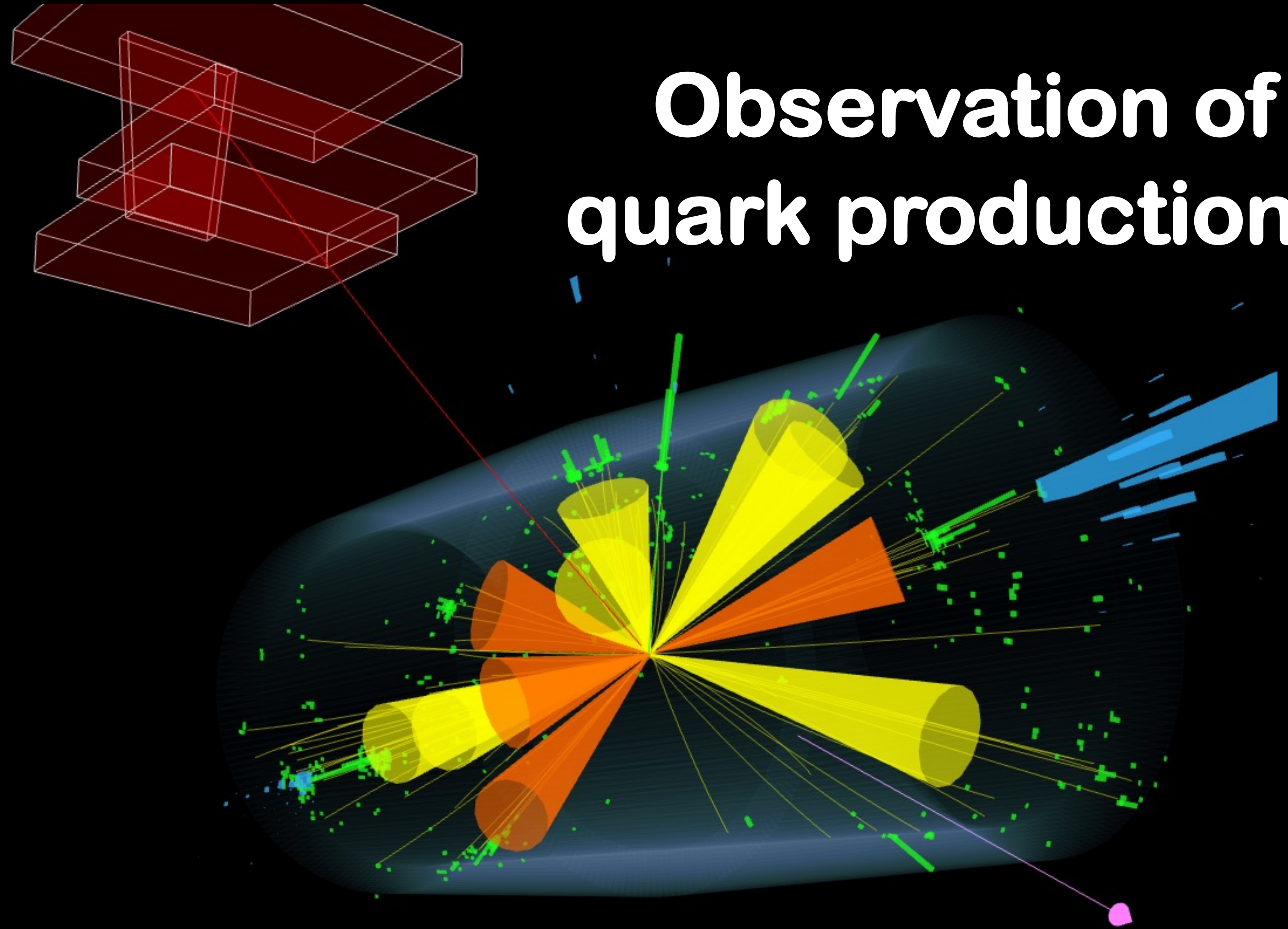
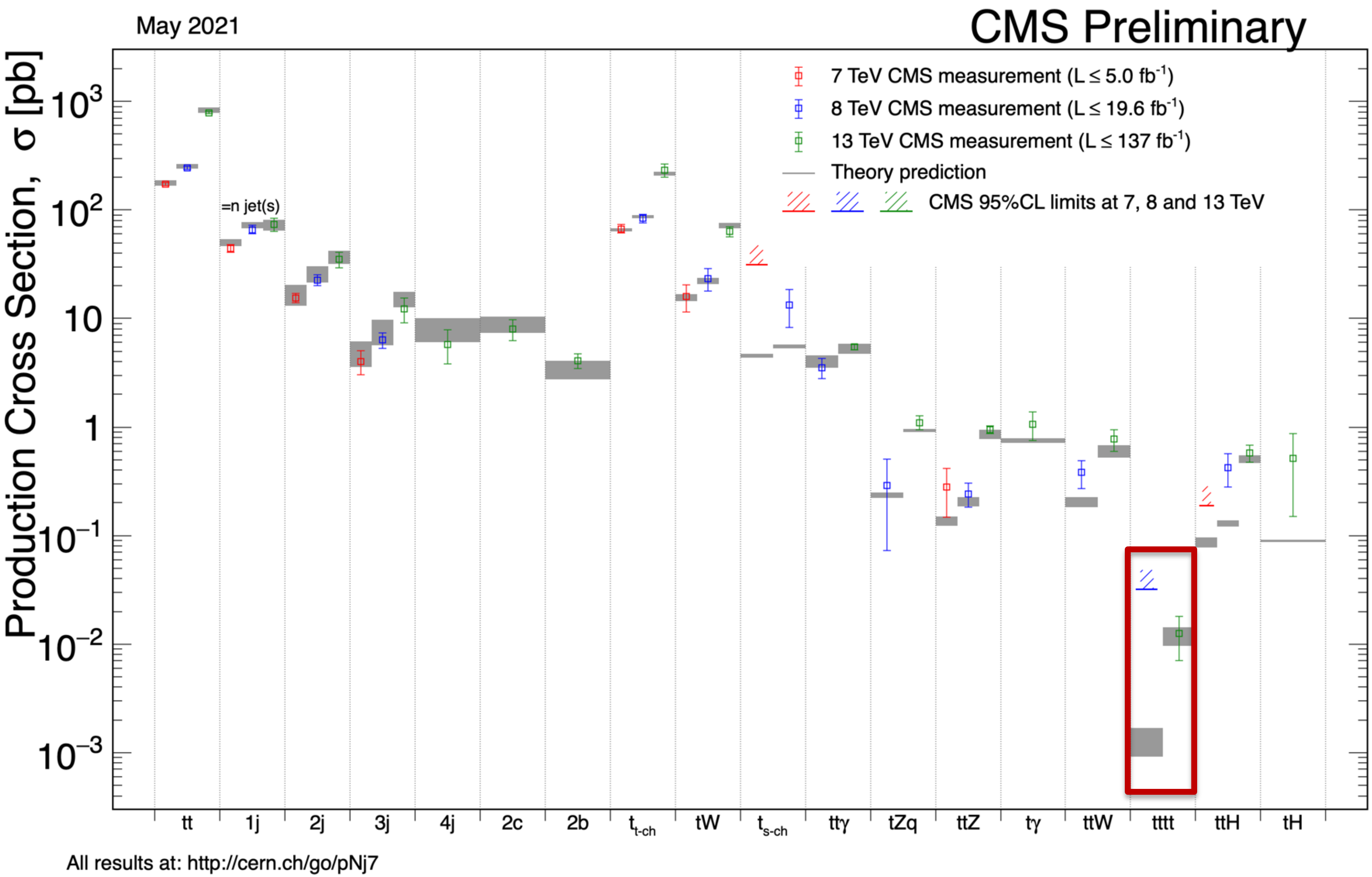
Observation of 4-top quark production in CMS



Didar Dobur
on behalf of the CMS collaboration
University of Ghent

Lepton Photon conference, 16-21 July, Melbourne

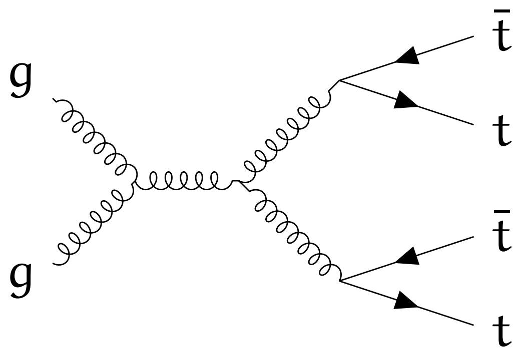
Four top production

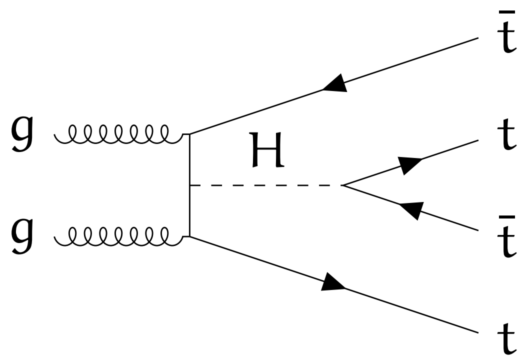


Rarest of all!

tttt

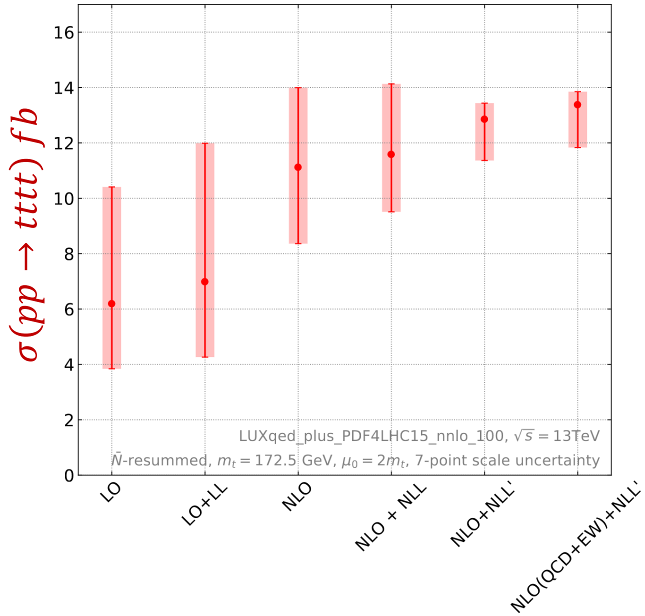
Four top production





Rare but also interesting for H-top coupling or probing new physics

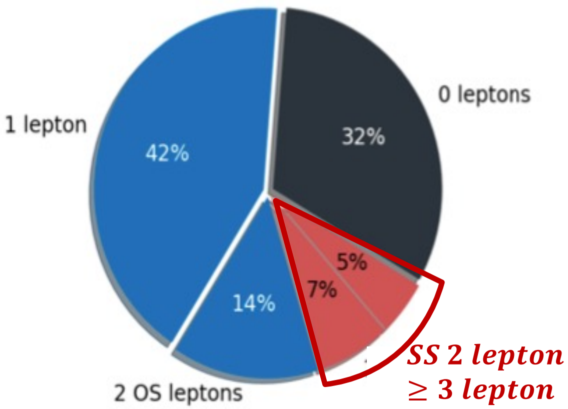
- Recent progress on the theoretical side for SM cross section prediction
- Full NLO accuracy (QCD+EWK) and resummation of soft gluion emission at NLL



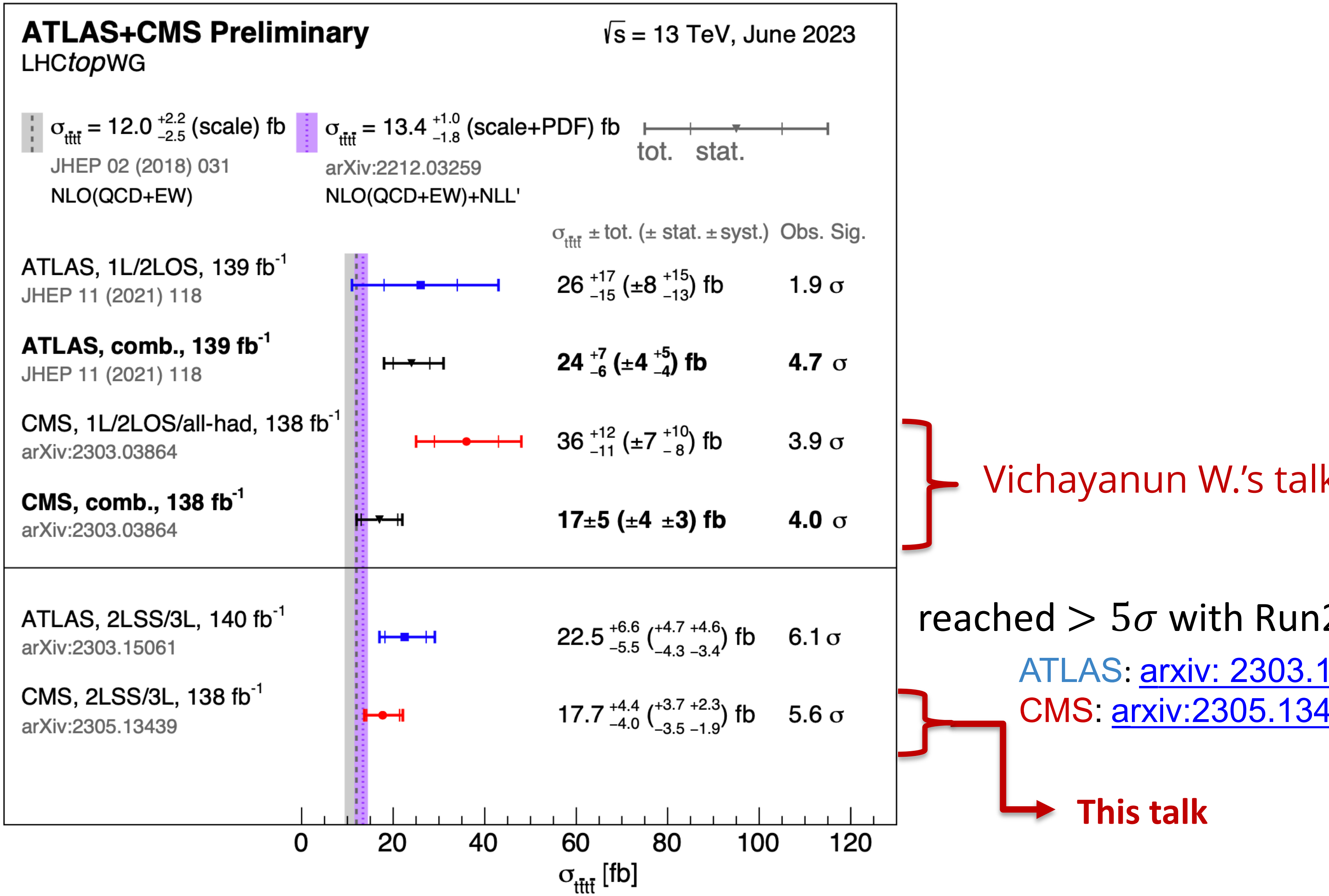
Reduced uncertainties

$$\sigma_{\mathrm{tttt}}^{\mathrm{NLO}} = 13.4^{+1.0}_{-1.8}\ \mathrm{fb}$$

- Experimentally rich: leptons and jets…
- 2 same-sign (SS) and multi-lepton channels: ~220 events in Run2



Experimental state-of-the-art



reached $> 5\sigma$ with Run2 data

ATLAS: [arxiv: 2303.15061]

CMS: [arxiv:2305.13439]

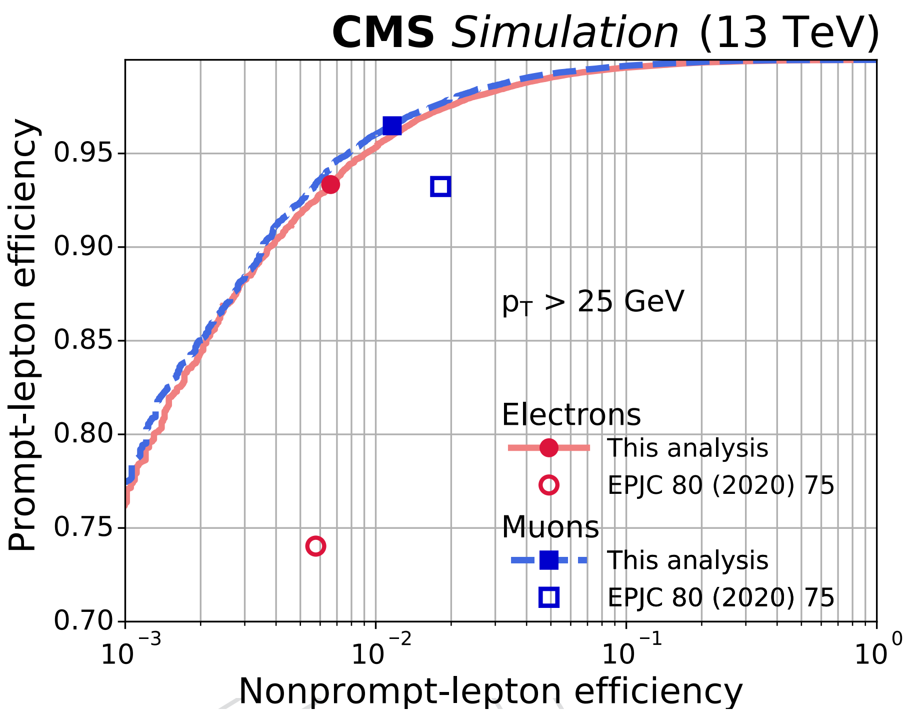
Improvements in object identification

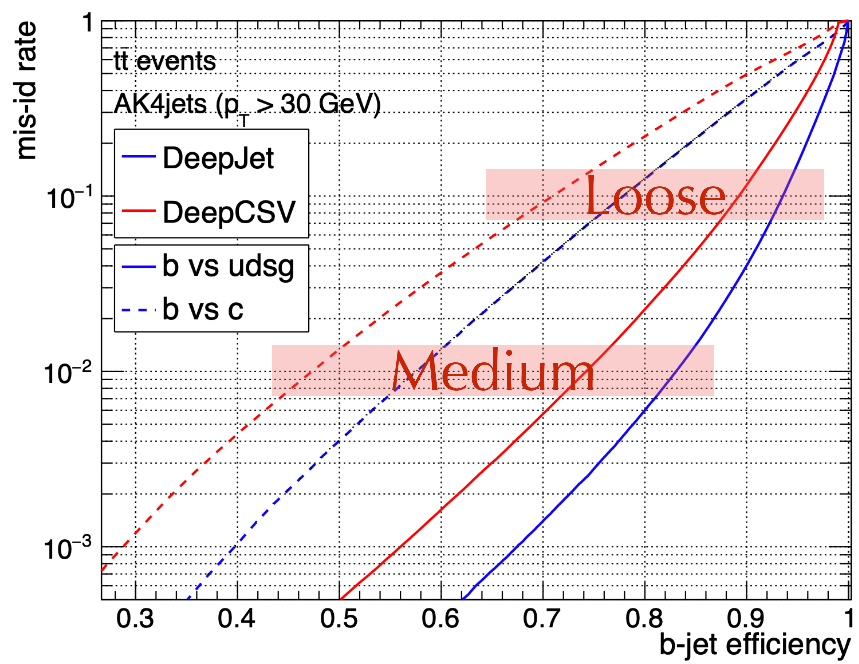
- **Electrons** (**muons**):
  - $p_T > 10$ GeV, $|\eta| < 2.5$ (2.4)
  - $p_T > 25, 20, 10, 10$

- **Jets**:
  - $p_T > 25$ GeV, $|\eta| < 2.4$
  - DeepJet b tagging ($\varepsilon = 90\%$)
  - Use DeepJet score in MVA

- MVA based lepton identification:
  - Electrons: 20% increased signal eff.
  - Muons: halved nonprompt background

- ~10% increased efficiency per b-jet for the same mis-tag rate





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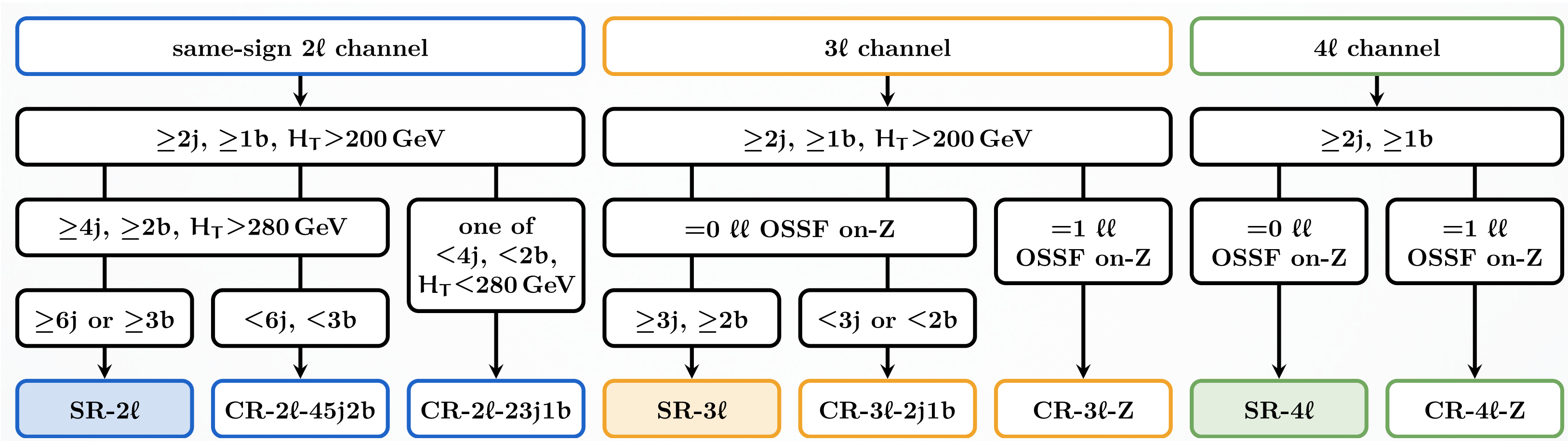
Analysis strategy

Event categorization based on jet and b-tagged jets, number of leptons and Z candidates



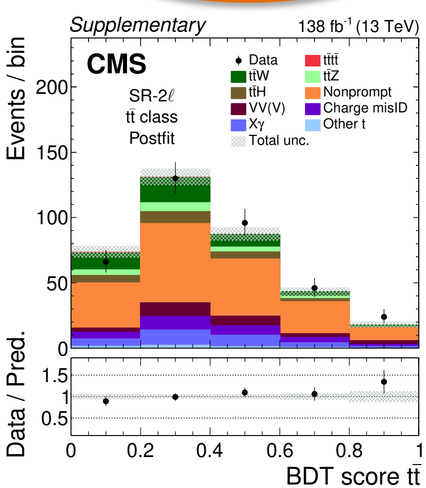
~70 signal events

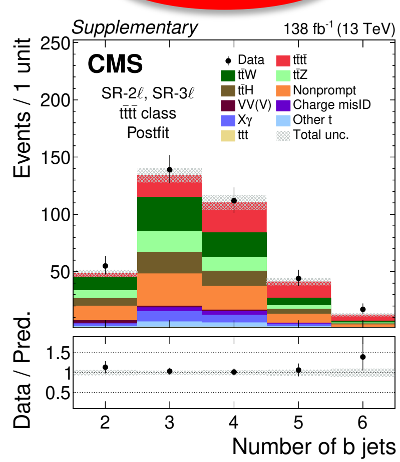
Multiclass BDT

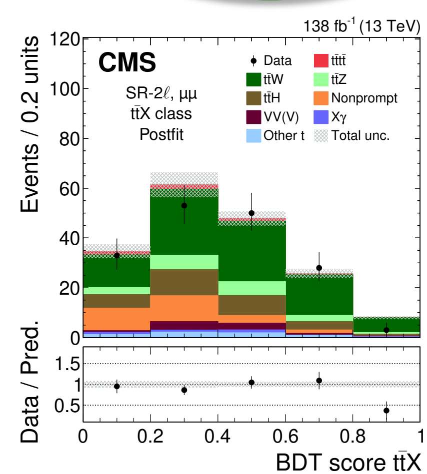
tt

tttt

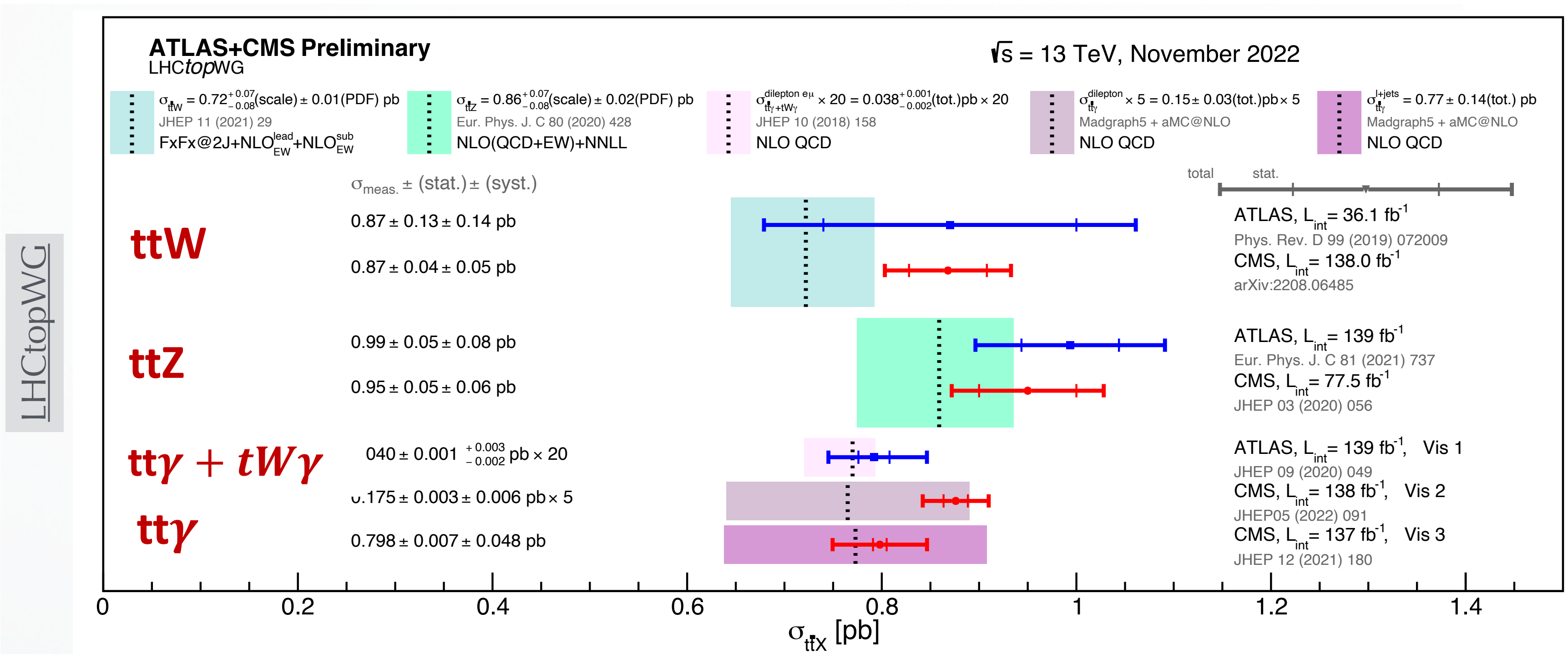
ttX







tt+V/H backgrounds



- ttV x-sections measured with $\leq 10\%$ uncertainty
- Known deviations from SM predictions
- ttH is measured to be consistent with theory
- Use simulations with state-of-the-art x-sections

$\sigma_{t\bar{t}Z} = 859 \pm 80$ fb
(**NLO+NNLL**)

$\sigma_{t\bar{t}W} = 722 \pm 74$ fb
(**NLO, FxFx**)

$\sigma_{t\bar{t}H} = 504 \pm 39$ fb
NLO+NNLL

ttV/H + extra (b) jets modeling

Modeling of ttW+Njet

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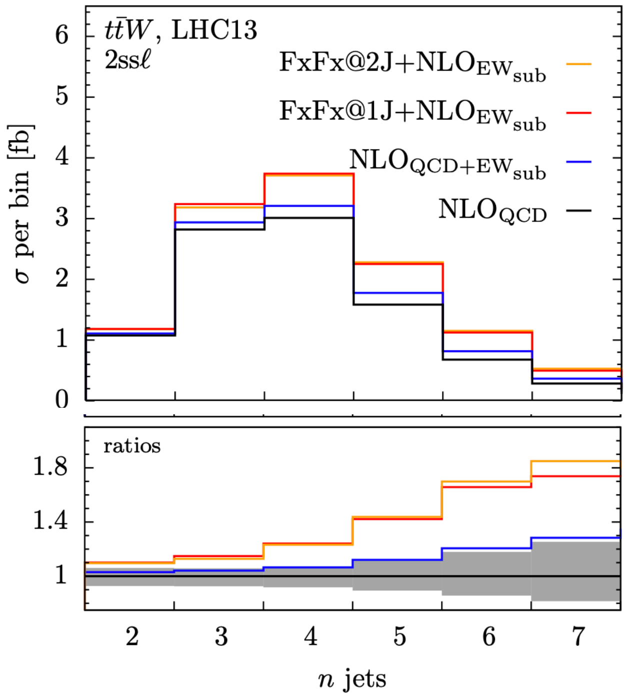

- EWK and higher order corrections effect Jet multiplicity
- Add a shape uncertainty on ttW reaches up to **55%** at Njets ≥ 7

Modeling of ttX + bjet

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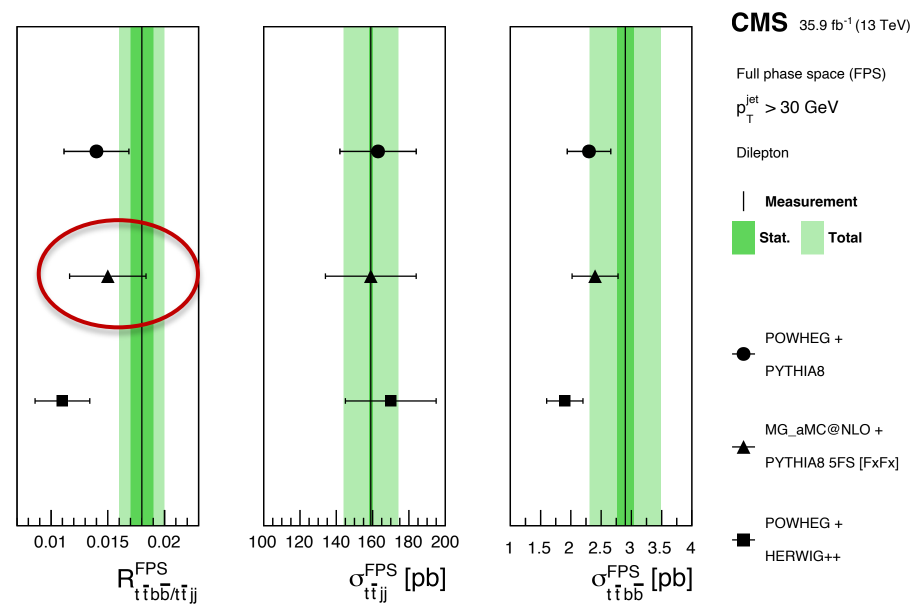
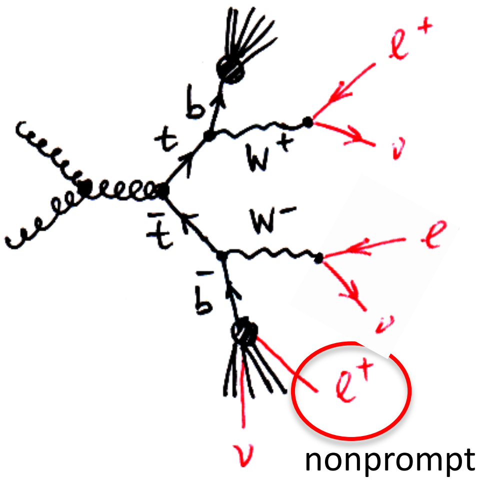
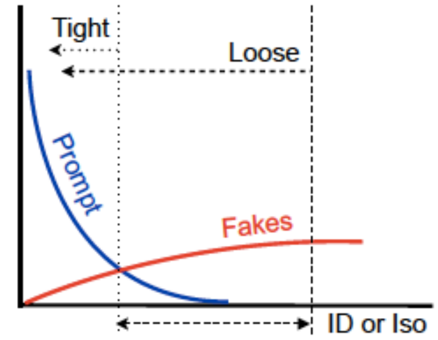


- Additional uncertainty for b-jet multiplicity for ttW, ttZ, and ttH
- Based on measured tt+bb cross sections and tt+bb/tt+jj ratios assign a **40%** symmetric uncertainty

mis-identified leptons

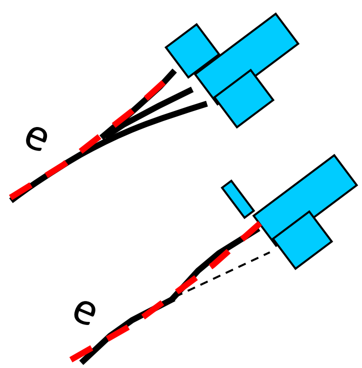


- **Nonprompt leptons**
  - Mainly arise from ttBar
  - Use data to predict (TL-method)

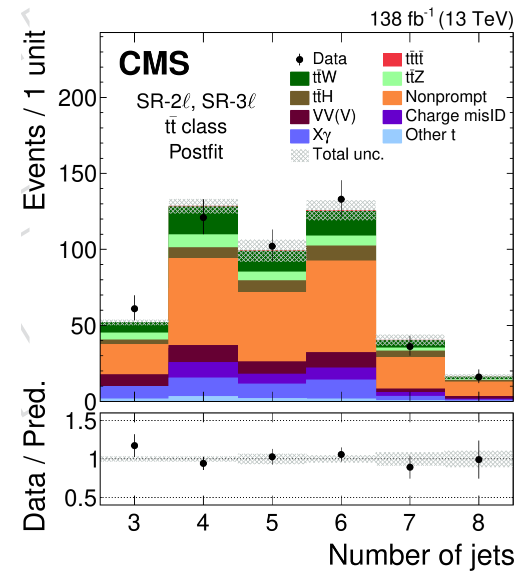


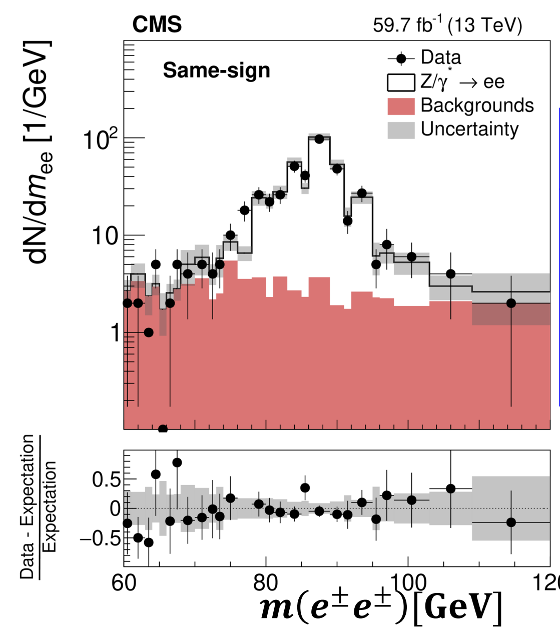
  - Multiple nuisance parameters for systematic effects

- **Charge mis-identification**
  - Prompt leptons, mainly electrons
  - Use DY data to measure charge mis-id rate (varies $10^{-3} - 10^{-4}$)
  - SFs on simulation when needed



Validation in data





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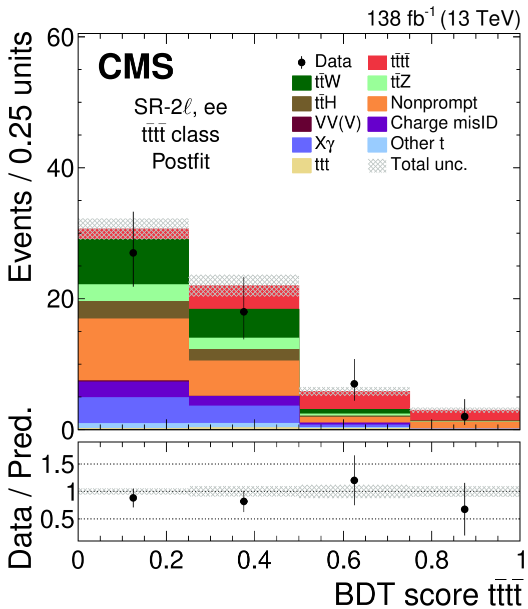
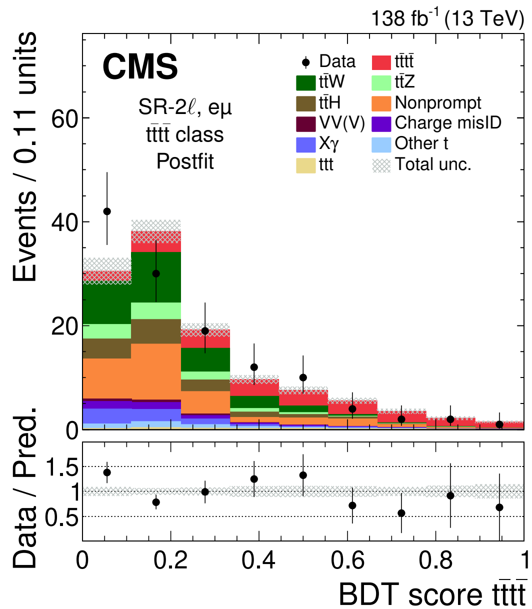
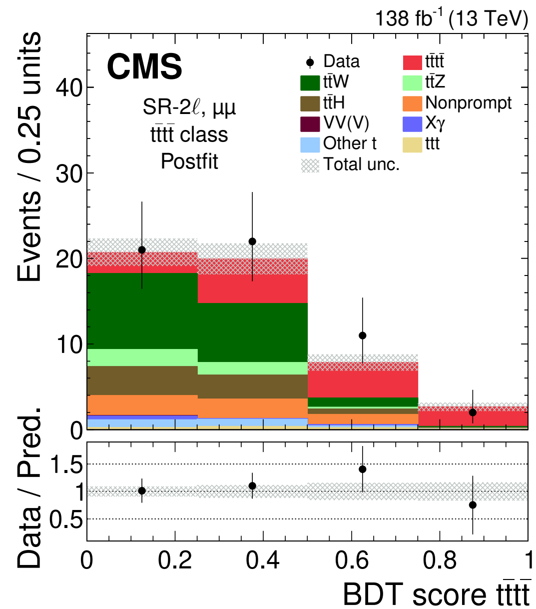
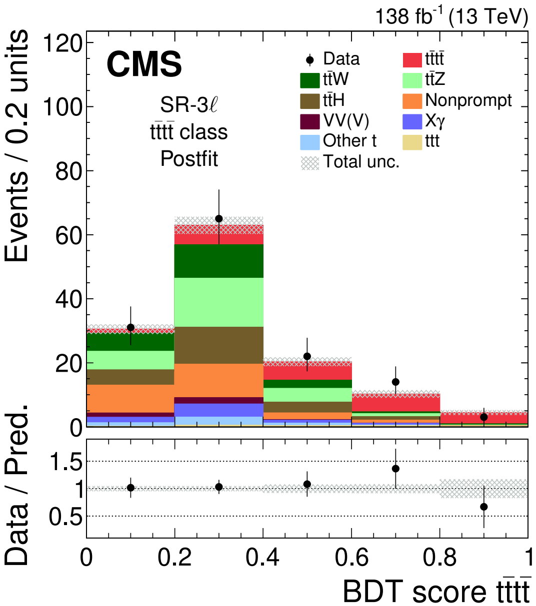
Results (1)



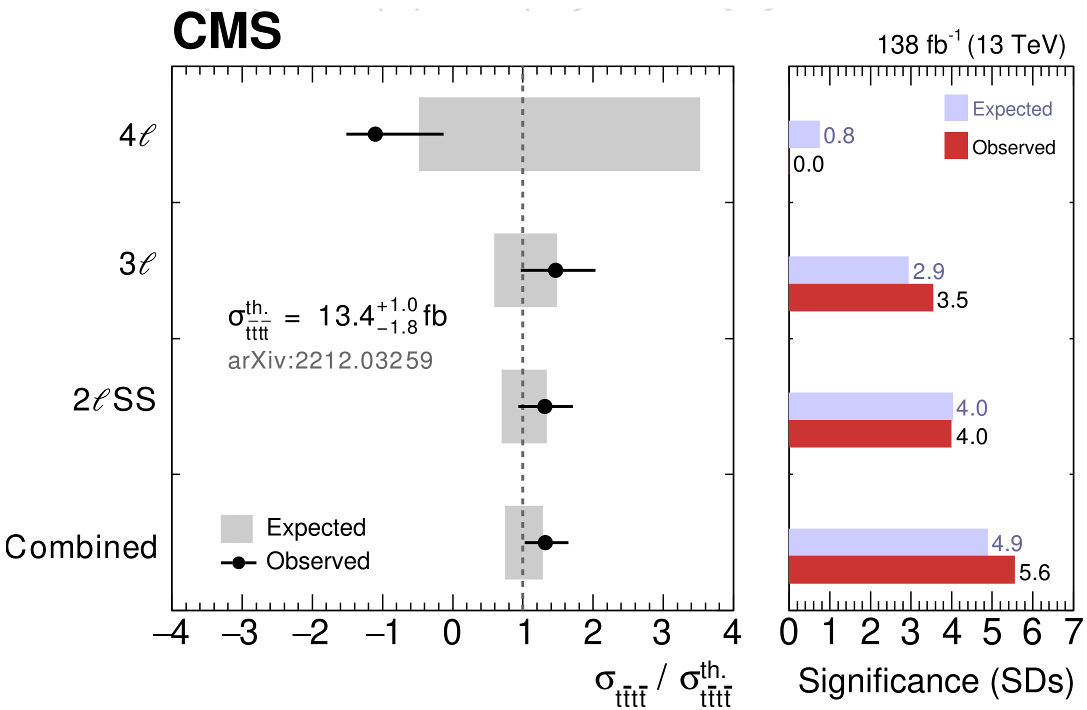






- Simultaneous binned profile likelyhood fit to BDT output nodes of signal, ttX and tt in each search region and control regions
- Extract tttt, ttW and ttZ simultaneously
- Very good agreement across postfit distributions

Results (2)



- Measurement is still stat. limitted
- Main syst. uncertainties:
  - b-jet identification modeling
  - Jet energy scale
  - ttW+(b)jet modeling
  - Signal modeling uncertainties

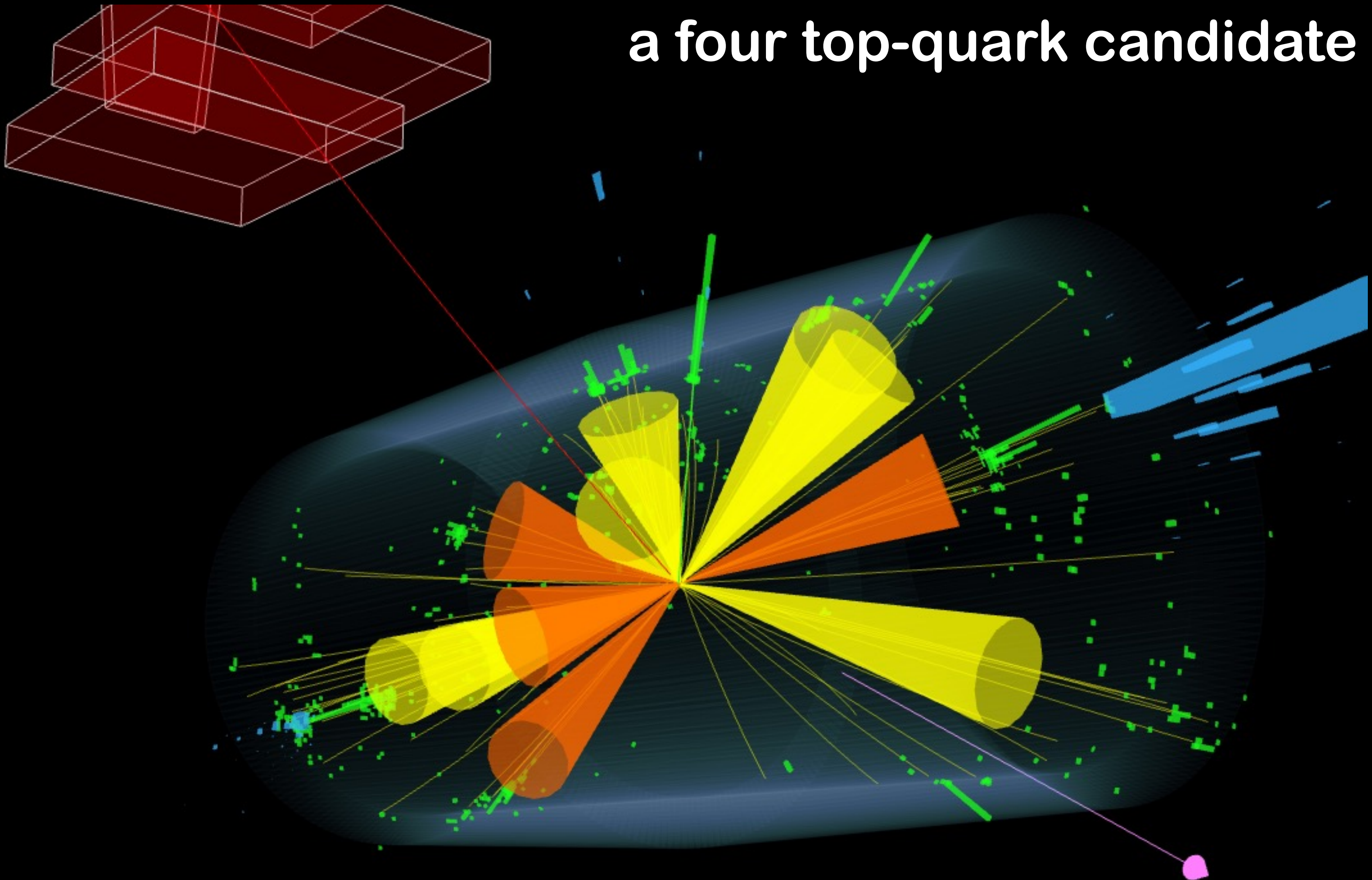
$$\sigma(t\bar{t}t\bar{t}) = 17.7\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.3}_{-1.9}\,(\text{syst})\,\text{fb},$$

20% **13%**

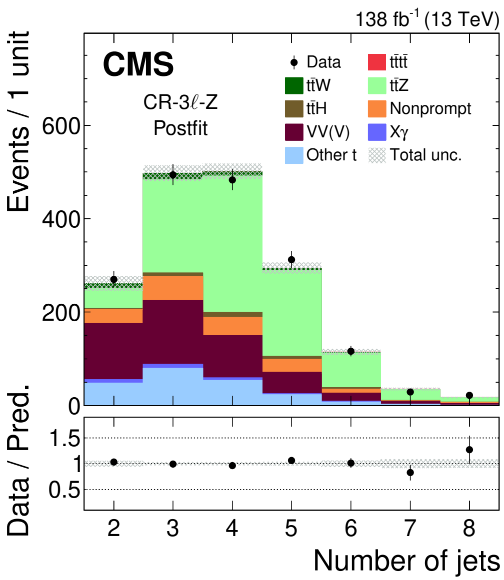
$$\sigma_{t\bar{t}t\bar{t}}/\sigma^{th.}_{t\bar{t}t\bar{t}} = 1.3 \pm 0.3$$

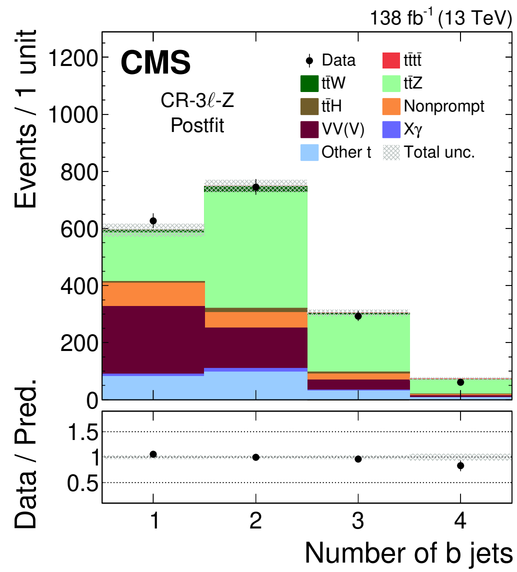
Consistent with the SM prediction within 1σ

a four top-quark candidate



Results: ttW/ ttZ



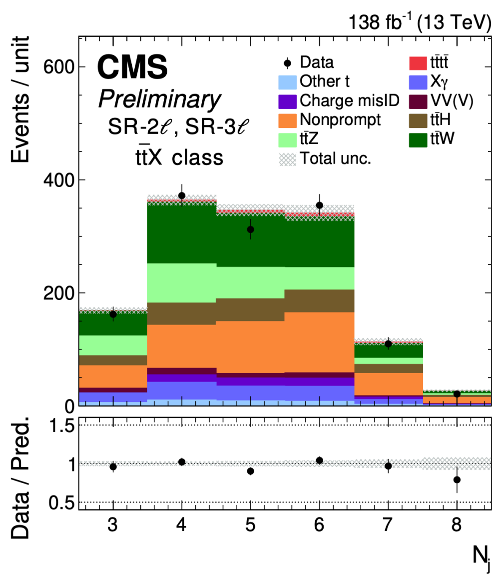


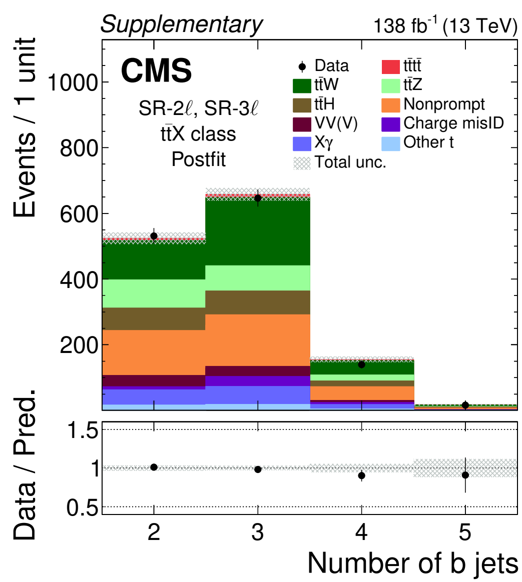
ttZ and ttW x-sections are consistent with dedicated measurements

$$\sigma(ttZ) = 945 \pm 81 \text{ fb}$$

$$\frac{\sigma^{exp.}}{\sigma^{th.}} = 1.1 \pm 0.1$$

Njet & Nbjet distributions well described

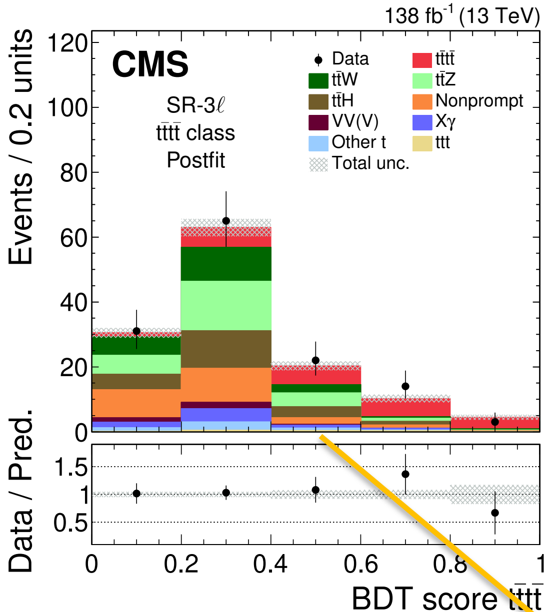


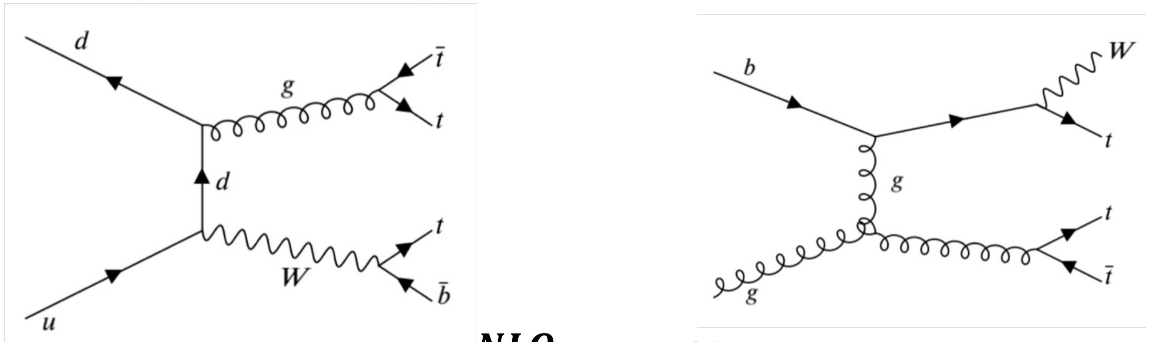


$$\sigma(ttW) = 990 \pm 98 \text{ fb}$$

$$\frac{\sigma^{exp.}}{\sigma^{th.}} = 1.37 \pm 0.13$$

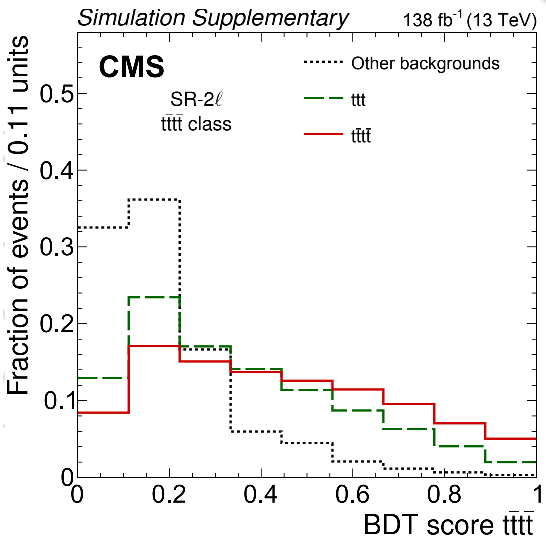
Results: 3 tops or 4 tops ?



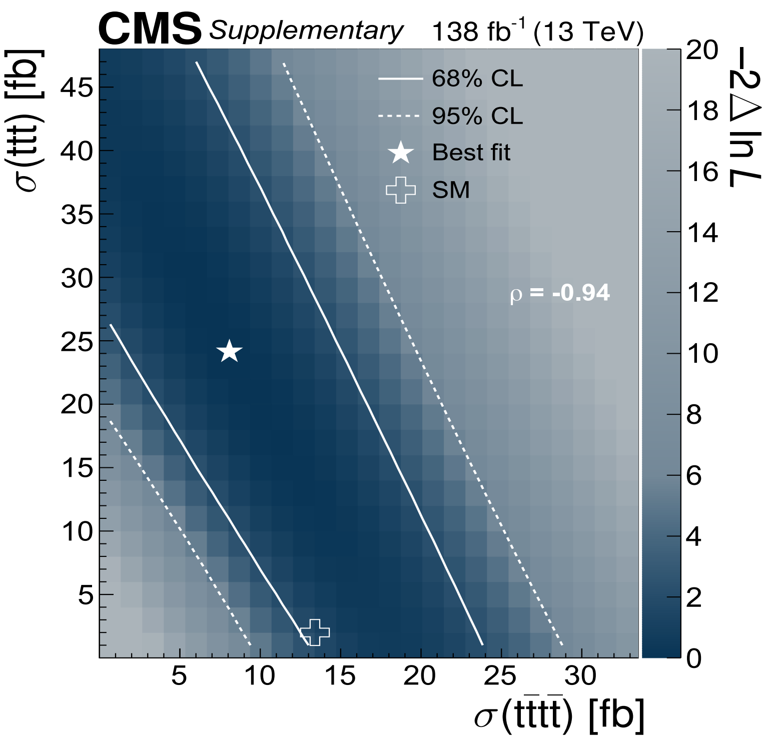


$$\sigma^{NLO} = 2\ fb$$

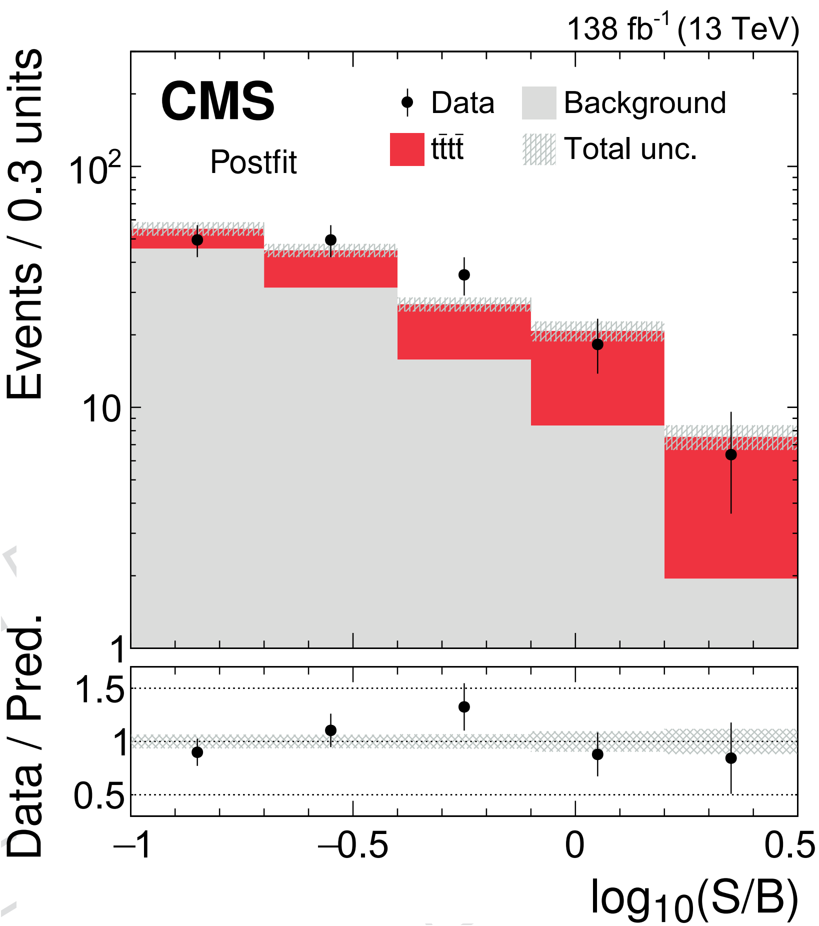
Simultaneous 3-top and 4-top signal extraction



3-top contribution



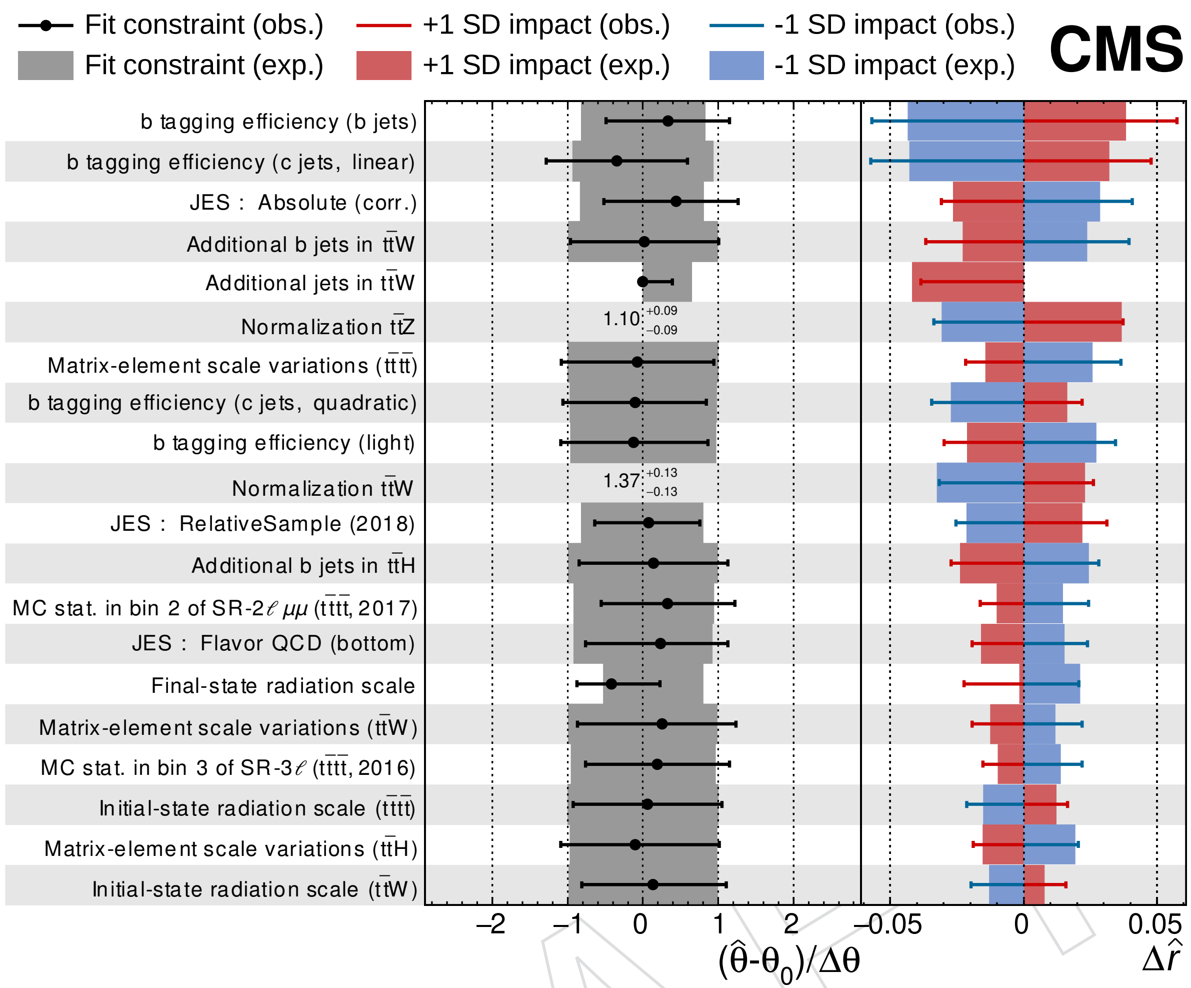
Summary and outlook



- Reached first observation with Run II data
  - Improved analysis techniques and object identification was key
- Combined Run2&3 data analysis certainly interesting
- Better understanding of some backgrounds like ttW, tWZ, tripple-top is crucial
- More studies for ttV+HF needed

backup

Results (2)



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$\mu = 1.3$ **20% (stat.)** **13% (syst.)**

$$\sigma(t\bar{t}W) = 990 \pm 58\,(\text{stat}) \pm 79\,(\text{syst})\;\text{fb}$$

$$\sigma(t\bar{t}Z) = 945 \pm 43\,(\text{stat}) \pm 69\,(\text{syst})\;\text{fb}$$

input variables to lepton ID BDT

Table 1: List of the input variables to the prompt-lepton ID BDTs. The nearest jet ($\mathrm{j_{near}}$) is defined as the jet that includes the PF particle corresponding to the reconstructed lepton, and its momentum is recalibrated after subtracting the contribution from the lepton. The last two rows list input variables only used in the electron or muon ID BDTs, respectively, and are defined in Refs. [1, 2].

Symbol	Definition
$p_{\mathrm{T}}(\ell)$	Lepton transverse momentum
$\lvert\eta(\ell)\rvert$	Lepton pseudorapidity
$I_{\mathrm{rel}}^{\mathrm{fixed}}$	Relative isolation using a fixed distance $\Delta R < 0.4$
$I_{\mathrm{rel}}^{\mathrm{ch}}$	Relative isolation using a p_{T}-dependent distance and including only charged particles
$I_{\mathrm{rel}}^{\mathrm{neu}}$	Relative isolation using a p_{T}-dependent distance and including only neutral particles
$N_{\mathrm{ch}}(\mathrm{j_{near}})$	Number of charged particles associated with the nearest jet
$p_{\mathrm{T}}^{\mathrm{ratio}}$	Ratio of the lepton p_{T} to the nearest jet p_{T}, i.e., $p_{\mathrm{T}}(\ell)/p_{\mathrm{T}}(\mathrm{j_{near}})$; or $1/(1+I_{\mathrm{rel}}^{\mathrm{fixed}})$ if no nearest jet is found
$p_{\mathrm{T}}^{\mathrm{rel}}$	Component of the lepton momentum in direction transverse to the nearest jet, i.e., $p(\ell)\sin\theta(\vec{p}(\ell),\vec{p}(\mathrm{j_{near}}))$
$\mathrm{DJ}(\mathrm{j_{near}})$	DEEPJET score of the nearest jet
$\log\lvert d_{xy}\rvert$	Distance of closest approach from the lepton track to the PV in the transverse plane on a logarithmic scale
$\log\lvert d_{z}\rvert$	Distance of closest approach from the lepton track to the PV in the longitudinal plane on a logarithmic scale
$d/\delta d$	Significance of the distance of closest approach from the lepton track to the PV
$P_{\mathrm{ID}}^{\mathrm{e}}$	Electron ID discriminant
P_{seg}^{μ}	Muon segment compatibility