

# Evidence for four-top production at the Large Hadron Collider

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# Outline

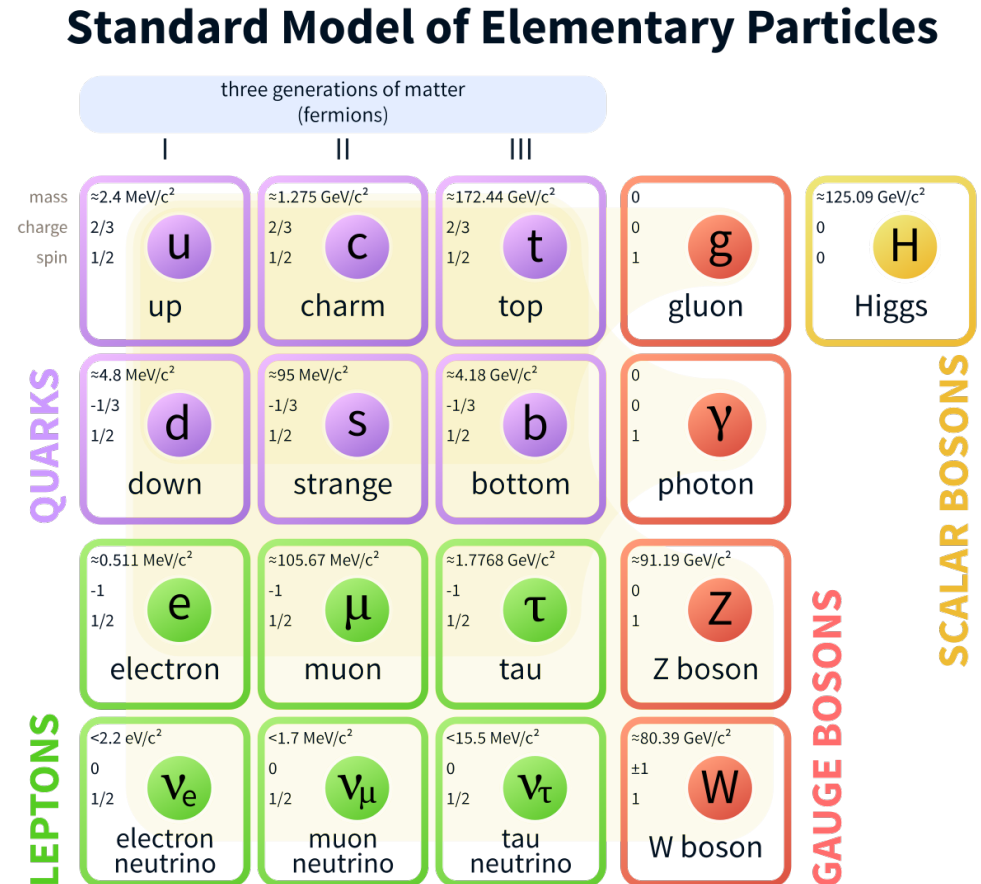
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- 1 – Physics at high energy
  - Standard model and its limitations
  - Large Hadron Collider and the ATLAS detector
- 2 – Why search for 4 top quarks?
  - Theoretical motivations
  - State of art of the previous searches
- 3 – Analysis strategy
  - Signal & background estimation and discrimination
  - Statistical interpretation model
- 4 – Results and discussions
  - Compatibility with the standard model prediction
  - Prospective on the 4 tops search
- Conclusion

# 1 – The physics at high energy

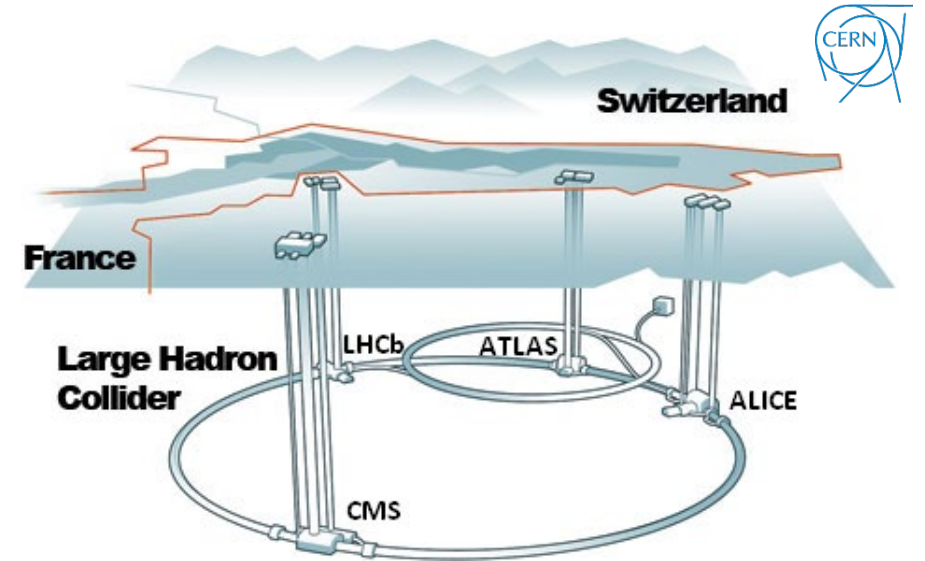
# The Standard Model and its limitations

- The Standard Model (SM) has been successful in predicting many experimental results with an extreme accuracy
- However, it contains a number of theoretical and experimental limitations
  - Gravity, hierarchy problem, dark matter, baryonic asymmetry
- The SM is an *effective theory* (i.e. only valid at low energy)
  - There is a scale  $\Lambda_{\text{New Physics}}$  where the SM will fail to predict the experimental results

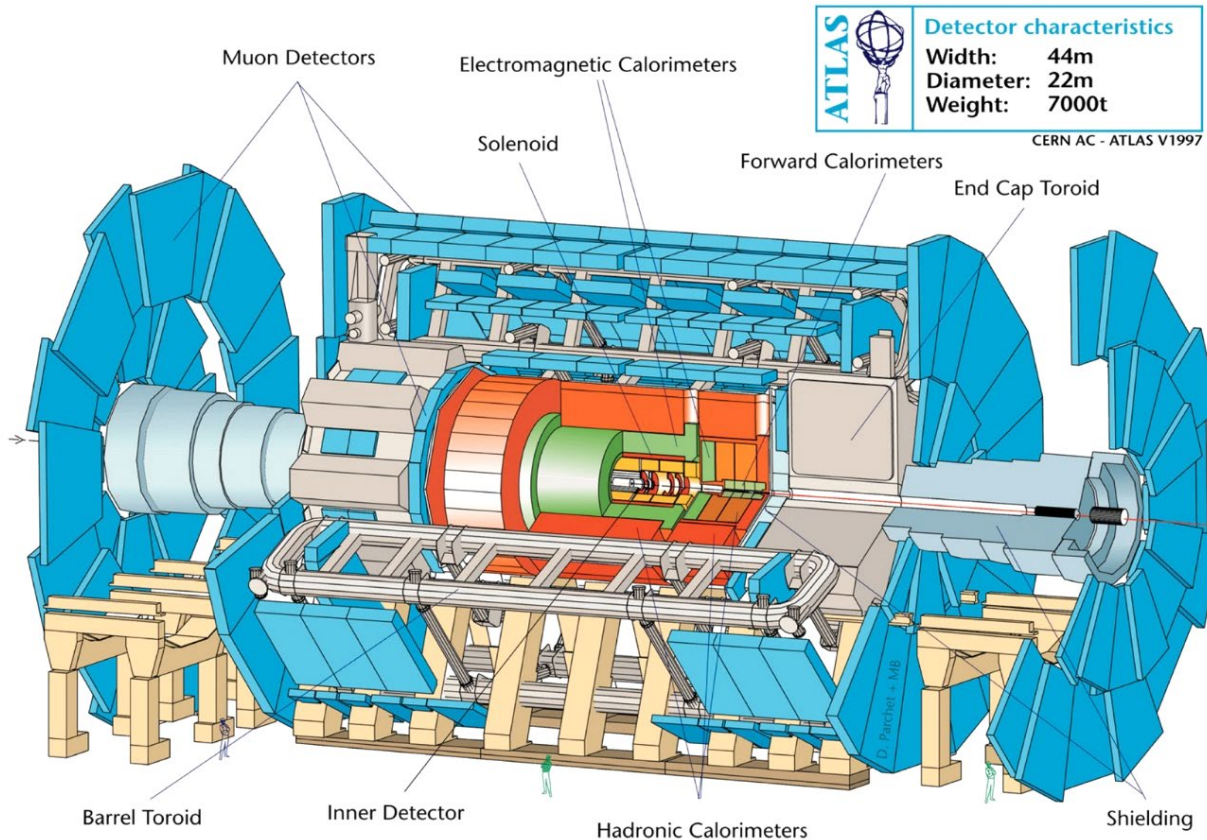


# Exploring high energy physics with the LHC

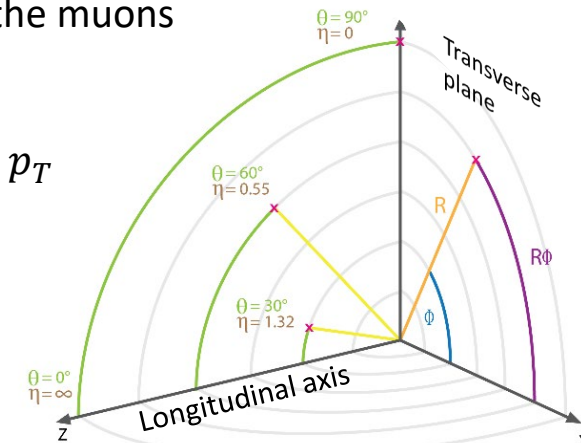
- LHC: Large Hadron Collider
  - Largest and most powerful particle accelerator
  - Proton-proton (or lead-lead) collisions at 13 TeV
  - 40M collisions per second
- Four main experiments:
  - **ATLAS** and **CMS**: multi-purpose detectors
  - **LHCb**: flavor physics, b-quark sector physics
  - **ALICE**: heavy ions physics



# The ATLAS experiment



- Inner detector + Solenoid magnet (2T)
  - Measures the track of the charged particles
  - Particle momentum and charge measurements
- Calorimeters
  - Measure energy and position of photons, electrons and hadrons
  - Allow to reconstruct **jets** of hadrons
- Muon spectrometer + toroidal magnets
  - Measures the track of the muons
- Cylindric coordinates:
  - Transverse momentum  $p_T$
  - Rapidity  $\eta$



# Detecting the particles

## Electron $e$

- Track in the inner detector + Energy deposit in the calorimeter

## Muons $\mu$

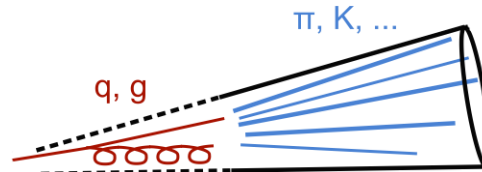
- Tracks both in the inner detector and in the muon spectrometer

## $b$ -jets

- Classify jets coming from  $b$ -quark
- Tagging algorithm based on multivariate algorithm
- Efficiency of 70-77% for true  $b$

## Jets

- Quark or gluon signature as a shower of hadronized particles



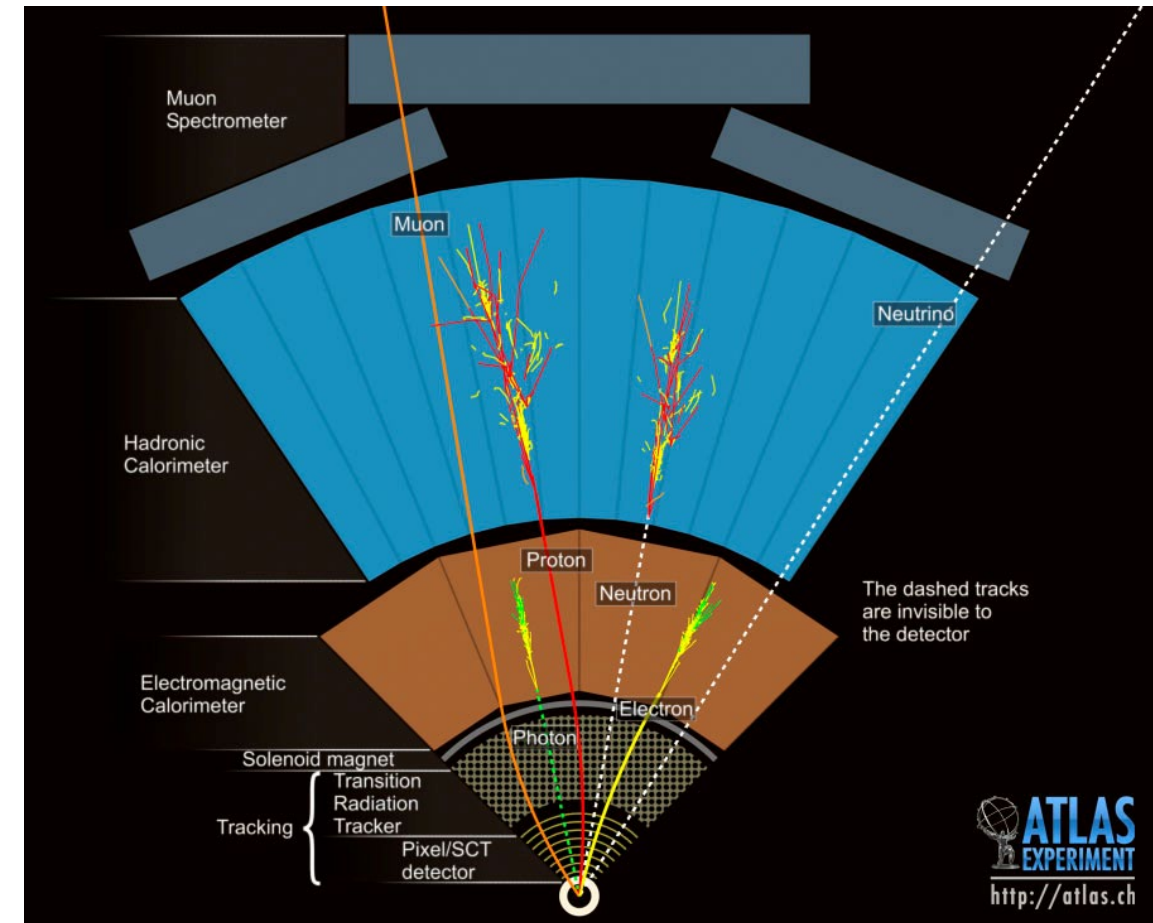
- Anti-kt algorithm using energy deposits in the calorimeters

## Transverse missing momentum

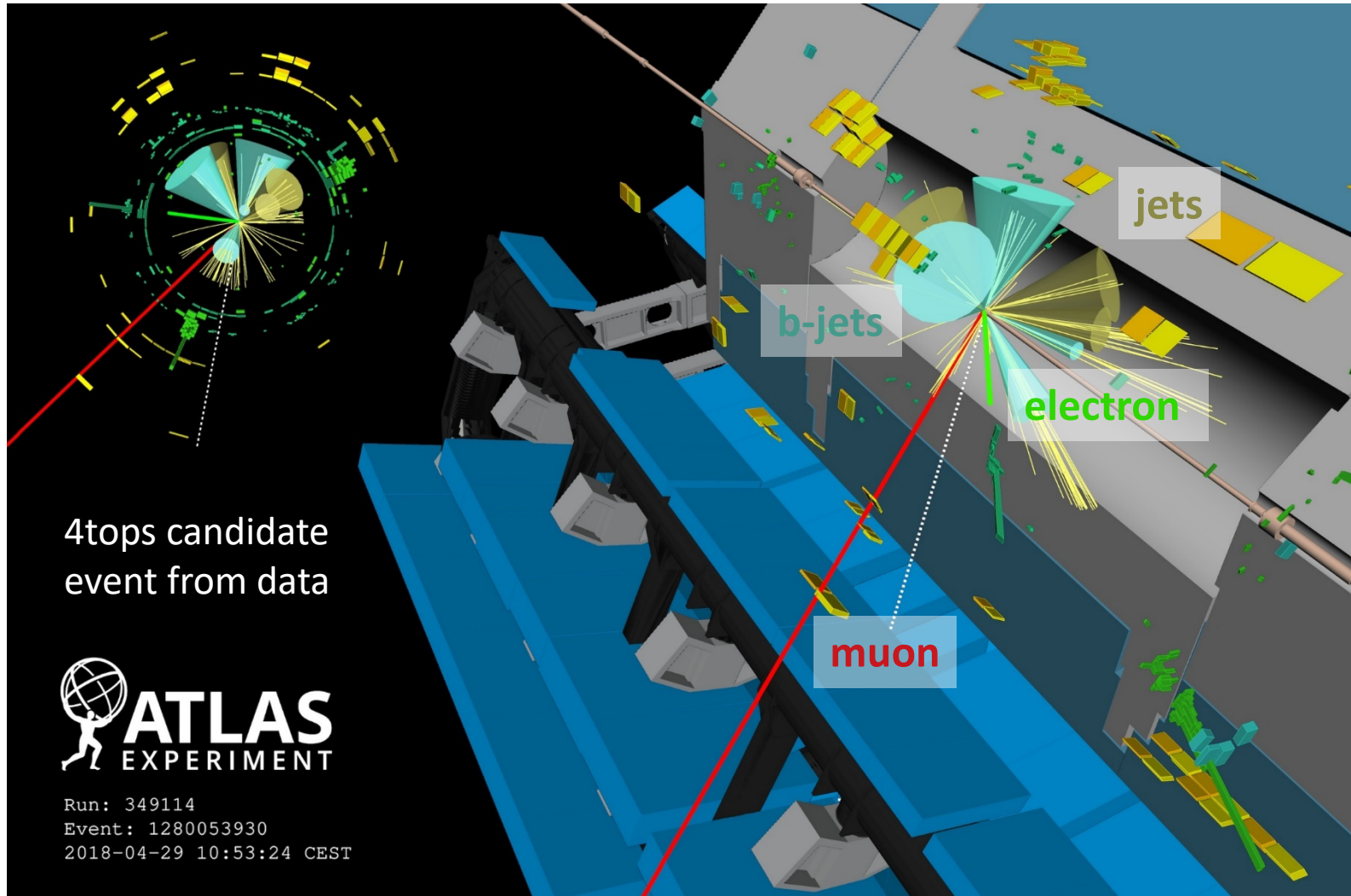
- Total transverse momentum of invisible particles (neutrinos)
- Reconstructed as:

$$\vec{E}_T^{\text{miss}} = - \sum_{\text{all objects}} \vec{p}_T$$

## Particle detection in ATLAS:



# Example of event display



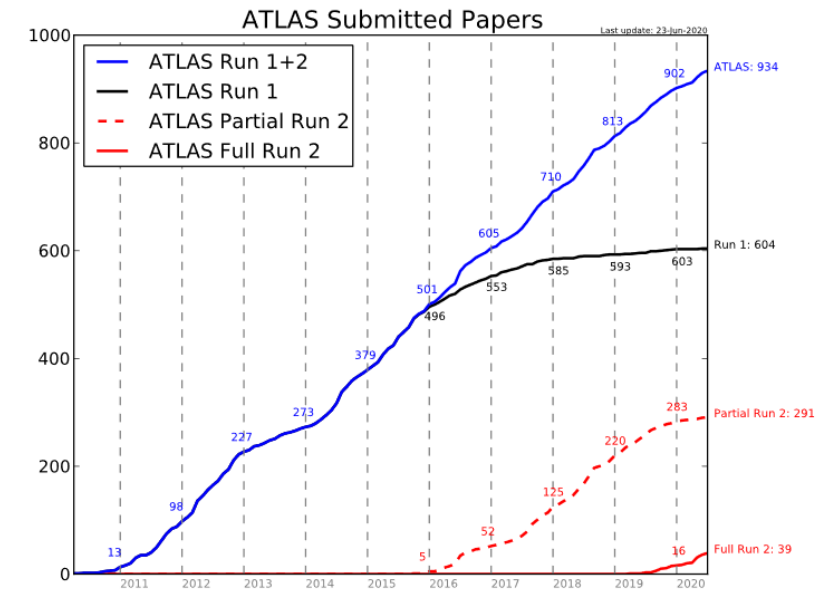
# LHC operations and achievements

## LHC Timeline:

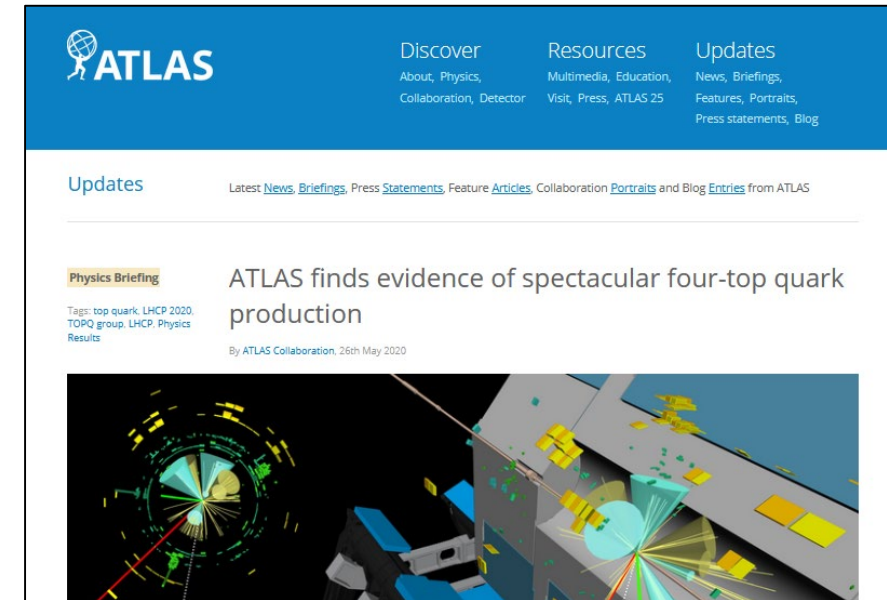
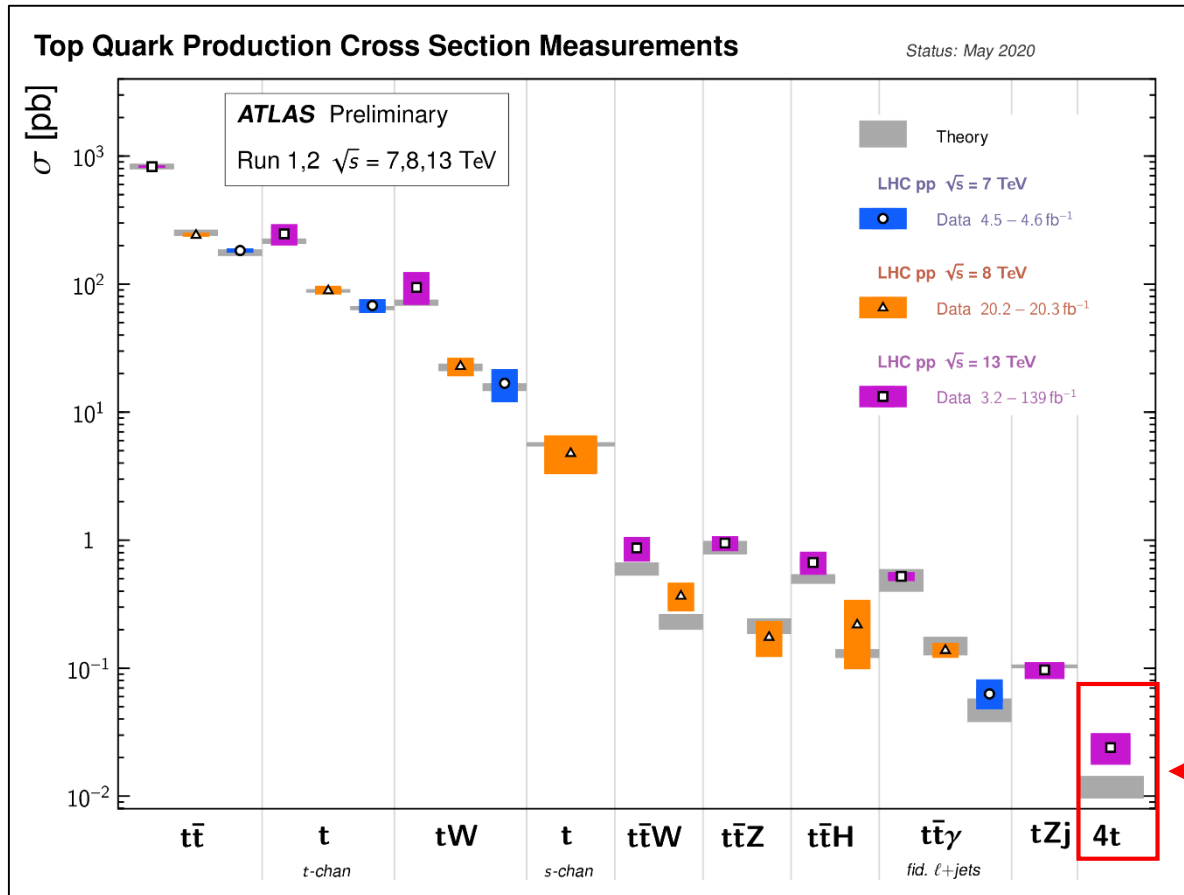


HL-LHC: High Luminosity LHC  
LS: Long Shutdown  
TeV: Tera electron Volt

- Run 1 :
  - Higgs discovery (2012)
  - Standard model measurements
  - Search for new physics
- Run 2 :
  - Higgs precision measurements
  - New physics scenario exclusion
  - Rare standard model process
    - E.g. evidence of 4tops



# Example of results

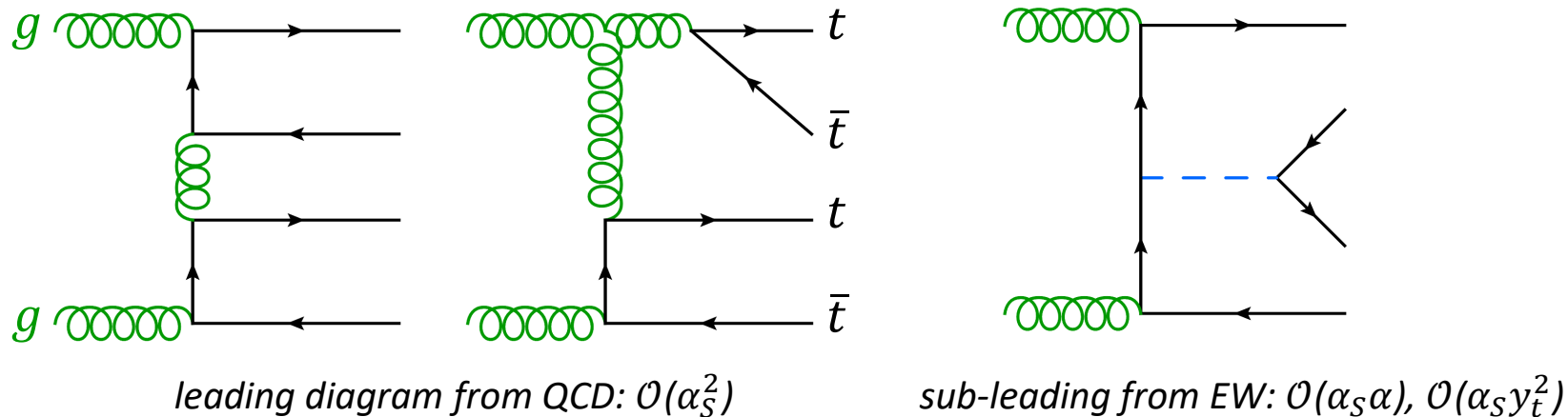


- New results: Evidence of 4tops !
  - Published in [pre-print](#) in July 29<sup>th</sup> 2020
  - Accepted for publication by EPJC
  - One of the [highlighted](#) recent results from ATLAS

## 2 – Why search for 4tops ?

# The 4tops production in the SM

- According to the SM,  $\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 12.0 \pm 2.4$  fb at NLO in QCD+EW at 13TeV [1]
  - Very low cross-section: 5 order of magnitude below  $\sigma(pp \rightarrow t\bar{t})$  - Never observed at the LHC



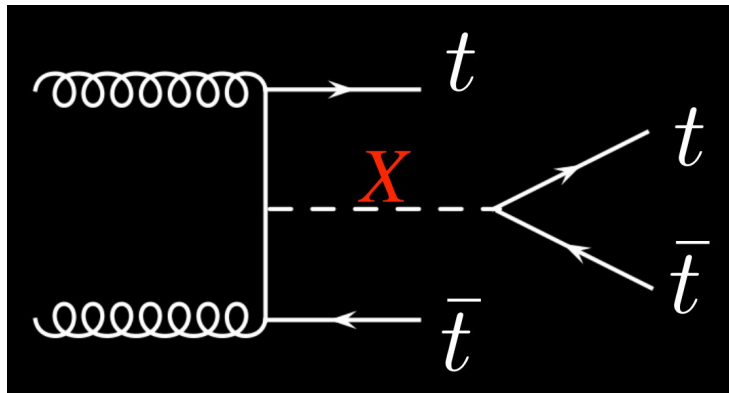
- Interference term between QCD and EW amplitudes largely suppress the overall EW contribution
- Though, measuring the 4tops cross section allows to put limits on the value of the top yukawa coupling

[1] arXiv:[1711.02116](https://arxiv.org/abs/1711.02116)

# Sentive to many new physics scenarios

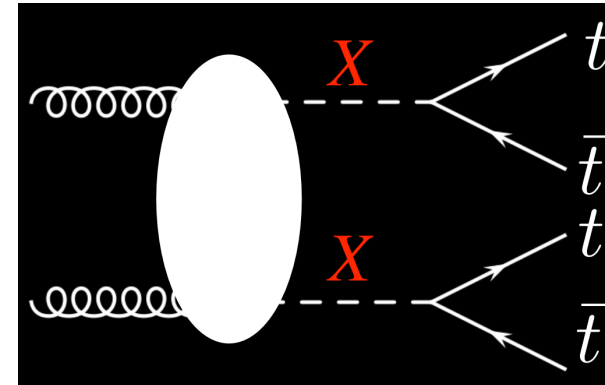
- Many Beyond-the-Standard-Model theories predict an 4tops cross-section enhancement
- Two possible BSM scenarios:

*ttH-like diagram:*



E.g. Two Higgs Double Models  
Top-philic resonances

*Pair production of new particles:*



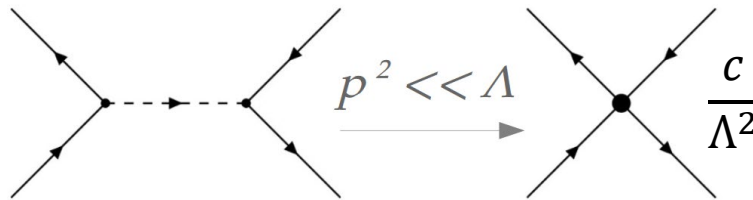
E.g. sgluons, KK gluons

# Effective Field Theory

- New physics at higher energy scale ( $\Lambda > E_{\text{LHC}}$ ) can be modeled with higher-order operators :

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

- E.g. four-fermion operators:

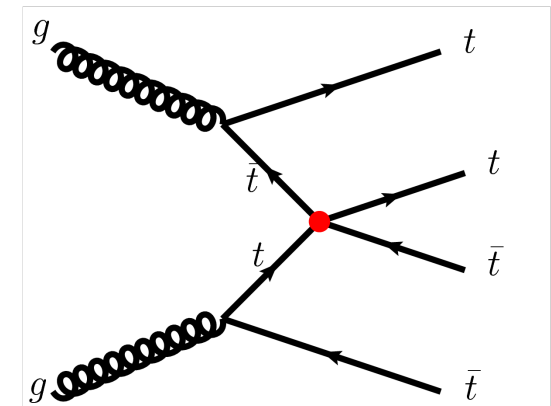
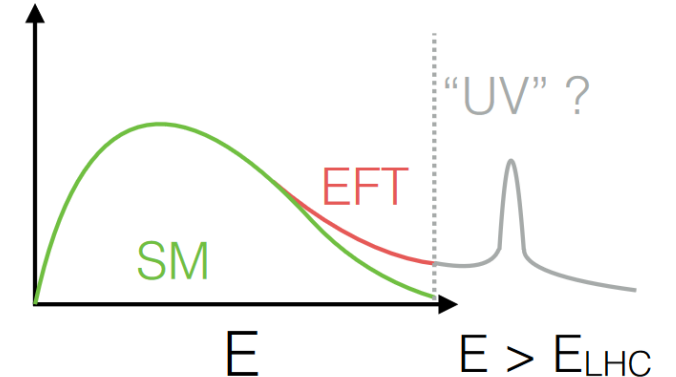


- Model-independent method to search or put limits of any UV-complete model at high scale

- The 4tops cross-section measurement allows to put strong limits on four-top-quarks operators

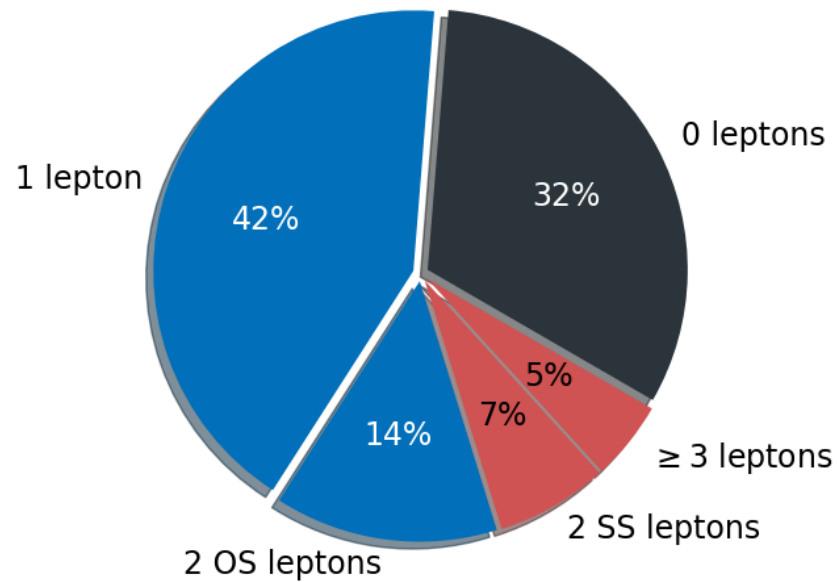
- E.g.

$$\mathcal{L}_{4t} = \frac{|C_{4t}|}{\Lambda^2} (\bar{t}_R \gamma^\mu t_R) (\bar{t}_R \gamma_\mu t_R)$$

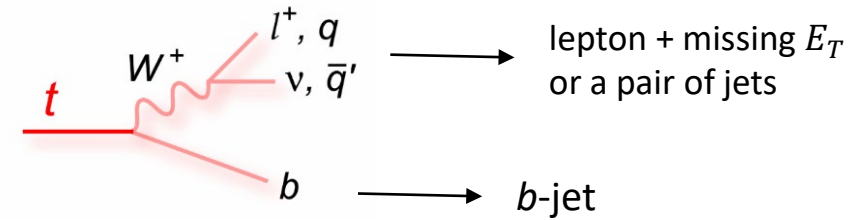


# A very complex process

- Lead to large multiplicity and complex final state
  - $pp \rightarrow t\bar{t}t\bar{t}, t \rightarrow b\ell\nu$  or  $bqq'$



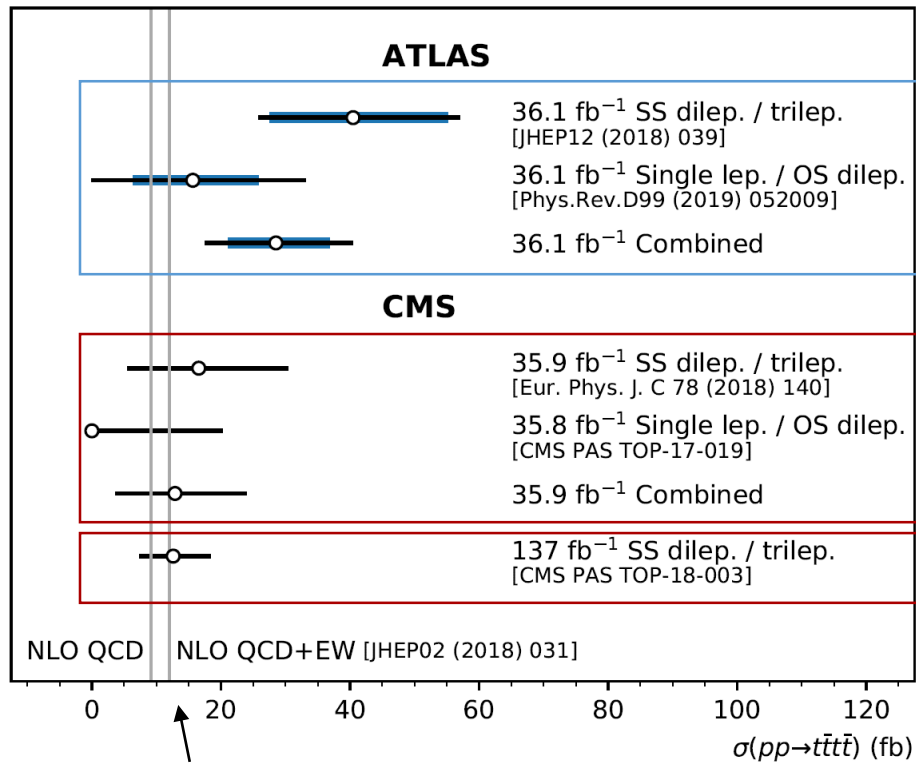
SS: same-sign  
OS: opposite-sign



- Produce from 0 to 4 leptons, 4 to 10 jets from which 4 are from  $b$ -quarks
- Final state with large activities, not thoroughly explored by previous analyses
- Contaminated by background sources that are at the edge of our prediction reach

# Previous measurements

from SM@2019



Observed (Expected) significance:

Last ATLAS result: **2.8 (1.0)  $\sigma$**   
with an excess observed in the same-sign/three lepton final states

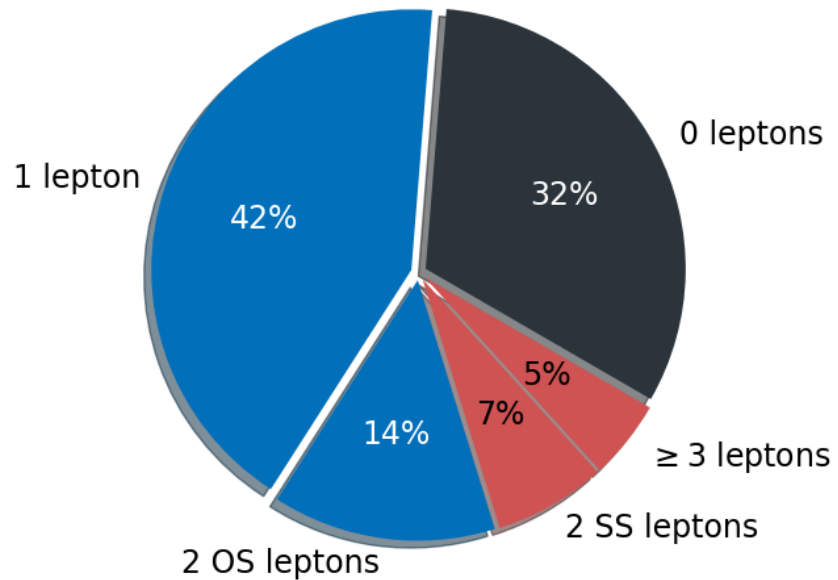
Old CMS combined result: **1.4 (1.1)  $\sigma$**

New CMS result: **2.6 (2.7)  $\sigma$**

➤ *Goal:* Achieve  $3\sigma$  combined significance with the full run-2 data

# 3 – Analysis strategy

# How to search for 4 tops ?



Select proton-proton collision events with:

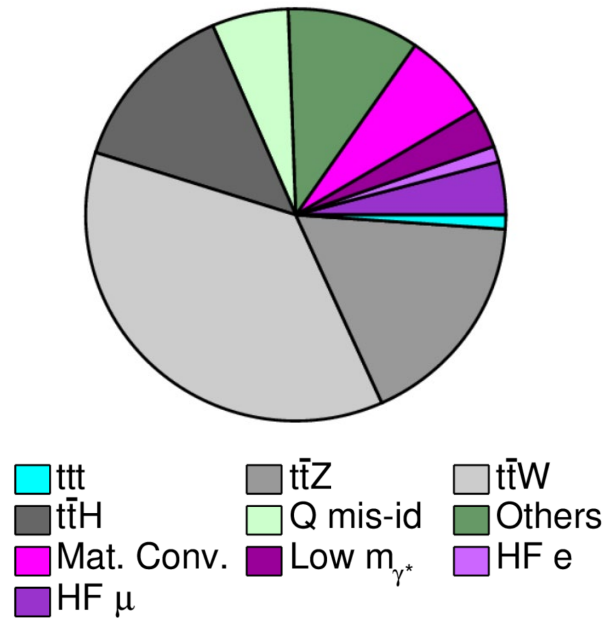
- Two same-sign leptons or at least three leptons
    - Easier to identify, contaminated by less background
  - At least 6 jets, which at least two are b-tagged
  - With large activities:  $H_T = \sum_{jets, \ell} p_T > 500 \text{ GeV}$
- 330 total number of events (4 tops + background)

= Signal region

# The background composition

*Background composition*

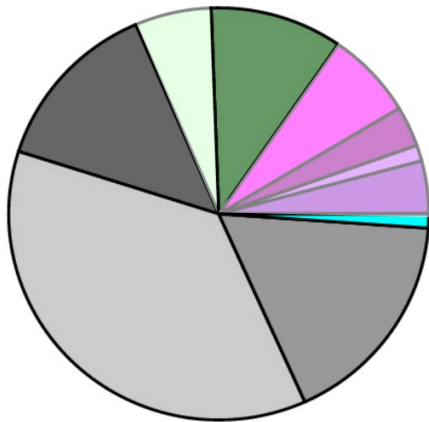
$\geq 6$  jets,  $\geq 2$   $b$ -jets,  $H_T \geq 500$  GeV



# The background composition

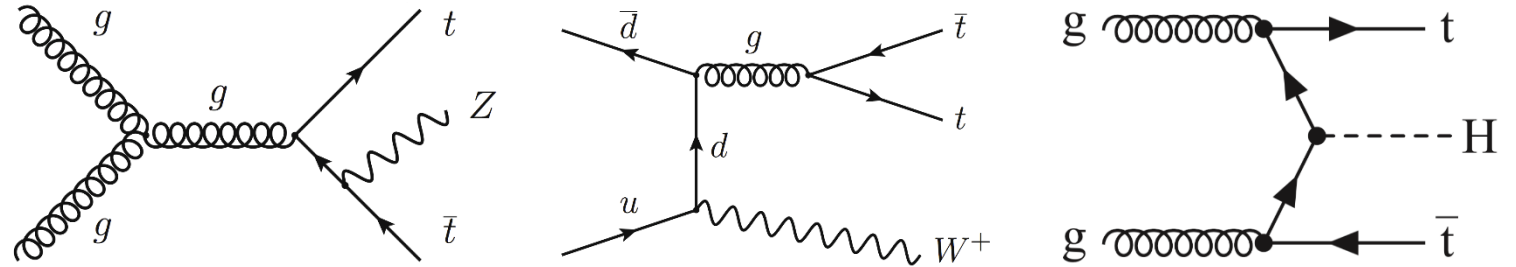
## Background composition

$\geq 6$  jets,  $\geq 2$   $b$ -jets,  $H_T \geq 500$  GeV



## Physics background, e.g. $t\bar{t}+X$ ( $\sim 80\%$ ):

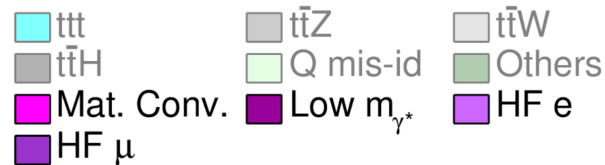
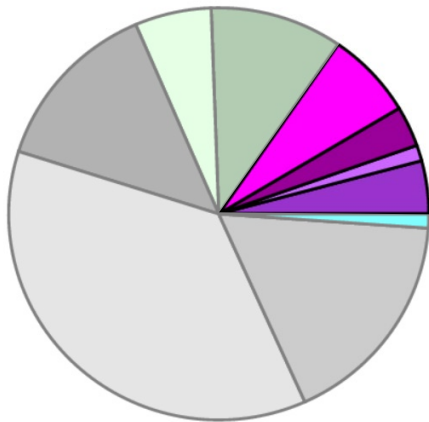
- Irreducible background – process leading to the same final states
- Estimated using Monte Carlo simulations



# The background composition

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$\geq 6$  jets,  $\geq 2$   $b$ -jets,  $H_T \geq 500$  GeV



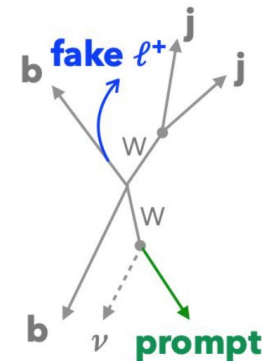
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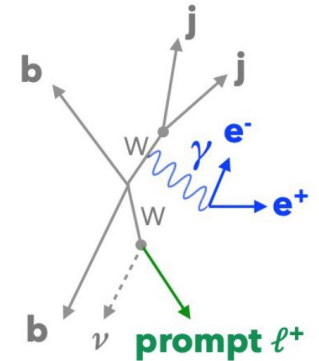
Fake/non-prompt lepton background ( $\sim 15\%$ ):

- Events from  $pp \rightarrow t\bar{t}$  with a lepton coming from a secondary physics source (*e.g.* heavy-flavor hadrons decay, photon conversion)
- Estimated using  $t\bar{t}$  MC simulation split in different source of fake lepton

**Semileptonic  
b-decay**  
(HFe, HF $\mu$ )



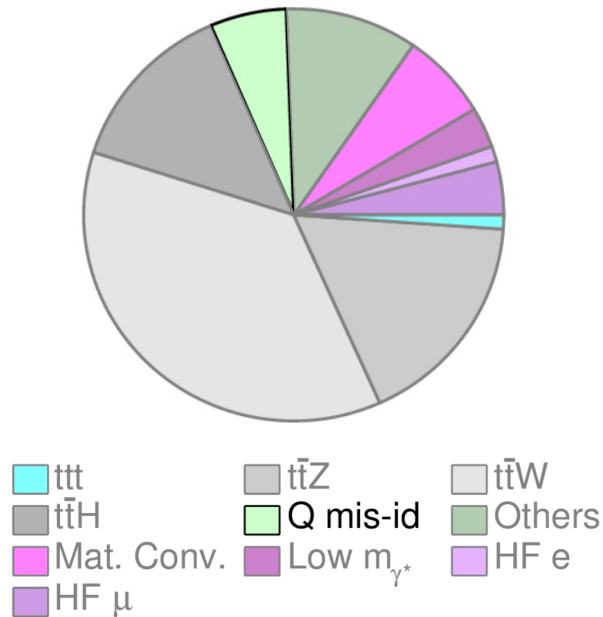
**Photon  
conversions**  
(Low  $m_{\gamma^*}$ ,  
Mat. Conv.)



# The background composition

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$\geq 6$  jets,  $\geq 2$   $b$ -jets,  $H_T \geq 500$  GeV



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## Electron charge mis-identification ( $\sim 5\%$ ):

- Opposite-sign lepton events reconstructed as same-sign due to wrong charge assignment (photon conversion, low-curvature track)
- Estimated using a data-driven method using data enriched in  $pp \rightarrow Z \rightarrow ee$

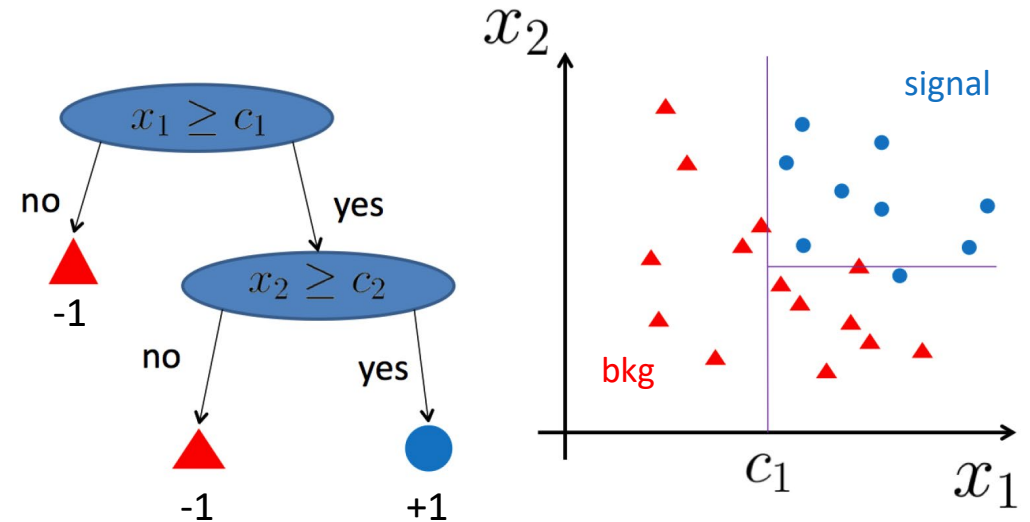
# Separating the signal from the background

- *Multivariate* analysis technique: combine several discriminating observables into a single variable that differentiate the background from the signal

- Using **Boosted Decision Trees** (BDTs) techniques
  - Train sequentially  $N$  **decision trees** to classify signal events (+1) and background events (-1)
  - The mis-classified events from a tree  $n$  are weighted to force the tree  $n+1$  to correctly classify them
  - The normalized sum of the decision of all the  $N$  trees is the **BDT score**:

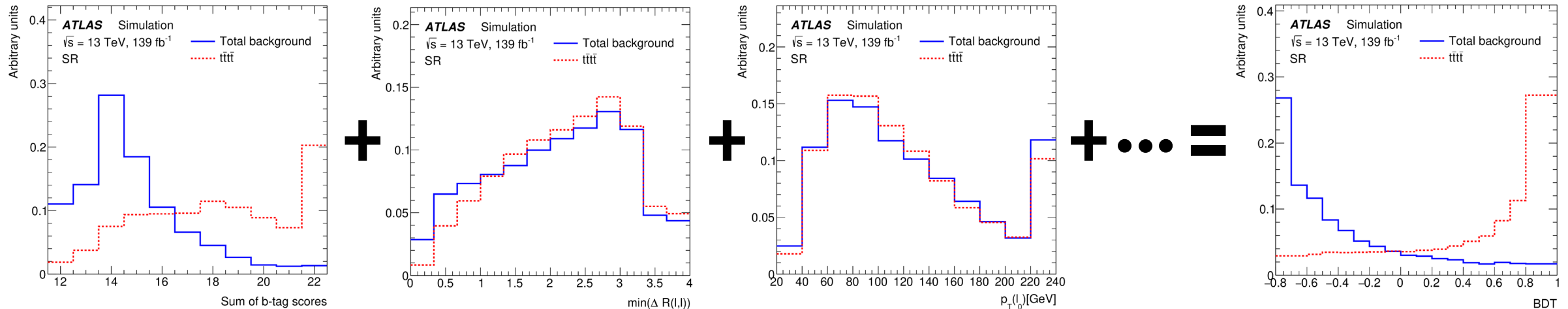
$$\text{BDT score} = \sum_{\text{trees}} \text{Decision} / N$$

Decision tree principle:

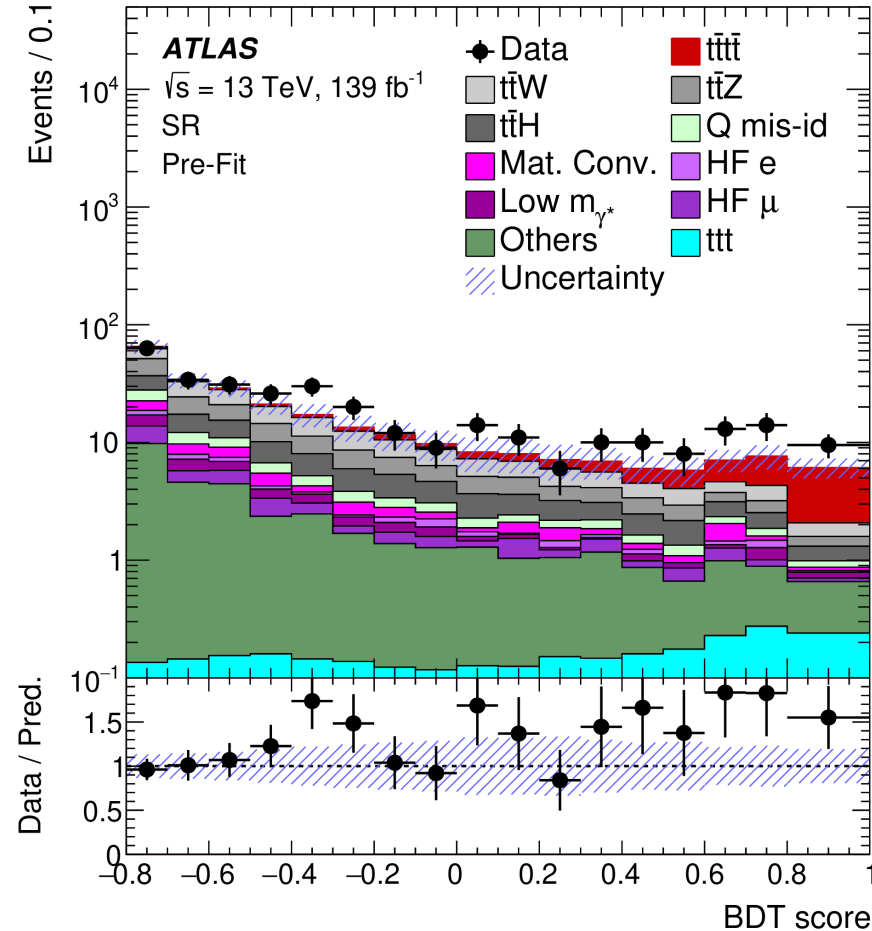


# BDT training for the 4tops search

- Boosted Decision Trees are trained using Monte Carlo simulations of 4tops and the different background sources
- Using the event topology, the kinematic of the reconstructed objects and their angular distance as the input variables for the Boosted Decision Trees



# Extracting the cross section



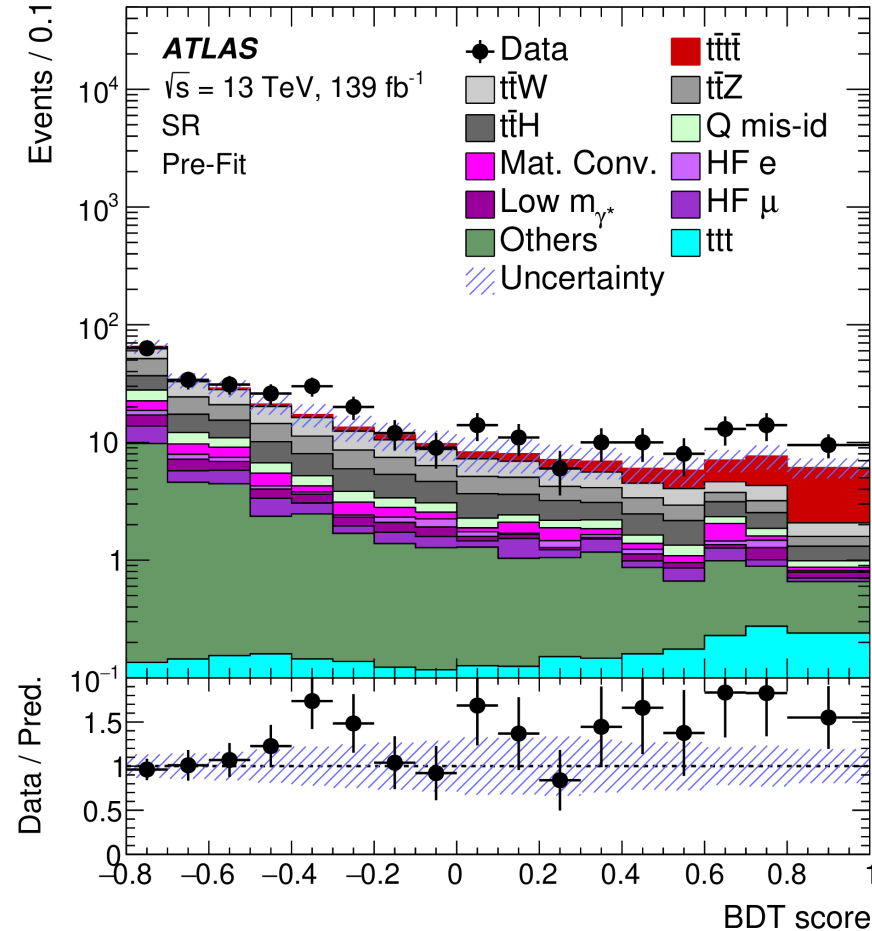
- The cross section  $\sigma(pp \rightarrow t\bar{t}t\bar{t})$  is extracted using **a profile likelihood fit** on the BDT distribution

- Likelihood maximization:

$$\mathcal{L}(\mu, \theta) = \underbrace{\left( \prod_{i \in \text{bin, reg}} \mathcal{P}_{\text{Poisson}}(n_i | \mu s_i(\theta) + \sum_j b_{ij}(\theta)) \right)}_{\text{Poisson distribution term}} \times \underbrace{\mathcal{G}(\theta)}_{\text{Gaussian constraint term}}$$

- $\mu = \sigma(pp \rightarrow t\bar{t}t\bar{t}) / \sigma_{SM}(pp \rightarrow t\bar{t}t\bar{t})$  is the "signal strength"
- $(n_0, \dots, n_{N_{\text{bin}}})$  is the observed data in every bins
- $s_i(\theta)$  are the signal yields in all bins
- $b_{ij}(\theta)$  are the background yields in all bins (index  $i$ ) for every source (index  $j$ )
- $\theta = (\theta_0, \dots, \theta_{N_{\text{syst}}})$  is the nuisances parameters (NPs) associated to the  $N_{\text{syst}}$  systematic uncertainties

# Extracting the cross section



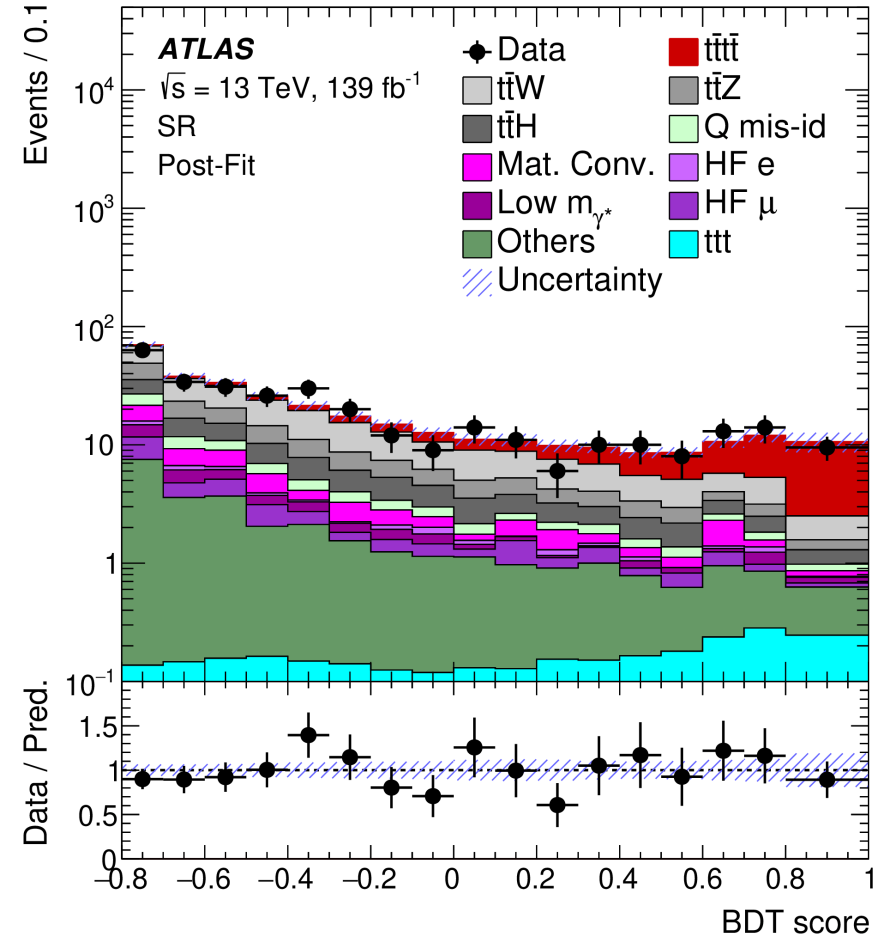
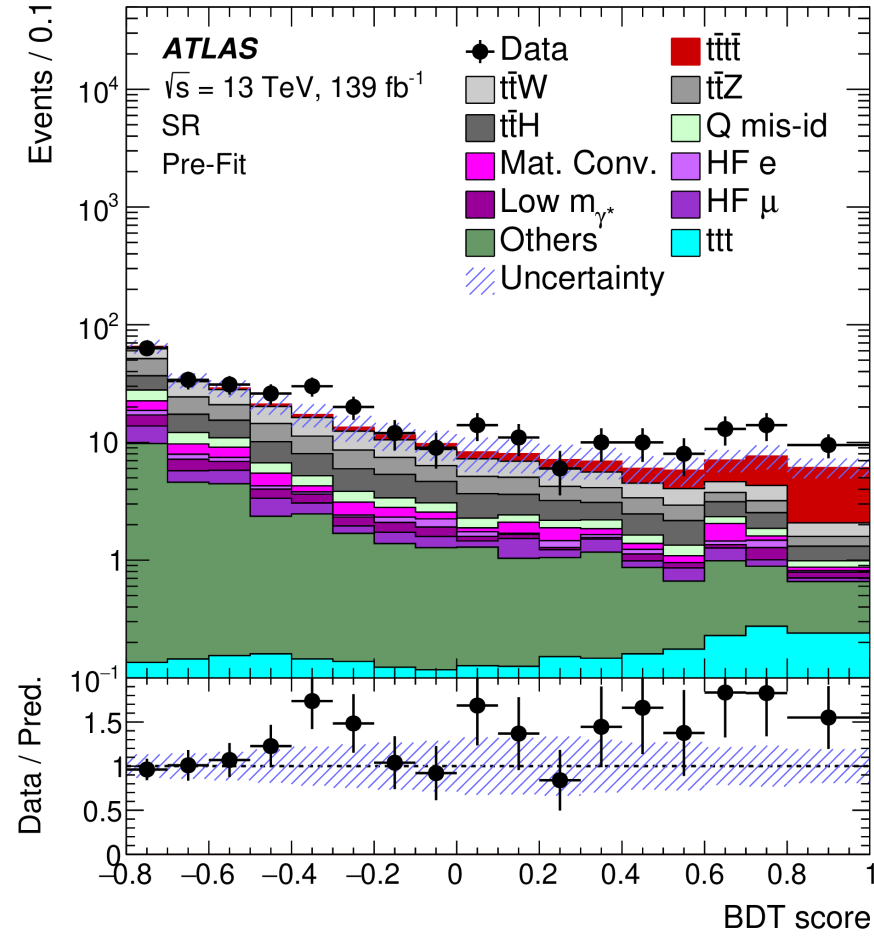
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- Fit the background and the signal to the data
- Constrain (i.e. reduce) the systematic uncertainties
- Extract the best-fit signal strength  $\mu$  (i.e. the amount of 4tops events)

# Extracting the cross section



# Control Regions

- Four bkg-dominated regions are **simultaneously fitted** to correct some background sources:

| Region      | Channel                            | $N_j$            | $N_b$    | Other requirements   | Fitted variable   |
|-------------|------------------------------------|------------------|----------|--|-------------------|
| SR          | 2LSS/3L                            | $\geq 6$         | $\geq 2$ | $H_T > 500$  | BDT               |
| CR Conv.    | $e^\pm e^\pm    e^\pm \mu^\pm$     | $4 \leq N_j < 6$ | $\geq 1$ | $m_{ee}^{CV} \in [0, 0.1 \text{ GeV}]$<br>$200 < H_T < 500 \text{ GeV}$  | $m_{ee}^{PV}$     |
| CR HF e     | $eee    ee\mu$                     | -                | $= 1$    | $100 < H_T < 250 \text{ GeV}$  | counting          |
| CR HF $\mu$ | $e\mu\mu    \mu\mu\mu$             | -                | $= 1$    | $100 < H_T < 250 \text{ GeV}$  | counting          |
| CR ttW      | $e^\pm \mu^\pm    \mu^\pm \mu^\pm$ | $\geq 4$         | $\geq 2$ | $m_{ee}^{CV} \notin [0, 0.1 \text{ GeV}],  \eta(e)  < 1.5$<br>for $N_b = 2, H_T < 500 \text{ GeV}$ or $N_j < 6$<br>for $N_b \geq 3, H_T < 500 \text{ GeV}$ | $\Sigma p_T^\ell$ |

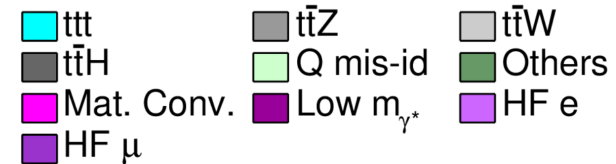
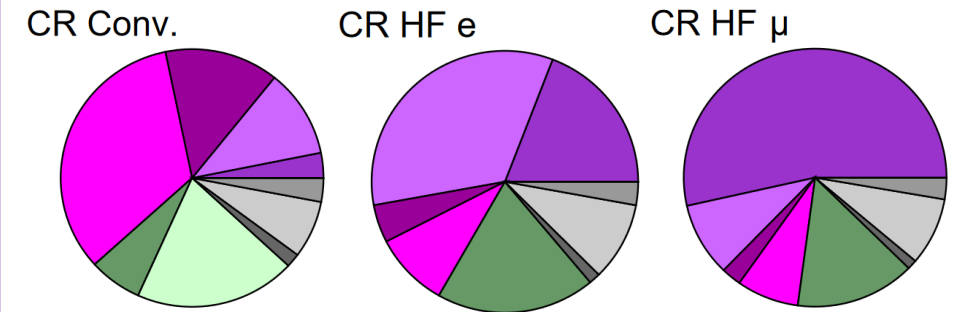
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- Fake background normalisation :**

- Known to be mis-modeled by MC simulation
- Rely on the accuracy of the detector sim.



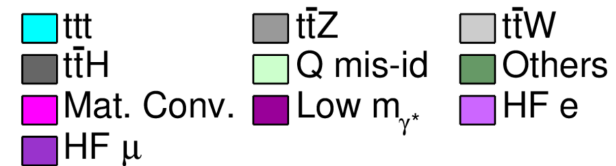
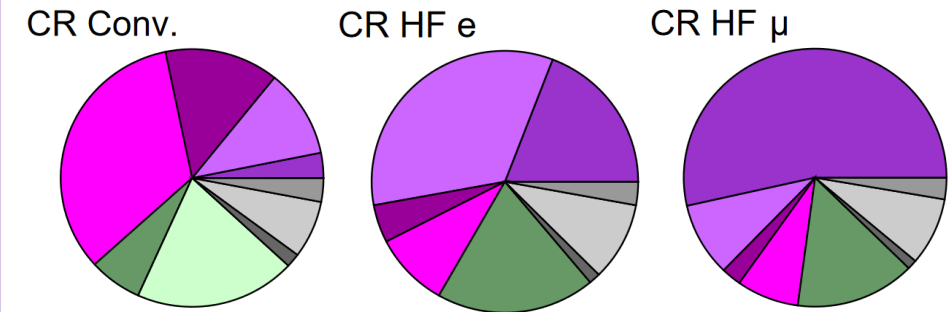
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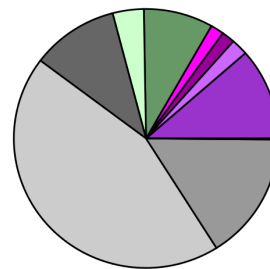
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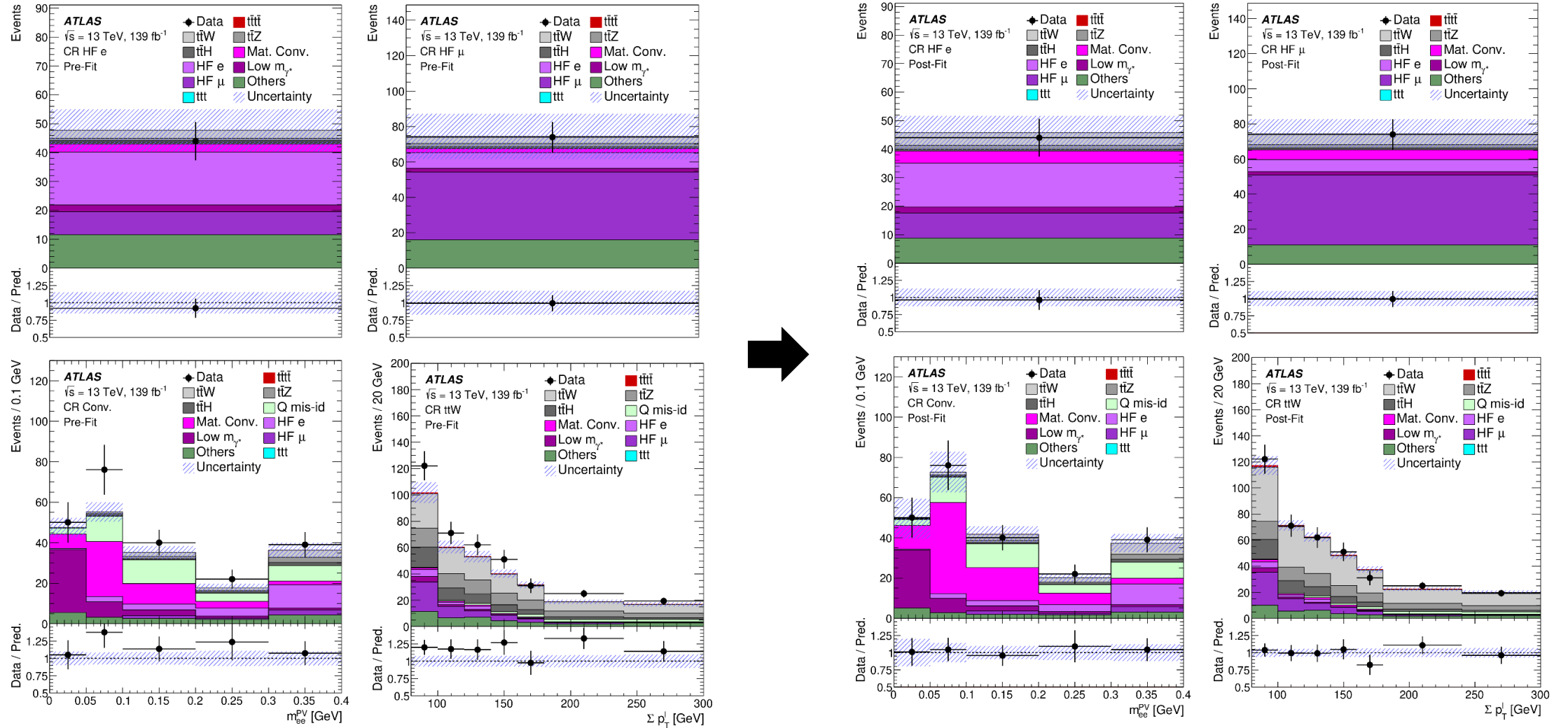
## ttW background normalisation:

- Cross-section known to be under-estimated, as observed by several ATLAS and CMS analyses
- Still poorly studied experimentally and theoretically

CR ttW



# Fit for the control regions

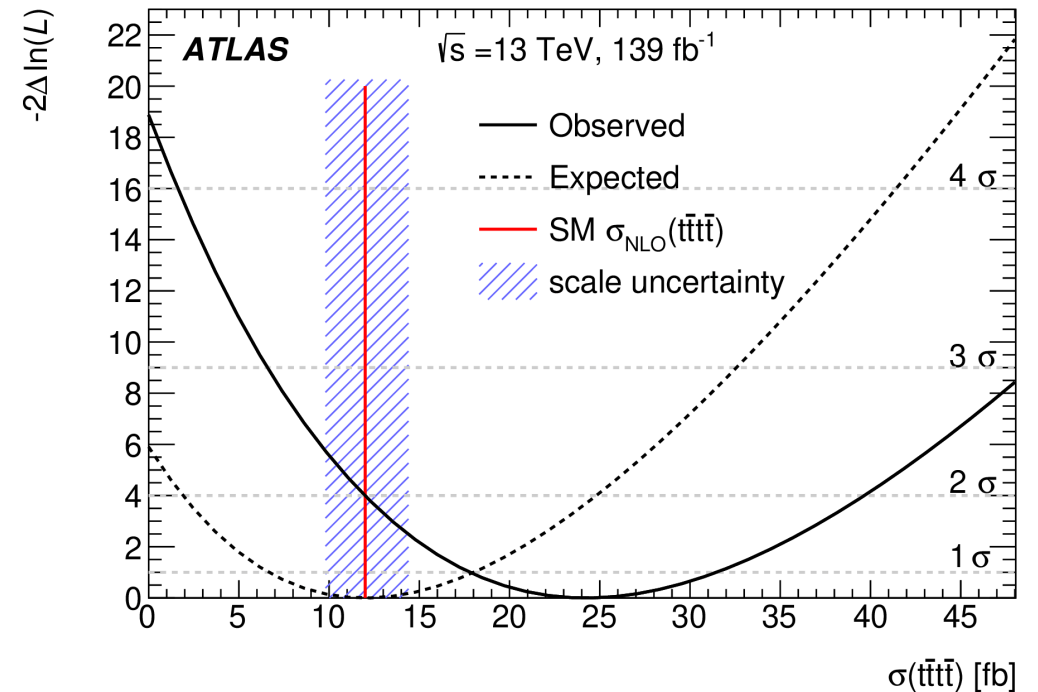


| Parameter | $\text{NF}_{t\bar{t}W}$ | $\text{NF}_{\text{Mat. Conv.}}$ | $\text{NF}_{\text{Low } m_{\gamma^*}}$ | $\text{NF}_{\text{HF } e}$ | $\text{NF}_{\text{HF } \mu}$ |
|-----------|-------------------------|---------------------------------|--|----------------------------|------------------------------|
| Value     | $1.6 \pm 0.3$           | $1.6 \pm 0.5$                   | $0.9 \pm 0.4$                          | $0.8 \pm 0.4$              | $1.0 \pm 0.4$                |

# 4 – Results, cross-checks and discussions

# The final result

- The measured cross section is twice the SM prediction
  - Measured cross section:  $\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 24_{-6}^{+7} \text{ fb}$
  - Compared to theoretical prediction:  $\sigma_{SM} = 12.0 \pm 2.4 \text{ fb}$
  - $1.7\sigma$  tension with SM prediction
- An excess of 4tops is observed
- The significance wrt/ background-only hypothesis:
  - $4.3\sigma$  ( $2.4\sigma$ ) observed (expected)
- Provides the strongest evidence of the  $t\bar{t}t\bar{t}$  production



# Systematic uncertainties

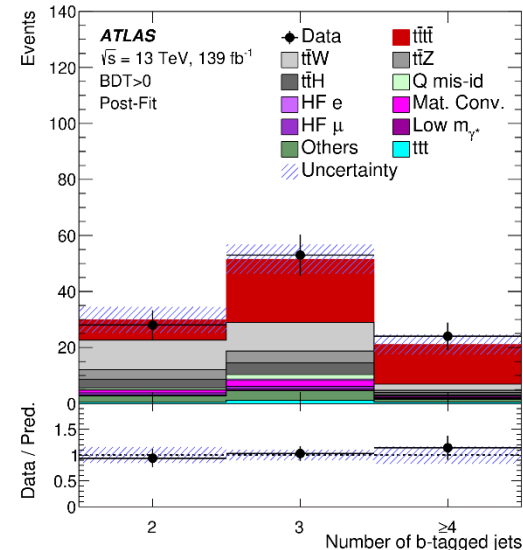
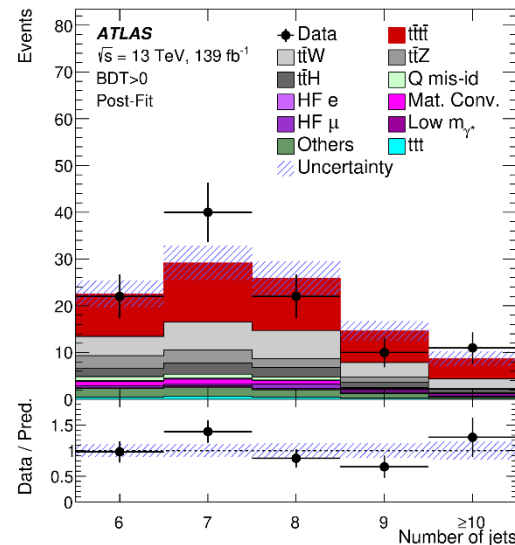
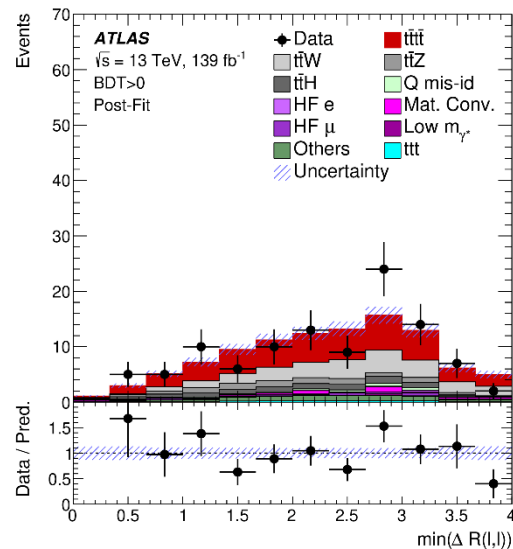
| Uncertainty source   | $\Delta\mu$ |       |
|--|-------------|-------|
| <b>Signal modelling</b>  |             |       |
| $t\bar{t}t\bar{t}$ cross section                                       | +0.56       | −0.31 |
| $t\bar{t}t\bar{t}$ modelling   | +0.15       | −0.09 |
| <b>Background modelling</b>  |             |       |
| $t\bar{t}W$ +jets modelling  | +0.26       | −0.27 |
| $t\bar{t}t$ modelling  | +0.10       | −0.07 |
| Non-prompt leptons modelling   | +0.05       | −0.04 |
| $t\bar{t}H$ +jets modelling  | +0.04       | −0.01 |
| $t\bar{t}Z$ +jets modelling  | +0.02       | −0.04 |
| Other background modelling   | +0.03       | −0.02 |
| Charge misassignment   | +0.01       | −0.02 |
| <b>Instrumental</b>  |             |       |
| Jet uncertainties  | +0.12       | −0.08 |
| Jet flavour tagging (light-flavour jets)                               | +0.11       | −0.06 |
| Simulation sample size   | +0.06       | −0.06 |
| Luminosity   | +0.05       | −0.03 |
| Jet flavour tagging ( $b$ -jets)                                       | +0.04       | −0.02 |
| Jet flavour tagging ( $c$ -jets)                                       | +0.03       | −0.01 |
| Other experimental uncertainties                                       | +0.03       | −0.01 |
| Total systematic uncertainty   | +0.70       | −0.44 |
| <b>Statistical</b>   |             |       |
| Non-prompt leptons normalisation (HF, Mat. Conv., Low $m_{\gamma^*}$ ) | +0.05       | −0.04 |
| $t\bar{t}W$ normalisation  | +0.04       | −0.04 |
| Total uncertainty  | +0.83       | −0.60 |

## Leading uncertainty:

- **Signal modelling uncertainty:**
  - On the theoretical cross section ( $\sim 20\%$ )
  - On the choice of the parton shower
- **Limited statistics of the run-2 data**
- **$t\bar{t}W$  background modelling**
  - Discussions in a few slides
- **3-tops production cross section**
  - Lower cross section but similar BDT shape
- **Instrumental background**
  - Jet energy scale and resolution
  - $b$ -tagging efficiencies on light jets

# Cross-checks

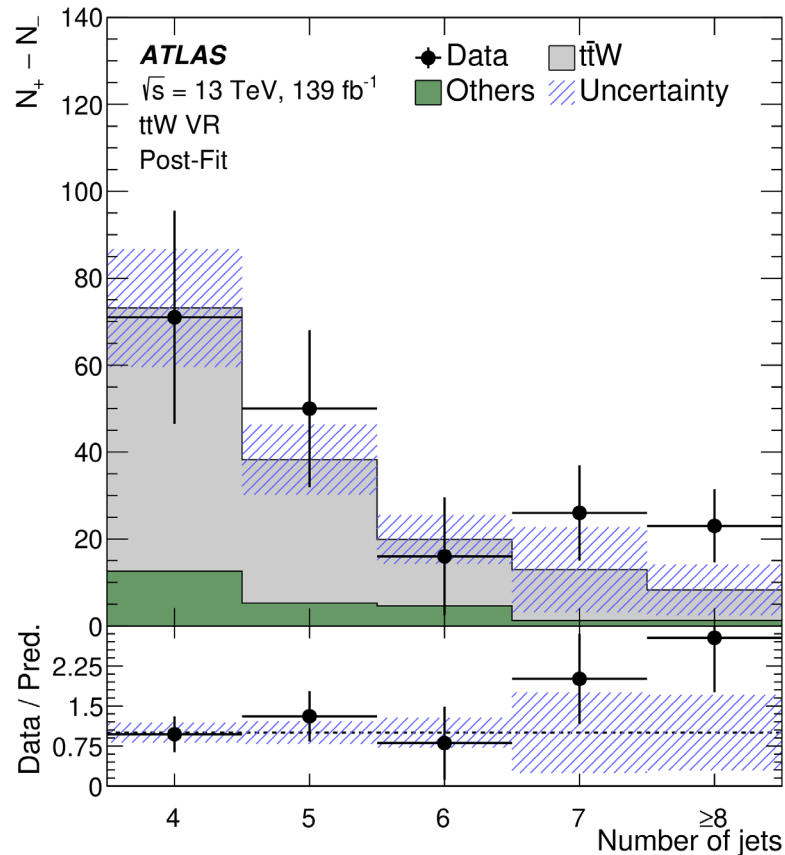
- Many tests were performed to check the stability of the results:
  - Fitting different data-taking year period
  - Splitting regions wrt/ to the lepton multiplicity
  - Using only positively-charged or negatively charged same-sign leptons
  - Using the  $H_T$  distribution instead of the BDT score distribution
- All tests give consistent measured  $\sigma(pp \rightarrow t\bar{t}t\bar{t})$
- Looking at several distributions of the events with a positive BDT score:



- The excess is very signal-like (compatible with a 4tops excess)

# Validating the ttW background

$N_+$ : Number of events with positively-charged leptons  
 $N_-$ : number of events with negatively-charged leptons



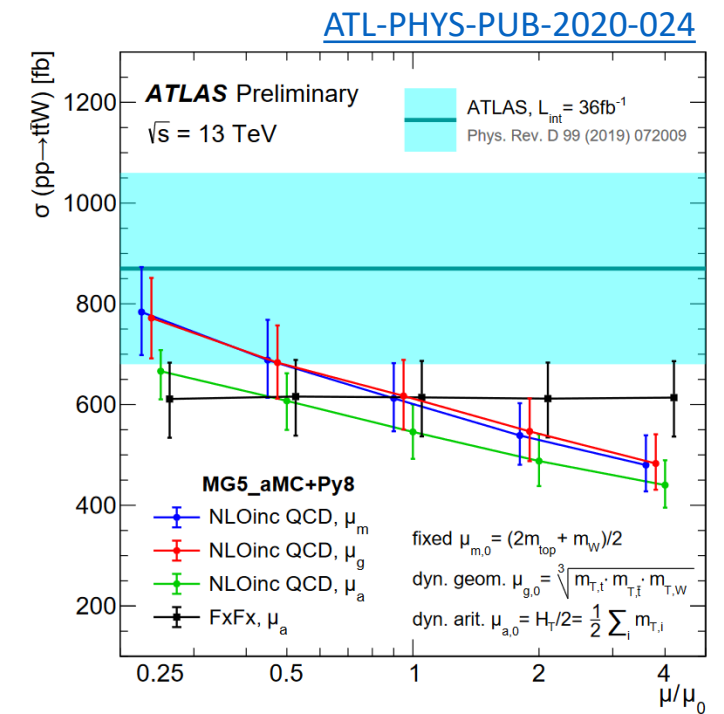
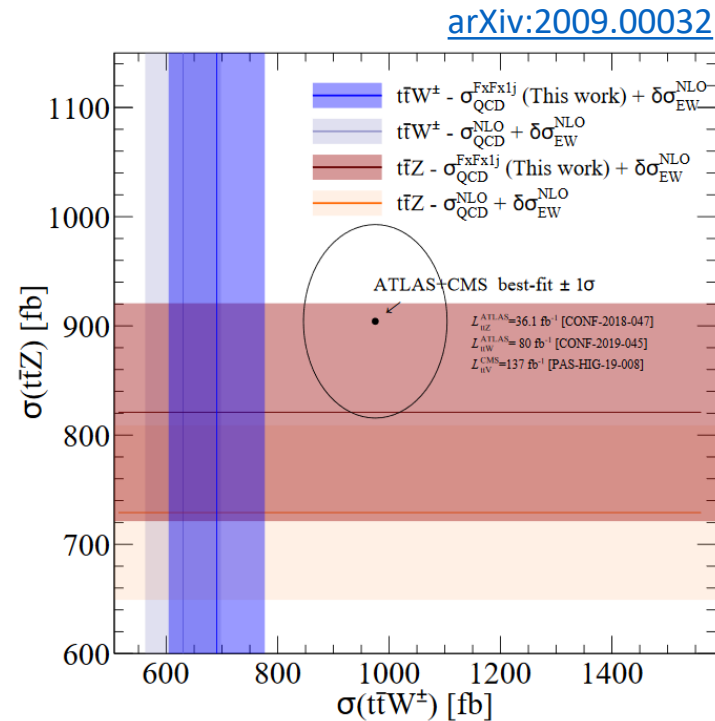
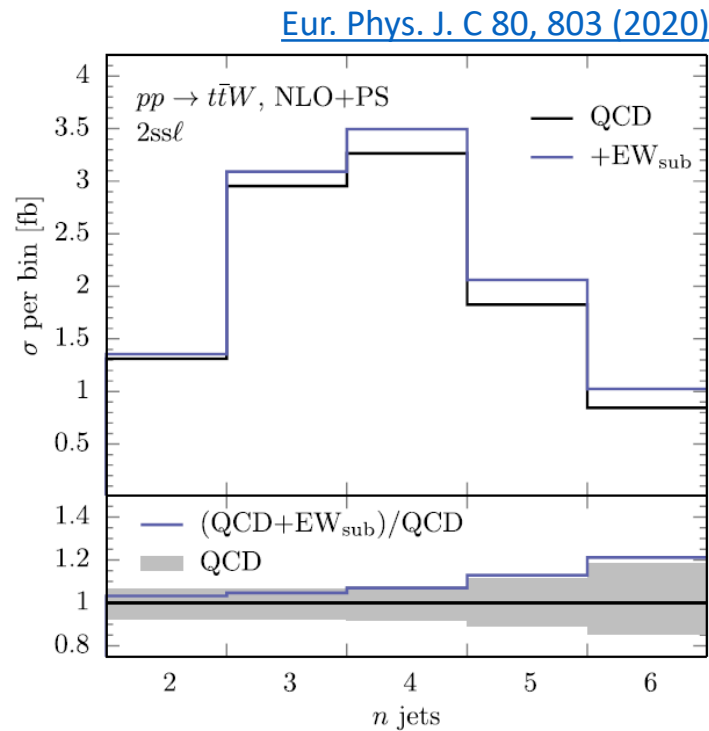
- The ttW modelling is validated in the signal region by looking at charge of the leptons
    - The ttW leads to more positive lepton events than negative lepton because  $\sigma(ttW^+) > \sigma(ttW^-)$
- $\text{PDF}(u\bar{d}) > \text{PDF}(\bar{u}d)$

(~twice more valence up quarks than down quarks in a proton)
- Systematic uncertainties are applied to cover the **mis-modelling** at high jet multiplicities
    - High impact on the measured cross section
    - The largest systematic uncertainty

# Toward a better ttW modelling

- Current theoretical developments on ttW modelling will improve future  $t\bar{t}t\bar{t}$  analyses

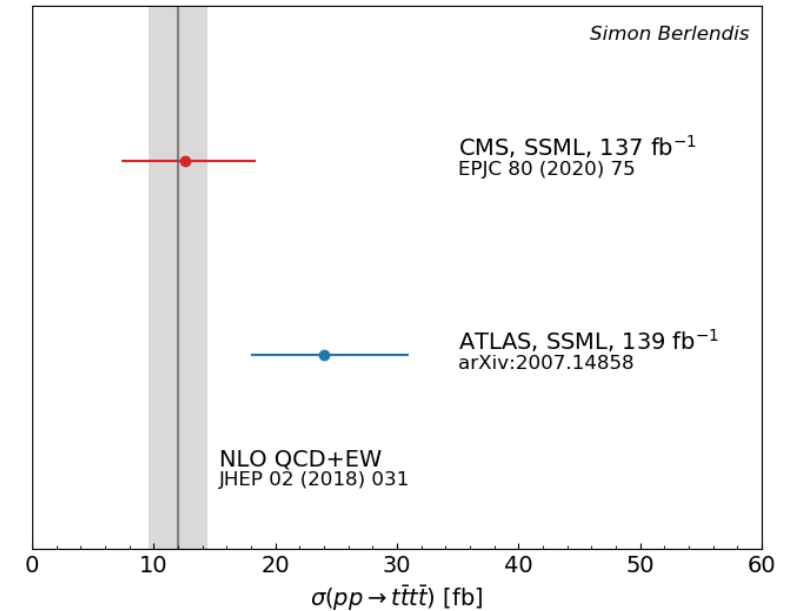
Few examples:



# So what is the origin of the excess ?

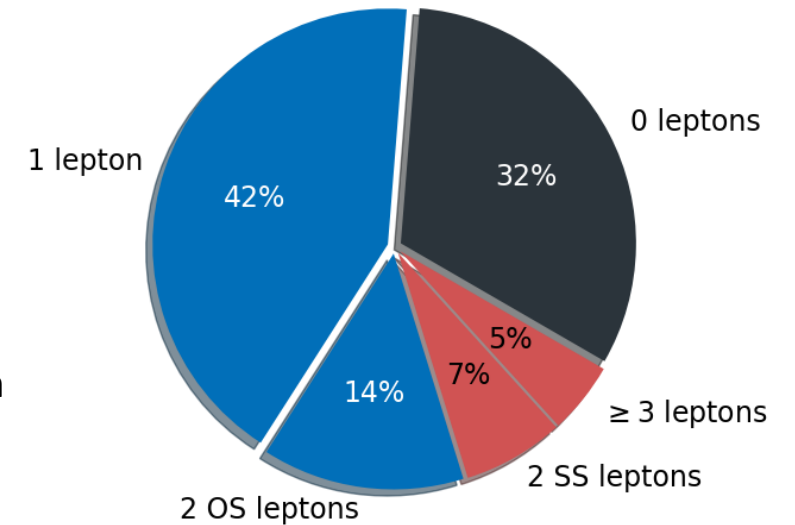
- Most plausible explanation: **statistical fluctuation**
  - The significance of the excess is only  $1.7\sigma$  ( $\sim 5\%$  in p-value)
  - CMS did not observe such excess:  $\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2} \text{ fb}$
- Less-plausible explanations:
  - Background estimation is badly modelled (ttW?)
  - The systematic uncertainties are under-estimated
  - The SM prediction is wrong (missing corrections?)
  - New physics ?

➤ More studies/analyses are needed to have a final answer !



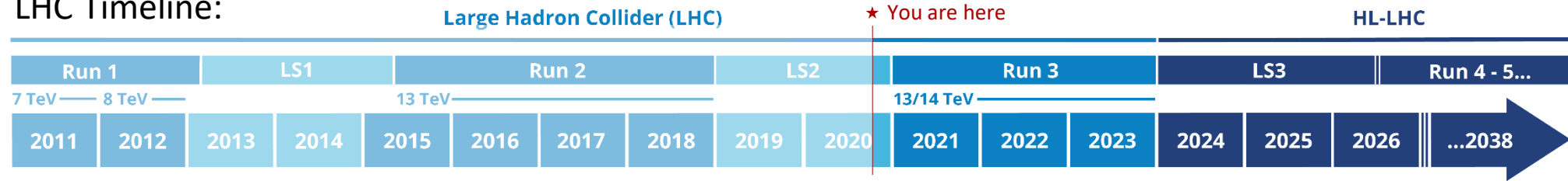
# The future of 4tops

- Search in other final states: **1 lepton or 2 opposite-sign lepton**
  - Very challenging: higher background (dominated by  $pp \rightarrow t\bar{t}$ )
  - But will provide valuable cross-check on  $\sigma(pp \rightarrow t\bar{t}t\bar{t})$
- Re-analysis **same-sign leptons or three leptons** with newer techniques:
  - New b-tagging techniques that will provide better bkg vs signal separation
  - Better ttW modelling from new Monte Carlo simulations
- Combination with CMS:
  - Compare analysis strategy (e.g. selections, background estimation)
  - Combine the measured  $\sigma(pp \rightarrow t\bar{t}t\bar{t})$



# In a longer term...

## LHC Timeline:



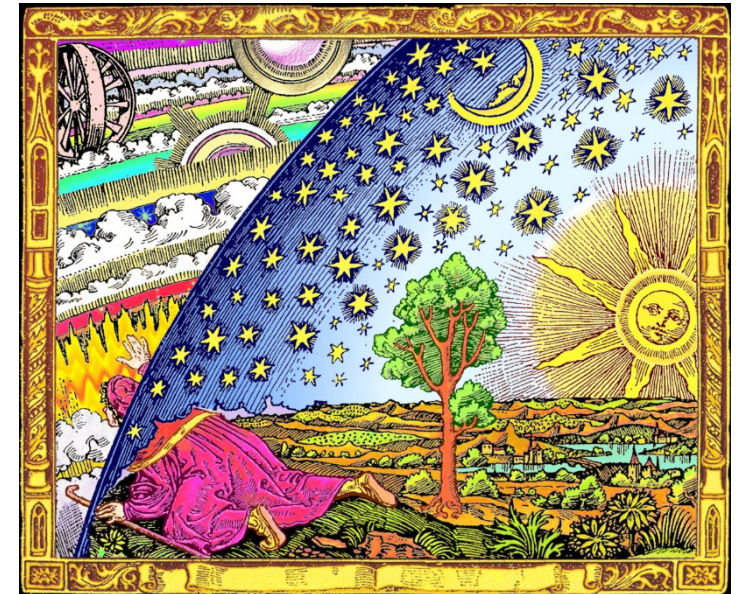
HL-LHC: High Luminosity LHC  
LS: Long Shutdown  
TeV: Tera electron Volt

- Run 3, starting from 2022 (SARS-COV-2 delay...)
  - Double the data luminosity (i.e. amount of data taken) with possibly higher energy (14 TeV)
  - Will significantly reduce the statistical uncertainty on the measured  $\sigma(pp \rightarrow t\bar{t}t\bar{t})$
- HL-LHC, starting from 2026, will last  $\sim 10$  years:
  - Will multiply the data luminosity by a factor 10 !
  - Will allow very-precise measurements on rare processes like  $t\bar{t}t\bar{t}$
  - Evidence on the production of HH

# Conclusion

# Conclusion

- The LHC has shown to be a powerful tool for exploring uncharted territories of particle physics
    - Enable us to search, measure and study rare processes like  $t\bar{t}t\bar{t}$
    - Push the limits of our understanding of the physics at high energy
  - Still many questions to solve and new regions to explore !
    - We are far from having a perfect understanding of our data  
The search for  $t\bar{t}t\bar{t}$  is a good example
    - The Standard Model continues to have experimental and theoretical limitations
- The hunt for new physics is still on !



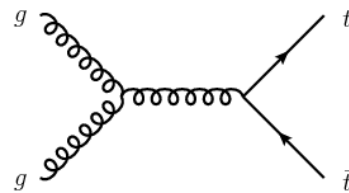
[Flammarion engraving](#)

- Backup

# The Standard Model (SM)

- Particle classification:
  - The **gauge bosons** are the **force mediators**
  - The **quarks** and **leptons** are the **elementary fermions**
  - The **Higgs boson** is a **scalar boson**
- Invariance under the local gauge group:
  - $\underbrace{SU(3)}_{\text{Strong}} \otimes \underbrace{SU(2) \otimes U(1)}_{\text{Electroweak}}$
- The Standard Model (SM) describes the particle interactions
  - Allows to compute the production cross section ( $\sigma$ ) of a given process
  - Can be compared with experimental results

ex:  $gg \rightarrow t\bar{t}$  production



- Particle classification:
  - The **gauge bosons** are the **force mediators**
  - The **quarks** and **leptons** are the **elementary fermions**
  - The **Higgs boson** is a **scalar boson**
- Invariance under the local gauge group:
  - $SU(3) \otimes SU(2) \otimes U(1)$

# The imperfections of the Standard Model

---

- **Gravity** is not included in the SM
  - Only the strong force and the electroweak (EW) force are included
- The **hierarchy** problem
  - Why the EW energy scale (100 GeV) is so small compared to the Planck scale ( $10^{18}$  GeV) ?
- The **Dark Matter** (DM) puzzle
  - From several astrophysics observation
  - No DM candidate in the SM
- The **matter-antimatter asymmetry** of the universe
  - The SM can't explain the observed asymmetry
- Neutrino masses
- Higgs potential stability
- Grand Unification Theory
- Strong CP phase
- ...

The SM is an effective theory. At high energy, **deviations** from the SM predictions are expected, revealing the presence of **new physics (NP)**.

# Fine tuning

- Quadratic mass corrections:

- Fine-tuning to the 32<sup>th</sup> decimal digit

$$\text{---} \overset{h}{\bullet} \text{---} = \text{---} \overset{h}{\phantom{\bullet}} \text{---} + \text{---} \text{---} \text{---} \text{---} + \dots$$

$$m_h^2 = m_h^{02} - \frac{3}{8\pi^2} y_t^2 \Lambda_{\text{UV}}^2 + \dots$$

- Even after renormalization, logarithm corrections:

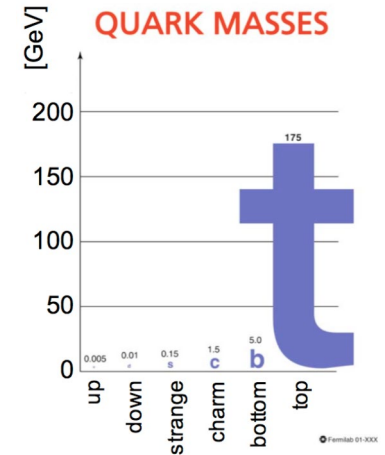
$$\Delta m_h = M_{\text{NP}} \ln(\Lambda_{\text{UV}}/M_{\text{NP}}) + \dots$$

- Solutions:

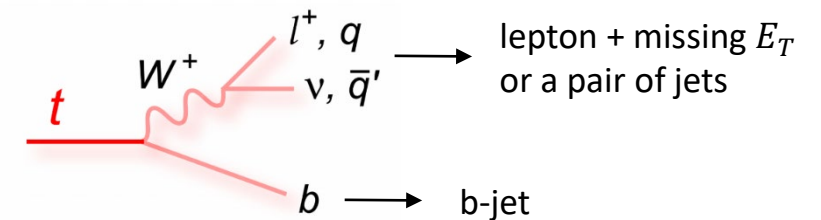
- New symmetry
  - Composite Higgs
  - Dynamical Higgs mass value
  - ...

# The top quark: a unique particle

- The top quark is the heaviest particle ( $m_t = 175 \text{ GeV}$ ) of the Standard Model with an almost-unitary coupling with the higgs boson ( $\lambda_t \sim 1$ )
- These features give a special role to the top quark in many theories beyond the Standard Model
  - Theories that try to explain the hierarchy between the EW scale and the NP scale
- The top quark has also the advantage to decay electroweakly before hadronizing
- Relatively easy to identify at the LHC

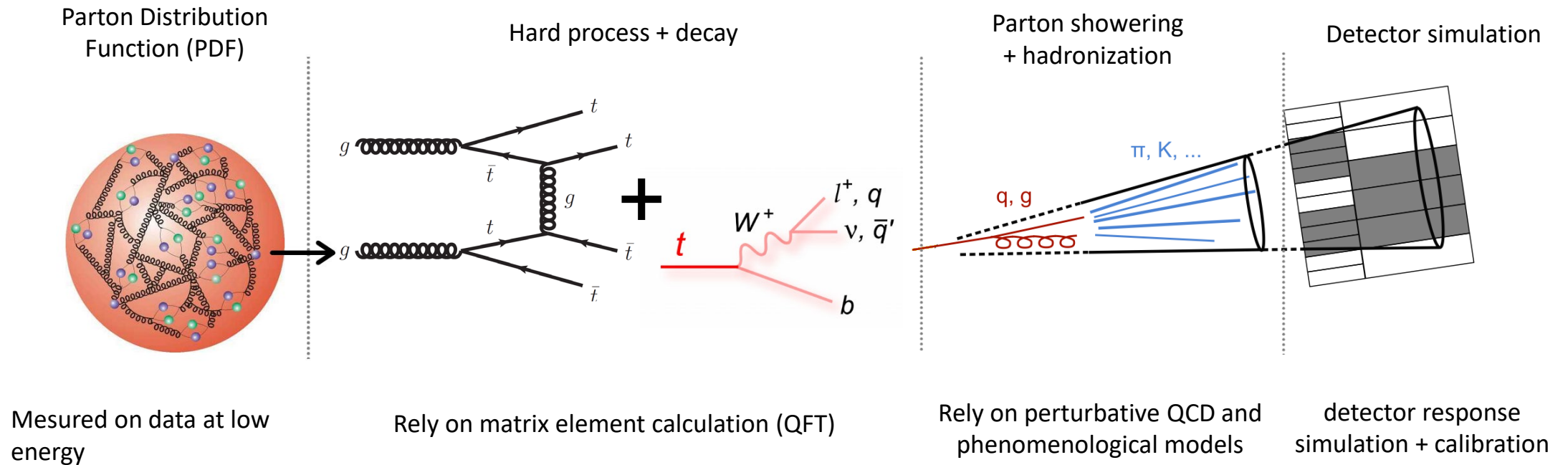


Study of different top quark production modes is one of the main program of research at the LHC



# Simulation techniques

- Dedicated Monte Carlo based simulation techniques to generate collision events for a given process
  - Based on assumptions, approximations and models tuned to data



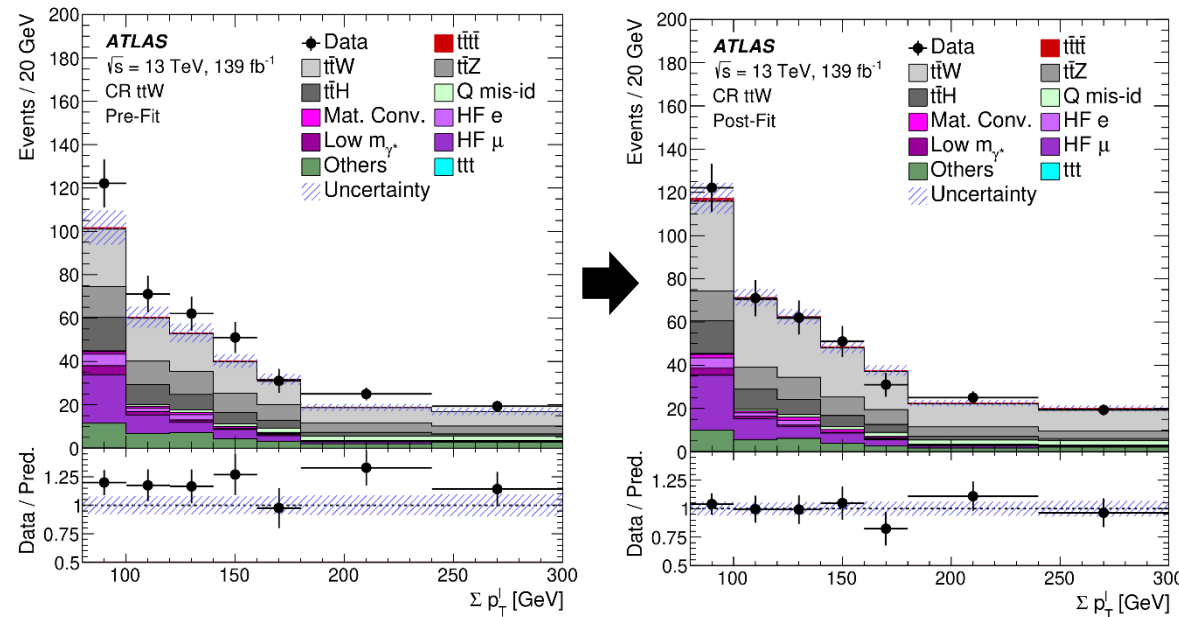
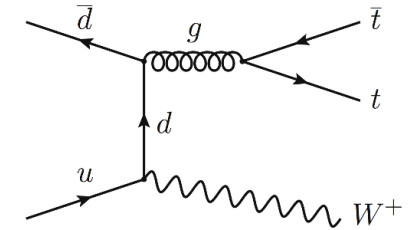
# Object Definition

|                            | Electrons                        |                                 | Muons            |                        | Jets              | <i>b</i> -jets    |
|----------------------------|----------------------------------|---------------------------------|------------------|------------------------|-------------------|-------------------|
|                            | loose                            | tight                           | loose            | tight                  |                   |                   |
| $p_T$ [GeV]                | $> 10$ or $> 28$                 |                                 | $> 10$ or $> 28$ |                        | $> 25$            | $> 25$            |
| $ \eta $                   | $< 1.37$ or $1.52 - 2.47$        |                                 | $< 2.5$          |                        | $< 2.5$           | $< 2.5$           |
| ID quality                 | mediumLH<br>ECIDS ( $ee, e\mu$ ) | tightLH<br>ECIDS ( $ee, e\mu$ ) | medium           |                        | cleaning<br>+ JVT | MV2c10 70% or 77% |
| Isolation                  | none                             |                                 | none             | FixedCutTightTrackOnly |                   |                   |
| Track vertex :             |                                  |                                 |                  |                        |                   |                   |
| – $ d_0/\sigma_{d_0} $     | $< 5$                            |                                 | $< 3$            |                        |                   |                   |
| – $ z_0 \sin \theta $ [mm] | $< 0.5$                          |                                 | $< 0.5$          |                        |                   |                   |

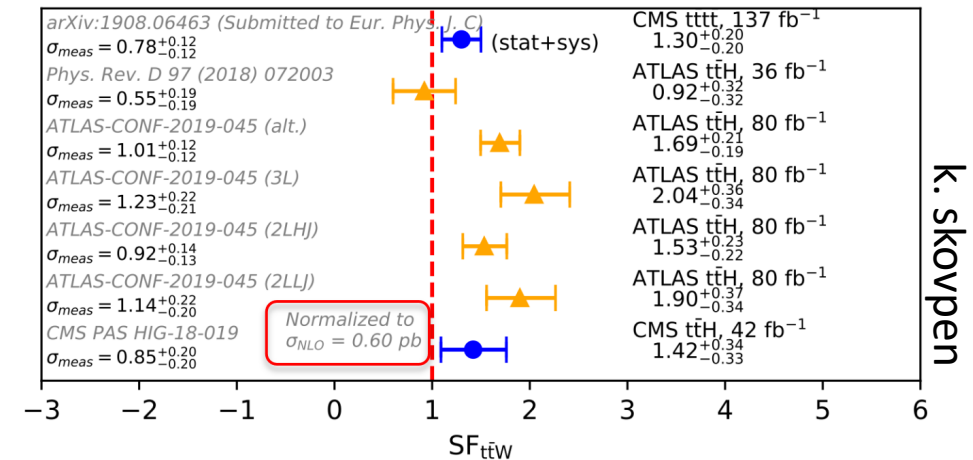
Table 3: Summary of object identification and definitions.

# The problem of the ttW background

- An excess of events is also observed in ttW-dominated event region
  - The ttW cross section is found to be higher than what the SM predicts
  - A ttW normalisation factor of  $1.6 \pm 0.3$  is extracted from the likelihood fit

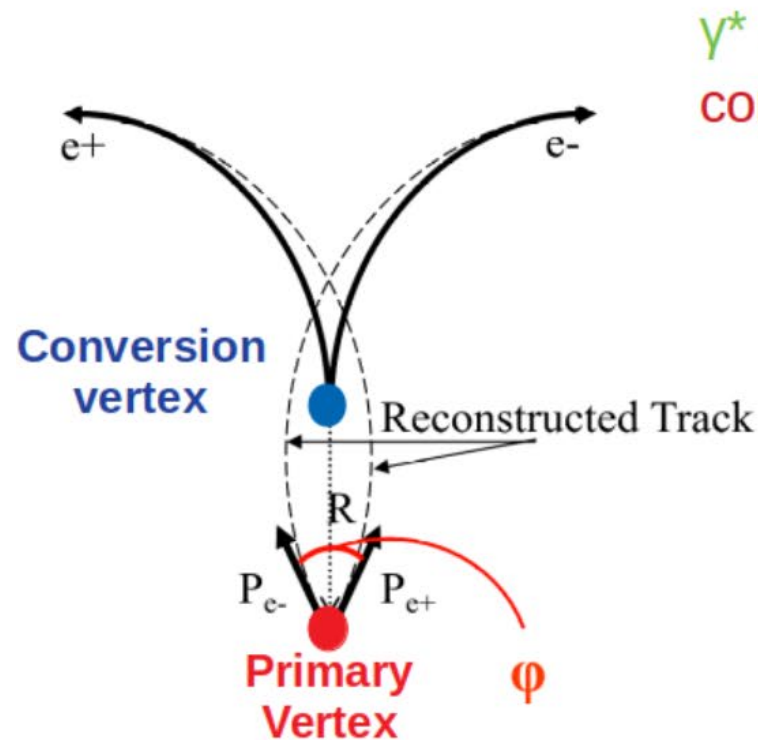


Observed by other analyses targeting the similar event topology :



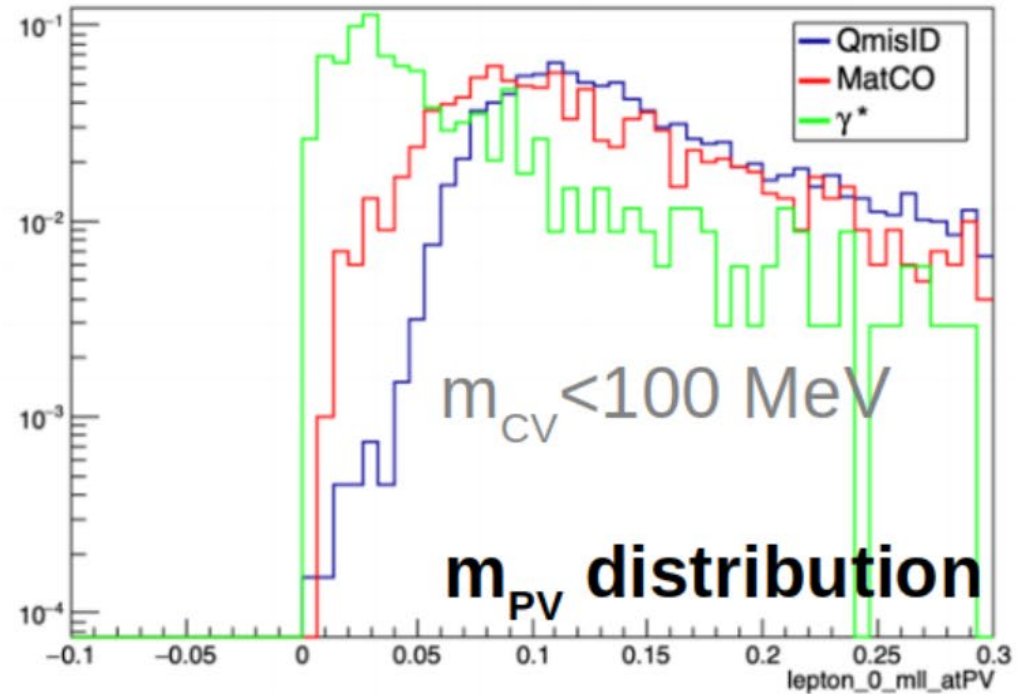
➤ The ttW background is known to be badly modelled by the Monte Carlo simulation

# Invariant mass at the primary (conversion) vertex

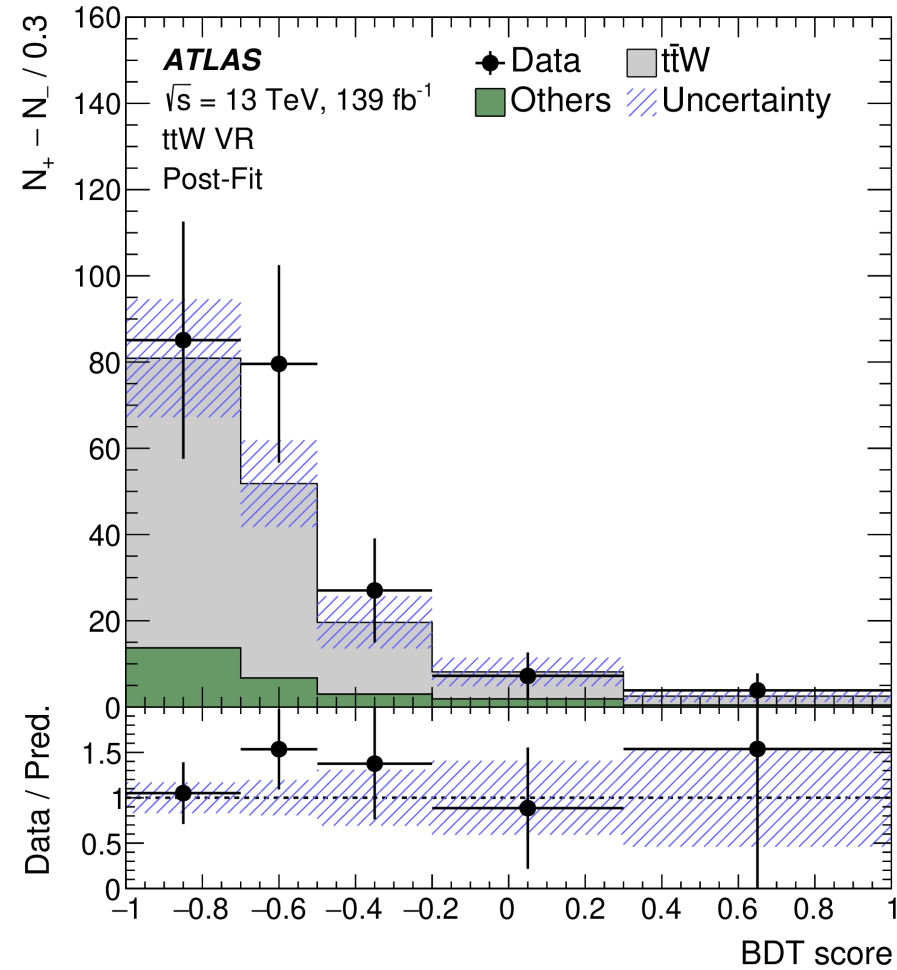
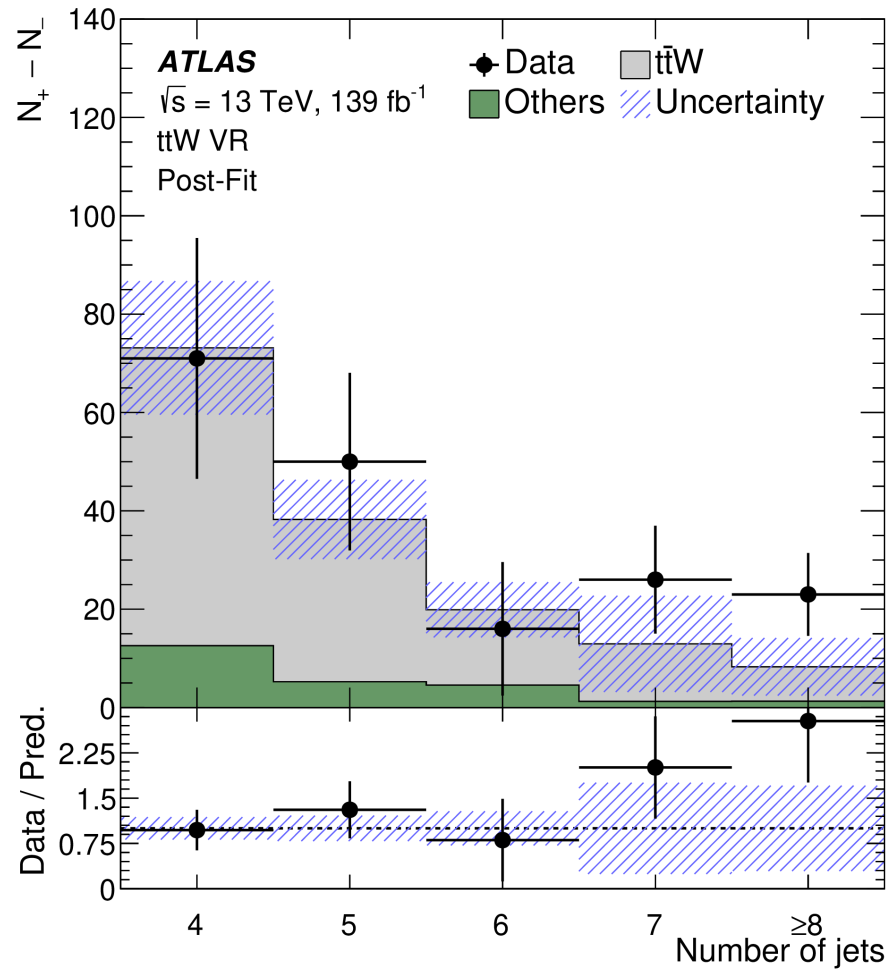


$$\gamma^* \rightarrow m_{CV} \sim m_{PV} \sim 0$$

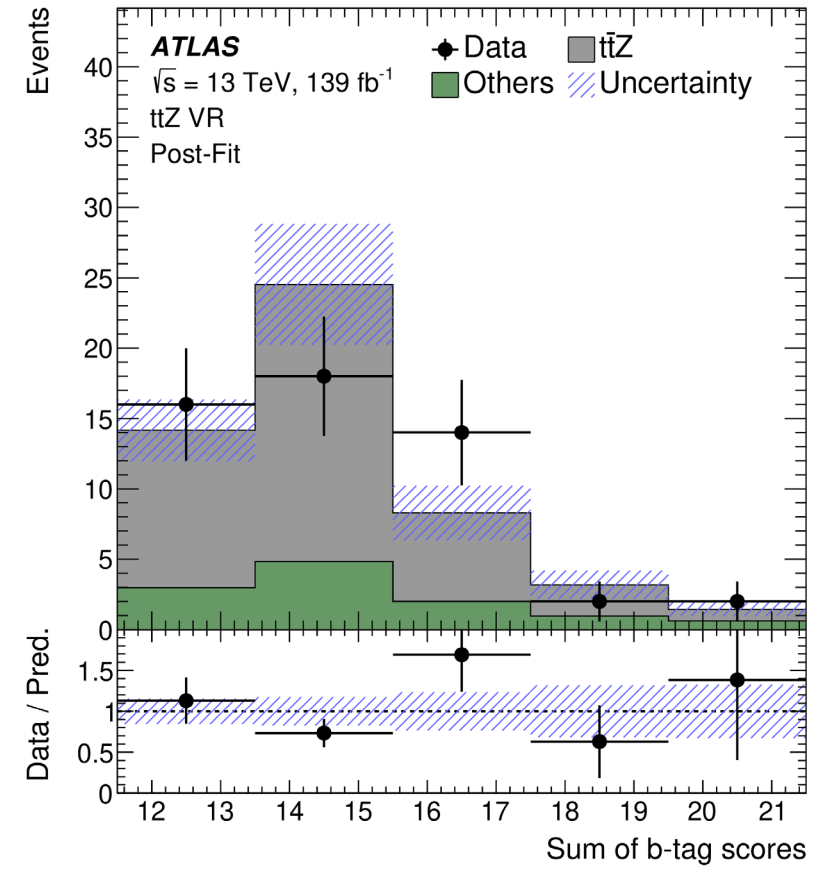
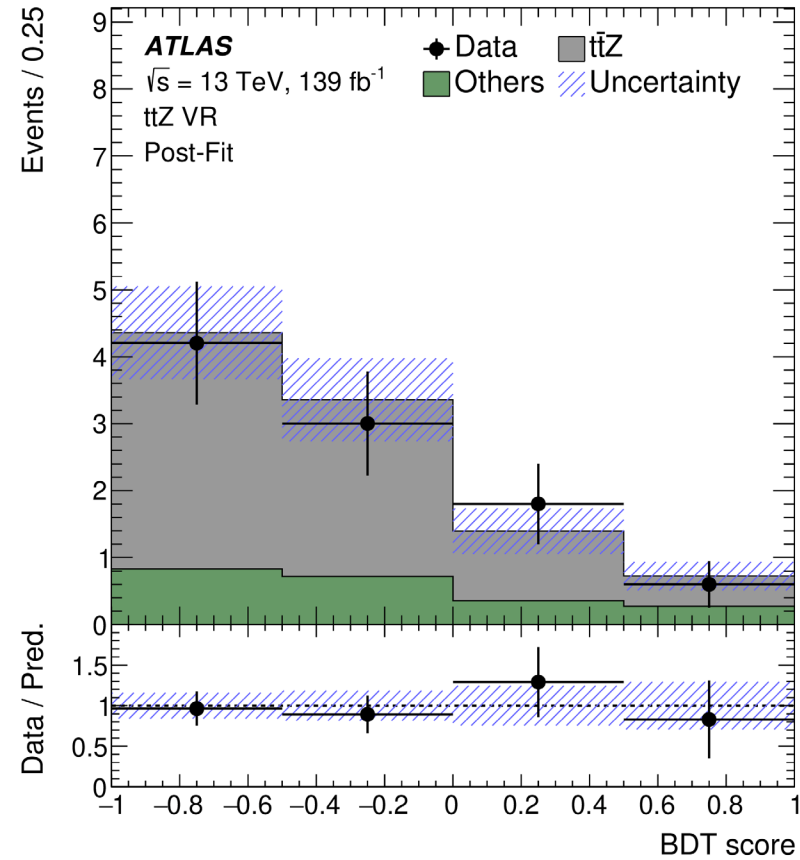
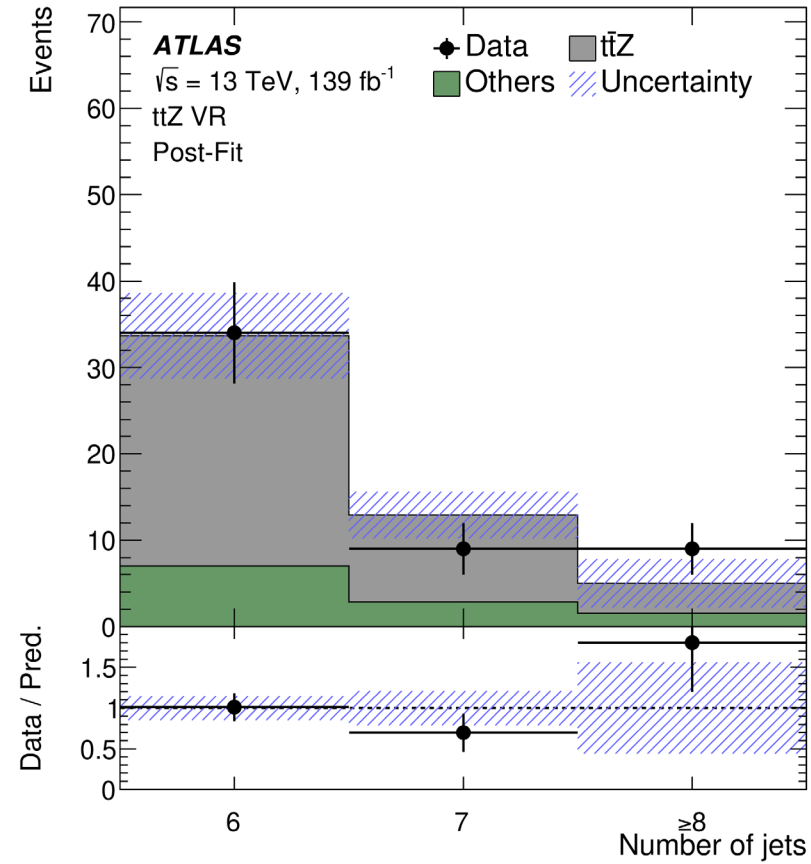
$$\text{conv} \rightarrow m_{CV} \sim 0 \text{ but higher } m_{PV}$$



# ttW validation region



# ttZ validation region



# BDT input variables for SSML

| Rank | Variable                             | Category  | Description  | IR |
|------|--------------------------------------|-----------|--|----|
| 1    | $\Sigma W_{MV2c10}$                  | b-tagging | Sum of MV2c10 pseudo-continuous b-tagging score over all jets  | ✓  |
| 2    | $p_T^{\ell_0}$                       | Lepton    | Transverse momentum of leading lepton  | ✓  |
| 3    | $E_T^{\text{miss}}$                  | Energy    | Missing transverse energy  | ✓  |
| 4    | $\Delta R(\ell, \ell)_{\min}$        | Distance  | The minimum distance between any lepton pair   | ✓  |
| 5    | $p_T^{\text{jet}_5}$                 | Jet       | Transverse momentum of 6th leading jet   | ✓  |
| 6    | $\Delta R(\ell, b)_{\max}$           | Distance  | The maximum distance between leptons and b-tagged jets   | ✓  |
| 7    | $H_T^{\text{no lead jet}}$           | Energy    | Scalar sum of all lepton and jet pT except leading jet   | ✓  |
| 8    | $\Sigma \Delta R(\ell, \ell)_{\min}$ | Distance  | Sum of the distance between leading and sub-leading leptons in SS or leading, sub-leading and third-leading leptons in $3\ell$ | ✓  |
| 9    | $p_T^{\text{jet}_0}$                 | Jet       | Transverse momentum of leading jet   | ✓  |
| 10   | $\Delta R(j, b)_{\min}$              | Distance  | The minimum distance between b-tagged jets and jets  | ✓  |
| 11   | $p_T^{b\text{-jet}_0}$               | Jet       | Transverse momentum of leading b-tagged jet  | ✓  |
| 12   | $p_T^{\text{jet}_1}$                 | Jet       | Transverse momentum of sub-leading jet   | ✓  |

# Systematics in SSML

| Uncertainty source   | $\Delta\mu$ |       |
|--|-------------|-------|
| <b>Signal modelling</b>  |             |       |
| $t\bar{t}t\bar{t}$ cross section                                       | +0.56       | −0.31 |
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| <b>Instrumental</b>  |             |       |
| Jet uncertainties  | +0.12       | −0.08 |
| Jet flavour tagging (light-flavour jets)                               | +0.11       | −0.06 |
| Simulation sample size   | +0.06       | −0.06 |
| Luminosity   | +0.05       | −0.03 |
| Jet flavour tagging ( $b$ -jets)                                       | +0.04       | −0.02 |
| Jet flavour tagging ( $c$ -jets)                                       | +0.03       | −0.01 |
| Other experimental uncertainties                                       | +0.03       | −0.01 |
| Total systematic uncertainty   | +0.70       | −0.44 |
| <b>Statistical</b>   |             |       |
| Non-prompt leptons normalisation (HF, Mat. Conv., Low $m_{\gamma^*}$ ) | +0.05       | −0.04 |
| $t\bar{t}W$ normalisation  | +0.04       | −0.04 |
| Total uncertainty  | +0.83       | −0.60 |

Pre-fit impact on  $\mu$ :

$\square \theta = \hat{\theta} + \Delta\theta$   $\square \theta = \hat{\theta} - \Delta\theta$

Post-fit impact on  $\mu$ :

$\blacksquare \theta = \hat{\theta} + \Delta\hat{\theta}$   $\blacksquare \theta = \hat{\theta} - \Delta\hat{\theta}$

—●— Nuis. Param. Pull

