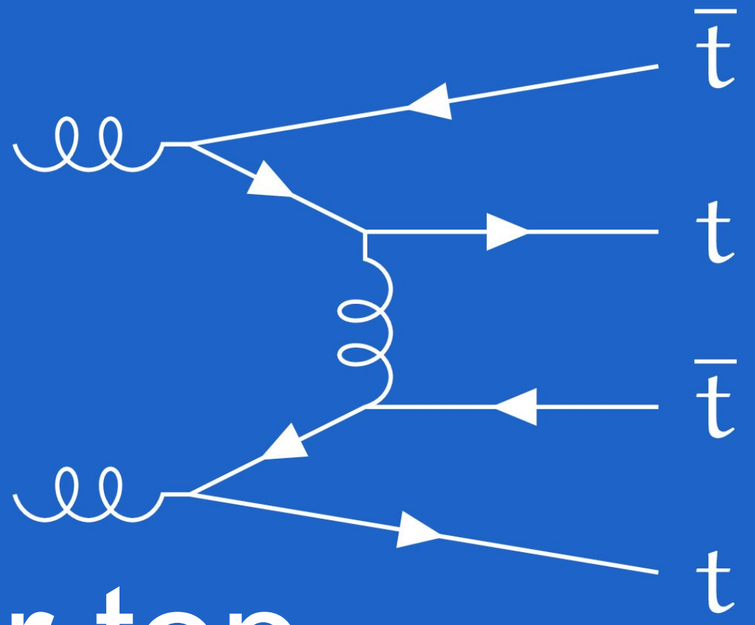


First observation of four top quark production at CMS

Niels Van den Bossche on behalf of the CMS Collaboration

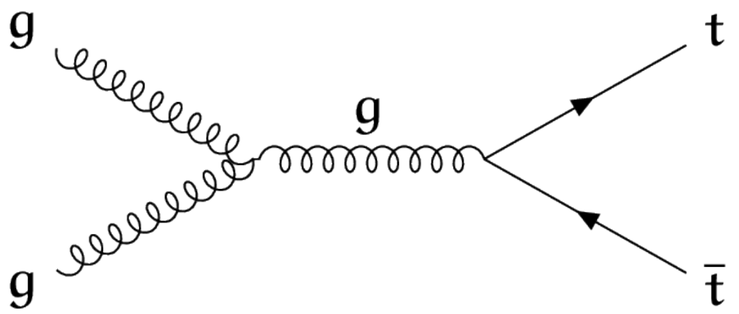
Be.HEP Solstice, June 23, 2023

GHENT UNIVERSITY

CMS Compact Muon Solenoid

Quick introduction on top quark physics

Heaviest standard model particle
- Discovered at Tevatron in 1995
- LHC is first **top quark factory**
- Usually produced in pairs: **$t\bar{t}$ production**
  - Cross section at 13 TeV: 833.9 pb



LHC is first collider where **precision top physics** is possible
- Precise measurements of top quark properties
  - Even the **top-Higgs Yukawa** coupling
- Measurements of top associated production: e.g. $t\bar{t}$ + W boson
- Search for new physics in top sector
  - Directly through new particles
  - Indirectly through EFT,...

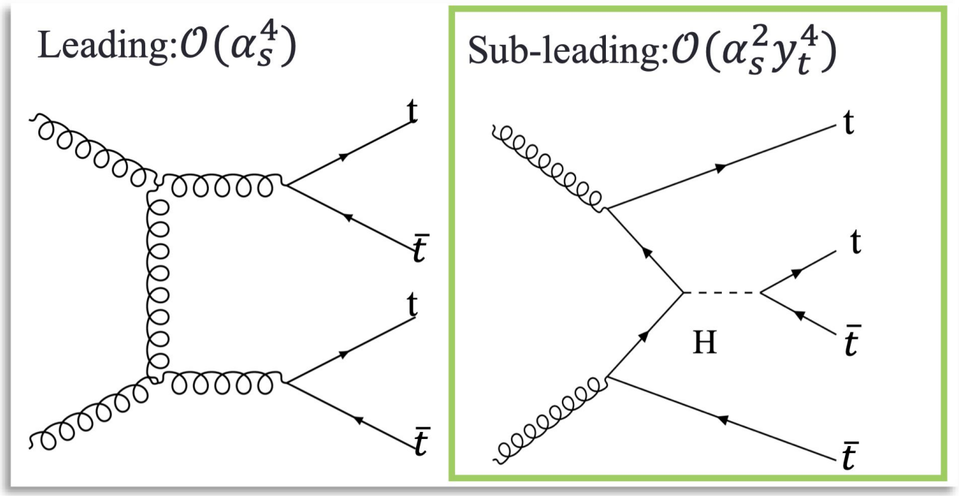
What is four top production?

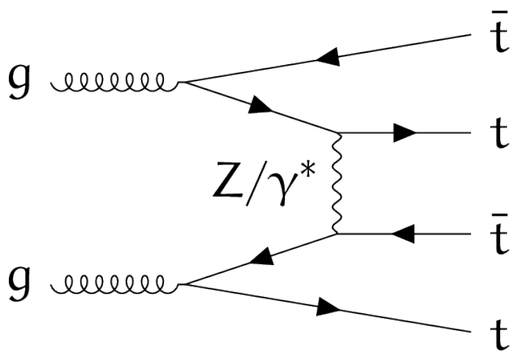
Four top production is an **extremely rare standard model (SM)** process:

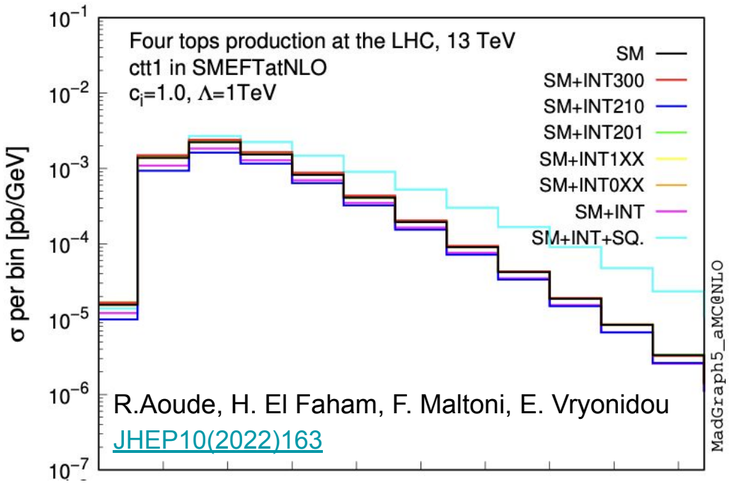
- $\sigma(tttt)_{NLO+NLL'}=13.4^{+1.0}_{-1.8}$ fb at 13 TeV [M. Van Beekveld, A. Kulesza, L. Moreno Valero; ArXiv:2212.03259]

But why are we interested?

- Sensitivity to **top-Higgs Yukawa** coupling
- Large EW corrections, partly in **top-top scattering**
- BSM physics: 2HDM, SUSY, …
- EFT: sensitivity to color singlet 4-fermion operators







Signatures

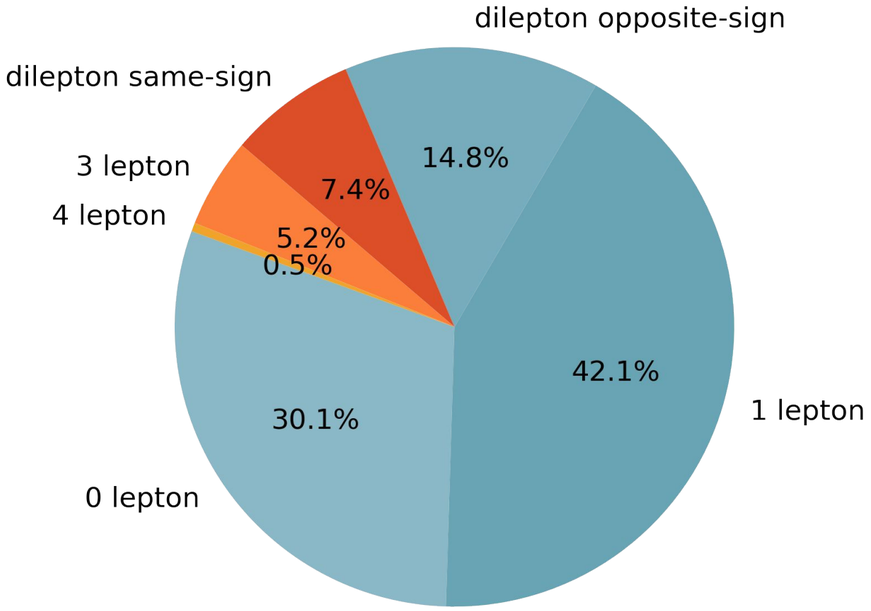
Large object multiplicity final state

Each top decays to W+b, so the detector signature is characterized by:

- **4 b-quarks** leading to jets
- the decay products of **4 W bosons**
  - 2 quarks or a lepton + neutrino

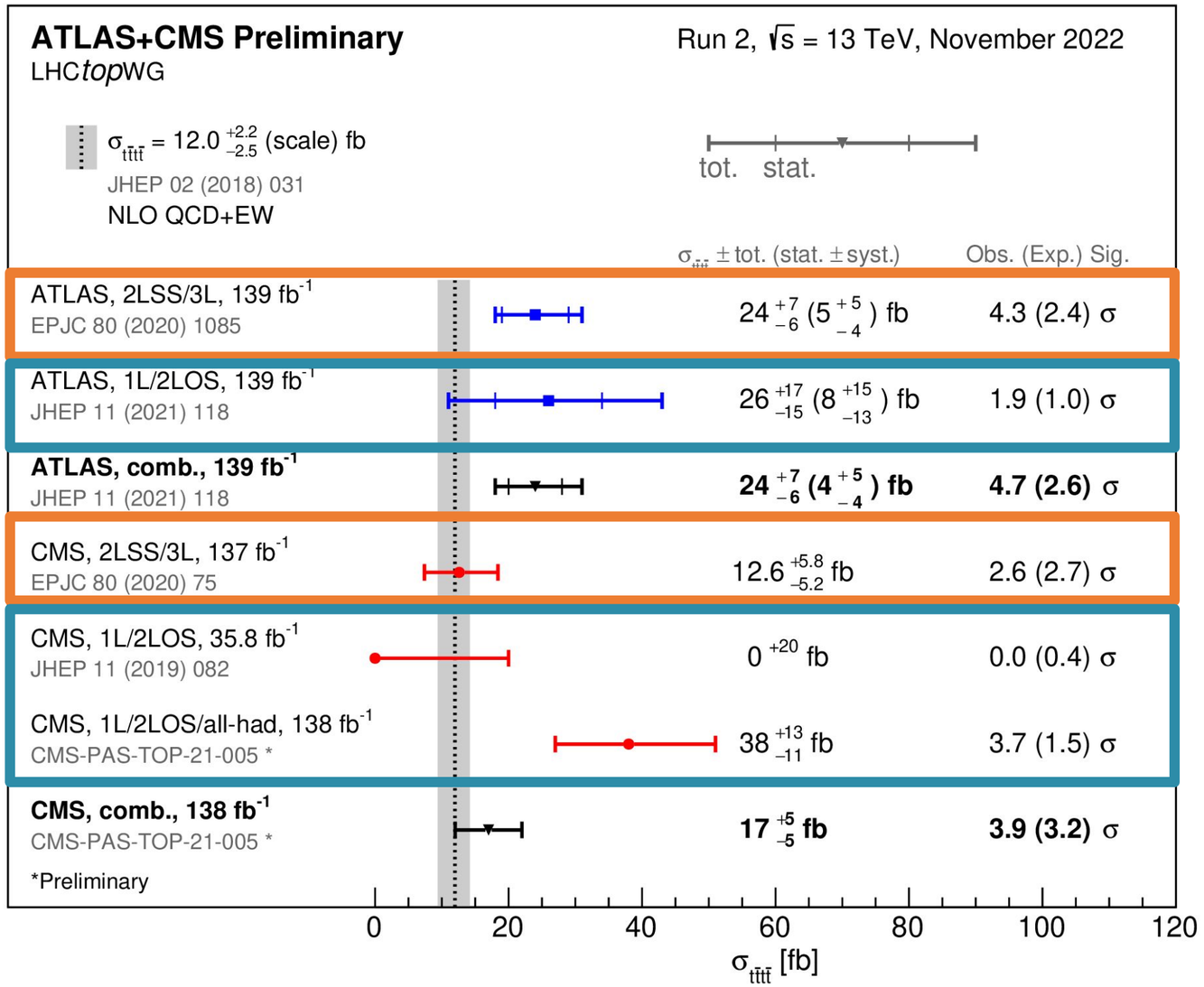
Three analysis strategies:

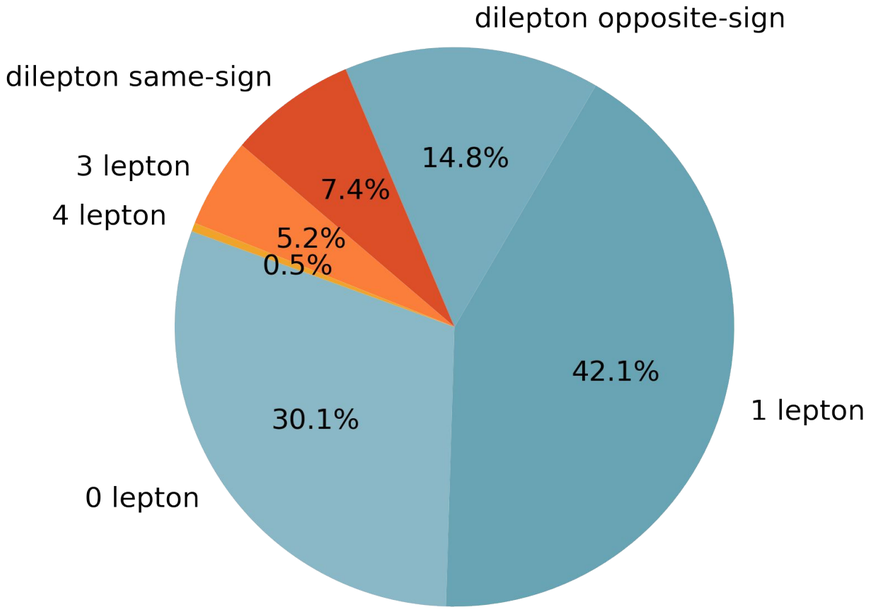
- All hadronic: huge QCD background
- Single lepton and opposite sign dilepton (1L, OSDL)
  - Large branching fraction but large irreducible background (from $t\bar{t}$)
- Same-sign dilepton and multilepton (SSDL, ML)
  - Small branching fraction and high purity
  - “Golden channels” of four tops



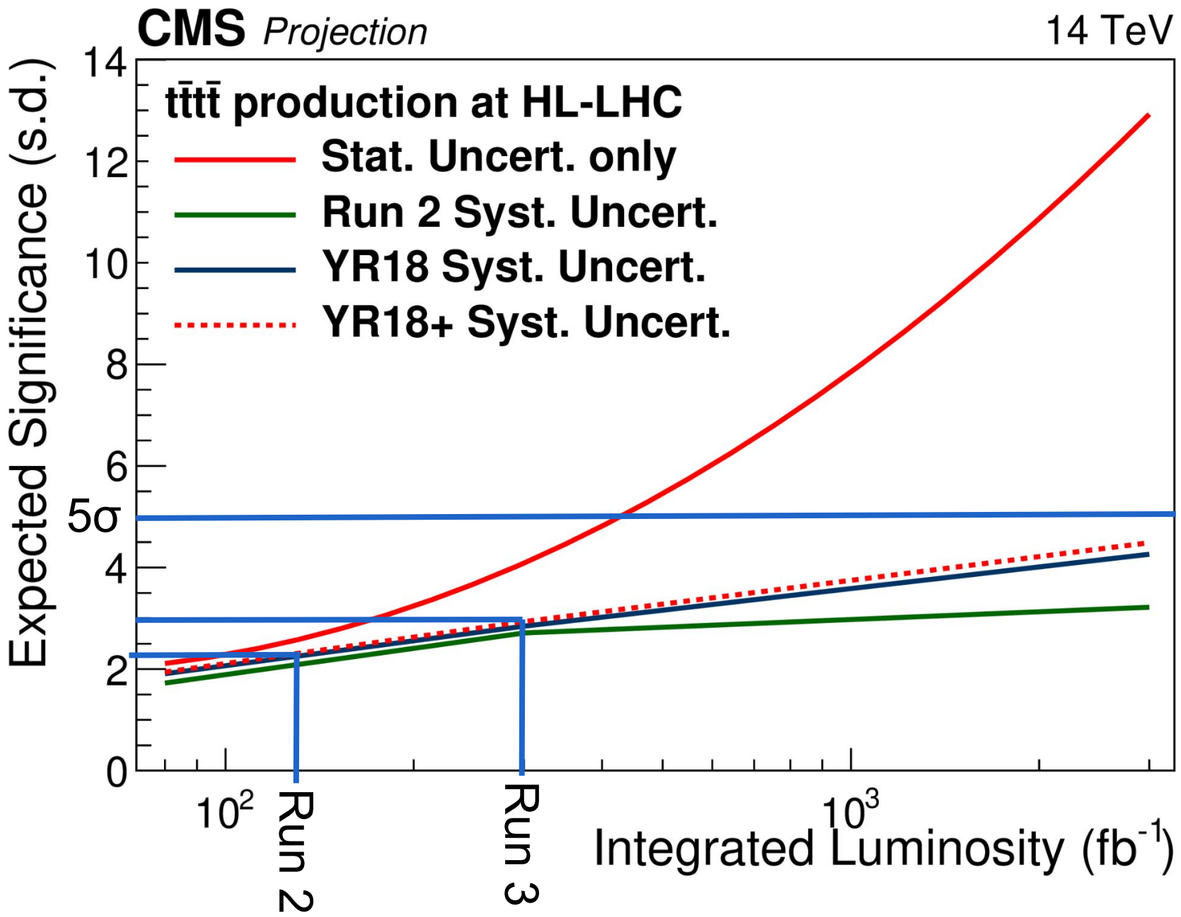
Note: only muons or electrons are counted as leptons, taus decay inside the detector and can lead to hadrons

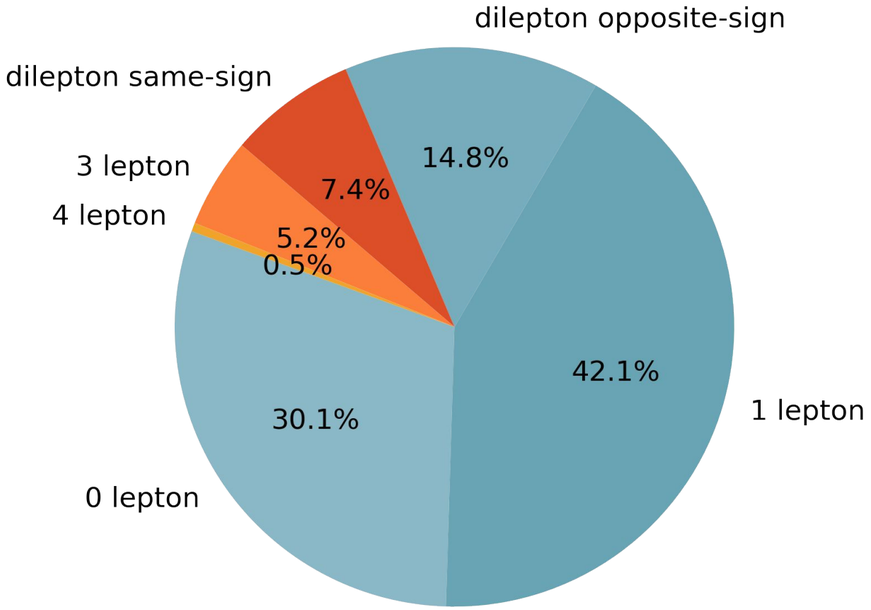
Translated into results





And a 2018 projection



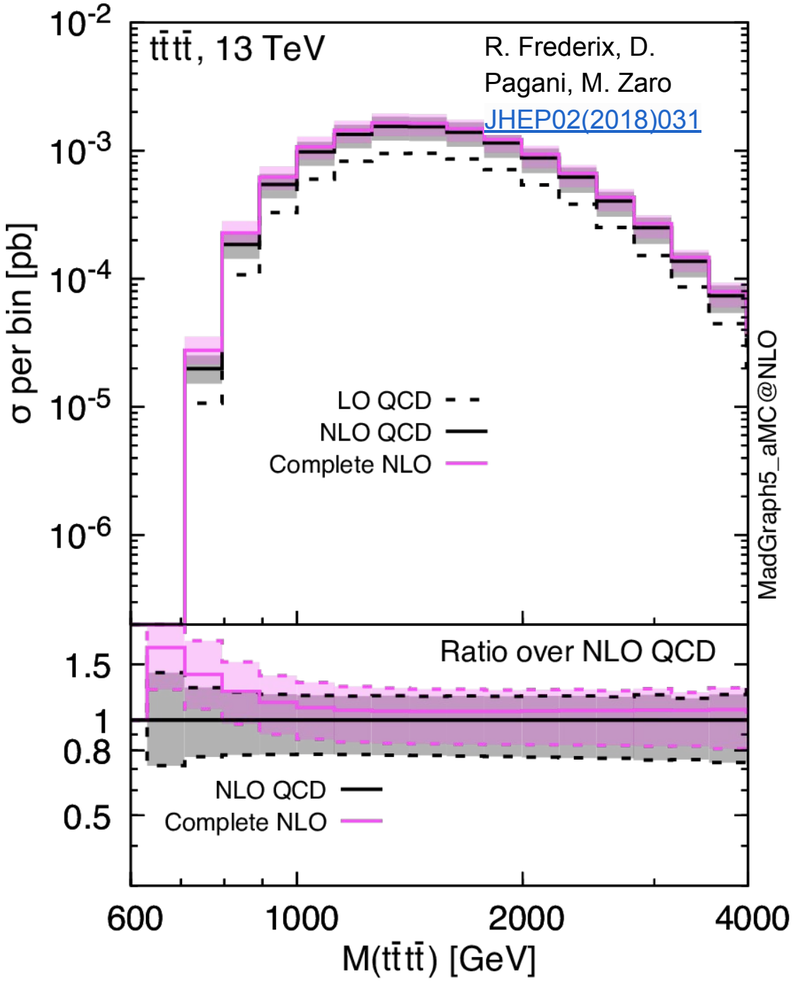


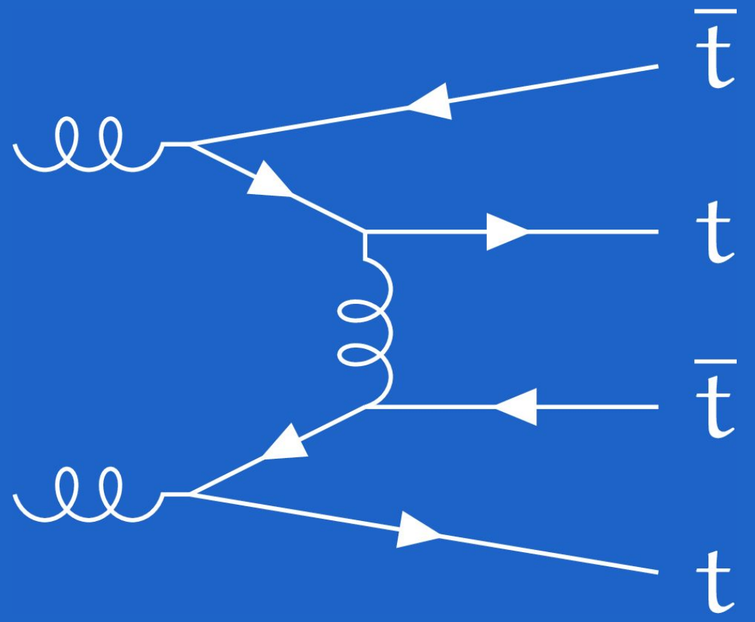
Experimental challenges

Extremely rare:

- 1 four top event for every 65k top-pair events
- 1850 four top events expects in Run 2 dataset
- 240 in same-sign dilepton and multilepton final states
  - Further reduced by acceptance effects and efficiencies of the detector, object reconstruction

Signature easily imitated by more common processes with additional radiation





Analysing same-sign dilepton and multilepton channels

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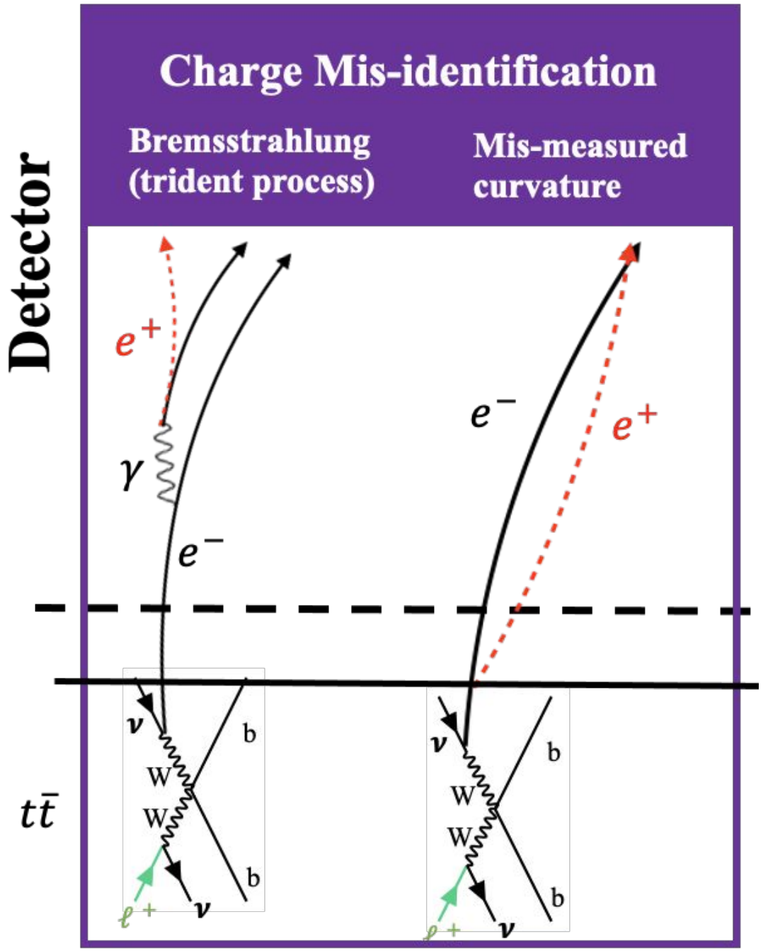
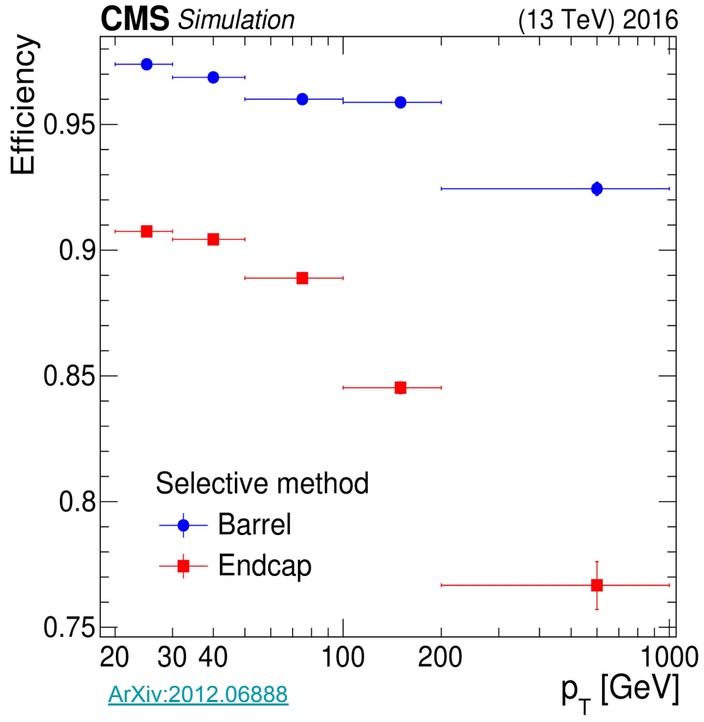
Selecting leptons

- pT as low as possible →big effect on acceptance
  - pT > 10 GeV
  - Triggers: pT > 25 (20) GeV for (sub)leading leptons
- Already 2 important backgrounds at this first step:
  1) Charge mis-identified leptons
     - tt̄ □ 2l, 2v, 2b

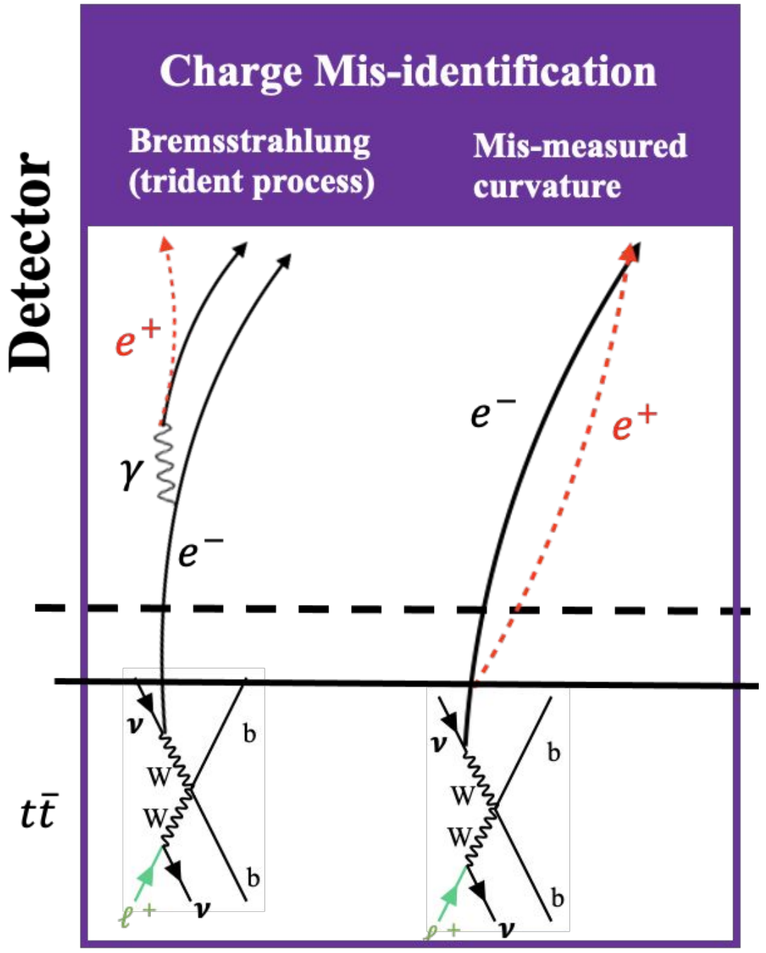


Selecting leptons: charge misidentification

- CMS performs 3 charge measurements
- Usually perform majority vote
- In an analysis like this: require all to be the same
  - Has an impact on the selection efficiency

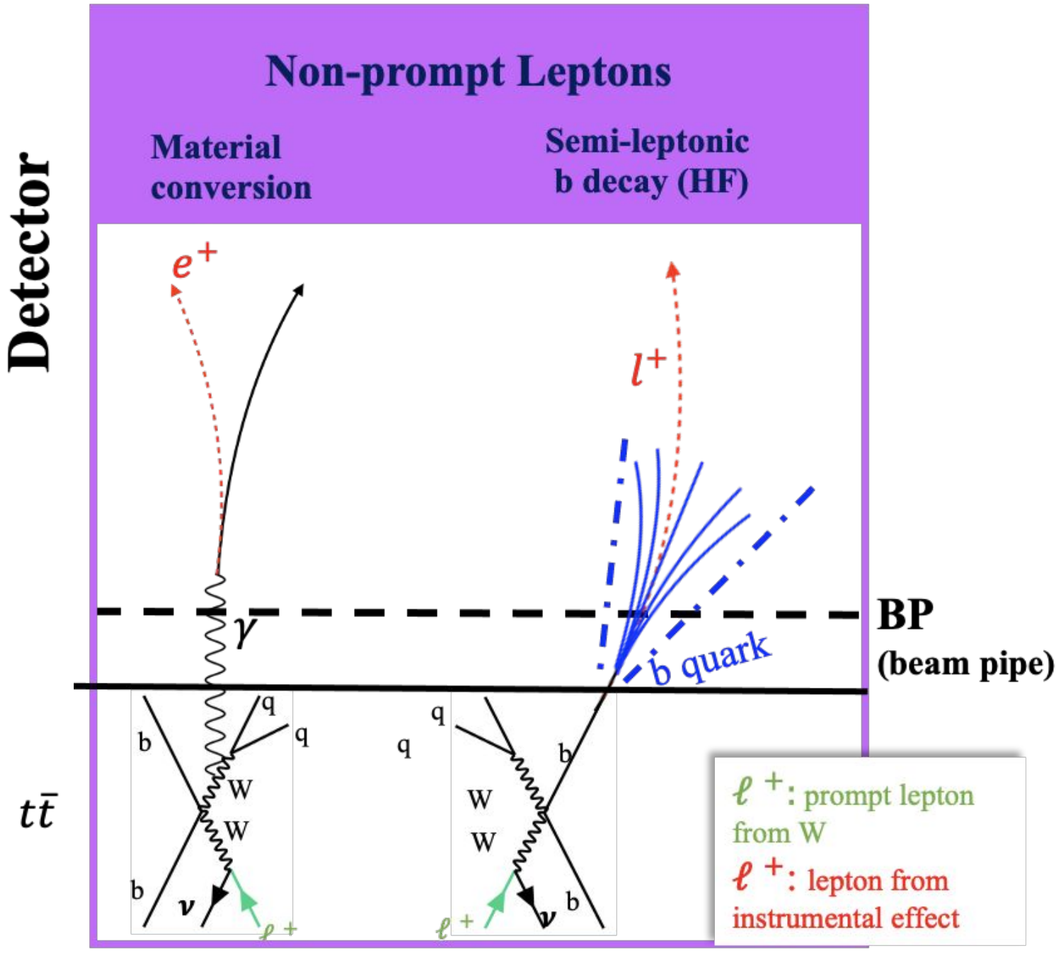


ArXiv:2012.06888



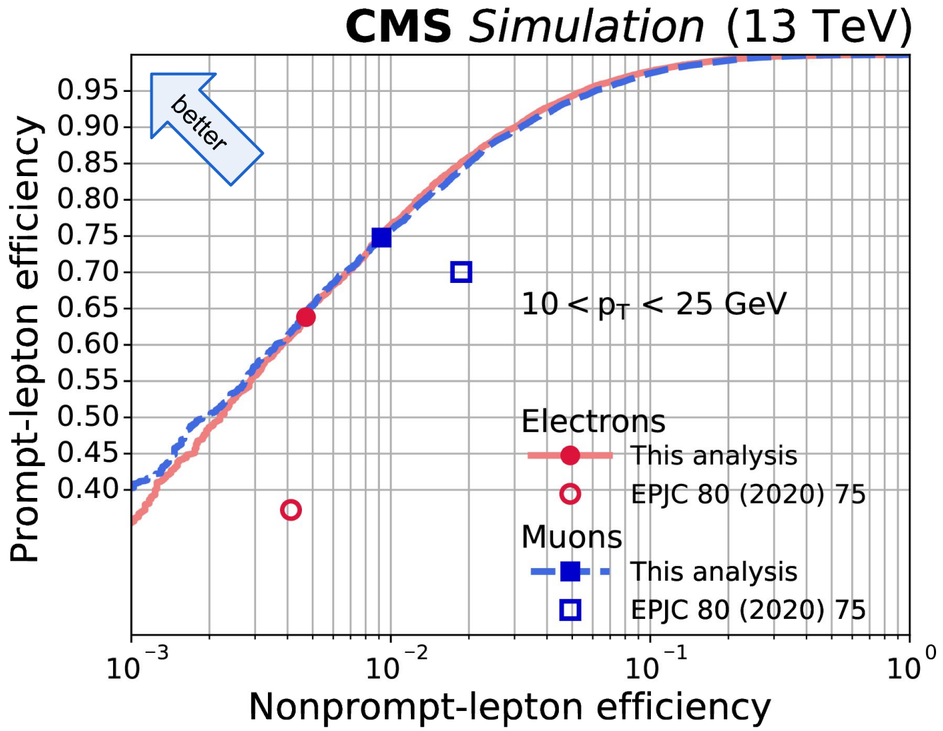
Selecting leptons

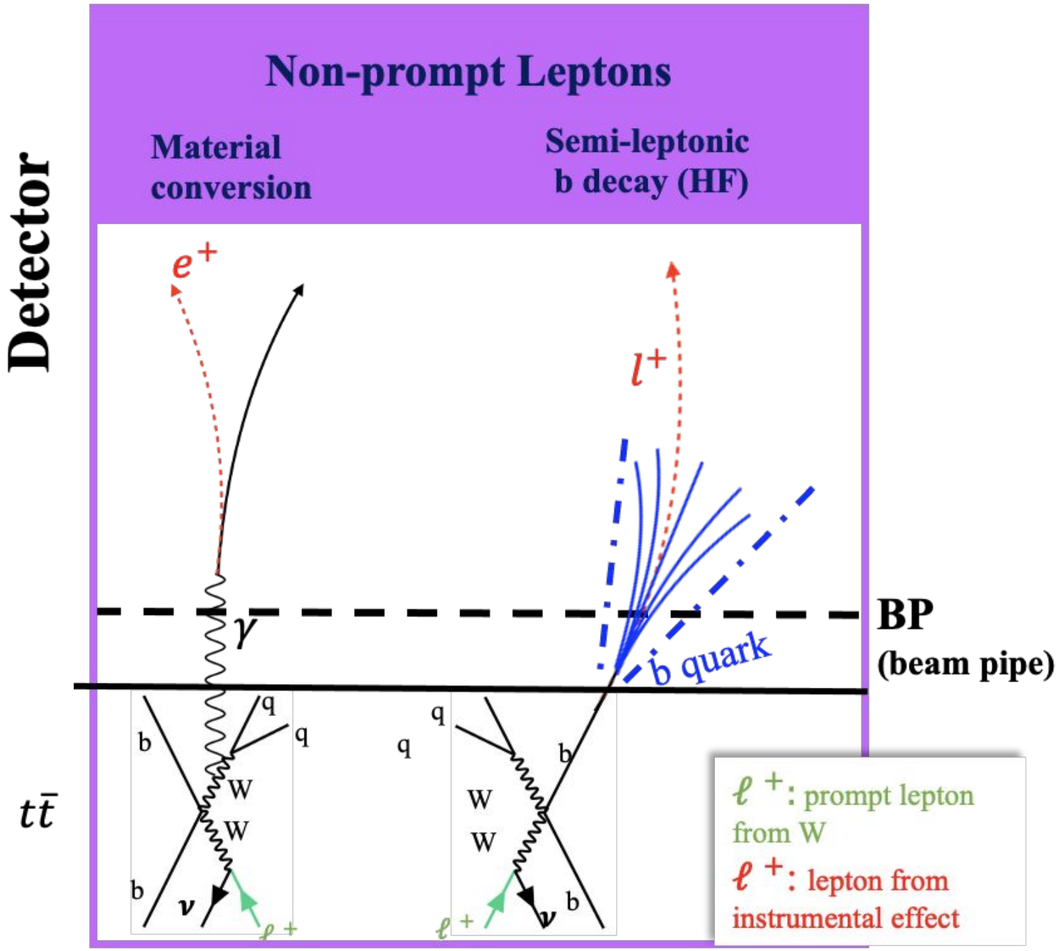
- pT as low as possible →big effect on acceptance
  - pT > 10 GeV
- Already 2 important backgrounds at this first step:
  1) Charge mis-identified leptons
     - tt̄ → 2l, 2v, 2b
  2) Additional “nonprompt” leptons
     - tt̄ → 2l, 2v, 2b OR 1l, 1v, 2b, 2q



Selecting leptons: nonprompt reduction

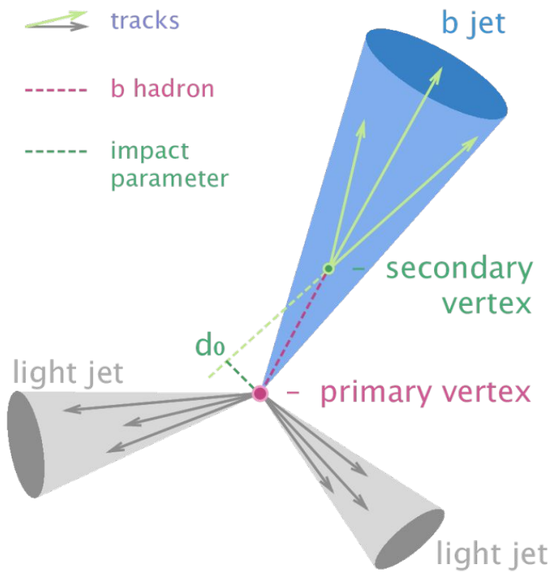
- Use a BDT to distinguish prompt vs nonprompt leptons
- Similar used in ttH, tZq,… measurements
- Major improvement at low momentum

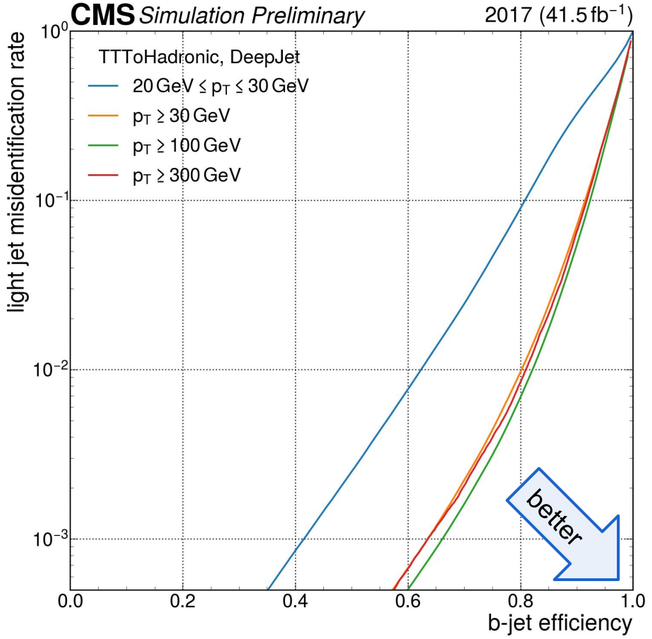




Selecting jets

- Again, pT as low as possible: pT > 25 GeV
- b-tagging of jets:
  - Properties of jets coming from b-quarks slightly different than jets from lighter quarks
  - With Machine Learning, we can try to identify which ones come from b-quarks
  - Continuously improving: use model with RNN architecture





Event selection

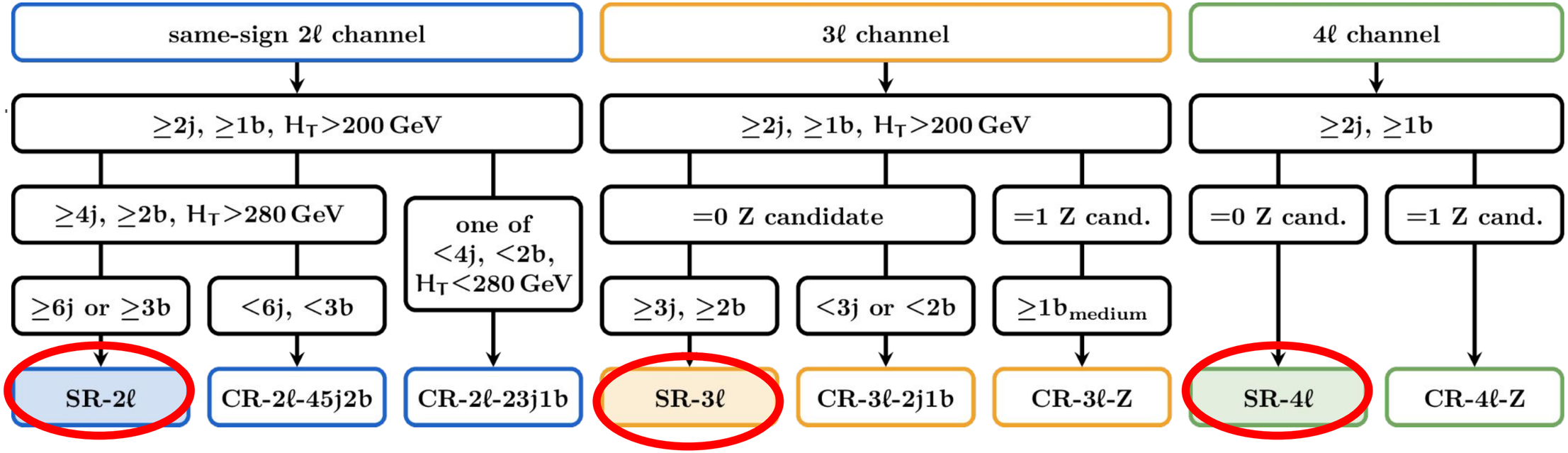
- Select four top phase space:
  - Cuts on number of (b)-jets and available energy in the event
  - Also remove events with Z-boson resonances
- 2 strategies:
  1. Cut out a high purity region and find a fitting variable
     - Usually fitting variable is a BDT output
     - Why bother with finding high purity?
  2. Keep as many signal events and let machine learning do the work

Based on this idea: 3 signal regions, differ on the number of leptons

- Selection also optimized for each signal region

Event selection

- Select four top phase space:
  - Cuts on number of (b)-jets and available energy in the event

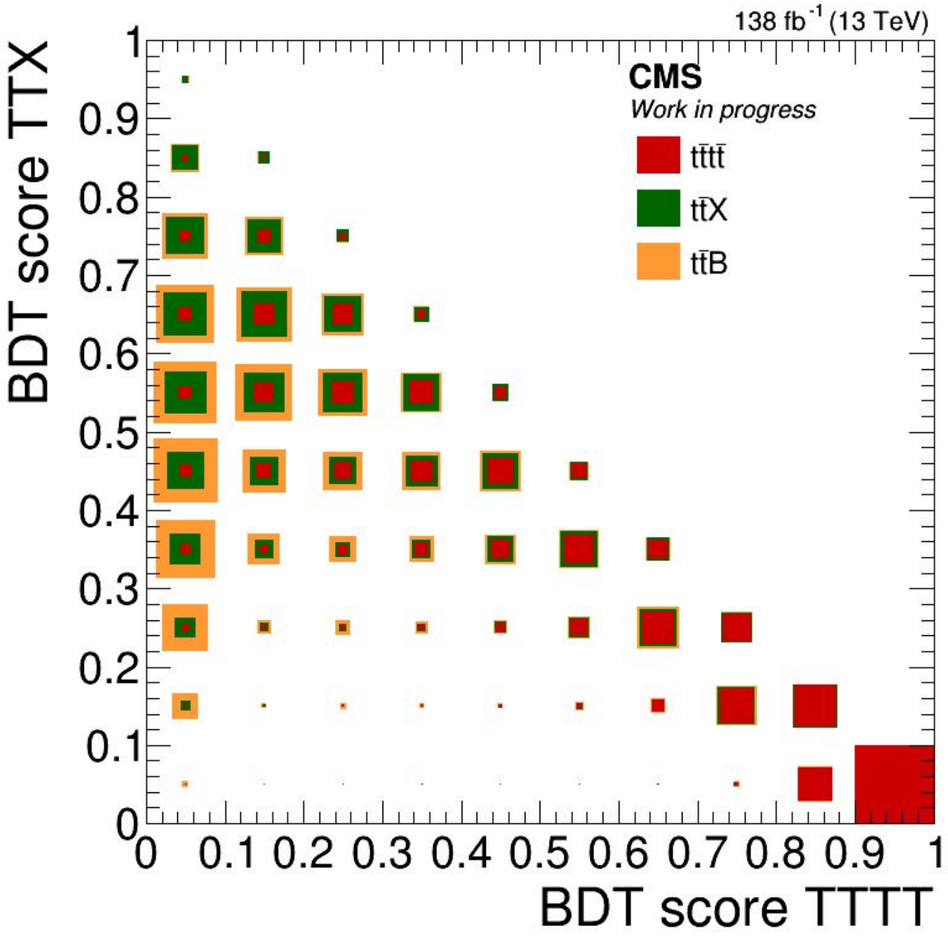


Based on this idea: 3 signal regions, differ on the number of leptons

- Selection also optimized for each signal region

Last step: machine learning

- In each Signal Region: **multiclassification BDT with 3 classes:**
  - tttt-class: signal
  - ttX-class: ttW+ttZ+ttH
  - tt-class: nonprompt and charge mis-ID background
- Trained on various variables:
  - Angles between leptons, jets
  - Top reconstruction variables
- BDTs surprisingly powerful, would be interesting to compare with a GNN

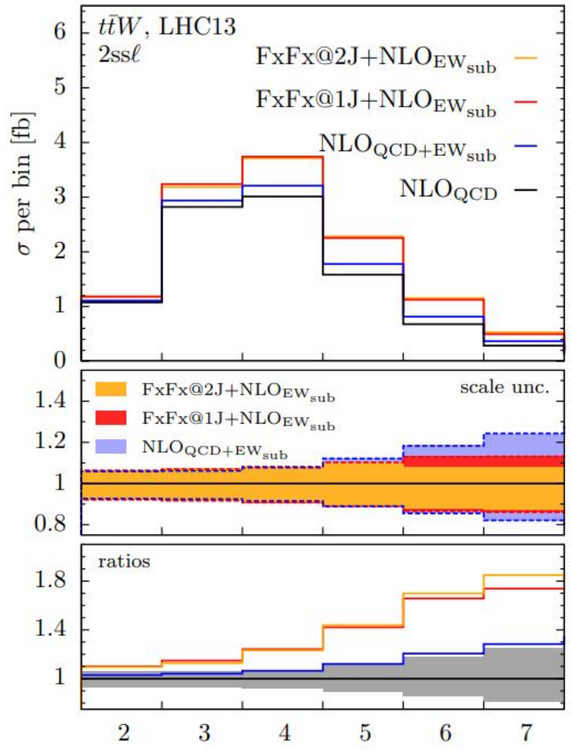


Backgrounds: ttX processes

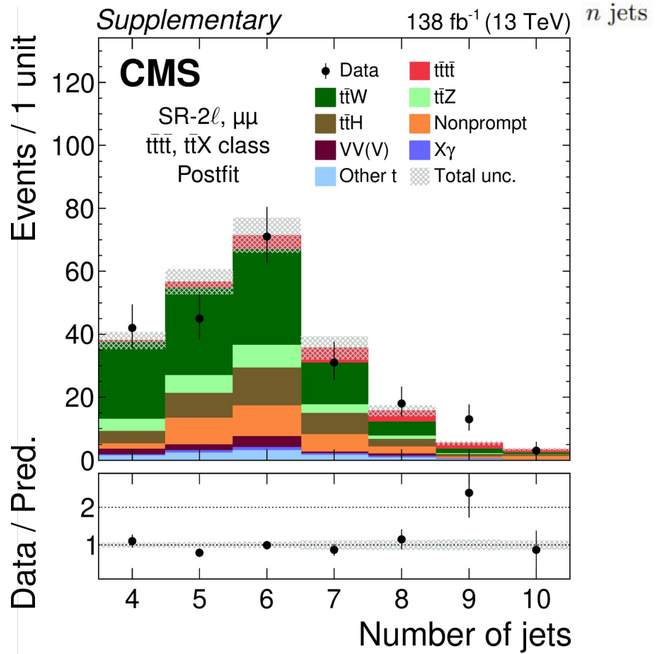
- Irreducible backgrounds: ttW, ttZ, ttH
  - Hard process does contain less particles -> easily distinguished?
  - No! These processes occur with **additional (b-)jets**

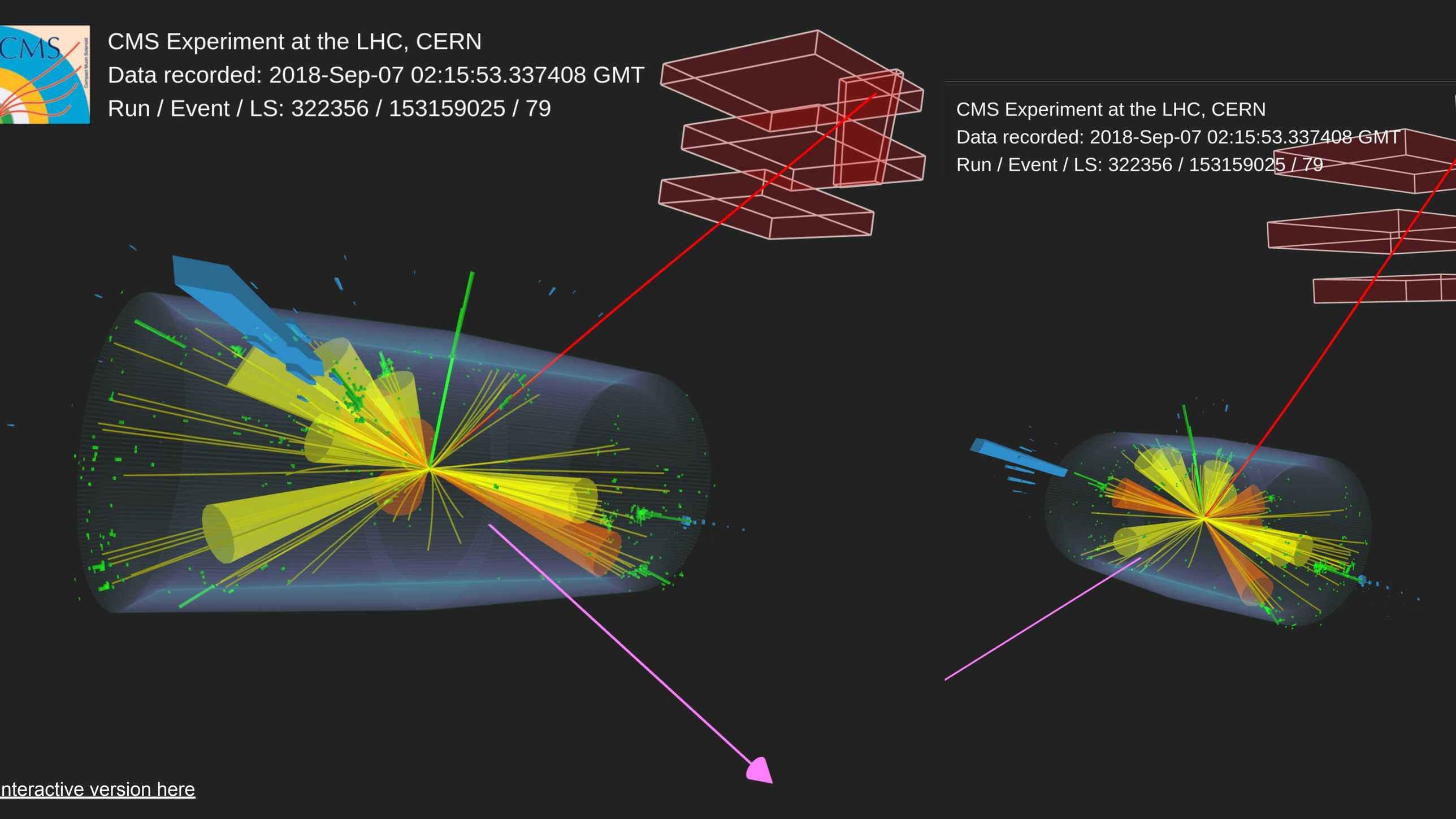
General treatment:

- Predicted from simulations
- Input theory cross sections
  - Let cross section of ttW and ttZ float free in fit
- Uncertainty on **ttX+b(b)**
- Uncertainty on **ttW+jets**
  - Motivated by difficult modelling



R. Frederix, I. Tsinikos
JHEP11(2021)029

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CMS Experiment at the LHC, CERN
Data recorded: 2018-Sep-07 02:15:53.337408 GMT
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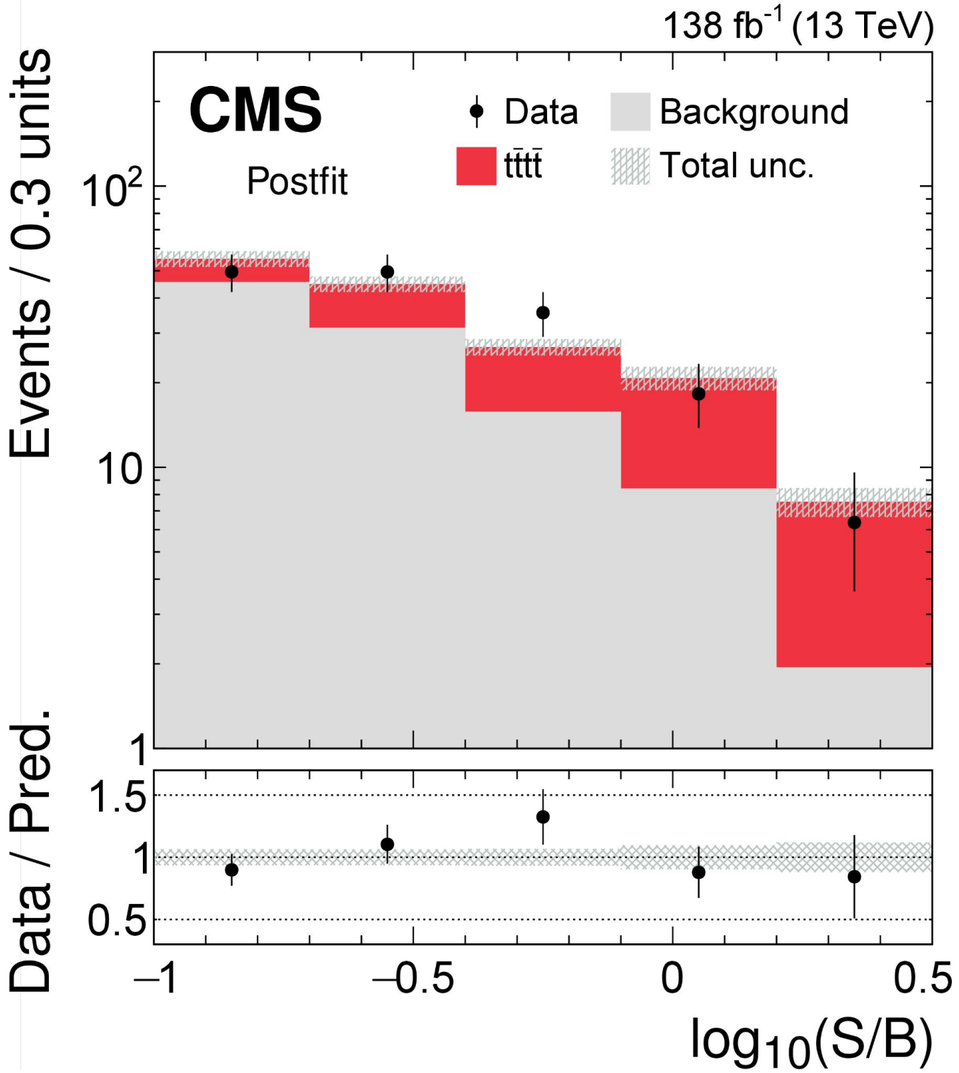
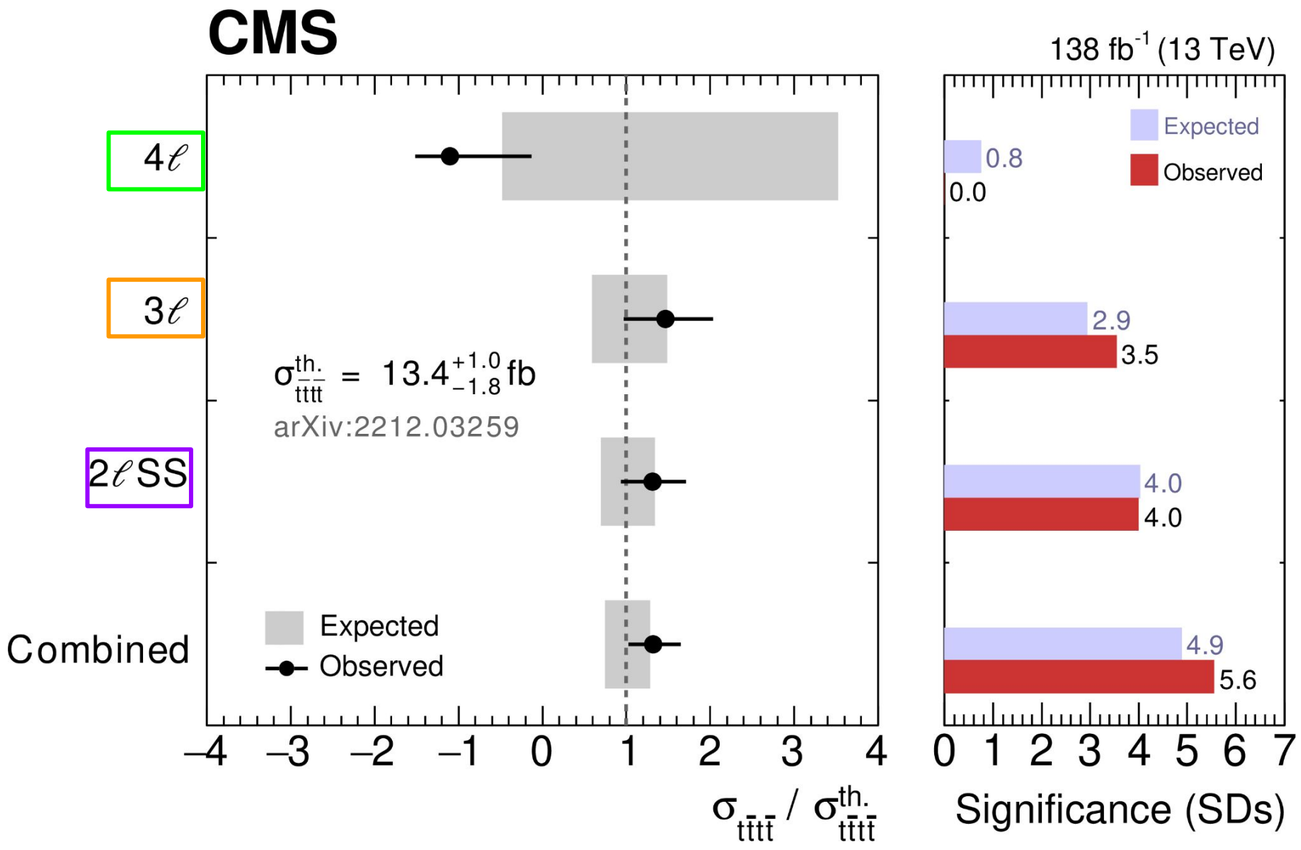
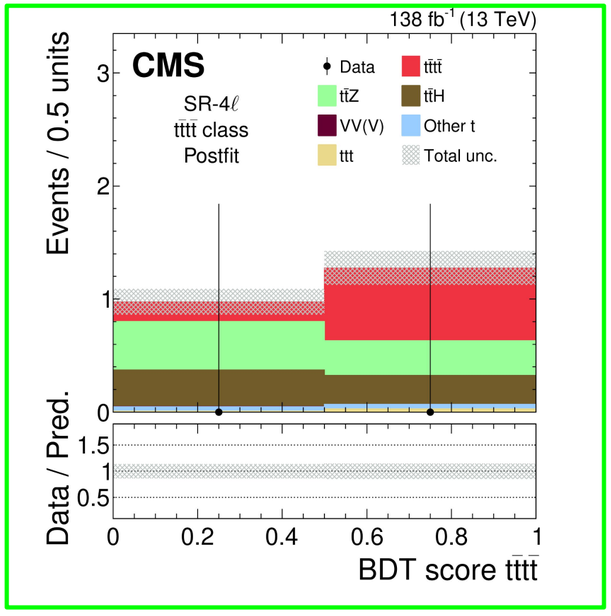
Results

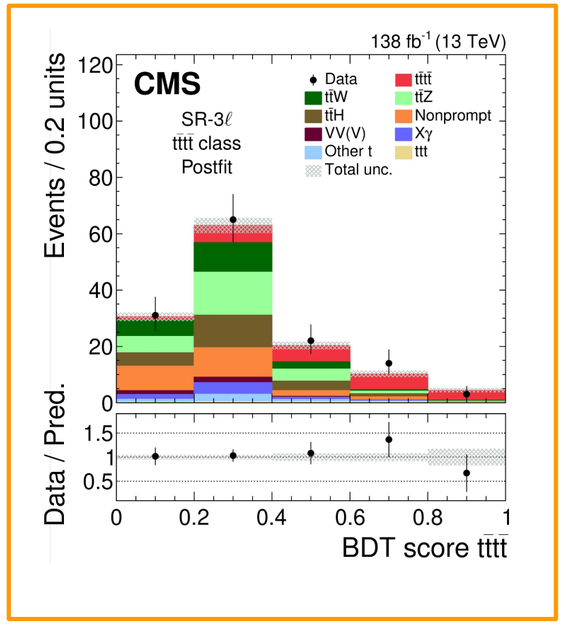
- Template fit to
  - 1 distribution from each control region
  - BDT output score per BDT class in signal regions
- First observation of four top production
  - 5.6σ observed, 4.9σ expected
- $\sigma(\mathrm{t\bar{t}t\bar{t}}) = 17.7\,^{+3.7}_{-3.5}\,(\mathrm{stat})\,^{+2.3}_{-1.9}\,(\mathrm{syst})\,\mathrm{fb} = 17.7\,^{+4.4}_{-4.0}\,\mathrm{fb}$
  - Result consistent with Standard Model

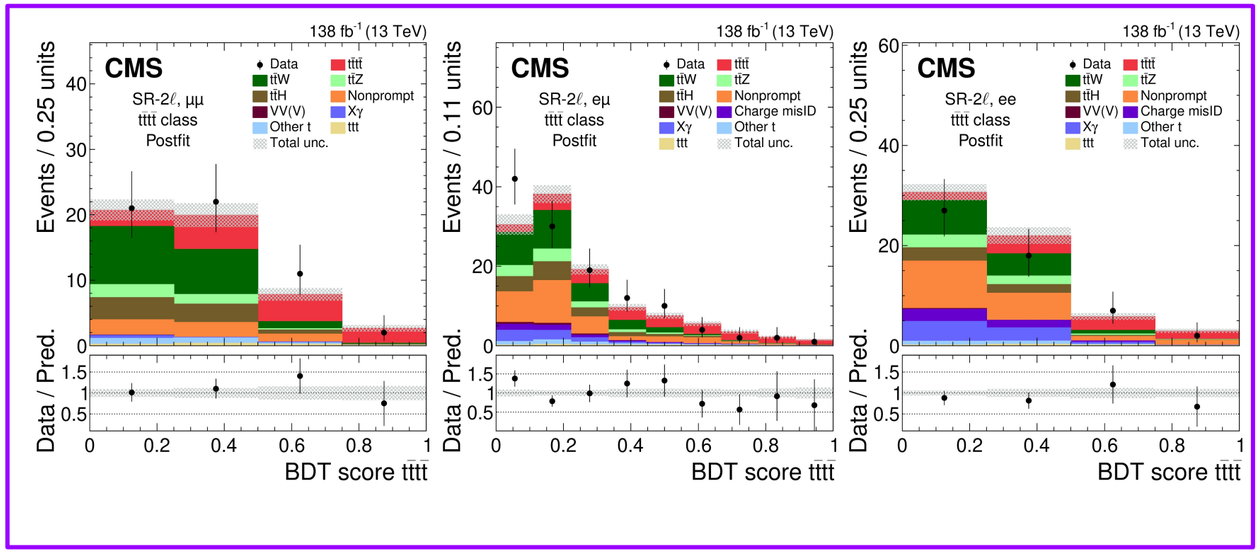


Results per channel



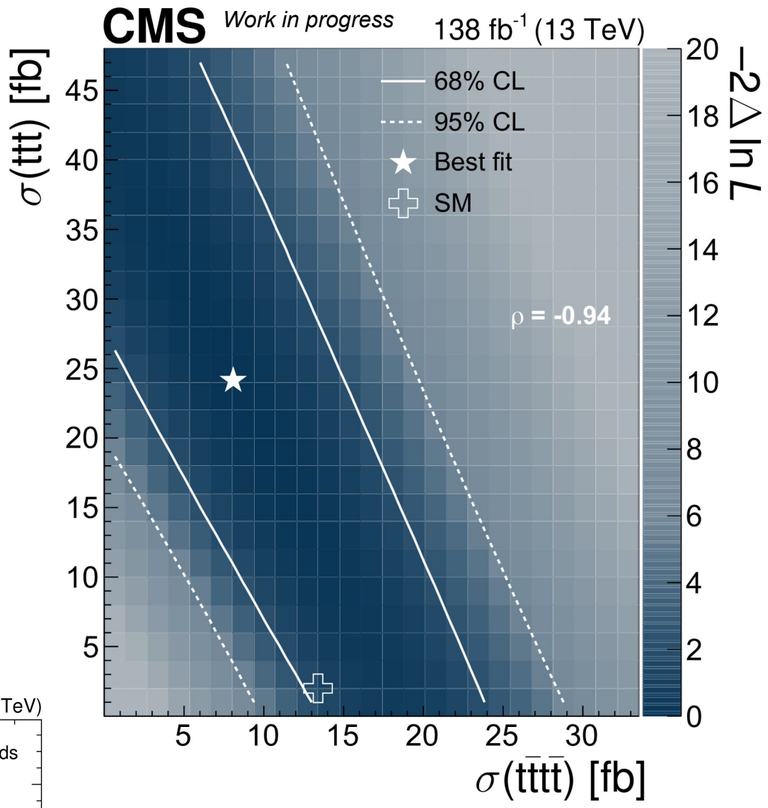


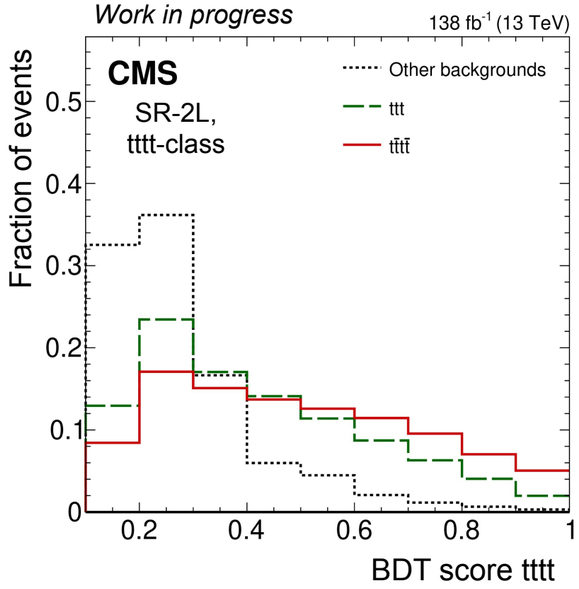




Triple tops: the highly correlated brother

- Triple top production is a collection of 2 processes:
  - ttt + quark
  - ttt + W boson
- Especially last one: four tops with one b-quark less
- Luckily 10 times more rare
  - Cross section: 2 fb @ NLO QCD + LO EW
  - Calculation provided by Gauthier Durieux, looking forward to future exchange





Summary and outlook

- Four top production is observed for the first time at CMS (also at ATLAS):
  - CMS: ArXiv:2305.13439
  - ATLAS: ArXiv:2303.15061
- Measured cross section compatible with standard model prediction
- Run 3 is promising:
  - Many improvements on the jet side
  - New machine Learning developments for b-tagging

ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore