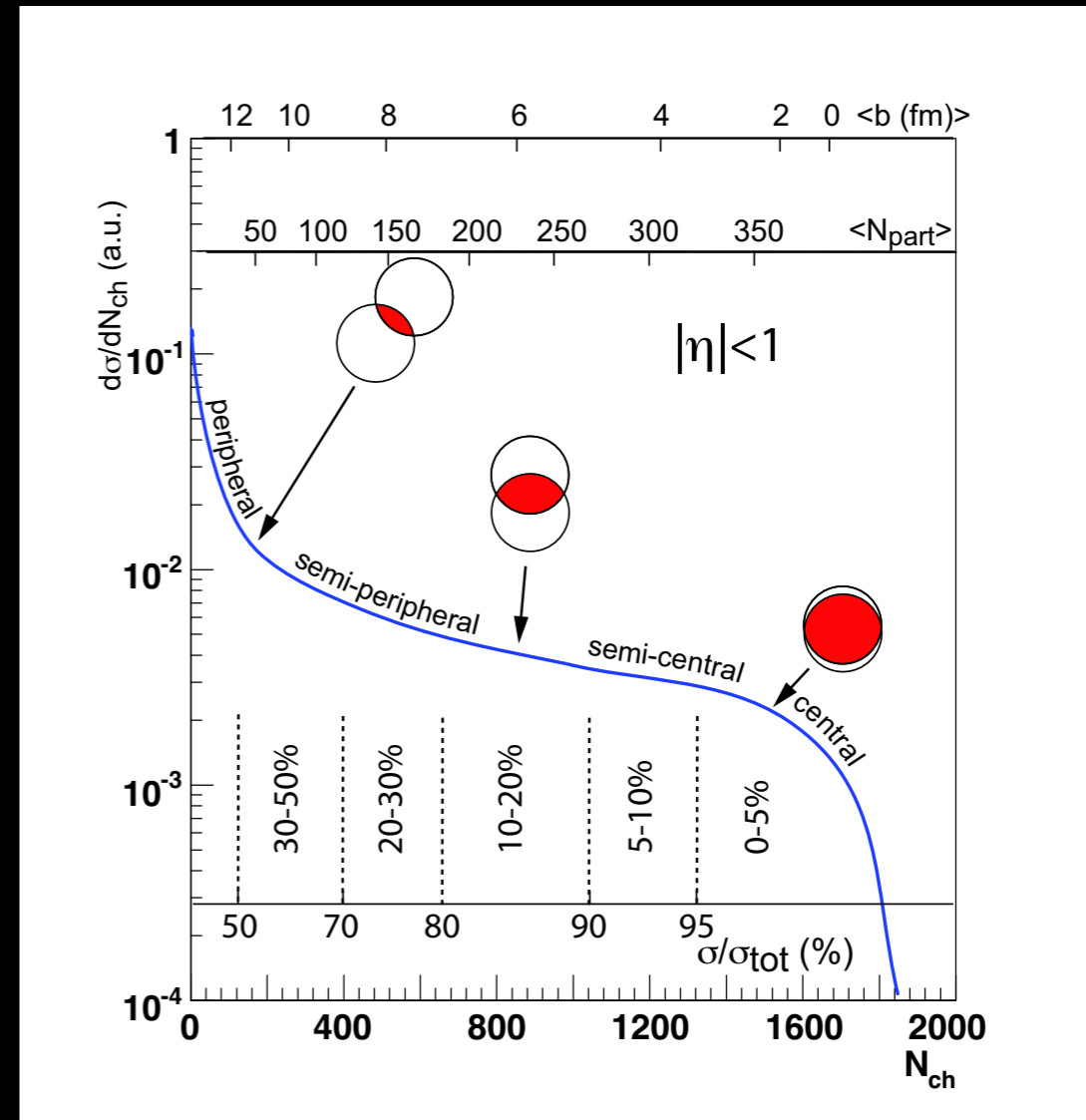
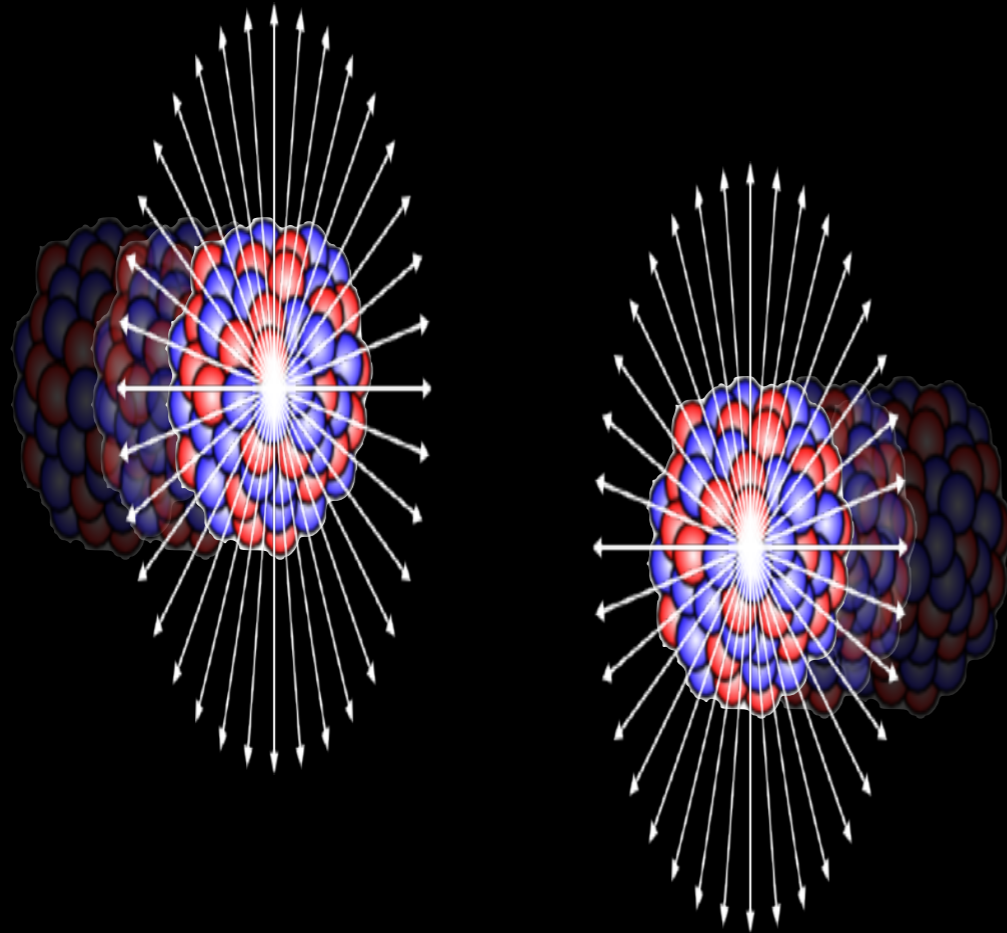


Dilepton production from $\gamma\gamma$ fusion in hadronic Pb+Pb collisions with ATLAS



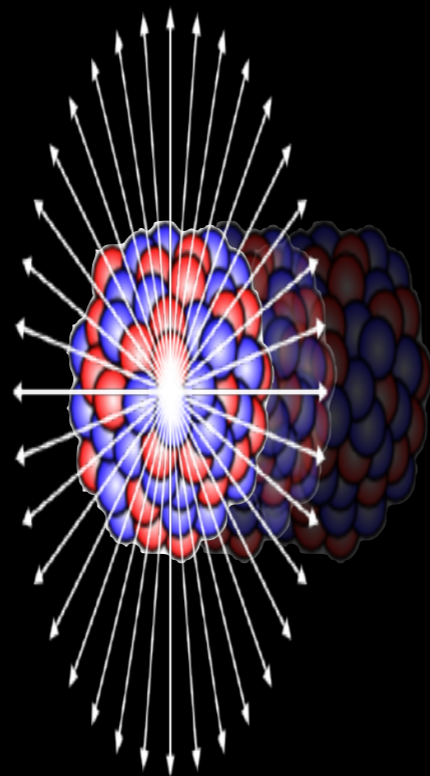
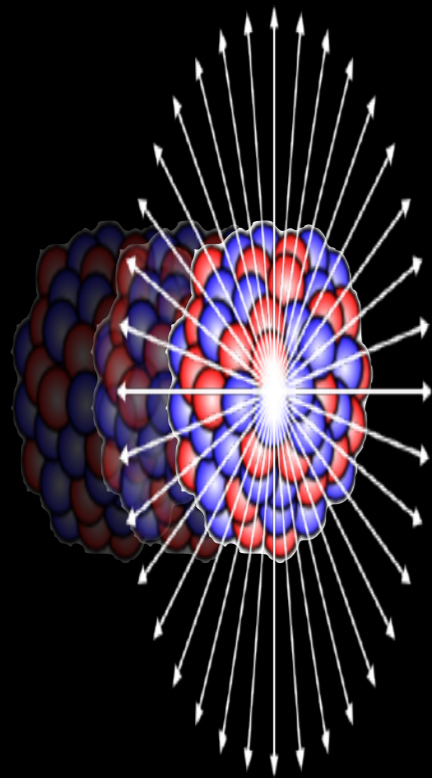
Peter Steinberg, BNL for the ATLAS Collaboration
IS 2023 / 19-24 June 2023





In hadronic HI collisions, particle production follows the geometry of each collision:
the closer together the ions are (smaller b), the more produced particles

Soft processes $\sim N_{\text{part}}$ (participants), hard processes $\sim N_{\text{coll}}$ (binary collisions)



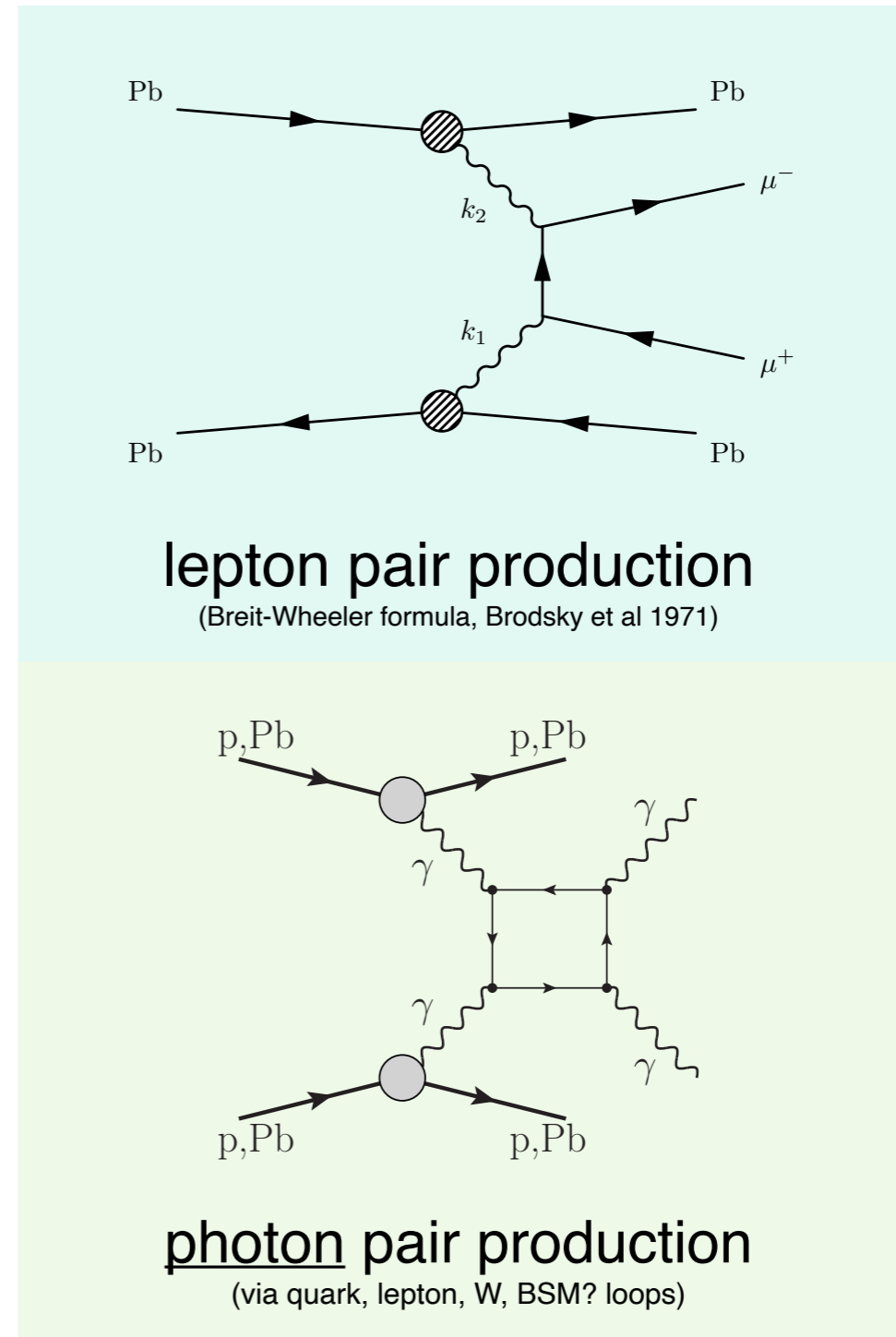
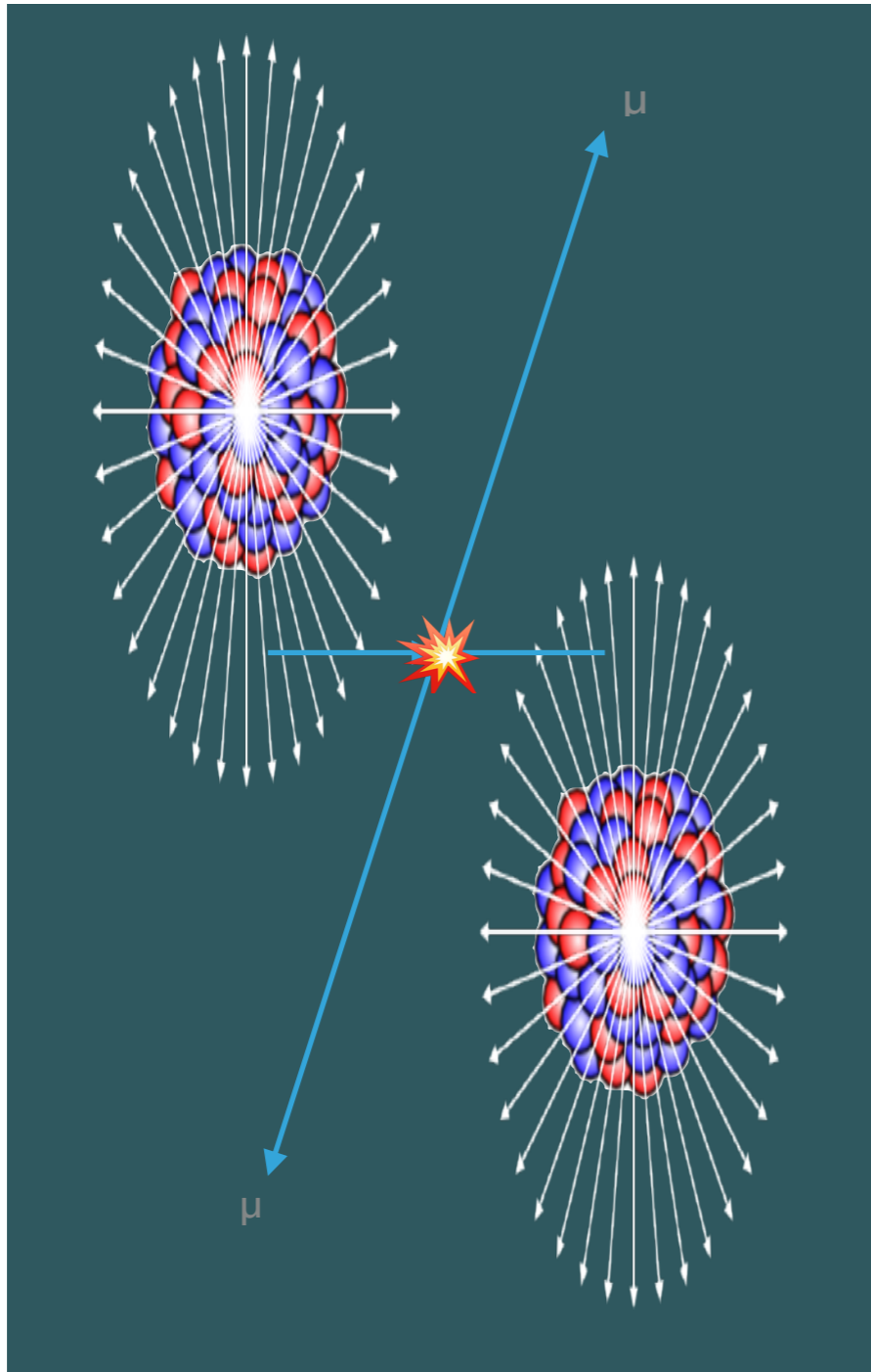
Stripped nuclei have very strong EM fields
($B \sim 10^{15}$ T!)

Z=82 packed into a subatomic volume traveling ultra relativistic speeds (Lorentz contracted)!

Classical fields can be understood as a source of nearly-real high energy photons!

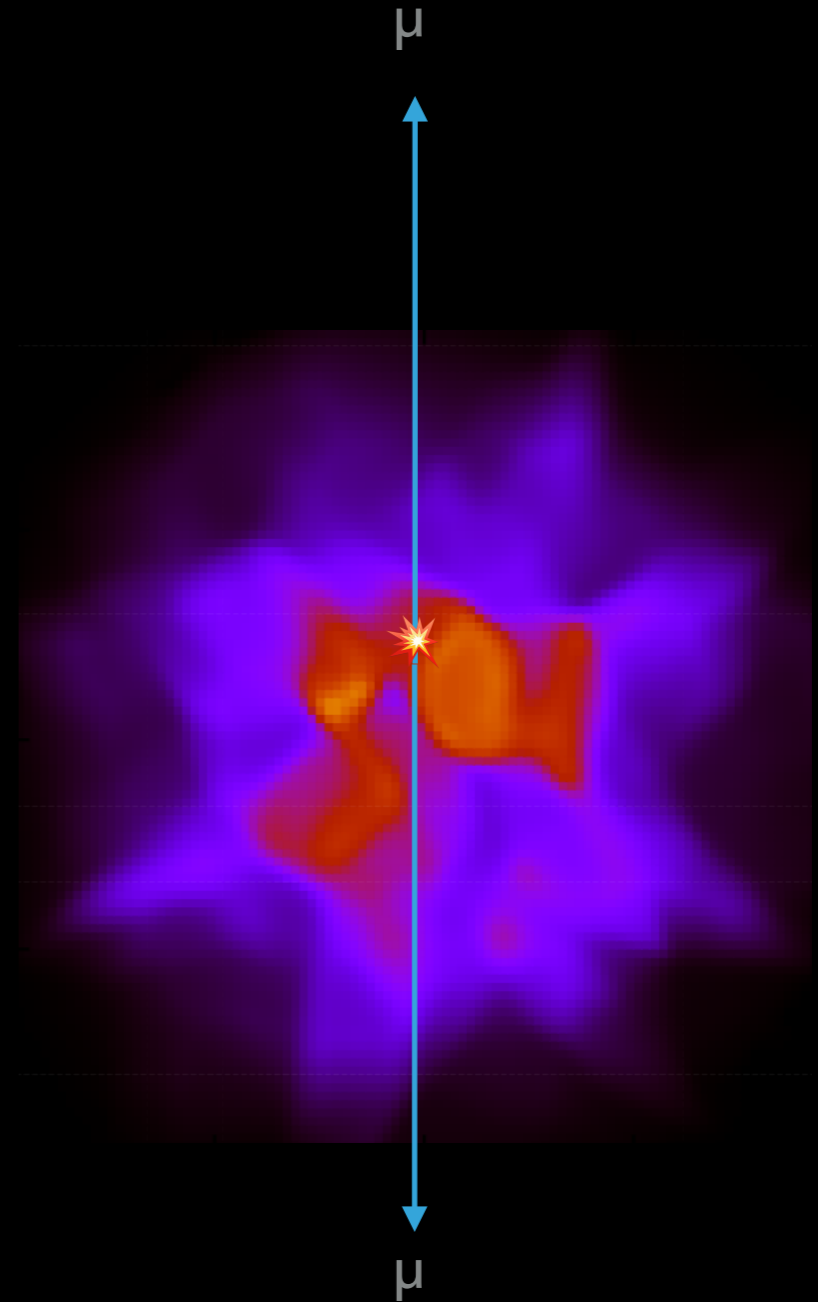
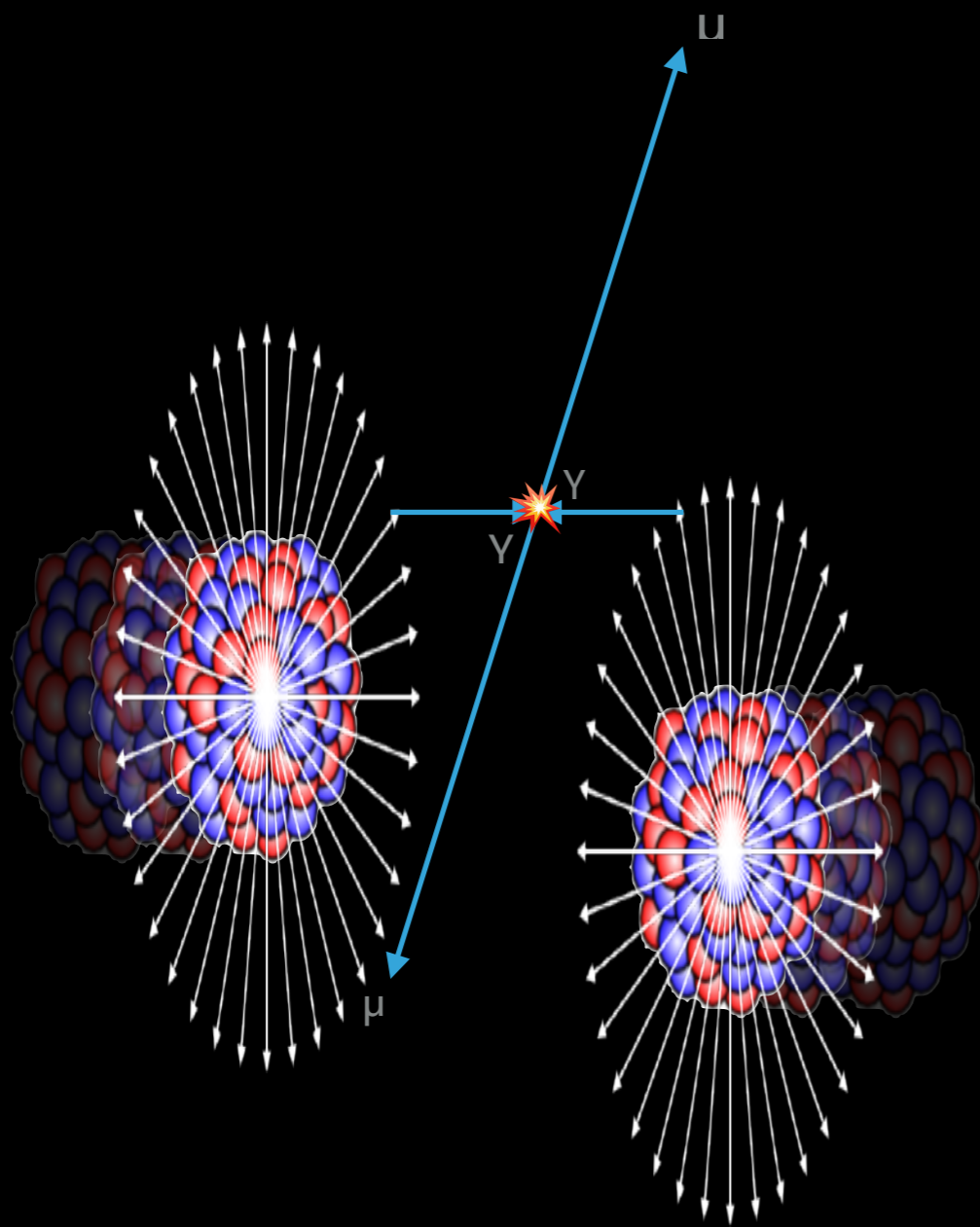
A powerful QCD laboratory is also a powerful QED laboratory!

Exclusive $\gamma\gamma$ processes



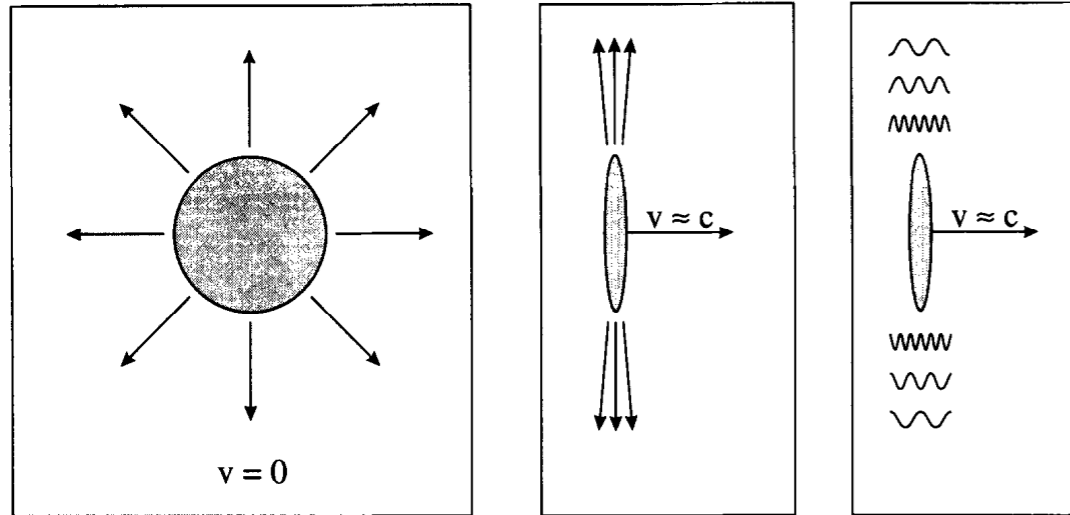
Heavy ion collisions are excellent QED & BSM laboratories!

Exclusive $\gamma\gamma$ processes in nonUPC



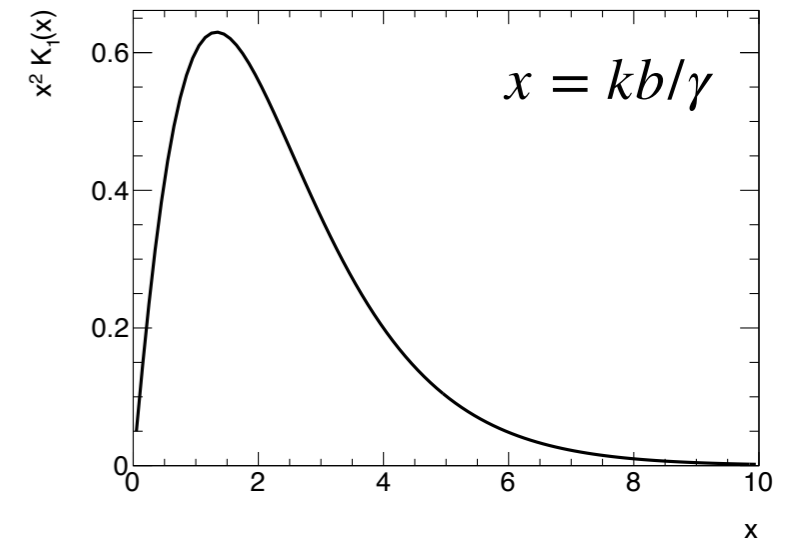
- **Even as the nuclei overlap, one can still expect to observe dileptons from gamma-gamma processes**
 - Can they resolve any aspects of the QGP evolution or initial B fields?

Impact parameter of photon flux



For a point charge:

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



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:

SciPost Phys. 11, 064 (2021)

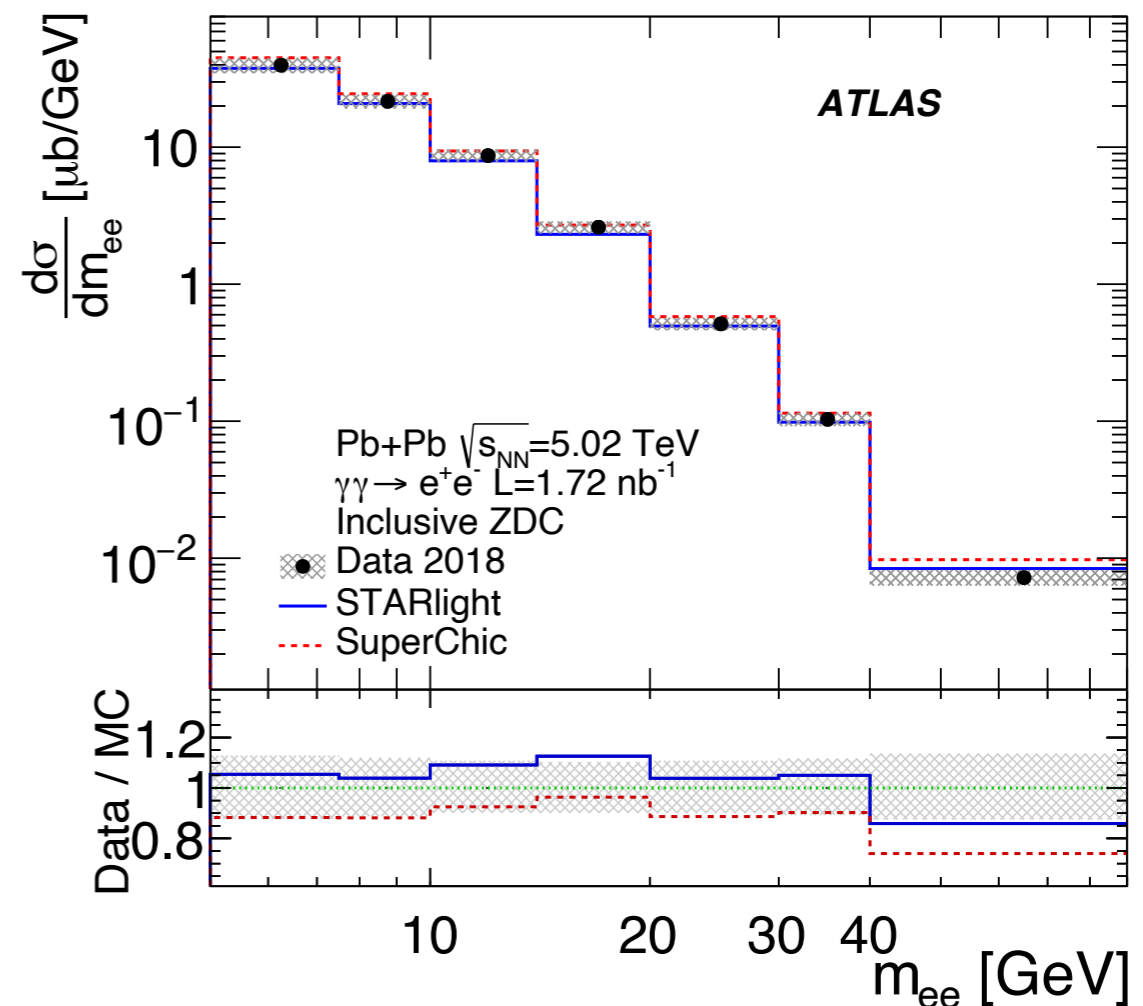
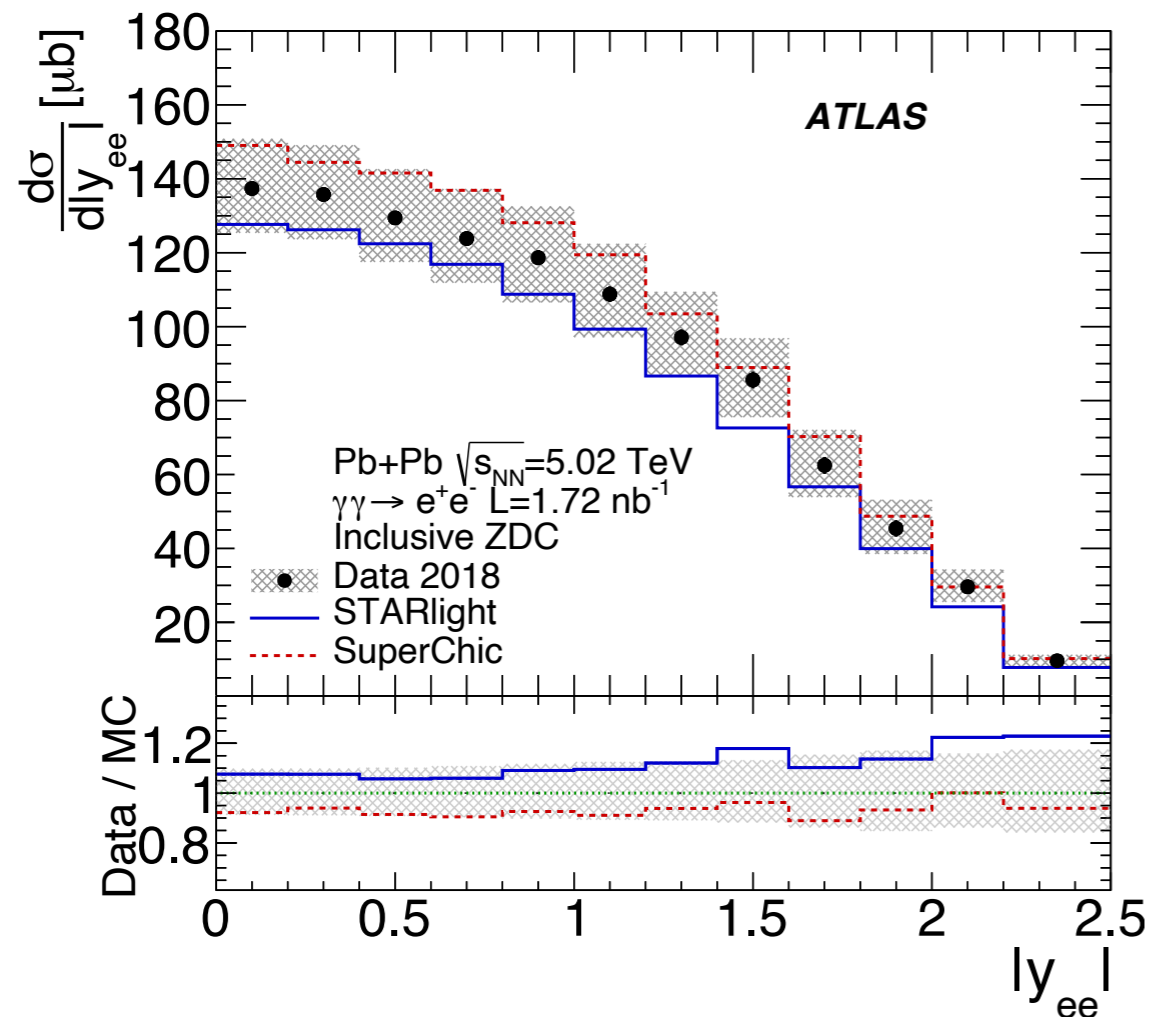
$$\sigma_{N_1 N_2 \rightarrow N_1 X N_2} = \int dx_1 dx_2 n(x_1) n(x_2) \hat{\sigma}_{\gamma\gamma \rightarrow X} \quad \text{no radial cutoffs!}$$

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

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

UPC dileptons: rapidity and mass

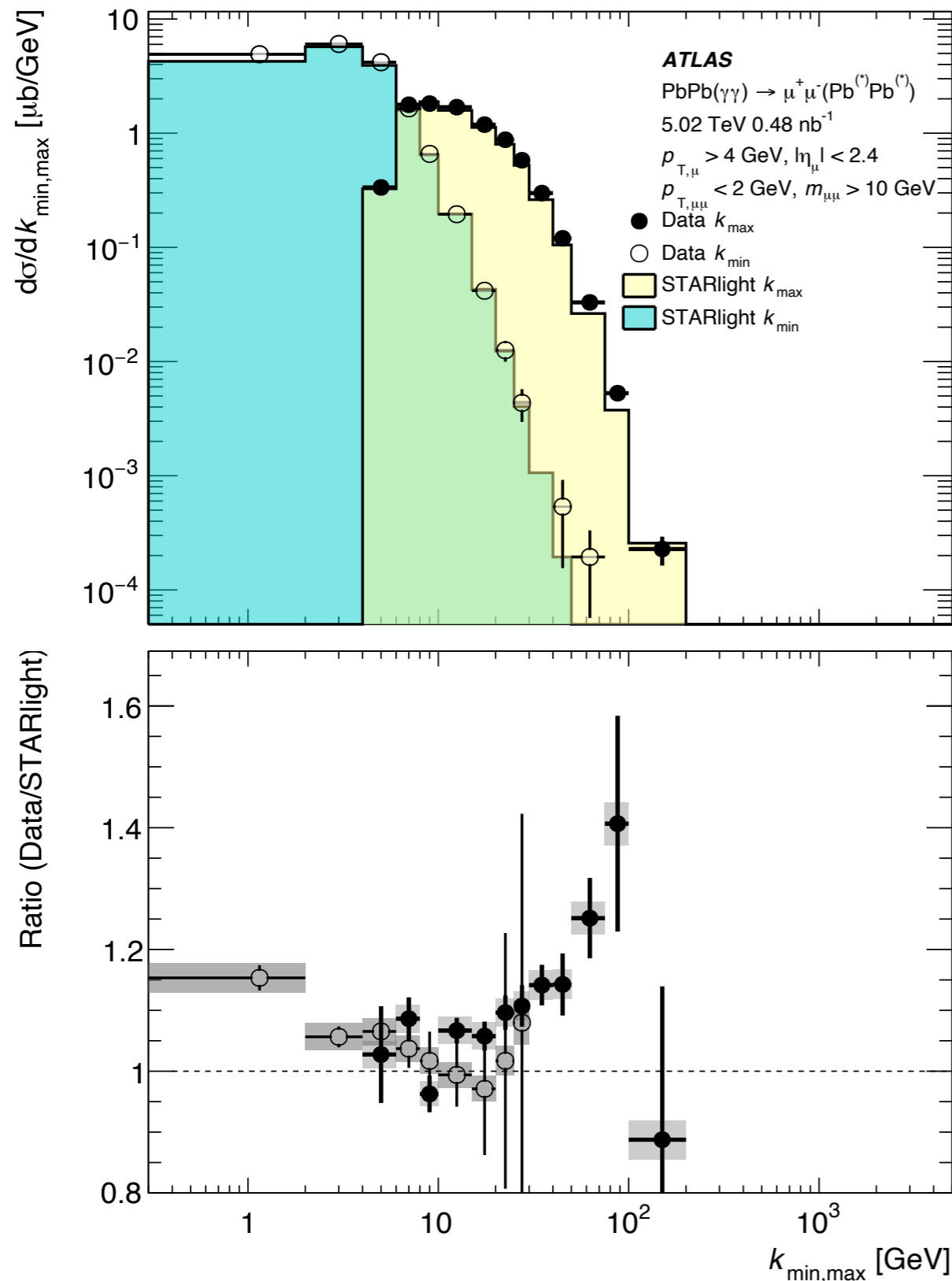
$$p_{Te} > 2.5 \text{ GeV}, |\eta_e| < 2.47, m_{ee} > 5 \text{ GeV}, p_{Tee} < 2 \text{ GeV}$$



Dielectron cross sections have systematically disagree with STARLIGHT: similar spectral shape in mass, but steady rise with $|y_{ee}|$.

SuperChic describes shape of distribution better, but overpredicts data (perhaps due to absence of HO contributions, e.g. Tang & Zha, *JHEP* 08 (2021) 083)

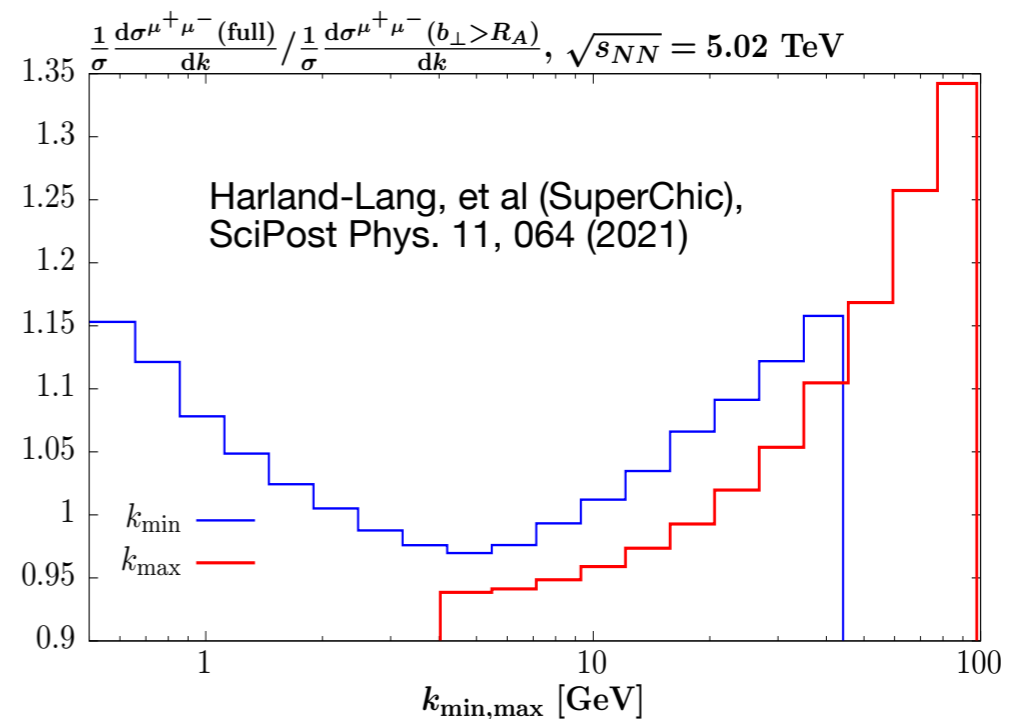
UPC dileptons: initial photon energy



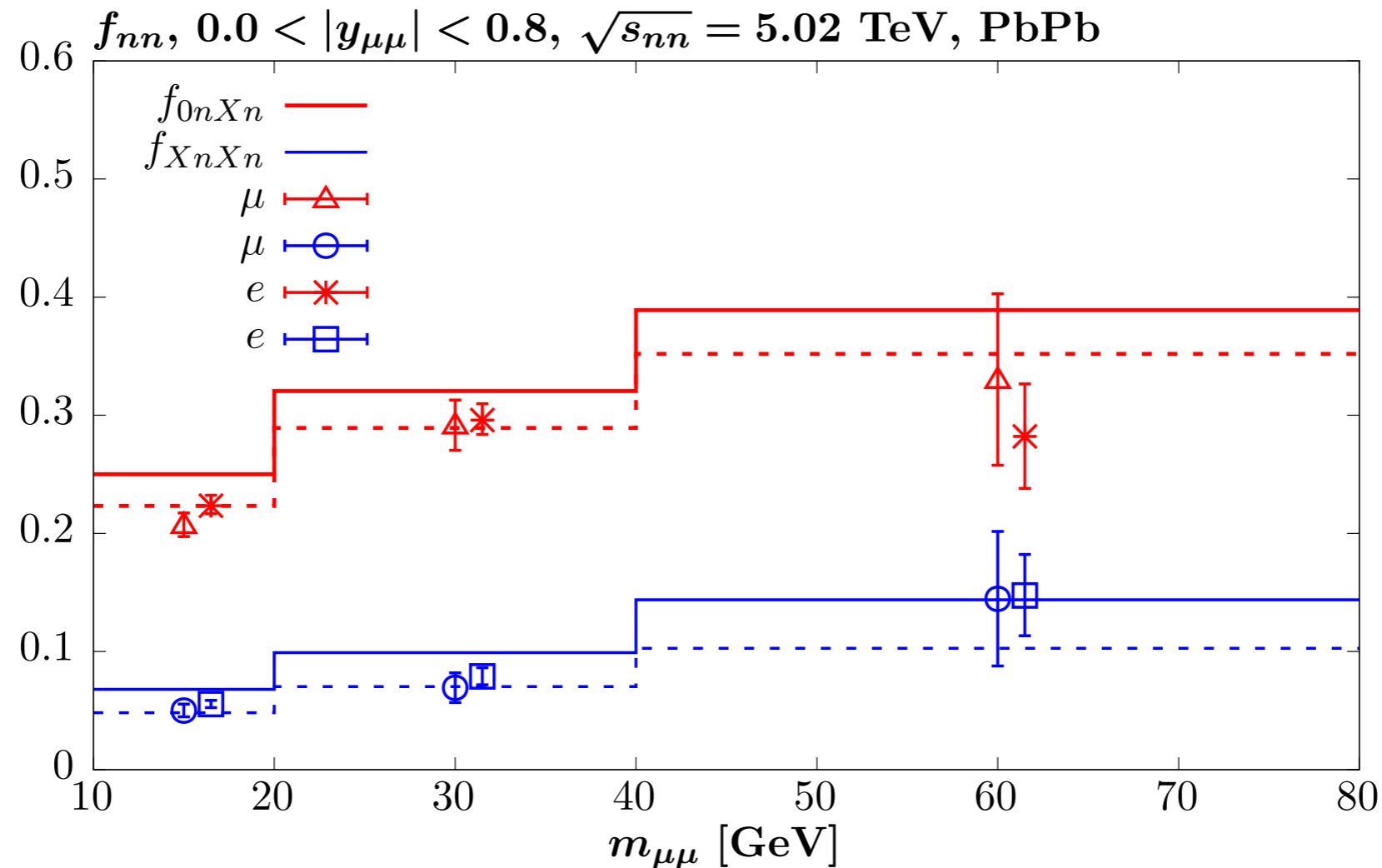
Can combine $m_{\mu\mu}$ and $y_{\mu\mu}$ to estimate photon energies

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

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



ZDC selected event-fractions reflect impact parameter dependence of $n(k,b)$

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

nonUPC $\mu\mu$ 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

$$d_{0\text{pair}} \equiv \sqrt{d_{01}^2 + d_{02}^2},$$

- **HF rejection using transverse and longitudinal impact parameters**

- $d_{0\text{pair}} < 0.1$ mm, $(z_0 \sin \theta)_{\text{pair}} < 0.2$ mm

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

- **Pair variables reflecting transverse kicks** →

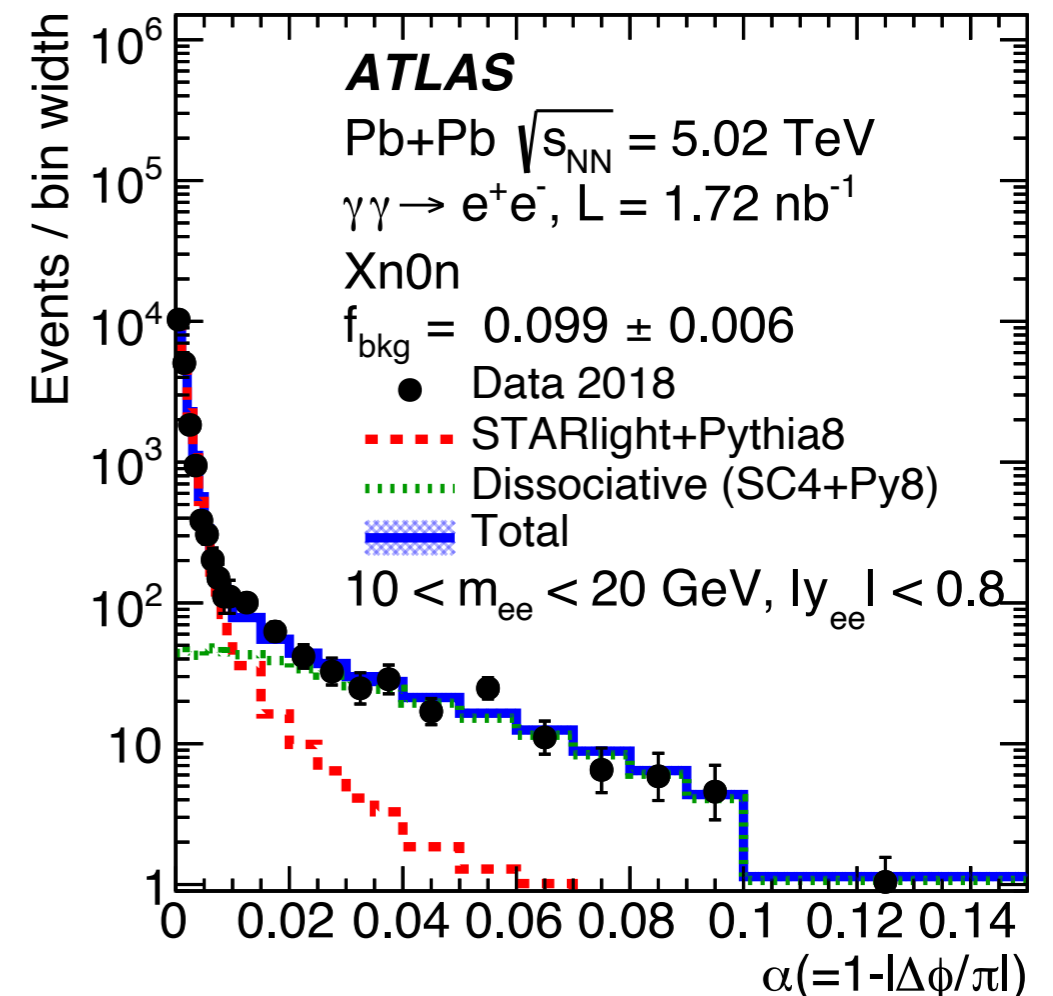
- **acoplanarity** $(\alpha = 1 - |\Delta\phi|/\pi)$
- **pair k_T** $= 0.5(p_{T1} + p_{T2})\pi\alpha$
- **pair momentum asymmetry** $A = |p_{T2} - p_{T1}|/(p_{T2} + p_{T1})$

- **Fiducial regions based on α or k_T**

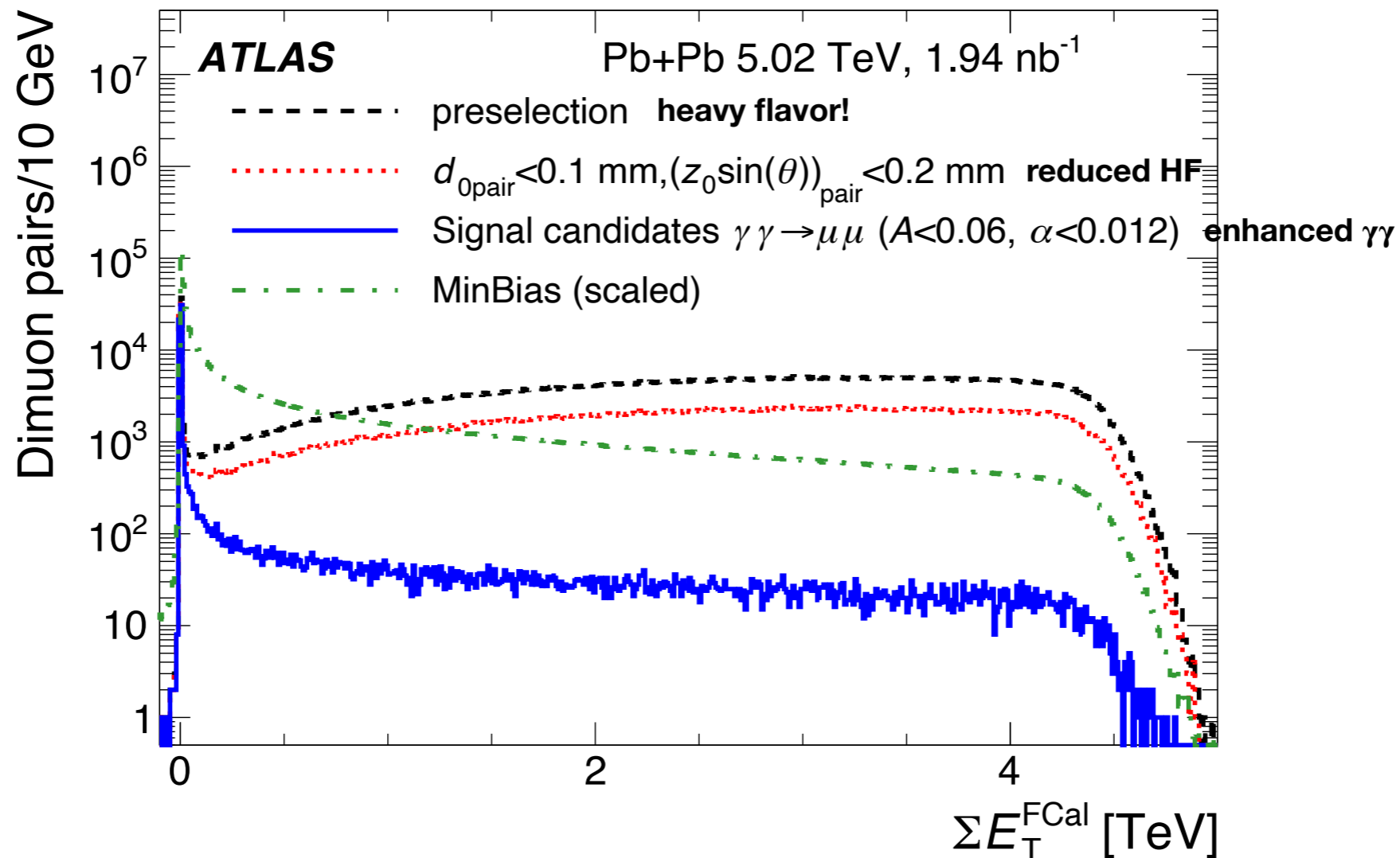
- “Fid- α ”: $A < 0.06$ & $\alpha < 0.012$ (69490 pairs)
- “Fid- k_T ”: $A < 0.06$ & $k_T < 150$ MeV (67789 pairs)

- **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



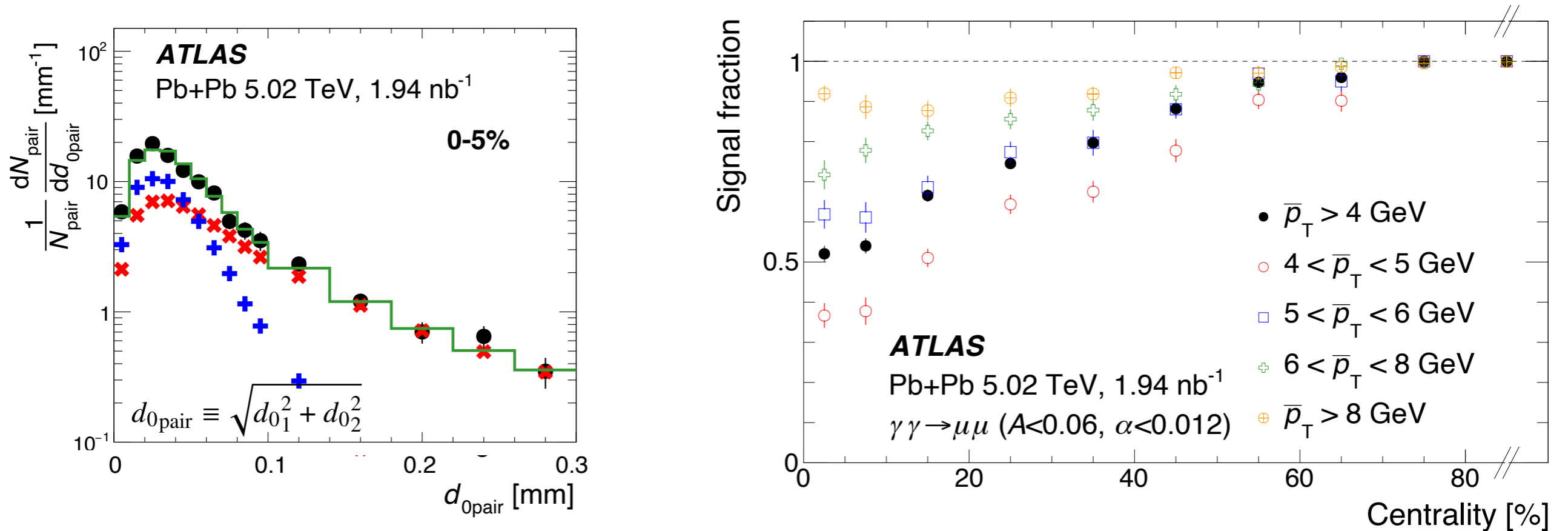
“Centrality” distribution for nonUPC $\mu\mu$



Distribution of forward transverse energy, which ATLAS uses to estimate per-event centrality

Two features: large UPC contribution near zero, and flat ΣE_T distribution, extending to central events - very different than expected for hard processes

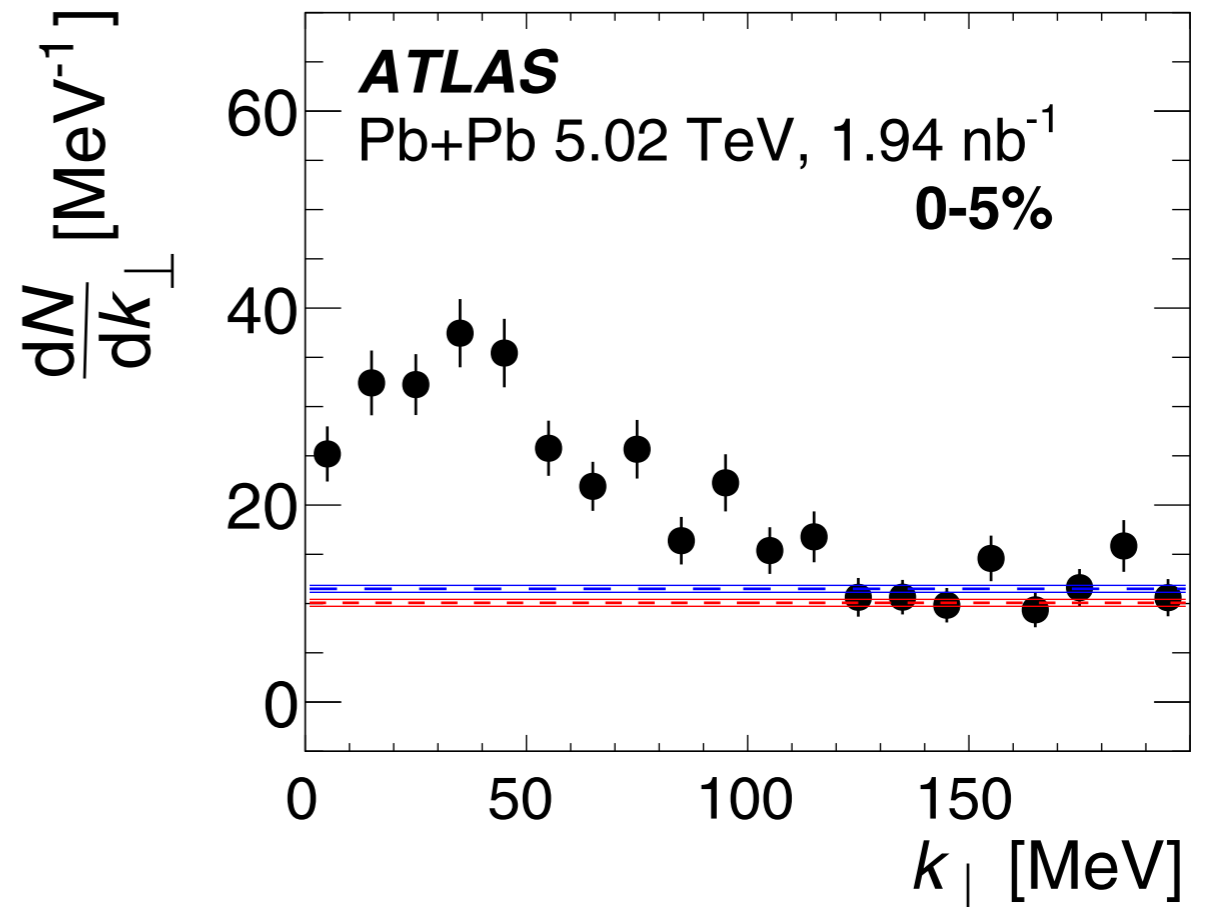
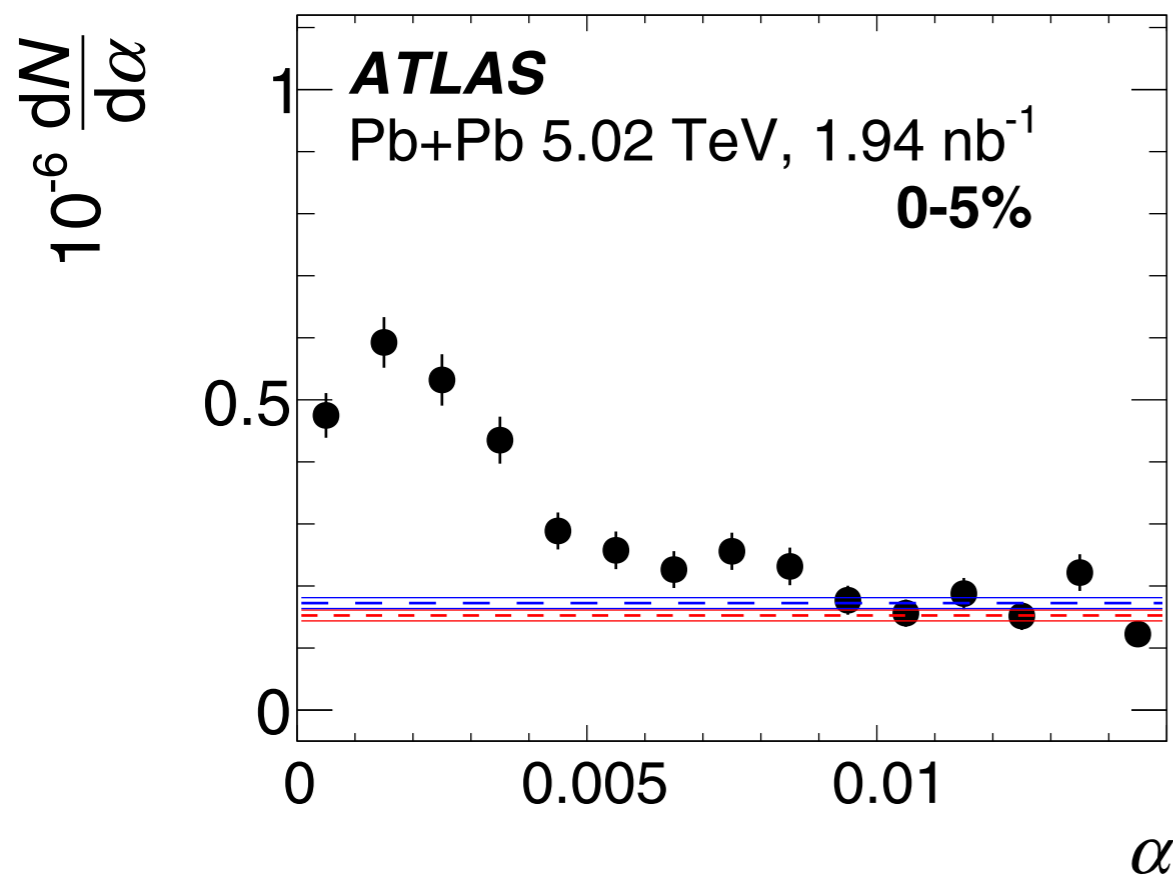
Signal extraction



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

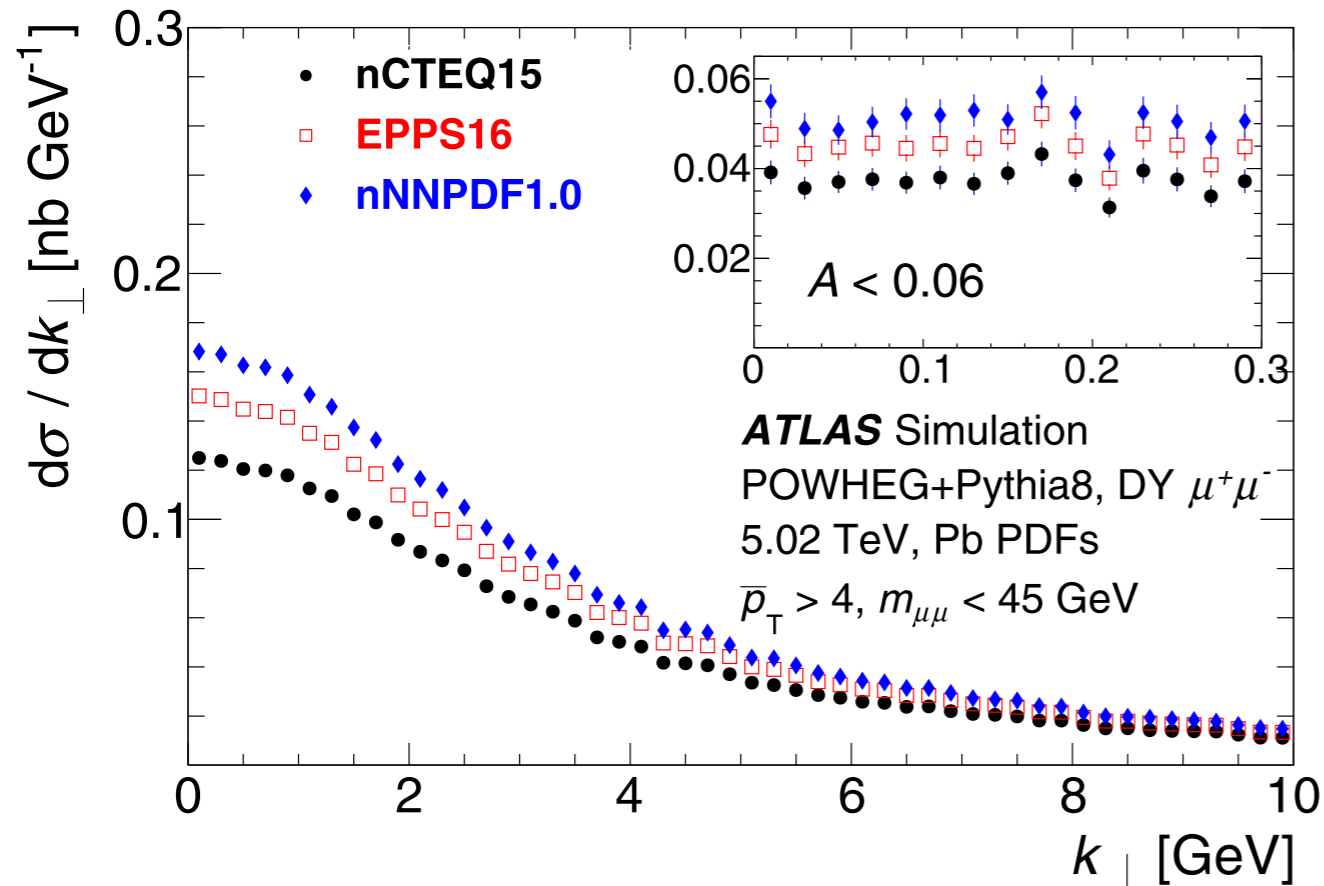
Background is negligible for very peripheral events, but is nearly half the yield in central events!

Background estimates & excess



Background estimate from template fits describe most of observed backgrounds, but there is a centrality dependent excess, observable by fitting the distributions by a constant at large (“asymptotic”) α and k_{\perp}

Drell-Yan contributions



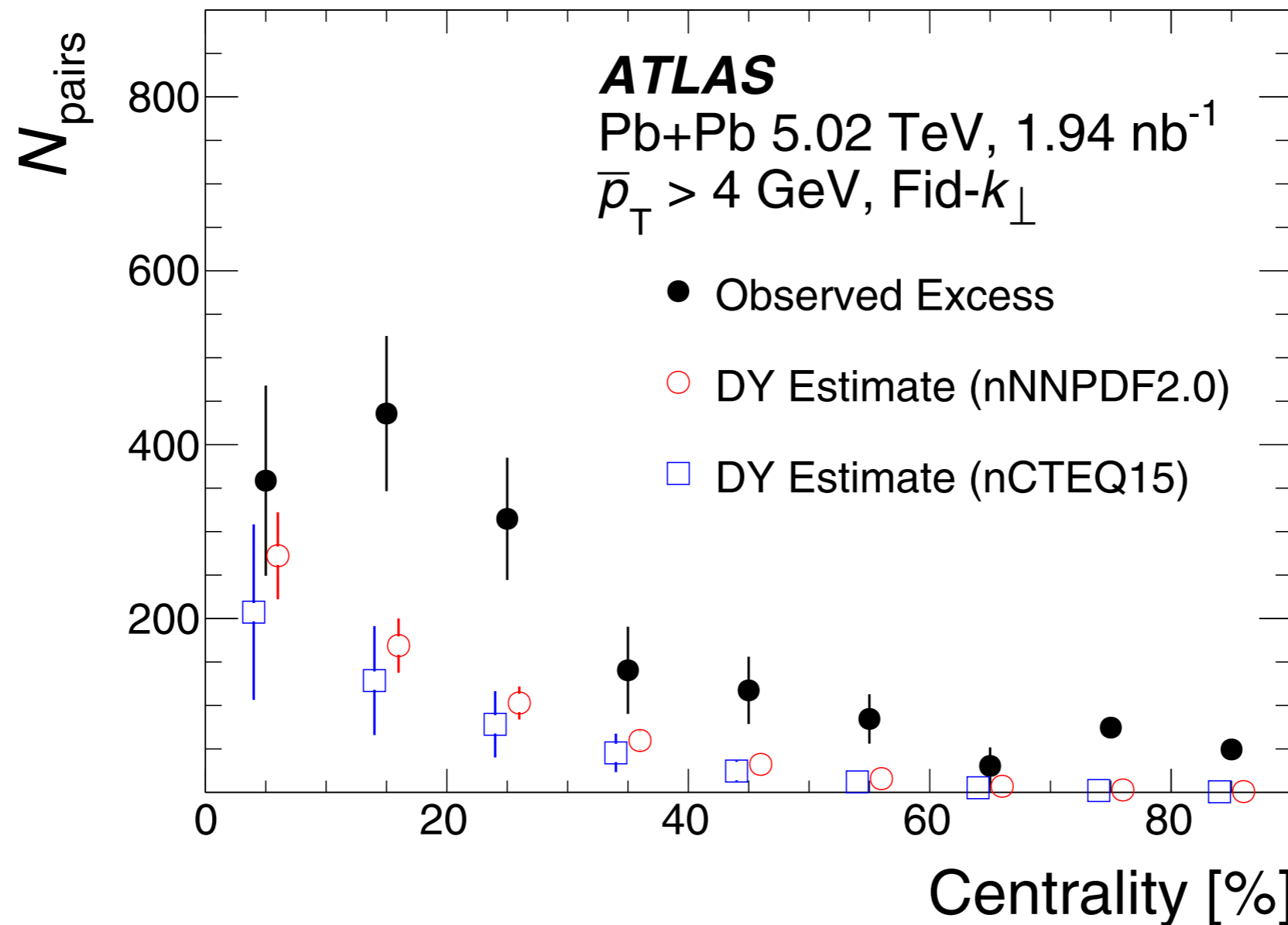
Drell-Yan dimuons result from scattering of quarks and anti-quarks typically with low- x , so sensitive to nuclear shadowing.

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 approximately flat

PDF set	$\sigma_{\text{DY,NN}}^{\text{Fid-}\alpha}$ (pb)	$\sigma_{\text{DY,NN}}^{\text{Fid-}k_{\perp}}$ (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

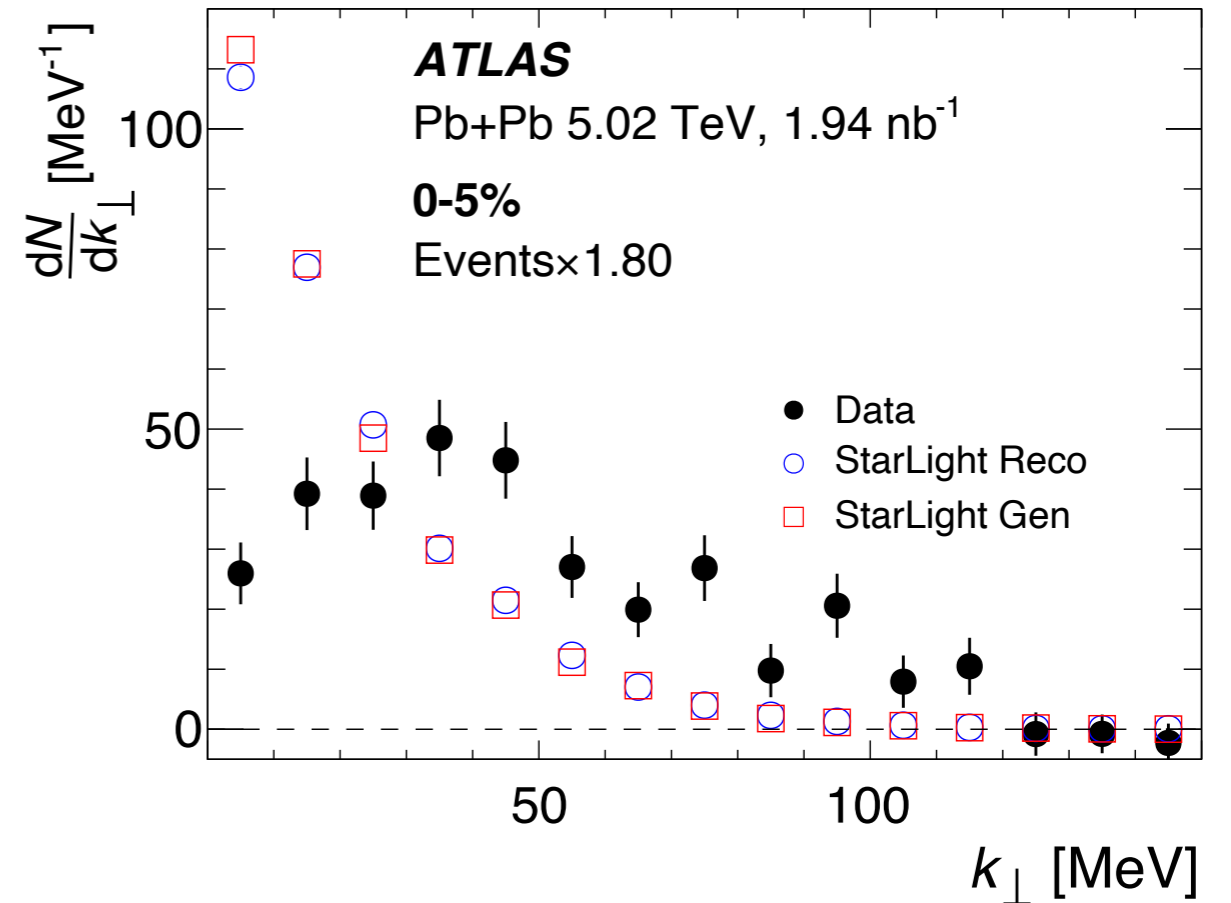
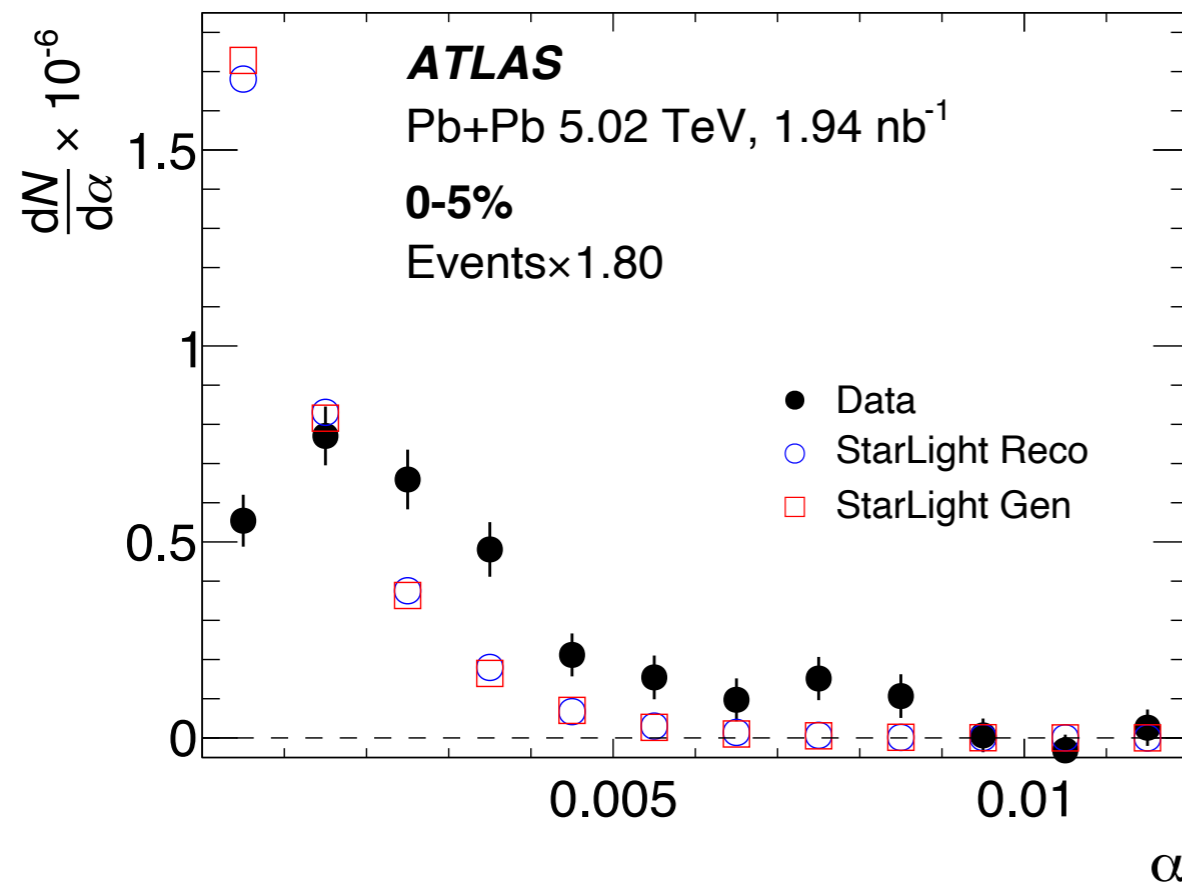
Drell-Yan corrections



Observed excess has similar centrality dependence as DY estimates,
but excess remains after subtraction, for both α and k_T

Inconsistent with dissociative contributions (similar rapidity distributions at low and high k_T), so treated as systematic uncertainty

Signal distributions

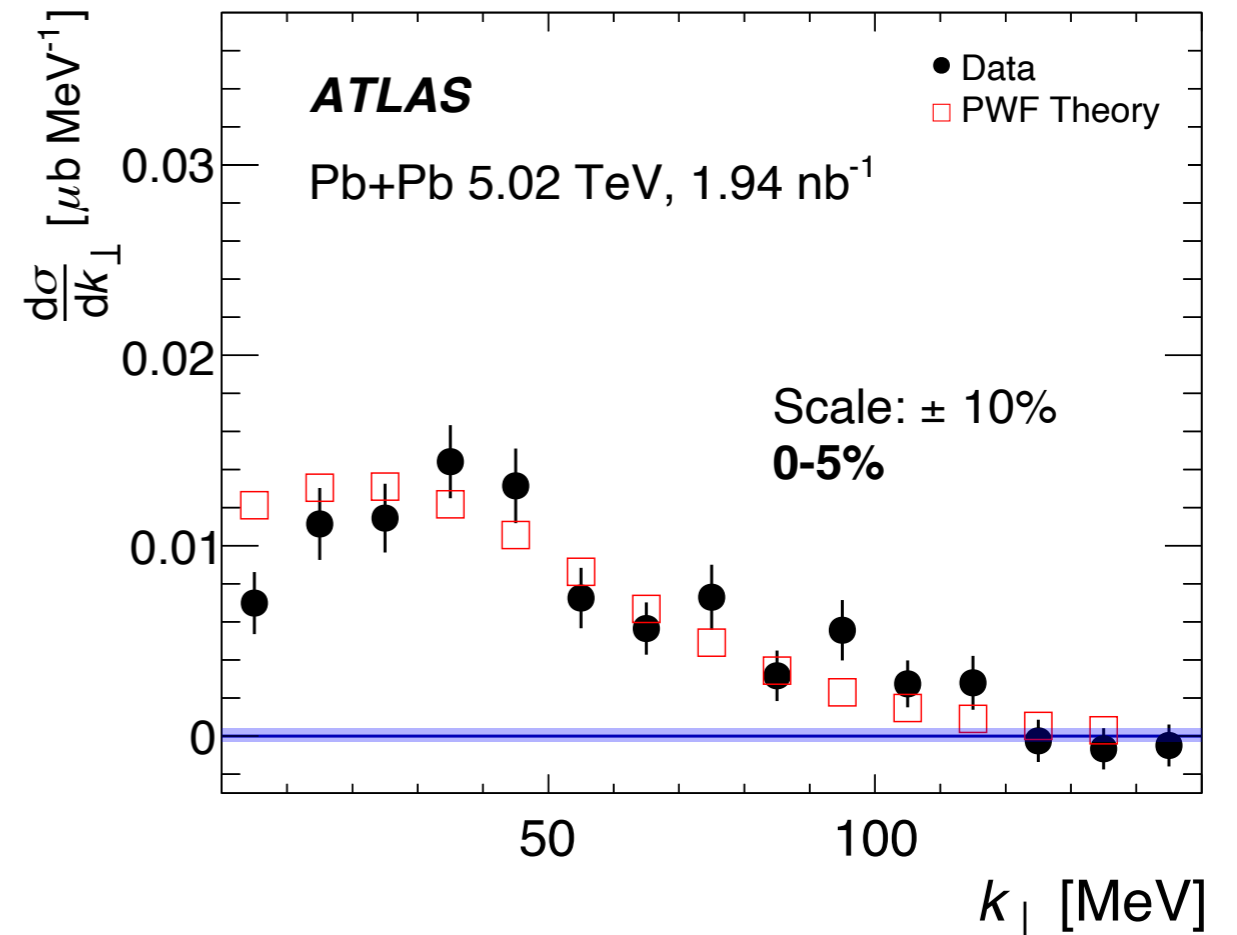
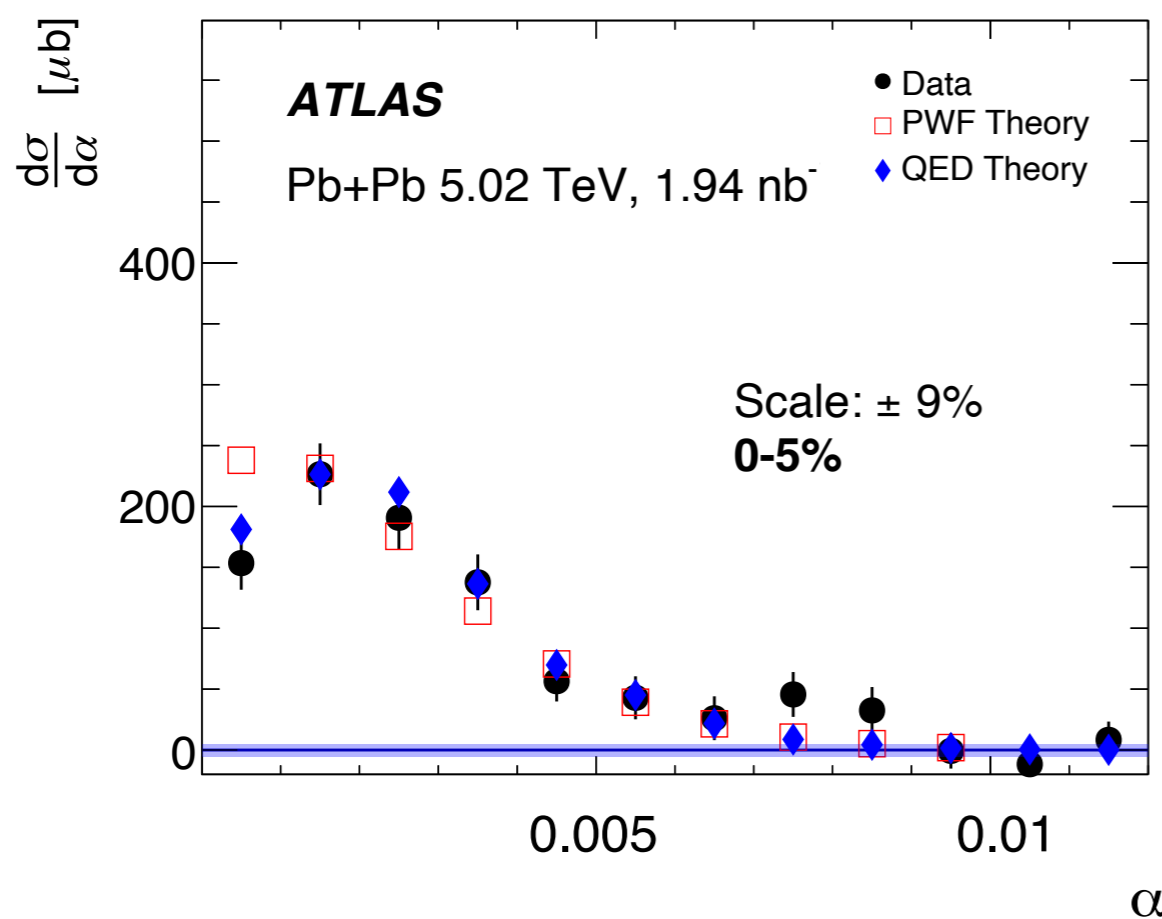


After background subtraction (heavy flavor using templates, and Drell -Yan), broadening studied in both variables.

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

k_{\perp} better behaved than α , with no dependence on muon p_T

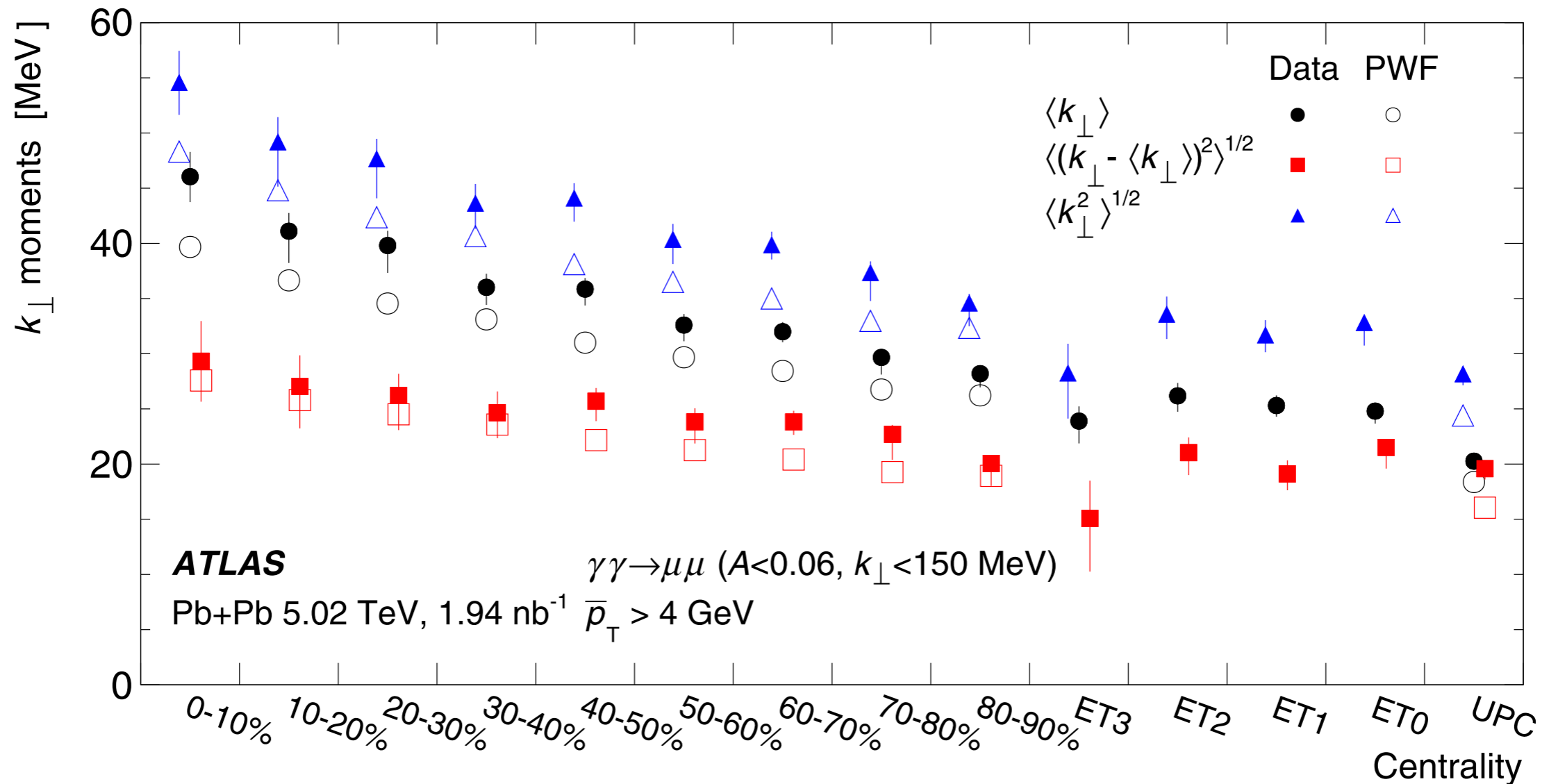
Theory comparisons



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)*
 - **does not capture dip feature!**
- *QED calculations based on generalized EPA (Zha et al)*
 - **surprisingly good description of dip**

Centrality evolution

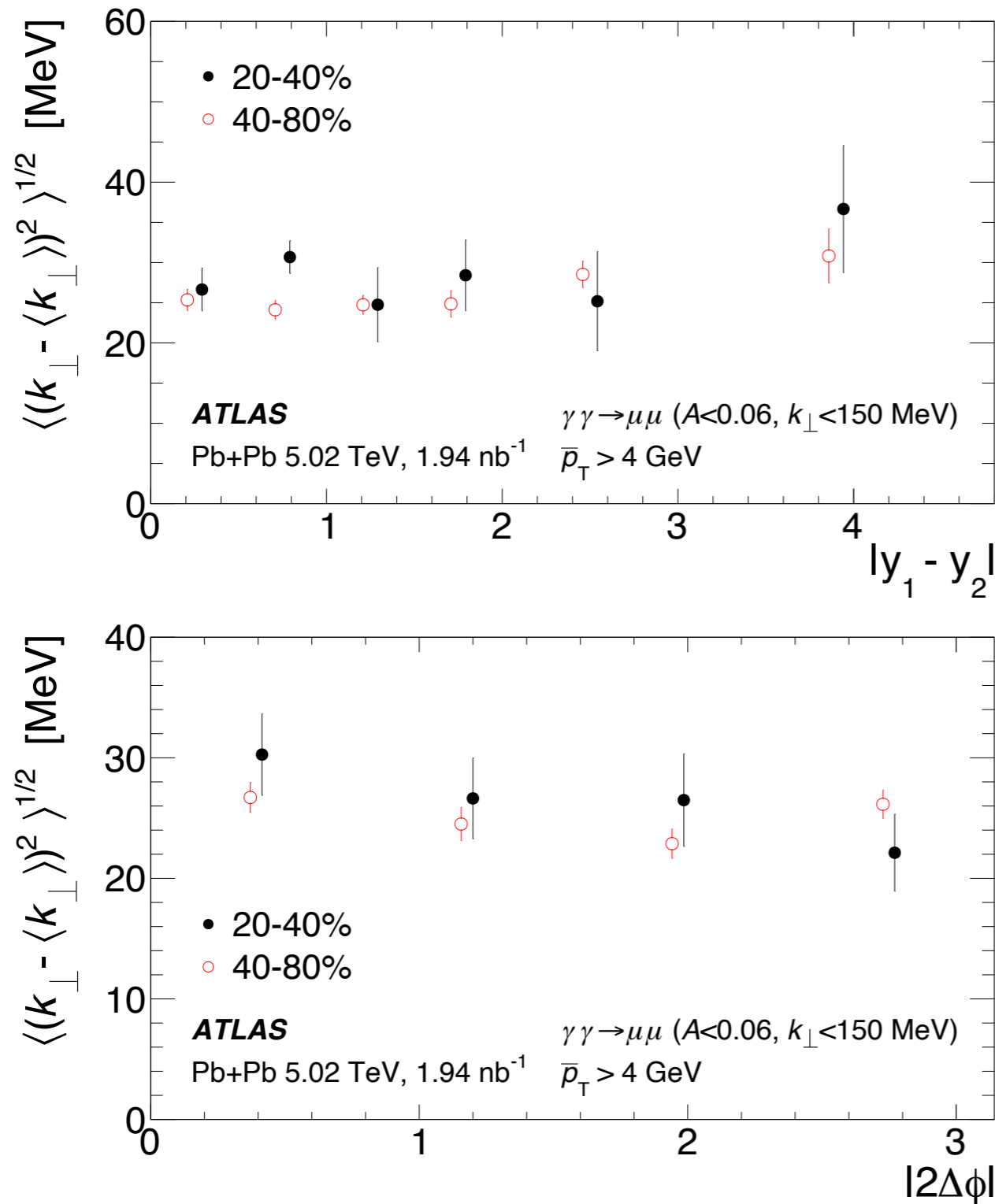


Model independent way to show evolution in α and k_T

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



B-fields lead to $\tanh(\Delta y)$ behavior (Klein et al)

B fields follow impact parameter vector, so may show $2(\phi_{\mu\mu} - \psi_2)$ dep. $\phi_{\mu\mu} = \frac{1}{2}(\phi_1 + \pi + \phi_2)$

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

Current data show no $\tanh(\Delta y)$ 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 ZDC they probe impact parameter dependence of fluxes
- **Non-UPC interactions provide a fascinating laboratory for QED calculations and a possible testing ground for effects associated with strong magnetic fields**
 - New measurements shown here provide comprehensive study of their behavior
 - 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