# Search for new physics with leptons, jets and missing transverse momentum at the LHC


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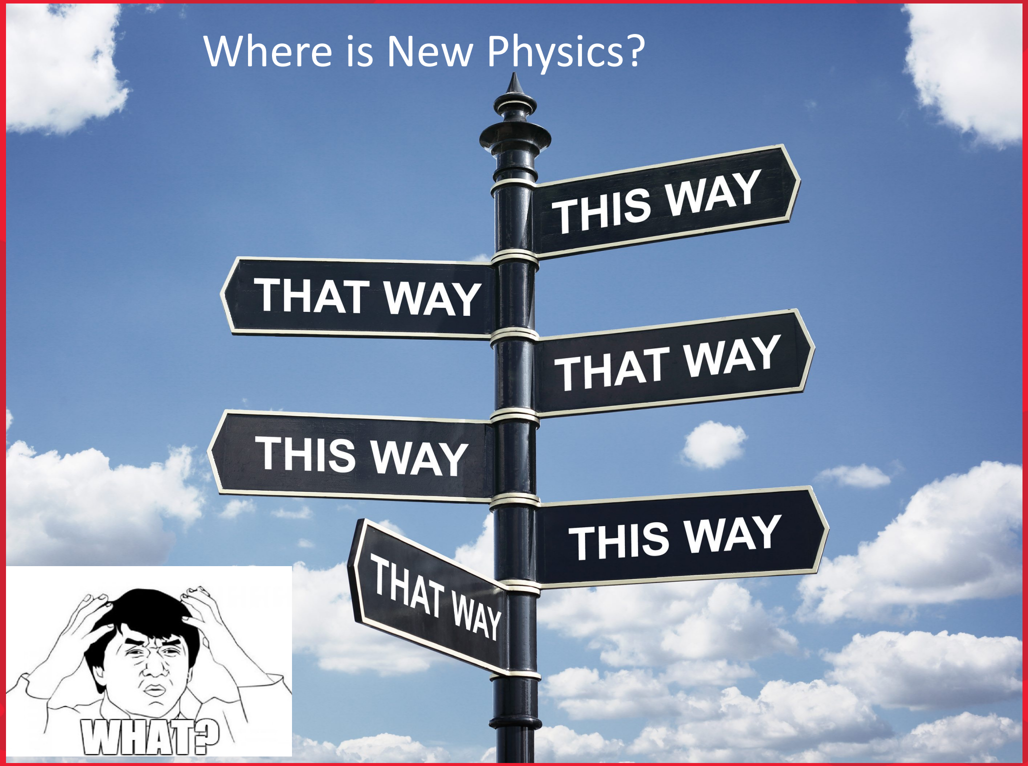


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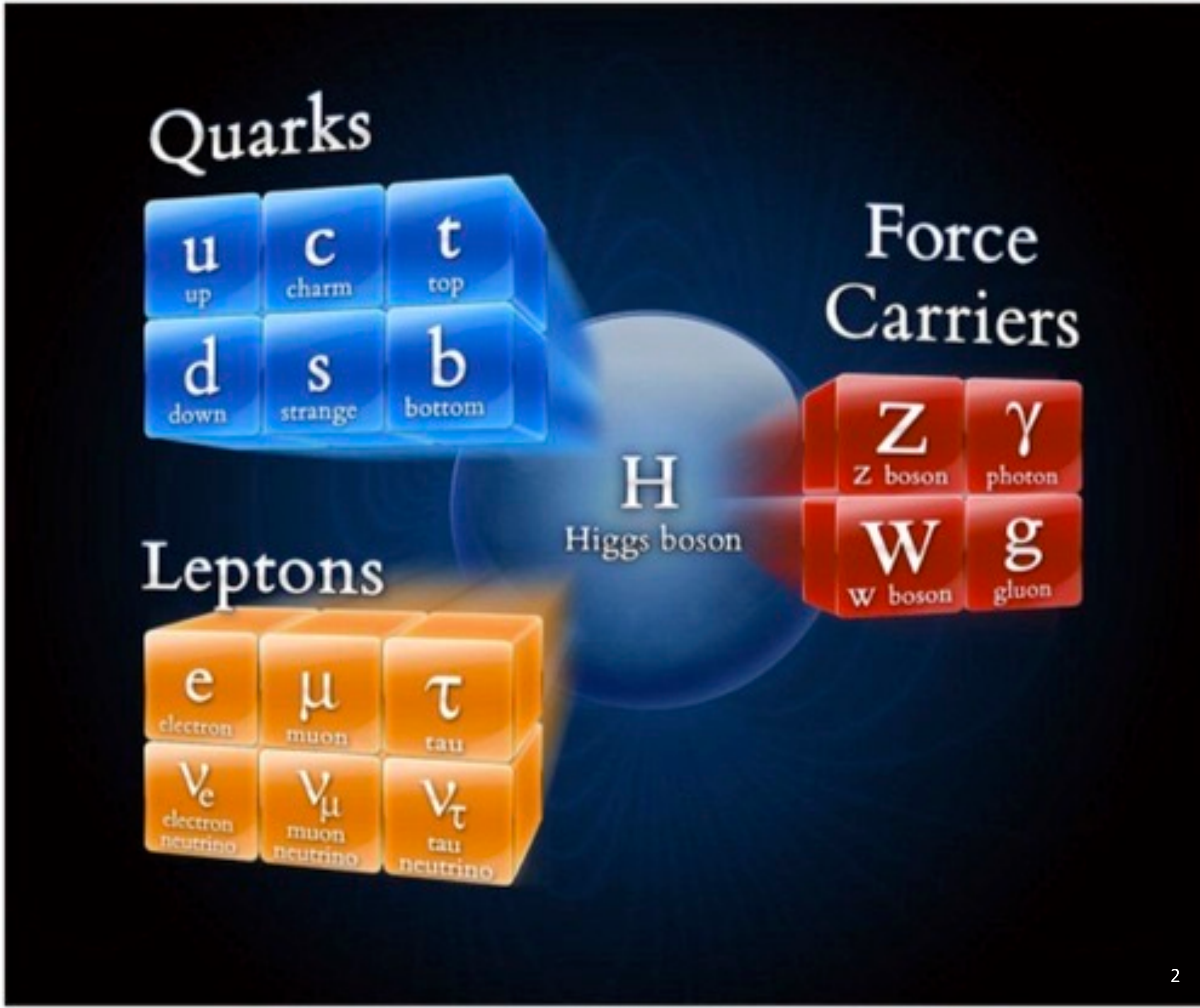
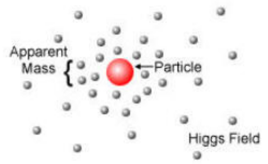
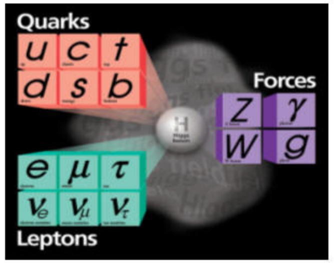
# The Standard Model

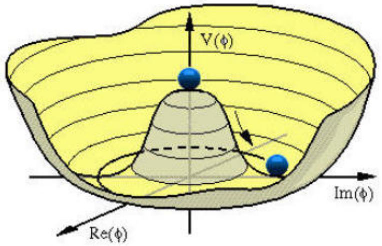
The three fundamental forces have been tested with high precision



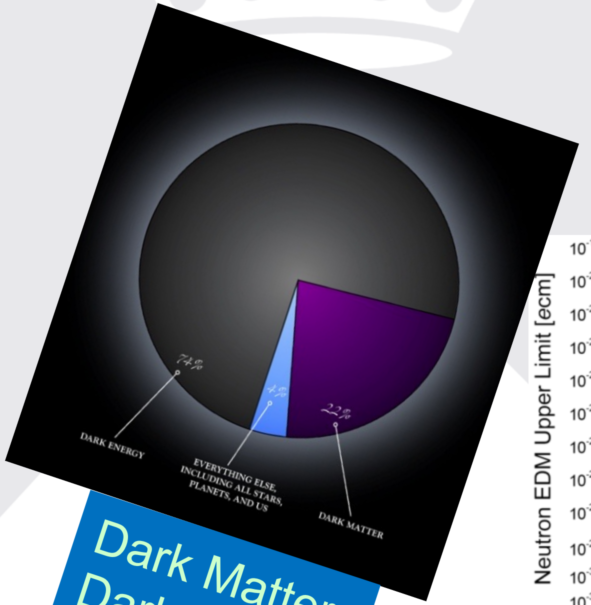
# We all believe SM is not the end of the story



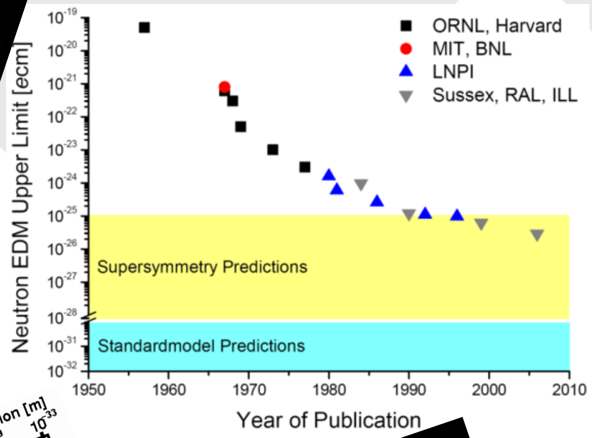



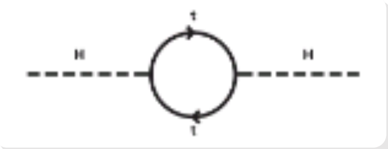

Electroweak Symmetry Breaking

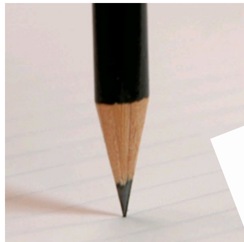



Dark Matter
Dark Energy

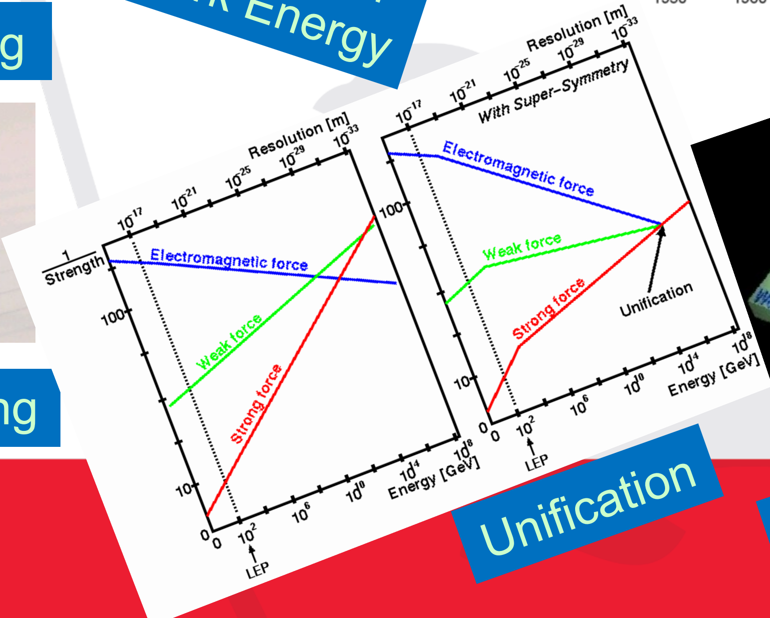
Strong-CP problem



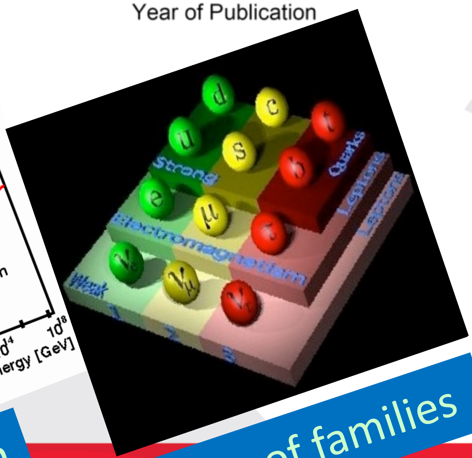



Fine tuning



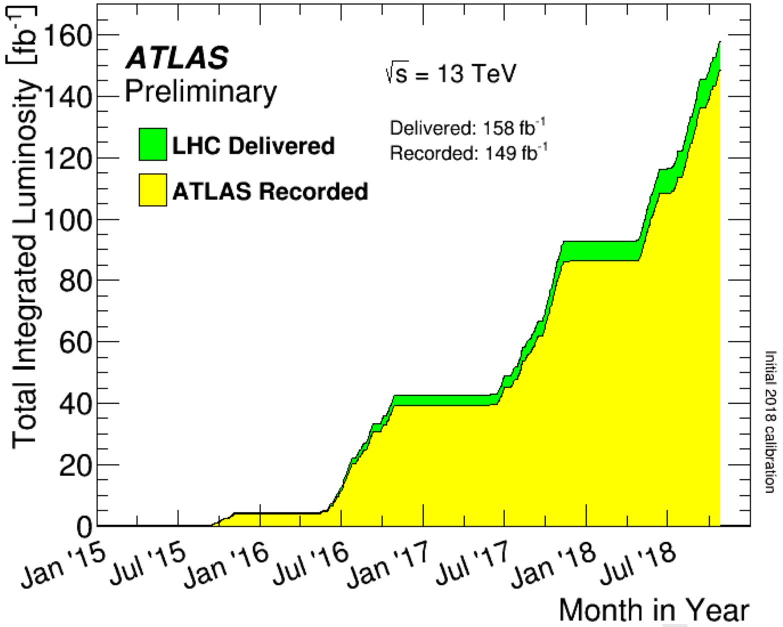

Unification




Number of families

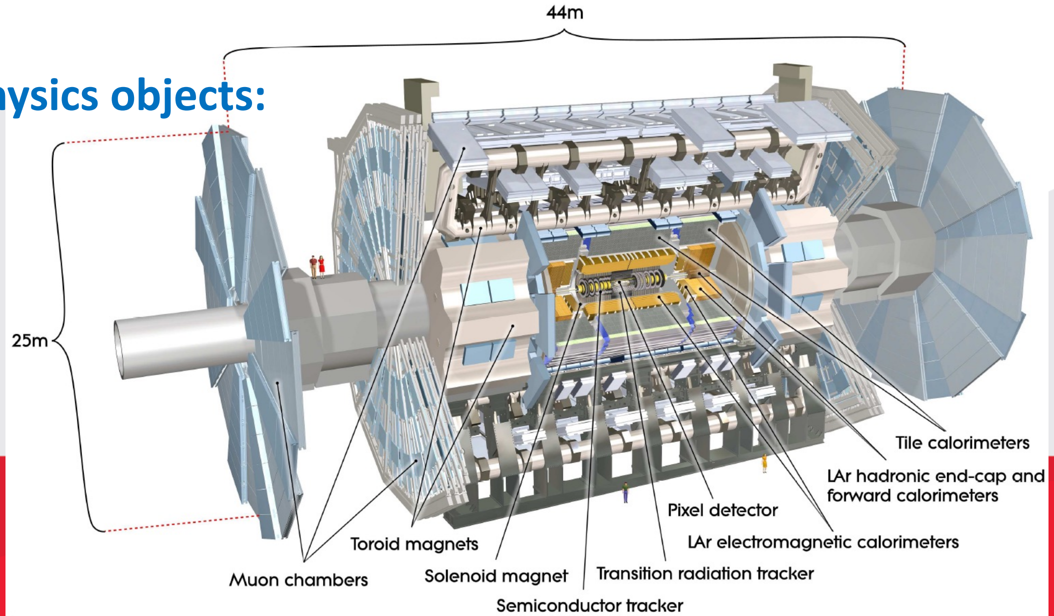
# Large Hadron Collider

# Detector and data



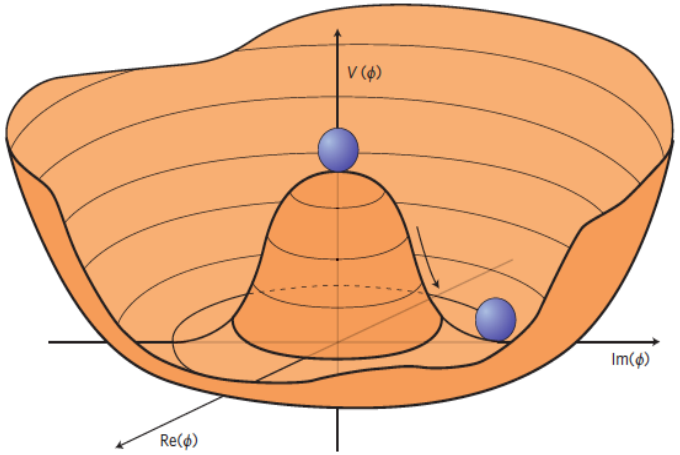

- **Excellent data taking efficiency and excellent data quality**
- **Good for physics**
  - **2011: 4.6 $fb^{-1}$ of 7 TeV data**
  - **2012: 20.3 $fb^{-1}$ of 8 TeV data**
  - **2015+2016: 36.1 $fb^{-1}$ of 13 TeV data**
  - **2015+2016+2017: 80 $fb^{-1}$ of 13 TeV data**
  - **2015+2016+2017+2018: 149 $fb^{-1}$ of 13 TeV data**

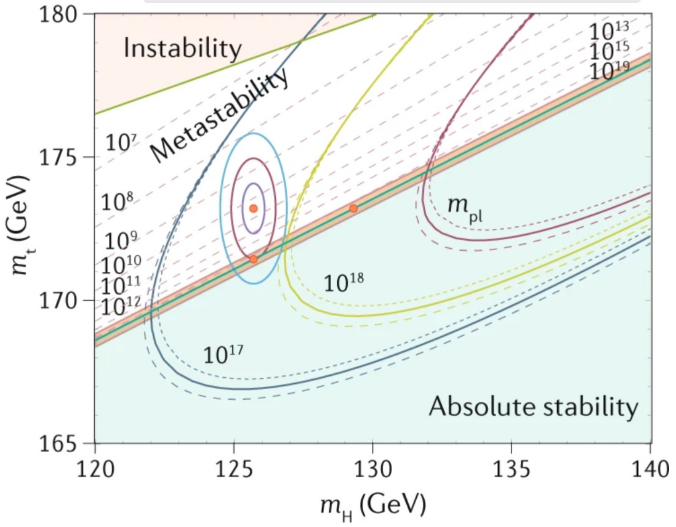
- **General purpose detectors with $4\pi$ coverage**
- **Sub-detector systems used to identify and reconstruct the physics objects:**
  - **Charged leptons**
  - **Photons**
  - **Jets**
  - **Missing transverse momentum (neutrinos)**

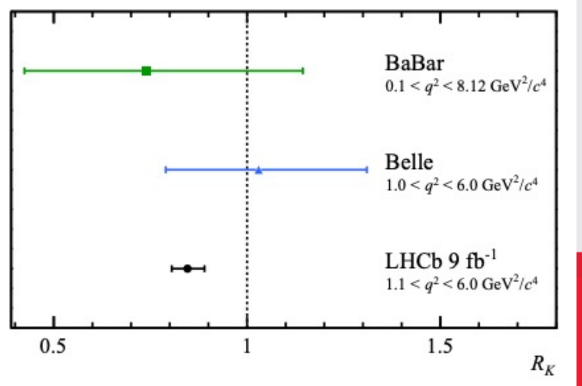


# Introduction

- The discovery of the Higgs boson opens a new portal to search for new physics, led to the 2013 Nobel Prize
  - Subsequent property measurements look for deviations from the SM
    - ➢ Top-Yukawa is one of the most interesting places to search for new physics
  - The Higgs self-coupling measurement is the only way to experimentally reconstruct Higgs potential
  - Same-sign lepton processes are typically rare but can significantly suppress backgrounds
    - ➢ can be used to probe the fundamental constants above
- Recent evidence of Lepton Flavour Violation from LHCb in $b \rightarrow s l^+ l^-$ can be explained by the presence of heavy $Z'$ and Leptoquarks

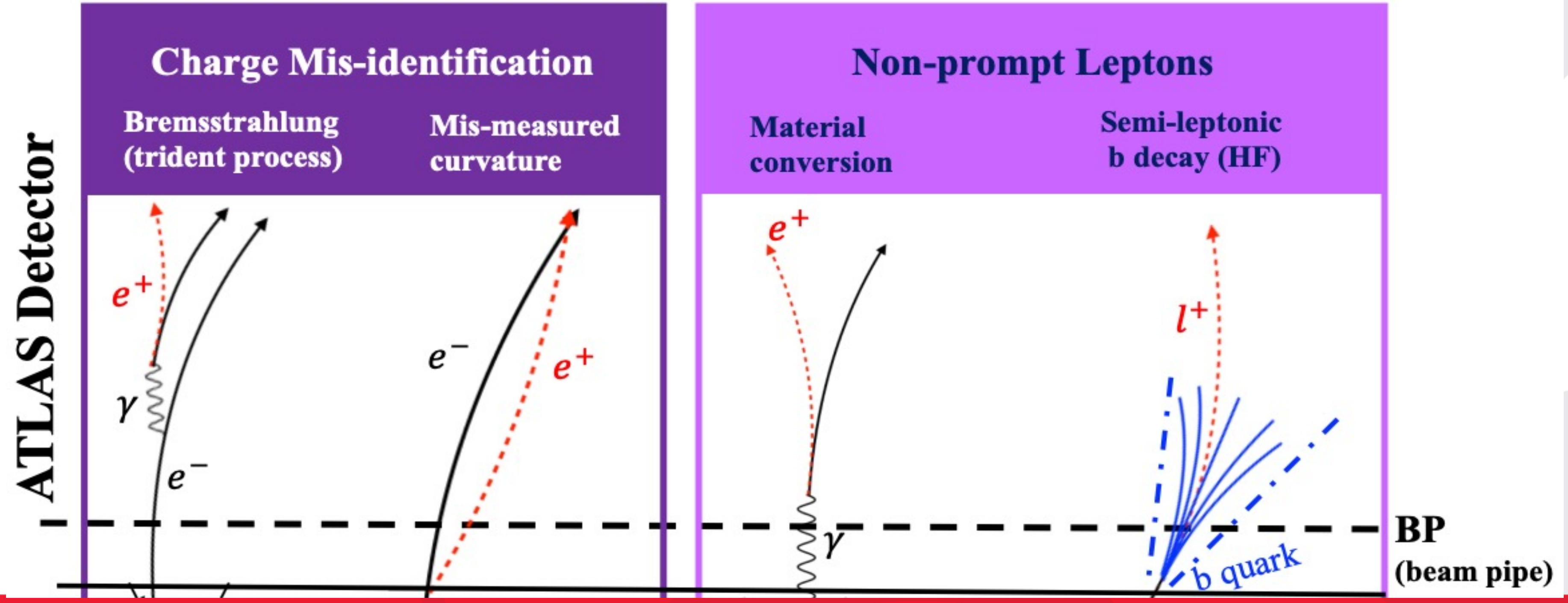


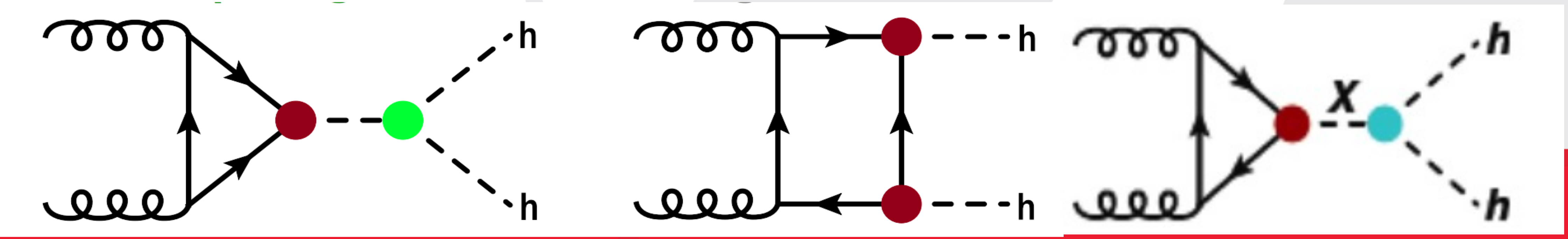
# Common fake lepton backgrounds in same-sign signatures

- **Fakes are usually the dominant backgrounds in the same-sign signatures**
  - **Charge misidentification ↷ data-driven using the $Z \rightarrow e^+e^-$ peak**
  - **Non-prompt leptons ↷ dedicated control regions for different fake origins**



# Search for $hh \to WW^*WW^*$

- The Higgs self-coupling measurement is the only way to experimentally reconstruct the Higgs potential
  - Vacuum structure
  - EW phase transition and EW baryogenesis
  - The fate of the universe
  - Probe new physics (is the Higgs boson alone?)
- Small SM cross section $\sigma = 33.41$ (10.15) pb at 13 (8) TeV due to the destructive interference between processes involving Higgs-self coupling and the box diagram with two tth vertices



# Search for $hh \rightarrow WW^*WW^*$

- Rare decay channel of $WW^*WW^*$ for di-Higgs production
  - branching ratio ~4.6%
  - First time we search for di-Higgs decaying to $WW^*WW^*$
- Production rates can be enhanced by BSM models
  - Non-resonant and resonant hh production (h represents SM Higgs, X represents the heavy Higgs in 2HDM)
    - ➢ $m_X = 260, 300, 400, 500$ GeV
  - First time we test $X \rightarrow SS$ model (S denotes a new Higgs-like scalar)
    - ➢ $m_X = 340$ GeV, $m_S = 135, 145, 155, 165$ GeV
    - ➢ $m_S = 135$ GeV, $m_X = 280, 300, 320, 340$ GeV

| | bb | WW | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 33% | | | | |
| WW | 25% | 4.6% | | | |
| ττ | 7.4% | 2.5% | 0.39% | | |
| ZZ | 3.1% | 1.2% | 0.34% | 0.076% | |
| γγ | 0.26% | 0.10% | 0.029% | 0.013% | 0.0005% |

10.23731/CYRM-2017-002

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# Analysis Strategy

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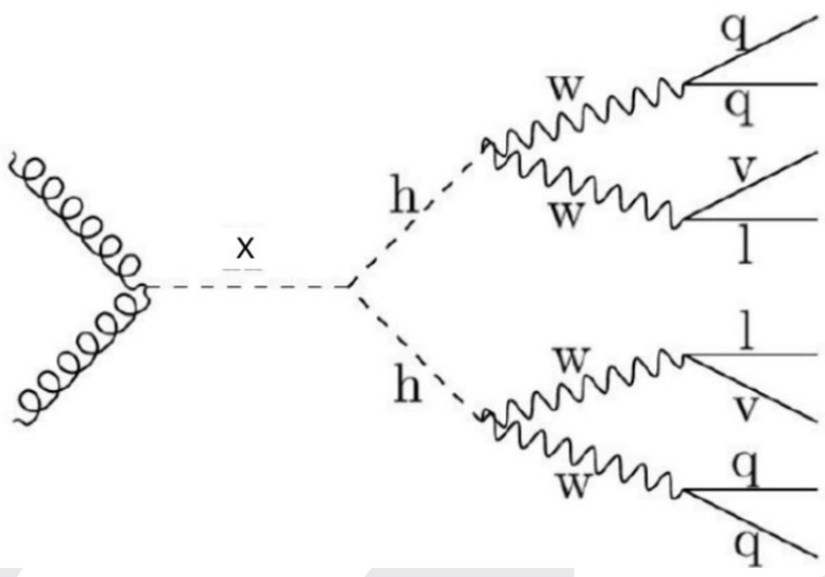
- Three channels based on the number of light flavour leptons ($e, \mu$) with b veto
    - Two same-sign leptons, missing transverse momentum and at least two jets
        - ➢ $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$
    - Three leptons, with a total charge of $\pm 1$, missing energy and at least two jets
        - ➢ SFOS12: $eee, ee\mu, \mu\mu e, \mu\mu\mu$
        - ➢ SFOS0: $e\mu\mu, \mu ee$
    - Four leptons, with a total charge of 0
        - ➢ SFOS01: ($e\mu$+$e\mu$), ($ee + e\mu$), ($\mu\mu$+$e\mu$)
        - ➢ SFOS2: ($4e$), (4$\mu$), (2$\mu$+2$e$)
- Optimise selections based on $S/\sqrt{B}$ for each channel and for each mass point
    - Cut and count analysis

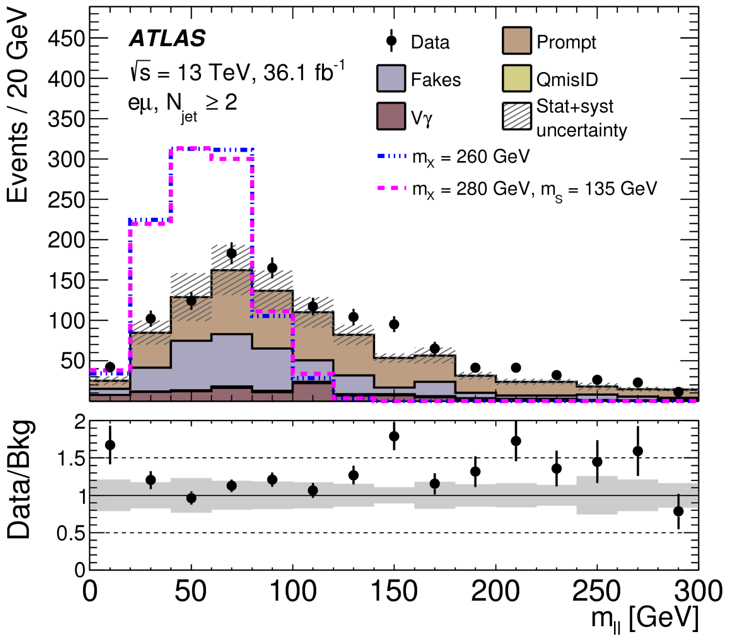


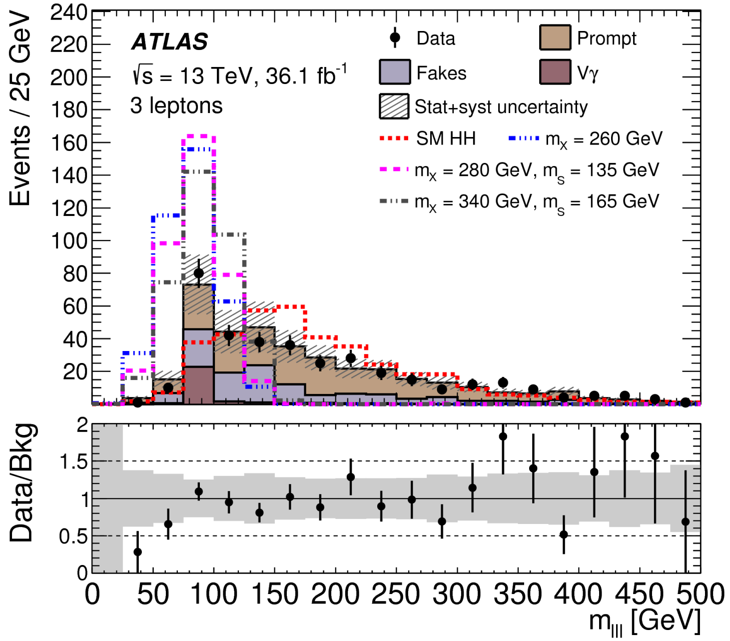
# Optimisation

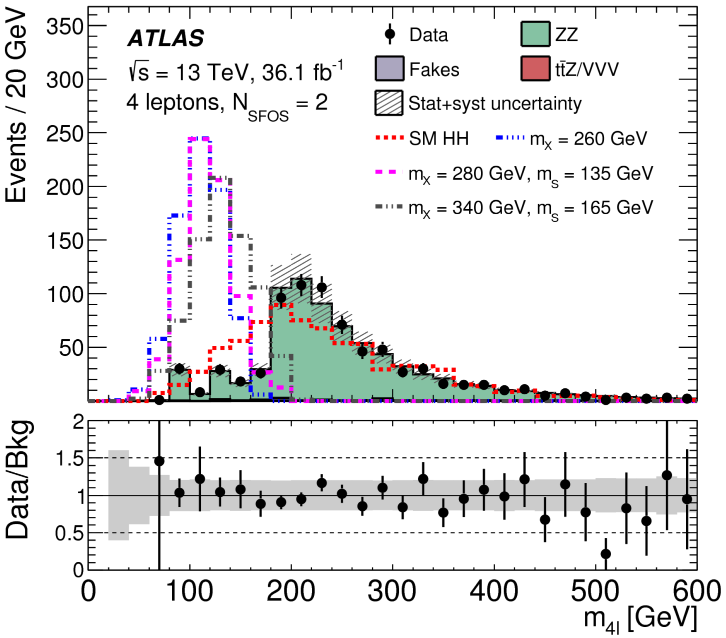
[JHEP 05 (2019) 124]

- **Optimisation strategy**
  - **Two leptons and three leptons**
    - ➢ Prompt lepton backgrounds originate from VV, tV, ttV, VVV
    - ➢ MET > 10 (30) GeV for two (three) leptons
    - ➢ Rank and select four observables for further optimization using TMVA
  - **Four lepton**
    - ➢ Prompt lepton backgrounds dominated by ZZ
    - ➢ Use $m_{4l} < 180$ and $m_{4l} > 180$ GeV to improve sensitivity

**Systematics dominated by JES/JER and fake lepton estimation**



# Results

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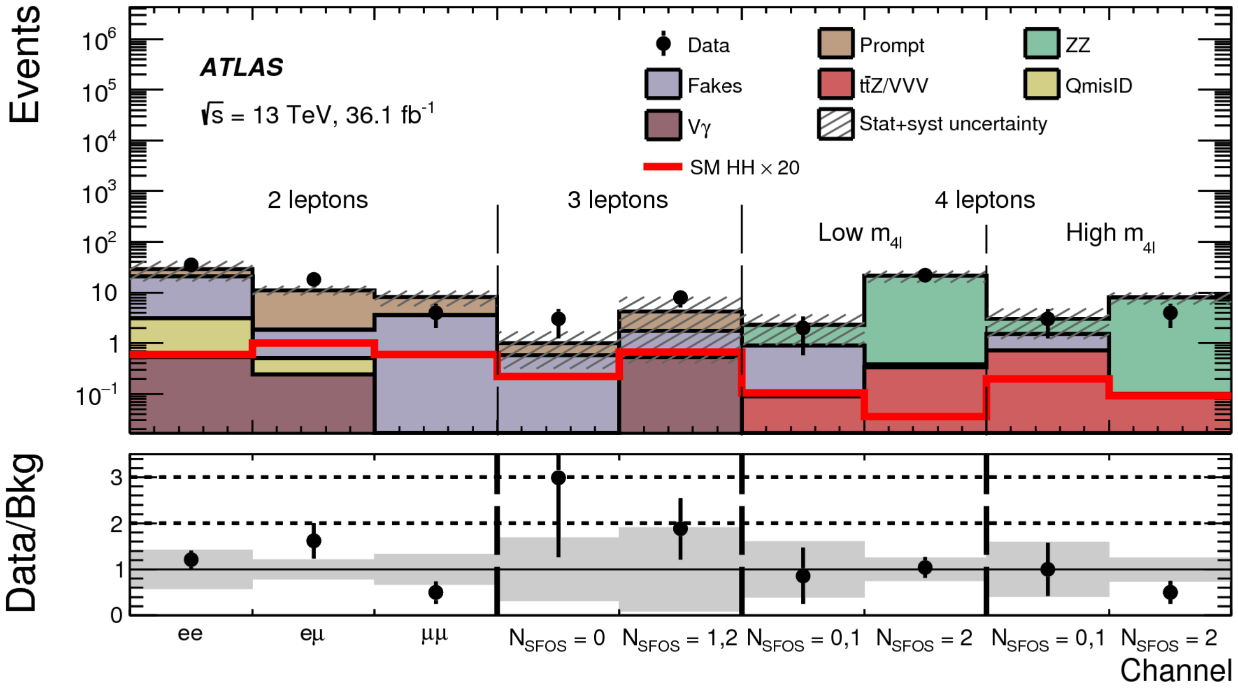


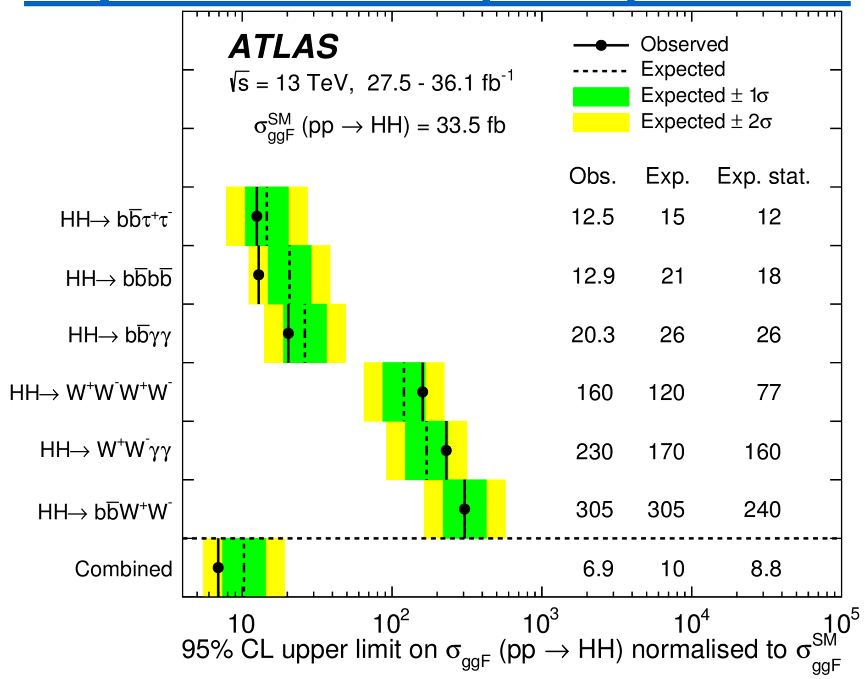


- No significant excess above the SM background
- Combined limit on the non-resonant di-Higgs cross-section: 160 (110) x SM cross section
- Room for improvement
  - Use Advanced machine learning techniques to improve sensitivity
  - Explore hadronic $\tau$ channels

# Resonant results

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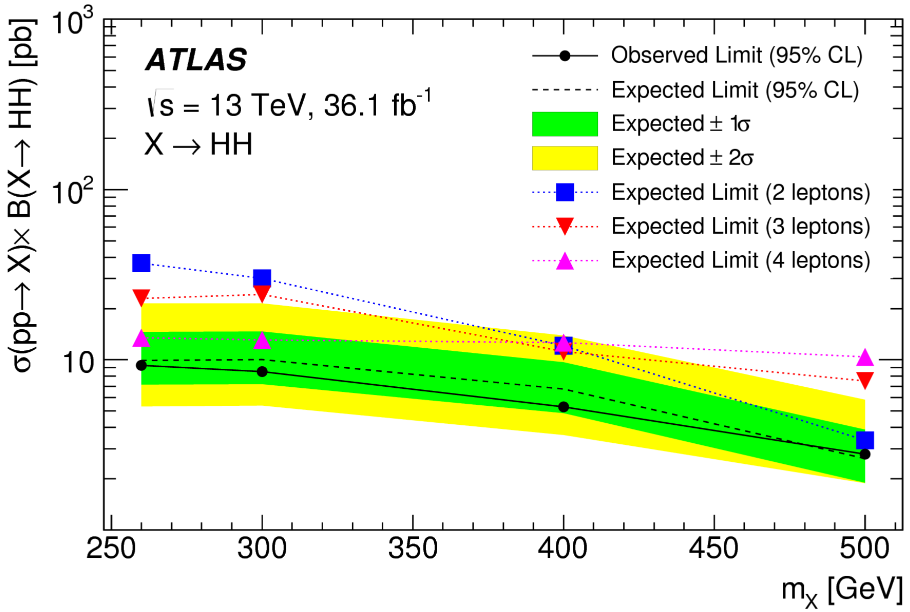
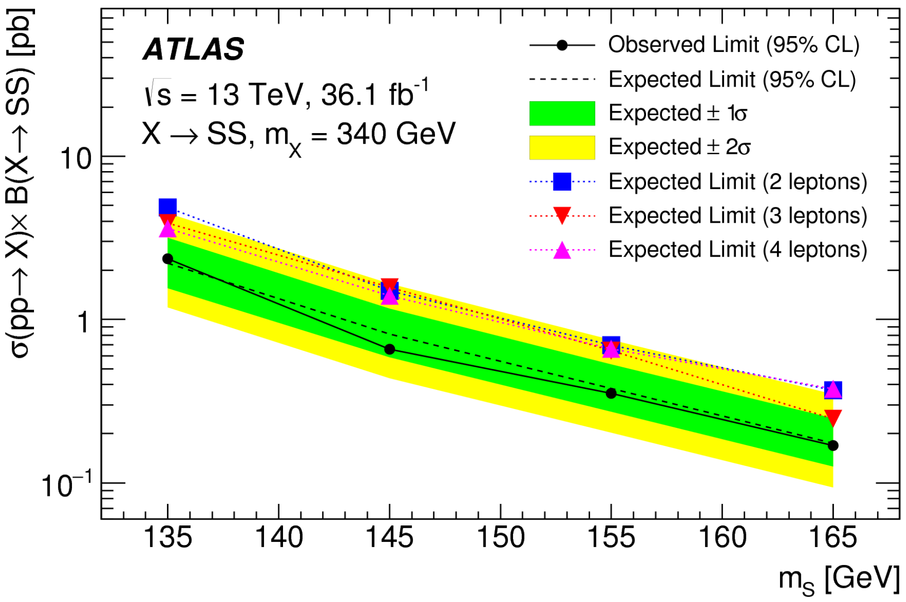
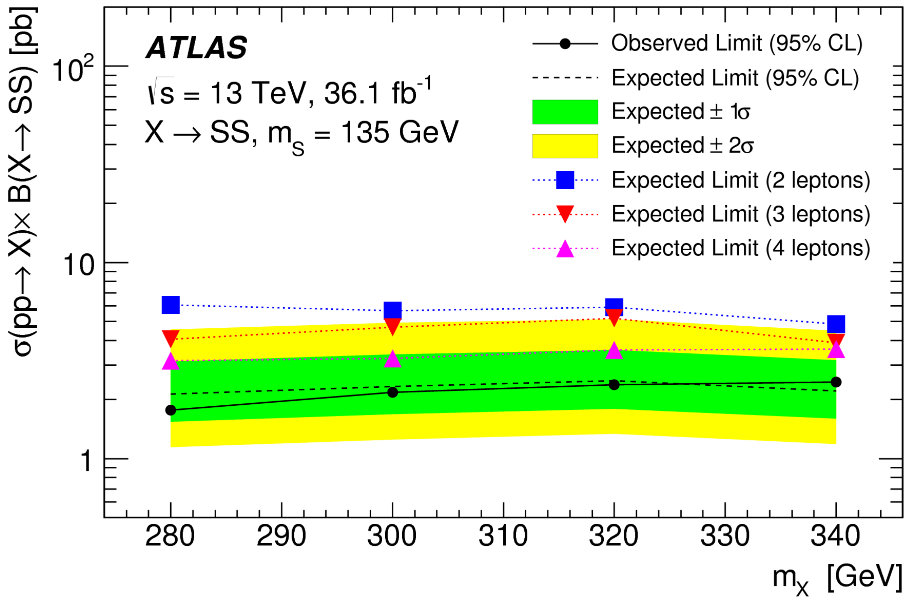


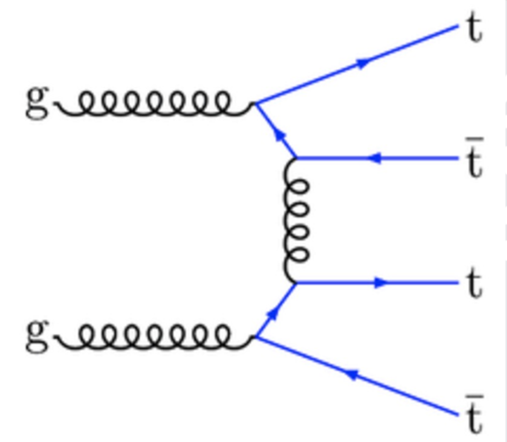

- **Higher sensitivity to $X \rightarrow SS$ model as $m_S \rightarrow 2m_W$**



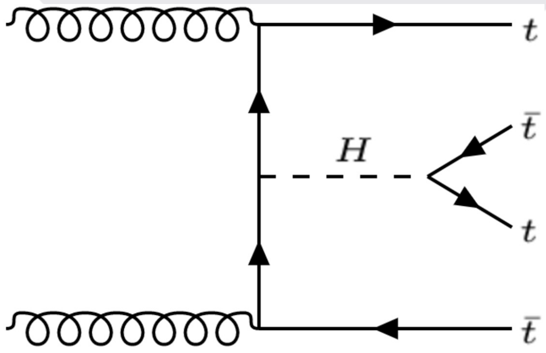



# Evidence for $t\bar{t}t\bar{t}$

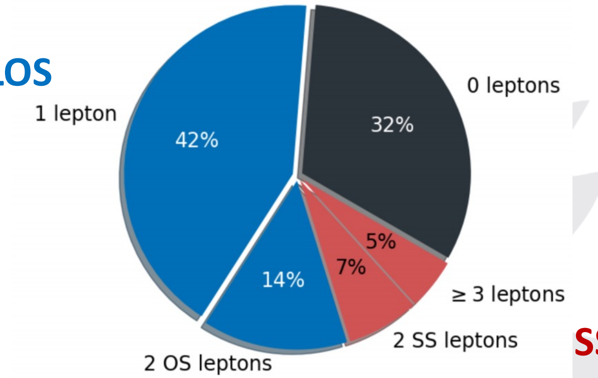
Eur. Phys. J. C 80 (2020) 1085




- The most massive final state ~ 700 GeV
- A rare process sensitive to the magnitude and CP nature of top-Higgs coupling
  - $\sigma_{t\bar{t}t\bar{t}} = 12 \pm 2.4$ fb at 13 TeV NLO QCD+EW
- Sensitive to new physics e.g., two Higgs doublet model
- Both 1LOS and SSML have been explored at LHC
  - Clean signature with high (b-) jet multiplicity and hadronic activities
  - 1LOS: large branching ratio; large background from $t\bar{t}$+heavy/light jets
  - SSML: ~12% branching ratio; small background from $t\bar{t}V$, non-prompt leptons and wrong charge assignment




1LOS

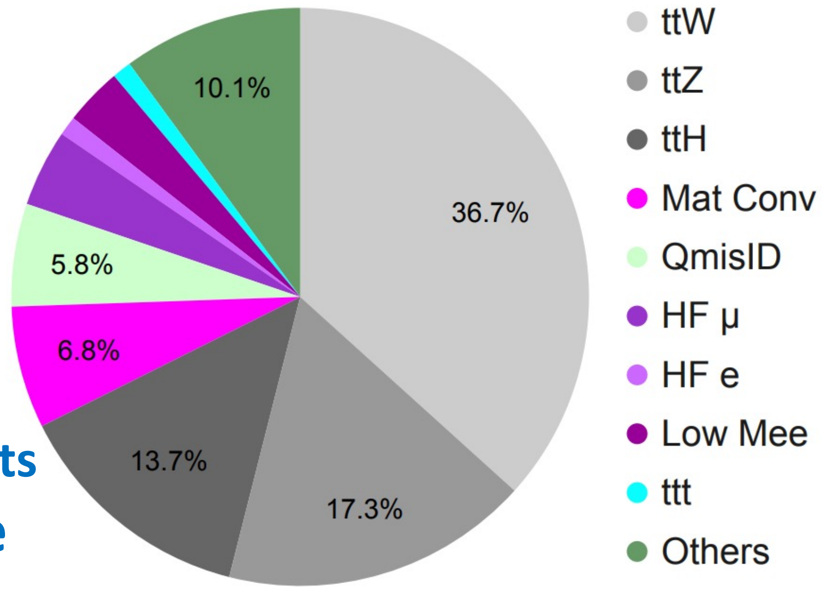



SSML

# Analysis strategy in SSML

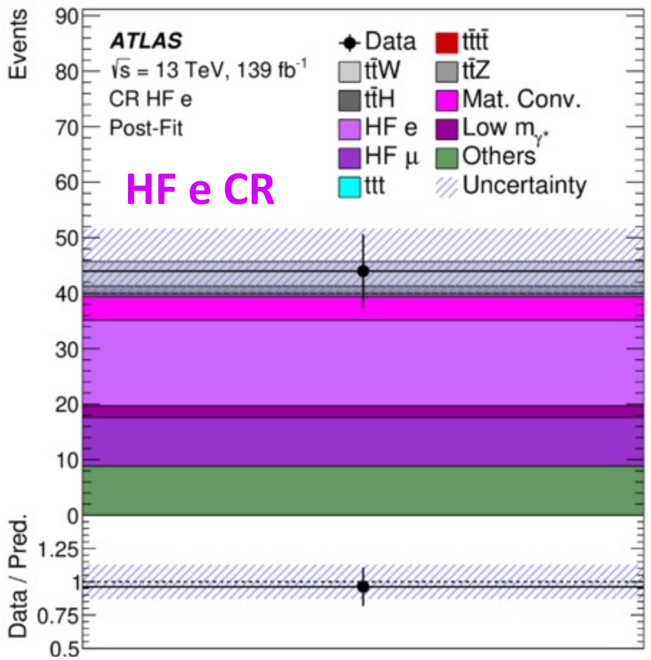
- Targets at least two of the W bosons decay leptonically
- Baseline selection
  - $\geq 6$ jets
  - $\geq 2$ b-tagged jets
  - $H_T > 500$ GeV
    - ➢ $H_T$ is the sum of the transverse momenta of leptons and jets
- Backgrounds dominated by the irreducible and reducible backgrounds
  - Irreducible backgrounds from simulation except ttW
    - ➢ ttW, ttZ, ttH and smaller background (VV, VVV, tV, tVV, ttWW, $ttt$)
  - Reducible backgrounds: non-prompt leptons and charge mis-ID (QmisID)
    - ➢ Electrons/muons from heavy flavour decay HF μ (e)
    - ➢ Electrons from $\gamma$ conversion in detector Mat Conv
    - ➢ A virtual photon leading to an $e^+e^-$ pair Low Mee

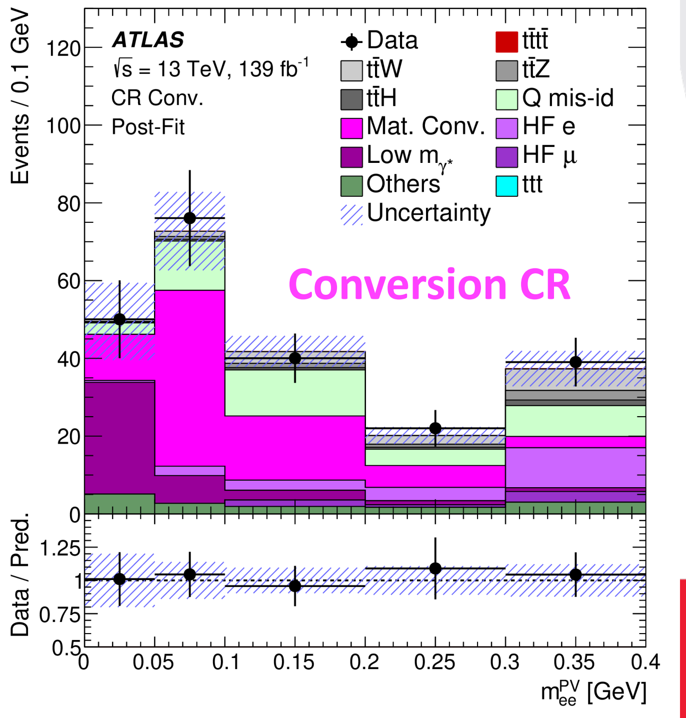
**Backgrounds:**

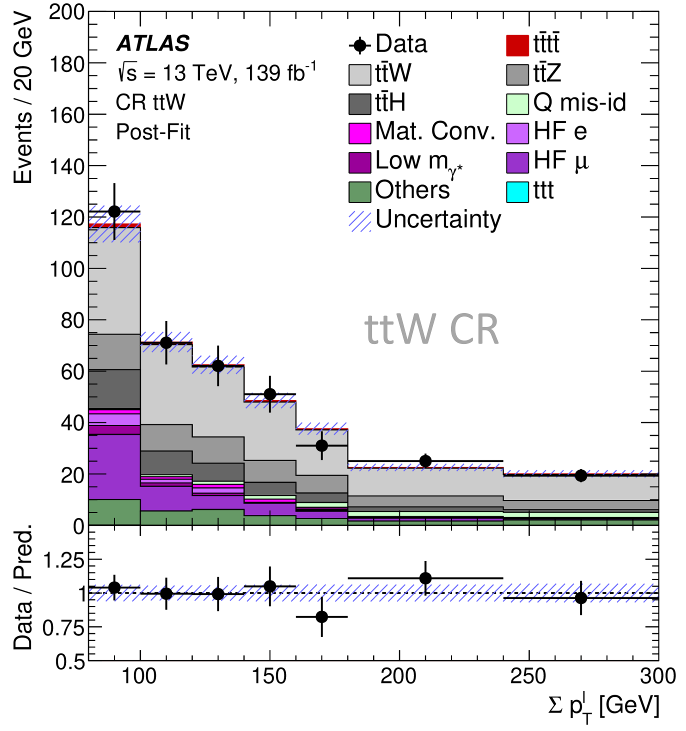


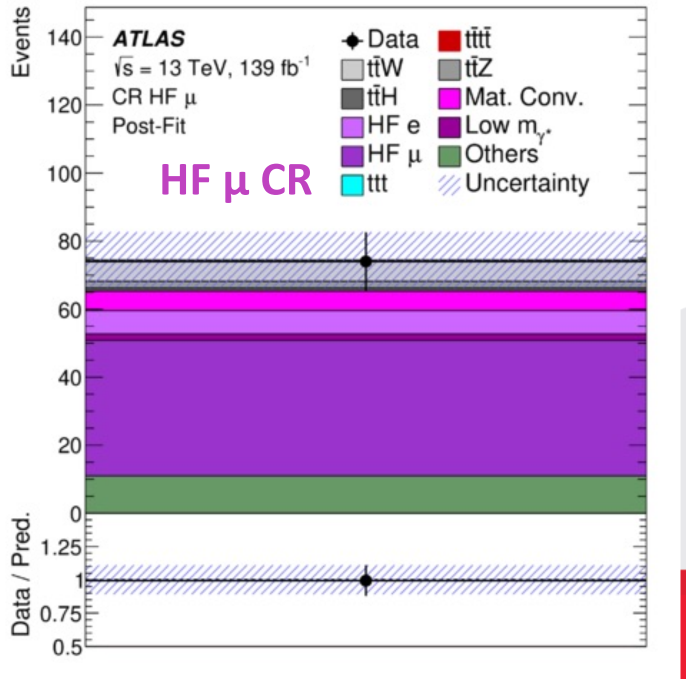
# Template fit method

- Use template fit method to estimate major backgrounds
  - Background shapes taken from MC
  - Normalisation is allowed to float in the fit
  - Dedicated control regions to constrain the normalization factors
  - Validation regions to test modellings



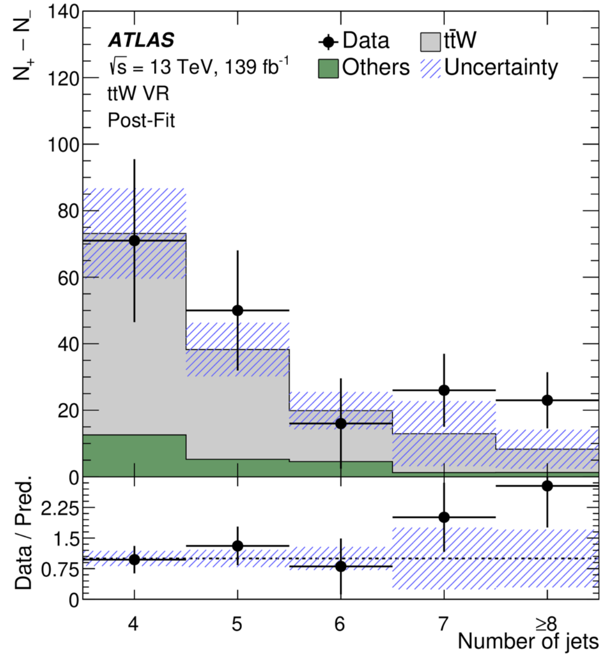



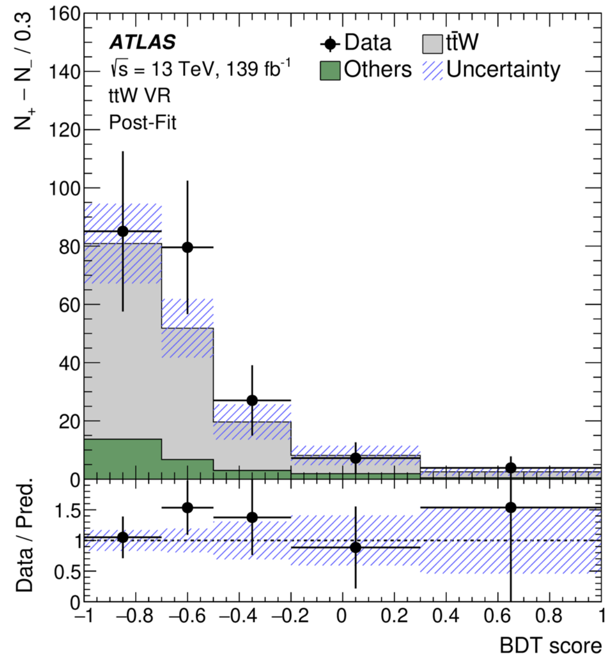



# Template fit results

- Apart from $t\bar{t}W$, all the other normalisation factor (NF) is consistent with 1
  - Compatible with the already published ttH multilepton results, [ATLAS-CONF-2019-045]
  - Validation region is defined using $t\bar{t}W$ charge asymmetry
    - ➢ $t\bar{t}W^{+}$: $t\bar{t}W^{-}$ ~ 2:1
    - ➢ Difference removes charge symmetric processes
    - ➢ Precision dominated by $t\bar{t}$W +>=7 jets, 125%(300%) $t\bar{t}$W for 7 (>=8) jets, as well as $t\bar{t}$W + additional b jets (50%)

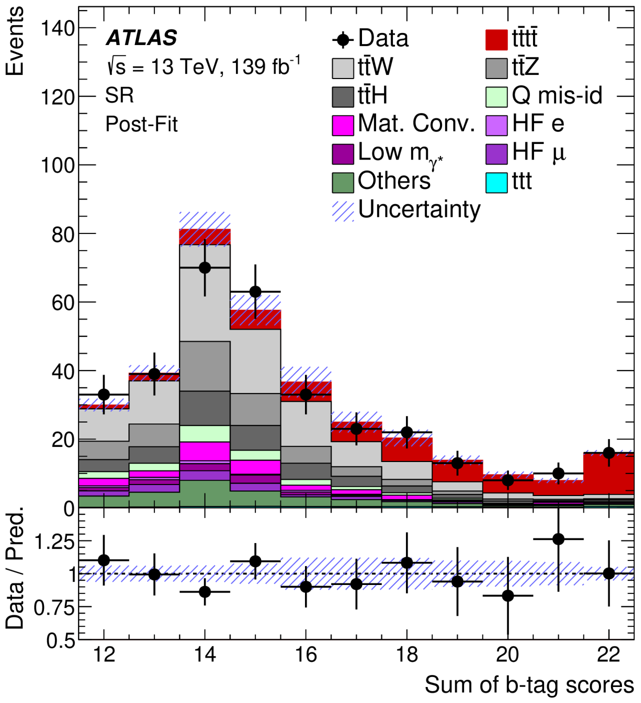
| Parameter | $NF_{t\bar{t}W}$ | $NF_{\text{Mat. Conv.}}$ | $NF_{\text{Low } M_{ee}}$ | $NF_{\text{HF } e}$ | $NF_{\text{HF } \mu}$ |
|---|---|---|---|---|---|
| Value | $1.6 \pm 0.3$ | $1.6 \pm 0.5$ | $0.9 \pm 0.4$ | $0.8 \pm 0.4$ | $1.0 \pm 0.4$ |

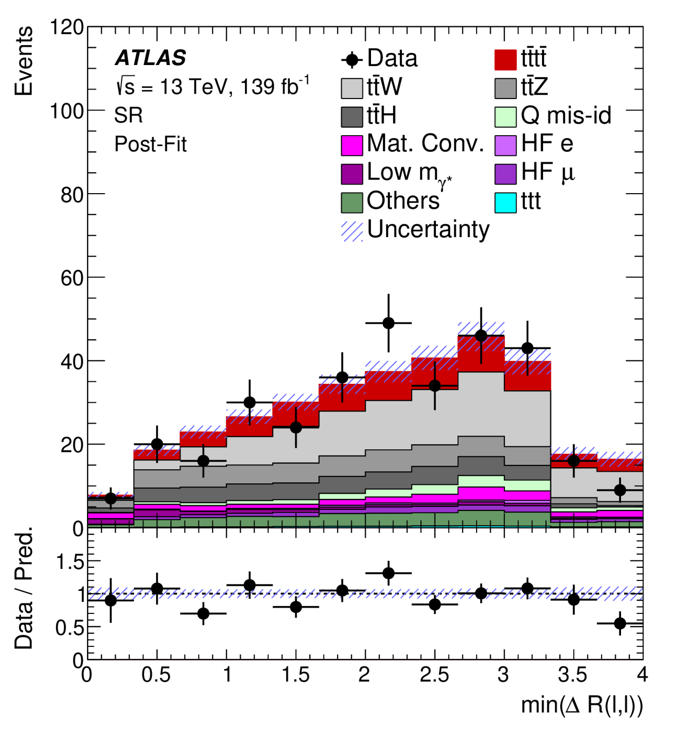


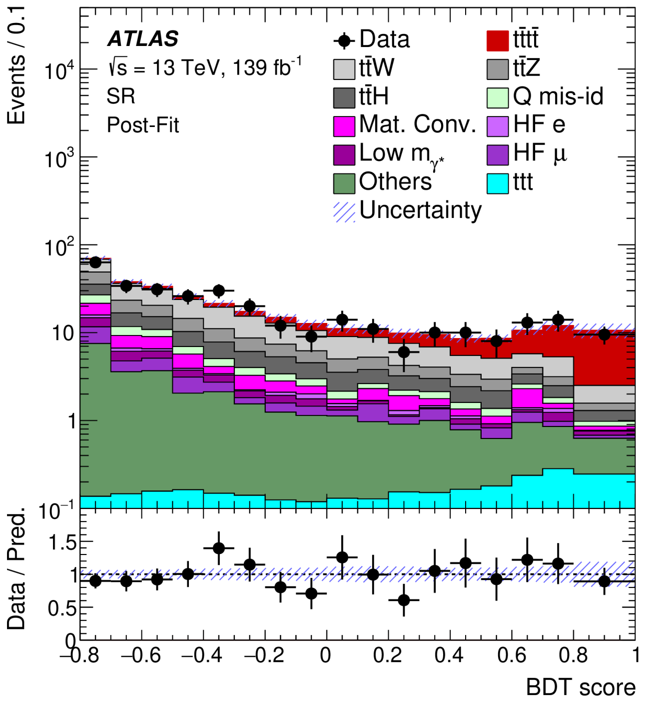



# Signal optimisation

- **Use advanced machine learning techniques by combining b-tagging and kinematics of leptons and jets into a single BDT score**
- **Check modellings of all inputs are reasonable**



# Evidence for $t\bar{t}t\bar{t}$

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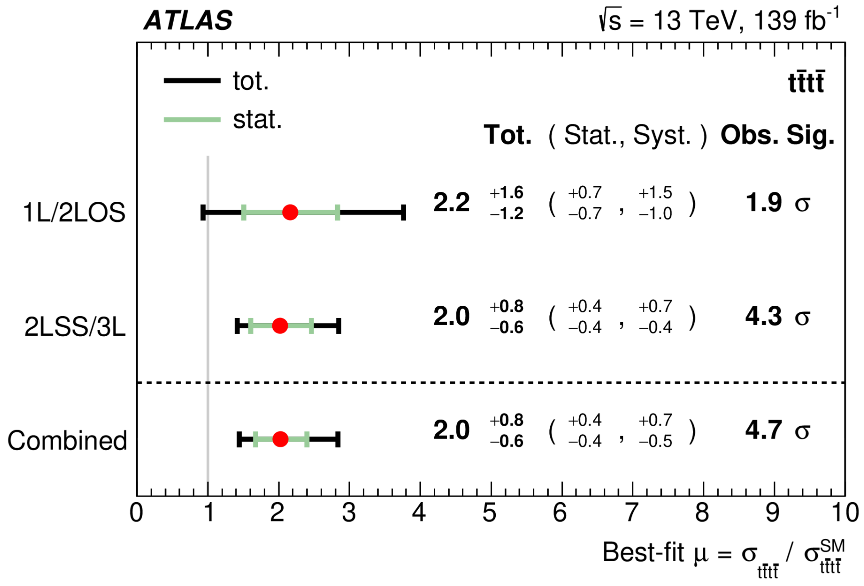
- First evidence of $t\bar{t}t\bar{t}$ production in SSML at ATLAS, observed (expected) significance $4.3(2.4)\sigma$, $\sigma_{t\bar{t}t\bar{t}}^{measured} = 24^{+7}_{-6}$ fb

Systematic dominated by signal modelling and ttW modelling at high (b-)jet multiplicity

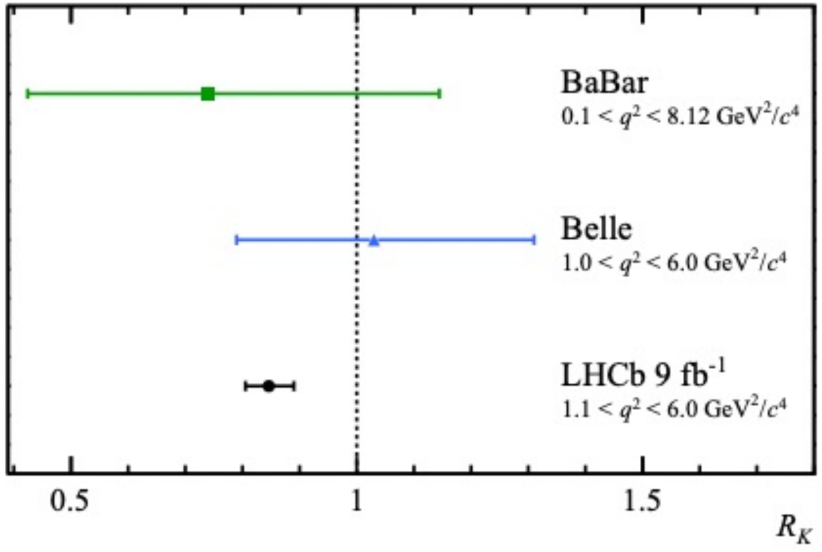


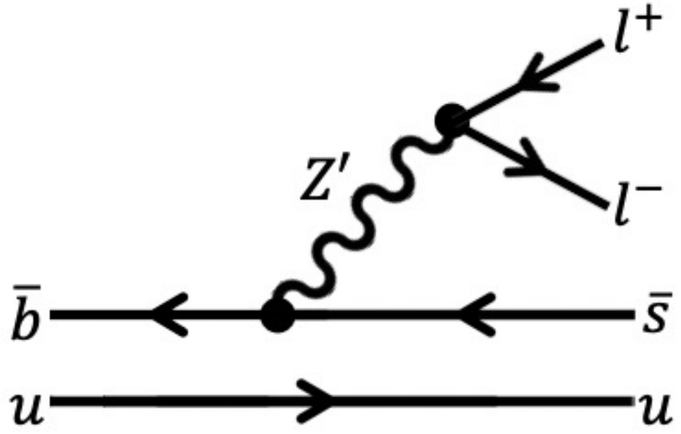

1LOS+SSML: $4.7\ (2.6)\ \sigma$ observed (expected )

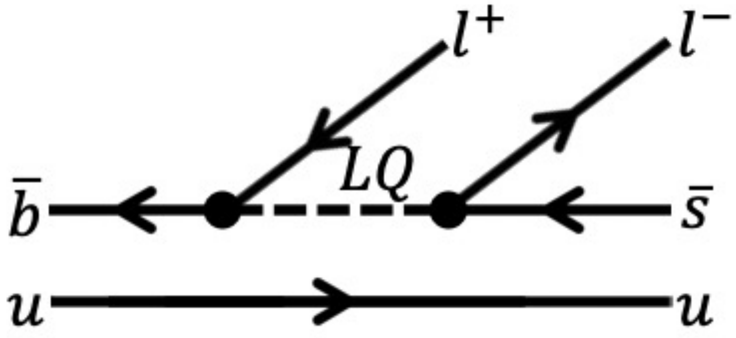
CMS SSML results: 2.6(2.7) $\sigma$ observed(expected)

# Lepton universality tests

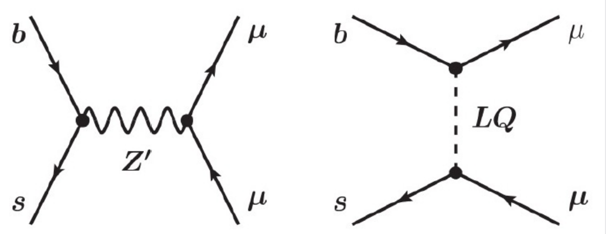
- The more recent Lepton Universality tests in $b \to s l^+ l^-$ by LHCb shows 3.1 standard deviations from SM prediction
- Possible explanations involve tree-level new physics competing with SM loop and box diagrams



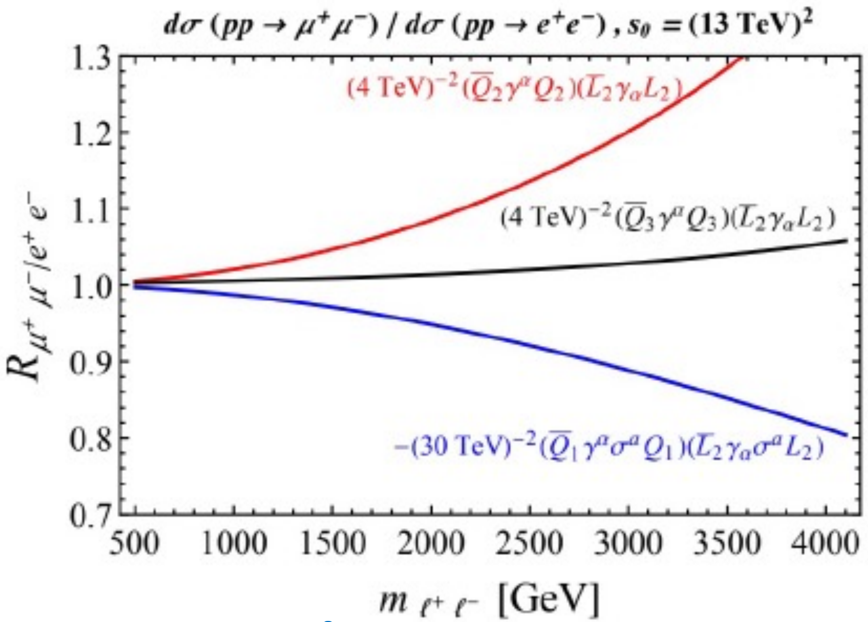



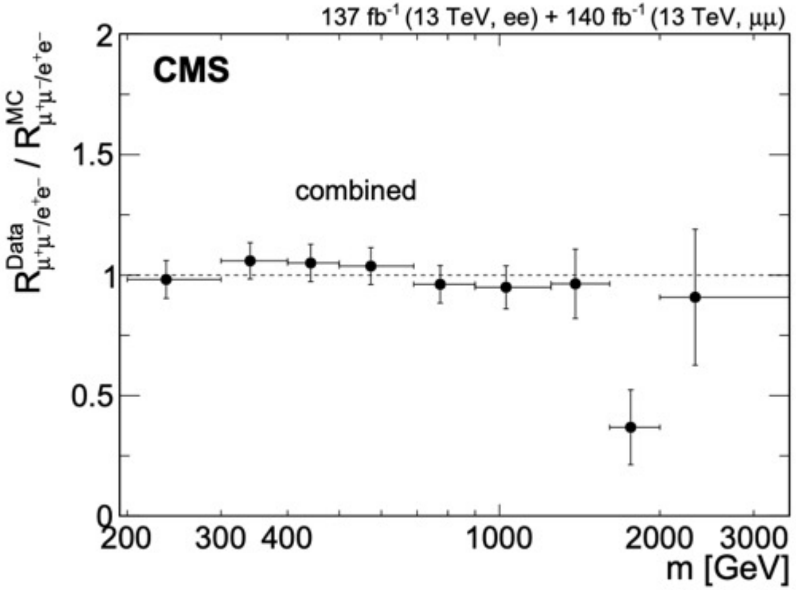
# Lepton universality tests




- **The recent evidence lepton flavour violation has prompted relevant tests in ATLAS and CMS**
- **Presence of heavy neural boson $Z'$ or Leptoquarks have implementations at high-$p_T$ tail in the Drell-Yan process**




[arXiv: 2704.09015]

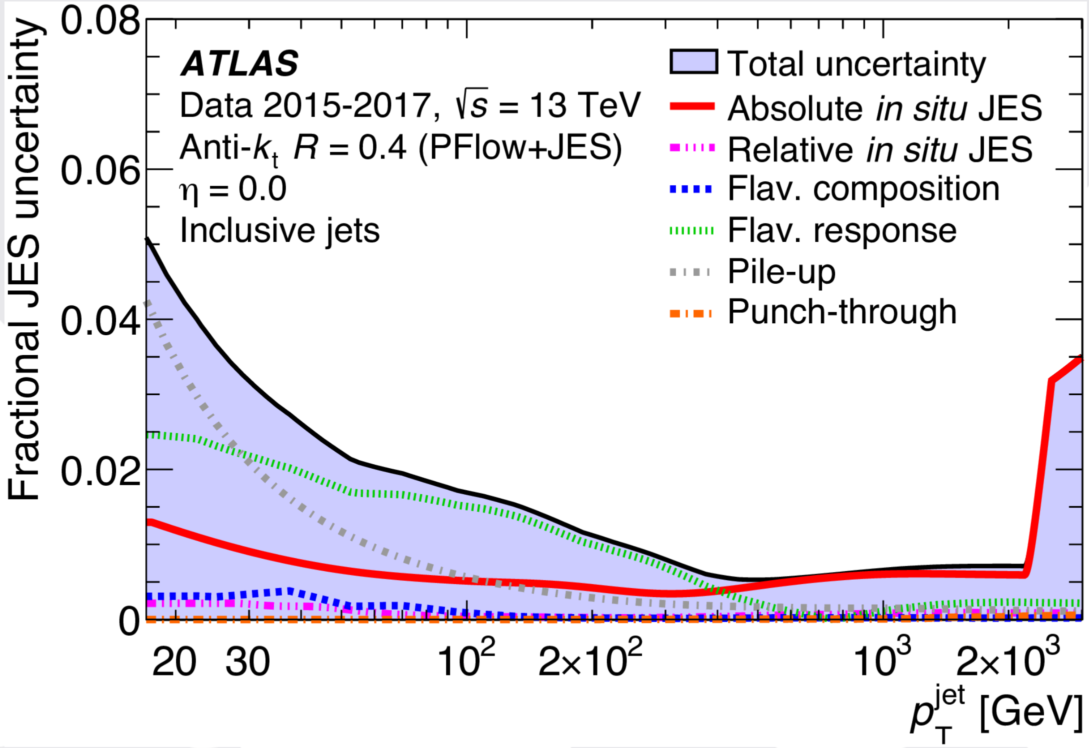



[JHEP 07 (2021) 208]

Currently the corresponding ATLAS analysis contacts/editors

# Jet reconstruction and calibration at ATLAS

- **60% of ATLAS publications have jets in the final state including the above three publications**
- **Jets are reconstructed using anti-$k_t$ algorithm with radius 0.4 or 1**
  - **Inputs are built from energy deposits in the calorimeter and the tracks in the inner detector**
  - **Led the calibration efforts for both small- and large-R jets**
    - ➢ **Provided the consolidated jet calibration that has been widely used in Run II analysis**

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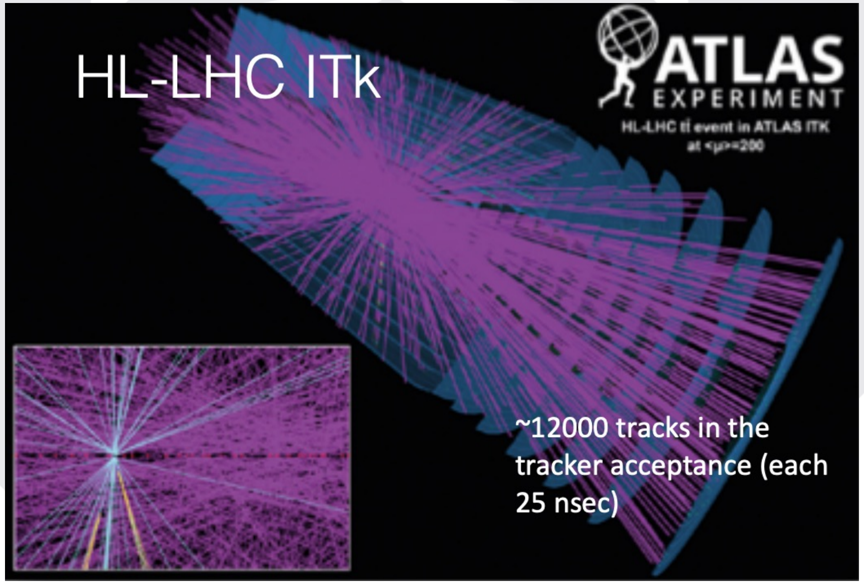
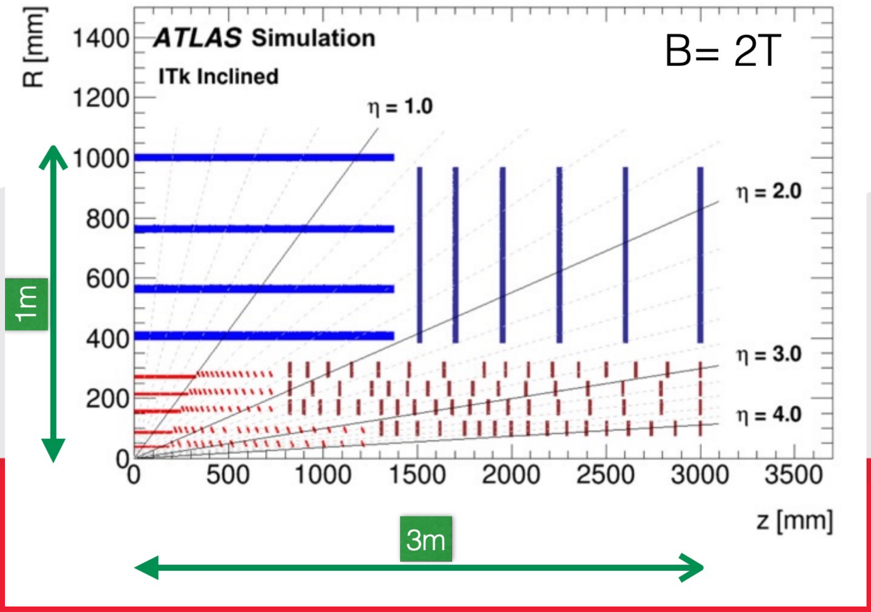
# Inner tracker upgrade at ATLAS

- **The Goal of ITk upgrade is to have similar performance as the current detector but in harsher environment**
  - **All silicon**
    - ➢ **Precision charged particle trajectories and vertex reconstruction**
  - **$|\eta|$ range extended to 4 (current 2.5)**
  - **Pixel: 5 barrel layers+ ring disks**
  - **Strip: 4 barrel layers+ 6 endcap rings**

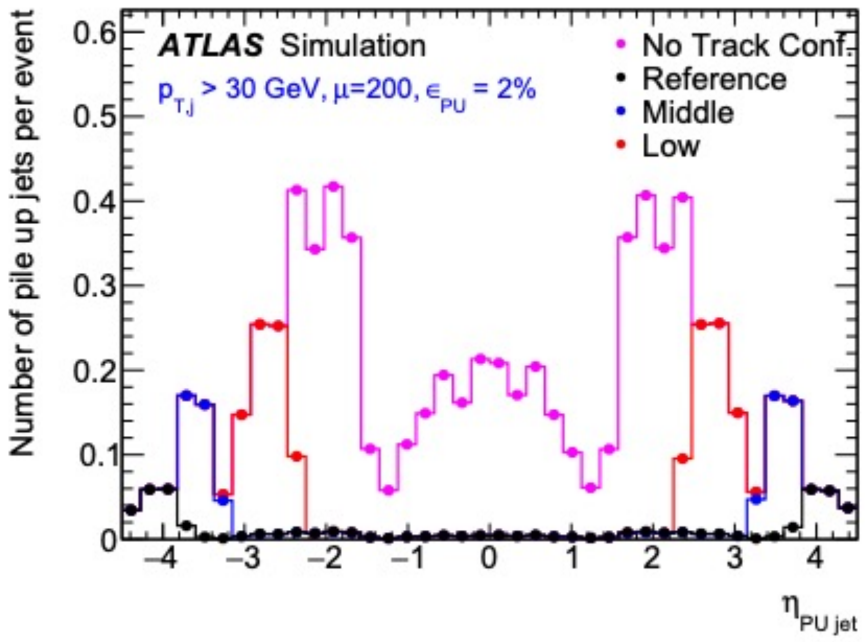


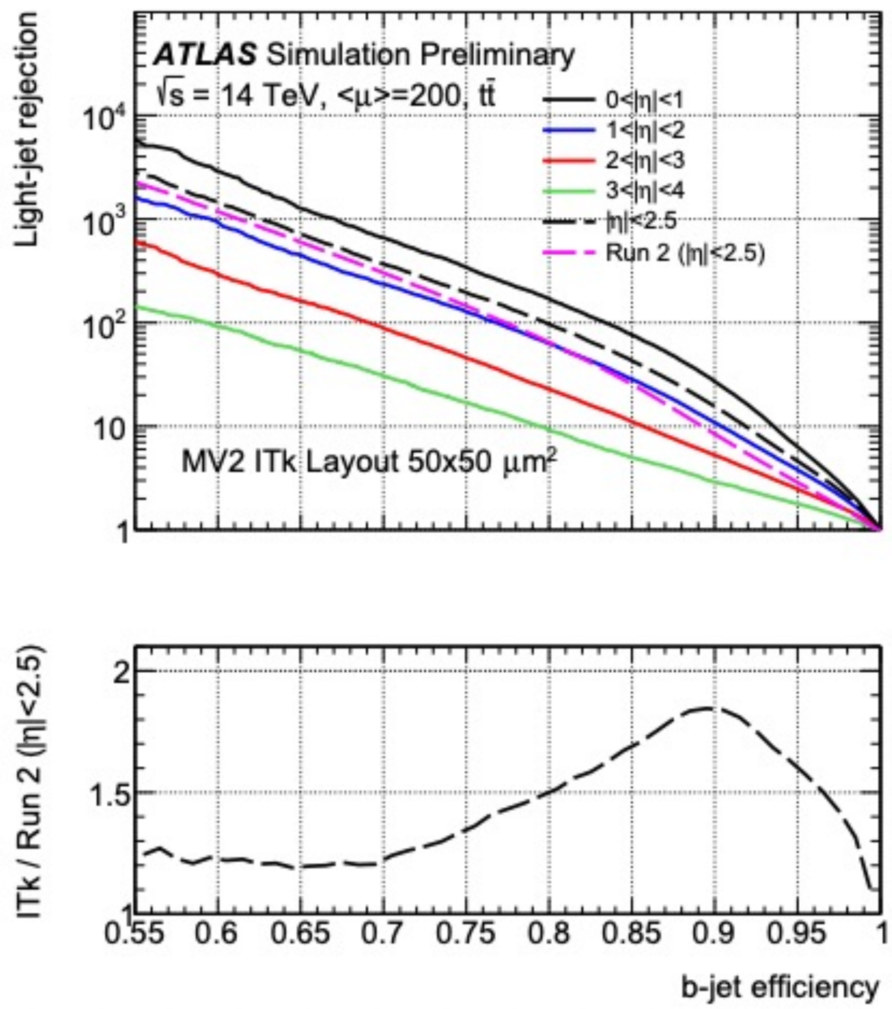



# Expected performance of the Itk

- **Itk upgrade is expected to improve**
  - **Pile-up rejection and hence MET resolution**
  - **Light jet-rejection in b-tagging**
  - **Forward pile-up/b tagging due to extended coverage**

**Further improvement in forward region can brought by the timing information from High Granularity Timing Detector (HGTD)**



# Looking forward

- **The discovery of the Higgs boson in 2012 opens a new portal to search for new physics**
- **No significant excess over the SM prediction has been observed yet**
  - **Precision measurement of the Higgs properties is still the best chance we got to search for new physics**
  - **Hints of new physics may come from lepton flavour universality tests**

# Inner tracker upgrade at ATLAS

- **DESY is committed to building the endcap ITk**
- **Recently helped investigate the sources of adhesive oozing out of numerous bond pad top Kapton openings (cover layer openings) during co-curing process**
  - **Examine the bustape under the micro-tape to check which openings are covered with adhesive**
  - **Electrical tests of the petal core circuits using a robot**