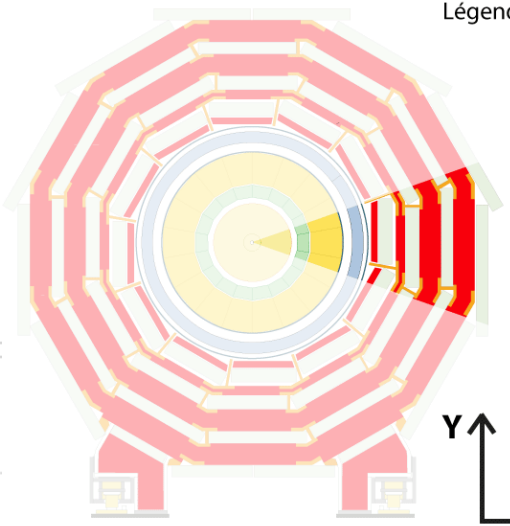
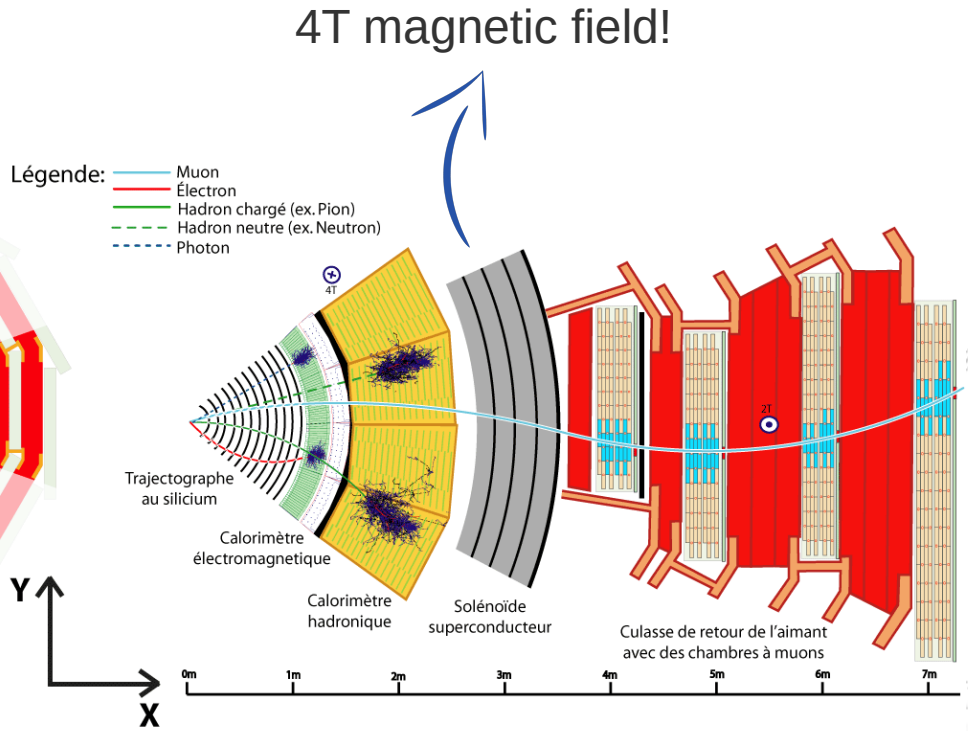
Measurements of $t\bar{t}$ production and fermion associated $t\bar{t}$ production in CMS

Federica Cecilia Colombina (DESY)
on behalf of the CMS Collaboration

The CMS detector

- General-purpose detector along the LHC ring
- Cylindrical structure with different layers
  - Tracker
  - ECAL
  - HCAL
  - Solenoid magnet
  - Muon chambers
- Two-level trigger
  - ~40 MHz → ~1 kHz





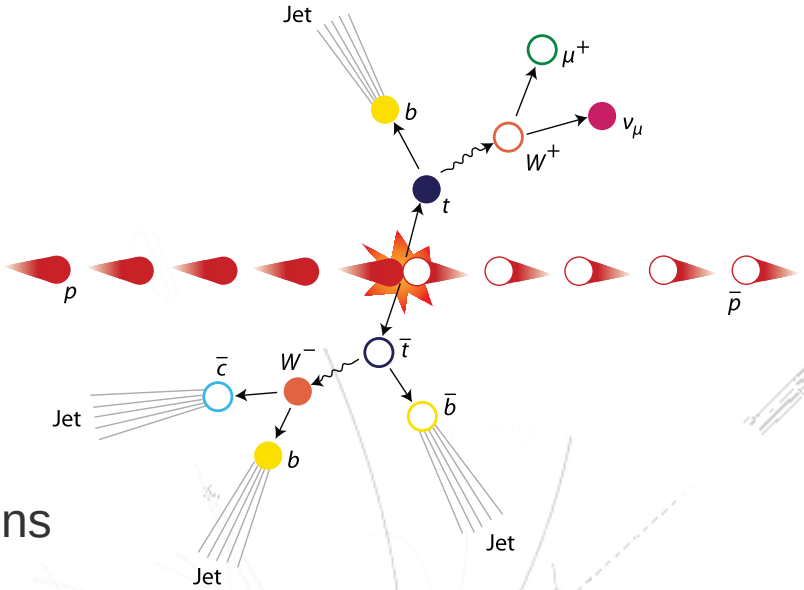
LHCPhysics
Belgrade, 22 - 26 May 2023

The top quark

- **Heaviest** known elementary particle
  - Large Yukawa coupling to the Higgs boson
  - Decays before hadronization

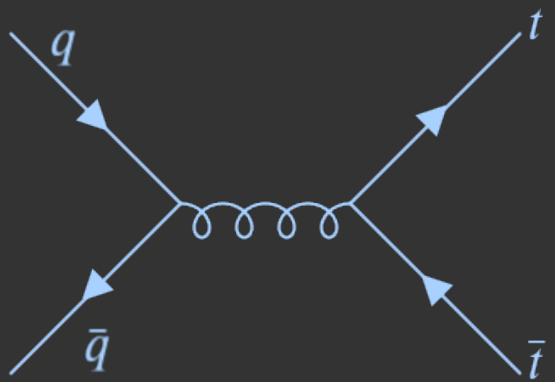
allows to study bare quark properties

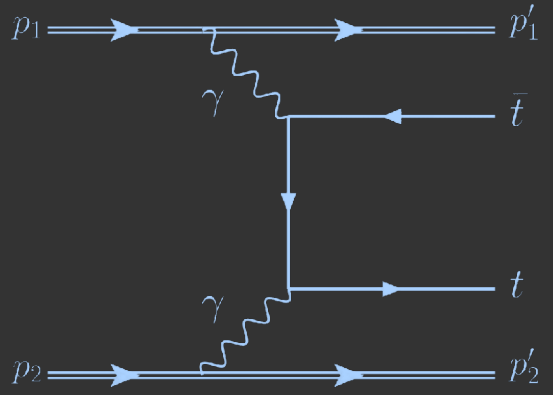
- Special role in QCD
  - provides access to α_S and PDF
- Sensitive to **BSM scenarios**, allows **EFT** interpretations



LHCPhysics
Belgrade, 22 - 26 May 2023

Pair production

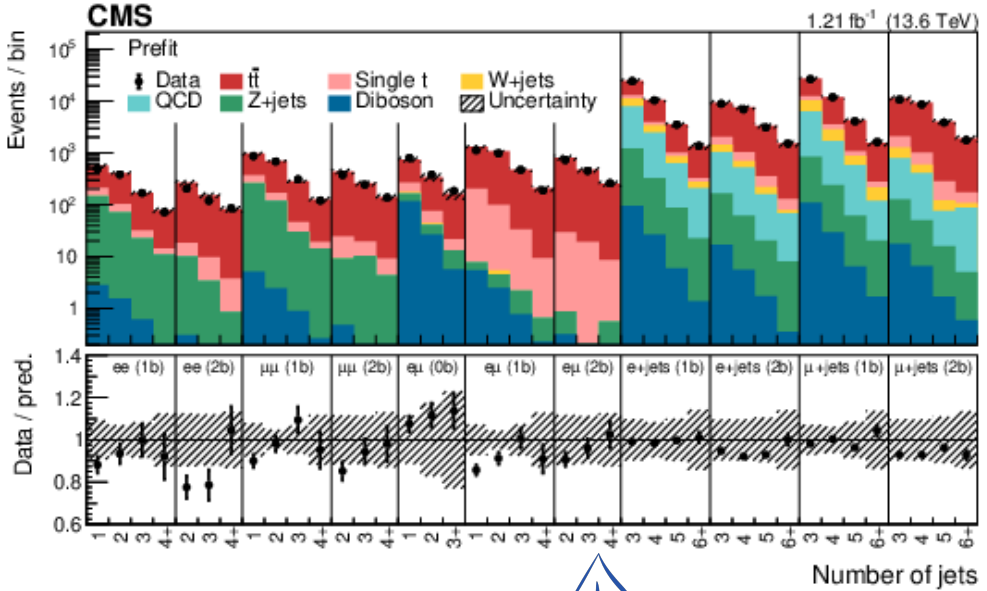




Inclusive $t\bar{t}$ cross section

CMS TOP-22-012

- Run-3 started in July 2022
  - **13.6 TeV**
  - aim to 300 fb^{-1} of integrated luminosity
- First measurement at new energy
  - $t\bar{t}$ cross section expected to rise by **10%**
- **1.21 fb^{-1}** of luminosity
- **2ℓ** and **ℓ+jets** combined for the first time
- b-jet efficiencies measured simultaneously in the fit

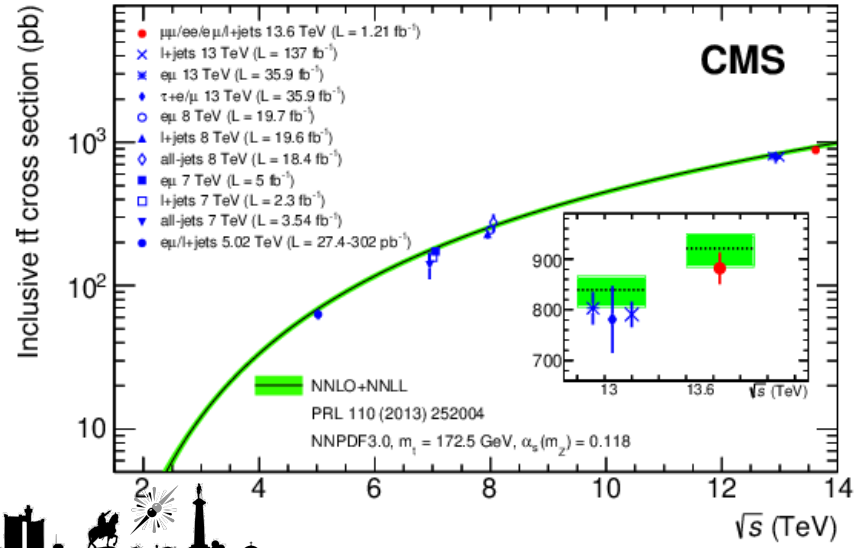


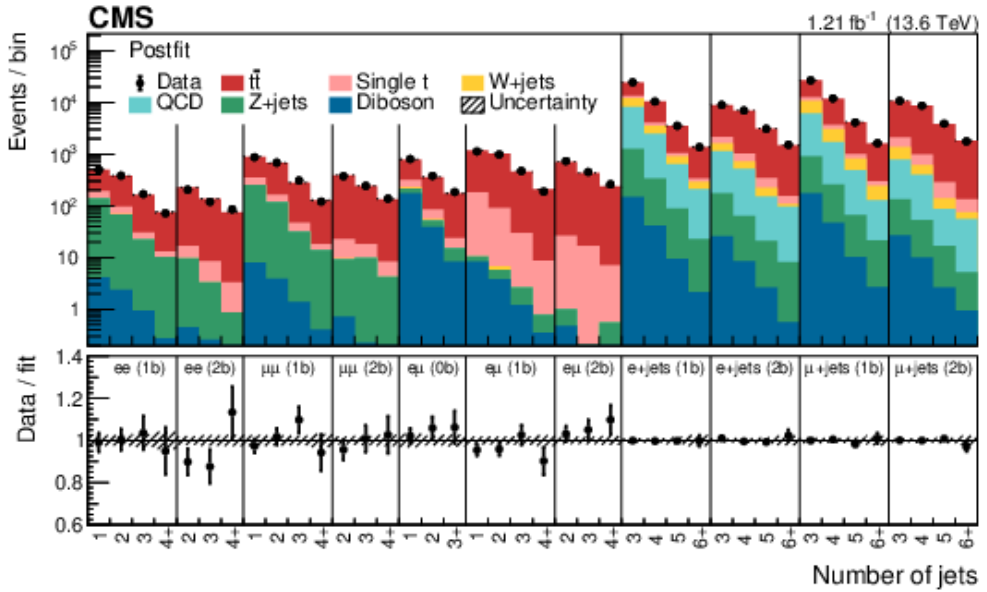
profile likelihood fit in lepton and b-jet categories

Inclusive $t\bar{t}$ cross section

CMS TOP-22-012

- **3.5%** total uncertainty!
- Main uncertainties: luminosity, lepton and b-tag efficiencies





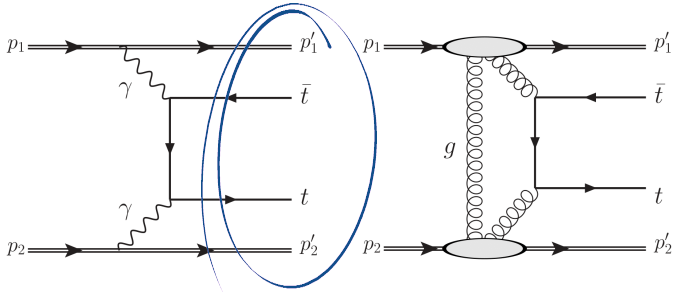
$$\sigma_{t\bar{t}} = 882 \pm 23\,(stat.+syst.) \pm 20\,(lumi)\ pb$$

$$\sigma_{t\bar{t}}^{th} = 921^{+29}_{-37}\ pb$$

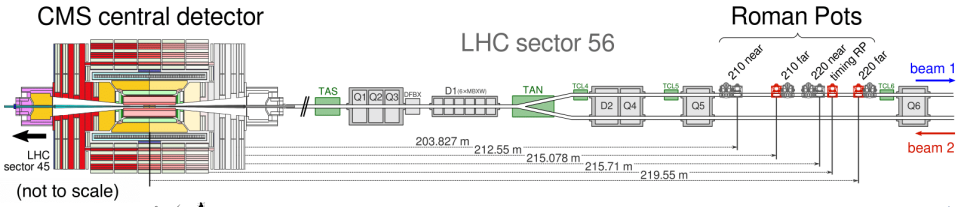
Exclusive $t\bar{t}$ production

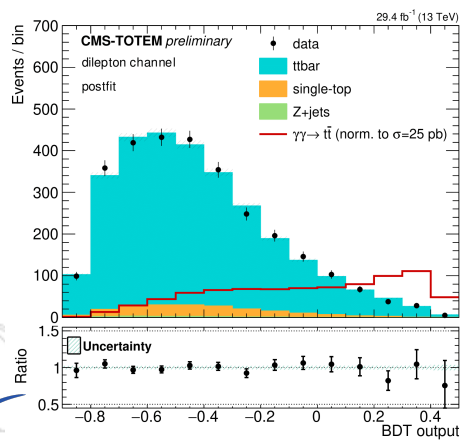
CMS TOP-21-007

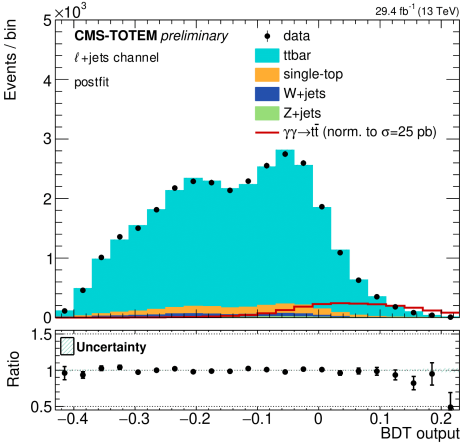
- **Really rare**, ~0.1 fb
- Observation expected with HL-LHC
- Intact protons in final state
  - allows full $t\bar{t}$ reconstruction
- Proton-tagged events in **2017**
  - binned fit to BDT output
- CMS-TOTEM Precision Proton Spectrometer



Observed (expected) limits:
0.59 pb (1.14 pb)



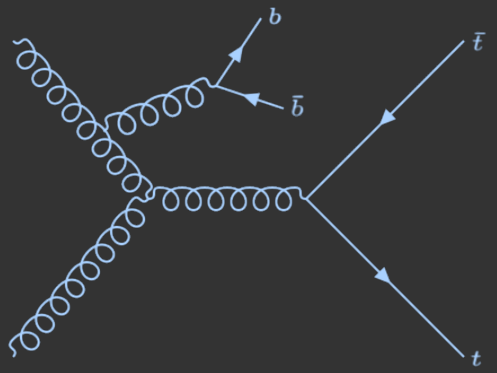


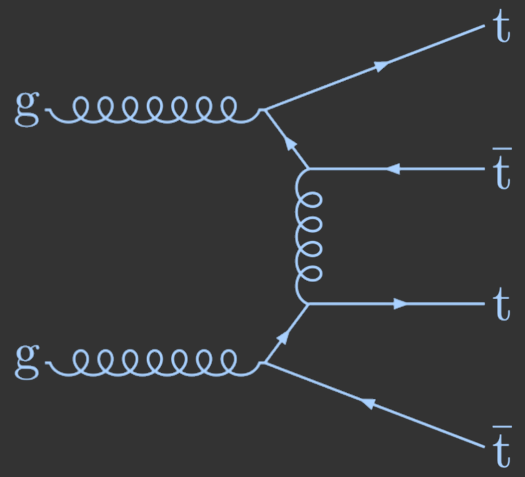


Signal normalized to σ=25 pb

LHCPhysics
Belgrade, 22 - 26 May 2023

Associated production with fermions





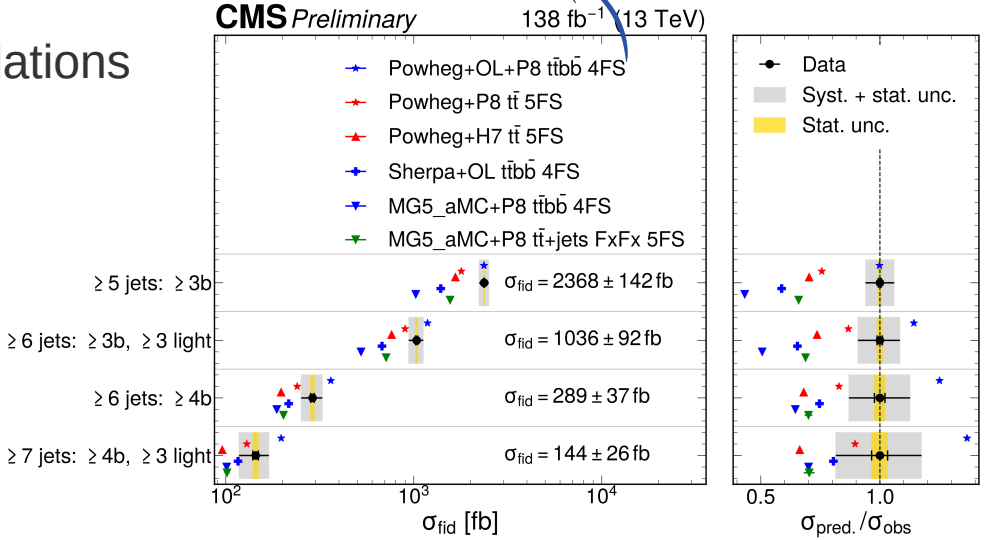
Inclusive and differential $t\bar{t}b\bar{b}$

CMS PAS TOP-22-009

- Challenging to model
  - Important test for pQCD and PS calculations
- Important background to $t\bar{t}H$ and $t\bar{t}t\bar{t}$
- 1ℓ, ≥5 jets, ≥3 b-jets

- Binned maximum likelihood fit
- Inclusive cross section generally **higher** than predicted by ~10-50%

reduced normalization and factorization scale



Most precise measurement of the $t\bar{t}b\bar{b}$ cross section to date!

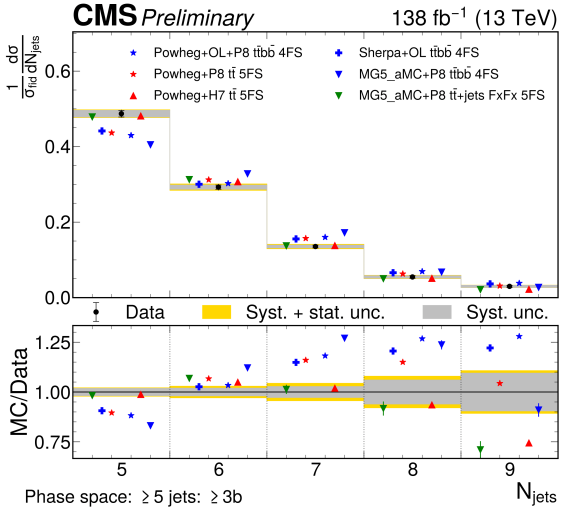
Inclusive and differential $t\bar{t}b\bar{b}$

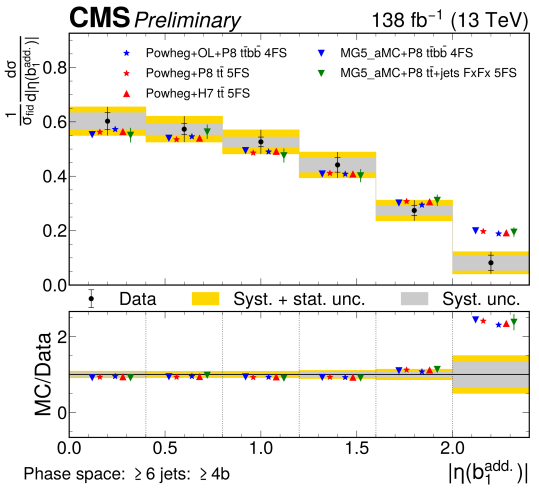
CMS PAS TOP-22-009

- Normalized differential cross sections tested for different generators
- Two classes of observables, depending on bb^{add}
  - no identification
  - MVA algorithm

more accurate, but depends on event generator

- No simulation describes all the distributions properly
  - strongly depends on scale and shower tuning



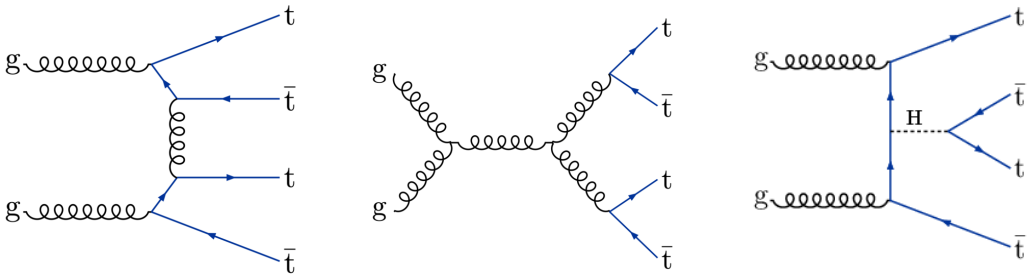


LHCPhysics
Belgrade, 22 - 26 May 2023

Four top quark production

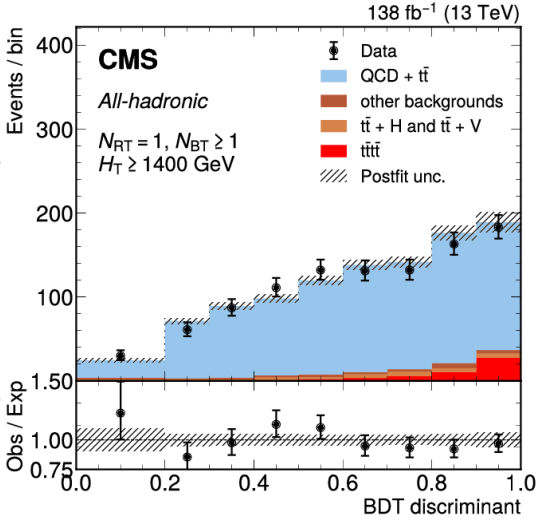
CMS TOP-21-005

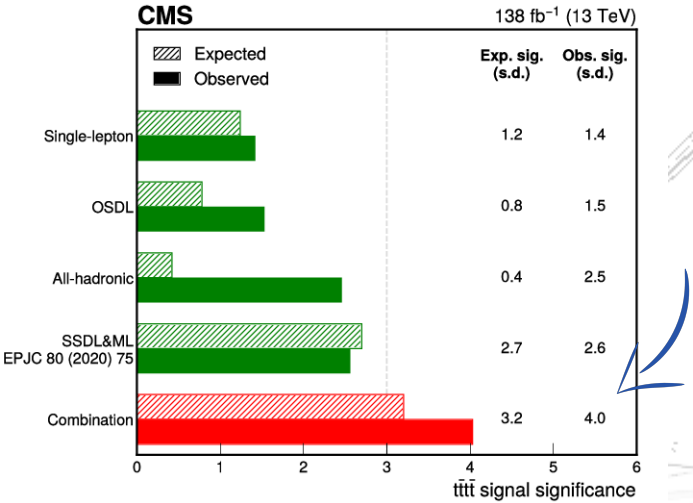
- One of the **rarest** processes of the SM
- Sensitive to top quark Yukawa coupling
- Opens the way to new physics: BSM, SUSY, EFT



- BDT classifier and likelihood fit
- All-hadronic final state included for the first time:

  2.5σ (obs) / 0.4σ (exp)





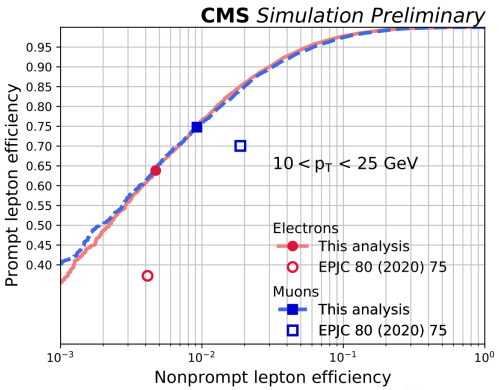
Four top quark production

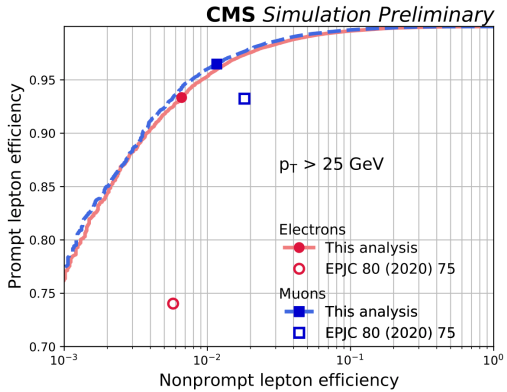
CMS PAS TOP-22-013

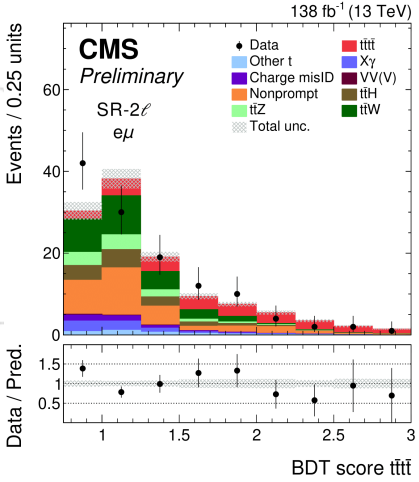
- Optimization of 2020 analysis
  - lepton MVA-based ID → TOP MVA
  - b-tagging algorithm → DeepJet
  - BDT (signal vs background)
- **2ℓ** (same charge), **3ℓ** and **4ℓ** channels
- Observation from CMS:
  5.5σ (obs) / 4.9σ (exp)

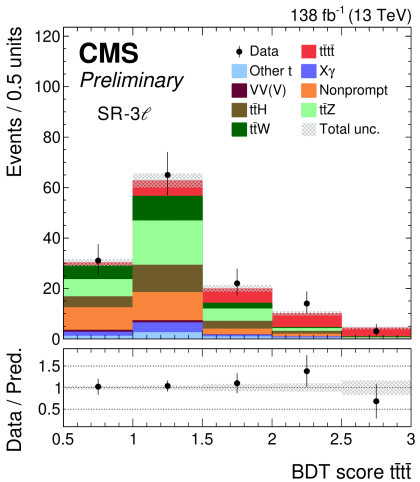
$$\sigma_{t\bar{t}t\bar{t}} = 17.9^{+3.7}_{-3.5}(stat.)^{+2.4}_{-2.1}(syst.)\,fb$$

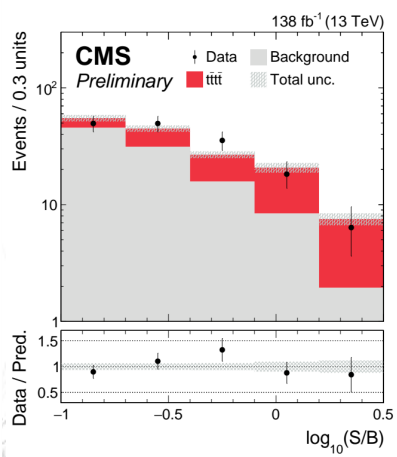
$$\sigma^{th}_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8}\,fb$$











LHCPhysics
Belgrade, 22 - 26 May 2023

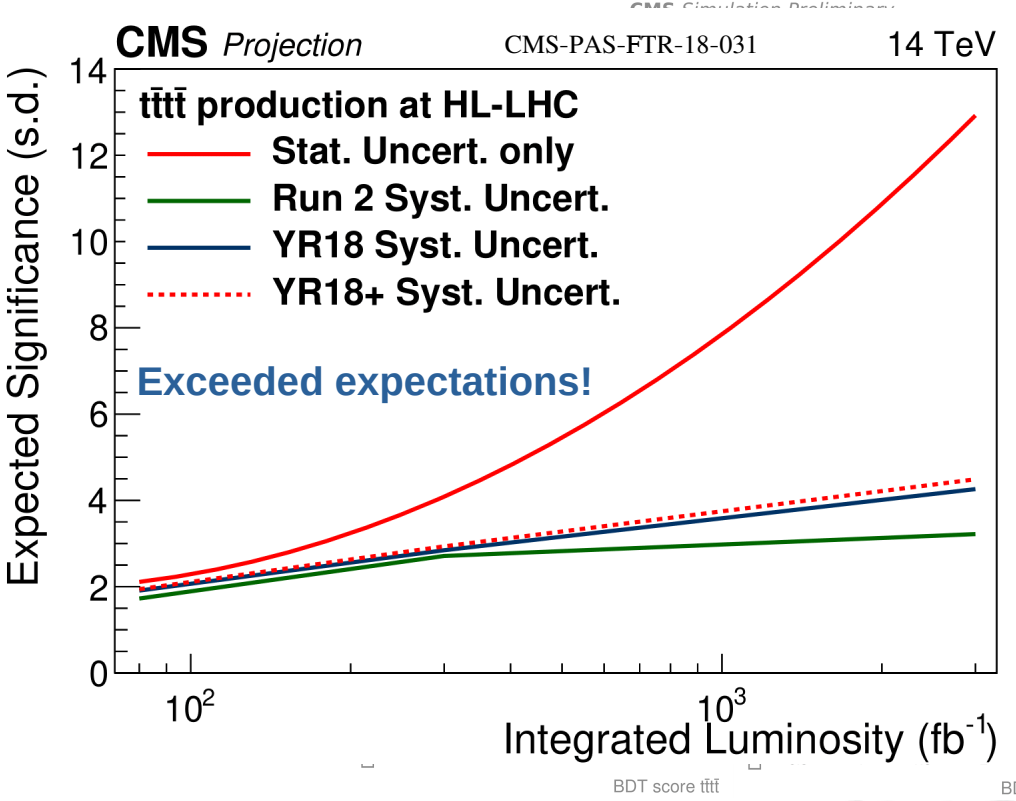
Four top quark production

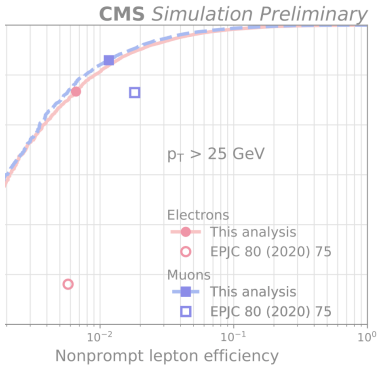
CMS PAS TOP-22-013

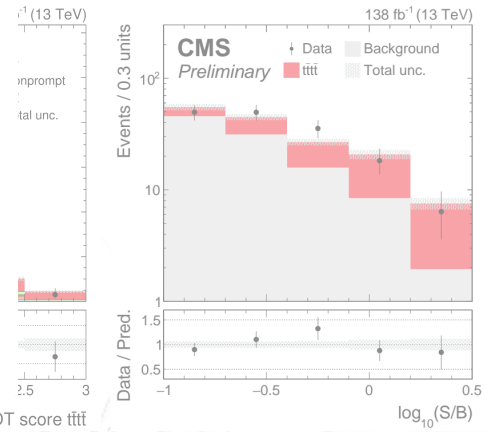
- Optimization of 202
  - lepton MVA-ba
  - b-tagging algor
  - BDT (signal vs
- **2ℓ** (same sign), **3ℓ**
- Observation from C
  5.5σ (obs) / 4.9σ (

$$\sigma_{t\bar{t}t\bar{t}} = 17.9^{+3.7}_{-3.5}(stat.$$

$$\sigma^{th}_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.}$$

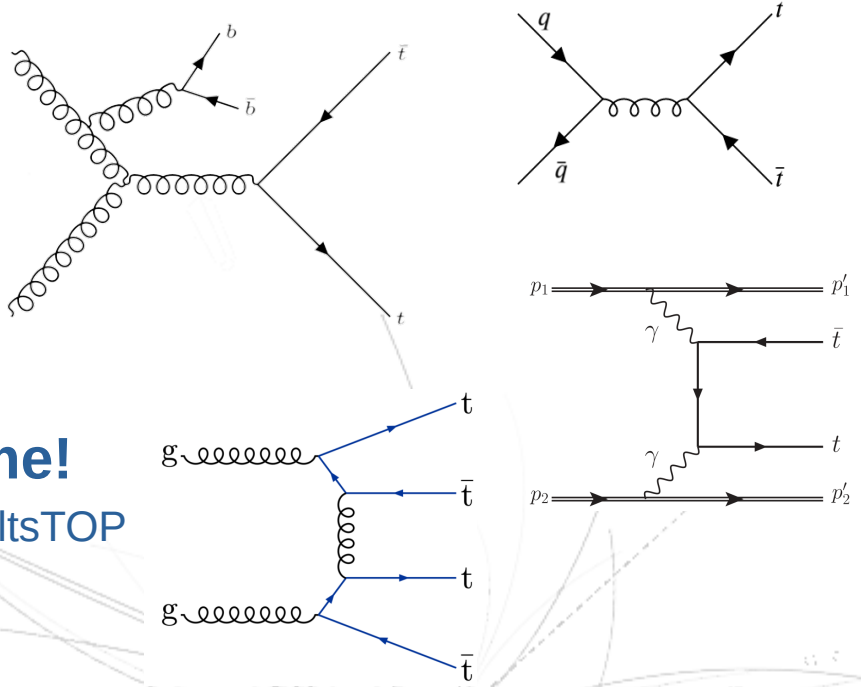






Summary

- After almost 30 years, top quark physics still offers **unique** opportunities:
  - modeling of theory prediction
  - test of SM
  - search for new physics
- Many new results at **13** and **13.6 TeV**
  - precision measurements ($t\bar{t}$, $t\bar{t}$+jets)
  - rare processes (exclusive $t\bar{t}$, 4-top)

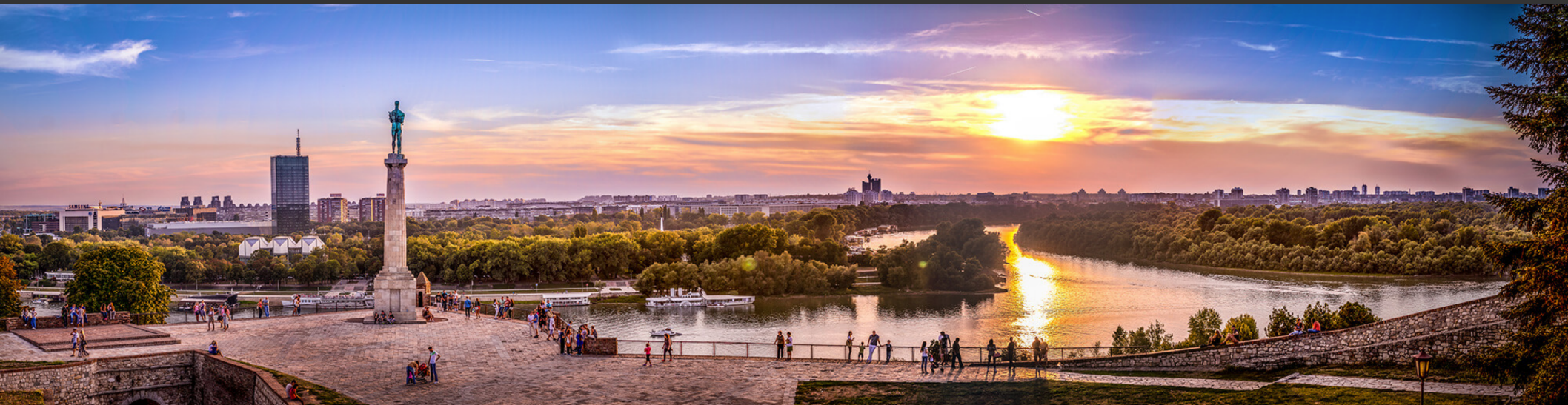


Run-3 has started, the best is yet to come!

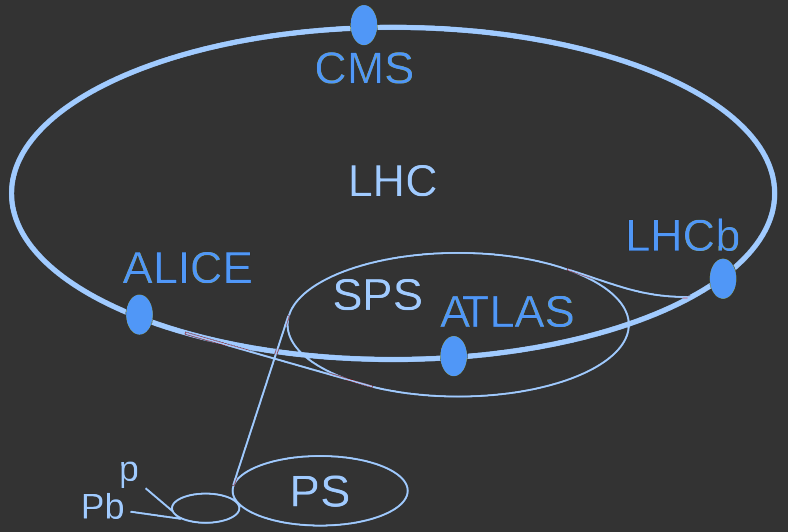
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

LHCPhysics
Belgrade, 22 - 26 May 2023

Thank you !



Backup

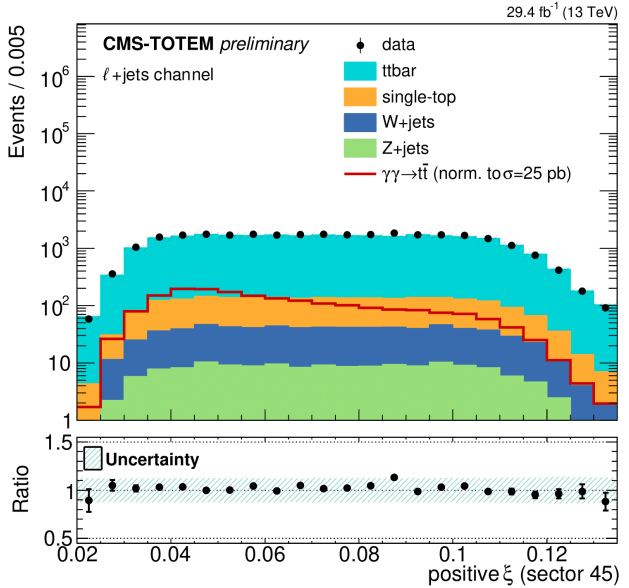


Exclusive $t\bar{t}$ production

CMS PAS TOP-21-007

multi-track inefficiency >50%

- Proton reconstruction efficiency affected by strip and pixel detecotrs efficiency, acceptance and reconstruction algorithm
- **Pileup protons** estimated from data: region (*pool*) with no b- and proton-tag requirements
  - probability of having protons P(0,0), P(1,0), P(1,0), P(2,2) estimated
  - bkg (MC, SR): proton pair added from pool and P(2,2) added as weight
  - signal (MC, SR): if reco protons are missing, taken from pool with probability as weight



$$\xi = (|\vec{p}_i| - |\vec{p}_f|)/|\vec{p}_i|$$

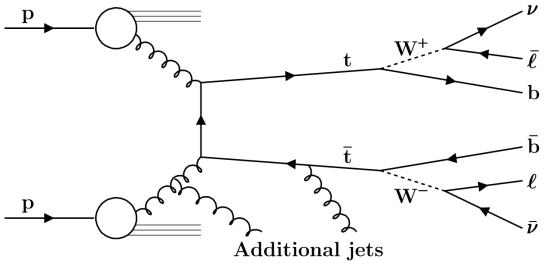
LHCPhysics
Belgrade, 22 - 26 May 2023

Differential $t\bar{t}$+jets cross section

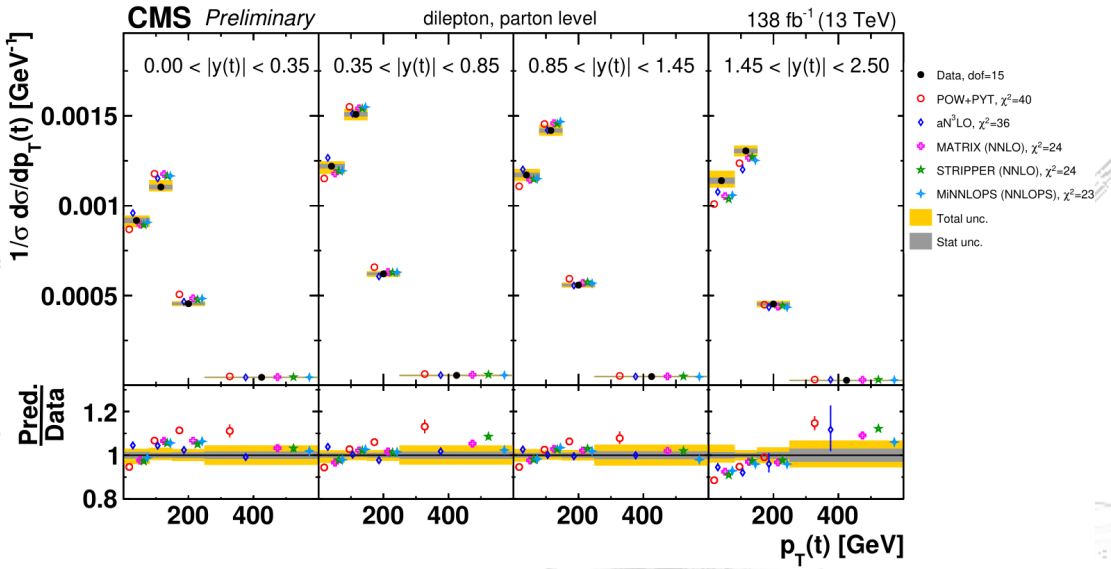
CMS PAS TOP-20-006

- $t\bar{t}$ and $t\bar{t}$+jets, useful test for
  - pQCD
  - BSM
- 2ℓ final states (e/μ)

- Many (N)NLO MC generators predict **harder p_T spectra** than seen in data
- Jet multiplicity-dependent **shape differences** between data and models



multi-differential measurements



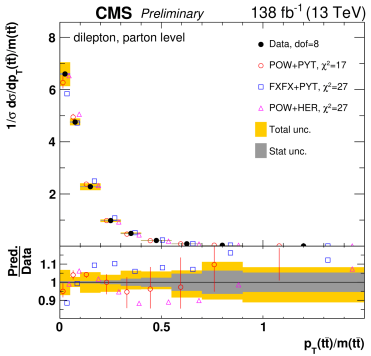
LHCPhysics
Belgrade, 22 - 26 May 2023

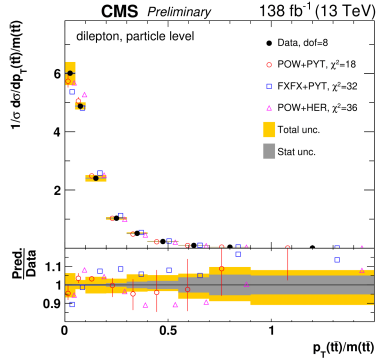
Differential $t\bar{t}$+jets cross section

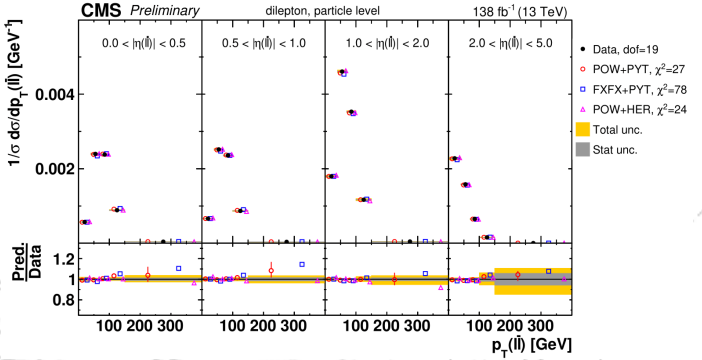
CMS PAS TOP-20-006

- Improvements from previous analyses:
  - new observables
  - refined binnings
  - extended phase space
  - reduced uncertainties

- Measurements performed at parton and particle level
- Stronger disagreement in multi-differential measurements







LHCPhysics
Belgrade, 22 - 26 May 2023

Inclusive and differential $t\bar{t}b\bar{b}$

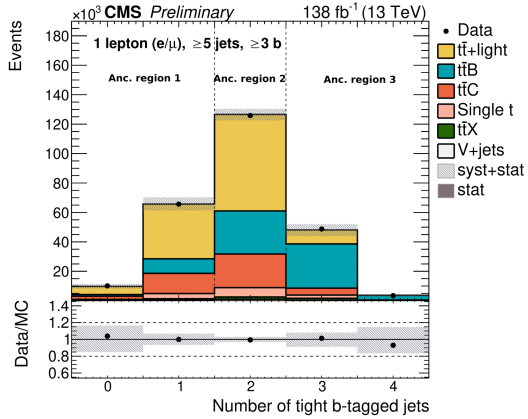
CMS PAS TOP-22-009

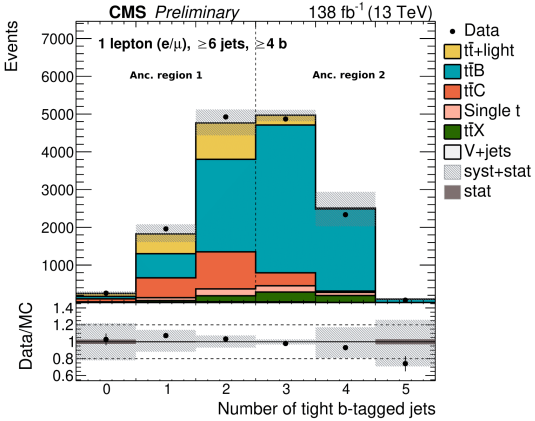
- Fiducial phase space regions:
  - 5j3b → $t\bar{t}b$
  - 6j4b → $t\bar{t}b\bar{b}$
  - 5j3b → $t\bar{t}bj$
  - 6j4b → $t\bar{t}b\bar{b}j$

  additional light jets
- "extra" b jets defined as pair of b-jets with smallest

$$\Delta R_{bb} = \sqrt{(\Delta \phi_{bb})^2 + (\Delta \eta_{bb})^2}$$

- Additional b-jets defined in 6j4b region
- Main unc. (inclusive): b-tag, JES, renormalization sclale
- Differential measurement dominated by stat. unc.





LHCPhysics
Belgrade, 22 - 26 May 2023

Four top quark production

CMS TOP-21-005

- Sensitivity dominated by statistical unc., $t\bar{t}H$ cross section and $t\bar{t}$+heavy-jets modeling

Analysis	Signal strength (μ)			Cross section (fb)			Significance (s.d.)	
		(stat.)	(syst.)		(stat.)	(syst.)	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