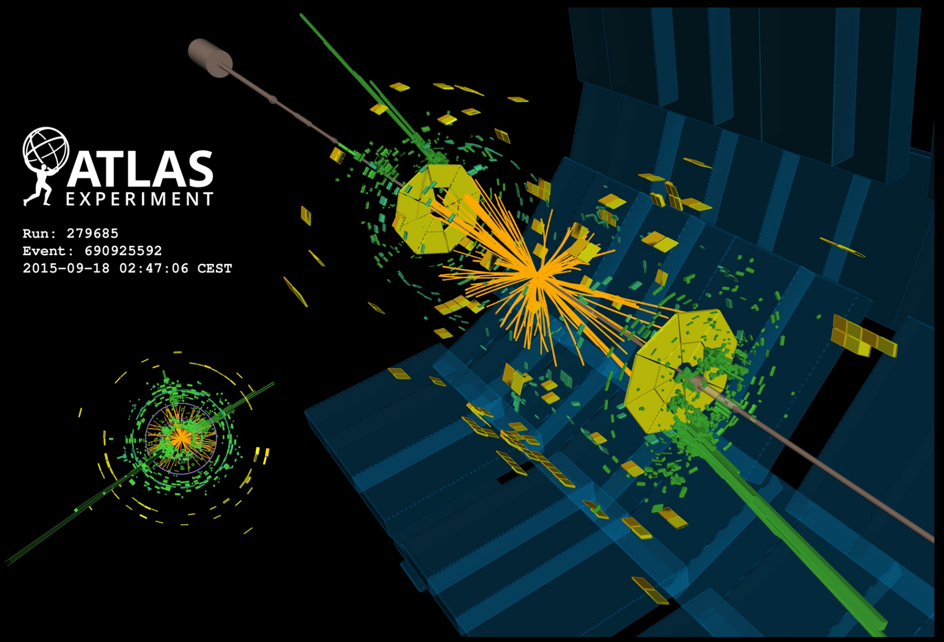
Probing the Standard Model with Top Quarks, Jets and Photons in the ATLAS Experiment



Ethan Simpson,
on behalf of ATLAS

The Particle Safari: ATLAS Tour

Fauna

Top Quarks

- Most massive species
- Population: 180 million
- Elusive – gone quickly!

Photons

- Massless
- Colourless
- Probe of QED

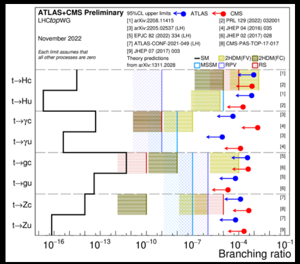
Jets

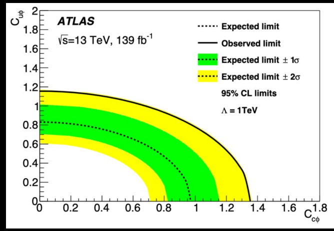
- Powerful tool
- Constant development of techniques

All important in the HEP ecosystem

FCNCs

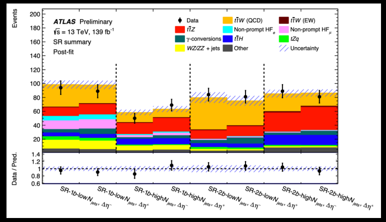
- Top-gluon
- Top-Z boson
- Top-photon
- Top-Higgs

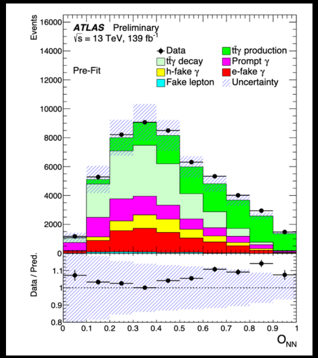




Charge Asymmetries

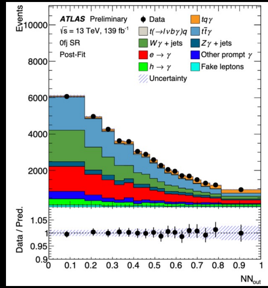
- $t\bar{t}W$
- $t\bar{t}\gamma$

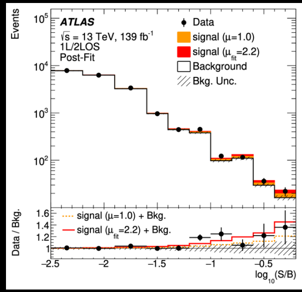




Rare Top Cross-Sections

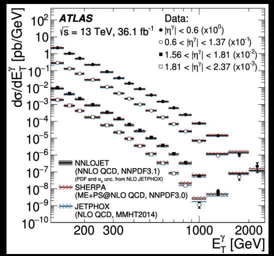
- Single-top photon
- 4-tops

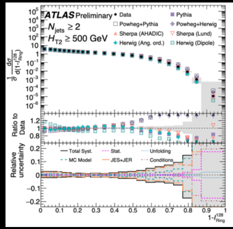


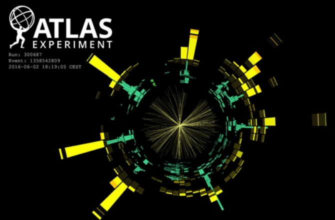


SM Measurements

- Inclusive photon
- Event isotropies



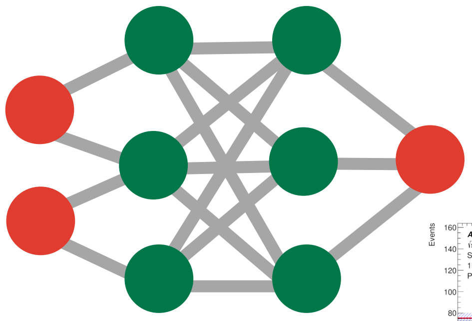


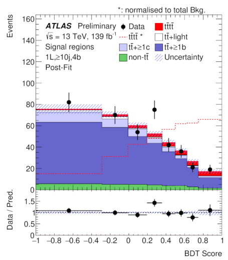


Top Tools

Consider searches or rare processes with large backgrounds

Machine Learning for signal / background

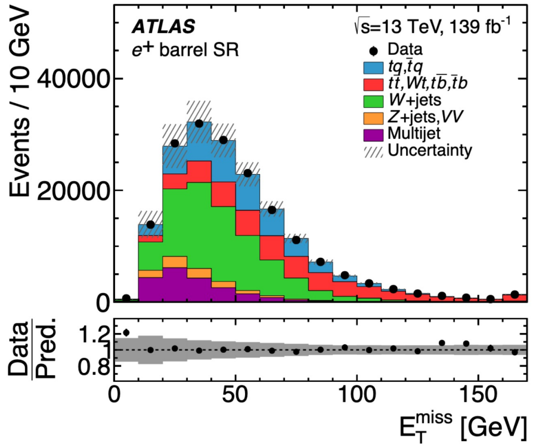




- Boosted Decision Trees
- Deep Neural Nets

Data-driven backgrounds

- Scale Factors
- Fake Factors



Binned profile likelihood fits

$$\mathcal{L}\left(\boldsymbol{n}, \boldsymbol{\theta}^0 \mid \mu, \boldsymbol{\theta}\right) = \prod_{i \in \text{ bins}} \mathcal{P}\left(n_i \mid \mu \cdot S_i(\boldsymbol{\theta}) + B_i(\boldsymbol{\theta})\right) \times \prod_{j \in syst} \mathcal{G}\left(\theta_j^0 \mid \theta_j, \Delta\theta_j\right)$$

- Signal Regions + Control Regions
- Systematics as nuisance parameters

Top Flavour-Changing Neutral Currents

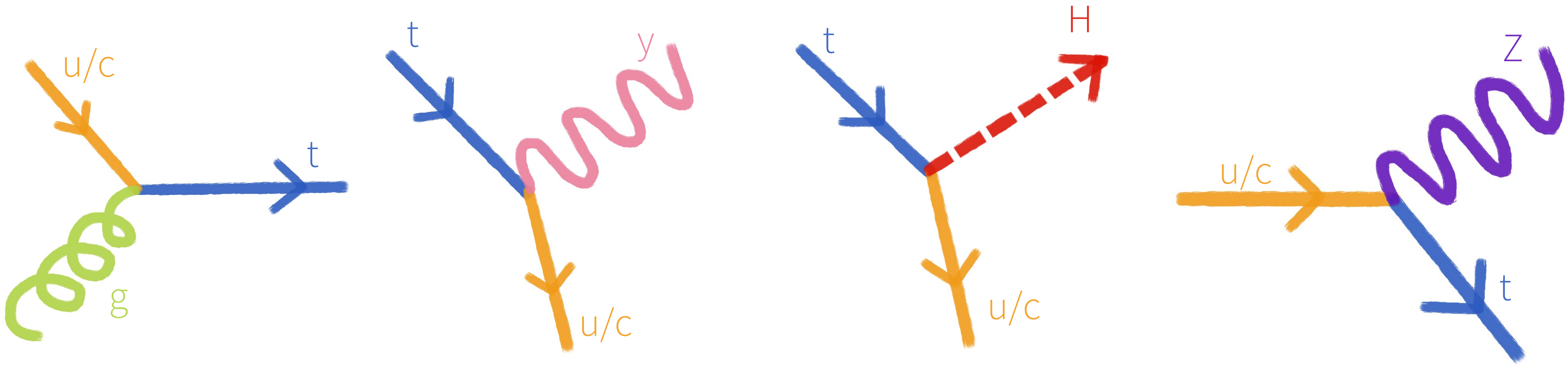
FCNCs

- In SM, forbidden at tree-level. Suppressed at higher-orders.
- Top FCNC branching ratios:
  BR ~ 10^{-12} - 10^{-16}

- Enhanced by many BSM models: SUSY,
  composite Higgs,
  warped extra dimensions.

FCNCs

- In SM, forbidden at tree-level. Suppressed at higher-orders.
- Top FCNC branching ratios:
  BR ~ 10^{-12} - 10^{-16}
- Enhanced by many BSM models: SUSY,
  composite Higgs,
  warped extra dimensions.



Gluon Photon Higgs Z-boson

FCNC Methods

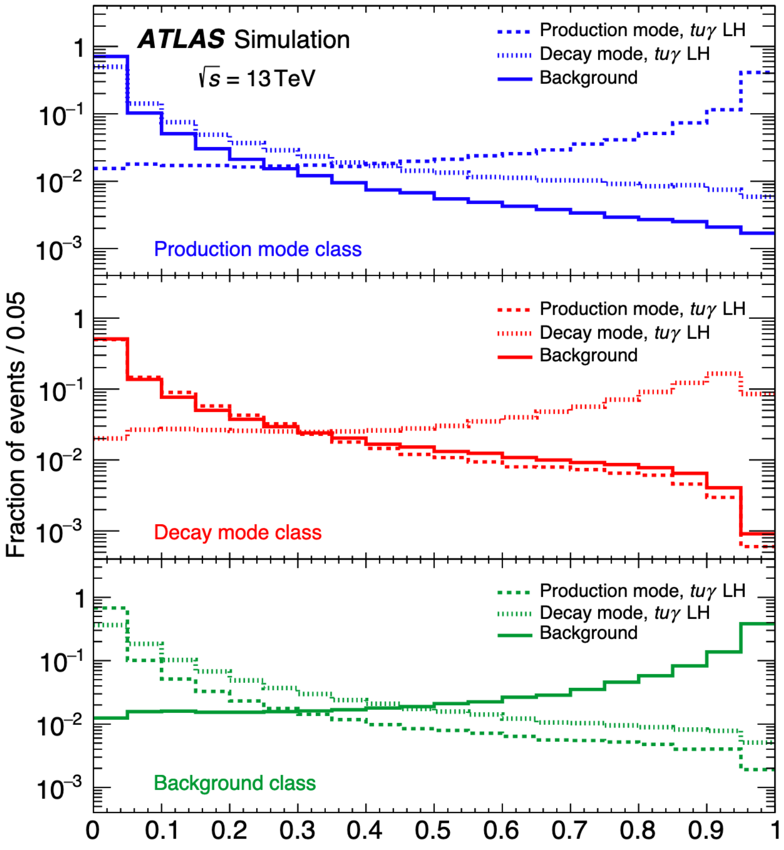
1. Event Selection
2. Define regions
3. Background Discrimination
   - Data-Driven methods
   - ML techniques
4. Binned likelihood fit
5. EFT interpretation

FCNC Methods

1. Event Selection
2. Define regions
3. Background Discrimination
   - Data-Driven methods
   - ML techniques
4. Binned likelihood fit
5. EFT interpretation

Highlight: $tq\gamma$ Neural Net

- Multi-class NN: 37 inputs, 6 hidden layers

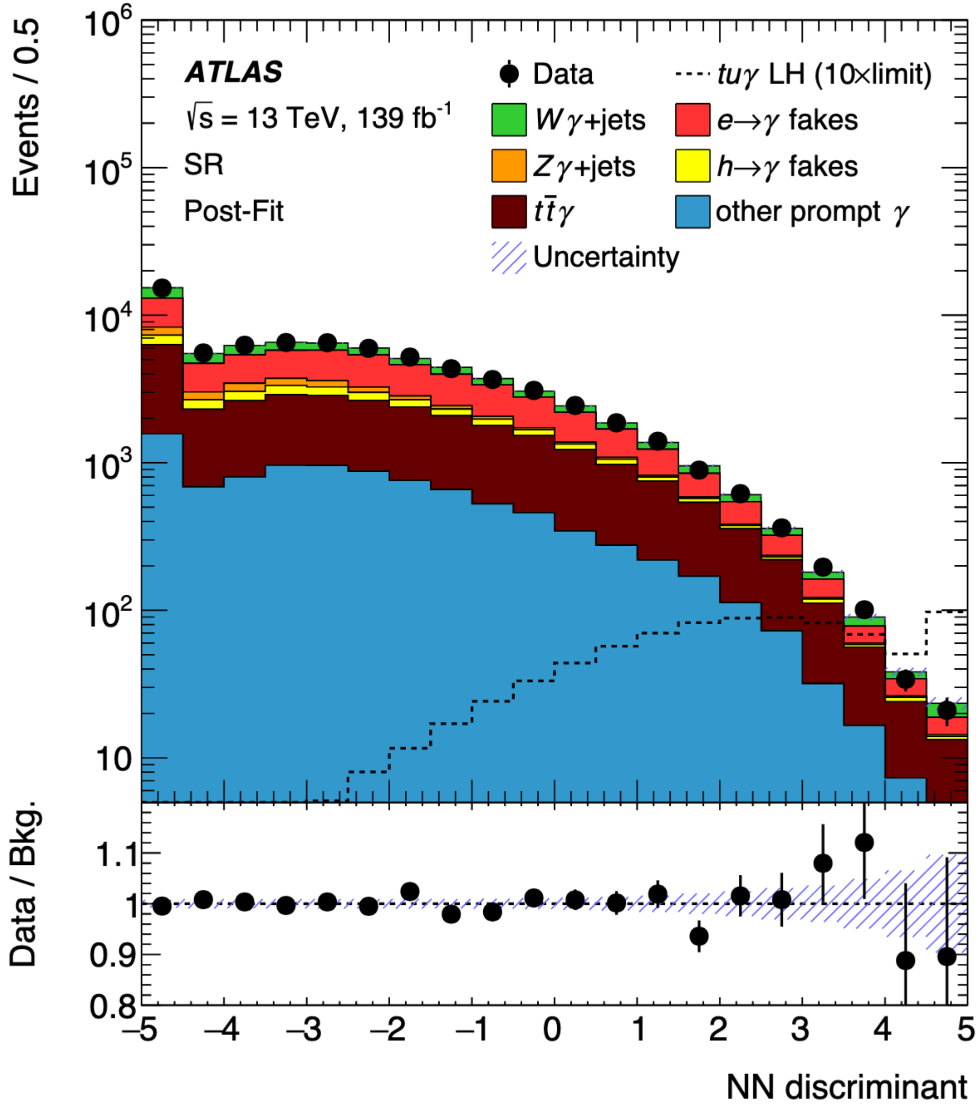


FCNC production

FCNC decay

SM background

FCNC Results

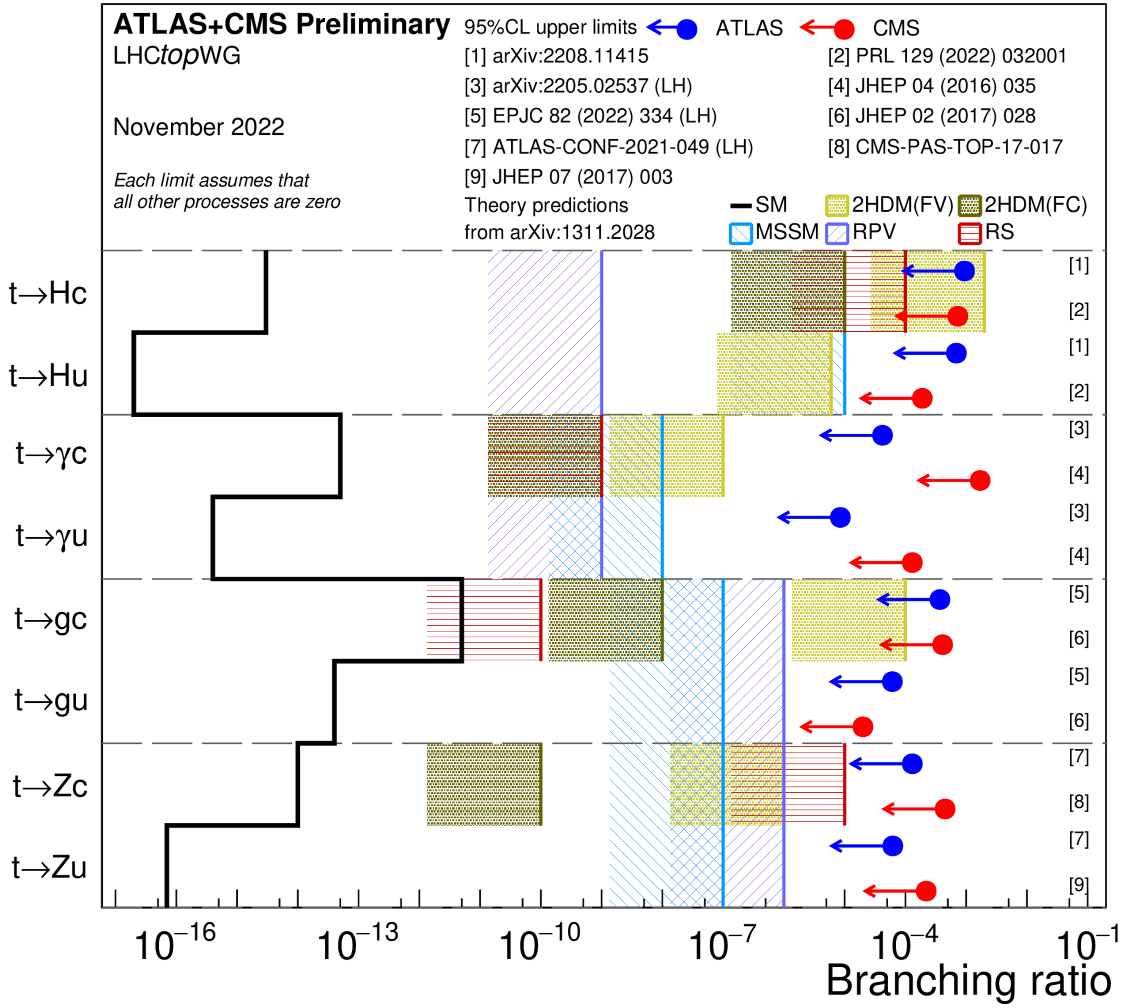


Data consistent with background only: exclusion of FCNC signal

Coupling	BR limits $[10^{-5}]$ Expected	Observed
$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46

Branching ratios for u/c + handedness

FCNC Results

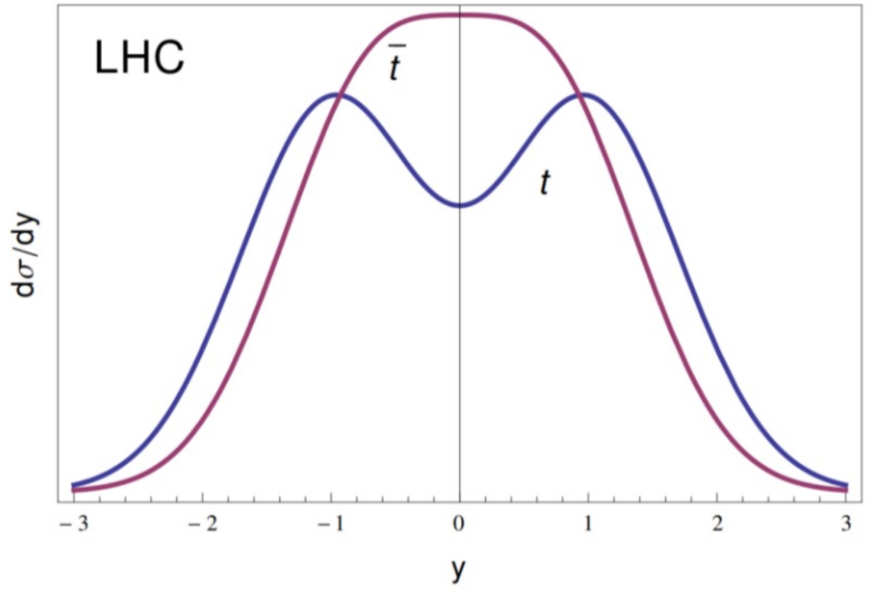


- Gluon, photon and Z-boson: consistent with SM
- Higgs: 2.3σ excess over SM background.
- Higgs result dominated by statistical uncertainties
- ATLAS & CMS results begin to reach precision to exclude NP models.

Charge Asymmetry Measurements with Electroweak Bosons

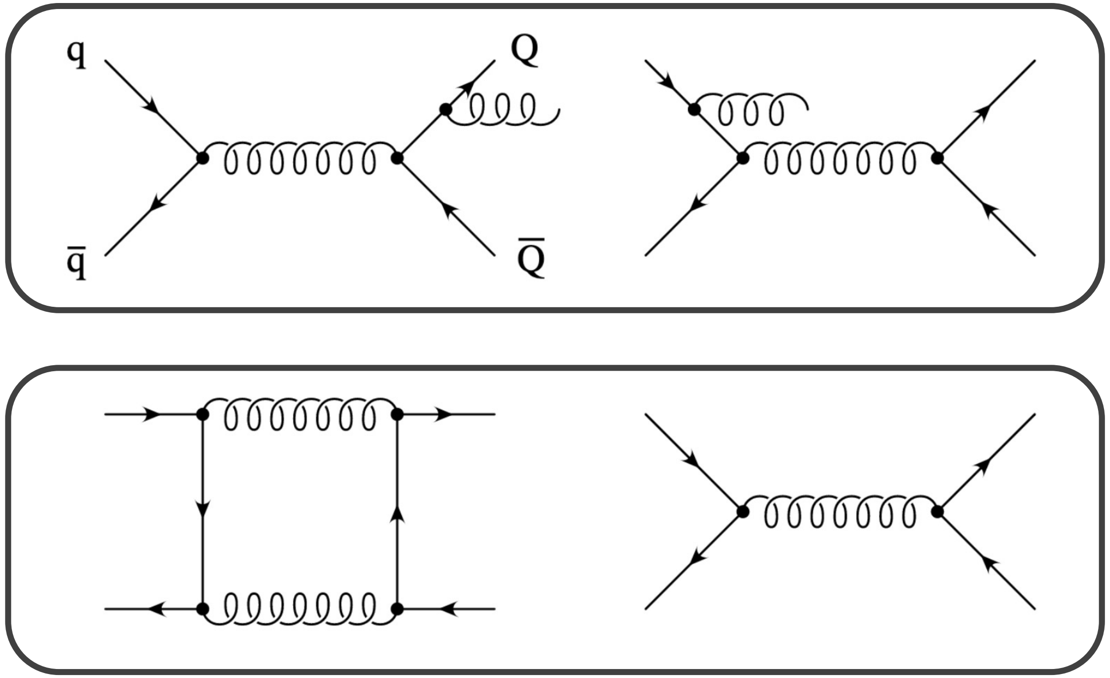
Charge Asymmetries

In LHC $pp \rightarrow t\bar{t}$, tops more forward; anti-tops more central.



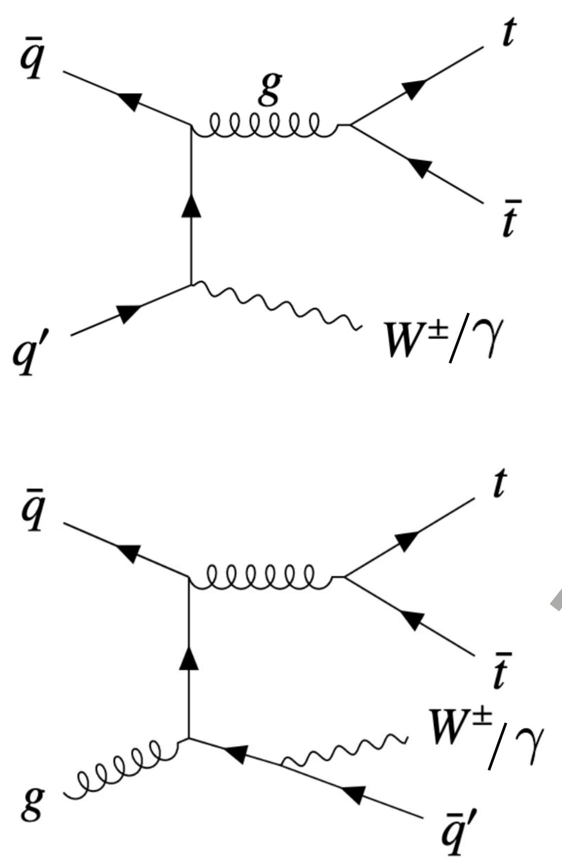
Charge asymmetry is a difference in rapidities.

- $q\bar{q}$ NLO interference:



Charge Asymmetries

In LHC $pp \rightarrow t\bar{t}X$, charge asymmetry altered.



New diagrams change qq/gg fraction.

Aim: Measure A_c for various associated production topologies.

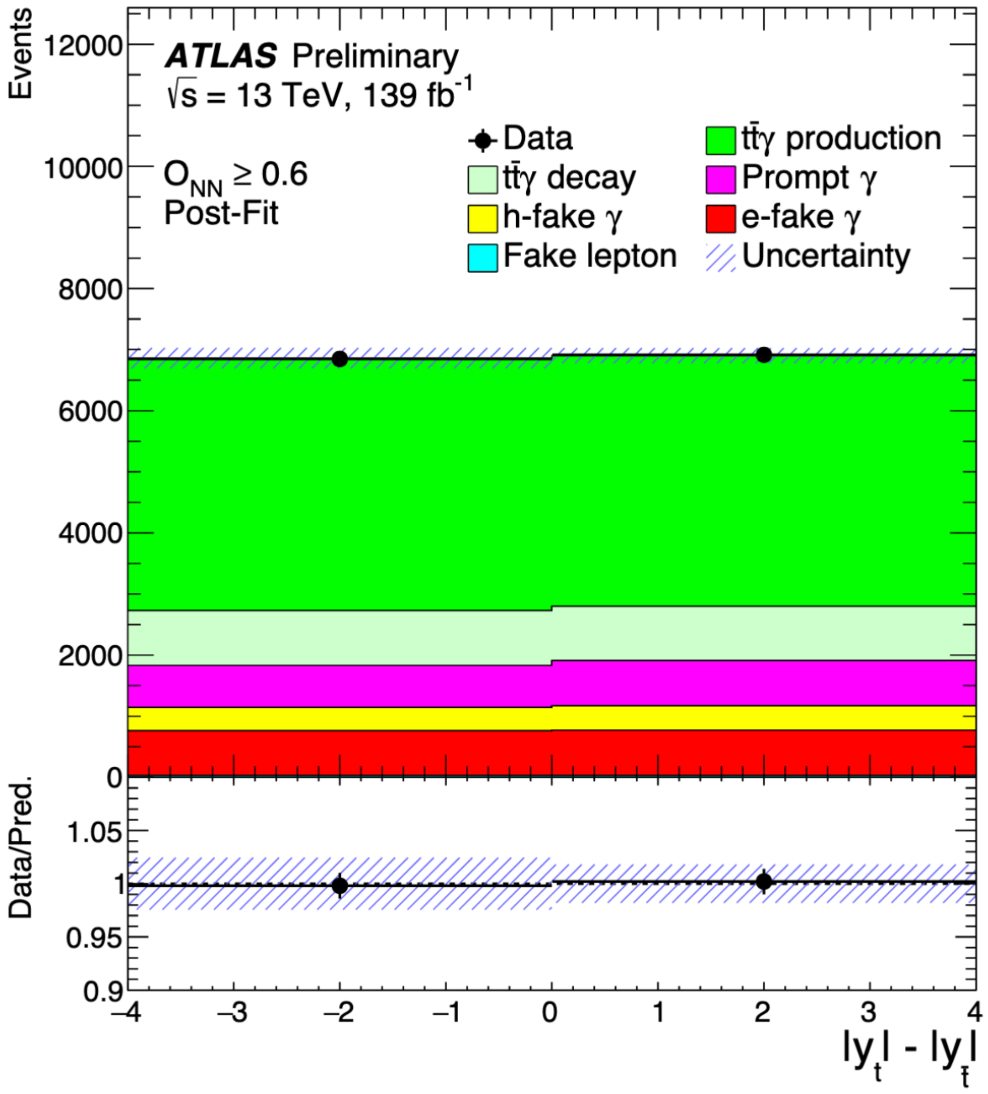
- Consider **$tt\gamma$** and **ttW** topologies.
- Use boson as probe.
- Both results are stat-limited..

$t\bar{t}\gamma$

- A_C of top quarks.
- Semi-leptonic decay.
- Top reconstruction:
  kinematic likelihood methods
- S/B through NN
- PL unfolding:
  A_C at particle-level only.

$A_C = 0.006 \pm 0.024\ (\text{stat}) \pm 0.018\ (\text{syst})$ fb

- Jet/b-tagging major systematic.

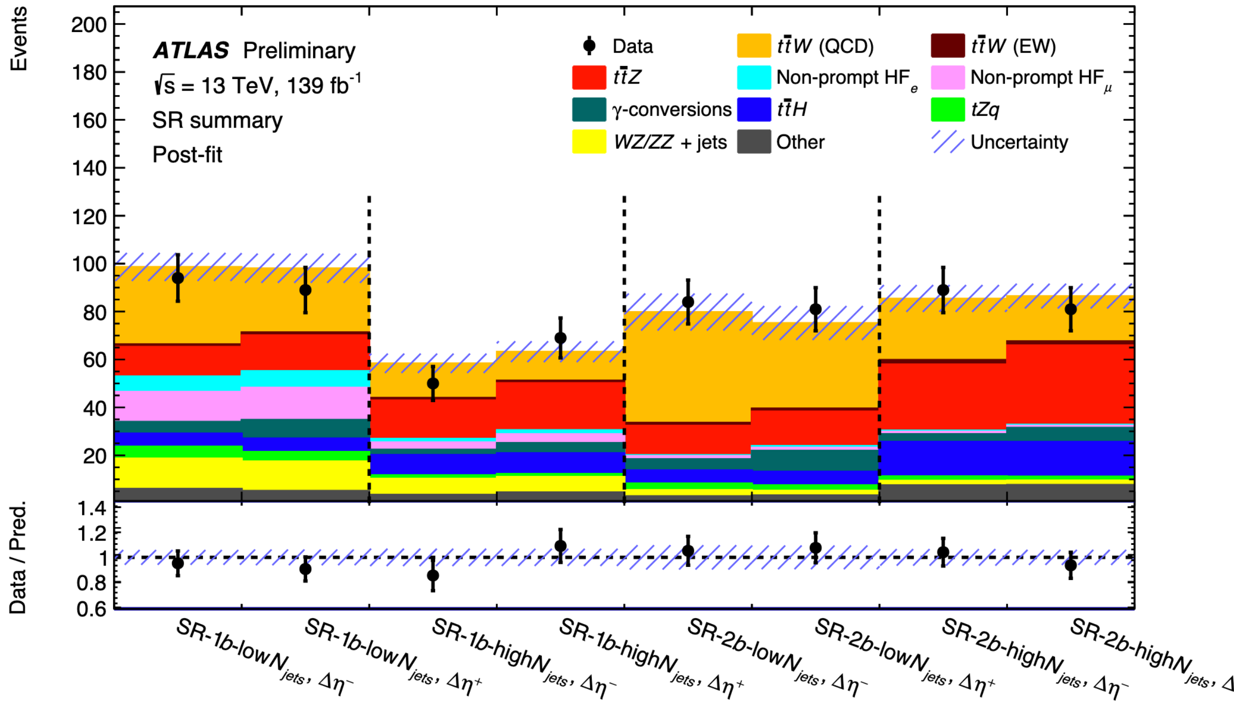


$t\bar{t}W$

- Leptonic charge asymmetry
- Dileptonic decays:
  3 tight leptons.
- BDT classifies same-sign leptons from tops (71%)
- Extract Ac at detector-level

A_c = -0.123 ± 0.136 (stat) ± 0.051 (syst) fb

- Also particle-level unfolding
- Modelling uncertainties

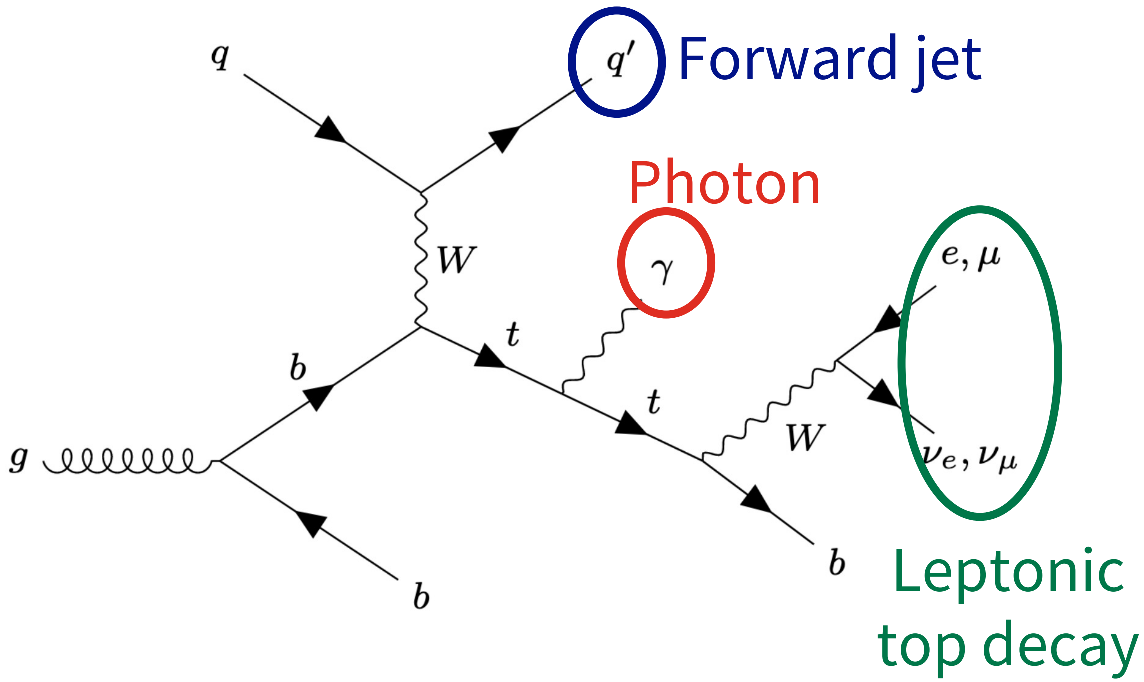


4SR + 4CR, based on jet multiplicities
(CRs constrain ttZ, ttH, fake leptons)

Rare Top Cross-Sections

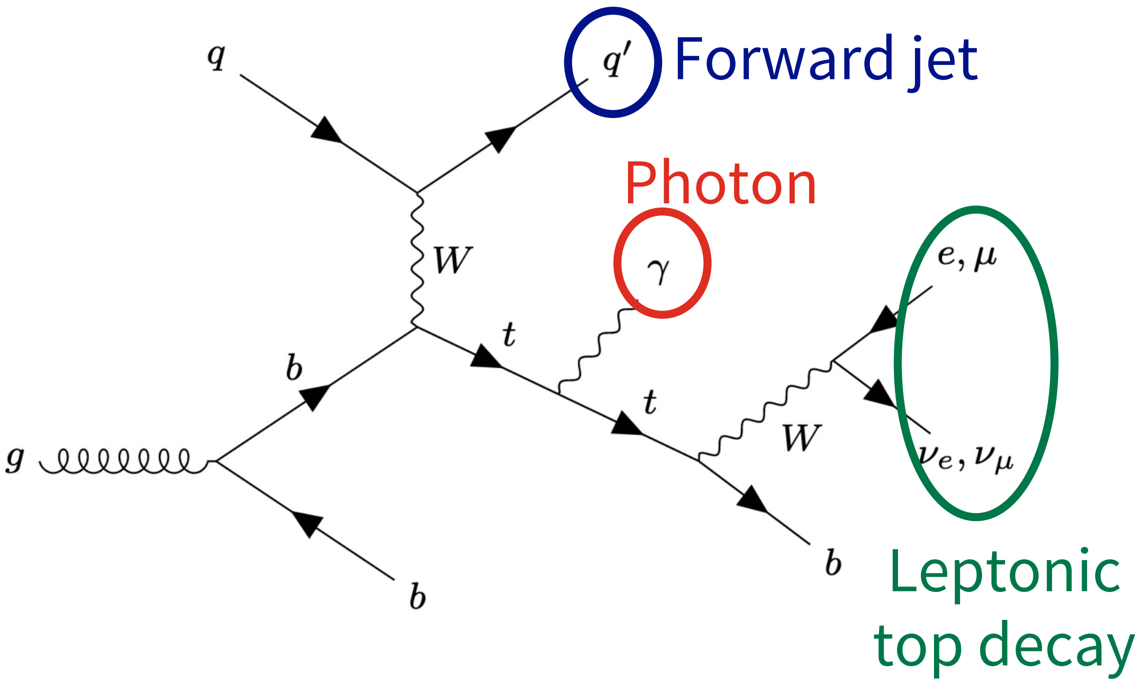
Single Top + Photon

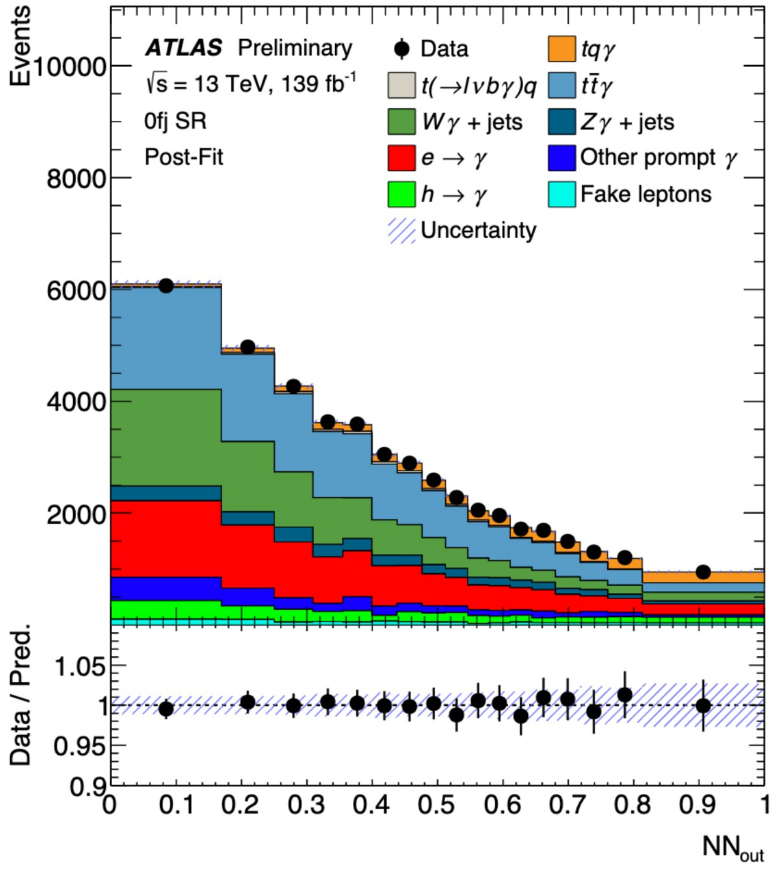
First observation of electroweak top-photon production!



Single Top + Photon

First observation of electroweak top-photon production!





Parton result:

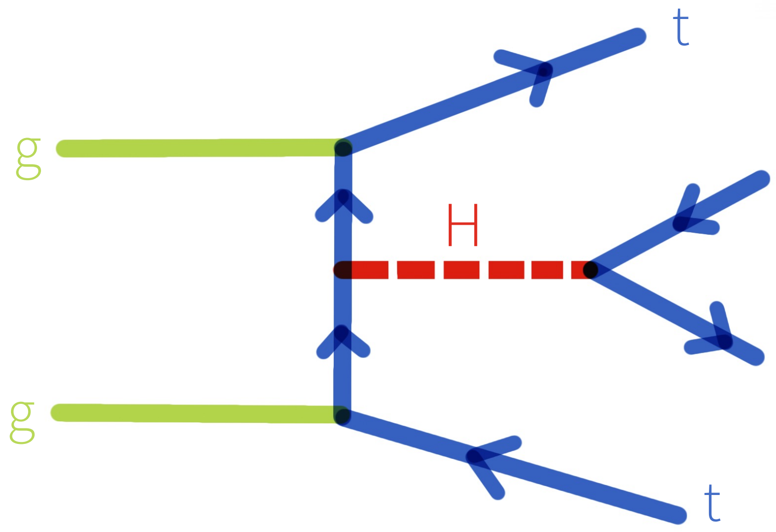
$\sigma_{tq\gamma}$ = 580 ± 19 (stat) ± 36 (syst) fb

→ 9.1 σ over SM background.

4-Tops

Aim: Measurement of 4-tops production

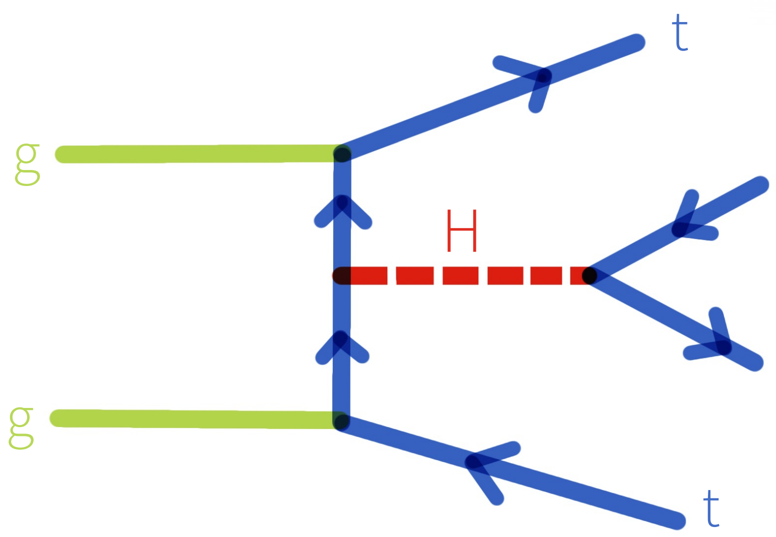
- No 5σ observation
- Sensitive to NP (high-scale)
- Sensitive to top-Higgs Yukawa

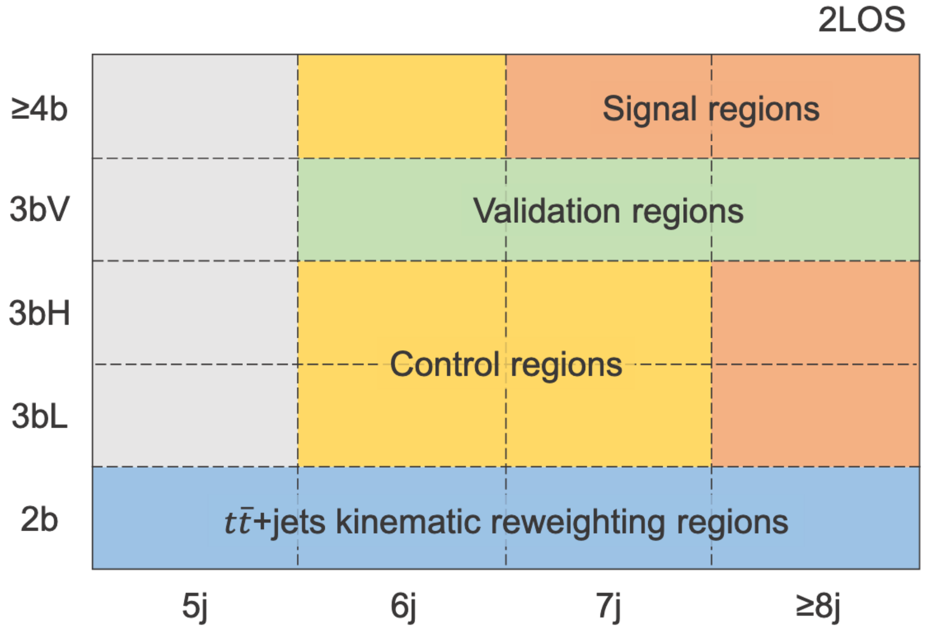


4-Tops

Aim: Measurement of 4-tops production

- No 5σ observation
- Sensitive to NP (high-scale)
- Sensitive to top-Higgs Yukawa





Final States

- High-multiplicity final states
- tt + jets major background
- <u>1 lepton</u> final state OR
  <u>2 lepton same-sign</u>

4-Tops Results

Binned profile likelihood fit using H_T^{all}

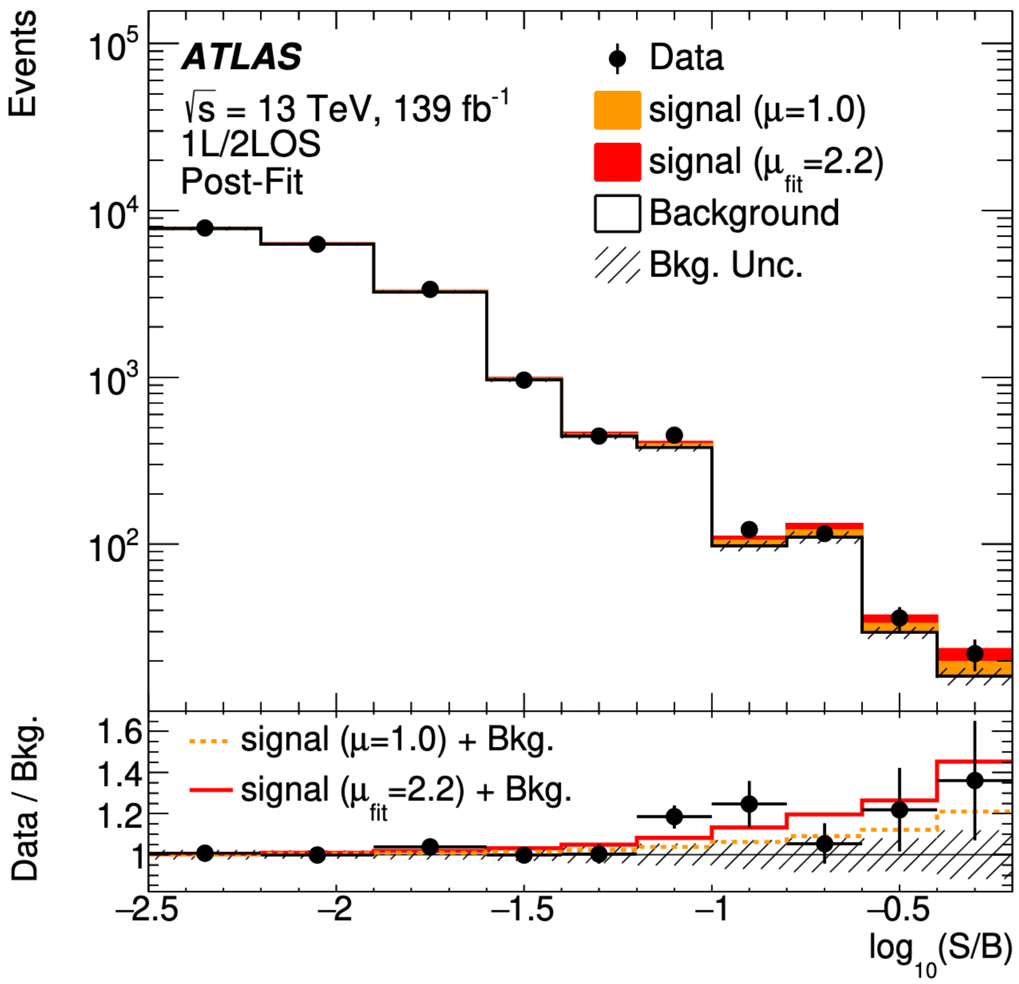
Measurement

$$\sigma_{t\bar{t}t\bar{t}} = 26 \pm 8 \ (\mathrm{stat.}) \ {}^{+15}_{-13} \ (\mathrm{syst.}) \ \ \mathrm{fb}$$

SM Prediction

$$\sigma^{\mathrm{SM}}_{t\bar{t}t\bar{t}} = 12 \pm 2.4 \ \mathrm{fb}.$$

Modelling systematics dominant.

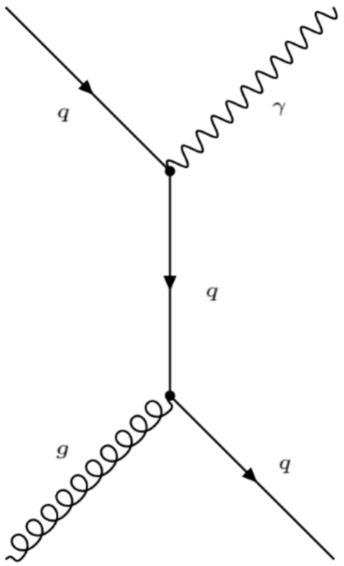


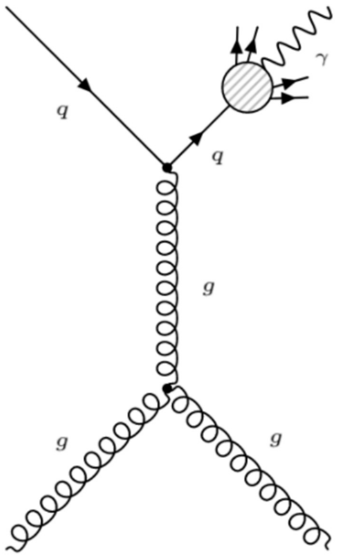
Prompt Photon Production

Prompt Photon Production

Aim: Differential measurements of inclusive prompt photon cross-section

- Colourless probes of QCD
- Test of NLO MC generators

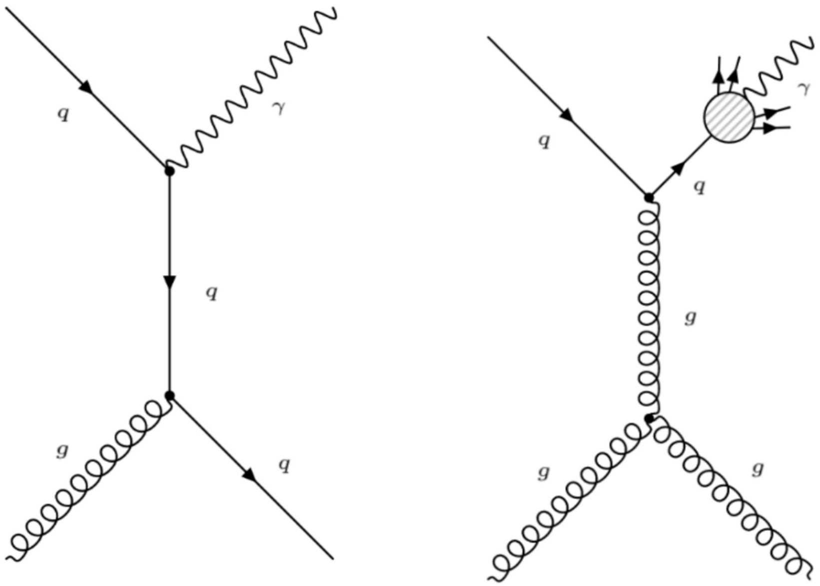




Prompt Photon Production

Aim: Differential measurements of inclusive prompt photon cross-section

- Colourless probes of QCD
- Test of NLO MC generators



Photon selection

- Apply cut on E_T^{iso}
- Photon ID requirements

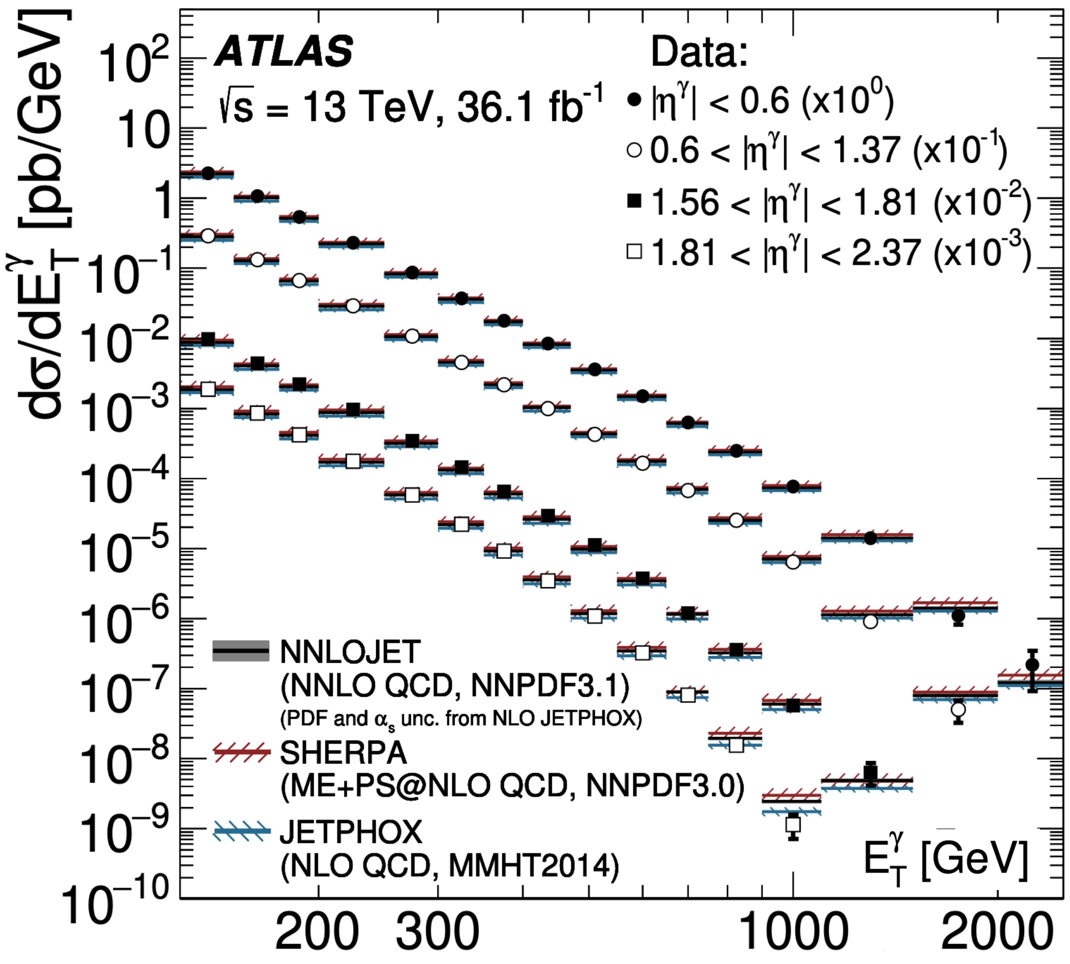
Data-driven background estimate

- Remove fakes from jets
- 2D sideband method (ABCD method)

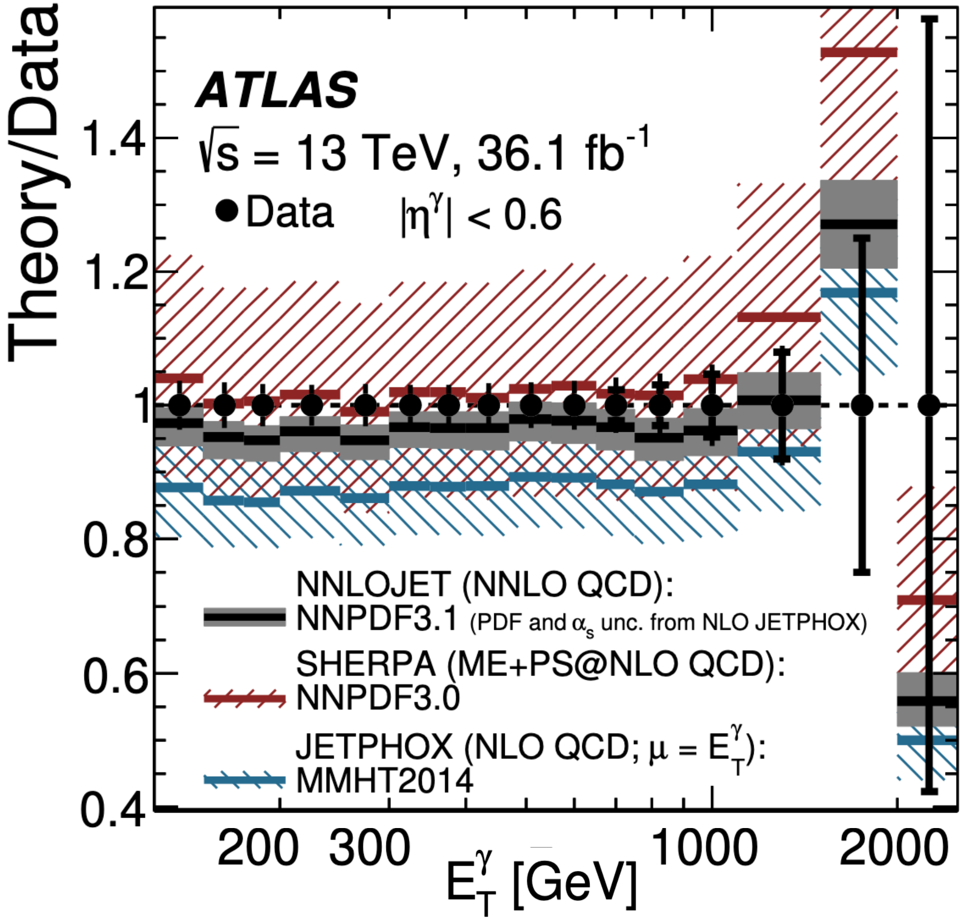
Unfolding

- To particle-level
- Bin-by-bin method
- Bayesian unfolding cross-check

Prompt Photon Production

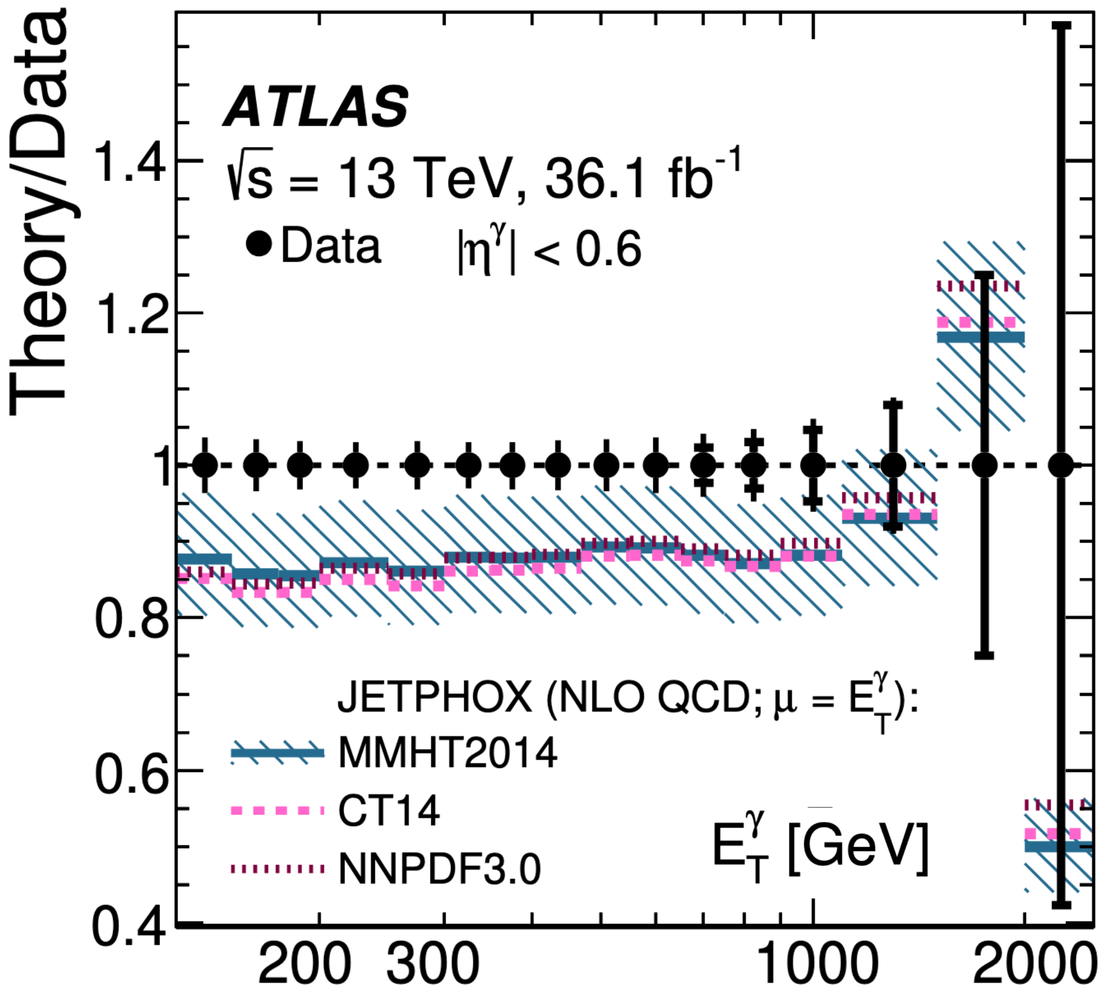


- NLO description is adequate; NNLO superior.



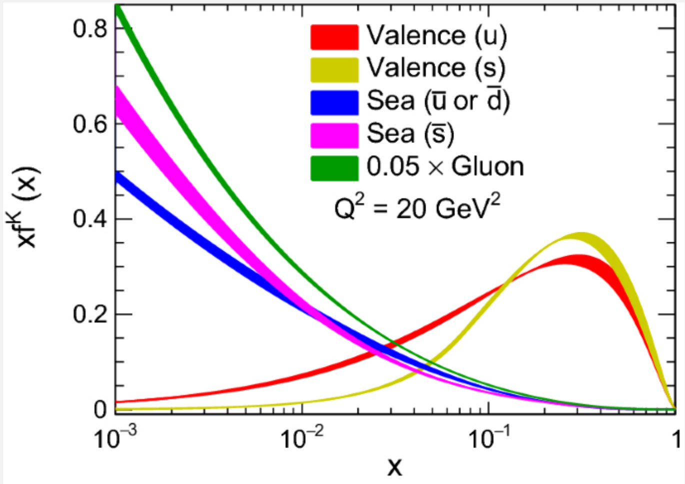
- Reach extended significantly (increased statistics).

Prompt Photon Production

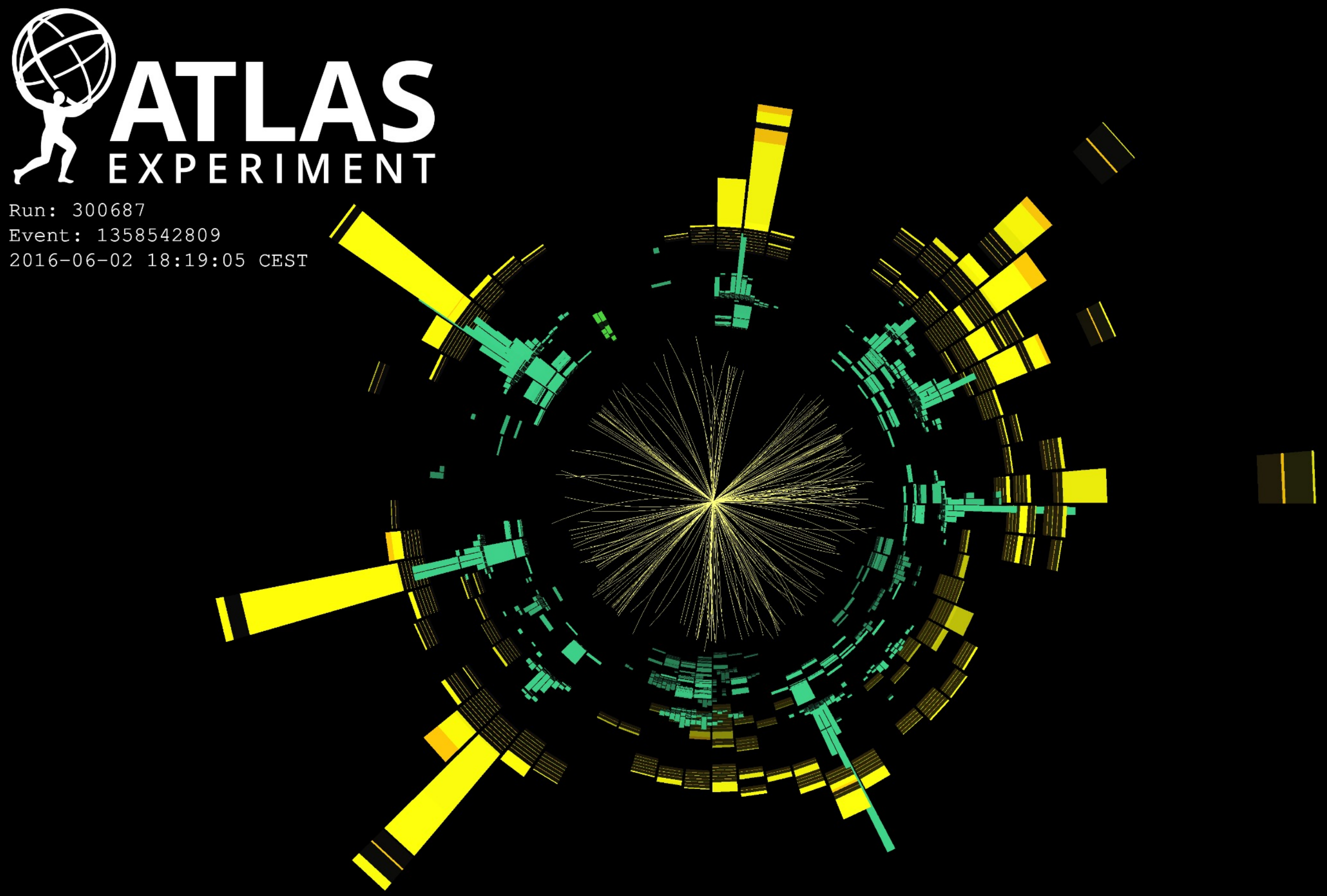


- Different parameterisation of the PDFs
- None agree spectacularly.

Constrain gluon density in PDF?

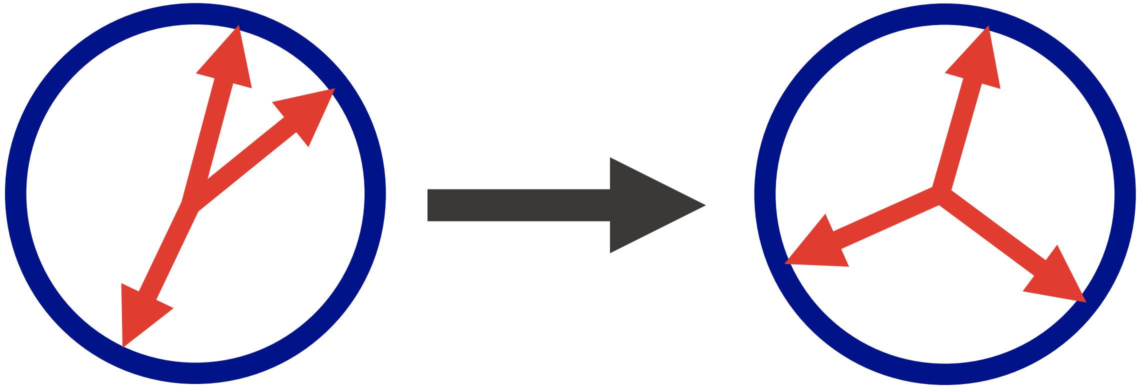


Multijet Event Isotropies



Event Isotropies

How isotropic is an event?



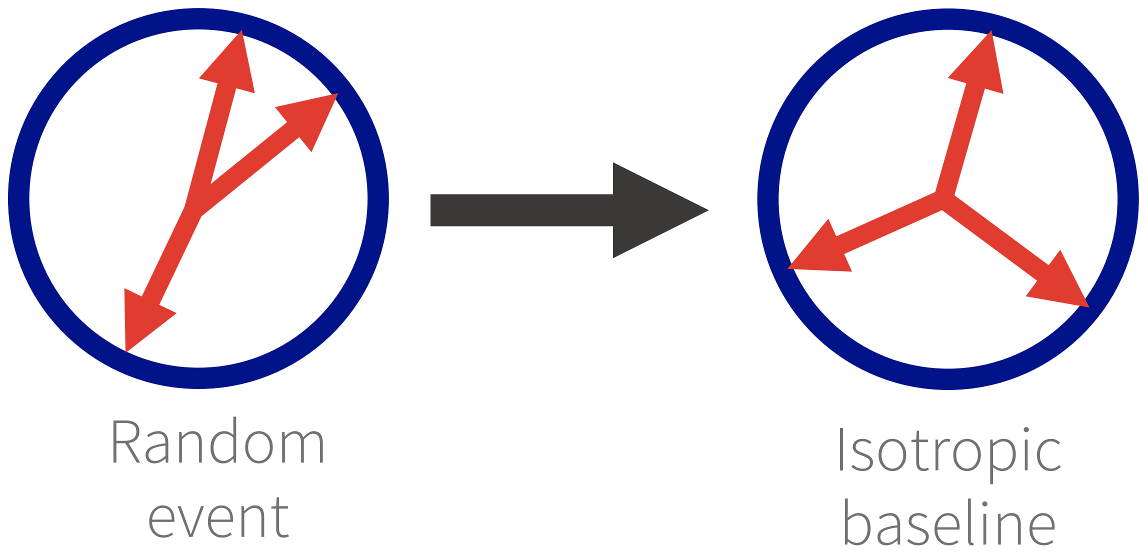
Random event

Isotropic baseline

Optimal way to redistribute energy to arrive at isotropic?

Event Isotropies

How isotropic is an event?



Optimal way to redistribute energy to arrive at isotropic?

Energy-Mover's Distance

The reconfiguration which minimises this particular function

Different isotropic baselines define different observables:

$\mathcal{I}_{\mathrm{Ring}^{128}}$

$\mathcal{I}_{\mathrm{Ring}^{2}}$ → This one means dijet-like!

$\mathcal{I}_{\mathrm{Cyl}^{16}}$

Event Isotropies

Aim: Proof-of-concept of new event-shape observables

Utility:

- Complemetary event-shape observables
- Expose new area of QCD phase-space
- Comparison between MC generators.

Event Isotropies

Aim: Proof-of-concept of new event-shape observables

Utility:

- Complemetary event-shape observables
- Expose new area of QCD phase-space
- Comparison between MC generators.

Analysis targets dijet and multijet events

1. Define

$\mathcal{I}_{\mathrm{Ring}^{128}}$

$\mathcal{I}_{\mathrm{Ring}^{2}}$

$\mathcal{I}_{\mathrm{Cyl}^{16}}$

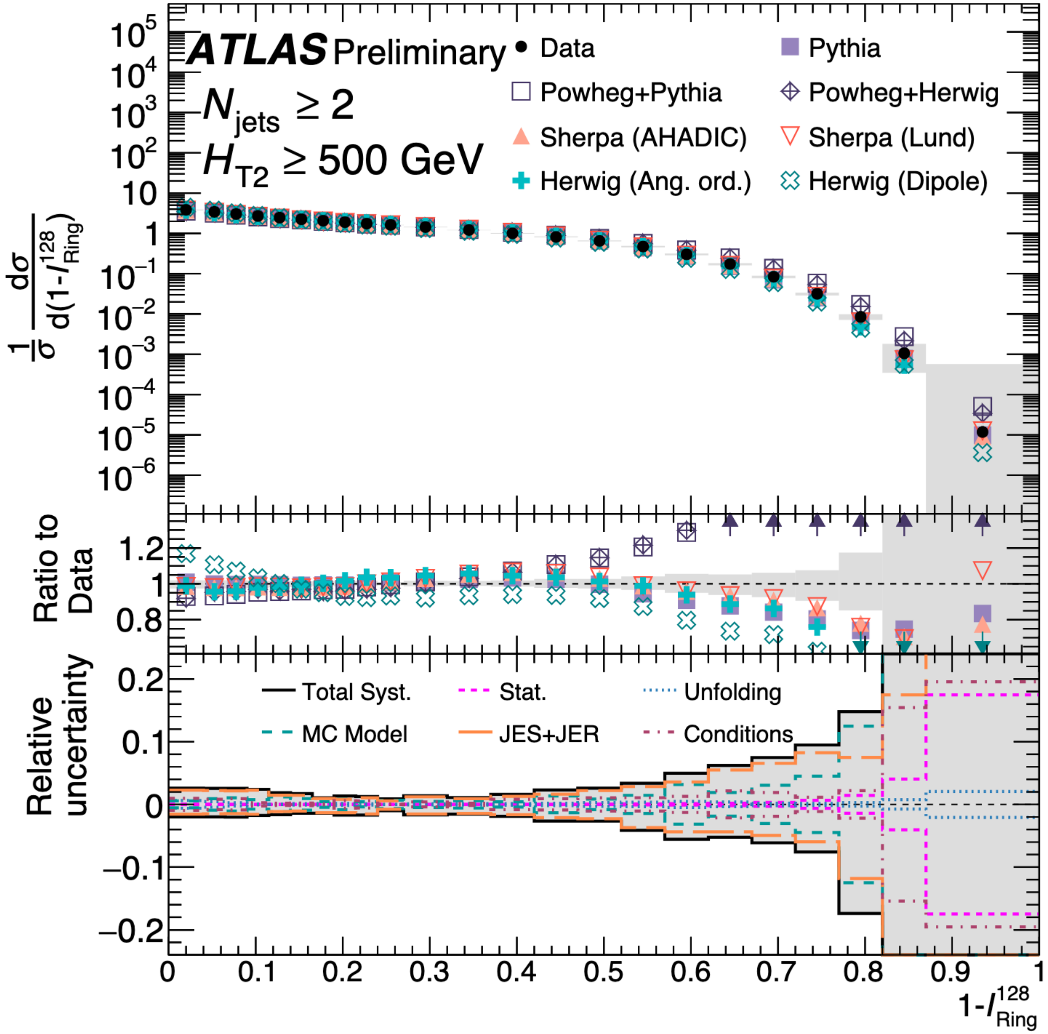
2. Measure

Isotropy observables as a function of global event kinematics H_{T2} N_{jets}

3. Unfold

to particle-level using Iterative Bayesian Unfolding

Event Isotropies



Circular isotropy

- MC agreement best for dijet-like events.
- Worse for isotropic events.
- Observables shown here are not well-described by MC

Conclusions

Conclusions

Precision Top

- Observation rare processes
- Exclusion of forbidden processes.
- Statistics-limited
- Modelling-limited

Precision Photons

- Colourless probe
- Precision differential xsecs

Jet Tools

- Ubiquitous
- New event-shape observables

Thank you for listening

Analyses

1. FCNC Top-gluon: https://link.springer.com/article/10.1140/epjc/s10052-022-10182-7
2. FCNC Top-photon: https://www.sciencedirect.com/science/article/pii/S0370269322005135?via%3Dihub
3. FCNC Top-Higgs: https://arxiv.org/abs/2208.11415
4. FCNC Top-Z:
5. ttW charge asymmetry: https://cds.cern.ch/record/2827435/files/ATLAS-CONF-2022-062.pdf?version=1
6. ttA charge asymmetry: https://cds.cern.ch/record/2816331/
7. Single-top-photon: https://cds.cern.ch/record/2805217
8. 4-tops: https://link.springer.com/article/10.1007/JHEP11(2021)118
9. Isolated photon: https://link.springer.com/article/10.1007/JHEP10(2019)203
10. Event isotropies: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-056/

Auxiliary Material

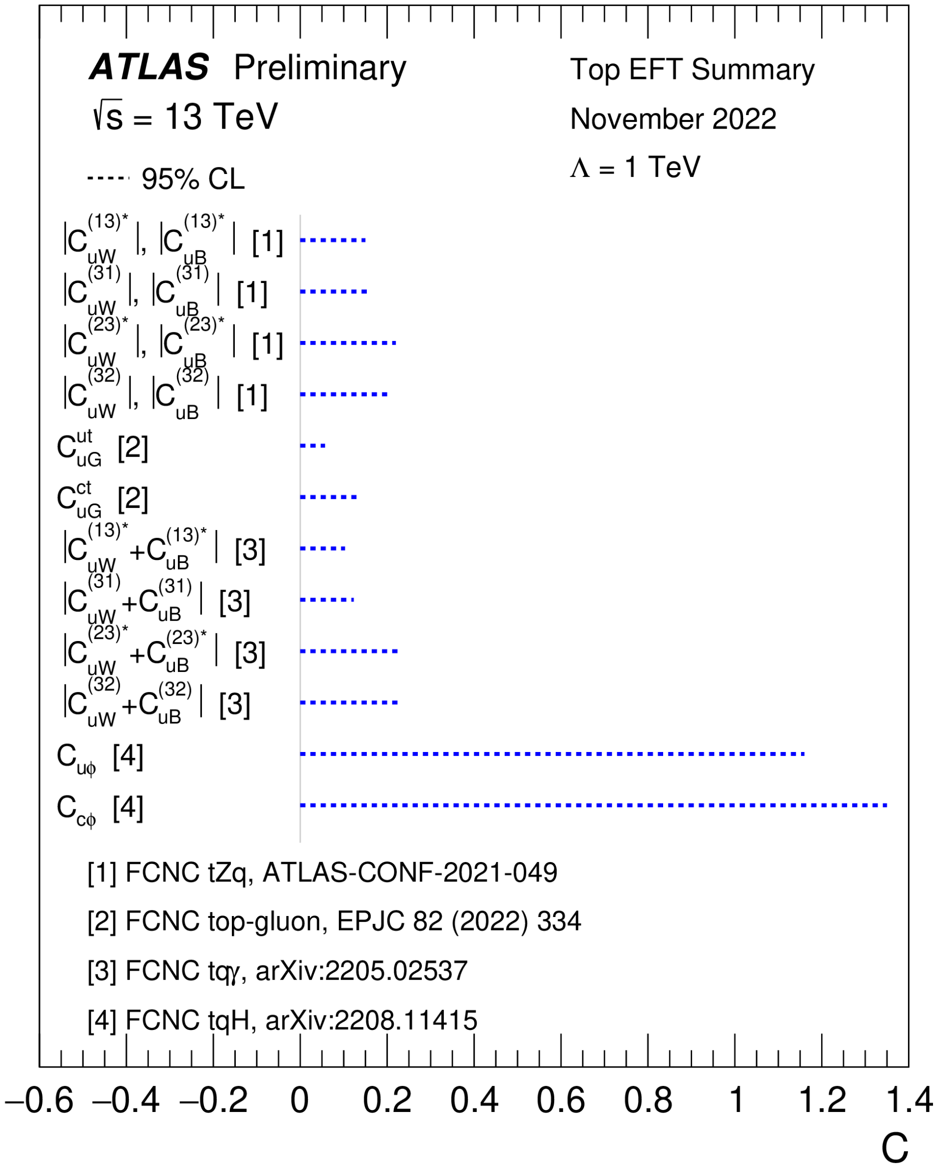
FCNC EFT

EFT operators with relaxed flavour assumptions.

Branching ratios translated into upper limits on dim-6 Wilson coefficients…

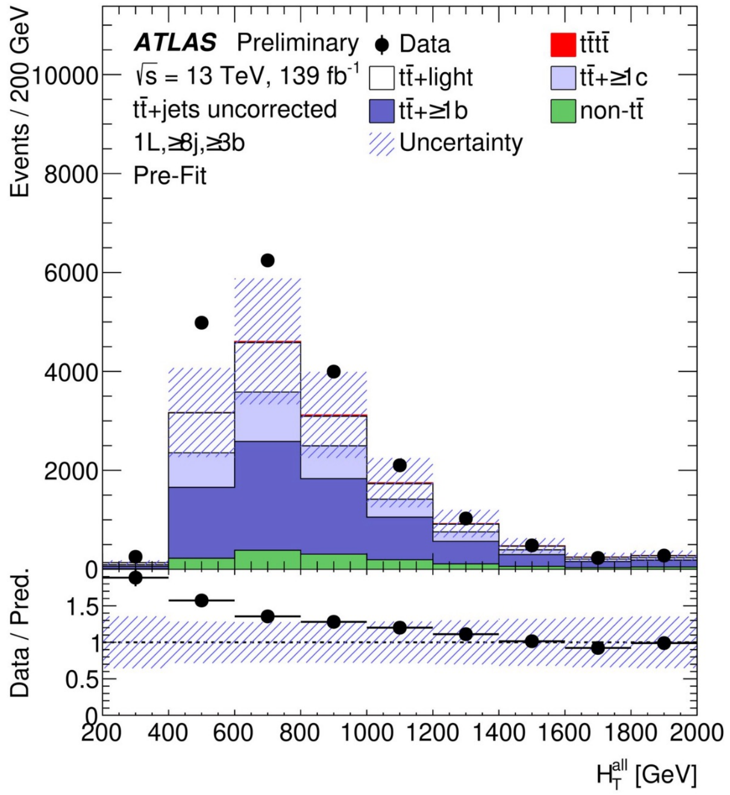
Observable	Vertex	Coupling	Observed	Expected
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$

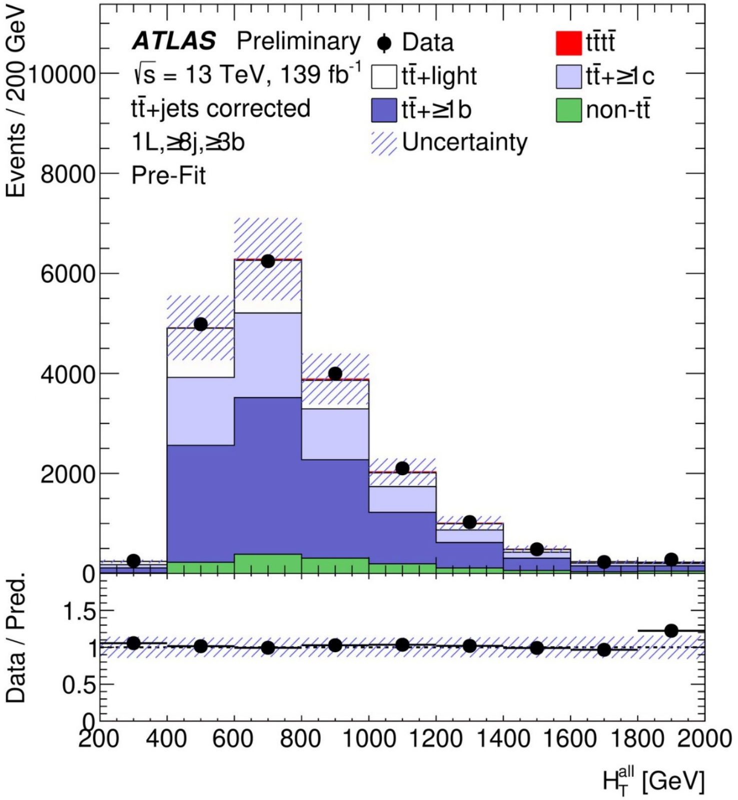
tZu analysis probes handedness of FCNC interaction.



4Tops Backgrounds

$t\bar{t}$ + jets is a substantial background.
Also challenging to model.





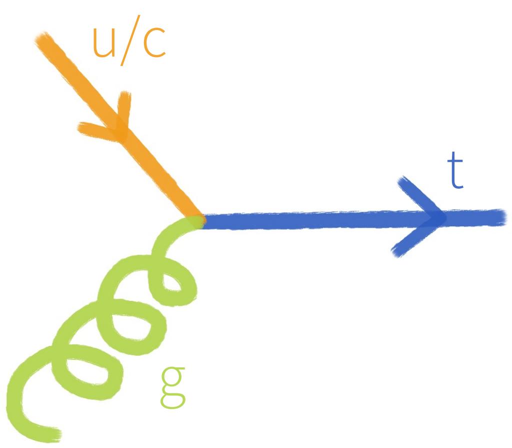
Adjust MC based on data:

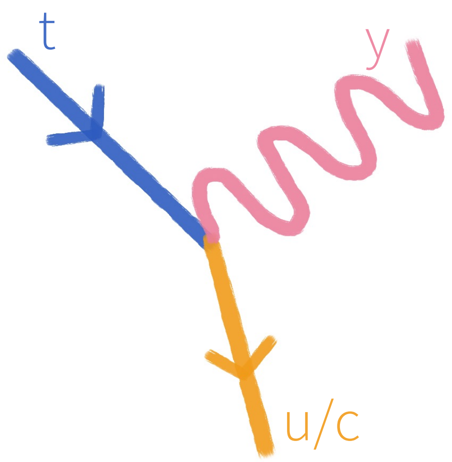
All corrections derived from data with low number of b-jets

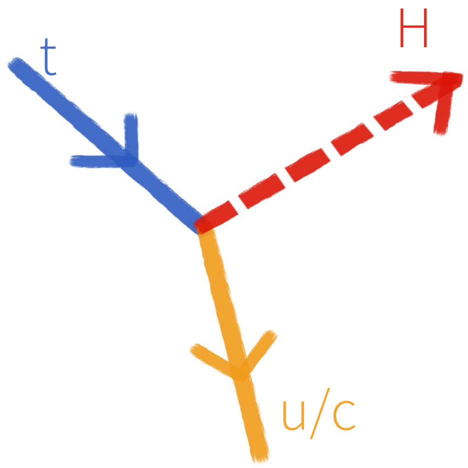
1. Flavour rescaling:
   Factors derived from PL fit
2. Kinematics reweighting:

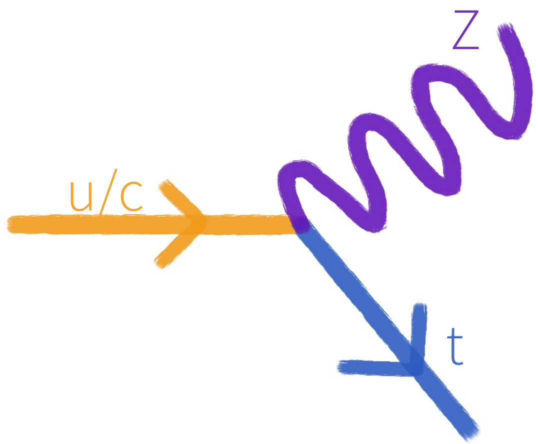
$$\begin{pmatrix} N_{\text{jets}} \\ N_{\text{LR-jets}} \\ H_T^{\text{all}} \\ \Delta R_{\text{avg}}^{jj} \end{pmatrix}$$

Considered FCNCs









Gluon

- $q\,g \longrightarrow t$
- Single-top final state
- Leptonic top decay

Photon

- $q \longrightarrow t\,\gamma$
- $t \longrightarrow q\,\gamma$
- Final-state photon

Higgs

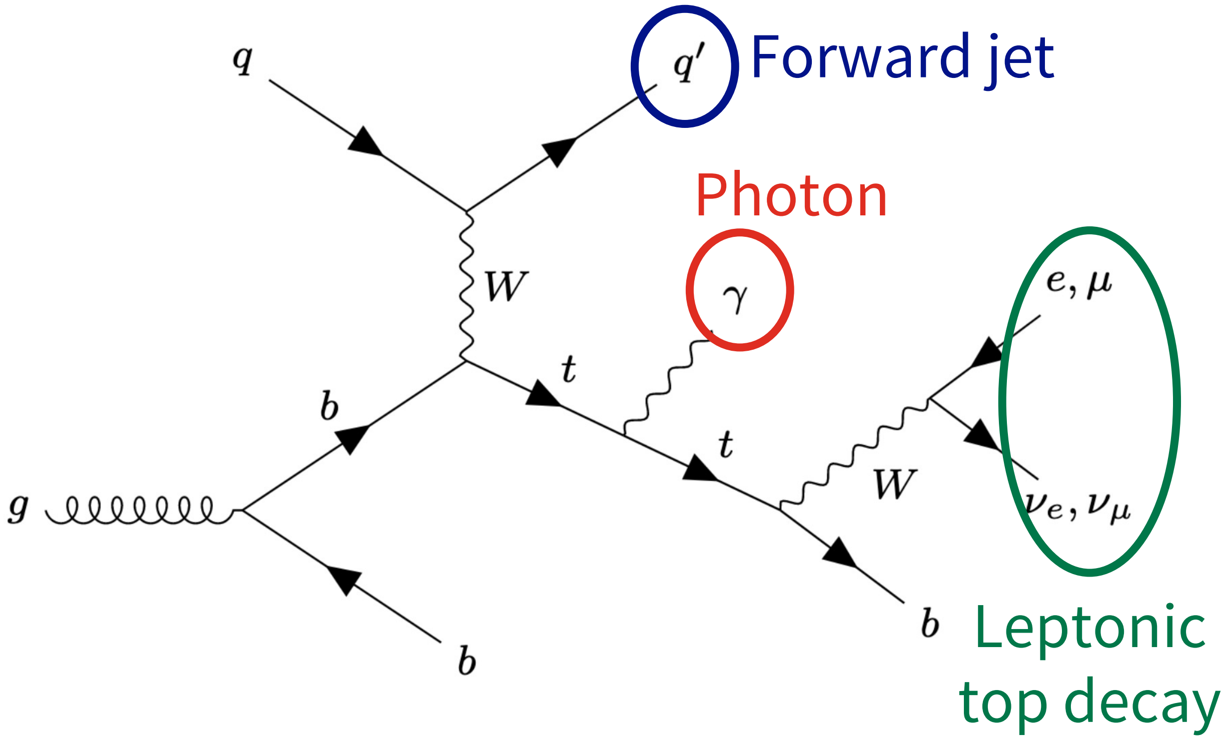
- $p\,p \longrightarrow t\,H$
- $t \longrightarrow q\,H$
- Higgs decay: $H \longrightarrow \tau^{+}\tau^{-}$

Z-boson

- $q\,g \longrightarrow t\,Z$
- $t \longrightarrow u\,Z$
- Trileptonic final state

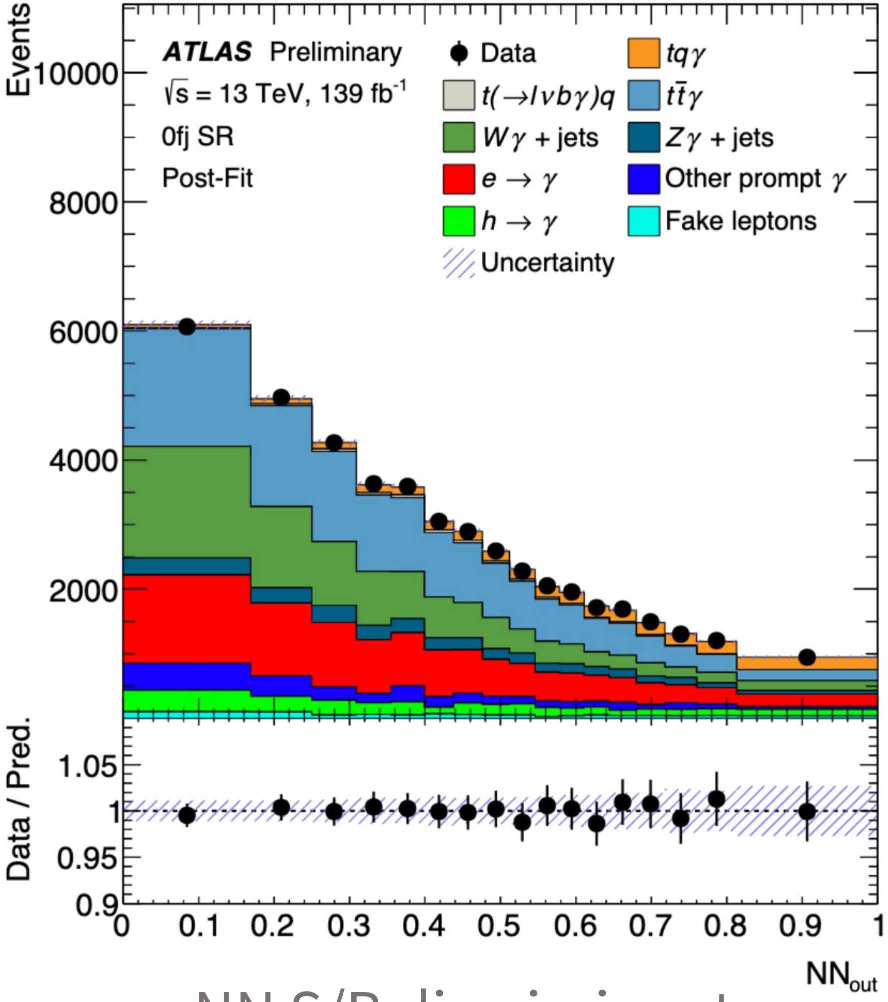
Single-Top Photon Production

First observation of electroweak top-photon production!



- Data-driven fake photon estimation (using Z DY)
- Yield of 5% in 0fj and 10% if 1fj

Single-Top Photon Production



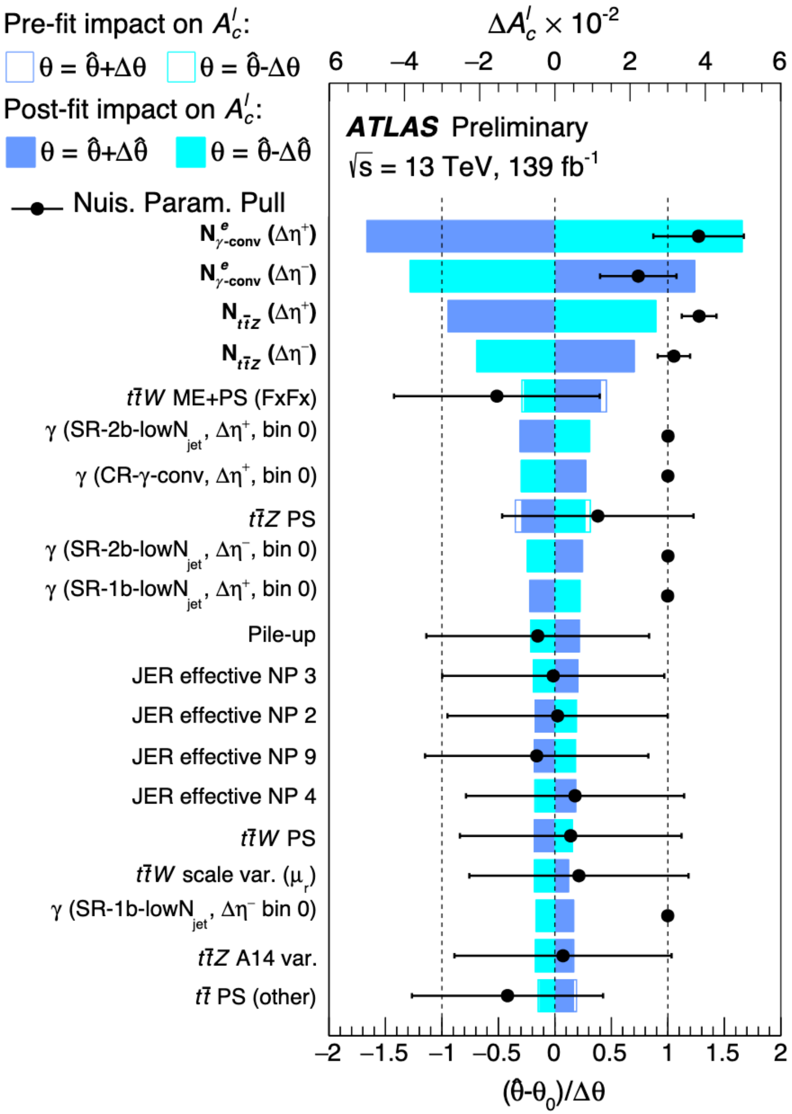
NN S/B discriminant

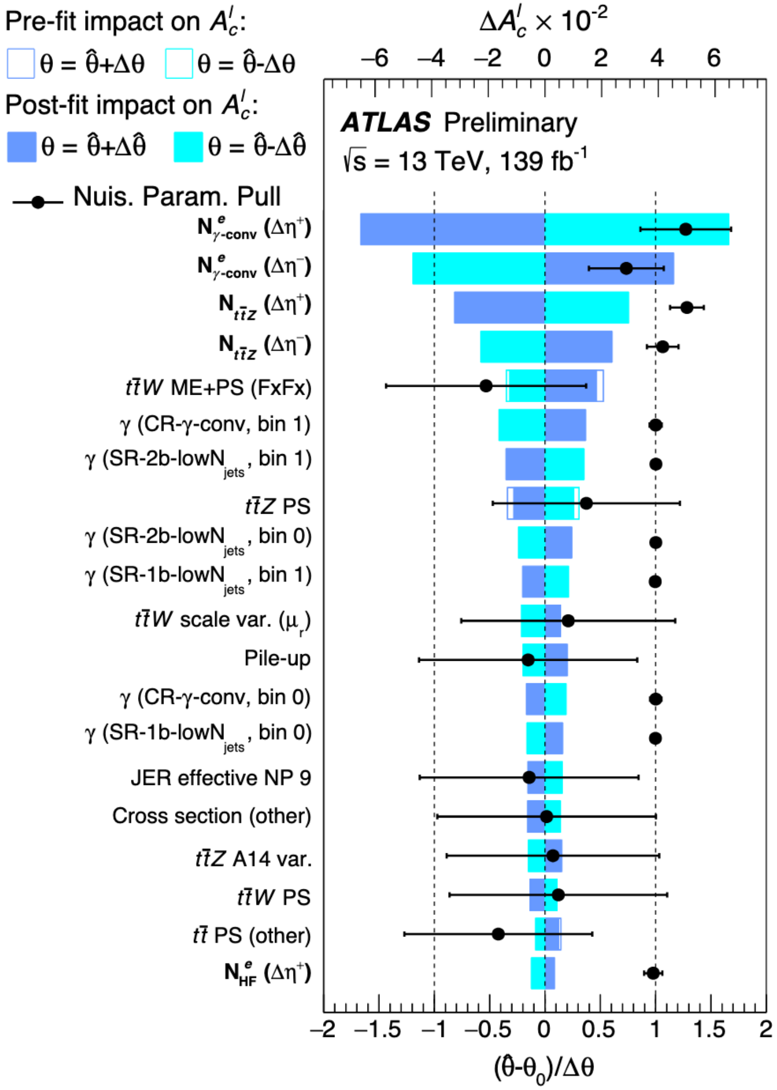
Profile likelihood fit applied to NN outputs to extract cross-section

Significance: 9.1 σ
Parton: 580 + 19 (stat) + 36 (syst) fb
Particle: 287 + 8 (stat) + 31 (syst) fb

- Dominant uncertainty is $t\bar{t}\gamma$ production.
- 40% higher excess over SM prediction is consistent with CMS.

ttW Charge Asymmetry





Bold entries indicate uncertainties on freely-floating background normalisation.

4-Tops Extras