CMS Top Physics Highlights

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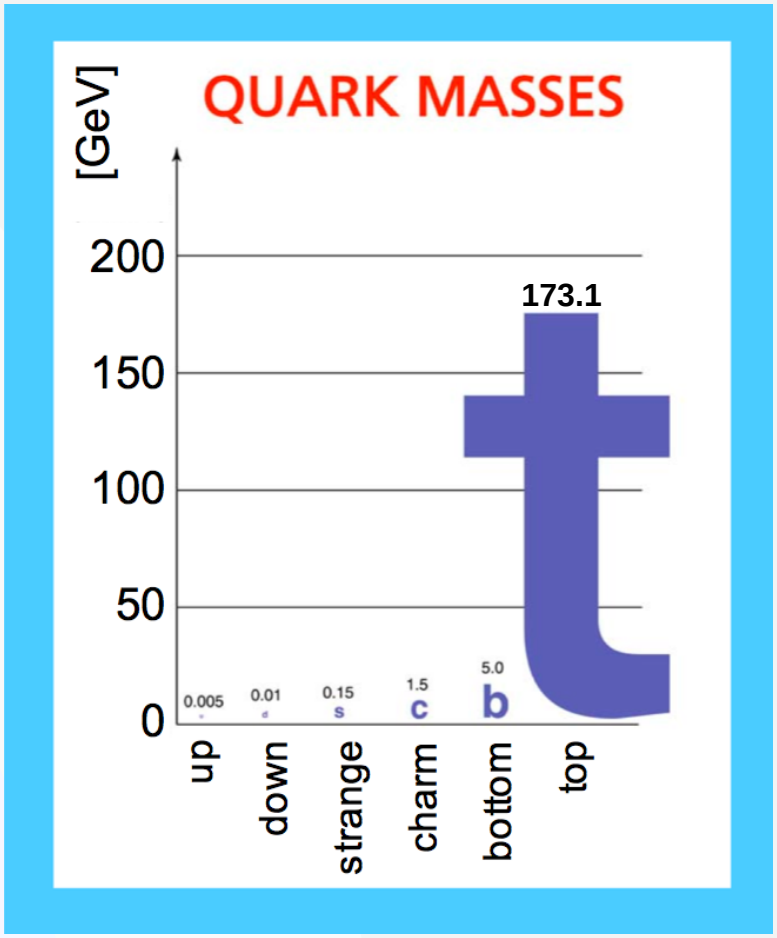
on behalf of the CMS Collaboration

8th International Conference on New Frontiers in Physics (ICNFP 2019), 28/08/2019

Top quark is unique

- Heaviest known elementary particle
  - → ½ spin, +⅔ e, color charge
  - → large coupling to Higgs boson
  - → may play special role in electroweak symmetry breaking: $y_t = \sqrt{2} m_t / \upsilon \simeq 1$
- Decays before forming hadrons
  - → unique opportunity to study properties of bare quark
- Deviations of top quark properties from SM predictions may reveal new physics

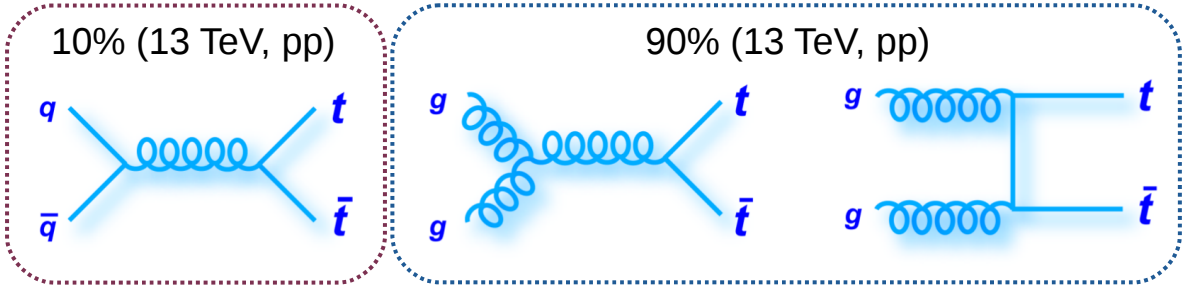


5 orders of magnitude among quark masses

Top quark production and decay

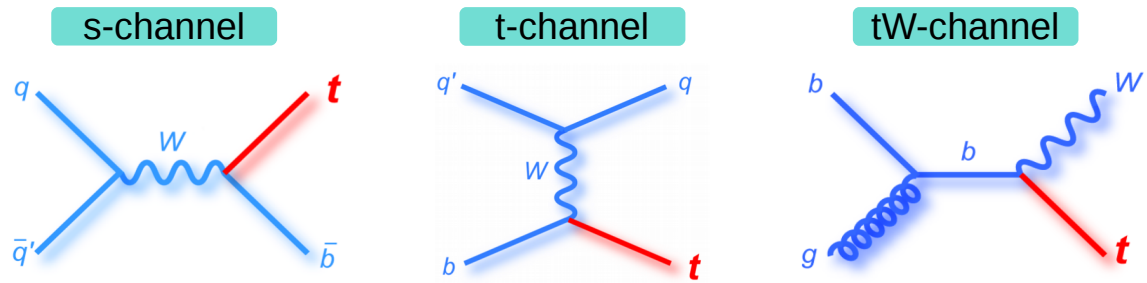
Top quark pair ($t\bar{t}$) production

- dominant production mode
- via strong interaction



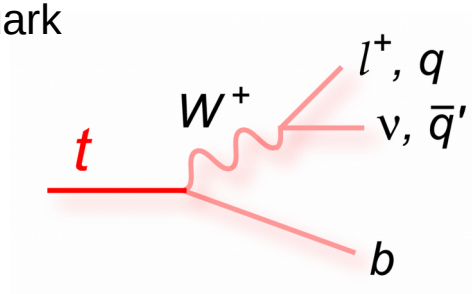
Single top quark production

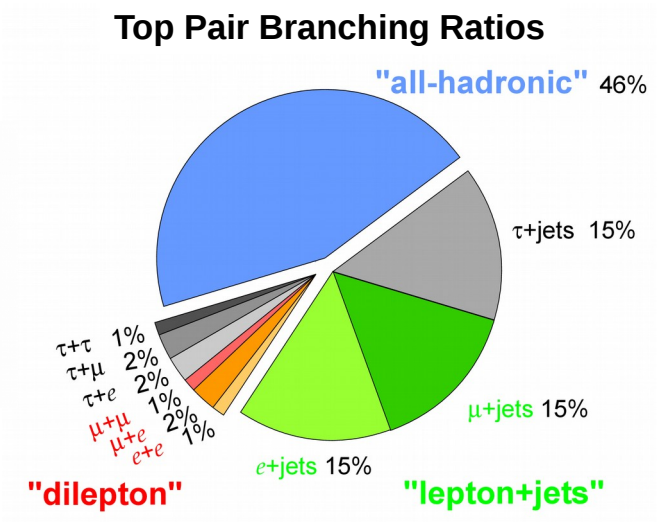
- via weak interaction
- at LO, production in 3 channels



Decay and channels

- in most cases to W boson and b quark
  → via weak interaction
- final state topology governed by decay mode of W boson
  → $t\bar{t}$ decay channels:
  all-hadronic, **lepton+jets**, **dilepton**





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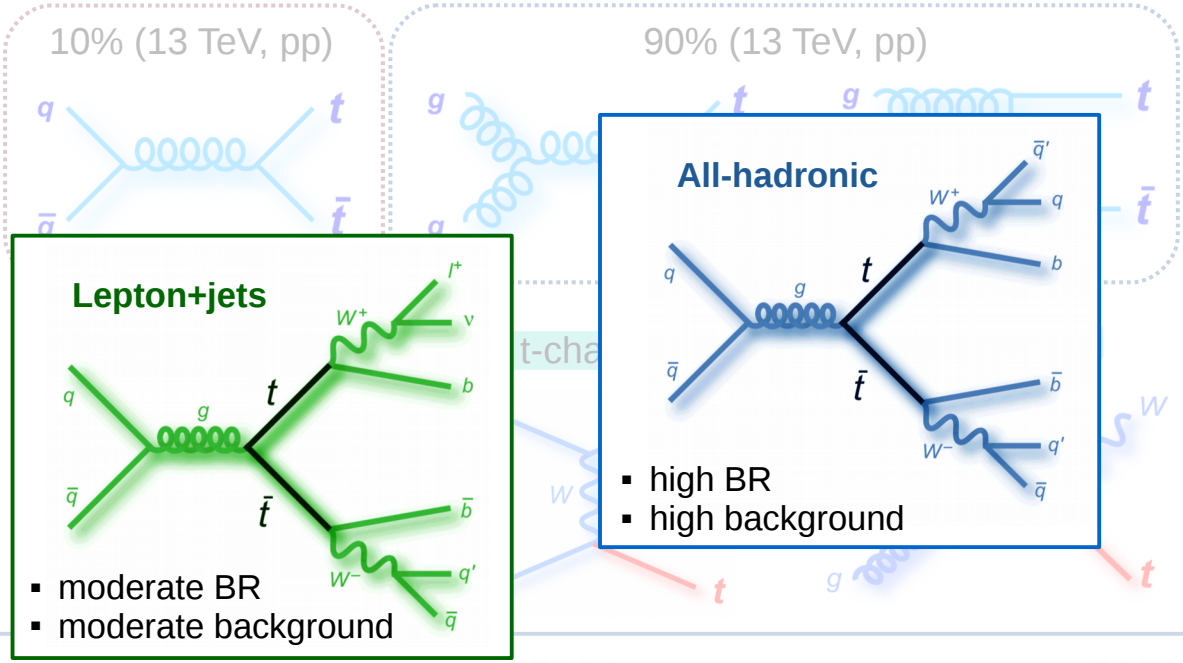
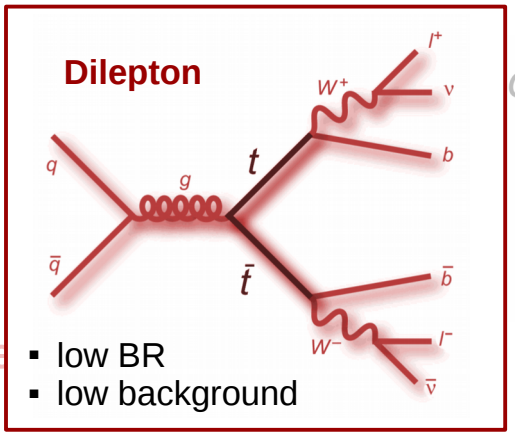
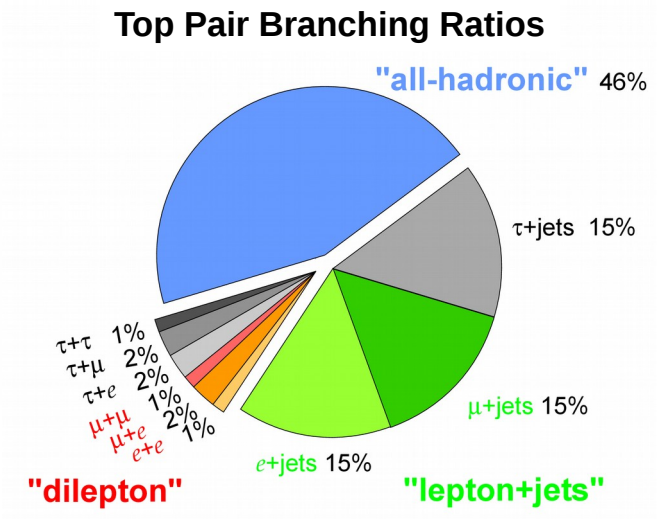


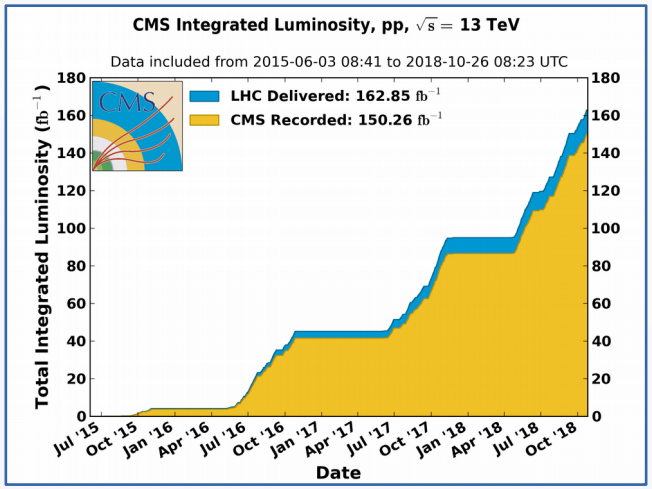
Decay and channels

- in most cases to W boson and
  → via weak interaction
- final state topology governed by decay mode of W boson
  → $t\bar{t}$ decay channels:
  all-hadronic, lepton+jets, dile





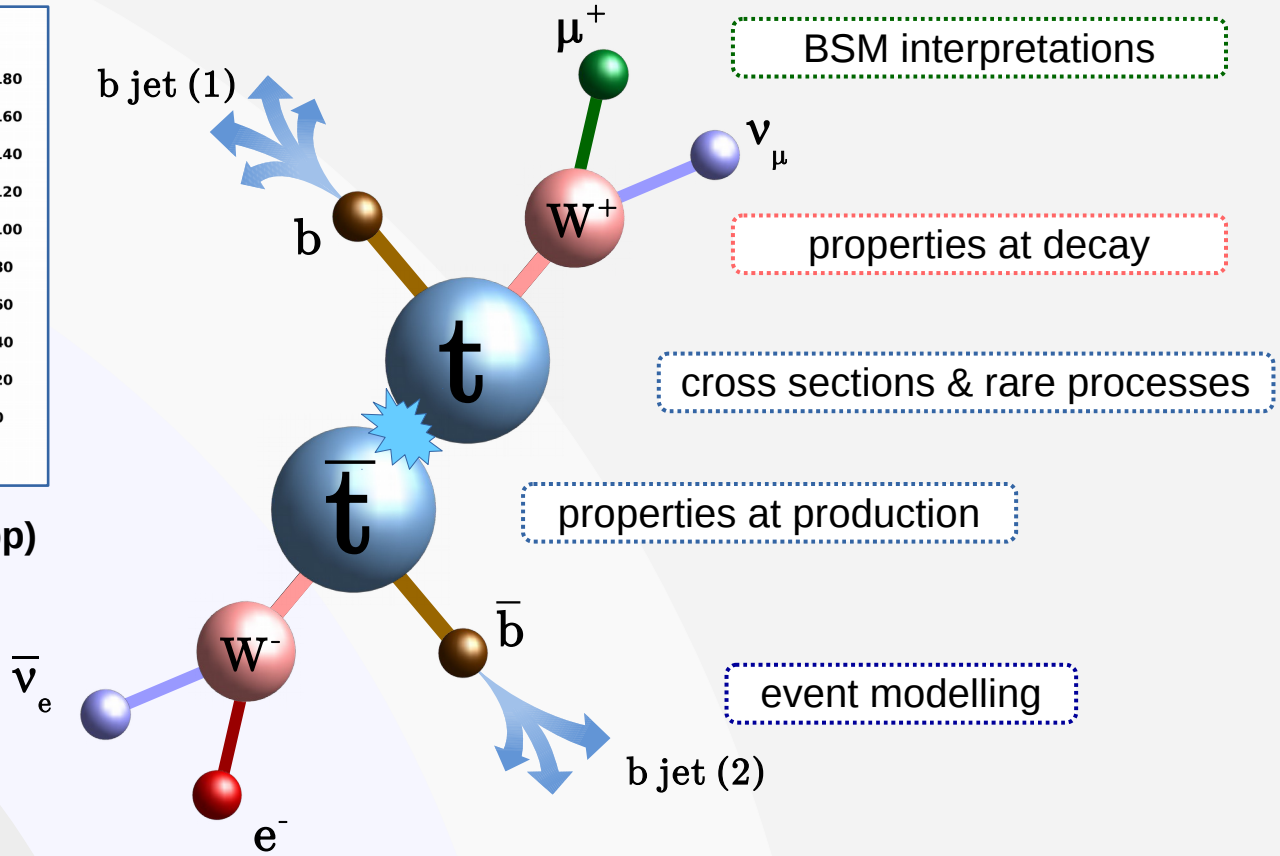
Top quark physics at CMS



Full Run2 data @ 13 TeV LHC (pp)

- **125M** top quark pairs
- **45M** single top quarks

→ ultimate precision at Run2



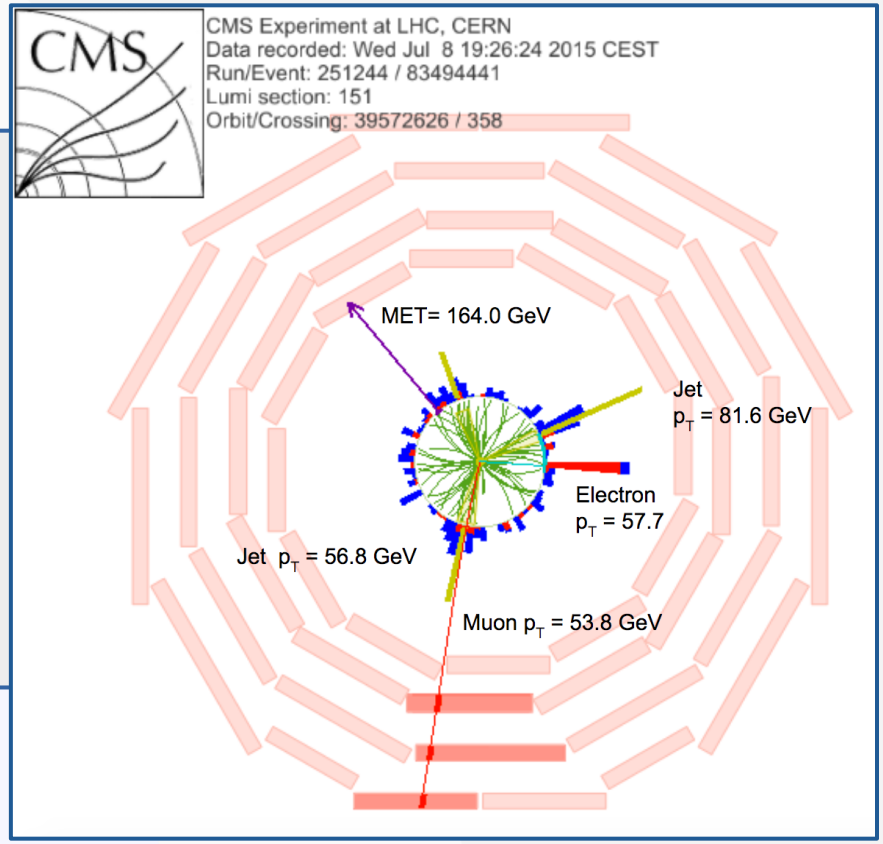
This talk:

- selection of recent CMS results from Run2
- all presented results based on ~36 fb^{-1} of 13 TeV data, unless the opposite stated

Top quark pair production

Rate and dynamics of $t\bar{t}$ production are key to studies in top quark sector

- precision tests of SM predictions
- new physics may couple to $t\bar{t}$, e.g. SUSY, Z', dark matter
- background for Higgs boson processes, rare processes, and beyond-SM searches

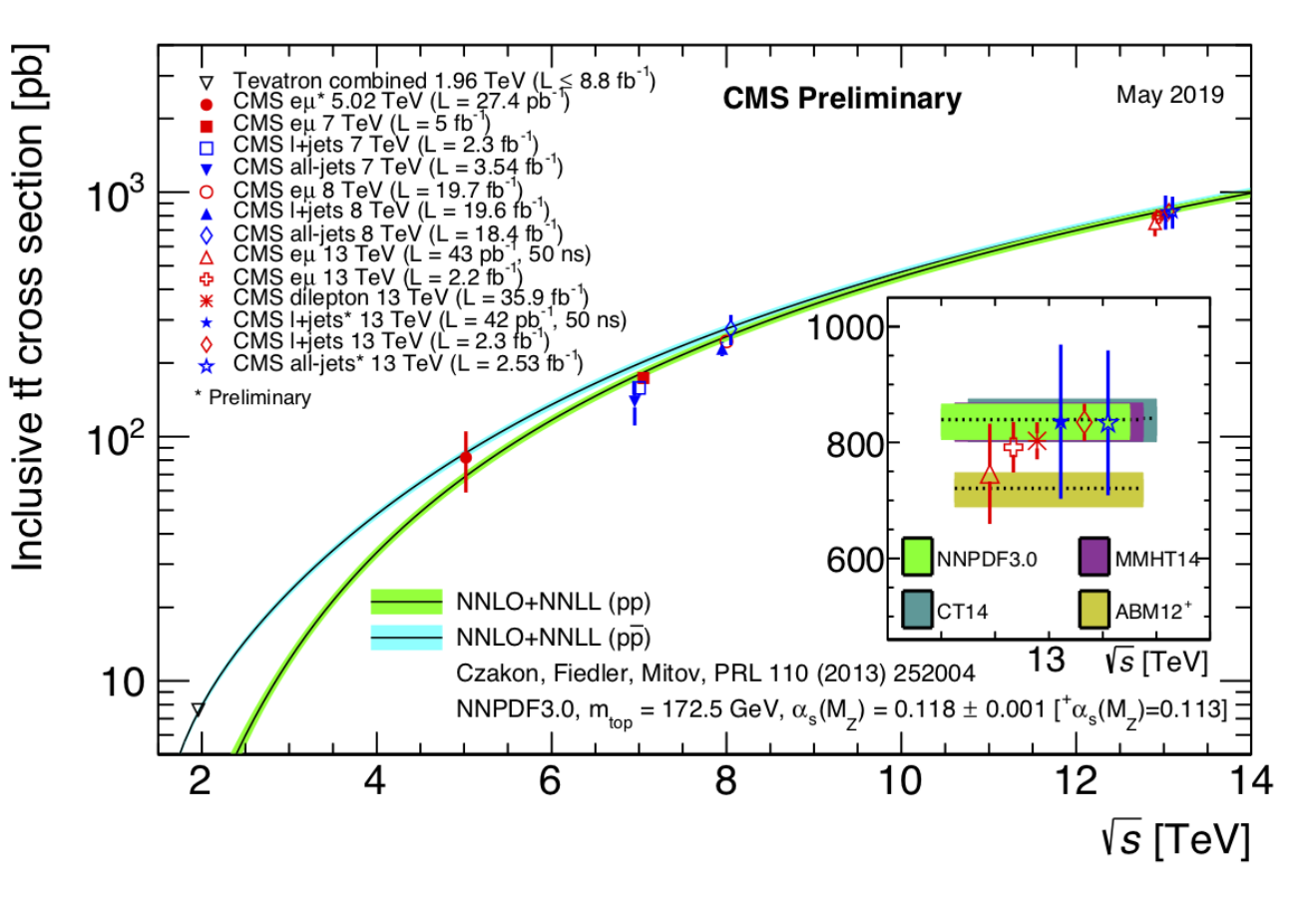


Dilepton event candidate

Inclusive $t\bar{t}$ cross section at CMS: overview

Measurements at different energies and in all $t\bar{t}$ decay channels

- Good agreement with NNLO+NNLL calculations
- Most precise results in dilepton and lepton+jets channel (about 4%)



Inclusive $t\bar{t}$ cross section

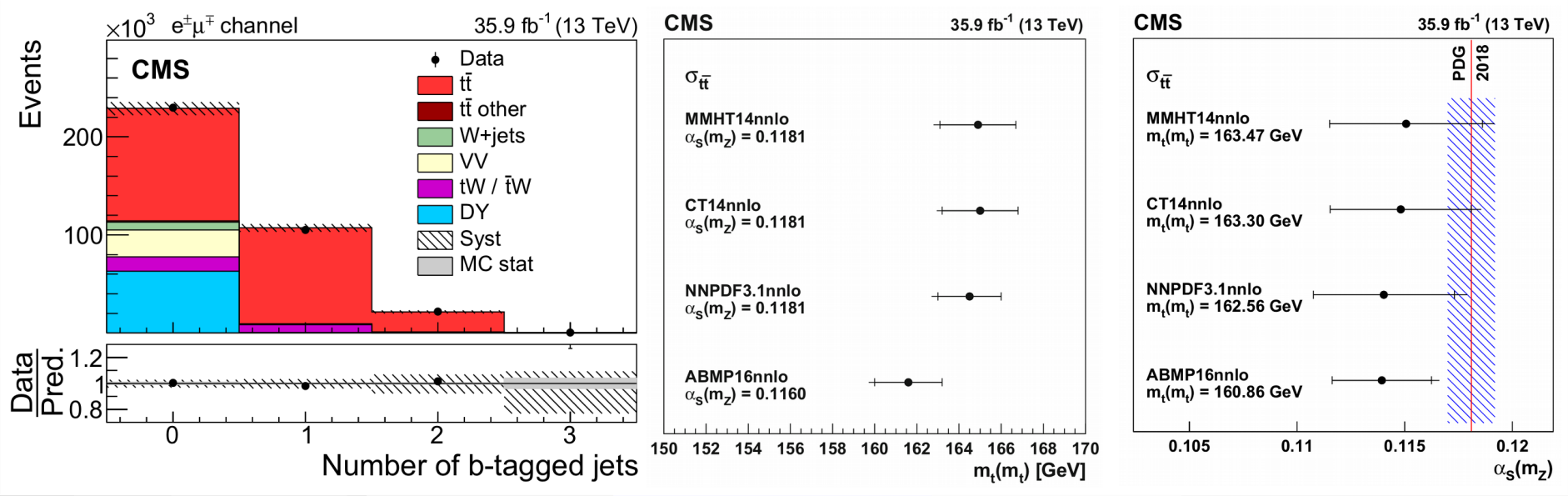
- **Measurement of $\sigma_{t\bar{t}}$ from a likelihood fit with a high precision**

EPJC 79 (2019) 368

- Dilepton events in **eμ, ee, μμ** categories classified according to number of jets and b-tags
- Standalone measurement of $\sigma_{t\bar{t}}$ for m_t^{MC} = 172.5 GeV
  - **$\sigma_{t\bar{t}}$ = 803 ± 2 (stat) ± 25 (syst) ± 20 (lumi) pb (4%)**
  - good agreement with predictions

NNLO + NNLL prediction (JHEP 2013 (2013) 80):
$\sigma_{t\bar{t}} = 832\,^{+20}_{-29}$ (scale) ± 35 (PDF+α_S) pb

- Also did simultaneous measurement of $\sigma_{t\bar{t}}$ and m_t^{MC}
  - resulting $\sigma_{t\bar{t}}$ used, together with a theoretical prediction at NNLO accuracy, to determine the $m_t(m_t)$, m_t^{pole} and to extract a value of α_S with different sets of PDFs (more info on top mass later)



Inclusive $t\bar{t}$ cross section

- **Testing lepton universality using $t\bar{t}$ decays to lepton+tau final states**

new

CMS-PAS-TOP-18-005

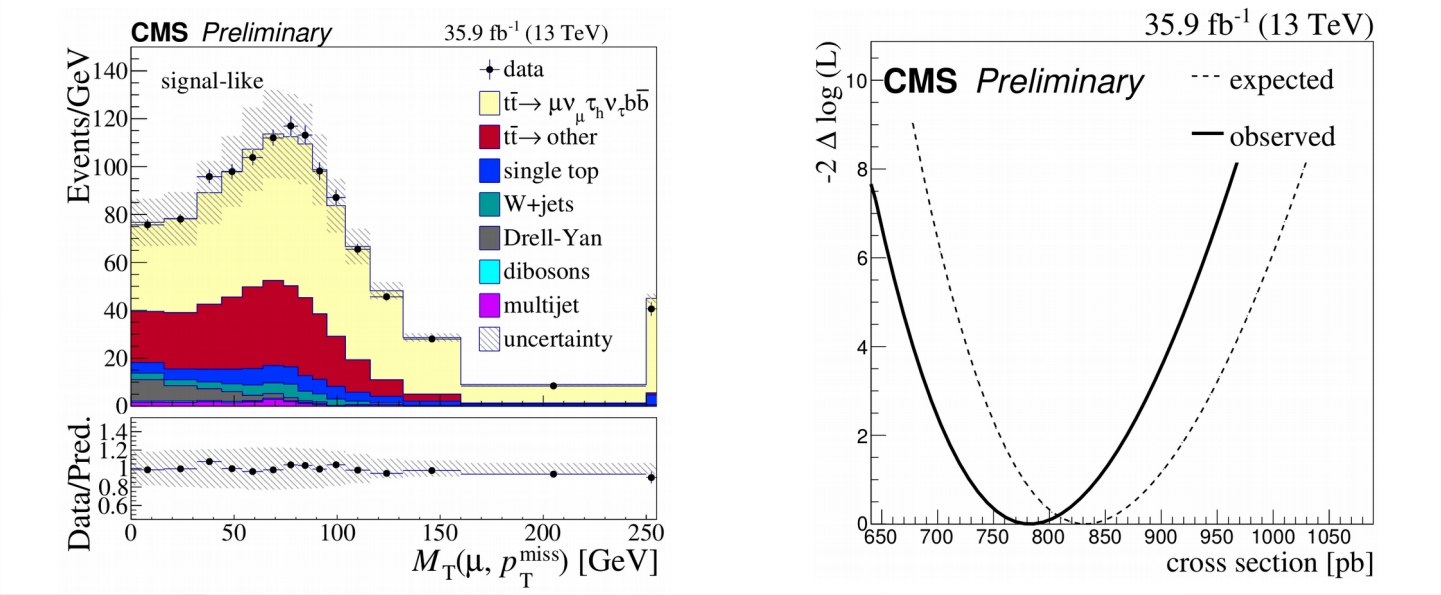
- Measurement of $\sigma_{t\bar{t}}$ for the process: $t\bar{t} \to (\ell\nu_\ell)(\tau_h\nu_\tau)b\bar{b}$, $\ell = e,\mu$
  - a likelihood fit of the transverse mass $M_T(\ell, p_T^{miss})$ in signal-like and background-like categories

$$\sigma_{t\bar{t}}(\ell\tau_h) = 781 \pm 7\ (\text{stat}) \pm 62\ (\text{syst}) \pm 20\ (\text{lumi})\ \text{pb}\ (8\%)$$

- Ratio to the dilepton cross section (see previous slide) consistent with lepton universality

$$R(\ell\tau_h / \ell\ell) = 0.973 \pm 0.009\ (\text{stat}) \pm 0.066\ (\text{syst})$$

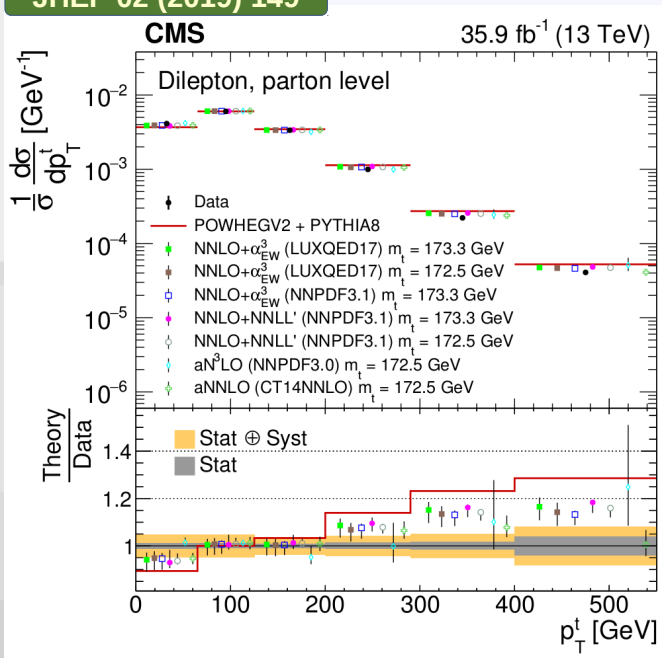
- Ratio of the partial to the total width: $\Gamma(t \to \tau\nu_\tau b) / \Gamma_{total} = 0.1050 \pm 0.0009\ (\text{stat}) \pm 0.0071\ (\text{syst})$



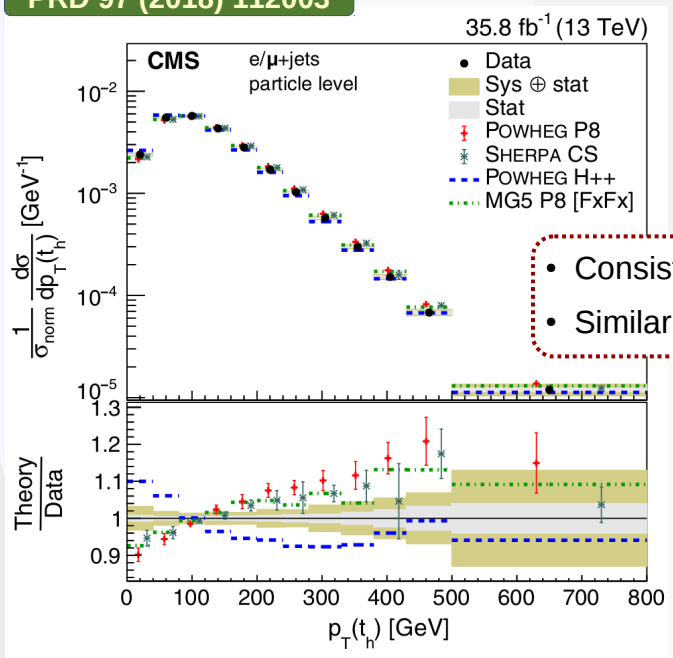
Differential $t\bar{t}$ cross sections

- **Study of $\sigma_{t\bar{t}}$ as a function of many observables in different $t\bar{t}$ decay channels**
  - → deeper probe of $t\bar{t}$ process in various corners of phase space
  - → sensitivity to subtle hints of new physics
- Dedicated event selection and reconstruction of top quark candidates in each channel
- <u>Unfolding</u> back to **parton** and **particle** levels to correct for detector effects and acceptance
- Good agreement with SM, but none MC predictions describe <u>all</u> distributions
  - → parton-level spectra better described by fixed-order calculations of NNLO accuracy

JHEP 02 (2019) 149



PRD 97 (2018) 112003



Spectra for top quark p_T

Left: dilepton (parton)
Right: e/μ+jets (particle)

- Consistent results among channels
- Similar trends at parton and particle levels

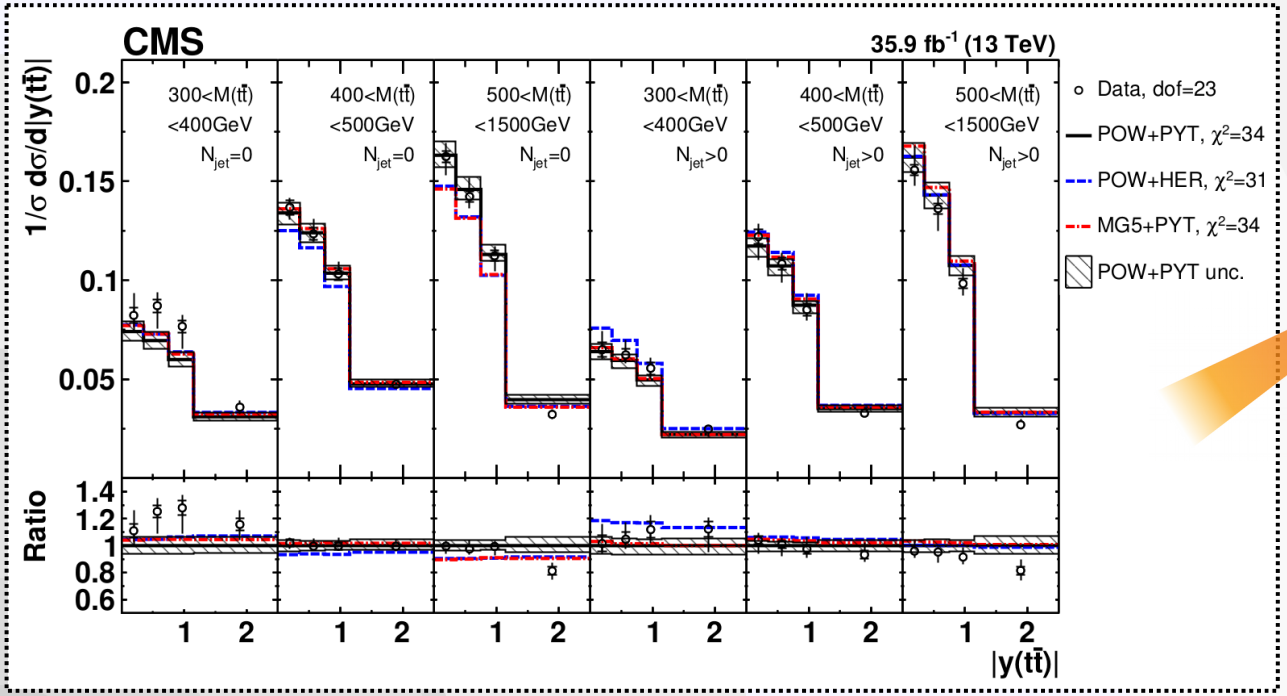
Only small glimpse of results
e.g. **JHEP 02 (2019) 149** presents about **100** differential spectra

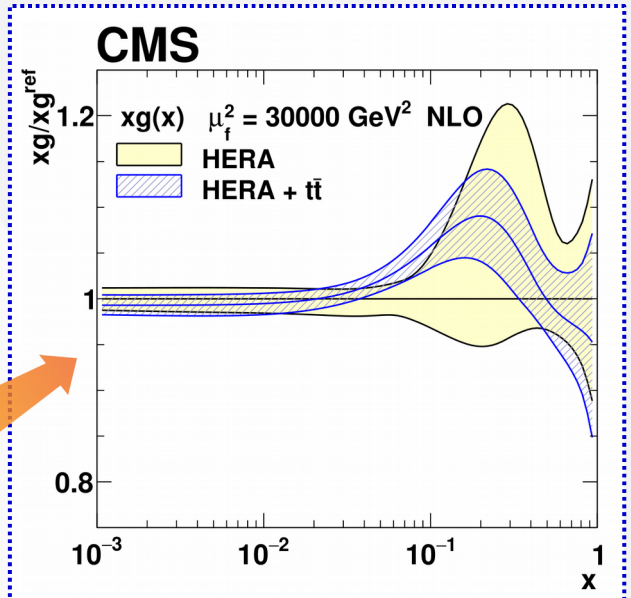
Multi-differential $t\bar{t}$ cross sections in dilepton channel

- **Measurement of $t\bar{t}$ 2D and 3D differential cross as a function of top quark and $t\bar{t}$ kinematics, and number of extra jets**
  → unfolding in several dimensions allows detailed study of various corners of phase space

arXiv:1904.05237
- submitted to EPJC -

- $t\bar{t}$ triple-differential cross sections provide novel sensitivity to the gluon PDF
- Cross sections as a function of **|y(tt)|** -vs- **M(tt)** -vs- **N_{jets}** used to perform world's first simultaneous fit of the **gluon PDF**, strong coupling **α_s** and top quark pole mass **m_t^{pole}** (will be discussed later)





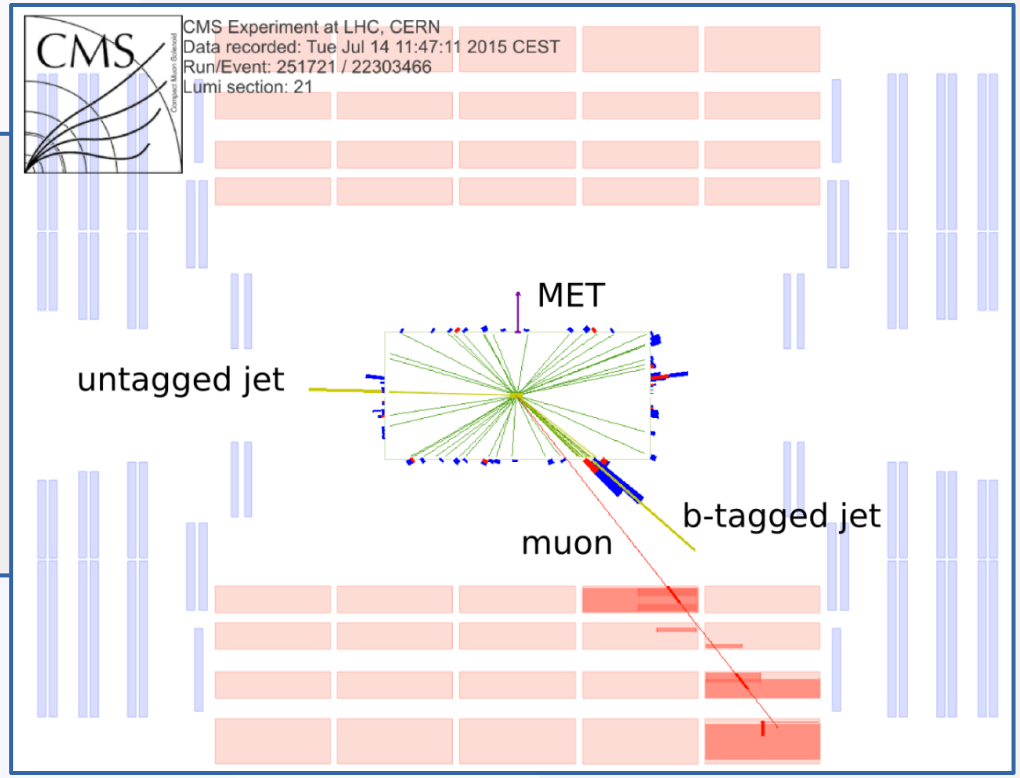
$$\alpha_s(M_Z) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$$

$$m_t^{pole} = 170.5 \pm 0.8(\text{total})\ \text{GeV}$$

Single top quark production

Deep insight into EWK processes

- direct measurement of $|V_{tb}|$
- sensitivity to proton structure
- search for anomalous top quark couplings (e.g. in FCNC interactions)

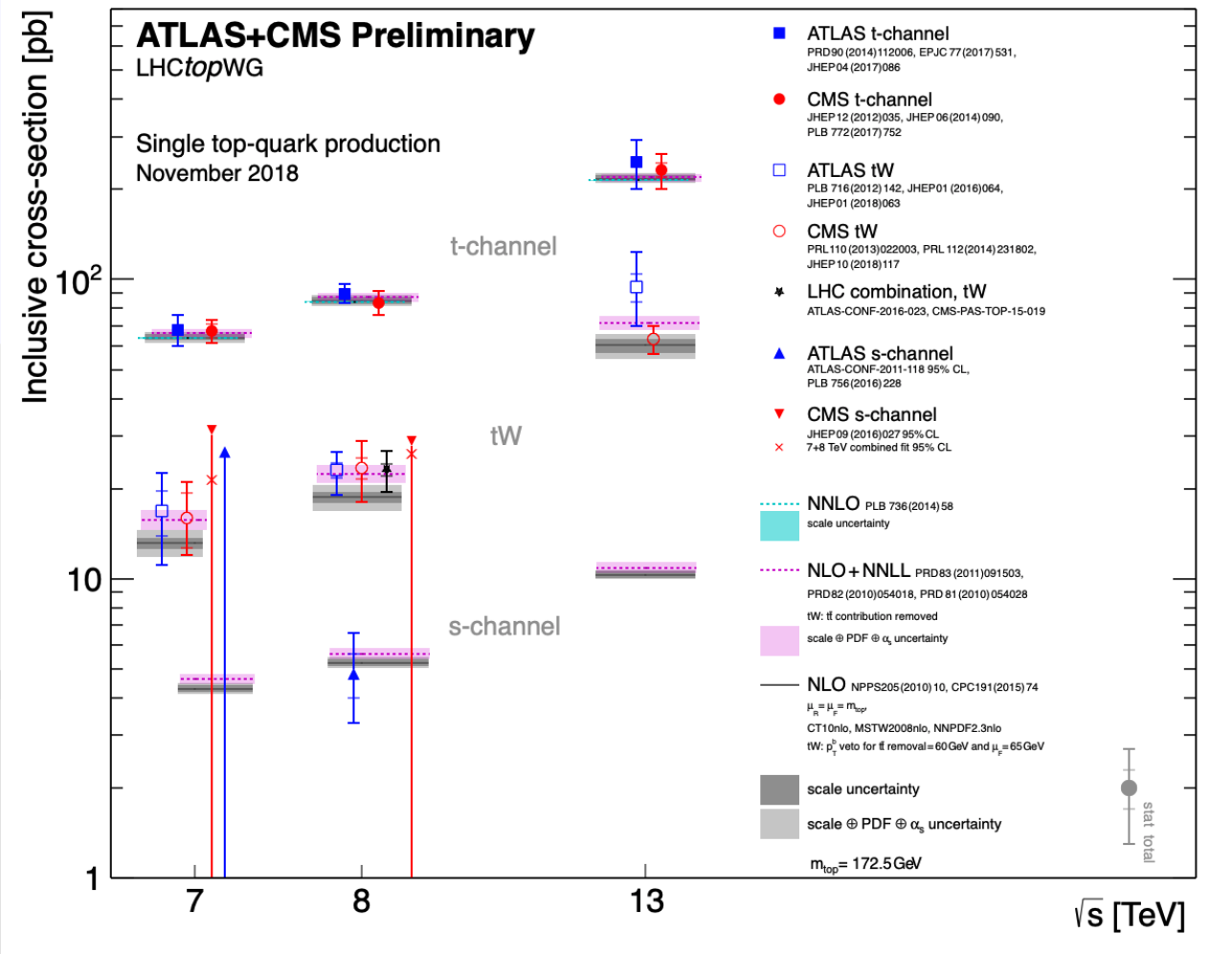


t-channel event candidate

Inclusive single top cross sections: overview

Comprehensive study of dominant modes for single top quark production

- Good agreement between experiments and with SM predictions at all energies

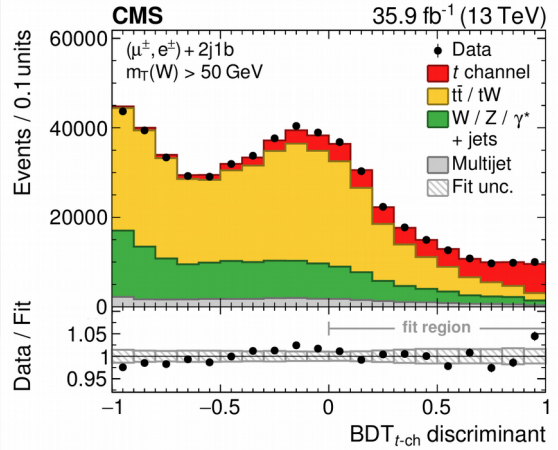


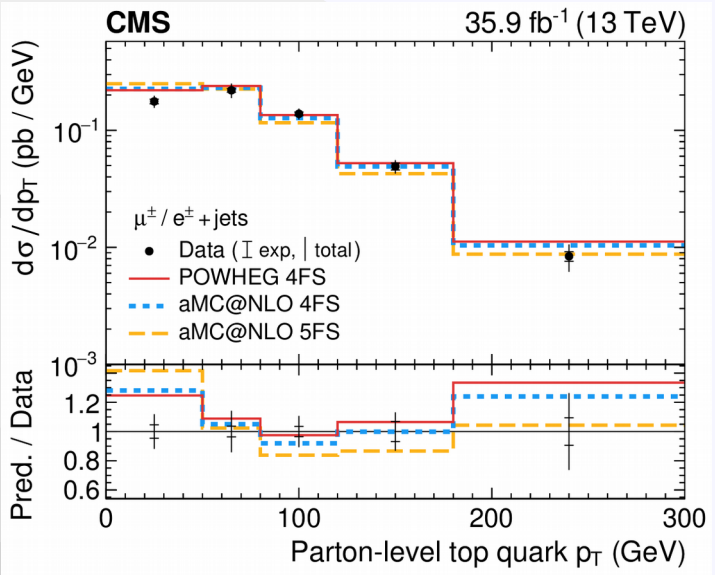
Differential single top t-channel cross sections

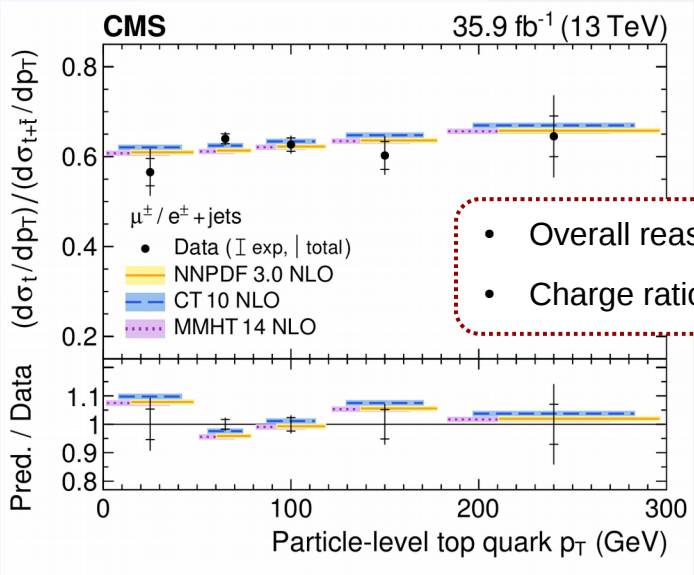
- **Measurement of cross sections as a function of kinematic obervables of top quarks, charged leptons and W boson from top quark decay**

arXiv:1907.08330
- submitted to EPJC -

- **Events with 1 isolated e or μ, and 2 or 3 jets:**
  → top quarks reconstructed from decay products
- **Strategy:**
  → discrimination of signal and background via BDT
  → uncertainties profiled in a likelihood fit
  → unfolding of extracted yields to parton and particle levels
- Differential charge ratios computed as $\sigma_{t\text{-ch},t}/\sigma_{t\text{-ch},t+\bar{t}}$





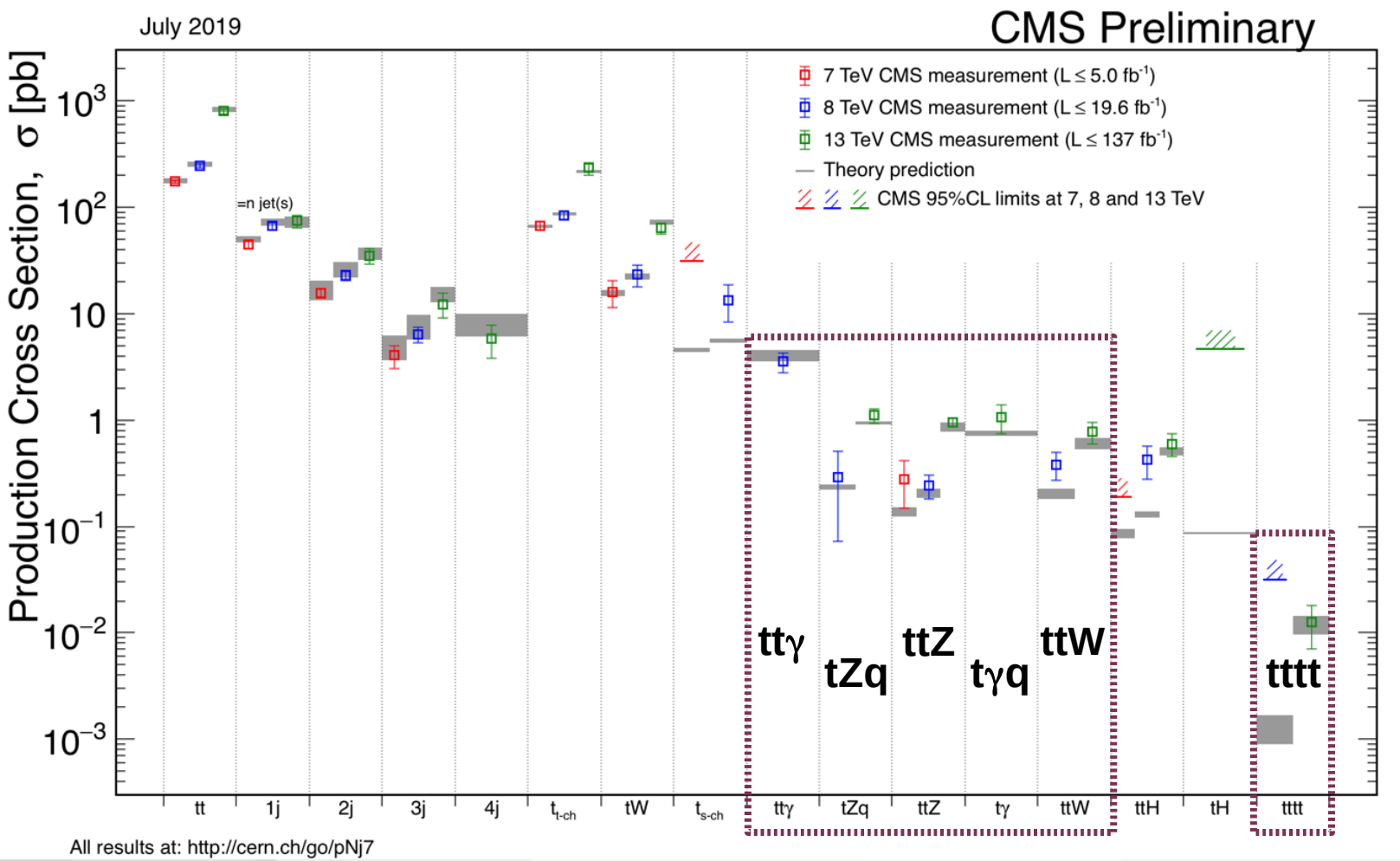


- Overall reasonable agreement with SM
- Charge ratios agree with all PDF sets

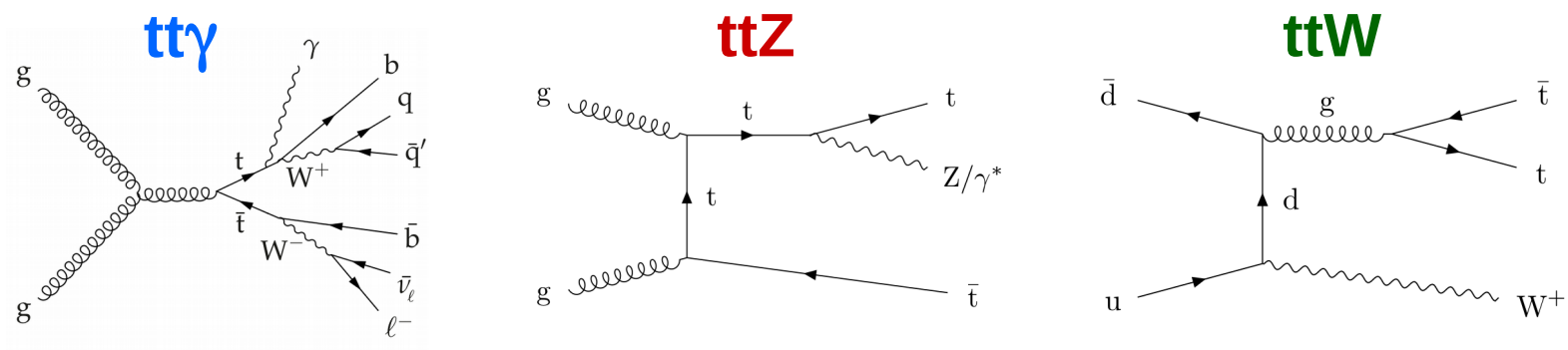
Rare modes of $t\bar{t}$+X and t+X production

$t\bar{t}$+X and t+X production at CMS: overview

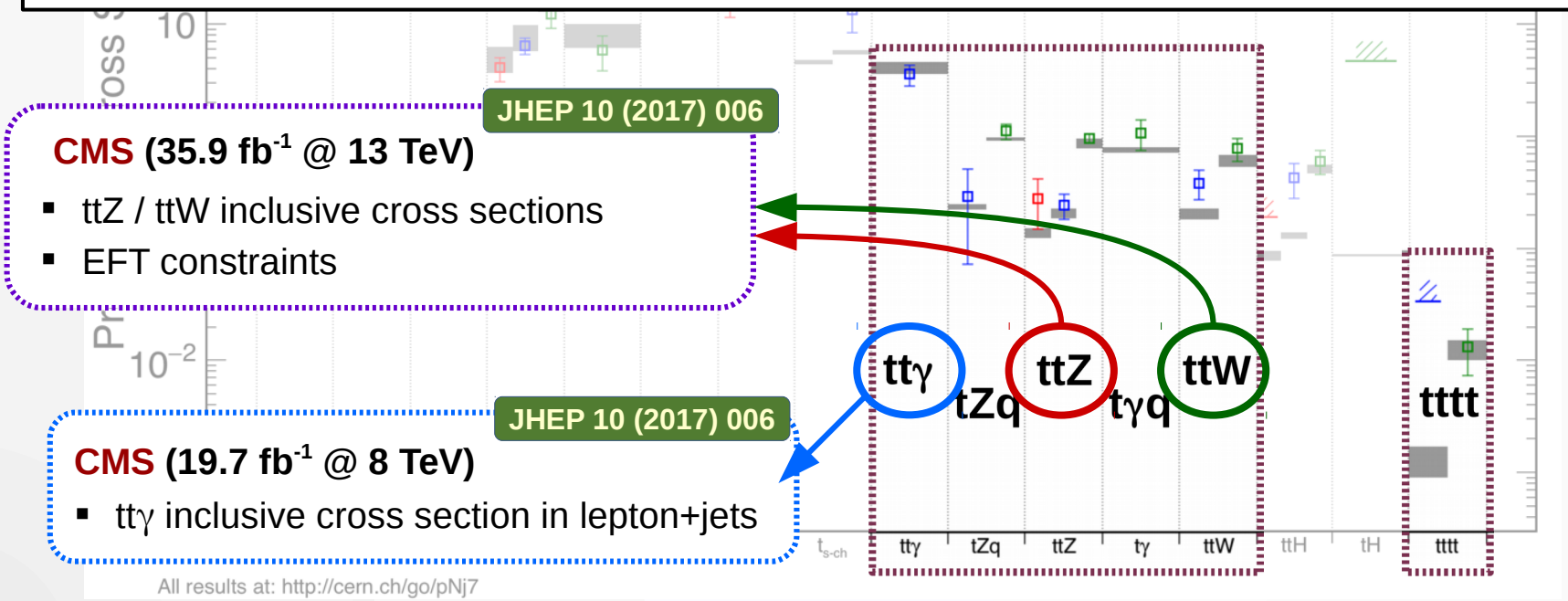
- **Rare processes with production cross sections typically smaller than 1 pb**
- Analyses require various machine learning tecnhiques to gain signal sensitivity
- New possibilities for studies of rare processes owing to full Run2 dataset (~140 fb^{-1})



$t\bar{t}$+V production



- Enhancements in BSM models → great potential for EFT studies
- ttZ/ttW processes serve as important backgrounds for many analyses, e.g. ttH, tttt, tt+DM



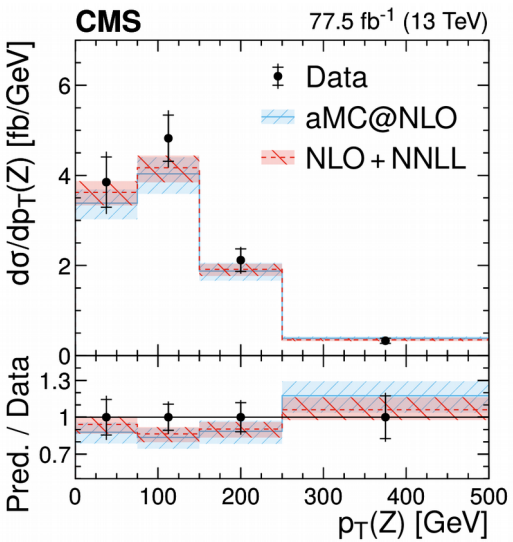
Recent $t\bar{t}Z$ cross sections (77.5 fb^{-1})

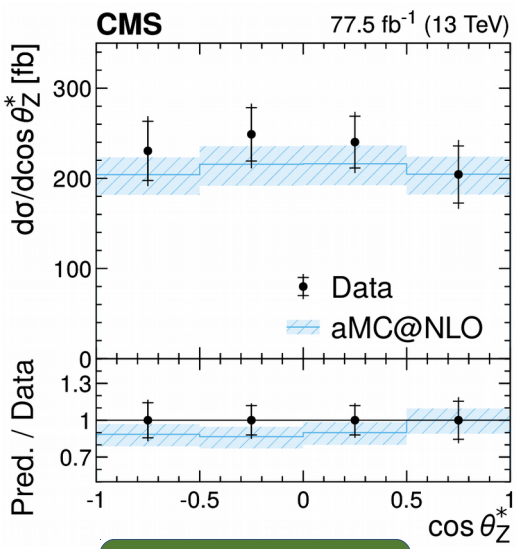
- Studying events with 3 or 4 leptons
  → further categorisation w.r.t. N_{jets} and $N_{b\text{-}tags}$
- Z boson detected via its decay to lepton pair
- Most precise σ(ttZ) to date

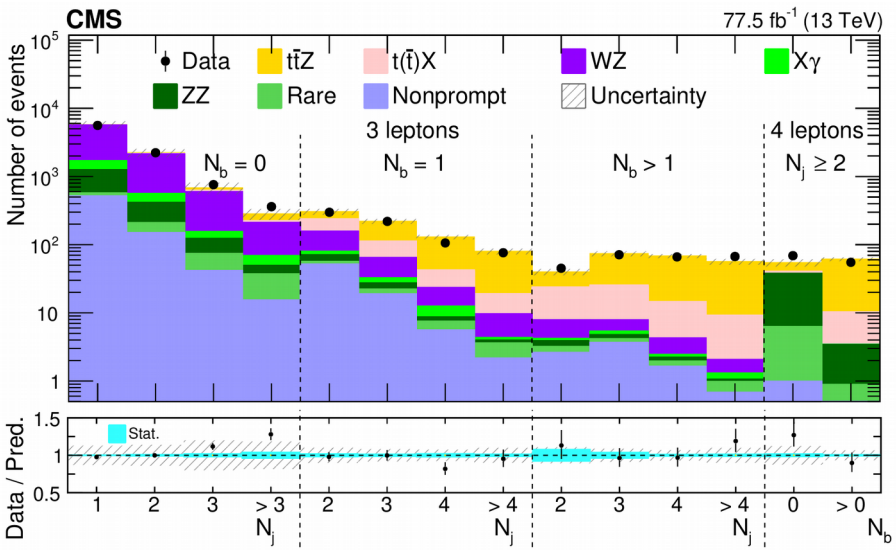
$\sigma(pp \to ttZ)$ = 0.95 ± 0.05 (stat) ± 0.06 (syst) pb

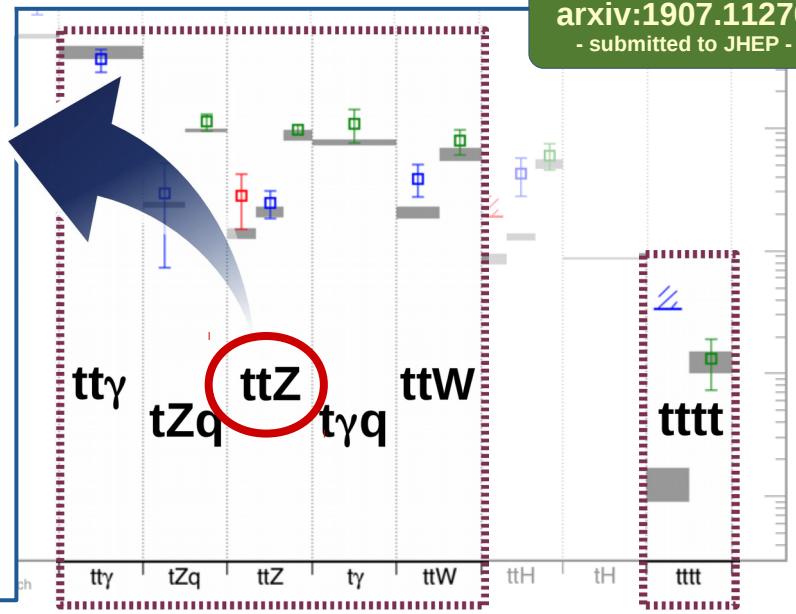
SM NLO prediction: 0.84 ± 0.10 pb

- First differential measurements as function of $p_T(Z)$ and angular distribution of $\ell(-)$ from Z









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

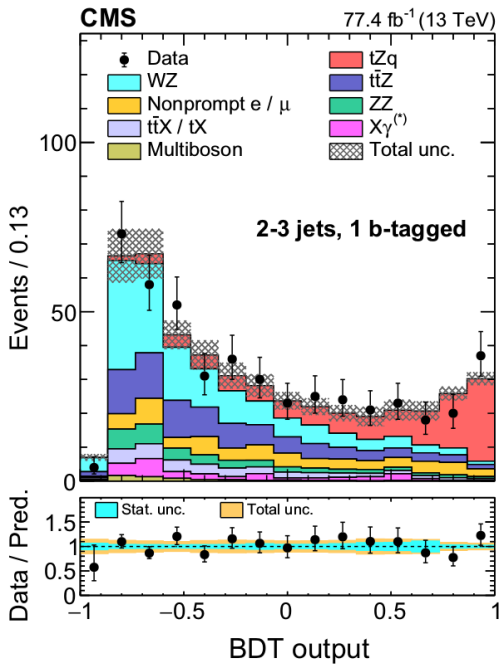
Observation of tZq production (77.4 fb^{-1})

PRL 122 (2019) 132003

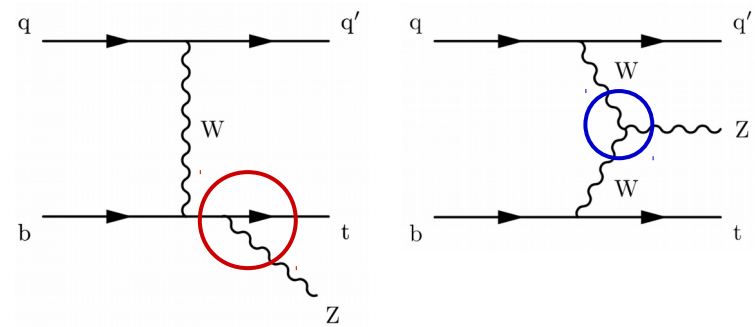
- Studying events with 3 leptons (e or μ) and at least 2 jets
  - → 3 signal regions w.r.t. N_{jets} and $N_{b\text{-tags}}$
  - → dedicated BDT in each region
- tZq signal strength measured from a fit to BDT outputs, and event yields in control regions
- Observation of tZq with > 5σ significance

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

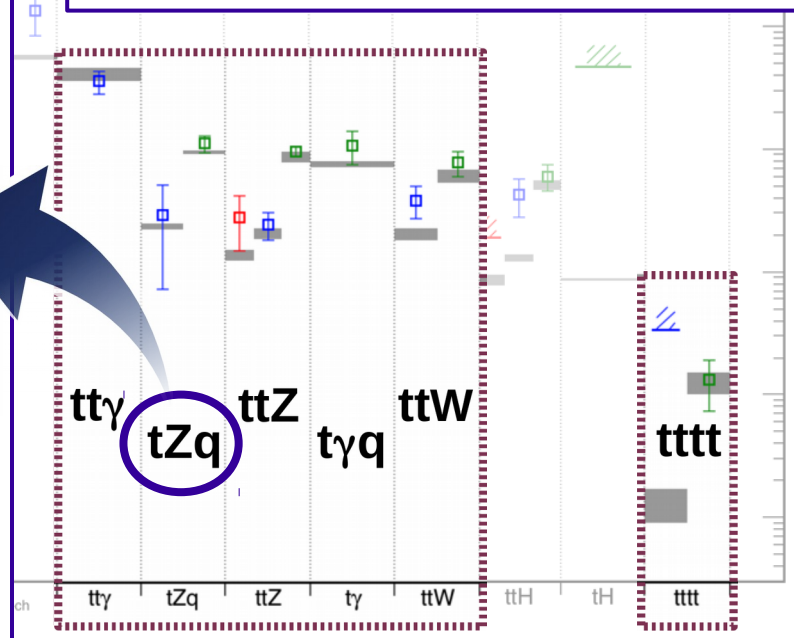
Agrees with SM NLO prediction: 94.2 ± 3.1 fb



sections typically smaller than 1 pb



- Direct sensitivity to **tZ** and **WWZ** couplings
- Enhancement in BSM models



First evidence of tγq process

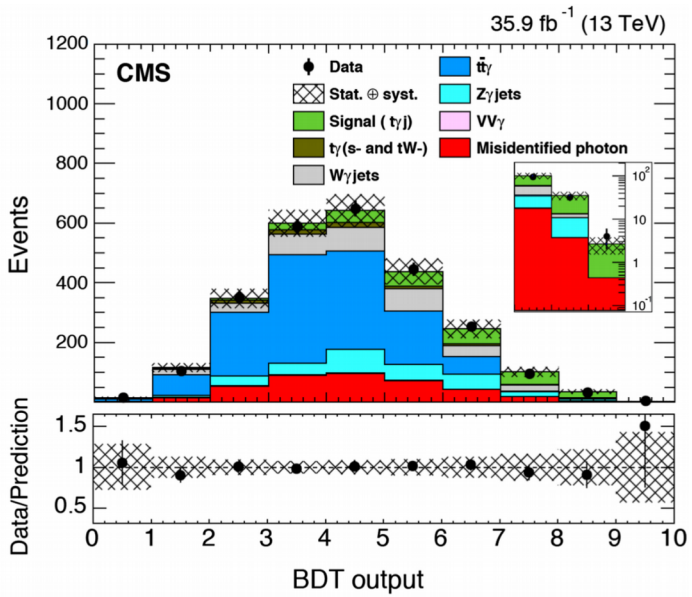
PRL 121 (2018) 221802

- Studying events with a muon, a photon, MET, and at least 2 jets (with exactly 1 b-tag)

  → BDT based on topological and kinematic event properties in signal region
- Simultaneous fit of BDT output in signal region and the ttγ control region
- Evidence of tγq: 4.4σ observed (3.0σ expected)

$\sigma(pp\to t\gamma q)\times BR(t\to\mu\nu b)$ = 115 ± 17 (stat) ± 30 (syst) fb

Agreement with SM NLO prediction: 81 ± 4 fb



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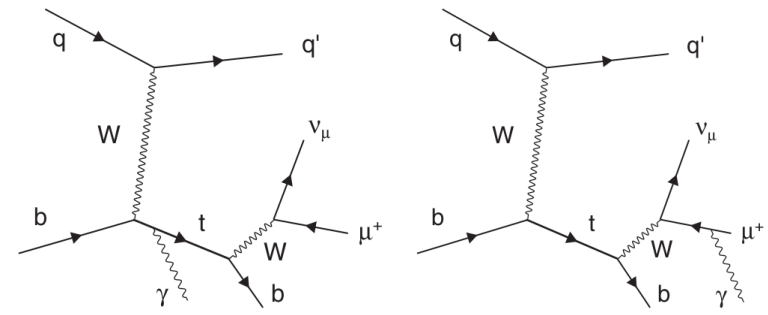
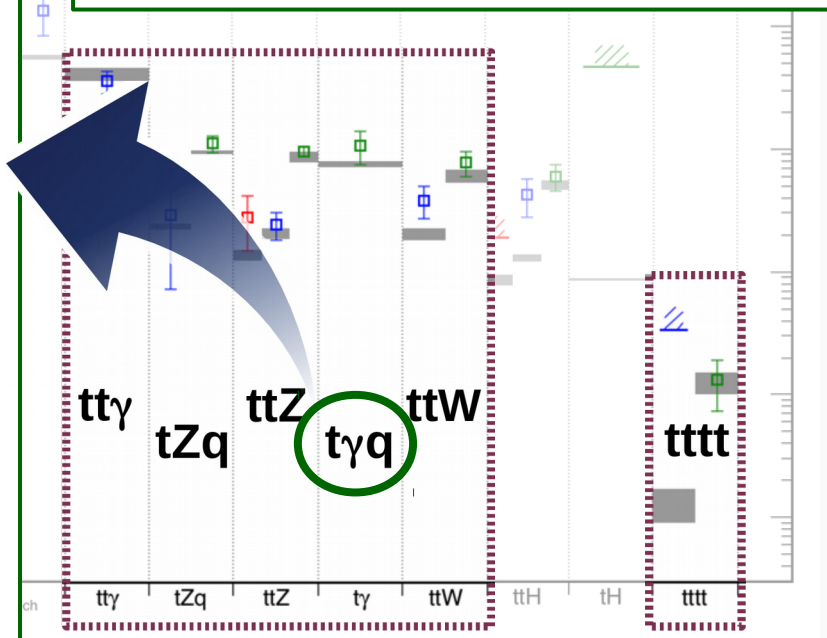
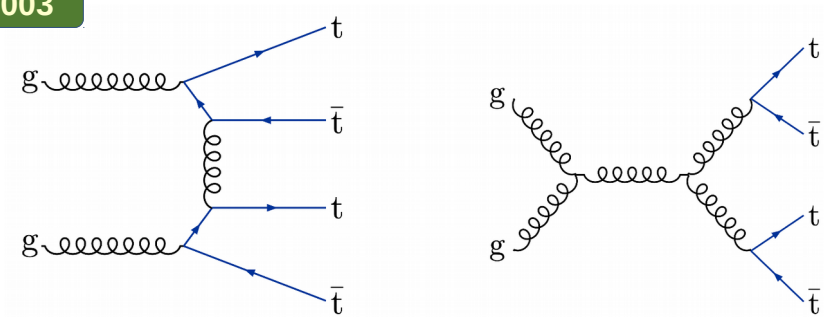


- Sensitivity to top quark charge and its electric and magnetic dipole moments



Search for production of 4 top quarks (137 fb^{-1})

- **Results based on full Run2 data** CMS-PAS-TOP-18-003
- Studying same-sign dileptonic (e or μ) and trileptonic events with several jets
  → BDT analysis: signal regions w.r.t S/B separation
- Measurement of σ(pp→$t\bar{t}t\bar{t}$) fitting event yields in all BDT categories

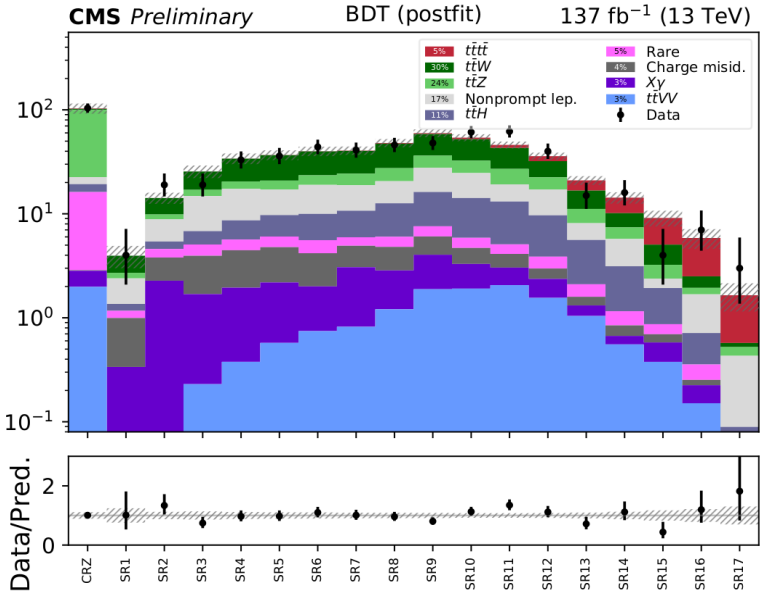


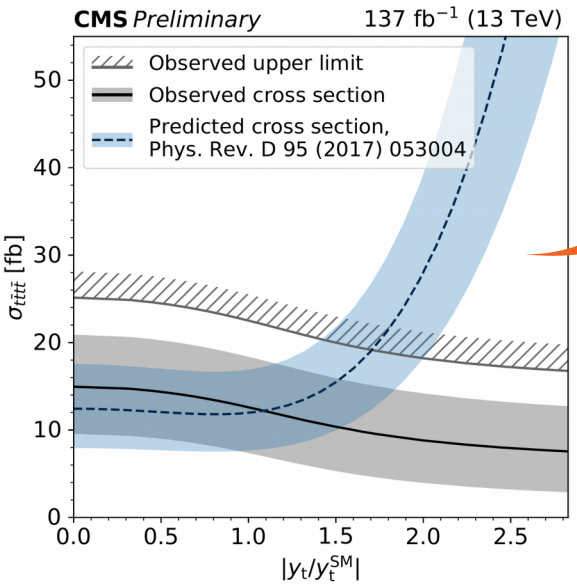
σ(pp→$t\bar{t}t\bar{t}$) = 12.6 $^{+5.8}_{-5.2}$ (total) fb

NLO+EW prediction: 12.0 $^{+2.2}_{-2.5}$ fb

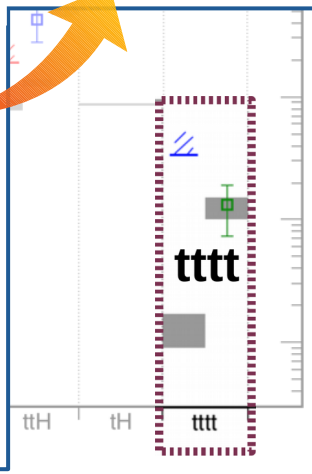
- extremely rare process that can receive significant enhancement in BSM models
- direct probe of top-Higgs Yukawa coupling

- Significance: 2.6σ observed (2.7σ expected)
- Constraints on top quark Yukawa coupling



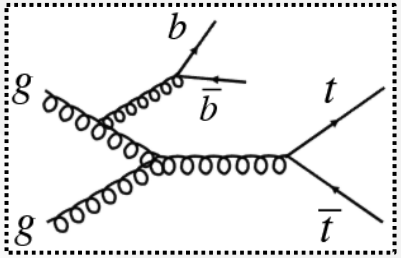


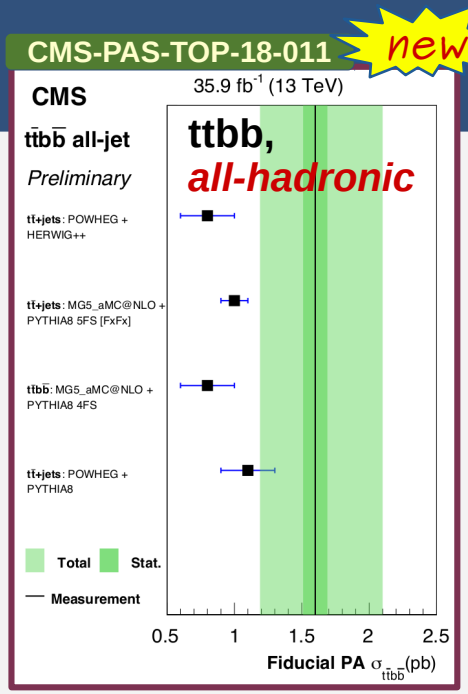
$|y_t/y_t^{SM}| < 1.7$ (95% CL)

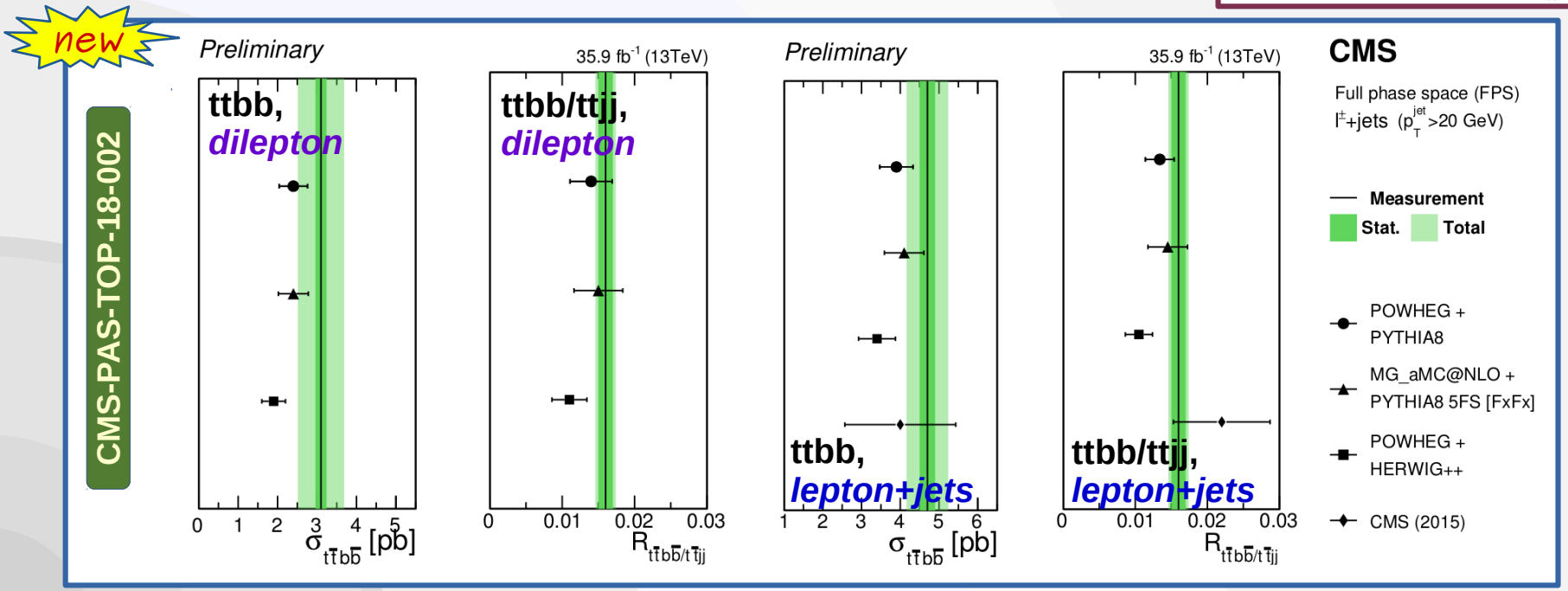


$t\bar{t}+b\bar{b}$ production

- **Scrutinizing $t\bar{t}+b\bar{b}$ production in dileptonic, lepton+jets and all-hadronic channels**
  - → major background for $t\bar{t}+H(b\bar{b})$ and tttt
  - → complex final state governed by very different scales, i.e. m_t and p_T^{jet}, → <u>challenging modelling</u>
- Measurements of $\sigma(t\bar{t}b\bar{b})$, $\sigma(t\bar{t}jj)$ and their ratio
  - → comparisons to NLO MC predictions
  - → overall good agreement, but $\sigma(t\bar{t}b\bar{b})$ slightly higher in data







Top quark properties

- Some **top quark properties** are predicted by the SM, some are not (e.g. mass, V_{tq})
  - important input to theory
  - precision measurements can reveal signs of new physics
  - wide variety of properties can be studied

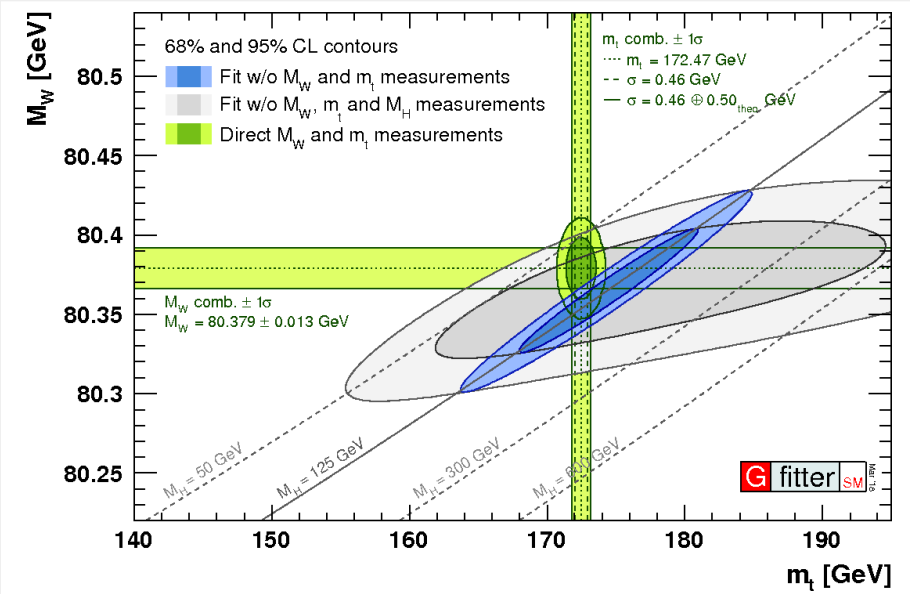
- **In this talk:**

top quark mass

spin correlation & polarisation

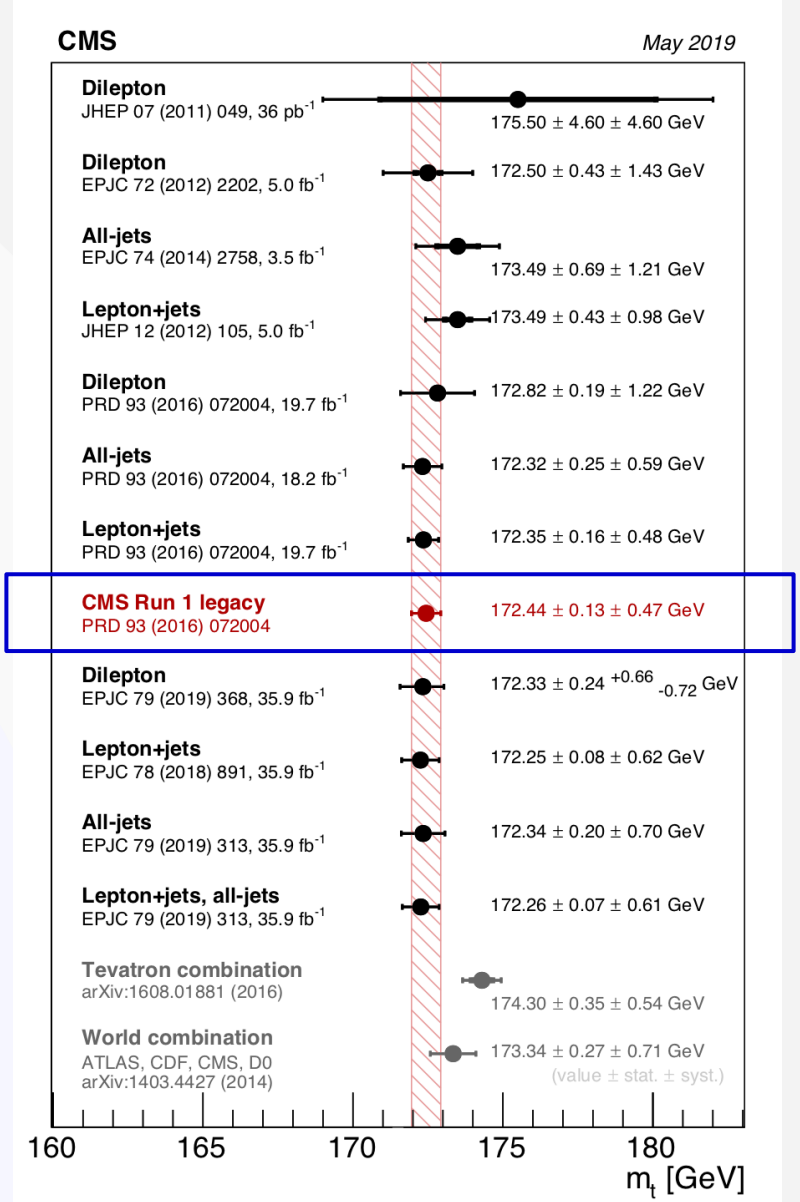
Top quark mass

- Fundamental parameter in the SM
  → not an observable
- Renormalisation scheme dependent
  → i.e. m_t^{MC} vs m_t^{pole}, $m_t(m_t)$
- Input to precision tests of SM
  → m_t, m_W, m_H interplay at loop level
  → need to measure m_t with highest possible precision



m(top) at CMS: direct measurements

- Directly measured from reconstructed top quark decay products
  → most precise way to determine m_t
- Higher precision through combination of many measurements in many channels
  → uncertainties below 500 GeV (< 0.3%)
- However, probing mass as defined in MC
  → $\mathbf{m_t^{MC}}$ can't be exactly interpreted in terms of on-shell mass in perturbation theory, i.e. $\mathbf{m_t^{pole}}$



m(top) at CMS: indirect measurements

- Extraction from a fit to a sensitive observable

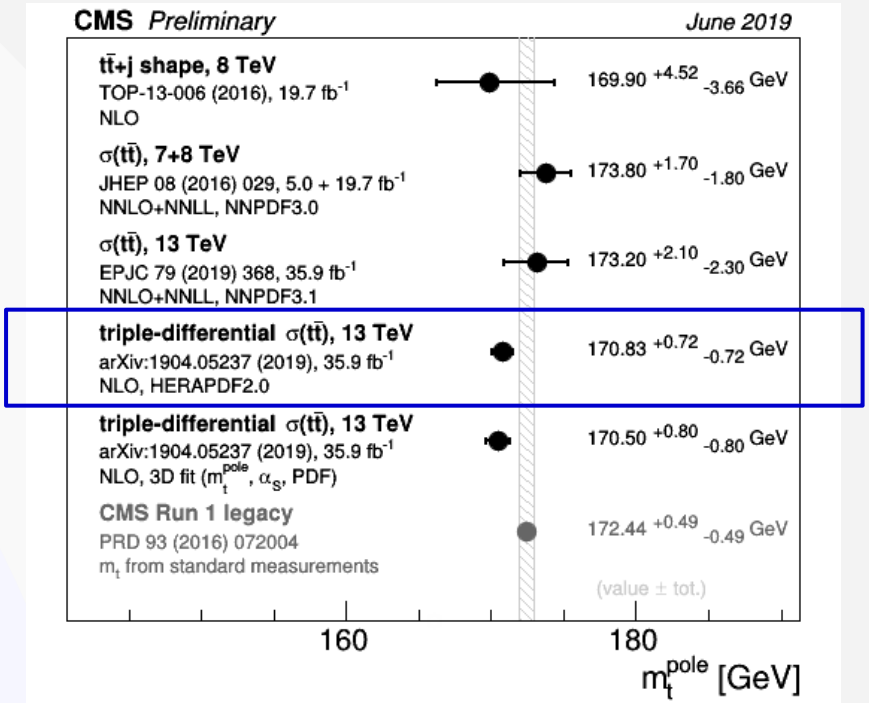
  → e.g. $\sigma(t\bar{t})$, exploiting dependence of theoretical predictions on m_t

- Overall smaller precision w.r.t. direct measurements

  → measurements with sub-GeV uncertainties started to appear only recently

- Probing theoretically well-defined parameter, e.g. $\mathbf{m_t^{pole}}$, $\mathbf{m_t(m_t)}$

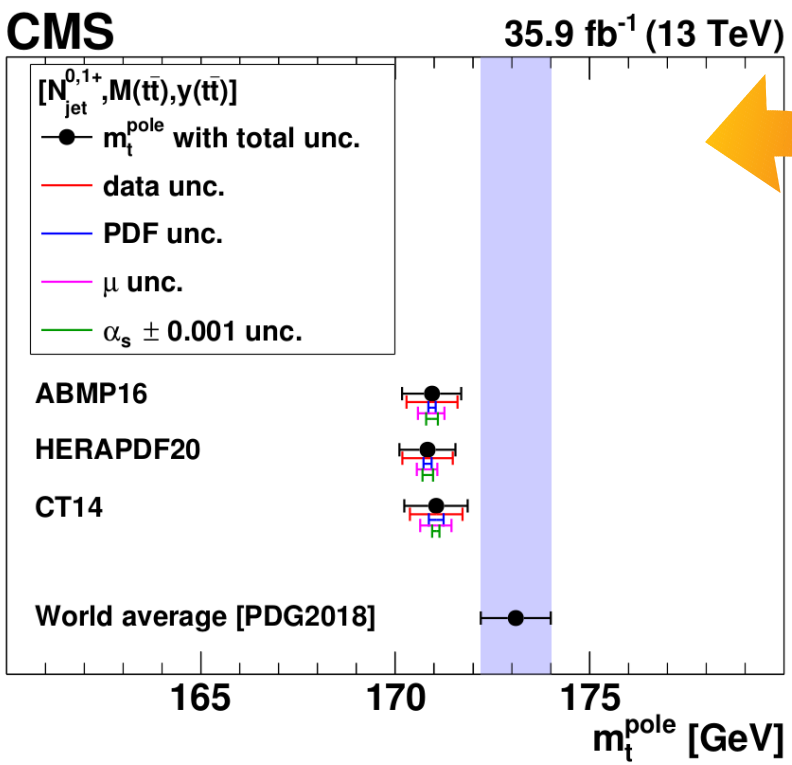
  → e.g. difference between $\mathbf{m_t^{pole}}$ and $\mathbf{m_t^{MC}}$ estimated to be < 1 GeV



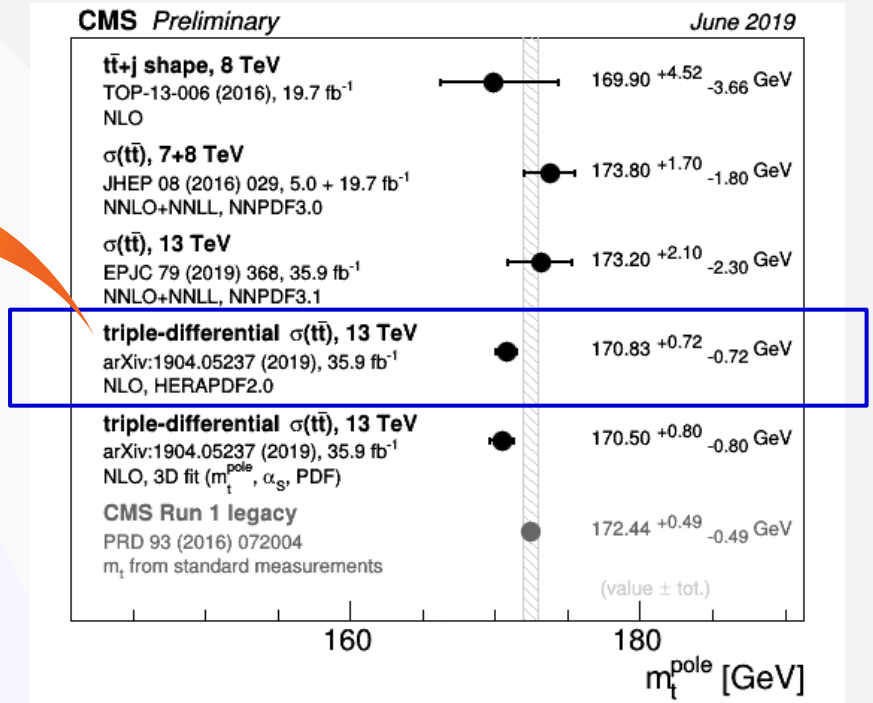
m(top) at CMS: indirect measurements

arXiv:1904.05237
- submitted to EPJC -

- Novel extraction of **gluon PDF**, **α_s** and **m_t^{pole}** from **triple-differential $\sigma(t\bar{t})$** and **NLO predictions**
  (analysis details in slide 12)



Precision of 0.5%



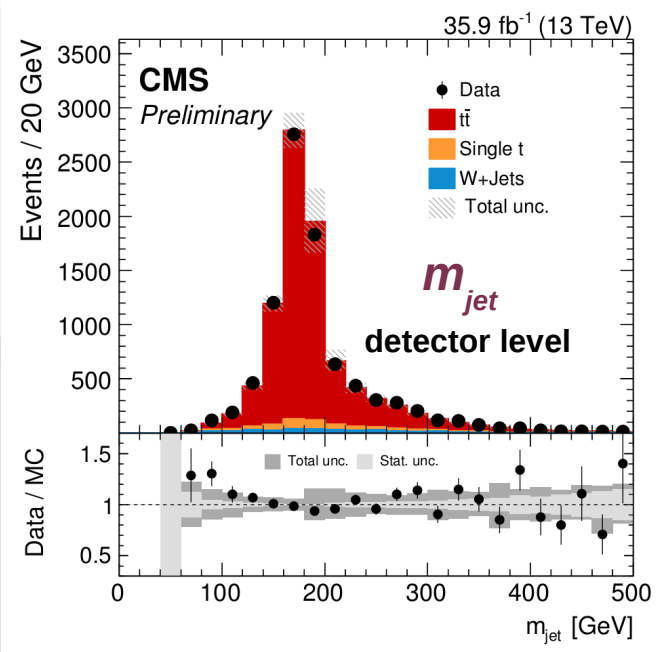
Top quark mass in boosted topologies

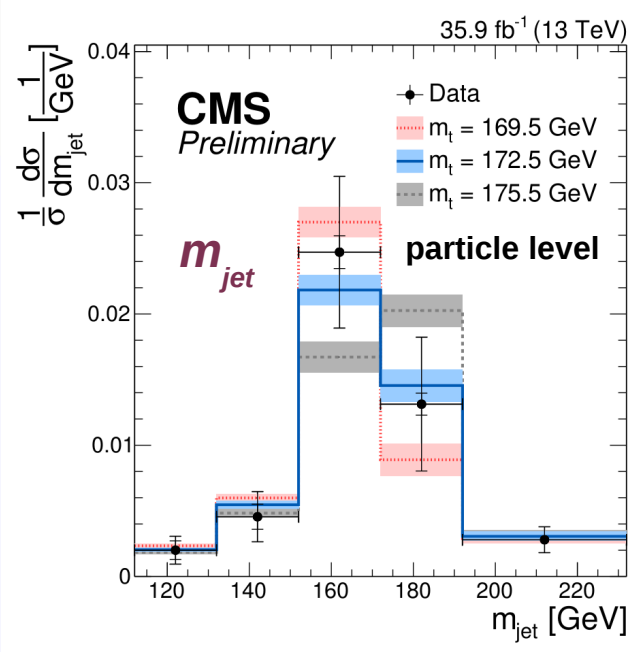
new

CMS-PAS-TOP-19-005

- **First measurement of the top quark mass in the highly boosted regime to better understand ambiguities between m_t^{pole} and m_t^{MC}**
- Differential **$\sigma(t\bar{t})$** measured as a function of jet mass m_{jet} via unfolding in lepton+jets events
  - → boosted top quarks (p_T > 400 GeV): a <u>single jet</u> includes all **$t \to bW \to bq\bar{q}'$** decay products, i.e. fat jet
  - → improved resolution of m_{jet} owing to novel XCone algorithm [JHEP 11 (2015) 072] used to reconstruct fat jets
- Location of the m_{jet} peak can be calculated analytically and is **sensitive to m_t**
- Top quark mass extracted from $d\sigma(t\bar{t})/dm_{jet}$

m_t^{pole} = 172.56 ± 2.47 GeV (1.4%)



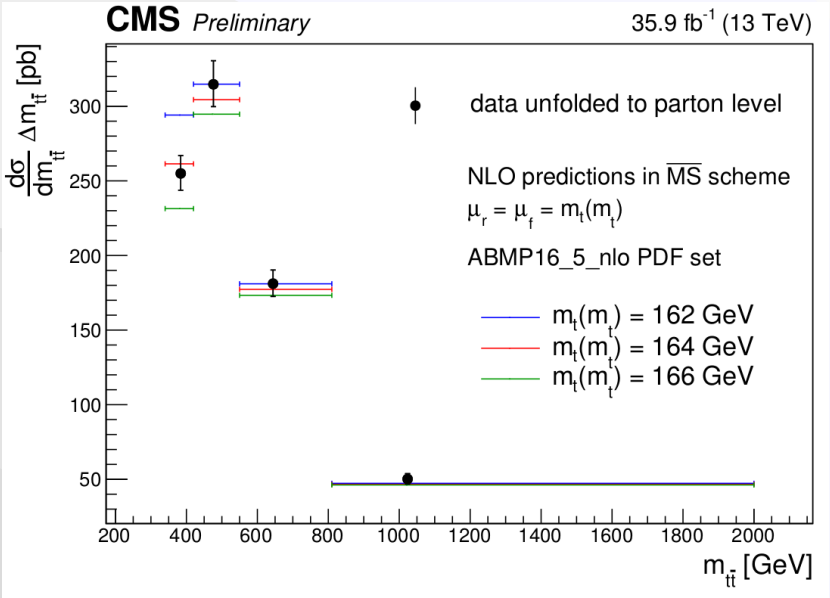


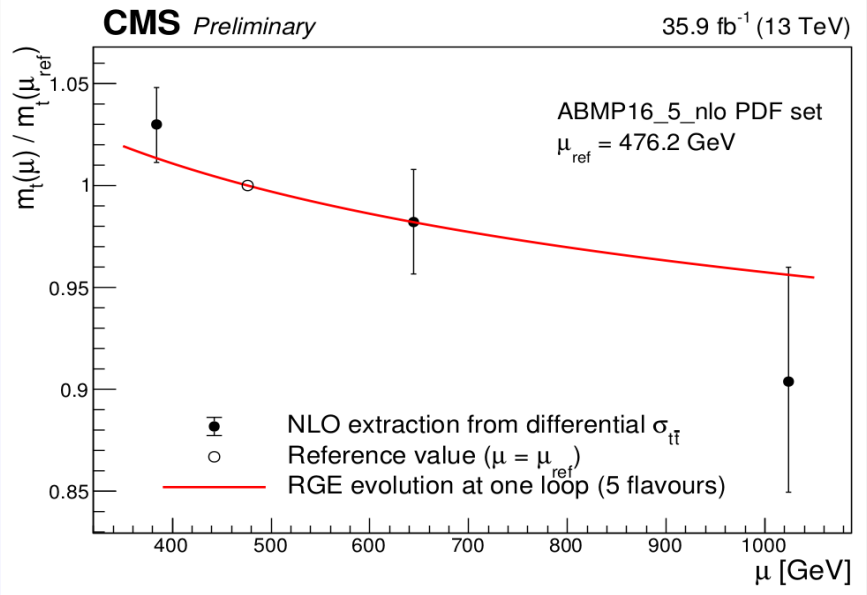
Running of top quark mass

new

CMS-PAS-TOP-19-007

- **First measurement of the running, i.e. scale dependence, of the top quark mass defined in the $\overline{MS}$ scheme, i.e. $m_t(m_t)$**
- Differential **$d\sigma(t\bar{t})/dm(t\bar{t})$** measured using events with <u>oppositely charged electron and muon</u>
  → maximum-likelihood fit to multidifferential distributions of final state observables at parton level
  → constraining systematic uncertainties in-situ and accounting for dependence on m_t^{MC}
- $m_t(m_t)$ extracted in bins of $m(t\bar{t})$ via a fit to NLO predictions to determine **the running of $m_t(\mu)$**
- Observed running found to be compatible with scale dependence predicted by renormalization group equations





Spin correlations and polarization

- In SM, top quarks from pair production are almost unpolarized, but have correlated spins
- Top quark lifetime (~10^{-25} s) is much shorter than the spin decorrelation time scale (~10^{-21} s)
  - angular distributions of top quark decay products provide access to spin of top quark
- Best sensitivity in the **dilepton** channel: spin analyzing power of the lepton ~1

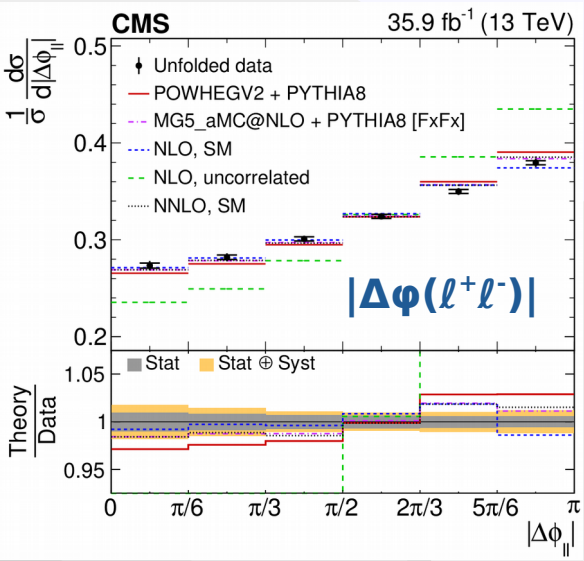
Spin correlations & polarization in dileptons

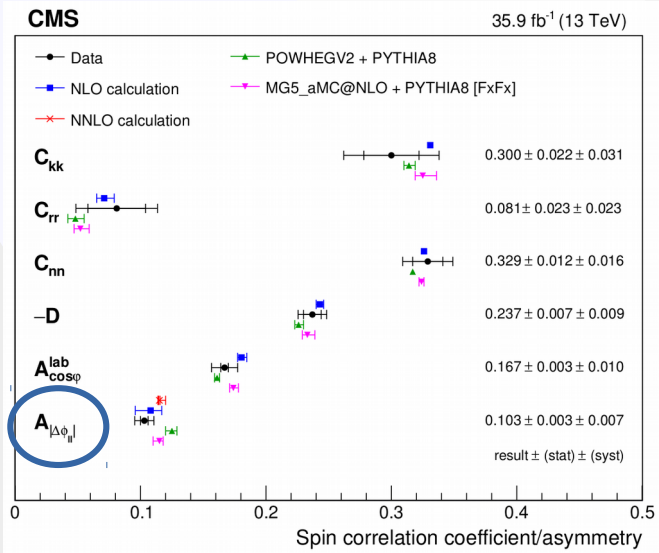
arxiv:1907.03729
- submitted to PRD -

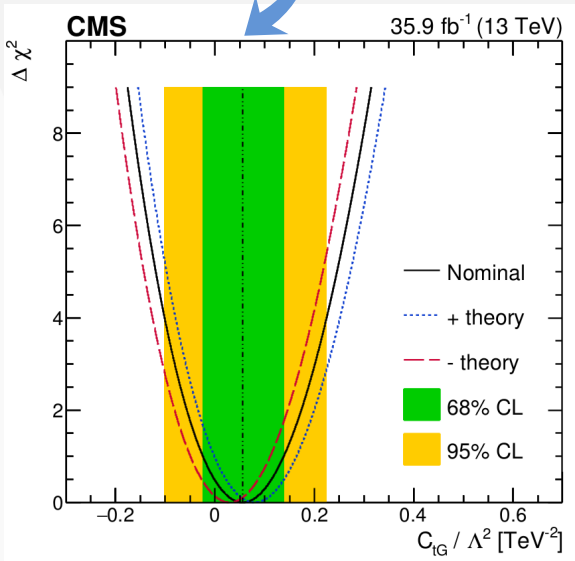
- **Probing spin-dependent parts of the $t\bar{t}$ production density matrix**
- Measurement of $t\bar{t}$ differential cross sections as a function of observables sensitive to top quark polarization and $t\bar{t}$ spin correlations (strategy follows **JHEP 02 (2019) 149** presented previously)
  - e.g. **$\Delta\varphi(\ell^+\ell^-)$:** difference in azimuthal angles between two leptons in the laboratory frame
- Extraction of spin coefficients and asymmetries

$$A_{|\Delta\phi_{\ell\ell}|} = \frac{N(|\Delta\phi_{\ell\ell}| > \pi/2) - N(|\Delta\phi_{\ell\ell}| < \pi/2)}{N(|\Delta\phi_{\ell\ell}| > \pi/2) + N(|\Delta\phi_{\ell\ell}| < \pi/2)}$$

- Results used to improve current constraints on **the anomalous top quark CMDM in EFT**
- All results in agreement with SM expectations







Summary

- Probing nature with many measurements in top quark sector with CMS
  - top quark cross sections and properties at high precision
  - rare top quark production modes may be accessed better than ever
  - wide variety of results offer great potential for BSM searches (e.g. many interpretations in EFT not covered today)
  - constantly providing valuable input for improvement of theoretical predictions
- All results are in agreement with SM and no evidence of new physics
- Next generation of new exciting results to come with study of full Run2 data from LHC

See more:
http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/

Summary

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THANK YOU FOR YOUR ATTENTION

See more:
http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/

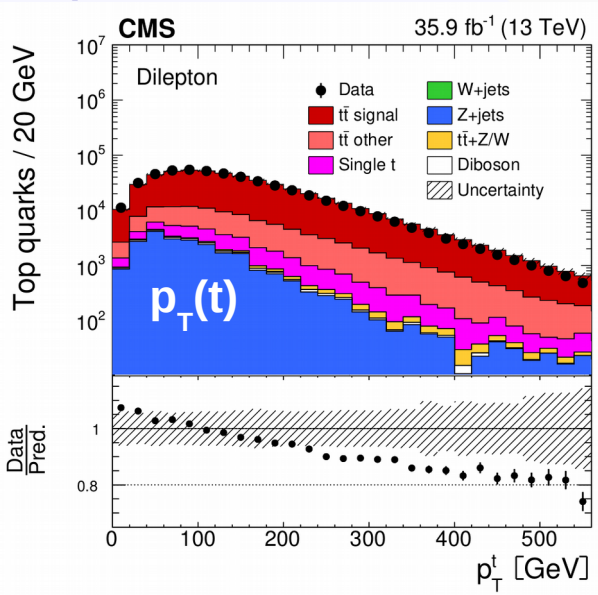
BACKUP

Differential $t\bar{t}$ cross sections

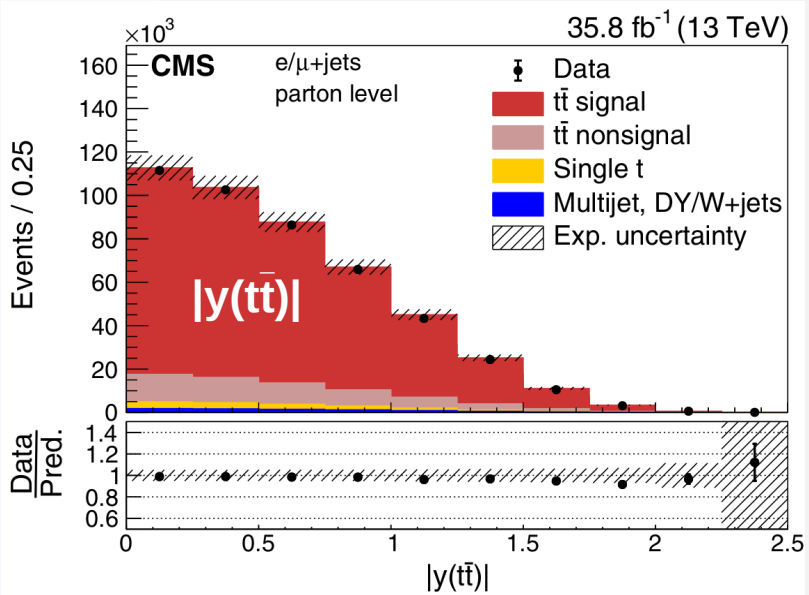
- **Study of $\sigma_{t\bar{t}}$ as a function of many observables in various $t\bar{t}$ decay channels**
  - → deeper probe of $t\bar{t}$ process in various corners of phase space
  - → sensitivity to subtle hints of new physics
- Dedicated event selection and reconstruction of top quark candidates in each channel

detector level

dilepton JHEP 02 (2019) 149



e/μ+jets PRD 97 (2018) 112003



- <u>Unfolding</u> to correct measured spectrum for detector effects and acceptance, i.e. back to:
  - **parton level**: results can be compared to predictions from perturbative calculations
  - **particle level**: reduced dependence on theoretical assumptions used in the simulation

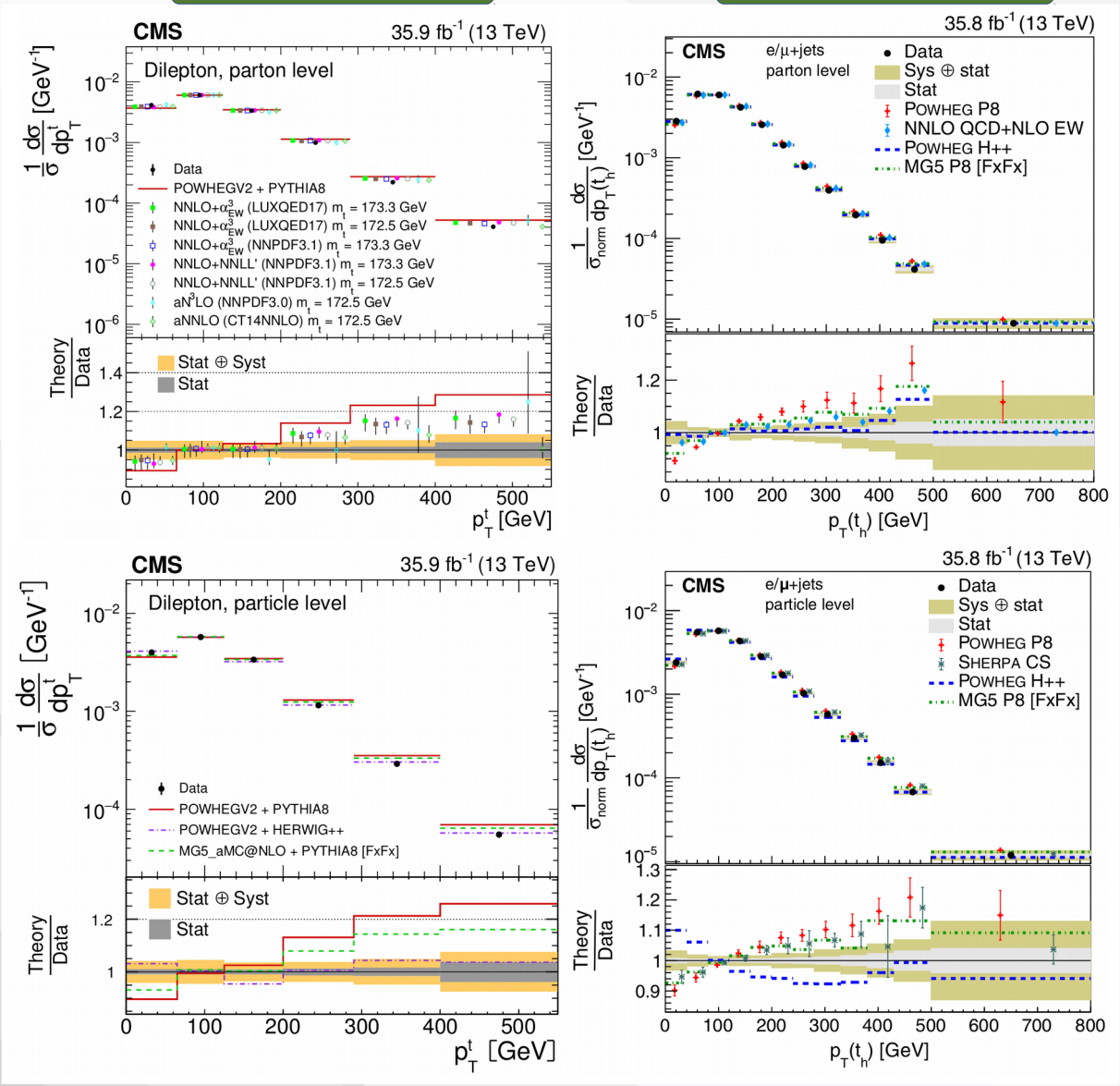
Differential $t\bar{t}$ cross sections

JHEP 02 (2019) 149

PRD 97 (2018) 112003

parton level

particle level



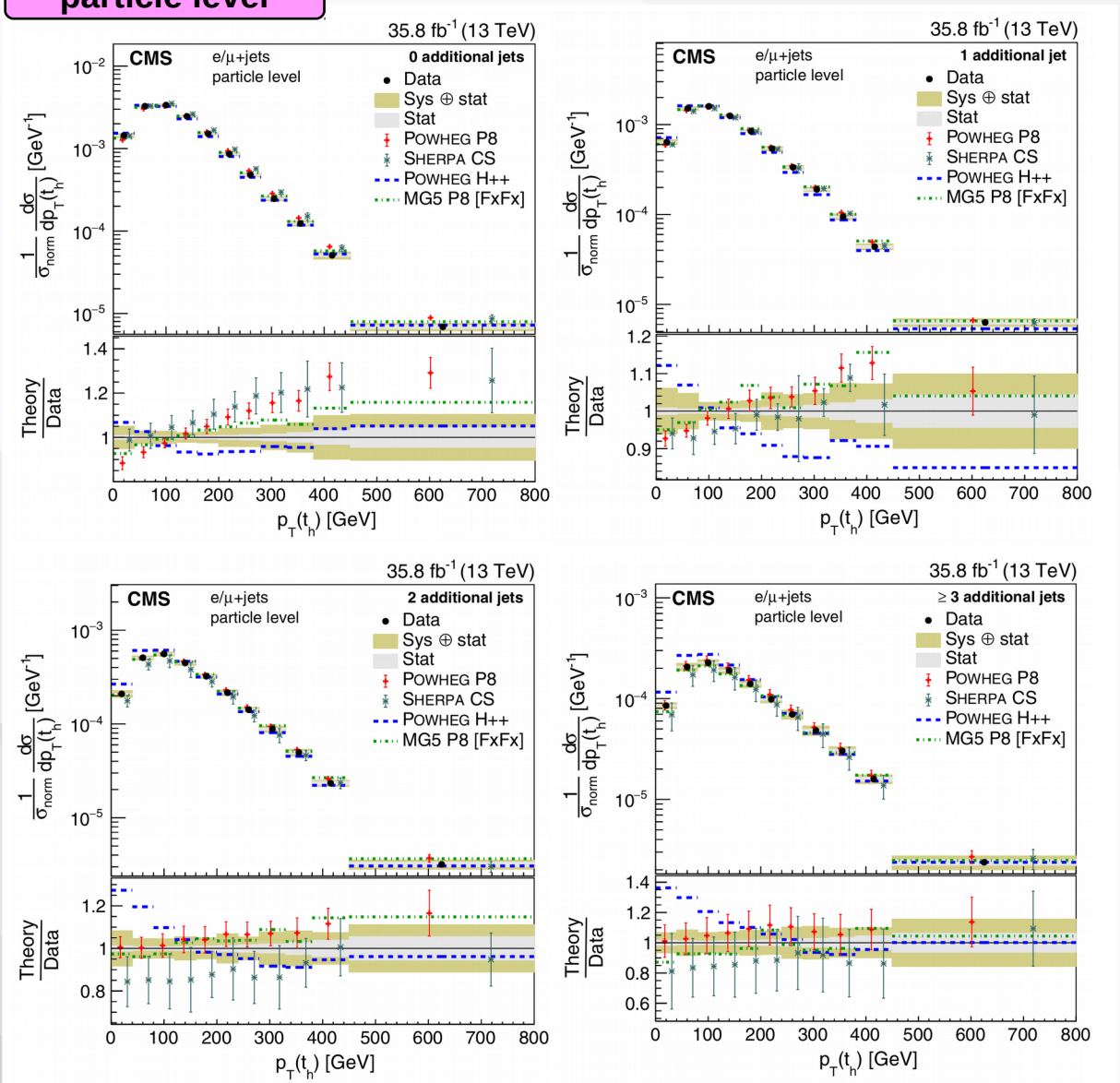
Left: dilepton
Right: e/μ+jets

- **Normalized differential spectra for top quark p_T**
- Consistent results among channels
- Similar trends at parton and particle levels
- Good agreement with SM, but none MC predictions describe <u>all</u> distributions
- Parton-level spectra better described by fixed-order calculations of NNLO accuracy

Only small glimpse of results
e.g. **JHEP 02 (2019) 149** presents about **100** differential spectra

Double-differential $t\bar{t}$ cross sections in ℓ+jets channel

particle level

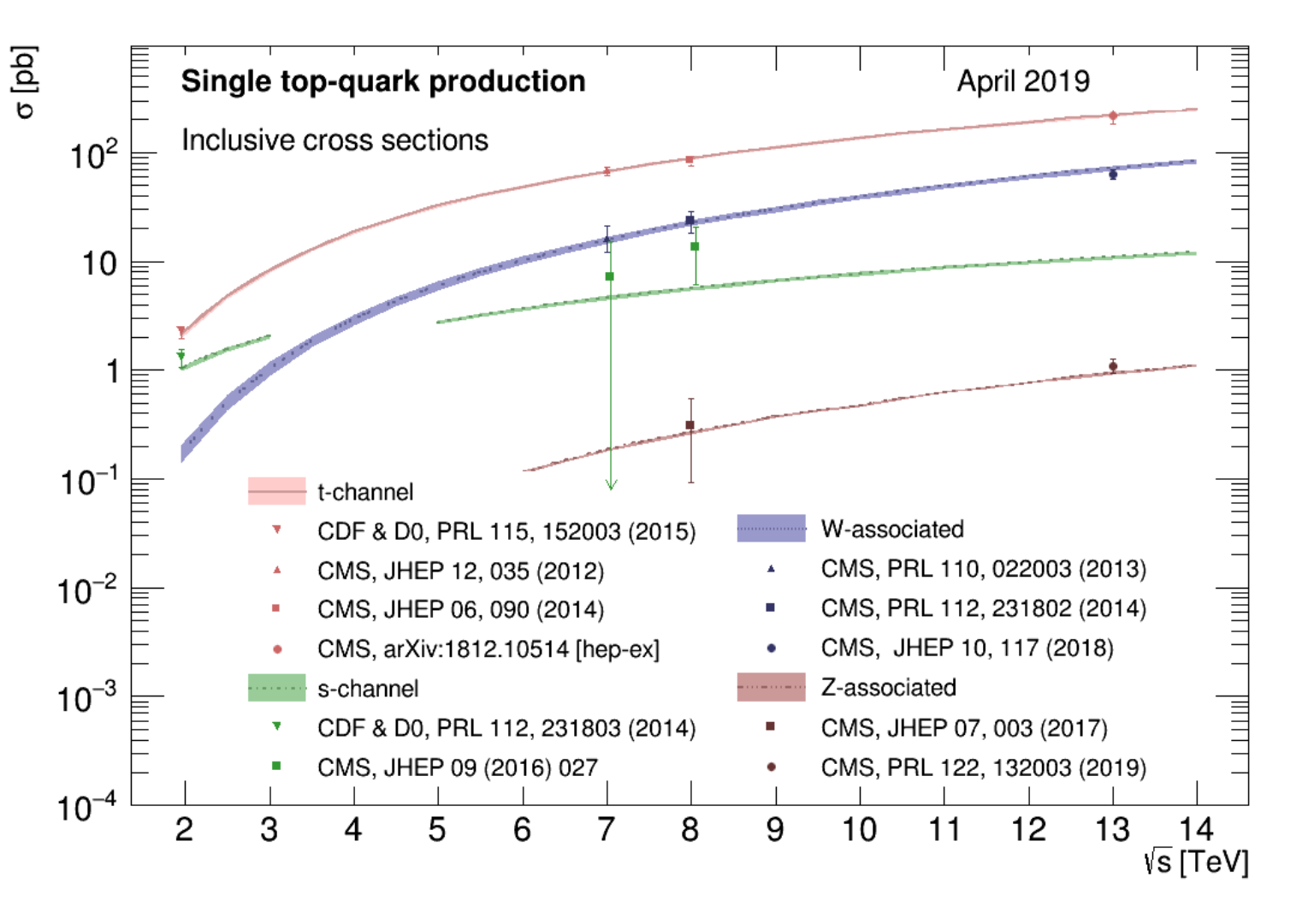


PRD 97 (2018) 112003

- **Results unfolded in two dimensions as a function of:**
  - top quark and $t\bar{t}$ kinematics
  - jet multiplicity
- Provide more sensitivity in various corners of phase space
- **Plots:** 2D unfolding in $p_T(t_h)$ and number of additional jets
  - slope in $p_T(t_h)$ diminishes at higher jet multiplicities
  - Herwig++ shows different trends w.r.t. other generators

Only small glimpse of results
PRD 97 (2018) 112003 presents about **175** differential spectra

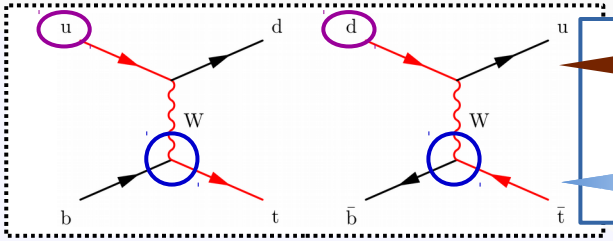
Inclusive single top cross sections at CMS: overview



Inclusive single top t-channel cross section

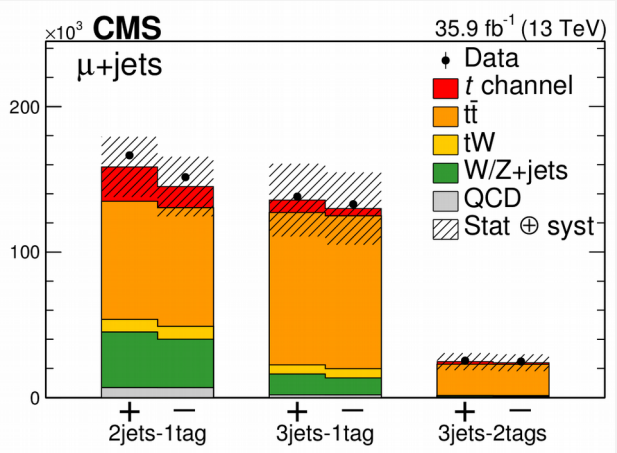
- **Measuring the t-channel production of single top quarks and antiquarks**

arXiv:1812.10514
- submitted to PLB -



different production rates for **t** and **t̄** owing to **proton PDF**

direct sensitivity to **V_{tb}**



- **Events with one e or μ, and multiple jets:**
  different categories of jet and b jet multiplicity and multivariate discriminators are applied to separate signal from background

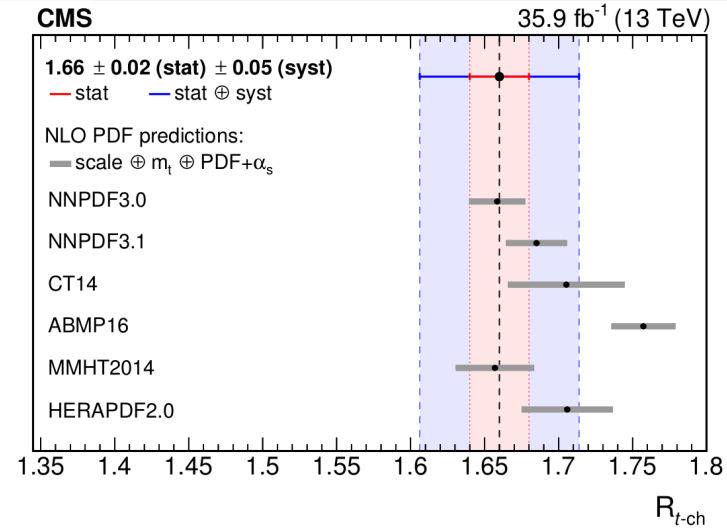
- Cross sections measured from a likelihood fit to BDT output in all categories

$$\sigma_{t\text{-ch},t} = 136 \pm 1\ (\text{stat}) \pm 22\ (\text{syst})\ \text{pb}$$
$$\sigma_{t\text{-ch},\bar{t}} = 82 \pm 1\ (\text{stat}) \pm 14\ (\text{syst})\ \text{pb}$$

- Ratio $R_{t\text{-ch}} = \sigma_{t\text{-ch},t}/\sigma_{t\text{-ch},\bar{t}}$ measured for different PDF sets

- Resulting V_{tb}

$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{t\text{-ch},t+\bar{t}}}{\sigma^{\text{theo}}_{t\text{-ch},t+\bar{t}}}} = 1.00 \pm 0.08\,(\text{exp}) \pm 0.02\,(\text{theo})$$



NLO prediction: Comput. Phys. Commun. 191 (2015) 74

$\sigma_{t\text{-ch},t} = 136.0\ ^{+4.1}_{-2.9}\ (\text{scale}) \pm 3.5\ (\text{PDF}+\alpha_S)$ pb $\sigma_{t\text{-ch},\bar{t}} = 81.0\ ^{+2.5}_{-1.7}\ (\text{scale}) \pm 3.2\ (\text{PDF}+\alpha_S)$ pb

Most precise $R_{t\text{-ch}}$ to date

Inclusive tW production cross section

- **Probing associated tW production**

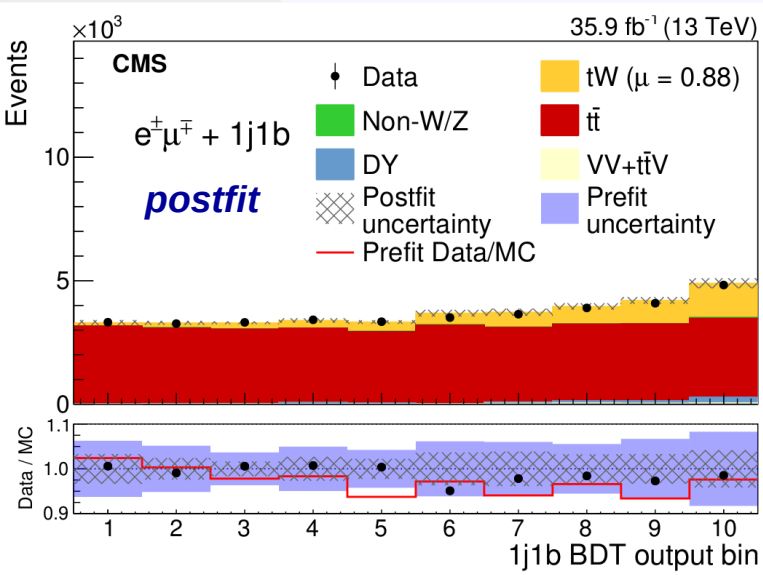
JHEP 10 (2018) 117

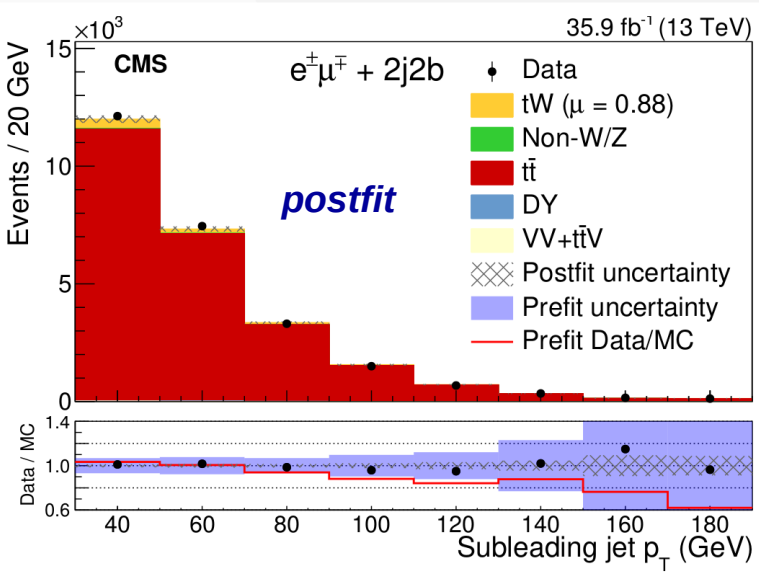
- Events with oppositely charged **e** and **μ**, and at least **1 b quark jet**
- Measurement of σ_{tW} using a likelihood fit
  - → events classified into categories w.r.t. number of jets and b quark jets
  - → fitting BDT output (in 1j1b and 2j1b categories) and subleading jet pT (in 2j2b category)

σ_{tW} = 63.1 ± 1.8 (stat) ± 6.4 (syst) ± 2.1 (lumi) pb (11%)

arXiv:1506.04072

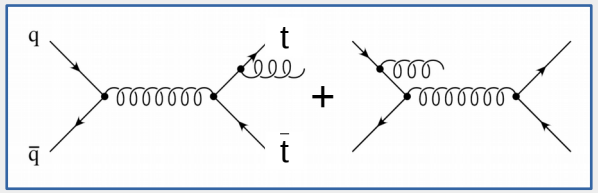
aNNLO prediction: σ_{tW} = 71.7 ± 1.8 (scale) ± 3.4 (PDF) pb



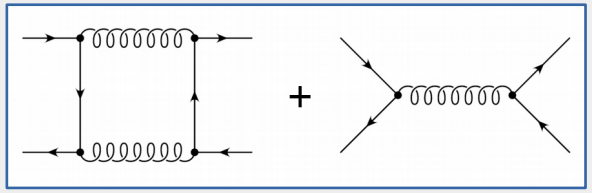


Charge asymmetry

- Non-zero charge asymmetry in $t\bar{t}$ production through $q\bar{q}$ interaction beyond LO



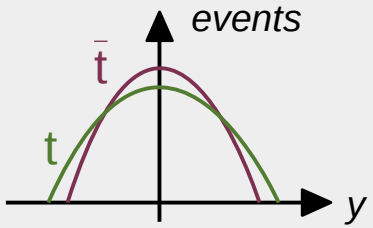
FSR & ISR



Box diagram & tree-level

Modified pictures from:
PRL 81:49-52,1998

- Enhanced by BSM scenarios, e.g. axigluons, Z' bosons
- At LHC, different width of rapidity for top quarks and anti-quarks



- Measure **$t\bar{t}$** charge asymmetries **A_C** from $\Delta|y|(t,\bar{t}) = |y_t| - |y_{\bar{t}}|$

$$A_c^{t\bar{t}} = \frac{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) - \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) + \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}$$

$t\bar{t}$ charge asymmetry

- **Using results from $t\bar{t}$ differential cross sections in dileptons** (analysis details in slides 10-11)
  - → extracted at parton and particle levels
  - → in addition, extraction of **leptonic** asymmetry

$$A_c^{\ell\bar{\ell}} = \frac{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) - \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) + \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}$$

- Resultant charge asymmetries consistent with SM

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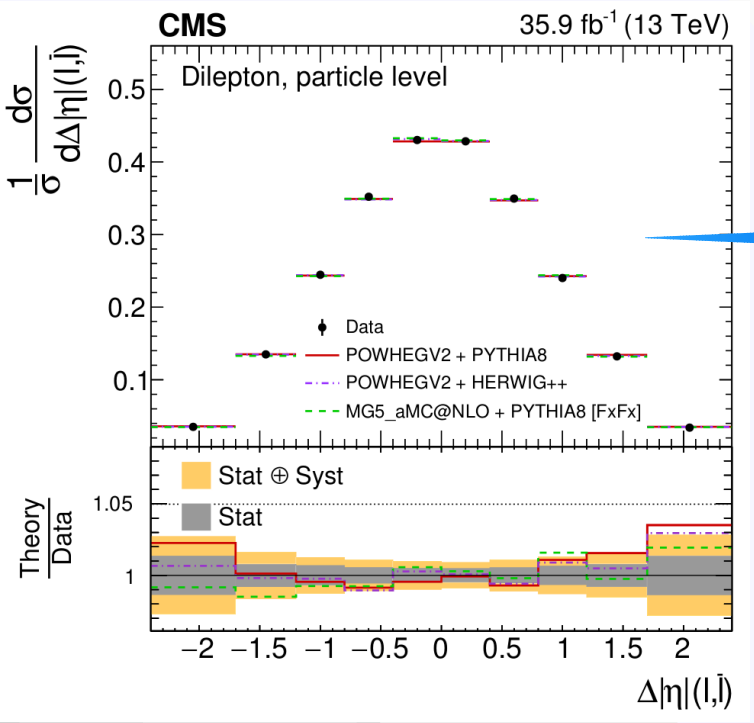
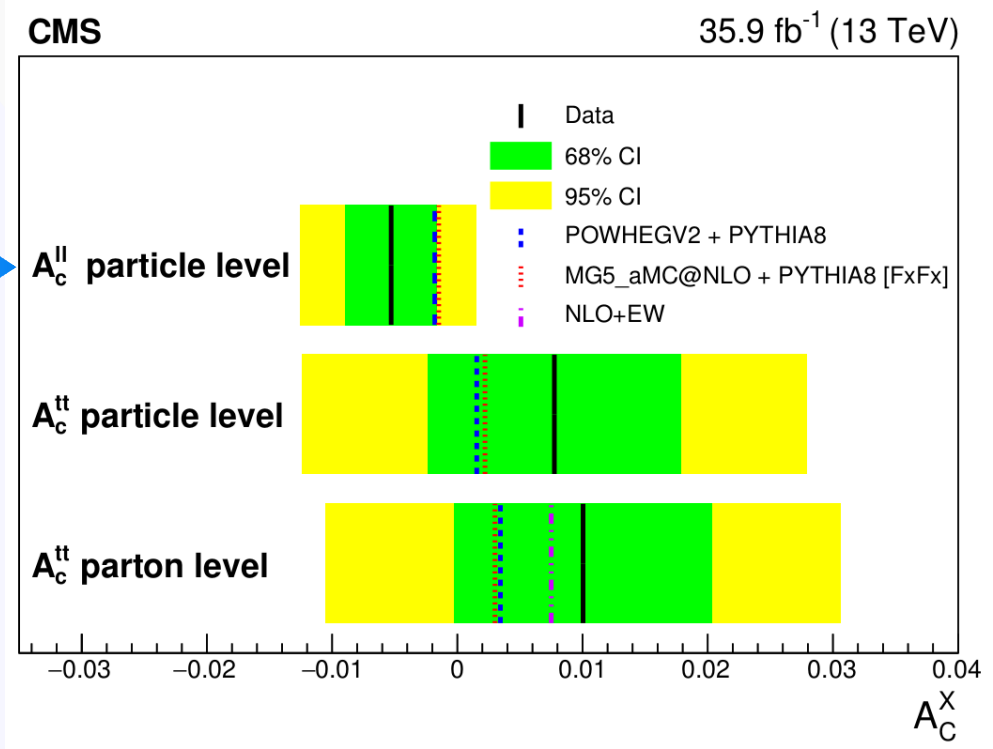
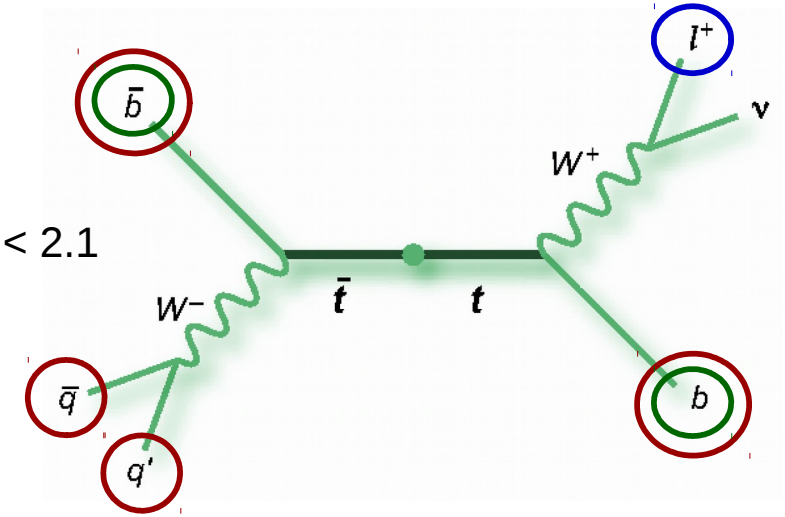




Event selection

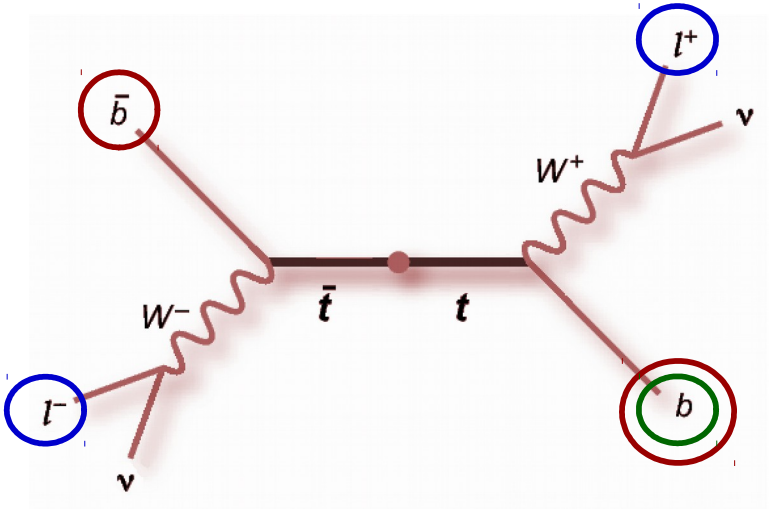
Lepton+jets:

- **Exactly 1 high-p_T isolated lepton (e or μ)**
  - p_T > around 30 GeV (analysis dependent), $|\eta| < 2.1$
- **≥ 4 jets**: p_T > 30 GeV, $|\eta| < 2.4$
- **≥ 2 b-tagged jets**



Dileptons:

- **≥ 2 OS, high-p_T isolated leptons (ee, μμ, μe)**
  - p_T > 20 GeV, $|\eta| < 2.4$
- **QCD veto**: m_{ll} > 20 GeV
- **≥ 2 jets**: p_T > 30 GeV, $|\eta| < 2.4$
- **≥ 1 b-tagged jets**
- **ee, μμ channels**: E_T^{miss} > 40 GeV
  Z veto: $|m_Z - m_{ll}|$ > 15 GeV

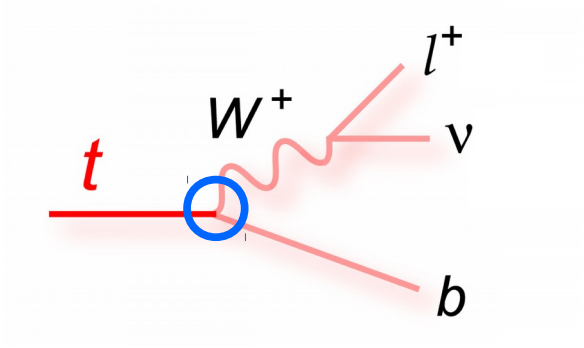


In addition: <u>kinematic reconstruction</u> of $t\bar{t}$ system

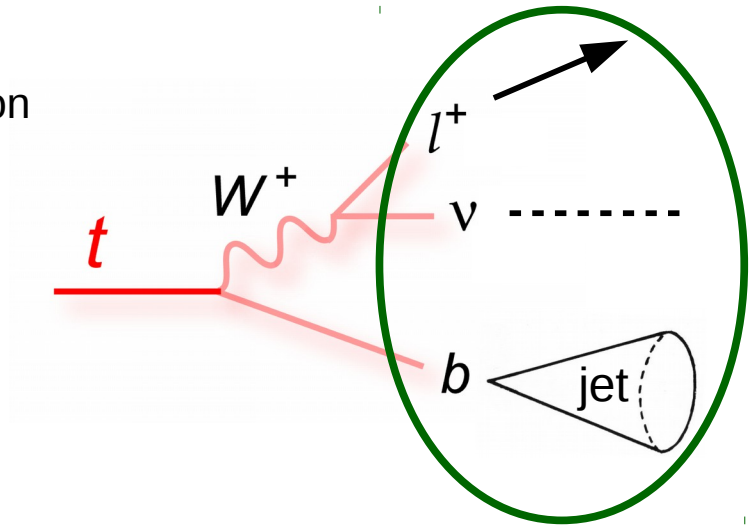
Definition of differential cross sections

- Differential results corrected (unfolded) back to **true level**, i.e. parton or particle level

- **Parton level** top quark
  → after QCD radiation and before decay
  → results can be compared to predictions from perturbative calculations
  → *study of various parameters, e.g.:* α_s, m_t, PDFs



- **Particle level** top quark
  → reconstructed from stable particles after hadronization
  → minimized dependence on theoretical assumptions used in the simulation
  → *useful for testing of new physics models, MC validation and tuning*



Constraining top quark CMDM in EFT

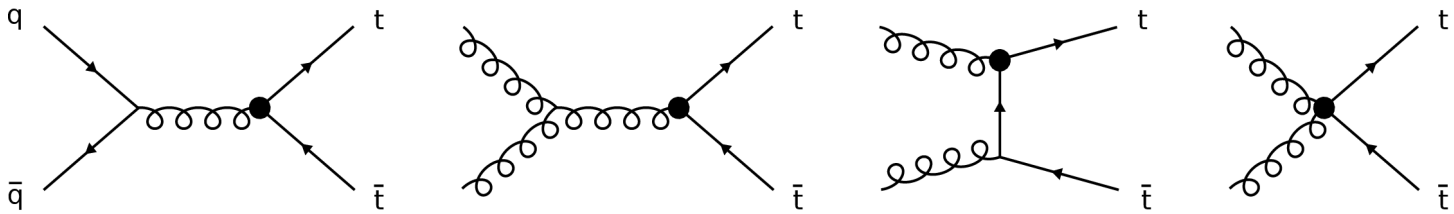
- **Effective field theory (EFT):** modelling of new physics effects at high-energy scale Λ_{NP}
- **EFT approach:** extension of SM Lagrangian by higher-dimensional operators O_i

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda_{NP}^2} O_i + h.c.$$

→ size of new physics effects parametrized by ratio C_i/Λ^2_{NP} (C_i – dimensionless coefficient)

- Dimension-6 operator O_{tG} models **top quark chromomagnetic dipole moment** (CMDM)

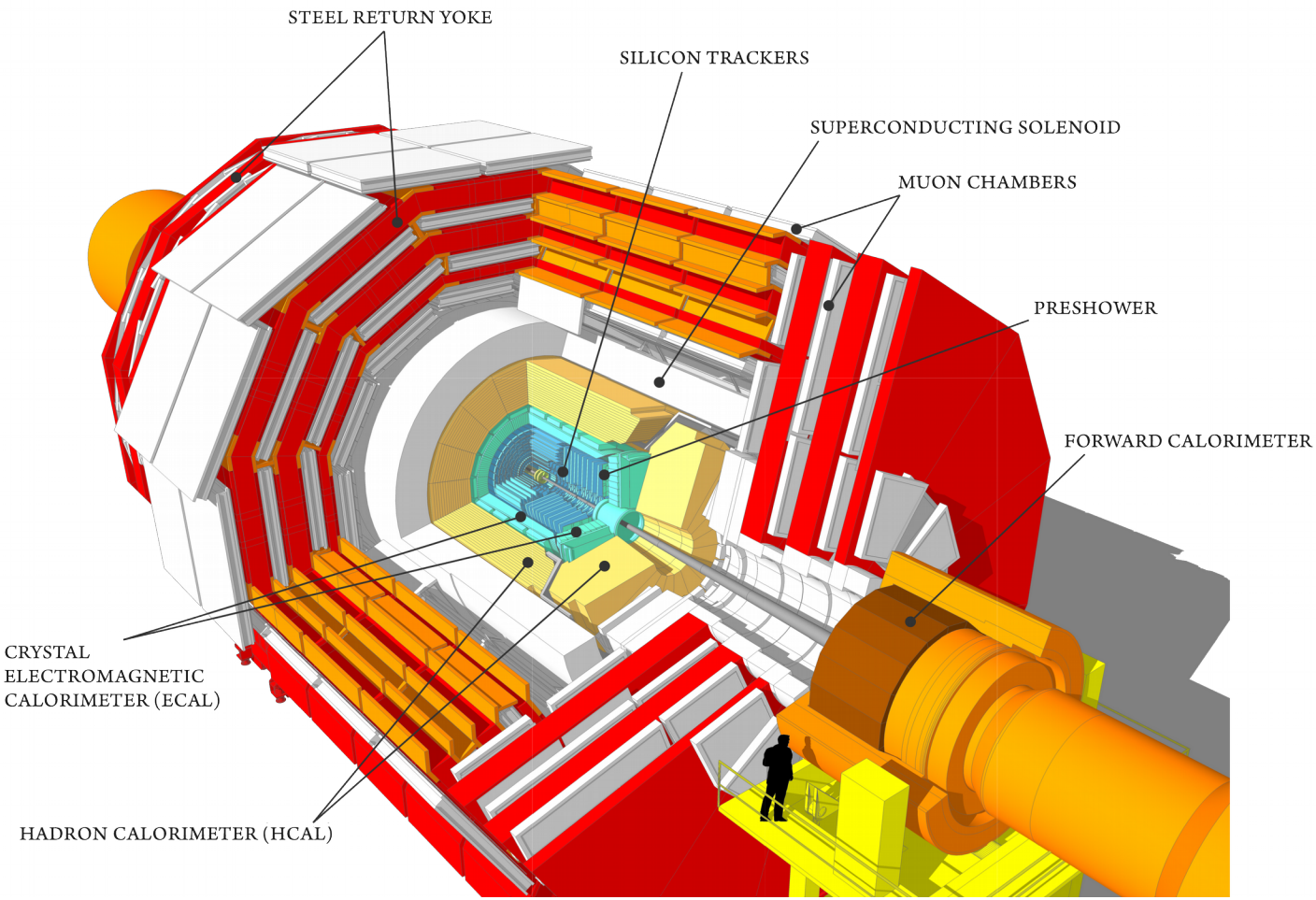
→ modification of $gt\bar{t}$ vertex and introduction of new $ggt\bar{t}$ vertex



→ changes in chirality of top quarks alter $t\bar{t}$ spin correlation

- **$\Delta\varphi(l,\bar{l})$** sensitive to changes in $t\bar{t}$ production rate and event dynamics induced by O_{tG}

CMS: Compact Muon Solenoid



CMS – general purpose particle detector:

- cylindrical geometry, installed around LHC beampipe
- length: 21.6 m, diameter: 14.6 m, weight: 12 500 tons
- multiple subdetectors