

Top quark charcuterie:

A sampler plate of recent cross section measurements involving the production of top quarks at the CMS experiment



FPD Seminar @ SLAC
29.10.2024

Evan Altair Ranken.



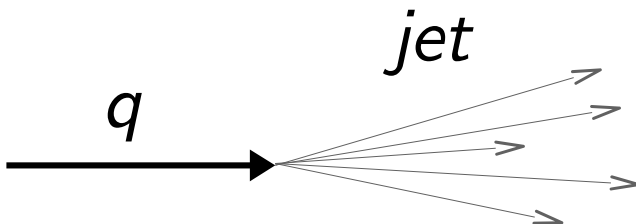
- ♦ *Aperetif:* Who ordered top quarks?
 - ♦ What are they?
 - ♦ How are they produced?
 - ♦ Why study them at the LHC?
- ♦ *Menu:* An assortment of top cross section measurements
 - ♦ Top pair production at 13.6 TeV and 5 TeV
 - ♦ Top + W production at 13.6 TeV
 - ♦ Top pair production: invisible component
- ♦ *Digestif:* A brief word about the future

Top quarks: intro

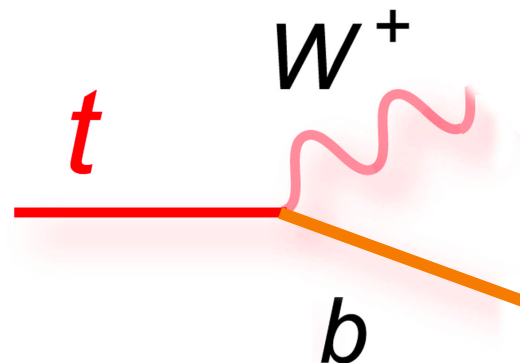
- ◆ **Heaviest** known fundamental particle with mass $m_{\text{top}} = 172.5 \text{ GeV}$
 - ◆ Only quark which decays **before** hadronizing
 - ◆ Most direct experimental access to quark properties



Other quarks

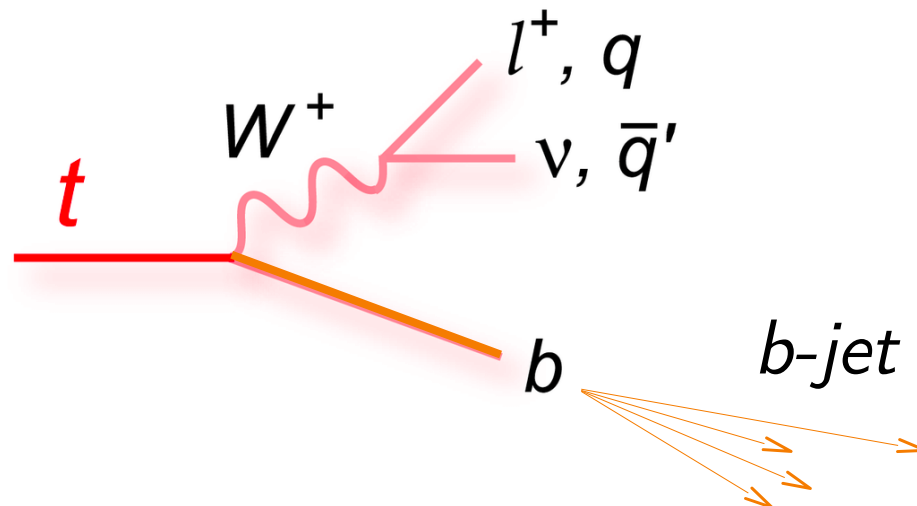


Top quark



Decays to W boson and b quark with >99% reliability

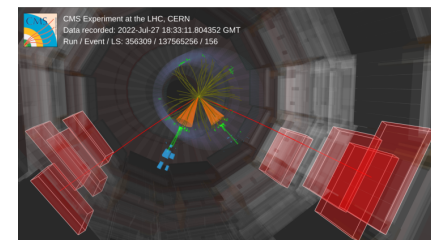
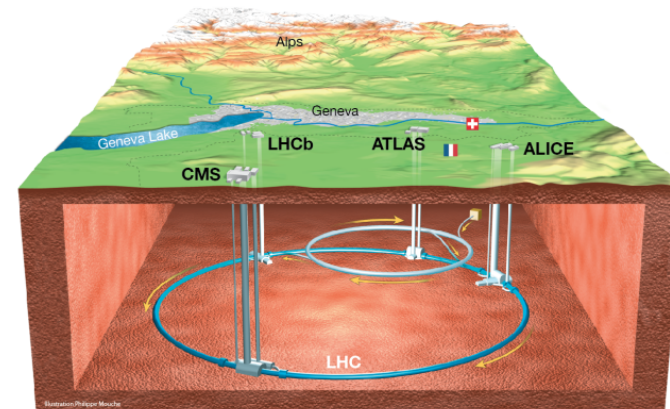
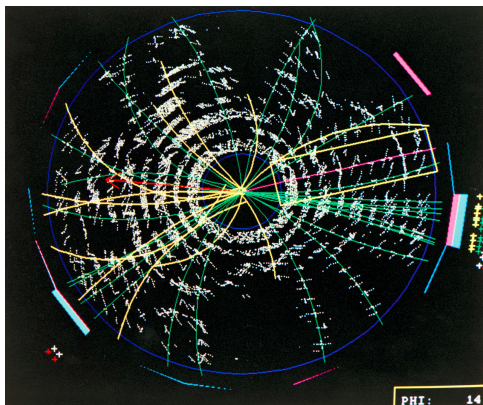
- ◇ **W boson** can decay into quarks or a lepton and neutrino
- ◇ **b-quark** hadronizes, forming a b-jet



Top quarks: new in town

First observed at the **Tevatron** in 1995

- ◇ $p\bar{p}$ collisions at center of mass energy $\sqrt{s} = 1.96 \text{ TeV}$
- ◇ Limited measurements possible



Now, the **LHC** has become a **top factory**

The only place in the world where top quarks can be produced + studied

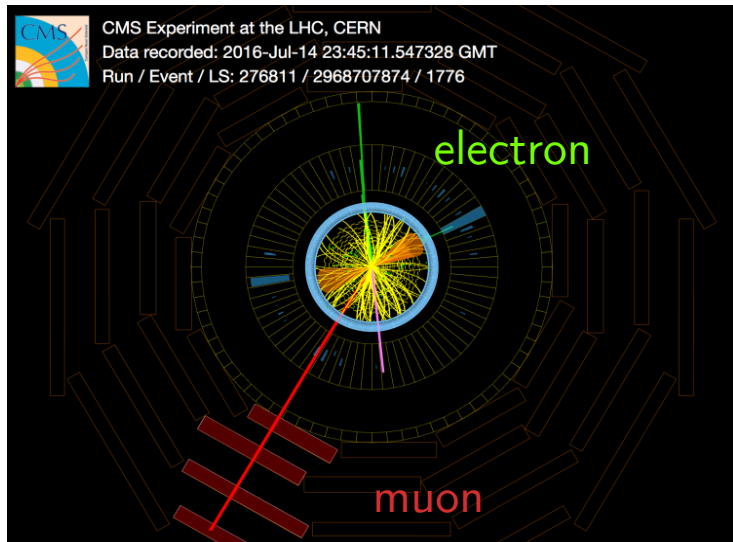
Many precision measurements possible!

Top quark experimental signatures



leptons from top quark decays have
high transverse momentum (p_T)

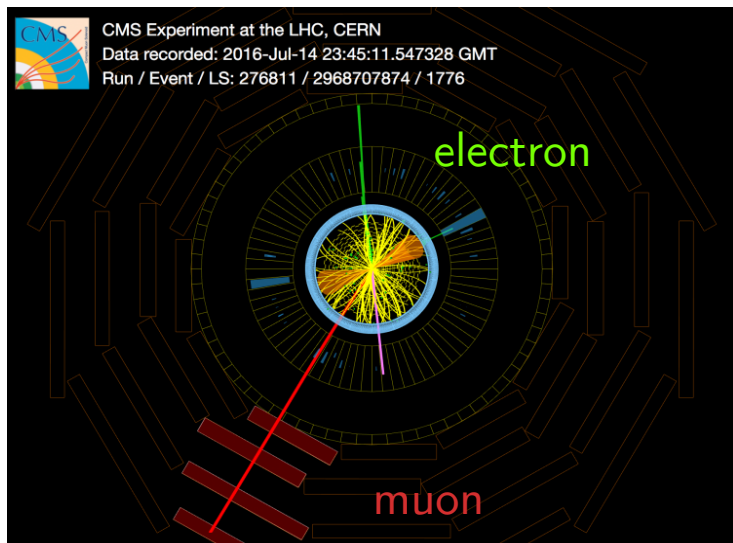
Easy to ID and reconstruct in detector



Top quark experimental signatures

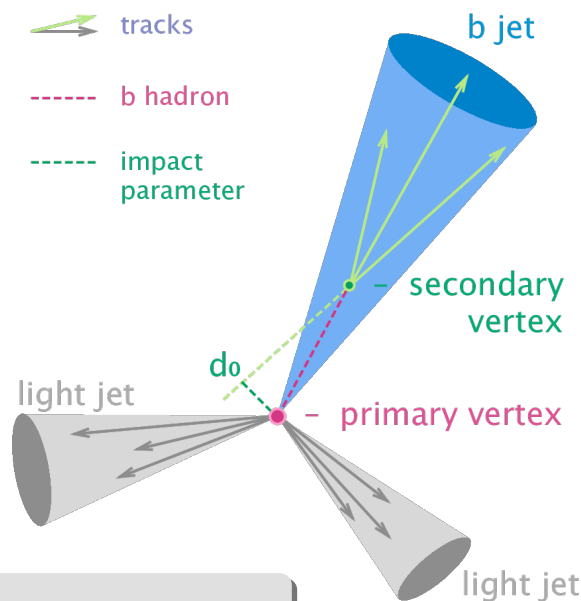
leptons from top quark decays have
high transverse momentum (p_T)

Easy to ID and reconstruct in detector



b-jets spawn a b-hadron which travels a bit
before further hadronization

Can be distinguished from other jets b-tagging



presence of **additional light jets**

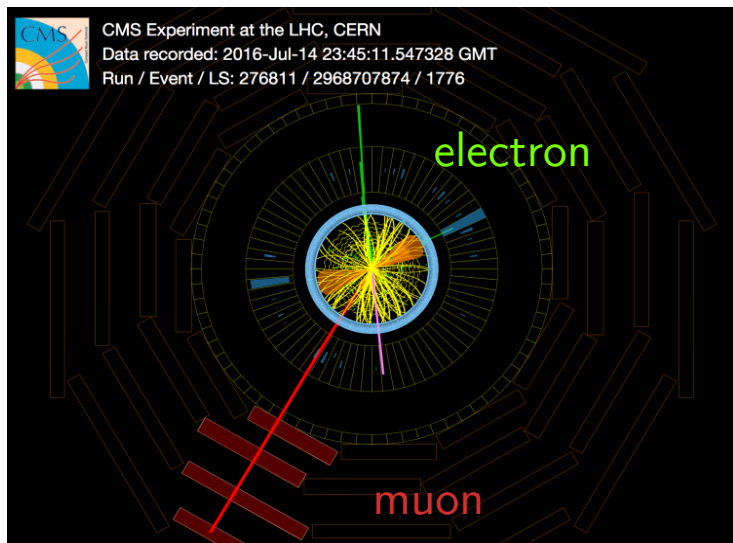
Top quark experimental signatures

leptons from top quark decays have
high transverse momentum (p_T)

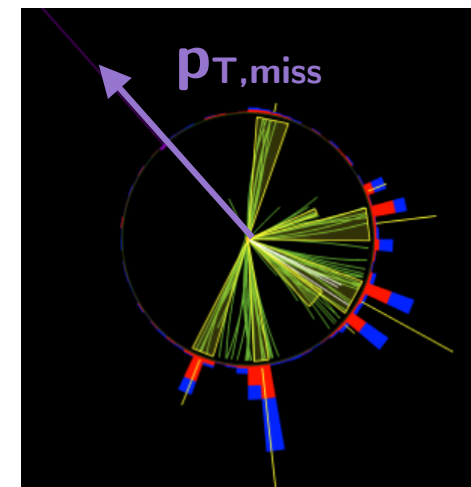
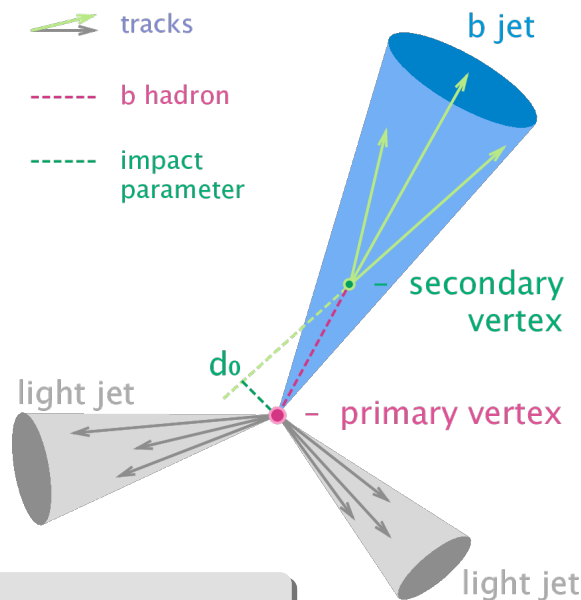
Easy to ID and reconstruct in detector

b-jets spawn a b-hadron which travels a bit
before further hadronization

Can be distinguished from other jets b-tagging



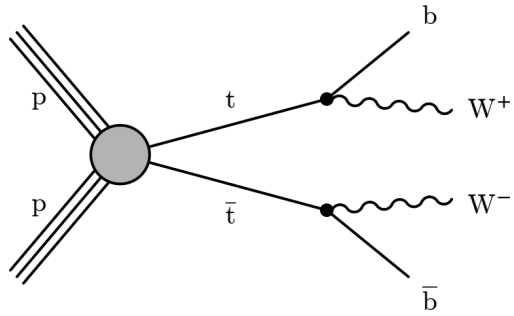
presence of **additional light jets**



transverse momentum
imbalance from ν

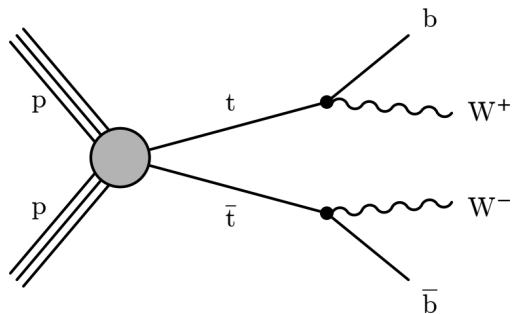
Top quark production modes

At the LHC most common production mechanism is top quark anti-quark pairs:



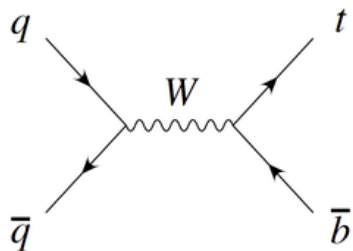
Top quark production modes

At the LHC most common production mechanism is top quark anti-quark pairs:

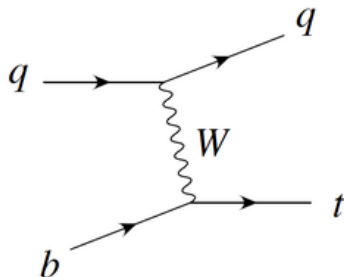


Single top quark production modes:

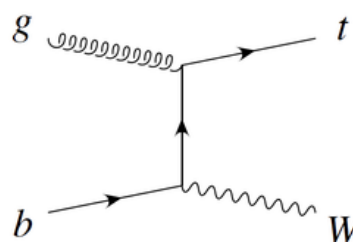
s-channel



t-channel

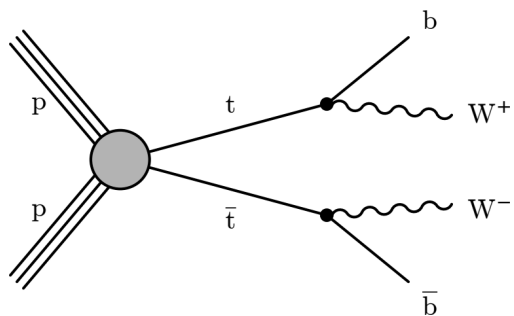


tW production



Top quark production modes

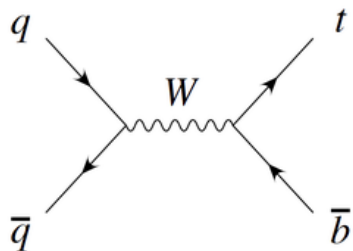
At the LHC most common production mechanism is top quark anti-quark pairs:



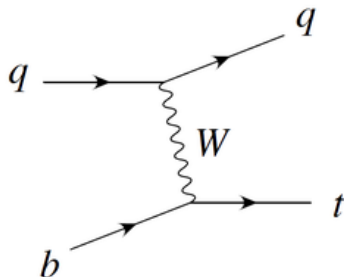
...and many other associated modes $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, tH , tWZ , $t\bar{t}t\bar{t}$...

Single top quark production modes:

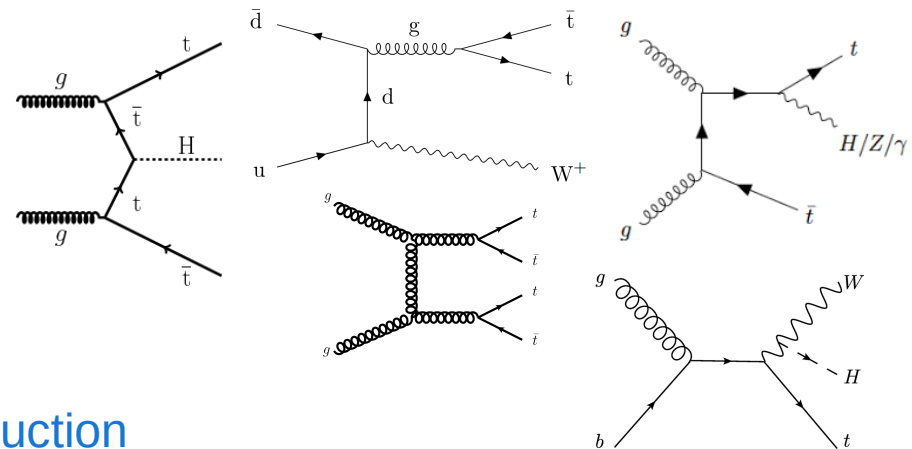
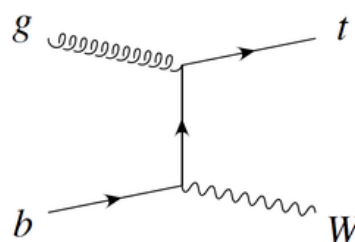
s-channel



t-channel



tW production



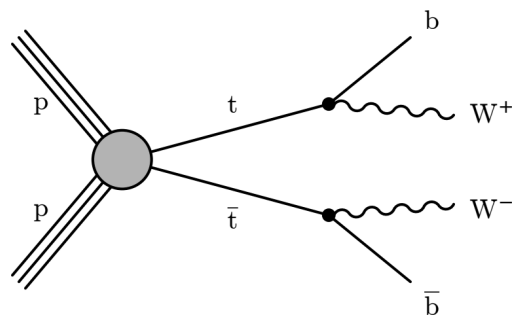
- ♦ Often the first and simplest thing to measure in high-energy particle physics
- ♦ Units of area – @LHC often measured in **picobarns**
- ♦ The master formula:

$$N_{\text{events}} = \underbrace{\mathcal{L}_{\text{int}}}_{\substack{\text{Integrated luminosity} \\ [\text{fb}^{-1}]}} \cdot \underbrace{\sigma(\text{process})}_{\substack{\text{cross section} \\ [\text{pb}]}}$$

- ♦ Intuitively, σ gives the *rate of production* of a physics process (under fixed collision rate)

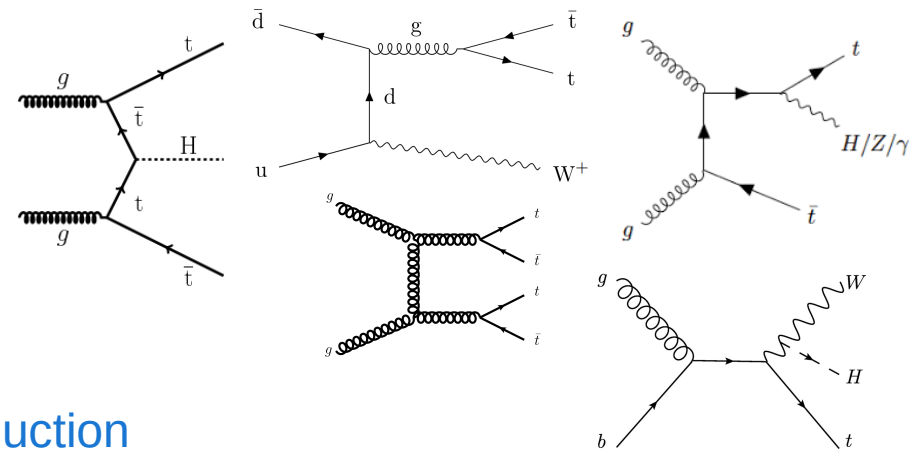
Top quark production modes

At the LHC most common production mechanism is top quark anti-quark pairs:



@13 TeV:
 $\sigma = 834 \text{ pb}$

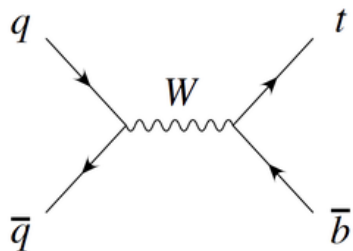
...and many other associated modes $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, tH , tWZ , $t\bar{t}t\bar{t}$...



$\sigma \lesssim 1 \text{ pb}$

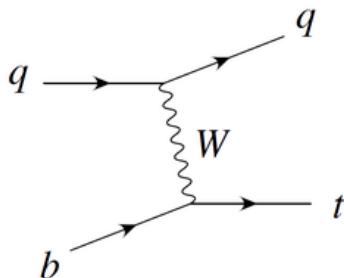
Single top quark production modes:

s-channel



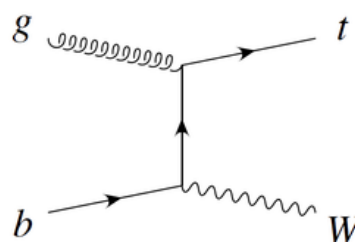
$\sigma = 11 \text{ pb}$

t-channel



$\sigma = 214 \text{ pb}$

tW production



$\sigma = 79 \text{ pb}$

Whats going on at the LHC?



CMS has been collecting LHC proton-proton collision data since 2010 at various center of mass energies ($\sqrt{s}$)

◇ **Run 1: 2010 – 2012**

6 fb⁻¹ at $\sqrt{s}$ = 7 TeV

23 fb⁻¹ at $\sqrt{s}$ = 8 TeV

◇ **Run 2: 2015 – 2012**

160 fb⁻¹ at $\sqrt{s}$ = 13 TeV

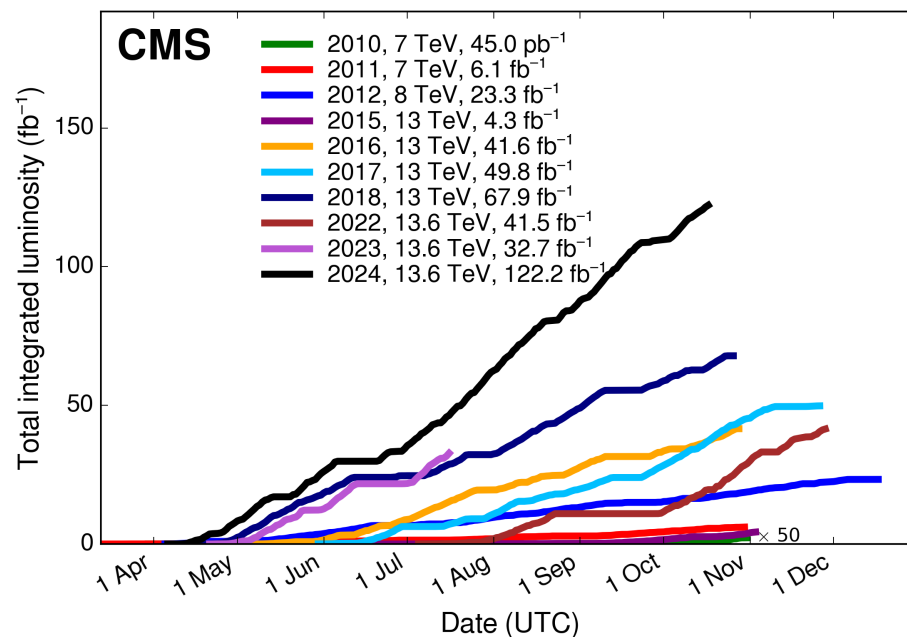
302 pb⁻¹ at $\sqrt{s}$ = 5 TeV

◇ **Run 3: 2022 – ongoing (2026)**

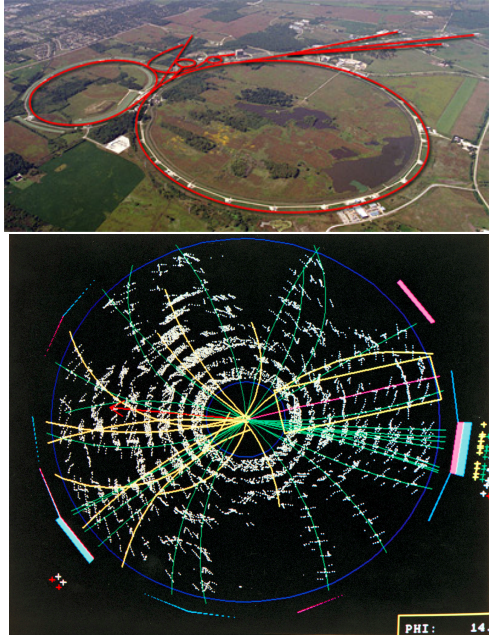
196 fb⁻¹ at $\sqrt{s}$ = 13.6 TeV

...as of two weeks ago!

still in early stages of analysis

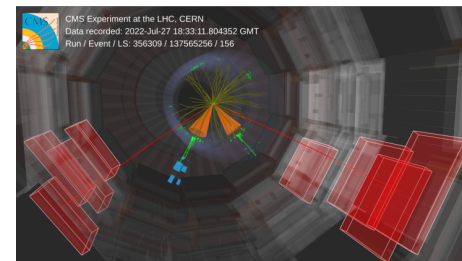
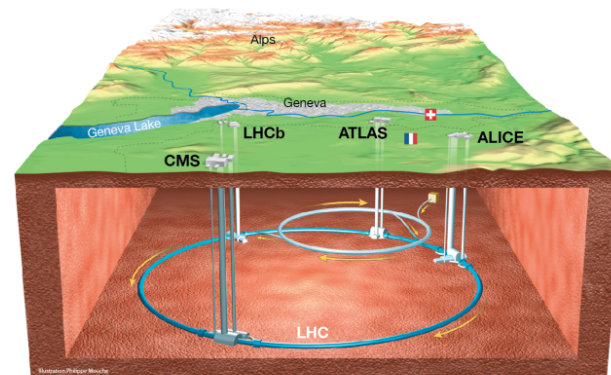
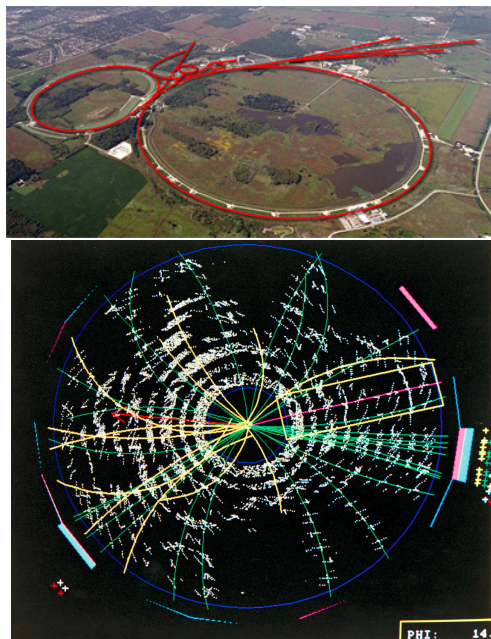


The LHC: a top quark factory



The Tevatron experiments recorded
about 10 fb^{-1} of int. luminosity:
 $\sim 75\,000$ top quark pairs produced

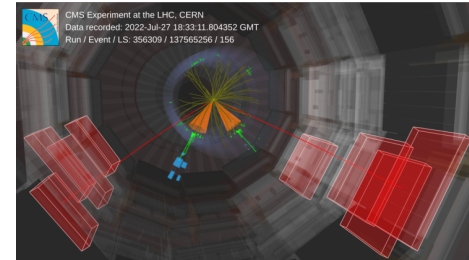
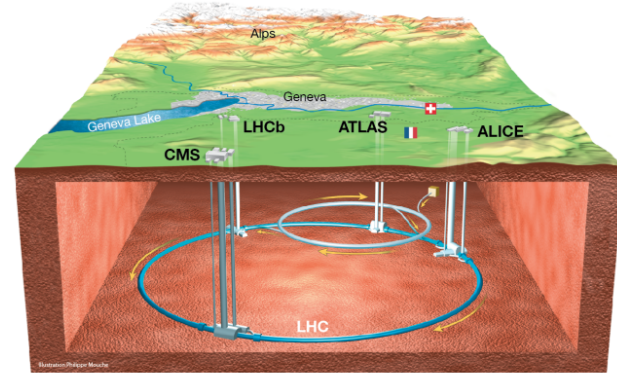
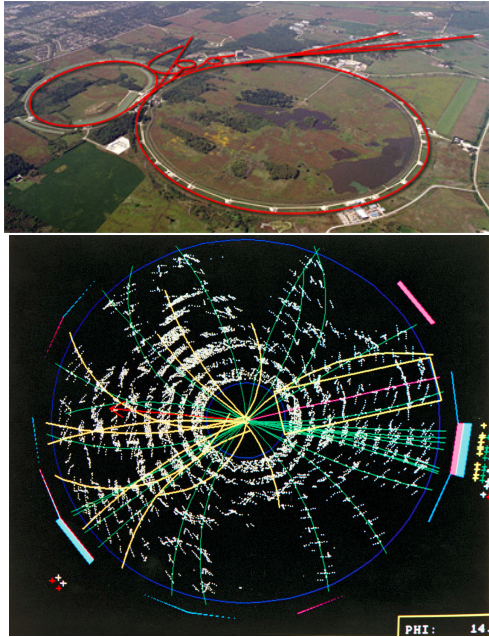
The LHC: a top quark factory



The Tevatron experiments recorded
about 10 fb^{-1} of int. luminosity:
~75 000 top quark pairs produced

At the CMS experiment,
over 100 000 000 top quark pairs
have been produced...

The LHC: a top quark factory



The Tevatron experiments recorded
about 10 fb^{-1} of int. luminosity:
~75 000 top quark pairs produced

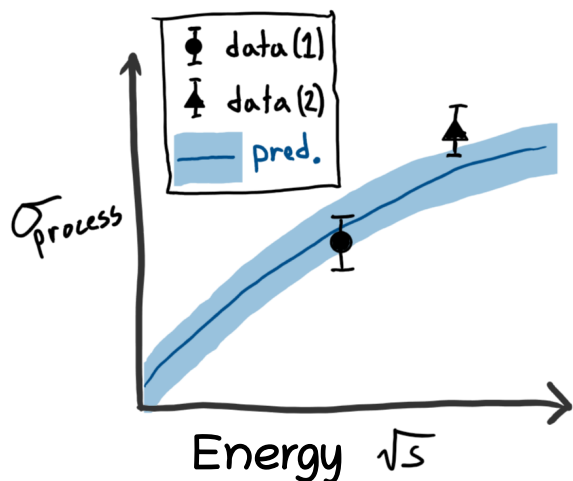
At the CMS experiment,
over 100 000 000 top quark pairs
have been produced... **this year**

Inclusive cross sections

- ◆ Overall “rate” of a process
- ◆ Precise measurements and comparison to prediction
- ◆ Varies with c.m. energy:

$\sqrt{s}$: 5 TeV $\rightarrow$ 13.6 TeV

$\sigma_{pp \rightarrow t\bar{t}}$: 69 pb $\rightarrow$ 924 pb

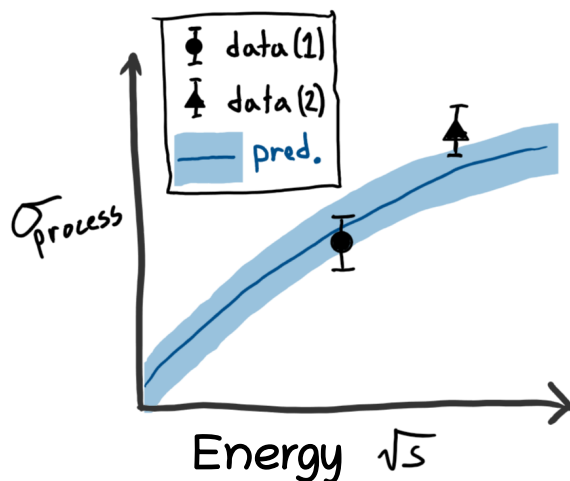


Inclusive cross sections

- ◆ Overall “rate” of a process
- ◆ Precise measurements and comparison to prediction
- ◆ Varies with c.m. energy:

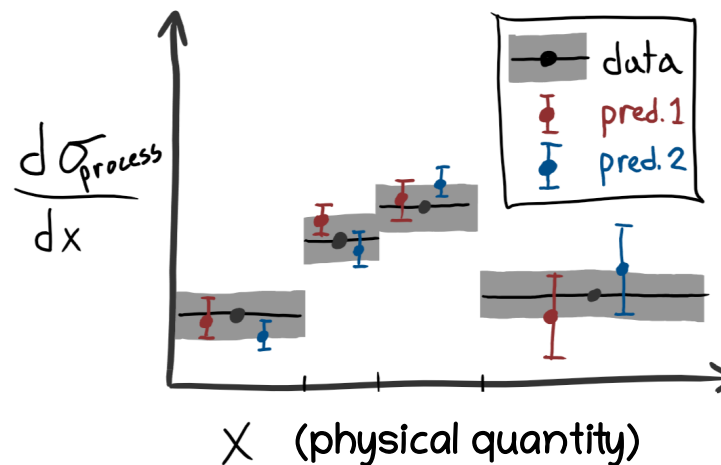
$\sqrt{s}$: 5 TeV $\rightarrow$ 13.6 TeV

$\sigma_{pp \rightarrow t\bar{t}}$: 69 pb $\rightarrow$ 924 pb



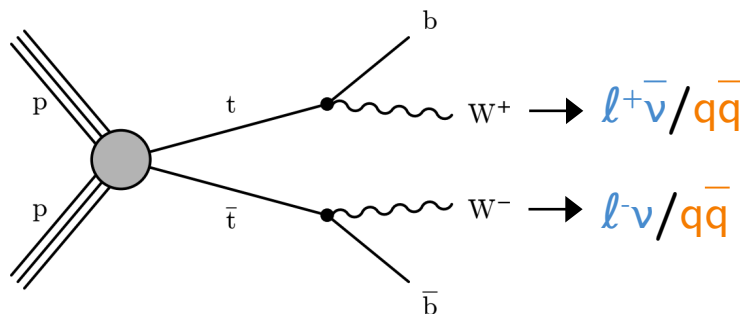
Differential cross sections

- ◆ $d\sigma_{t\bar{t}}/dx$: probe dependence on some variable “x”
- ◆ Detailed examination of SM and BSM predictions
- ◆ Many possible measurements, including parameter extraction



Top quarks come in pairs

- ◆ Top quark pair production has different final states



$t\bar{t}$ final state characterized by
leptons from W decays:
dilepton / lepton(ℓ)+jets / all hadronic

- ◆ Leaves distinct signatures:
 - ◆ **dilepton**: 2 high- p_T leptons, 2 heavy b-flavor jets ***cleanest channel***
 - ◆ **lepton+jets**: 1 high- p_T lepton, 2 heavy flavor jets, additional jets
 - ◆ **all hadronic**: all jets $\rightarrow$ top taggers, boosted regime

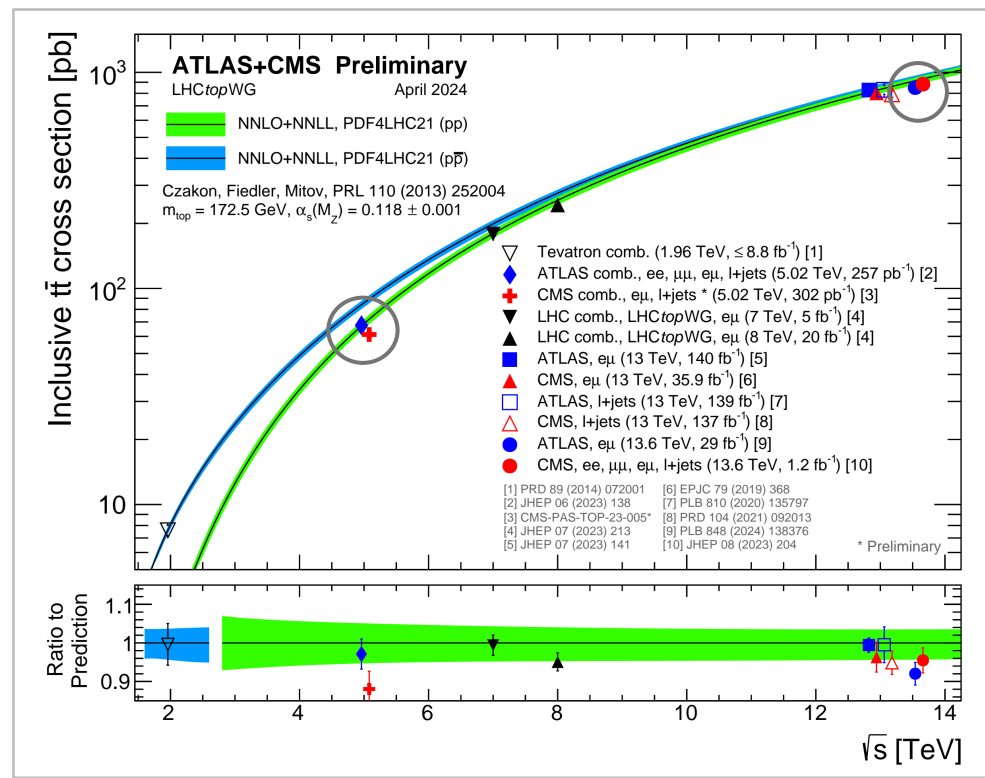
- ♦ *Aperetif:* Who ordered top quarks?
 - ♦ What are they?
 - ♦ How are they produced?
 - ♦ Why study them at the LHC?
- ♦ *Menu:* an assortment of top cross section measurements
 - ♦ Top pair production at 13.6 TeV and 5 TeV
 - ♦ Top + W production at 13.6 TeV
 - ♦ Top pair production: invisible component
- ♦ *Digestif:* A brief word about the future

Top quark pair production

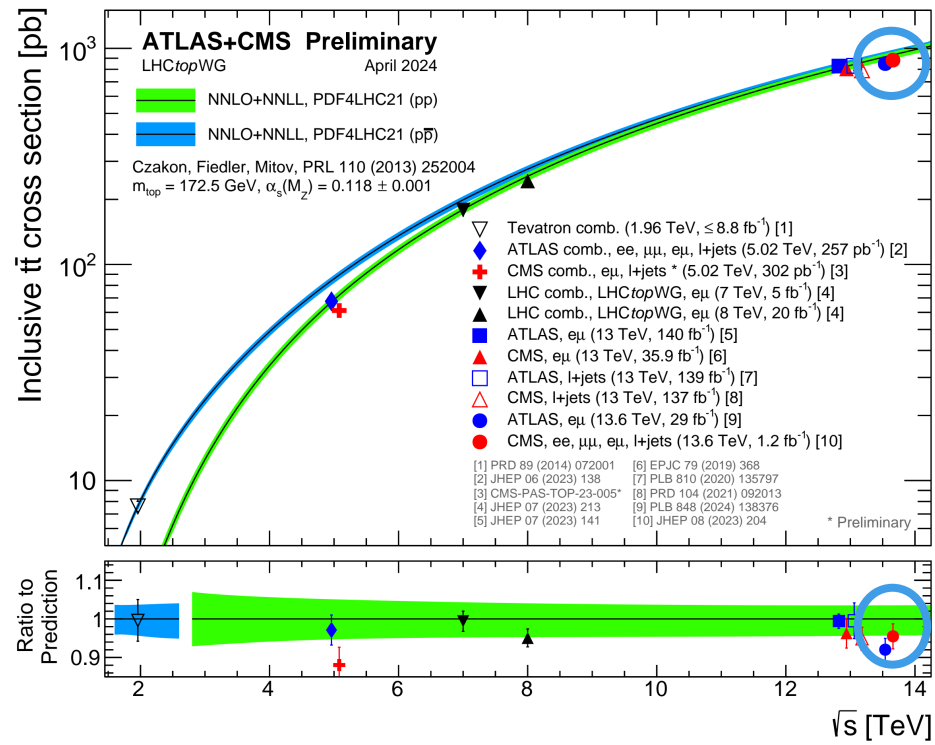


Recent inclusive results at the highest and lowest LHC energies

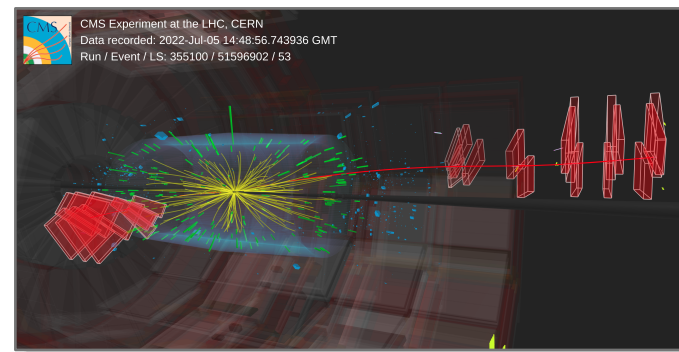
- ◆ $\sigma_{t\bar{t}}$ measured at **6 energies ever**, now **5 energies at LHC** experiments
- ◆ **@13.6 TeV**
 - ◇ CMS provided first physics measurement published in LHC Run 3
- ◆ **@ 5.02 TeV**
 - ◇ Recent update to measurement from special LHC program in 2017 at 5 TeV
 - ◇ Low luminosity: 302 pb^{-1}



Top quark pairs @ 13.6 TeV



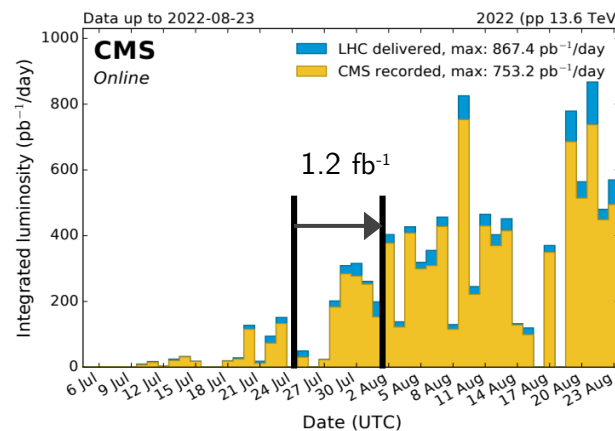
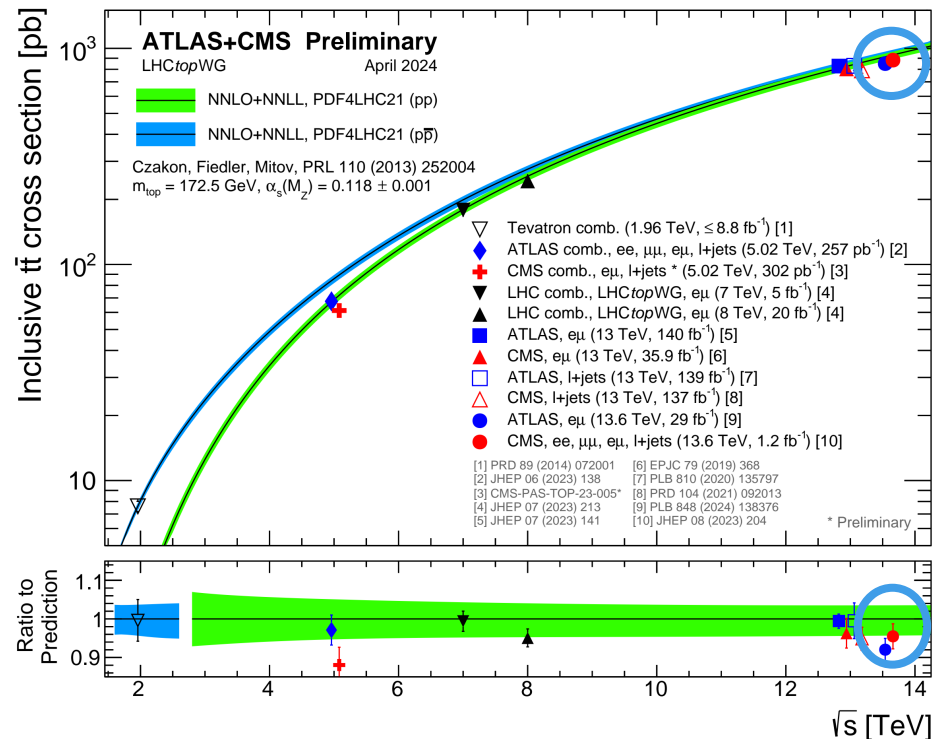
July 5, 2022: stable beams at 13.6 TeV



Top quark pairs @ 13.6 TeV



Prompt measurement using $\sim 1 \text{ fb}^{-1}$ of data from early weeks of 2022 data-taking



Channel Combination

$e\mu$, $e\bar{e}$, $\mu\mu$, e +jets, μ +jets

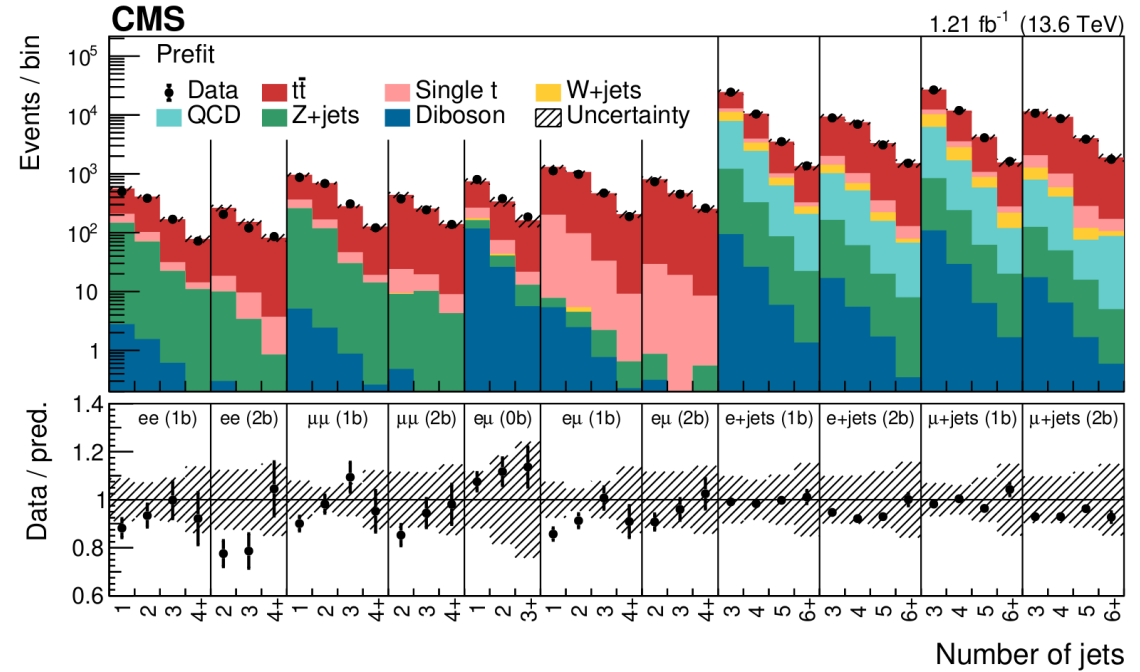
→ use information from multiple channels to constrain nuisance parameters *in-situ*

Inclusive cross section @ 13.6 TeV



◆ Bins:

- Lepton flavor
 - └► b-jet multiplicity
 - └► Jet multiplicity



Inclusive cross section @ 13.6 TeV



- ◆ **Bins:**

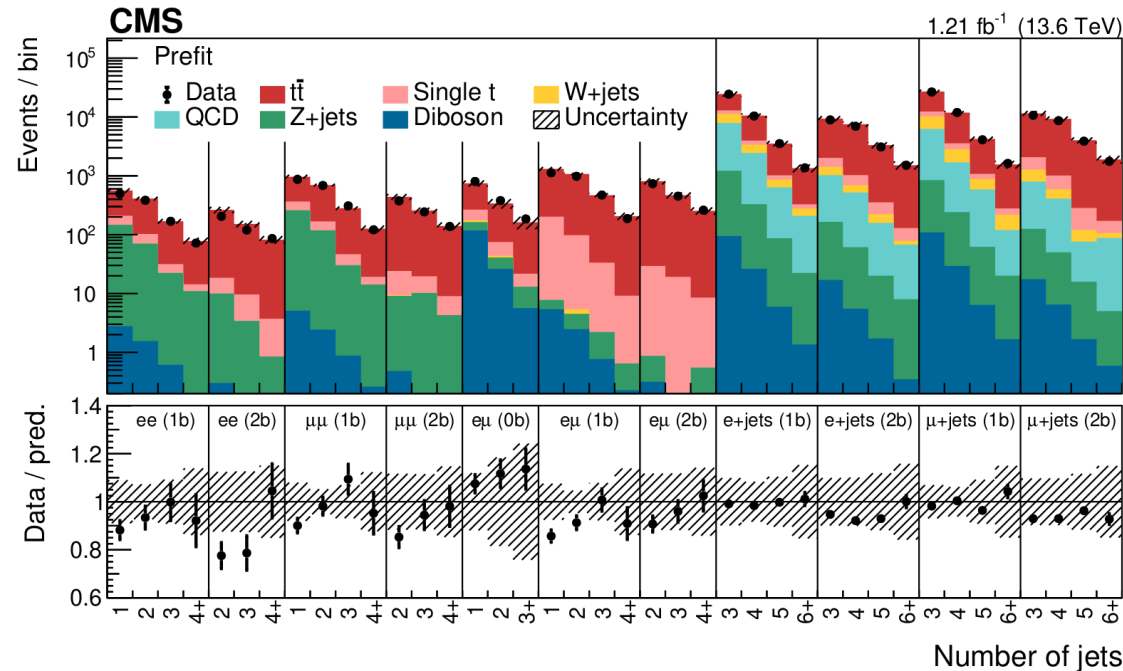
- Lepton flavor

- b-jet multiplicity

- Jet multiplicity

- ◆ **b-tag efficiency** scale factors determined by fit

- ◆ **SM pred.** $\sigma_{t\bar{t}} = 924^{+32}_{-40}\text{pb}$



Inclusive cross section @ 13.6 TeV



- ◆ **Bins:**

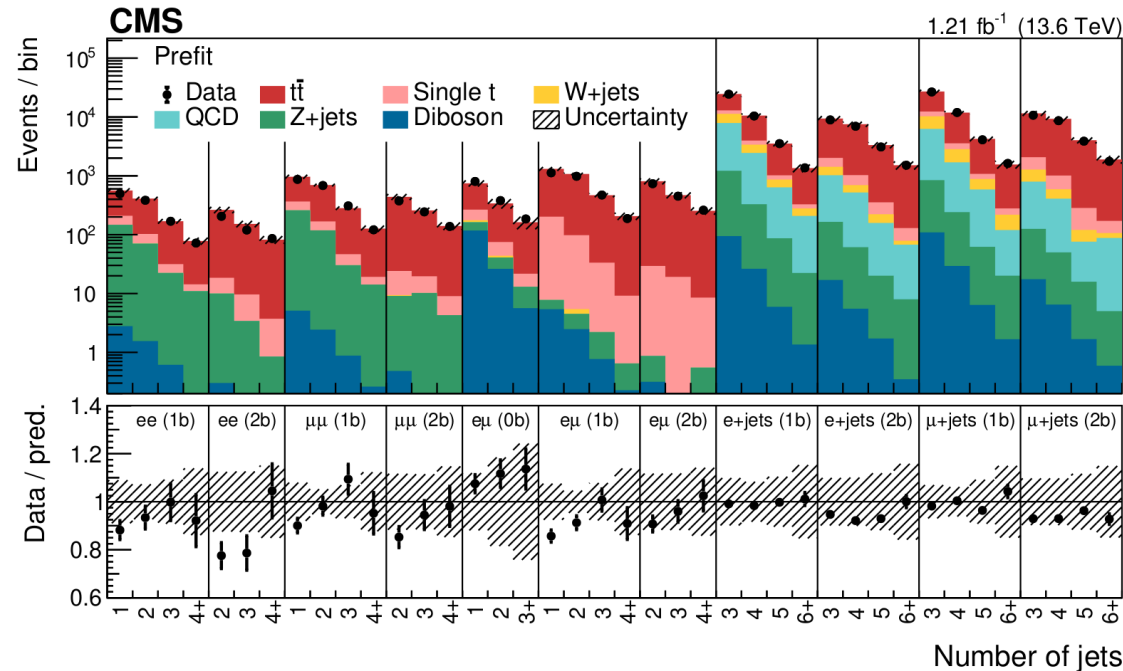
- Lepton flavor

- ↳ b-jet multiplicity

- ↳ Jet multiplicity

- ◆ **b-tag efficiency** scale factors determined by fit

- ◆ **SM pred.** $\sigma_{t\bar{t}} = 924^{+32}_{-40}\text{pb}$



Result [\(JHEP 08 \(2023\) 204\)](#)

$$\sigma_{t\bar{t}} = 881 \pm 23(\text{stat.} + \text{syst.}) \pm 20(\text{lumi.}) \text{ pb}$$

Inclusive cross section @ 13.6 TeV

◆ Bins:

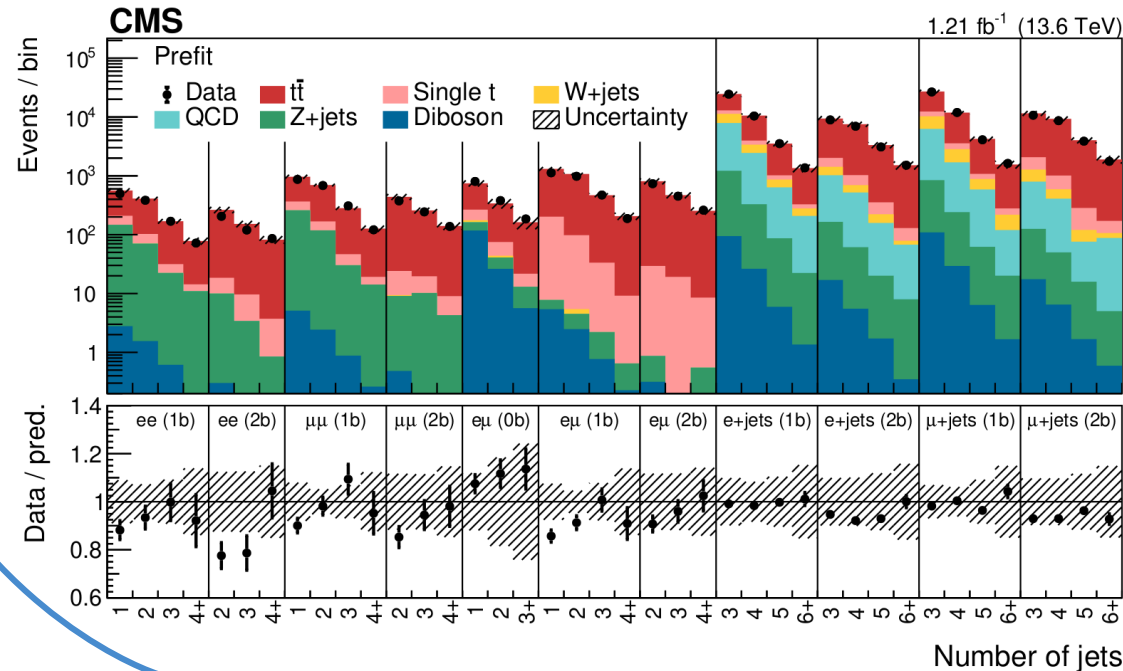
► Lepton flavor

└─► b-jet multiplicity

└─► Jet multiplicity

◆ b-tag efficiency scale factors determined by fit

◆ SM pred. $\sigma_{t\bar{t}} = 924^{+32}_{-40}\text{pb}$



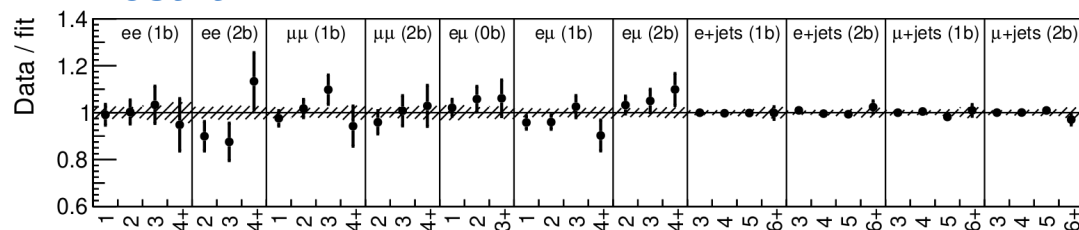
Result (JHEP 08 (2023) 204)

$$\sigma_{t\bar{t}} = 881 \pm 23(\text{stat.} + \text{syst.}) \pm 20(\text{lumi.}) \text{ pb}$$

high-purity cut and count cross-check:

$$\sigma_{t\bar{t}}^{\text{e}\mu\text{-only}} = 888 \pm 34(\text{stat.} + \text{syst.}) \pm 20(\text{lumi.}) \text{ pb}$$

Postfit



Inclusive cross section @ 13.6 TeV



Uncertainty breakdown:

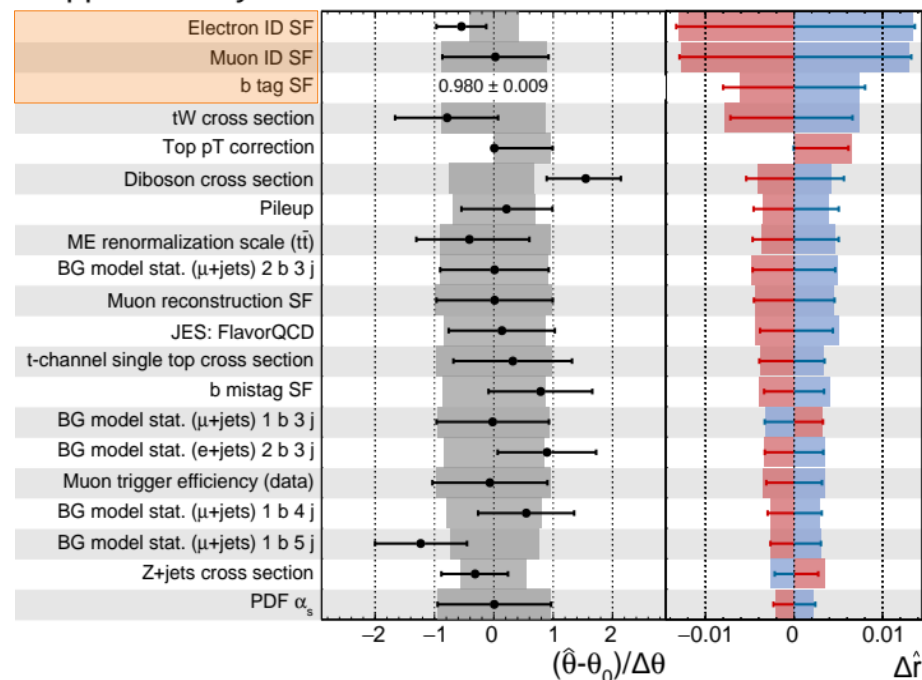
Source	Uncertainty (%)	= Resulting uncertainty in $\sigma_{t\bar{t}}$
Lepton ID efficiencies	1.6	
Trigger efficiency	0.3	
JES	0.6	
b tagging efficiency	1.1	
Pileup reweighting	0.5	
ME scale, $t\bar{t}$	0.5	
ME scale, backgrounds	0.2	
ME/PS matching	0.1	
PS scales	0.3	
PDF and α_s	0.3	
Top quark p_T	0.5	
tW background	0.7	
t -channel single- t background	0.4	
Z+jets background	0.3	
W+jets background	<0.1	
Diboson background	0.6	
QCD multijet background	0.3	
Statistical uncertainty	0.5	
Combined uncertainty	2.5	
Integrated luminosity	2.3	
Total unc. (with lumi.)	3.4	

2 leading uncertainties:
lepton, b-tag eff.

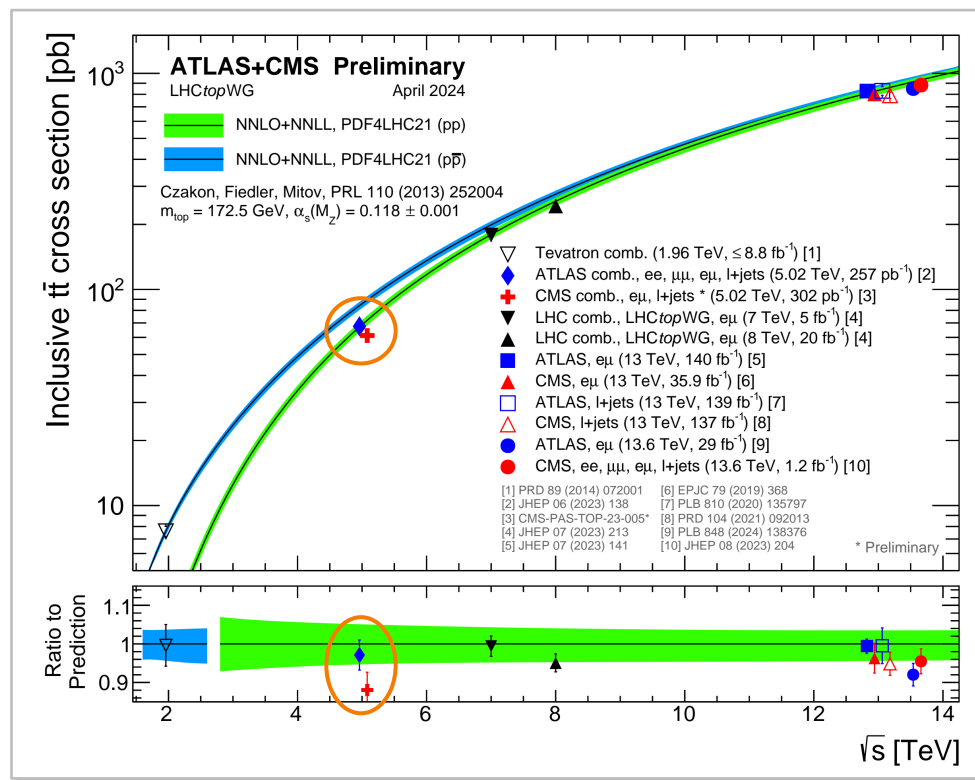
Not statistics limited

Lumi comparable to likelihood stat+syst unc.

CMS $\hat{r} = 0.959 \pm 0.025$



From 13.6 TeV to 5.02 TeV

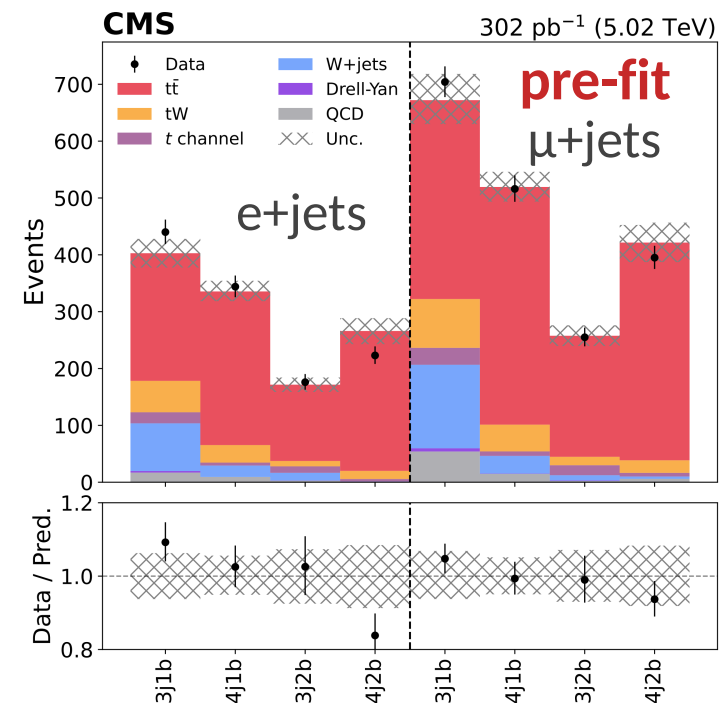


Inclusive cross section @ 5.02 TeV



2017 data @ 5.02 TeV : low pileup, cleaner reconstruction

- ◆ Previous CMS measurements:
 - ◇ 27.4 pb^{-1} (ℓ +jets) [JHEP 03 \(2018\) 115](#)
 - ◇ 302 pb^{-1} (dilepton $e\mu$) [JHEP 04 \(2022\) 144](#)
- ◆ **New** preliminary measurement in ℓ +jets channel with 302 pb^{-1} lumi: [CMS-PAS-TOP-23-005](#)



Signal dominated, range in purity from
~ 60% (3j1b) to >90% (4j2b)

Inclusive cross section @ 5.02 TeV



2017 data @ 5.02 TeV : low pileup, cleaner reconstruction

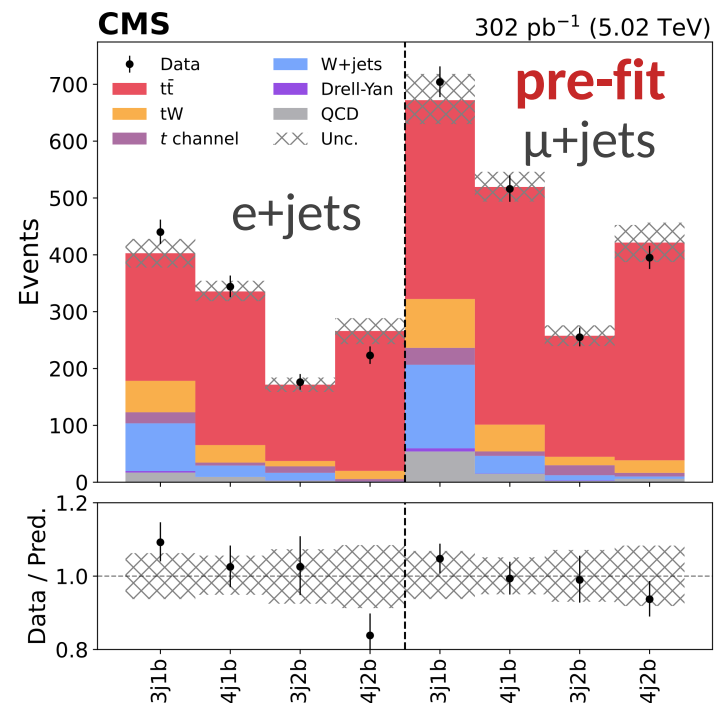
◆ Previous CMS measurements:

- ◆ 27.4 pb^{-1} (ℓ +jets) [JHEP 03 \(2018\) 115](#)
- ◆ 302 pb^{-1} (dilepton $e\mu$) [JHEP 04 \(2022\) 144](#)

- ◆ **New** preliminary measurement in ℓ +jets channel with 302 pb^{-1} lumi: ~~CMS-PAS TOP-23-005~~

→ Submitted last night! ([CMS-TOP-23-005](#) up soon)

- ◆ Exactly **1 lepton**: $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$
- ◆ Opposite flavor lepton veto: $p_T > 10 \text{ GeV}$
- ◆ At least **3 jets**: $p_T > 25 \text{ GeV}$, $|\eta| < 2.4$
- ◆ MET requirement: $|\mathbf{p}_{T,\text{miss}}| > 30 \text{ GeV}$
- ◆ At least **1 b jet**, DeepCSV (~70% efficiency)



Signal dominated, range in purity from ~ 60% (3j1b) to >90% (4j2b)

Inclusive cross section @ 5.02 TeV



2017 data @ 5.02 TeV : low pileup, cleaner reconstruction

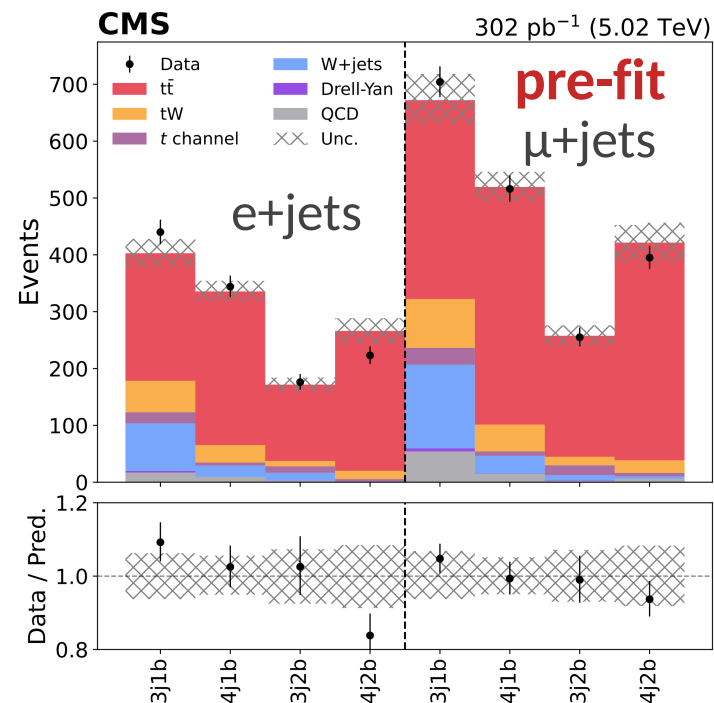
◆ Previous CMS measurements:

- ◆ 27.4 pb^{-1} (ℓ +jets) [JHEP 03 \(2018\) 115](#)
- ◆ 302 pb^{-1} (dilepton $e\mu$) [JHEP 04 \(2022\) 144](#)

- ◆ **New** preliminary measurement in ℓ +jets channel with 302 pb^{-1} lumi: ~~CMS-PAS TOP-23-005~~

→ Submitted last night! ([CMS-TOP-23-005](#) up soon)

- ◆ Exactly **1 lepton**: $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$
- ◆ Opposite flavor lepton veto: $p_T > 10 \text{ GeV}$
- ◆ At least **3 jets**: $p_T > 25 \text{ GeV}$, $|\eta| < 2.4$
- ◆ MET requirement: $|\mathbf{p}_{T,\text{miss}}| > 30 \text{ GeV}$
- ◆ At least **1 b jet**, DeepCSV ($\sim 70\%$ efficiency)



Signal dominated, range in purity from $\sim 60\%$ (3j1b) to $>90\%$ (4j2b)

Inclusive cross section @ 5.02 TeV



Measurement setup:

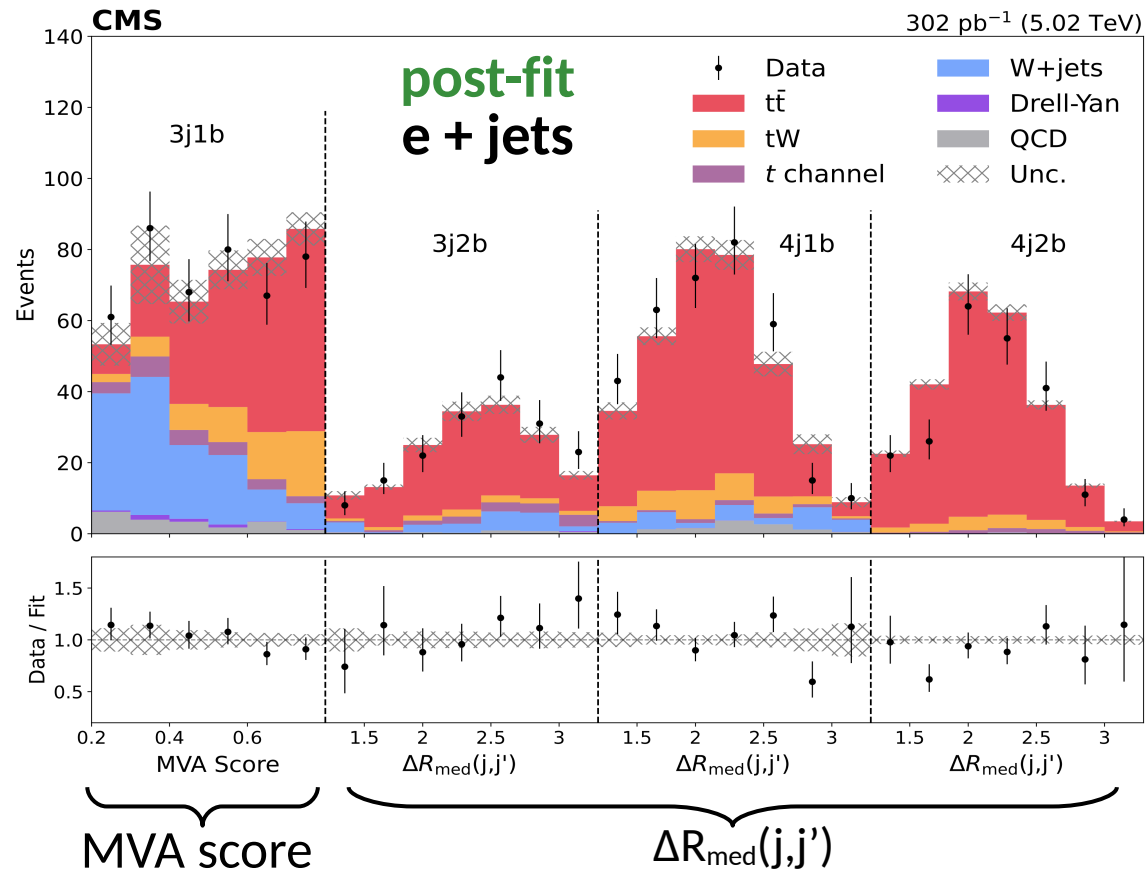
- ◆ Categorize by jet & b-jet multiplicity
- ◆ Further binning in each category to distinguish signal vs. backgrounds:

$\Delta R_{\text{med}}(j, j')$ – median distance between jets

$$\Delta R^2 = \Delta \eta^2 + \Delta \phi^2$$

MVA: (3j1b category)

- ◆ Distinguish **signal vs W+jets** in category with least purity
- ◆ Random forest via Sklearn
- ◆ 8 Input variables (jet + lepton kinematics)



Inclusive cross section @ 5.02 TeV



Measurement setup:

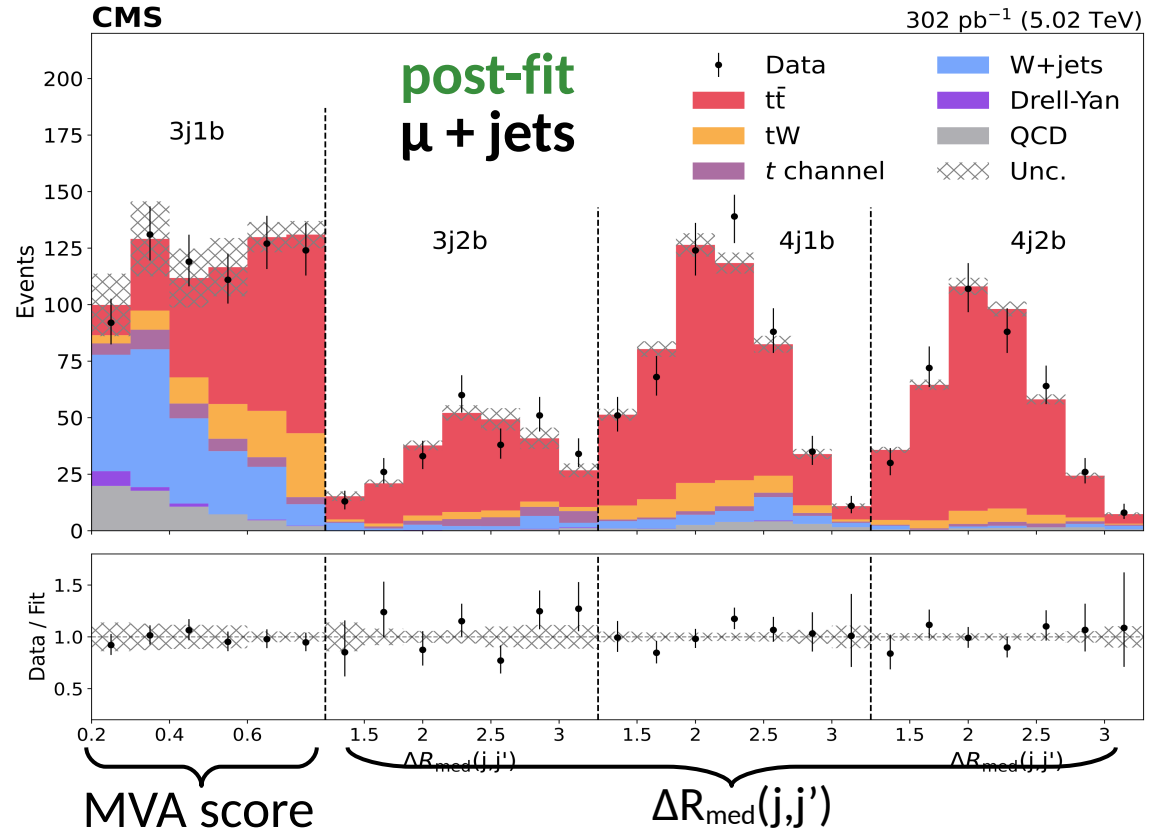
- ◆ Categorize by jet & b-jet multiplicity
- ◆ Further binning in each category to distinguish signal vs. backgrounds:

$\Delta R_{\text{med}}(\mathbf{j}, \mathbf{j}')$ – median distance between jets

$$\Delta R^2 = \Delta \eta^2 + \Delta \phi^2$$

MVA: (3j1b category)

- ◆ Distinguish **signal vs W+jets** in category with least purity
- ◆ Random forest via Sklearn
- ◆ 8 Input variables (jet + lepton kinematics)



Inclusive cross section @ 5.02 TeV



$$\sigma_{\text{pred.}} = 69.5_{-2.3}^{+2.0}(\text{scale}) \pm 2.9(\text{PDF} + \alpha_s) \text{ pb}$$

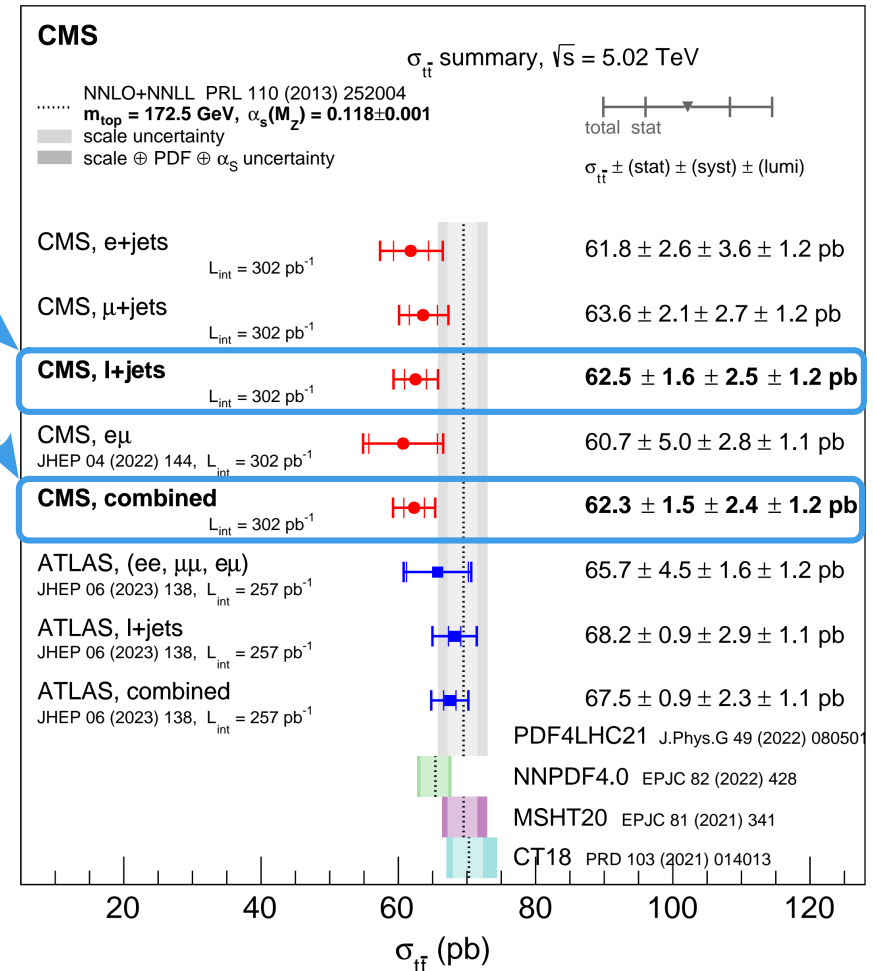
Result + combination: [CMS-TOP-23-005](#)

- Improves previous CMS measurements:

- ℓ +jets only result: **13% $\rightarrow$ 5.1% unc.**
(vs. [JHEP 03 \(2018\) 115](#))
- $e\mu/\ell$ +jets combo: **8.4% $\rightarrow$ 4.9% unc.**
(vs. [JHEP 04 \(2022\) 144](#))

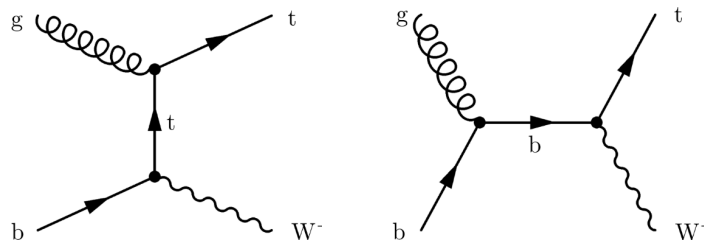
- Limiting uncertainties:

- b-tagging, trigger, lepton ID efficiencies
- Statistics

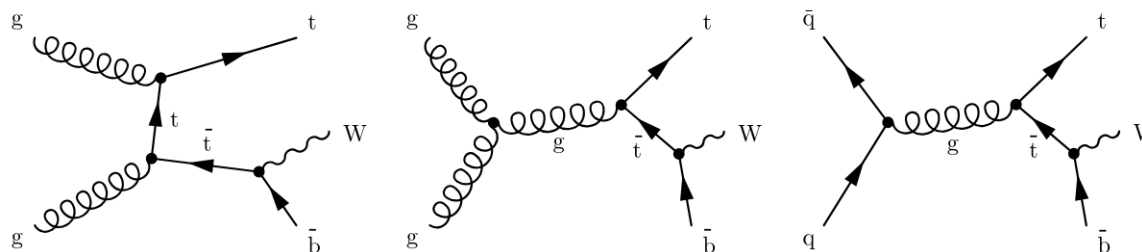


- ♦ *Aperetif:* Who ordered top quarks?
 - ♦ What are they?
 - ♦ How are they produced?
 - ♦ Why study them at the LHC?
- ♦ *Menu:* an assortment of top cross section measurements
 - ♦ Top pair production at 13.6 TeV and 5 TeV
 - ♦ Top + W production at 13.6 TeV
 - ♦ Top pair production: invisible component
- ♦ *Digestif:* A brief word about the future

- Simple at leading order (LO)

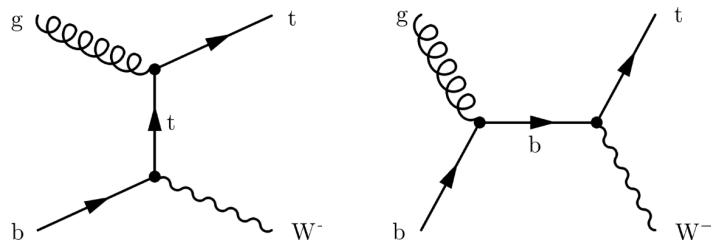


- @NLO: **overlap** with $t\bar{t}$ production – diagrams can contain two on-shell top quarks

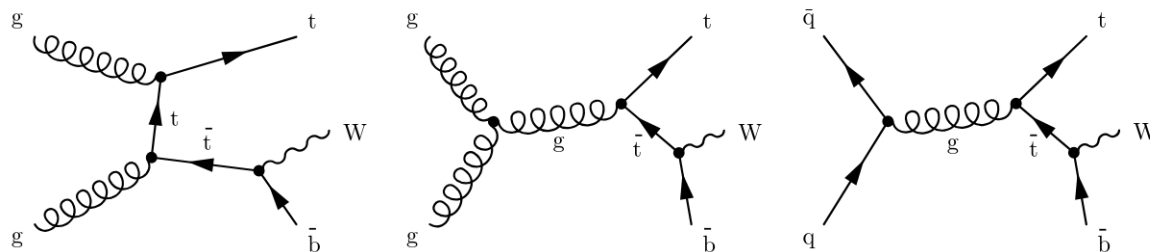


- Diagram removal (DR):** remove these diagrams from signal definition
- Diagram subtraction (DS):** subtract gauge-invariant term to cancel $t\bar{t}$ diagrams locally

- Simple at leading order (LO)

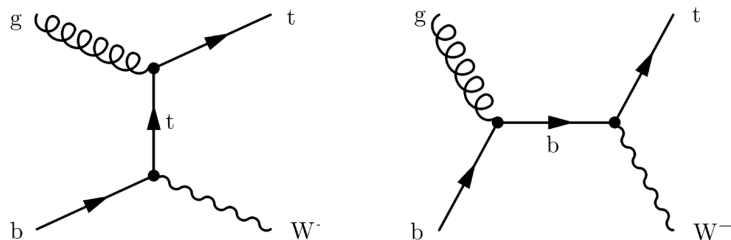


- @NLO: **overlap** with tt production – diagrams can contain two on-shell top quarks



- Diagram removal (DR):** remove these diagrams from signal definition
- Diagram subtraction (DS):** subtract gauge-invariant term to cancel tt diagrams locally
- Alternative (only possible recently): full pp $\rightarrow$ WbWb simulation (not in this talk)

t+W at 13.6 TeV



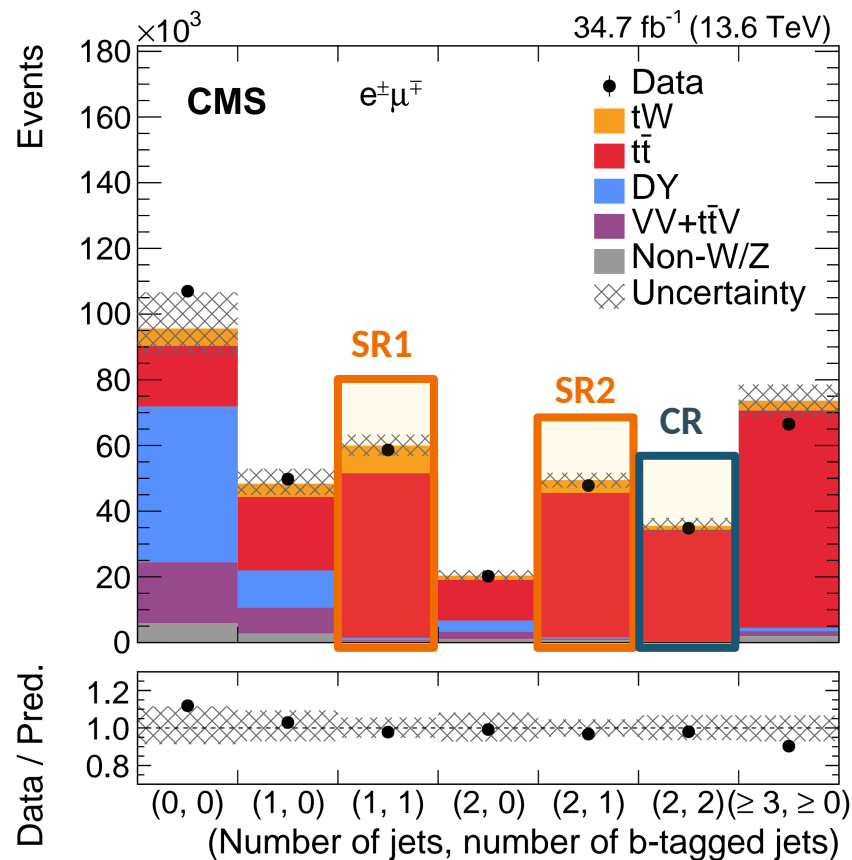
- ◆ Uses data collected in 2022
 - ◇ 34.7 fb⁻¹ integrated luminosity
- ◆ Target events where both W-bosons decay leptonically → e[±]μ[∓]

Signal regions:

SR1: 1 jet, 1 b-tag
SR2: 2 jets, 1 b-tag

Control region:

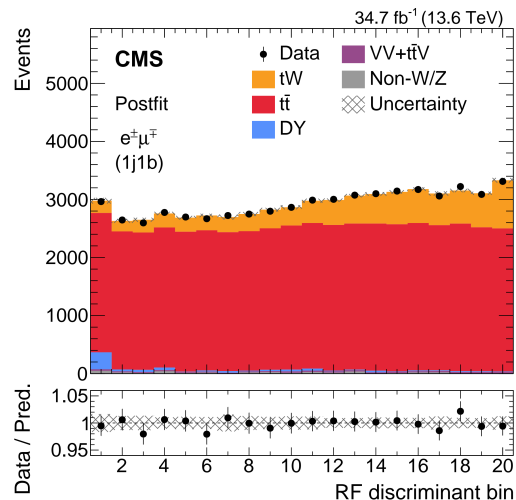
CR: 2 jets, 2 b-tags
(t $\bar{t}$ -enriched)



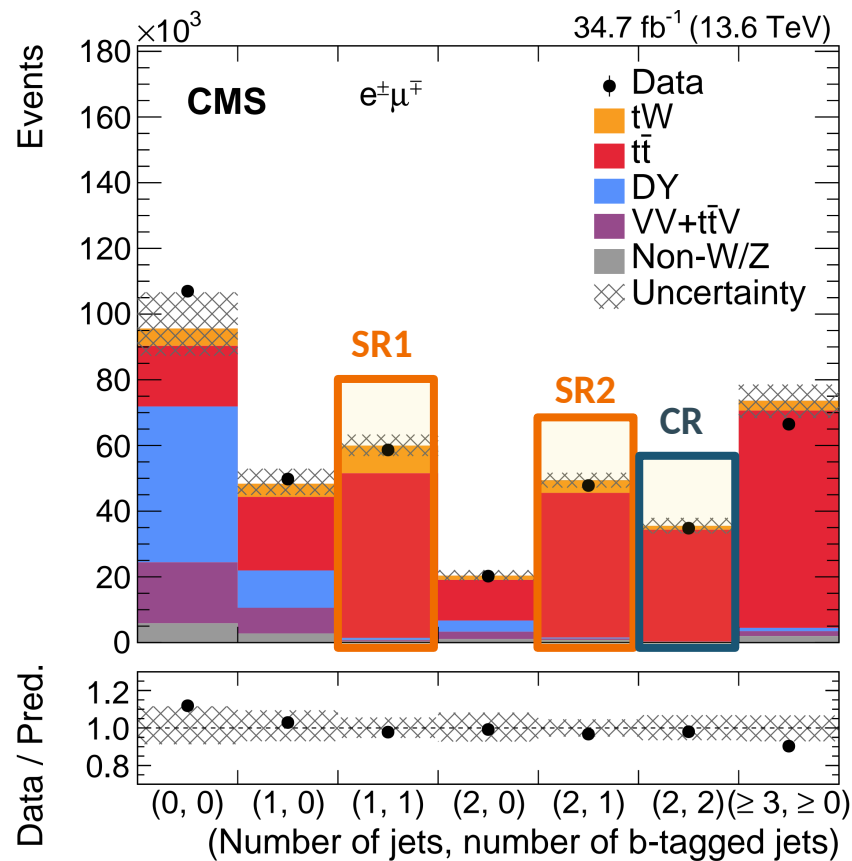
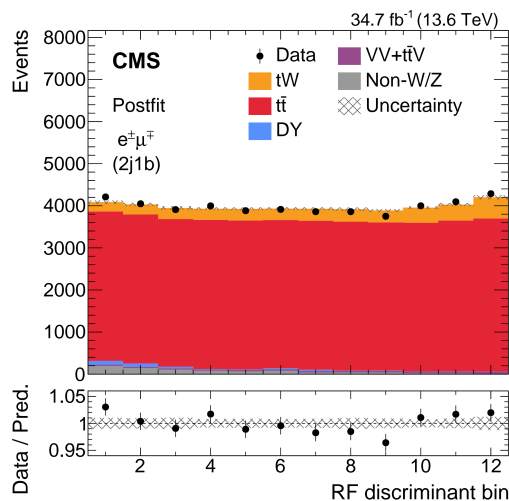
High backgrounds in SRs!

- use Random Forest (RF) multiclassifier
 - 3 output nodes:
 - tW, tt, Z+jets or tt → l+jets
 - utilize “loose jet” info (p_T : 20 – 30 GeV)

SR1



SR2



t+W at 13.6 TeV: inclusive result



◆ **Result:** $\sigma_{tW} = 82.3^{+10.5}_{-10.3} \text{ pb}$

◆ 13% total uncertainty:

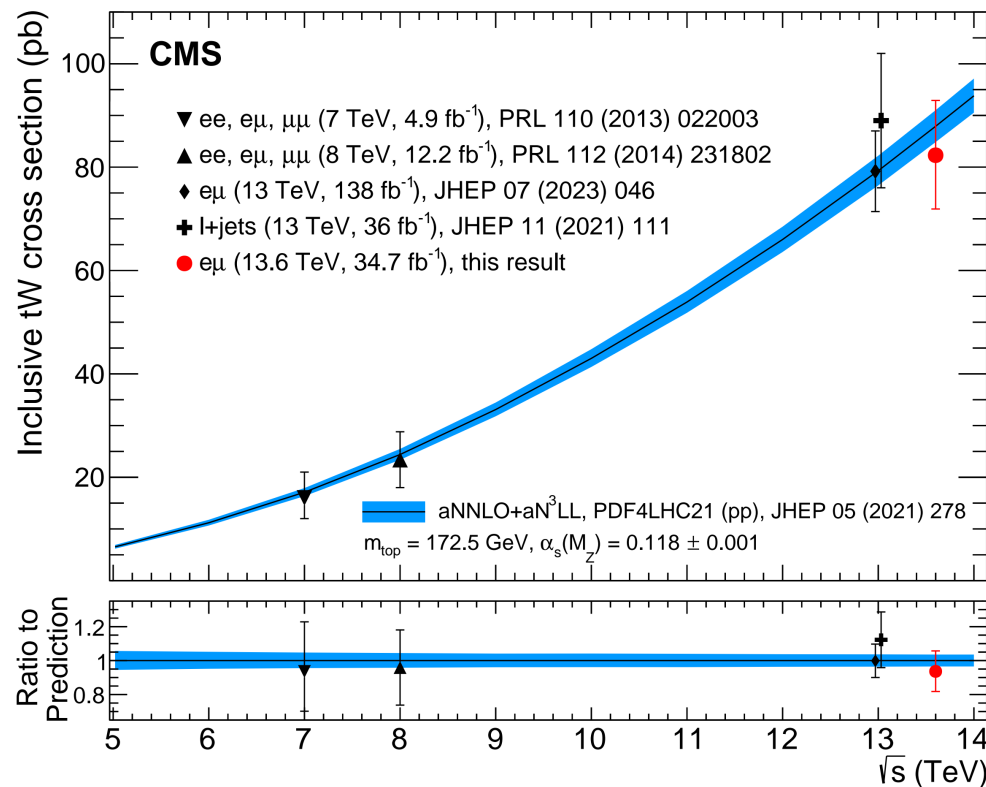
$$\pm 2.1(\text{stat})^{+9.9}_{-9.7}(\text{syst}) \pm 3.3(\text{lumi}) \text{ pb}$$

◆ Consistent with **SM prediction**

$$\sigma_{tW}^{\text{pred.}} = 87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4(\text{PDF} + \alpha_s) \text{ pb}$$

◆ Improved precision per luminosity, partly due to RF discriminant

Submitted to JHEP



Also target differential cross sections!

- Normalized fiducial cross sections obtained via unfolding to particle level with TUnfold
- Measured in 1j1b region, veto on “loose jets” with p_T 20-30 GeV
- 6 variables targeted:

leading lepton p_T

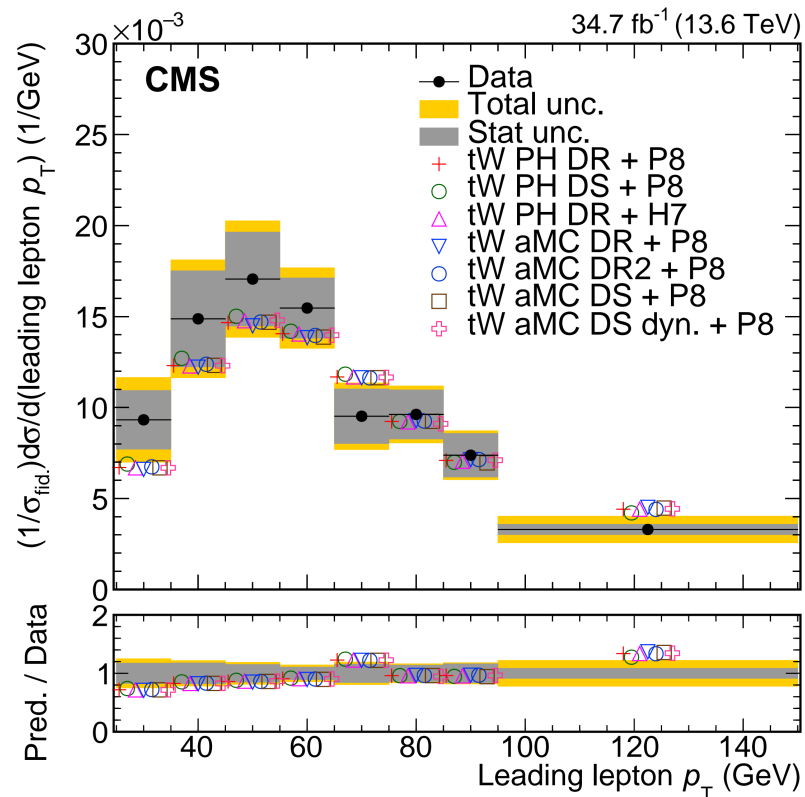
$p_z(e, \mu, j)$

jet p_T

$m(e, \mu, j)$

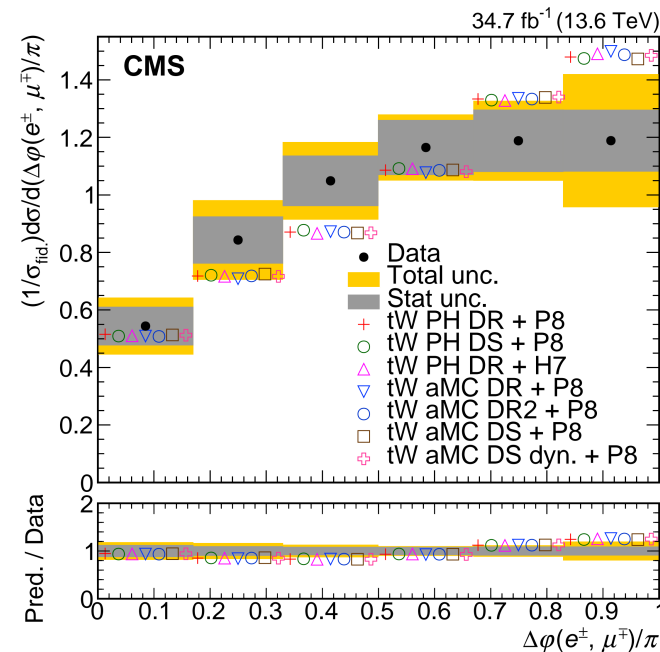
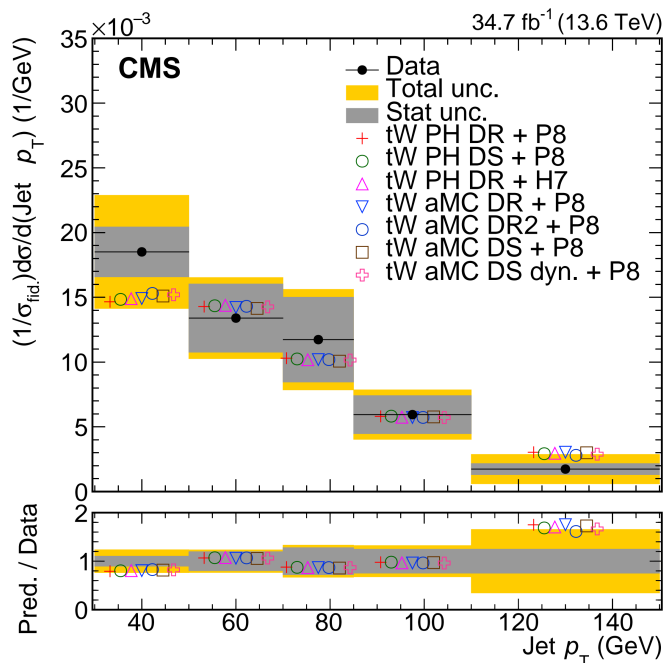
$\Delta\phi(e, \mu)$

$m_T(e, \mu, j, p_{T, \text{miss}})$



t+W at 13.6 TeV: differential results

- Overall good agreement between different simulations, diagram removal strategies
- Some features visible in data vs simulation



leading lepton p_T

$p_z(e, \mu, j)$

jet p_T

$m(e, \mu, j)$

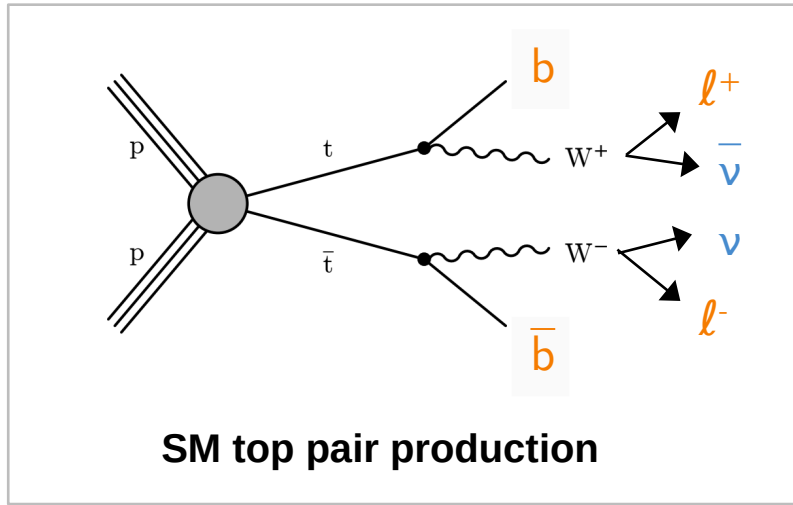
$\Delta\phi(e, \mu)$

$m_T(e, \mu, j, p_{T, \text{miss}})$

- ♦ *Aperetif:* Who ordered top quarks?
 - ♦ What are they?
 - ♦ How are they produced?
 - ♦ Why study them at the LHC?
- ♦ *Menu:* an assortment of top cross section measurements
 - ♦ Top pair production at 13.6 TeV and 5 TeV
 - ♦ Top + W production at 13.6 TeV
 - ♦ Top pair production: invisible component
- ♦ *Digestif:* A brief word about the future

A new differential measurement

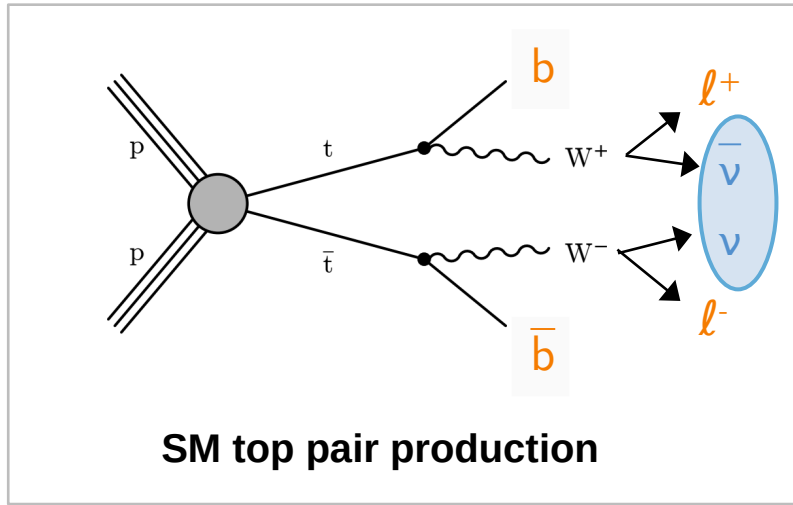
- ♦ $t\bar{t}$ differential measurements:
 - ♦ Visible event (b, ℓ)
 - ♦ Intermediate particles (t, W)



A new differential measurement

- ♦ $t\bar{t}$ differential measurements:

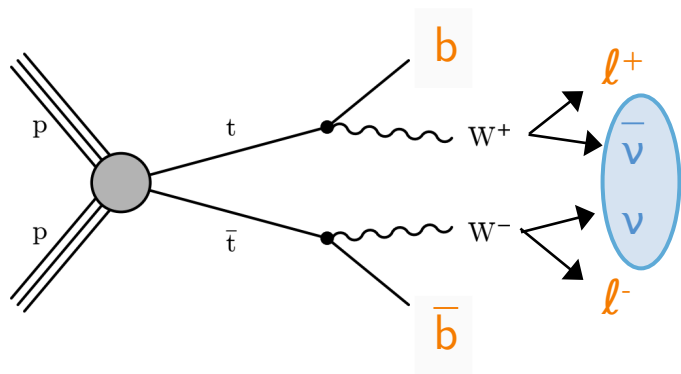
- ♦ Visible event (b, ℓ)
- ♦ Intermediate particles (t, W)
- ♦ Invisible event ($\nu, ?$)



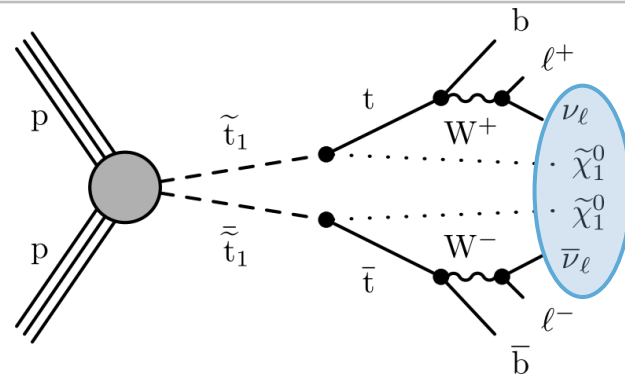
A new differential measurement

- ◆ $t\bar{t}$ differential measurements:

- ◇ Visible event (b, ℓ)
- ◇ Intermediate particles (t, W)
- ◇ Invisible event ($\nu, ?$)



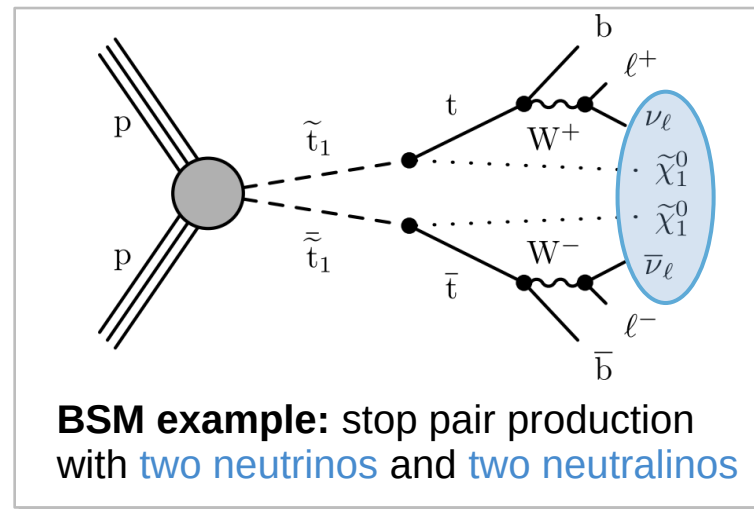
SM top pair production



BSM example: stop pair production
with two neutrinos and two neutralinos

A new differential measurement

- ◆ $t\bar{t}$ differential measurements:
 - ◇ Visible event (b, ℓ)
 - ◇ Intermediate particles (t, W)
 - ◇ Invisible event ($\nu, ?$) → first measurement!
- ◆ In BSM scenarios, the additional particles can contribute to undetected momentum
- ◆ Differential measurement of $\nu\nu$ system kinematics:
 - ◇ First precision test of invisible event component via differential measurement
 - ◇ New means of distinguishing SM vs BSM scenarios

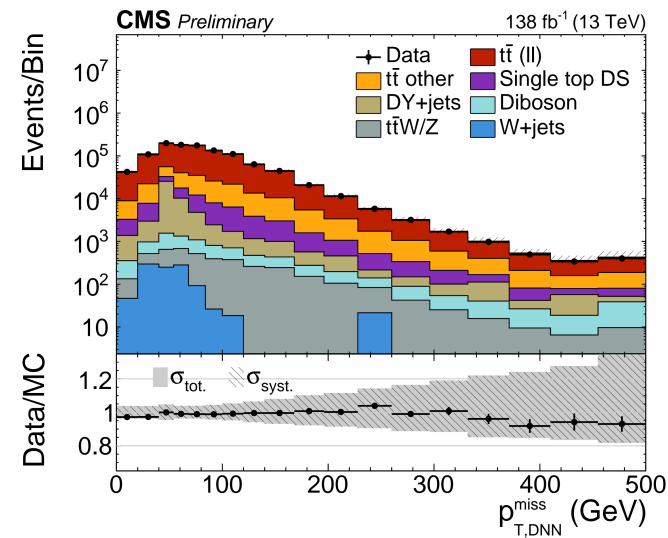
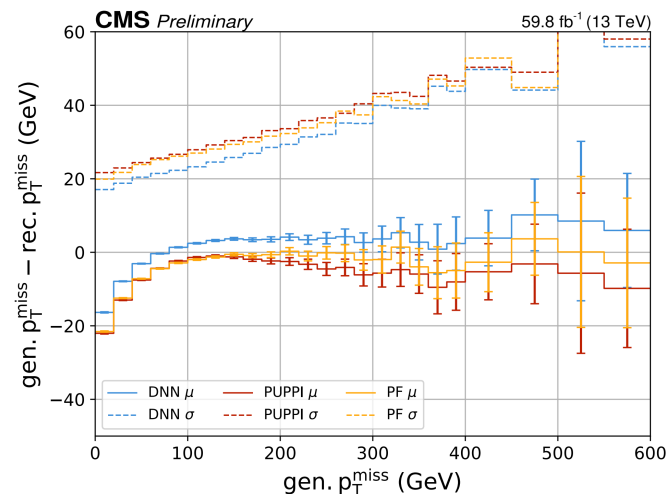


$t\bar{t}$ di-neutrino system kinematics



$p_{T,miss}$ (MET) reconstruction challenges

- ◆ Challenging object to reconstruct:
 - ◇ Relies on modeling of other **neutrinos** produced via **secondary interactions** (especially in **b-jets**)
 - ◇ Requires accurate reconstruction of **all visible particles** in detector (especially **jets**)
- ◆ **DNN** used to improve **MET** resolution
 - ◇ Trained on difference between **PUPPI MET** and generator level MET
 - ◇ 17 inputs involving jet kinematics



$t\bar{t}$ di-neutrino system kinematics



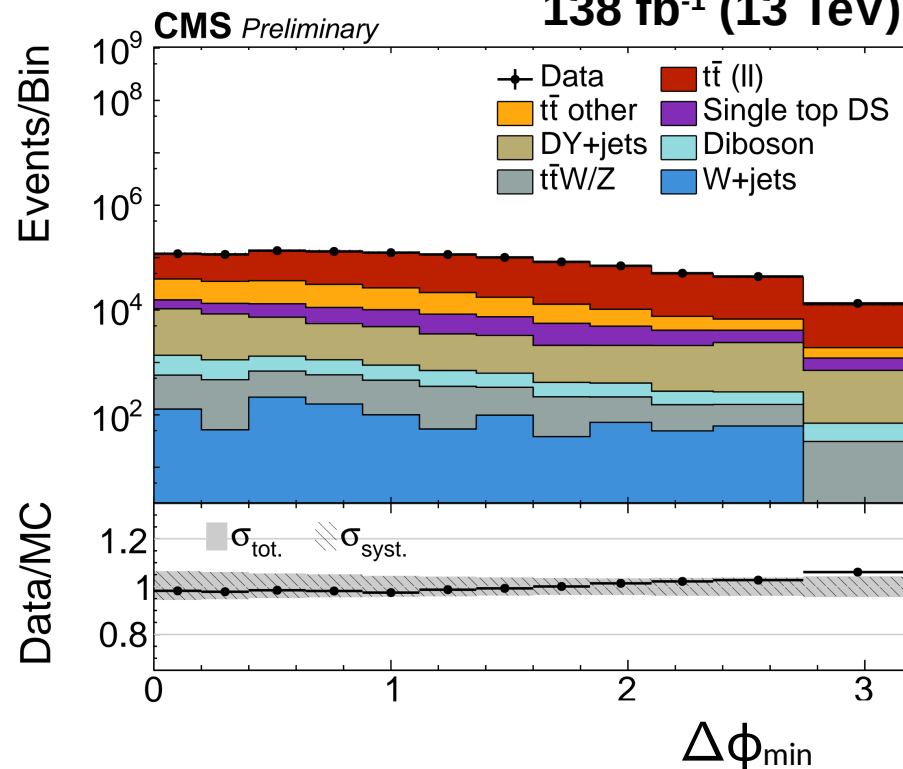
- Using **DNN MET**, focus on **two variables** sensitive to BSM contributions

- $p_{T,\text{miss}} = p_T(\nu\bar{\nu})$
- $\min[\Delta\phi(p_{T,\text{miss}}, \ell)] \equiv \Delta\phi_{\min}$

Selection:

- 2 leptons** (ee, eμ, μμ)
 $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$
- ≥2 b-tagged jets** (Deepjet, ~95% eff.)
 $p_T > 30 \text{ GeV}$, $|\eta| < 2.4$
- $\Delta R(\ell, \text{jet}) > 0.4$
- $p_{T,\text{miss}} > 40 \text{ GeV}$ (ee, μμ only)

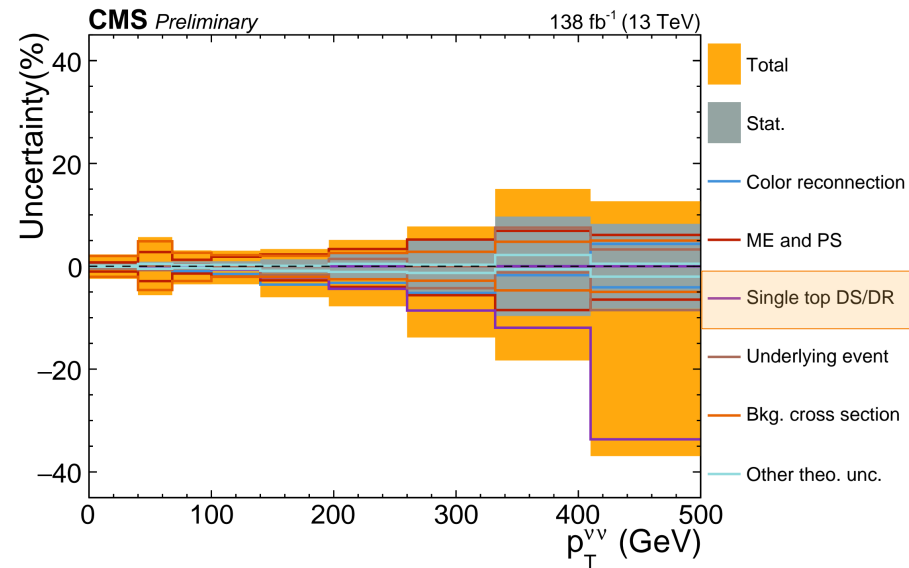
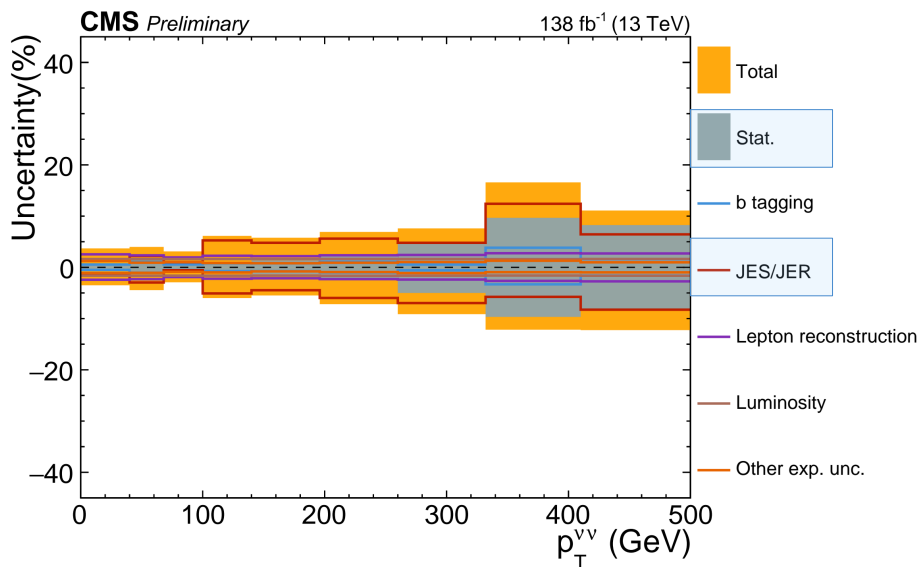
Full Run 2 dataset
138 fb⁻¹ (13 TeV)



→ Also measure **2D distribution**

Experimental uncertainties

Jet Energy Scale/Resolution + statistics
are leading uncertainties



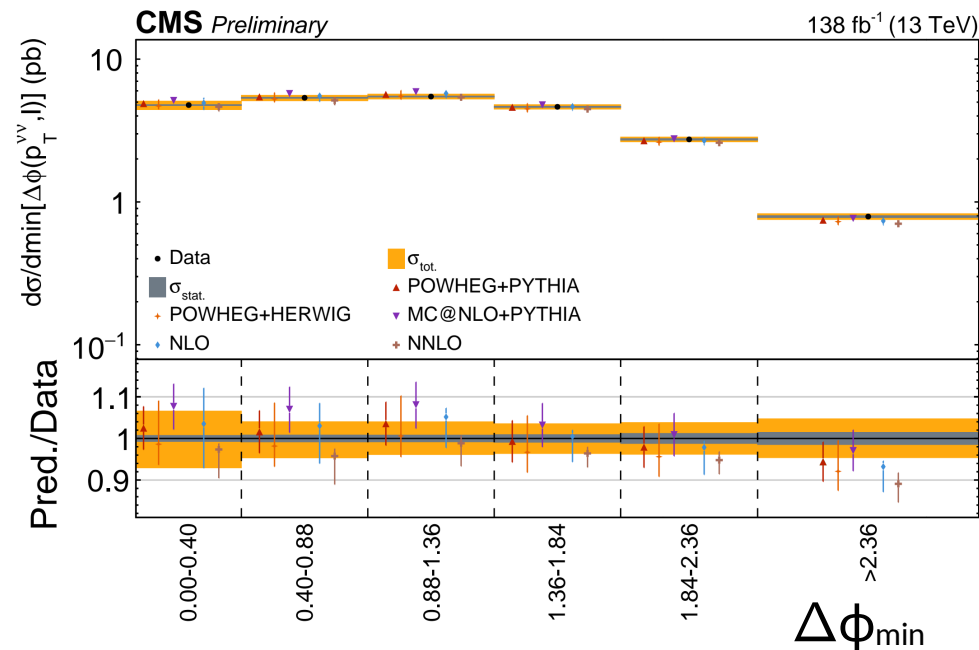
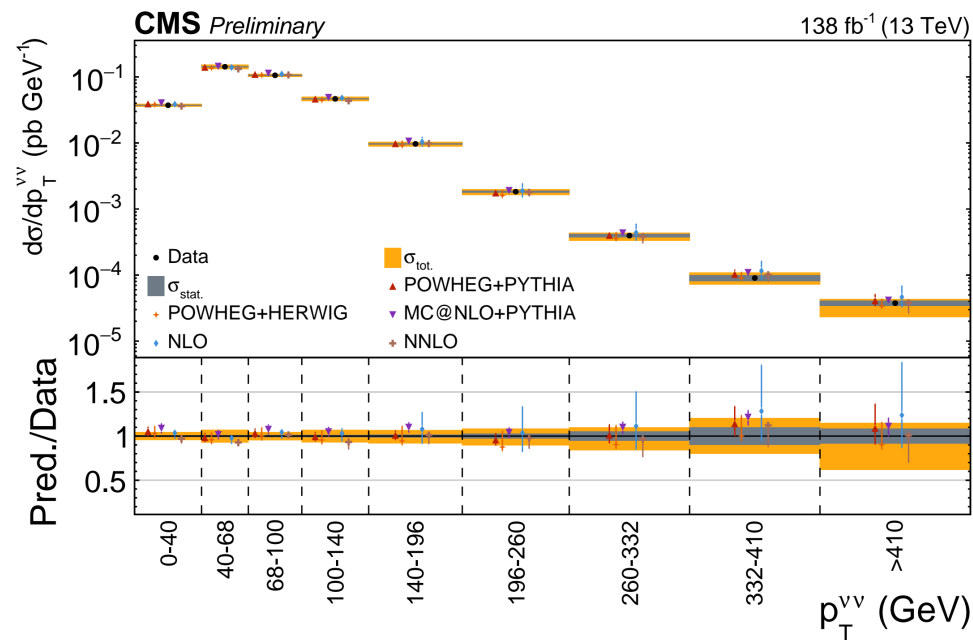
Theoretical uncertainties

Dominated by **tW interference**
(diagram subtraction vs. removal)

Results: differential cross sections



Unfolded results show very good agreement for first measurement of this distribution

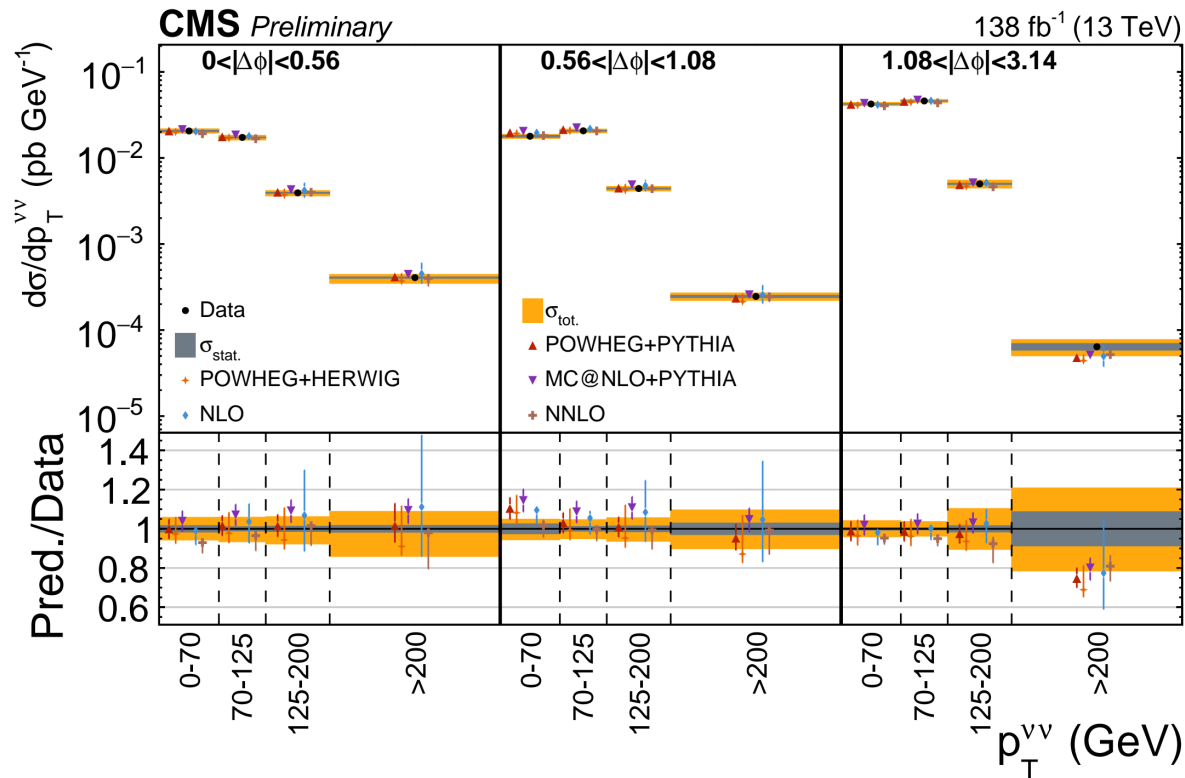


POWHEG shows best agreement
(but differences are small)

Results: differential cross sections



- ◆ 2D differential cross section also measured, shows good agreement
- ◆ Slightly better description from **NNLO fixed-order** prediction

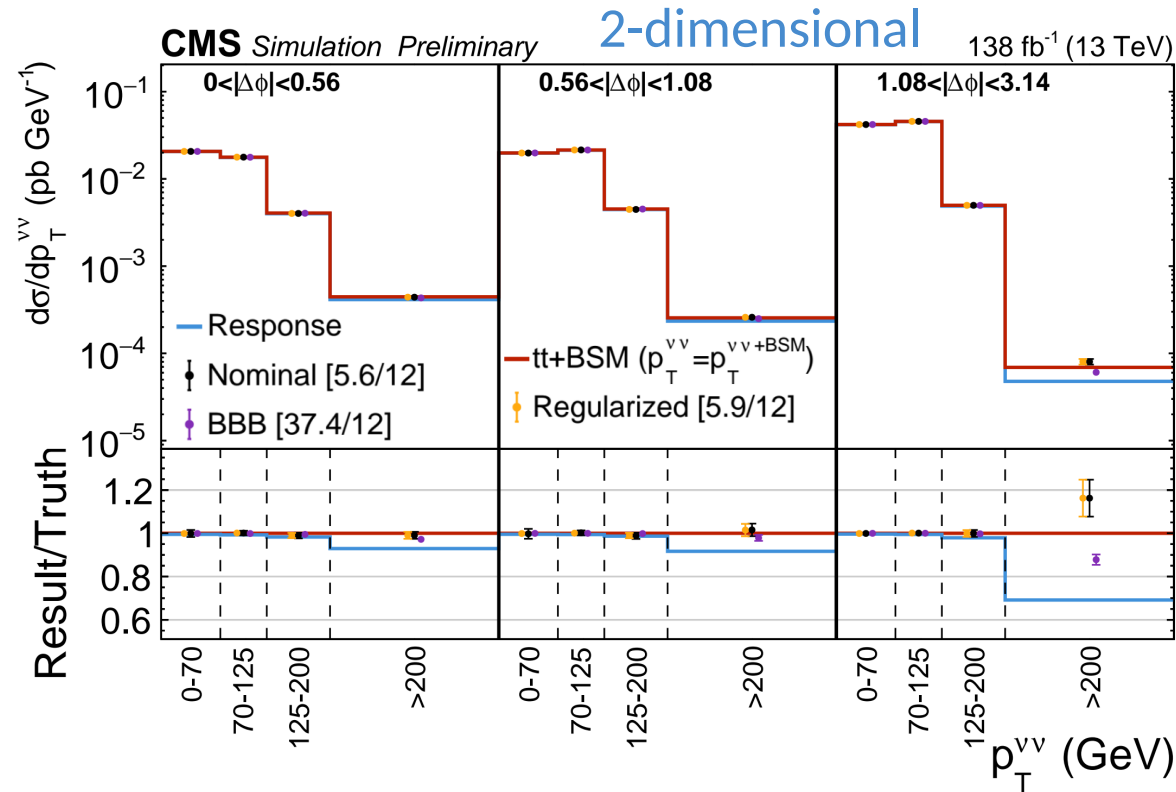


Normalized diff. cross sections
measured as well

(see backup)

Di-neutrino system: closure test

- To verify sensitivity to BSM physics, closure test performed with **injected BSM signal**

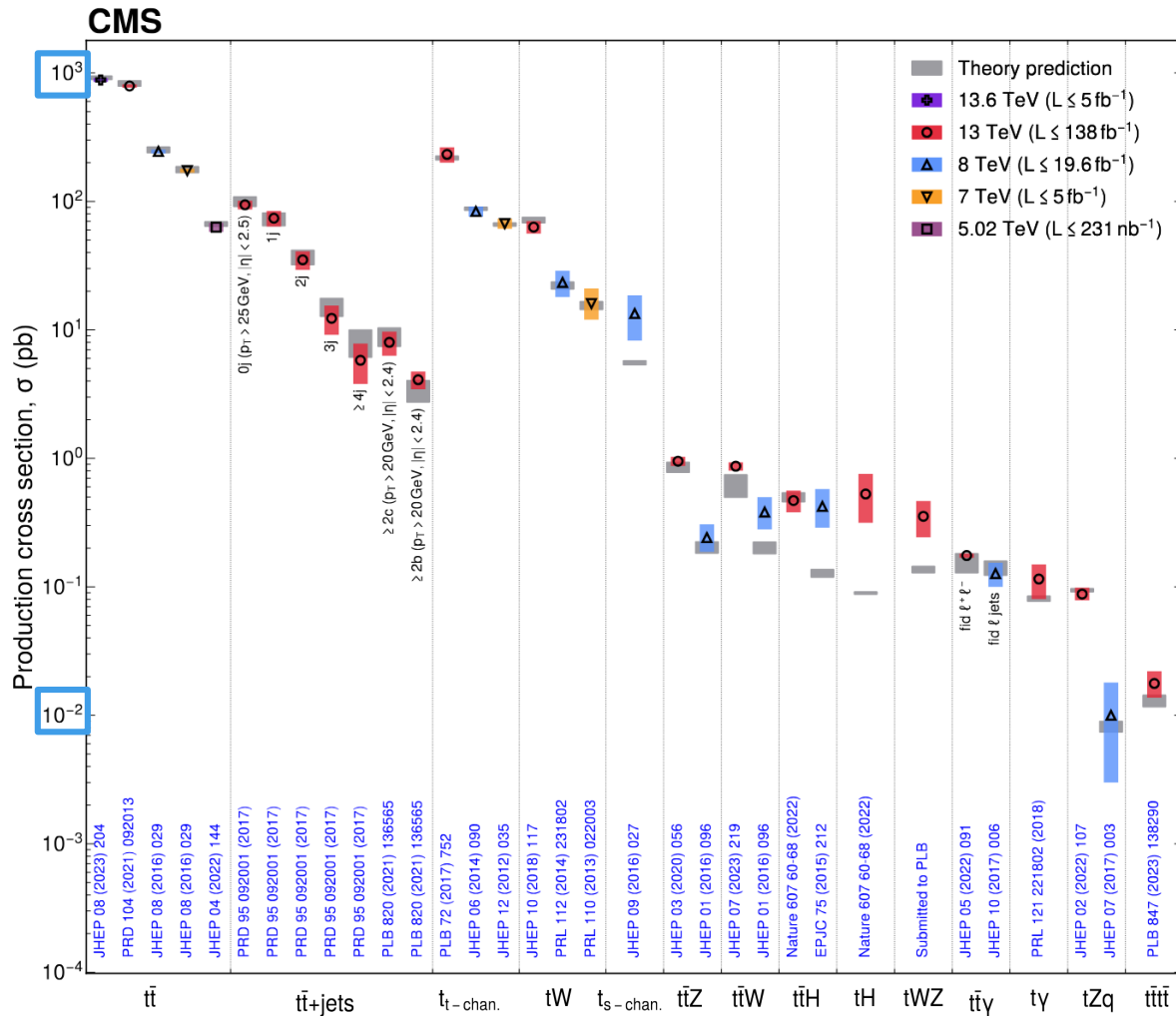


- Pseudodata used with enhanced BSM contribution
- Different unfoldings compared to expected distribution (red)
- Nominal distribution used for response matrix shown (blue)
- $[\chi^2 / \text{ndf}]$ shown in legend

➞ **Correct distributions reproduced**

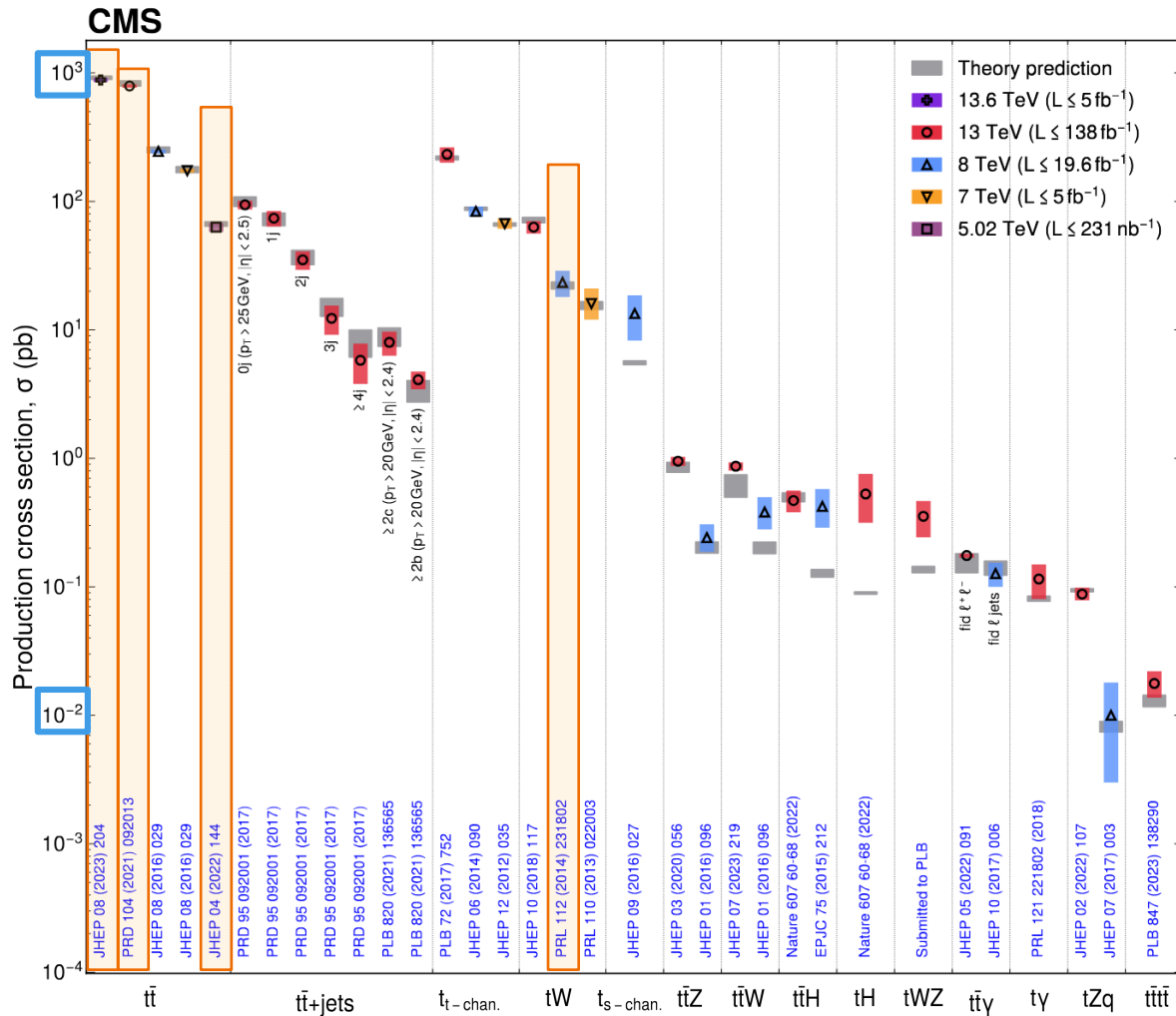
- ♦ *Aperetif:* Who ordered top quarks?
 - ♦ What are they?
 - ♦ How are they produced?
 - ♦ Why study them at the LHC?
- ♦ *Menu:* an assortment of top cross section measurements
 - ♦ Top pair production at 13.6 TeV and 5 TeV
 - ♦ Top + W production at 13.6 TeV
 - ♦ Top pair production: invisible component
- ♦ *Digestif:* A brief word about the future

The big picture of top cross sections



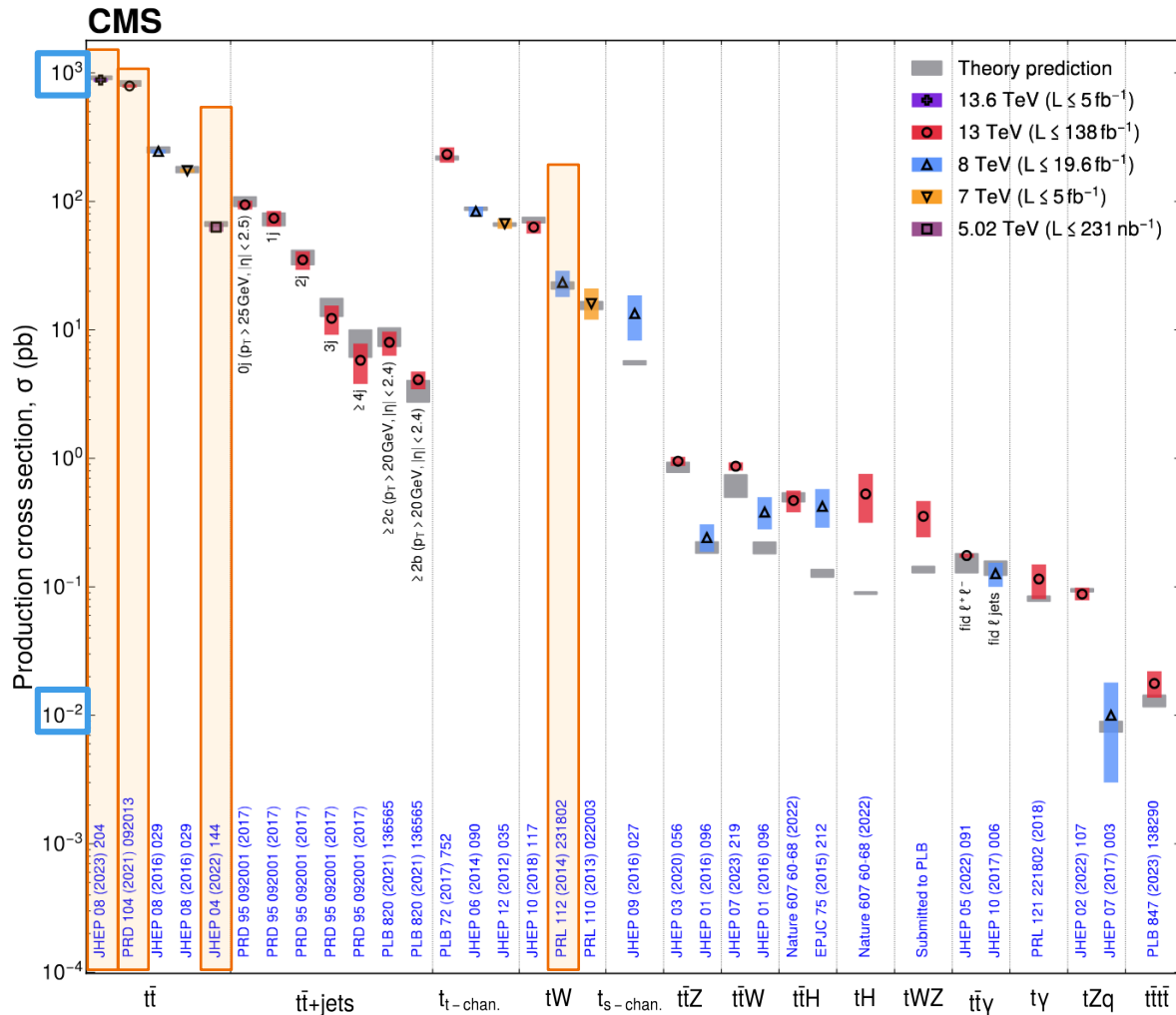
- Measured inclusive cross sections involving top quark production at CMS span almost **five orders of magnitude!**

The big picture of top cross sections



- Measured inclusive cross sections involving top quark production at CMS span almost **five orders of magnitude!**
- We have covered a sample of recent measurements related to the processes highlighted on the left
- This plot shows only inclusive cross sections, but we have seen that there is much to be gleamed from differential results as well

The big picture of top cross sections



- Measured inclusive cross sections involving top quark production at CMS span almost **five orders of magnitude!**
- We have covered a sample of recent measurements related to the processes highlighted on the left
- This plot shows only inclusive cross sections, but we have seen that there is much to be gleamed from differential results as well

Figure from CMS review article:

[arXiv:2405.18661](https://arxiv.org/abs/2405.18661)

The future of LHC & CMS



- ◆ LHC Run 3 is poised to deliver **up to 200 fb⁻¹** additional lumi by end of 2026

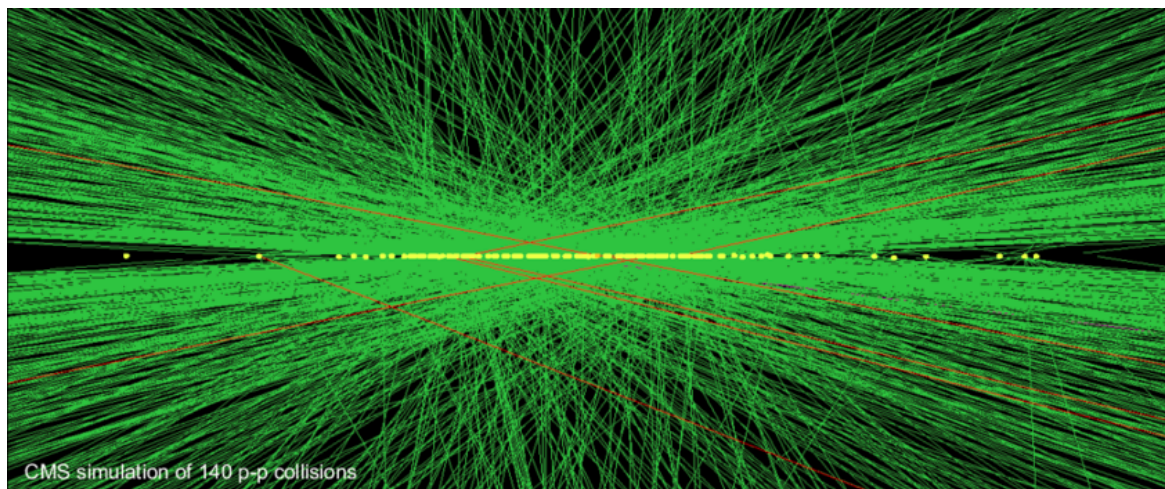
- ◆ LHC Run 3 is poised to deliver **up to 200 fb⁻¹** additional lumi by end of 2026

...but after a long break for upgrades...

- ◆ LHC Run 3 is poised to deliver **up to 200 fb⁻¹** additional lumi by end of 2026

...but after a long break for upgrades...

- ◆ **High Luminosity LHC (HL-LHC)** will begin !
- ◆ Run 4 and Run 5 (now planned 2030 - 2041) will target **3000 fb⁻¹**



We offered a taste of recent CMS top cross section measurements:

- ♦ Just last year, CMS published the first physics measurement of LHC Run 3:
 σ_{tt} at $\sqrt{s} = 13.6$ TeV

[JHEP 08 \(2023\) 204](#)

- ♦ As of yesterday, CMS has improved our measurement of **σ_{tt} at $\sqrt{s} = 5.02$ TeV**
with an impressively precise effort in the lepton+jets channel

[CMS-TOP-23-005](#)

- ♦ CMS measured the inclusive cross section of **tW production** at **$\sqrt{s} = 13.6$ TeV**,
providing differential measurements as well

[arXiv:2407.06444](#)

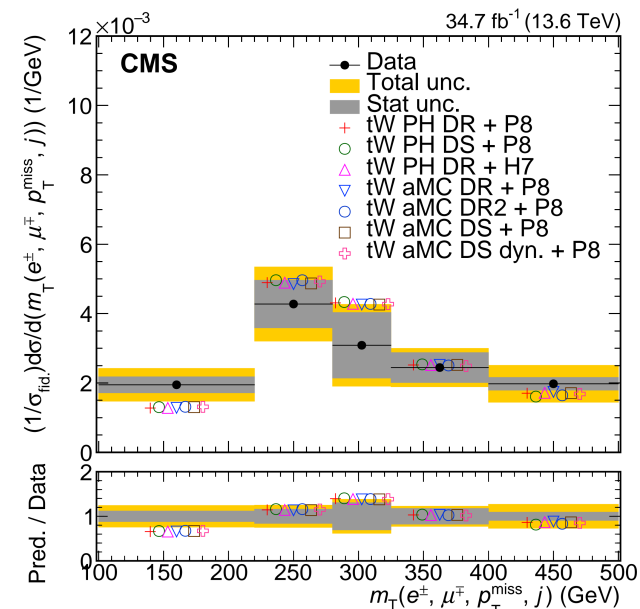
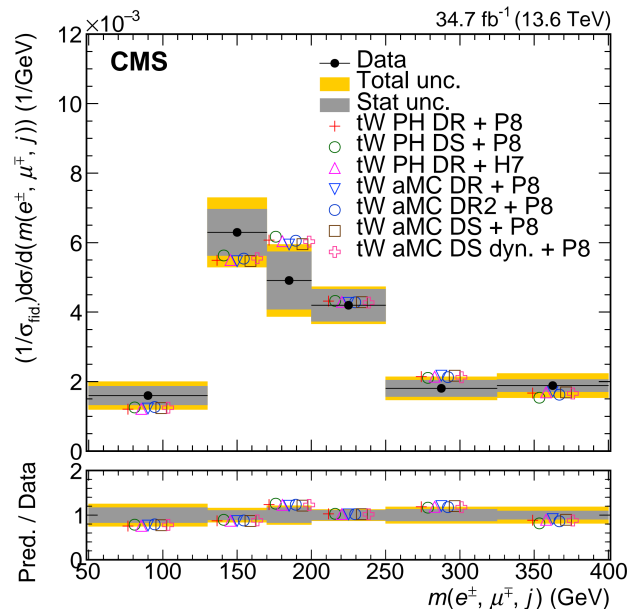
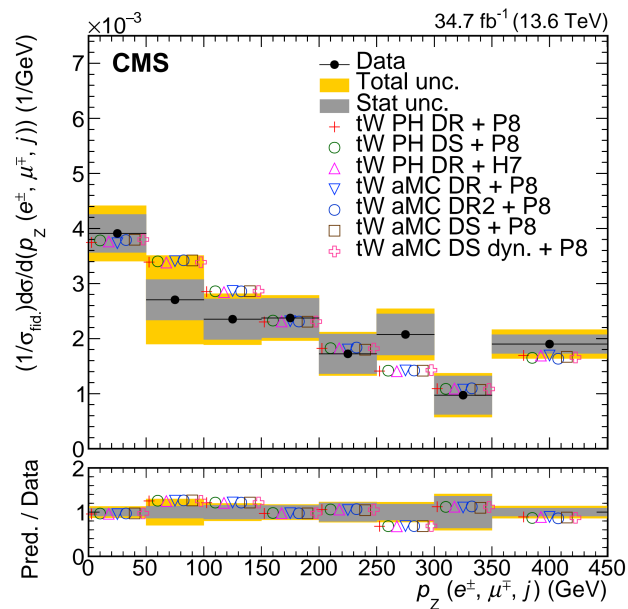
- ♦ CMS presented a preliminary measurement of the **dineutrino system**
kinematics, the **first** differential result focusing on **invisible event component!**

[CMS-PAS-TOP-24-001](#)

...And we showcased the general importance of top quark measurements at the LHC

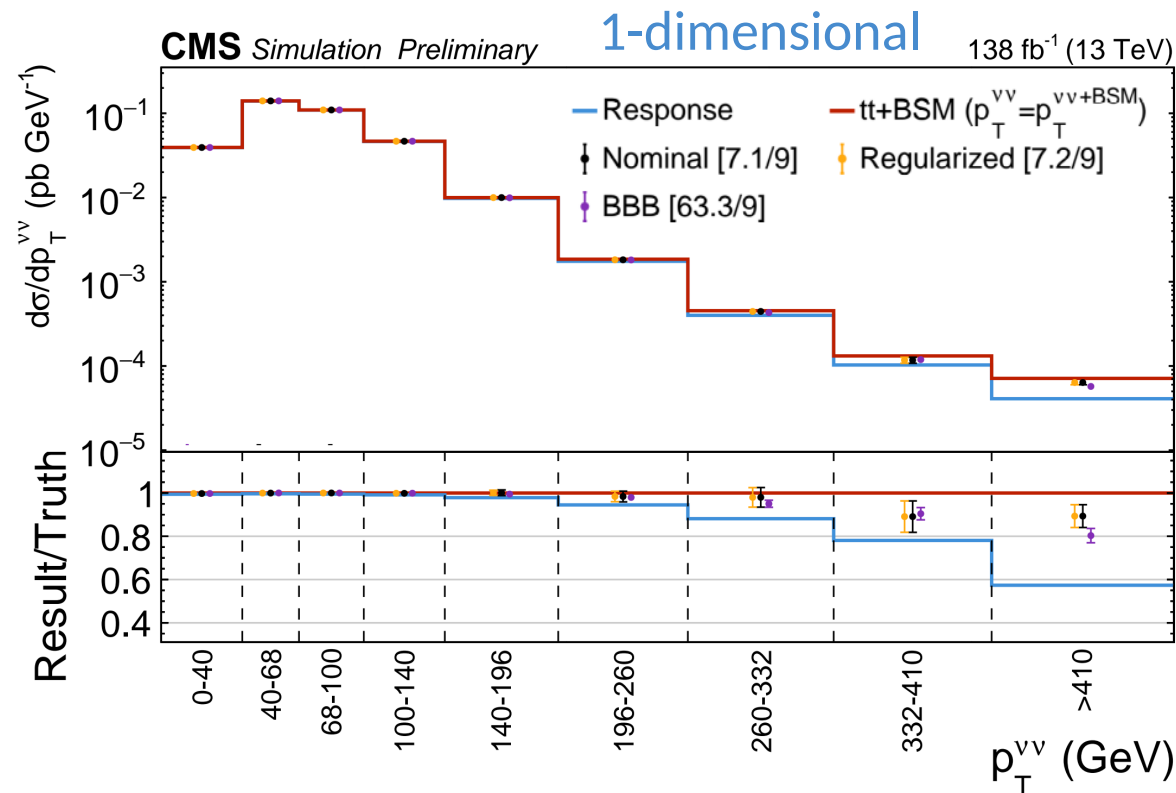
- ◆ The LHC is not just a machine for Higgs measurements – it is a **top quark factory!** (and so much more!)
- ◆ The LHC has allowed for unprecedented statistics and precision in top quark physics, deepening our understanding of the standard model
- ◆ CMS has performed measurements of top quark production cross sections across **5 orders of magnitude** in terms of production rate – and we are **just getting started!**

◆ Other differential distributions from tW at 13.6 TeV



Di-neutrino system: closure test

- ◆ To verify sensitivity to BSM physics, closure test performed with **injected BSM signal**



- ◆ Pseudodata used with enhanced BSM contribution
- ◆ Different unfoldings compared to expected distribution (red)
- ◆ Nominal distribution used for response matrix shown (blue)
- ◆ [χ^2 /ndf] shown in legend

➞ **Correct distributions reproduced**

Normalized differential cross sections



- ◆ Unfolded results show good agreement
 - ◇ 1D: POWHEG+PYTHIA shows best agreement
 - ◇ 2D: NNLO fixed-order fits best

