LHC as a Photon Collider

with the ATLAS detector

FZU Seminar

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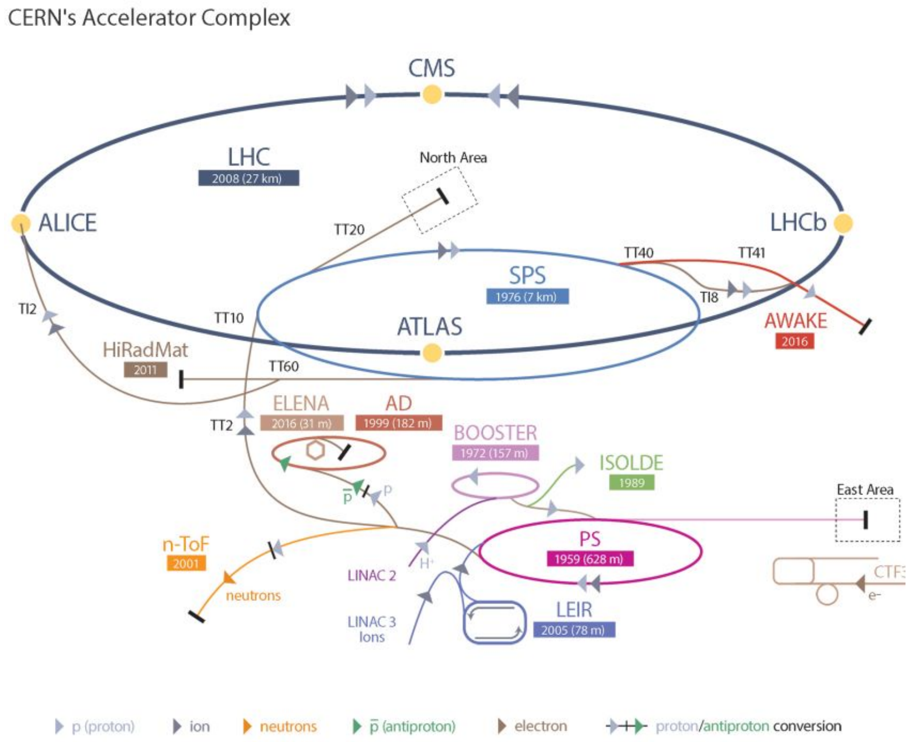
Co-funded
by the European Union

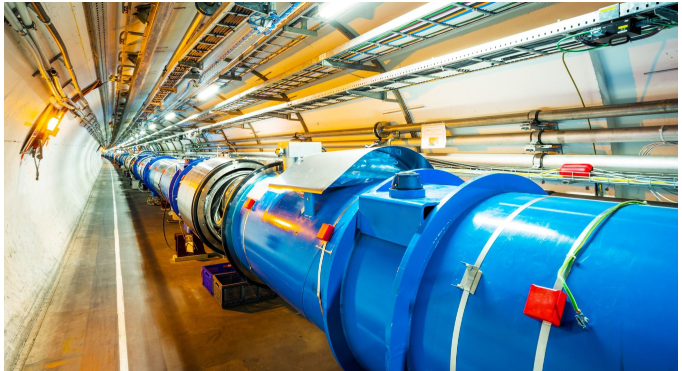
PHYSICS
FOR
FUTURE

The Large Hadron Collider

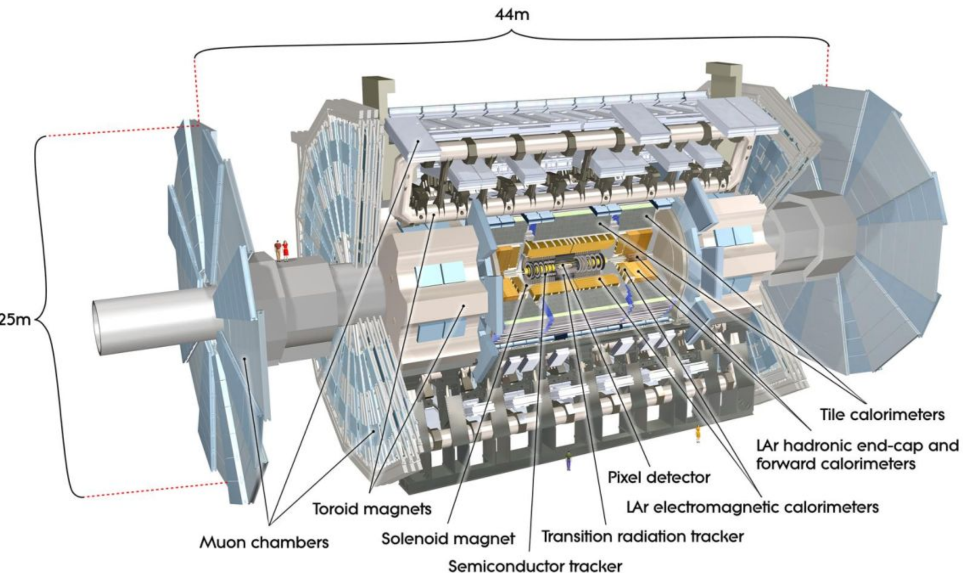


Probably no need to introduce ...

- Hadron-hadron collider (**p-p, PbPb, ...**)
- Particles colliding in bunches
- Center-of-mass from 900 GeV up to 13.6 TeV, today:
  - 13 TeV for p-p
  - 5.02 for Pb-Pb
- 4 major experiments

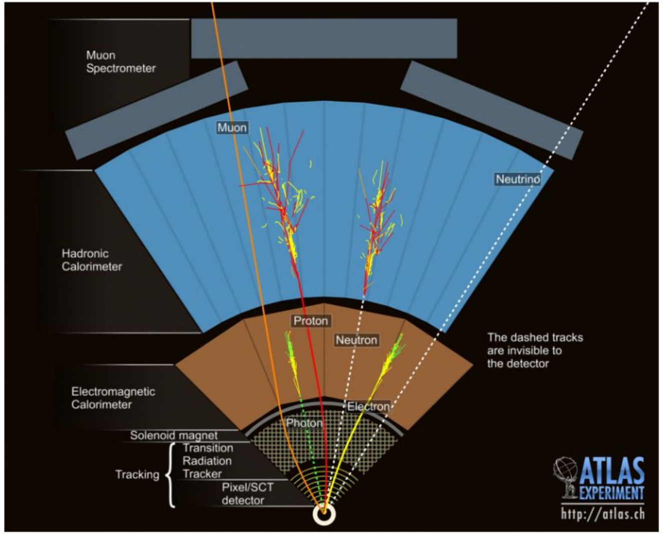


The ATLAS

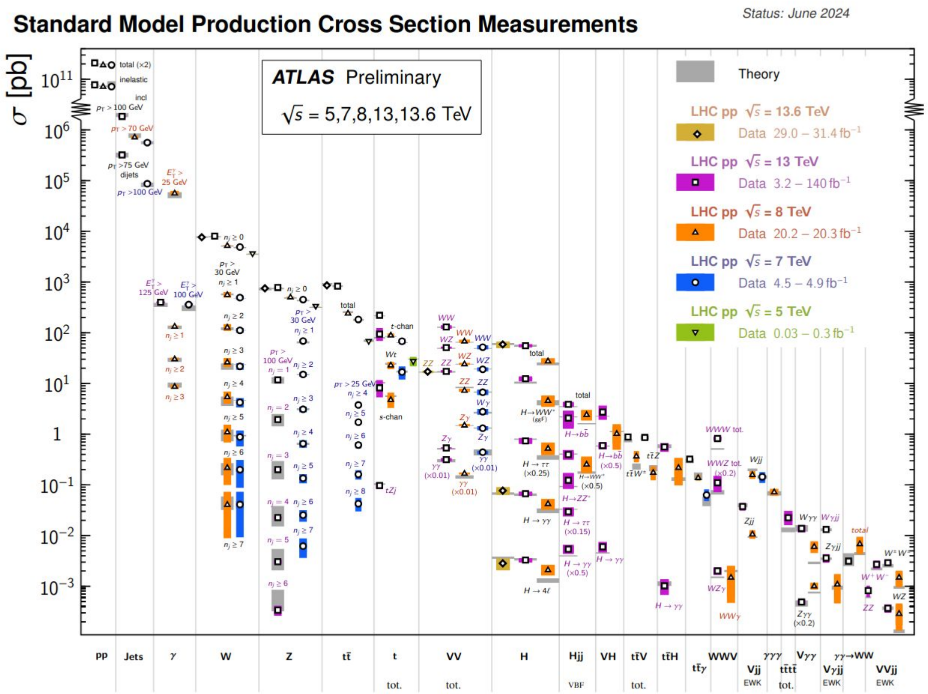


Multi-purpose detector able to measure wide range of final states

-> for this talk tracker most important,
detecting charged particles, reconstructing vertices



ATLAS Physics program



Measurements over several orders of magnitudes of cross-section:

- Precision Standard Model
  (W mass, weak mixing angle, alpha_S)
- Higgs Physics
- Top physics
- B-physics
- New physics searches

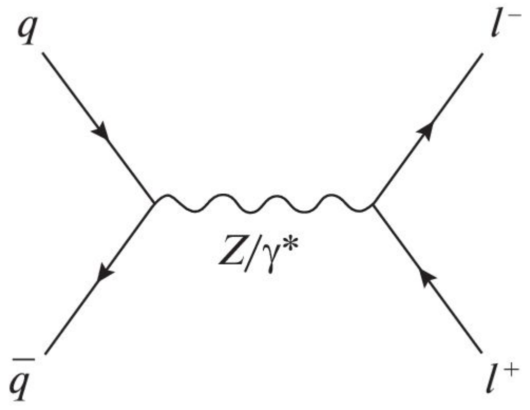
…

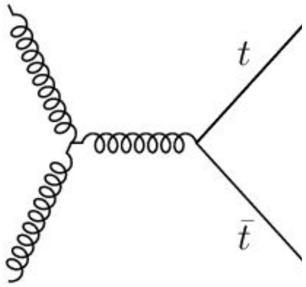
Invariant masses from ~J/Psi
up to several TeV (beyond Standard Model)

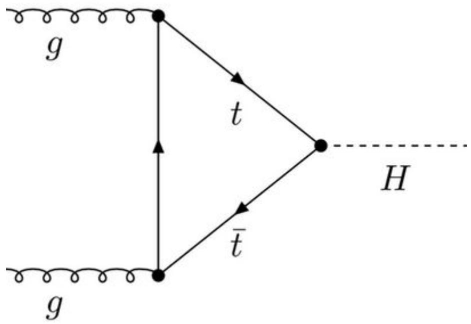
Typical collision on ATLAS – what we look for

We are usually looking for some fundamental process, hard scattering

examples: Drell-Yan, Higgs production, ttbar …





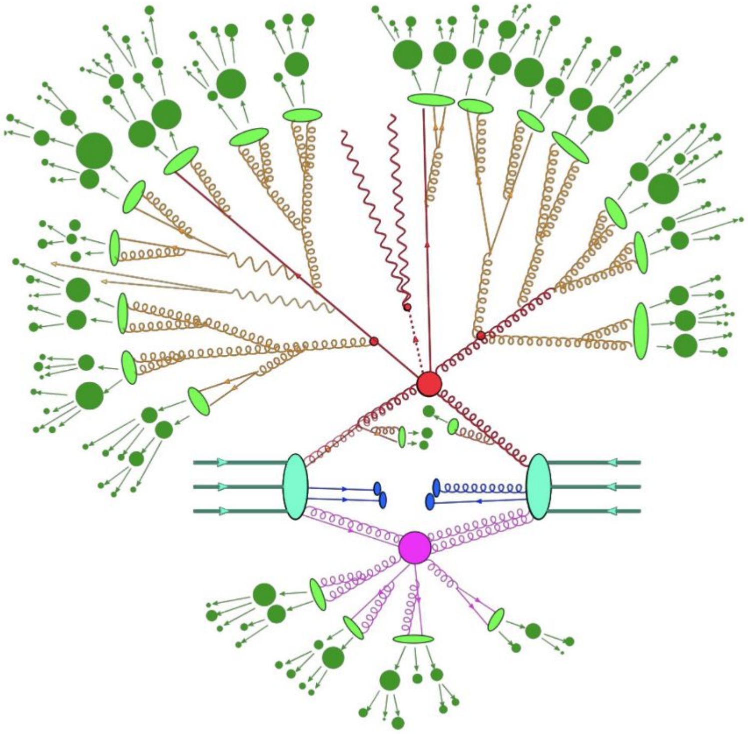


… quarks and gluons in the initial state

Typical collision on ATLAS – what we get

Large particle activity! On top of hard scattering:

- Parton showers
- Hadronization
- Multi-parton interactions of the protons
- Beam remnants
- Nucleon-nucleon interactions in PbPb



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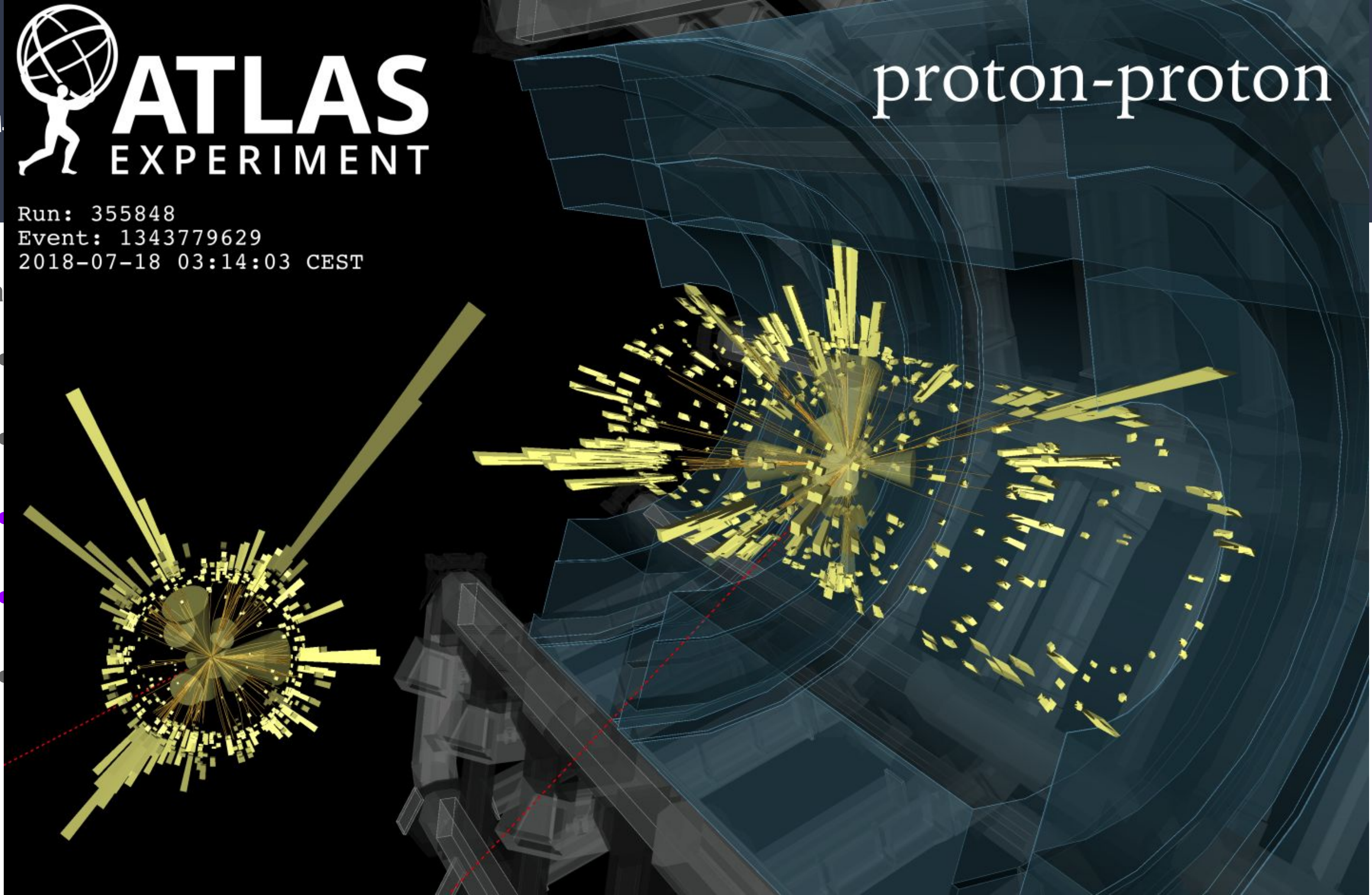
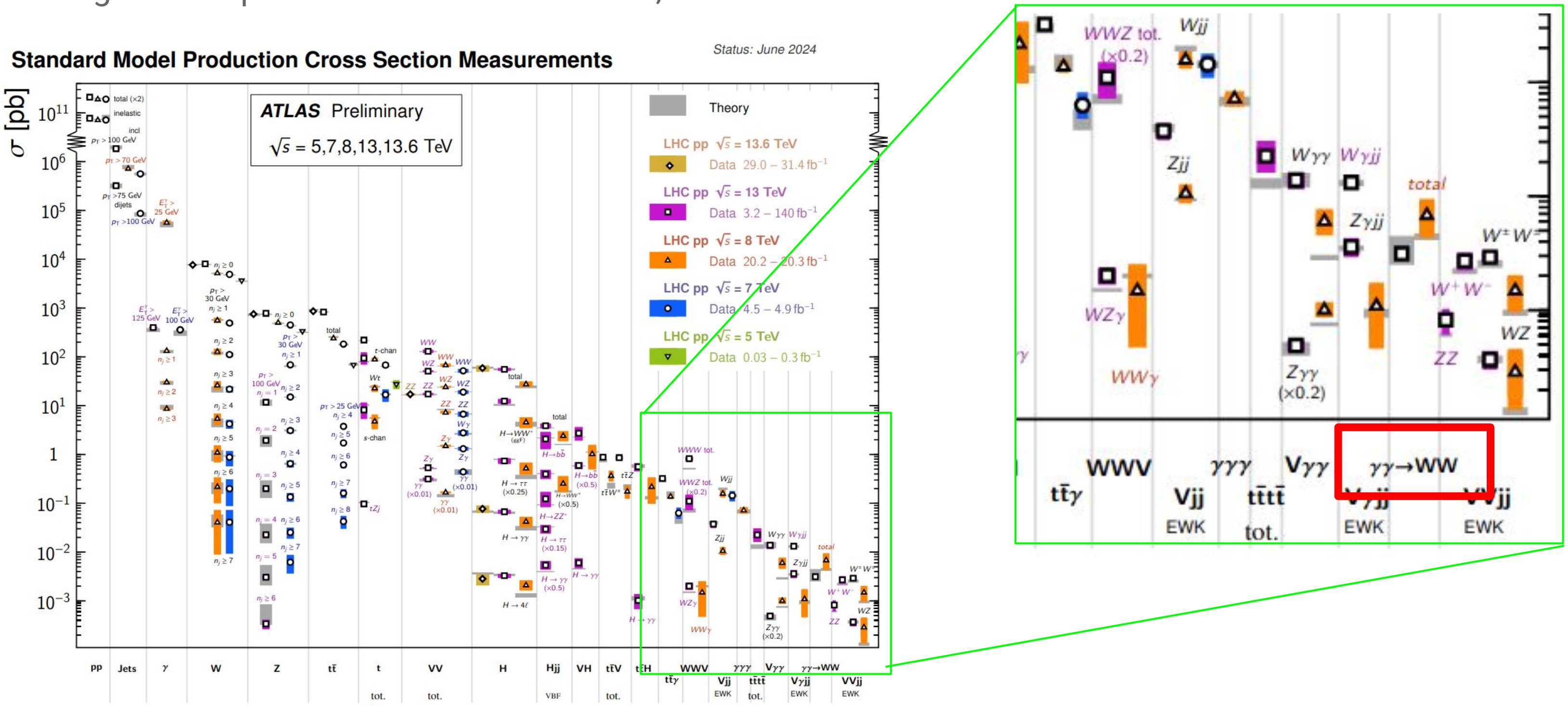

ATLAS
EXPERIMENT
proton-proton
Run: 355848
Event: 1343779629
2018-07-18 03:14:03 CEST

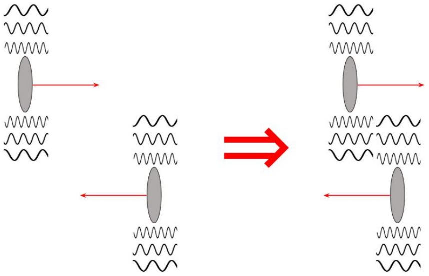
Rare processes

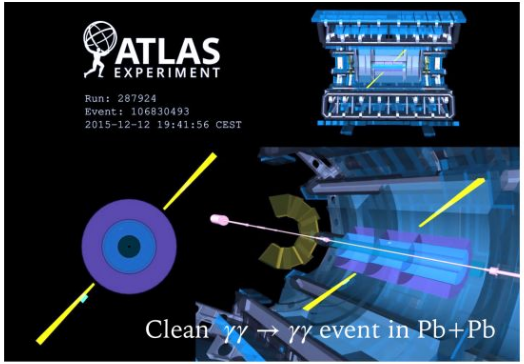
Among the rare processes ATLAS measures, one stands out …



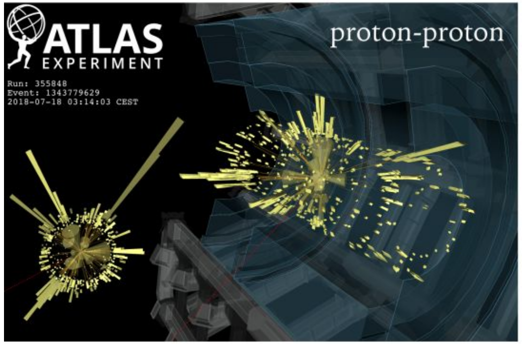
The Large ~~Hadron~~ Photon Collider

… but! Protons/heavy ions are charged particles:
boosted EM field behaves as field of quasi-real photons





No color means low particle activity!

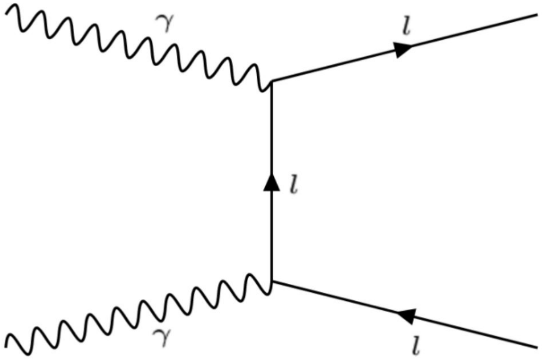


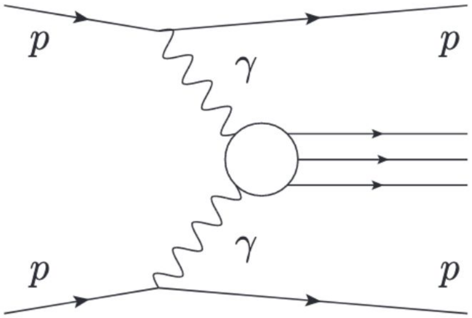
Regular LHC event = large activity from strong interaction

Photon-photon processes

Photons do not have charge
→ cannot interact directly!

Can interact via charged mediator,
e.g lepton, W boson…





Characteristics:

- No color exchange
  → **low particle activity**
- Photons quasi-real = small momentum transfer
  → **low transverse momentum of the system**
- In coherent production, **protons stay intact**
- Photon flux is relatively small
  = low cross-section → **low yield**

ATLAS measurements

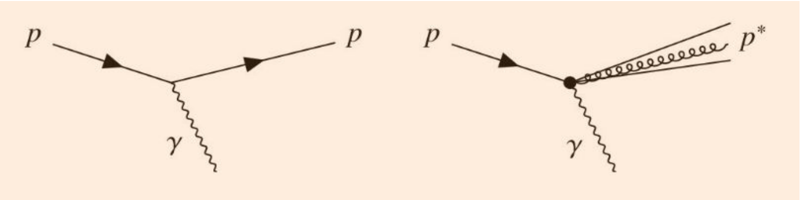
Back when I started there were only 2-3 measurements,
now the γγ→X program is really diverse!

Process	Physics goal
γγ→ee/μμ	Standard candle
γγ→γγ	ALPs & photon self-coupling
γγ→ττ	Tau g-2
γγ→WW (leptonic)	EW symmetry breaking
??????	Anomalous couplings
??????	SM loop suppressed
??????	Search for dark matter
??????	Anomalous couplings

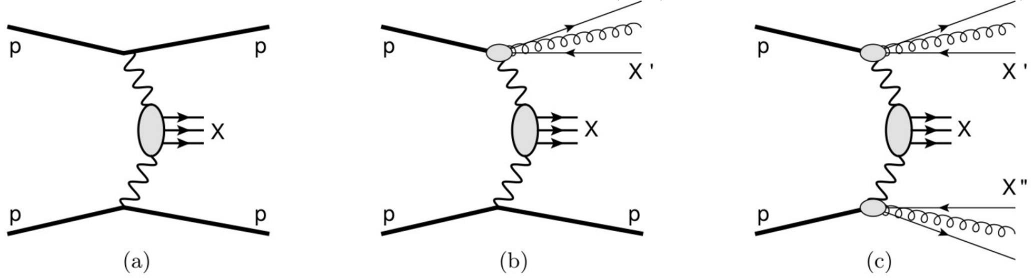
Photon production in *proton–proton*

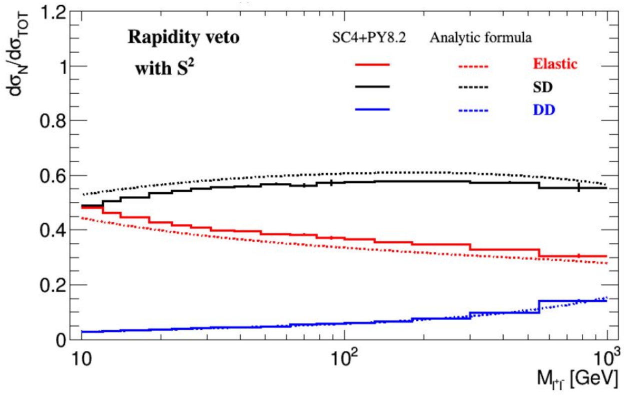
Proton dissociation

With higher transverse energy of the photon,
the proton can dissociate! *Soft-QCD = difficult modeling*



Exclusive Single-dissociative (SD) Double-dissociative (DD)

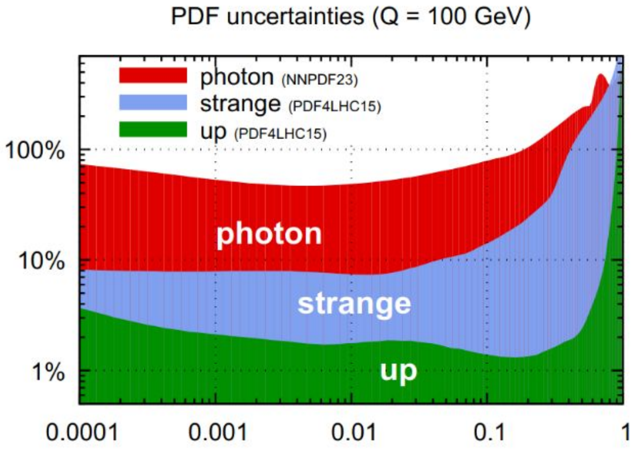




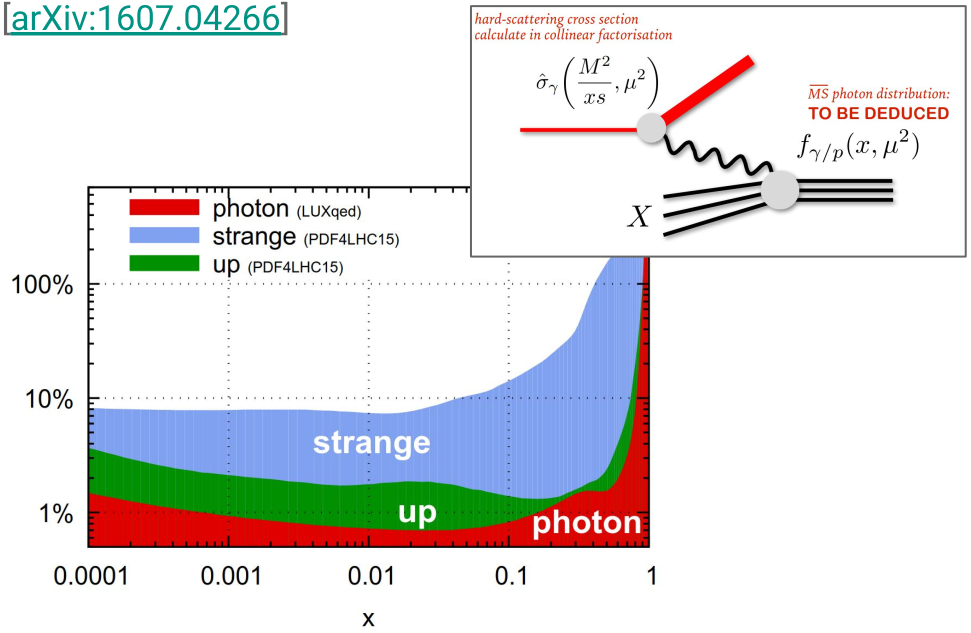
Remnants outside of detector acceptance so cannot be rejected

How bright is proton?

Photon Parton Distribution Functions (PDFs) used to have large uncertainties O(100%)



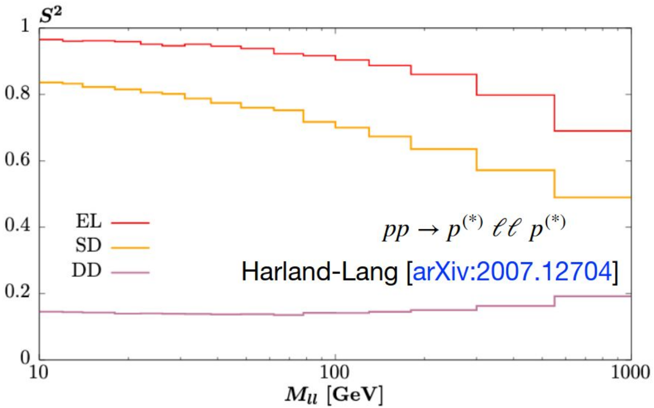
"Recent" (~2016) development with photon PDF from DIS structure functions with reduced uncertainties [arXiv:1607.04266]

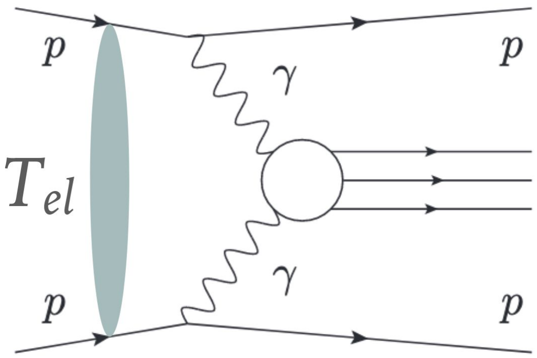


Underlying event

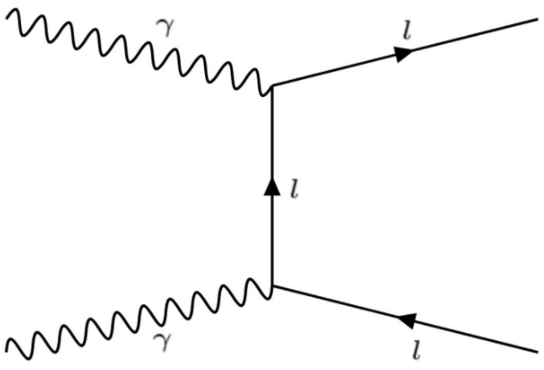
Additional between the protons can still take place on top of the yy-> events!
Soft-QCD = difficult modeling

- Reduces cross-section of *exclusive* production
- Usually described through **survival factor**





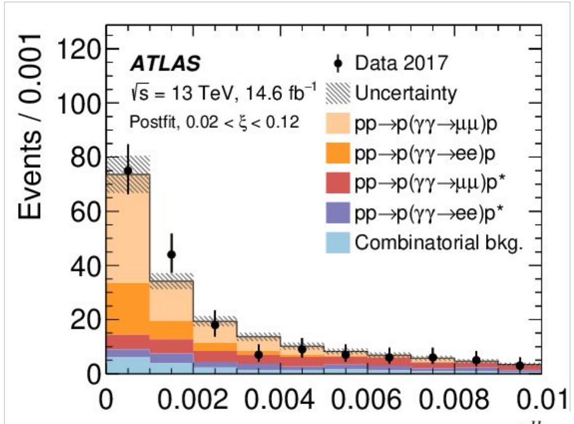
Standard candle

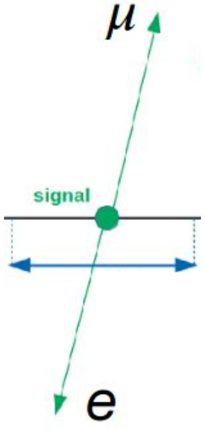


- yy→ll highest cross-section, has been observed for some time
- Well understood = standard candle of yy→X

Selection

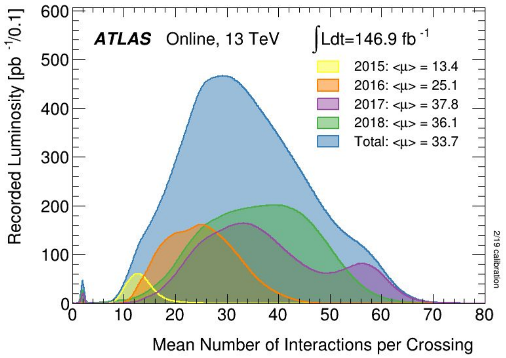
- Low particle activity = clear signature which can be separated from other processes (e.g. Drell-Yan Z→ll)
- Only 2 leptons in final state + low virtuality = leptons are back-to-back





$$A_\phi^{ll} = 1 - |\Delta\phi_{\ell\ell}|/\pi < 0.01$$

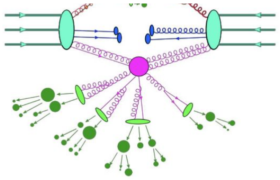
Problem of pile-up

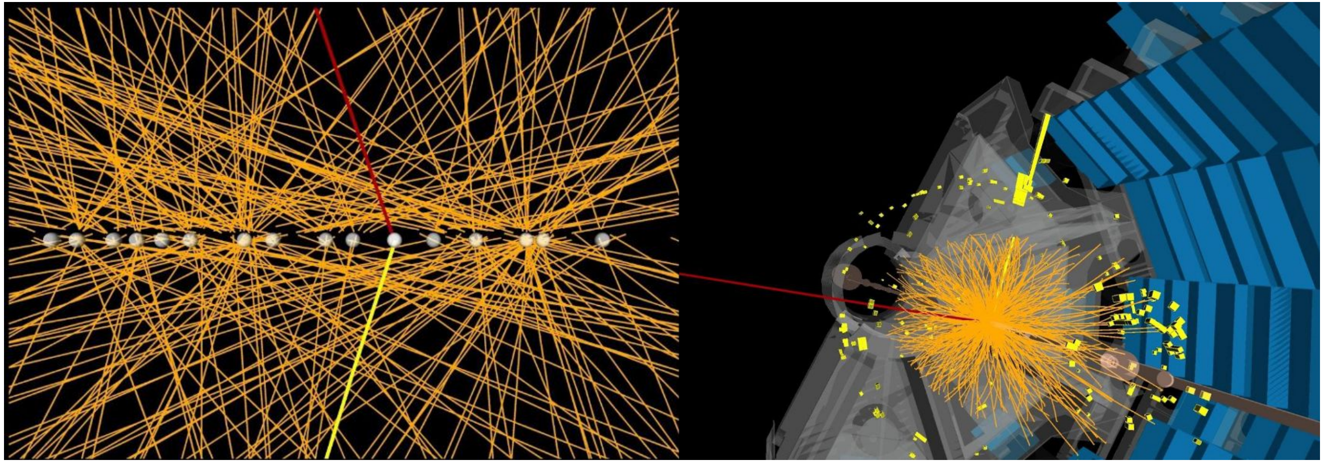


- Searching for events with low activity!

  X **additional protons in the collision interact**, more products in the events
  → we call this pile-up

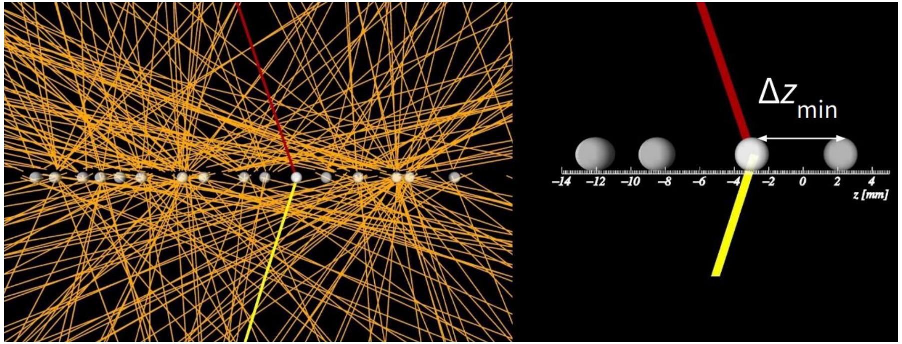
- At 13 TeV this is ~34 additional interactions on average!





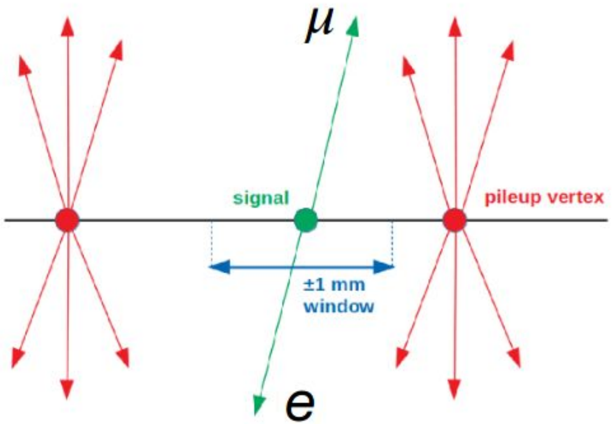
We are getting bunch of these in each collision

Exclusive selection

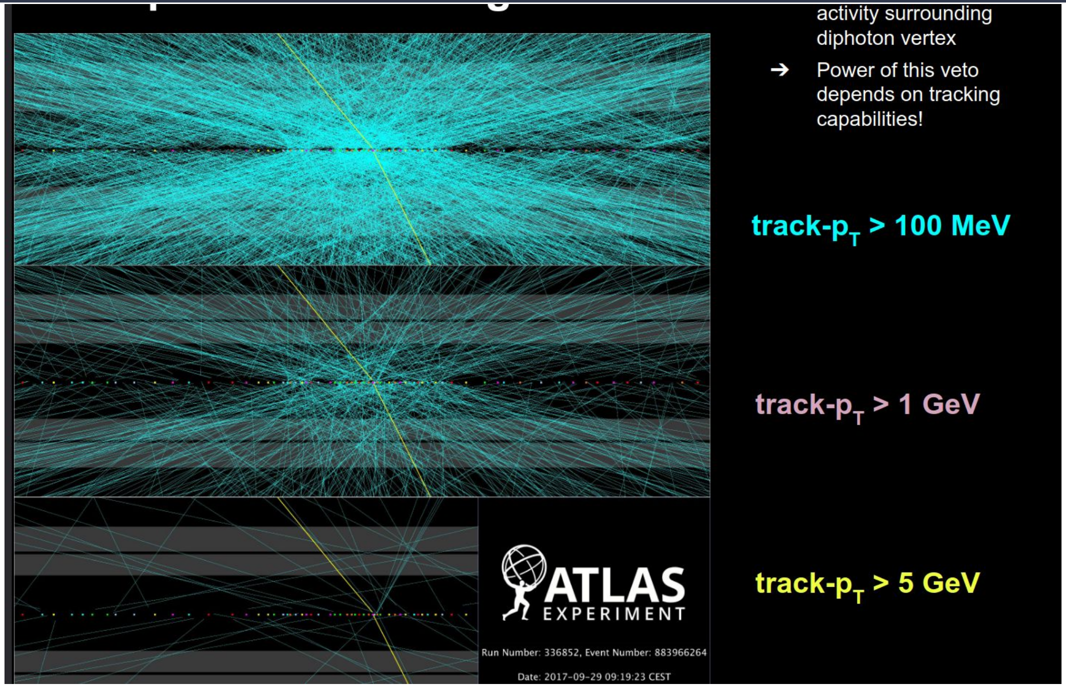


- Looking for region along the beamline containing only two leptons within 2mm window:
  → Optimizing *background rejection*
  vs *signal efficiency* due to presence of pile-up

- Only charged particle with tracks can be rejected this way as their origin can reconstructed



Tracking momentum threshold

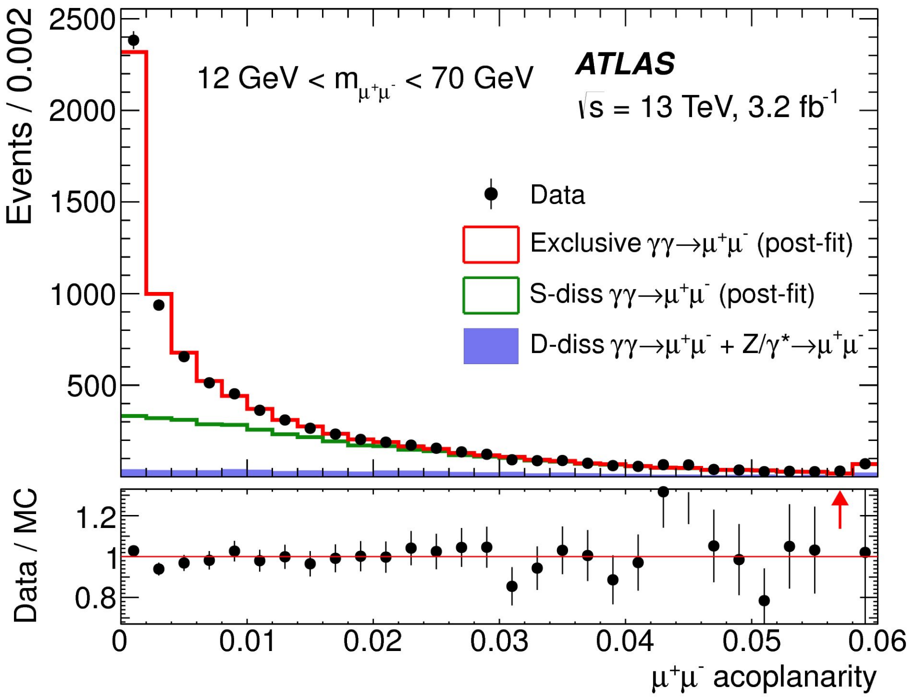


- Lower pt threshold of the tracks
  = higher discriminative power against bkg,
  but also lower signal efficiency due to pile-up
  (lower threshold nevertheless better)

- On ATLAS the default it 500 MeV, lower values not really feasible for full Run 2 data
  (CPU + disk requirements)

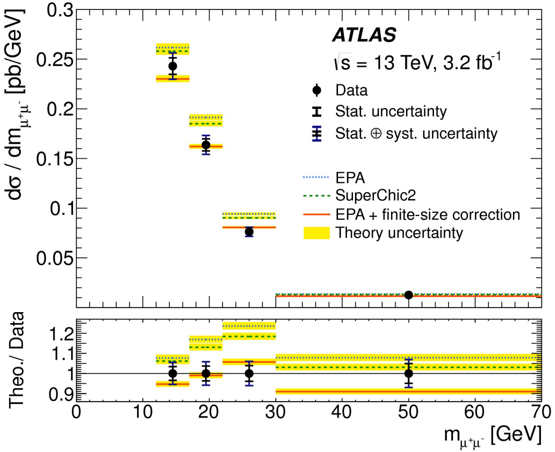
γγ→ll results

DOI:10.1016/j.physletb.2017.12.043

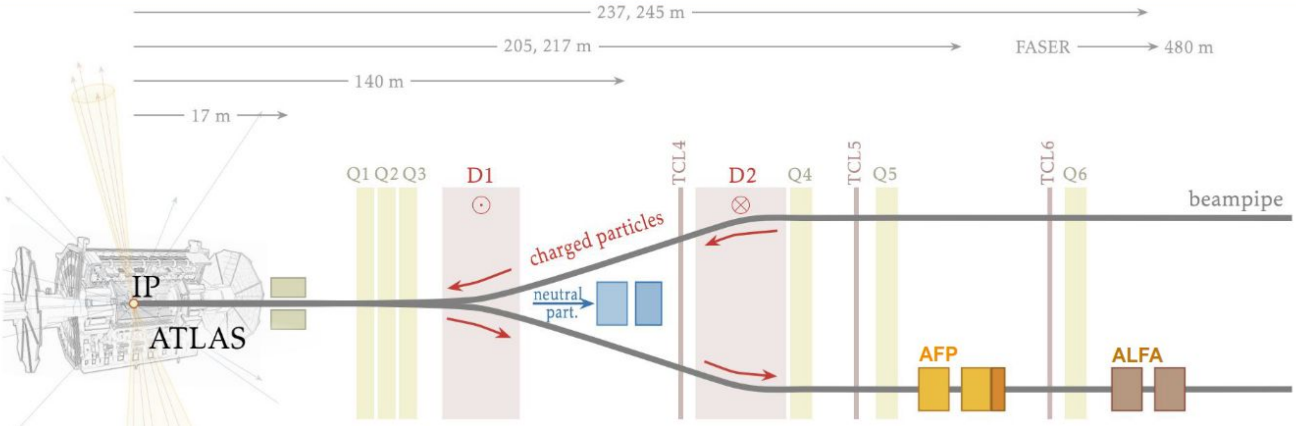


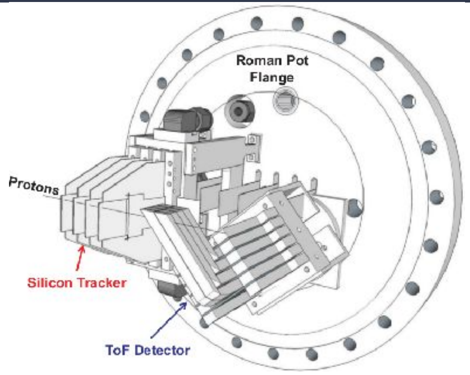
ATLAS and CMS measured this process at 7 GeV

Remeasurement with 2015 data (3.2fb-1)



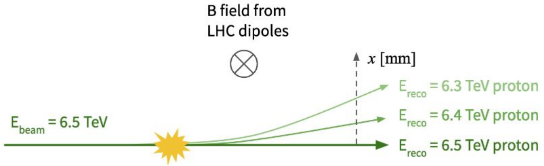
The Atlas Forward Proton (AFP) detector





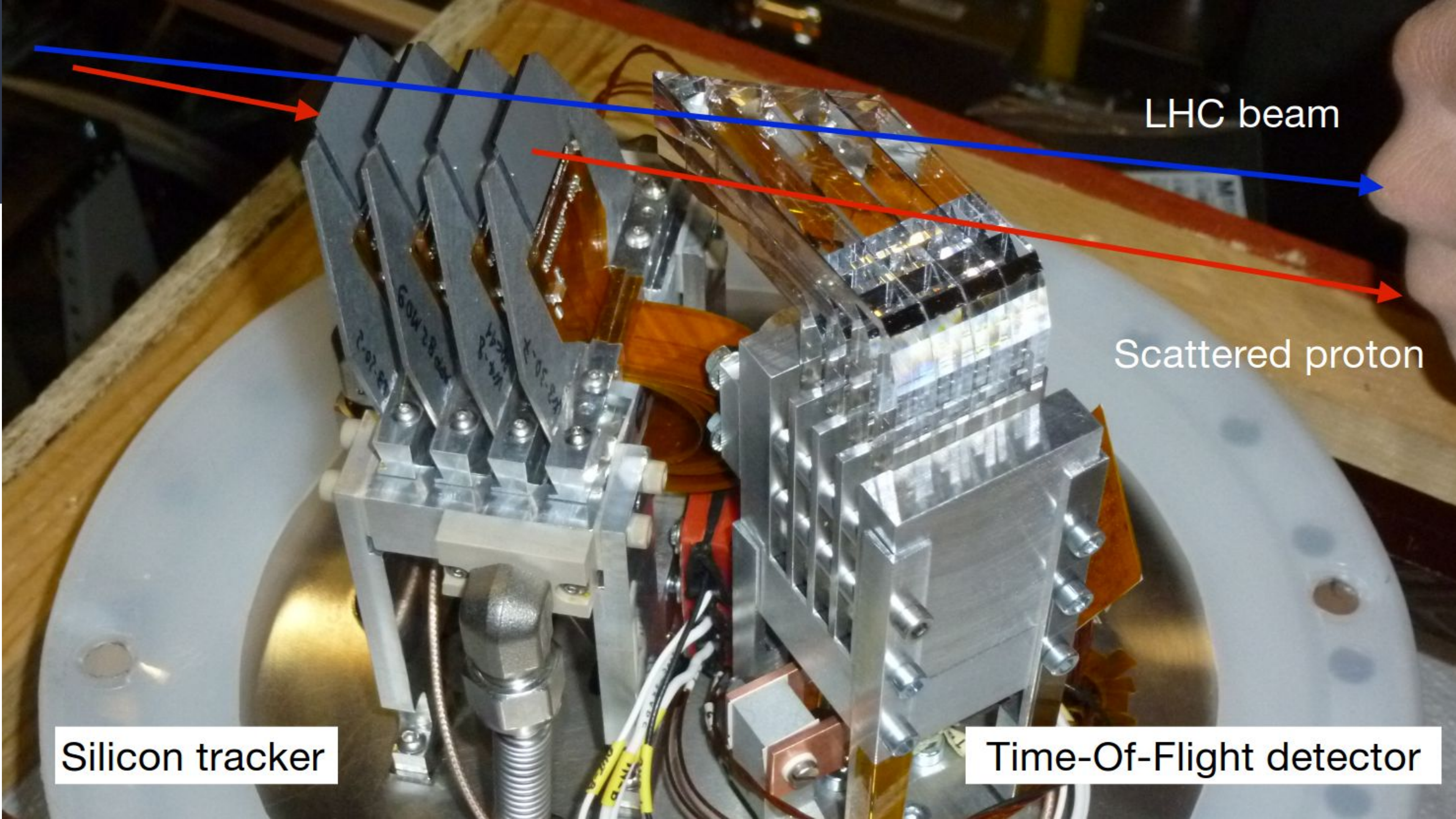
- Inserted near the beam at ~200 meters from the ATLAS interaction point
- Allows to measure deflected protons → energy from the scattering angle:

$$\xi_{\text{AFP}} = 1 - E_{\text{scattered}} / E_{\text{beam}}$$

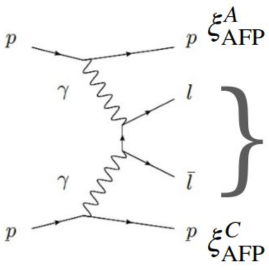


AFP
ATLAS Forward Proton
Low & high μ
$0.02 < \xi < 0.12$
soft & hard diffraction, $\gamma + \gamma$

- 4 Roman Pots, 2-4 mm from beam
- tracker: 3D sillicon pixel sensor
- spatial res. $\sigma_x = 6\mu m$
- ToF: 16 Quartz Cherenkov bars
- **timing res. $\sigma_t \approx 25$ ps**


LHC beam
Scattered proton
Silicon tracker
Time-Of-Flight detector

Forward measurement



$$\xi^{A,C}_{ll} = (m_{ll}/\sqrt{s})e^{\pm y_{ll}}$$

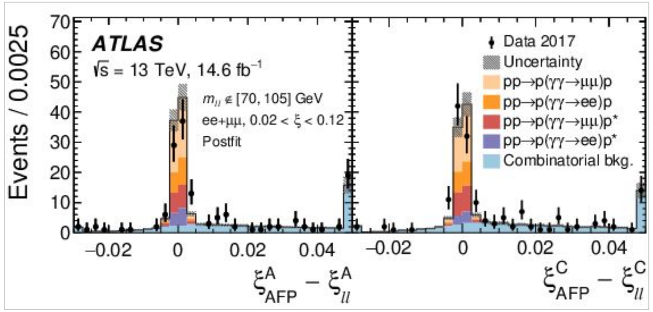
$$\xi_{\mathrm{AFP}} = 1 - E_{\mathrm{reco}}/E_{\mathrm{beam}}$$

Energy of scattered proton can be also determined from final state leptons!

AFP signature can be matched to central detector
→ background suppression

$$|\xi_{\ell\ell} - \xi_{\mathrm{AFP}}| < \sigma(\xi_{\ell\ell}) + \sigma(\xi_{\mathrm{AFP}})$$

Deflected proton = no dissociation → only SD/excl



DOI:10.1103/PhysRevLett.125.261801

Photon production in *heavy ion*

Difference in heavy ions

Cross-section proportional to charge of colliding particle (~Z^4!!!)
→ larger photon flux in Pb-Pb (Z=82)

✖

ATLAS records much larger luminosity for p-p

Both factors similar → effective luminosity is comparable

Both p-p and Pb-Pb play important role!

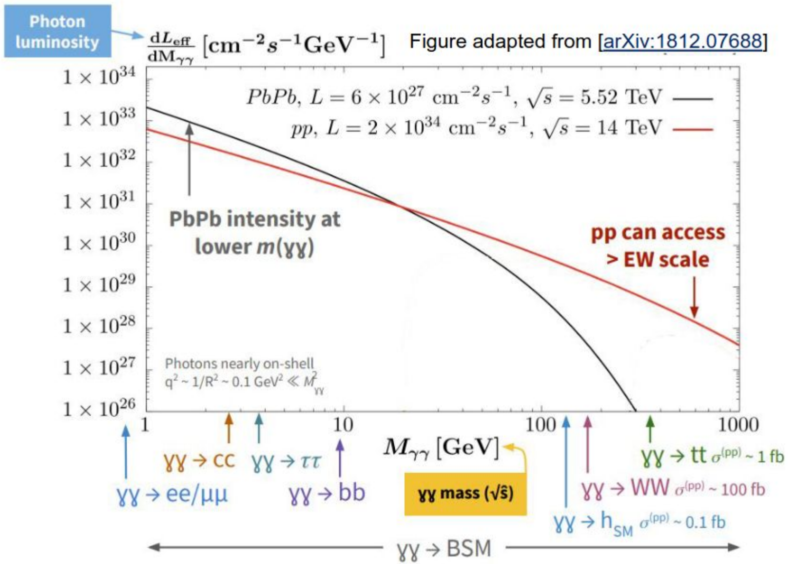


Figure adapted from [arXiv:1812.07688]

In Pb-Pb there is no pile-up!

- Activity can be rejected in all sub-detectors, not only tracker!
- Allows reconstruction of particles at lower energies

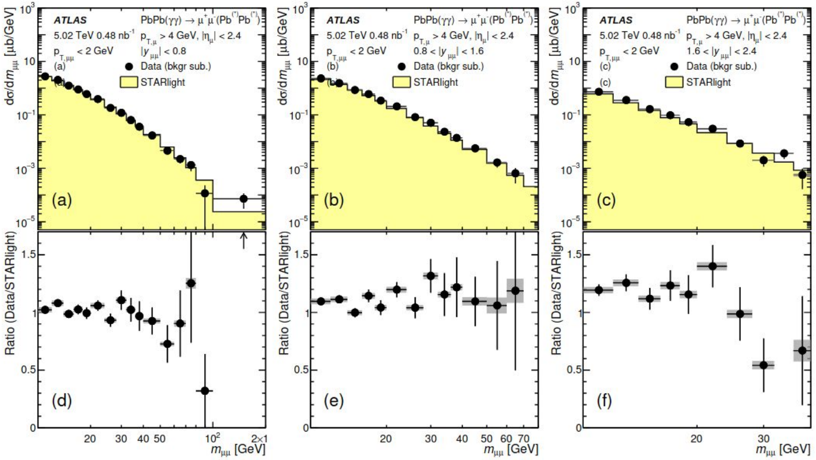
Photon energy inversely proportional to impact parameter

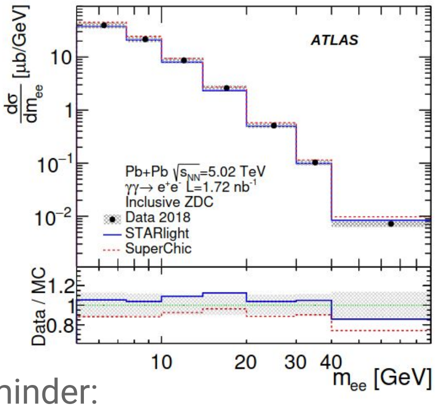
Larger size of Pb limits achievable energy of the photon
→ **limits invariant mass of the final state**

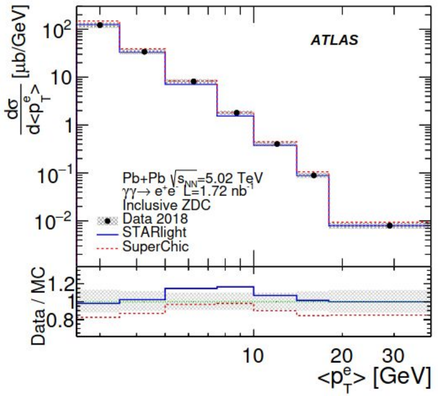
Muons: DOI:10.1103/PhysRevC.104.024906
Electrons: DOI:10.1007/JHEP06(2023)182

Dilepton production in Pb–Pb

- yy→ll measured in both ee and mumu channel at Pb-Pb collisions (5.02 Tev)
- Differential measurement!

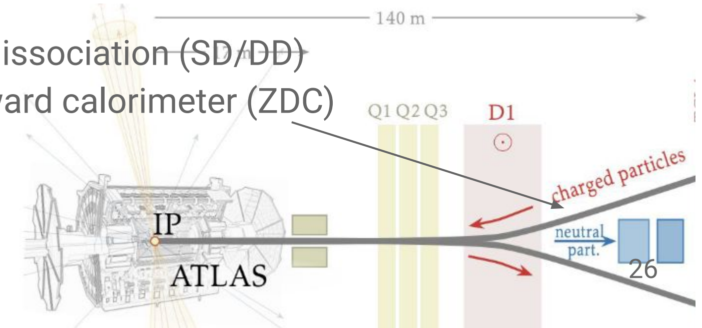






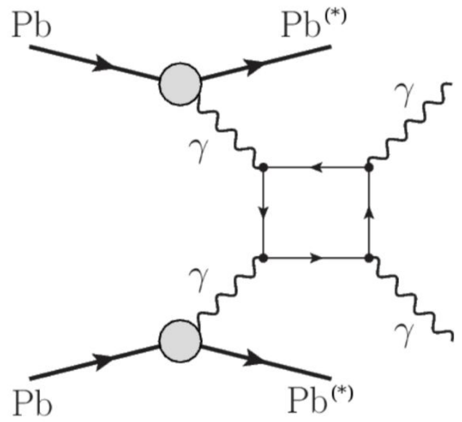
Reminder:
No pile-up = rejection of activity in the whole detector

+ rejecting dissociation (SD/DD) using forward calorimeter (ZDC)

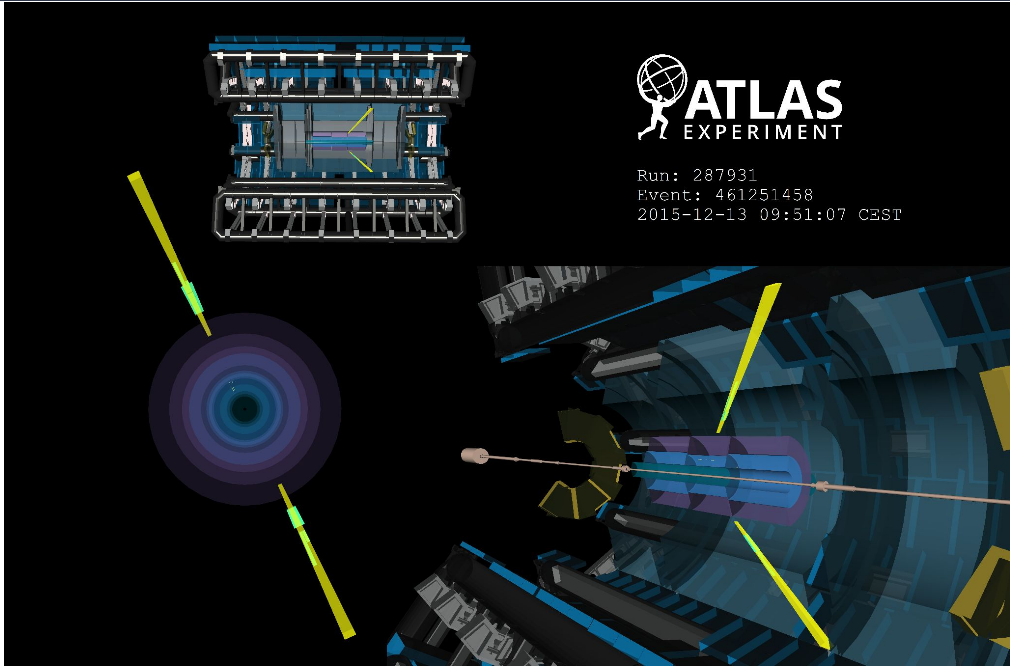


Nothing but light

Light-by-light scattering possible, nothing but photons in final state!



- Exceptionally rare mode, only handful of events



ATLAS observation (arXiv:1904.03536) and differential measurement (https://doi.org/10.1103/PhysRevLett.123.052001) measured in PbPb collision at s = 5.02 TeV

Strength of heavy-ion

Advantage of heavy-ion

- no pile-up!
- higher effective luminosity at low inv. mass

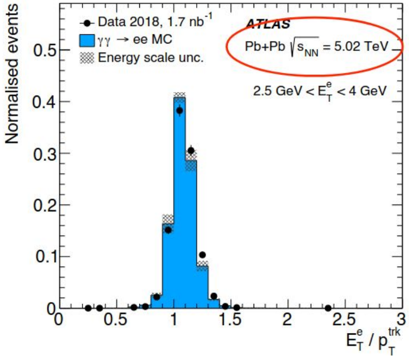
Clean environment allows to

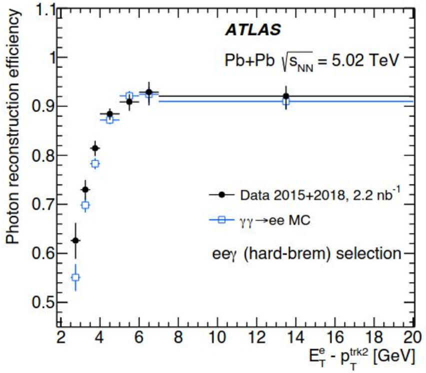
- Standard low-pt tracking

- Dedicated photon triggers to record events!
  Down to 1 GeV (compare to ~20 GeV for p-p)

- **Photon reconstruction down to 2.5 GeV**,
  compared to ~7 GeV in p-p

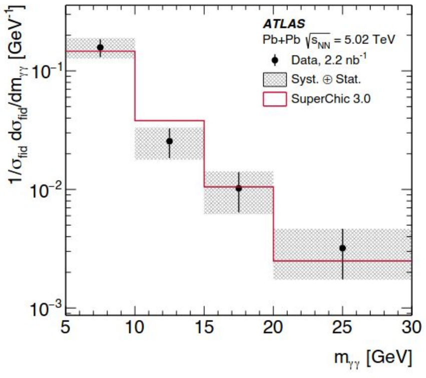
  -> Dedicated object correction in yy→ee/yy→eey
  (electrons/photon ~ same trace in calorimeters)

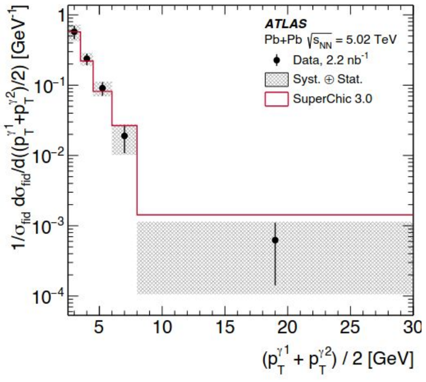


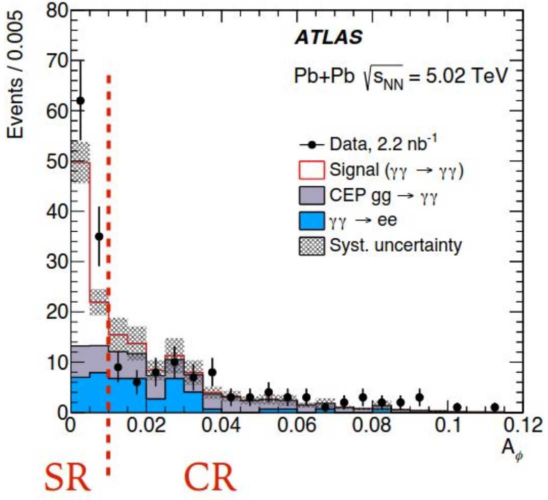


Results

97 events observed, 45 signal + 27 background expected

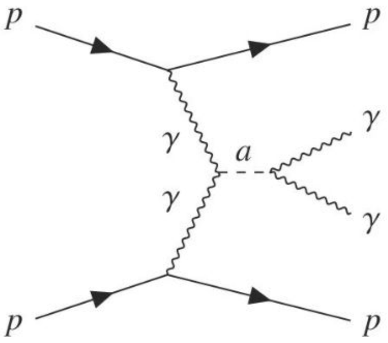


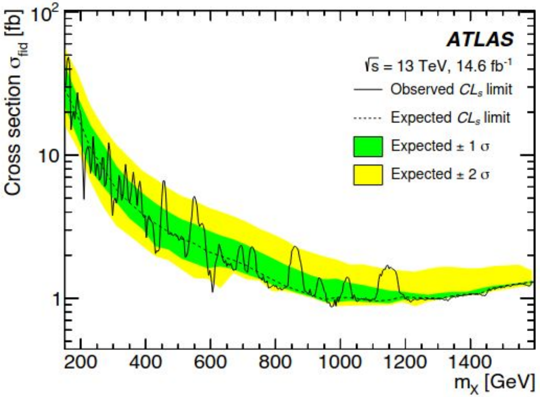




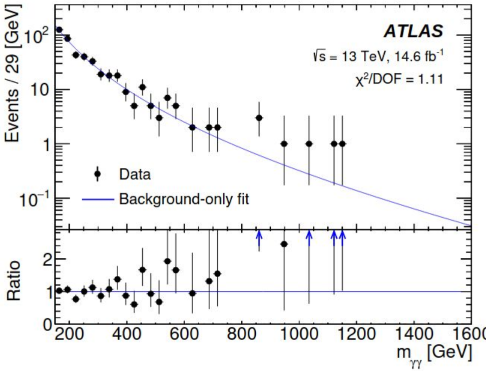
Background mainly from yy→ee (mis-identification)
+ gg→yy

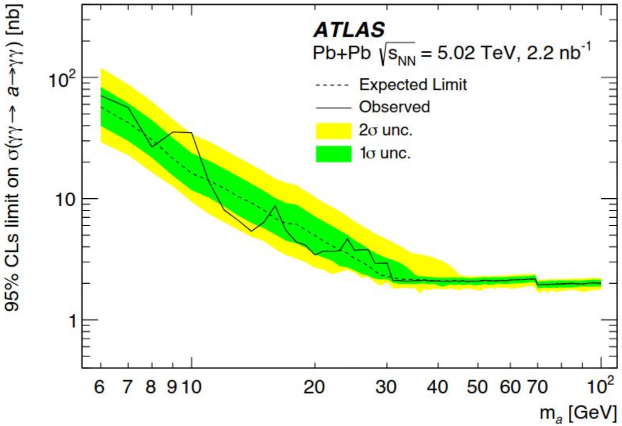
Heavy axion-like particle (ALP) search in γγ→γγ

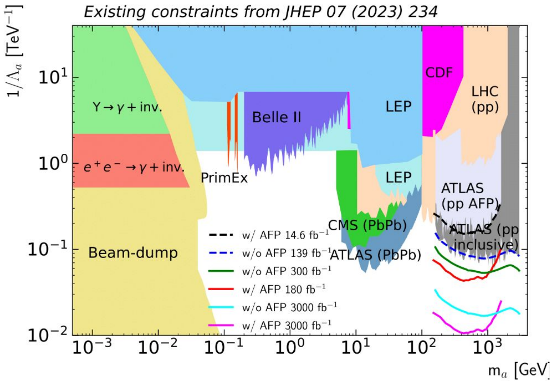




Also in p-p collision with forward proton tagging ([JHEP 07 (2023) 234](https://doi.org/10.1007/JHEP07(2023)234))







https://cds.cern.ch/record/2890623/

Other rare final states

g−2

Lepton magnetic moments related to lepton spin

$$\mu = g\frac{e}{2m}\mathbf{S}$$

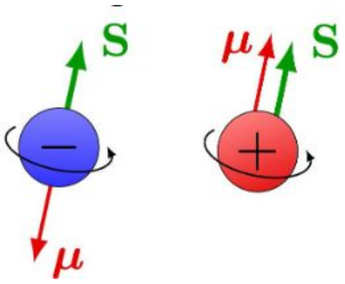
- Dirac (Born level) g=2
- Schwinger term (leading loops): $a_l = \alpha_{EM} / 2\pi \cong 0.0012$

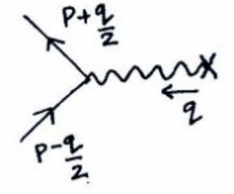
… and so on. One of most precise prediction ..

… and for muons and electrons

one of the most precise measurements …

But tau leptons too elusive due to short lifetime





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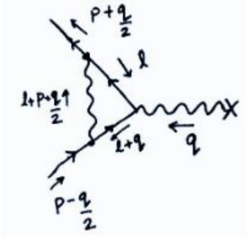


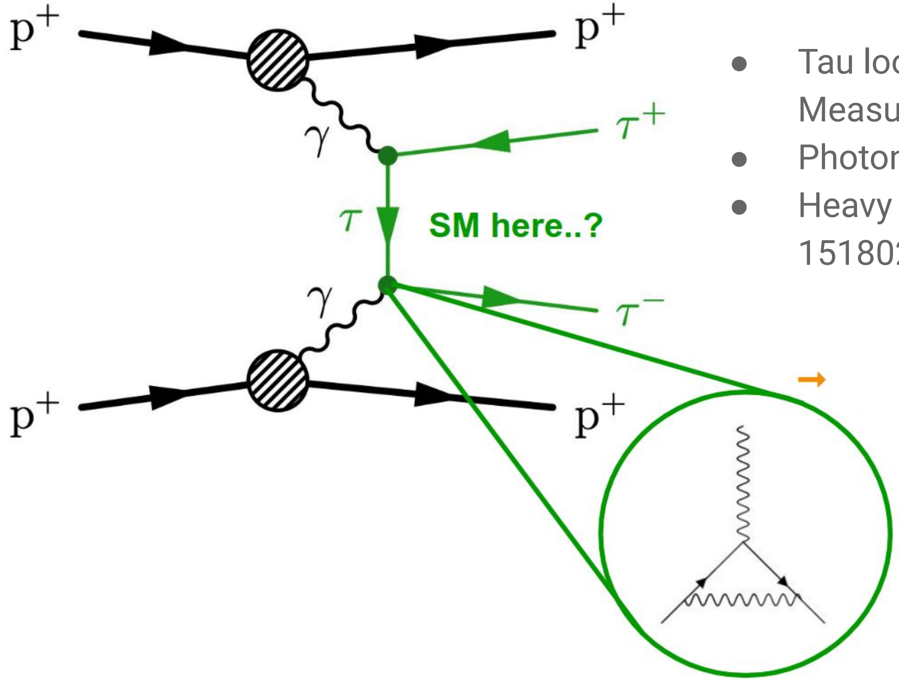
+

...

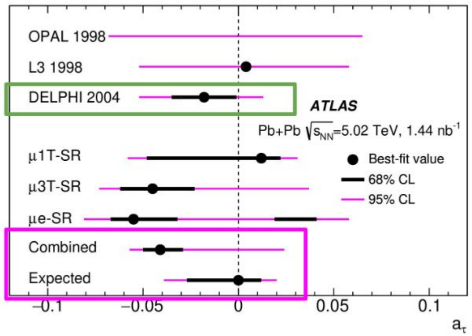
$a_\tau^{SM} \cong 0.0018$

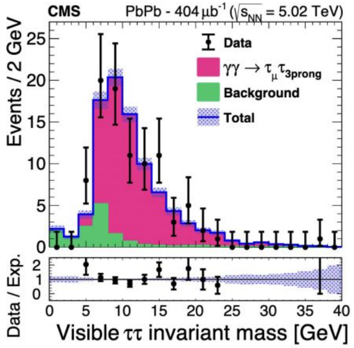
yy→$\tau\tau$

DOI:10.1103/PhysRevLett.131.151802



- Tau loop interaction with photon still untested!
  Measurement precision bellow Schwinger term
- Photon-induced production can be used to test the EM dipoles!
- Heavy ion measurement done by both ATLAS [PRL 131 (2023) 151802] and CMS [PRL 131 (2023) 151803]





Better constraining power on anomalous τ g-2 in pp collisions due to higher mass reach

γγ→ττ in p-p

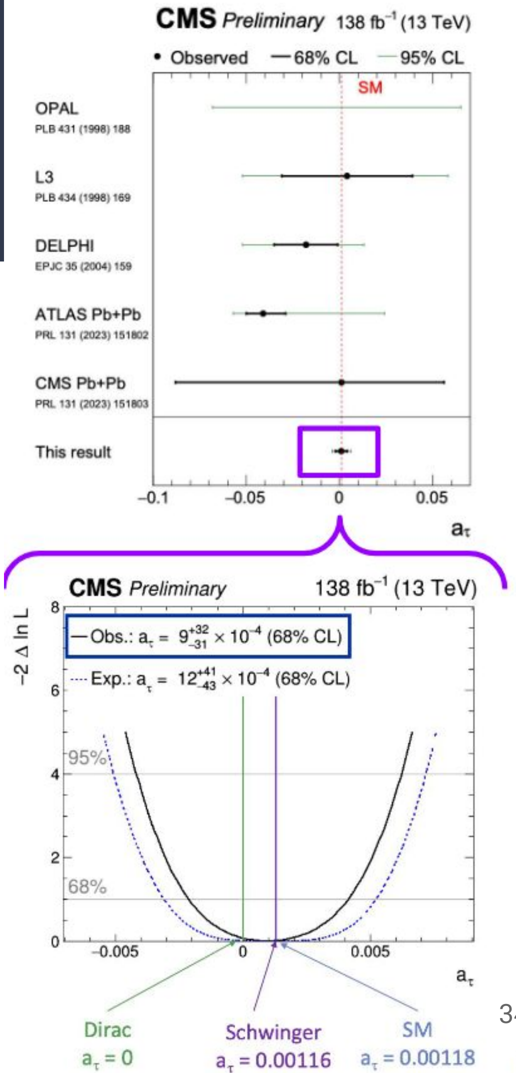
Recent ATLAS proposal arXiv:2403.06336

Strategy to measure tau $g-2$ via photon fusion in LHC proton collisions

Lydia Beresford,[1,*] Savannah Clawson,[1,†] and Jesse Liu[2,‡]
[1] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[2] *Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*

… but CMS was faster this time! [arXiv:2406.03975]

- Combined fully leptonic (OS) tau decays with semi-leptonic + fully hadronic
- **Improving 20 year old LEP limits on tau g-2 by a factor of five!!**
- Precision on tau g-2 still 3✕ Schwinger term
- Constraints on anomalous coupling



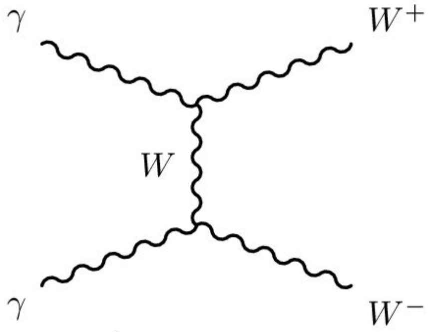
C. Caillol, CERN - LPCC seminar, March 12th 2024

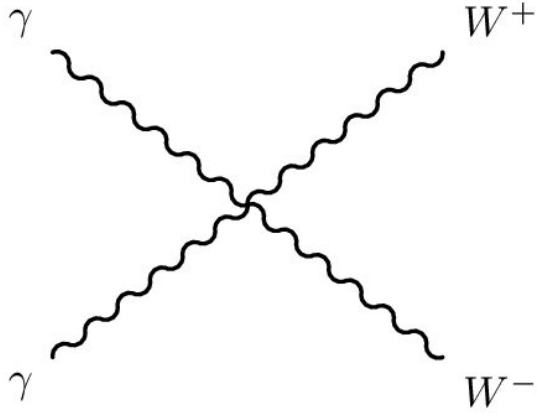
γγ→WW measurement

- Test of the *Electroweak* sector of Standard Model
  - Direct access to γWW/γγWW vertices

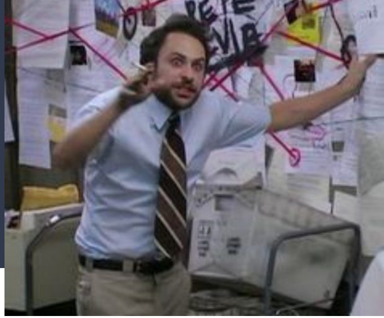
- 1st measurement at 7/8 TeV by both ATLAS and CMS, ~3σ evidence
- 13 TeV started by Oldrich Kepka and I back in 2016

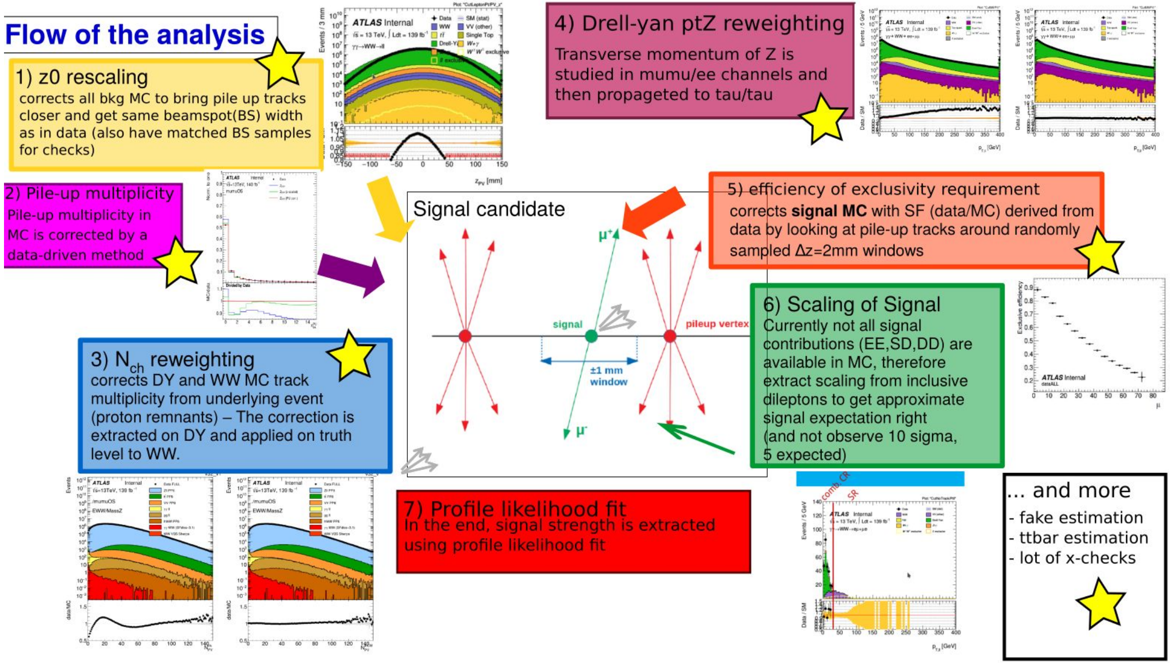
  → can go into more detail :)





Analysis strategy





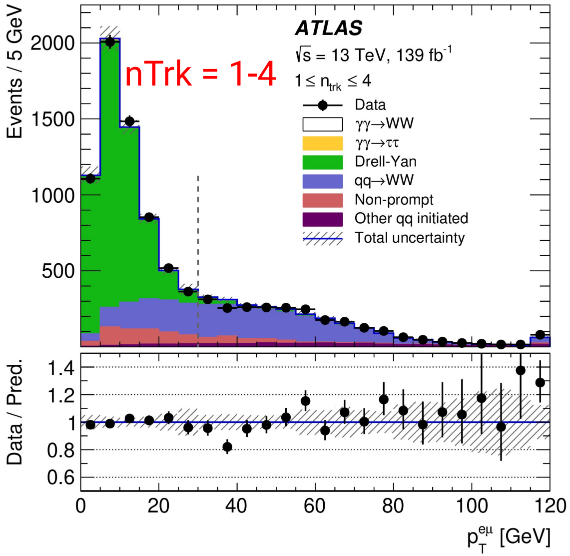
To get observation, analysis relied on numerous data-driven correction:

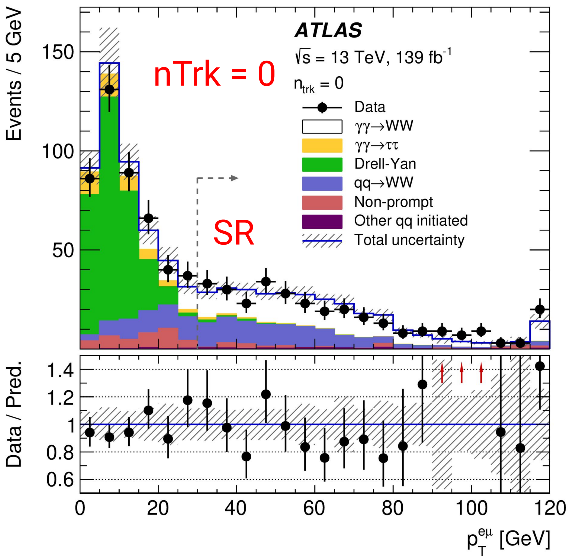
- pile-up modeling
- underlying event of background
- modeling of signal

…

… impossible to cover all

Analysis regions



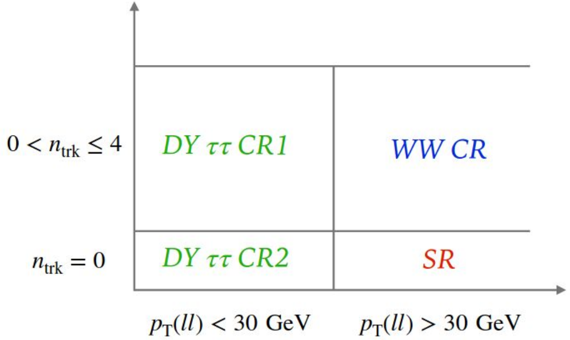


Signal concentrated at:

- low multiplicity, because yy→X
- large pT(ll), because WW→lvlv

Control regions for the inclusive W at 1-4 tracks

Additional CRs for DY Z→tautau



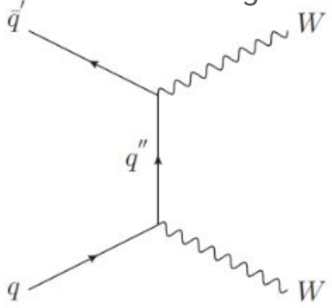
Looking at e+mu final state to reject:

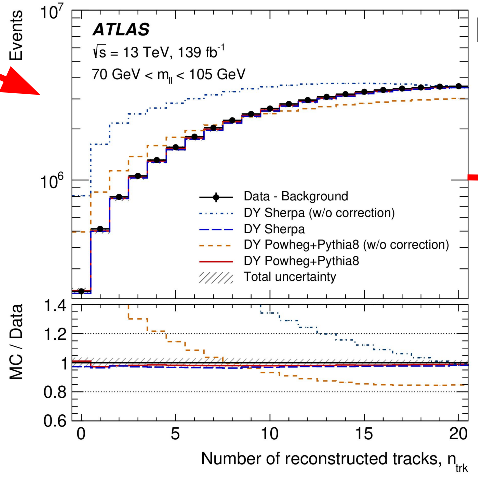
- Drell-Yan Z→ee/mumu
- yy→ee/mumu

Problem with background

Track multiplicity from underlying event *poorly* modeled in most Monte Carlo

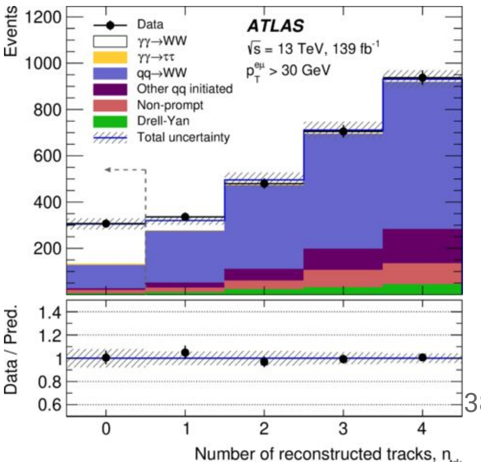
This includes dominant background from qq→WW:





Derived in Z->ll

Applied in WW->lvlv



Unfolding particle spectra in Drell-yan to derive correction (large statistics + smaller background)

Matching to WW based on pt(Z) vs pt(WW) since particle activity primarily driven by pT of the system (assumption validated using several hadronization models)

Observation!

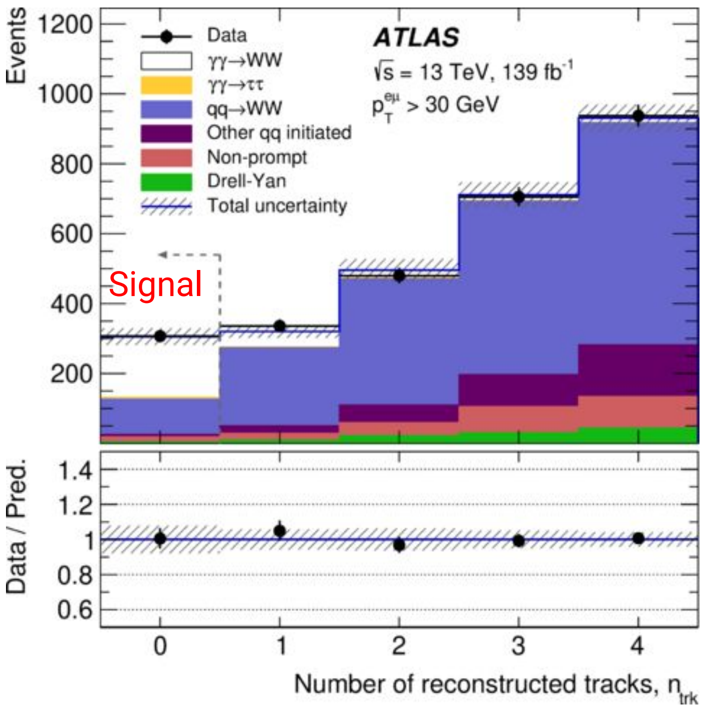
Profile likelihood fit in all analysis region to derive signal significance

8.4σ observed
(6.7σ expected)

(previous result ~3 sigma)

[PLB 816 (2021) 136190]

Source	Impact [%]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons	1.5
Background, statistical	6.7
Modelling	
Pileup modelling uncertainties	1.1
Underlying event modelling uncertainties	1.4
Signal modelling uncertainties	2.1
WW modelling uncertainties	4.0
Other background uncertainties	1.7
Luminosity	1.7
Total	8.9



… and now what?

Legacy analysis ongoing using the same data… why?

“On ATLAS the default [tracking threshold] is 500 MeV,
lower values not really feasible for full Run 2 data”

→ this was not entirely true :)

We cannot do low-pt tracking in all ATLAS events …

… but we can do it for small subset! Tracks down to 100 MeV for events from signal and control regions of the original analysis.

Berkeley Note

Working on legacy low-pt analysis! Better background rejection expected:

- Differential measurement
- EFT interpretation

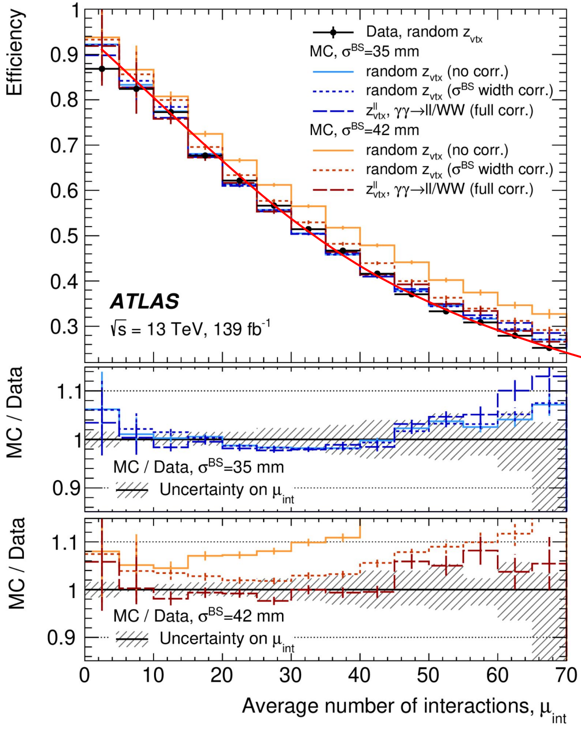
yy→X in HL-LHC

~ 200 interactions per bunch crossing expected at HL-LHC!

Tracking threshold might increase

- pseudorapidity coverage will increase
- dedicated tracking can still be run

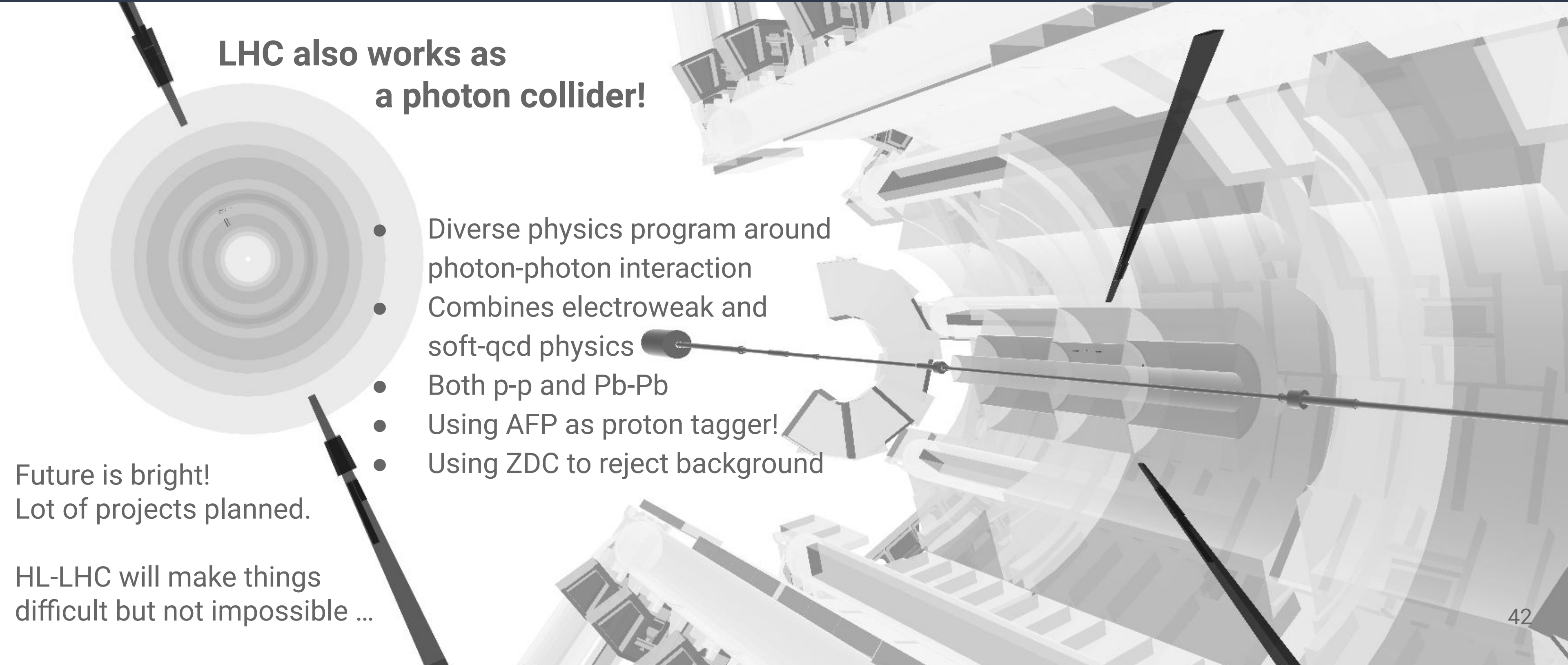
Unfortunately **no AFP** (forward tagging) in HL-LHC :/



As PU increases, signal efficiency approaches 0

(with constant background rejection)

To summarize



LHC also works as a photon collider!

- Diverse physics program around photon-photon interaction
- Combines electroweak and soft-qcd physics
- Both p-p and Pb-Pb
- Using AFP as proton tagger!
- Using ZDC to reject background

Future is bright!
Lot of projects planned.

HL-LHC will make things difficult but not impossible …

Thank you for your attention!

Backup

Di-lepton vertex

At such specific conditions, details matter!

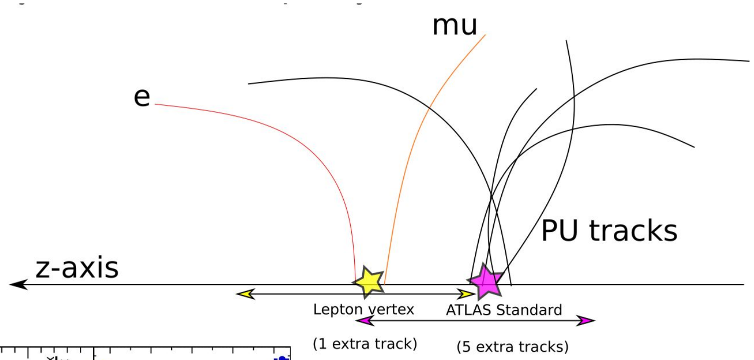
Standard ATLAS primary vertex:
- fit all nearby tracks

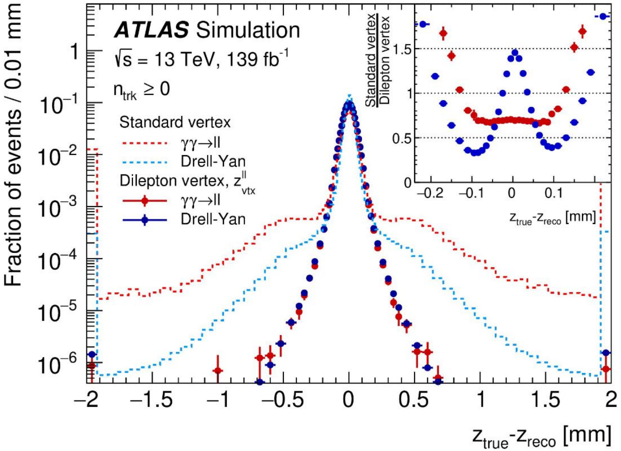
With exclusive selection, the tracks are either:

- leptons from yy->ll
- pile-up tracks

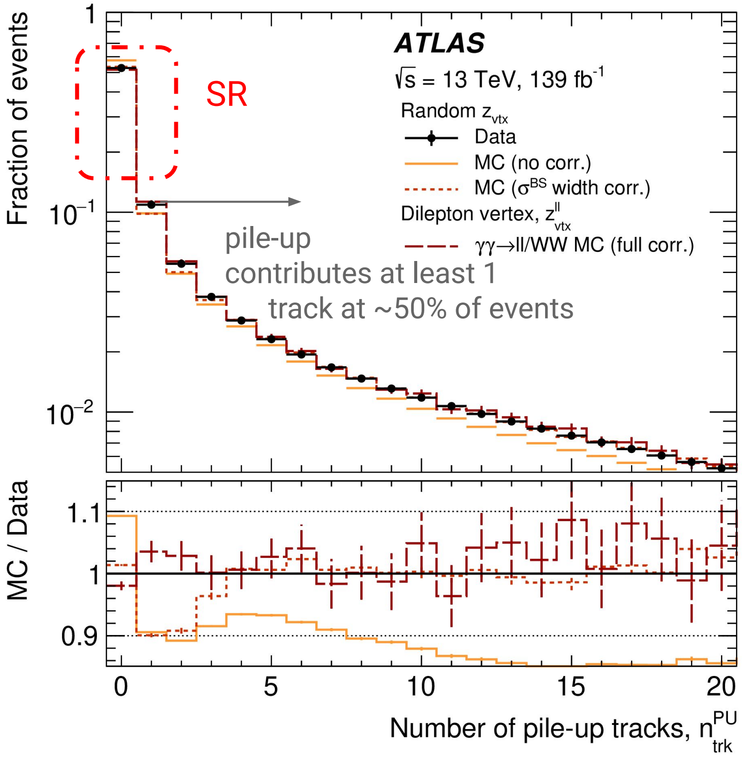
Pile-up leads to bias in position, averaging position instead:

$$z_{\text{vtx}}^{\ell\ell} = \frac{z_{\ell_1}\sin^2\theta_{\ell_1} + z_{\ell_2}\sin^2\theta_{\ell_2}}{\sin^2\theta_{\ell_1} + \sin^2\theta_{\ell_2}}$$





Pile-up modeling



- Selecting on 0 extra tracks near the dilepton vertex
- Contribution of pile-up tracks reduces efficiency

- Need precise modeling of the pile-up contribution
- Data-driven weight
  -> looking at track multiplicity far from dilepton vertex