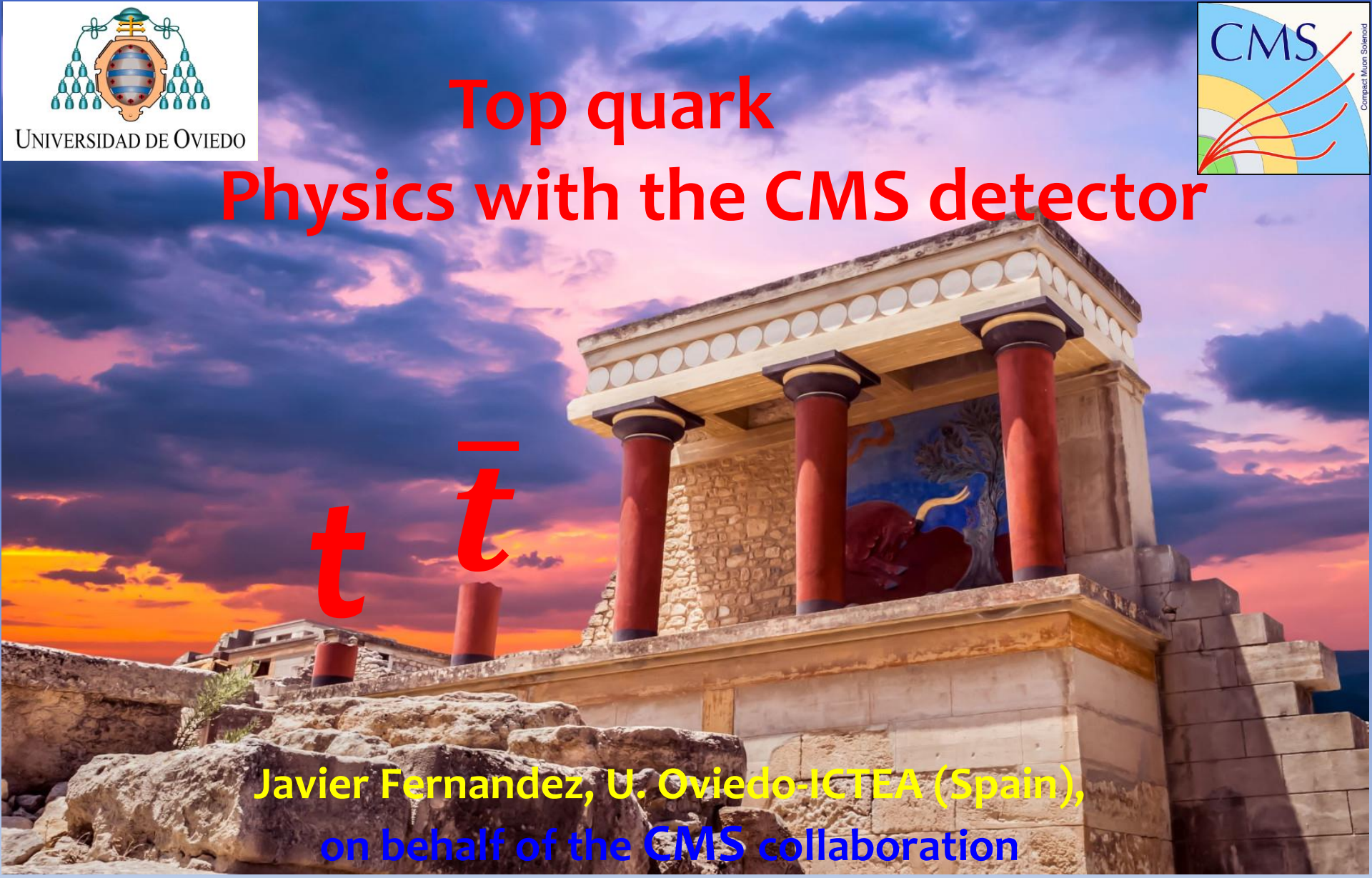


Top quark Physics with the CMS detector

$t\bar{t}$

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

XI International Conference on New Frontiers in Physics (ICNFP 2022) September 2022

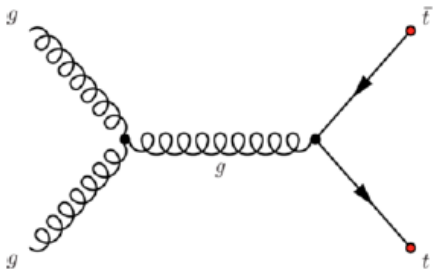
Outline

Focus on latest results

- top quark pair production ($t\bar{t}$):
  - inclusive & differential cross section measurements
  - top properties (mass, charge asymmetry)
- single top production:
  - inclusive & differential cross section
  - tW and associated production tZq
- top quark pair + X :
  - $t\bar{t}$ associated production with bosons
  - $t\bar{t}\,t\bar{t}$ & $t\bar{t}\,b\bar{b}$

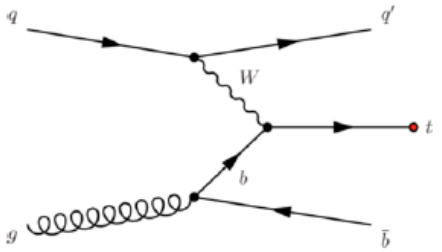
top quark pair production

σ(pp @ 13 TeV) = 832 pb



single top quark production

σ(pp @ 13 TeV) = 299 pb

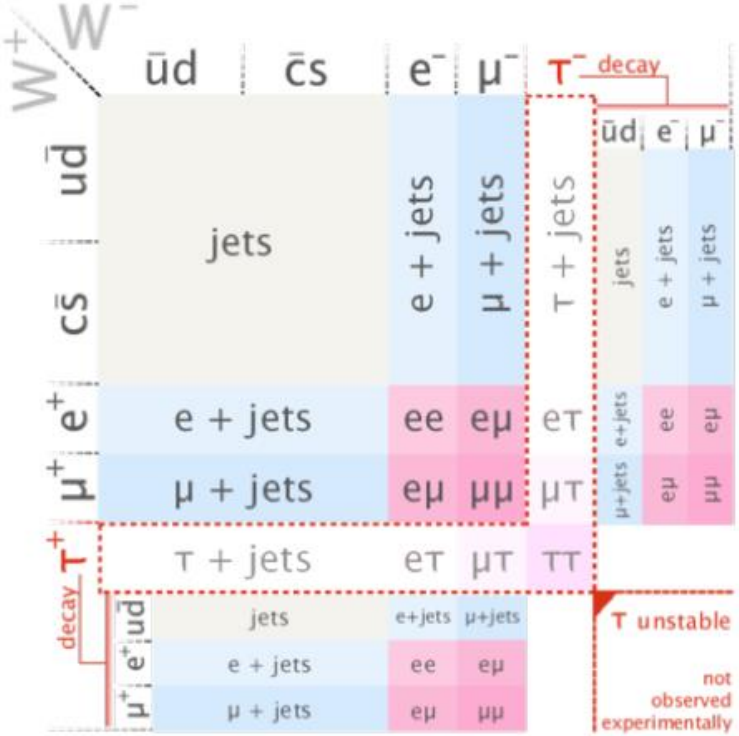


Caveat: References TOP-XX-YYY = CMS-PAS-TOP-XX-YYY

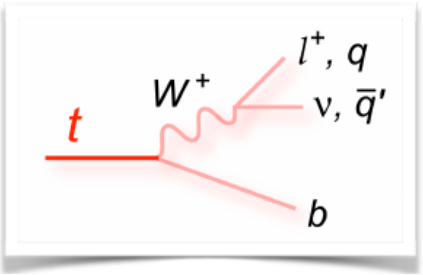
Is top quark special?

- 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

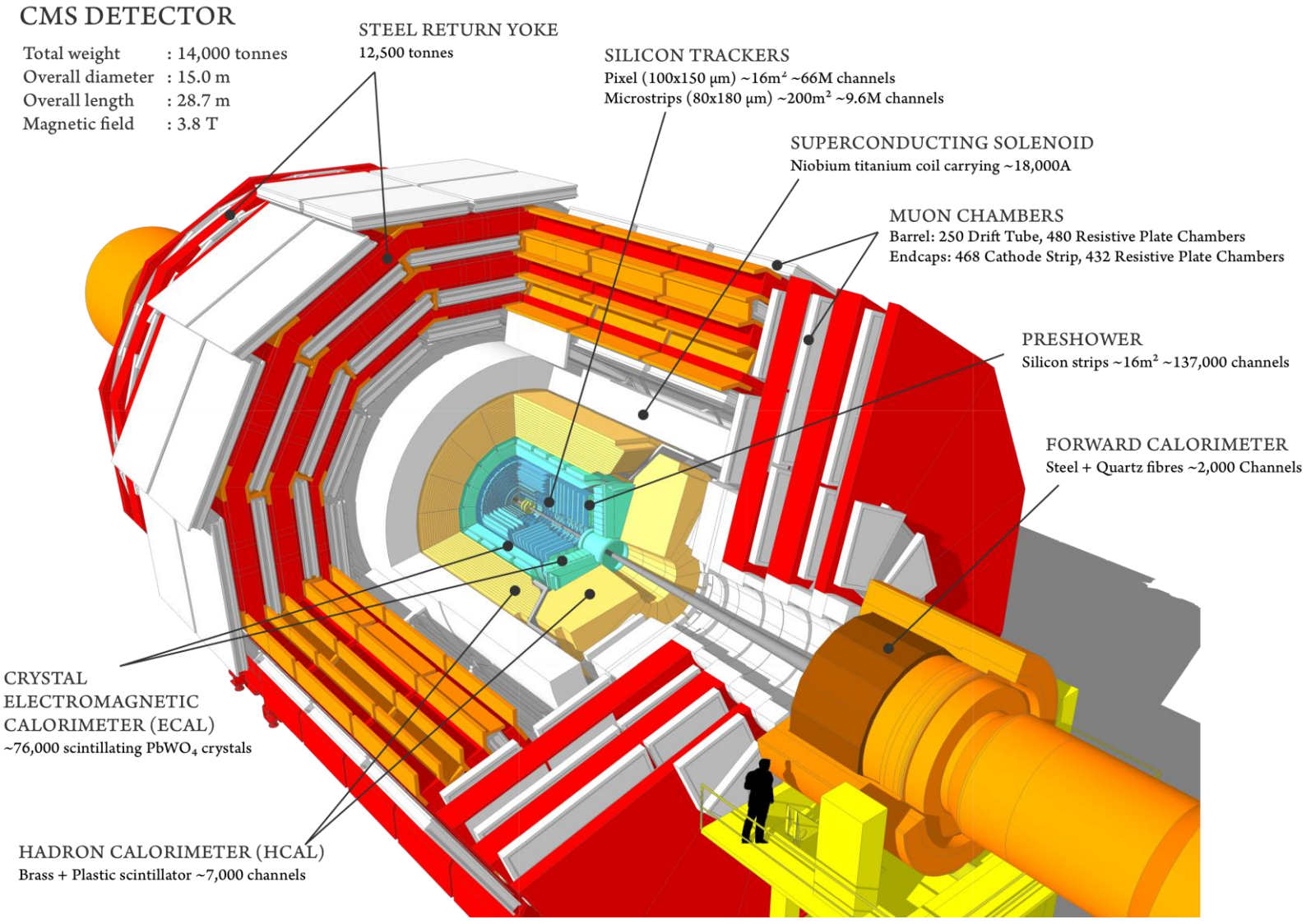
full hadronic
semileptonic
dileptonic



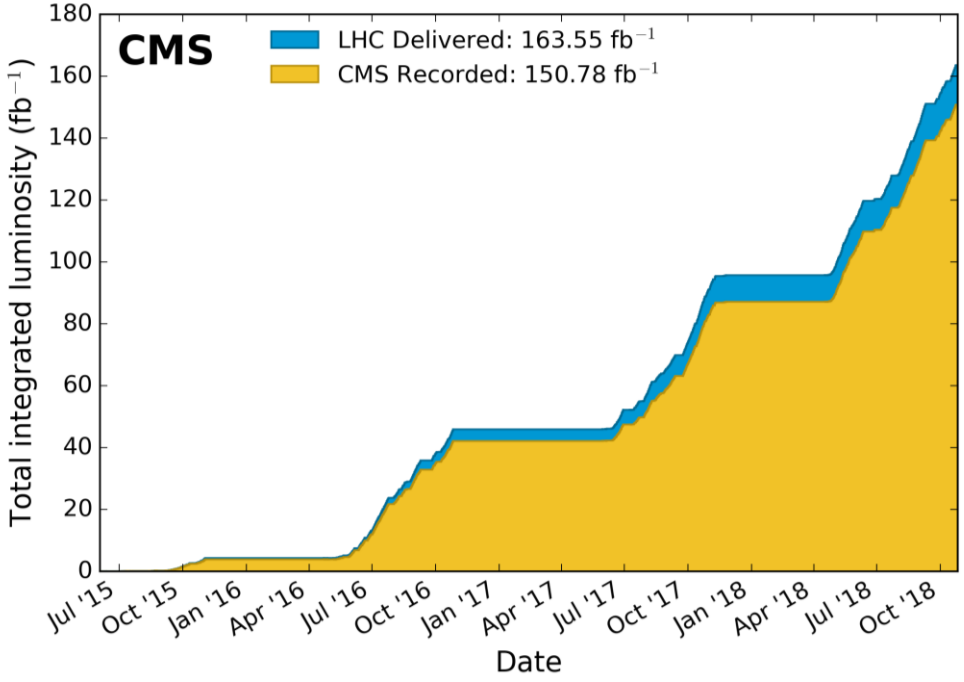
BR(t→Wb) = 0.957



The CMS detector

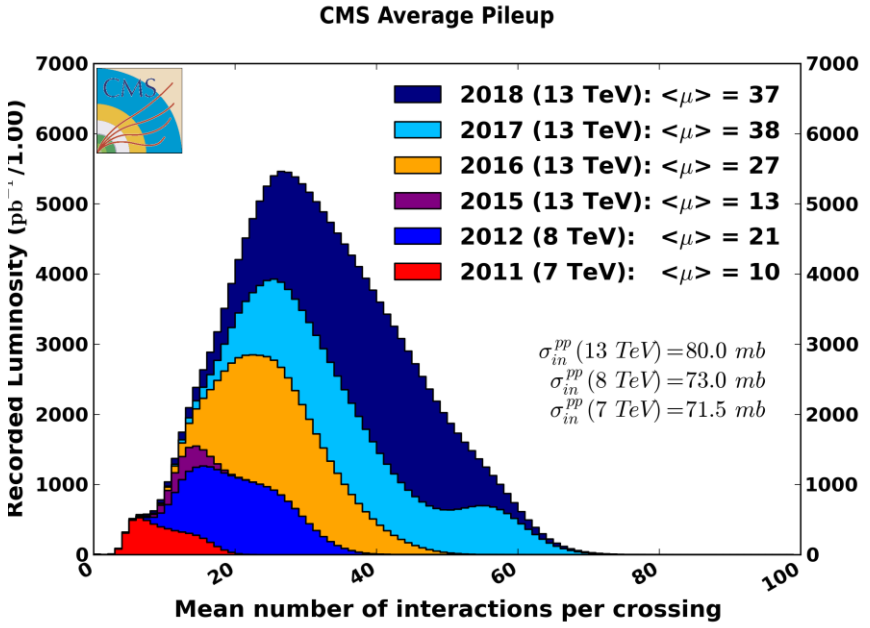


LHC: the perfect machine?



LHC is a "Top Factory" covering O(10^6) range in top production cross sections:

- Allows precise cross section & property measurements, searches for rare processes, etc



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

TOP QUARK PAIR PRODUCTION

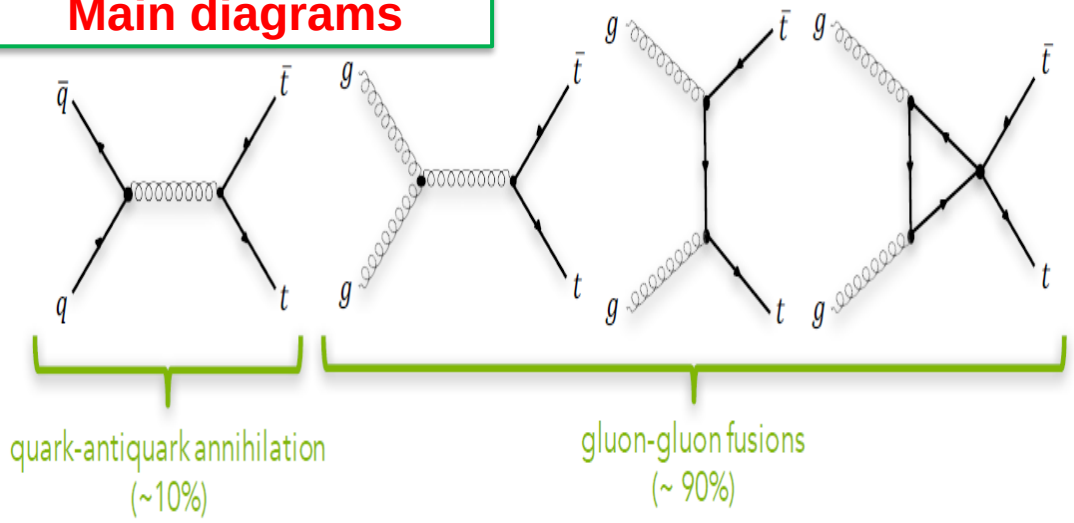
Top quark pair production @LHC

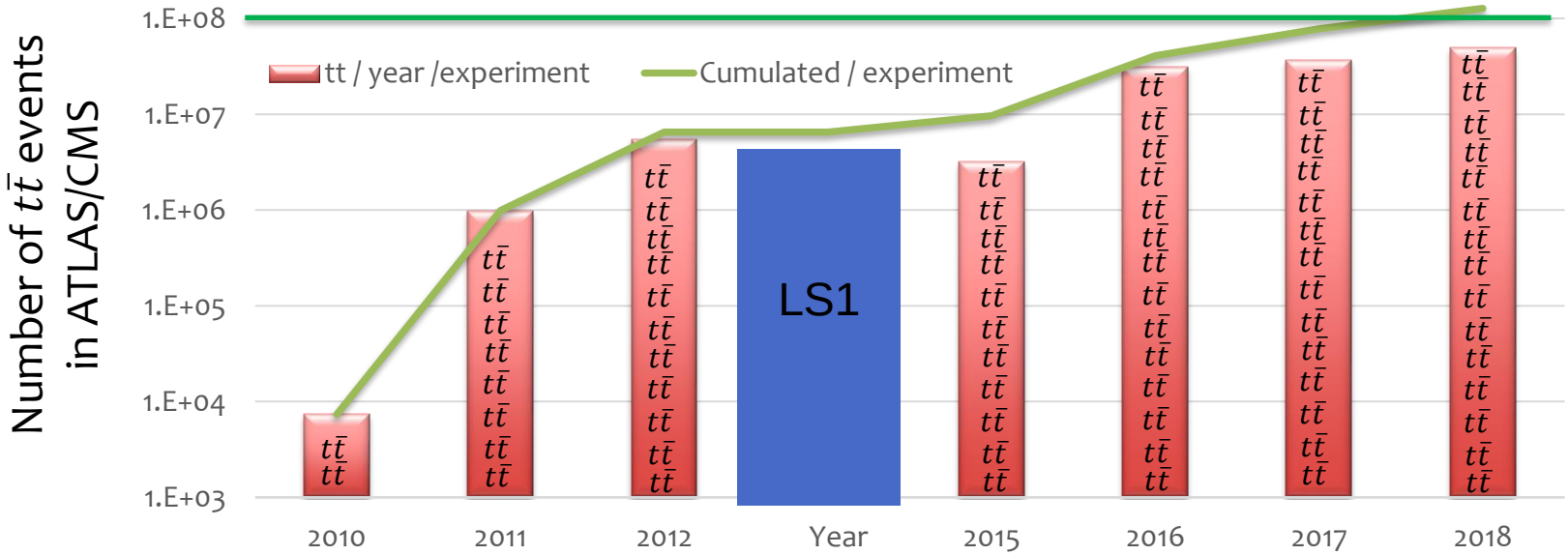
$\sqrt{s}$ (TeV)	σ ($m_t = 172.5$ GeV)
5	$68.9 \pm 1.9(\text{scale}) \pm 2.7(\text{PDF} + \alpha_S)$
7	$177.3^{+4.7}_{-6.0}(\text{scale}) \pm 9.0(\text{PDF} + \alpha_S)$
8	$252.9^{+6.4}_{-8.5}(\text{scale}) \pm 11.7(\text{PDF} + \alpha_S)$
13	$832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF} + \alpha_S)$

5.2 - 4.8%

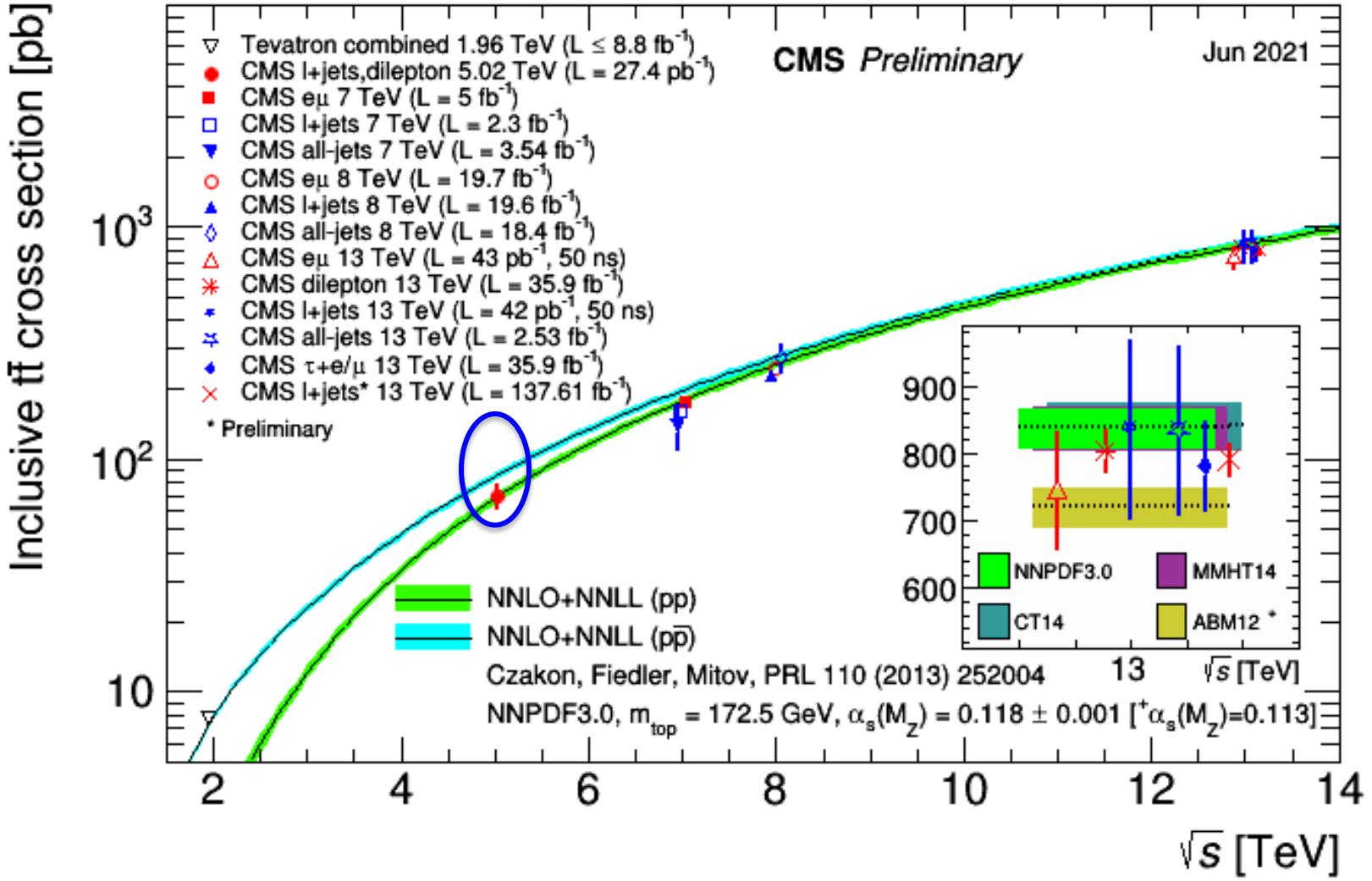
Full NNLO+NNLL calculation [arXiv:1303.6254]

Main diagrams





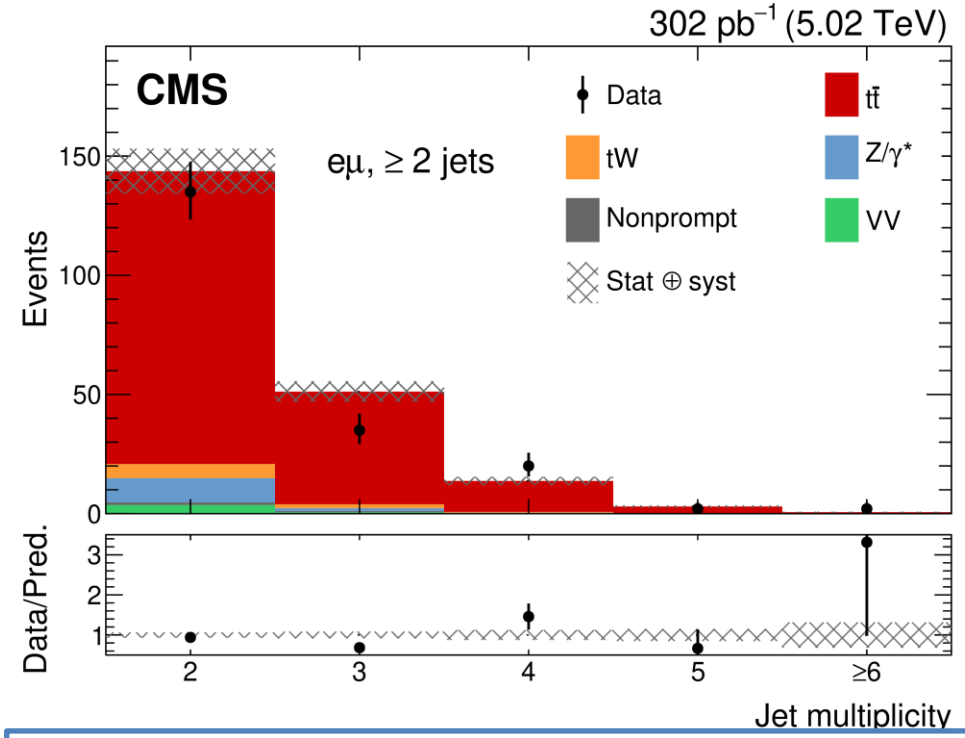
The full picture

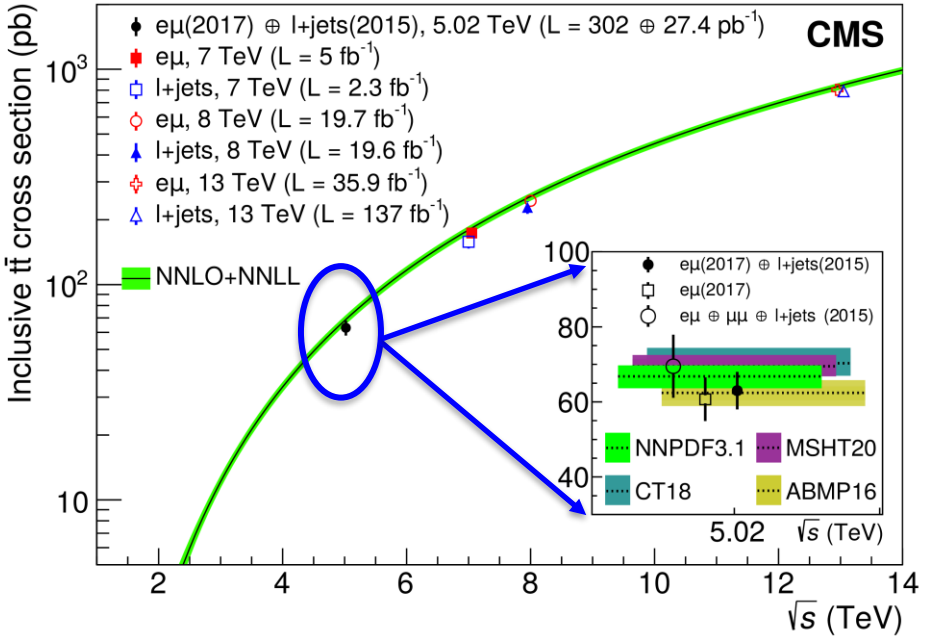


Impressive agreement up to now..

Latest inclusive measurement

Inclusive eμ, 302pb^{-1}, $\sqrt{s}$ = 5.02TeV [JHEP 04 (2022) 144]





σ =60.7 ± 5.0 (stat) ± 2.8 (syst) ± 1.1 (lum) pb (9.6%)

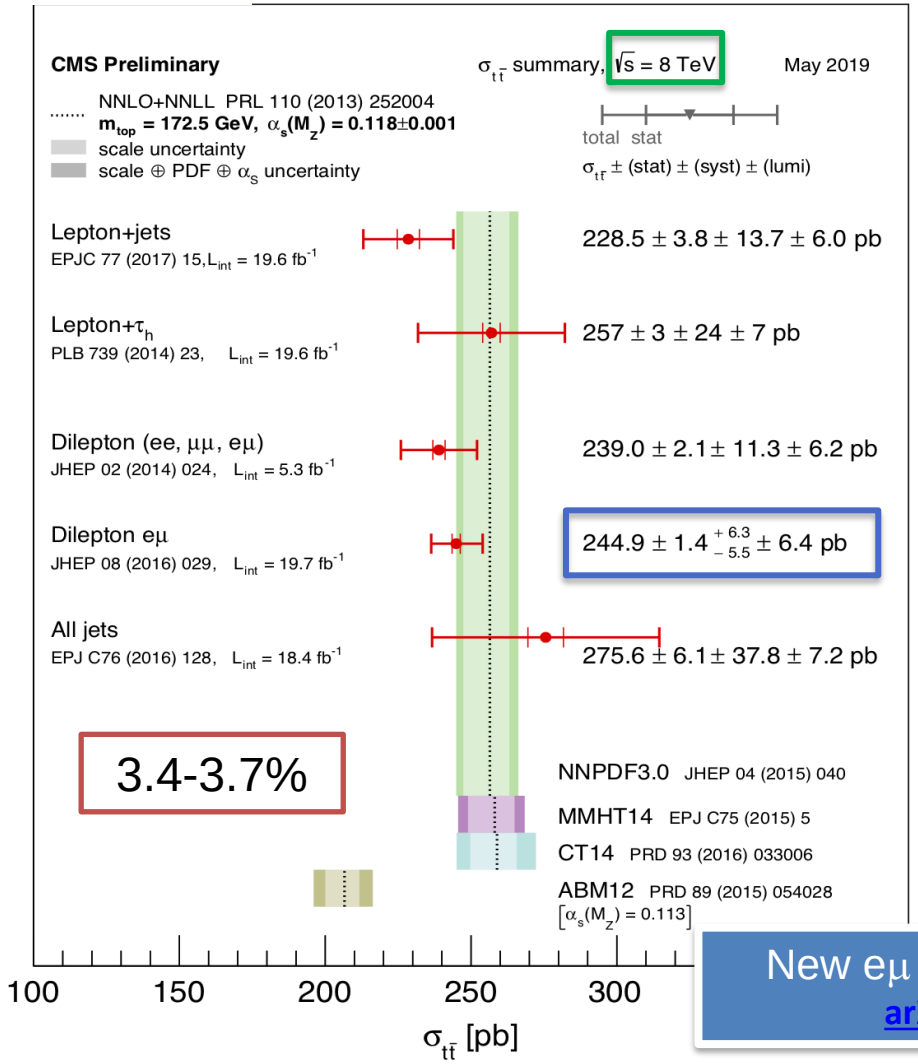
- events with one electron and one muon of opposite charge, and at least two jets
- Dataset from year 2017

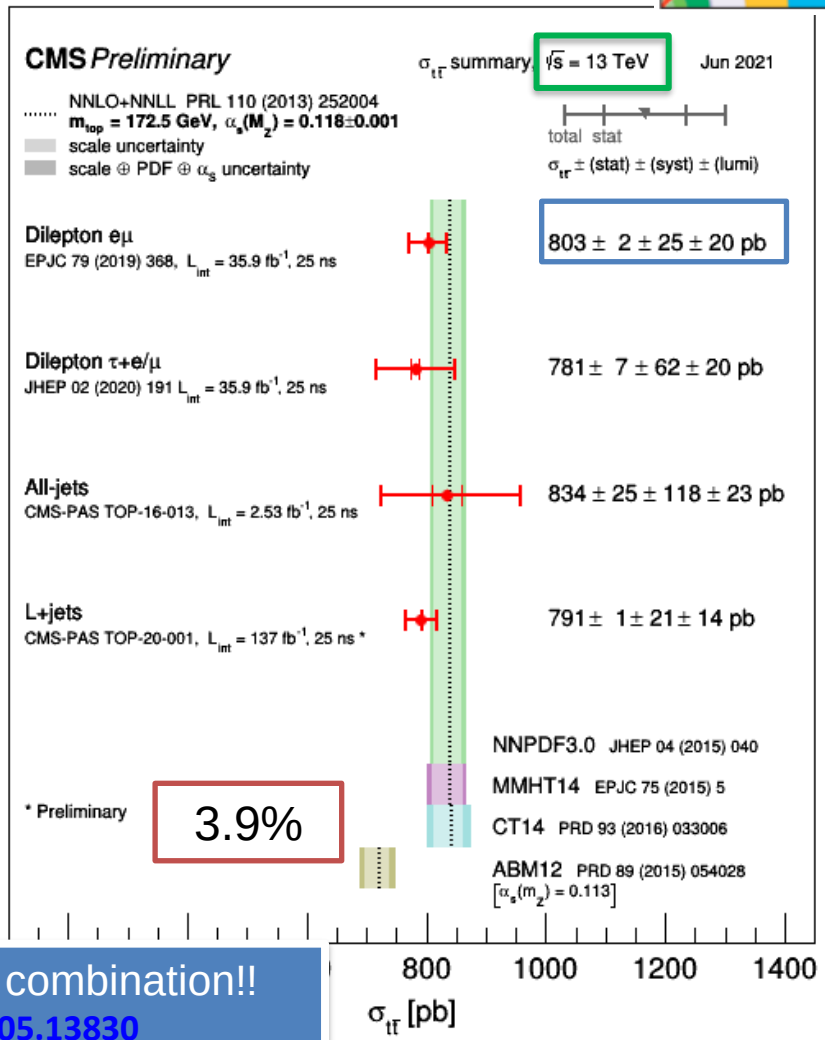
- combination with the single lepton + jets measurement, data set collected in 2015 at the same $\sqrt{s}$ and corresponding to an integrated luminosity of 27.4 pb^{-1}

$\sigma_{Combined}$=63.0 ± 4.1 ± 3.0 pb (8.0%)

$\sigma_{NNLO+NNLL}$=66.8 +2.9 -3.1 pb

The detailed picture





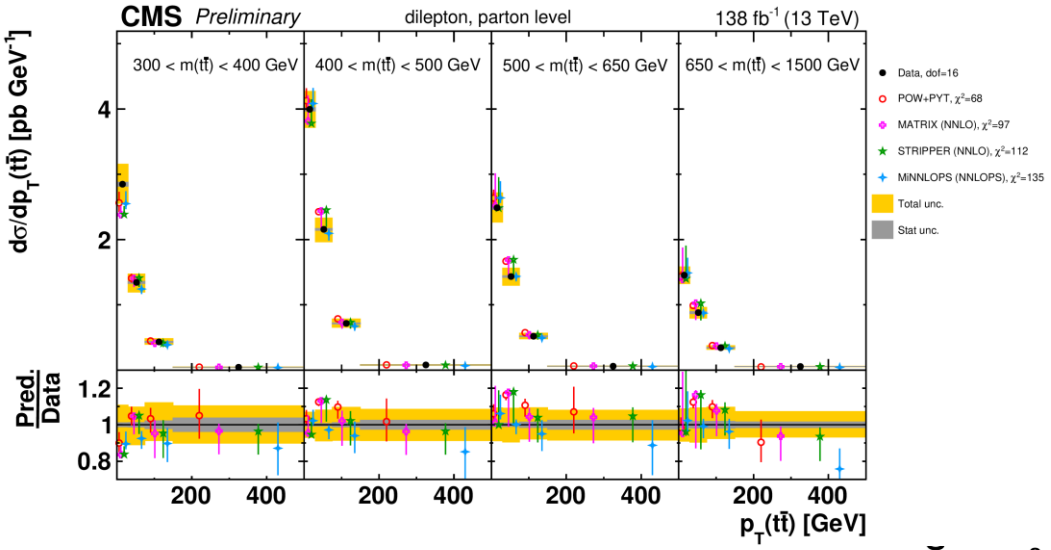
New eμ LHC combination!!
arXiv:2205.13830

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

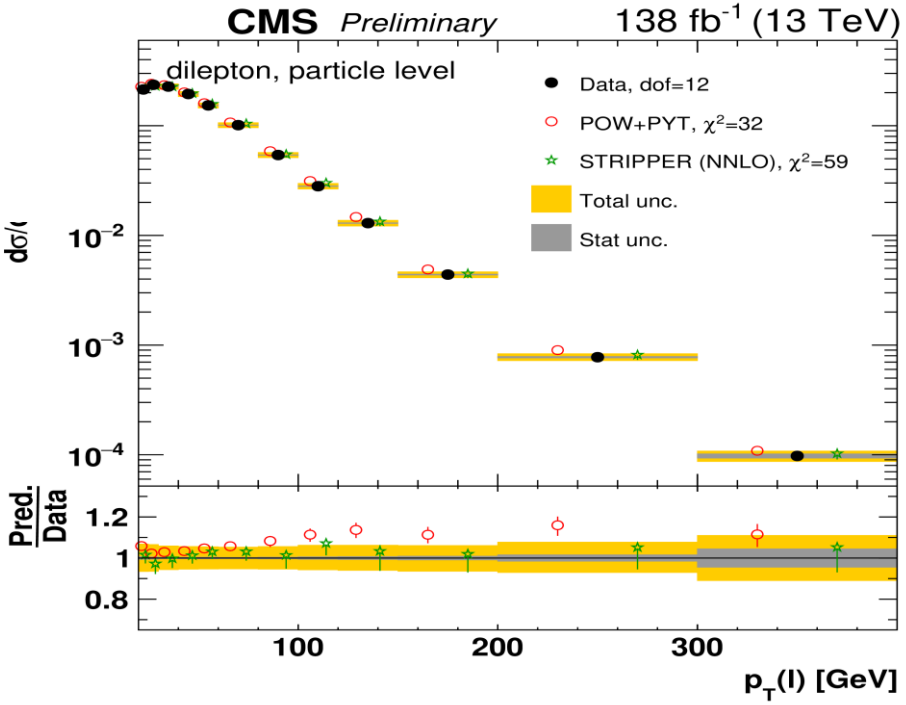
Need to look at differential measurements!!

Latest differential measurements

Multi-differential dilepton 138 fb^{-1} $\sqrt{s}$ = 13 TeV TOP-20-006



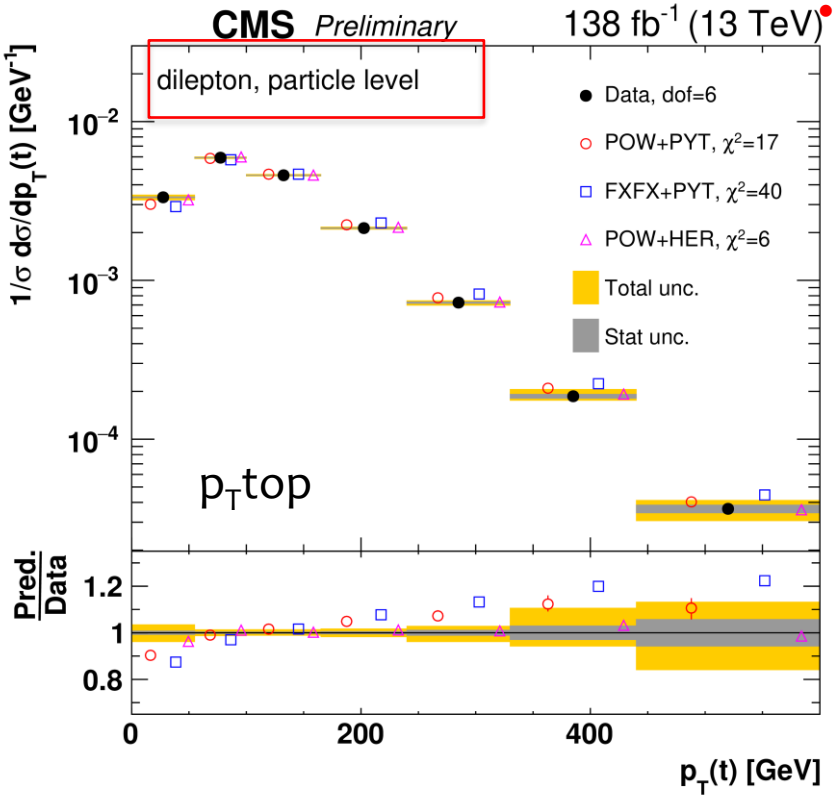
- Very sensitive to the QCD predictions
- Uncertainties halved compared to previous results



- **dilepton events (ee, eμ, μμ):**
  - high purity & large statistics sample
- **measurements:**
  - absolute & normalized differential xsec, parton and particle level
  - **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

Multi-differential dilepton 138 fb^{-1} $\sqrt{s}$ = 13 TeV [TOP-20-006]

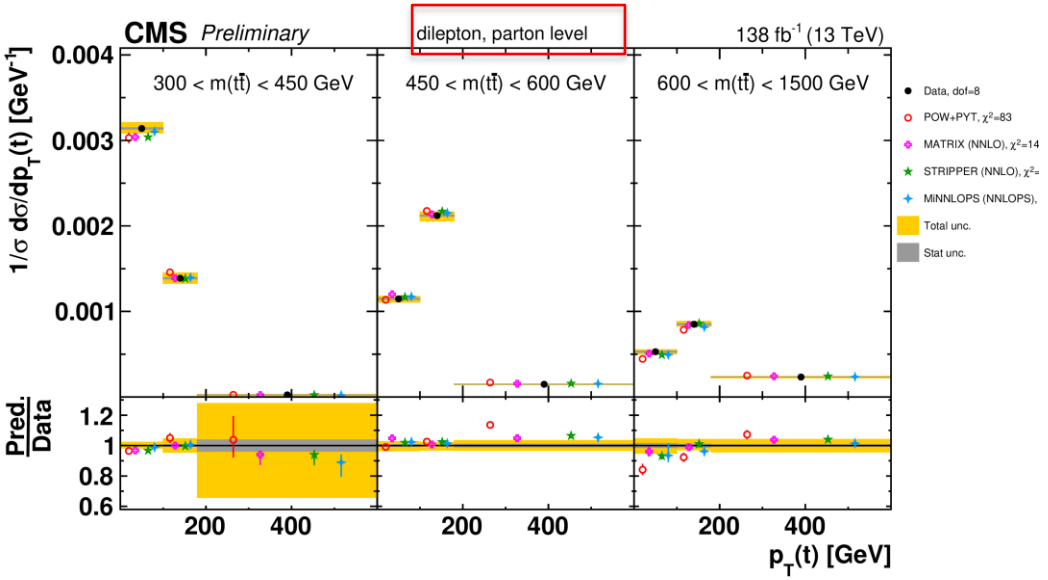


Fully resolved at NNLO, but only calculations for dedicated observables:

- MiNNLOPS a first step for a full NNLO MC (arXiv:2112.12135)

PowhegV2+Pythia8 (NLO) chosen as default generator setup in CMS for Run2:

- Reasonable agreement except in top quark "direct" observables p_T, p_T^{tt}, m_{tt}
- Only Herwig7, but problem most pronounced at high m_{tt}
- Need for full NNLO MC + PS predictions

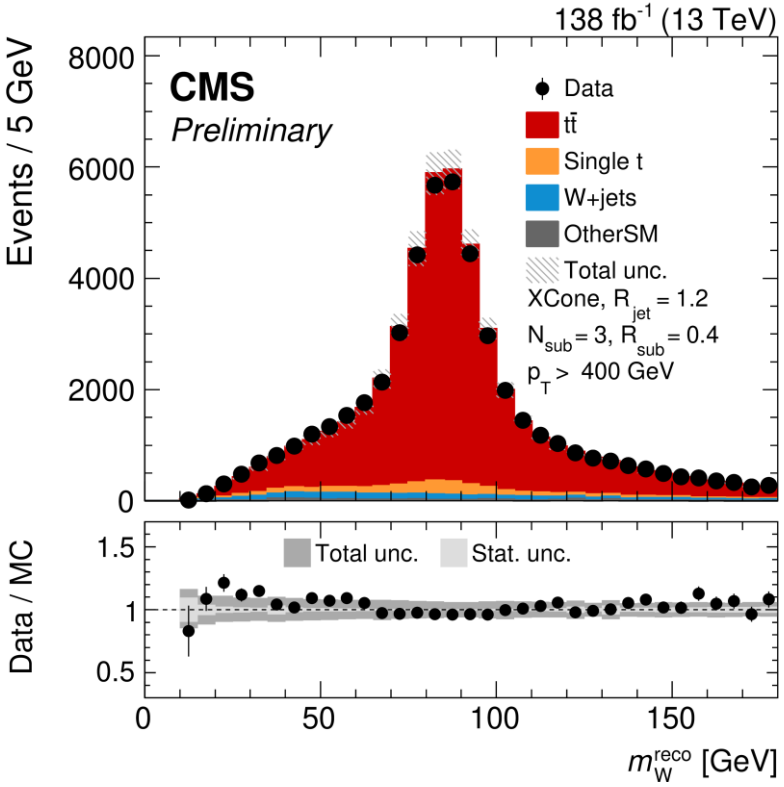


$p_T$top

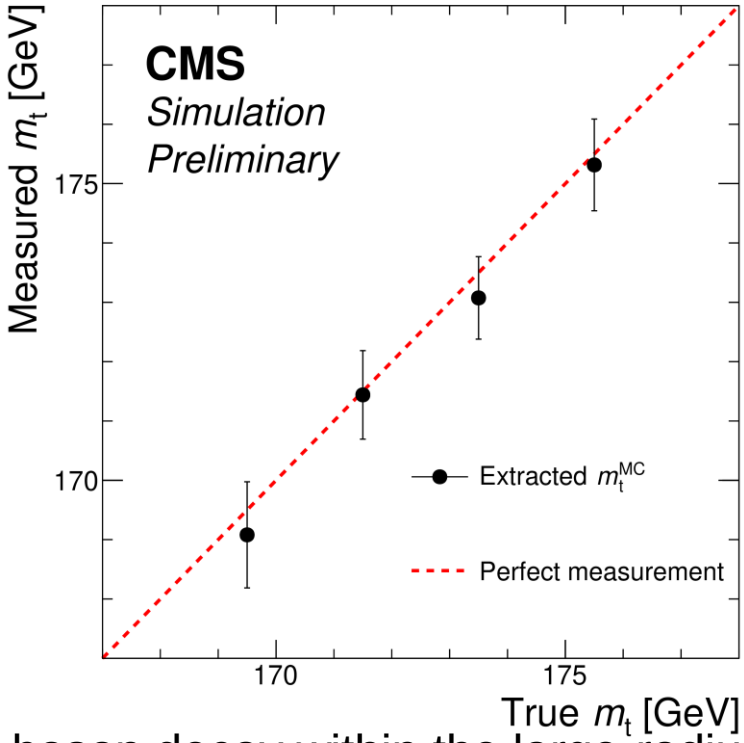
Latest top mass measurements (I)

top quark mass in hadronic decays of boosted top quarks TOP-21-012

- measurement of the jet mass distribution in hadronic decays of boosted top quarks
- l+jets, 138 fb^{-1} $\sqrt{s}$ = 13 TeV, large jet with pT>400GeV. Precision improved by factor >3



m_t = 172.76 ± 0.81 GeV



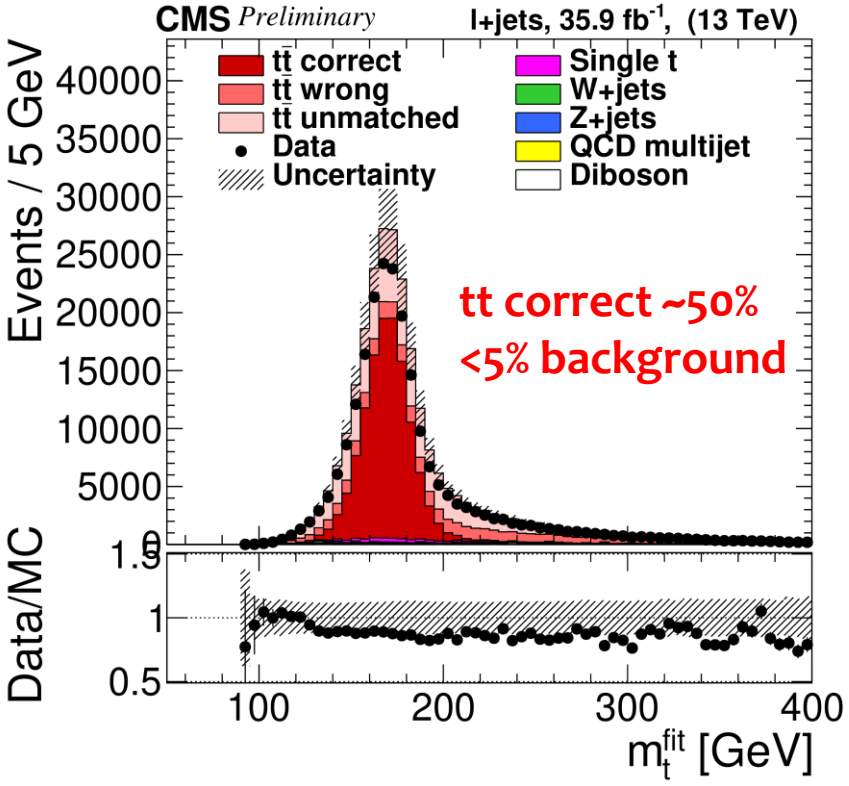
- Jet mass calibrated using the hadronic W boson decay within the large-radius jet.
- Uncertainties in the modelling of the final state radiation are reduced by studying angular relations of the jet substructure, compatible with earlier precision meas.

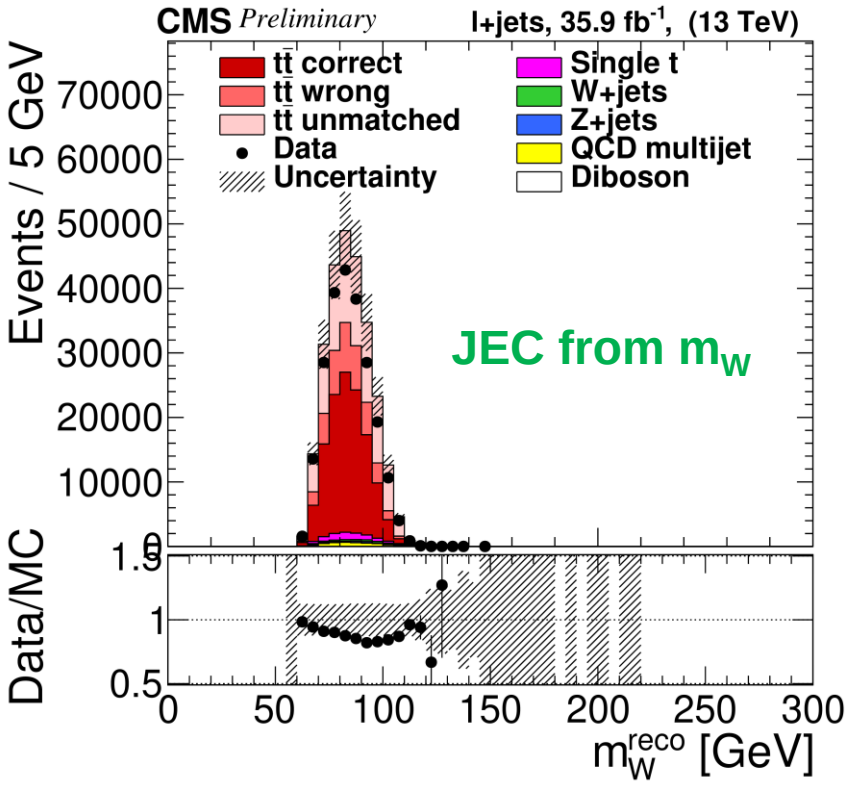
Latest top mass measurements (II)

A profile likelihood approach for the top quark mass TOP-20-008

- baseline observable: m_{top} from kinematic fit
- l+jets, 36 fb^{-1} $\sqrt{s}$ = 13 TeV

m_t = 171.77 ± 0.38 GeV Most precise m_{top}

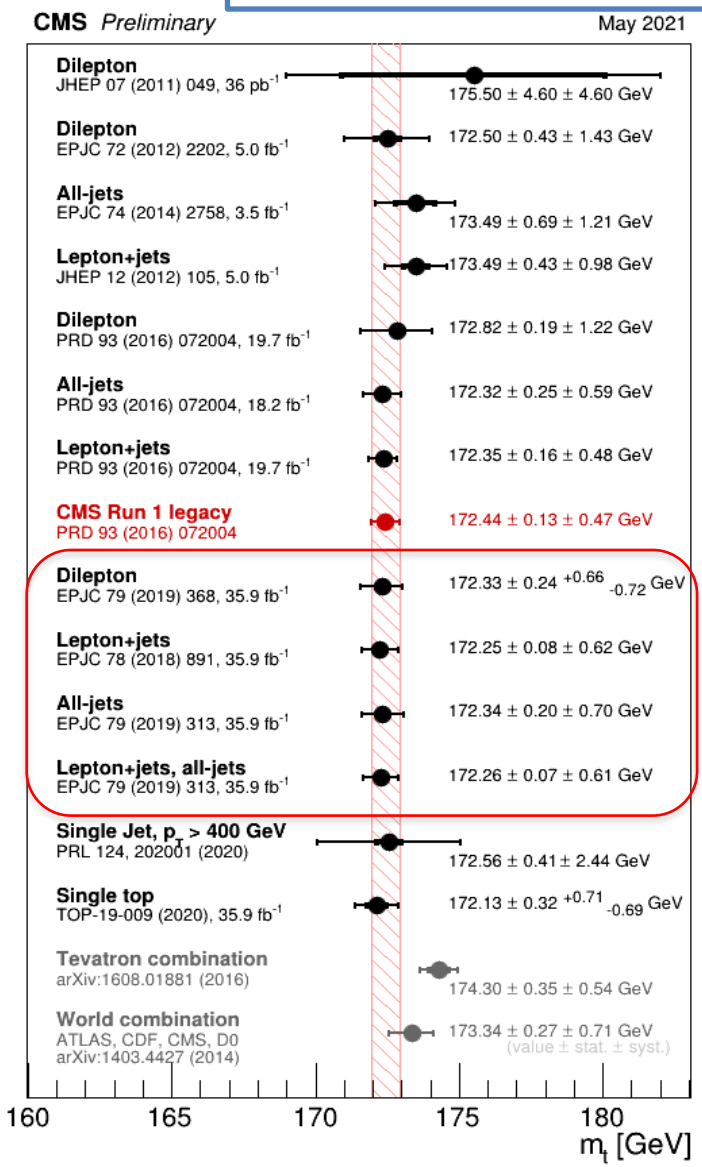


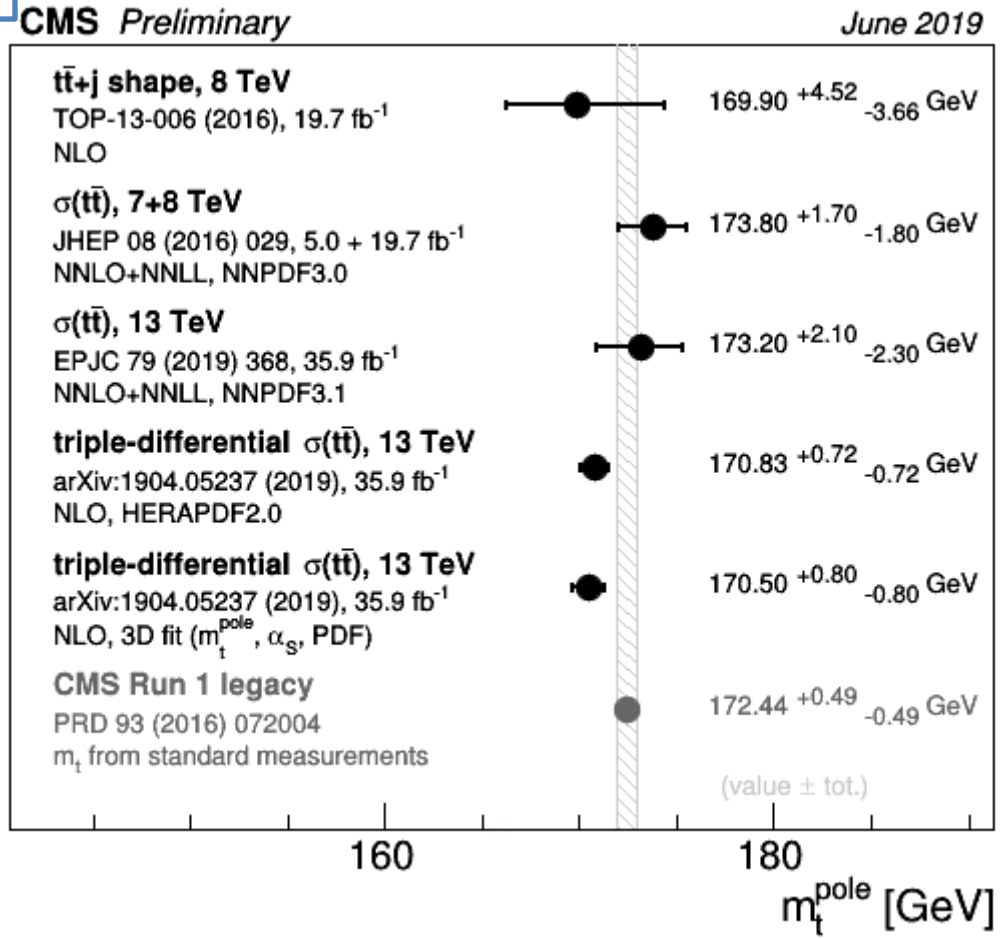


- 4 complementary observables to constrain systematics → total reduction by 40%
- largest uncertainty from b Jet Energy Calib, parton shower and color reconnection

Top quark mass measurements

Uncertainty <1 GeV!!!





Latest top mass pole measurement: TOP-21-008

Pole mass with NLO theory prediction

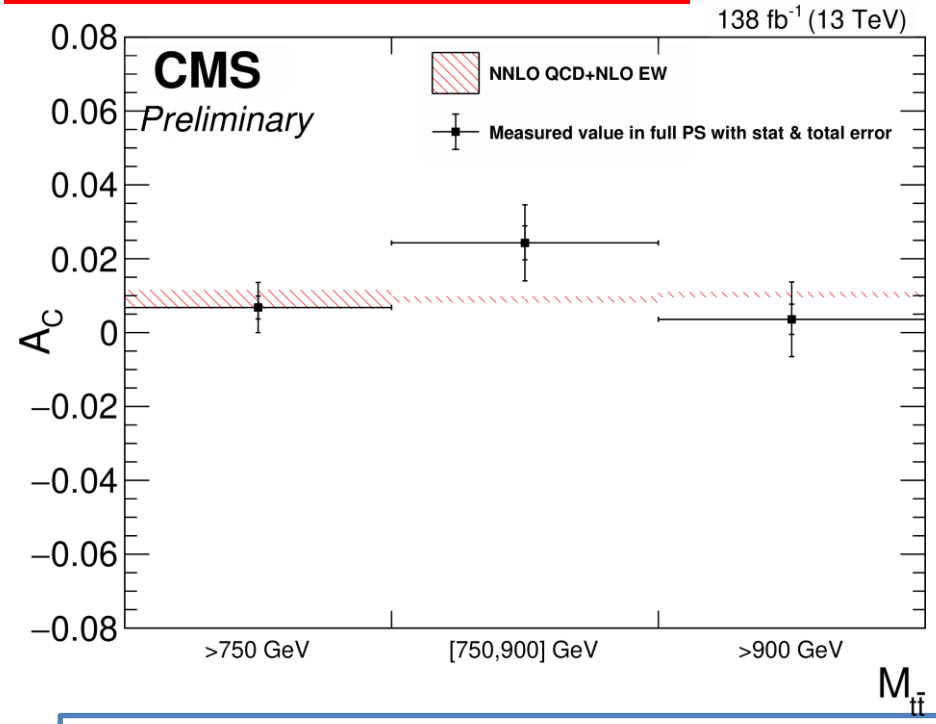
- m_t = 172.94 ± 1.37 GeV (ABMP16NLO)
- m_t = 172.16 ± 1.44 GeV (CT18NLO)

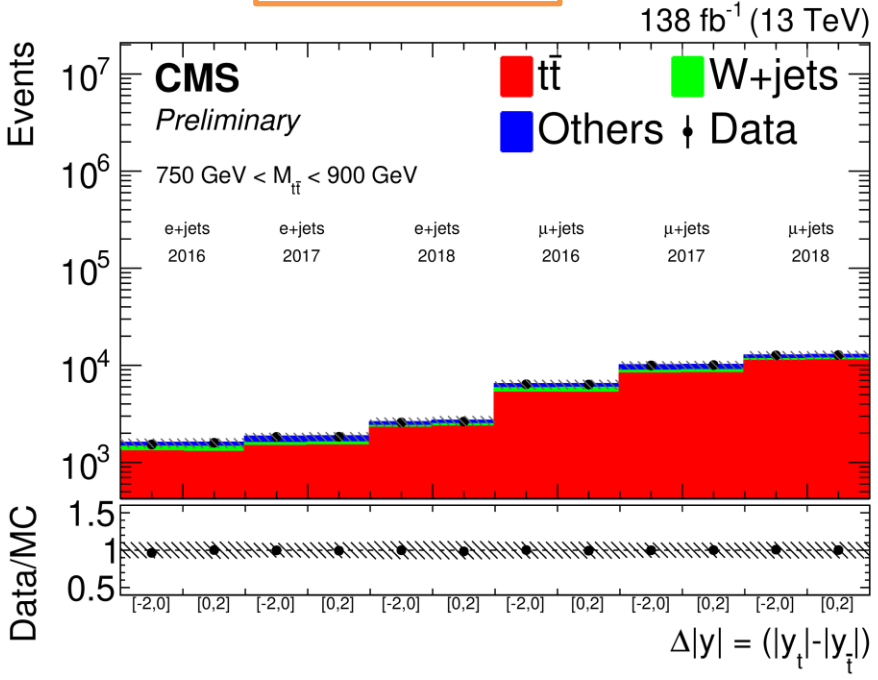
$t\bar{t}$ charge asymmetry (boosted)

l+jets, 138 fb^{-1} $\sqrt{s}$ = 13 TeV

TOP-21-014

Highly boosted m_{tt} >750GeV



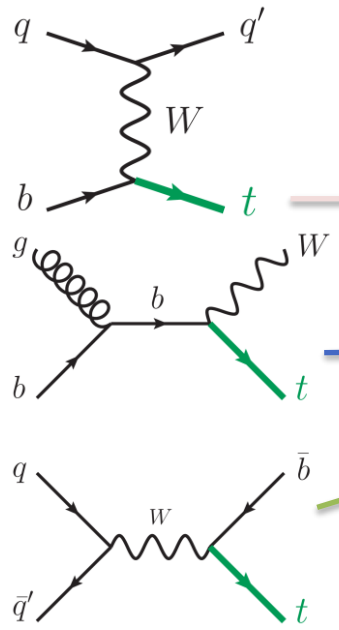


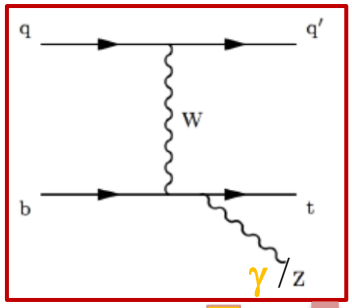
First measurement at 13TeV of the charge asymmetry for highly boosted $t\bar{t}$:

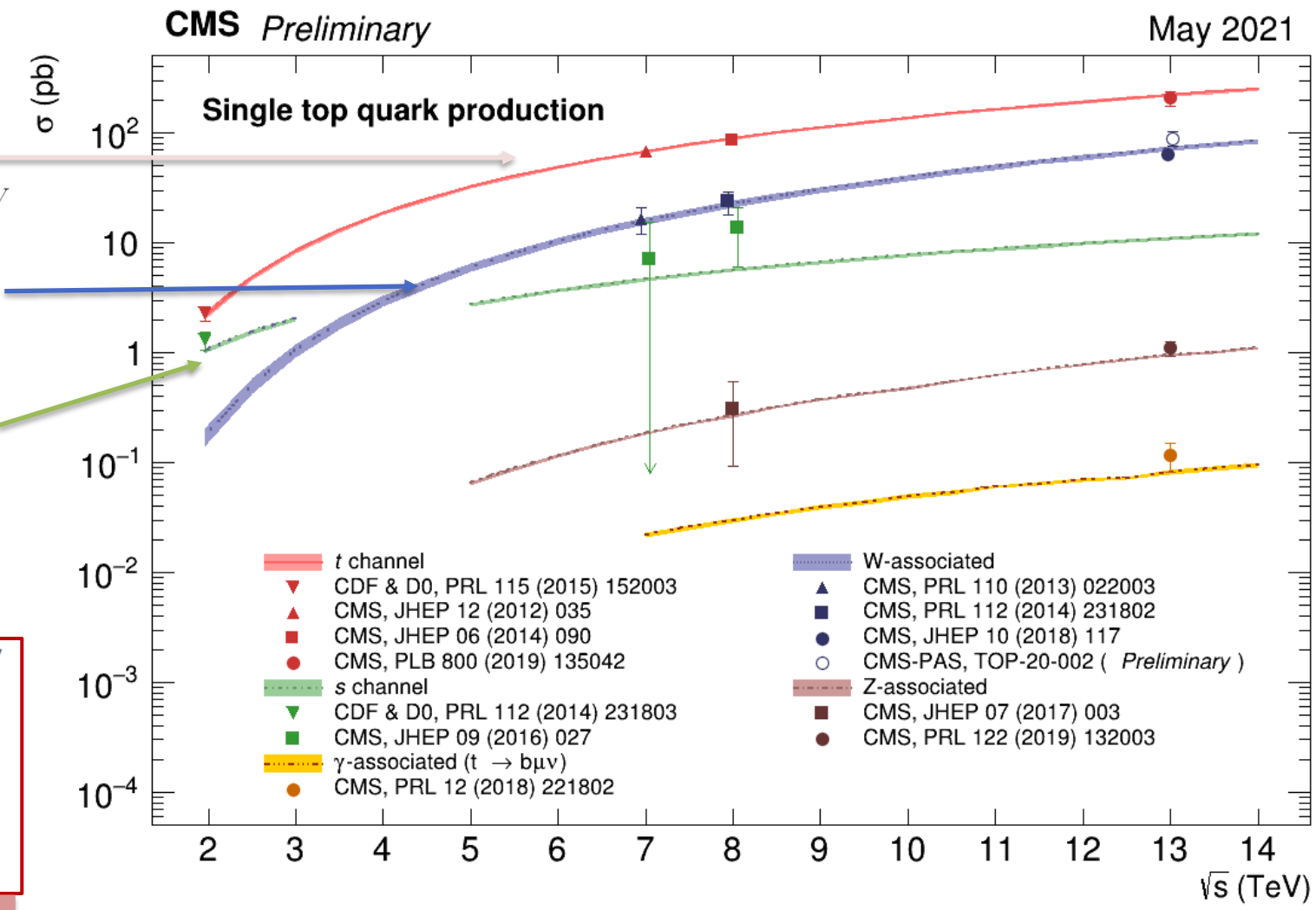
- asymmetry corrected for detector and acceptance effects using a binned maximum likelihood fit
- AC full = $0.0069\ ^{+0.0065}_{-0.0069}$
- NNLO prediction with EW NLO corrections: $0.0094\ ^{+0.0005}_{-0.0007}$

SINGLE TOP QUARK PRODUCTION

Single top-quark in Run2



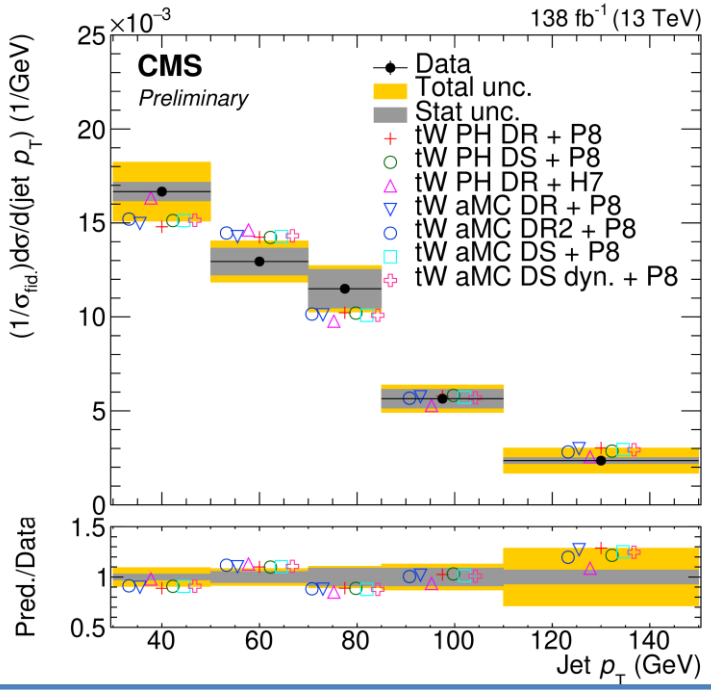


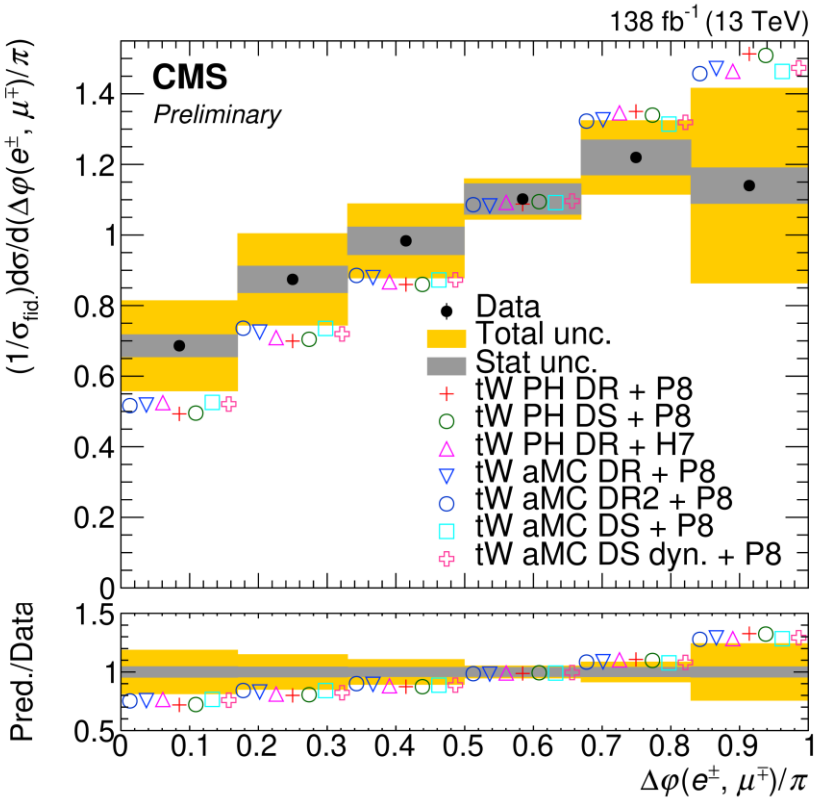


tW inclusive and differential cross-section

eμ 138 fb^{-1} $\sqrt{s}$ = 13 TeV

TOP-21-010 (preliminary)





- Differential as a function of properties of the event: $p_T(l,j)$, $\Delta\phi$, $p_z(l,j)$, m(l,j), MET
- Uncertainties vary depending on the chosen distribution and range from ~10% up to ~40% (in relative terms) in the bulk of the distributions, larger in the tails.
- The different approaches to produce tW events show similar values in all distributions, pointing to small effects of the **tW** / **$t\bar{t}$** interference in the defined fiducial region and on these distributions.

Differential associated production tZq

3 leptons, 138 fb^{-1} $\sqrt{s}$ = 13 TeV, Inclusive & first differential

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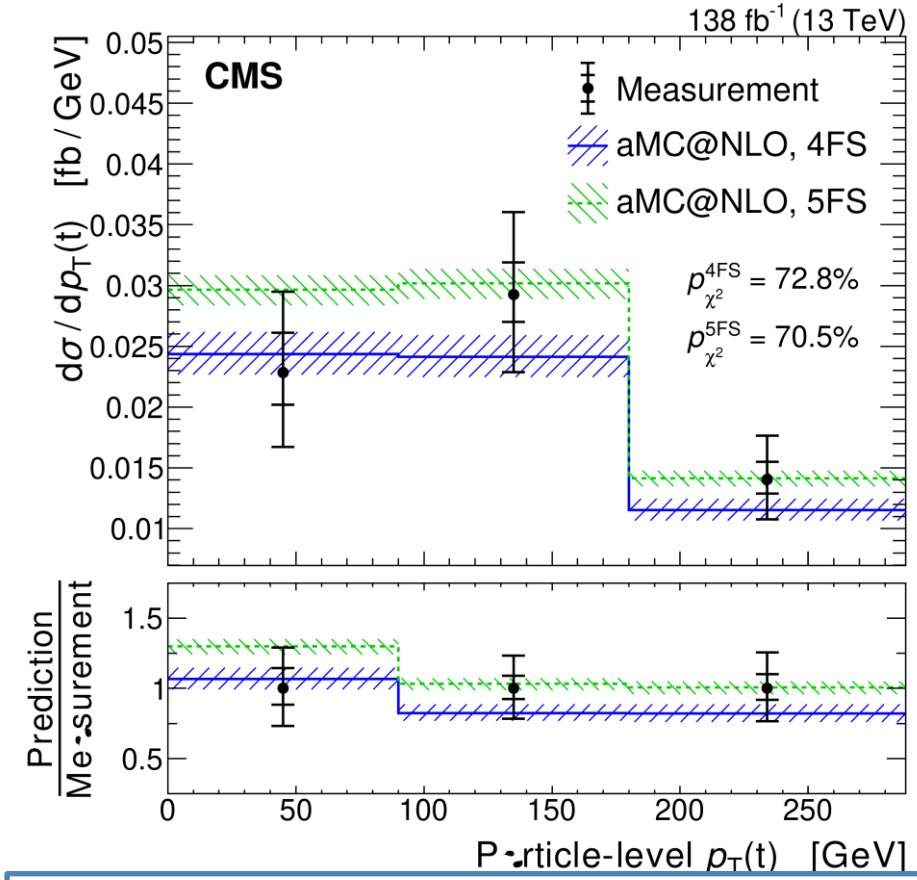
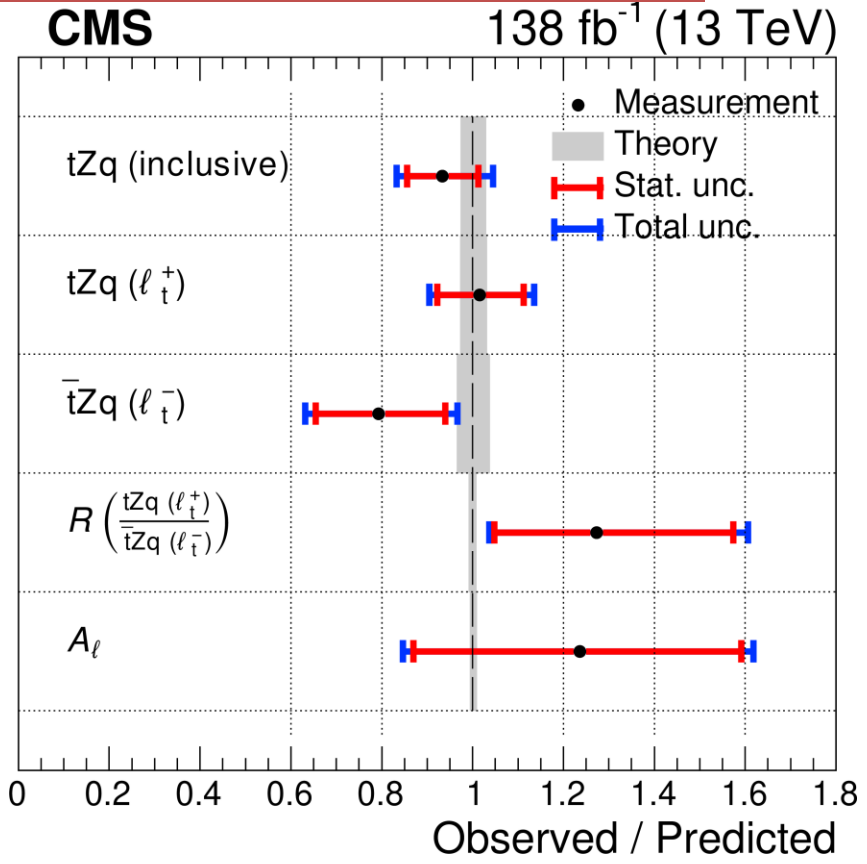


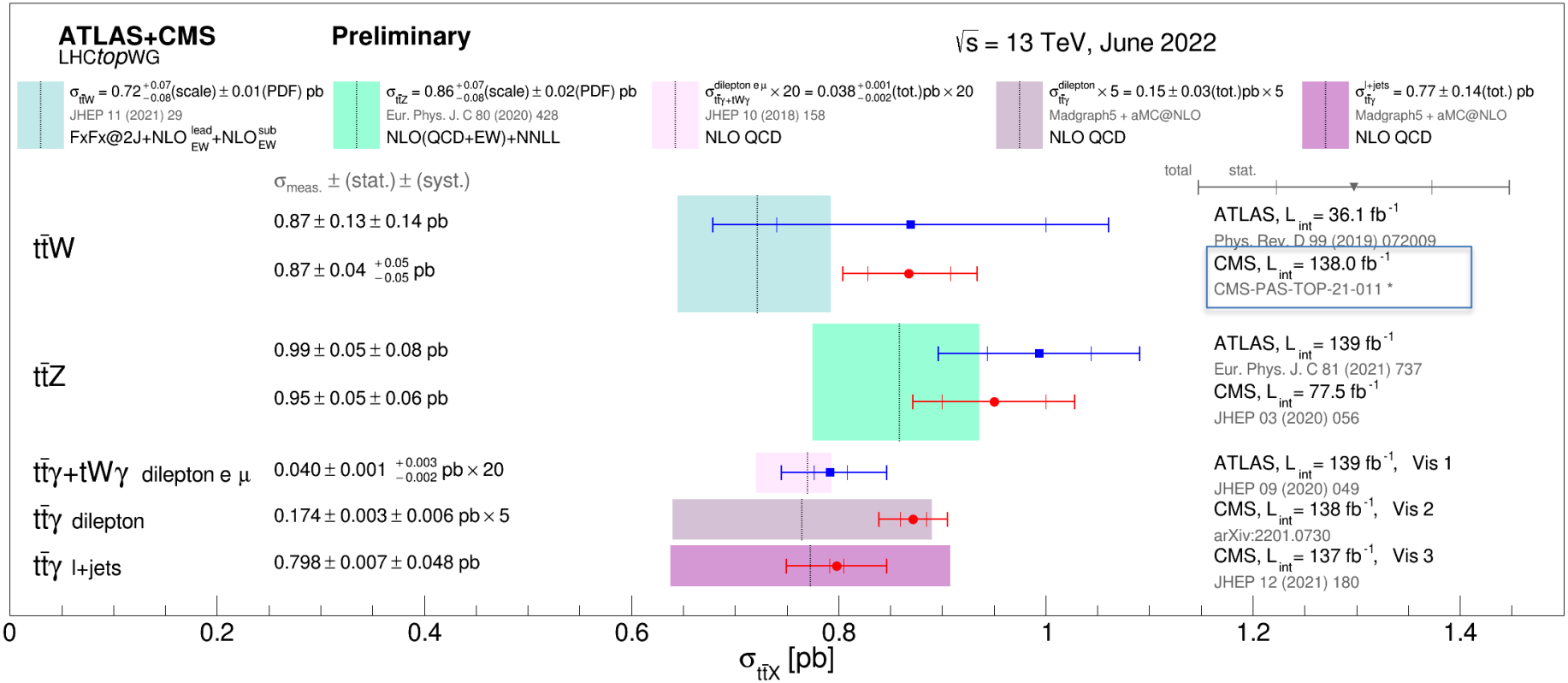


Most precise inclusive tZq cross section measurement to date, with relative precision ~ 25% better than previous results

For the first time, the inclusive tZq cross sections are also measured separately for t and $\bar{t}$ production

$t\bar{t} + X$

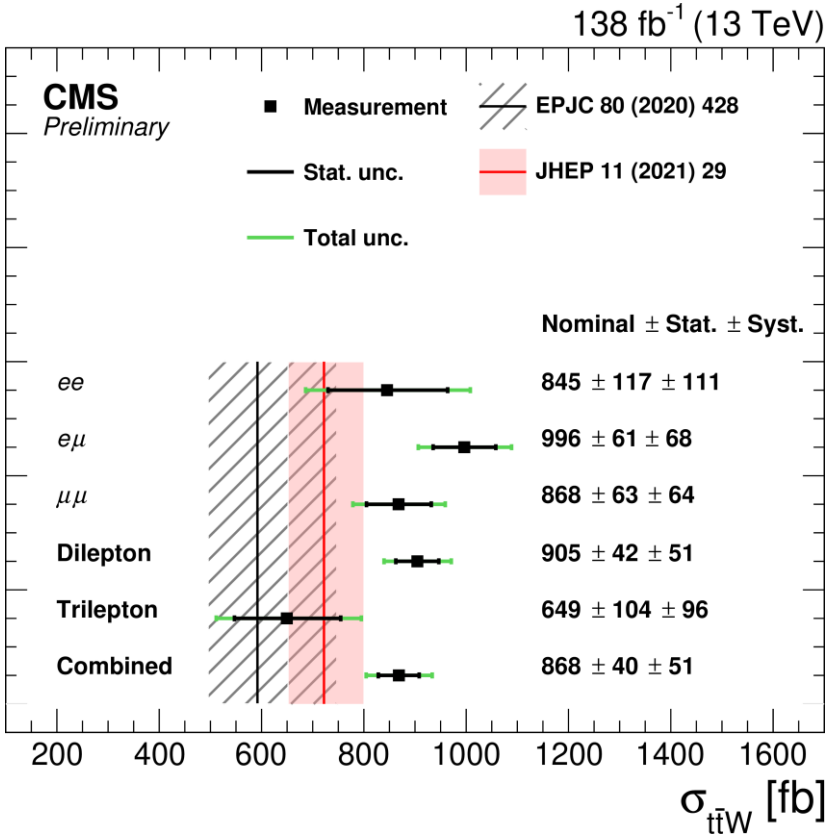
$t\bar{t}+V$

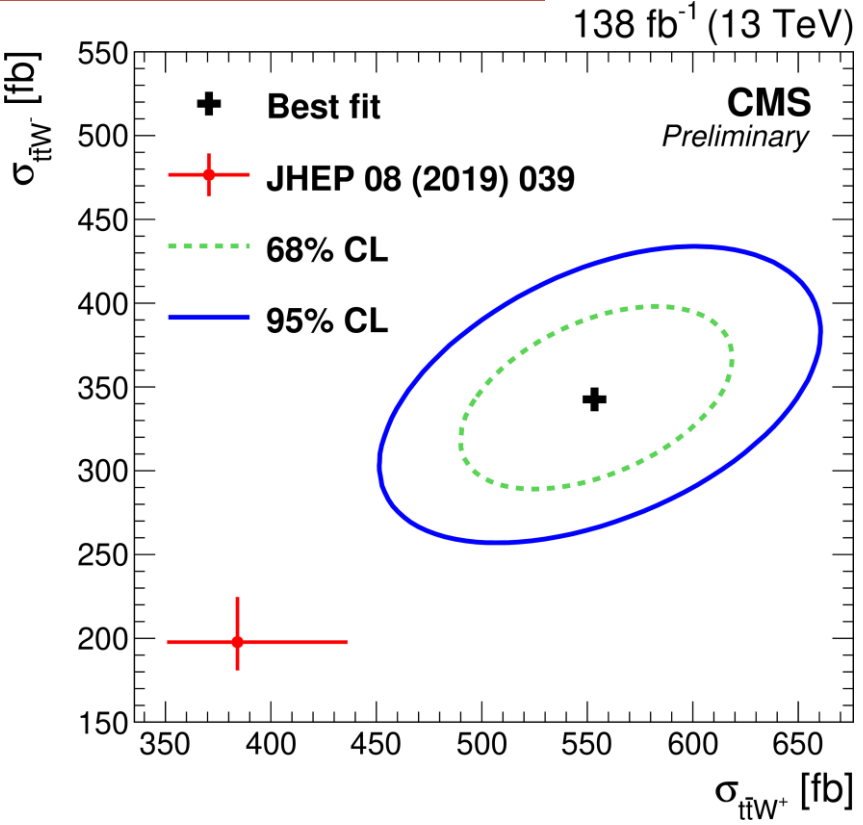


- Direct measurement of top couplings to gauge bosons →inputs to Effective Field Theories
- $t\bar{t}+W$ and $t\bar{t}+Z$ are dominant irreducible backgrounds for $t\bar{t}H$ and 4tops

Latest ttW measurement

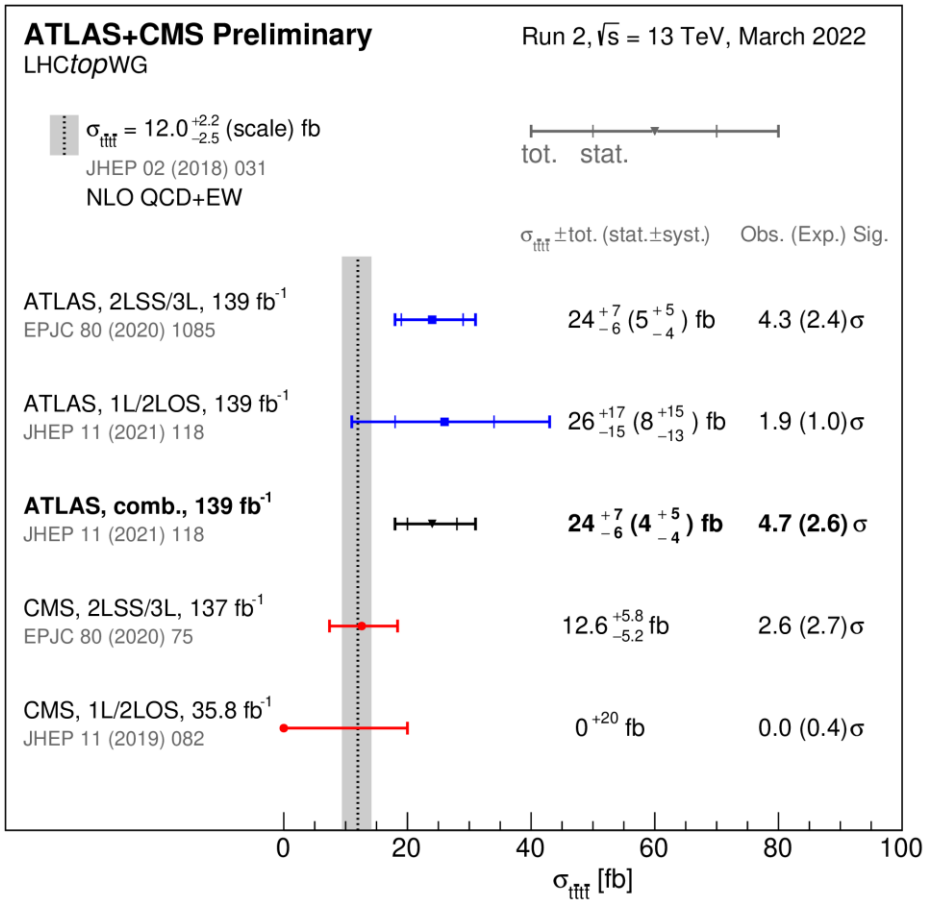
2SS or 3 leptons, 138 fb^{-1} $\sqrt{s}$ = 13 TeV TOP-21-011

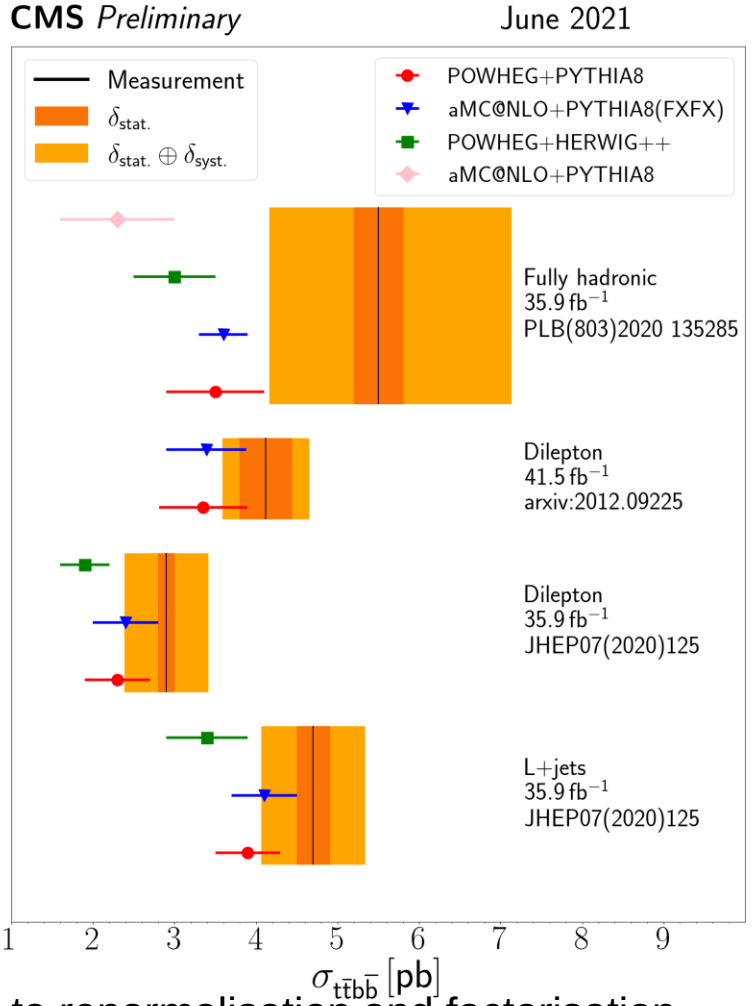




- Compared to prediction from NLO+NNLL & NLO with improved FxFxME merging
- Leading systematics: ttH norm (2.6%), lumi(1.9%), ttW scale (1.8%)
- Cross section visibly larger than NLO+NNLL prediction
- R (ttW$^+$/ttW$^-$) lower than SM by 2σ

$t\bar{t}t\bar{t}$ & $t\bar{t}b\bar{b}$





- 4tops: theory band represents uncertainties due to renormalisation and factorisation scales. CMS is improving the analysis in the 1L/2LOS with more stats
- $t\bar{t}$ + $b\bar{b}$: Summary of CMS cross section measurements in the full phase space, compared with different predictions

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

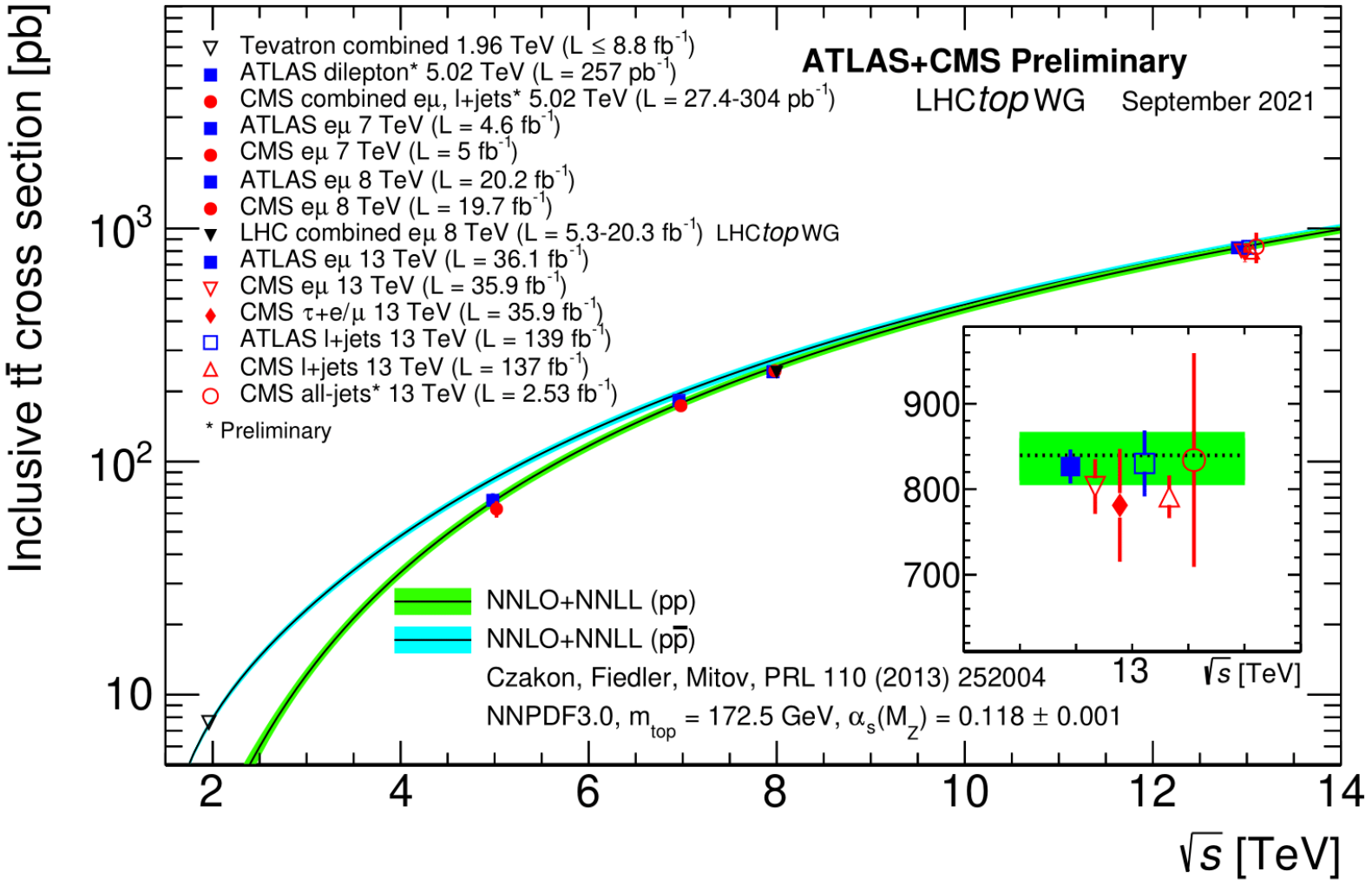
- **Rich program** on top quark physics:
  - Top quark pair production
  - Single quark top and variants
  - Associated productions and $t\bar{t}$ $t\bar{t}$ / $b\bar{b}$

- **More results** to come:
  - Run3 already started, new $\sqrt{s}$ = 13.6TeV
  - Expected $\int L \sim 450$ fb^{-1}

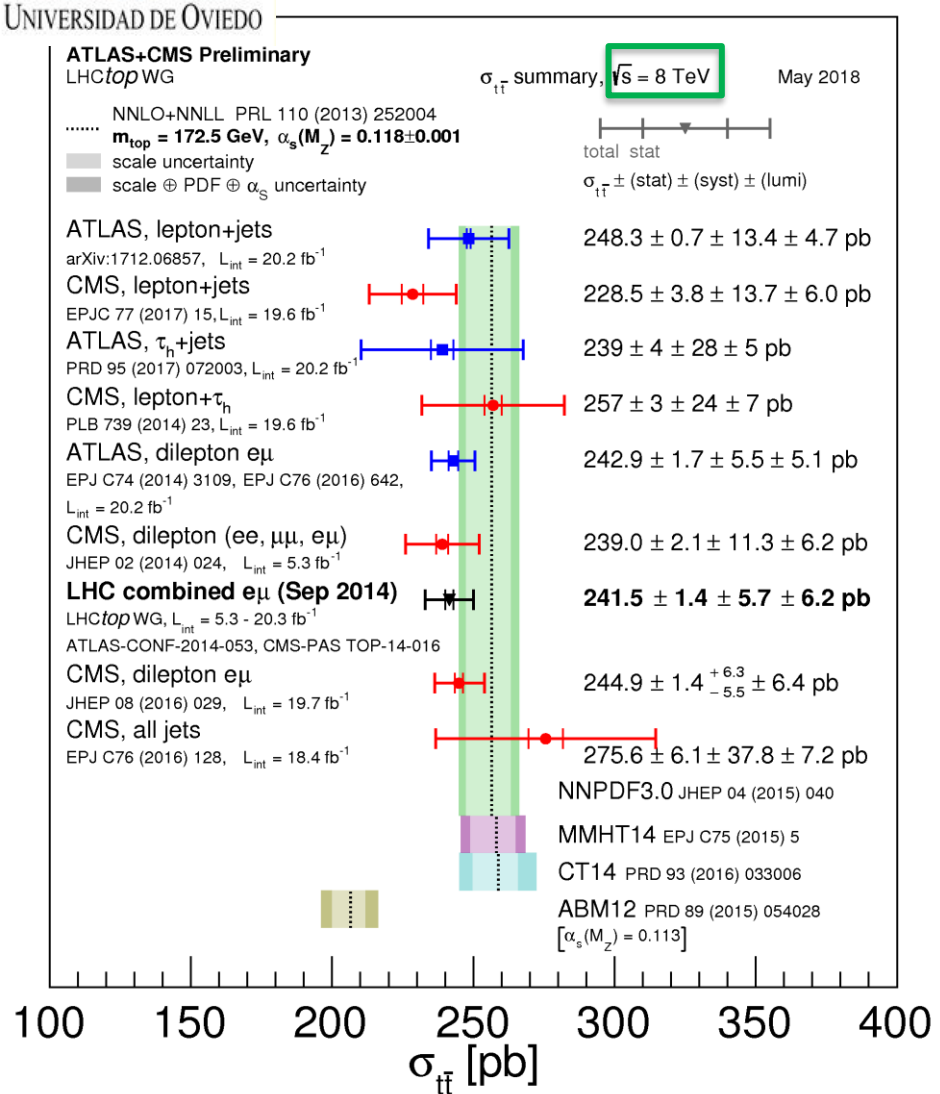
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

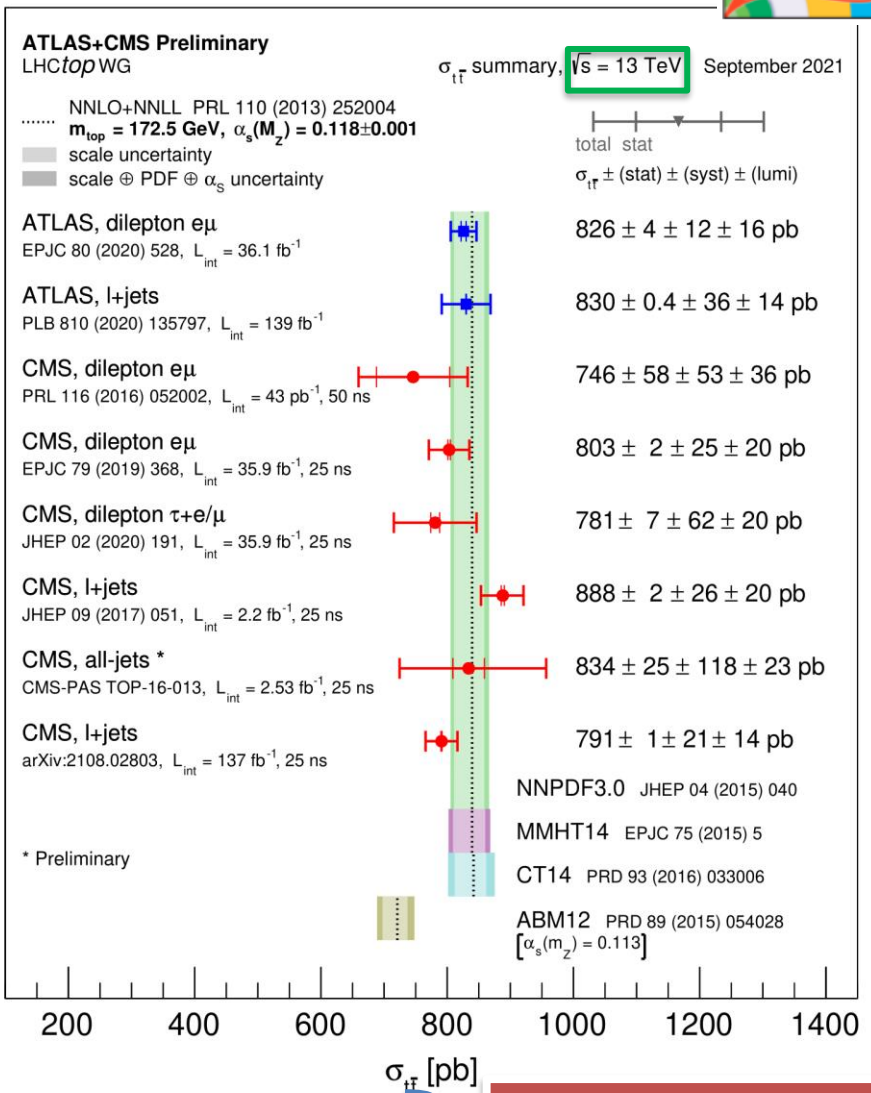
BACKUP

The LHC full picture



The LHC detailed picture





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

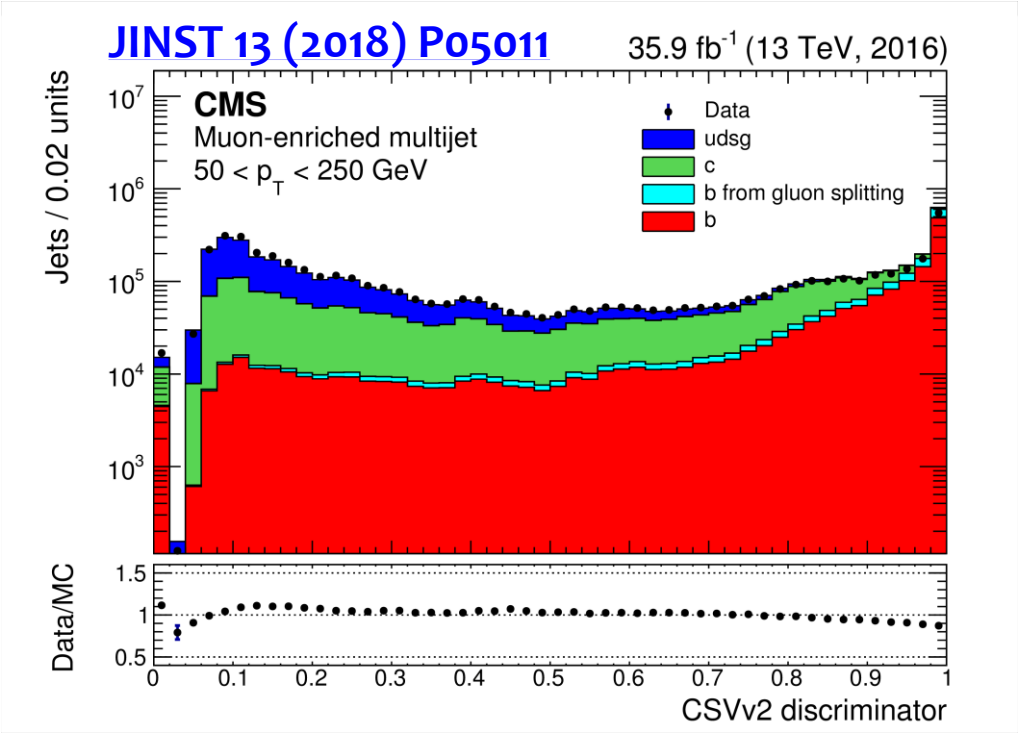
Need to look at differential measurements!!

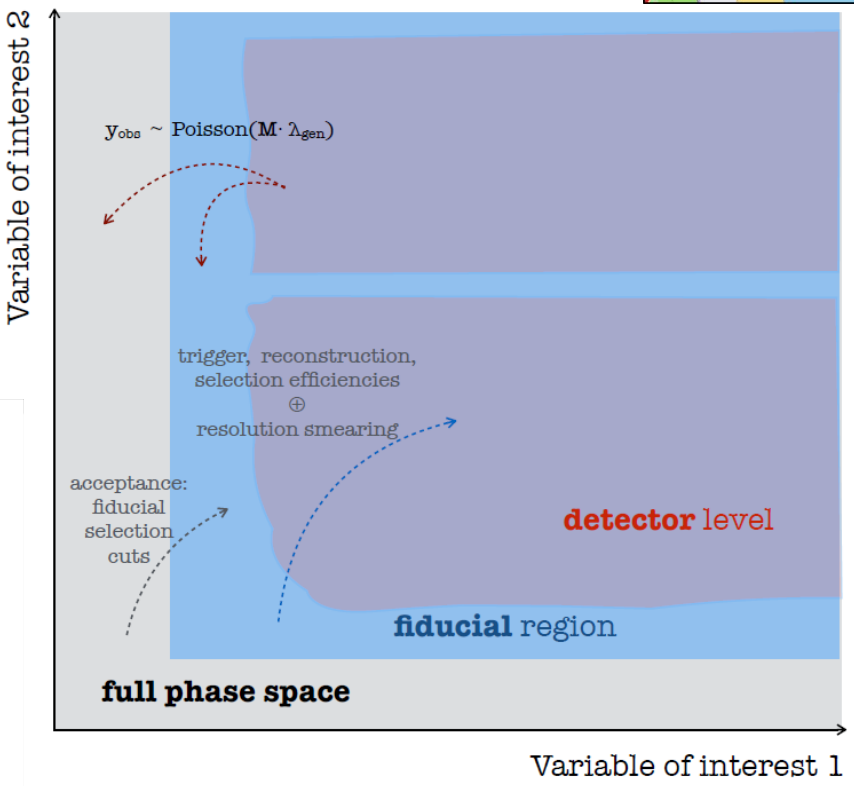
The challenges

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%)





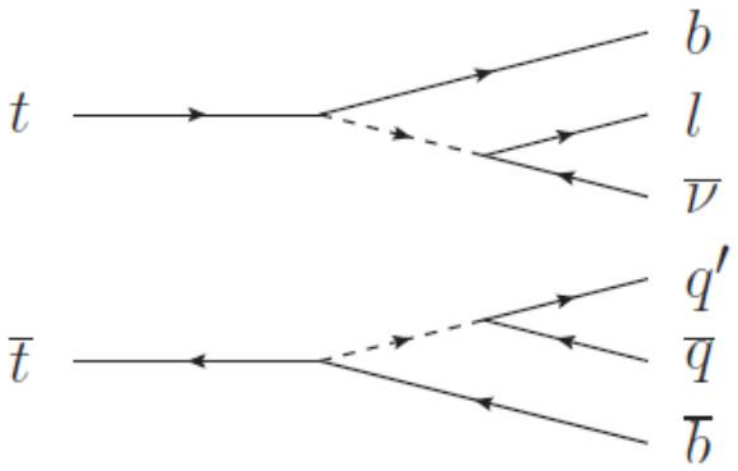
- **Theoretical challenges:**

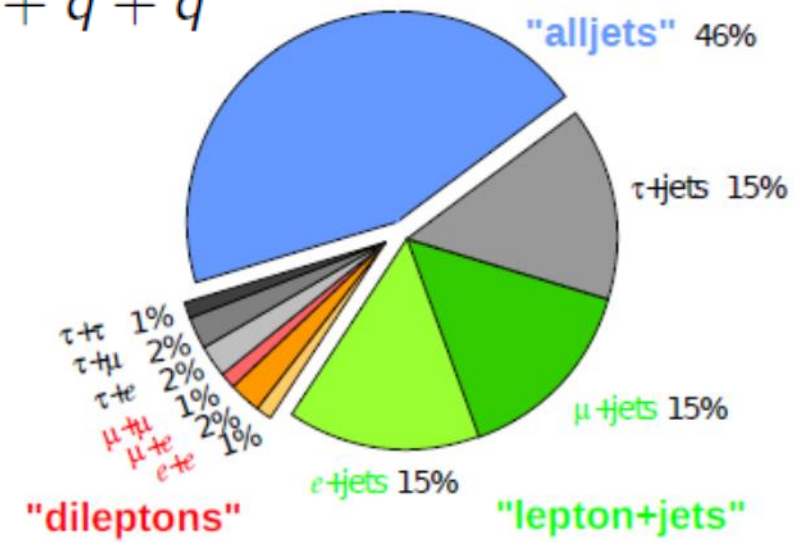
- enter through unfolding to parton & particle level
- parton shower & underlying event modelling

CMS-NOTE-2017-004

Decay channels

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



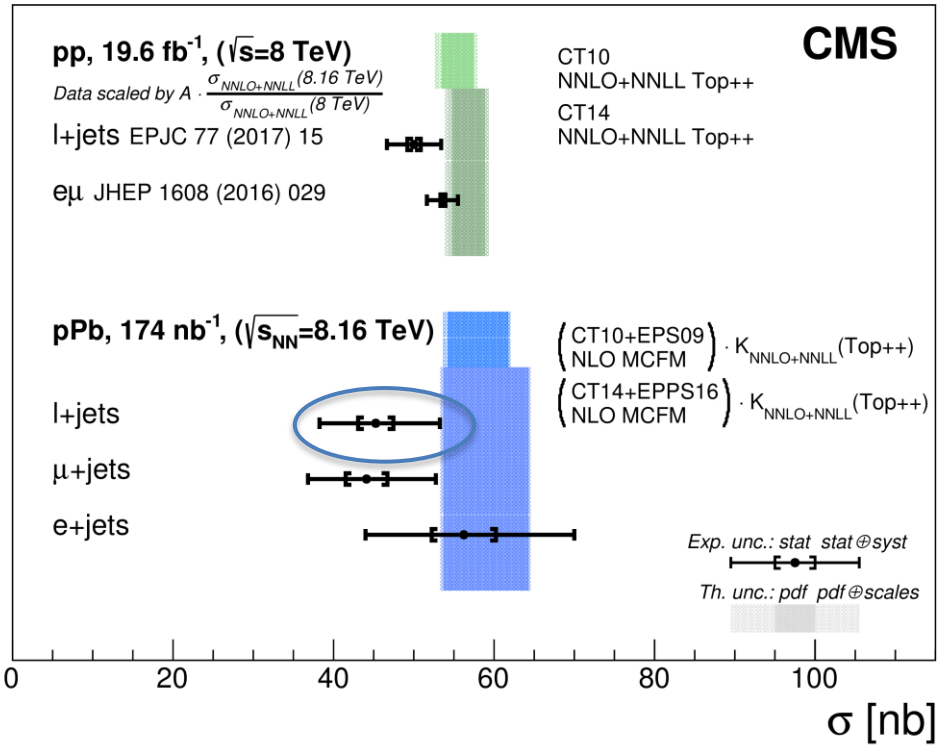


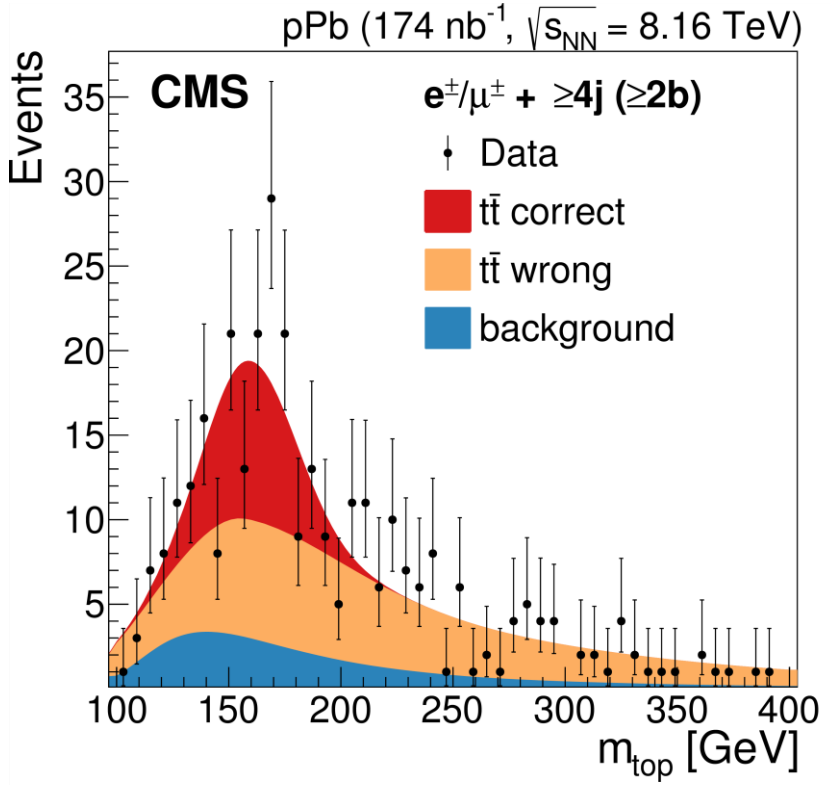
- Top is an important background to many searches, and properties are sensitive to New Physics

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

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

Phys. Rev. Lett. 119 (2017) 242001



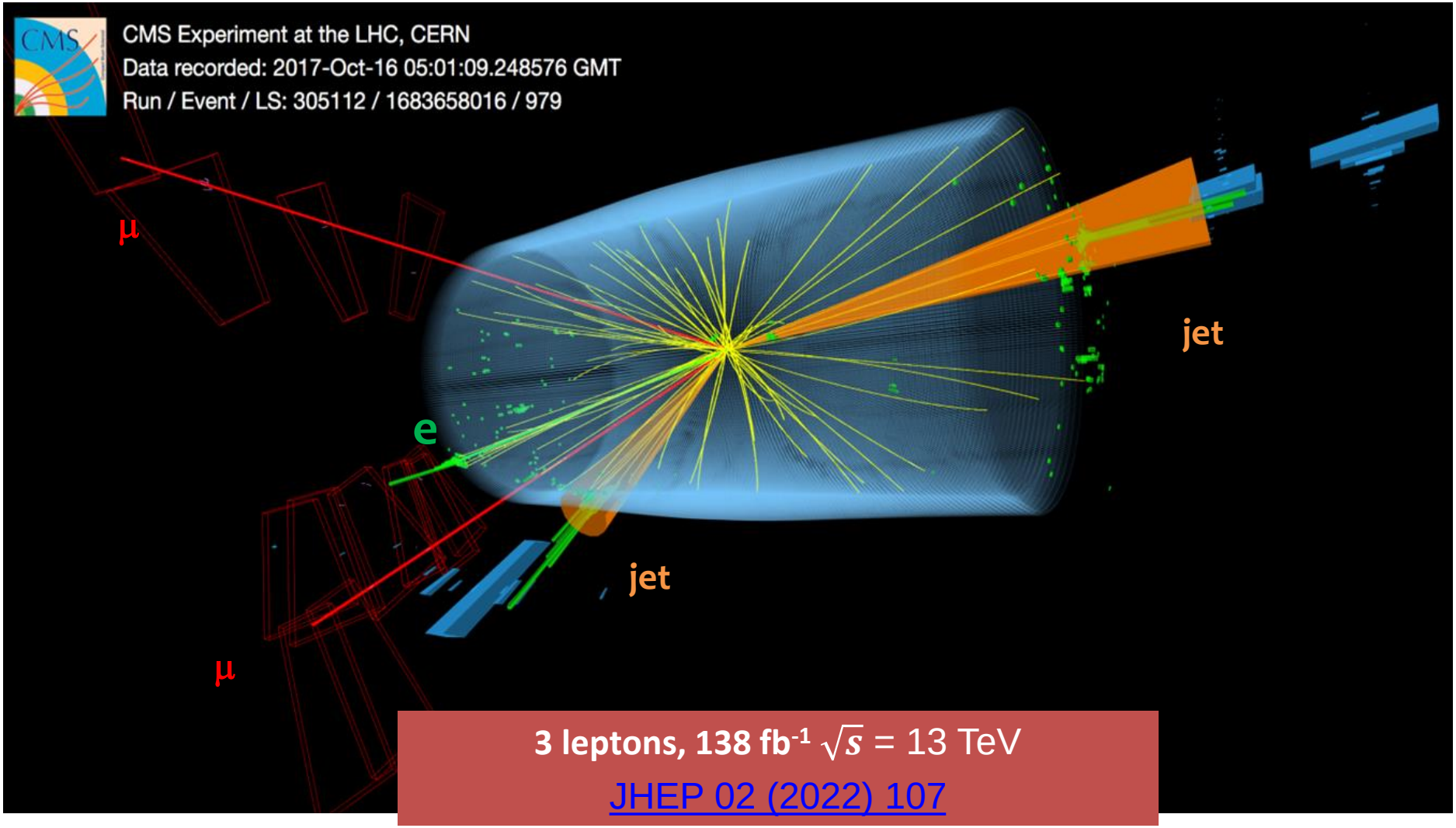


- Novel and theoretically precise probe of the nuclear gluon density at high virtualities
- Considering different event categories with 0, 1, ≥ 2 b-tagged jets
- $t\bar{t}$ cross section extracted from comb. unbinned max. likelihood fit of $m$jj' (W→ jj')

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

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

tZq candidate



3 leptons, 138 fb^{-1} $\sqrt{s}$ = 13 TeV

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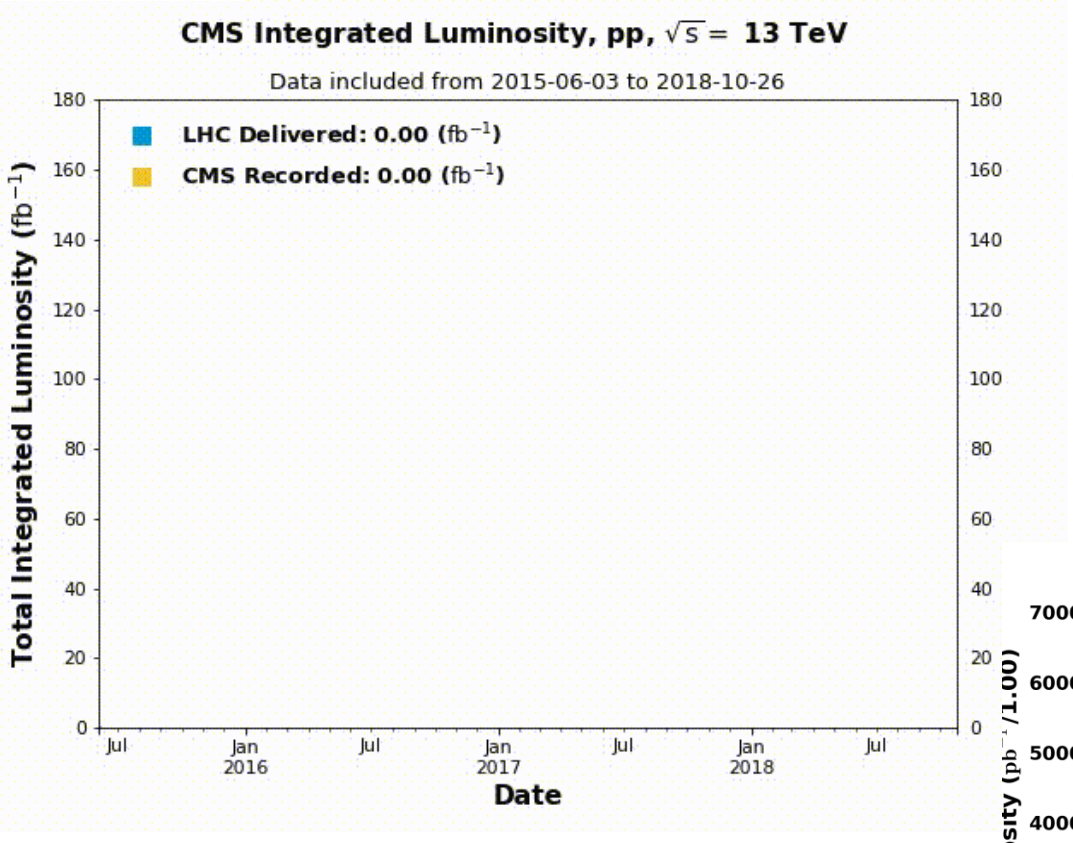
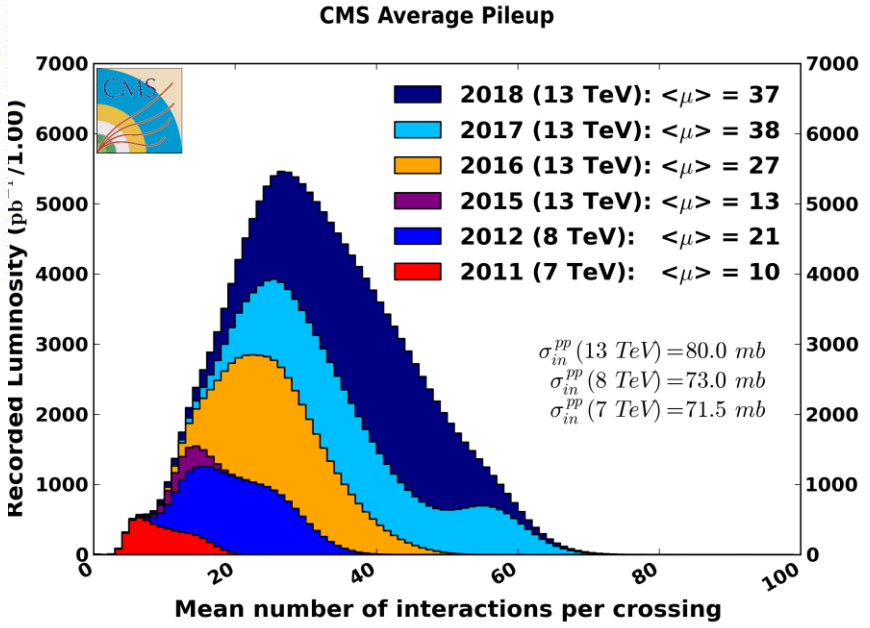
LHC: the perfect machine?



LHC is a "Top Factory" covering O(10^6) range in top production xsec:

- Allows precise xsec & property measurements, searches for rare processes



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