Measurement of single-top and top-pair production processes with ATLAS and CMS

EPS-HEP2023 conference - Hamburg

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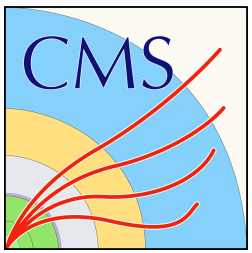
on behalf of the ATLAS and CMS collaborations

CPPM – CNRS/IN2P3 – Aix-Marseille Université

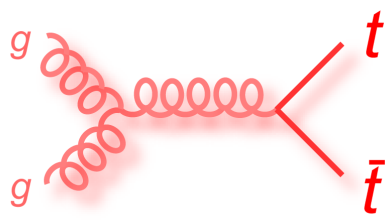
Tuesday, August 22nd 2023

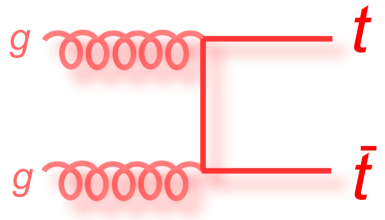


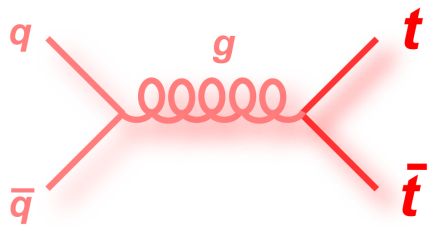
Introduction

- The top quark: Standard Model heaviest particle $m_t = 172.69 \pm 0.30$ GeV (PDG)
- In pp collisions: 4 production modes at LO, via QCD or EW

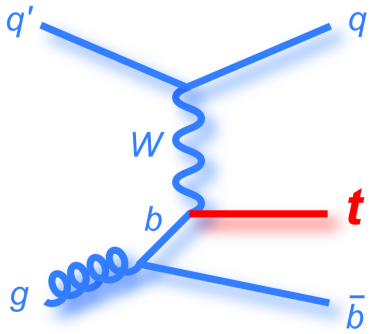
top-quark pair
$\sigma \simeq 834$ pb @13 TeV
(NNLO+NNLL)

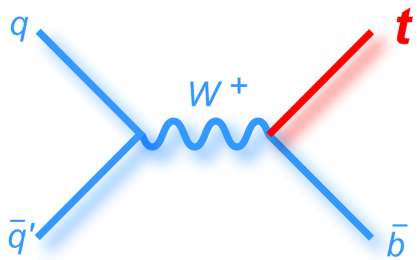


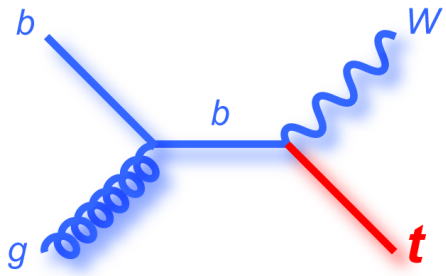




single-top







t-channel
$\sigma \simeq 214$ pb @13 TeV
(NNLO)

s-channel
$\sigma \simeq 11$ pb @13 TeV
(NNLO)

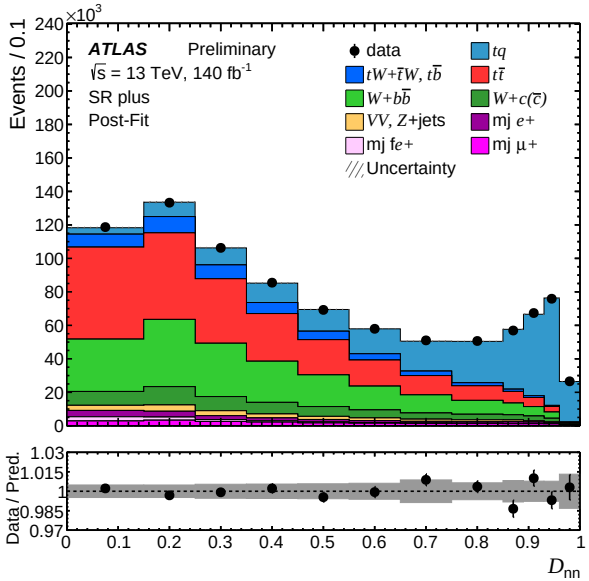
tW
$\sigma \simeq 79$ pb @13 TeV
(NLO+NNLL)

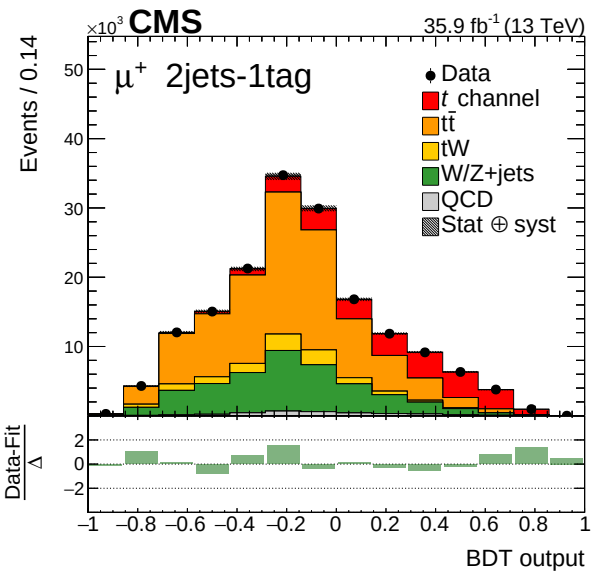
- LHC is a top factory: $\sim 120 \cdot 10^6$ pairs during run-2 in each of ATLAS and CMS
- This talk: recent cross-section measurements with run-2 data (mostly)
  - $\rightarrow$ run-3 results to be presented in this session by E. Ranken later this morning

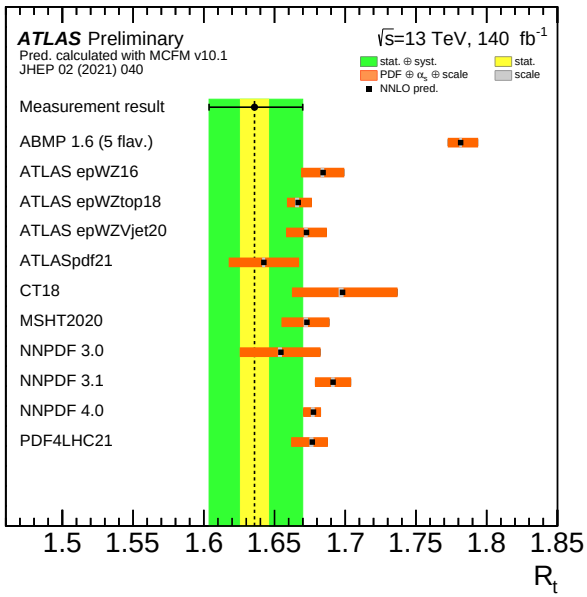
t-channel 13 TeV cross-section – ATLAS, CMS

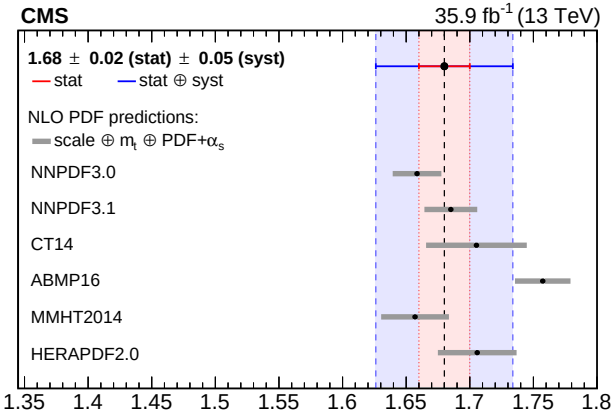
ATLAS-CONF-2023-026 – Phys. Lett. B **800** (2019) 135042

- Typical signal region: $1e/\mu$, $1b$-jet, 1 forward jet
  - NN or BDT to separate signal from backgrounds
- Recent ATLAS preliminary result, full run-2 data 140fb^{-1}
  - $\sigma_t = 137 \pm 8\text{pb}$ $\quad \sigma_{\bar{t}} = 84 \pm^{+6}_{-5}\text{pb}$,
  - $\sigma_{t+\bar{t}} = 221 \pm 13\text{pb}$ $\quad R_t = 1.636^{+0.036}_{-0.034}$
- Earlier CMS paper, 2016 data 35.9fb^{-1}
  - $\sigma_t = 130 \pm 19\text{pb}$ $\quad \sigma_{\bar{t}} = 77 \pm 12\text{pb}$,
  - $\sigma_{t+\bar{t}} = 207 \pm 31\text{pb}$ $\quad R_t = 1.68 \pm 0.06$







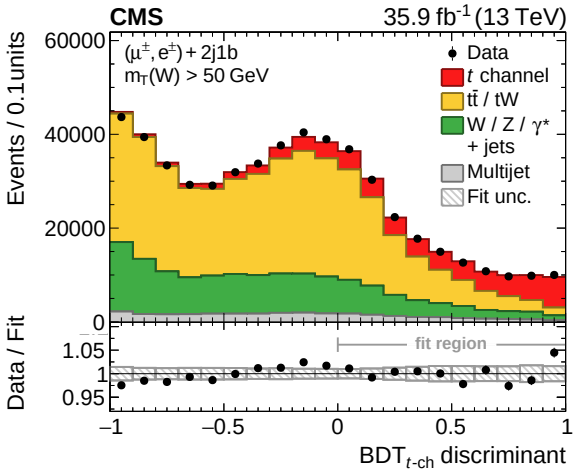


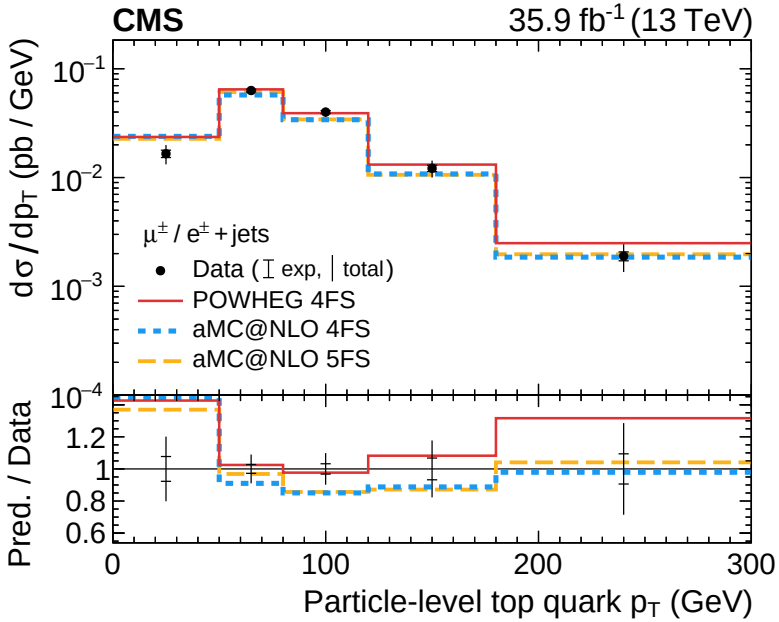
- Cancellation of systs.
- Sensitivity to PDFs

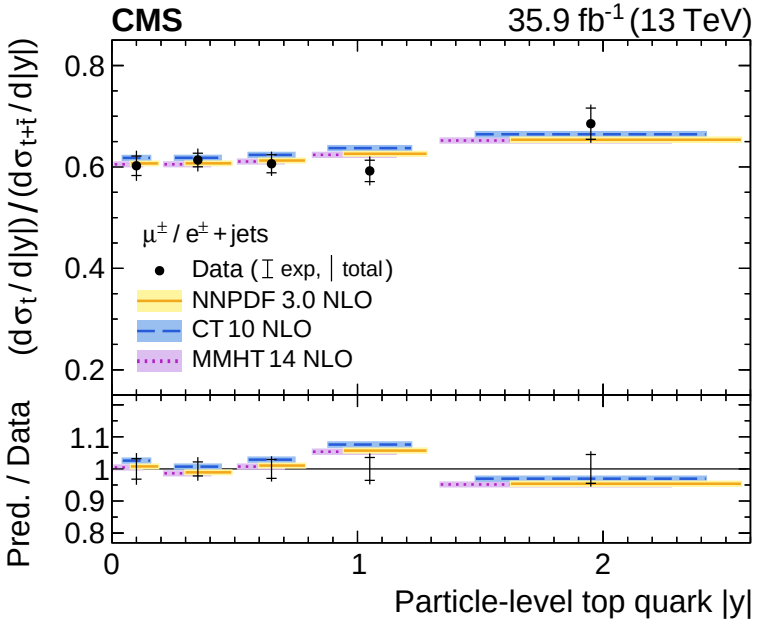
t-channel 13 TeV differential cross-sections – CMS

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

- CMS paper, 2016 data 35.9fb^{-1}
  - same selection as for inclusive cross-section, using BDT
  - input variables with low correlation to those measured
- Unfolding at parton and particle level, combining t and $\bar{t}$
  - top p_T and $|y|$, lepton p_T and $|y|$, W p_T, $\cos\theta^*_{pol}$
- Differential measurements of R_t (except for $\cos\theta^*_{pol}$)
  - additional sensitivity to PDFs





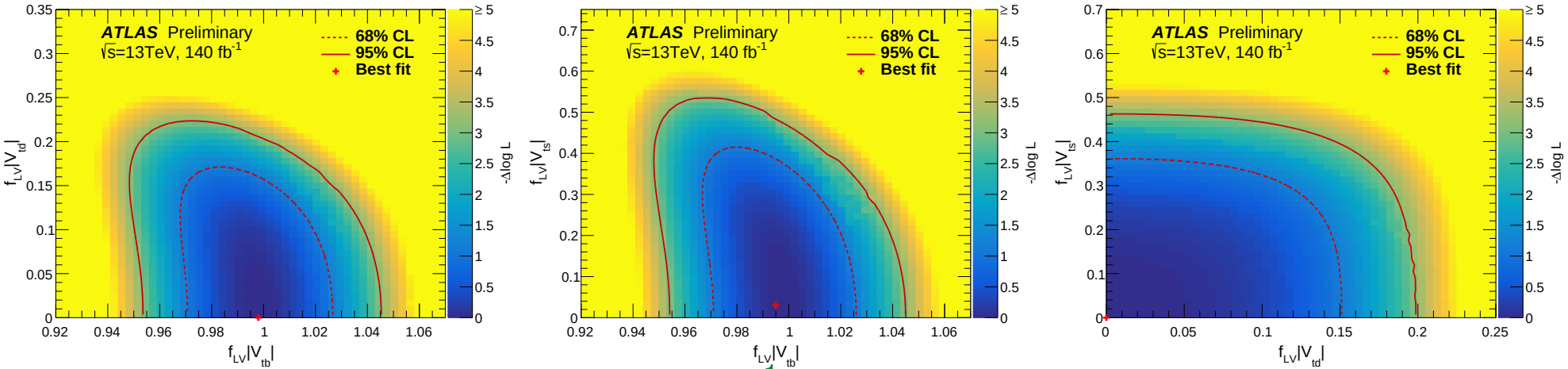


t-channel 13 TeV CKM matrix elements - ATLAS, CMS

ATLAS-CONF-2023-026 – Phys. Lett. B **808** (2020) 135609

- Wtq vertex ($q = b, s, d$) in production and decay $\Rightarrow \sigma$ and Γ sensitive to $|V_{tq}|$
- Recent ATLAS preliminary result, full run-2 data 140fb^{-1} - different scenarios:
  - $|V_{tb}| = 1.016 \pm 0.031$ $|V_{tb}| \gg |V_{td}|, |V_{ts}|$, left-handed coupling only
  - $|V_{tb}| > 0.95$ (95% CL) also asuming $|V_{tb}| \in [0, 1]$
  - 2D contours, with relaxing contraints on $|V_{td}|$ and $|V_{ts}|$:

$|V_{ts}| = 0$ $|V_{td}| = 0$ $|V_{tb}| = 1$

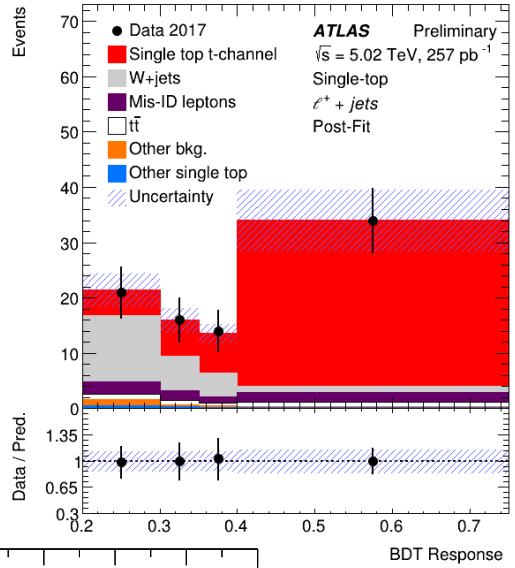


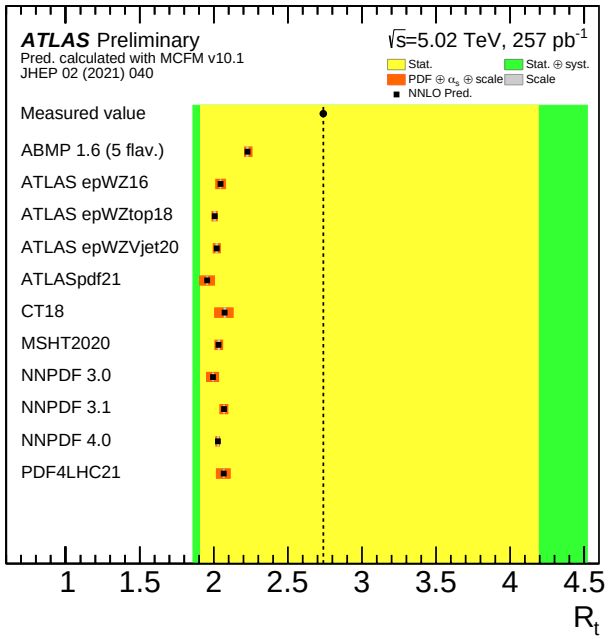
- Earlier CMS paper, 2016 data 35.9fb^{-1}, dedicated BDTs - different scenarios:
  - $|V_{tb}| > 0.95$ and $|V_{td}|^2 + |V_{ts}|^2 < 0.057$ (95% CL), $|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2 = 1$ (SM)
  - $|V_{tb}| = 0.988 \pm 0.051$, $|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$, non-unitary CKM
  - $|V_{tb}| = 0.988 \pm 0.024$, $|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$, $\frac{\Gamma_t^{obs}}{\Gamma_t} = 0.99 \pm 0.42$, invis. decays

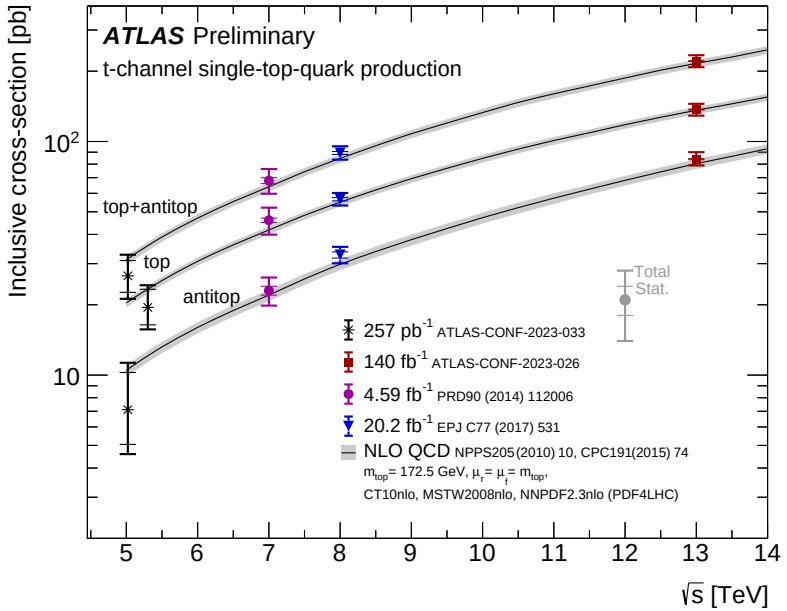
t-channel 5 TeV inclusive cross-section – ATLAS

ATLAS-CONF-2023-033

- ATLAS reliminary result, 5 TeV *pp* collisions 257pb^{-1}
  - similar analysis strategy as for 13 TeV collisions
  - significance: 6.1σ (6.4σ expected)
- Measurements compatible with SM predictions
  - $\sigma_t = 19.5^{+3.8}_{-3.1}(stat)^{+2.9}_{-2.2}(syst)$pb, $\sigma_{\bar{t}} = 7.1^{+3.2}_{-2.1}(stat)^{+2.8}_{-1.5}(stat)$pb,
  - $\sigma_{t+\bar{t}} = 26.6^{+4.3}_{-4.0}(stat)^{+4.4}_{-3.6}(syst)$pb, $R_t = 2.74^{+1.44}_{-0.83}(stat)^{+1.04}_{-0.29}(syst)$
- Additional probe for PDFs, at lower energies



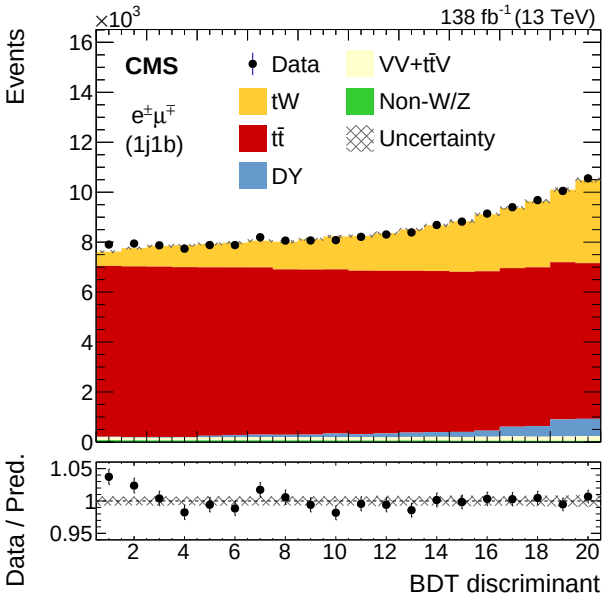


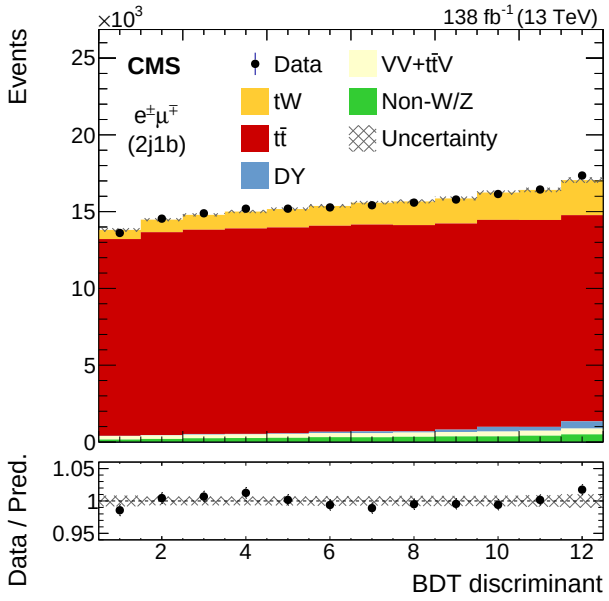


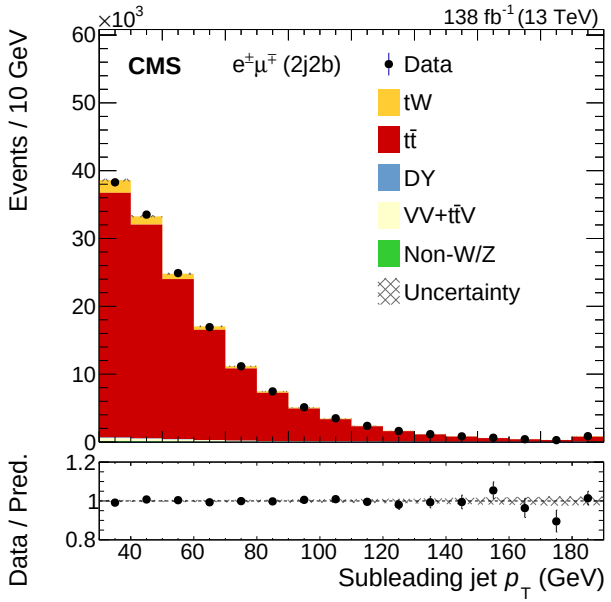
tW 13 TeV inclusive cross-section – CMS, ATLAS

JHEP **07** (2023) 046 – JHEP **01** (2018) 63

- *tW* observed with run-1 data, with dilepton decays - same strategy with run-2 data
  - typical selection: 2 e/μ, 1 or 2 jets, 1 b-tag (+ control regions)
  - multivariate discriminants to separate *tW* from backgrounds (especially $t\bar{t}$)
- Recent CMS paper, full run-2 data 138fb^{-1} - $e\mu$ events
  - $\sigma = 79.2 \pm 0.9(\text{stat})^{+7.7}_{-8.0}(\text{syst}) \pm 1.2(\text{lumi})$ pb





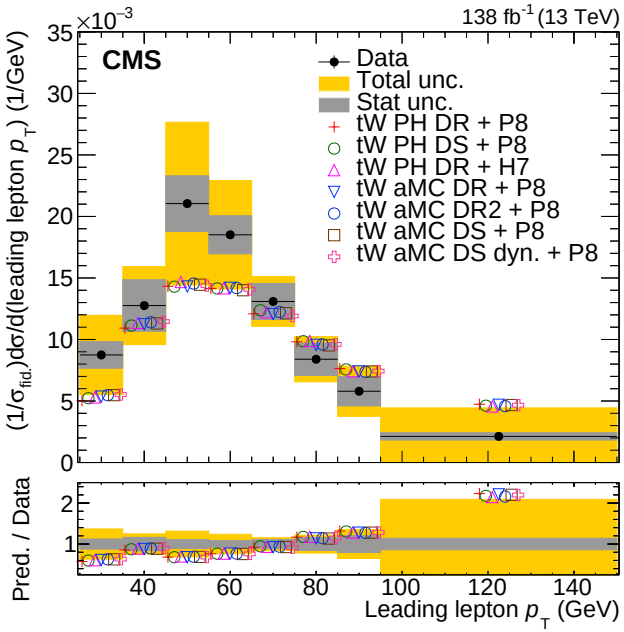


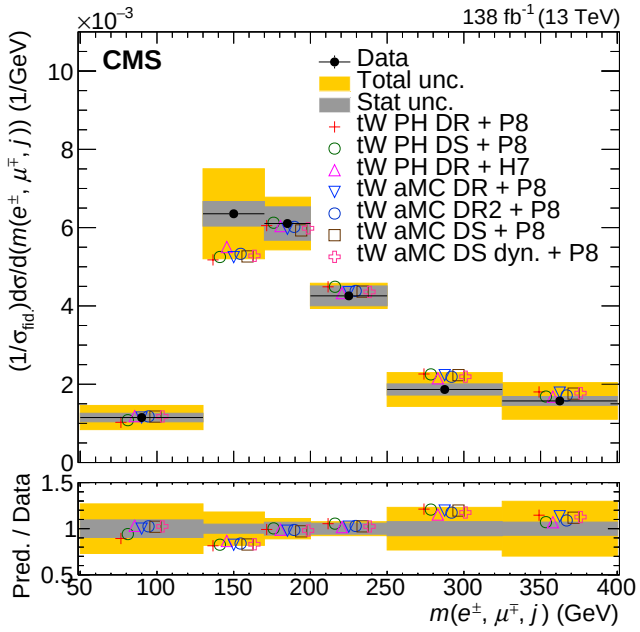
- Earlier ATLAS paper, 2015 data 3.2fb^{-1} - dilepton events
  - $\sigma = 94 \pm 10(\text{stat})^{+28}_{-22}(\text{syst}) \pm 2(\text{lumi})$ pb

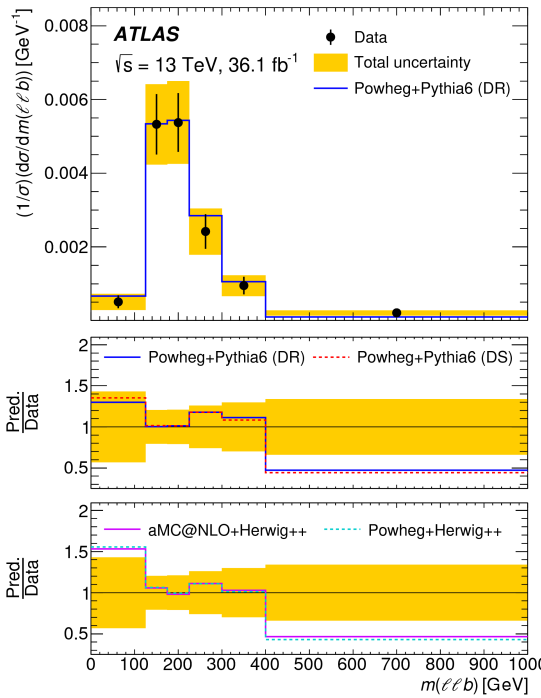
tW 13 TeV differential cross-section – CMS, ATLAS

JHEP **07** (2023) 046 – Eur. Phys. J. C **78** (2018) 186

- Same CMS paper, full run-2 data 138fb^{-1}
- Unfolding at particle level, using a maximum likelihood fit
  - $p_{\mathrm{T}}(\ell_1)$, $p_{\mathrm{T}}(j)$, $\Delta\phi(e,\mu)$, $p_z(e,\mu,j)$, $m_T(e,\mu,j,E_{\mathrm{T}}^{miss})$, $m(e,\mu,j)$
  - various MC models tested - none agree with all measured distributions
- Earlier ATLAS paper, 2015+2016 data 36.1fb^{-1}
  - $E(b)$, $m(\ell_1,b)$, $m(\ell_2,b)$, $E(\ell\ell b)$, $m_T(\ell,\ell,b,\nu\nu)$, $m(\ell\ell b)$
  - measurements dominated by statistical uncertainties



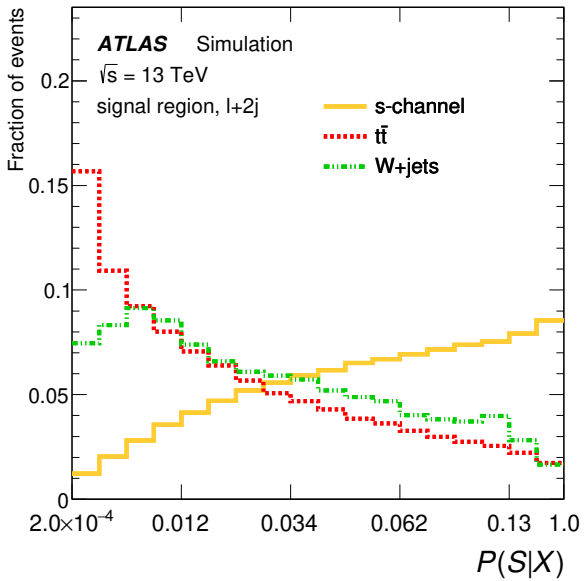


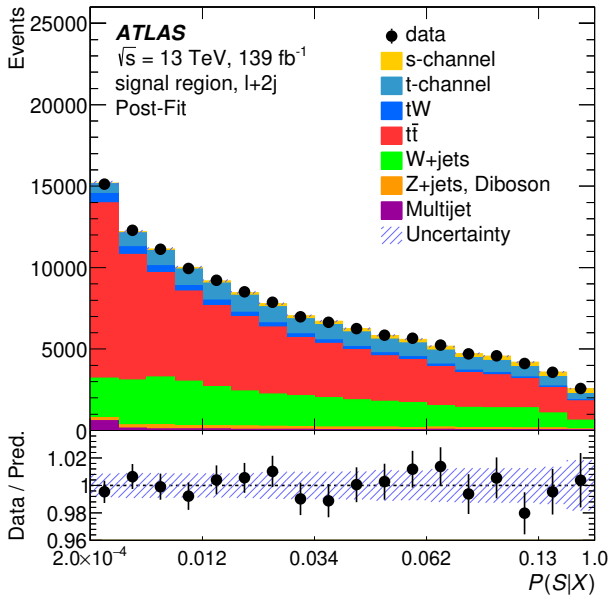


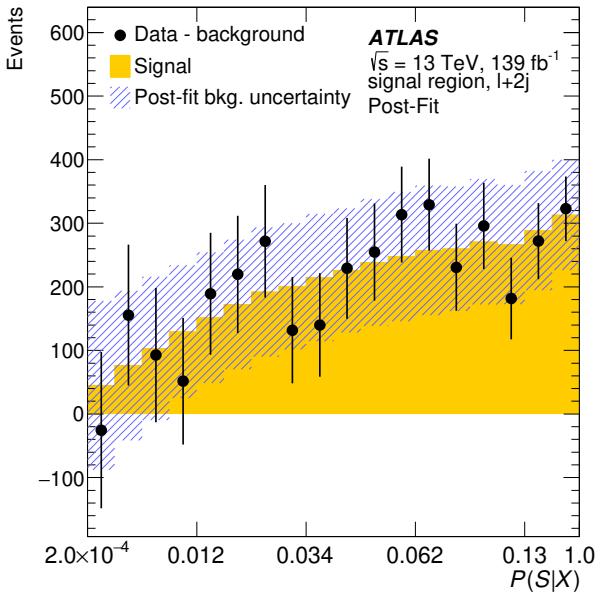
s-channel 13 TeV inclusive cross-section – ATLAS

JHEP **06** (2023) 191

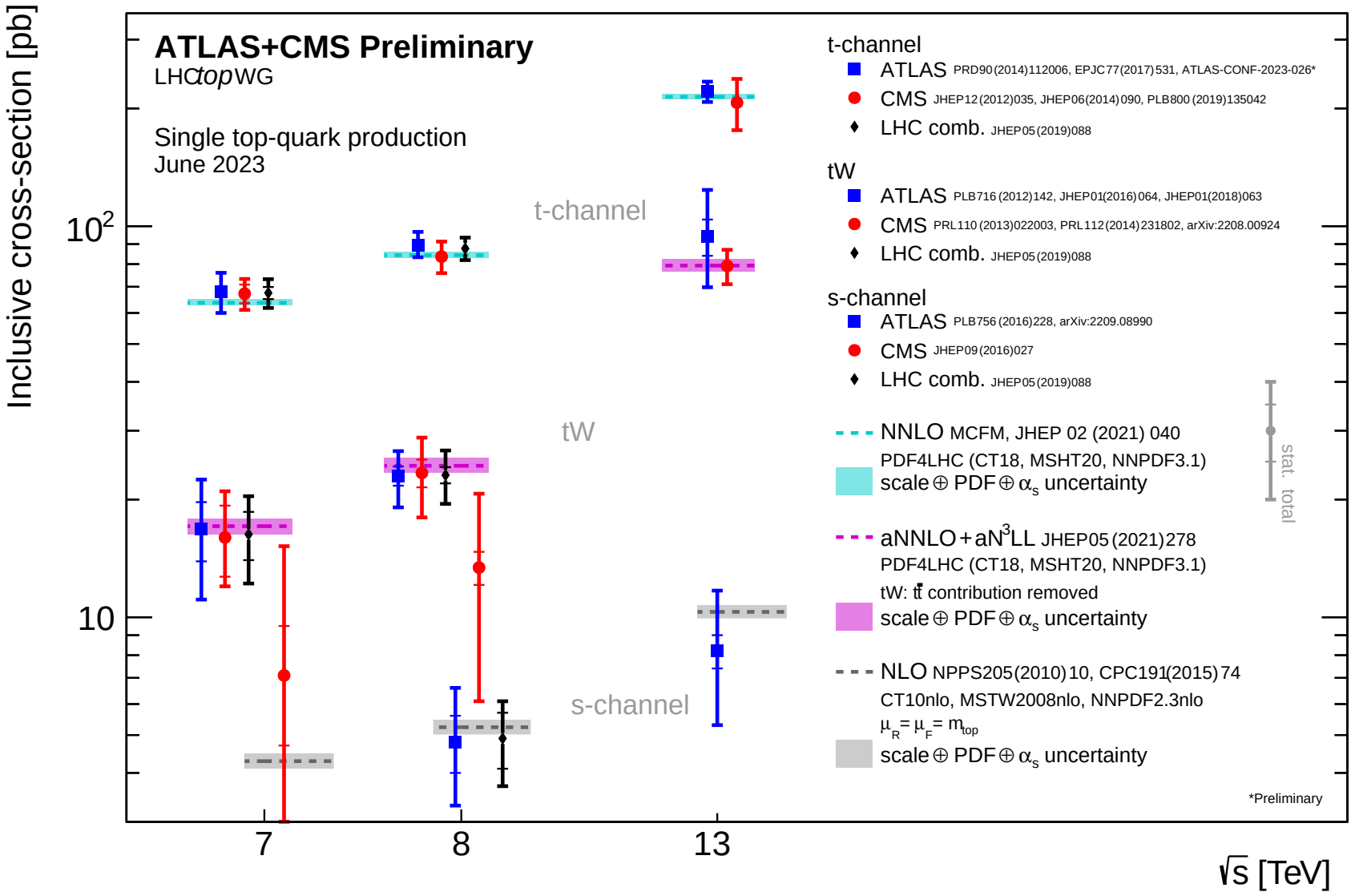
- s-channel is the most challenging - only evidence in run-1 (ATLAS, 8 TeV)
  - $q\bar{q}$ process, vs. gg-dominated $t\bar{t}$: S/B decreases when $\sqrt{s}$ increases
- Recent ATLAS paper, full run-2 data 139fb^{-1} - selection: 1e/μ, 2jets, 2 b-tagged
  - matrix-element method: per-event signal probability used as discriminant
  - using LO matrix-element for signal and background processes
- The measurement is dominated by systematic uncertainties
  - $\sigma = 8.2 \pm 0.6(\text{stat})^{+3.4}_{-2.8}(\text{syst})$ pb - compatible with SM prediction
  - significance: 3.3 σ (3.9 σ expected) - same sensitivity as with 8 TeV data







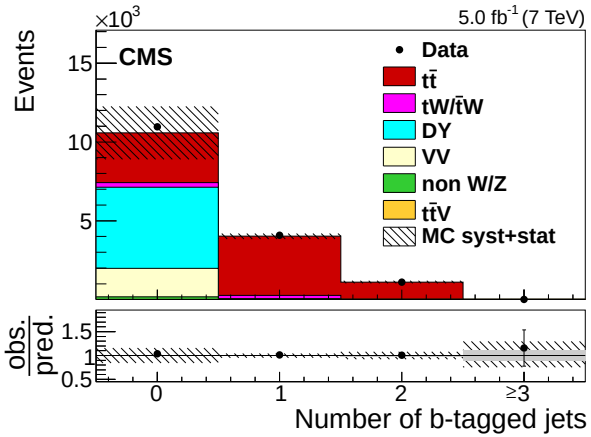
Single-top *pp* cross-sections summary

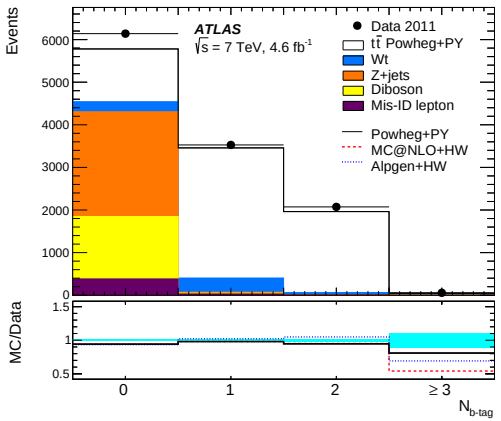


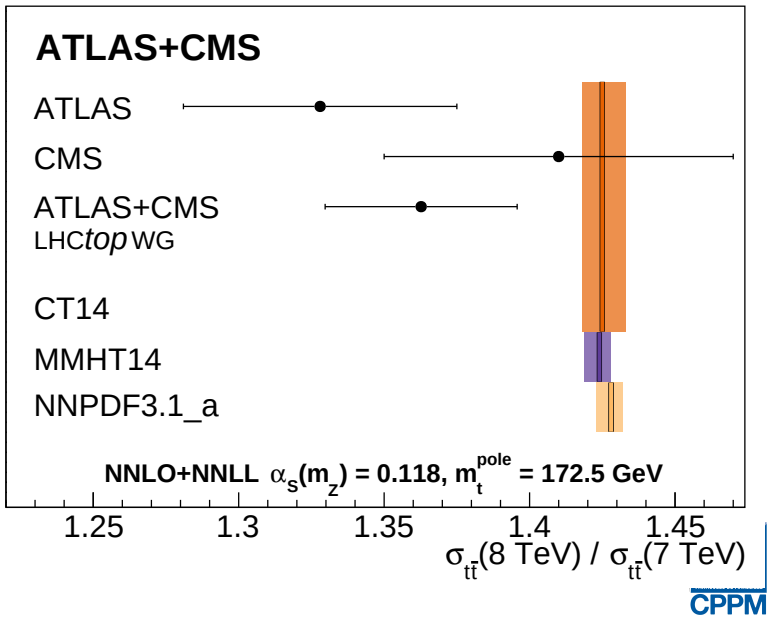
ATLAS+CMS combination of 7 & 8 TeV $t\bar{t}$ cross-sections

arXiv:2205.13830 [hep-ex], accepted by JHEP – inputs: JHEP **08** (2016) 029, Eur. Phys. J. C **74** (2014) 3109

- Precise $t\bar{t}$ inclusive cross-sections measured at run-1
  - counting dilepton events, with *b*-tagged jets – dominated by luminosity uncertainty
- Combined fit of both experiments and energies
  - $\sigma(7\ \mathrm{TeV}) = 178.5 \pm 4.7$ pb [2.7%] $\quad \sigma(8\ \mathrm{TeV}) = 243.3^{+6.0}_{-5.9}$ pb [2.5%]
  - ratio: $R_{8/7} = 1.363 \pm 0.015(\mathrm{stat}) \pm 0.028(\mathrm{syst})$
- 25% (28%) better than 7(8) TeV best measurement
  - reduction of stat. uncertainty by up to 40% – still dominated by luminosity (1.7%)
  - 45% improvement for $R_{8/7}$ wrt. best measurement







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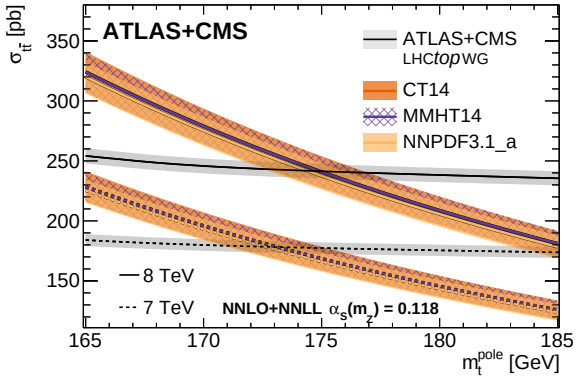
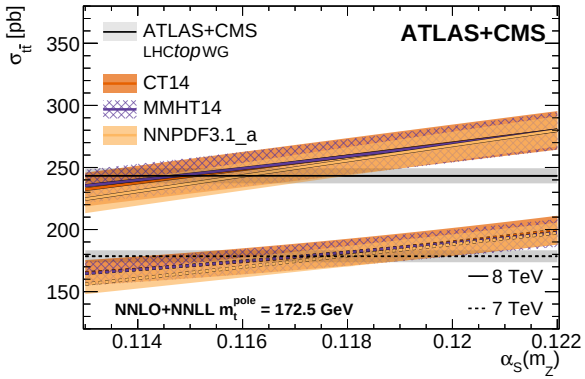
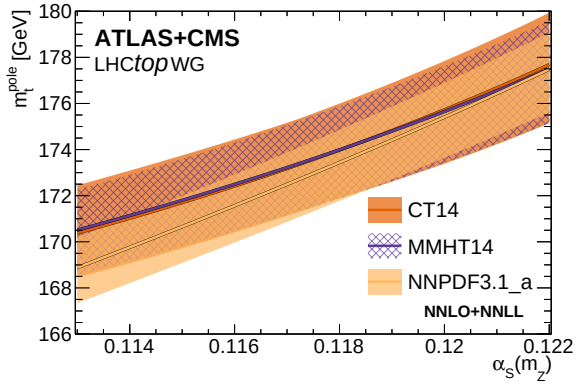
- Dependence of $\sigma_{t\bar{t}}$ on m_t^{pole} and $\alpha_s(m_Z)$
  - ◇ used to infer these parameters from the measured $\sigma_{t\bar{t}}$
- 1.2% uncert. on m_t^{pole} (for $\alpha_s(m_Z) = 0.118 \pm 0.001$)
  - ◇ among the best estimates so far
- 1.8% uncert. on $\alpha_s(m_Z)$ (for $m_t^{pole} = 172.5 \pm 1.0\text{GeV}$)
  - ◇ best estimate among those from top-quark events

PDF set	m_t^{pole} ($\alpha_s = 0.118 \pm 0.001$)	$\alpha_s(m_Z)$ ($m_t = 172.5 \pm 1.0$ GeV)
CT14	$174.0\ ^{+2.3}_{-2.3}$ GeV	$0.1161\ ^{+0.0030}_{-0.0033}$
MMHT2014	$174.0\ ^{+2.1}_{-2.3}$ GeV	$0.1160\ ^{+0.0031}_{-0.0030}$
NNPDF3.1_a	$173.4\ ^{+1.8}_{-2.0}$ GeV	$0.1170\ ^{+0.0021}_{-0.0018}$



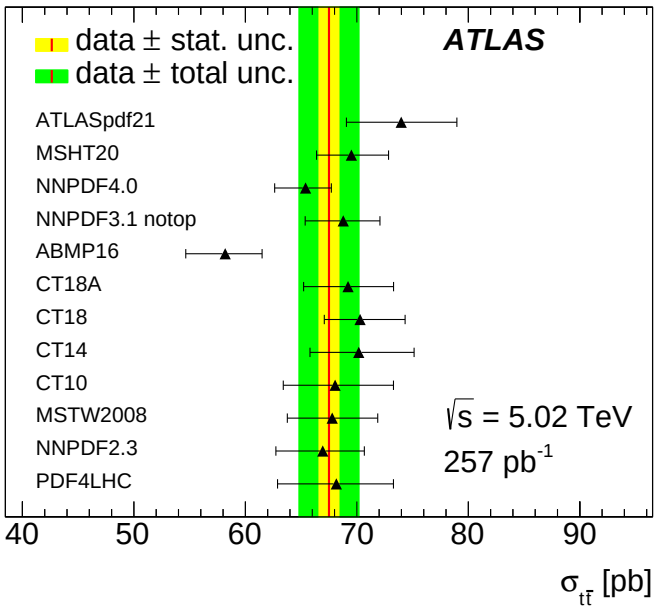


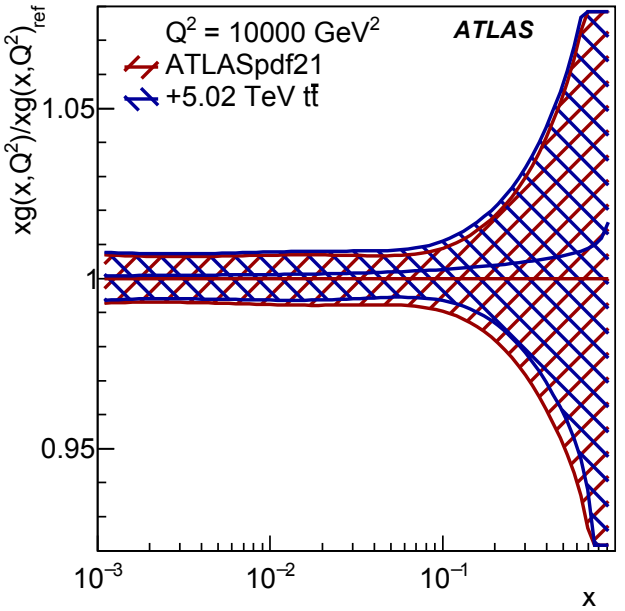


5.02 TeV $t\bar{t}$ inclusive cross-section – ATLAS, CMS

JHEP **06** (2023) 138 – JHEP **04** (2022) 144

- Reference *pp* collision runs were collected during run-2, at $\sqrt{s} = 5.02$ TeV
  - ◇ regime less dominated by *gg* (75% instead of 89% at 13 TeV)
  - ◇ provides usefull constraints for PDFs at low *x*
- Recent ATLAS paper: 2017 data 257pb^{-1}, in dilepton and l+jets channels
  - ◇ $\sigma = 67.5 \pm 0.9(\text{stat}) \pm 2.3(\text{syst}) \pm 1.1(\text{lumi})\text{pb}$
- Earlier CMS paper: 2017 data 302pb^{-1}, in the $e\mu$ channel
  - → combined with result from 2015 data 27.4pb^{-1}, in the l+jets channel
  - ◇ $\sigma = 63.0 \pm 4.1(\text{stat}) \pm 3.0(\text{syst} + \text{lumi})\text{pb}$

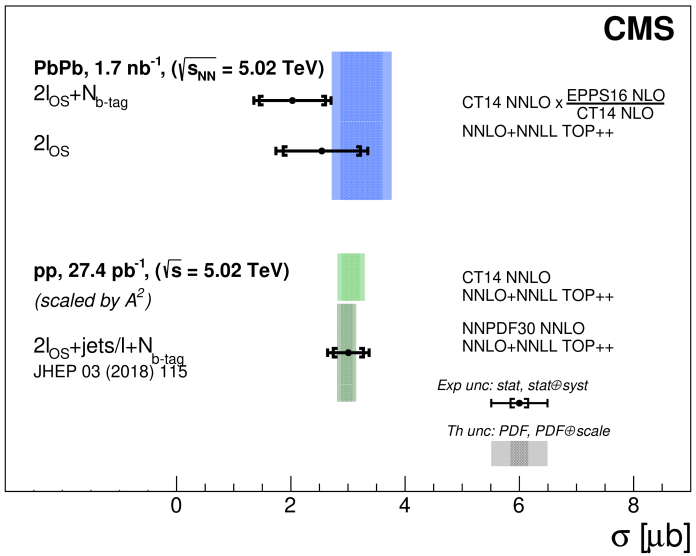


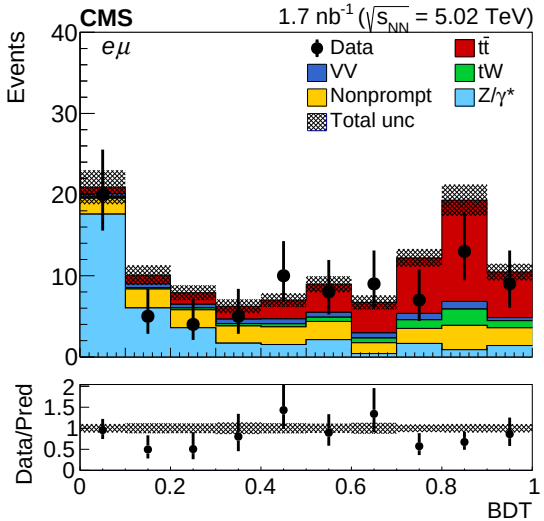


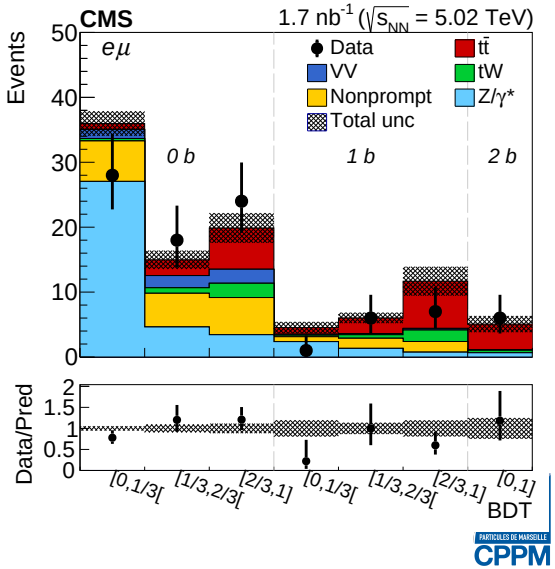
CMS $\sqrt{s_{NN}} = 5.02$ TeV $t\bar{t}$ cross-section in Pb–Pb collisions

Phys. Rev. Lett. **125** (2020) 222001

- CMS paper: evidence of $t\bar{t}$ in *PbPb* collisions
  - using dilepton channel, with a BDT to identify signal
- Two methods: lepton properties only, or with b-tagging
  - w/o b-tagging: $\sigma = 2.54^{+0.84}_{-0.74} \mu b$ - 3.8σ (4.8σ expected)
  - w/ b-tagging: $\sigma = 2.03^{+0.71}_{-0.64} \mu b$ - 4.0σ (5.8σ expected)
- Results compatible with SM predictions (NNLO+NNLL)
  - also with *pp* cross-section at the same $\sqrt{s_{NN}}$, scaled by A^2
- New probe for nuclear PDFs at large *x*







CMS $\sqrt{s_{NN}} = 5.02$ TeV $t\bar{t}$ cross-section in Pb–Pb collisions

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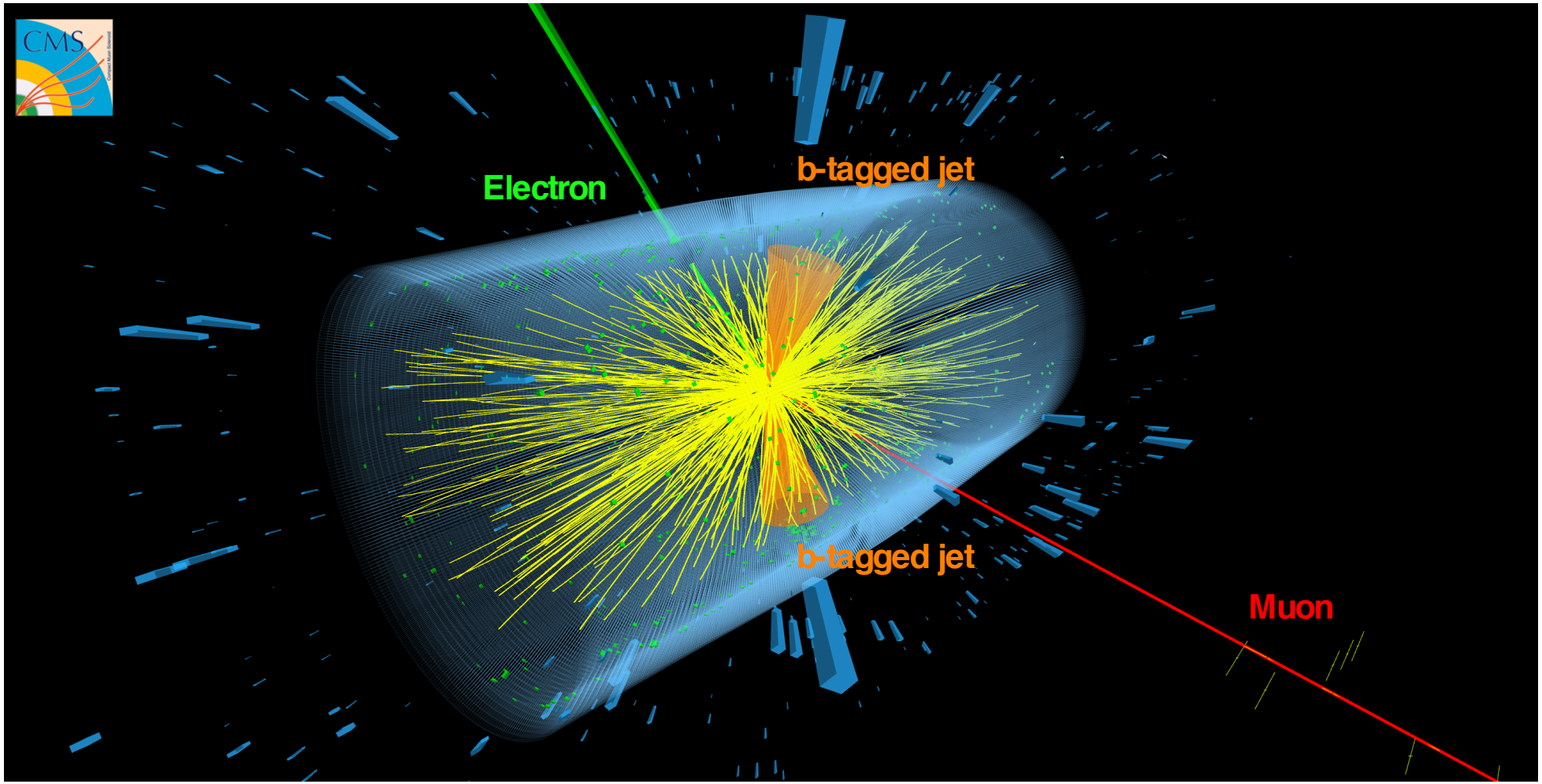
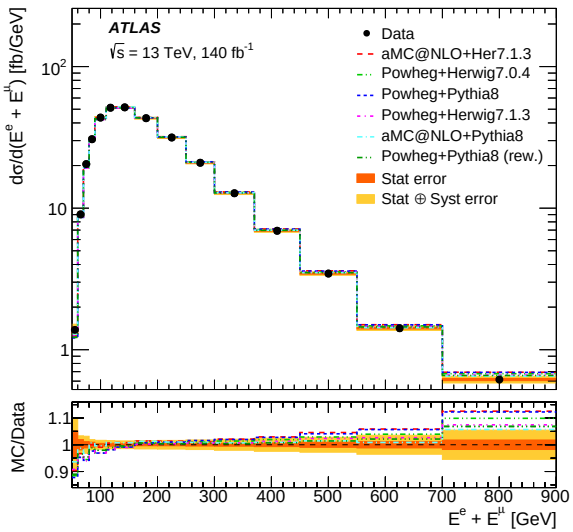
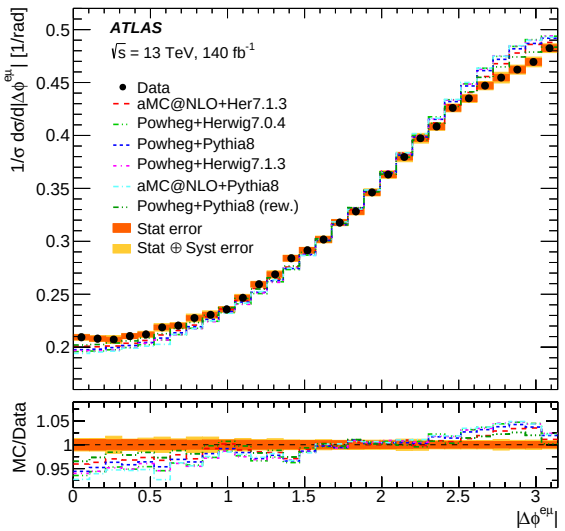


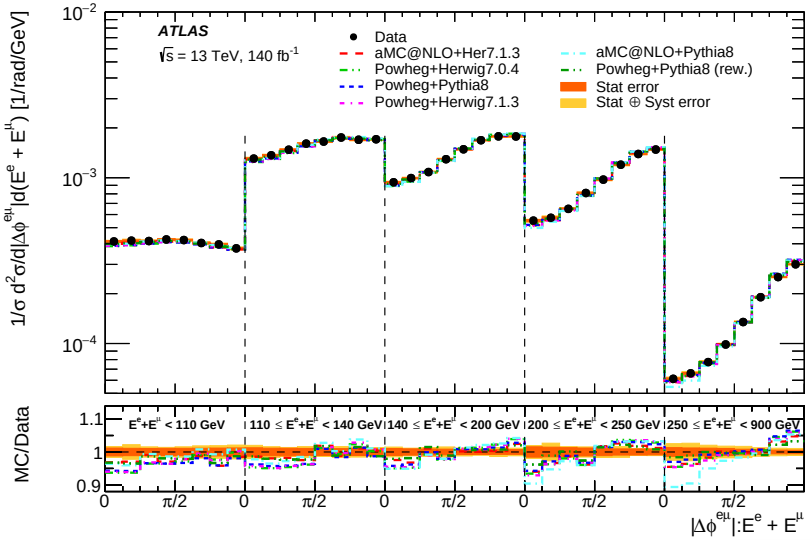
13 TeV $t\bar{t}$ differential cross-section with $e\mu$ events – ATLAS

arXiv:2303.15340 [hep-ex], accepted by JHEP

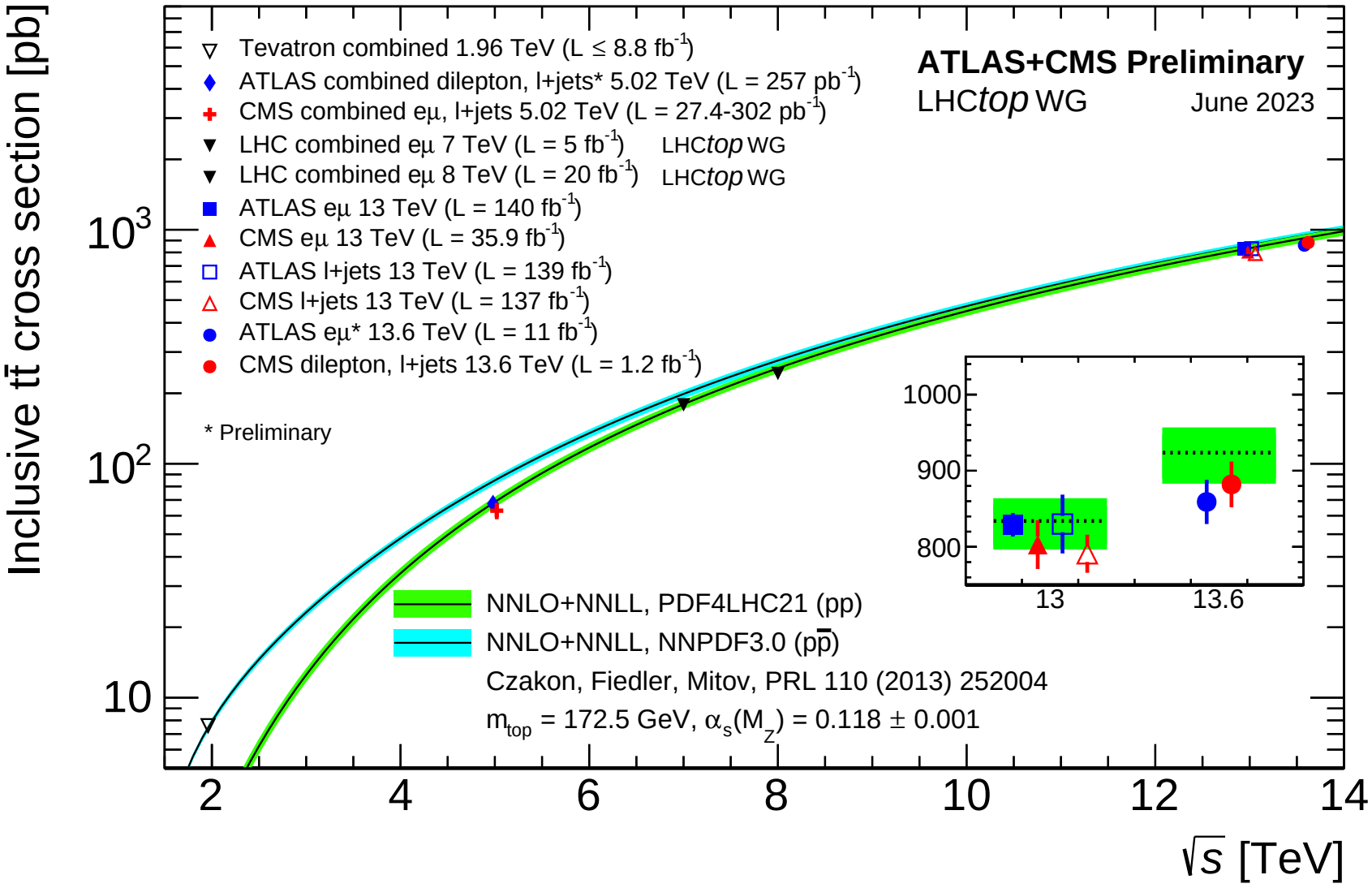
- Recent ATLAS paper, full run-2 data 140fb^{-1}
  - differential cross-sections, wrt. leptonic variables - similar method as for run-1 analysis
- Single- and double-differential cross-sections
  - no MC model can describe all measured distribution
- Inclusive cross-section also measured
  - $\sigma = 829 \pm 1(\text{stat}) \pm 13(\text{syst}) \pm 8(\text{lumi}) \pm 2(\text{beam})\text{pb}$ [1.8%]
  - most precise measurement so far







$t\bar{t}$ pp cross-section summary



Conclusion

- Many recent results for $t\bar{t}$ and single-top - hard to summarise!
- Huge LHC run-2 statistics gives unprecedented precision for $t\bar{t}$
- New CM energies are probed, providing more handle on QCD and PDFs
- Precision measurements for t-channel and tW, while s-channel is challenging
- These many measurements open many possibilities for future interpretations
- See the several other experimental talks this week with LHC results on top physics!