Inclusive and differential top quark pair production from 5 to 13.6 TeV at CMS

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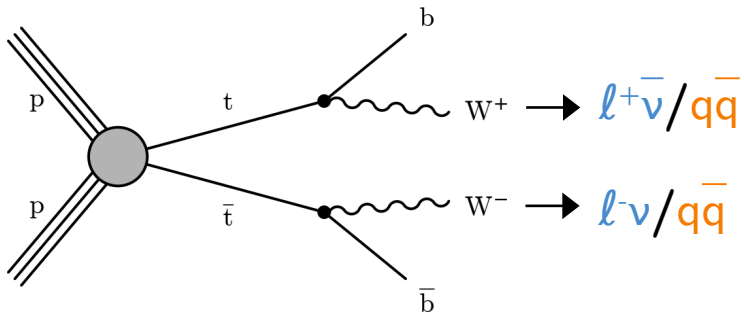
On behalf of the CMS collaboration

Top quarks: better in pairs

- World's heaviest particle, mainly produced in pairs at LHC
- Decays before hadronizing, almost exclusively to b + W



$t\bar{t}$ final state characterized by leptons from W decays:

dilepton / lepton(ℓ)+jets / all hadronic

- Leaves distinct signature:
  - High-p_T **leptons**
  - b quarks which become heavy-flavor **b jets**
  - Missing transverse momentum (**MET/$p_{T,miss}$**) from undetected neutrinos
  - **Additional jets** in ℓ+jets channel

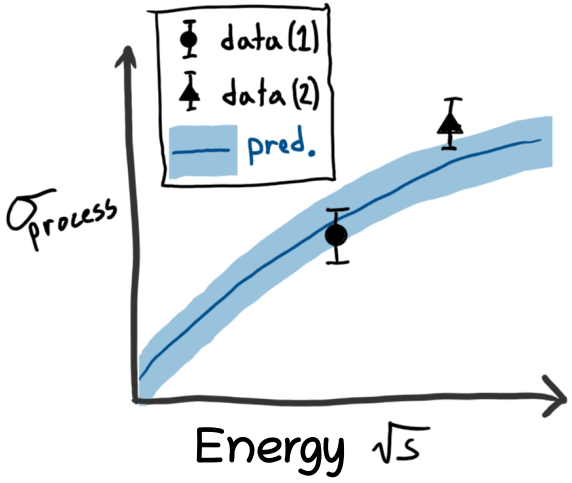
Inclusive and differential measurements

Inclusive cross section $\sigma_{pp \to t\bar{t}}$

- Varies by over an order of magnitude @ LHC

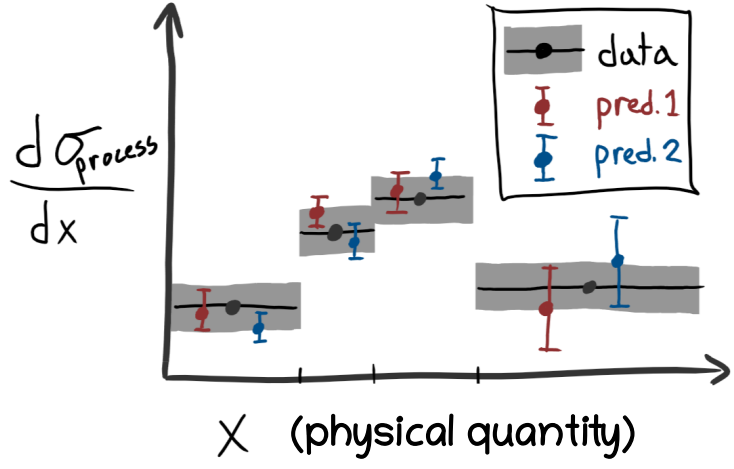
  $\sqrt{s}$: 5 TeV → 13.6 TeV
  $\sigma_{t\bar{t}}$: 69 pb → 924 pb

- Precise measurements and comparison to prediction



Differential cross sections

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



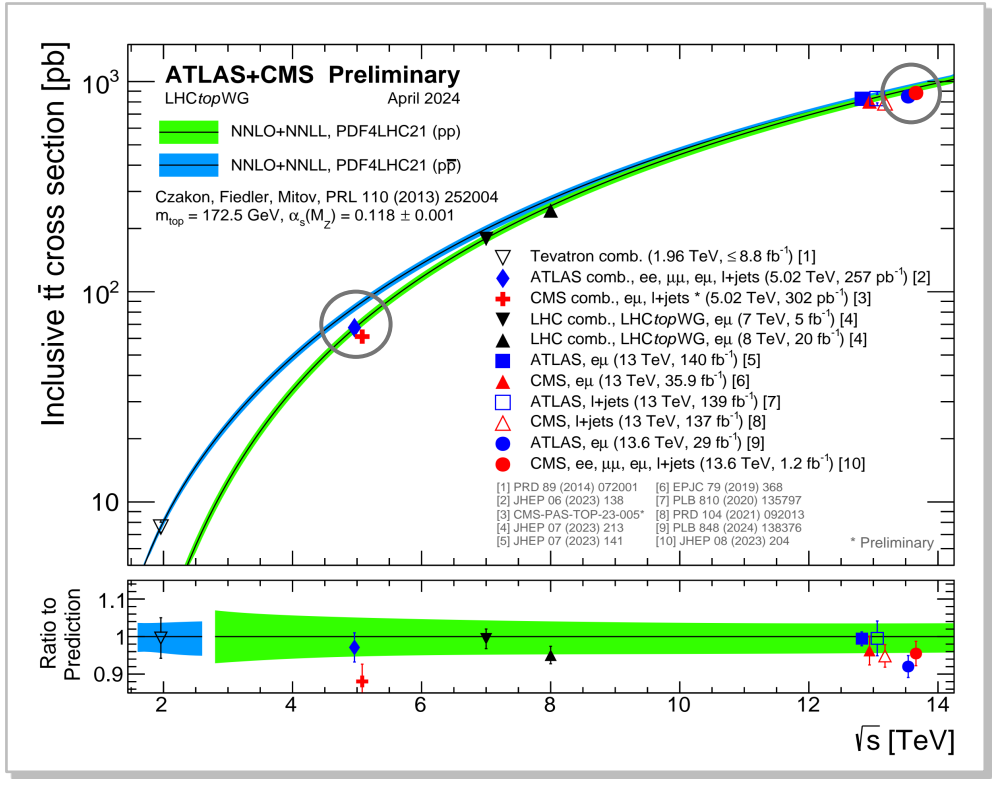
Inclusive cross section measurements

New 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:
  - Approx 1 fb^{-1} of data from early weeks of 2022 data-taking
  - Channel combination

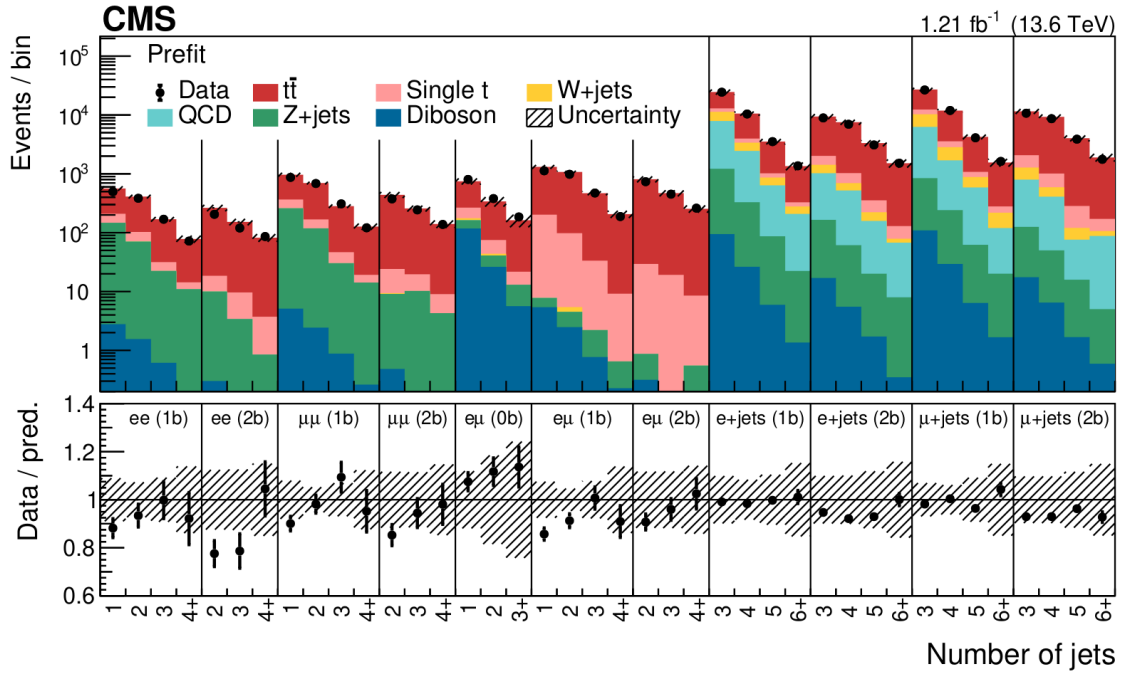
eμ, ee, μμ, e+jets, μ+jets

→ 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
- **b-tag efficiency** scale factors determined by fit
- **SM pred.** $\sigma_{t\bar{t}} = 924^{+32}_{-40}\text{pb}$



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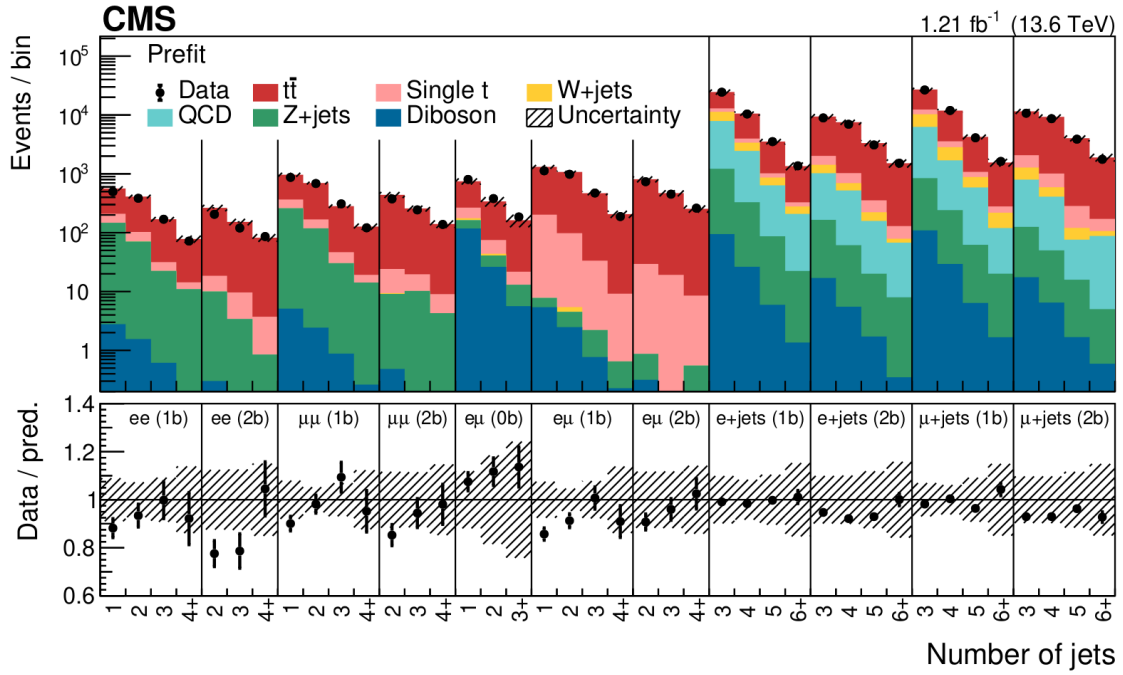

Result (JHEP 08 (2023) 204)

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

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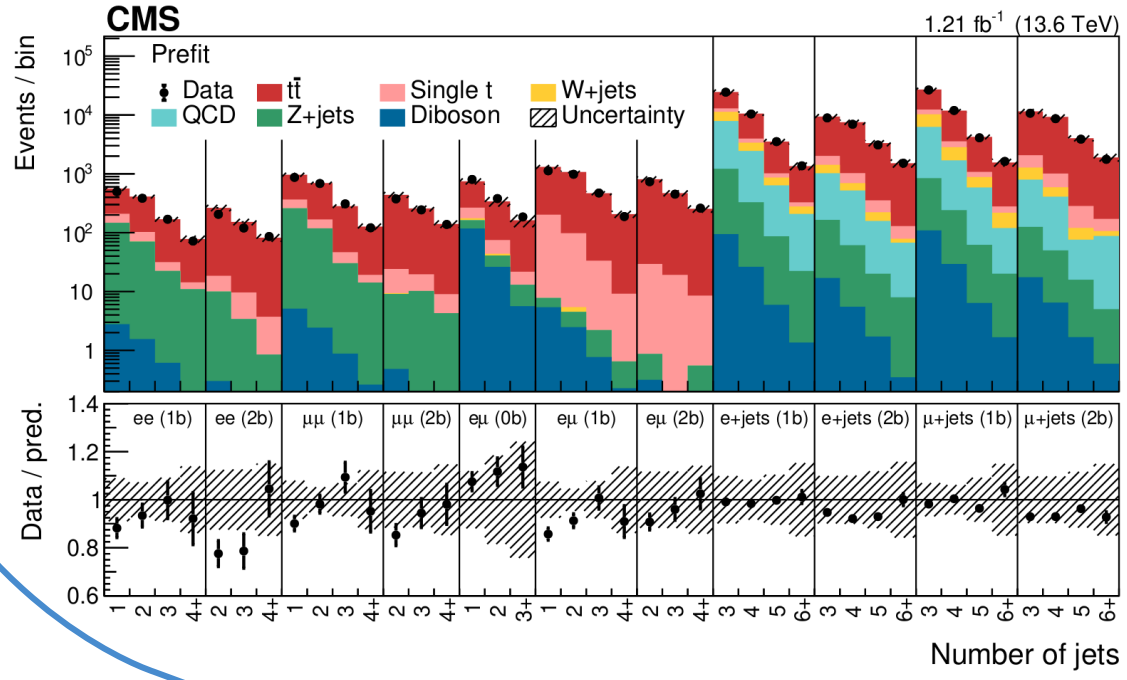

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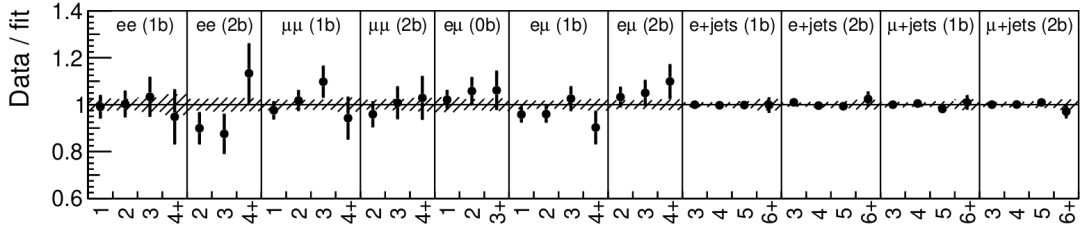
high-purity cut and count cross-check:

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

Postfit



Inclusive cross section @ 13.6 TeV

Uncertainty breakdown:

Source	Uncertainty (%)
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

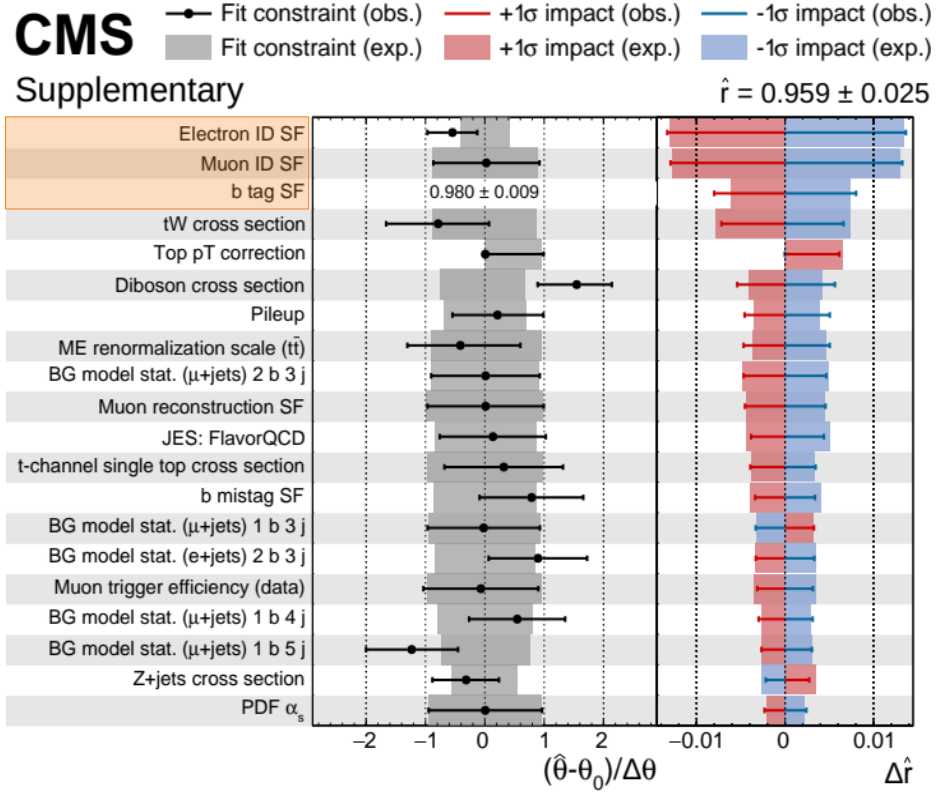
= Resulting uncertainty in $\sigma_{t\bar{t}}$

2 leading uncertainties:

lepton, b-tag eff.

Not statistics limited

Lumi comparable to likelihood stat+syst unc.

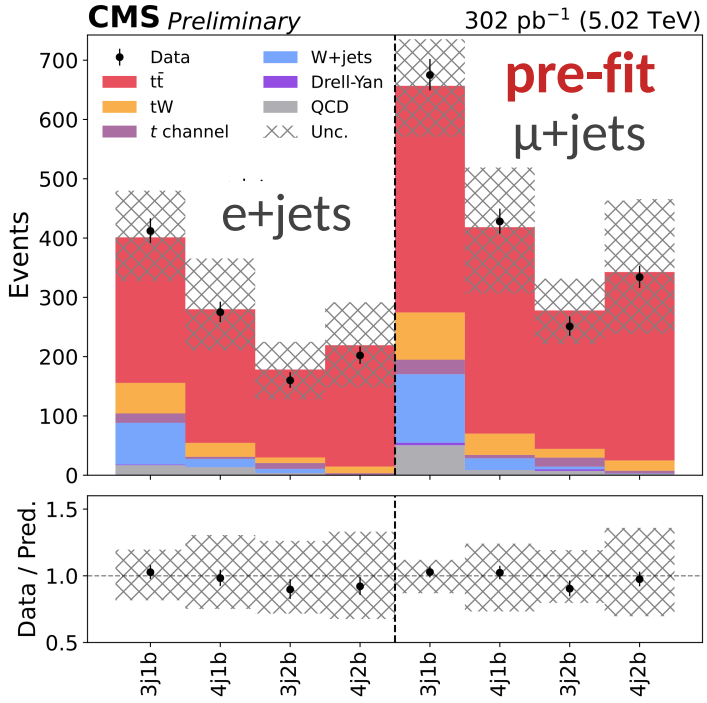


Inclusive cross section @ 5.02 TeV

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 eμ) JHEP 04 (2022) 144
- *New* dedicated measurement in ℓ+jets channel with **302 pb^{-1} lumi**: CMS-PAS-TOP-23-005

- Exactly **1 lepton: p_T > 20 GeV**, $|\eta| < 2.4$
- Opposite flavor lepton veto: p_T > 10 GeV
- At least **3 jets: p_T > 25 GeV**, $|\eta| < 2.4$
- MET requirement: **$|p_{T,miss}|$ > 30 GeV**
- At least **1 b jet**, DeepCSV (~75% efficiency)



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

Inclusive cross section @ 5.02 TeV

Measurement setup:

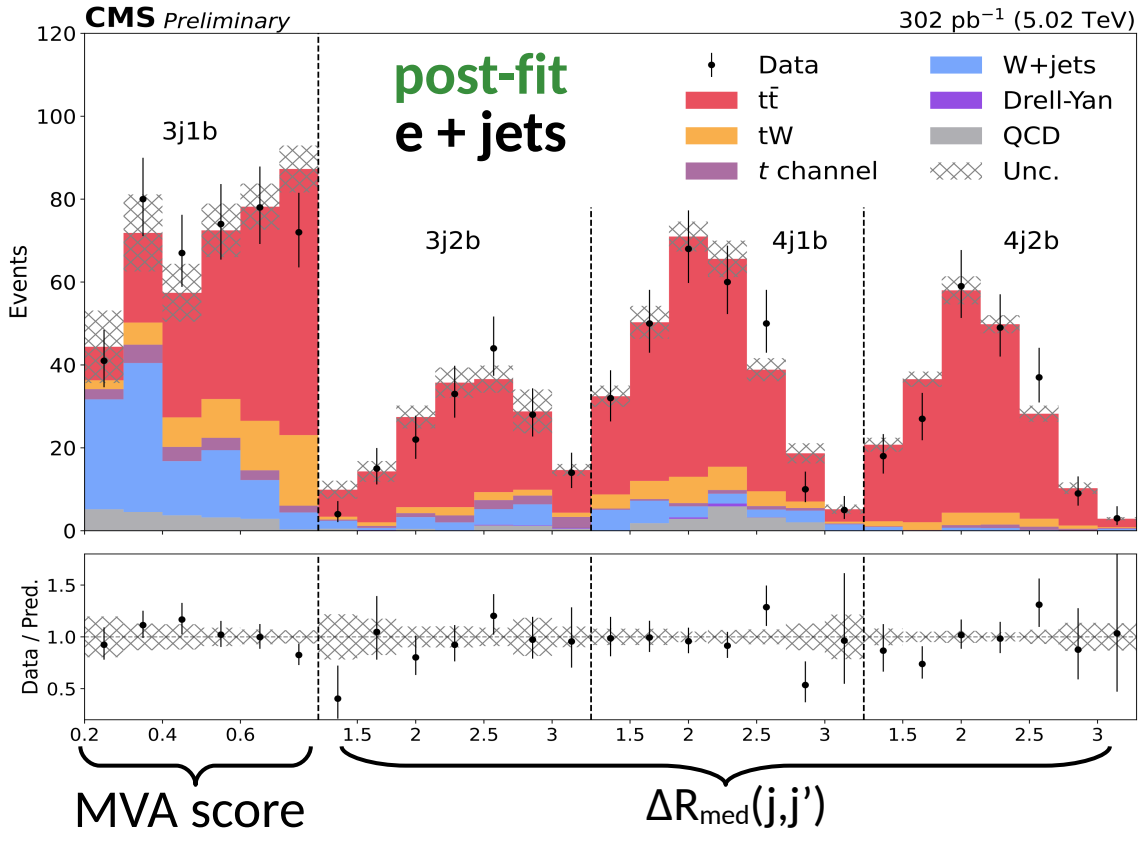
- Categorize by jet & b-jet multiplicity
- Further binning in each category to distinguish signal vs. backgrounds:

$\Delta R_{med}(j,j')$ – 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)



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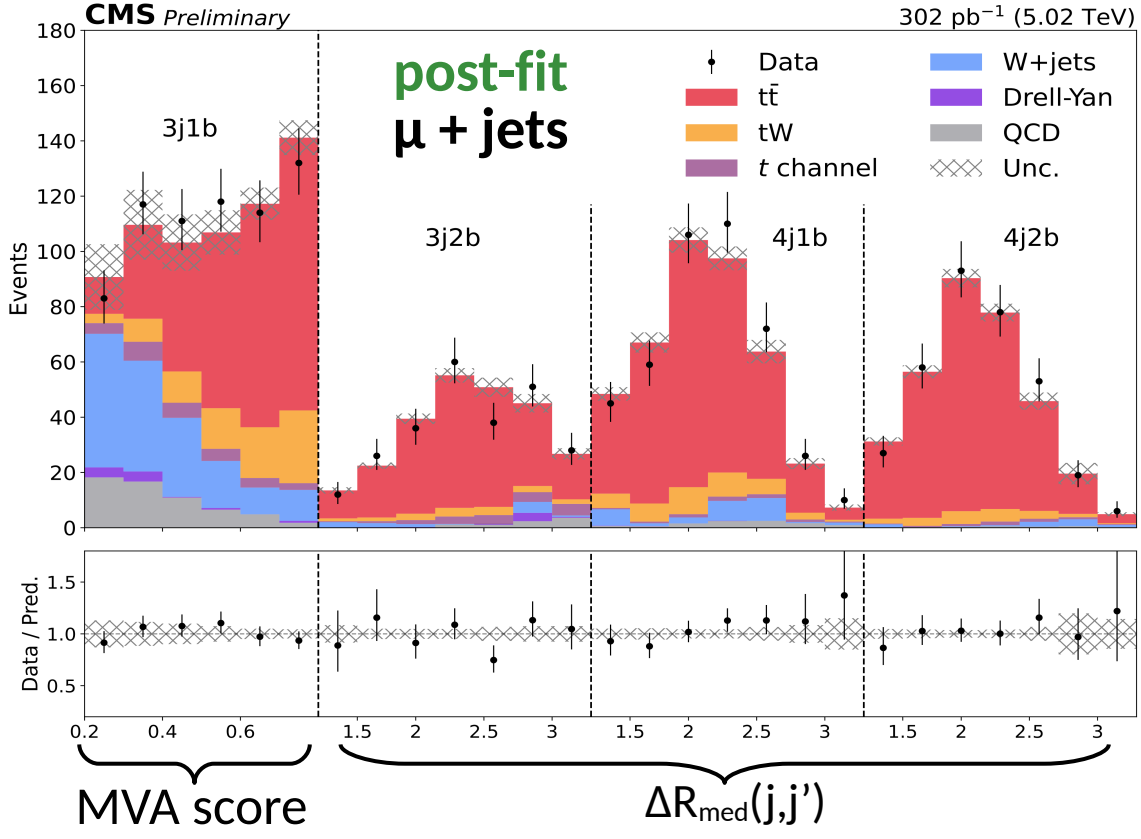
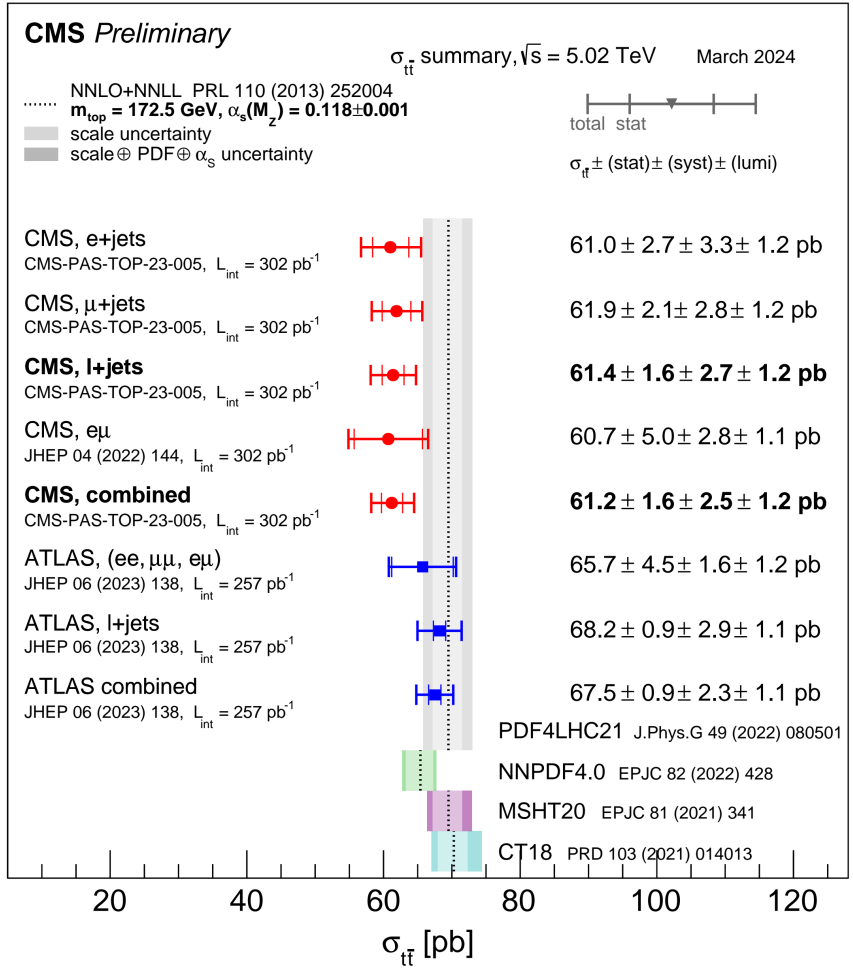


Inclusive cross section @ 5.02 TeV

Result + combination CMS-PAS-TOP-23-005

- Improves previous CMS measurements:
  - ℓ+jets only result: **13% → 5.5% unc.**
    (vs JHEP 03 (2018) 115)
  - eμ/ℓ+jets combo: **8.4% → 5.1% unc.**
    (vs. JHEP 04 (2022) 144)
- **Limiting uncertainties:**
  - b-tagging, trigger, lepton ID efficiencies
  - Statistics

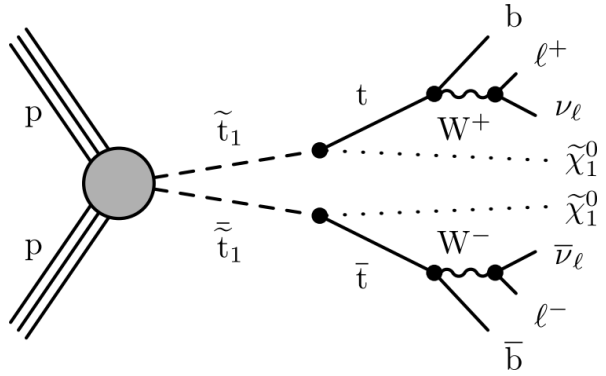


A new differential measurement

- **$t\bar{t}$ differential measurements**:
  - Visible event (b, ℓ)
  - Intermediate particles (t, W)
  - Invisible event (v, ?) → **first measurement!**

- In BSM scenarios, the additional particles can contribute to undetected momentum

- Differential measurement of vv system kinematics:
  - First precision test of invisible event component via differential measurement
  - New means of distinguishing SM vs BSM scenarios



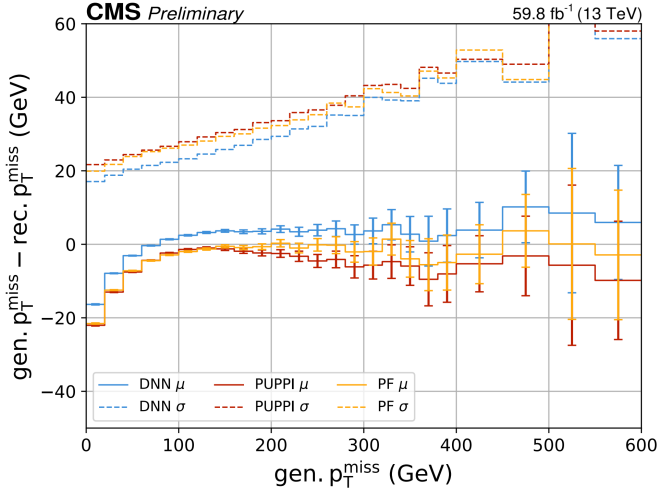
Example: stop pair production with two neutrinos and two neutralinos

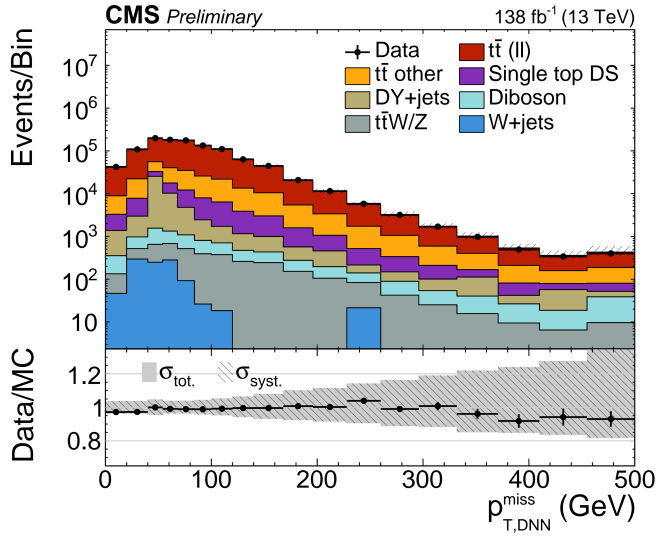
$t\bar{t}$ di-neutrino system kinematics

$p_{T,miss}$ (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



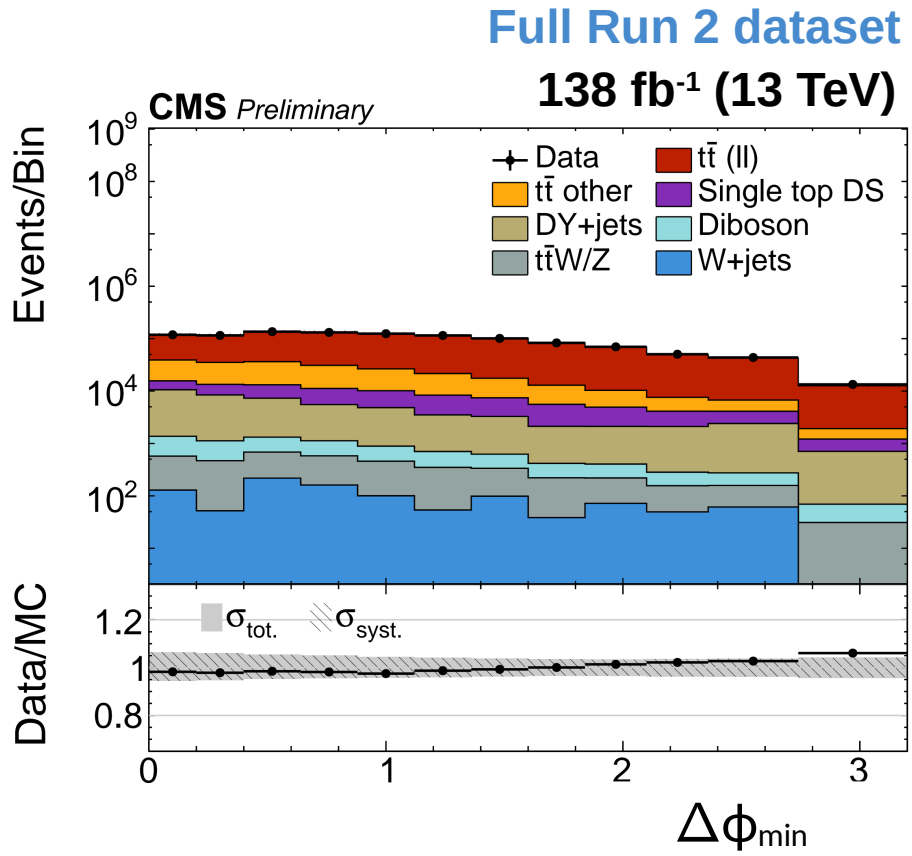


$t\bar{t}$ di-neutrino system kinematics

- Using **DNN MET**, focus on two variables sensitive to BSM contributions
  - $p_{T,miss} = p_T(\nu\bar{\nu})$
  - $\min[\Delta\phi(p_{T,miss}, \ell)] \equiv \Delta\phi_{min}$

Selection:

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

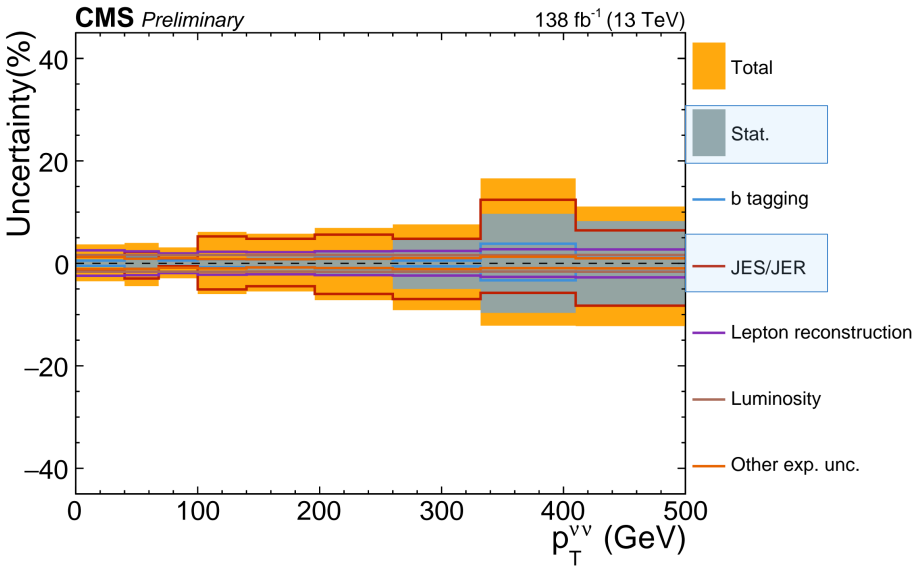


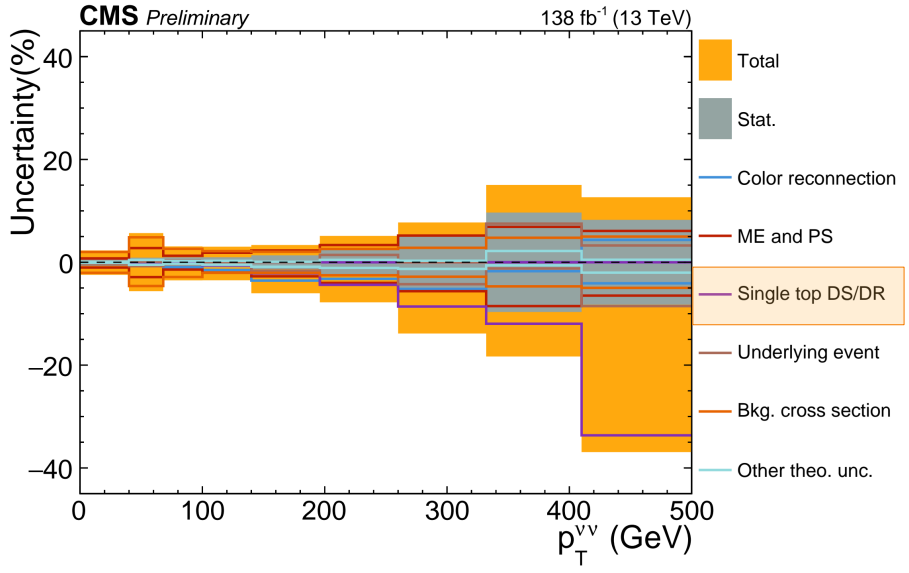
→ Also measure **2D distribution**

Dominant uncertainties

Experimental uncertainties

Dominated by JES/JER, statistics



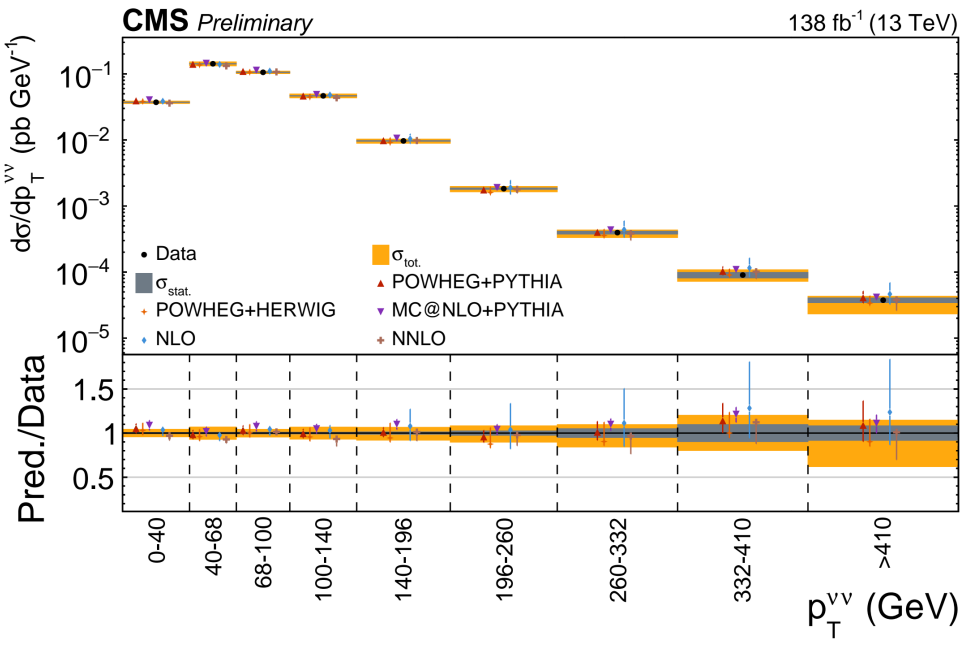


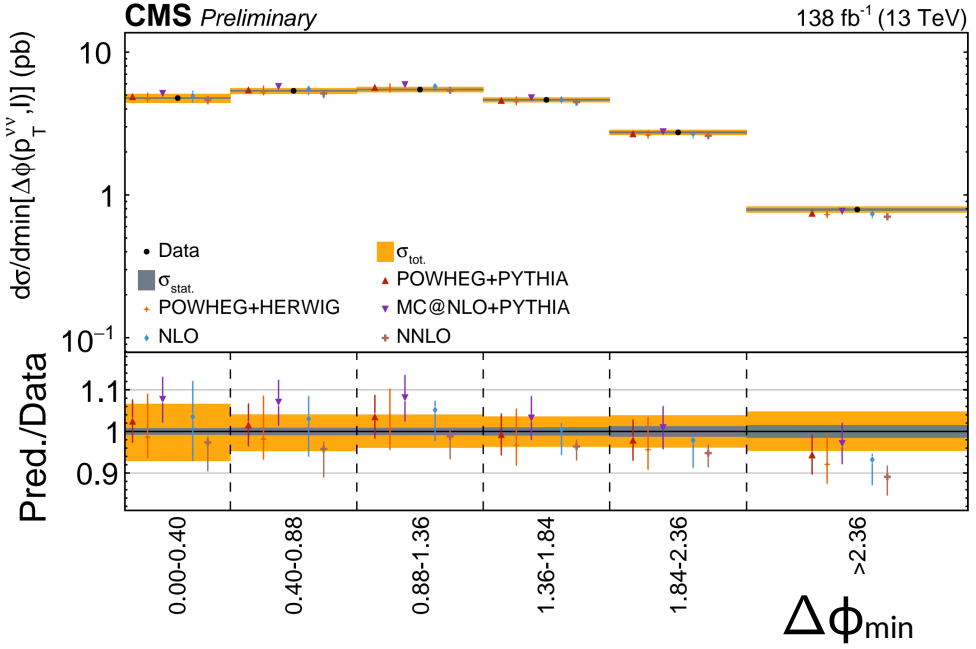
Theoretical uncertainties

Dominated by tW interference
(diagram subtraction vs. removal)

Results: differential cross sections

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

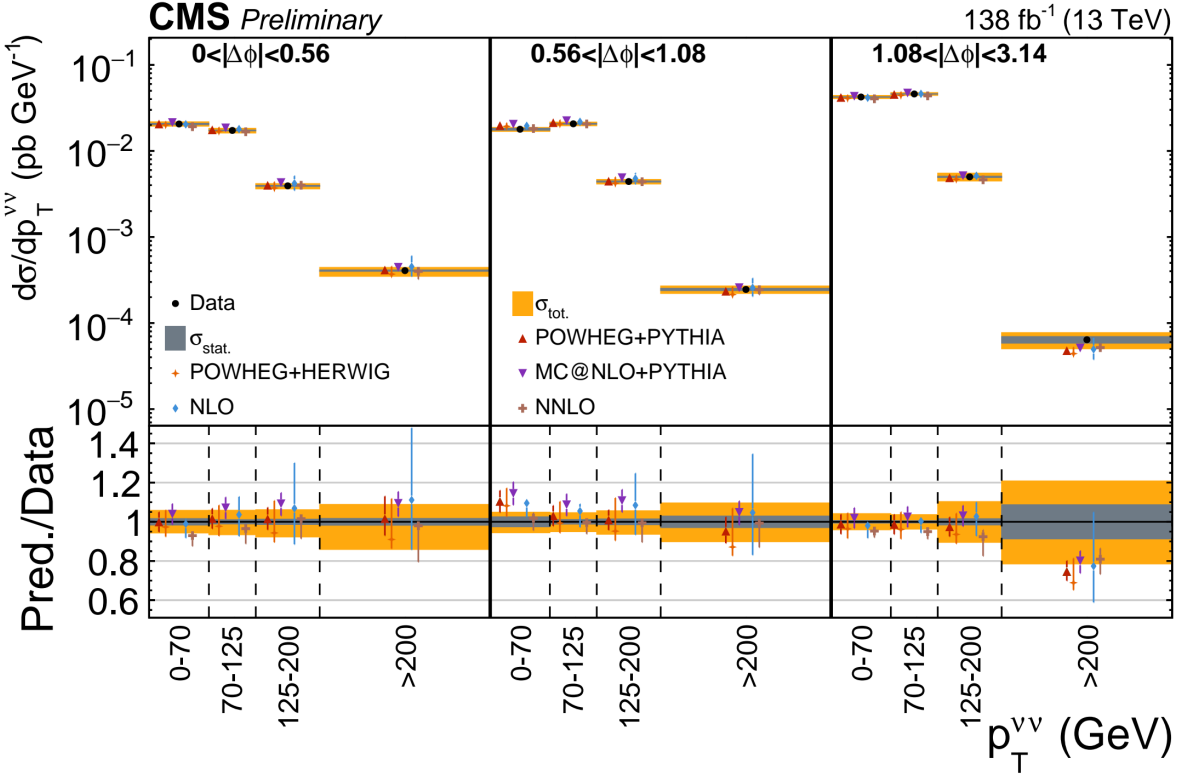




POWHEG+PYTHIA show best agreement (but differences are small)

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)

Conclusions

CMS continues to perform a variety of interesting precision measurements targeting tt cross sections (inclusive and differential)

- 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

- Recently, 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-PAS-TOP-23-005

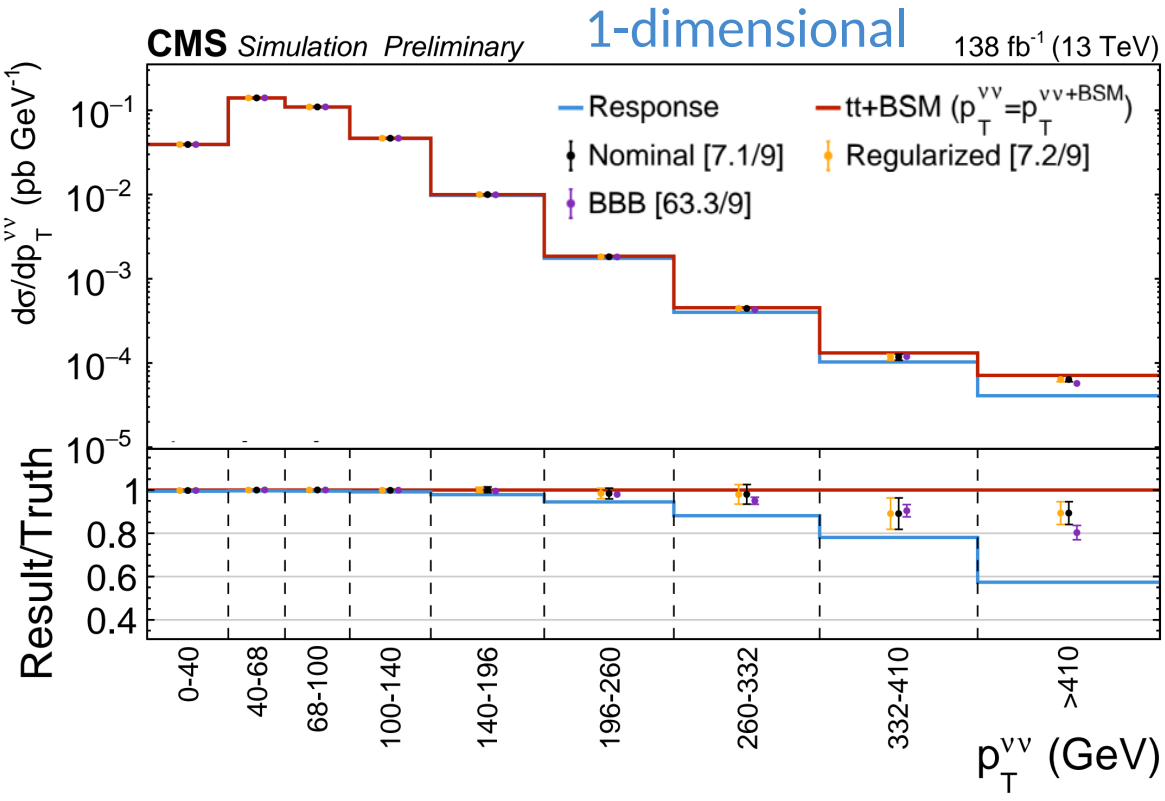
- CMS presents a brand new preliminary measurement of the **dineutrino system** kinematics, the **first** differential result focusing on **invisible event component!**

  Online soon: CMS-PAS-TOP-24-001

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)
- [χ^2 /ndf] shown in legend

↳ **Correct distributions reproduced**

Di-neutrino system: closure test

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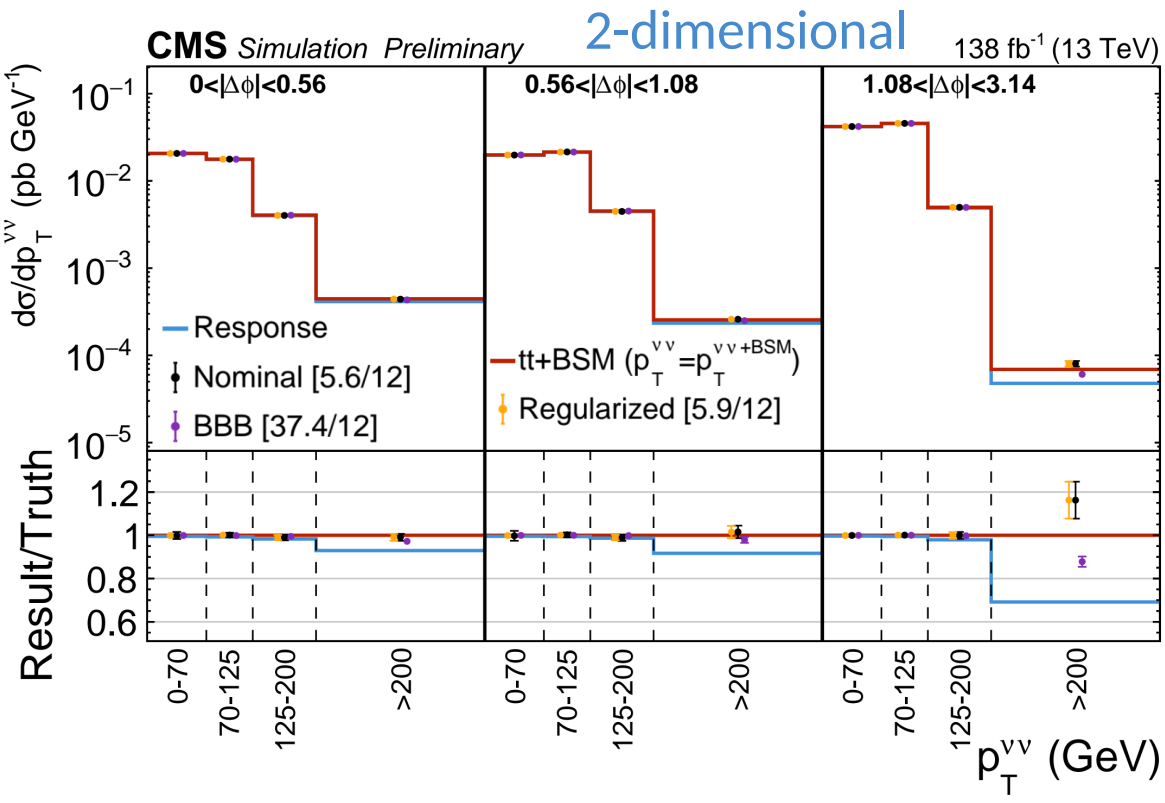

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Normalized differential cross sections

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