First evidence for the production of four top quarks in events with zero to two leptons with the CMS Run 2 dataset

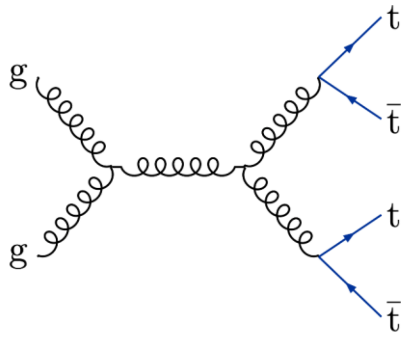
Vichayanun Wachirapusitanand
Chulalongkorn University, Bangkok, Thailand
On behalf of CMS Collaboration

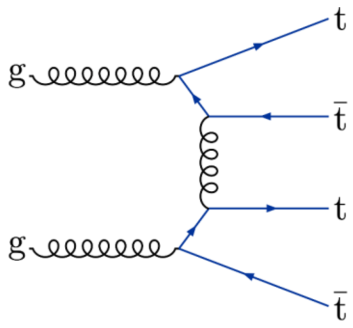
31st International Symposium on Lepton Photon Interactions at High Energies
19 July 2023

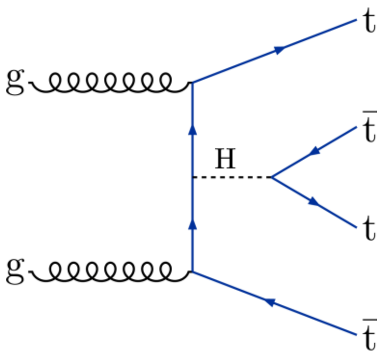
*not AI generated

Why search for four-top quark production?

- Test of Standard Model:
  - $\sigma_{t\bar{t}t\bar{t}}$ = 13.4 +0.5 -1.5 fb at NLO in QCD with EW corrections and NLL'
    M. van Beekveld, A. Kulesza, and L. M. Valero, arXiv:2212.03259
- High sensitivity to top Yukawa coupling and CP-violation
- Probe of four-heavy-quark operators







CMS-TOP-21-005

CERN-EP-2023-014
2023/03/08

First evidence reported from CMS

Evidence for four-top quark production in proton-proton collisions at $\sqrt{s} = 13$ TeV

Includes difficult final states

Most diverse final states ever included

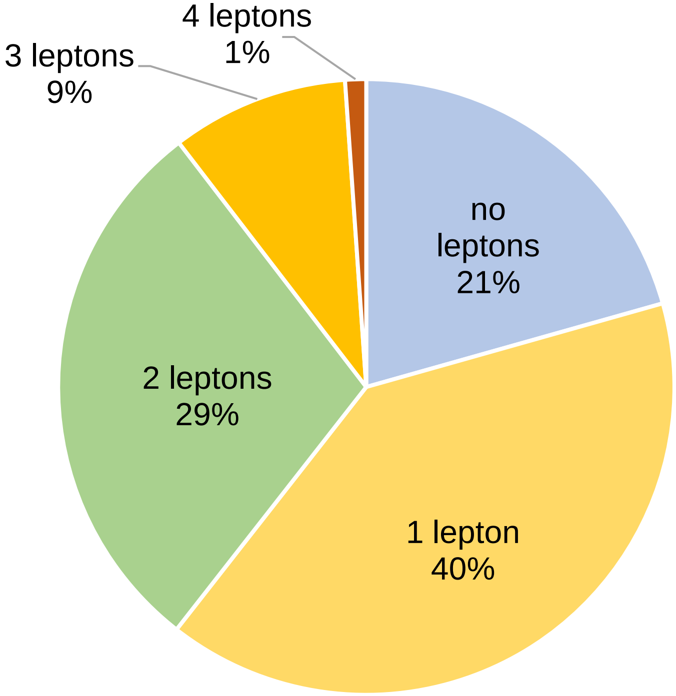
The CMS Collaboration

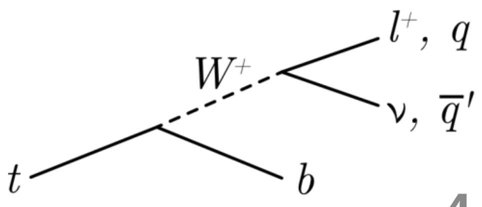
CMS Collaboration, arXiv:2303.03864
Accepted by Phys. Lett. B

Final states analysed

Why? Challenging final states provide complementary information and allow to further improve the sensitivity to four-top quark production.

Final state	2016	2017	2018
Single-lepton (SL)		NEW	
Opposite-sign dilepton (OSDL)	JHEP 11 (2019) 082	NEW	
All-hadronic		FIRST TIME EVER	
Same-sign dilepton & Multilepton (SSDL&ML)		Eur. Phys. J. C 80 (2020) 75	





Highlights from new results

	2017 + 2018 OSDL	Run 2 SL	Run 2 all-hadronic
Important backgrounds	$t\bar{t}+b\bar{b}$ and $t\bar{t}H$	$t\bar{t}+b\bar{b}$ and $t\bar{t}H$	$t\bar{t}$ + QCD
Background estimation method	Monte Carlo simulation	Monte Carlo simulation	Monte Carlo simulation + data-driven method
Highlights	H_T analysis with **better MC simulation and b-tagging algorithms**	Optimises event categories based on lepton flavour, jets, and **resolved top quarks**	Estimates **data-driven background** (with BDT shape) using machine learning methods.

No leptons
and lots of jets,
very difficult

Main background estimation for SL and OSDL

Main background is $t\bar{t}$+jets

$t\bar{t}$+jets MC samples at NLO

↓

Normalised to $t\bar{t}$ NNLO cross section

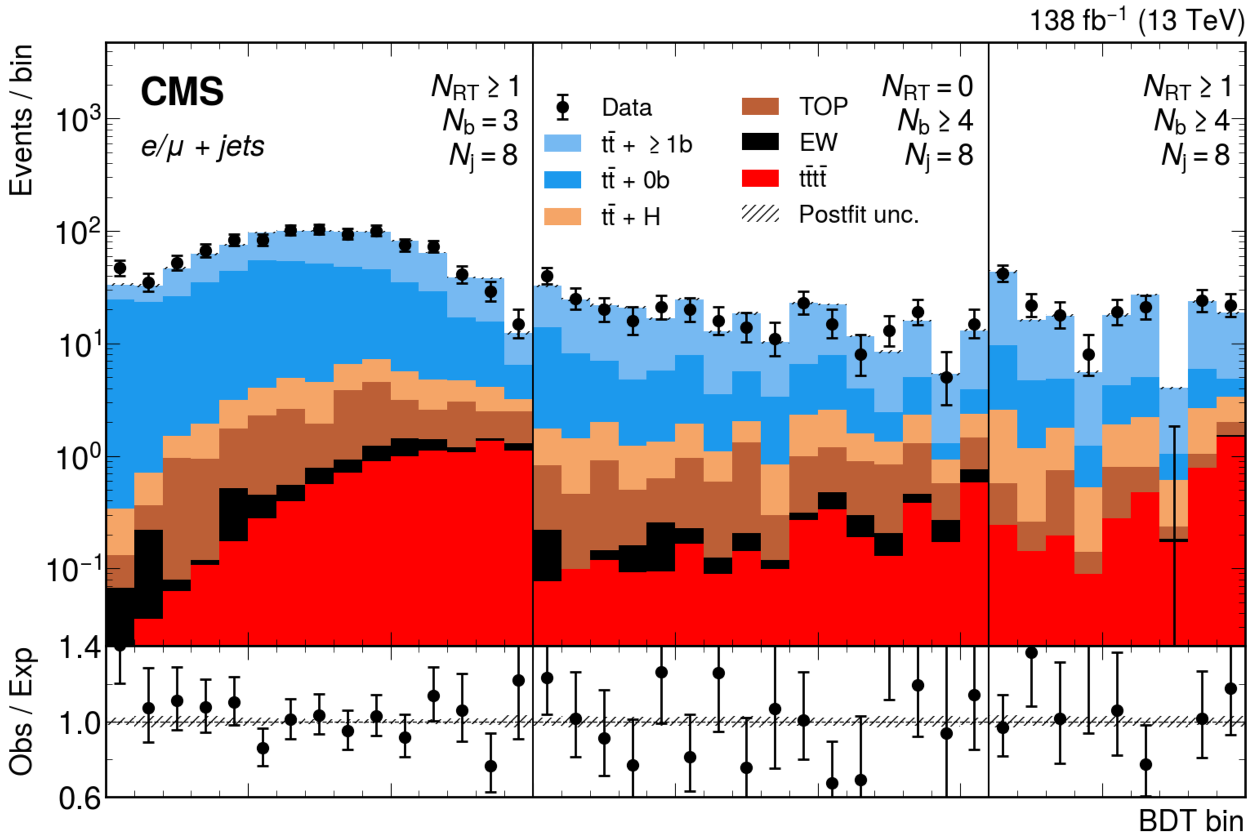
↓

$t\bar{t}$+≥1b events reweighted to match cross section measured by CMS

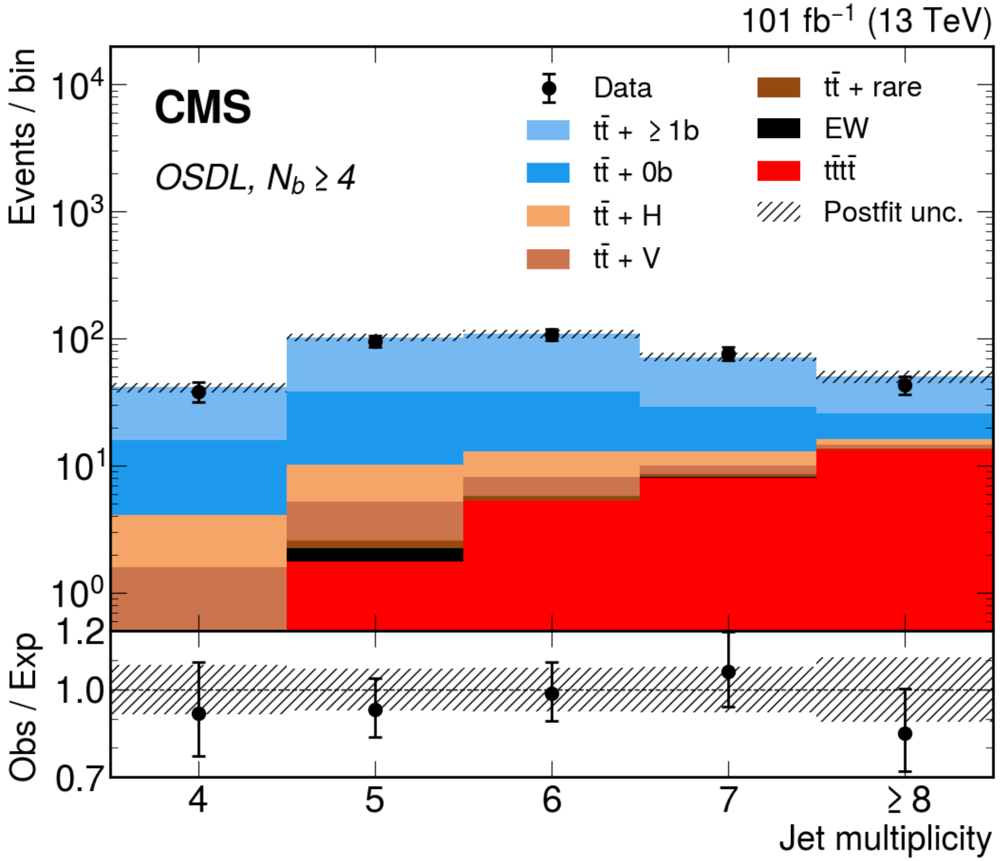
$t\bar{t}$+jets must be split into $t\bar{t}$+≥1b and $t\bar{t}$+0b

- $t\bar{t}$+$b\bar{b}$ has 30% cross section uncertainty.
  CMS Collaboration,
  Phys. Lett. B 803 (2020) 135285
- $t\bar{t}$ with heavy flavour normalisation determined as most impactful uncertainty in previous analysis.
  - 11% in Run 2 SSDL&ML analysis

SL and OSDL distributions



(single-lepton)

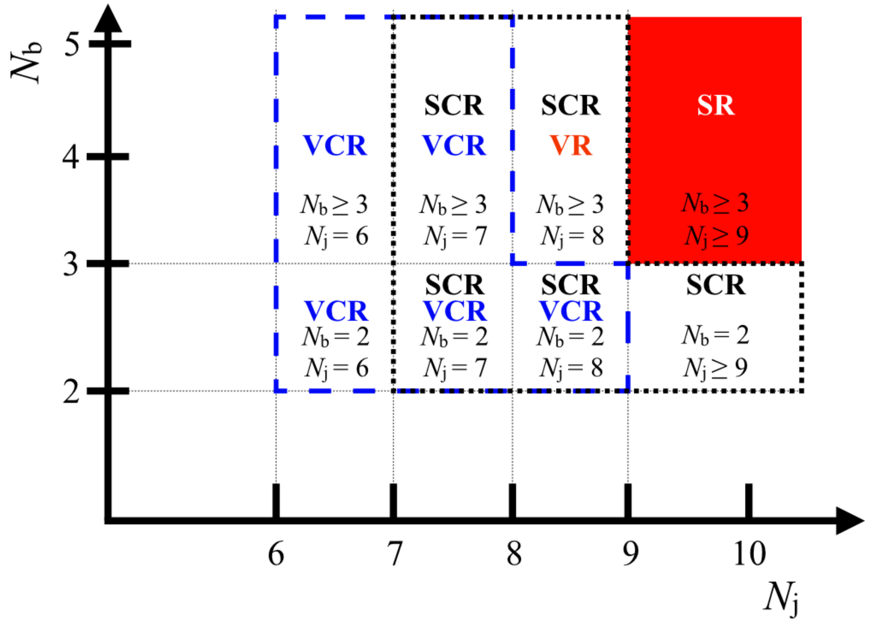


(opposite-sign dilepton)

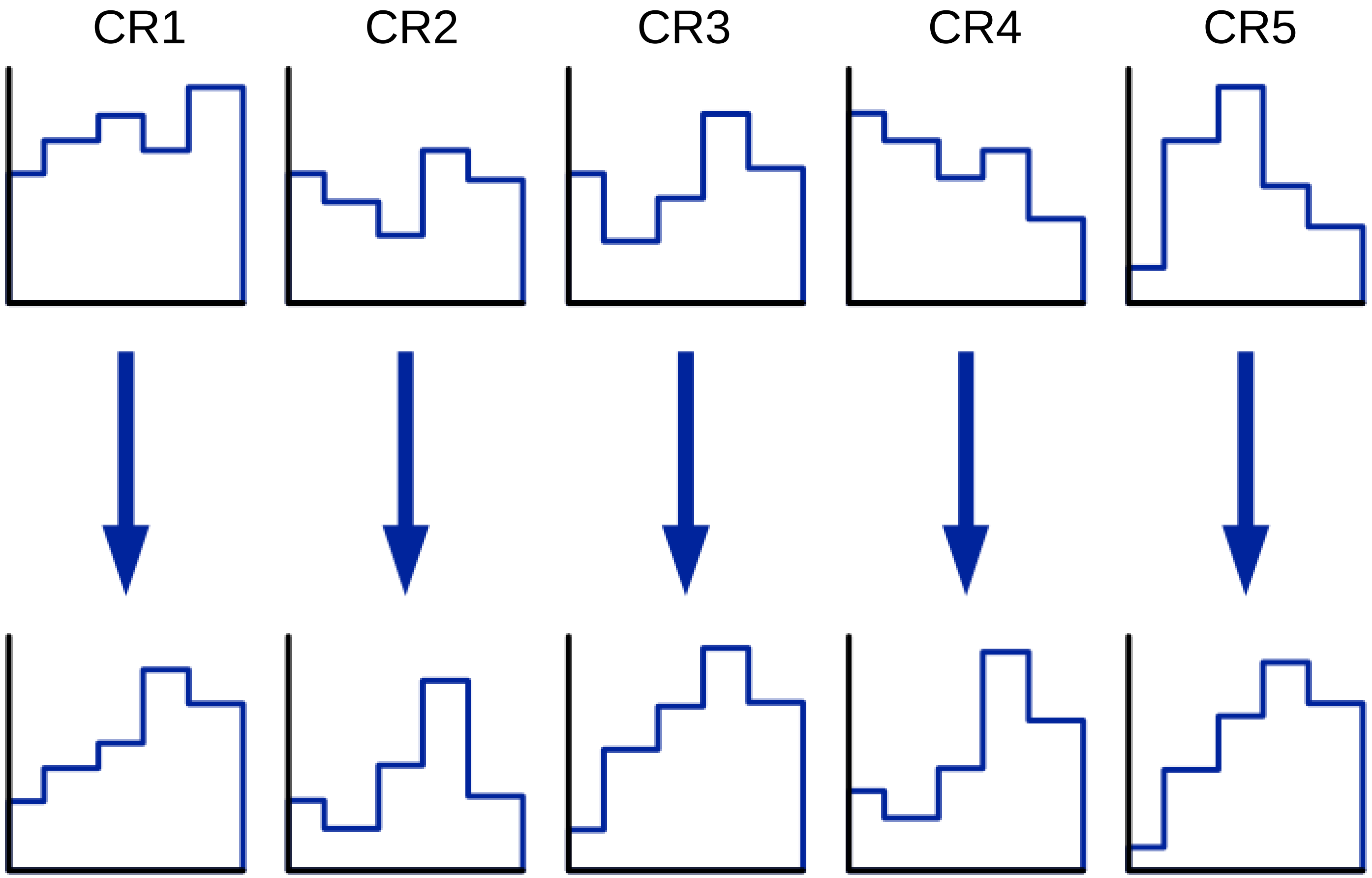
Main background estimation for all-hadronic

Main background is QCD and $t\bar{t}$

- QCD is hard to simulate (not enough events and detector effects difficult to model)
- *normalisation* in SR from data using extended ABCD method.
- *shape* using normalising autoregressive flow
  S. Choi and H. Oh, arXiv: 2008.03636
  - transforms the source distribution to target distribution



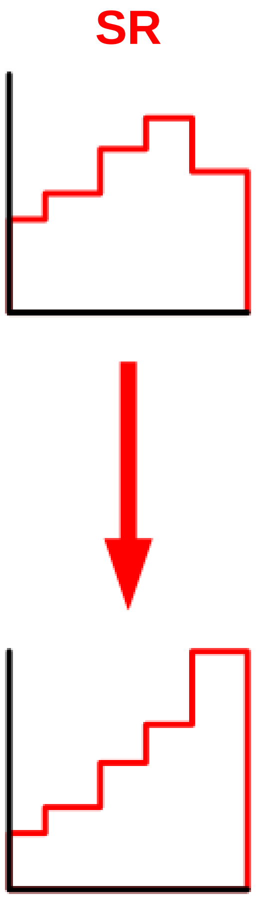
BDT distribution estimation using autoregressive flow



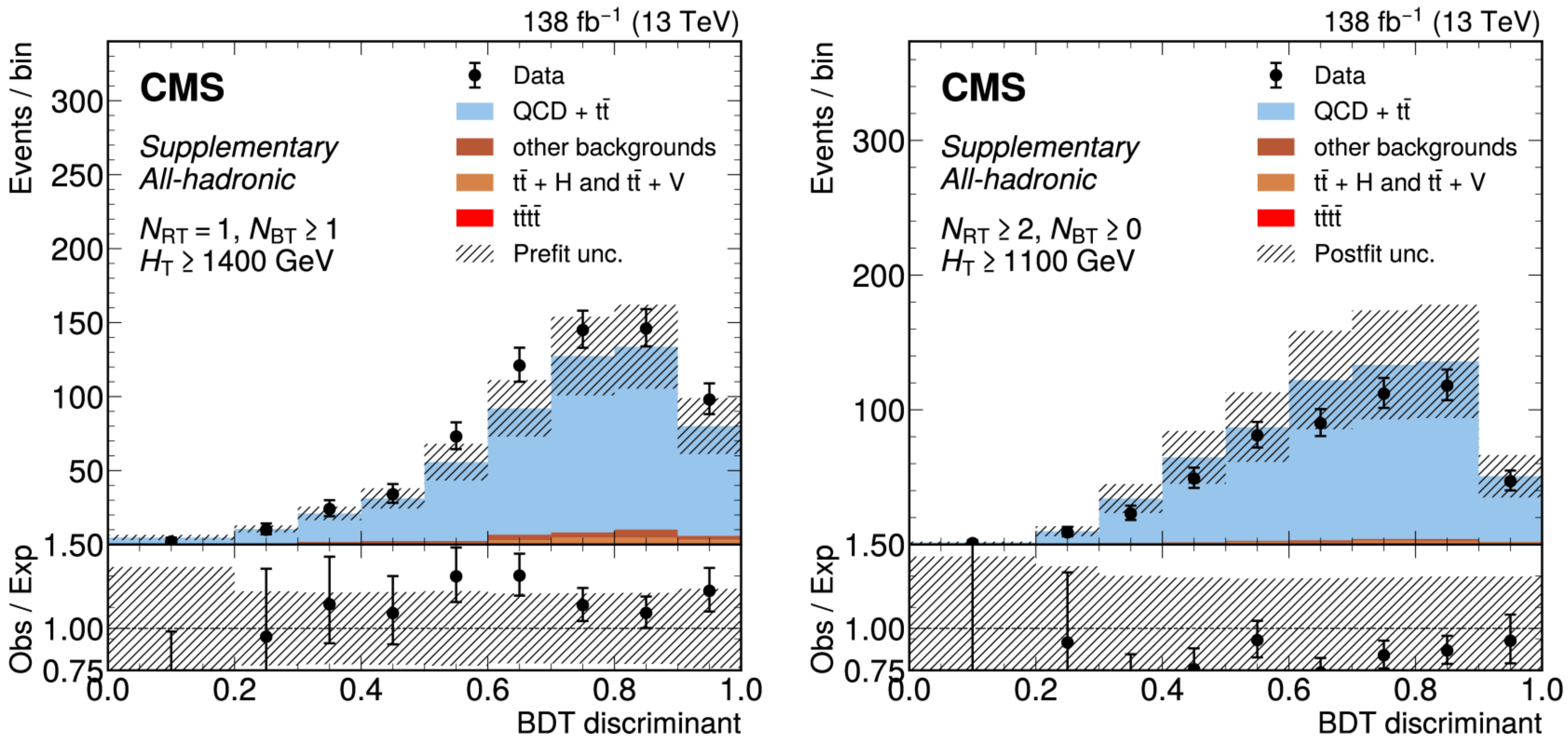
Input: $t\bar{t}$ MC

Neural autoregressive flow transform the input into the target within CR data, applies the transformation in SR.

Target: background SR estimated from data



Background validation

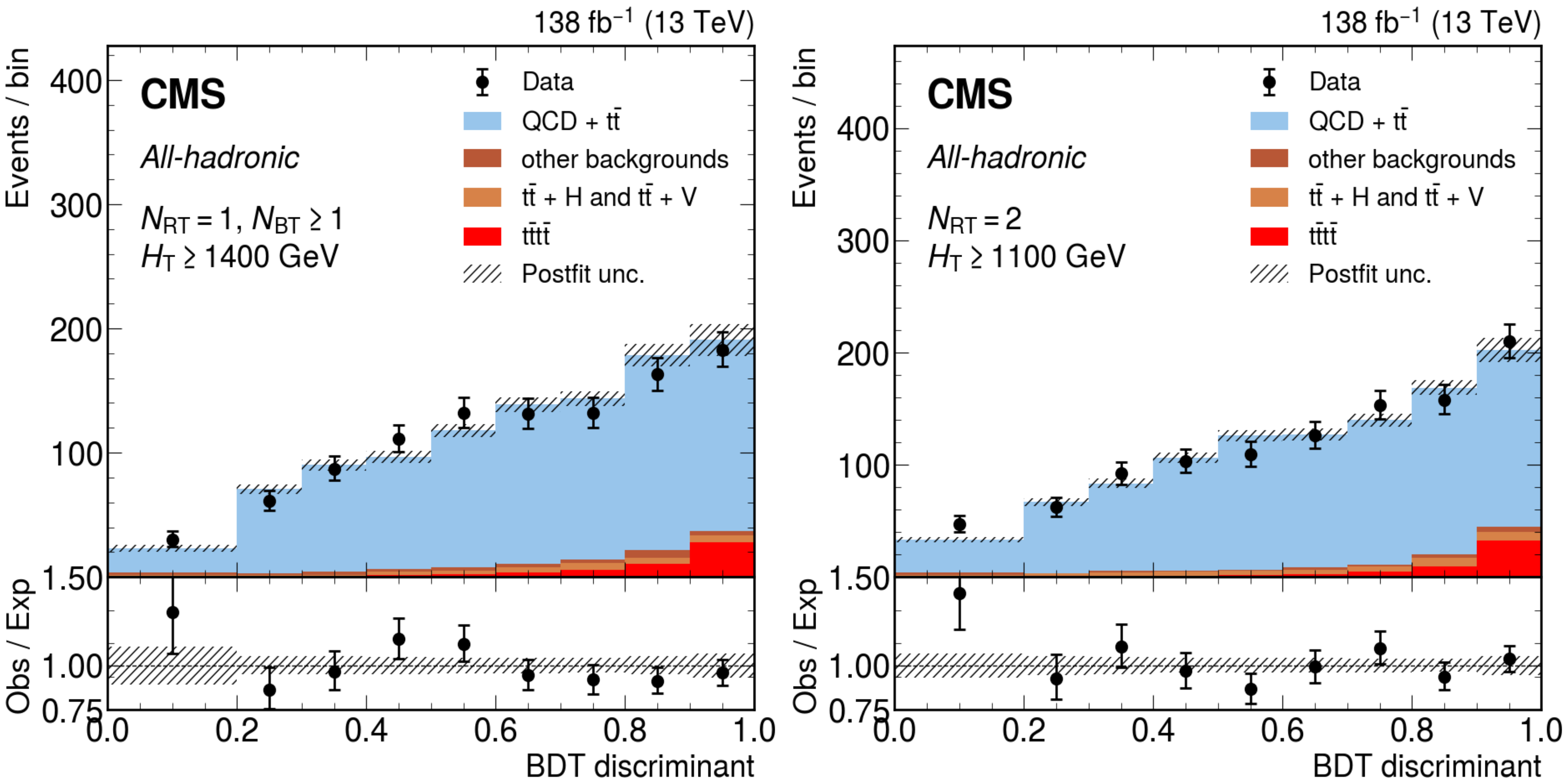


Prefit BDT distributions in validation region **with 8 jets and 3+ b-tagged jets**

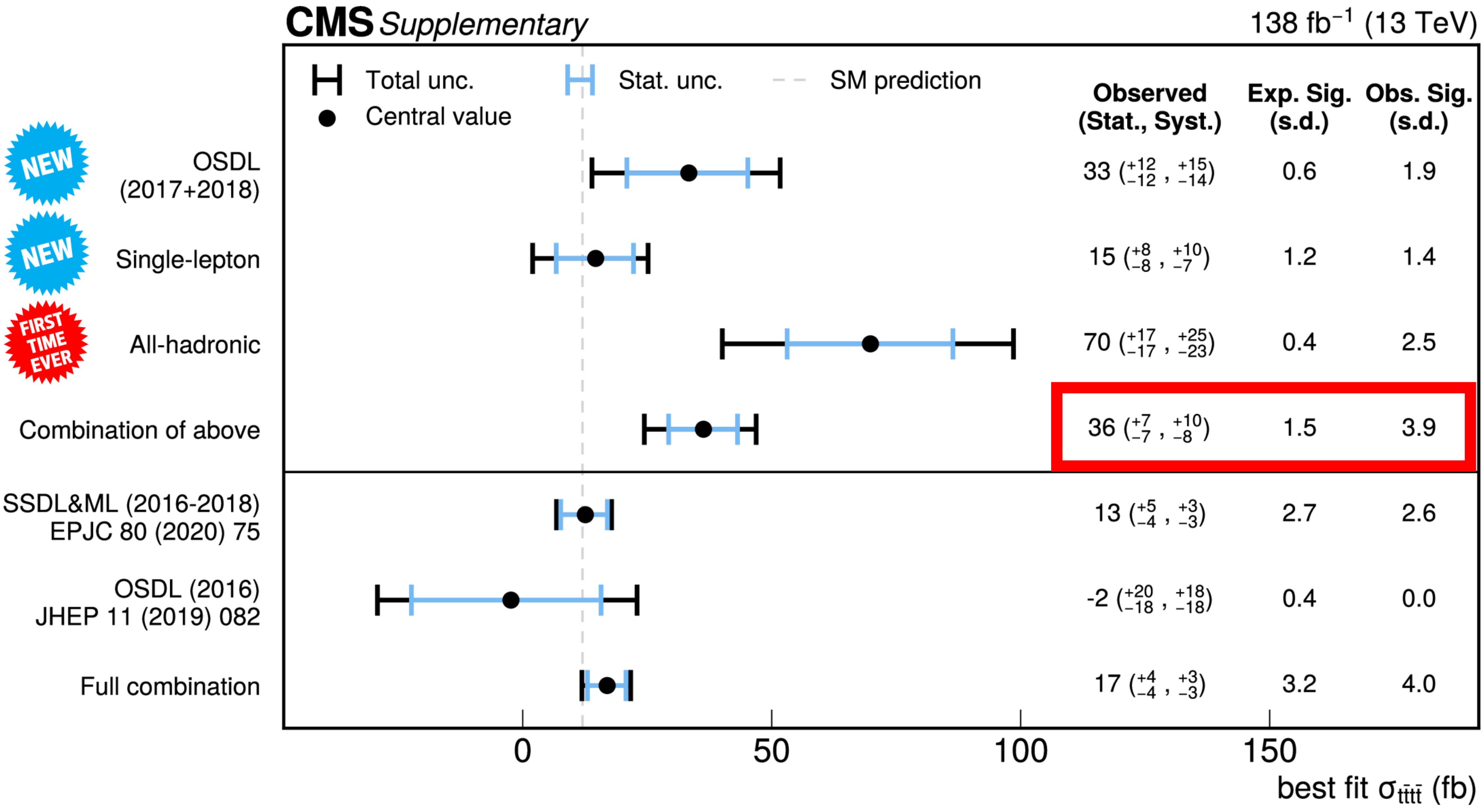
(All plots in backup)

N_{RT} = number of resolved tops
N_{BT} = number of boosted tops

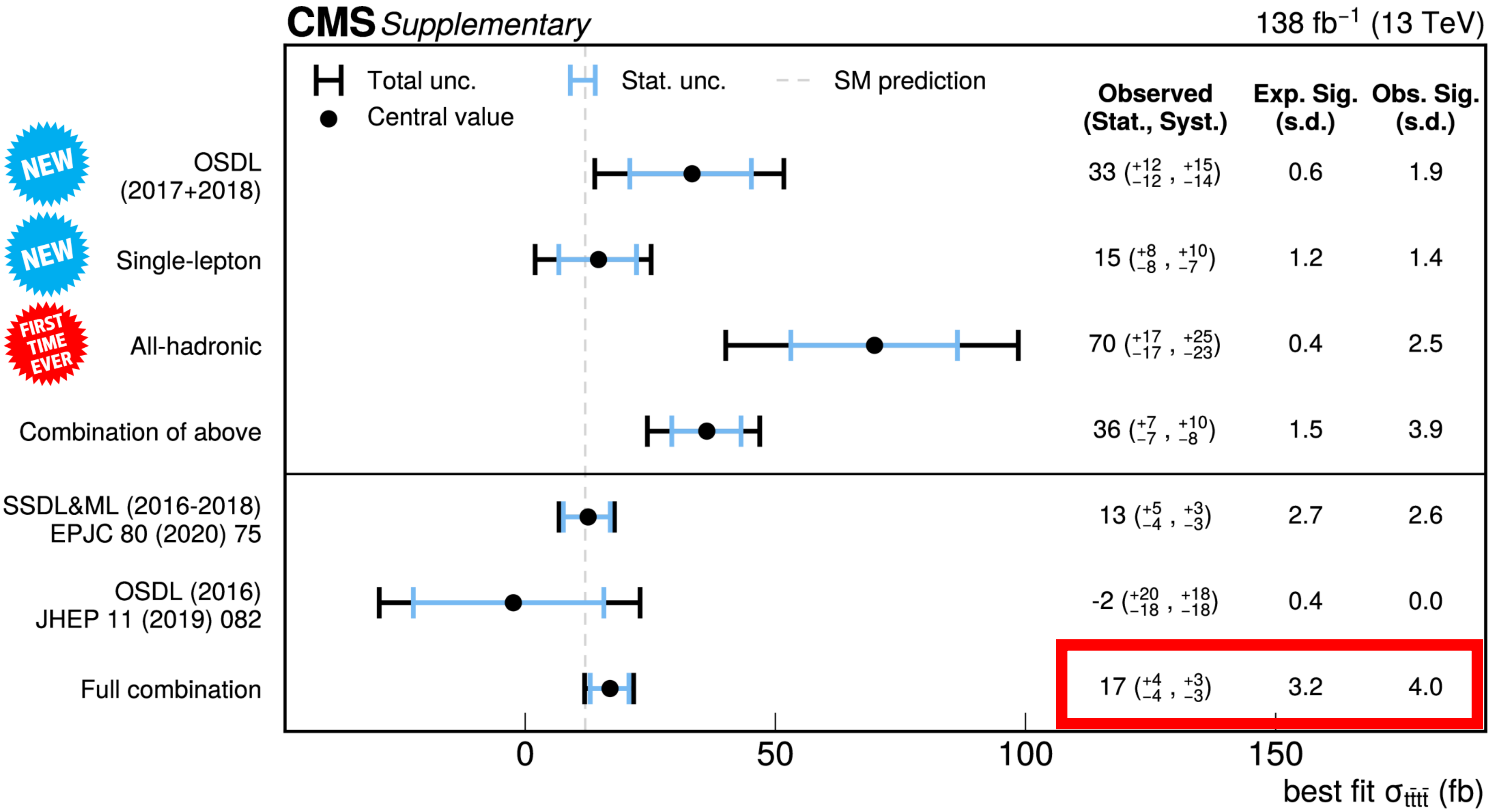
All-hadronic SR distributions



N_{RT} = number of resolved tops
N_{BT} = number of boosted tops



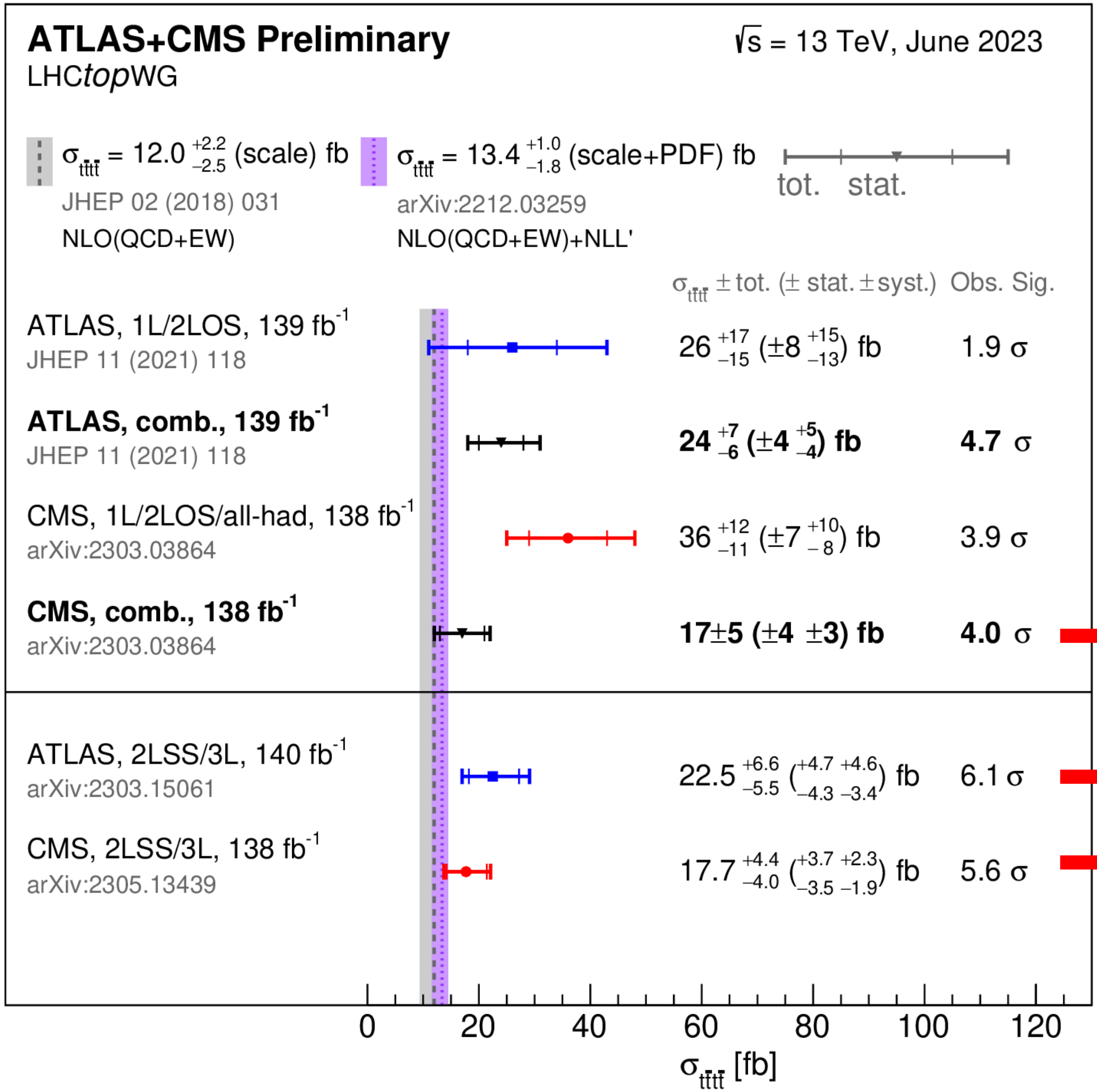
CMS Supplementary
138 fb^{-1} (13 TeV)
Total unc.
Stat. unc.
SM prediction
Central value
Observed (Stat., Syst.)
Exp. Sig. (s.d.)
Obs. Sig. (s.d.)
NEW
OSDL (2017+2018)
$33\ (^{+12}_{-12}, ^{+15}_{-14})$ 0.6 1.9
NEW
Single-lepton
$15\ (^{+8}_{-8}, ^{+10}_{-7})$ 1.2 1.4
FIRST TIME EVER
All-hadronic
$70\ (^{+17}_{-17}, ^{+25}_{-23})$ 0.4 2.5
Combination of above
$36\ (^{+7}_{-7}, ^{+10}_{-8})$ 1.5 3.9
SSDL&ML (2016-2018) EPJC 80 (2020) 75
$13\ (^{+5}_{-4}, ^{+3}_{-3})$ 2.7 2.6
OSDL (2016) JHEP 11 (2019) 082
$-2\ (^{+20}_{-18}, ^{+18}_{-18})$ 0.4 0.0
Full combination
$17\ (^{+4}_{-4}, ^{+3}_{-3})$ 3.2 4.0
0
50
100
150
best fit $\sigma_{t\bar{t}t\bar{t}}$ (fb)


CMS Supplementary
138 fb^{-1} (13 TeV)
Total unc.
Stat. unc.
SM prediction
Central value
Observed (Stat., Syst.)
Exp. Sig. (s.d.)
Obs. Sig. (s.d.)
NEW
OSDL (2017+2018)
33 ($^{+12}_{-12}$, $^{+15}_{-14}$) 0.6 1.9
NEW
Single-lepton
15 ($^{+8}_{-8}$, $^{+10}_{-7}$) 1.2 1.4
FIRST TIME EVER
All-hadronic
70 ($^{+17}_{-17}$, $^{+25}_{-23}$) 0.4 2.5
Combination of above
36 ($^{+7}_{-7}$, $^{+10}_{-8}$) 1.5 3.9
SSDL&ML (2016-2018) EPJC 80 (2020) 75
13 ($^{+5}_{-4}$, $^{+3}_{-3}$) 2.7 2.6
OSDL (2016) JHEP 11 (2019) 082
-2 ($^{+20}_{-18}$, $^{+18}_{-18}$) 0.4 0.0
Full combination
17 ($^{+4}_{-4}$, $^{+3}_{-3}$) 3.2 4.0
0
50
100
150
best fit $\sigma_{t\bar{t}t\bar{t}}$ (fb)

Uncertainties with most impacts

	Impacts on signal strength
Statistical uncertainties	22%
$t\bar{t}H$ cross section uncertainty	4.6%
$t\bar{t}+b\bar{b}$ modelling uncertainty	3.7%
Background estimation in all-hadronic	up to 2.7%
Jet energy scale	2.4%
Renormalisation and factorisation scales	2.1%
Leptonic fake rate (SSDL&ML background)	1.9%
B tagging and light quark mistagging eff.	up to 1.8%

Apart from $t\bar{t}$ background, $t\bar{t}H$ background is now another important background for four top searches.



This talk

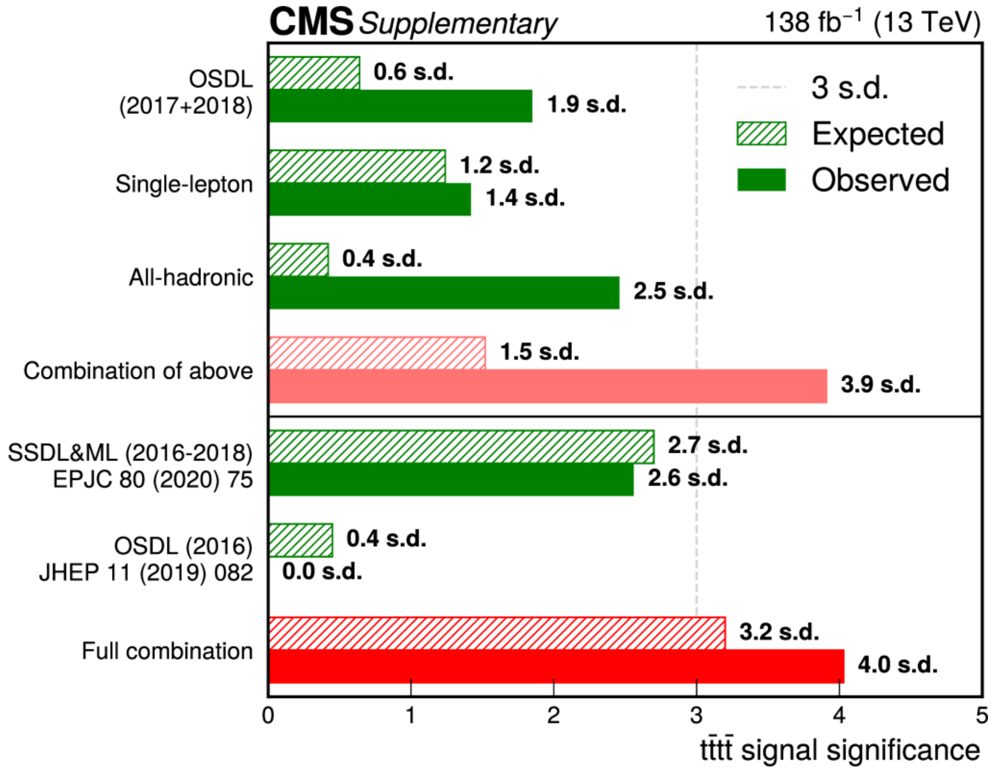
(See today's talk by Teresa Barillari
and another talk by Marcel Vos this Friday)

(See today's talk by Didar Dobur)

→ Precision four tops next?

Summary

- The first evidence of four-top quark production is presented, which is calculated from single-lepton, opposite-sign dilepton, and all-hadronic final states using Run 2 data in CMS.
- $t\bar{t}H$, in addition to $t\bar{t}$ + heavy flavour, becomes another important background for future four-top quark production analyses.
- The all-hadronic final state uses novel machine learning techniques to estimate QCD + $t\bar{t}$ backgrounds.
- The measured cross section from this result is consistent with recent results in SSDL&ML final state and with latest SM predictions.



Backup

How difficult is this work?

Final states involved in this work have different levels of complexity.

Dilepton
Two leptons,
easy to detect

Single-lepton
One lepton,
reasonable difficulty

All-hadronic
No leptons
and lots of jets,
very difficult

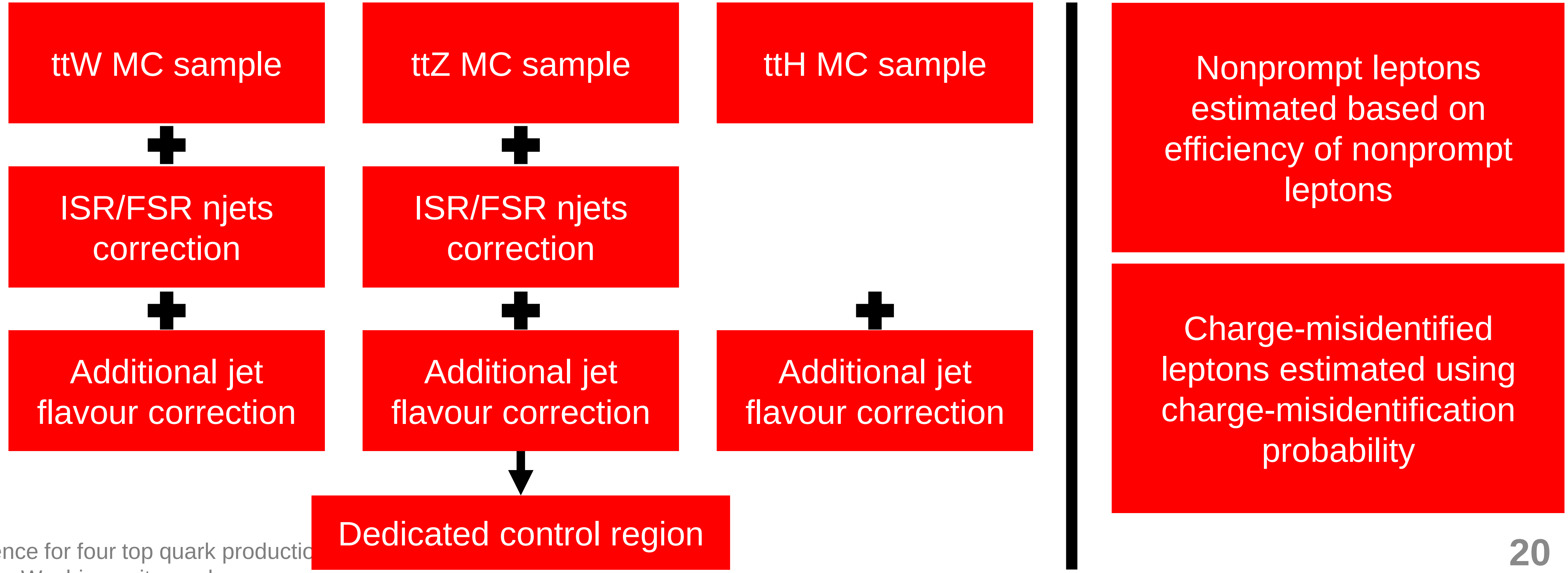
easier **(in terms of signal isolation)** harder

Analysis strategy

	Run 2 SL	2017 + 2018 OSDL	Run 2 all-hadronic
Event selection	One lepton, $p_T > 20$ GeV, 4+ jets ($p_T > 30$ GeV), 2+ b-tagged jets, $H_T > 500$ GeV	Two leptons, $p_T > 25$ and 15 GeV, 4+ jets ($p_T > 30$ GeV), 2+ b-tagged jets, $H_T > 500$ GeV	No leptons, 9+ jets ($p_T > 30$ GeV), 3+ b-tagged jets, $H_T > 700$ GeV
Dominant background	$t\bar{t}+b\bar{b}$ and $t\bar{t}H$	$t\bar{t}+b\bar{b}$ and $t\bar{t}H$	$t\bar{t}$ + QCD
Background estimation method	Monte Carlo simulation	Monte Carlo simulation	Monte Carlo simulation + data-driven method
Analysis categories	40 categories/year, by lepton flavour, jets, and resolved top quarks	45 categories/year, by lepton flavour, jets, and b-tagged jets	12 categories/year, by resolved tops, boosted tops, and H_T
Discriminating variable	BDT	H_T	BDT

Main background estimation SSDL&ML final state, CMS

Main backgrounds are ttW, ttZ, ttH, and ttbar with nonprompt leptons



Analysis techniques in a nutshell

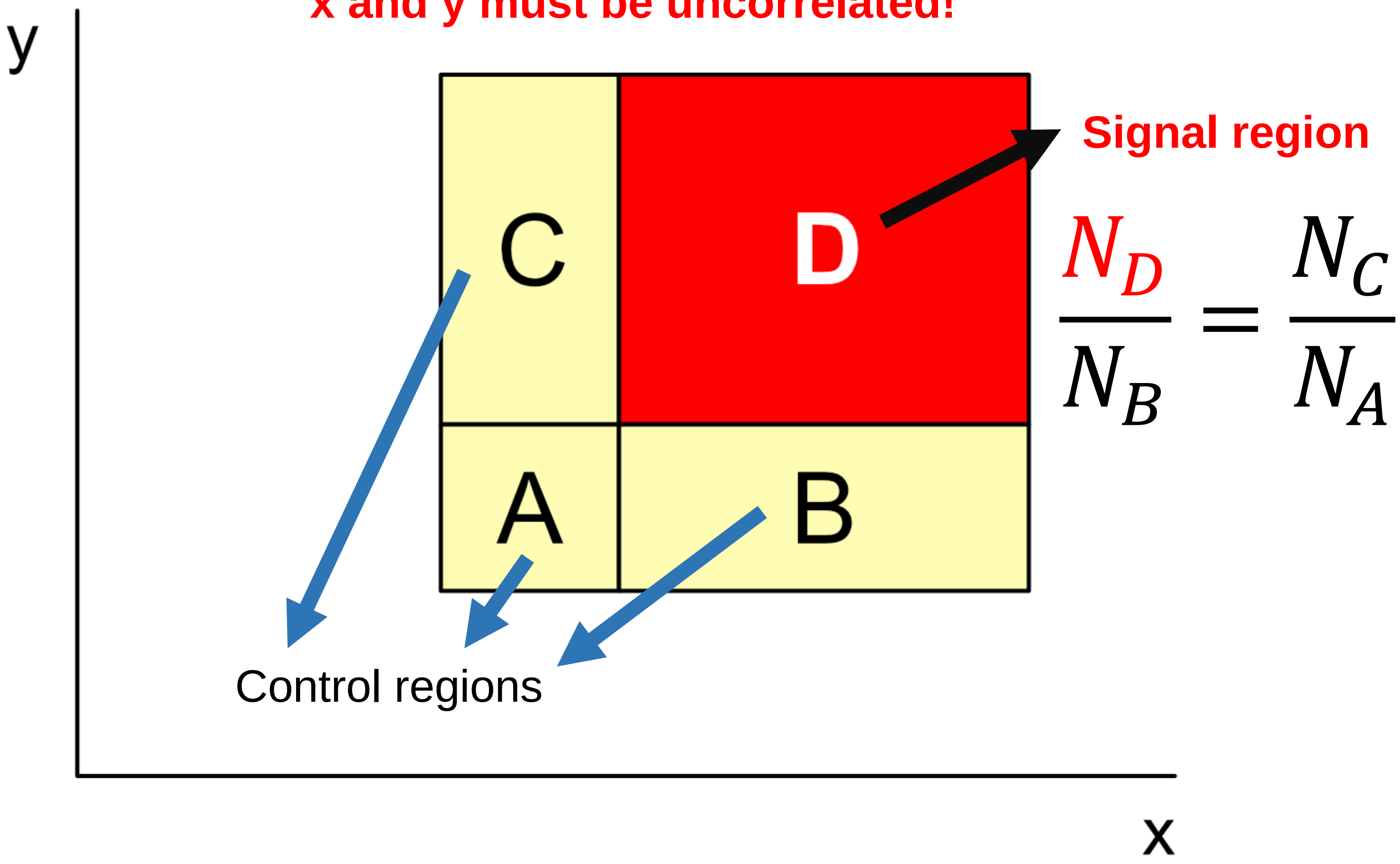
Final state	CMS 2016	CMS 2017	CMS 2018	ATLAS 2015 - 2018
All-hadronic	BDT	BDT	BDT	
1L	BDT	BDT	BDT	BDT
2LOS	BDT	*HT*	*HT*	
2LSS+3L	BDT			BDT
Event categorisation	Large number of event categories based on number of physics objects			Small number of event categories providing separation between backgrounds

ABCD method

Key idea:
Use number of events in control regions (A, B, and C) to calculate background in signal region D.

The change in x and y from A → B and A → C must contribute to background in D.

x and y must be uncorrelated!



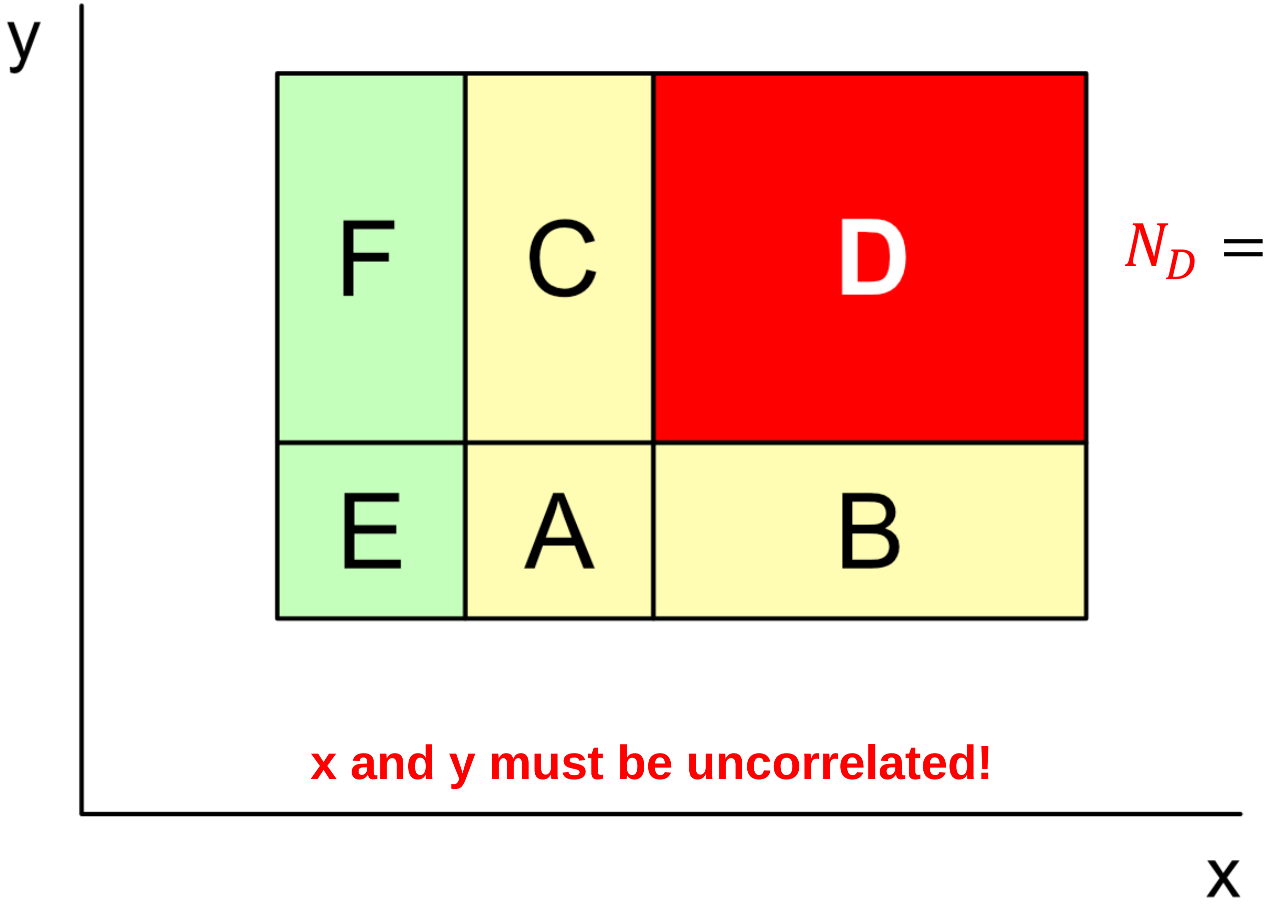
$$\frac{N_D}{N_B} = \frac{N_C}{N_A}$$

S. Choi and H. Oh, arXiv: 1906.10831

Extended ABCD method

Key idea:
We want better estimation accuracy, so we introduce some more information from more control regions.

Calculations are more complex, but give a better accuracy in signal region.



$$N_D = \frac{N_B N_C}{N_A} \cdot \frac{N_C N_E}{N_A N_F}$$

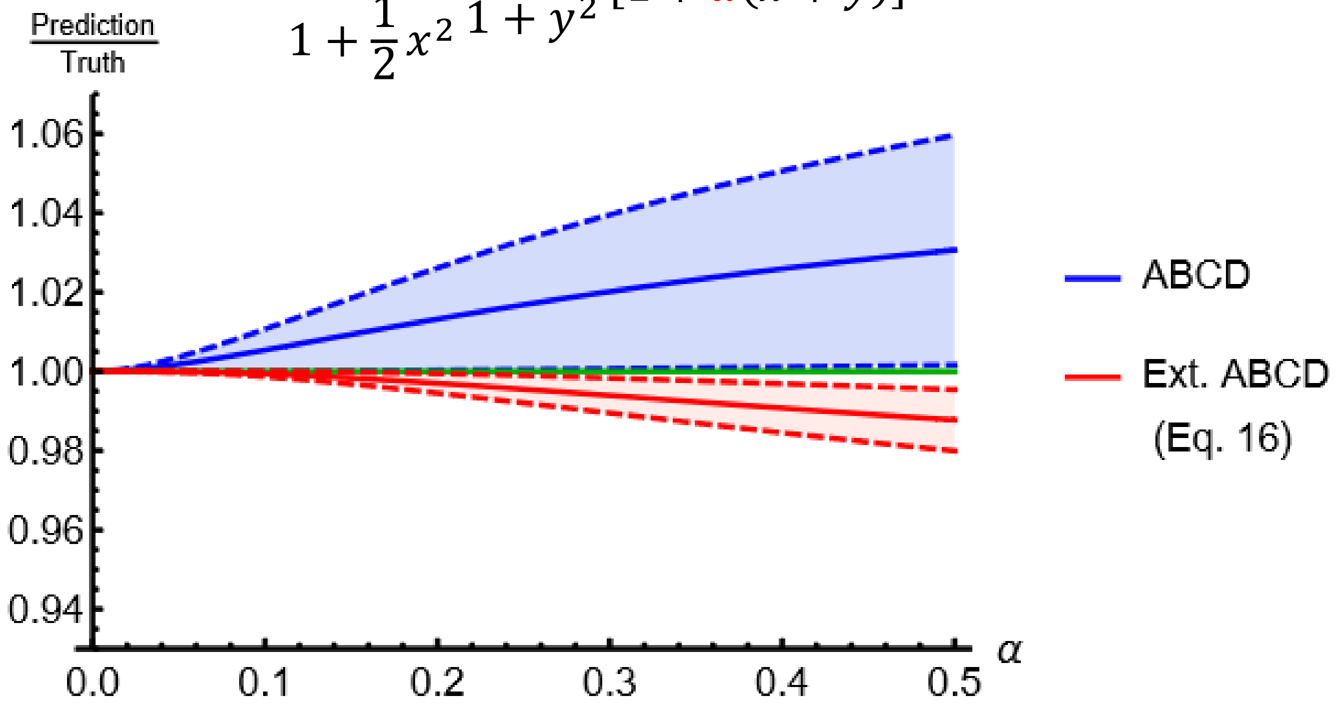
S. Choi and H. Oh, arXiv: 1906.10831

ABCD vs extABCD

Example 1:
toy distribution
ABCD and extABCD is used to estimate a smooth distribution.

extABCD method provides prediction closer to truth values.

$$\frac{1}{1+\frac{1}{2}x^2}\frac{1}{1+y^2}[1+\alpha(x+y)]$$



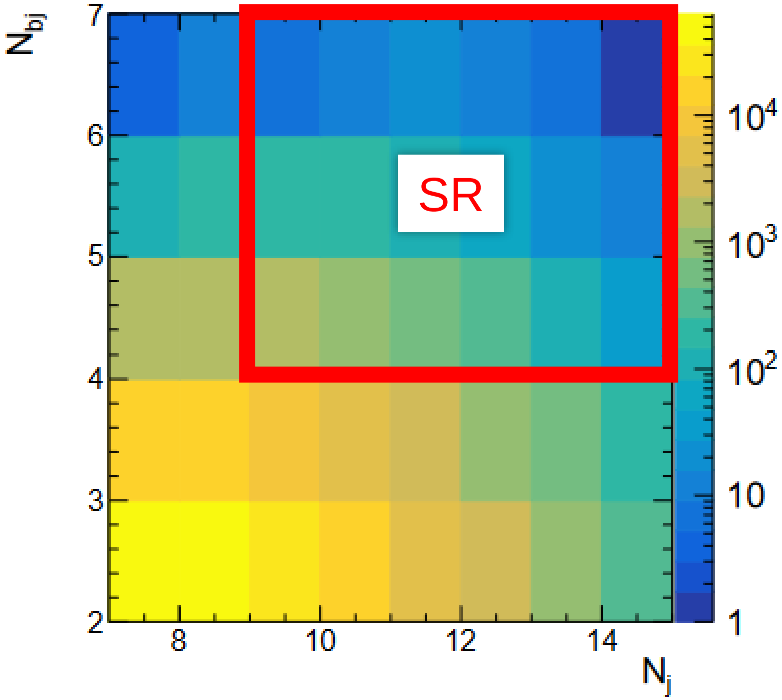
S. Choi and H. Oh, arXiv: 1906.10831

ABCD vs extABCD

S. Choi and H. Oh, arXiv: 1906.10831

Example 2.1: ttbar+jj distribution
ABCD and extABCD used to predict number of events in SR (9+ jets, 4+ b-tagged jets)

extABCD gives better prediction compared to vanilla ABCD. Results are different based on different CR definitions.



N_{bj}	N_j 7	8	≥ 9
2	63216	49685	55756
3	15046	14378	20068
≥ 4	1961	2388	4874

SR

Extrapolation method	Prediction ($\hat{F}_D$)	$\hat{F}_D/F_D$
ABCD (Eq. 12)	3333 ± 77	0.684 ± 0.015
Ext. ABCD (Eq. 14)	4149 ± 132	0.851 ± 0.027
Ext. ABCD (Eq. 15)	4352 ± 271	0.893 ± 0.056
Ext. ABCD (Eq. 16)	4247 ± 217	0.871 ± 0.045

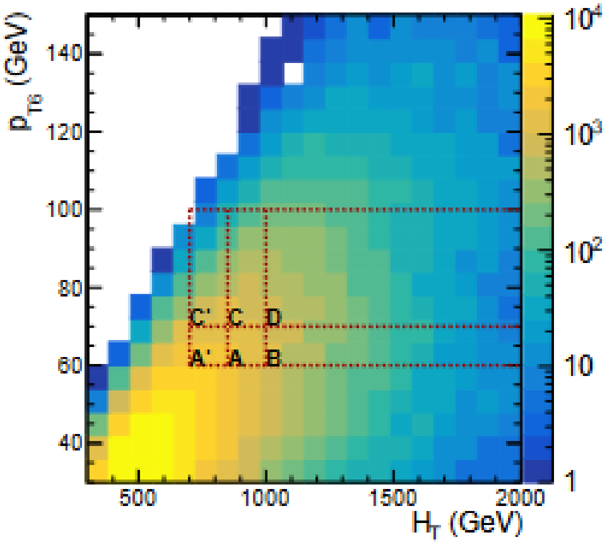
ABCD vs extABCD

Example 2.2: ttbar+jj distribution

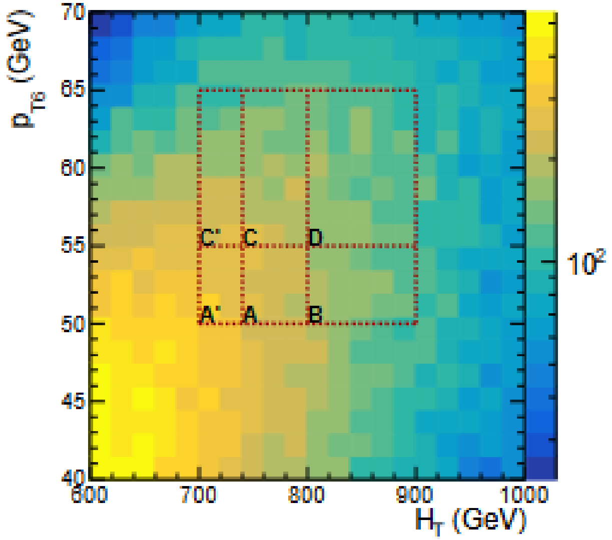
ABCD and extABCD used to predict number of events in SR (D)

extABCD gives better prediction compared to vanilla ABCD.

S. Choi and H. Oh, arXiv: 1906.10831



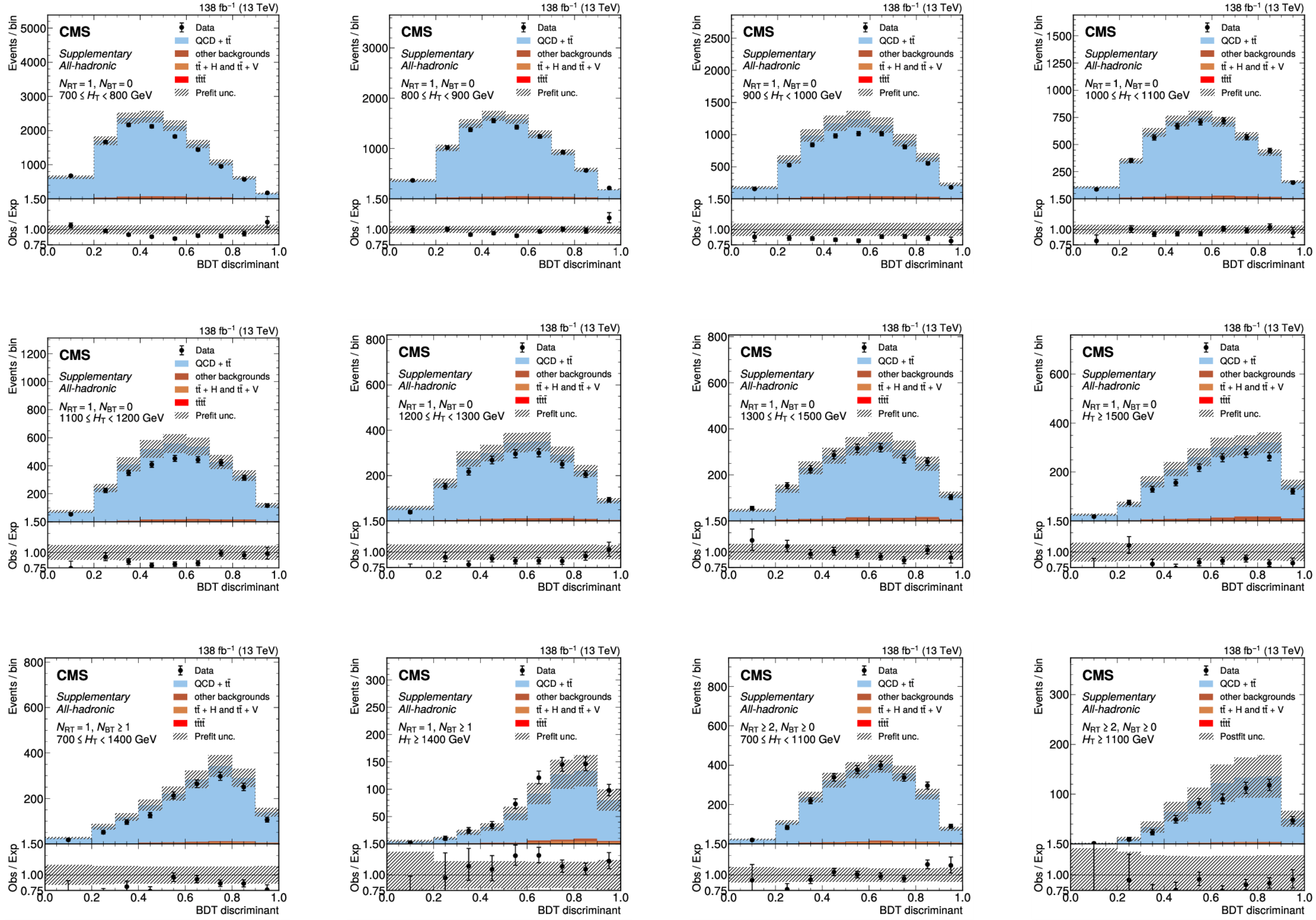
Case 1

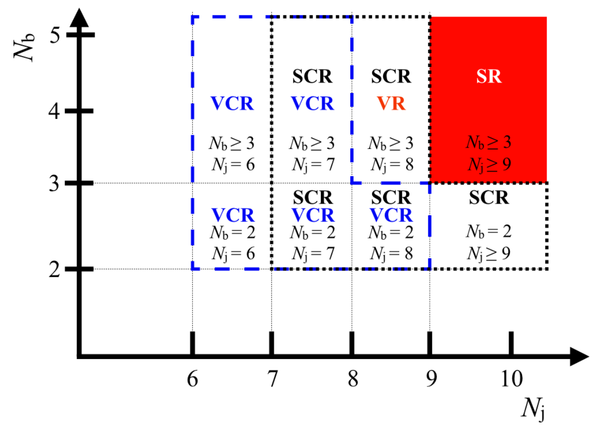


Case 2

	ABCD	Ext. ABCD	Truth
Case 1	4802 ± 122	9976 ± 488	9288
Case 2	3886 ± 128	4493 ± 291	4688

Prefit plots from validation region (VR) with 8 jets and 3+ b-tagged jets.





Comparison

	Measured cross section (fb)
This result (arXiv:2303.03864)	17 ± 4 (stat.) ± 3 (syst.)
CMS observation result (arXiv:2305.13439)	17.7 +3.7 -3.5 (stat.) +2.3 -1.9 (syst.)
ATLAS observation result (arXiv:2303.15061)	22.5 +4.7 -4.3 (stat.) +4.6 -3.4 (syst.)
SM (NLO+EW+NLL', arXiv:2212.03259)	13.4 +0.5 -1.5

→ (Didar Dobur)

Measured cross section from all results
are internally consistent and to SM prediction
at 13.4 +0.5 -1.5 fb (NLO+EW+NLL').

→ Precision four tops next?