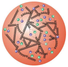
QCD Studies With CMS Data

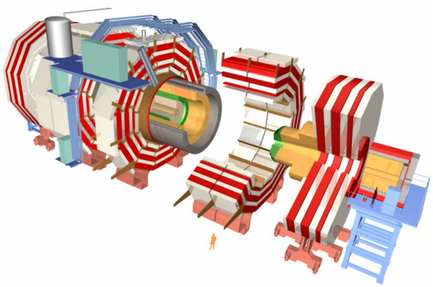
for Measurements of the Top-Quark Mass and the Strong Coupling Constant

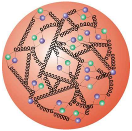
Sebastian Naumann-Emme

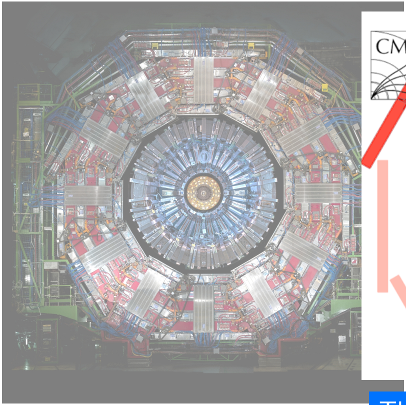
DESY

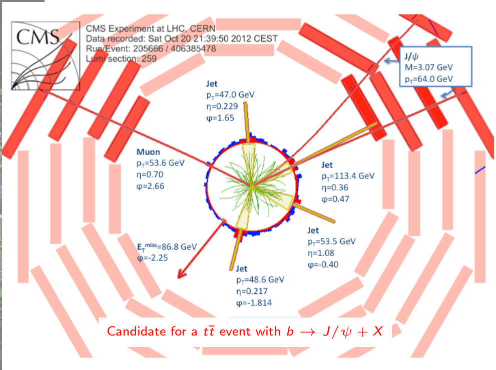
DPG-Frühjahrstagung, Mainz, 2014-03-25











Candidate for a $t\bar{t}$ event with $b \to J/\psi + X$

CMS 2011 / 2012

5 / 20 fb^{-1} of pp data
at $\sqrt{s} = 7$ / 8 TeV

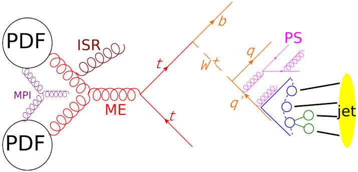
There is QCD in all these hadron collisions

Thorough understanding and accurate modeling of QCD needed:
for SM precision and for BSM searches

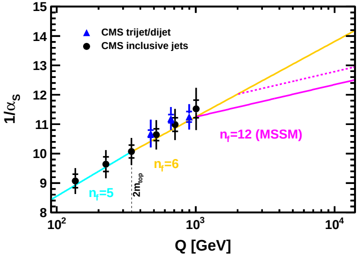
$\rightarrow$ *see K. Lipka's talk this morning*

In the following, will discuss two topics:

1. The top-quark mass
   - QCD modeling
   - Pole mass via the $t\bar{t}$ cross section

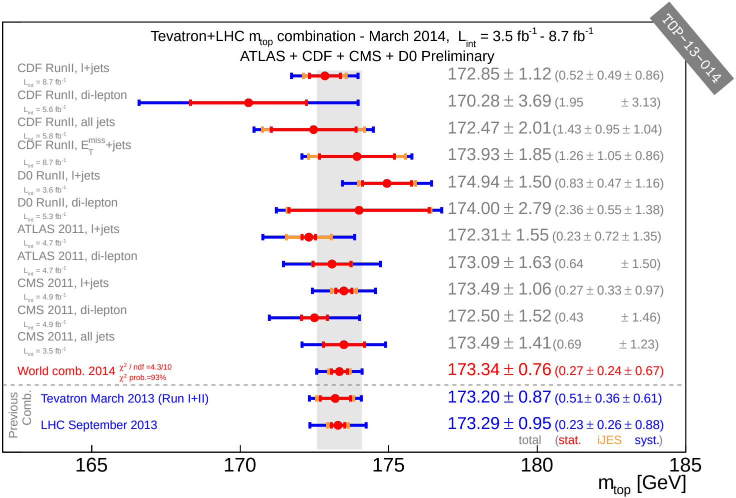


2. The strong coupling constant
   - From the $t\bar{t}$ cross section
   - From differential jet cross sections



Results are labeled with CMS publication IDs: `SMP-12-028` `TOP-13-007` etc.
Further details on the web:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

The Top-Quark Mass



As G. Cortiana pointed out few minutes ago,

a yet more precise knowledge and understanding of m_t is needed

$\rightarrow$ for EW precision fits, the fate of the universe. . .

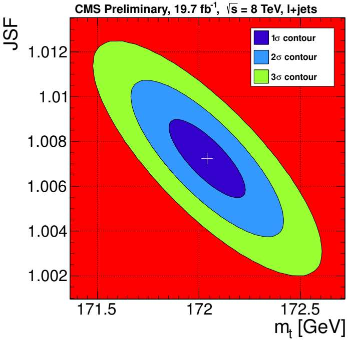
The Top-Quark Mass

World average: $m_t = 173.34 \pm 0.36$ (stat+JES) $\pm$ 0.67 (syst) GeV   TOP-13-014

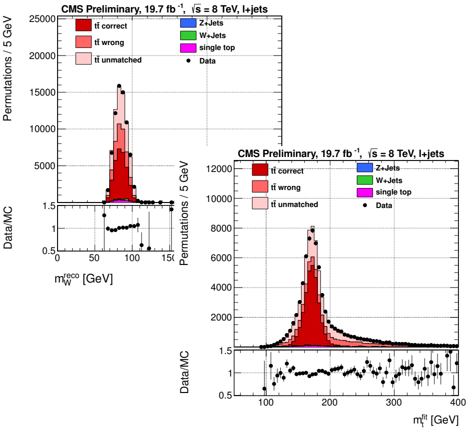
CMS' latest measurement, *presented at Moriond this morning*:

$m_t = 172.04 \pm 0.19$ (stat+JES) $\pm$ 0.75 (syst) GeV   TOP-14-001

Lepton+jets channel, kinematic fit and 2D ideogram method using m_W^{rec} and m_t^{fit}



JSF = 1.007 $\pm$ 0.002 (stat) $\pm$ 0.012 (syst)



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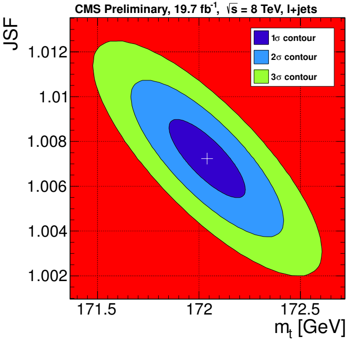
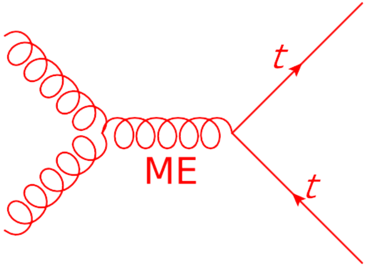


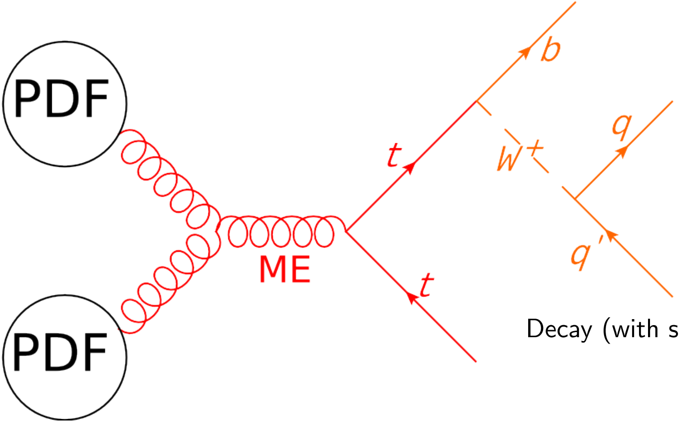
JSF = 1.007 ± 0.002 (stat) ± 0.012 (syst)

	δm_t (GeV)
Fit calibration	0.10
p_T- and η-dependent JES	0.18
Jet energy resolution	0.26
Missing transverse momentum	0.09
Lepton energy scale	0.03
b-tagging	0.02
Pileup	0.27
Non-$t\bar{t}$ background	0.11
Flavor-dependent JES	0.41
b fragmentation	0.06
Semileptonic B-hadron decays	0.16
Parton distribution functions	0.09
QCD scales (μ_R, μ_F)	0.13
ME-PS matching threshold	0.15
ME generator	0.23
Underlying event	0.17
Color reconnection effects	0.15

Modeling a $t\bar{t}$ Event

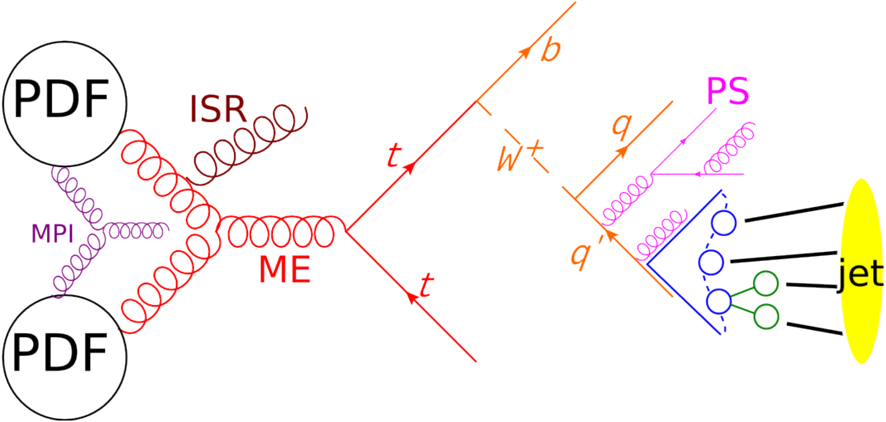


Hard-scattering matrix element (ME): MadGraph, Powheg, MC@NLO. . .



Decay (with spin correlations)

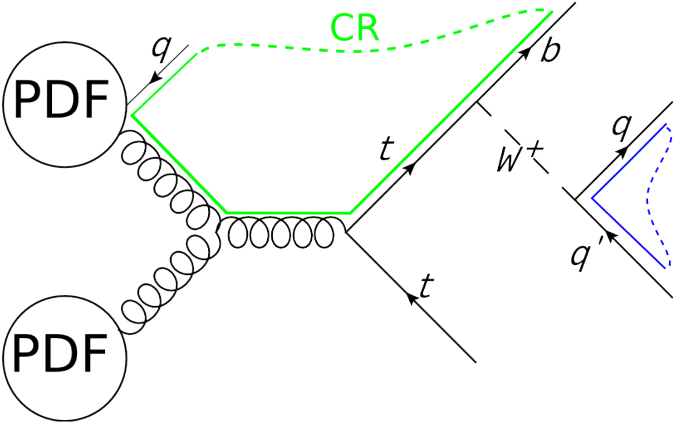
Parton distribution functions (PDFs): CTEQ, MSTW, NNPDF...



Multi-parton interactions (MPI)

Initial-state radiation (ISR)

Parton shower (PS) and hadronization:
Pythia (Lund string fragmentation) or
Herwig (cluster fragmentation)

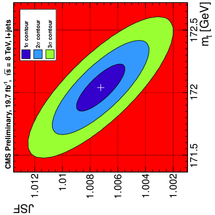


Color reconnections (CR)

Check dependence of m_t measurement on event kinematics,
comparing to different ME generators, hadronization models, UE tunes

→ probing in particular variables that could be sensitive to color-reconnection effects

TOP-14-001



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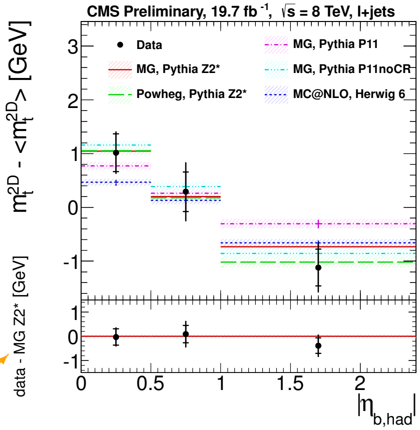
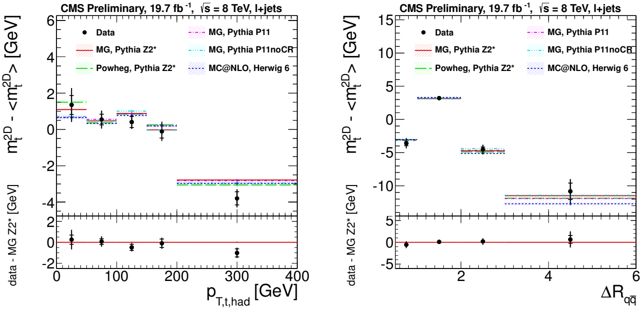


Difference to our standard MC: MadGraph+Pythia6 with Z2* tune

Differential Top-Mass Studies (cont.)

TOP-14-001



Observable	χ^2	Ndf
$p_{T,t,had}$	5.76	4
$\lvert\eta_{t,had}\rvert$	1.14	3
$p_{T,b,had}$	2.17	4
$\lvert\eta_{b,had}\rvert$	0.72	2
$m_{t\bar{t}}$	4.22	5
$p_{T,t\bar{t}}$	1.33	4
$\Delta R_{q\bar{q}}$	0.83	3
$\Delta R_{b\bar{b}}$	1.77	3
H_T^4	7.54	4
Jet multiplicity	1.16	2
$p^1_{T,q,had}$	1.28	4
$\lvert\eta^1_{q,had}\rvert$	6.27	2
$p_{T,W,had}$	1.60	4
$\lvert\eta_{W,had}\rvert$	1.35	3
Total	37.15	47

Studied 14 variables $\rightarrow$ summed χ^2/Ndf = 37/47 (prob. = 85%)
with MadGraph+Pythia6 and Z2* tune

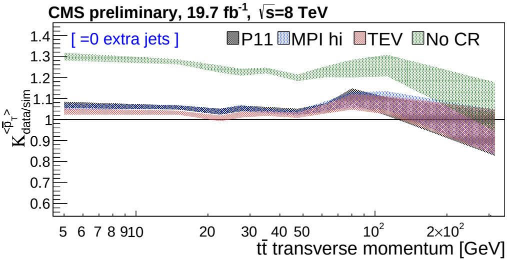
Within current statistics: data overall well modeled by MC

With more data: Will be able to constrain model uncertainties further

Underlying Event and Color Reconnection

UE study, using high-purity $t\bar{t}$ sample in the dilepton channel:

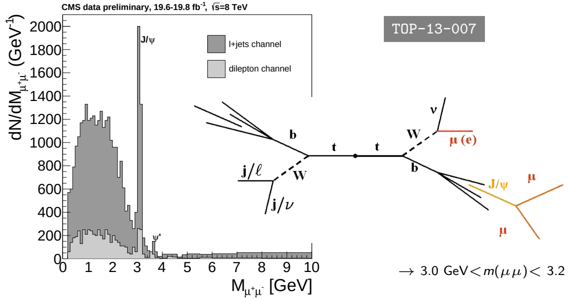
- Event-by-event axis: $\vec{p}_T(t\bar{t}) \equiv \vec{p}_T(b_1) + \vec{p}_T(b_2) + \vec{p}_T(\ell) + \vec{p}_T(\bar{\ell}) + \vec{p}_T^{\,miss}$
- Subtract b_1,b_2,ℓ,$\bar{\ell}$ to characterize the soft, underlying activity
- Look at data/MC ratios, e.g. for the average p_T of charged particles as a function of $p_T(t\bar{t})$



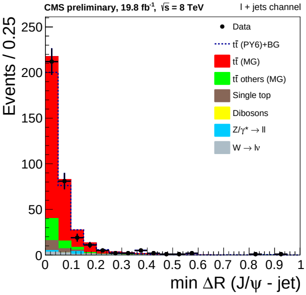
Default MC: MadGraph+Pythia6 with tune Z2*

Here: comparison to different "Perugia 11" tunes

Description of data ≈20% worse when switching off color reconnections



$\rightarrow$ 3.0 GeV $< m(\mu\mu) <$ 3.2 GeV

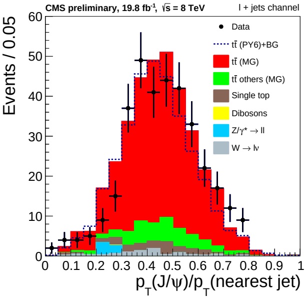


Clear signal of $b \rightarrow J/\psi + X$ in $t\bar{t}$ events

Overall rate and kinematic distributions reasonably well modeled

Future measurement: m_t via $m(\ell, J/\psi)$

Will require more precise fragmentation studies with LHC data



Conceptional Limitations of m_t Measurements

1. Aren't you just measuring a parameter of your MC event generators?
   - Practically all m_t measurements need calibration to MC
   - However, according to implementation:
     m_t^{MC} close to pole mass in the sense of Breit-Wigner mass peak
   - In 2011, A. Buckley et al.: "shift could be $\mathcal{O}(1\,\mathrm{GeV})$"
   - Discussion at TOP2013: "$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}}$ within 250–500 MeV",
     uncertainty being mainly from:
2. Isn't the pole mass ill-defined for a quark (colored object) anyway?
   - Intrinsic renormalon ambiguity: $\approx$ 270 GeV for m_t

$\curvearrowright$ Motivated to bring m_t measurements to uncertainties of $\lesssim$ 0.5 GeV
also at a hadron collider

But: proper modeling of non-perturb. effects required

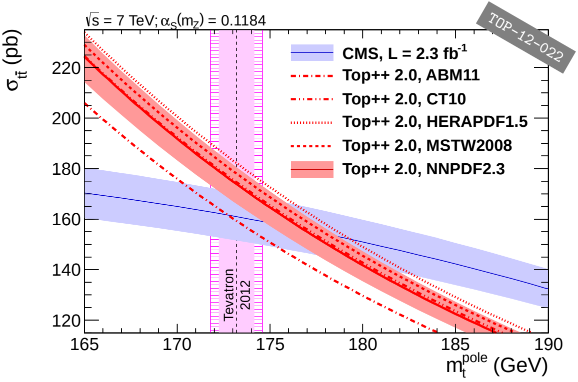
...especially when reconstructing invariant mass of decay products

Mass Dependence of $t\bar{t}$ Cross Section

Since last year: $\sigma(pp \rightarrow t\bar{t} + X)$ calculated at NNLO+NNLL QCD

$\rightarrow$ Uncertainties from higher orders (μ_R, μ_F), PDF, α_S, and m_t now ≈3% each

Compare to CMS' most precise result for $\sigma_{t\bar{t}}$: $\sqrt{s} = 7$ TeV, dileptons, 4% uncertainty



Due to acceptance corrections, meas. $\sigma_{t\bar{t}}$ also depends on m_t

For blue curve assume: $m_t^{MC} = m_t^{pole} \pm 1$ GeV

Full α_S-PDF correlations taken into account

Only minor differences between 4 of 5 PDF sets; ABM has smaller gluon density

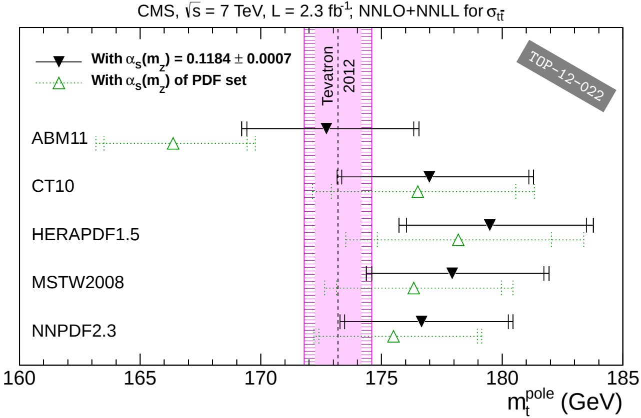
Top Mass Resulting from $t\bar{t}$ Cross Section

Obtain most probable mass value from marginalized joint posterior with Bayesian confidence interval

First NNLO determination of the top mass

Results compatible with average from "direct" m_t measurements

But approach not competitive in precision



$m_t^{\text{pole}} = 176.7\ ^{+3.8}_{-3.4}$ GeV with NNPDF2.3

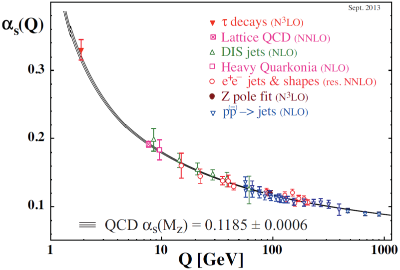
$\approx 176.7\ ^{+3.1}_{-2.8}\ (\sigma_{t\bar{t}}^{\text{meas}}) \pm 1.4\ (\text{PDF}) \pm 0.9\ (\mu_{R,F}) \pm 0.7\ (\alpha_S) \pm 0.9\ (E_{\text{LHC}}) \pm 0.5\ (m_t^{\text{MC}})$ GeV

The Strong Coupling Constant

Besides quark masses, α_S is the only free parameter of QCD Lagrangian

Renormalization Group Equation predicts its energy dependence

Measured in variety of processes and at different energies,
evolved to $Q = m_Z$ for comparison

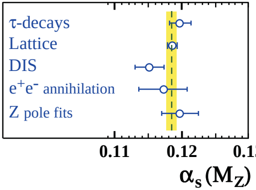


2013 world average: $\alpha_S(m_Z) = 0.1185 \pm 0.0006$ (based on NNLO and N^{3}LO)

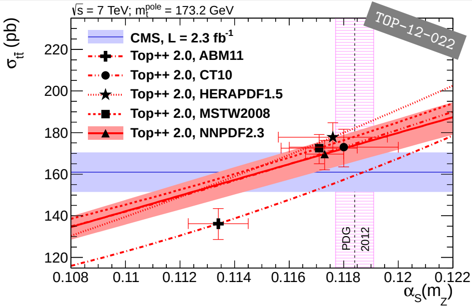
0.5% uncertainty, but still significant for precise calculations

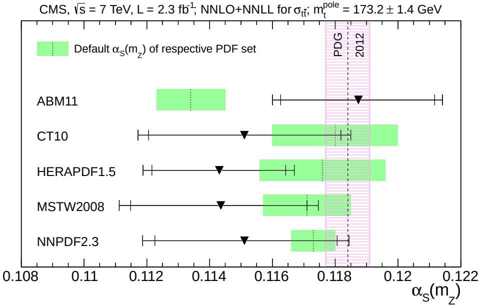
Tension between and within different categories (especially DIS structure funcs, but also e^+e^-)

Precision driven by low-Q data and lattice QCD



α_S from the $t\bar{t}$ Cross Section





Same approach as for the m_t extraction, but now leave α_S free

Need external m_t constraint: take Tevatron average, adding $\pm$ 1 GeV for $m_t^{MC} \stackrel{?}{=} m_t^{pole}$

First determination of α_S at NNLO from a hadron collider

$$\alpha_S(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

with NNPDF2.3

Competitive precision

(similar to results using LEP2 data)

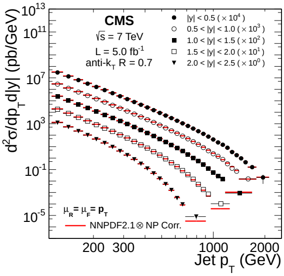
α_S from Jets

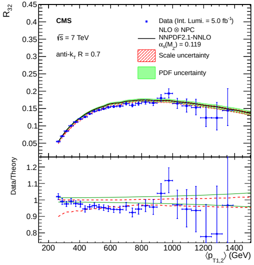
Three different measurements:

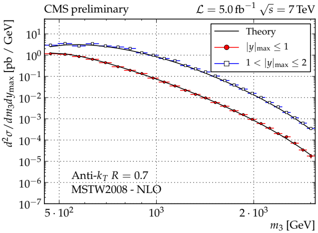
SMP-12-028 Double-diff. inclusive jet cross section: $\frac{d^2\sigma}{dp_T\, dy}$

QCD-11-003 Ratio of inclusive trijet/dijet cross sections: $R_{32}(\langle p_{T1,2}\rangle)$

SMP-12-027 Double-diff. trijet cross section: $\frac{d^2\sigma}{dm_3\, dy_{\max}}$





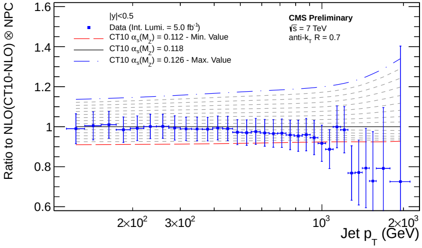


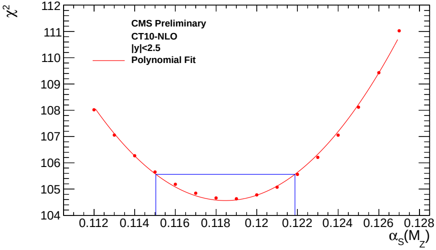
All three analyses using the 7 TeV data and same methodology for α_S:

1. Compare measured cross section to QCD prediction at NLO

   Using NLOJet++; adding MC-based non-perturbative corrections;
   for the inclusive jets additionally EW corrections

2. Use PDF sets provided for series of $\alpha_S(m_Z)$ values to determine α_S dependence → preserves PDF-α_S correlations

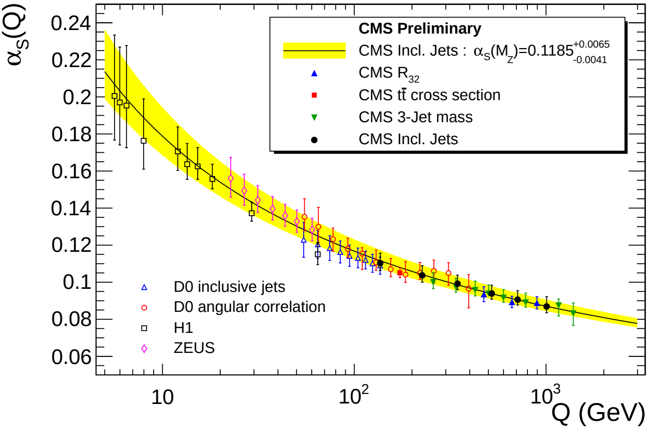


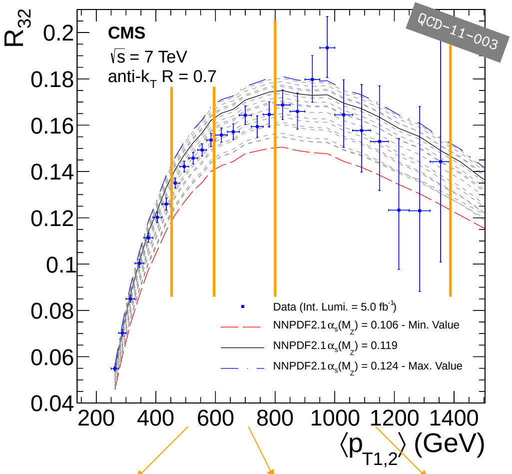


3. Obtain best $\alpha_S(m_Z)$ and uncertainty via χ^2 summed over bins

α_S from Jets: Results

		$\alpha_S(m_Z)$	δ_{rel}^{max}(scale/total)	probed Q
TOP-12-022	$t\bar{t}$ (NNLO)	$0.1151^{+0.0033}_{-0.0032}$	0.8% / 2.9%	$m_t = 173$ GeV
SMP-12-028	incl. jets (NLO)	$0.1185^{+0.0065}_{-0.0041}$	4.6% / 5.5%	$p_T = 0.1$–2.1 TeV
QCD-11-003	trijet/dijet (NLO)	$0.1148^{+0.0055}_{-0.0055}$	4.4% / 4.8%	$\langle p_{T1,2} \rangle = 0.4$–$1.4$ TeV
SMP-12-027	trijet mass (NLO)	$0.1160^{+0.0072}_{-0.0031}$	5.9% / 6.2%	$m_3/2 = 0.3$–1.4 TeV





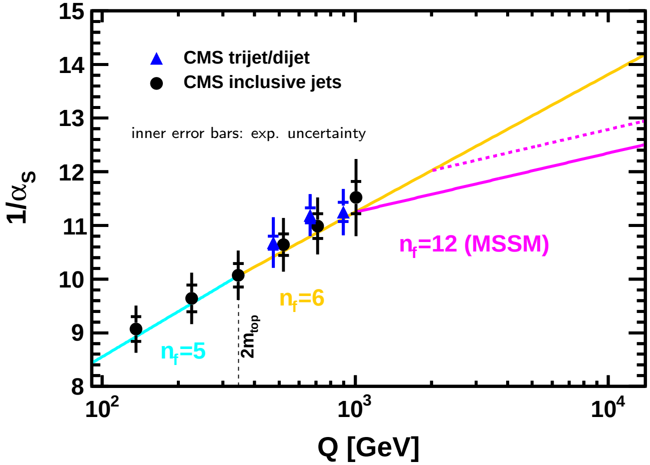
$\langle p_{T1,2} \rangle$ Q data points	420–600 GeV 474 GeV 6	600–800 GeV 664 GeV 5	800-1390 GeV 896 GeV 10
$\alpha_S(m_Z)$ prob(χ^2)	0.1147 $\pm$ 0.0061 49%	0.1132 $\pm$ 0.0050 21%	0.1170 $\pm$ 0.0058 77%
$\alpha_S(Q)$	0.0936 $\pm$ 0.0041	0.0894 $\pm$ 0.0031	0.0889 $\pm$ 0.0034

- By construction, we obtain for any Q bin directly $\alpha_S(m_Z)$
- If assumed evolution not valid: $\alpha_S(m_Z)$ shifted
- For illustration of running, can later evolve back: $\alpha_S(Q)$
- Note: RGE validity also assumed in employed PDFs
- Strength of R_{32} ratio: reduction of exp. and theor. uncertainties and of dependence on PDF evolution

Running of α_S at High Energies

$\alpha_S(Q)$ depends on number of active flavors at Q

1-loop approximation: $\frac{1}{\alpha_S(Q^2)} = \frac{1}{\alpha_S(\mu^2)} + \beta_0 \ln\left(\frac{Q^2}{\mu^2}\right)$ with $\beta_0 = \frac{33-2n_f}{12\pi}$



gauge-coupling unification at $\sim 10^{16}$ GeV?

Seeing / not seeing change of slope: evidence for / against new colored particles

Conclusions & Outlook

- Measuring m_t requires excellent understanding of QCD effects and the LHC data already allow us to study these
- $t\bar{t}$ cross section enabled first α_S at NNLO from a hadron collider
- Jets probing α_S up to TeV scale already,
  but higher precision requires NNLO prediction
- Probing the running of α_S at highest energies will require considerable work by theory and experiment
- Will we be able to measure the running of m_t?
  Maybe: $m_t^{\overline{\rm MS}}$ from differential $t\bar{t}$ cross section up to very high $p_T(t\bar{t})$

BACKUP

Hadronization:

- Flavor-dependent JES: Difference in jet energies from Pythia6 (Lund string fragmentation) to Herwig++ (cluster fragmentation), evaluated for light quarks, b-quarks, and gluons separately, then added in quadrature
- b fragmentation: Retuned Bowler-Lund fragmentation in Pythia to describe x_B data from ALEPH and DELPHI, difference to Z2* tune taken as systematic uncertainty
- Semileptonic B-hadron decays: Varied branching ratios within PDG uncertainties; direct impact on neutrino fractions

QCD-Model Uncertainties of TOP-14-001

Hard scattering:

- Parton distribution functions: Difference between CTEQ6.6L and envelope of PDF+α_S uncertainties from CT10, MSTW2008, and NNPDF2.3
- Renormalization and factorization scales: Q^2 $\times 0.25$ and $\times 4$
- ME-PS matching threshold: Default value of 20 GeV varied to 10 and 40 GeV
- ME generator: Difference between MadGraph (LO multileg) and Powheg (NLO); additionally difference between measured and predicted top p_T spectrum

Non-perturbative QCD:

- Underlying event: Comparison between Pythia tunes: P11 vs. P11mpiHi and P11TeV
- Color reconnections: Comparison between Pythia tunes: P11 vs. P11noCR

Compatibility of m_t Result at 7 and 8 TeV

Analyis at 7 TeV: TOP-11-015

$$m_t = 173.49 \pm 0.43 \text{ (stat+JES)} \pm 0.98 \text{ (syst) GeV}$$

	δm_t (GeV)
Fit calibration	0.06
p_T- and η-dependent JES	0.28
Jet energy resolution	0.23
Missing transverse momentum	0.06
Lepton energy scale	0.02
b-tagging	0.12
Pileup	0.07
Non-$t\bar{t}$ background	0.13
b-JES	0.61
Parton distribution functions	0.07
QCD scales (μ_R, μ_F)	0.24
ME-PS matching threshold	0.18
Underlying event	0.15
Color reconnection effects	0.54

Analyis at 8 TeV: TOP-14-001

$$m_t = 172.04 \pm 0.19 \text{ (stat+JES)} \pm 0.75 \text{ (syst) GeV}$$

	δm_t (GeV)
Fit calibration	0.10
p_T- and η-dependent JES	0.18
Jet energy resolution	0.26
Missing transverse momentum	0.09
Lepton energy scale	0.03
b-tagging	0.02
Pileup	0.27
Non-$t\bar{t}$ background	0.11
Flavor-dependent JES	0.41
b fragmentation	0.06
Semileptonic B-hadron decays	0.16
Parton distribution functions	0.09
QCD scales (μ_R, μ_F)	0.13
ME-PS matching threshold	0.15
ME generator	0.23
Underlying event	0.17
Color reconnection effects	0.15

Compatibility of m_t Result at 7 and 8 TeV

Analyis at 7 TeV: TOP-11-015

$$m_t = 173.49 \pm 0.43\ (\text{stat+JES}) \pm 0.98\ (\text{syst})\ \text{GeV}$$

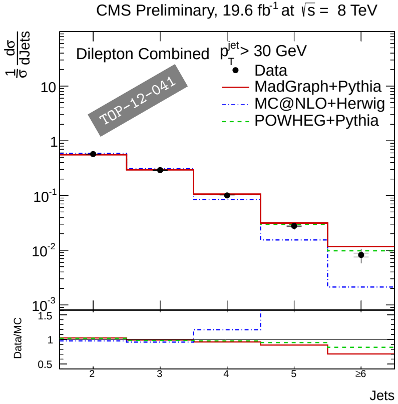
Analyis at 8 TeV: TOP-14-001

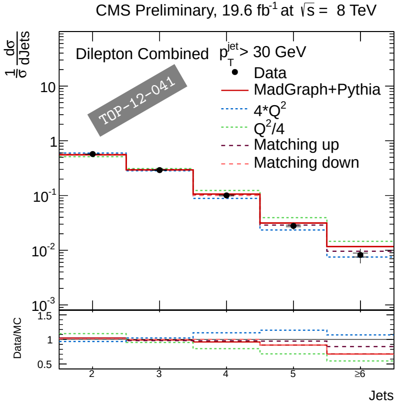
$$m_t = 172.04 \pm 0.19\ (\text{stat+JES}) \pm 0.75\ (\text{syst})\ \text{GeV}$$

- Shift from 7 to 8 TeV: -1.45 GeV
- Significance: $\sqrt{\delta^2_{7\text{TeV}} + \delta^2_{8\text{TeV}} - 2 \times \rho \times \delta_{7\text{TeV}} \times \delta_{8\text{TeV}}}$
- Correlation ρ:
  - 0 for (stat+JES)
  - low for experimental uncertainties, due to new MC/data corrections and scale factors
  - high for theory uncertainties, since no drastic change in $\sqrt{s}$
- Realistic assumptions for $\rho \curvearrowright$ significance of shift: 1.7–1.9σ

Additional Jets in Top-Pair Events

Differential $t\bar{t}$ cross section as a function of the jet multiplicity:





Compare to. . .

. . . different ME generators and hadronization models

. . . variations of Q^2 scale and threshold for ME-PS matching

Constraining PDFs with Jets

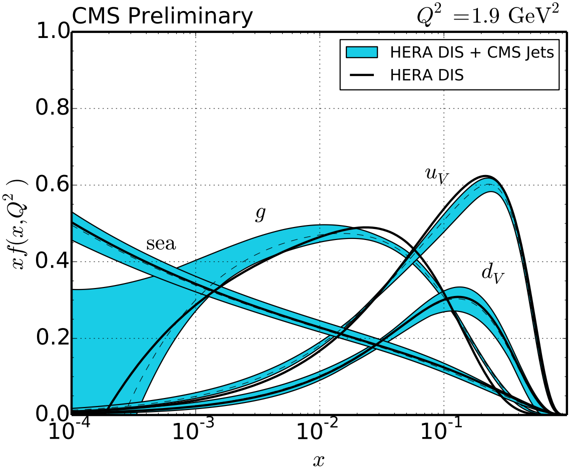
SMP-12-028

Using same CMS inclusive-jet data and NLO theory as before, can also study impact on PDFs:

Fits performed with HERAFitter framework

As baseline:
HERA-I DIS data, similar to HERAPDF1.0 but with more flexible parametrization

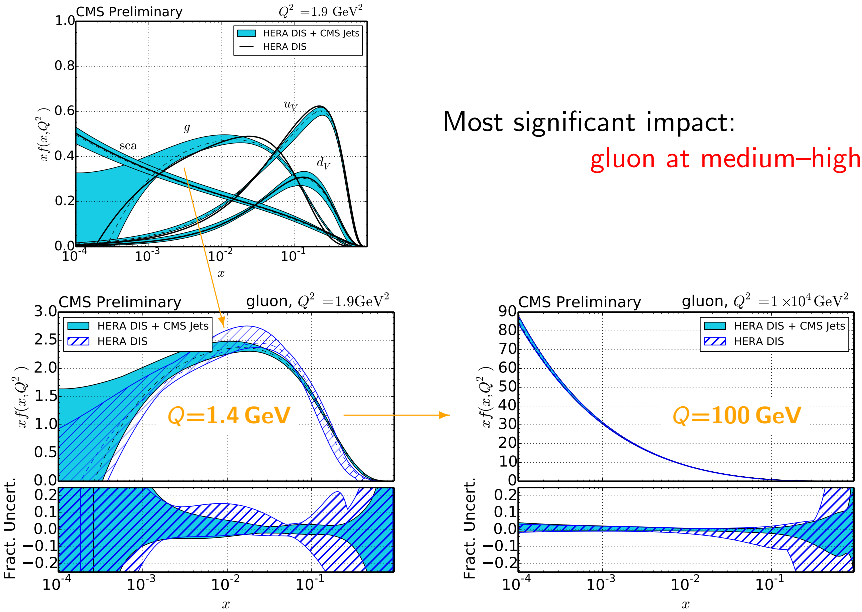
Fixed $\alpha_S(m_Z) = 0.1176$



Simultan. fit of PDF and α_S with HERA+CMS data yields: $\alpha_S(m_Z) = 0.1192^{+0.0017}_{-0.0015}$

experimental+non-perturb. uncertainty only

Constraining PDFs with Jets



Most significant impact:

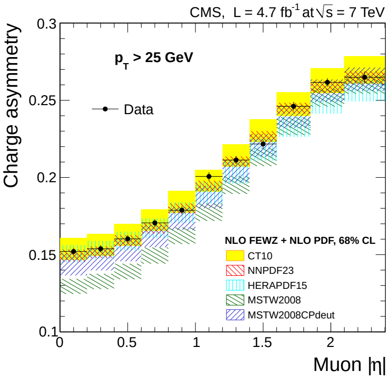
gluon at medium–high x

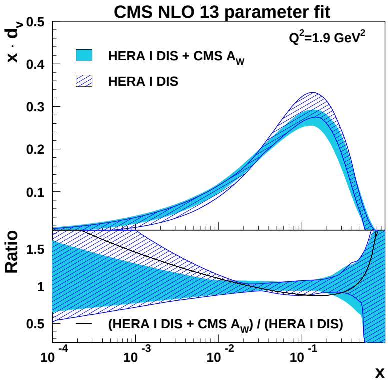
Constraining PDFs with W Asymmetry

SMP-12-021

$$A_W(\eta_\ell) = \frac{\frac{d\sigma}{d\eta_\ell}(W^+) - \frac{d\sigma}{d\eta_\ell}(W^-)}{\frac{d\sigma}{d\eta_\ell}(W^+) + \frac{d\sigma}{d\eta_\ell}(W^-)}$$

Muon charge asymmetry in W production: sensitive to d_v, u_v, d/u



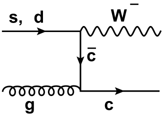


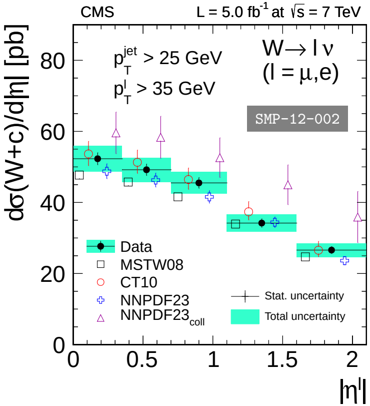
MSTW2008CPdeut: variant of MSTW2008 with more flexible parametrization and deuteron corrections; changes u_V and d_V

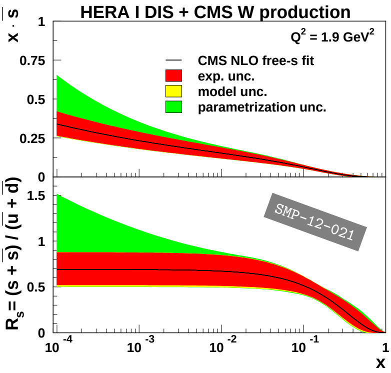
Again HERAFitter analysis with HERA-I DIS data as baseline; NLO from MCFM for W data

Constraining PDFs with W+charm

W+charm production directly sensitive to strangeness in the proton





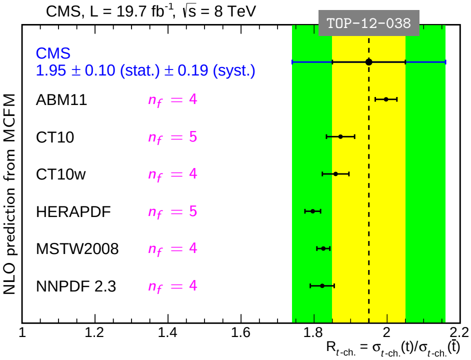


Strangeness in standard PDFs based on neutrino-scattering data

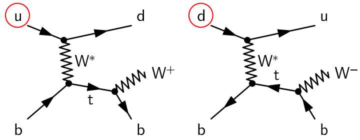
Adding W+c data to A_W and HERA-I DIS data enables free-s fit; result consistent with similar ATLAS analysis and recent NOMAD result

Measured $t\bar{t}$ cross sections start providing constraints on the gluon PDF

With the coming data, electroweak single-top production can be used to probe the b PDF and the u/d ratio (proton valence content: $u/d = 2$)



t-channel production:



Kinematic regime:

$0.02 \lesssim x \lesssim 0.5$

Complementary to measurements via W asymmetry, which probe $0.001 \lesssim x \lesssim 0.1$ at the LHC and $0.005 \lesssim x \lesssim 0.3$ at the Tevatron