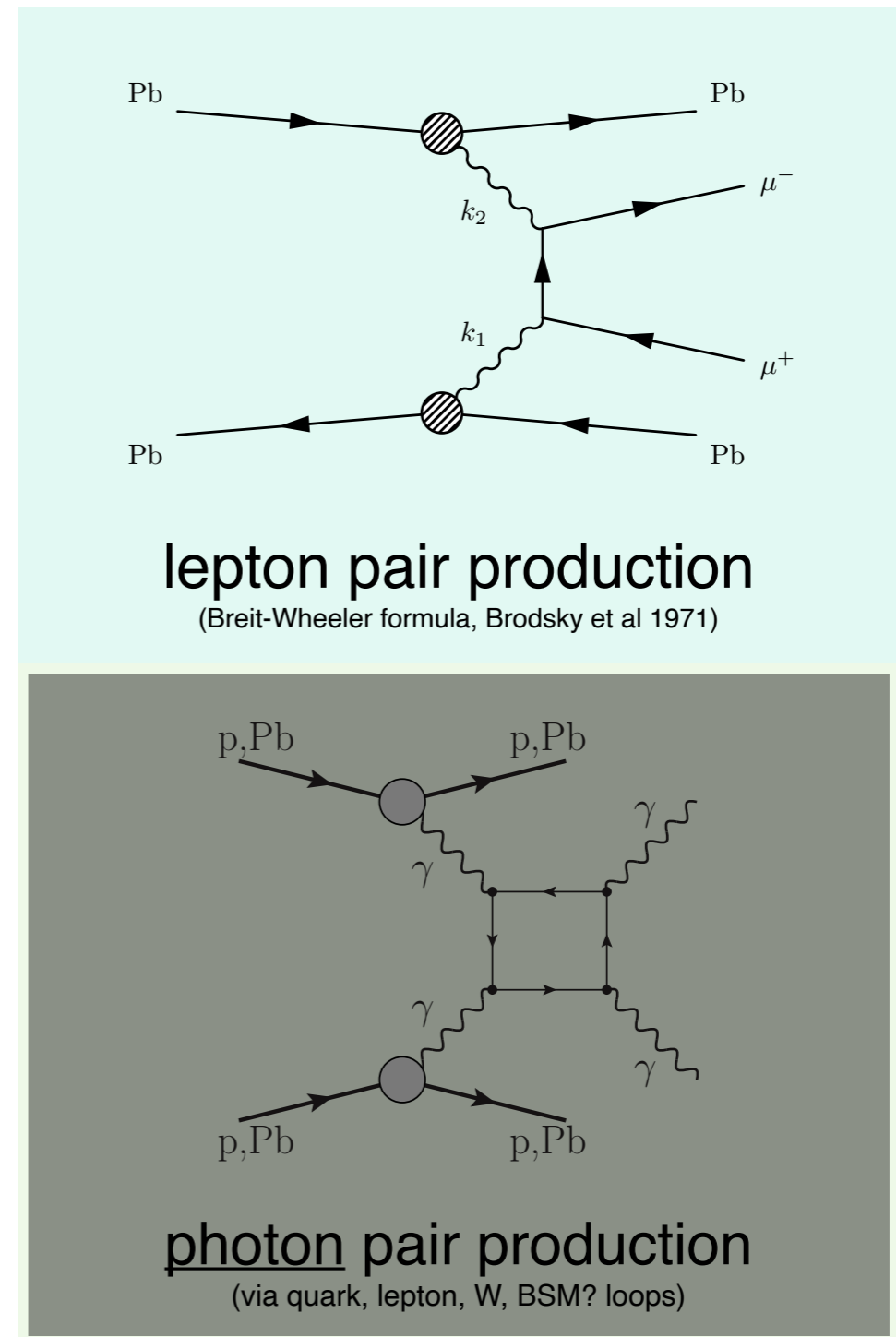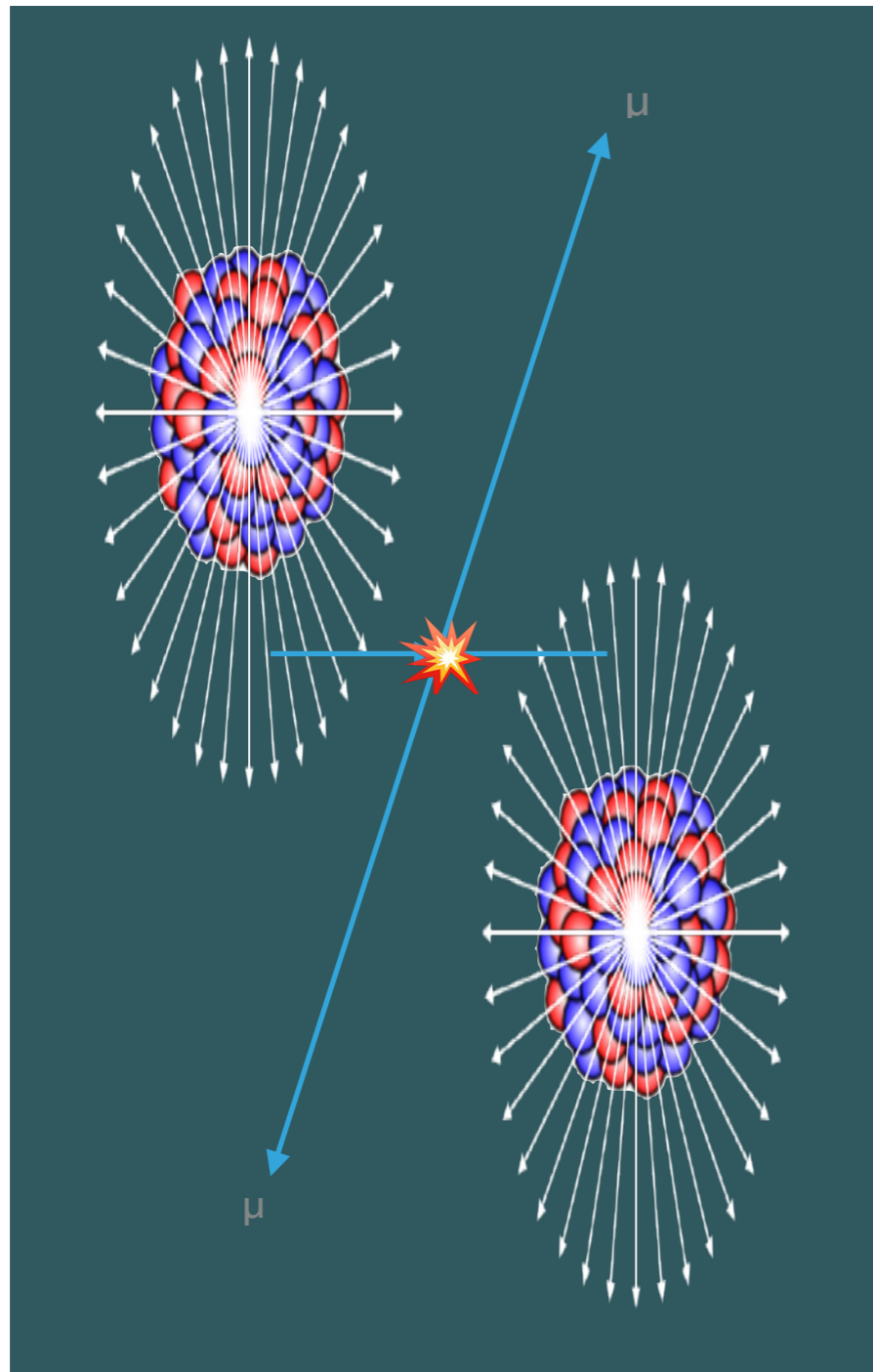# Dilepton production from $\gamma\gamma$ fusion processes in UPC & non-UPC in Pb+Pb collisions with the ATLAS detector

Peter Steinberg, BNL for the ATLAS Collaboration
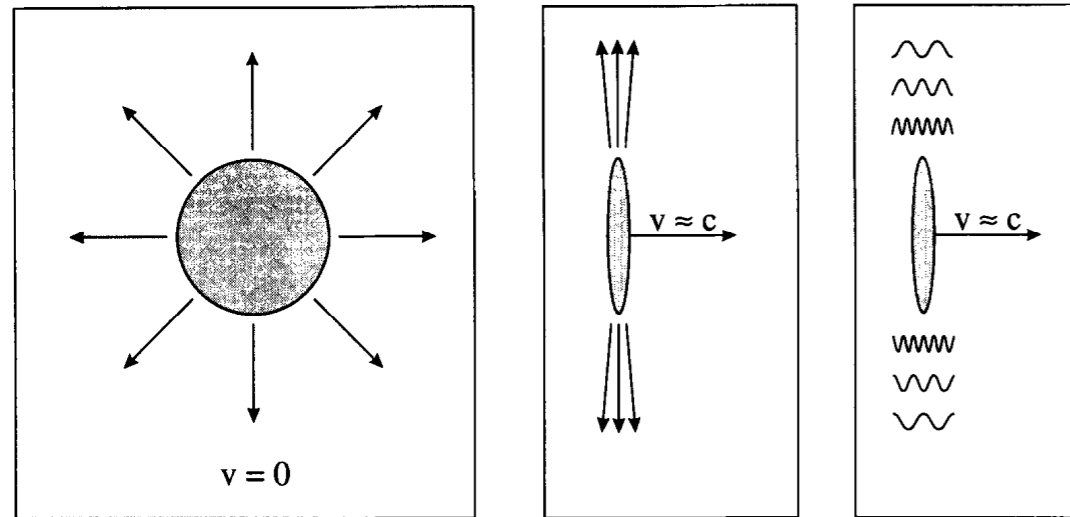**QM 2023 / 3-9 September 2023**

I STAND WITH UKRAINE

Brookhaven
National Laboratory

Exclusive γγ processes

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

<u>photon</u> pair production
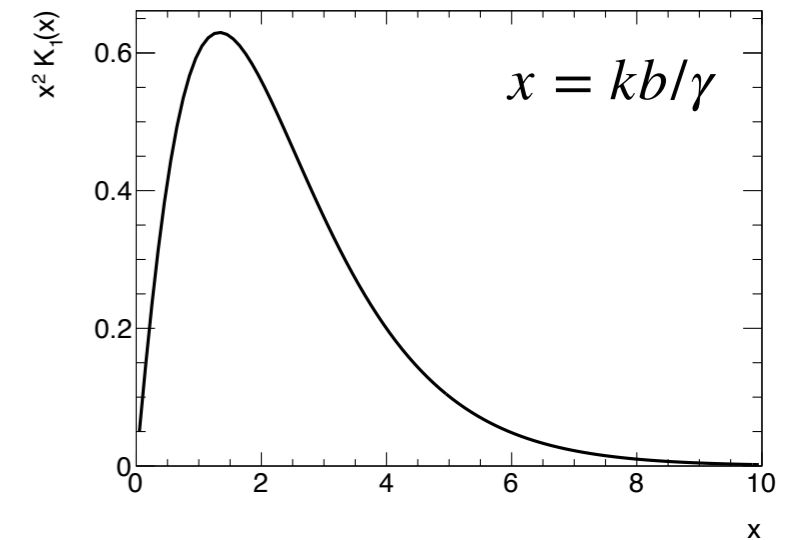(via quark, lepton, W, BSM? loops)

Heavy ion collisions are excellent QED & BSM laboratories!

Equivalent Photon Approximation

For a point charge:

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

$x = kb/\gamma$

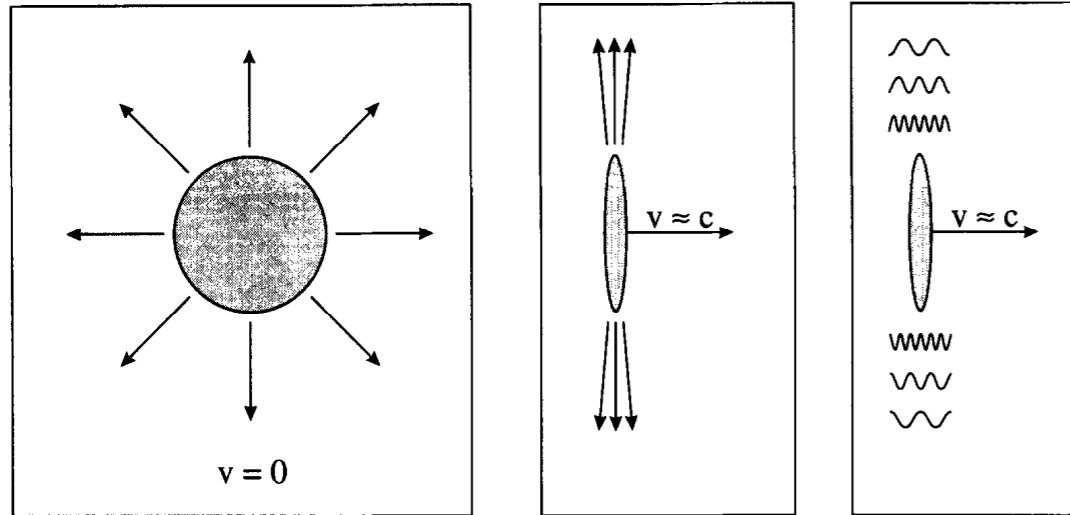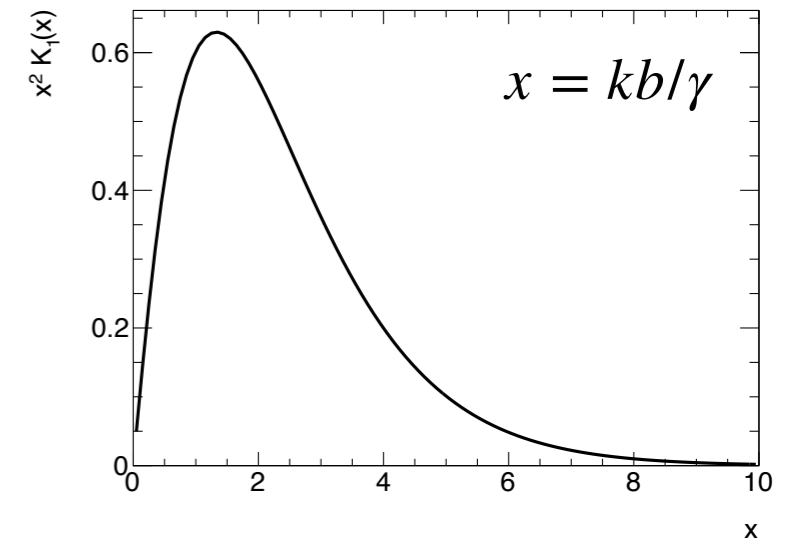| maximum energy $E_{\gamma,max} \sim \gamma(\hbar c/R)$	80 GeV in Pb+Pb@LHC 3 GeV in Au+Au@RHIC
typical p_T (& virtuality) $p_{Tmax} \sim \hbar c/R$	O(30) MeV @ RHIC & LHC
Coherent strengths (rates) scale as Z^2: nuclei >> protons	Flux of photons on other nucleus ~ Z^2, flux of photons on photons ~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

Two-photon fluxes, two approaches

For a point charge:

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

$x = kb/\gamma$

$v = 0$

$v \approx c$

$v \approx c$

STARlight formalism:

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

$$\frac{d^2 N}{dk_1 dk_2} = \int_{b_1 > R_1} d^2 b_1 \int_{b_2 > R_2} d^2 b_2 \, n(k_1, b_1) n(k_2, b_2) \, P_{\text{fn}}(b) \, (1 - P_{\text{H}}(b))$$

Radial cutoff to nuclear distributions

forward neutron topology

(no) hadronic interaction: Glauber calculation

SuperChic formalism:

$$\sigma_{N_1 N_2 \to N_1 X N_2} = \int dx_1 dx_2 \, n(x_1) n(x_2) \hat{\sigma}_{\gamma\gamma \to X}$$
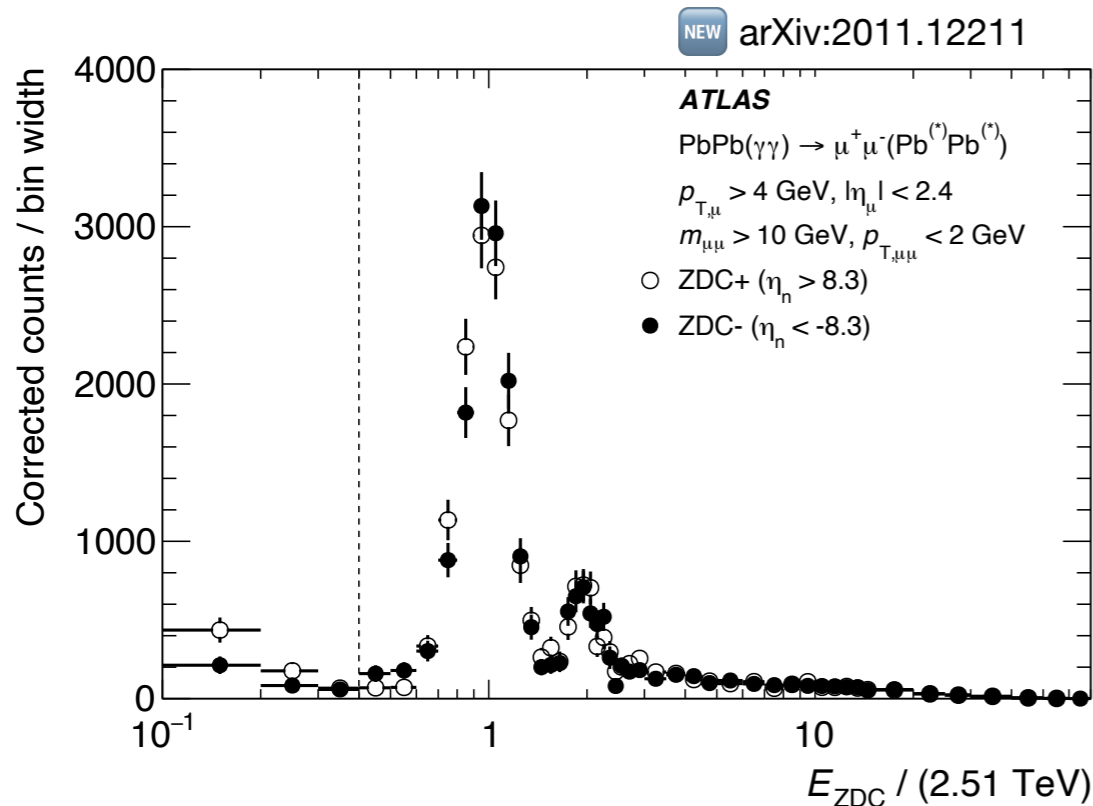
$$n(x_i) = \frac{\alpha}{\pi^2 x_i} \int \frac{d^2 q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2} \left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2} (1 - x_i) F_E(Q_i^2) + \frac{x_i^2}{2} F_M(Q_i^2) \right)$$

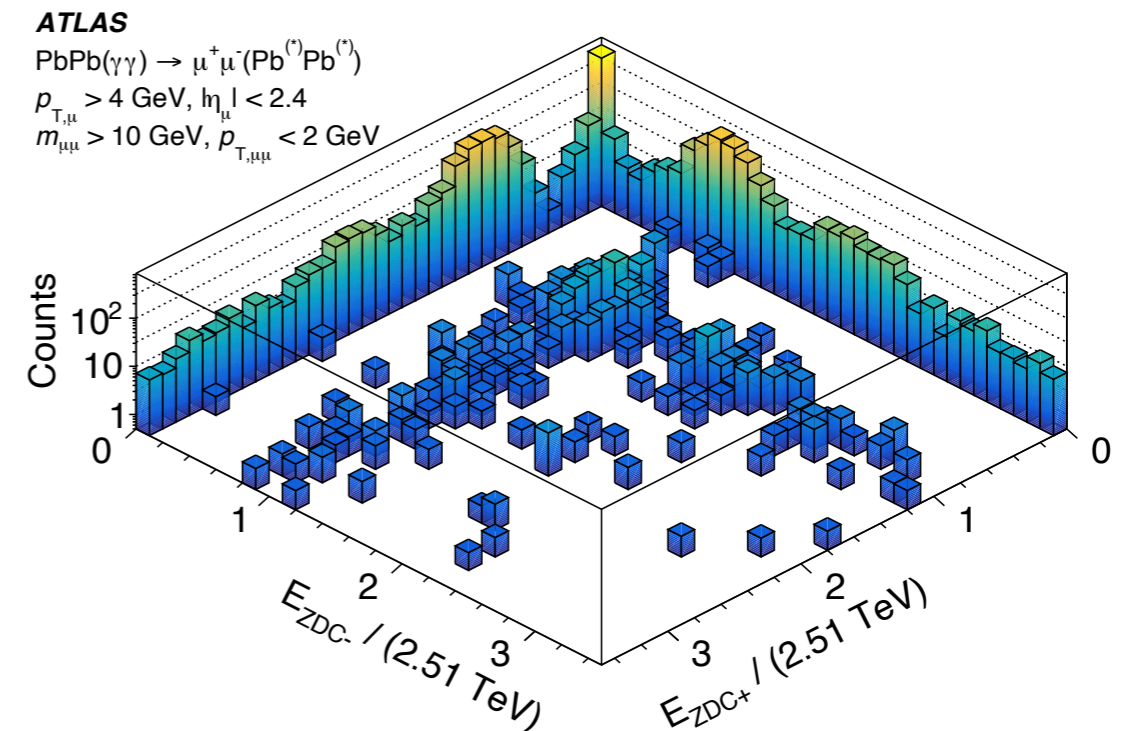includes survival and polarization effects, forward neutrons now available in SC4.2

ZDC selections

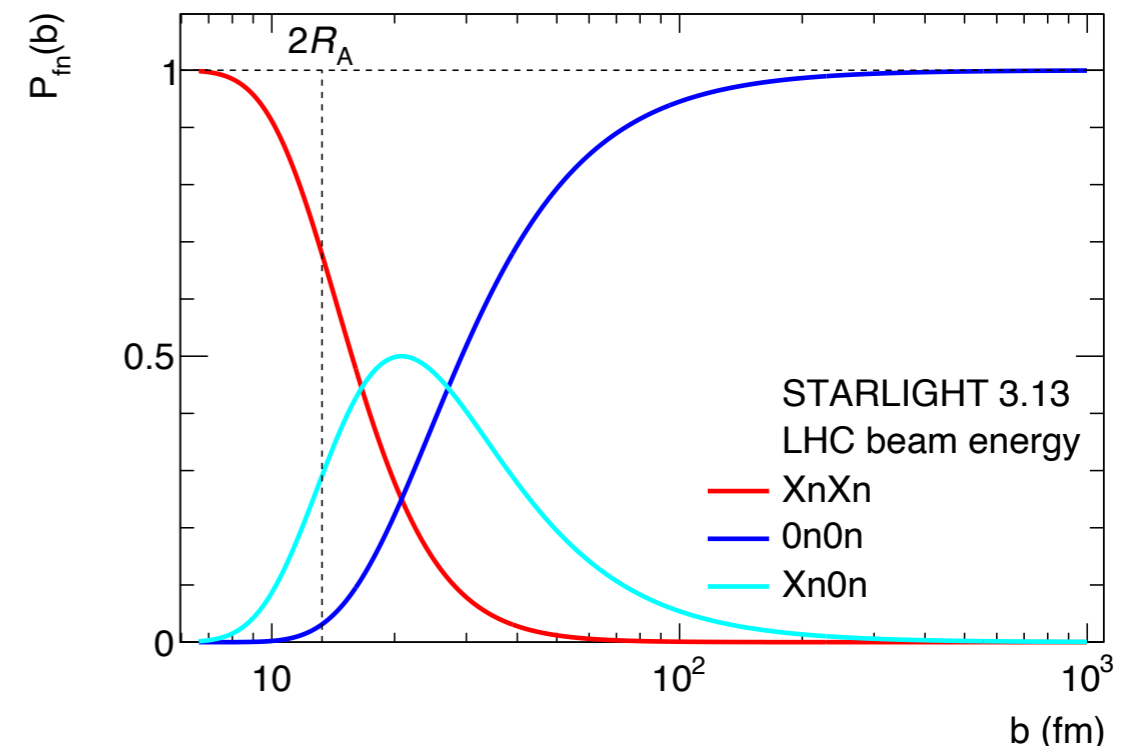ZDCs can distinguish 0n from 1n, 2n…

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
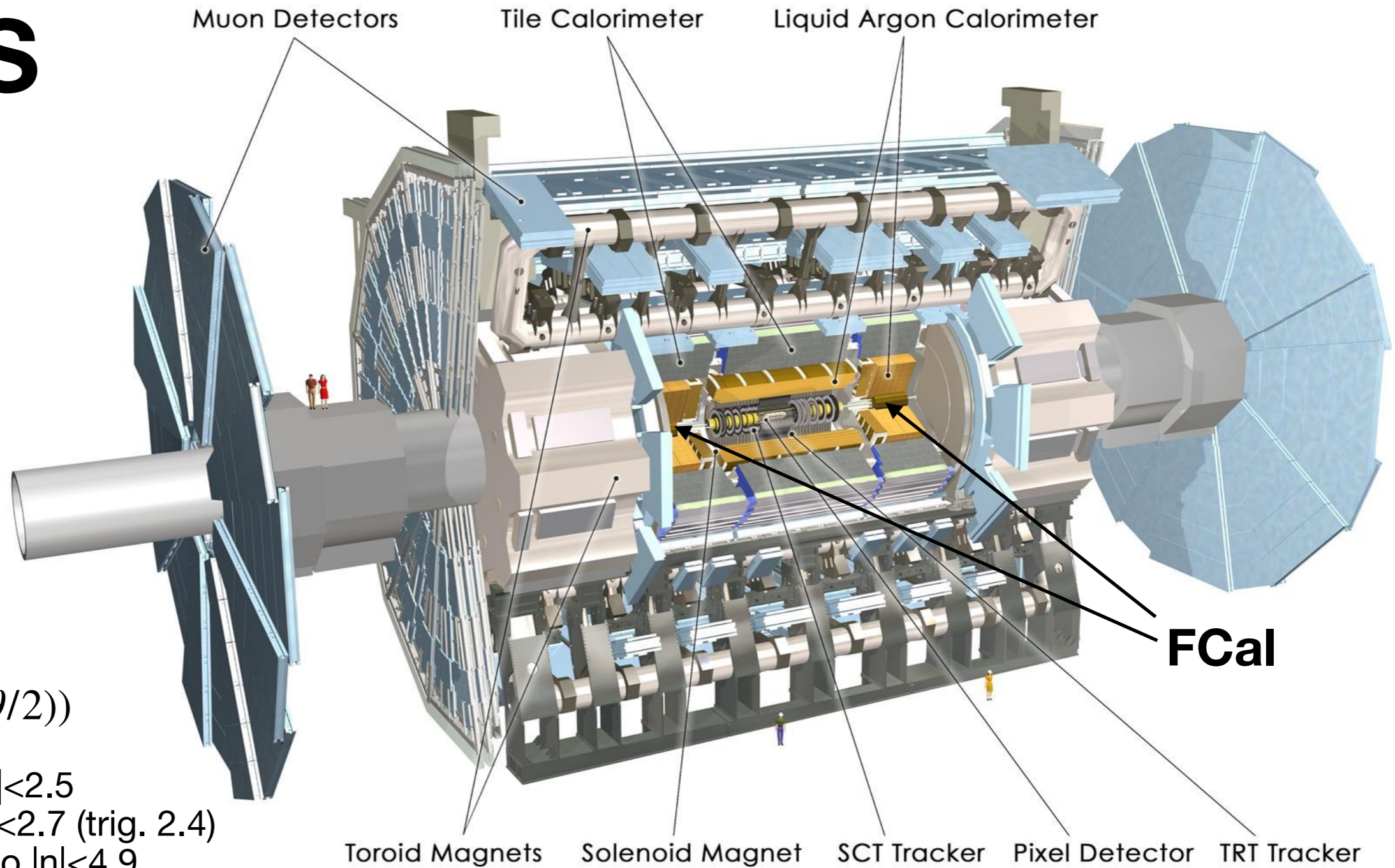
Klein & PAS, arXiv:2005.08172
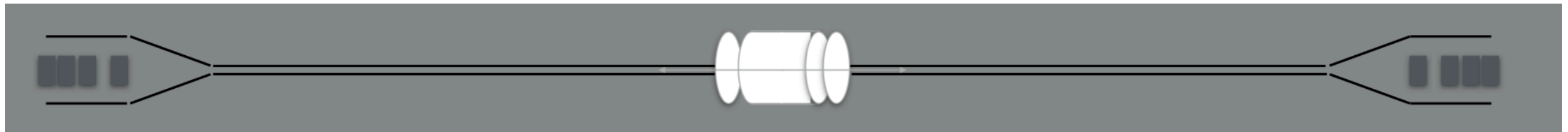
ATLAS

44m long
22m tall

Muon Detectors   Tile Calorimeter   Liquid Argon Calorimeter

FCal

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

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

Toroid Magnets   Solenoid Magnet   SCT Tracker   Pixel Detector   TRT Tracker

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

an exclusive dimuon event

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

Dimuons UPC Pb+Pb 5.02 TeV
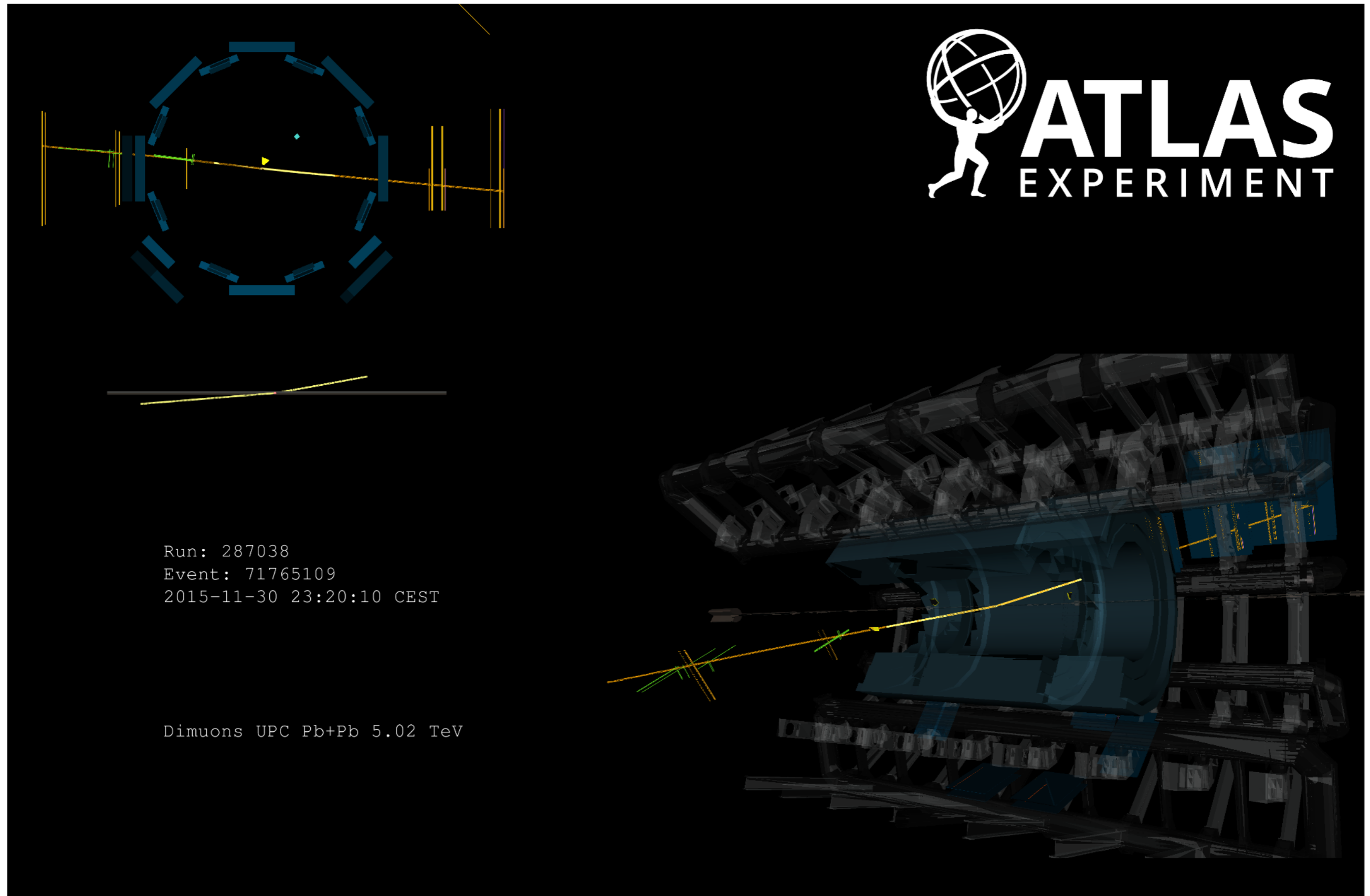
highest mass dimuon event in 2015 dataset - $m_{\mu\mu}$ = 173 GeV

an exclusive dielectron event
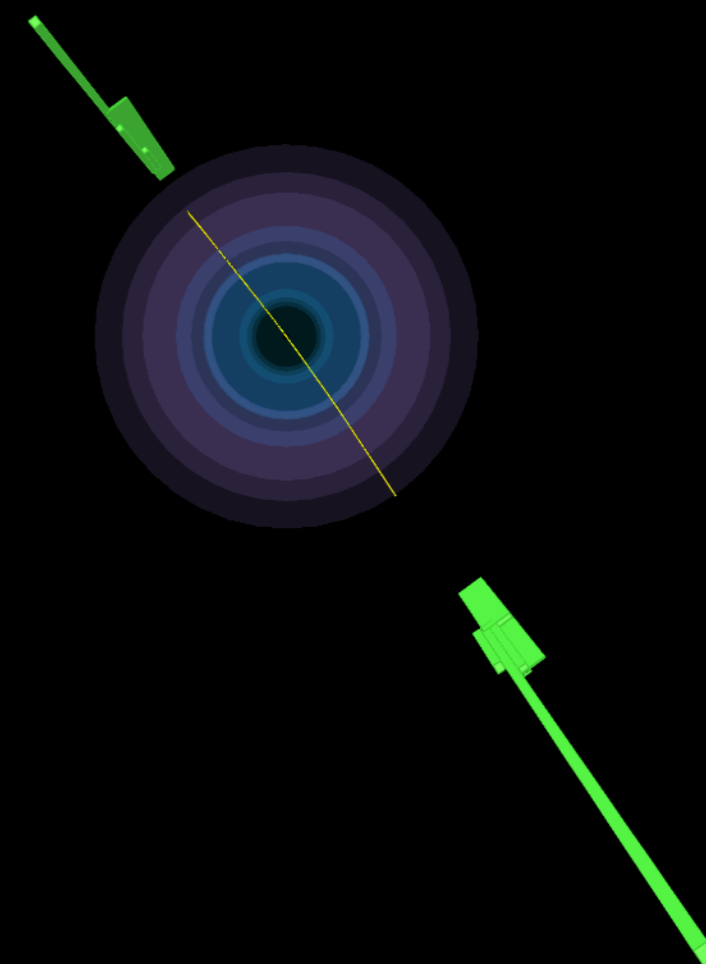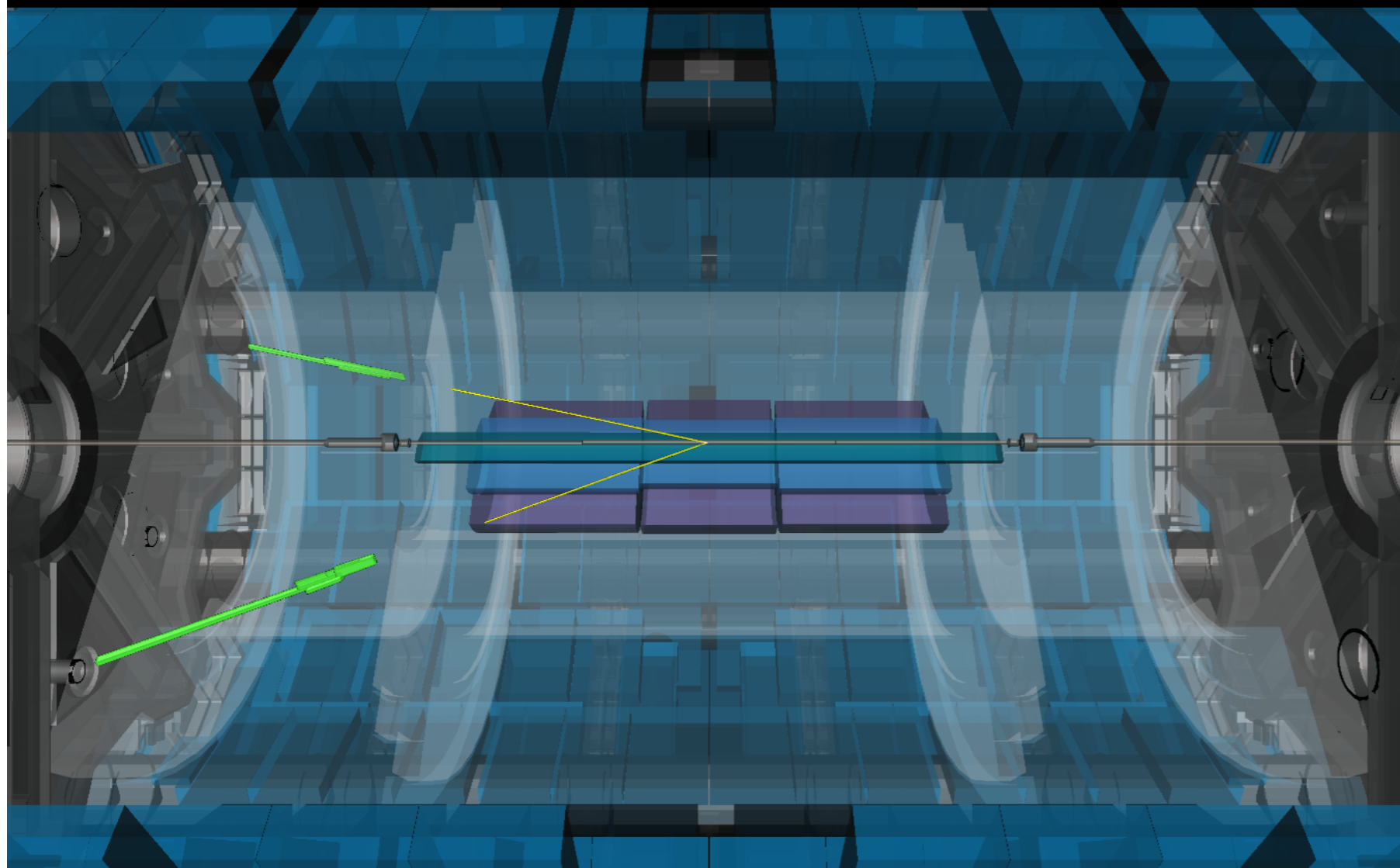
Exclusive dilepton processes & dissociation
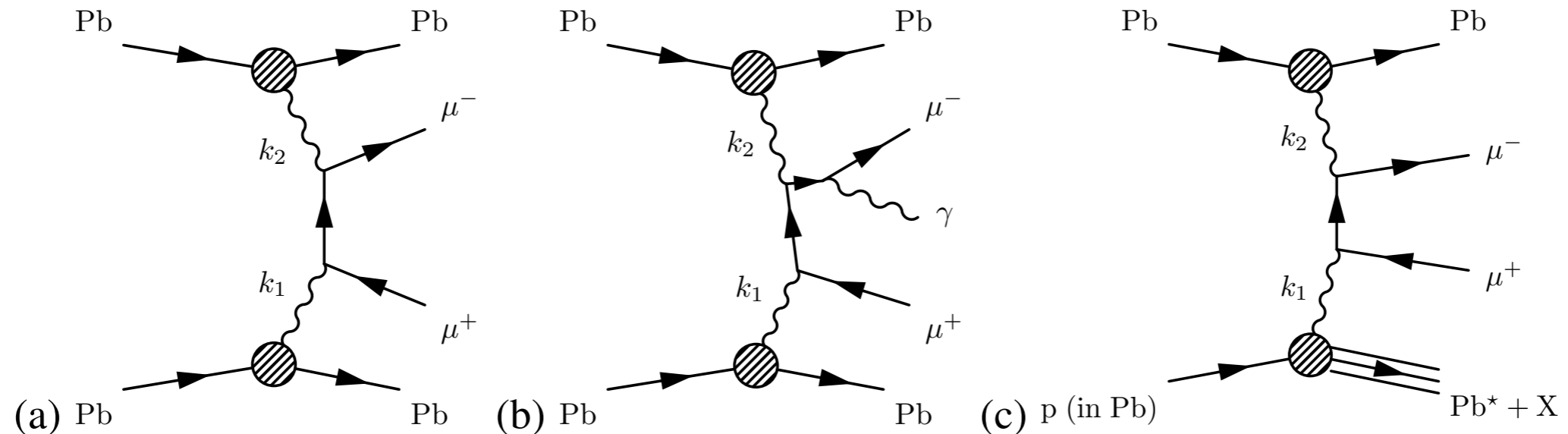
PbPb$(\gamma\gamma) \to \mu^+\mu^-(\text{Pb}^{(\star)}\text{Pb}^{(\star)})$ is the primary signal Breit-Wheeler process cross section implemented in STARlight, SuperChic, etc.

PbPb$(\gamma\gamma) \to \mu^+\mu^-\gamma(\text{Pb}^{(\star)}\text{Pb}^{(\star)})$ 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

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

Acoplanarity distributions in e⁺e⁻

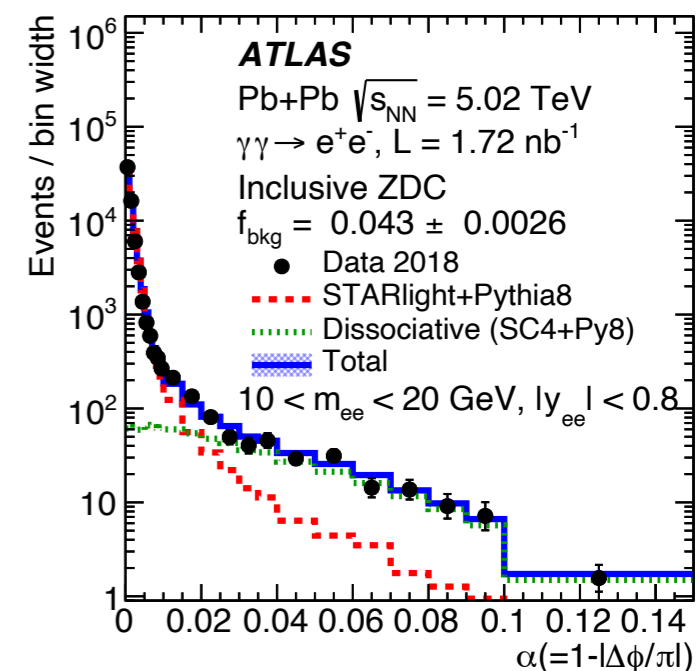$p_{\text{Te}} > 2.5$ GeV, $|\eta_e| < 2.47$, $m_{ee} > 5$ GeV, $p_{\text{Tee}} < 2$ GeV
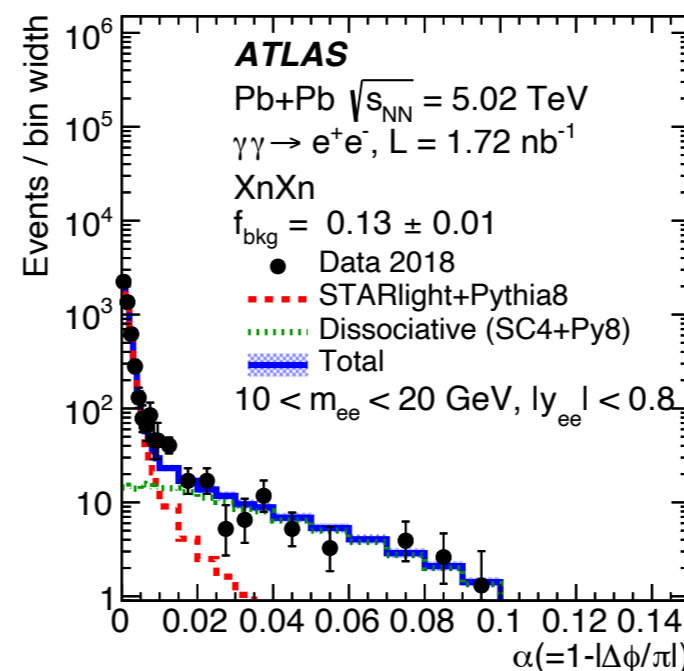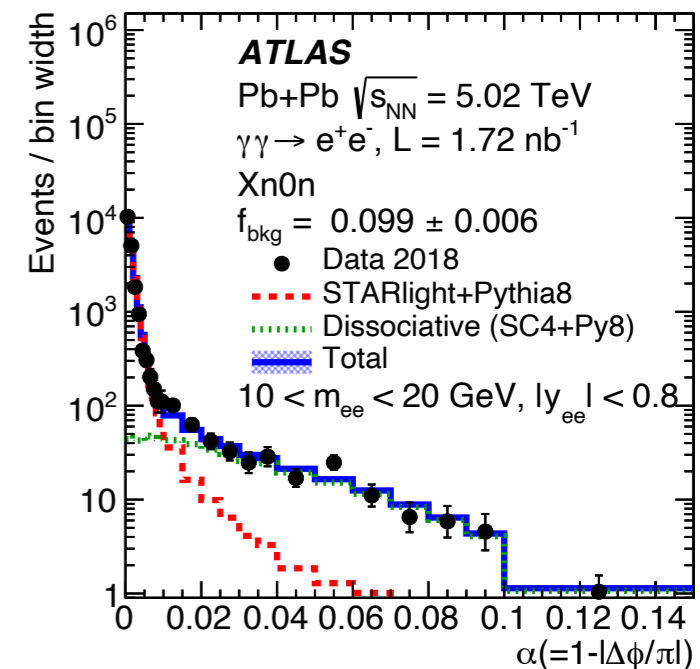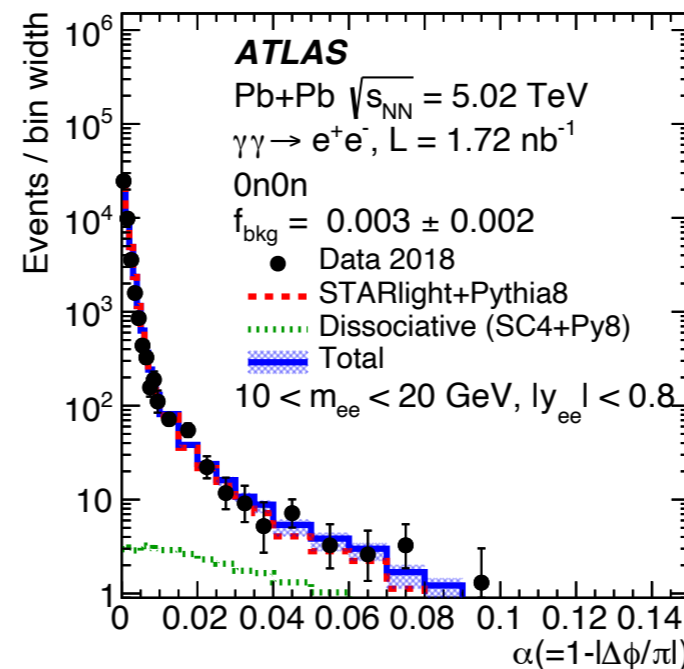
Acoplanarity is a key tool for distinguishing these processes:

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

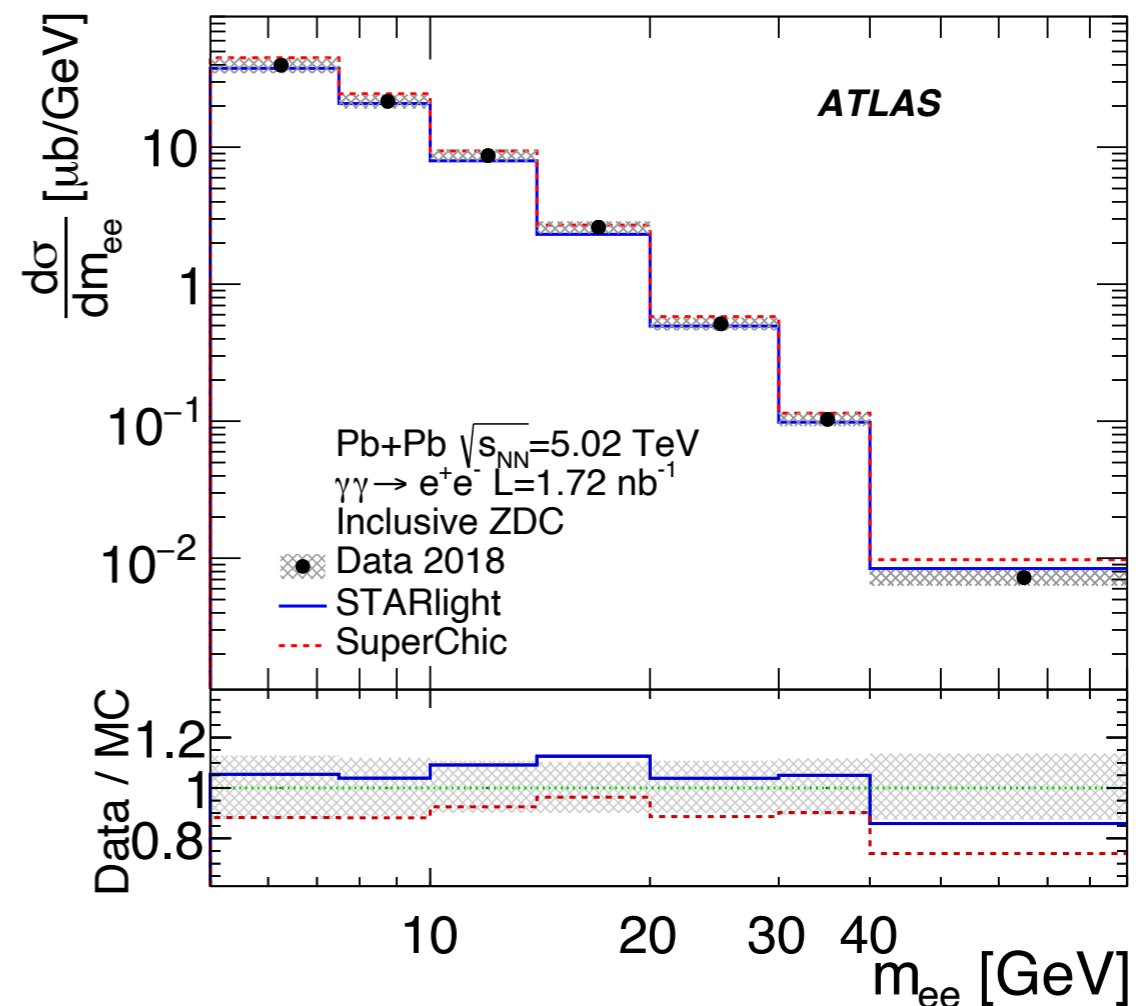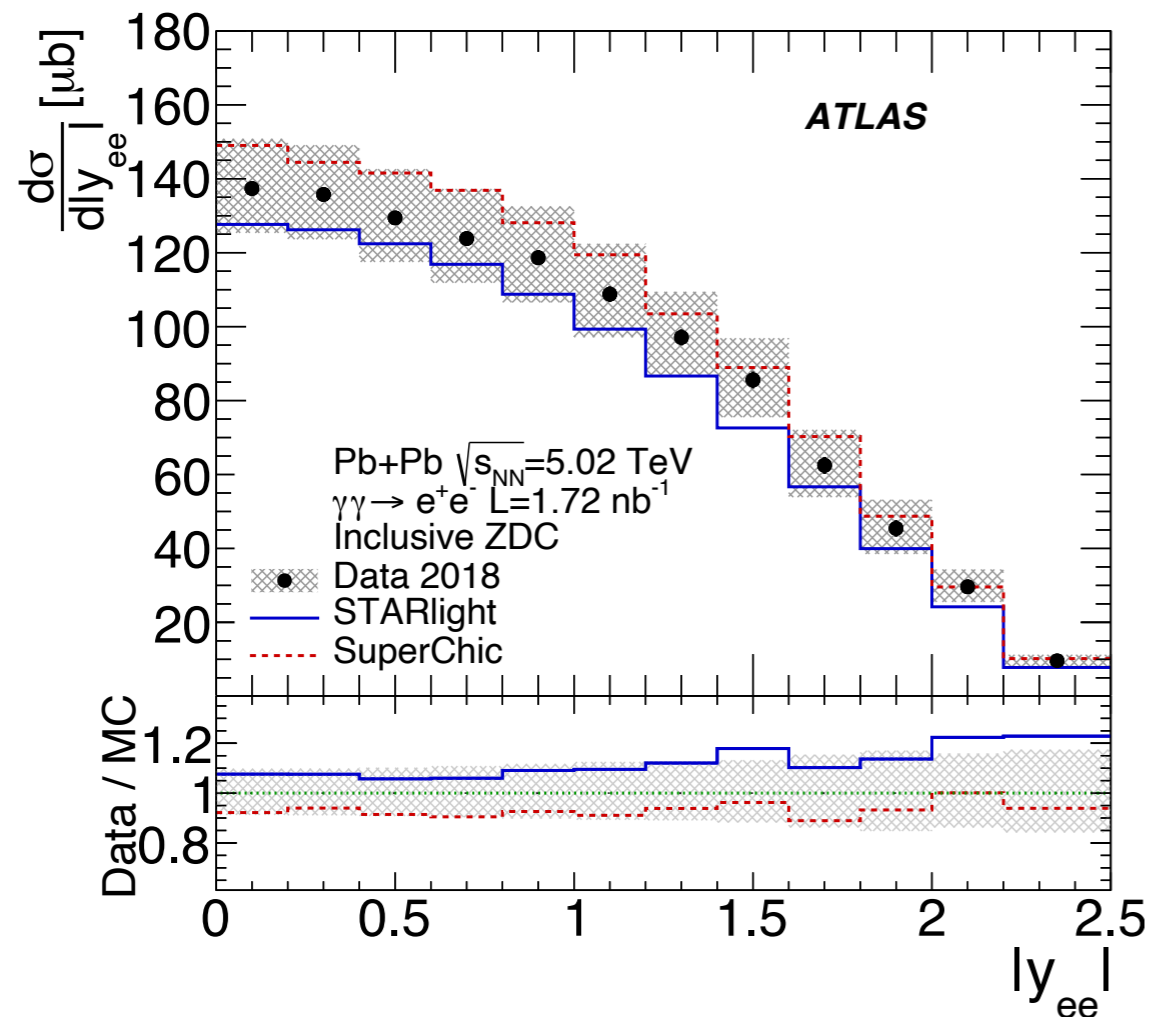Clear differences between samples selected with ZDC topologies:

0n0n - excellent agreement with STARlight+Pythia8

0nXn & XnXn clear contributions from dissociative contributions (modeled with SuperChic 4)

Top plots: Data / MC ratios vs m_{ee} [GeV] and vs $\langle p_T^e \rangle$ [GeV]. $p_{Te} > 2.5$ GeV, $|\eta_e| < 2.47$

$\frac{d\sigma}{d|y_{ee}|}$ [μb] vs $|y_{ee}|$

ATLAS

Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV
$\gamma\gamma \to e^+e^-$ L=1.72 nb^{-1}
Inclusive ZDC
Data 2018
STARlight
SuperChic

$\frac{d\sigma}{dm_{ee}}$ [μb/GeV] vs m_{ee} [GeV]

ATLAS

Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV
$\gamma\gamma \to e^+e^-$ L=1.72 nb^{-1}
Inclusive ZDC
Data 2018
STARlight
SuperChic

$\frac{d\sigma}{d\langle p_T^e \rangle}$ [μb/GeV]

Just as was seen with μμ, we see steady rise in the data/MC ratio as a function of $|y_{ee}|$, but similar spectral shape in m_{ee}.

STARlight tends to underpredict data while, SuperChic has better shape but overpredicts it: need for HO Coulomb corrections?

$\frac{d\sigma}{d|\cos\Theta^*|}$ [μb]

11

...gle and $<p_T^e>$

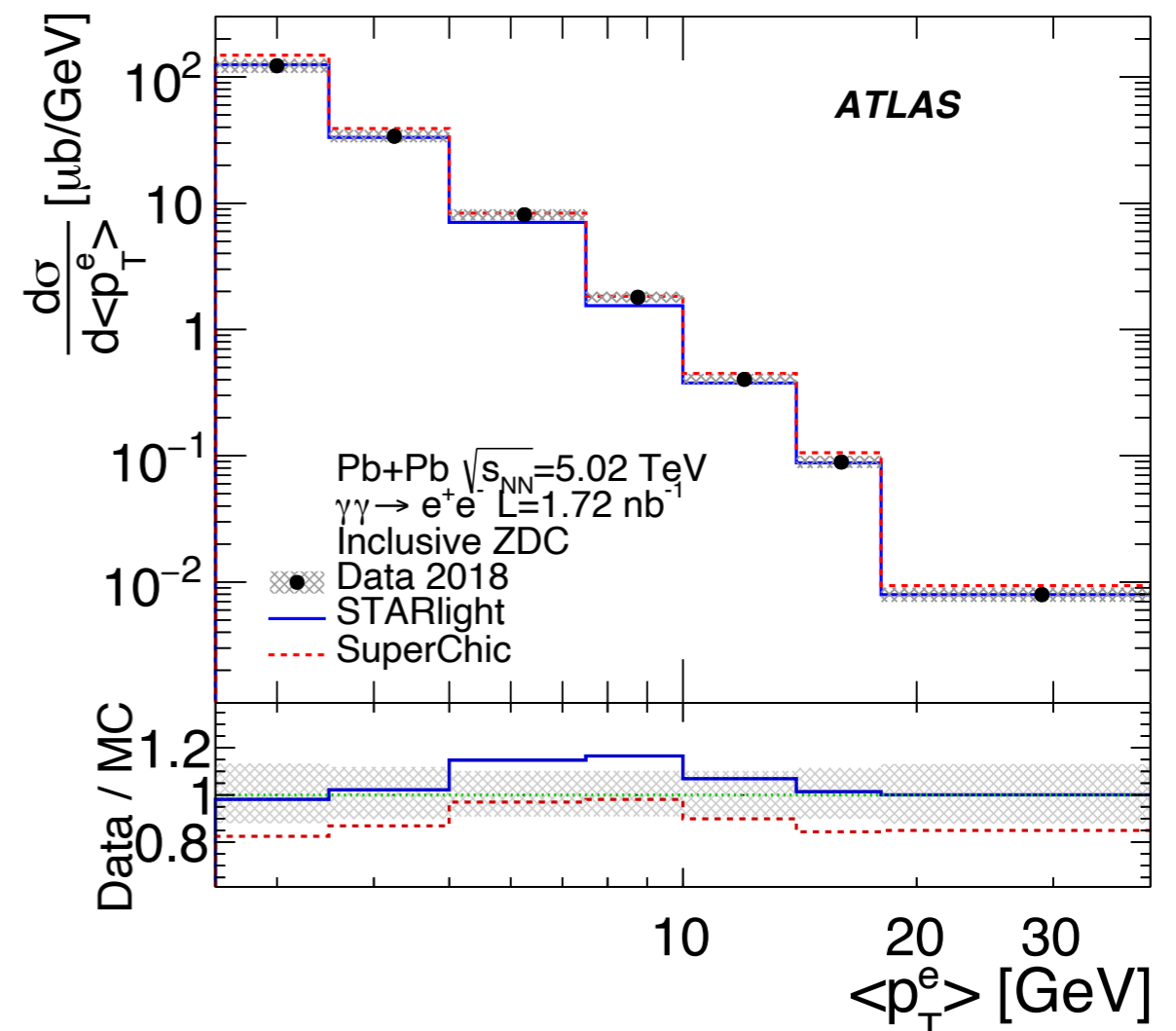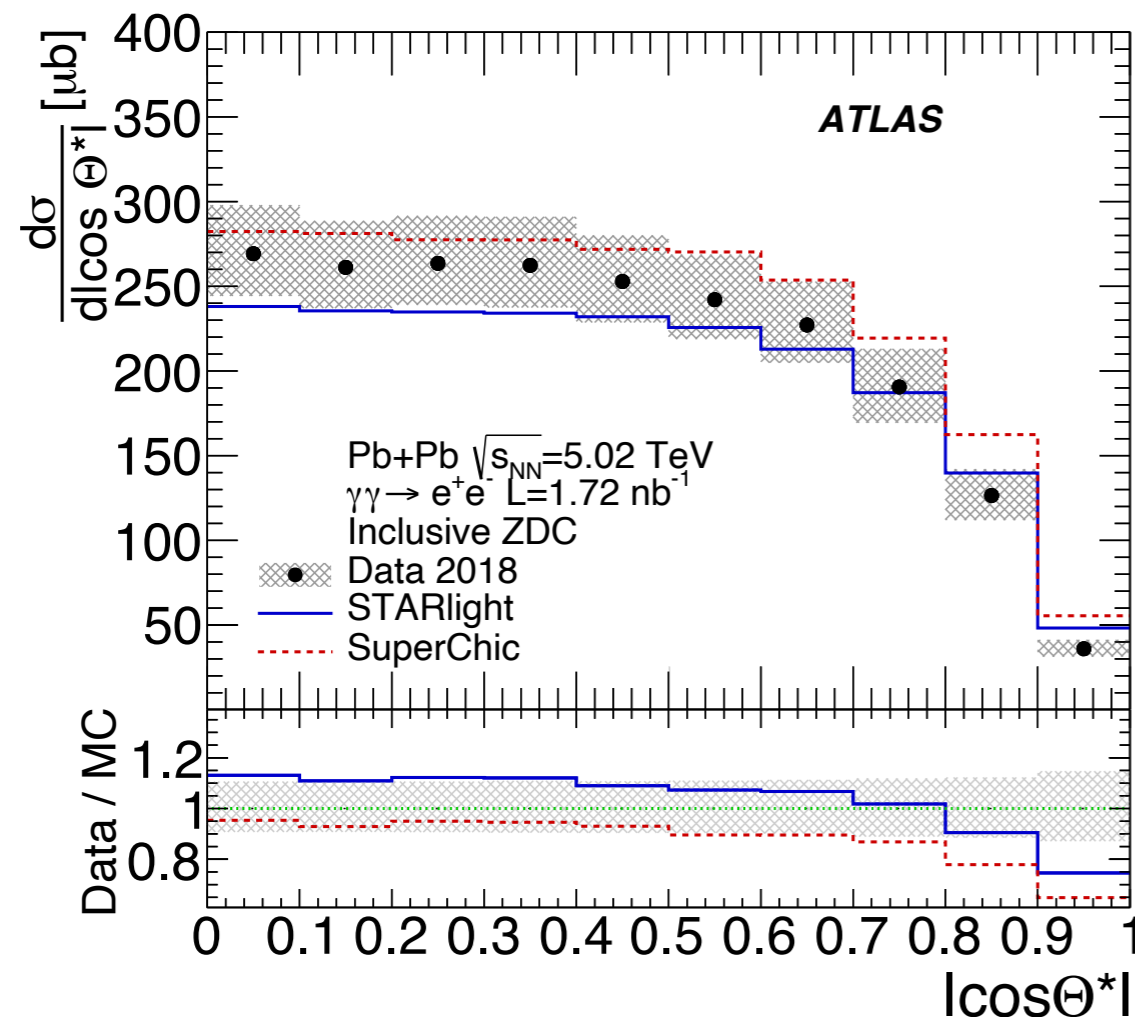$p_{Te} > 2.5$ GeV, $|\eta_e| < 2.47$, $m_{ee} > 5$ GeV, $p_{Tee} < 2$ GeV

Just as was seen with μμ, we see steady rise in the data/MC ratio as a function of $|y_{ee}|$, but similar spectral shape in m_{ee}.

STARlight tends to underpredict data while, SuperChic has better shape but overpredicts it: need for HO Coulomb corrections?

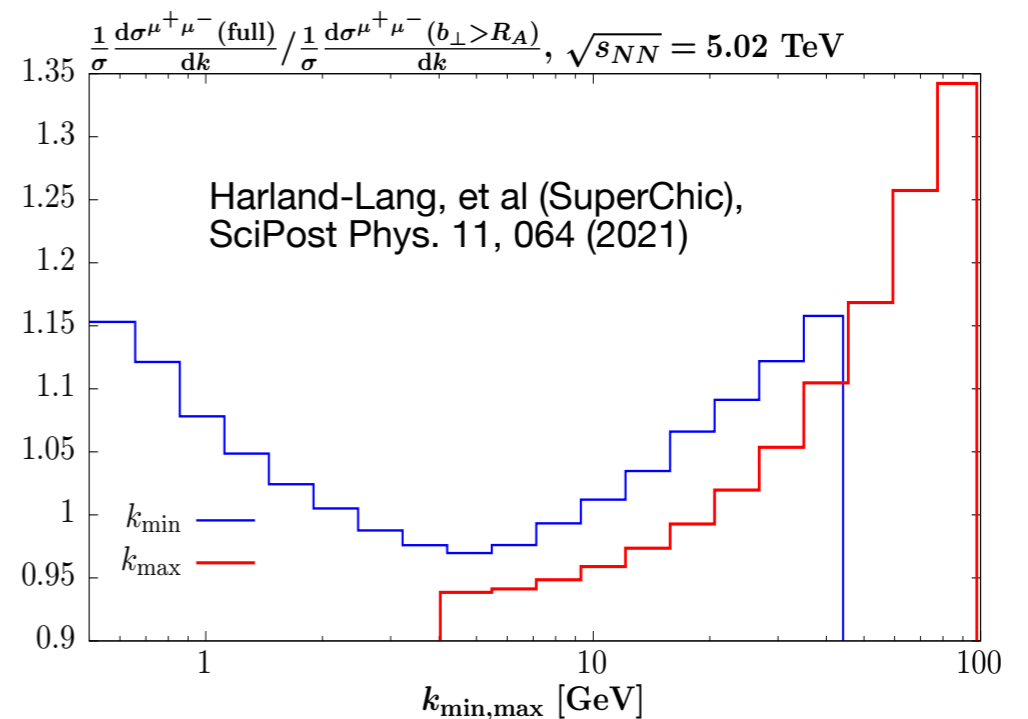# Photon energy distributions in μμ
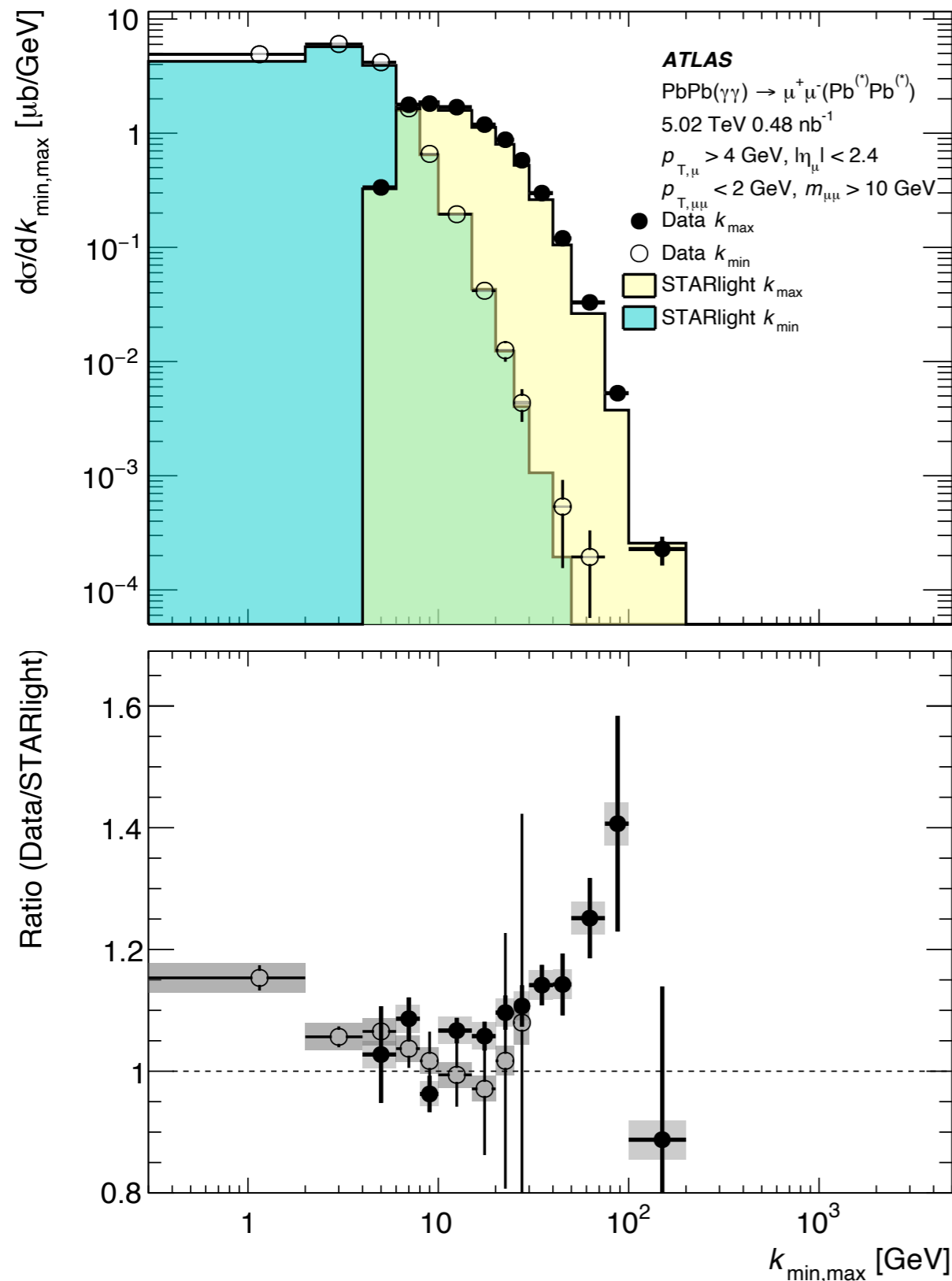
Can combine $m_{\mu\mu}$ and $y_{\mu\mu}$ to estimate photon energies

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

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

Superchic 4.2 vs. data
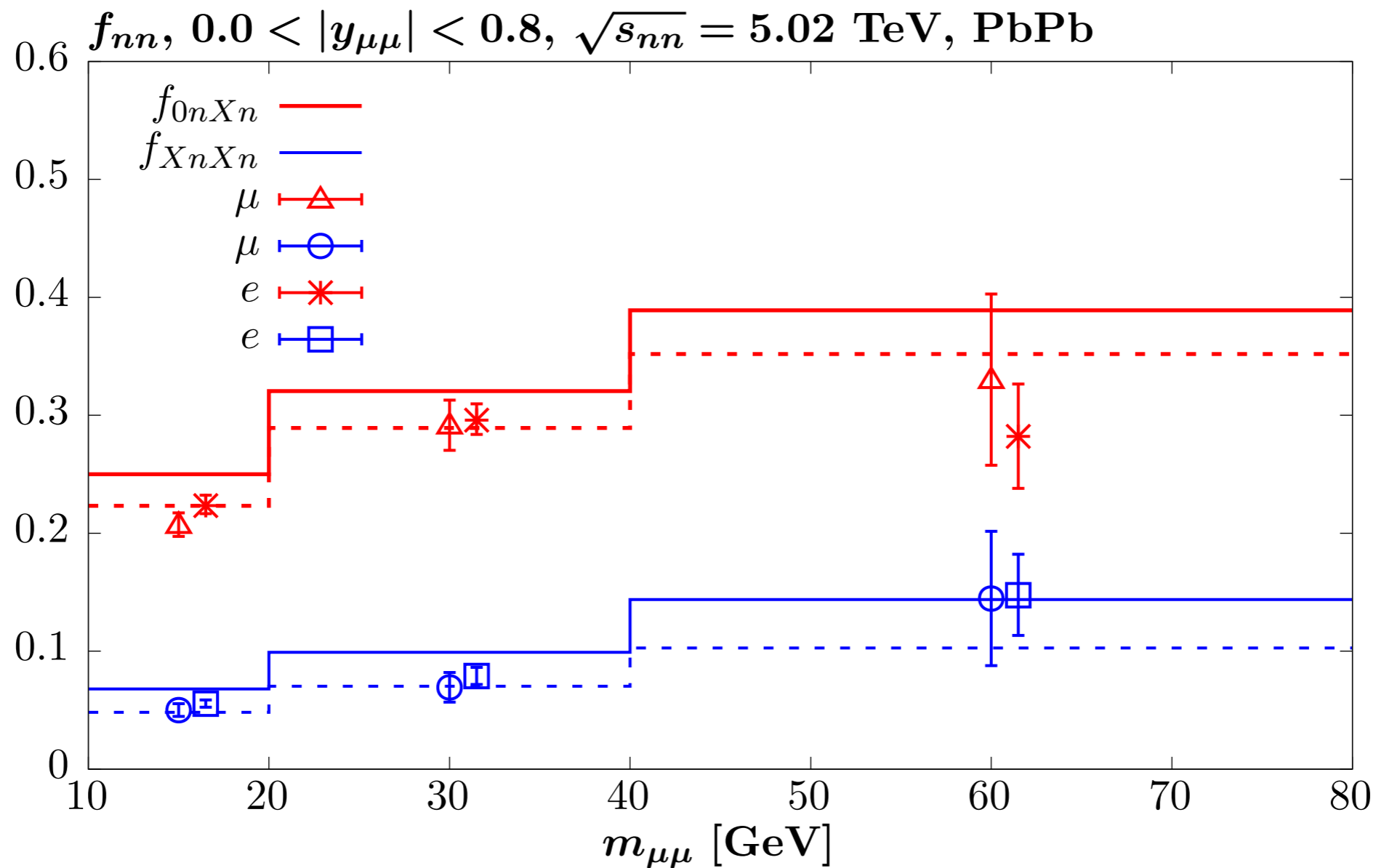
New implementation of neutron fragmentation,
good comparison w/ ee and µµ data with nominal fluxes (solid lines),
better description after reducing γA cross sections (dotted lines)

a_τ from $\tau^+\tau^-$ in Pb+Pb

μe

μ+1 track

μ+3 track
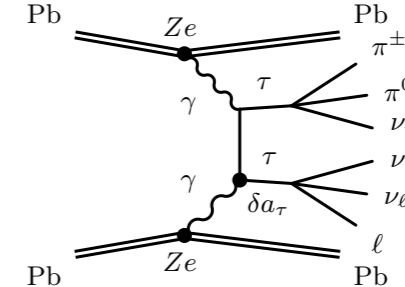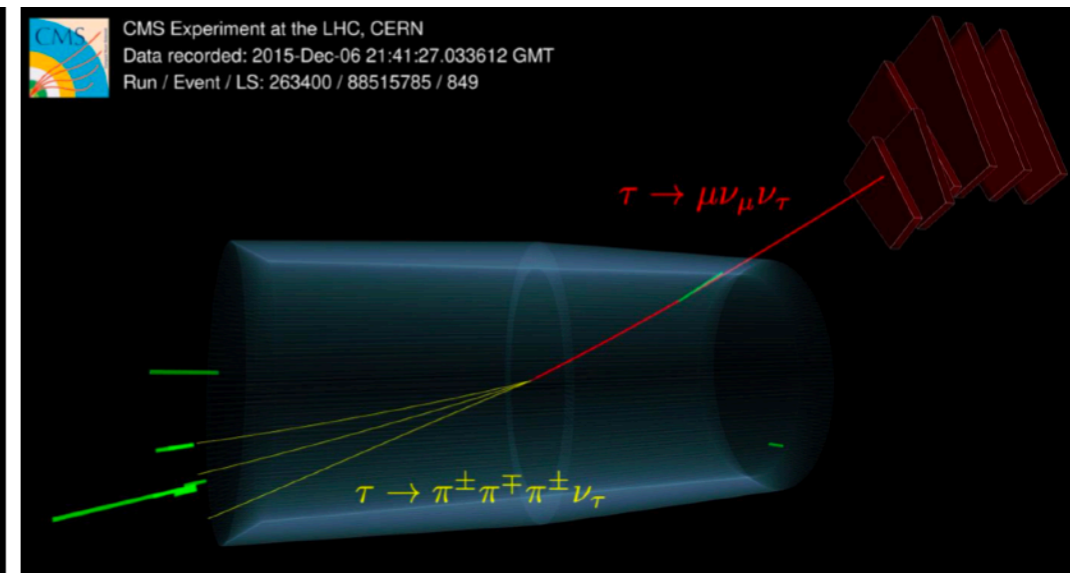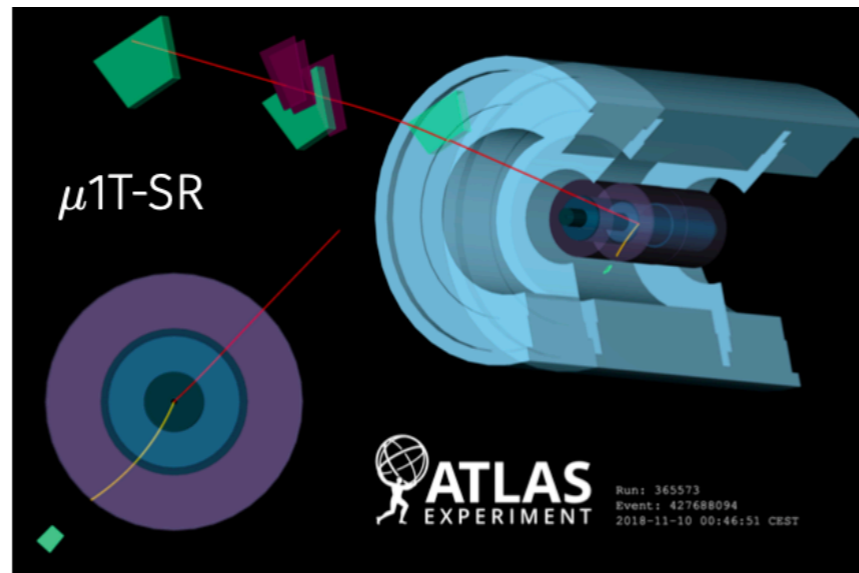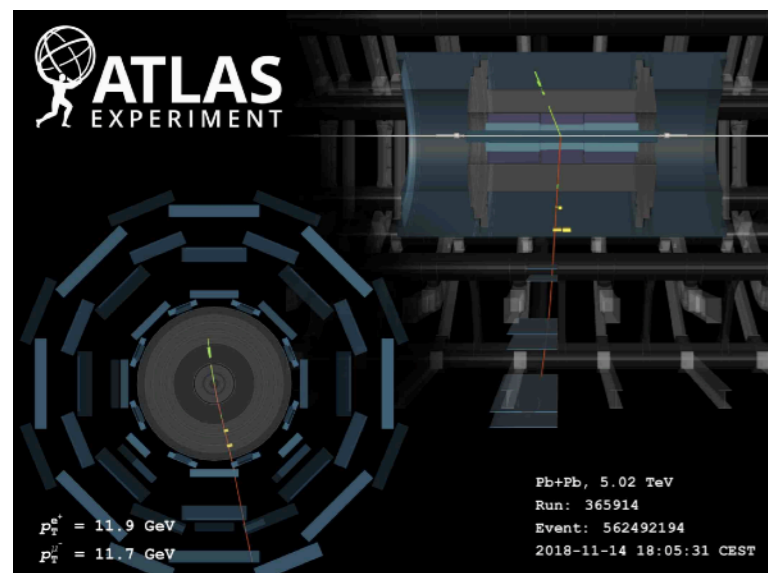

- **Anomalous magnetic moment of tau leptons sensitive to physics beyond the standard model**
  - Development of theory frameworks in 2019/2020, and new measurements from CMS and ATLAS from Run 2 Pb+Pb data from LHC!

- **Three channels available: eμ, μ+track, μ+3 tracks**
  - ATLAS uses all 3 channels in 2018 (1.44 nb^{-1}), requiring 0n0n and cluster veto to suppress dissociative and hadronic backgrounds
    - *fits for a_τ using modifications to $p_T(\mu)$ distributions, using μμ to normalize photon flux*

ATLAS: $\tau^+\tau^-$ likelihood fits
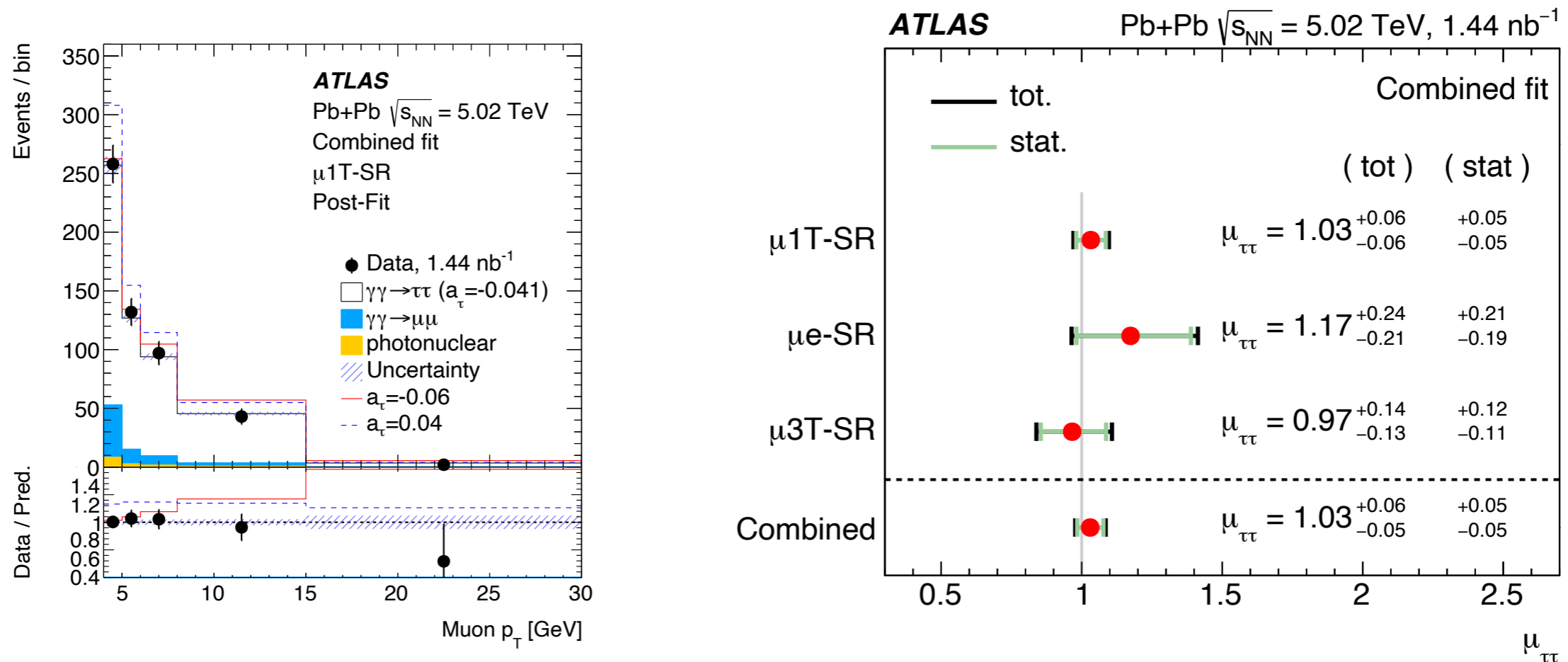
- **Profile likelihood fits in** **cay modes** **(~650 events), and the** **the photon flux**

- **Combined yield consis**

ATLAS: τ g-2 95% CL limits
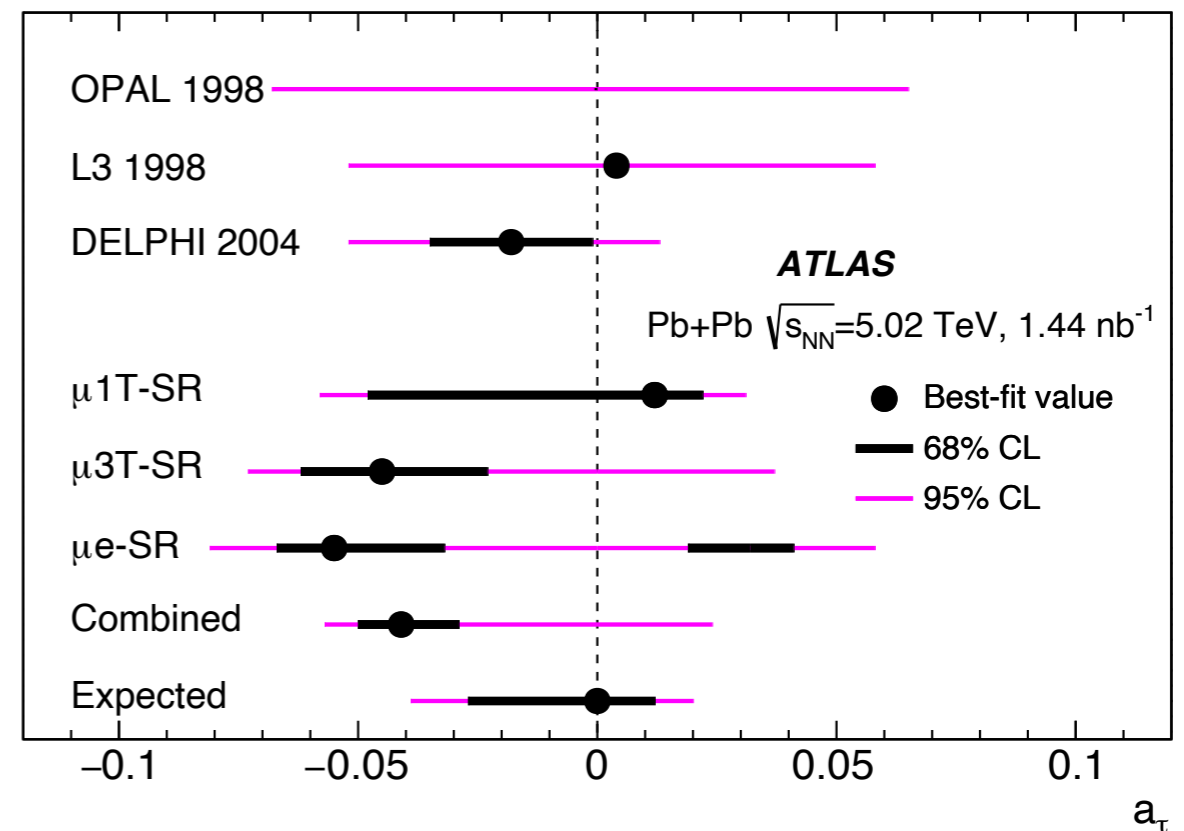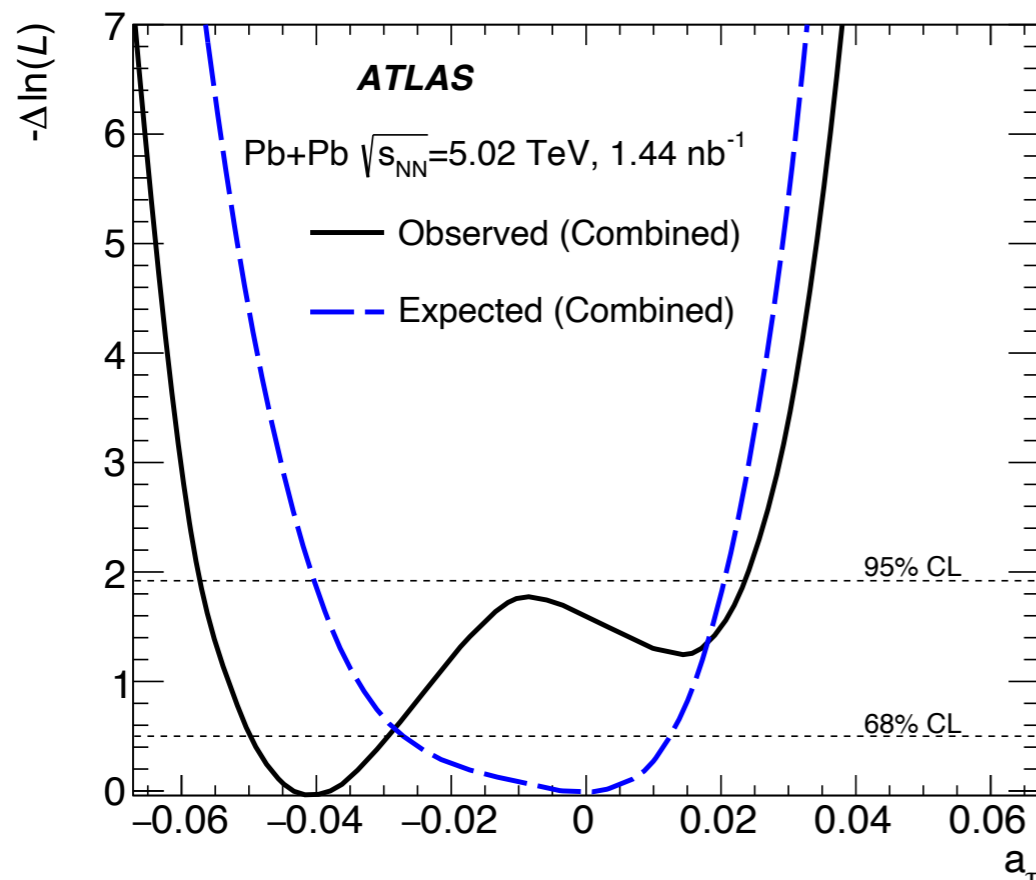
- **likelihoods as a function of a_τ derived using profile likelihood fit**
  - templates from Dyndal et al (PLB 809 (2020) 135682)

- **Observed 95% CL limits from $a_\tau \in$ (–0.057, 0.024)**
  - Limits similar to that extracted from DELPHI (e+e-) in 2004
  - Expecting substantial improvements from Run 3 & 4 data!

Exclusive γγ processes in nonUPC
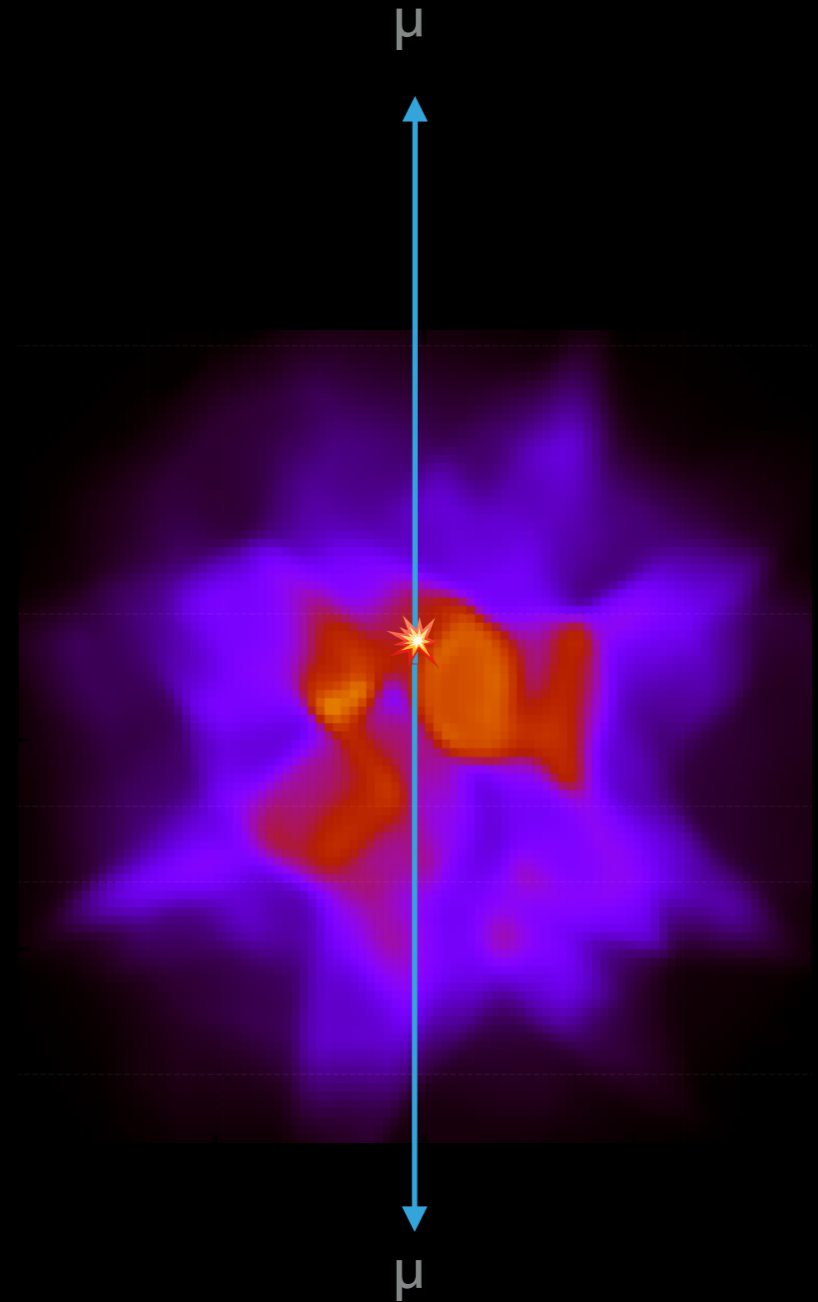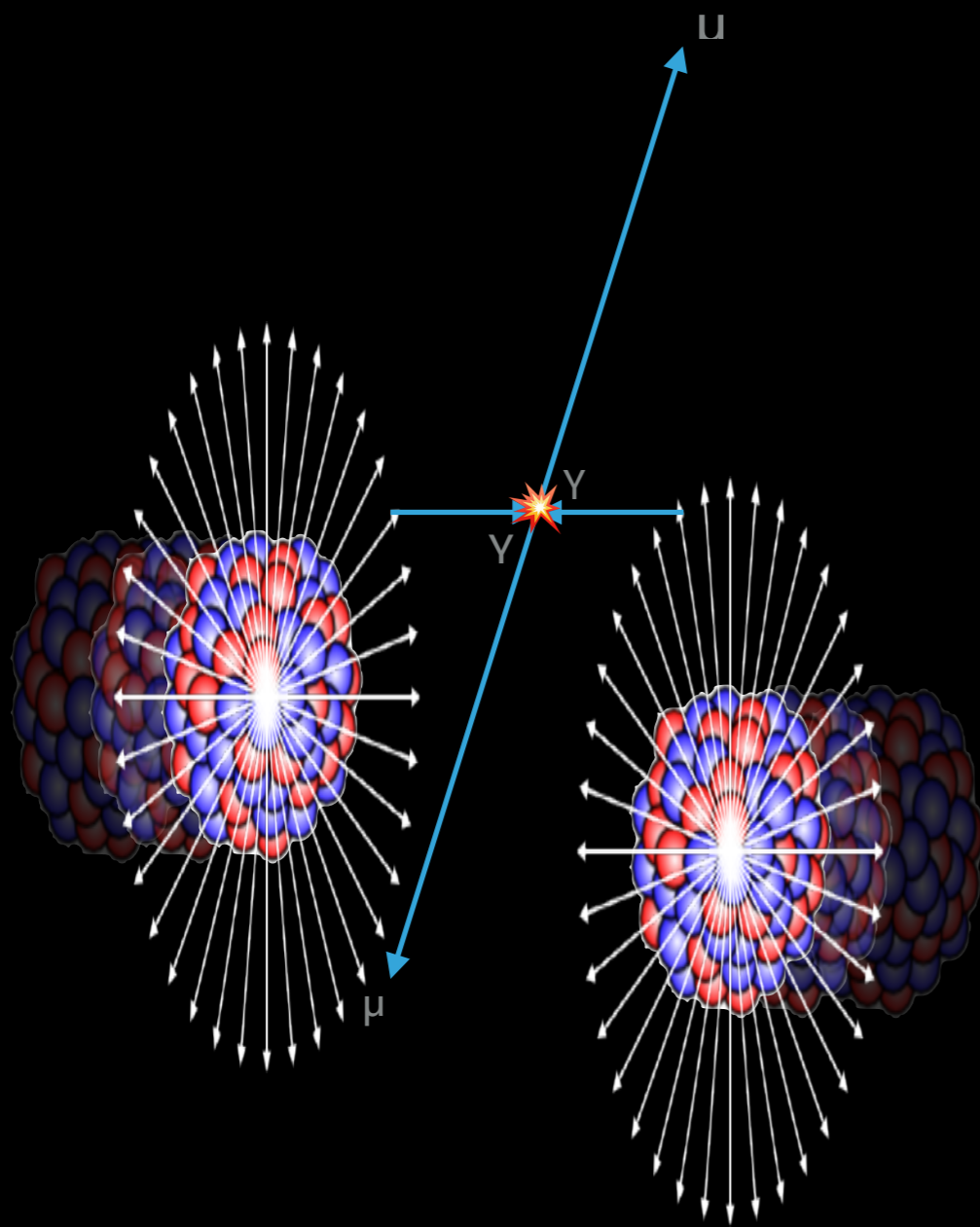
- **Even as the nuclei overlap, one can still expect to observe dileptons from gamma-gamma processes**
  - Can they resolve any aspects of the QGP evolution or initial B fields?

nonUPC µµ measurement

- **Use both 2015 and 2018 Pb+Pb datasets: total of 1.94 nb⁻¹**
  - 1.5% uncertainty on luminosity

- **Preselections**
  - Opposite-charge muon pairs with muon p_T>3.7 GeV, $|\eta|$<2.4
  - Pair mass < 45 GeV

- **HF rejection using transverse and longitudinal impact parameters**
  - d_{0pair} < 0.1 mm, $(z_0\sin\theta)_{pair}$ < 0.2 mm

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

$$(z_0 \sin\theta)_{\text{pair}} \equiv \sqrt{(z_0 \sin\theta)_1^2 + (z_0 \sin\theta)_2^2}.$$

- **Pair variables reflecting transverse kicks**
  - **acoplanarity** (α=1-$|\Delta\phi|/\pi$)
  - **pair** k_T = 0.5(p_{T1}+p_{T2})$\pi\alpha$
  - **pair momentum asymmetry** A = $|p_{T2}-p_{T1}|/(p_{T2}+p_{T1})$

- **Fiducial regions based on α or kT**
  - "Fid-α": A < 0.06 & α < 0.012 (69490 pairs)
  - "Fid-k_T": A < 0.06 & k_T < 150 MeV (67789 pairs)

- **Centrality based on forward transverse energy (as is typical for HI measurements)**
  - Regions beyond 90% not well defined due to UPC contamination, so utilize 4 regions based on absolute E_T value

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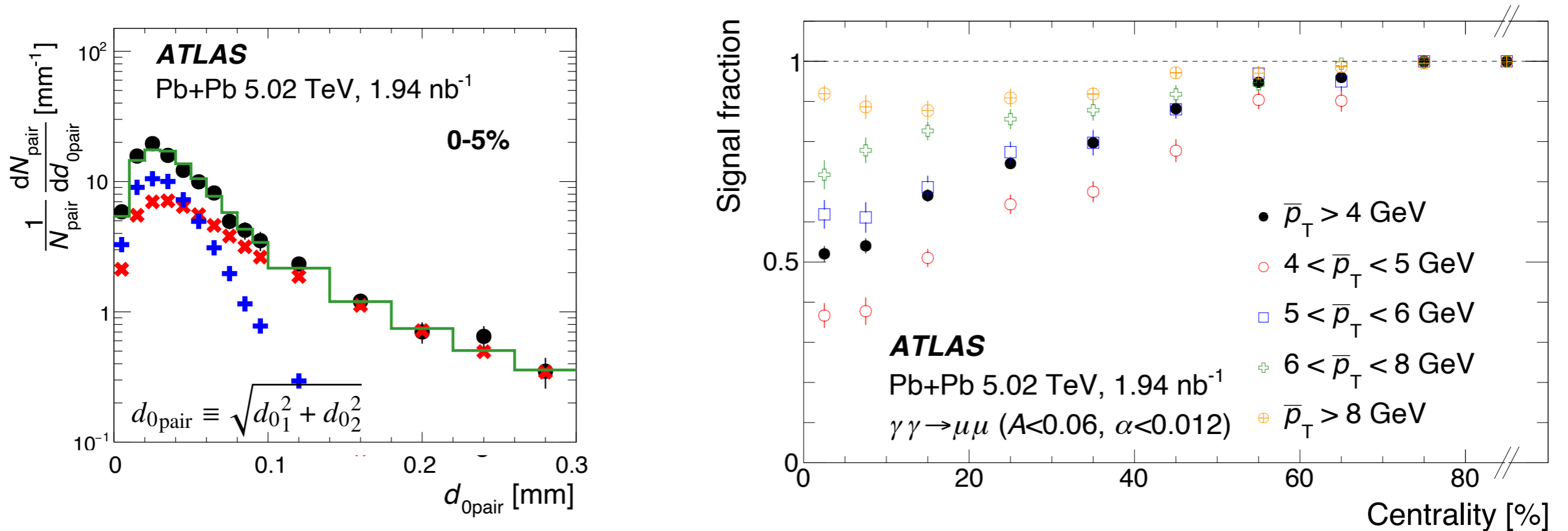
Pair d_0 distributions fit to signal (STARlight+HIJING) and HF background (data-driven, cut inversion) templates to extract signal fraction for each centrality selection.

Background is negligible for very peripheral events, but is nearly half the yield in central events!

Drell-Yan contributions

ATLAS Simulation
POWHEG+Pythia8, DY $\mu^+\mu^-$
5.02 TeV, Pb PDFs
$\overline{p}_T > 4$, $m_{\mu\mu} < 45$ GeV
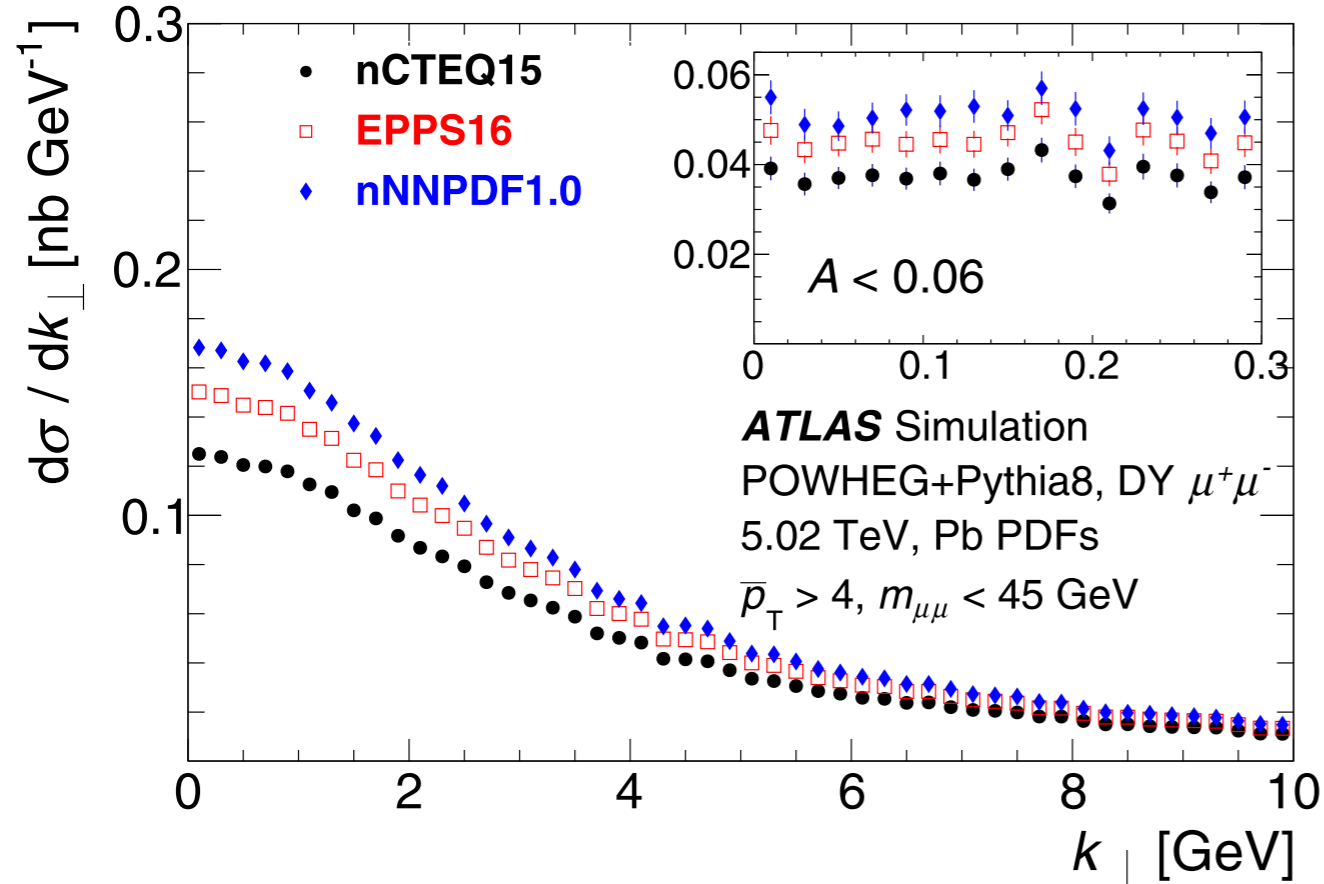
Drell-Yan dimuons result from scattering of quarks and anti-quarks typically with low-x, so sensitive to nuclear shadowing.

Calculated using 5 nPDF sets, which vary by about 30% (but all are at least 30% lower than CT14 NNLO)

While there is a strong dependence on α and k_T overall, within the Fid-α and Fid-k_T regions, the cross sections are ~flat in α and k_T: contribution similar to HF

PDF set	$\sigma_{DY,NN}^{Fid-\alpha}$ (pb)	$\sigma_{DY,NN}^{Fid-k_\perp}$ (pb)
nCTEQ15	12.9 ± 4.2	7.68 ± 2.66
EPPS16	15.2 ± 5.7	9.14 ± 3.60
nNNPDF1.0	16.6 ± 8.7	10.1 ± 5.38
nNNPDF2.0	17.1 ± 1.8	10.5 ± 1.15
TUJU19	17.2 ± 1.8	10.4 ± 1.6
CT14 NNLO	24.4 ± 2.3	15.2 ± 1.4

Signal distributions
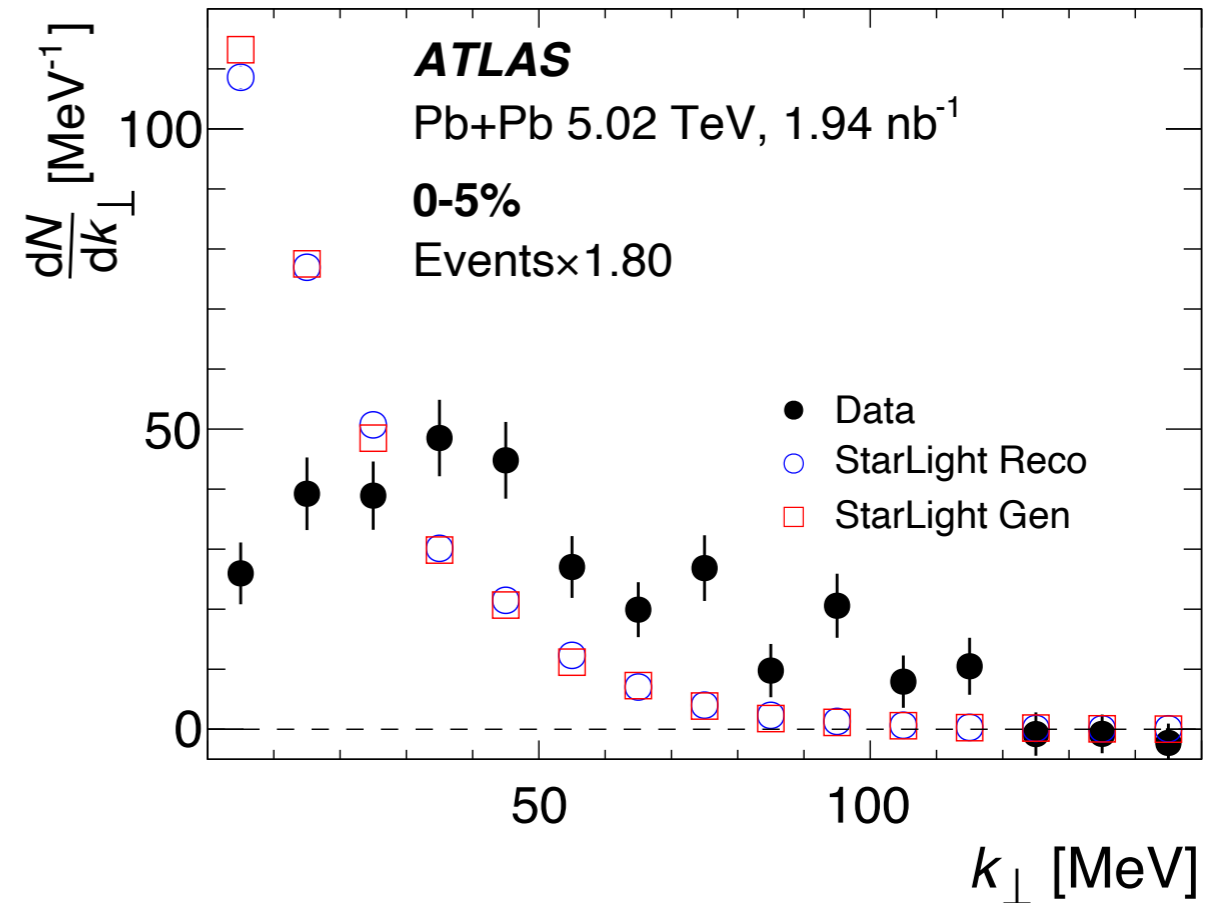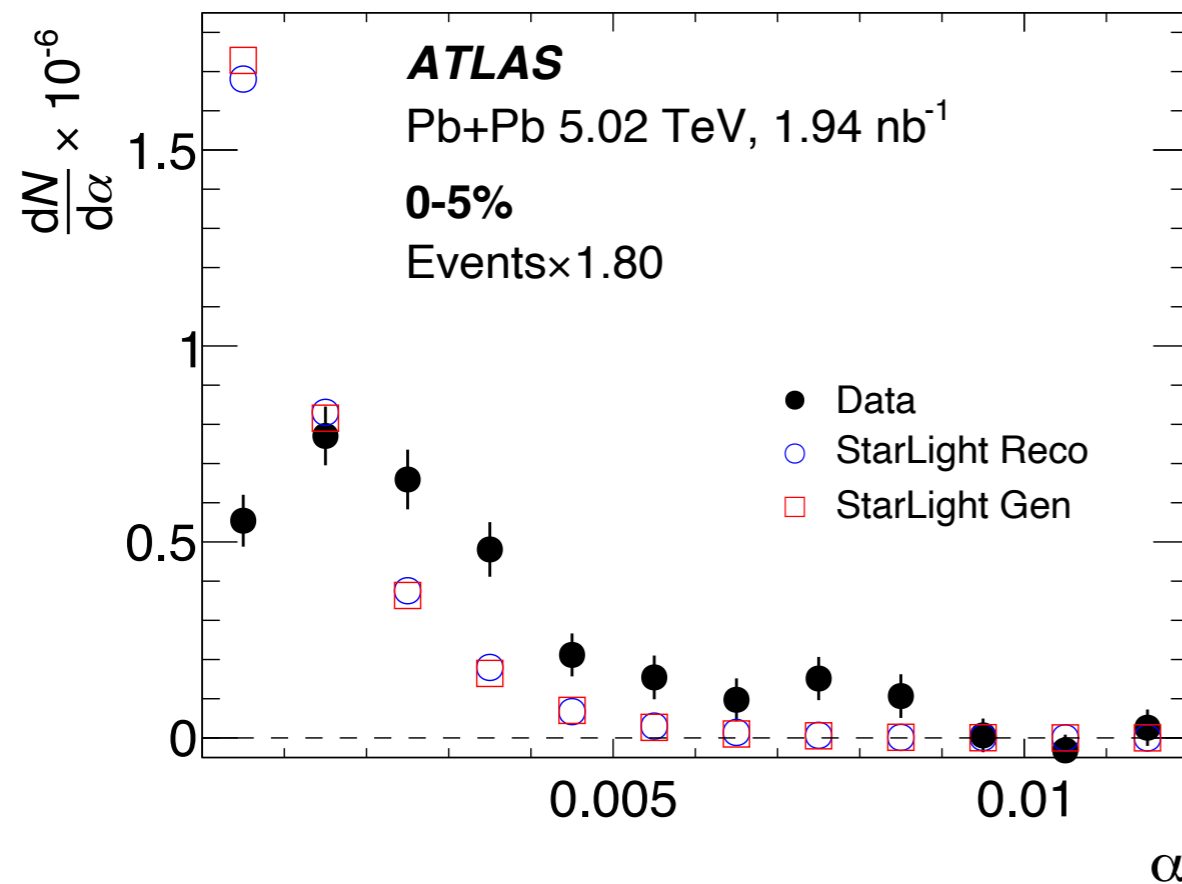
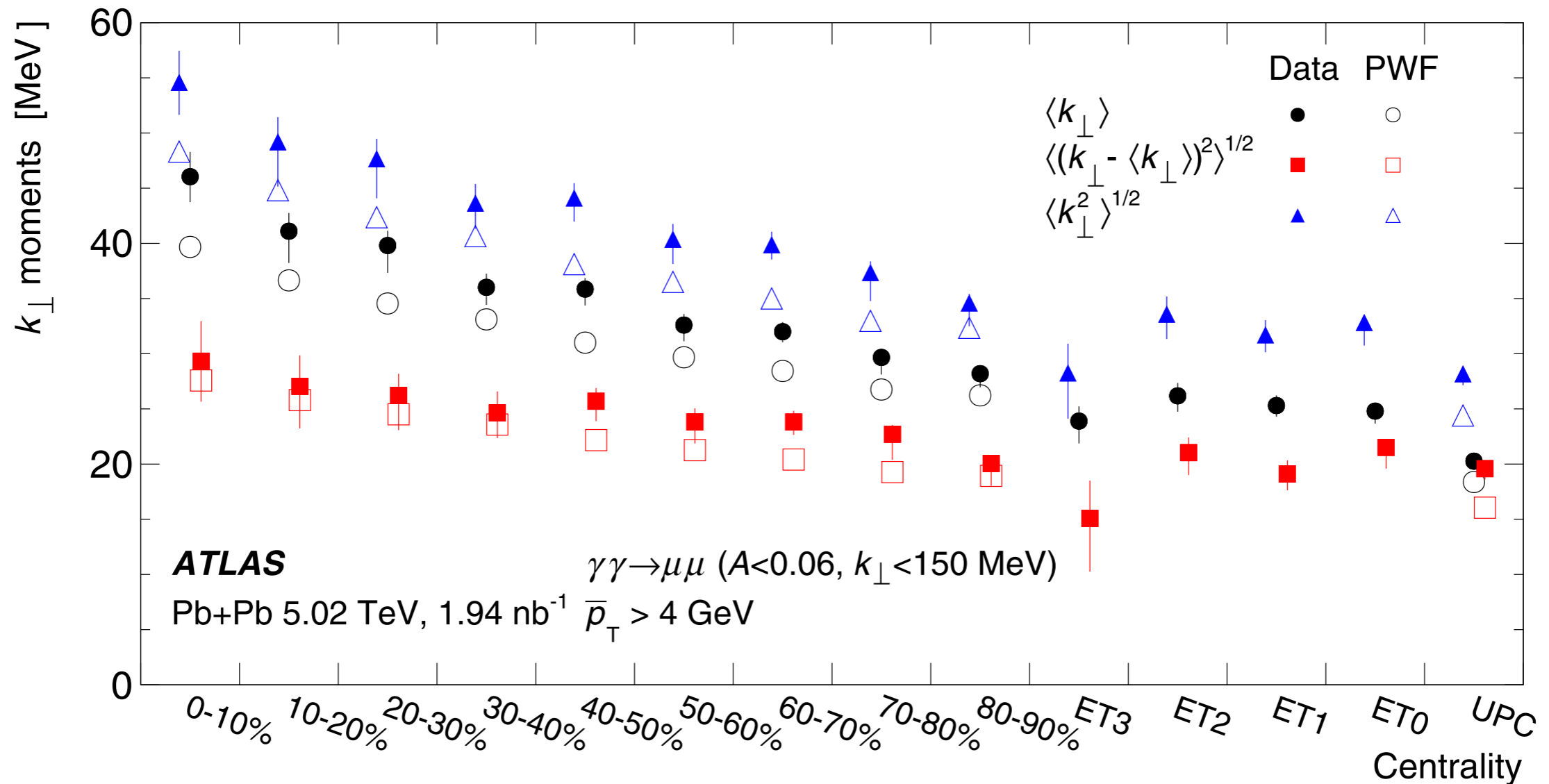After background subtraction (heavy flavor and Drell -Yan, both flat), broadening studied in both variables.

In more central events, angular variables are visibly broader than the distributions observed in standard UPC events, with a significant <u>dip</u> near zero

$k_\perp$ better behaved than α, with no dependence on muon p_T
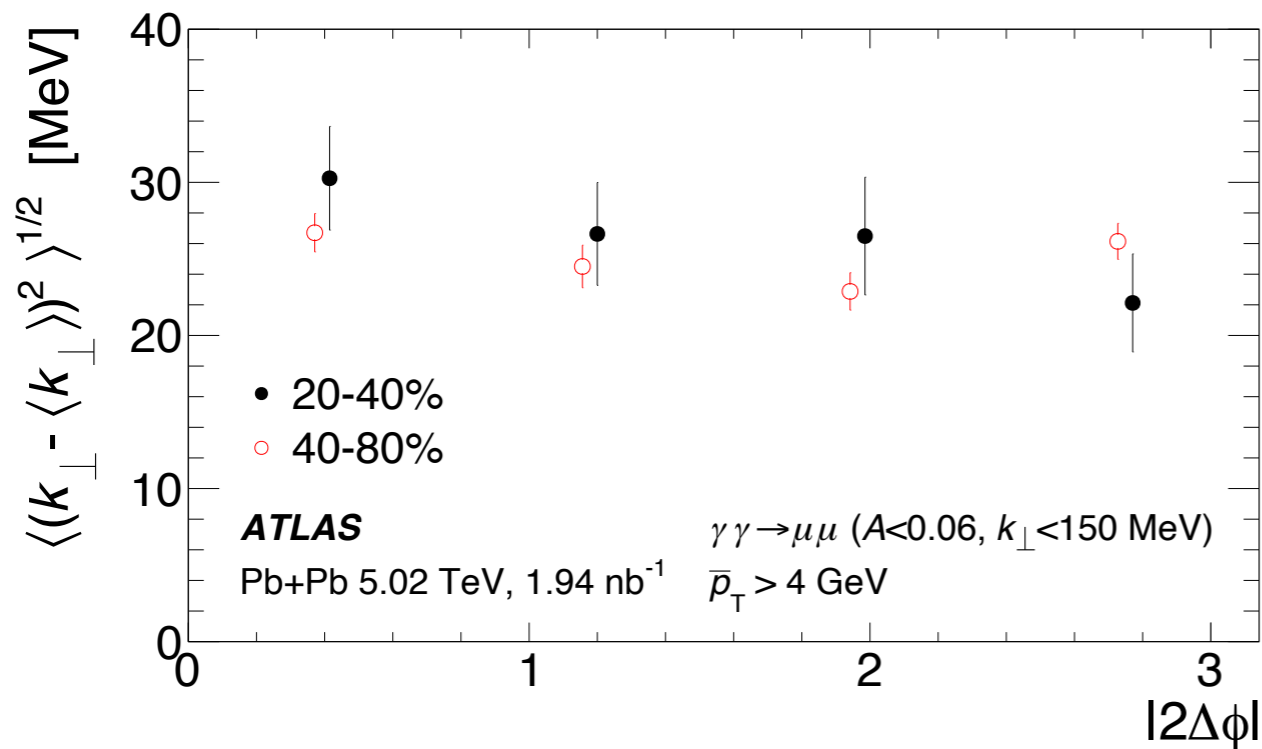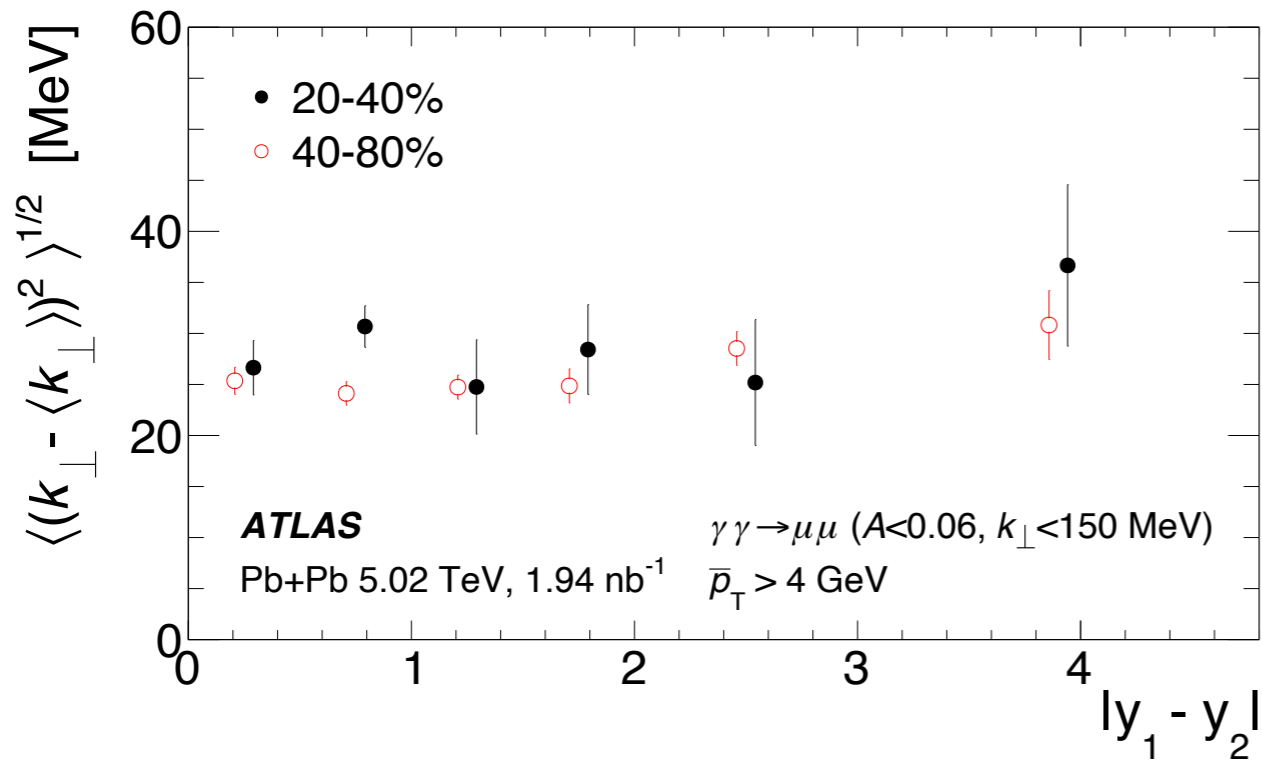
Centrality evolution

Model independent way to show evolution in α and k_T

k_T shown here, calculated from distributions prior to background subtraction and then corrected by an analytic expression

Even ET0 is increased relative to UPC, and increases with decreasing centrality, but data consistently exceeds PWF calculation (similar conclusions for α vs. PWF & QED)

Probing initial magnetic fields

ATLAS
Pb+Pb 5.02 TeV, 1.94 nb^{-1} $\gamma\gamma \to \mu\mu$ ($A < 0.06$, $k_\perp < 150$ MeV) $\bar{p}_T > 4$ GeV

- 20-40%
- 40-80%

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

> B-fields lead to tanh(Δy) behavior (Klein et al)
>
> B fields follow impact parameter vector, so may show $2(\phi_{\mu\mu} - \psi_2)$ dep.
>
> $$\phi_{\mu\mu} = \tfrac{1}{2}(\phi_1 + \pi + \phi_2)$$

Current data show 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, probe the geometric aspects of fluxes

- **Cross sections sections for UPC μμ (2021) and ee (just published!)**
  - Systematic studies of the calculations show broad agreement with data, but non-trivial differences
  - ZDC selections study "centrality dependence"

- **Tau lepton g-2 studied with 3 decay channels**
  - Limit after Run 2 already competitive with existing LEP2 limits

- **Non-UPC interactions provide a fascinating laboratory for QED calculations and a possible testing ground for effects associated with strong magnetic fields**
  - Non-trivial interference effects leading to "dips" at low α and k_T
  - Described well with QED calculations, but with no evidence for strong initial magnetic fields