

Measuring the top-quark's running mass

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Top-quark mass

What is the value of the top-quark mass ?

$$m_t = ?$$

Mass – a classical concept

Classical mechanics

- Mass is defined as product of density and volume of matter

- *The quantity of matter is that which arises jointly from its density and magnitude. A body twice as dense in double the space is quadruple in quantity. This quantity I designate by the name of body or of mass.*

Newton

Atomic theory

- Mass is conserved Lavoisier
- Mass of body is sum of mass of its constituents

$$M(X) = N_A m_a(X)$$

Special relativity

- Equivalence principle

$$E = mc^2$$

Einstein

PHILOSOPHIÆ NATURALIS

PRINCIPIA MATHEMATICA.

DEFINITIONES.

DEFINITIO I.

Quantitas materiæ est mensura ejusdem orta ex illius densitate et magnitudine conjunctim.

A ER densitate duplicata, in spatio etiam duplicato, fit quadruplus ; A in triplicato sextuplus. Idem intellige de nive & pulveribus per compressionem vel liquefactionem condensatis. Et par est ratio corporum omnium, quæ per causas quascunque diversimode condensantur. Medii interea, si quod fuerit, interstitia partium libere pervadentis, hic nullam rationem habeo. Hanc autem quantitatem sub nomine corporis vel massæ in sequentibus passim intelligo. Innotescit ea per corporis cuiusque pondus : Nam ponderi proportionalem esse reperi per experimenta pendulorum accuratissime instituta, uti posthac docebitur.

DEFINITIO II.

Quantitas motus est mensura ejusdem orta ex velocitate et quantitate materiæ conjunctim.

Motus totius est summa motuum in partibus singulis ; ideoque in corpore duplo majore, æquali cum velocitate, duplus est, & dupla cum velocitate quadruplus.

Quantum field theory

- Higgs boson gives mass to matter fields via Higgs-Yukawa coupling
 - large top quark mass m_t
- Classical part of QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F_b^{\mu\nu} + \sum_{\text{flavors}} \bar{q}_i (\mathrm{i} \not{D} - m_q)_{ij} q_j$$

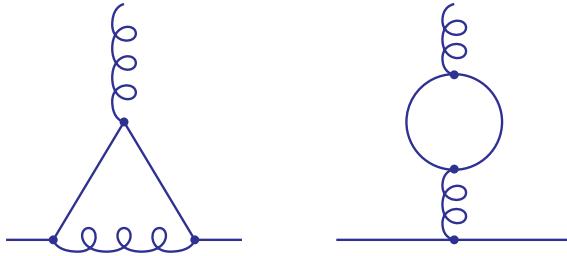
- field strength tensor $F_{\mu\nu}^a$ and matter fields q_i, \bar{q}_j
- covariant derivative $D_{\mu,ij} = \partial_\mu \delta_{ij} + \mathrm{i} g_s (t_a)_{ij} A_\mu^a$
- Formal parameters of the theory (no observables)
 - strong coupling $\alpha_s = g_s^2/(4\pi)$, quark masses m_q
- Parameters of Lagrangian have no unique physical interpretation
 - radiative corrections require definition of renormalization scheme

Challenge

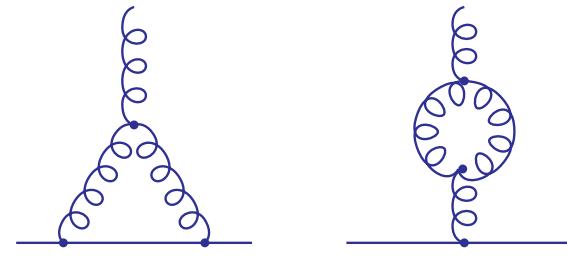
- Suitable observables for measurements of α_s, m_q, \dots
 - comparison of theory predictions and experimental data

Coupling constant renormalization

- Running coupling constant α_s from radiative corrections, e.g. one loop



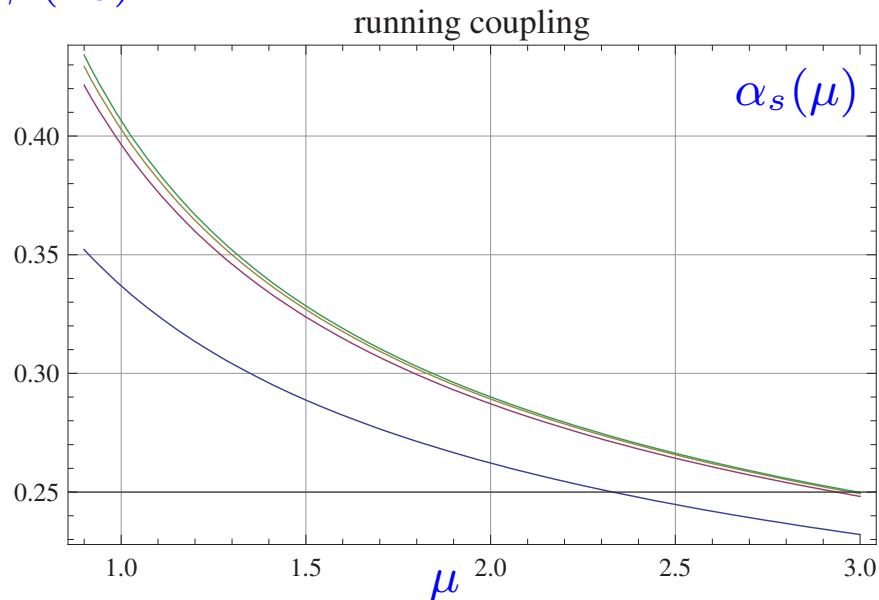
– screening (like in QED)



– anti-screening (color charge of g)

- QCD beta function $\mu^2 \frac{d}{d\mu^2} \alpha_s(\mu) = \beta(\alpha_s)$

- perturbative expansion to four loops
van Ritbergen, Vermaseren, Larin '97
- very good convergence of perturbative series even at low scales



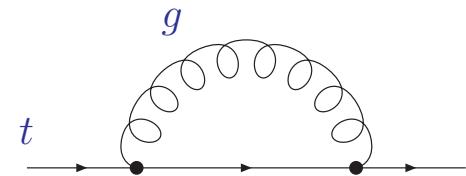
Quark mass renormalization

- Heavy-quark self-energy $\Sigma(p, m_q)$

$$\text{---} \rightarrow + \text{---} \circlearrowleft \Sigma \text{---} \rightarrow + \text{---} \circlearrowleft \Sigma \text{---} \circlearrowleft \Sigma \text{---} \rightarrow + \dots = \frac{i}{\not{p} - m_q - \Sigma(p, m_q)}$$

QCD

- QCD corrections to self-energy $\Sigma(p, m_q)$
 - dimensional regularization $D = 4 - 2\epsilon$
 - one-loop: UV divergence $1/\epsilon$ (Laurent expansion)



$$\Sigma^{(1),\text{bare}}(p, m_q) = \frac{\alpha_s}{4\pi} \left(\frac{\mu^2}{m_q^2} \right)^\epsilon \left\{ (\not{p} - m_q) \left(-C_F \frac{1}{\epsilon} + \text{fin.} \right) + m_q \left(3C_F \frac{1}{\epsilon} + \text{fin.} \right) \right\}$$

- Relate bare and renormalized mass parameter $m_q^{\text{bare}} = m_q^{\text{ren}} + \delta m_q$

$$\Sigma^{\text{ren}}(p, m_q) = \text{---} \circlearrowleft \text{---} = \text{---} \rightarrow + \text{---} \circlearrowleft \text{---} + \text{---} \times \text{---} + \dots$$

$(Z_\psi - 1)\not{p} - (Z_m - 1)m_q$

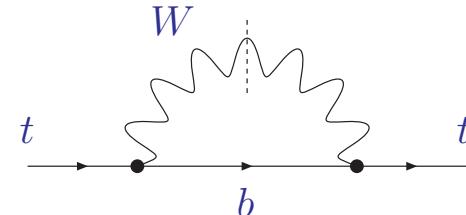
Quark mass renormalization

- Heavy-quark self-energy $\Sigma(p, m_q)$

$$\text{---} \rightarrow + \text{---} \rightarrow (\Sigma) \rightarrow + \text{---} \rightarrow (\Sigma) \rightarrow (\Sigma) \rightarrow + \dots = \frac{i}{\not{p} - m_q - \Sigma(p, m_q)}$$

EW sector

- EW corrections to top-quark self-energy
 - on-shell intermediate (virtual) W -boson
 - m_t complex parameter with imaginary part $\Gamma_t = 2.0 \pm 0.7 \text{ GeV}$
 - $\Gamma_t > 1 \text{ GeV}$: top-quark decays before it hadronizes



Mass renormalization scheme

Pole mass

- Based on (unphysical) concept of top-quark being a free parton
 - m_q^{ren} coincides with pole of propagator at each order

$$\not{p} - m_q - \Sigma(p, m_q) \Big|_{\not{p}=m_q} \rightarrow \not{p} - m_q^{\text{pole}}$$

- Definition of pole mass ambiguous up to corrections $\mathcal{O}(\Lambda_{QCD})$
 - heavy-quark self-energy $\Sigma(p, m_q)$ receives contributions from regions of all loop momenta – also from momenta of $\mathcal{O}(\Lambda_{QCD})$
 - bound from lattice QCD: $\Delta m_q \geq 0.7 \cdot \Lambda_{QCD} \simeq 200 \text{ MeV}$
Bauer, Bali, Pineda '11

\overline{MS} scheme

- \overline{MS} mass definition
 - one-loop minimal subtraction

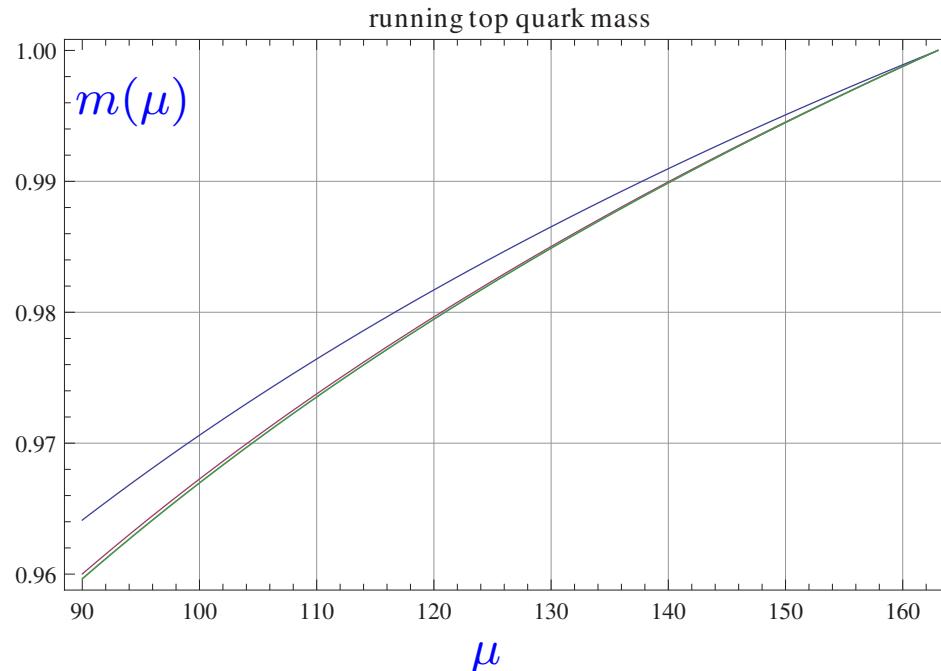
$$\delta m_q^{(1)} = m_q \frac{\alpha_s}{4\pi} 3C_F \left(\frac{1}{\epsilon} - \gamma_E + \ln 4\pi \right)$$

- \overline{MS} scheme induces scale dependence: $m(\mu)$

Running quark mass

Scale dependence

- Renormalization group equation for scale dependence
 - mass anomalous dimension γ known to four loops
Chetyrkin '97; Larin, van Ritbergen, Vermaseren '97
$$\left(\mu^2 \frac{\partial}{\partial \mu^2} + \beta(\alpha_s) \frac{\partial}{\partial \alpha_s} \right) m(\mu) = \gamma(\alpha_s) m(\mu)$$
- Plot mass ratio $m_t(163\text{GeV})/m_t(\mu)$



Scheme transformations

- Conversion between different renormalization schemes possible in perturbation theory
- Relation for pole mass and \overline{MS} mass
 - known to four loops in QCD Gray, Broadhurst, Gräfe, Schilcher '90; Chetyrkin, Steinhauser '99; Melnikov, v. Ritbergen '99; Marquard, Smirnov, Smirnov, Steinhauser '15
 - EW sector known to $\mathcal{O}(\alpha_{EW}\alpha_s)$ Jegerlehner, Kalmykov '04; Eiras, Steinhauser '06
 - example: one-loop QCD

$$m^{\text{pole}} = m(\mu) \left\{ 1 + \frac{\alpha_s(\mu)}{4\pi} \left(\frac{4}{3} + \ln \left(\frac{\mu^2}{m(\mu)^2} \right) \right) + \dots \right\}$$

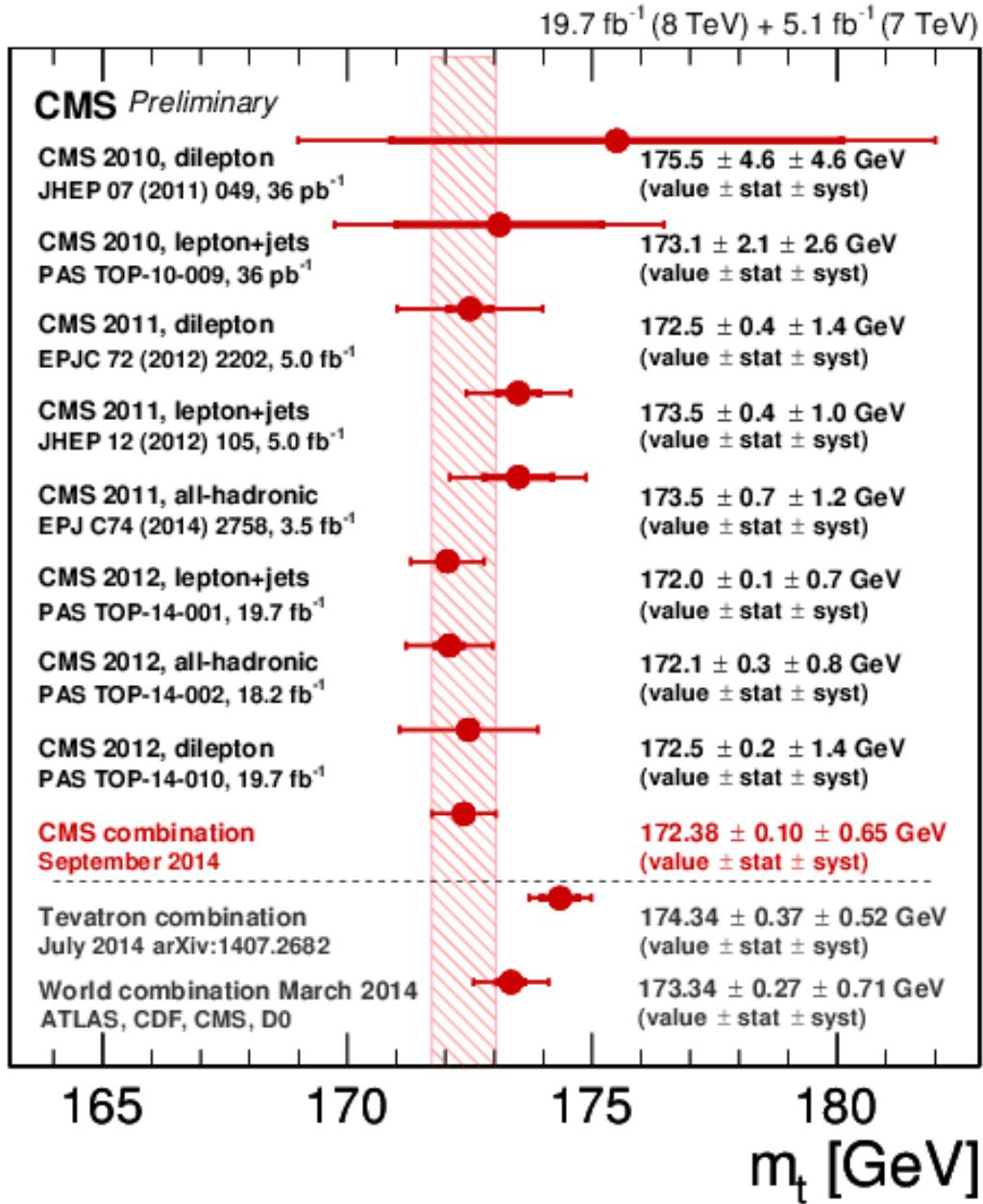
Top-quark mass

What is the value of the top-quark mass ?

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Some Answers

CMS coll. '14



World combination

Experiment: ATLAS, CDF, CMS & D0 coll. 1403.4427

$$m_t = 173.34 \pm 0.76 \text{ GeV}$$

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Theory:

That is, we can state as the final result for the likely relation between the top-quark mass measured using a given Monte Carlo event generator ("MC") and the pole mass as

$$m_{\text{pole}} = m_{\text{MC}} + Q_0 [\alpha_s(Q_0)c_1 + \dots]$$

where $Q_0 \sim 1 \text{ GeV}$ and c_1 is unknown, but presumed to be of order 1 and, according to the argument above, presumed to be positive.

A. Buckley et al. arXiv:1101.2599

Rates, shapes and peaks

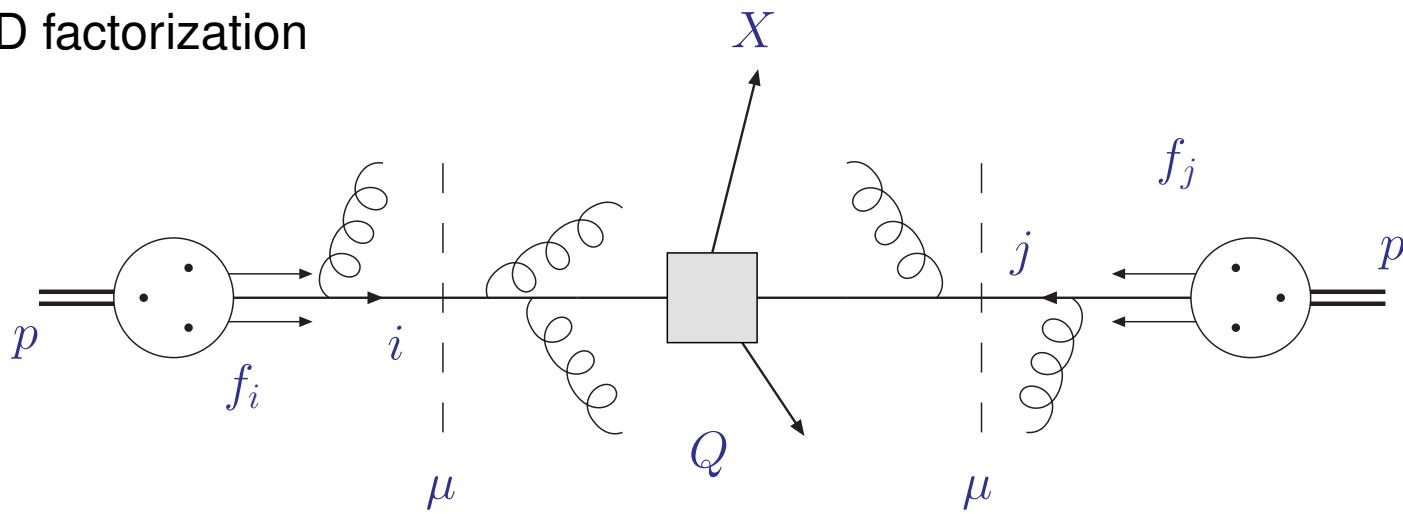
- Rates and shapes of distributions offer possibility for top mass determination with well-defined renormalization scheme
- Requirements:
 - theory predictions at least to NLO in QCD
 - sufficiently large sensitivity \mathcal{S} to m_t (kinematics)

$$\left| \frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \right| \simeq \mathcal{S} \times \left| \frac{\Delta m_t}{m_t} \right|$$

- Observables (examples):
 - inclusive cross section and differential distributions for $t\bar{t}$
 - distributions for $t\bar{t} + 1\text{jet}$ samples
 - single t and \bar{t} production

Top mass from total cross section

- QCD factorization



$$\sigma_{pp \rightarrow X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij \rightarrow X} (\alpha_s(\mu^2), Q^2, \mu^2, m_X^2)$$

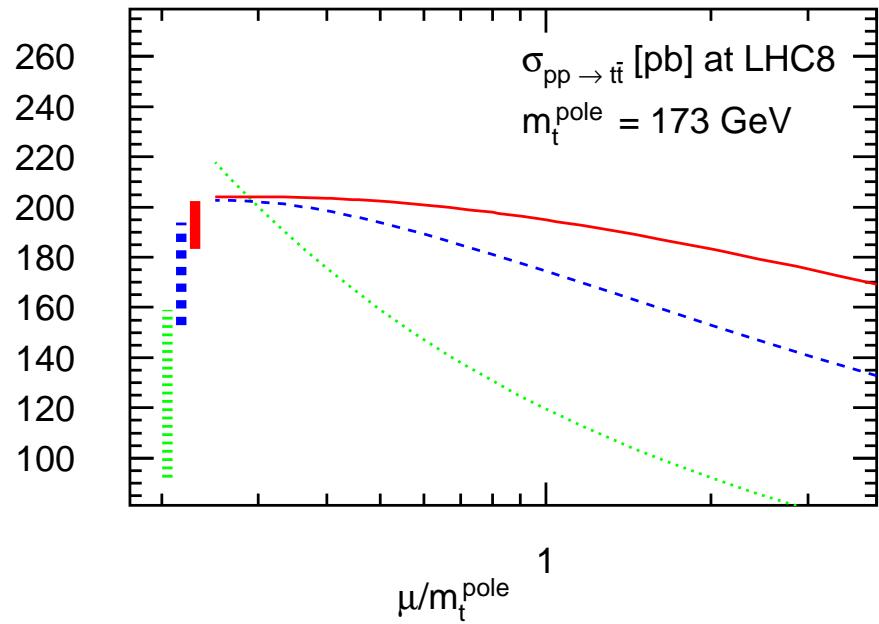
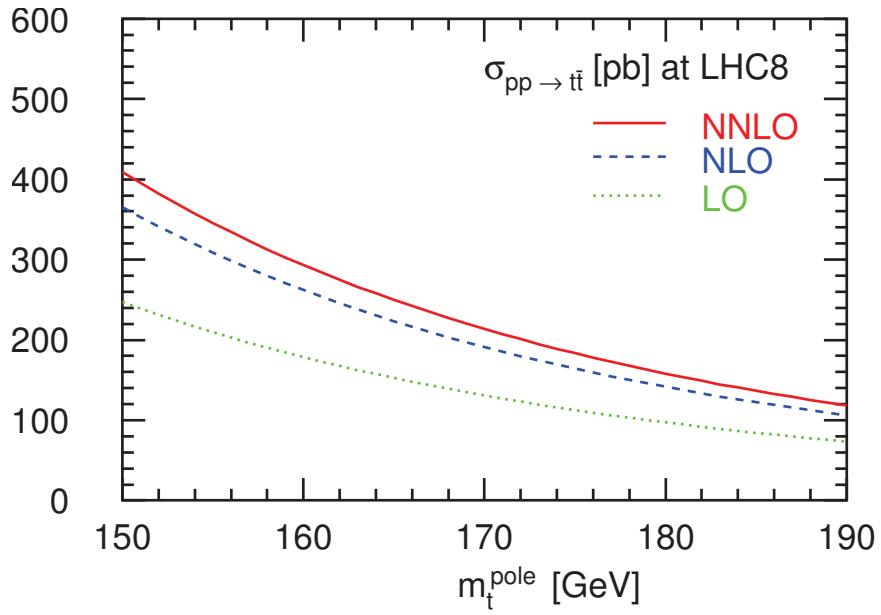
- Joint dependence on non-perturbative parameters:
parton distribution functions f_i , strong coupling α_s , masses m_X
- Intrinsic limitation in total cross section through sensitivity $\mathcal{S} \simeq 5$

$$\left| \frac{\Delta \sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \right| \simeq 5 \times \left| \frac{\Delta m_t}{m_t} \right|$$

Total cross section

Exact result at NNLO in QCD

Czakon, Fiedler, Mitov '13

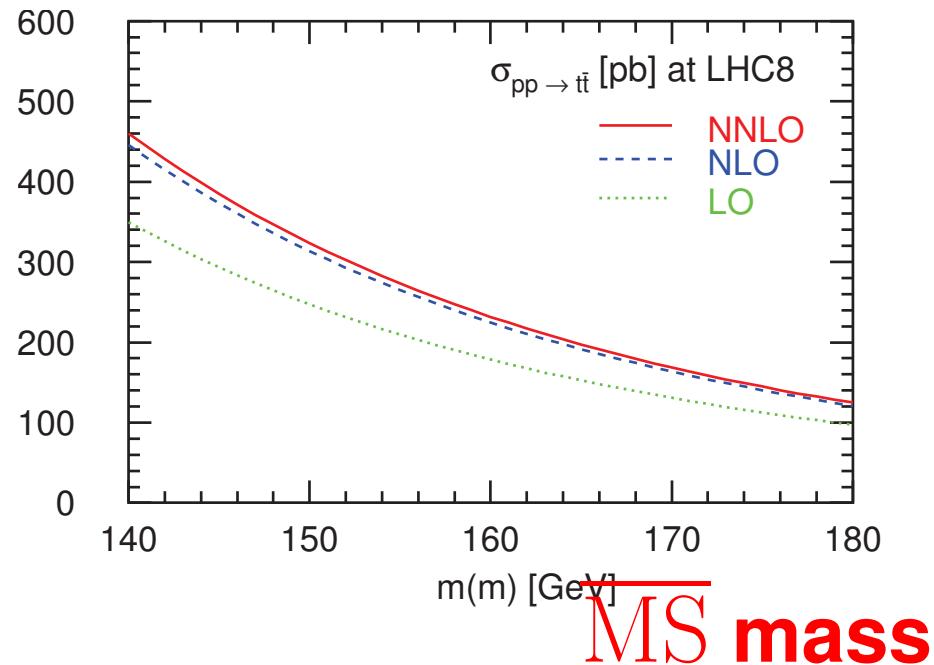
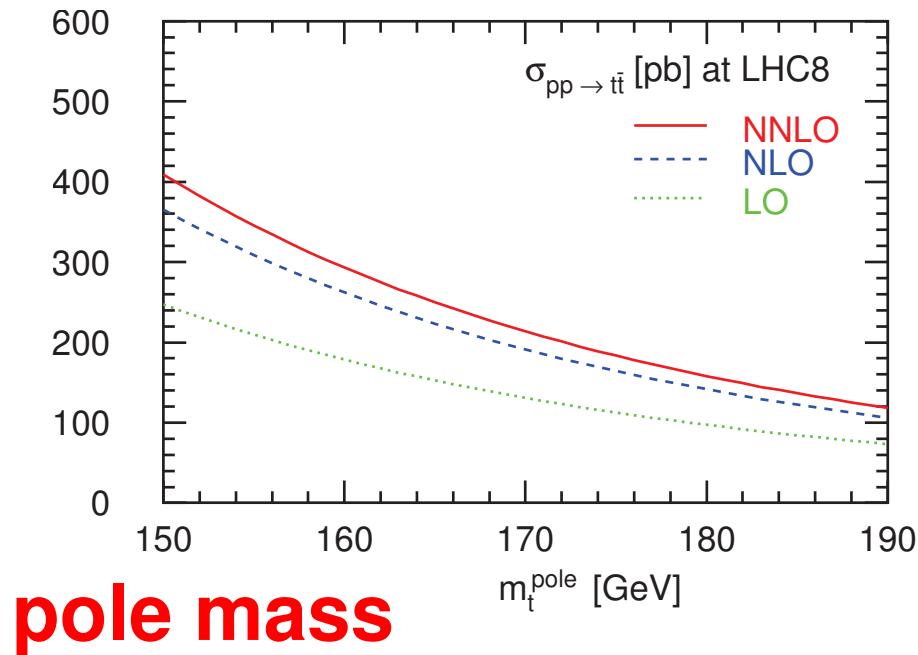


- NNLO perturbative corrections (e.g. at LHC8)
 - K -factor ($\text{NLO} \rightarrow \text{NNLO}$) of $\mathcal{O}(10\%)$
 - scale stability at NNLO of $\mathcal{O}(\pm 5\%)$

Total cross section with running mass

Comparison pole mass vs. $\overline{\text{MS}}$ mass (I)

Dowling, S.M. '13

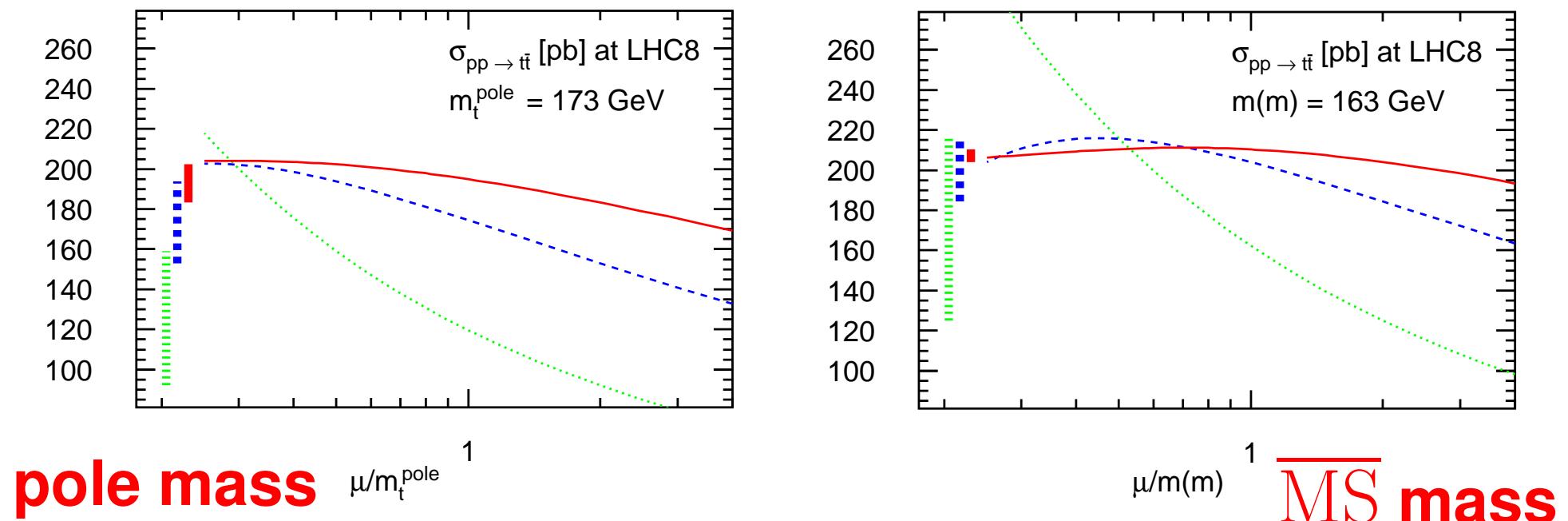


- NNLO cross section with running mass significantly improved
 - good apparent convergence of perturbative expansion
 - small theoretical uncertainty from scale variation

Total cross section with running mass

Comparison pole mass vs. $\overline{\text{MS}}$ mass (II)

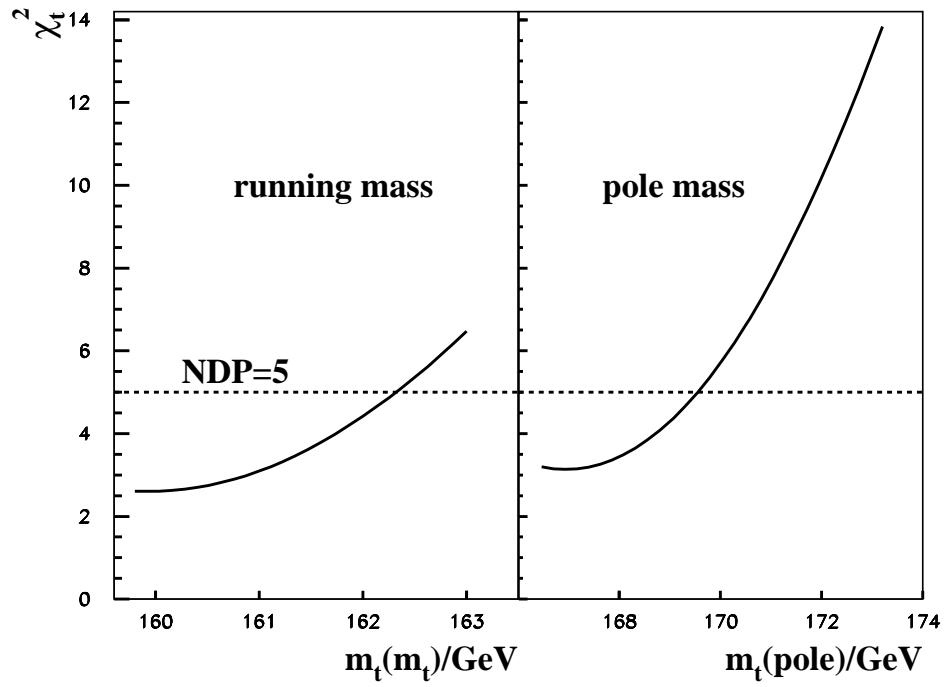
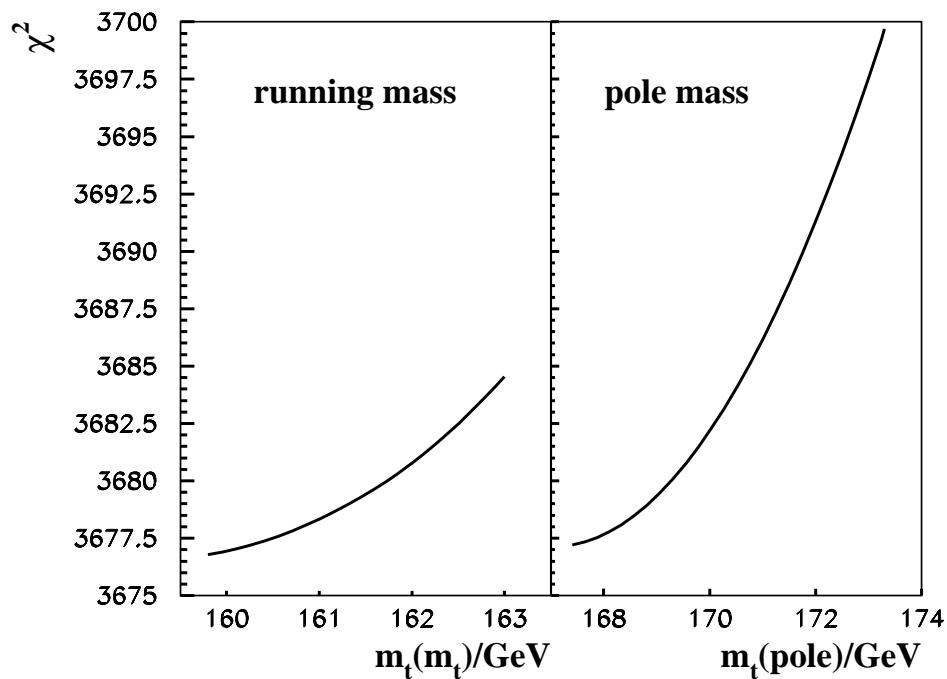
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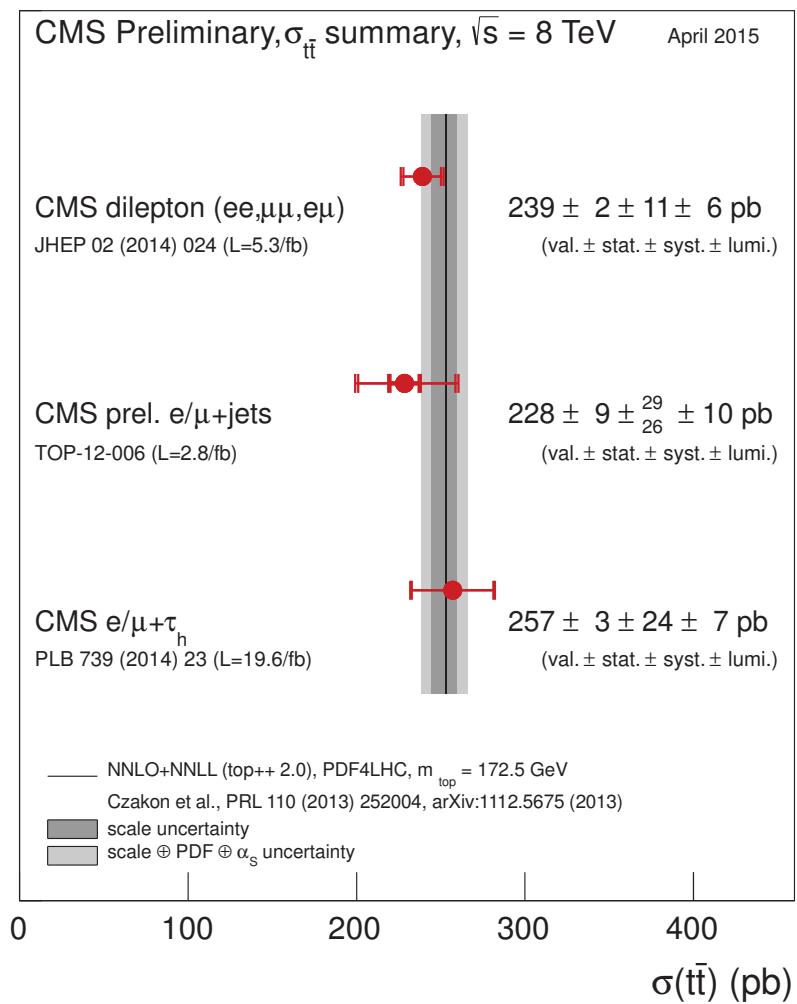
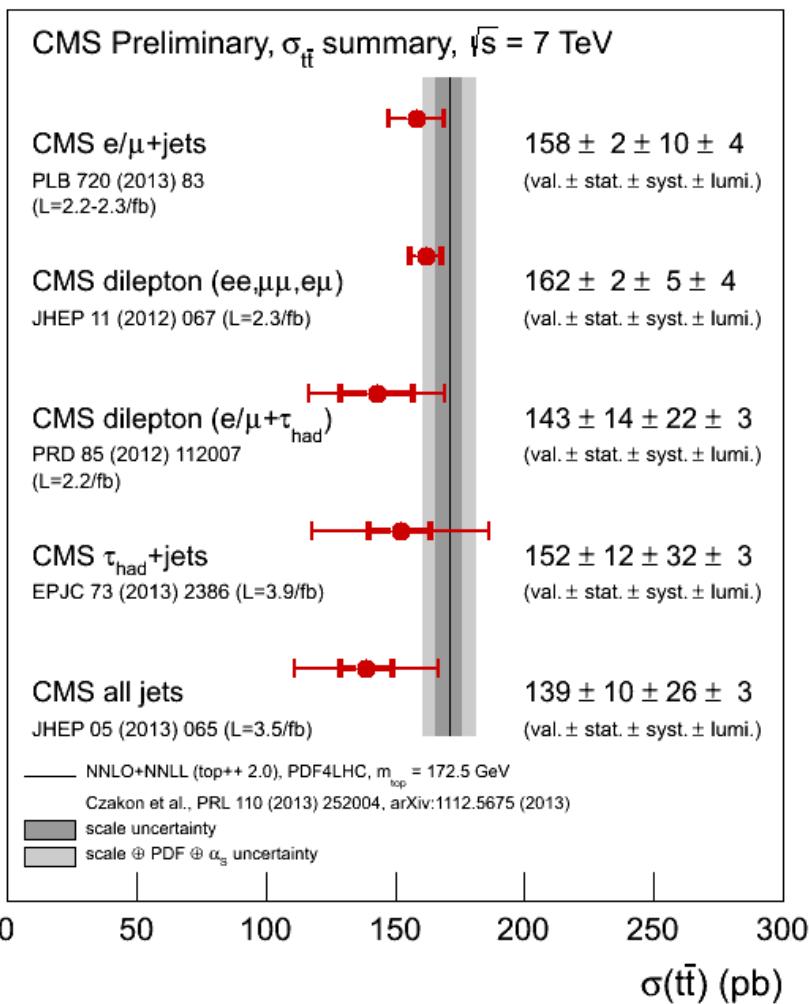
Top cross section data in ABM12 fit

- Fit with correlations
 - $g(x)$ and $\alpha_s(M_Z)$ already well constrained by global fit (no changes)
 - for fit with $\chi^2/NDP = 5/5$ obtain value of $m_t(m_t) = 162.3 \pm 2.3$ GeV (equivalent to pole mass $m_t = 171.2 \pm 2.4$ GeV) Alekhin, Blümlein, S.M. '13
 - χ^2 -profile steeper for pole mass (bigger impact of top-quark data and greater sensitivity to theoretical uncertainty at NNLO)



Future improvements

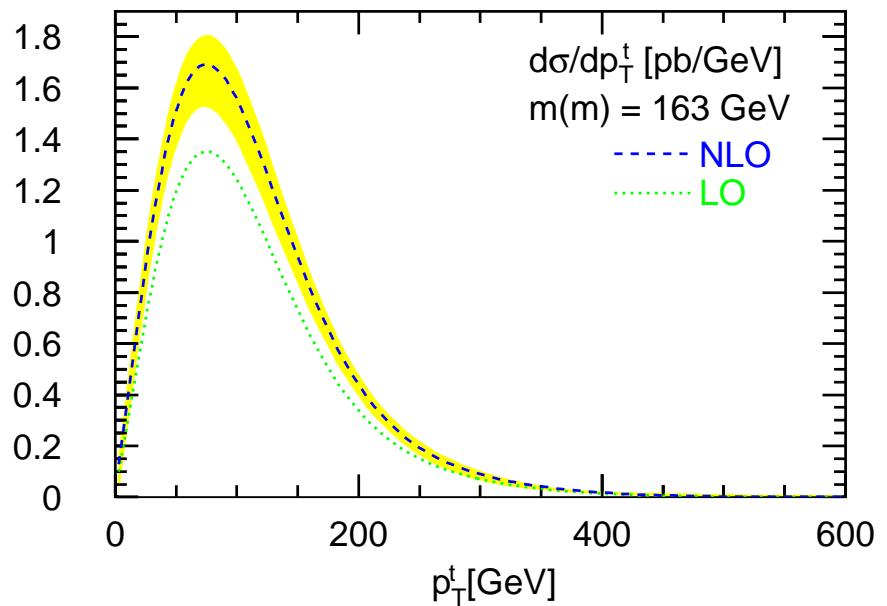
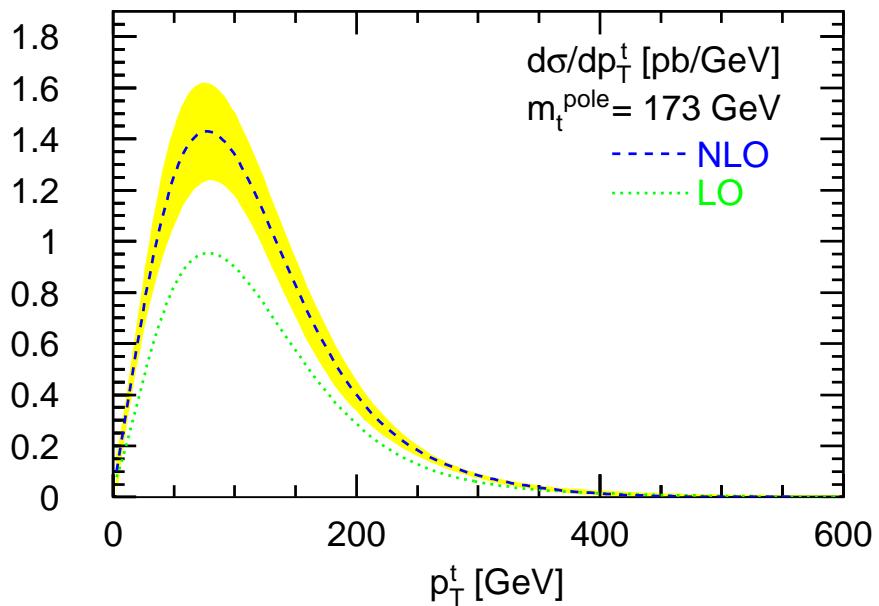
Fit to new data



- Precision cross section determinations at $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$
- CMS coll '15

Differential cross sections

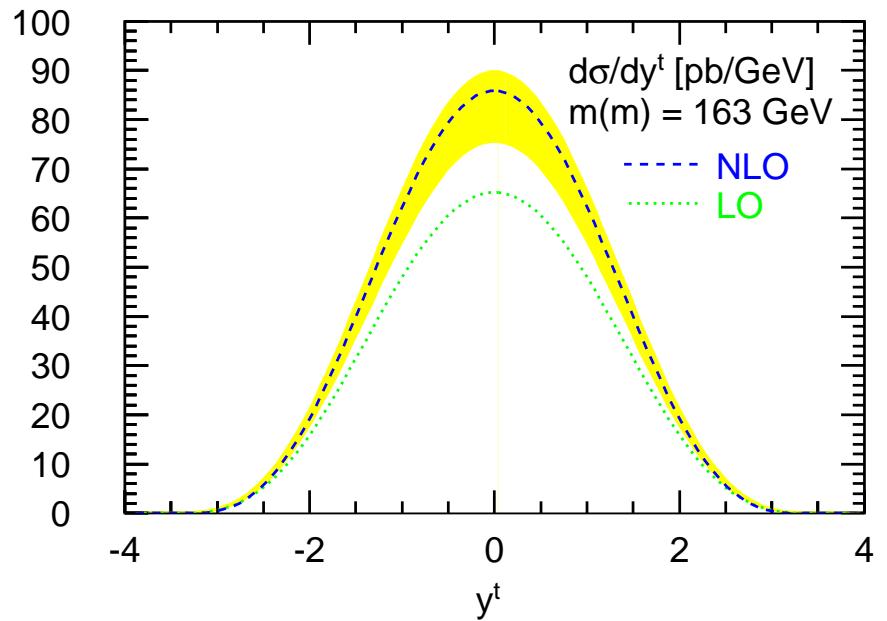
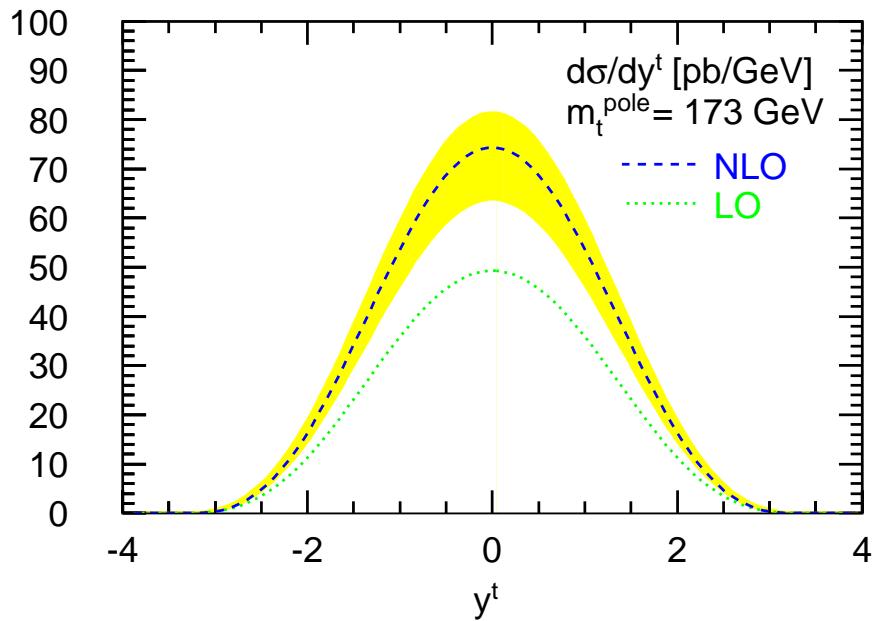
NLO in QCD



- Running mass for differential distributions show same features,
e.g. p_T^t -distribution Dowling, S.M. '13

Differential cross sections

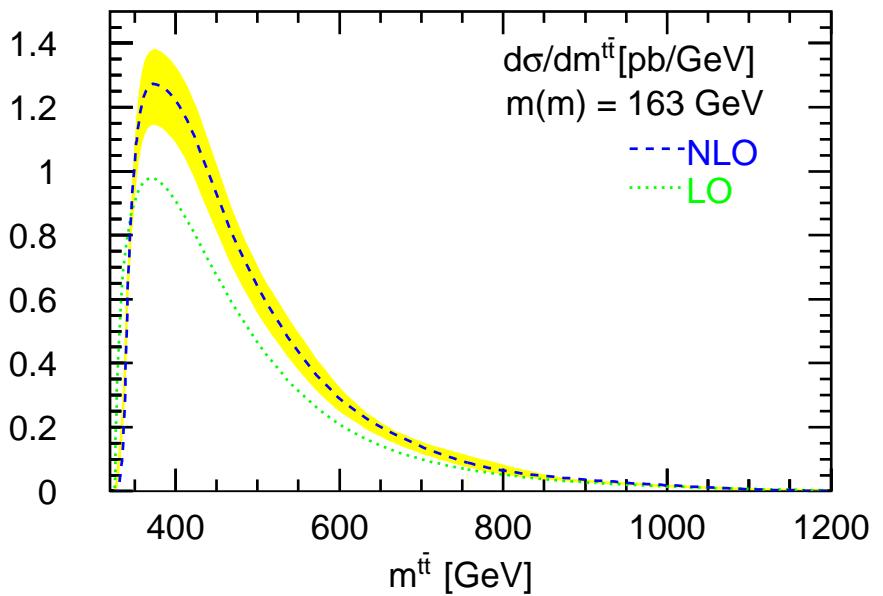
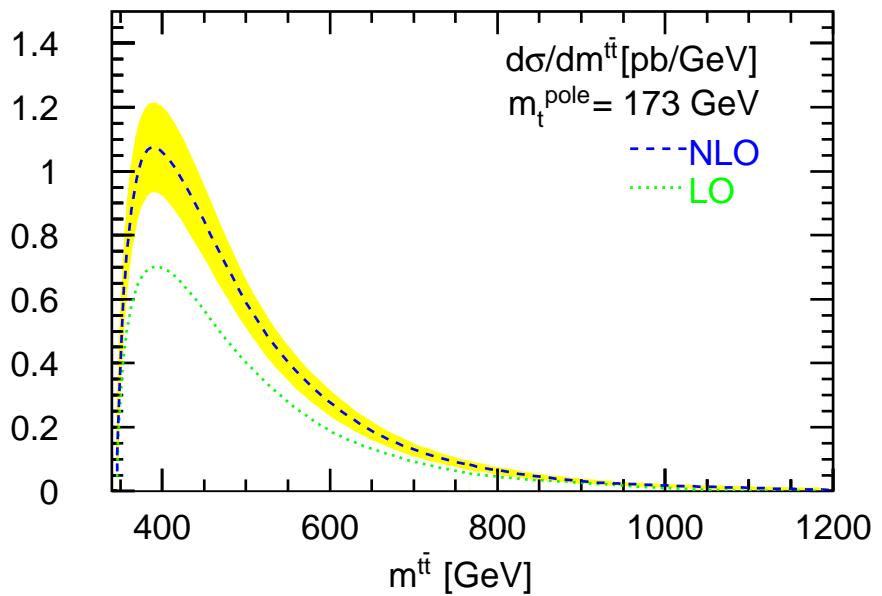
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e.g. y^t -distribution Dowling, S.M. '13

Differential cross sections

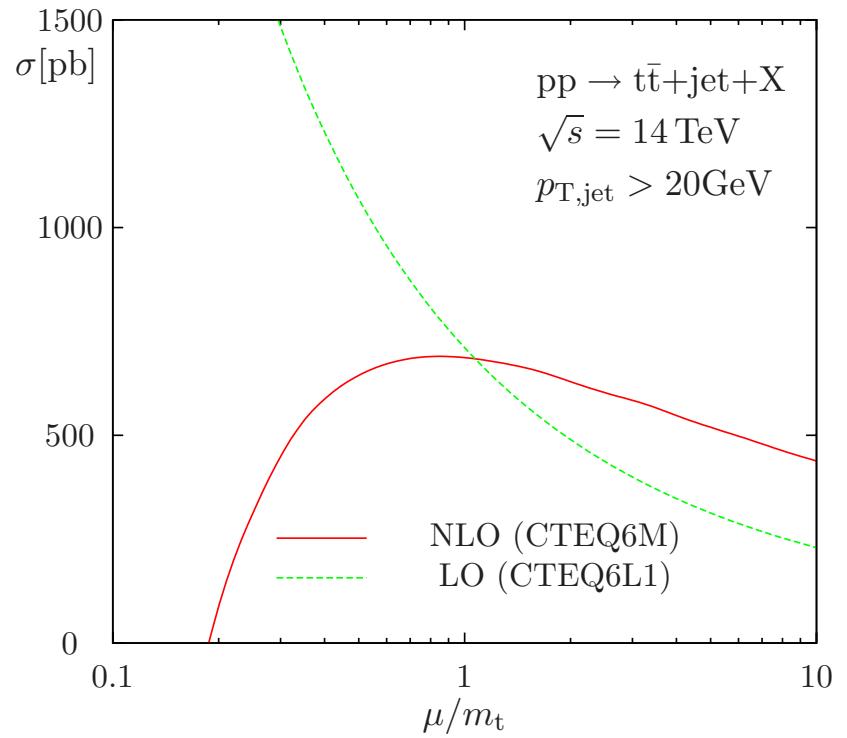
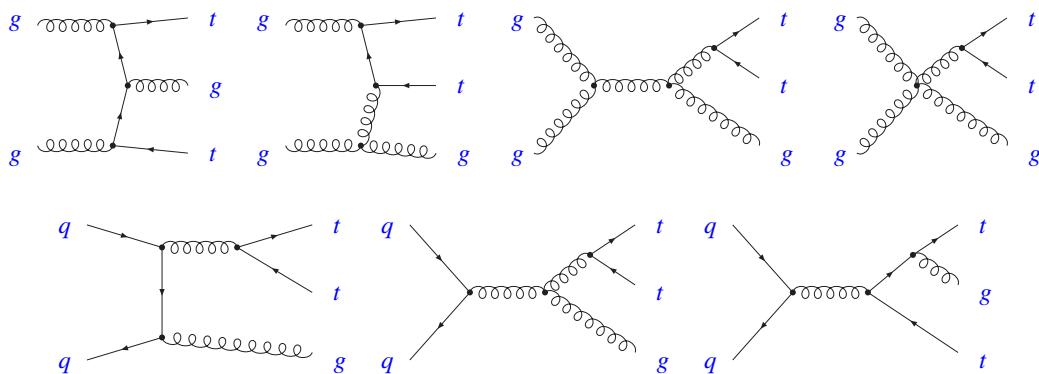
NLO in QCD



- Running mass for differential distributions show same features,
e.g. $m_{t\bar{t}}$ -distribution Dowling, S.M. '13

Top-quark pairs with one jet

- LHC: large rates for production of $t\bar{t}$ -pairs with additional jets
- NLO QCD corrections for $t\bar{t} + 1\text{jet}$ Dittmaier, Uwer, Weinzierl '07-'08
 - scale dependence greatly reduced at NLO
 - corrections for total rate at scale $\mu_r = \mu_f = m_t$ are almost zero



- Additional jet raises kinematical threshold
 - invariant mass $\sqrt{s_{t\bar{t}+1\text{jet}}}$

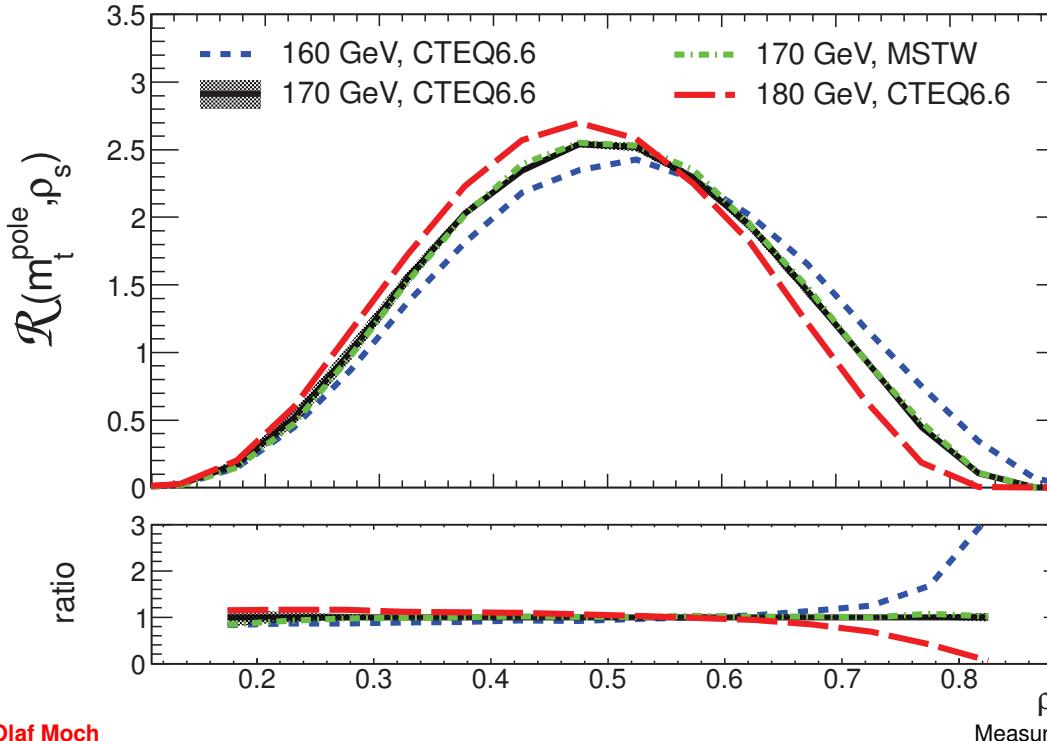
Top mass with $t\bar{t} + \text{jet-samples}$

- Normalized-differential $t\bar{t} + \text{jet}$ cross section

Alioli, Fernandez, Fuster, Irles, S.M., Uwer, Vos '13

$$\mathcal{R}(m_t, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{jet}}} \frac{d\sigma_{t\bar{t}+1\text{jet}}}{d\rho_s}(m_t, \rho_s)$$

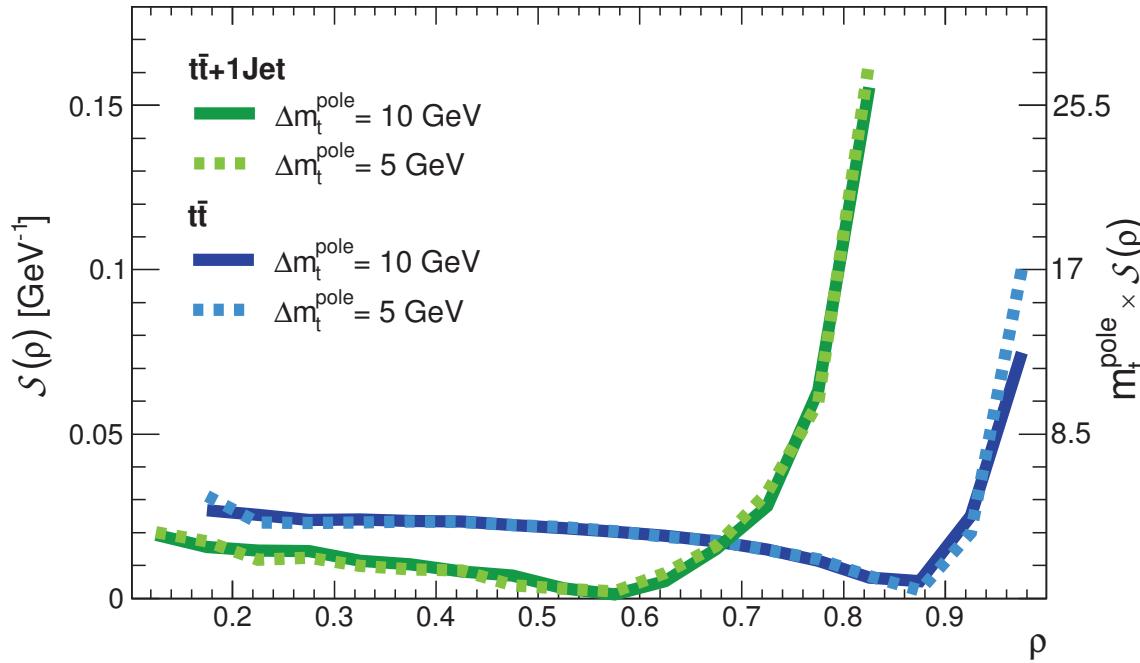
- variable $\rho_s = \frac{2 \cdot m_0}{\sqrt{s_{t\bar{t}+1\text{jet}}}}$ with invariant mass of $t\bar{t} + 1\text{jet}$ system and fixed scale $m_0 = 170 \text{ GeV}$
- Significant mass dependence for $0.4 \leq \rho_s \leq 0.5$ and $0.7 \leq \rho_s$



Mass sensitivity of $t\bar{t}$ + jet-samples

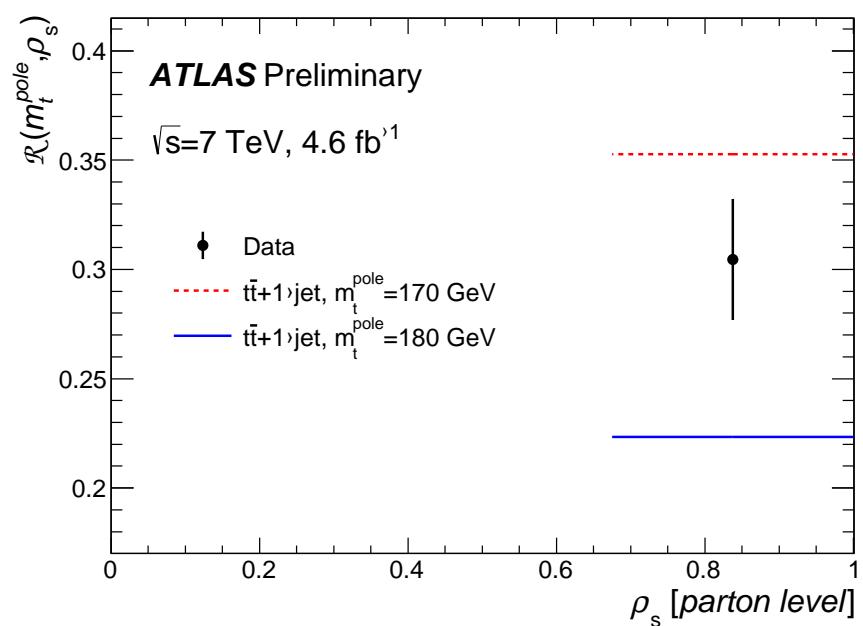
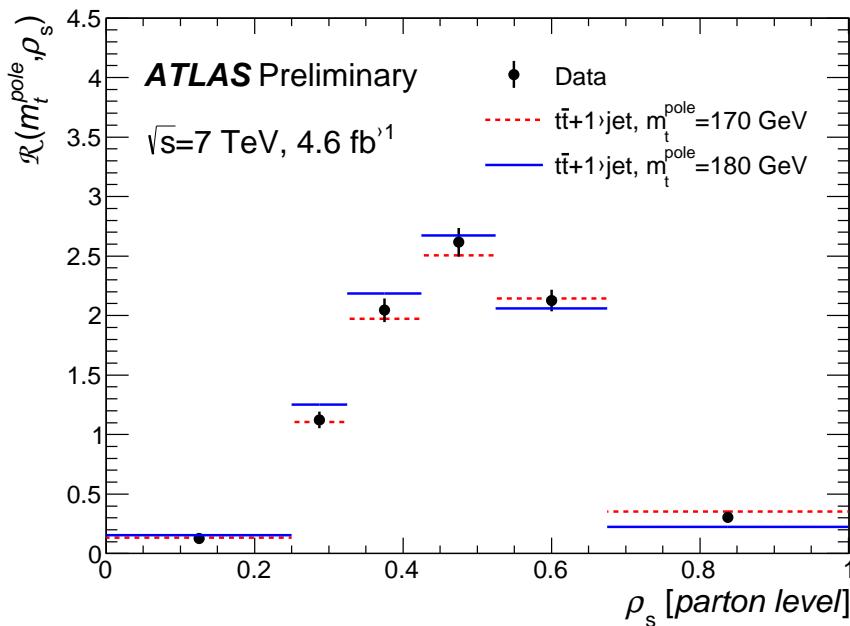
- Differential cross section $\mathcal{R}(m_t, \rho_s)$
 - good perturbative stability, small theory uncertainties, small dependence on experimental uncertainties, ...
- Increased sensitivity for system $t\bar{t}$ + jet compared

$$\left| \frac{\Delta \mathcal{R}}{\mathcal{R}} \right| \simeq (m_t S) \times \left| \frac{\Delta m_t}{m_t} \right|$$



ATLAS analysis

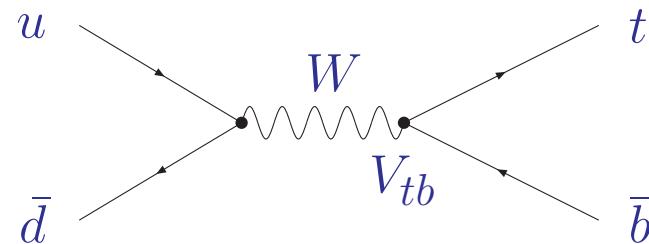
- Top-quark mass measurement ATLAS-CONF-2014-053
 $m_{\text{pole}} = 173.7 \pm 1.5(\text{stat.}) \pm 1.4(\text{syst.})^{+1.0}_{-0.5}(\text{theo.})$
 - pole scheme mass



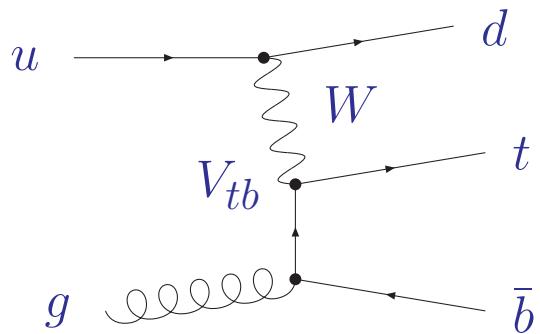
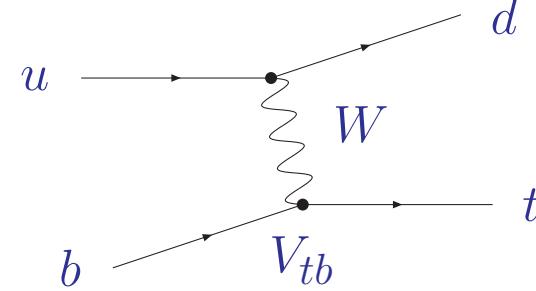
- High precision data in threshold region $0.7 \leq \rho_s$
 - cancellation of systematics in the normalized distribution
 - promising method for LHC at $\sqrt{s} = 13 \text{ TeV}$

Single top-quark production

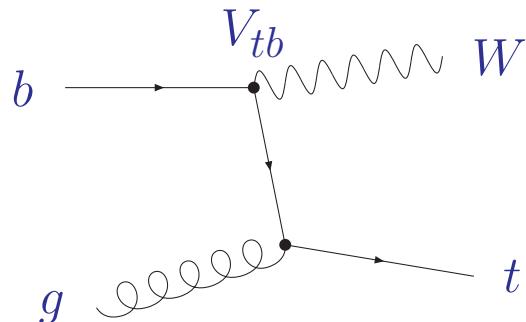
- Study of charged-current weak interaction of top quark
- s -channel production



- t -channel production
 - bg -channel at NLO enhanced by gluon luminosity



- Wt -production
 - contributes at LHC (small at Tevatron)



Theory status

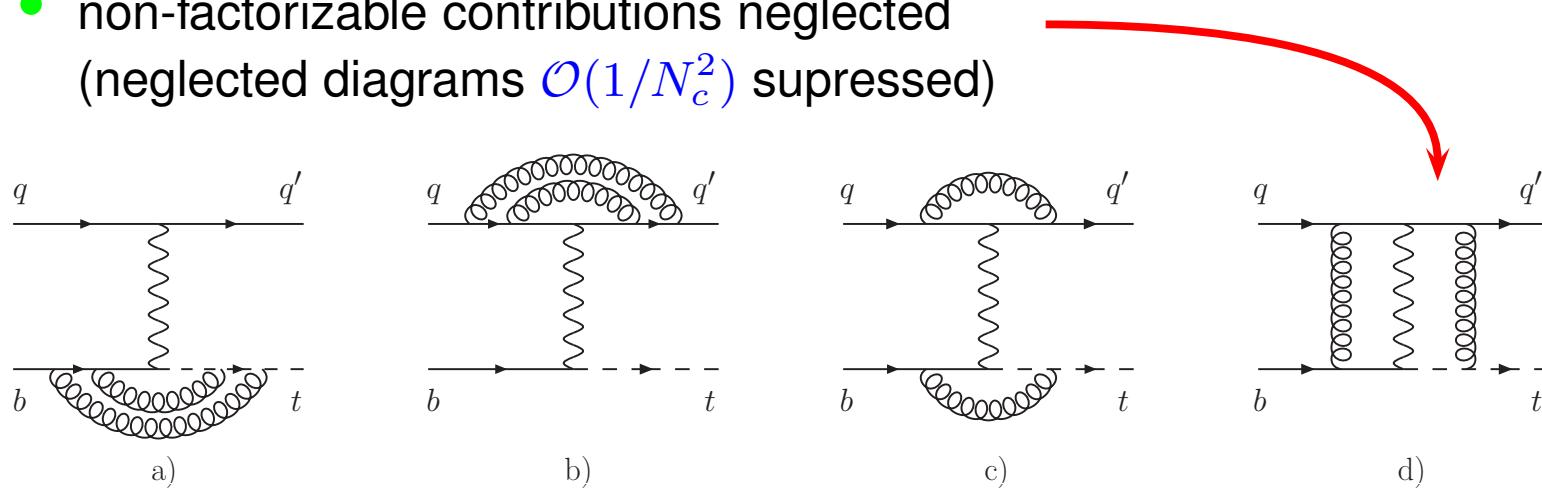
- QCD corrections known
 - complete NLO Harris, Laenen, Phaf, Sullivan, Weinzierl '02; Sullivan '04; Campbell, Frederix, Maltoni, Tramontano '09; [+ many people]
 - implementations merged with parton shower
 - in MC@NLO Frixione, Laenen, Motylinski, Webber, White '09
 - in POWHEG Aioli, Nason, Oleari, Re '09
 - NNLO (structure function approach) Brucherseifer, Caola, Melnikov '14

Treatment of heavy quarks

- Scheme with $n_l = 4$ light flavors + heavy quark of mass m_b at low scales
 - no mass singularities for $m_b, m_t \gg \Lambda_{QCD}$, no (evolving) PDFs
- Scheme with $n_l = 5$ light flavors
 - b PDF for $Q \ggg m_b$ generated perturbatively

QCD corrections at NNLO

- Computation of NNLO QCD corrections Brucherseifer, Caola, Melnikov '14
 - fully differential, with cuts on p_T
- QCD corrections treated in structure function approach
 - non-factorizable contributions neglected
(neglected diagrams $\mathcal{O}(1/N_c^2)$ suppressed)

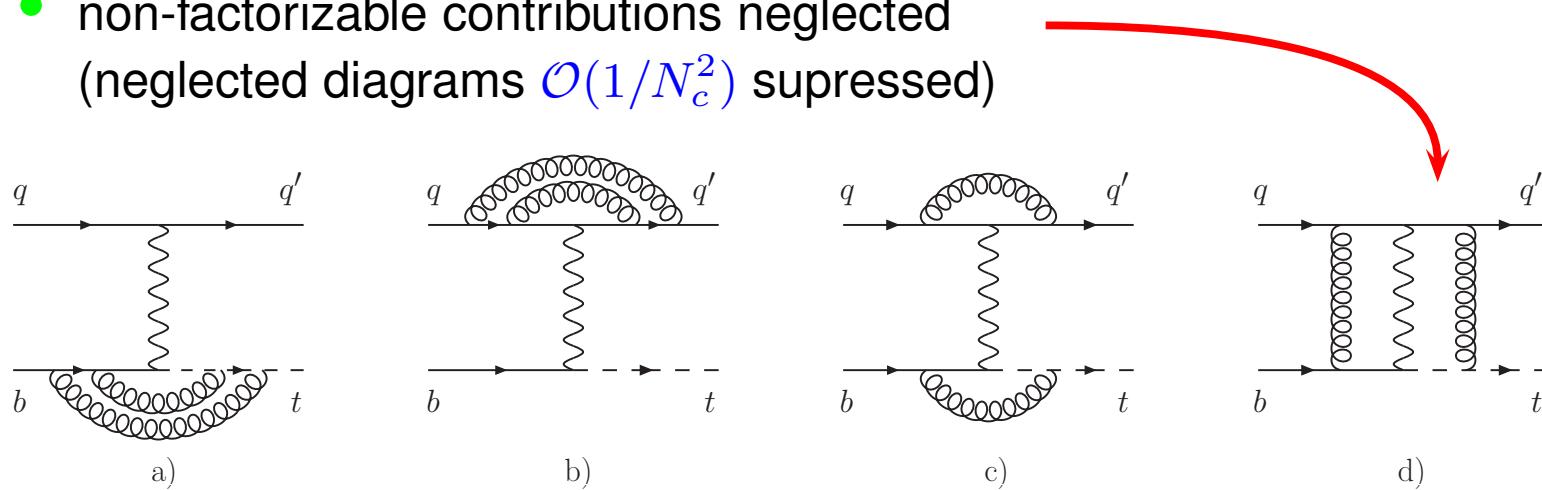


- QCD corrections to t -channel single top quark production at LHC8

p_\perp	$\sigma_{\text{LO}}, \text{pb}$	$\sigma_{\text{NLO}}, \text{pb}$	δ_{NLO}	$\sigma_{\text{NNLO}}, \text{pb}$	δ_{NNLO}
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	+2.4%	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	+4.9%	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	+9.3%	$36.5^{+0.1}_{-0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{-0.3}$	+13.6%	$25.4^{+0.1}_{-0.2}$	+1.6%

QCD corrections at NNLO

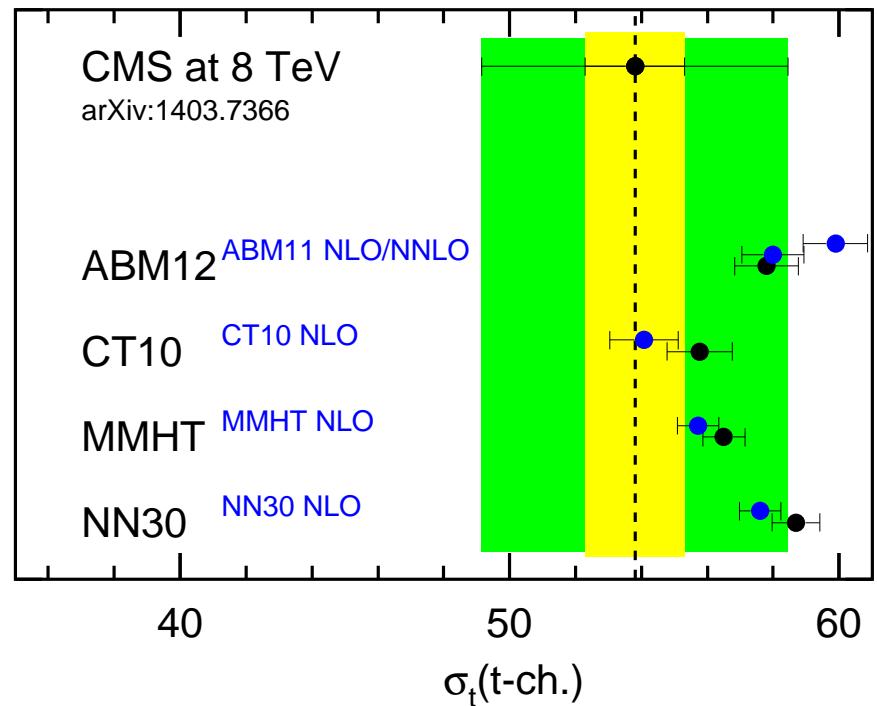
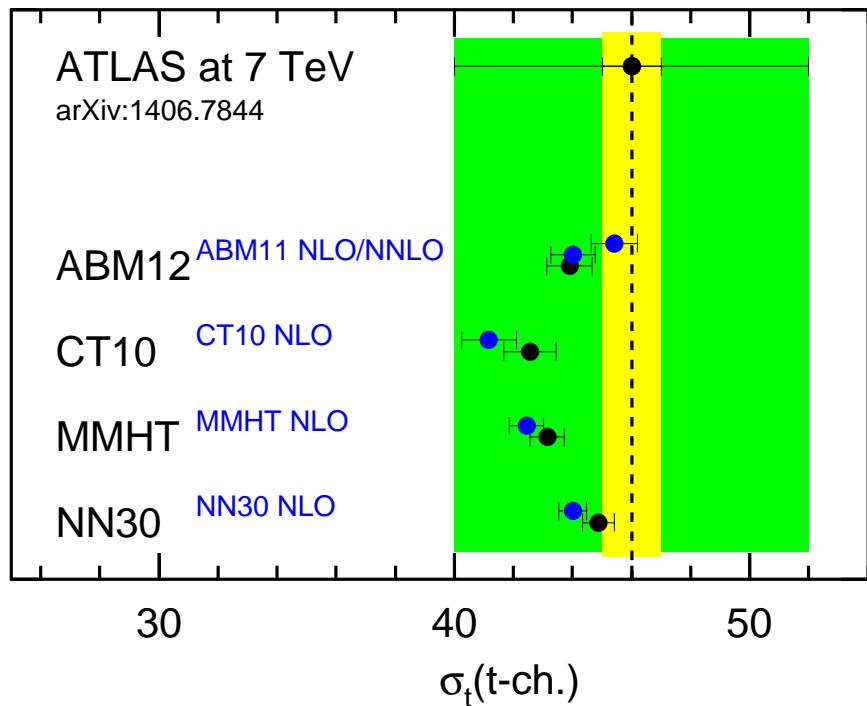
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- QCD corrections to t -channel single anti-top quark production at LHC8

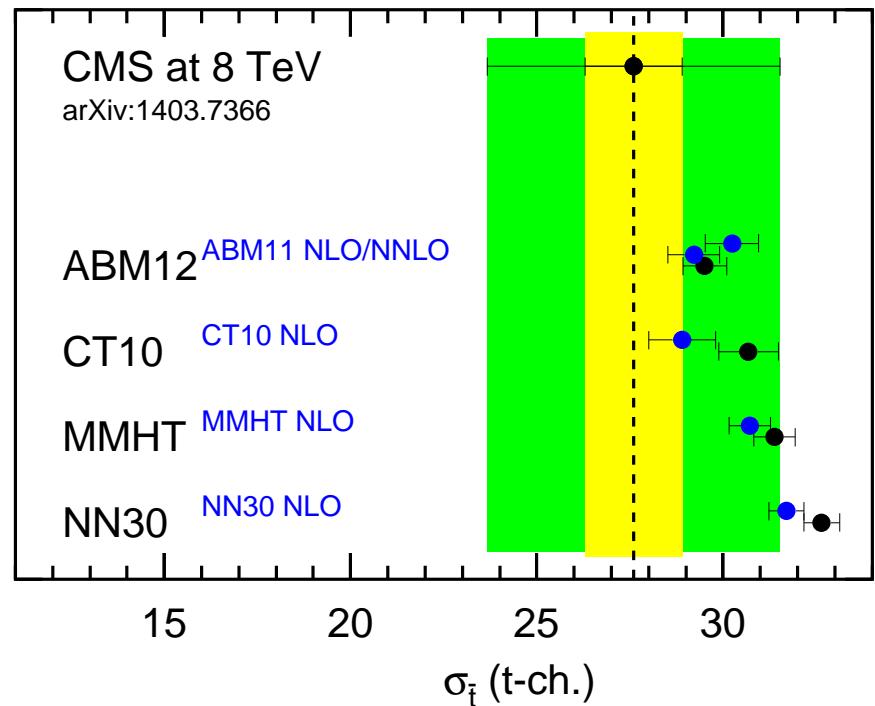
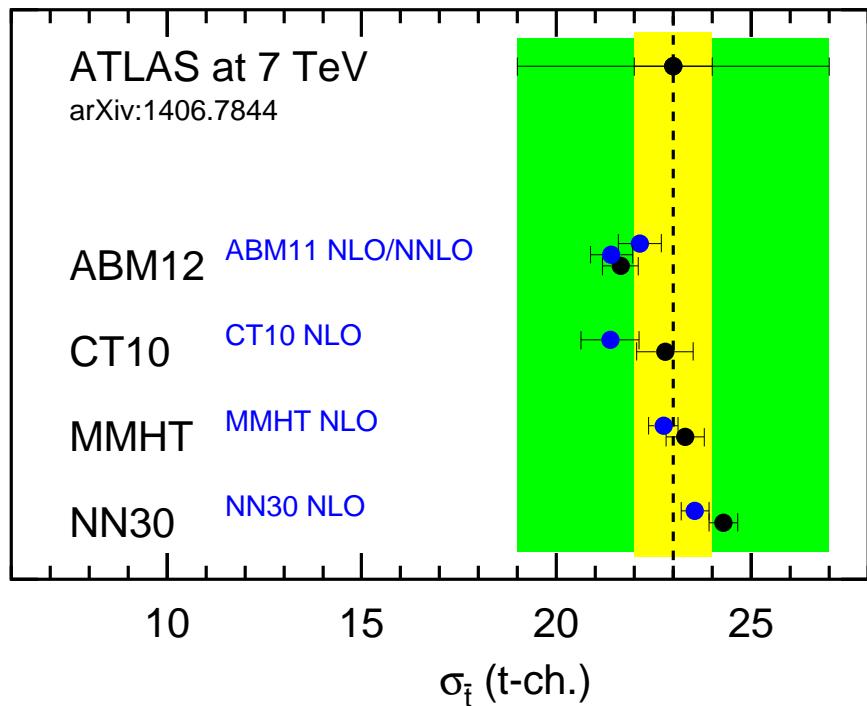
p_\perp	$\sigma_{\text{LO}}, \text{pb}$	$\sigma_{\text{NLO}}, \text{pb}$	δ_{NLO}	$\sigma_{\text{NNLO}}, \text{pb}$	δ_{NNLO}
0 GeV	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	+3.4%	$29.7^{+0.3}_{-0.1}$	-1.3%
20 GeV	$24.8^{+1.4}_{-2.0}$	$26.3^{+0.7}_{-0.3}$	+6.0%	$26.2^{+0.1}_{-0.1}$	-0.4%
40 GeV	$17.1^{+0.9}_{-1.3}$	$19.1^{+0.3}_{-0.1}$	+11.7%	$19.3^{+0.1}_{-0.2}$	+1.0%
60 GeV	$10.8^{+0.5}_{-0.7}$	$12.7^{+0.03}_{-0.2}$	+17.6%	$12.9^{+0.2}_{-0.2}$	+1.6%

Single top-quark t -channel production



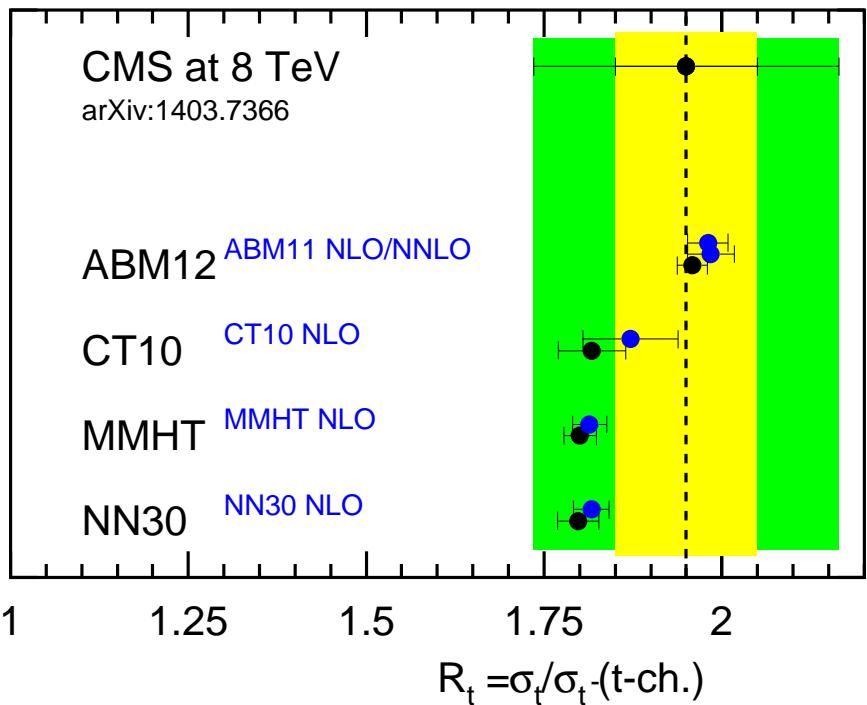
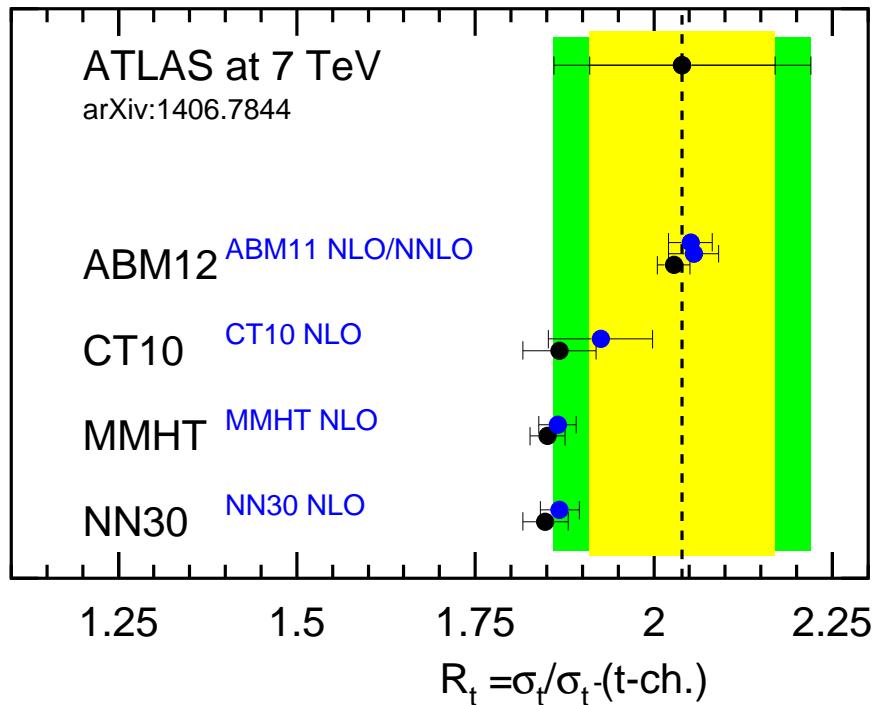
- Sensitivity to top-quark mass weaker than for $t\bar{t}$ -production
- Cross section correlated with u - and d -quark PDFs

Single anti-top-quark t-channel production



- Experimental statistical (yellow) and statistical+systematical (green) uncertainty
- Cross section evaluation with Hathor v2.0
Kant, Kind, Kintscher, Lohse, Martini, Mölitz, Rieck, Uwer '14

Standard candle



- Ratio of cross sections $R_t = \sigma_t / \sigma_{\bar{t}}$
- Highly sensitive check of ratio of \bar{u}/\bar{d} -quark PDFs

Higgs boson mass

Experimental result

Atlas arXiv:1307.1427; CMS coll. arXiv:1312.5353; (average arXiv:1303.3570)

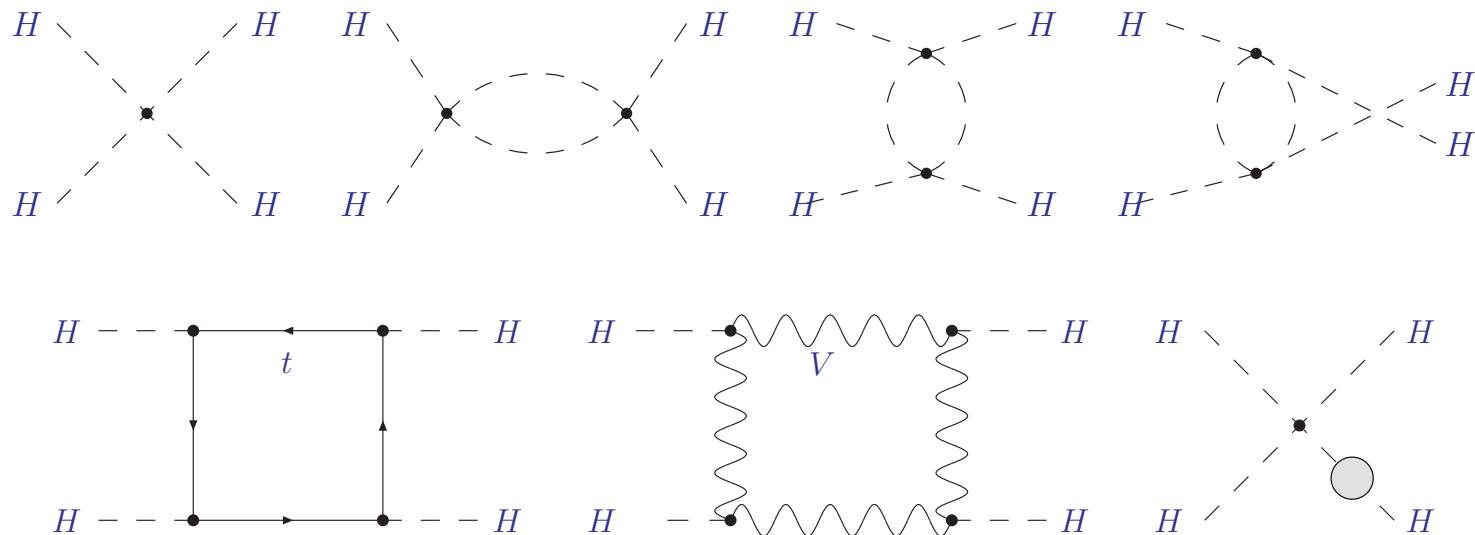
$$m_H = 125.15 \pm 0.24 \text{ GeV}$$

Higgs potential

Renormalization group equation

- Quantum corrections to Higgs potential $V(\Phi) = \lambda |\Phi^\dagger \Phi - \frac{v}{2}|^2$
- Radiative corrections to Higgs self-coupling λ
 - electro-weak couplings g and g' of $SU(2)$ and $U(1)$
 - top-Yukawa coupling y_t

$$16\pi^2 \frac{d\lambda}{dQ} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2g^2 + \frac{9}{8}g^4 - 6y_t^4 + \dots$$



Higgs potential

Triviality

- Large mass implies large λ
 - renormalization group equation dominated by first term

$$16\pi^2 \frac{d\lambda}{dQ} \simeq 24\lambda^2 \quad \rightarrow \quad \lambda(Q) = \frac{m_H^2}{2v^2 - \frac{3}{2\pi^2} m_H^2 \ln(Q/v)}$$

- $\lambda(Q)$ increases with Q
- Landau pole implies cut-off Λ
 - scale of new physics smaller than Λ to restore stability
 - upper bound on m_H for fixed Λ

$$\Lambda \leq v \exp \left(\frac{4\pi^2 v^2}{3m_H^2} \right)$$

- Triviality for $\Lambda \rightarrow \infty$
 - vanishing self-coupling $\lambda \rightarrow 0$ (no interaction)

Higgs potential

Vacuum stability

- Small mass
 - renormalization group equation dominated by y_t

$$16\pi^2 \frac{d\lambda}{dQ} \simeq -6y_t^4 \quad \rightarrow \quad \lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln(Q/Q_0)}{1 - \frac{9}{16\pi^2} y_0^2 \ln(Q/Q_0)}$$

- $\lambda(Q)$ decreases with Q
- Higgs potential unbounded from below for $\lambda < 0$
- $\lambda = 0$ for $\lambda_0 \simeq \frac{3}{8\pi^2} y_0^4 \ln(Q/Q_0)$
- Vacuum stability

$$\Lambda \leq v \exp \left(\frac{4\pi^2 m_H^2}{3y_t^4 v^2} \right)$$

- scale of new physics smaller than Λ to ensure vacuum stability
- lower bound on m_H for fixed Λ

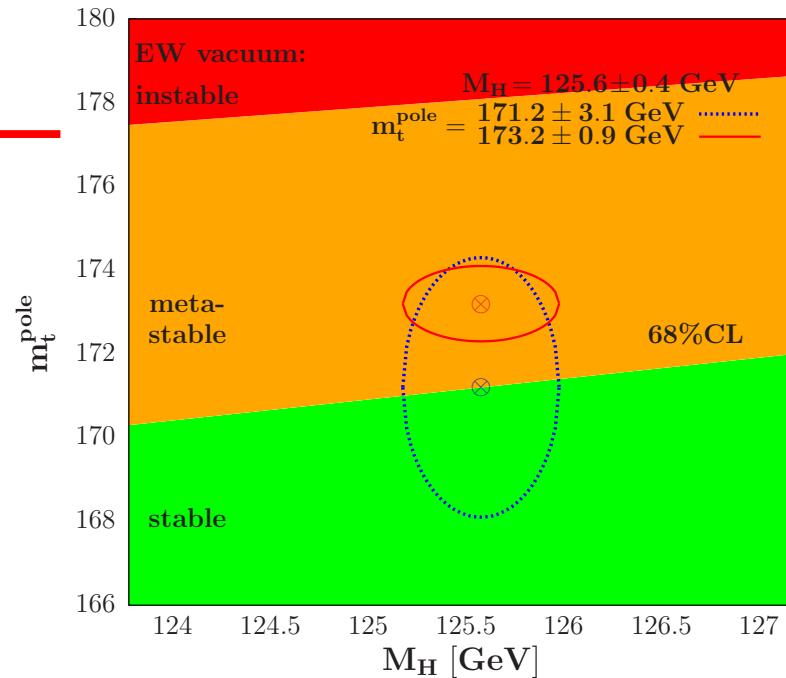
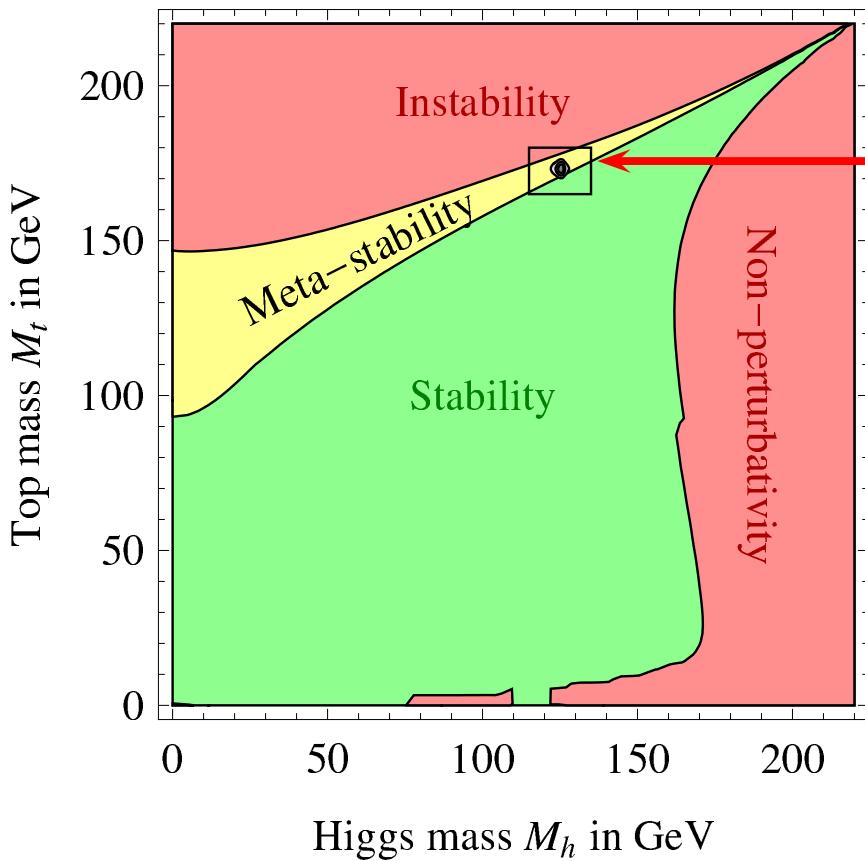
Implications on electroweak vacuum

- Relation between Higgs mass m_H and top-quark mass m_t
 - condition of absolute stability of electroweak vacuum $\lambda(\mu) \geq 0$
 - extrapolation of Standard Model up to Planck scale M_P
 - $\lambda(M_P) \geq 0$ implies lower bound on Higgs mass m_H

$$m_H \geq 129.6 + 2.0 \times \left(m_t^{\text{pole}} - 173.34 \text{ GeV} \right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 0.3 \text{ GeV}$$

- recent NNLO analyses Bezrukov, Kalmykov, Kniehl, Shaposhnikov '12; Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice et al. '12; Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia '13
- uncertainty in results due to α_s and m_t (pole mass scheme)
- Top-quark mass from total cross section (well-defined scheme)
 - $m_t^{\overline{\text{MS}}} (m_t) = 162.3 \pm 2.3 \pm 0.7 \text{ GeV}$ implies in pole mass scheme $m_t^{\text{pole}} = 171.2 \pm 2.4 \pm 0.7 \text{ GeV}$
 - mass determination accounts for correlation with gluon PDF and $\alpha_s(M_Z)$

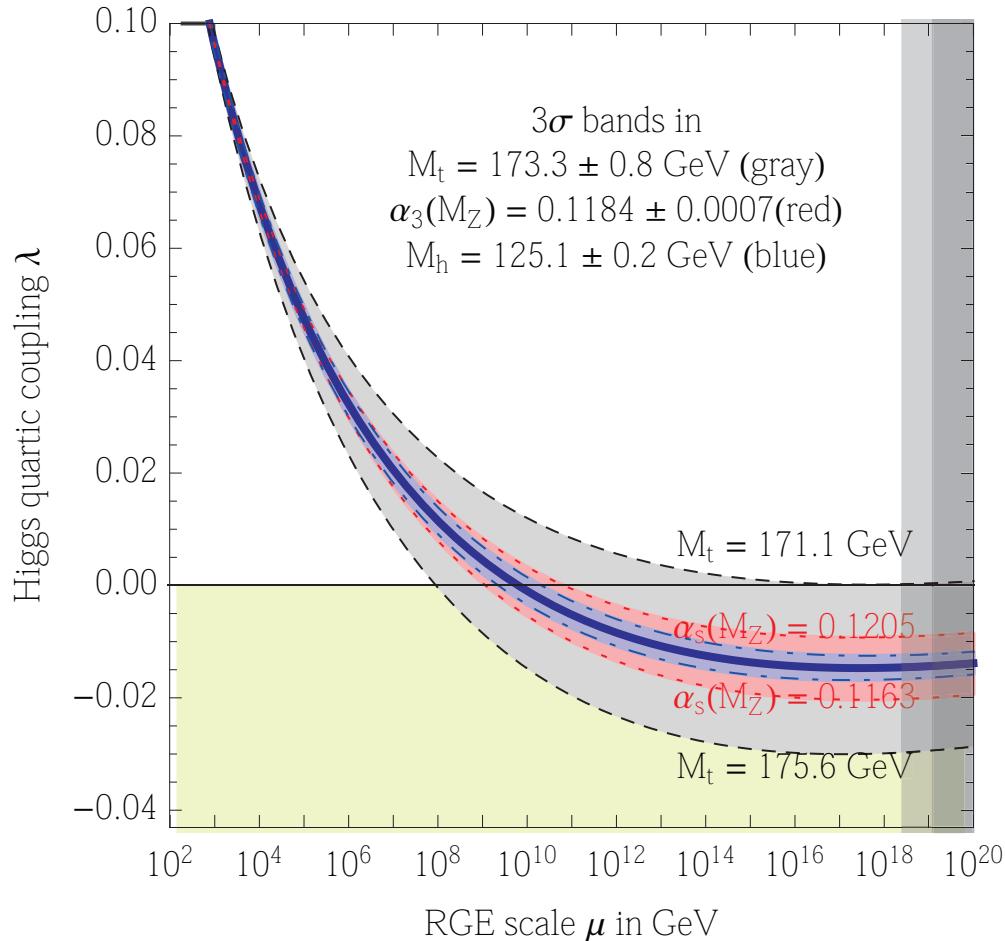
Fate of the universe



Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice et al. '12; Alekhin, Djouadi, S.M. '12; Masina '12

- Uncertainty in Higgs bound due to m_t from in \overline{MS} scheme
 - bound relaxes $m_H \geq 125.3 \pm 6.2$ GeV
 - “fate of universe” still undecided

Higgs self-coupling



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia '13

- Renormalization group evolution of λ with uncertainties in m_H , m_t and α_s
 - top-quark mass least precise parameter
- Vacuum stability bound at M_P in terms of m_t

$$m_t \leq (171.53 \pm 0.15 \pm 0.23_{\alpha_3} \pm 0.15_{m_h}) \text{ GeV} = (171.53 \pm 0.42) \text{ GeV}$$

Summary

Top-quark mass

- Running mass ($\overline{\text{MS}}$ scheme) at NNLO in QCD

$$m_t(m_t) = 162.3 \pm 2.3 \pm 0.7 \text{GeV}$$

Higgs mass

- Known to very high precision (pole mass)

$$m_H = 125.15 \pm 0.24 \text{GeV}$$

Fate of the universe

- Still undecided ...

Summary

Physics at the Terascale

- Discovery of Higgs boson opens new avenue for studies of Standard Model physics and beyond
- QCD and electroweak corrections at higher orders are crucial
- Precision tests of SM at LHC depend on non-perturbative parameters
 - masses m_t , M_W , m_H , ...
 - coupling constant $\alpha_s(M_Z)$
 - parton content of proton (PDFs)

Top-quark mass

- Top-quark mass is parameter of Standard Model Lagrangian
- Measurements of m_t require careful definition of observable
- Quality of perturbative expansion depends on scheme for top-quark mass
- Relation of Monte Carlo mass m^{MC} to pole mass with additional theory uncertainty $\Delta m_t(\text{th})$

Future tasks

- Joint effort theory and experiment