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Measurement of the $t\bar{t}\gamma$ production cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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Results and perspectives in Particle Physics

BMBF-Forschungsschwerpunkt ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103 ATLAS
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Introduction

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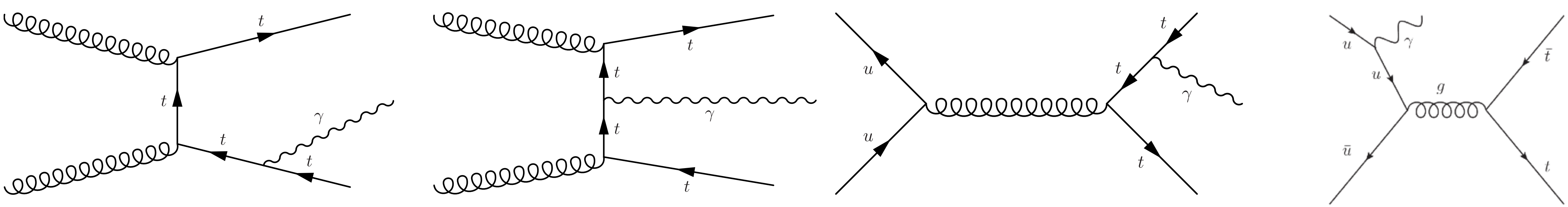
Motivation: probe the tγ (EM) coupling to the top quark

- Extensions to Standard model can modify top-quark couplings:
  - BSMs (composite top, technicolor, strongly coupled Higgs sector),
  - EFT coefficients can probe anomalous top couplings (O_{tG}, O_{tB}, O_{tW})

$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu},$$
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu},$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

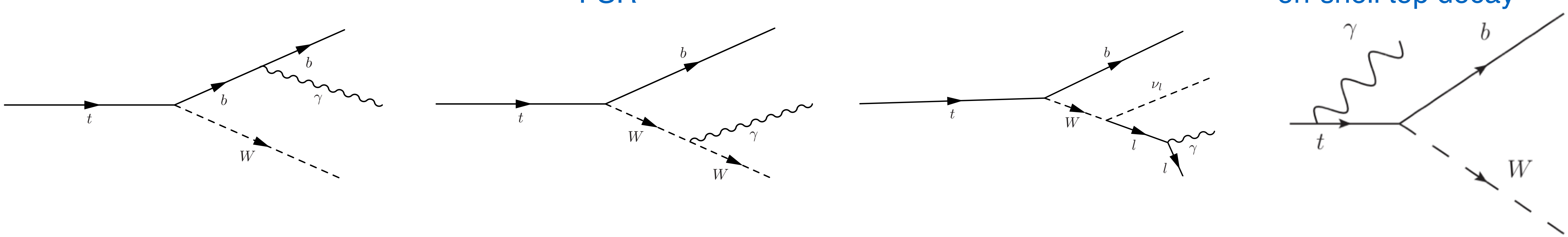
Radiative top production

off-shell top radiation — ISR



Radiative top decay

FSR — on-shell top decay

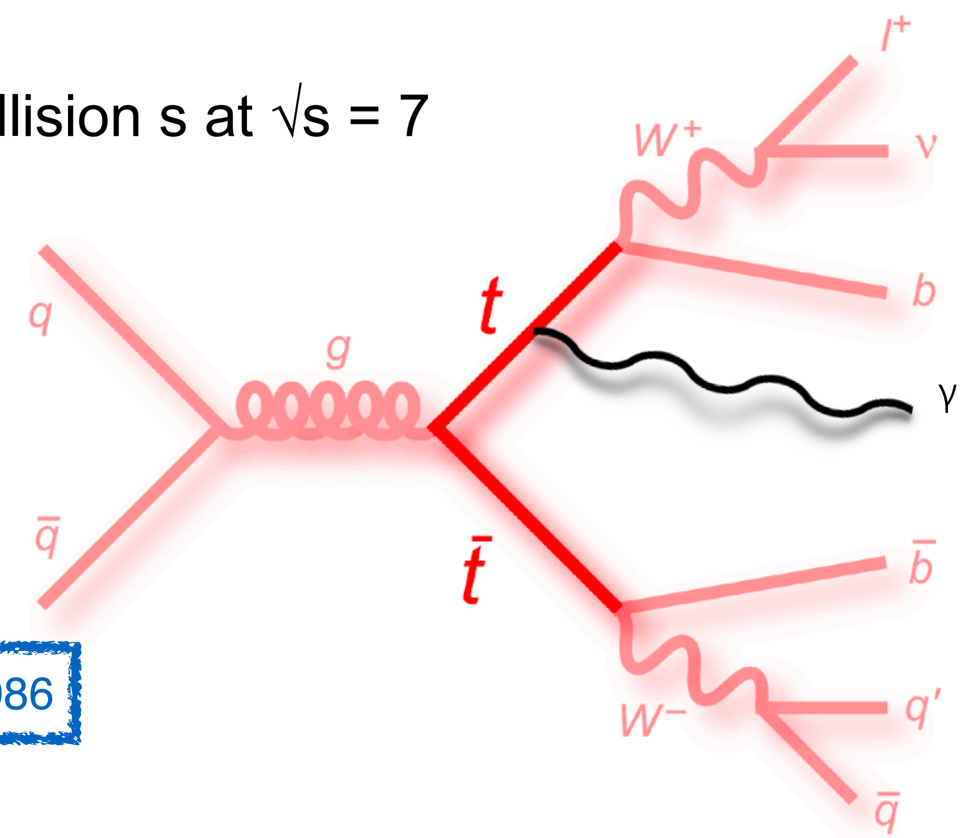


Introduction

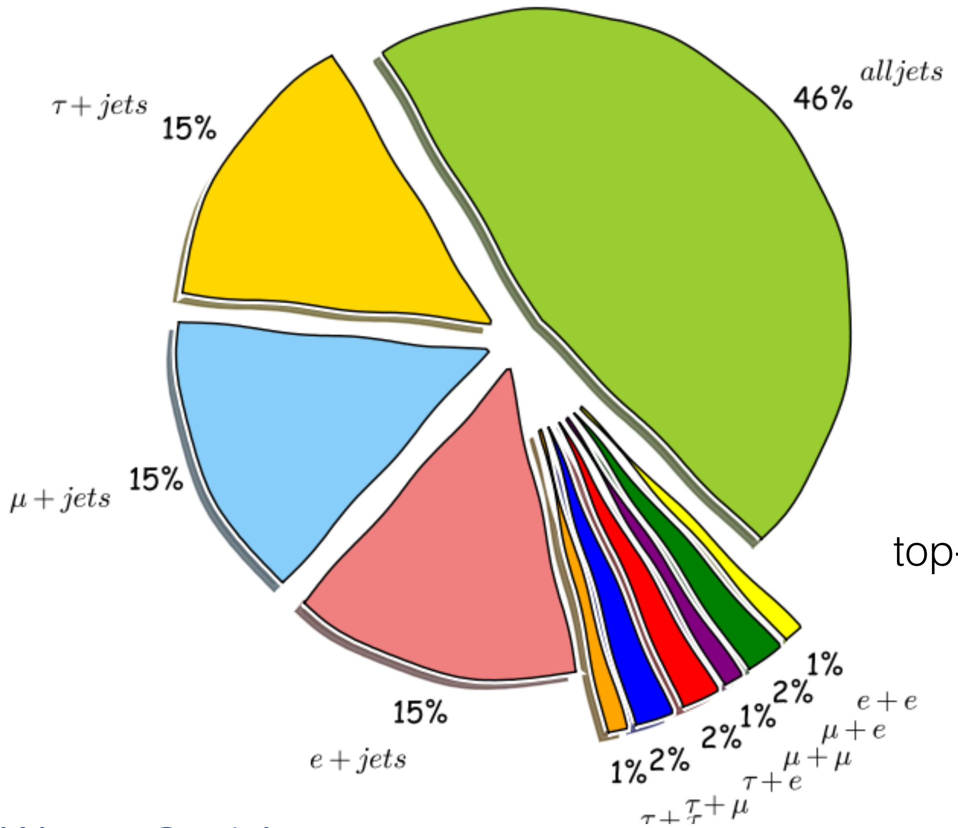
- Evidence was seen in $p\bar{p}$ collision at the Tevatron collider, $\sqrt{s}$ = 1.96 TeV by CDF collaboration in 2011[1]
- Observation reported by the ATLAS Collaboration in pp collision s at $\sqrt{s}$ = 7 TeV in 2015[2]
- Similar analysis by CMS at $\sqrt{s}$ = 8 TeV[3]

- All performed within the single lepton channel
- All agree with theoretical predictions

- This analysis also in single lepton channel JHEP 11 (2017) 086



+ cuts to remove infrared divergences

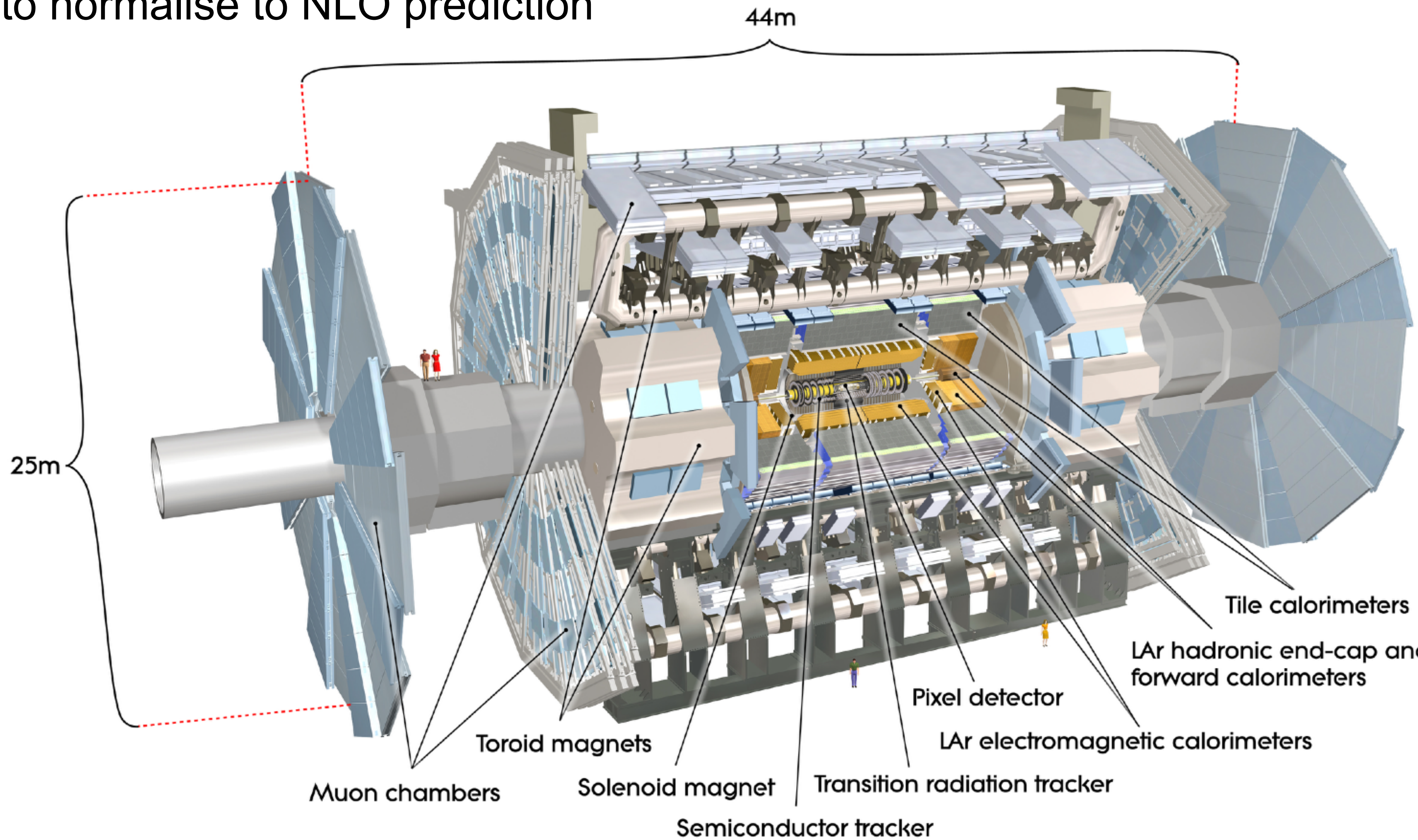


top-quark pair branching ratio

[1] Phys. Rev. D 84 (2011) 031104(R)
[2] Phys. Rev. D 91 (2015) 072007
[3] CMS-PAS-TOP-14-008

Data and Detectors

- Data collected in 2012 with the ATLAS detector at $\sqrt{s}$ = 8 TeV
  - 20.2 fb^{-1}
- Signal sample is generated with Madgraph5 and showered with Pythia6
- Matrix element calculation is LO
  - K-factors used to normalise to NLO prediction



The ATLAS detector

Object/Event level selections

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$t\bar{t}\gamma$ event selection	e + jets	μ + jets
leptons	1 e, p_T > 25 GeV	1 μ, p_T > 25 GeV
Photon	1 γ with p_T > 15 GeV, |η| < 2.37 (no isolation requirements)	
Jets	≥4 jets, ≥1 b-jet (70% efficiency)	
E_T^{miss}	> 30 GeV	> 20 GeV
$m_T(W)$	> 30 GeV	-
MET+$m_T(W)$	-	> 60 GeV
ΔR(jet,γ)	> 0.5	
ΔR(l,γ)	> 0.7 (suppress FSR photons)	
m(e,γ)	not in [85, 95] GeV	-

(orange) = Fiducial region definition

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Analysis Strategy

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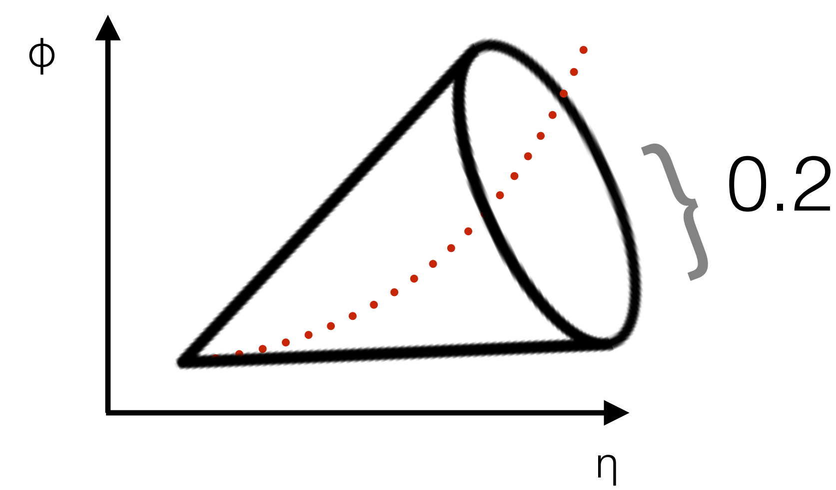
- Maximum likelihood fit to the p_T^{iso} distribution
  - Sum of p_T of all charged tracks in cone of ΔR=0.2 around photon

- **3 templates:**
  - Prompt signal and background photons
  - Hadronic fakes
  - Electron-fakes



- Two free parameters in fit:
  - Signal and hadronic background
- Electron and muon channel merged
- Differential measurements require **bin-by-bin unfolding**

$$A_i = \frac{N^{\mathrm{fid}}_{\mathrm{gen},i}}{N^{\mathrm{all}}_{\mathrm{gen},i}}$$

$$C_i = \frac{N_{\mathrm{reco},i}}{N^{\mathrm{fid}}_{\mathrm{reco},i}}$$

Acceptance and correction for bin i for a given distribution

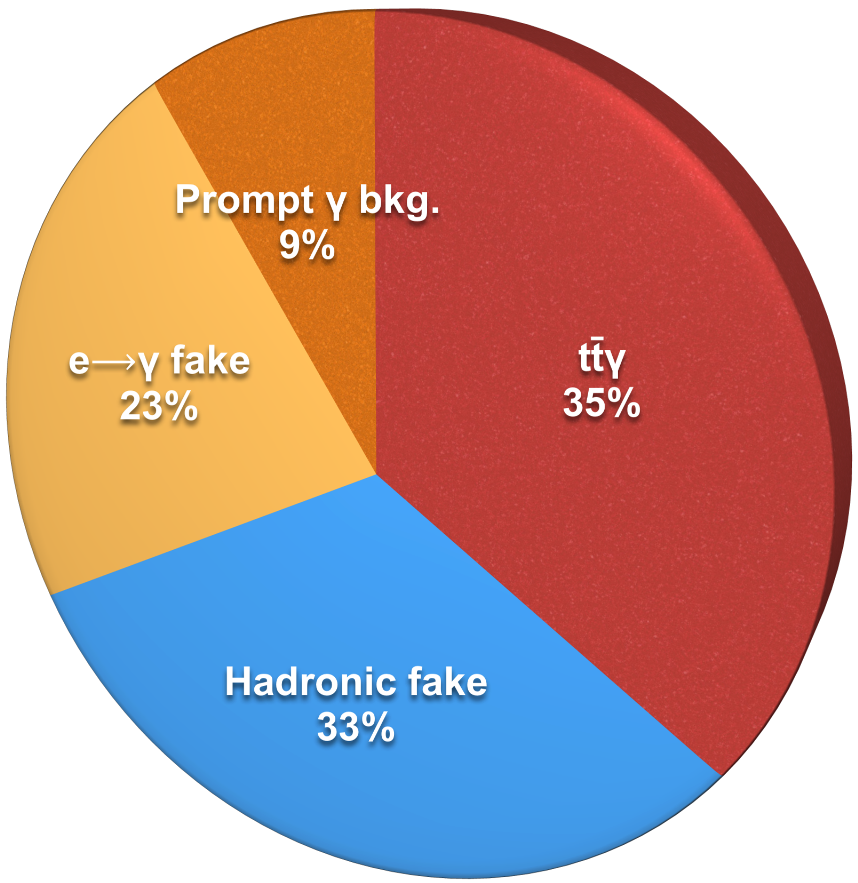
Background estimation

3 Main "classes" of background

- **Hadronic fakes**
  - Largest background
  - Mostly from $t\bar{t}$
  - Hadrons or photons from hadron decays that are misidentified as prompt photons
  - Data-driven template
  - *Free parameter in the fit*

- **Electron fake background**
  - Photons faked by electrons due to poorly reconstructed tracks, or misidentified electrons
  - Data-driven template
  - Fake rates from tag & probe method
    - Ratio of $Z \longrightarrow e$+fake γ / $Z \longrightarrow e^+e^-$
    - Applied to signal "region" where photon is replaced by electron

- **Backgrounds with prompt photons**
  - W+jets+γ: MC estimation with data-driven scale factors
  - Z+jets+γ, Single top+γ,VV+γ: MC estimation
  - Multijet+γ (Lepton fake estimation): Data-driven using matrix method



Templates

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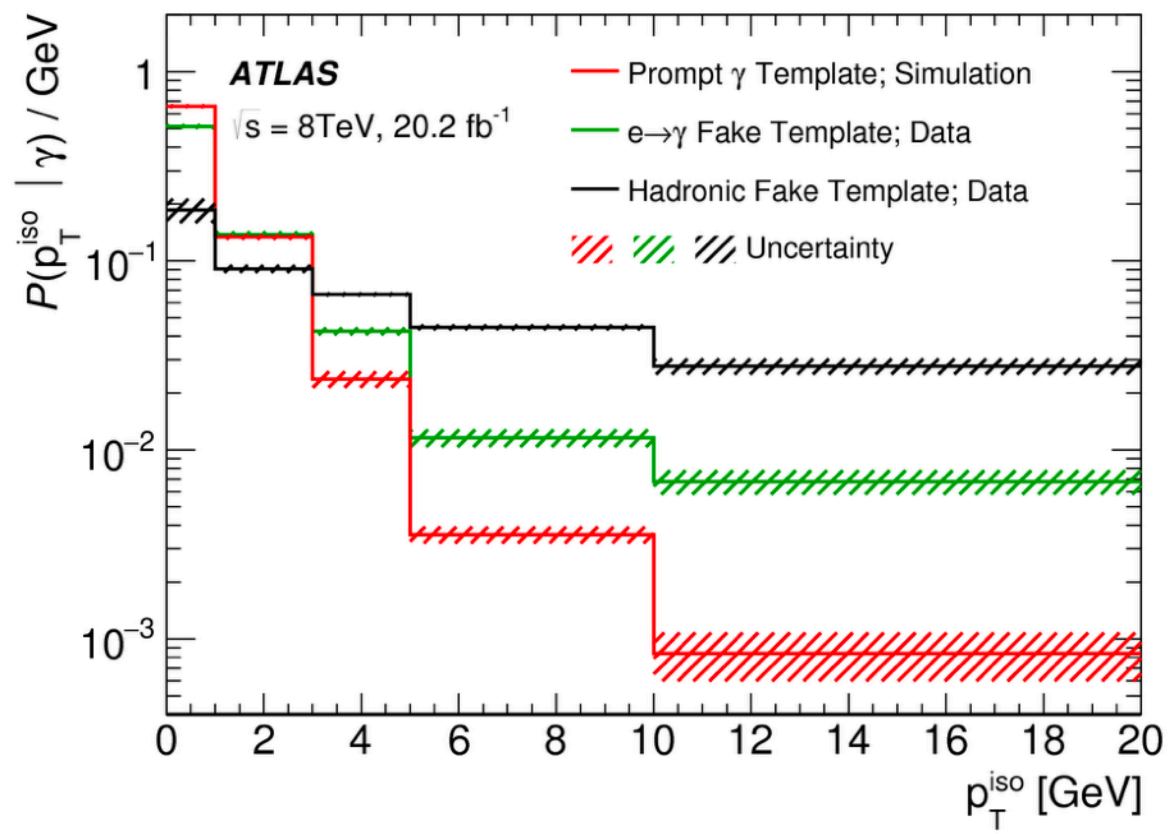
- **Prompt photon template**
  - "Prompt" includes signal $t\bar{t}\gamma$ and as well as W/Z+jets+γ, VV+γ, ST+γ, Multijet+γ
  - $t\bar{t}\gamma$ contribution extracted from signal MC
  - After full event selection reco γ truth matched to particle level within $\Delta R = 0.1$

- **Hadronic fake template**
  - Control region in data enriched with hadronic fakes
    - ≥ 1 γ that fails a specific photon ID criteria
    - ≥ 4 jets
    - $\Delta R(e,\gamma) > 0.1$
  - p_T and η dependence, template weighted accordingly
  - Prompt photon contamination as systematic uncertainty



- **Electron fake template**
  - Data enriched region by Z⟶e+fake γ
    - Back-to-back e and fake γ
    - $70 \text{ GeV} < m(e,\gamma) < 110 \text{ GeV}$
    - $p_T^{e} > p_T^{\gamma}$
    - MET > 30 GeV
  - p_T and η dependence, template weighted accordingly
  - Backgrounds subtracted using a sideband fit to m(e,γ) distributions
  - Variation of MET and mass range as systematic uncertainty

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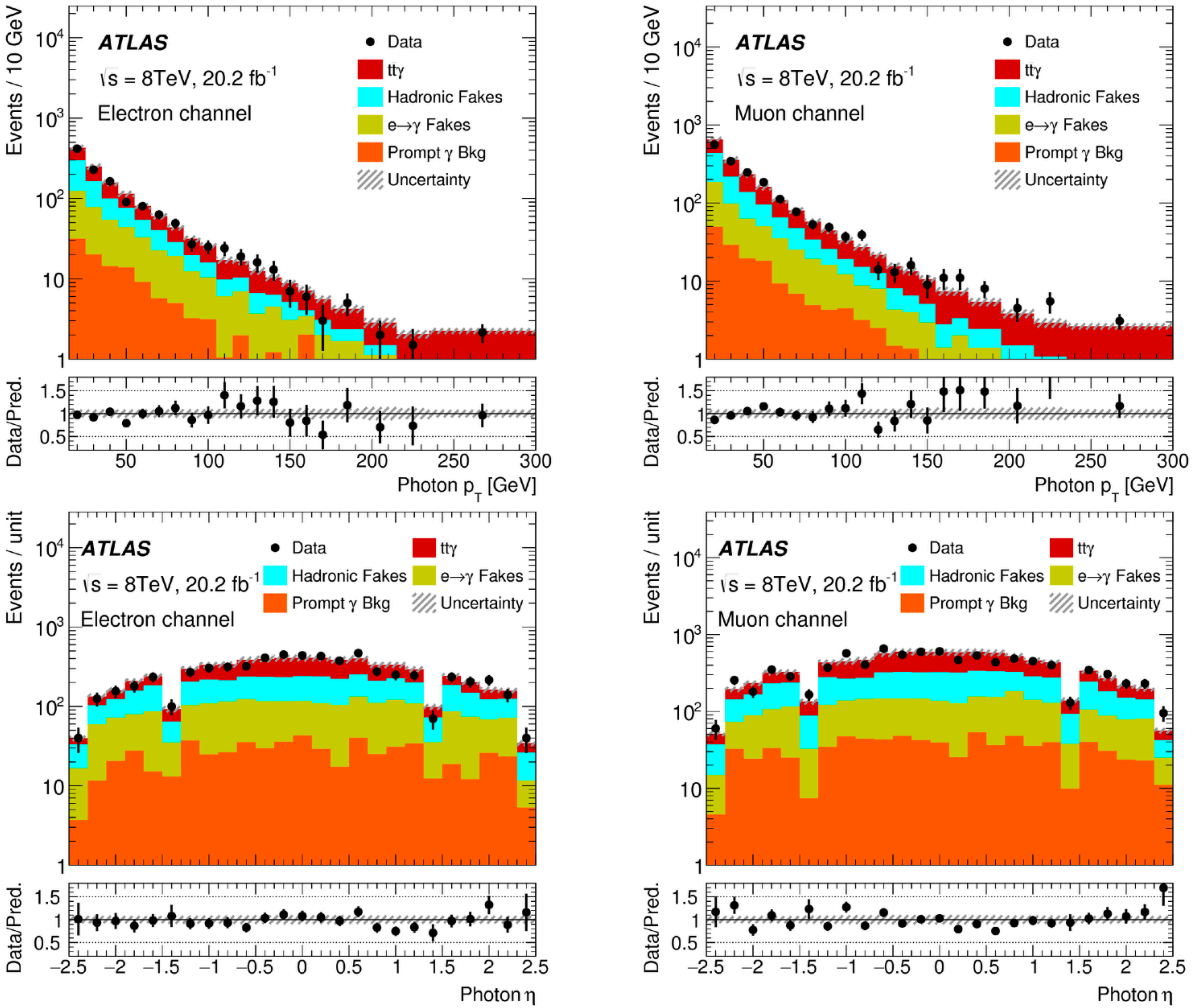

Maximum likelihood fit

Event yield in bin j of p_T^{iso} dist. of bin i of p_T/η dist.

Gaussian function for each systematic of mean of 0 and std. of 1

$$\mathcal{L} = \prod_{i,j} P(N_{i,j} | N^s_{i,j} + \sum_b N^b_{i,j}) \times \prod_t G(0|\theta_t, 1)$$

i=1: fiducial
i=5: differential

Observed # of data

Predicted # of signal

Predicted # of background

Systematic $\theta_t \in$ of $\boldsymbol{\theta}$

- The inclusive and fiducial cross section to be determined is related to the number of signal events by:

$$\mathcal{L} \cdot \sigma_i \cdot C_i \cdot f_{i,j} = N^s_{i,j}$$

Integrated Lumi. (20.2 fb^{-1})

Ratio of reconstructed events to the generated events in fid. region in bin i of p_T or η

Fraction of events falling into bin j of p_T^{iso} of bin i from signal template

Maximum likelihood fit

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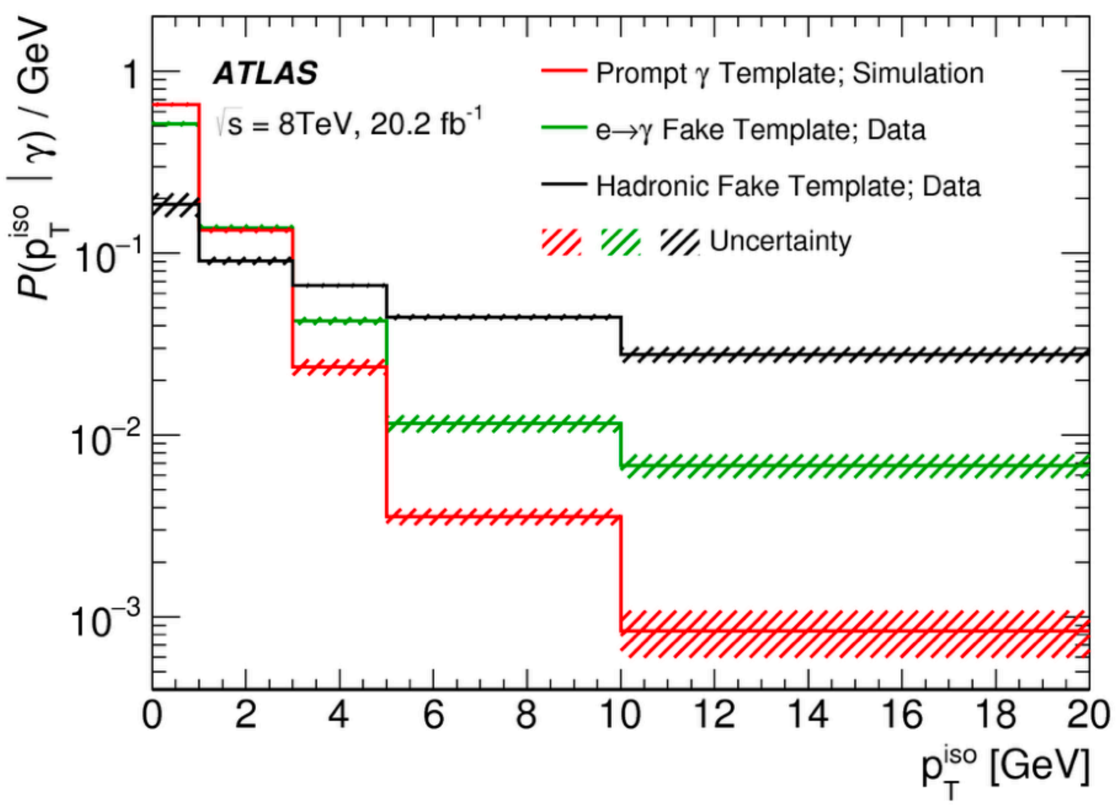
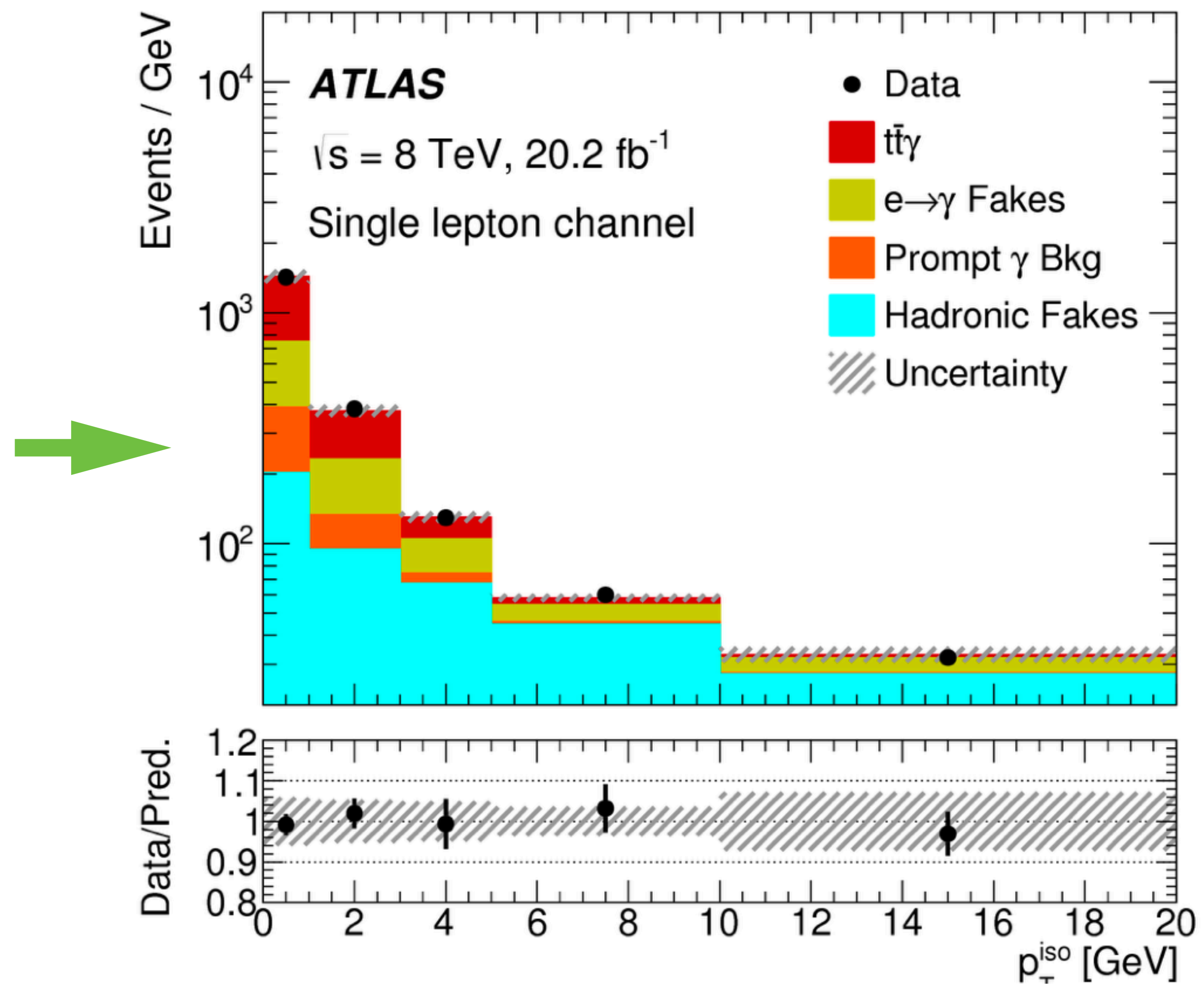
p_T^{iso} with the 3 templates



post-fit p_T^{iso} distribution



Good agreement between data/MC

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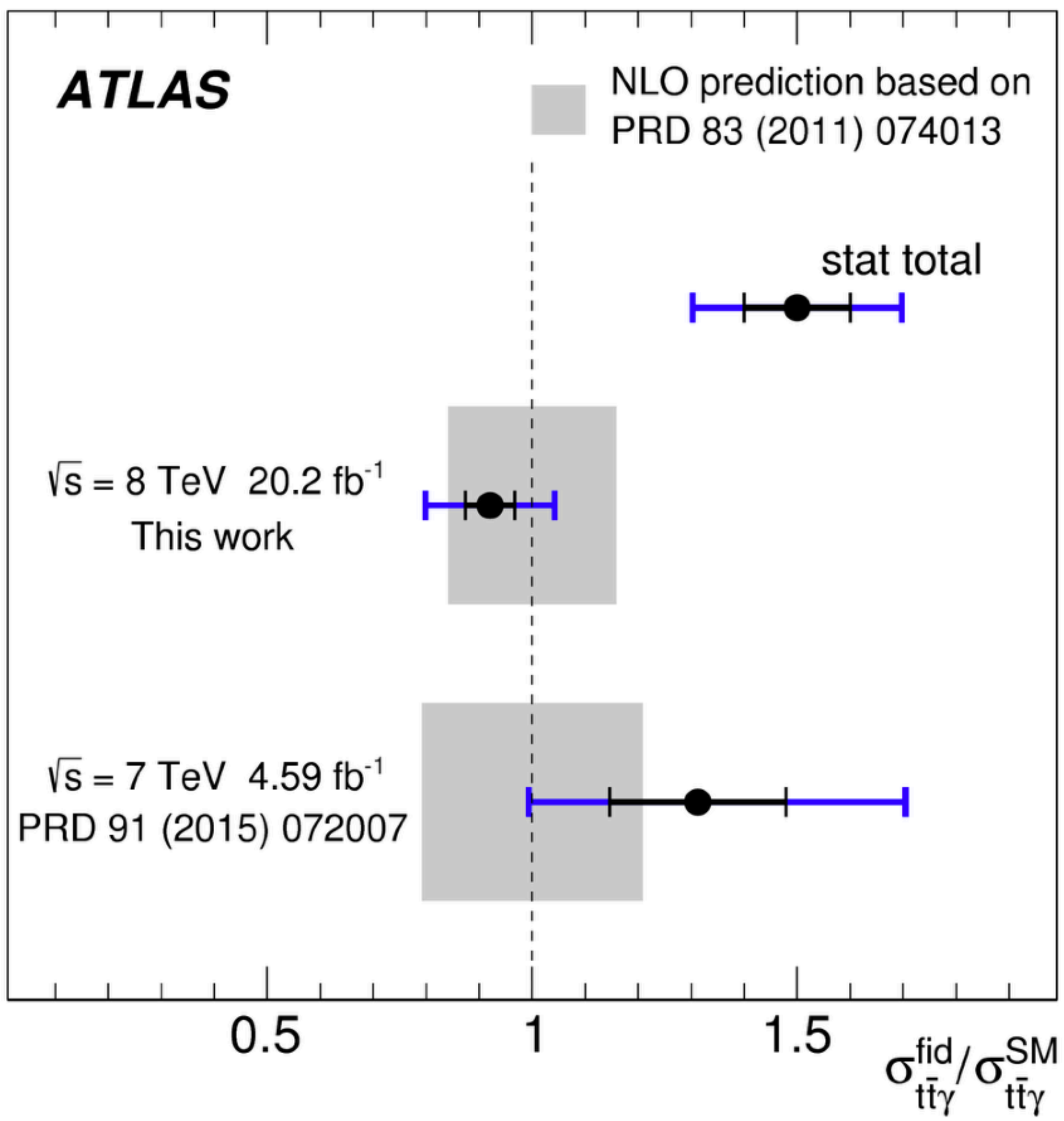
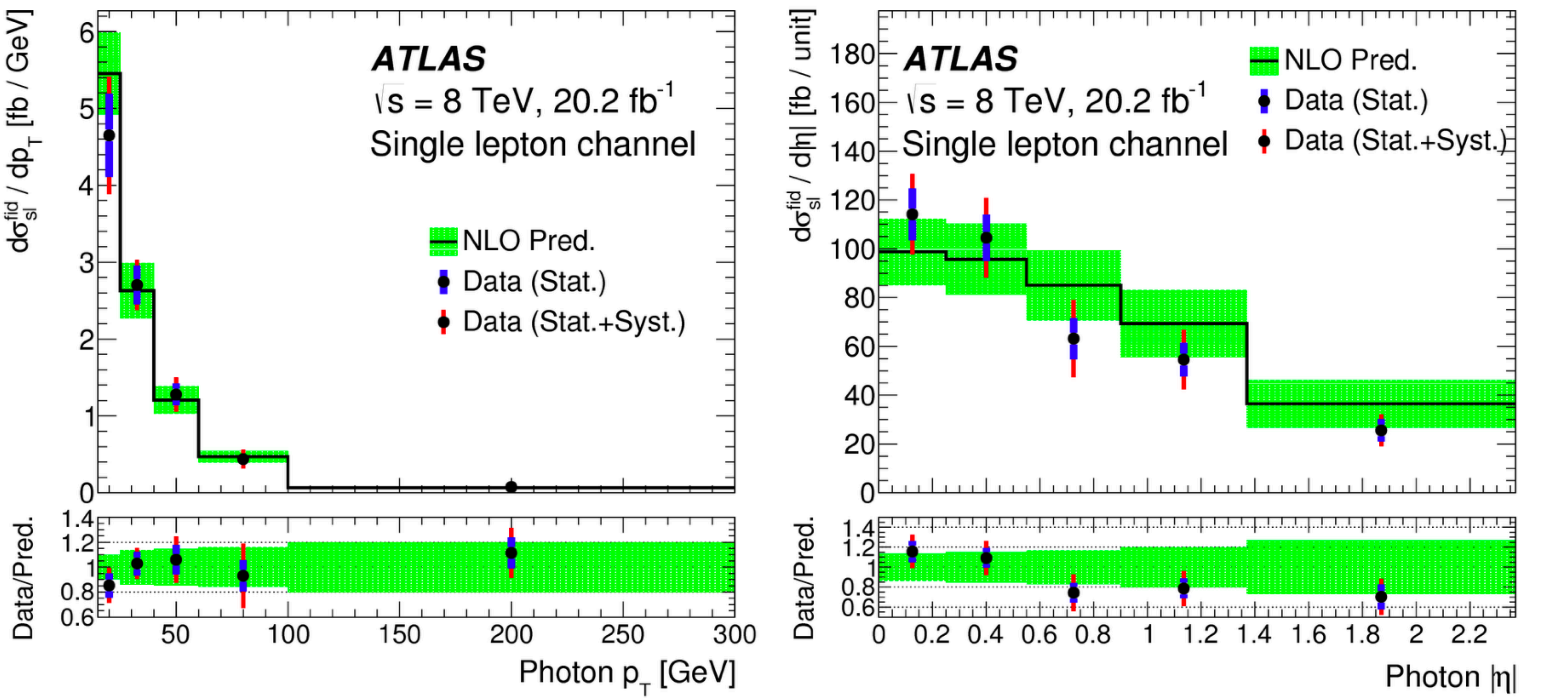
- Fiducial cross section: $\sigma_{\mathrm{sl}}^{\mathrm{fid}} = 139 \pm 7(\mathrm{stat.}) \pm 17(\mathrm{syst.})\ \mathrm{fb} = 139 \pm 18\ \mathrm{fb}$
- Theoretical cross section: $\sigma_{\mathrm{sl}}^{\mathrm{theory}} = 151 \pm 24\ \mathrm{fb}$



Source	Relative uncertainty [%]
Hadron-fake template	6.3
$e \to \gamma$ fake	6.3
Jet energy scale	4.9
$W\gamma$+jets	4.0
$Z\gamma$+jets	2.8
Initial- and final-state radiation	2.2
Luminosity	2.1
Photon	1.4
Single top+γ	1.2
Muon	1.2
Electron	1.0
Scale uncertainty	0.6
Parton shower	0.6
Statistical uncertainty	5.1
Total uncertainty	13

Measured fiducial cross section agrees with SM theoretical prediction at NLO



Measured differential cross section agrees with SM theoretical prediction at NLO

Conclusions

- **Fiducial** and **first differential** cross sections for **pp⟶$t\bar{t}\gamma$** in the **single lepton** channel at **√s = 8 TeV** with the **ATLAS detector** presented

- **Fiducial cross-section** is dominated by systematics
  - $\sigma_{\mathrm{sl}}^{\mathrm{fid}} = 139 \pm 7(\mathrm{stat.}) \pm 17(\mathrm{syst.})\ \mathrm{fb} = 139 \pm 18\ \mathrm{fb}$
  - Relative total uncertainty of 12.95%
    - Compared with 7 TeV analysis of ~27%

  - Hadronic fake and e⟶γ fake background largest contribution
  - Agreement with theoretical NLO prediction

- **Differential cross section** in η and p_T distributions
  - Agreement with theoretical NLO prediction

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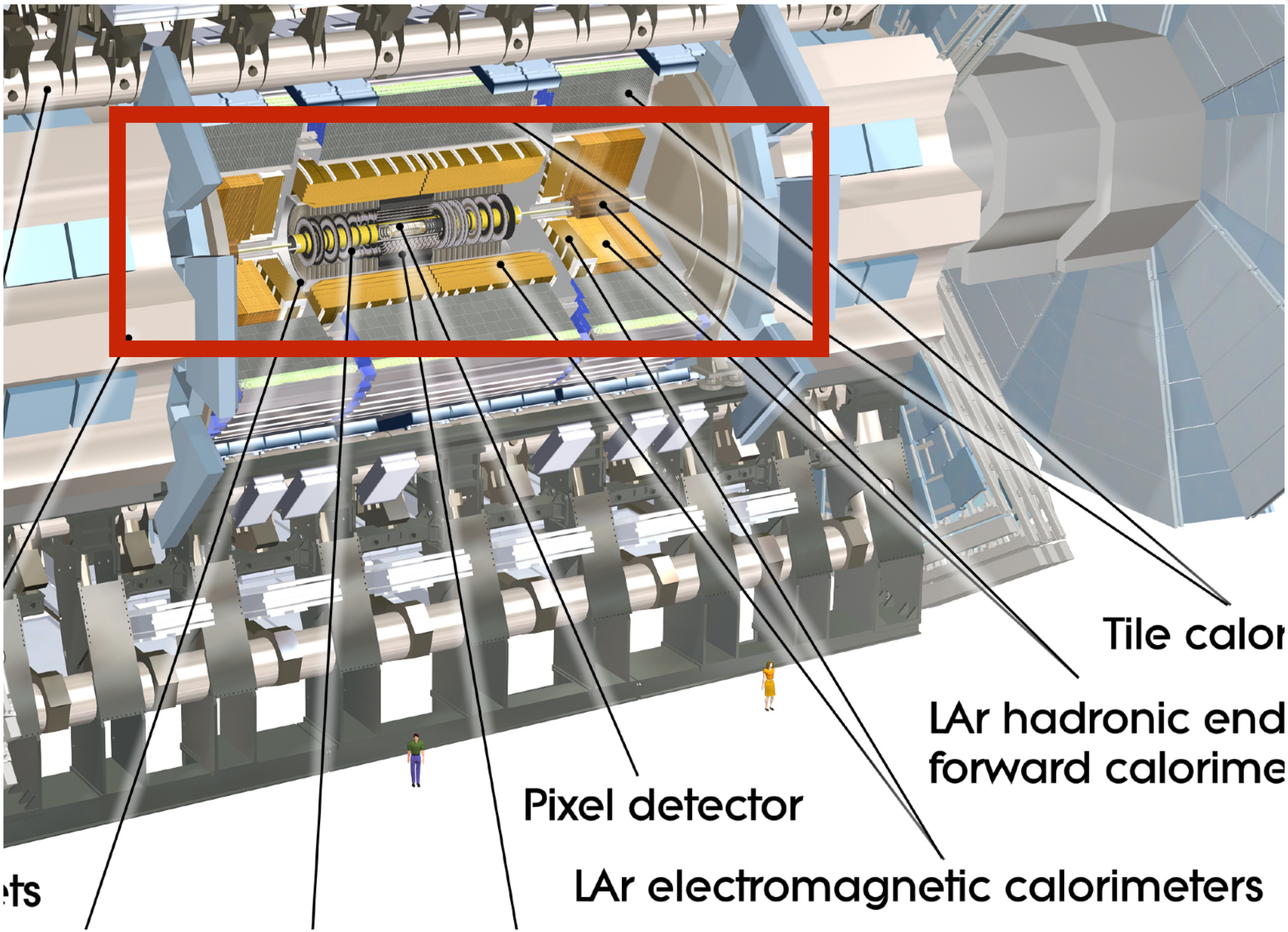
Backup slides

Data and Detectors



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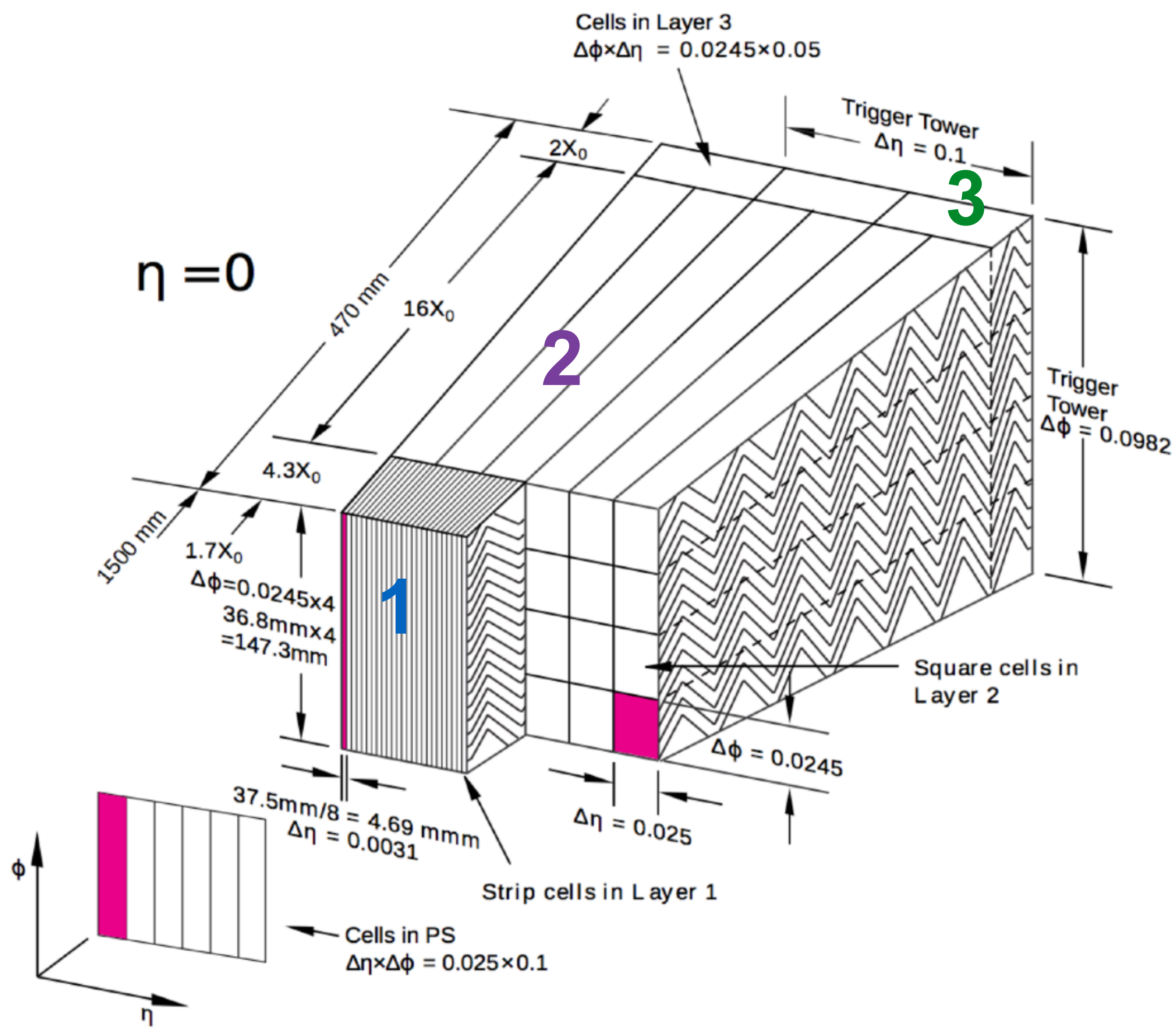
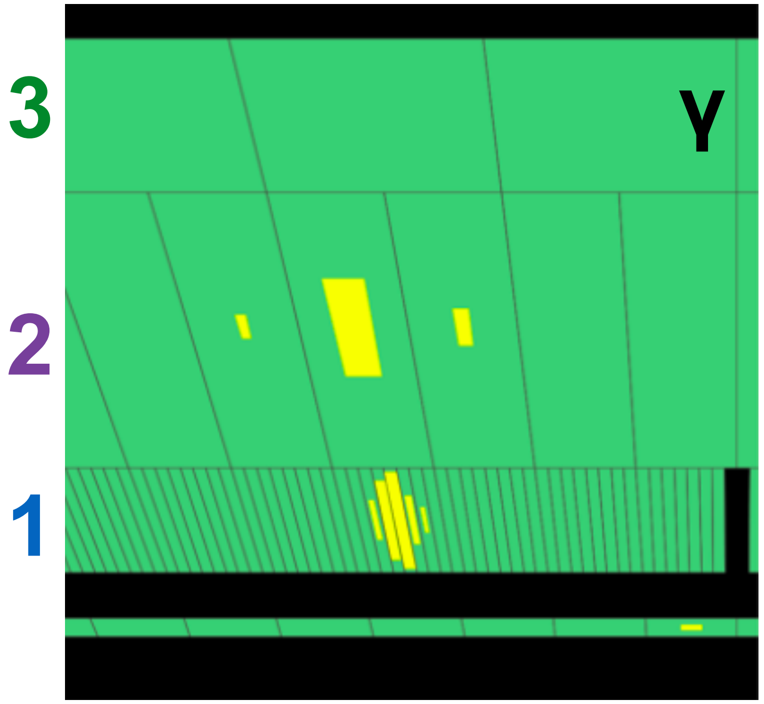
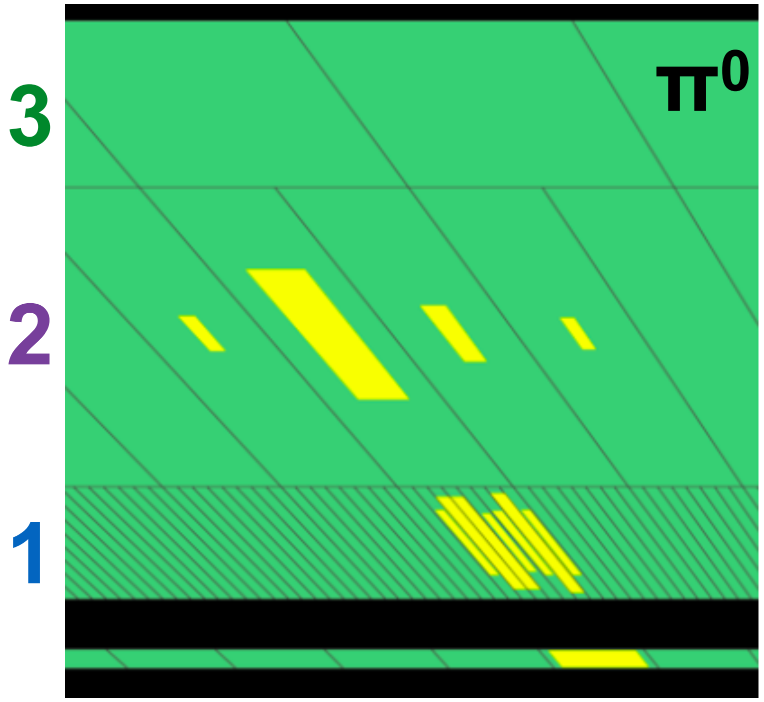


- Electromagnetic calorimeter (EMC) is lead/ liquid-Argon detector
- 3 layers
  - 1) Highest granularity in η direction
  - 2) Collects most of the shower energy for high-p_T electrons or photons
  - 3) Thin pre-sampling layer correcting energy lost by EM particles upstream





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- 3 layers
  - 1) Highest granularity in η direction
  - 2) Collects most of the shower energy for high-p_T electrons or photons
  - 3) Thin pre-sampling layer correcting energy lost by EM particles upstream
- Photons are narrow isolated showers in the EMC
- High density allows for rejection of π^0 and η mesons