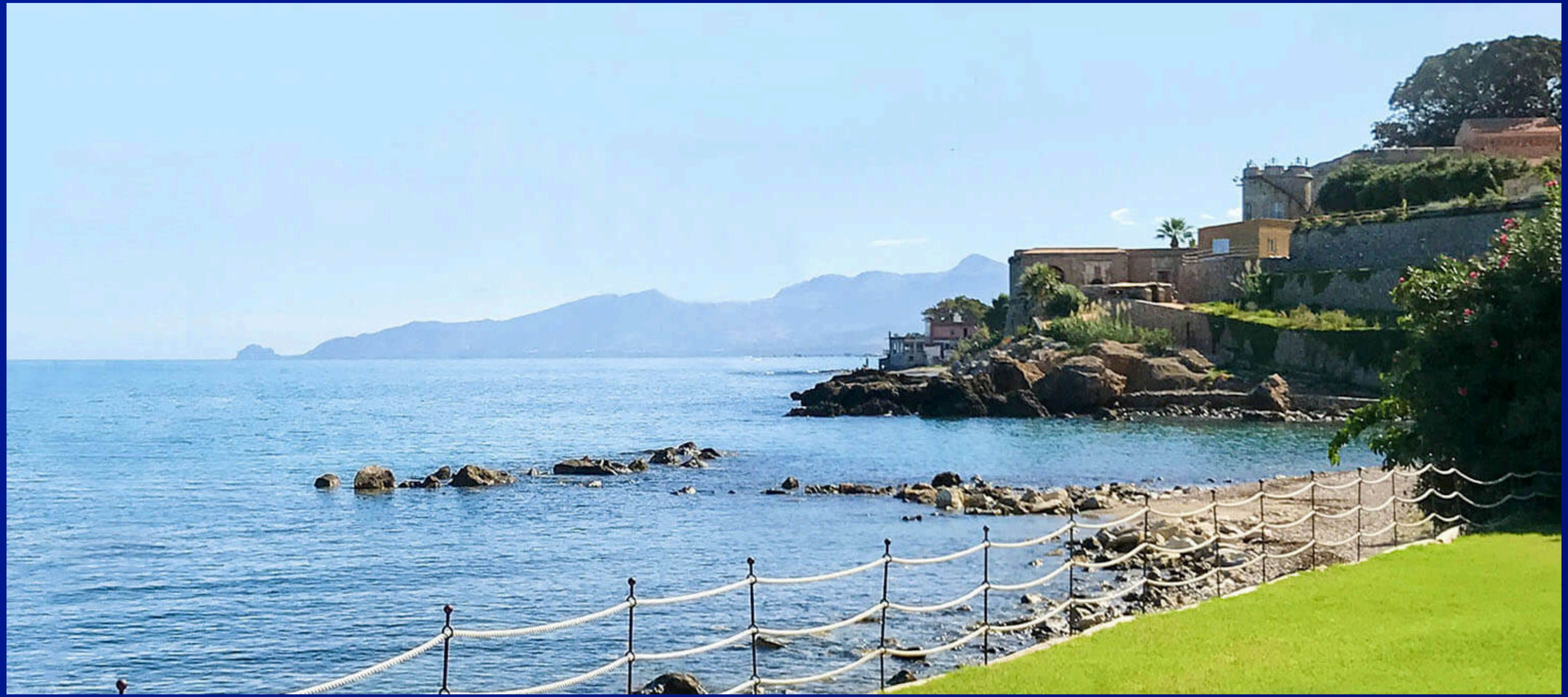
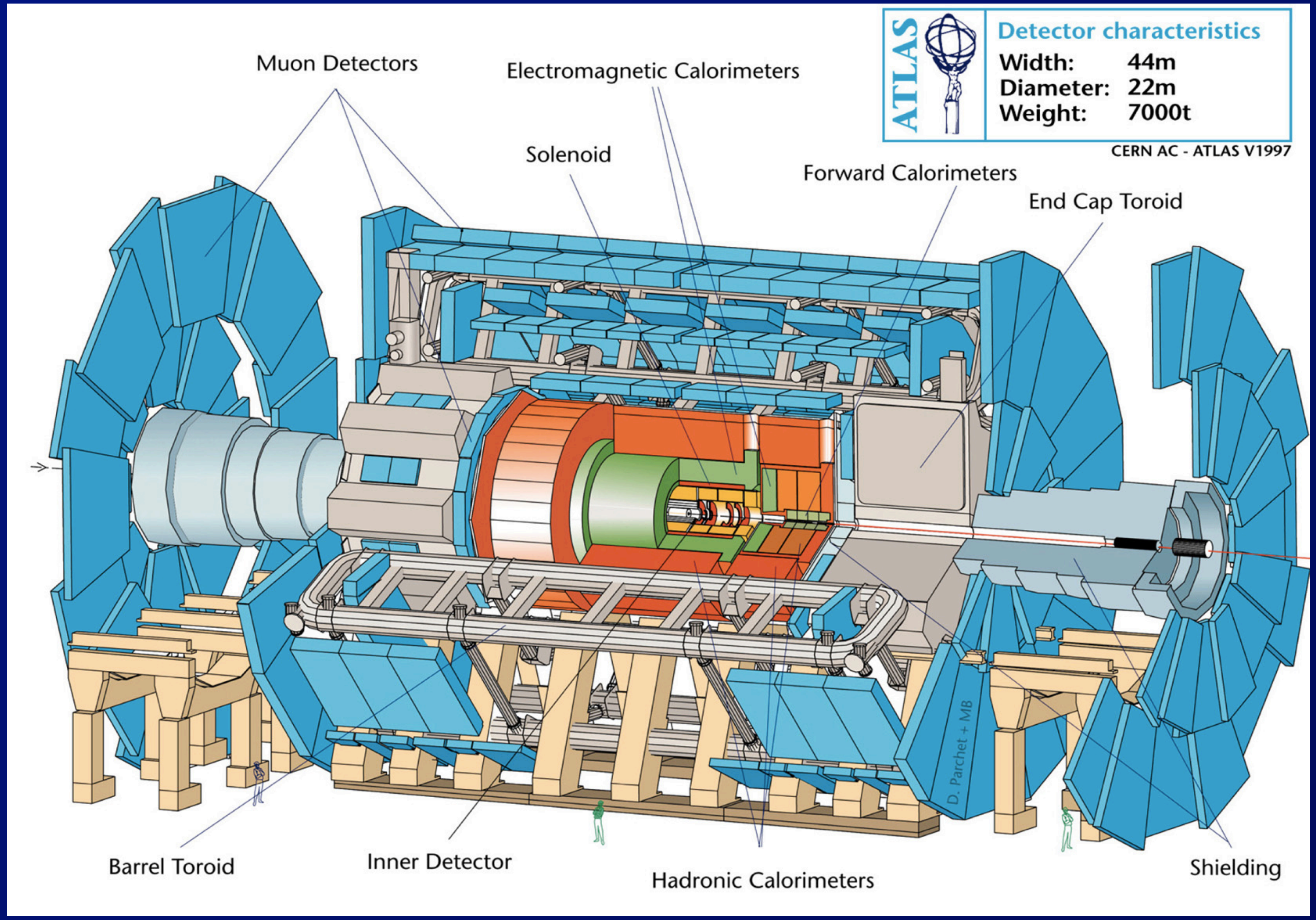
Overview of the latest ATLAS UPC+photonuclear (++) results

Prof. Brian Cole, Columbia University

September 11, 2024

Diffraction and Low-x





Outline

- Introduction
  - UPC and low-x/diffractive physics
- UPC Exclusive dilepton production
  - $\mu^+\mu^-$ production, ZDC topology dependence
- Non-UPC production of dileptons
  - Probe of nuclear low-x photon k_T distributions
- Photonuclear jet production in UPC
  - Direct probe of nuclear parton distribution functions
- Summary

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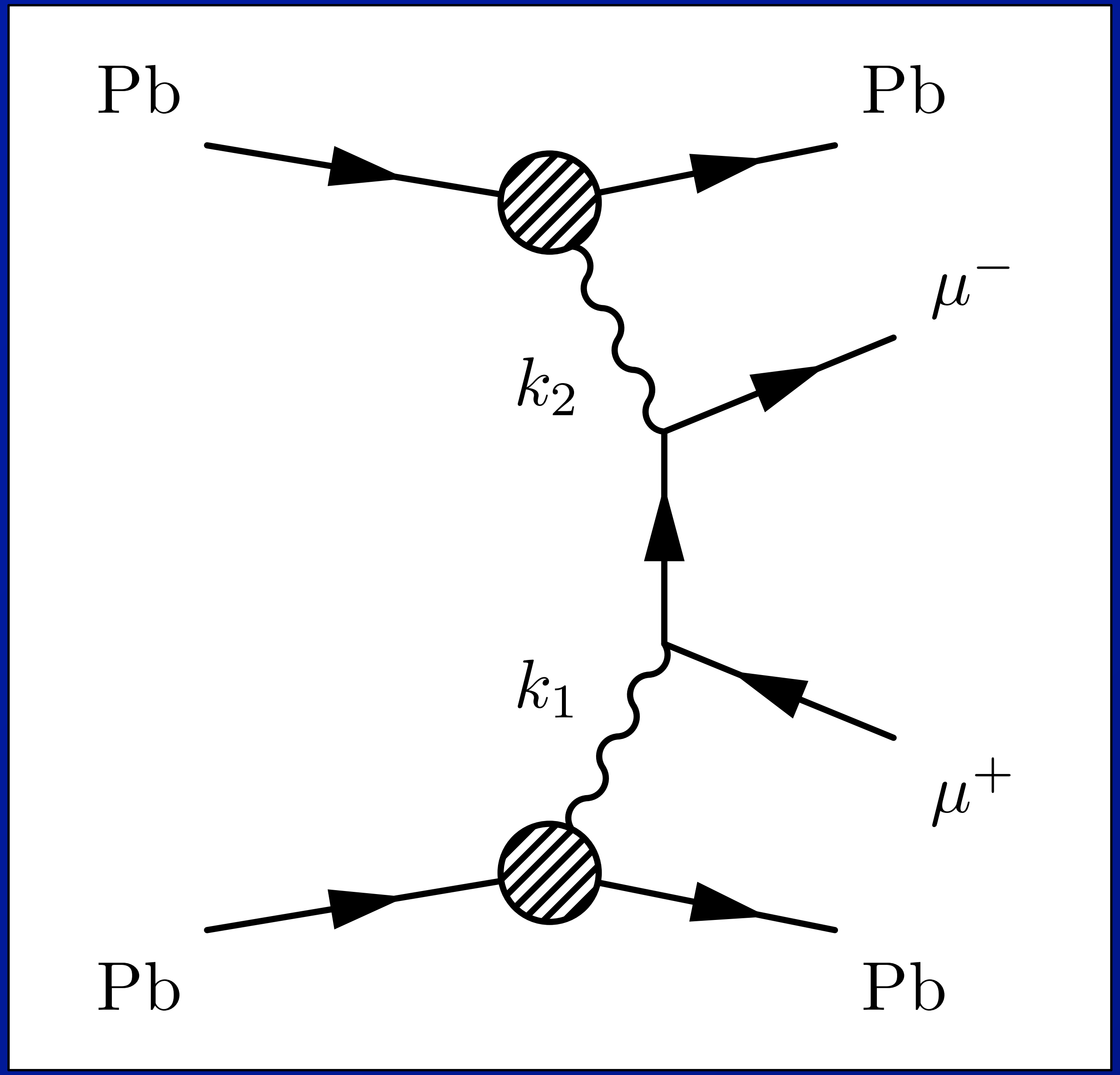
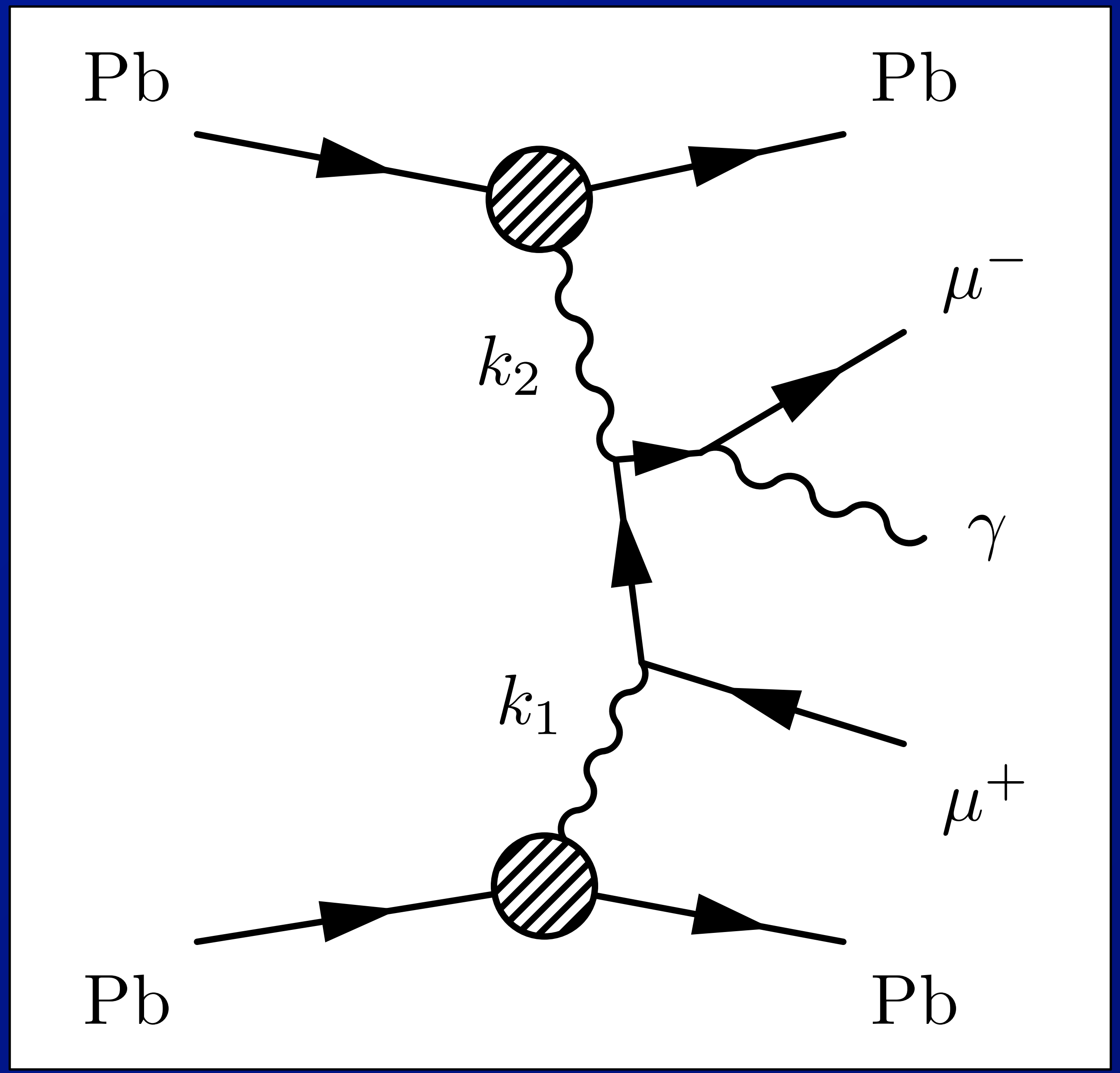
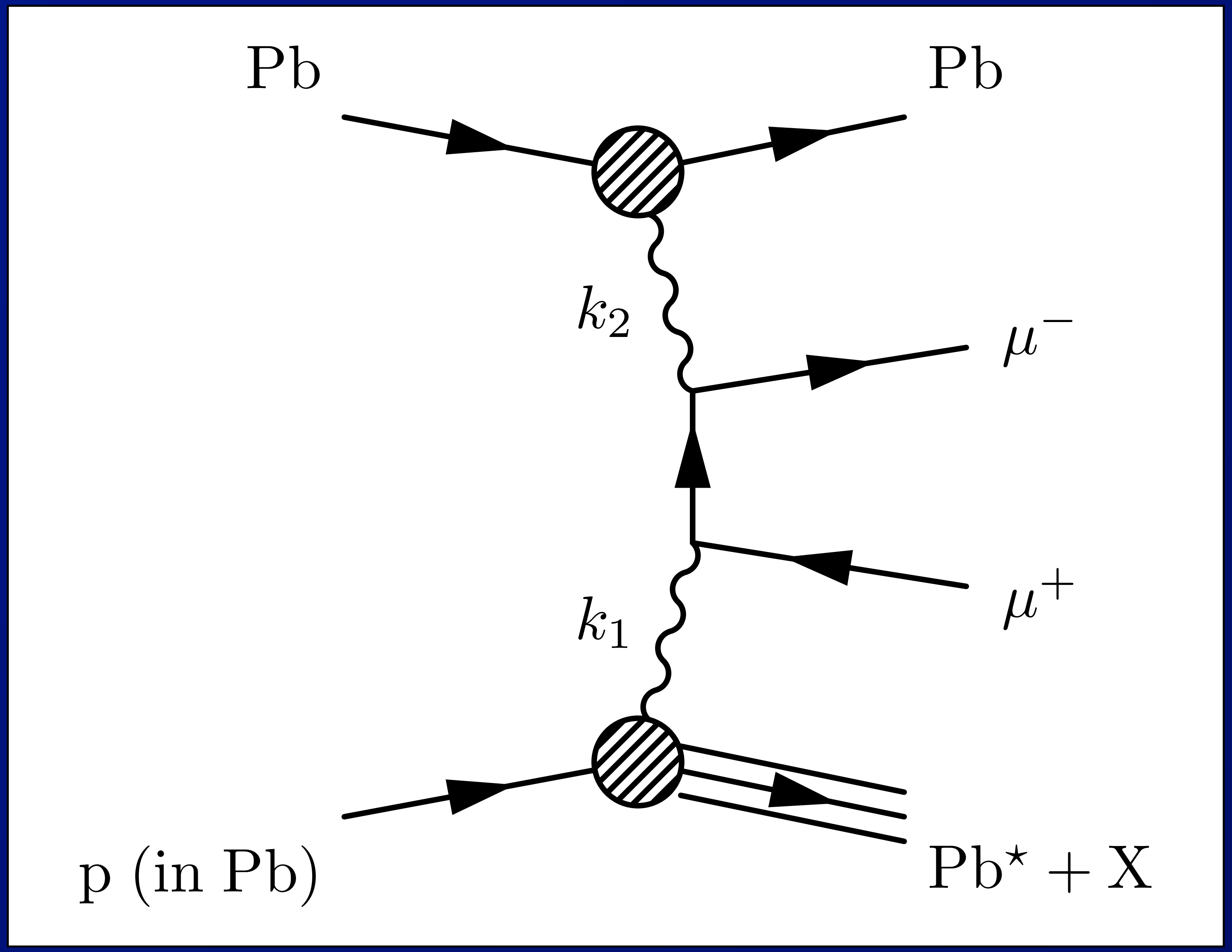
$\gamma+\gamma$ production of dileptons

Dilepton production in UPC γ+γ collisions







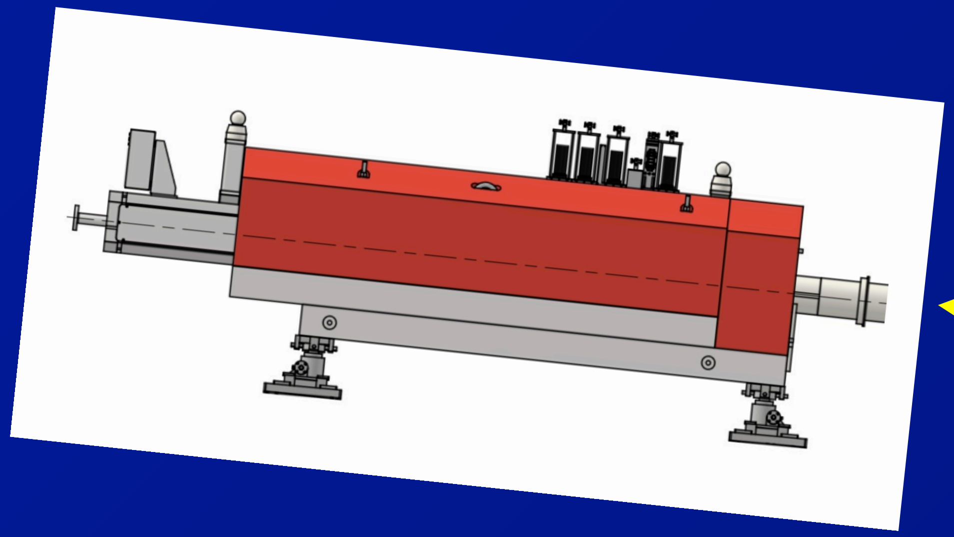
- Three contributions to $\gamma+\gamma \rightarrow \mu^+\mu^-$ processes:
  - Breit-Wheeler (LO QED)
  - Radiative (NLO QED)
  - ⇒ No nuclear breakup except for Coulomb Excitation processes
  - Dissociative - photon emitted from nucleon constituent
  - ⇒ Nuclear breakup

ZDC Neutron topology

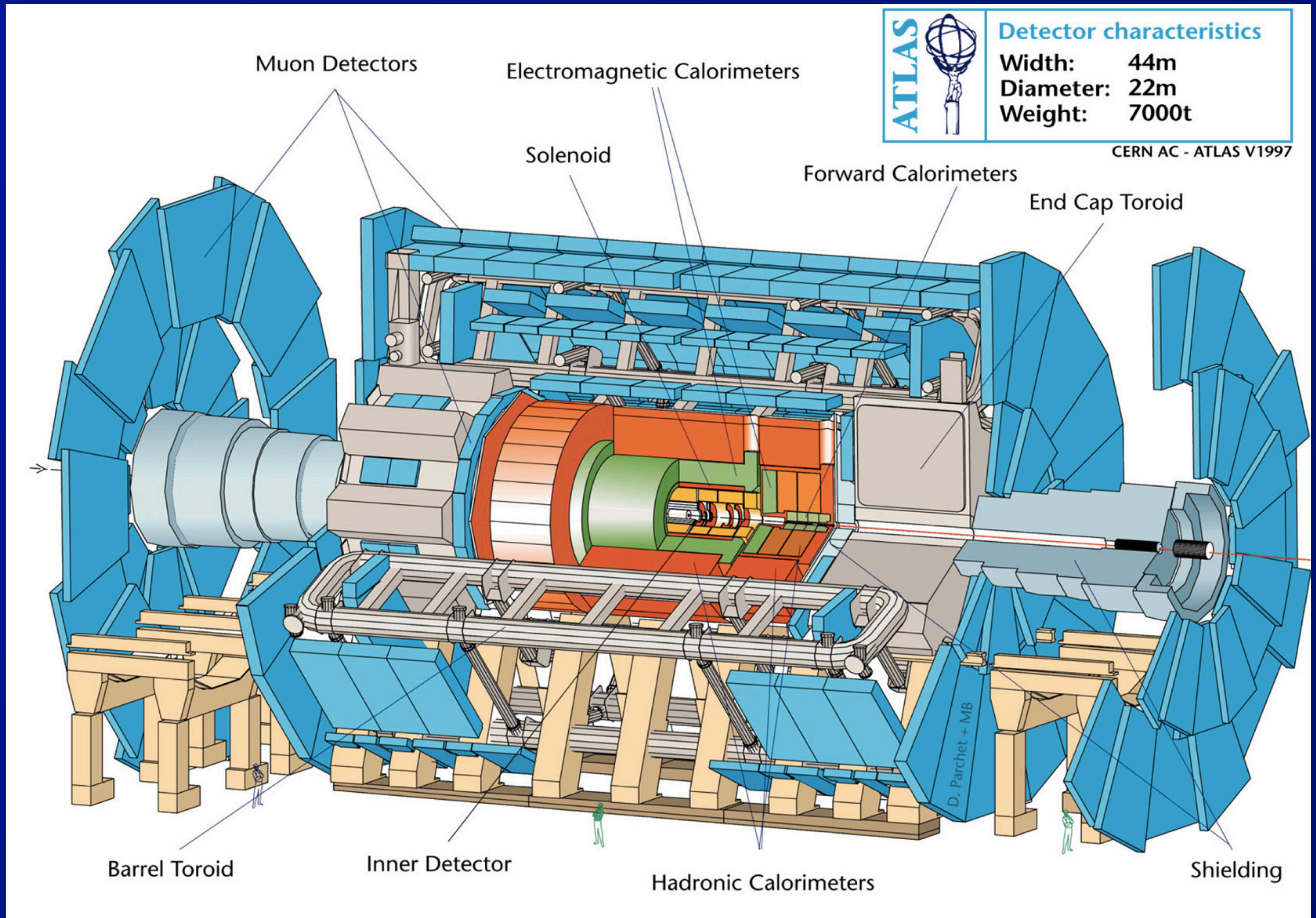
- ZDCs typically see ~ beam energy neutrons
  - ZDC topology often based on distinguishing 0 neutrons (0n) from 1 or more neutrons (Xn)

⇒Events with at least one neutron → Pb nucleus excited

ZDC



140 m



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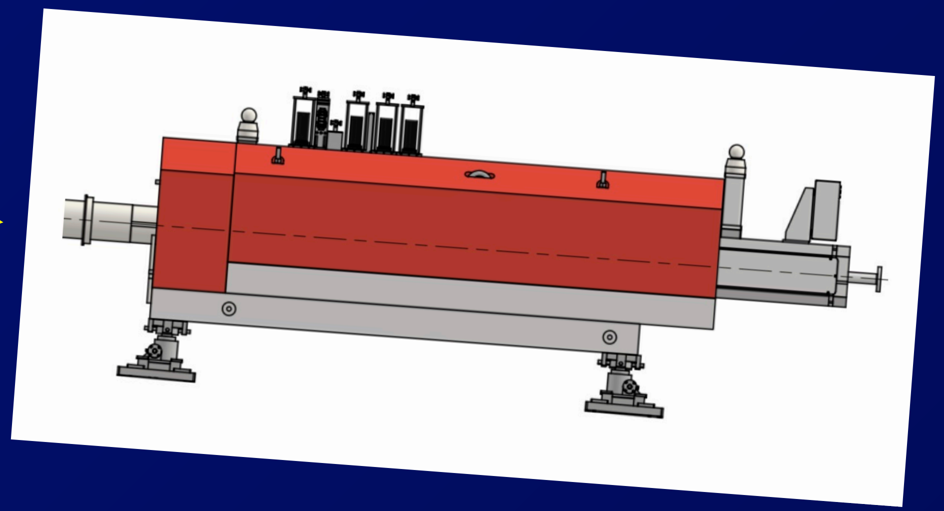

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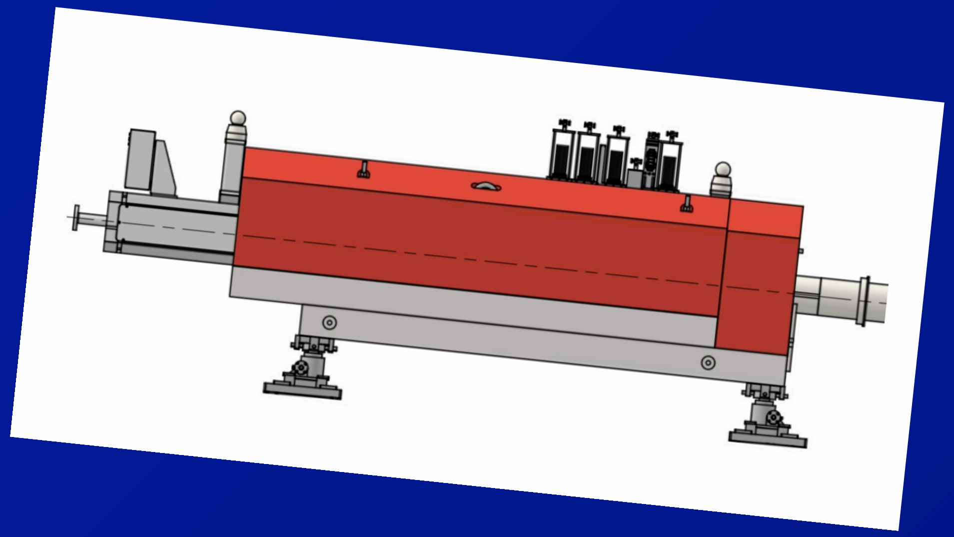
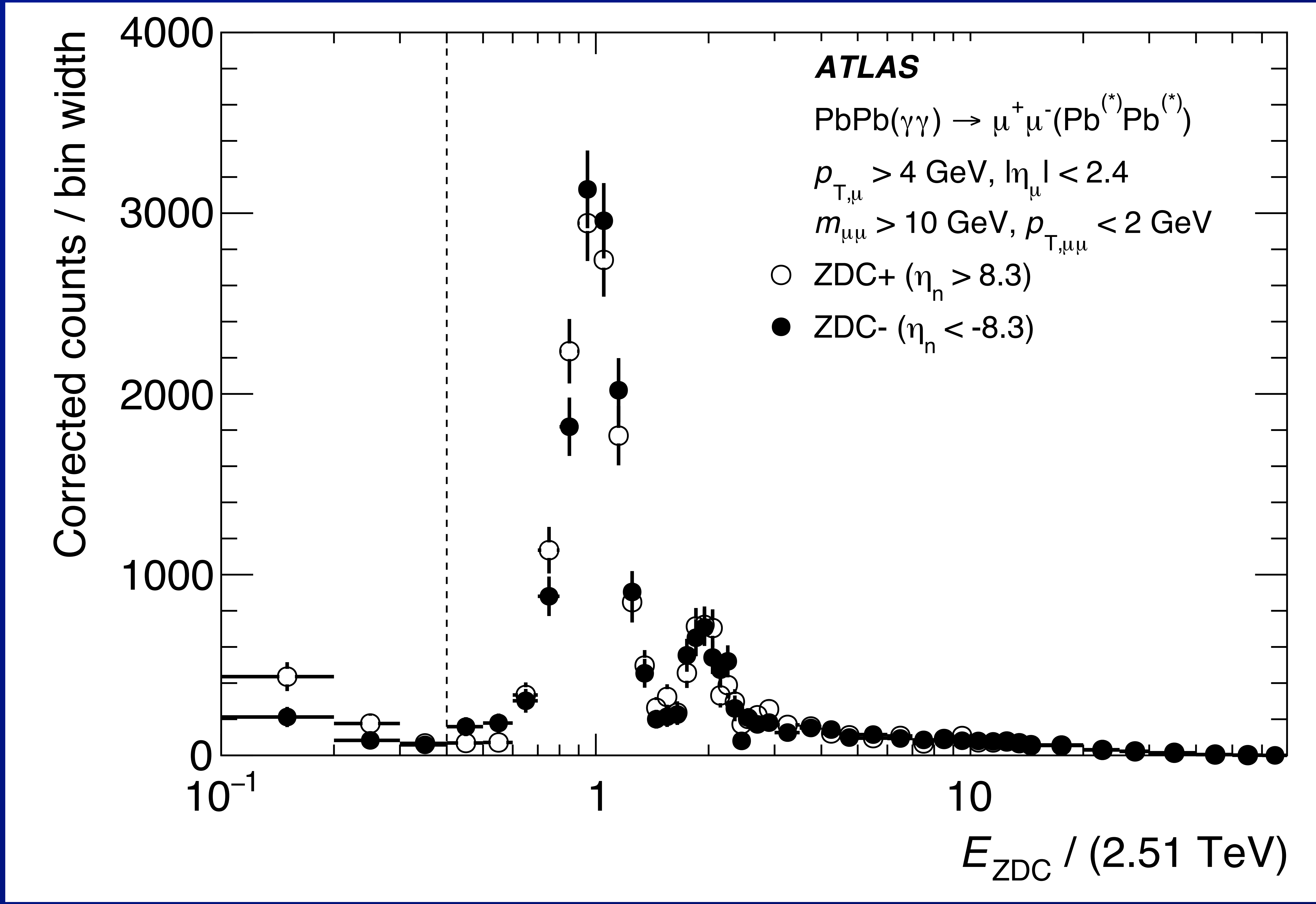
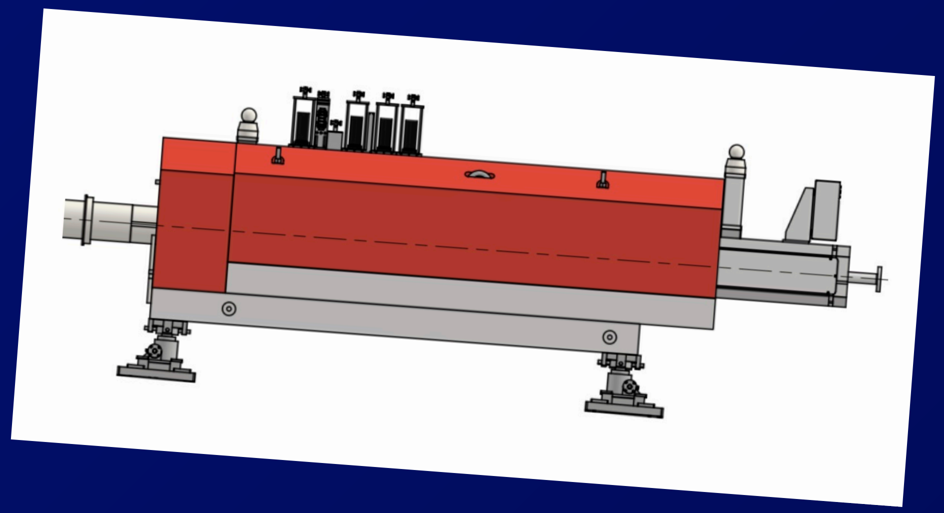




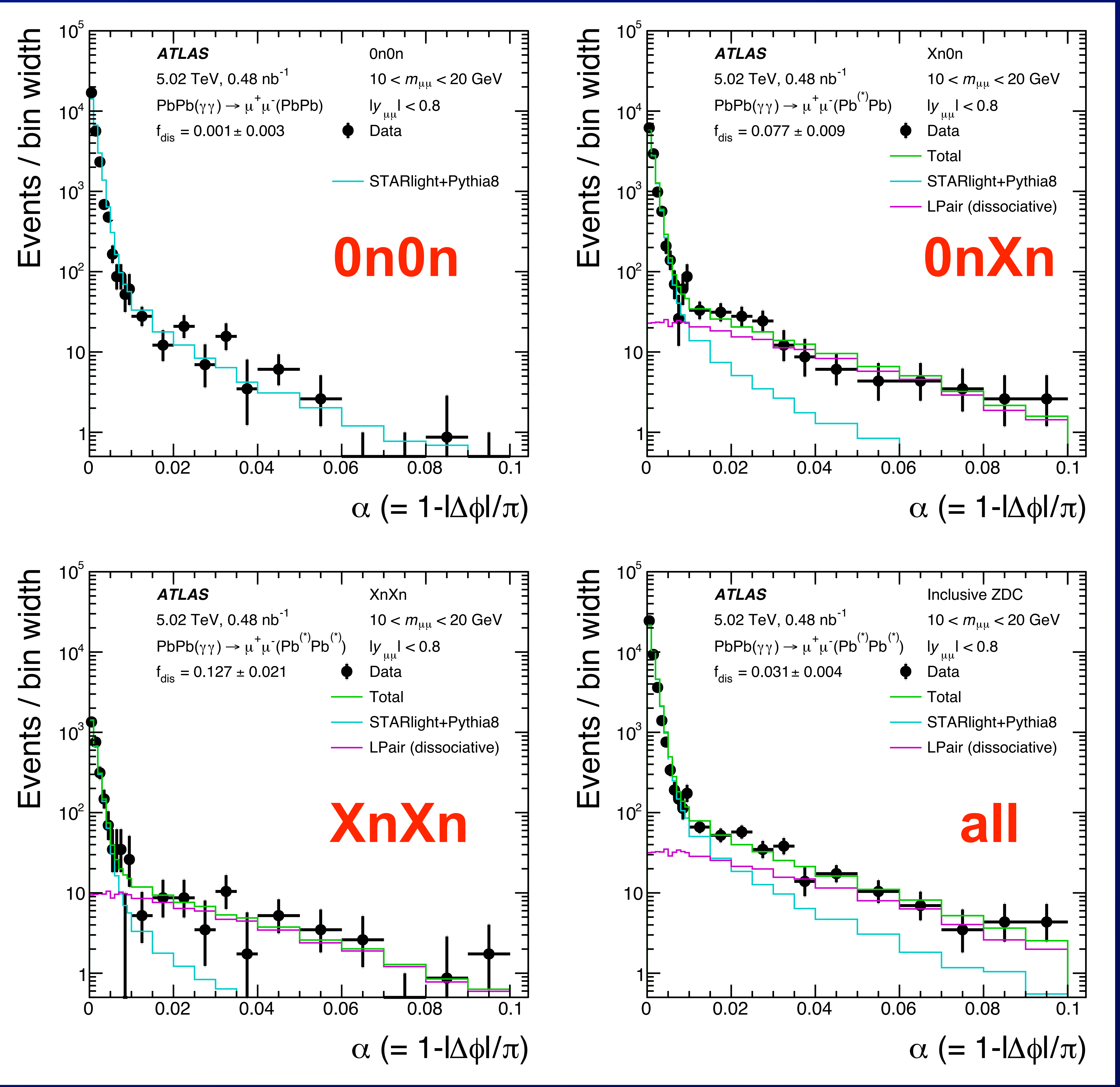
ZDC



ATLAS $\gamma + \gamma \rightarrow \mu^+\mu^-$ vs neutron topology

- Dimuon acoplanarity dist's for different ZDC topologies:

Phys. Rev. C 104 (2021) 024906



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- Dimuon acoplanarity dist's for different ZDC topologies:

⇒Template fits to data to evaluate different contributions

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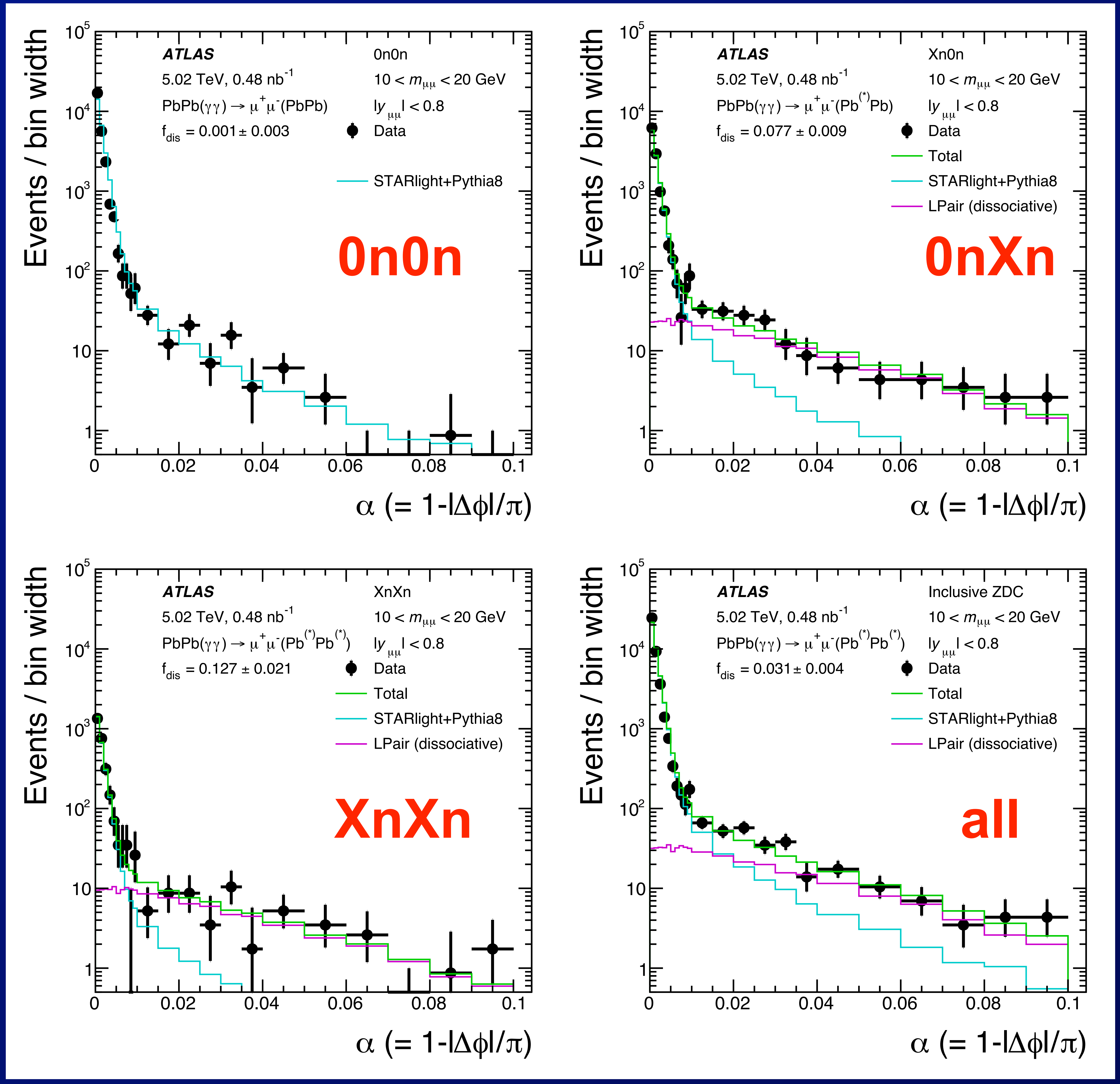

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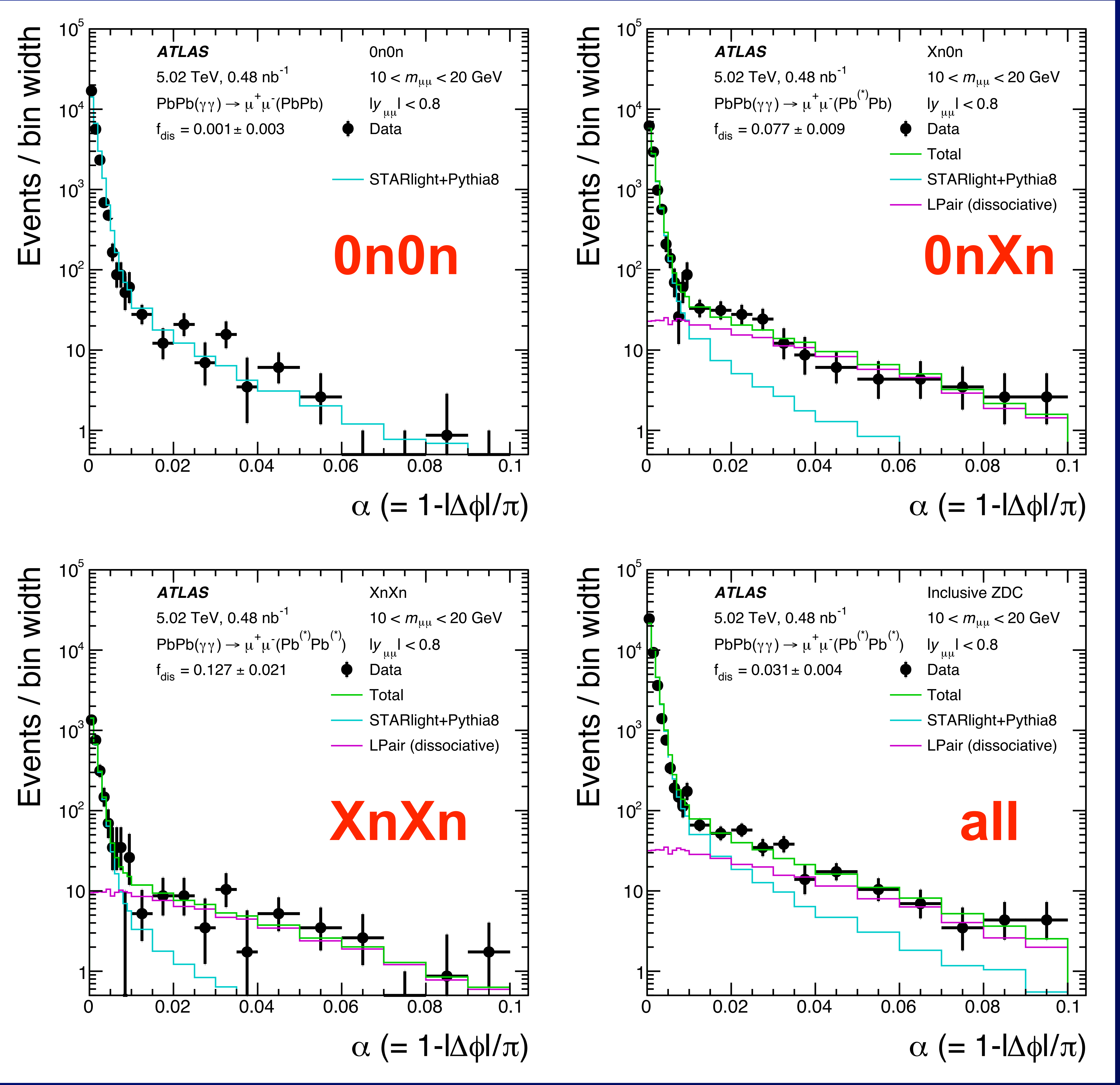

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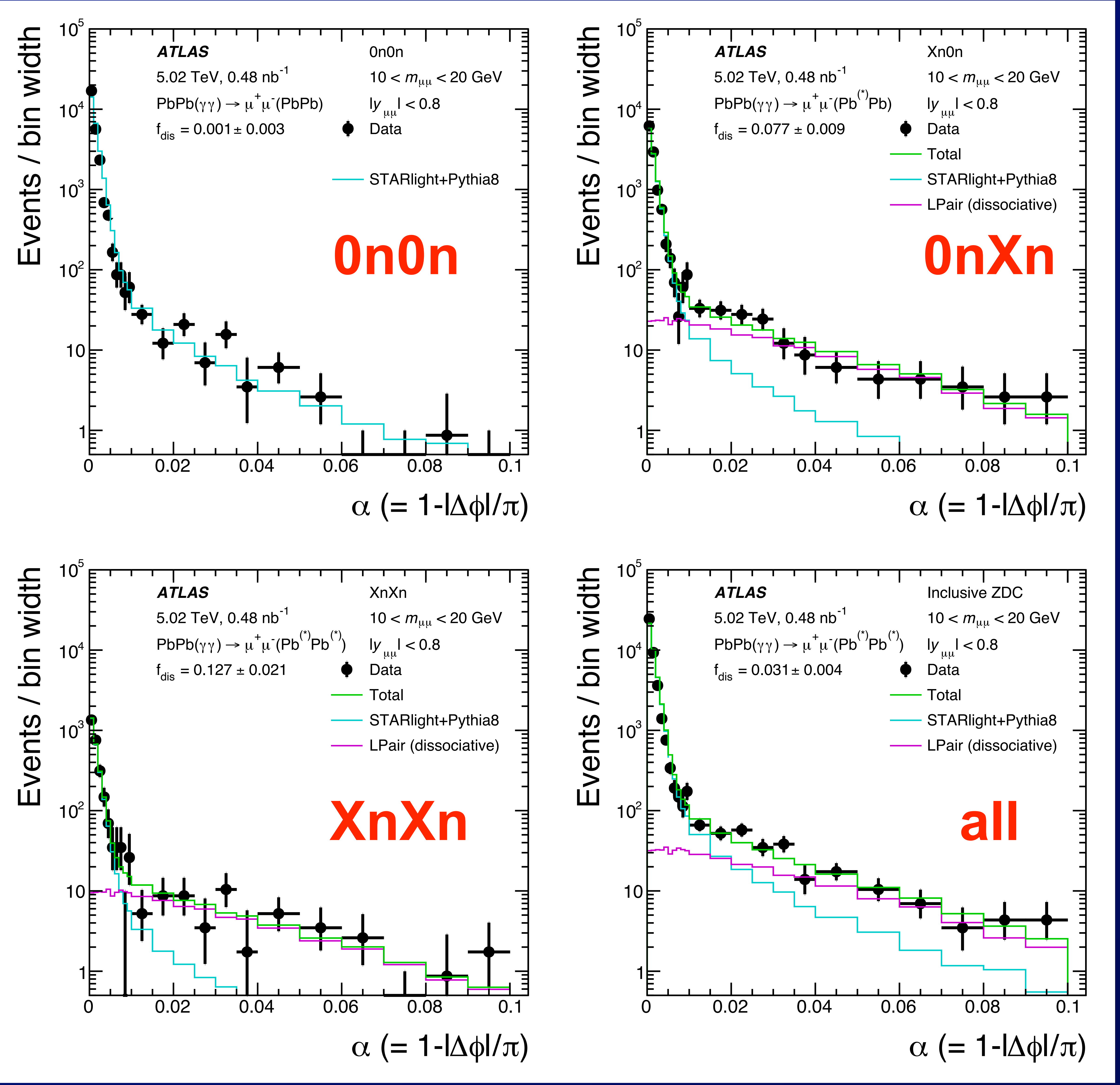

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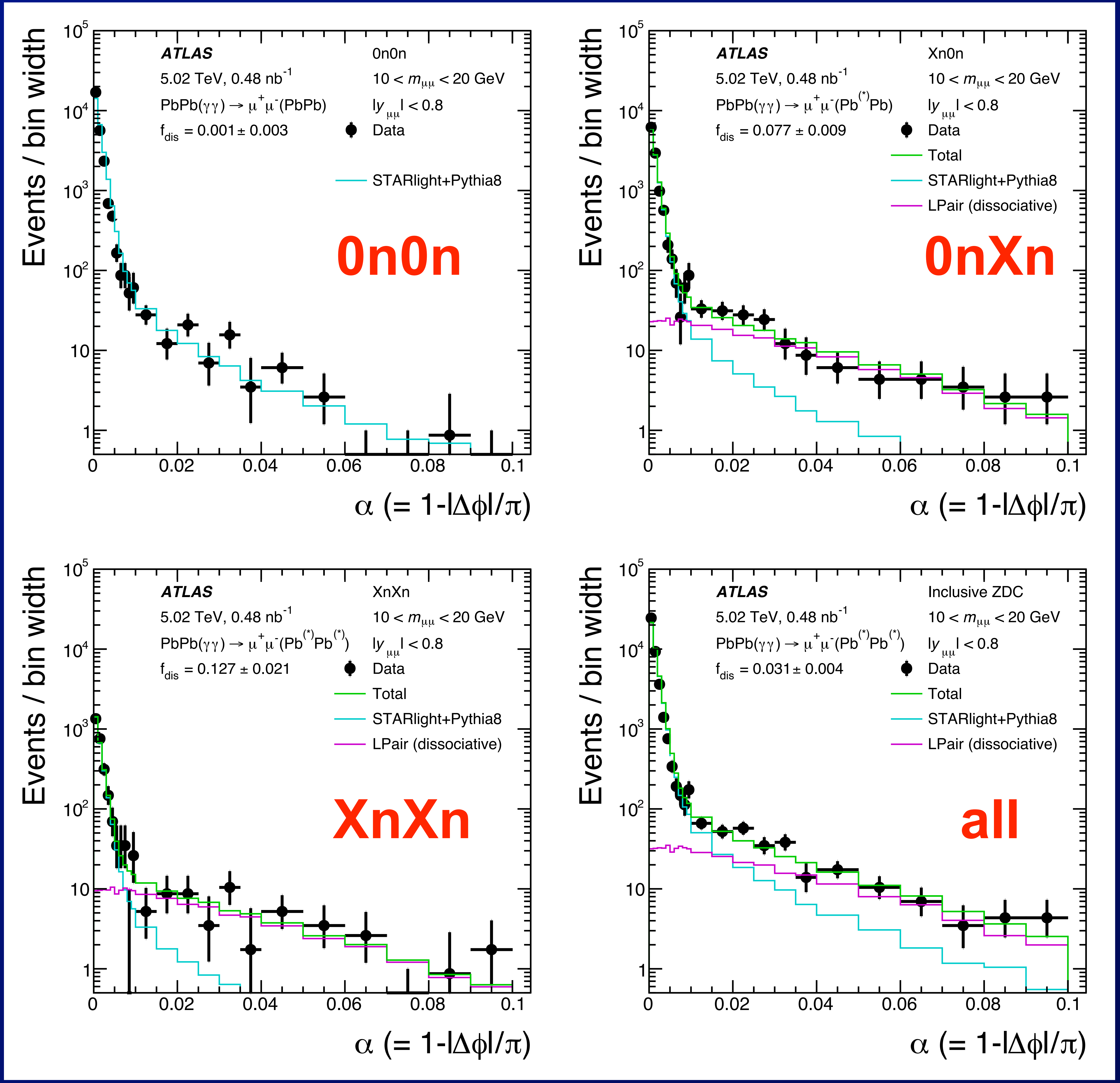
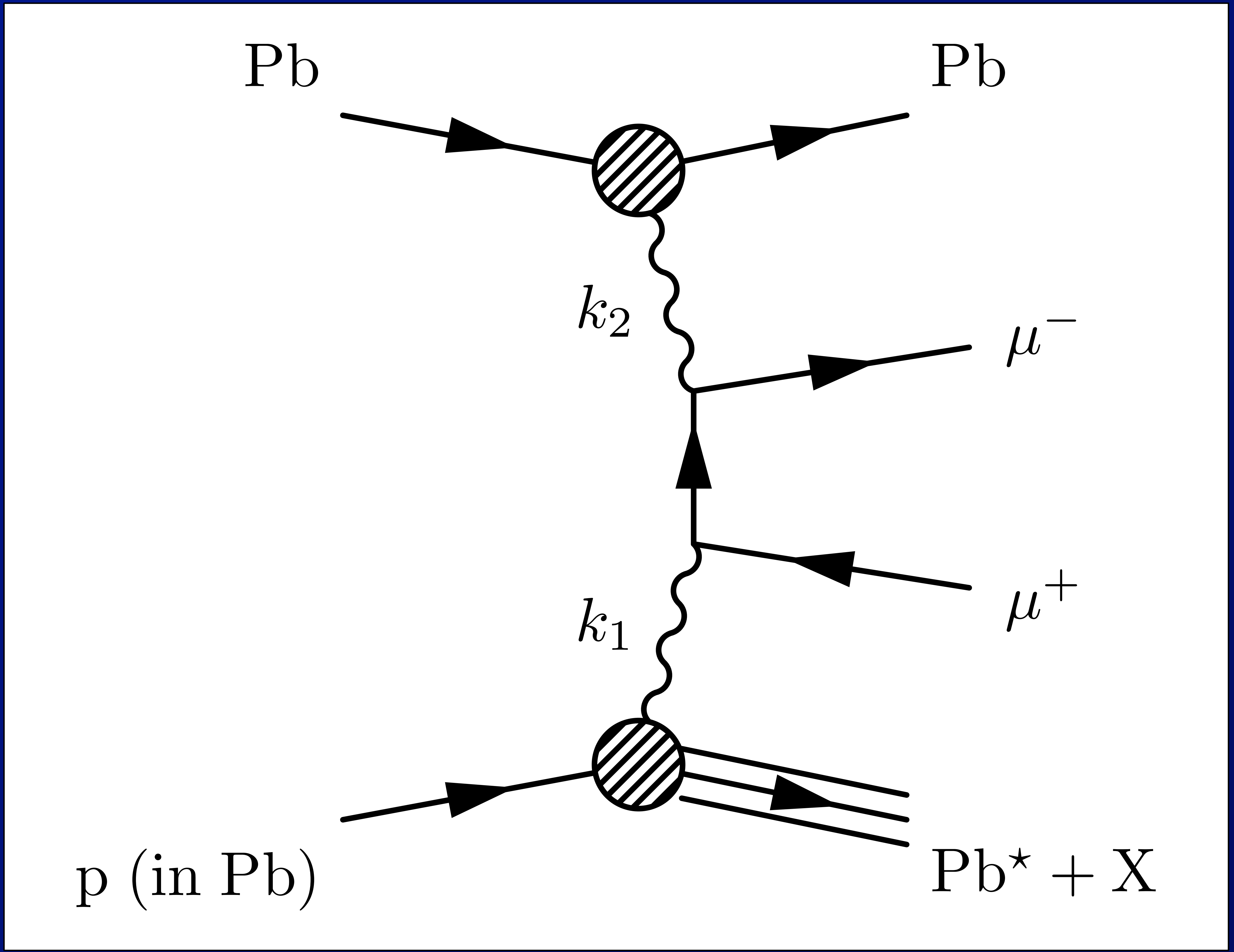
⇒ Large probability for Pb breakup in dissociative photon emission



ATLAS $\gamma + \gamma \to \mu^+\mu^-$ vs neutron topology

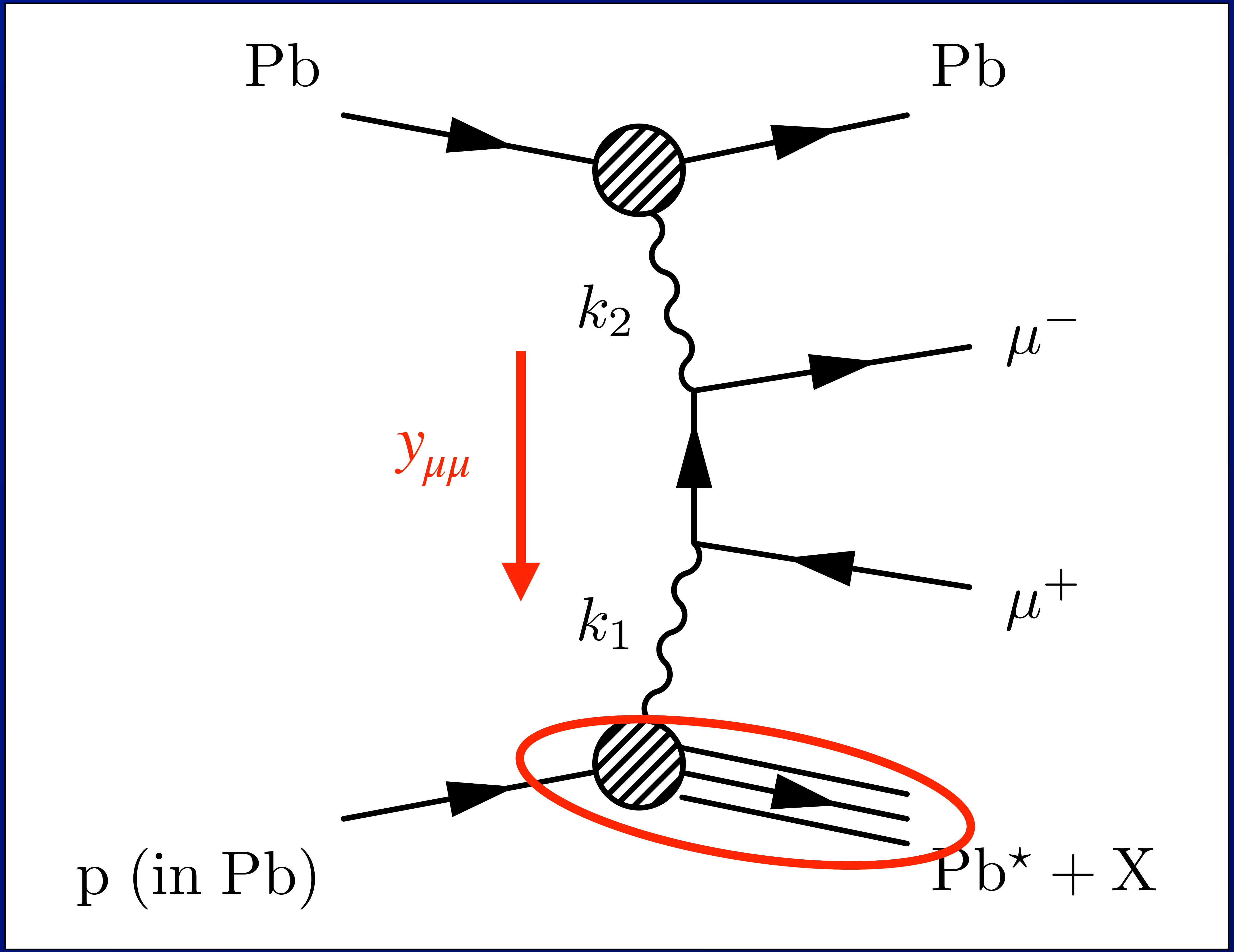
- Select 0nXn



ATLAS, Phys. Rev. C 104 (2021) 024906

ATLAS $\gamma + \gamma \to \mu^+\mu^-$ vs neutron topology

- **Select 0nXn**
  - signed $y_{\mu\mu}$, + in Xn direction



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ATLAS $\gamma + \gamma \rightarrow \mu^+\mu^-$ vs neutron topology

- **Select 0nXn**
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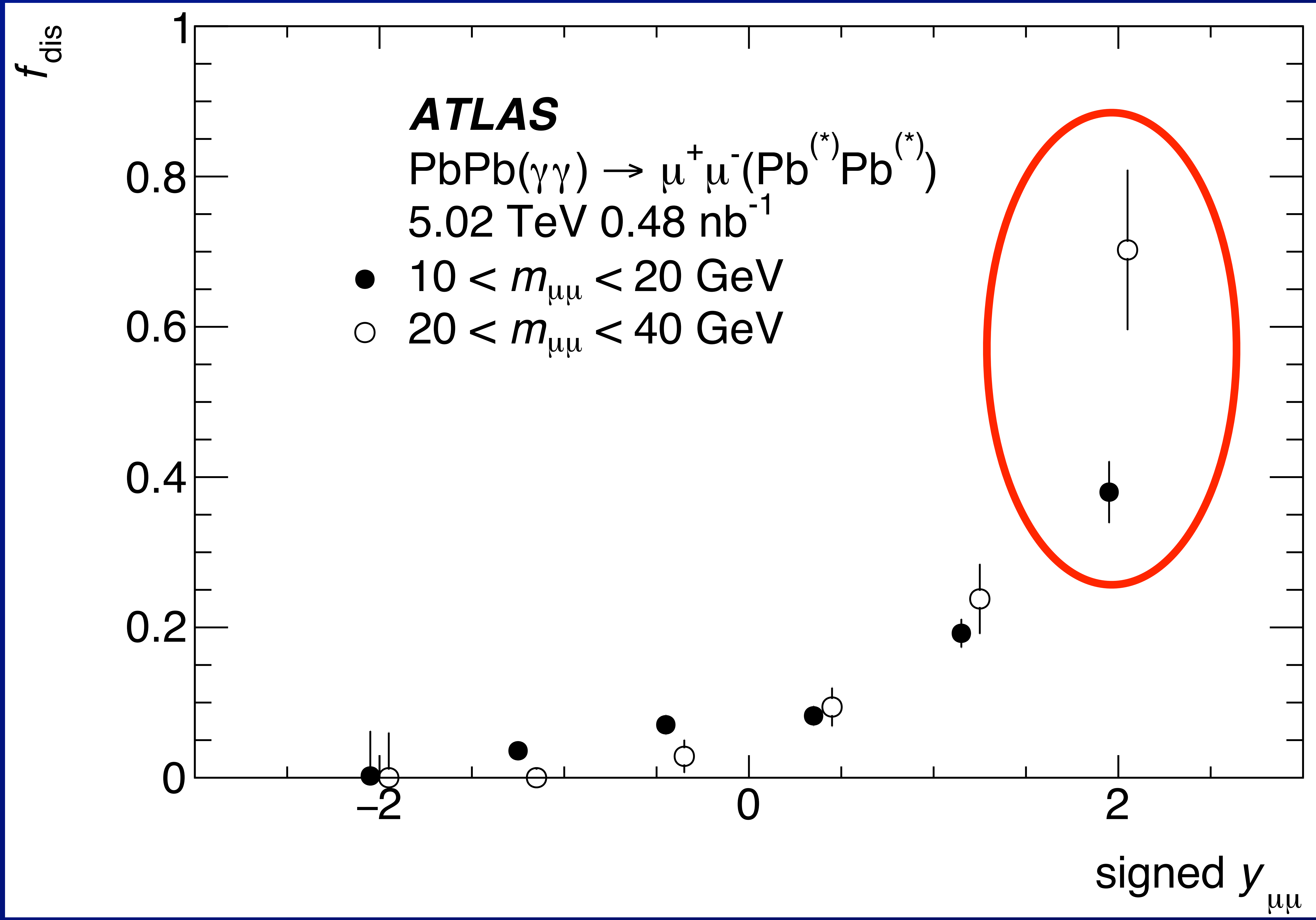
  - See large breakup fractions for positive $y_{\mu\mu}$



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ATLAS $\gamma + \gamma \rightarrow \mu^+\mu^-$ vs neutron topology

- Select 0nXn, use signed $y_{\mu\mu}$ relative to Xn direction:
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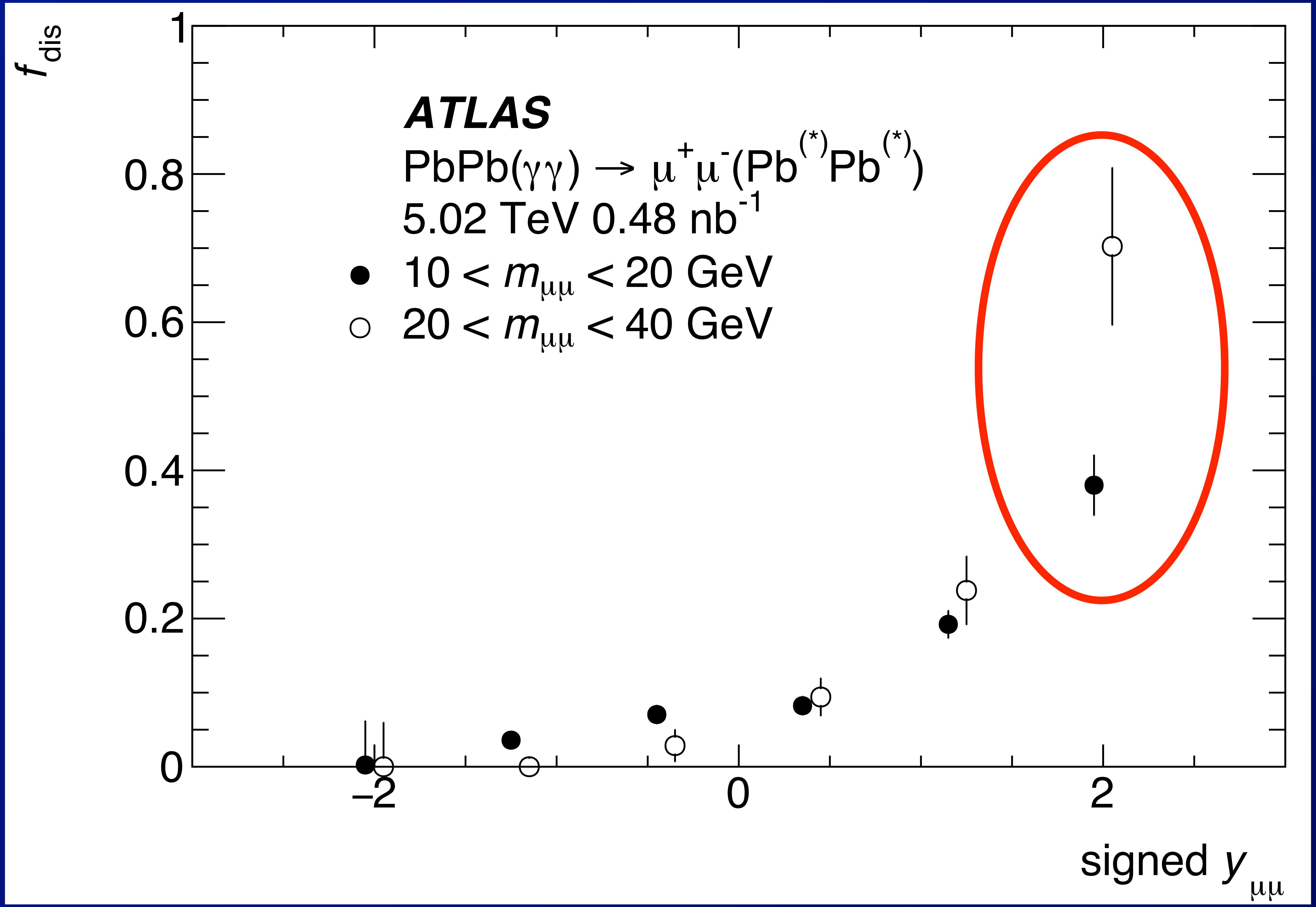
  ⇒i.e. for higher energy photons where dissociation dominates



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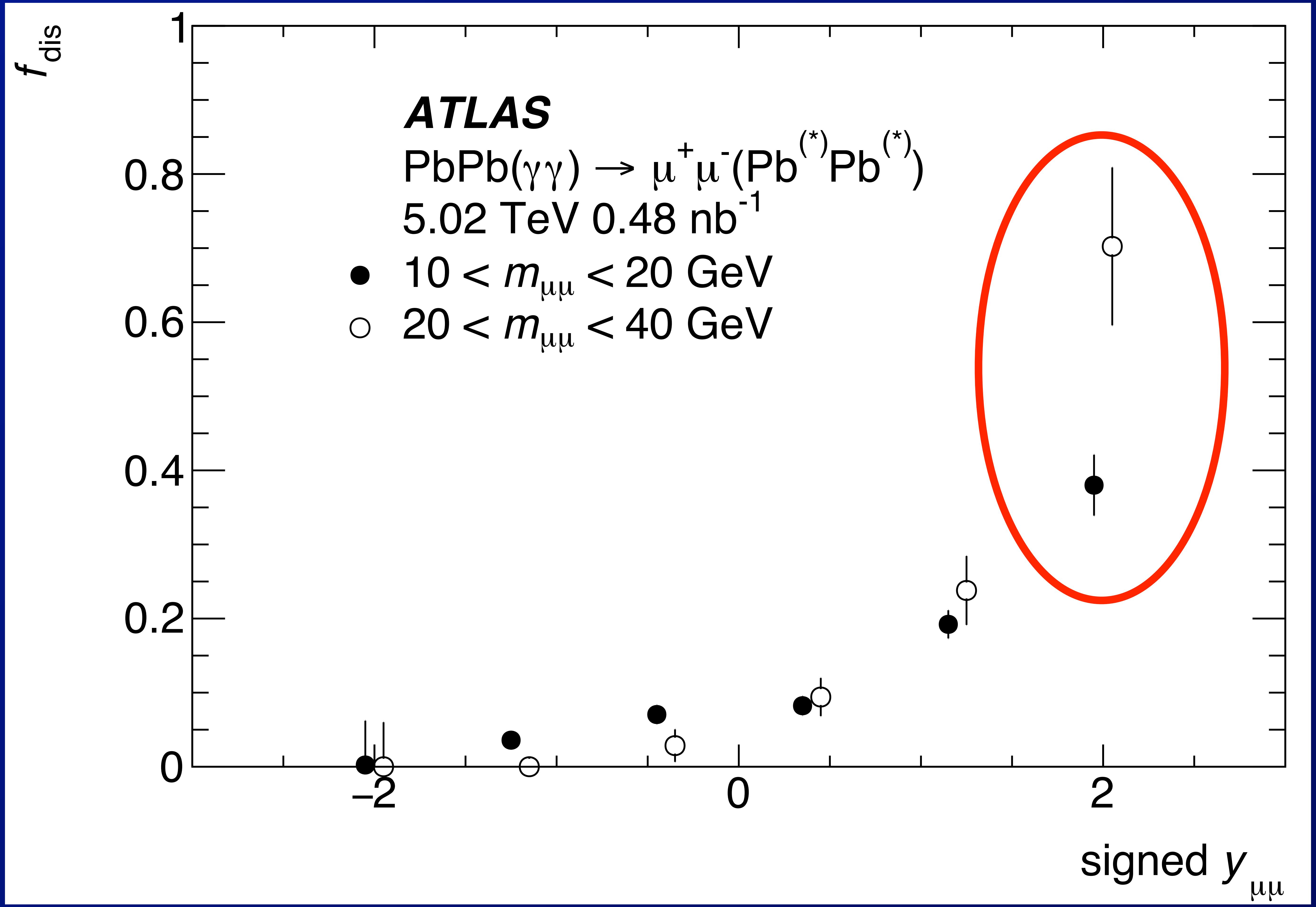

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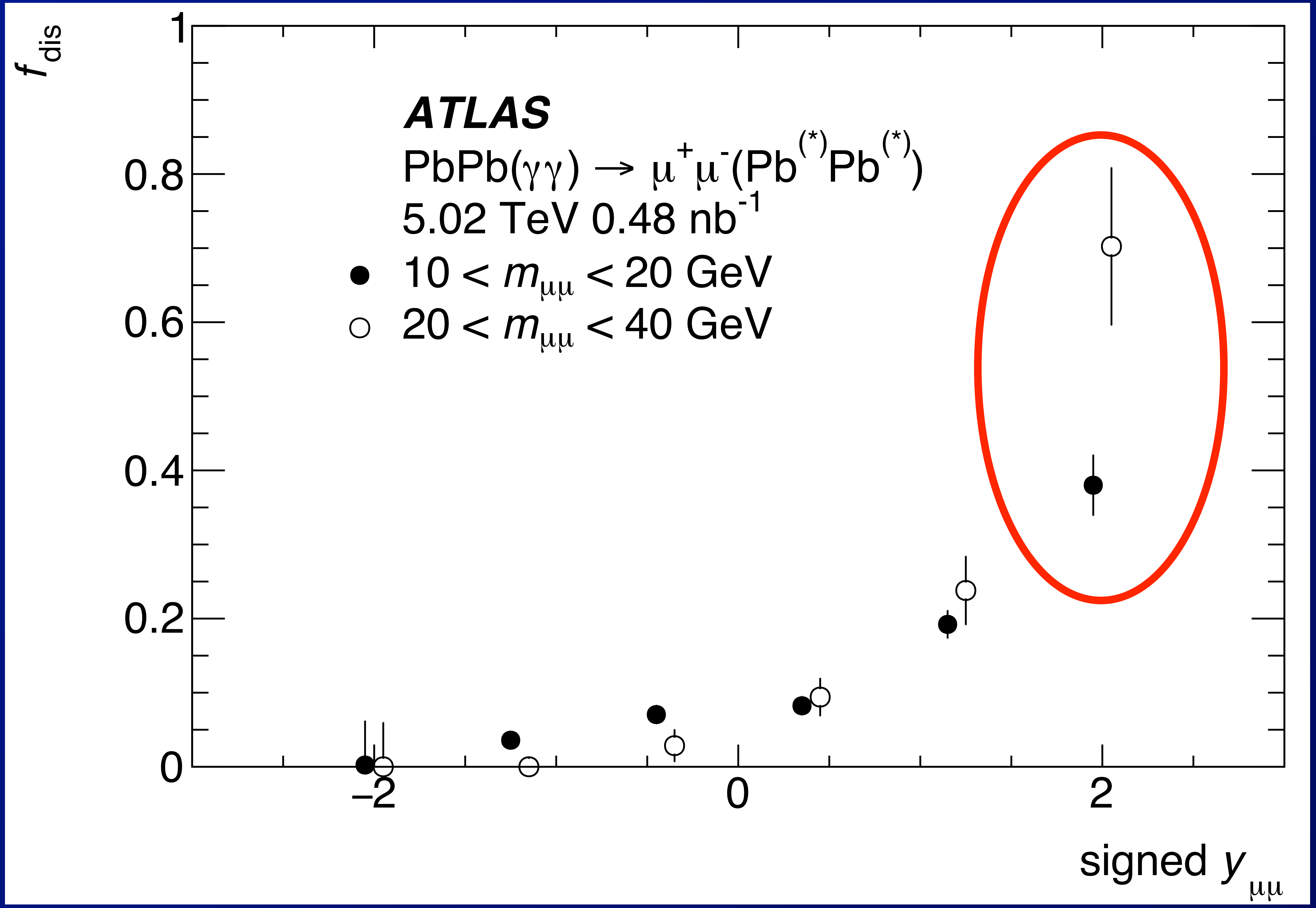

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  ⇒Measure nucleon $f_\gamma(x)$?

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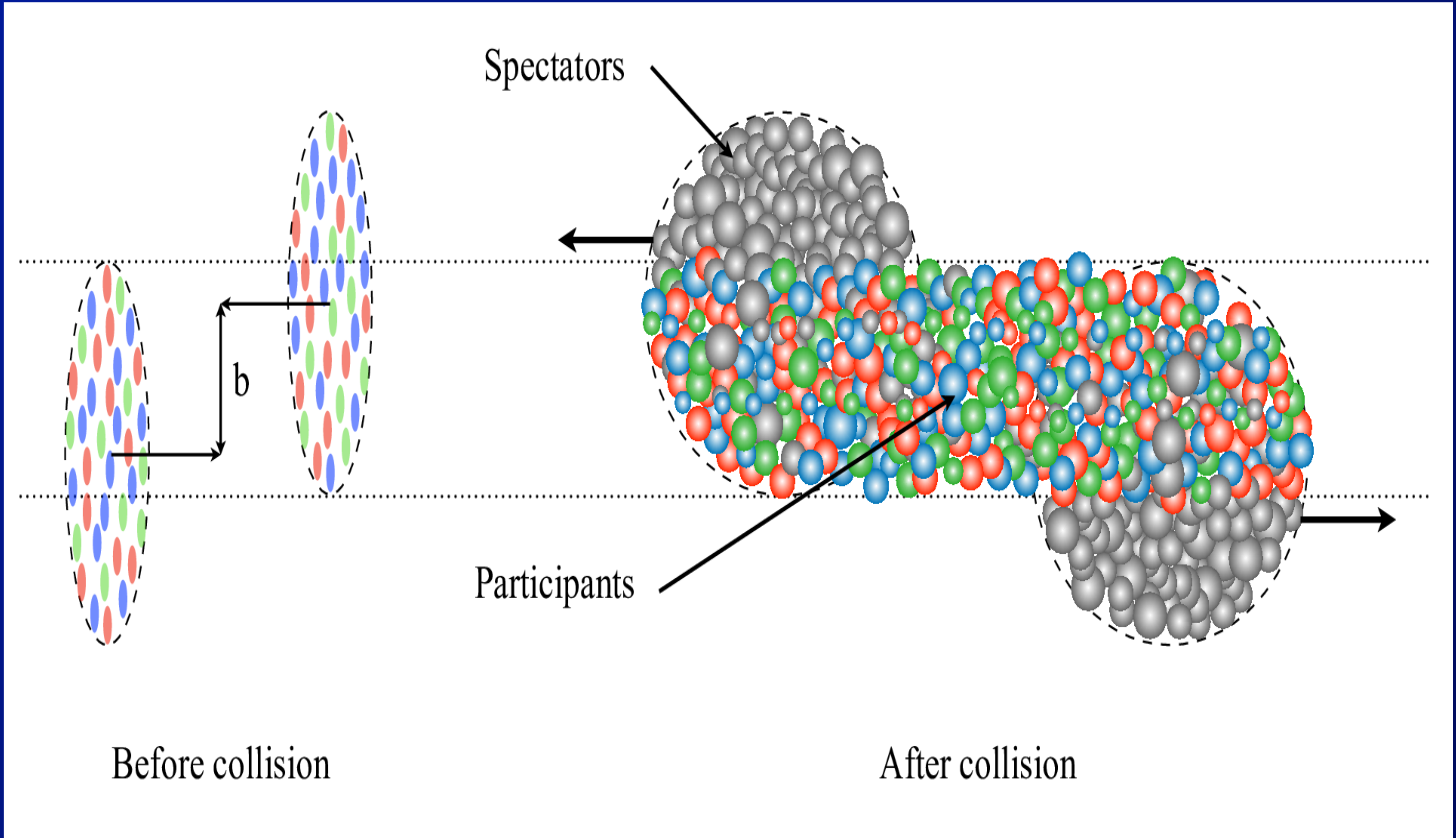
$\gamma+\gamma$ production of dileptons in hadronic Pb+Pb collisions

$\gamma + \gamma$ production of dileptons in hadronic Pb+Pb collisions !?!

$\gamma+\gamma \rightarrow \mu^+\mu^-$ in hadronic Pb+Pb collisions

- In the background of hadronic Pb+Pb collisions



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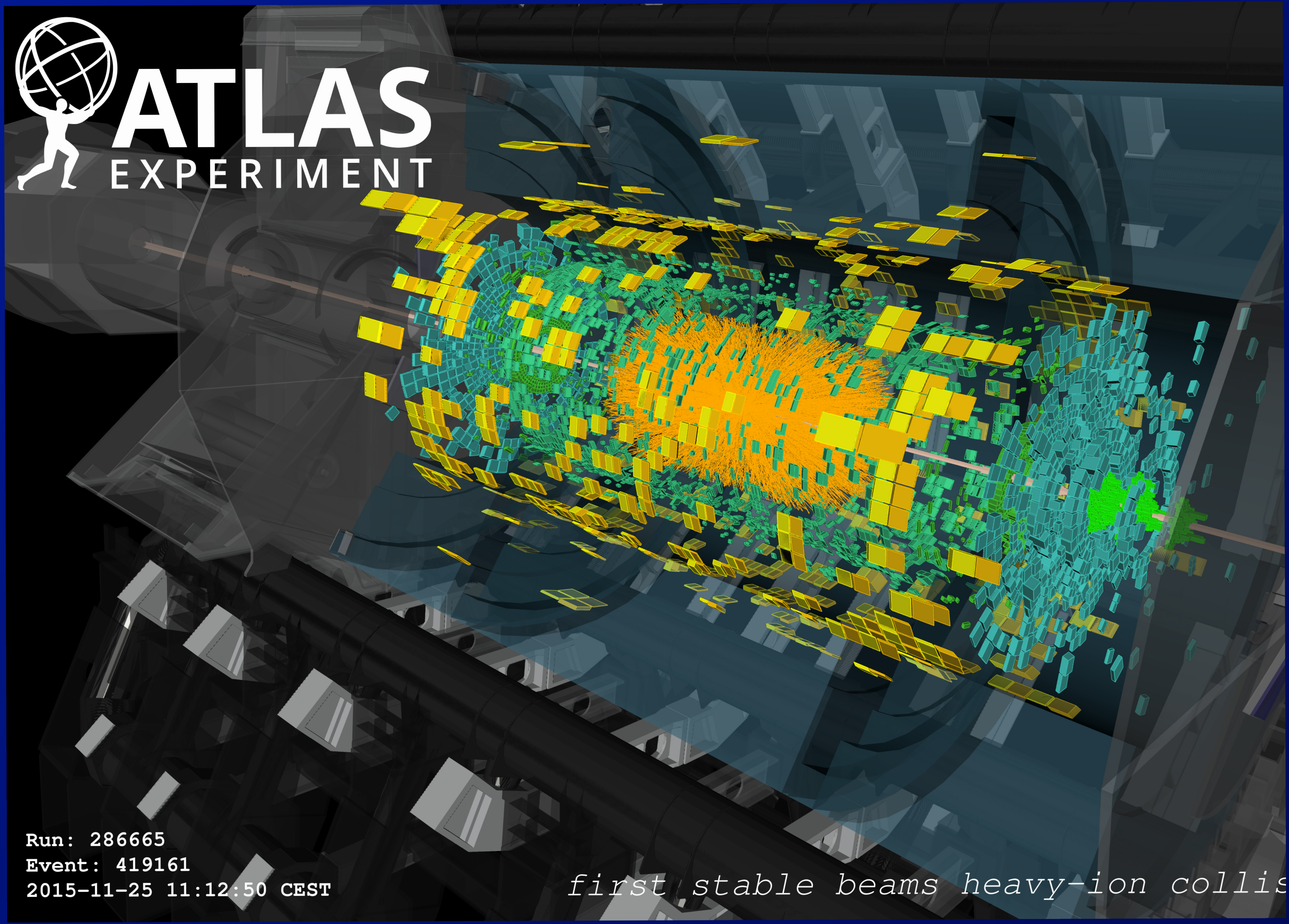

$\gamma+\gamma \rightarrow \mu^+\mu^-$ in hadronic Pb+Pb collisions

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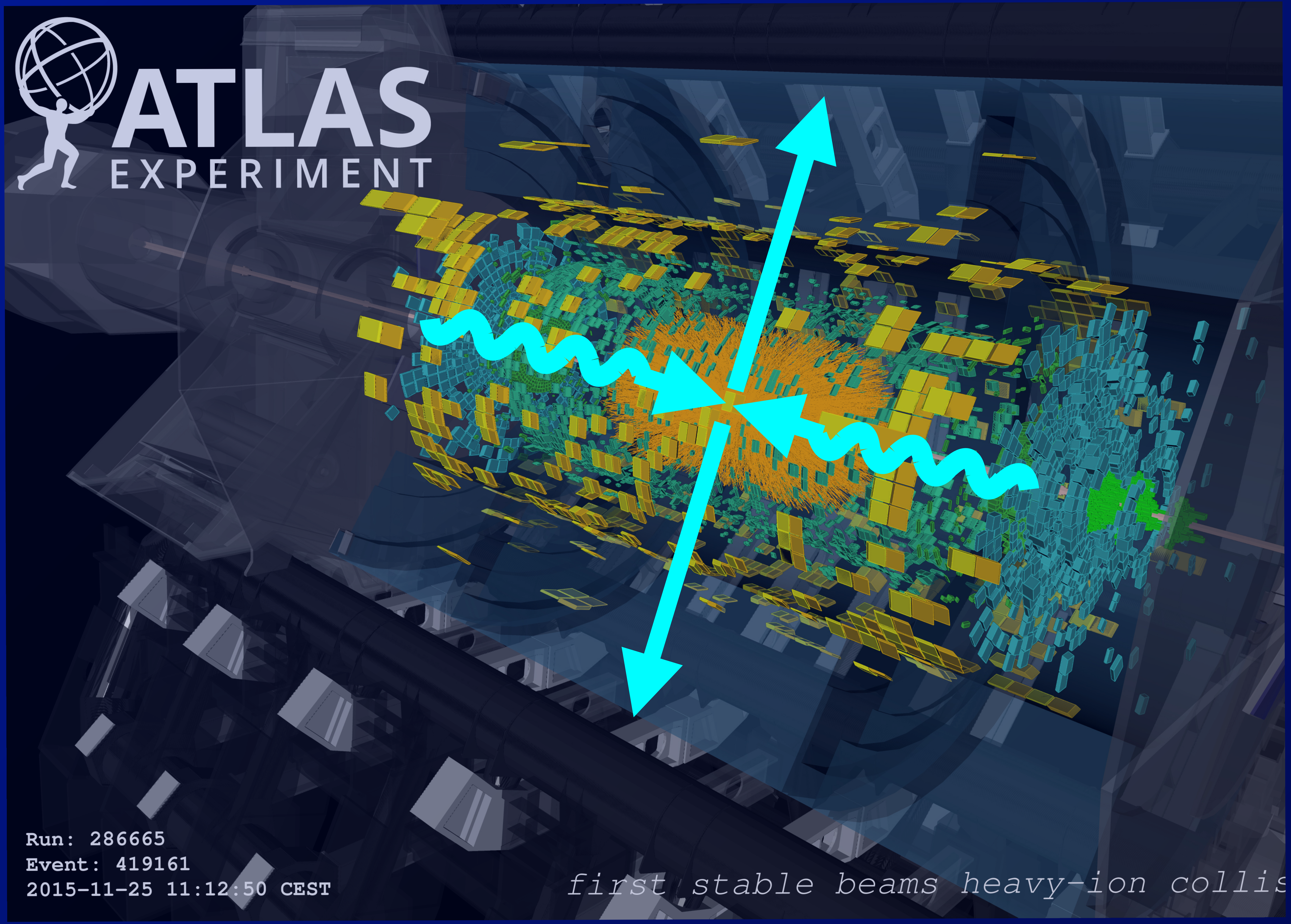
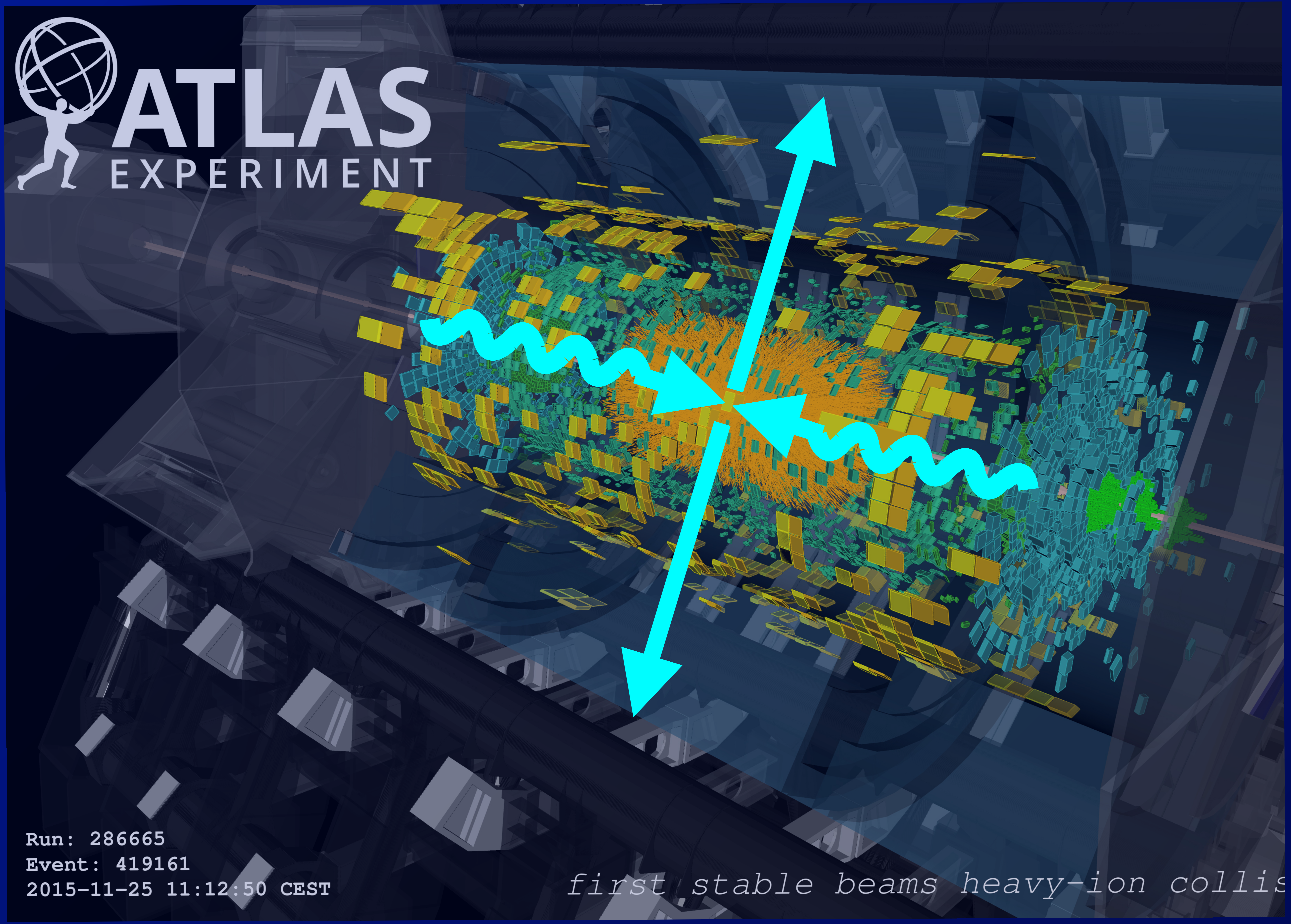


$\gamma+\gamma \rightarrow \mu^{+}\mu^{-}$ in hadronic Pb+Pb collisions

- In the background of hadronic Pb+Pb collisions
  - ATLAS has observed $\gamma+\gamma \rightarrow \mu+\mu-$ production
  - Even in very central collisions (0-5%)

⇒Why is this interesting?



γ+γ→μ⁺μ⁻ in hadronic Pb+Pb collisions

- Initially, the $\gamma + \gamma \rightarrow \mu^+\mu^-$ pairs were a nuisance

⇒Background to study of $b\bar{b}$ production

$\gamma+\gamma\rightarrow\mu^+\mu^-$ in hadronic Pb+Pb collisions

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$\Rightarrow$Background to study of $b\bar{b}$ production

- Then, we observed something interesting:

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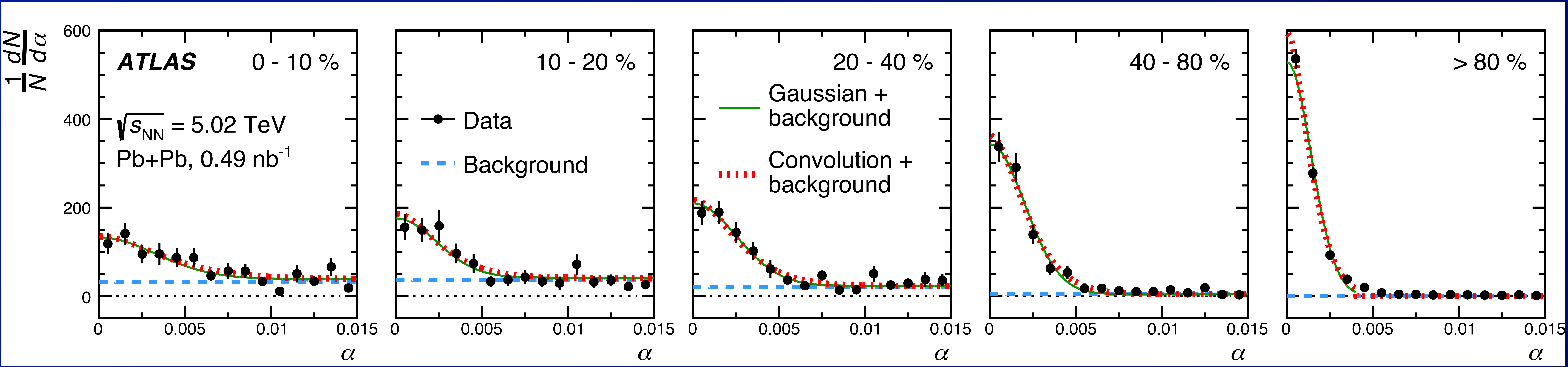
Phys. Rev. Lett. 121, 212301



⇒The acoplanarity between the muons broadened in central collisions

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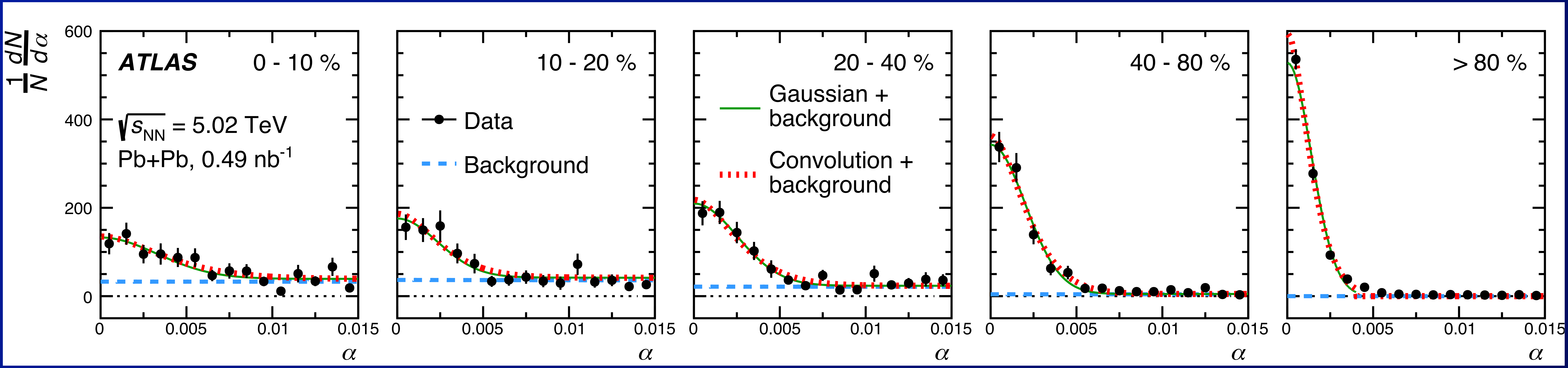

⇒The acoplanarity between the muons broadened in central collisions!

- Interaction of muons with EM fields of quark gluon plasma?

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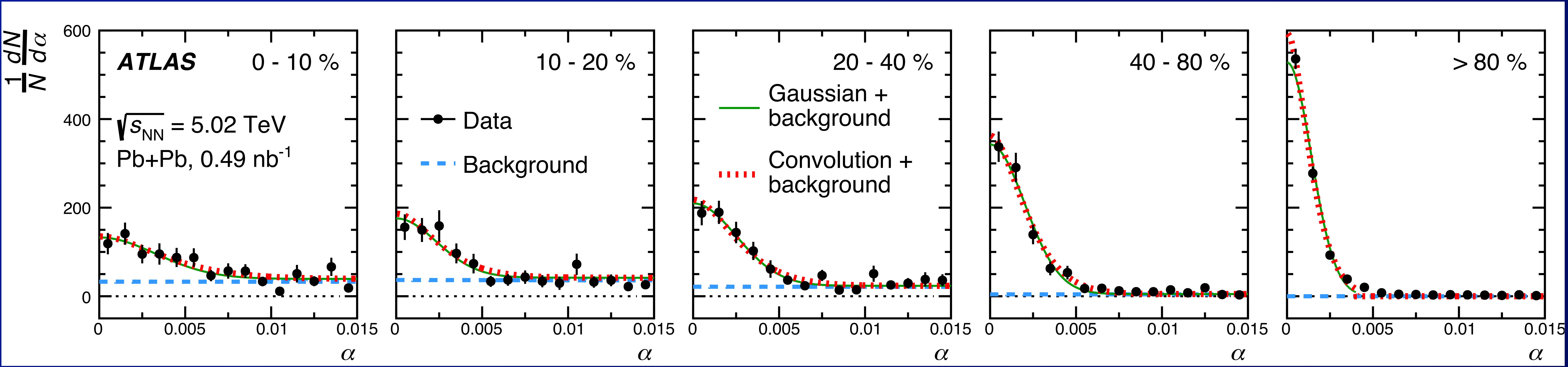


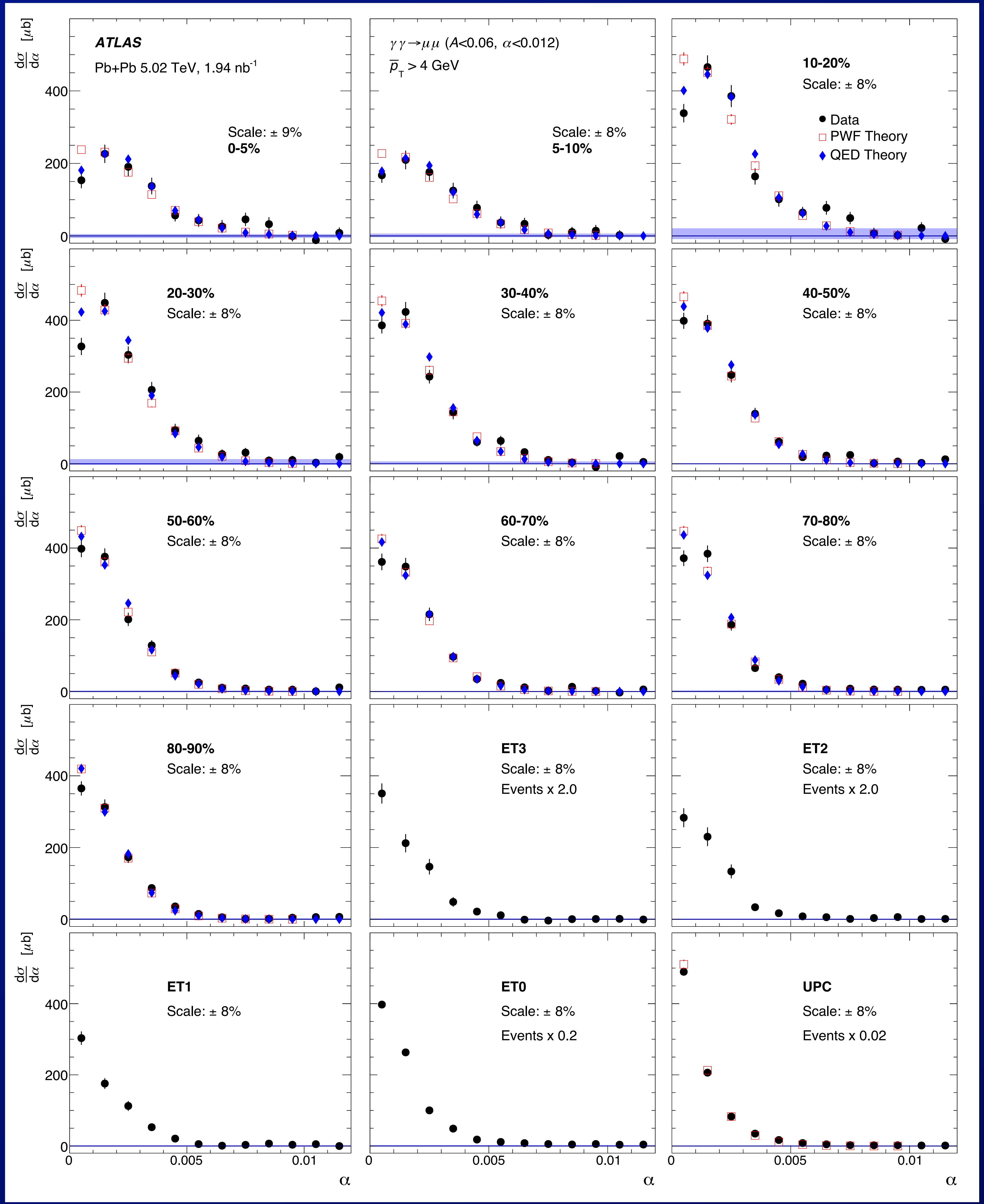
⇒The acoplanarity between the muons broadened in central collisions!

- Interaction of muons with EM fields of quark gluon plasma?

⇒NO!

$\gamma+\gamma\rightarrow\mu^+\mu^-$ production in hadronic Pb+Pb

- With 2018 Pb+Pb data, large increase in statistics, improved analysis

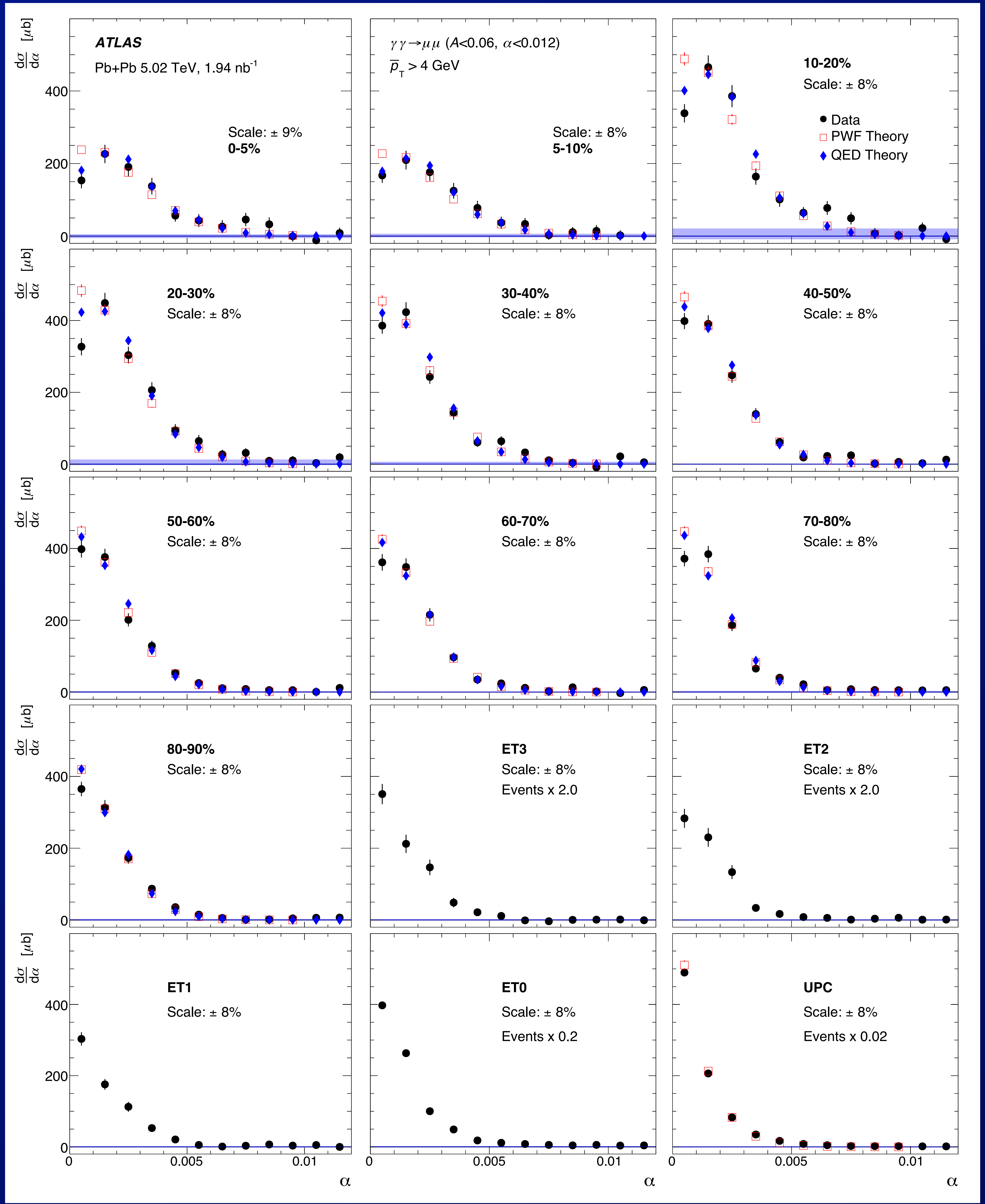


Phys. Rev. C 107, 054907

$\gamma+\gamma \rightarrow \mu^+\mu^-$ production in hadronic Pb+Pb

- **With 2018 Pb+Pb data, large increase in statistics, improved analysis**

⇒Continuous evolution from UPC to very central (0-5%) Pb+Pb collisions



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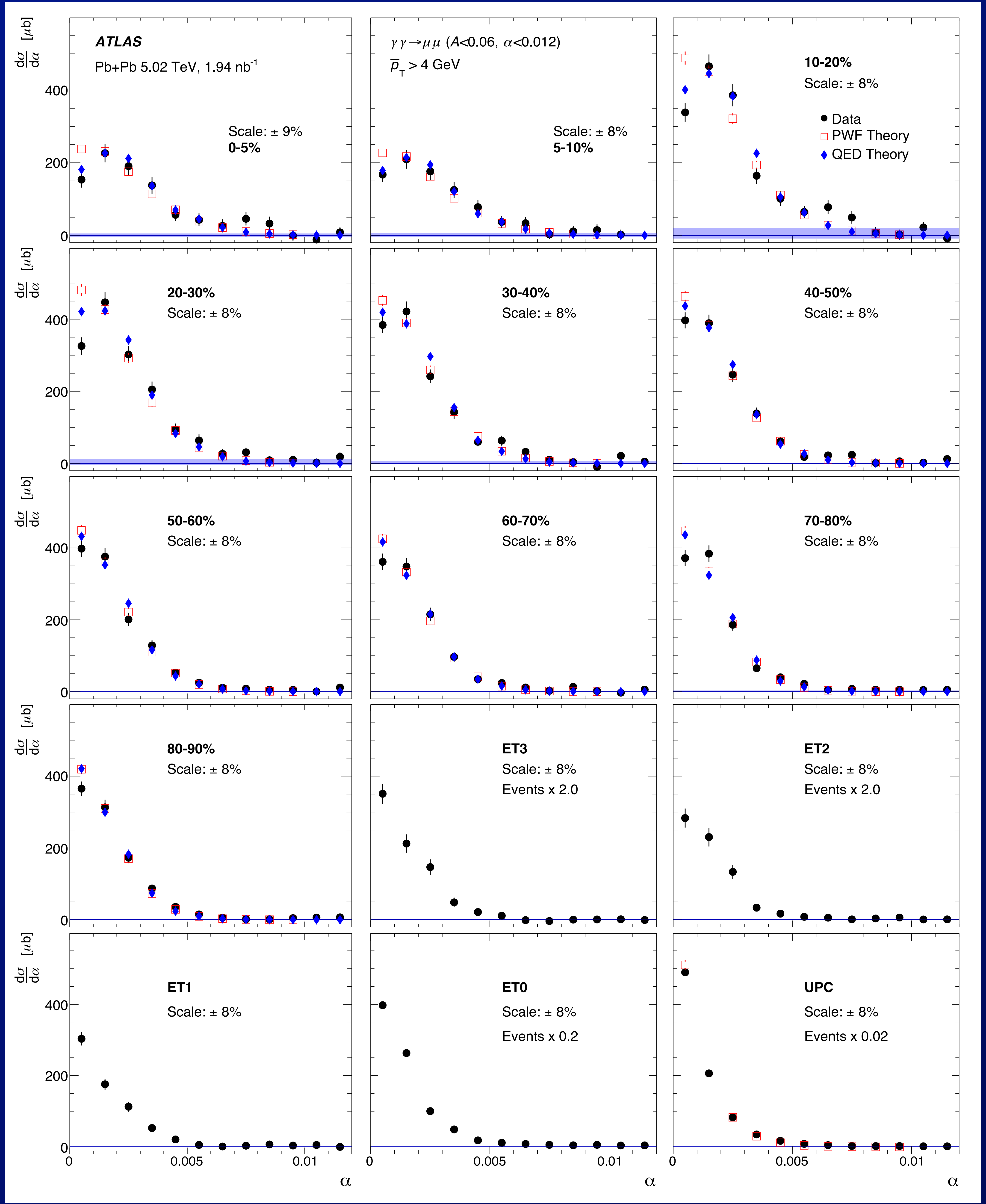
⇒Can be explained including initial-state photon k_T, dependence on b.



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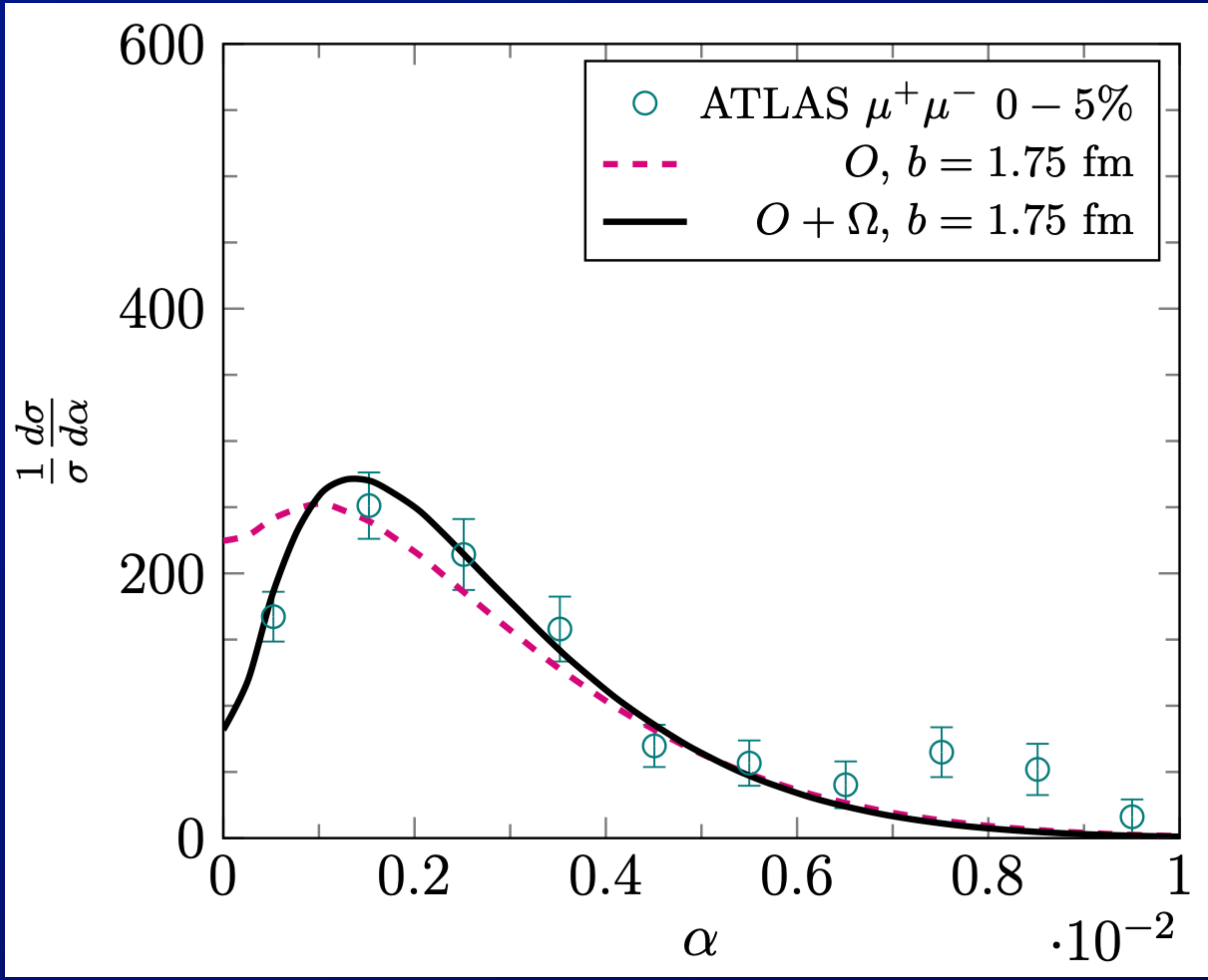
$\gamma+\gamma \rightarrow \mu^+\mu^-$ in hadronic Pb+Pb, polarization

- Recent paper with updated calculations based on photon Wigner function

Shi, Chen, Wei, Xiao, https://arxiv.org/abs/2406.07634

$$\frac{d\sigma}{dy_1 dy_2 d^2q_\perp d^2P_\perp d^2b_\perp} = \int \Gamma_{ij}(x_1, \vec{k}_{1T}, \vec{b}_{1\perp}) \otimes \Gamma_{kl}(x_2, \vec{k}_{2T}, \vec{b}_{2\perp}) \otimes \mathcal{H}^{ijkl}(\vec{P}_\perp). \quad (5)$$

$$\mathcal{H}^{ijkl}(\vec{P}_\perp) = \frac{\alpha_{\rm em}^2}{\hat{s}^2}\left[O^{ijkl}(\vec{P}_\perp) - 4\Omega^{ijkl}(\vec{P}_\perp)\right], \quad (6)$$



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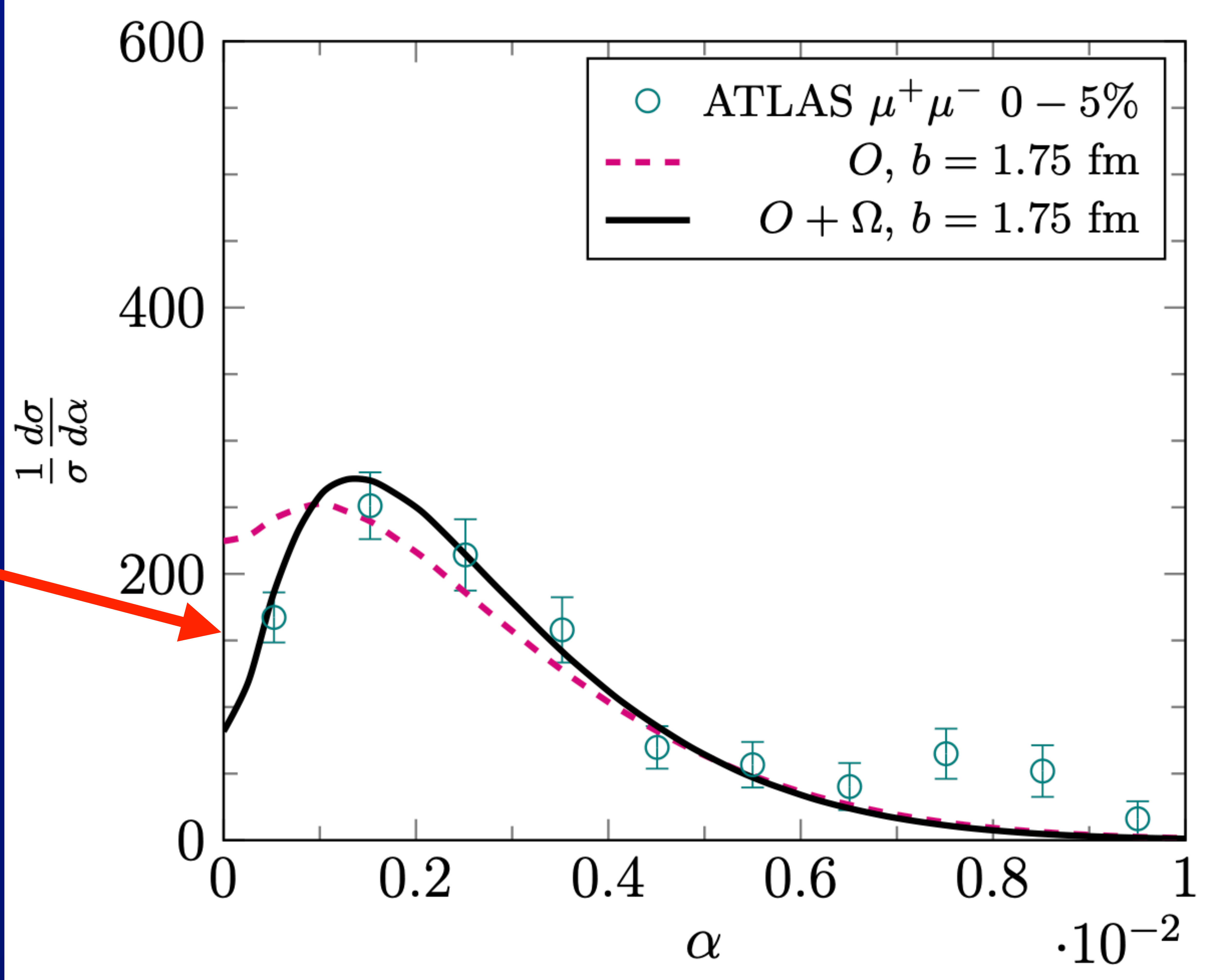
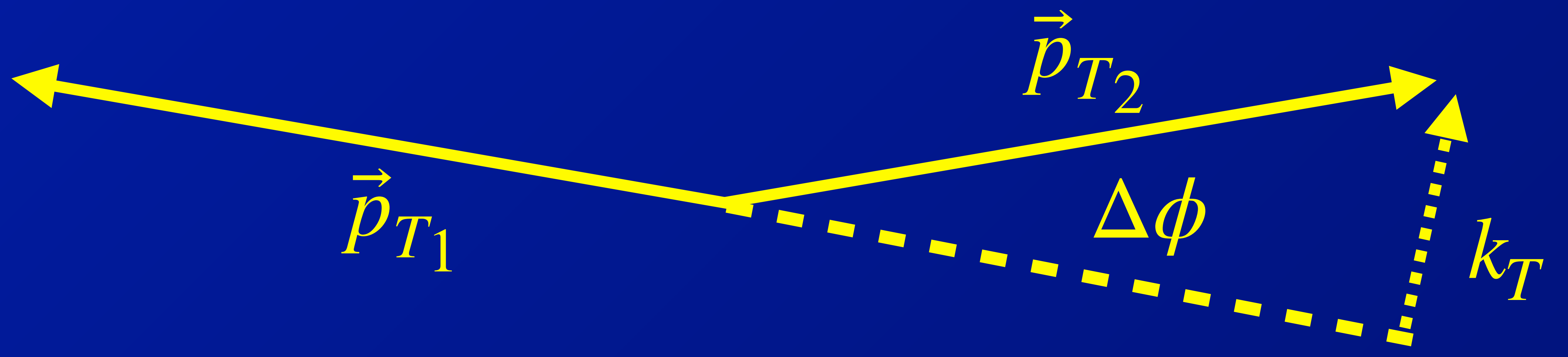
⇒Suppression of small-α pairs results from linear polarization of photons



$\gamma+\gamma\rightarrow\mu^+\mu^-$ production in hadronic Pb+Pb

- **Deflection better expressed in terms of perpendicular momentum (k_T) of one muon relative to the other**



– $$k_\perp \equiv \frac{1}{2}(p_{\mathrm{T}1}+p_{\mathrm{T}2})(\pi-|\phi_1-\phi_2|) = \pi\alpha\bar{p}_{\mathrm{T}},$$

⇒The physics contributes <u>transverse momentum</u> to the muons

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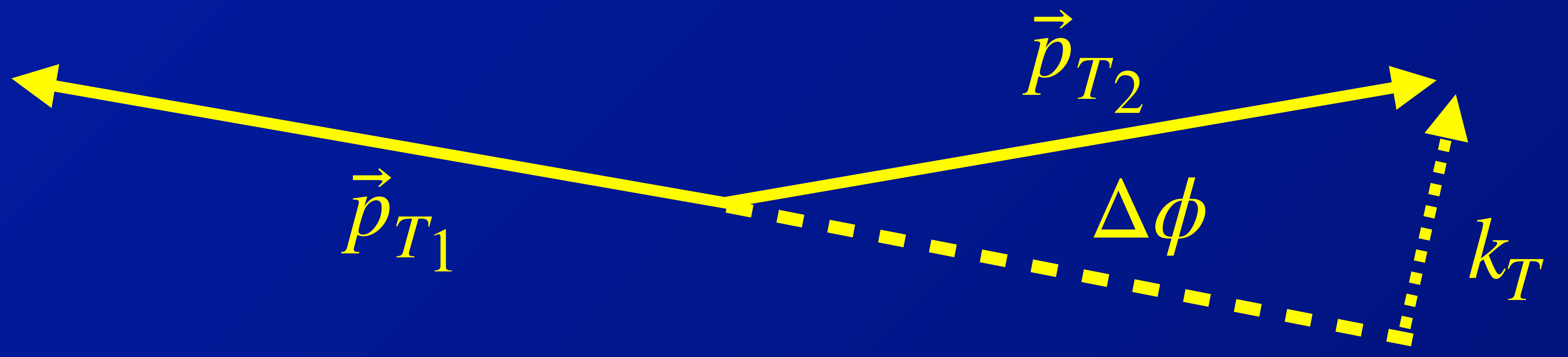

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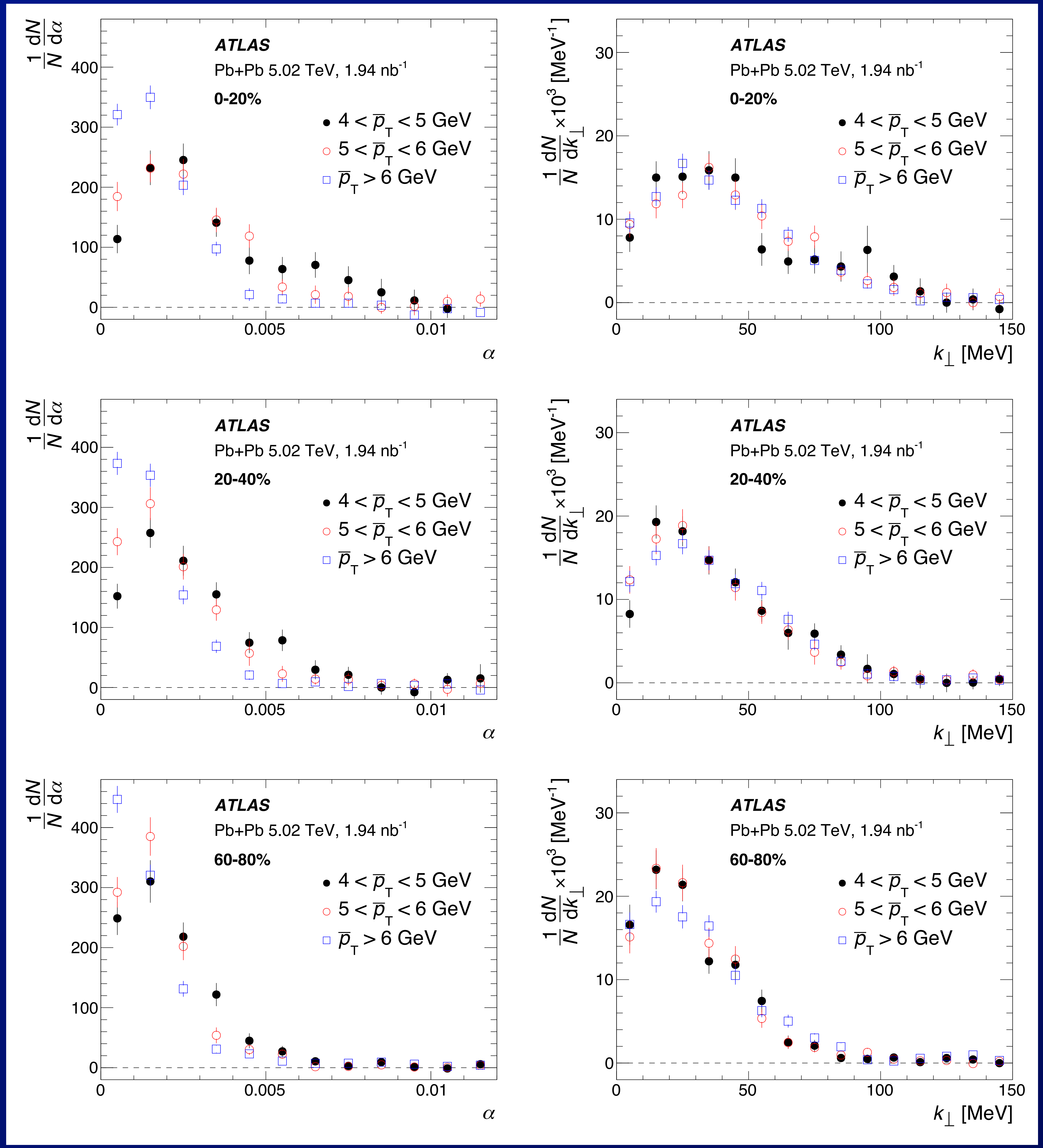

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$\gamma+\gamma \rightarrow \mu^+\mu^-$ production in hadronic Pb+Pb

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$\gamma+\gamma\rightarrow\mu^{+}\mu^{-}$ in hadronic Pb+Pb collisions

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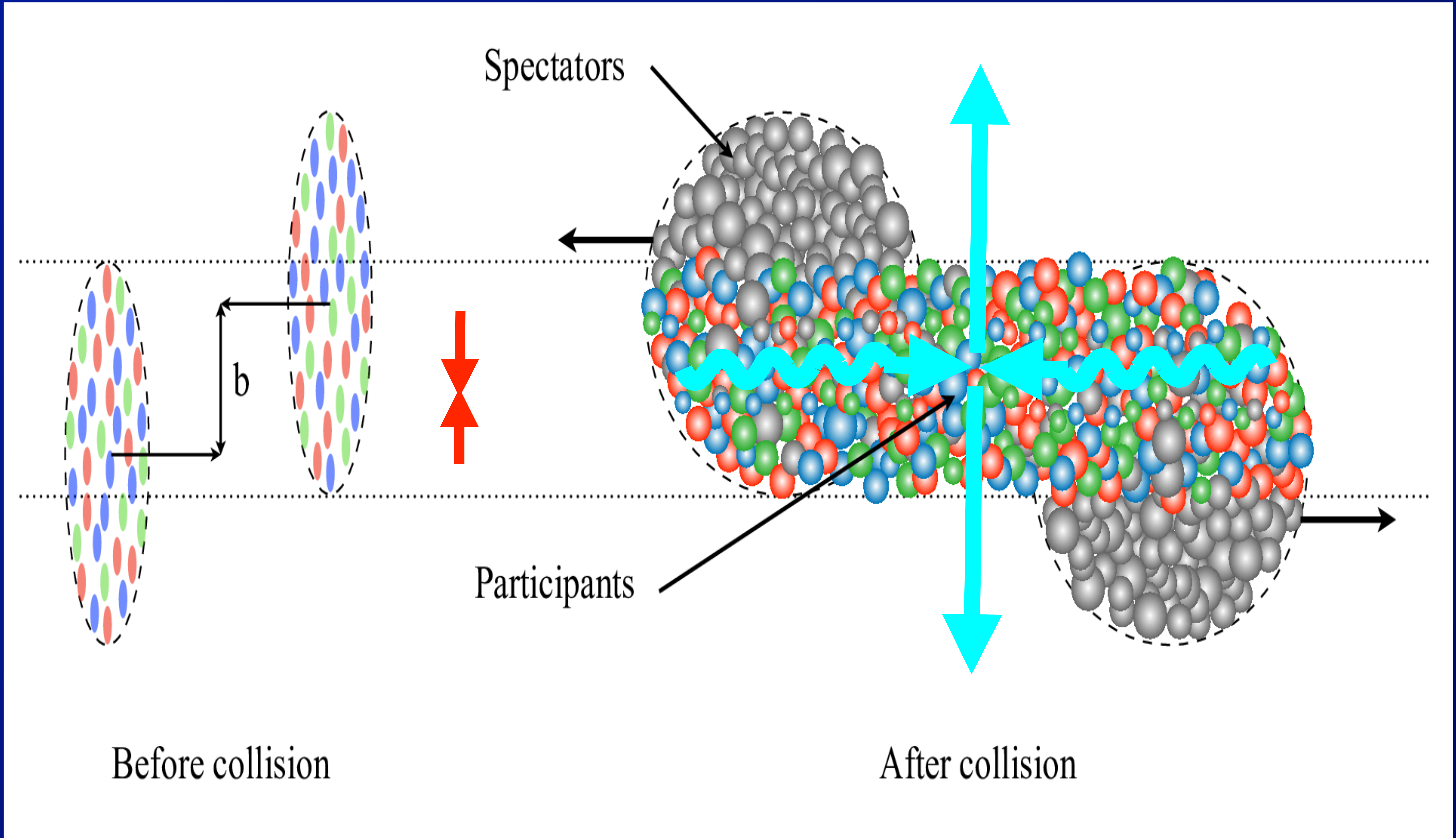

γ+γ dilepton production in hadronic Pb+Pb

- What happens as b → 0?
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- What sets the momentum scale for the peak in the k_T distribution?

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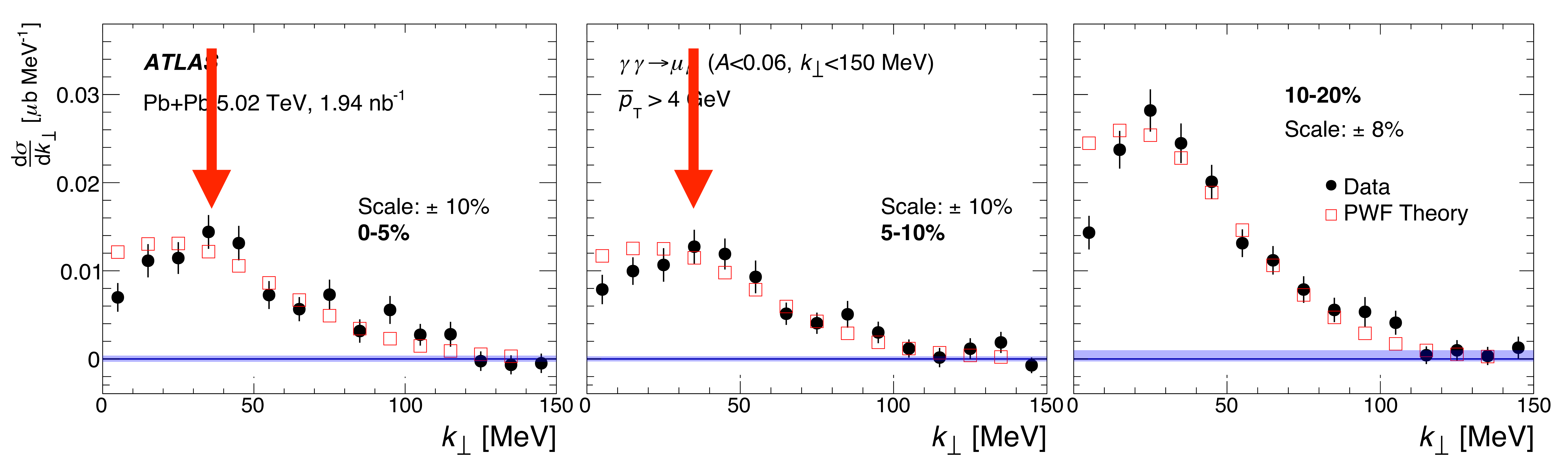

γ+γ dilepton production in hadronic Pb+Pb

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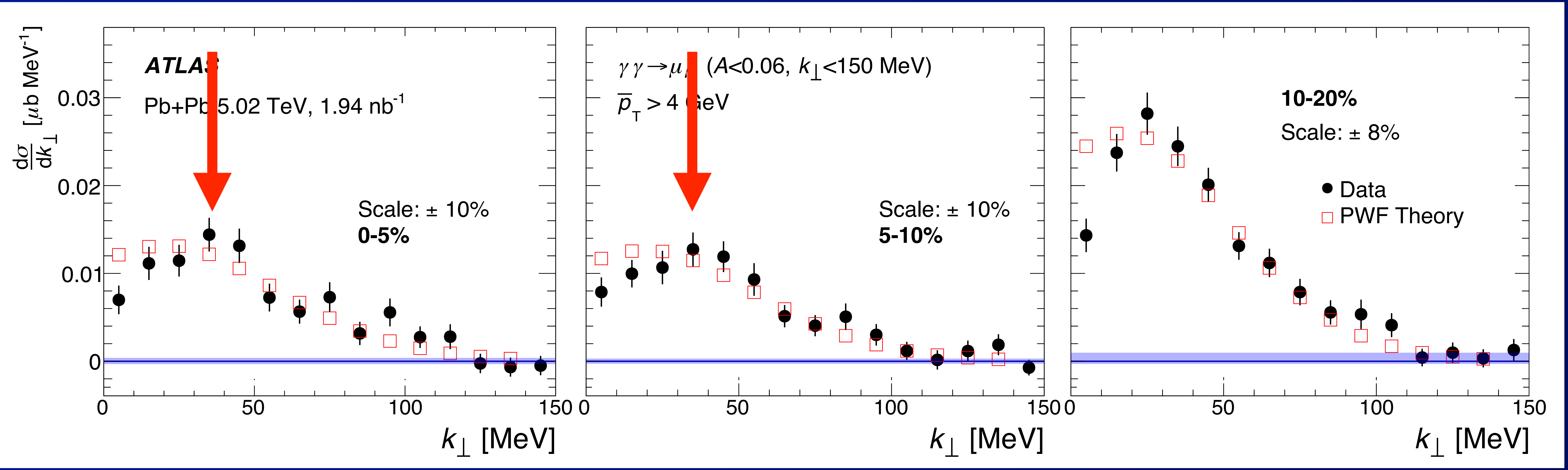
- What sets the momentum scale for the peak in the k_T distribution?

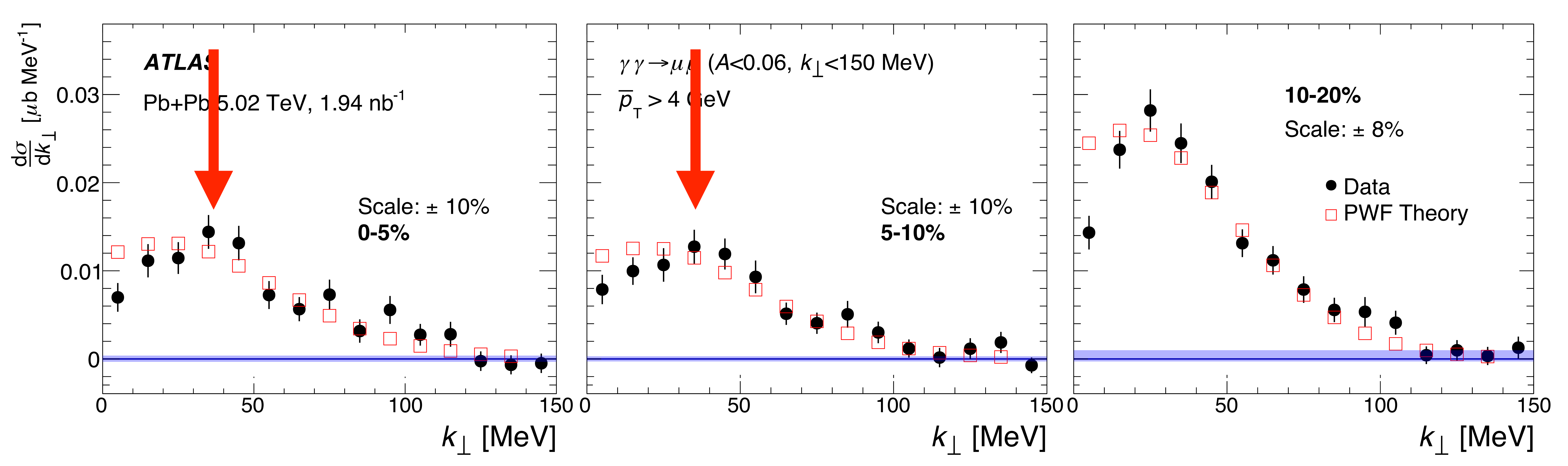
⇒ Intrinsic (electromagnetic) property of the Pb nucleus?

⇒ New constraint on EM form factor?



γ+γ dilepton production in hadronic Pb+Pb

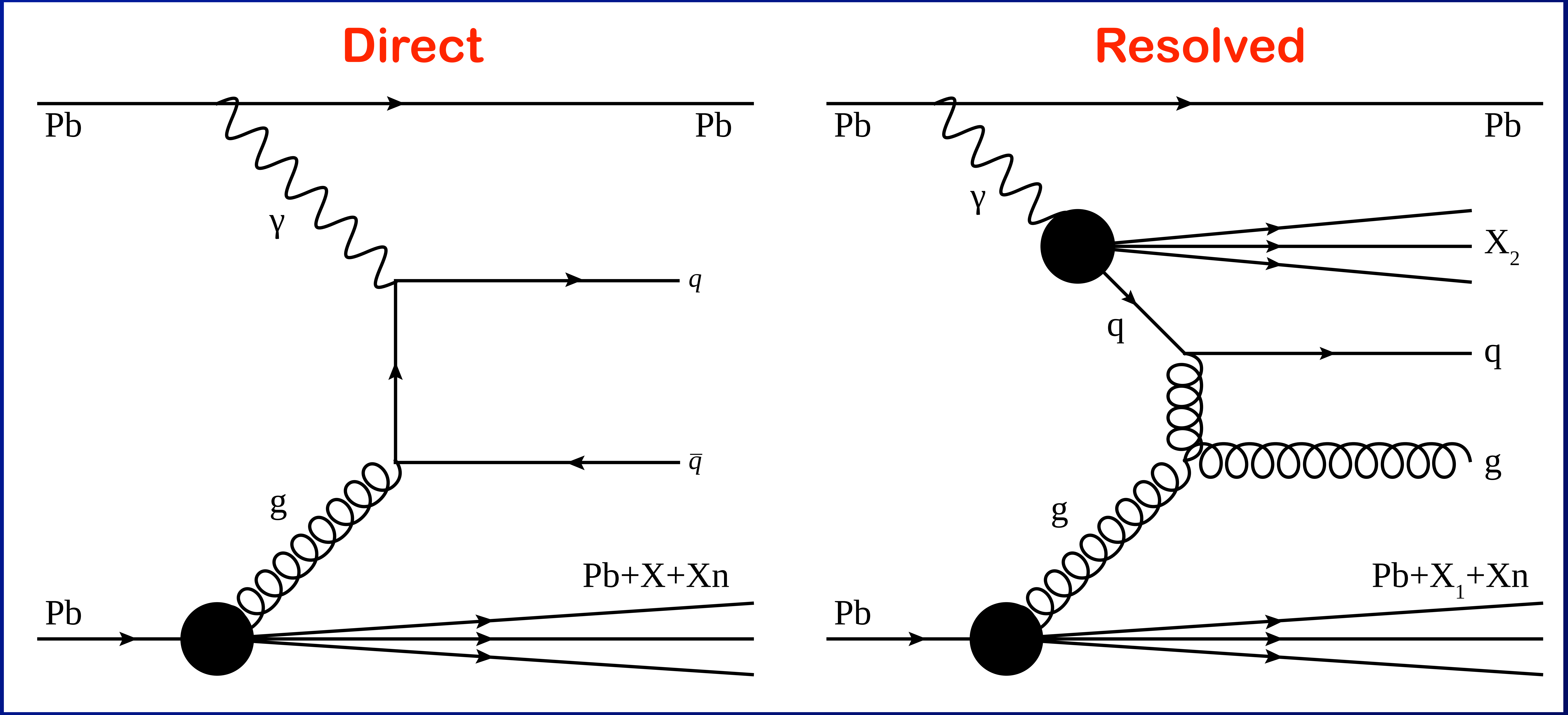
- **What happens as b → 0?**
  – No longer a relevant dimensionful scale …
- **What sets the momentum scale for the peak in the k_T distribution?**
  ⇒ Intrinsic (electromagnetic) property of the Pb nucleus?
  ⇒ New constraint on EM form factor?
- **With Run 3 data should be able to probe Pb+Pb centrally < 1%**



Photonuclear dijet/multijet production

UPC photonuclear jet production

- (Mostly) coherent photon from one nucleus
  - scatters off a parton from the other (direct)
  - breaks up, daughter parton scatters off other nucleus (resolved)



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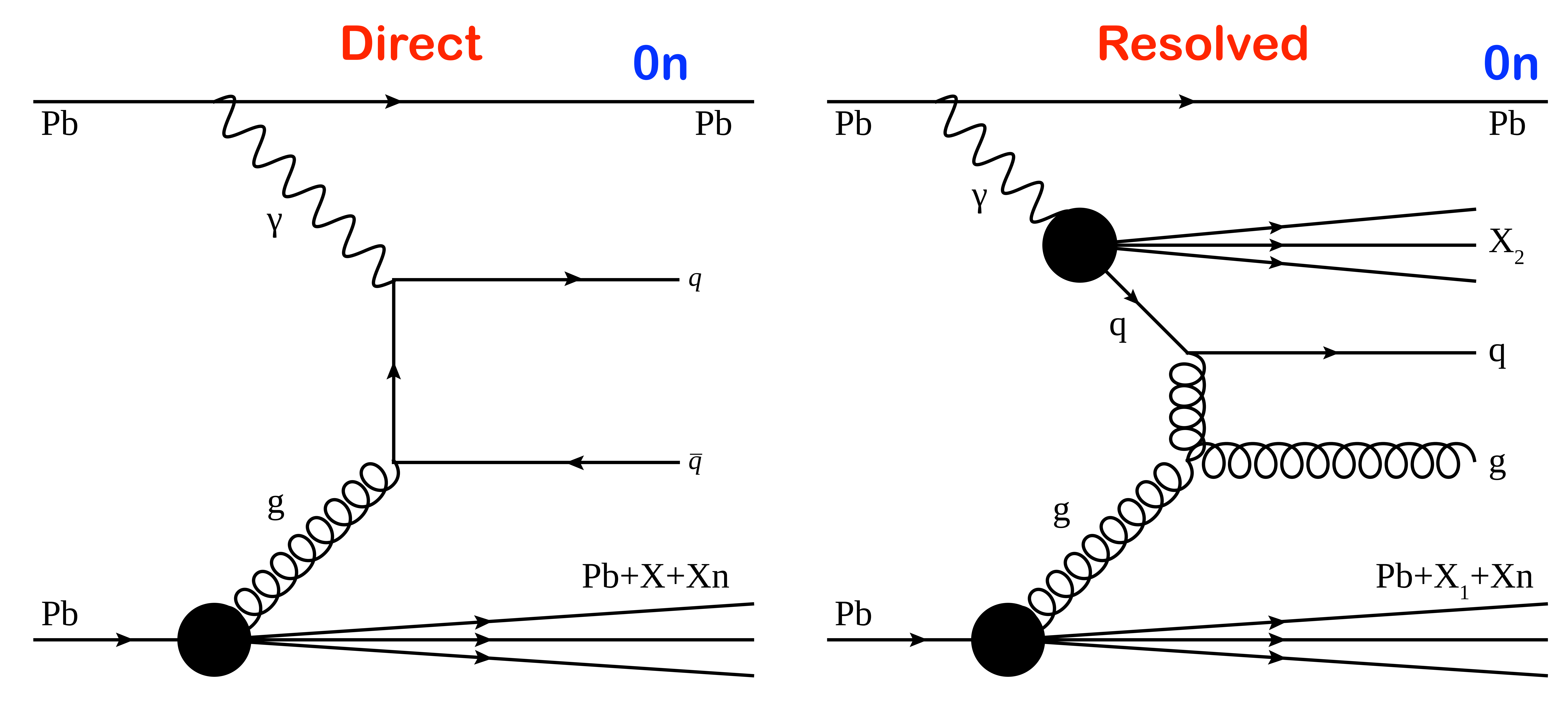
⇒ Venerable idea (Strikman, Frankfurt): use to measure nuclear PDFs



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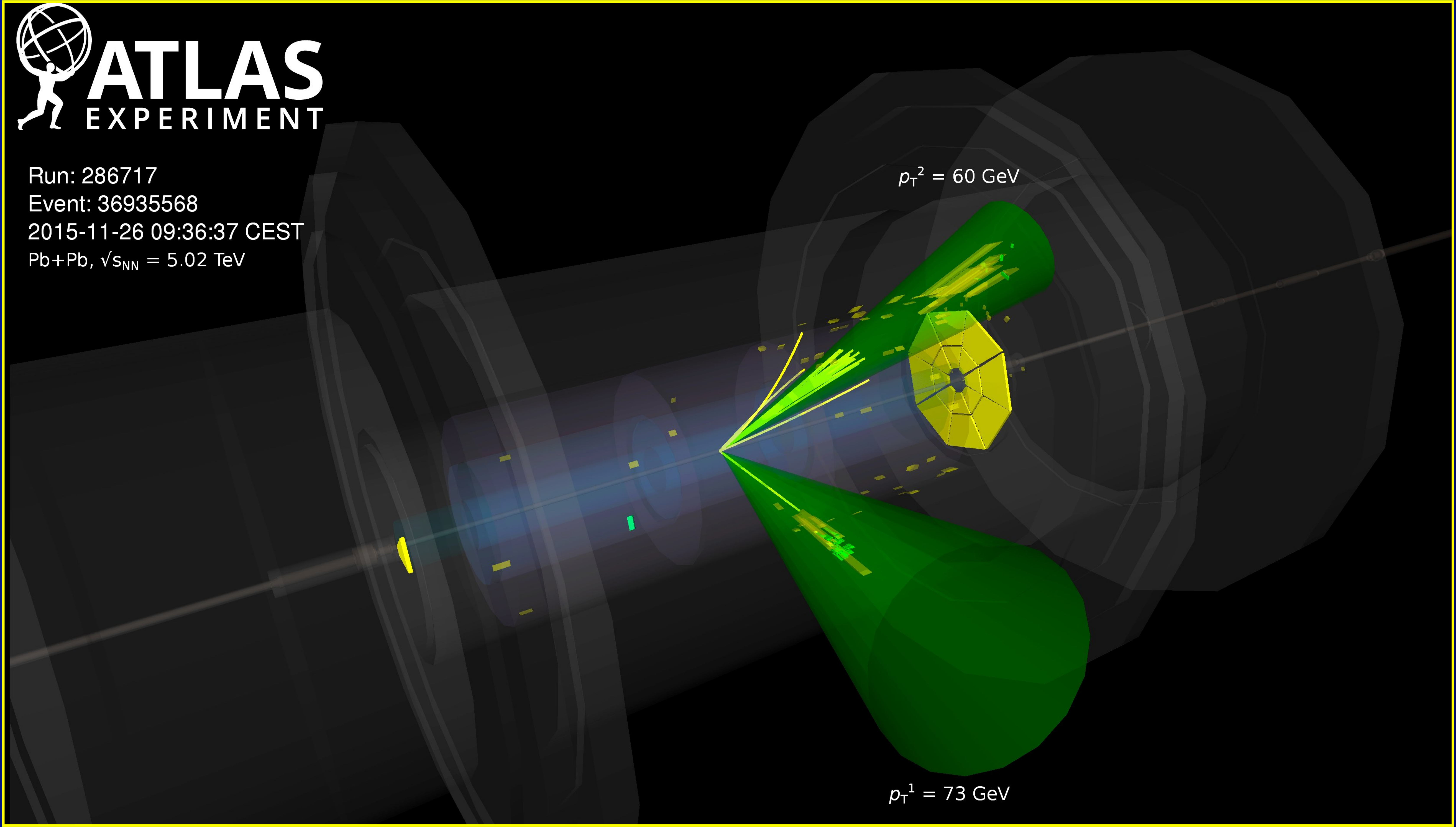
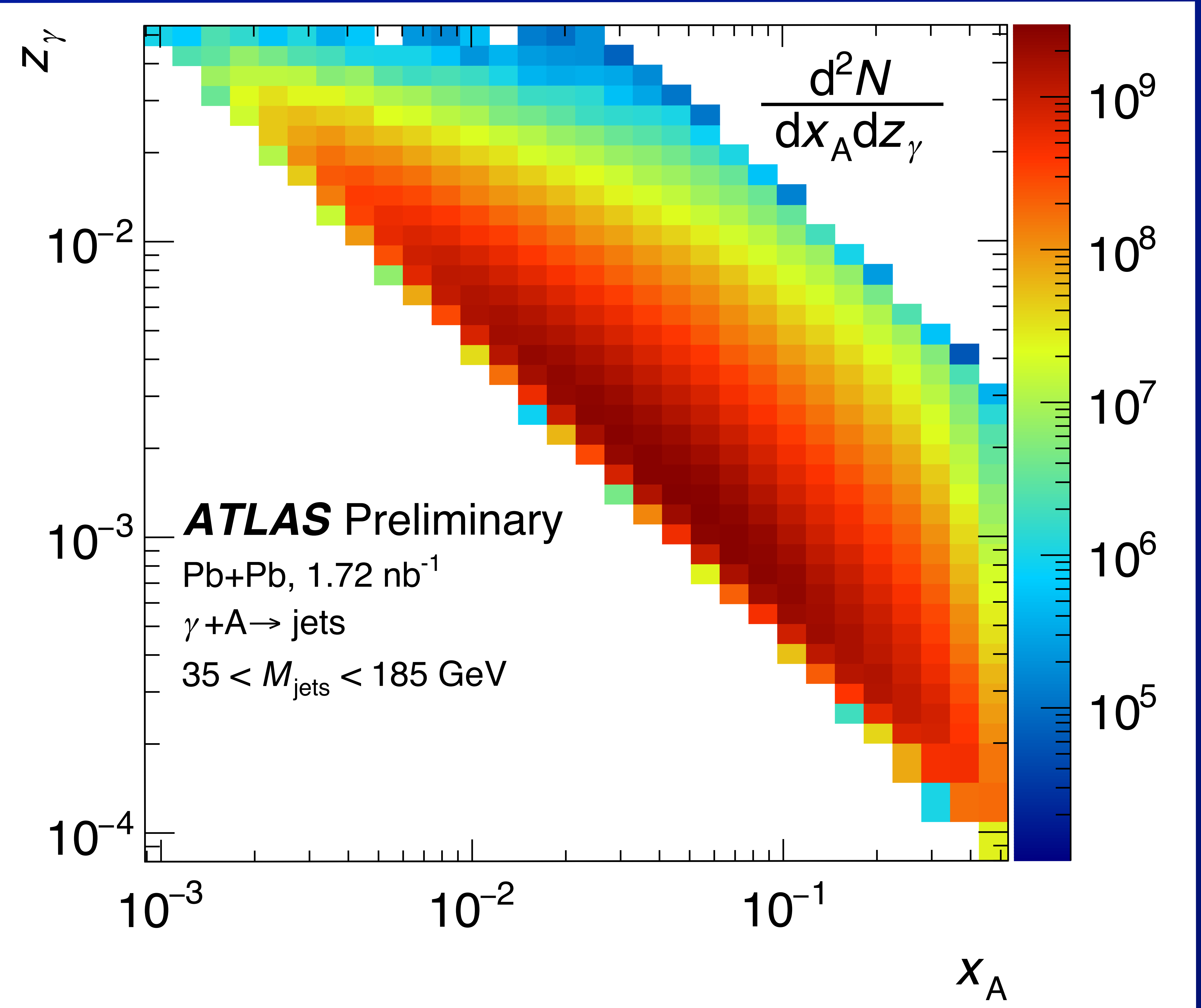
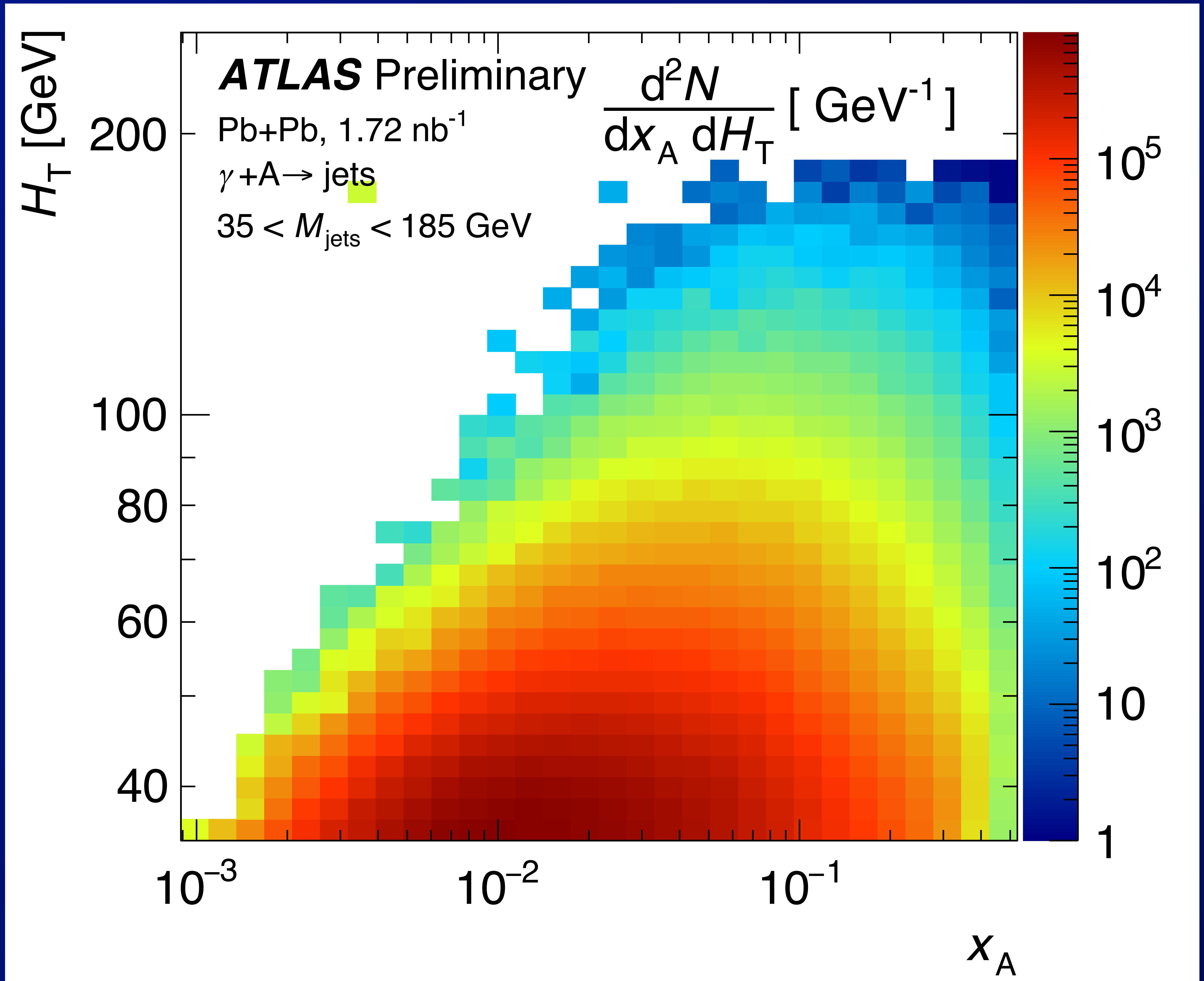


Photonuclear kinematics

- From the dijet (N jet) mass and rapidity, reconstruct LO kinematics:
  - $H_T = \sum_{\text{jets}} p_T \approx Q \qquad x_A = \frac{m_{\text{jets}}\, e^{-y_{\text{jets}}}}{\sqrt{S}} \qquad z_\gamma = y_\gamma \times x = \frac{m_{\text{jets}}\, e^{+y_{\text{jets}}}}{\sqrt{S}}$

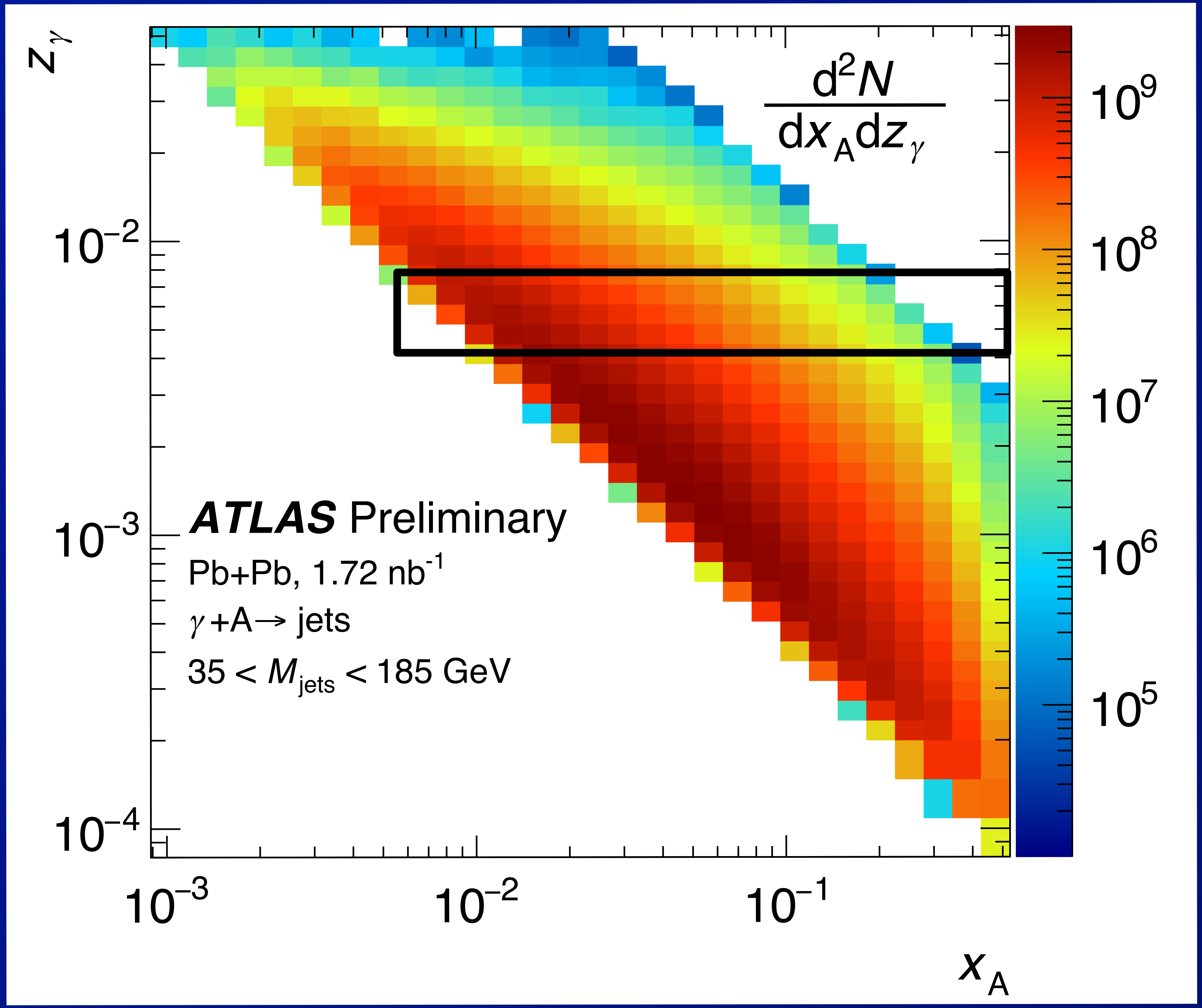


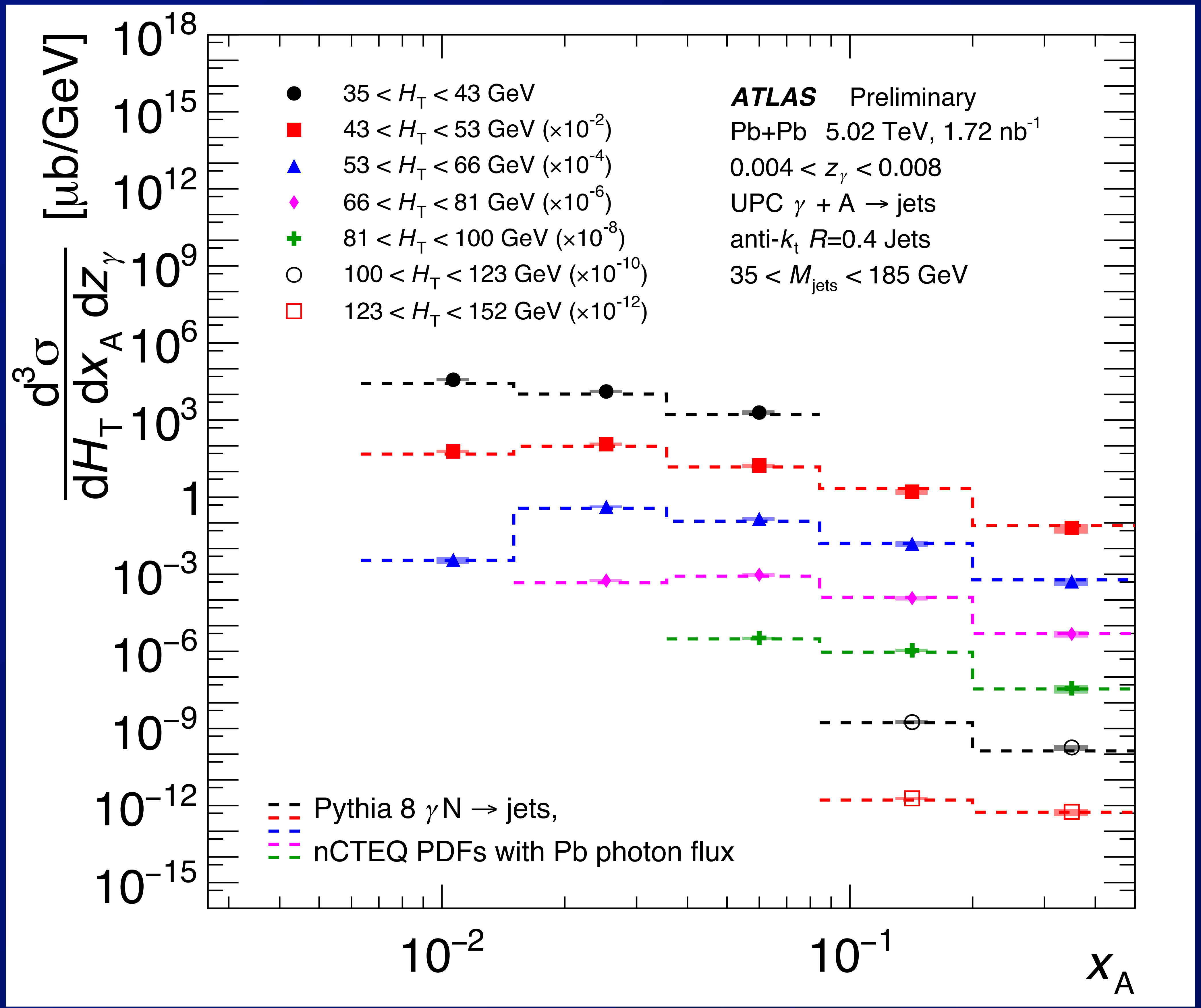


Cross-sections

- **Measure triple-differential cross-section:**
  - Unfolded to particle level (mostly jet response)

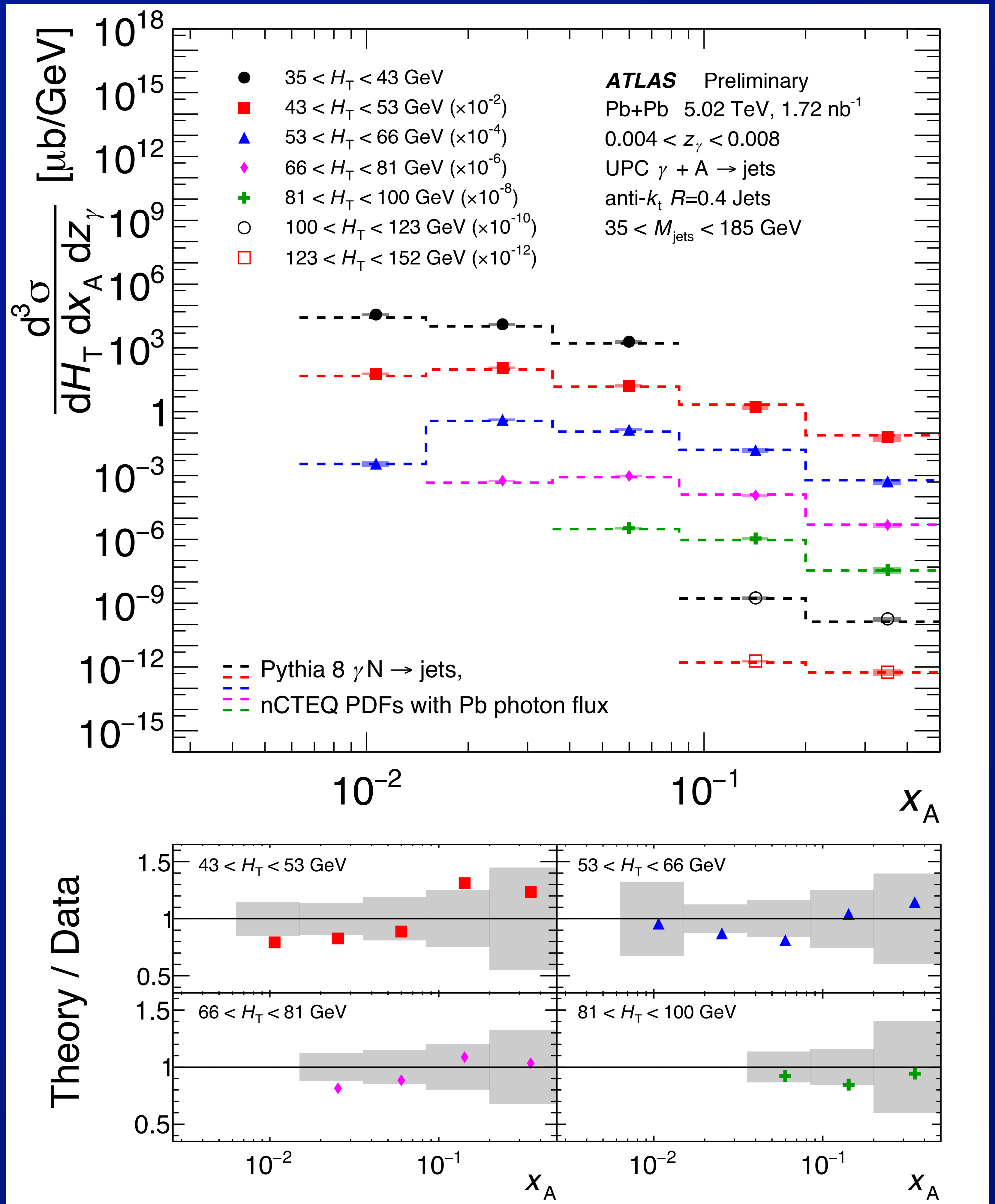
$$\Rightarrow \frac{d^3\sigma}{dH_T\, dx_A\, dz_\gamma} = \frac{1}{\mathcal{L}} \frac{N_{\mathrm{evt}}}{\Delta H_T\, \Delta x_A\, \Delta z_\gamma}$$

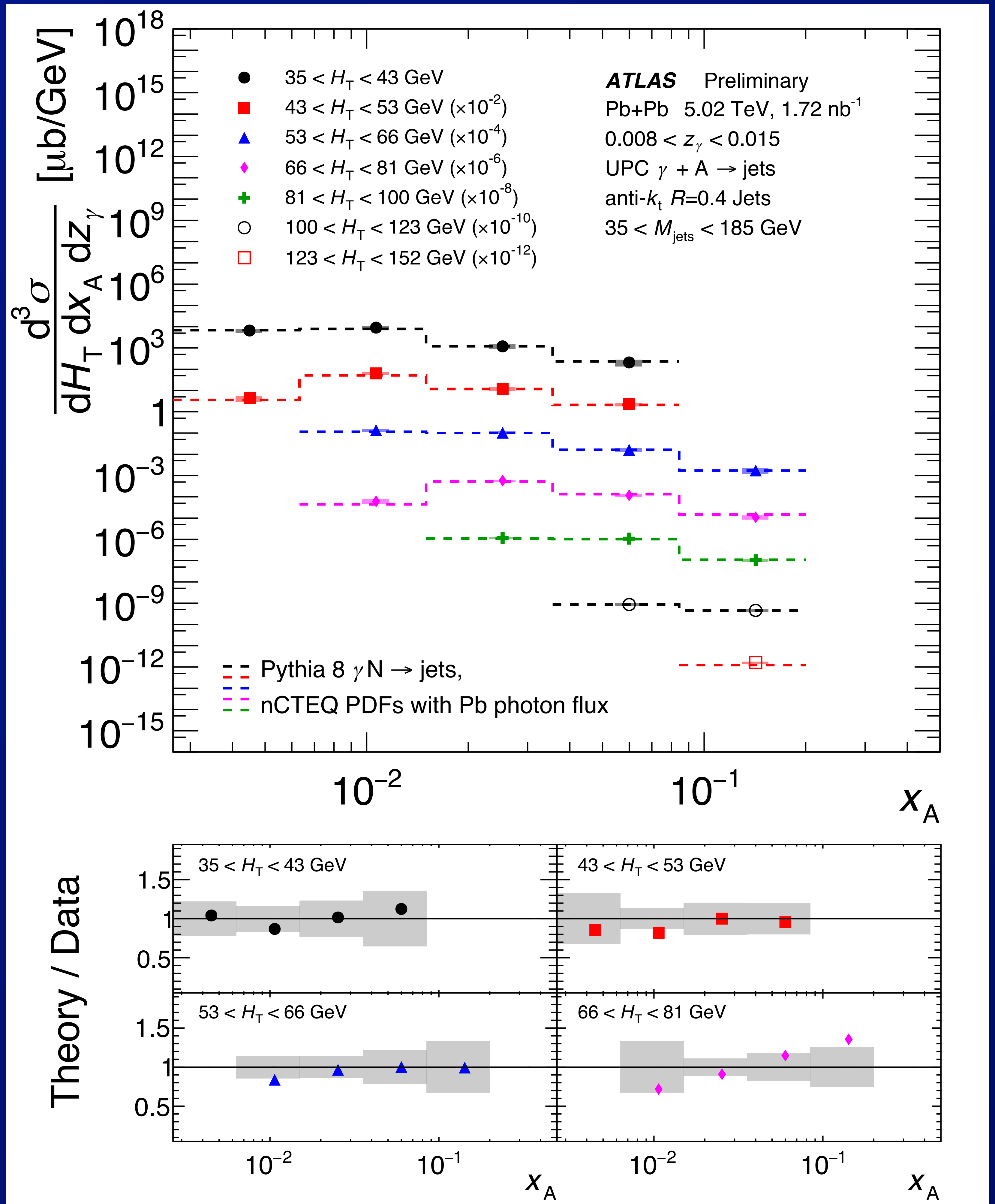




Compare to Pythia8 (with breakup correction)

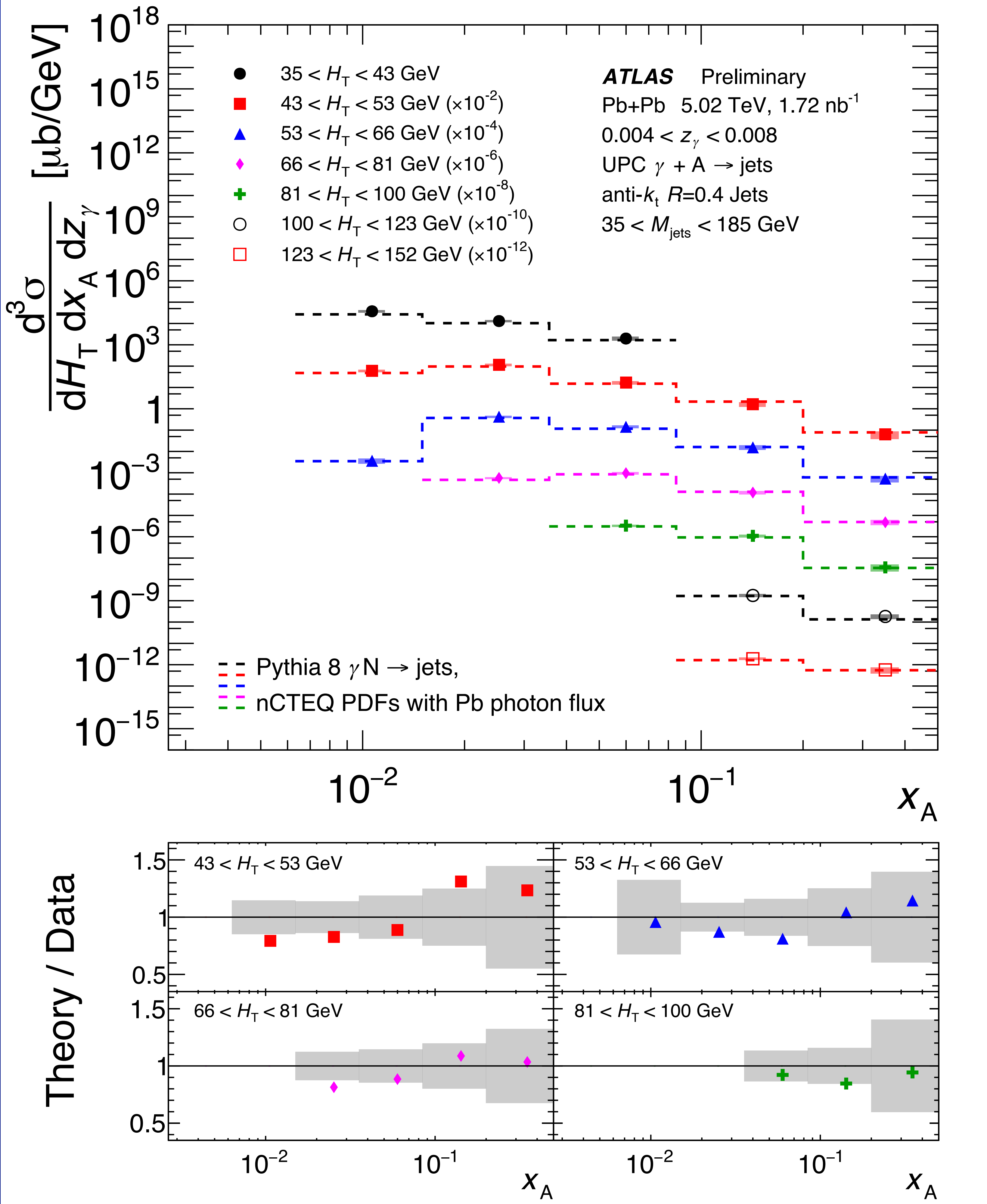
- Preliminary results with comparisons to Pythia8 w/ nCTEQ15 nPDFs

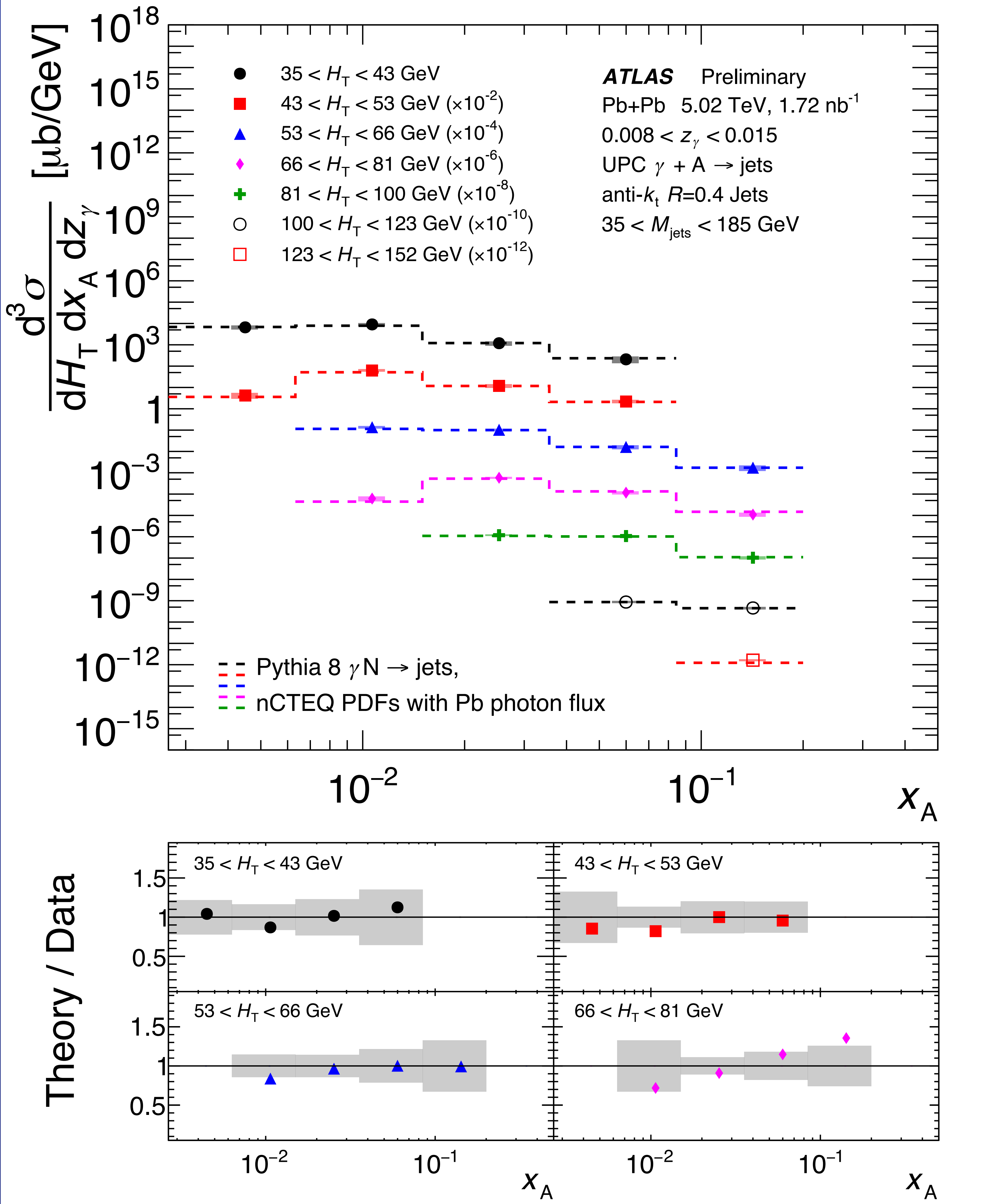




Compare to Pythia8 + breakup

- With recent completion of ATLAS low-μ jet calibration
  - Systematic uncertainties decreased significantly in final result





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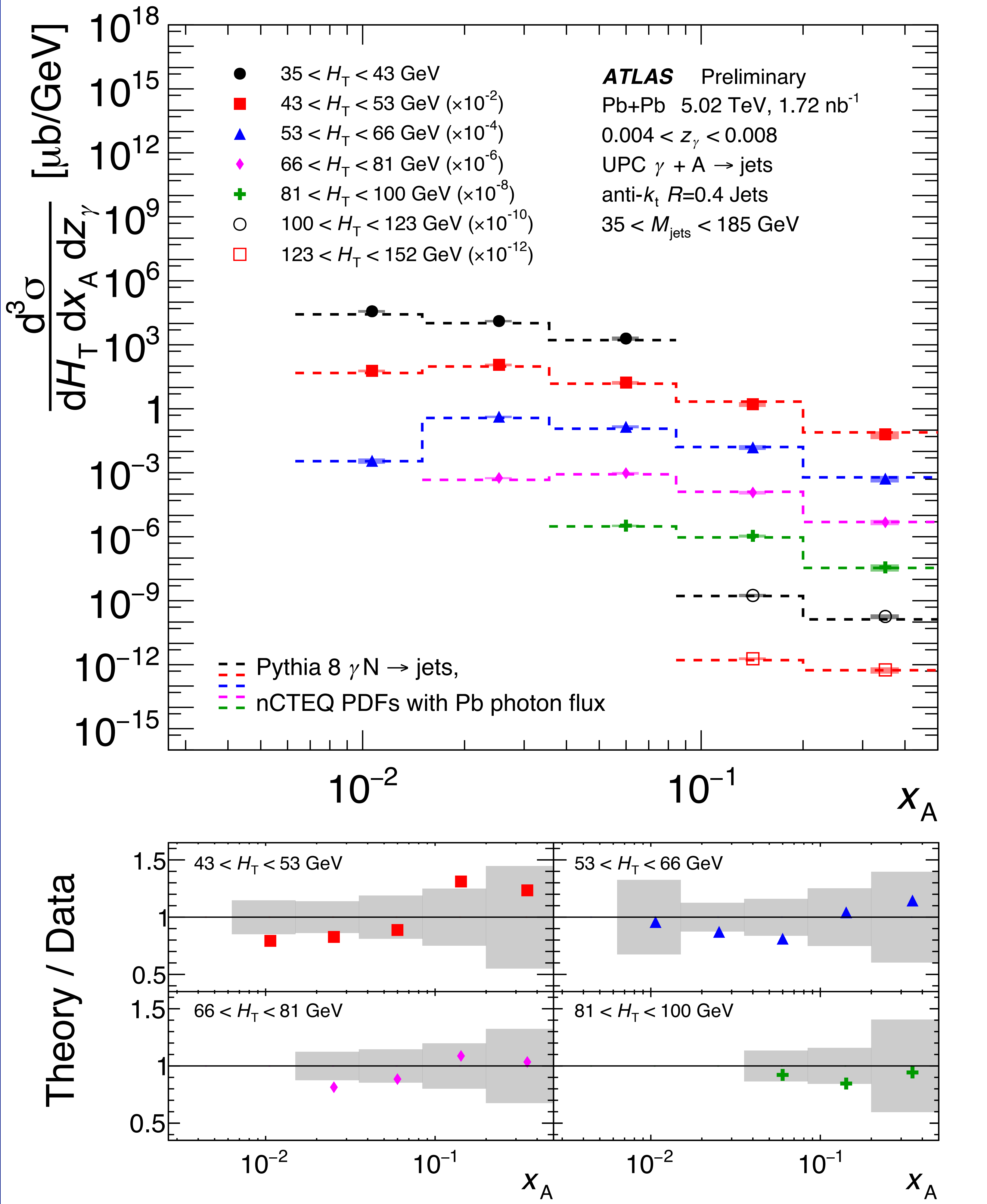
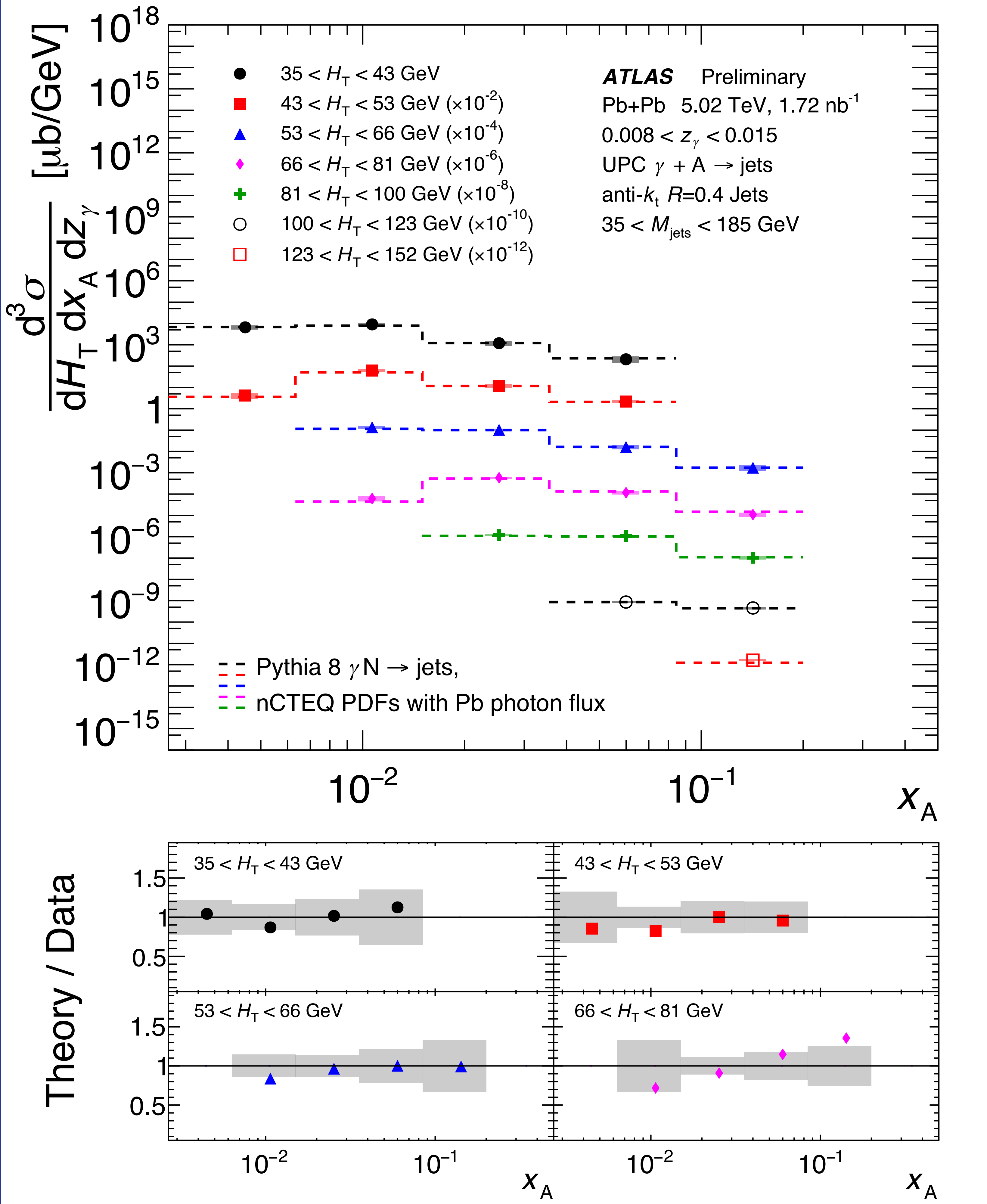
⇒expected September 2024





γ+A collisions, nuclear breakup

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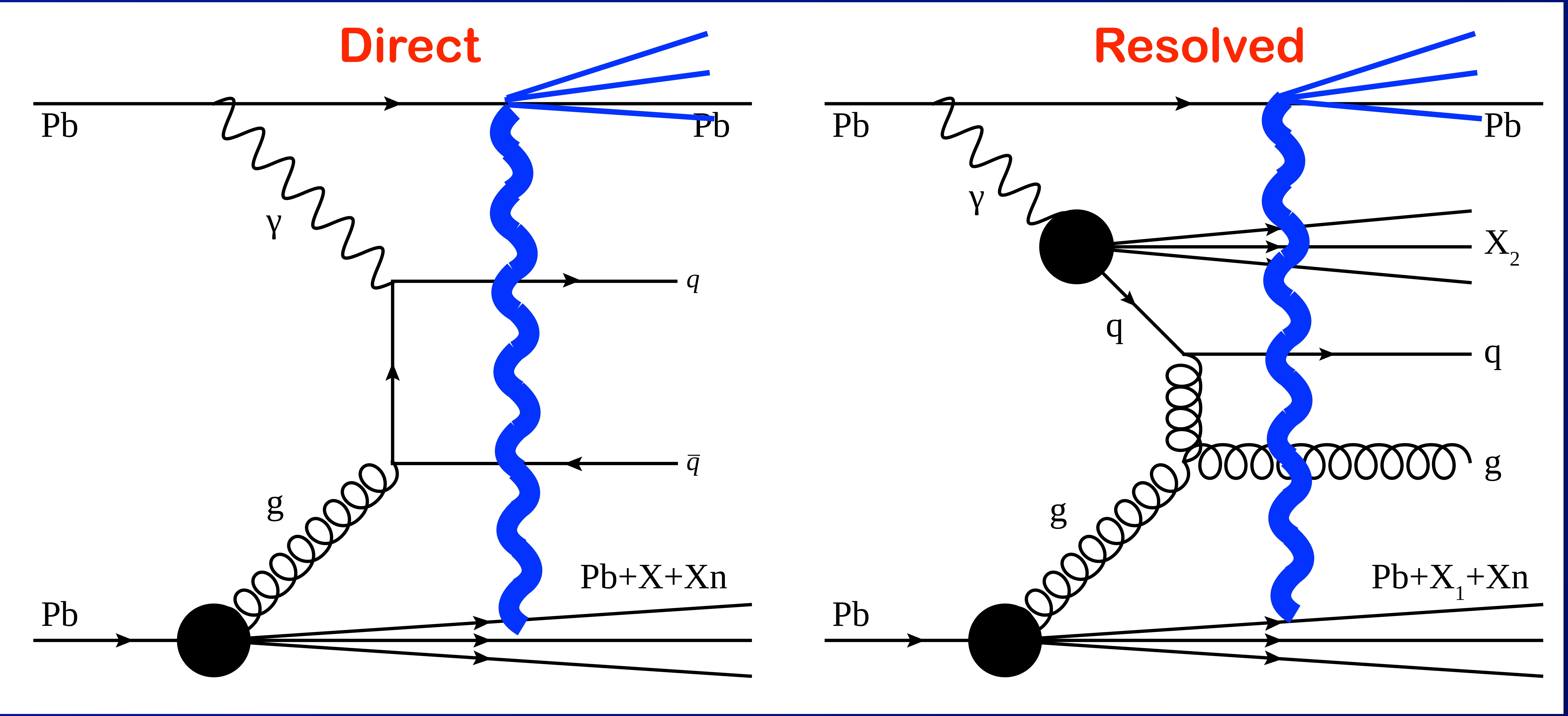

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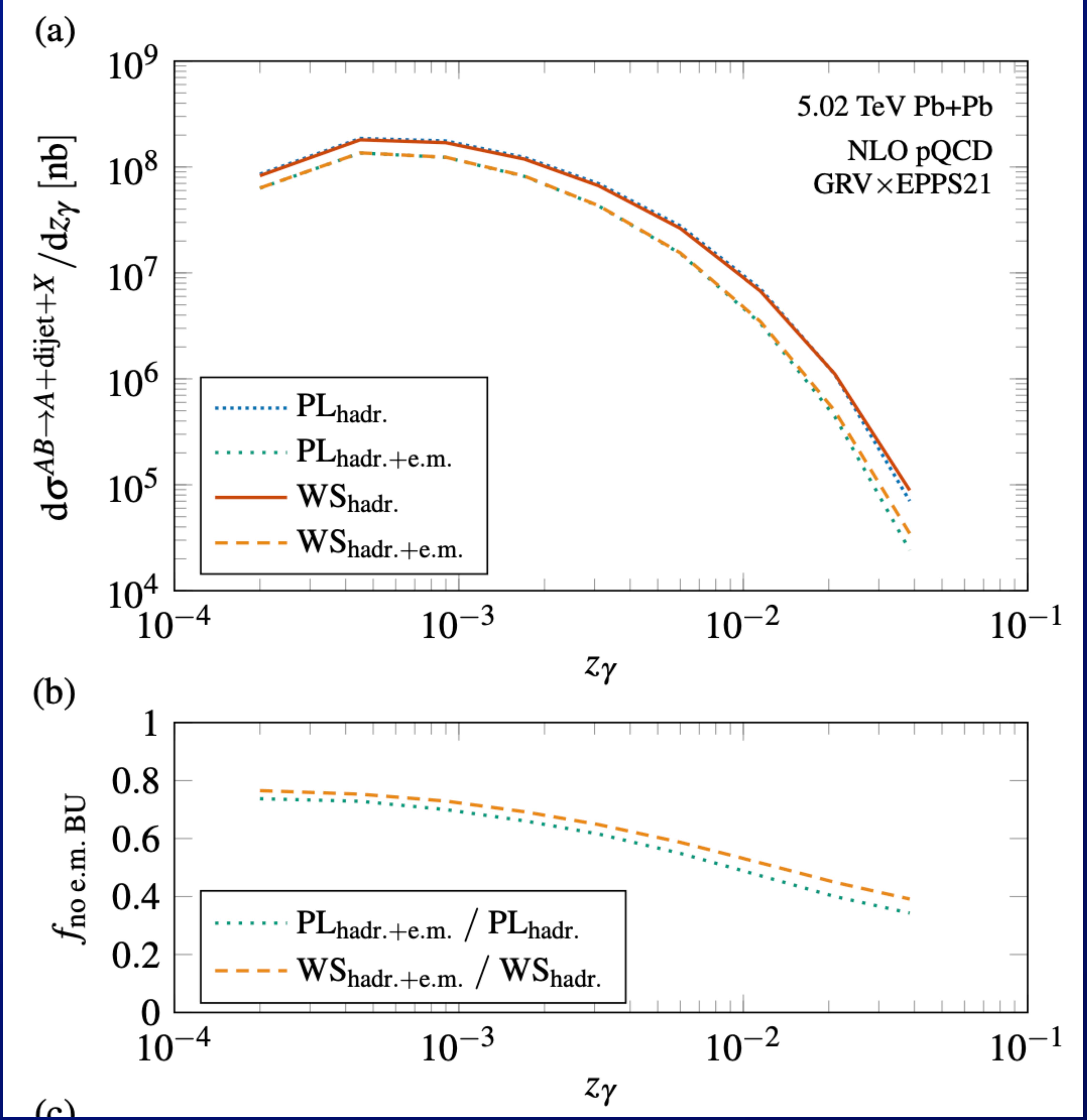
⇒e.g.



Eskola, Guzey et al, arxiv:2404.09731

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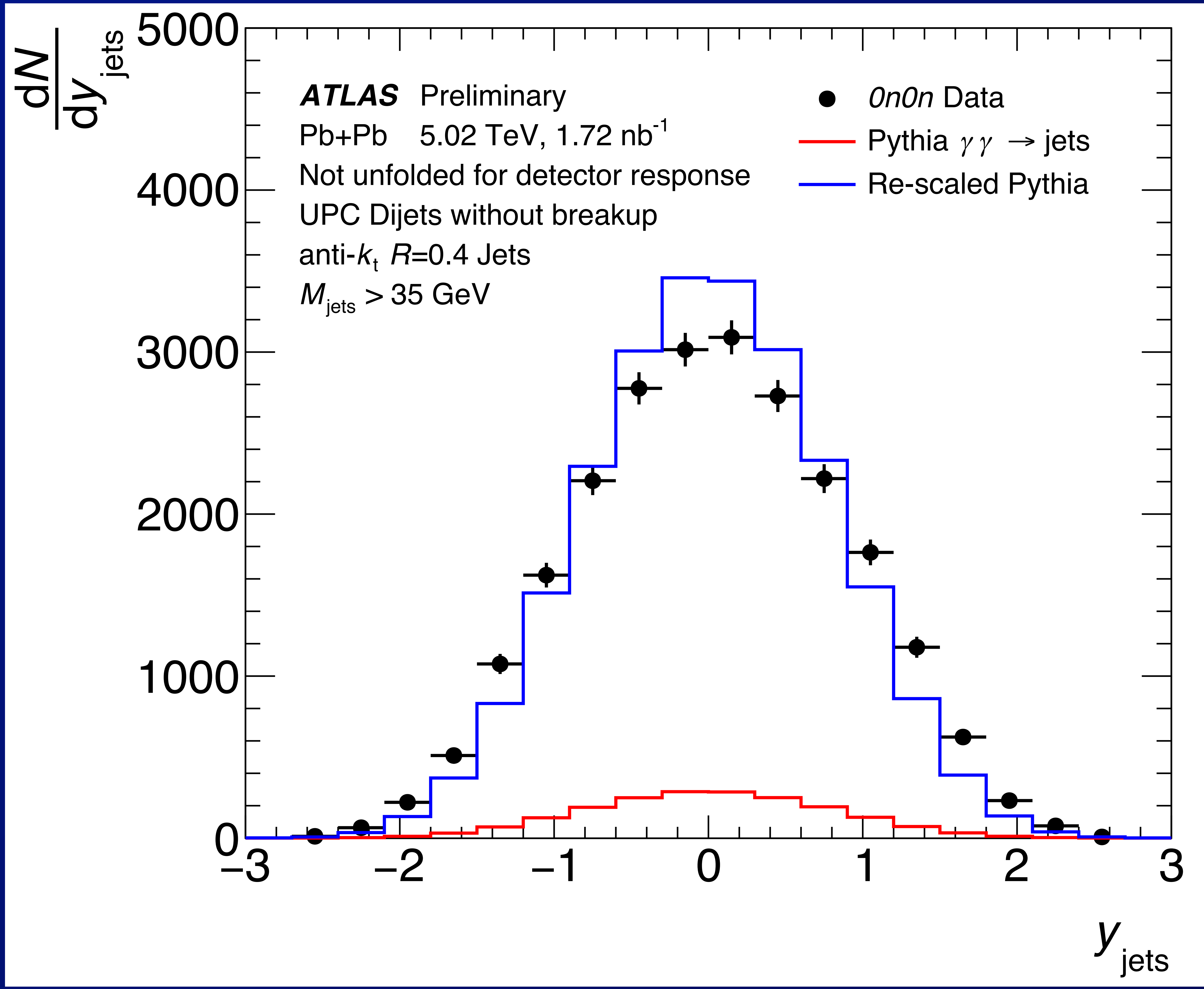

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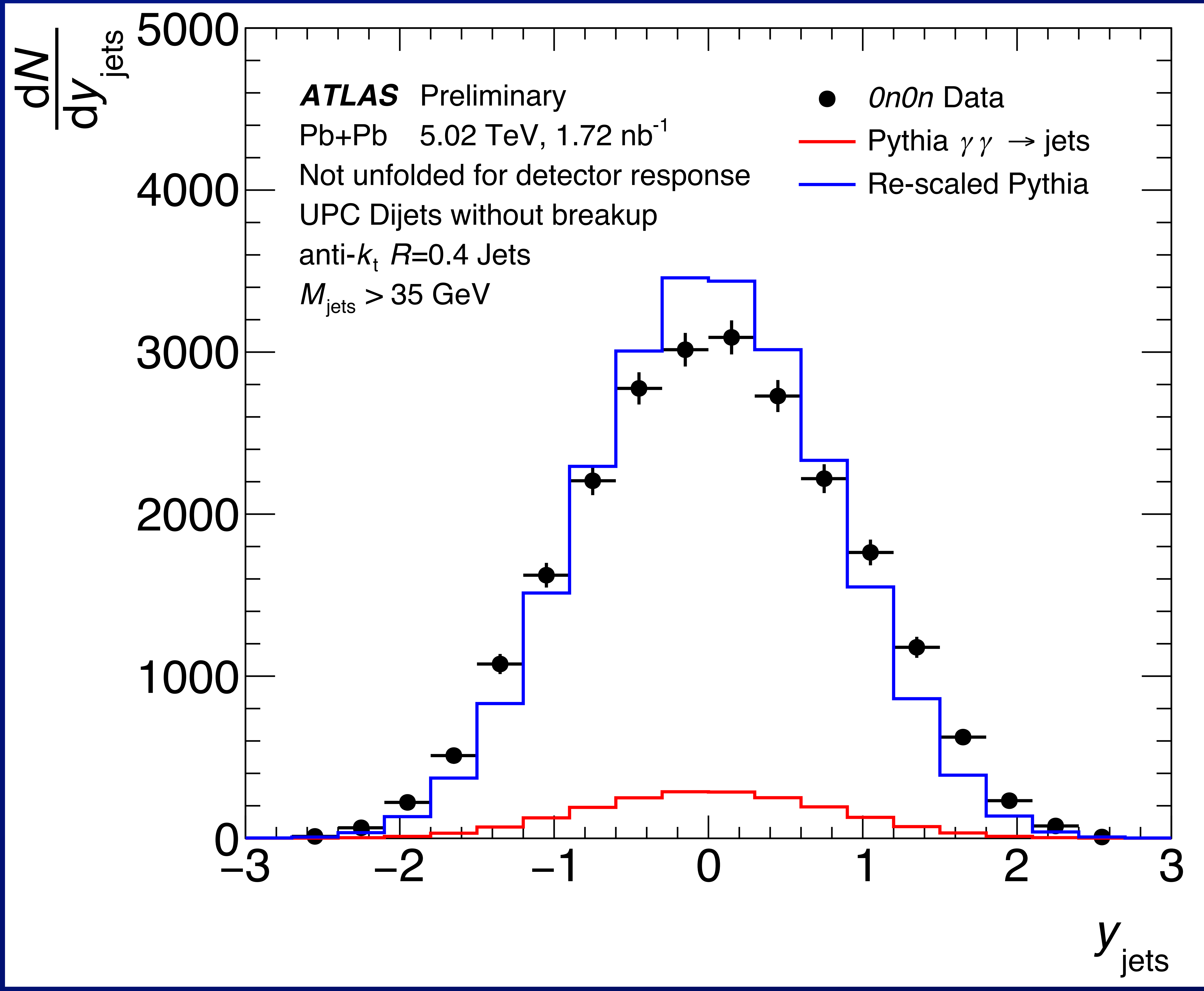

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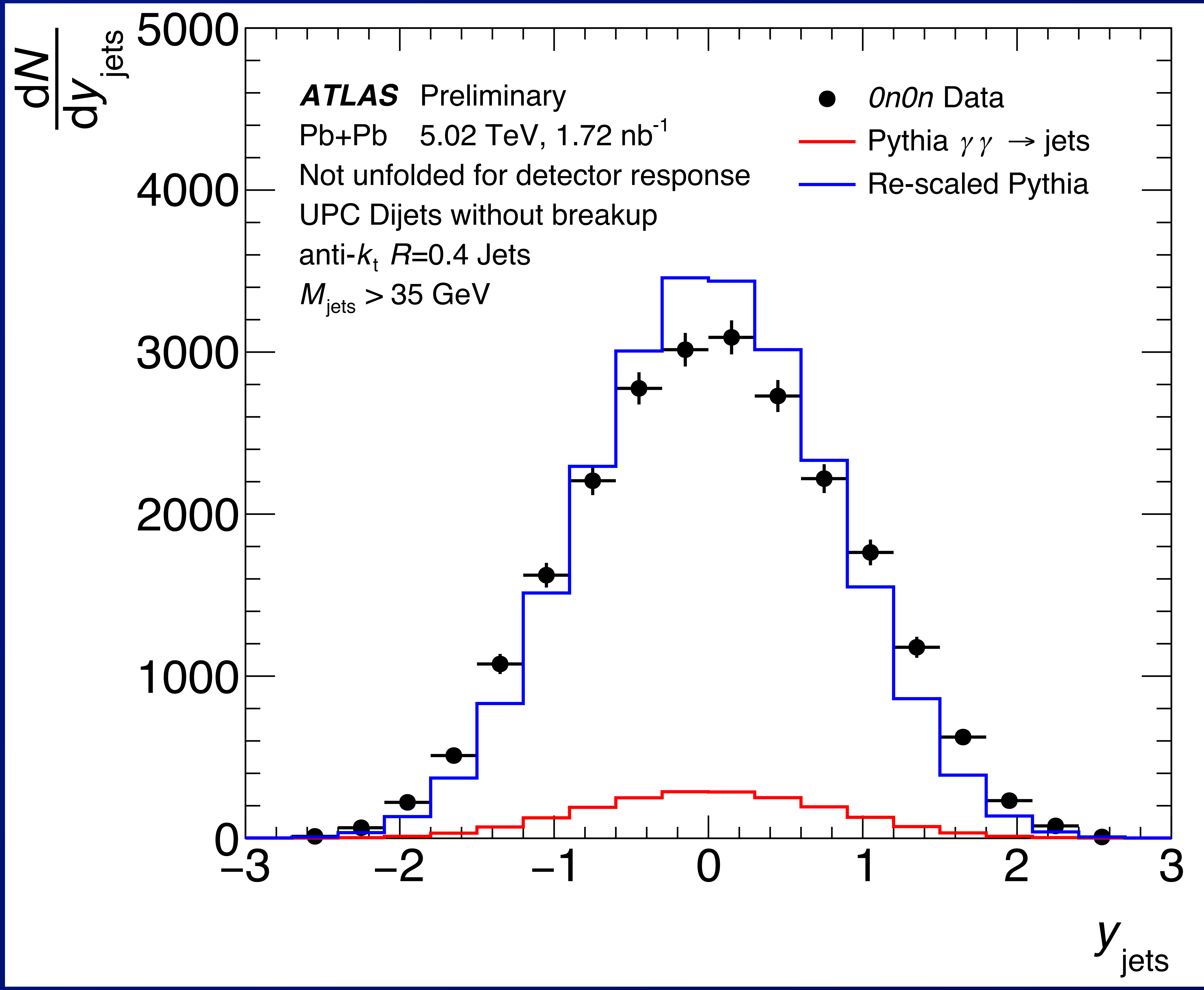

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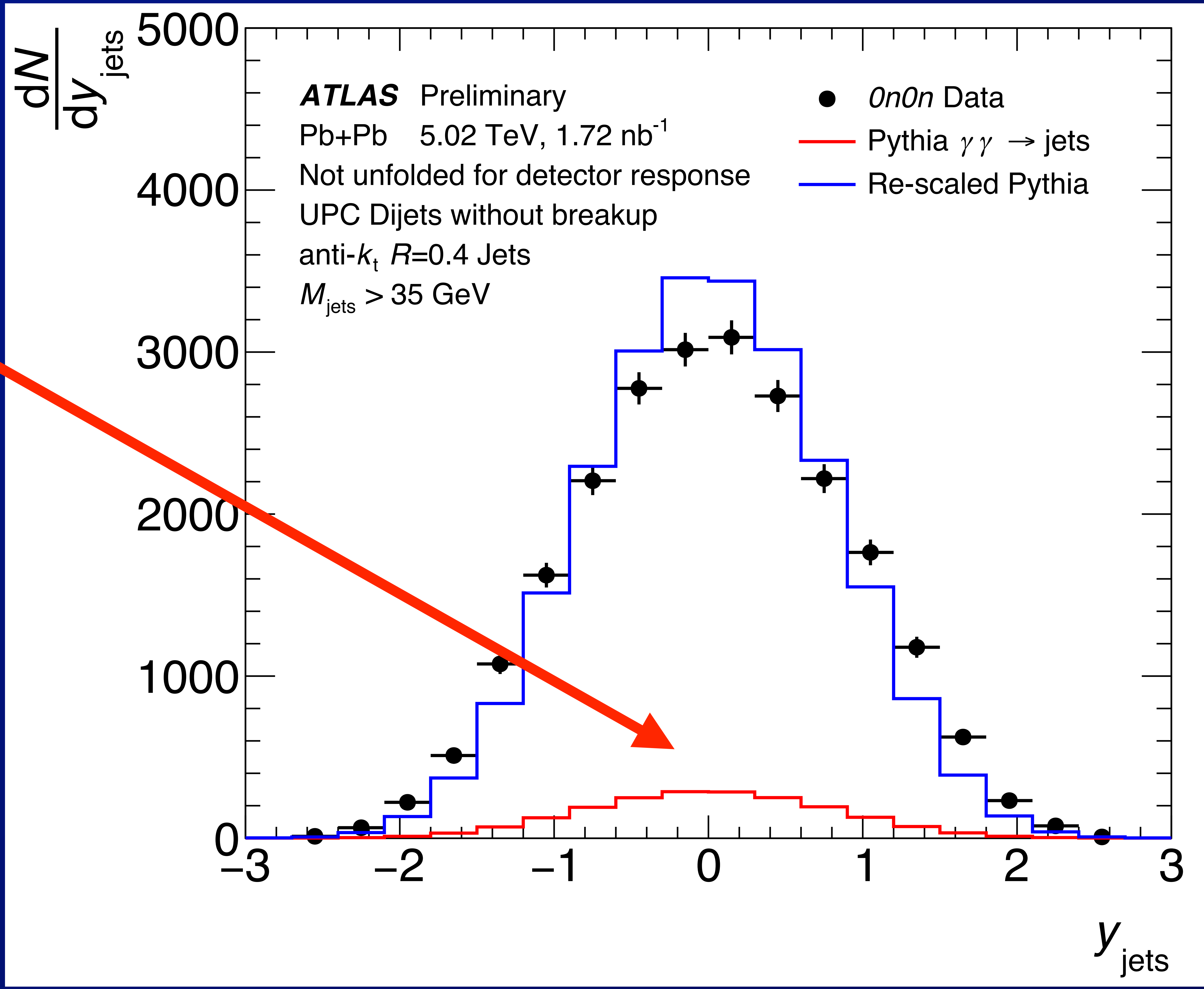

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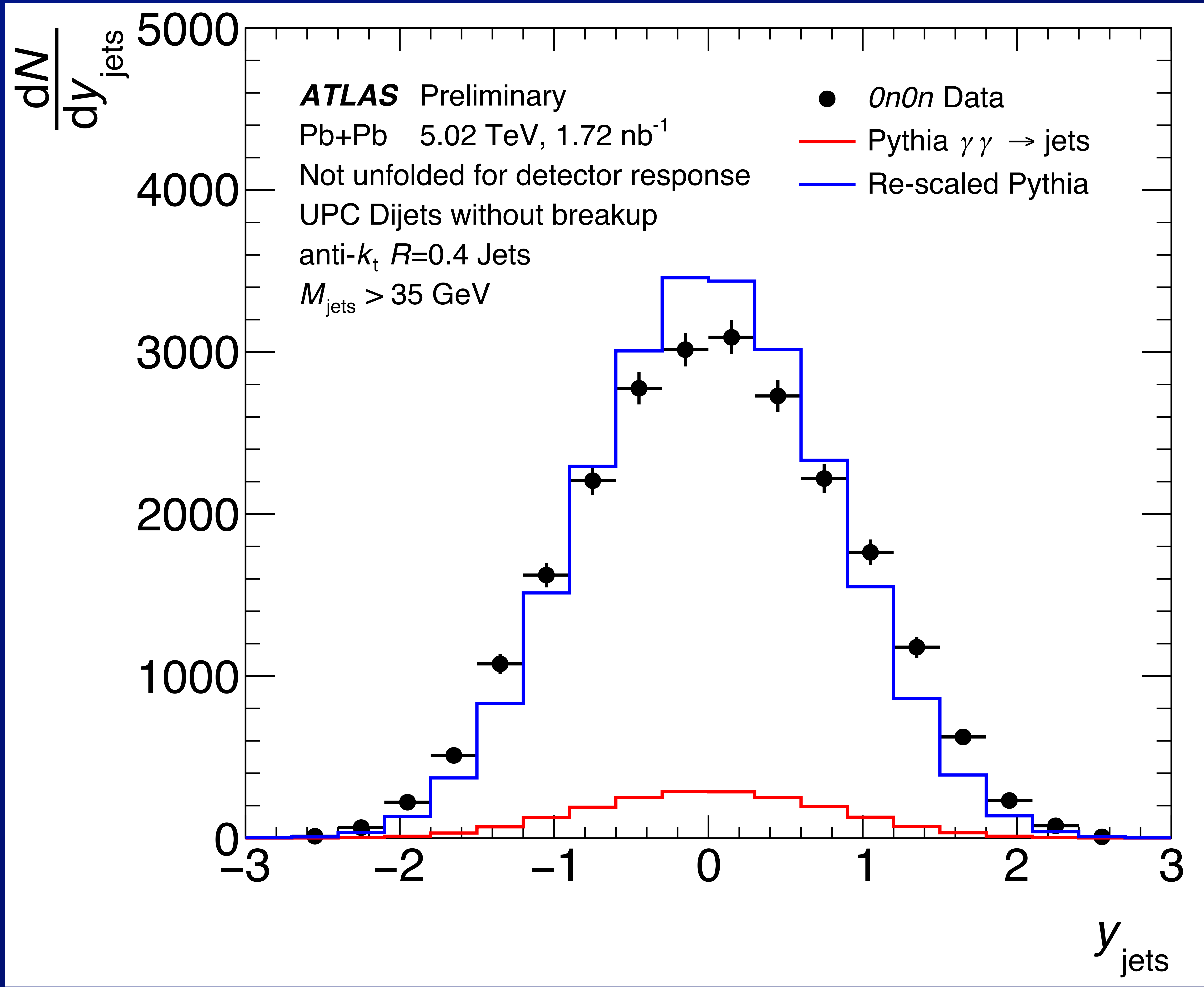
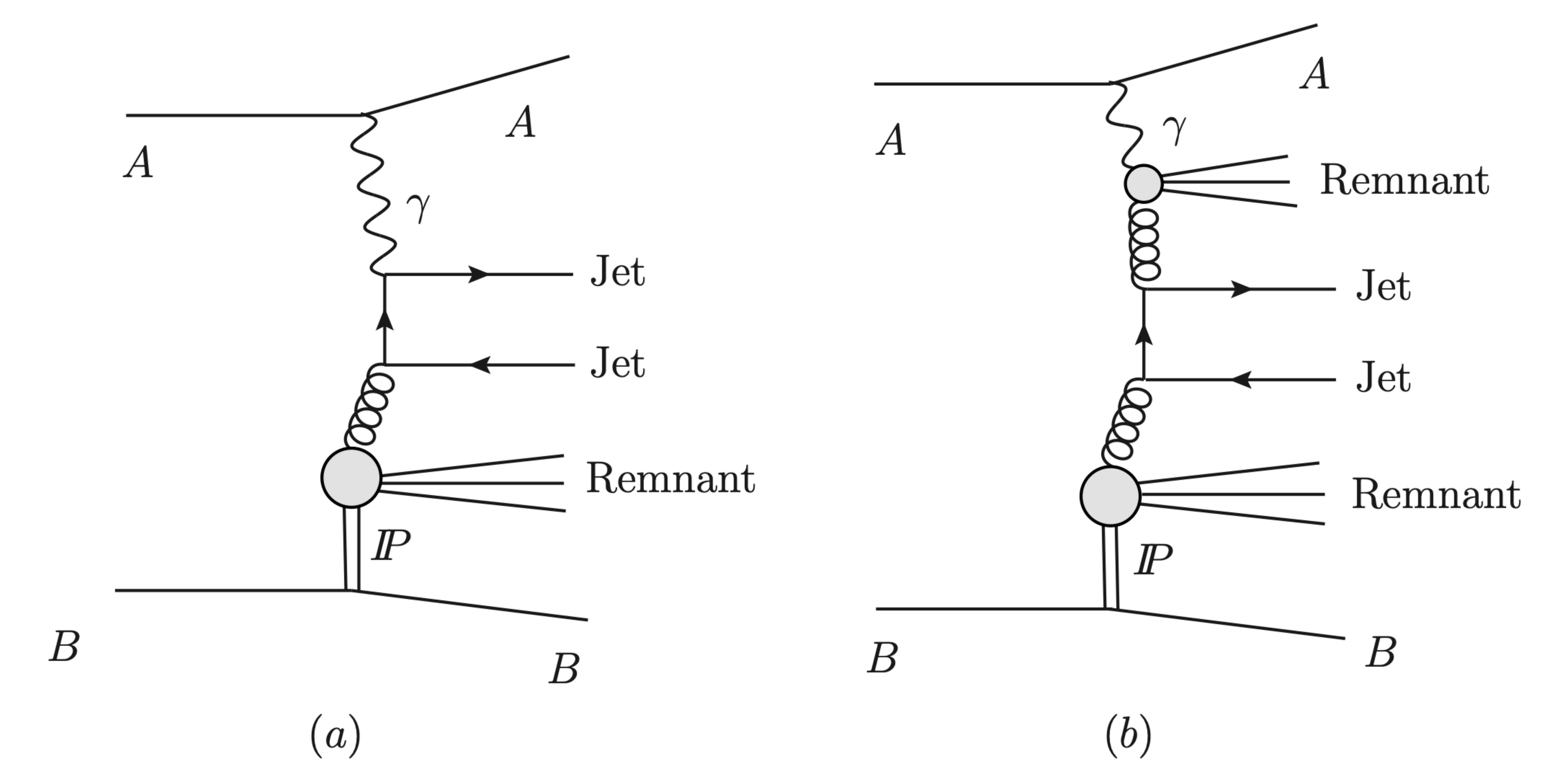


Diffractive photo production

- From Guzey & Klasen (JHEP 04 (2016) 158, arXiv: 1603.06055)
  - LO photo-diffraction diagrams



⇒0n0n requirement preferentially selects coherent pomeron

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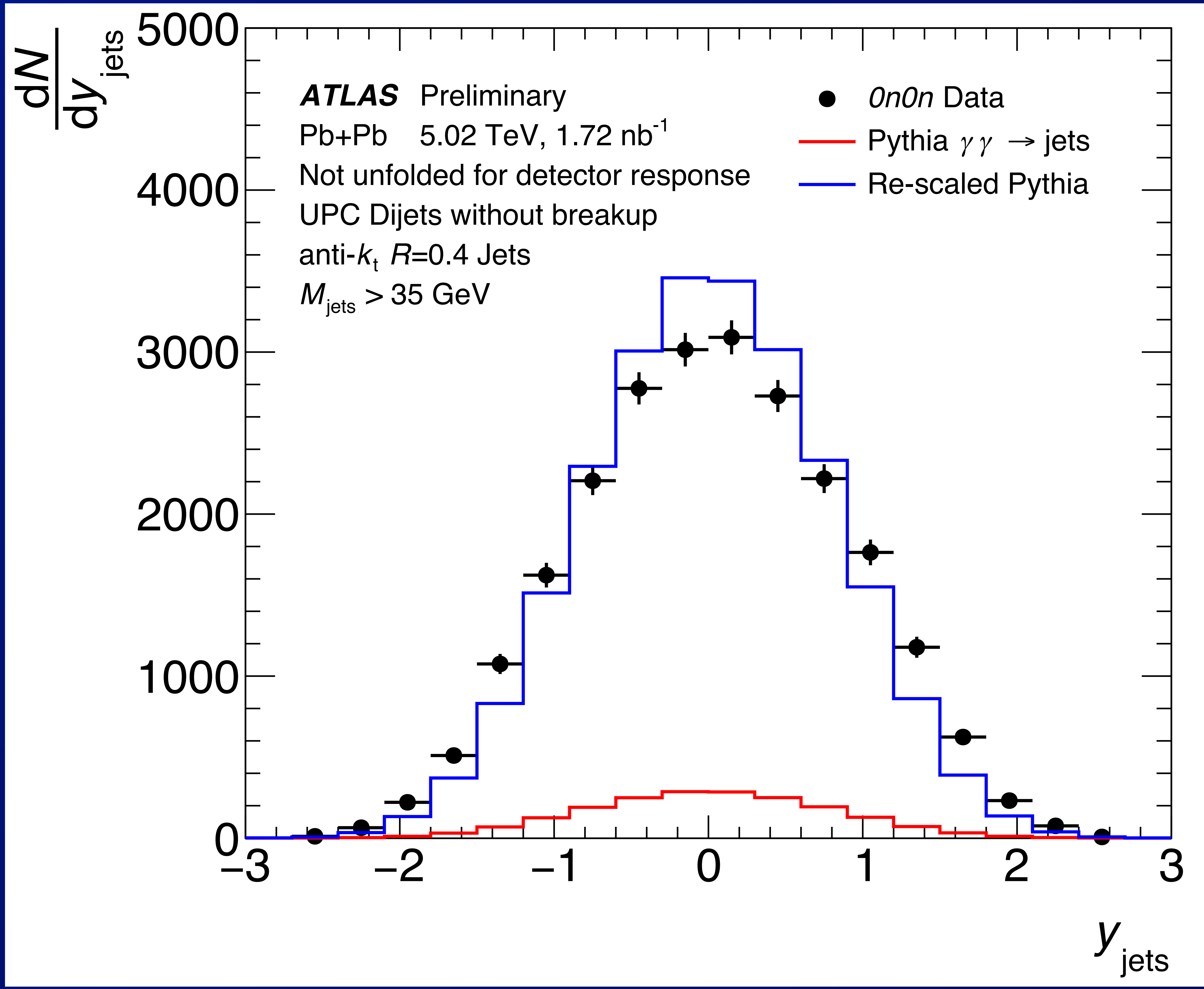

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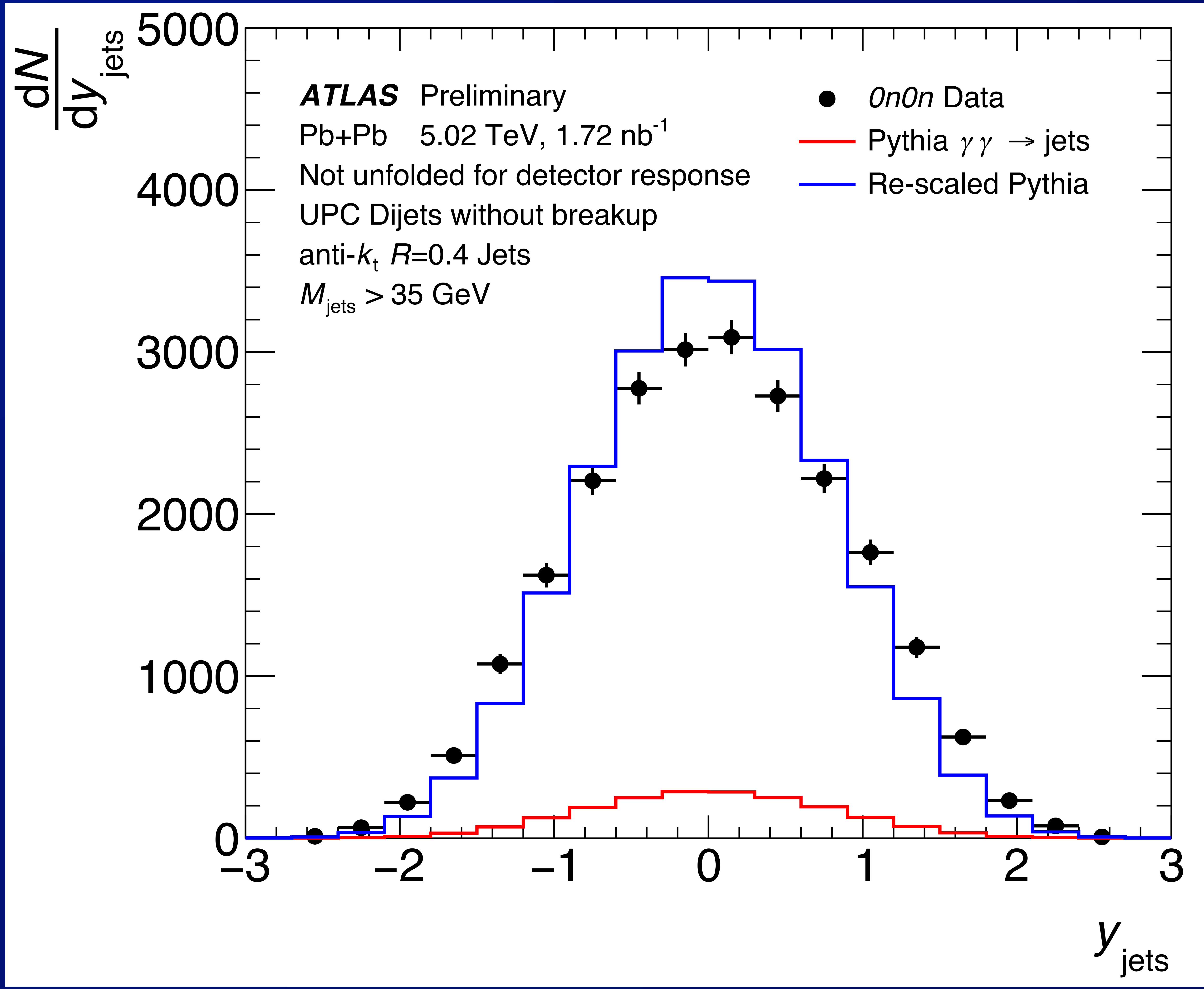

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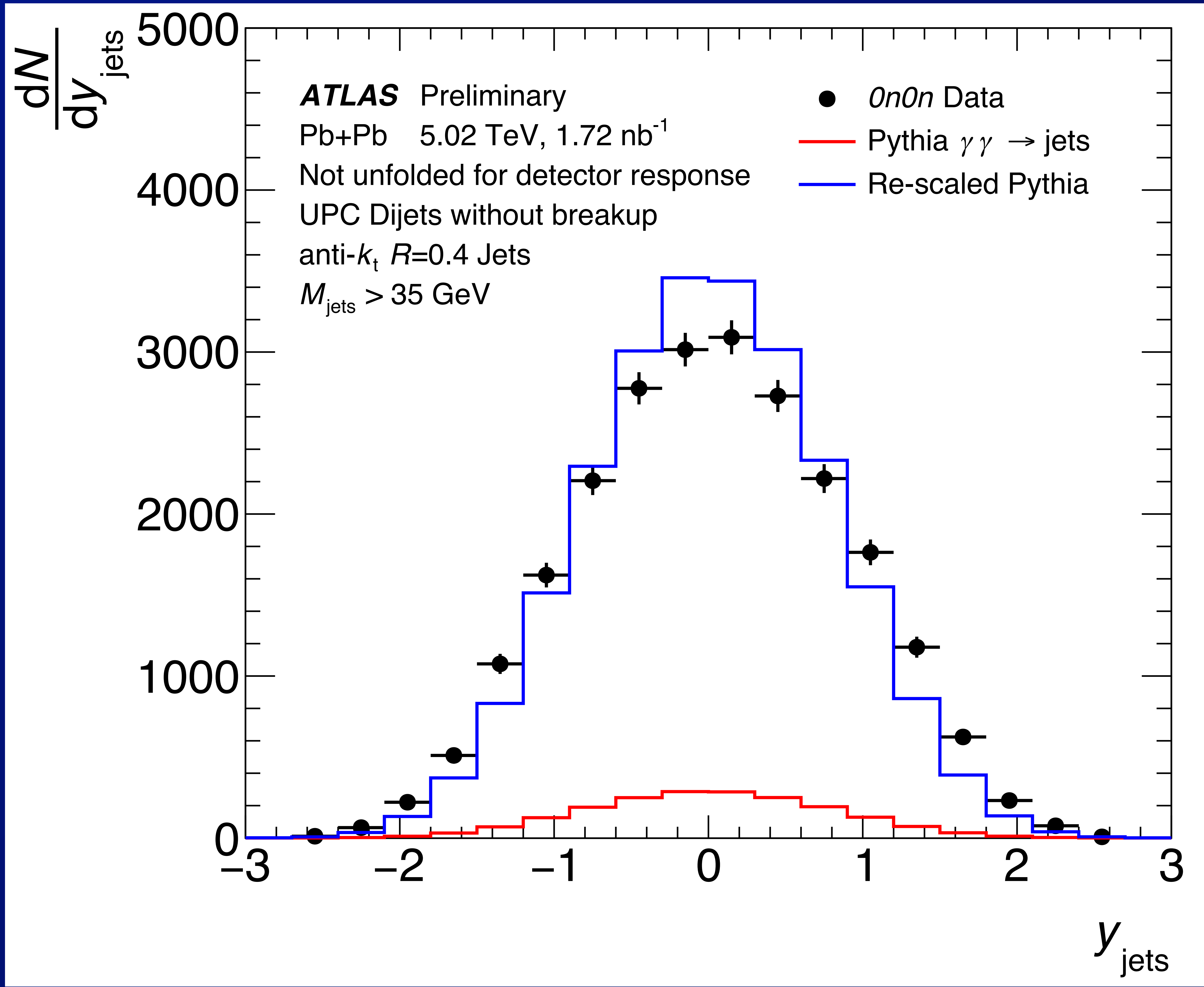

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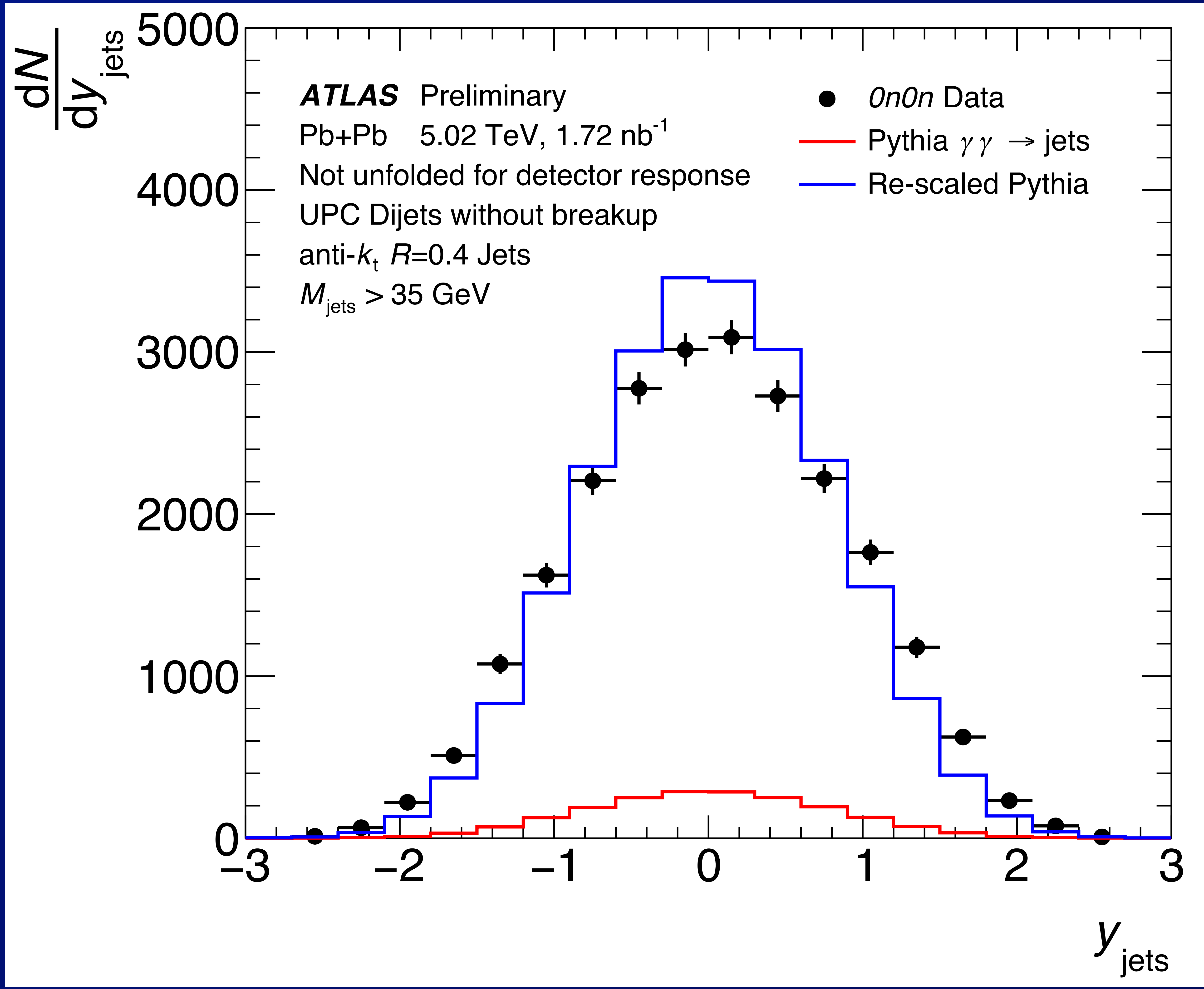

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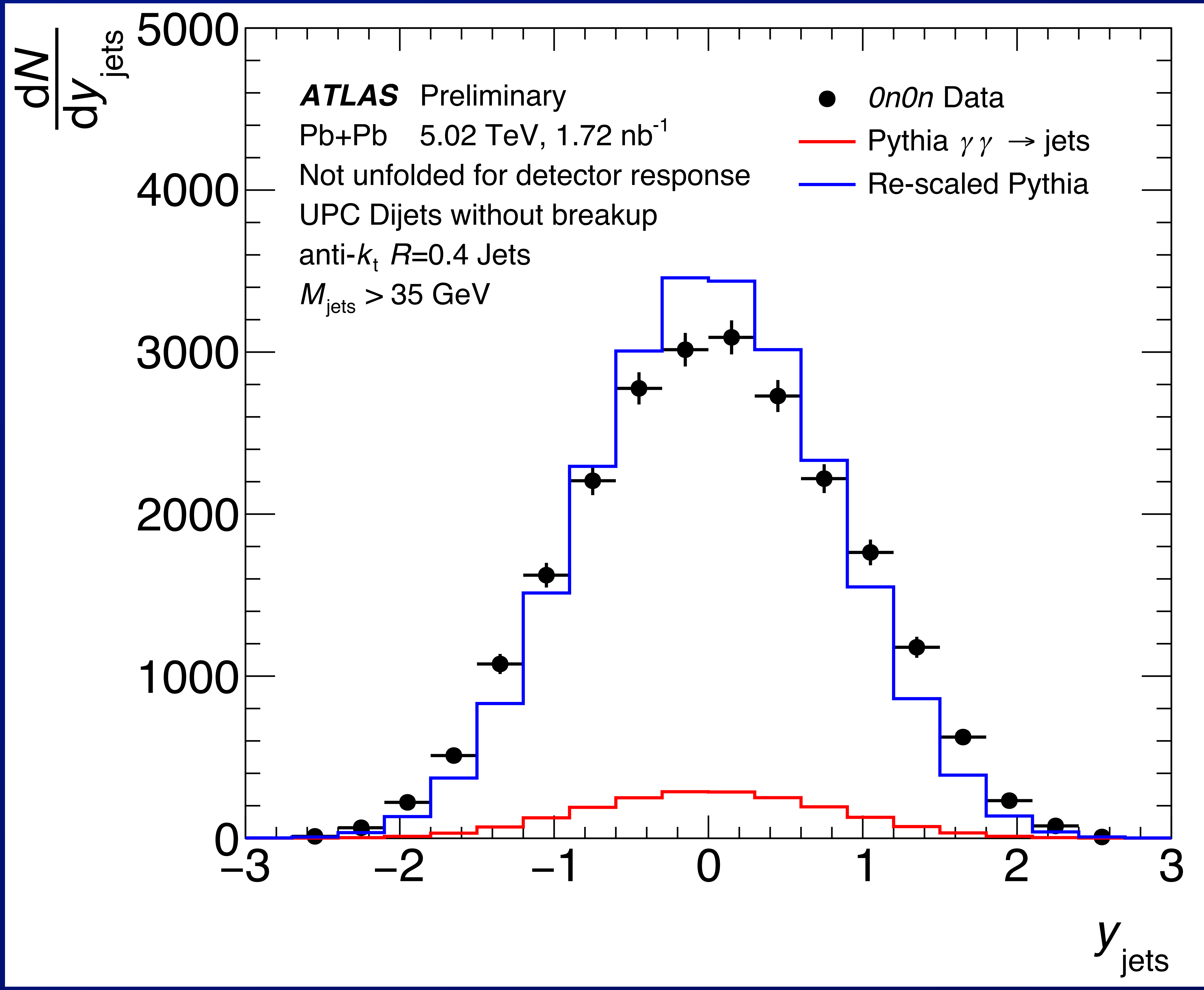

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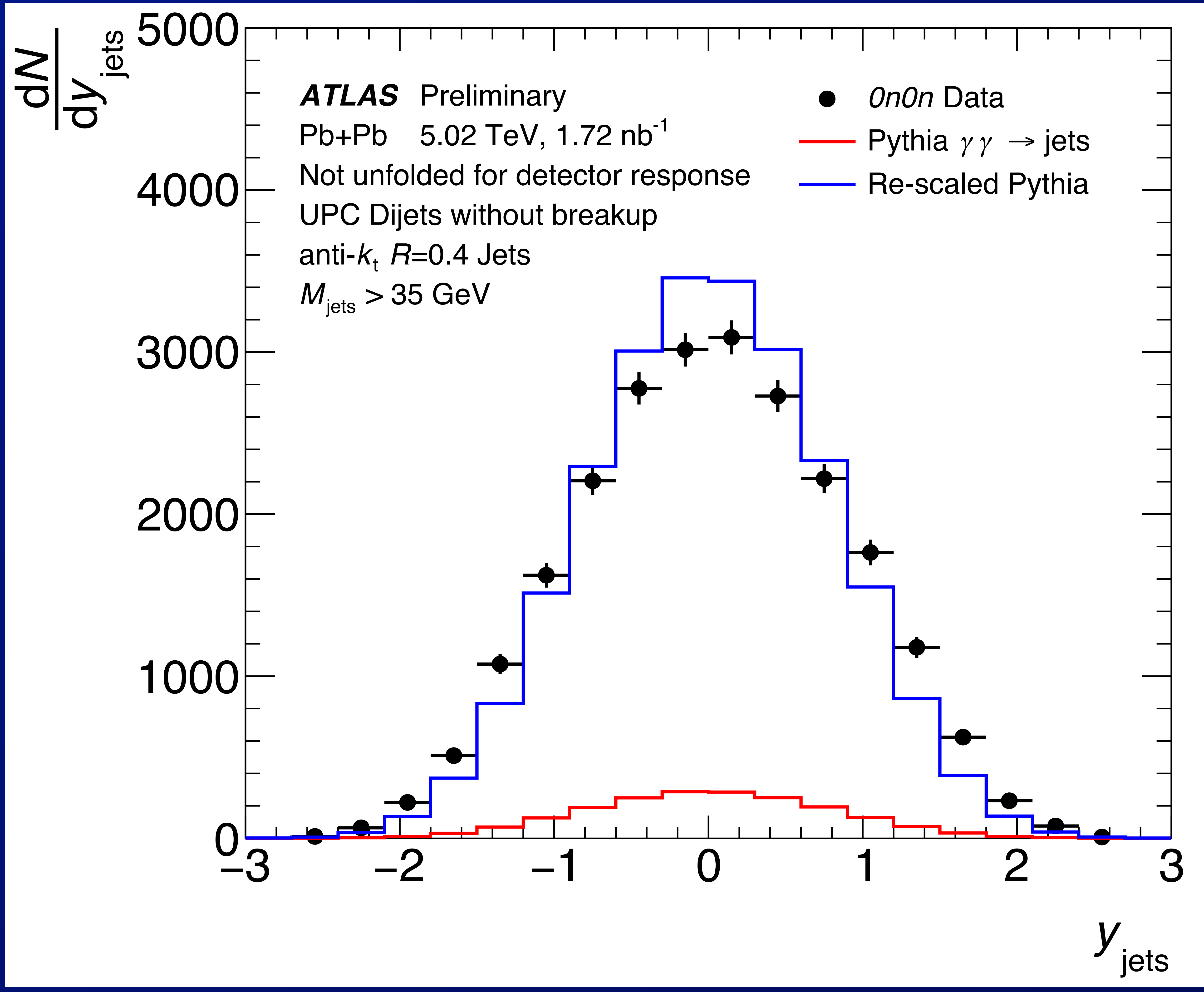
⇒We see significant rate!



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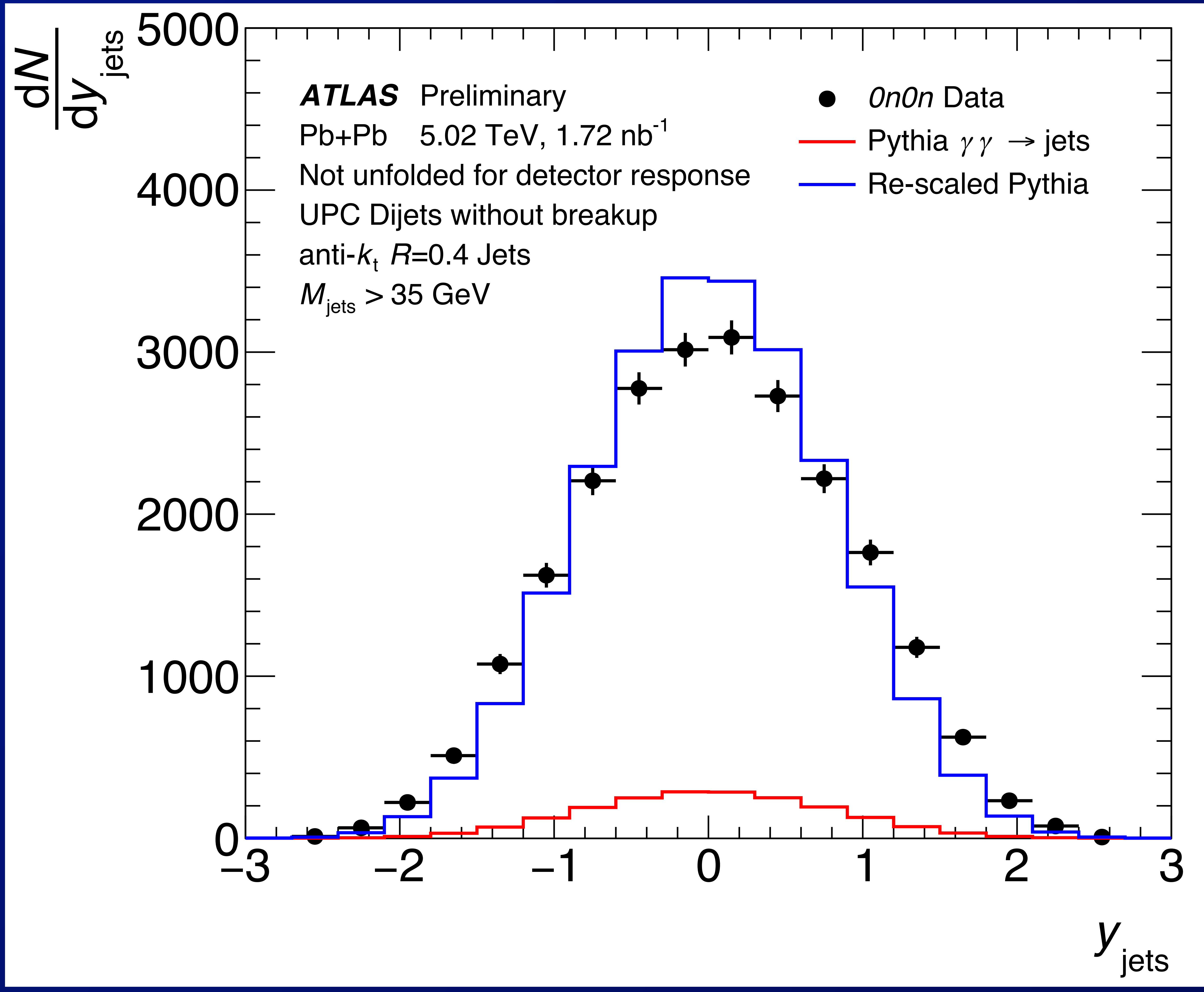
⇒We see few % of 0nXn



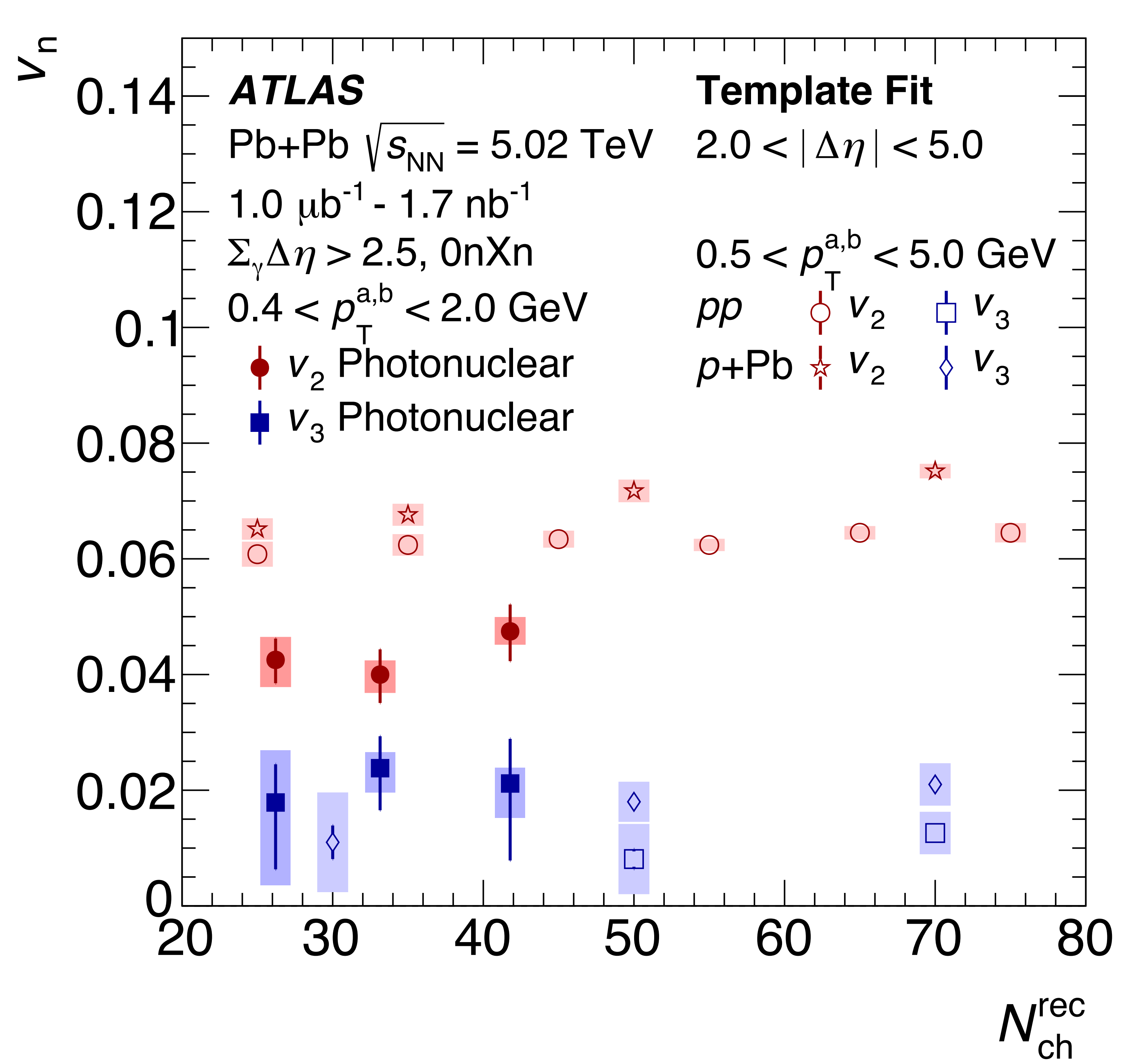
Ridge in small systems

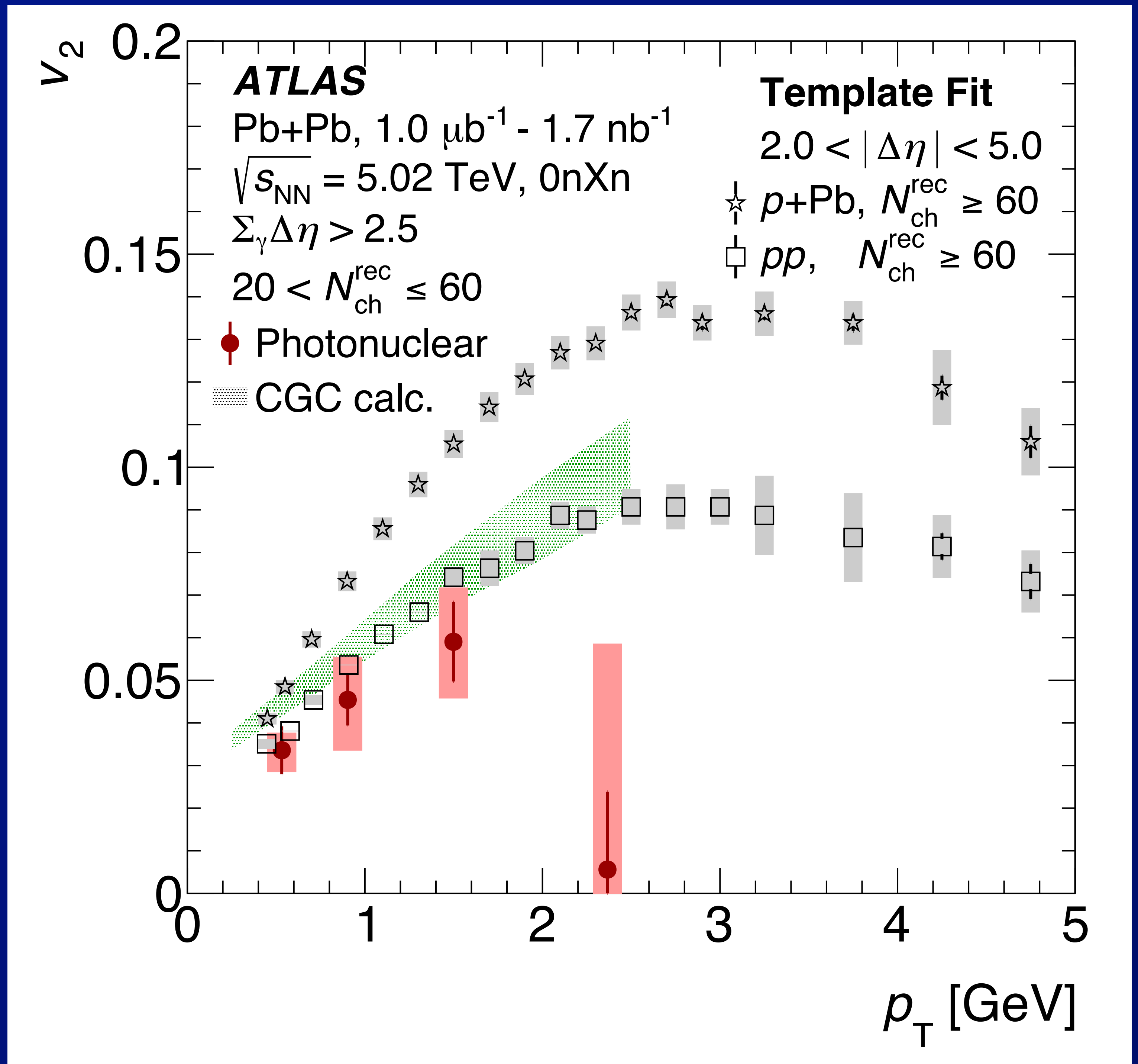
The ridge in inclusive photonuclear collisions

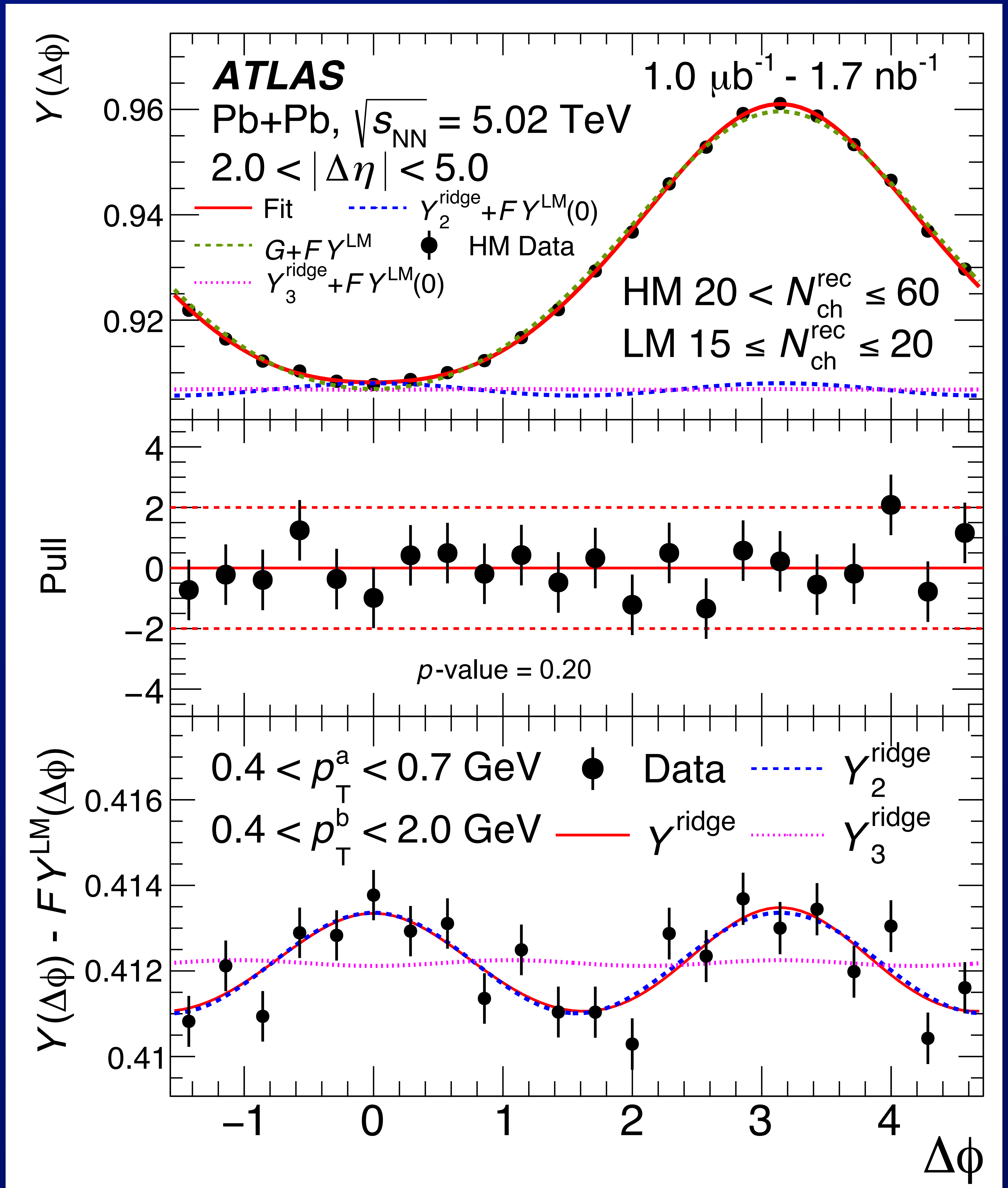
- ATLAS has observed clear indication of "ellipticity" in two-particle correlations in inclusive photonuclear collisions

⇒"Collectivity" or CGC?

- ATLAS is studying properties of the inclusive photonuclear collisions
  - Transverse momentum and flavor dist's.

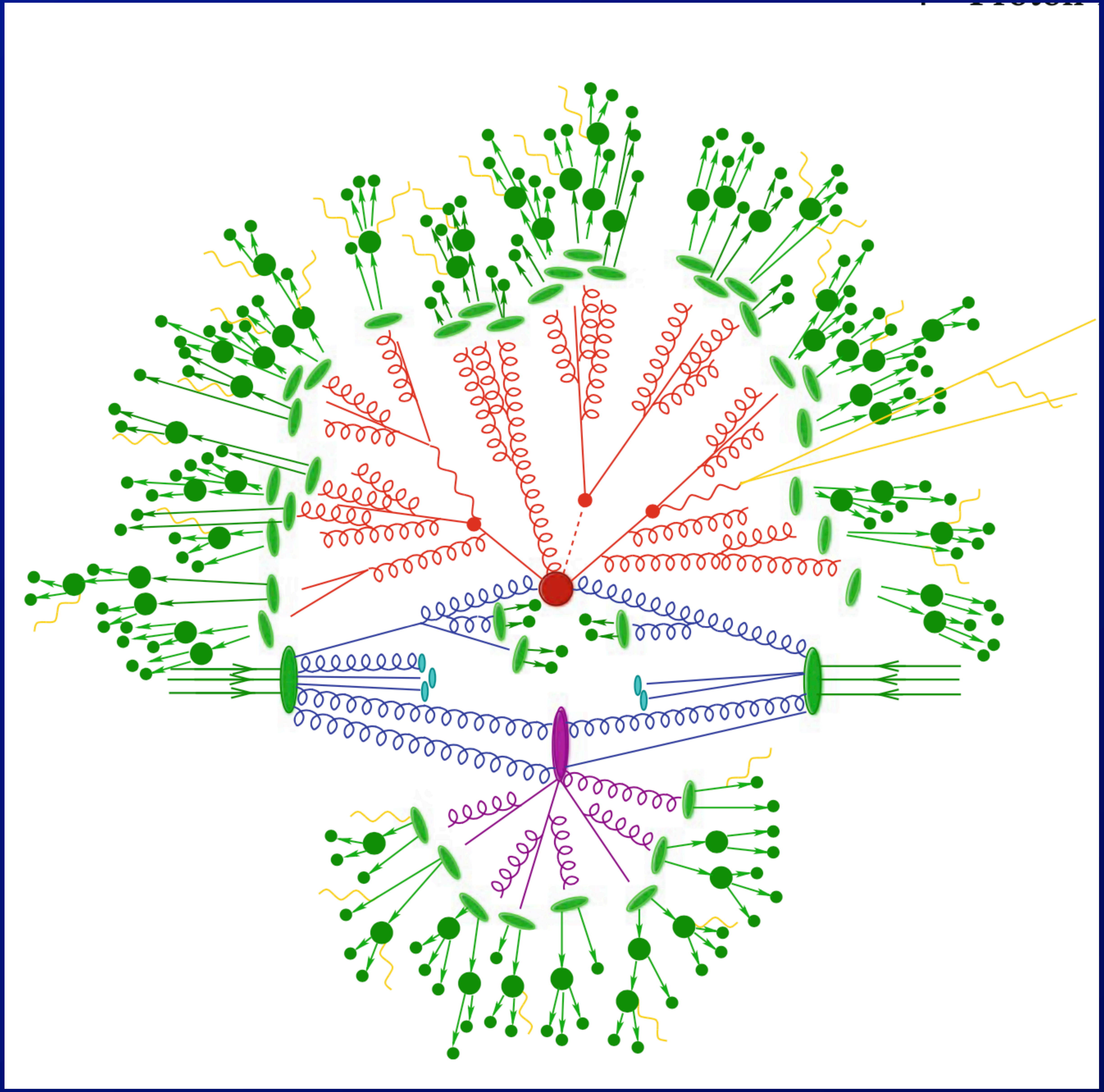






Coupling between ridge and hard-processes in pp

- To what extent does the soft(?) underlying event



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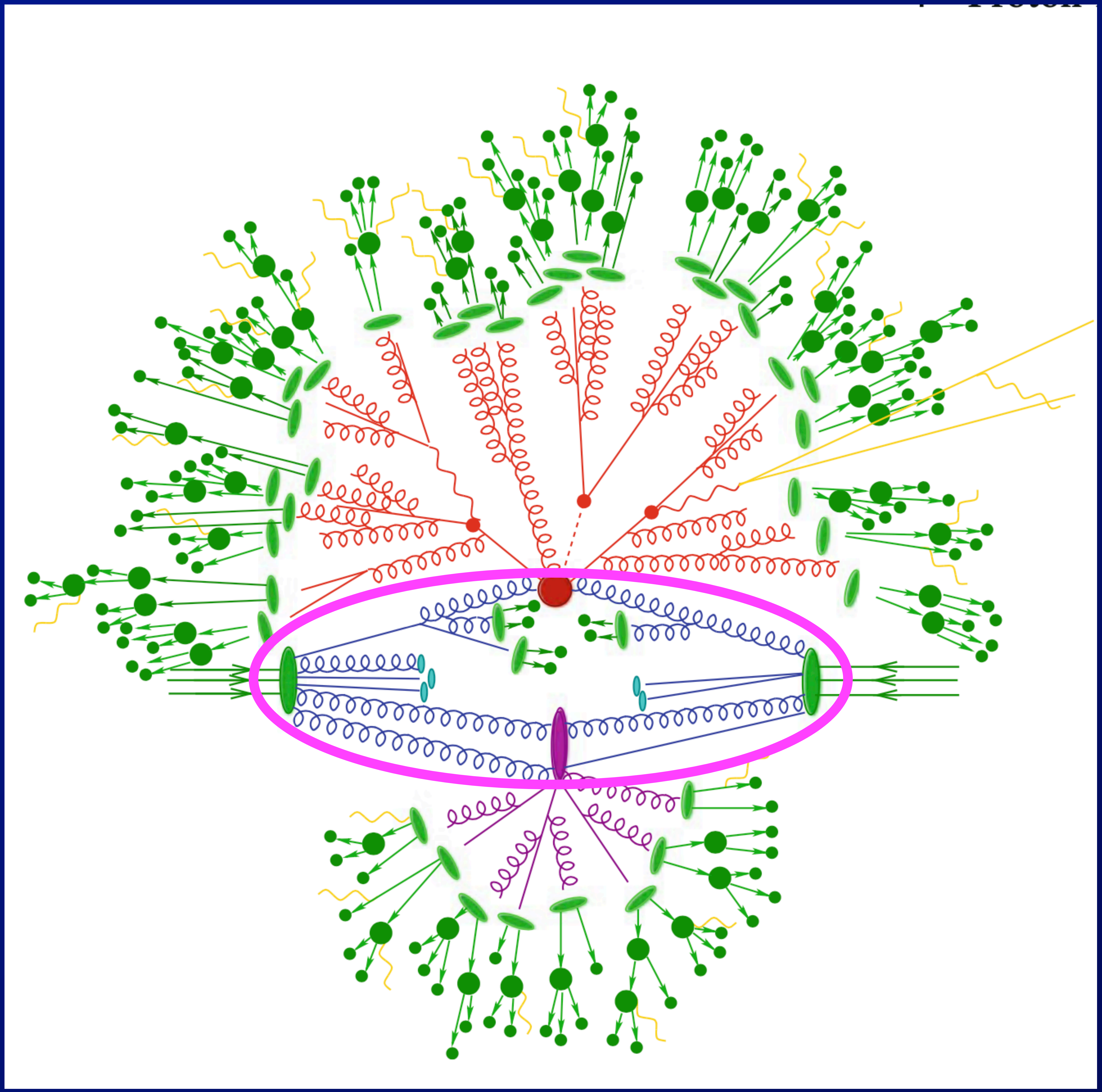

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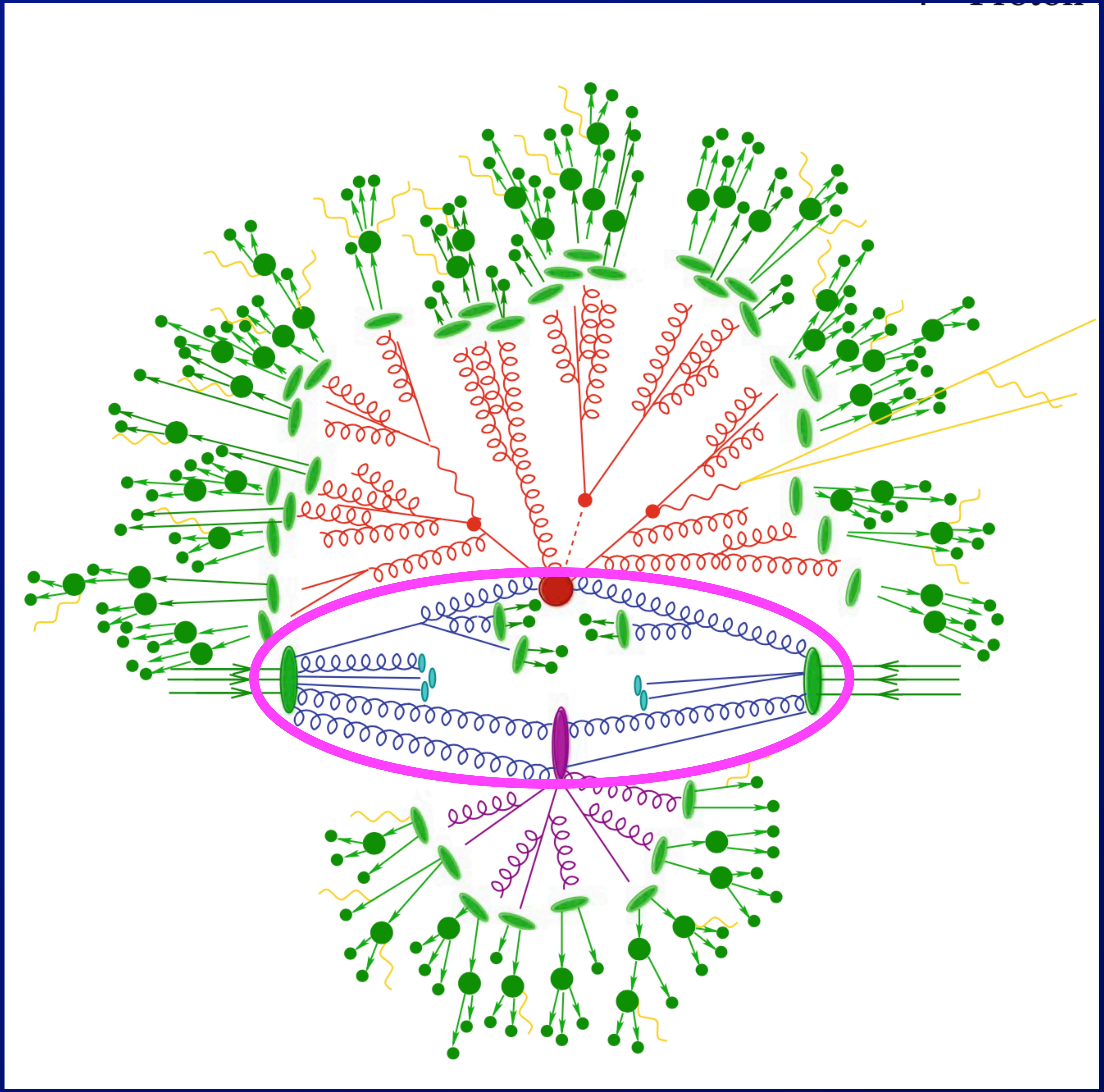

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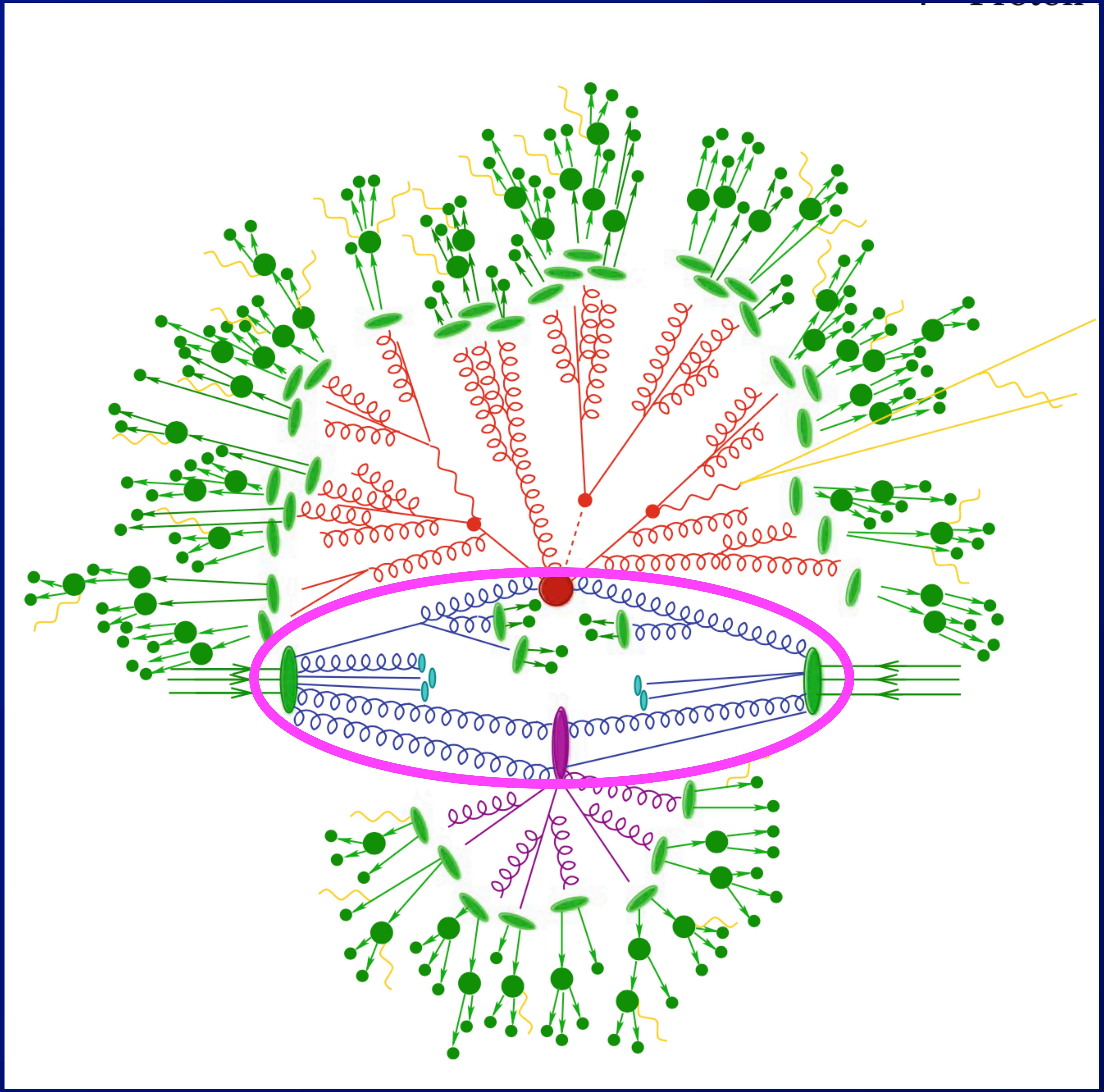

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- **To what extent does the soft(?) underlying event decouple from hard scattering processes?**
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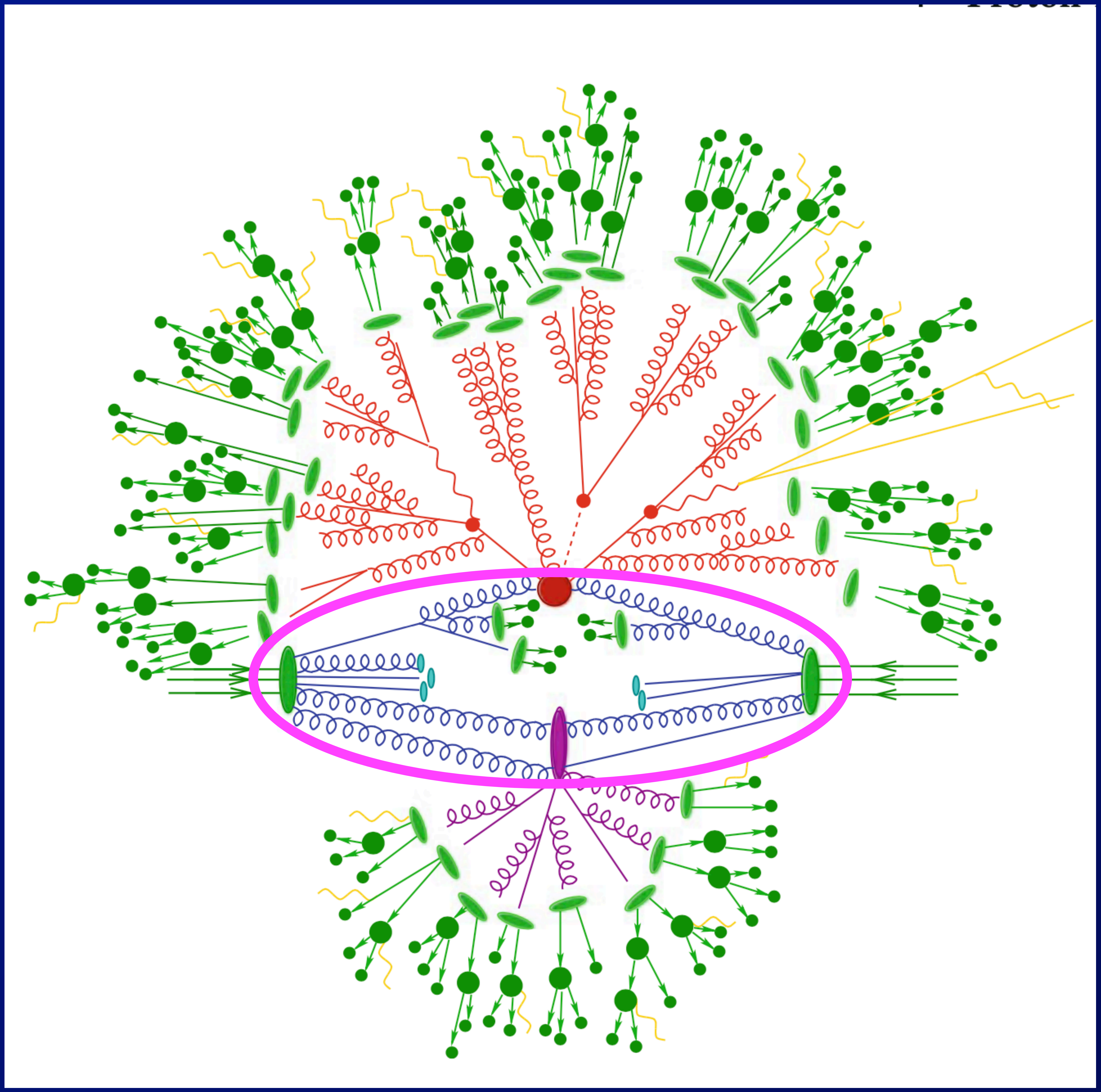

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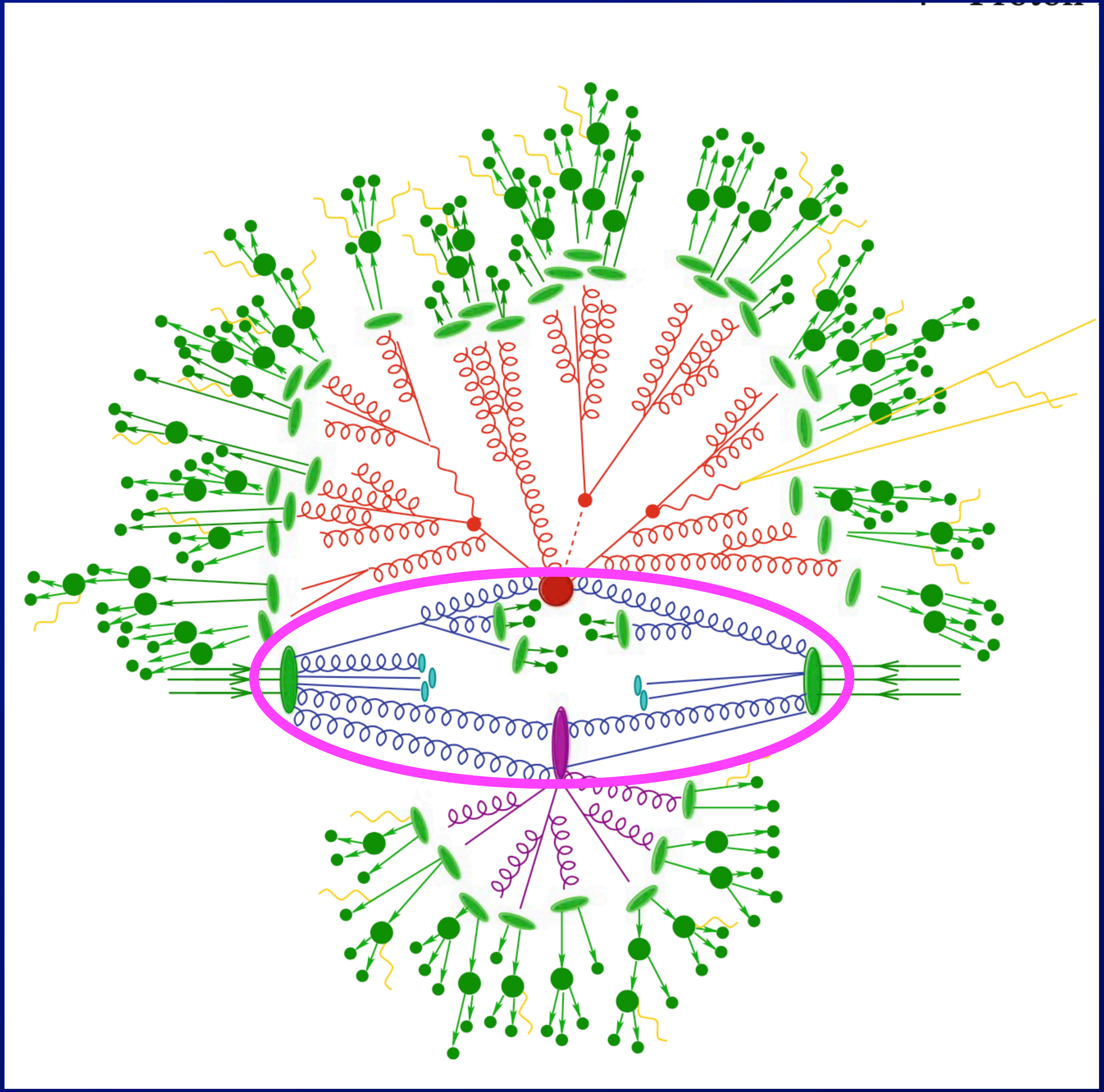

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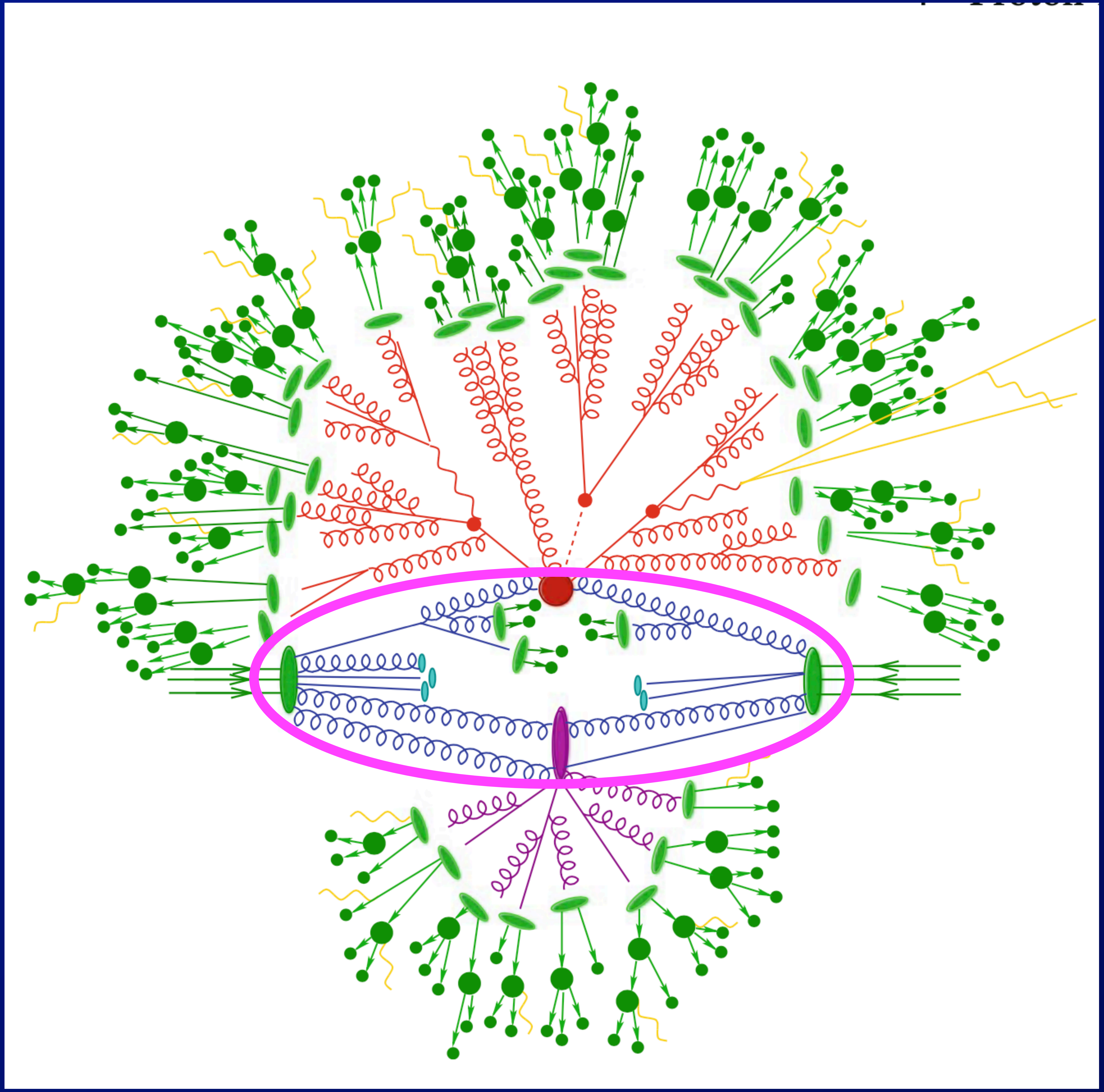

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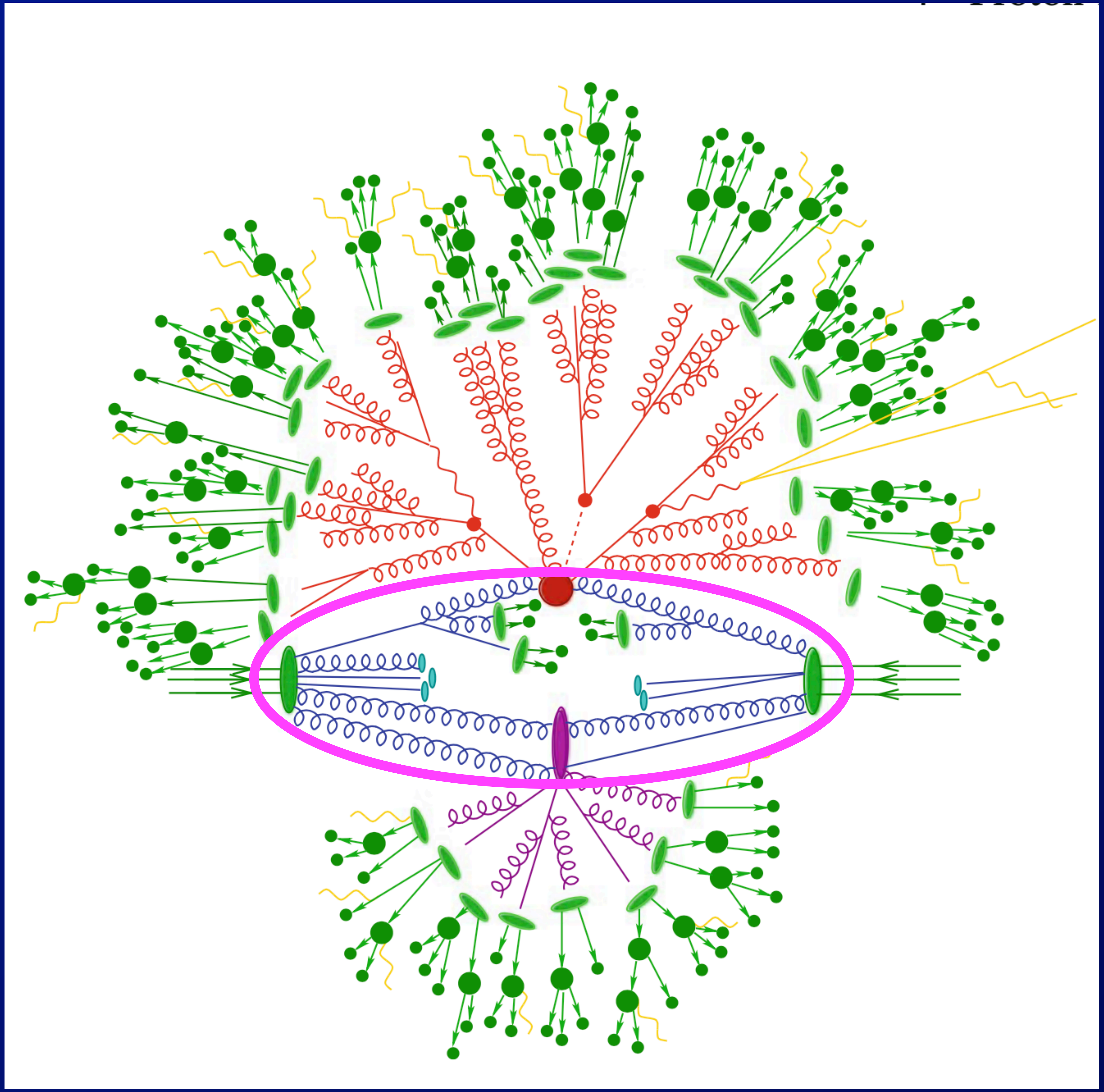
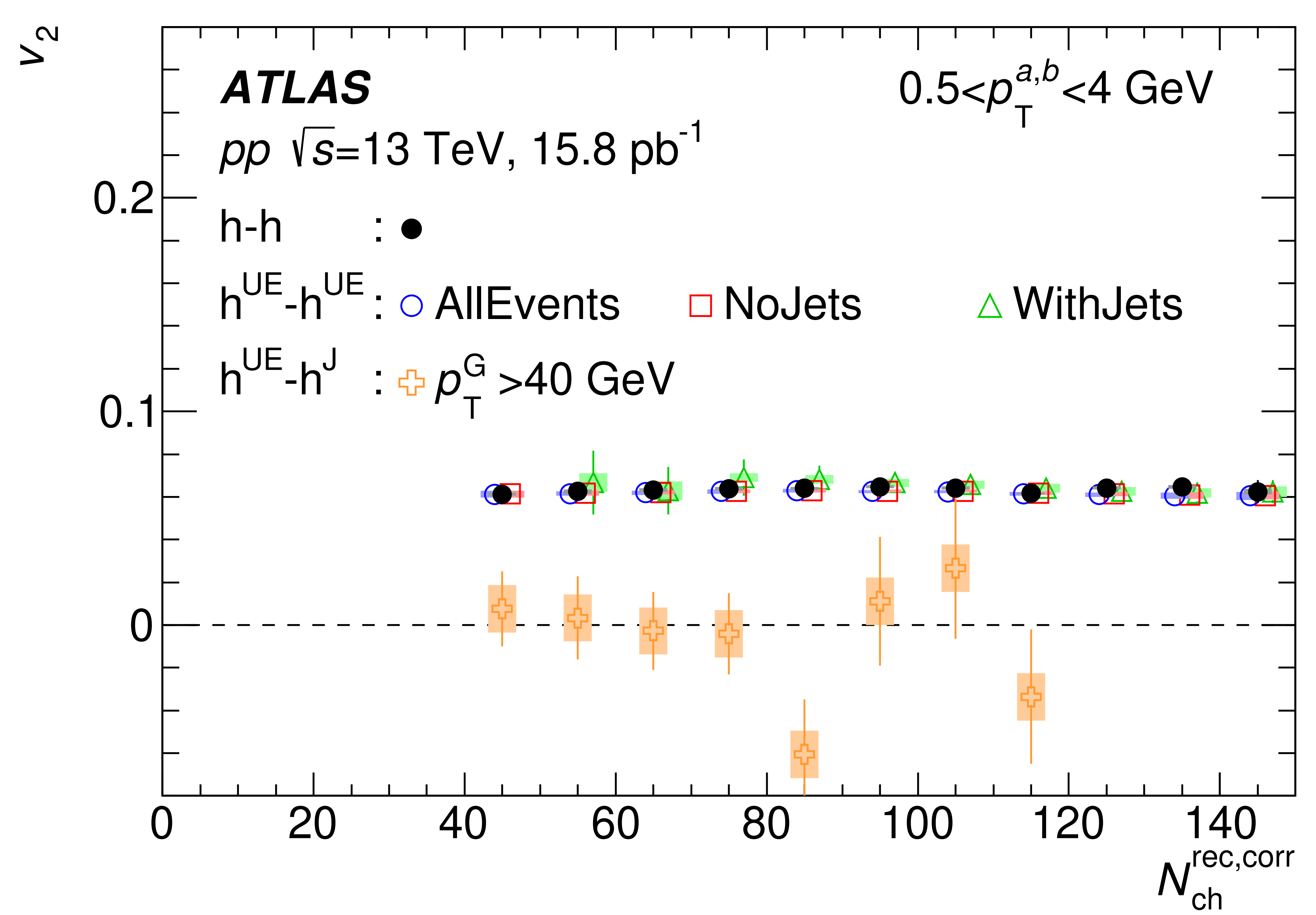
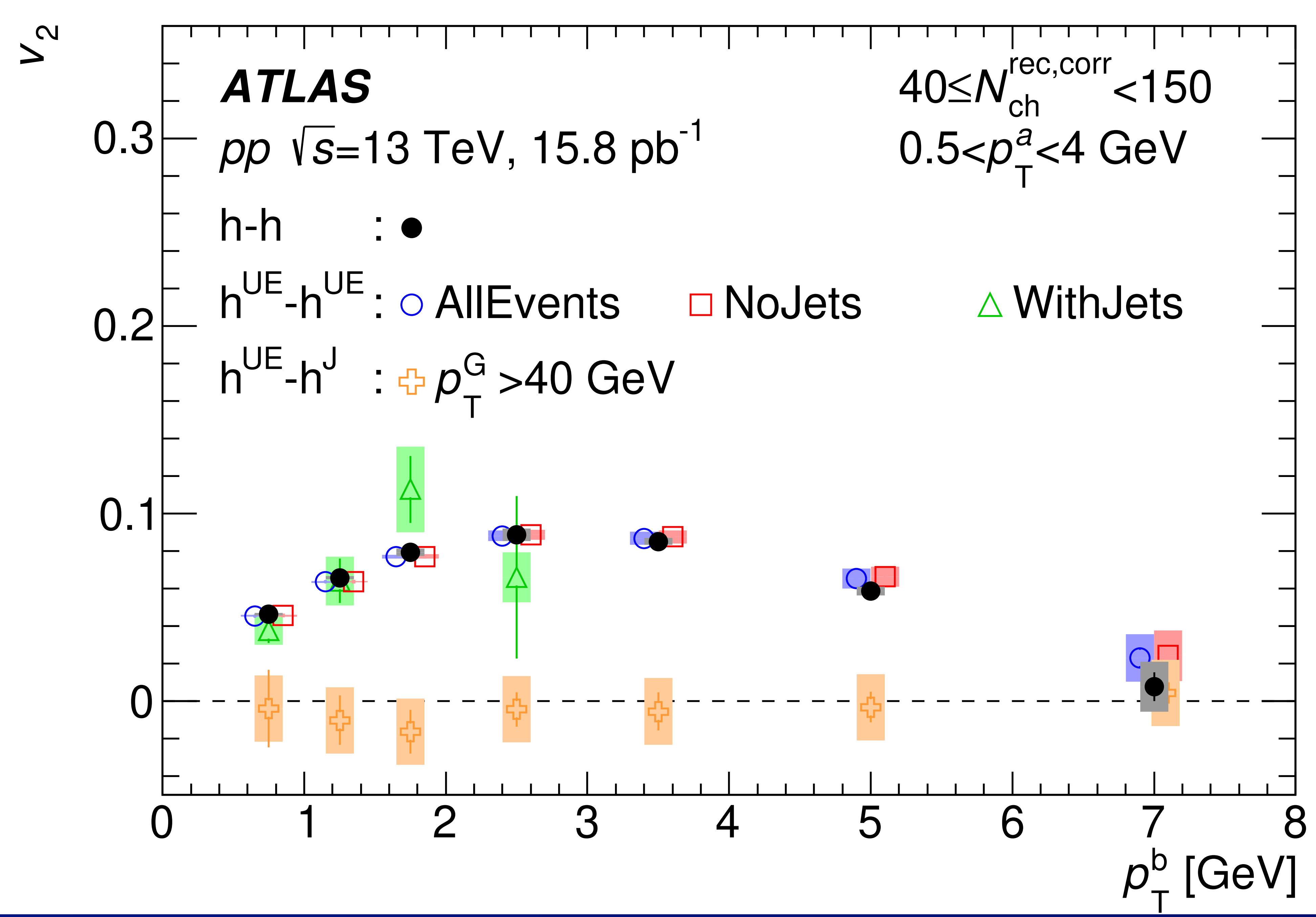


- Test by looking for correlations between jet fragments, UE

Coupling between ridge and hard-processes in pp





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⇒While UE in jet events shows usual 2-particle correlation

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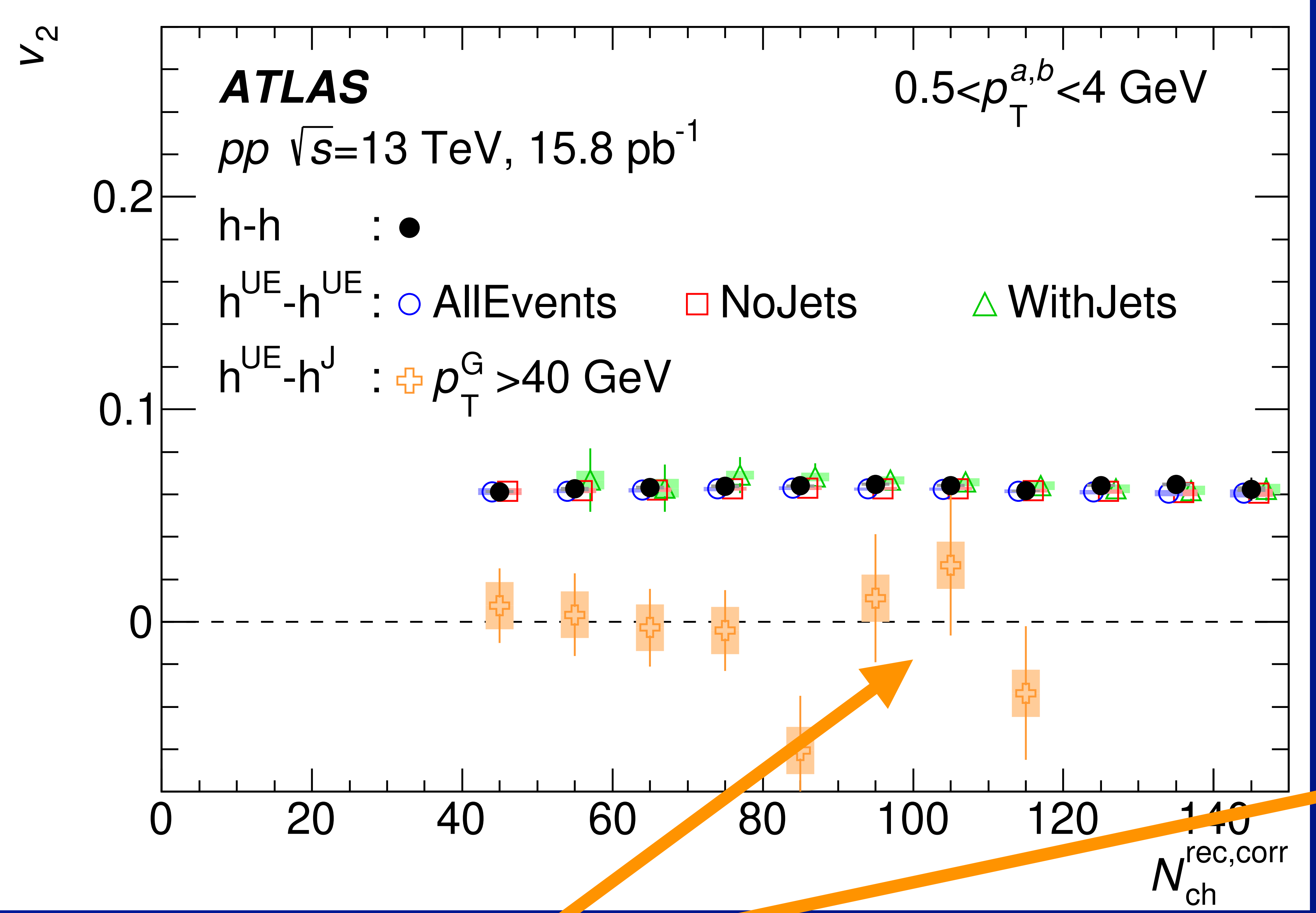

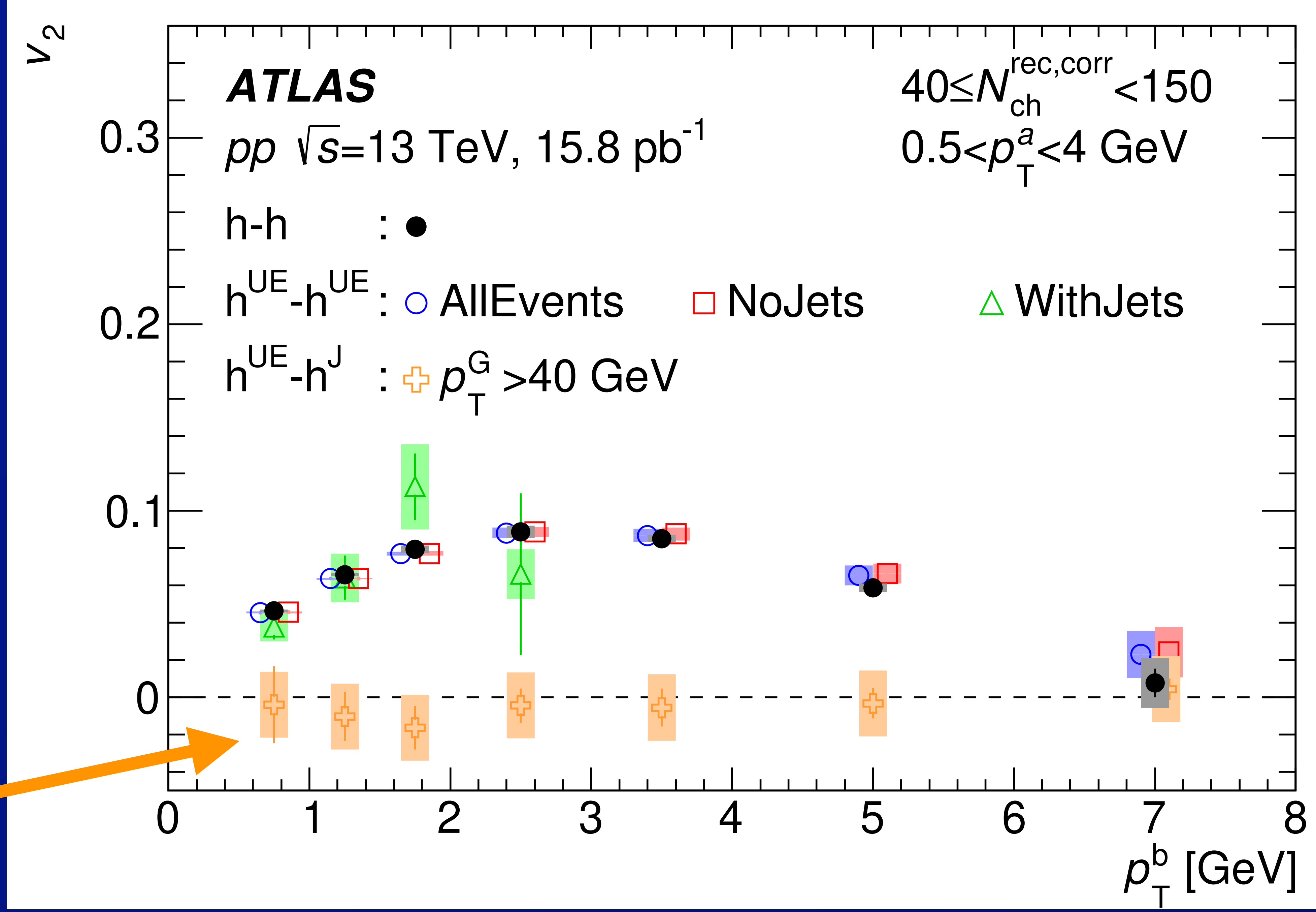

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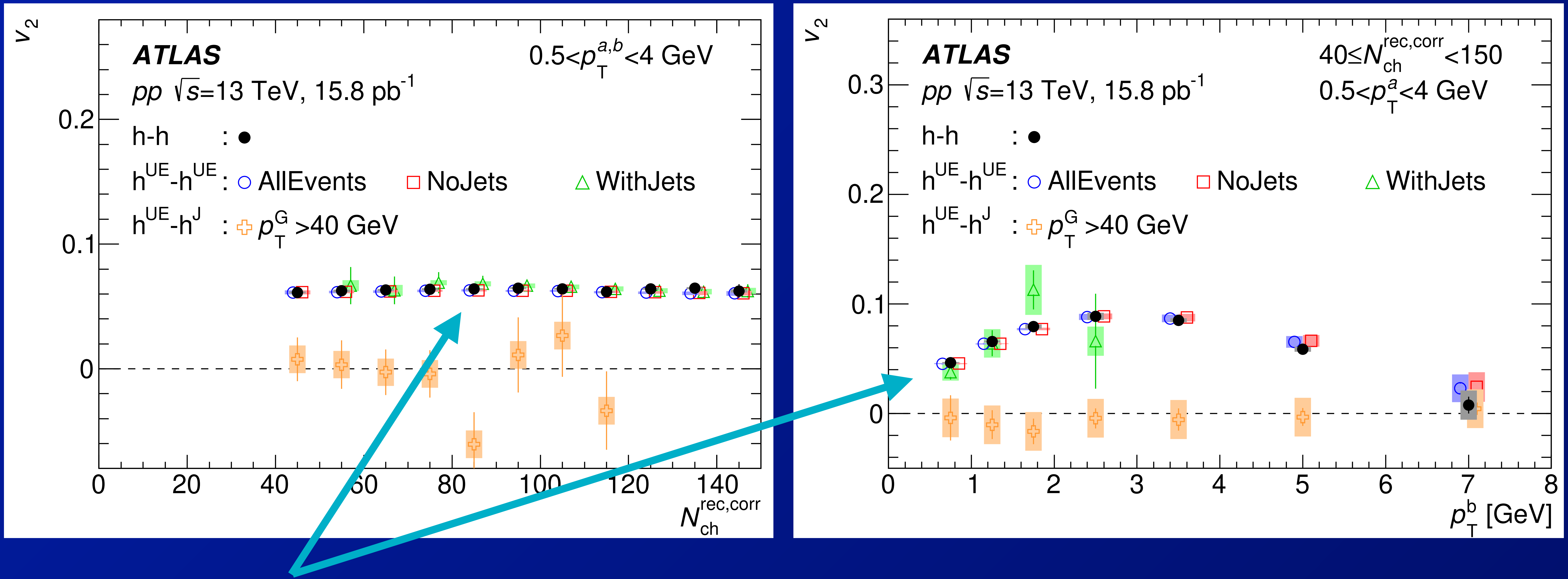

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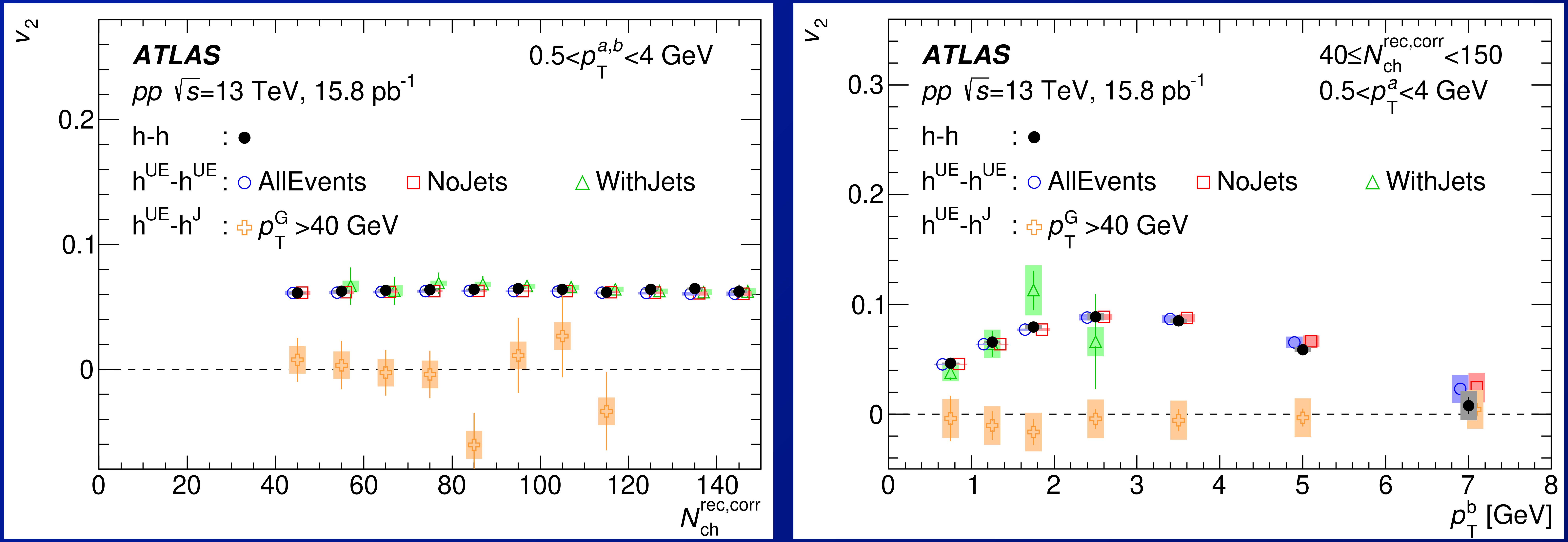

- Also, the elliptic modulation of soft UE caused serious problems

⇒ jet energy biased by cos(2ϕ) modulation of UE

– Eliminated by imposing p_T > 4 requirement on jet constituents

– Also forced us much higher in jet energy than we hoped

⇒More evidence that the ridge is global property of pp underlying event

Summary

- UPC exclusive dileptons
  - Understand discrepancy with recent predictions?
  - Use ZDC 0nXn topolgy to directly measure dissociative γ flux?
- Non-UPC $\gamma + \gamma \rightarrow \mu^{+}\mu^{-}$
  - Probe of low-x photons in nucleus
  - ⇒Physics similar to low-x partons, but Abelian
  - ⇒Same theoretical tools being used
- Photonuclear $\gamma + A \rightarrow$ jets
  - Final Run 2 result imminent.
  - ⇒Probe down to x ~ 10^{-3} with Q^2 ~ $(30\ \text{GeV})^2$
  - Plan to start on diffractive photonuclear measurement
  - ⇒What about the 0n0n non-diffractive contribution?

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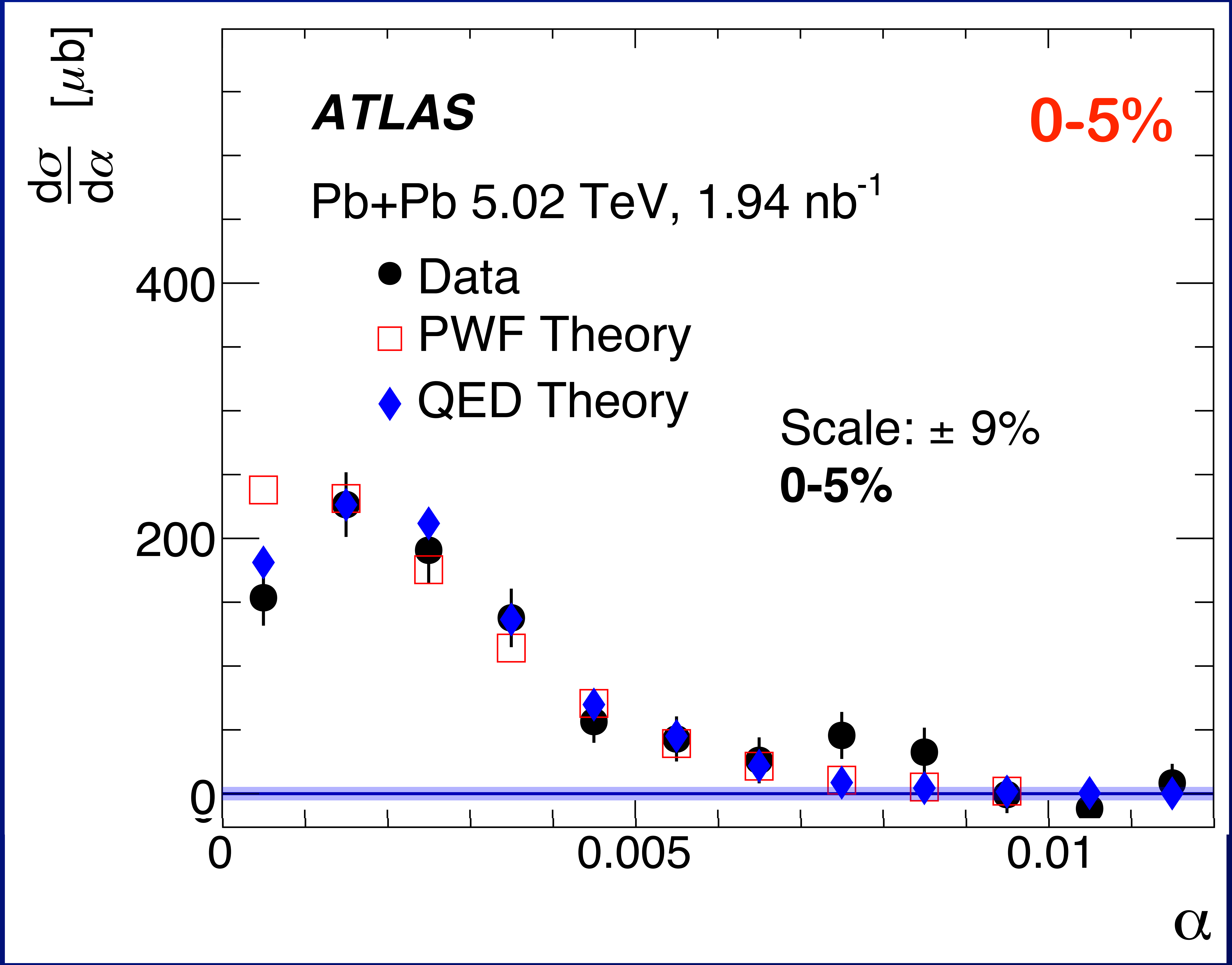
    ⇒What about the 0n0n non-diffractive contribution?
- **Ridge in UPC/small systems**
  - Work underway to study UE in inclusive photonuclear γ+A
  - In pp observe ~ complete decoupling of hard scattering/soft UE

Backup

γ+γ dilepton production in hadronic Pb+Pb

- Calculations including b-dependent photon k_T can describe broadening
  - But what about the suppression at small acoplanarity, k_T?

⇒Reproduced by "QED" but not (original) calculation using photon Wigner distribution

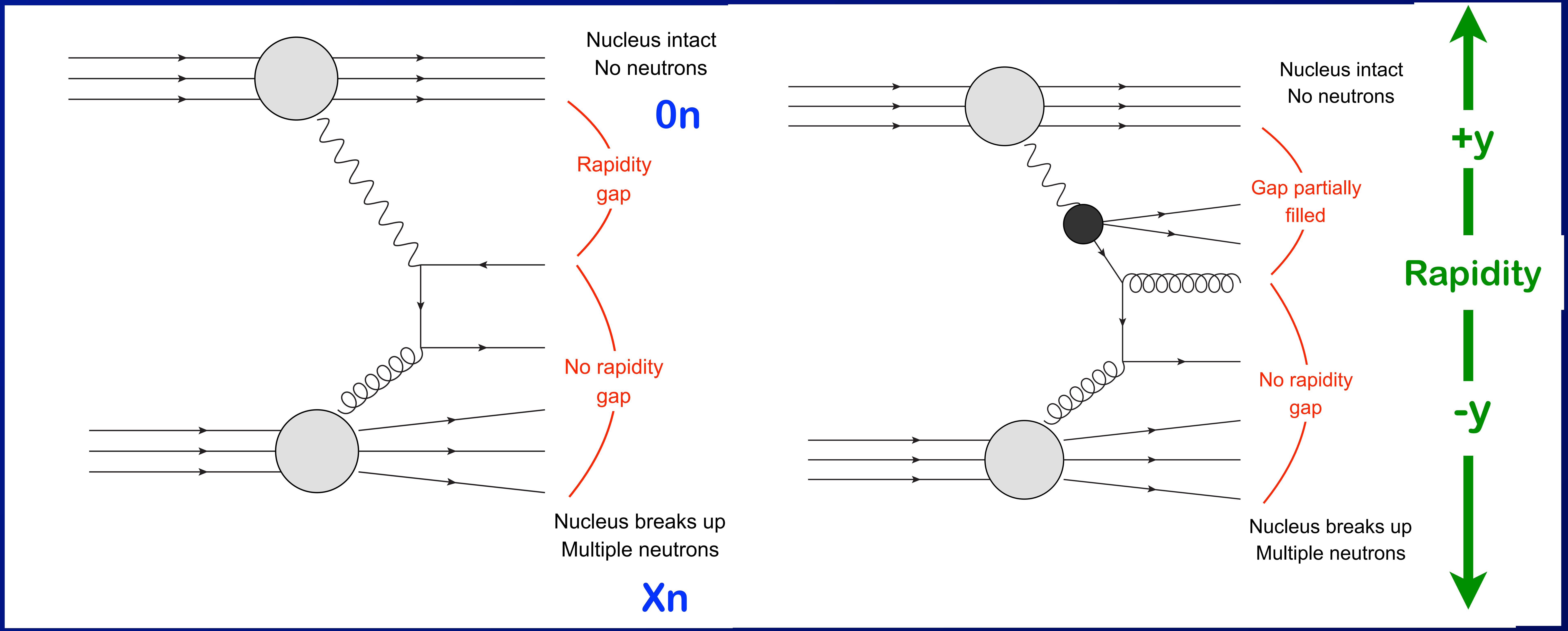


Event selection

- Two experimental handles: ZDC energy, gaps
  - no neutrons in photon-going direction

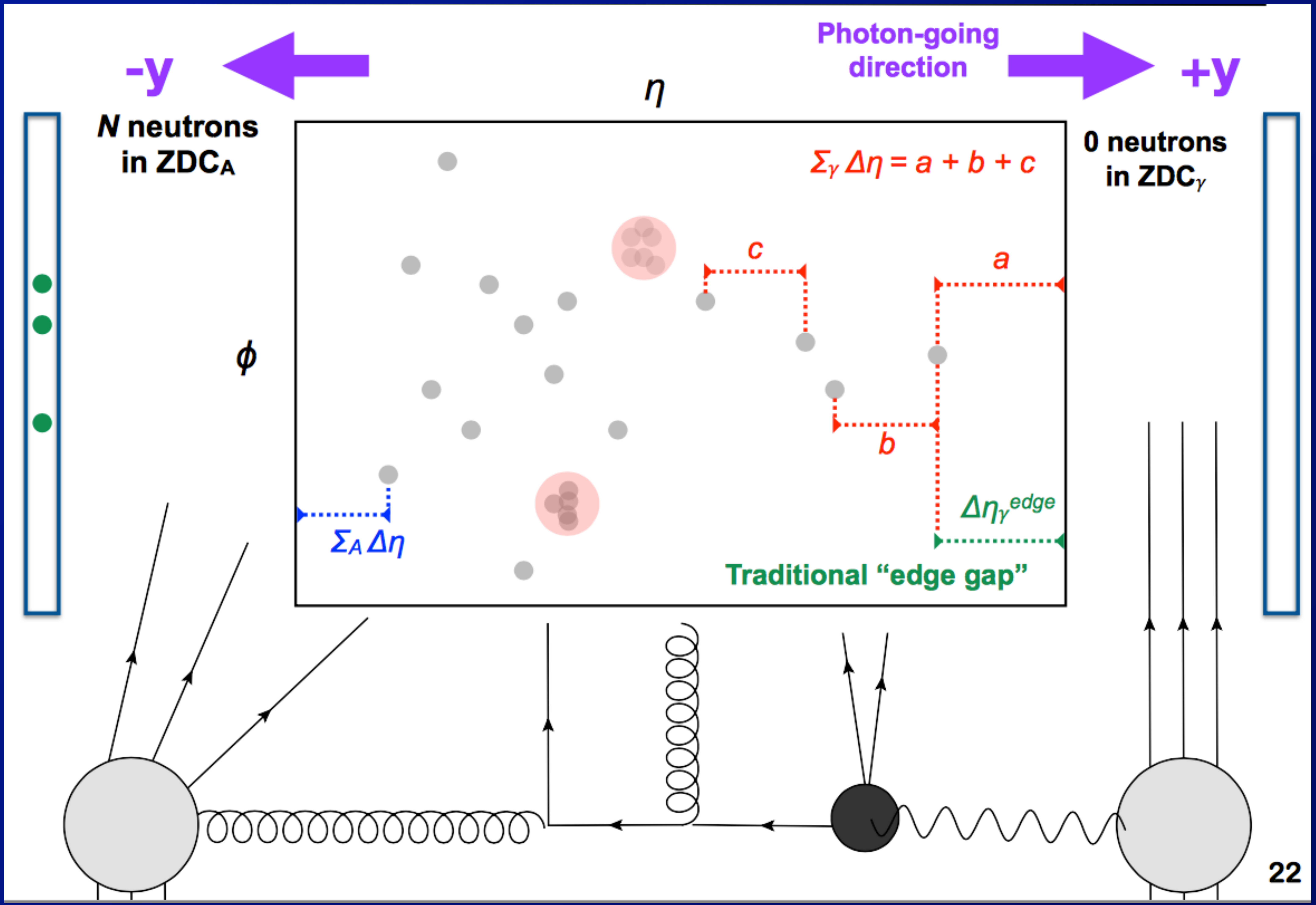
    ⇒Except for Coulomb excitation-induced breakup
  - Rapidity gap in photo-going direction

    ⇒Partially filled by photon remnant



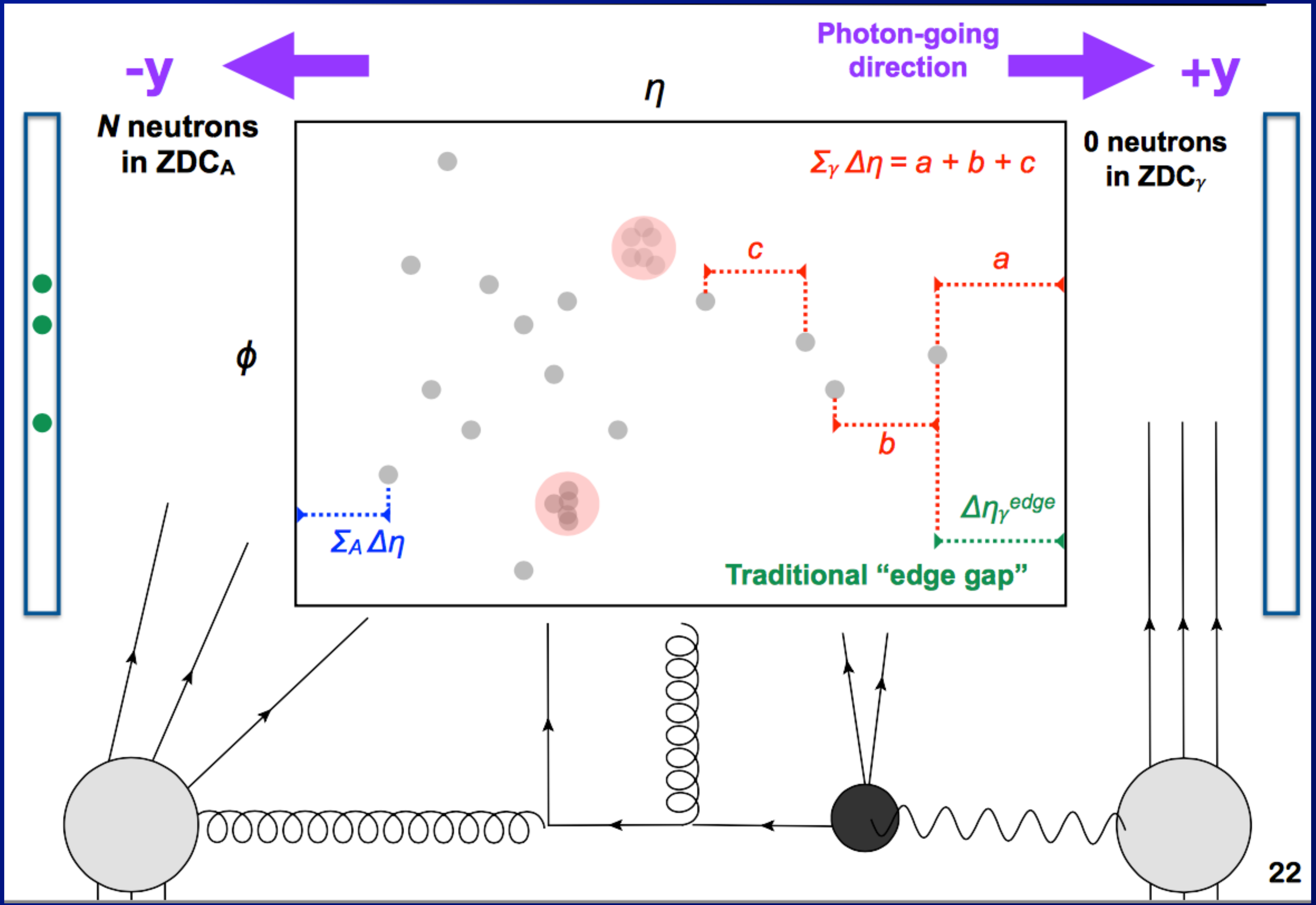
Gap analysis

- A resolved photon event



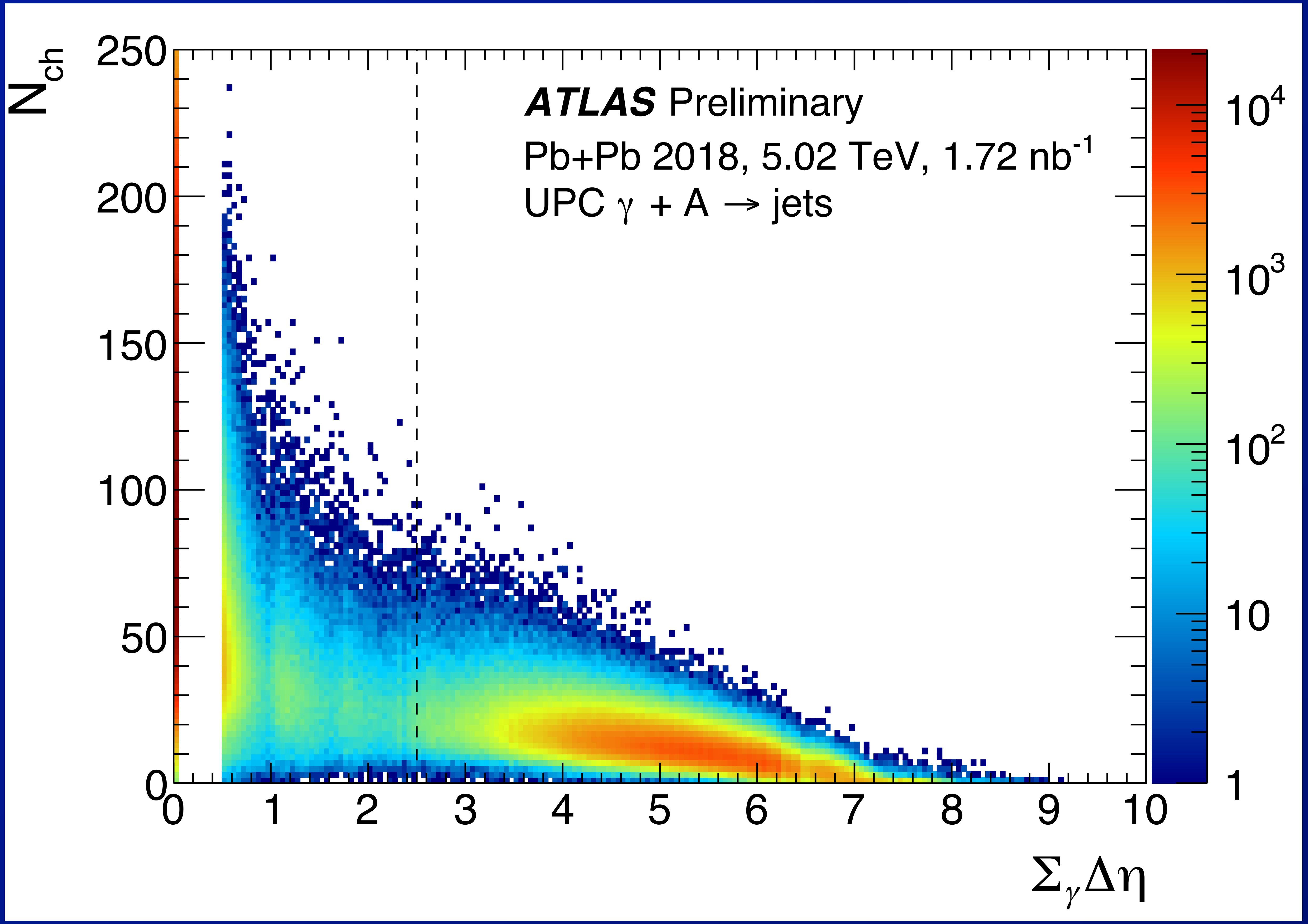
Gap analysis

- To include resolved contribution:
  - sum gaps greater than some size (0.5)



Σ gap selection in γ direction

- Evaluate ΣΔη between most forward jet and detector edge (4.9)
  - Plot versus charge particle multiplicity ($|\eta_{ch}|<2.5$)



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⇒Clear separation between photonuclear and hadronic events

Σ gap selection in γ direction

- Evaluate ΣΔη between most forward jet and detector edge (4.9)
  - Plot versus charge particle multiplicity ($|\eta_{ch}|<2.5$)

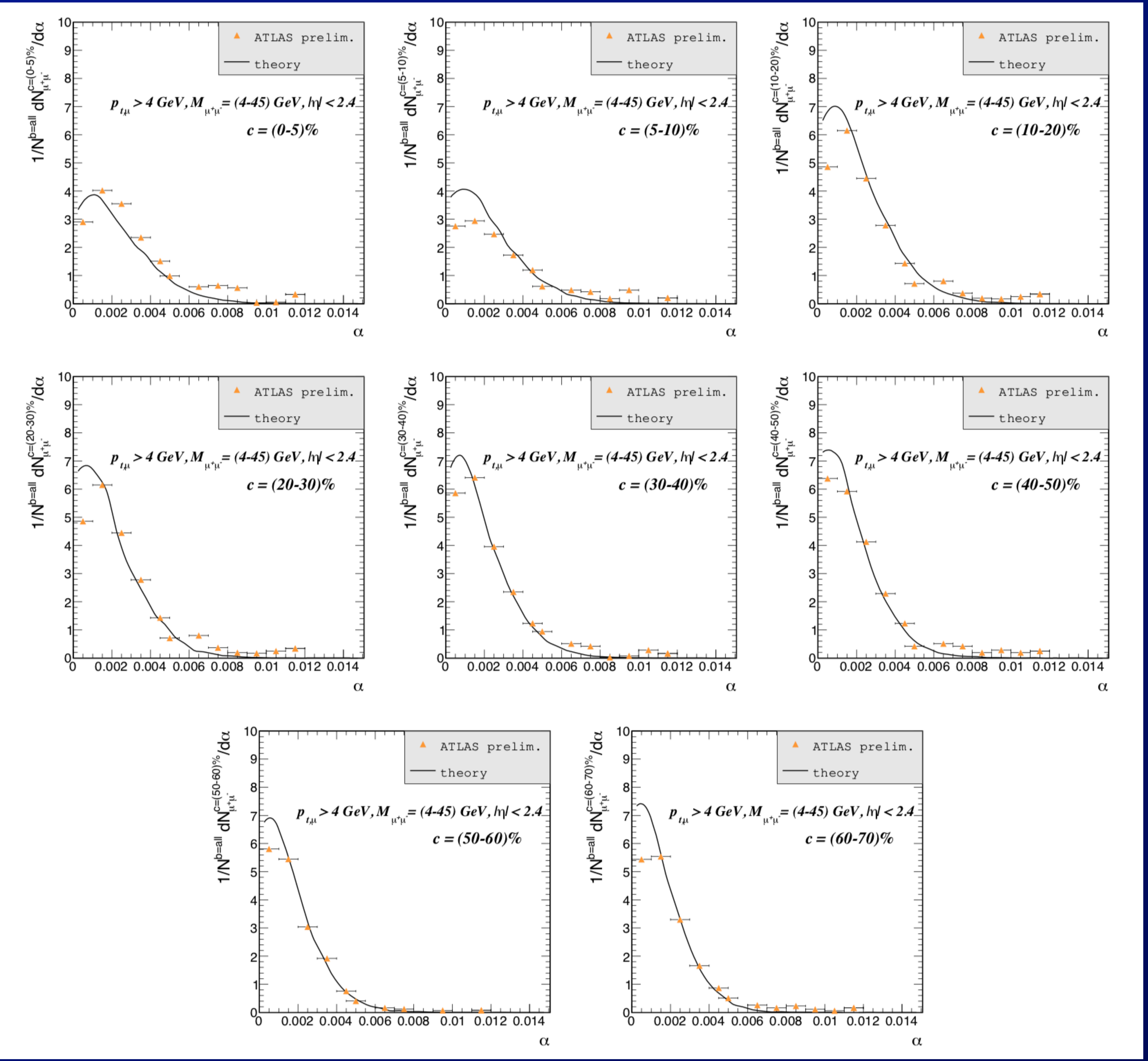
⇒Clear separation between photonuclear and hadronic events

⇒Few % hadronic background after $\Sigma_\gamma \Delta\eta > 2.5$ selection

ATLAS non-UPC $\mu^+\mu^-$ production

- Comparison of ATLAS 2018 preliminary data with calculation by Kl?usek-Gawenda *et al.*
  - also based on photon Wigner distribution

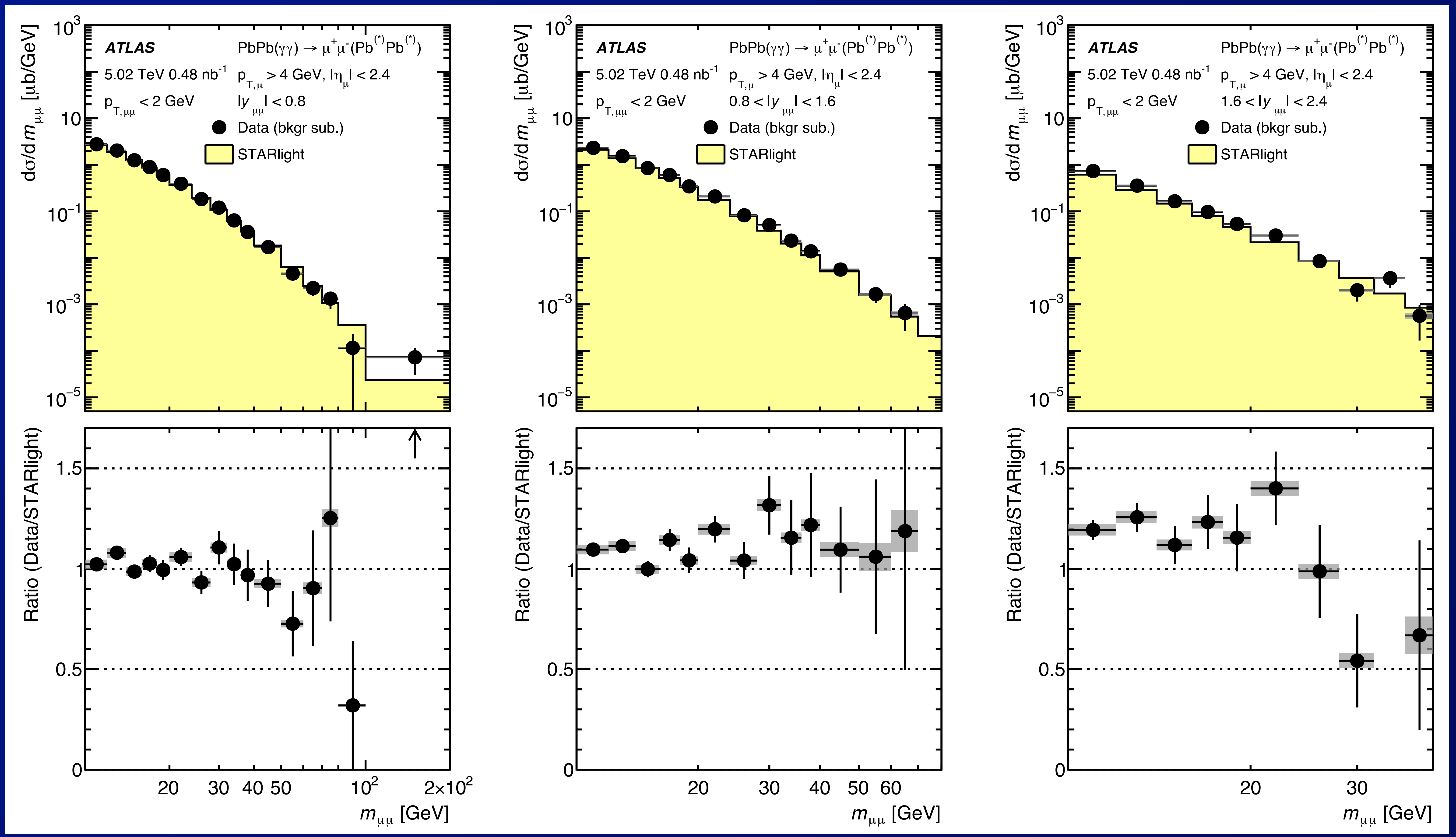
  ⇒Reproduces the broadening but not the depletion at small acoplanarity



New ATLAS $\mu^+\mu^-$ results

- Mass distributions in three $y_{\mu\mu}$ intervals:
  - Compared to predictions from STARlight
  - ⇒Very good agreement on shape of $m_{\mu\mu}$ distributions
  - ⇒But STARlight under-predicts the yield at larger rapidities

$0 < |y_{\mu\mu}| < 0.8$ | $0.8 < |y_{\mu\mu}| < 1.6$ | $1.6 < |y_{\mu\mu}| < 2.4$



ATLAS, 2011.12211 [nucl-ex]

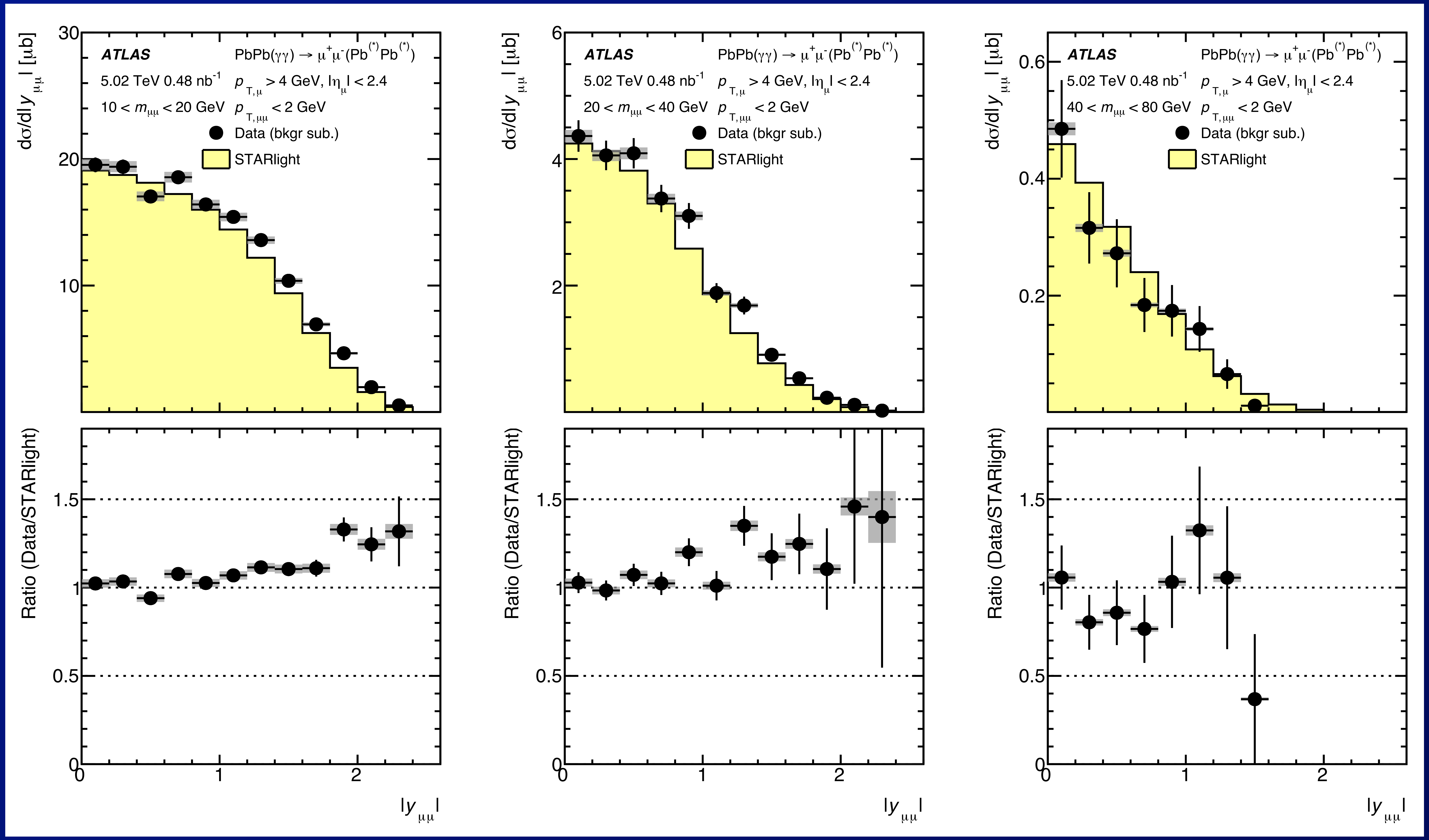
New ATLAS $\mu^+\mu^-$ results

- **Pair rapidity distributions in three $m_{\mu\mu}$ intervals:**
  - Compared to predictions from STARlight

    ⇒similar shapes

    ⇒but STARlight is systematically below the data at larger $y_{\mu\mu}$

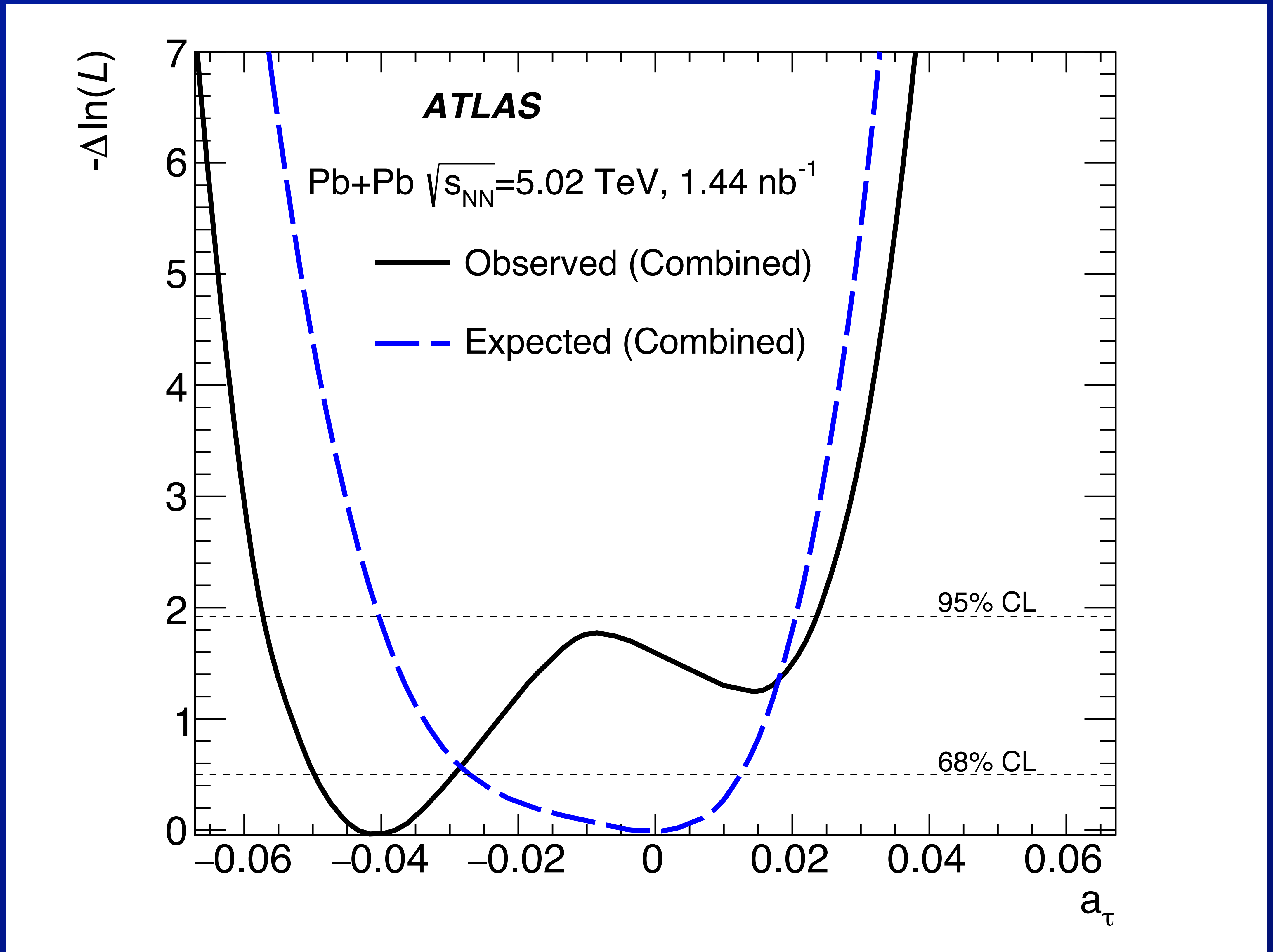
$10 < m_{\mu\mu} < 20$ GeV $20 < m_{\mu\mu} < 40$ GeV $40 < m_{\mu\mu} < 80$ GeV

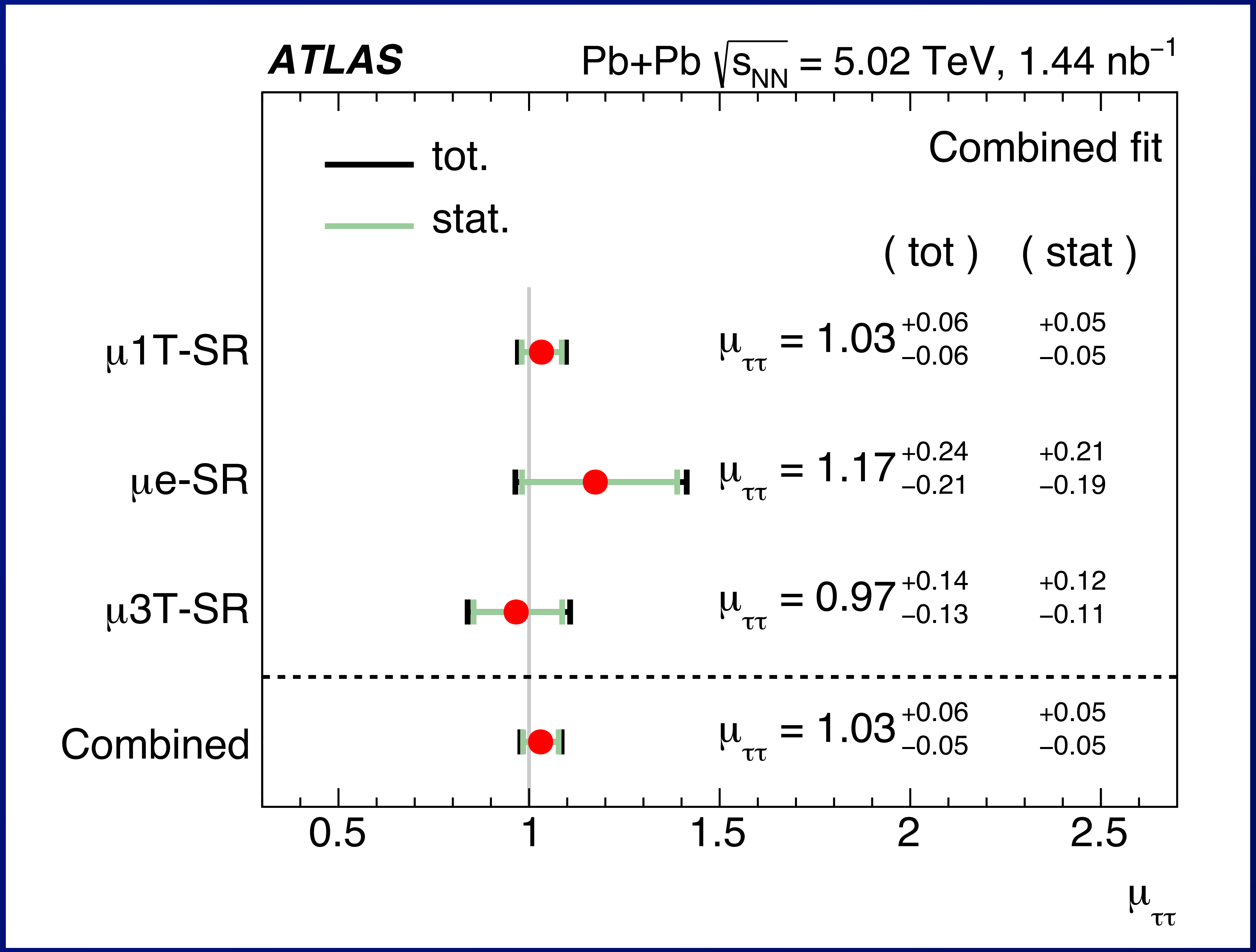


ATLAS, 2011.12211 [nucl-ex]

ATLAS $\gamma\gamma \to \tau\tau$ observation

- **Interference between SM and BSM contributions to $\tau^+\tau^-$ production make the a_τ CLs "unusual"**
  - Especially for μ+e, for which the yield (signal strength $\mu_{\tau\tau}$) is > 1
  - Even for the μ+1T with best statistical precision, $\mu_{\tau\tau}$ > 1 affects the a_τ fit

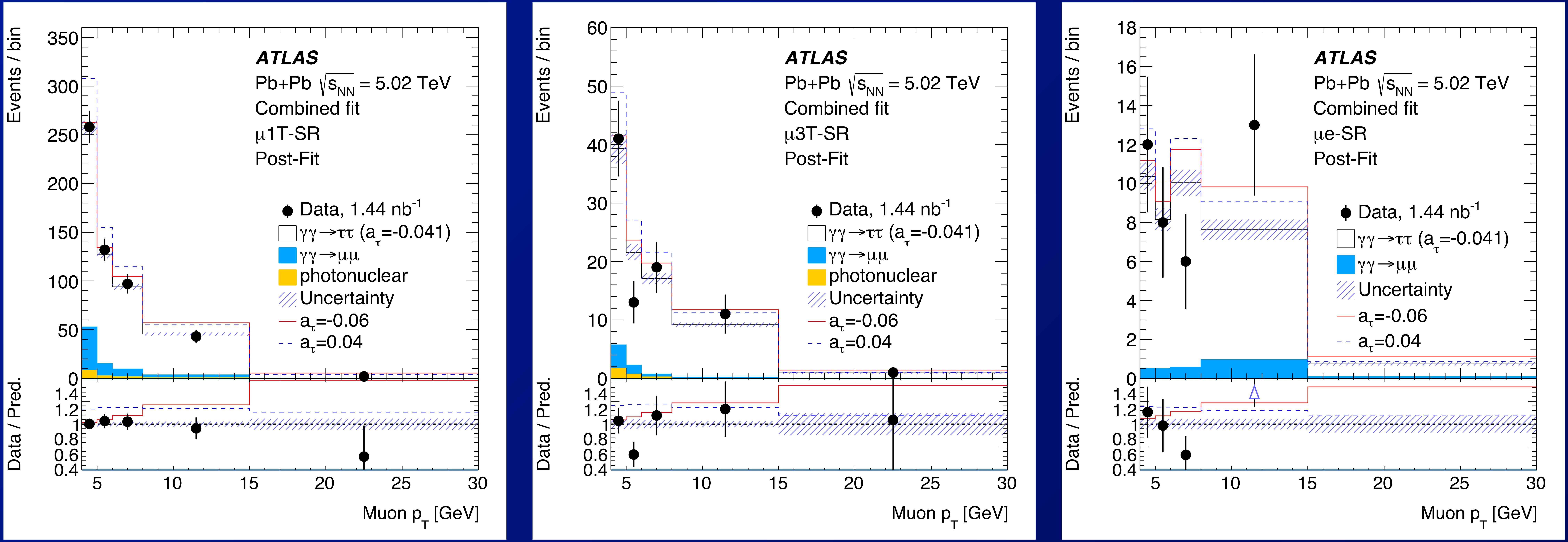




ATLAS γγ→ττ observation

- **Post-fit distributions of muon p_T in three signal regions**
  - Observed events 500, 85, 39
  - Expected backgrounds: 84 ± 19, 9 ± 3, 2.8 ± 0.7

⇒ Best fit $a_\tau \equiv (g_\tau - 2)/2 = -0.041$



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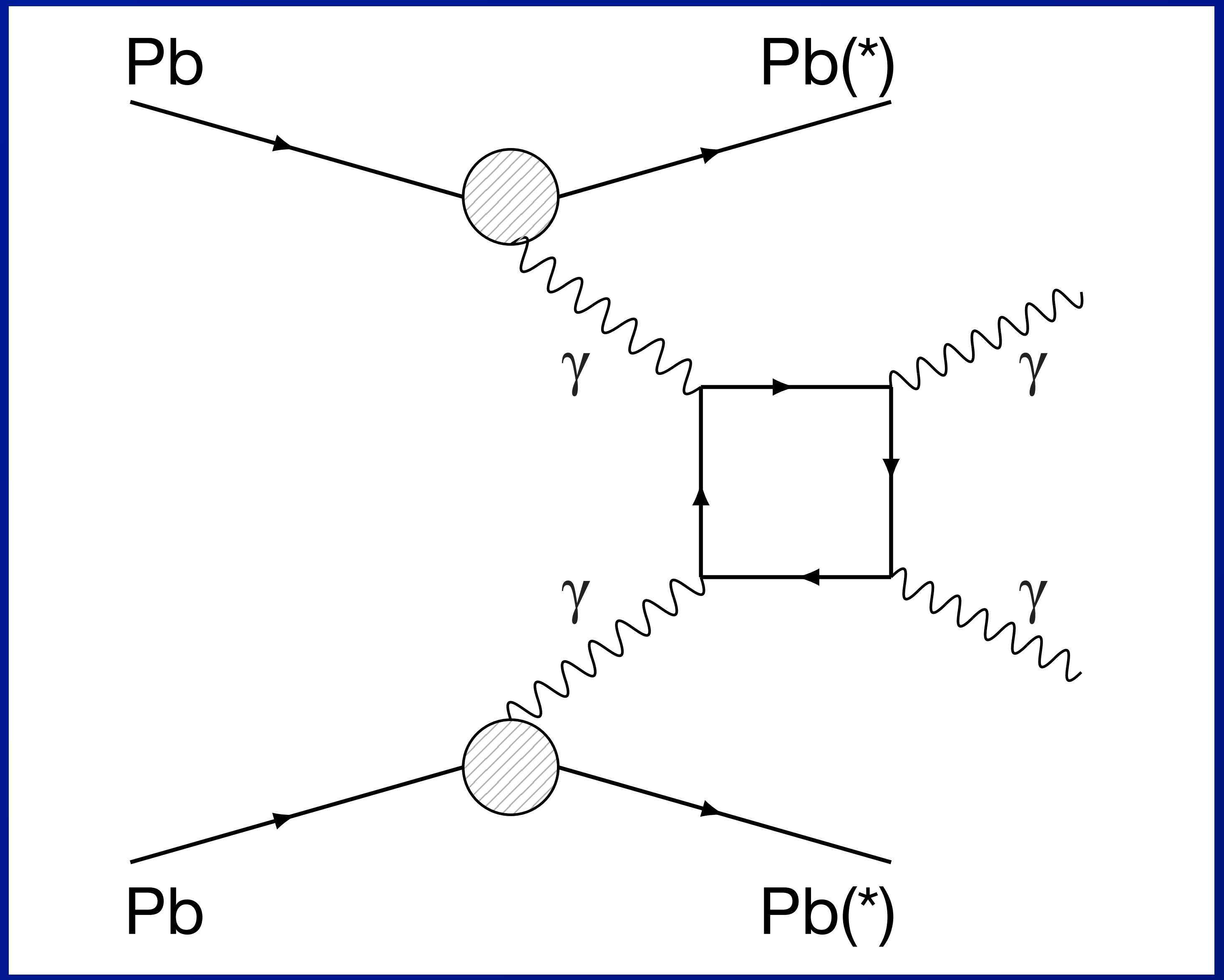
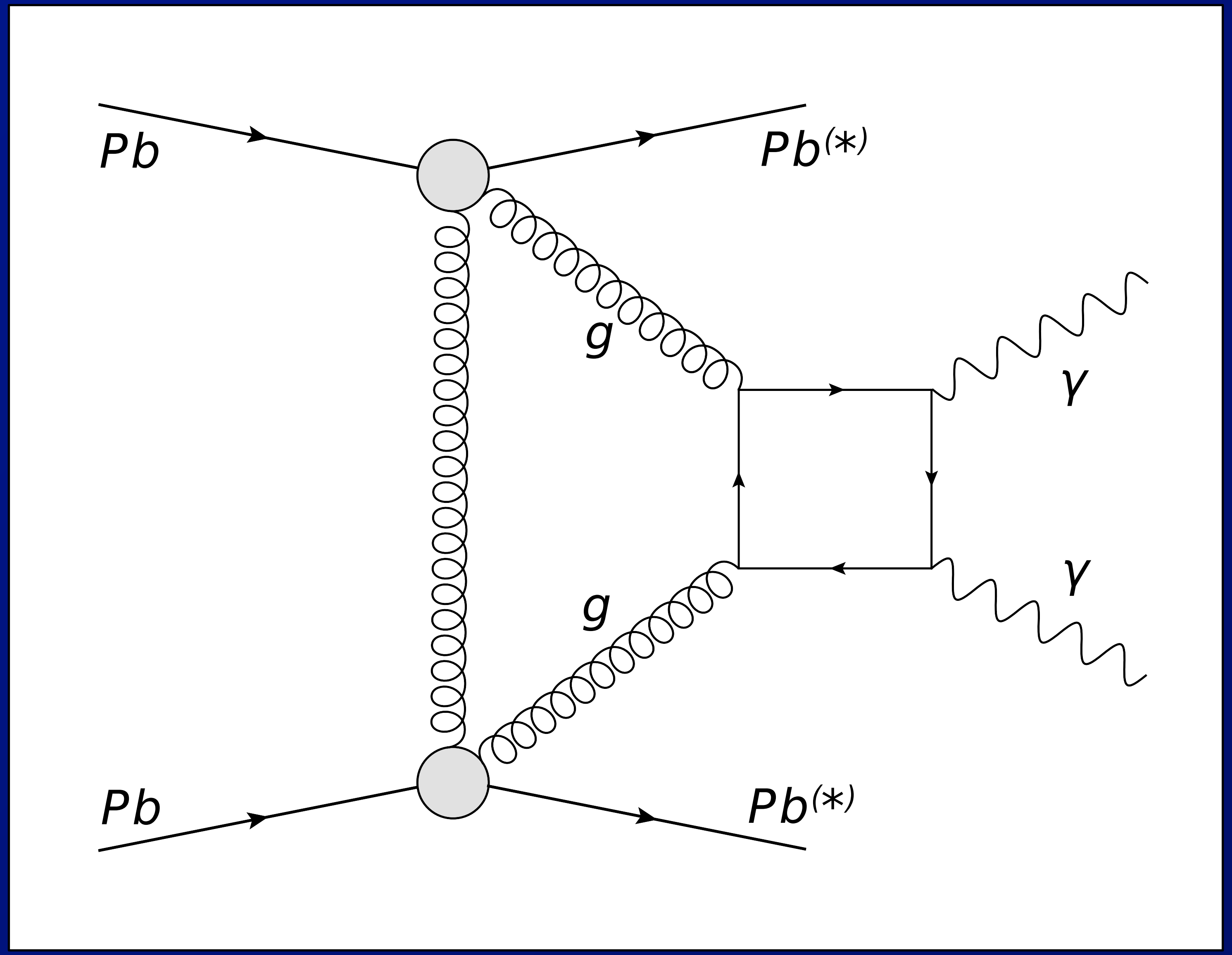
Light-by-light

- Light-by-light scattering of real photons was discovered @ LHC
  - –now being used to search from BSM physics
  - ⇒e.g. axion-like particles (ALP)

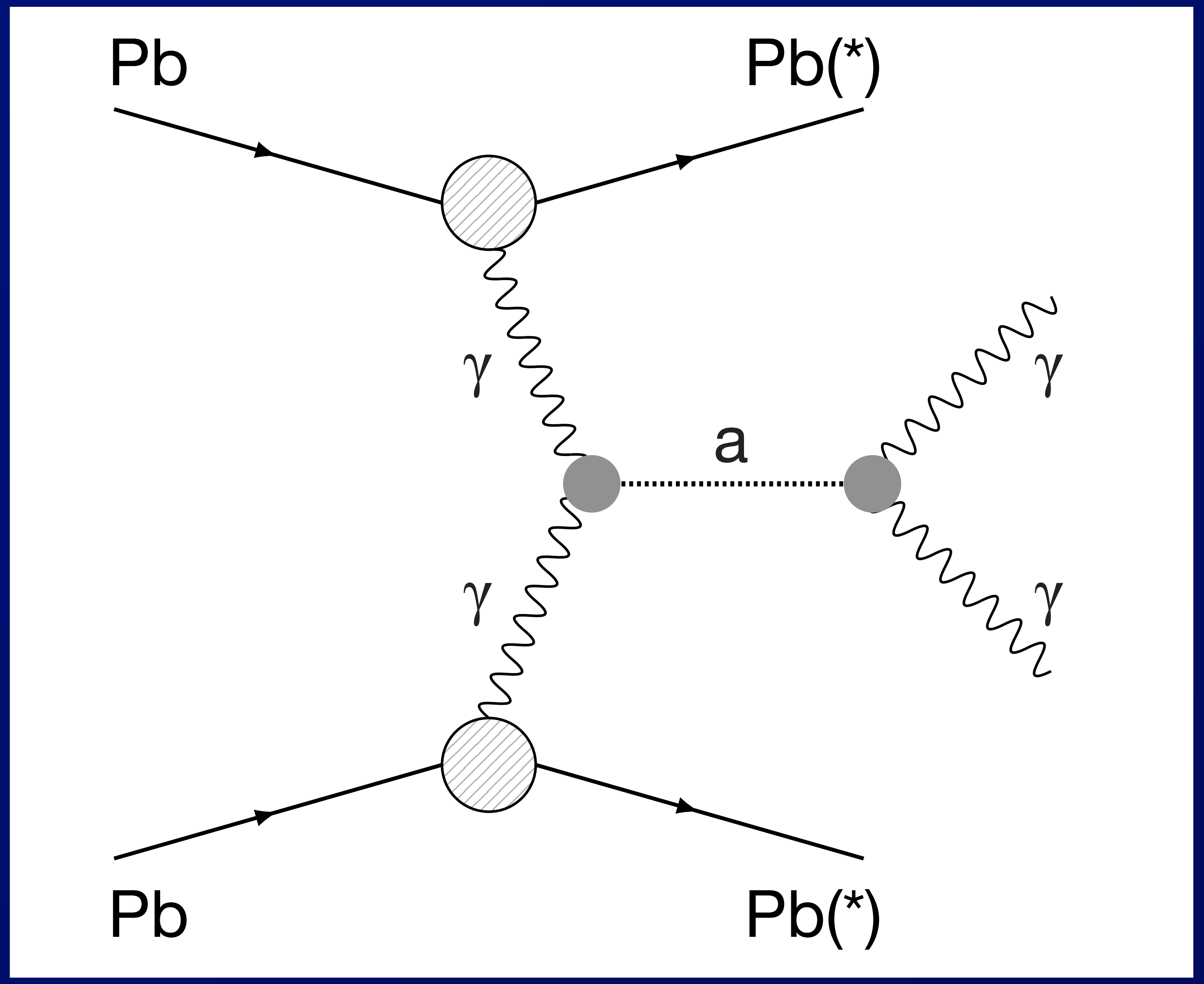
- Diagrams for three processes:
  - ⇒ Signal L-by-L, background CEP, L-by-L production of ALP



SM L-by-L



CEP g+g→γγ

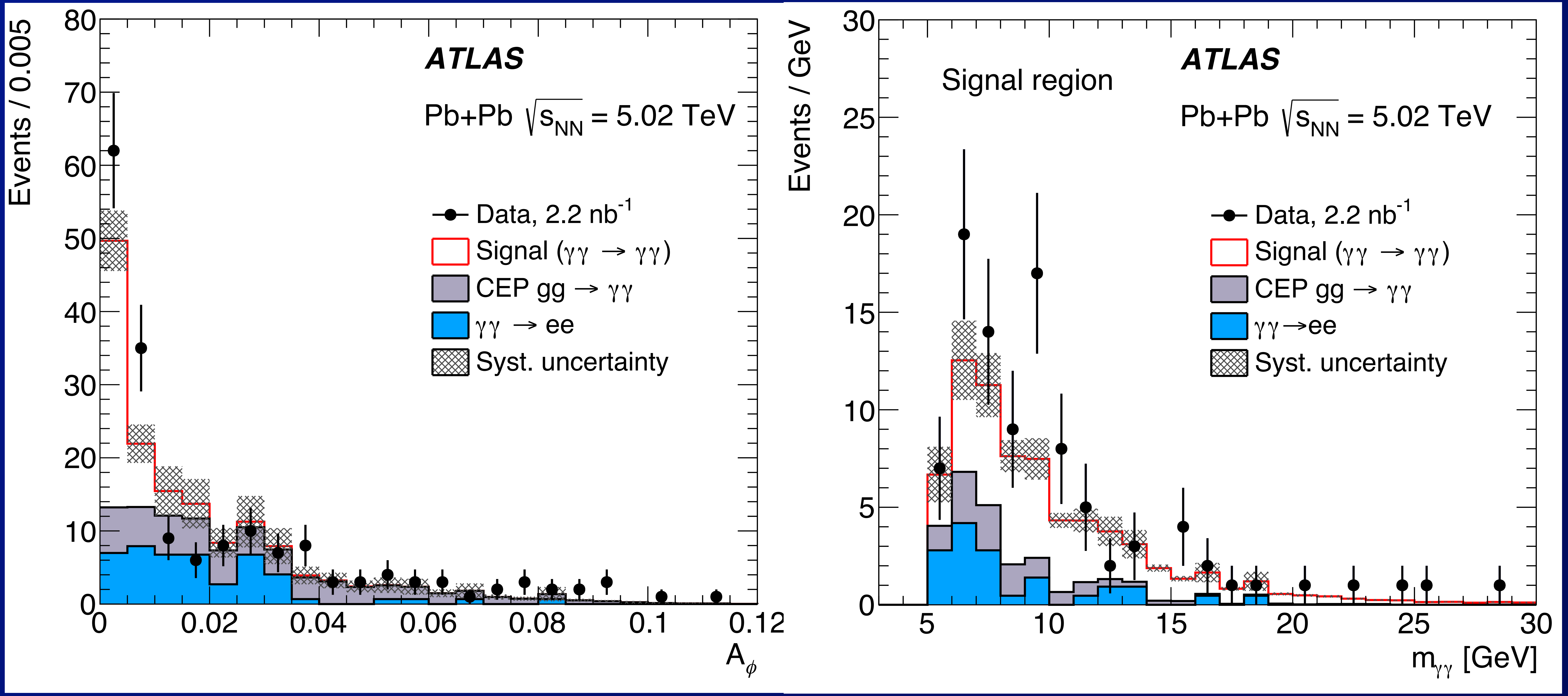


L-by-L ALP

ATLAS Differential Light-by-Light Measurement

- Exclusive γγ events (no tracks):
  - $m_{\gamma\gamma}$ > 5 GeV, $p_{T\gamma\gamma}$ < 1(2) GeV, A_ϕ < 0.01
  - CEP background from MC, normalized using data, ago > 0.01

- 97 events observed
  - background: 27 ± 5
  - ⇒ σ_{fid} = 120 nb ±17(stat.) ±13 (syst.) ± 4 (lumi.)
- Ratio to theory(ies):
  - ⇒ (combining) 1.5 ± 0.3

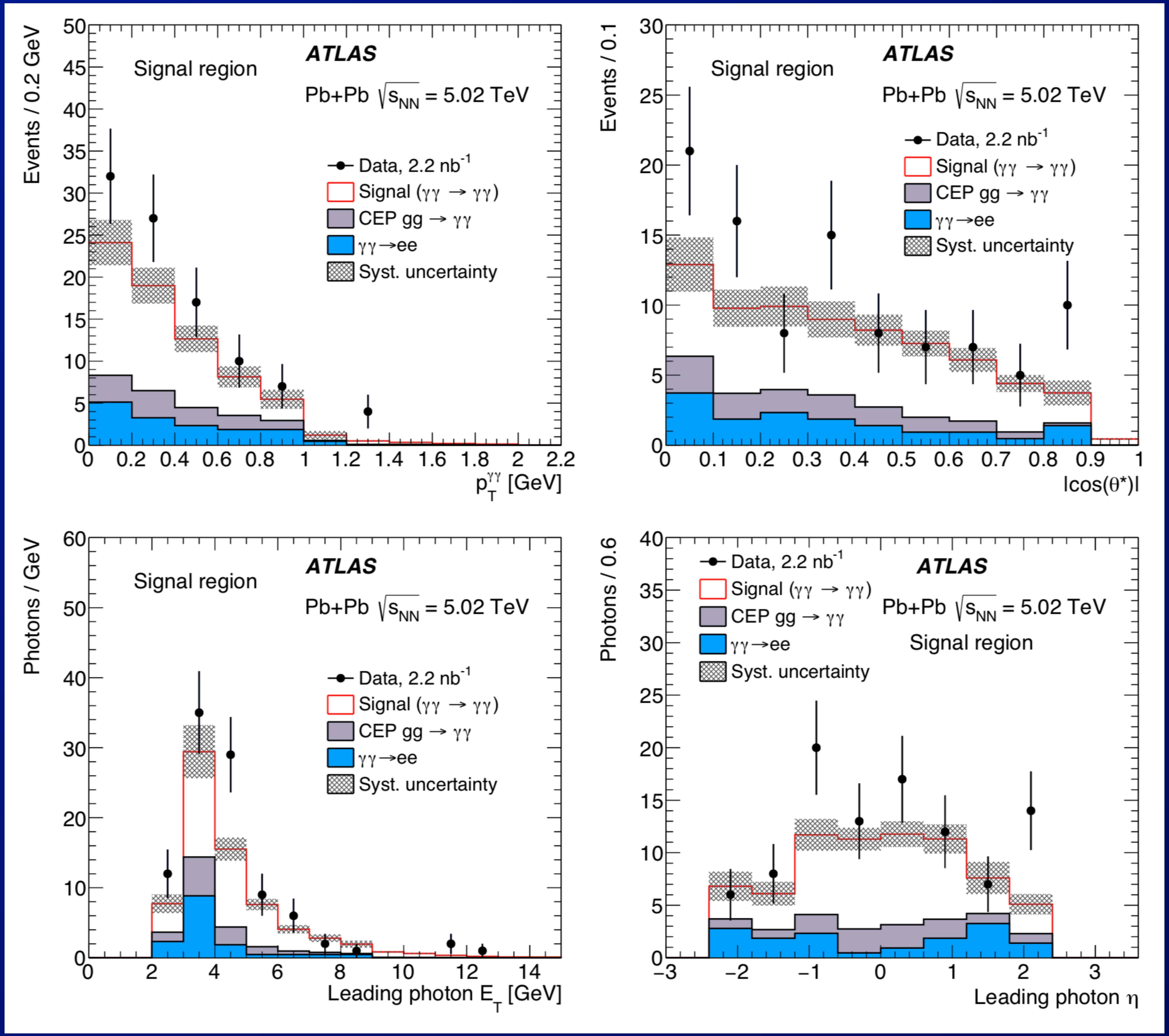


Phys. Rev. Lett. 123 (2019) 052001

ATLAS Differential Light-by-Light Measurement

- Combined 2015+2018 data
  - 2.2 nb^{-1}
- Exclusive γγ events:
  - $m_{\gamma\gamma} > 5$ GeV, $p_{T\gamma\gamma} < 1(2)$ GeV, $A_\phi < 0.01$
- Measured differential distributions
  - pair p_T
  - cos θ*
  - leading photon p_T
  - leading photon η

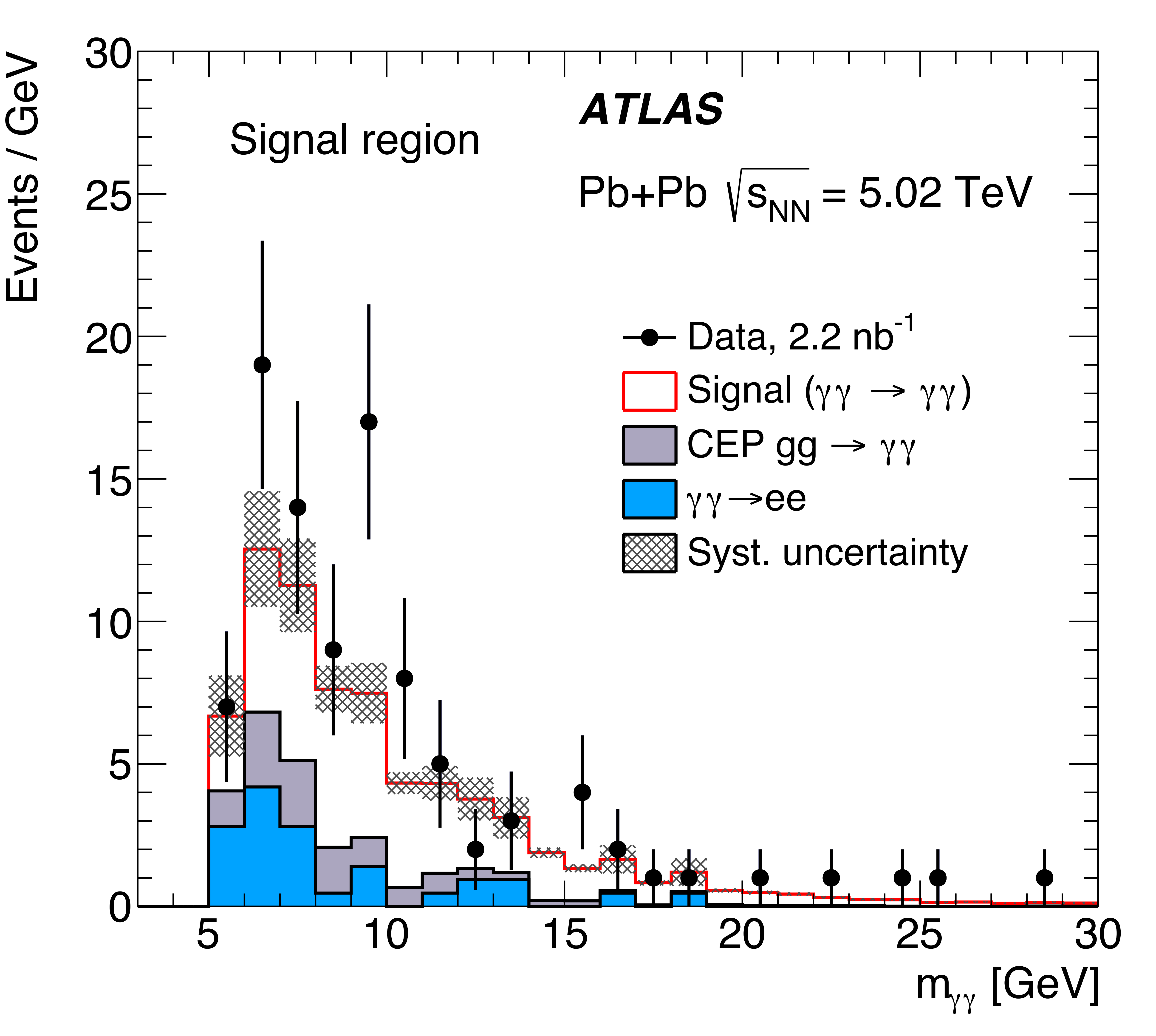
⇒Date well described by sum of signal and bkgd except for normalization



JHEP 03 (2021) 243

ATLAS Differential Light-by-Light Measurement

- Combined 2015+2018 data
- Exclusive γγ events:
  - $m_{\gamma\gamma} > 5$ GeV, $p_{T\gamma\gamma} < 1(2)$ GeV, $A_\phi < 0.01$
- Test for presence of ALP signal
  ⇒Narrow peak in $m_{\gamma\gamma}$ dist.



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ATLAS Differential Light-by-Light Measurement

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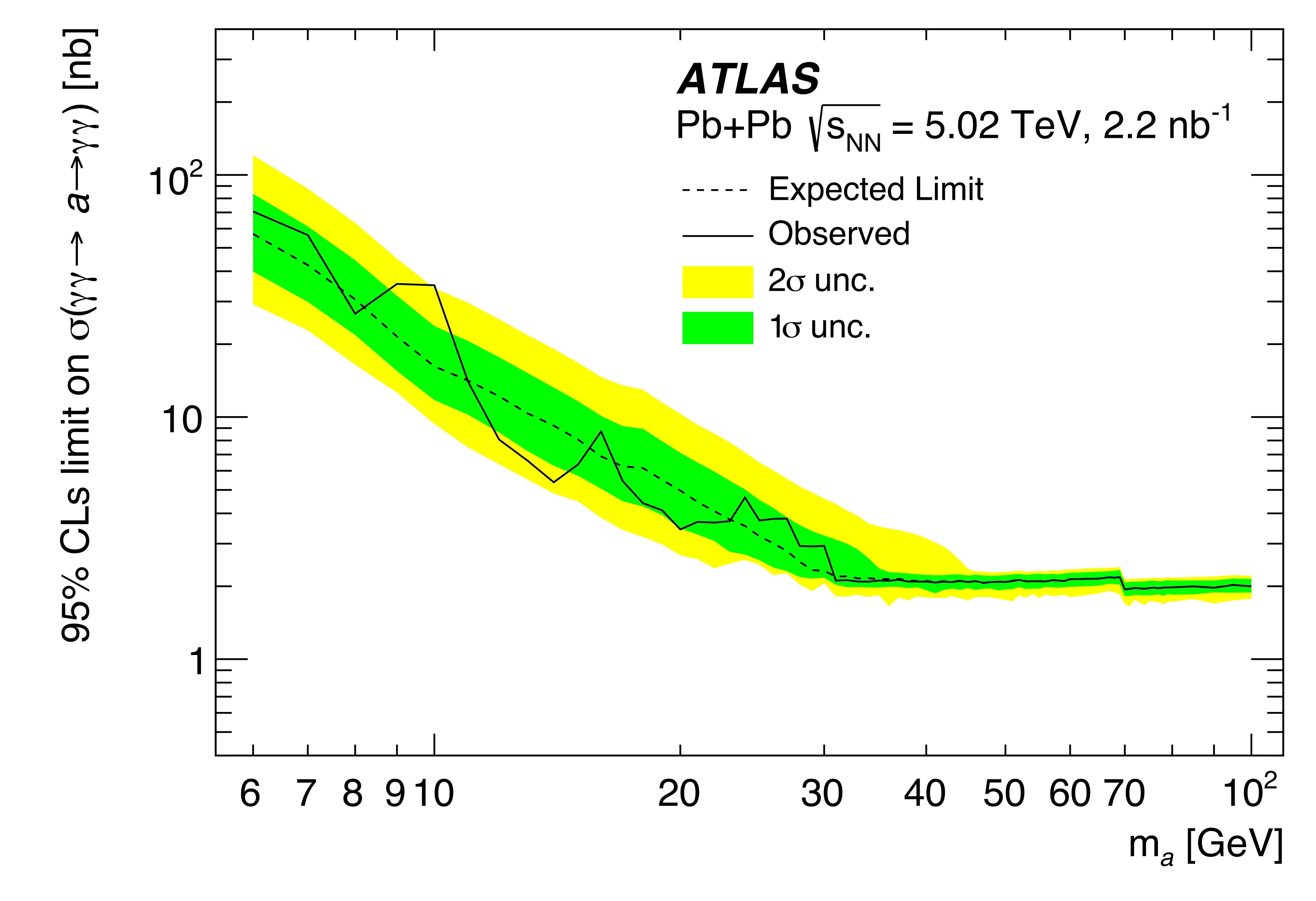
- Exclusive γγ events:
  - $m_{\gamma\gamma} > 5$ GeV, $p_{T\gamma\gamma} < 1(2)$ GeV, $A_\phi < 0.01$
- Test for presence of ALP signal
  ⇒Narrow peak in $m_{\gamma\gamma}$ dist.
- No significant deviation from background-only hypothesis
  ⇒set limits



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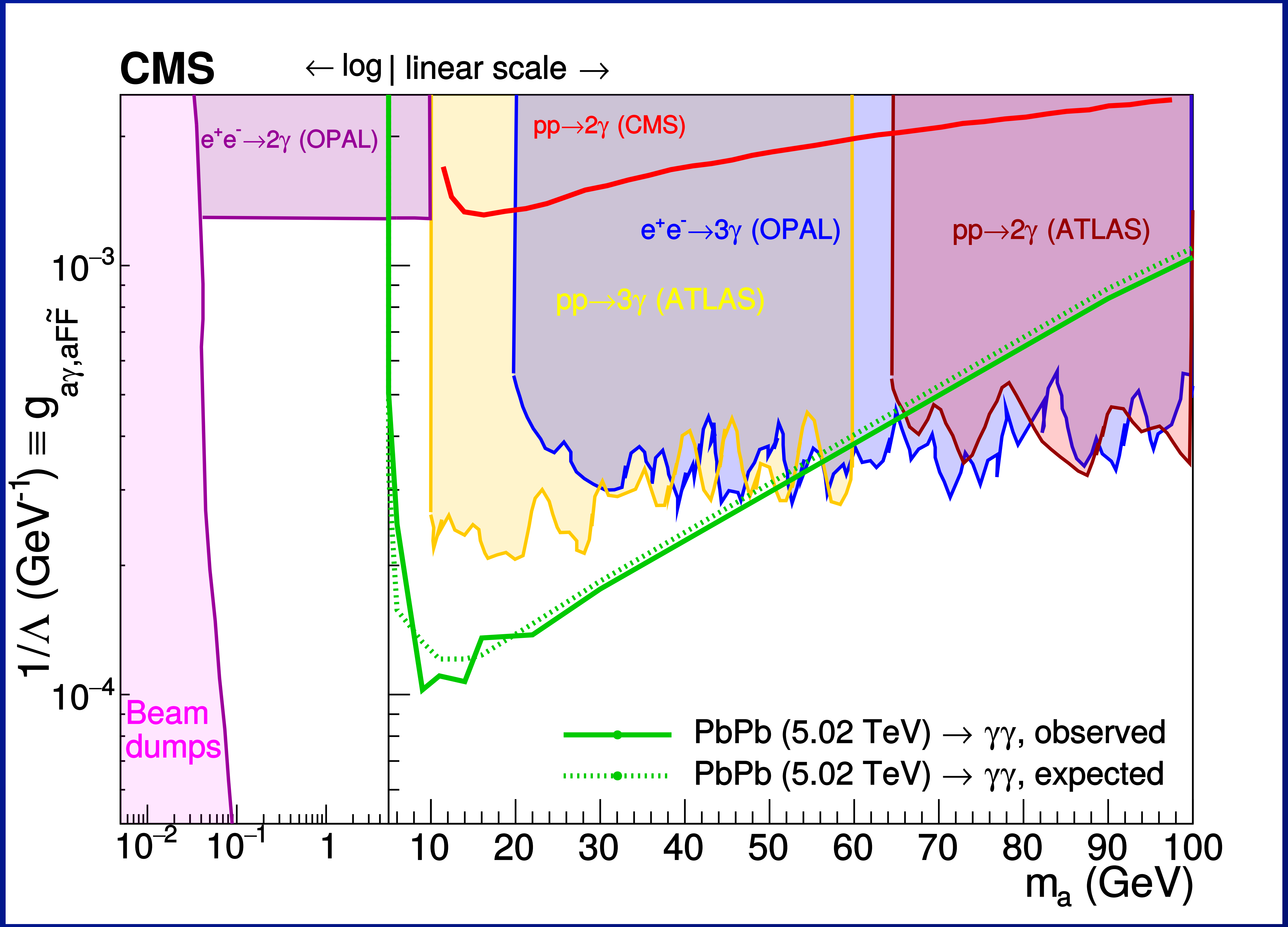
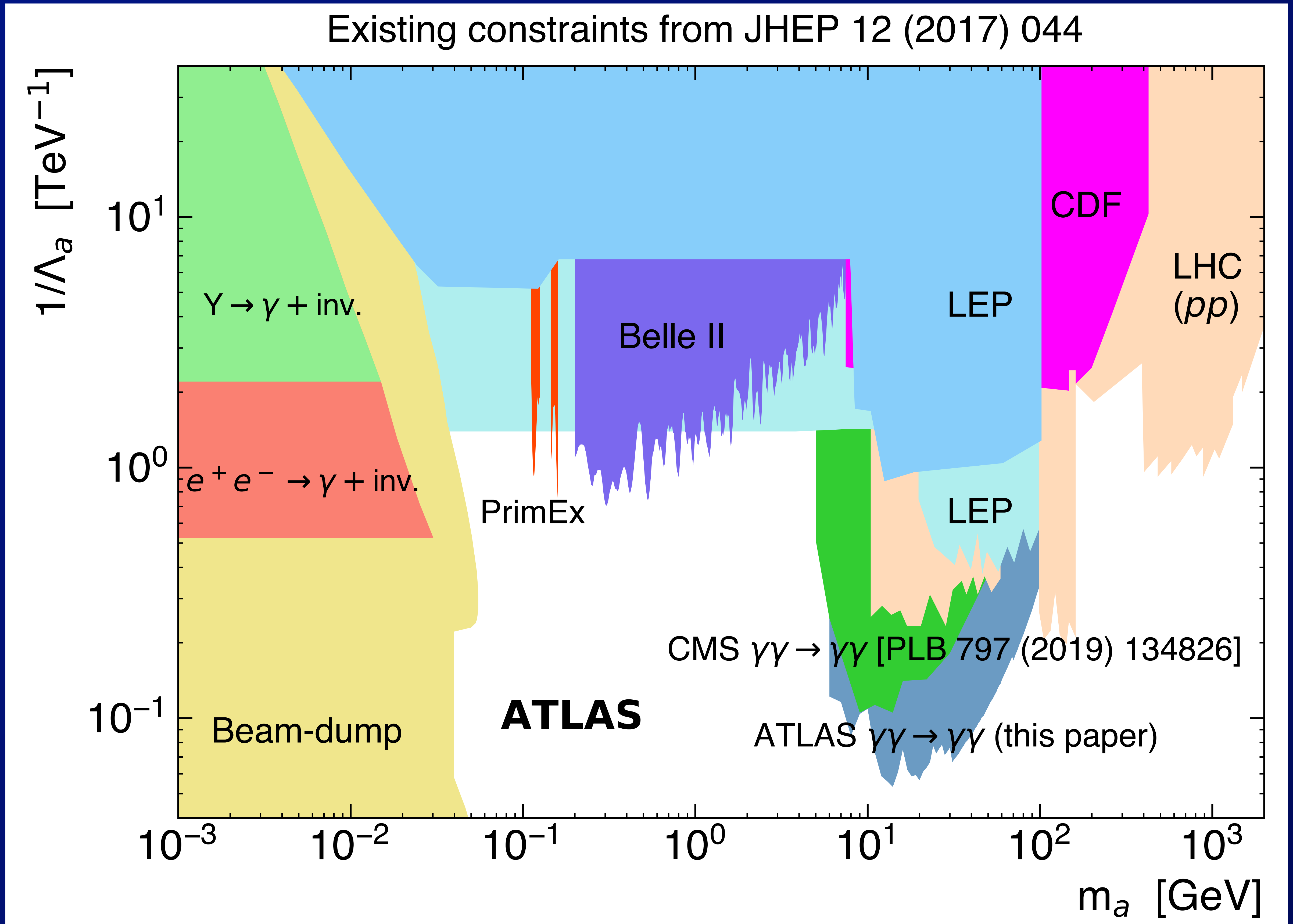
ATLAS and CMS limits on ALP in γγ

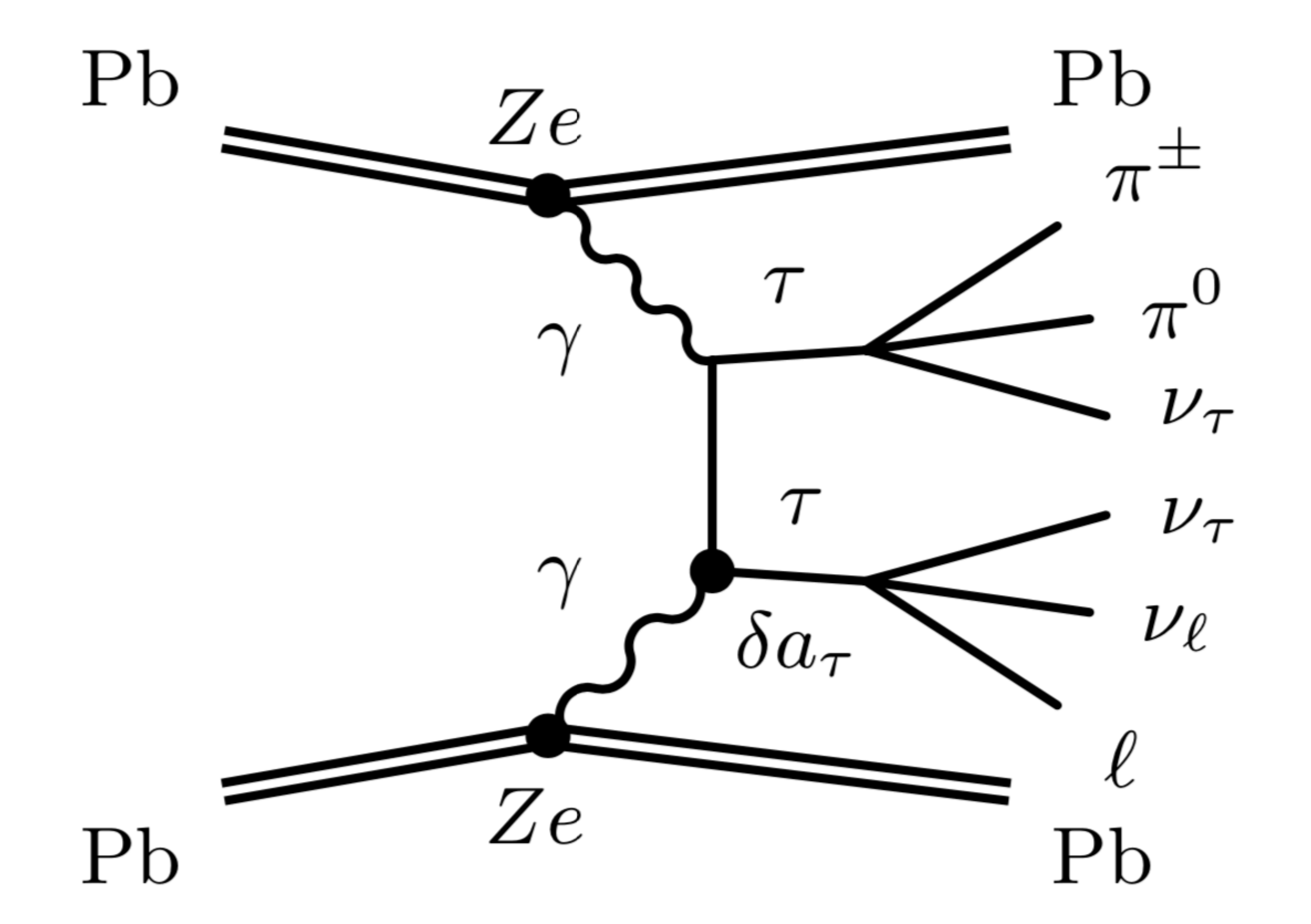
- No combination of ATLAS & CMS data (yet)
- LHC measurements in UPC light-by-light provide improved constraints on ALP production in mass range 5-100 GeV

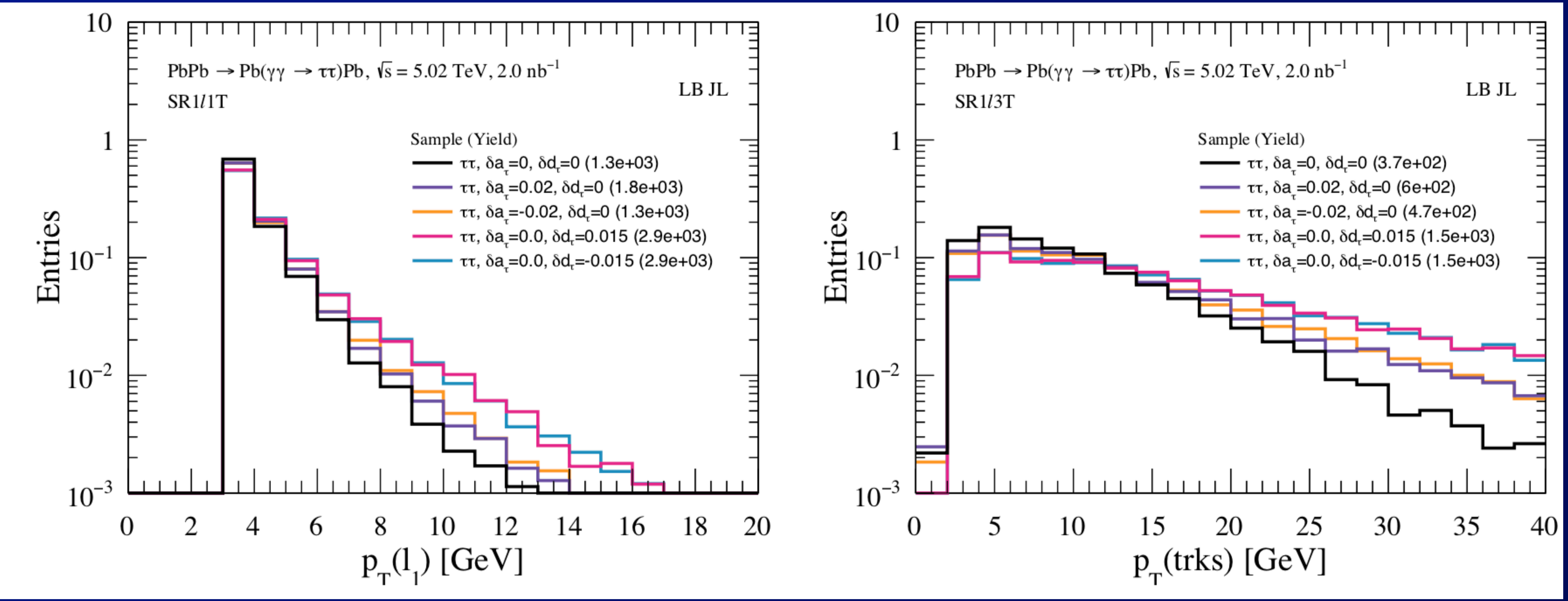




tau g-2 and ultra-peripheral $\tau^+ \tau^-$ production

- It was proposed by Beresford and Liu that competitive tau g-2 measurements could be made using UPC $\gamma+\gamma \rightarrow \tau^+ \tau^-$
  - mass increases sensitivity to BSM physics
    - ⇒e.g. in EFT, the kinematics of the taus & decay products are sensitive to higher-dimension operators





ATLAS $\gamma\gamma \to \tau\tau$ observation

Phys. Rev. Lett. 131 (2023) 151802

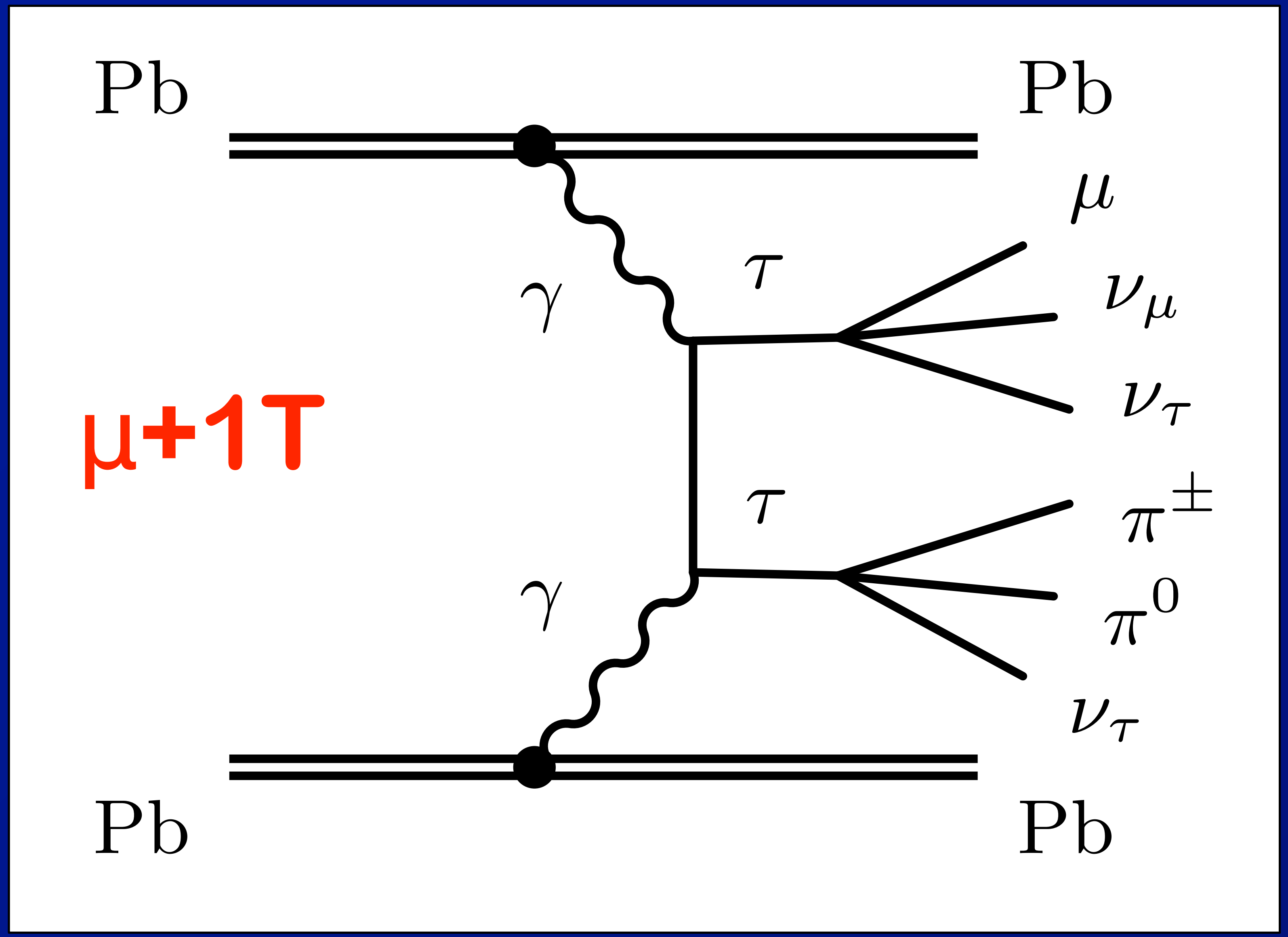
- ATLAS used three signal CRs to select events with 2 τ decays

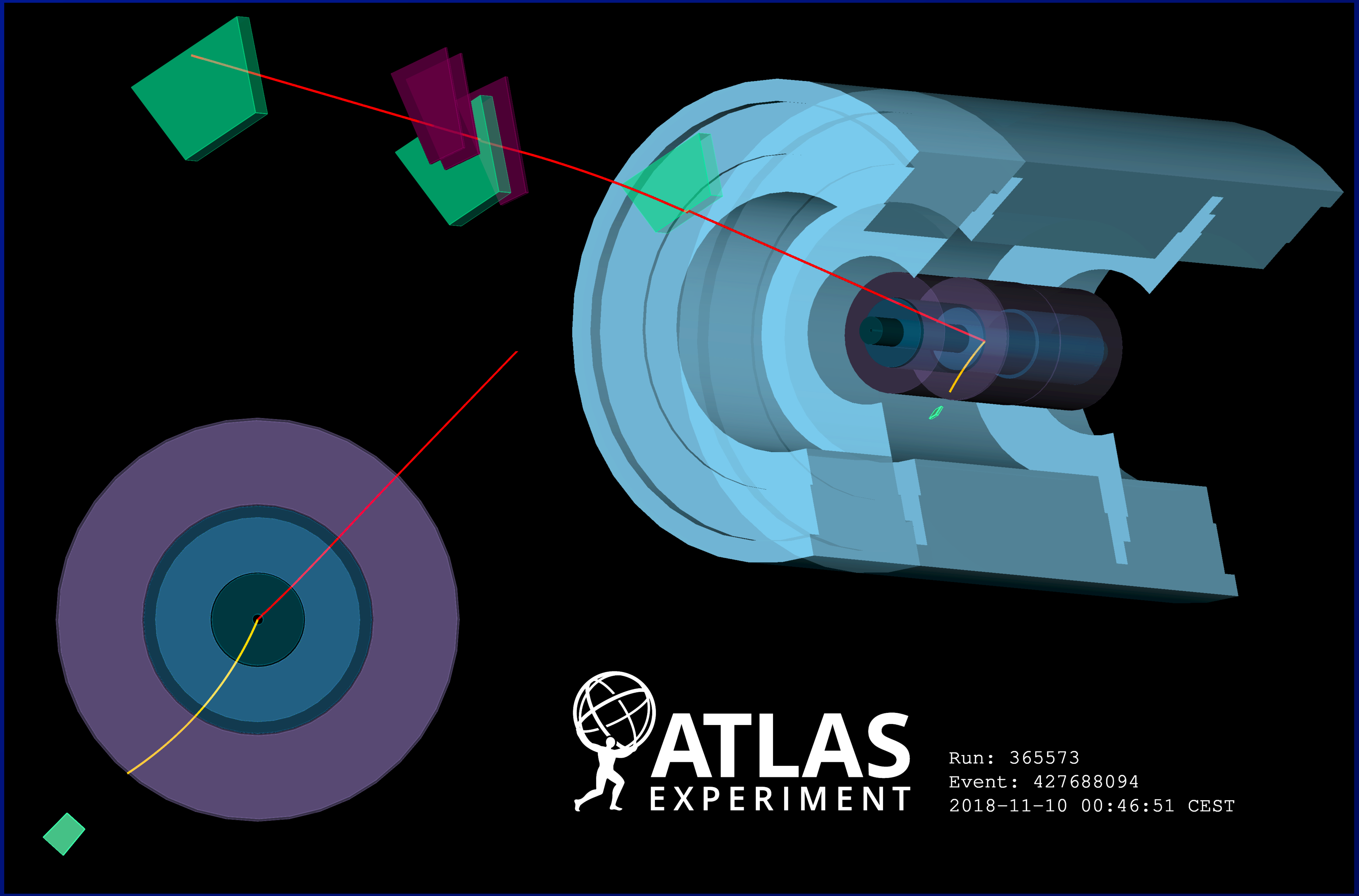
ATLAS γγ→ττ observation

- ATLAS used three signal CRs to select events with 2 τ decays

Phys. Rev. Lett. 131 (2023) 151802

– Muon + 1 track

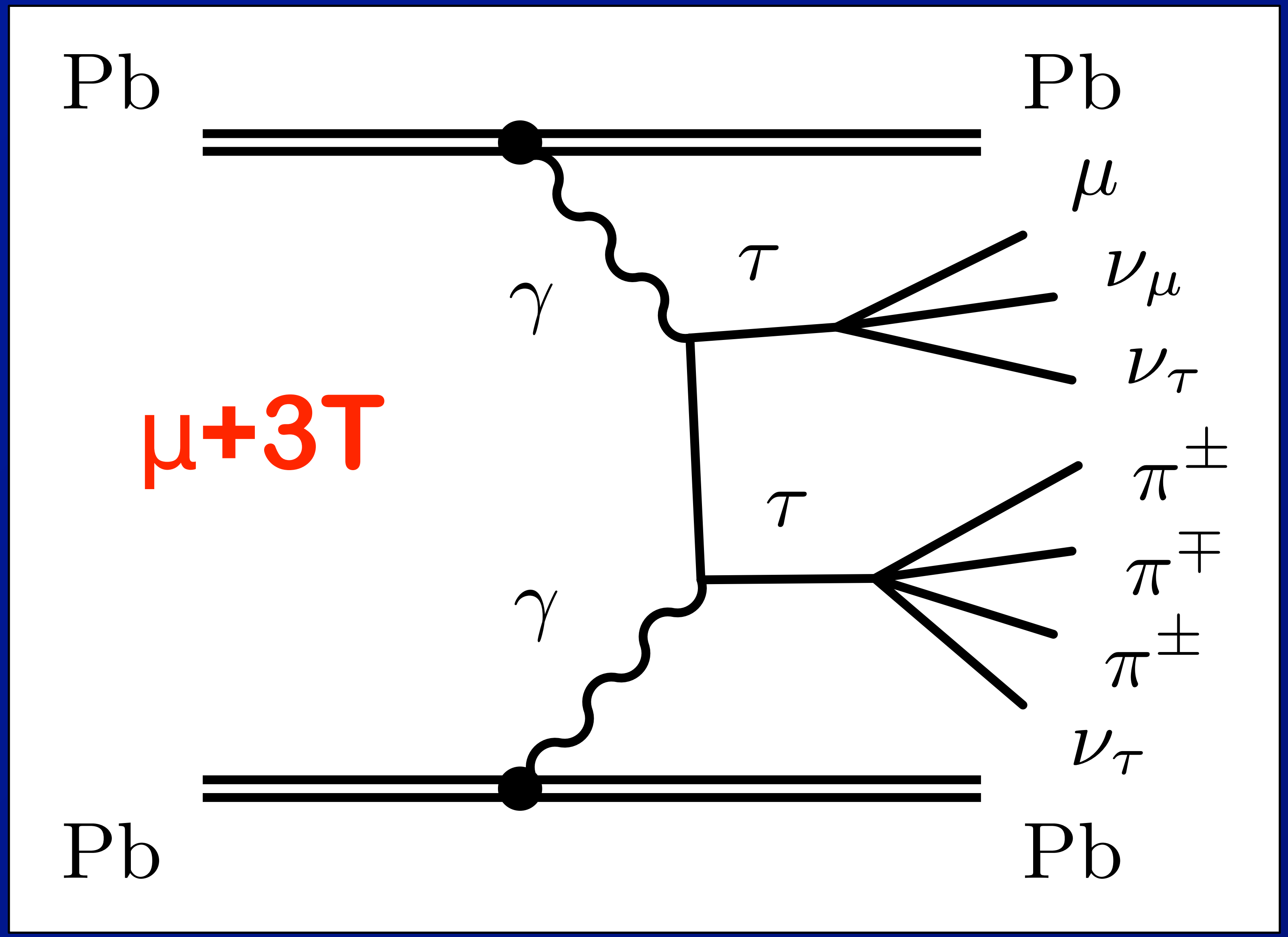


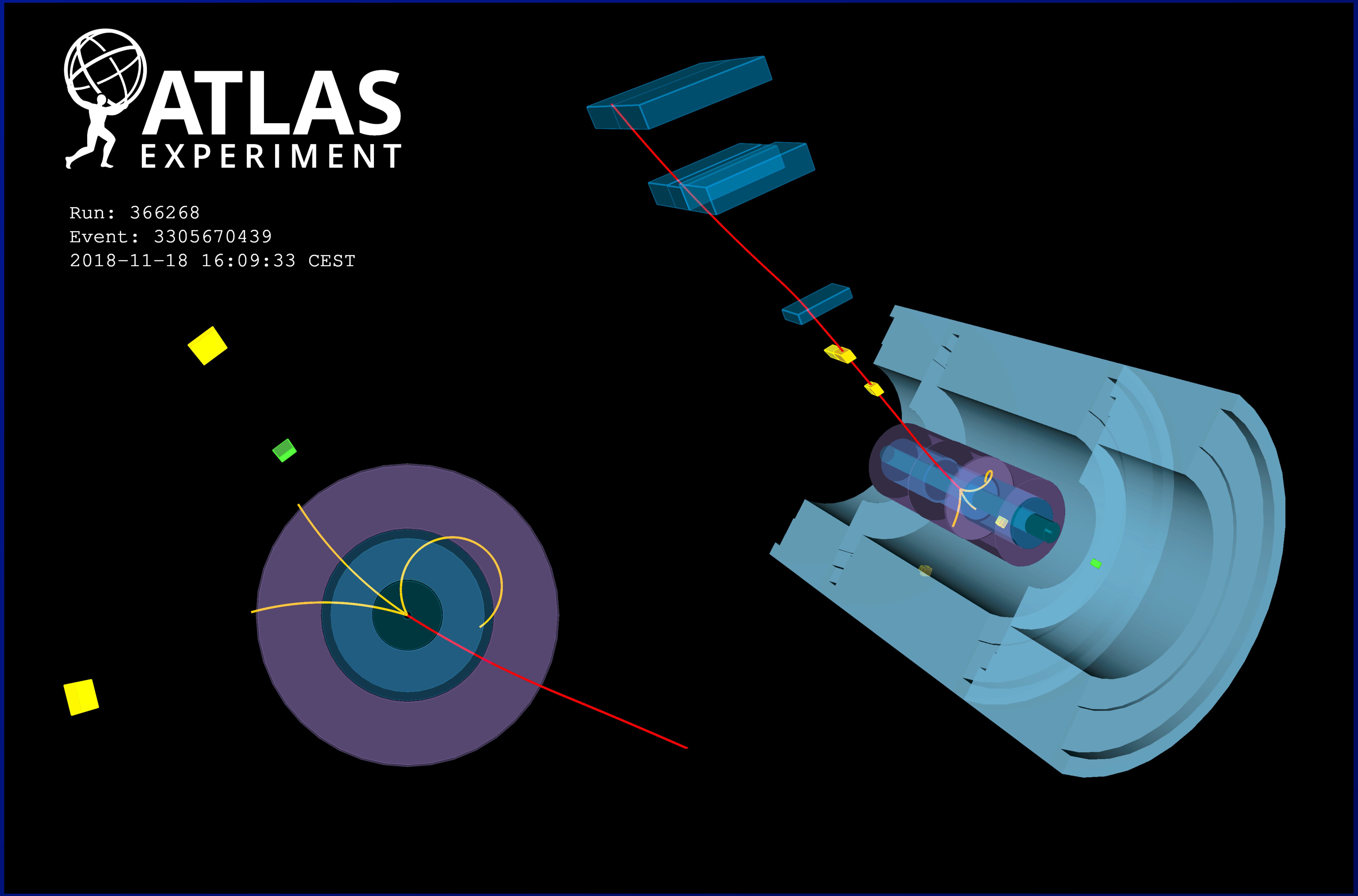


ATLAS $\gamma\gamma \rightarrow \tau\tau$ observation

Phys. Rev. Lett. 131 (2023) 151802

- ATLAS used three signal CRs to select events with 2 τ decays
  - Muon + 3 tracks

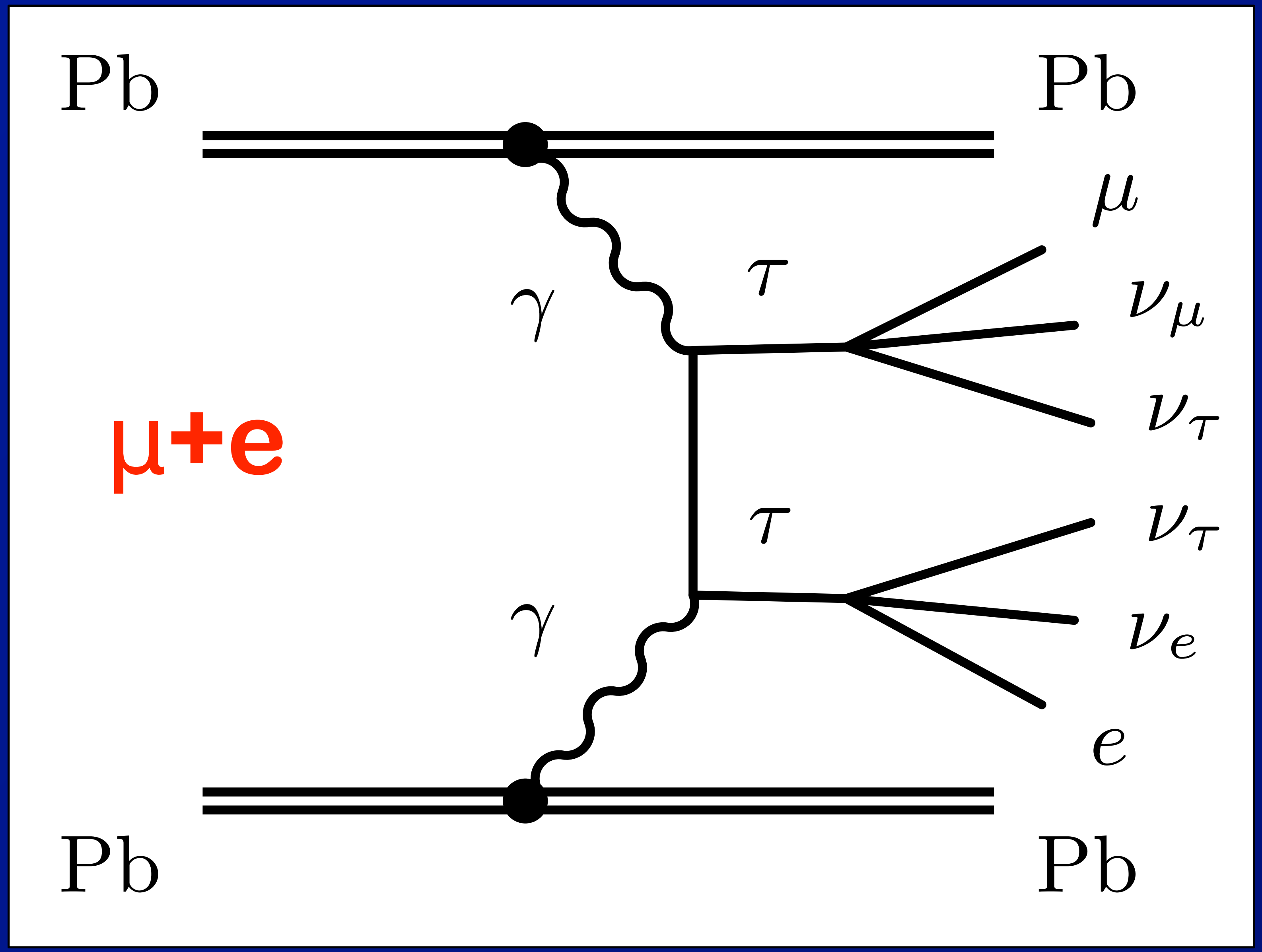


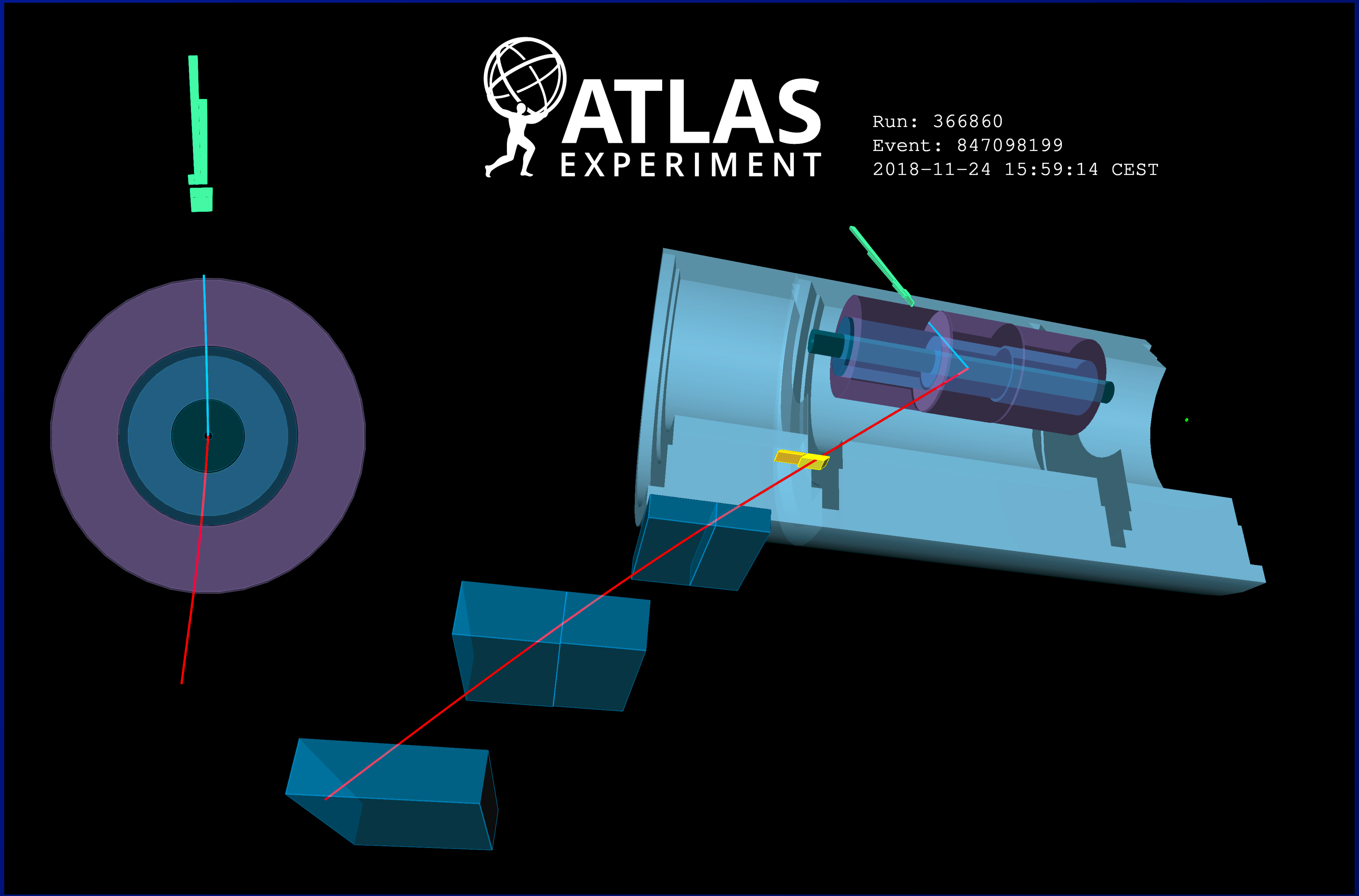


ATLAS γγ→ττ observation

Phys. Rev. Lett. 131 (2023) 151802

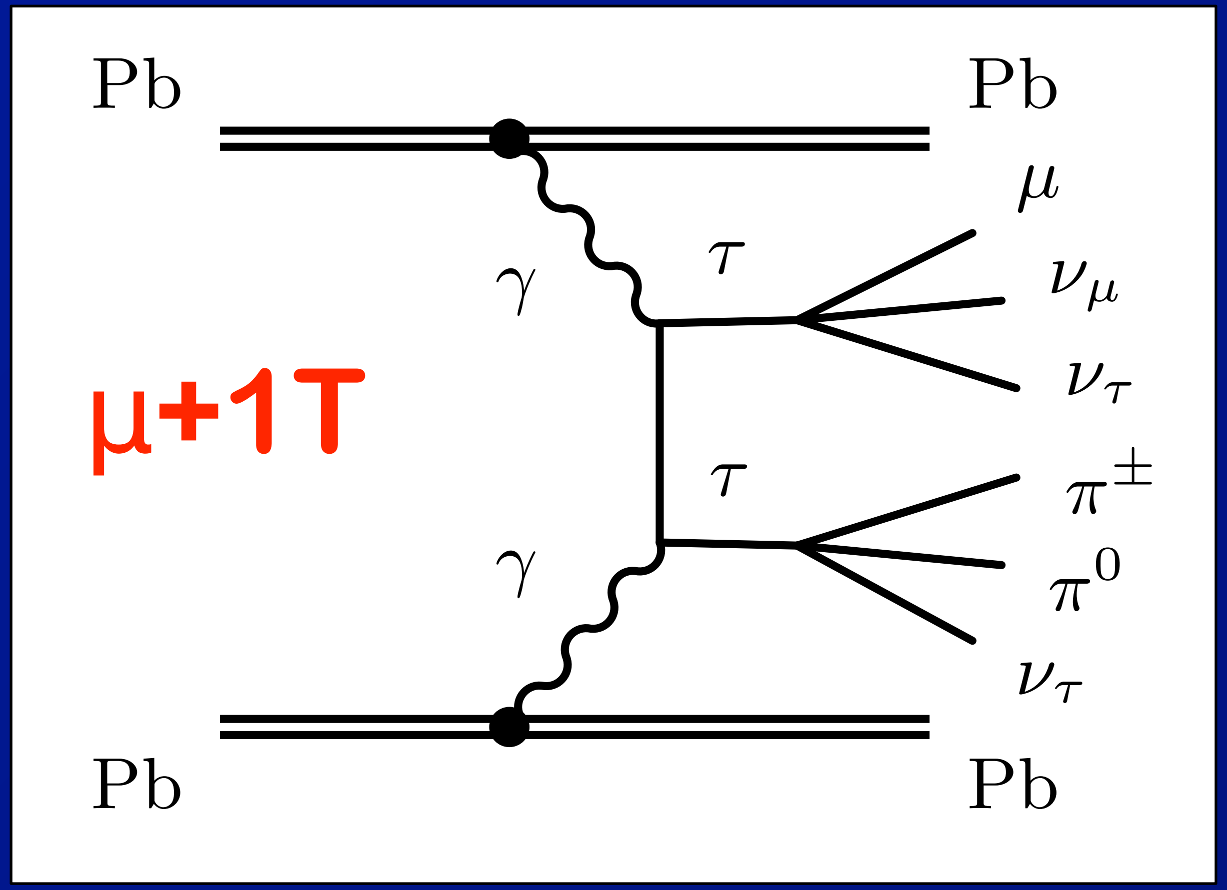
- ATLAS used three signal CRs to select events with 2 τ decays
  - Muon + electron

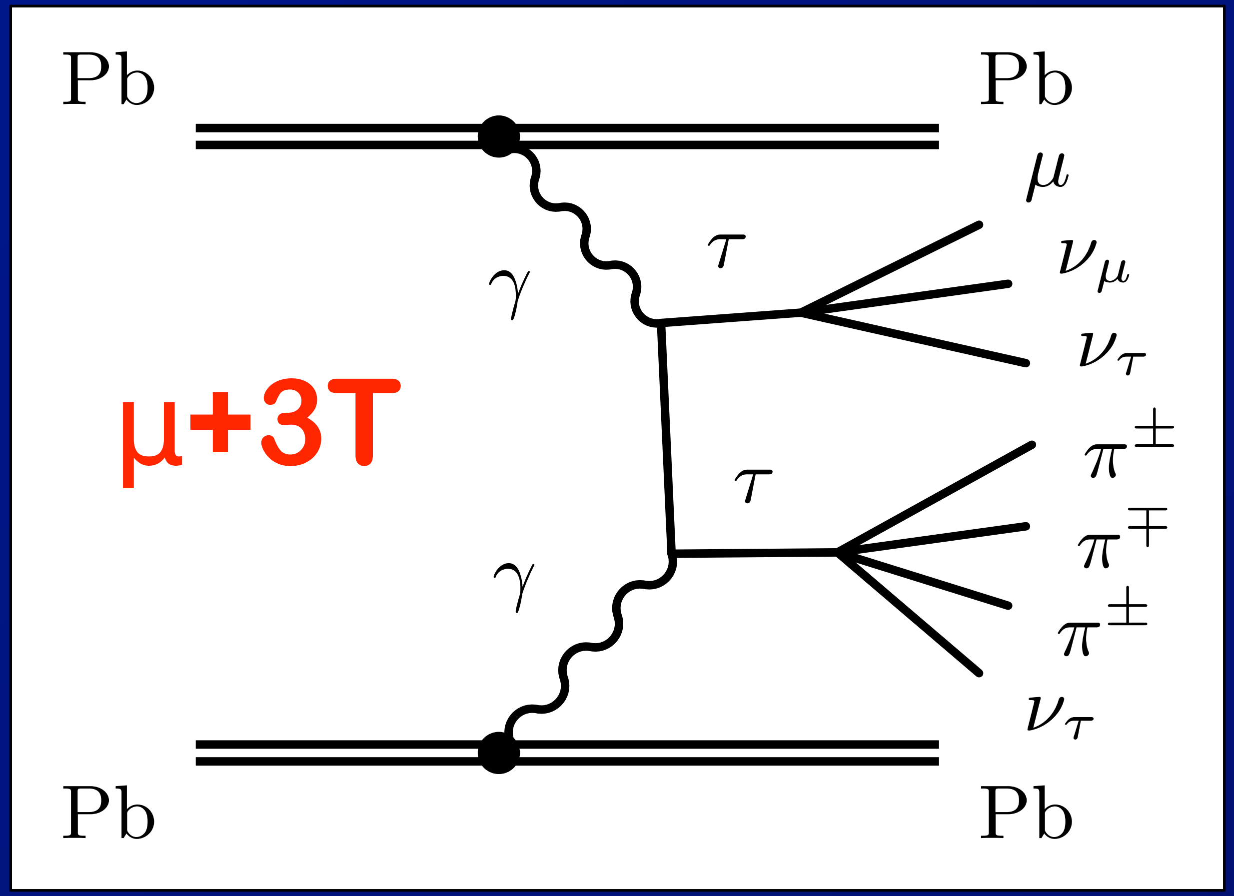


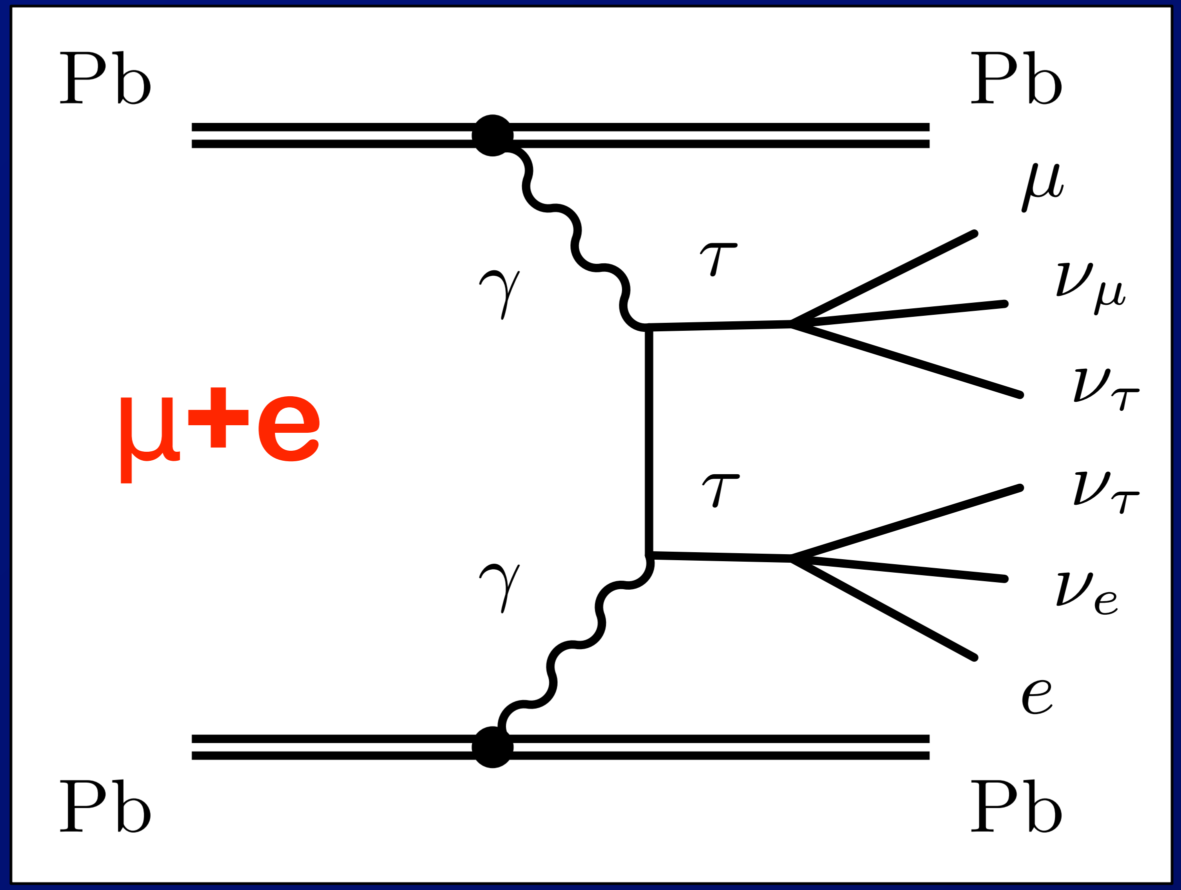


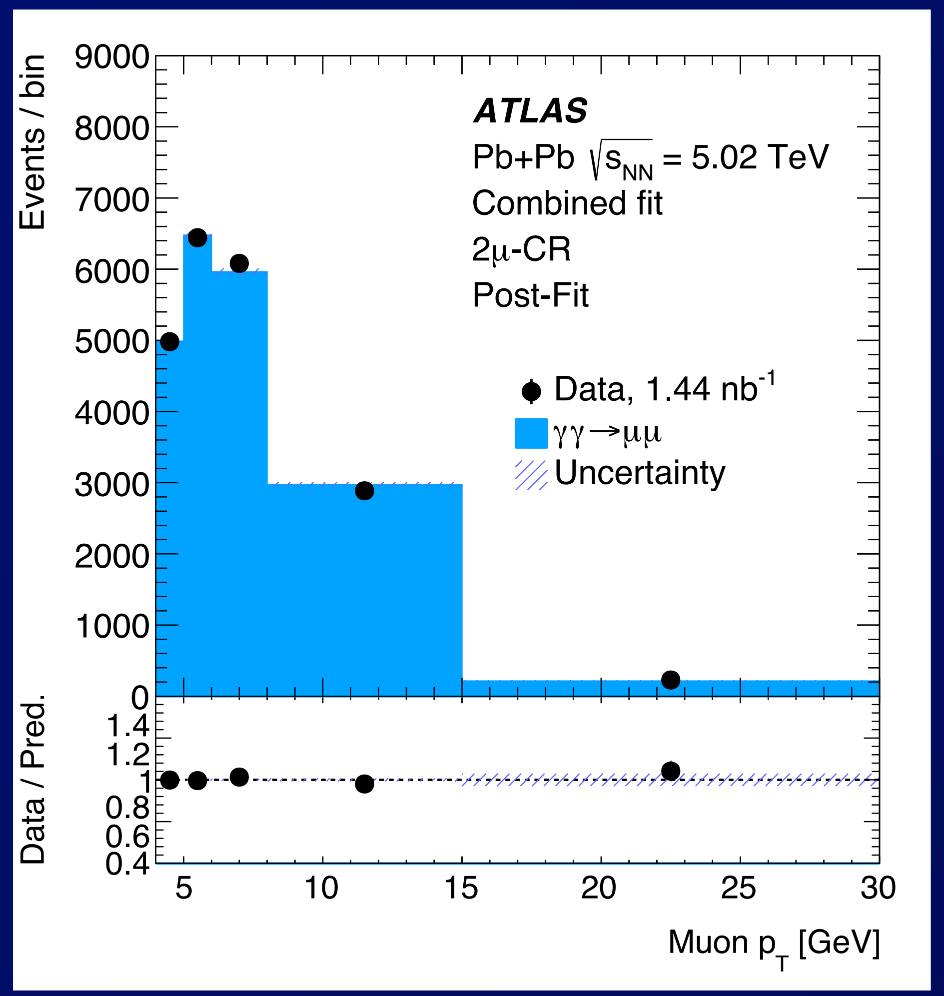
ATLAS $\gamma\gamma \rightarrow \tau\tau$ observation

- Using 1.44 nb^{-1} of Pb+Pb data from 2018
- Require (only) 1 muon, $p_{T\mu} > 4$ GeV, $|\eta_\mu| < 2.4$, "low-p_T" ID
  - Total charge = 0, no extra (topo)clusters in calorimeter
  - no forward neutrons (to suppress γ+A)
- 3 SRs:
  - For μ+1T, μ+3T: $A_\phi < 0.4$ + additional cuts on track p_T or 3-track mass
  - For μ+e, $p_{Te} > 4$ GeV, $|\eta_e| < 2.47$
- 3 CRs: 2μ-CR ($\mu^+\mu^-$ bkgd), μ2T-CR and μ4T-CR (photo-diff. bkgd)









Phys. Rev. Lett. 131 (2023) 151802

ATLAS $\gamma\gamma \to \tau\tau$ observation

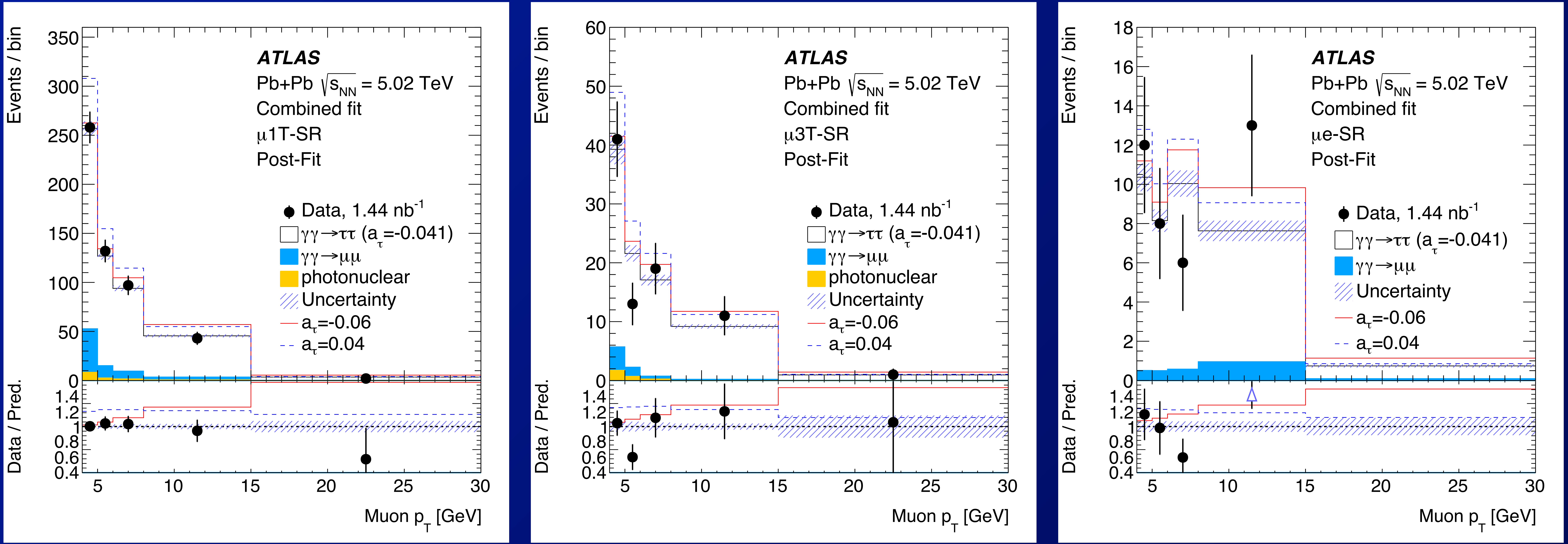
- Post-fit distributions of muon p_T in 3 ERs

Phys. Rev. Lett. 131 (2023) 151802

  - Expected backgrounds < 15% in all three channels

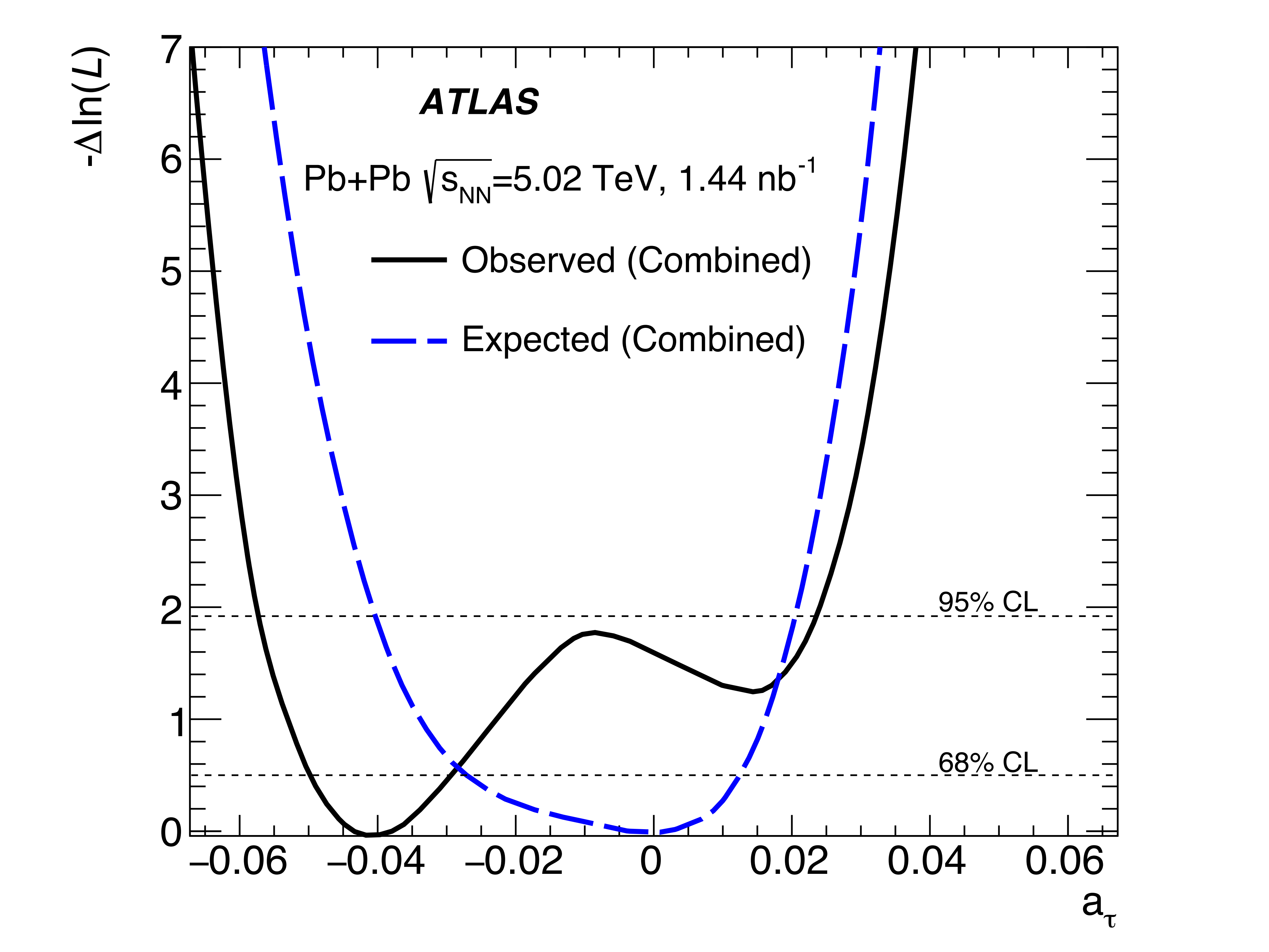
⇒ Best fit $a_\tau \equiv (g_\tau - 2)/2 = -0.041$

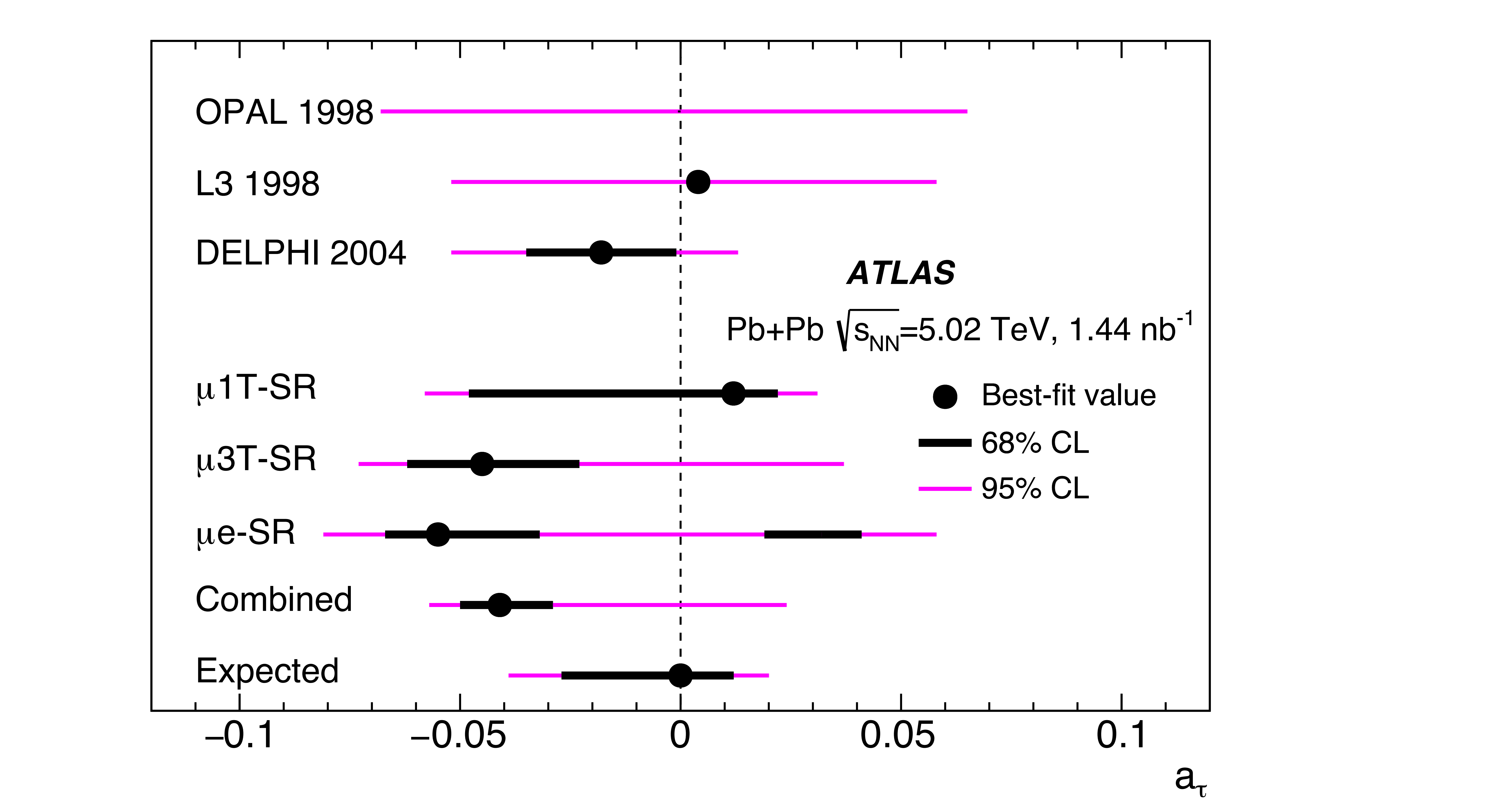
⇒ SM expectation: $a_\tau^{SM} = (117721 \pm 5) \times 10^{-8}$, i.e. $a_\tau^{SM} = 0.0012$



ATLAS $\gamma\gamma \rightarrow \tau\tau$ observation

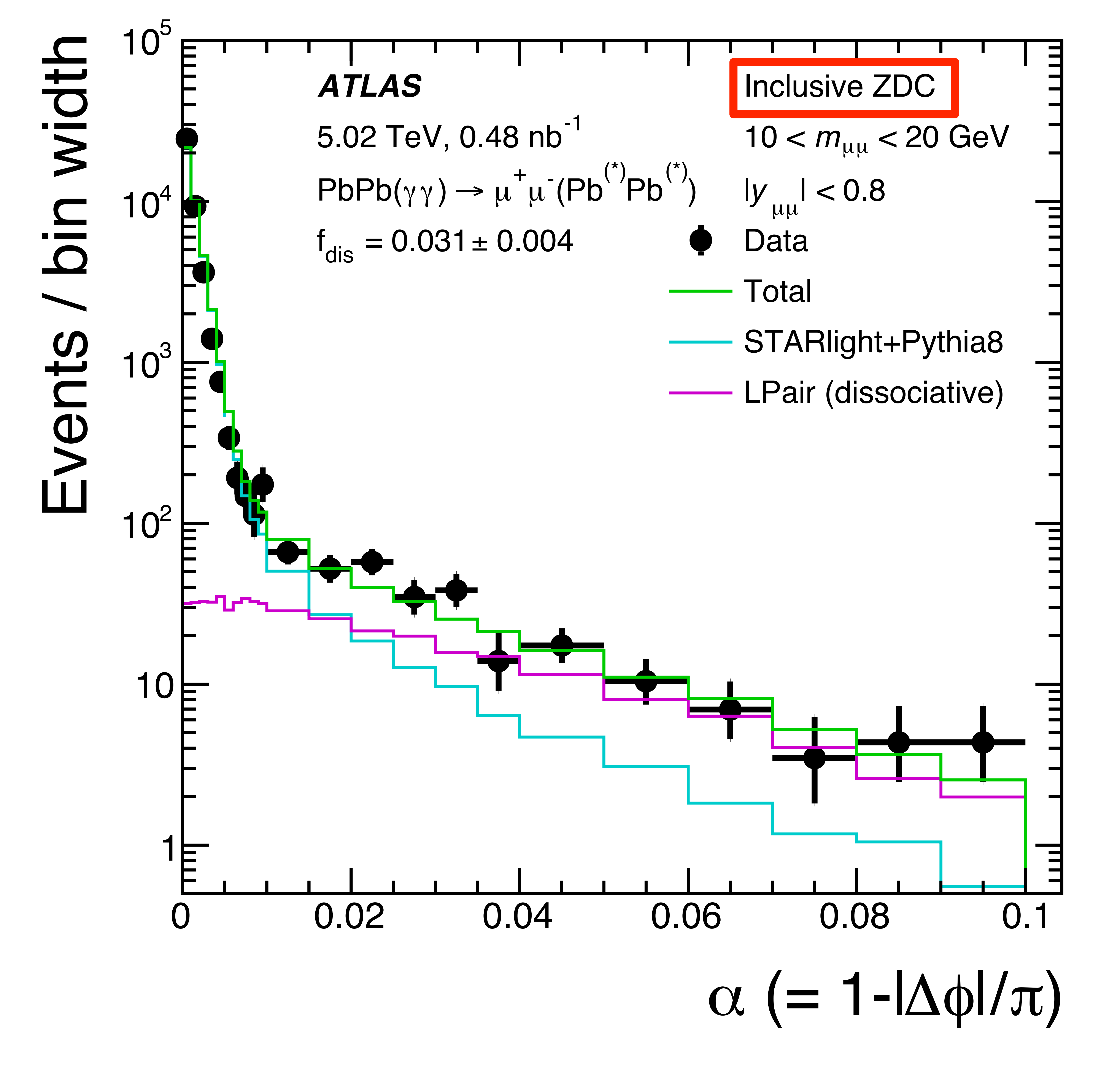
- LL Fit to a_τ assuming $\gamma\tau\tau$ coupling $F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i}{2m_\tau}\sigma^{\mu\nu}q_\nu$
  ⇒Similar parameterization to LEP analyses
- "Standard" evaluation of 68% and 95% CLs
  - But interference between SM and BSM contributions to $\tau^+\tau^-$ production make the a_τ CLs "unusual"





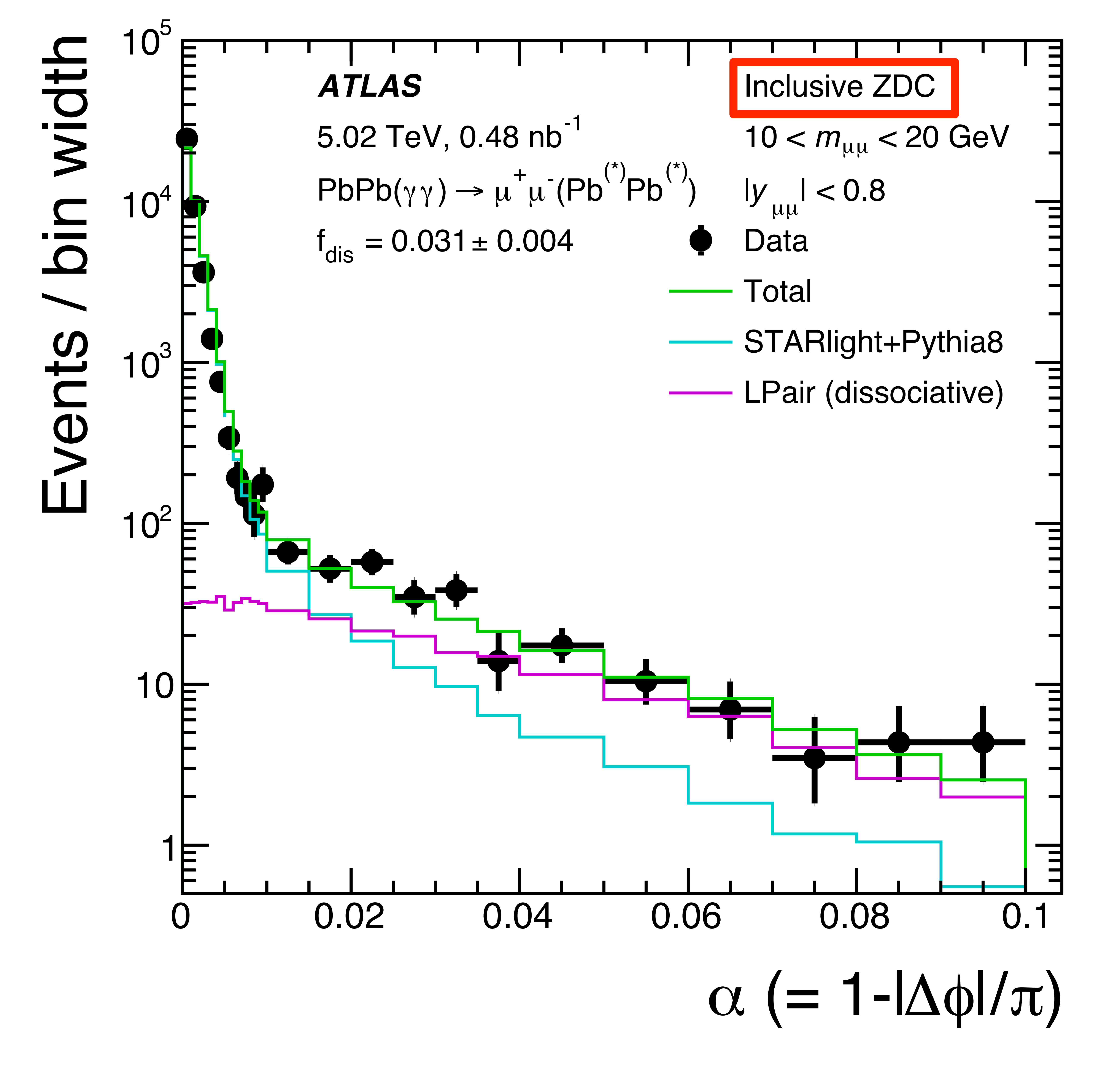
ATLAS exclusive $\mu^+\mu^-$ results

- Dimuon acoplanarity distributions w/ no ZDC selection.



ATLAS exclusive $\mu^+\mu^-$ results

- Dimuon acoplanarity distributions w/ no ZDC selection.
  - Observe tail to large acoplanarity values



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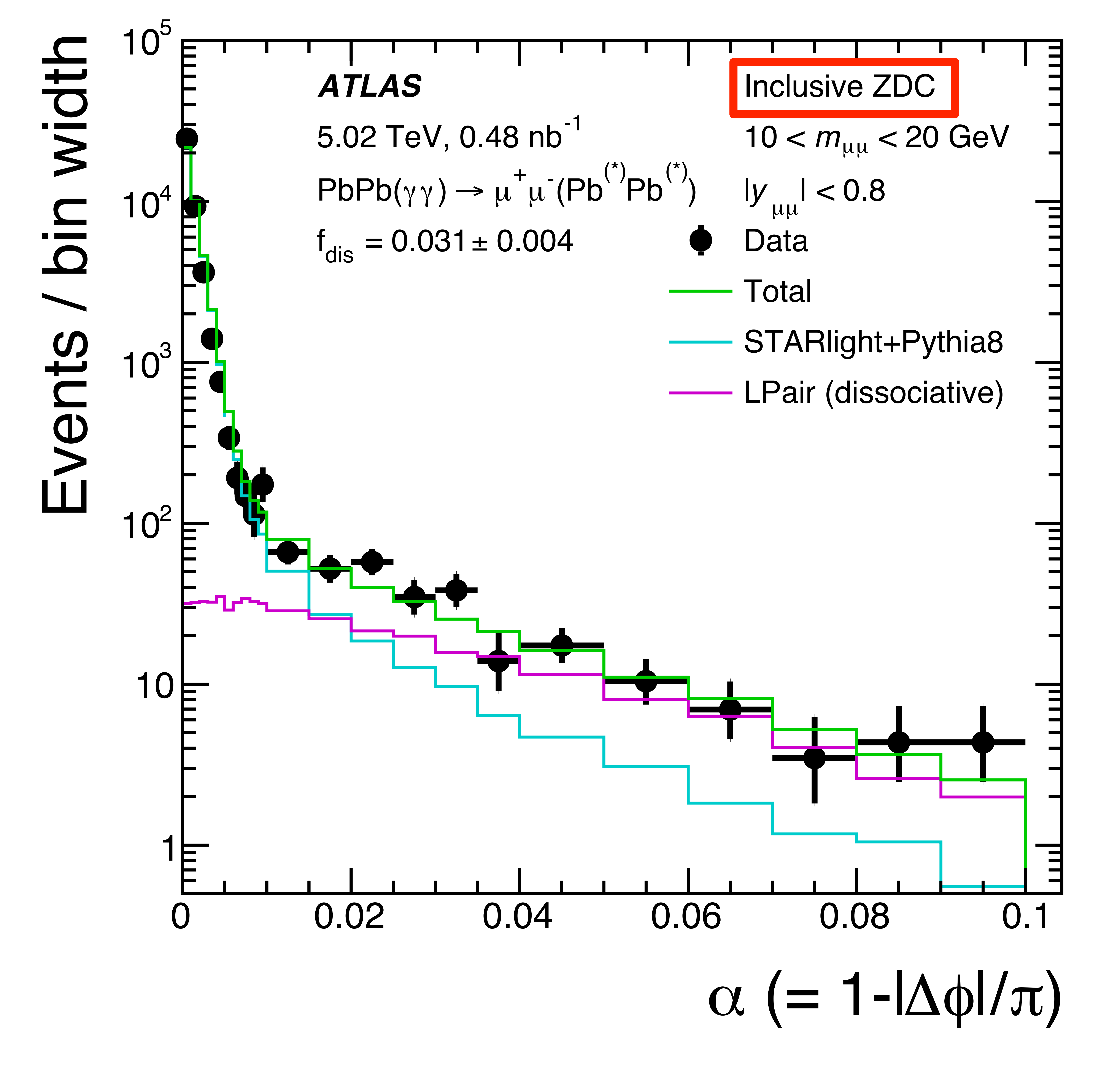
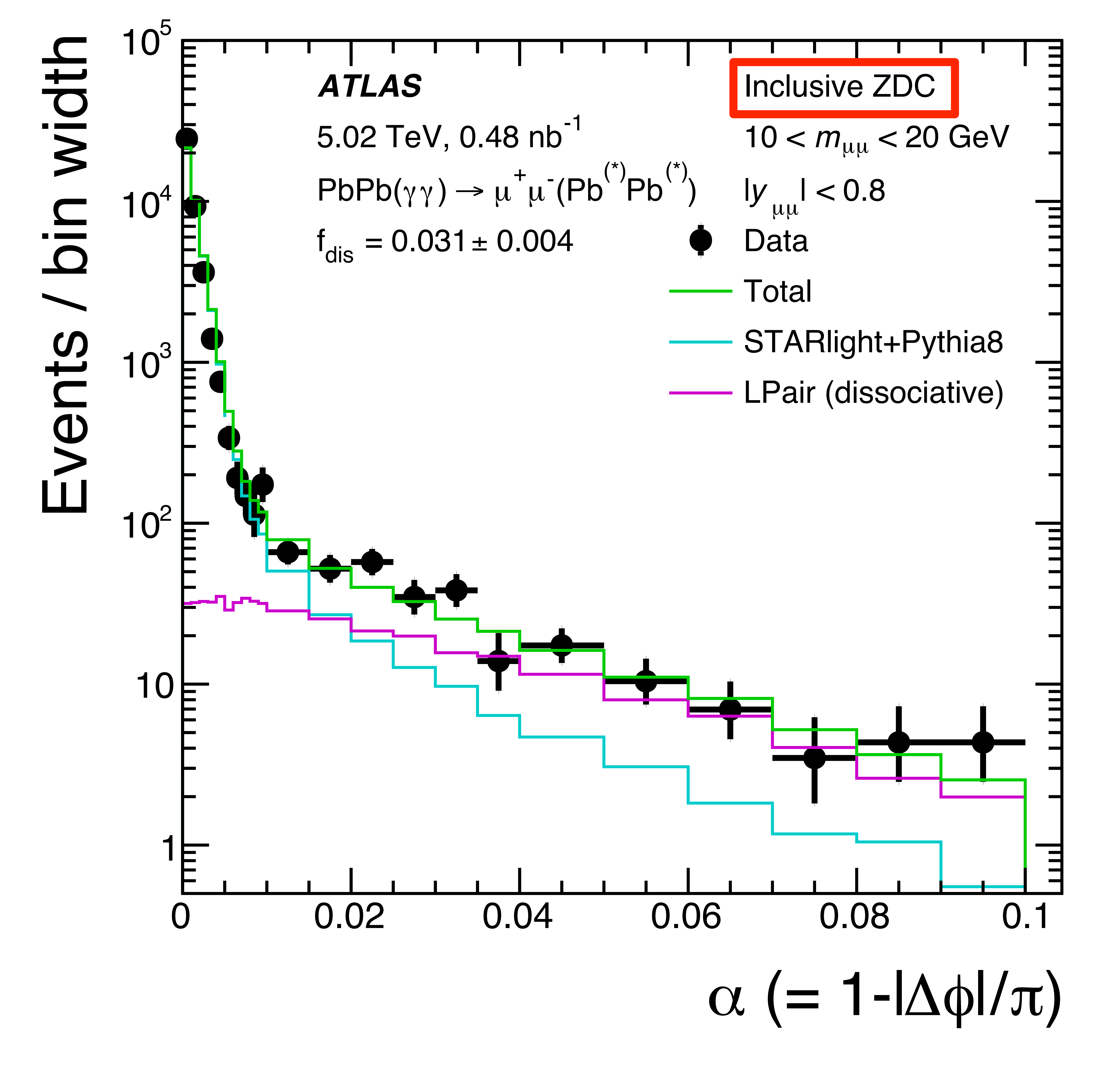
- Dimuon acoplanarity distributions w/ no ZDC selection.
  - Observe tail to large acoplanarity values
  - ⇒Mixture of QED, (single) dissociative γ*



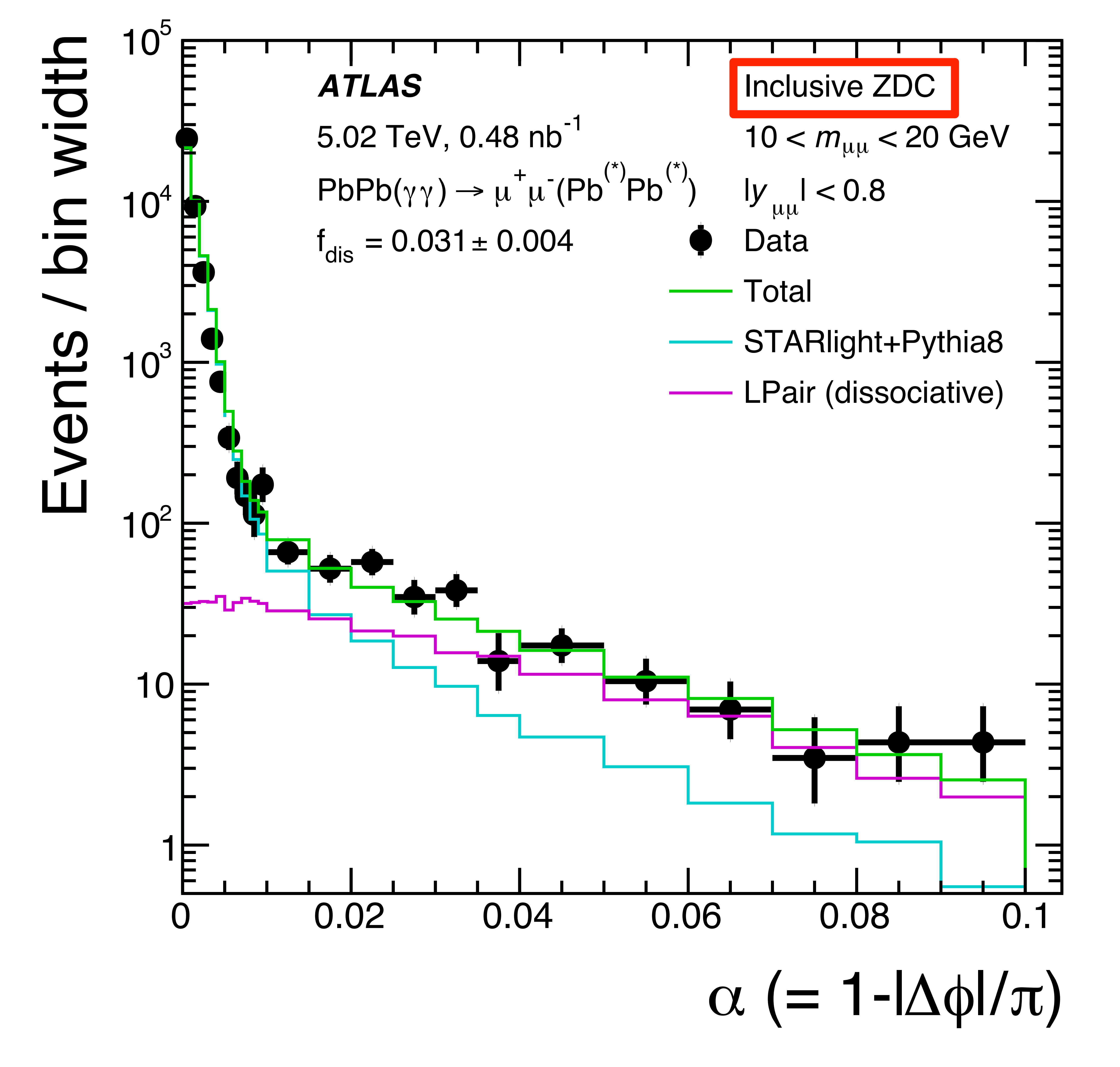
ATLAS exclusive $\mu^+\mu^-$ results

- Dimuon acoplanarity distributions w/ no ZDC selection.
  - Observe tail to large acoplanarity values
  - ⇒Mixture of QED, (single) dissociative γ*
- Use template fit to evaluate dissociative contribution
  - STARlight + Pythia8 (QED)
  - LPair (dissociative)



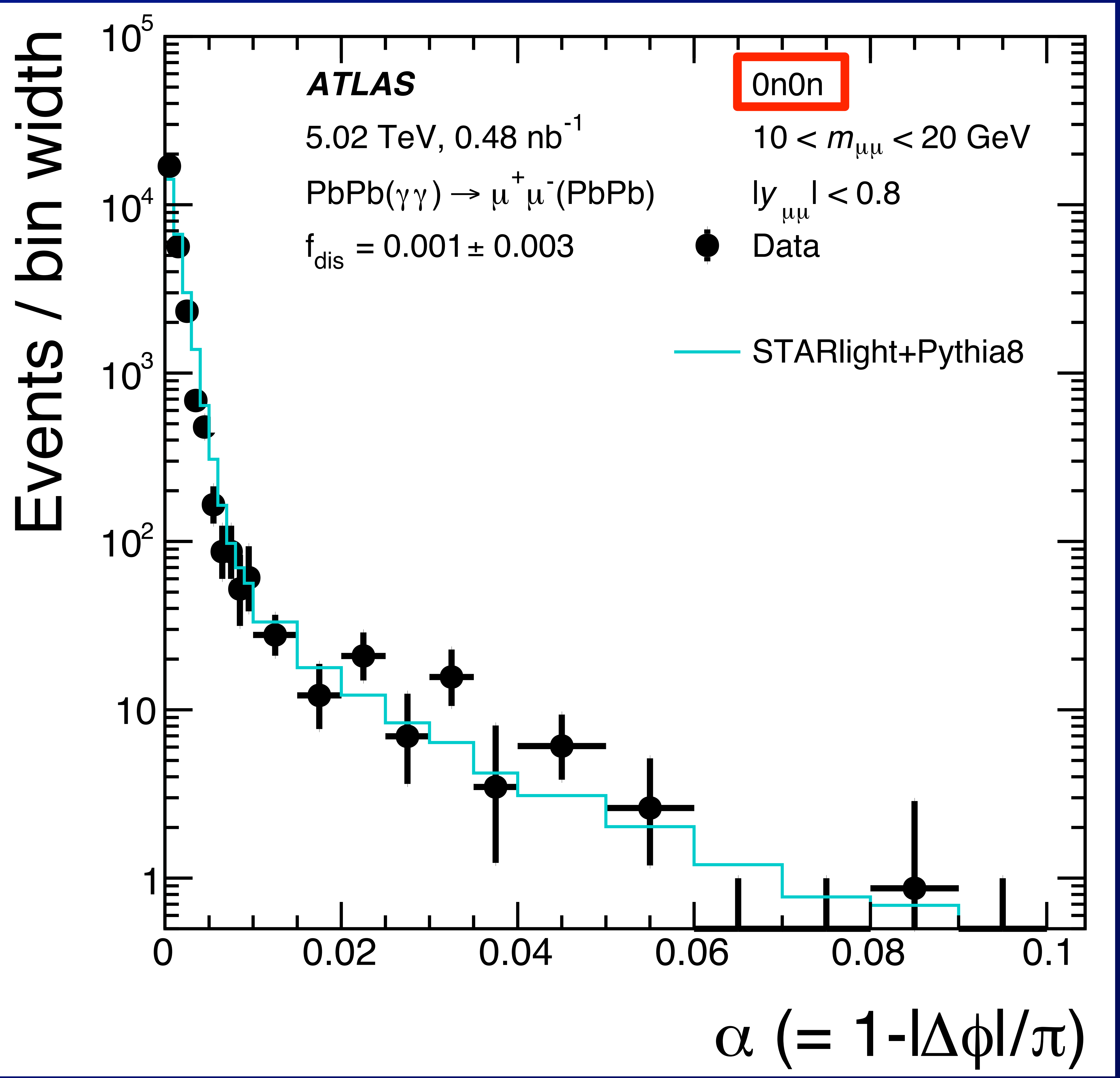
ATLAS exclusive $\mu^+\mu^-$ results

- Dimuon acoplanarity distributions w/ no ZDC selection.
  - Observe tail to large acoplanarity values
  - ⇒Mixture of QED, (single) dissociative γ^*
- Use template fit to evaluate dissociative contribution
  - STARlight + Pythia8 (QED)
  - LPair (dissociative)
  - ⇒3% (of total) dissociative γ
  - ⇒dissociative dominates at large acoplanarities



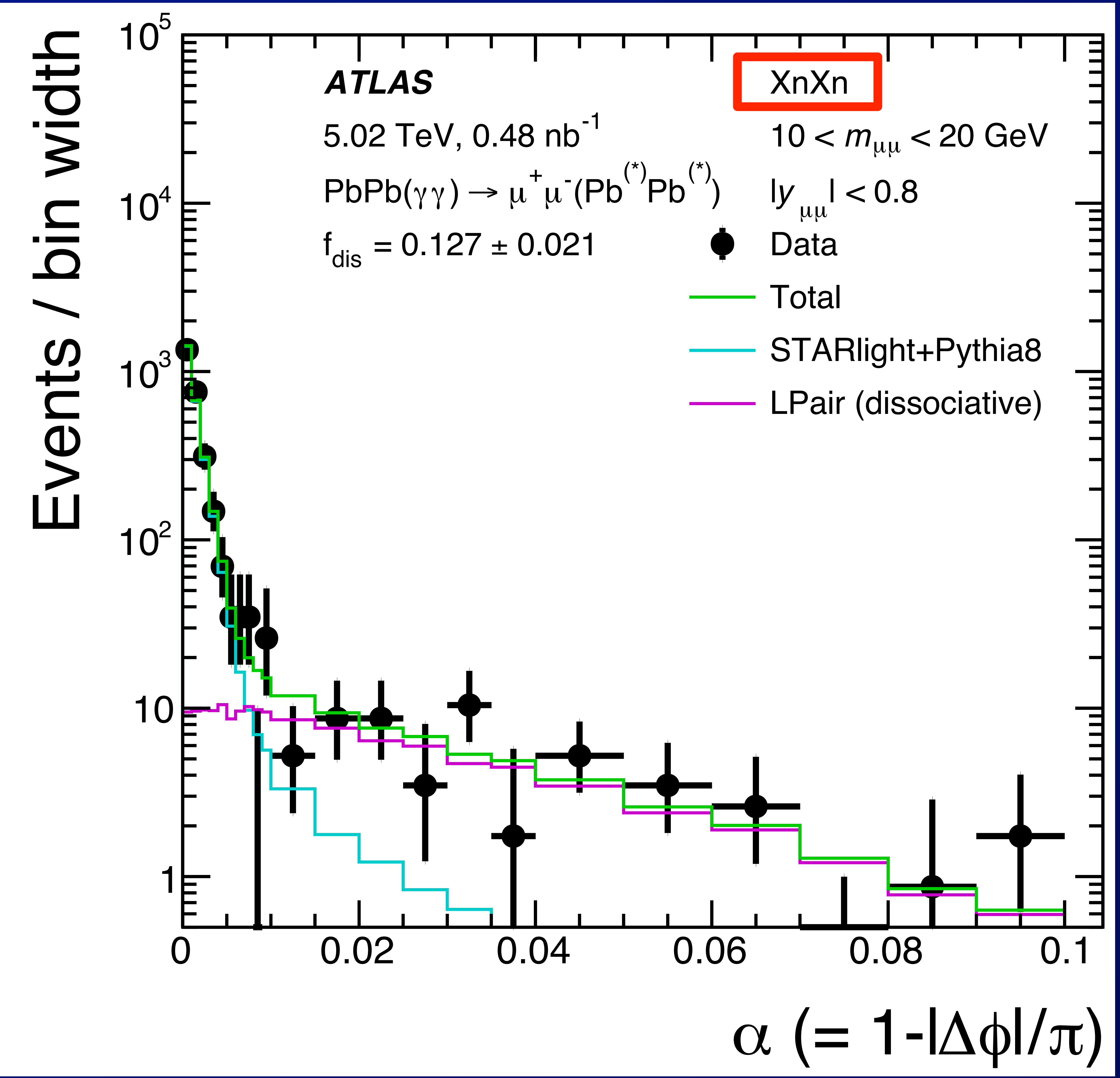
ATLAS exclusive $\mu^+\mu^-$ results

- **Dimuon acoplanarity distributions for 0n0n.**
  ⇒ no nuclear breakup
- **apply same template fitting procedure:**
  ⇒ ~ NO dissociative fraction
  ⇒ tail to large acoplanarities dominated by QED showering



ATLAS exclusive $\mu^+\mu^-$ results

- Dimuon acoplanarity distributions for XnXn.
  - ⇒ both nuclei breakup
- apply same template fitting procedure:
  - ⇒ 12% dissociative fraction
  - ⇒ dissociative dominates beyond the central core of the acoplanarity distribution



New ATLAS $\mu^+\mu^-$ results

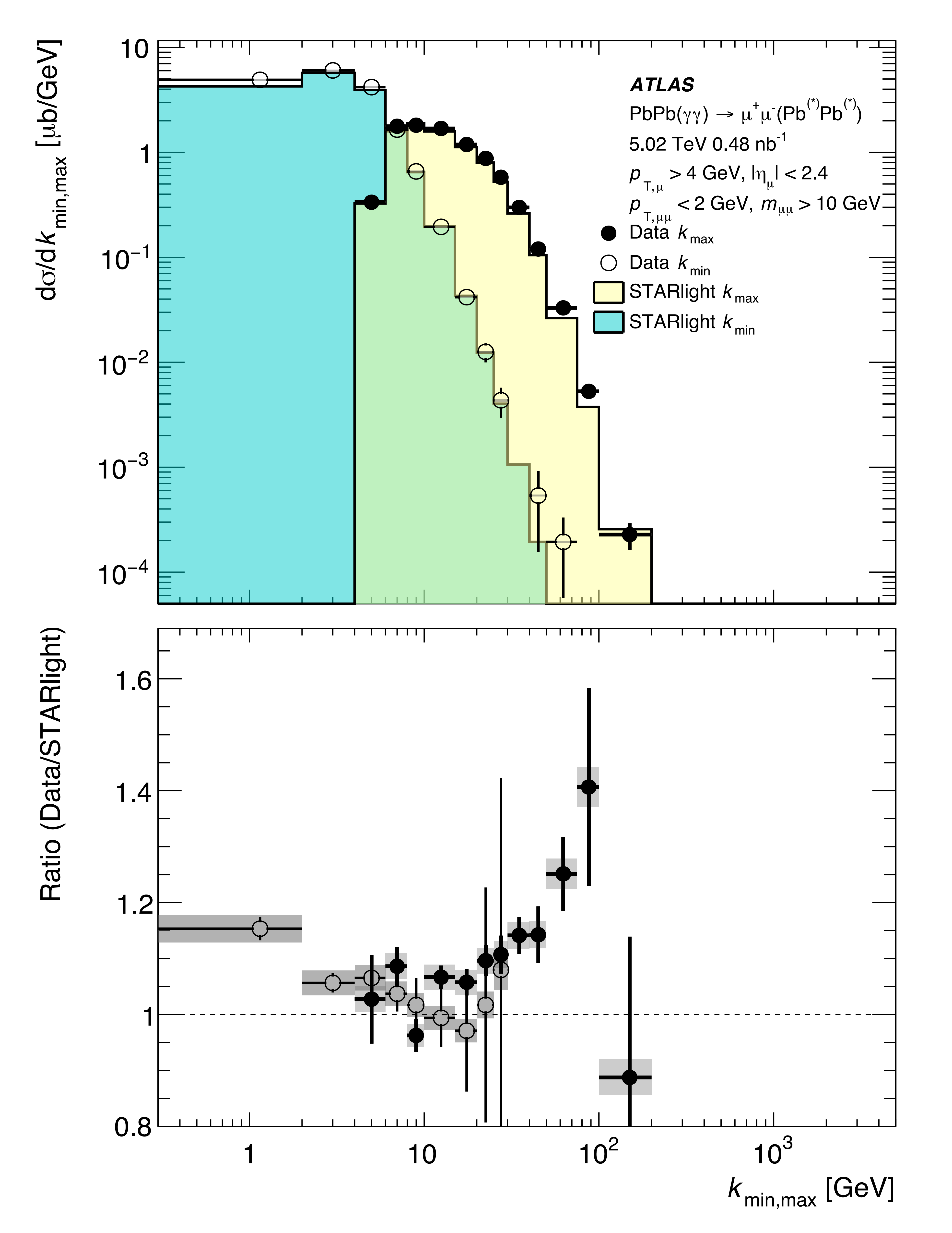
- **Determine the photon energies using the μμ pair kinematics:**
  - $$k_{\max,\min} = \frac{m_{\mu\mu}}{2} e^{\pm y_{\mu\mu}}$$
  - first direct measurement of the nuclear photon flux

  ⇒ but not only the coherent component

- **Compare to STARlight**
  - Excess observed in the data at higher photon energies

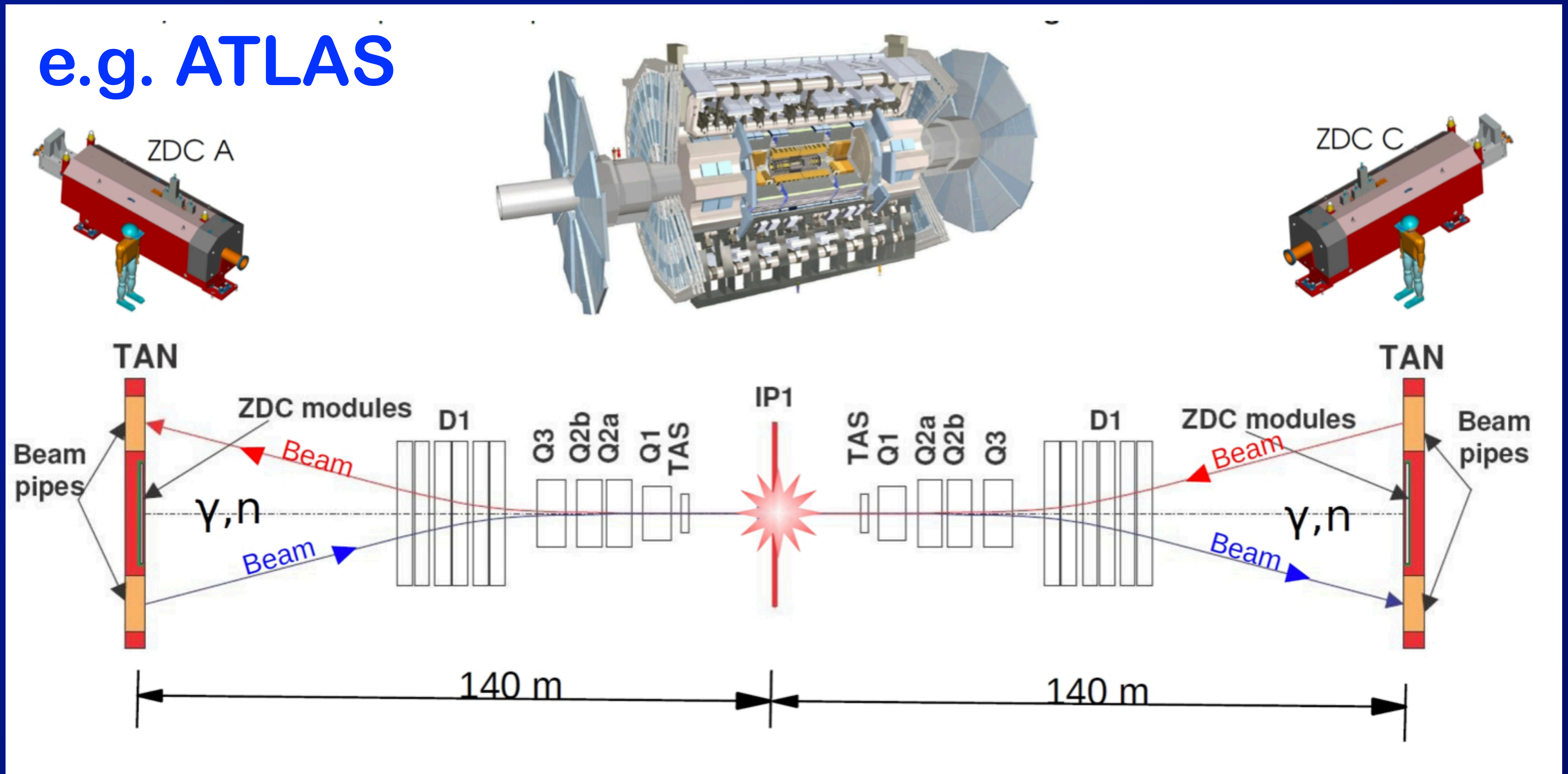
  ⇒ >~ 30-40 GeV

  ⇒ consistent with observations above



Nuclear breakup via Coulomb Excitation

- In UPC Pb+Pb, coherent photons dominate (Z^4)
  - Nuclei do not get excited
  - ⇒No forward neutrons in zero degree calorimeters

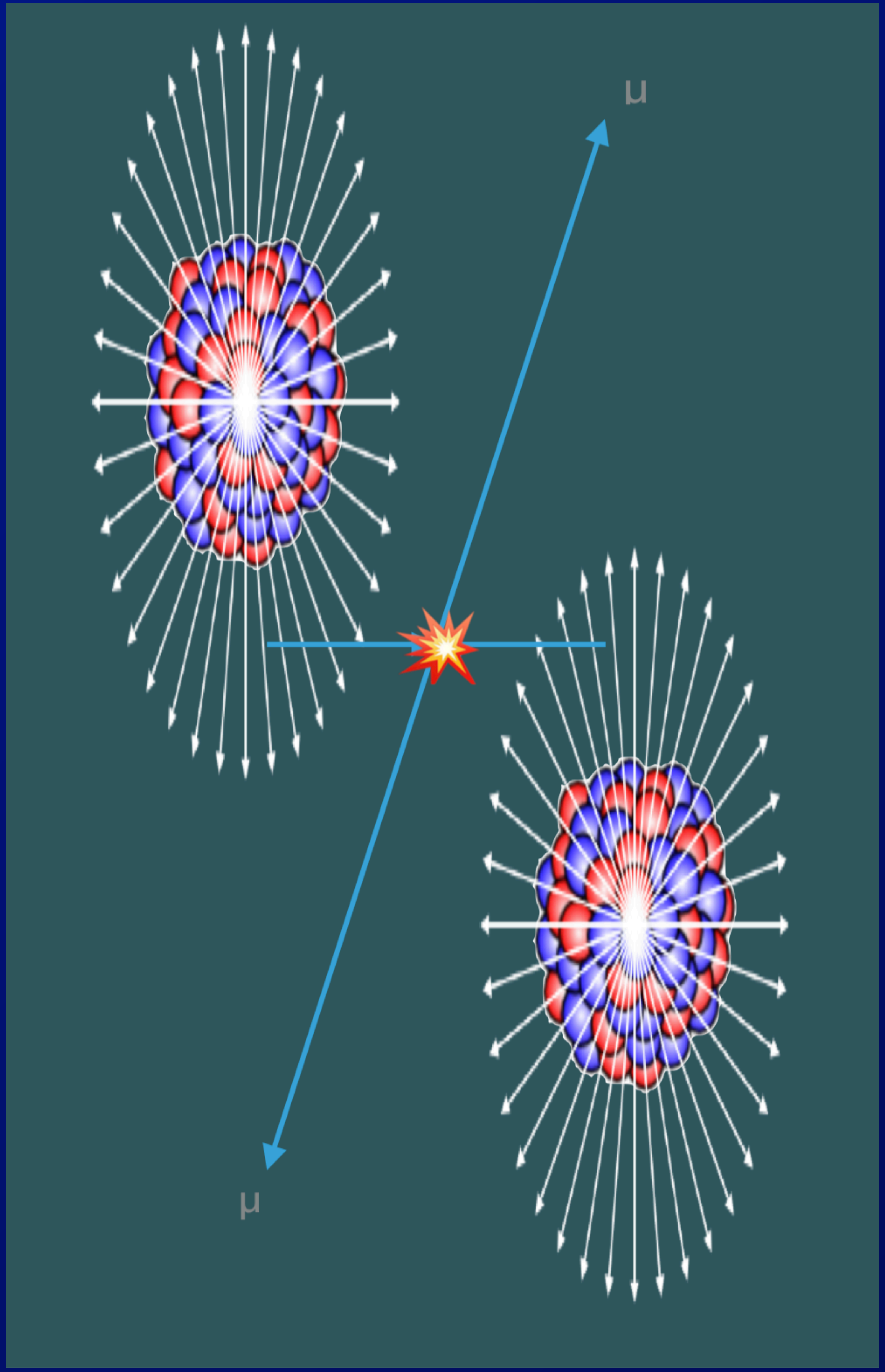


- However, long-range EM interactions (Coulomb Excitation) can induce GDR
  - ⇒ Emission of 1 or more neutrons

Introduction

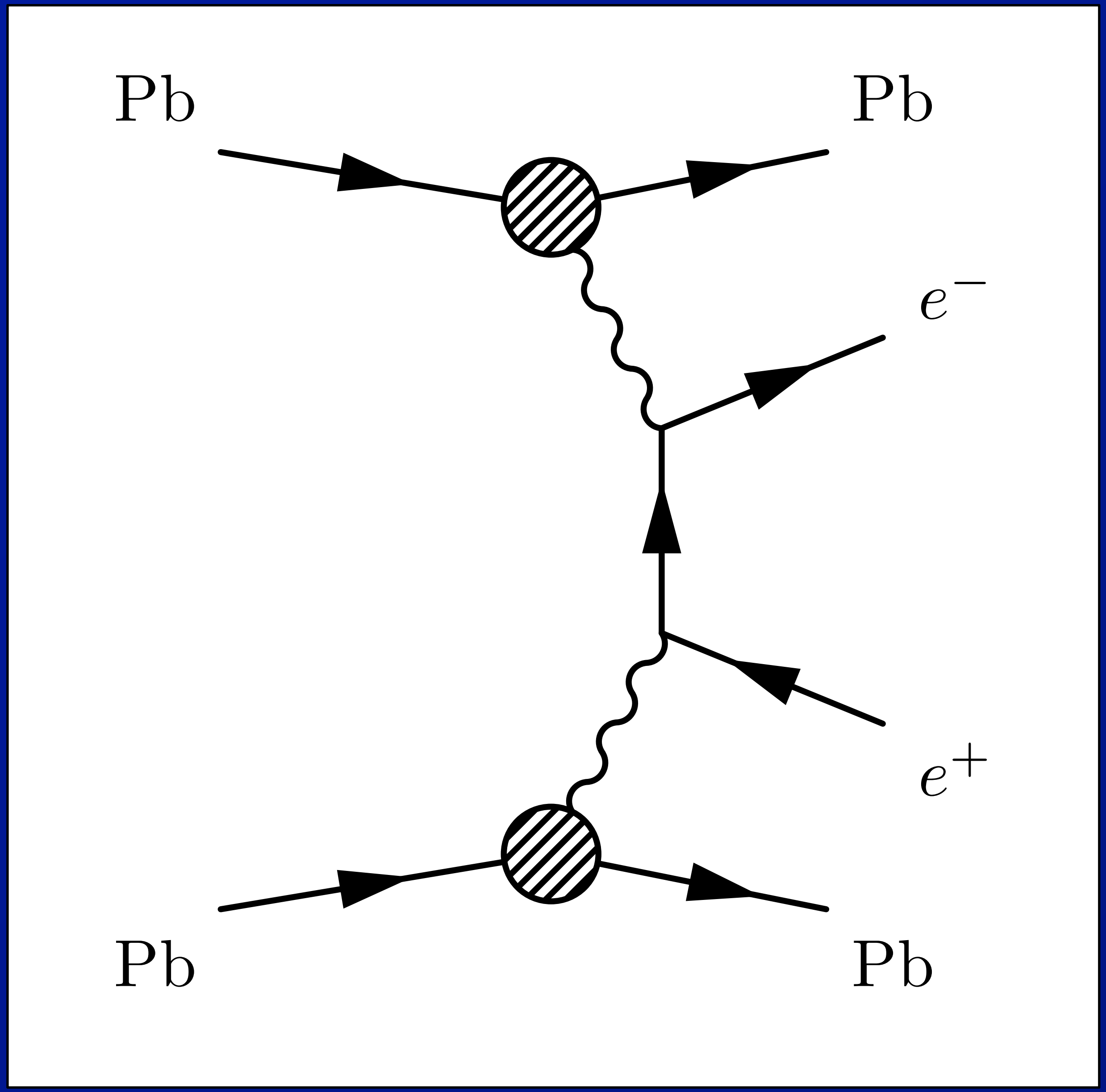
- **Weizsacker & Williams + Jackson + … :**
  - Highly relativistic particles act as sources of ~ real photons
- **Finger physics:**
  - When $\lambda > R/\gamma$, or equivalently $E \lesssim \hbar c\, \gamma/R$, the photons are emitted coherently
  - At LHC, Pb+Pb @ 5.02 TeV, coherence condition is $E \lesssim 80$ GeV
  - Photon flux $\propto Z^4$
- **During heavy ion operation, the LHC is also a Large Photon Collider**

$\Rightarrow \sqrt{s} > 100$ GeV

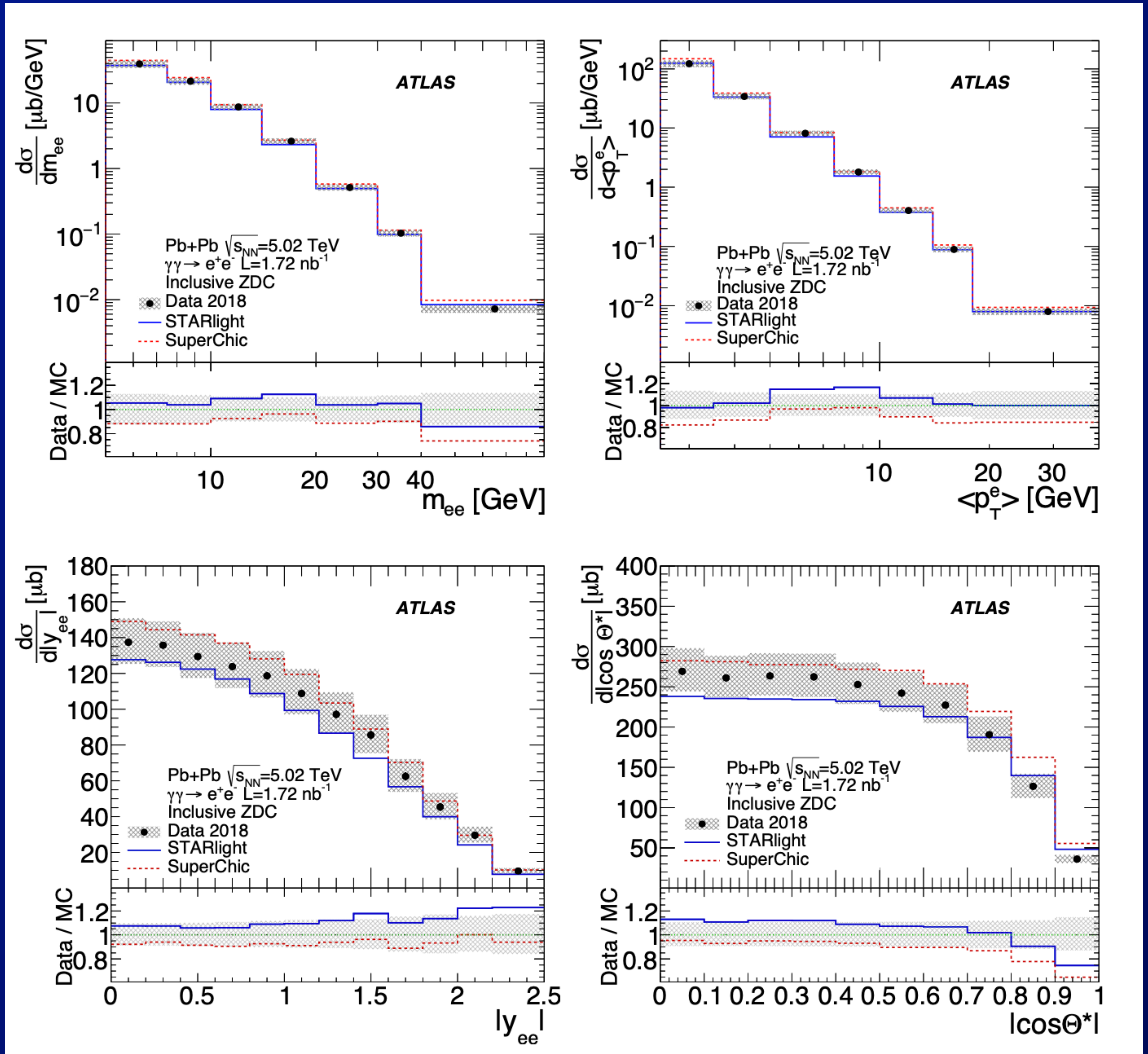


Dielectron production in γ+γ collisions

- At leading order in QED the $\gamma+\gamma \rightarrow l^+l^-$ process is simple



ATLAS UPC e^+e^-, JHEP 06 (2023) 182

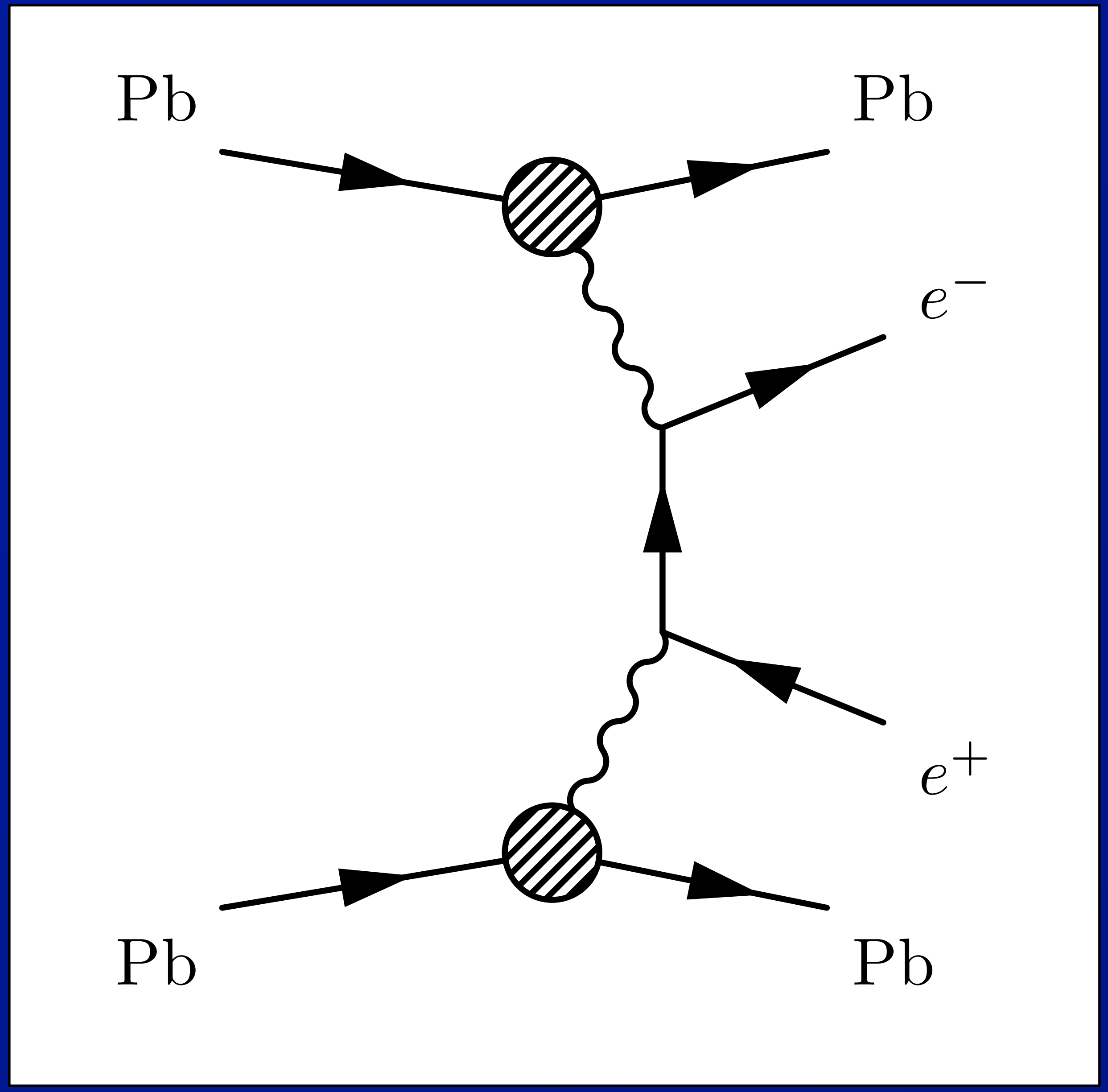


– Well-established calculations
– High-statistics measurements

⇒ Good agreement with theory(?)

Dielectron production in γ+γ collisions

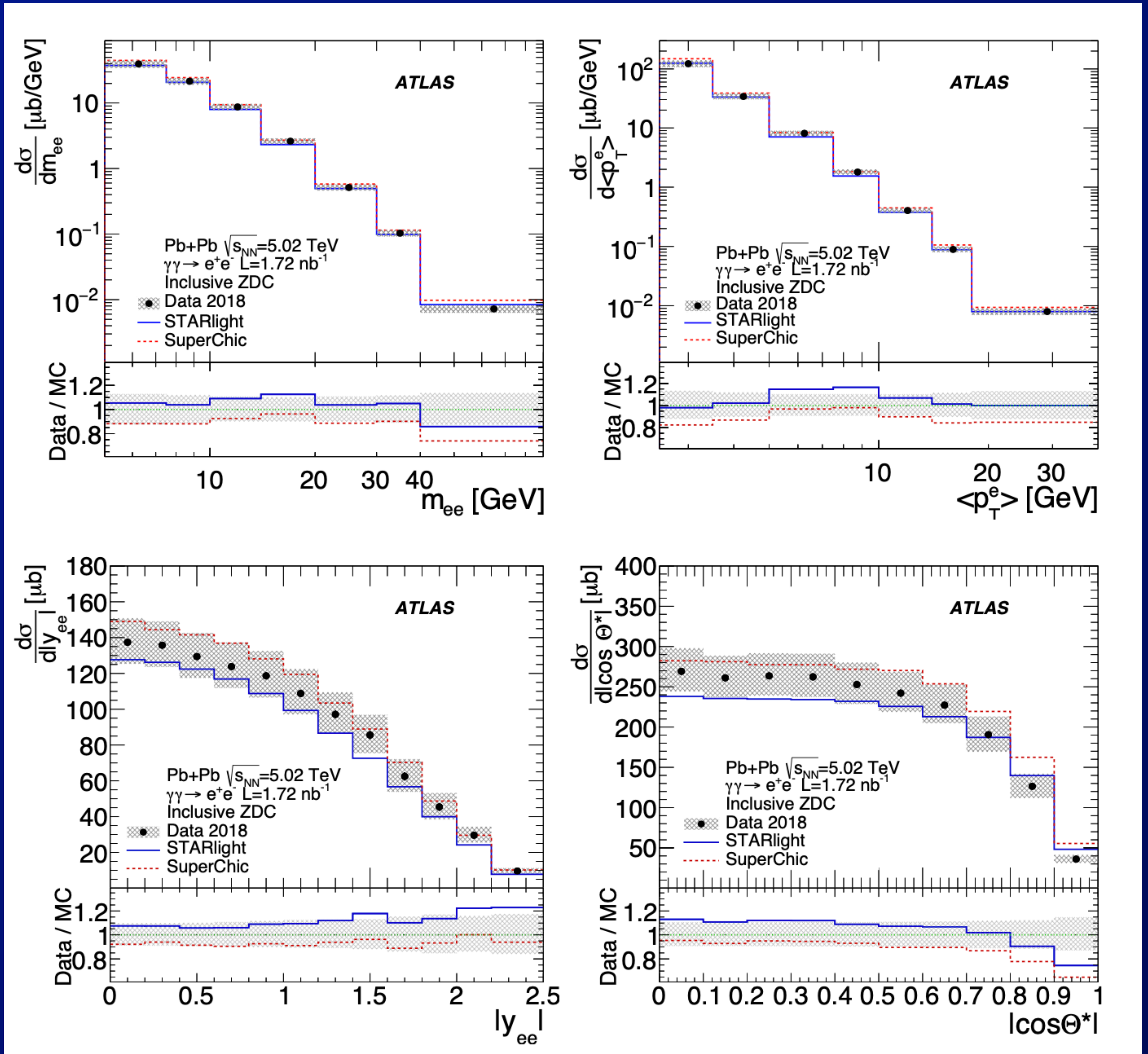
- At leading order in QED the γ+γ →l^+l^- process is simple



- –Well-established calculations
- –High-statistics measurements

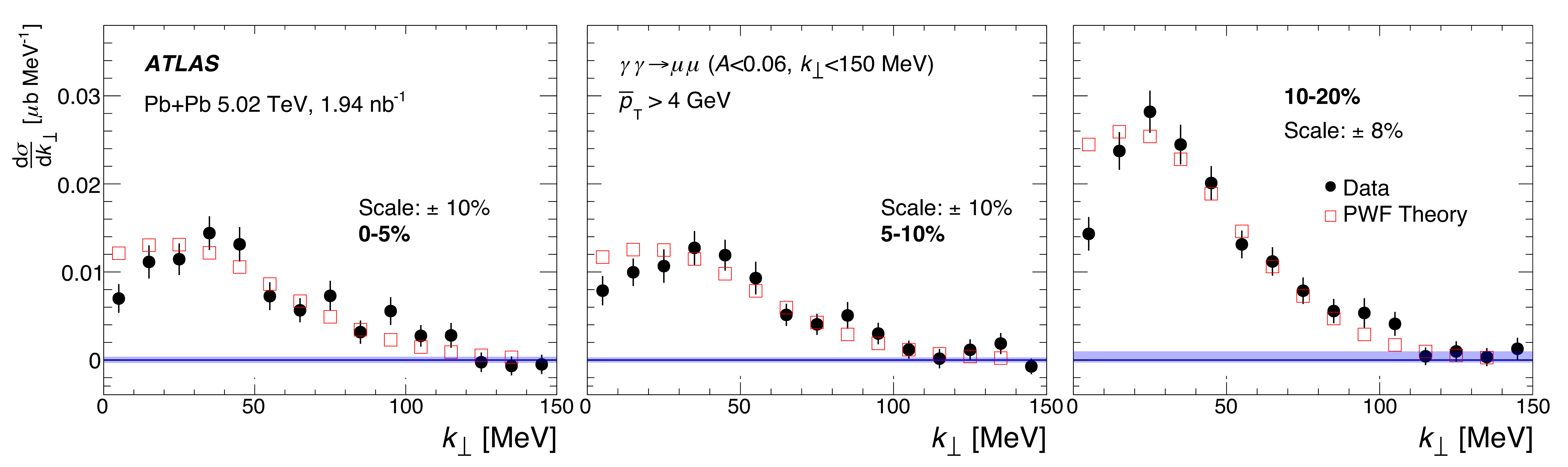
⇒Data systematically lower than SuperChic by ~ 10%

ATLAS UPC e^+e^-, JHEP 06 (2023) 182



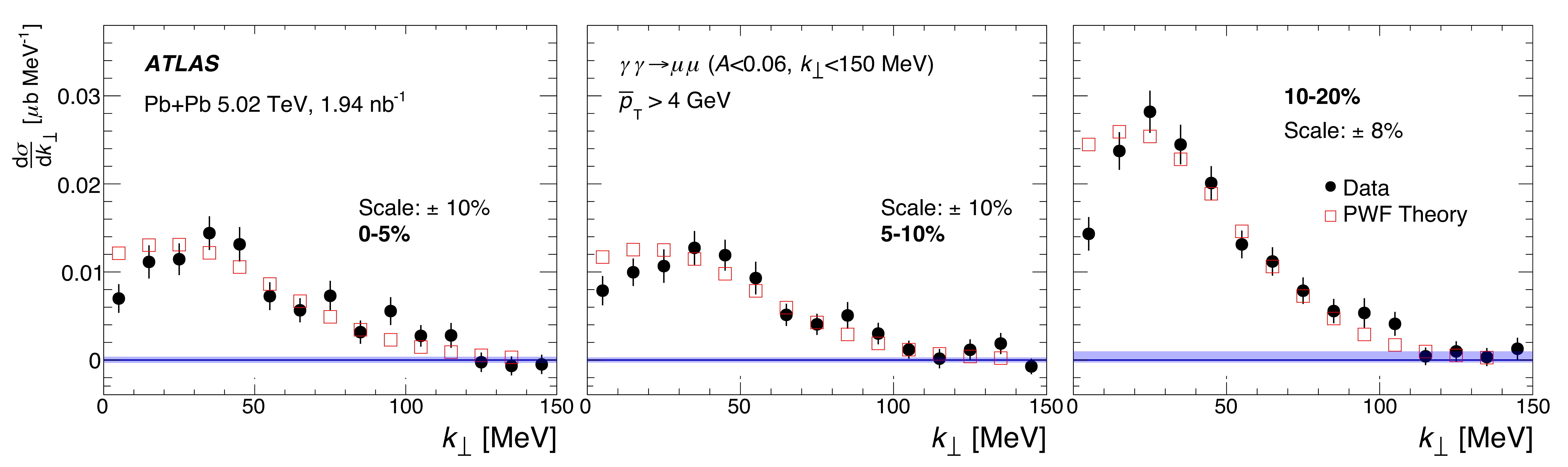
γ+γ dilepton production in hadronic Pb+Pb

- What happens as b → 0?
  - No longer a relevant dimensionful scale …
- With sufficient statistics and/or precision:



γ+γ dilepton production in hadronic Pb+Pb

- What happens as b → 0?
  - No longer a relevant dimensionful scale …
- With sufficient statistics and/or precision:
  - ⇒should we expect to see modulation in the k_T distribution?



γ+γ dilepton production in hadronic Pb+Pb

- **What happens as b → 0?**
  – No longer a relevant dimensionful scale …
- **With sufficient statistics and/or precision:**
  ⇒ should we expect to see modulation in the k_T distribution?
  ⇒ Due to the underlying Wigner distribution.