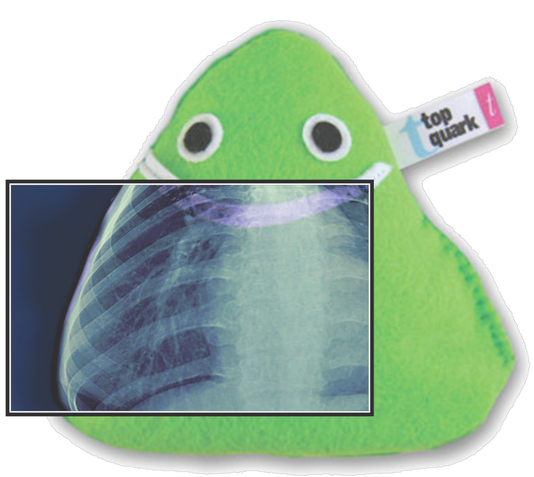
Top Quark Physics and QCD

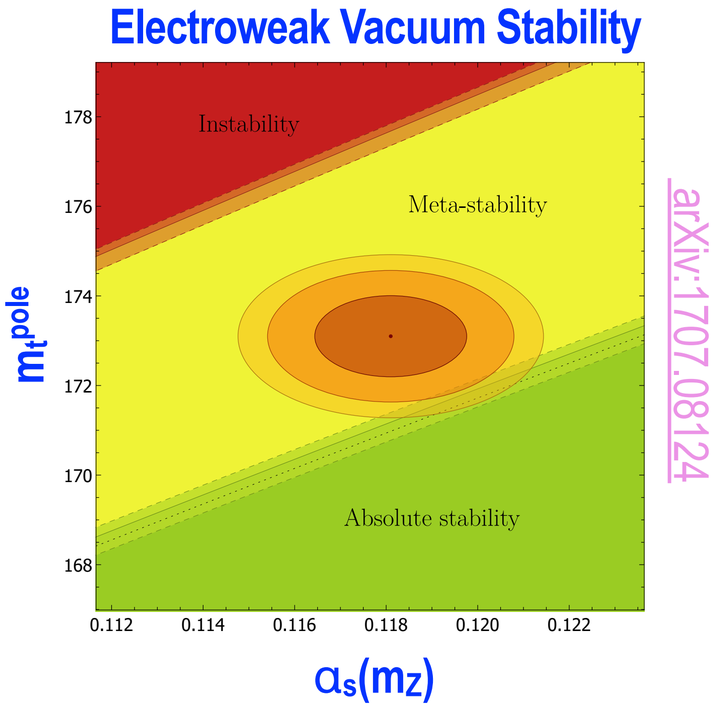


BNL Forum 2017, Oct 12, 2017

Olaf Behnke, DESY, *on behalf of ATLAS and CMS*

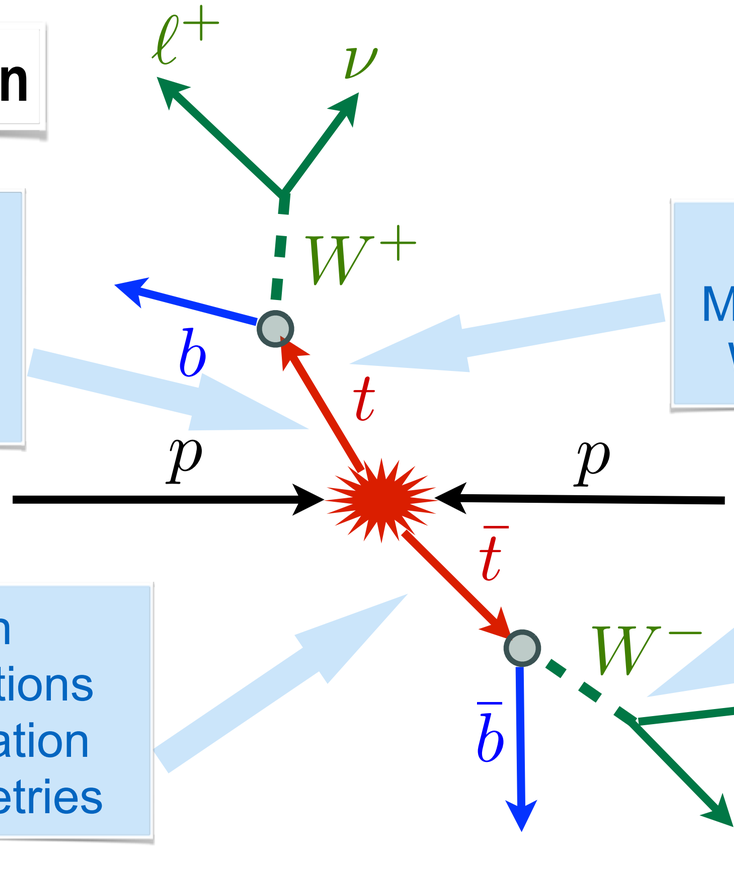
Top Quark Physics

- Heaviest elementary particle → strong coupling to H
- Timescales $\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$ → study bare quarks
- Measure SM parameters & search for new physics



arXiv:1707.08124

Top Quark Pair Production



Cross sections & spectra:
test QCD & BSM,
tt+X production
resonances, new particles

Mass
Mass Difference,
Width, Charge

Spin
Correlations
Polarisation
Asymmetries

W-Helicity Fractions
Branching Ratios,
V_{tb}, Rare Decays,
FCNC

Decay channels

$W^+W^- \to l\nu l\nu$
Dileptonic

$W^+W^- \to l\nu jj$
$l - jets$

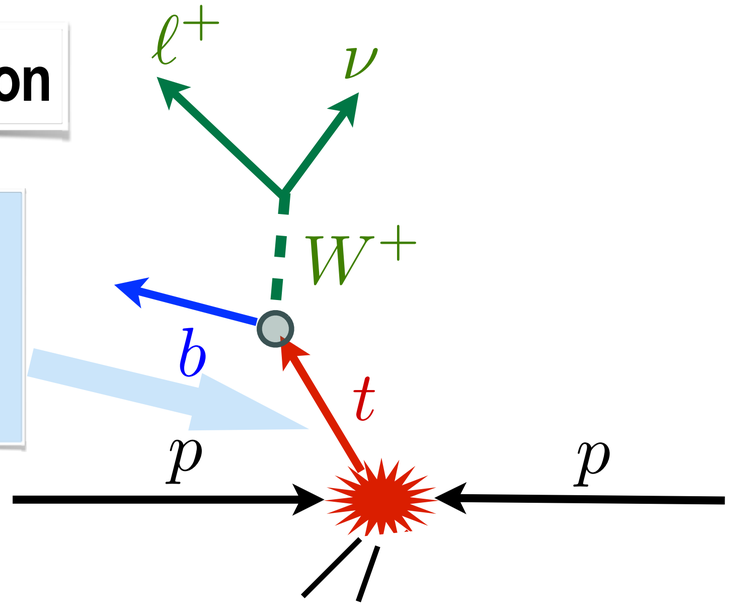
$W^+W^- \to jjjj$
$All - hadronic$

Top Quark Physics

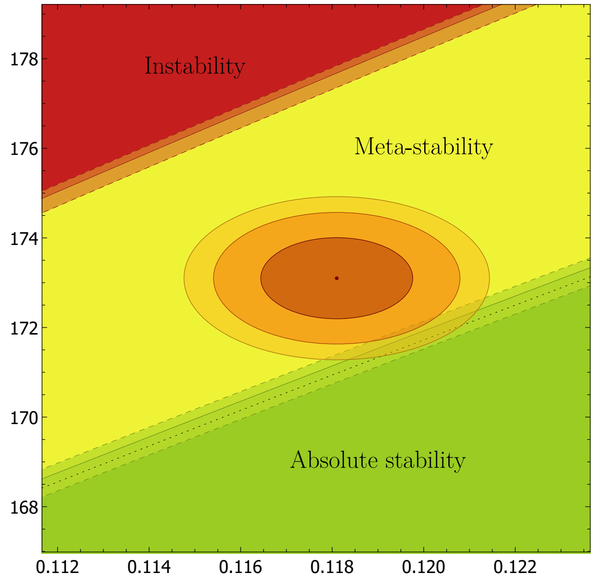
- Heaviest elementary particle → strong coupling to H
- Timescales $\underbrace{\frac{1}{m_t}}_{\text{production } 10^{-27}\text{ s}} < \underbrace{\frac{1}{\Gamma_t}}_{\text{lifetime } 10^{-25}\text{ s}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\text{hadronization } 10^{-24}\text{ s}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\text{spin-flip } 10^{-21}\text{ s}}$ → study bare quarks
- Measure SM parameters & search for new physics

EWK Single-Top Production

s and t channel, tW, tZ production,
polarisation, Vtb, FCNC, W-helicity, mass



Electroweak Vacuum Stability



arXiv:1707.08124

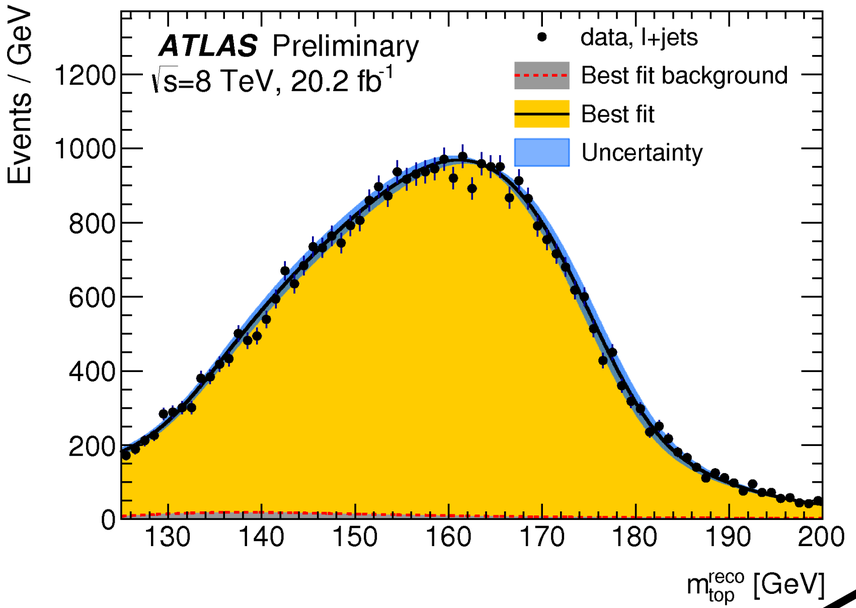
Decay channels

use only

$W^+ \to l\nu$

Top Quark Mass

- Most precise: template fits in l+jet channel



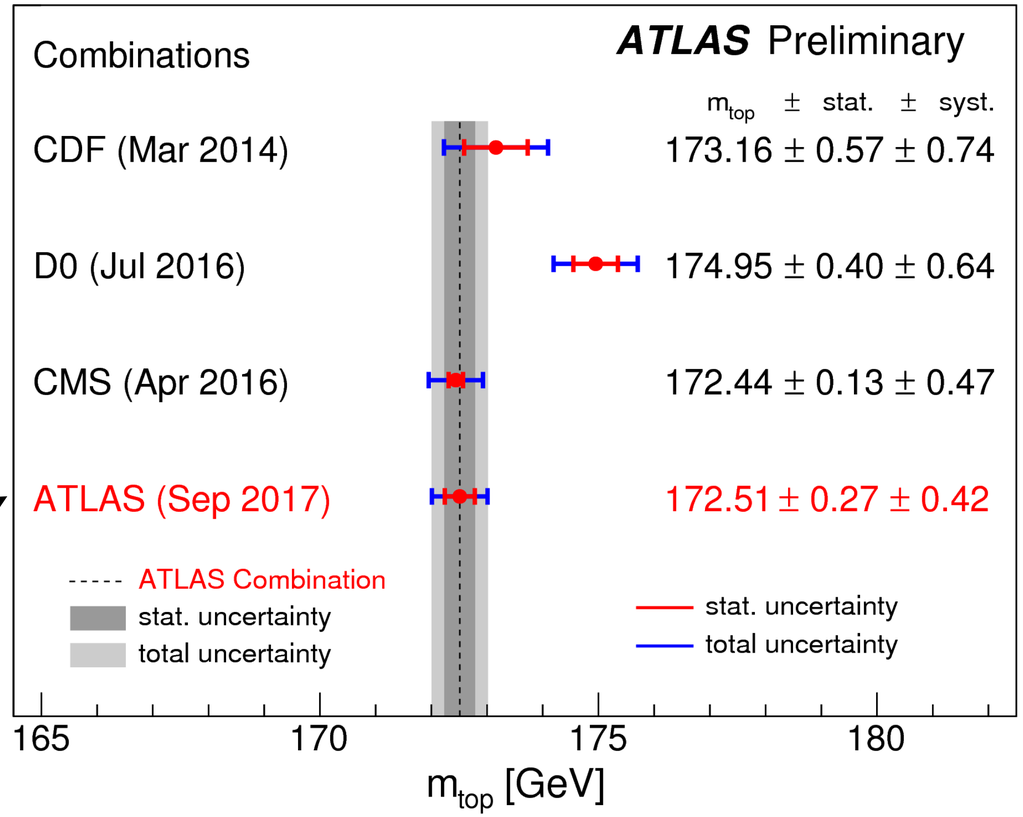
$m_{top} = 172.08 \pm 0.39 \pm 0.82$ GeV

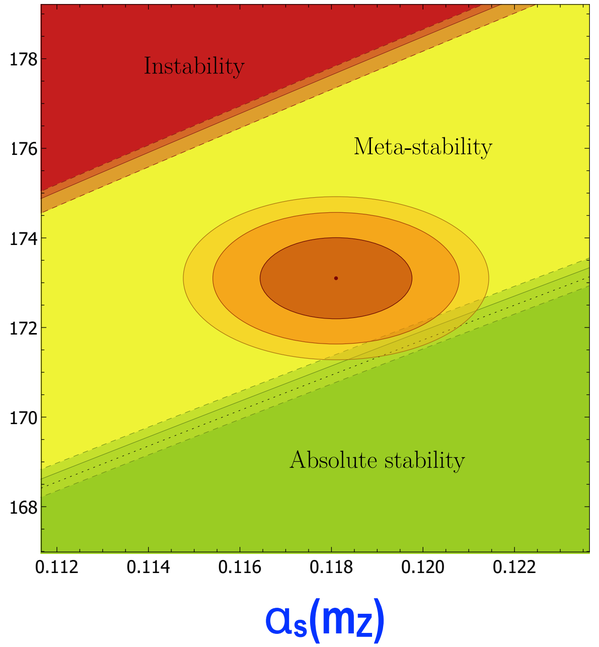
New CMS result at @13 TeV:

$m_{top} = 172.35 \pm 0.08 \pm 0.63$ GeV

CMS-PAS-TOP-17-007

ATLAS-CONF-2017-071

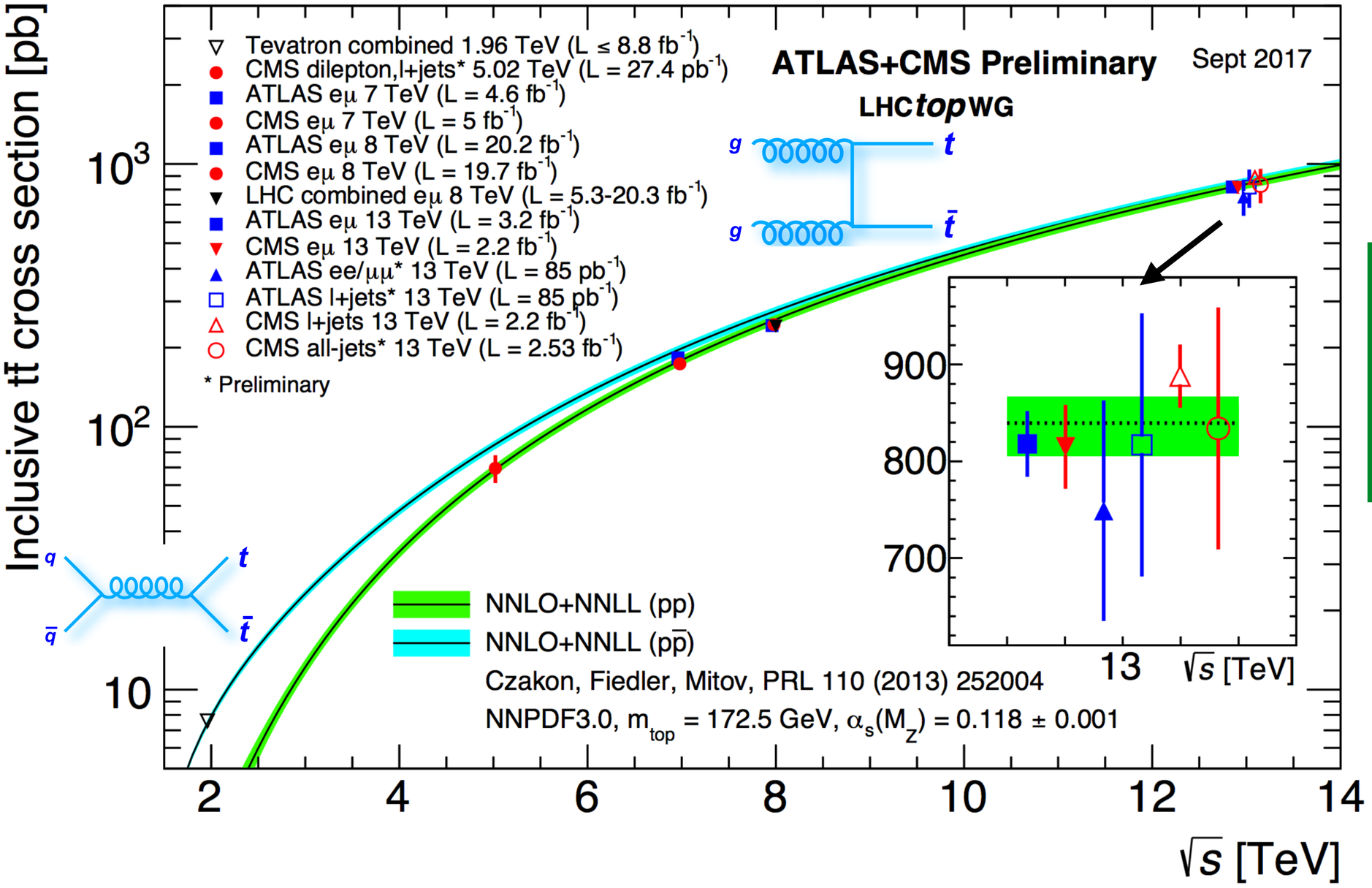




➡ Approaching
< 0.5 GeV precision

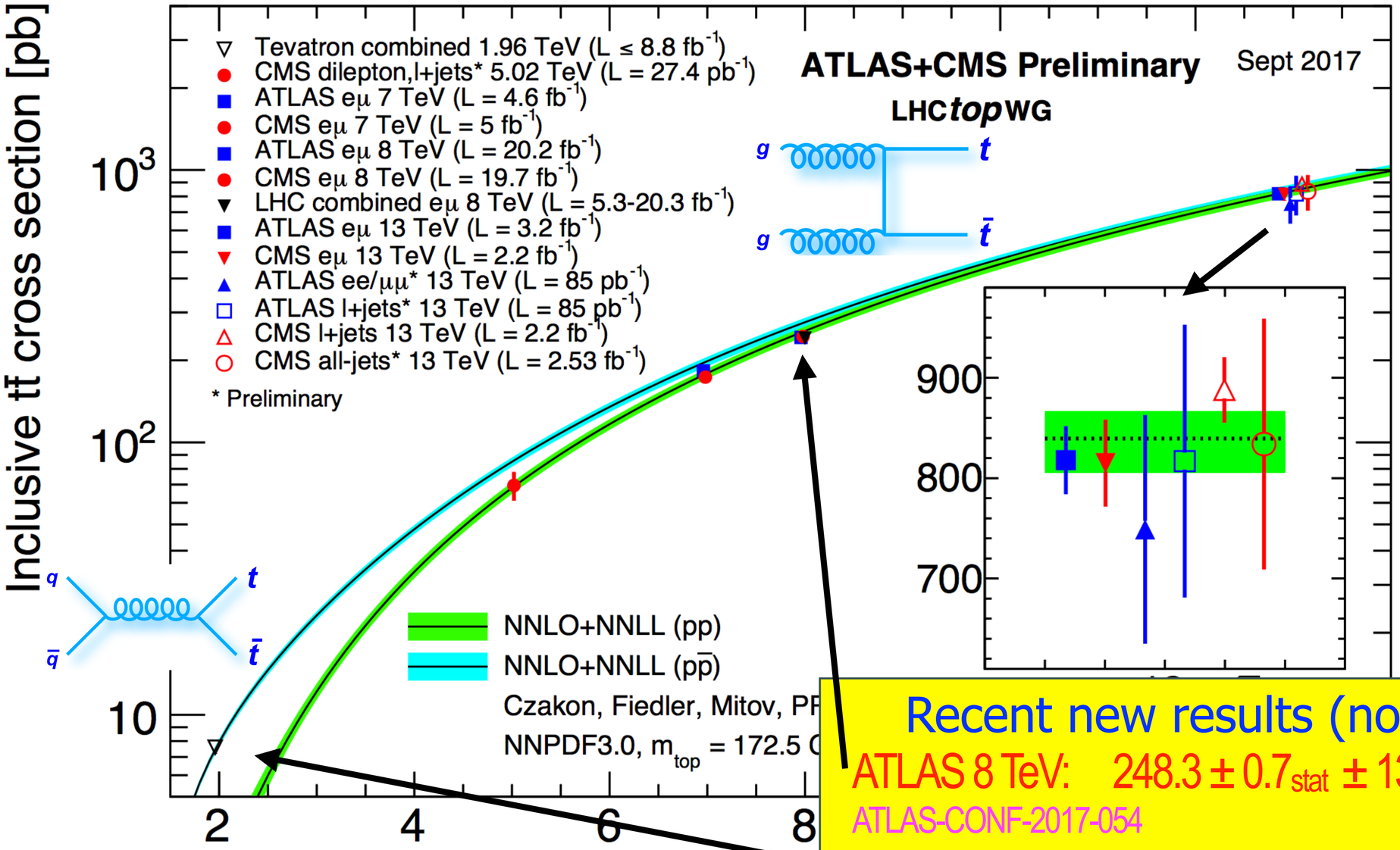
- Pole mass from cross sections $\sigma_{t\bar{t}}$ → most precise results: 173.2 ± 1.6 GeV ATLAS: CONF-2017-044
  173.8 ± 1.8 GeV CMS: JHEP 08 (2016) 029

Inclusive $t\bar{t}$ cross section $\sigma_{t\bar{t}}$



- Data described by NNLO theory
- competing precisions

Inclusive $t\bar{t}$ cross section $\sigma_{t\bar{t}}$



➡ Data described by NNLO theory

➡ competing precisions

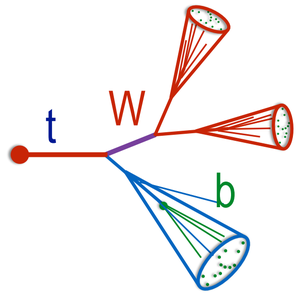
Recent new results (not yet in plot):

ATLAS 8 TeV: $248.3 \pm 0.7_{stat} \pm 13.4_{syst} \pm 4.7_{lumi}$ pb (5.7%)
ATLAS-CONF-2017-054

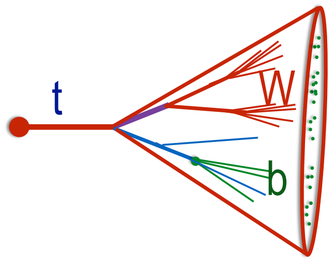
D0: 1.96 TeV: $7.26 \pm 0.13_{stat} \pm 0.57_{syst}$ pb (7.6%)
arXiv:1605.06168

$t\bar{t}$ differential distributions: p_T(top)

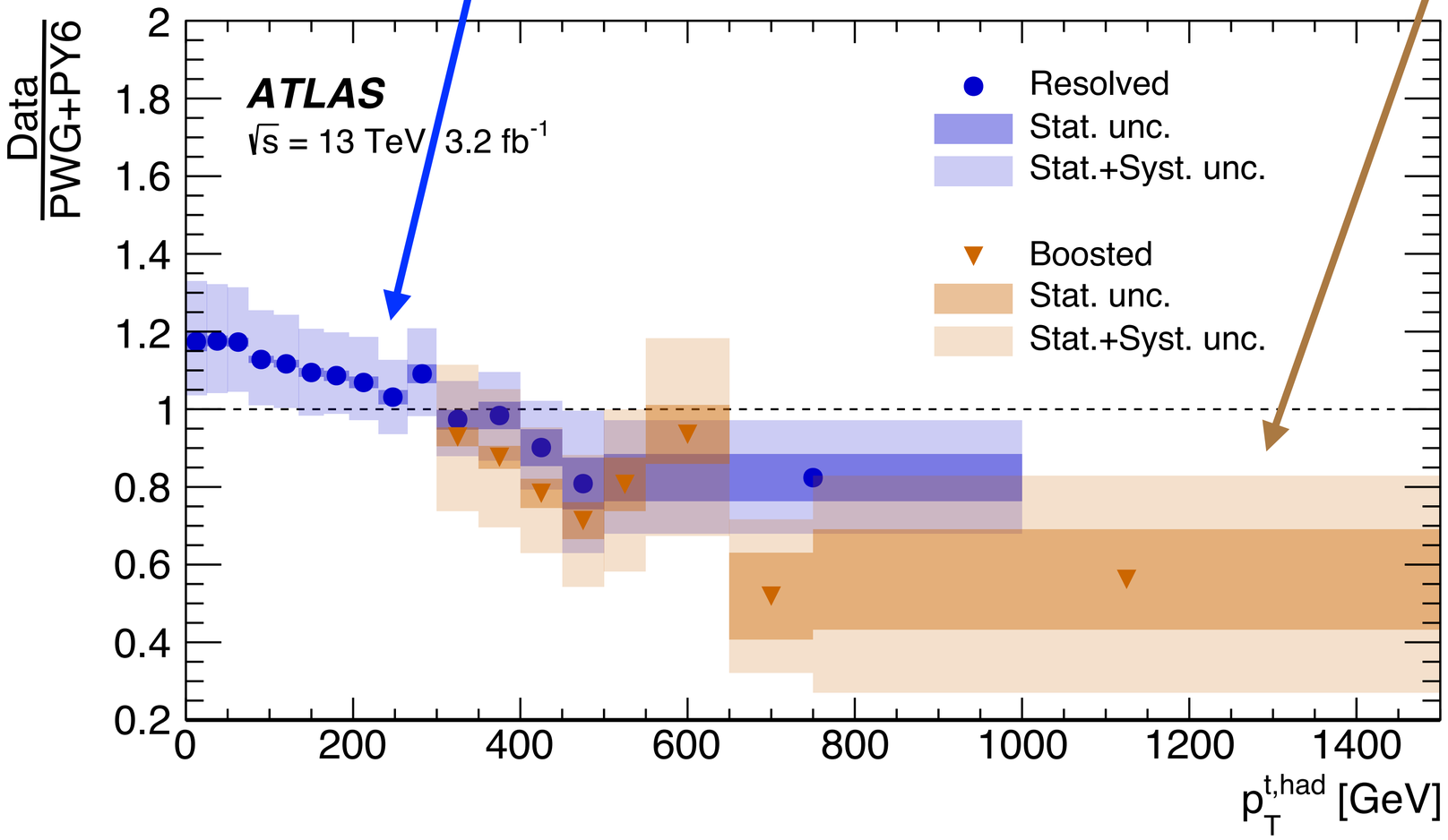
arXiv:1708.00727 **l+ jets**



"resolved": 3 jets k_T=0.4



"boosted": 1 (top-tagged) jet k_T=1.0



➡ NLO calculations: too hard p_T(top) spectrum

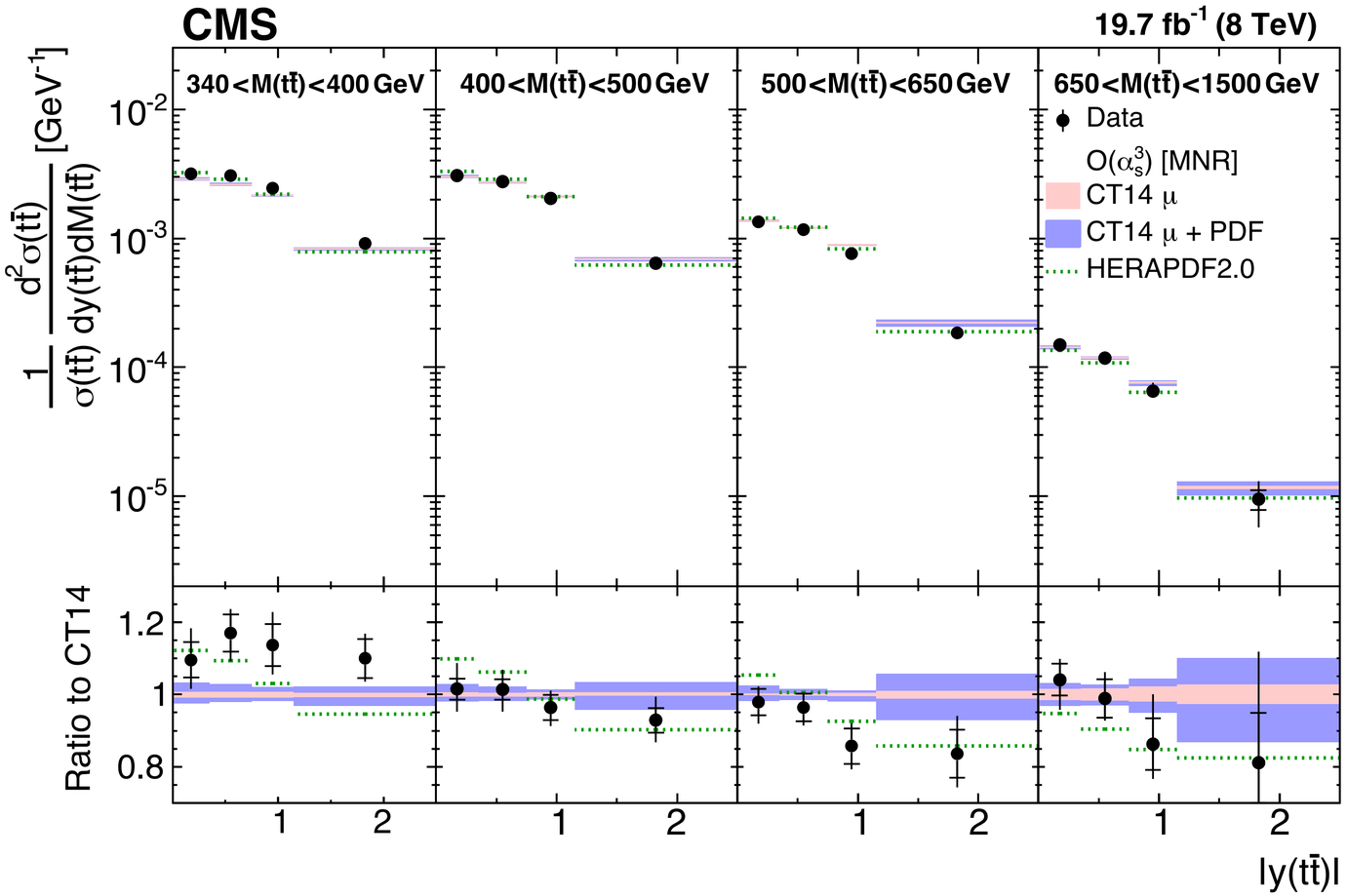
➡ Similar effect seen at 8 TeV, cured with NNLO

Many new precise differential cross sections:

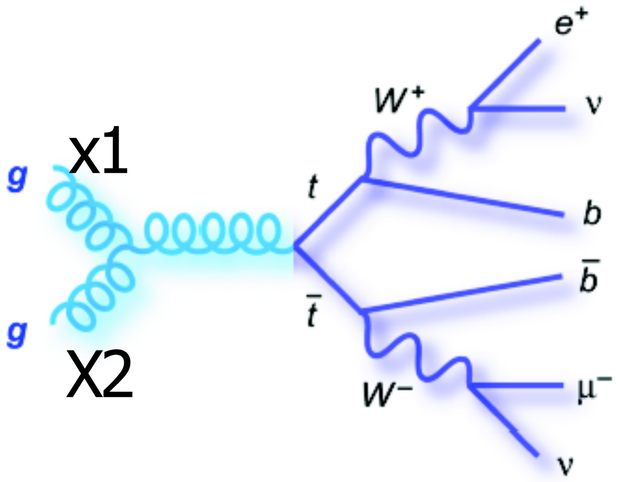
ATLAS: CONF-2017-044, CONF-2016-100, arXiv:1612.05220, arXiv:1607.07281
CMS: PAS-TOP-17-002, arXiv:1708.07638, arXiv:1610.04191, PAS-TOP-16-018, PAS-TOP-16-013

Double differential $t\bar{t}$ cross sections

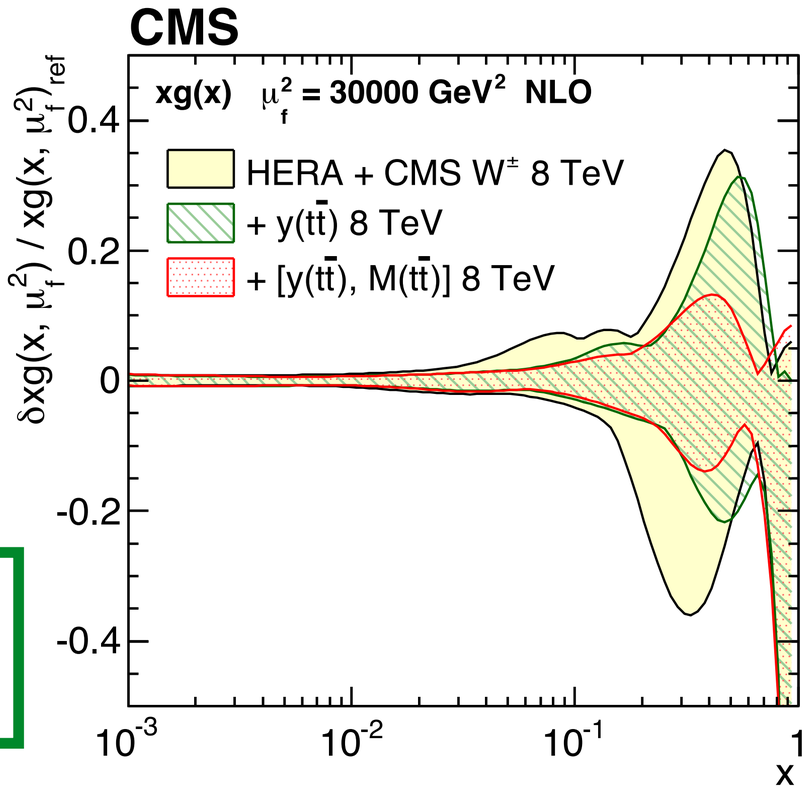
EPJC 77 (2017) 459



Leading order



$x1 = M(t\bar{t})/2Ep \bullet \exp(y(t\bar{t}))$



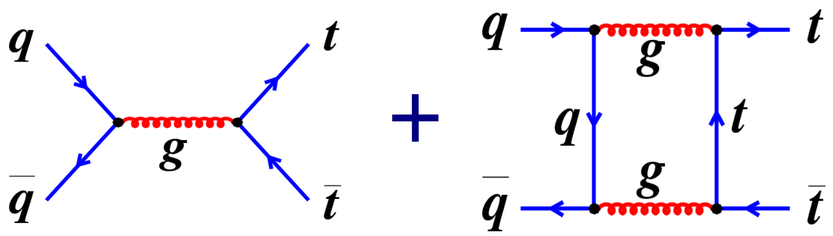
➡ improved gluon density at large x

➡ RUN II: Aim to constrain PDFs, α_s and m(top) simultaneously

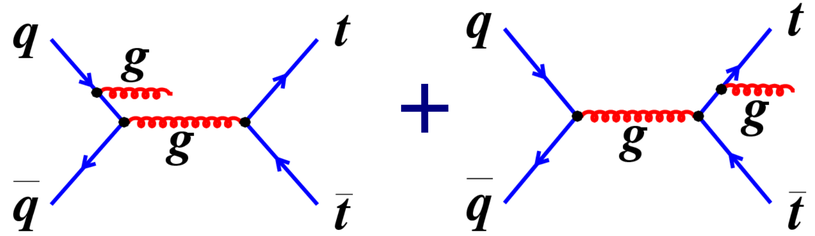
Charge Asymmetry A_C

- NLO: $q\bar{q}$ diagrams interfere
- Diluted @LHC due to large gg fraction

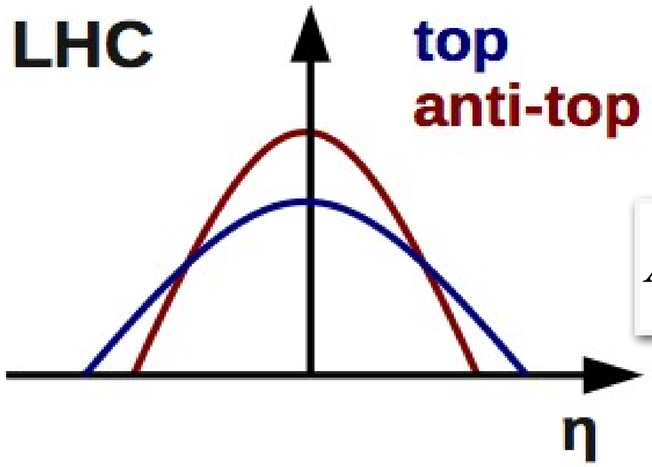
$q\bar{q}$ tree-level and box diagrams: positive asymmetry



ISR/FSR: negative asymmetry

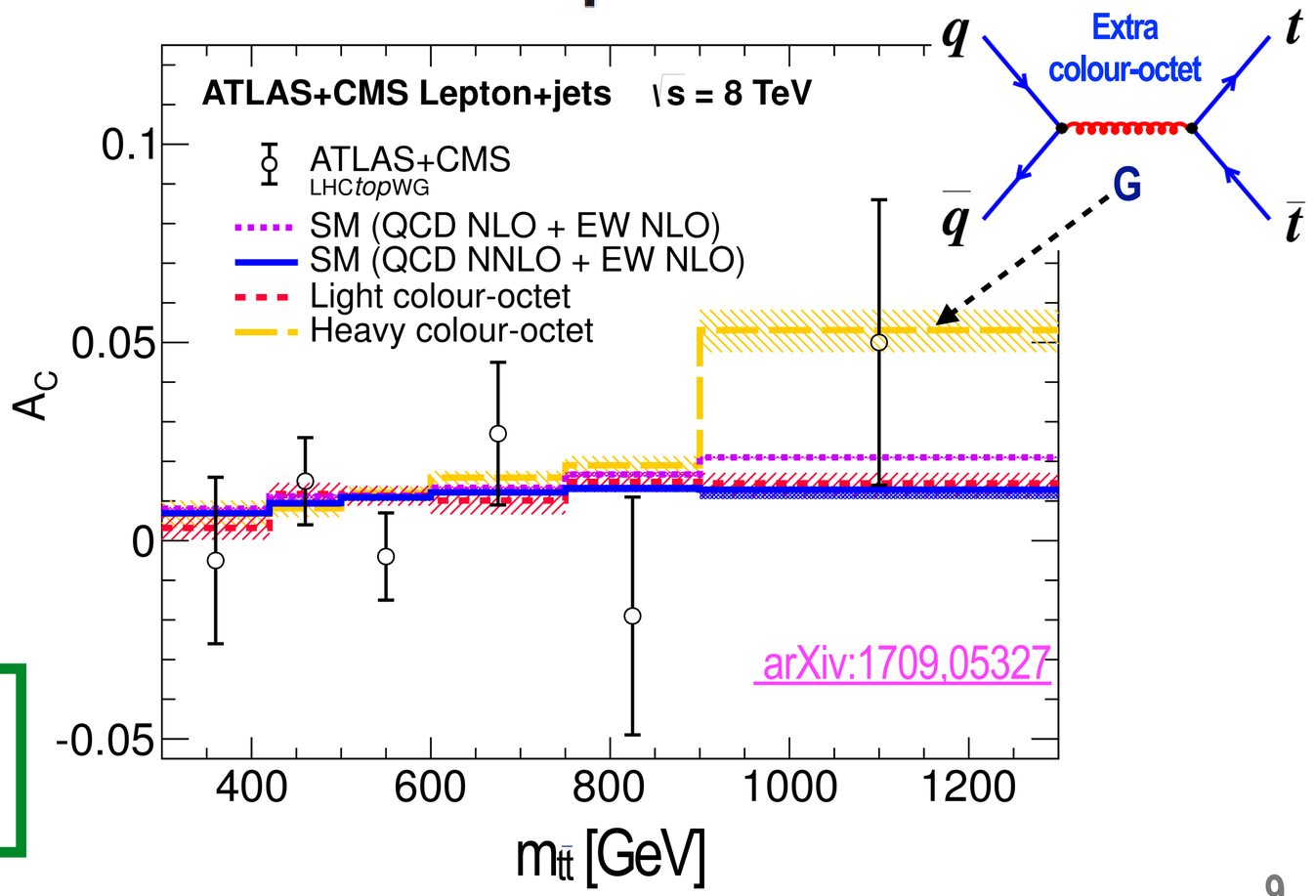


➡ Measurements consistent with SM and zero



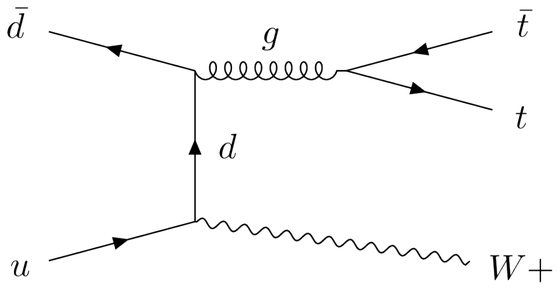
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

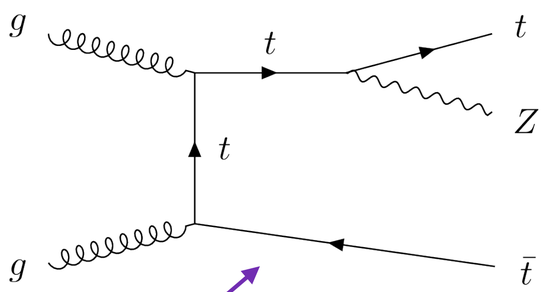


ttW and ttZ

CMS-PAS-TOP-17-005



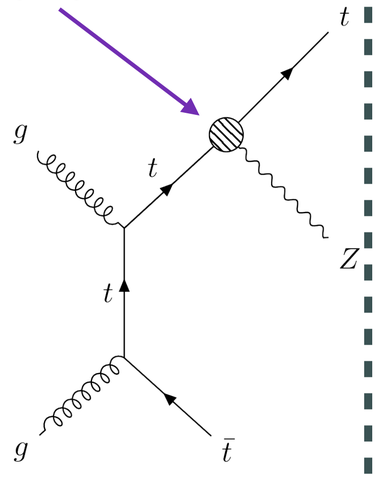
2ℓ (same-sign) + b-jets



3ℓ or 4ℓ + b-jets

- EFT approach: $L_{eff} = L_{sm} + \frac{1}{\Lambda^2}\sum_j c_j O_j + \ldots$
- Fitted coefficients:

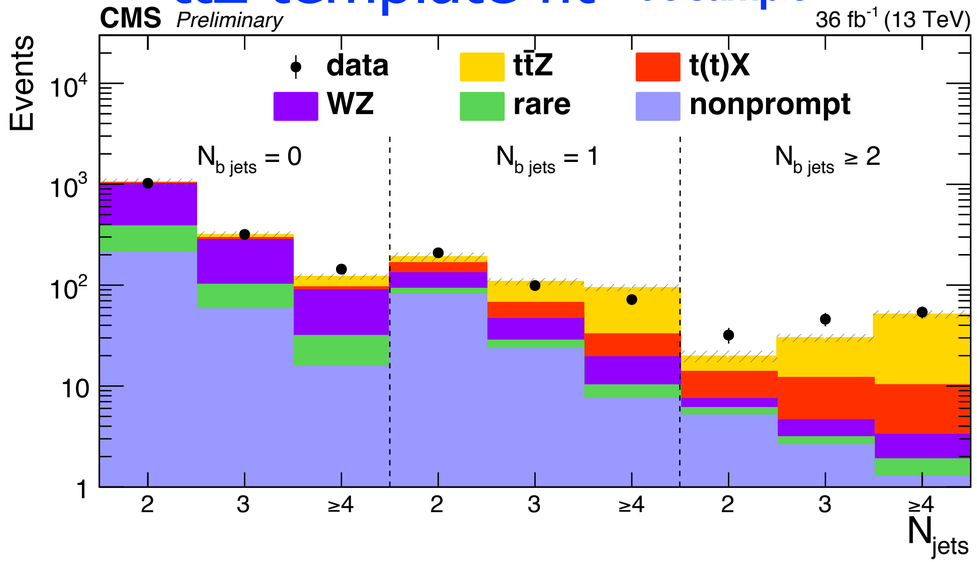
Wilson coefficient	Best fit $[\mathrm{TeV}^{-2}]$	1σ CL $[\mathrm{TeV}^{-2}]$
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	1.6	[0.0, 2.3]
$\lvert\bar{c}_{u}/\Lambda^2 + 10.9\ \mathrm{TeV}^{-2}\rvert$	11.1	[2.7, 15.6]
$\bar{c}_{uW}/\Lambda^2$	1.8	[-2.4, -0.8] and [0.7, 2.4]
$\bar{c}_{Hu}/\Lambda^2$	-9.4	[-10.3, -8.1] and [0.1, 2.1]

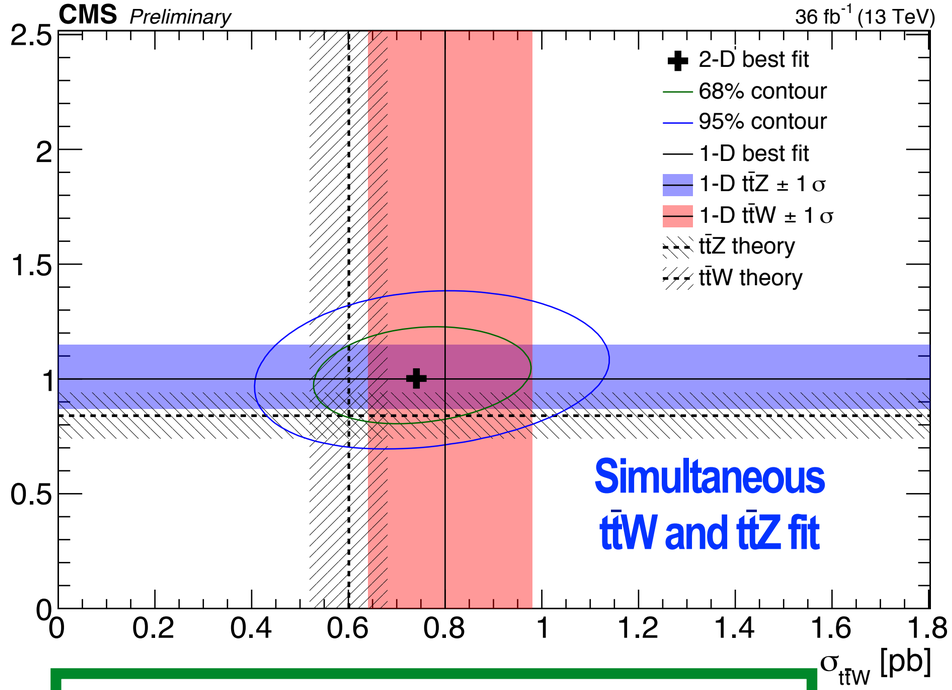


➡ no significant deviations from SM

ATLAS RUN II results: EPJC 77 (2017) 40

ttZ template fit 3ℓ sample

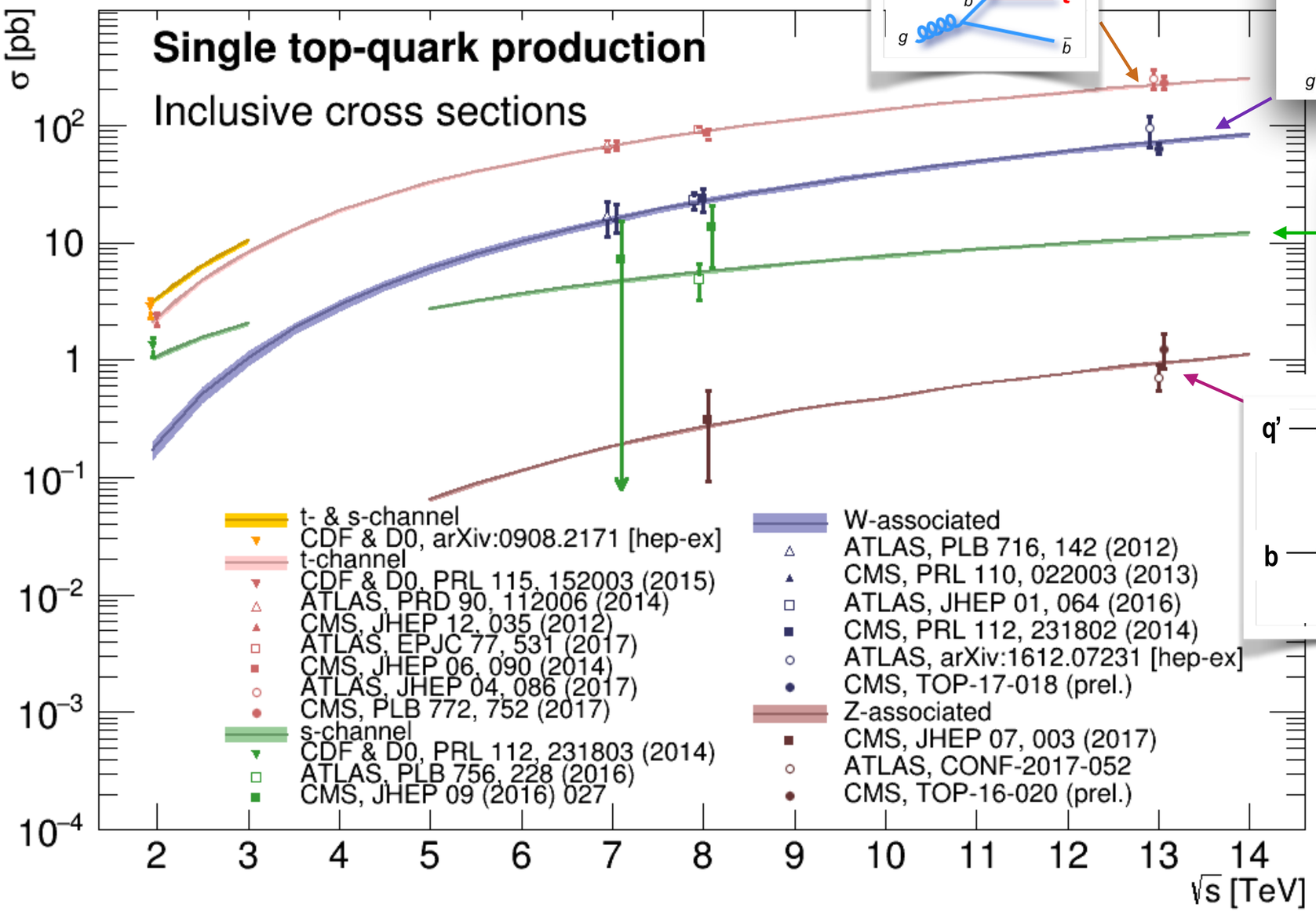




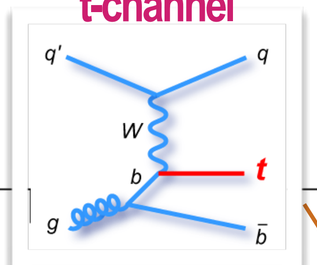
➡ ttZ in precision regime

Single-Top Quarks

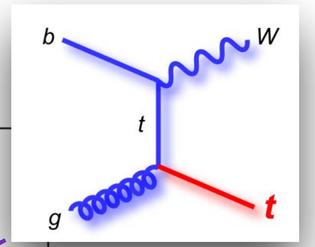
Picture from upcoming paper (A. Giammanco & R. Schwienhorst),
Theory curves: N. Kidonakis (t., tW, s, @ NLO+NNLL) & J. Andrea (tZ @ NLO)



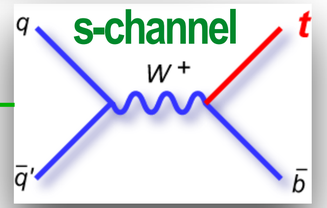
t-channel



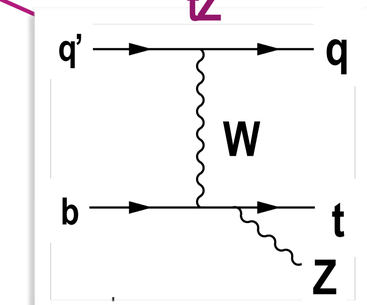
tW



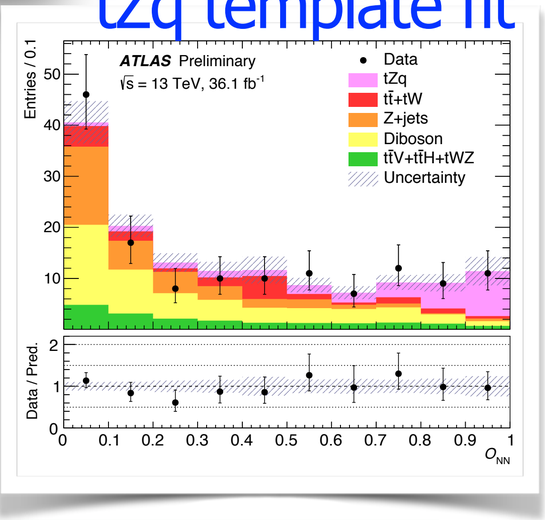
s-channel



tZ



tZq template fit



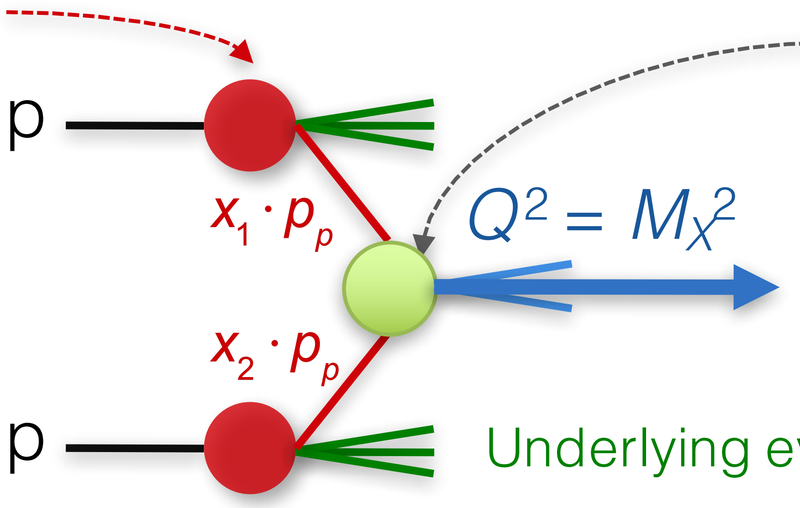
➡ Many new results!

➡ SM predictions 😀

QCD at LHC

Parton distribution functions PDFs

Representing structure of proton, extracted using experimental data and QCD properties



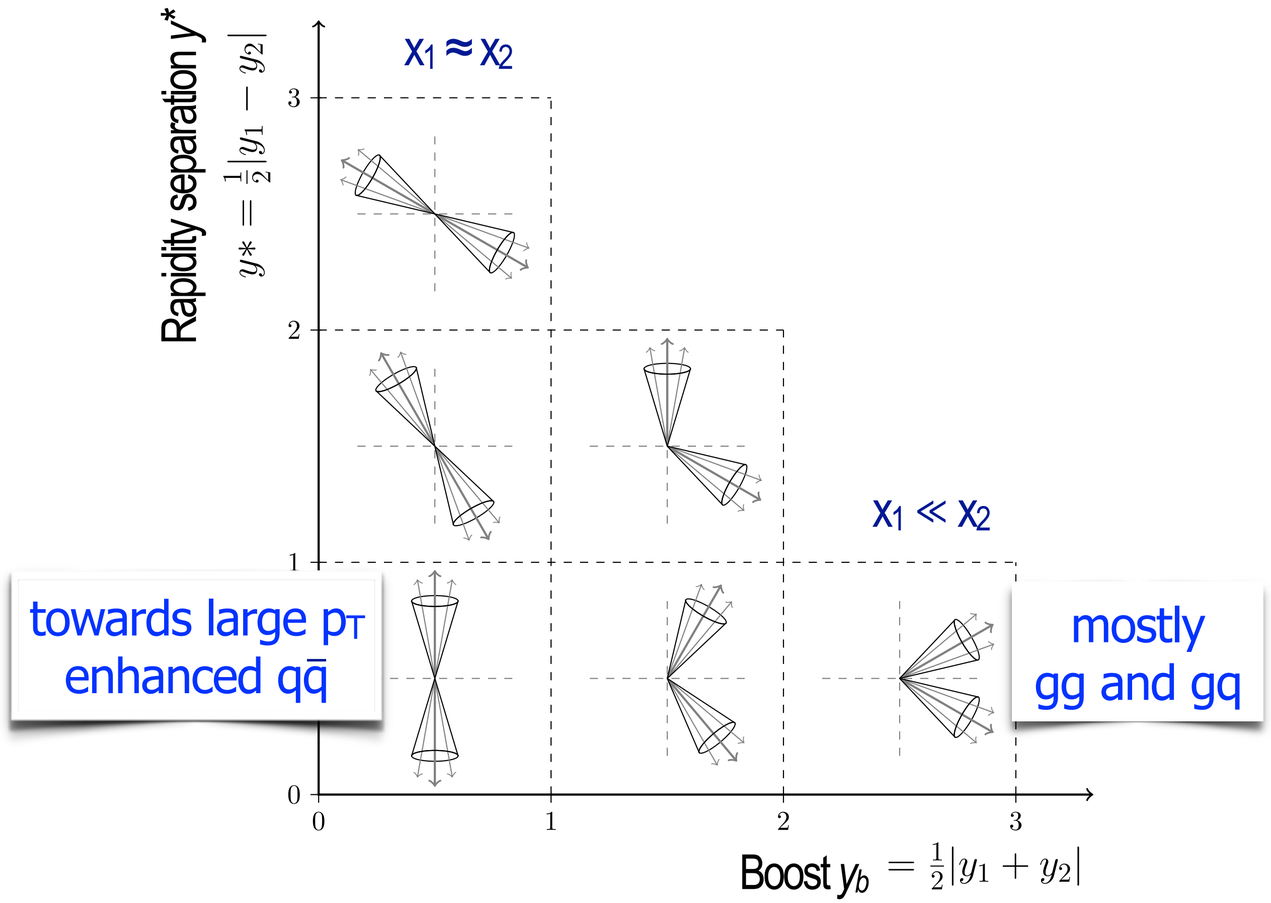
Hard scatter parton cross section

Higher order pQCD correction; accompanying radiation, jets, …

- Focus in the following on two new studies with high p_T jets

Triple differential dijets

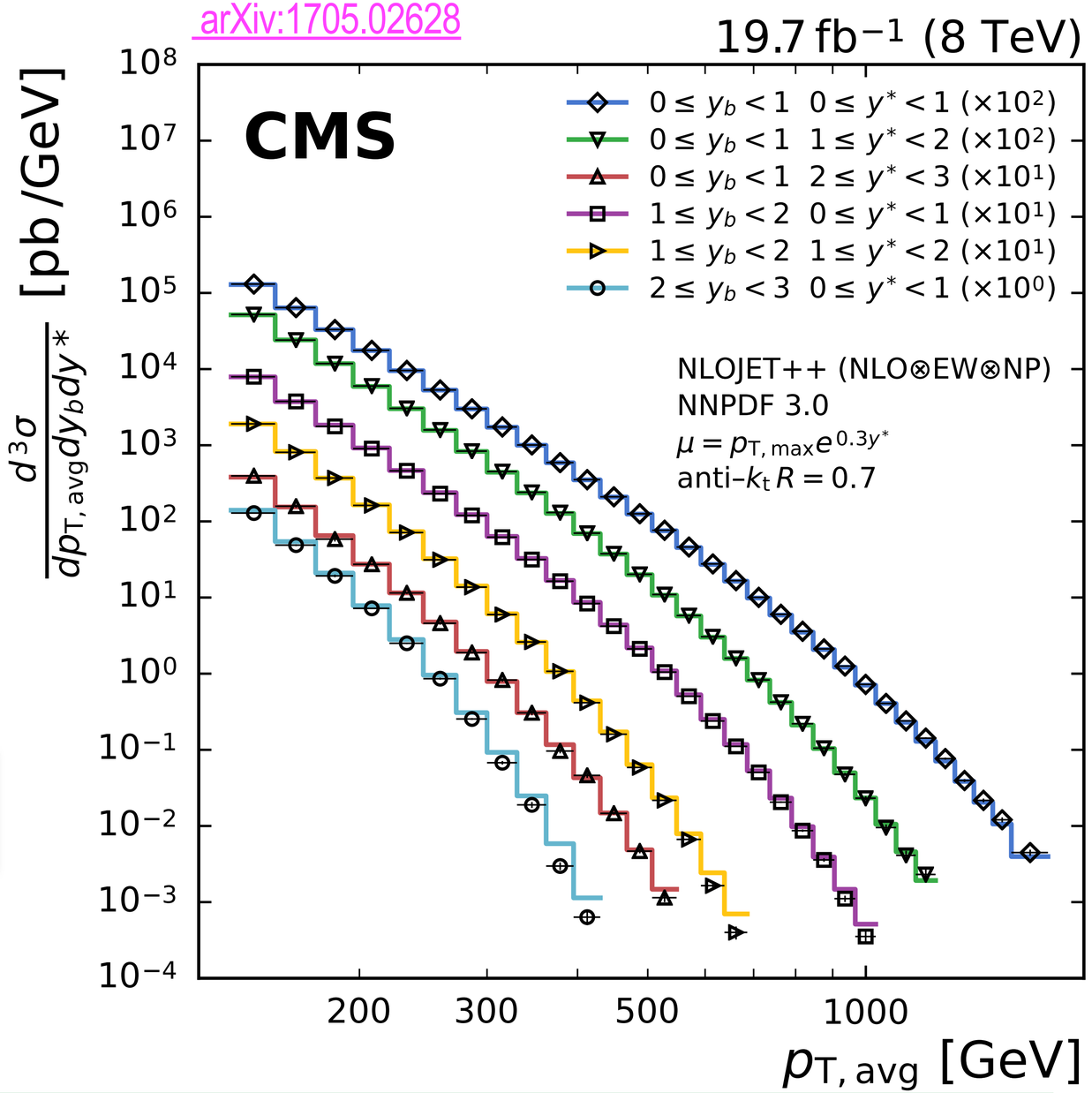
- measure p_T spectra in bins of y_b and y^*



towards large p_T enhanced $q\bar{q}$

mostly gg and gq

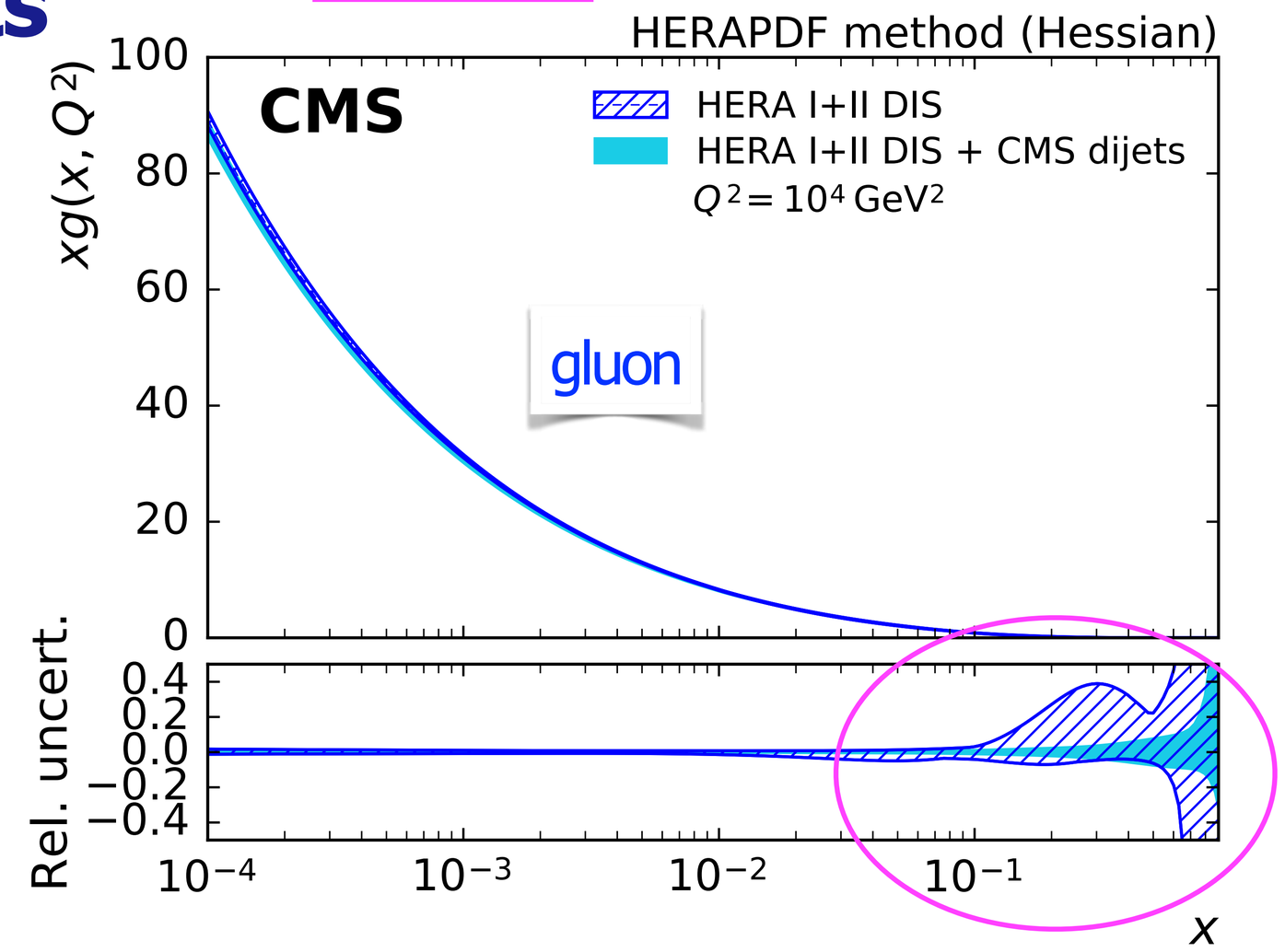
arXiv:1705.02628



➡ 122 precise points ~8 orders of magnitude, NLO describes data 😀 ⟹ useful for PDF + α_s fit

Triple differential dijets
PDF fit

arXiv:1705.02628



- Fit proton PDFs to HERA DIS and 122 CMS dijet points

➡ Highly improved gluon density in x range [0.1-0.7]

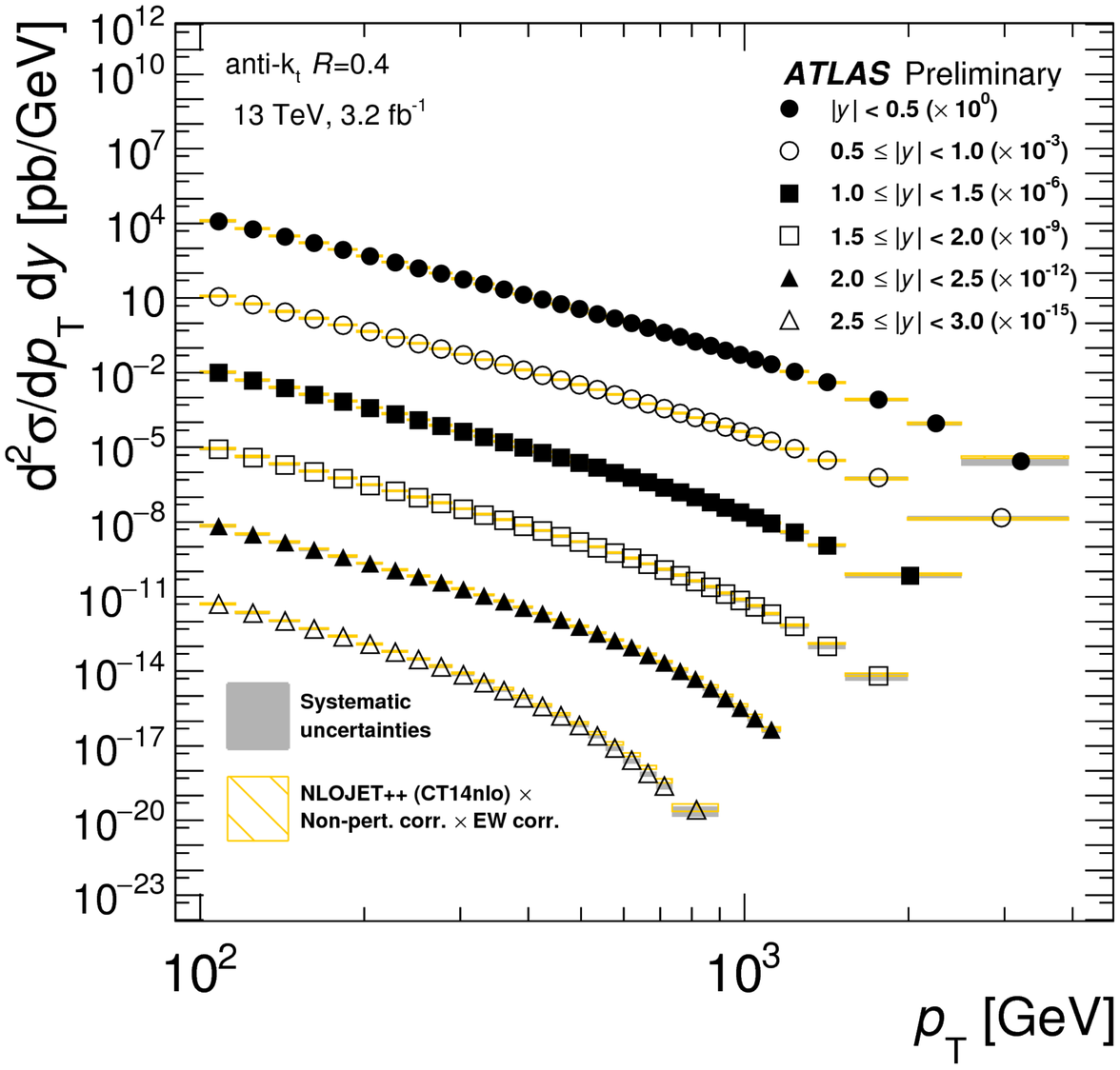
- Fit in addition α_s

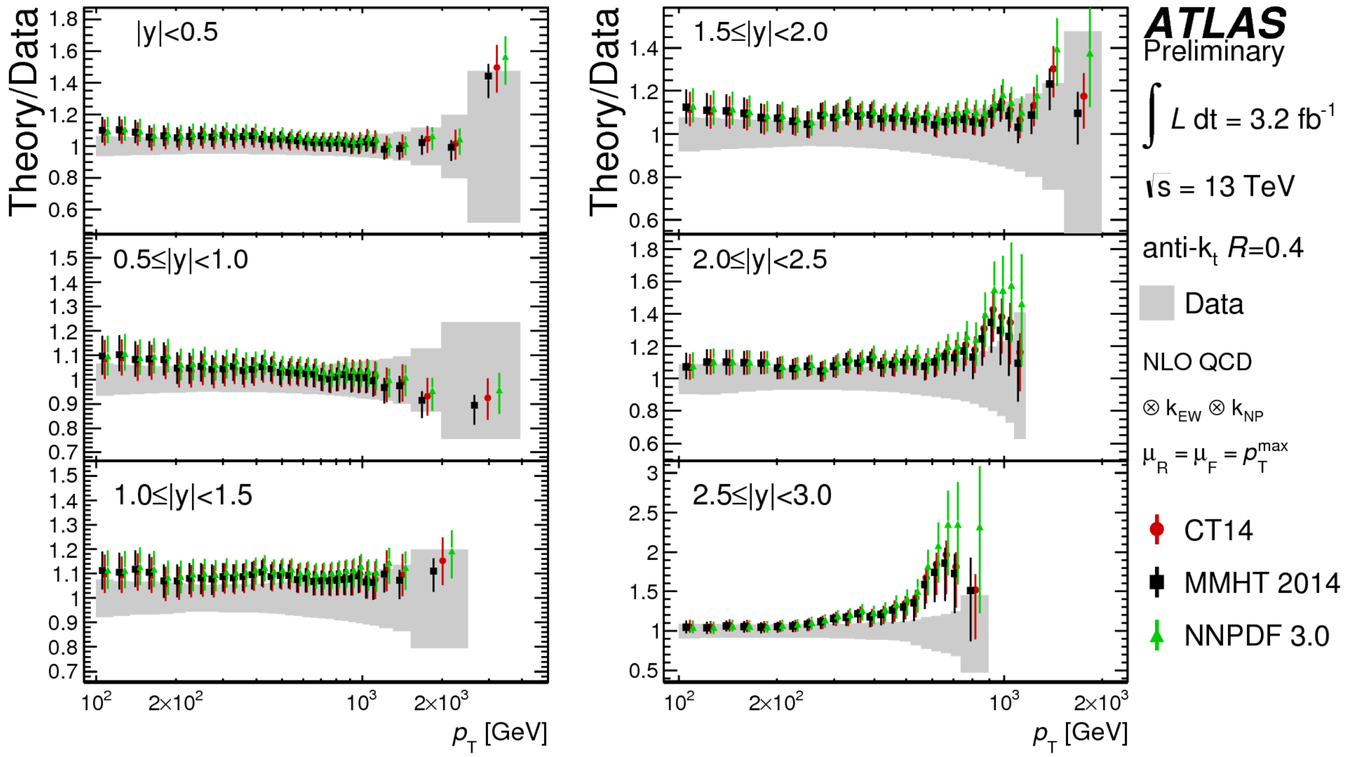
$\alpha_s(M_Z) = 0.1199 \pm 0.015\ (exp)\ ^{+0.0031}_{-0.0020}\ (theo)$

➡ One of the most precise α_s determinations from LHC

Inclusive jets and NLO

ATLAS-CONF-2017-048



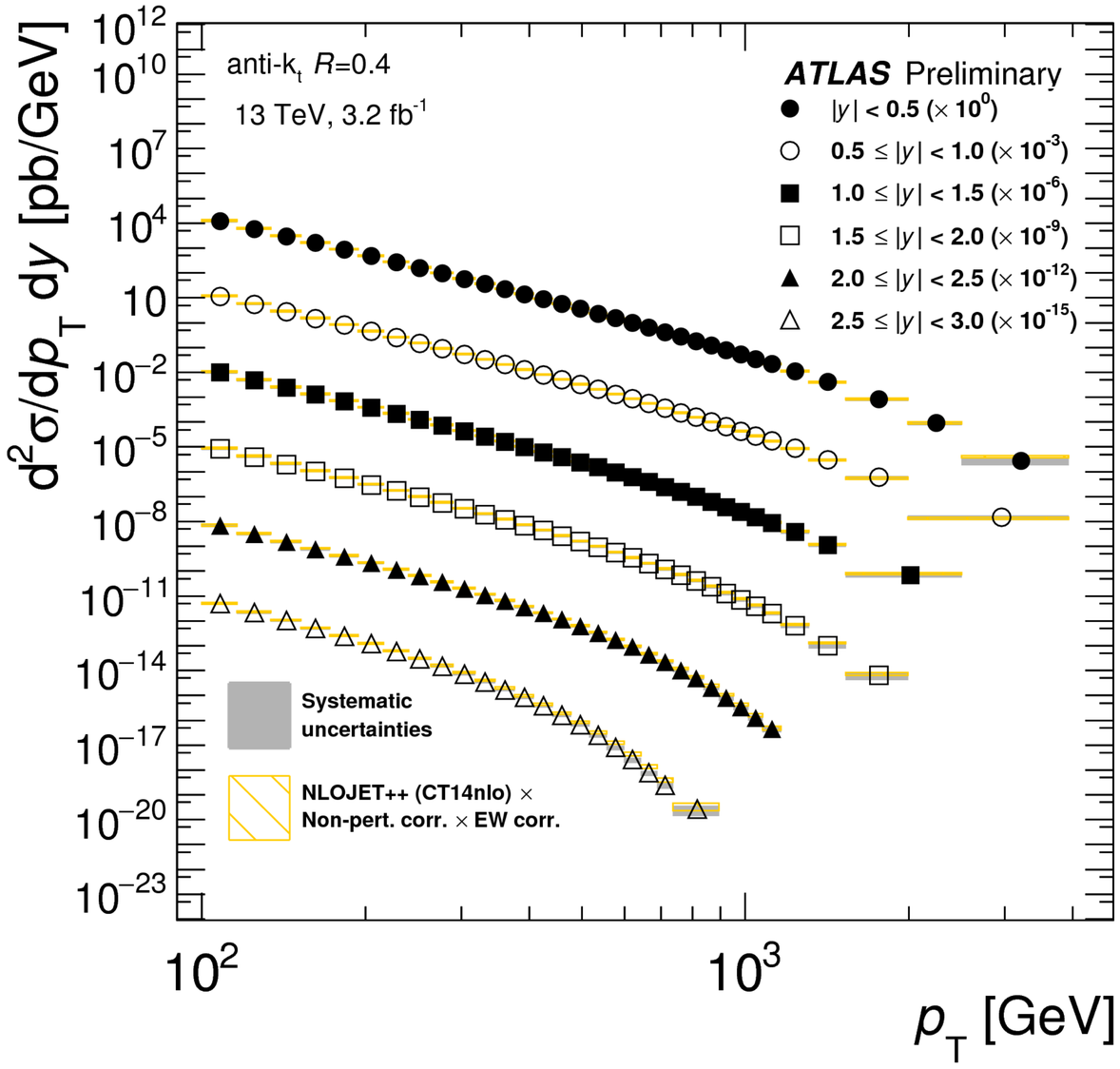


- Data vs NLO $\chi^2/ndf \sim 400/177$
  - including all data & theory uncertainties
  - Improves by o(60) when varying experimental bin-to-bin systematic correlations

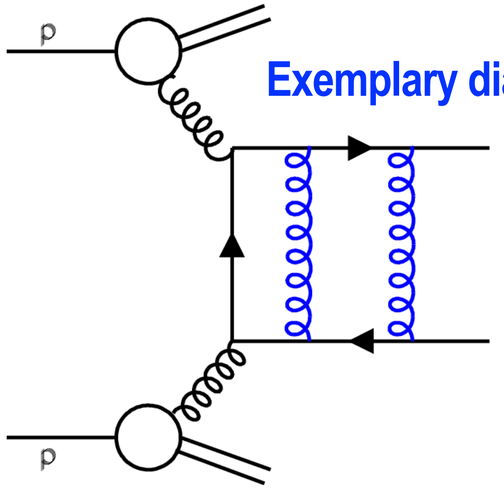
➡ Tensions between data and theory - also seen for 8 TeV jet data JHEP09 (2017) 020

Inclusive jets and NNLO

ATLAS-CONF-2017-048

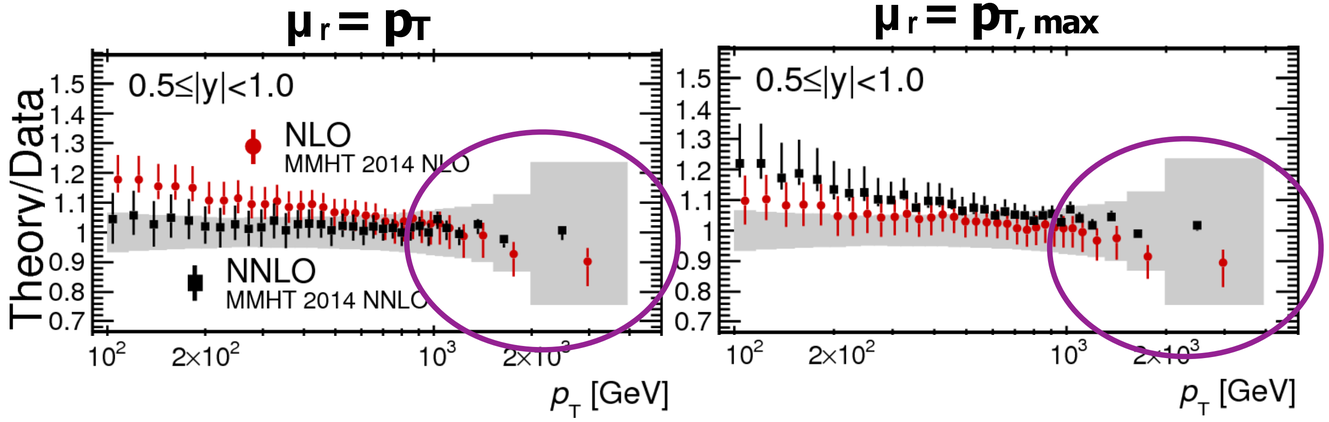


- New: full NNLO calculation available



Exemplary diagram

J. Currie, N. Glover, J. Pires, PRL 118 (2017), arXiv: 1611.01460, see also arXiv: 1704.00923



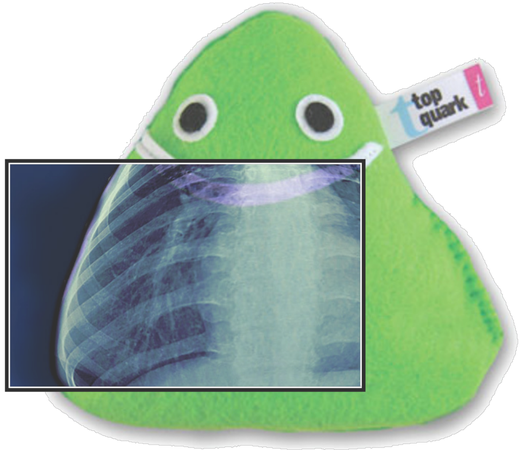
NNLO points not yet including PDF and α_s uncertainties

➡ NNLO seems to improve perturbative stability only towards highest jet p_T

Summary

TOP

- LHC top quark factory ≈ 40M top events collected until 2016
  ⟹ thorough top quark examination, today glimpses shown:
  - Precision measurements: Mass, cross sections & spectra
  - tt +Z,W and t+W ,t+Z, accessing rare processes
  - SM 😀
- Collect until end of 2018 another 60M top events ⟹ more precise & extended measurements + accessing rarer channels (e.g. $t\bar{t}t\bar{t}$)



QCD

- Jet data & NNLO turn LHC into a QCD precision lab
  ⟹ constrain SM parameters: PDFs, α_s,
  ⟹ also helpful to improve searches