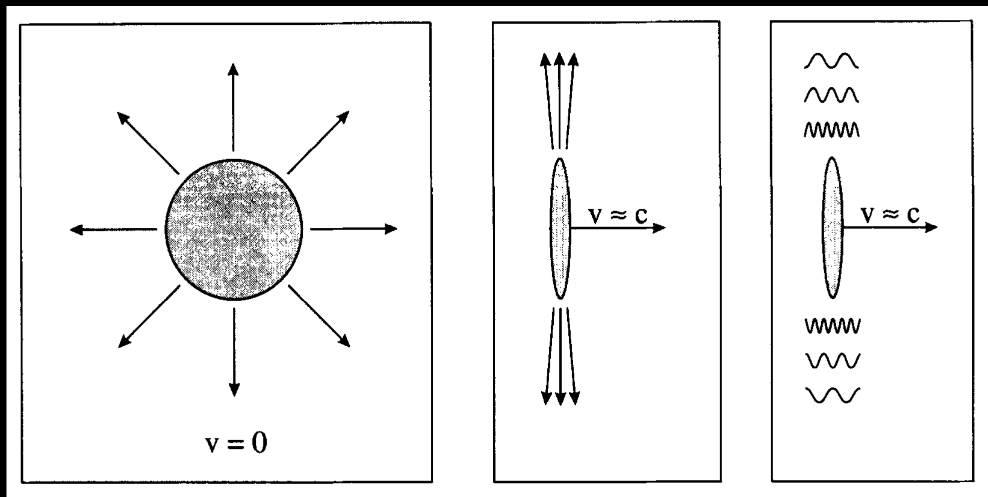
ELECTROMAGNETIC PROCESSES IN ULTRA-PERIPHERAL PB+PB COLLISIONS WITH ATLAS

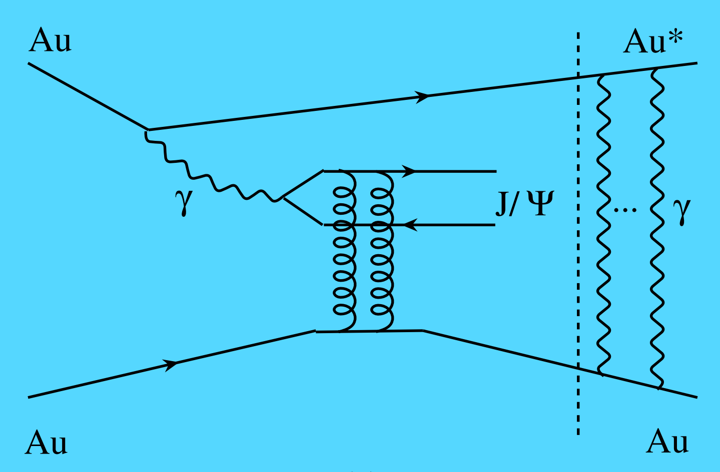
PETER STEINBERG, BNL
FOR THE ***ATLAS*** EXPERIMENT
20 SEPTEMBER 2017
INITIAL STAGES 2017, KRAKOW

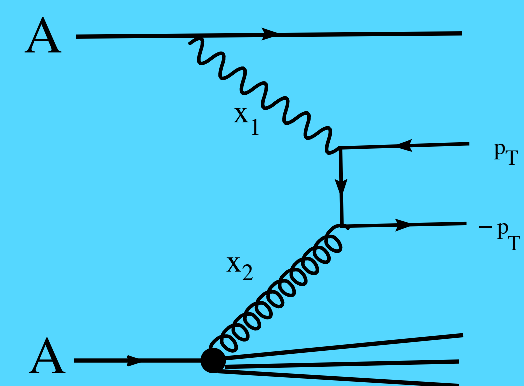
ATLAS UPC PROGRAM

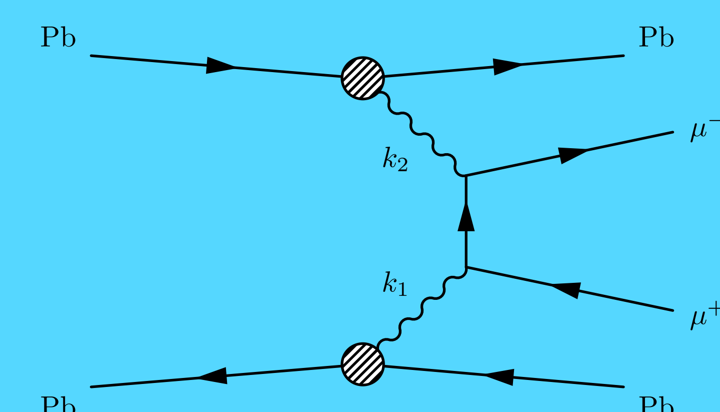


- Boosted nuclei are intense source of quasi-real photons
  - Typically treated using EPA (Weiszacker-Williams)
  - Quantize classical field
- Photons with $E \lesssim (\hbar c/R)\gamma$ are produced coherently (Z^2)
  - Up to ~80 GeV for Pb+Pb @ 5.02 TeV, 1.4 TeV for p+p!

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







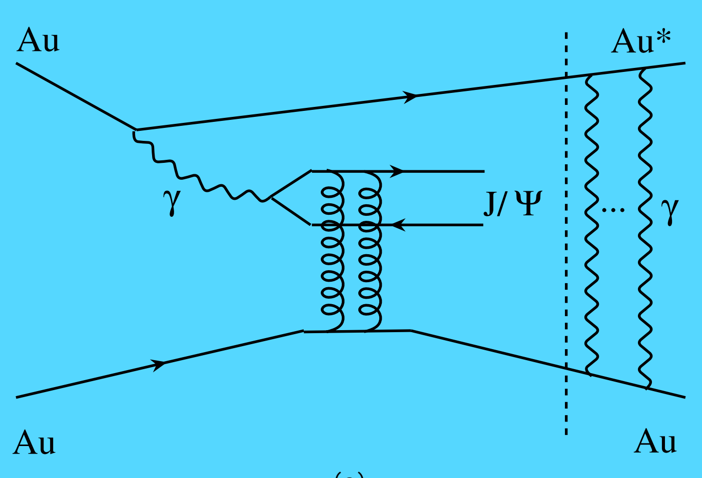
***Photon-pomeron**: production of vector mesons (sensitivity to nPDF)*

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

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

ATLAS UPC PROGRAM

- Exclusive dimuon production (ATLAS-CONF-2016-025)
    - *Calibrate photon fluxes and elementary QED*
- Exclusive diphoton production ("light-by-light scattering")
    - *Benchmark QED measurement* **Nature Phys. 13 (2017) no.9, 852-858**
- Photonuclear dijet production (ATLAS-CONF-2017-011)
    - *<u>Direct</u> study of nPDFs using EM processes*
    - *Early access to EIC physics*



Photon-pomeron:
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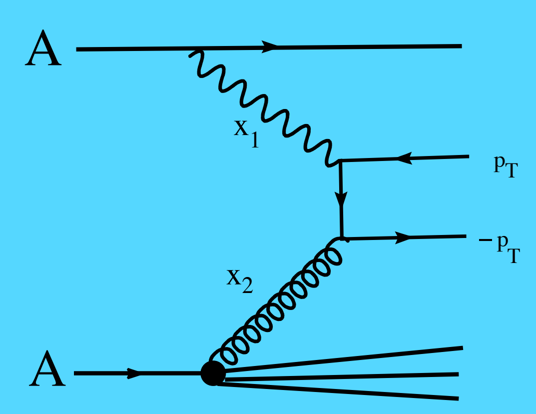

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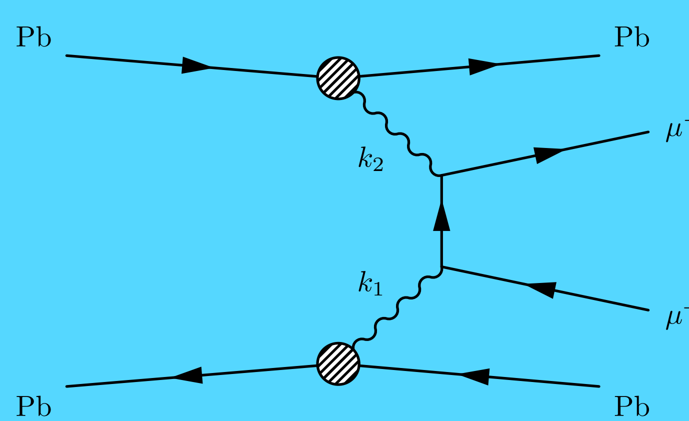

Photon-photon:
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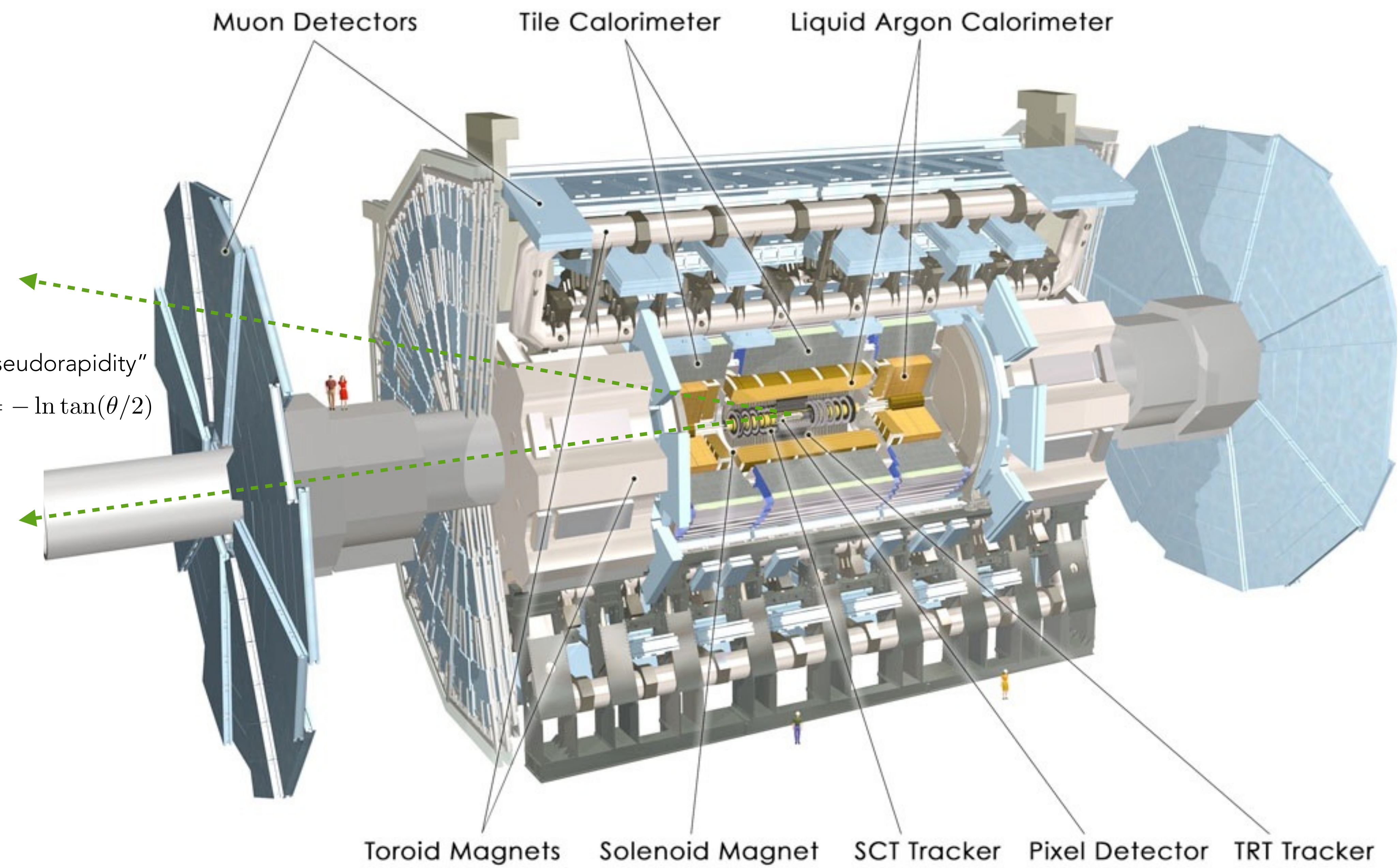
(& other exclusive states)

ATLAS DETECTOR @ THE LHC

“pseudorapidity”

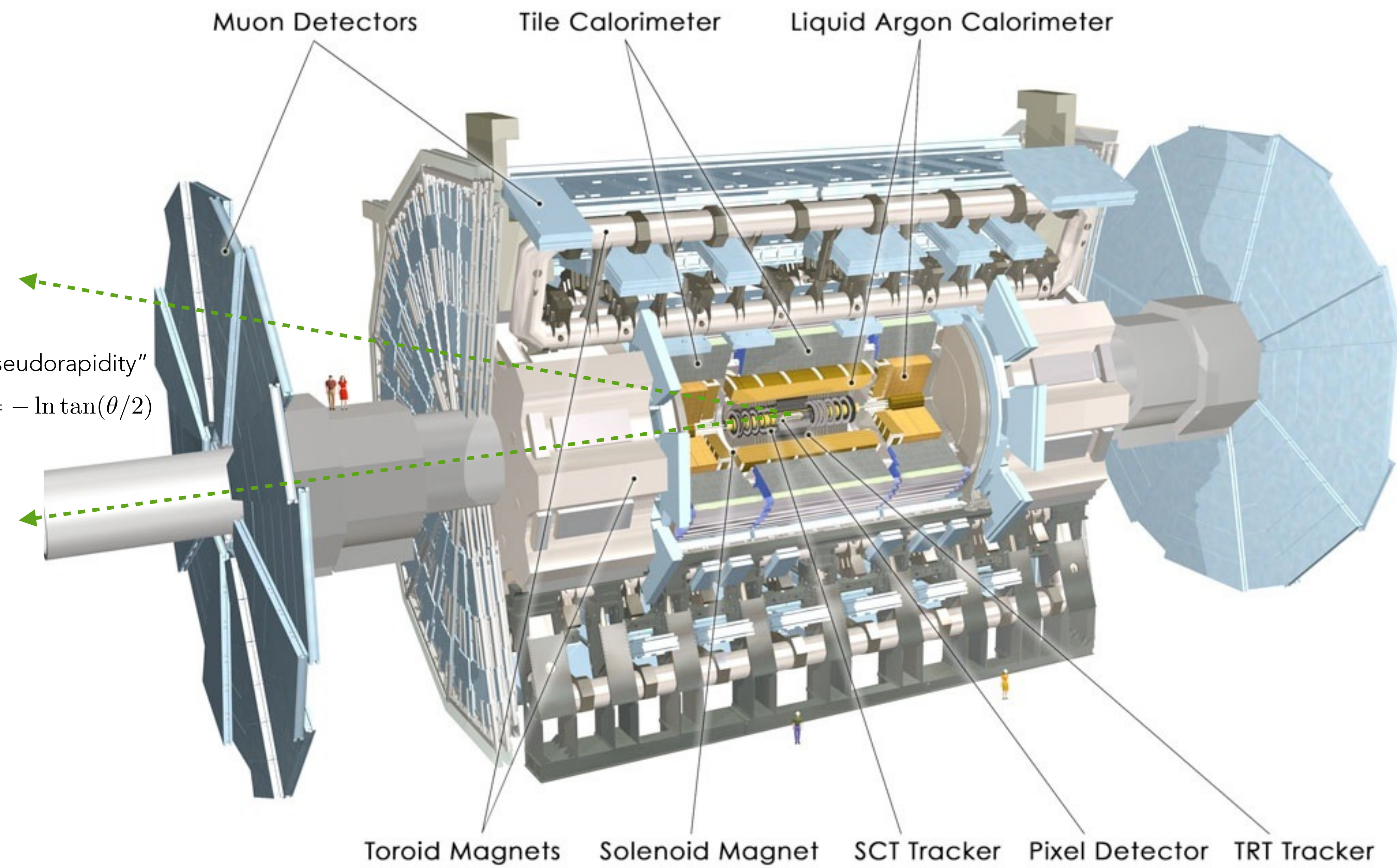
$\eta = -\ln\tan(\theta/2)$



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

ATLAS DETECTOR @ THE LHC

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



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ATLAS DETECTOR @ THE LHC

3. Precise μ tracking in |η|<2.7

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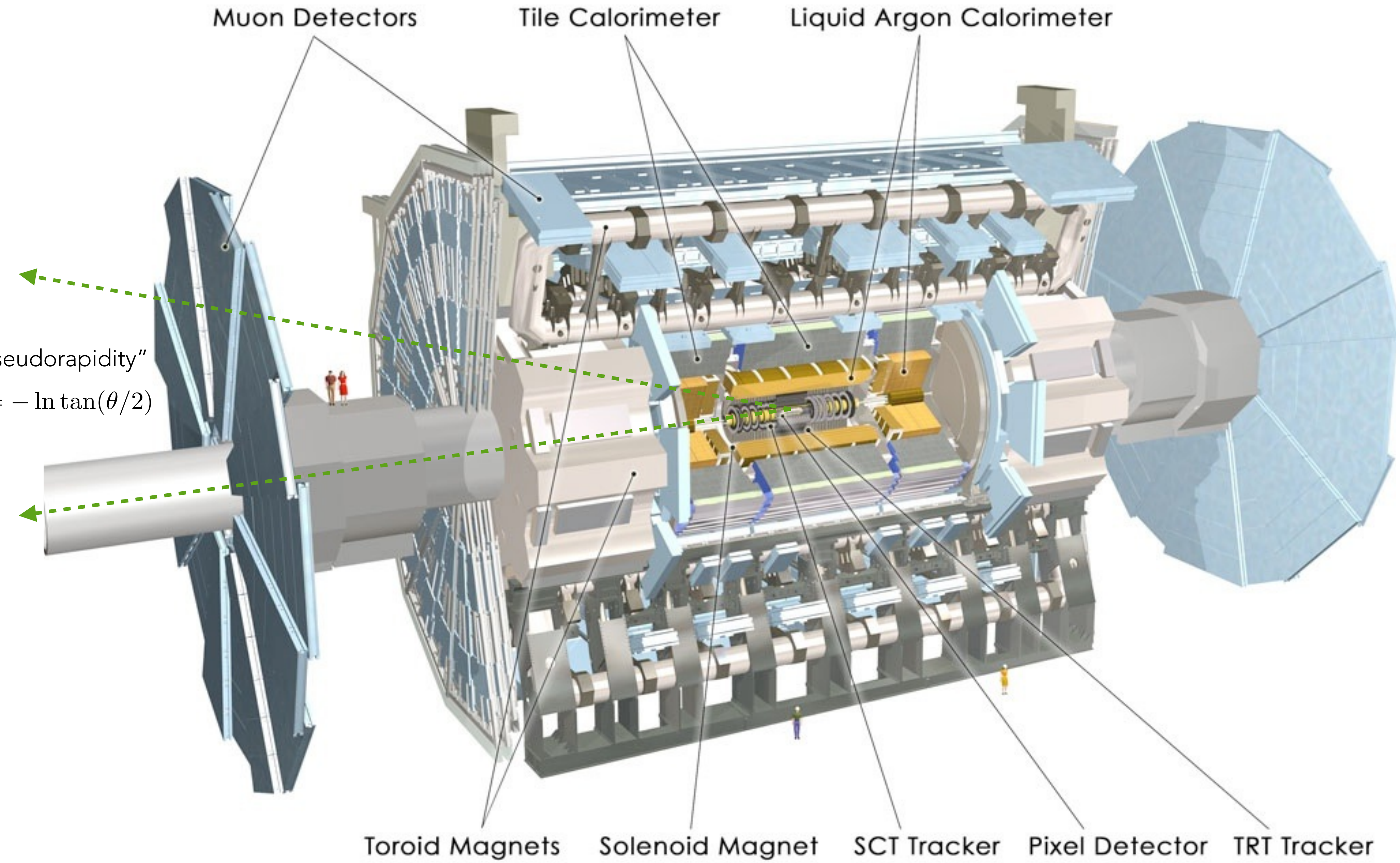

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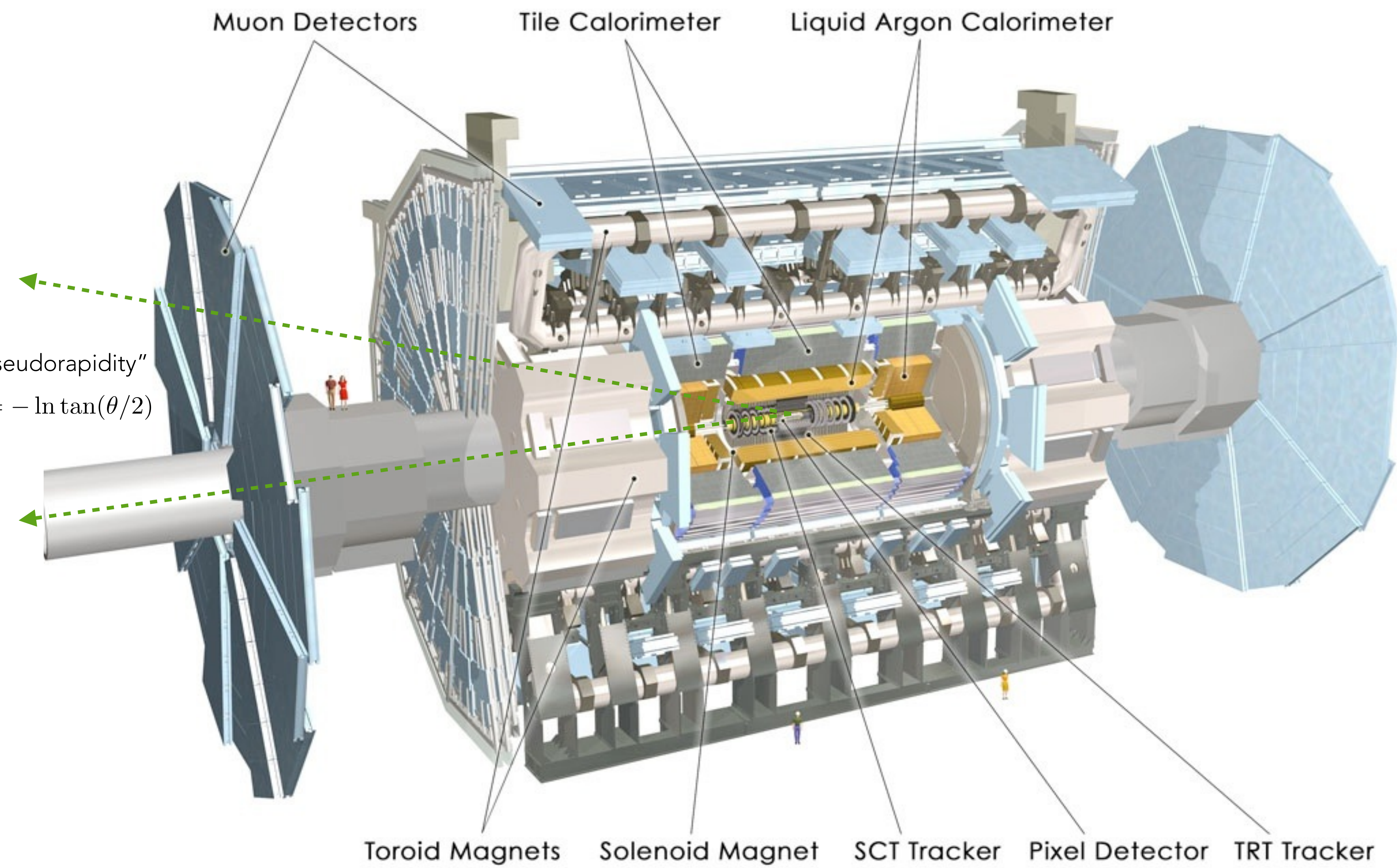


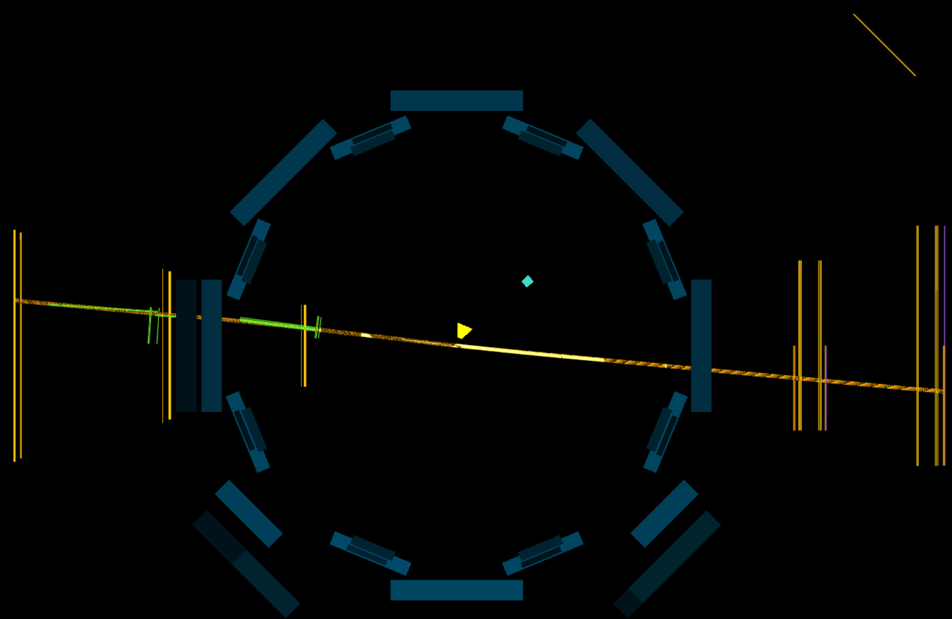
"pseudorapidity"

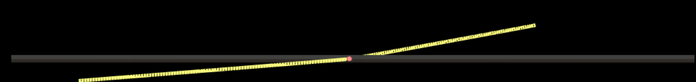
$\eta = -\ln\tan(\theta/2)$

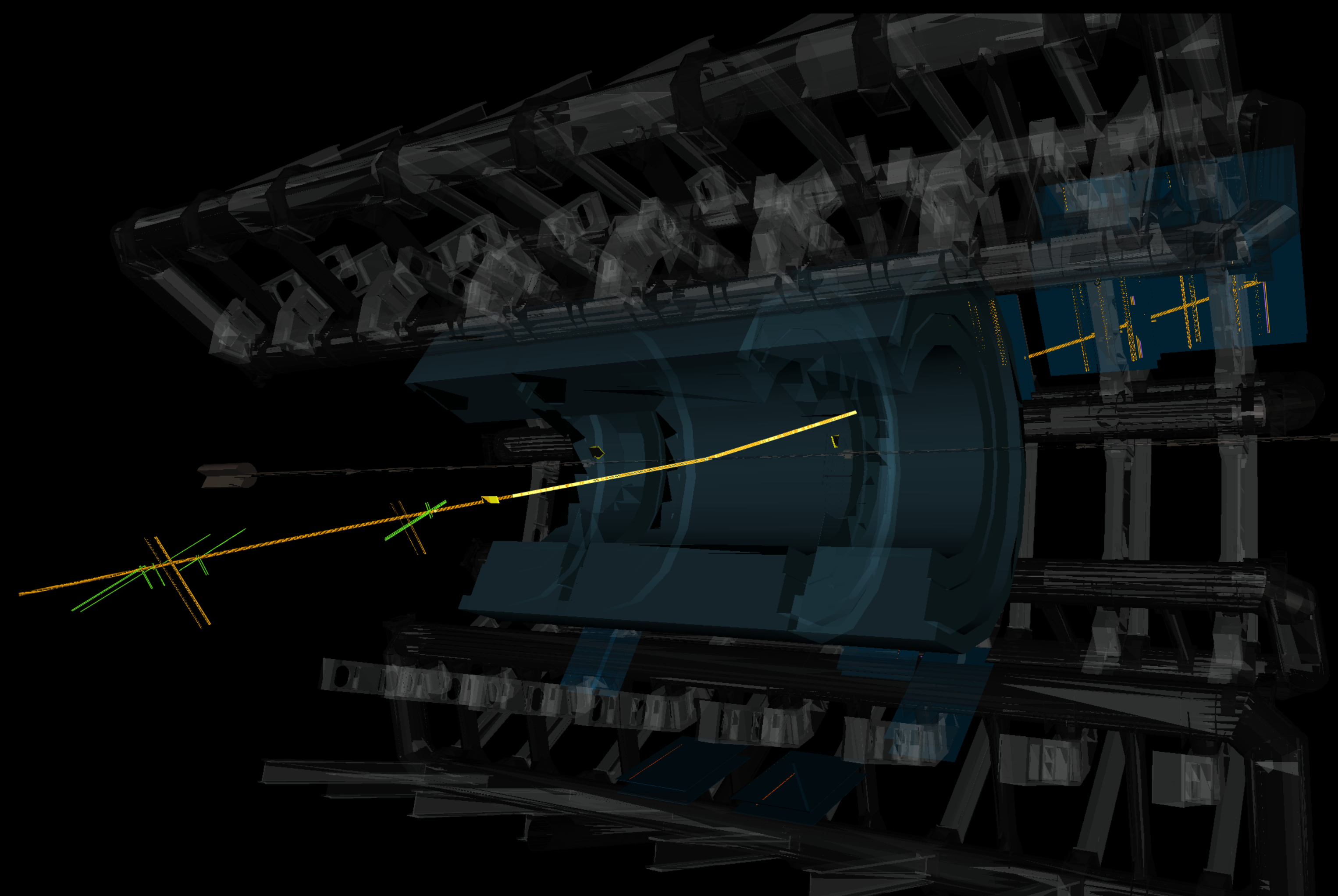
1. Precise charged-particle tracking in |η|<2.5

Exclusive final-states <u>require</u> a fully-hermetic detector!

EXCLUSIVE DIMUON PRODUCTION







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

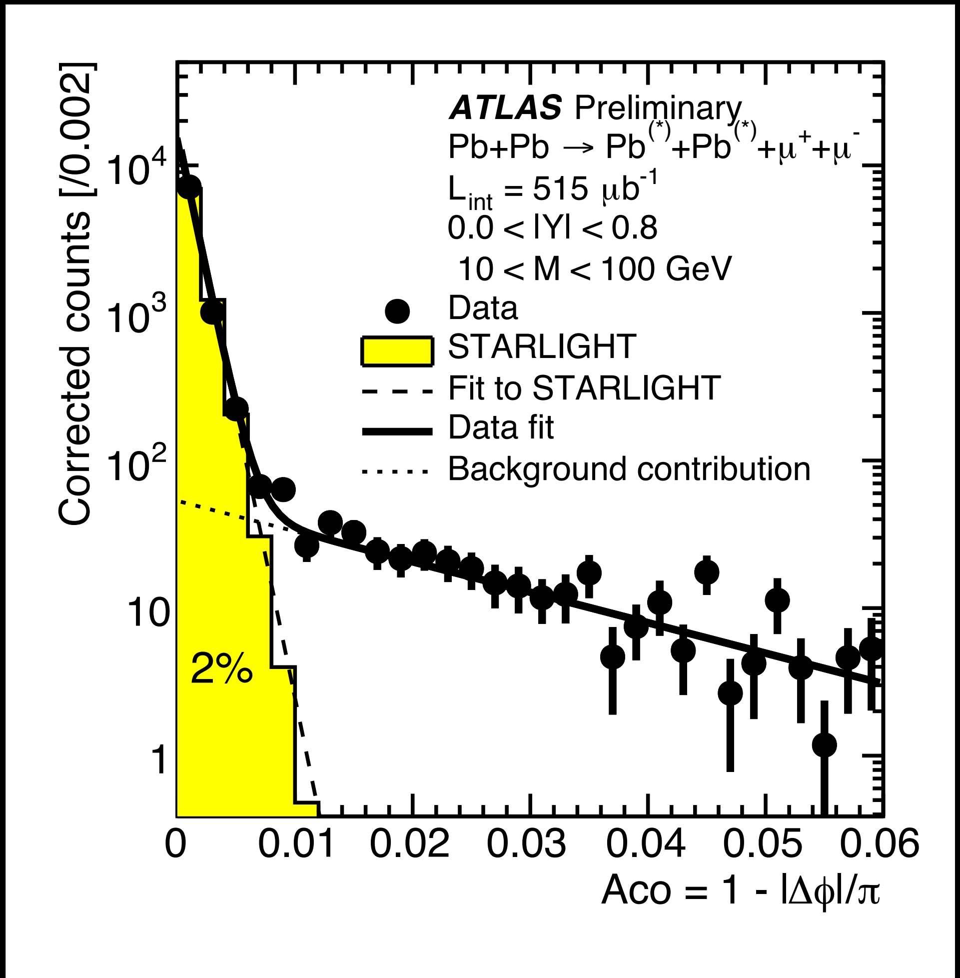
Dimuons UPC Pb+Pb 5.02 TeV

M=173 GeV!

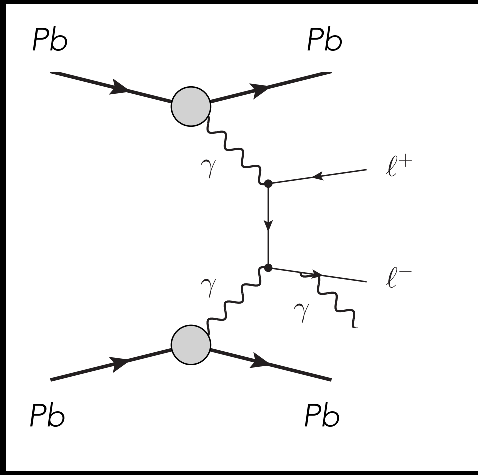
TRIGGER & EVENT SELECTION

ATLAS-CONF-2016-025

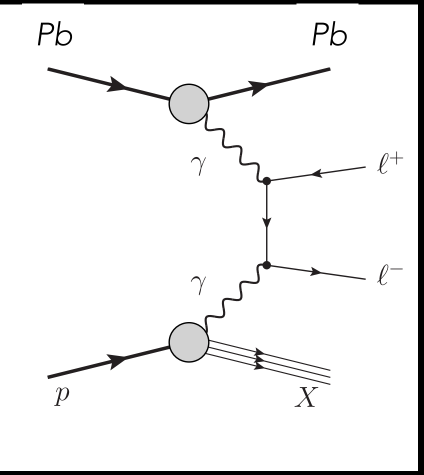
- Trigger selection
  - *Single muon from L1 trigger*
  - *Veto on inner MBTS counters and* $\Sigma E_T < 50$ *GeV*
- Event selection
  - *2 muons, and a 2-track vertex*
- Corrections
  - *μμ trigger and reconstruction efficiency,*
  - *overall vertex efficiency*
- Backgrounds, from acoplanarity (1-|Δϕ|/π) distributions
  - *higher-order QED (irreducible, not in STARLIGHT)*
  - *dissociative processes (can be suppressed using ZDC vetos, not done here)*
- Final systematics bracket assumptions of tail being **all signal** or **all background**.



NLO QED

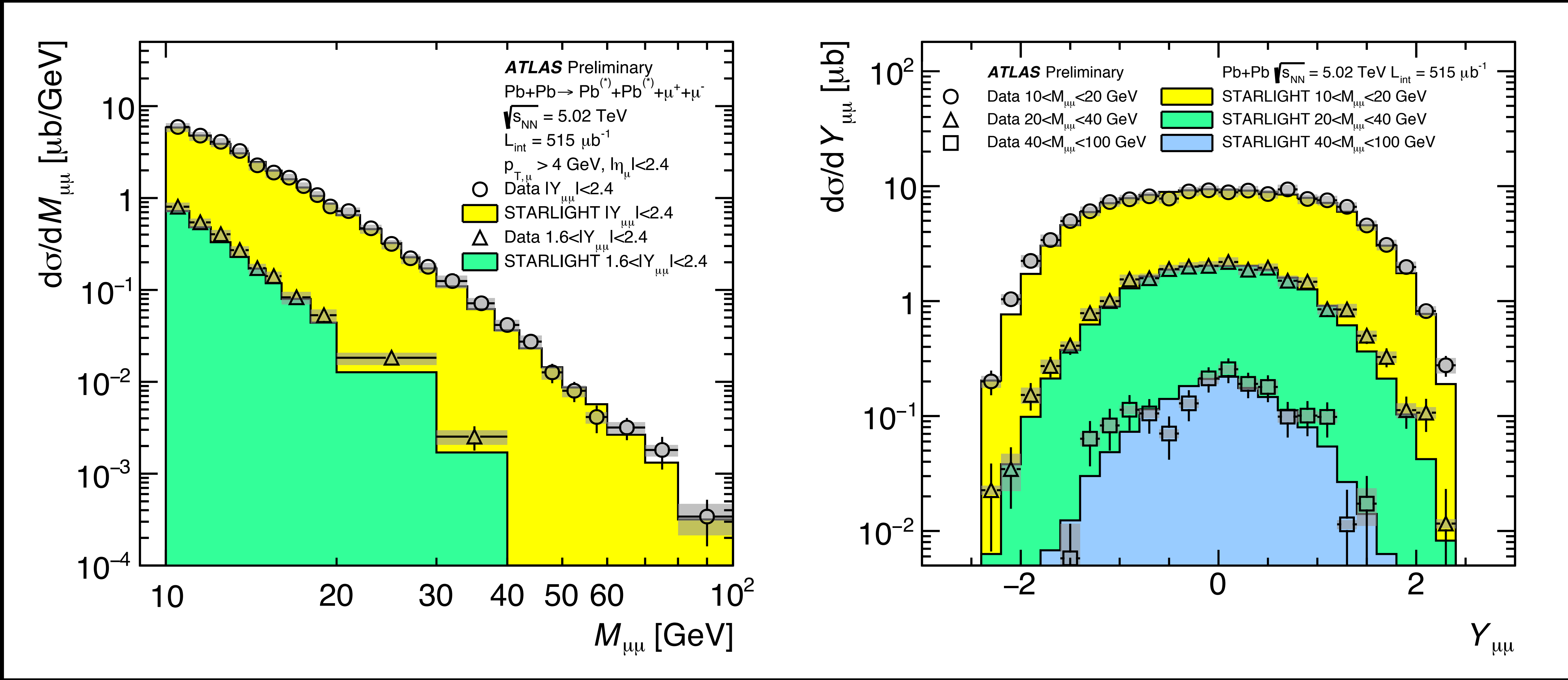


dissociation



DIMUON CROSS SECTIONS

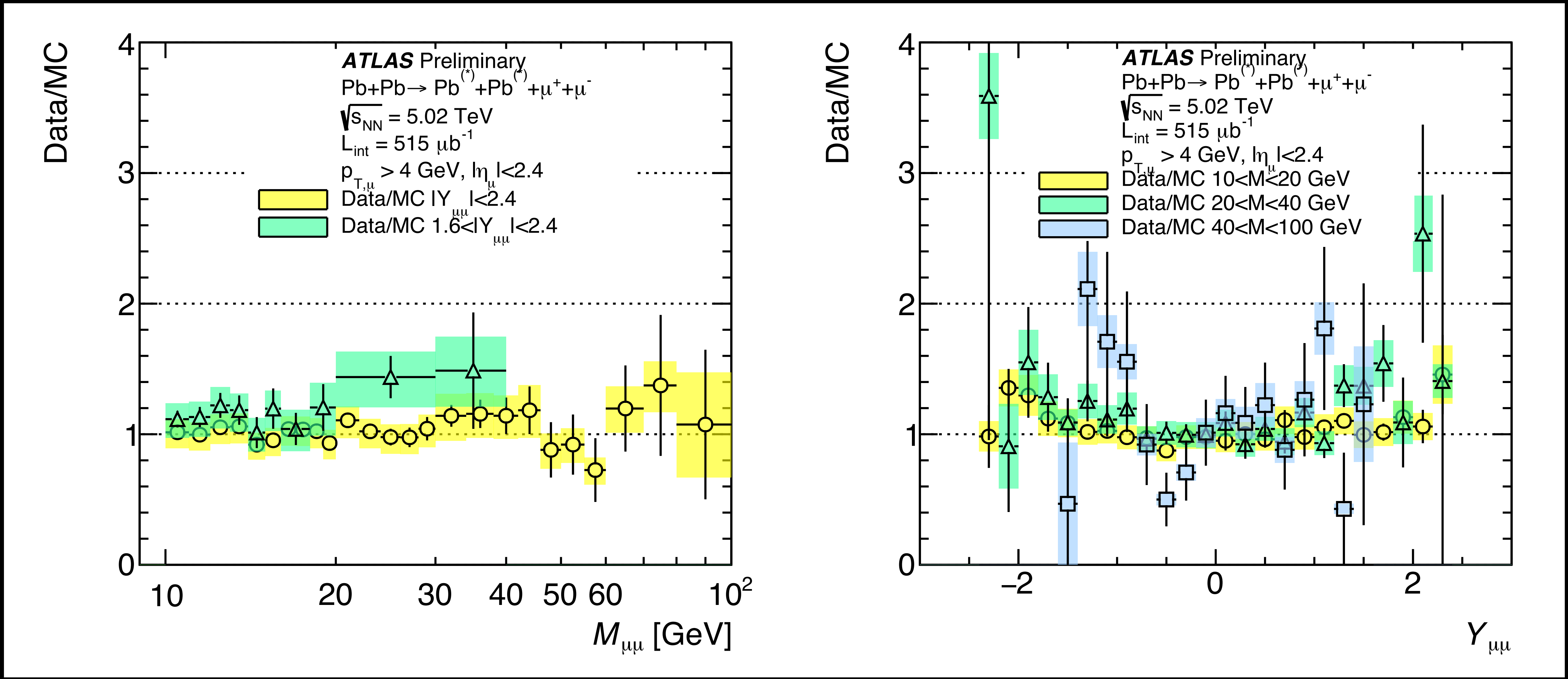
ATLAS-CONF-2016-025



STARLIGHT 1.1 provides good description of fully-corrected dimuon distributions, with hint of small excess at high $Y_{\mu\mu}$

DIMUON CROSS SECTIONS

ATLAS-CONF-2016-025



STARLIGHT 1.1 provides good description of fully-corrected dimuon distributions, with hint of small excess at high $Y_{\mu\mu}$

Ongoing detailed study of low lying dissociative processes which are backgrounds not in STARLIGHT

EXCLUSIVE DIPHOTONS (LIGHT BY LIGHT SCATTERING)

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

nature physics

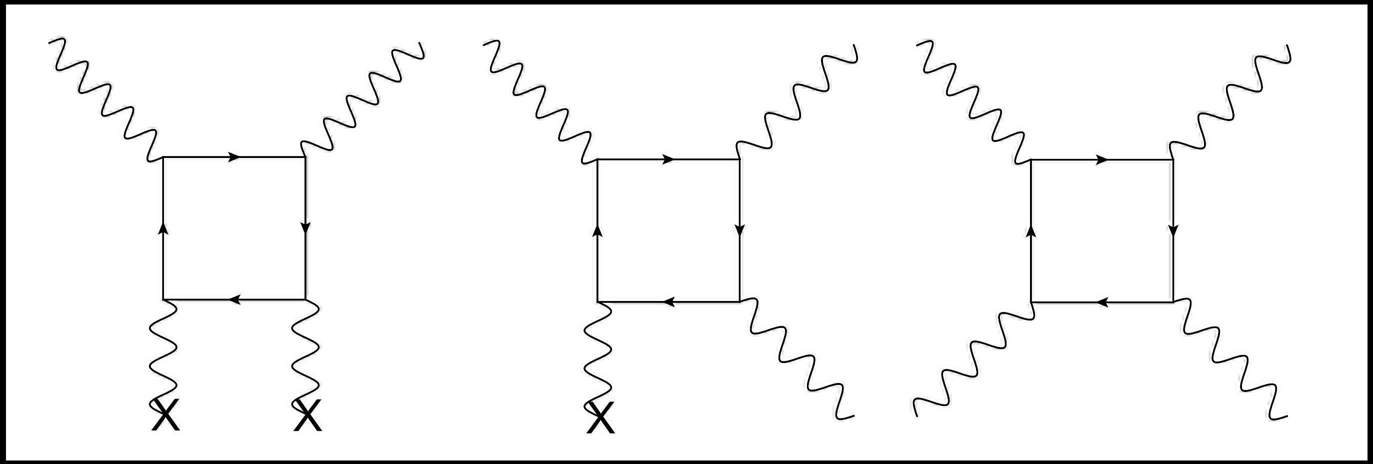
OPEN

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

ATLAS Collaboration†

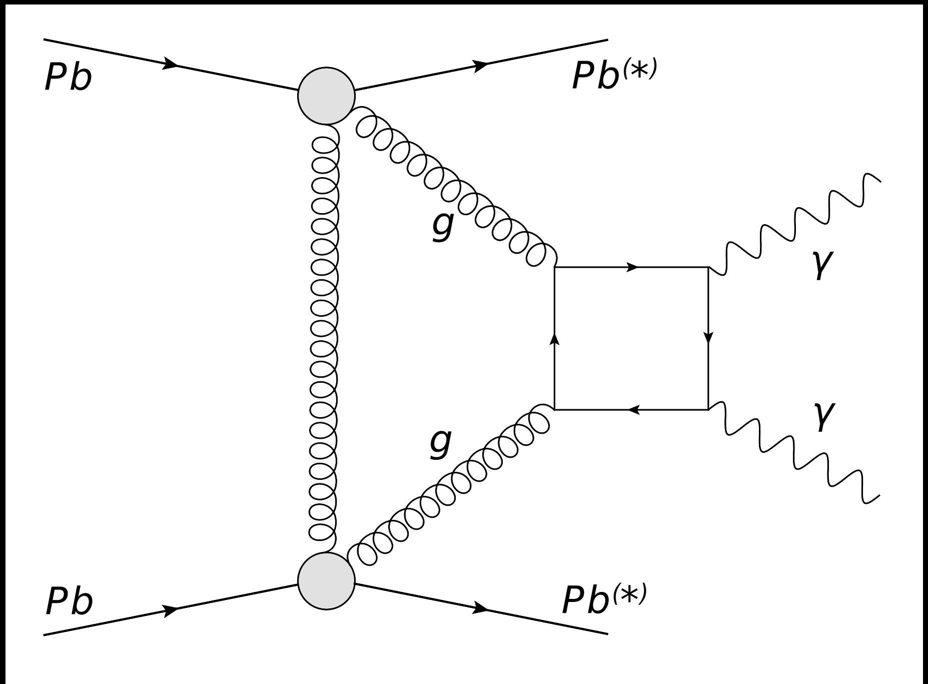
Light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics. This reaction is accessible at the Large Hadron Collider thanks to the large electromagnetic field strengths generated by ultra-relativistic colliding lead ions. Using 480 μb^{-1} of lead–lead collision data recorded at a centre-of-mass energy per nucleon pair of 5.02 TeV by the ATLAS detector, here we report evidence for light-by-light scattering. A total of 13 candidate events were observed with an expected background of 2.6 ± 0.7 events. After background subtraction and analysis corrections, the fiducial cross-section of the process $Pb + Pb (\gamma\gamma) \rightarrow Pb^{(*)} + Pb^{(*)}\gamma\gamma$, for photon transverse energy $E_T > 3$ GeV, photon absolute pseudorapidity $|\eta| < 2.4$, diphoton invariant mass greater than 6 GeV, diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01, is measured to be 70 ± 24 (stat.) ±17 (syst.) nb, which is in agreement with the standard model predictions.

LIGHT BY LIGHT SCATTERING

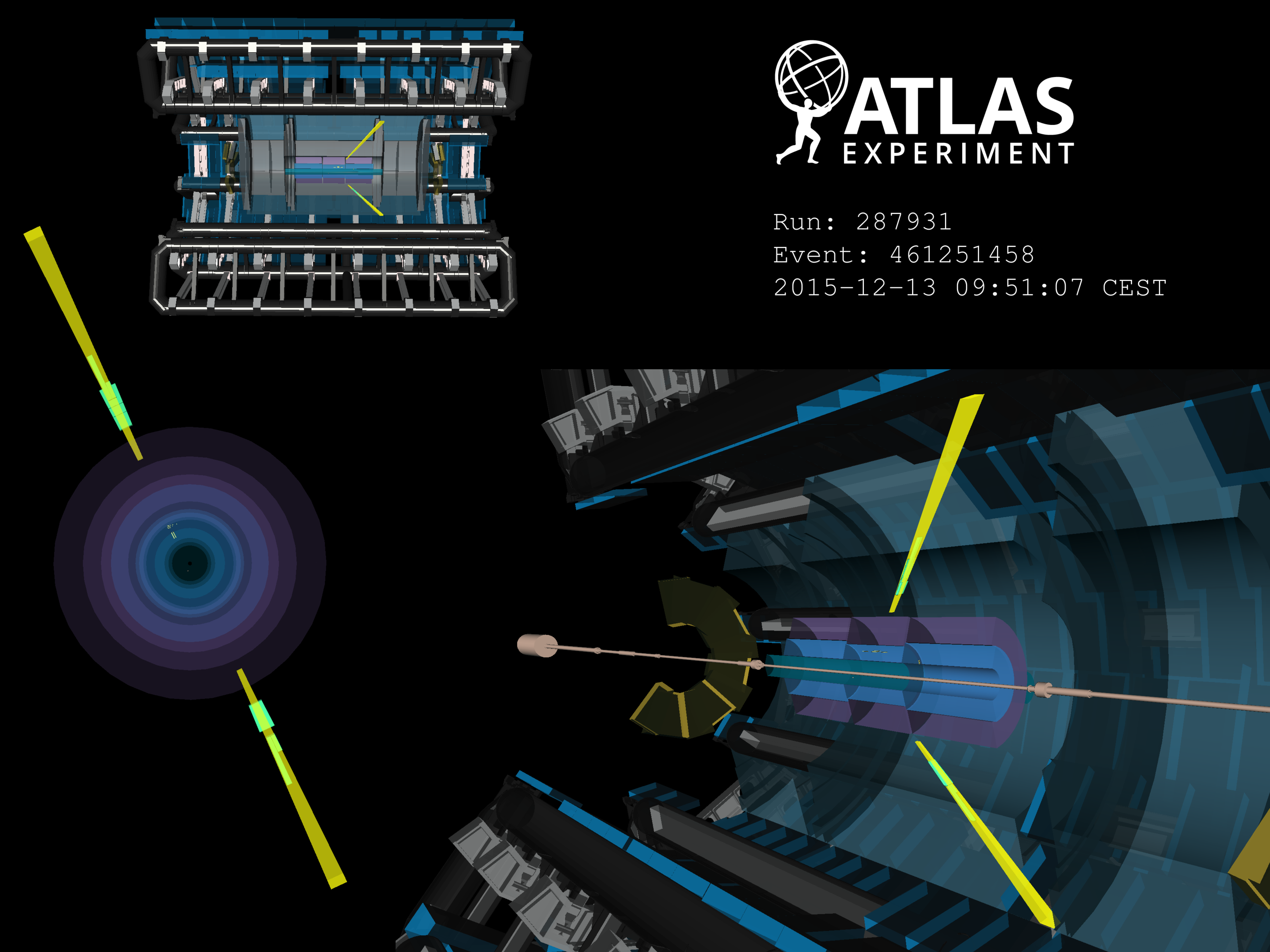


Delbruck scattering | Photon splitting | "direct" light-by-light

Same diagram, different initial states: direct LbyL not yet observed



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

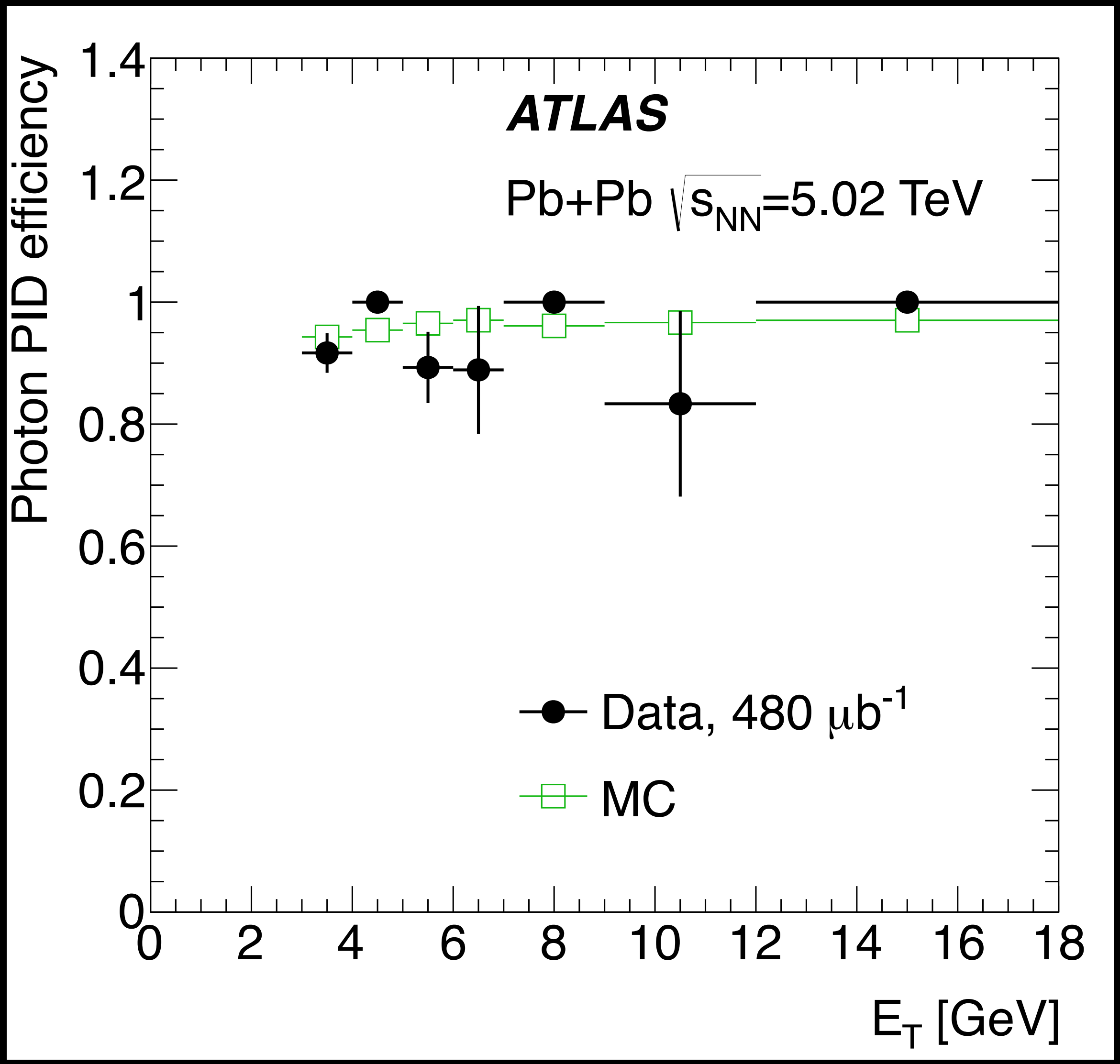

ATLAS
EXPERIMENT
Run: 287931
Event: 461251458
2015-12-13 09:51:07 CEST

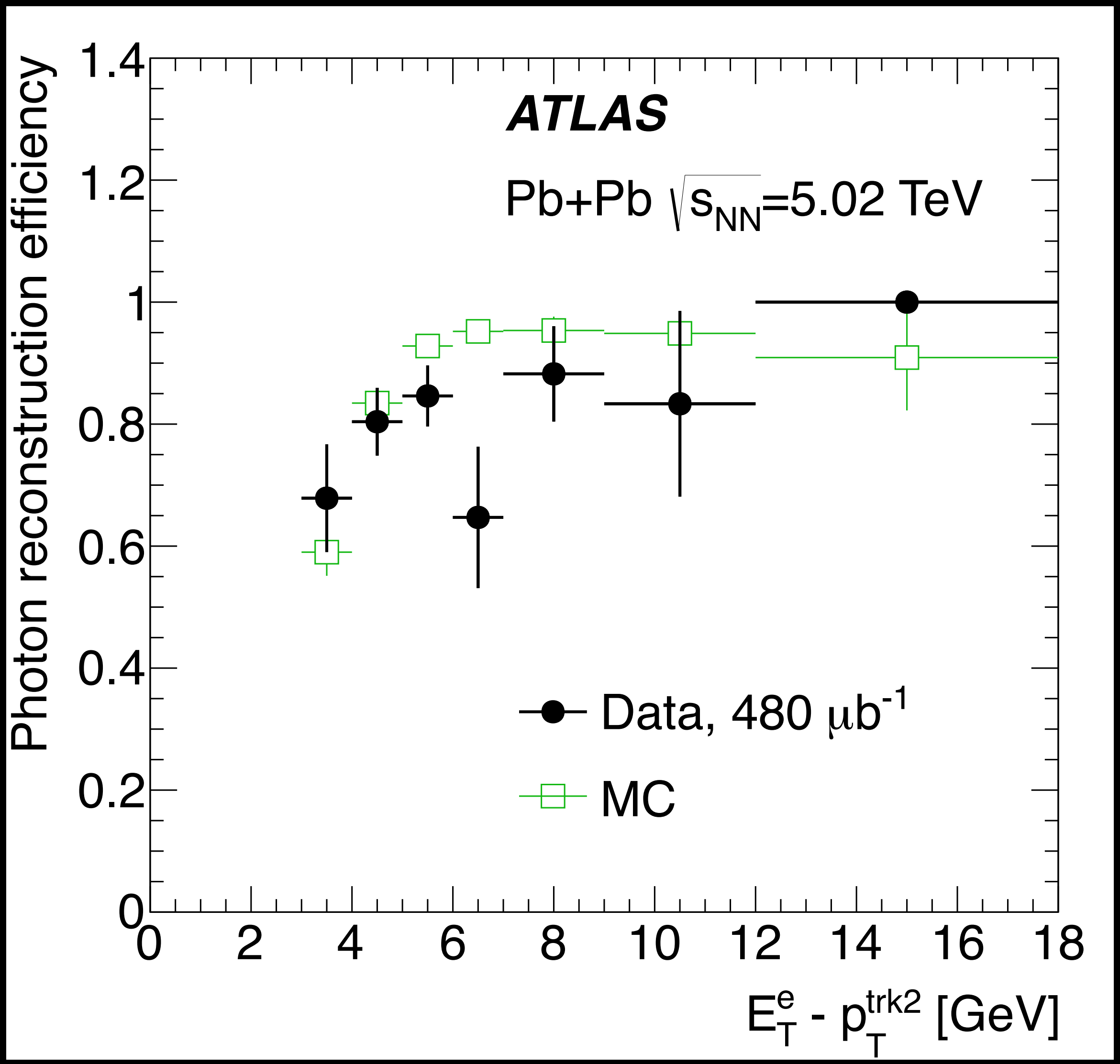
TRIGGER AND EVENT SELECTION

- 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, each satisfying three shower shape selections and* $p_T > 3$ *GeV,* $|\eta| < 2.37$ *(avoiding "crack" region)*
  - *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* $Aco = 1 - |\Delta\phi|/\pi < 0.01$

PID & RECONSTRUCTION EFFICIENCY

Nature Phys. 13 (2017) no.9, 852-858

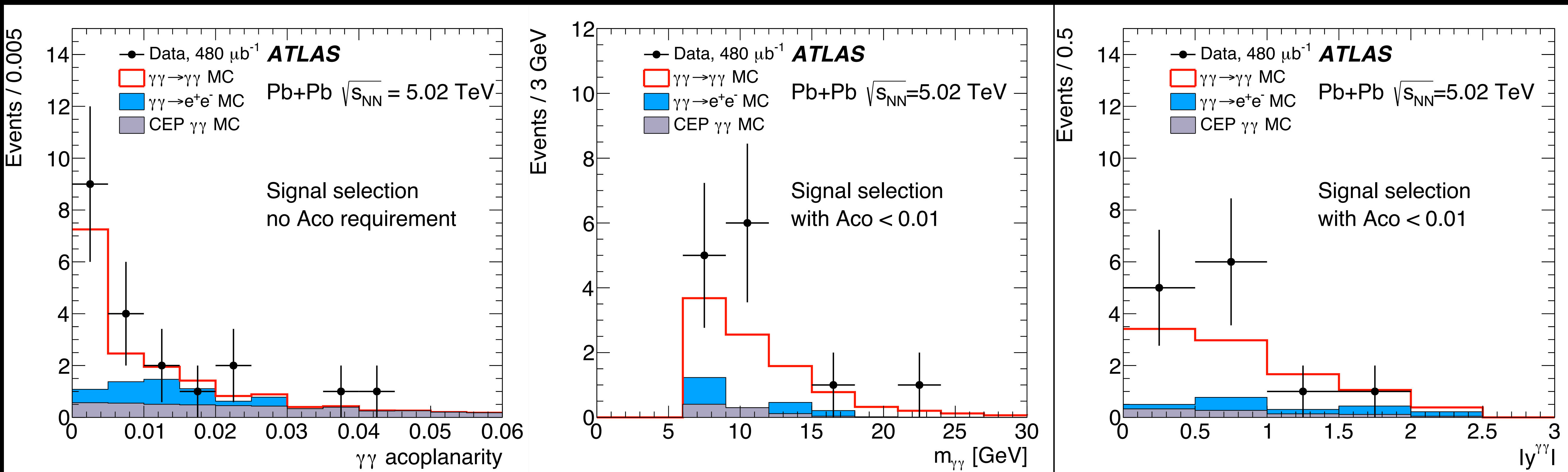




MC efficiencies validated using data-driven techniques, with small sample contributing to systematic uncertainties

KINEMATIC DISTRIBUTIONS

Nature Phys. 13 (2017) no.9, 852-858



Clear excess at small acoplanarity, not expected from background sources.

Good agreement with MC distributions, dominated by LbyL, for kinematic distributions, esp. $\boldsymbol{m_{\gamma\gamma}}$ and $\boldsymbol{y_{\gamma\gamma}}$.

CROSS SECTION & SIGNIFICANCE

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \times \int L dt}$$

Fiducial phase space:

$p_{T\gamma}$>3 GeV, $|\eta|$<2.4,

$m_{\gamma\gamma}$>6 GeV, $p_{T\gamma\gamma}$<2 GeV, Aco<0.01

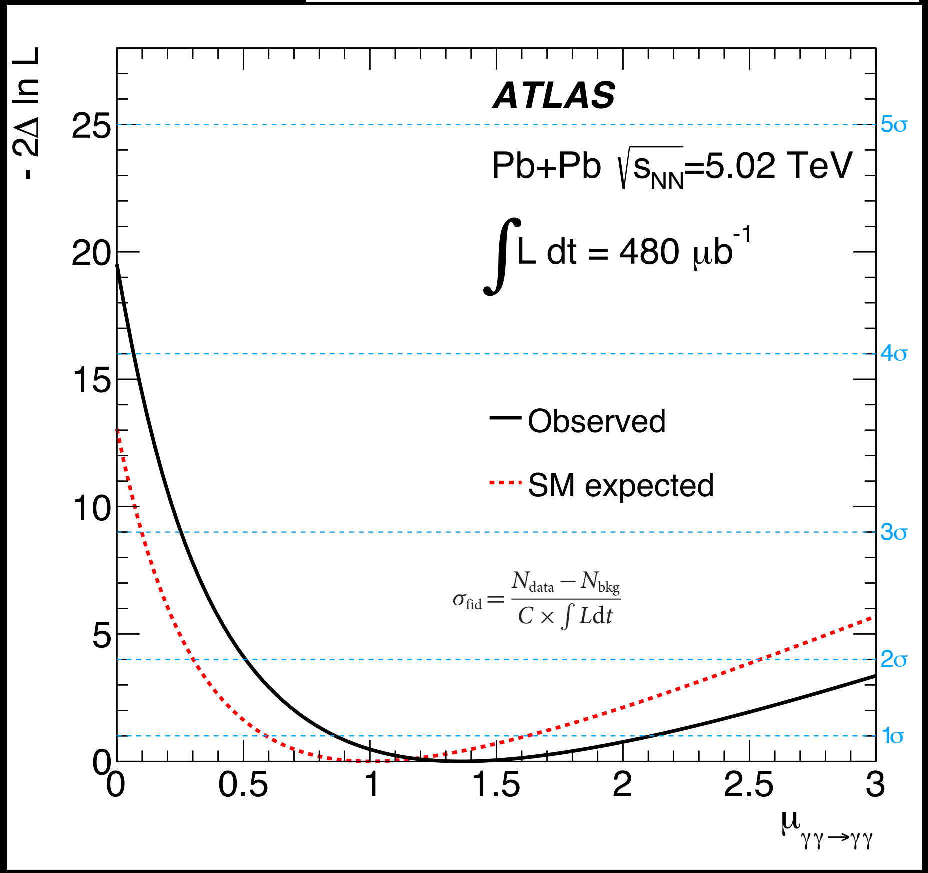
$C = 0.31 \pm 0.07$ from MC

Table 2 | Summary of systematic uncertainties.

Source of uncertainty	Relative uncertainty
Trigger	5%
Photon reco. efficiency	12%
Photon PID efficiency	16%
Photon energy scale	7%
Photon energy resolution	11%
Total	24%

The table shows the relative systematic uncertainty on detector correction factor *C* broken into its individual contributions. The total is obtained by adding them in quadrature.

Nature Phys. 13 (2017) no.9, 852-858



4.4σ significance observed

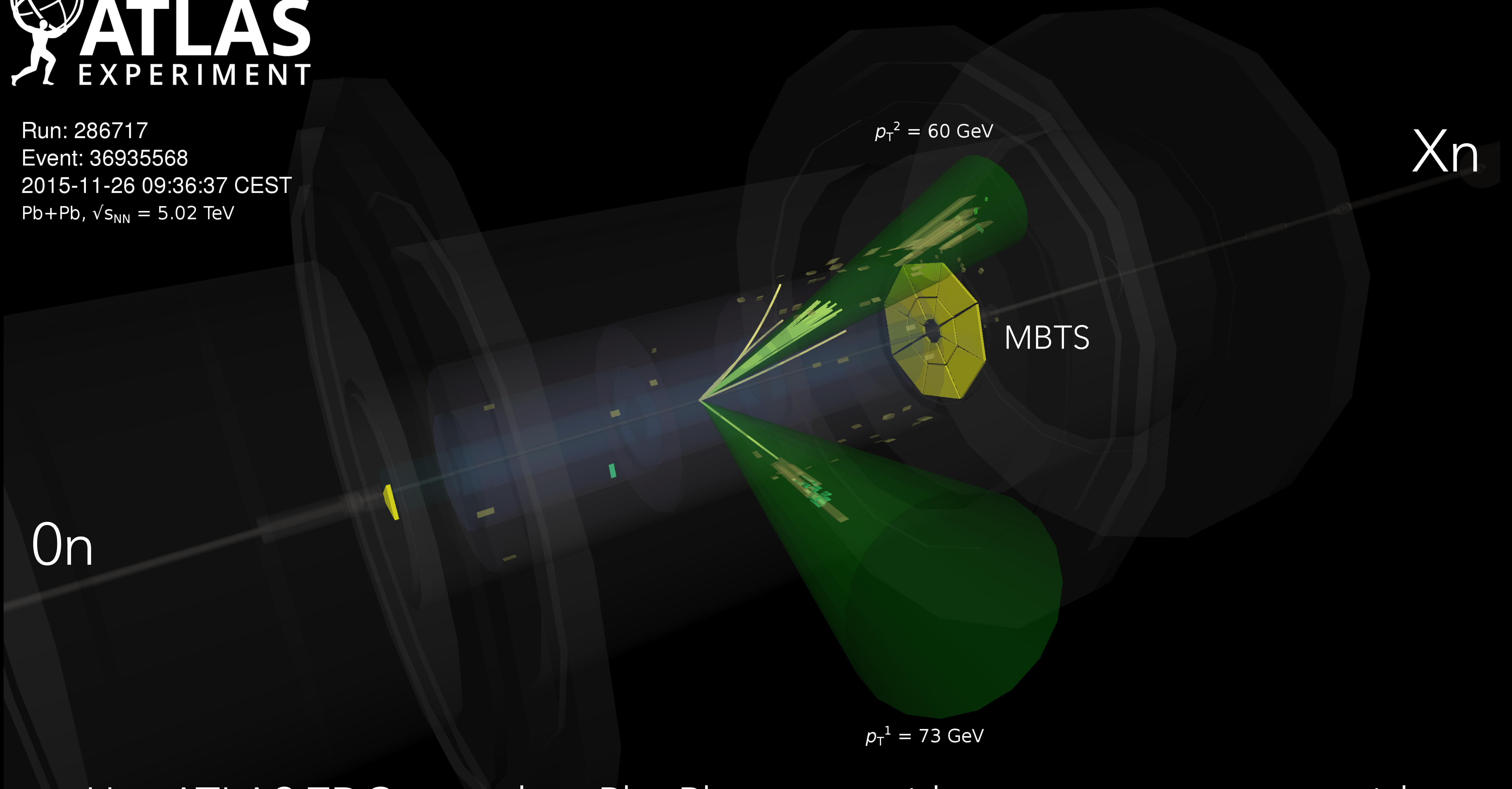
3.8σ expected

$\sigma_{\text{fid}} = 70 \pm 24(\text{stat.}) \pm 17(\text{syst.})$ nb

$\sigma_{\text{fid}} = 45 \pm 9$ nb d'Enterria, et al

$\sigma_{\text{fid}} = 49 \pm 10$ nb Klusek-Gawenda, et al

PHOTONUCLEAR DIJETS



Use ATLAS ZDCs to select Pb+Pb events with no neutrons on one side, and >0 neutrons on the other = "Xn0n" topology.

TRIGGER AND EVENT SELECTION

- UPC trigger
  - *ZDC "exclusive-or" topology*
    - *>0 neutrons in one direction, 0 in the other*
  - *Total transverse energy $5 < \Sigma E_T < 200$ GeV*
  - *Sampled integrated luminosity of 95 μb^{-1}*
- UPC Jet triggers
  - *"central" UPC trigger + anti-k_T R=0.4 jet in $|\eta|<3.2$ (300 μb^{-1})*
  - *"forward" UPC trigger + anti-k_T R=0.4 jet in $|\eta|>3.2$ (380 μb^{-1})*

- All events required to have a reconstructed vertex and one charged track if jet falls in inner detector acceptance

JET EVENT SELECTION

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

$$H_{\mathrm{T}} \equiv \sum_i p_{\mathrm{T}\,i}\,, \quad m_{\mathrm{jets}} \equiv \left[\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2\right]^{1/2}, \quad y_{\mathrm{jets}} \equiv \frac{1}{2}\ln\left(\frac{\sum_i E_i + \sum_i p_{z\,i}}{\sum_i E_i - \sum_i p_{z\,i}}\right),$$

H_T~Q

Additional selections: $|\Delta\phi|_{12}$ > 0.2, m_{jets} > 35 GeV

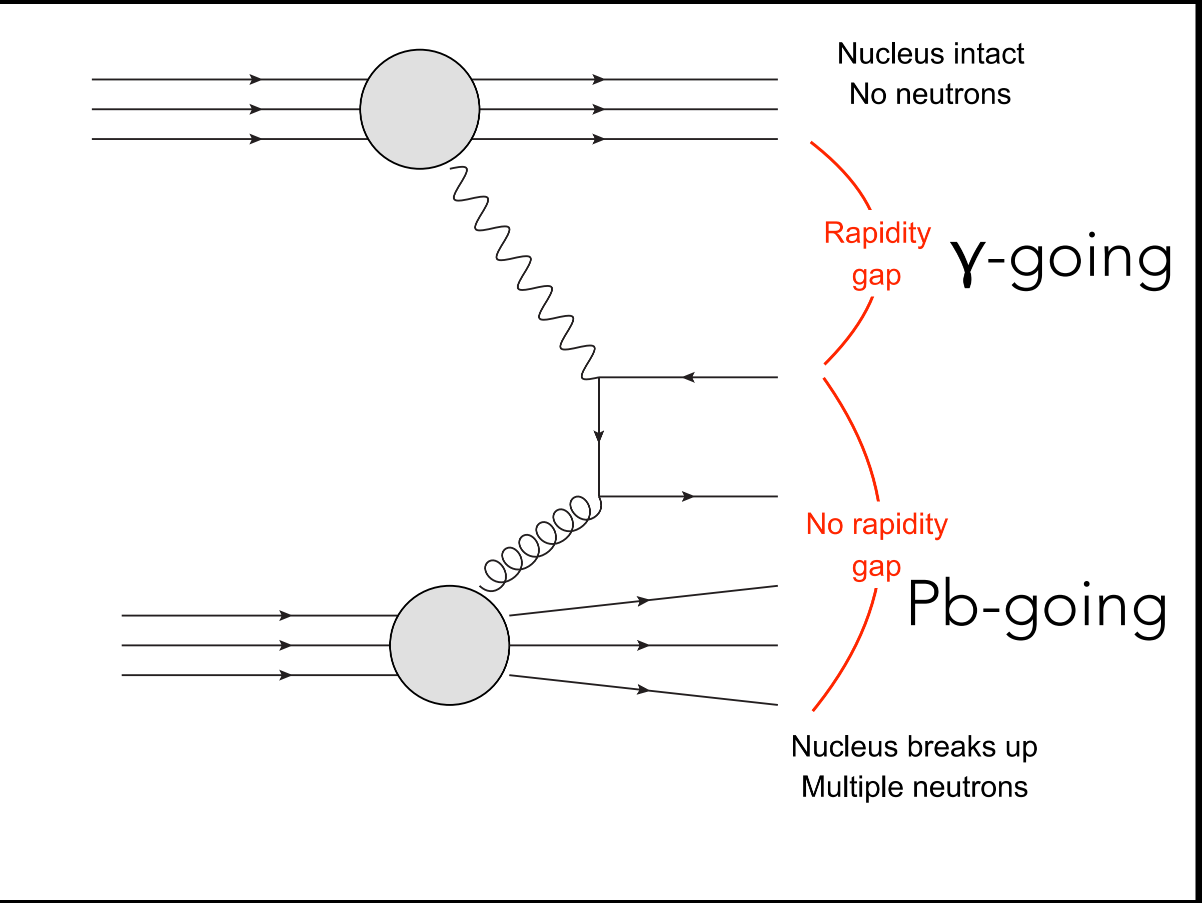
$$z_\gamma \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s}} e^{+y_{\mathrm{jets}}}\,, \quad x_{\mathrm{A}} \equiv \frac{m_{\mathrm{jets}}}{\sqrt{s}} e^{-y_{\mathrm{jets}}}$$

x_A is the per-nucleon momentum fraction carried by the struck parton, while $z_\gamma = x_\gamma \alpha$, where α is energy fraction of photon

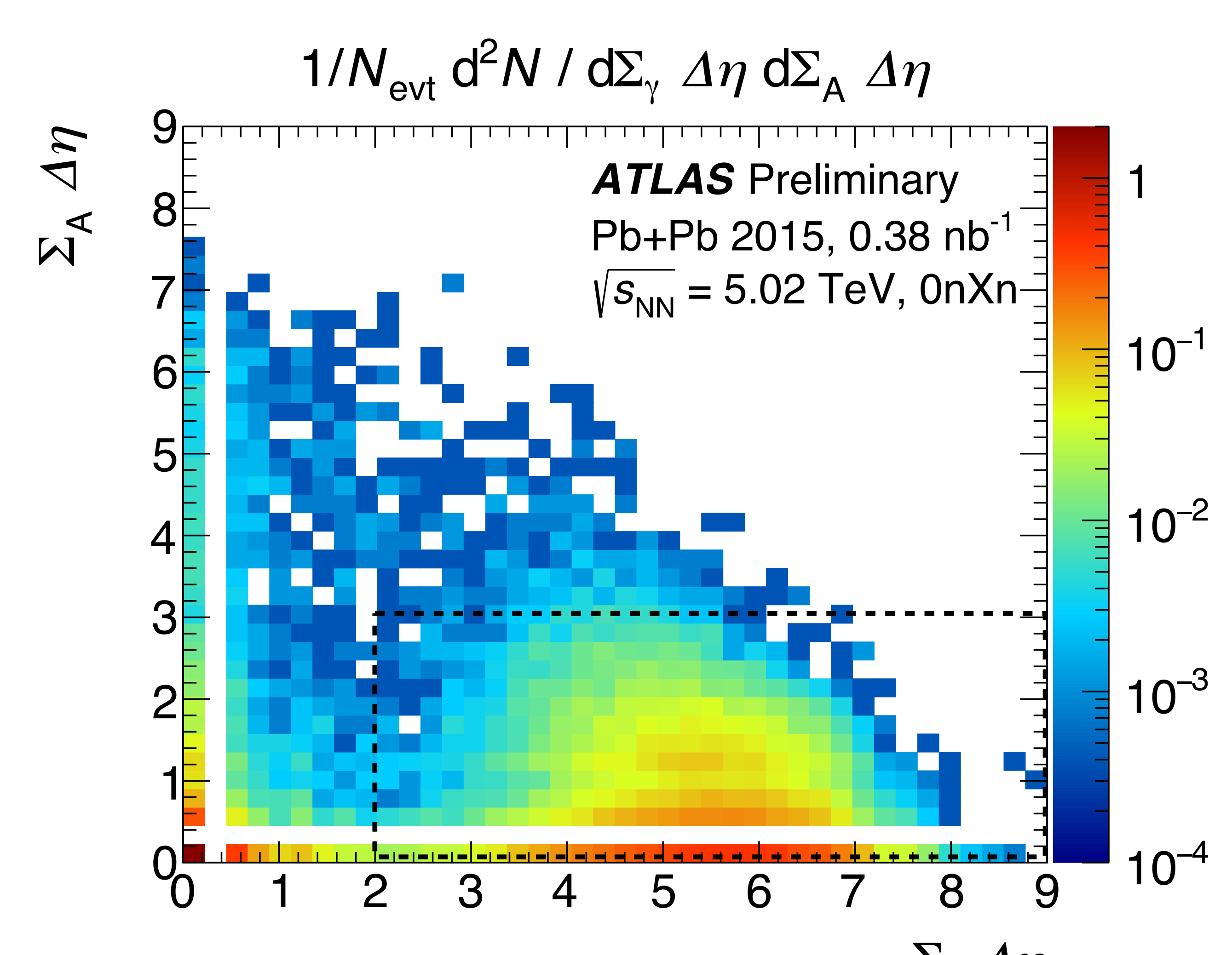
GAP EVENT SELECTION

ZDC Xn0n topology $\Sigma_A \Delta\eta < 3$ $\Sigma_\gamma \Delta\eta > 2$

sum of gaps associated with
photon-going and Pb-going sides



Direct production



ATLAS-CONF-2017-011

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.

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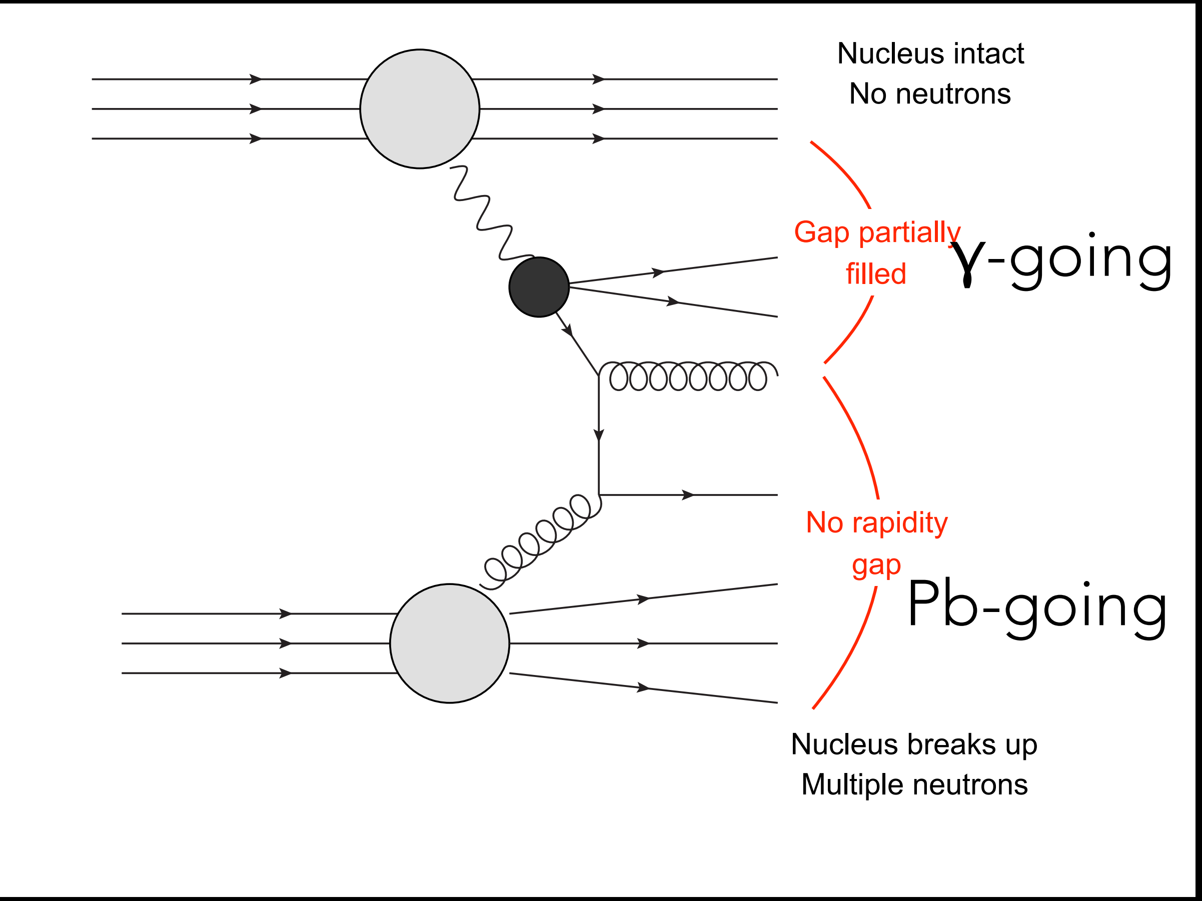
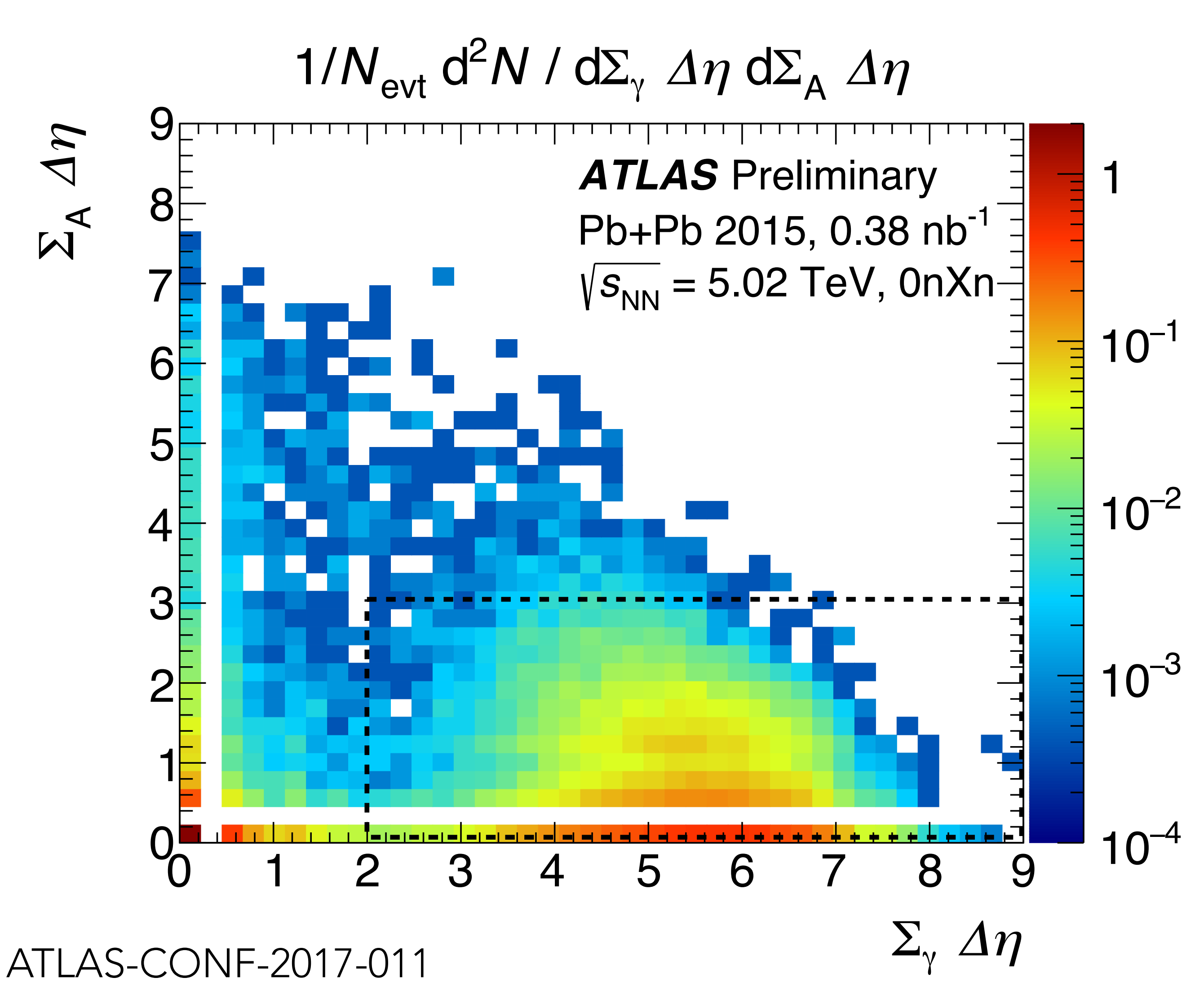
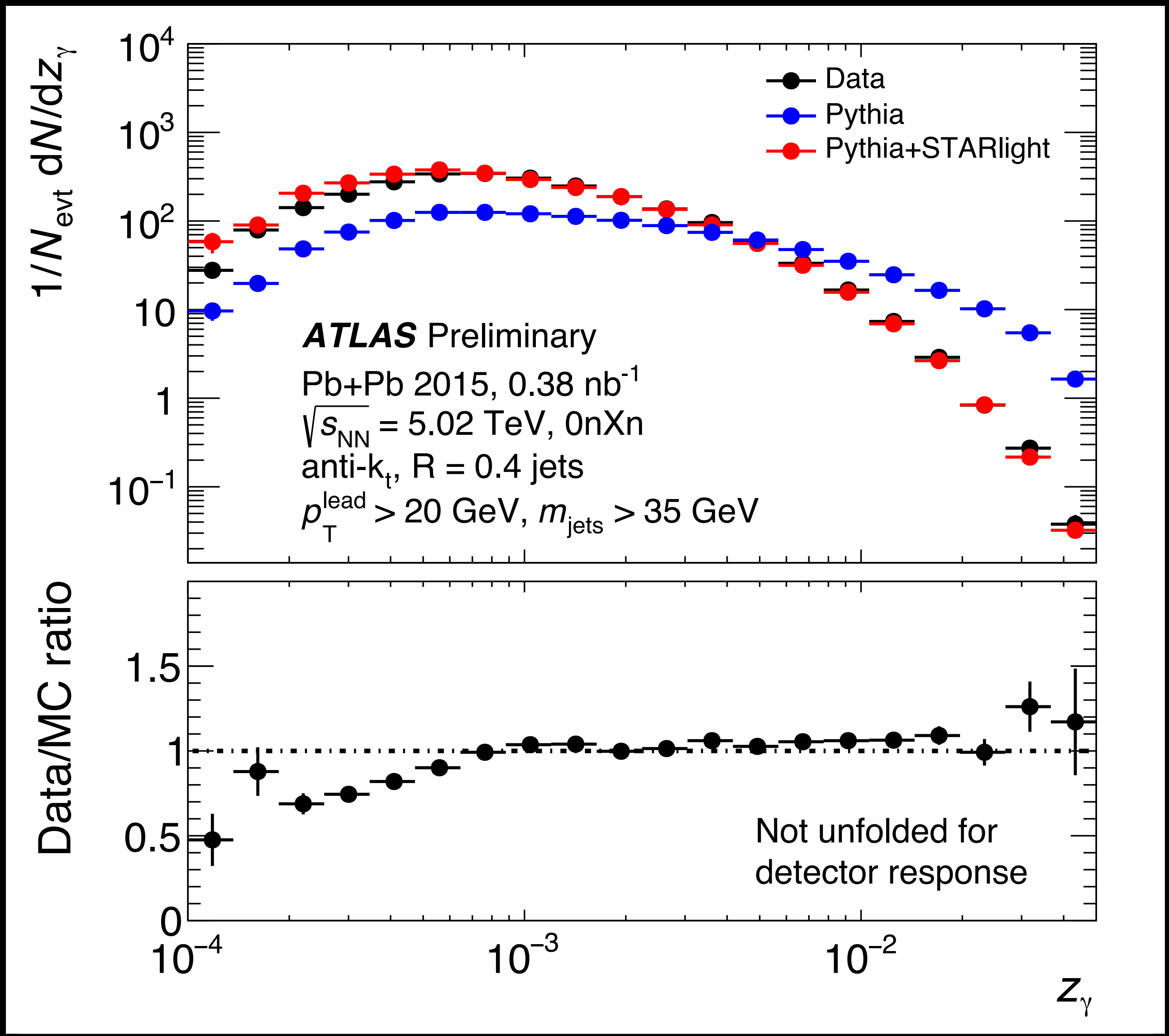


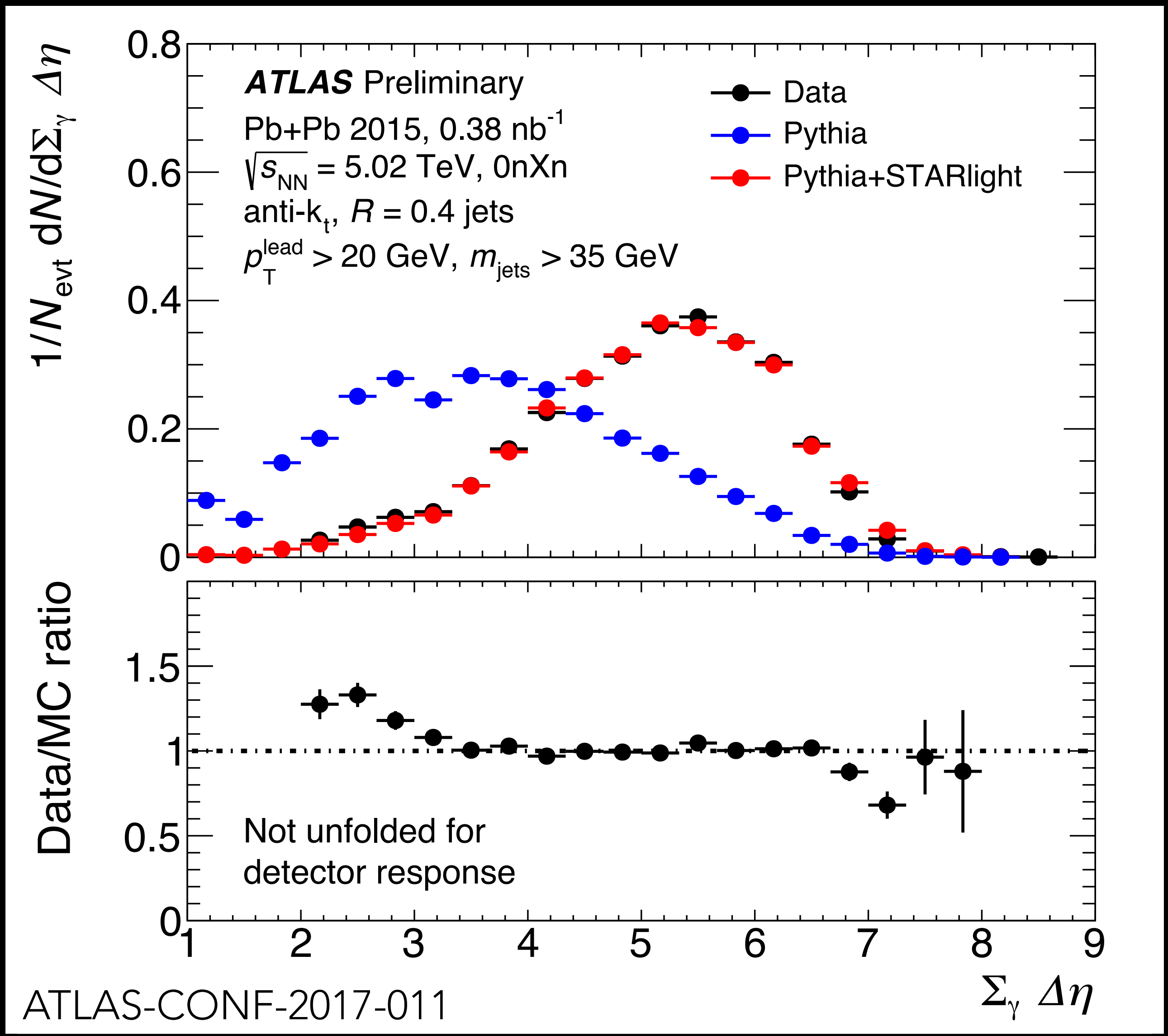


Resolved production

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.

REWEIGHING PHOTON SPECTRUM





Using PYTHIA6 simulations with photons (Q<30 MeV) from μ+p (no μ+n yet), PYTHIA6 incoming photon spectrum reweighted to match expectations for photon flux in γ+Pb from STARLIGHT

Data agrees well with MC shape (normalized to data) after reweighting.

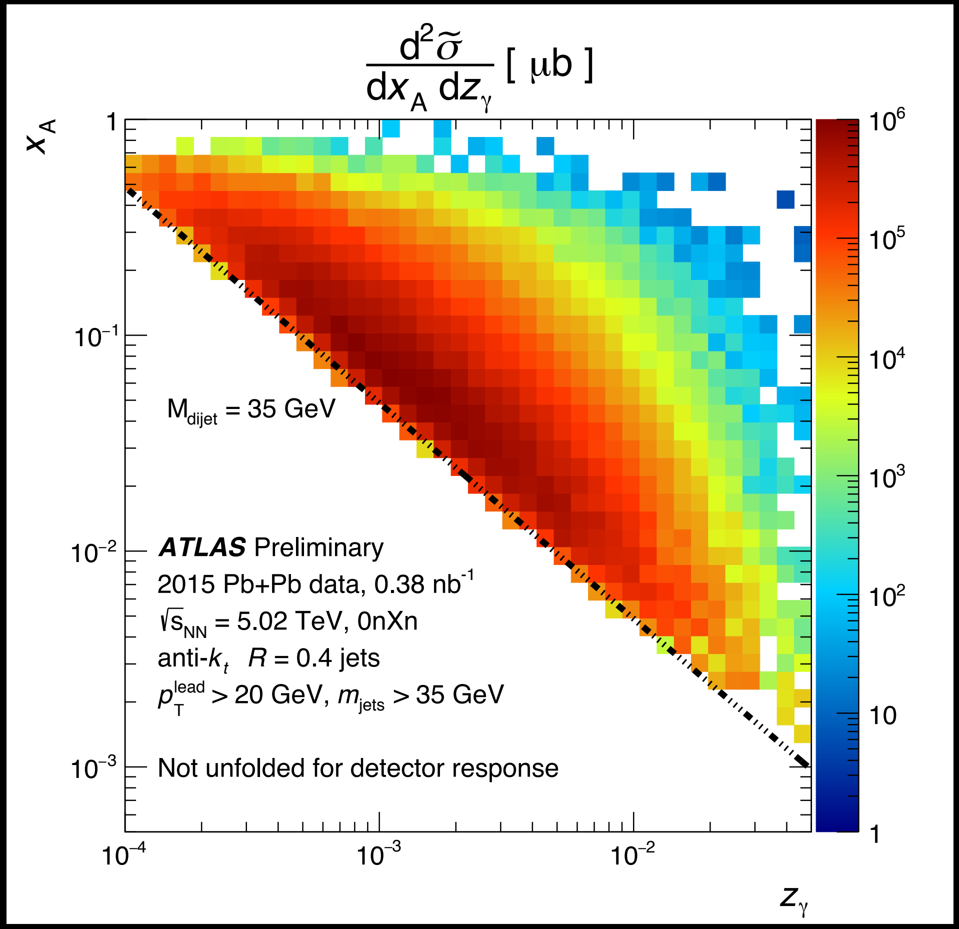
CROSS SECTIONS

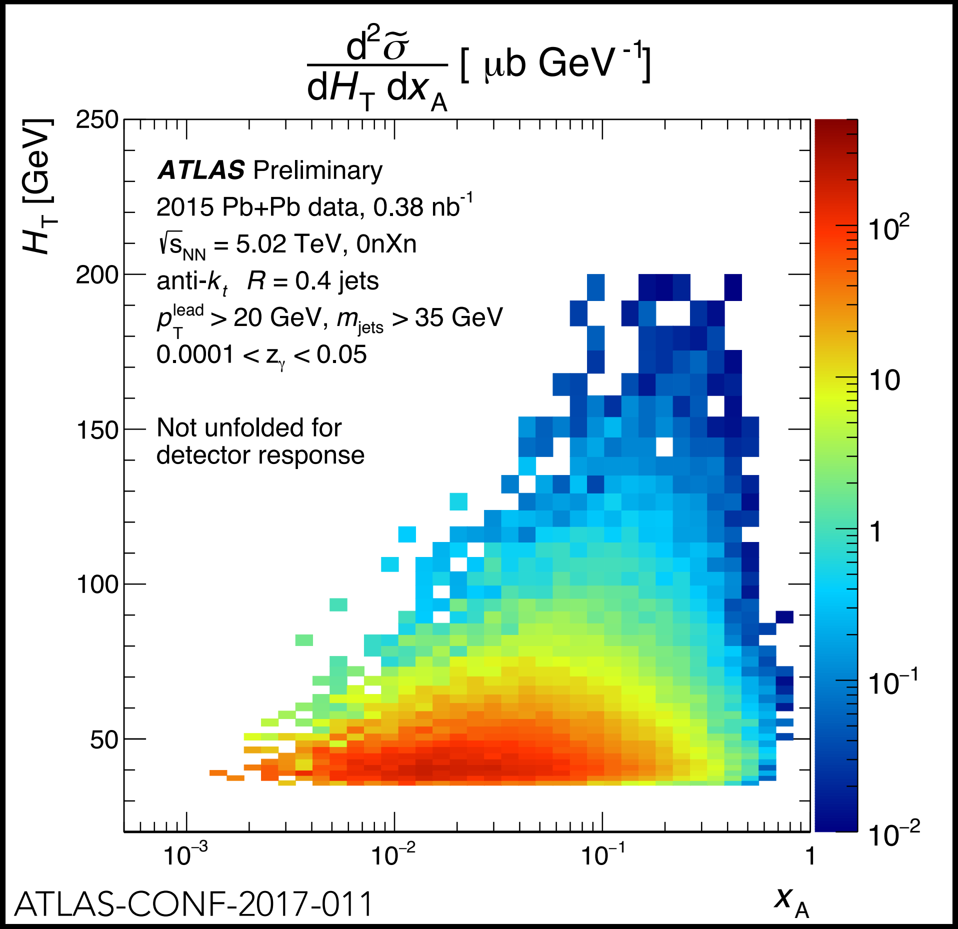
$$\frac{d^3\tilde{\sigma}}{dH_T x_A dz_\gamma} = \frac{1}{\mathcal{L}} \frac{\Delta N}{\Delta H_T \, \Delta x_A \, \Delta z_\gamma} \frac{1}{\varepsilon_{\text{trig}} \, \varepsilon_{\text{sel}}}$$

Measured yields corrected for trigger and event selection: gap definition induces losses in some kinematic regions

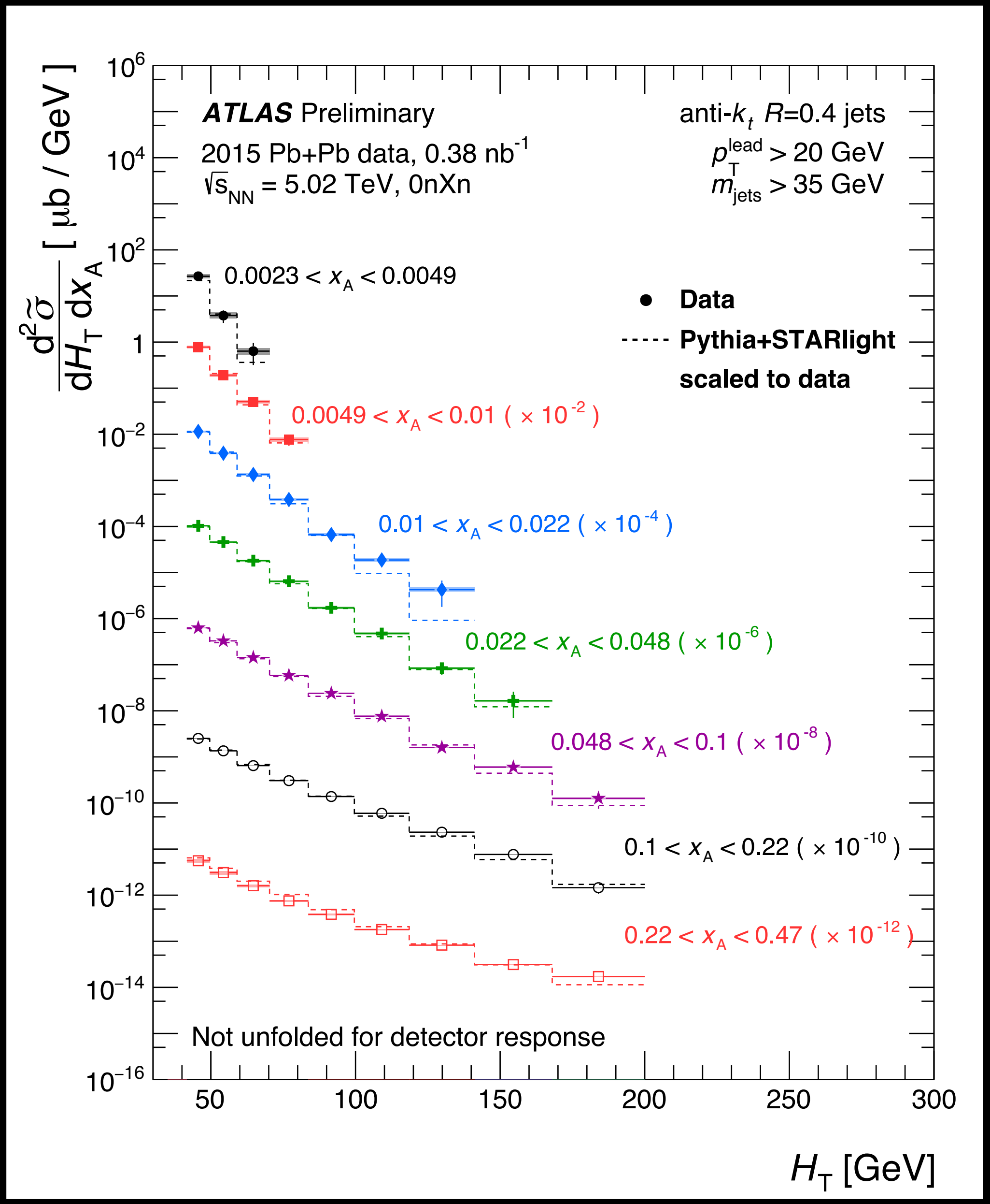
Single ZDC measured to have 2% trigger inefficiency

Pileup from EM dissociation (σ_{EMD} > 200 b!) gives 5% inefficiency in Xn0n trigger

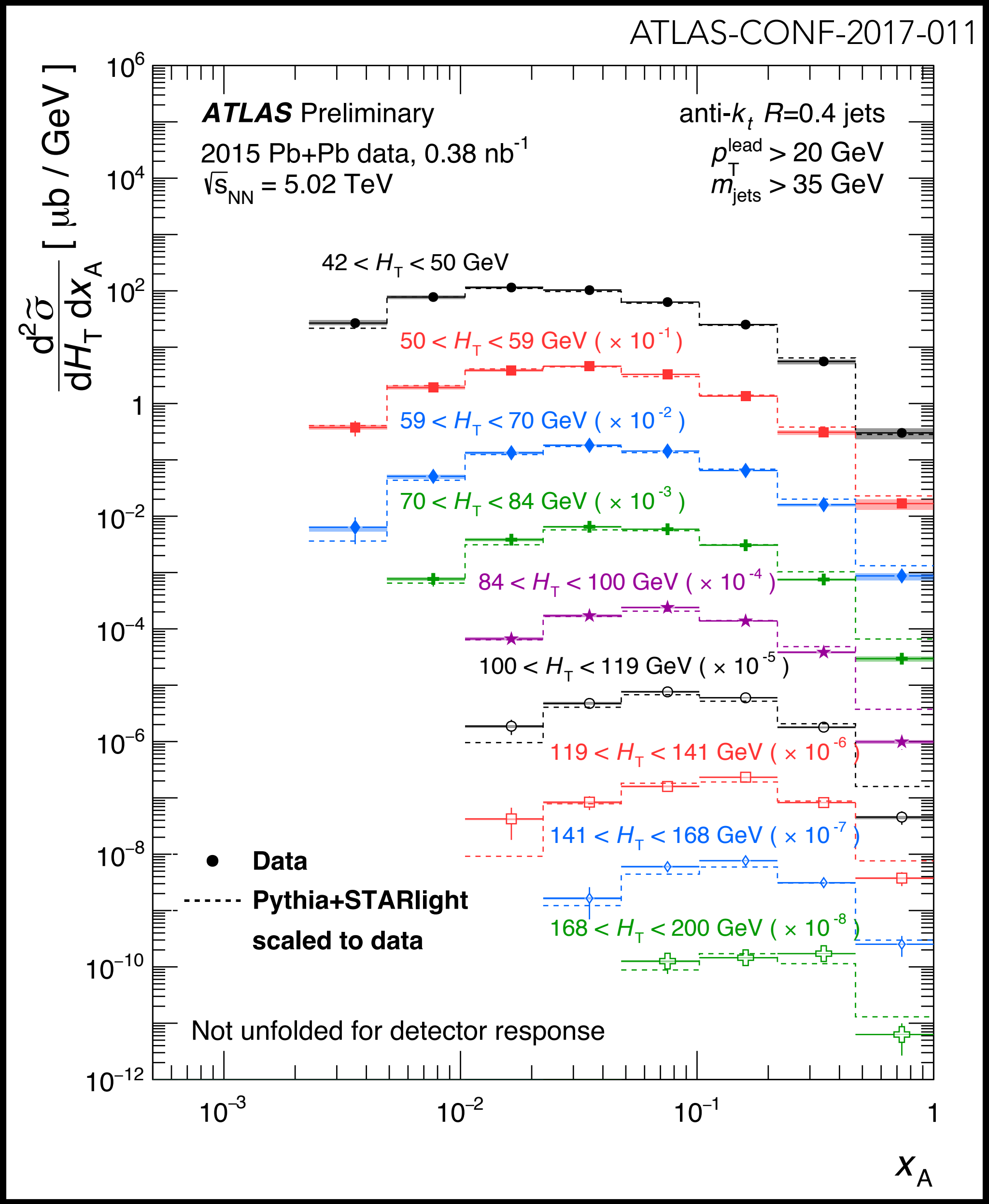




DOUBLE DIFFERENTIAL CROSS SECTIONS



vs. H_T, in x_A intervals



vs. x_A, in H_T intervals

Good agreement over wide kinematic range:

N.B. results not yet unfolded for detector response

CONCLUSIONS AND OUTLOOK

- ATLAS UPC program is covering topics not previously addressed by RHIC & LHC
  - *High mass dimuon production*
  - *Evidence for light-by-light scattering*
  - *Jet photoproduction*
- Extensive set of UPC triggers in 2016 p+Pb dataset
  - *First look at some processes, e.g. μμ*
  - *Prospects for extensive γ+p program*
- Looking forward to 2018 Pb+Pb run, to increase statistics and utilize experience from 2015 run
- Prospects to advance EIC e+A physics goals with precision photoproduction well before EIC construction