Review of four top quark production results

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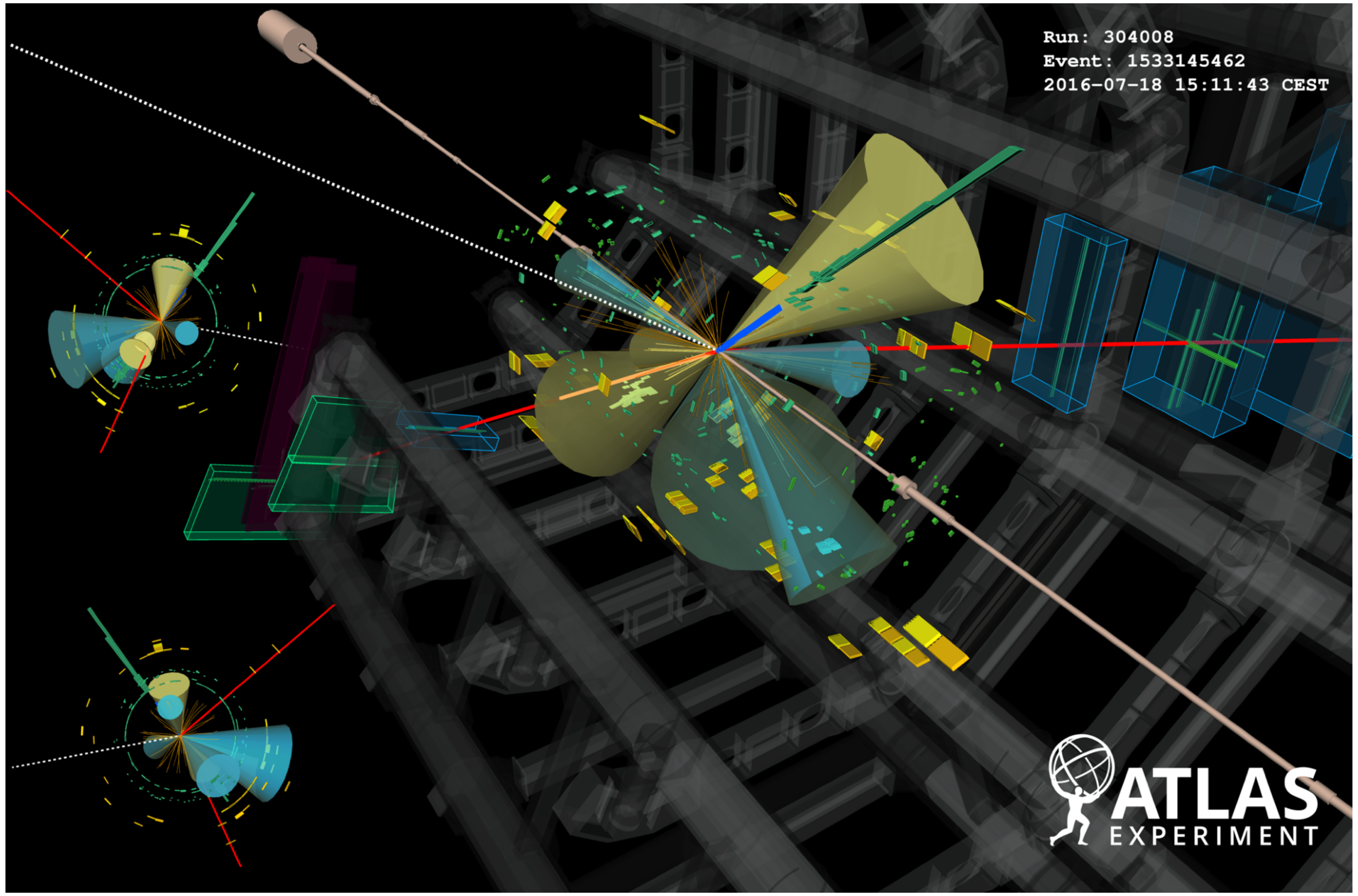


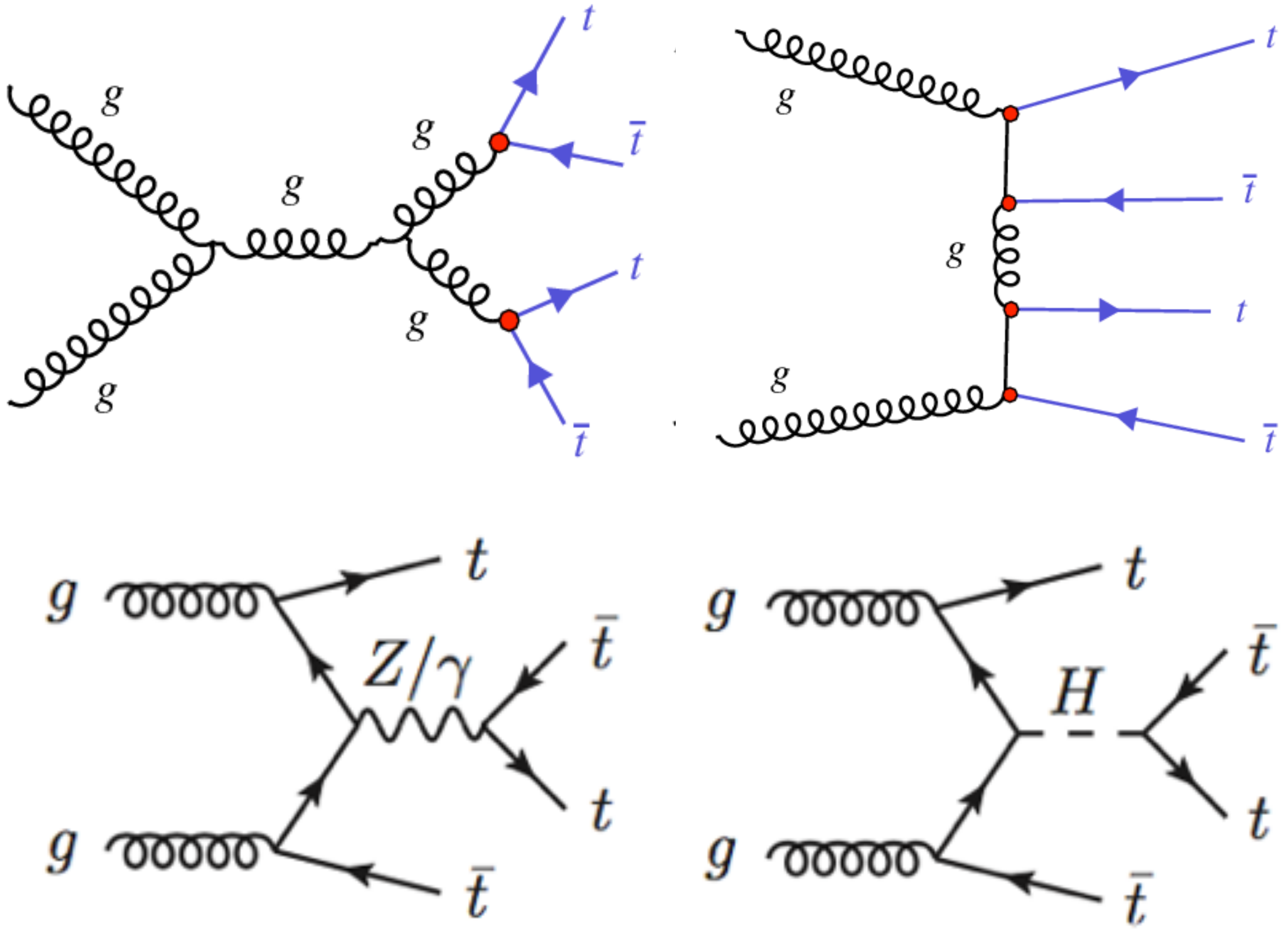
Four top quark production in the Standard Model

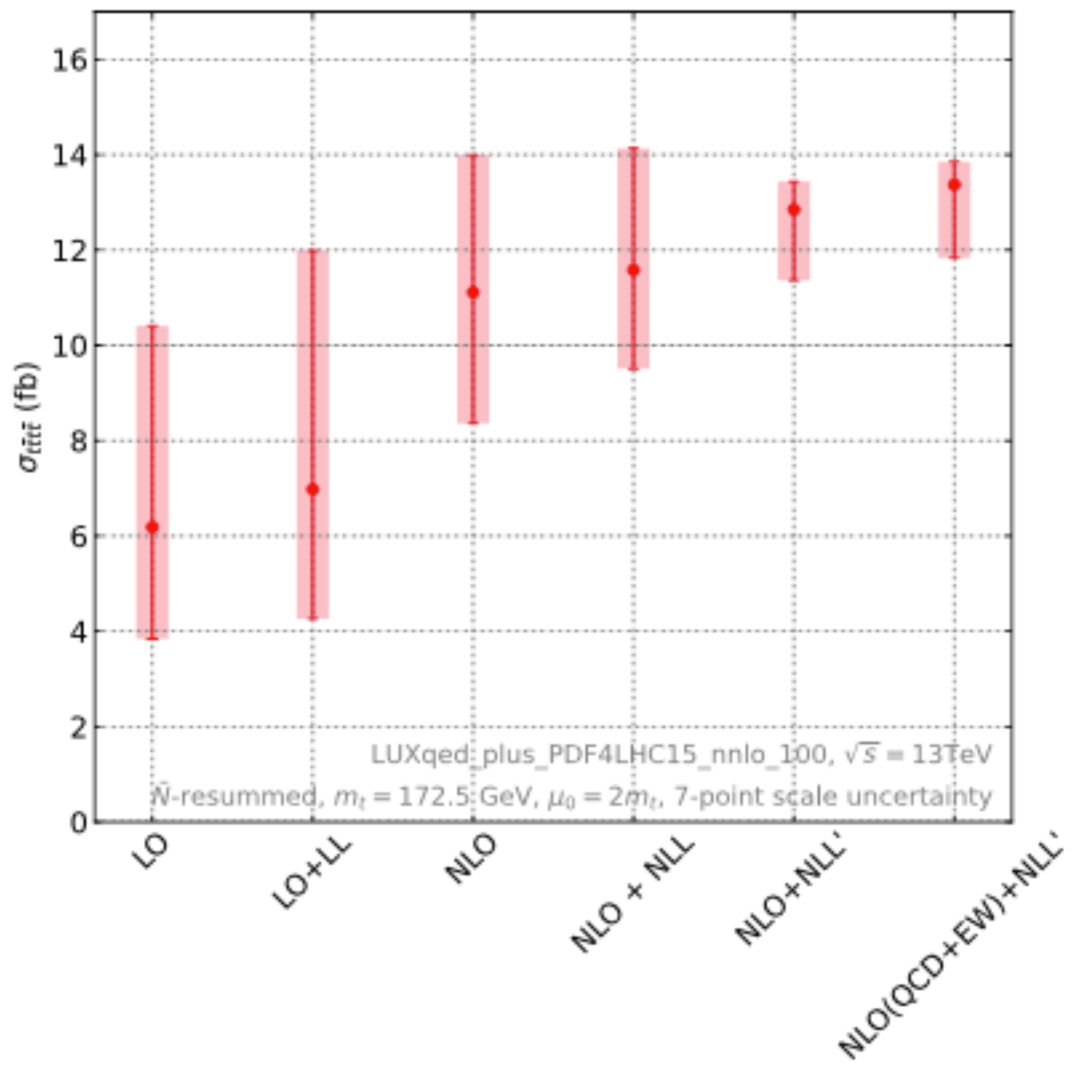
- One of the heaviest final states accessible at the LHC
  - NLO QCD: σ($t\bar{t}t\bar{t}$) = 12 fb ±20% [JHEP 02 (2018) 031]
  - NLO+NLL: σ($t\bar{t}t\bar{t}$) = 13.4 fb ±11% [arXiv:2212.03259]

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$	$11.12^{+19\%}_{-23\%}$	$7.59^{+64\%}_{-36\%}$	$11.97^{+18\%}_{-21\%}$	1.11 (1.08)

NLO K-factor around 10-15%
NLL resummation increase the XS by 15%
Decrease in scale uncertainties by 50%

- Naturally sensitive to many BSM models
  - top Higgs Yukawa coupling and its CP properties
  - Uniquely sensitive to EFT four heavy fermion operators
  - New mediator particles

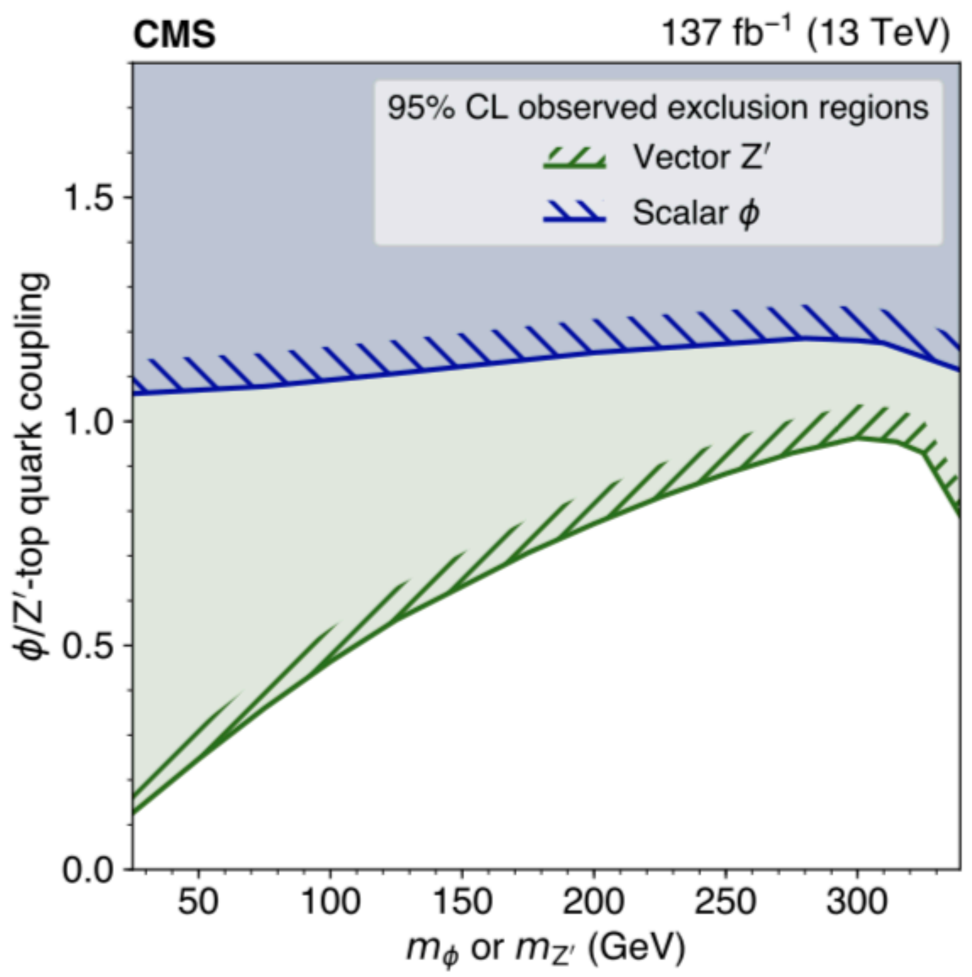


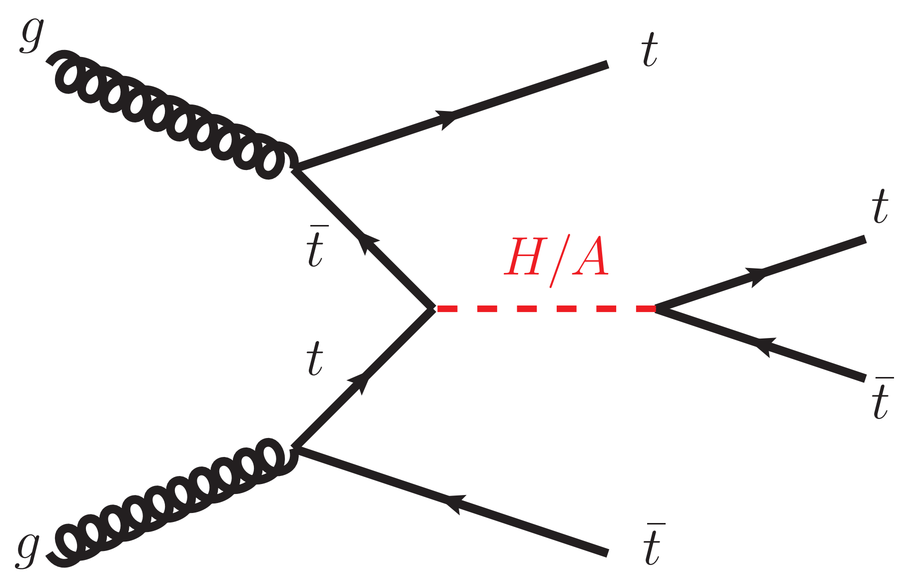


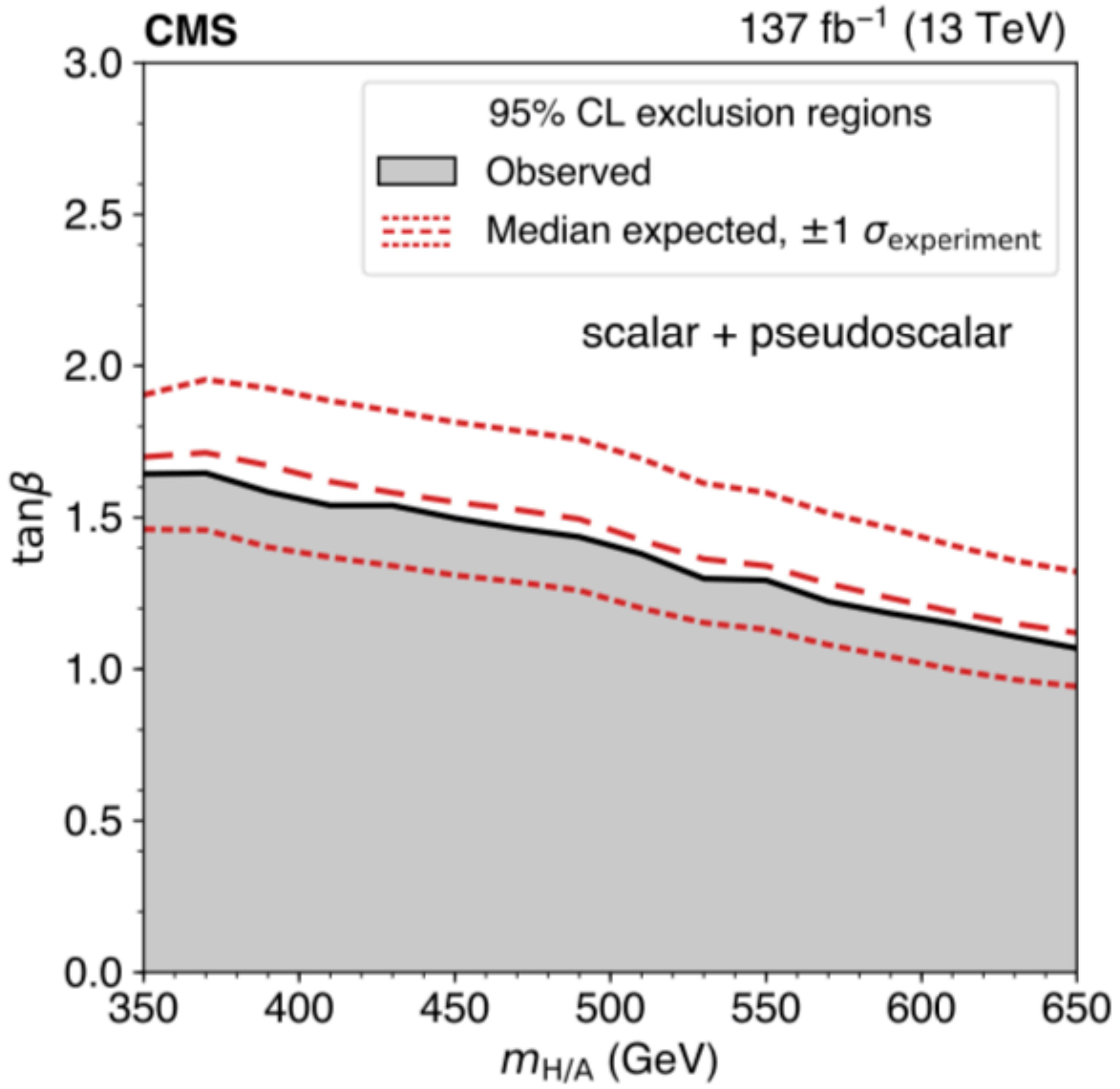
$\sqrt{s}$ (TeV)	$\sigma^{\mathrm{NLO}}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\mathrm{NLO+NLL}}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\mathrm{NLO+NLL'}}_{t\bar{t}t\bar{t}}$ (fb)	$\mathrm{K_{NLL'}}$
13	$11.00(2)^{+25.2\%}_{-24.5\%}$ fb	$11.46(2)^{+21.3\%}_{-17.7\%}$ fb	$12.73(2)^{+4.1\%}_{-11.8\%}$ fb	1.16
13.6	$13.14(2)^{+25.1\%}_{-24.4\%}$ fb	$13.81(2)^{+20.7\%}_{-20.1\%}$ fb	$15.16(2)^{+2.5\%}_{-11.9\%}$ fb	1.15
$\sqrt{s}$ (TeV)	$\sigma^{\mathrm{NLO(QCD+EW)}}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\mathrm{NLO(QCD+EW)+NLL}}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\mathrm{NLO(QCD+EW)+NLL'}}_{t\bar{t}t\bar{t}}$ (fb)	$\mathrm{K_{NLL'}}$
13	$11.64(2)^{+23.2\%}_{-22.8\%}$ fb	$12.10(2)^{+19.5\%}_{-16.3\%}$ fb	$13.37(2)^{+3.6\%}_{-11.4\%}$ fb	1.15
13.6	$13.80(2)^{+22.6\%}_{-22.9\%}$ fb	$14.47(2)^{+18.5\%}_{-19.1\%}$ fb	$15.82(2)^{+1.5\%}_{-11.6\%}$ fb	1.15

4top production as probe to new physics

- Higgs oblique parameter :
  - the Wilson coefficient that modifies the Higgs propagator (arXiv:1903.07725)
  - Modify the 4top signal and the $t\bar{t}H$ cross section (rescaled by $(1-\hat{H})^2$)

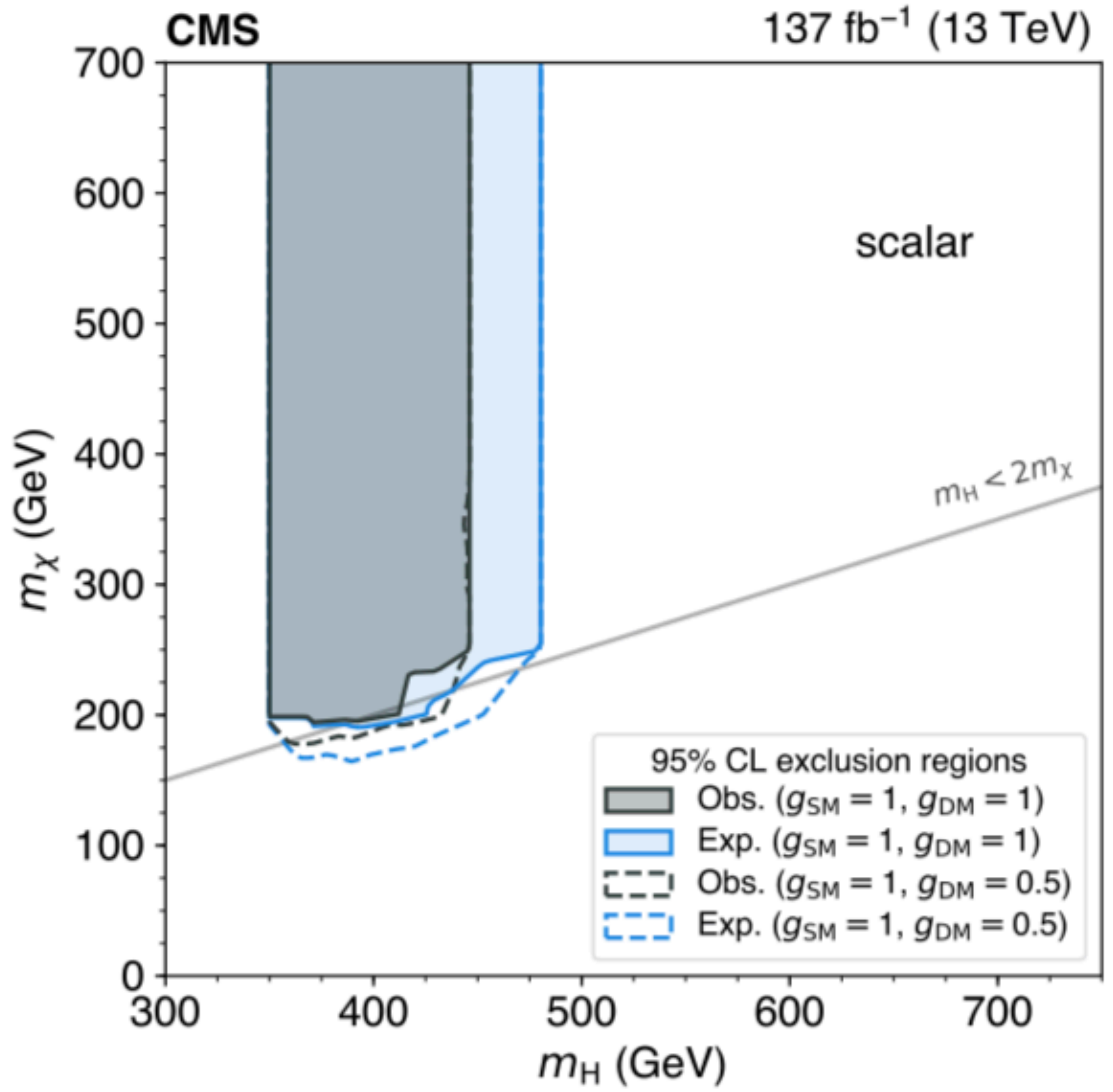






- New particles with m<2mt
  - Virtual scalar (Φ) or vector (Z′)
  - Recalculate σ(4top) limit with 10% more systematics (effect of the BSM on the signal acceptance)

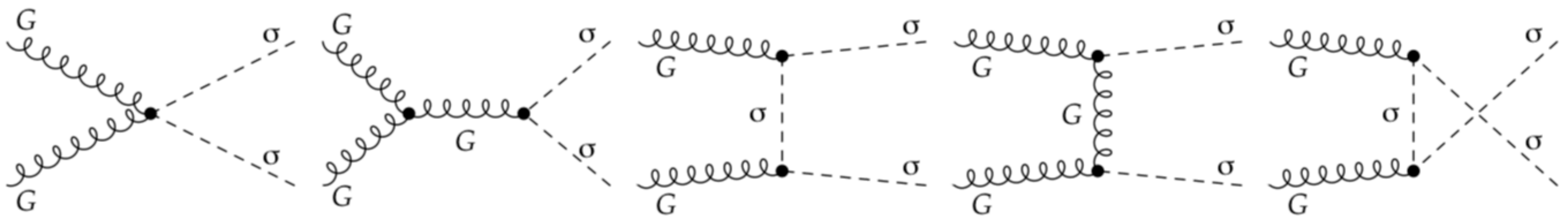
- New particles with m>2mt
  - Heavy Higgs (H/A): could be interpreted in terms of 2HDM parameters or as simplified dark matter models (dirac fermion dark matter X in addition to A/H)



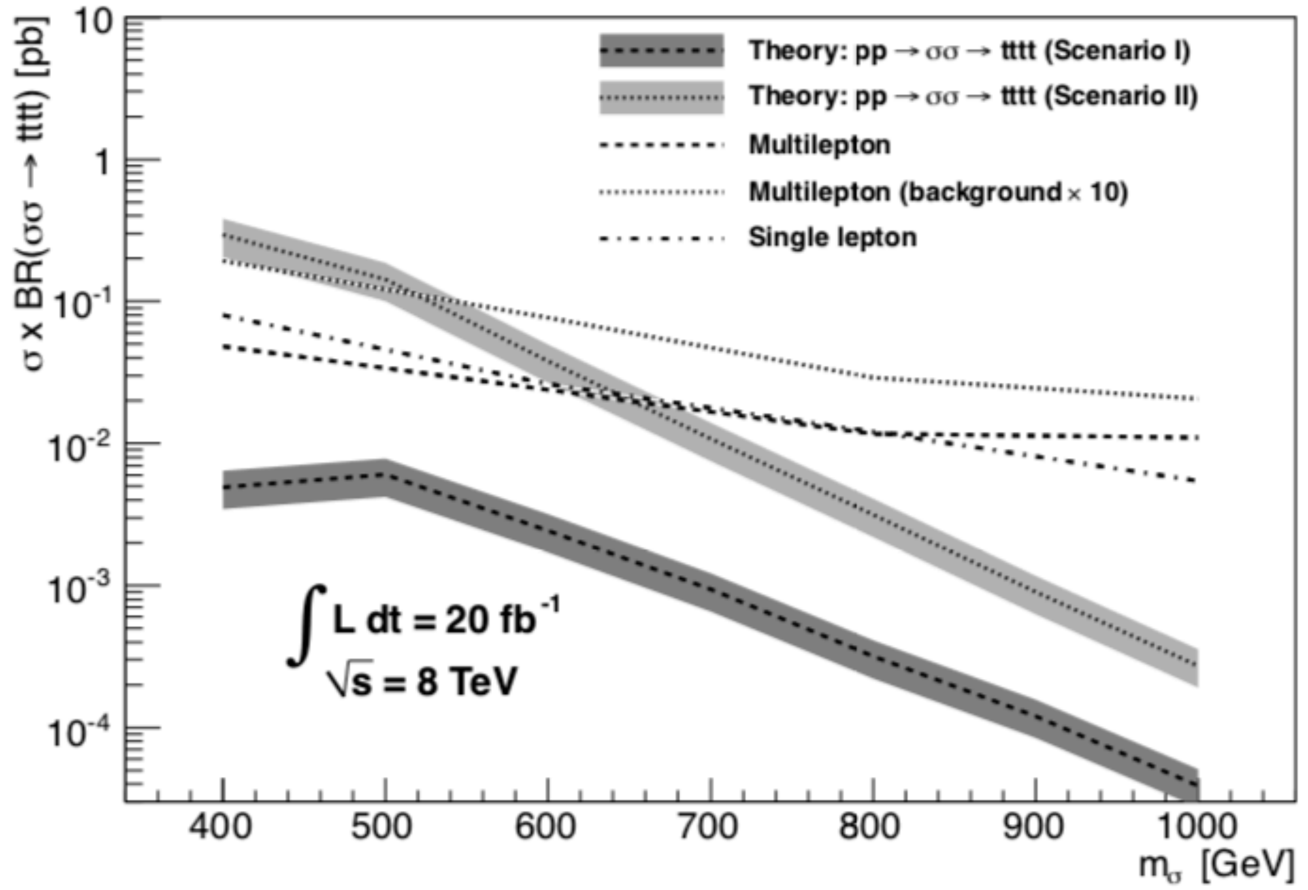
Interpretations performed by CMS: arXiv:1908.06463

Other possible models with 4top signature

- sgluon production
  - S. Calvet et al: arXiv:1212.3360
  - Sgluon decaying to tj or $t\bar{t}$: can lead to a 4top signature



	Single lepton analysis	Multilepton analysis	Multilepton analysis (background ×10)
$tjtj$	$590\ ^{+40}_{-30}$ GeV	$570\ ^{+30}_{-50}$ GeV	$440\ ^{+40}_{-15}$ GeV
$tjtt$	$480\ ^{+70}_{-80}$ GeV	$520\ ^{+35}_{-90}$ GeV	-
$tttt$ (Scenario I)	-	-	-
$tttt$ (Scenario II)	$640\ ^{+40}_{-30}$ GeV	$650\ ^{+30}_{-40}$ GeV	$520\ ^{+50}_{-110}$ GeV



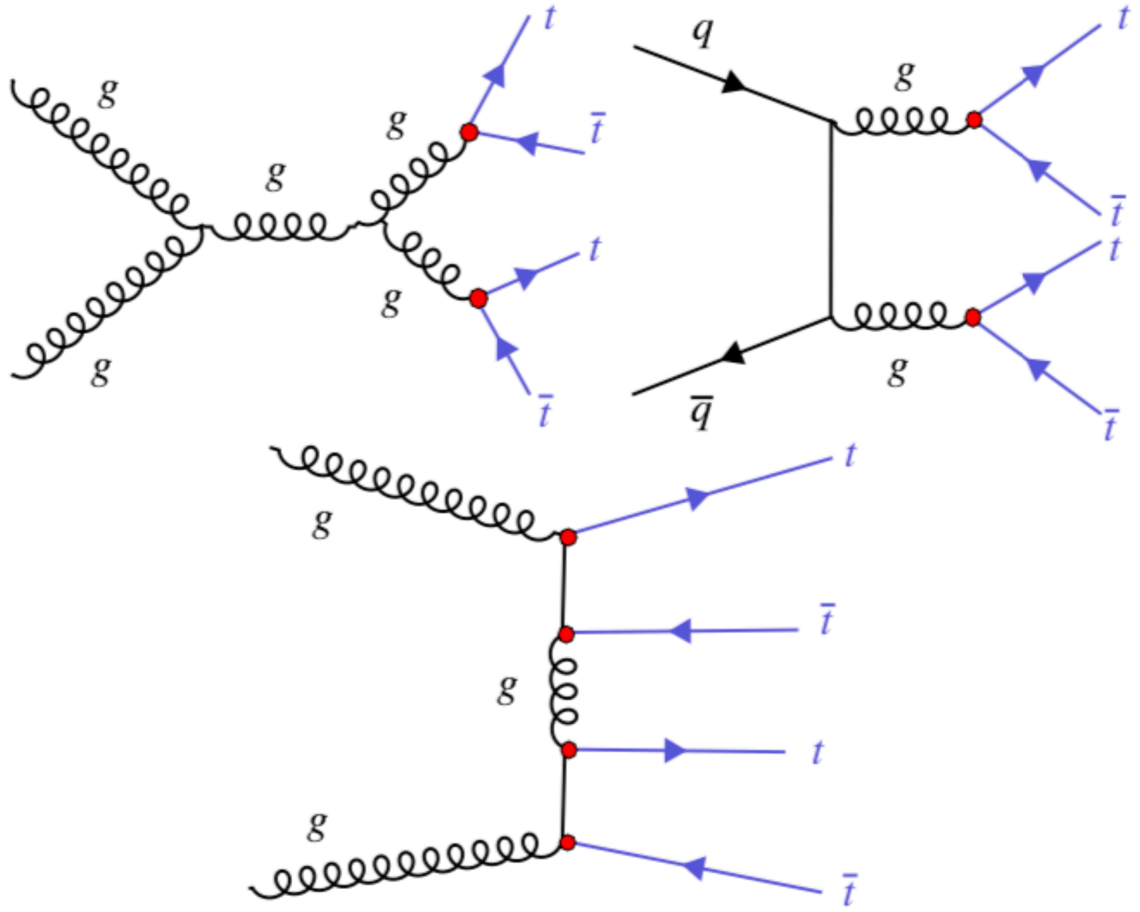
- Strong and weak dipole moments
  - Malekhosseini et al: arXiv:1804.05598
  - Parametrize the 4top cross section as a function of $d^{g,Z}_V$ or $d^{g,Z}_A$
  - Extract limits from the 4top rate

$$\sigma(pp \to t\bar{t}t\bar{t})(fb) = \sigma_{\rm SM} + 154.827 \times d_V^g + 3404.44 \times (d_V^g)^2,$$

$$\sigma(pp \to t\bar{t}t\bar{t})(fb) = \sigma_{\rm SM} + 2731.27 \times (d_A^g)^2,$$

$$\sigma(pp \to t\bar{t}t\bar{t})(fb) = \sigma_{\rm SM} - 0.689188 \times d_V^Z + 37.0581 \times (d_V^Z)^2,$$

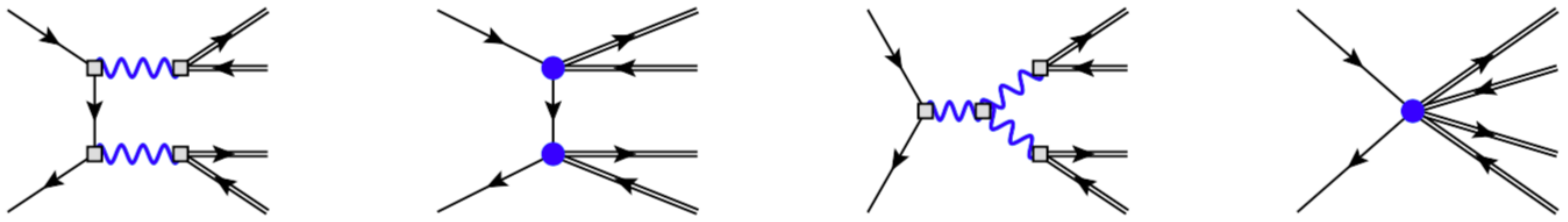
$$\sigma(pp \to t\bar{t}t\bar{t})(fb) = \sigma_{\rm SM} + 27.962 \times (d_A^Z)^2,$$



Coupling	Current four-top with 35.6 fb^{-1}	Future four-top with 300 fb^{-1}
d_V^g	[-0.20, 0.11]	[-0.07,0.03]
d_A^g	[-0.16, 0.16]	[-0.05, 0.05]
d_V^Z	[-1.42,1.45]	[-0.45, 0.47]
d_A^Z	[-1.65, 1.65]	[-0.53, 0.53]

4-top EFT operators

- 4-fermion operators relevant for 4top
  - Only constrained by $t\bar{t}t\bar{t}$ or $t\bar{t}bb$
  - Operators that preserved SU(2)$_L$:
    O^1_{QQ}, O^8_{QQ}, O^1_{Qt}, O^8_{Qt}, O^1_{tt}



$$c^1_{QQ} \equiv 2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}, \qquad c^1_{Qt} \equiv C^{1(3333)}_{qu},$$

$$c^8_{QQ} \equiv 8C^{3(3333)}_{qq}, \qquad c^8_{Qt} \equiv C^{8(3333)}_{qu},$$

$$c^1_{tt} \equiv C^{1(3333)}_{uu},$$

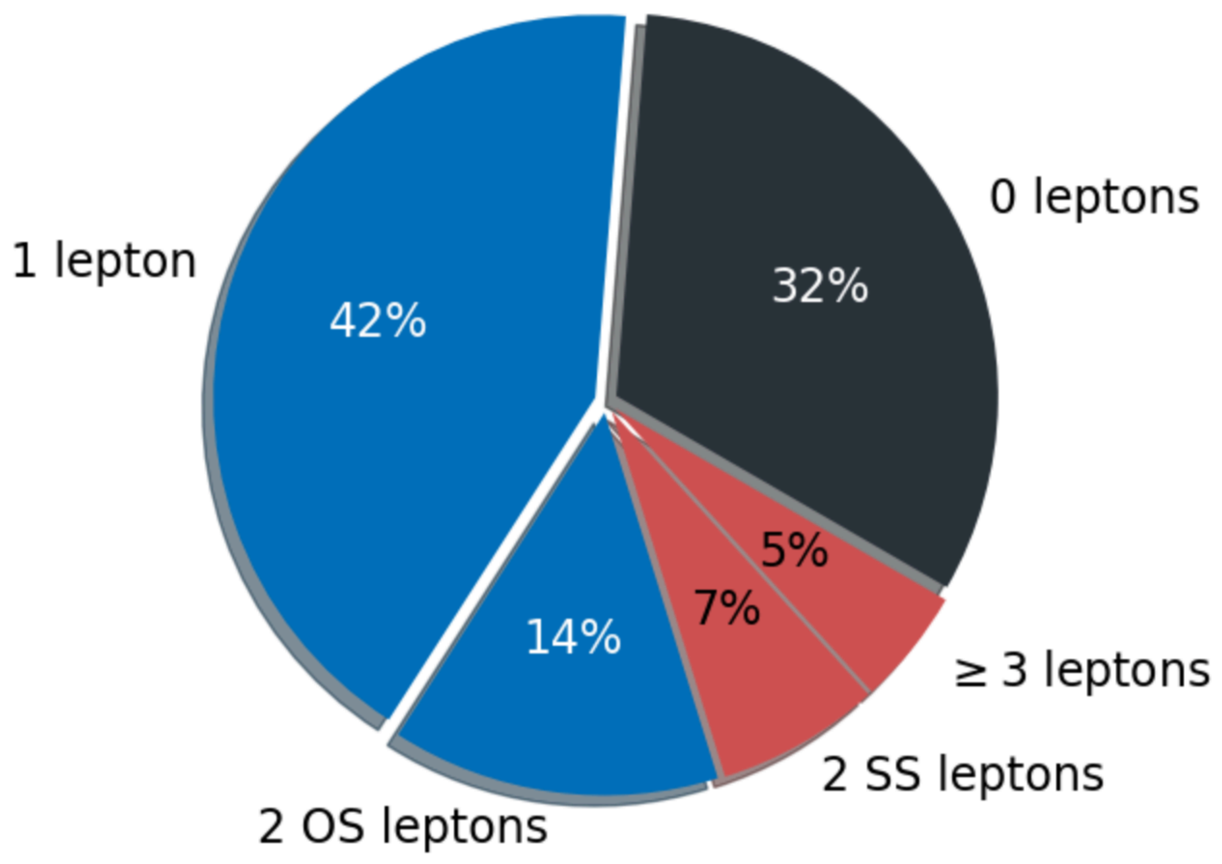
- Other operators could affect the backgrounds:
  - $t\bar{t}W$: 3 O(Λ-2) operators
  - $t\bar{t}H/Z$: 7 O(Λ-2) operators
  - 14 qqtt operators

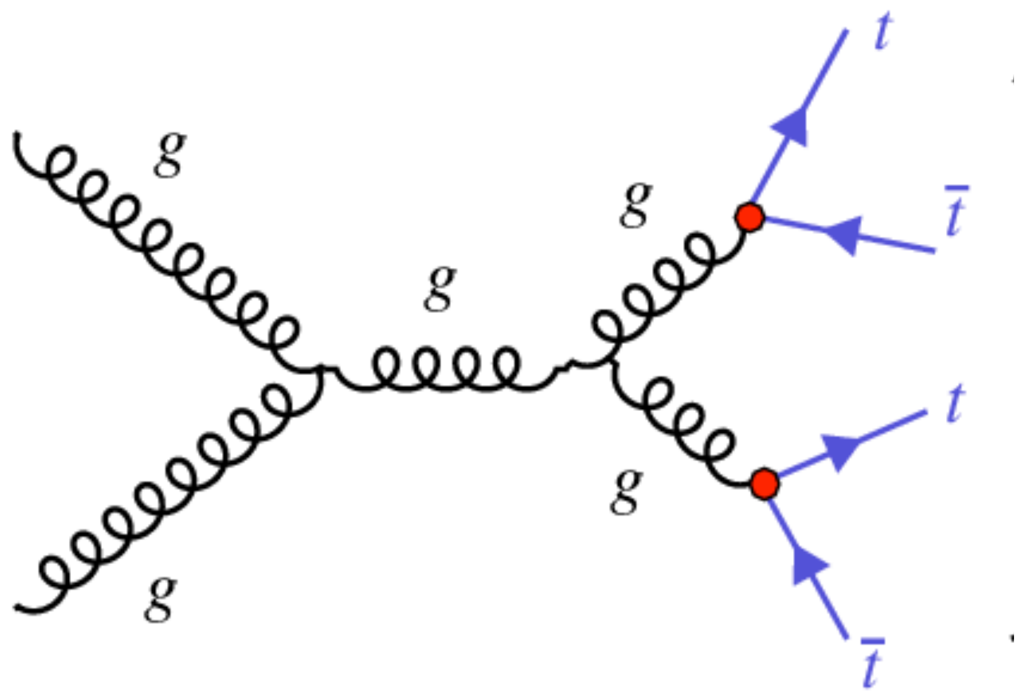
Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)							
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1									✓
OQb8									✓
Ott1								✓	
Otb1									✓
Otb8									✓
OQtQb1									(✓)
OQtQb8									(✓)

- Reduced set for tttt only at LO:
  - 4 operators that conserved SU(2)$_L$: O^8_{QQ},= 1/3 O^1_{QQ} (see for instance 1807.02130)
  - Could also test SU(2)$_L$ breaking operators

Overview of the experimental results

- Final states: high jets and b-jets multiplicity
  - Analysis strategy depends on the number of leptons from the top decays
    - All hadronic (all-had): reasonable branching fraction and large irreducible background (multijets)
    - Single lepton and two lepton opposite sign (1L/2LOS): large branching fraction and large irreducible background ($t\bar{t}bb$)
    - Same-sign di-lepton and multi-lepton (multilepton or SSML): smaller branching fraction and higher purity





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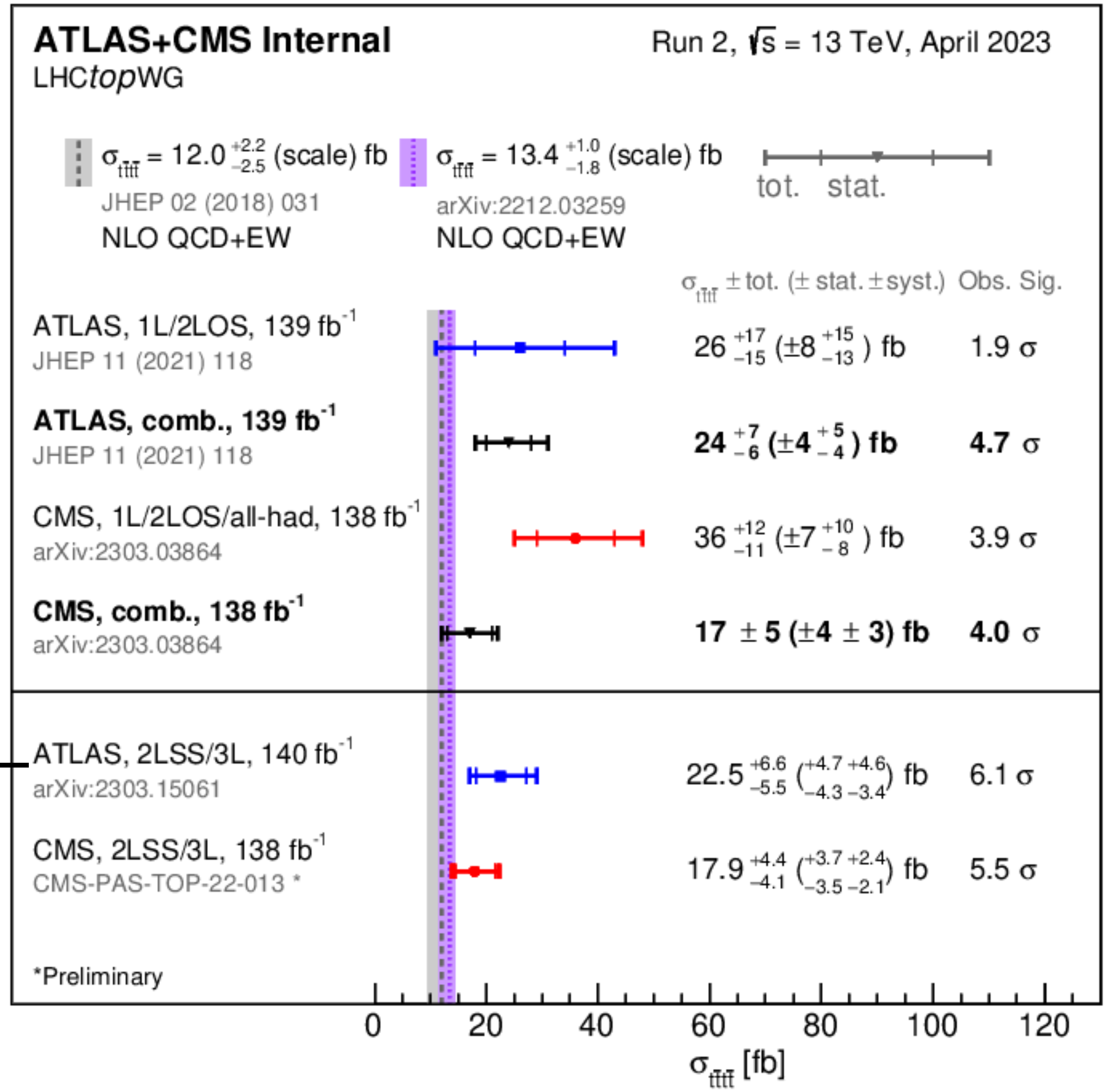
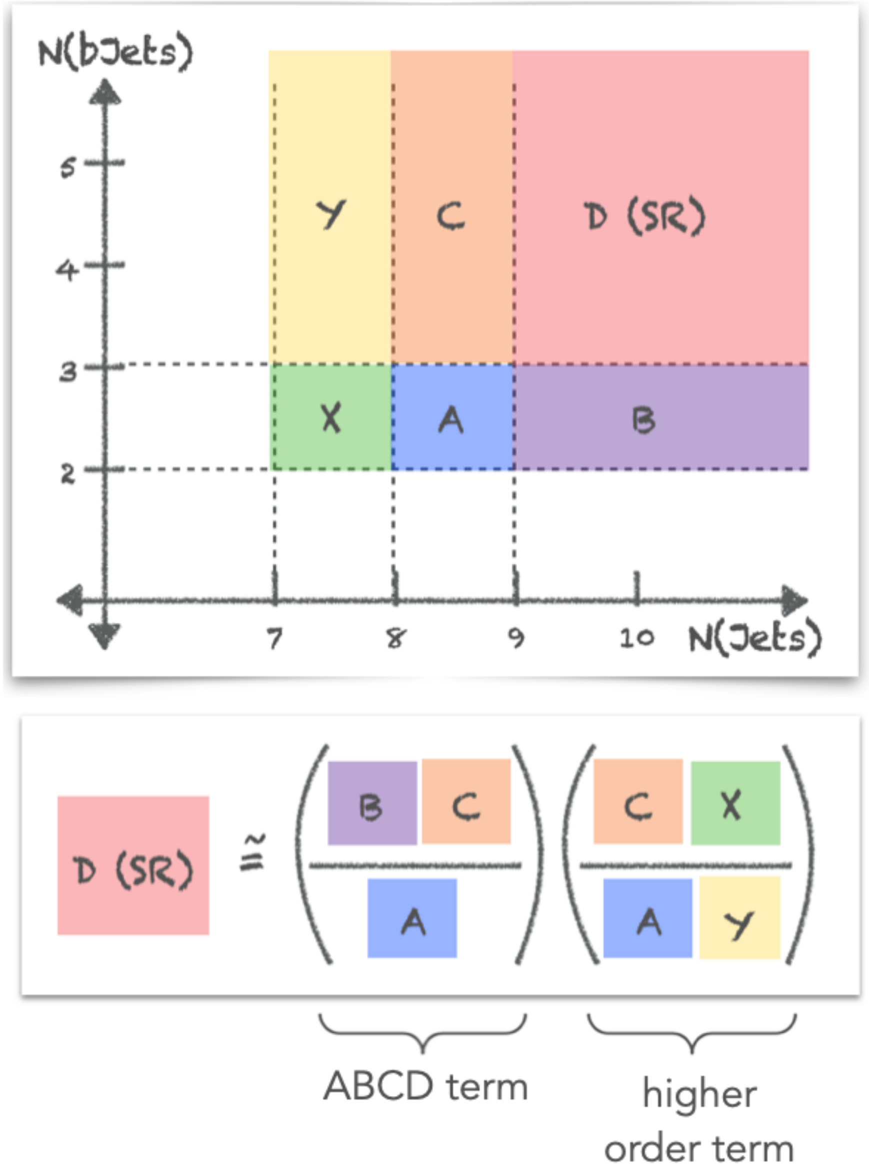


Discussed in Xiang's talk ←

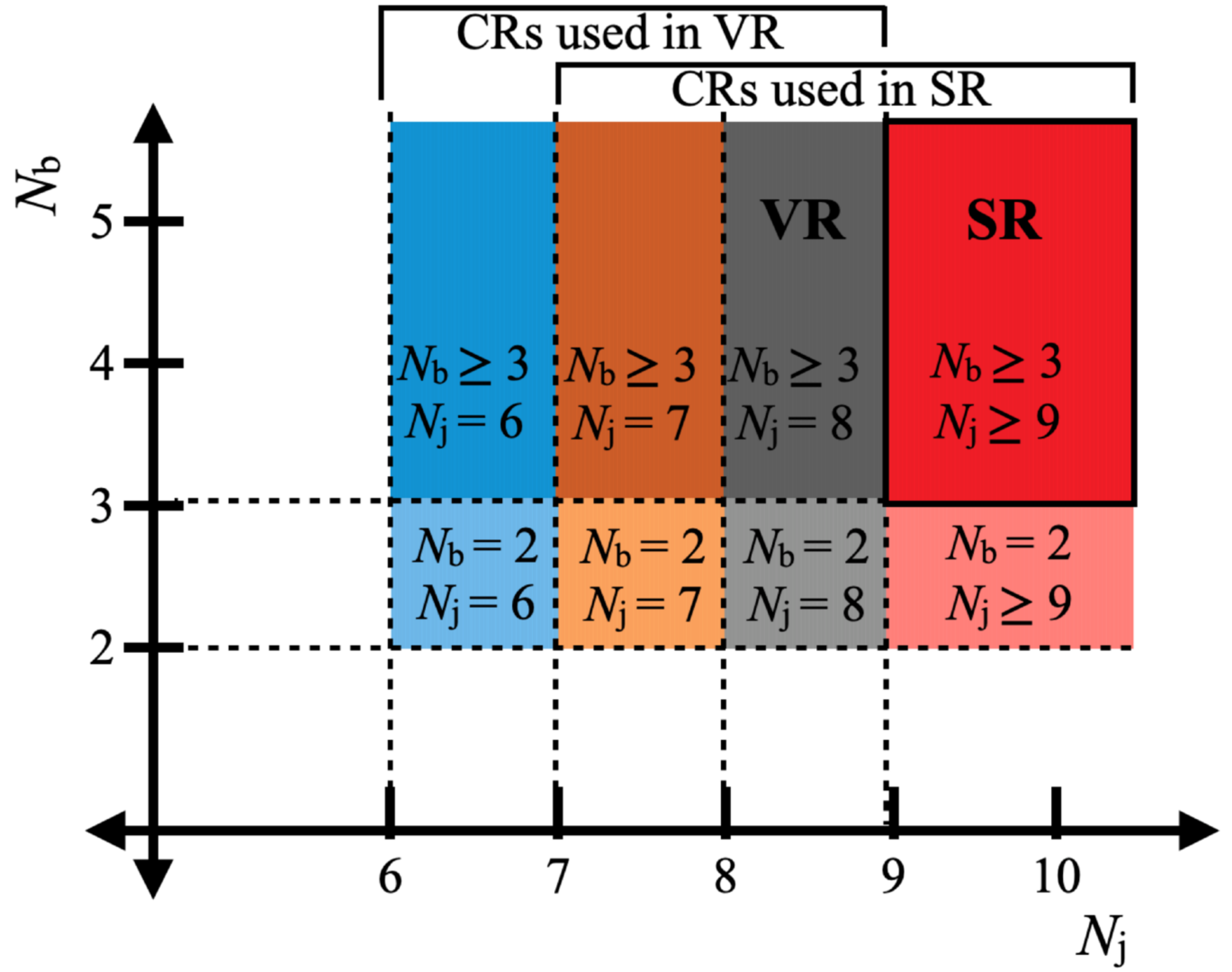
CMS result in the all hadronic channel

- Very challenging channel because of the multijet background
- Analysis strategy:
  - Signal region: Ht > 700 GeV, at least 9 jets with at least 3 b-jets (S/B ~ 10^{-5})
  - Split in numbers of resolved and boosted tops and Ht into 12 regions
  - BDT trained in each category to separate $t\bar{t}t\bar{t}$ from QCD multijet (20 input variables including Nj and Nb, kinematics of the jets)

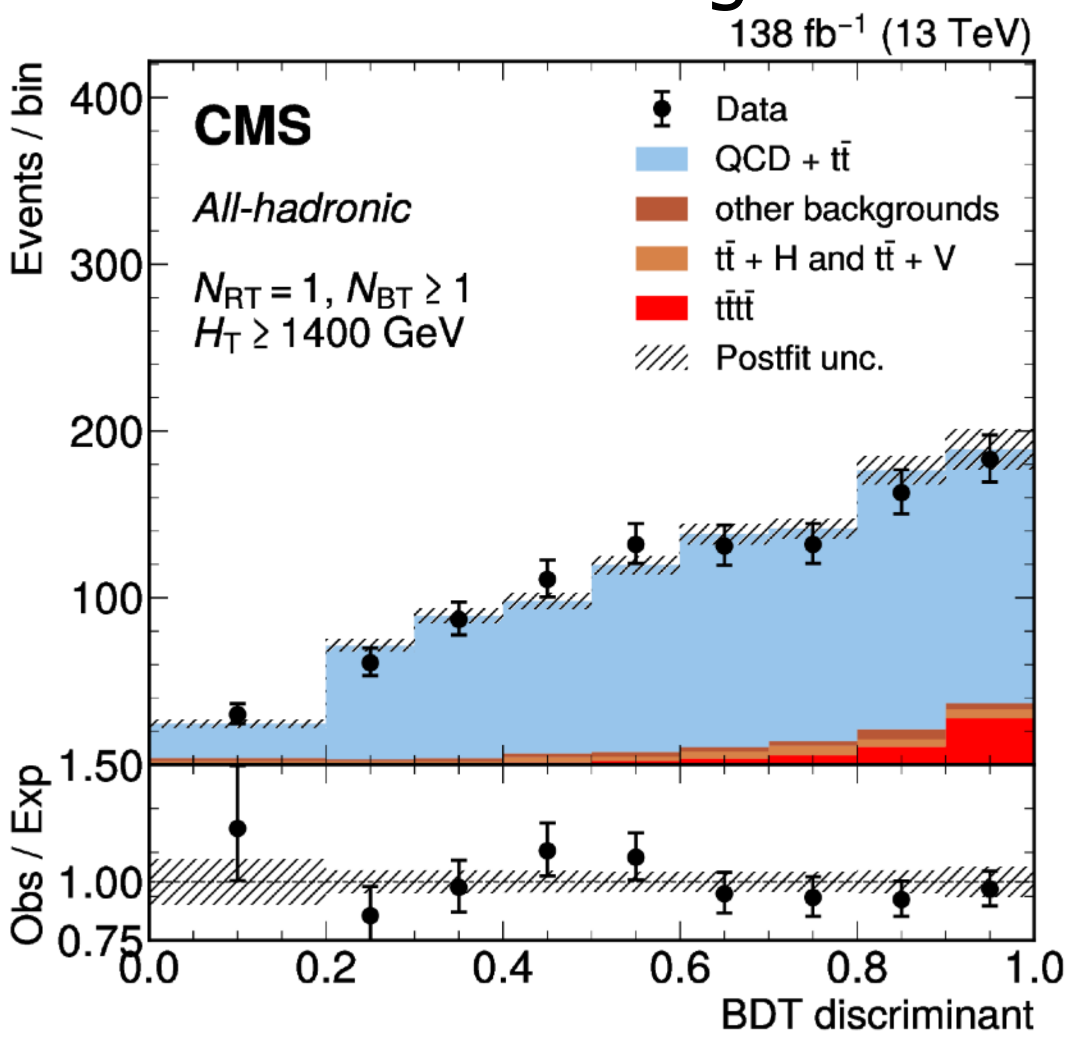
arXiv:2303.03864

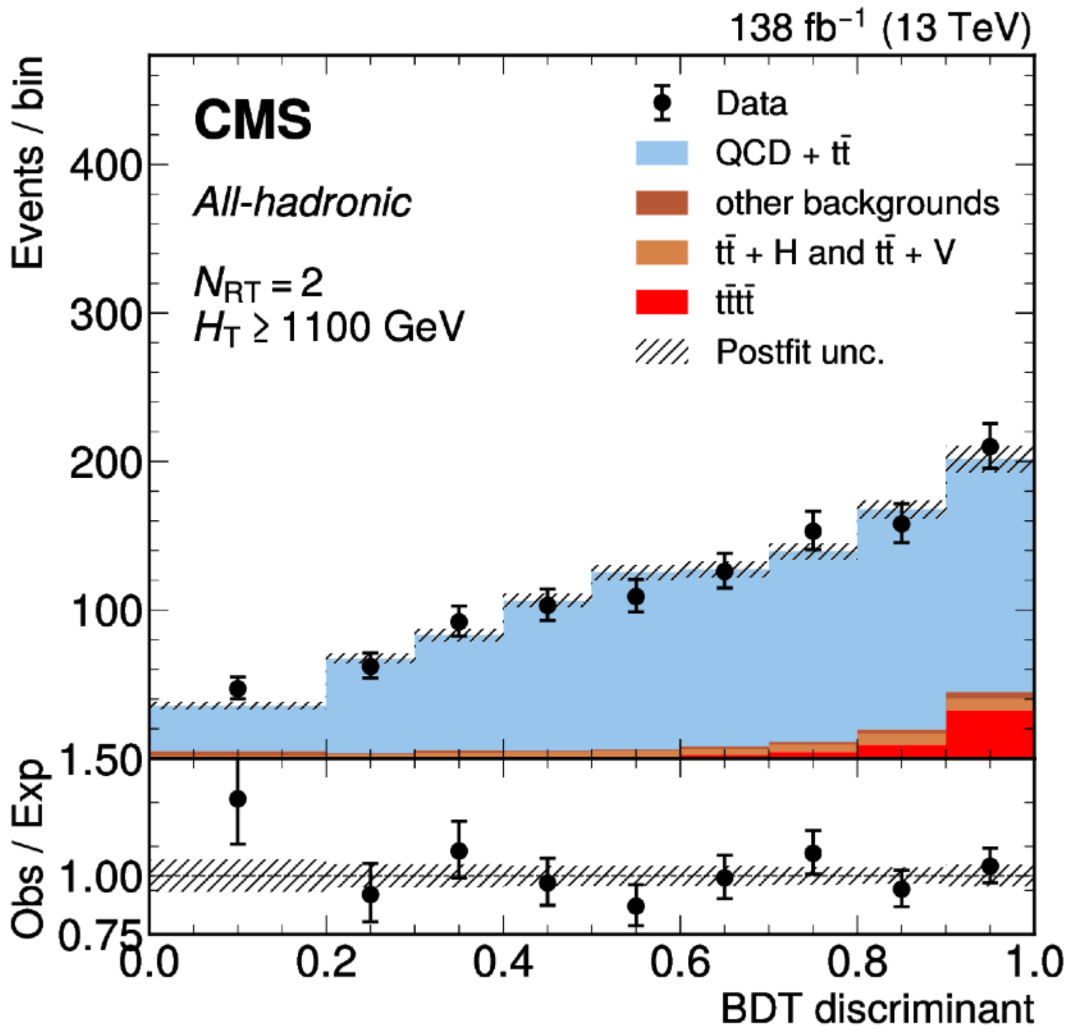


- Background estimation:
  - 5 control regions with lower jets/b-jets multiplicity
  - Absolute normalisation from an 'extended ABDC method'
  - BDT shape in each SR predicted using a DNN trained on the 5 CRs
    - normalizing autoregressive flow trained on the CRs to learn a bijective transformation of HT and BDT from a source ($t\bar{t}$ MC) to a target ($t\bar{t}$ and QCD background)
    - Shape checked in validation regions



Expected: 0.4 σ
Observed: 2.5 σ



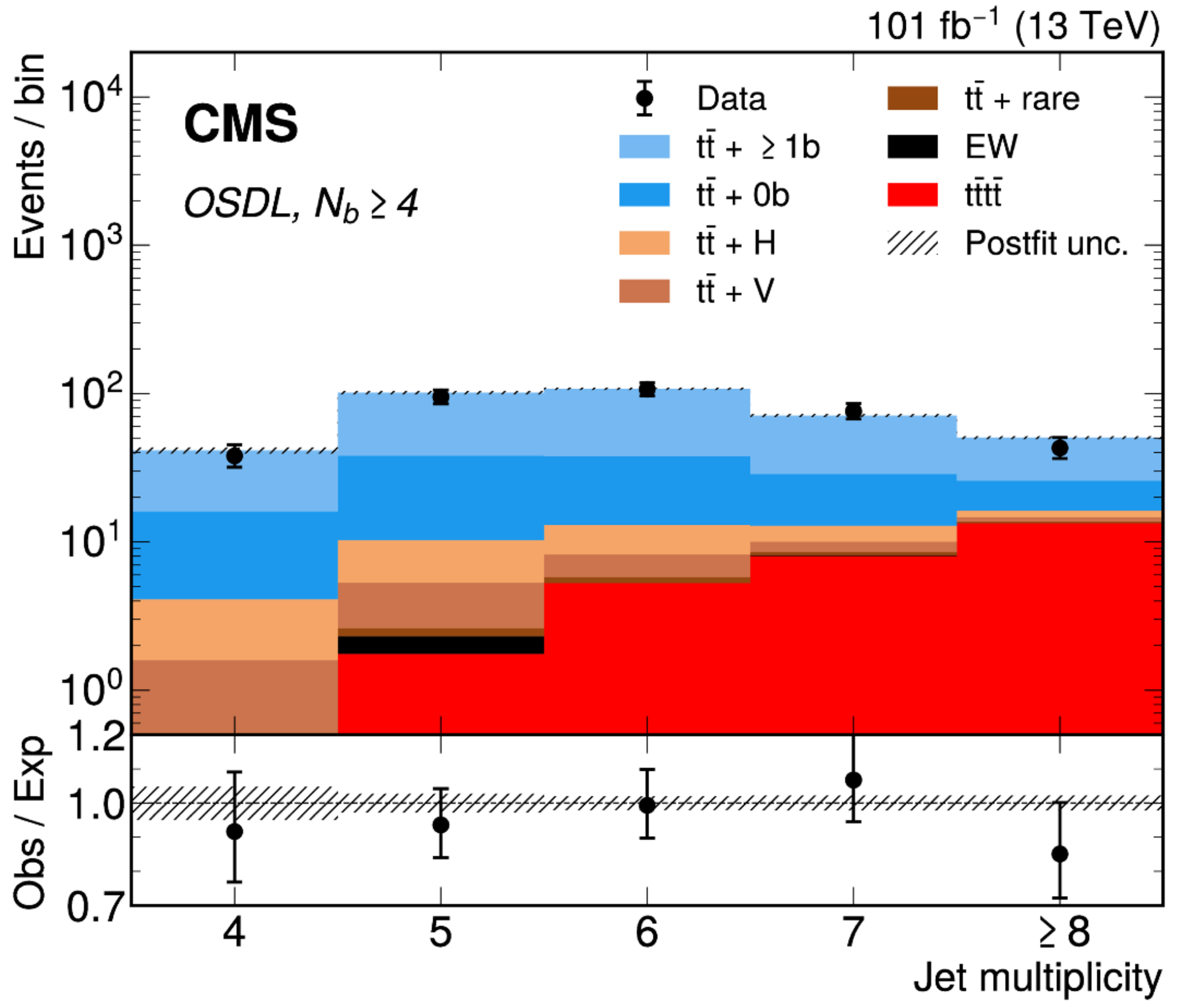


CMS result in the 1L/2LOS channel

arXiv:2303.03864

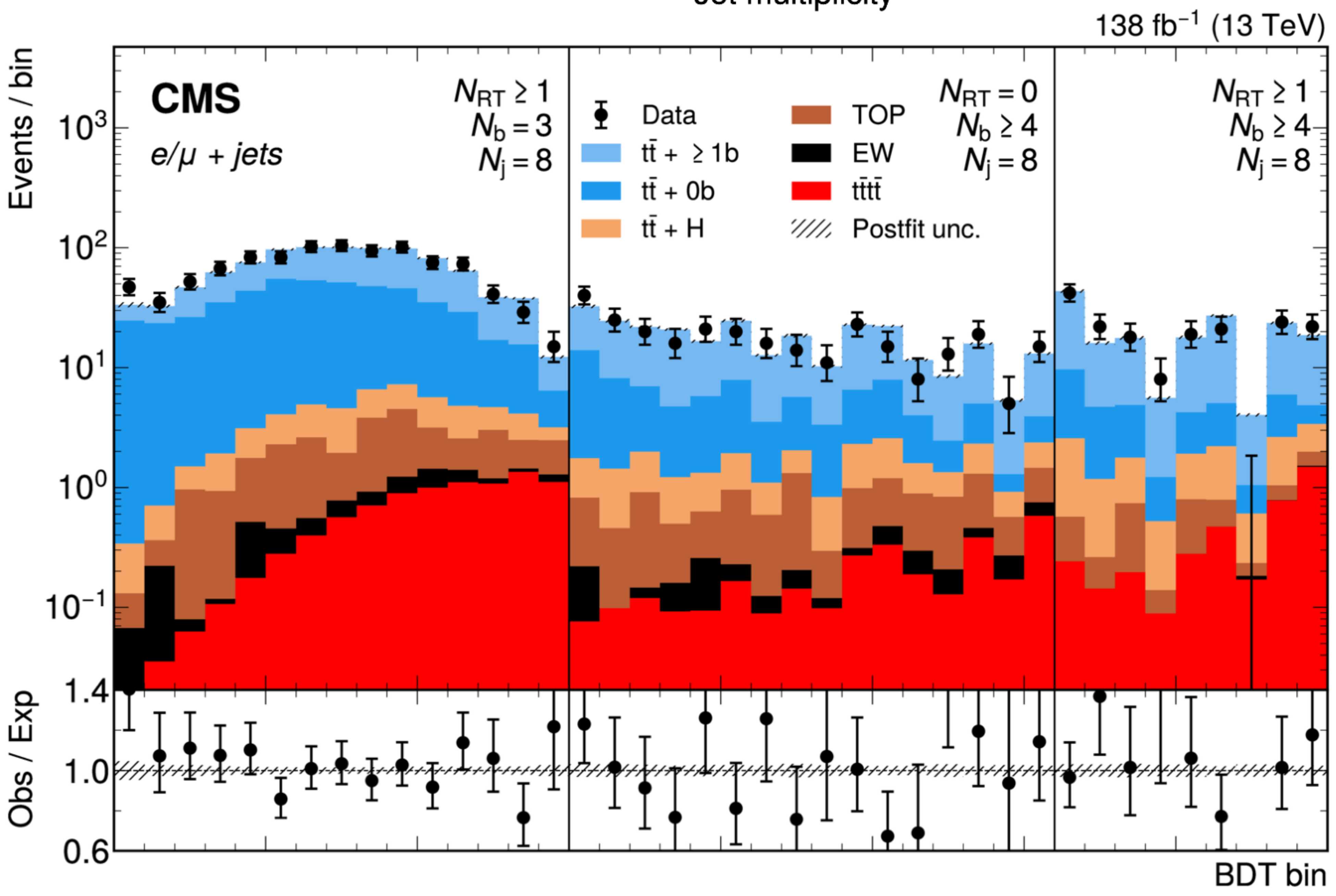
- Analysis strategy in the 2LOS channel:
  - Selection: exactly 2 opposite charge leptons, at least 4 jets with at least 2 b-jets, Ht > 500 GeV
  - Split in numbers of jets, b-jets and by lepton flavour
  - Signal region: ≥ 7 jets, ≥ 3 b-jets , CR: lower multiplicity
  - Correction for events with $t\bar{t}$+jets (no b's) : 0.78 ± 0.05
  - The Ht distribution is used in the fit

Expected: 0.6 σ
Observed: 1.8 σ



- Analysis strategy in the 1L channel:
  - Signal region: exactly one lepton, at least 6 jets with at least 3 b-jets, Ht > 500 GeV
  - Split in numbers of jets, b-jets and resolved top
  - BDT trained to separate $t\bar{t}t\bar{t}$ from $t\bar{t}$ and $t\bar{t}$+X background using 70 input variables, validated in the Nb=2 region
  - Split in numbers of resolved top, boosted and Ht into 12 regions

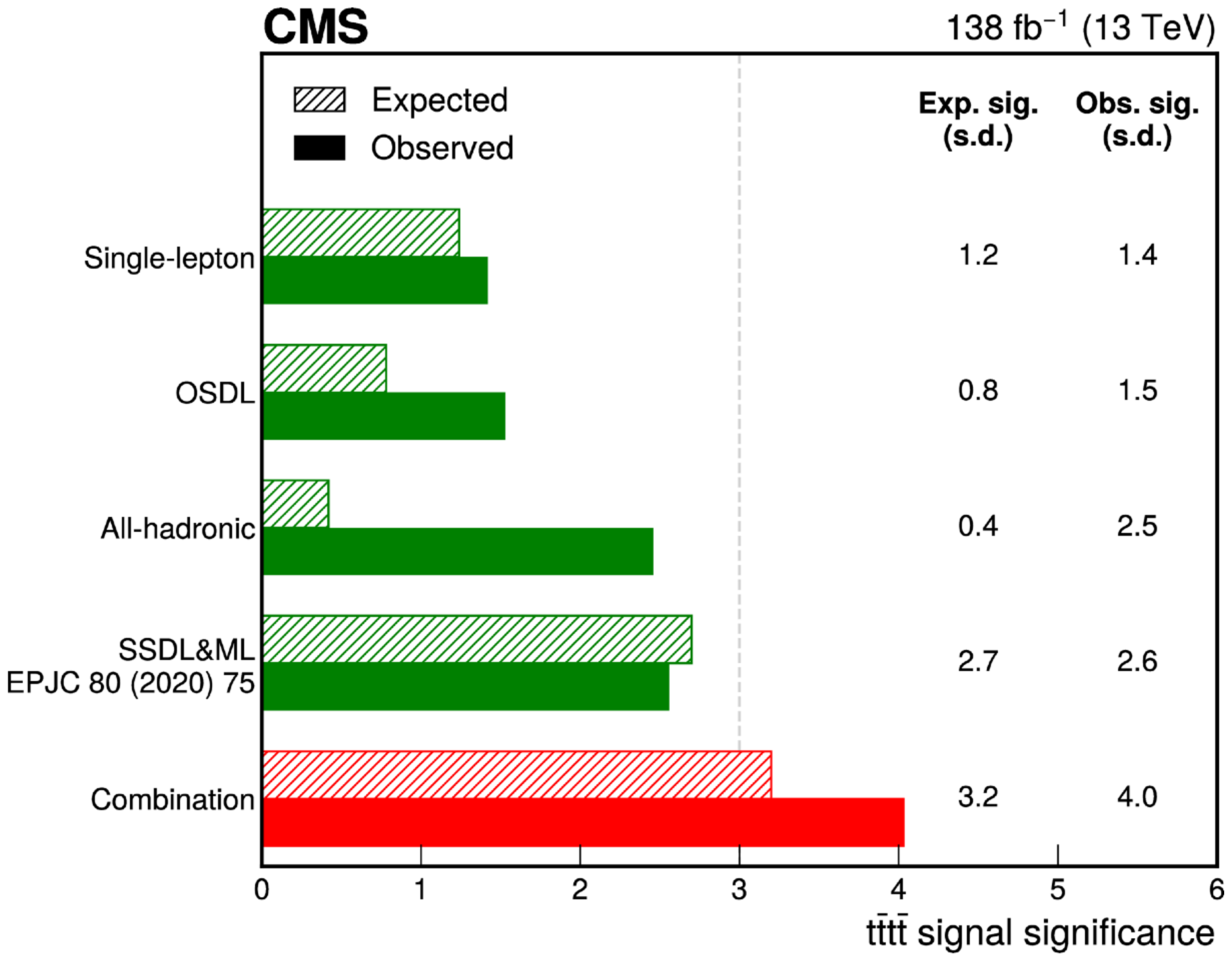
Expected: 1.2 σ
Observed: 1.4 σ



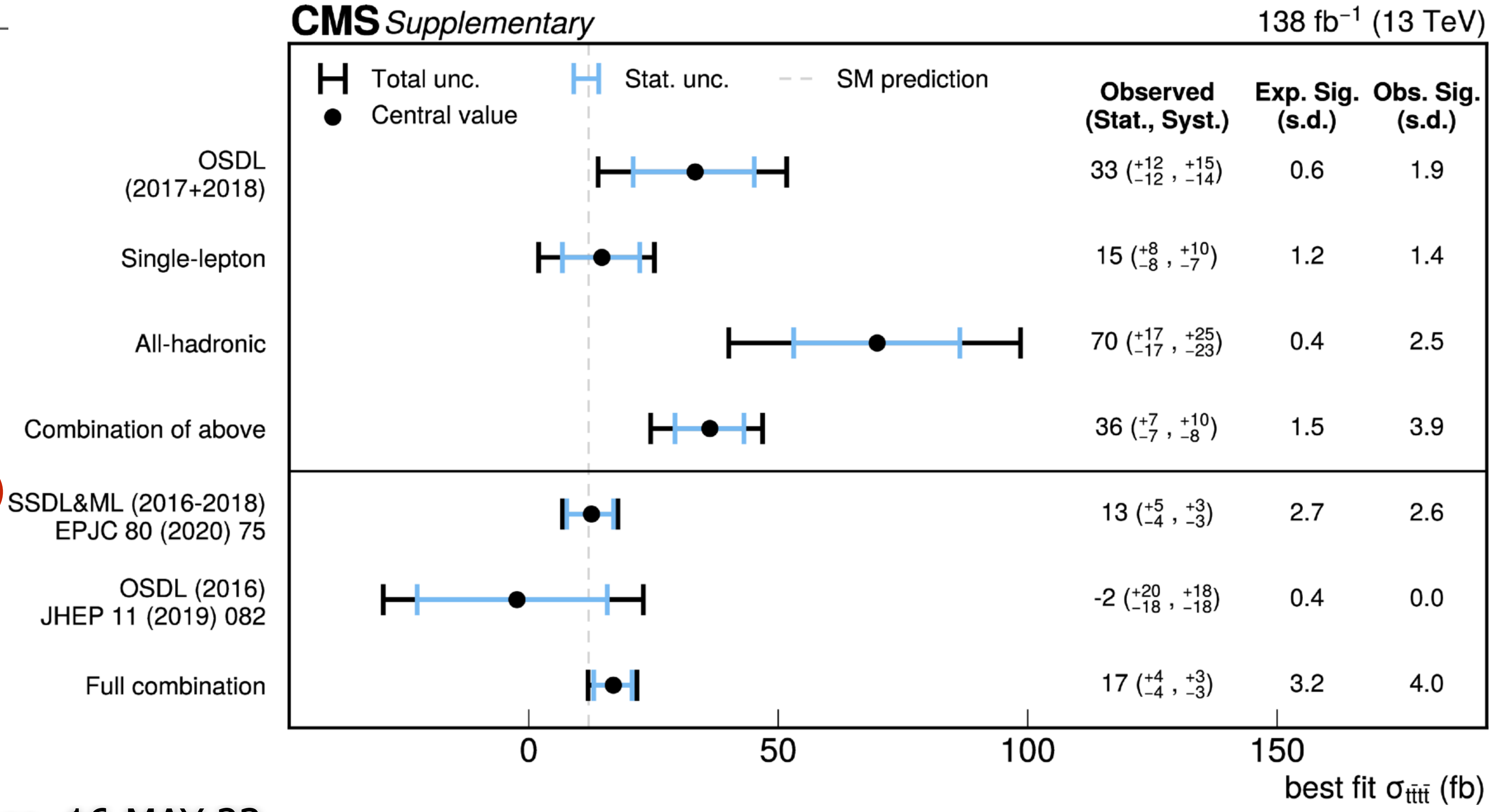
CMS evidence combination

- Combined likelihood fit to all channels
  - Systematic uncertainties treated as nuisance parameters
  - Correlated for shared systematics
  - Including the 'old' multilepton analysis
- Combination achieved evidence
  - Limited by statistics
  - 2 largest systematics: $t\bar{t}H$ cross section and modelling of $t\bar{t}$ with b's

arXiv:2303.03864



Analysis	Signal strength (μ)	(stat.)	(syst.)	Cross section (fb)	(stat.)	(syst.)	Significance (s.d.) Exp.	Obs.
OSDL (2017+2018)	2.8	±1.0	$^{+1.9}_{-1.2}$	33	±12	$^{+15}_{-14}$	0.6	1.8
Single-lepton	1.2	$^{+0.7}_{-0.6}$	±0.6	15	±8	$^{+10}_{-7}$	1.2	1.4
All-hadronic	5.8	±1.4	±2.0	70	±17	$^{+25}_{-23}$	0.4	2.5
Combination of above	2.5	±0.5	±0.5	36	±7	$^{+10}_{-8}$	1.5	3.9
SSDL&ML (2016–2018) [21]	1.0	±0.4	$^{+0.3}_{-0.2}$	13	$^{+5}_{-4}$	±3	2.7	2.6
OSDL (2016) [22]	-0.2	$^{+1.7}_{-1.5}$	±1.5	-2	$^{+20}_{-18}$	±18	0.4	0
Full combination	1.4	±0.3	±0.2	17	±4	±3	3.2	4.0



ATLAS 1L/2LOS results

- Analysis strategy:

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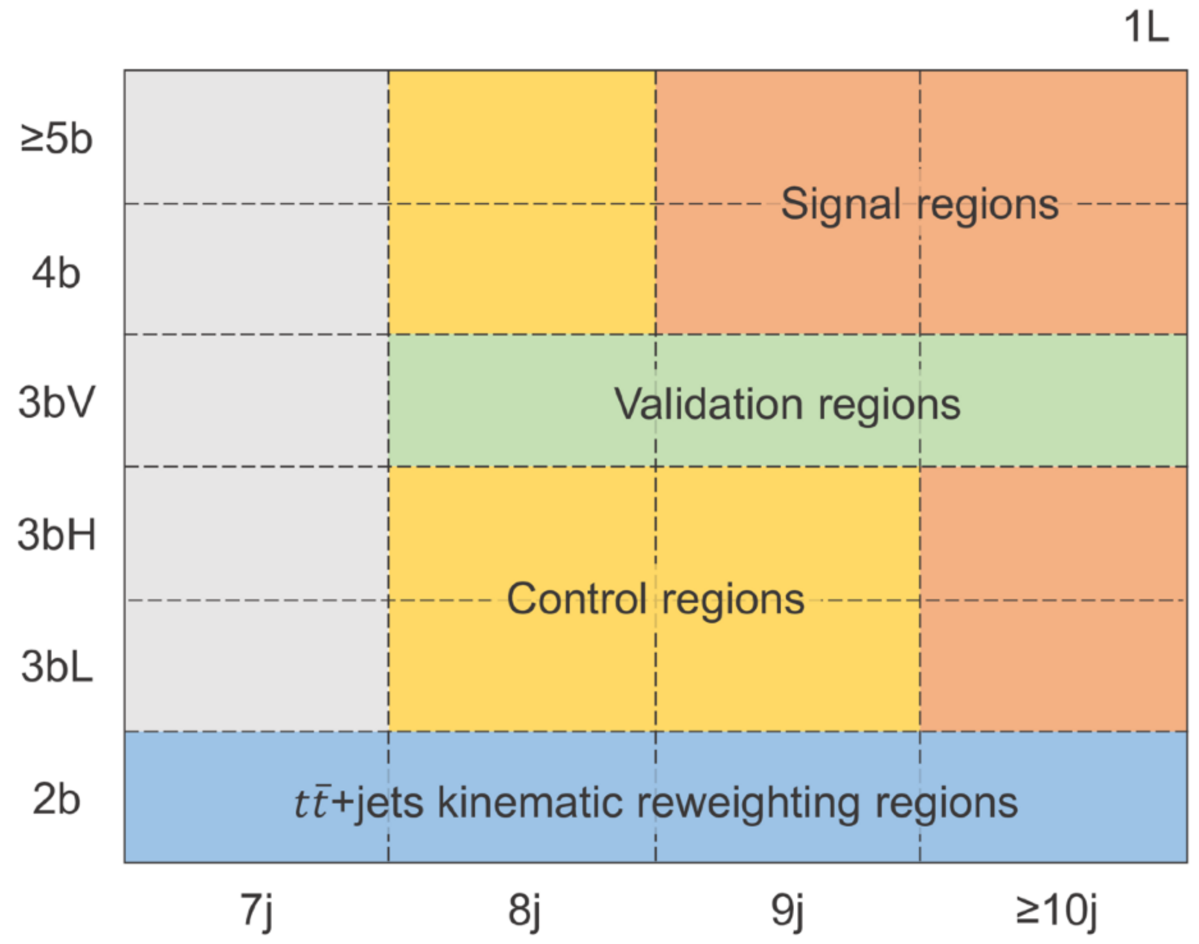
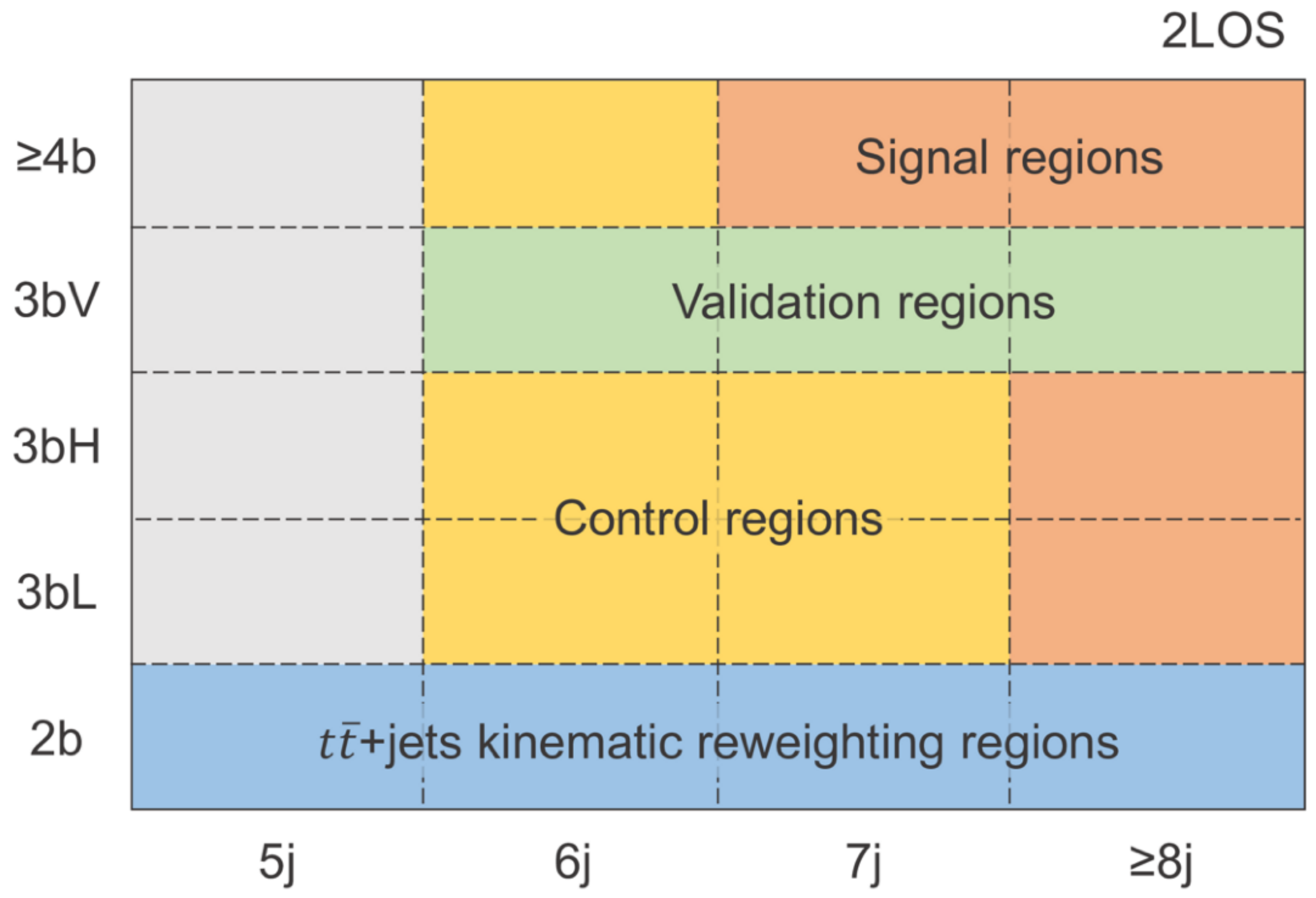
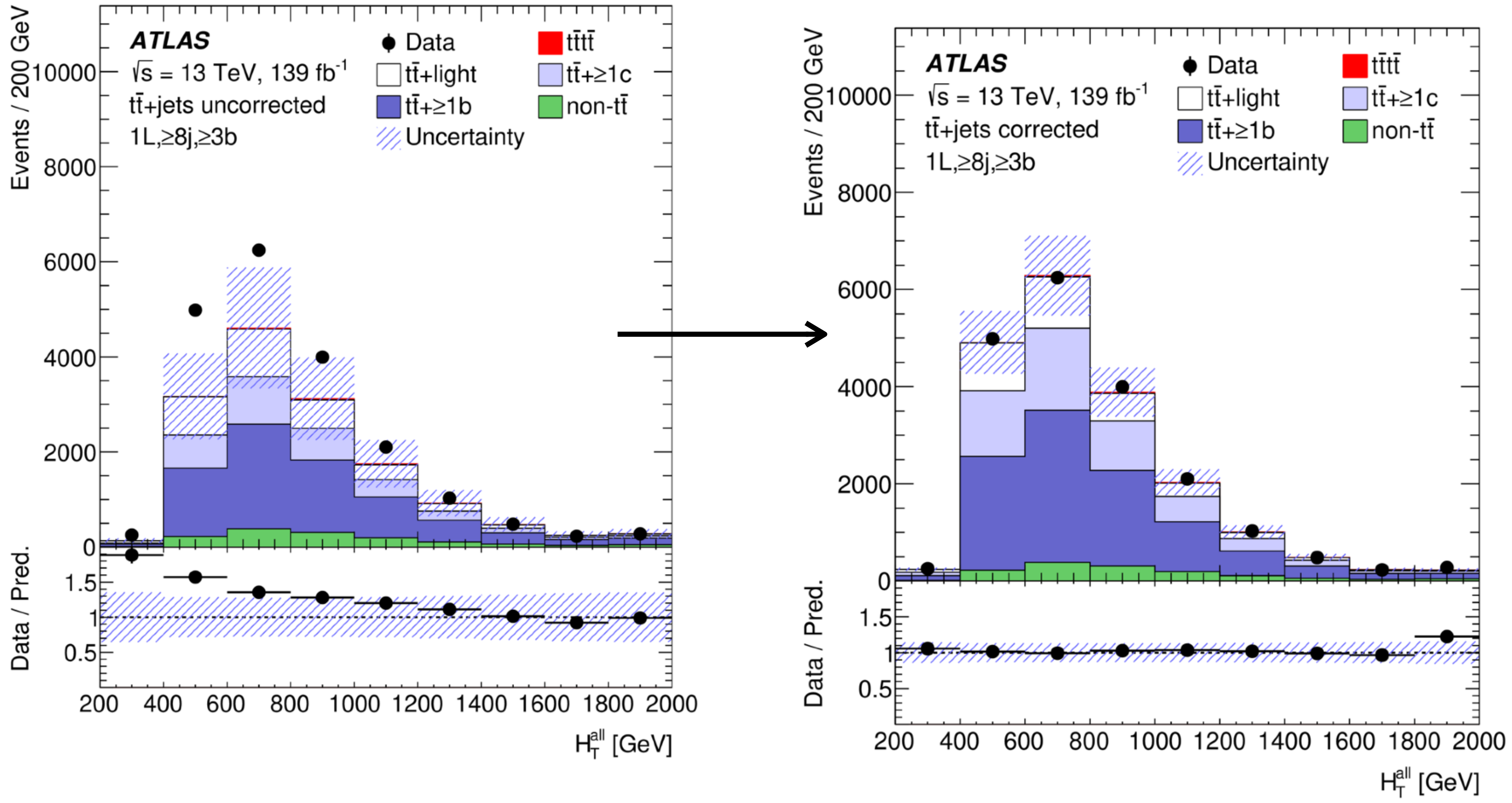
- Key point: estimation of the $t\bar{t}$+jets/b background, challenging to get from MC
  - Use events with $t\bar{t}$+2b events to derive pre-fit correlation factor classifying the events according to the flavour of the particle jets
  - Sequential reweightings in N_{jets}, $N_{large\ jets}$, Ht, ΔR(jj)

- Signal region: exactly one lepton, at least 7(5) jets with at least 3 b-jets in the 1L(2LOS) channel
- Split in numbers of jets, b-jets: 12 (9) regions for 1L(2LOS) channel

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	= 2	-
3bL	≤ 2	= 3	-
3bH	= 3	= 3	= 3
3bV	= 3	= 3	≥ 4
≥4b (2LOS)	-	≥ 4	-
4b (1L)	-	= 4	-
≥5b (1L)	-	≥ 5	-





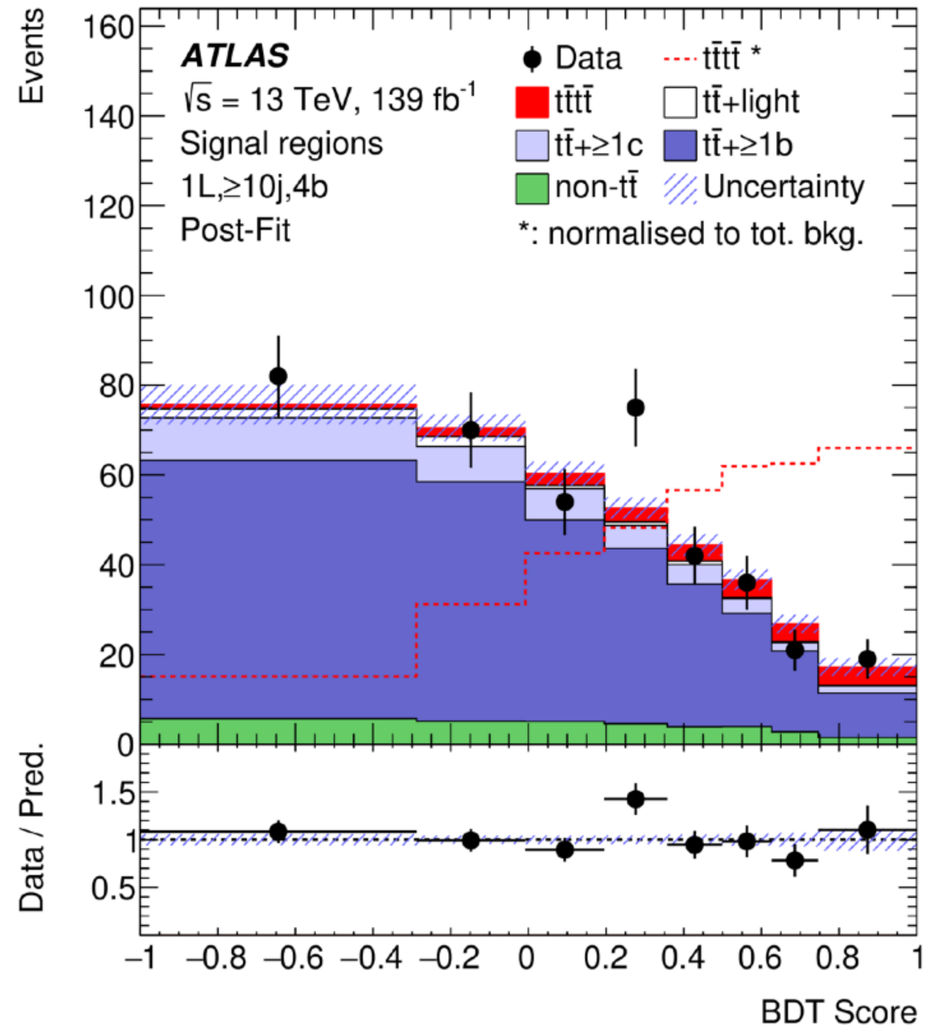


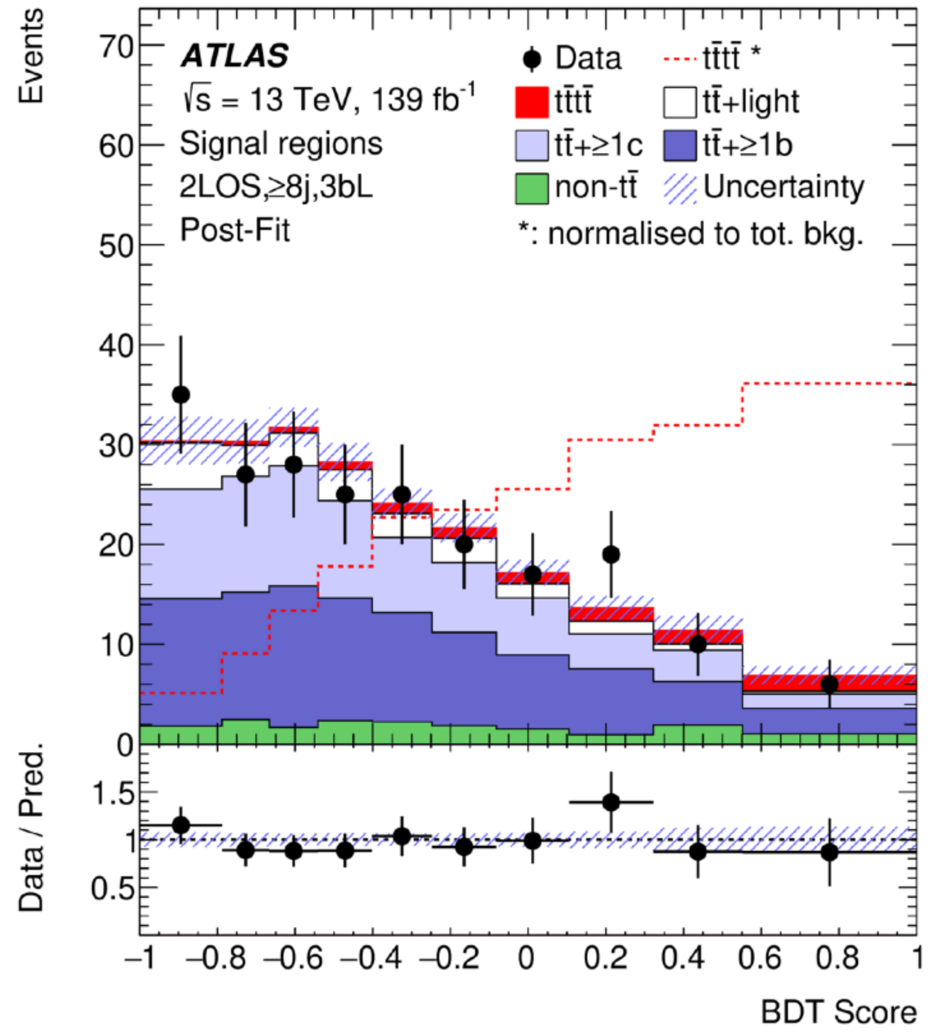
ATLAS 1L/2LOS results

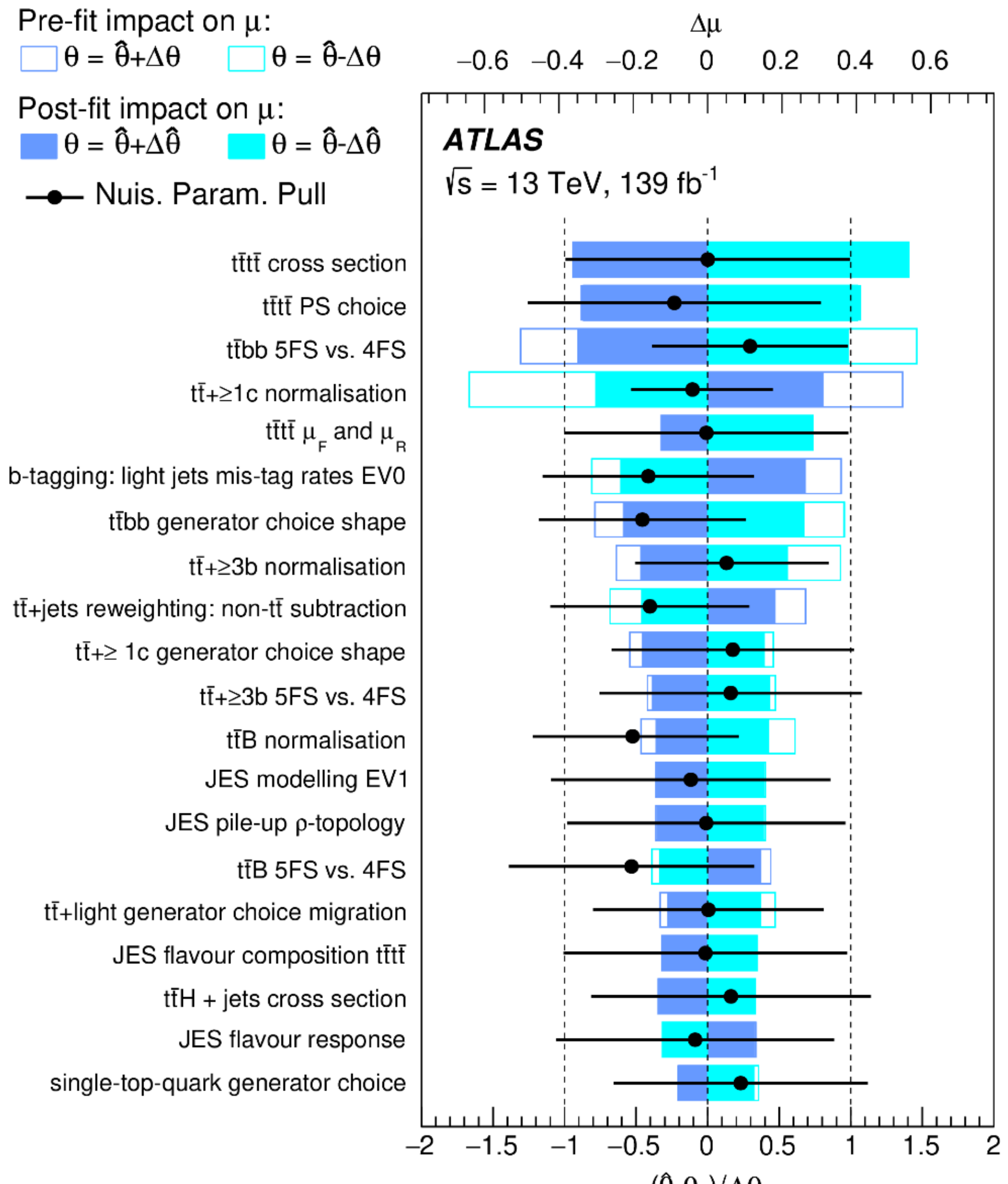
- Signal extraction:
  - BDT trained to separate $t\bar{t}t\bar{t}$ from $t\bar{t}$/ $t\bar{t}$+X background
  - Profile likelihood fit of the CR and SR regions including systematics:
    - Main systematics: signal modelling, $t\bar{t}$+b modelling

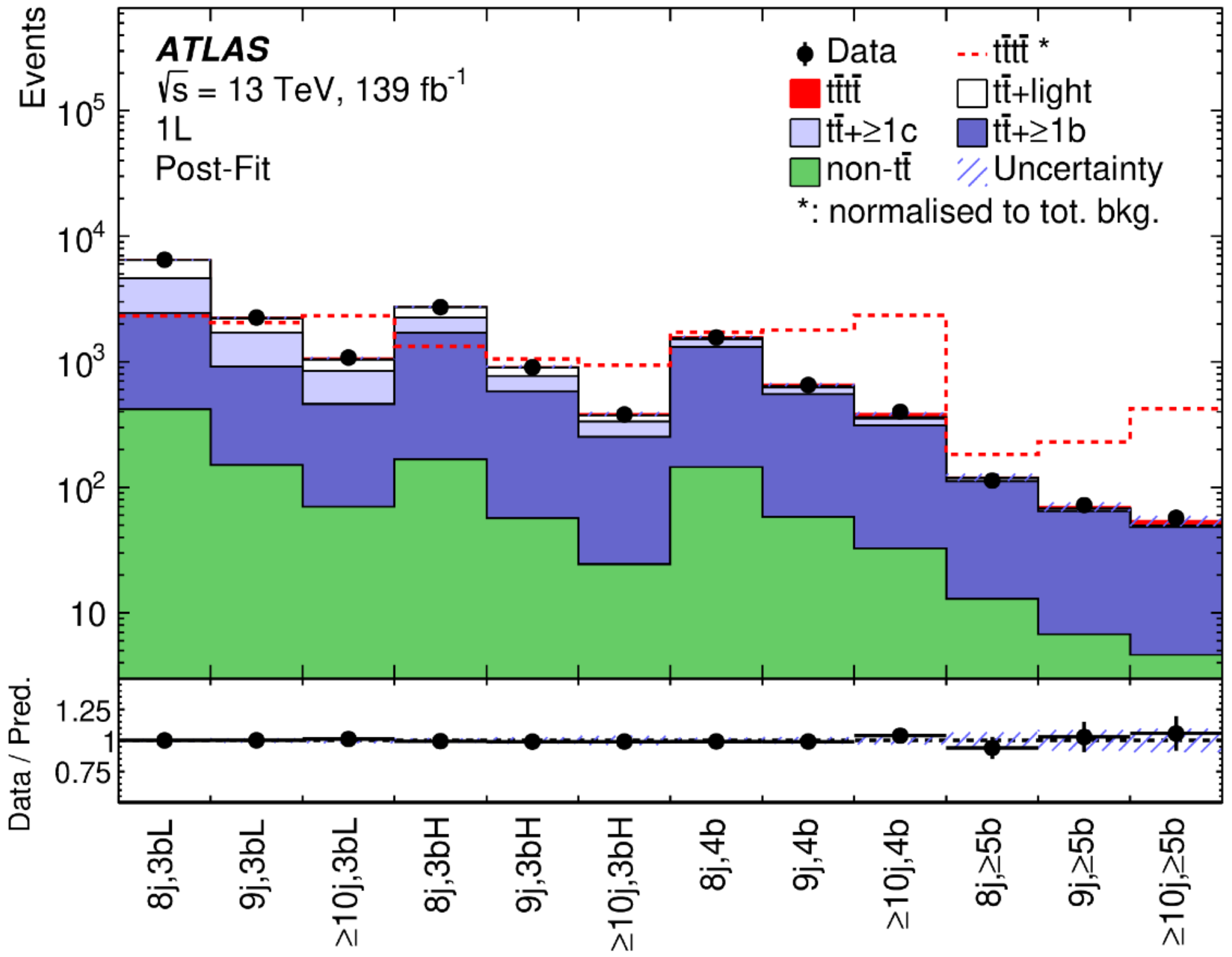
Name	Description
$\sum b$-tag	Sum of pseudo-continuous b-tagging score over the six jets with the highest score
N_{jets}	Number of jets
$\Delta R_{bb}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets
$H_{\text{T}}^{\text{all}}$	Scalar sum of all jet and lepton transverse momenta
C^{all}	Centrality ($\sum_i p_{\text{T}i} / \sum_i E_i$) of the leptons and jets
$p_{\text{T}}^{\text{lead}}$	Transverse momentum of the leading jet
$\Delta R_{b\ell}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets and leptons
$\Delta R_{jj}^{\text{avg}}$	Average ΔR between all pairs of jets
m_{jjj}	Invariant mass of the closest triplet of jets
$E_{\text{T}}^{\text{miss}}$	Missing transverse momentum
m_{T}^{W}	W reconstructed transverse mass $m_T(\ell, E_{\text{T}}^{\text{miss}})$ (1L)
$N_{\text{LR-jets}}$	Number of large-R jets with a mass above 100 GeV
$\sum d_{12}$	Sum of the first k_t splitting scale d_{12} of all large-R jets
$\sum d_{23}$	Sum of the second k_t splitting scale d_{23} of all large-R jets

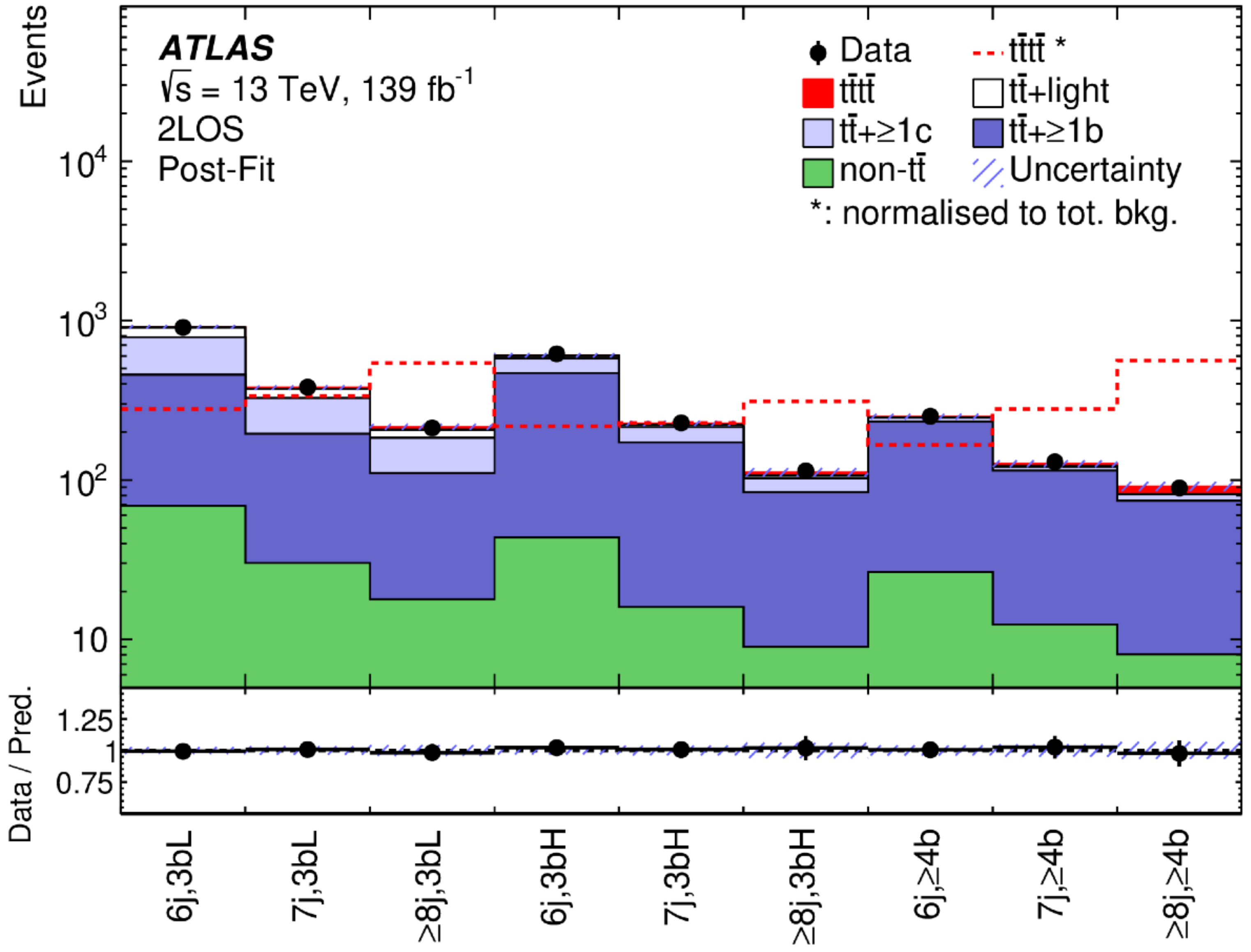
Expected: 1.0 σ
Observed: 1.9 σ









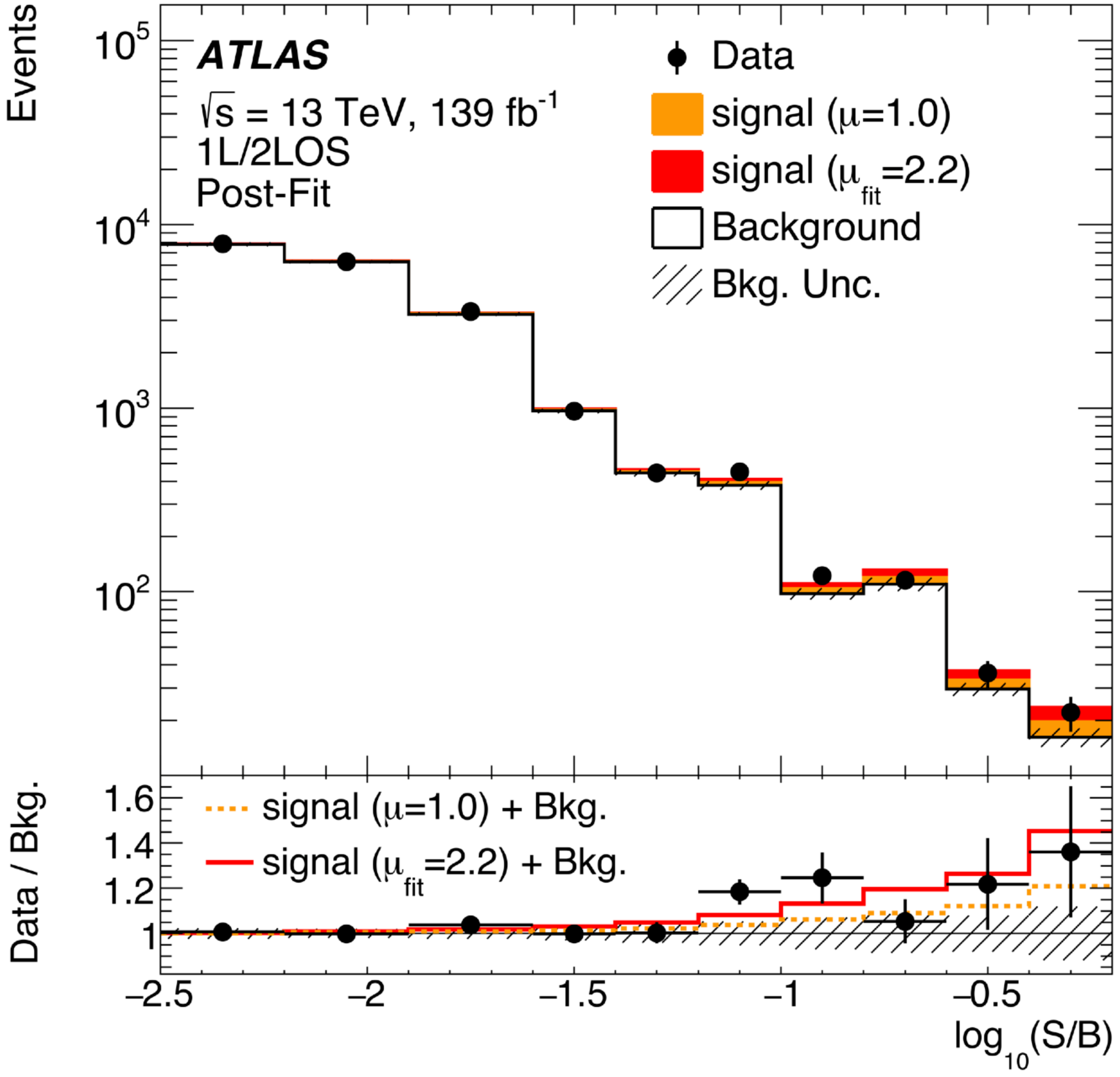


ATLAS 1L/2LOS + 2LSS/3L combination

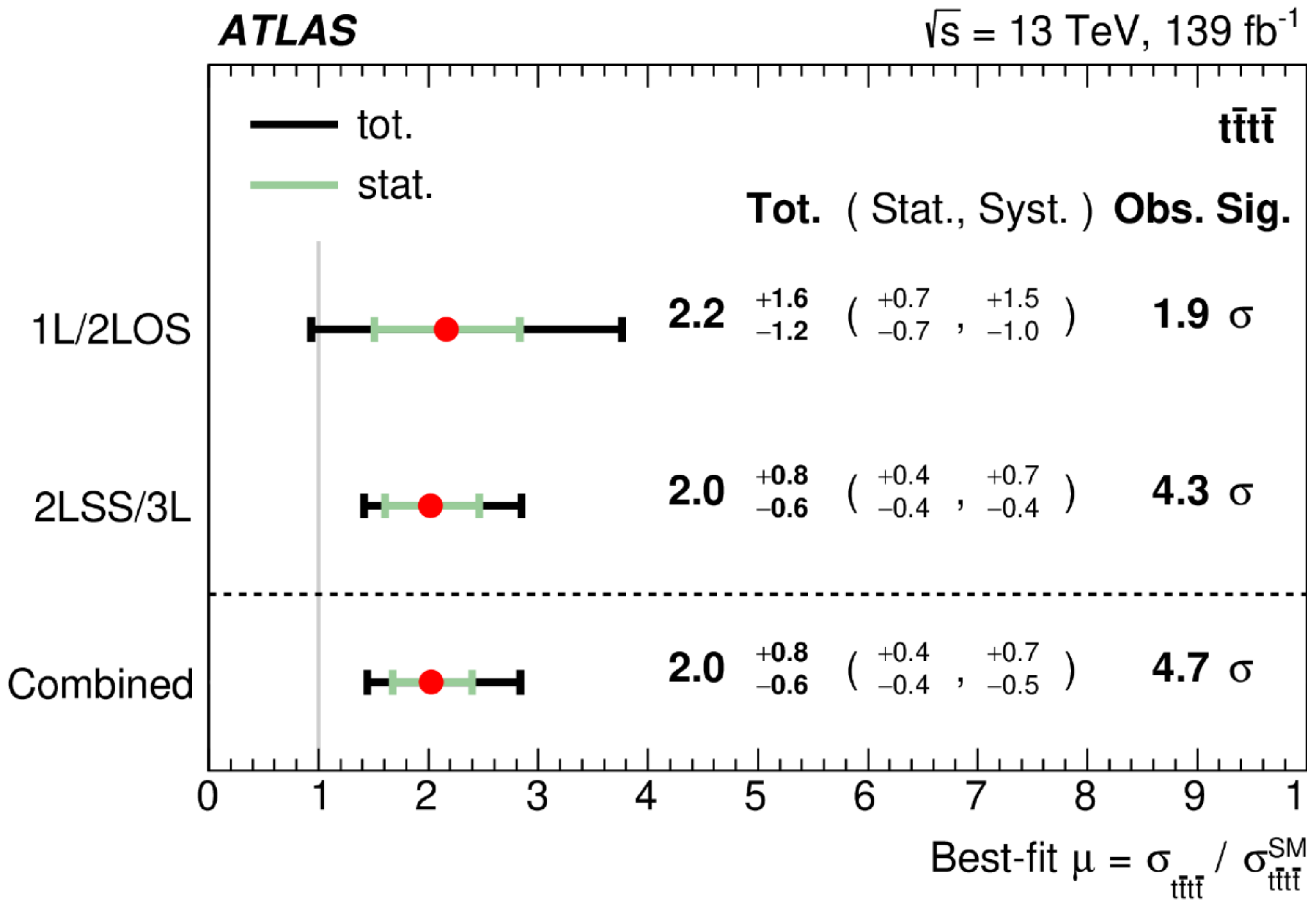
- Combined likelihood fit to 1L/2LOS channel and the old multilepton result
  - $t\bar{t}$+jets systematic uncorrelated, other systematics correlated

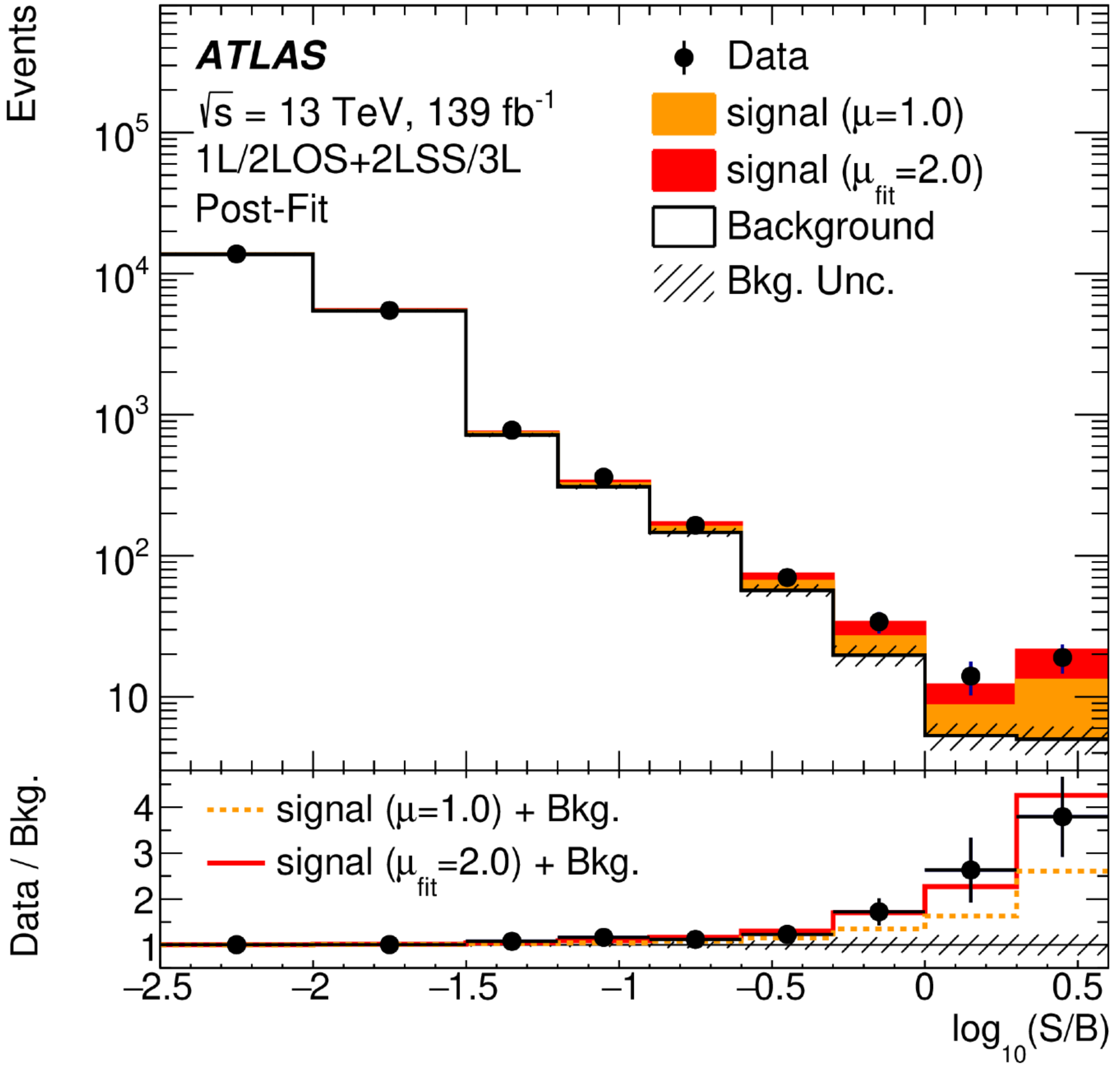
$$\mu = 2.0 \pm 0.4\,(\text{stat.})\,^{+0.7}_{-0.5}\,(\text{syst.}) = 2.0\,^{+0.8}_{-0.6}$$

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4\,(\text{stat.})\,^{+5}_{-4}\,(\text{syst.})\,\text{fb} = 24\,^{+7}_{-6}\,\text{fb}$$



Expected: 2.6 σ
Observed: 4.7 σ





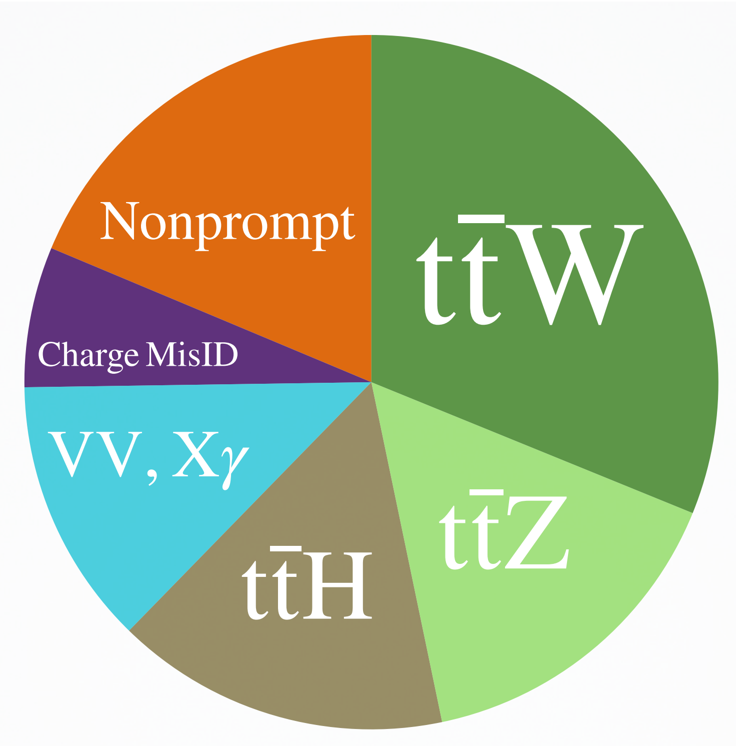
New CMS result in the multilepton channel

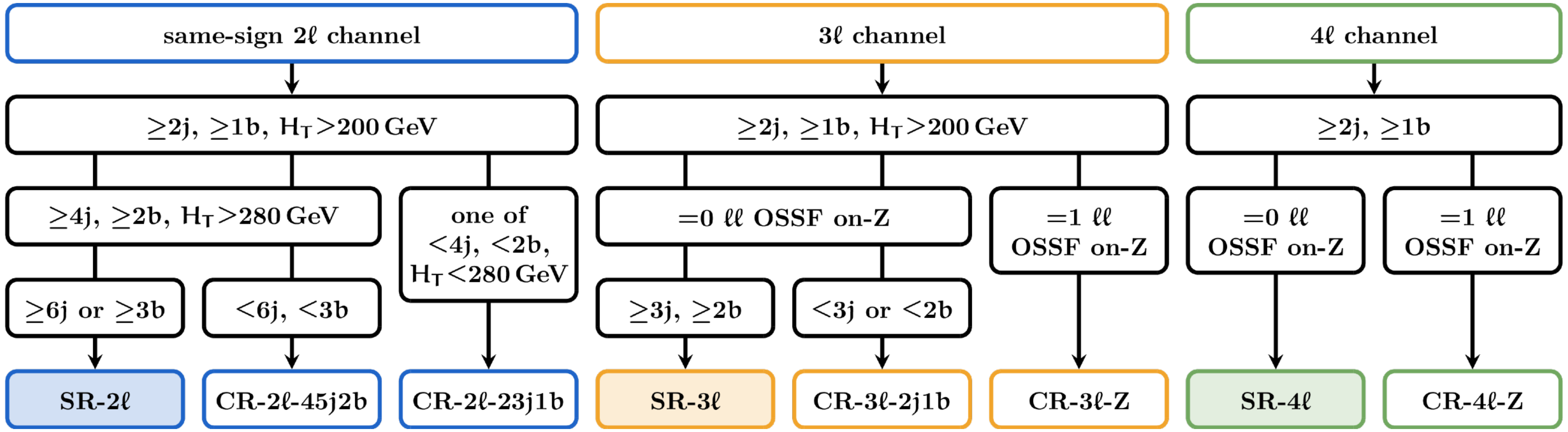
- **Re-analysis of the full Run 2 dataset**
  - Two same-sign leptons, three leptons, four leptons
  - Benefit from improvements in b-tagging and fake lepton rejections
    - BDT trained to distinguish between prompt and nonprompt leptons

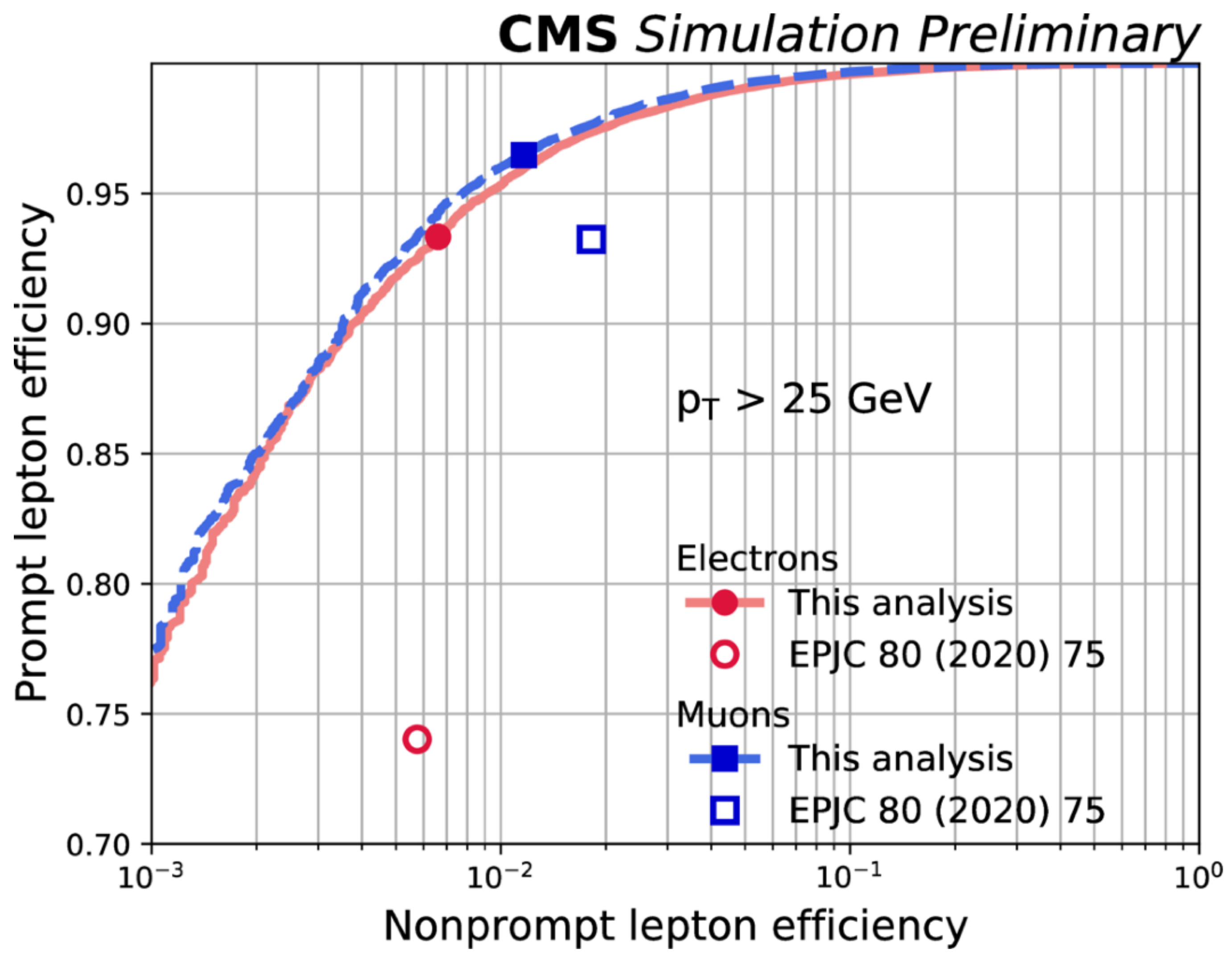
- **dataset split by lepton multiplicity**
  - Jets an b-jets multiplicity to define SR and CR
  - Train 2 multiclass BDTs (2LSS, 3L/4L) to separate signal from $t\bar{t}$+X and $t\bar{t}$
    - $t\bar{t}$+X estimated from MC with some normalisation from data
    - QmisID and non prompt background from data

CMS-PAS-TOP-22-013

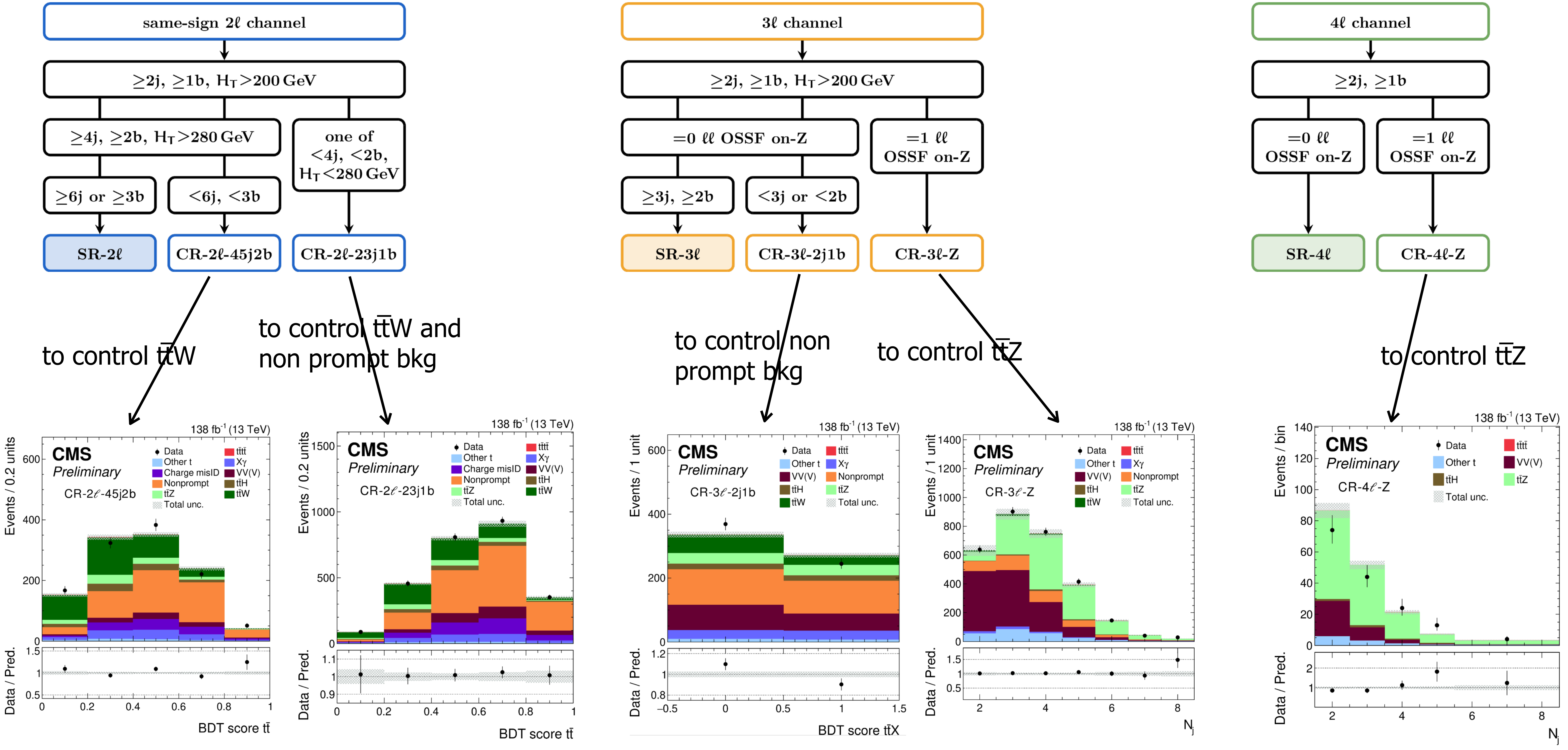
Symbol	Definition
p_T	Lepton p_T
$\lvert\eta\rvert$	Absolute value of the lepton η
I_{rel}^{fixed}	Relative isolation using a fixed distance $\Delta R < 0.4$
I_{rel}^{ch}	Relative isolation using a p_T-dependent distance and including only charged particles
I_{rel}^{neu}	Relative isolation using a p_T-dependent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





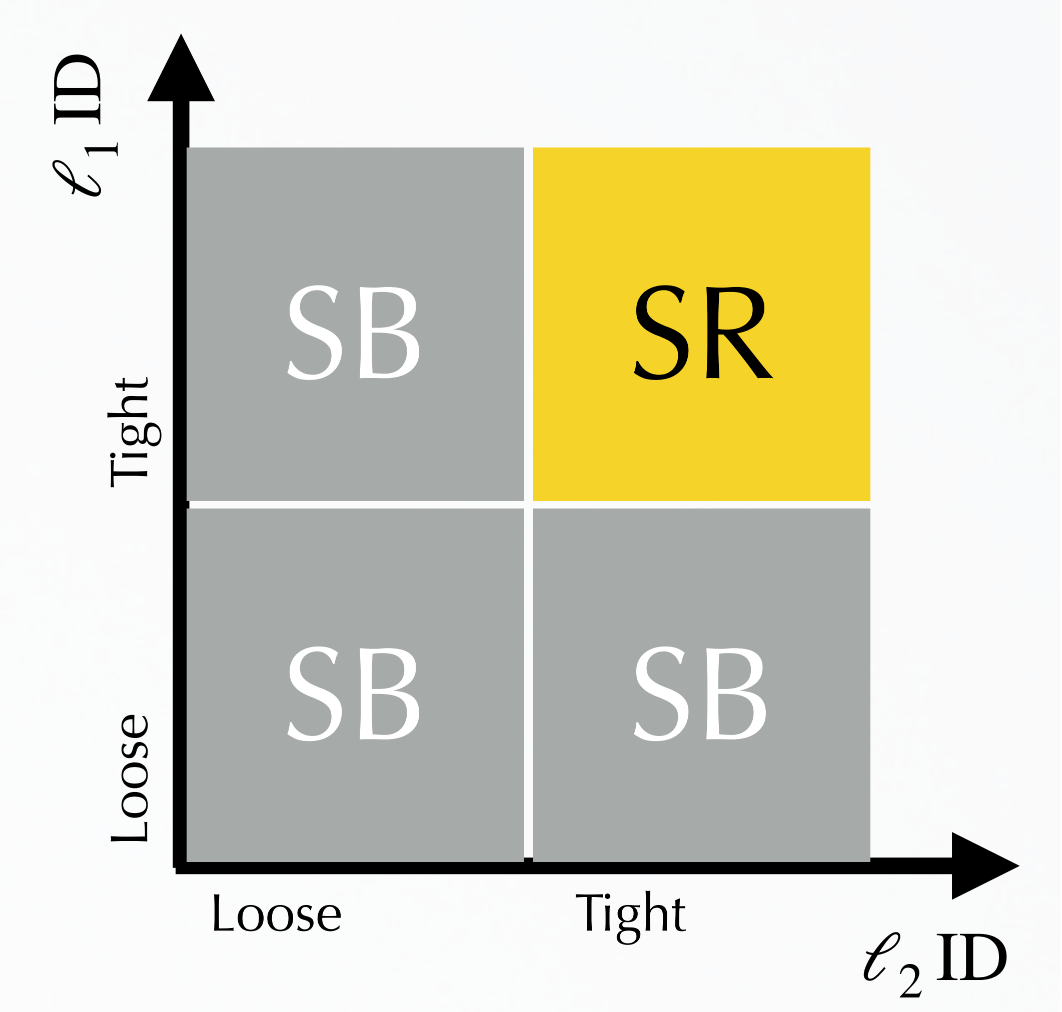


$t\bar{t}$+X background



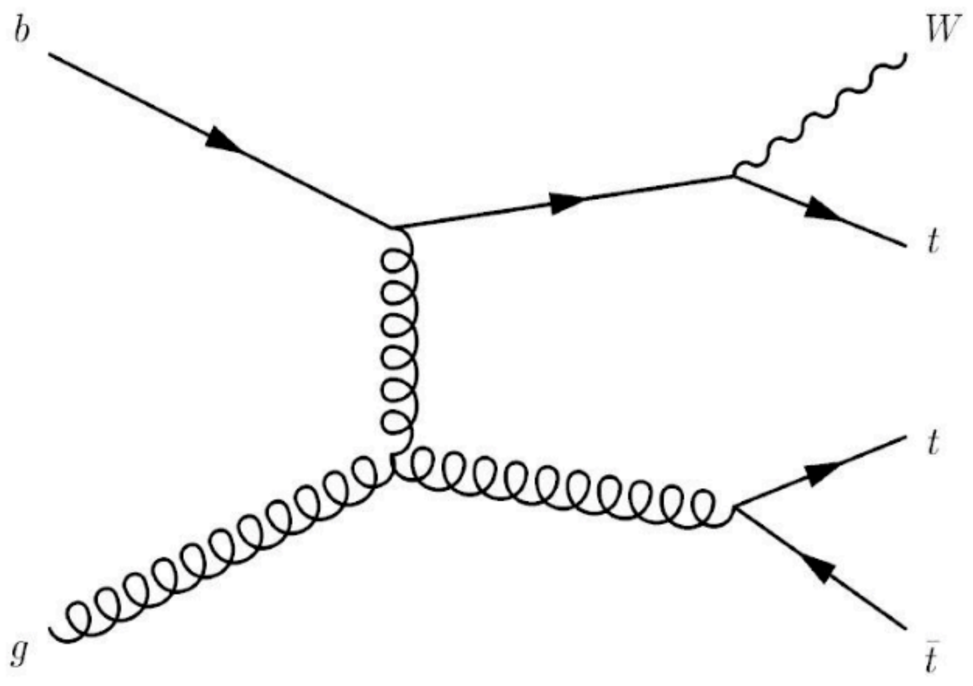
Other backgrounds

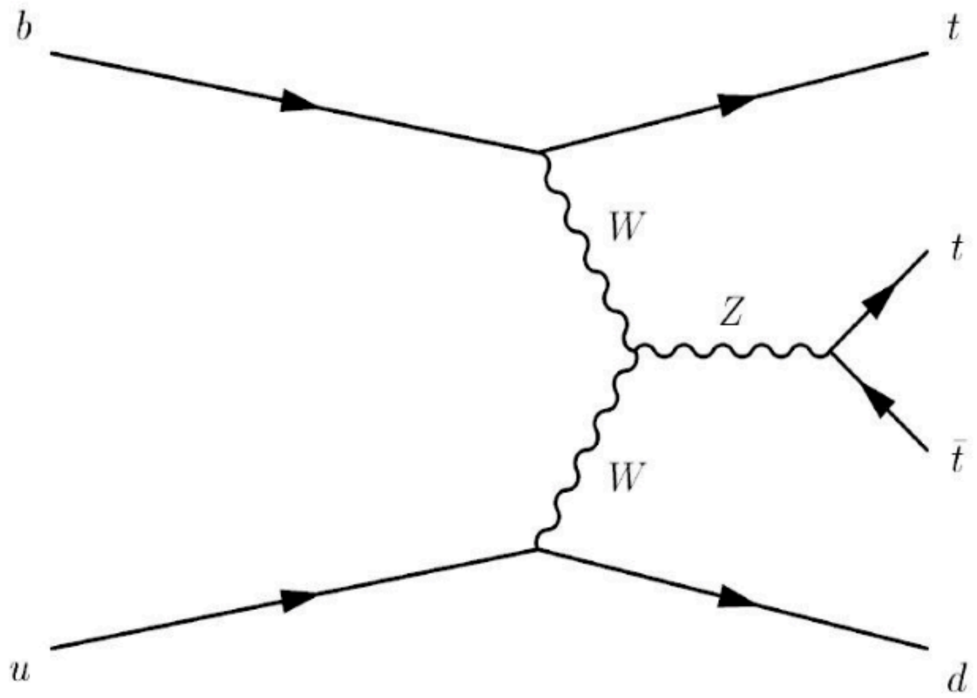
- Background from non prompt leptons:
  - Evaluated using the tight-to-loose ratio method
    - fake rates measured in multijet data events
    - applied in regions with loose lepton requirements



- Background from charge mis-id electrons:
  - Charge misID probabilities measured in MC
  - Correction factors applied to these measured in Z OS / SS events

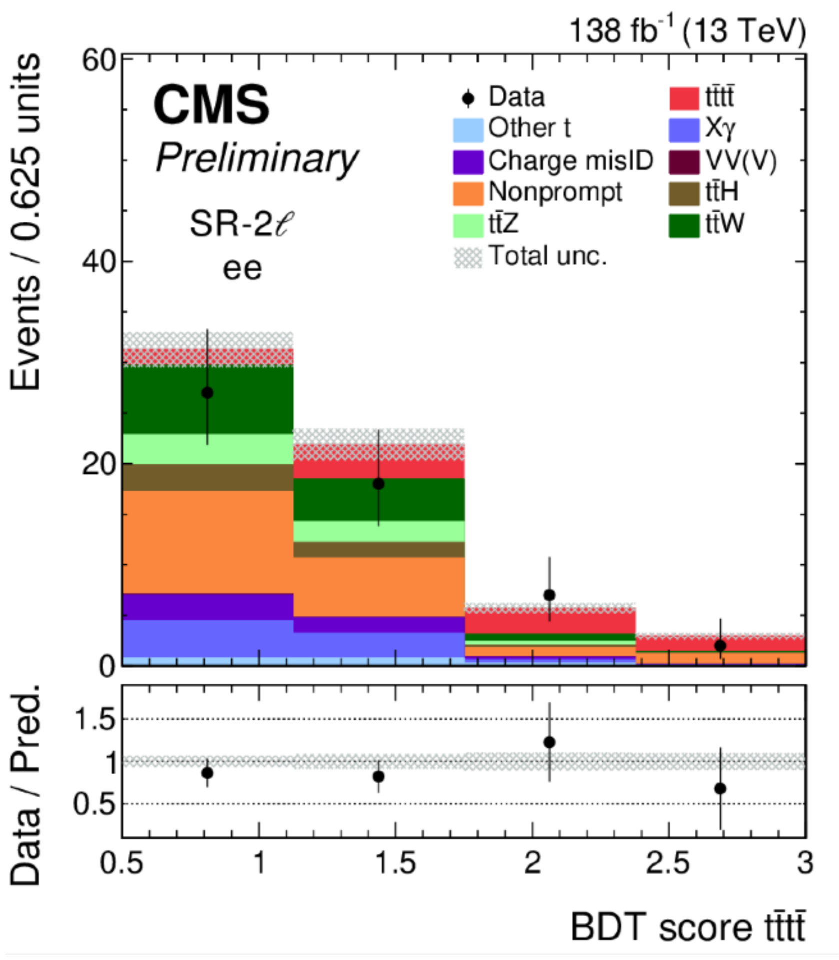
- $t\bar{t}t$ events
  - Cross section around 1 fb (small but very signal like)
  - Normalised to the LO cross section
  - 20% uncertainties

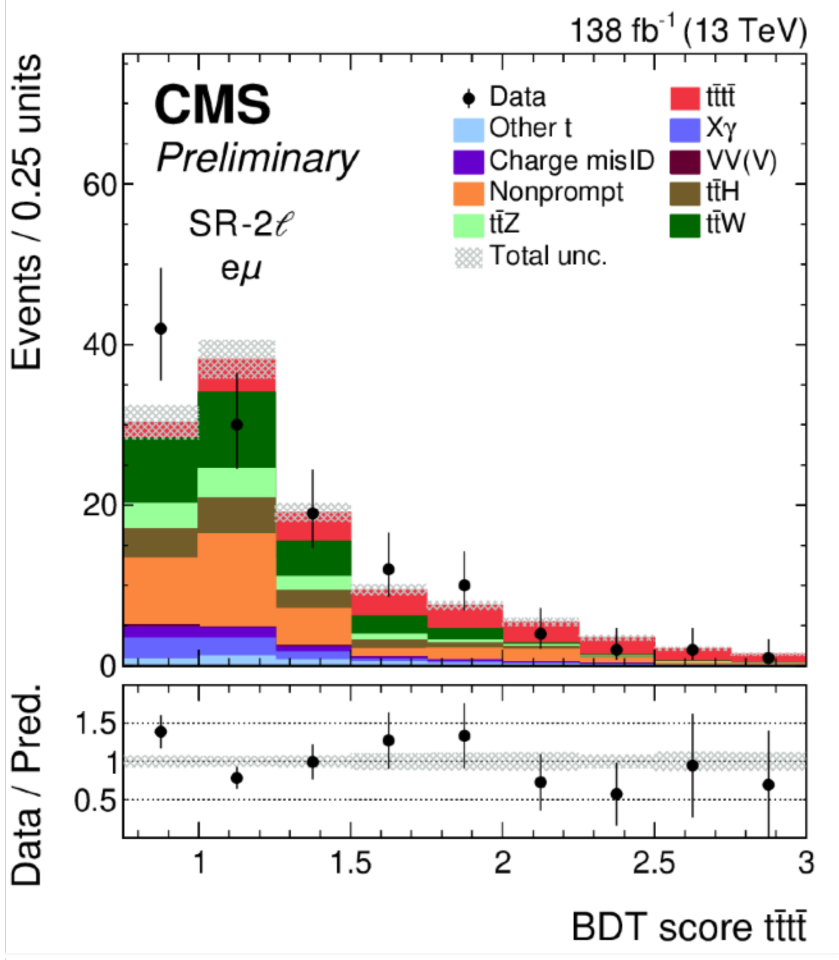


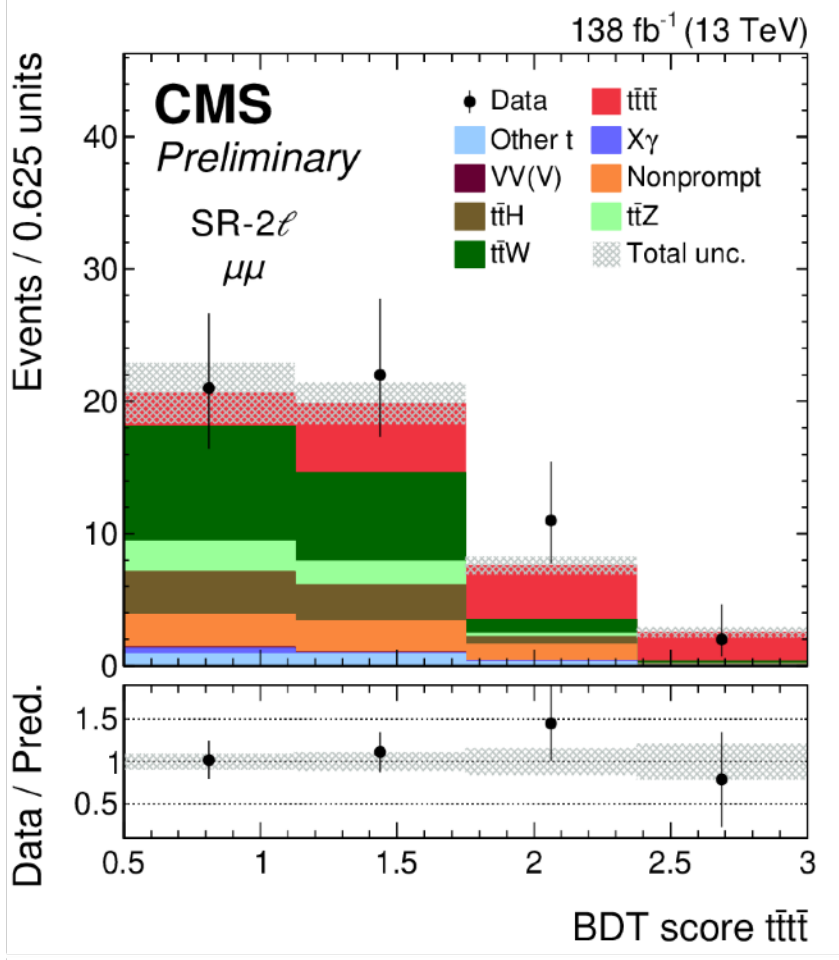


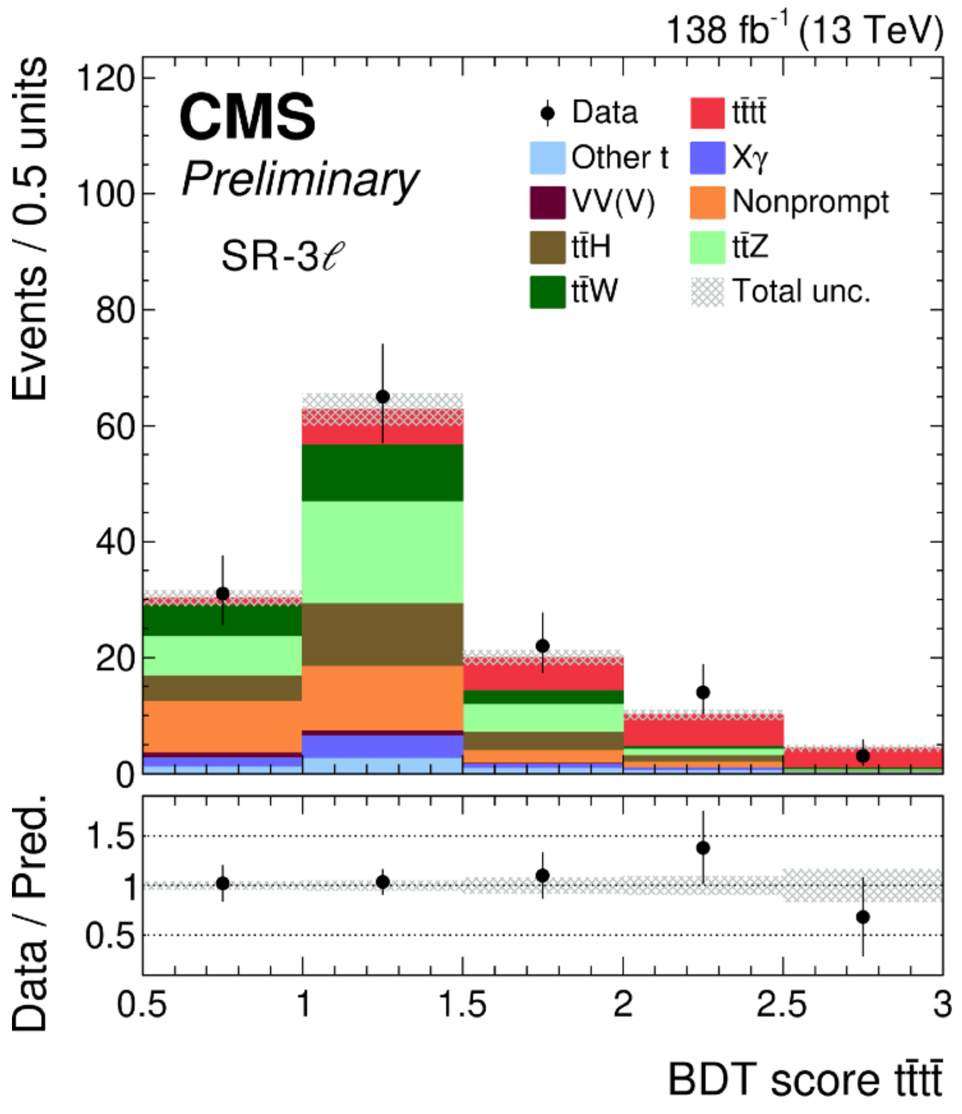
Final fit

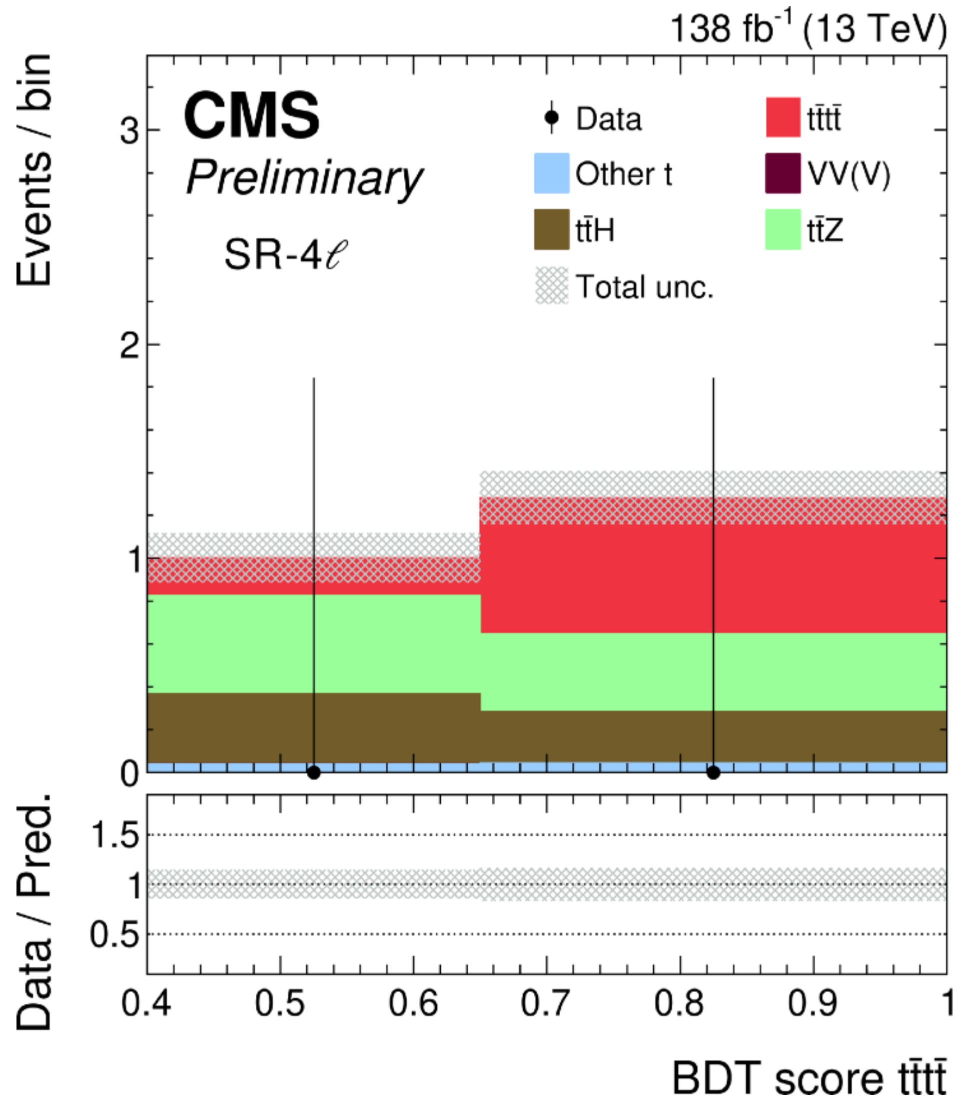
- Includes all CR and SR
  - SR further split into three subregions $t\bar{t}t\bar{t}$, $t\bar{t}$+X , $t\bar{t}$ based on the highest value of three BDT scores









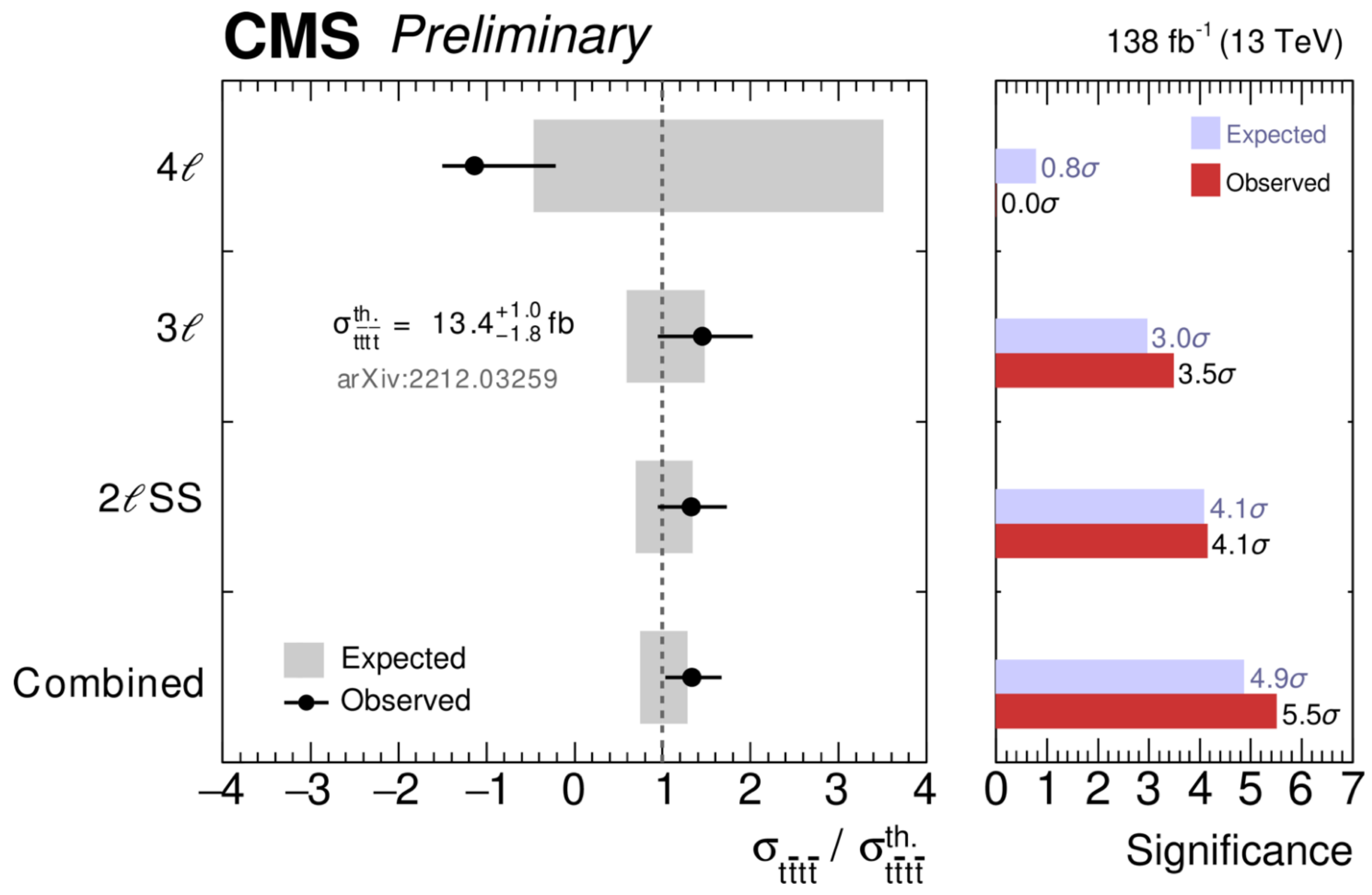


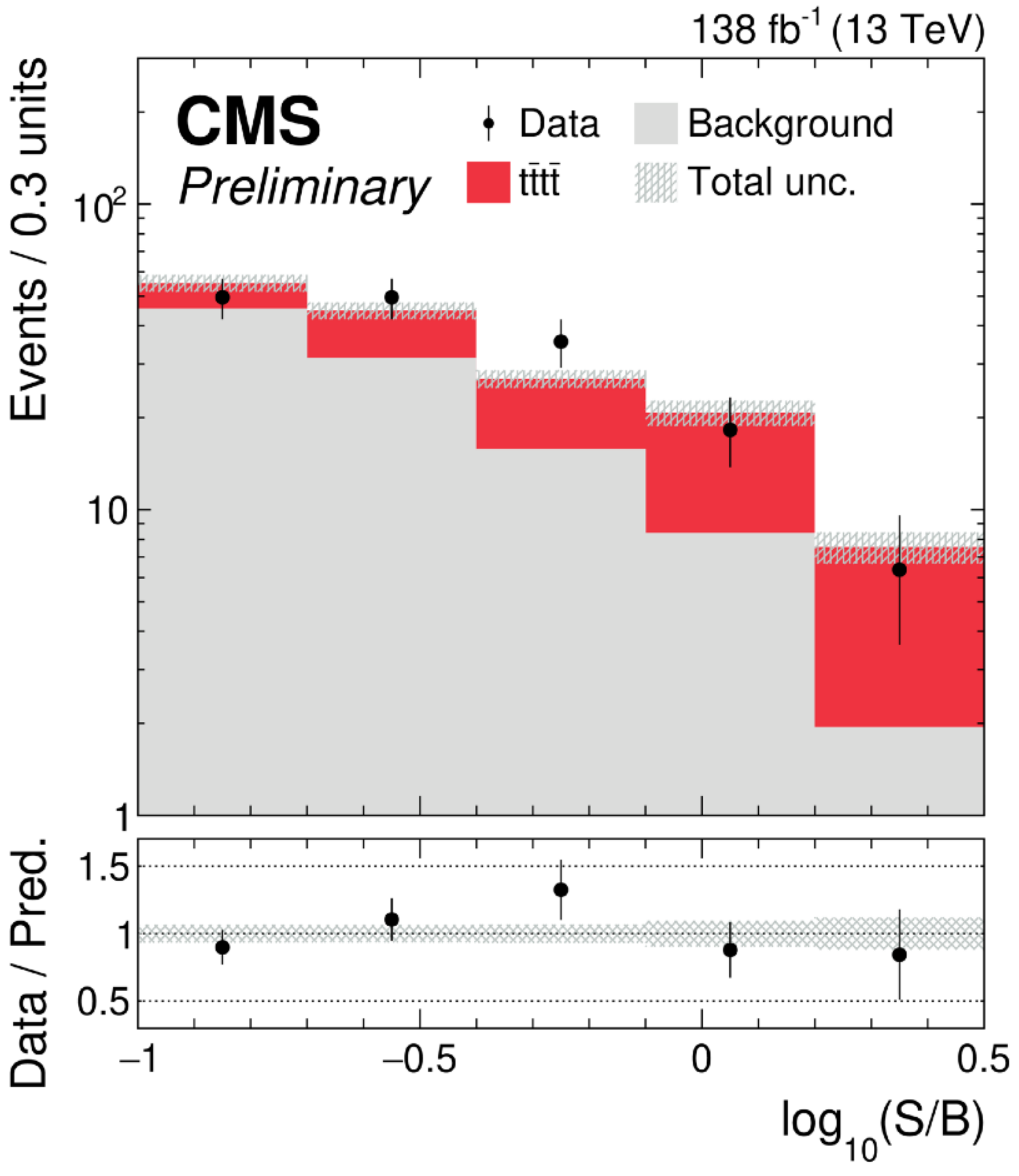
Symbol		Definition
$\max_2$ DJ		Second-highest DeepJet score of any jet
$\Delta R(\ell_1,\ell_2)$		ΔR between leading and subleading lepton
$\min \Delta R(\mathrm{b},\mathrm{b})$		Smallest ΔR between any two b jets
$\min_2 \Delta R(\ell,\mathrm{b})$		Second smallest ΔR between any lepton and b jet
$\Delta\phi(\ell_1,\ell_2)$	†	$\Delta\phi$ between leading and subleading lepton
$\min_1 \Delta R(\ell,\mathrm{b})$	†	Smallest ΔR between any lepton and b jet
$m(\mathrm{t}_1)$		Invariant mass of any three jets, of which one is a b jet, that is closest to the top quark mass
$\max_3$ DJ		Third-highest DeepJet score of any jet
$\mathrm{DJ}(\mathrm{j}_1)$		DeepJet score of the leading jet
$m(\mathrm{W}_1)$		Invariant mass of any two jets used for $m(\mathrm{t}_1)$ that is closest to the W boson mass
$p_\mathrm{T}(\mathrm{j}_4)$	†	Fourth-highest p_T of any jet
$\mathrm{DJ}(\mathrm{j}_2)$		DeepJet score of the subleading jet
$p_\mathrm{T}(\mathrm{j}_5)$		Fifth-highest p_T of any jet
H_T		Scalar sum of p_T of all jets
$p_\mathrm{T}(\ell_2)$	†	Second-highest p_T of any lepton
$\mathrm{DJ}(\mathrm{j}_3)$	†	DeepJet score of the jet with the third-highest p_T
$m_\mathrm{T}(\ell_1)$		Transverse mass of the leading lepton and $p_\mathrm{T}^\mathrm{miss}$
$p_\mathrm{T}(\mathrm{j}_1)$		Highest p_T of any jet
$p_\mathrm{T}(\ell_1)$		Highest p_T of any lepton
$p_\mathrm{T}^\mathrm{miss}$		Missing transverse momentum
$m_\mathrm{T}(\ell_2)$	†	Transverse mass of the subleading lepton and $p_\mathrm{T}^\mathrm{miss}$
$p_\mathrm{T}(\mathrm{j}_2)$	†	Second-highest p_T of any jet
$m(\mathrm{t}_2)$	†	Invariant mass of any three jets, of which one is a b jet and none of which is used for $m(\mathrm{t}_1)$, that is closest to the top quark mass
N_j		Number of jets
$m_\mathrm{T2}(\mathrm{b})$	†	m_T2 variable constructed from the leading and subleading b jet
$m_\mathrm{T2}(\ell+\mathrm{b})$	†	m_T2 variable constructed from two lepton+jet systems built with the leading two leptons and the leading two b jets
$N_\mathrm{b}^\mathrm{tight}$		Number of jets passing the "tight" DeepJet working point (tighter than in the event selection)
$m(\mathrm{W}_2)$	†	Invariant mass of any two jets used for $m(\mathrm{t}_2)$ that is closest to the W boson mass
$\max_4$ DJ	†	Fourth-highest DeepJet score of any jet
$N_\mathrm{b}^\mathrm{medium}$	†	Number of jets passing the "medium" DeepJet working point (tighter than in the event selection, but looser than "tight")
$p_\mathrm{T}(\ell_3)$	‡	Third-highest p_T of any lepton
$p_\mathrm{T}(\mathrm{j}_3)$	‡	Third-highest p_T of any jet
$m_\mathrm{T2}(\ell)$	‡	m_T2 variable constructed from the leading and subleading lepton
$\mathrm{DJ}(\mathrm{j}_4)$	‡	DeepJet score of the jet with the fourth-highest p_T

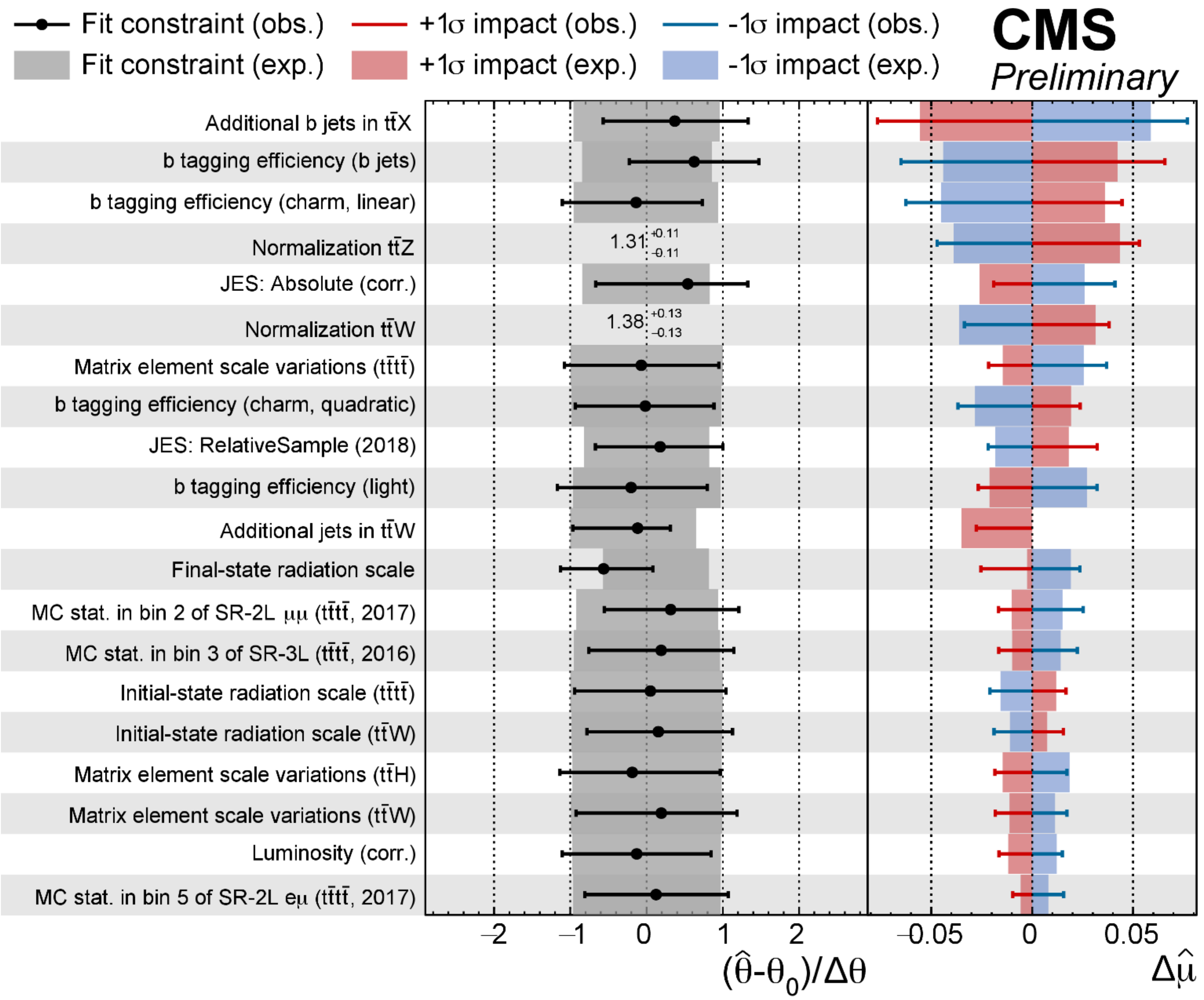
Results: 4top observation

Channel	Obs. (exp.) significance	$\sigma(pp \to t\bar{t}t\bar{t})$
2ℓ	4.1 (4.1) s.d.	$17.6\,^{+4.7}_{-4.3}\,(\text{stat})\,^{+2.8}_{-2.7}\,(\text{syst})$ fb
3ℓ	3.5 (3.0) s.d.	$19.4\,^{+7.1}_{-6.4}\,(\text{stat})\,^{+2.9}_{-2.3}\,(\text{syst})$ fb
4ℓ	0.0 (0.8) s.d.	—
Combined	5.5 (4.9) s.d.	$17.9\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.4}_{-2.1}\,(\text{syst})$ fb

1.1 σ compatible with the SM computation (NLO+NLL)







$$\sigma(pp \to t\bar{t}W) = 997 \pm 58\,(\text{stat})\,^{+79}_{-72}\,(\text{syst})\,\text{fb},$$

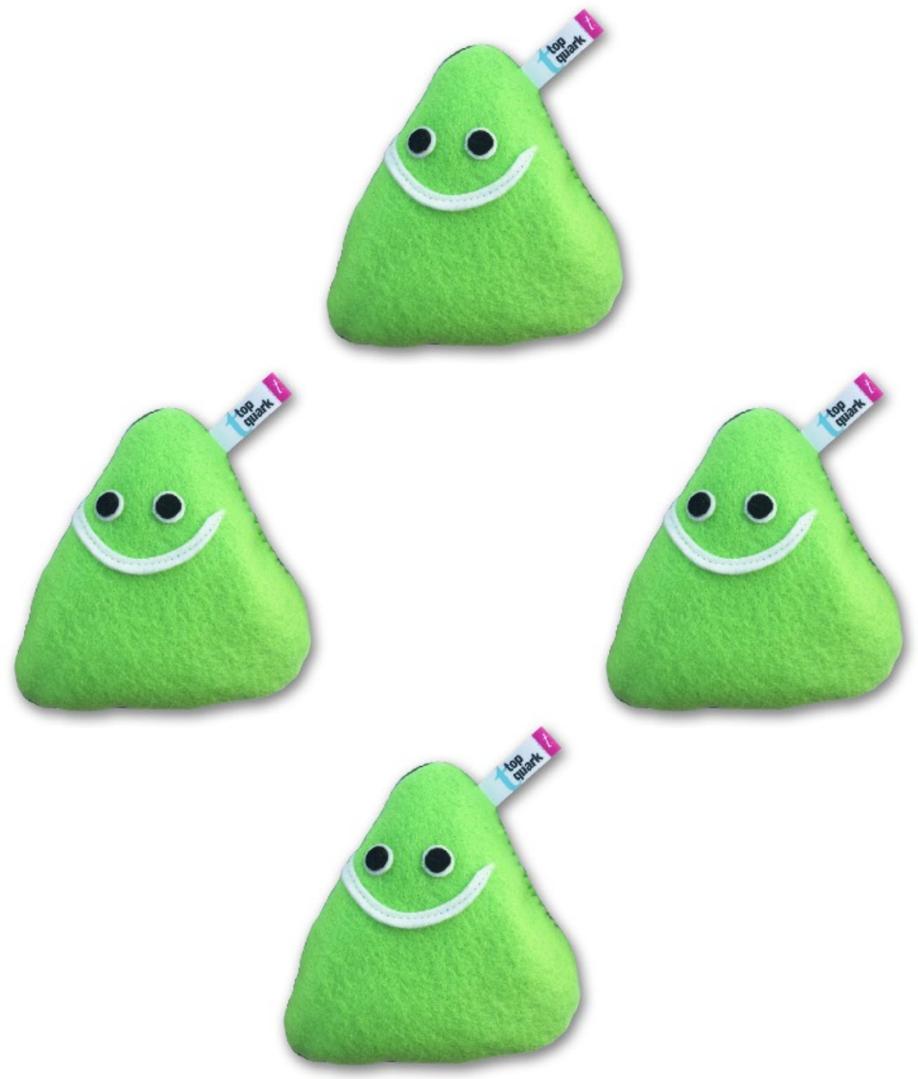
$$\sigma(pp \to t\bar{t}Z) = 1134\,^{+52}_{-43}\,(\text{stat}) \pm 86\,(\text{syst})\,\text{fb}.$$

Measured $t\bar{t}W$ ($t\bar{t}Z$) cross sections : in agreement with SM within 2.3 σ (2.2 σ)

Conclusion

- The past years/months have seen the development of 4top physics
  - SM computations
  - BSM scenario
  - Since March 2023, ATLAS and CMS have observed $t\bar{t}t\bar{t}$ production

- This is just the beginning
  - Run 3 at 13.6 TeV means 18% higher $t\bar{t}t\bar{t}$ cross section
  - Next is first to see if the measured cross section is higher or not compared to the SM
  - Then $t\bar{t}t$ studies, differential measurements …



Four Top Quarks' Poem

In the LHC's depths, where particles dance,
Four top quarks emerge, a rare chance,
Heaviest of all, the secrets they hold,
The universe's mysteries, soon to unfold.

Advancements in techniques, signals refined,
With Graph Neural Networks, clarity we find,
Six point one standard deviations amassed,
A threshold surpassed, discovery at last.

New doors now opened, as we further explore,
The cosmic labyrinth, seeking truths to implore,
With future endeavors, our knowledge expands,
Unveiling the secrets, the universe commands.

ChatGPT

A recent review (pre-observation)