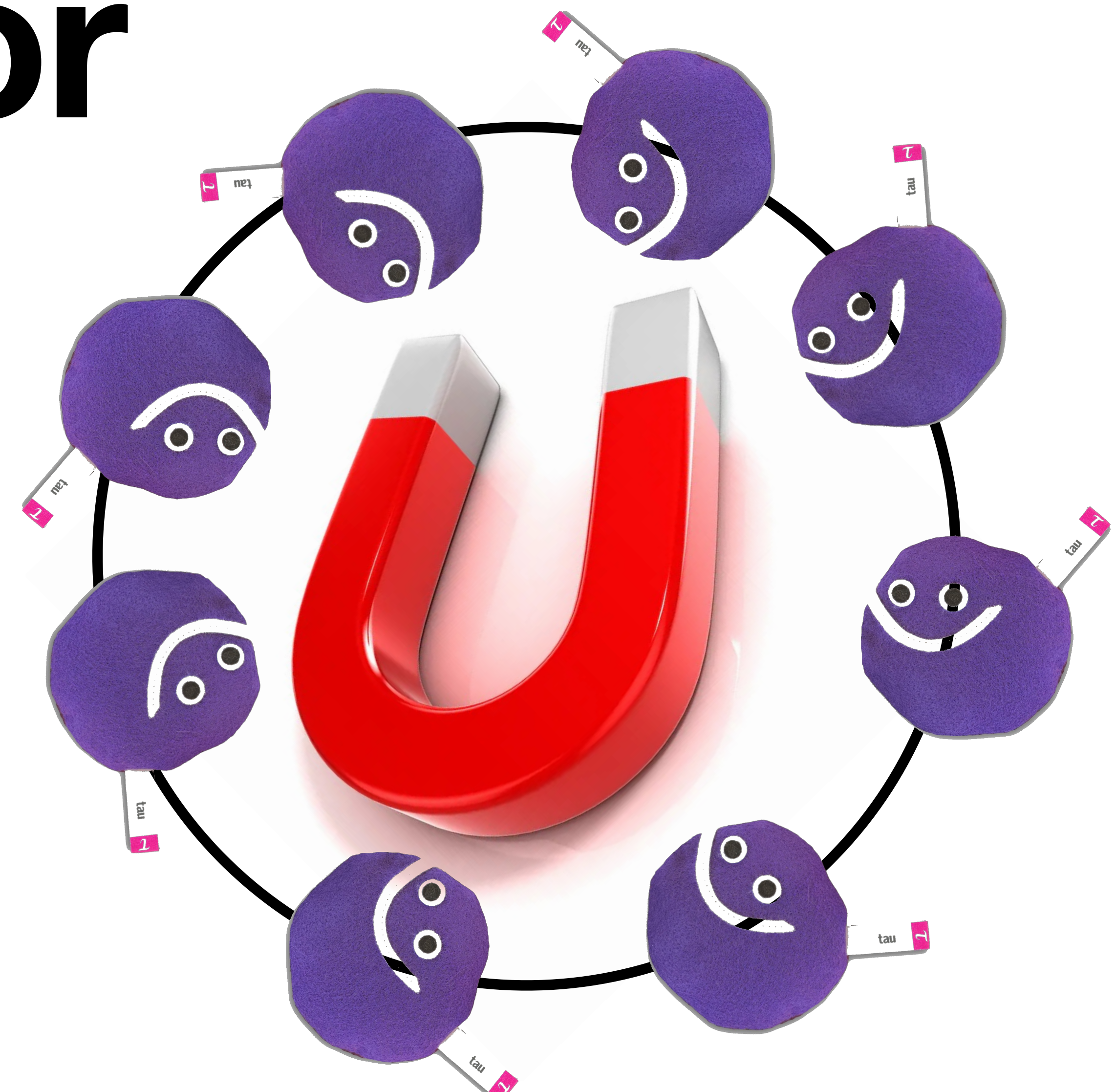
UNIVERSITY of WASHINGTON

Tau g-2 with the ATLAS detector

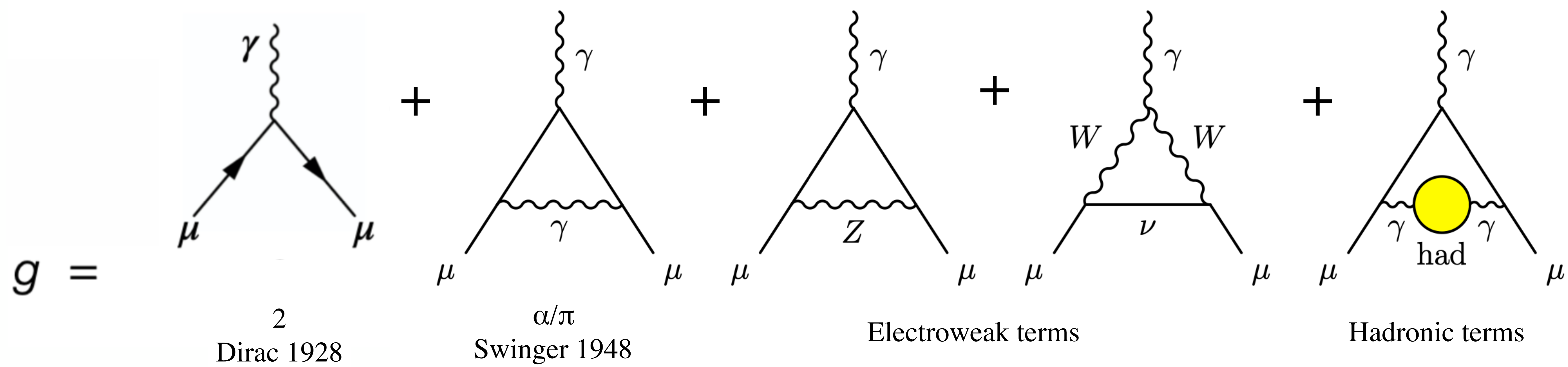
Quentin Buat
(University of Washington)



TAU2023 Workshop — December 6, 2023

Anomalous magnetic dipole moment

- Charged particles with a spin have an intrinsic magnetic moment
- For spin 1/2 particles: $\mu = \mathrm{g} \times q/2m \times S$



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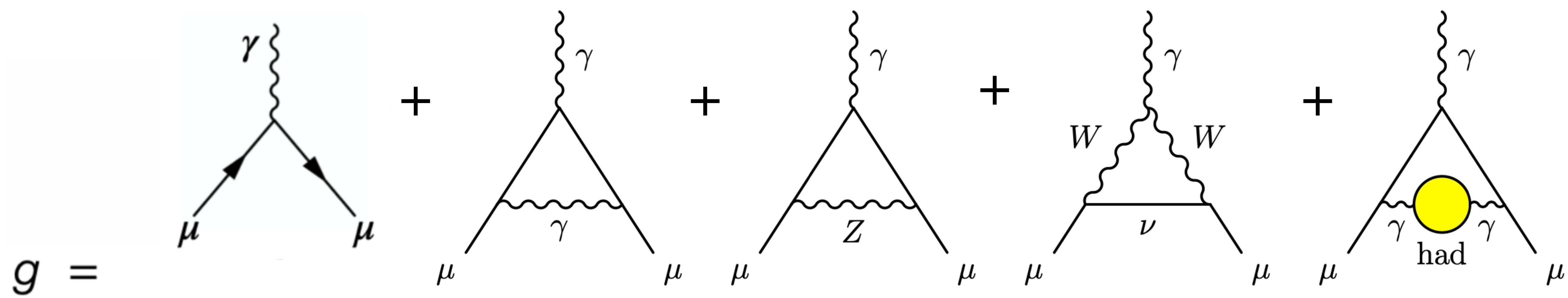
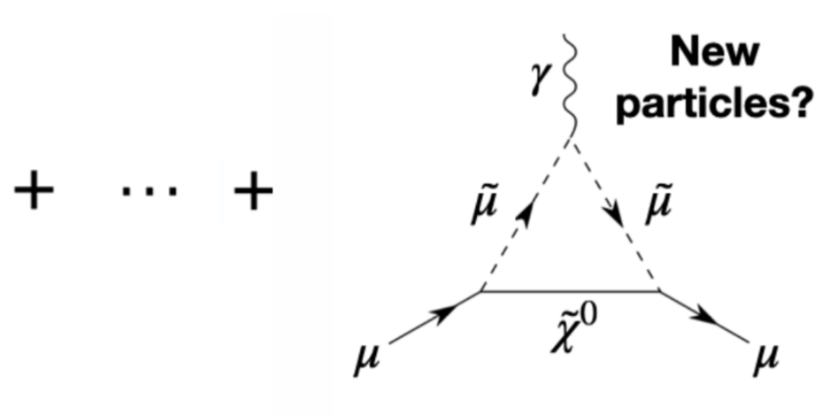


2
Dirac 1928

α/π
Swinger 1948

Electroweak terms

Hadronic terms



In many BSM models, couplings of new particle is enhanced for heavier leptons

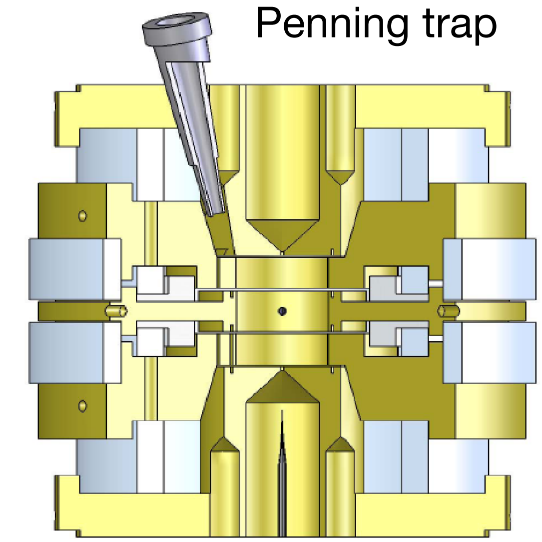
For a scalar particle

$(m_\mu/m_e)^2$	$(m_\tau/m_\mu)^2$
~42.10^3	300

$$a = \frac{g-2}{2}$$

Measurements for the electron and the muon

Penning trap

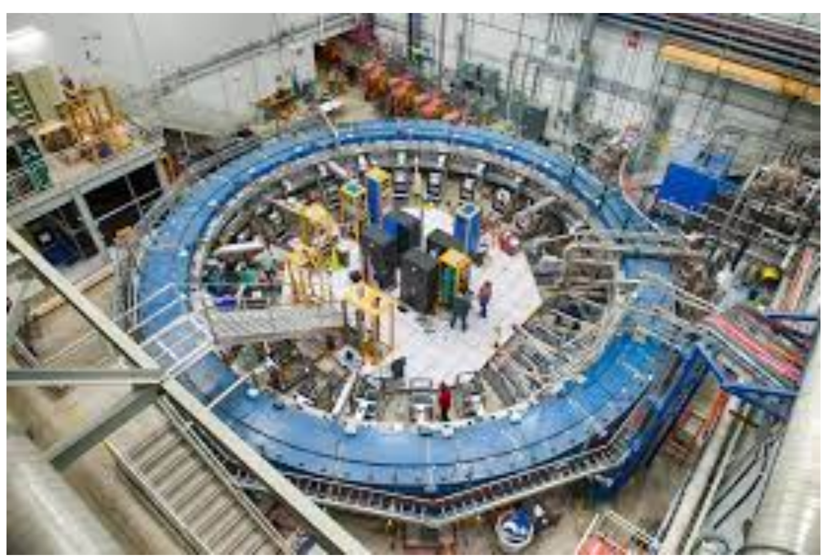


Electron

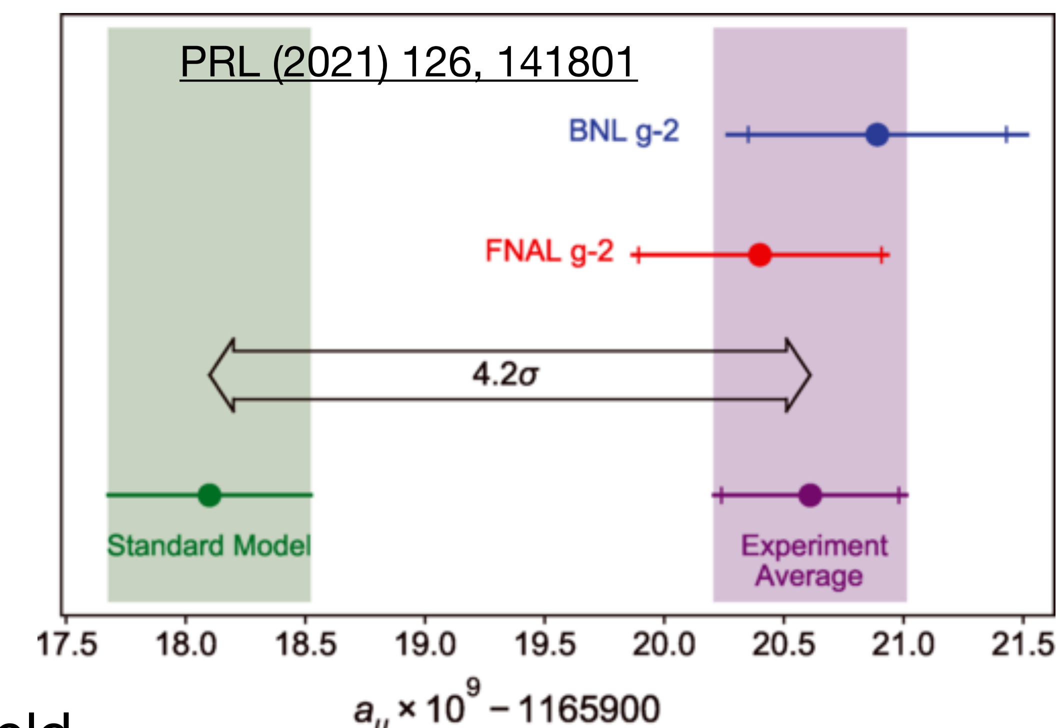
PDG: (g–2)/2 = 0.00115965218062 (12)

ppt level precision, most accurate and verified prediction in Physics

Muon



Muon g-2 experiment at Fermilab



Measure muon precession in a magnetic field

So, what about the tau lepton?

Tau Lepton Measurement

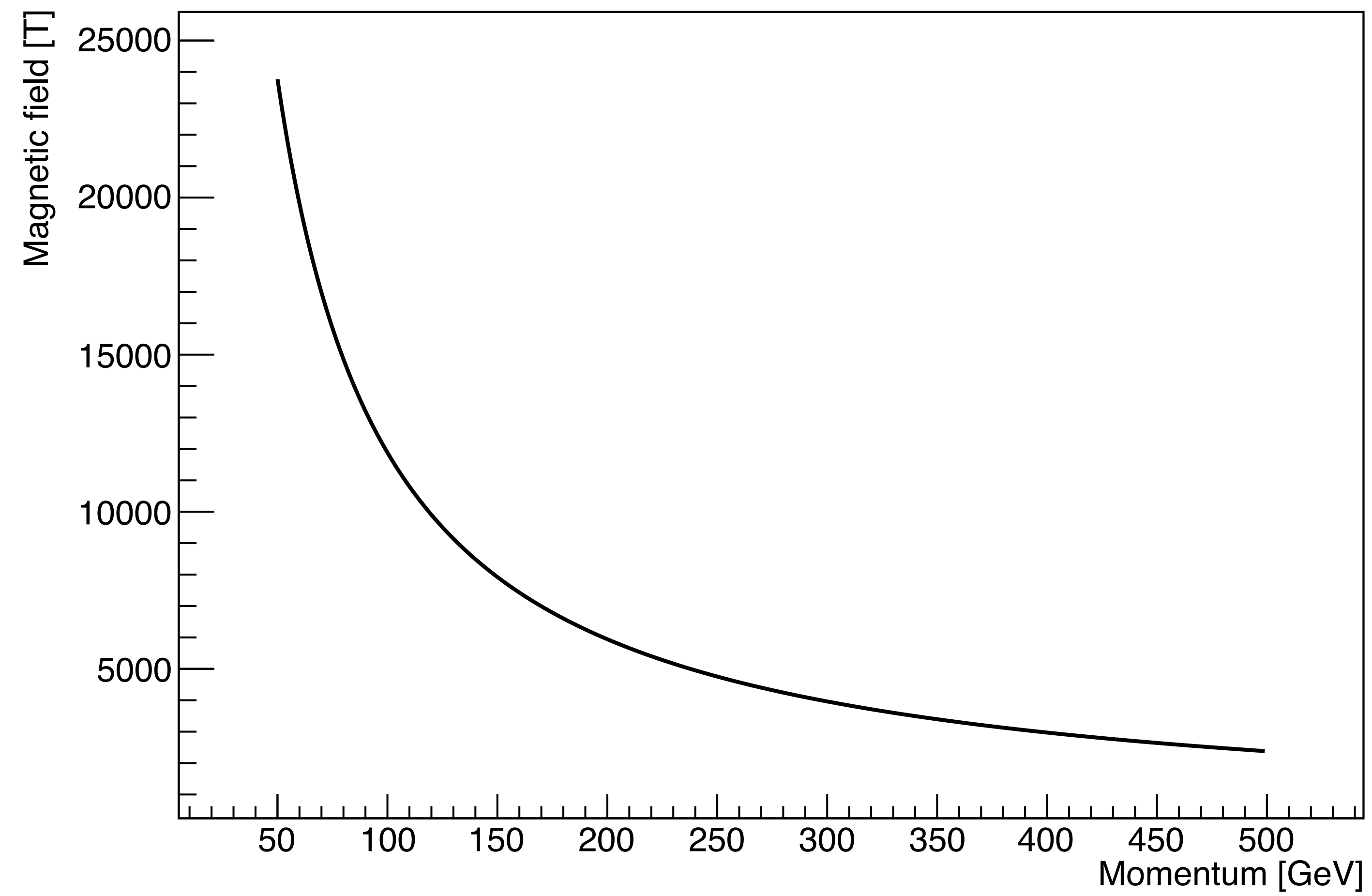
Constraining tau g-2

Trap them?

Tau mean lifetime = 0.29 ps

Bend them?

Magnetic field to bend a tau lepton before it decays with a 5° angle



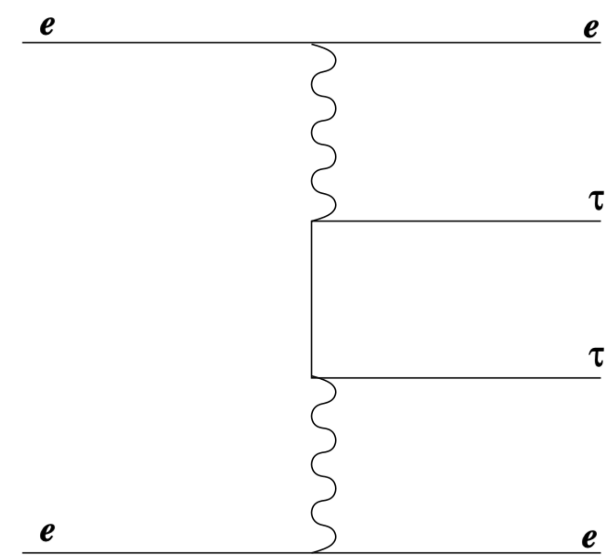
Use collider data!

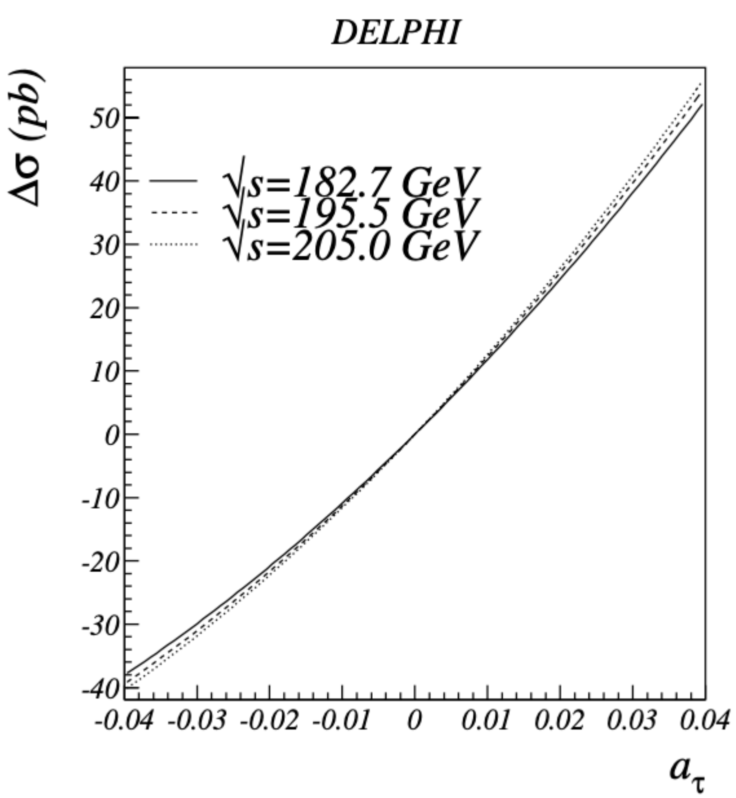
DELPHI Measurement: EPJC 35, 159–170 (2004)
a_τ^{SM} calculations: S. EIDELMAN and M. PASSERA, MPLA 22, 03, 159-179 (2007)

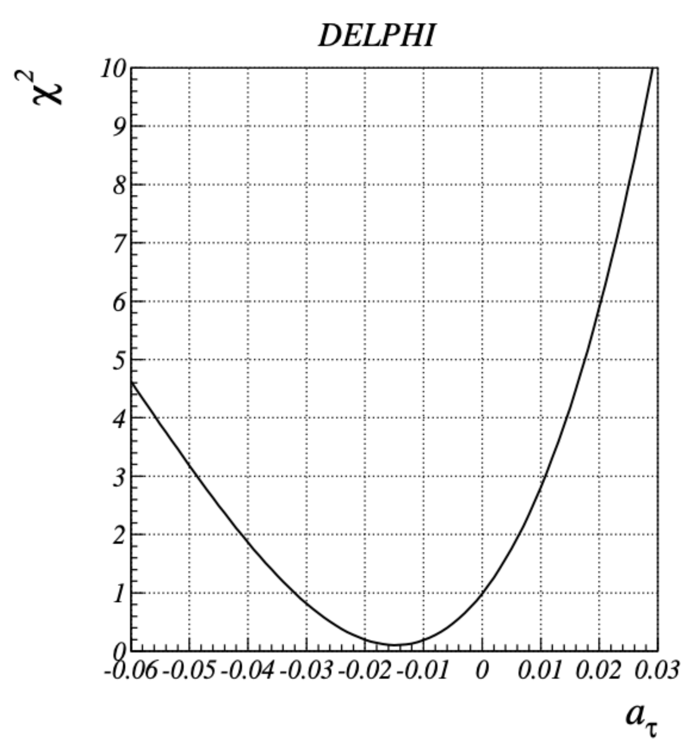
LEP result

- PDG value: DELPHI (2004)
- Measure photo-production of tau lepton pairs
  - σ_{meas} = 429 ± 17 pb ($\Delta\sigma/\sigma$=4%)
- Sensitive to a_τ

$\sqrt{s}$ ~ 200 GeV, L = 650 pb^{-1}







Results limited by experimental uncertainties

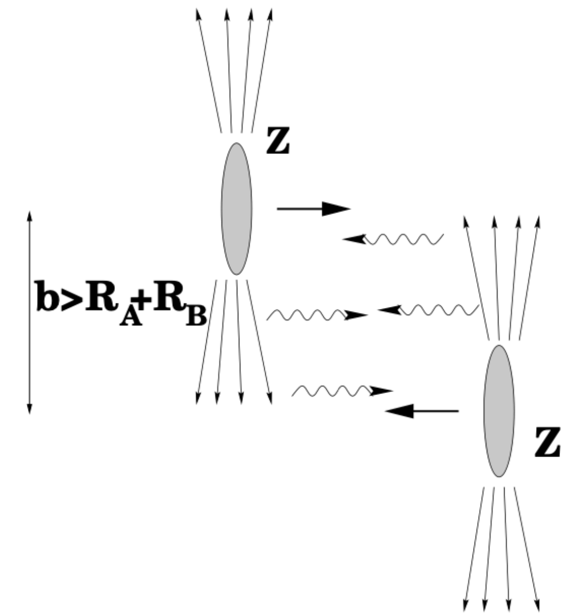
$$a_\tau^{exp} = -0.018\,(17)$$
$$a_\tau^{SM} = 0.00117721\,(5)$$

1-loop QED, Schwinger term

$$\alpha/2\pi = 0.0012$$

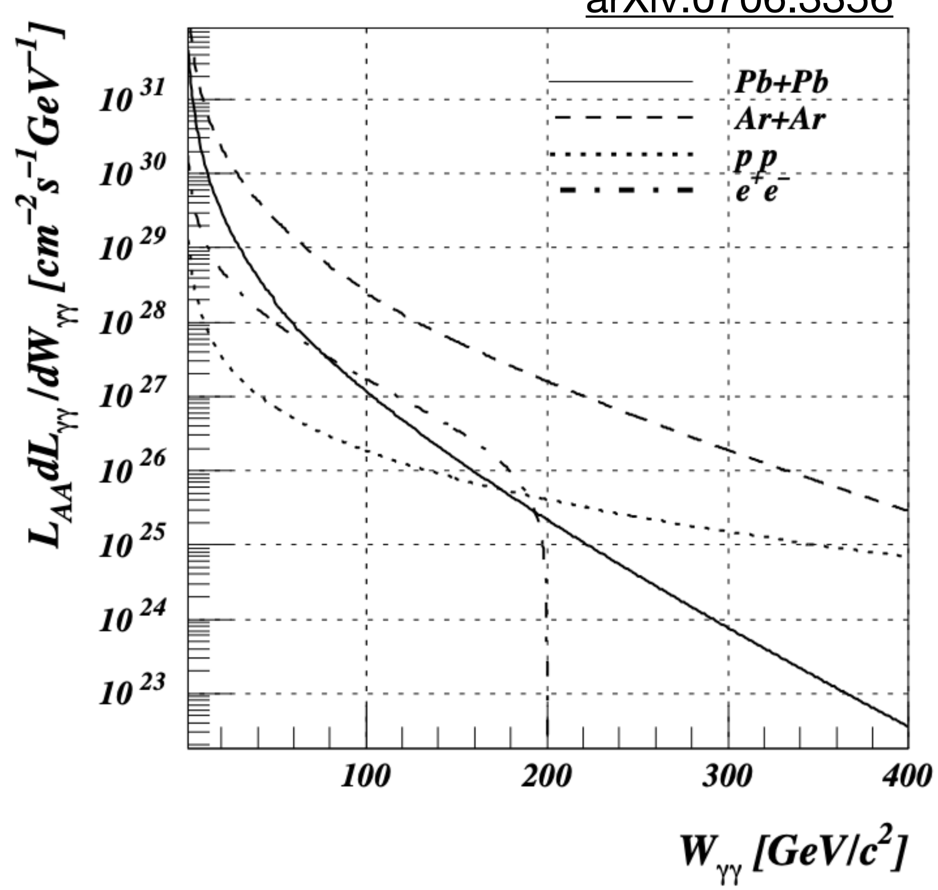
Constraints also set by L3 & OPAL ($Z \to \tau\tau\gamma$)

Photo-production at colliders



- Beam of charged particles is surrounded by an EM field
    - Strong EM field produced by the charged particle can induce interactions at very large radius

arXiv:0706.3356

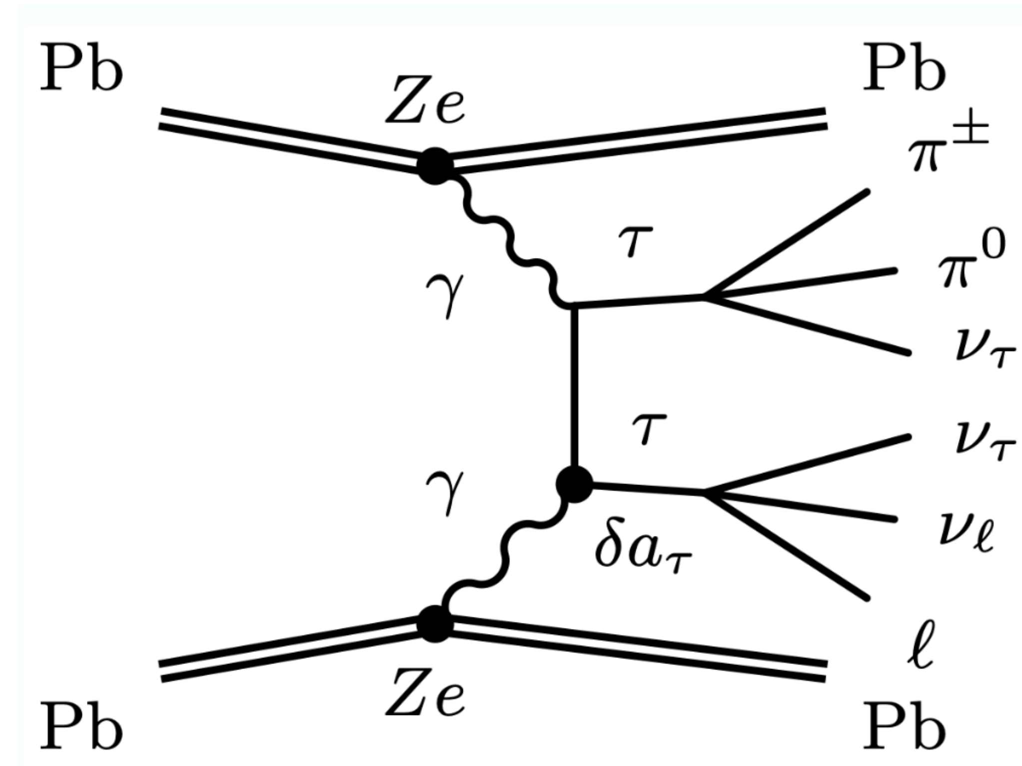


- Photon flux scales as Z^2 (Z=atomic number)
- Very large boost (multigev/TeV beam) enables production of large variety of processes:
    - W^+W^-, $q\bar{q}$, $\gamma\gamma$, $\ell\ell$ are all studied at the LHC

Measurement program at the LHC

Ultra peripheral Pb-Pb collisions

- Pb-Pb dataset is much smaller than p-p
    - i.e 10^8 smaller in this result ($L=1.44nb^{-1}$) when compared with pp Run2 $L=140fb^{-1}$
- BUT



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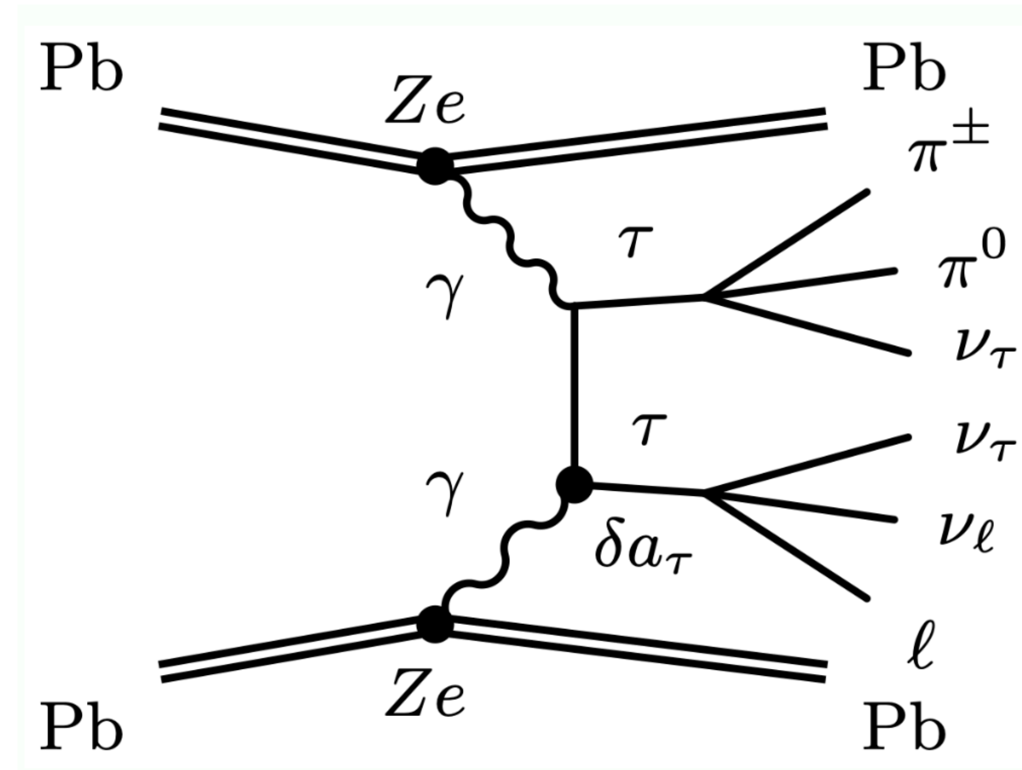
    - Photo-production scales with Z^4
        - Z(Pb) = 82 → 4.5×10^7 enhancement over pp



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    - Photon virtuality ($|q^2|$) goes in $1/R_A$: roughly 6 times smaller for Pb than p. Photon momentum in nucleus rest frame ~ 25 MeV in Pb-Pb collisions

$\tau\tau\gamma$ coupling:

$$F_1(q^2)\,\gamma^\mu + F_2(q^2)\,\frac{i}{2m_\tau}\sigma^{\mu\nu}q_\nu$$

tree level coupling:

$$F_1(q^2 \to 0) = 1$$

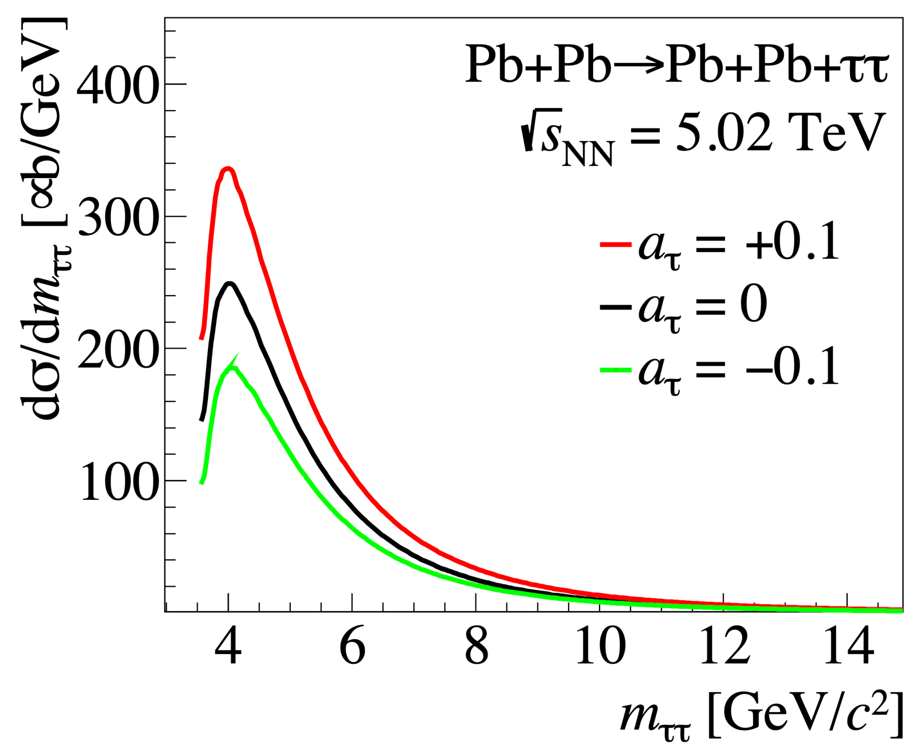
higher-order corrections:

$$F_2(q^2 \to 0) = a_\tau$$

Measurement program at the LHC

Ultra peripheral Pb-Pb collisions

N. Burmasov et al arxiv:2111.11383



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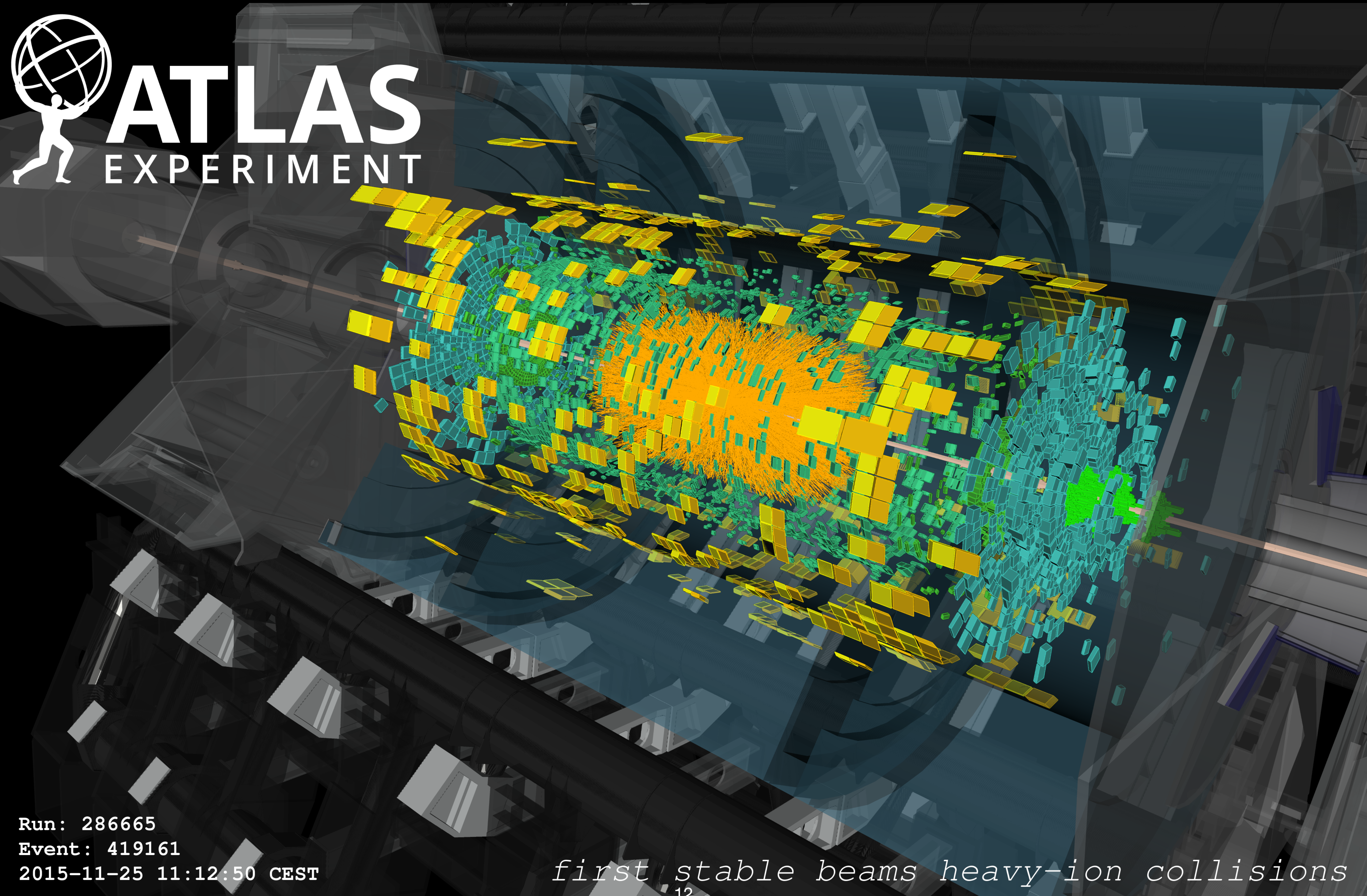
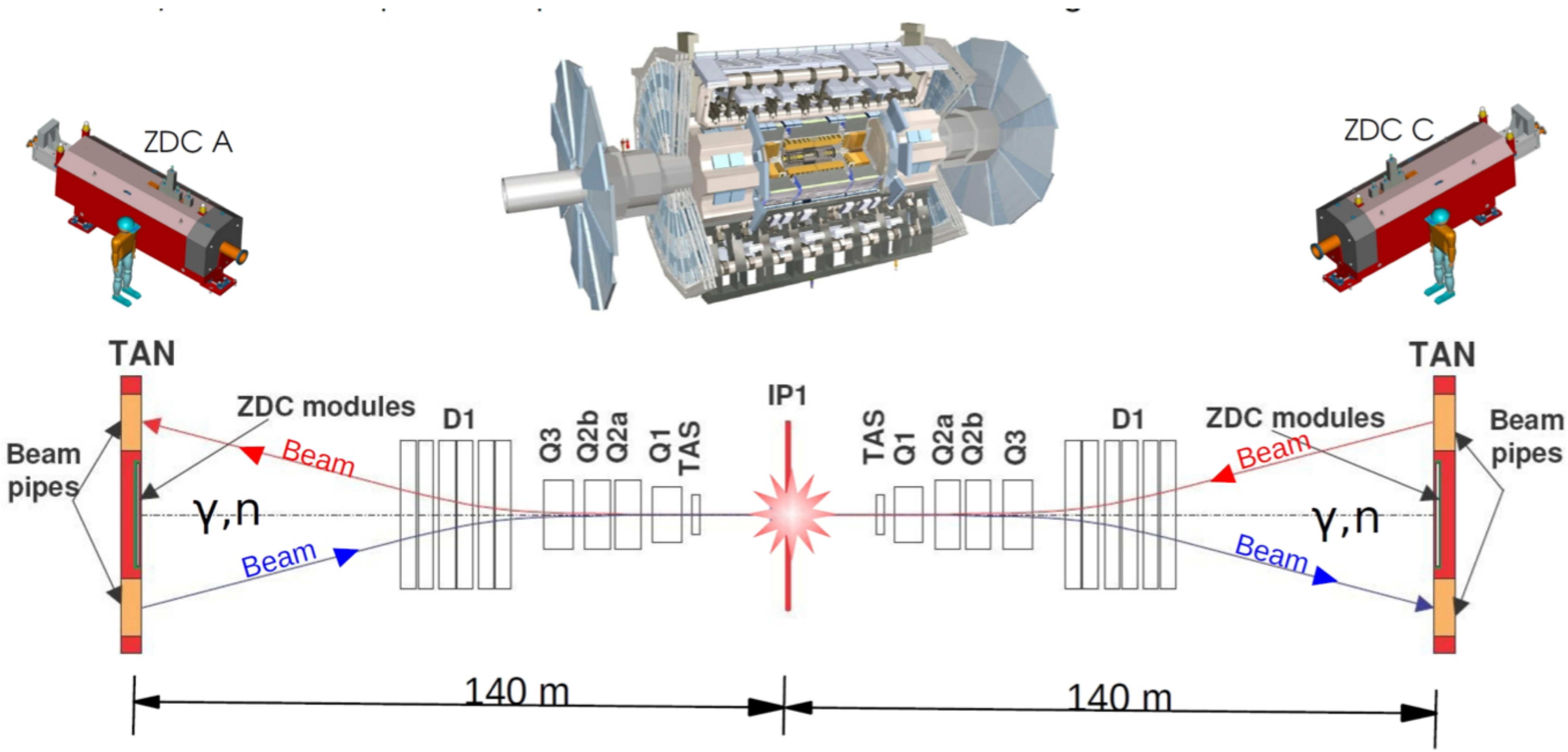
  - Average int. per bunch crossing is < 0.01 (to be compared with 33 for LHC pp Run2)
    - Negligible contamination from previous collisions, allow to reach the lower p_T thresholds

Still … A typical Pb-Pb collision event



The ATLAS Detector

And its Zero Degree Calorimeters

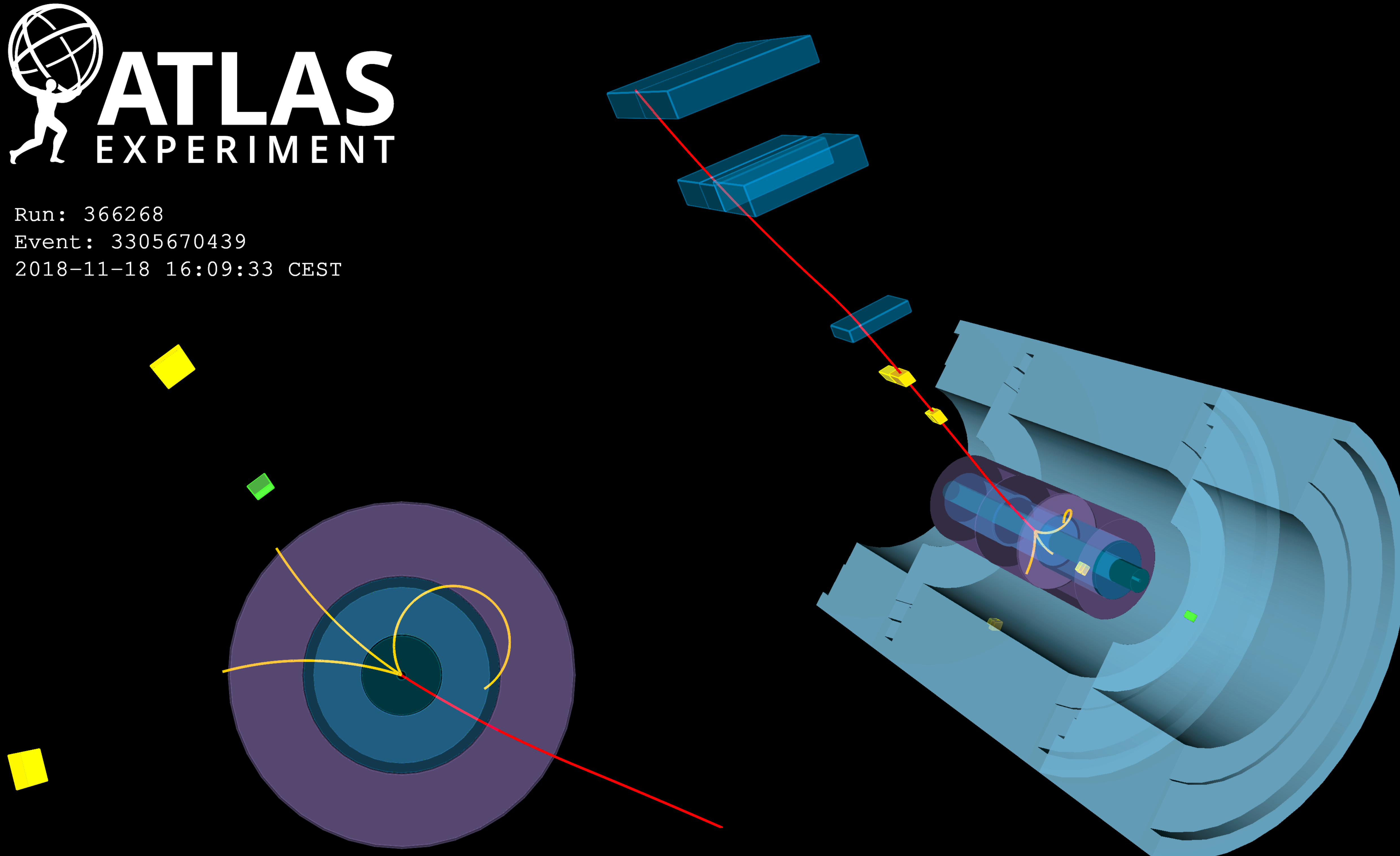


Coulomb breakup of a nuclei typically produces neutrons

Detects them with radiation hard calorimeters away from the interaction point

➡ select very clean ultra peripheral collisions

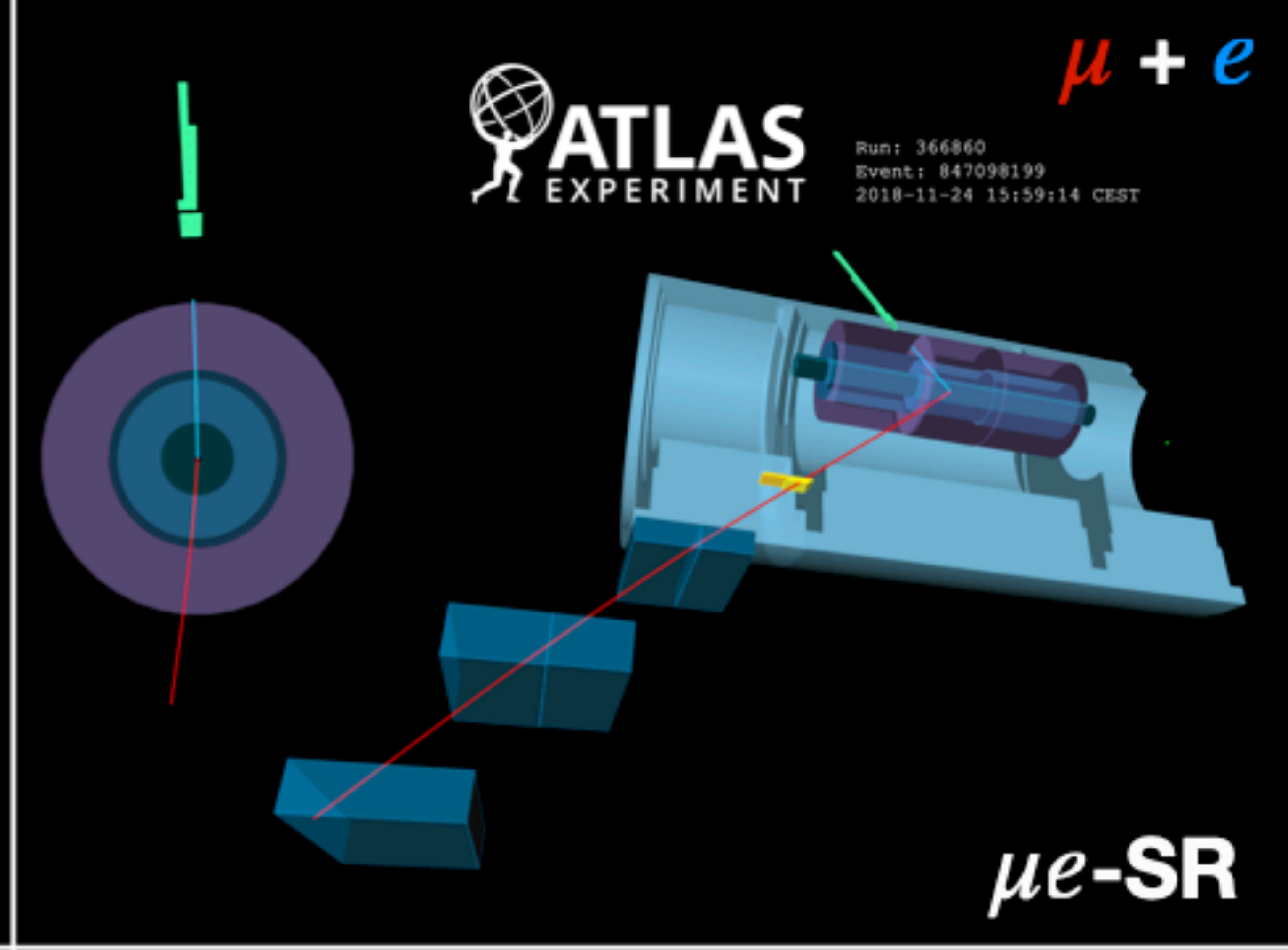
$\gamma\gamma \to \tau\tau$ event in Pb-Pb collisions

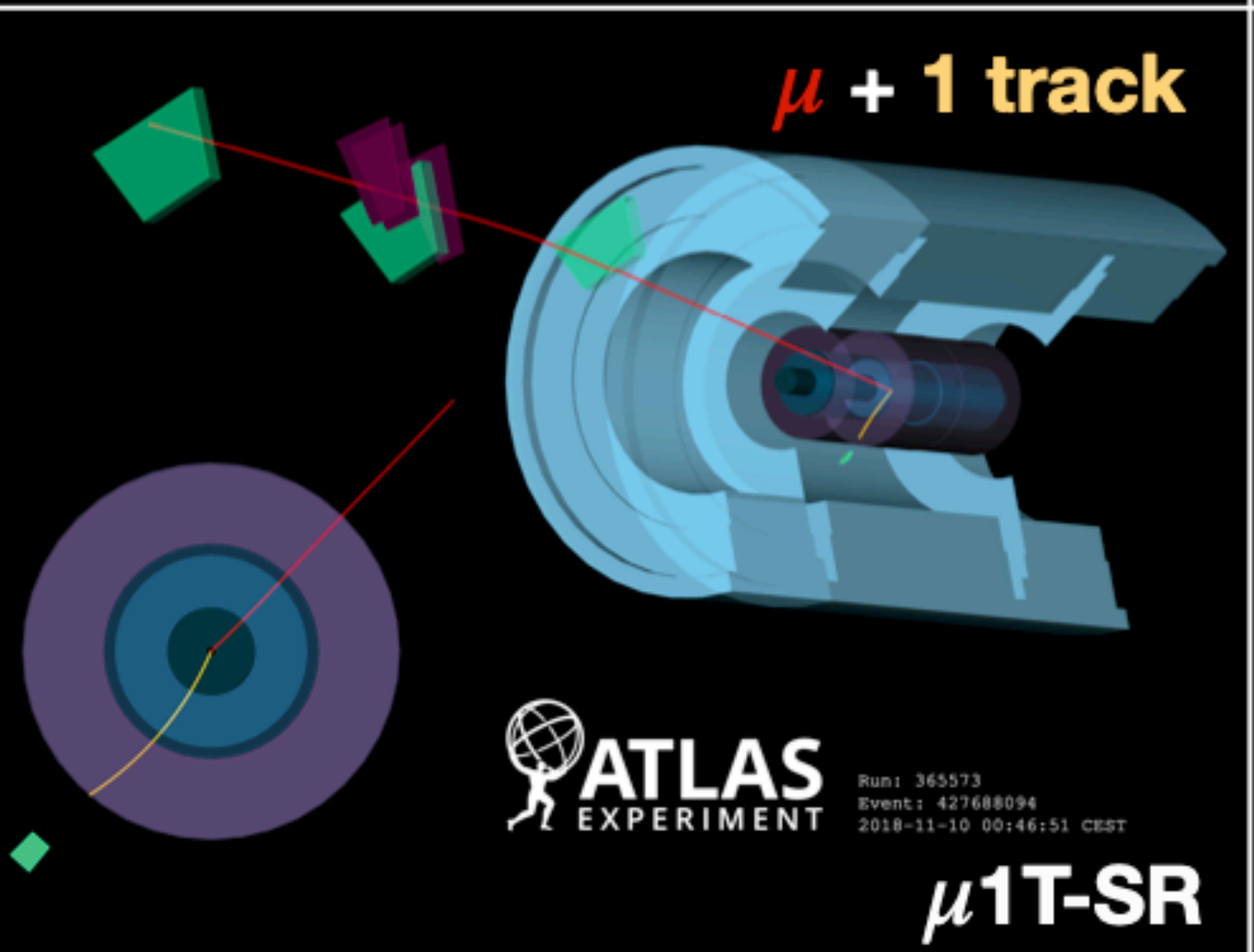


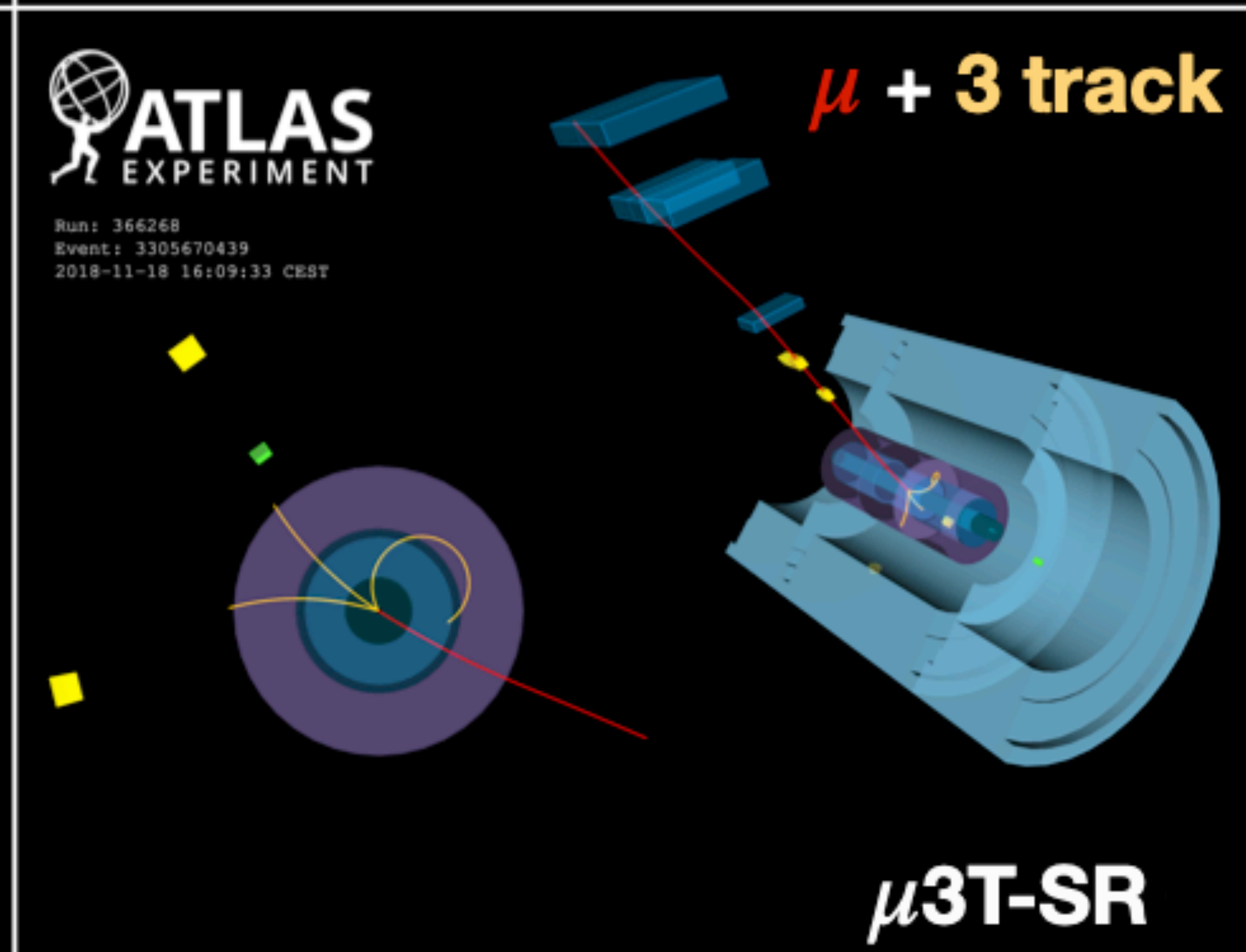
First Publication

Focus on events with
a muon in the final state

Easy to trigger
$p_T(\mu) > 4$ GeV

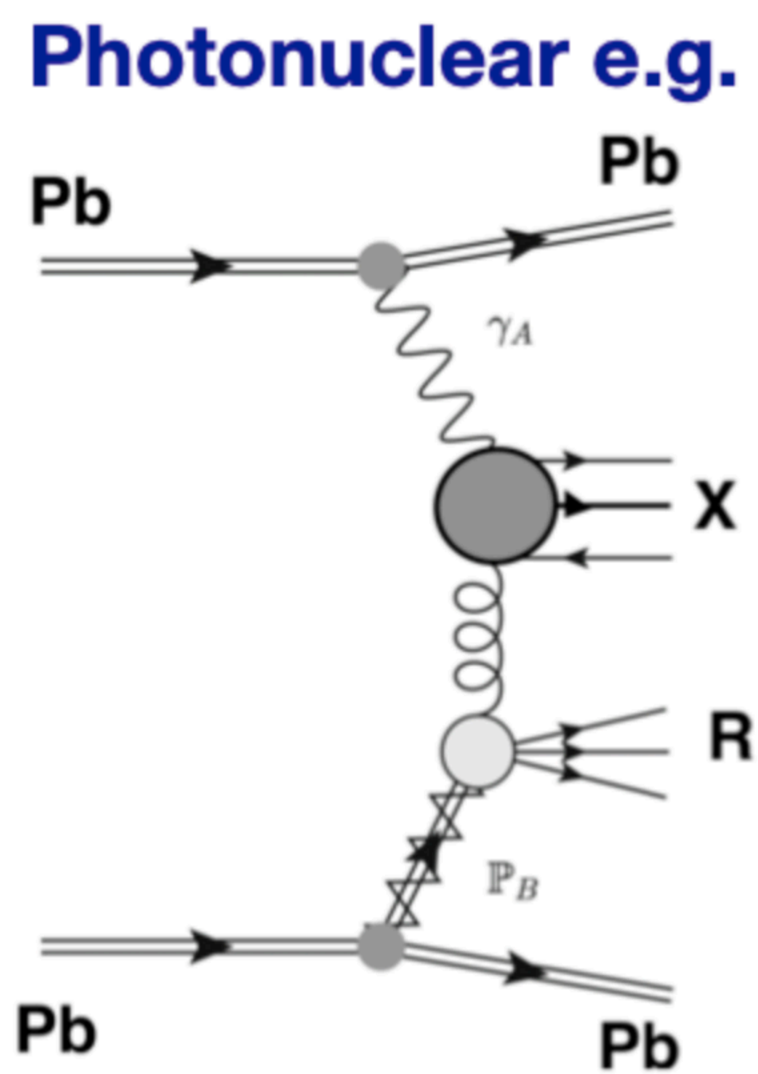


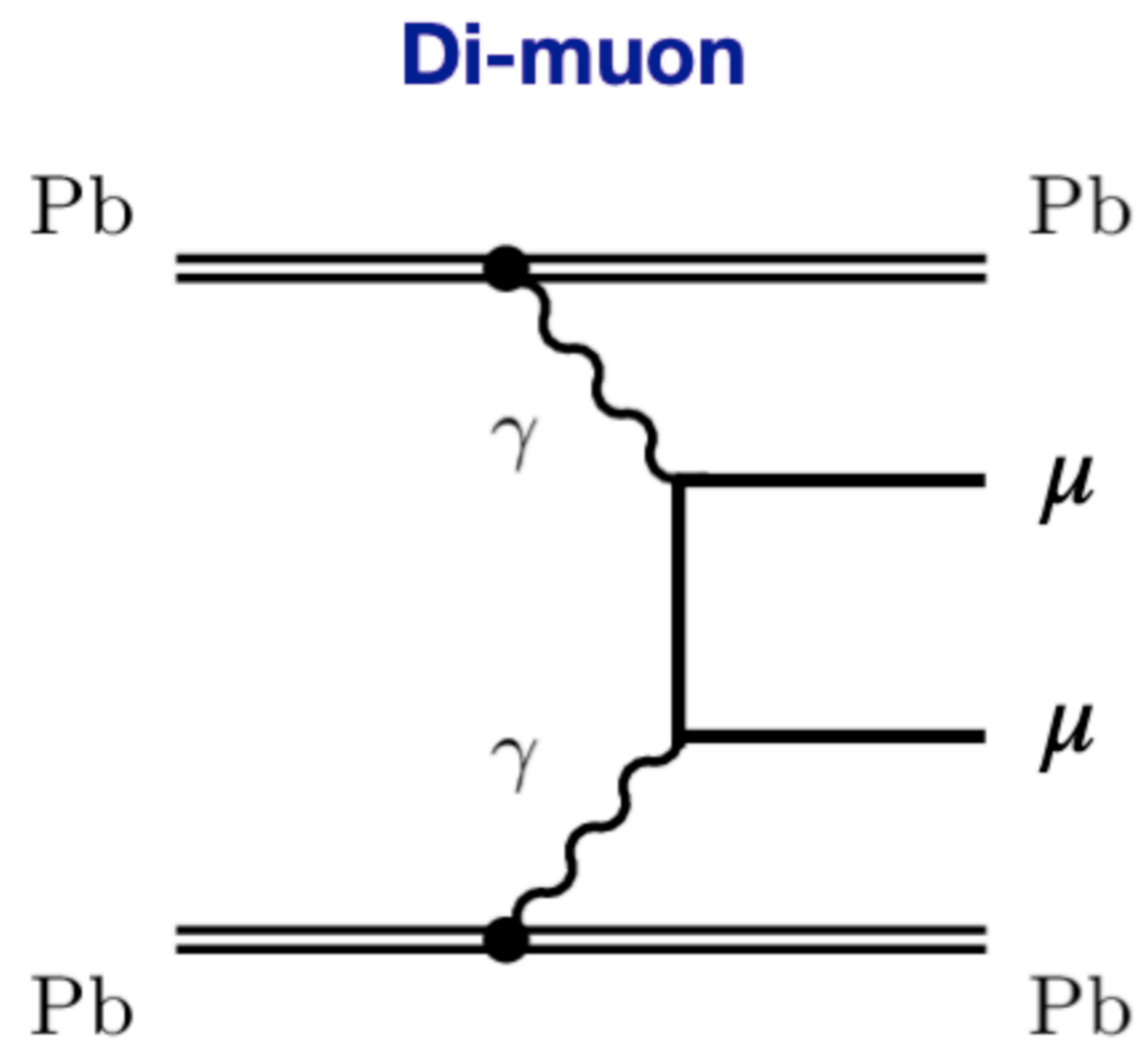




Still .. some backgrounds remain

Two dominant backgrounds





Data driven estimate

Invert Signal Region selection

Criteria inverted: ZDC energy and unmatched clusters who are signature of extra activity

Estimated using simulations

$\gamma\gamma \to \mu\mu$ with Starlight+Pythia

$\gamma\gamma \to \mu\mu\gamma$ with Madgraph

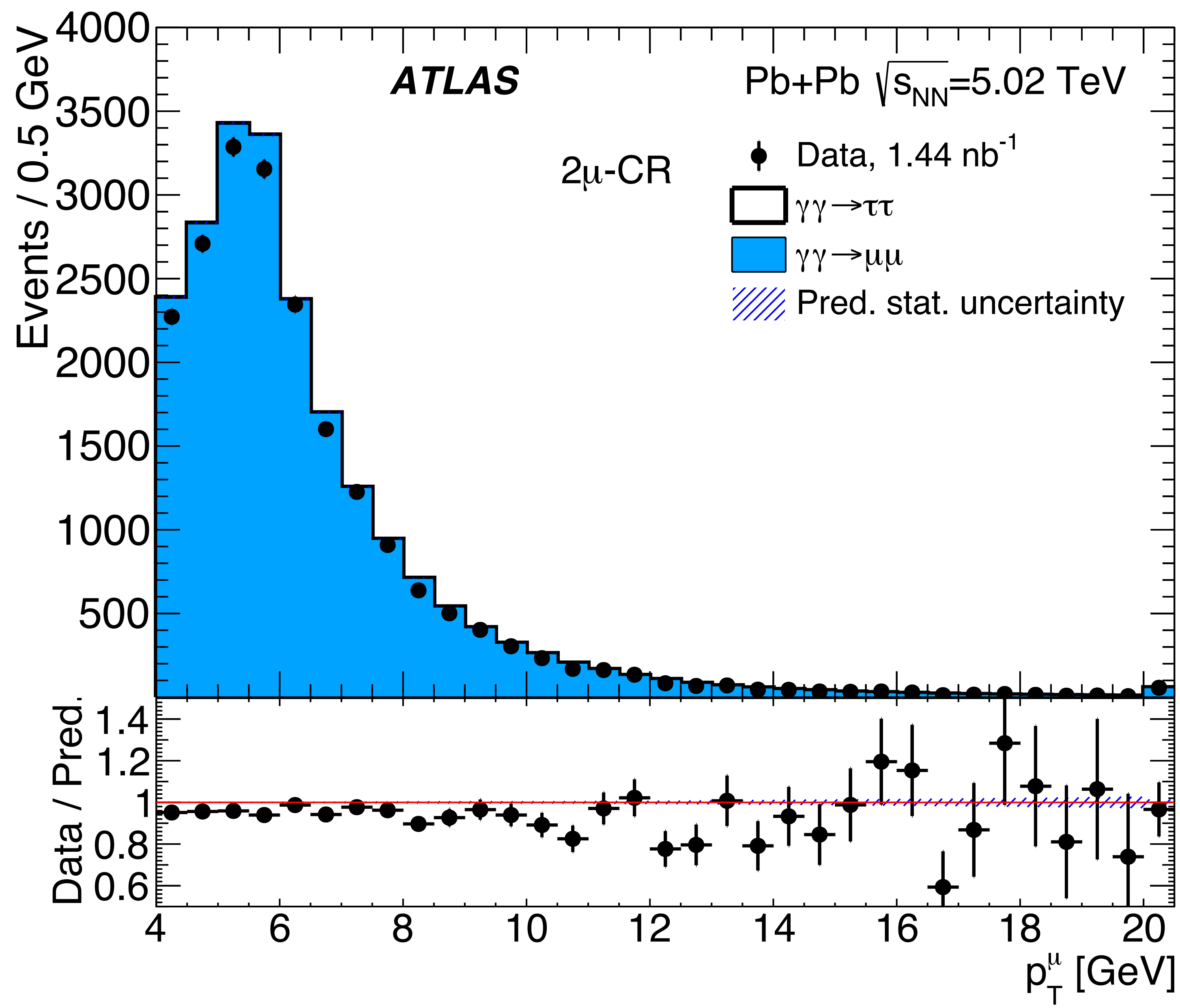
Photon flux reweighed to SuperChic 3

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

Checking simulation with data in a control region

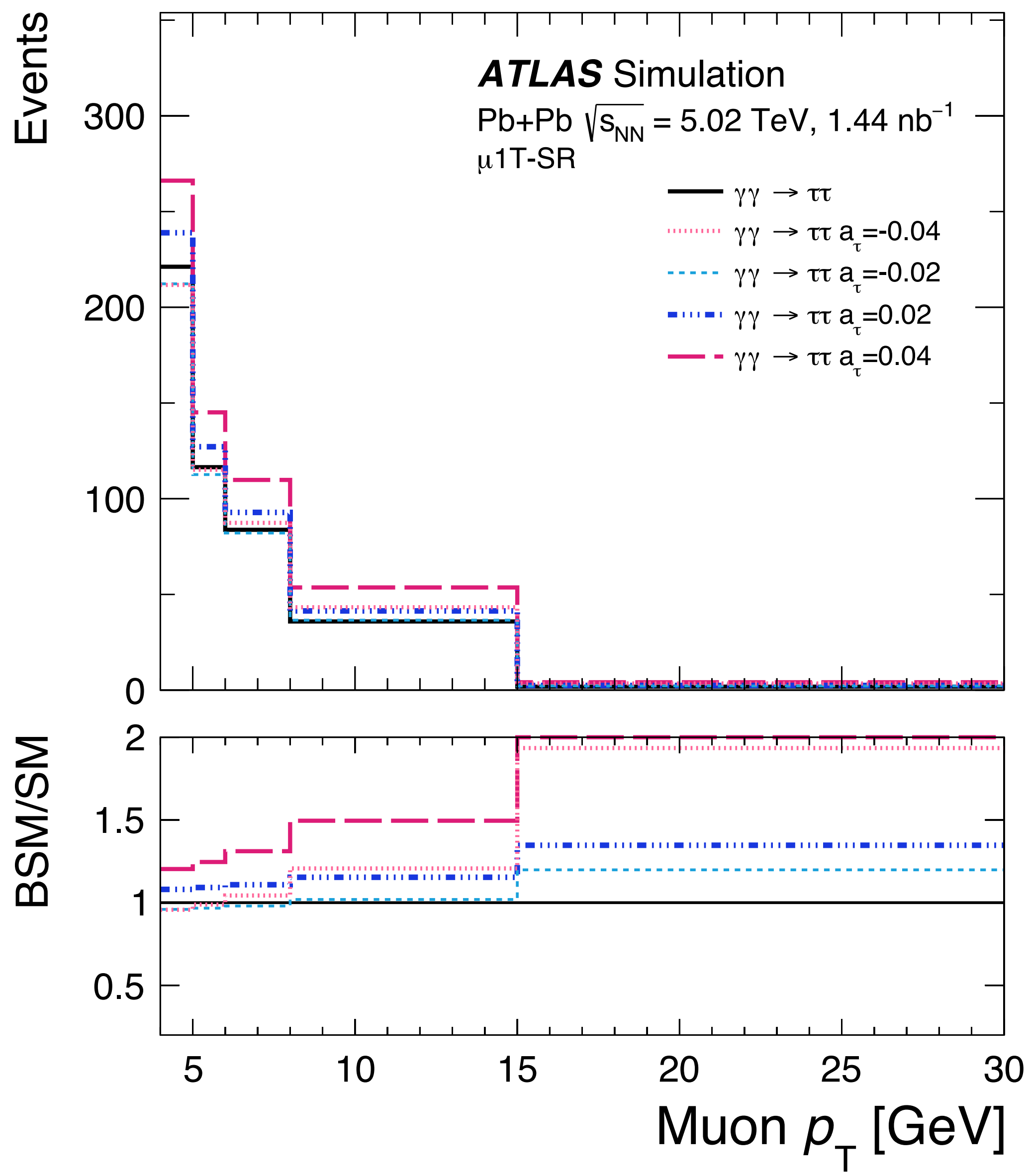
Superchic 3 overshoots by 6%
Starlight undershoots by 13%

Difference: systematic uncertainty on the photon flux



a_τ measurement strategy

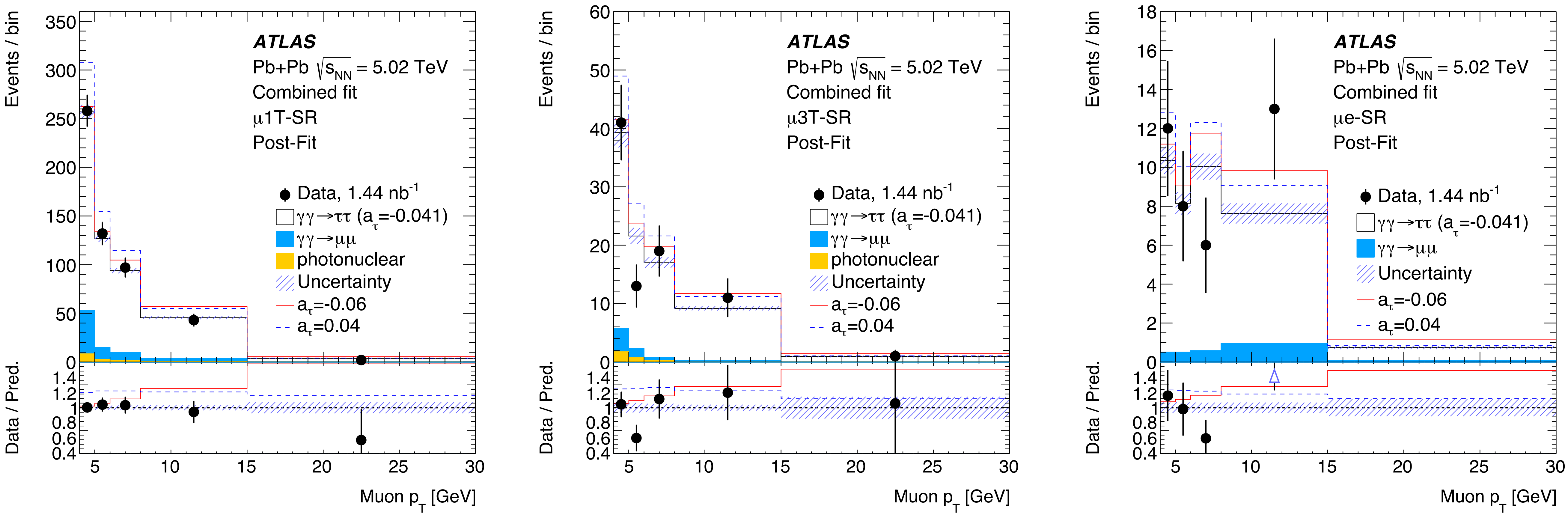
- Binned likelihood fit over the three SRs and the $\gamma\gamma \rightarrow \mu\mu$ control region
  - Simultaneous fit of SRs and the CR alleviates photon flux and luminosity uncertainties
- Leverage sensitivity from cross-section and muon transverse momentum distribution



Fit results

Muon transverse momentum in signal regions

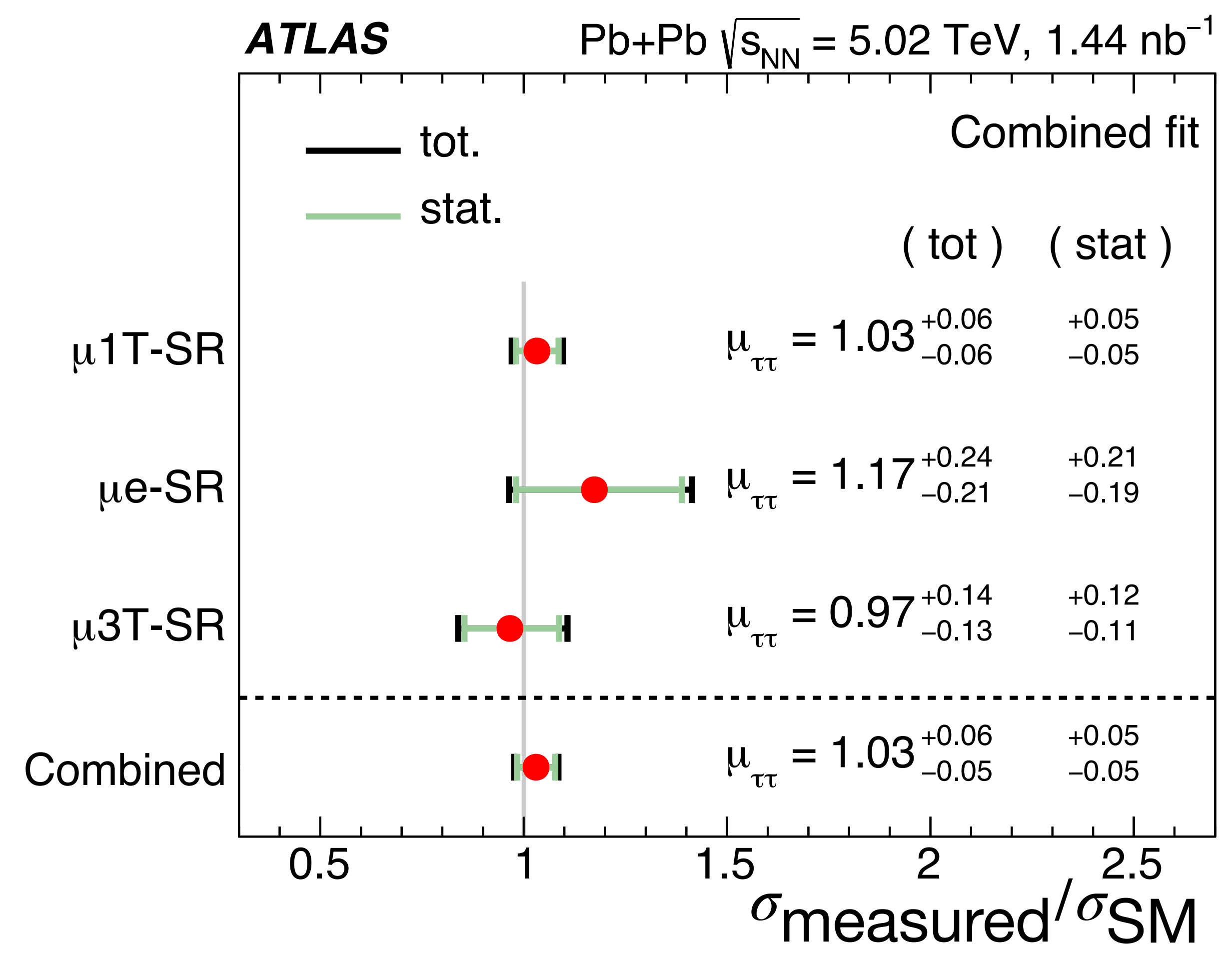
μ + 1 track   μ + 3 tracks   μ + e



Large signal
Good modelling observed

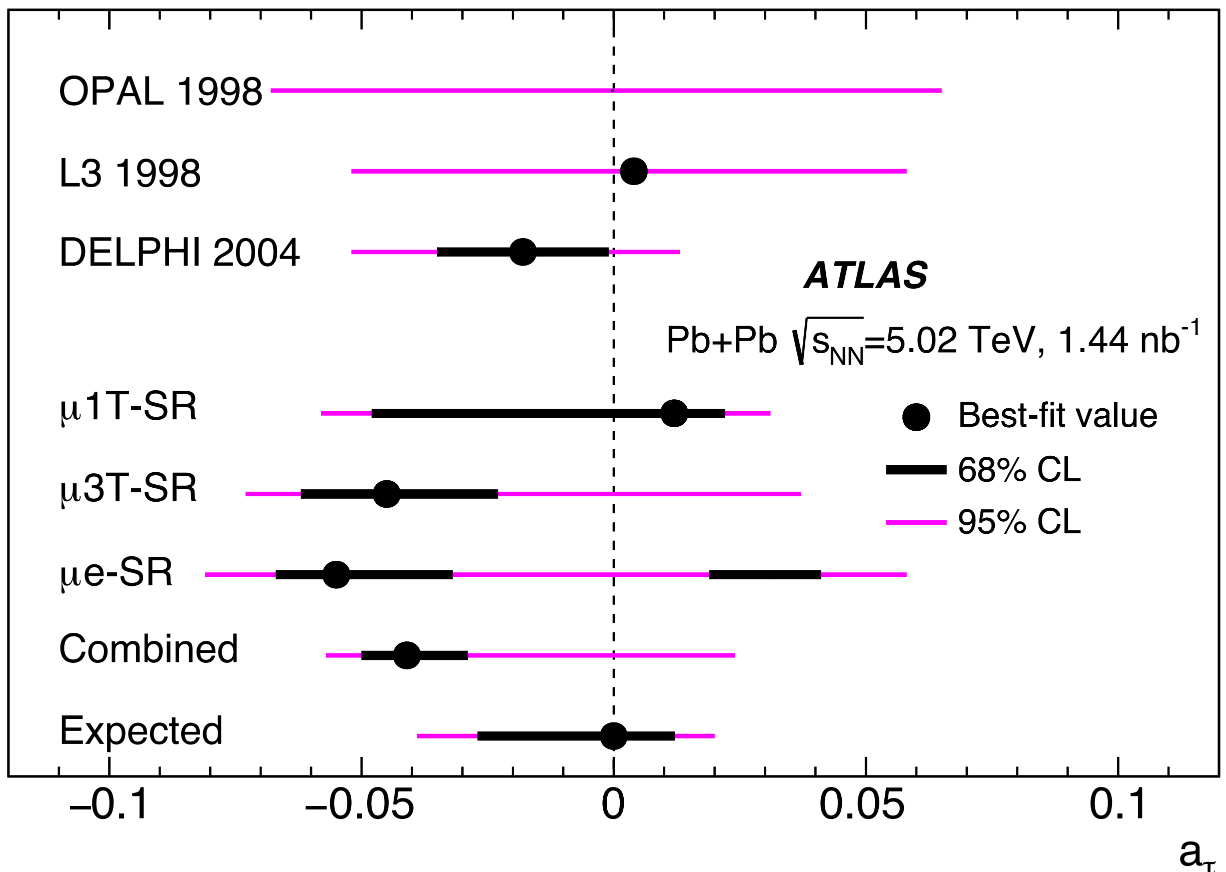
$\gamma\gamma \to \tau\tau$ cross-section measurement

- Very good agreement with SM predictions
- Precision limited by dataset size
- Very good agreement between decay modes



a_τ measurement result

ATLAS Collaboration, arXiv:2204.13478



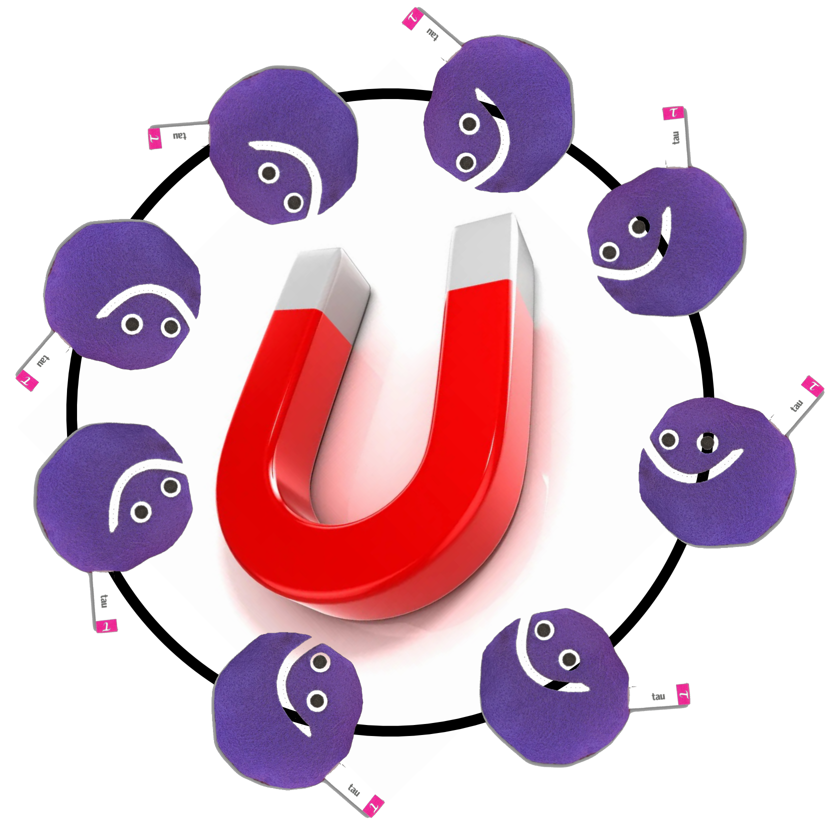
This result: $a_\tau = -0.041(-0.058 < a_\tau < 0.025 @ 95\,\%\,CL)$

DELPHI: $a_\tau = -0.018(-0.052 < a_\tau < 0.013 @ 95\,\%\,CL)$

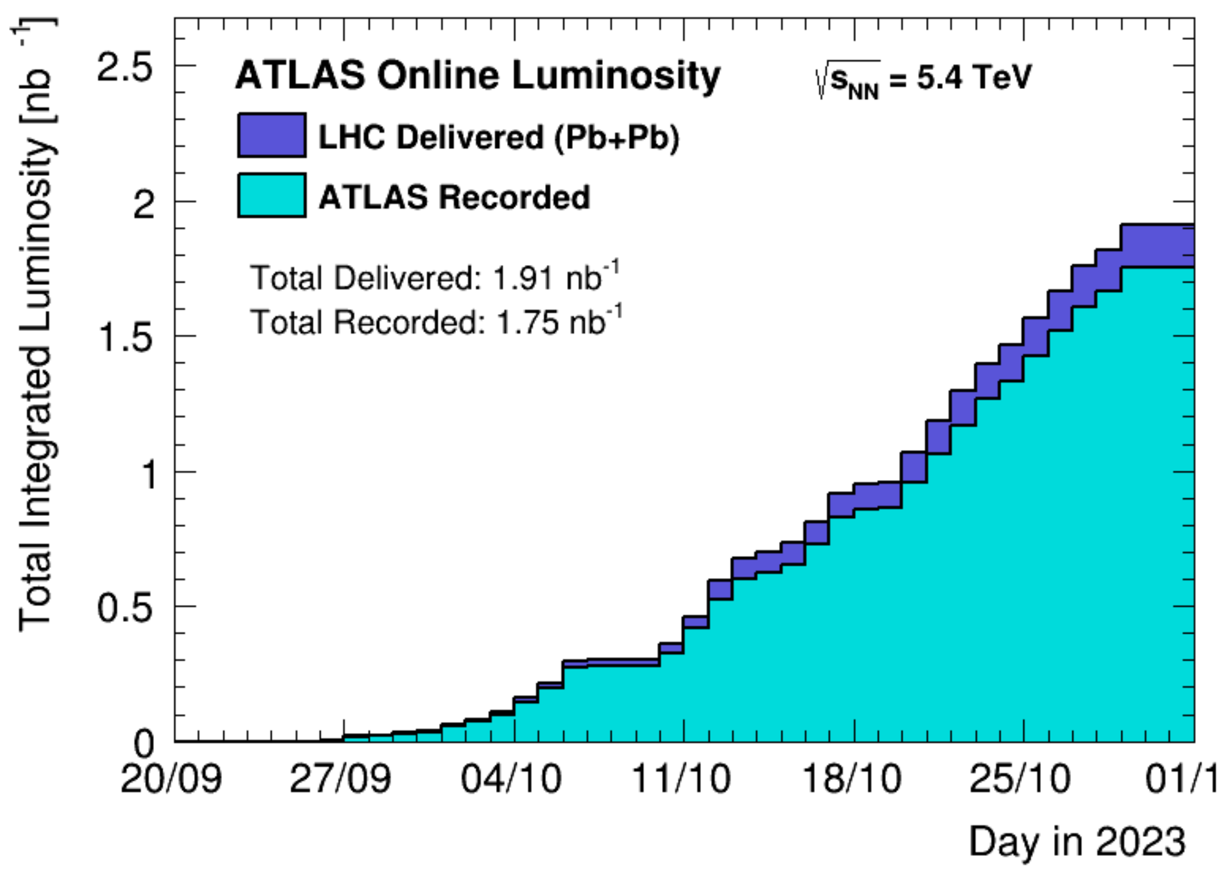
Prediction: $a_\tau^{\text{SM}} = 0.00117721\,(5)$ – (Schwinger term $\alpha/2\pi = 0.0012$)

Similar study from CMS: arXiv:2206.05192

Summary



- PbPb → Pb ($\gamma\gamma \rightarrow \tau^+\tau^-$) Pb process observed in ATLAS with >5σ significance
  - Data is in good agreement with SM expectations
  - New constraints on a_τ
- **Tau g-2** still largely unconstrained BUT new measurement strategy at the LHC on track to beat LEP result
  - In many BSM models, new particles couple more strongly to tau than electron or muon
- More data and more channels to analyse!



Additional material

Anomalous magnetic dipole moment

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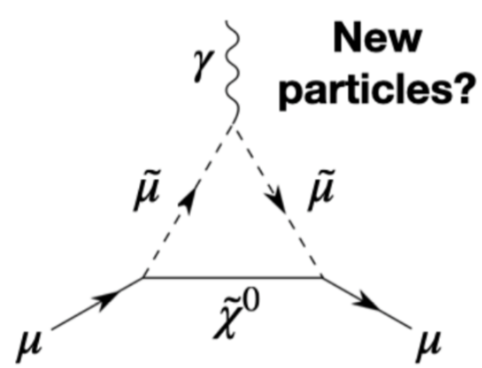
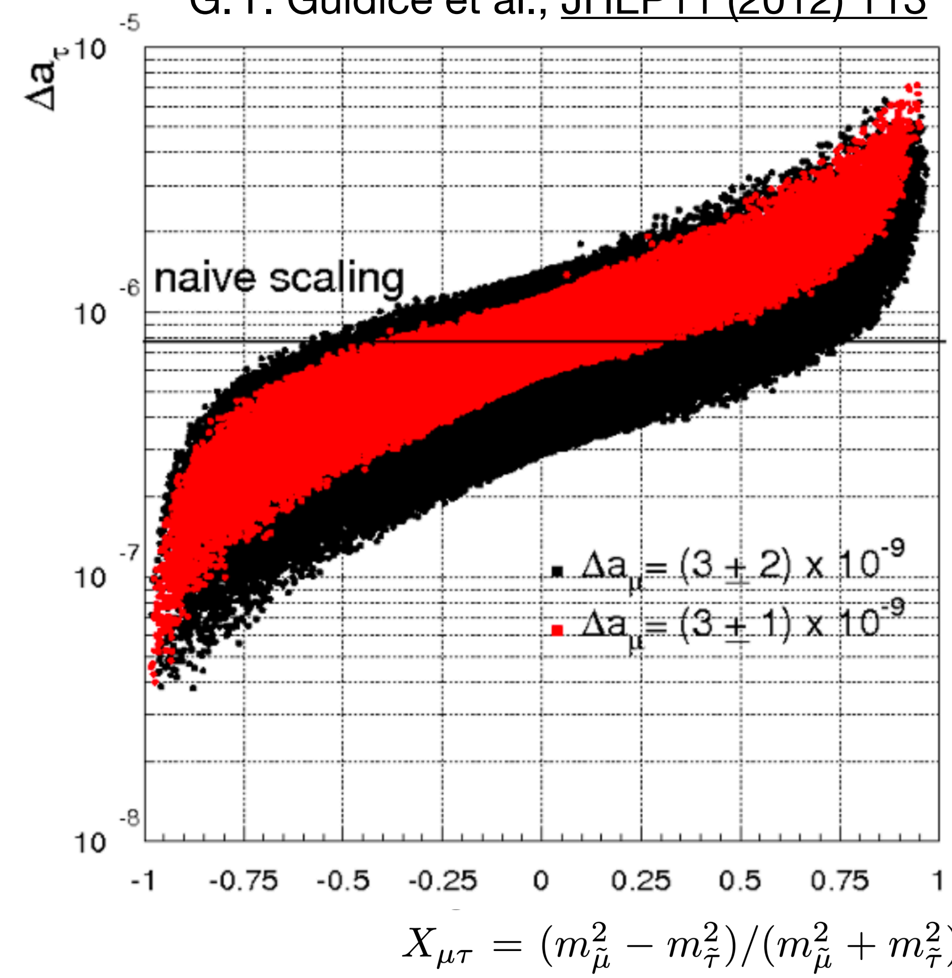
$g = \quad + \quad \cdots \quad +$



G. F. Guidice et al., JHEP11 (2012) 113



Lepton Flavor Conserving sleptons with non degenerate masses

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a_τ^{SM} calculations: S. EIDELMAN and M. PASSERA, MPLA 22, 03, 159-179 (2007)

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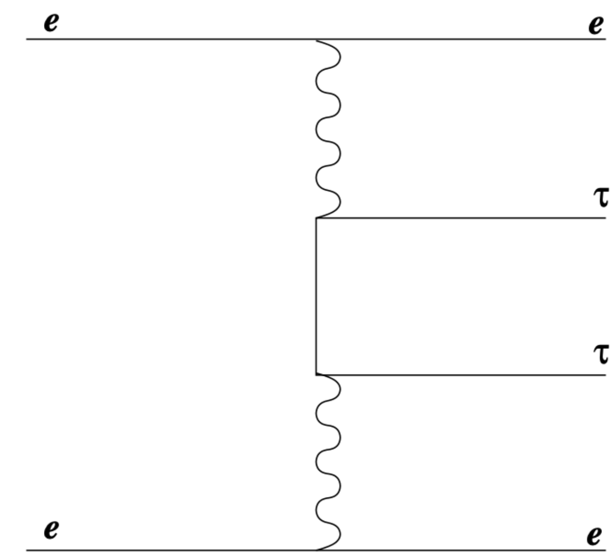

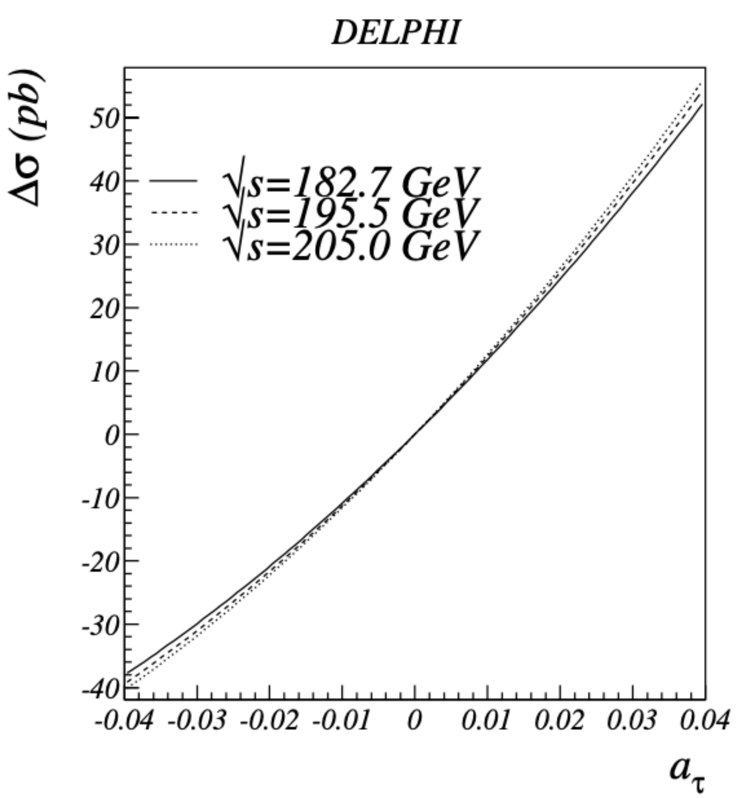

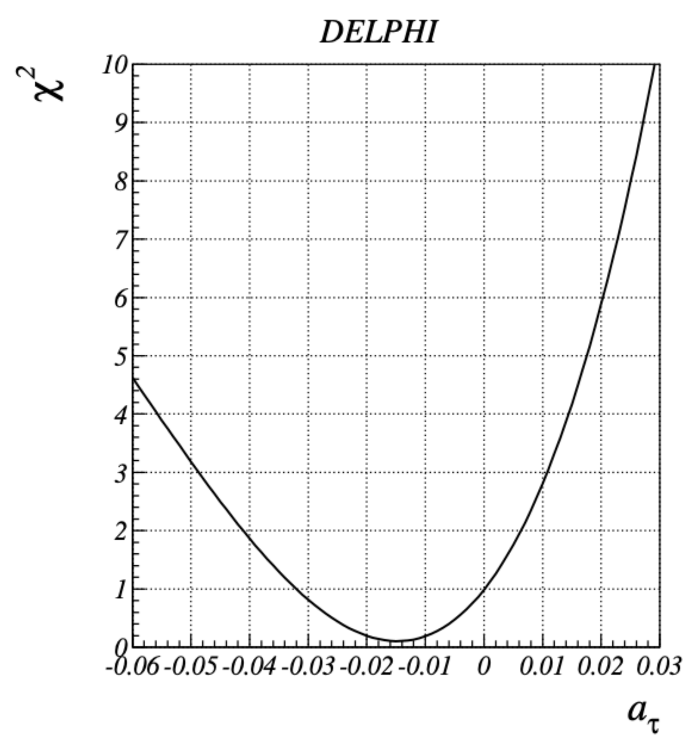

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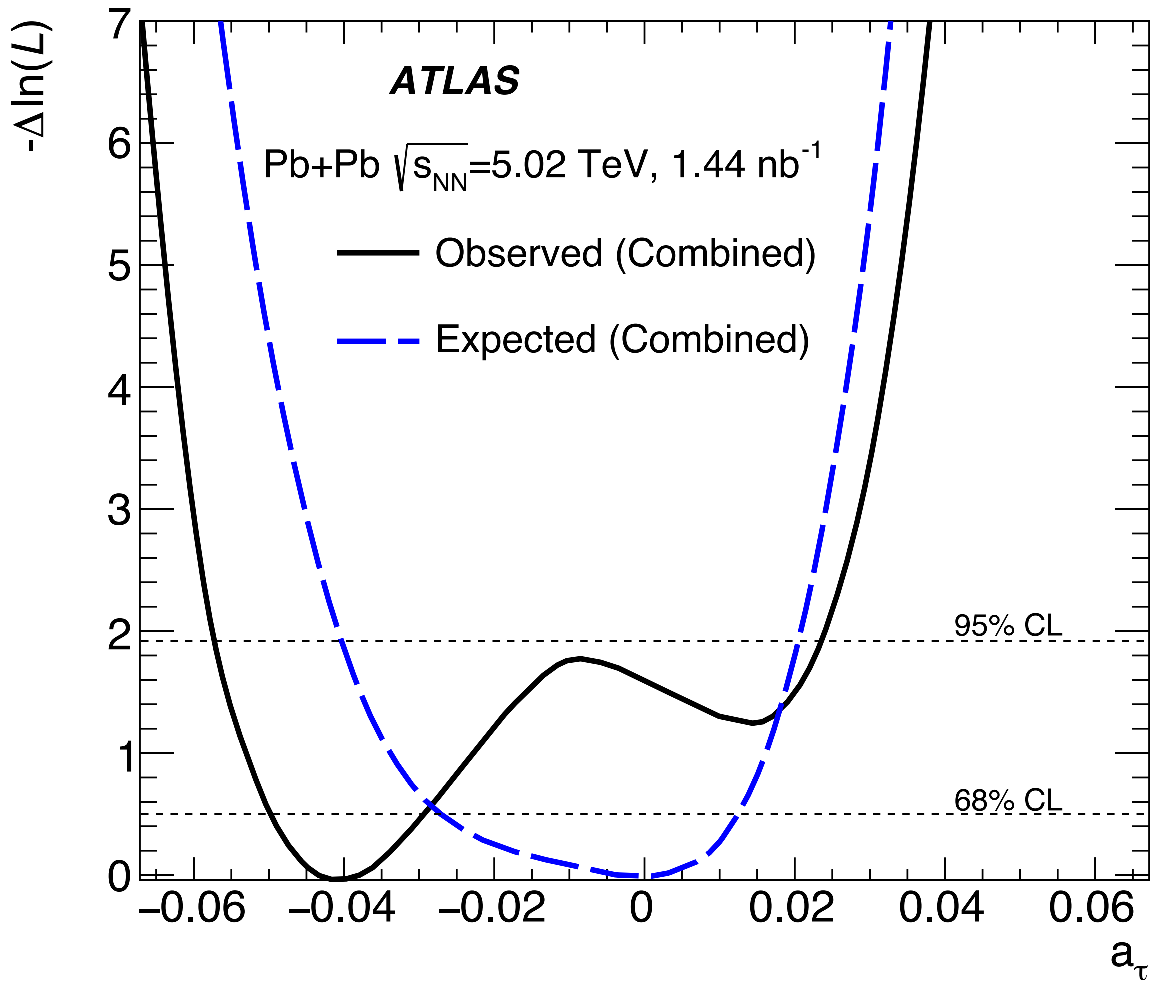

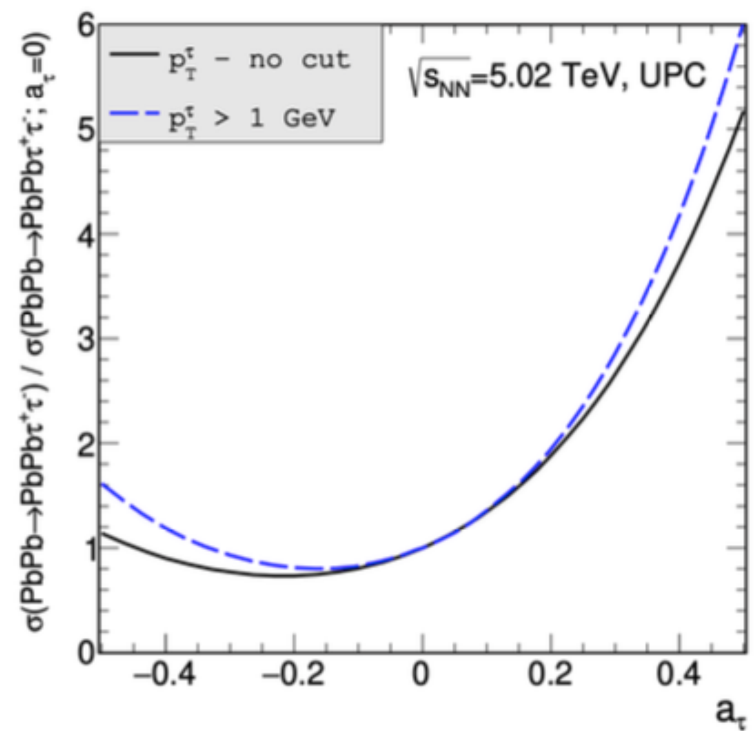

Dyndal, Kłusek-Gawenda, Szczurek & Schutt PLB (2020)

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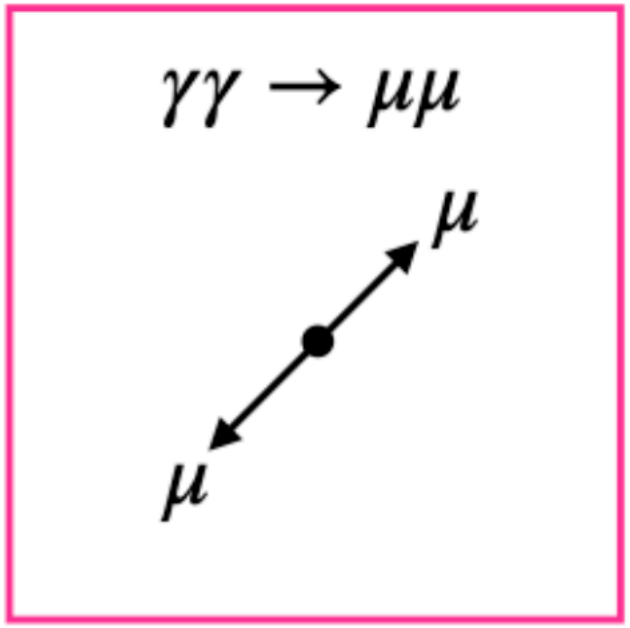
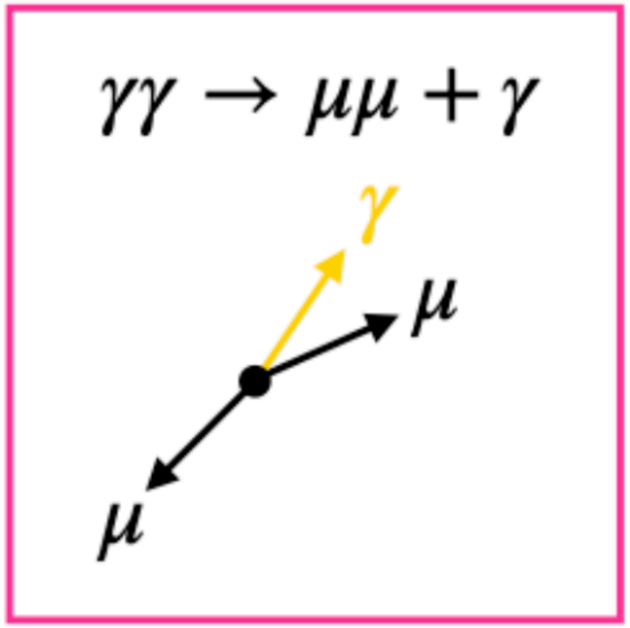
$\gamma\gamma \rightarrow \mu\mu(\gamma)$ background

Key characteristics

- Expect perfect balance of the final state particles:
  - Acoplanarity: directional balance in the transverse plan
  - $\Delta R(\mu,$ track(s)$(+\gamma))$: directional balance in the transverse and longitudinal direction
  - $p_T(\mu,$ track(s)$(+\gamma)) > 1$ GeV: transverse momentum balance



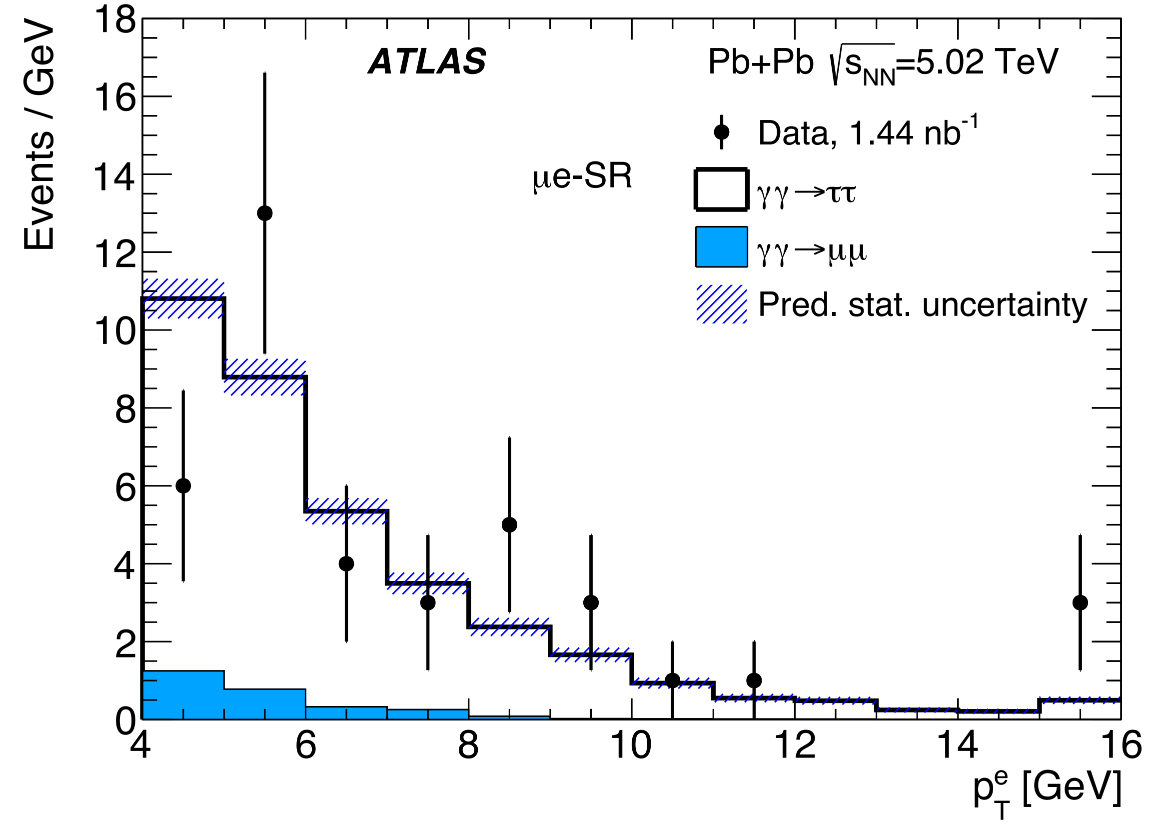


Signal region summary

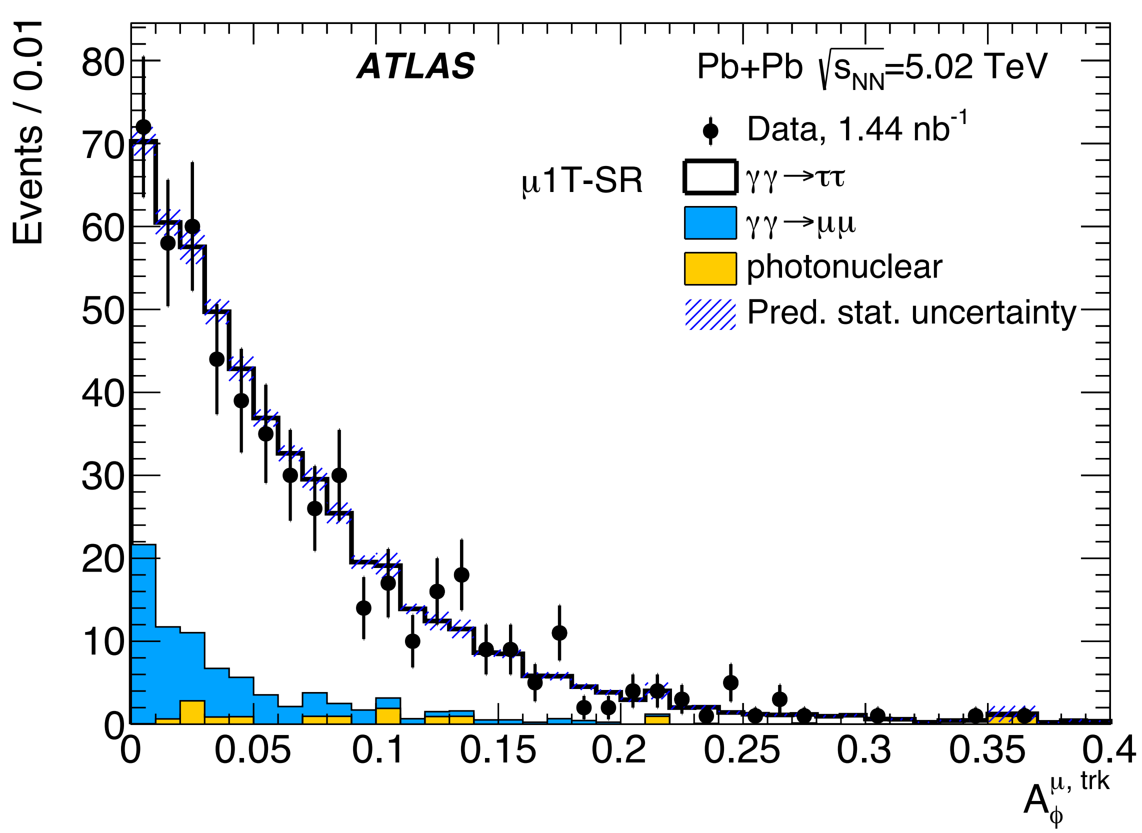
Pre-fit distributions

- Good modeling
- Minimal backgrounds

μ + e SR: N_{obs} = 39, N_{bkg} = 2.8 ±0.7



μ + 1 track SR: N_{obs} = 532, N_{bkg} = 84 ± 1



μ + 3 tracks SR: N_{obs} = 85, N_{bkg} = 10 ± 3

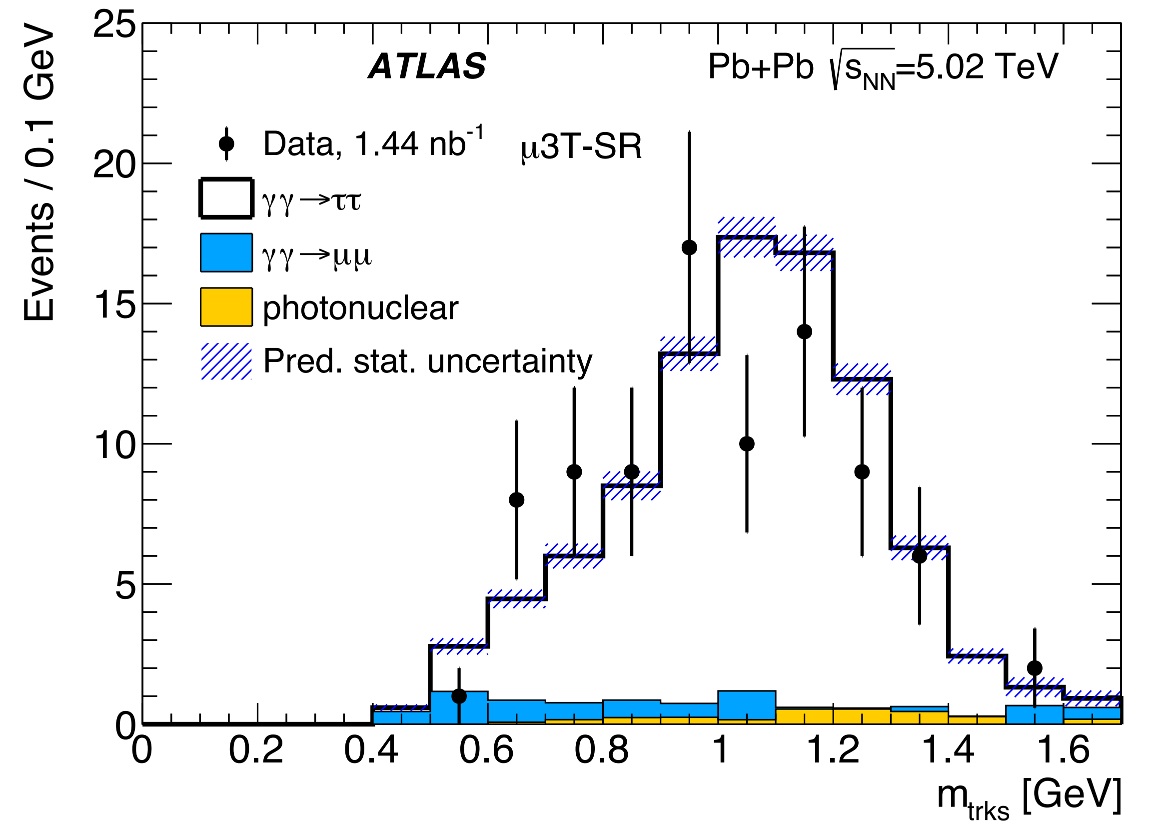
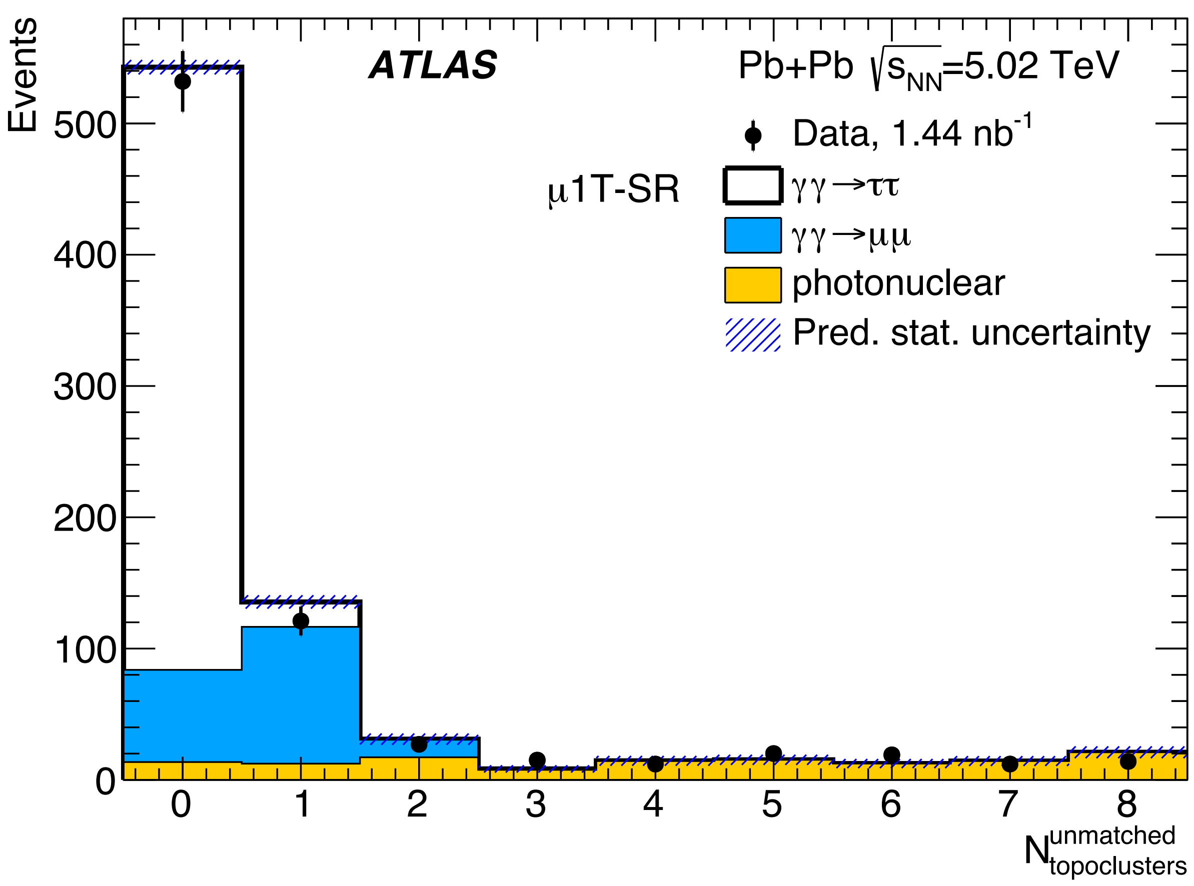
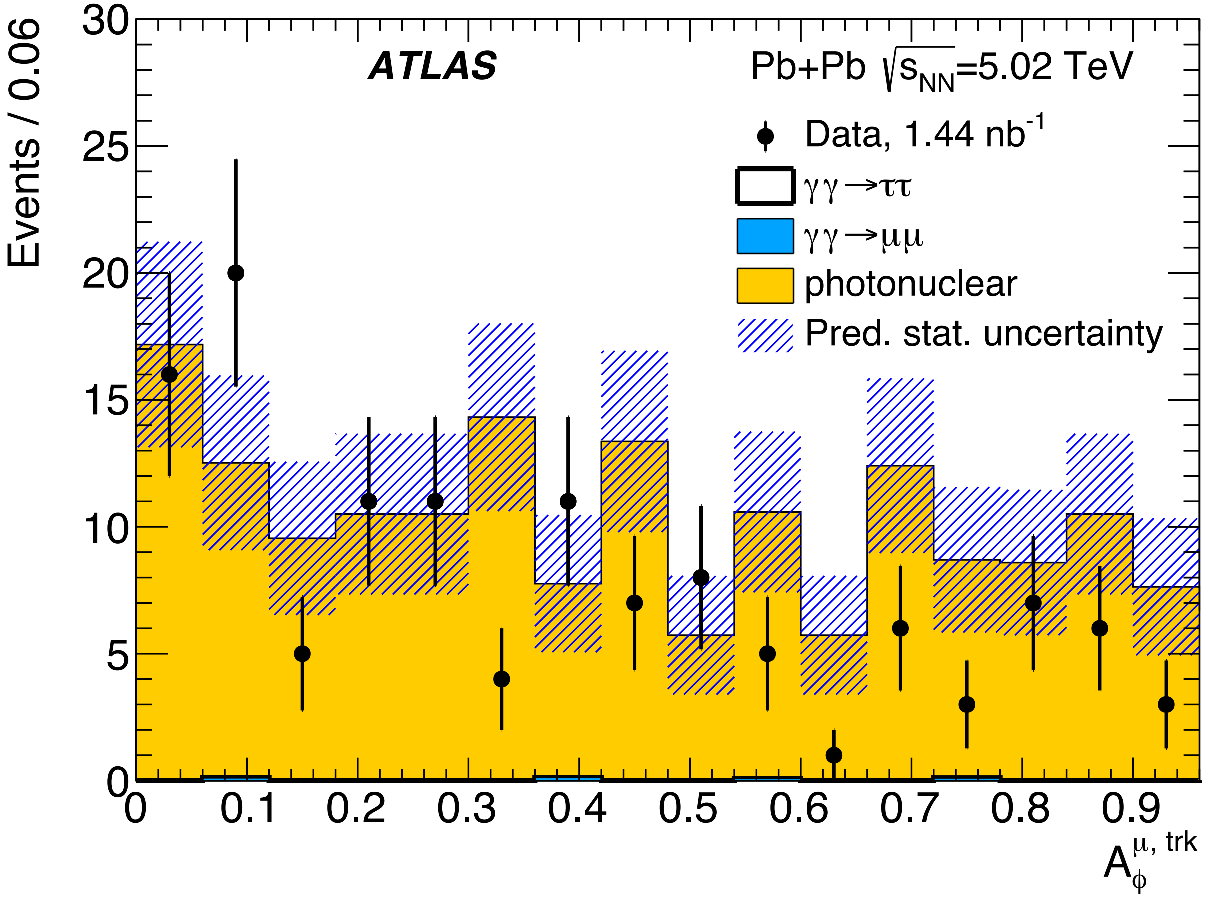


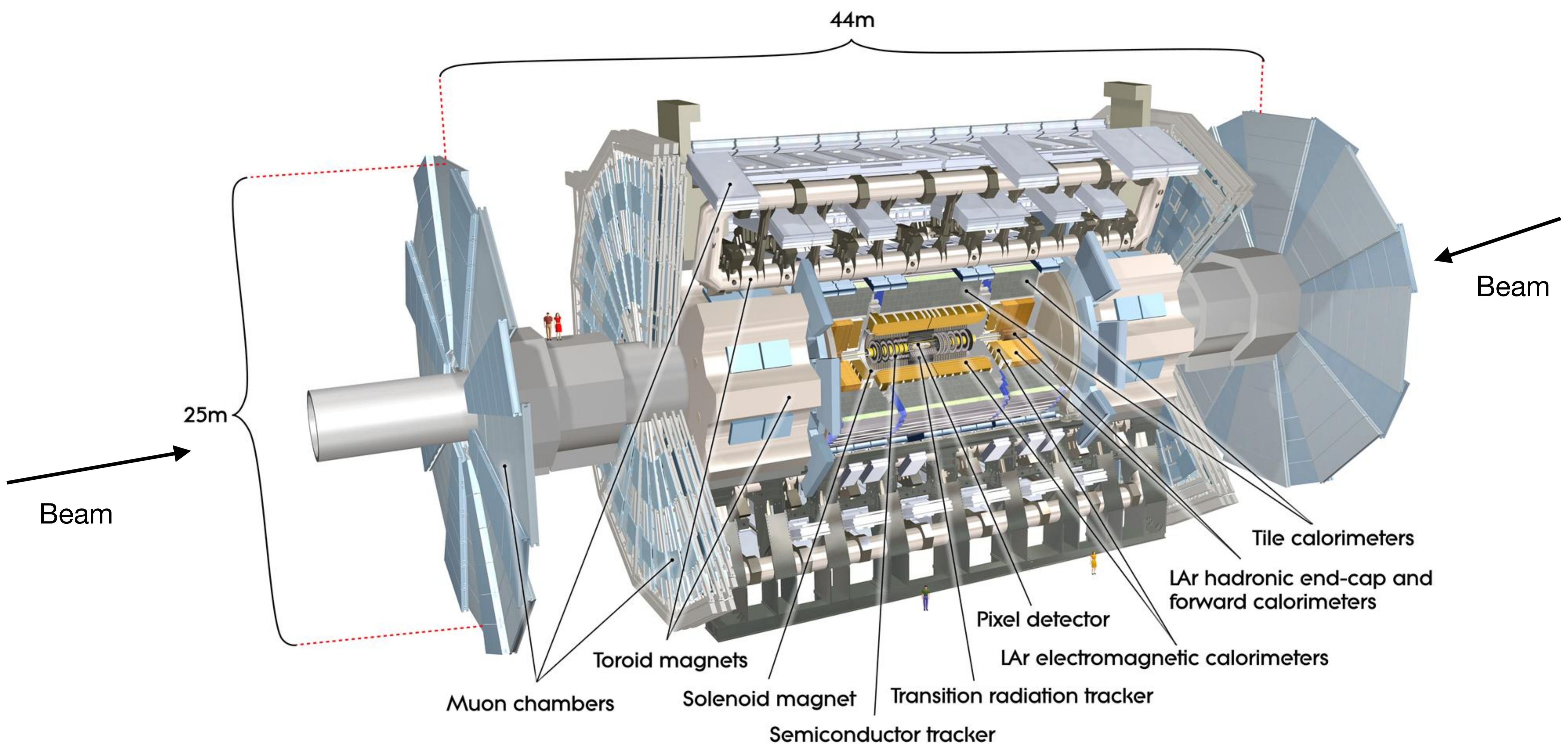
Photo-nuclear background

mu-1T signal region





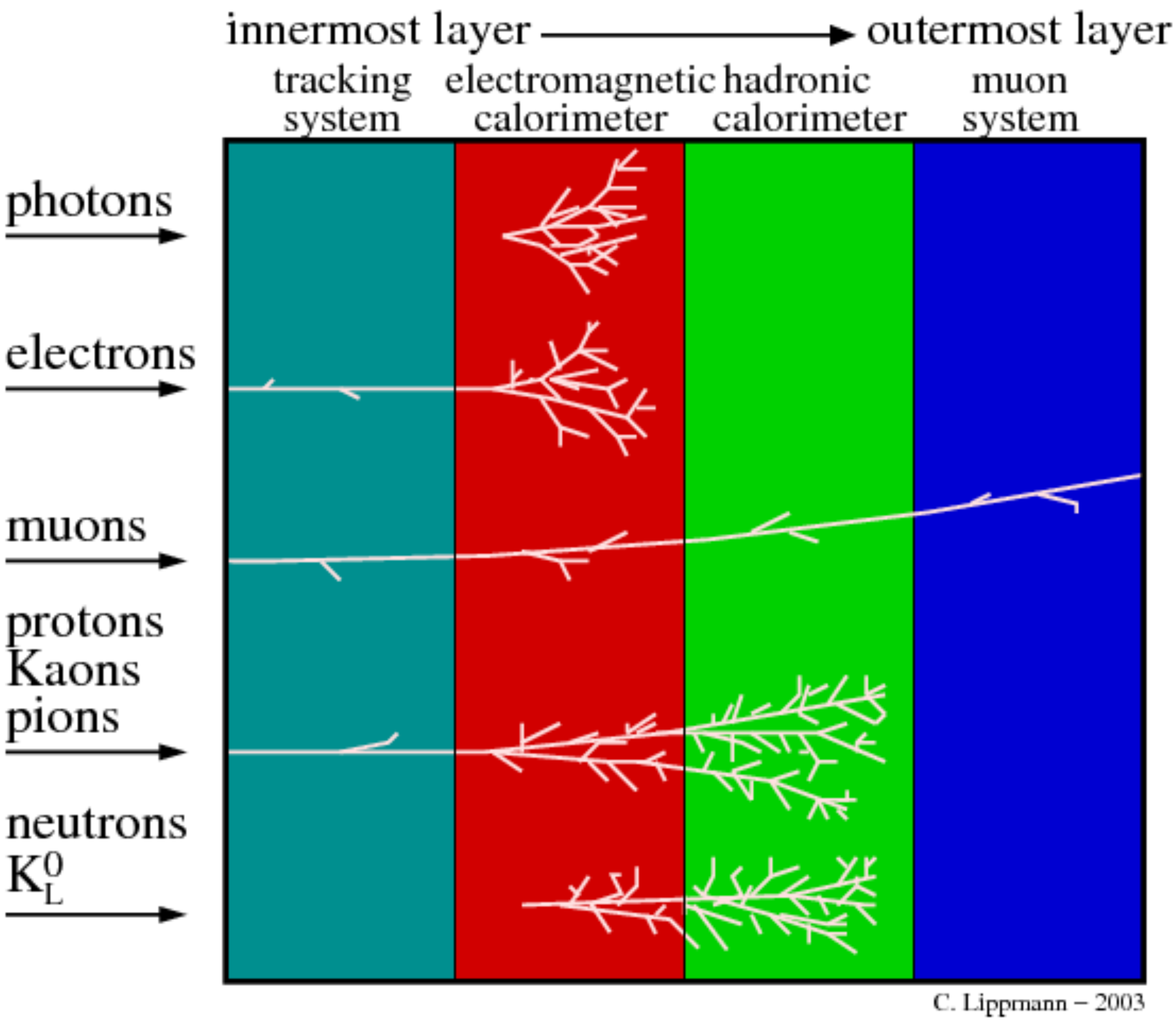
The ATLAS Detector



Ultraperipheral collisions: no nuclear breakup

As low momentum as the detector can allow to maximise the collected signal events

Detecting particles with ATLAS



Transverse energy (momentum) threshold

$E_T > 1.5$ GeV

$p_T > 4$ GeV

$p_T > 4$ GeV

p_T(track) > 100 MeV

E_T(cluster) $> 0.1\ (1)$ GeV in the barrel (endcap) of the calorimeter

Tau Leptons decay

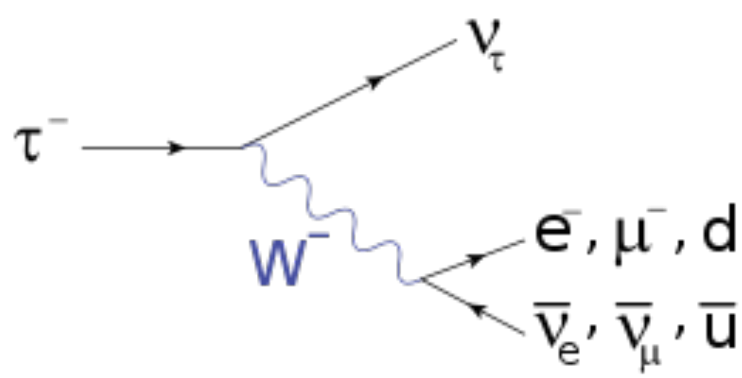
The Tau Lepton

Mass: 1.7 GeV

Mean lifetime 0.29 ps

Proper decay length: 87 μm

(ATLAS first active layer: 33mm)



	Decay mode	BR (%)
Hadronic	1 prong $\pi^{\pm}(\geq 0\pi^0) + 1\nu$	46
	3 prongs $\pi^{\pm}\pi^{\pm}\pi^{\pm} (\geq 0\pi^0) + 1\nu$	19
	Electronic ($e + 2\nu$)	17.5
	Muonic ($\mu + 2\nu$)	17.5

ATLAS can only detect the visible decay products

First publication:

- Visible final states considered: $\mu + e$, μ + 1prong, μ + 3prongs
- Easy to trigger on the muon
- Branching ratio: ~28% of all $\gamma\gamma \rightarrow \tau\tau$ events

Uncertainty	Impact on $\mu_{\tau\tau}$ [%]
muon Level-1 trigger (sys)	1.0
τ decay modeling	1.0
tracking eff. (overall ID material)	0.9
muon Level-1 trigger (stat)	0.7
topocluster reco. eff.	0.6
muon reco. eff. (stat)	0.6
tracking eff. (PP0 material)	0.6
topocluster energy calib.	0.5
muon reco. eff. (sys)	0.5
photonuclear template var. (μ1T-SR)	0.5
Total systematic	2.6

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	Projectile	Z	A	$\sqrt{s}$, A GeV	Luminosity, $cm^{-2}s^{-1}$
L	p	1	1	14000	$1.4 \cdot 10^{31}$
H	Ar	18	40	7000	$5.2 \cdot 10^{29}$
C	Pb	82	208	5500	$4.2 \cdot 10^{26}$
R	p	1	1	500	$1.4 \cdot 10^{31}$
H	Cu	29	63	230	$9.5 \cdot 10^{27}$
I	Au	79	197	200	$2.0 \cdot 10^{26}$
C					

Table 1
Average luminosities at LHC and RHIC for pp, medium and heavy ion beams.