Inclusive and differential results of top quark pair production from ATLAS+CMS

16th International Workshop on Top Quark Physics (TOP2023)

24-29 September 2023, Traverse City, Michigan (USA)

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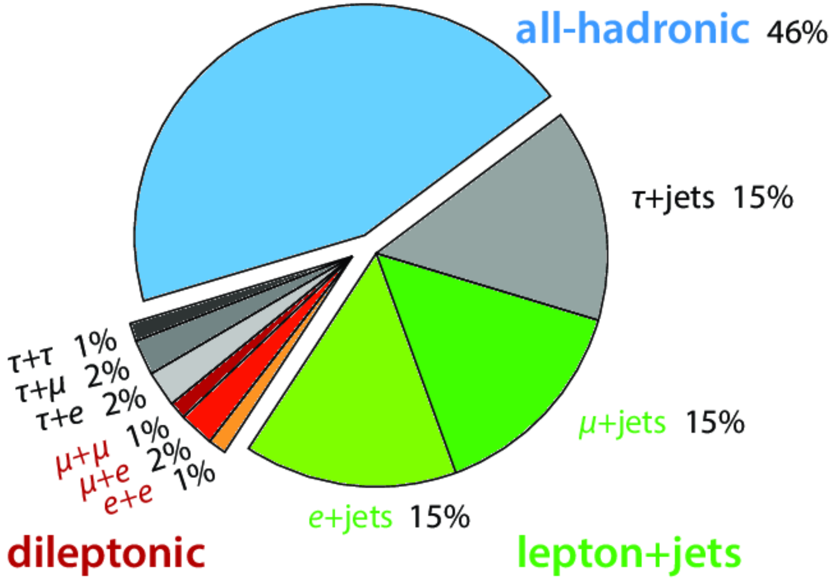
on behalf of the CMS and ATLAS Collaborations

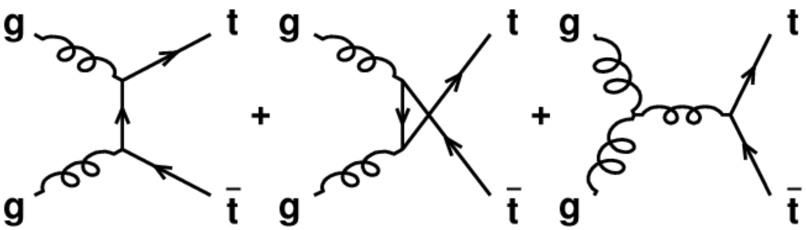
$t\bar{t}$ production at the LHC

Top is most massive particle of the SM

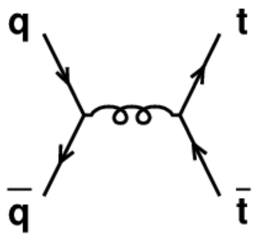
Produced in pairs in large quantities
- Already ~100M in ATLAS+CMS in Run 3



~90%



~10%



$\sigma_{t\bar{t}}$ theory prediction and measurements at similar precision
- Stringent test of perturbative QCD and EW theory
- Input to Global PDFs fits
- Extraction of α_S, m_{top}

$t\bar{t}$ at 13.6TeV

ATLAS & CMS effectively collecting run 3 data
- First analyses on tt – CMS result on last years' TOP

tt involves variety of different particles
- Distinctive signature
- Uses information of all main detector components
- Great opportunity to validate new data

> 10% increased cross section

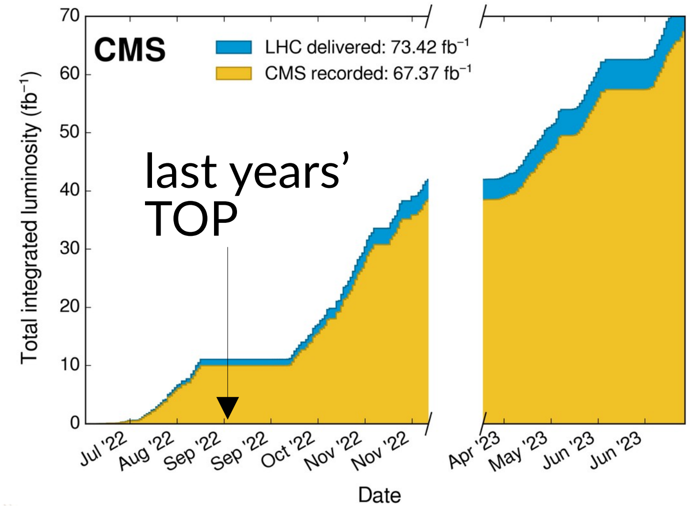
$\sqrt{s}$: 13 TeV → 13.6 TeV

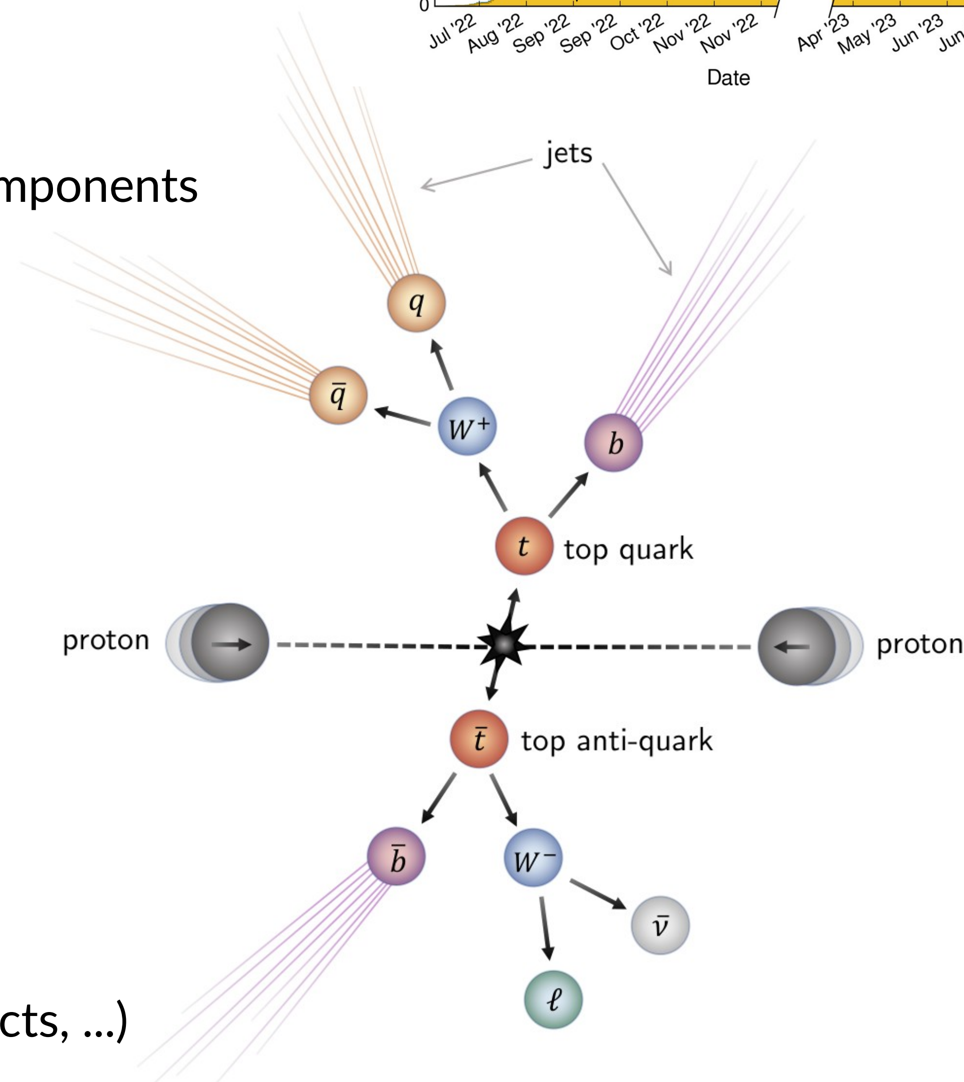
$\sigma_{t\bar{t}}$: 834 pb → 924 pb

Expected uncertainty smaller than expected change in cross section

First meaningful test of the SM at new energy frontier

This year: updated results (luminosity, objects, ...)





CMS measurement at 13.6TeV

Combination of various channels: eμ, ee, μμ, e+jets, μ+jets

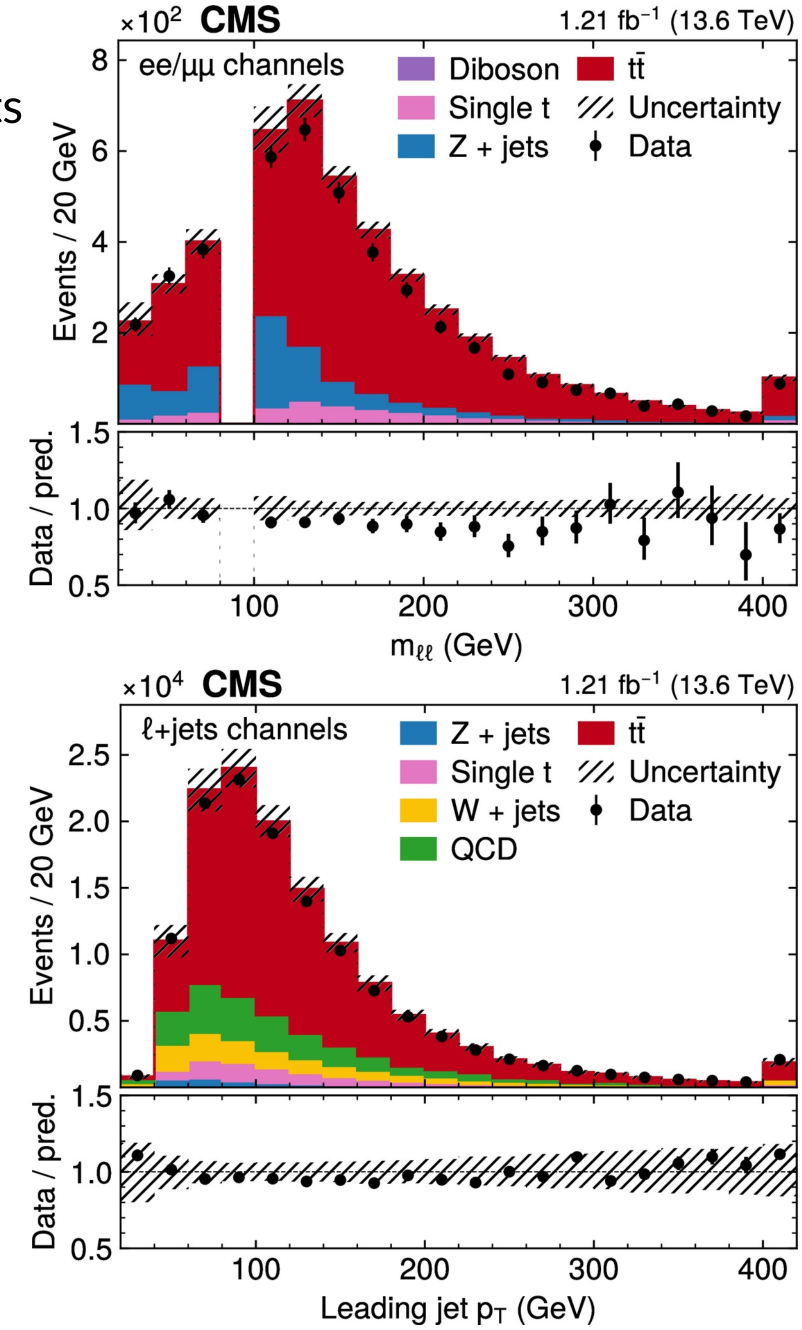
- ~1 fb^{-1} of data collected in summer 2022

Changes w.r.t. preliminary result:

- New jet reconstruction algorithm
  - Pileup per particle probability identification (PUPPI)
- Free floating lepton efficiencies → dedicated scale factors

QCD multijet events in l+jets channels

- Estimated in data from matrix/fake rate method
  - Fake rate measured in 1 jet events
  - Applied to events in anti iso region



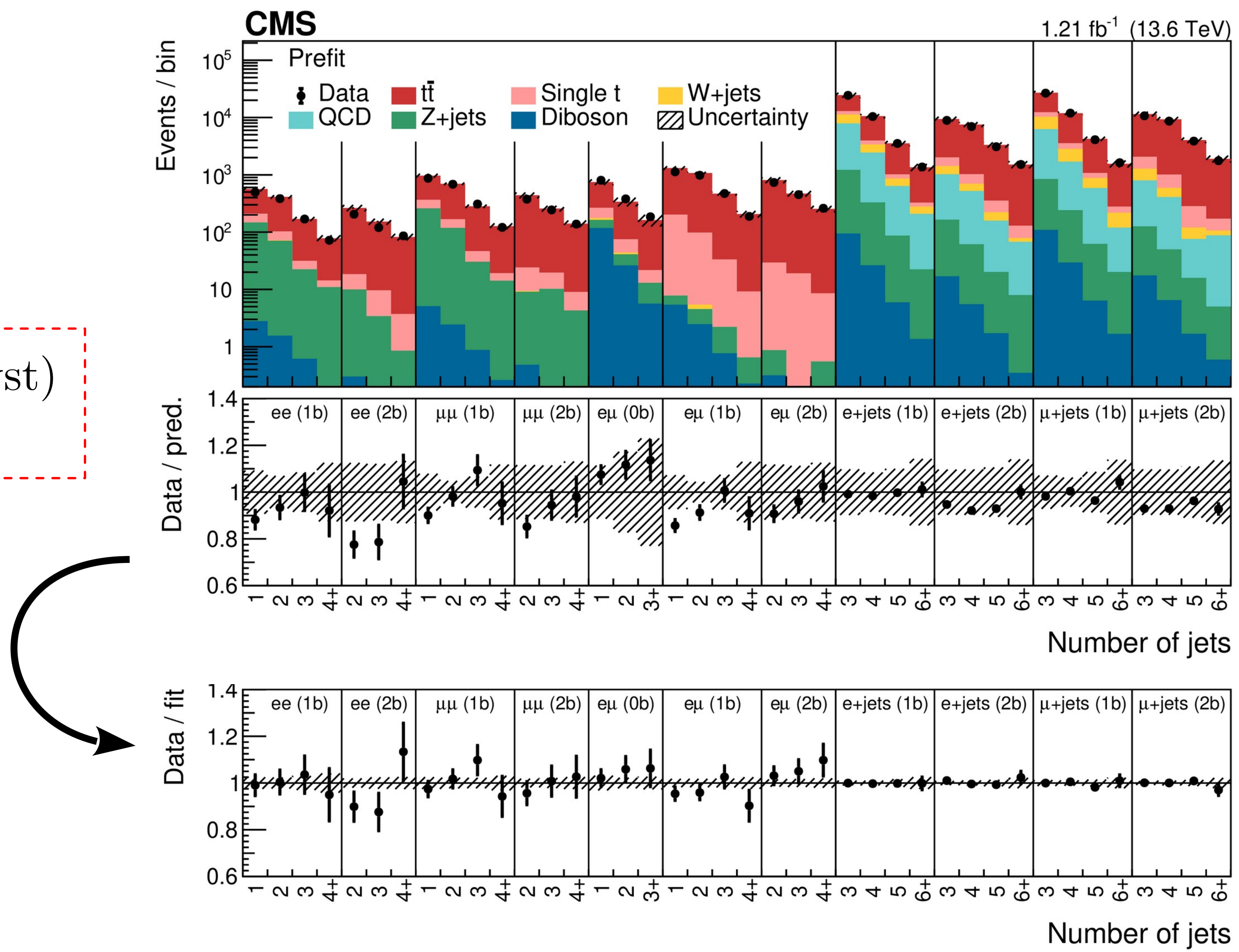
CMS measurement at 13.6TeV

Likelihood fit performed in bins of:

- Lepton flavor
- Number of b-jets
- Number of jets

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

~11% → ~3.5%



ATLAS measurement at 13.6TeV

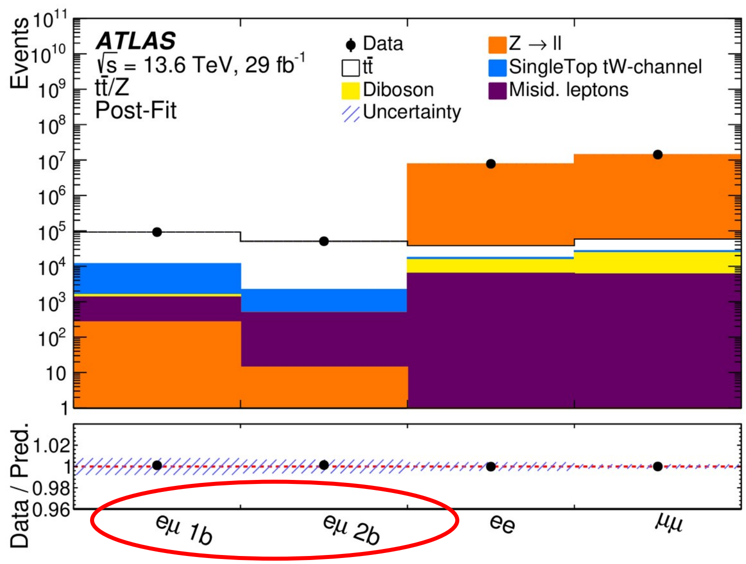
Measurement targets most pure eμ channel

- Updated using full 2022 data, 29fb^{-1}

Simultaneously extracting σ_Z in ee and μμ channels

Using b-tag counting – minimize b-tagging systematic

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}},$$
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\mathrm{bkg}},$$

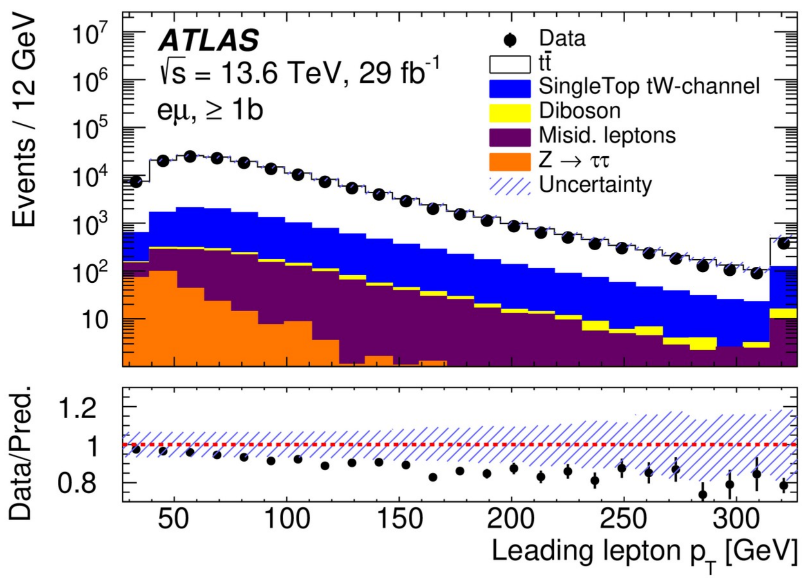


Results

$$\sigma_{t\bar{t}} = 850 \pm 3(\mathrm{stat}) \pm 18(\mathrm{syst}) \pm 20(\mathrm{lumi})\mathrm{pb}$$

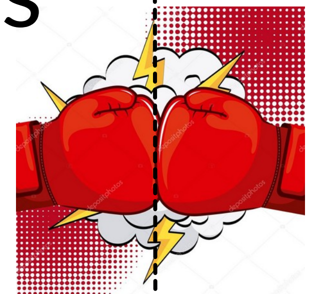
~11% → ~3.2%

$$\sigma_{t\bar{t}}^{\mathrm{NNLO+NNLL}} = 924^{+32}_{-40}\mathrm{pb}$$



[arXiv:2308.09529]

ATLAS uncertainties

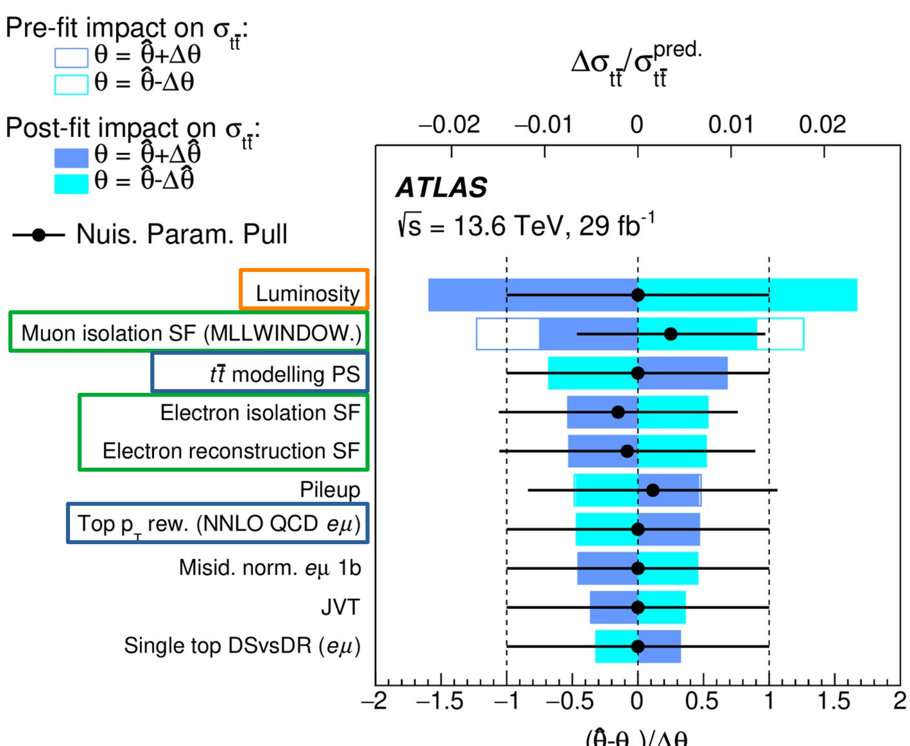


Luminosity

Leptons

Signal modeling

Moderate pulls & constraints



[arXiv:2303.10680]

CMS uncertainties

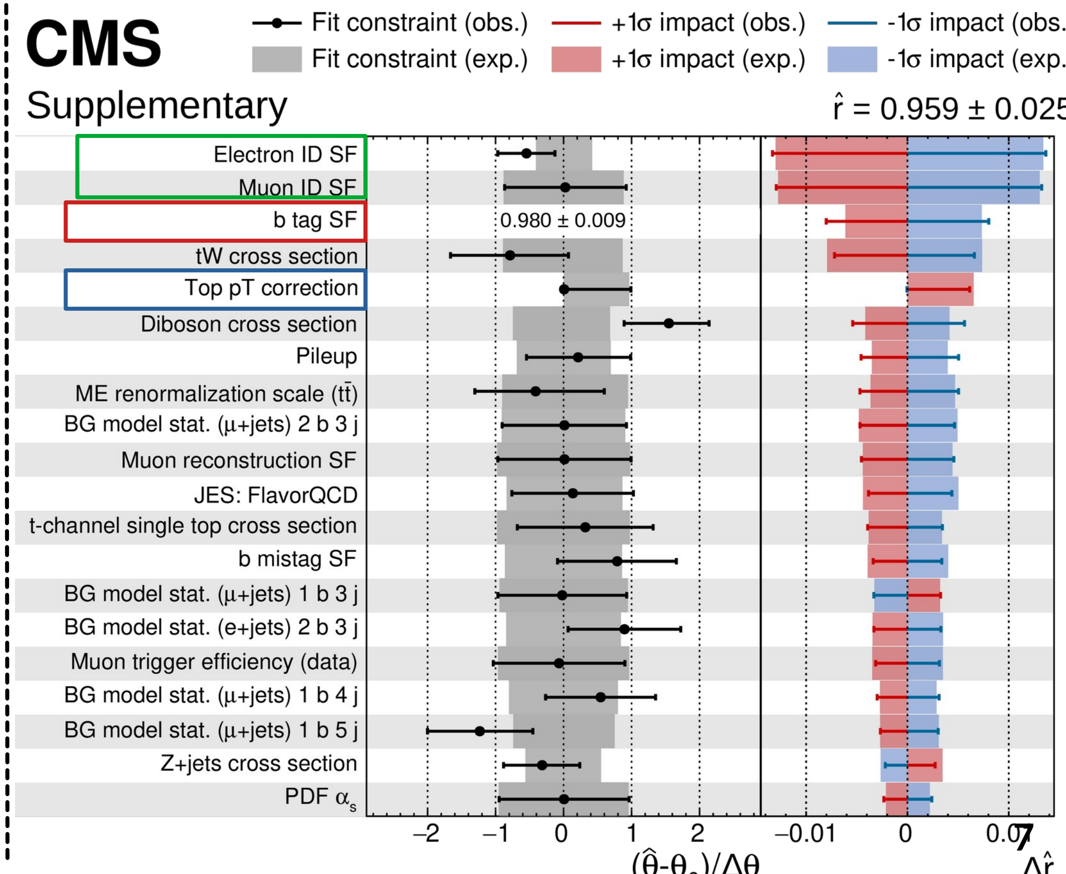
Luminosity (externalized)

Leptons

B tagging

Significant pulls & constraints

- Expected from in situ measurement via channel combination

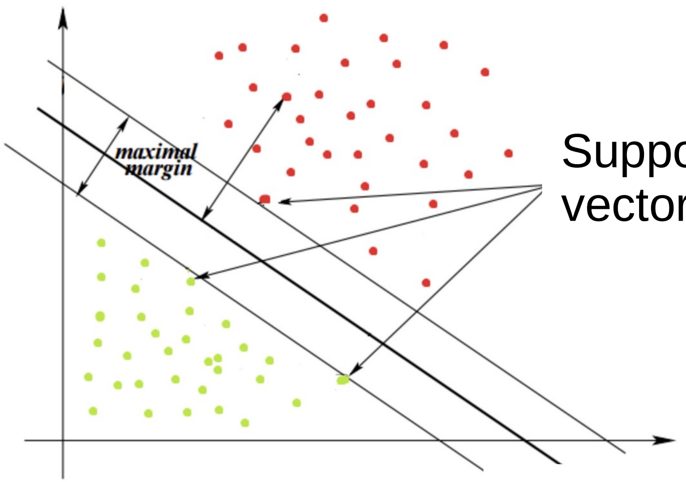


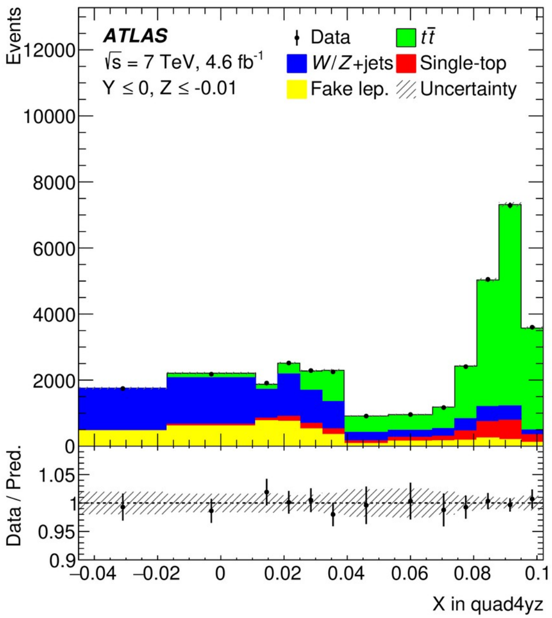
$\sigma_{t\bar{t}}$ at 7 TeV using support vector machines

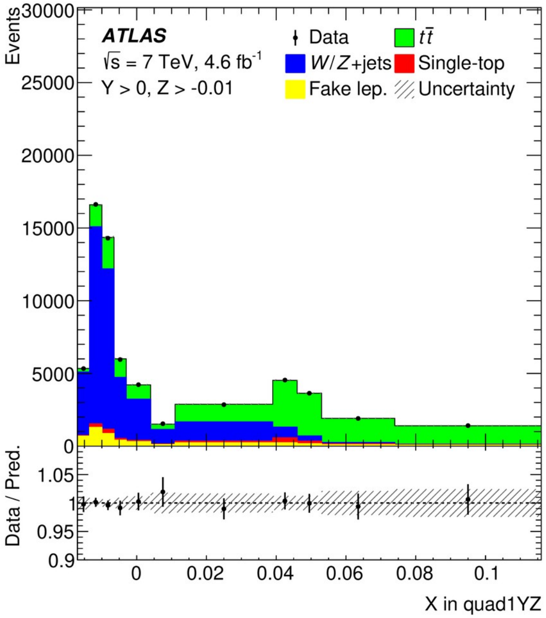
lepton+jets channel, using full 2011 data: 4.6fb^{-1}

3 SVMs → 3 dimensional space to construct multi-class discriminant

- $t\bar{t}$ vs. W/Z+$b\bar{b}$ vs others
- Discriminating variables in 4 regions







Firm mathematical foundation
Simple geometric interpretation
Minimum is global minimum
Robust against overtraining

Profile likelihood fit results in

$$\sigma_{t\bar{t}} = 168.5 \pm 0.7(\text{stat})^{+6.2}_{-5.9}(\text{syst})^{+3.4}_{-3.2}(\text{lumi})\text{pb}$$

Consistent with SM

~2σ tension to ATLAS 7TeV dileptonic

Improved precision w.r.t previous ATLAS result in lepton+jets channel at 7TeV 12% → 4%

Jet substructure in boosted $t\bar{t}$ events at 13TeV

Understanding/modeling of jet substructure
- Input for jet identification, tuning studies, ...

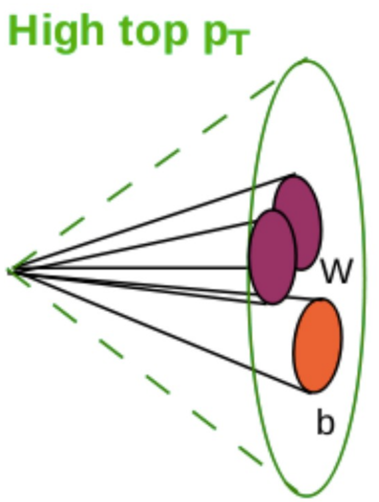
Test color reconnection, parton shower, hadronization
- Energy flow of jet (e.g. quarks vs. gluons)
- Three and two prong structure (e.g. top tagging)

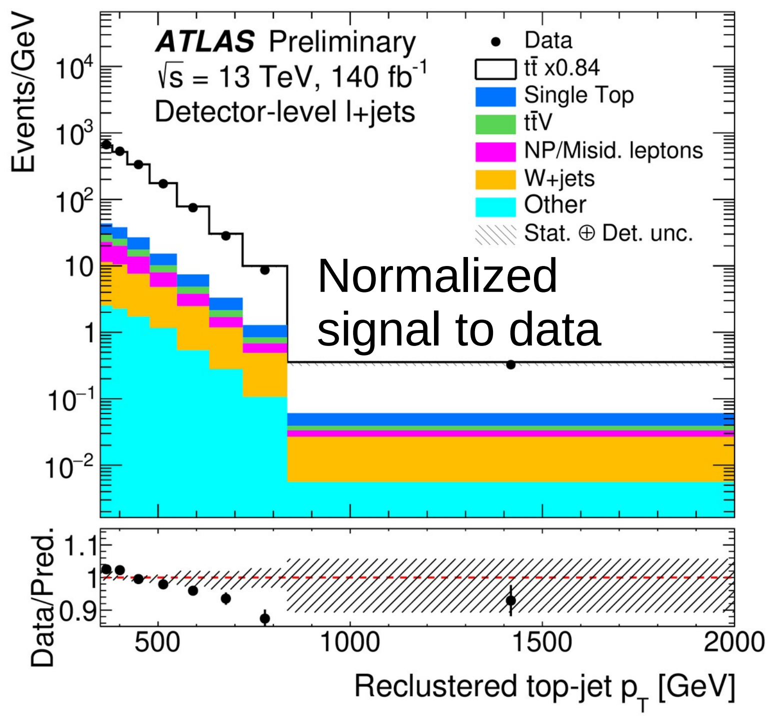
Using full Run 2 pp data: 140fb^{-1}

Lepton+jets channel:
- Large-R jet with p_T>350GeV
- Matrix method for nonprompt leptons

All-hadronic final state:
- Two large-R jets with p_T > 500 (350) GeV
- ABCD method for multijet background

Excess in data of 15-20% observed
- Consistent with p_T(top) mismodeling





Jet substructure in boosted $t\bar{t}$ events at 13TeV

Differential cross sections measured at particle level

- 8 Measured variables
- Iterative Bayesian unfolding

Leading uncertainties

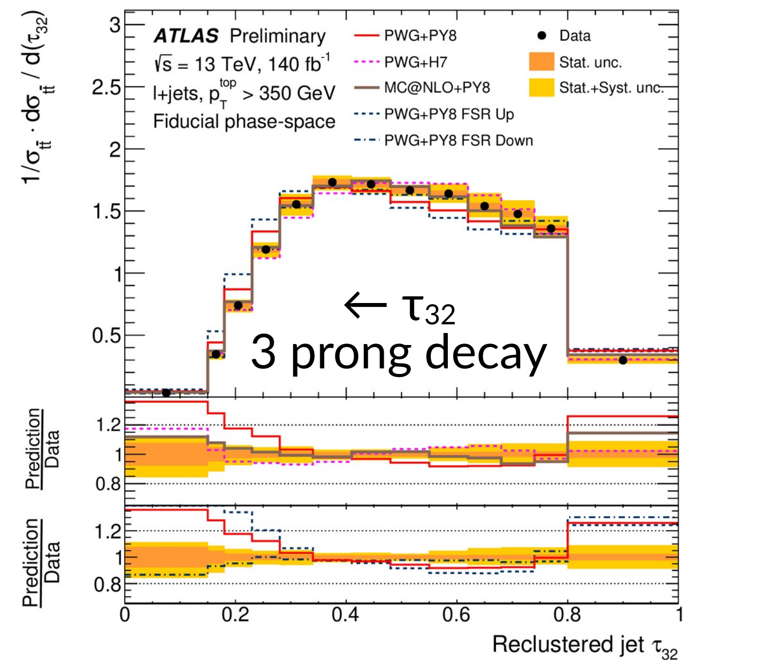
- Modeling: ISR/FSR, Parton shower
- Experimental: JES/JER

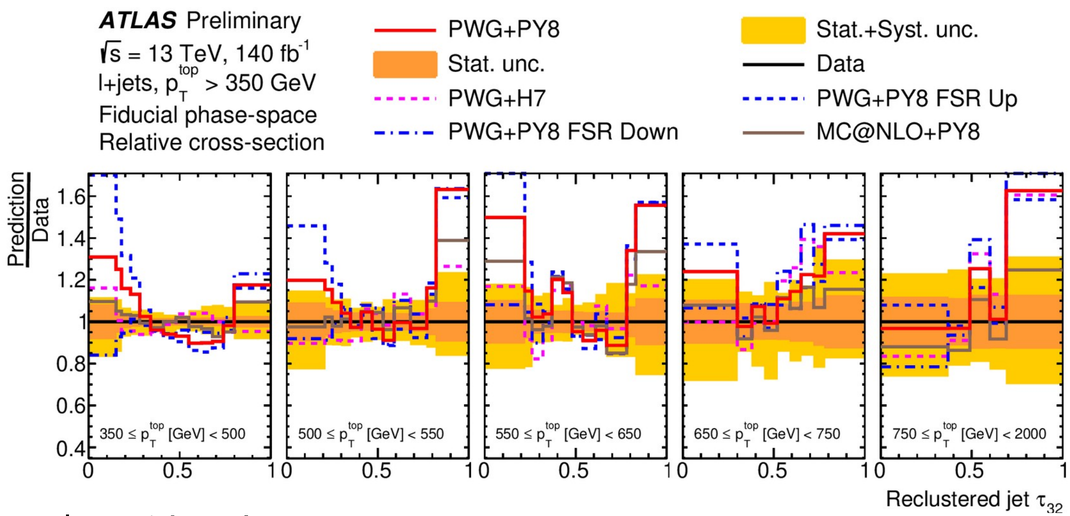
Qualitative and quantitative assessment

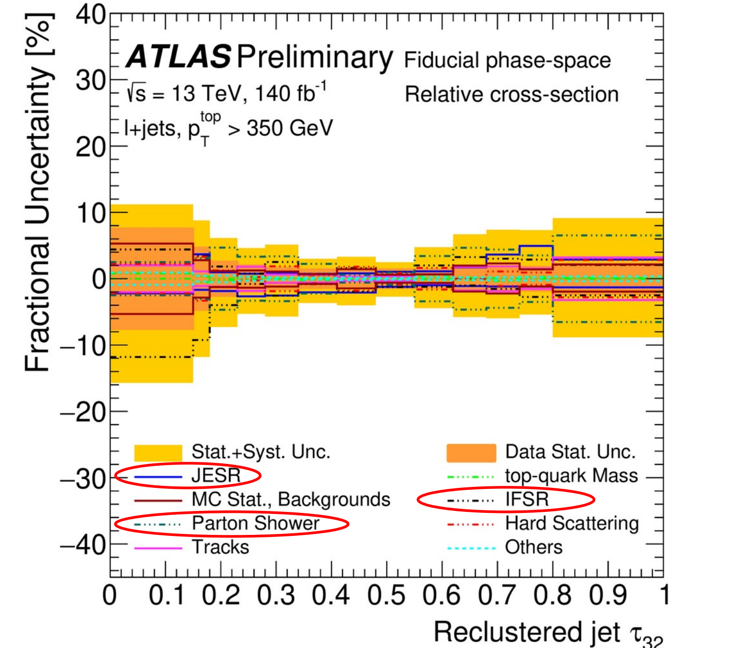
- E.g. FSR Up disfavored by data

Correlations with m(top) and p_T(top) are of particular interest in use of tagger for analyses

- 2D distributions measured







$\sigma_{t\bar{t}}$ in eμ channel at 13TeV

Using full Run 2 pp data: 140fb^{-1}

- Background for mis. ID leptons from SS events
- Correction for Z→ττ from Z→ee/μμ
- Correction of lepton isolation scale factors in $t\bar{t}$
- B-tag counting method (w/o fit)

$$\sigma_{t\bar{t}} = 829 \pm 1(\text{stat}) \pm 13(\text{syst}) \pm 8(\text{lumi}) \pm 2(\text{beam})\text{pb}$$

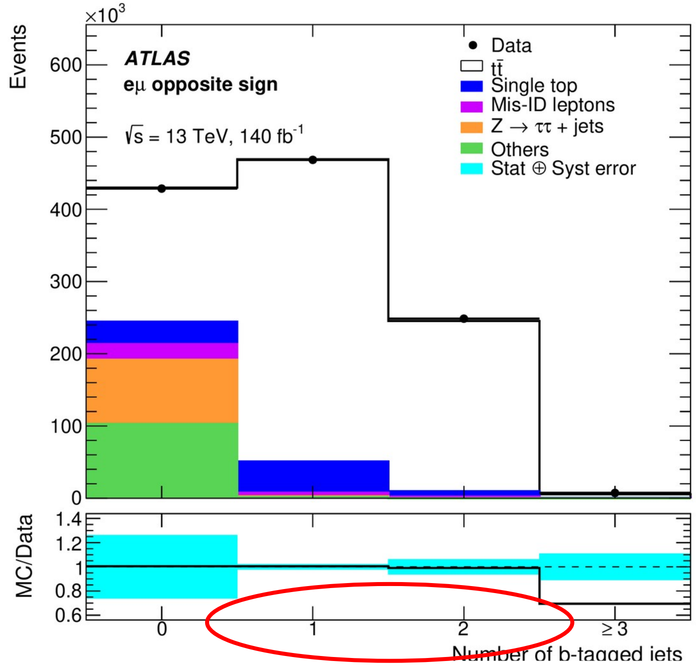
~1.8%

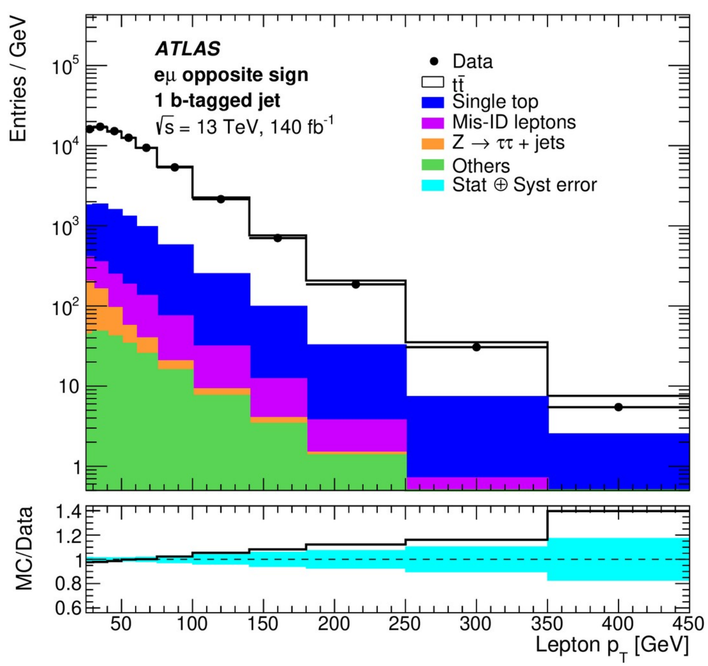
Leading systematics:

- Luminosity (0.93% see link)
- Top p_T reweighting (0.6%)
- tW background (0.6%)
- Lepton selection

In agreement with theory

$$\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 832^{+20}_{-29}(\text{scale})^{+23}_{-23}(m_{\text{top}})^{+35}_{-35}(\text{PDF}+\alpha_s)\text{pb}$$





[JHEP 07 (2023) 141]

Differential $\sigma_{t\bar{t}}$ in eμ channel at 13TeV

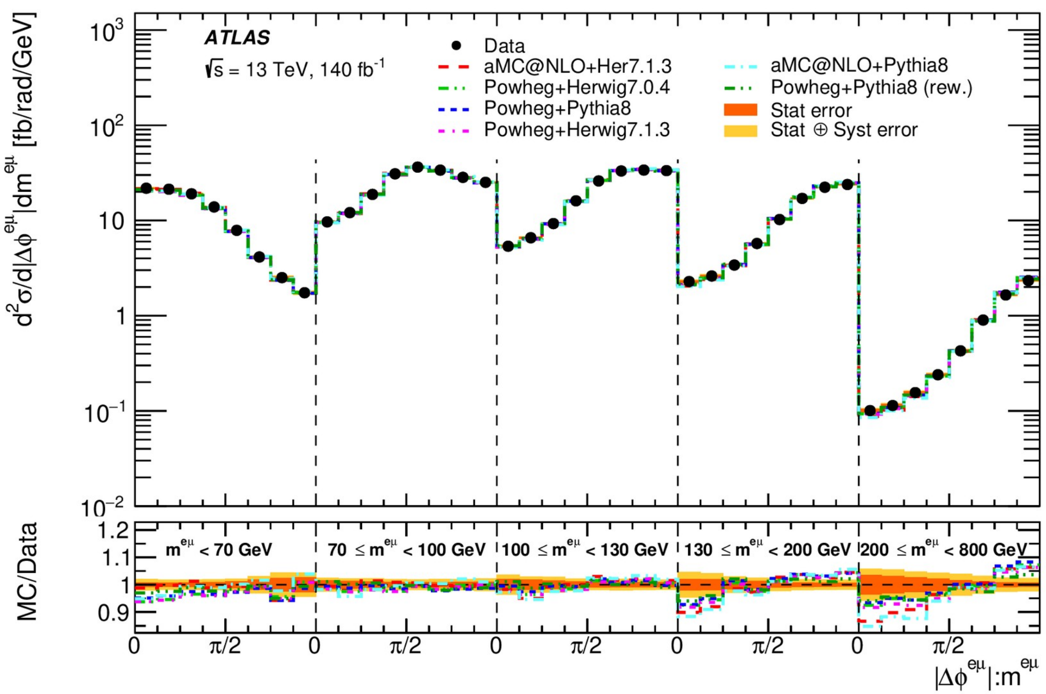
Bin by bin unfolding

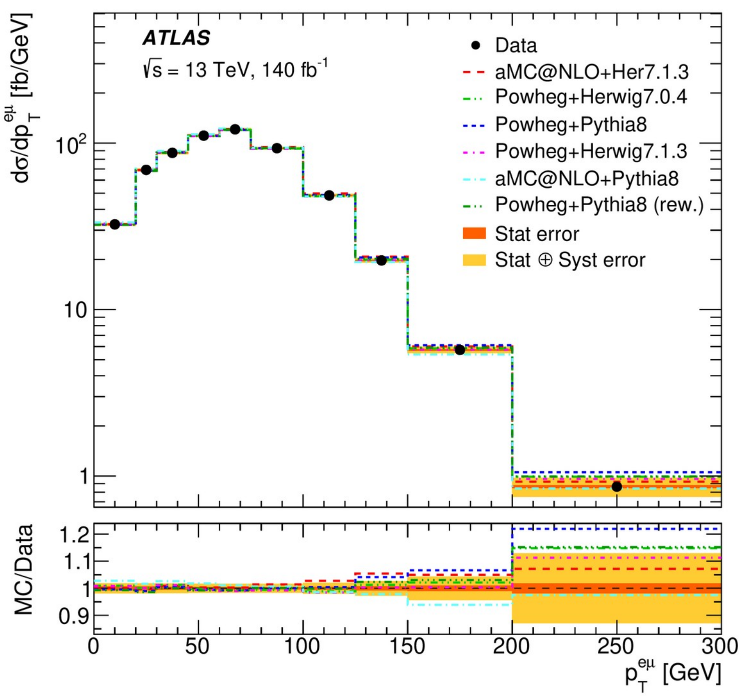
Single and double differential cross sections at particle level

- 8 kinematic variables for lepton

No generator able to describe measurement in all bins

- Mismodeling is enhanced in double differential measurements
- E.g. data suggests leptons to be less separated, especially at high masses





Differential $\sigma_{t\bar{t}}$ in dilepton channel at 13TeV

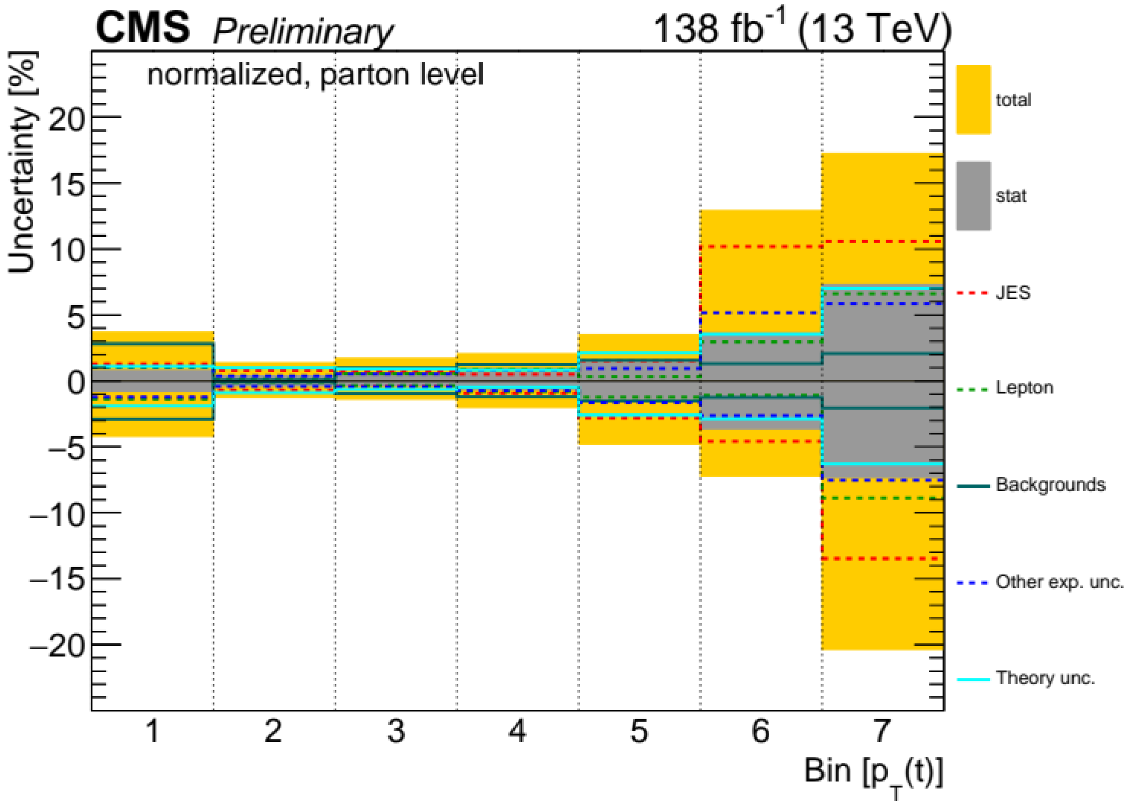
1D, 2D and 3D cross sections measured using full Run 2 data

- Unfolded results at parton and particle level from χ^2 fit using TUnfold
- Full event reconstruction (two versions)

Uncertainties reduced by factor of 2 w.r.t. previous results

Dominated by:

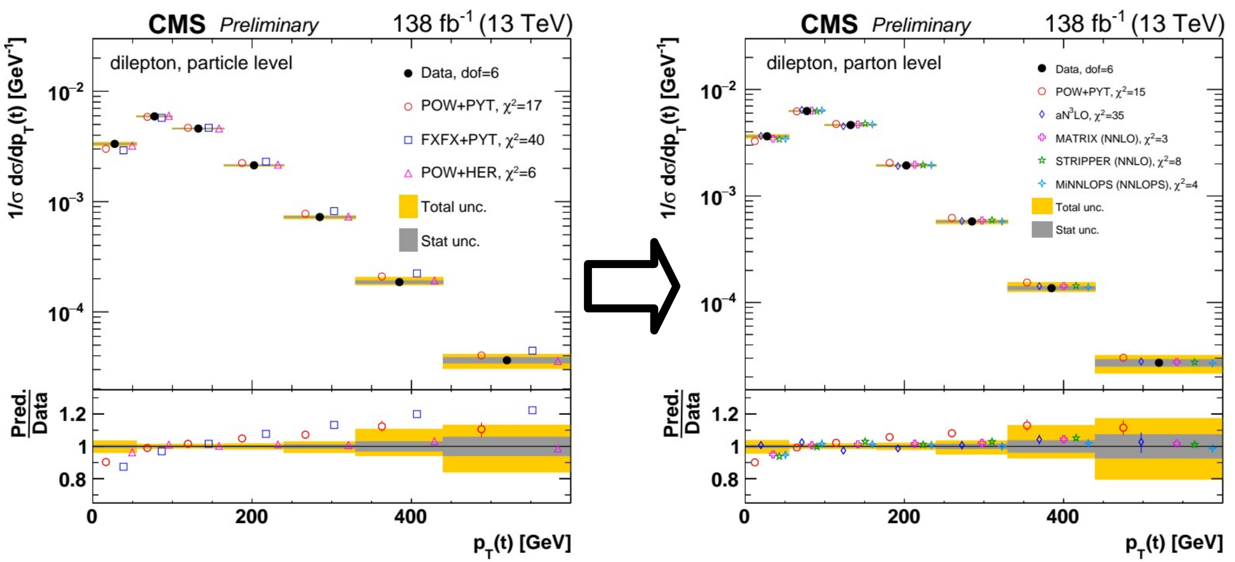
- Jet energy scale
- backgrounds
- lepton selection



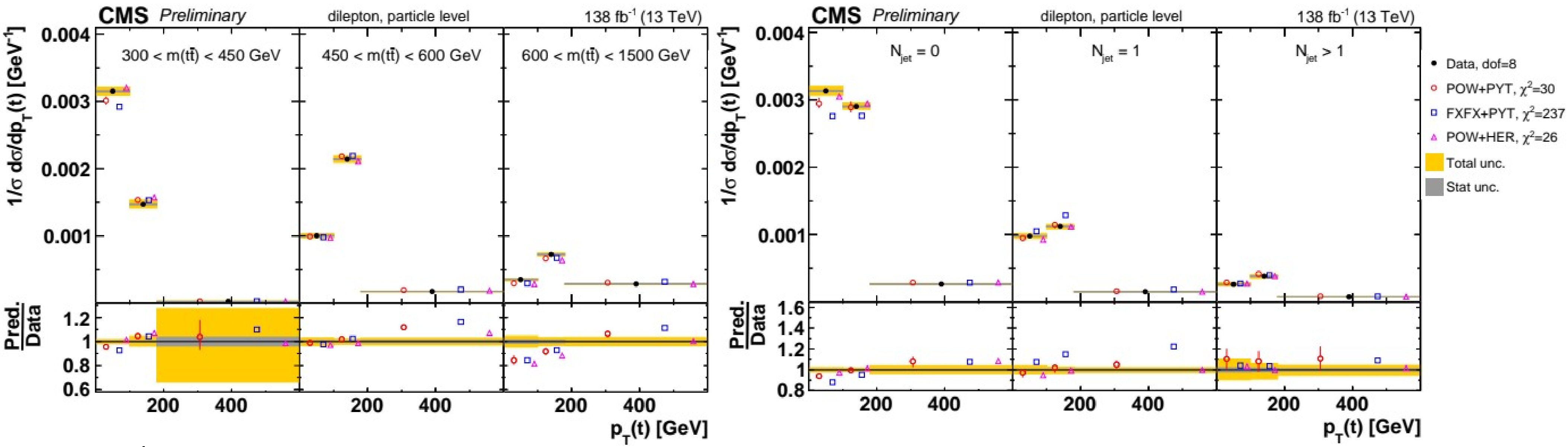
Differential $\sigma_{t\bar{t}}$ in dilepton channel at 13TeV

Compared to
- NLO event generators
- beyond NLO calculations
- PDF sets

Higher order predictions improve p_T(top) modeling



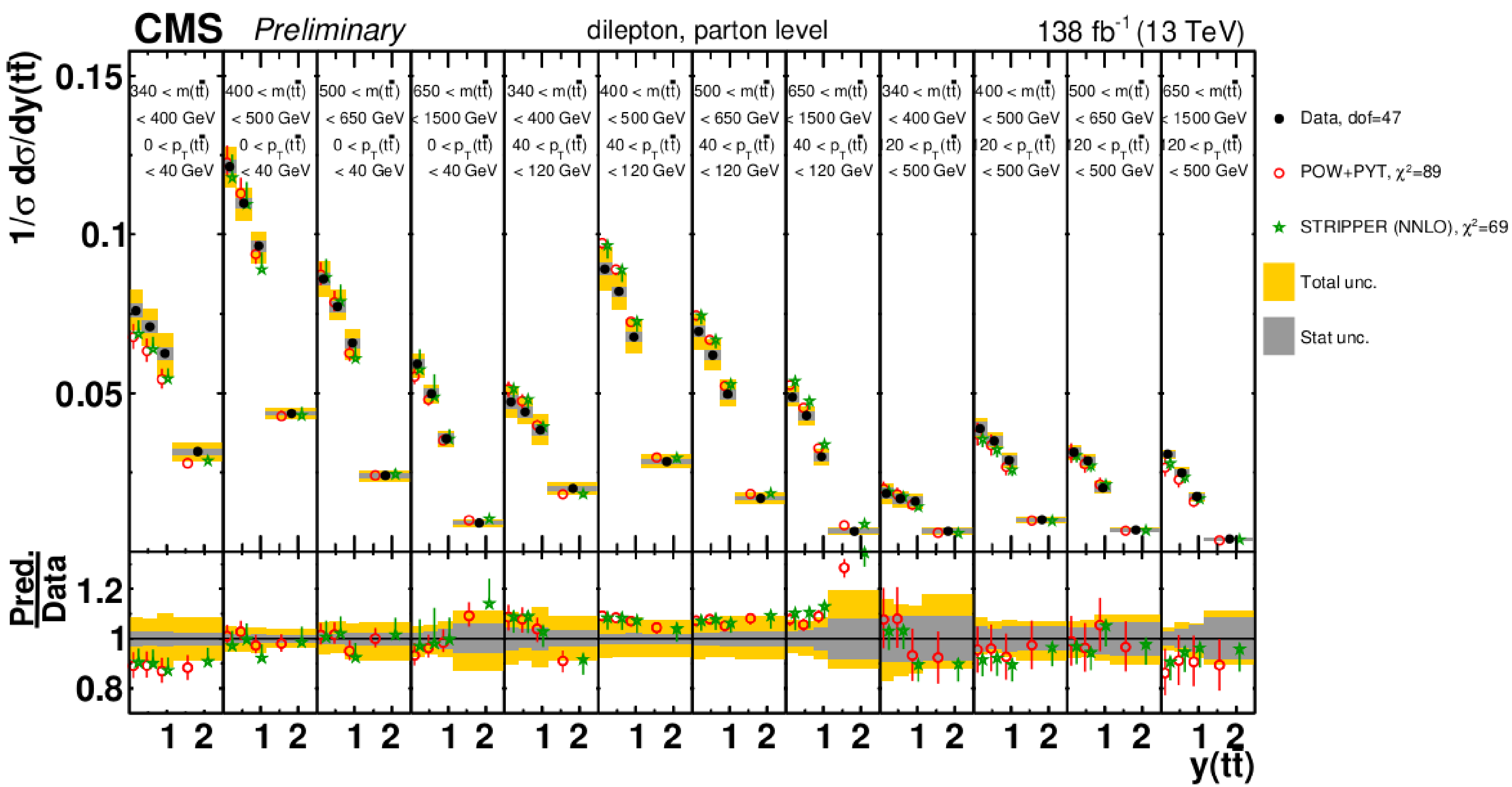
Further insight from 2D distributions
- Mismodeling of p_T(t) enhanced in high m(tt) and localized at low Njet multiplicity



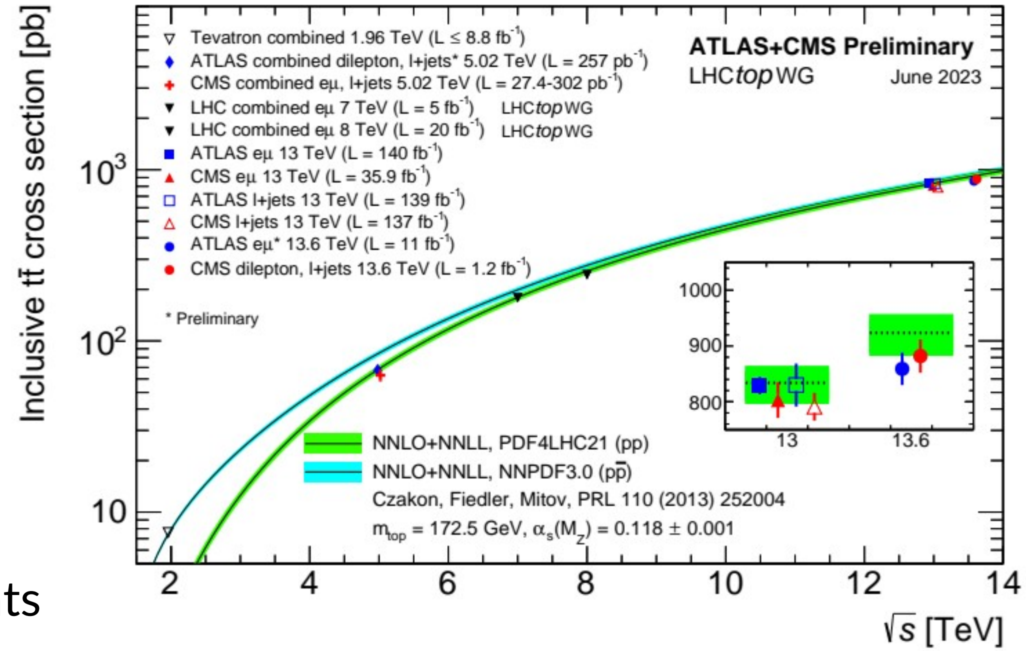
Differential $\sigma_{t\bar{t}}$ in dilepton channel at 13TeV

None of the predictions describe data well in all bins

- Deviations increase in multi-differential cross sections
- Promising input for future PDF fits – in particular for gluon PDF at large x



Summary



$\sigma_{t\bar{t}}$ now measured at 6 different energies

- Generally good agreement with trend towards lower values

Most precise measurements using full Run 2 data

- Multi differential cross section measurements reveal mismodeling in several regions
- Valuable input to global PDF fits / α_S, m_{top} extraction

New methodologies/techniques required to go beyond this precision

Many related topics not covered in this talk

- $\sigma_{t\bar{t}}$ in proton-lead collisions [ATLAS-CONF-2023-063] (see talk)
- $\sigma_{t\bar{t}}$ at 5 TeV [JHEP 06 (2023) 138] (see talk)
- $\sigma_{t\bar{t}}$ differential to test Lorentz invariance violation [CMS-PAS-TOP-22-007] (see talk)
- ...

Backup

$t\bar{t}$ at 5TeV

ATLAS and CMS collected pp data at 5TeV
in heavy ion reference runs

- Low PU – low trigger thresholds, clean events

ATLAS measurement in dilepton and l+jets channels

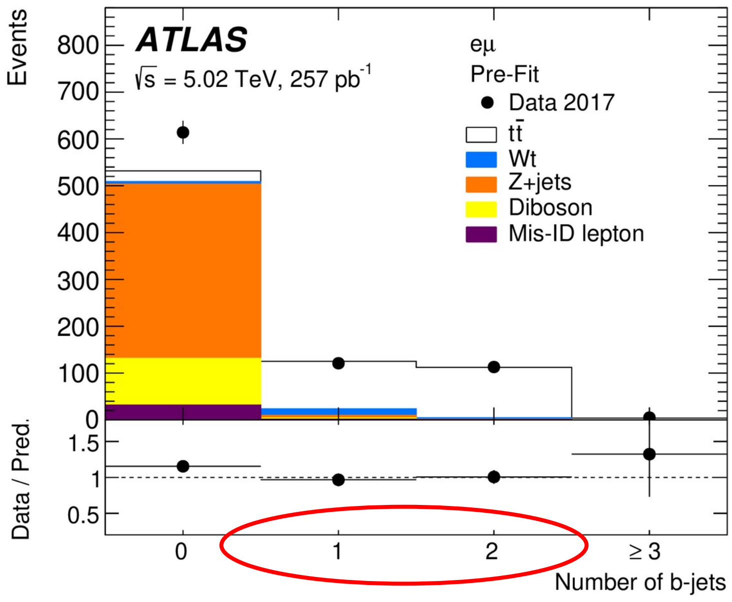
Dilepton: eμ, ee, μμ

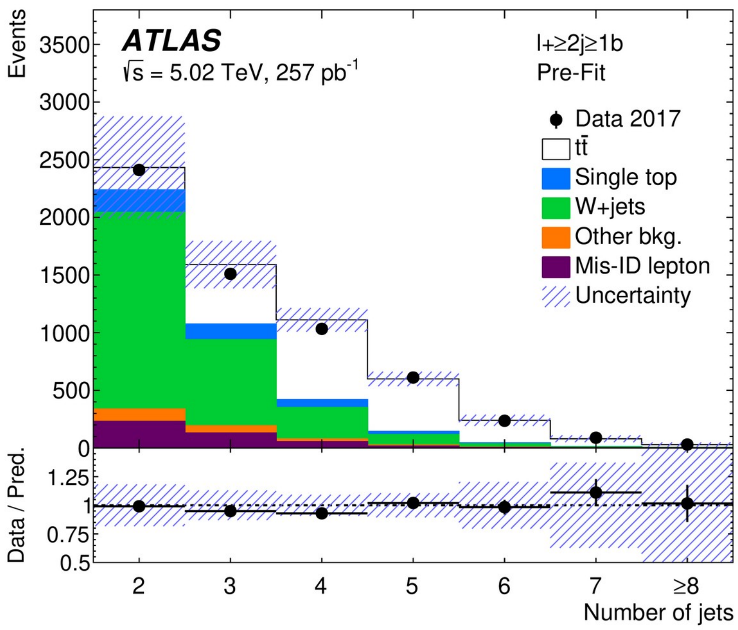
- b-tag counting method (binned in m_{ll} for ee, μμ)
- Result statistics limited

Lepton + jets

- Matrix method for QCD backrgound
- BDTs in different jet/bjet categories
- Result systematics limited:
  - W bkg., luminosity

Both channels combined using convino

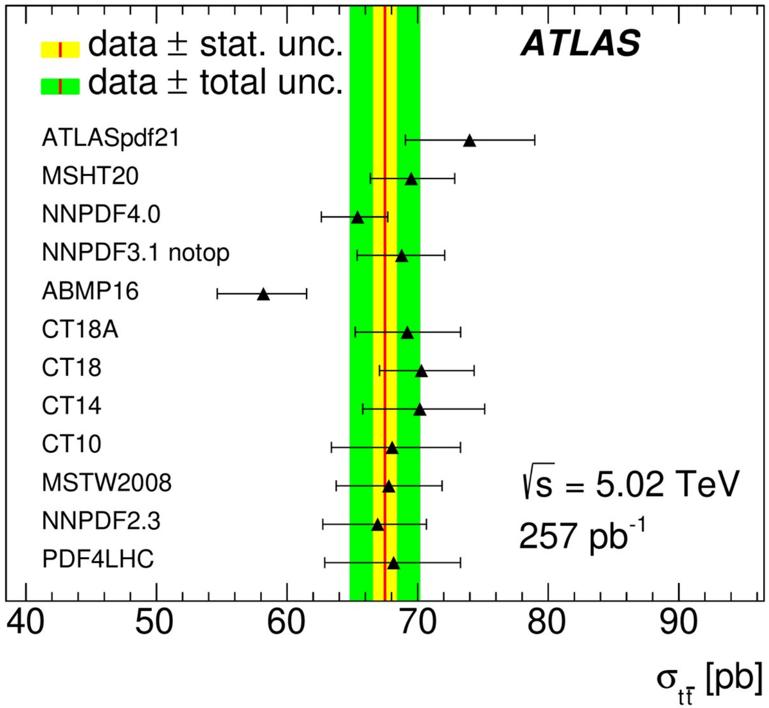


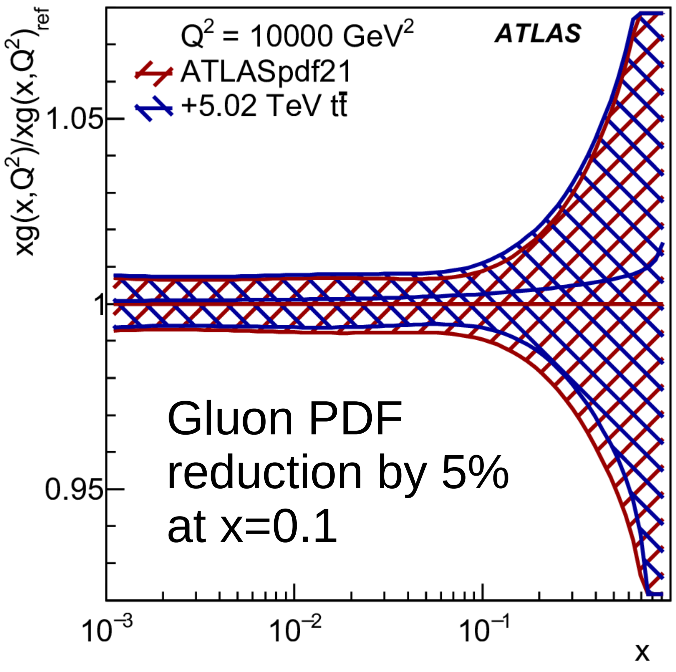


$t\bar{t}$ at 5TeV

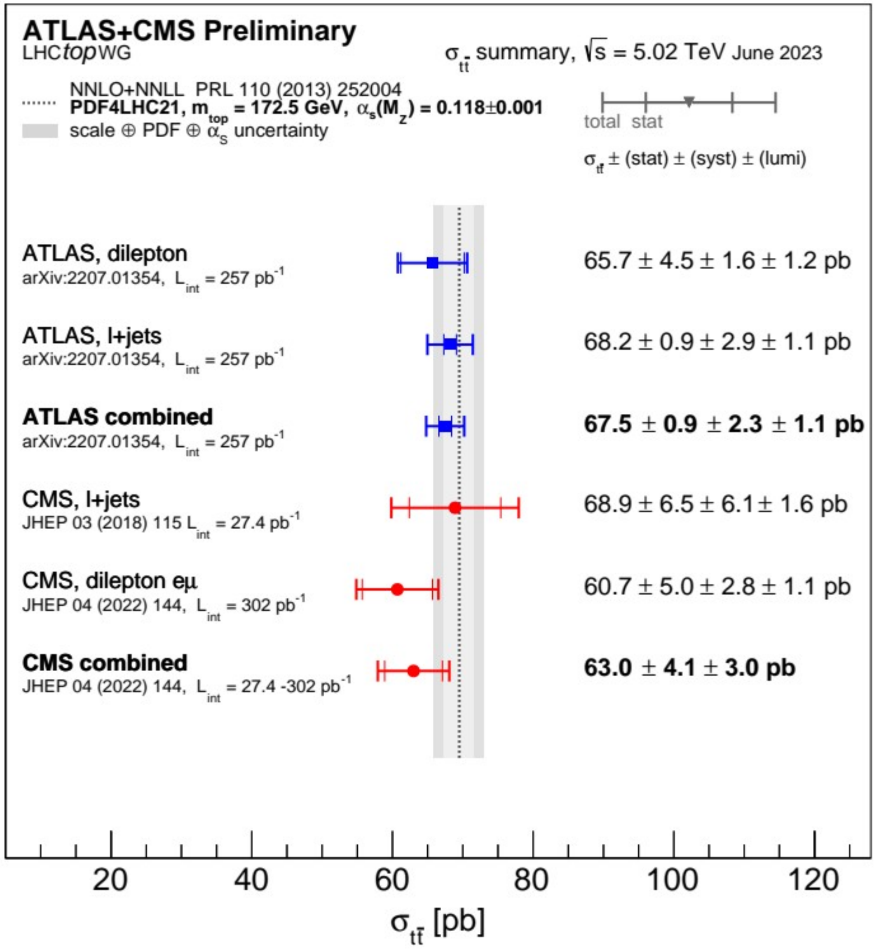
Increased fraction of qq initiated events

- 11% at 13TeV → 25% at 5TeV
- Complementary constraints on gluon PDF



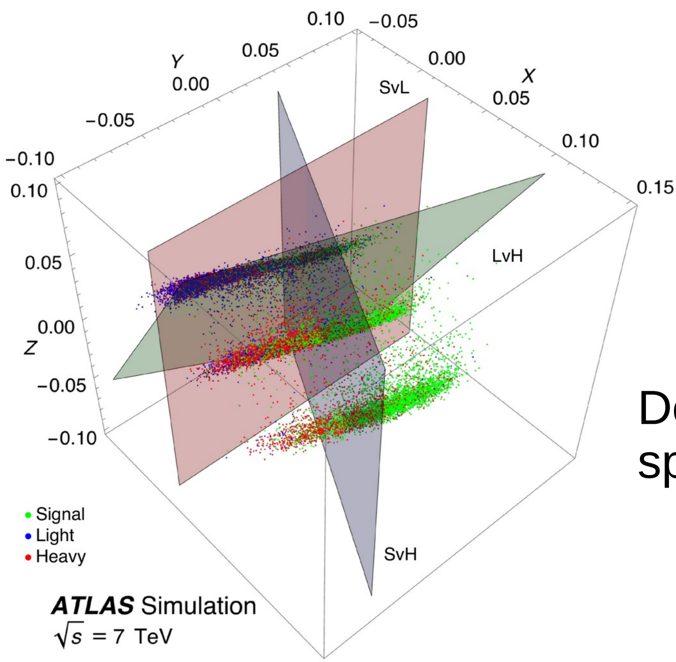


$t\bar{t}$ at 5TeV

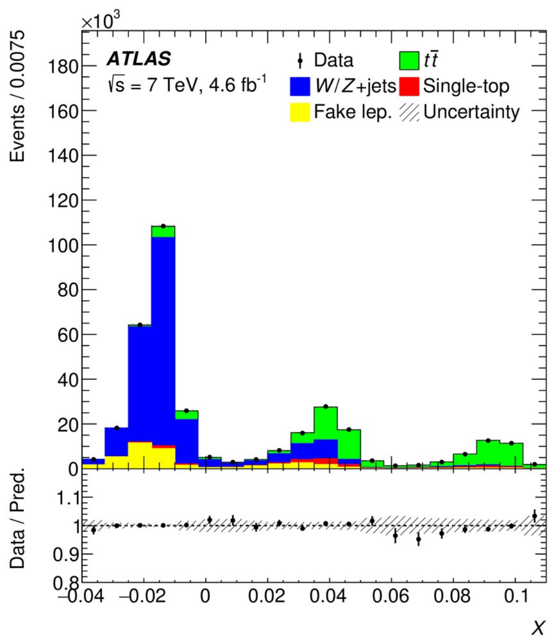


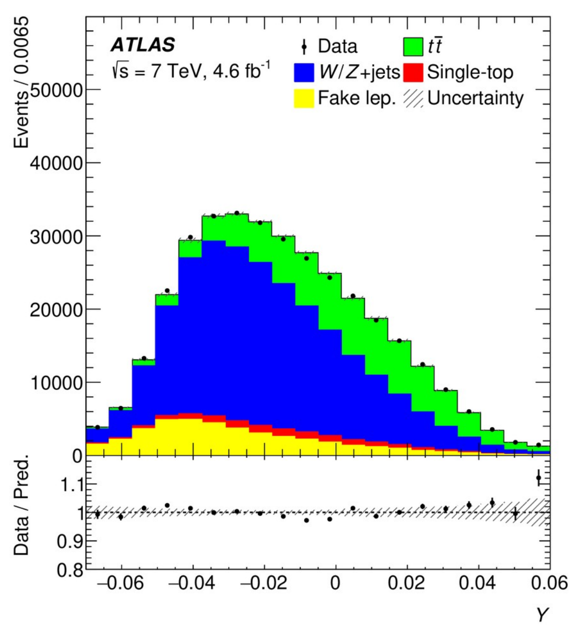
~4.0%

$\sigma_{t\bar{t}}$ at 7 TeV using support vector machines



Decision space





Number	Feature	Divided by
1	E_T^{miss} [GeV]	250
2	$\phi(E_T^{miss})$ [radians]	2π
3	Lepton E [GeV]	400
4	Lepton $p_{\|}$ [GeV]	400
5	Lepton p_z [GeV]	400
6	Mass(lepton+jets) [GeV]	750
7	Fox–Wolfram moment 1	1
8	Fox–Wolfram moment 2	1
9	Fox–Wolfram moment 3	1
10	Fox–Wolfram moment 4	1
11	Fox–Wolfram moment 5	1
12	Sum all jets E_T [GeV]	500
13	Sum all jets E [GeV]	750
14	Sum all jets $p_{\|}$ [GeV]	750
15	Sum all jets $p_{\perp}$ [GeV]	750
16	Sum all jets p_z [GeV]	750
17	H_T [GeV]	500
18	p-tensor eigenvalue 1	1
19	p-tensor eigenvalue 2	1
20	Number of jets	10
21	Number of b-tags	10

$\sigma_{t\bar{t}}$ at 7 TeV combination

Jet substructure – variables

8 Measured variables

- Les Houches angularity (LHA): $\lambda_{0.5}^{1}$
  - Boradness of jet: separate quark/gluon jets
- Dispersion: λ_{0}^{2}
- Scaled p_T dispersion $p_T^{d,*}$
  (Mitigate correlation with particle multiplicity)
  - Momentum distribution of jet constituents
- Energy Correlation Functions (ECFs) ratios C3 and D2
- N-subjettiness τ3, τ32 ≡ τ3/τ2, τ21 ≡ τ2/τ1
  - E.g. 3 prong jet has τ3→0

$$\lambda_{\beta}^{\kappa} = \sum_{i \in J} z_i^{\kappa} \left(\frac{\Delta R(i, \hat{n})}{R} \right)^{\beta}$$

Sum over constituents of jet J

Jet axis

Fraction of jet's pT

$$\tau_N = \frac{1}{d_0} \sum_k p_{\mathrm{T},k} \min \left\{ \Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k} \right\},$$

$$\text{with } d_0 = \sum_k p_{\mathrm{T},k} R_0.$$

D2 and τ32 measured in 2D with m(top) and pT(top)

Jet substructure – modeling and jets

Nominal setup: Powheg+Pythia
Parton shower and hadronization uncertainty: Powheg+Herwig
PS matching: comparing to MG5_aMC@NLO+Pythia

Jet reconstruction:
- Trimmed large-R (1.0) jets from calorimeter → all-hadronic channel
- Small=R jets (0.4) using tracking and colorimeter with particle flow
- Trimmed large-R (1.0) reclustered (RC) from small-R jets → lepton+jet channel
  - Good resolution, pileup subtraction
- Variable-R track jets using variable-R algorithm (pT dependent 0.02-0.4)

Only charged components of top quark jets considered
- Resolution improvement of 50% w.r.t. previous results
- Reduced uncertainties

Jet substructure – Signal and background

All-hadronic: use top tagging with DNN via unbiased tag and probe procedure

- 16 categories in: N(top quark tags), N(b tags)
- Signal region: both large-R jets b tagged, one being top tagged

Backgrounds:

- MC for tW, tt, W, Z, ttV
- Misidentified lepton in lepton+jet channel
  - Matrix method: loose and tight leptons
- Mutlijet background for all-hadronic channel
  - ABCD method

Signal regions

Validation regions

Control regions

2nd large-R jet		1st large-R jet: t0b0	t1b0	t0b1	t1b1
	t1b1	J	K	L	S
	t0b1	B	D	H	N
	t1b0	E	F	G	M
	t0b0	A	C	I	O

CMS 13TeV dilepton channel

Sensitivity to pQCD

PDF sensitivity

Sensitivity to top mass

Additional PDF sensitivity

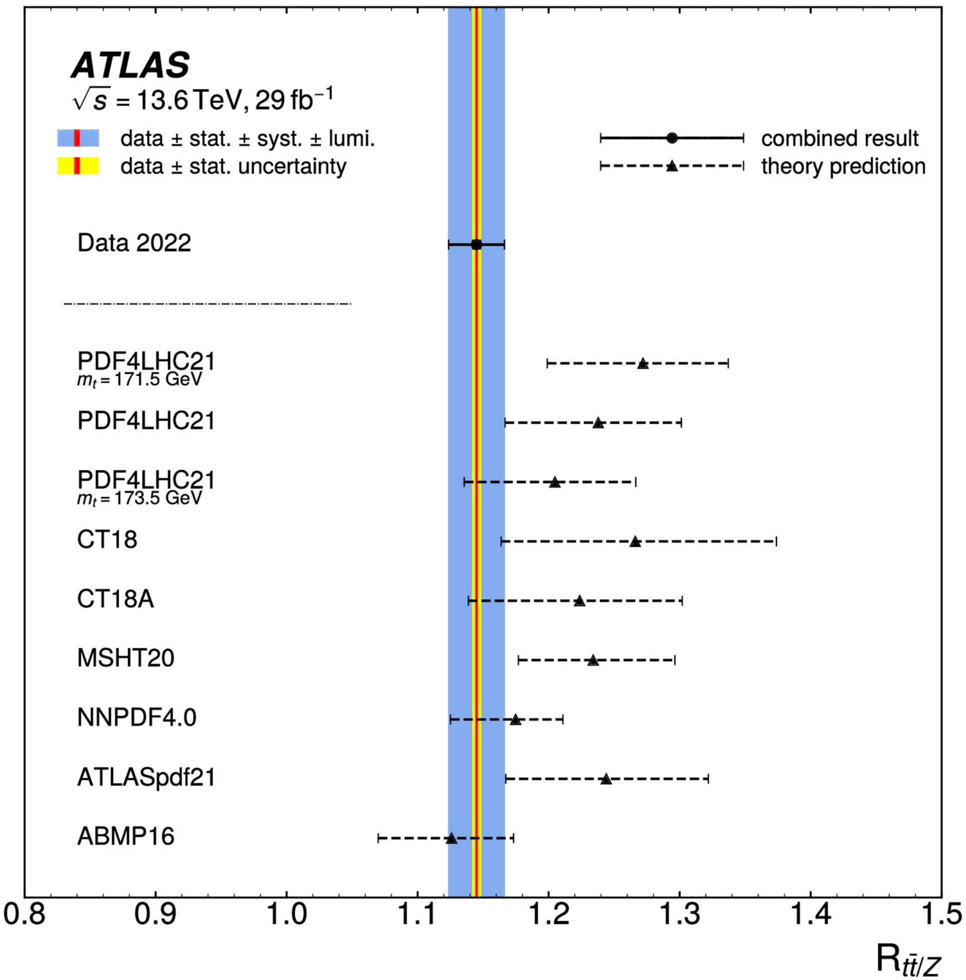
ATLAS measurement at 13.6TeV

Measurement of $\sigma_{t\bar{t}}$ to σ_Z ratio is sensitive to gluon to quark PDF ratio

- Luminosity uncertainty cancels out in ratio

$$R_{t\bar{t}/Z} = 1.145 \pm 0.003(\mathrm{stat}) \pm 0.021(\mathrm{syst}) \pm 0.002(\mathrm{lumi})\mathrm{pb}$$

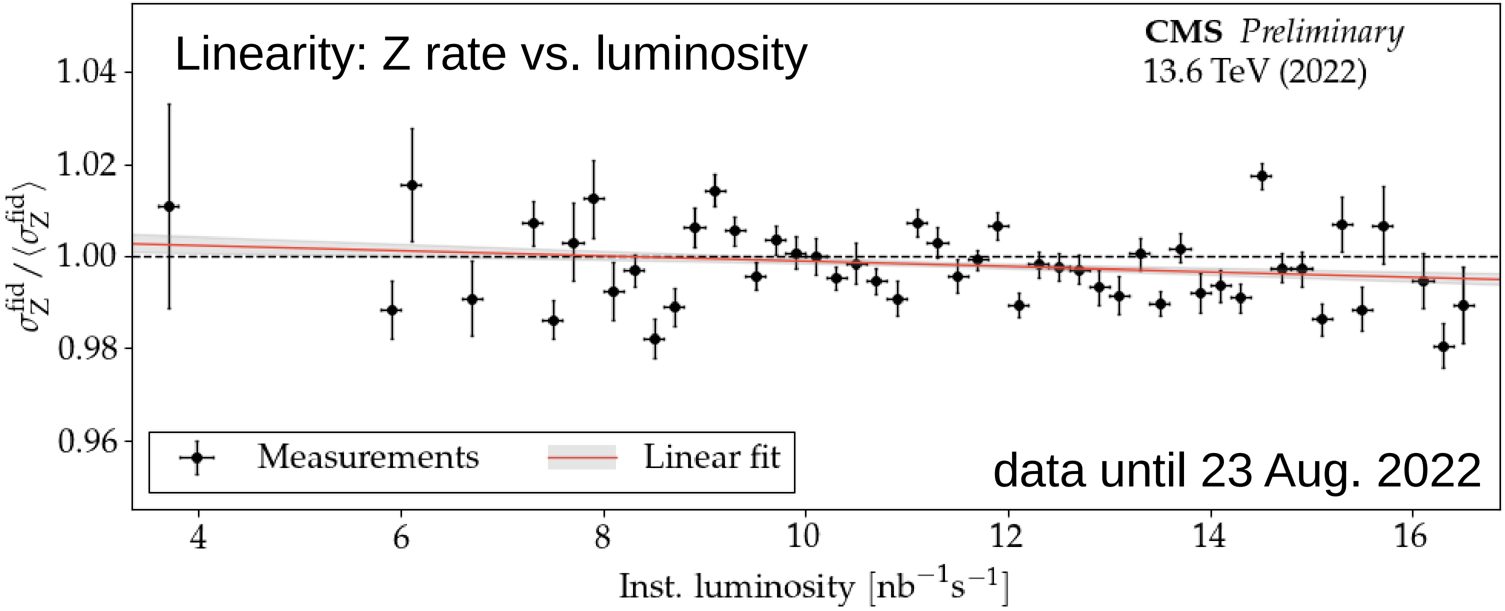
Good agreement with compared PDF sets



$\sigma_{t\bar{t}}$ and luminosity

Luminosity is crucial input for $\sigma_{t\bar{t}}$ measurements
Z boson rate to measure luminosity ([CMS-DP-2023-003])

- Used to cross check luminosity measurement in CMS
- Evaluate linearity and time stability → good agreement



Promising method also for high precision luminosity determination

- First complete estimate of systematic uncertainty on 2017 data by CMS ([arXiv:2309.01008])
- See also: poster sessions