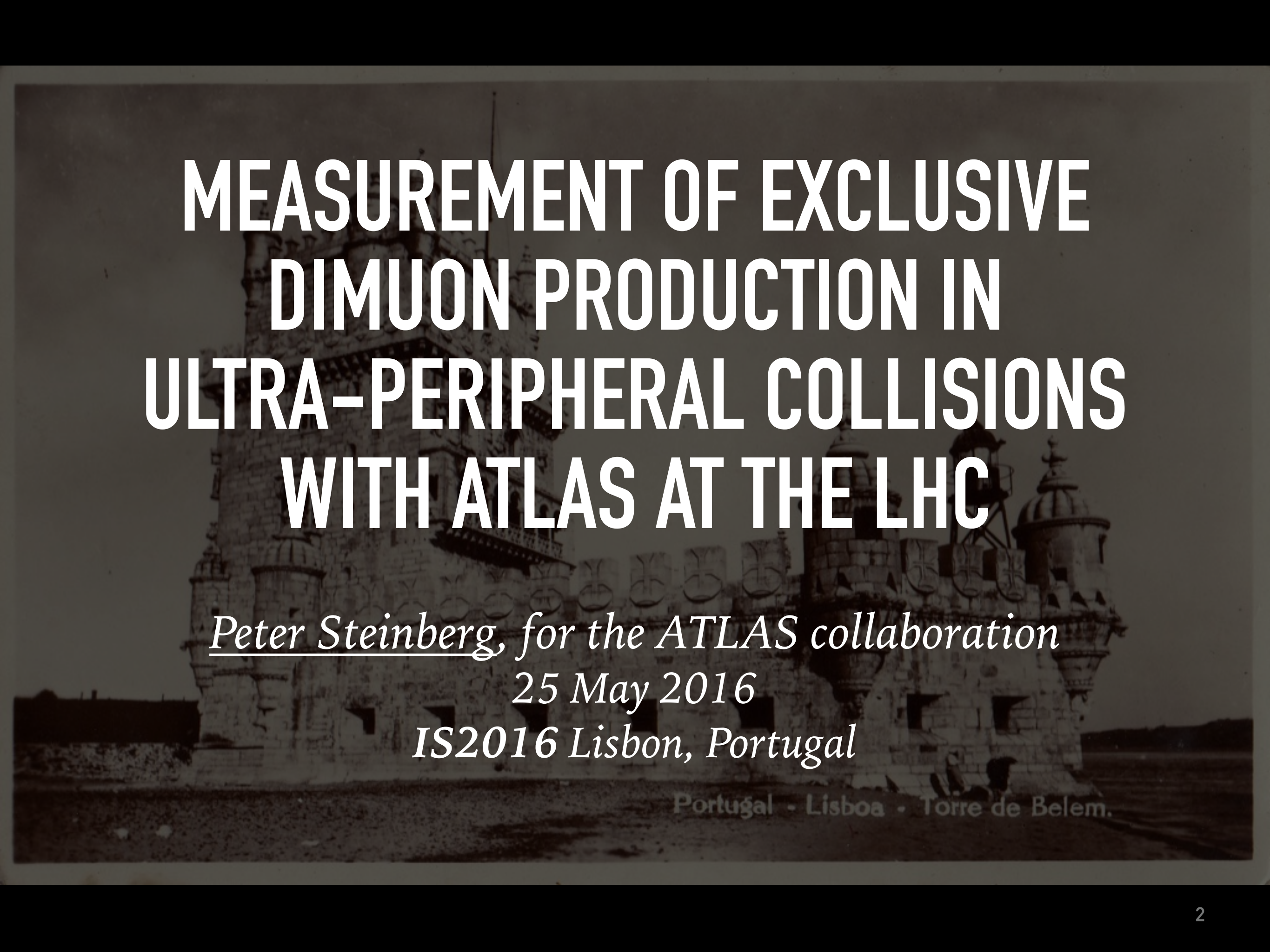




Portugal - Lisboa - Torre de Belem.



MEASUREMENT OF EXCLUSIVE DIMUON PRODUCTION IN ULTRA-PERIPHERAL COLLISIONS WITH ATLAS AT THE LHC

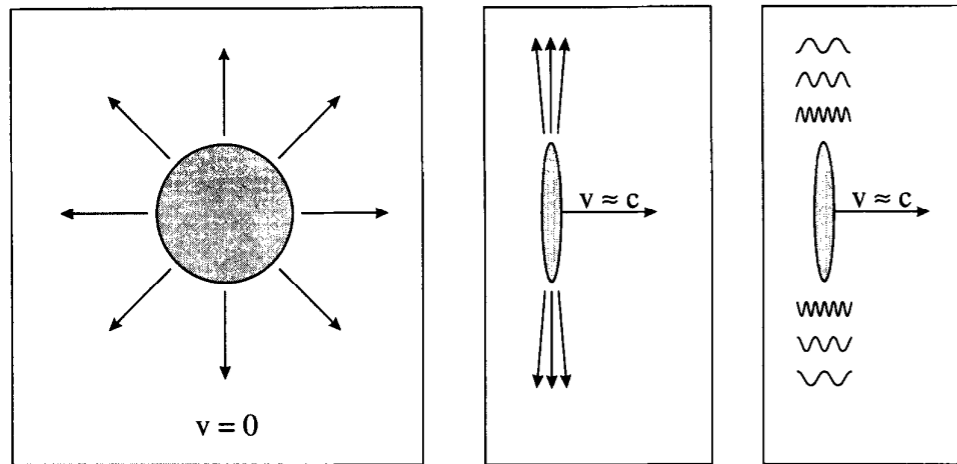
Peter Steinberg, for the ATLAS collaboration

25 May 2016

IS2016 Lisbon, Portugal

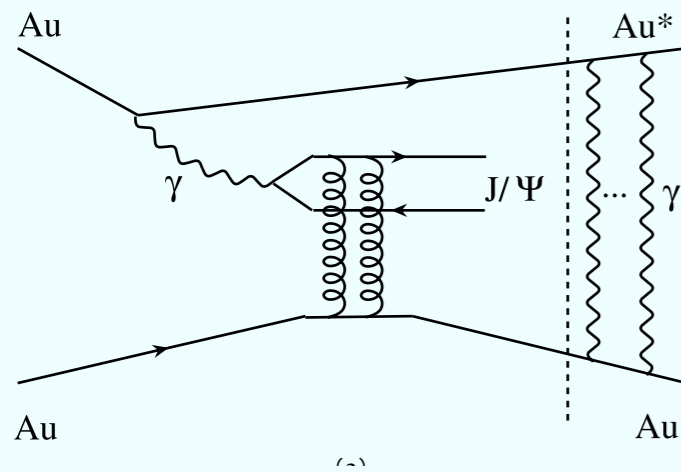
Portugal - Lisboa - Torre de Belem.

ULTRA PERIPHERAL COLLISIONS



- Boosted nuclei are intense source of quasi-real photons
 - Typically treated using EPA (Weizsacker-Williams)
 - Photons with $E \approx (\hbar c/R)\gamma$ are produced coherently (Z^2)
 - Up to ~ 80 GeV at 5.02 TeV

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



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

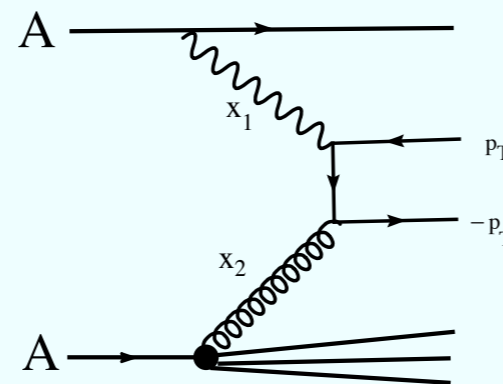
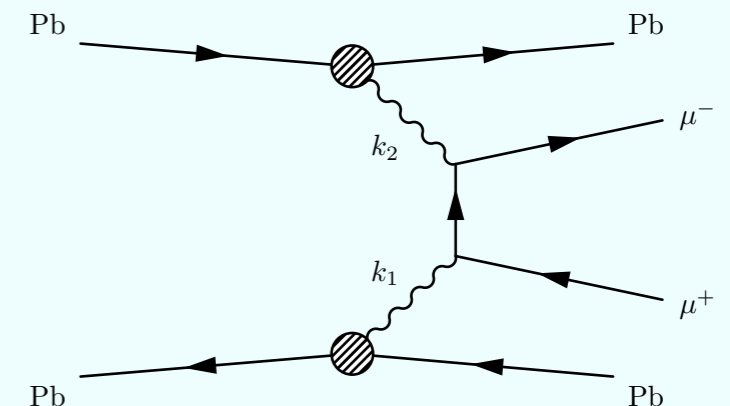
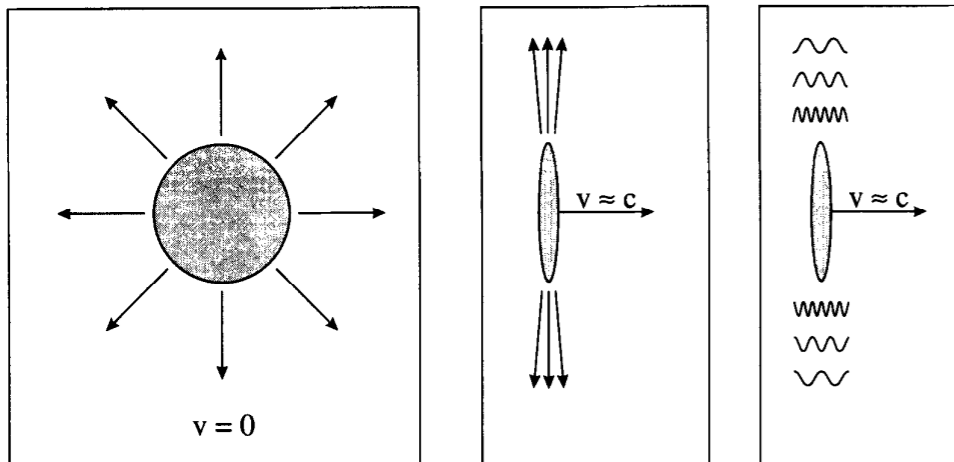


Photo-nuclear:
dijet production
(probe nPDF directly)



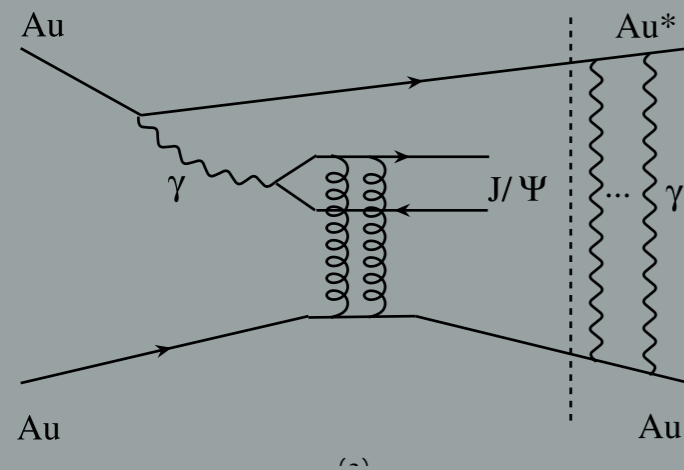
Photon-photon:
dilepton production
(& other exclusive states)

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ATLAS has first results on this one 



Photon-pomeron:
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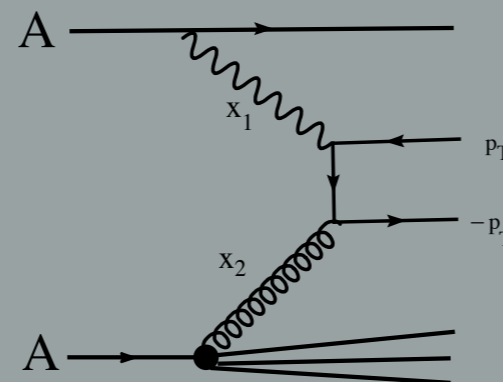
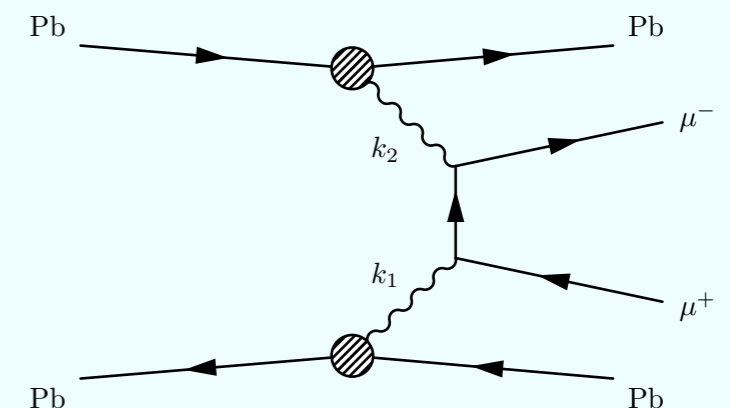


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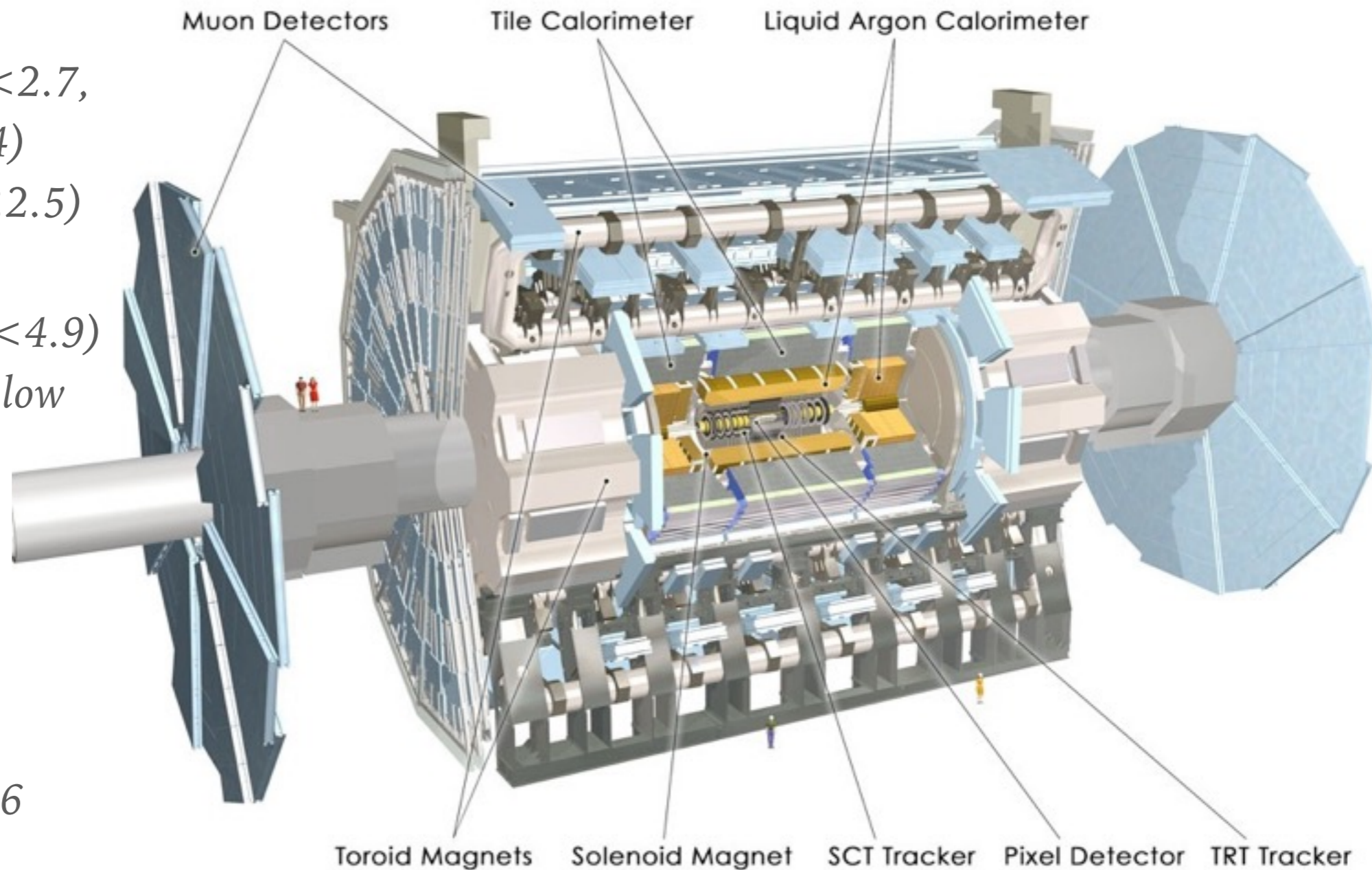
ATLAS EXPERIMENT

.....

Measurement performed primarily with ATLAS muon spectrometer ($|\eta| < 2.7$, L1 triggering in $|\eta| < 2.4$) and inner detector ($|\eta| < 2.5$)

Calorimeter system ($|\eta| < 4.9$) used to select events with low transverse energy

MBTS scintillators cover forward region ($2.07 < |\eta| < 3.86$), with inner ring covering $2.76 < |\eta| < 3.86$



ZDC installed for 2015 but not used in this analysis

DATA & MONTE CARLO SAMPLES

- Uses $L_{\text{int}} = 515 \mu\text{b}^{-1}$ of data with a special UPC muon trigger
 - Loose muon L1 trigger
 - Limit of total $E_T < 50 \text{ GeV}$ at L1
 - Maximum of 1 hit in both MBTS inner rings
 - At least one track with 400 MeV measured by high-level trigger tracking algorithm
 - Efficiency of MBTS part measured in data to be $98 \pm 1\text{-}2\%$
- Two different simulated samples used
 - 1.5M Single muons (2-10 GeV, $|\eta| < 3$, realistic v_z)
 - used to determine reconstruction efficiency
 - 1.5M **STARLIGHT 1.1** events simulating
$$\text{Pb} + \text{Pb} \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)} + \mu^+ + \mu^-$$
 - Integrated over nuclear excitation states, since no ZDC requirements made
 - Used for studying vertex efficiency, effect of μ resolution/smearing
 - Truth level used for comparison cross sections

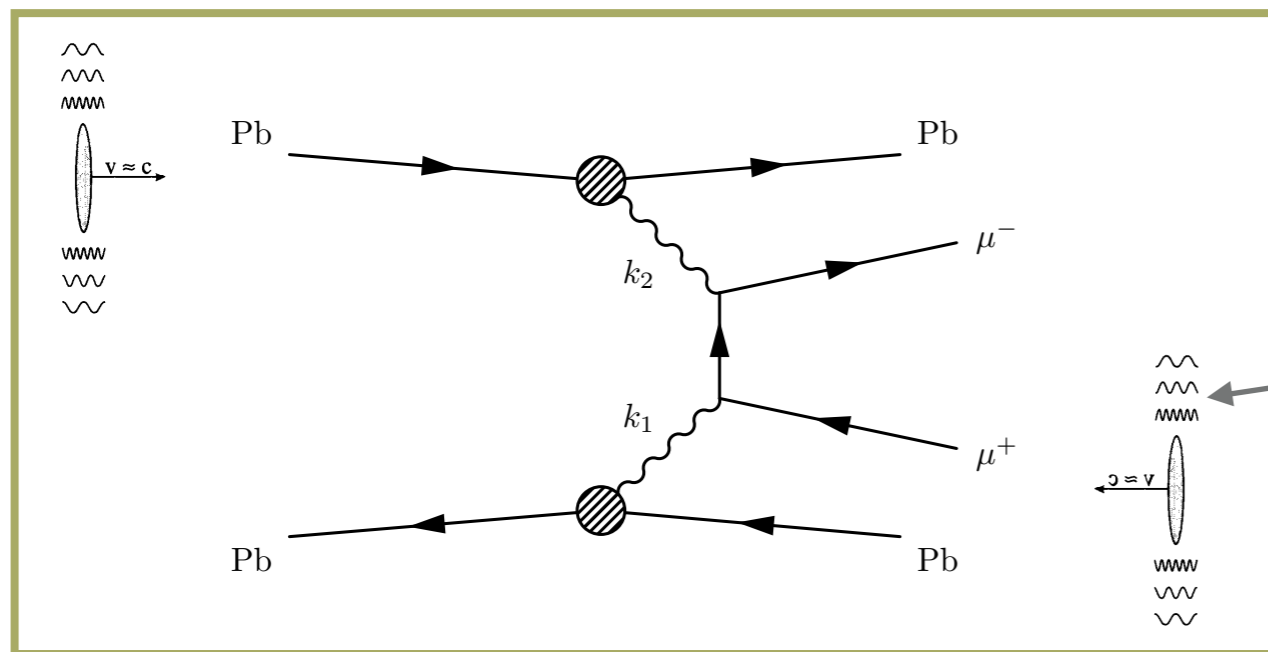
DILEPTONS FROM PHOTON-PHOTON COLLISIONS: THEORY

.....
STARLIGHT cross sections implement formalism from Baltz, et al (PRC80 044902, 2009)

$$\frac{d^2\sigma}{dM_{\mu\mu}dY_{\mu\mu}} = \frac{d^2\mathcal{L}_{\gamma\gamma}}{dM dY} \times \sigma(\gamma\gamma \rightarrow \mu\mu)$$

$\gamma\gamma$ luminosity QED cross section

Lumi. $\frac{d^2\mathcal{L}}{dM dY} = \mathcal{L}_{AA} \frac{M}{2} \int_{b_1 > R_A} d^2b_1 \int_{b_1 > R_A} d^2b_2 n(k_1, b_1) n(k_2, b_2) P(b) [1 - P_H(b)]$ $Z^4 \sim 45M!$



Nuclear photon flux from EPA:

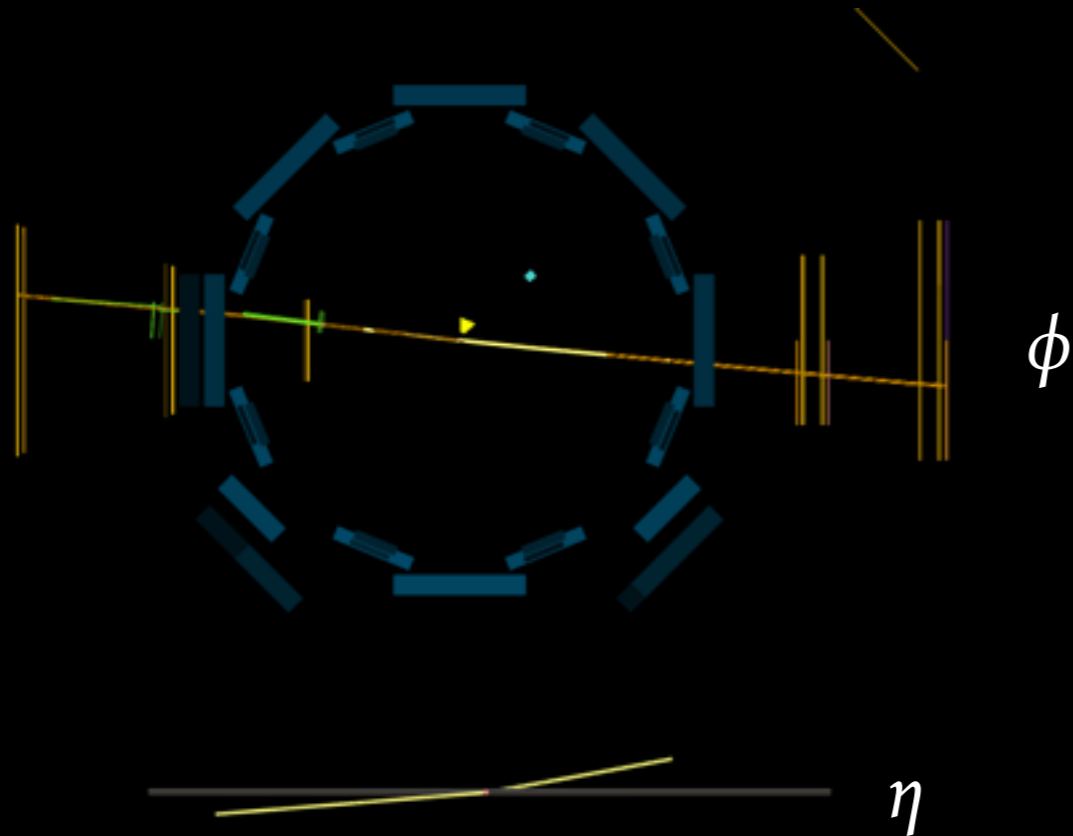
$$n(k, b) = \frac{d^3 N}{dk d^2 b} = \frac{Z^2 \alpha}{\pi^2 k b^2} x^2 K_1^2(x)$$

$x = bk/\gamma$

QED $\sigma_{\gamma\gamma} = \frac{4\pi\alpha^2}{W^2} \left[\left(2 + \frac{8M^2}{W^2} - \frac{16M^4}{W^4} \right) \ln \frac{W + \sqrt{W^2 - 4M^2}}{2M} - \sqrt{1 - \frac{4M^2}{W^2}} \left(1 + \frac{4M^2}{W^2} \right) \right]$

EVENT SELECTION

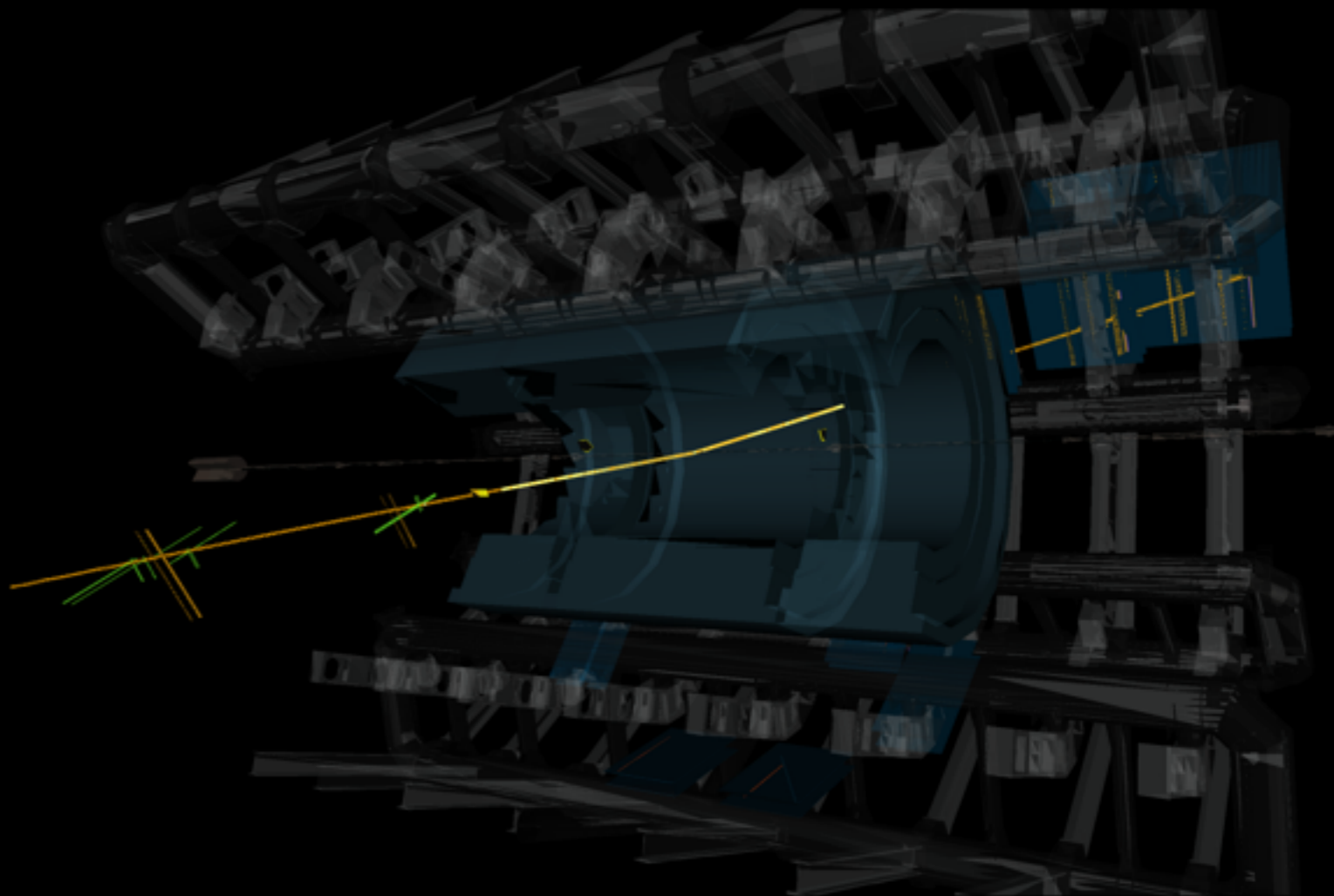
- For all triggered events (248k), a sequence of selections is applied
 - All events must come from runs for which detector was in good condition
 - Two good muons are required
 - both of which passing “tight” working point selections, requiring good compatibility between muon spectrometer and inner detector measurements
 - At least one of the muons must match a Level-1 muon (in cone with $\Delta R < 0.5$)
 - Muons pass fiducial kinematic acceptance, ensuring good performance of ATLAS muon spectrometer
 - **$p_{T1}, p_{T2} > 4 \text{ GeV}, |\eta_1|, |\eta_2| < 2.4, M_{\mu\mu} > 10$**
 - There exists a primary vertex in the event
 - Both muons match good inner detector tracks, which comprise the primary vertex
 - The muons have unlike signs
 - No other good tracks in the vertex than the muons
 - No other good tracks in the event
- After selections, 12069 events remain



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

*Highest-mass UPC dimuon event
 in 5.02 TeV data:*

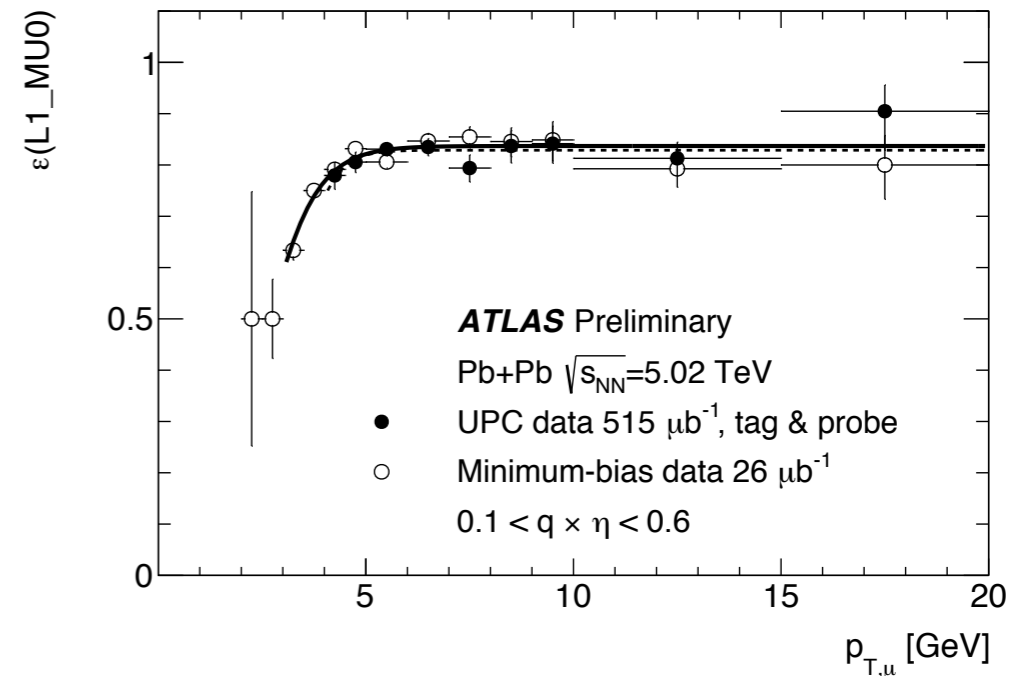
$$M_{\mu\mu} = 173 \text{ GeV}$$



CORRECTIONS

- To compare cross sections with theory calculations, must correct for detector effects

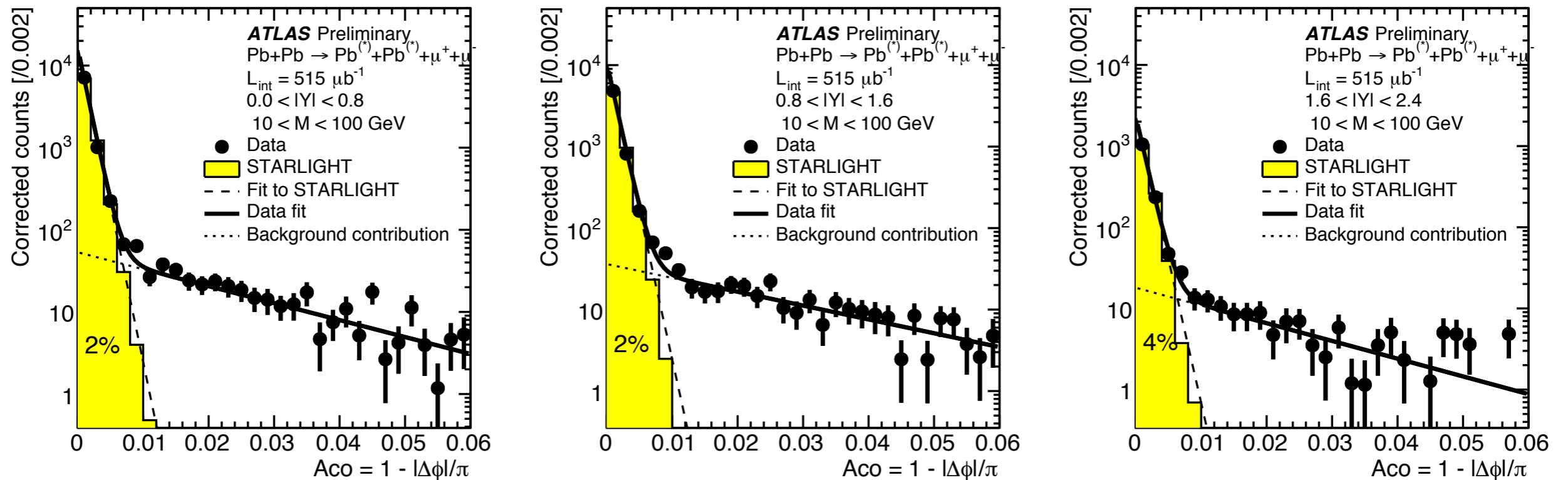
- Muon Trigger efficiency ($>80\%$) \longrightarrow
- Muon reconstruction and identification efficiency ($>90\%$)
- Vertex reconstruction efficiency ($\sim 97\%$ in MC)
- Contributions from possible backgrounds
- Effects from momentum resolution found to be negligible (within $\sim 1\%$)



- Event weight formed from factorized trigger (T) & reco (R) efficiency correction (each separately as function of p_T and $q \times \eta$)

$$\frac{1}{w} = \epsilon_R(\mu_1)\epsilon_R(\mu_2)(1 - (1 - \epsilon_T(\mu_1))(1 - \epsilon_T(\mu_2)))$$

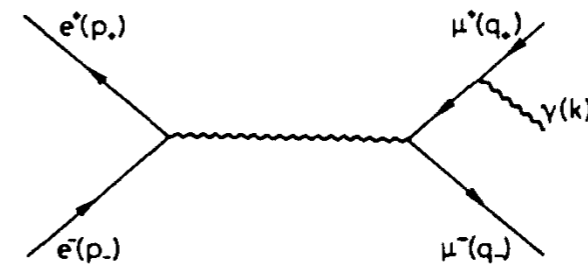
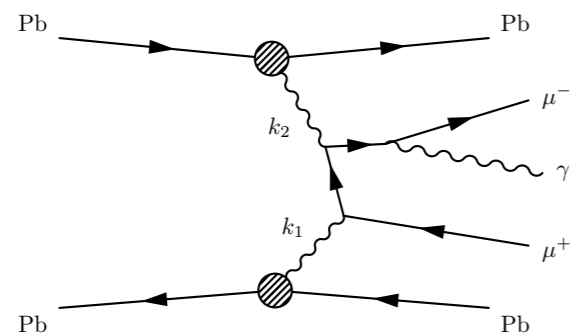
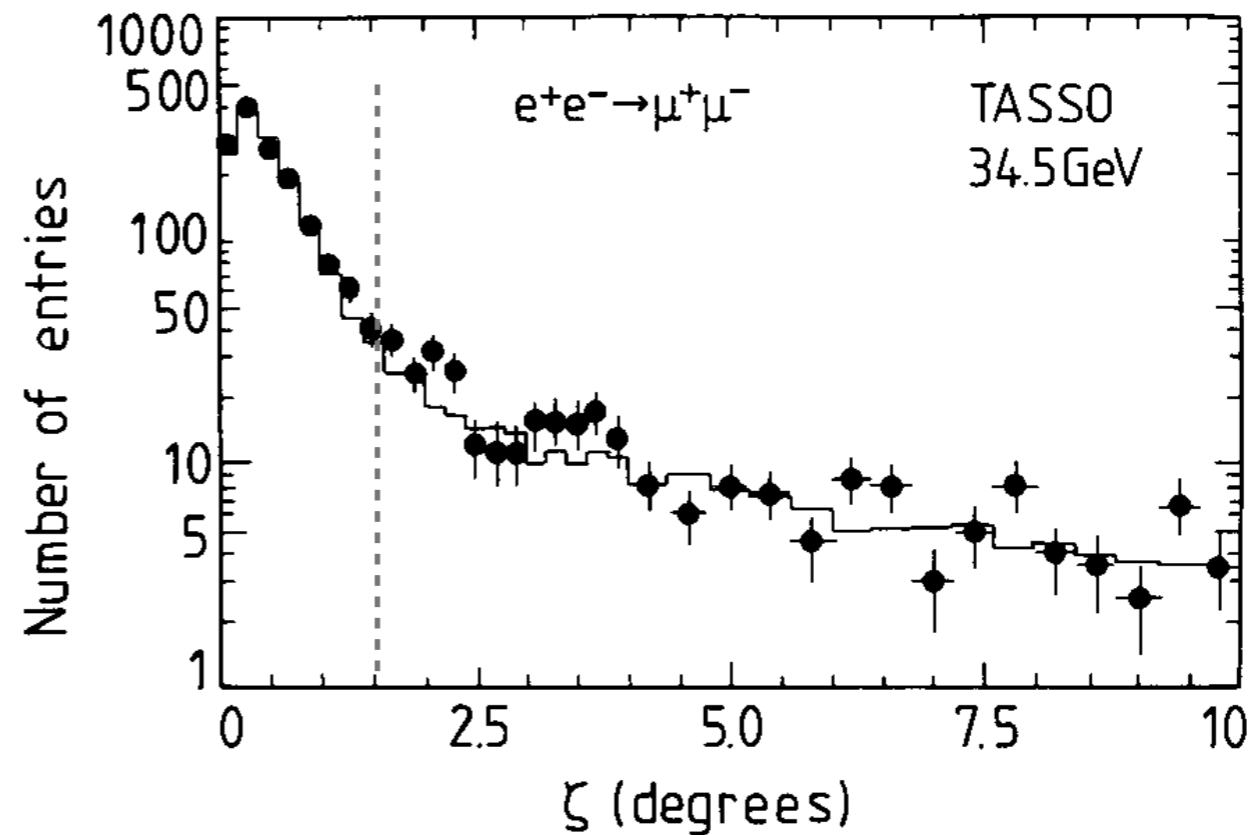
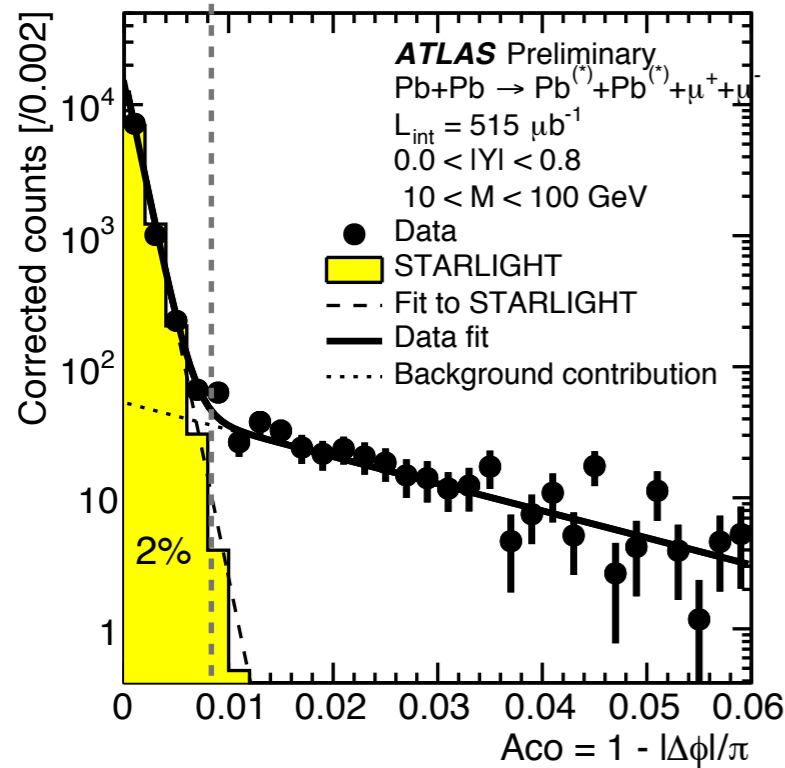
ACOPLANARITY DISTRIBUTIONS



- Due to nuclear form factor, UPC dimuon distributions should have pair $p_{T\mu\mu} \sim 0$ and thus small acoplanarity ($A_{co} = 1 - |\Delta\phi|/\pi$)
- A_{co} distributions shown here in 3 rapidity bins, $10 < M_{\mu\mu} < 100 \text{ GeV}$
- Good agreement with STARLIGHT in the bulk
 - N.B. STARLIGHT does not incorporate QED final-state radiation (FSR)

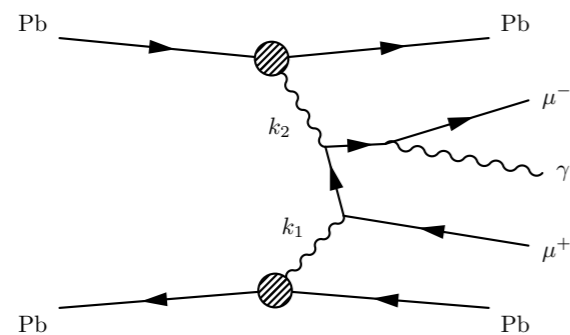
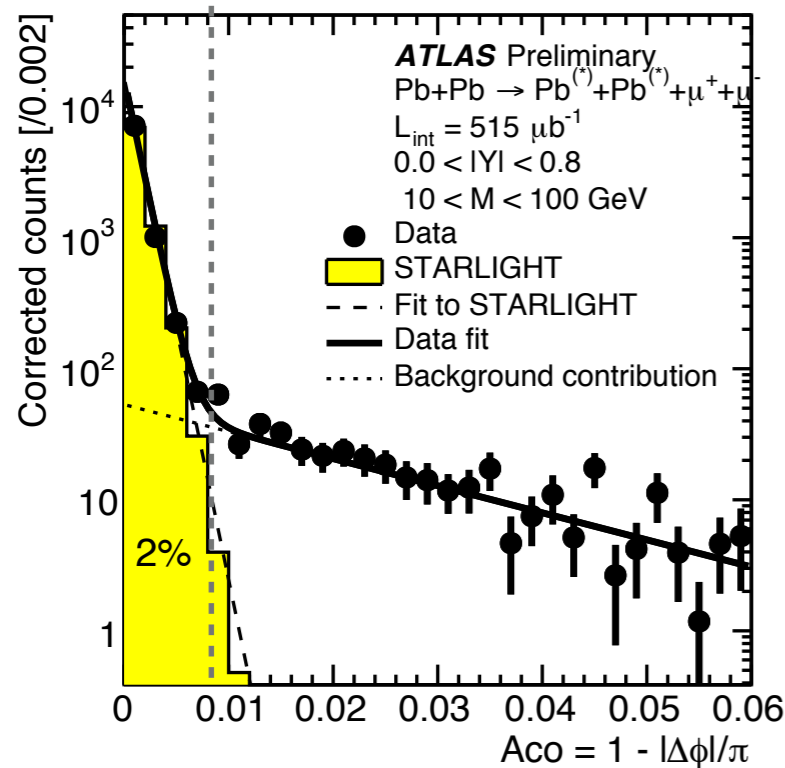
ACOPLANARITY & HIGHER-ORDER QED

M. Althoff et al.: Electroweak Couplings from $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$



- Radiative corrections $\mathcal{O}(\alpha^3)$ involve an additional real photon in the final state
- Expected to broaden $\mu^+\mu^-$ acoplanarity distribution, similar to what is seen in e^+e^- (e.g. TASSO, shown here)
 - Dotted line positioned at $A_{\text{co}}=0.008$ (corresponding to 1.44 degrees)

ACCOUNTING FOR ACOPLANARITY TAILS



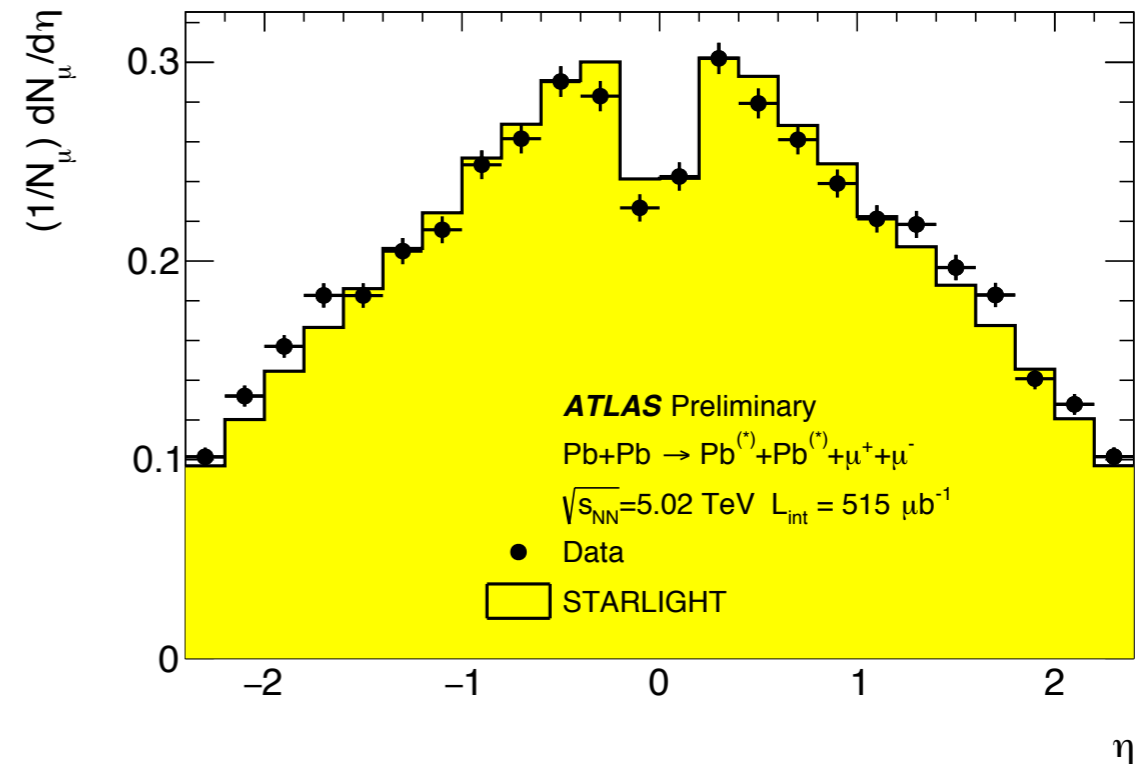
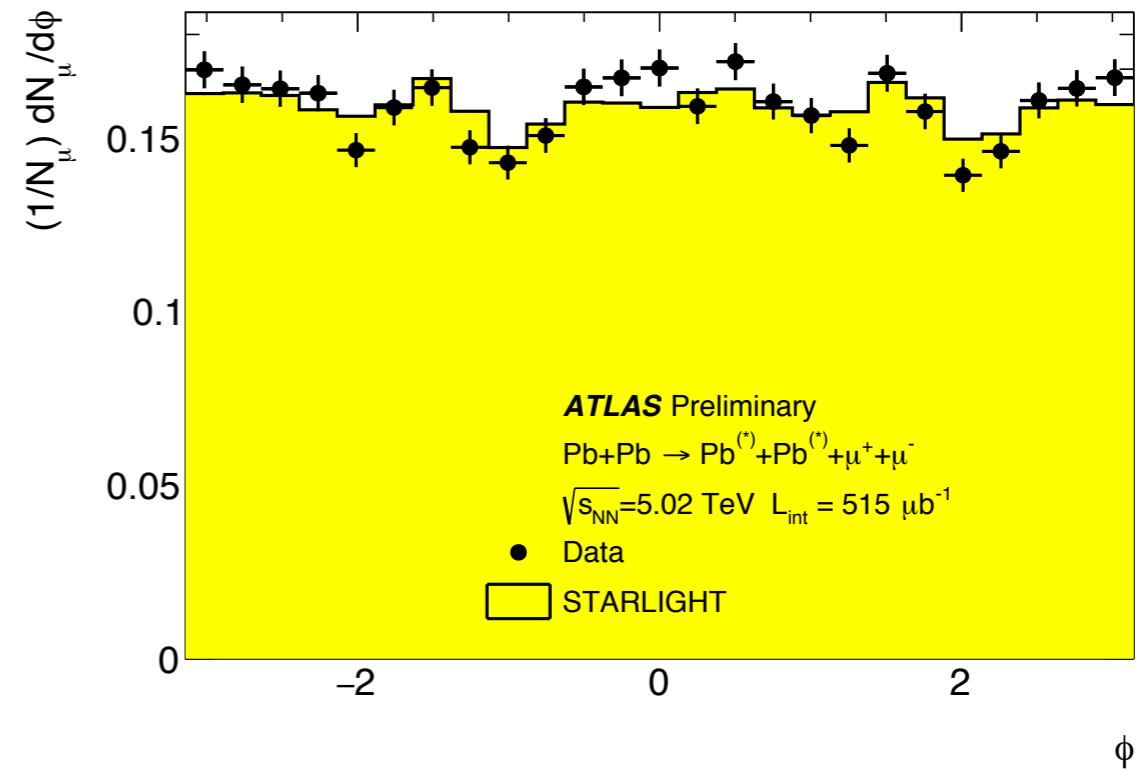
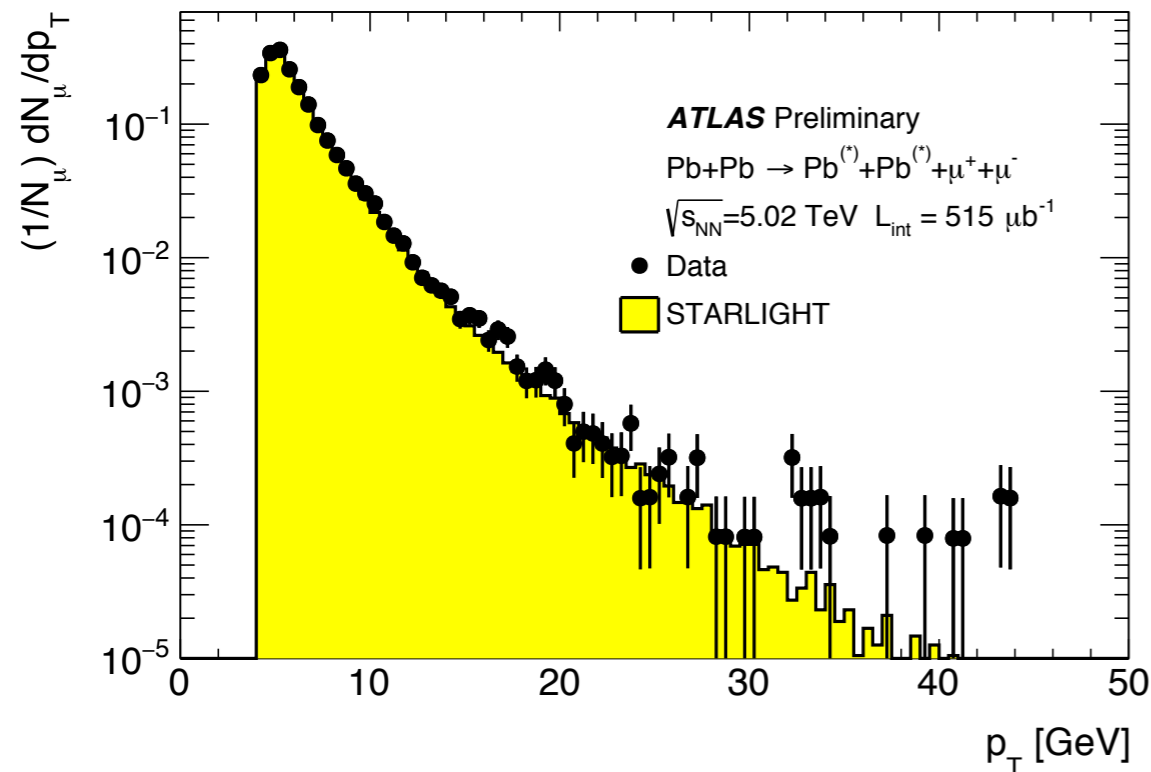
- Reported cross sections allow for both scenarios to be true
- The tails are all backgrounds: thus we select $A_{co} < 0.008$, and use the fits shown previously to extrapolate the tail into this region.
 - This is a 2-4% correction, depending on $Y_{\mu\mu}$
- The tails are all signals: all events are used, regardless of A_{co}
- The average of the results is presented as the central value
 - The systematic uncertainty is half the difference

SYSTEMATIC UNCERTAINTIES

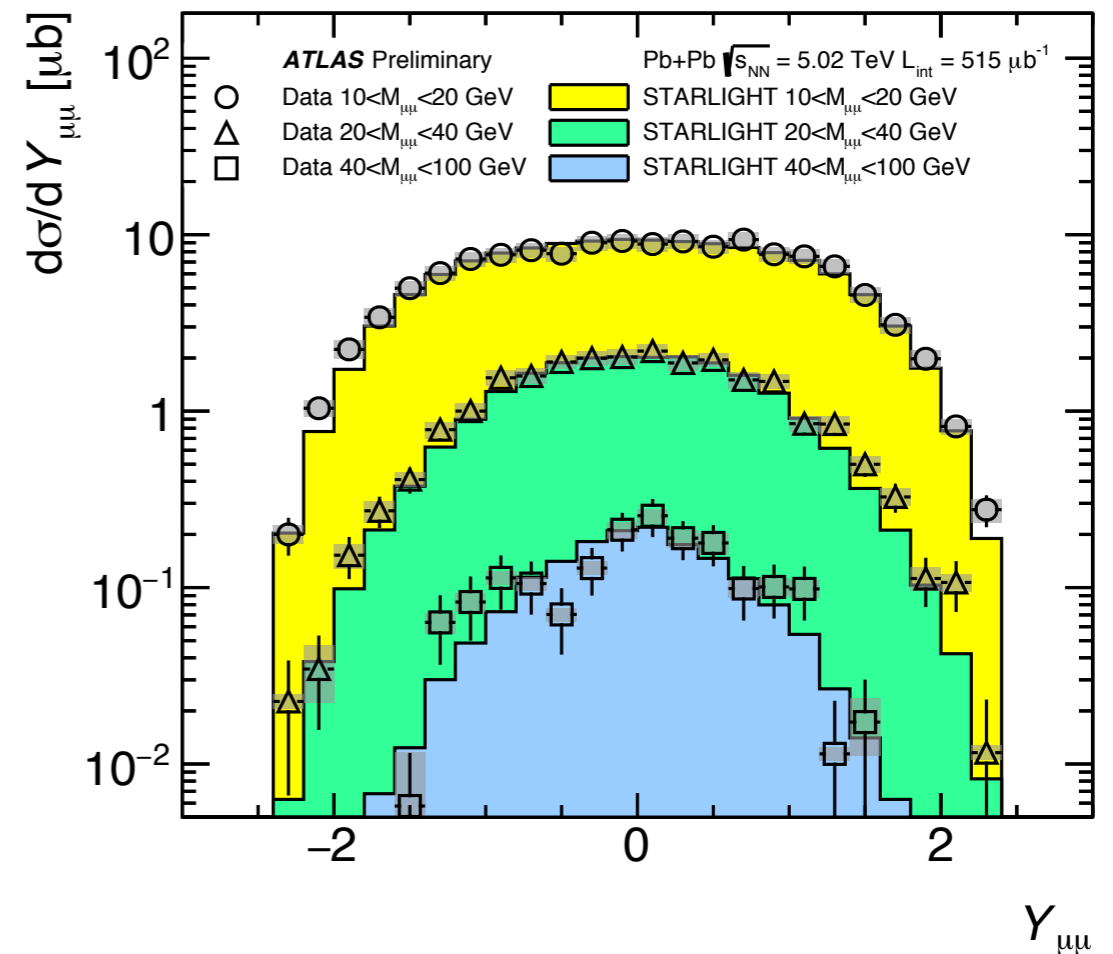
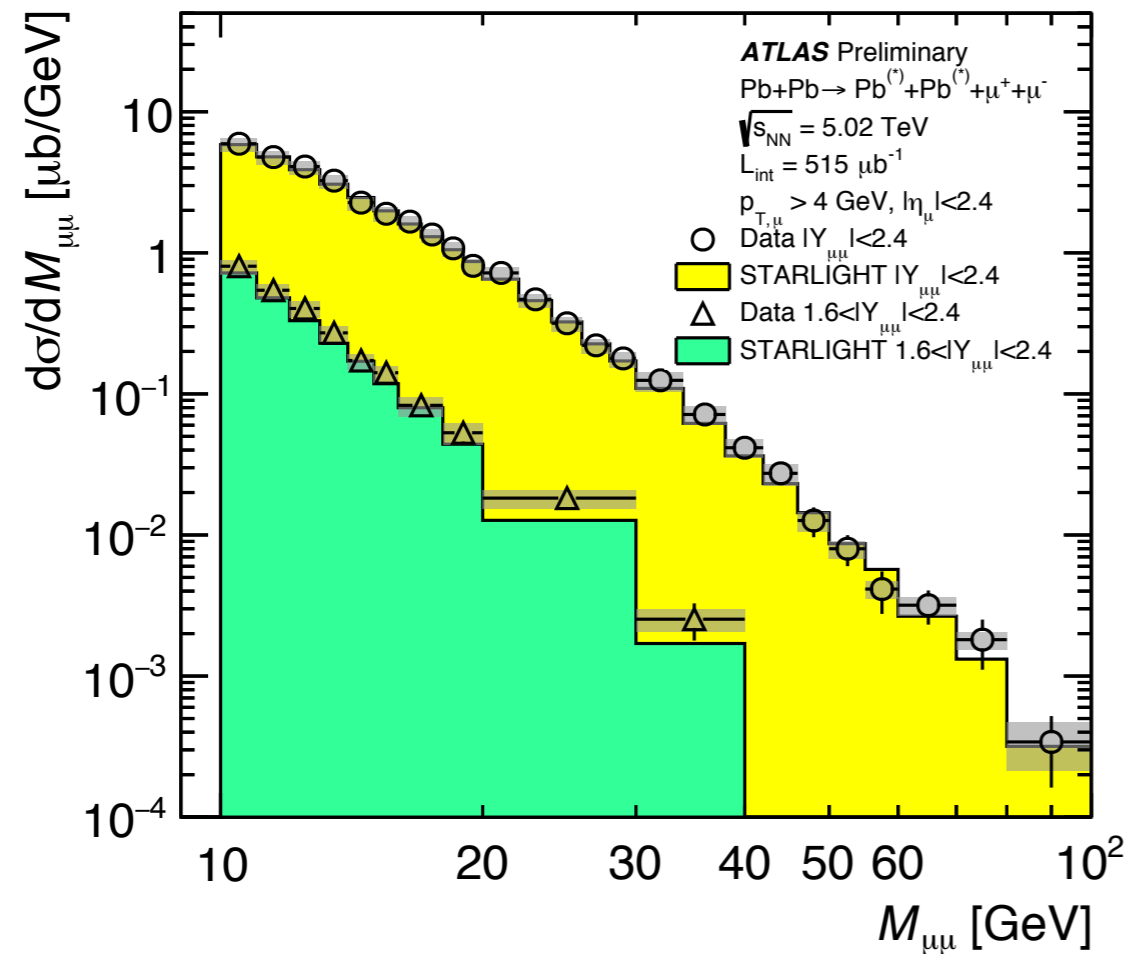
- Muon trigger efficiencies
 - Agreement between minimum-bias and T&P methods good to 5%
- Reconstruction efficiencies
 - Nominal muon uncertainties, based on systematic assessment of data/MC differences, are 2-4%
 - Using looser (“medium”) identification requirements gives good agreement for $M_{\mu\mu} < 30$ GeV, and 10% difference for $M_{\mu\mu} > 30$ GeV.
- Unfolding uncertainties
 - 1% uncertainty assigned due to fluctuations in bin-by-bin factors
- Vertex efficiency
 - Data vs. MC gives 2.2% difference. 3% uncertainty assigned
- Background estimation
 - Uncertainty includes assumptions that Aco tails are all background, and all signal
- MC closure is good to 2% level
- Luminosity uncertainty assigned to be 7%
- ~10-12% uncertainty overall

RESULTS: SINGLE MUON DISTRIBUTIONS

- Distributions of single muons, after full dimuon selections
- Data only corrected for dimuon trigger efficiency

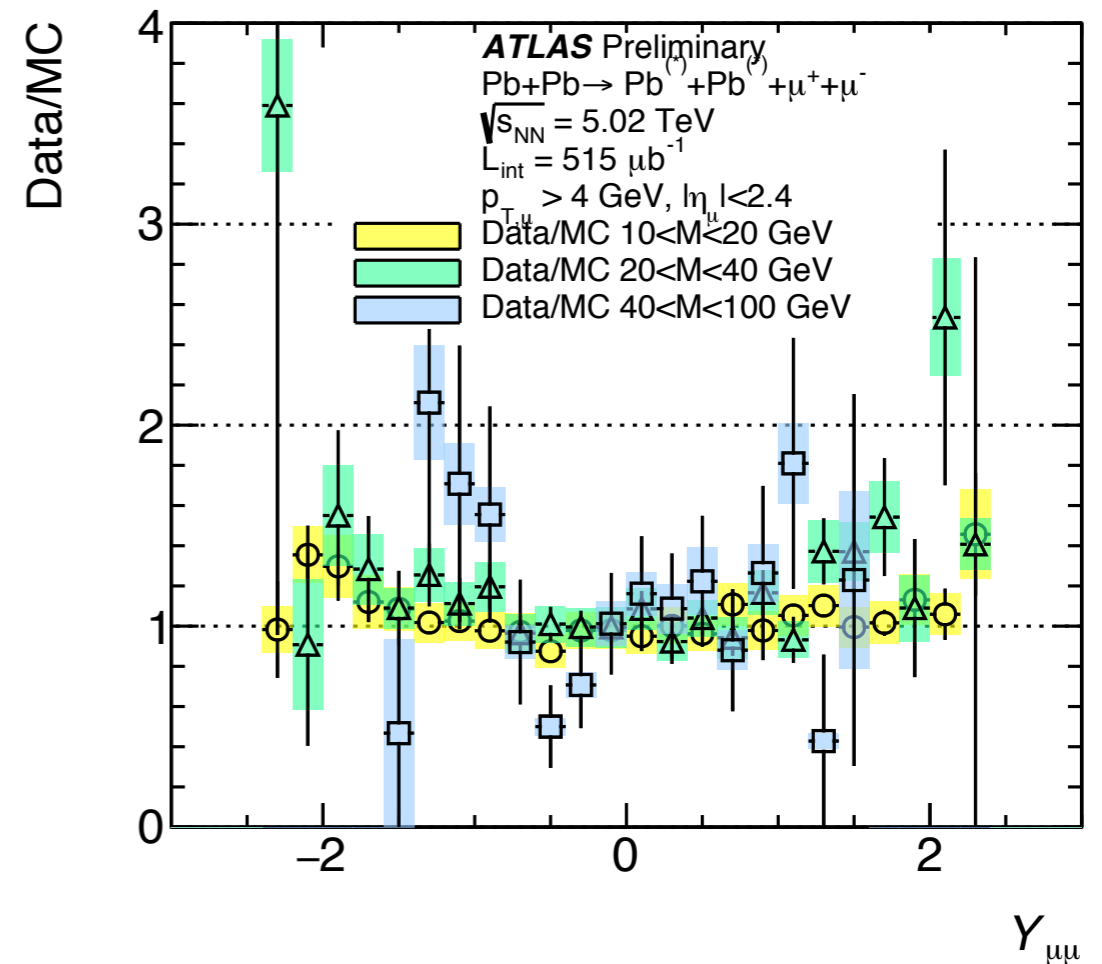
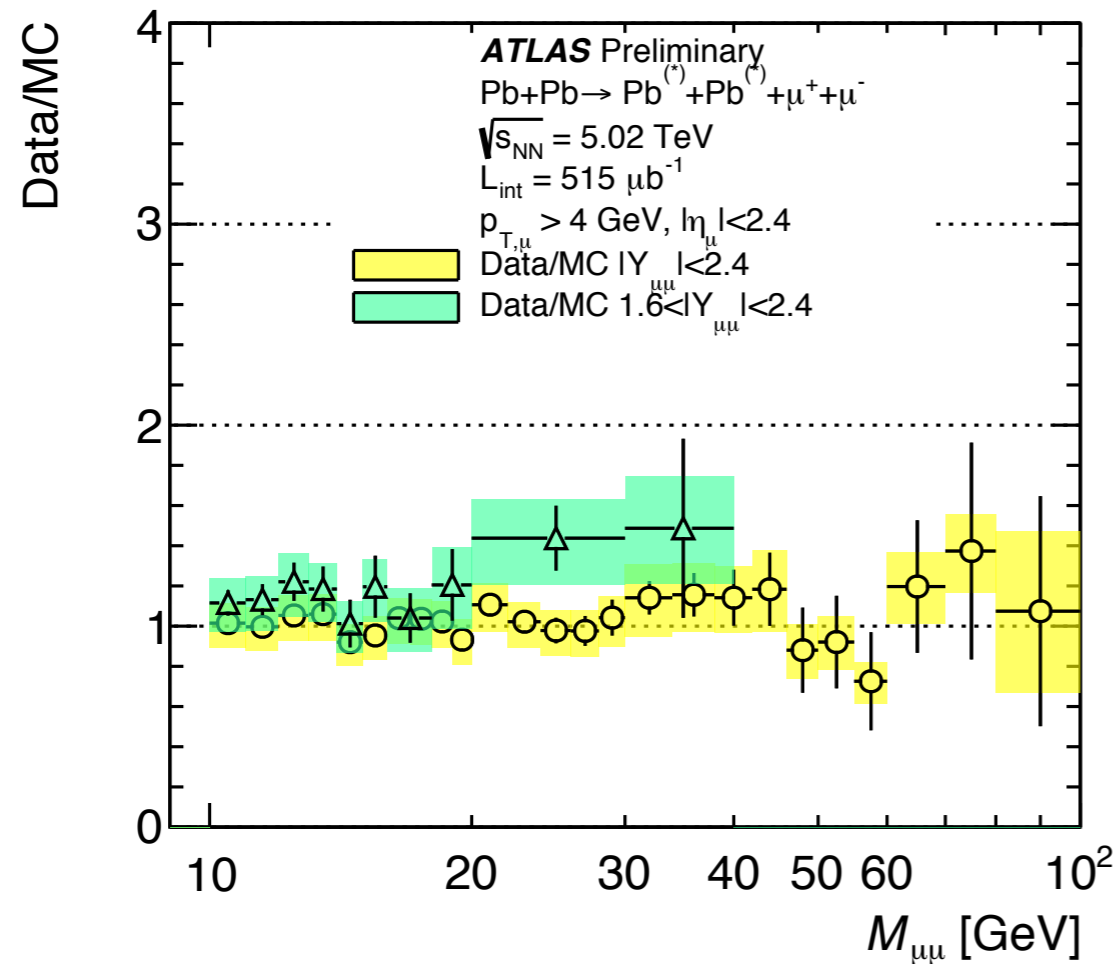


PAIR CROSS SECTIONS VS. MASS AND RAPIDITY



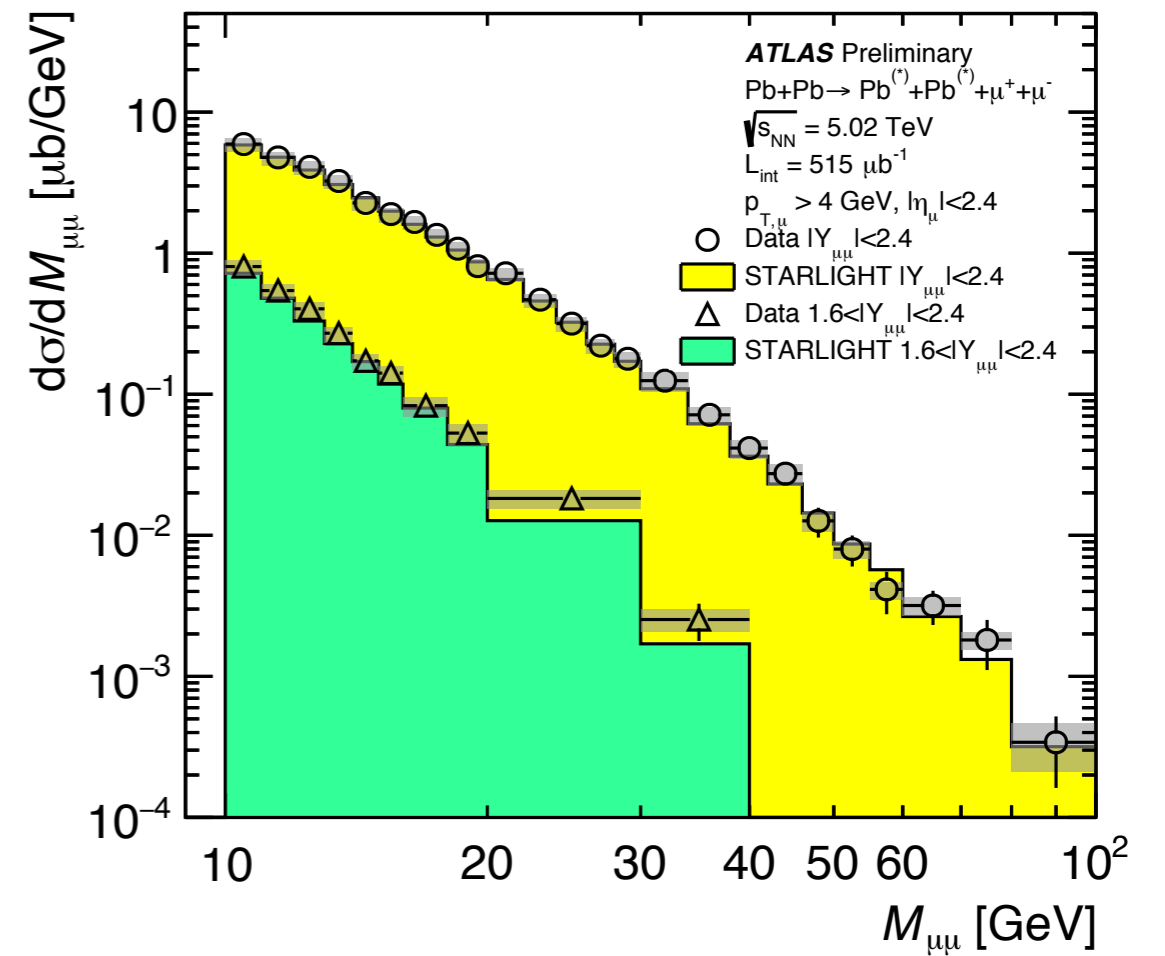
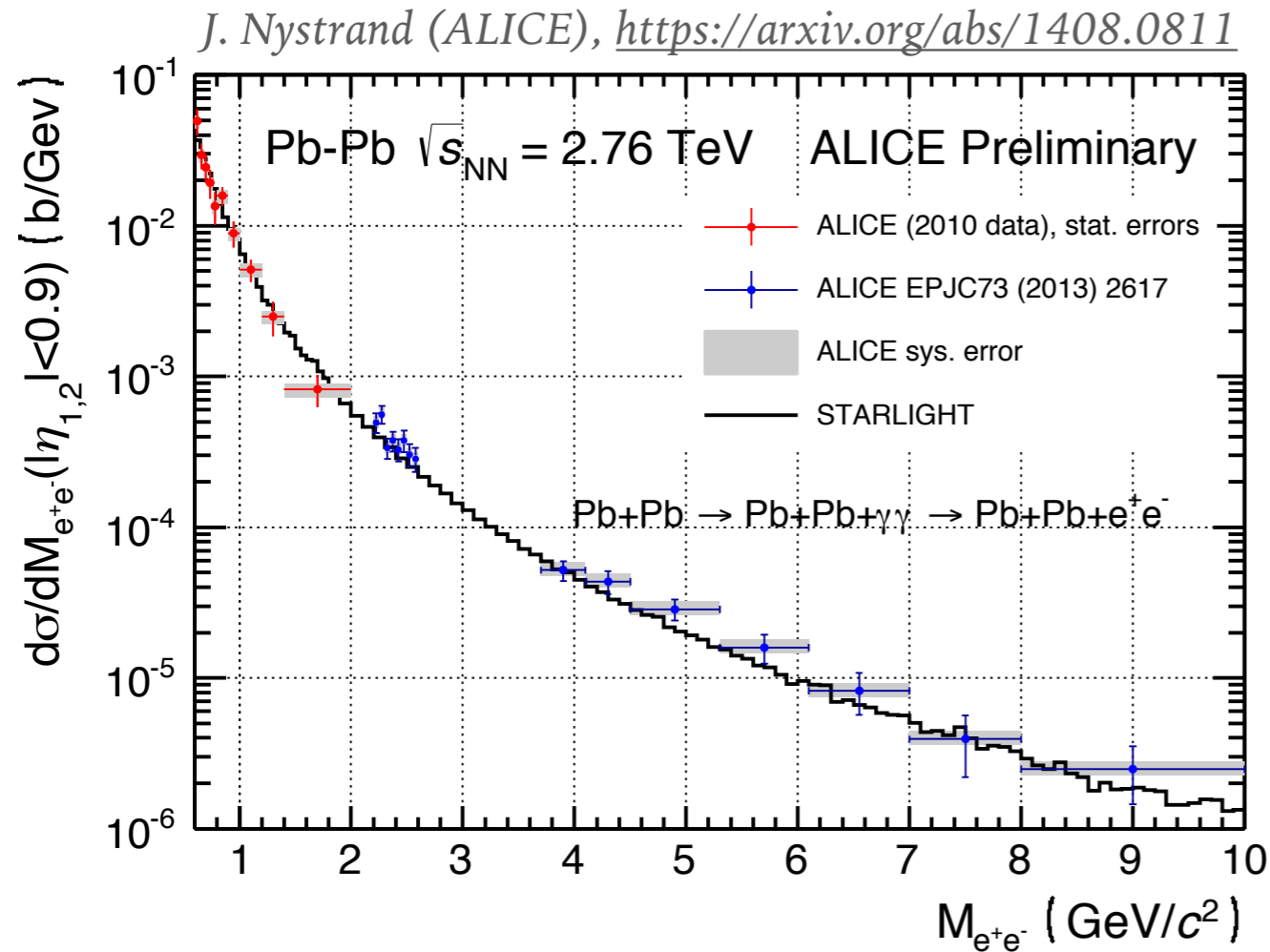
- $d\sigma/dM_{\mu\mu}$ shown for $|Y_{\mu\mu}| < 2.4$ and $|Y_{\mu\mu}| > 1.6$
- $d\sigma/dY_{\mu\mu}$ shown for $10 < M_{\mu\mu} < 20$, $20 < M_{\mu\mu} < 40$, $40 < M_{\mu\mu} < 100 \text{ GeV}$
- Truth STARLIGHT 1.1 (for $\gamma=2705$) shown in solid histograms

RATIOS RELATIVE TO STARLIGHT



- Ratios relative to STARLIGHT
- Surprisingly good agreement over full range in $M_{\mu\mu}$ and $Y_{\mu\mu}$
- Verifies both overall Z^4 scaling of $\gamma\gamma$ luminosity & γ spectrum

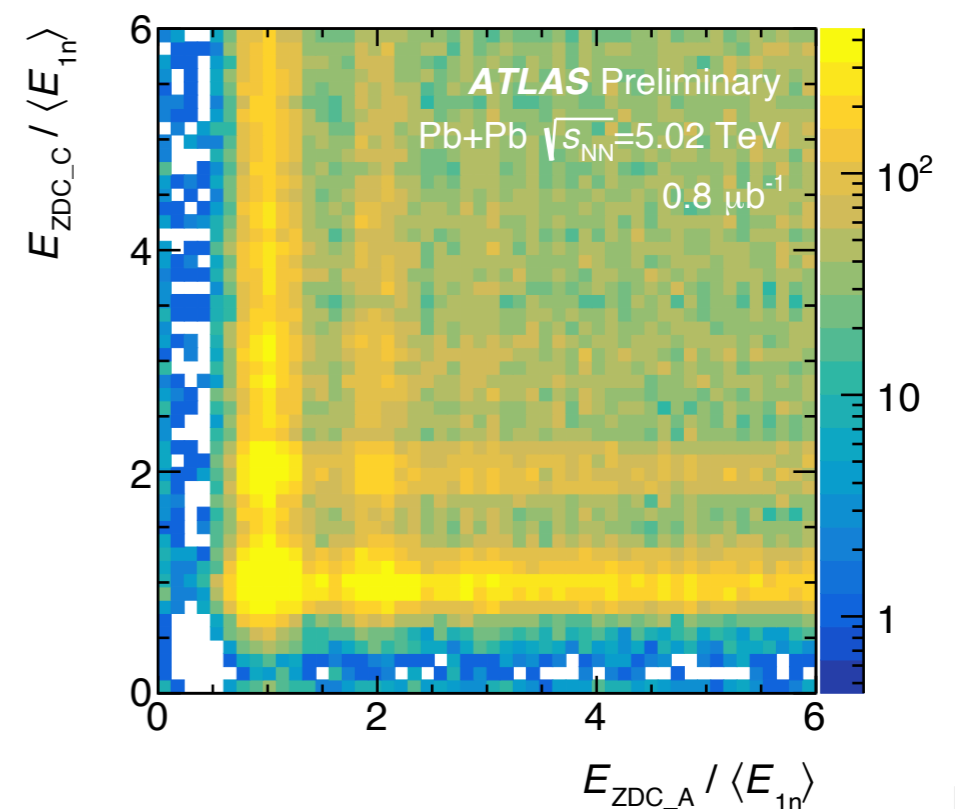
ALICE & ATLAS RESULTS



Different beam energies, but confirms expectations over >2 orders of magnitude in M_{ll}

CONCLUSIONS & OUTLOOK

- First ATLAS measurement of high-mass muon pairs from ultra-peripheral collisions in lead-lead collisions at 5.02 TeV
- Good agreement with STARLIGHT 1.1 calculations
 - Verification of expected photon flux
 - Precision now limited by lack of higher-order QED calculations
- These measurements are just the first step in the ATLAS UPC program
 - Adding ZDC selections will probe impact parameter dependence in more detail
 - ZDC-tagged events should have smaller impact parameter, and thus harder colliding photon spectra
- Next steps will be to probe nuclear wave function, including
 - Vector mesons (ρ and J/Ψ)
 - Jet production in photonuclear processes

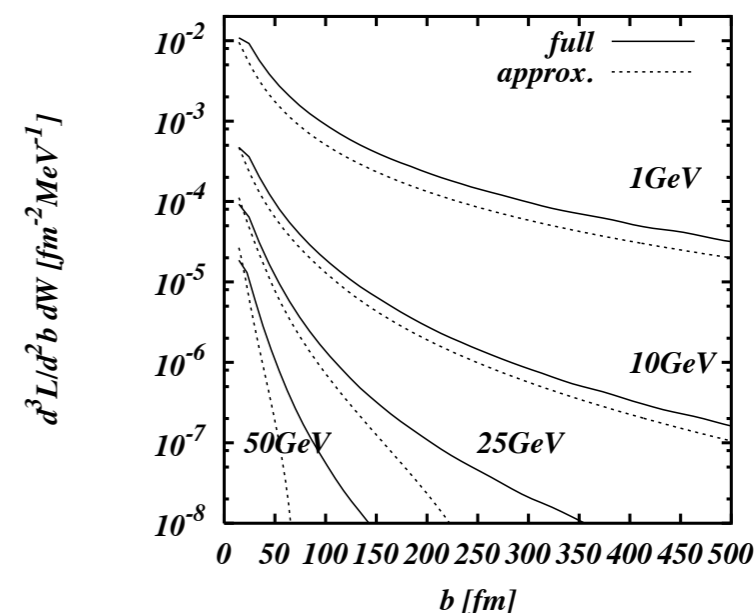


EXTRA SLIDES

CONNECTION WITH FORWARD NEUTRONS

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- In principle, the nuclei can exchange additional photons during the collision, exciting one or both nuclei (e.g. nucl-th/0307031) via the giant dipole resonance (GDR) (referred to as “Pb^{*}”)
 - Excited nuclei emit one or more neutrons
- These are more likely for smaller impact parameters between the nuclei
- However, the impact parameter also controls the two-photon luminosity
 - Higher masses are enhanced more at smaller impact parameters
- Thus, expect ZDC-tagged events to have harder spectra than events only triggered on the muons
 - In this measurement we only trigger on the muons, such that the ZDC could be used to independently study this effect
- The next iteration of this measurement will include ZDC selections



MUON TRIGGER EFFICIENCY

- Single-muon trigger efficiency measured using 2015 Pb+Pb data
- Measured in two ways
 - Single muons in minimum-bias HI data
 - Coincidence of tight offline muon and Level-1 muon in $\Delta R < 0.5$
 - Perform in FCal E_T bins (here using < 1000 GeV)
 - Tag and probe (T&P) in UPC dimuon events
 - For events with two tight muons, at least one of which coincides with Level-1 muon (to trigger event), if the pair has $p_T < 500$ MeV, then the other muon can be used as a probe
- Good ($< 5\%$) consistency between the two, limited by statistical precision of T&P:
 - Fits performed to minimum-bias data since it has better statistical precision