Constraining QCD Parameters Using the $t\bar{t}$ Cross Section

(Top-Quark Mass, Strong Coupling Constant and Parton Densities)

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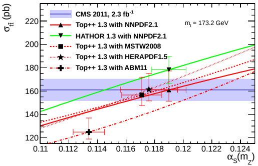
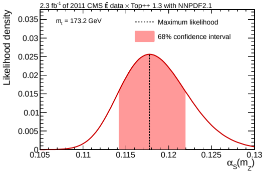
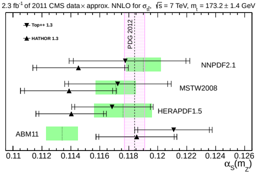






Motivation: *Quantum Chromodynamics*

Free parameters of the QCD Lagrangian:

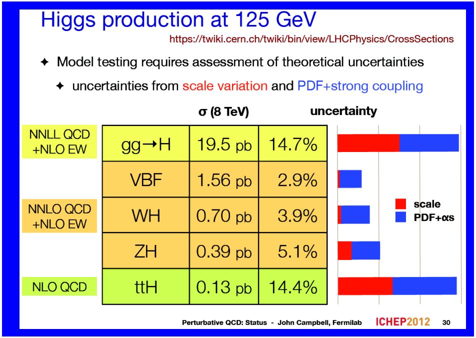
- The quark masses
- The strong coupling constant α_S

Factorization theorem:

$$\sigma \propto \mathrm{PDFs}(x, \mu_F) \otimes \hat{\sigma}(x, \mu_F, \mu_R, \alpha_S(\mu_R))$$

$\hat{\sigma}$: hard scattering matrix element, perturbatively calculable

PDFs: parton distribution functions, determined from experimental data



Higgs production at 125 GeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- ✦ Model testing requires assessment of theoretical uncertainties
  - ✦ uncertainties from scale variation and PDF+strong coupling

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%

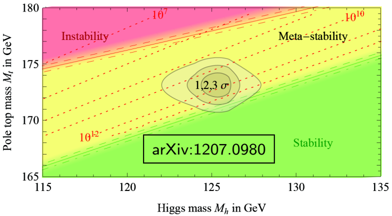
Perturbative QCD: Status - John Campbell, Fermilab ICHEP2012 30

Strong constraints on PDFs from various experiments, successfully evolved up to LHC energies

Still sizable uncertainties related to PDFs and α_S on QCD predictions, including Higgs and $t\bar{t}$ cross sections

LHC data will give a better handle on some kinematic regions, e.g. the gluon at medium/high momentum fractions x

Motivation: *Top-Quark Mass*



arXiv:1207.0980

Due to its mass, the top quark yields the dominant contribution to higher-order corrections from virtual particle loops

→ Constraints on new particles via electroweak fits and. . . even on the "ultimate fate of our universe"

Impressive precision both at Tevatron and LHC: $\delta(m_t) = \mathcal{O}\ (1\ \text{GeV})$

However, these direct measurements are calibrated using Monte Carlo, i.e. (N)LO + parton showers

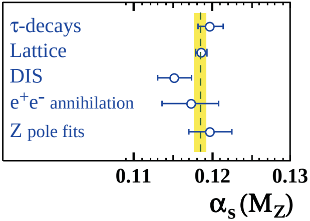
m_t^{MC} assumed to be similar to the pole mass but not identical:

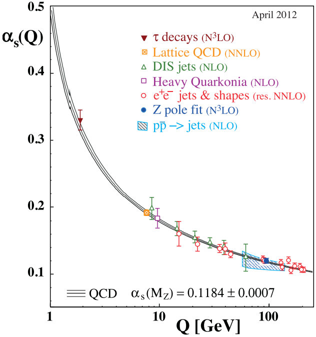
$$m_t^{\text{pole}} - m_t^{\text{MC}} \approx 1\ \text{GeV ???}$$ [arXiv:1101.2599]

Renormalized ("short-distance") masses also interesting, e.g. in the $\overline{\text{MS}}$ scheme (note: $m_t^{\text{pole}} - m_t^{\overline{\text{MS}}} \approx 9$ GeV, relation known to three-loop level)

Motivation: *Strong Coupling Constant*

2012 world average: 0.1184 ± 0.0007





α_S has been measured in a variety of processes and at different energies

Results are typically translated assuming the validity of the $\alpha_S(Q)$ evolution and compared at $Q = m_Z$

Precision of $\alpha_S(m_Z)$ world average: 0.6%

Average dominated by low-Q data

Still only few points above 209 GeV (LEP)

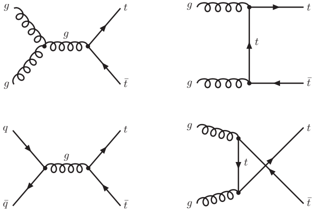
Jet data up to the TeV scale but suffering from relatively large theory uncertainties and only NLO available

$t\bar{t}$ Production

$t\bar{t}$ production occurs at $Q = 2m_t$ + boost ≈ 360 GeV

Tree level: gg fusion (dominant at the LHC) and $q\bar{q}$ annihilation

In addition to these, there are also $qq' \rightarrow t\bar{t}$ and $qg \rightarrow t\bar{t}$



Total $t\bar{t}$ cross section at $\sqrt{s} = 7$ TeV measured to an accuracy of 4%, most precise result: CMS in the dileptonic decay channel `CMS-TOP-11-005`

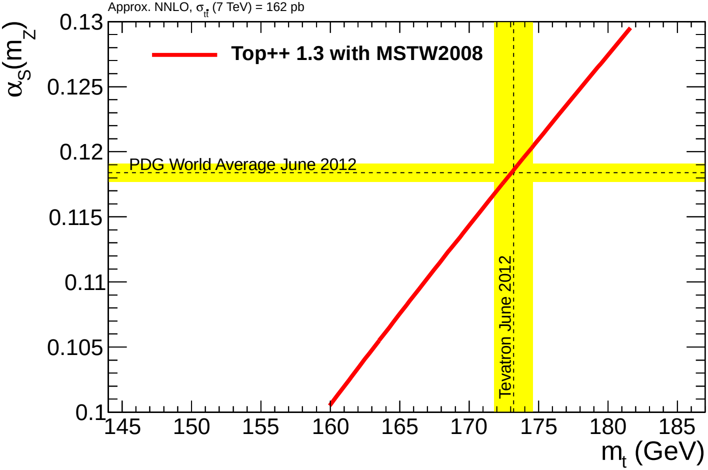
Predictions for $q\bar{q}, qq‘, qg \rightarrow t\bar{t}$ available up to exact NNLO

Calculations for $gg \rightarrow t\bar{t}$ still only to NNLL, different approximations by the theory groups, with significant tension

But: full NNLO expected “soon” (next months)

α_S vs. m_t (for a given $\sigma_{t\bar{t}}$)

Beside $\sqrt{s}$, two main parameters that determine the predicted $\sigma_{t\bar{t}}$: α_S and m_t, both currently known with $\approx$ the same precision



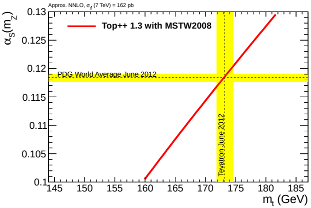
Scale and PDF uncertainties not shown here!

α_S vs. m_t (for a given $\sigma_{t\bar{t}}$)

Beside $\sqrt{s}$, two main parameters that determine the predicted $\sigma_{t\bar{t}}$:
α_S and m_t, both currently known with ≈ the same precision

We can take the measured $\sigma_{t\bar{t}}$ and either . . .

- fix α_S to extract the most probable m_t
  (this is what has been done already
  in the last years)
  or, alternatively, . . .
- fix m_t to extract α_S

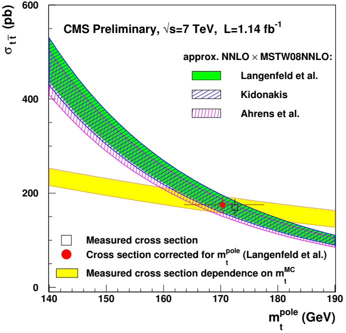


A simultaneous determination of m_t and α_S from the inclusive $\sigma_{t\bar{t}}$ fails

→ Any variation of one of the two parameters in the predicted $\sigma_{t\bar{t}}$ can be compensated by a variation of the other

→ At some point in time, differential cross sections should do the trick!

m_t Extraction (September 2011)



`CMS-PAS-TOP-11-008`

Most probable m_t values in pole and $\overline{\text{MS}}$ scheme, using two different PDF sets and different approx. NNLO calculations

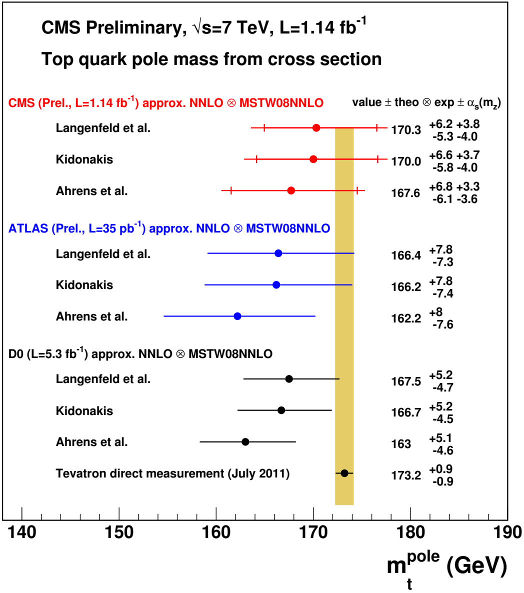
Uncertainty on measured $\sigma_{t\bar{t}}$ was still 11%

With updated $\sigma_{t\bar{t}}$, resulting uncertainties would decrease from 6-7 GeV to $\lesssim$ 4 GeV

Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{\text{MS}}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

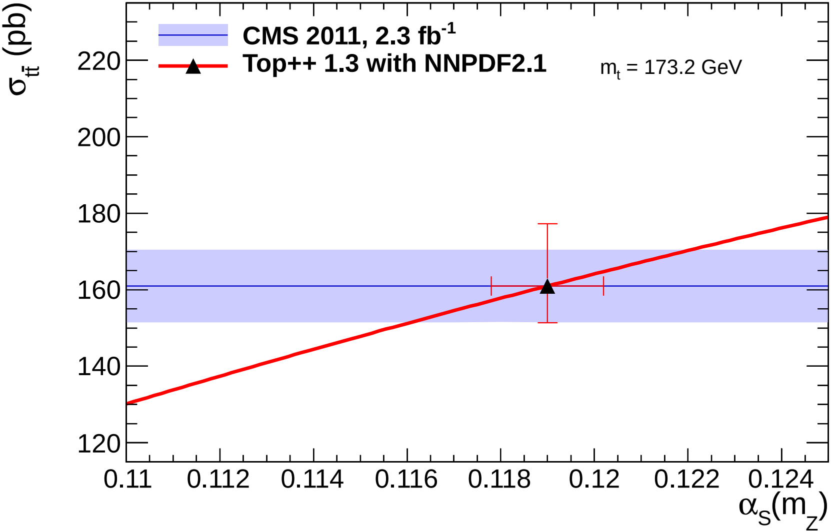
Approx. NNLO × HERAPDF15NNLO	m_t^{pole} / GeV	$m_t^{\overline{\text{MS}}}$ / GeV
Langenfeld et al. [7]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$
Ahrens et al. [9]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$

m_t Extraction (September 2011)



← Note the α_S uncertainties (neglected by ATLAS and D0)

α_S Extraction



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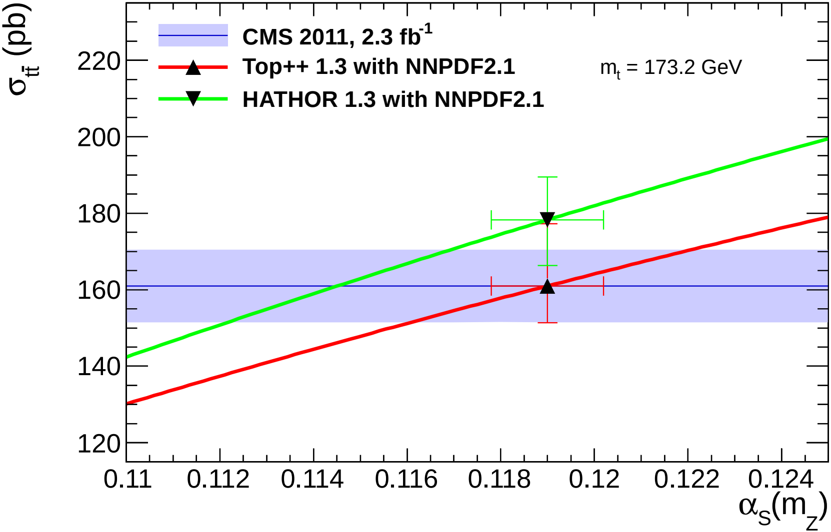

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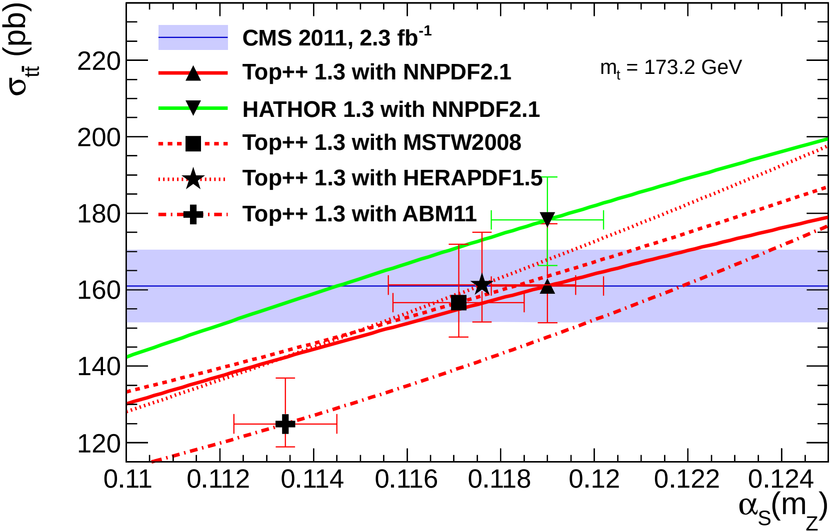

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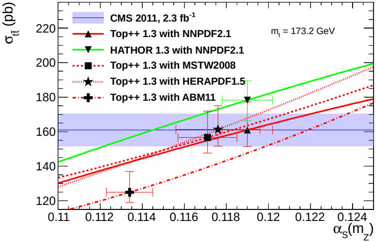
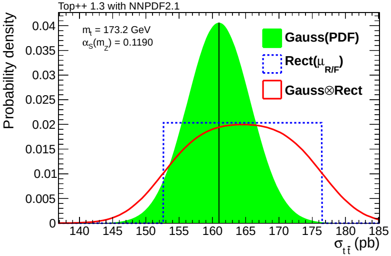
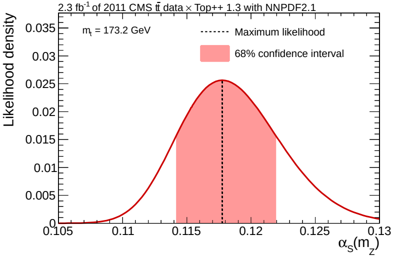


- Slope of predicted $\sigma_{t\bar{t}}$ determined by α_S evolution in the PDF set
- New high-energy approx. in HATHOR 1.3 increased prediction by ≈ 6% (without this Top++ and HATHOR were much closer)
- For a given $\alpha_S(m_Z)$, only small differences seen between NNPDF, MSTW and HERAPDF while ABM yields lower $\sigma_{t\bar{t}}$ prediction
  → reason: smaller gluon PDF in ABM
- Default ABM α_S rather small
  → explanation: higher-twist corrections (for low-Q data) and different treatment of error correlations between datasets in ABM α_S fit

α_S Extraction: *Probabilities and Likelihoods*



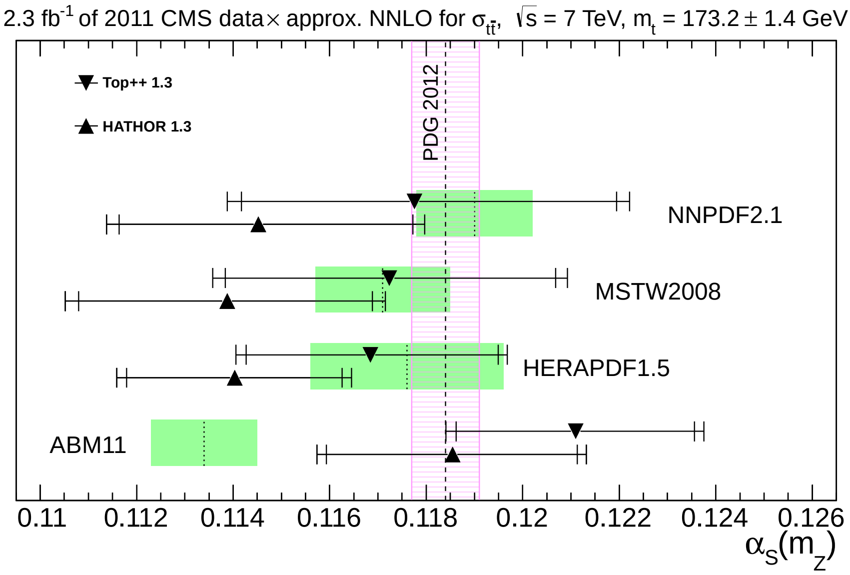
1.) Theory uncertainties (pred. $\sigma_{t\bar{t}}$): Convolve a Gaussian for the PDF uncertainty with a rectangular covering the whole range given by the variation of renormalization and factorization scale



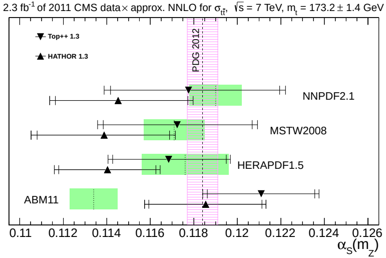
2.) Theory × measurement: Obtain a likelihood by folding the probability function for the predicted $\sigma_{t\bar{t}}$ with a Gaussian probability function for the measured $\sigma_{t\bar{t}}$

$$L(\alpha_S) = \int f_{\exp}(\sigma|\alpha_S)\ f_{\mathrm{th}}(\sigma|\alpha_S)\ d\sigma$$

α_S Extraction: *Results*



α_S Extraction: *Results*



		Most likely value	Uncertainty	
			Total	From δm_t
Top++ 1.3	with NNPDF2.1	0.1178	$^{+0.0045}_{-0.0039}$	$^{+0.0015}_{-0.0015}$
HATHOR 1.3		0.1145	$^{+0.0034}_{-0.0031}$	$^{+0.0013}_{-0.0013}$
Top++ 1.3	with MSTW2008	0.1172	$^{+0.0037}_{-0.0037}$	$^{+0.0013}_{-0.0014}$
HATHOR 1.3		0.1139	$^{+0.0033}_{-0.0034}$	$^{+0.0013}_{-0.0013}$
Top++ 1.3	with HERAPDF1.5	0.1168	$^{+0.0028}_{-0.0028}$	$^{+0.0010}_{-0.0011}$
HATHOR 1.3		0.1140	$^{+0.0024}_{-0.0024}$	$^{+0.0010}_{-0.0010}$
Top++ 1.3	with ABM11	0.1211	$^{+0.0027}_{-0.0027}$	$^{+0.0010}_{-0.0010}$
HATHOR 1.3		0.1185	$^{+0.0028}_{-0.0028}$	$^{+0.0010}_{-0.0010}$

Which m_t to use as constraint?

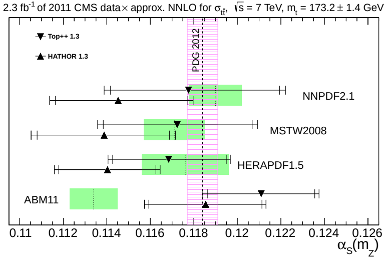
- No significant differences between results from Tevatron, ATLAS and CMS and between the size of their uncertainties

  $\curvearrowright$ Chose latest Tevatron average: 173.18 ± 0.94 GeV

- MC-based masses might deviate by $\mathcal{O}$ (1 GeV) from the pole mass

  $\curvearrowright$ Increased uncertainty accordingly: total δm_t of 1.4 GeV

α_S Extraction: *Results*



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- Results obtained with NNPDF, MSTW, HERAPDF very similar to each other while ABM yields larger α_S due to smaller gluon PDF
- The new high-energy approx. of HATHOR 1.3 results in 3% lower extracted α_S (without this, results from Top++ and HATHOR almost identical)
- Results consistent with world average and competitive with those from jet data

Summary and Outlook

CMS-PAS-TOP-12-022

First determination of α_S from $t\bar{t}$ production:

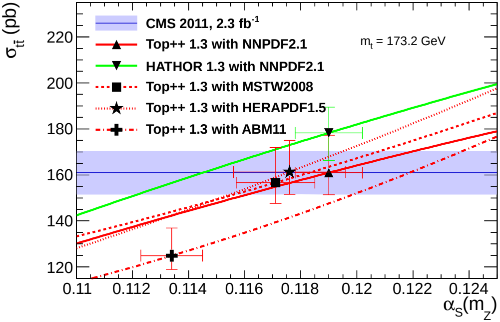
- Based on the very same technique as the m_t extraction from $\sigma_{t\bar{t}}$
- Interesting energy regime for α_S measurements
- Rather competitive precision (equal or superior to results from jets)
- Another example for the stringent tests of QCD possible with $t\bar{t}$ data
- Most complete study of α_S and PDF dependence of $\sigma_{t\bar{t}}$ so far
- Waiting for the full NNLO to resolve the current tension between different approximations

Outlook:

- Aiming at a simultaneous determination of α_S, m_t and gluon PDF from (differential) $t\bar{t}$ cross sections in addition to other data

BACKUP

α_S Dependence of the Measured $\sigma_{t\bar{t}}$



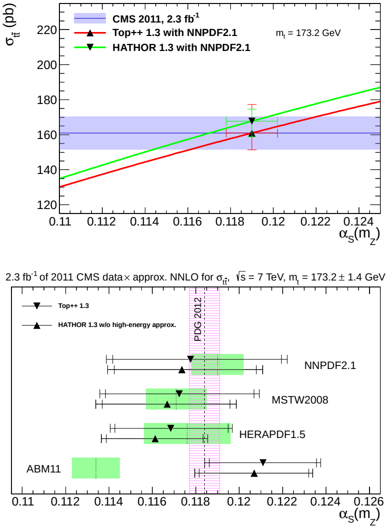
What about the α_S dependence of the measured $\sigma_{t\bar{t}}$?

- Studied α_S dependence of the MC-based acceptance corrections
- Found measured $\sigma_{t\bar{t}}$ to change by less than 1% when increasing/decreasing assumed $\alpha_S(m_Z)$ by 0.0100 from central value of 0.1180

→ Increase uncertainty (blue bland) on measured $\sigma_{t\bar{t}}$ accordingly

New High-Energy Approximation of HATHOR

W/o the high-energy approximation:



With the high-energy approximation: