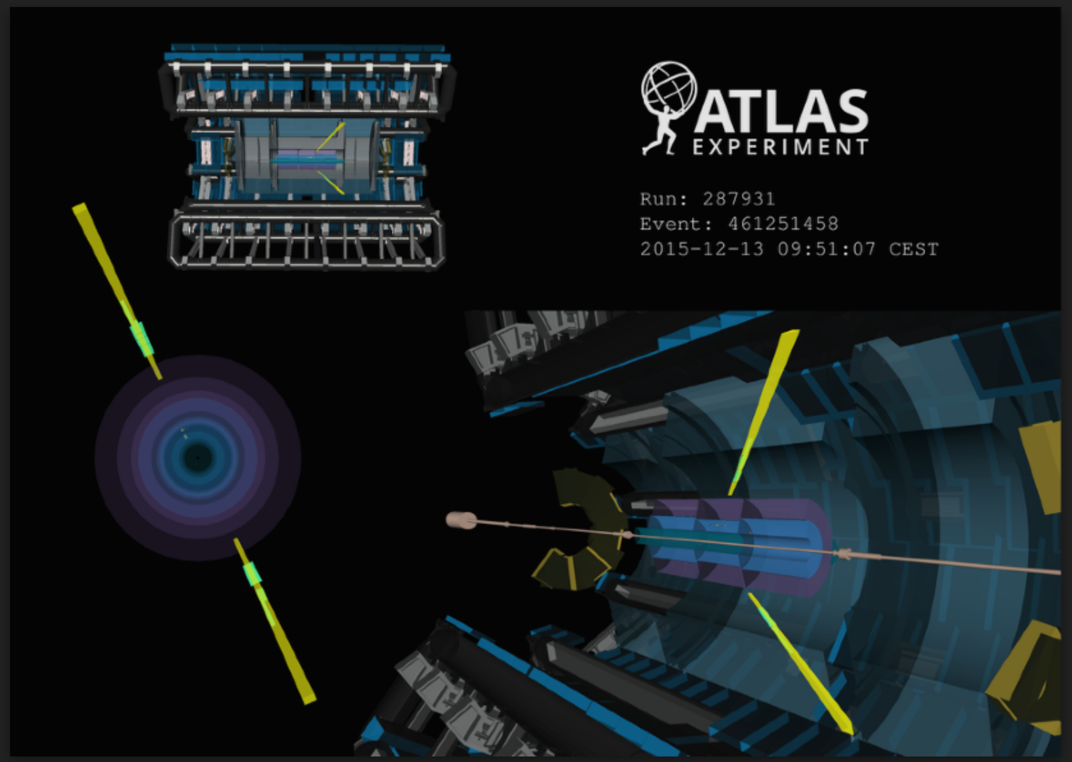
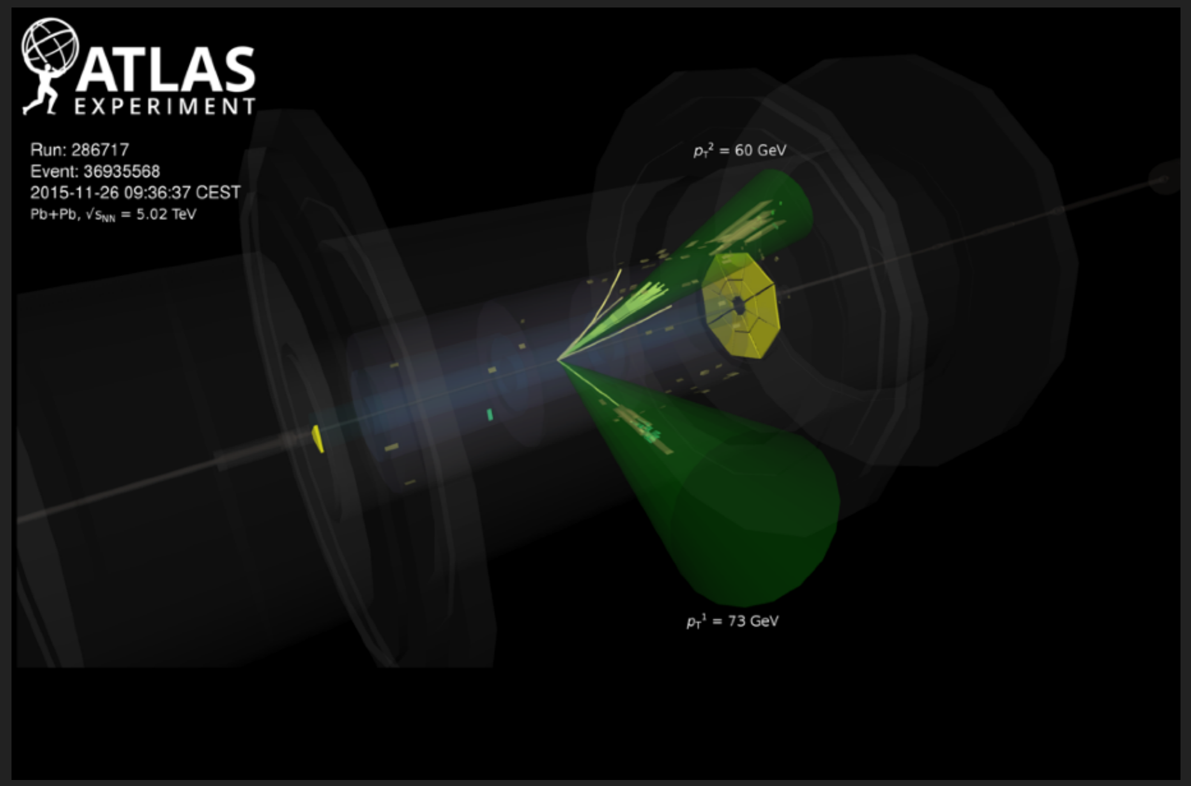
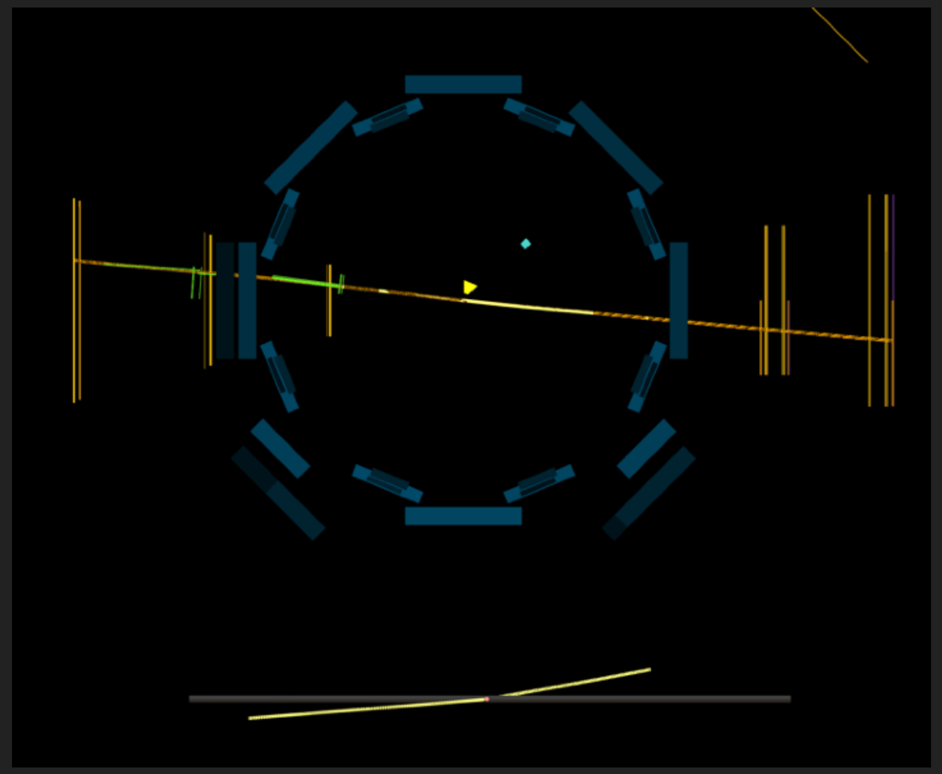






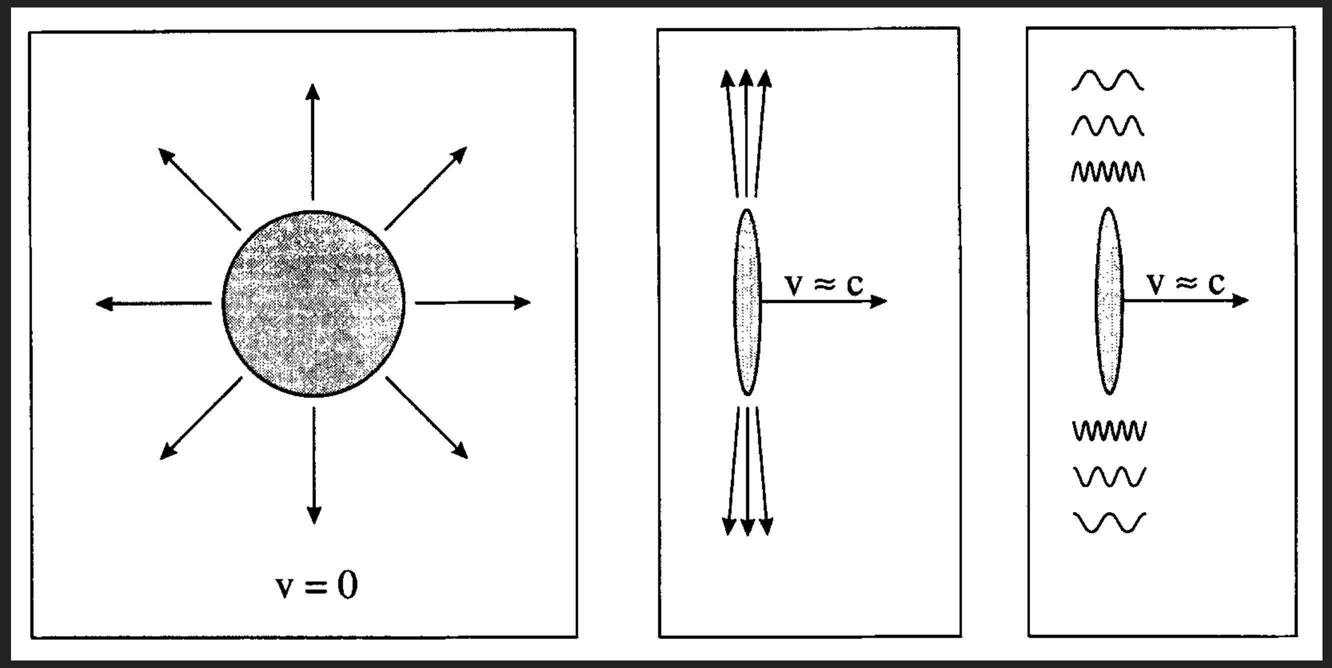
PETER STEINBERG, BNL FOR THE ATLAS COLLABORATION

ELECTROMAGNETIC PROCESSES WITH QUASIREAL PHOTONS IN PB+PB COLLISIONS: QED, QCD, AND THE QGP

💡 🌈 🔥

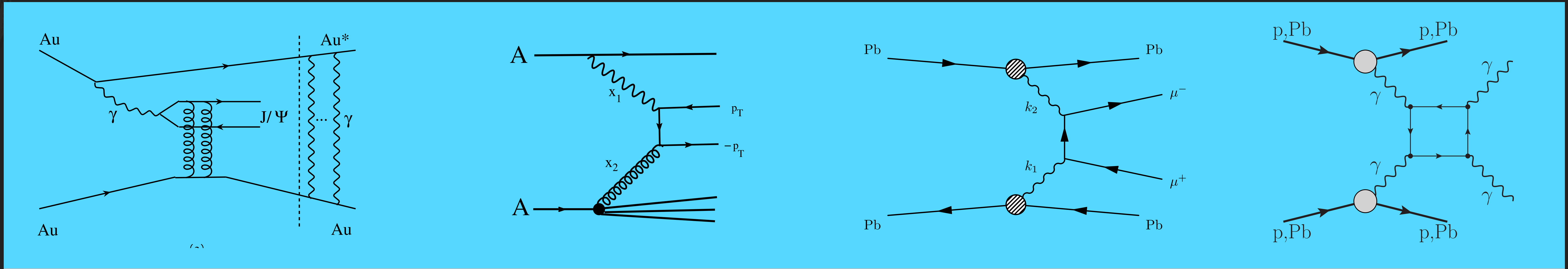
HARD PROBES 2018: INTERNATIONAL CONFERENCE ON HARD AND ELECTROMAGNETIC PROBES OF HIGH-ENERGY NUCLEAR COLLISIONS

QUASI-REAL PHOTONS FROM NUCLEI



- Boosted nuclei are intense source of quasi-real photons
  - Typically treated using EPA (Weiszacker-Williams)
  - Provides distributions for EM quanta from classical field
- Photons with $E \lesssim (\hbar c/R)\gamma$ are produced coherently (Z^2)
  - Up to ~80 GeV for Pb+Pb @ 5.02 TeV, 1.4 TeV for p+p!

Experiments at RHIC & LHC have begun a systematic investigation of UPC, including:

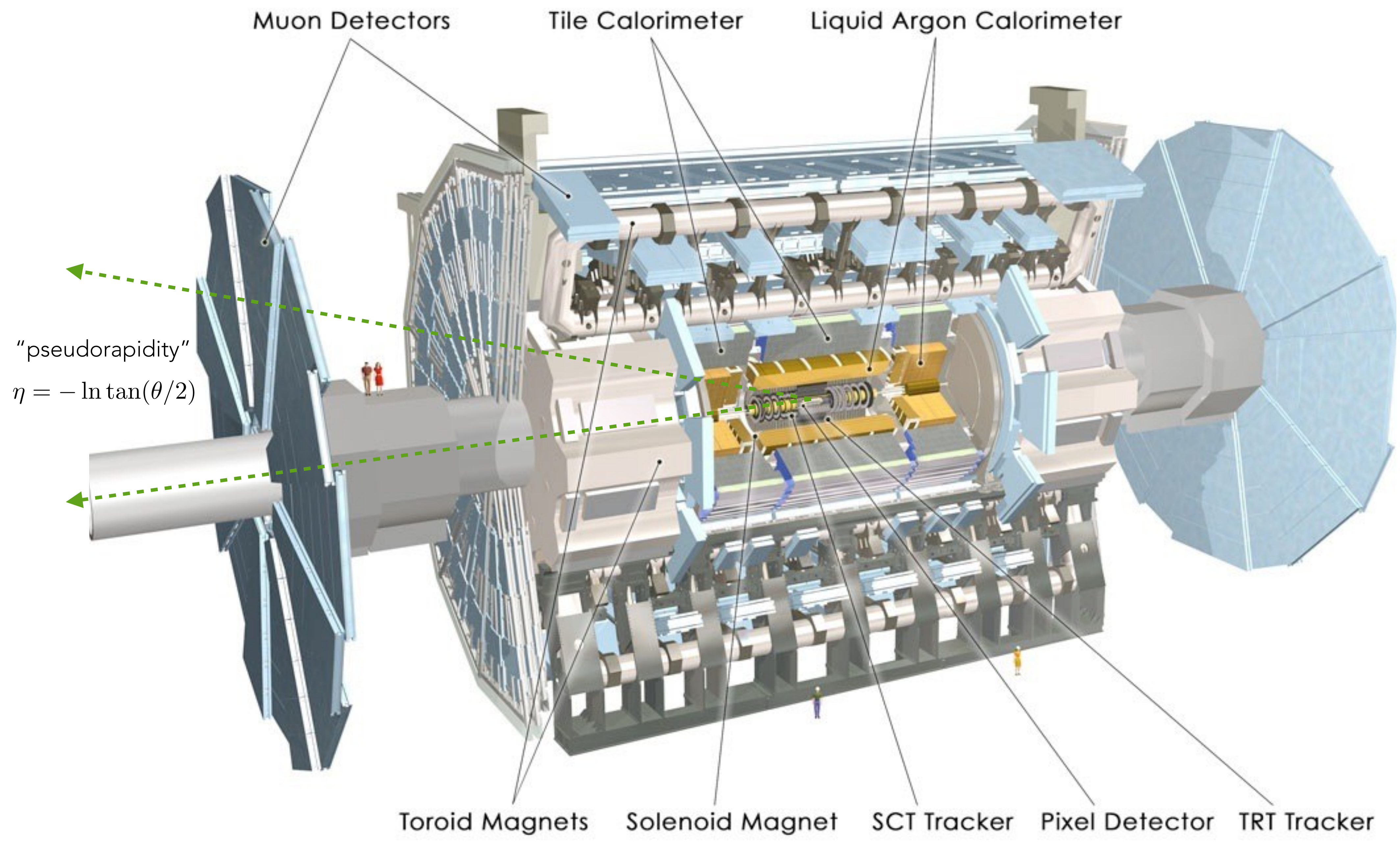


***Photon-pomeron**:*
production of vector mesons
(sensitivity to nPDF)

***Photo-nuclear**:*
jet photoproduction
(probe nPDF directly)

***Photon-photon**:*
dilepton**, **diphoton
(& other exclusive states)

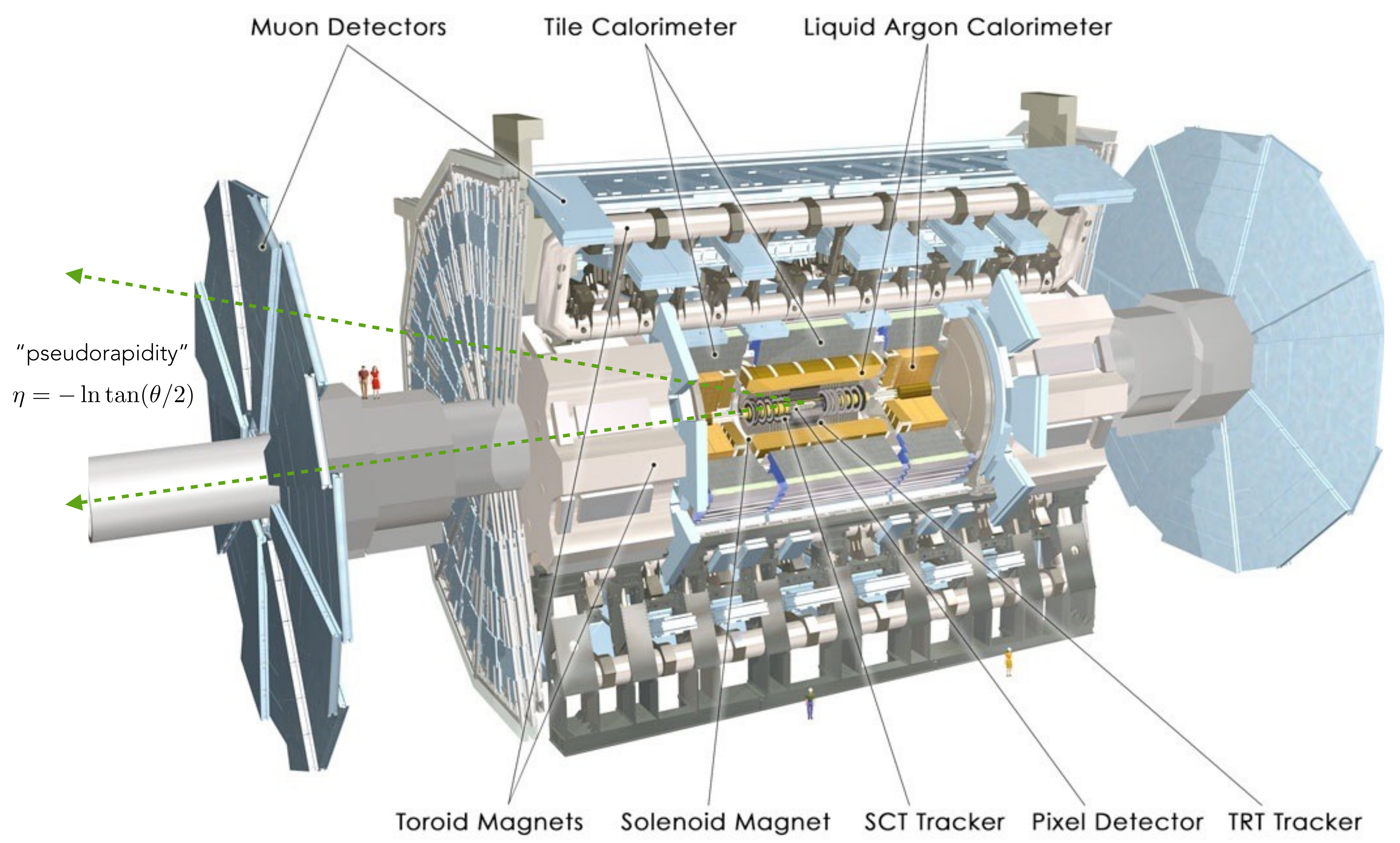
ATLAS DETECTOR



1. Precise charged-particle tracking in $|\eta|<2.5$

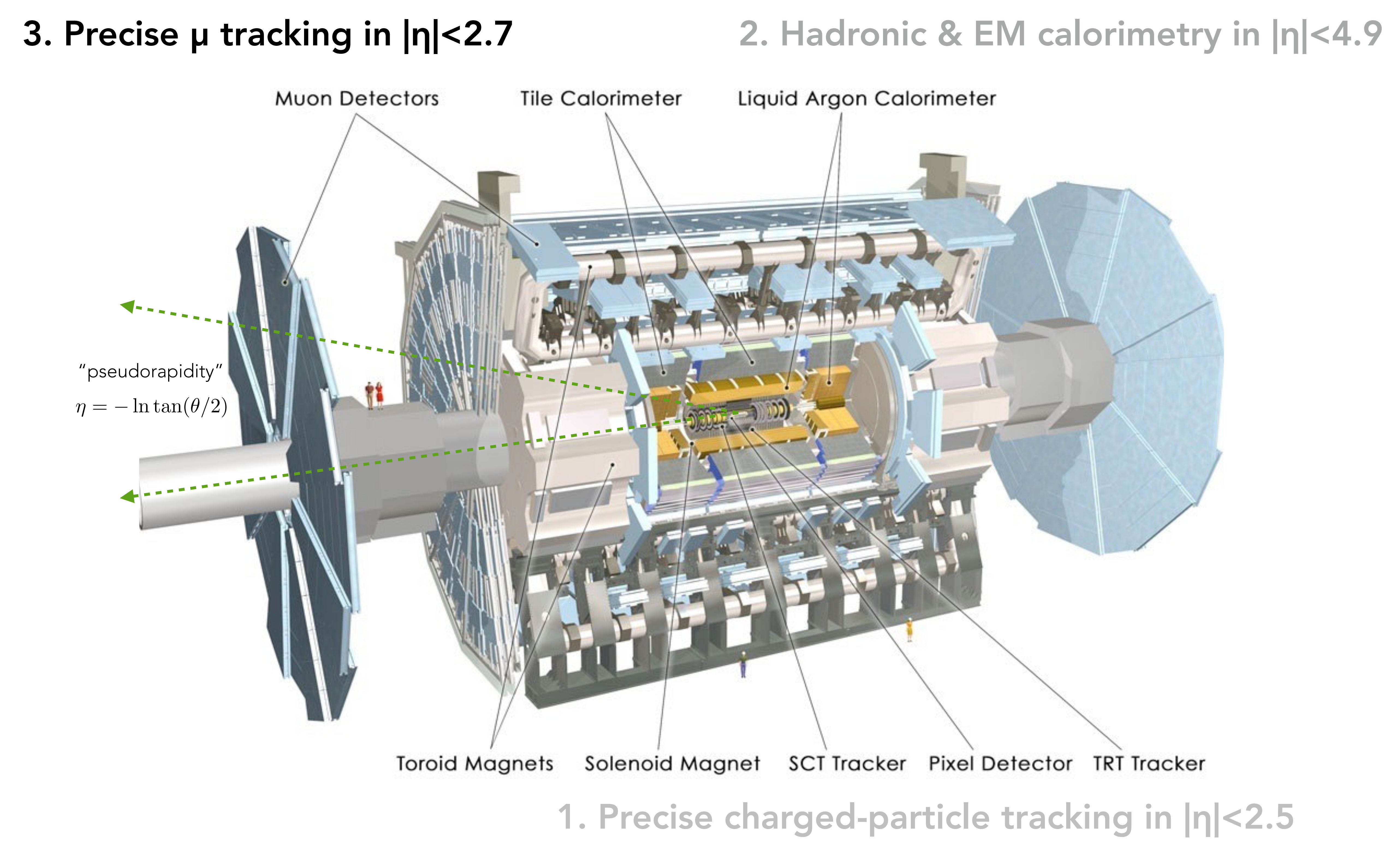
ATLAS DETECTOR

2. Hadronic & EM calorimetry in |η|<4.9



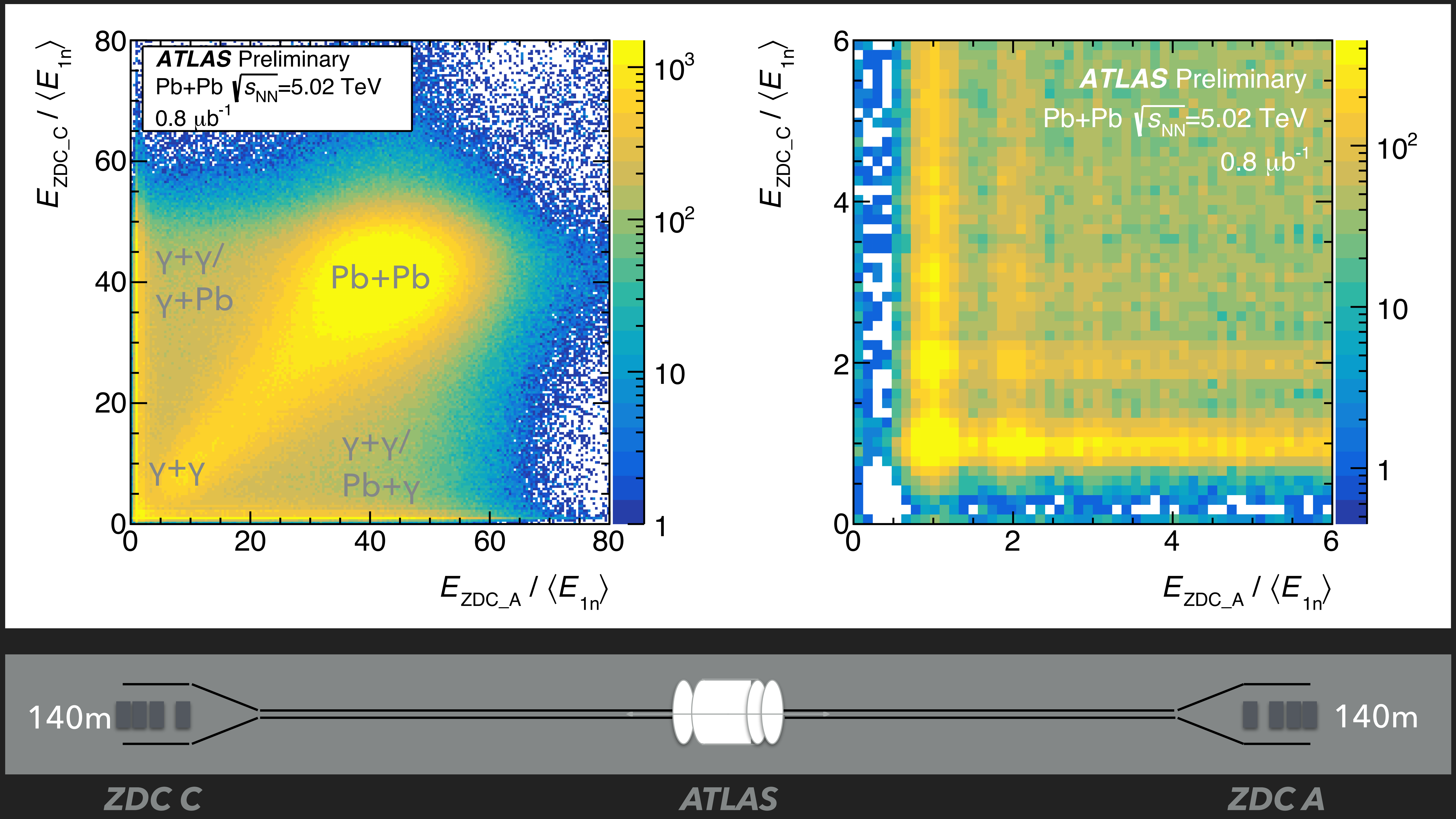
1. Precise charged-particle tracking in |η|<2.5

ATLAS DETECTOR



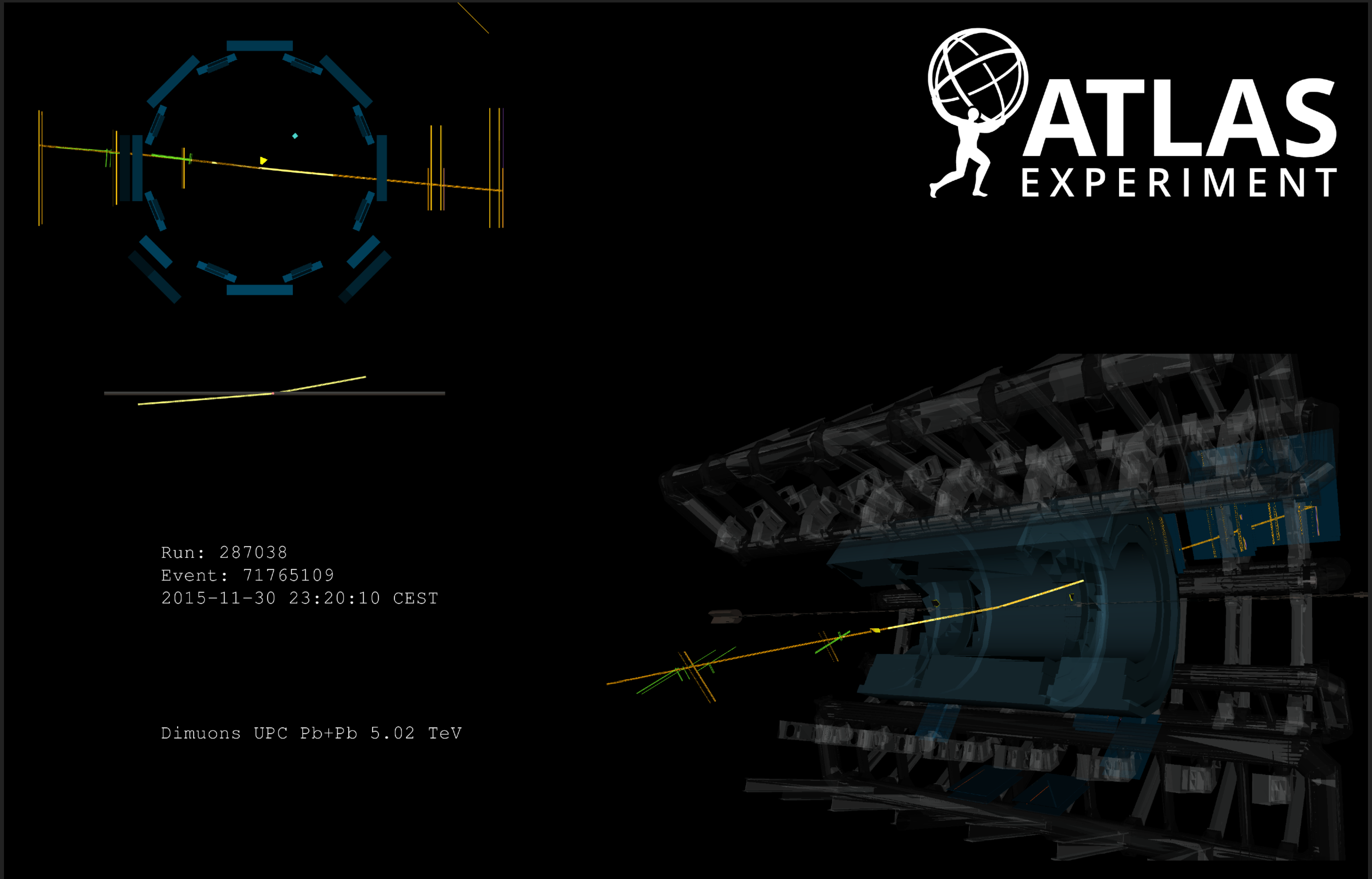
Exclusive final-states require a fully-hermetic detector!

ZERO DEGREE CALORIMETERS



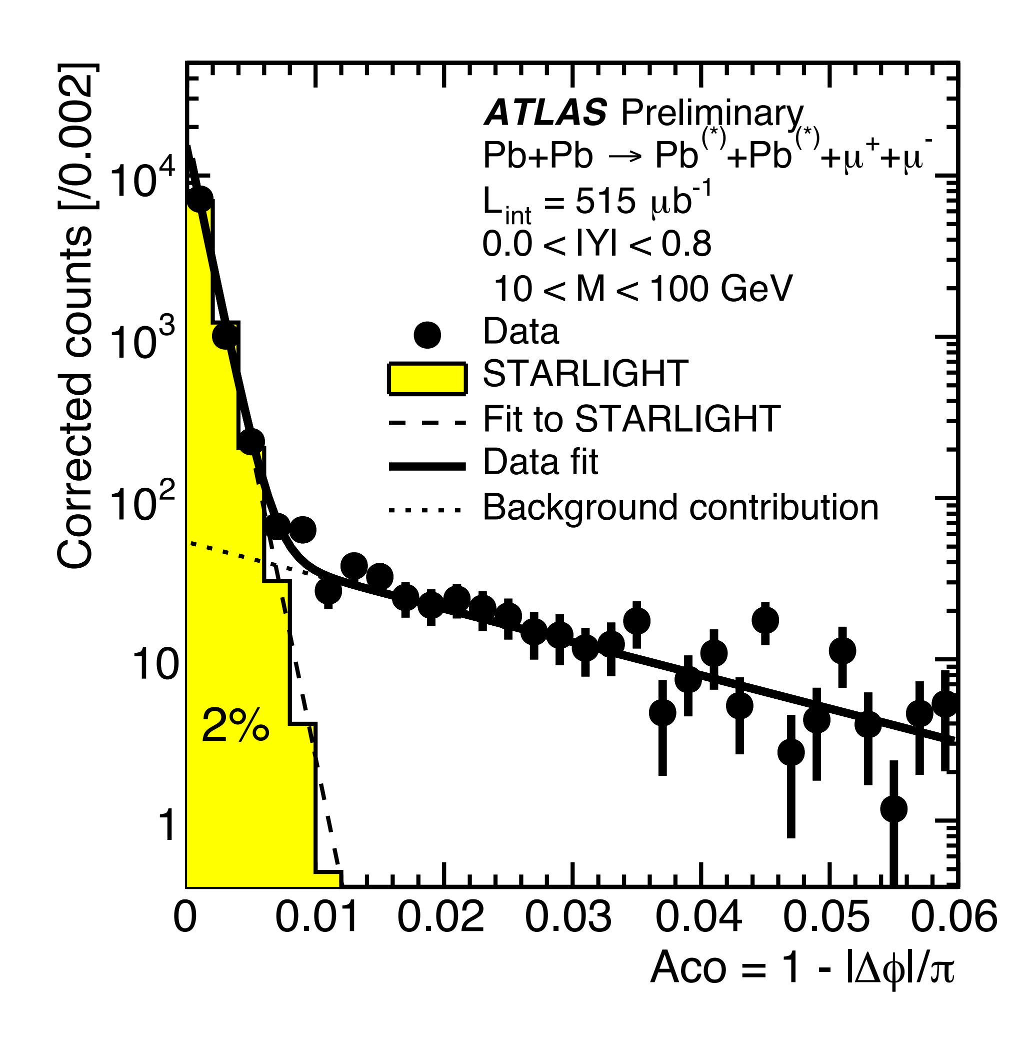
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/HION-2015-001/

M=173 GEV EXCLUSIVE DIMUON EVENT



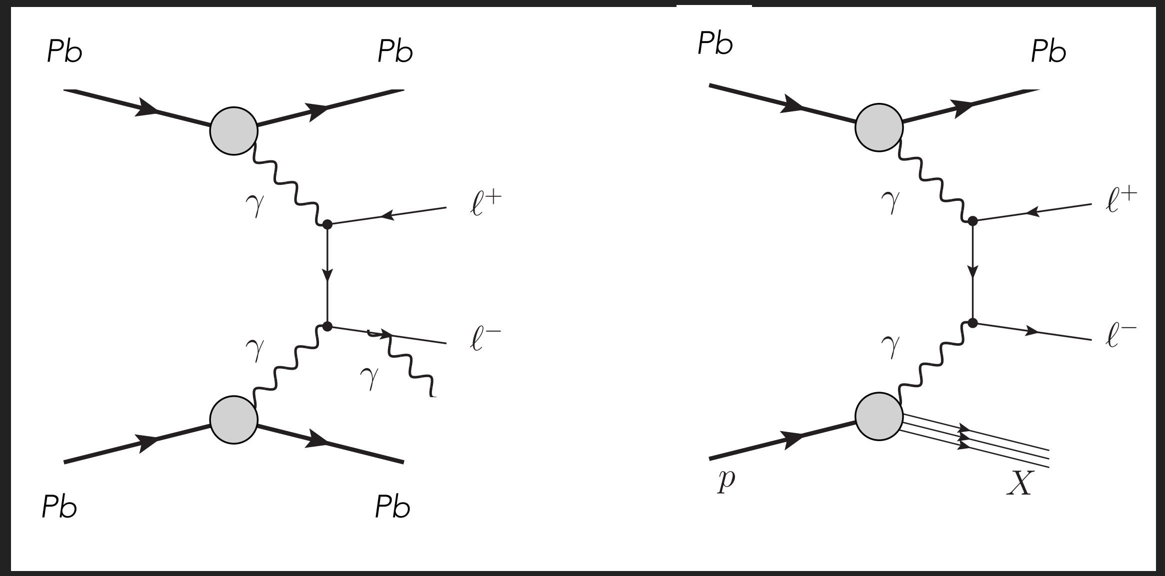
EXCLUSIVE DIMUON PRODUCTION

ATLAS-CONF-2016-025



NLO QED

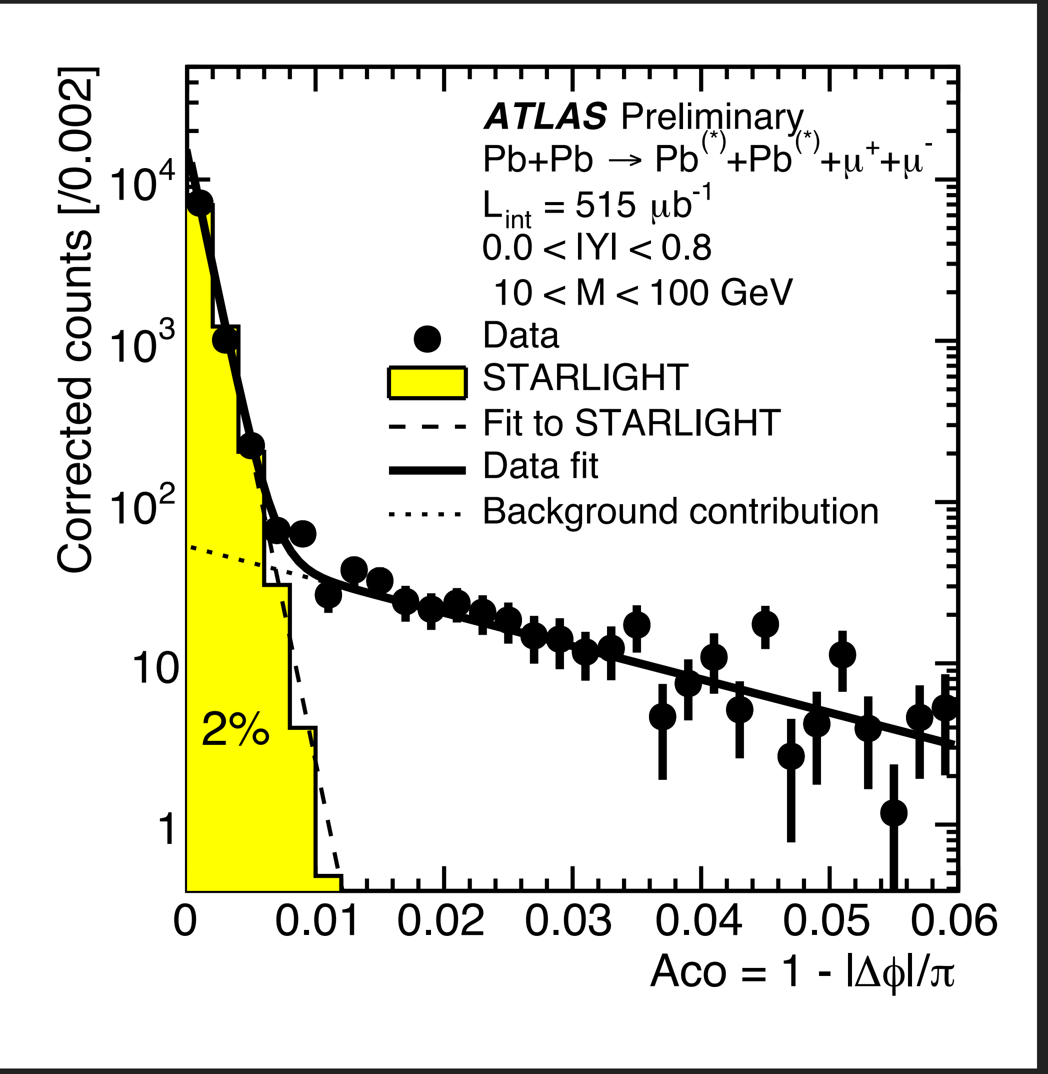
dissociation

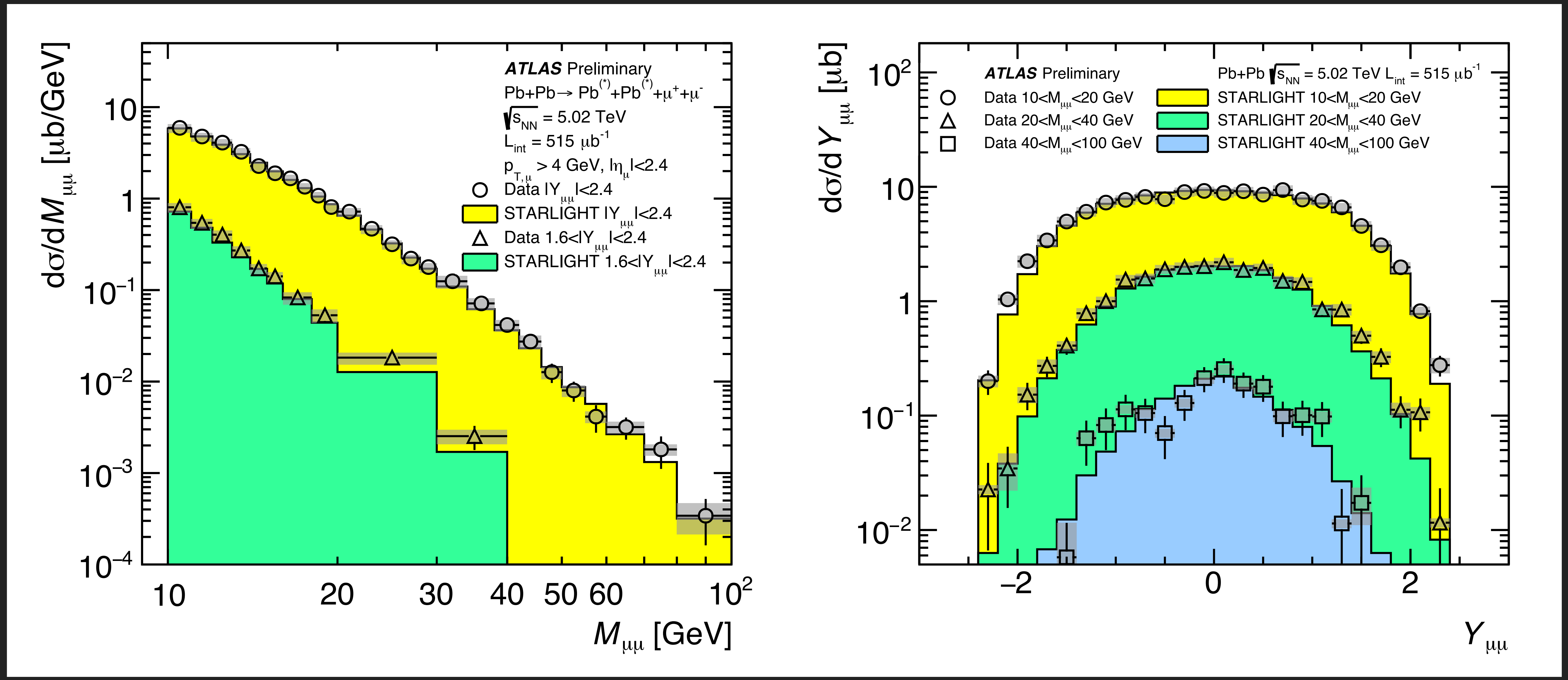


Exclusive dimuon event distributions corrected for trigger, reco & vertex efficiency, systematics cover whether long acoplanarity tails are all signal or all background

EXCLUSIVE DIMUON PRODUCTION

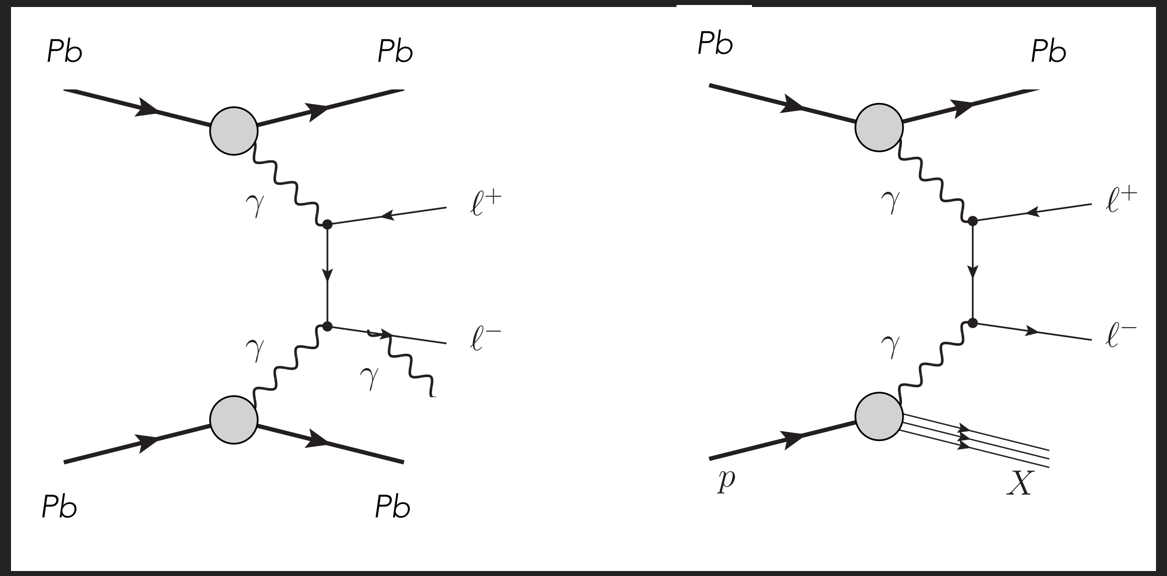
ATLAS-CONF-2016-025





NLO QED

dissociation



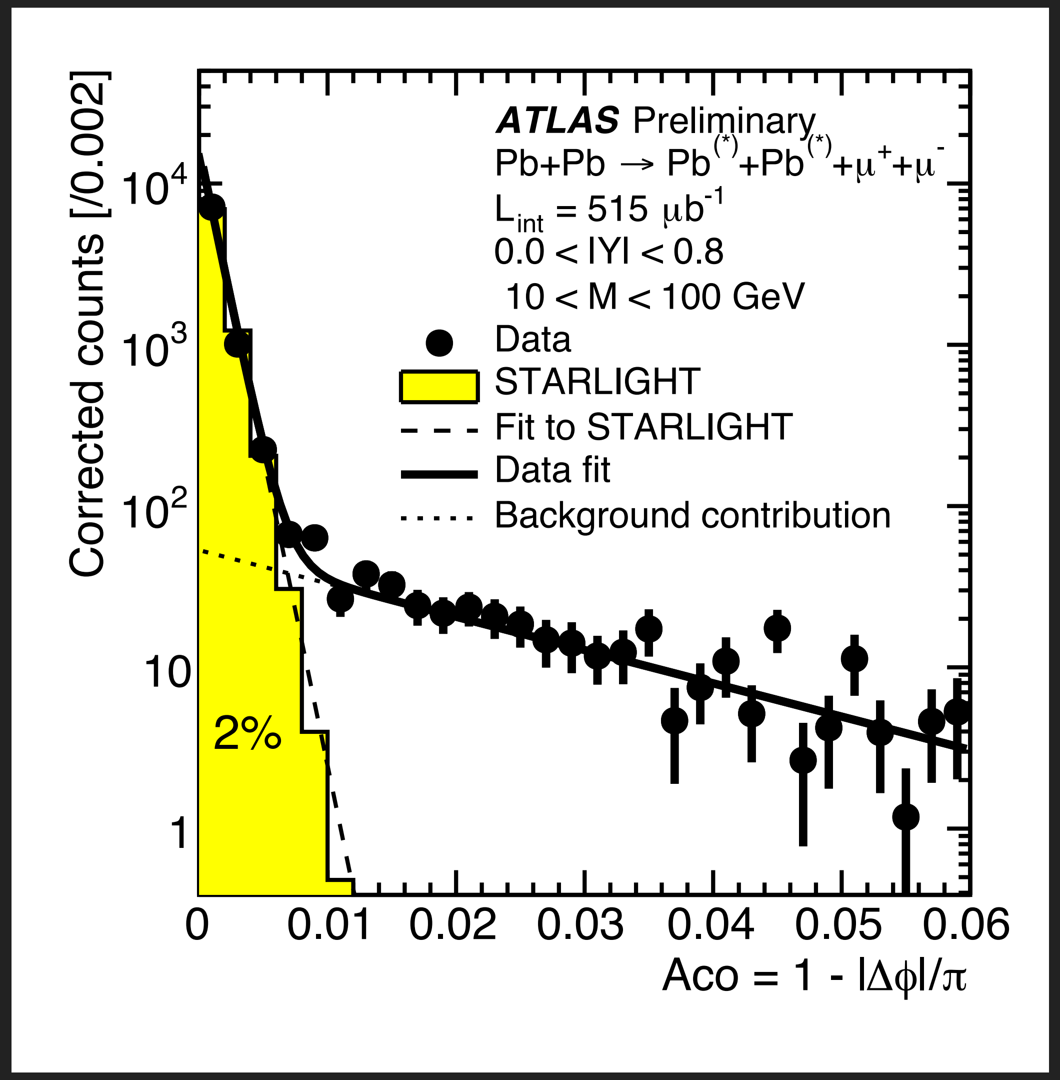
Exclusive dimuon event distributions corrected for trigger, reco & vertex efficiency, systematics cover whether long acoplanarity tails are all signal or all background

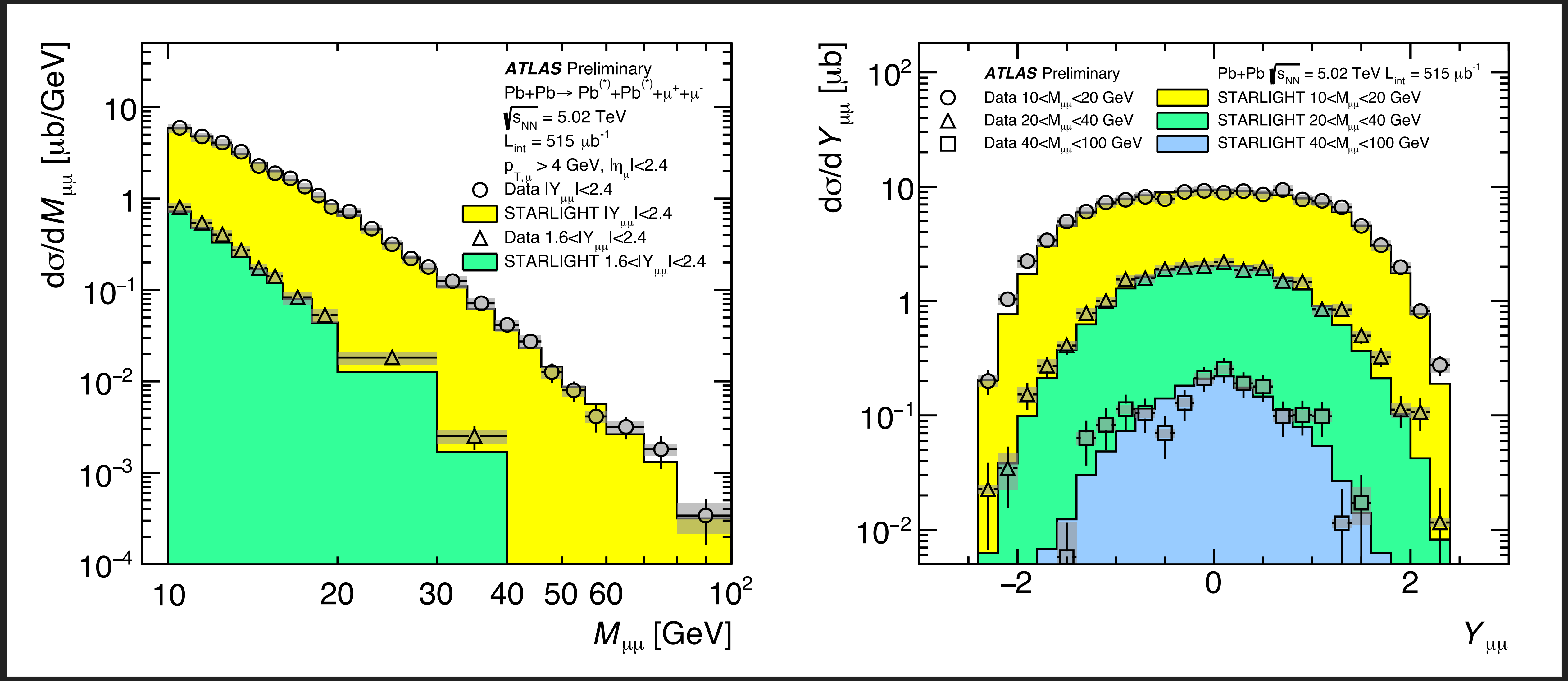
STARLIGHT 1.1 provides good description of fully-corrected dimuon distributions, with hint of small excess at high $Y_{\mu\mu}$ (but NB missing physics: e.g. higher-order QED)

ATLAS EXPERIMENT

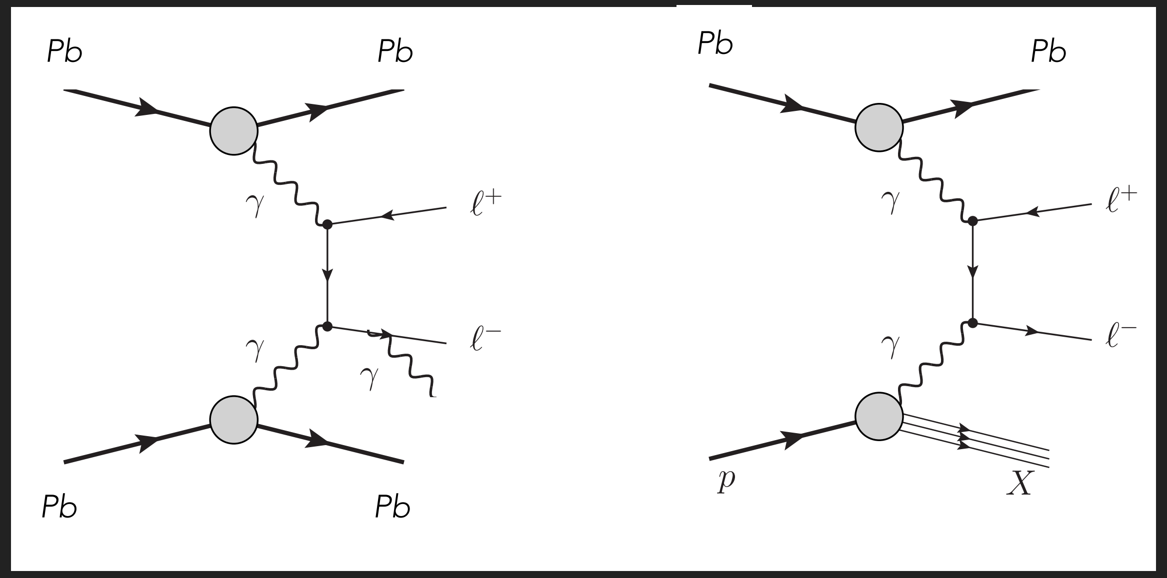
EXCLUSIVE DIMUON PRODUCTION

ATLAS-CONF-2016-025





NLO QED dissociation



Exclusive dimuon event distributions corrected for trigger, reco & vertex efficiency, systematics cover whether long acoplanarity tails are all signal or all background

STARLIGHT 1.1 provides good description of fully-corrected dimuon distributions, with hint of small excess at high $Y_{\mu\mu}$ (but NB missing physics: e.g. higher-order QED)

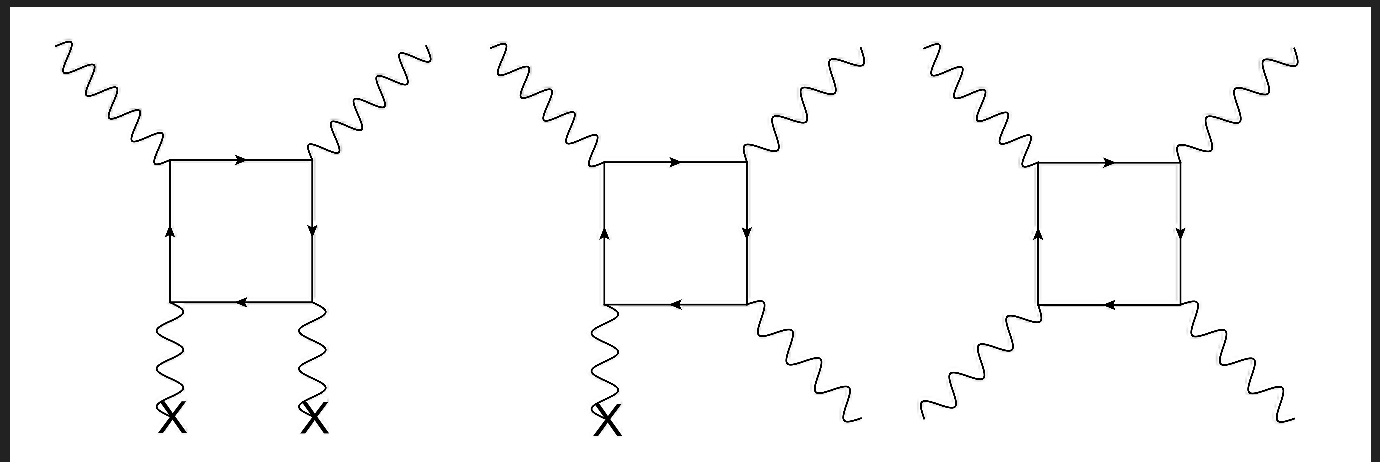
Next steps: proper handling of beyond LO effects, selections on ZDC to constrain impact parameter dependence!

ATLAS EXPERIMENT

LIGHT-BY-LIGHT SCATTERING

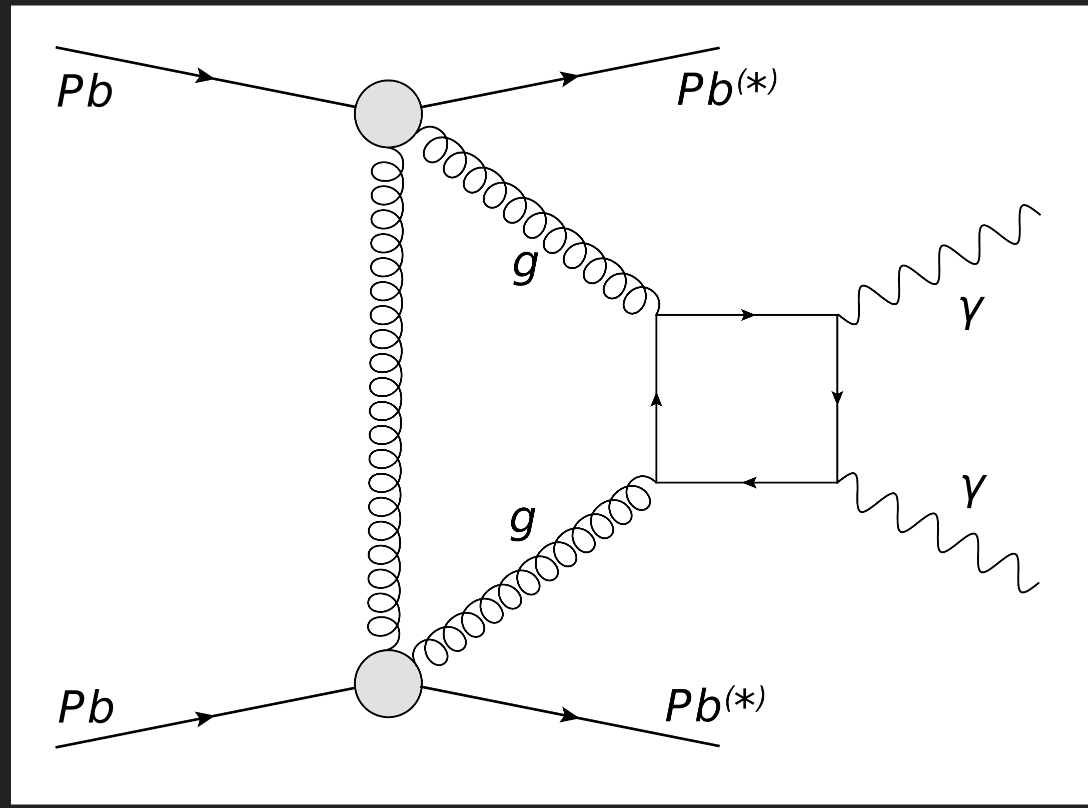
https://doi.org/10.1038/NPHYS4208

Decades old prediction of QED, but loops are sensitive to all sectors standard model which couple to photons, and BSM physics



Delbruck scattering | Photon splitting | "direct" light-by-light

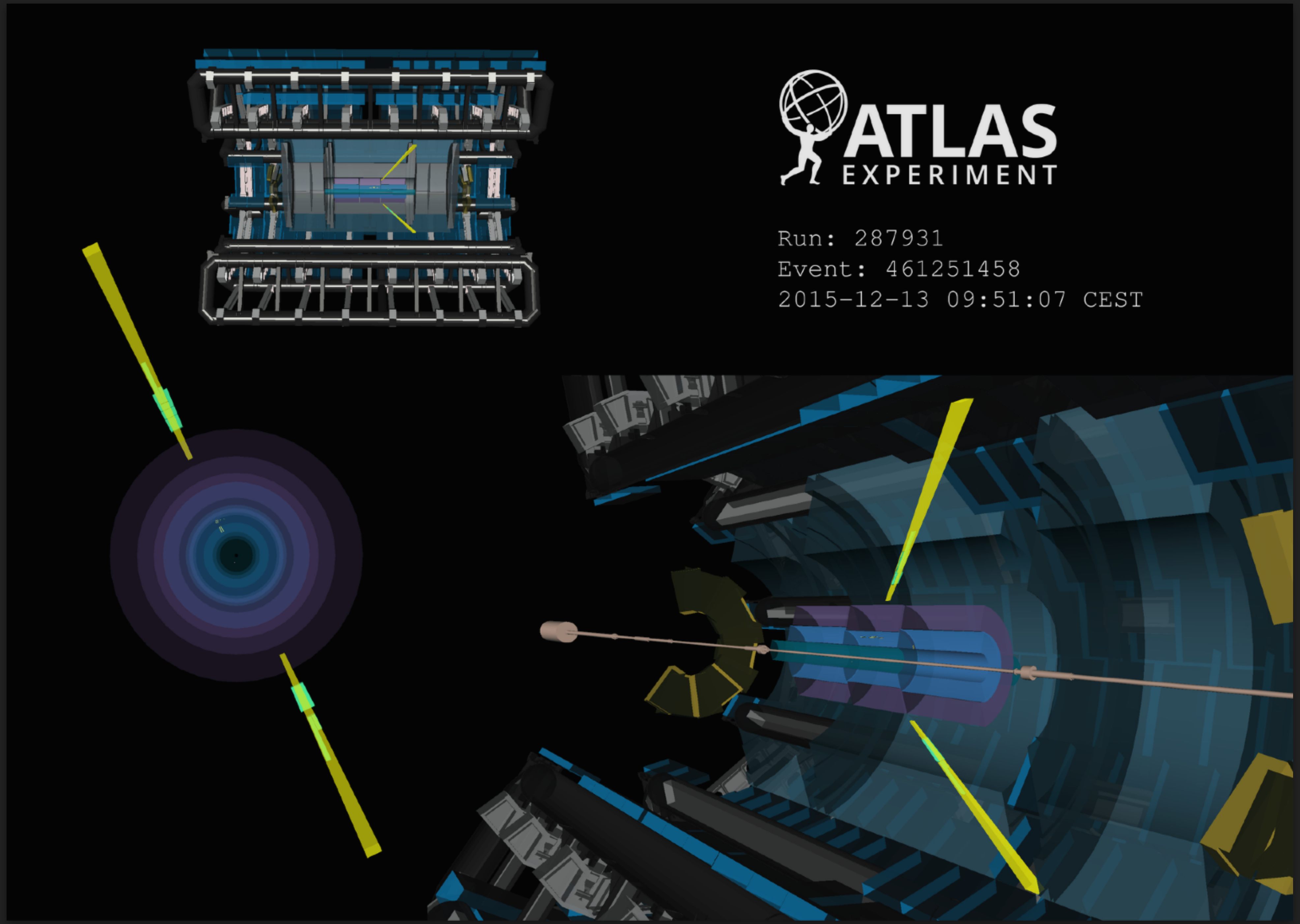
Same diagram, different initial states: direct LbyL not observed before 2016



Backgrounds from mid-ID dielectrons, as well as "central exclusive production" (QCD) of two-photons

LIGHT-BY-LIGHT MEASUREMENT

https://doi.org/10.1038/NPHYS4208



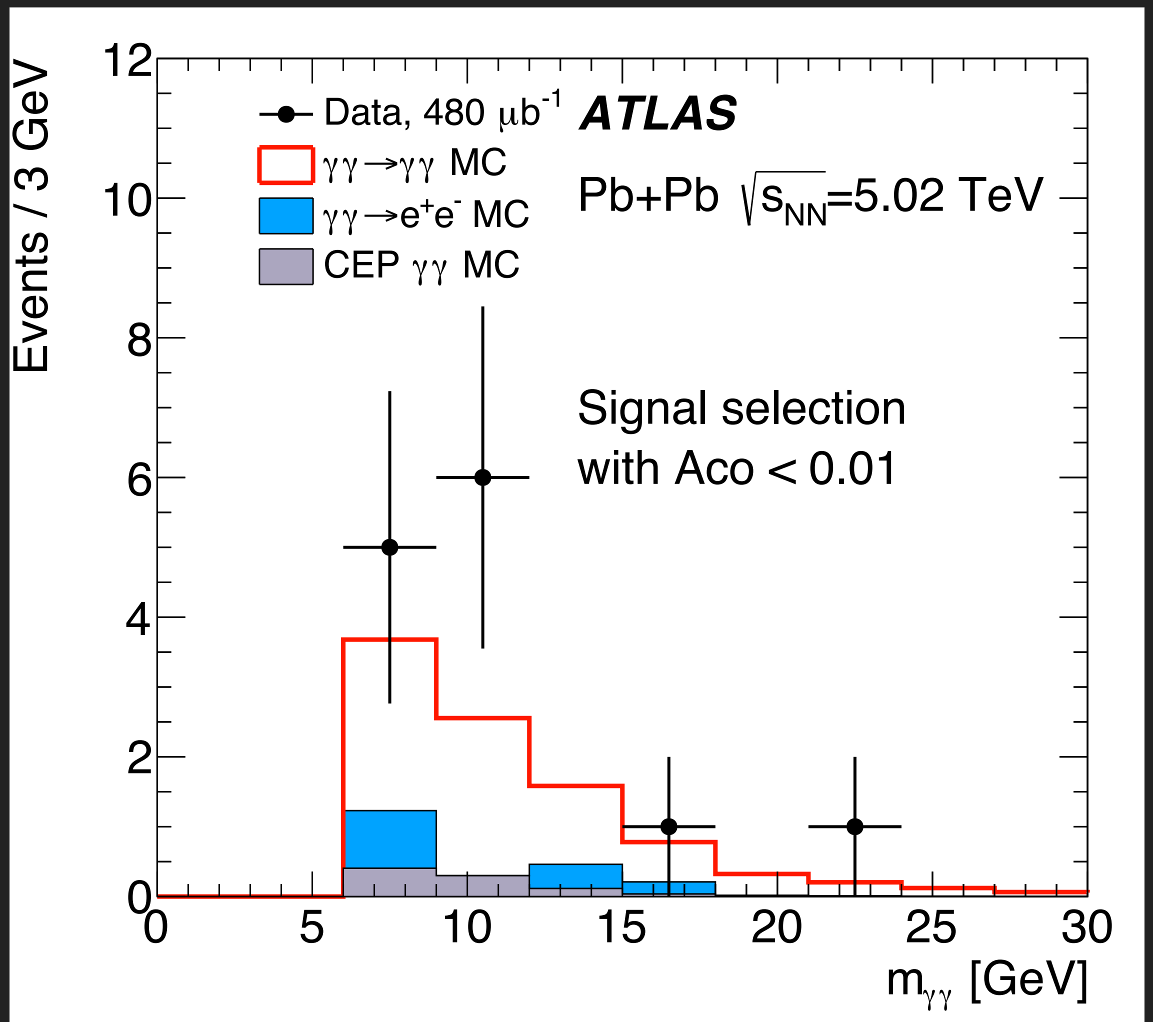
- Trigger
  - *transverse energy in calorimeter $5 < \Sigma E_T < 200$ GeV*
  - *Veto on >1 hit in inner ring of either MBTS detector ($3 < |\eta| < 3.8$)*
  - *Veto on >10 hits in Pixel detector*

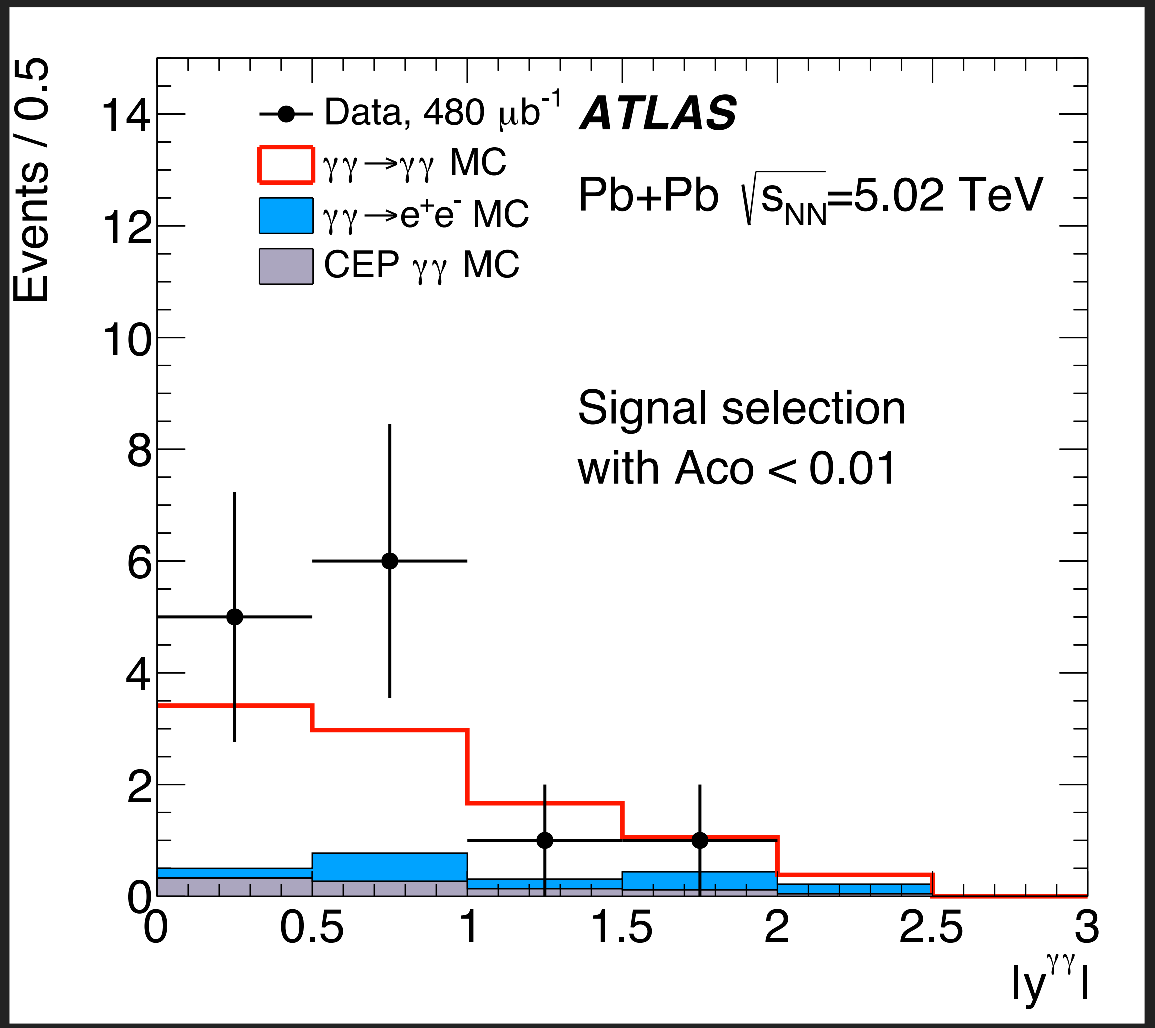
- Event selection
  - *Two photon candidates, $p_T > 3$ GeV, $|\eta| < 2.37$, each satisfying shower shape selections*
  - *No tracks with $p_T > 100$ GeV, $|\eta| < 2.5$, one hit in pixel*
  - *Pair $m_{\gamma\gamma} > 6$ GeV $p_{T\gamma\gamma} < 2$ GeV*
  - *Pair acoplanarity $Aco = 1 - |\Delta\phi|/\pi < 0.01$*

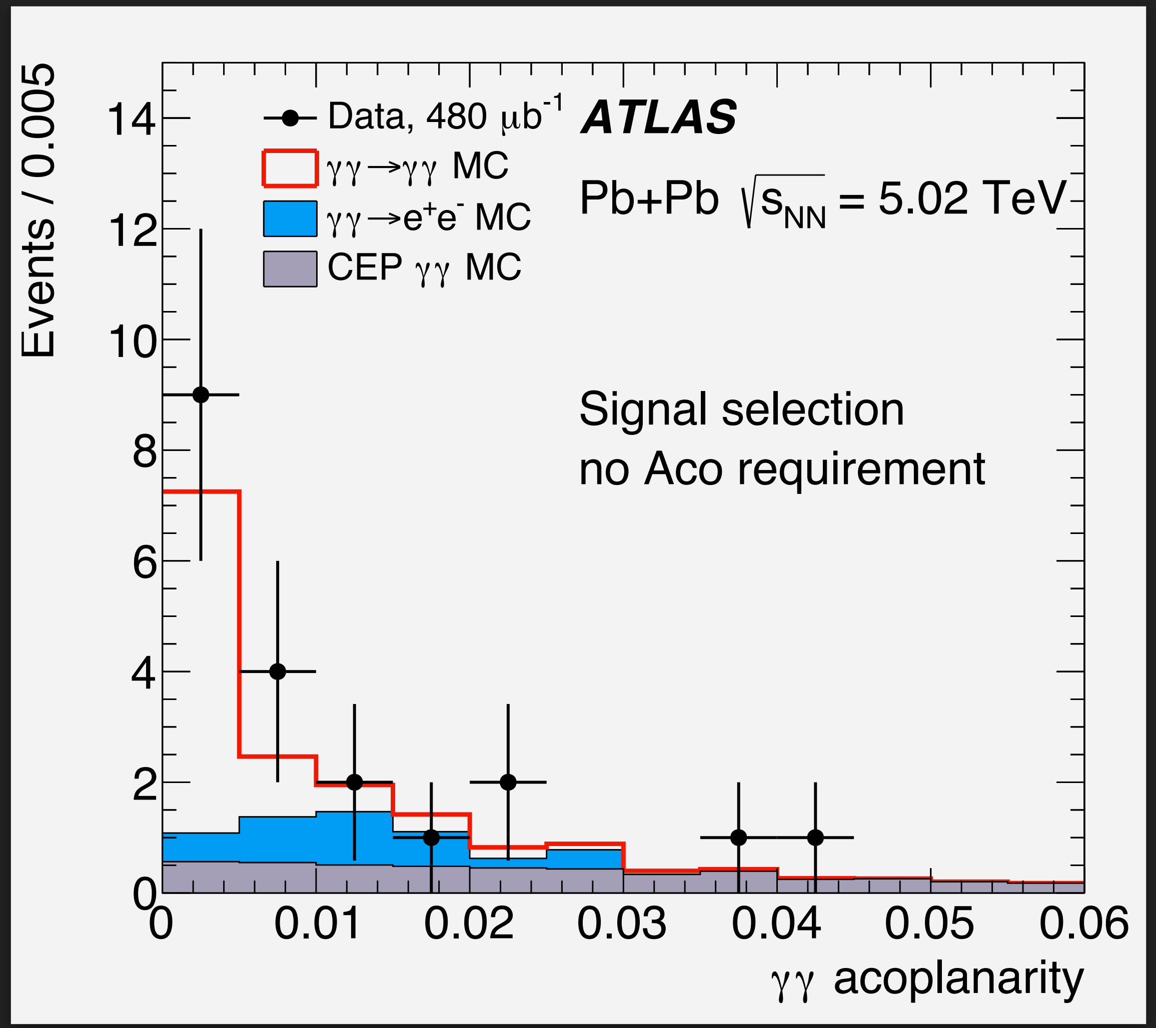
ATLAS EXPERIMENT

EVIDENCE FOR LIGHT-BY-LIGHT

https://doi.org/10.1038/NPHYS4208







Invariant masses out to 20-25 GeV,
Pair rapidity out to 2

Clear enhancement at low acoplanarity

ARTICLES
PUBLISHED ONLINE: 14 AUGUST 2017 | DOI: 10.1038/NPHYS4208
nature physics
OPEN

Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration†

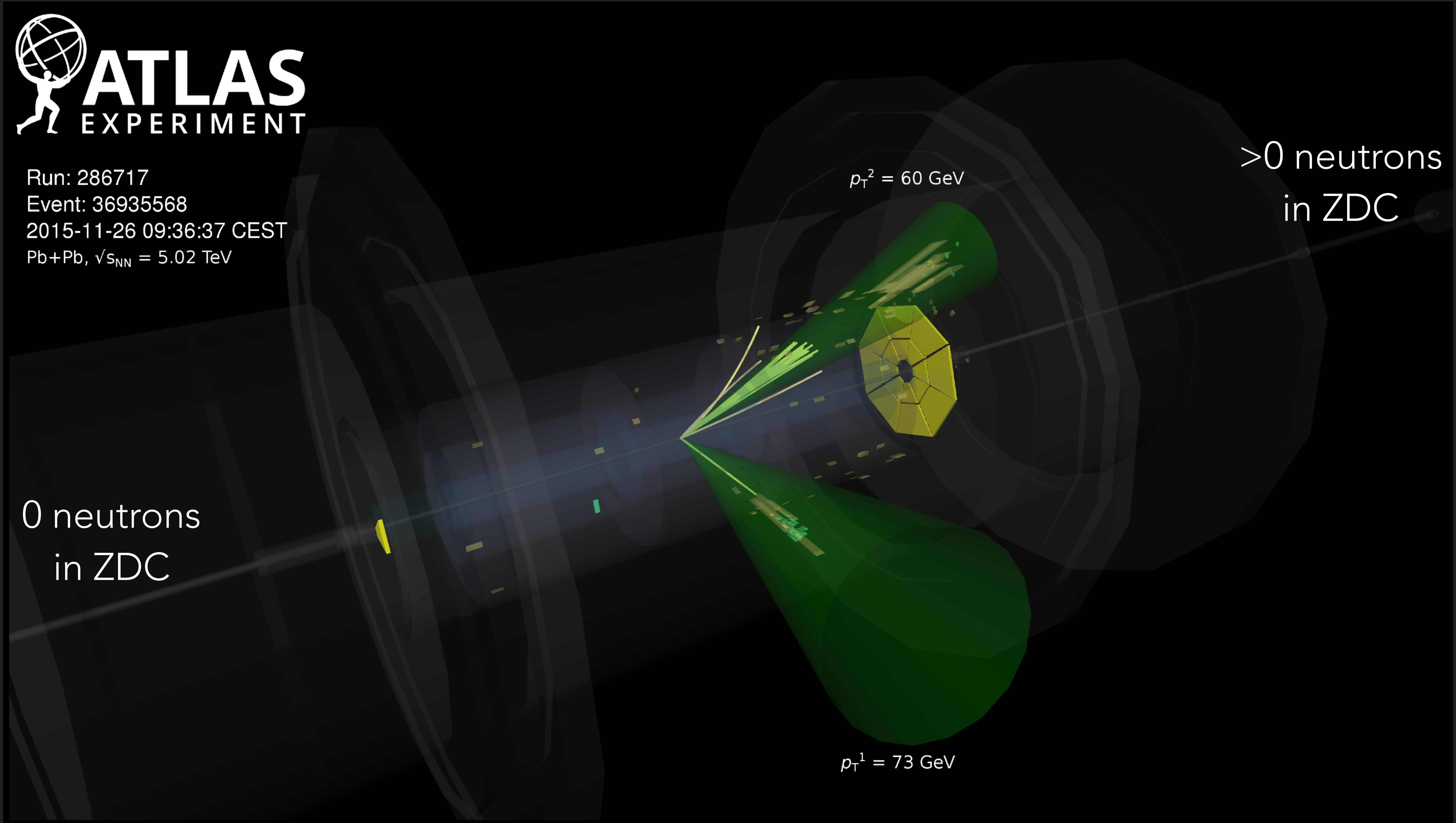
σ_{fid} = 70±24 (stat.) ±17(syst) nb

4.4σ significance observed
3.8σ expected

Looking forward to improvements in 2018!

PHOTONUCLEAR DIJETS

ATLAS-CONF-2017-011



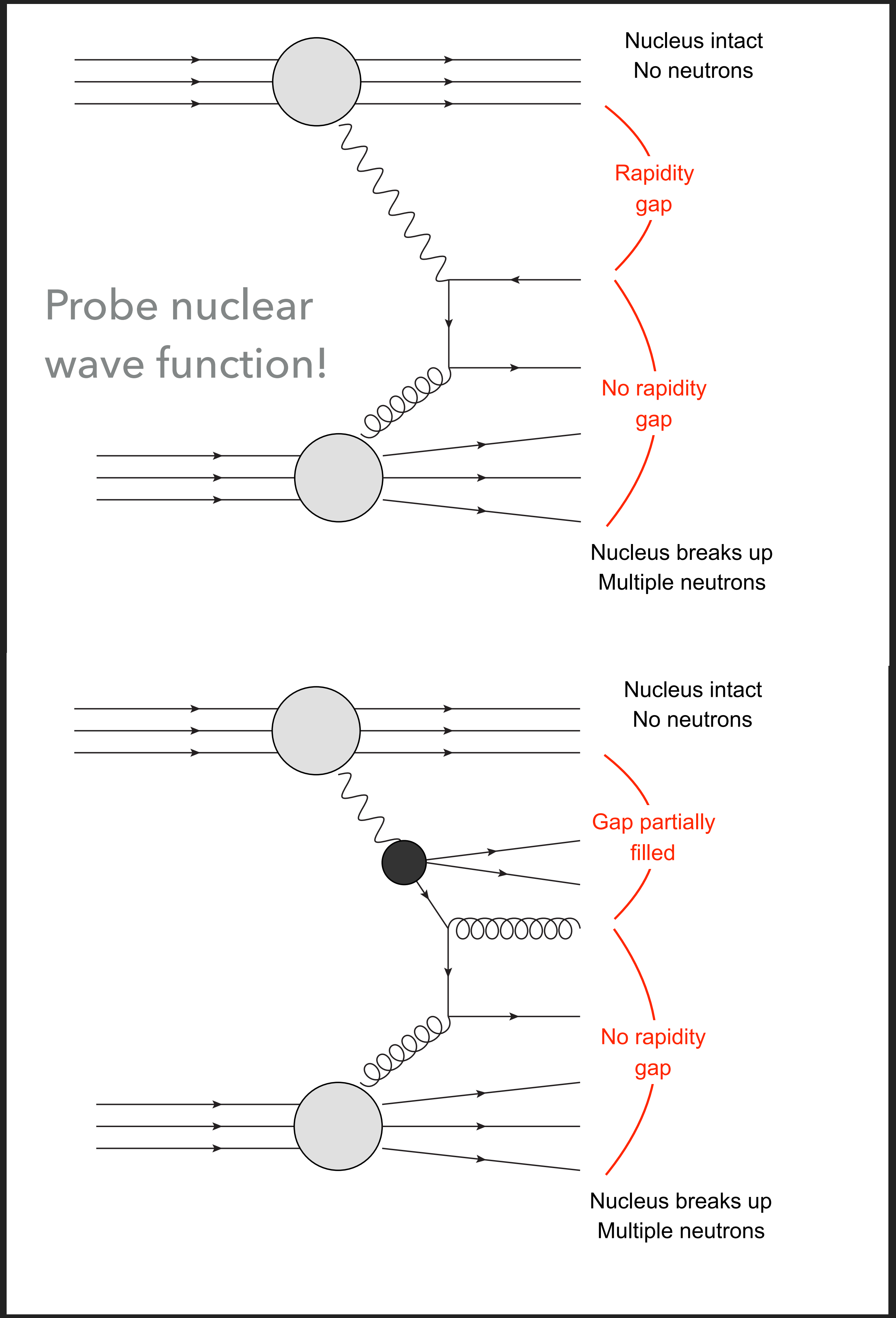
Two or more jets (anti-k_T R=0.4) with p_T > 15 GeV, $|\eta|$<4.4
At least one with p_T > 20 GeV, $|\Delta\phi|_{12}$ > 0.2, m_{jets} > 35 GeV

PHOTONUCLEAR DIJETS PROBE NUCLEAR PARTON STRUCTURE

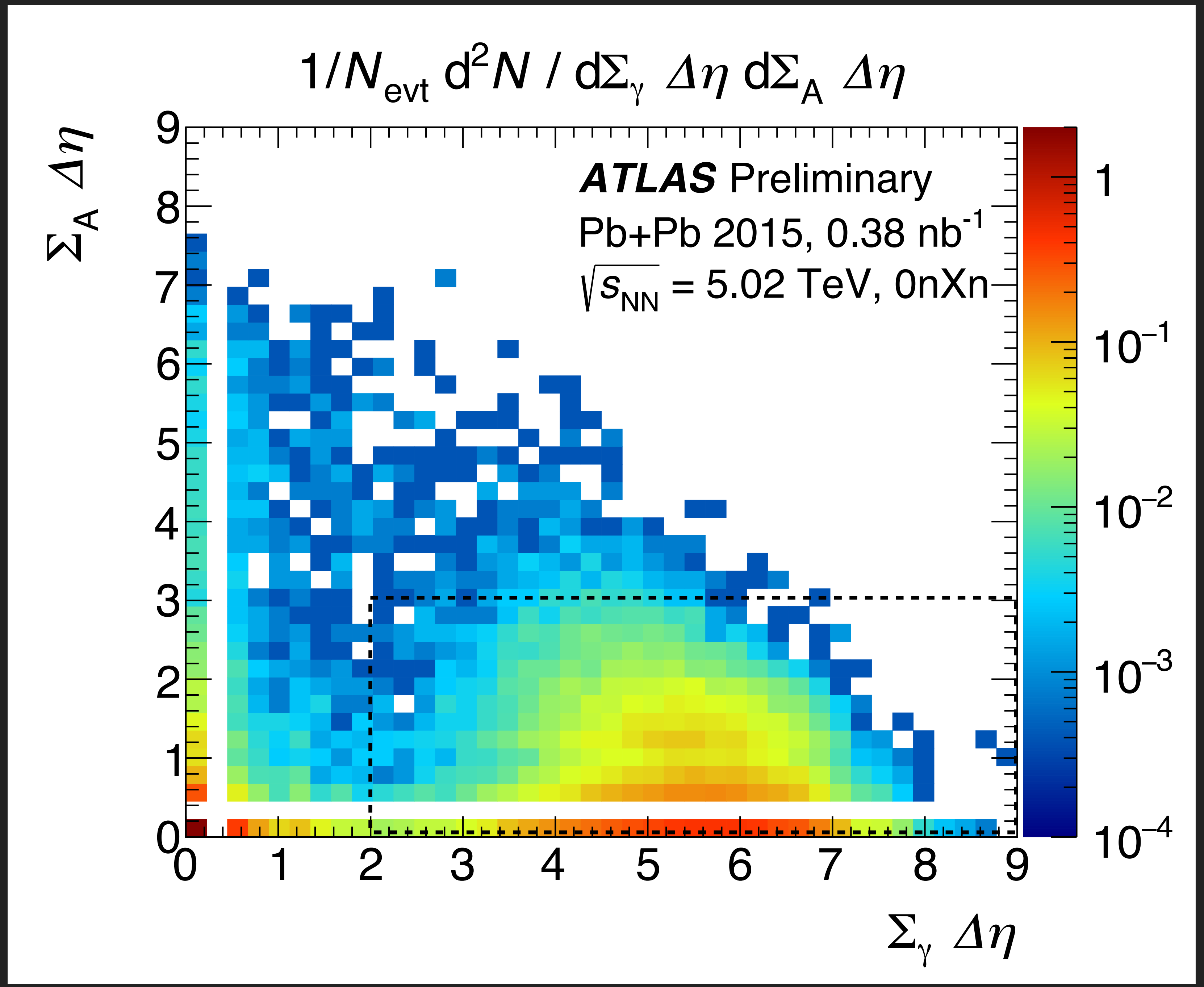
ATLAS-CONF-2017-011

$\Sigma_A \Delta\eta < 3$ sum of gaps associated with
$\Sigma_\gamma \Delta\eta > 2$ photon-going and Pb-going sides

Probe nuclear wave function!



Resolved processes "fill" gaps

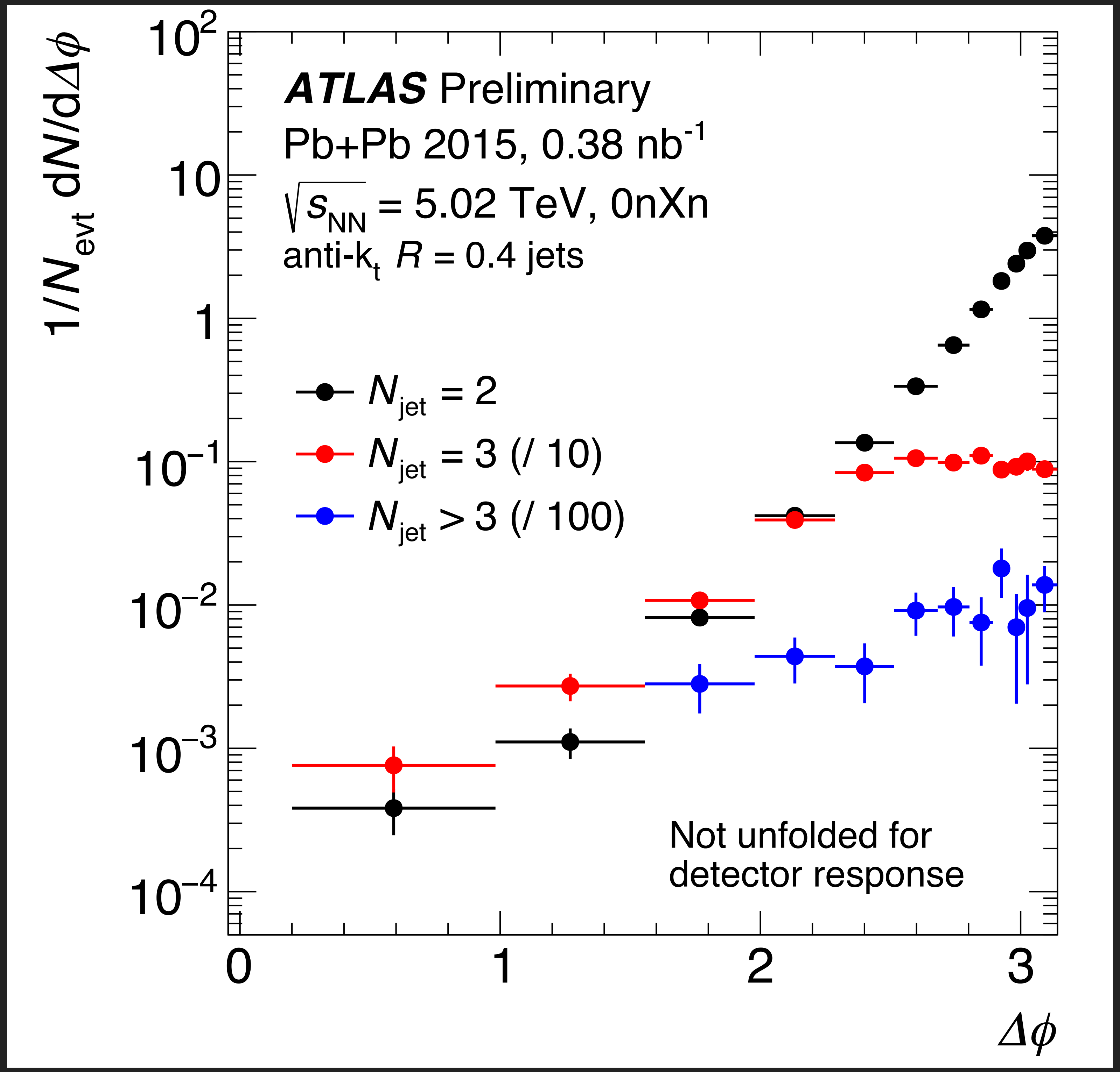


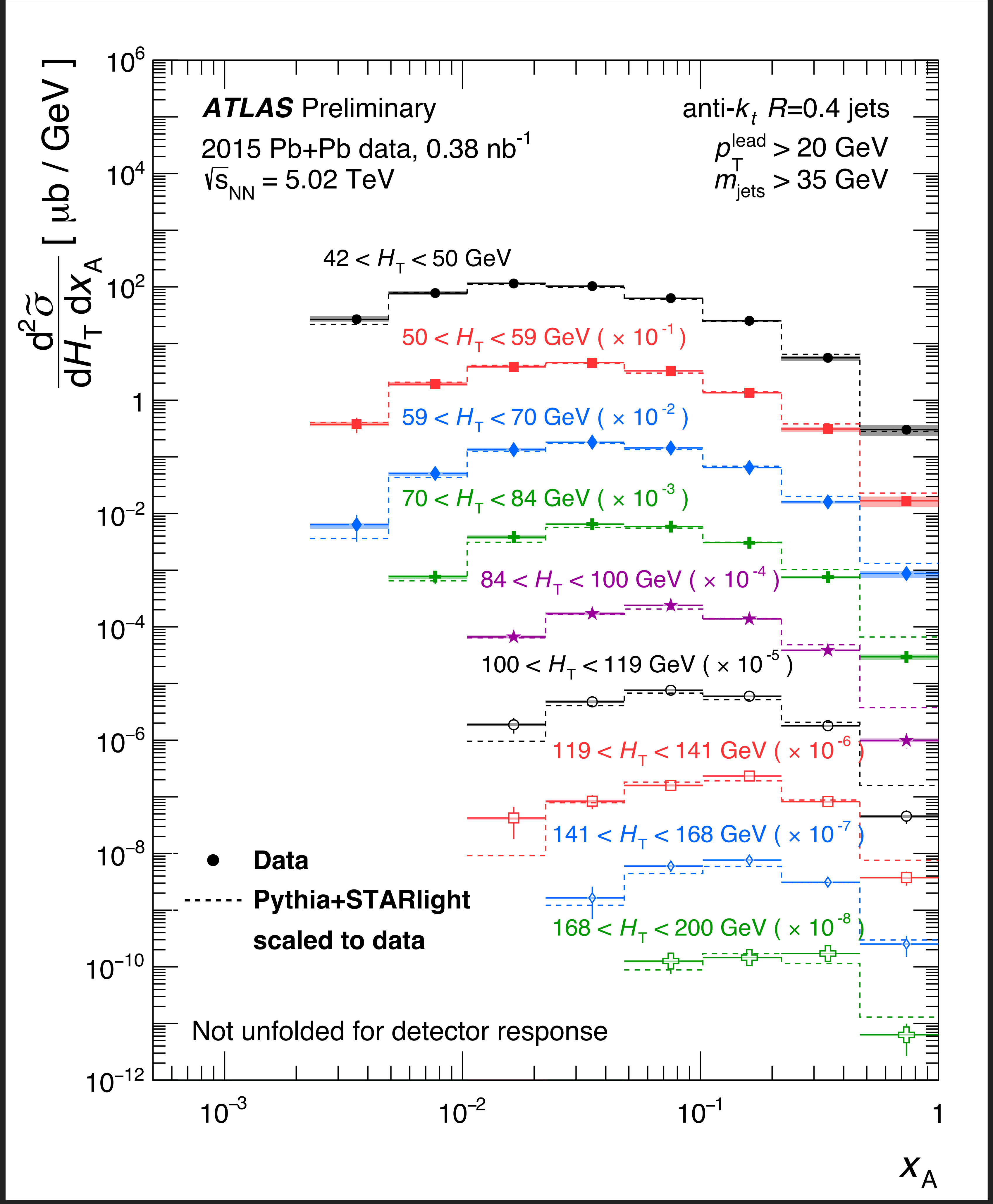
Upper bound on Pb-going gap suppresses of γγ collisions and non-photonuclear UPC processes (e.g. μμ, ee, qq).

Expect no substantial contributions from hadronic diffrative processes.

PHOTONUCLEAR DIJETS

jet variables: $H_{\mathrm{T}} \equiv \sum_i p_{\mathrm{T}\,i}, \quad x_{\mathrm{A}} \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s}} e^{-y_{\mathrm{jets}}}$





ATLAS-CONF-2017-011

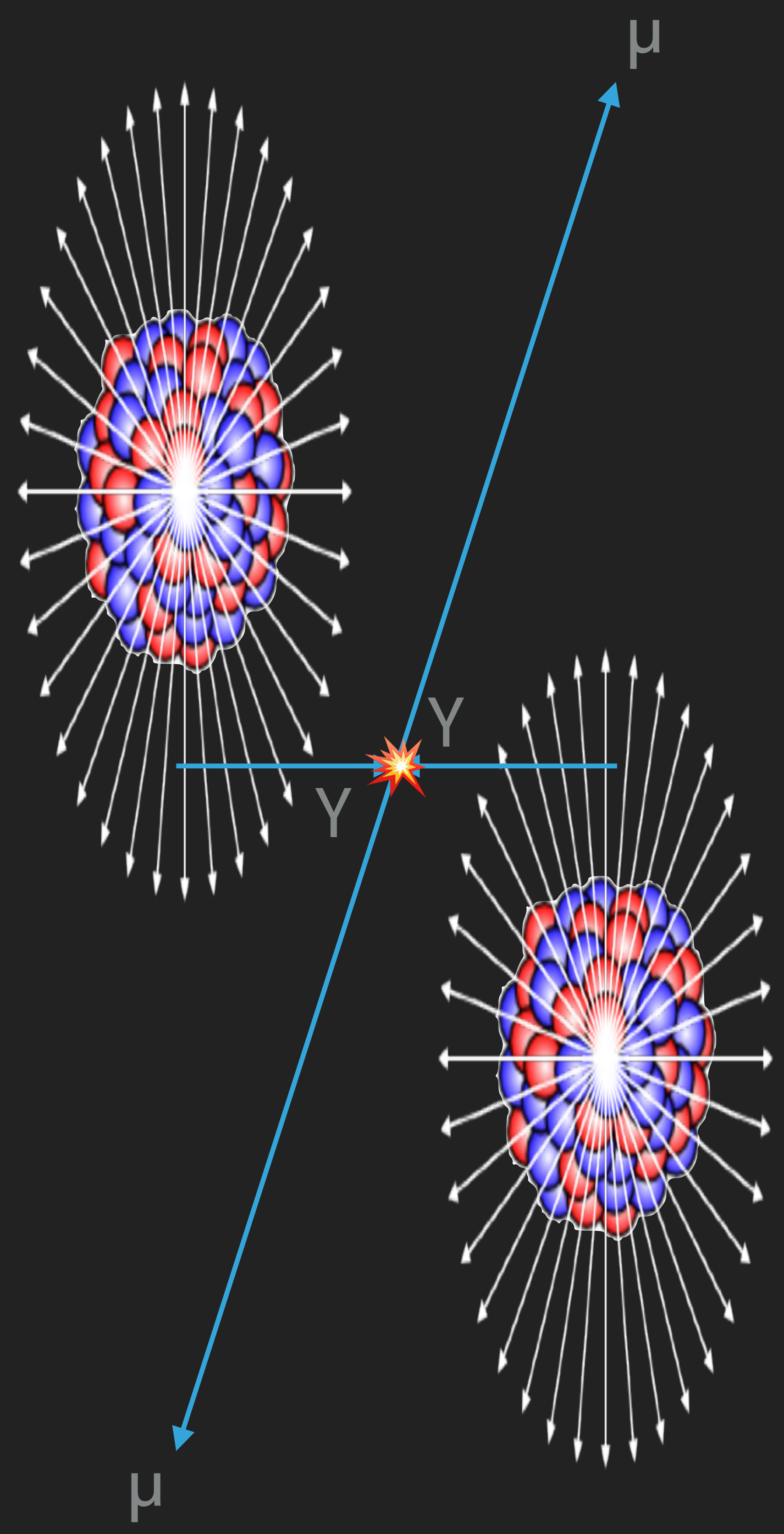
Good agreement with PYTHIA6 w/ γ spectrum reweighed to STARLIGHT 1.1

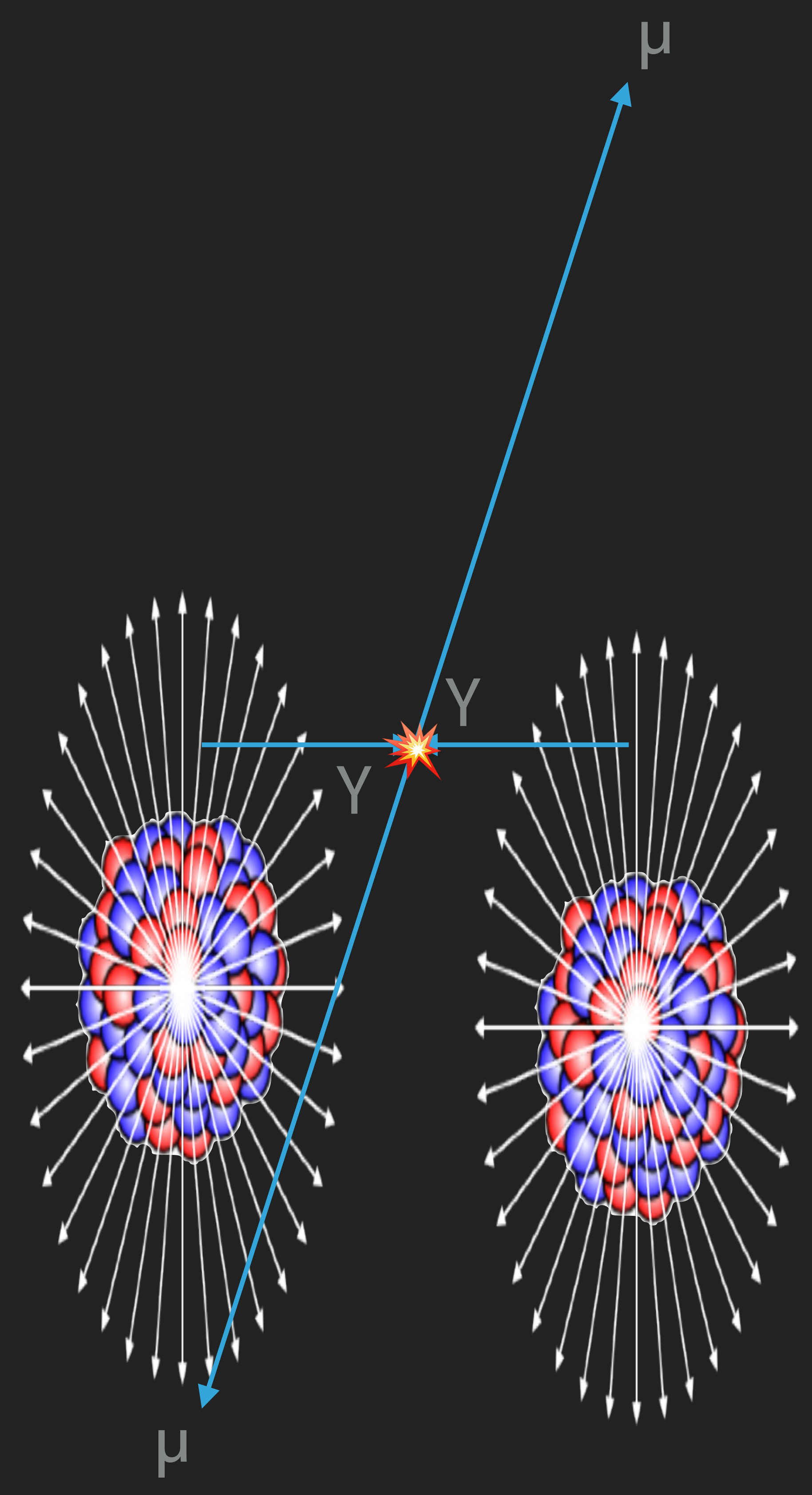
Access to e+A physics now: input to EIC program

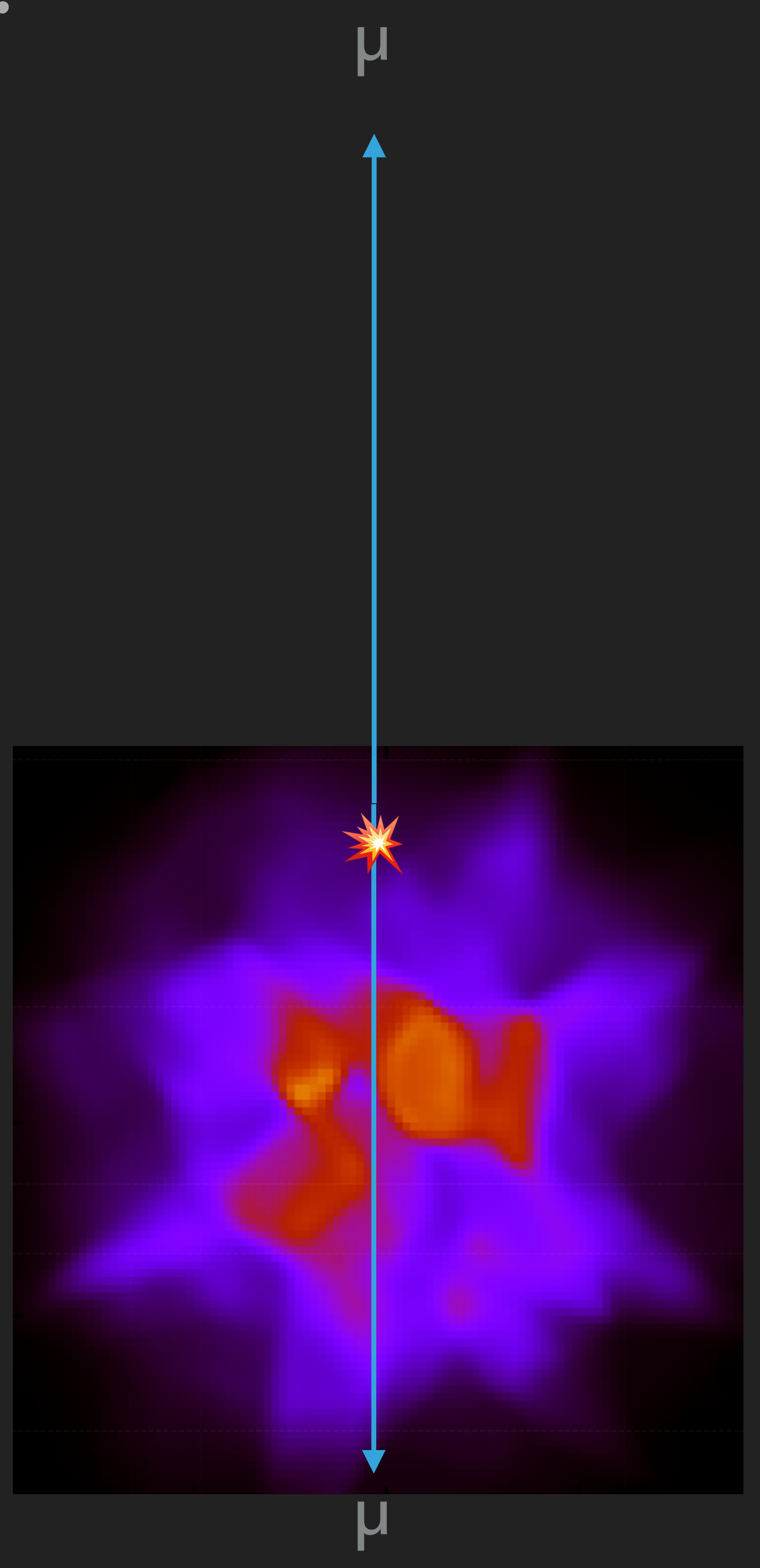
UPC DIMUONS IN "NON-UPC" EVENTS

ATLAS-HION-2018-11

- UPC dimuon rates calculated assuming the nuclei "miss"
  - *However, you can still produce them when they don't!*







Can a "non-UPC" μμ event "see" the QGP?

More details in poster by A. Angerami

EVENT AND MUON SELECTION

ATLAS-HION-2018-11

- Trigger
  - *Dimuon trigger, each with 4 GeV at L1, and 4 GeV in HLT*
- Muon selection
  - *Tight selection, p_T>4 GeV, $|\eta|$<2.4*
  - *Selections on transverse and longitudinal impact parameter < 1.5 mm*
- Pair requirement
  - *Opposite sign pairs with $4 < M_{\mu\mu} < 45$ GeV*
- Trigger & reconstruction efficiencies determined using J/Ψ
  - *Applied to each muon as $w^{-1} = \epsilon_{trig}\epsilon_{reco}$*

ANALYSIS STRATEGY

ATLAS-HION-2018-11

- Acoplanarity: difference in azimuthal angle (cf. UPC dimuons)

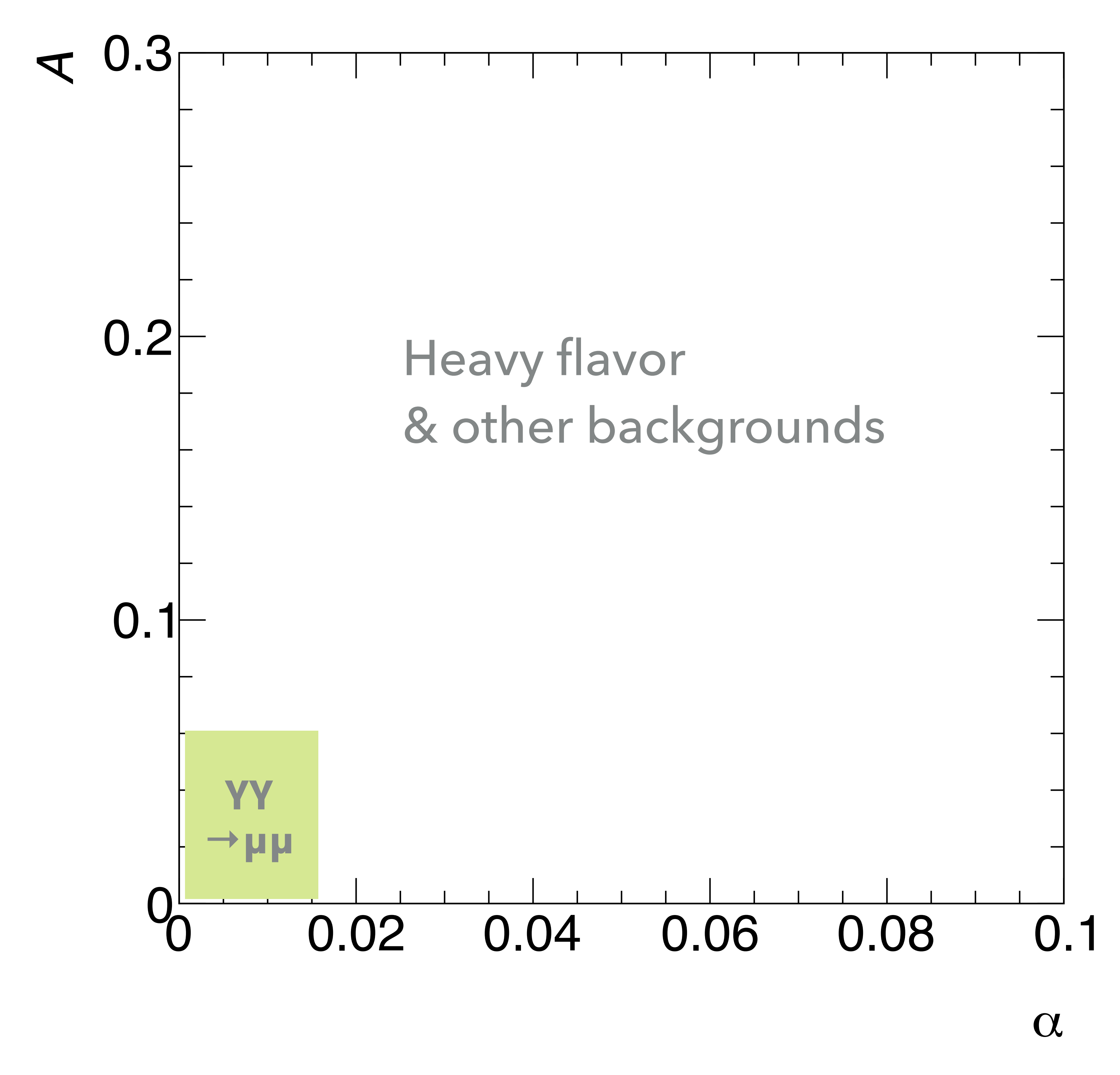
$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

- Asymmetry: difference in transverse momentum, divided by sum

$$A \equiv \left|\frac{p_T^+ - p_T^-}{p_T^+ + p_T^-}\right|$$

- Combined impact parameter, larger for HF decays

$$d_{0\,\mathrm{pair}} \equiv d_0^+ \oplus d_0^-$$



Decompose measured spectra for A and α to isolate contribution from signal μμ

Heavy flavor dimuons have a clear signature of larger impact parameters

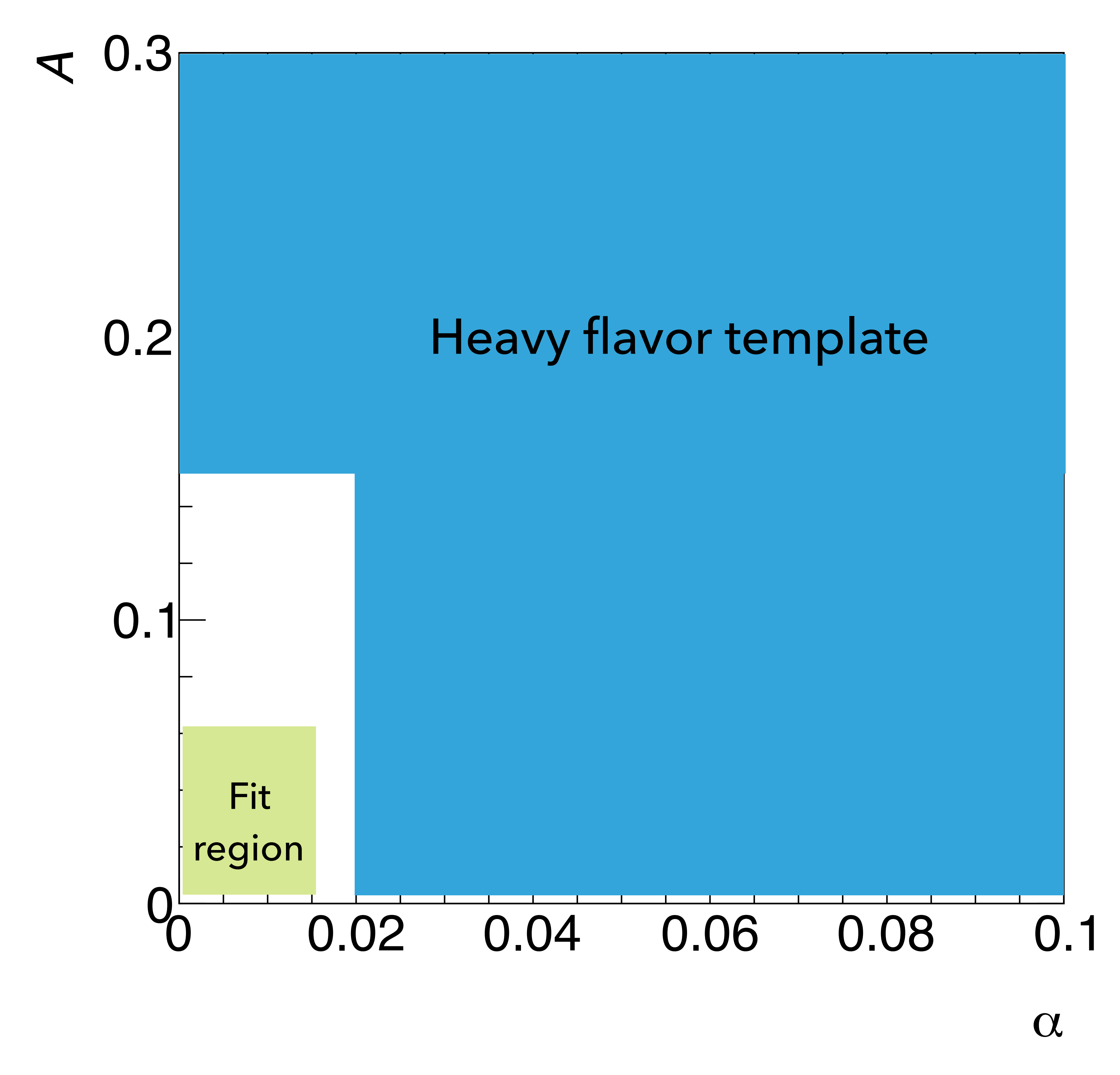
BACKGROUND FRACTION FROM TEMPLATES

ATLAS-HION-2018-11

For each centrality selection:

- Create HF templates in $d_{0,\text{pair}}$, by selecting α>0.02 & A>0.15
  - *Use PYTHIA8 template for centralities with low statistics*
- Signal template by fully simulated STARLIGHT 1.1
- Fit to form:

$$\mathcal{F}(d_{0\,\text{pair}}) \equiv f\,\mathcal{S}(d_{0\,\text{pair}}) + (1-f)\mathcal{B}(d_{0\,\text{pair}})$$



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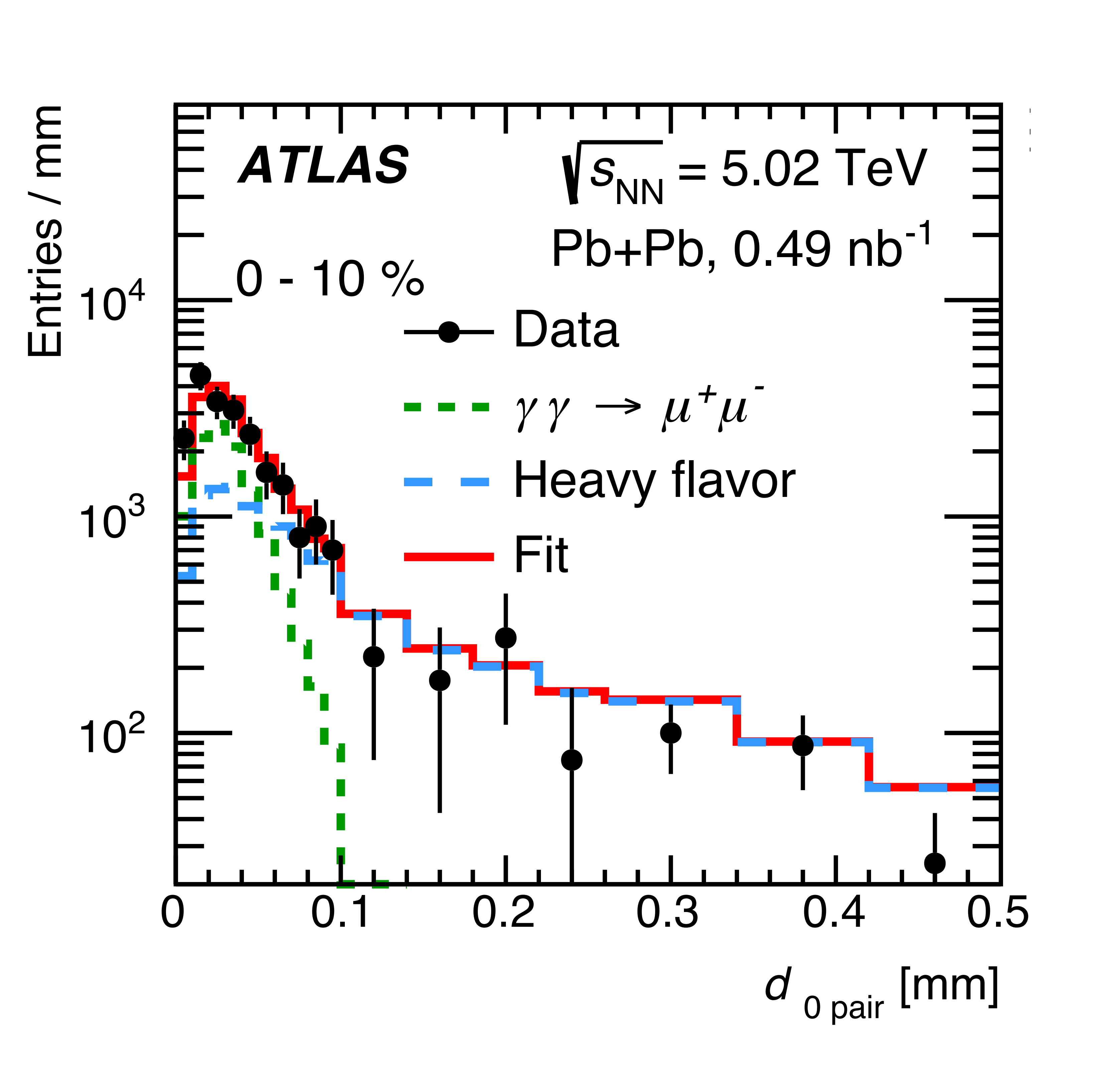


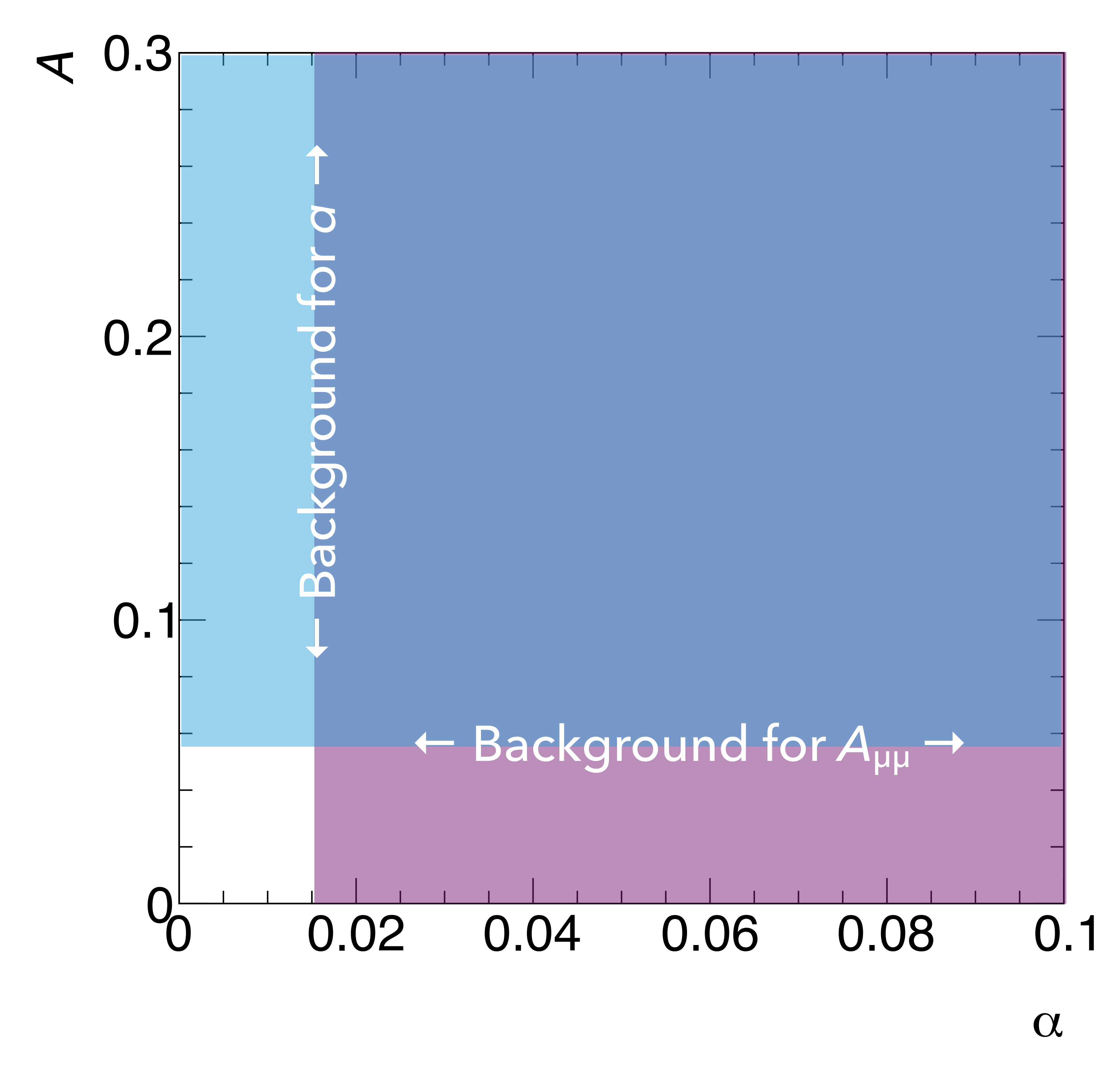
BACKGROUND DISTRIBUTIONS BY CUT INVERSION

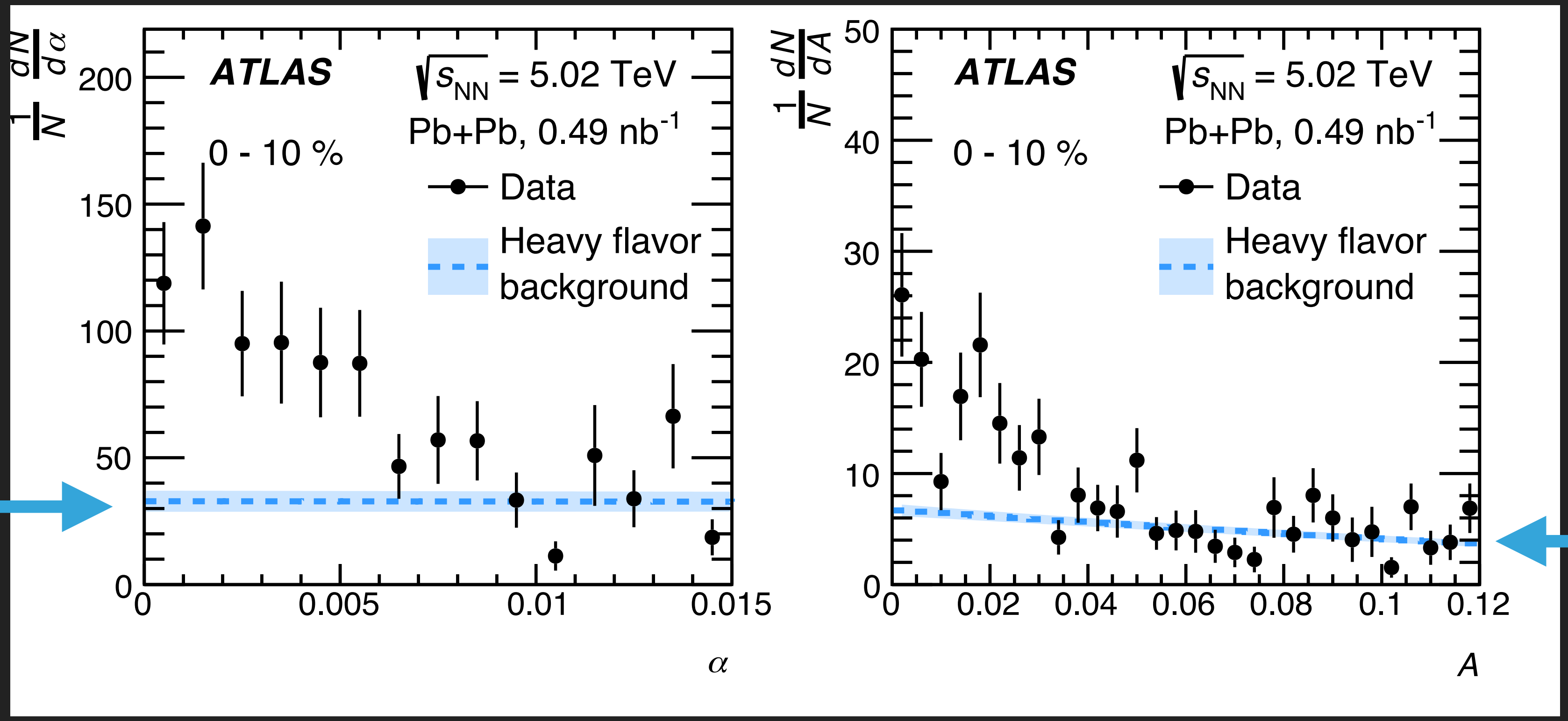
ATLAS-HION-2018-11

For each centrality selection:

- Background for A: $\alpha>0.015$
- Background for α: A>0.06

- Fit to 2nd order polynomial
  - *systematics by const. & linear fits*





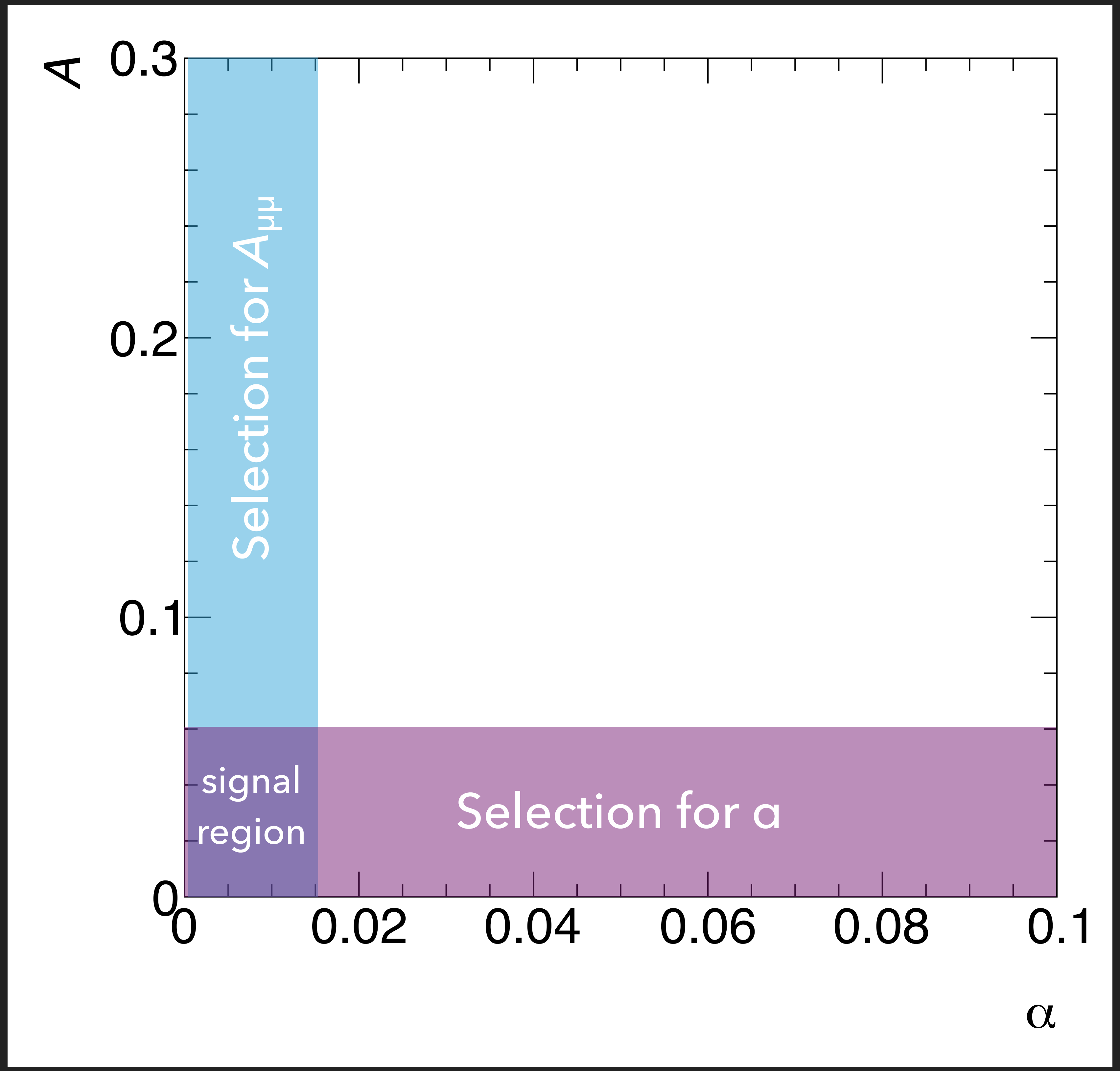
ATLAS EXPERIMENT

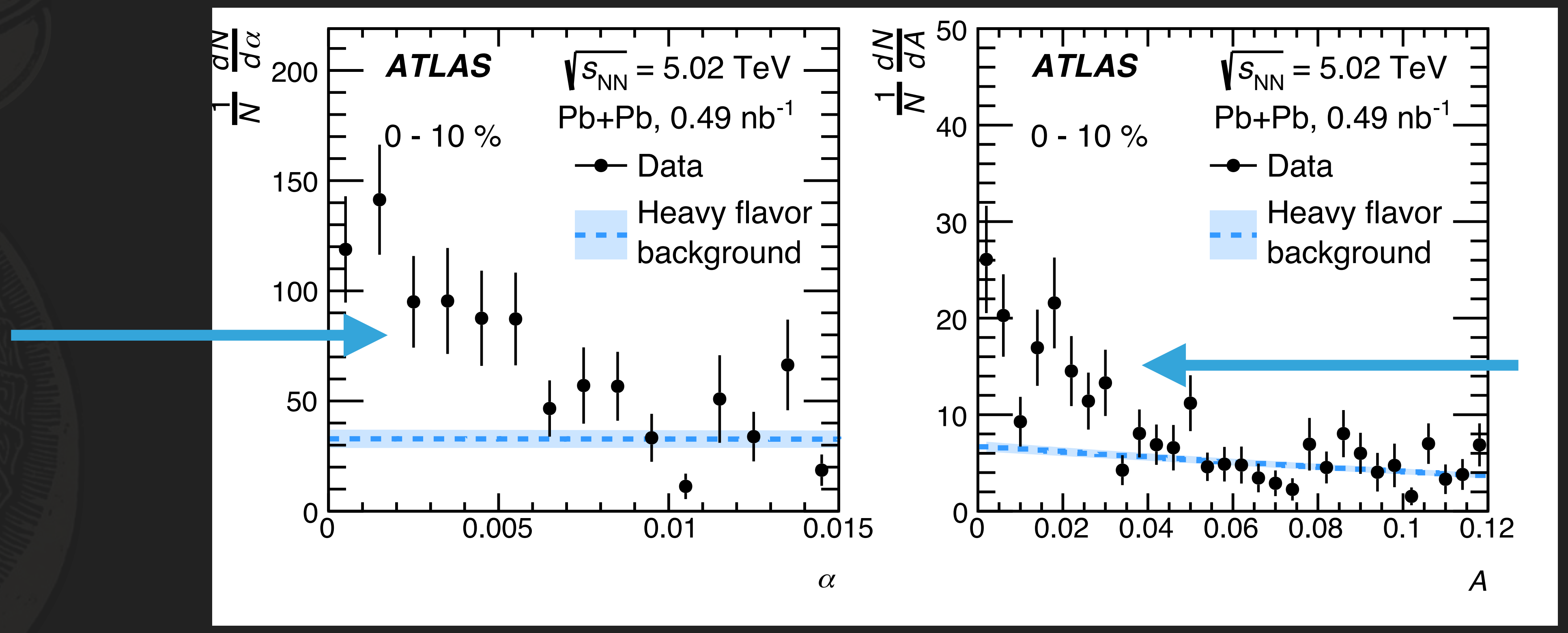
BACKGROUND SUBTRACTION

ATLAS-HION-2018-11

For each centrality selection:

- Now focus on signal region
  - Select $A_{\mu\mu}$<0.06 to study α
  - Select α<0.015 to study A
- Normalize background to signal fraction and subtract





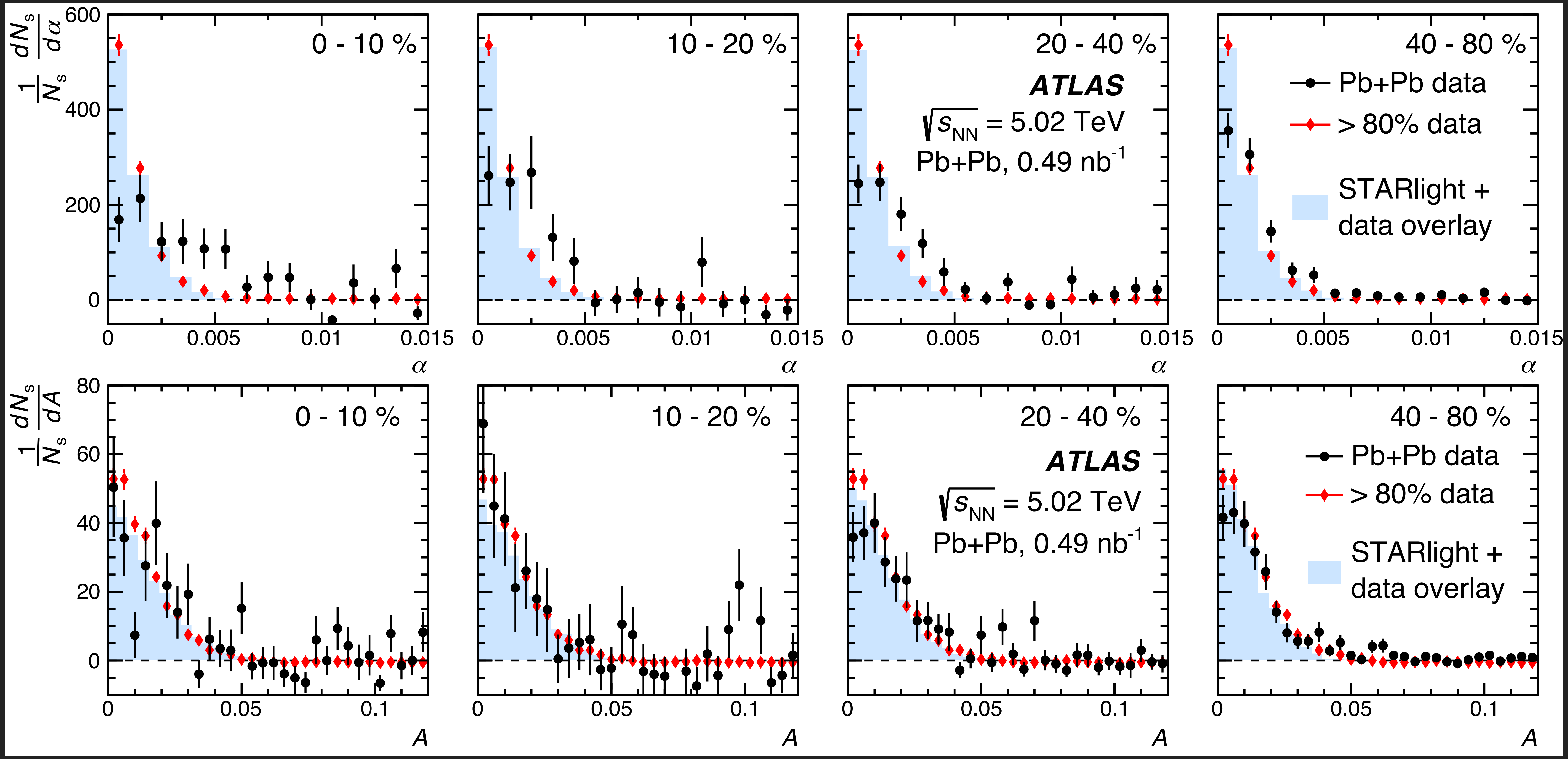
ATLAS EXPERIMENT

CORRECTED SIGNAL DISTRIBUTIONS

ATLAS-HION-2018-11

α

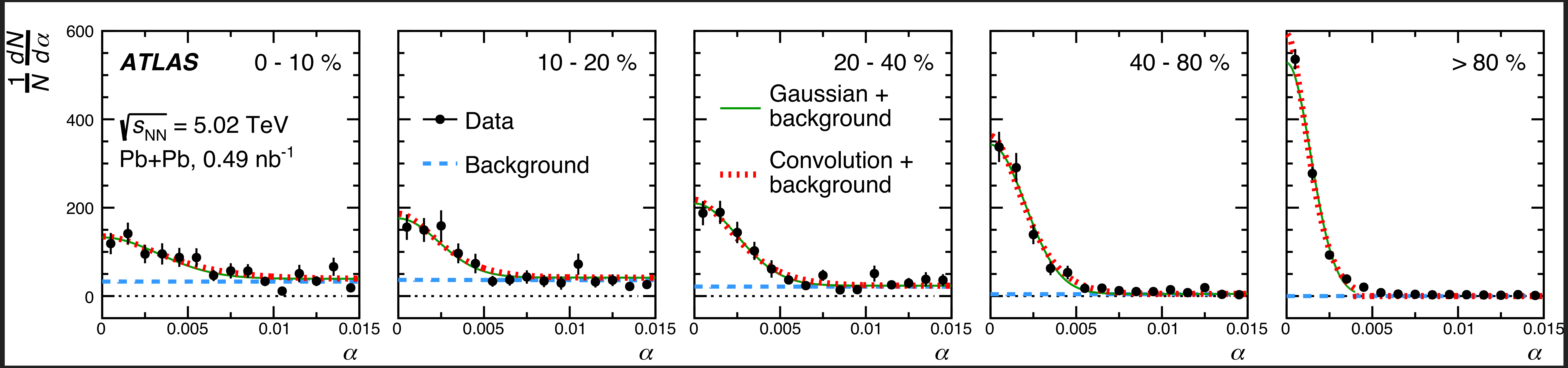
A



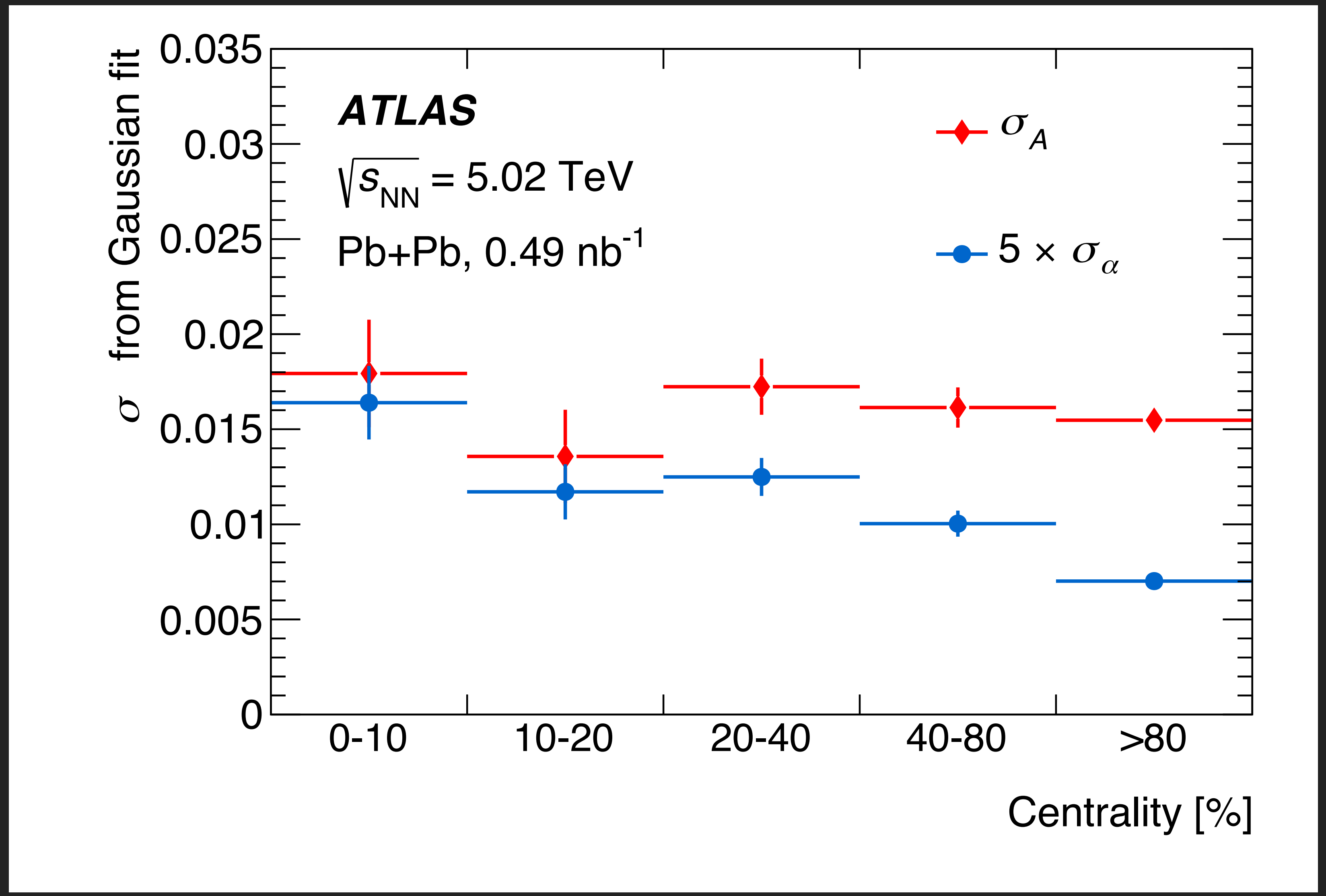
- Simulated STARLIGHT events show no centrality-dep. broadening
- HF-determined backgrounds saturate tails
  - *No obvious contribution from Drell-Yan, ϒ, or dissociative processes*

FITS TO DIMUON ACOPLANARITY

ATLAS-HION-2018-11



- Fit width of signal distributions using Gaussian + background template
  - *Alternate fit convolving over σ(p_T)*
- α width clearly grows with centrality
  - *Asymmetry distributions have limited sensitivity due to momentum resolution*



ATLAS EXPERIMENT

EXTRACTING RMS k_T FROM DIMUON DISTRIBUTIONS

ATLAS-HION-2018-11

- Assume broadening from small transverse momentum imparted to each muon

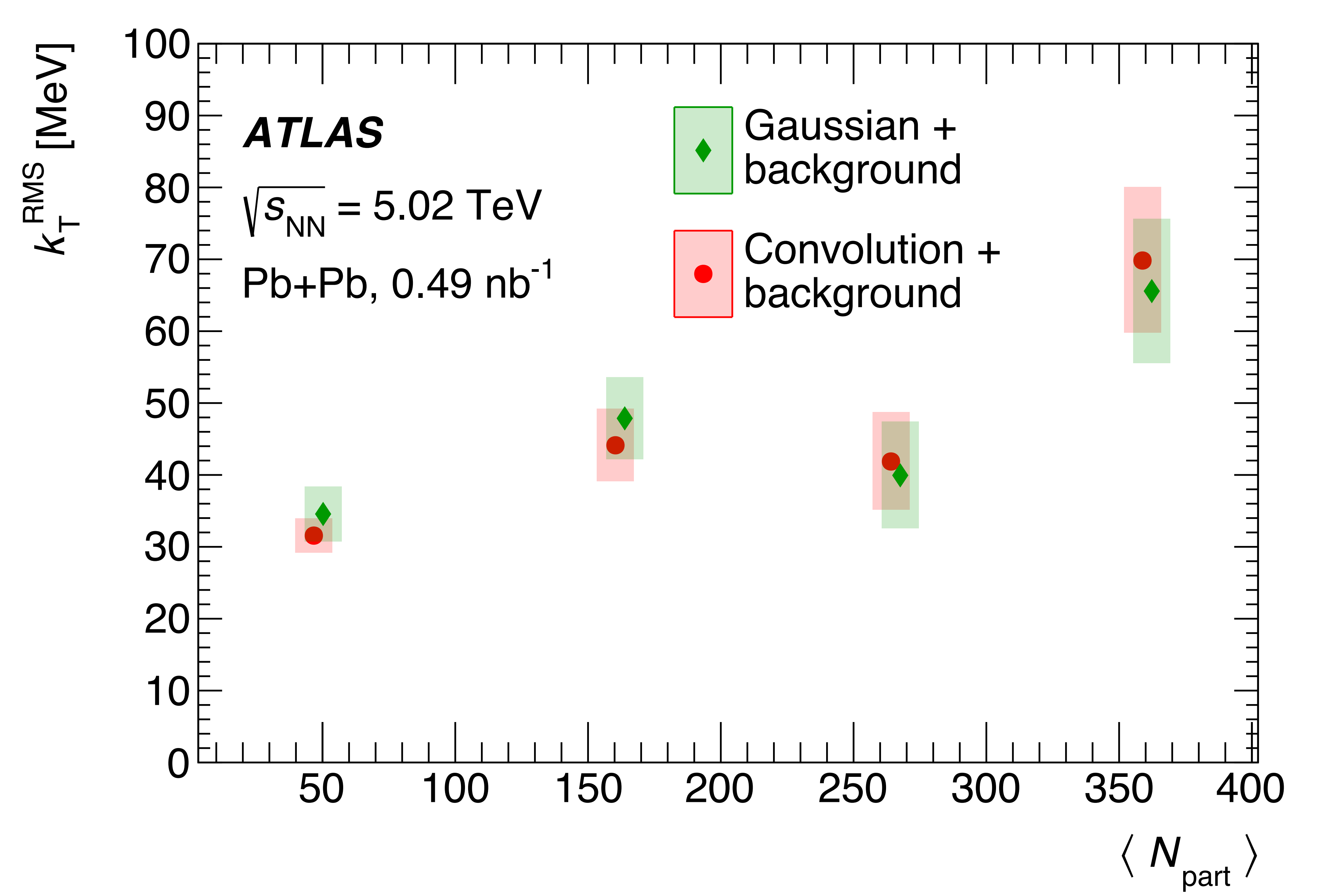
$$\langle\alpha^2\rangle = \langle\alpha^2\rangle_0 + \frac{1}{\pi^2}\frac{\left\langle \vec{k}_{\mathrm{T}}^2 \right\rangle}{\left\langle p_{\mathrm{T\,avg}}^2 \right\rangle}$$

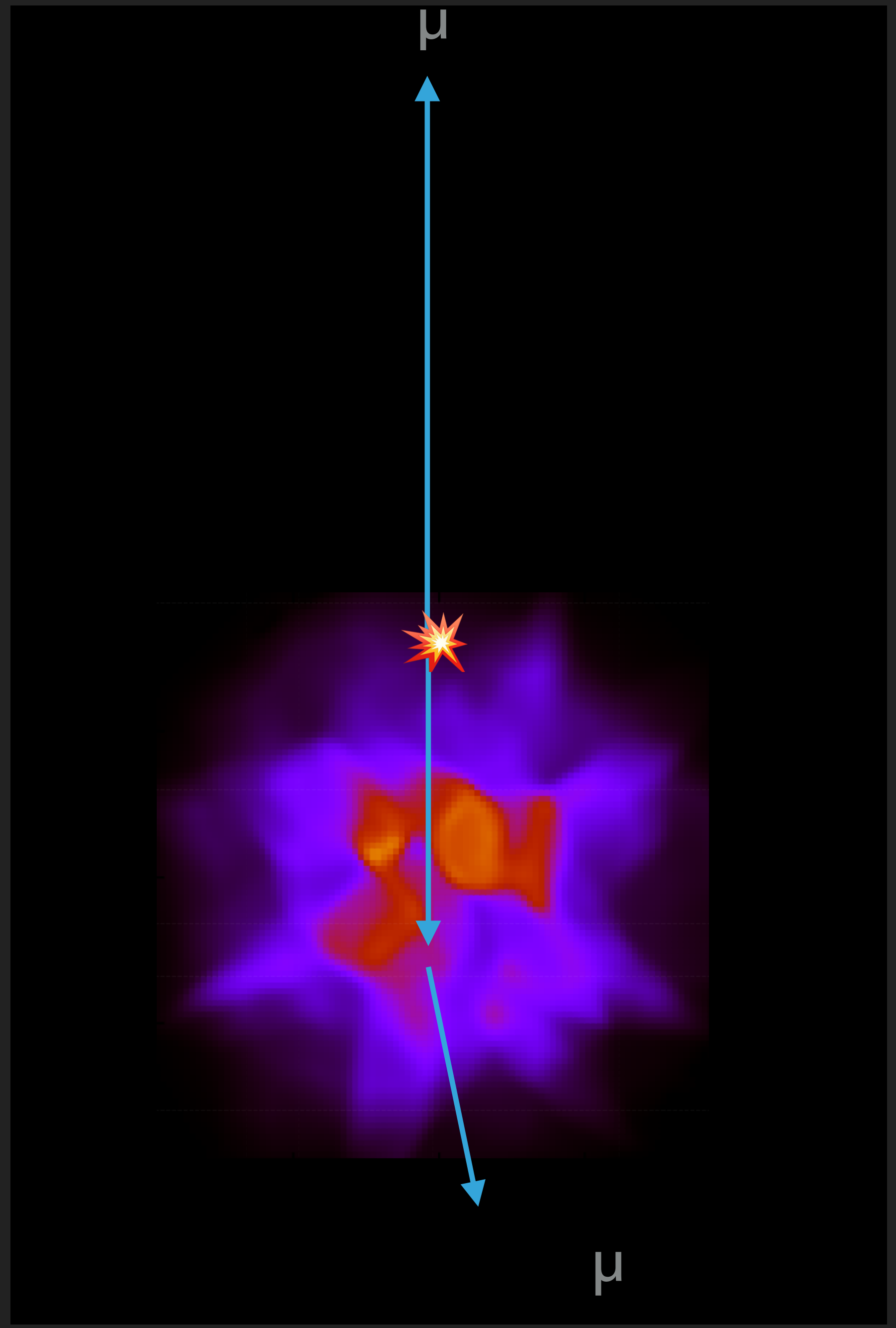
- $\langle k^2_T \rangle$ extracted using
  - *$\langle\alpha^2\rangle$ from centrality-dependent σ*
  - *Nominal variance $\langle\alpha^2\rangle_0$ from fit to >80% centrality (UPC)*
  - *Nominal $p^2_{T,avg}$ from fits to measured distributions*

Centrality [%]	$\langle N_{\mathrm{part}}\rangle$	$p_{\mathrm{T\,avg}}^{\mathrm{RMS}}$ [GeV]	Gaussian fit $\sigma_A(\times 10^2)$	Gaussian fit $\sigma_\alpha(\times 10^3)$	Gaussian fit $k_{\mathrm{T}}^{\mathrm{RMS}}$ [MeV]	Convolution fit $k_{\mathrm{T}}^{\mathrm{RMS}}$ [MeV]
0 – 10	359	7.0 ± 0.1	$1.79^{+0.10}_{-0.09}$	$3.3^{+0.4}_{-0.4}$	64^{+10}_{-10}	70^{+10}_{-10}
10 – 20	264	7.7 ± 0.4	$1.36^{+0.12}_{-0.10}$	$2.3^{+0.3}_{-0.3}$	38^{+7}_{-7}	42^{+7}_{-7}
20 – 40	160	7.4 ± 0.3	$1.72^{+0.04}_{-0.04}$	$2.5^{+0.2}_{-0.2}$	46^{+6}_{-6}	44^{+5}_{-5}
40 – 80	47	6.8 ± 0.3	$1.61^{+0.01}_{-0.01}$	$2.0^{+0.1}_{-0.1}$	31^{+4}_{-4}	32^{+2}_{-2}
> 80	-	7.0 ± 0.3	$1.55^{+0.01}_{-0.01}$	$1.54^{+0.02}_{-0.02}$	-	-

FITS TO EXTRACT RMS k_T

ATLAS-HION-2018-11

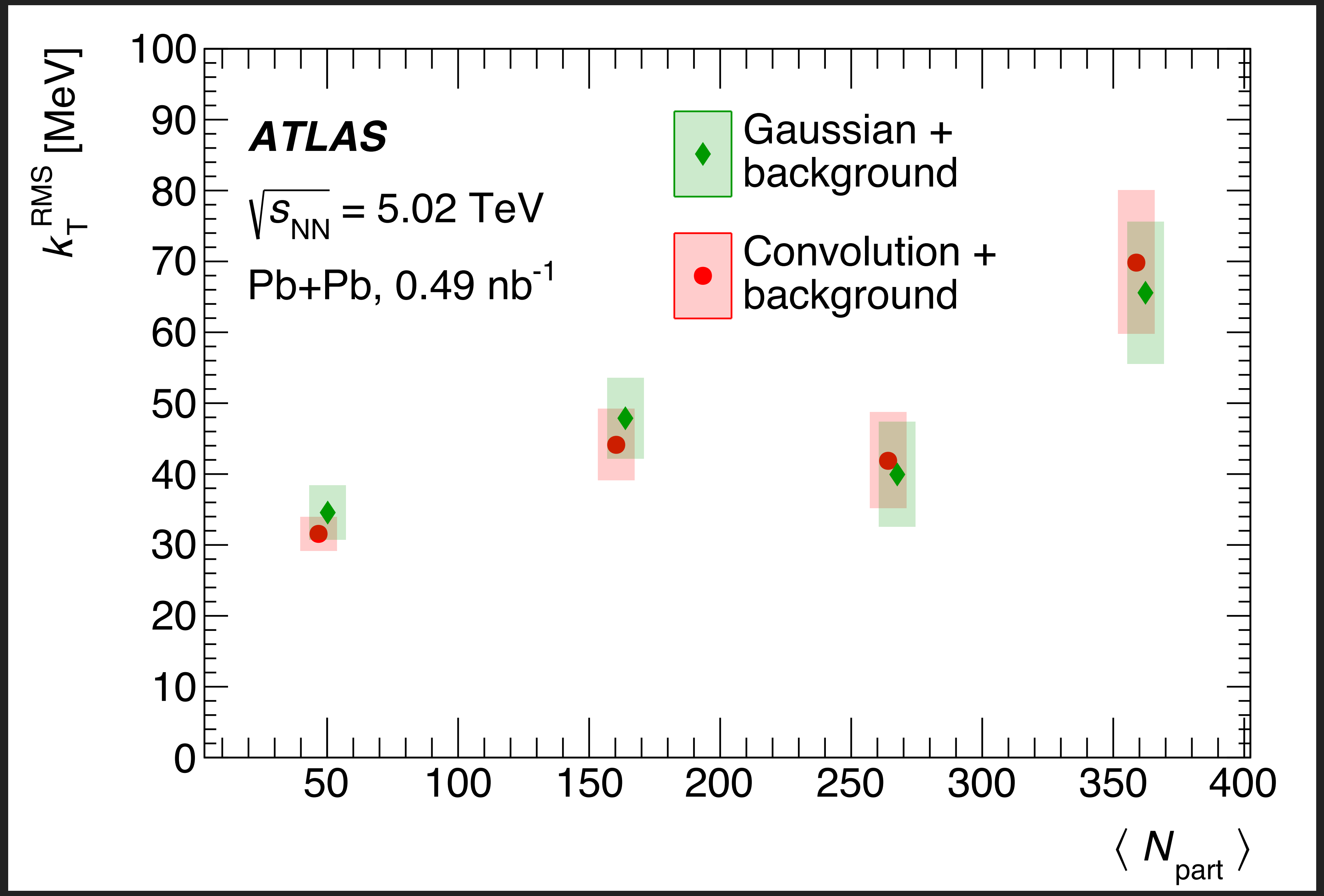


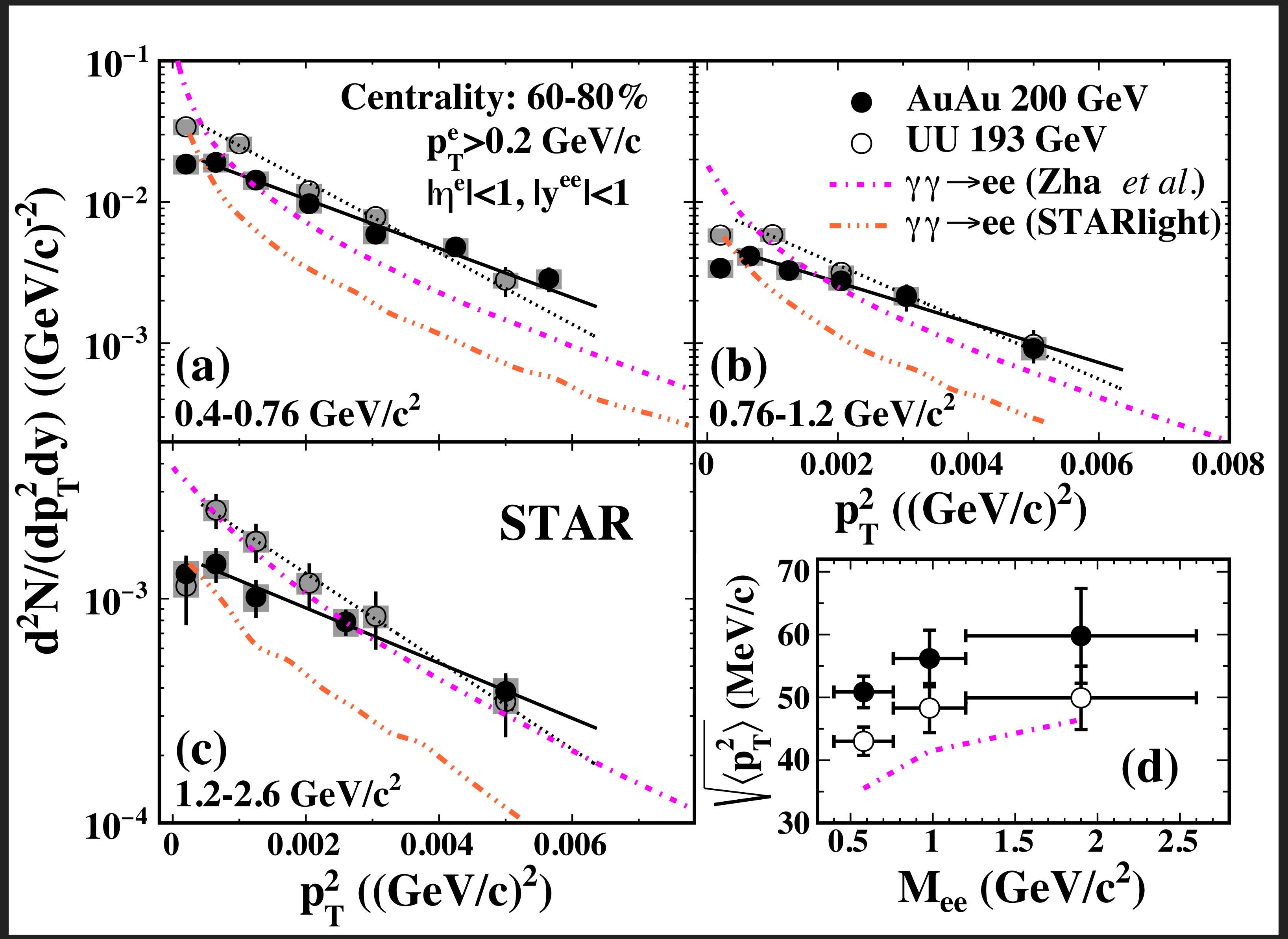


- Additional per-muon RMS k_T beyond that found for >80% centrality (UPC)
- Small in absolute terms, but grows systematically with centrality up <k_T> ~ 70 MeV
- Specific "tomographic" interpretation could be modified by other mechanisms for influencing muons in the context of a heavy ion collision (e.g. strong EM fields)

NON-UPC DILEPTONS AT LHC AND RHIC

STAR, arxiv:1806.02295,
Phys. Rev. Lett. 121, 132301 (2018)

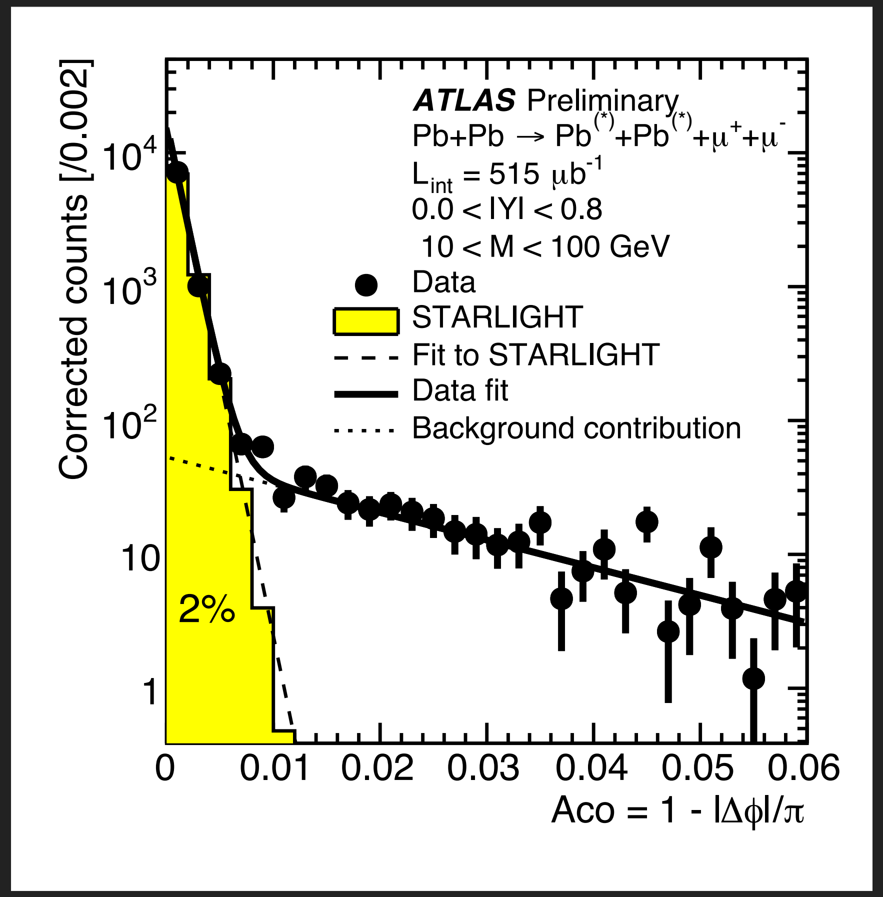




- ATLAS data compares non-UPC data to >80% (UPC)
- STAR compares 60-80% central to EPA-based calculations
  - Similar spectral shape from both models
  - Data sees larger RMS(p_T) than models
- Some p_T broadening seems to be a generic feature
  - STAR postulates it might be residual B field from initial state

CONCLUSIONS

- EM-induced processes in Pb+Pb collisions in ATLAS teaches us about :



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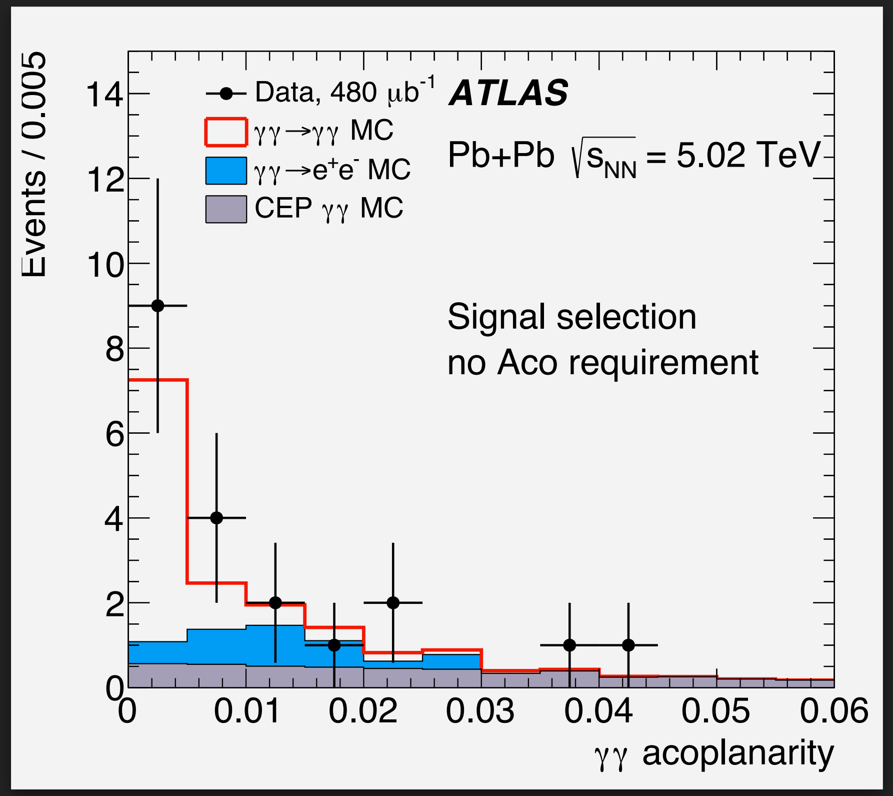

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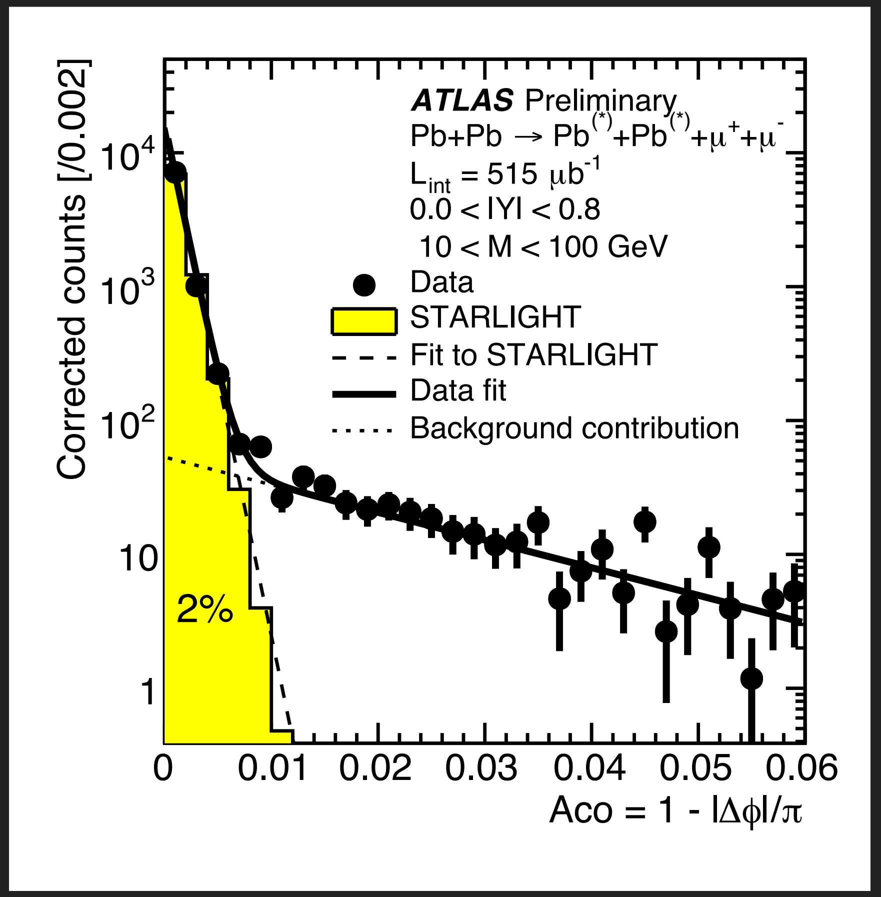

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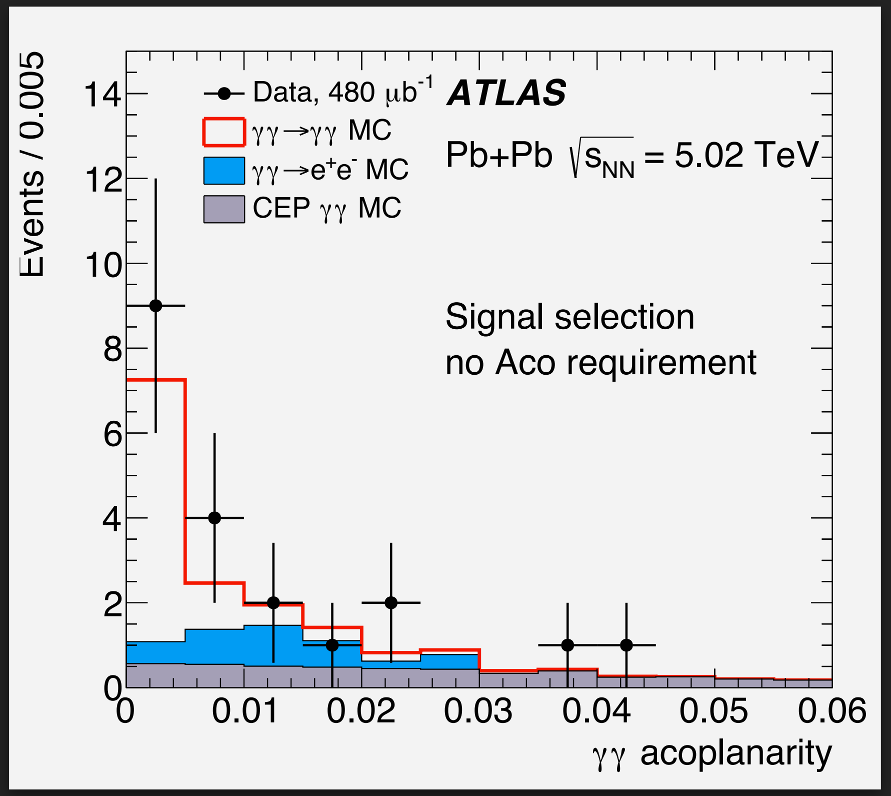

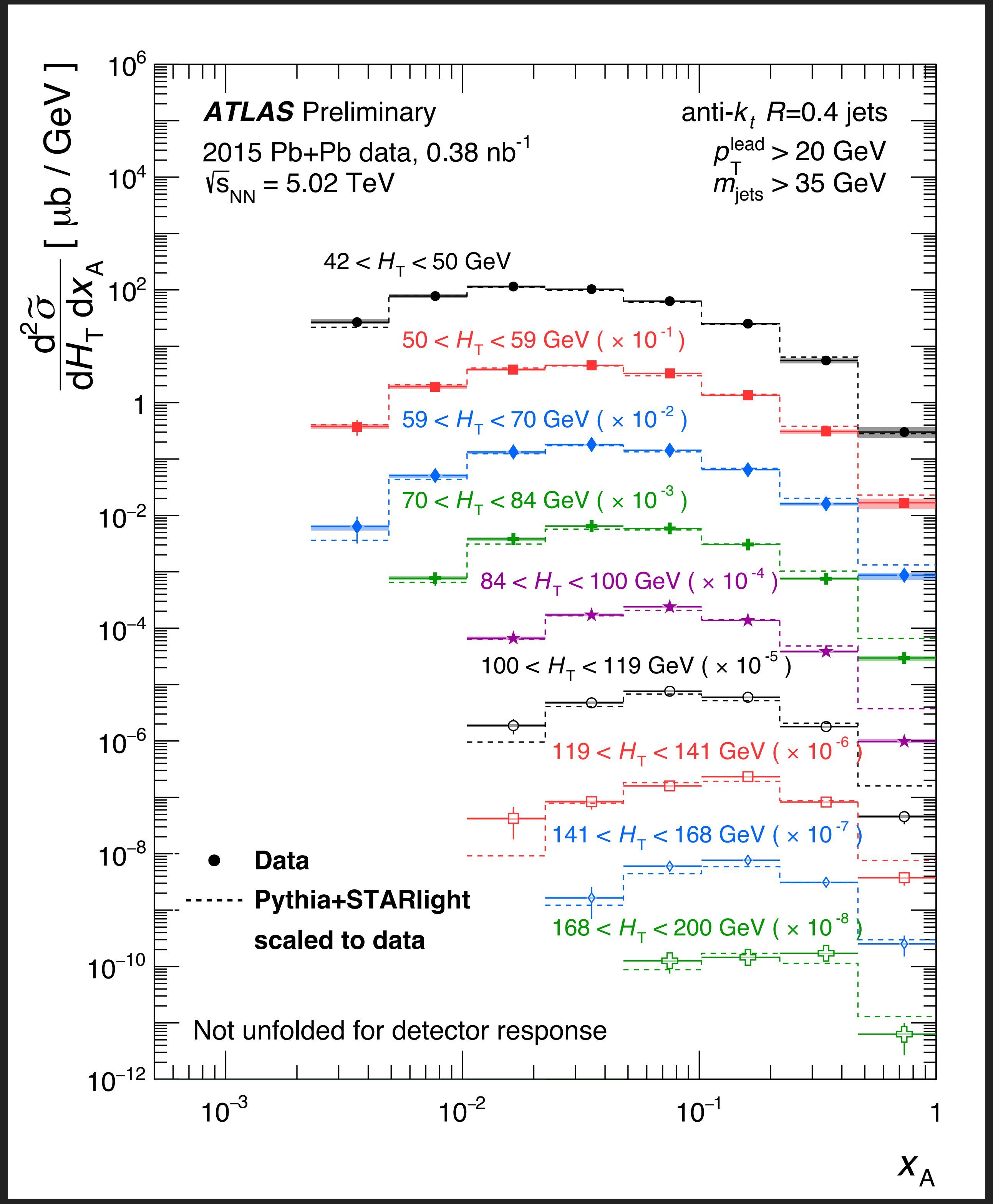

QCD

CONCLUSIONS

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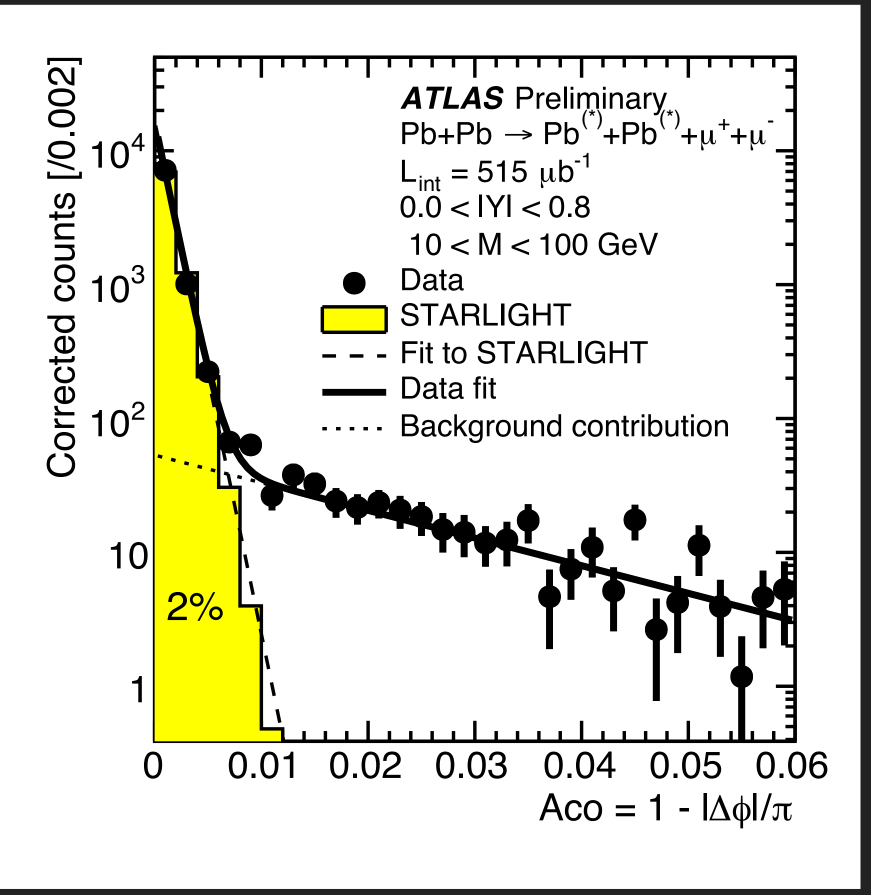

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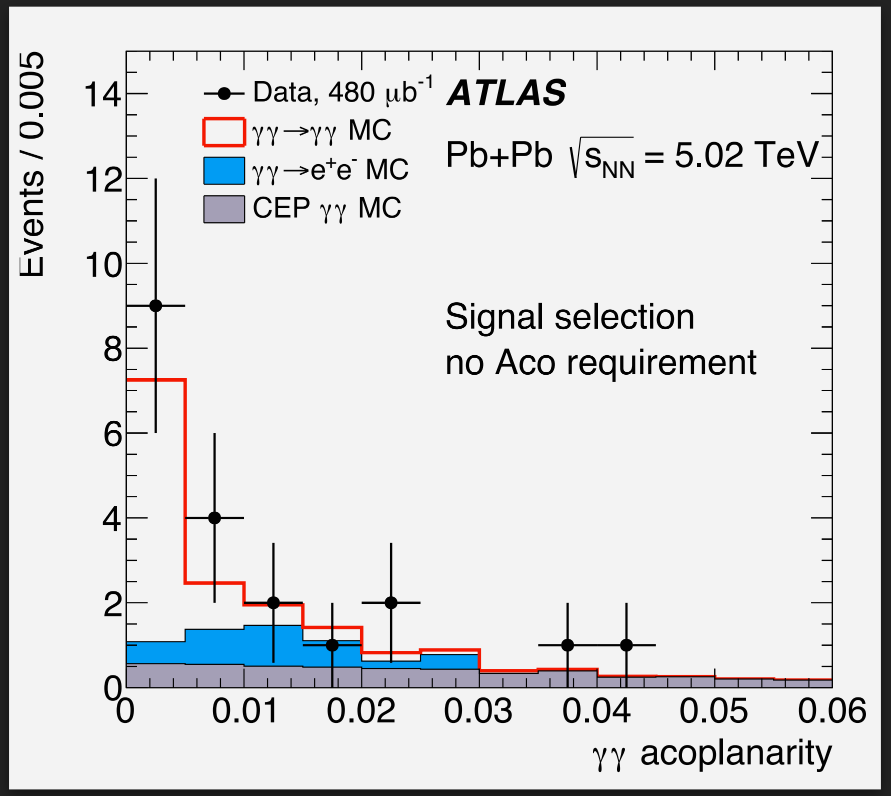

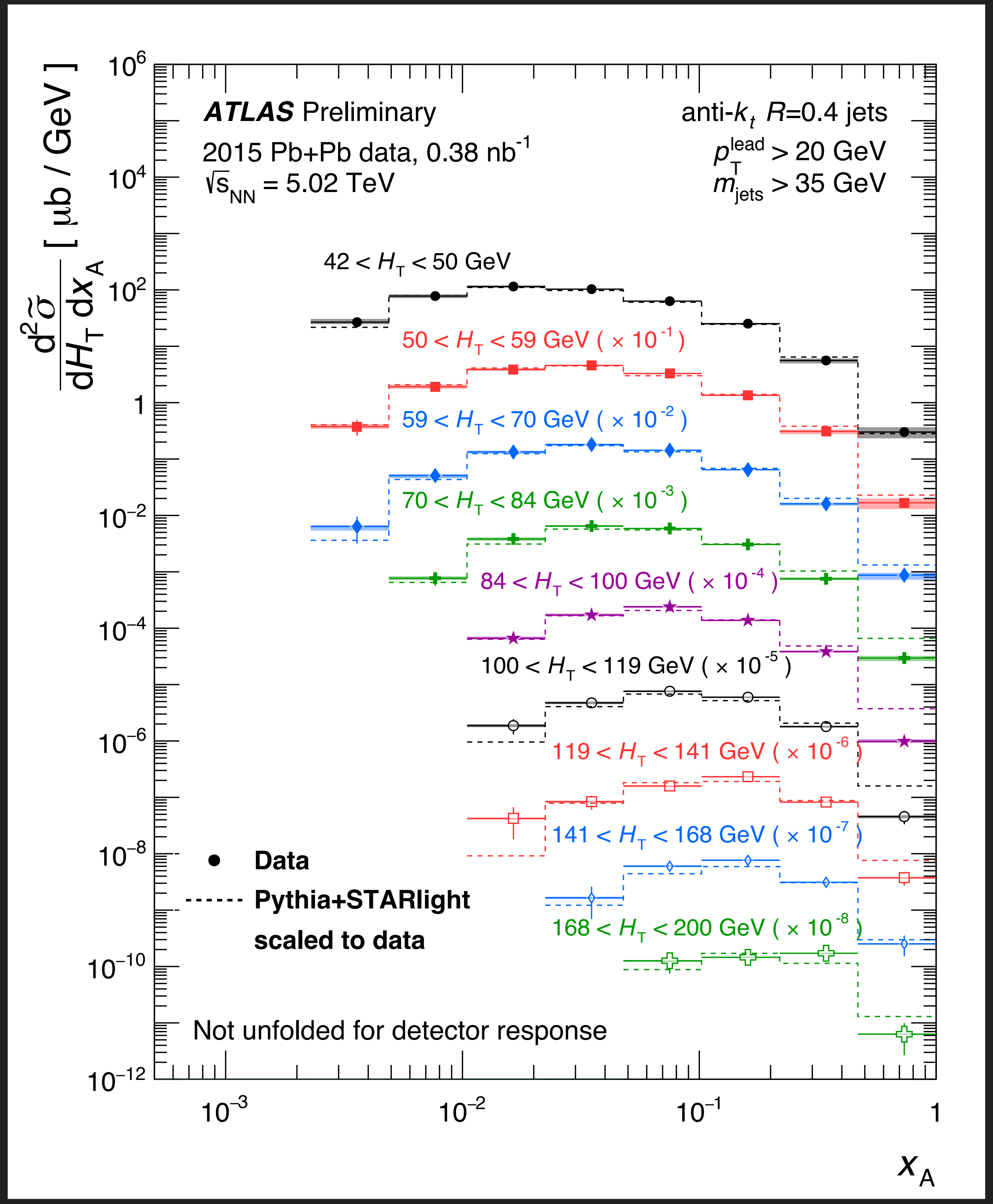

QCD

QGP?