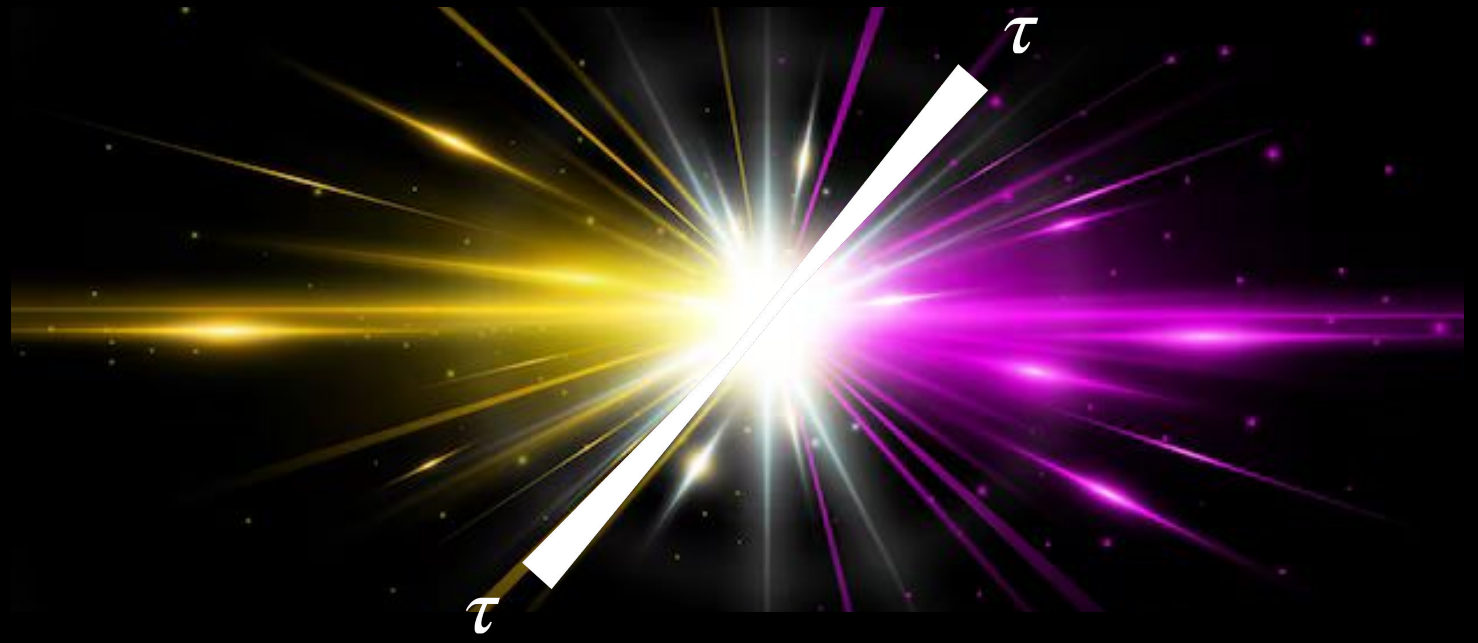
Measuring photon-induced tau-lepton pair production with ATLAS



Lydia Beresford on behalf of the ATLAS collaboration

EPS-HEP, 8th July 2025

HELMHOLTZ

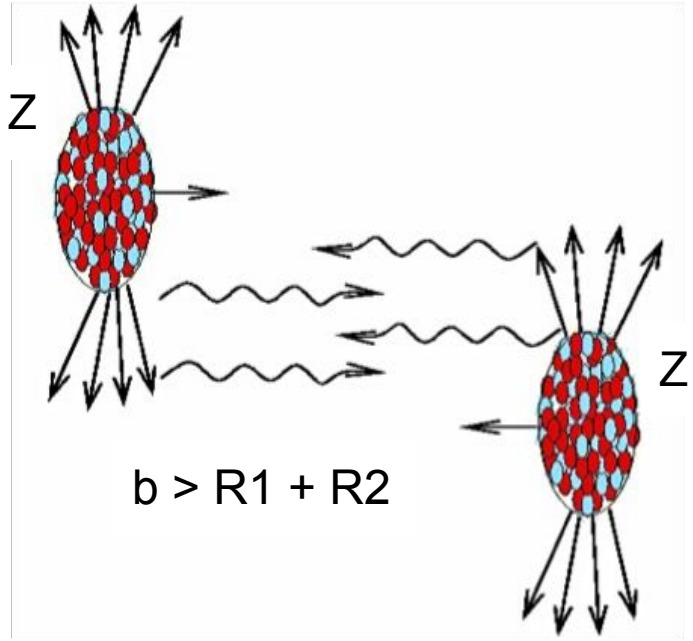
DESY.

LHC as a photon collider

LHC heavy ions are charged so surrounded by EM fields

→ Cloud of quasi-real photons

Ultra-peripheral collision (UPC): impact parameter > 2 x ion radius (b > R1+R2)

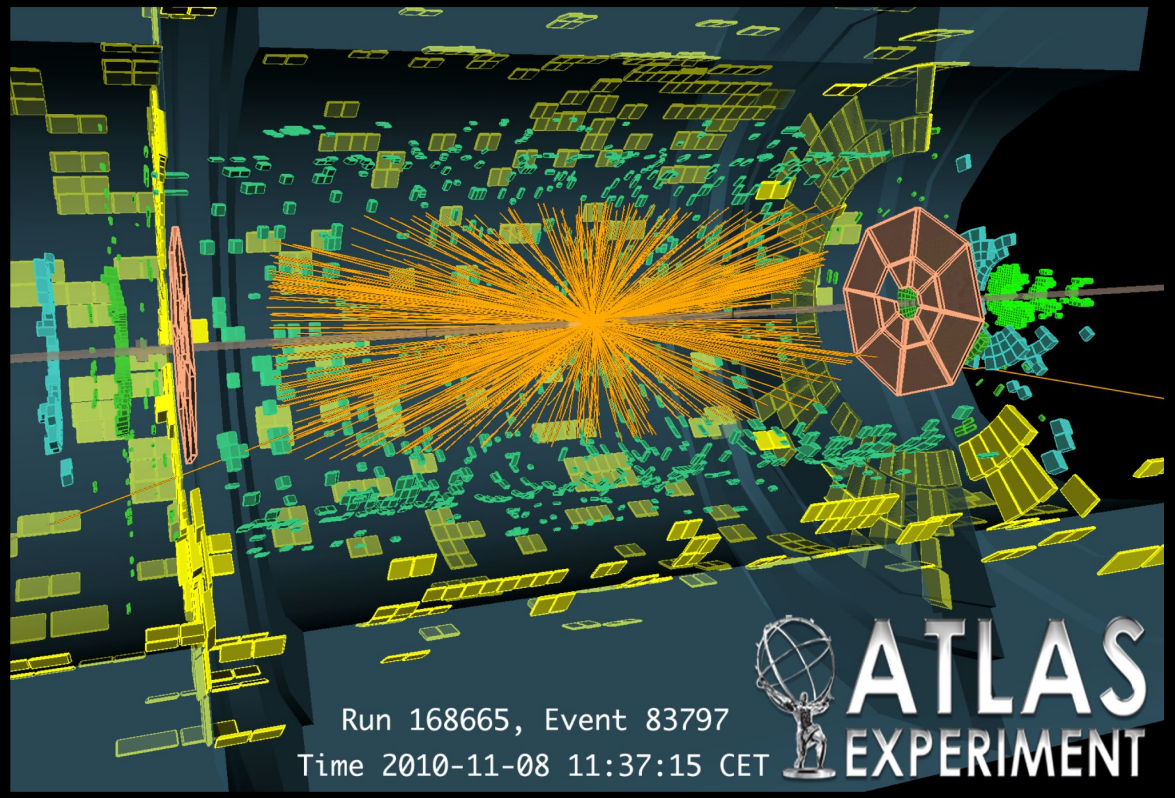


Photon-collisions in UPC Pb+Pb:

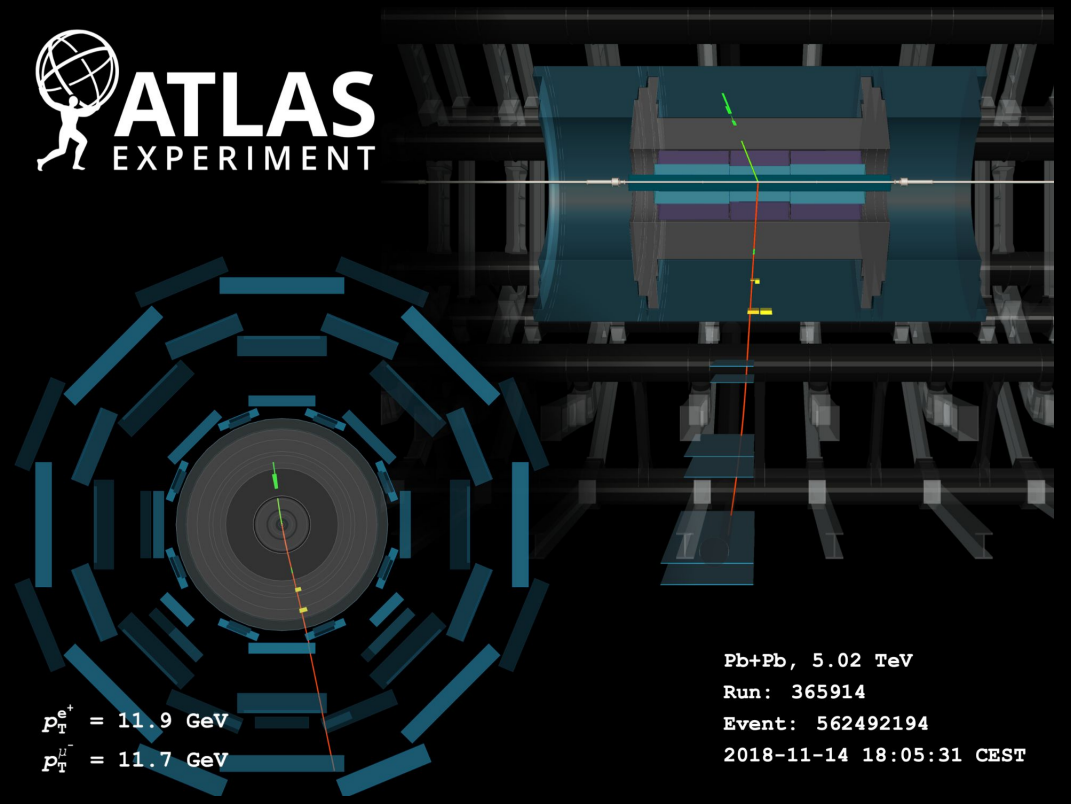
- Z^4 cross-section enhancement (Z=82)
- Low trigger thresholds → Access unique phase space wrt protons
- Super clean with ~0 pile-up

LHC heavy ion collisions

Head-on Pb+Pb collision



Ultra-peripheral Pb+Pb collision



Overview

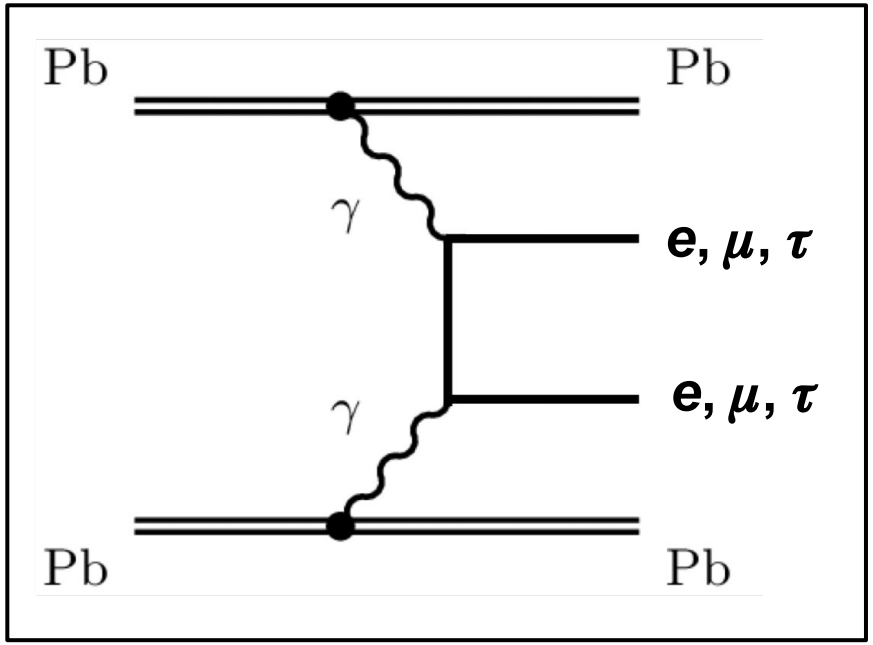
ATLAS has measured differential cross-sections for a range of UPC processes in $\sqrt{s_{NN}}$ = 5.02 TeV Pb+Pb collisions:

Leptons:

- $\gamma\gamma \to ee$ JHEP 06 (2023) 182
- $\gamma\gamma \to \mu\mu$ PRC 104, 024906

3rd generation leptons:

$\gamma\gamma \to \tau\tau$ observation PRL 131, 151802



Today: 1st differential $\gamma\gamma \to \tau\tau$ cross-section measurements in Pb+Pb at LHC

ATLAS-CONF-2025-004

From observation to measurement

Use 1.93 nb^{-1} ATLAS Pb+Pb Run 2 data set (2015+2018), $\sqrt{s_{NN}}$ = 5.02 TeV

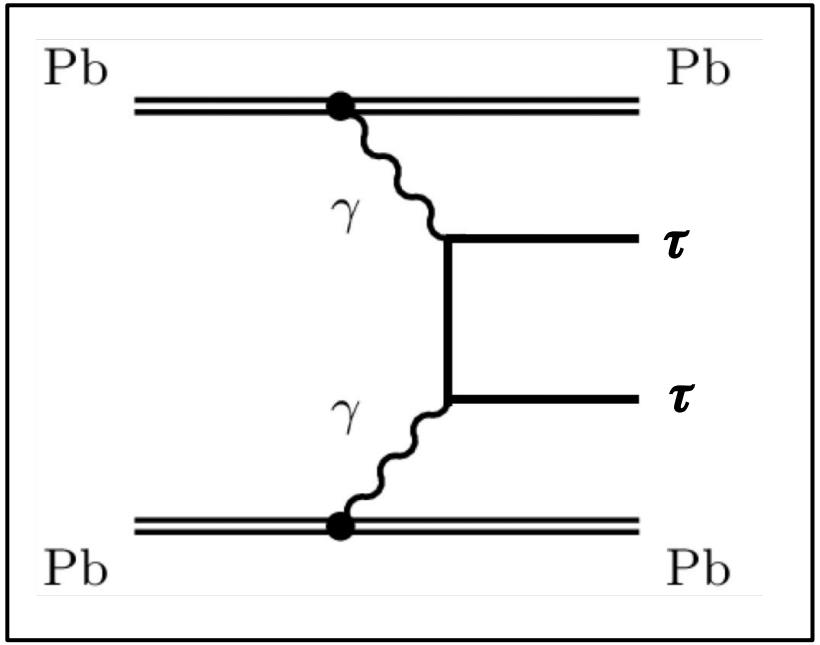
Two-photon luminosity:
Depends on photon-flux & survival factor

Total cross-section:

$$\sigma(A_1A_2 \xrightarrow{\gamma\gamma} A_1A_2 + X) = \int dk_1 dk_2 \, \frac{d^2N_{\gamma\gamma}}{dk_1 dk_2} \, \hat{\sigma}_{\gamma\gamma\to X}$$

Hard scattering:

Sensitive to tau-lepton anomalous electromagnetic moments, spin correlations, tau-lepton decay modelling etc



Tau decays

The only lepton heavy enough to decay to hadrons

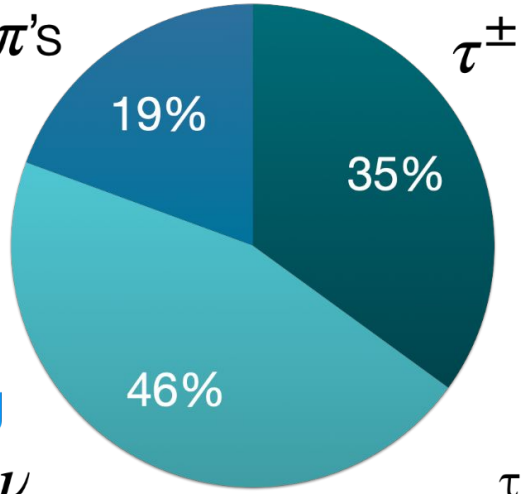
3 prong

$\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$

+ $\geq$ 0 neutral π's

Leptonic

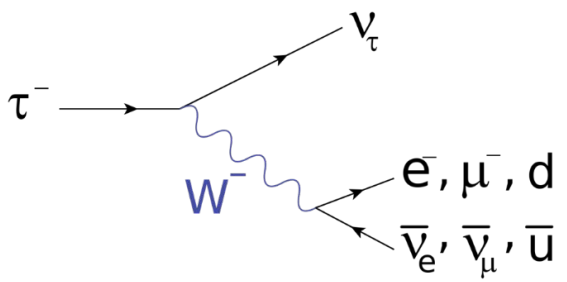
$\tau^{\pm} \rightarrow l^{\pm}\nu_{l}\nu_{\tau}$



1 prong

$\tau^{\pm} \rightarrow \pi^{\pm}\nu_{\tau}$

+ $\geq$ 0 neutral π's



$\gamma\gamma \rightarrow \tau\tau$ MC: Starlight + Tauola (Pythia 8 & Photos for QED FSR),

Photon flux re-weighted to SuperChic 3

Signature

Low momentum taus (up to a few 10s GeV)

Below ATLAS hadronic tau reconstruction threshold

Use leptons: $p_T(e/\mu) > 4$ GeV & tracks: $p_T(\text{trk}) > 100$ MeV

Signal Regions (SRs)

μ+e

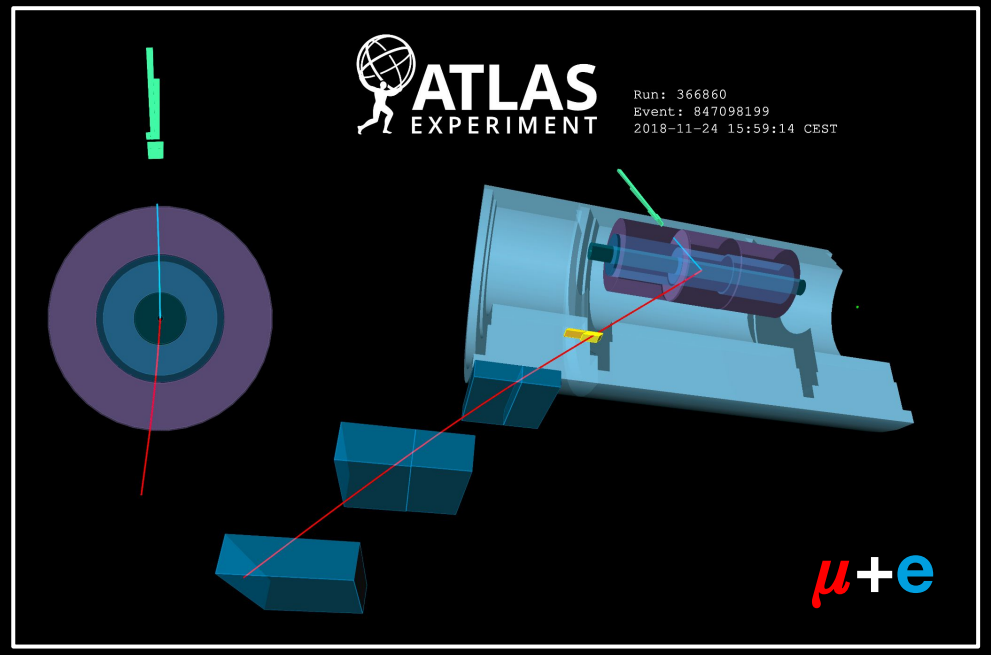
μ+**1 track** (from lepton or hadron)

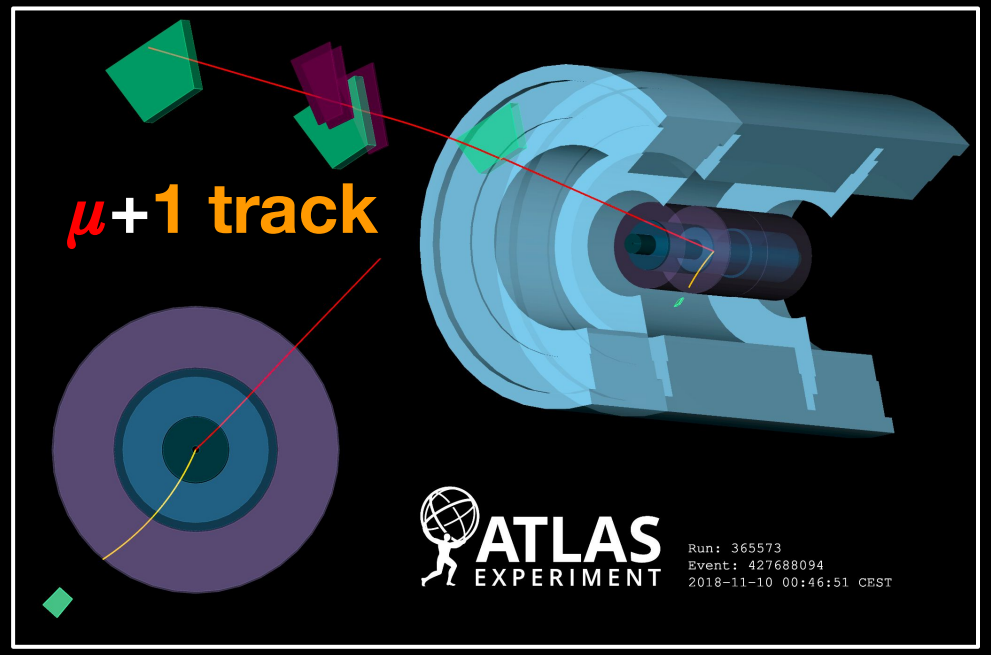
μ+**3 track** (from 3-prong τ decay)

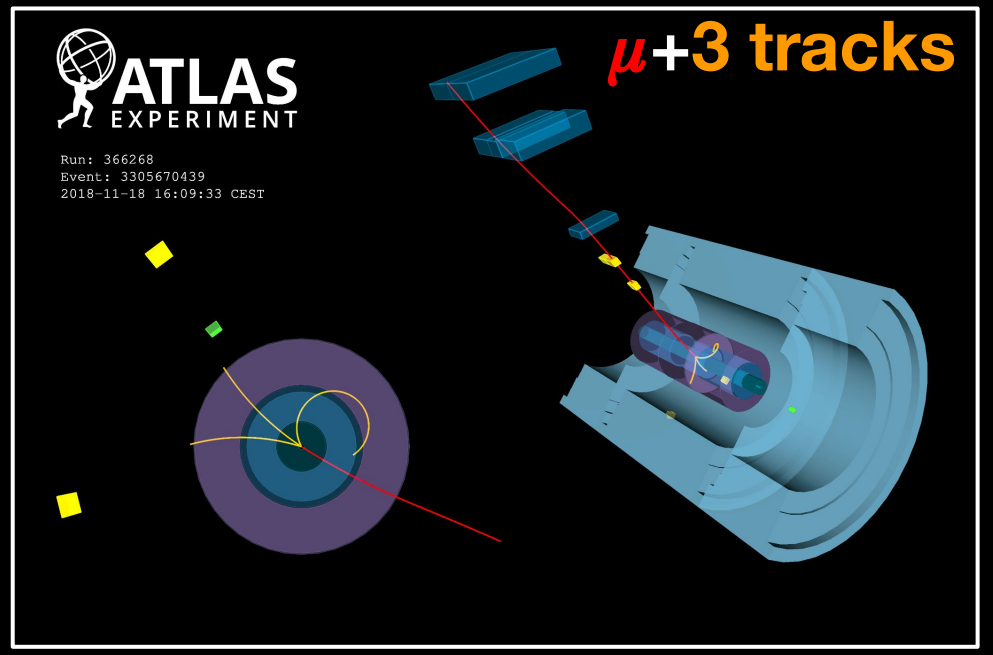
← **Trigger on muon**

p_T > 4 GeV

Signal candidates

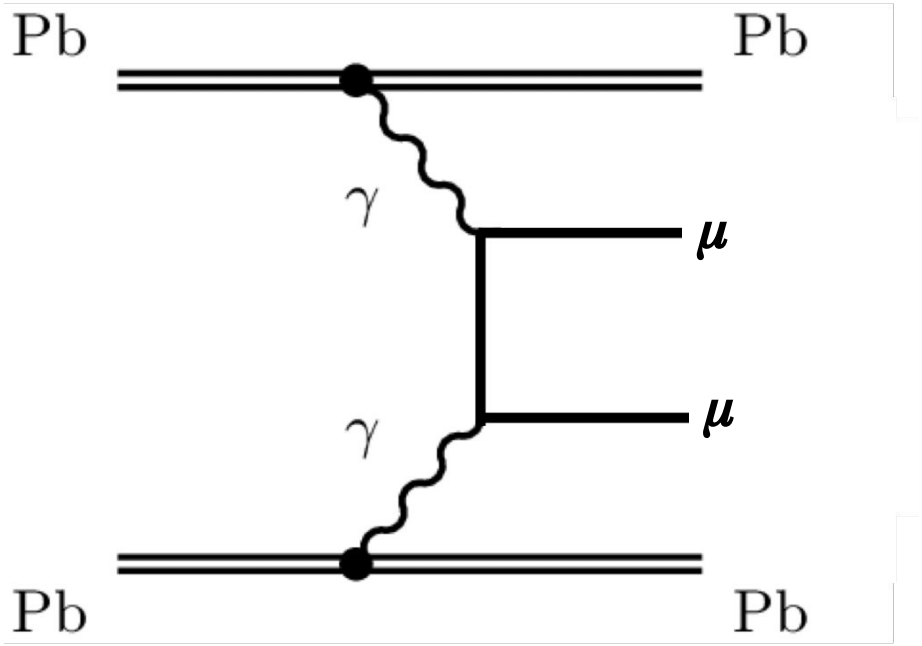




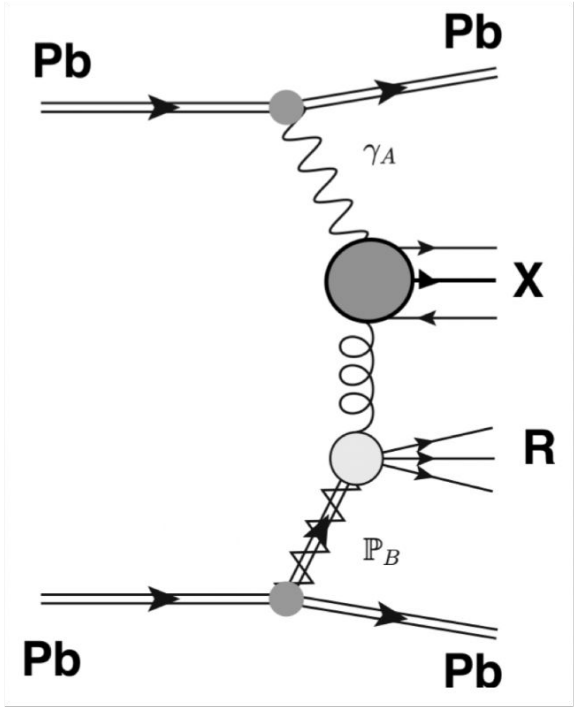


Main backgrounds

$\gamma\gamma \to \mu\mu(\gamma)$



Diffractive photo-nuclear



Estimate with MC

$\gamma\gamma \to \mu\mu$ Starlight + Pythia8

$\gamma\gamma \to \mu\mu\gamma$ Madgraph 5

Photon flux re-weighted to SuperChic 3

Data-driven estimate

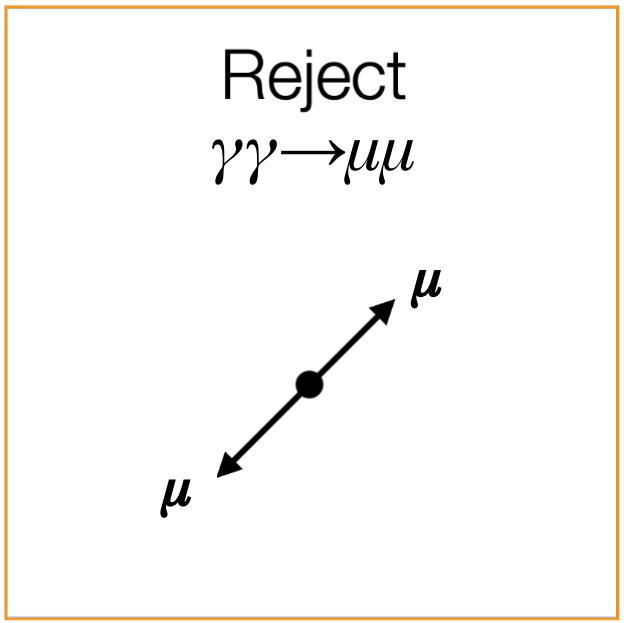
Often leads to nuclear breakup

→ Forward neutrons

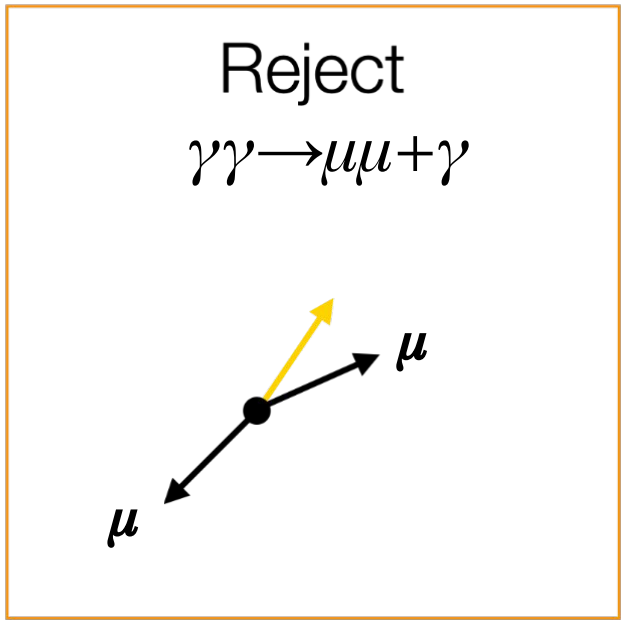
Rejecting background: $\gamma\gamma \rightarrow \mu\mu(\gamma)$

Exactly μ+e *or* μ+1 or 3 tracks *separated from* μ

For μ1T-SR:



$p_T(\mu,trk) > 1$ GeV

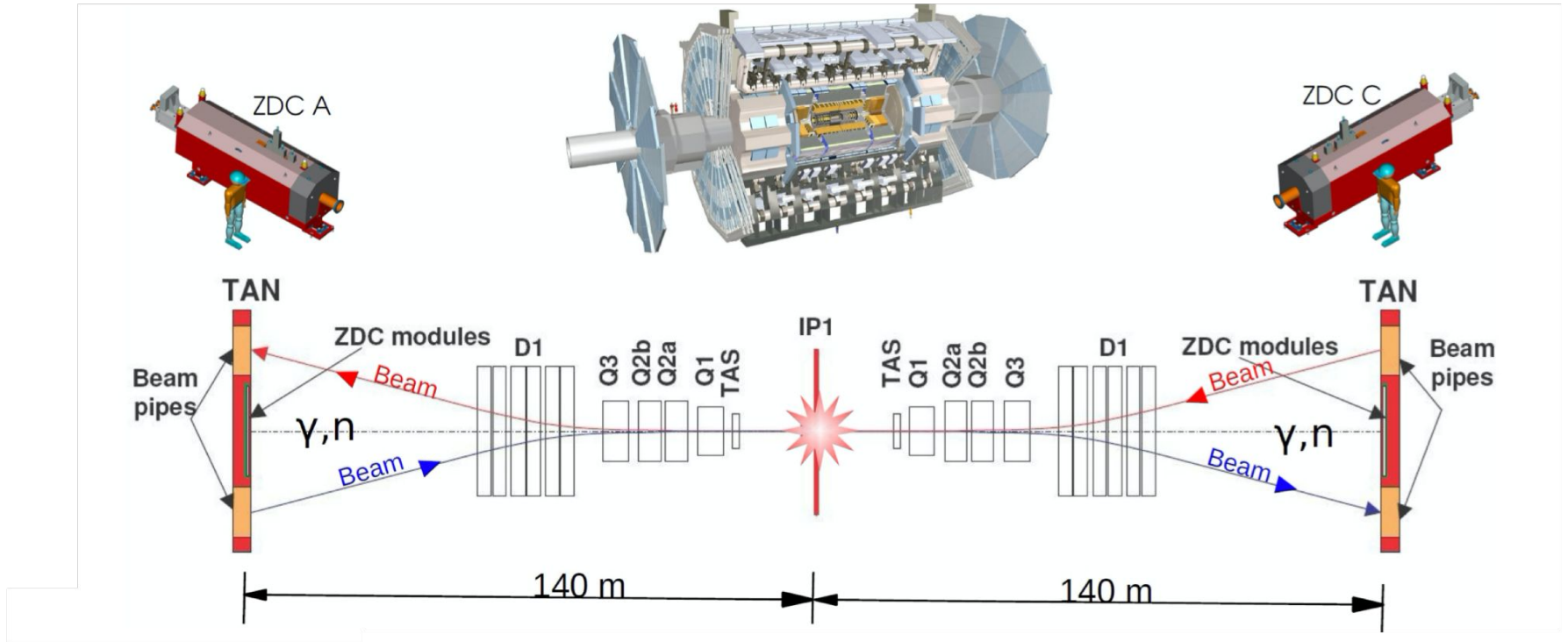


$p_T(\mu,trk,\gamma/cluster) > 1$ GeV

$E_T(\gamma) > 1.5$ GeV; p_T(cluster) > 1 GeV ($|\eta|<2.5$), 100 MeV ($2.5<|\eta|<4.5$)

Rejecting background: Photo-nuclear etc

- Zero Degree Calorimeter Energy E_{ZDC} < 1 TeV on side A & C (0n0n)
- No unmatched clusters i.e. not near μ or track(s), for μ+track(s) SRs
- m(trks) < 1.7 GeV for μ3T-SR



ZDC rapidity coverage: $|\eta| > 8.1$

0n0n weights

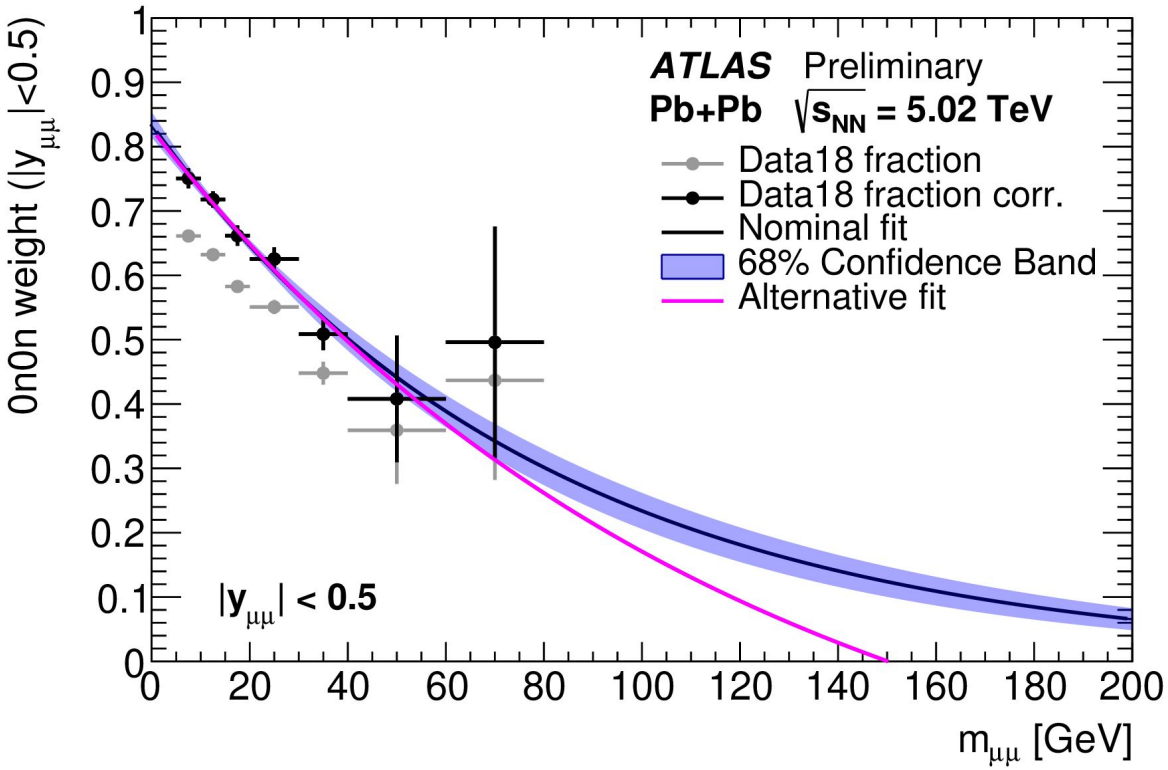
Data: ZDC selection applied

MC: Inclusive in forward neutrons & ZDC response not simulated in MC

→ **Apply data-driven 0n0n weights to MC**

- Derive data-driven weights using $\gamma\gamma \to \mu\mu$ in di-muon mass & rapidity bins
- Correct weights for EM pileup in ZDCs
- Fit falling functions

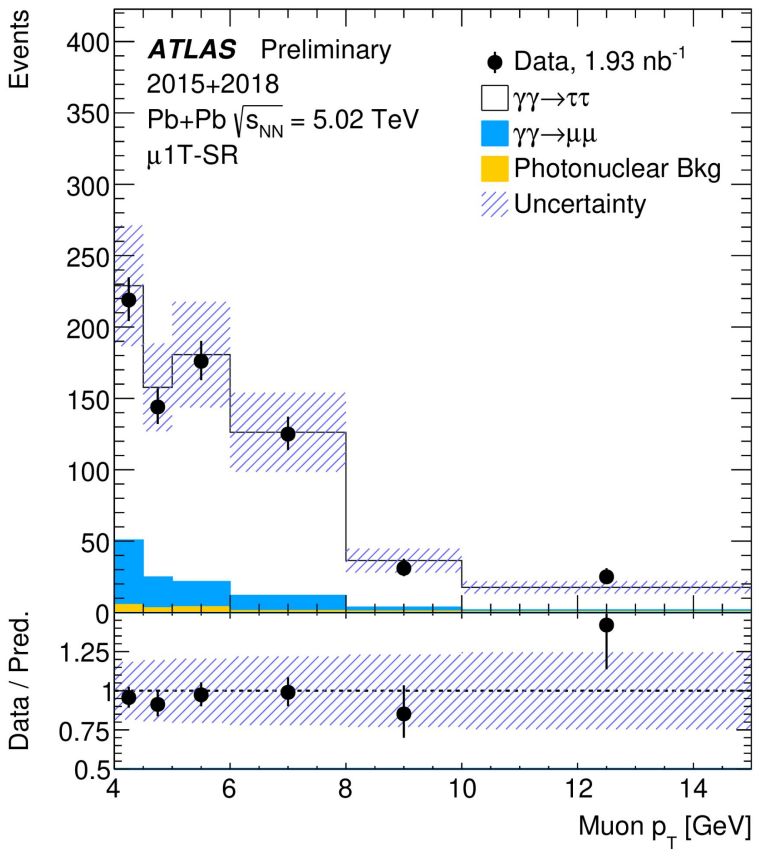
Fraction of 0n0n events



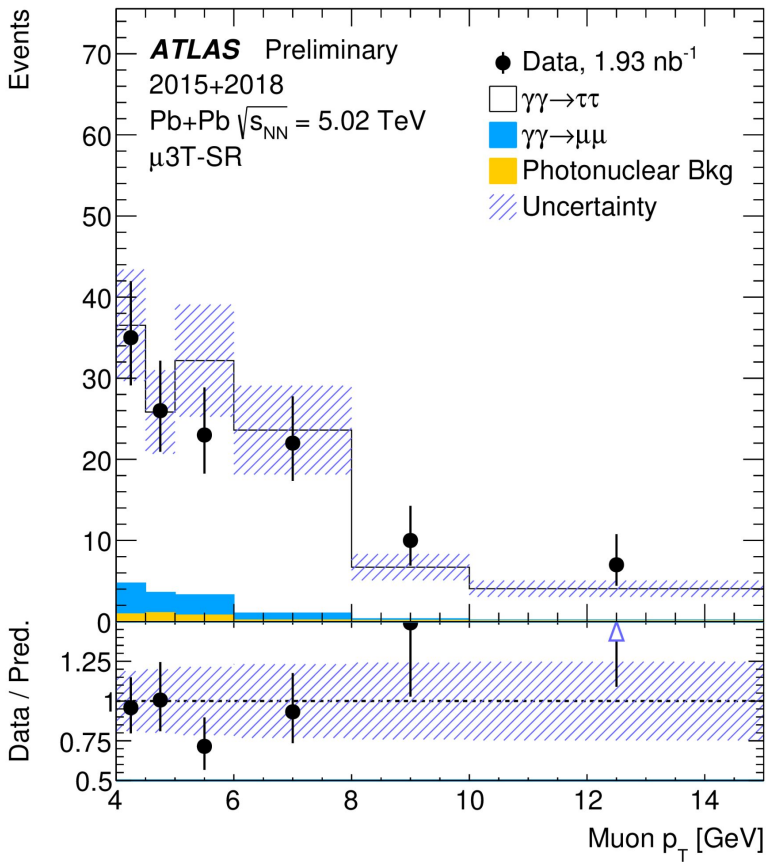
Signal region summary: muon p_T

Overall good data-MC agreement and minimal backgrounds

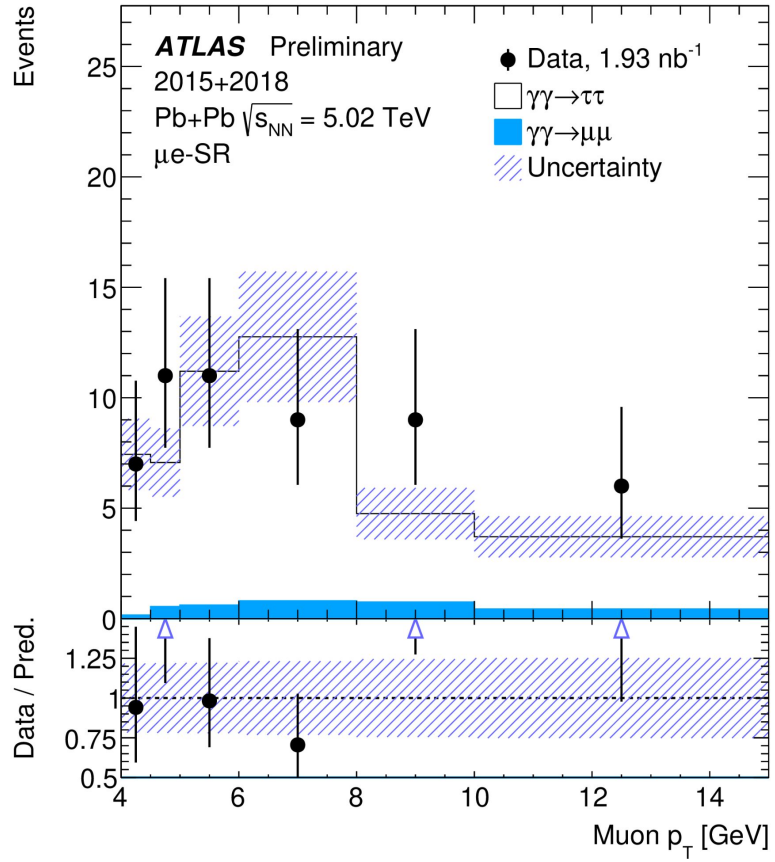
μ1T-SR (723 events)



μ3T-SR (124 events)



μe-SR (53 events)



Fiducial definitions for cross-sections

Similar to object & signal region selections at reconstructed level

Object selections

Object	Requirements
Leptons (e,μ)	$p_{\mathrm{T}} > 4$ GeV and $\lvert\eta\rvert < 2.5$
Hadrons	$p_{\mathrm{T}} > 100$ MeV and $\lvert\eta\rvert < 2.5$
Low-p_{T} Leptons (e_{low},μ_{low})	100 MeV $< p_{\mathrm{T}} < 4$ GeV and $\lvert\eta\rvert < 2.5$
Track particles (t)	Hadron or low-p_{T} lepton

Fiducial Regions (FRs)

Region	μ1T-FR	μ3T-FR	μe-FR
$0n0n$ topology	$0n0n$ weights for MC		
N_μ	$= 1$	$= 1$	$= 1$
N_e	$= 0$	$= 0$	$= 1$
$N_t(\Delta R > 0.1$ from μ or e)	$= 1$	$= 3$	$= 0$
$\Sigma_{\mu,t(s)\text{ or }e}$ charge	$= 0$	$= 0$	$= 0$
$p_{\mathrm{T}}^{\mu,t}$	> 1 GeV	—	—
m_{3t}	—	< 1.7 GeV	—
$A_\phi^{\mu,t(s)}$	< 0.4	< 0.2	—

Measured variables

Measure following variables in each fiducial region to access $\tau\tau$ kinematics

Variable	μ1T-FR	μ3T-FR	μe-FR
Muon p_{T}	p_{T}^{μ}	p_{T}^{μ}	p_{T}^{μ}
Track(s)/Electron p_{T}	$p_{\mathrm{T}}^{\mathrm{trk}}$	$p_{\mathrm{T}}(\mathbf{p}_{\mathrm{trks}})$	p_{T}^{e}
$p_{\mathrm{T}}\,(\mu, \mathrm{trk(s)}/e)$	$p_{\mathrm{T}}(\mathbf{p}_{\mu} + \mathbf{p}_{\mathrm{trk}})$	$p_{\mathrm{T}}(\mathbf{p}_{\mu} + \mathbf{p}_{\mathrm{trks}})$	$p_{\mathrm{T}}(\mathbf{p}_{\mu} + \mathbf{p}_{e})$
$m(\mu, \mathrm{trk(s)}/e)$	$m(\mathbf{p}_{\mu} + \mathbf{p}_{\mathrm{trk}})$	$m(\mathbf{p}_{\mu} + \mathbf{p}_{\mathrm{trks}})$	$m(\mathbf{p}_{\mu} + \mathbf{p}_{e})$
$\eta(\mu, \mathrm{trk(s)}/e)$	$\eta(\mathbf{p}_{\mu} + \mathbf{p}_{\mathrm{trk}})$	$\eta(\mathbf{p}_{\mu} + \mathbf{p}_{\mathrm{trks}})$	$\eta(\mathbf{p}_{\mu} + \mathbf{p}_{e})$
$\Delta\eta\,(\mu, \mathrm{trk(s)}/e)$	$\eta_{\mu} - \eta_{\mathrm{trk}}$	$\eta_{\mu} - \eta(\mathbf{p}_{\mathrm{trks}})$	$\eta_{\mu} - \eta_{e}$
$A_{\phi}^{\mu,\mathrm{trk(s)}/e}$	$1 - \lvert\phi_{\mu} - \phi_{\mathrm{trk}}\rvert/\pi$	$1 - \lvert\phi_{\mu} - \phi(\mathbf{p}_{\mathrm{trks}})\rvert/\pi$	$1 - \lvert\phi_{\mu} - \phi_{e}\rvert/\pi$

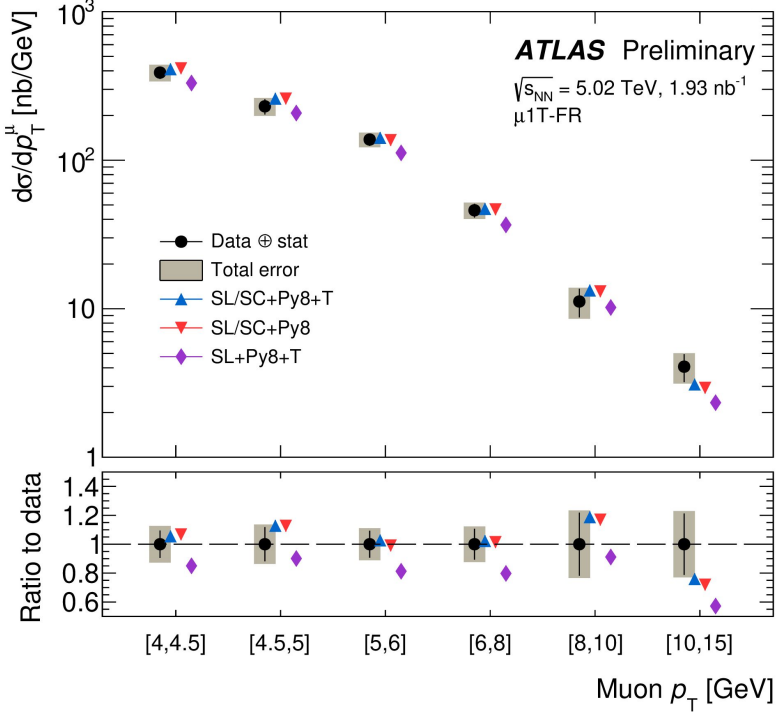
21 differential cross-sections

Unfold using Bayesian iterative unfolding & bootstrap method for stat correlations

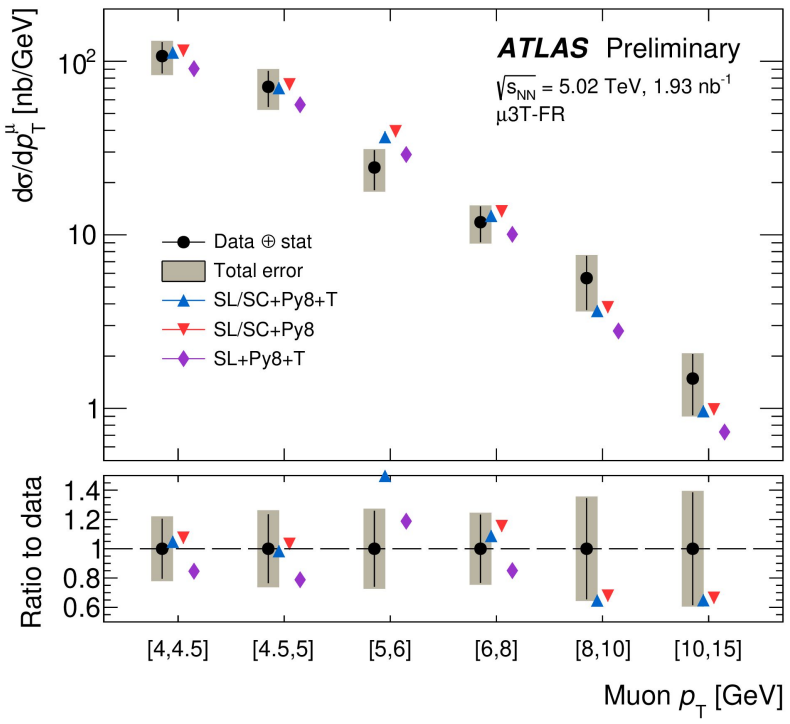
Differential cross-section: muon p_T

Other variables in backup

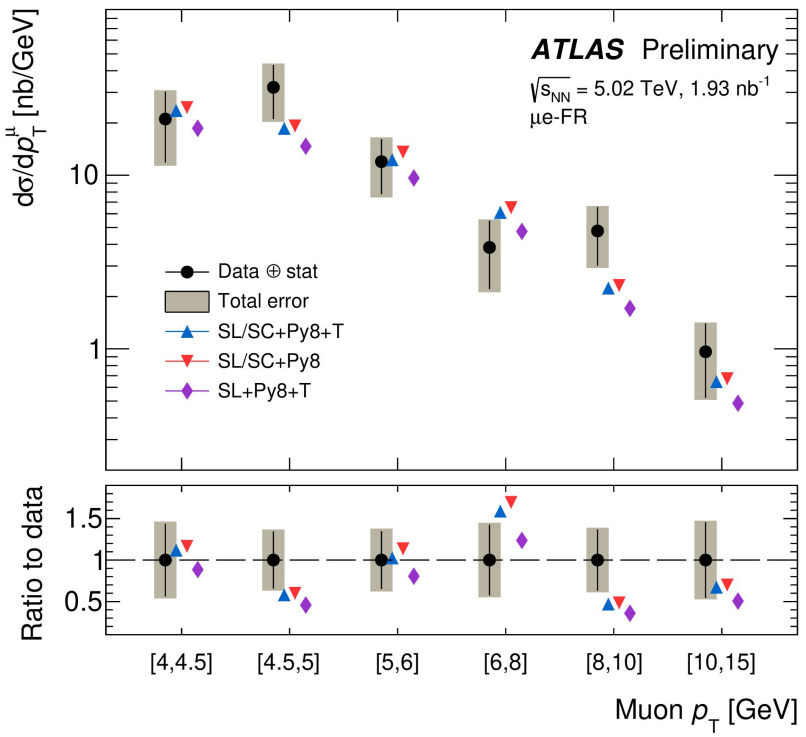
μ1T-FR



μ3T-FR



μe-FR



Statistically limited ~10-50% stat uncertainty per bin

Total systematic uncertainty ~5-10% per bin

Differential cross-section: muon p_T

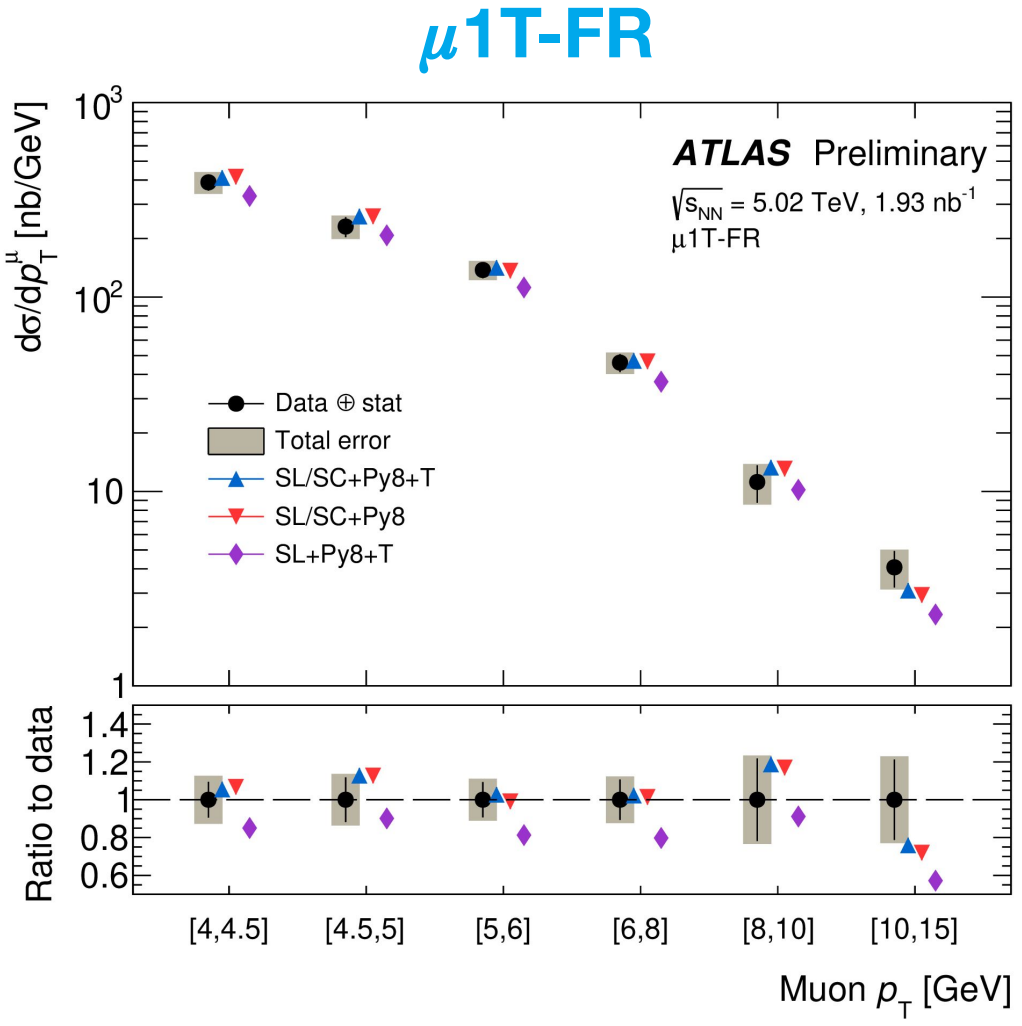
Compare to:

- ▲ STARlight (SuperChic photon-flux) + Pythia8 + Tauola
- ▼ STARlight (SuperChic photon-flux) + Pythia8
- ♦ STARlight + Pythia8 + Tauola

Photon-flux depends on nuclear charge distribution

♦ **STARlight:** Point charge with cutoff in impact parameter integration (at b~R_{Pb})

▲▼ **SuperChic:** Woods-Saxon with no cutoff



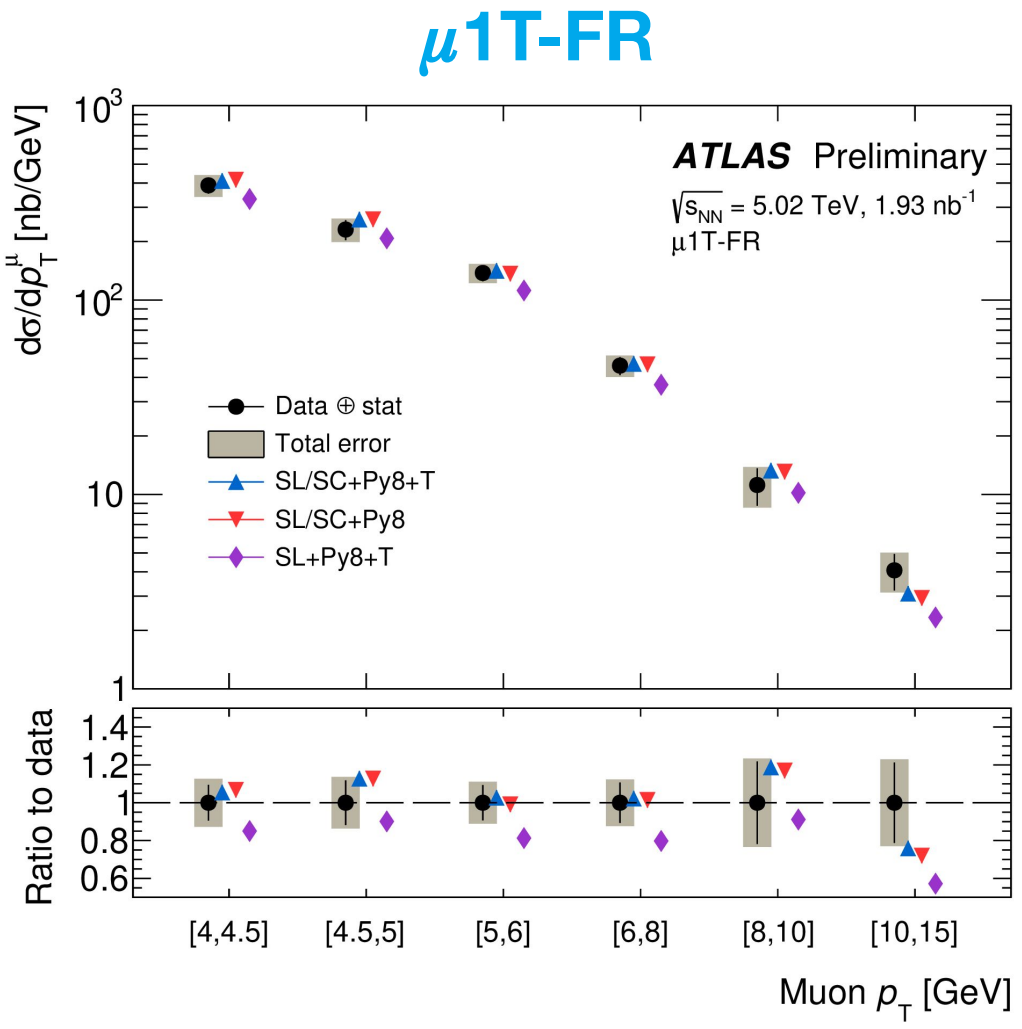
Observations

Compare to:

- ▲ STARlight (SuperChic photon-flux) + Pythia8 + Tauola
- ▼ STARlight (SuperChic photon-flux) + Pythia8
- ♦ STARlight + Pythia8 + Tauola

SuperChic photon flux ▲▼ agrees better than STARlight photon flux ♦

- ~20% difference due to STARlight cutoff in impact parameter integration (at b~R_{Pb})
- Observed also in $\gamma\gamma \rightarrow ee/\mu\mu$

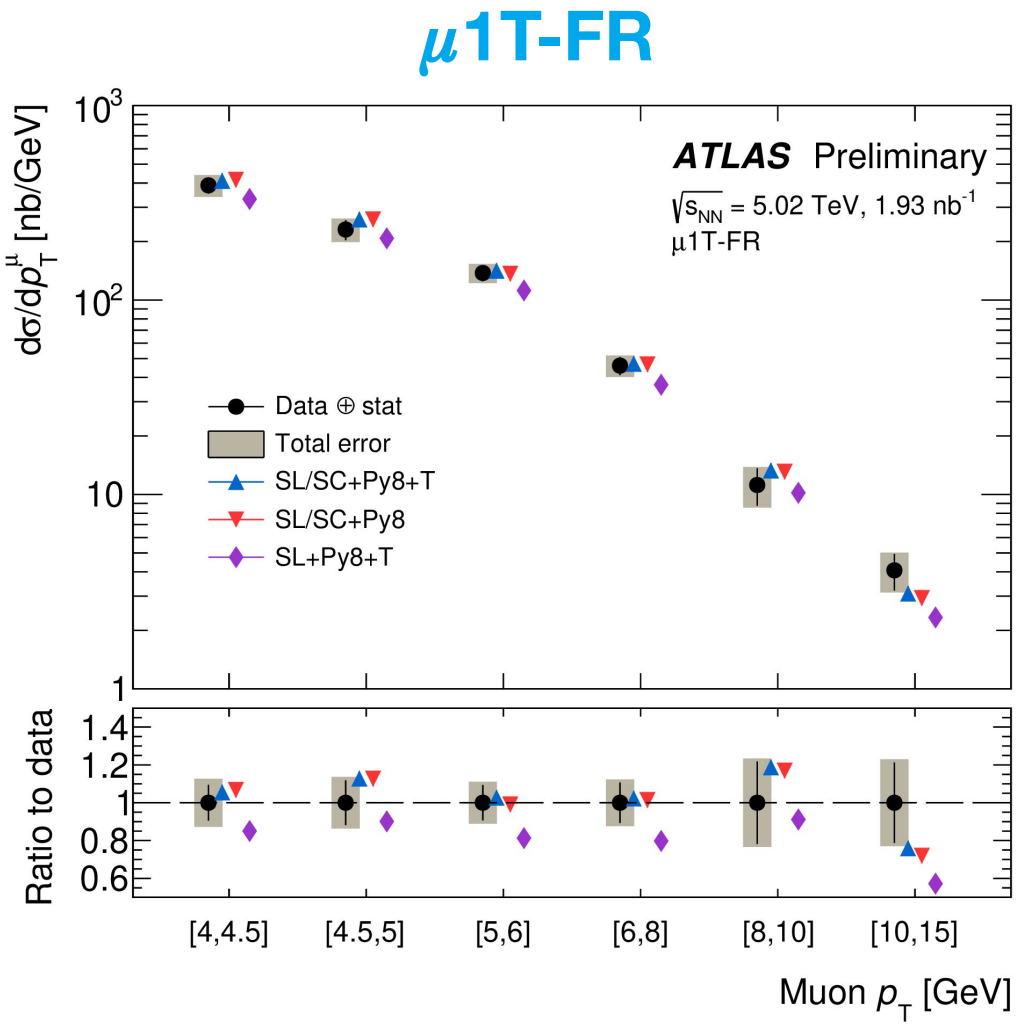


Observations

Compare to:

- ▲ STARlight (SuperChic photon-flux) + Pythia8 + Tauola
- ▼ STARlight (SuperChic photon-flux) + Pythia8
- ♦ STARlight + Pythia8 + Tauola

Tauola ▲vs Pythia8 ▼Tau lepton decays agree to within percent-level differences



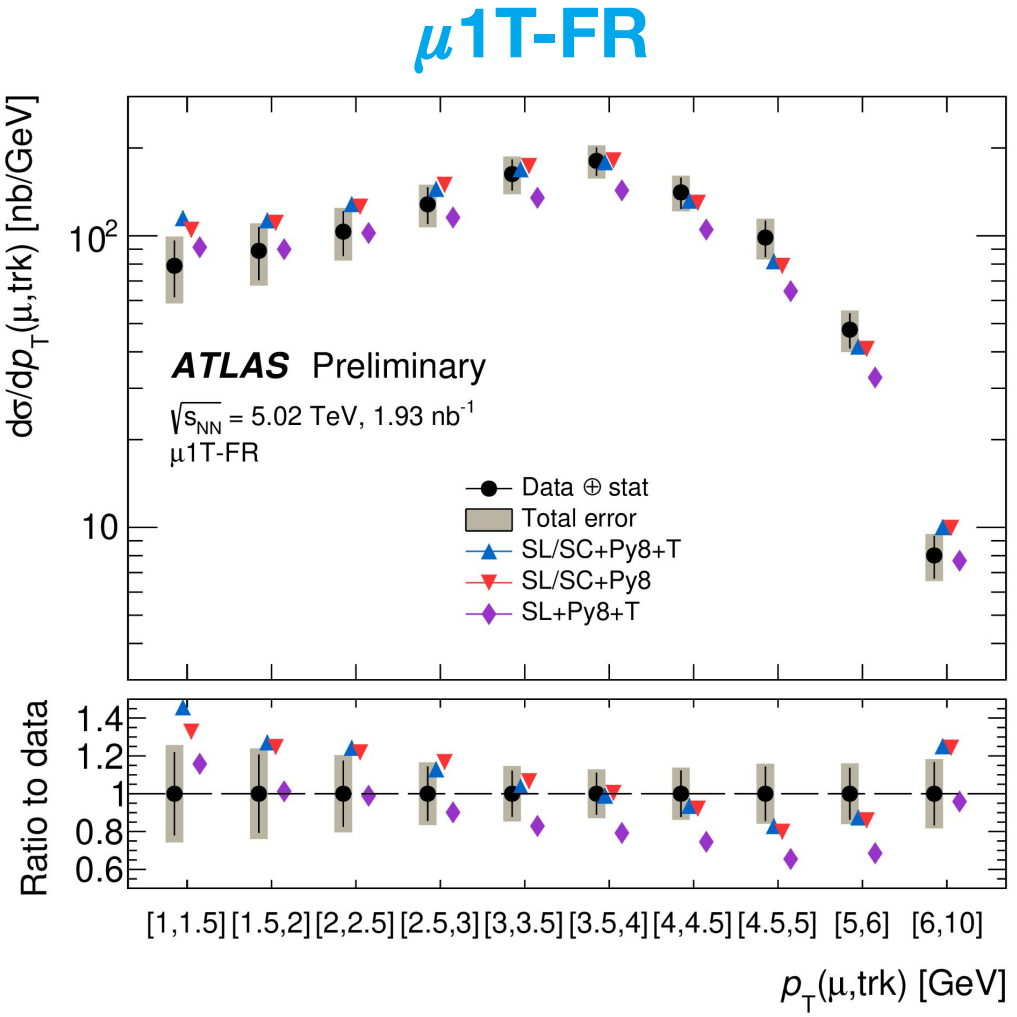
Observations

Compare to:

- ▲ STARlight (SuperChic photon-flux) + Pythia8 + Tauola
- ▼ STARlight (SuperChic photon-flux) + Pythia8
- ♦ STARlight + Pythia8 + Tauola

Some systematic data-MC deviations e.g. $p_T(\mu,trk)$

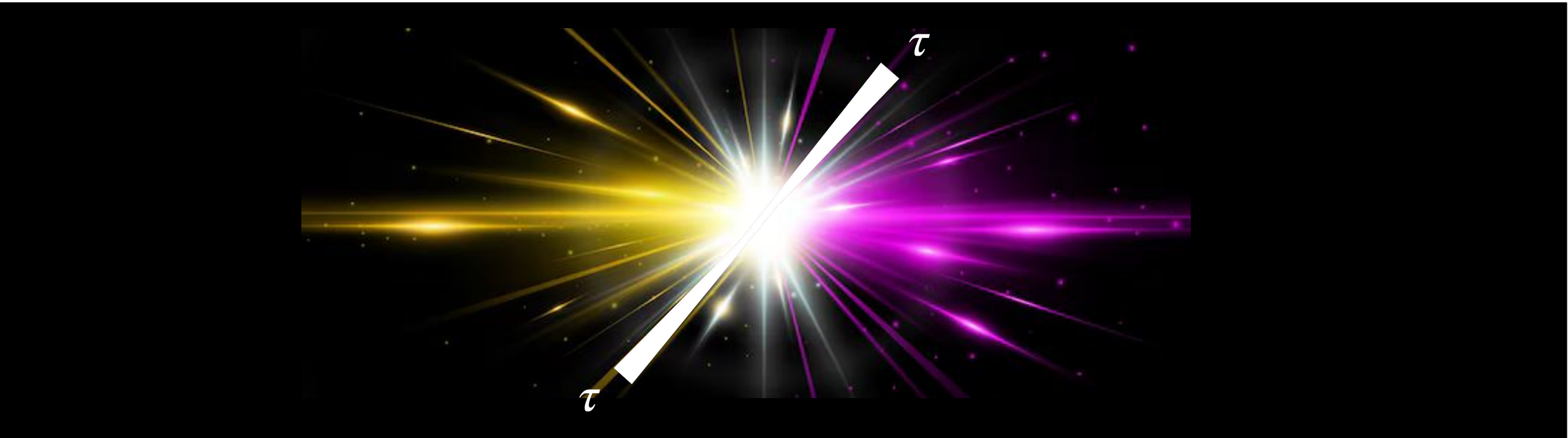
- Potentially due to (transverse) spin correlations
- Included for $\gamma\gamma \to \tau\tau$ in latest Tauola & TauSpinner release PRD.109.013002



Summary

ATLAS-CONF-2025-004

- **First differential cross-section measurements of $\gamma\gamma \rightarrow \tau\tau$ in UPC Pb+Pb**
- **Measured 21 differential cross-sections:** 7 variables in 3 Fiducial Regions
- **Sensitive to spin correlation effects and electromagnetic moments**



Backup

Signal region definitions

Region	μ1T-SR	μ3T-SR	μe-SR
Trigger	Single-muon based		
$0n0n$ topology	$E_{\mathrm{ZDC}}^{A,C} < 1$ TeV for data, $0n0n$ weights for MC		
$N_{\mu}^{\mathrm{baseline}}$	$= 1$	$= 1$	—
N_{μ}^{sig}	$= 1$	$= 1$	$= 1$
N_{e}^{sig}	$= 0$	$= 0$	$= 1$
$N_{\mathrm{trk}}(\Delta R > 0.1 \text{ from } \mu^{\mathrm{sig}})$	$= 1$	$= 3$	—
$N_{\mathrm{trk}}(\Delta R > 0.1 \text{ from } \ell^{\mathrm{sig}})$	—	—	$= 0$
$N_{\mathrm{clust}}^{\mathrm{unmatched}}$	$= 0$	$= 0$	—
$\sum_i q_i$ with $i = \mu, \mathrm{trk(s)}/e$	$= 0$	$= 0$	$= 0$
$p_{\mathrm{T}}^{(\mu,\mathrm{trk})}$	> 1 GeV	—	—
$p_{\mathrm{T}}^{(\mu,\mathrm{trk},\gamma)}$	> 1 GeV	—	—
$p_{\mathrm{T}}^{(\mu,\mathrm{trk,cluster})}$	> 1 GeV	—	—
m_{trks}	—	< 1.7 GeV	—
$A_{\phi}^{\mu,\mathrm{trk(s)}}$	< 0.4	< 0.2	—

Yields

Region	μ1T-SR	μ3T-SR	μe-SR
background	99.3 ± 18.9	9.9 ± 2.0	3.4 ± 0.9
Photonuclear background	15.6 ± 11.4	3.2 ± 2.1	—
Combined background	114.9 ± 22.0	13.1 ± 2.9	3.4 ± 0.9
Combined signal+background	750.4 ± 151.0	129.5 ± 26.8	47.5 ± 10.8
Data	723	124	53

Other backgrounds deemed negligible:

Using MC: $\gamma\gamma \to ee(\gamma)$, $\gamma\gamma \to$dijets, Non-diffractive photo-nuclear processes

Using data-driven estimate: Simultaneous rho production due to multiple UPC scattering

Photon-flux weights

Apply photon-flux re-weighting to SuperChic differentially in truth y_{ll} and m_{ll}

$\gamma\gamma \rightarrow ee$

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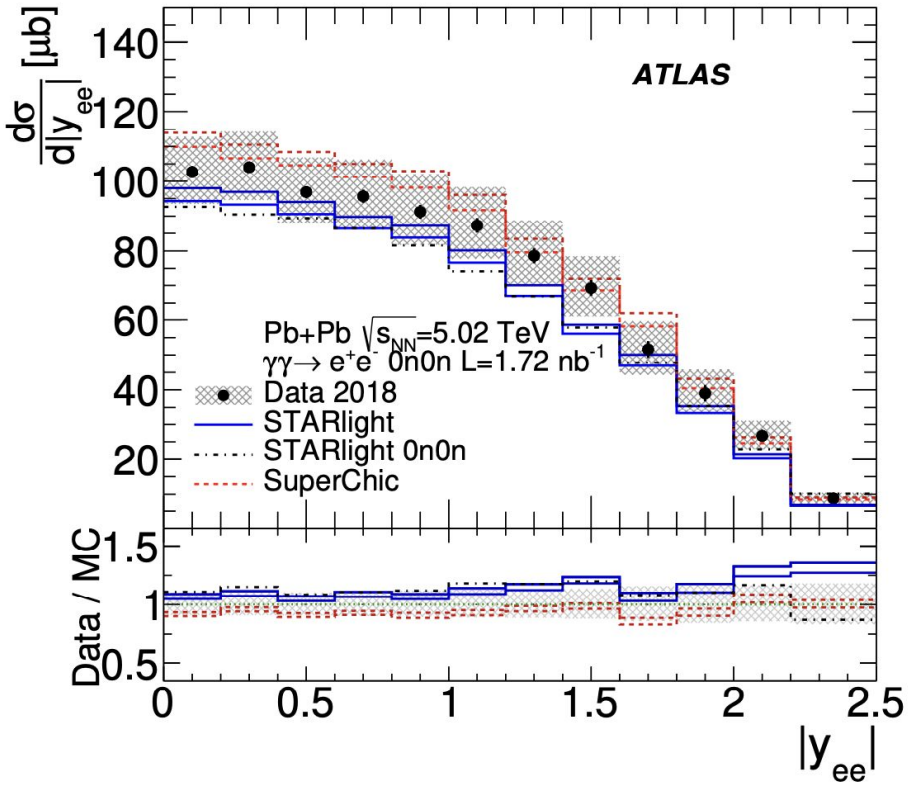
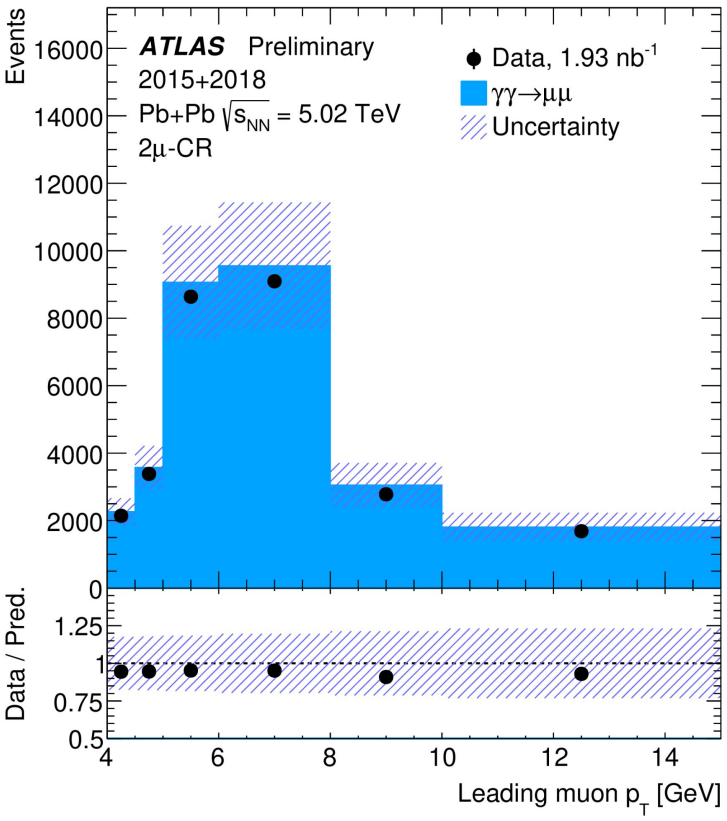


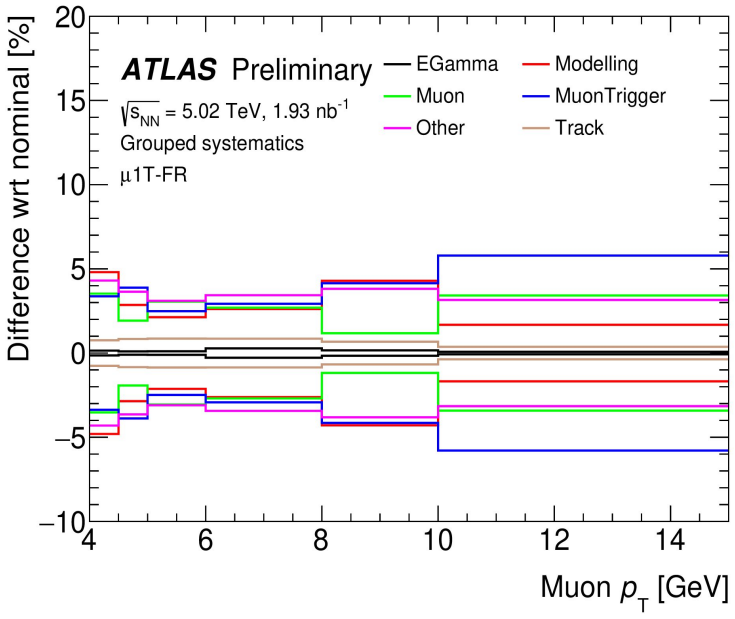
$\gamma\gamma \rightarrow \mu\mu$ CR after re-weighting

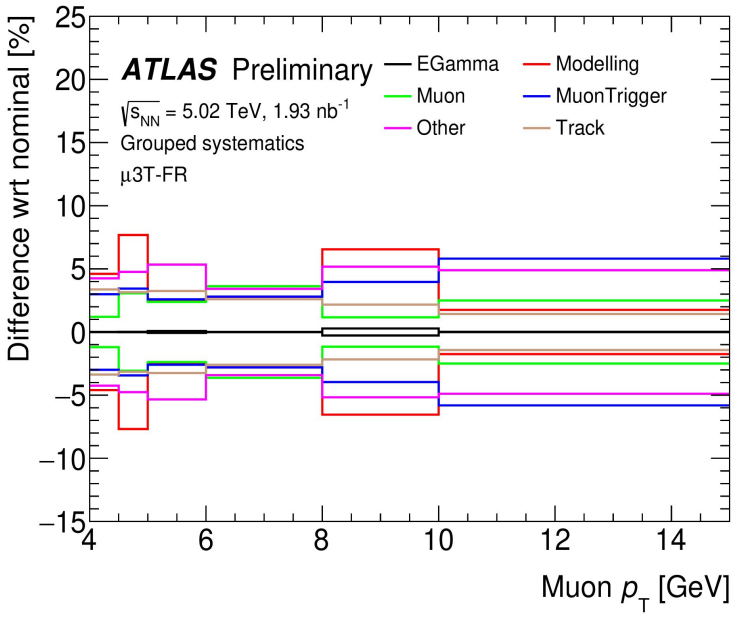
ATLAS-CONF-2025-004

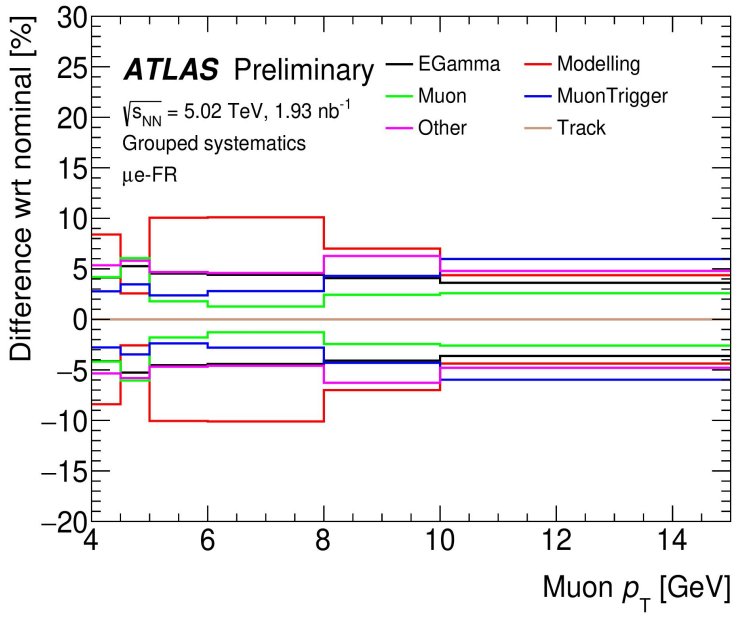


Systematic uncertainties

Largest individual sources: trigger scale factors, tau decay modelling







EGamma, Muon: Calibration & performance

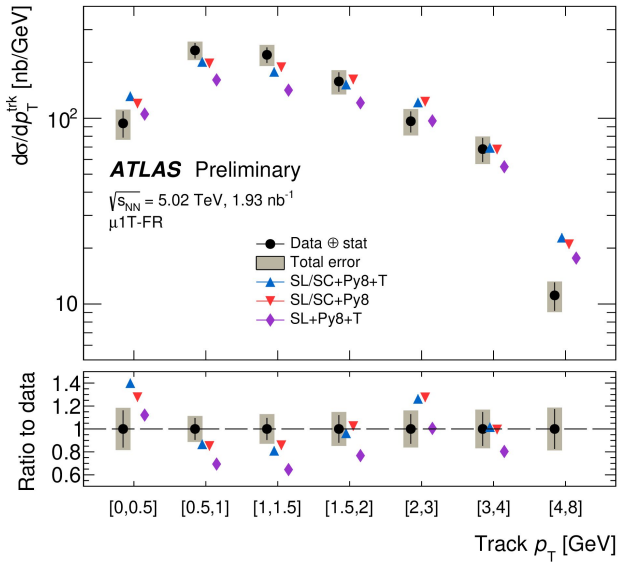
Track: Reconstruction efficiency

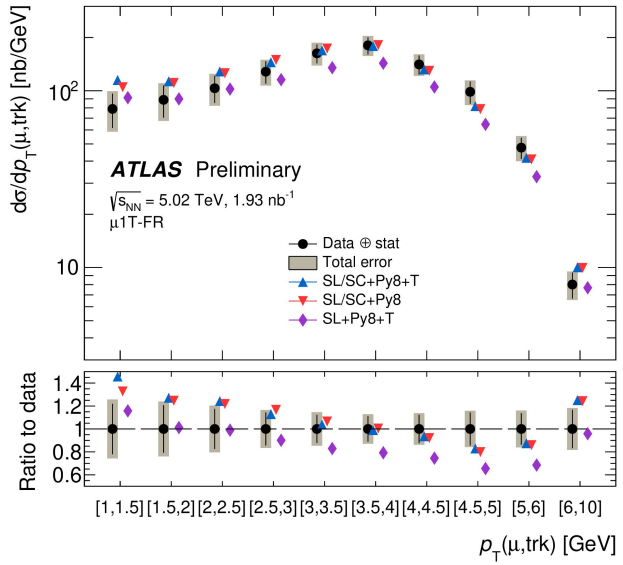
MuonTrigger: Trigger scale factors

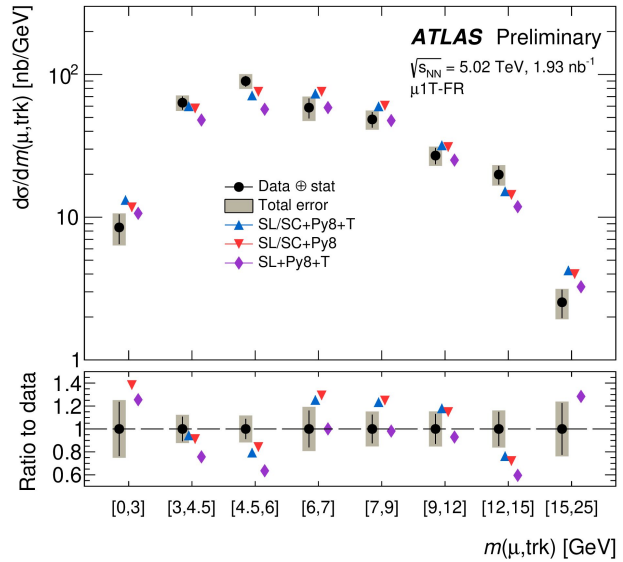
Other: Luminosity, unfolding closure, background subtraction, MC statistics

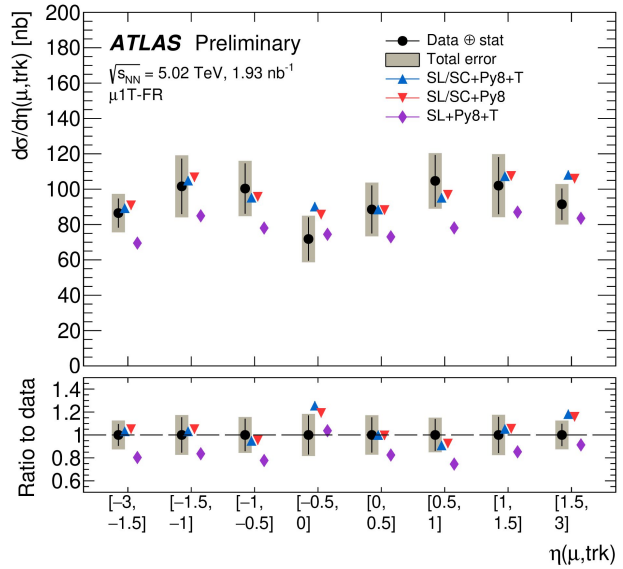
Modelling: 0n0n weights alternative fits, Photon flux STARLight vs SuperChic, Tau decay Pythia8 vs Tauola

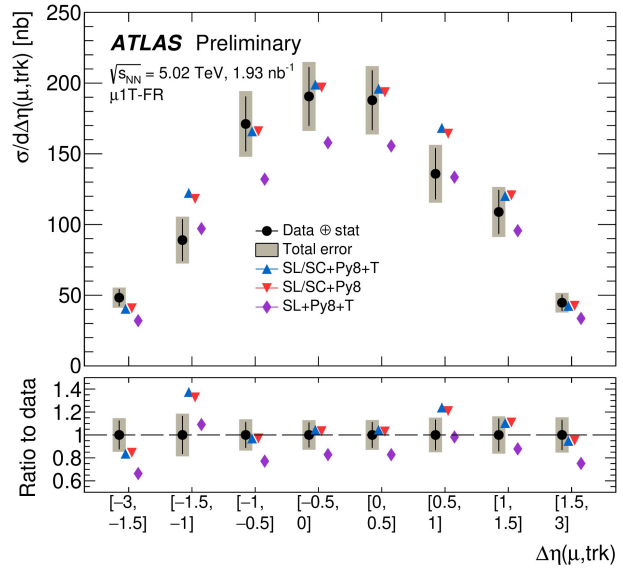
μ1T-FR cross-sections (except muon p_T)

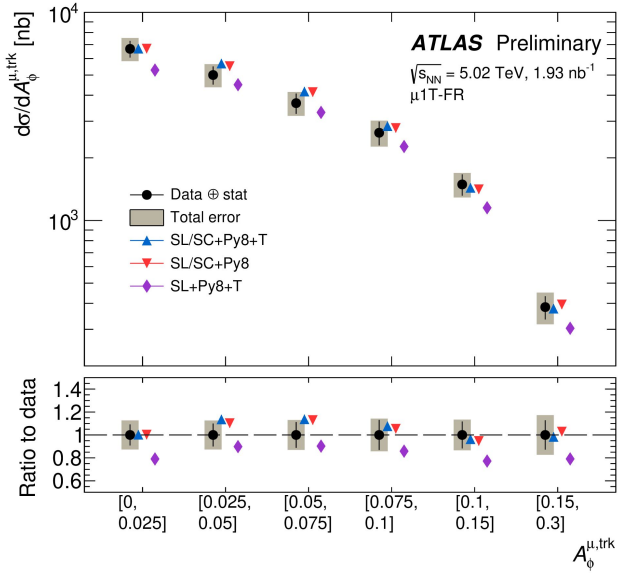




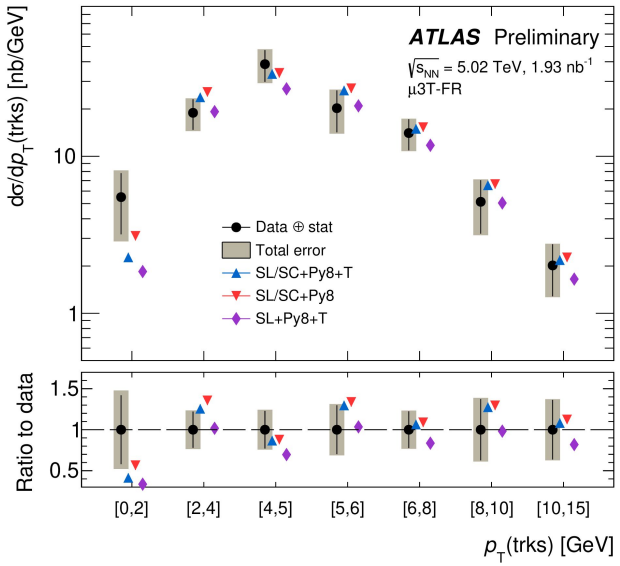


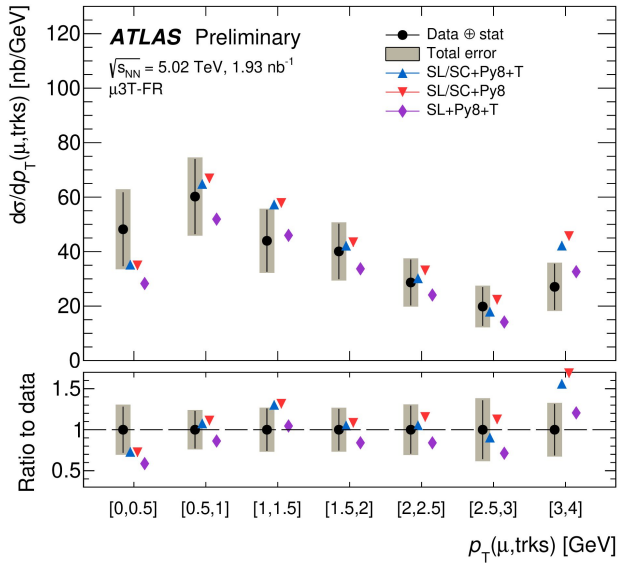


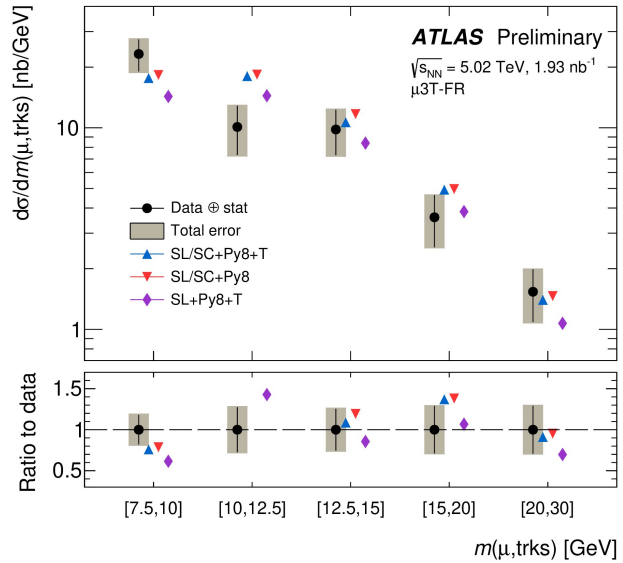


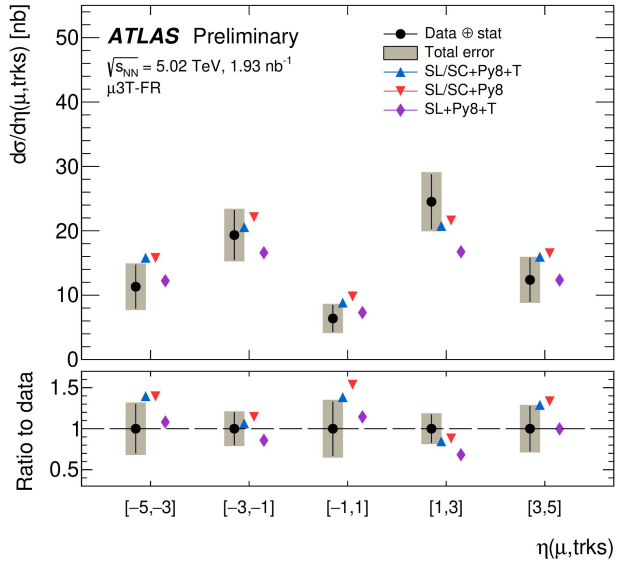


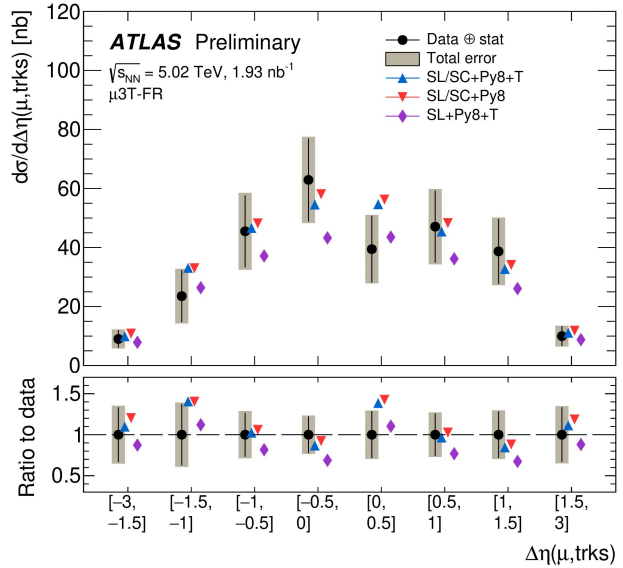
μ3T-FR cross-sections (except muon p_T)

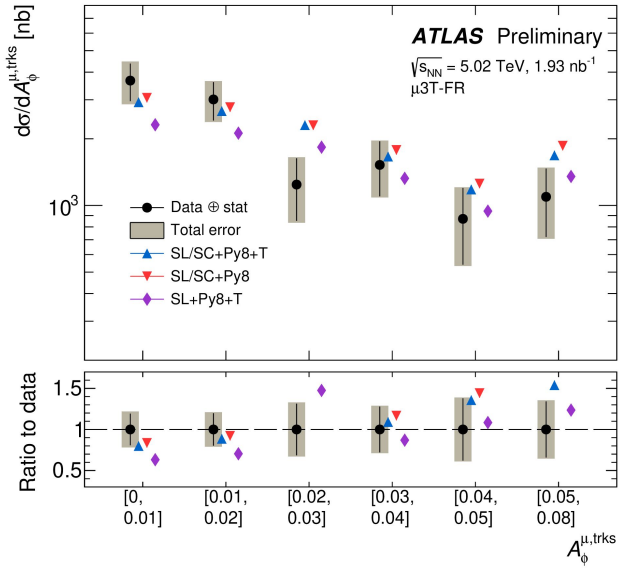












μe-FR cross-sections (except muon p_T)