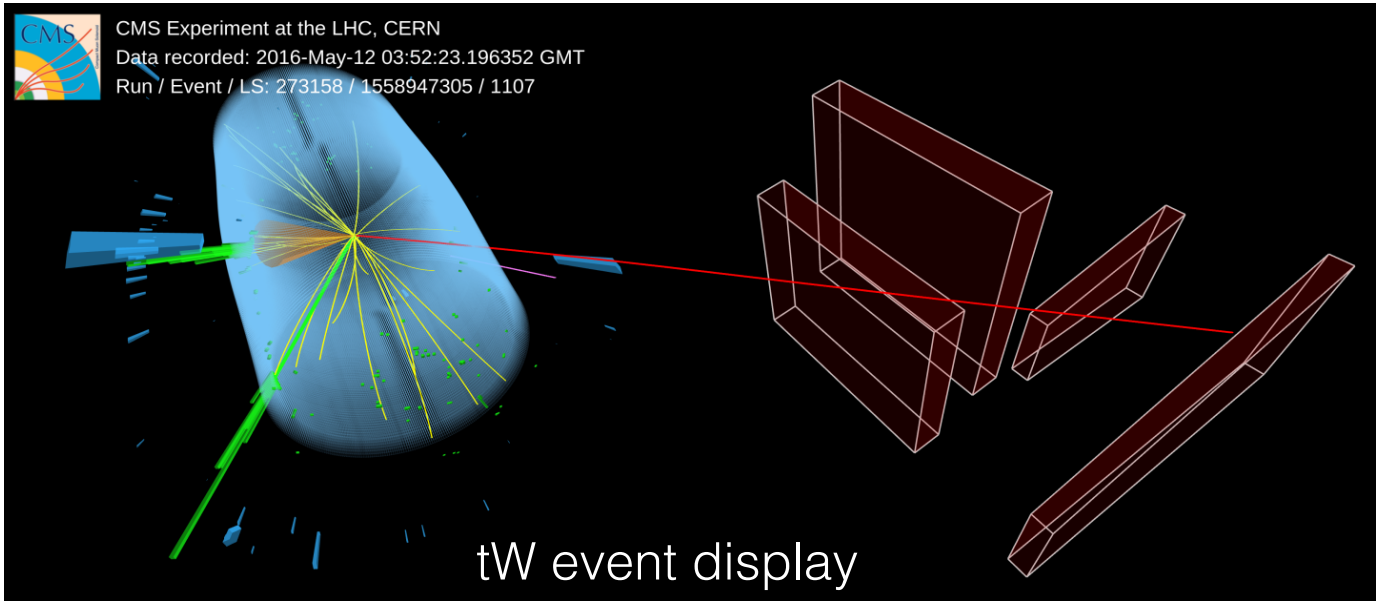
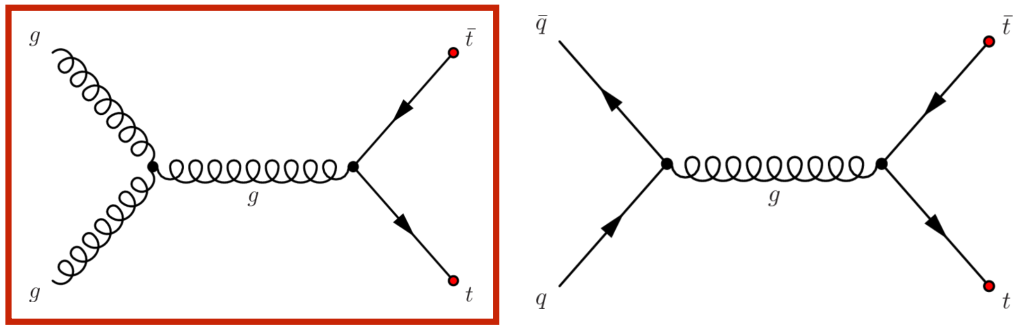
Top quark cross sections at CMS

Blois2021 - 20/10/2021



Nicolas Chanon - IP2I Lyon, CNRS/IN2P3 (France)
for the CMS Collaboration

The LHC: a top quark factory

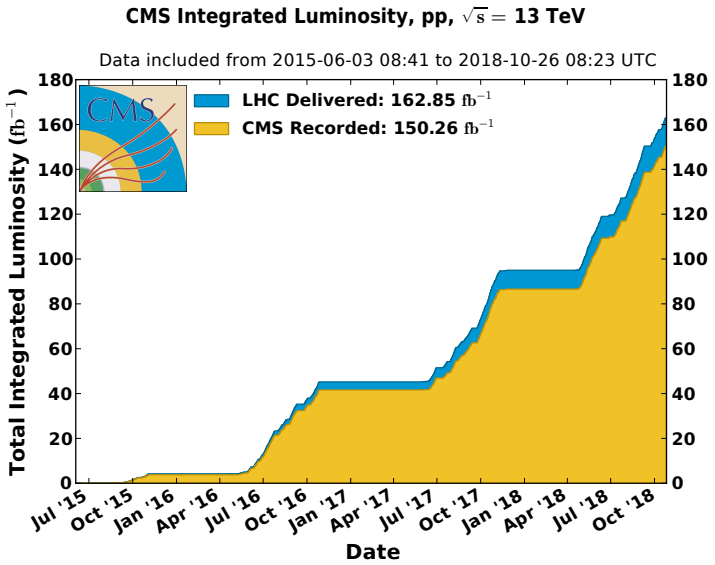


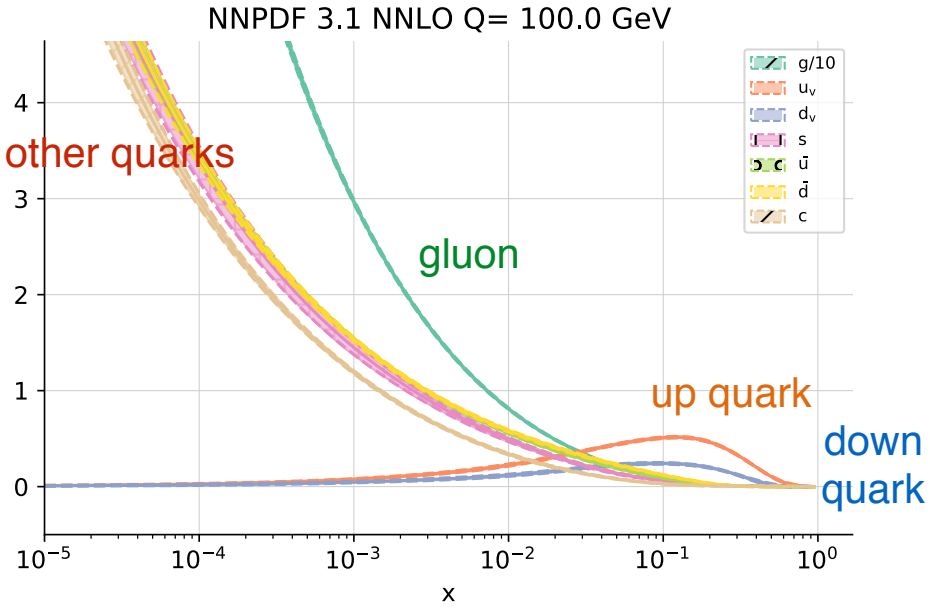
From Tevatron to LHC, x100 increase in cross section:

- Higher gluon luminosity in LHC proton-proton collisions
- Higher center-of-mass energy

Integrated luminosity

- About 150 fb-1 recorded at Run II (2015-2018)





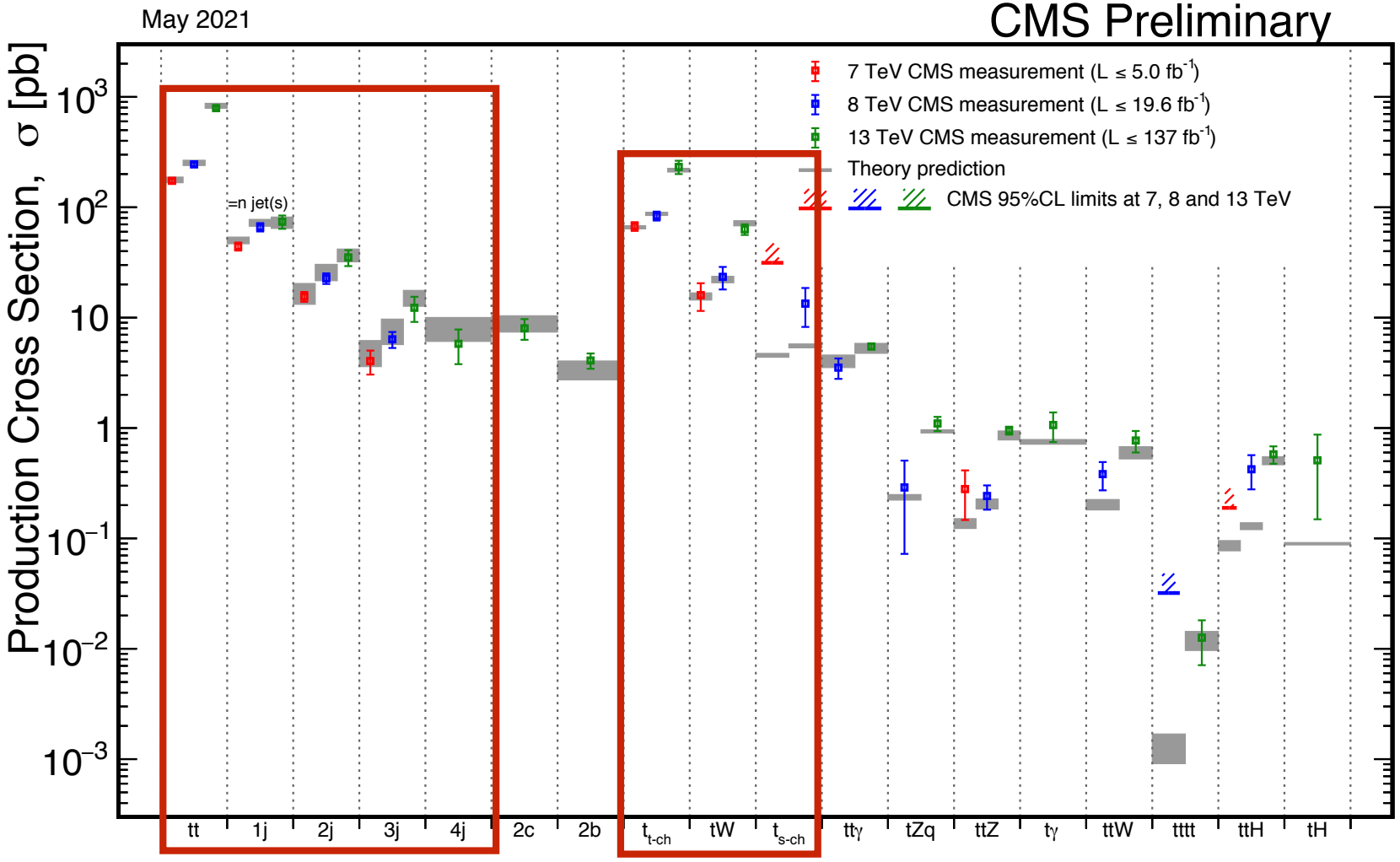
A top quark produced on-shell needs $x \simeq m_t/2s^{1/2} \simeq 0.01$:

gluon pdf is dominant

Outline

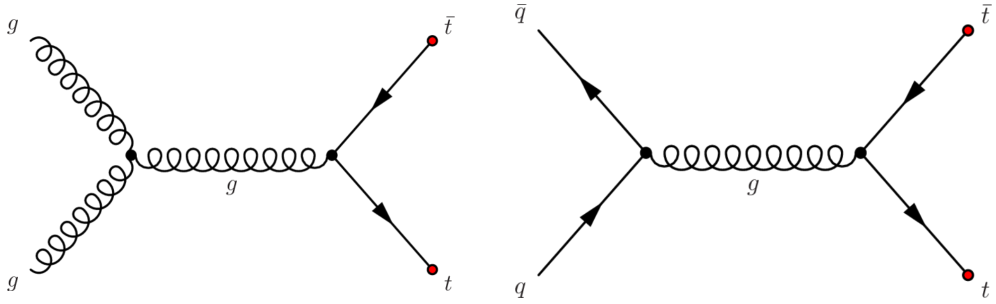
A selection of Run 2 measurements of top-antitop and single top cross sections, with three recent highlights:

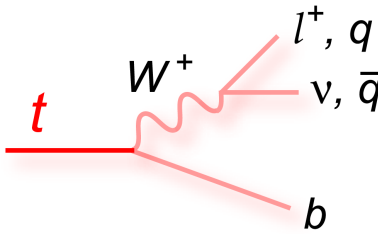
- Inclusive top pair cross section a 5 TeV
- Top pair differential measurement in full kinematic range
- tW differential measurement in lepton+jets channel

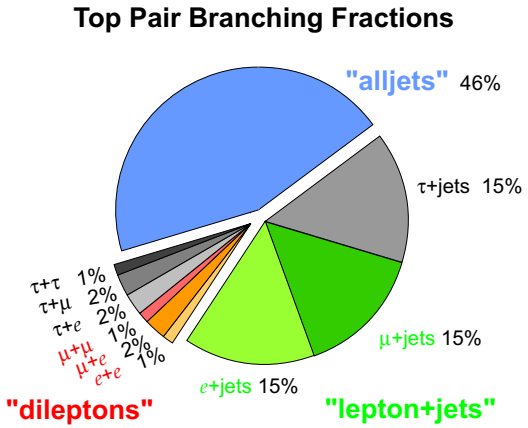


All results at: http://cern.ch/go/pNj7

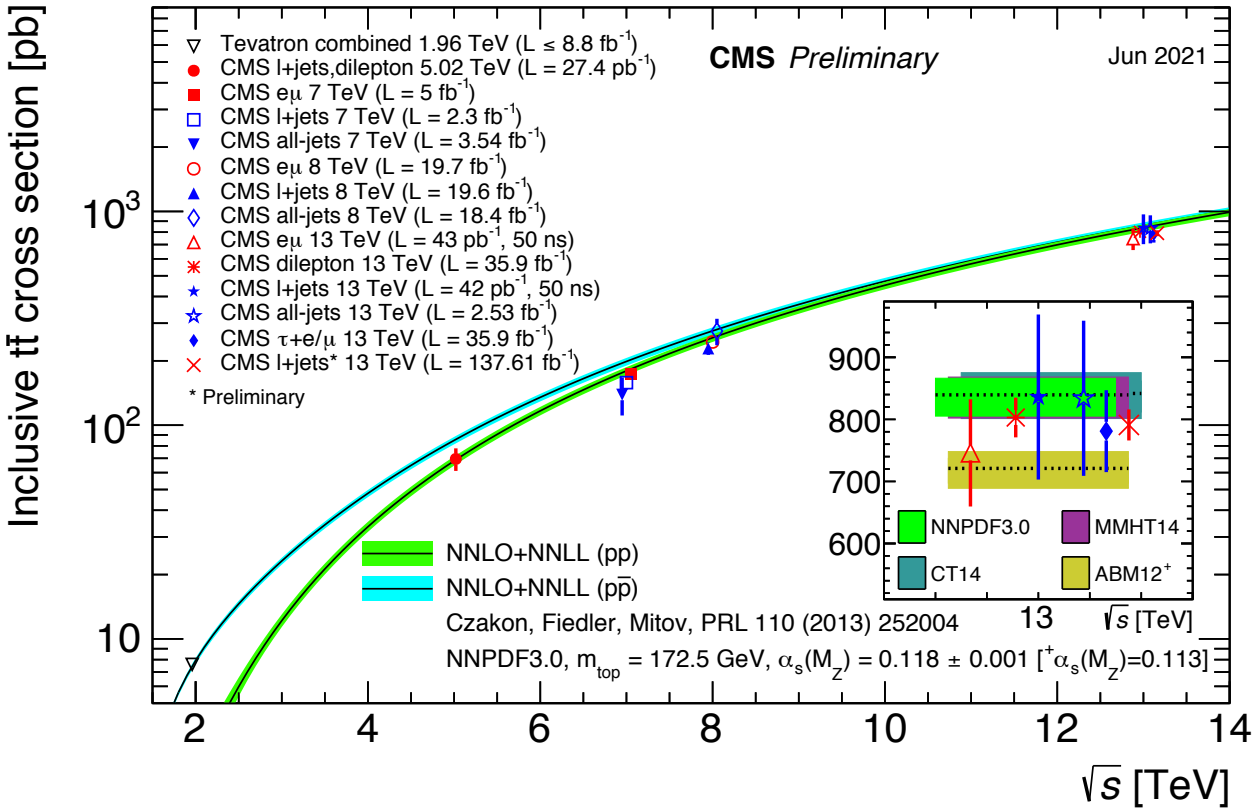
Top pair cross sections

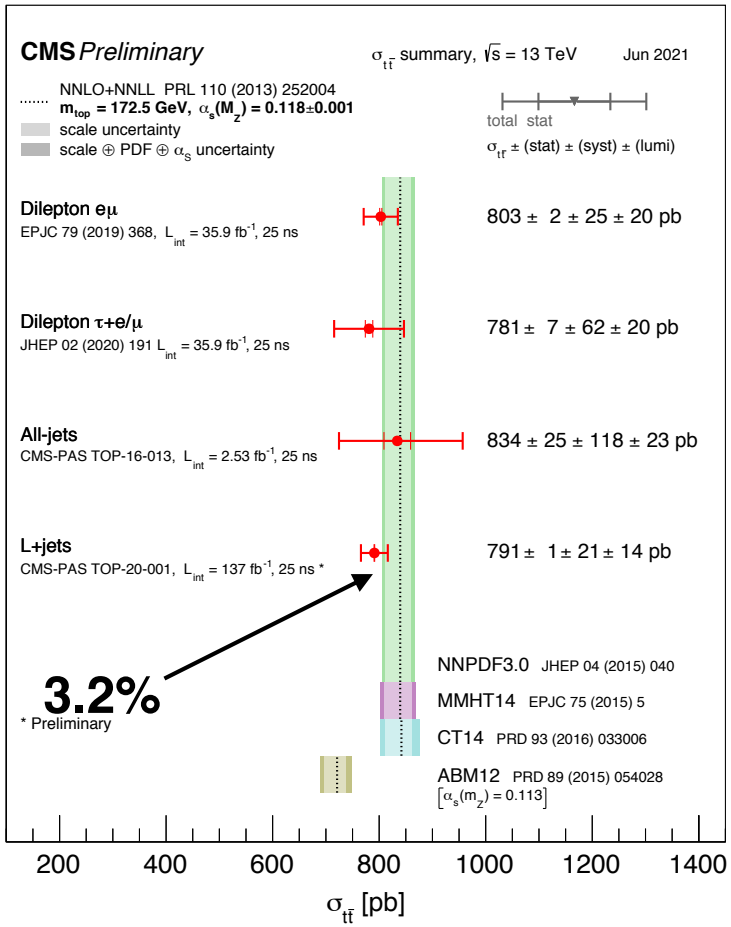






A test of perturbative QCD



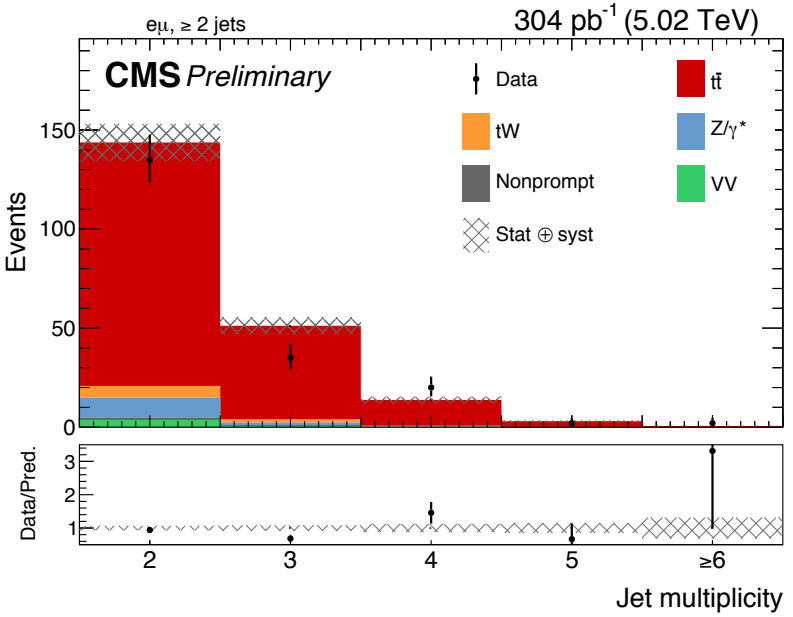


Inclusive top pair cross section a 5 TeV

CMS-TOP-20-004

eμ channel analyzed:

- 304 pb-1 of 2017 p-p data at 5.02 TeV
- Lepton pT > 10 GeV, jets pT > 25 GeV, mll > 20 GeV
- Drell-Yan background estimated from data (other backgrounds from simulation)



Cross section measurement as simple **counting experiment**:

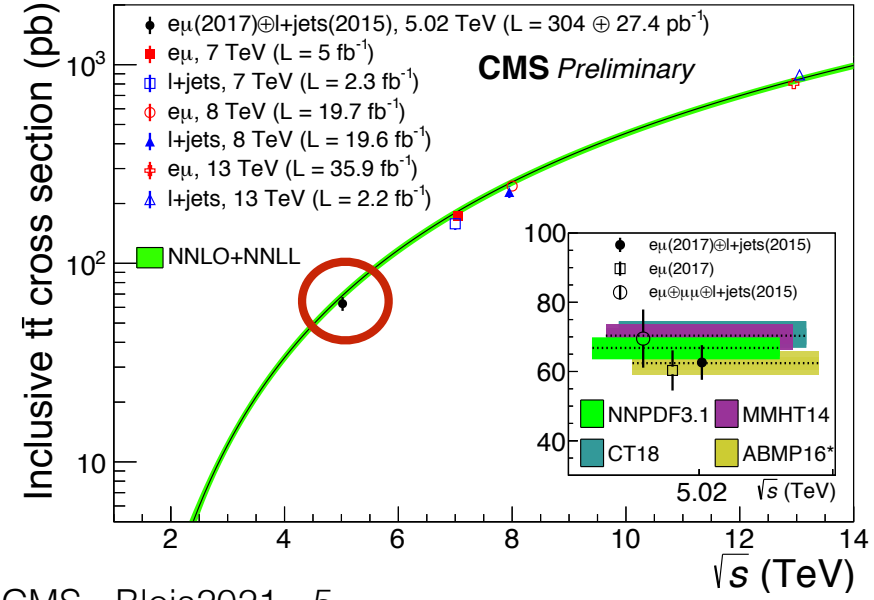
$$\sigma_{t\bar{t}} = \frac{N - N_{bkg}}{\varepsilon \mathcal{A} \mathcal{B} \mathcal{R} \mathcal{L}}$$

Source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
tW	1.0
Nonprompt leptons	0.4
Drell–Yan	1.8
VV	0.8
Trigger efficiency	1.3
L1 prefiring	1.4
Electron efficiency	1.6
Muon efficiency	0.6
JES	2.2
JER	1.2
μ_R, μ_F scales	0.2
PDF⊕$\alpha_S(m_Z)$	0.3
Final state radiation	1.1
Initial state radiation	< 0.1
h_{damp}	1.0
Underlying event tune	0.7
Total systematic	4.3
Integrated luminosity	1.5
Statistical uncertainty	8.2

$$\sigma_{t\bar{t}} = 60.3 \pm 5.0\ (\text{stat}) \pm 2.8\ (\text{syst}) \pm 0.9\ (\text{lumi})\ \text{pb}$$

Combination with l+jets channel (28 pb-1 of 2015 data):

$$\sigma_{t\bar{t}} = 62.6 \pm 4.1\ (\text{stat}) \pm 3.0\ (\text{syst+lumi})\ \text{pb}$$

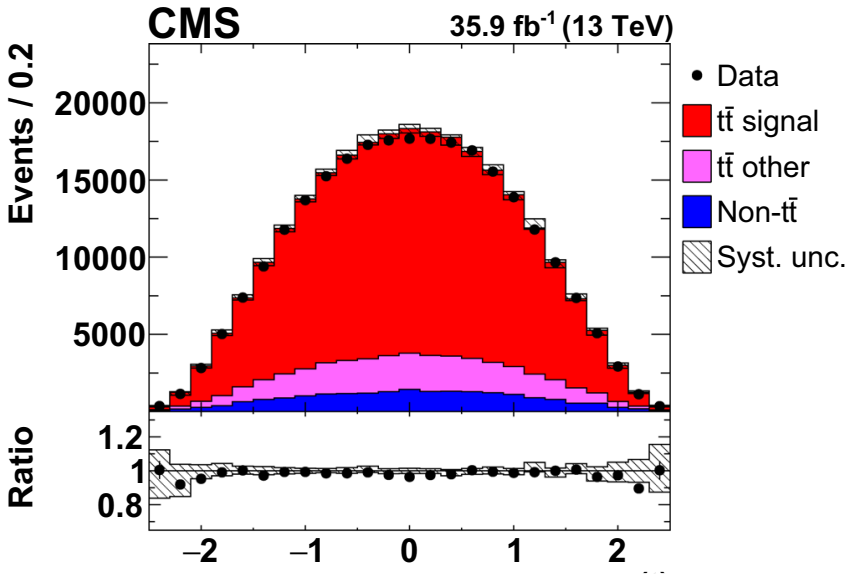


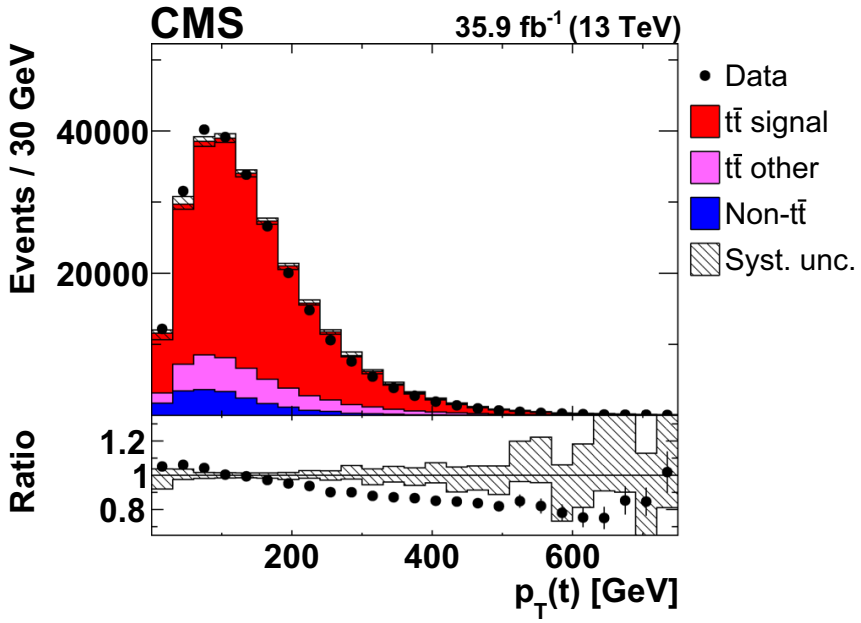
Top pair multi-differential measurement in dilepton channel

CMS-TOP-18-004, Eur. Phys. J. C 80 (2020) 658

eμ, ee, μμ channels analyzed:

- Two isolated leptons with pT > 25, 20 GeV in |η|<2.4
- mll > 20 GeV to suppress low mass resonances
- In ee, μμ channels: Z-veto |Mz-Mll|>15 GeV and pTmiss > 40 GeV
- Jets pT>30 GeV in |η|<2.4
- B-jets identified with algorithm combining secondary vertex + track-based lifetime information (CSV)
- **ttbar system reconstructed** with a kinematic fit (90% efficiency). Not imposing top mass constraint for m(ttbar) reconstruction.





Top pair multi-differential measurement in dilepton channel

CMS-TOP-18-004, Eur. Phys. J. C 80 (2020) 658

Differential measurement:

- Signal extracted by subtracting background event yield from simulation in each bin
- **Unfolding**: merged distributions of eμ, ee, μμ are corrected for detector effects using response matrix (with regularization)
- Overall good agreement between data and SM predictions

Cross section in bin i

Number of unfolded signal events

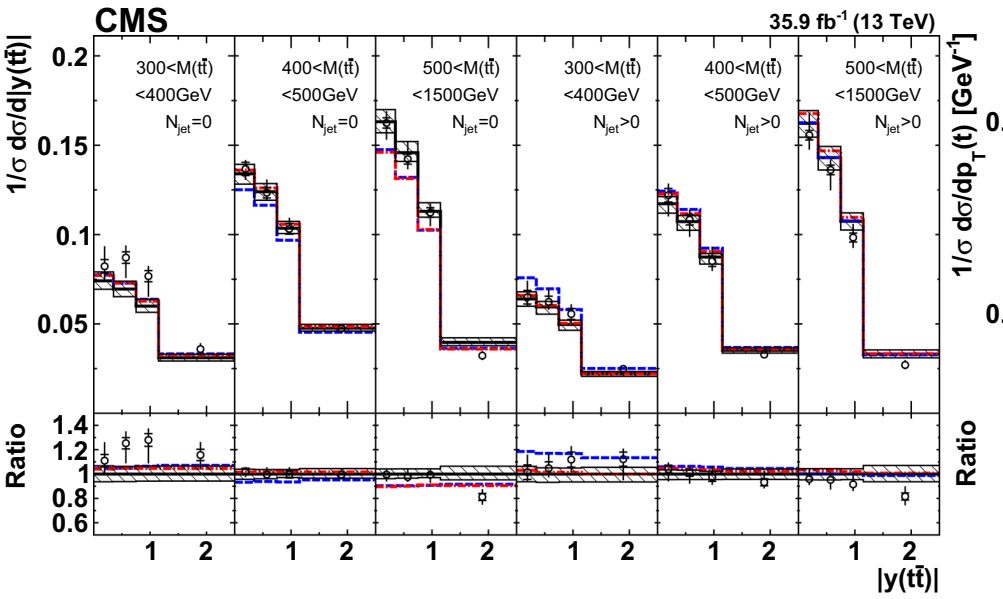
$$\frac{\sigma_i}{\sigma} = \frac{1}{\sigma}\frac{\hat{M}_i^{\mathrm{unf}}}{\mathcal{B}\,\mathcal{L}}$$

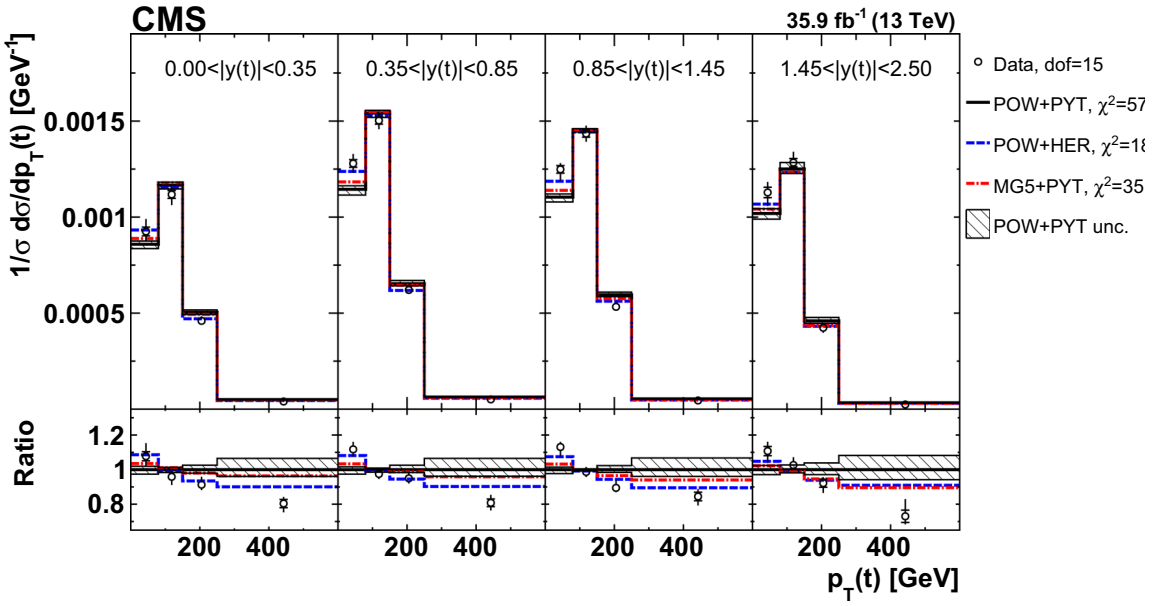
Total cross section

Branching ratio

Luminosity

Trend observed at high top pT as observed in other ttbar analyses



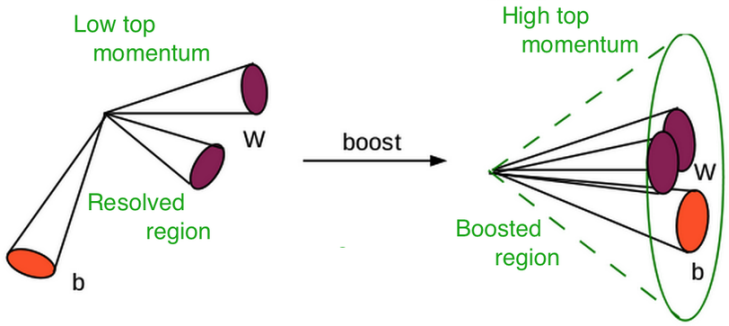


Top pair differential measurement in full kinematic range

CMS-TOP-20-001, arXiv:2108.02803, submitted to PRD

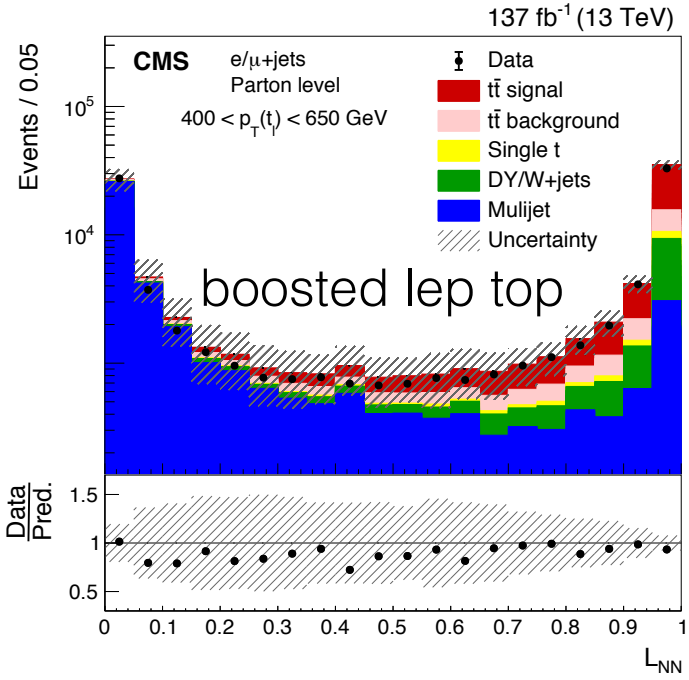
e+jets and μ+jets channels analyzed:

- Combines **low-pT analysis with resolved top**, and **high-pT analysis** where **top decay products overlap**
- Isolated muon and electrons pT>30 GeV in |η|<2.4
- Jets pT > 30 GeV in |η|<2.4,
- B-tagging with DeepCSV: 2 tight or 1 tight 1 loose



Reconstruction:

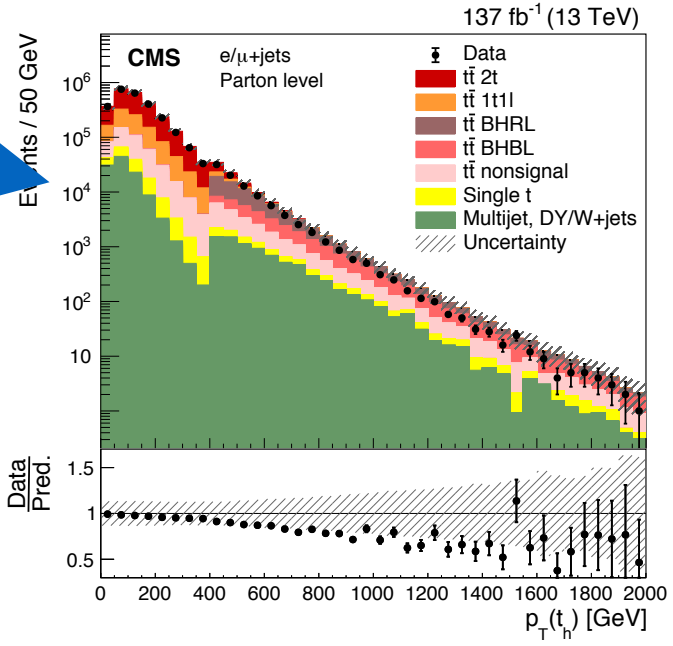
- **Resolved ttbar reconstruction**: solve quadratic equation for p_neutrino. Jets assignment with a likelihood.
- **Boosted hadronic top** reconstructed with anti-kt 0.8 jets, **pT > 400 GeV**, |η|<2.4, jet mass > 120 GeV. PUPPI algorithm used for pileup mitigation. A neural network is used to identify the subjets (ak5) from top.
- **Boosted leptonic top**: top **pT > 400 GeV**, non-isolated lepton with pT > 50 GeV close to a ak4 jet, same neutrino reconstruction. A neural network is trained to identify leptons arising from a W against multi jet background



Top pair differential measurement in full kinematic range

CMS-TOP-20-001, arXiv:2108.02803, submitted to PRD

Smooth transition between low pT and high pT regimes:



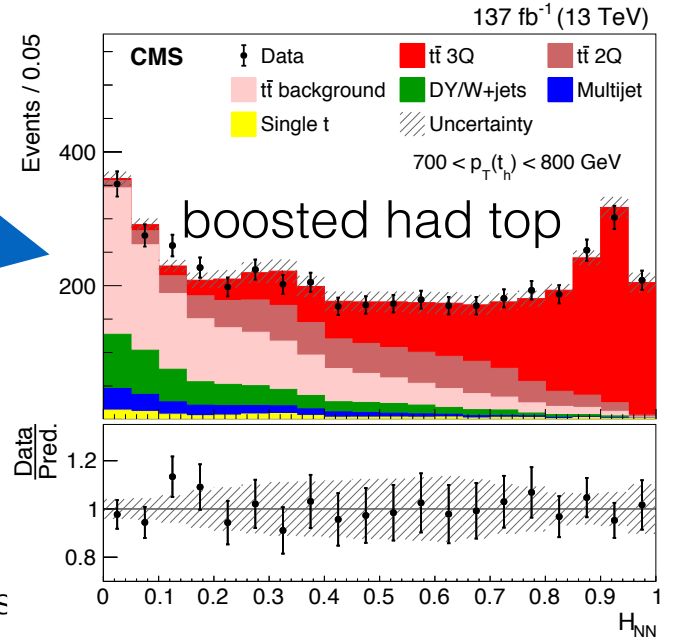
Categories:

2t	1t1l	BHRL	BHBL
2 tight b jets resolved reconstruction	1 tight b jet 1 loose b jet resolved reconstruction	boosted t_h resolved t_l	boosted t_h boosted t_l

Boosted
background subtraction using template fit of H_{NN}

separate for e and μ channels
separate for 3 years of data

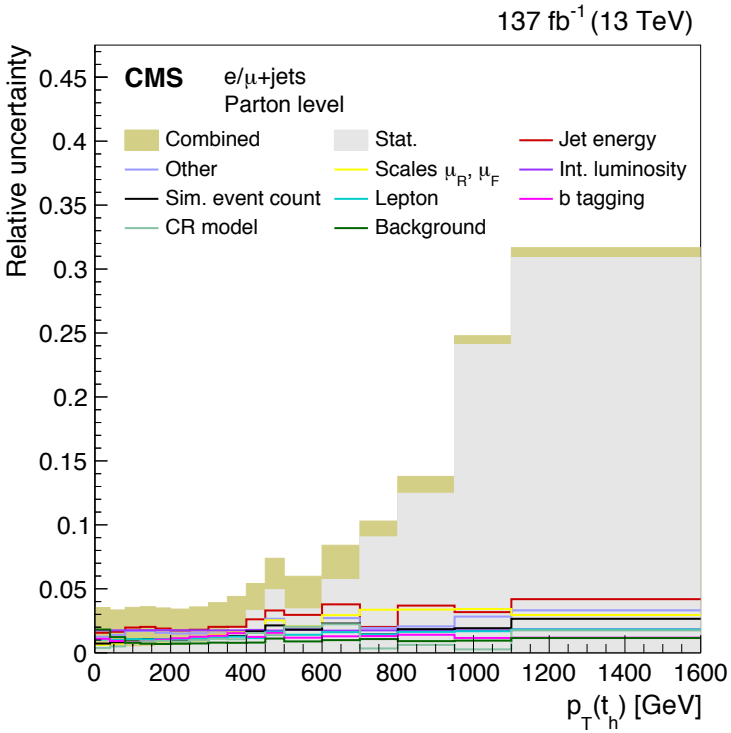
Combination fit of cross sections

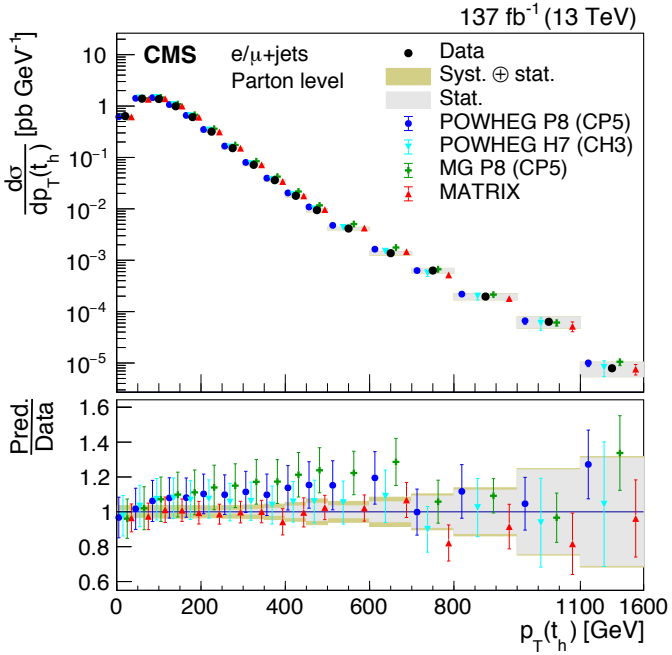


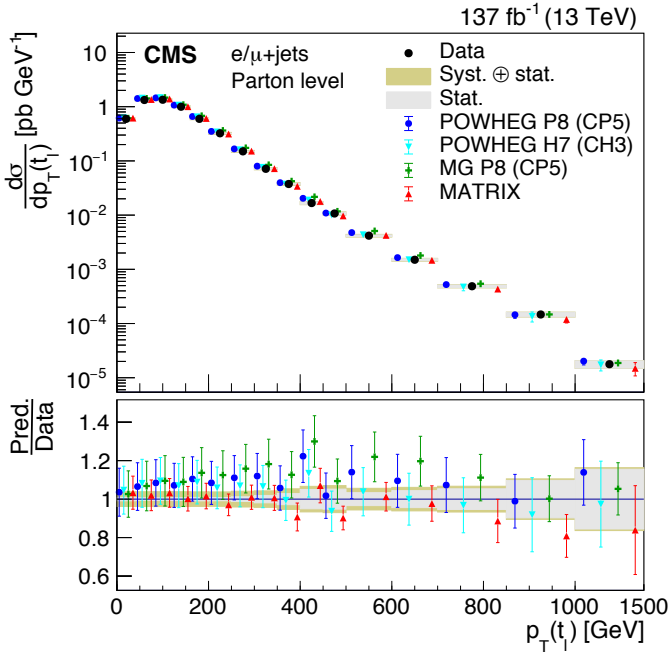
Top pair differential measurement in full kinematic range

CMS-TOP-20-001, arXiv:2108.02803, submitted to PRD

- **Unfolding** detector effects to particle-level
- Fiducial volume defined as closely as possible to reconstructed selection
- Systematic uncertainties estimated by repeating the fit with varied response matrix







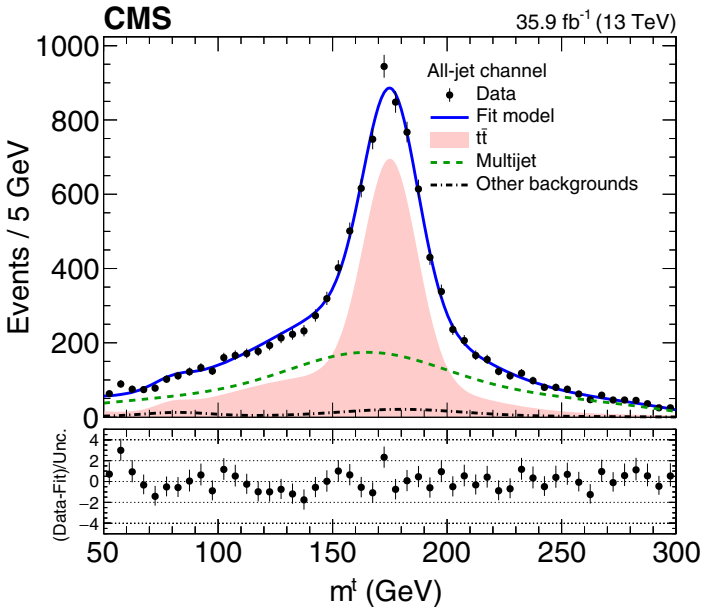
Data/MC agreement at high pT **improved at NNLO** (Matrix), within uncertainties

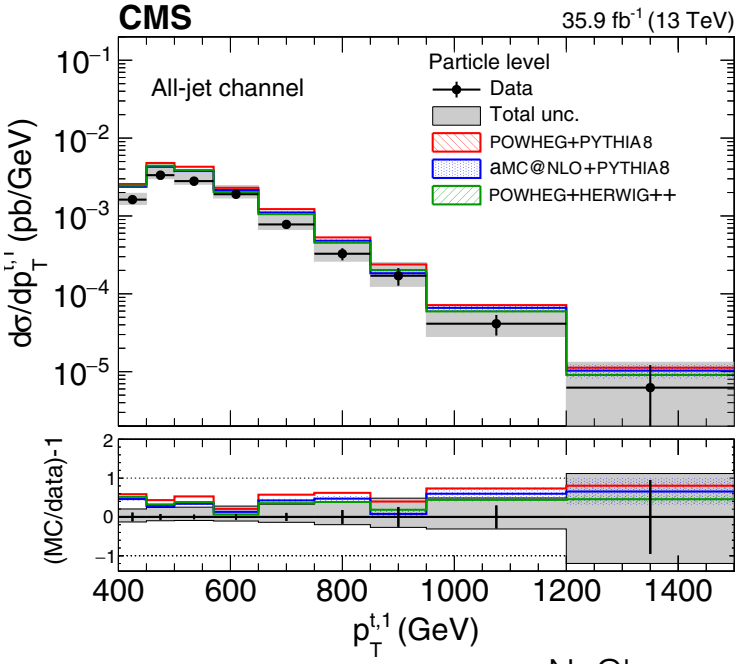
Top pair cross section in hadronic channel

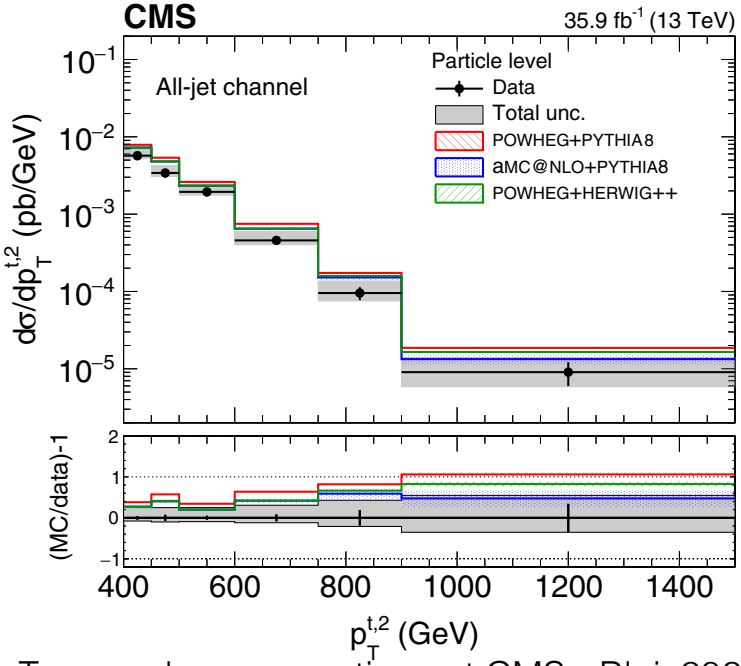
CMS-TOP-18-013, Phys. Rev. D 103 (2021) 052008

l+jets and **all-jets channels:**

- **All-jets channel:** two anti-kt jets, distance parameter 0.8
- **Top pT > 400 GeV**
- Soft-drop algorithm used to remove soft, wide-angle radiations and improve mass resolution
- B-tagging with CSV on subjets reconstructed with CA algorithm
- N-subjetiness variables used to identify the top, and combined in a neural network



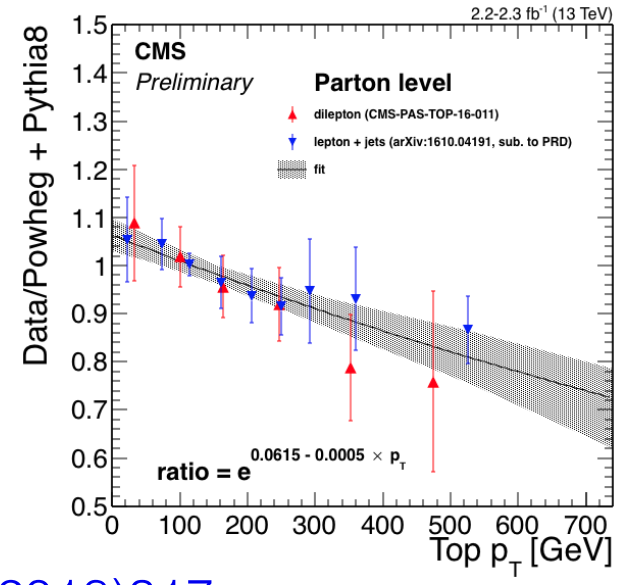


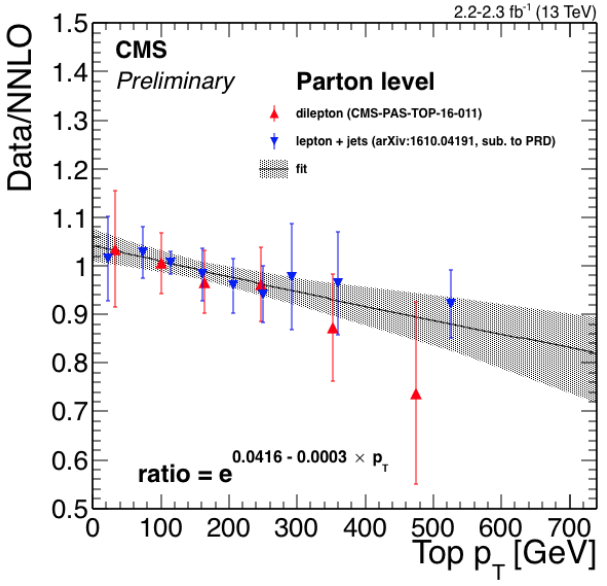


similar trend as in dilepton and l+jets channels

A note on Top pT in ttbar production

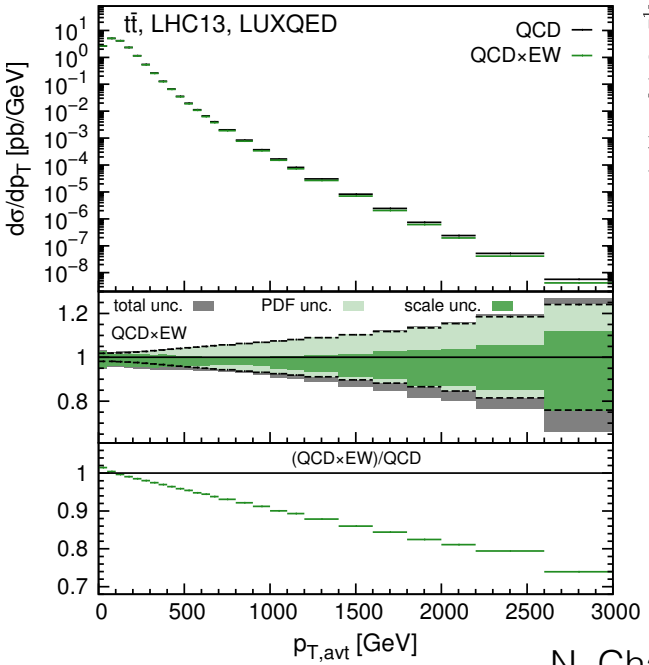
Ratio of data to fixed order NNLO QCD and to NLO+parton shower:





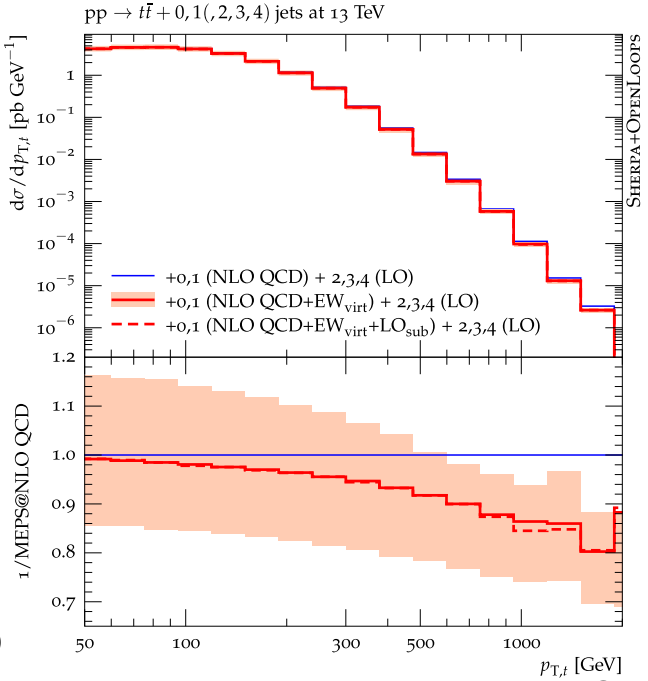
[JHEP10(2017)186](#)

NNLO QCD + NLO EW:



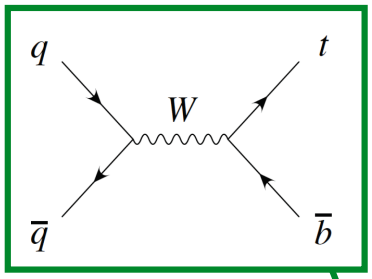
[EPJC78(2018)317](#)

NLO multijet merging + NLO EW:

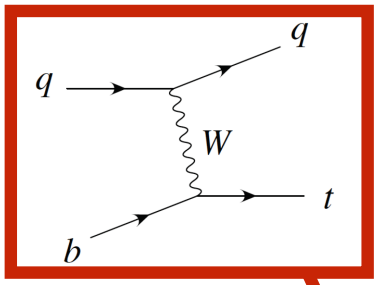


- **Electroweak corrections** are part of the solution
- **Resummation** of soft gluons at NNLL might also be required
- **Parton-level, particle-level** studies ongoing
- Latest measurements **to be compared with latest generators**

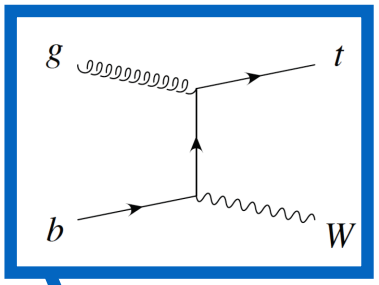
Single top cross sections



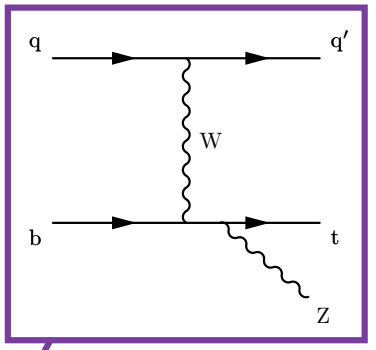
s-channel



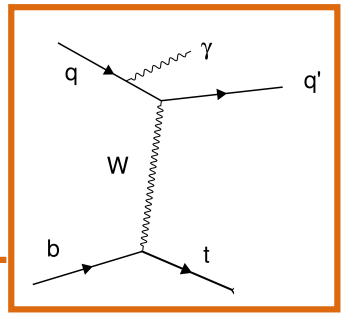
t-channel



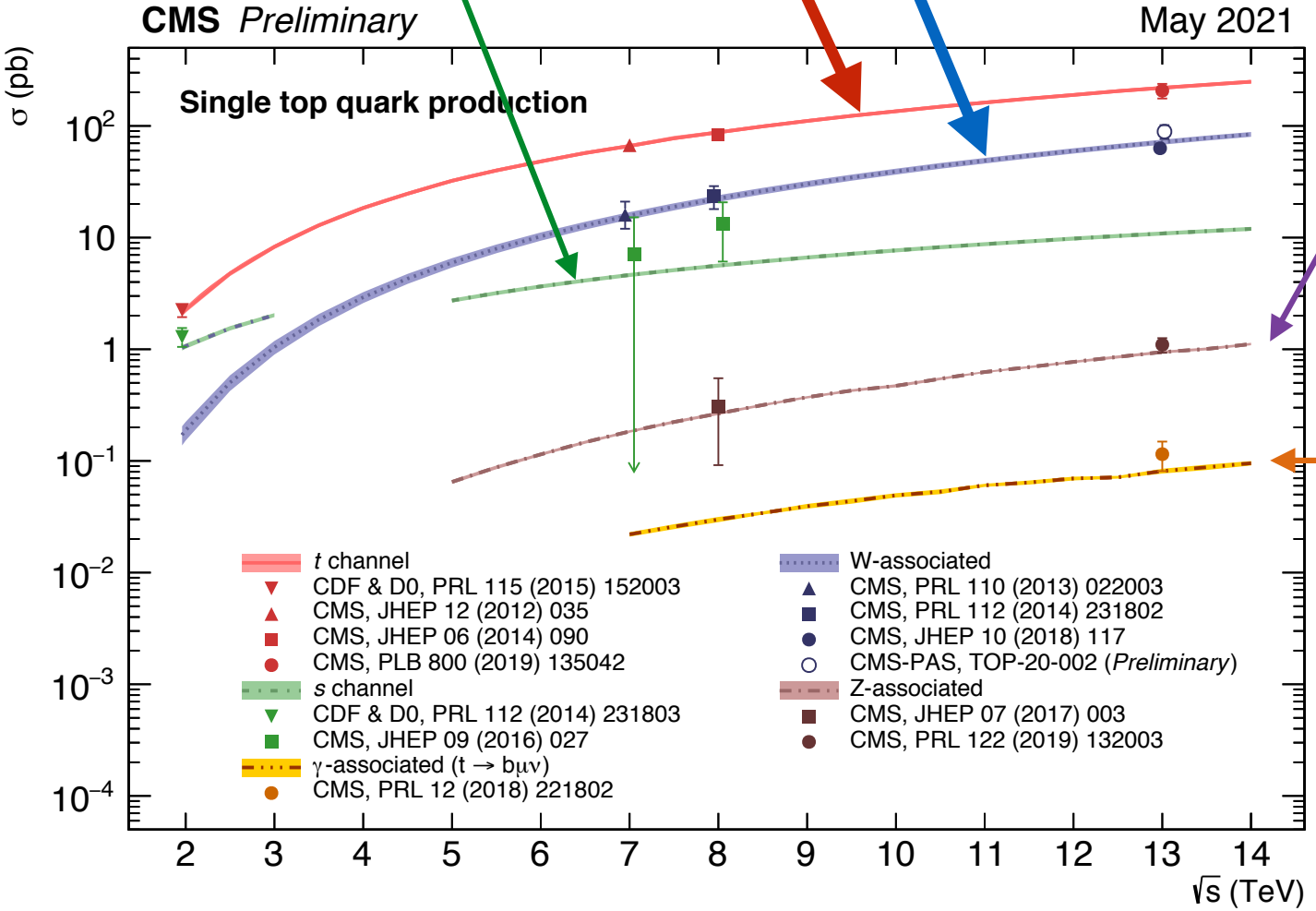
tW-channel



single top +Z



single top +photon

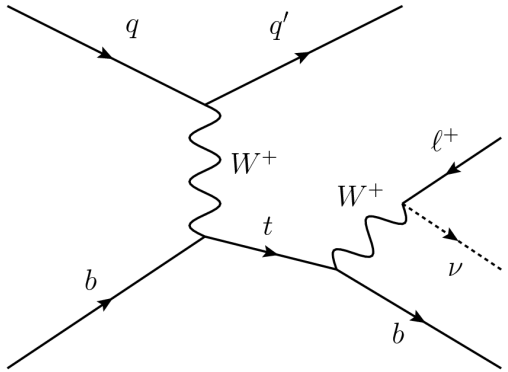


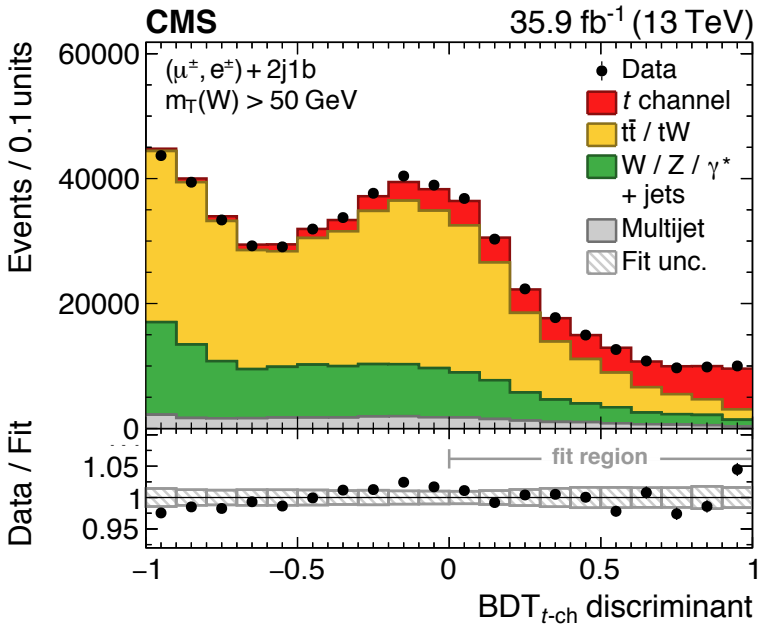
t-channel differential measurement

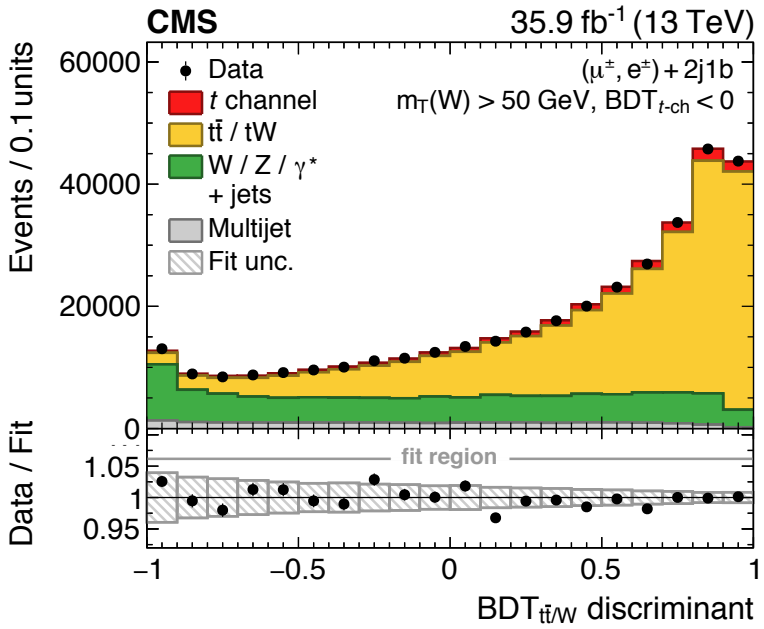
Eur. Phys. J. C 80 (2020) 370

lepton+jets channel analyzed:

- Trigger on single lepton
- Muon (electron) pT > 26 (35) GeV. Veto additional leptons
- Jets pT > 40 GeV in |η|<4.7
- One b-jet in η|<2.4
- **Define 3 categories**: 2j1b (signal region), 2j0b (W+jet control region) and 3j2b (ttbar control region)
- QCD estimated from data (revert isolation)
- **Discriminant**: W mT (3j2b), BDT t-channel, BDT ttbar/W+jets





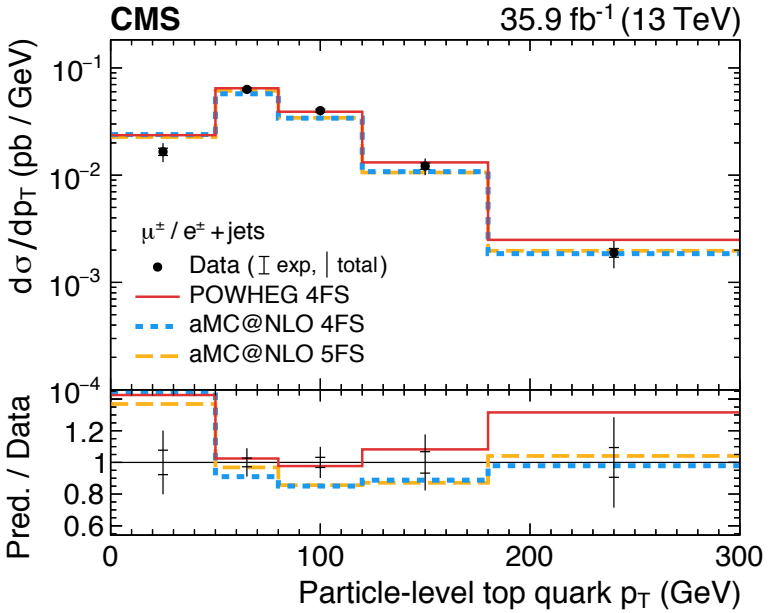


t-channel differential measurement

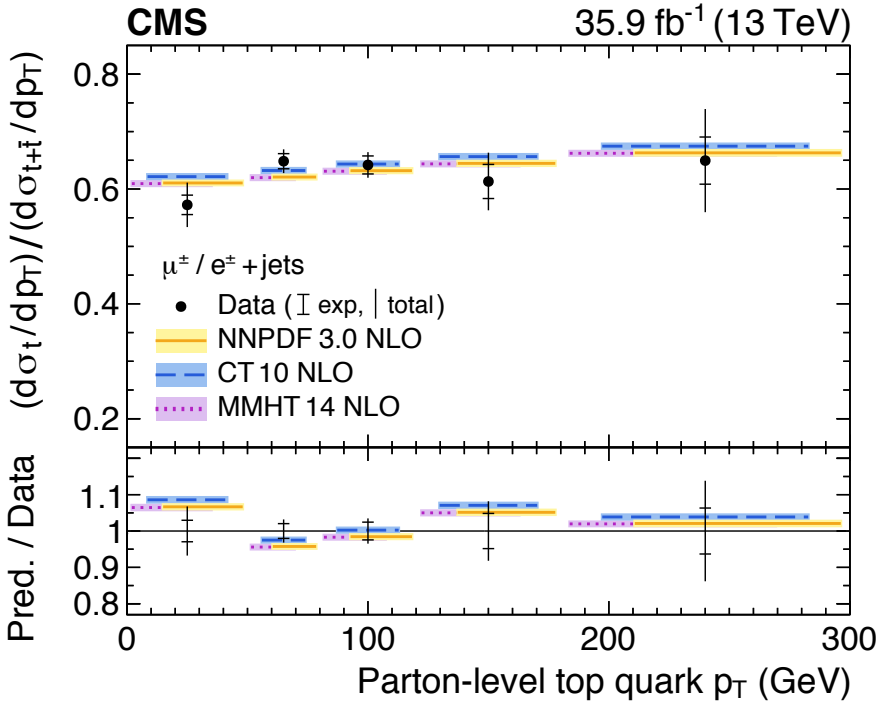
Eur. Phys. J. C 80 (2020) 370

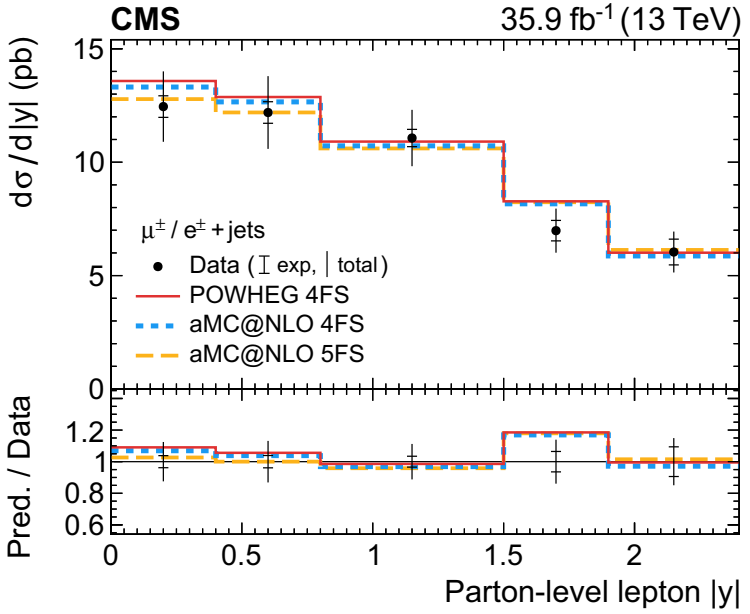
Differential cross sections:

- Unfolding to parton-level (and particle level)
- **Reasonable agreement with NLO theory predictions**, within the uncertainties



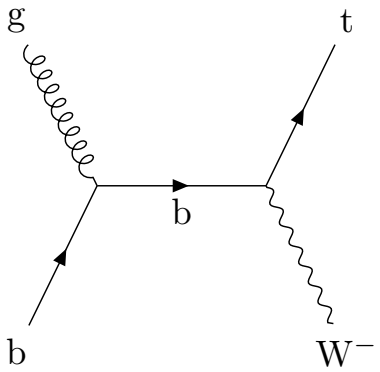
The **charge ratio** is sensitive to the parton content in the proton: >0.6 and increases with top pT





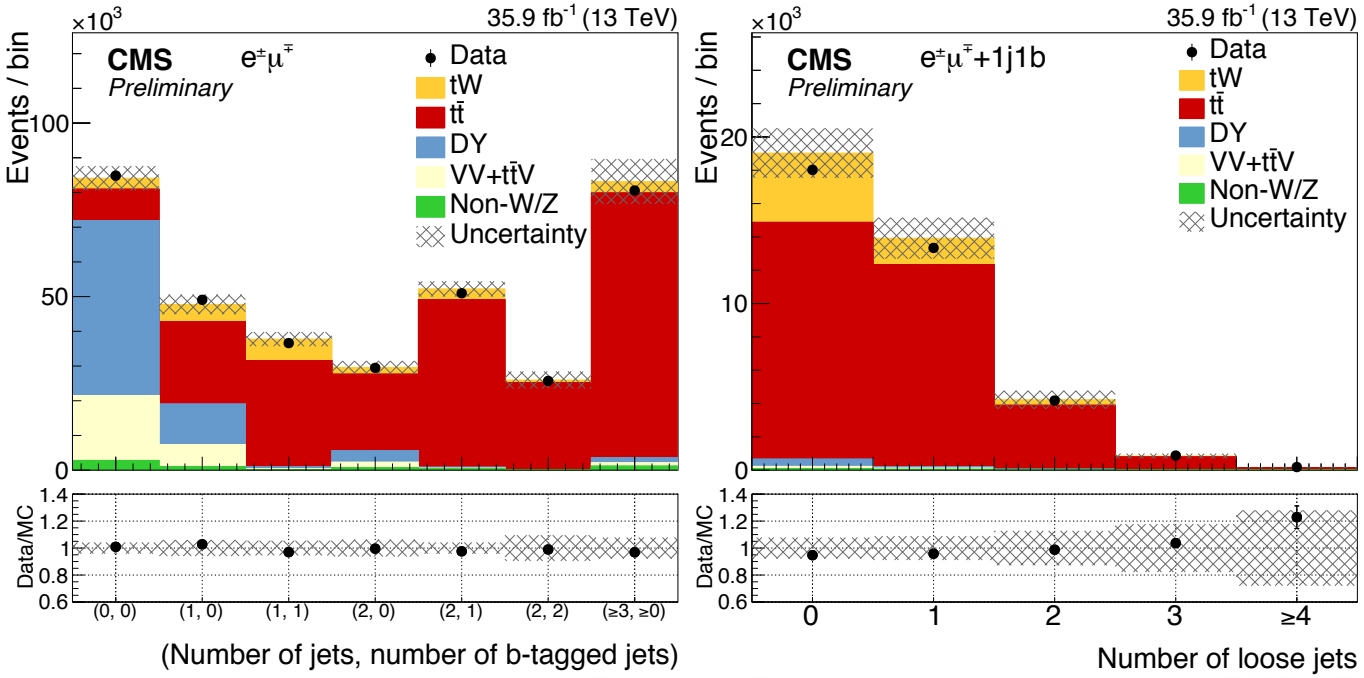
tW differential measurement in dilepton channel

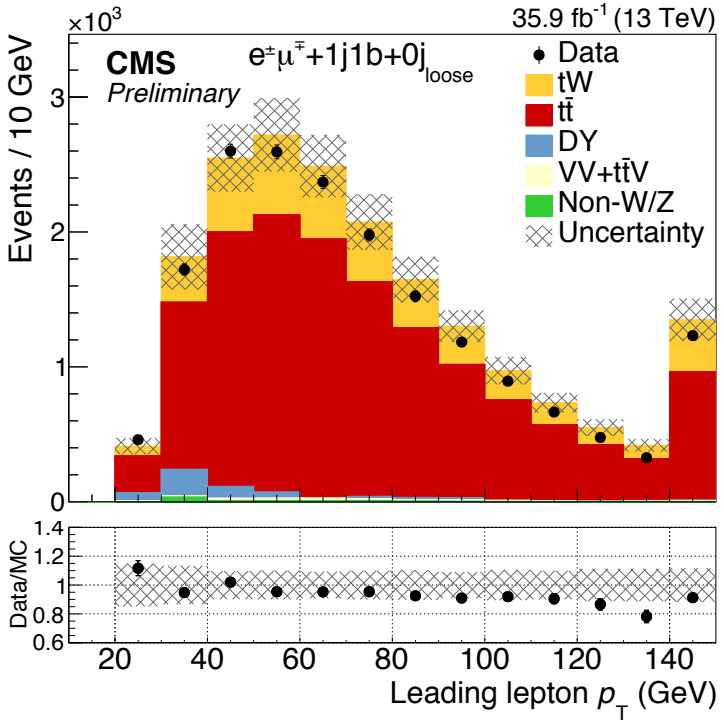
CMS-TOP-19-003



eμ channel analyzed:

- Two isolated leptons with pT>25, 20 GeV
- mll>20 GeV, jets pT>30 GeV
- **Signal region** defined as:
  - exactly 1 jet tagged as b-jet (CSVv2),
  - and 0 additional loose jets





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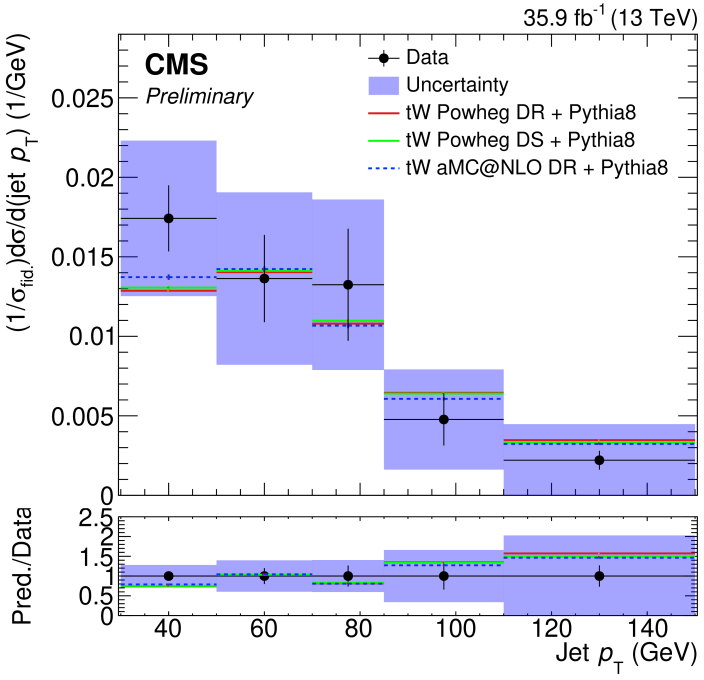
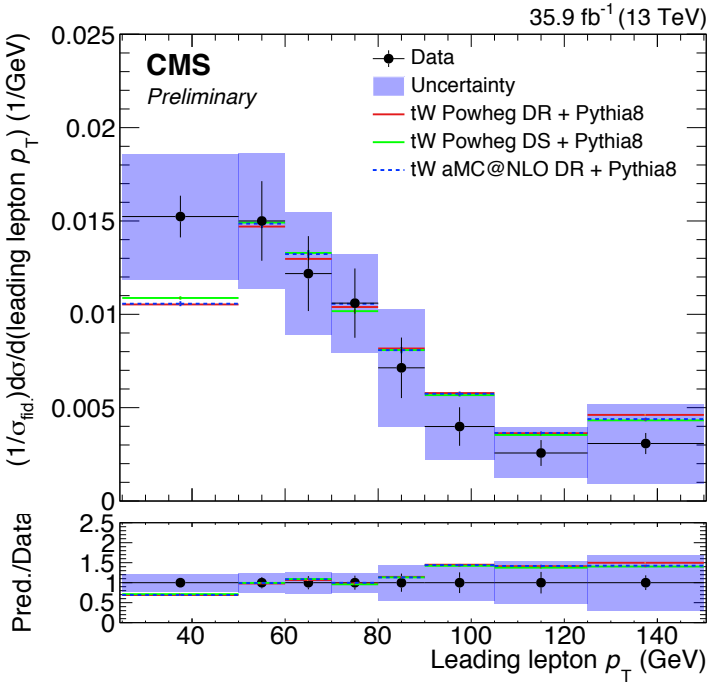
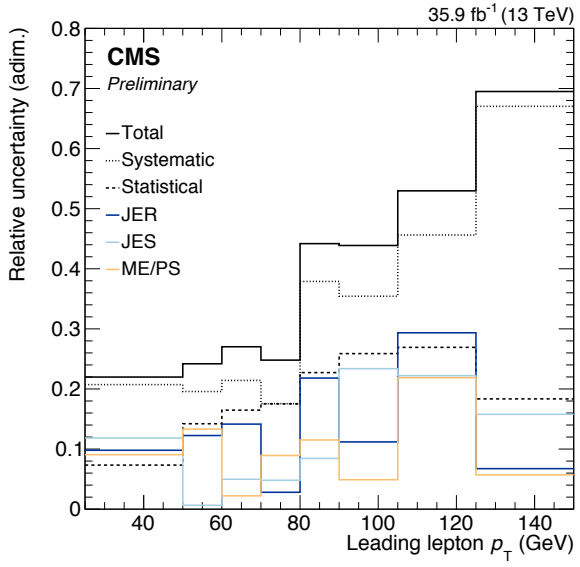
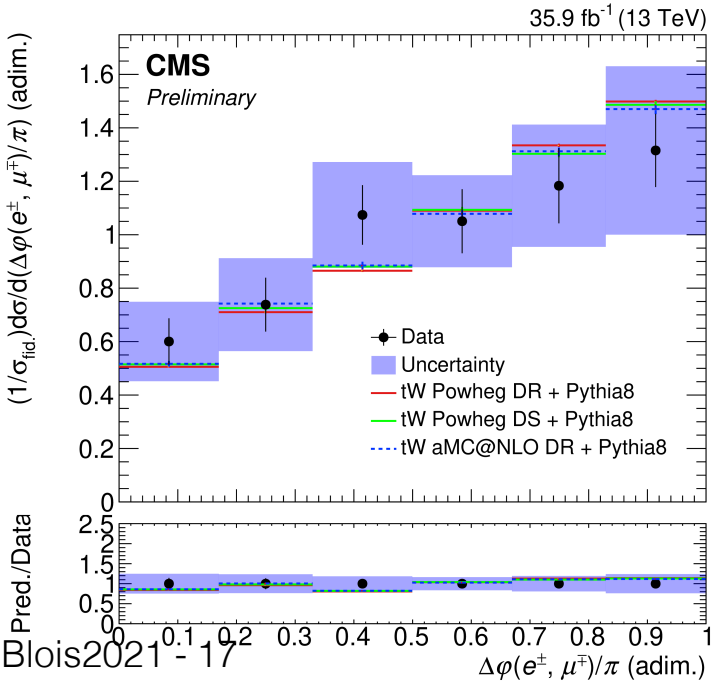
- **Background subtracted** from simulation in each bin of the kinematic distributions
- **Fiducial** cross section very similar to reconstructed level
- **Unfolding** with response matrix, no regularization
- **Interference between tW and ttbar at NNLO**: comparisons with predictions using DR (diagram removal) and DS (diagram subtraction) schemes.



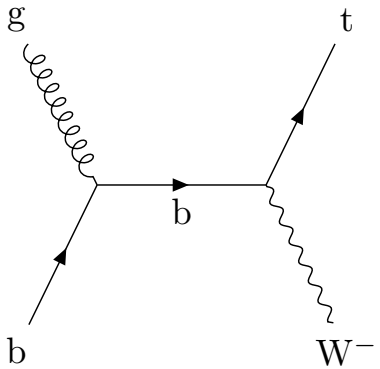






tW cross section in lepton+jets channel

arXiv:2109.01706, submitted to JHEP

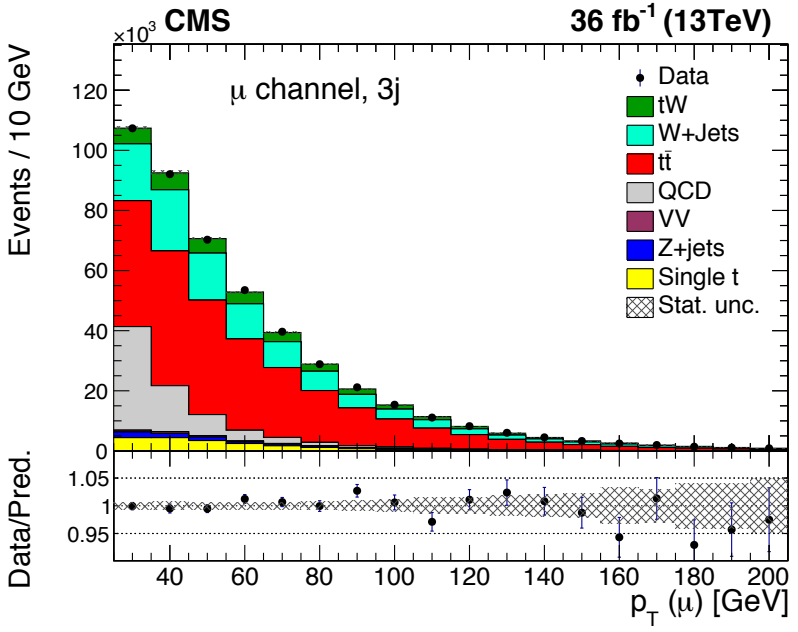


e+jets and μ+jets channels analyzed:

- Trigger on single lepton
- Select a single isolated lepton pT > 26 (30) GeV
- Require jets pT > 30 GeV away from leptons
- Exactly one b-jet is requested (CSVv2 algorithm)
- QCD background estimated from data: revert lepton isolation
- **3 regions defined**: 2 jets (W+jets control region), 3 jets (signal region) and 4 jets (ttbar control region)

Sample	Muon channel 3j	2j	4j
tW	26083 ± 62	29814 ± 66	10612 ± 40
$t\bar{t}$	274100 ± 360	198120 ± 300	186200 ± 300
W+jets	79500 ± 1200	319800 ± 3200	18000 ± 480
QCD multijet	66830 ± 360	277610 ± 940	7700 ± 110
Single t	15786 ± 55	55250 ± 100	4124 ± 28
Z+jets	7290 ± 500	26950 ± 960	2080 ± 240
VV	2860 ± 160	7480 ± 250	754 ± 83
Total prediction	472500 ± 2700	915000 ± 5800	229400 ± 1300
Data	472540	923880	223720

Sample	Electron channel 3j	2j	4j
tW	15726 ± 35	17479 ± 36	6596 ± 23
$t\bar{t}$	156050 ± 200	109980 ± 160	108410 ± 160
W+jets	50230 ± 670	192400 ± 1800	12090 ± 310
QCD multijet	21120 ± 410	87880 ± 680	2370 ± 79
Single t	8937 ± 30	30335 ± 54	2379 ± 15
Z+jets	6960 ± 300	24170 ± 590	1840 ± 140
VV	1635 ± 84	4050 ± 130	463 ± 44
Total prediction	260700 ± 1700	466300 ± 3500	134000 ± 780
Data	270330	462940	136190



tW cross section in lepton+jets channel

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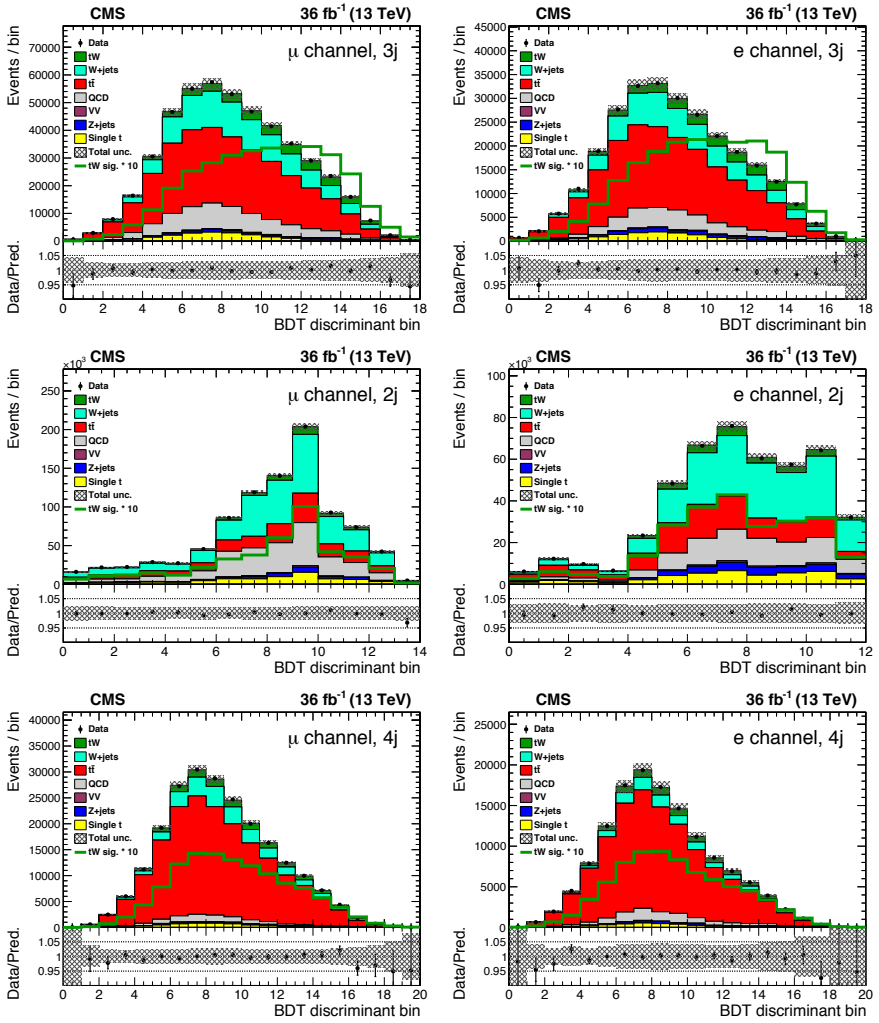
- A **BDT** is trained against ttbar, exploiting the difference in jet kinematics
- tW extraction likelihood fit of the 3 regions



First observation of tW process in l+jets channel (>5σ)

Cross section: $89 \pm 4\,(\text{stat}) \pm 12\,(\text{syst})\,\text{pb}$

Source	Relative uncertainty (%)
Experimental	
Jet energy scale	6
b tagging efficiency	4
Luminosity	3
Lepton energy scale	2
Trigger efficiency	1
Jet energy resolution	1
b tagging misidentification rate	<1
Unclustered energy	<1
Pileup	<1
Normalization	
QCD multijet normalization	7
W+jets normalization	6
Z+jets normalization	3
Single t normalization	1
$t\bar{t}$ normalization	1
VV normalization	<1
Theoretical	
h_{damp}	4
Diagram removal/diagram subtraction	3
Underlying event tune	3
Colour reconnection model	1
Parton distribution function	1
Matrix element/parton shower matching	1
Final-state radiation	<1
Initial-state radiation	<1
Total systematic uncertainty	14
Statistical uncertainty	5
Total uncertainty	15

Conclusions

Top pair cross sections

- ttbar cross sections measured in **full kinematical range**
- **Multi-differential** cross sections being measured
- Used to measure precisely alpha_s, contrain pdf, measure top mass
- **Boosted techniques** are used to access the high-pT regime
- **NLO+PS predictions overestimate data at high pT**, in all final states. Work ongoing to compare measurements with latest theory predictions

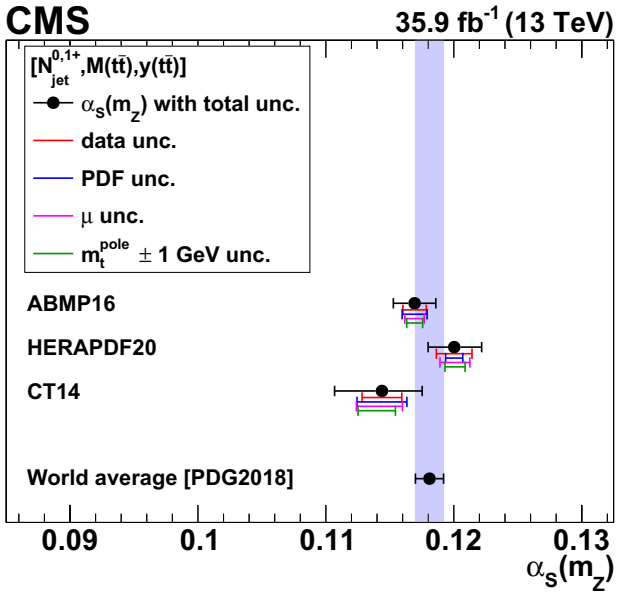
Single top cross sections

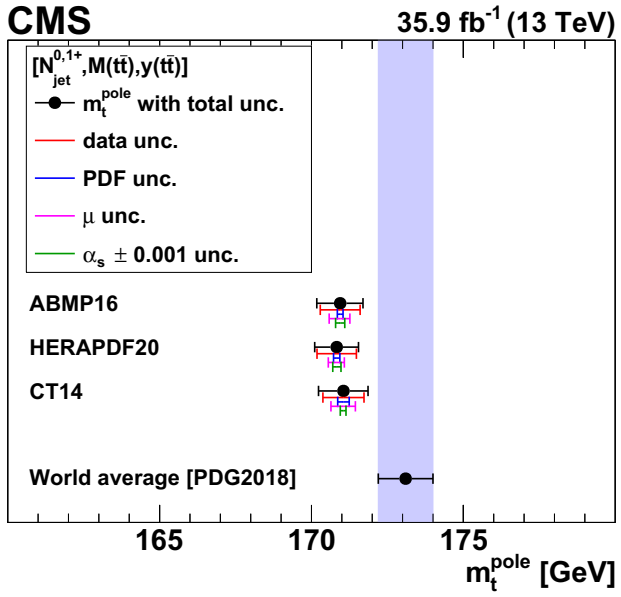
- **Differential** cross sections measured in **t-channel and tW channel**
- Accessing **more difficult final states with tW lepton+jets**
- s-channel still to be observed at the LHC

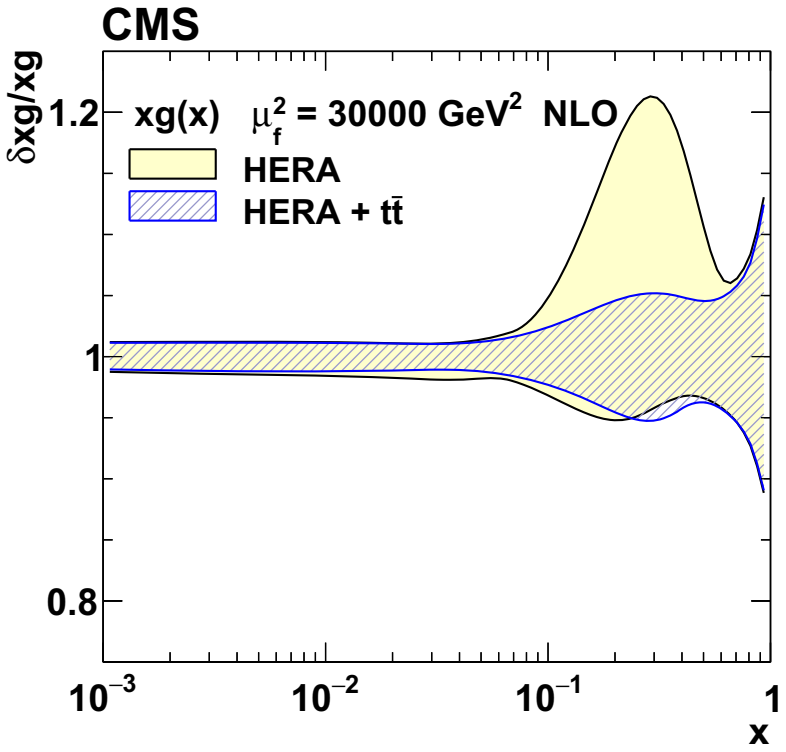
Back-up slides

Top pair multi-differential measurement in dilepton channel

CMS-TOP-18-004, Eur. Phys. J. C 80 (2020) 658







BDT in tW lepton+jets

- mass of the hadronically decaying W boson candidate,
- invariant mass of the b-tagged jet and the sub-leading (in p_{T}) non-b-tagged jet,
- angular separation between the two non-b-tagged jets,
- angular separation between the reconstructed leptonic W boson candidate and leading (in p_{T}) non-b-tagged jet,
- p_{T} of the selected lepton,
- energy of the two non-b-tagged jets,
- angular separation between the b-tagged jet and the selected lepton,
- transverse momentum of the system made of the three jets, lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$.