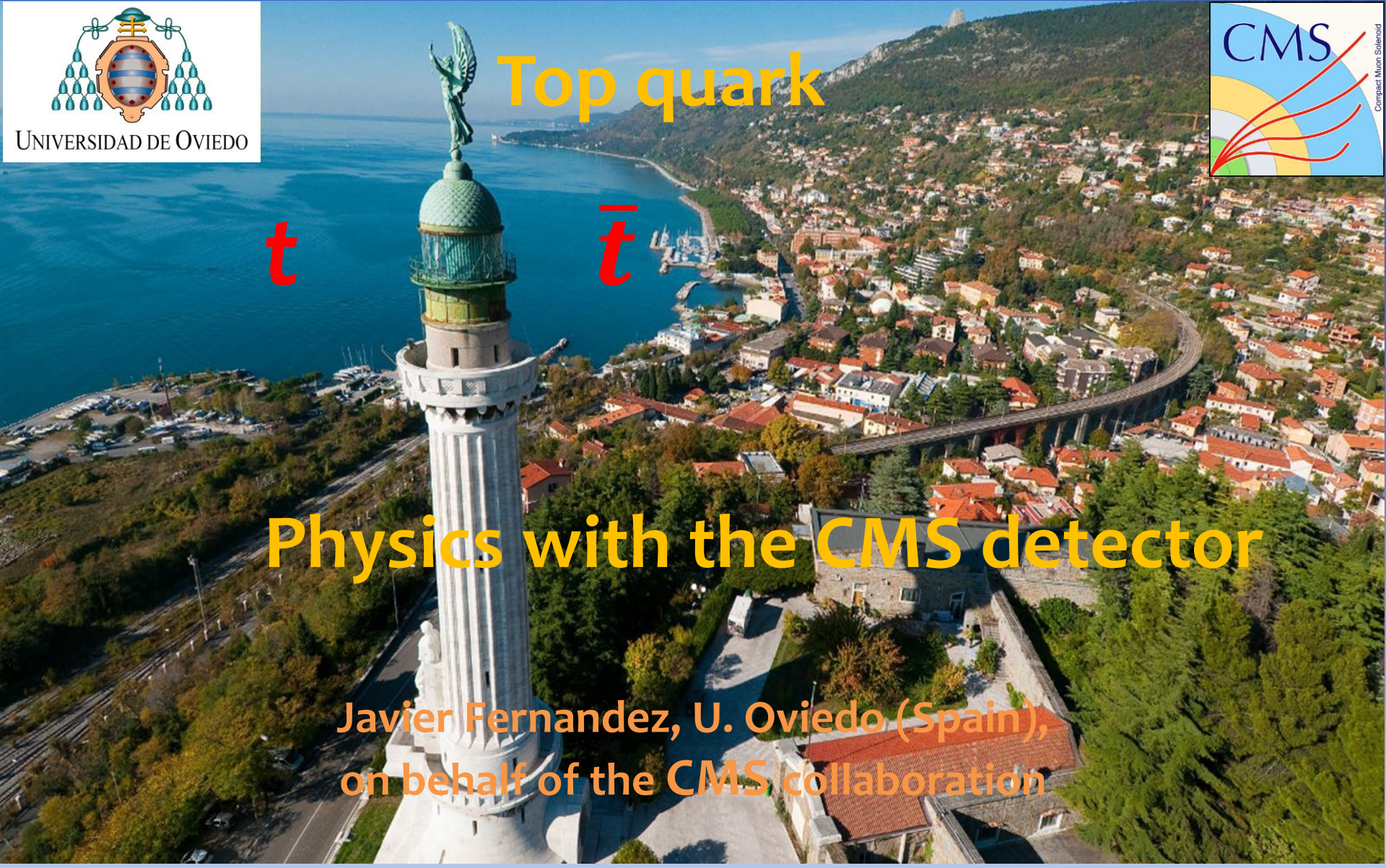


Top quark

t $\bar{t}$

Physics with the CMS detector

Javier Fernandez, U. Oviedo (Spain),
on behalf of the CMS collaboration

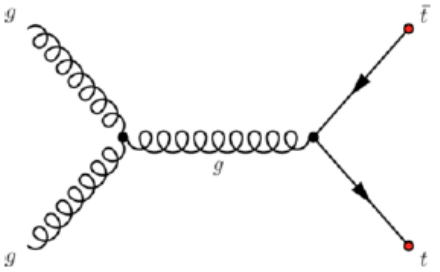
Interpreting the LHC Run 2 data and Beyond
27 May 2019, ICTP Trieste

Outline

- top quark pair production ($t\bar{t}$): Focus on latest results
  - inclusive & differential cross section measurements
  - underlying event and jet substructure observables
  - constraints of fundamental QCD parameters
  - top properties (mass, Yukawa coupling, polarization)
  - top pair spin correlations
- single top production:
  - inclusive cross section (legacy Run1 ATLAS/CMS)
  - differential cross section
  - associated production with a photon & tZq
- top quark pair + X :
  - four top ($t\bar{t}\,t\bar{t}$): 1ℓ, 2ℓ, 2ℓ SS & multi-lepton
  - $t\bar{t}$ associated production with a Z boson
  - $t\bar{t}\,b\bar{b}$

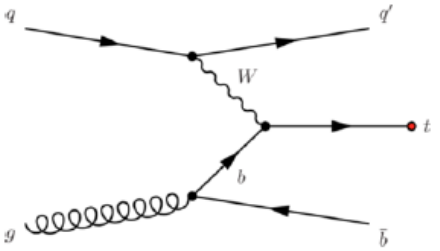
top quark pair production

σ(pp @ 13 TeV) = 832 pb



single top quark production

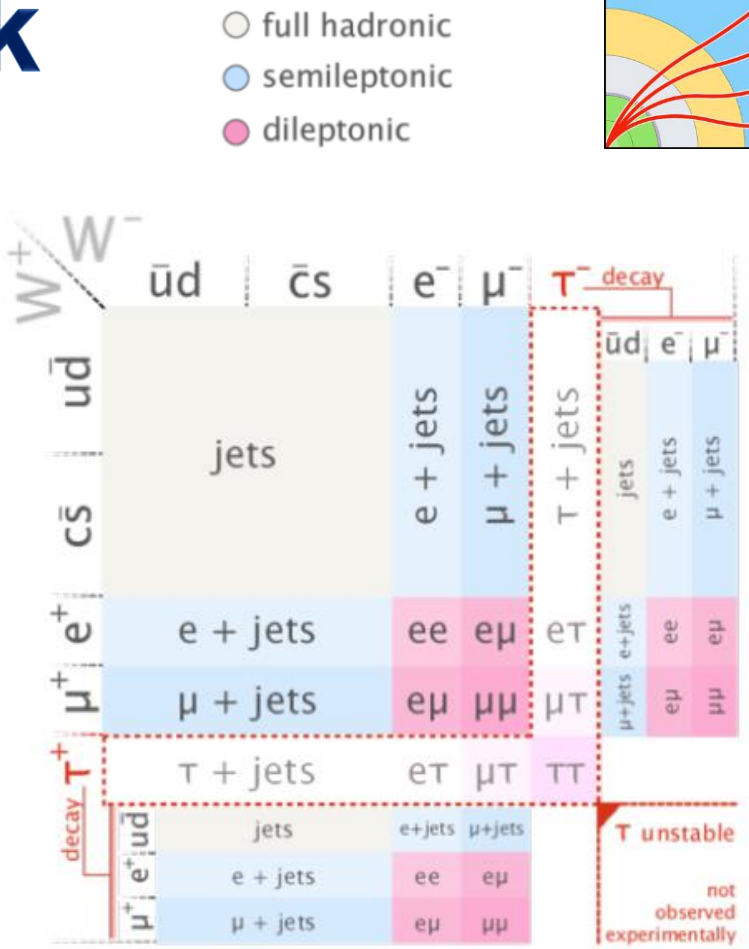
σ(pp @ 13 TeV) = 299 pb



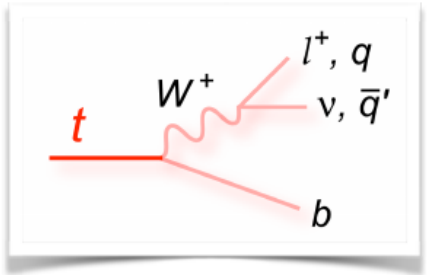
Caveat: References TOP-XX-YYY = CMS-PAS-TOP-XX-YYY

Is top quark special?

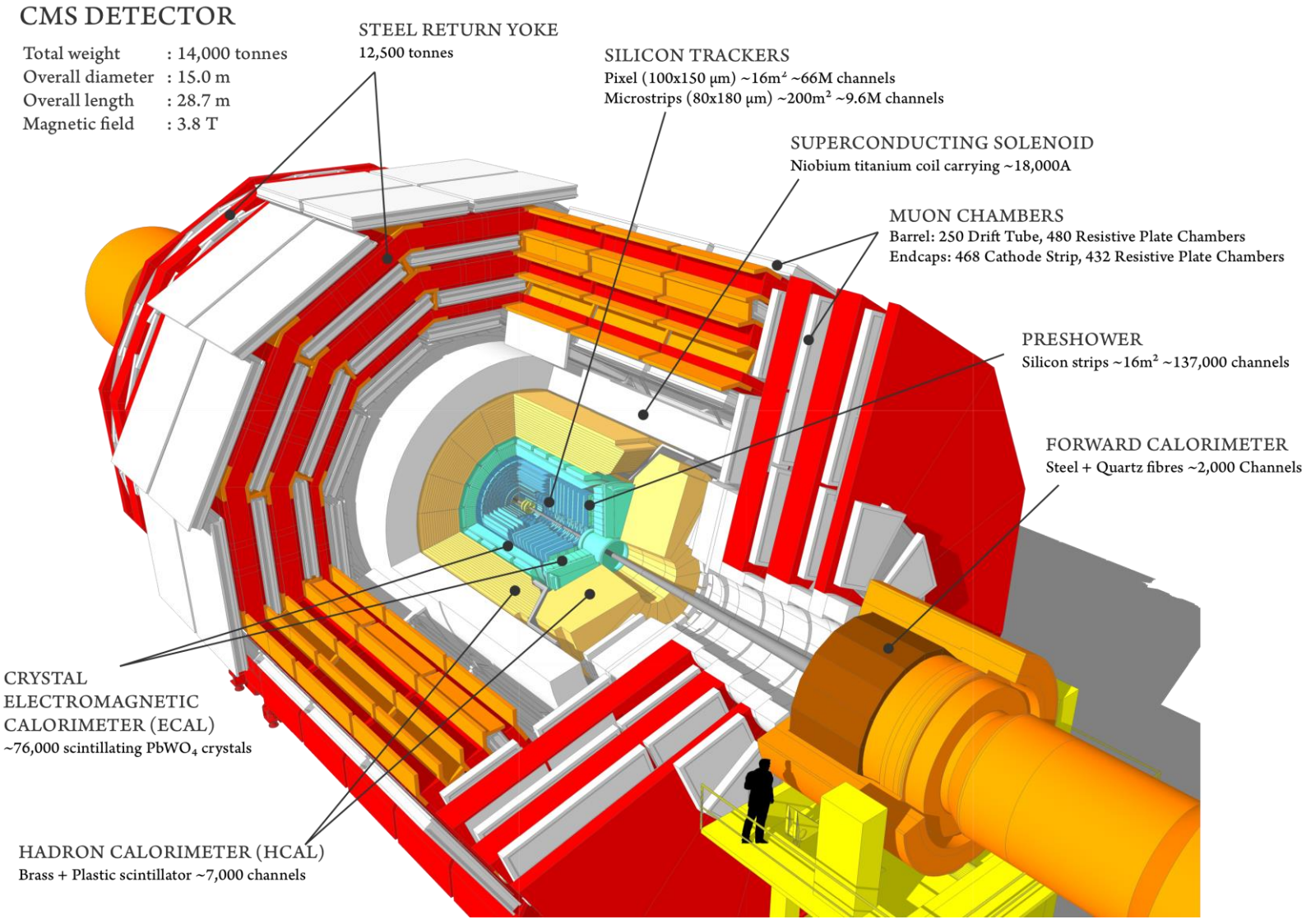
- top quark is the most massive known particle
  - significant contribution of top loops
- the top Yukawa coupling is close to unity
  - coincidence or special dynamics?
- it decays before it can hadronize
  - no bound states with top can be formed
  - its decay products (W, b) largely preserve the top quark spin polarization
- top properties provide critical tests for the SM predictions
  - very sensitive to BSM effects



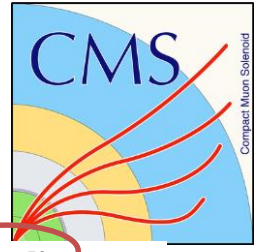
BR(t→Wb) = 0.957

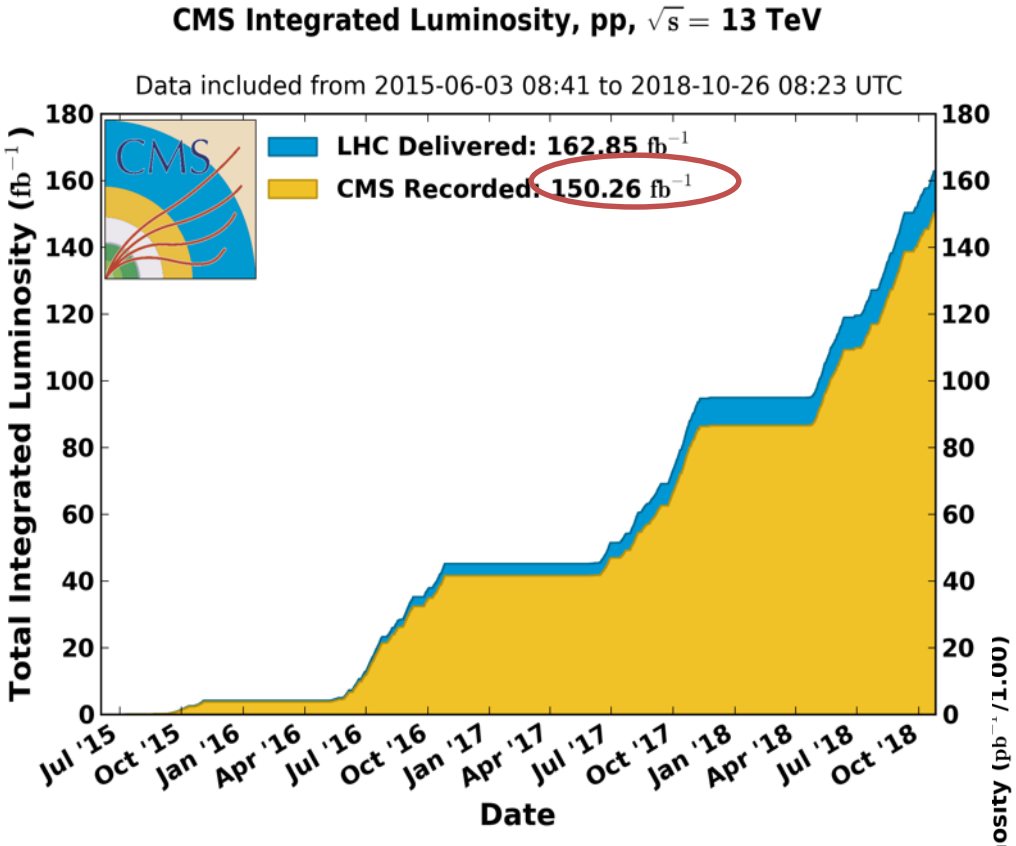


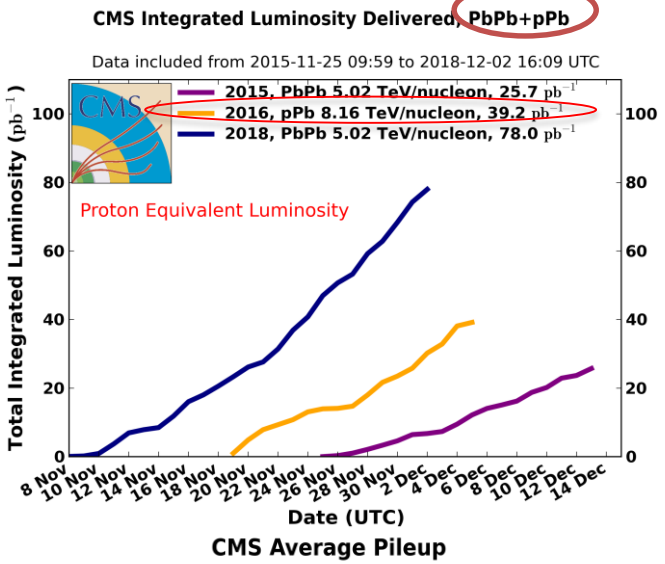
The CMS detetcor

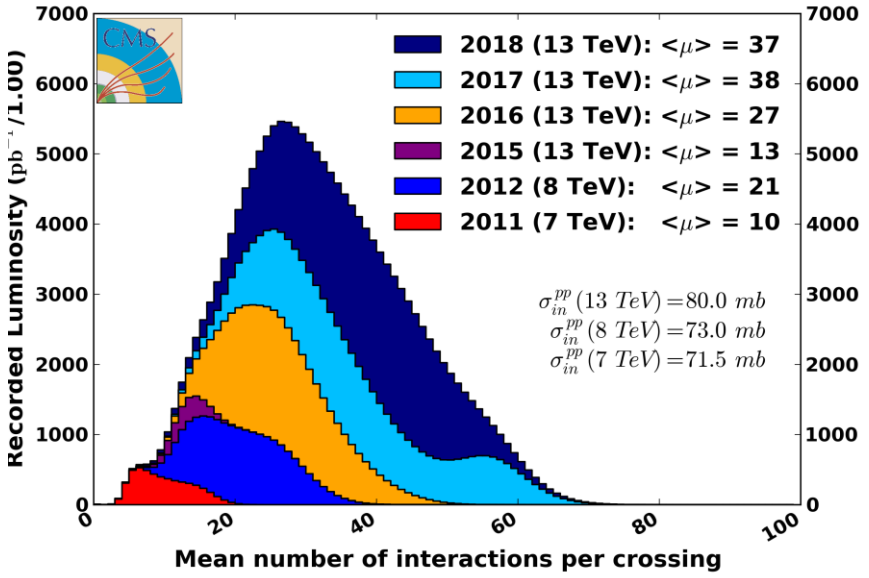


LHC: the perfect machine?









Run2: proton-proton @ 13 TeV in 2015 - 2018

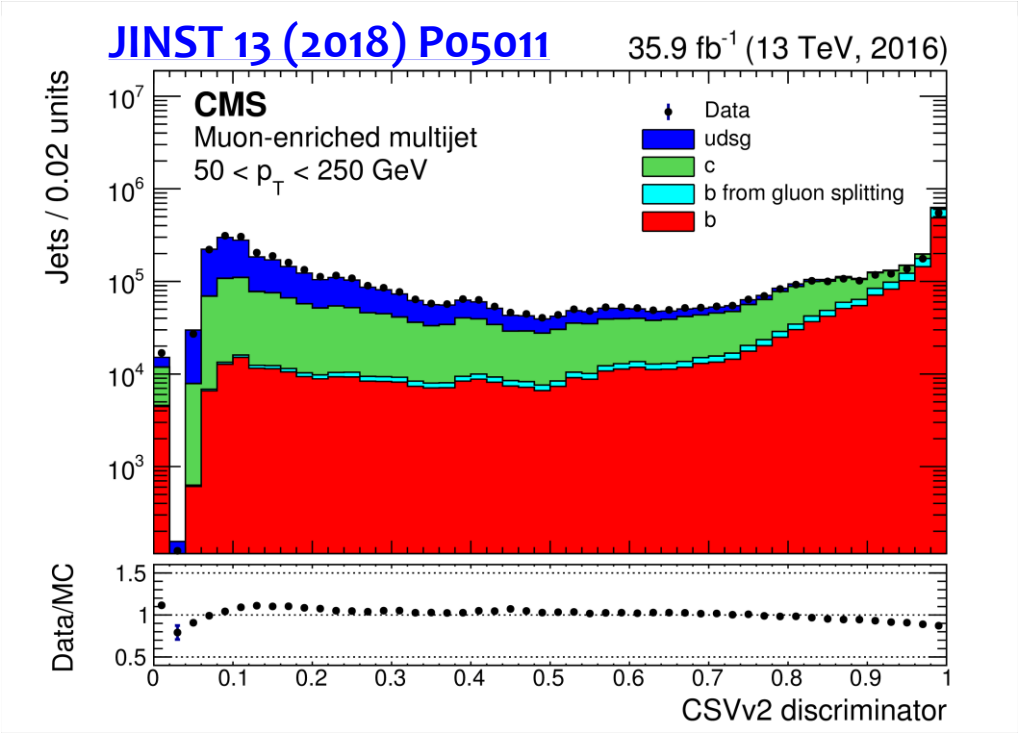
- total luminosity ≈ 163 fb^{-1}
- ~10^8 top quark pairs produced
- on average 34 interactions per bunch crossing

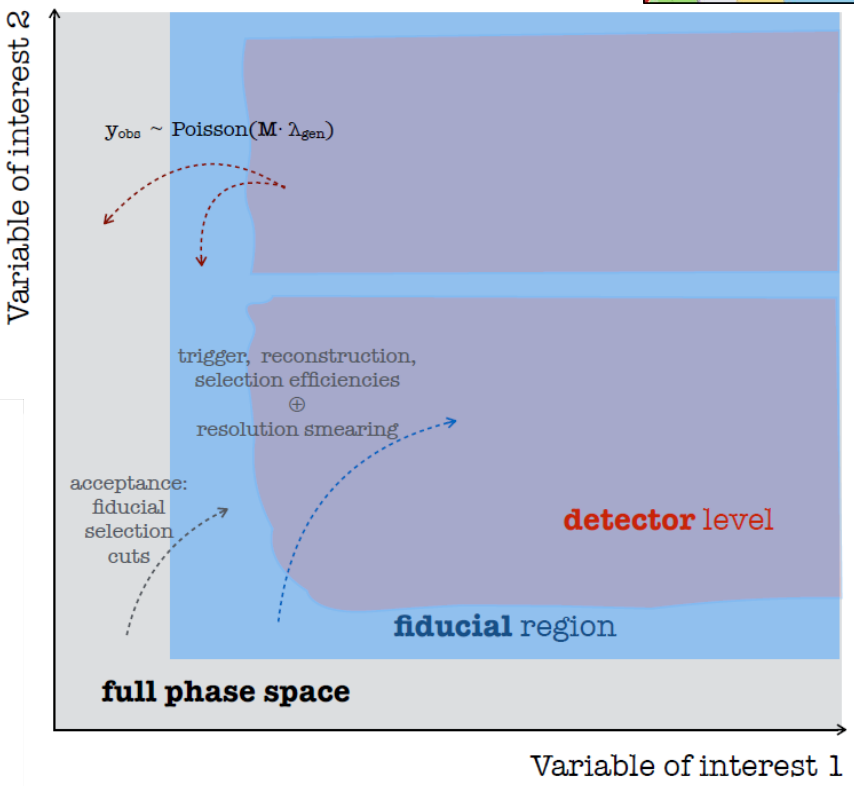
The challenges

All types of objects involved (jets, b-jets, missing transverse momentum, leptons)

- **Experimental challenges:**

- jet energy scale (< 2%)
- b-tagging efficiency (< 3%) & fake rate
- lepton triggering & identification (< 2%)





- **Theoretical challenges:**

- enter through unfolding to parton & particle level
- parton shower & underlying event modelling

CMS-NOTE-2017-004

TOP QUARK PAIR PRODUCTION

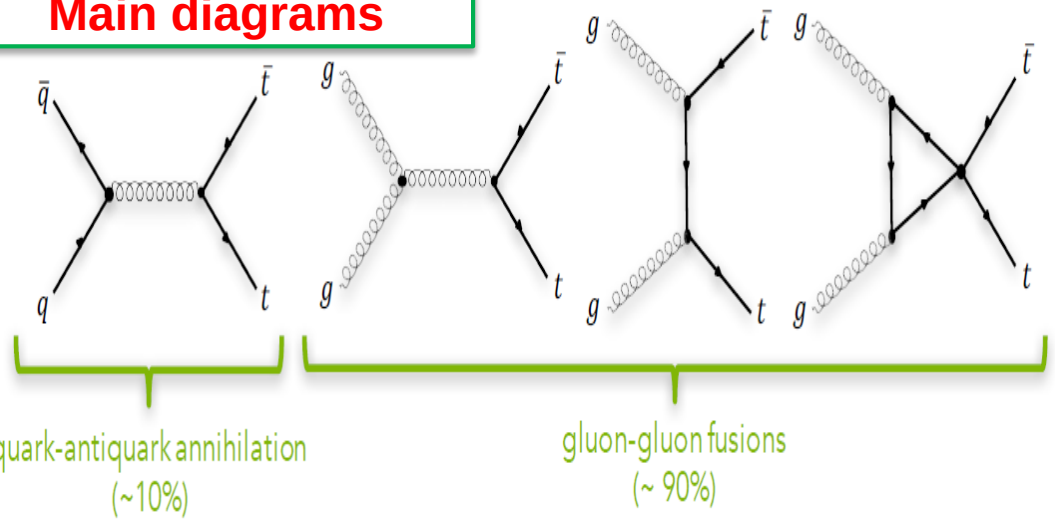
Top quark pair production @LHC

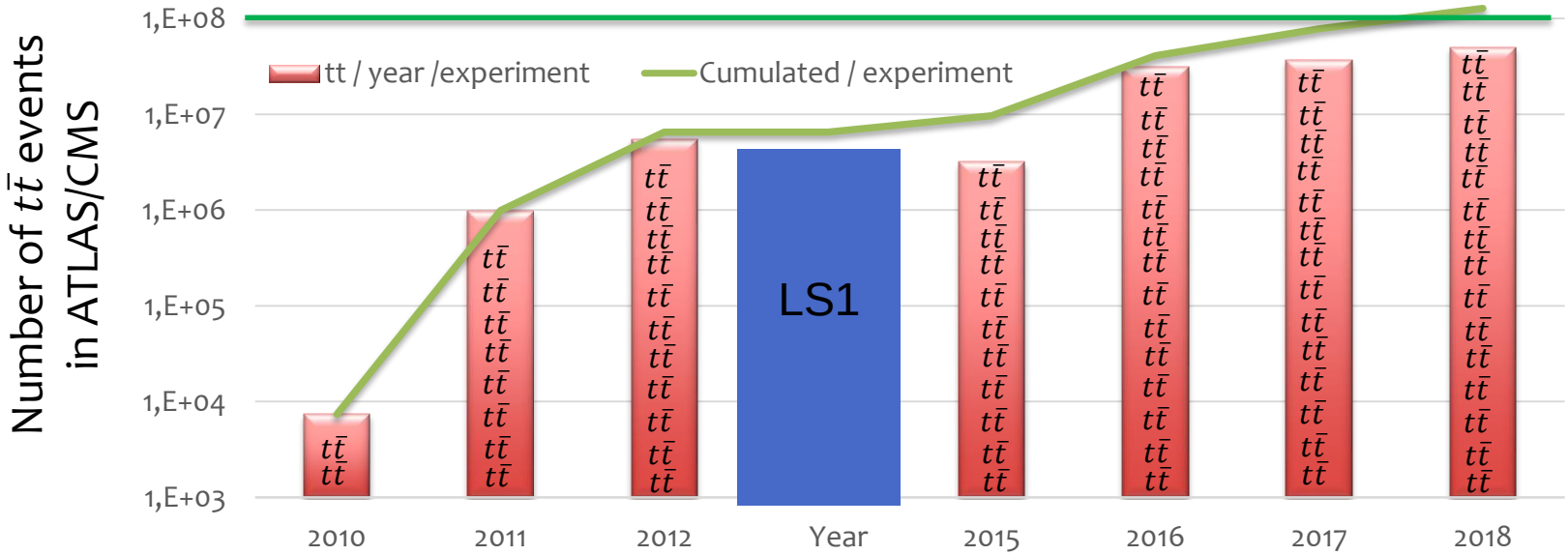
$\sqrt{s}$ (TeV)	σ ($m_t = 172.5$ GeV)
5	$68.9 \pm 1.9(\text{scale}) \pm 2.7(\text{PDF} + \alpha_S)$
7	$177.3^{+4.7}_{-6.0}(\text{scale}) \pm 9.0(\text{PDF} + \alpha_S)$
8	$252.9^{+6.4}_{-8.5}(\text{scale}) \pm 11.7(\text{PDF} + \alpha_S)$
13	$832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF} + \alpha_S)$

5.2-4.8%

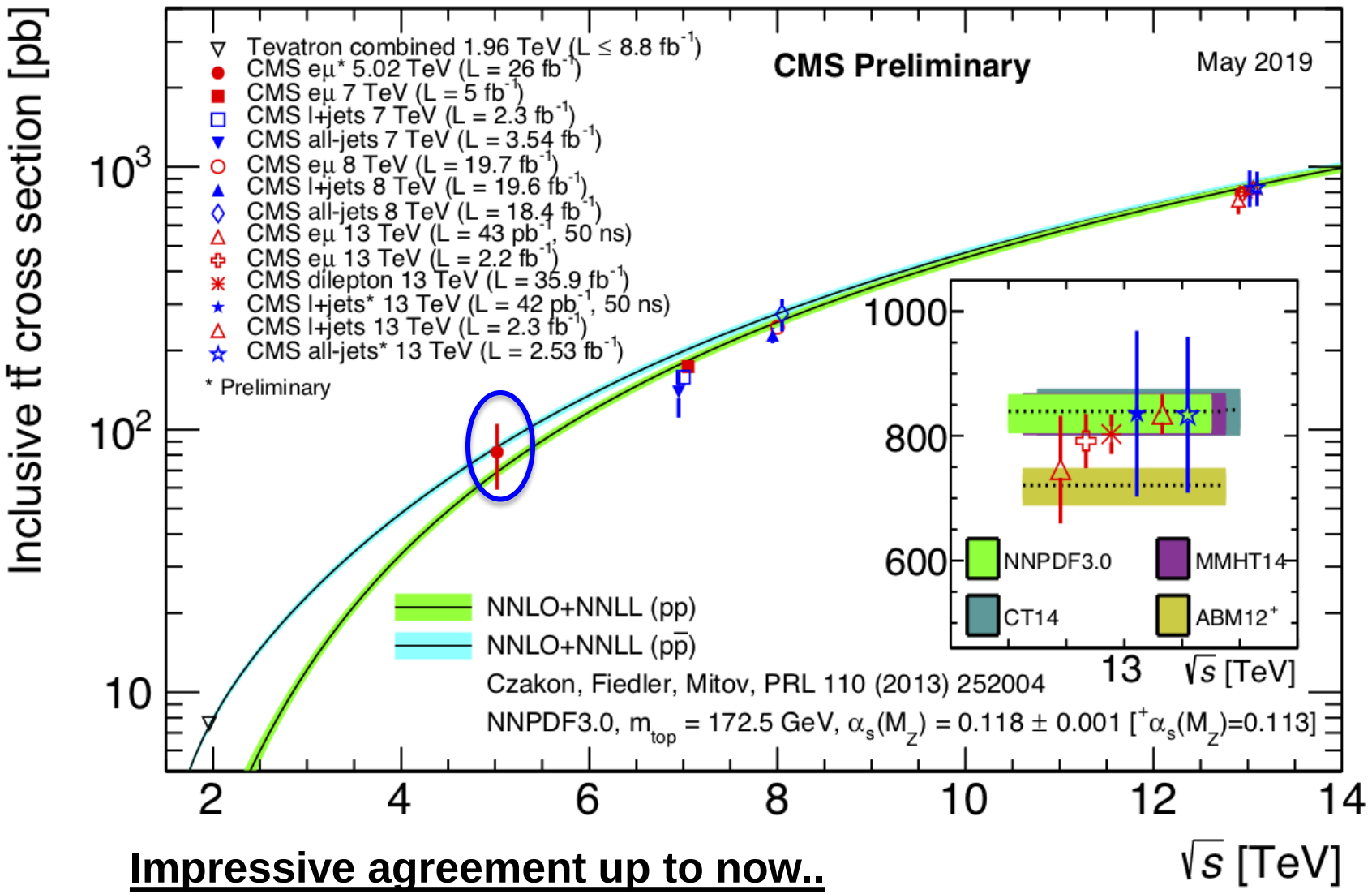
Full NNLO+NNLL calculation [arXiv:1303.6254]

Main diagrams



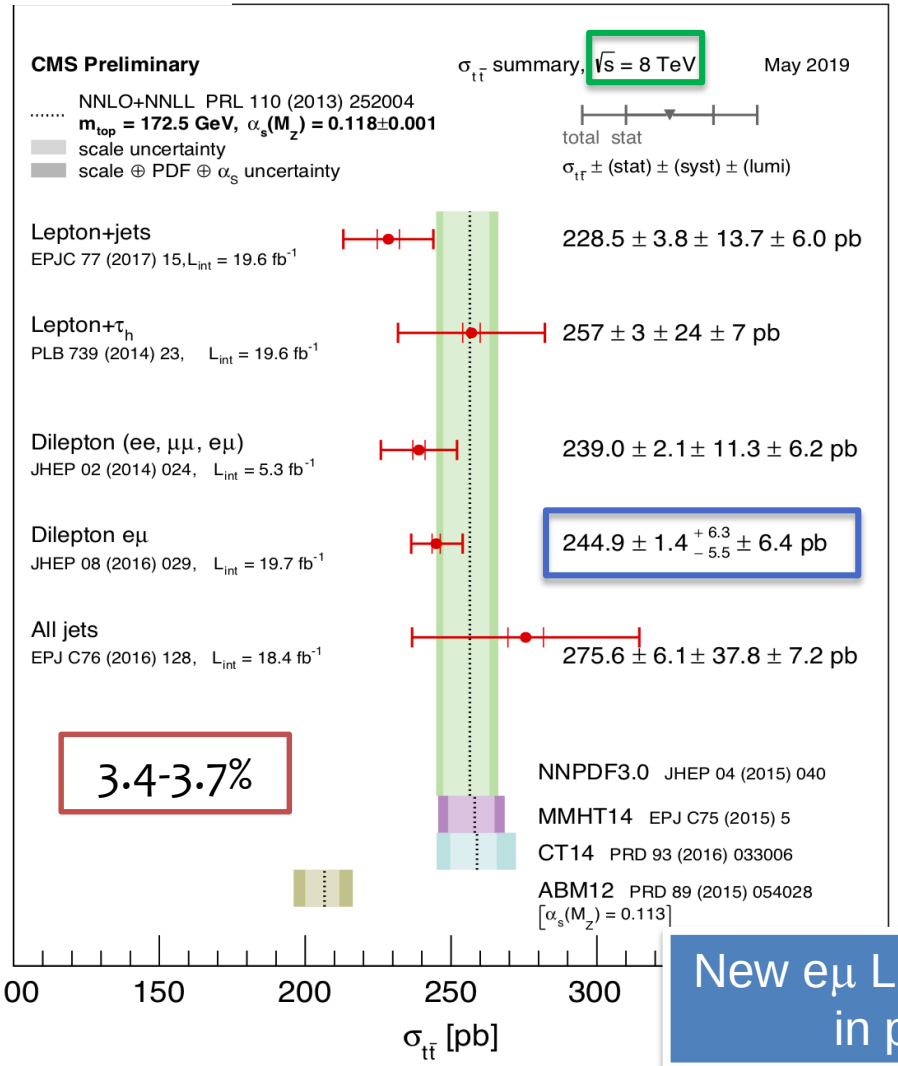


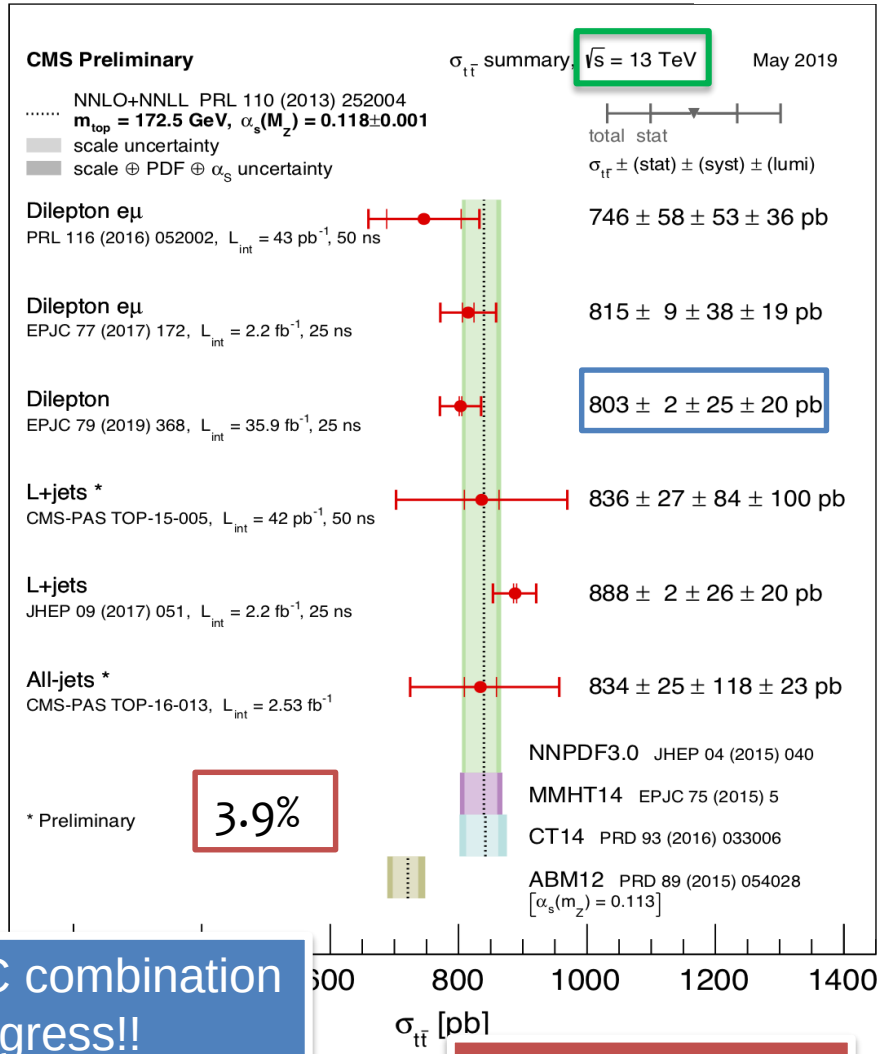
The full picture



Impressive agreement up to now..

The detailed picture





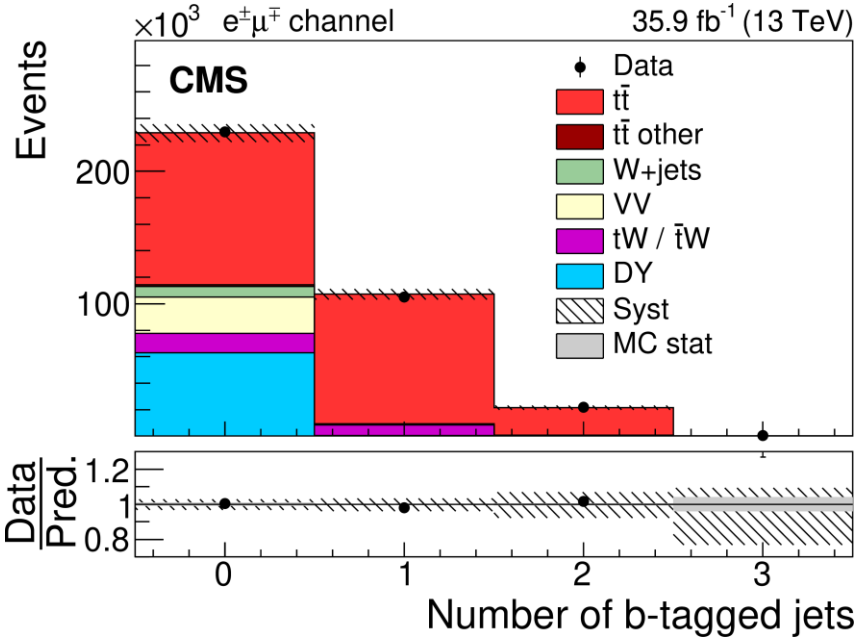
New eμ LHC combination in progress!!

- Inclusive measurements are in good agreement with theory
- Exp. uncertainty comparable to theoretical uncertainty

Need to look at differential measurements!!

Latest inclusive measurements

Inclusive dilepton 2016 $\sqrt{s}$ = 13 TeV.
TOP-17-001 EPJC 79 (2019) 368

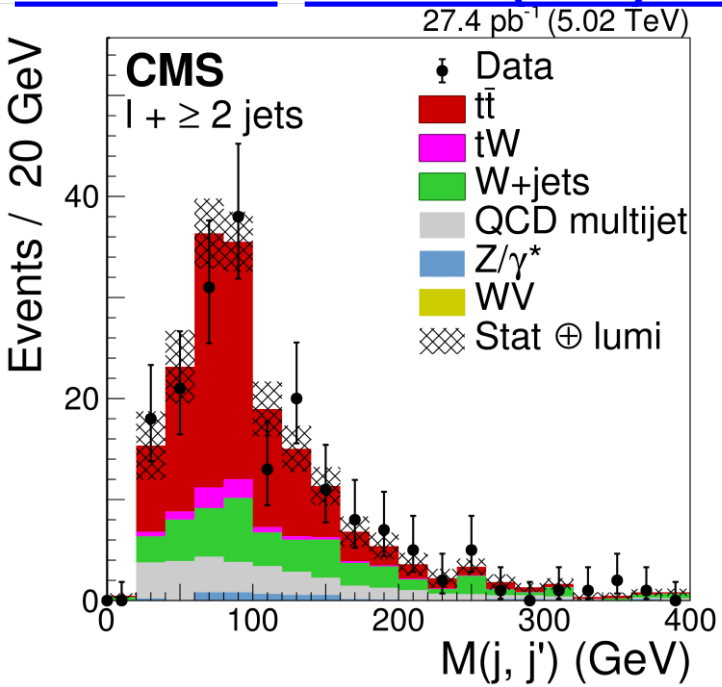


- Categorization based on b-tagged jet
- In situ constraint of experimental uncertainties from maximum likelihood fit on μμ, ee, eμ 3.9%

σ_{tt}=803 ± 2 (stat) ± 25 (syst) ± 20 (lumi) pb

NNLO + NNLL
$\sigma_{t\bar{t}}^{theo} = 832\,^{+20}_{-29}\,(scale) \pm 35\,(PDF + \alpha_S)$ pb

Inclusive dilepton & l+jets $\sqrt{s}$ = 5.02TeV
TOP-16-023 JHEP 03 (2018) 115



- Complementary data, reference for future Pb-Pb and p-Pb measurements
- l+jets analysis: Fit to ΔR non-b-tagged jets in samples with 0, 1, 2 b-tags
- Dilepton (eμ,μμ) analyses: Counting

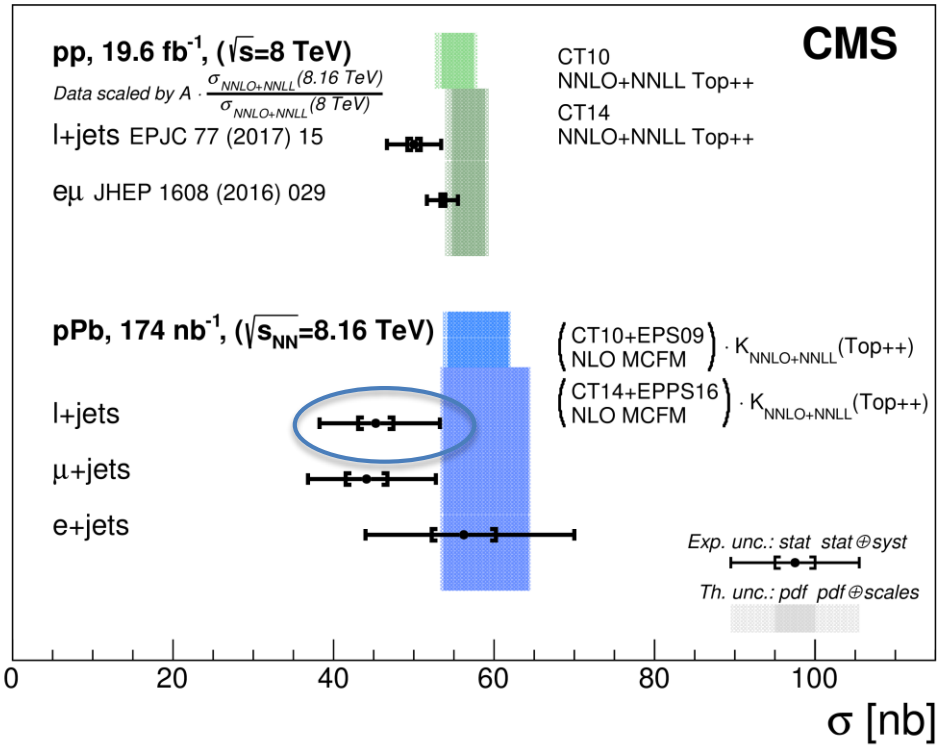
$\sigma_{Combined}$=69.5 ± 6.1 ± 5.6 ± 1.6 pb (12%)

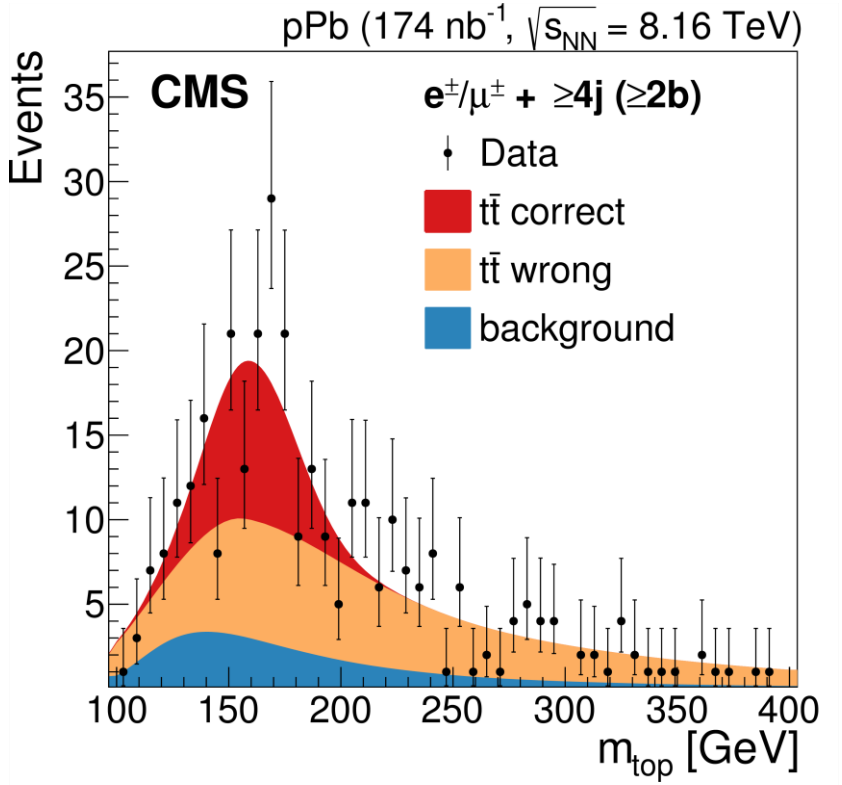
$\sigma^{NNLO} = 68.9\,^{+1.9}_{-2.3}\,(scale) \pm 2.3\,(PDF)\,^{+1.4}_{-1.0}\,(\alpha_s)$ pb

$t\bar{t}$ in proton-nucleus (Pb) collisions

First observation at $\sqrt{s}$=8.16TeV (2016)

Phys. Rev. Lett. 119 (2017) 242001





- Novel and theoretically precise probe of the nuclear gluon density at high virtualities
- Considering different event categories with 0, 1, ≥ 2 b-tagged jets
- $t\bar{t}$ cross section extracted from comb. unbinned max. likelihood fit of $m$jj' (W→ jj')

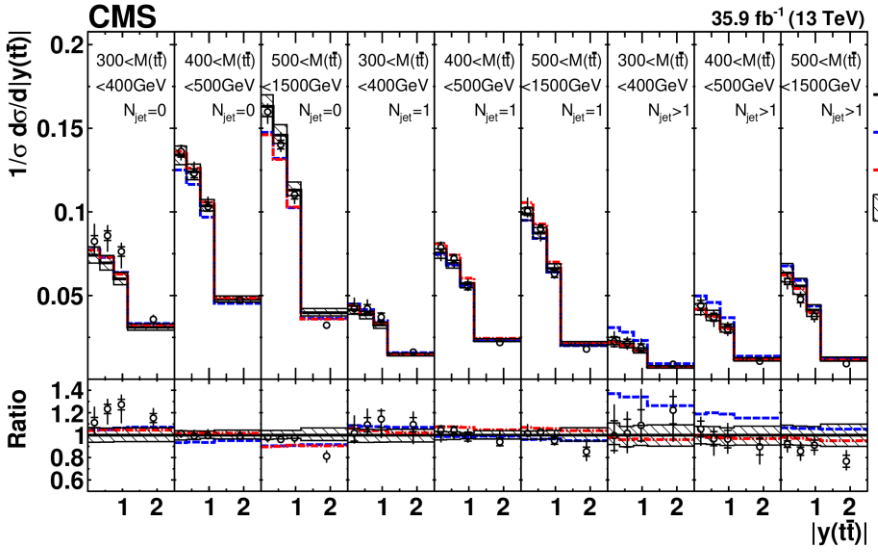
$$\sigma_{t\bar{t}}^{\mu+\text{jets}} = 44 \pm 3\,(\text{stat}) \pm 8\,(\text{syst})\,\text{nb},$$
$$\sigma_{t\bar{t}}^{\text{e}+\text{jets}} = 56 \pm 4\,(\text{stat}) \pm 13\,(\text{syst})\,\text{nb}$$

$$\sigma_{t\bar{t}} = 45 \pm 8\,(total)nb$$

Latest differential measurements

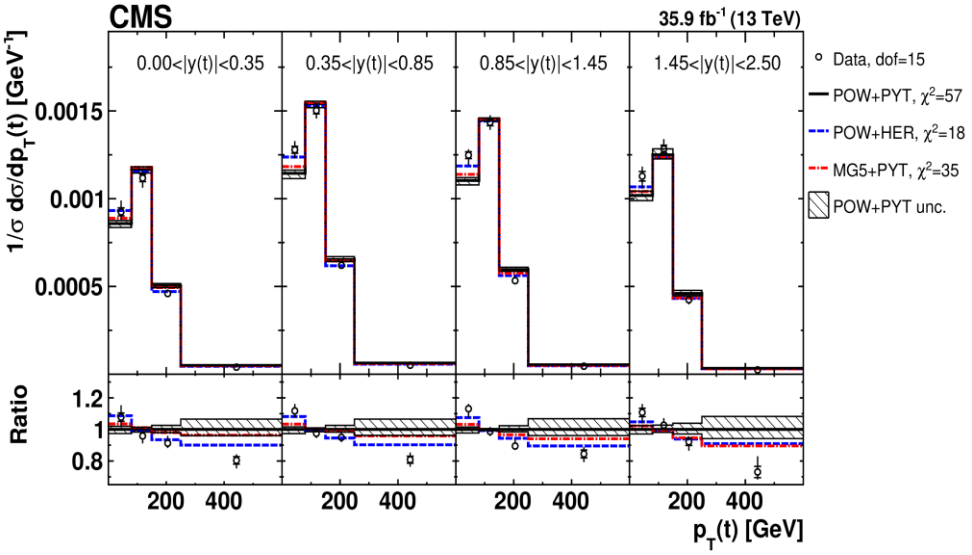
Multi-differential dilepton 2016 $\sqrt{s}$ = 13 TeV

TOP-18-004 arXiv:1904.05237



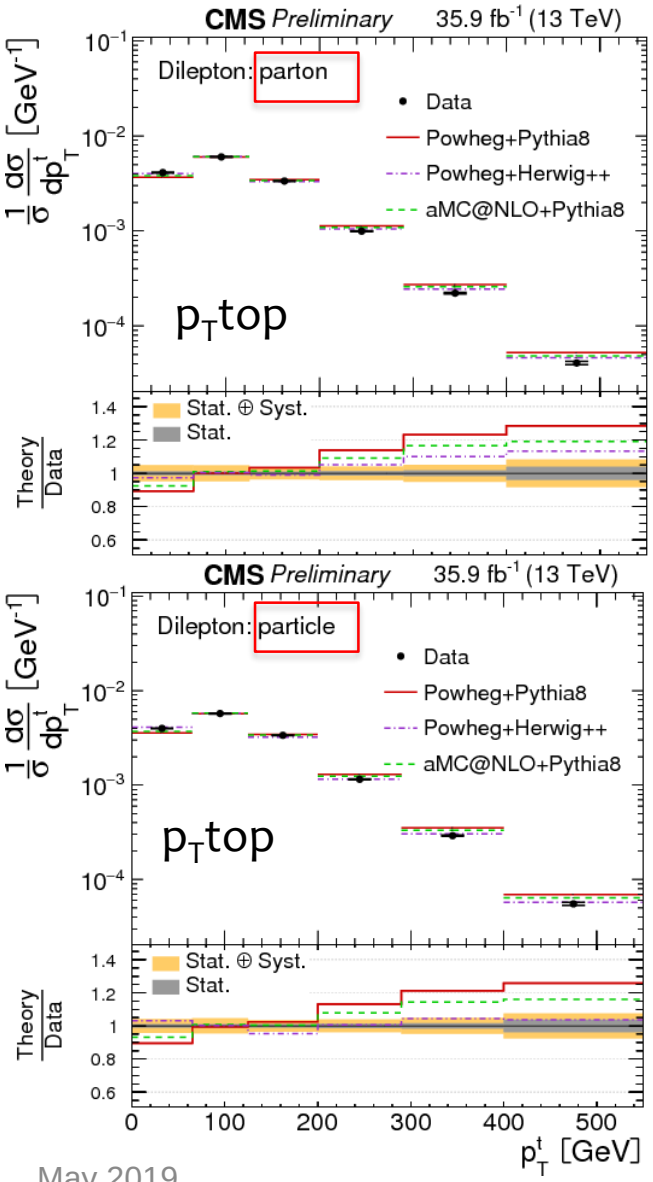
- **QCD analysis (see slide 18):**
  - Multi-differential measurements are very sensitive to the QCD predictions
  - extraction of α_S
  - measurement of m_t
  - simultaneous fit of PDFs, α_S and m_t
  - significant impact on gluon PDF

- **dilepton events (ee, eμ, μμ):**
  - high purity & statistics sample
- **measurements:**
  - normalized differential cross sections
  - **double** differential (top p_T in |y| bins, |y(tt)| in m_{tt} bins, etc)
  - triple differential (|y(tt)| in m_{tt} and jet multiplicity bins)

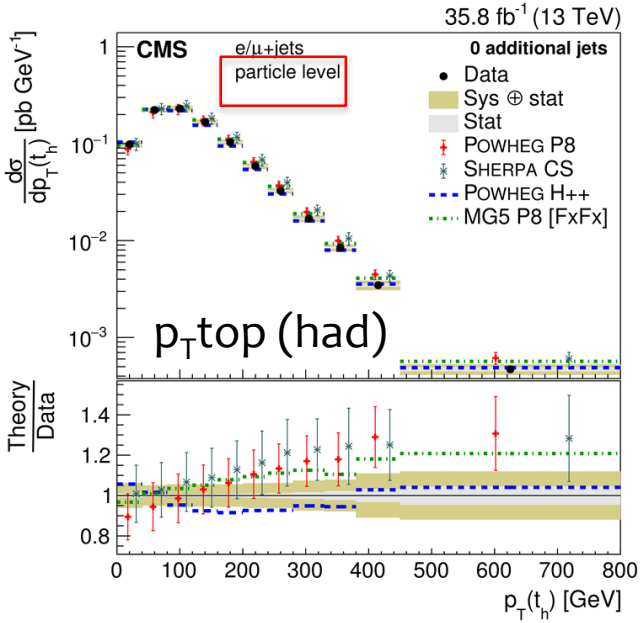


Top quark p_T discrepancy

[CMS-TOP-17-014 JHEP 02 (2019) 149]



- 13TeV eμ (2016)
- Parton level in the full phase space
- Particle level, within a phase space close to experimental acceptance (fiducial phase-space)

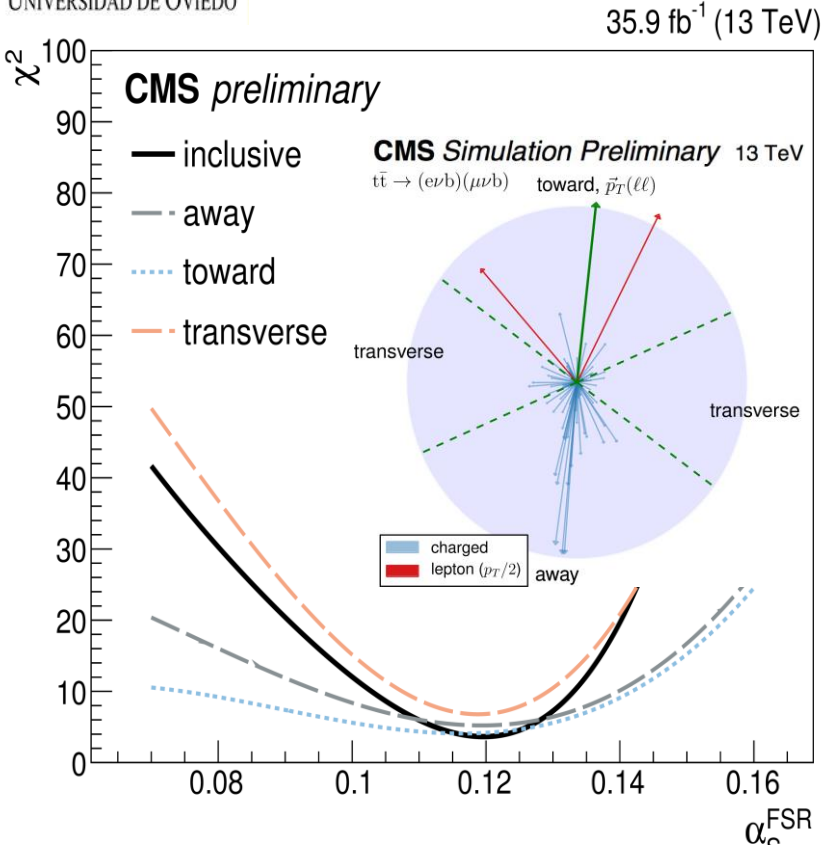


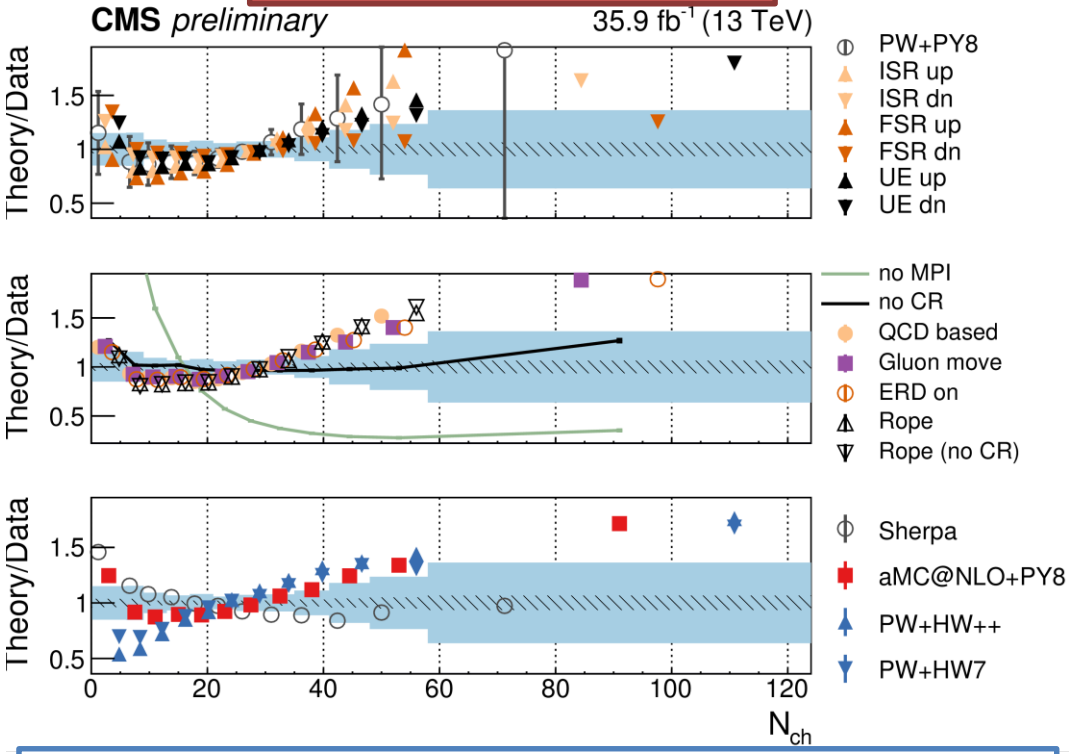
- **PowhegV2+Pythia8** (NLO) chosen as default generator setup in ATLAS and CMS for Run2:
  - ❖ Reasonable agreement except in top quark "direct" observables p_T, p_T^{tt}, m_{tt}
  - ❖ Only Herwig++ seems to have a different trend but it has been superseded by Herwig7
  - ❖ Need for full NNLO MC + PS predictions

[CMS-TOP-17-002 PRD 97 (2018) 112003]

Underlying Event tune in $t\bar{t}$

[CMS-TOP-17-015](#)
[EPJC 79 (2019) 123](#)





- Dilepton data $\sqrt{s}$ = 13TeV from 2016

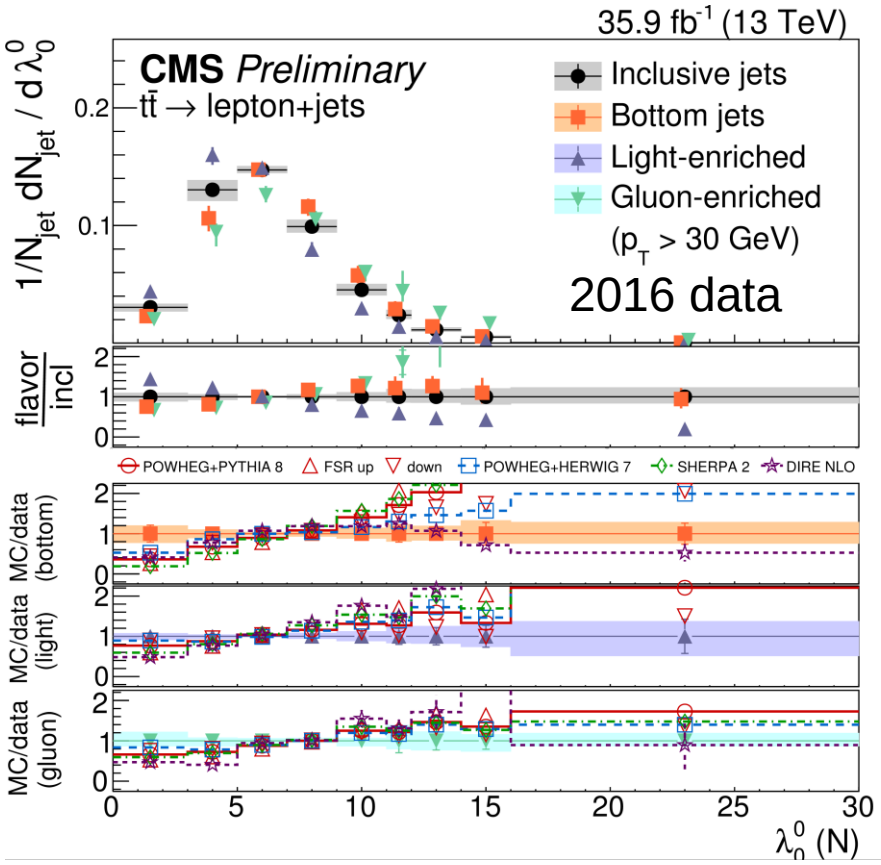
Number of charged particles per event ~20

- Characterize, for the first time, the **properties of the UE** at a factorization scale which is typically above **twice the top quark mass**

- The sensitivity of the measured σ to different parameters employed in state-of-the-art MC simulation programs is demonstrated by comparing the results with different simulations

Jet substructure observables

CMS-TOP-17-013
PRD 98 (2018) 092014



arXiv:1408.3122

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

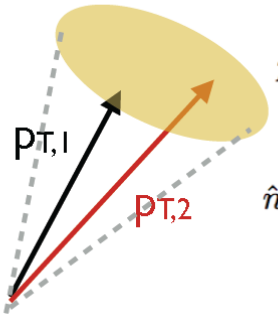
momentum fraction

$$z_i = p_T^i / \textstyle\sum_i p_T^i$$

winner-take-all scheme

$$p_{Tr} = p_{T1} + p_{T2}$$

$$\hat{n}_r = \begin{cases} \hat{n}_1 & \text{if } p_{T1} > p_{T2} \\ \hat{n}_2 & \text{if } p_{T2} > p_{T1} \end{cases}$$



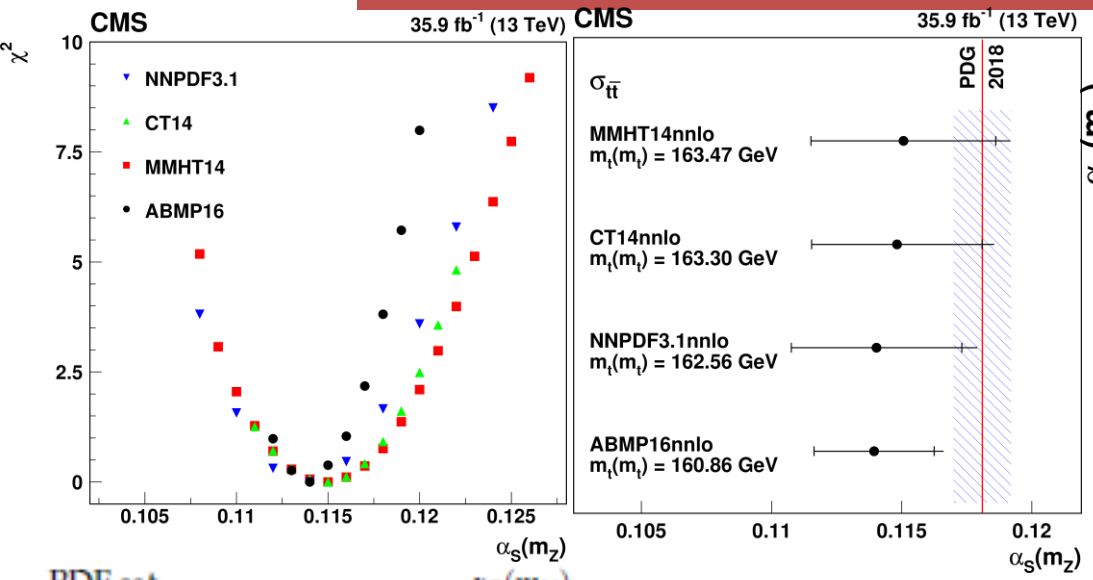
Jet substructure observables (~15) sensitive to modelling of the system by the MC

- Confronts **inclusive** and **flavour-specified jets** with a wide array of models
- **Scan $\alpha_S^{FSR}(M_Z)$ in UE (previous slide) and jet shapes (this analysis) compatible:**

(CMS-TOP-17-015) **$\langle p_T \rangle$ 0.120 ± 0.006** ; (CMS-TOP-17-013) **λ_1^1(width) 0.123 ± 0.001**

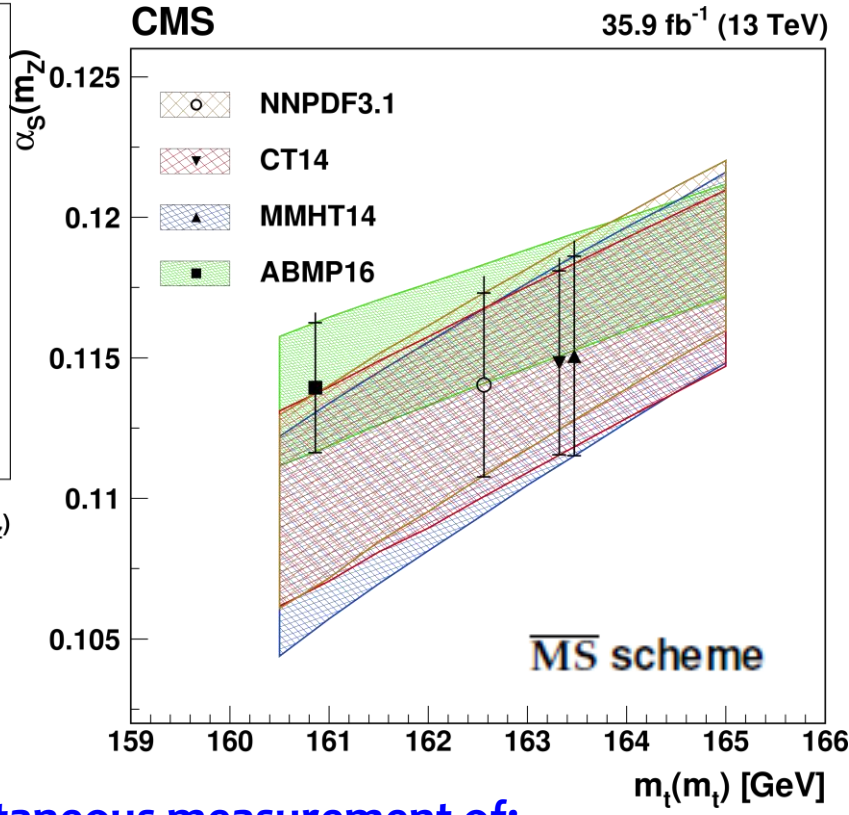
QCD from inclusive fit

Inclusive dilepton 2016 $\sqrt{s}$ = 13 TeV.
TOP-17-001 EPJC 79 (2019) 368



PDF set	$\alpha_S(m_Z)$
ABMP16	$0.1139 \pm 0.0023\,(\text{fit + PDF})\,^{+0.0014}_{-0.0001}\,(\text{scale})$
NNPDF3.1	$0.1140 \pm 0.0033\,(\text{fit + PDF})\,^{+0.0021}_{-0.0002}\,(\text{scale})$
CT14	$0.1148 \pm 0.0032\,(\text{fit + PDF})\,^{+0.0018}_{-0.0002}\,(\text{scale})$
MMHT14	$0.1151 \pm 0.0035\,(\text{fit + PDF})\,^{+0.0020}_{-0.0002}\,(\text{scale})$

PDF set	m_t^{pole} [GeV]
ABMP16	$169.9 \pm 1.8\,(\text{fit + PDF + }\alpha_S)\,^{+0.8}_{-1.2}\,(\text{scale})$
NNPDF3.1	$173.2 \pm 1.9\,(\text{fit + PDF + }\alpha_S)\,^{+0.9}_{-1.3}\,(\text{scale})$
CT14	$173.7 \pm 2.0\,(\text{fit + PDF + }\alpha_S)\,^{+0.9}_{-1.4}\,(\text{scale})$
MMHT14	$173.6 \pm 1.9\,(\text{fit + PDF + }\alpha_S)\,^{+0.9}_{-1.4}\,(\text{scale})$



Simultaneous measurement of:

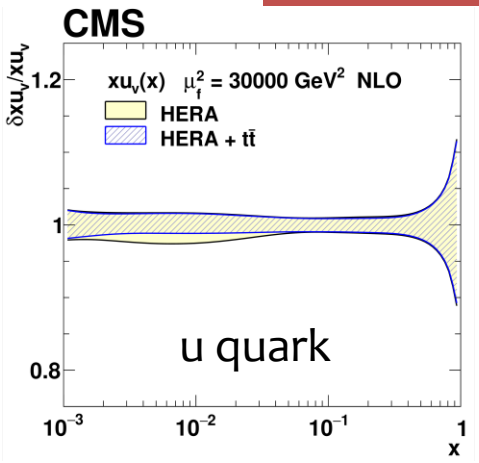
$$\sigma_{t\bar{t}} = 815 \pm 2\,(\text{stat}) \pm 29\,(\text{syst}) \pm 20\,(\text{lumi})\ \text{pb}$$

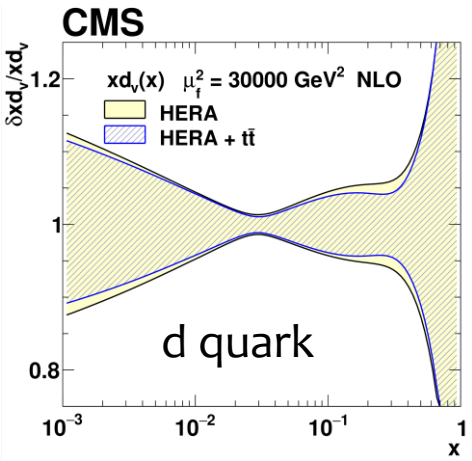
$$m_t^{\text{MC}} = 172.33 \pm 0.14\,(\text{stat})\,^{+0.66}_{-0.72}\,(\text{syst})\ \text{GeV}.$$

QCD from differential measurements

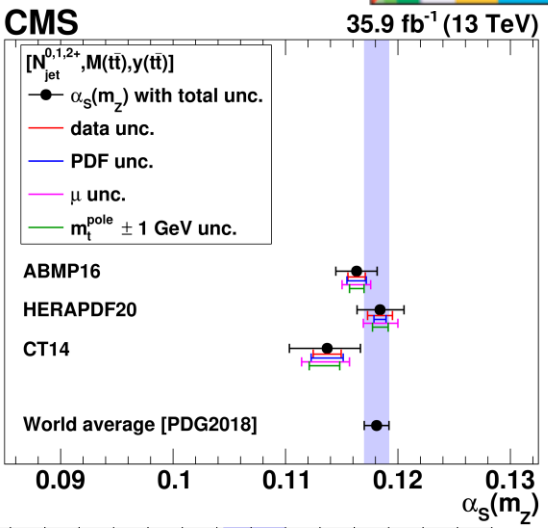
Multi-differential dilepton 2016 $\sqrt{s}$ = 13 TeV

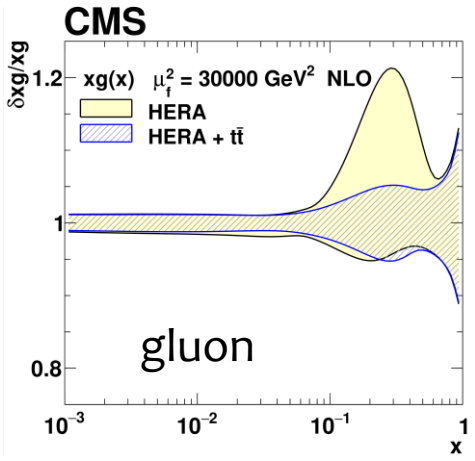
TOP-18-004 arXiv:1904.05237

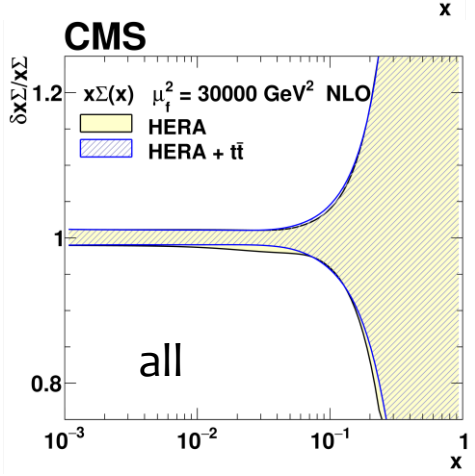


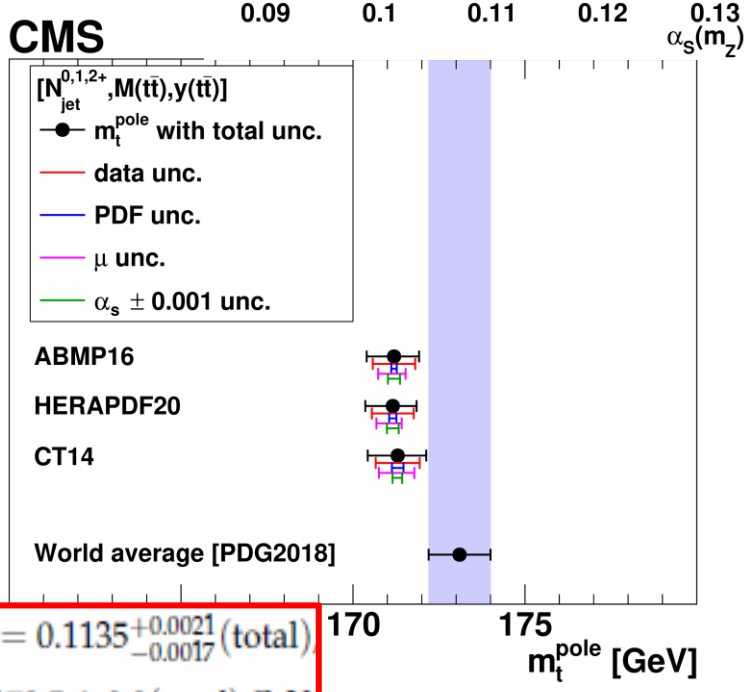


Significant reduction of gluon PDF uncertainty at high-x









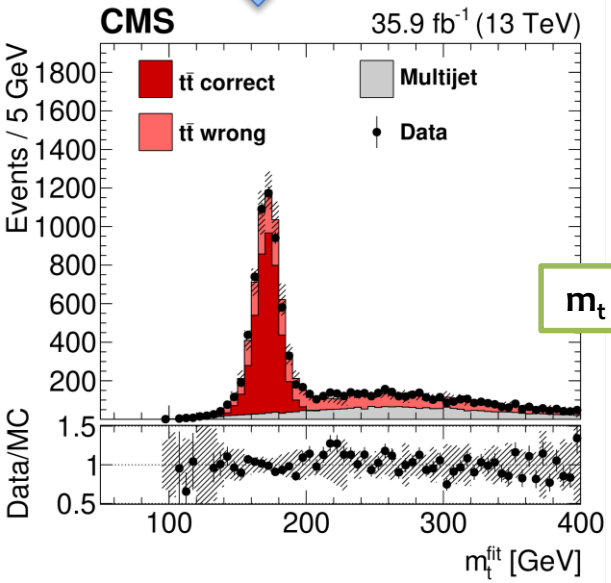
$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{model})^{+0.0008}_{-0.0001}(\text{param})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total}),$$

$$m_t^{\text{pole}} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\,\text{GeV} = 170.5 \pm 0.8(\text{total})\,\text{GeV}.$$

Latest top mass measurement

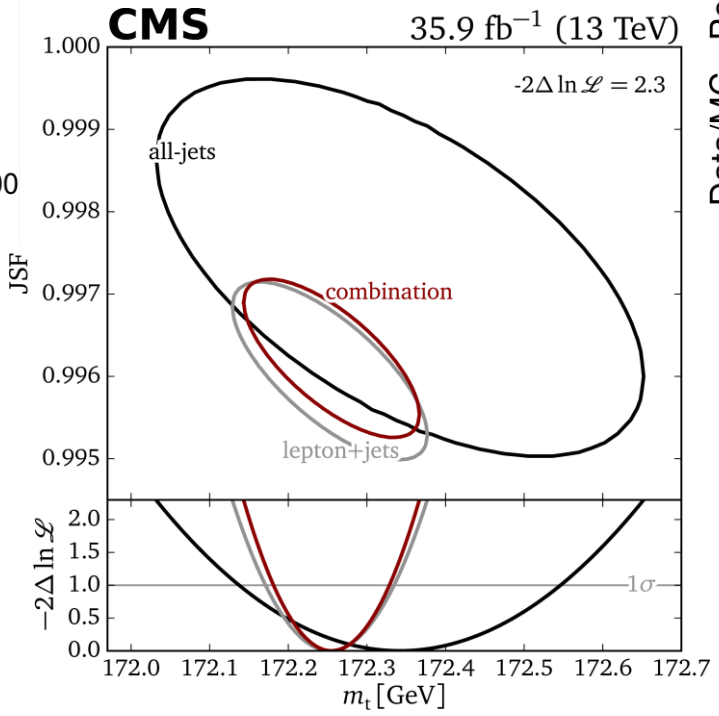
All-jets and combination with lepton+jets (TOP-17-007)

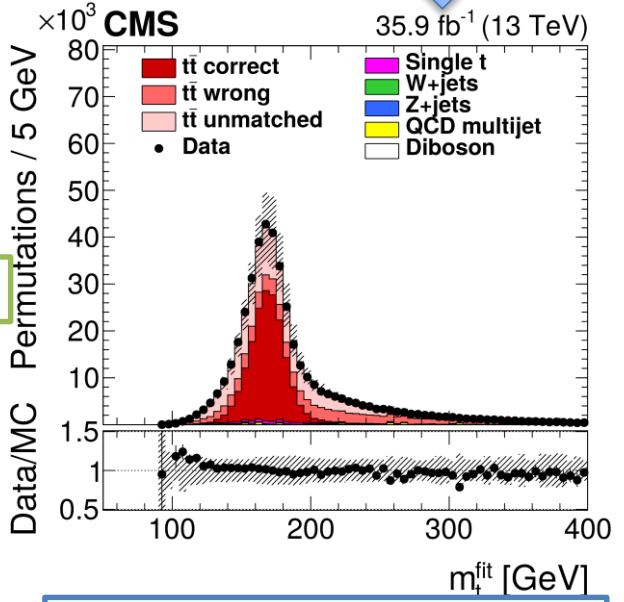
TOP-17-008 EPJC 79 (2019) 313



- Simultaneous fit for JES & m_t
- Ideogram method
- First m_t combination through a joint likelihood

m_t = 172.26 ± 0.07 (stat+JSF) ± 0.61 (syst) GeV





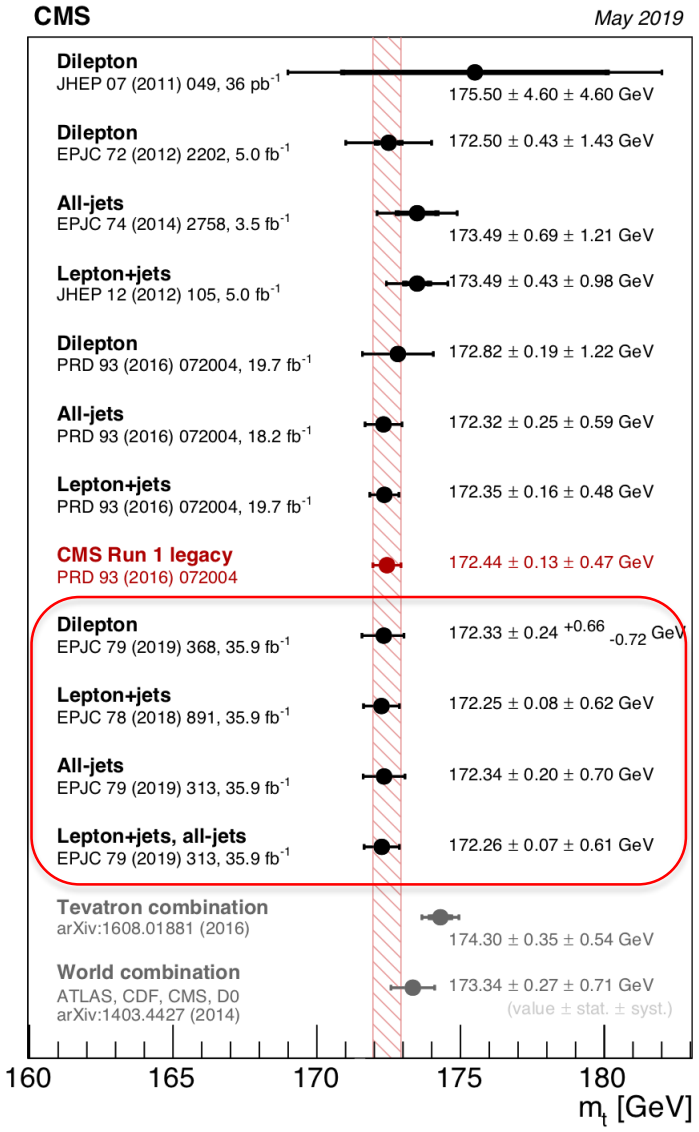
All-jets channel

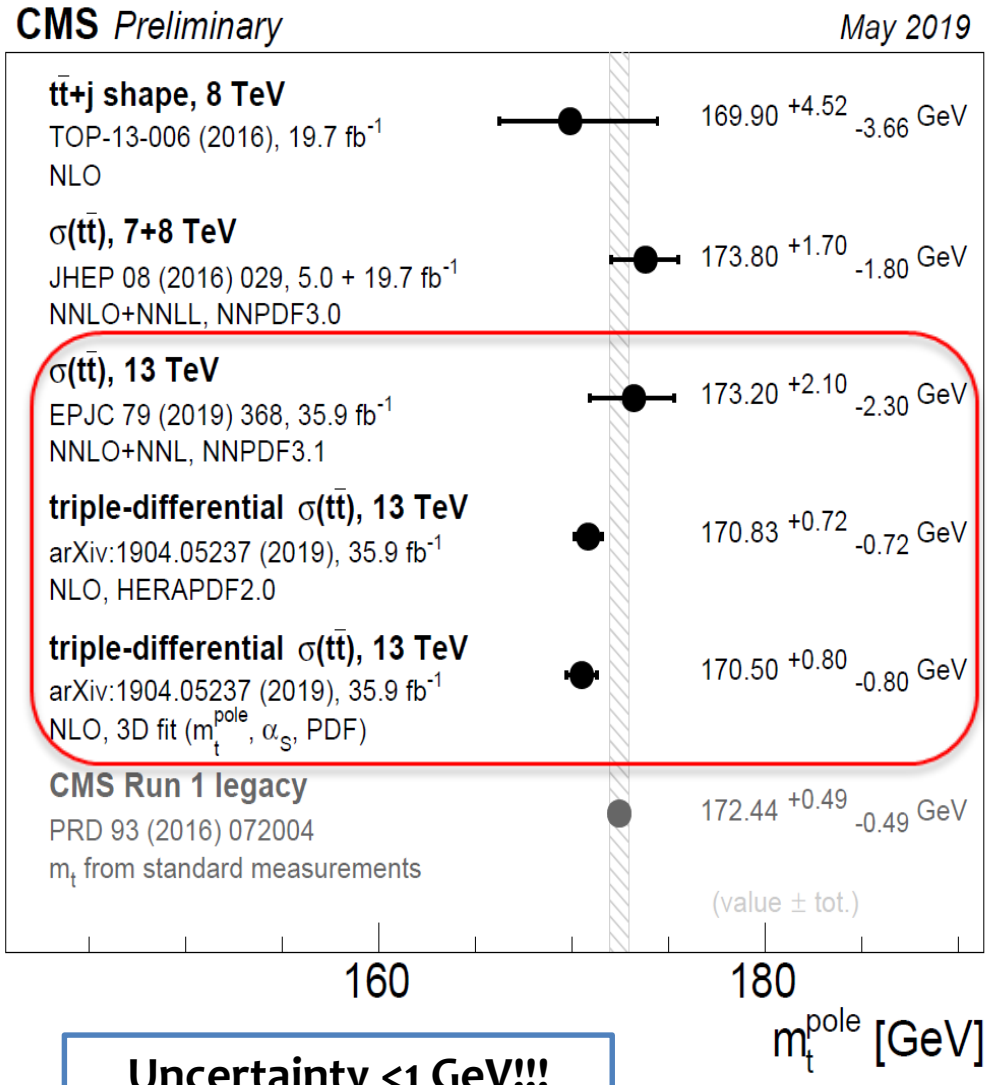
- Much less statistics due to trigger thresholds and QCD background
- Less ambiguous top reconstruction
- Similar systematics

l+jets channel

- Large statistics
- Practically background free
- Ambiguity in top reconstruction due to neutrino

Top quark mass measurements





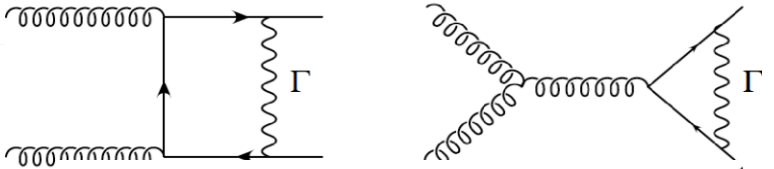
Uncertainty <1 GeV!!!

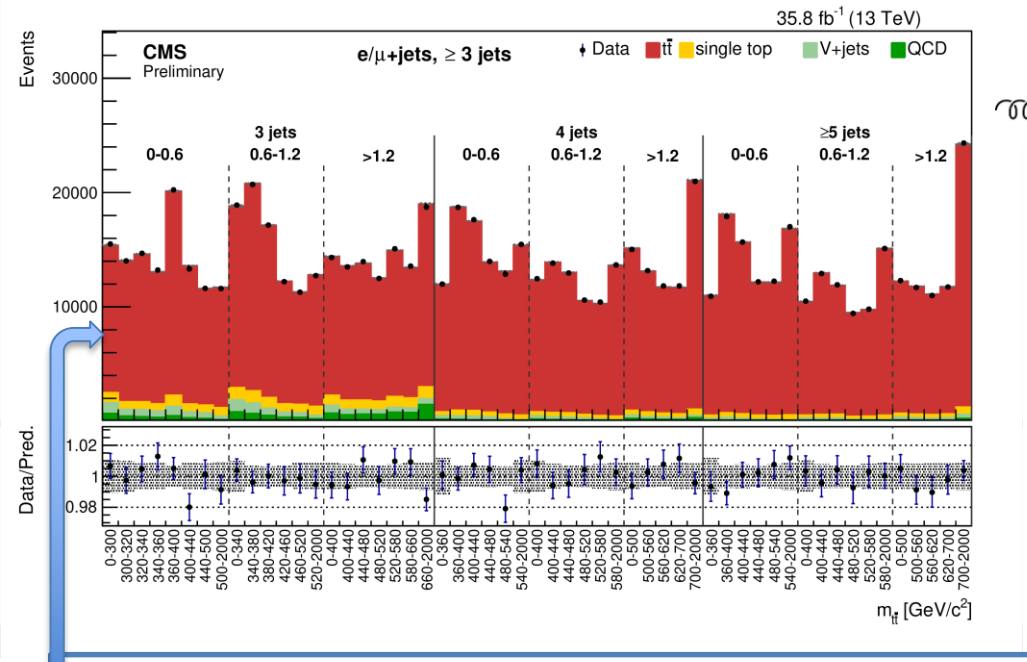
Top Yukawa coupling in $t\bar{t}$

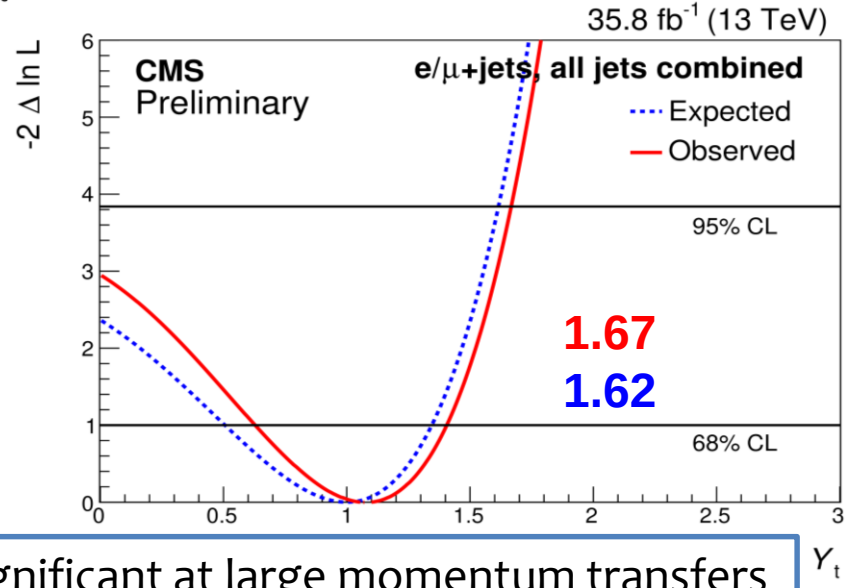
e/μ+jets 2016 13TeV
TOP-17-004 (preliminary)

Weak force mediated corrections only affect σ at order ~$\alpha^2_s\alpha_{weak}$ (not in MC)

$$m_t = Y_t \frac{v_{EWK}}{\sqrt{2}}$$



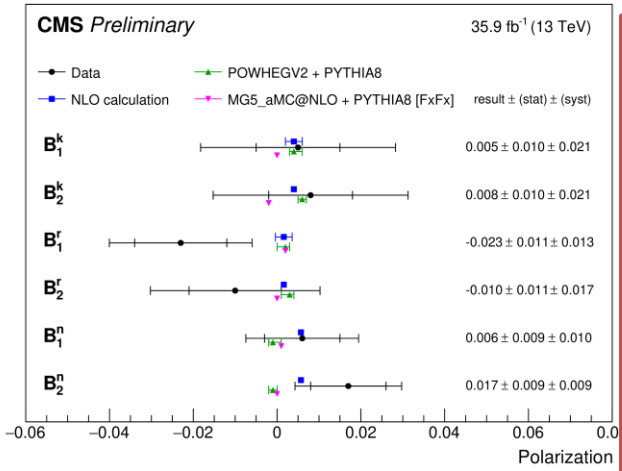


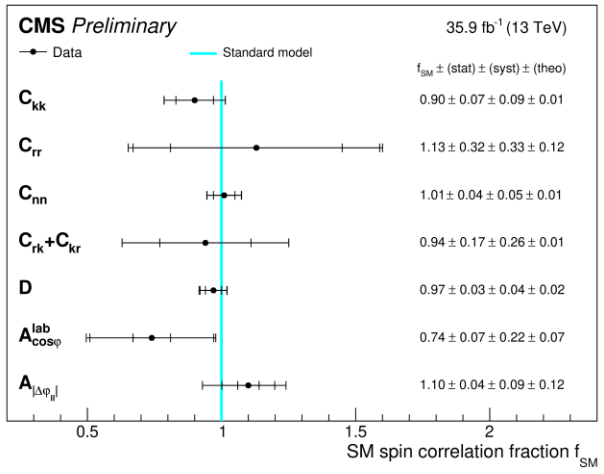


- **QCD dominates,** EWK corrections become significant at large momentum transfers and near the top pair production threshold sensitive to the top Yukawa coupling Y_t
- At least **three jets** in the final state: novel technique introduced to reconstruct events with one missing jet **enhancing the experimental sensitivity** in the low M_{tt}
- The **data yields** in M_{tt} , $|y_t - y_{\bar{t}}|$, and njets are compared with distributions representing different Yukawa couplings (0, 1, 2, 4). Upper limit set

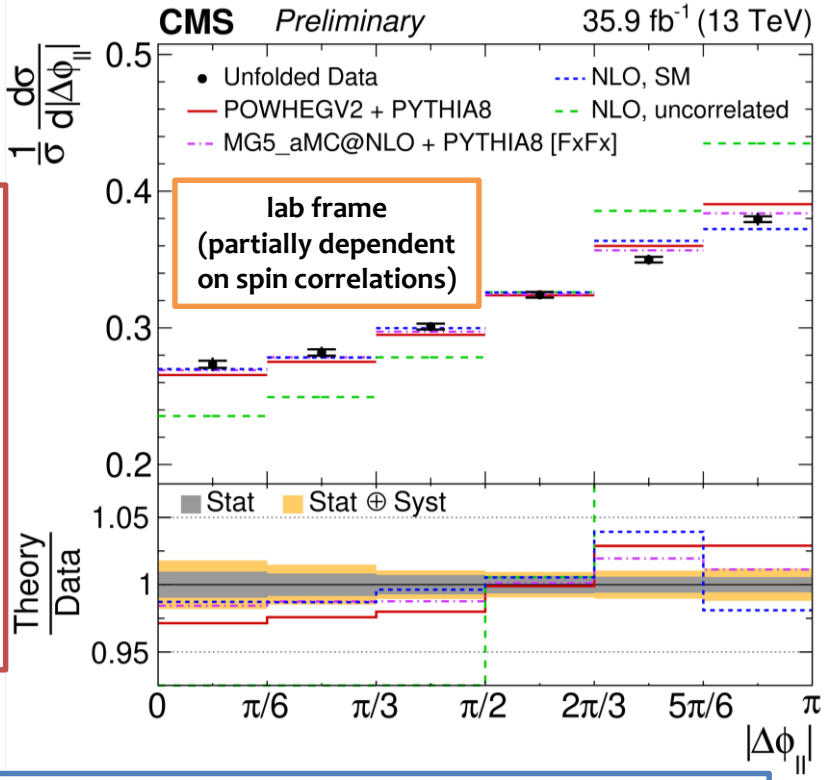
Top quark polarization and $t\bar{t}$ spin correlation

Dilepton 2016 13TeV
TOP-18-006 (preliminary)





Used in a simultaneous fit to constrain the anomalous chromomagnetic dipole moment of the top quark to:
$-0.07 < C_{tG}/\Lambda^2 < 0.16$ TeV^{-2} at 95% CL

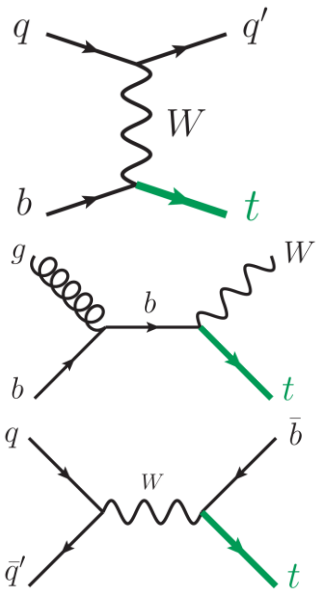


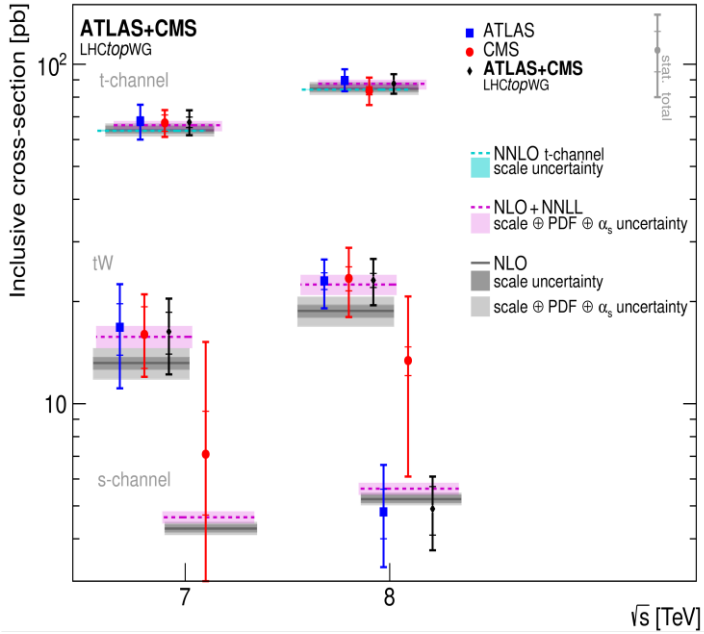
Leptons carry maximal information related to the top spin polarization and spin correlation in $t\bar{t}$:

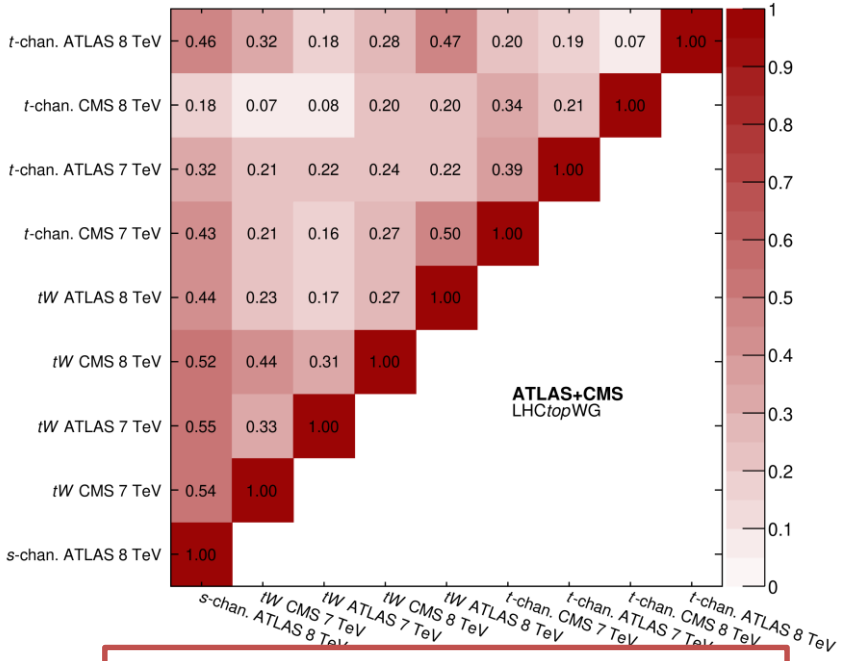
- Stringent test of SM
- Measured through lepton angular distributions around reference axes in the $t\bar{t}$ CM frame
- Results compatible with SM but large uncertainties

SINGLE TOP PRODUCTION

Run1 (7,8 TeV) ATLAS/CMS

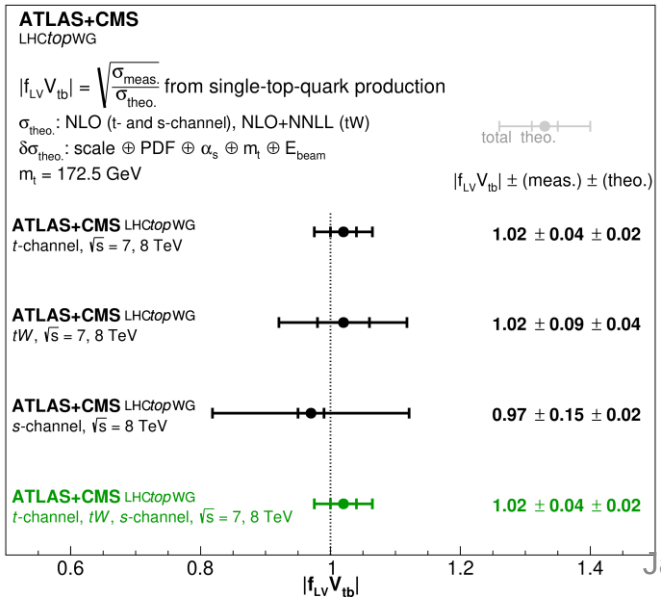






correlation matrix between measurements

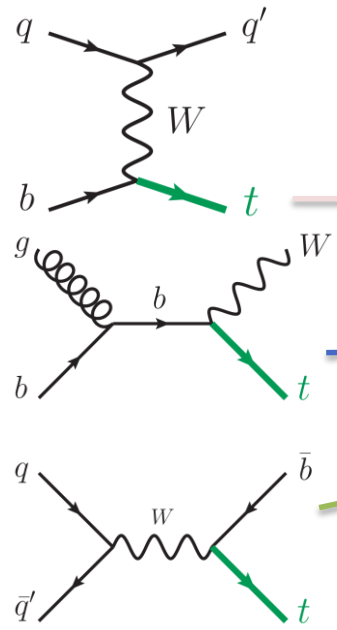
Run 1 CMS- [TOP-17-006](#) [JHEP05(2019)088](#)

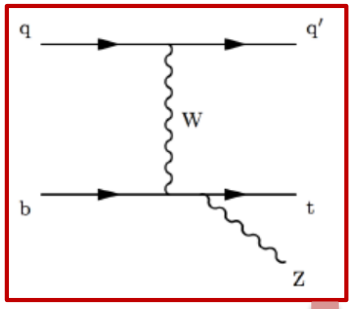


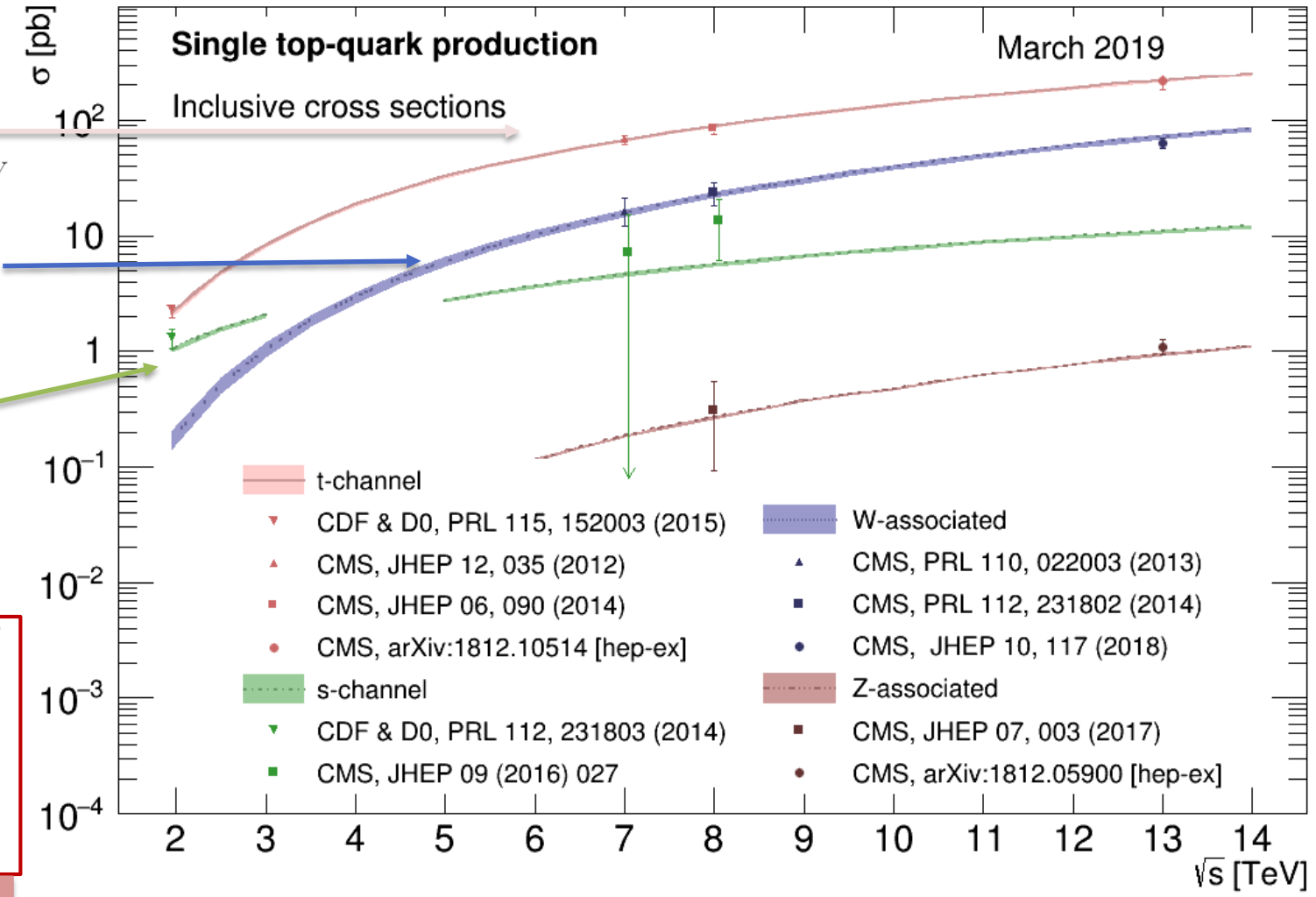
Combination of single-top-quark production cross-sections and $|f_{LV} V_{tb}|$ determinations at $\sqrt{s}$= 7 and 8 TeV

Joint effort between the ATLAS and CMS Collaborations under the LHCtopWG

Single top-quark in Run2



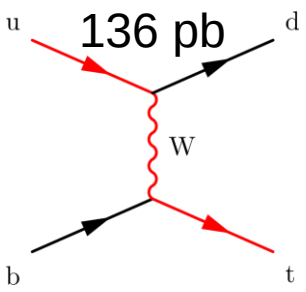


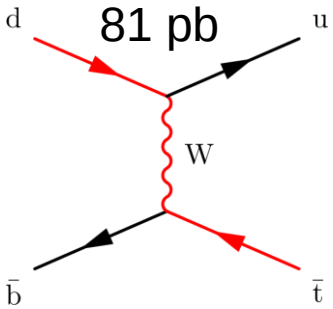


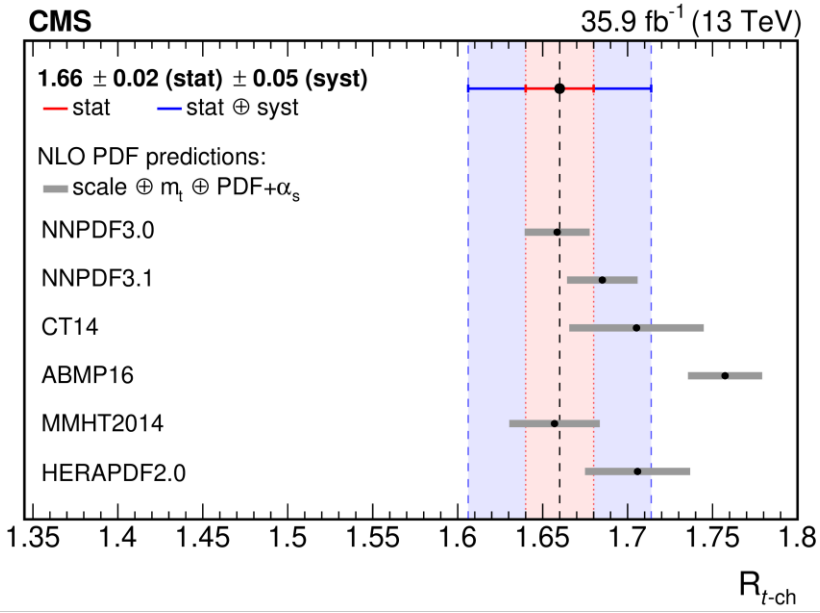
Single top quark and antiquark t-channel

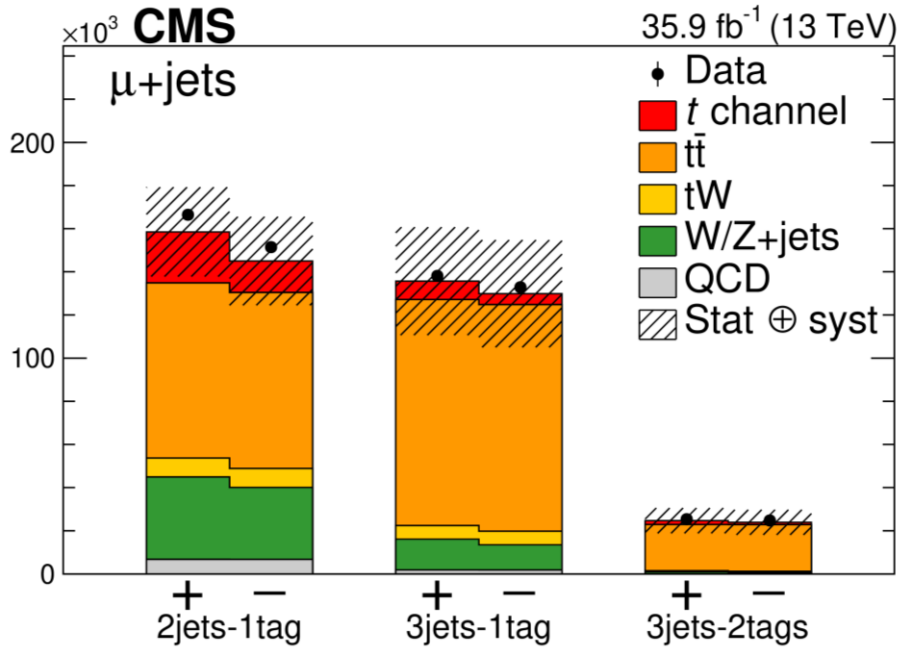
e/μ 2016 13TeV

TOP-17-011 arXiv:1812.10514





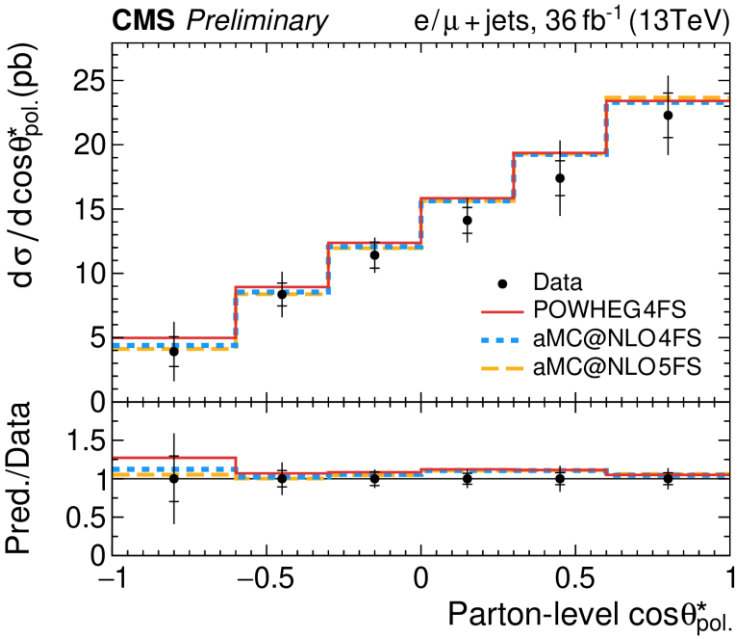


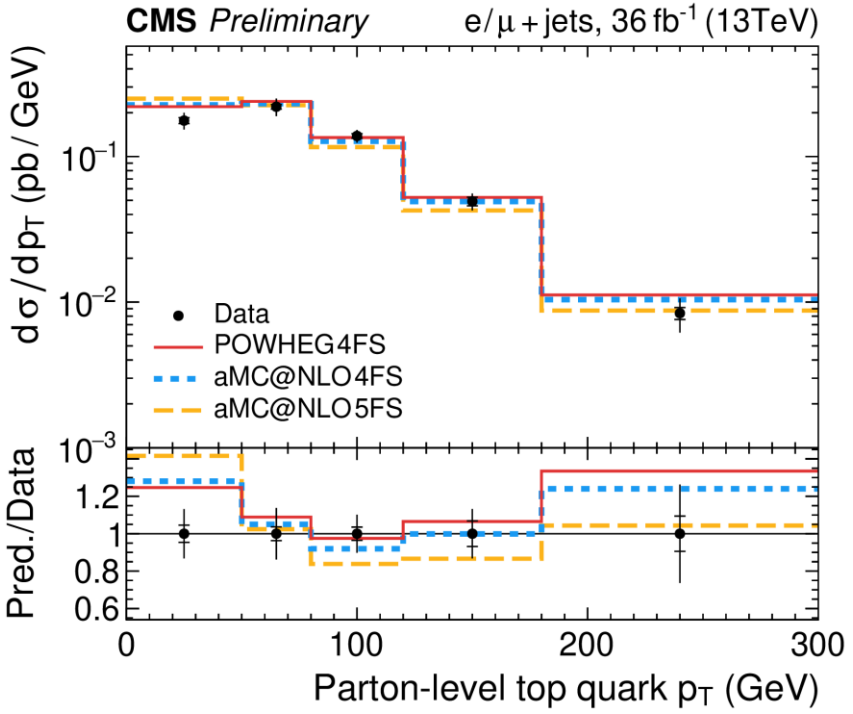


- employment of **multivariate** discriminants with several kinematic variables as inputs
- combined fit in **categories** based on number of jets and b jets
- inclusive cross section and **ratio top/antitop**

Single top differential cross-section (t-channel)

e/μ 2016 13TeV
TOP-17-023
(preliminary)





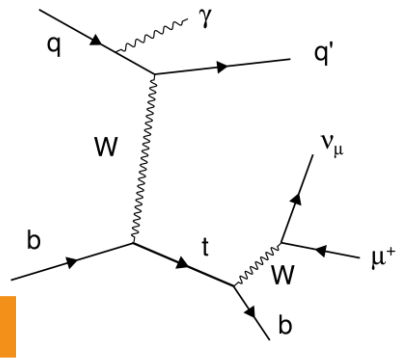
- multivariate discriminants with several kinematic variables as inputs
- **absolute & normalized** cross sections vs various observables
- unfolded to **parton & particle levels**
- differential charge ratio
- better agreement observed with **4FS predictions**
- measurement of polarization angle

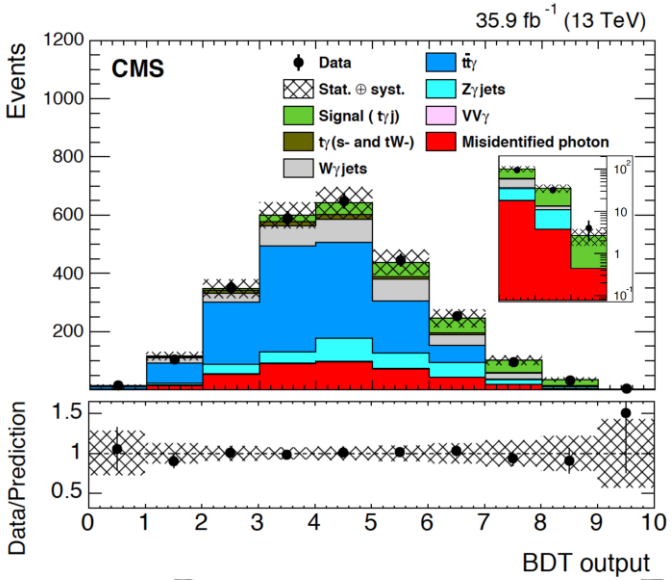
More details in Victor Rodriguez's talk on Wednesday!

Evidence for tγ

μ+γ 2016 13TeV

TOP-17-016 PRL 121 (2018) 221802





theory: 81 ± 4 fb

$$\sigma(pp \to t\gamma j)\mathcal{B}(t \to \mu\nu b) = 115 \pm 17\,(stat) \pm 30\,(syst)\,fb$$

Process	Event yield
$t\bar{t}+\gamma$	1401 ± 131
$W\gamma$+jets	329 ± 78
$Z\gamma$+jets	232 ± 55
Misidentified photon	374 ± 74
$t\gamma$ (s- and tW-channel)	57 ± 8
$VV\gamma$	8 ± 3
Total background	2401 ± 178
Expected signal	154 ± 24
Total SM prediction	2555 ± 180
Data	2535

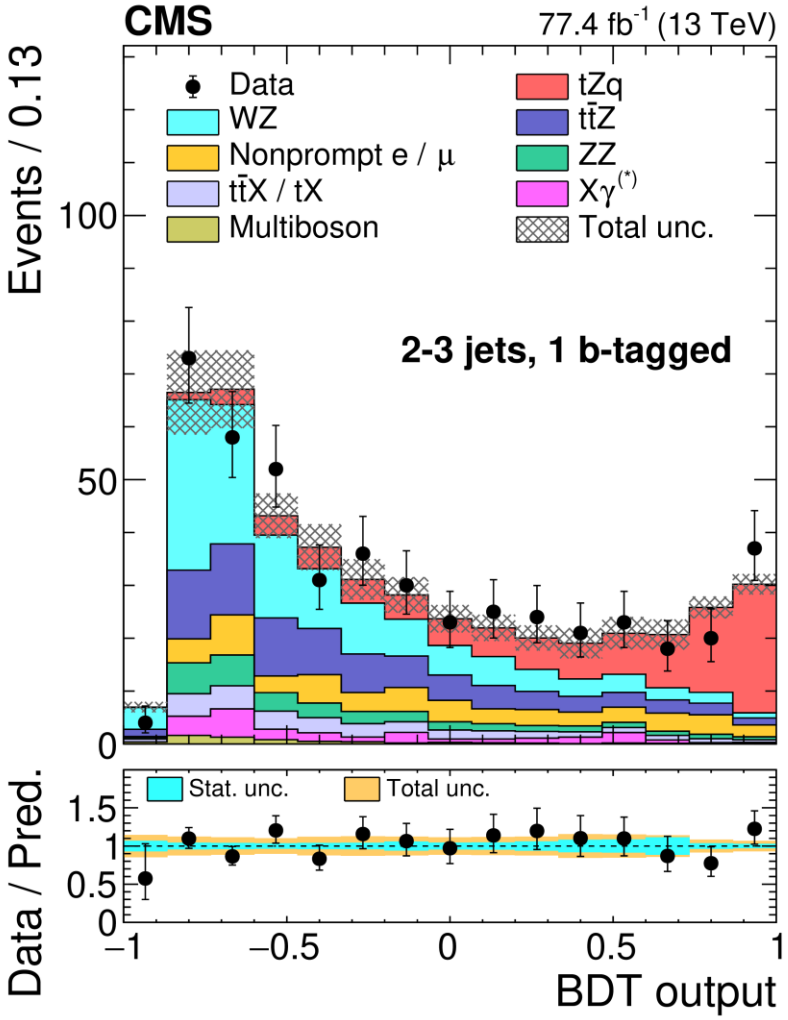
- γ **can be radiated** from top, muon or incident parton quark
- **motivation**
  - important test of SM
  - sensitive to the top charge and electric and magnetic dipole moments
  - background for BSM searches
- **experimental measurement**
  - muon channel
  - complicated final state with all types of objects
  - multivariate classifica2on (BDT)
  - template fit on the BDT output

Associated production tZq

3 leptons 2016/17 13TeV

TOP-18-008 PRL 122 (2019) 132003

theory: 94.2 ± 3.1 fb



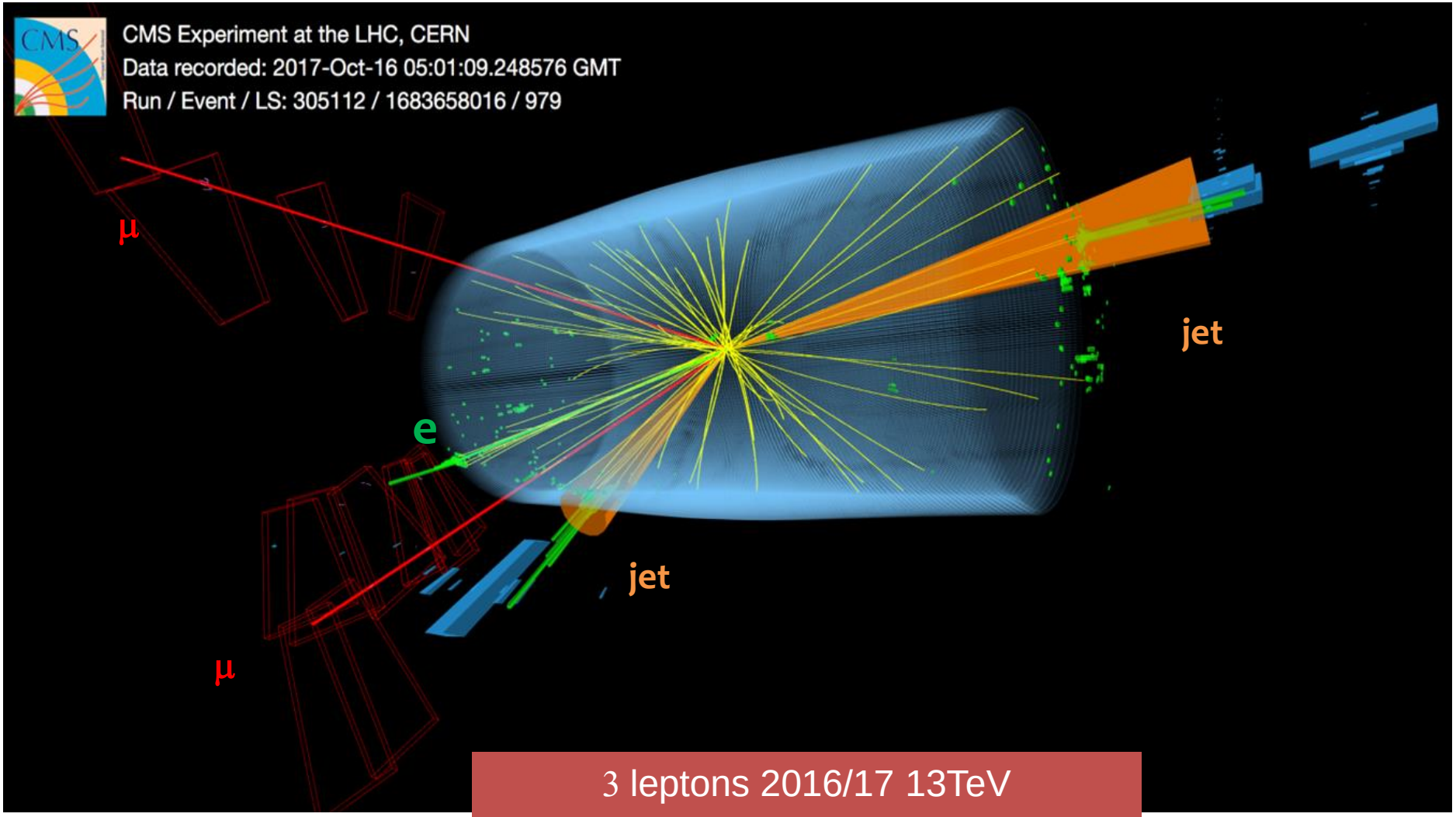
- **motivation**
  - sensitive to multiple SM effects (WWZ triple gauge coupling, gZ, tbW couplings, etc)
  - modified tZq production can be due to flavor changing neutral currents

Observation
8.2 (7.7) σ observed
(expected) significance

- **experimental measurement**
  - leptonic decays with exactly 3 leptons and at least 2 additional jets
  - complicated final state with all types of objects
  - multivariate classification (BDT)
  - template fit on the BDT output in several categories

$$\sigma(pp \to tZq \to t\ell^+\ell^- q) = 111 \pm 13\,(\text{stat})\,^{+11}_{-9}\,(\text{syst})\,\text{fb}$$

tZq candidate



3 leptons 2016/17 13TeV

TOP-18-008 PRL 122 (2019) 132003

$t\bar{t}$ + X

$t\bar{t}\,t\bar{t}$ production (2ℓSS & multilepton)

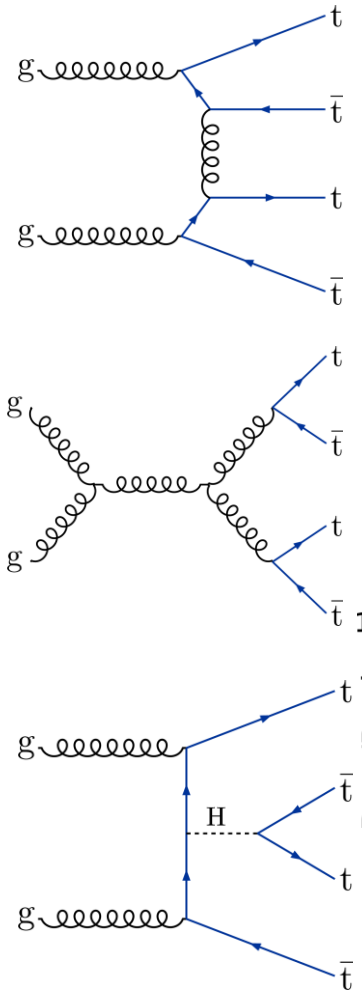
At least 3leptons 2016/17/18 13TeV

TOP-18-003 (preliminary)

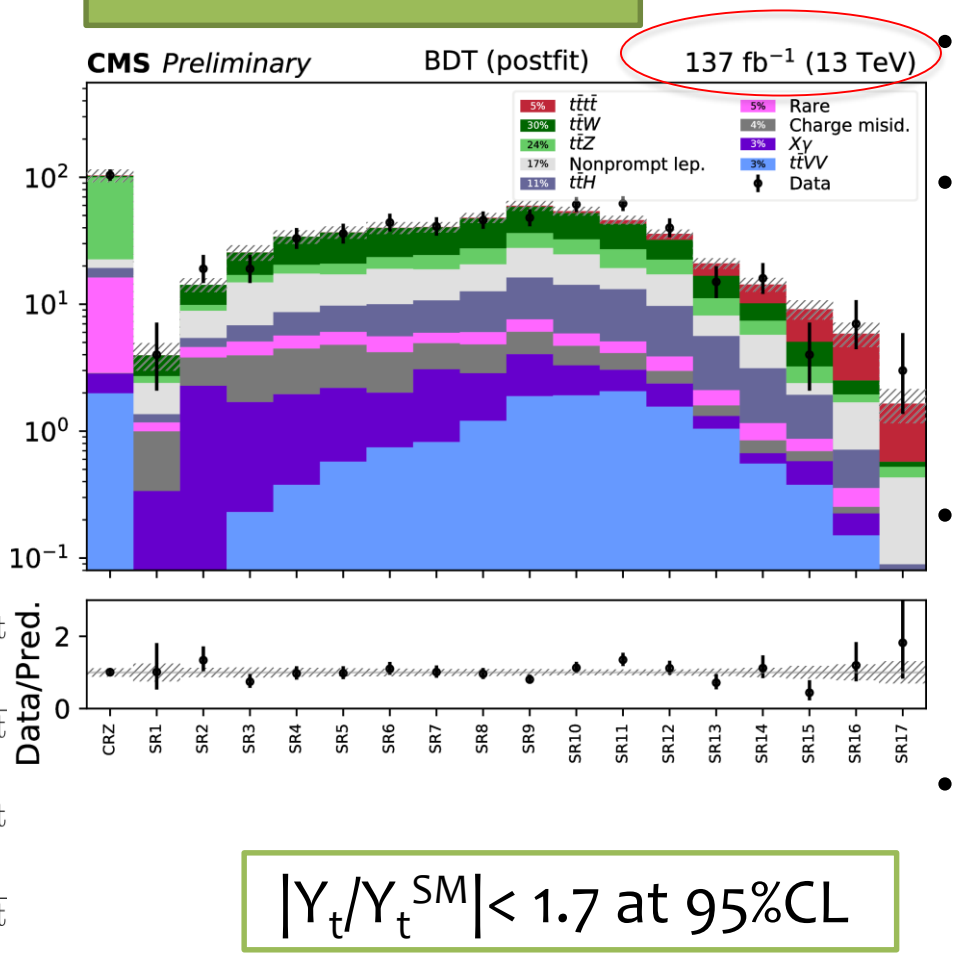
$$\sigma_{meas} = 12.6^{+5.8}_{-5.2}\ fb$$

$$\sigma_{th} = 12.0^{+2.2}_{-2.5}\ fb$$

2.6σ significance



Full Run2 dataset!!



- **sensitive** to SM parameters
- complicated search with either 2 same sign leptons or at least 3 leptons in the final state
- **multivariate** classification & cut based cross check analysis
- constrain of the top **Yukawa coupling**

$|Y_t/Y_t^{SM}| < 1.7$ at 95%CL

$t\bar{t}\,t\bar{t}$ production (1ℓ & 2ℓ)

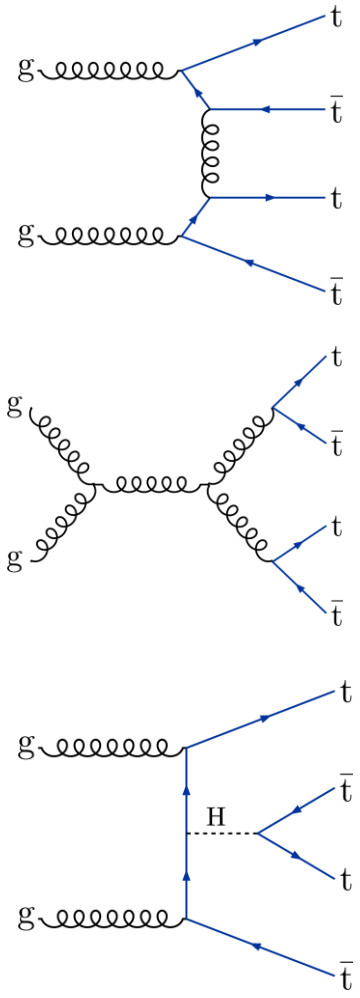
At least 3leptons 2016/17/18 13TeV

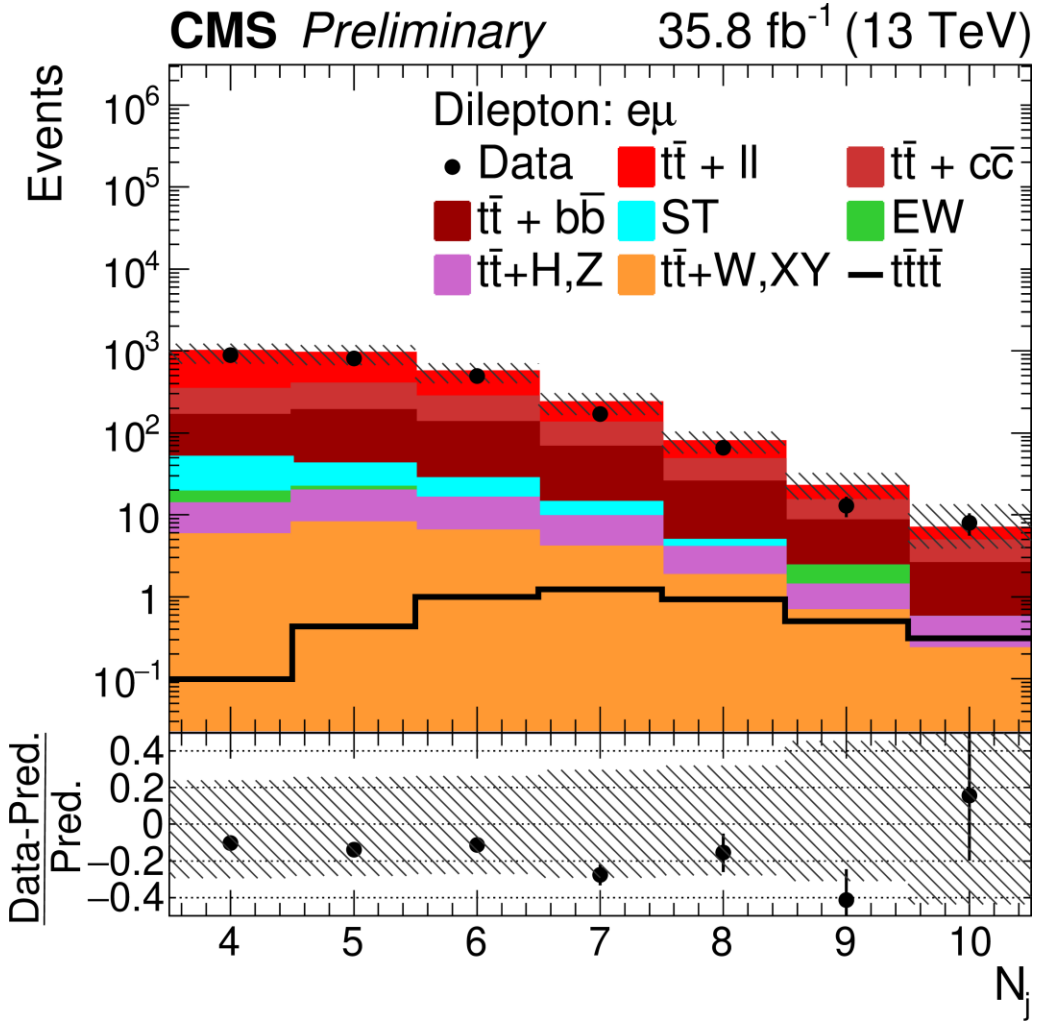
TOP-17-019 (preliminary)

Combined with SS and multi

$\sigma(t\bar{t}\,t\bar{t}) = 13^{+11}_{-9}$ fb

1.6σ



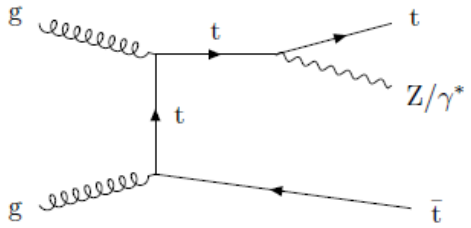


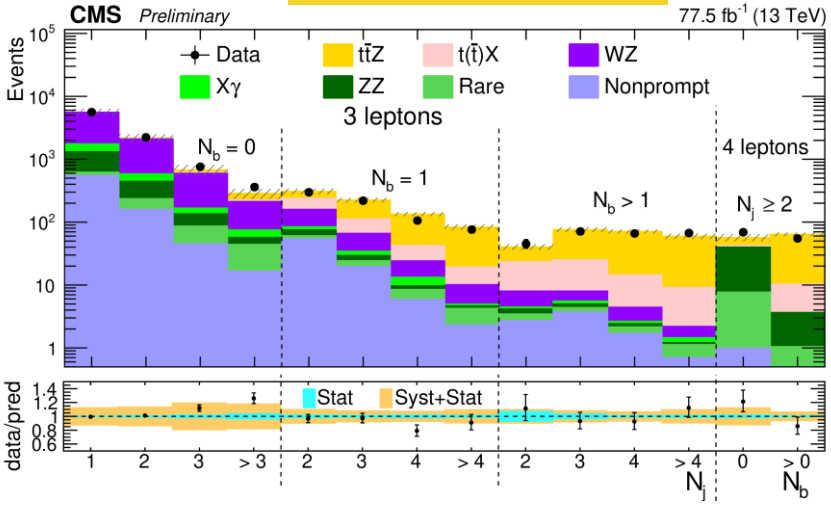
- A MVA using global event and jet properties based on BTDs is used to discriminate $t\bar{t}\,t\bar{t}$ from $t\bar{t}$ production.
- Upper limit of 48 fb at 95%CL
- complicated search with large $t\bar{t}$+X background

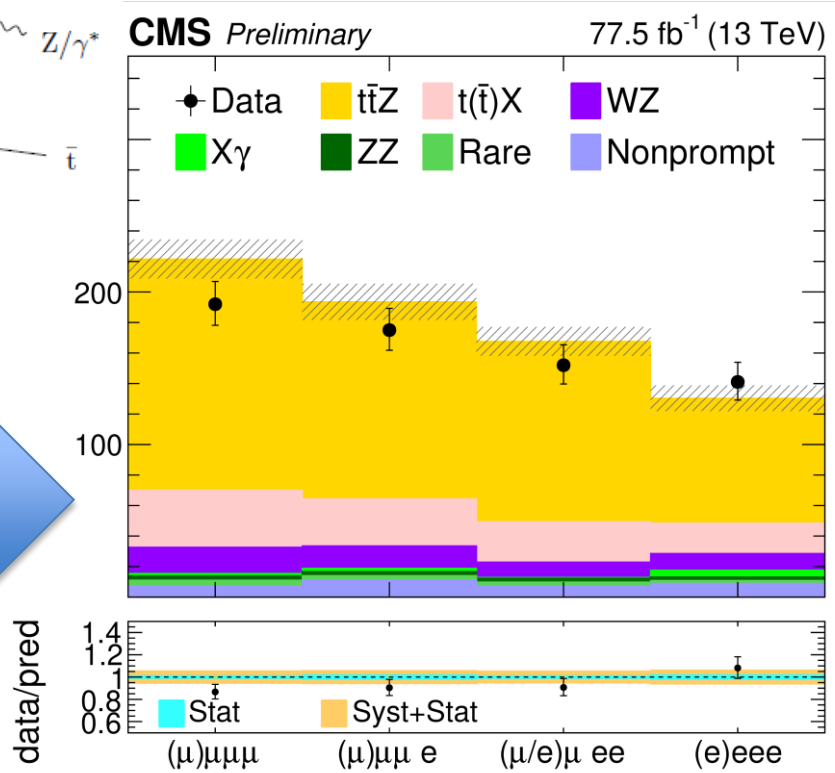
Associated $t\bar{t}$ +Z

3 & 4 lepton 2016/17 13TeV
TOP-18-009 (preliminary)

$\sigma_{th}^{NLO} = 0.839 \pm 0.101\ pb$







$\sigma(t\bar{t}Z) = 1.00^{+0.06}_{-0.05}\ (stat)^{+0.07}_{-0.06}(\text{syst})\ \text{pb}$

- sensitive to **BSM** effects and direct **probe** of the top coupling with Z
- important background to searches
- multi-lepton channel (3 or 4 leptons, two of which satisfy the Z mass hypothesis)
- measurement using the jet mul2plicity in bins of b tagged jets
- **uncertainties reduced** by multi-category fit

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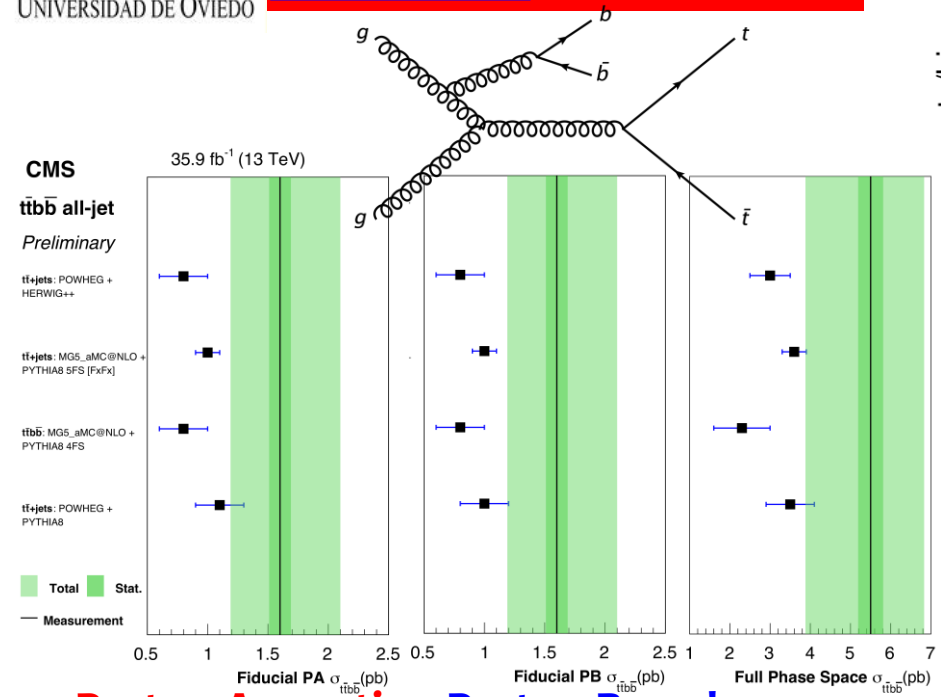
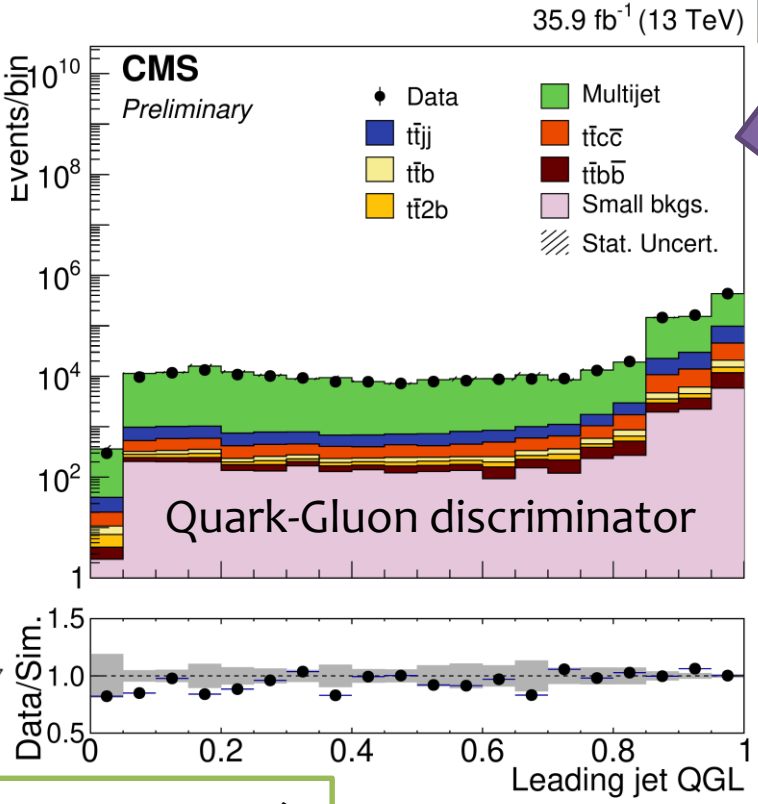
All-jet 2016 13TeV
TOP-18-011 (preliminary)

$t\bar{t}\,b\bar{b}$



Parton Agnostic **Parton Based**



NEW!!

$$\sigma(t\bar{t}b\bar{b}) = 5.5 \pm 0.3(stat)^{+1.6}_{-1.3}(\text{syst})\ \text{pb (full phase space)}$$

- at least **eight jets**, of which two b-tagged. **Signal**= 4 **quark-jets, Background: gluons**
- combination of MVA techniques to **reduce** the large background consisting uniquely of jets produced through the strong interaction (gluons), and to **discriminate** the jets originating from the top quark decays and additional jets
- measured cross sections are compared with predictions of several event generators and are found to be **generally higher than the theoretical prediction**

Summary

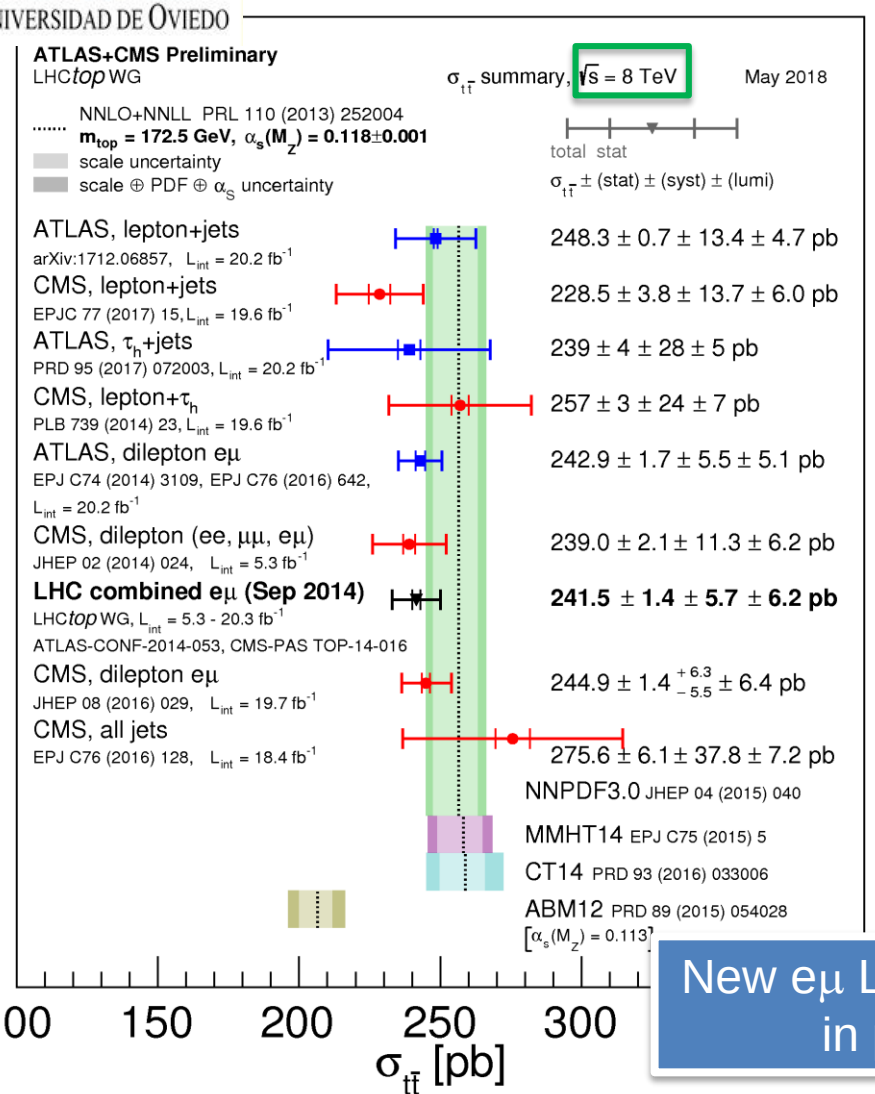
- Inclusive results at $\sqrt{s}$ = 13TeV in **good agreement** with predictions, need to go for differential studies:
  - Run2 allows to explore the full phase space of top production
  - Run1 pursuing LHC combinations at 7 and 8 TeV

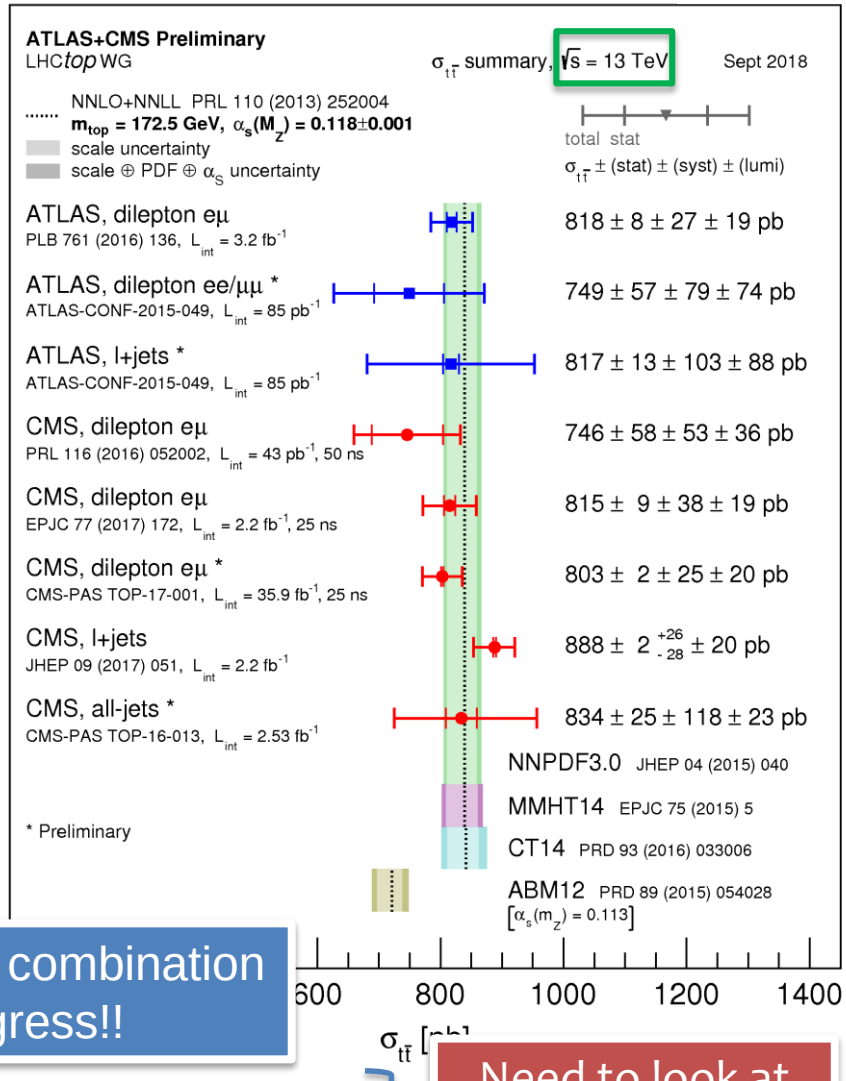
- **Rich program** on top quark physics:
  - Top quark pair production
  - Single quark top and variants
  - Associated productions and $t\bar{t}$ $t\bar{t}$

- **More results** to come:
  - Few analyses have incorporated the 2017/2018 data set: more than 70% of total Run2 cumulated luminosity
  - An enormous dataset to analyze yet

BACKUP

The LHC detailed picture





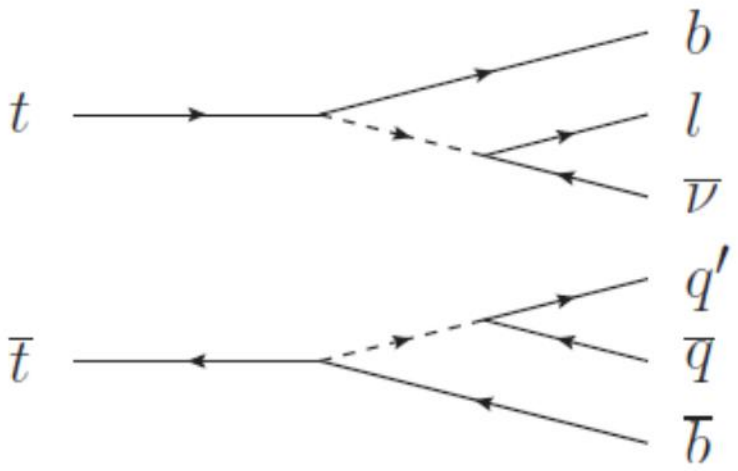
New eμ LHC combination in progress!!

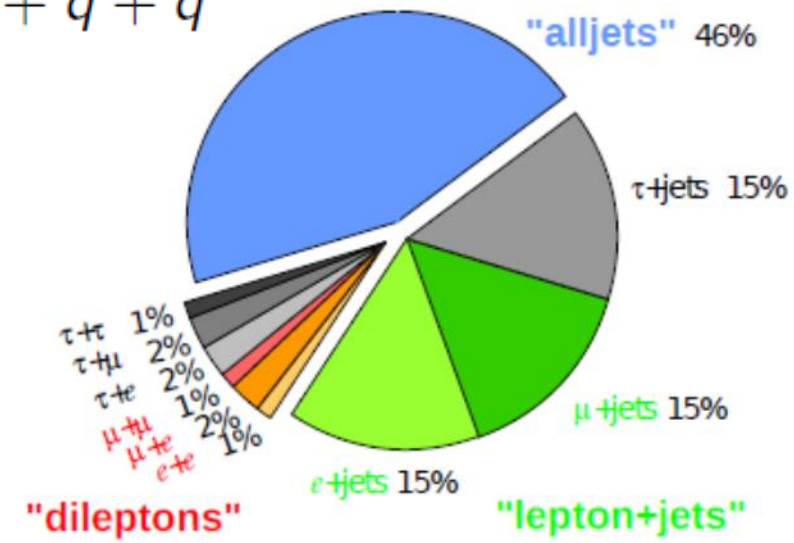
- Inclusive measurements are in good agreement with theory
- Exp. uncertainty comparable to theoretical uncertainty

Need to look at differential measurements!!

Decay channels

- Leptonic decay: $t \to b + W \to b + l + \nu$
- Hadronic decay: $t \to b + W \to b + q + q'$





- Top is an important background to many searches, and properties are sensitive to New Physics