Experimental Calibration of the Top-Quark Monte-Carlo Mass

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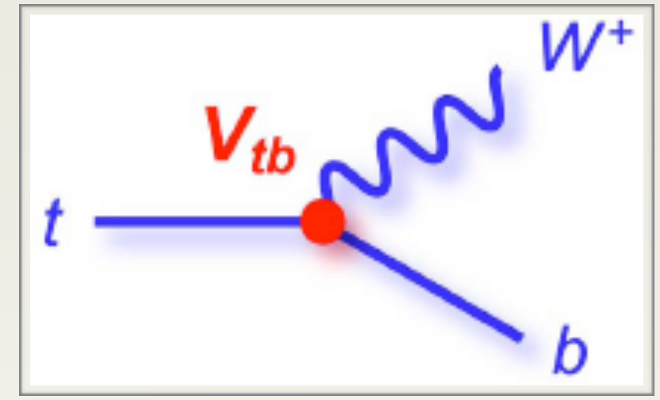
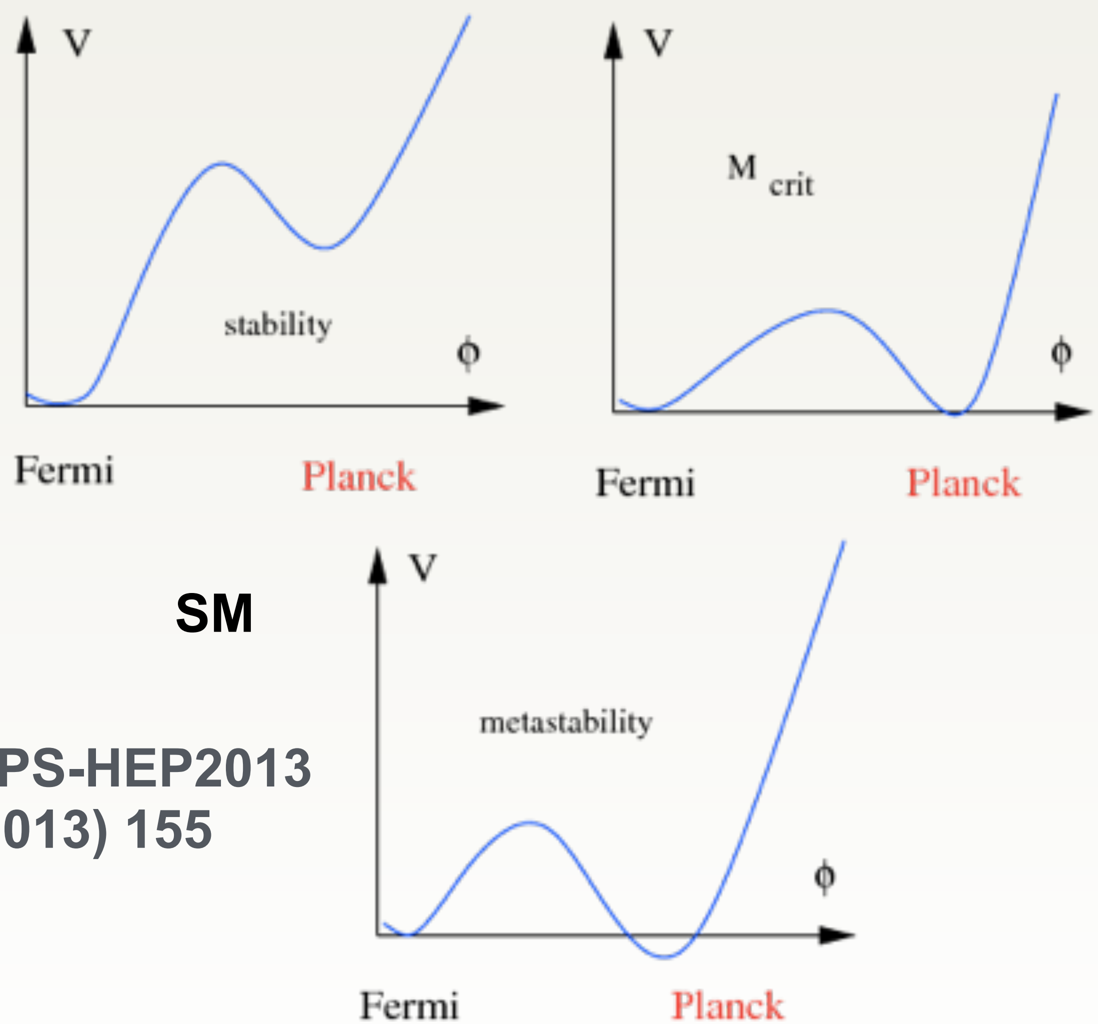
The Top Quark and its Mass

⇔ **Heaviest fundamental particle in SM**

- Possible to study bare-quark properties
- Uniquely strong coupling to Higgs field
- Special role in electroweak symmetry breaking
- New physics may couple preferably to top quarks



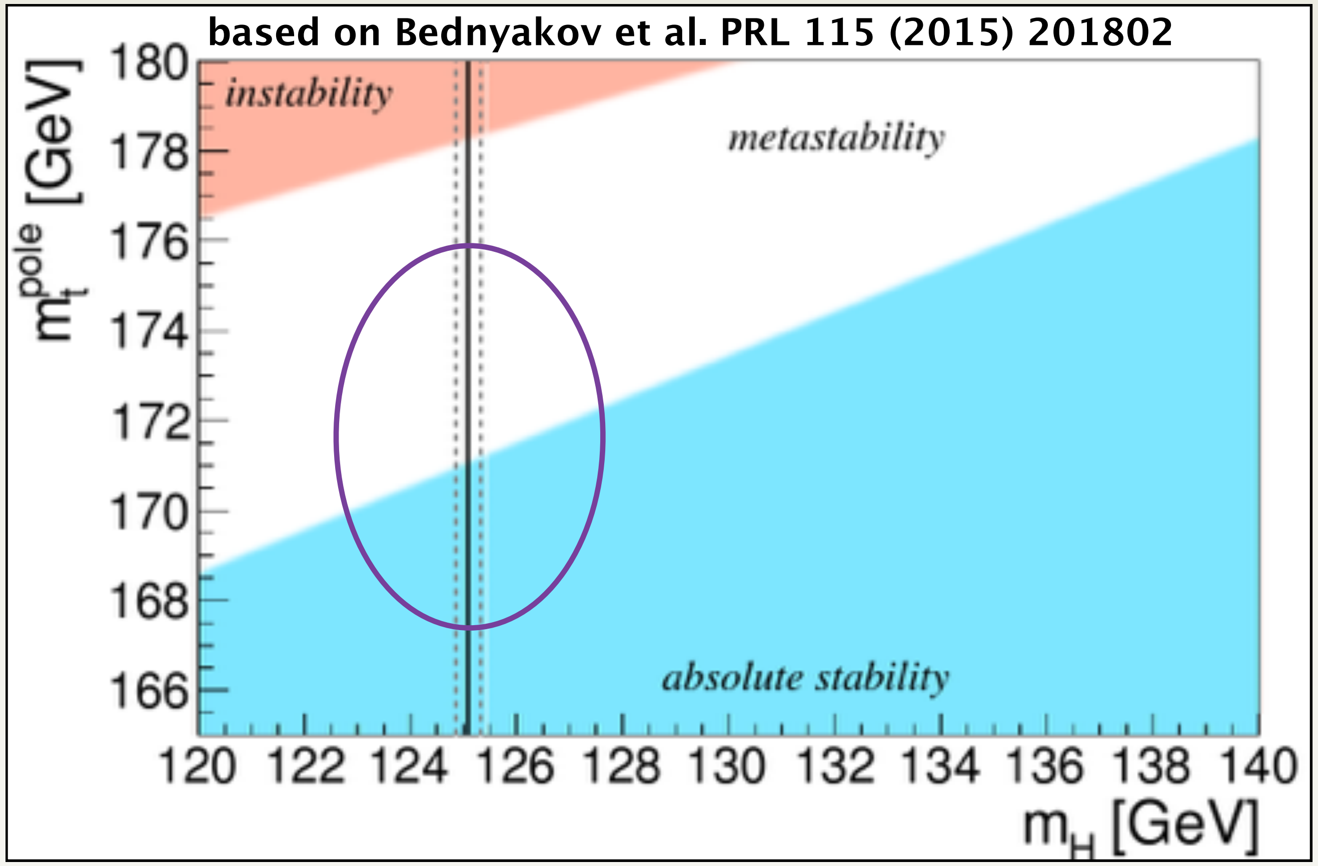


SM

PoS EPS-HEP2013 (2013) 155

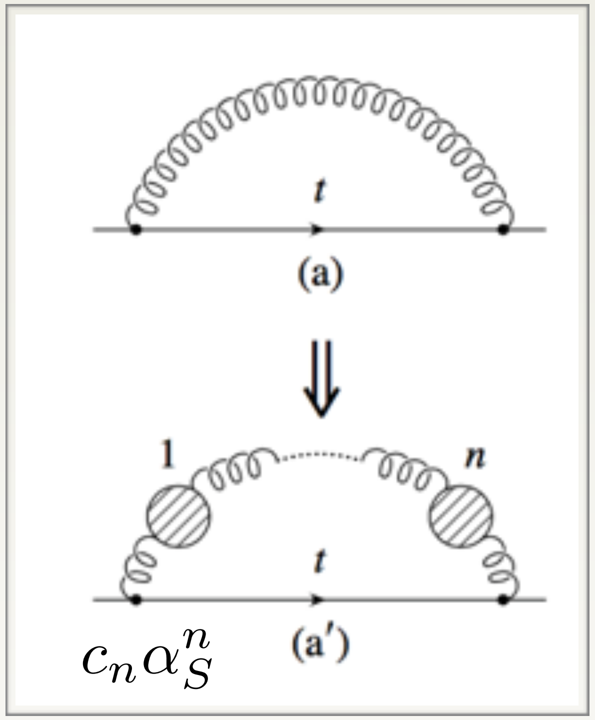
- Important role in EWK fits
- EWK vacuum stability critically depends on
  - Higgs-boson mass
  - Top-quark (pole) mass

Top-Quark Mass In Calculations



$$m_H = 125.09 \pm 0.24\,\mathrm{GeV}$$

ATLAS, CMS Collaborations,
PRL 114 (2015) 191803



- Beyond LO: self-energy corrections
- Top-quark mass is renormalisation scheme dependent
  - pole mass: $\mathbf{m_{t,pole}}$ → $O(\Lambda_{QCD})$ ambiguity (c_n diverge ~ n!)
  - running masses m(μ), e.g. MSbar mass: $\mathbf{\bar{m}_t(\mu)}$
  - ...any many others (see G. Corcella's talk)

➡ "well-defined" m_t for calculations

Top-Quark Mass in Monte-Carlo Simulation

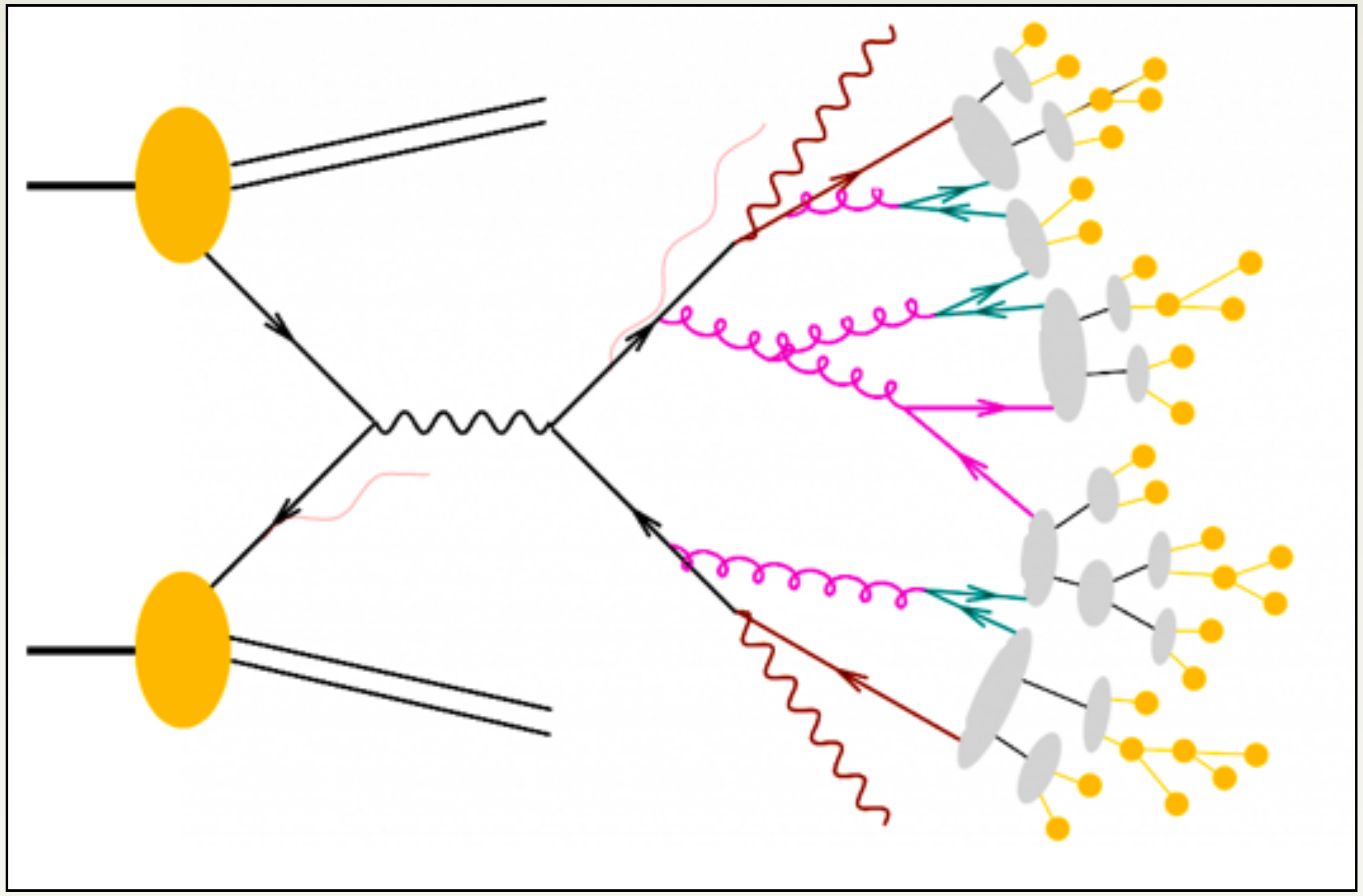
- Initial protons
  - Compound objects
  - Described by PDFs
- Hard interaction
  - Calculable in pQCD

production

- Hard decay
- Parton shower
- Hadronization

Decay to final state

→ **visible signature**

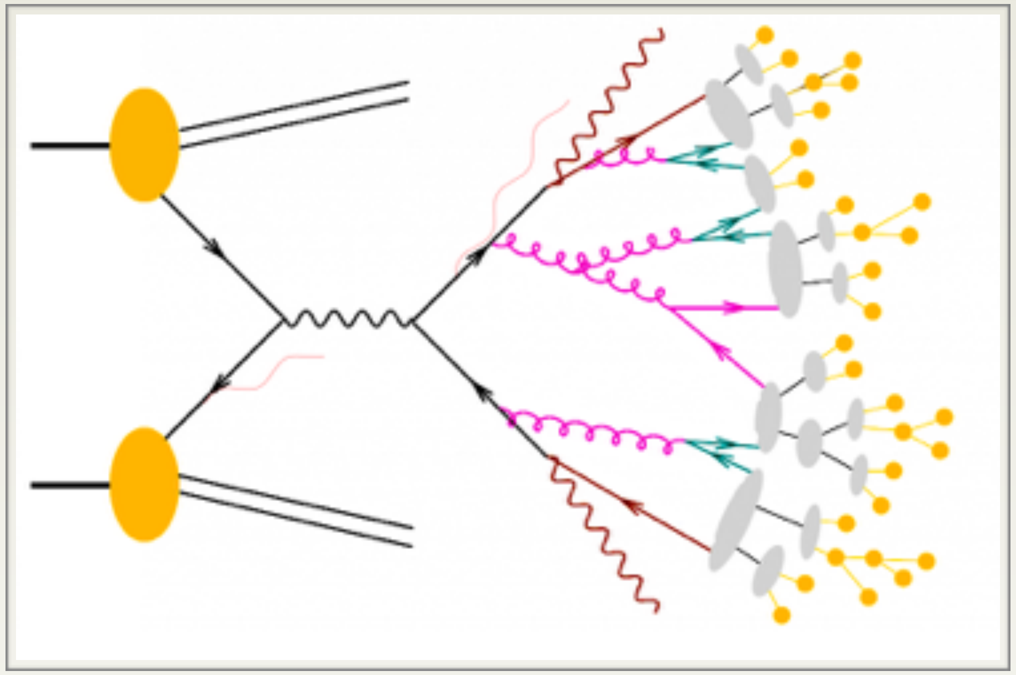


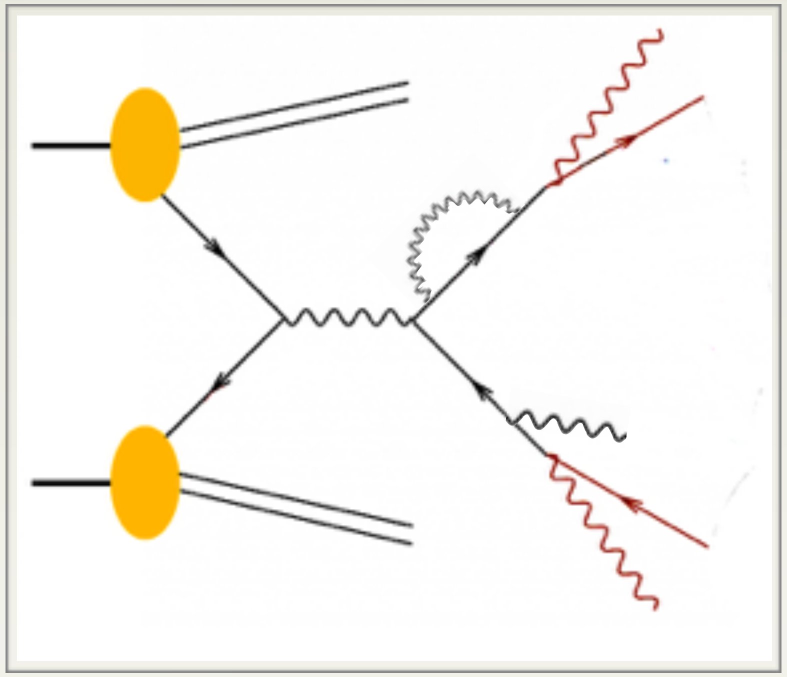
→ **visible signature**

- Based on heuristic models and approximations with parameters tuned to data
- Also top-quark mass can be tuned to describe data

➡ Mass measurement

Relation between MC- and well-defined Mass





- Direct top-quark mass measurements
  - Using final states from MC simulation (models)
  - Measure MC parameter $\mathbf{m_{t,}}$ **(MC)** (in principle depends on generator)

$m_{t,MC}$=172.44±0.49 GeV

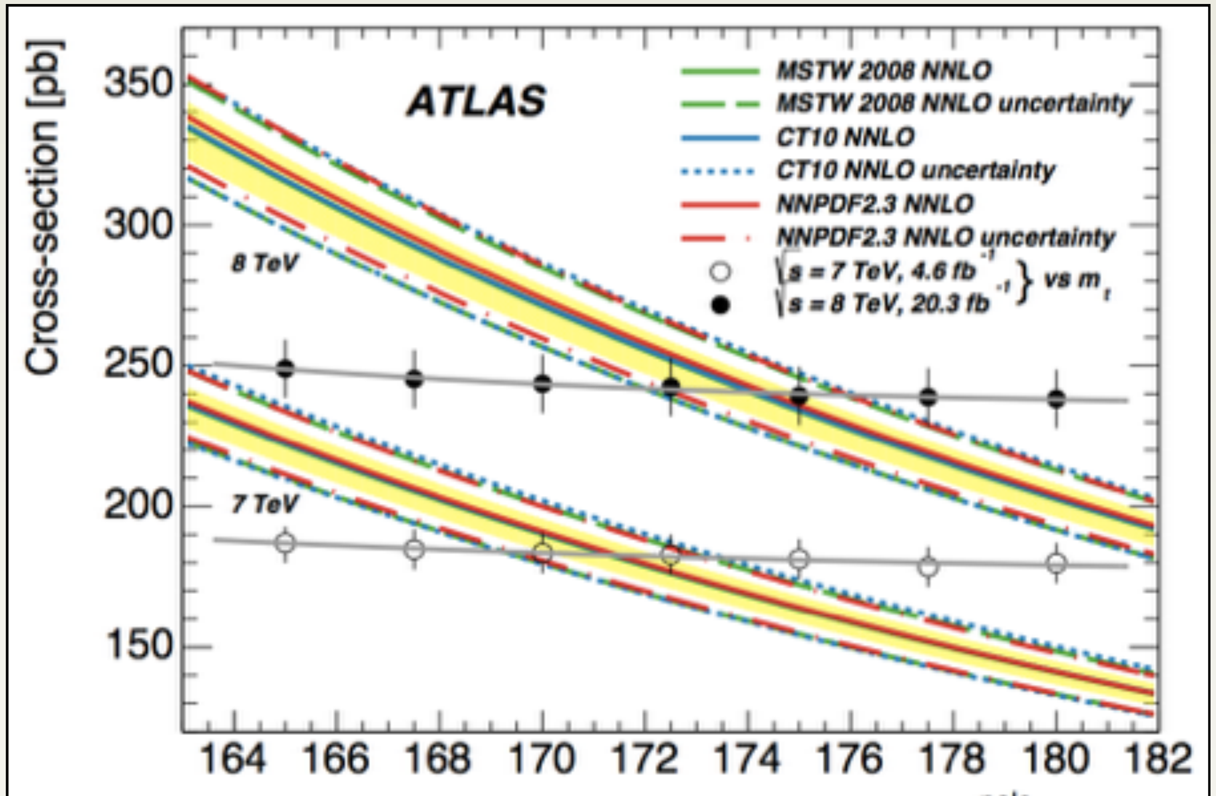
CMS Collaboration
PRD 93 (2016) 072004

Hoang, Steward, NPPS 185 (2008)
Butenschoen et al., PRL 117 (2016) 232001

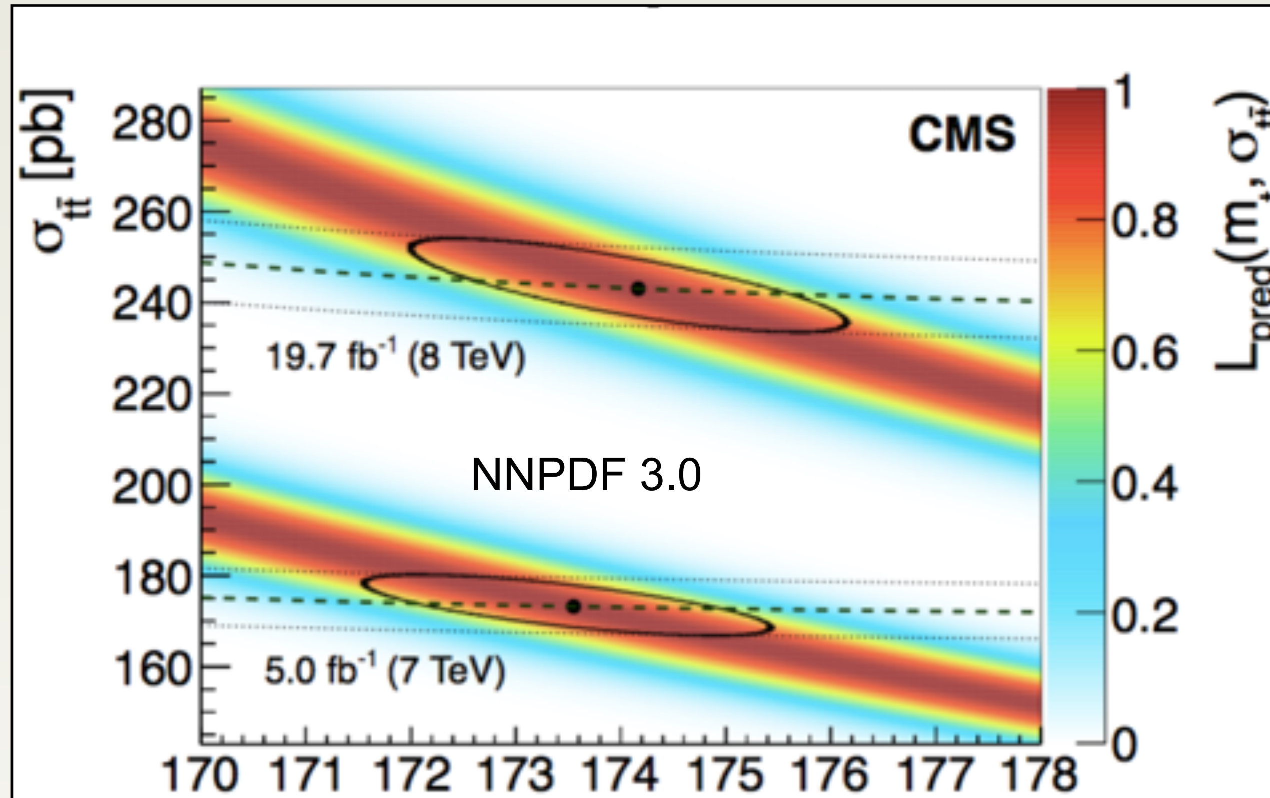
- Exact interpretation of $m_{t,MC}$ in terms of well-defined m_t
  - Uncertainty ≈1 GeV (pp), studies to reduce uncertainty ongoing (see G. Corcellas talk)
  - For measurements: often <u>assumed</u> $m_{t,pole} - m_{t,MC} \approx 1$ GeV

Buckley et al, Phys. Rept. 504 (2011)

Determine well-defined Mass directly



EPJC 76 (2016) 642



JHEP08 (2016) 029

- Predicted production cross section depends significantly on m_t
- NNLO predictions using well-defined m_t (here pole mass) available

Czakon et al. PRL 110 (2013) 252004

- Measure σ_{tt} precisely (in eμ channel)

- Dependence of measurement on m_t(MC) mild

Pole-Mass Results

- Combine result from 7 and 8 TeV

➡Most precise single pole mass determination
  - (Higher precision can be reached in global PDF fits O(1 GeV))
  arXiv:1701.05838

- Uncertainties from measured and predicted σ_{tt} contribute equally
- Main difference between ATLAS and CMS: CMS uses more recent PDF sets.

EPJC 76 (2016) 642

ATLAS

$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$

JHEP08 (2016) 029

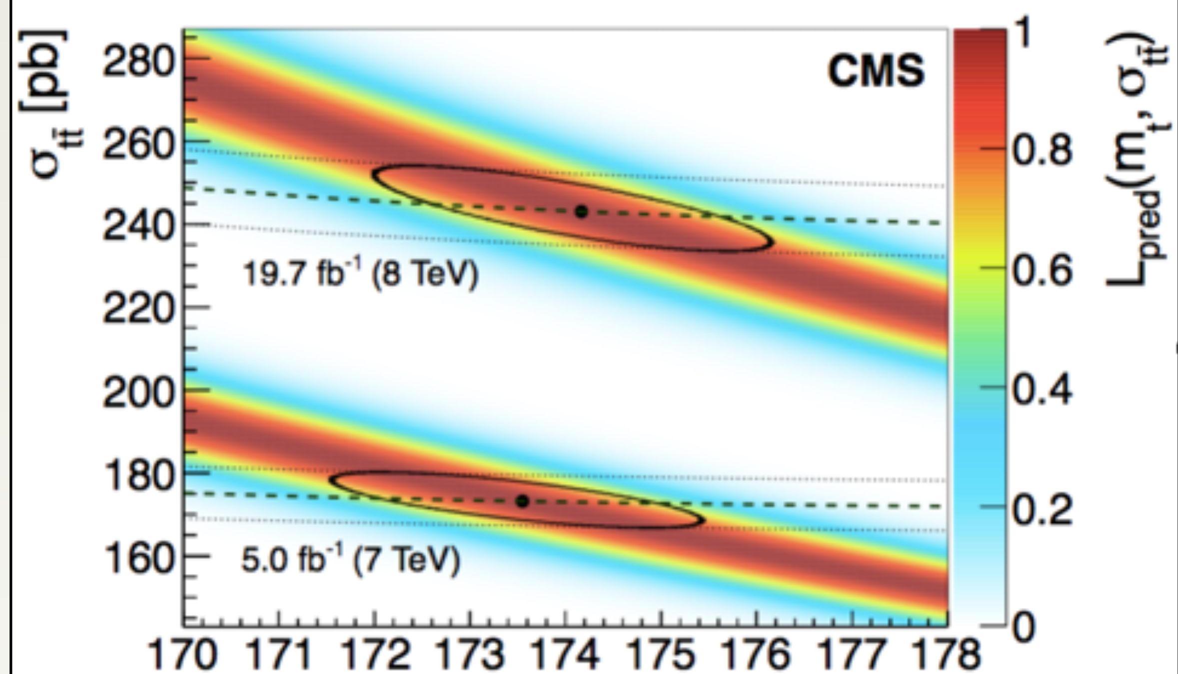
CMS	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$

- Working on a combination of results for σ_{tt} from ATLAS and CMS
  - significant gain in precision expected [1]
  - paper will include subsequent pole-mass extraction (recent PDF sets)

[1] JK "Update on t-tbar production results", LHCtopWG open meeting 17.5.2016

MC Mass in Measurements

- Dependence of experimental result is evaluated using MC mass
- "[...]an additional uncertainty $\Delta m_{t\pm}$ in the obtained cross section dependence is introduced. It is evaluated by shifting the measured dependence by ±1 GeV [...]"
  JHEP08 (2016) 029



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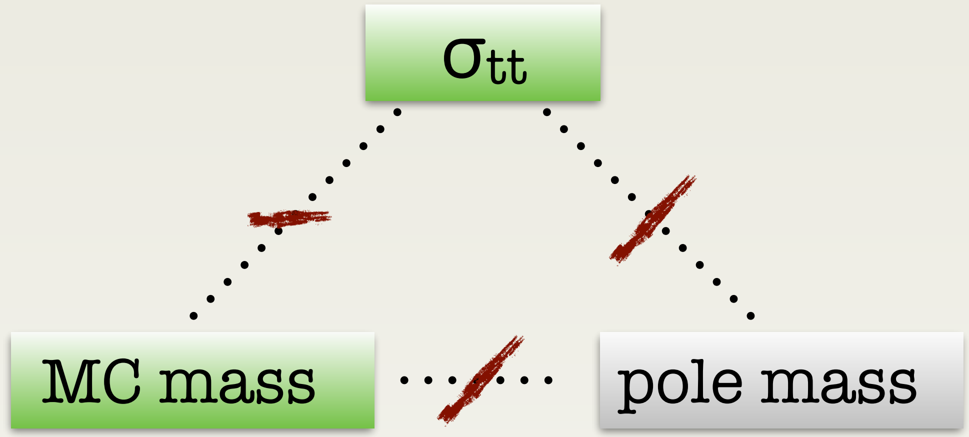
- Still: quantitative assumption on relation between MC mass and pole mass (or other well-defined mass) needed

- Assumption can be avoided
  - Use existing measurements of MC mass → precise but easily inconsistent (which MC, uncertainties and correlations, ...)
  - Measure MC mass simultaneously

Mitigate dependence on MC mass

- Assume all dependencies to be unknown
- Absorb MC mass dependence in uncertainty on σ_{tt} through simultaneous fit
  - Shape of e.g. m_{lb}: MC mass
  - Normalisation: σ_{tt}
  - ➡ **Measurement of σ_{tt} and MC mass**



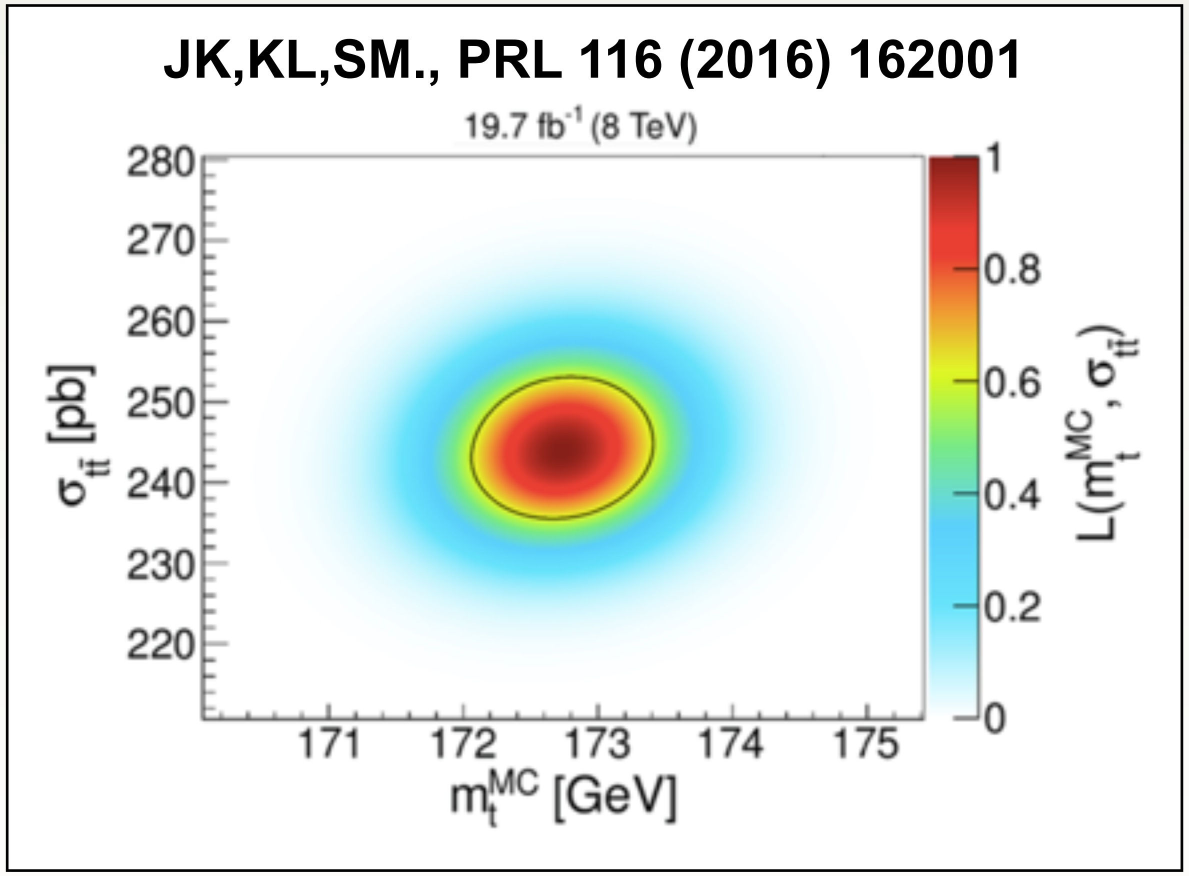
➡ Improved physics interpretation of measured σ_{tt}(~~m_t~~)

- Only assumption some weak qualitative relation between MC mass and well-defined mass

➡ Determine pole or $\overline{\text{MS}}$ mass (or any other) from direct comparison

➡ No assumptions on the relation between MC mass and pole/$\overline{\text{MS}}$ mass needed

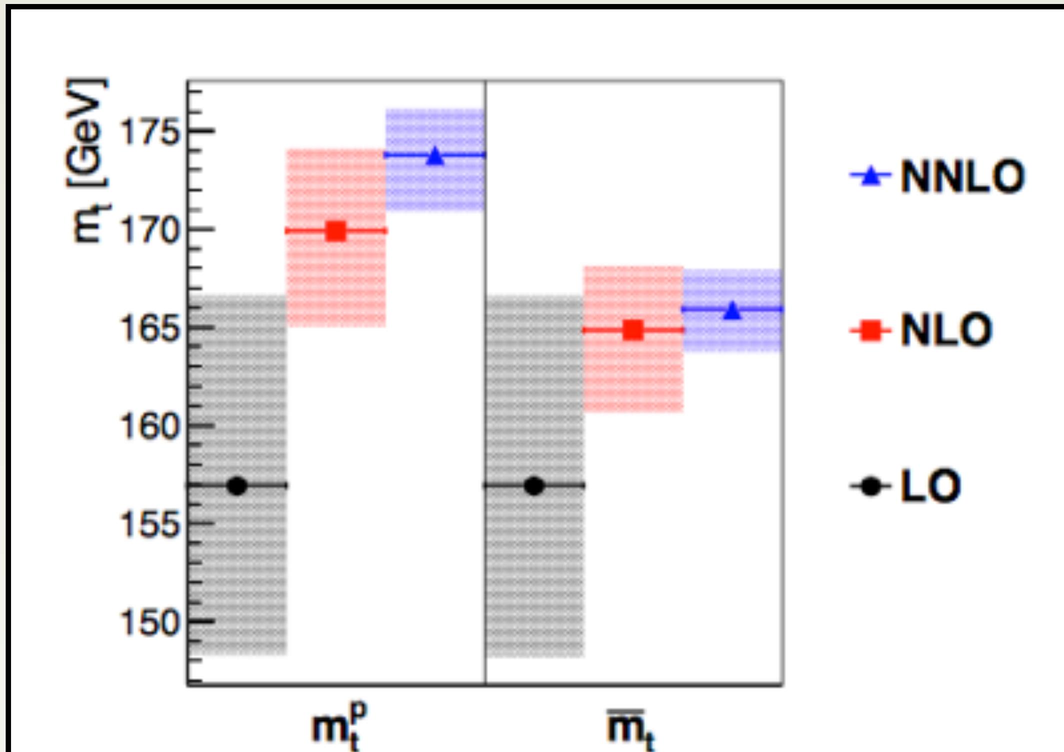
➡ Difference can be measured



MSbar mass scheme

- Study on extracted top-quark mass
  - Consider measured σ_{tt} independent of m_t
  - Extract m_t by comparison with predicted σ_{tt} (m_t)

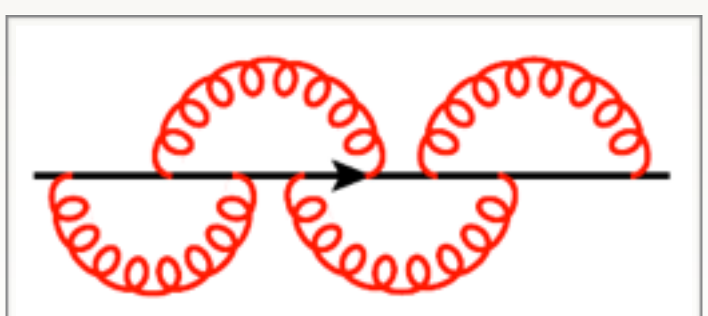
➡Using $\bar{m}_t$ improves perturbative convergence



JK,KL,SM, PRL 116 (2016) 162001

- Conversion between $\overline{\mathrm{MS}}$ and pole mass known up to 4-loop QCD
  - Indicates the size of higher-order corrections to $m_{t,pole}$ beyond NNLO (2-loop): about 250 MeV

Marquard et al., PRL 114 (2015) 142002



$$m_t^{\mathrm{pole}}(k) = m_t^{\overline{\mathrm{MS}}}(\mu)\left[1 + \sum_{n=1}^{k} c_n \left(\frac{\mu}{m_t^{\overline{\mathrm{MS}}}(\mu)}\right) \alpha_S^n(\mu)\right]$$

Resulting m_t

Well-defined m_t:

- Without assuming any relation to m_t(MC)
- Higher precision than accounting for slope (CMS/ATLAS/Tevatron)
- Consistently lower for ABM
- About 1 GeV difference between directly measured and converted pole mass → sizeable corrections beyond NNLO

	$\alpha_S(M_Z)$	$\bar{m}_t$ [GeV]	m_t^p [GeV]	$m_t^{p,c}$ [GeV]
ABM12	0.113	$158.4\pm^{1.2}_{1.9}$	$166.6\pm^{1.6}_{1.9}$	$168.0\pm^{1.3}_{2.1}$
NNPDF3.0	0.118	$165.2\pm^{1.1}_{1.7}$	$174.0\pm^{1.4}_{1.7}$	$175.1\pm^{1.2}_{1.9}$
MMHT2014	0.118	$165.4\pm^{1.1}_{1.9}$	$174.3\pm^{1.4}_{1.8}$	$175.3\pm^{1.3}_{2.1}$
CT14	0.118	$165.5\pm^{1.5}_{2.0}$	$174.4\pm^{1.8}_{2.0}$	$175.4\pm^{1.7}_{2.2}$

JK,KL,SM, PRL 116 (2016) 162001

	$\bar{\Delta}_m$ [GeV]	Δ_m^p [GeV]	$\Delta_m^{p,c}$ [GeV]
ABM12	$-14.3\pm^{1.4}_{2.0}$	$-6.1\pm^{1.7}_{2.0}$	$-4.7\pm^{1.5}_{2.2}$
NNPDF3.0	$-7.6\pm^{1.3}_{1.9}$	$1.3\pm^{1.6}_{1.9}$	$2.4\pm^{1.5}_{2.0}$
MMHT2014	$-7.3\pm^{1.3}_{2.1}$	$1.5\pm^{1.6}_{2.0}$	$2.6\pm^{1.5}_{2.2}$
CT14	$-7.2\pm^{1.7}_{2.1}$	$1.6\pm^{1.9}_{2.1}$	$2.7\pm^{1.8}_{2.3}$

m_t - m_t(MC):

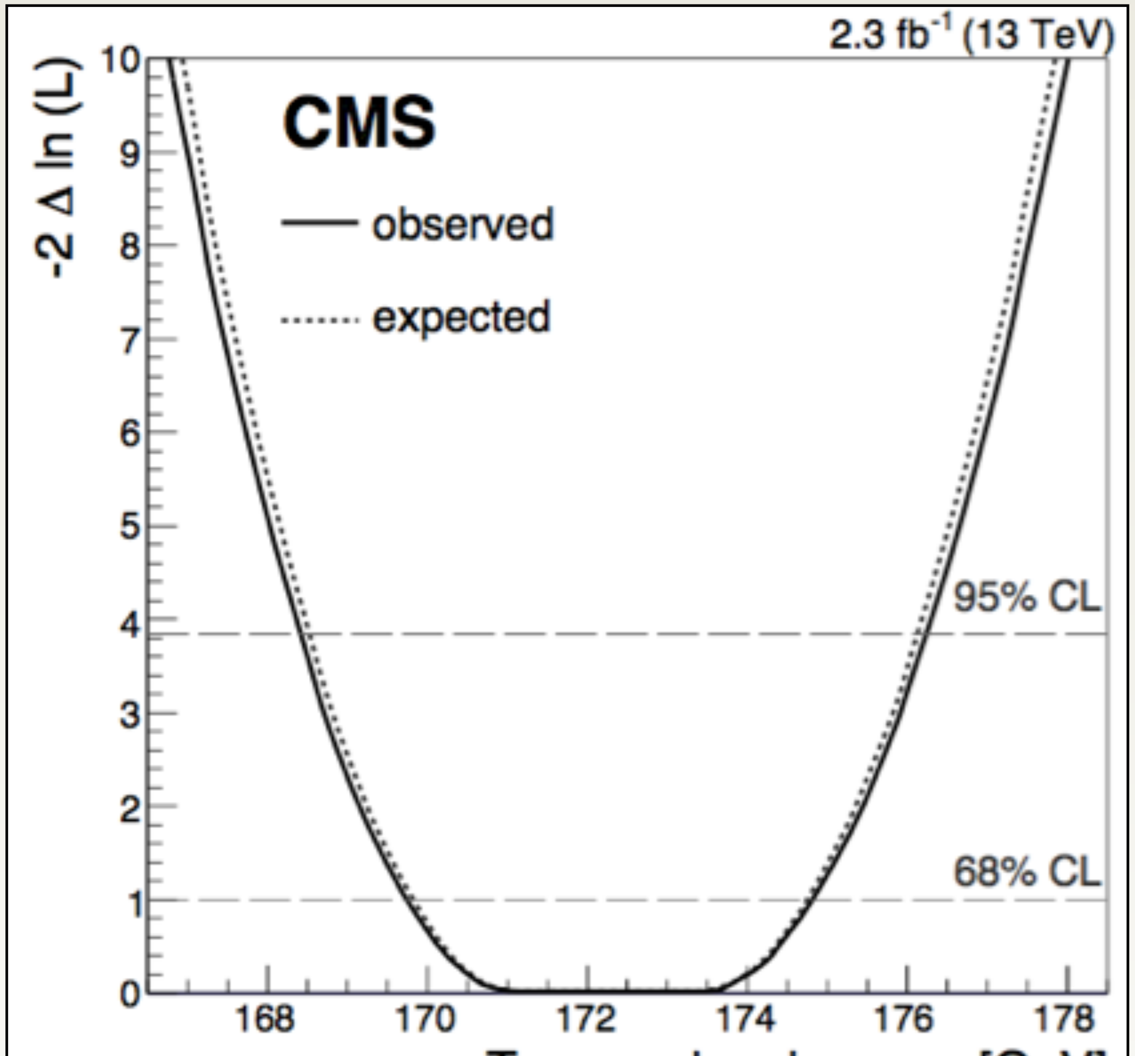
- Directly measurable
- First consistent experimental calibration
- Precision ~2 GeV
- Consistent with assumption of m_t - m_t(MC)≈1 GeV for most PDF sets

Application: Inclusive Cross Sections: 13 TeV

Strategy

- Measure σ_{tt} in l+jets channel
  - Simultaneous nuisance parameter fit of cross sections and MC mass (m_{lb})
- Incorporate likelihood for NNLO prediction
  - Model scale variations with box prior
- Determine m_t from joint likelihood measured $\otimes$ predicted

m_t(pole) = 172.7 +2.4 - 2.7 GeV
(CT14, α_S = 0.118)

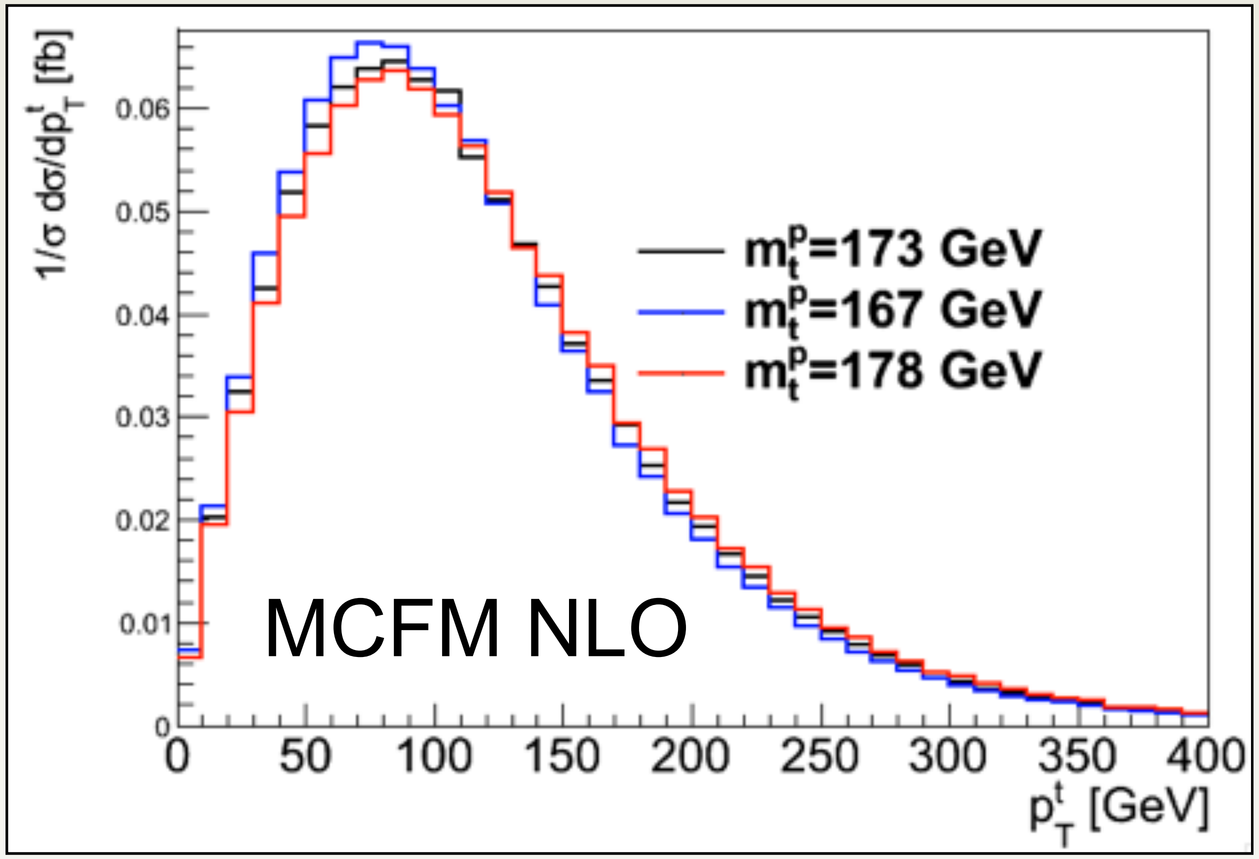


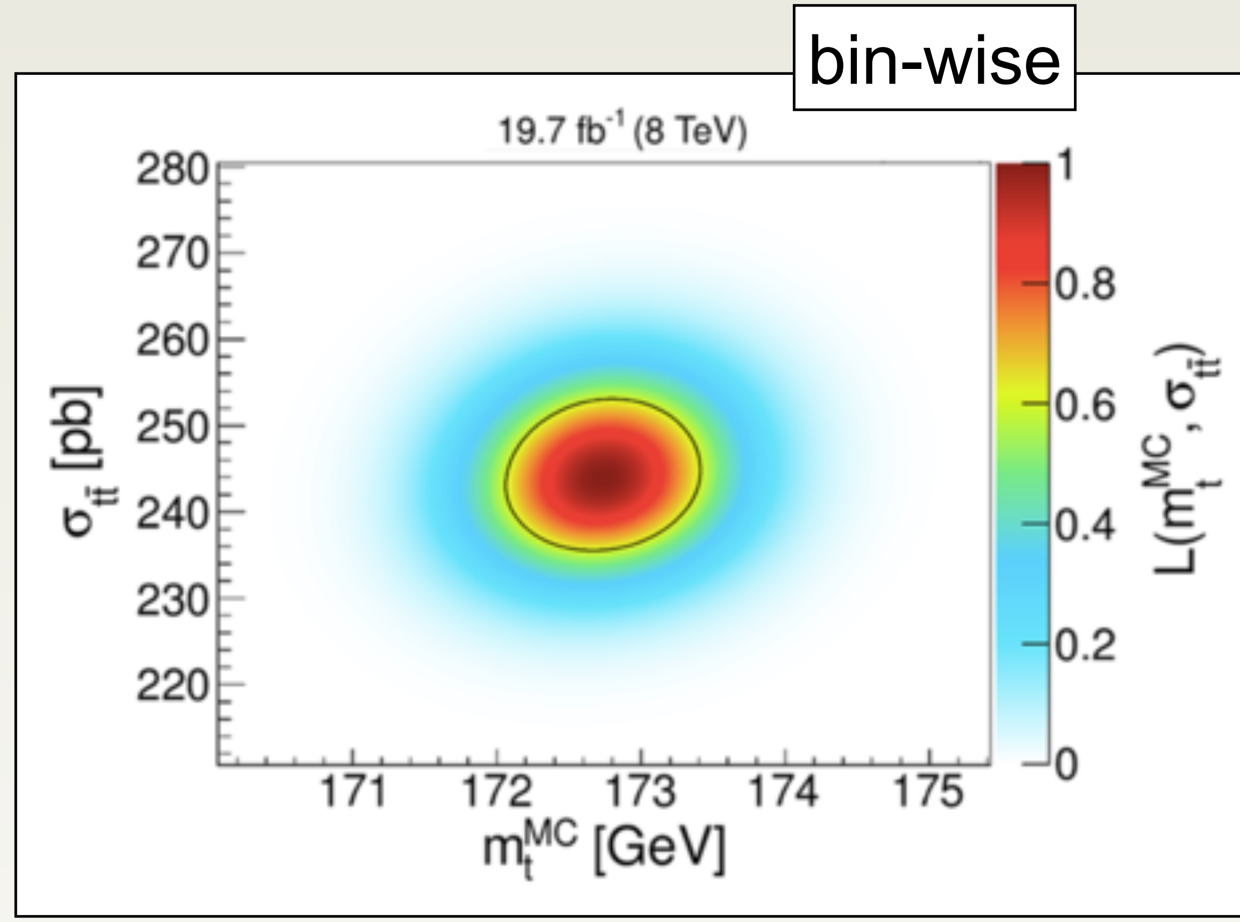
arXiv:1701.06228

Source	Δm_t [GeV]
Uncertainties from the fit in the fiducial region	+2.1 / −2.0
Extrapolation to the full phase space	+0.7 / −1.1
Beam energy	+0.5 / −0.8
μ_R / μ_F and PDF+α_S	+0.9 / −1.1
Total	+2.4 / −2.7

← 2x larger than for dilepton measurement (jets in final state)

Extend to Differential Distributions





- Residual dependence on MC mass can be absorbed while unfolding similarly as for the inclusive cross section

JK,KL,SM, PRL 116 (2016) 162001

- Measurement of $d\sigma/dX$ (~~m_t~~)
- Could be used for simultaneous parameter extraction through direct comparison: α_S, pole mass / $\overline{\text{MS}}$ mass, ...
- Will likely provide higher precision

Summary

- Important to clearly define which top-quark mass is measured

- More and more precise direct pole-mass measurements
  - Using inclusive and differential cross sections
  - @ NNLO: down to ~2 GeV uncertainty in a single measurement

- Consistent way of mitigating m_t(MC) dependence in (cross-section) measurements
  - Improves physics interpretation of measured quantity
  - Allows to extract any mass in a well-defined scheme from direct comparison
  - Offers possibility to measure relation between m_t and m_t(MC) fully consistently
  - Precision is likely to increase when extending to differential measurements