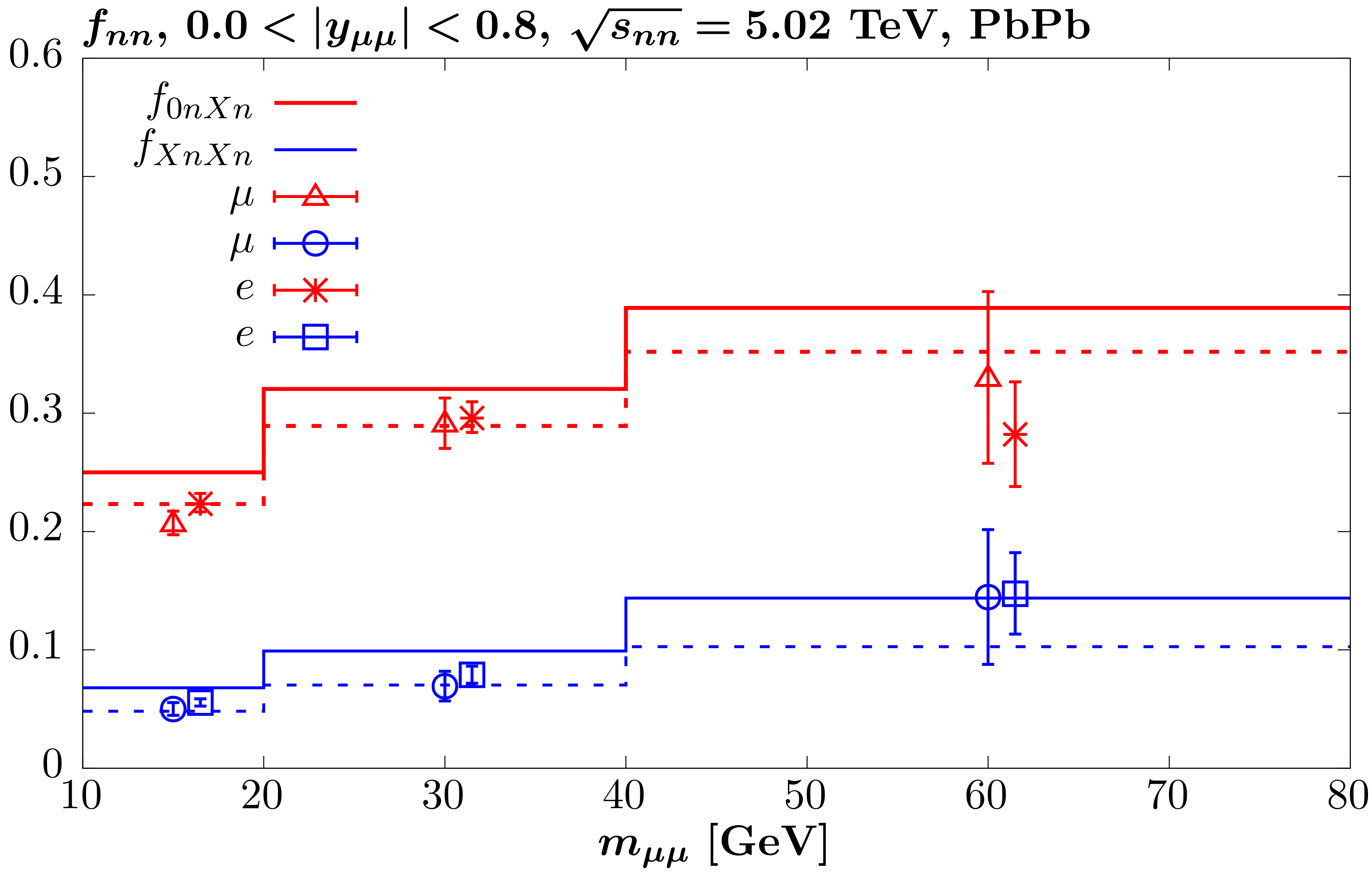
$p_{T\mu} > 4$ GeV, $|\eta_\mu| < 2.4$, $m_{\mu\mu} > 10$ GeV, $p_{T\mu\mu} < 2$ GeV



Fractions of events with Xn0n, and XnXn:
test the impact parameter dependence of the photon fluxes.

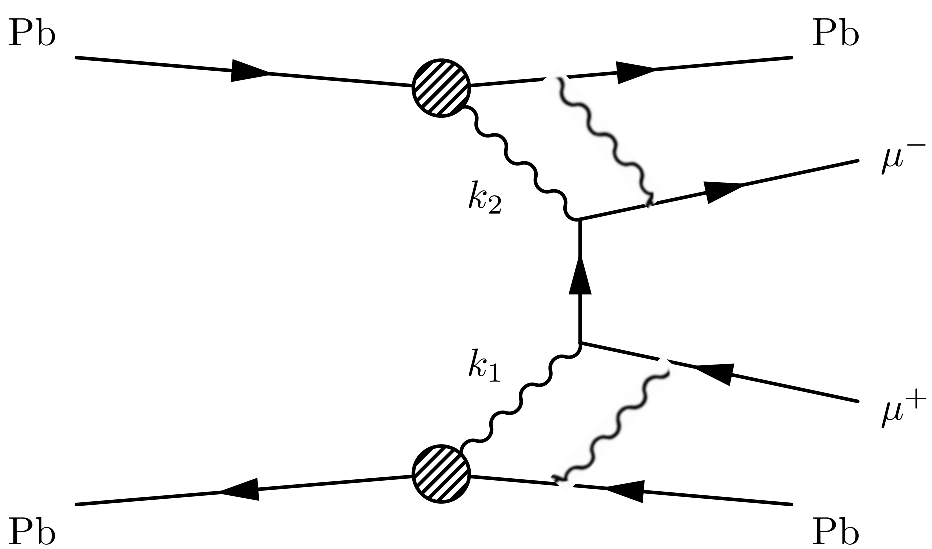
Reasonable description but differ in detail:
crucial to understand this for precision calculations

Superchic 4.2 vs. data

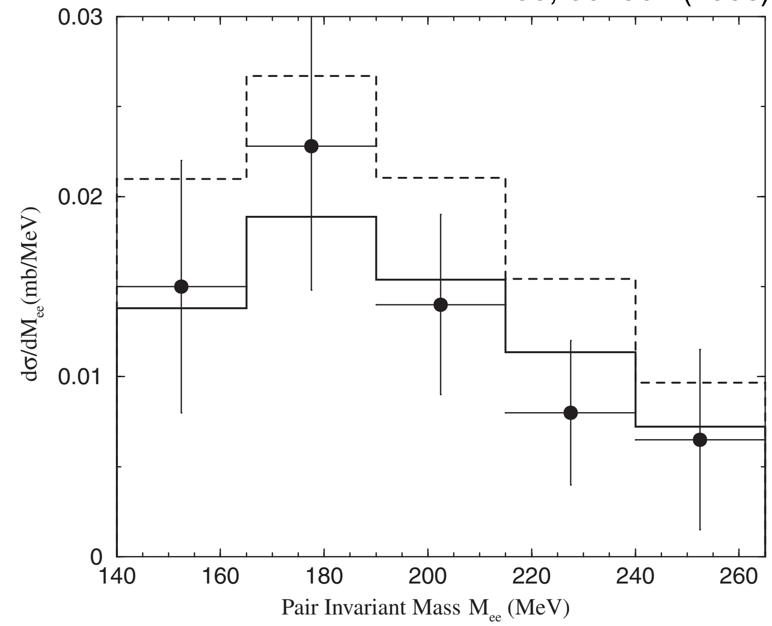


New implementation of neutron fragmentation, good comparison to ee and μμ data, but better description after reducing γA cross sections

Higher order contributions

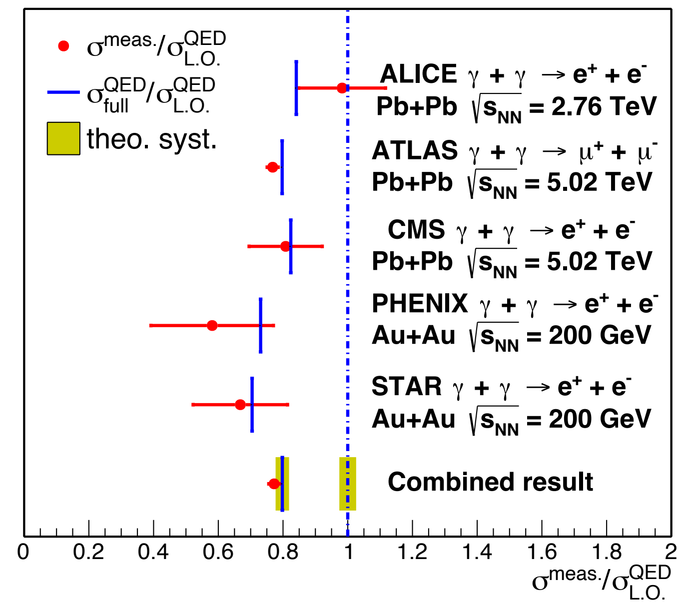


PRL 100, 062302 (2008)



Baltz, 2008
~20% reduction in cross sections at low e+e- masses

JHEP 08 (2021) 083



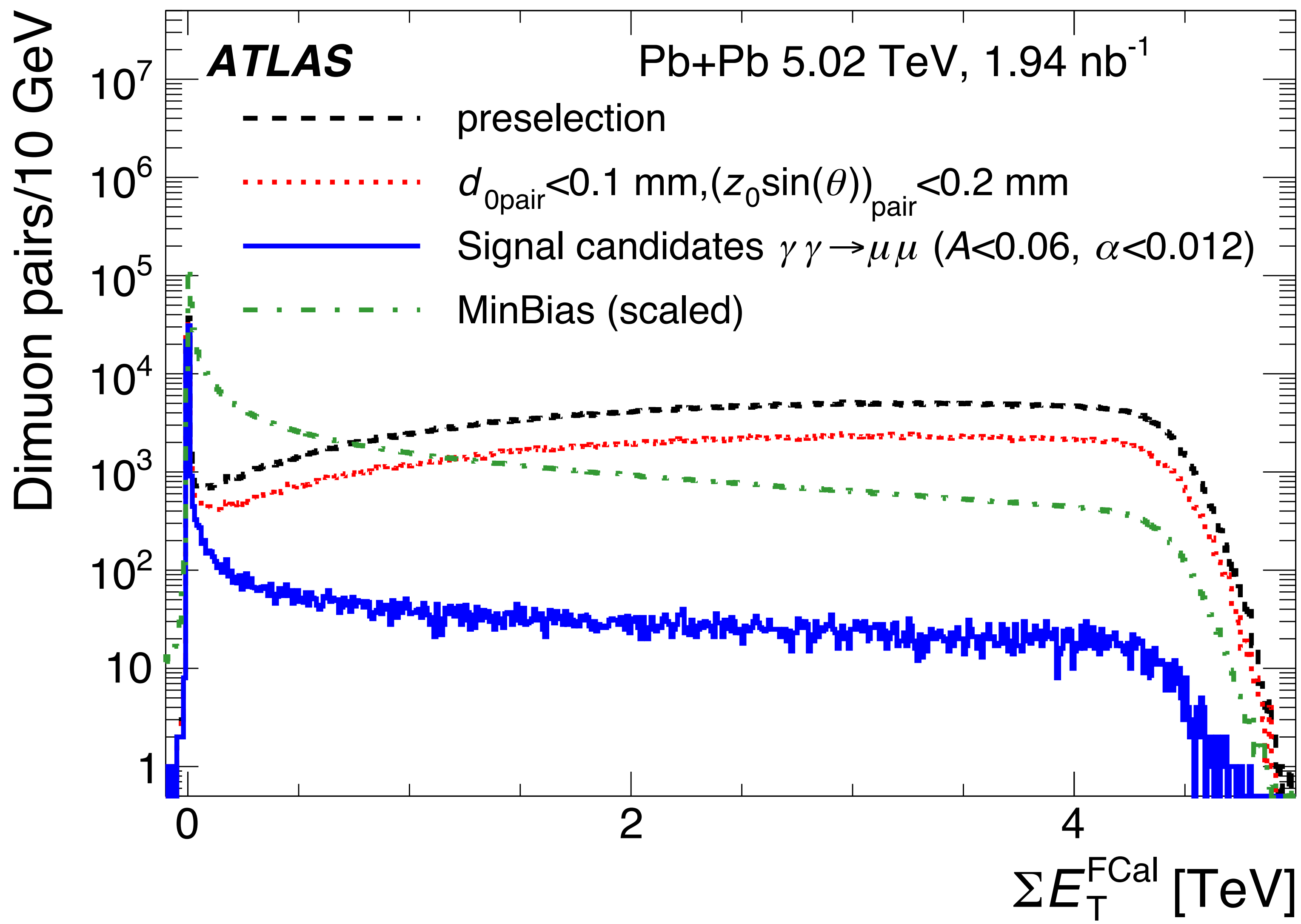
Tang & Zha, 2021
large reductions in all kinematic regions going from LO to HO

HO Coulomb corrections not included in either STARlight or SuperChic:
These corrections generally lower the cross sections,
perhaps up to 20% (e.g. Tang & Zha) compensating for the increase!

However, some disagreement between groups on just how much:
some authors predict impact on muons should be negligible.

May be important for correct fluxes: **watch this space**!

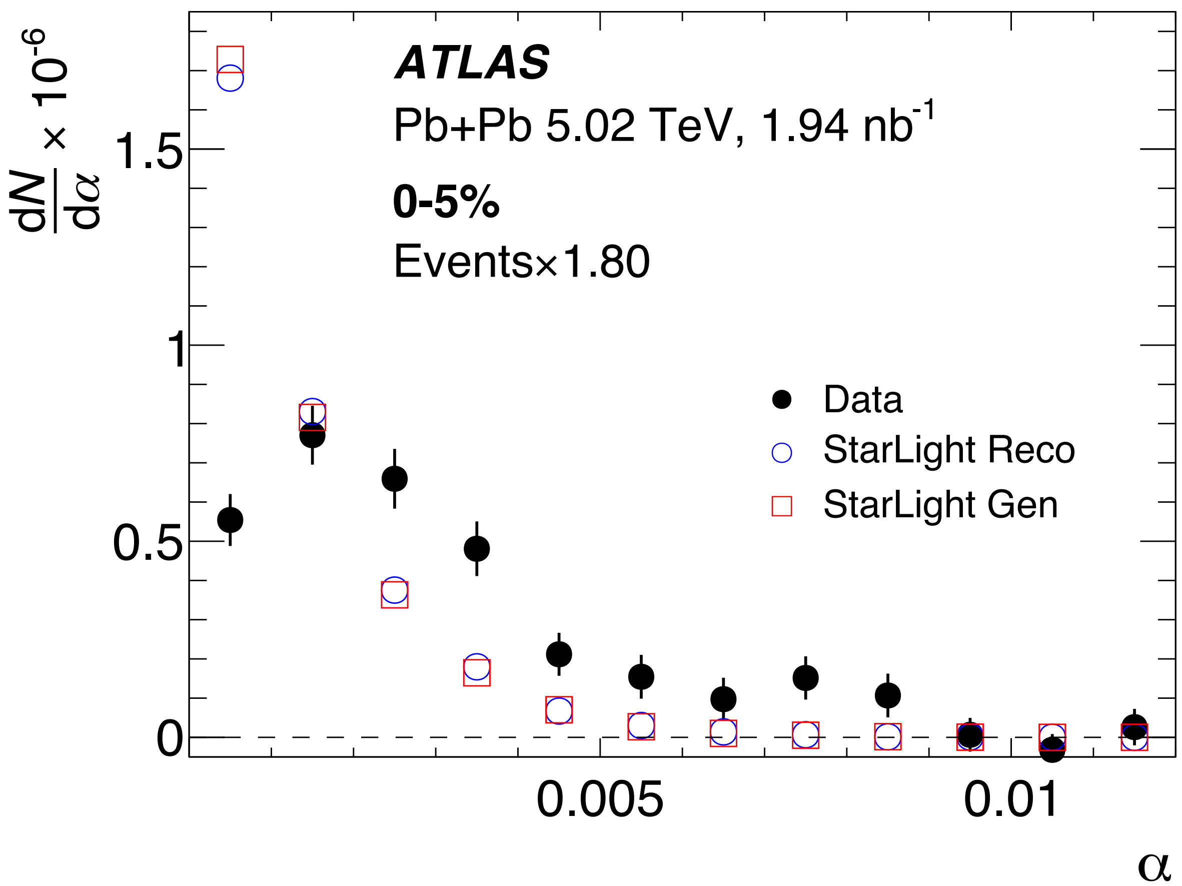
“non UPC” dileptons in hadronic collisions

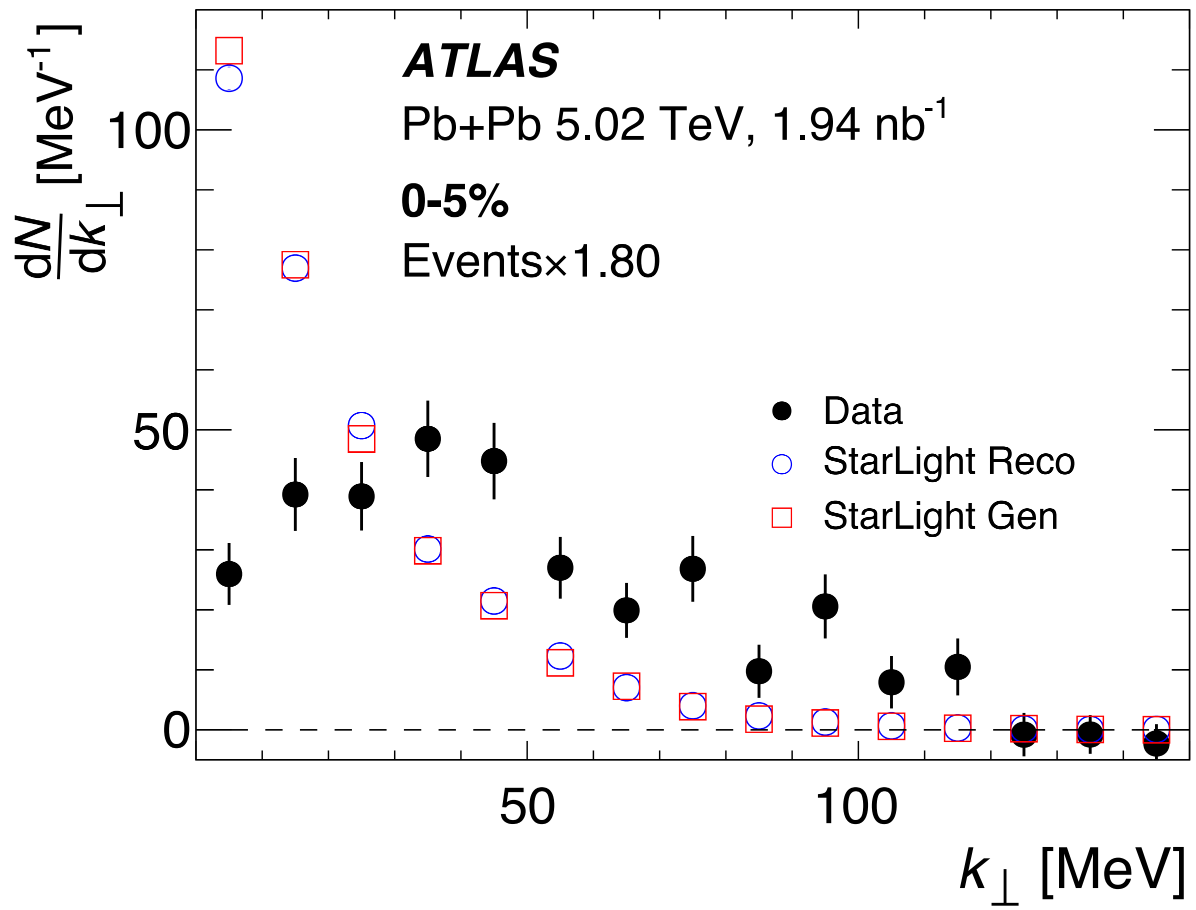


Select events using dimuon triggers, with cuts on transverse and longitudinal impact parameters, as well as pair selections on α and A to suppress heavy flavor leptons: unusually-flat ΣE_T distribution

Percentiles of minbias distribution used to define “centrality” bins, which reflect the impact parameter between the nuclei.

Signal distributions



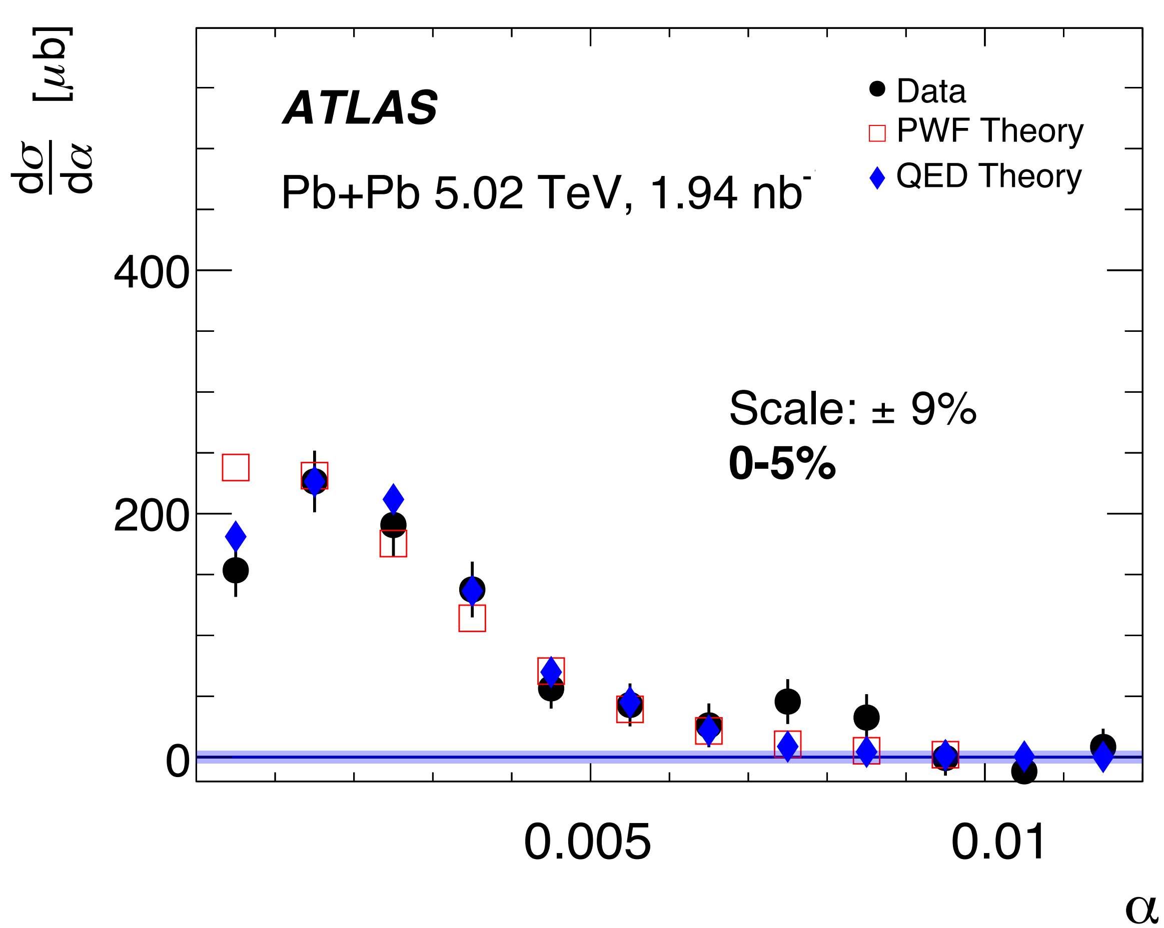


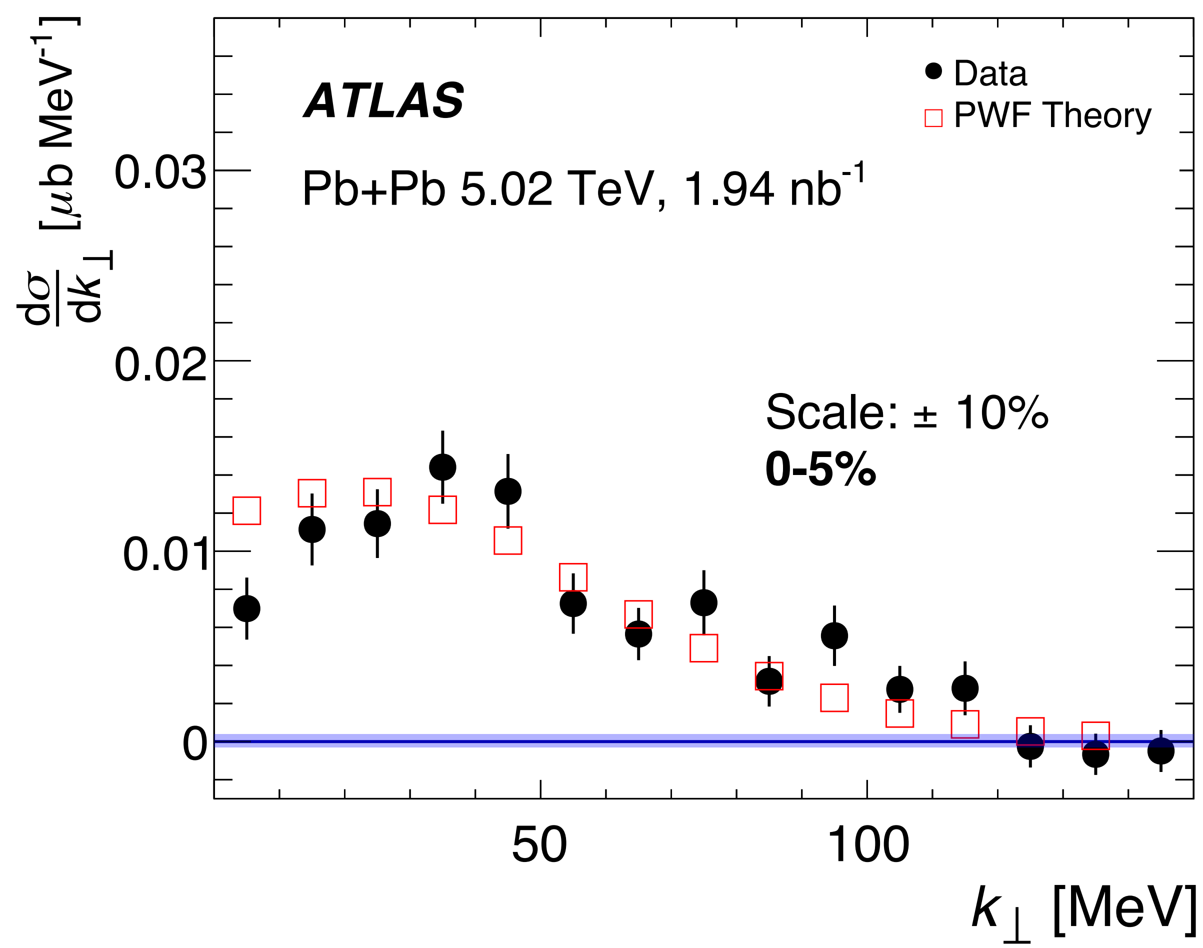
After background subtraction (heavy flavor using templates, and Drell -Yan), broadening studied in two variables: acoplanarity α and $k_\perp = \pi\alpha p_T$

In more central events, angular variables are visibly broader than the distributions observed in standard UPC events.

$k_\perp$ better behaved, with no dependence on muon p_T

Theory comparisons



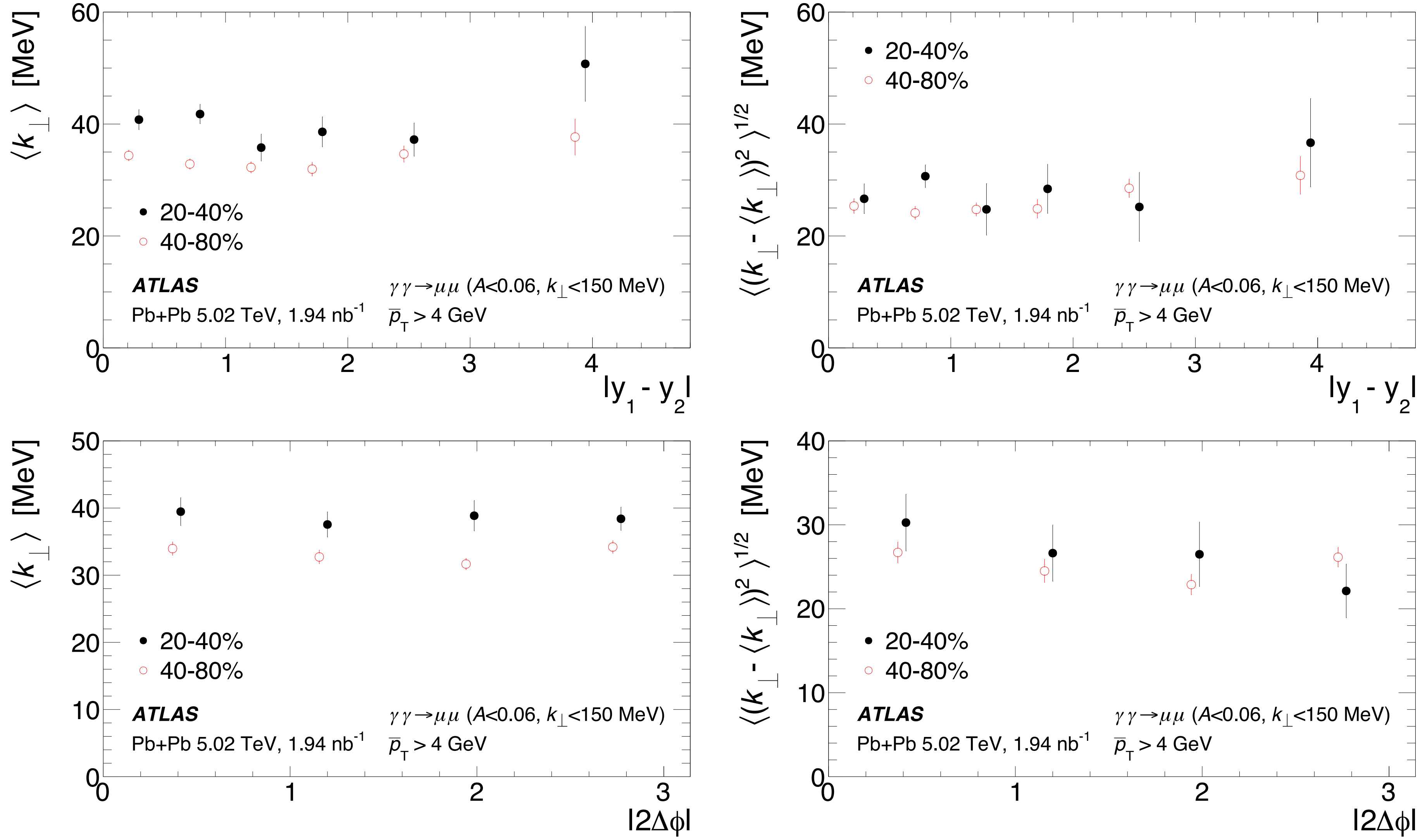


Recent theory calculations are able to describe the data in some detail:

- *Photon Wigner Functions: QM based description of full position & momentum space (Klein et al)*
- *QED calculations based on generalized EPA (Zha et al)*

arXiv:2206.12594

Probing initial magnetic fields



B-fields lead to tanh(Δy) behavior (Klein et al)

B fields follow impact parameter vector, so may show $2(\phi-\psi_2)$ dep.

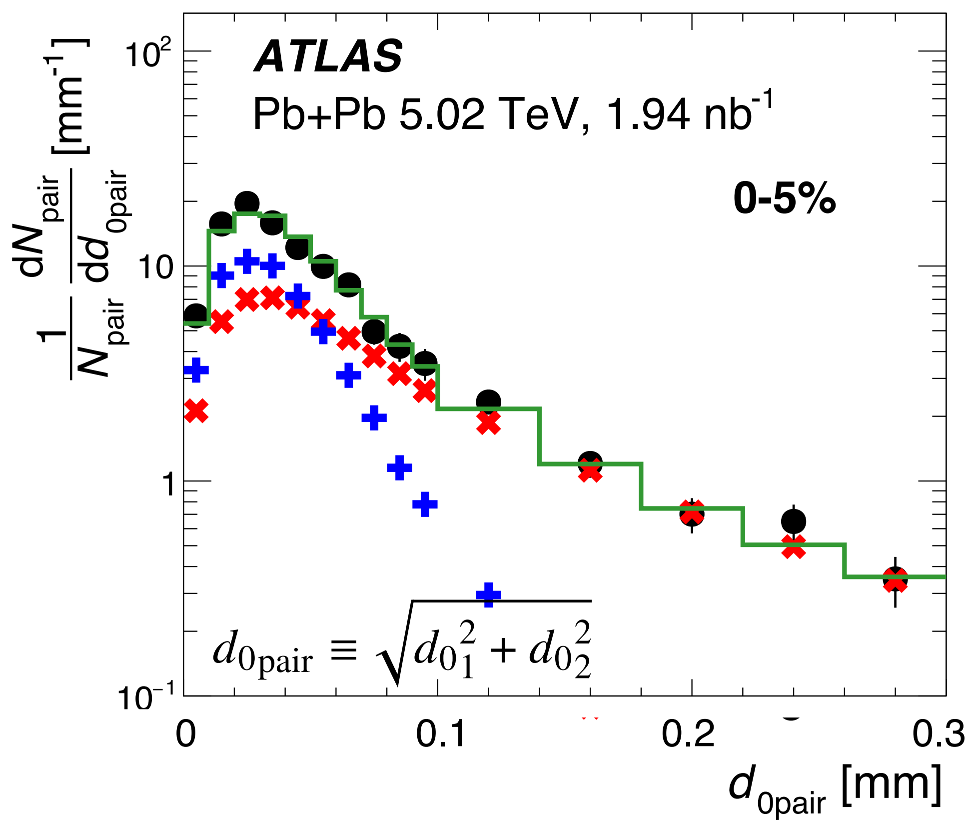
In principle, strong magnetic fields created in initial impact of heavy ions, which have been predicted to impact trajectories of muons.

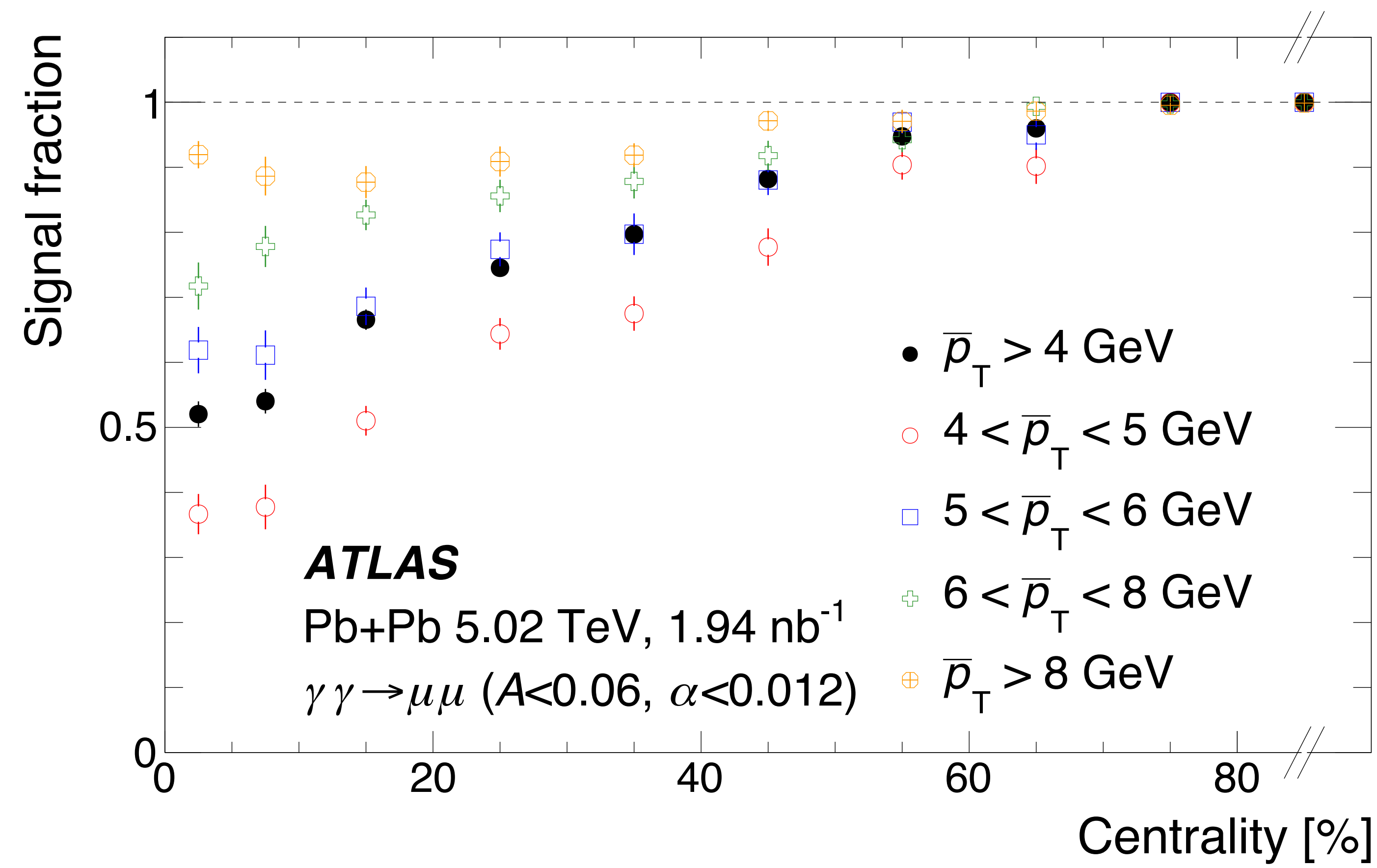
So far, no tanh(Δy) dependence of broadening (either mean or variance) and no dependence on event plane

Conclusions

- **Ultraperipheral collisions are a unique opportunity to study photon-photon and photon-nucleus (& nucleon) physics in a clean environment, synergistic w/ EIC**
- **Dileptons provide the most direct & precise way to check the assumed photon fluxes**
  - Important for precise calculations of LbyL and tau g-2!
- **Using the ATLAS ZDC, they also help probe the geometric aspects of the fluxes!**
- **Cross sections sections for UPC μμ (2021) and ee (just published!)**
  - μμ fiducial region: $p_T > 4$ GeV, $|\eta|<2.4$, $m_{\mu\mu} > 10$ GeV
  - ee fiducial region: $p_T > 2.5$ GeV, $|\eta|<2.47$, $m_{ee} > 5$ GeV
  - Systematic studies of the calculations show broad agreement with data, but non-trivial differences
- **Non-UPC interactions provide a fascinating laboratory for QED calculations and a possible testing ground for effects associated with strong magnetic fields**

Signal extraction





Pair d_0 distributions fit to signal (STARlight+HIJING) and HF background (data-driven) templates to extract signal fraction for each centrality selection.

This method cannot estimate Drell-Yan contributions, which are estimated and subtracted using nPDF calculations