Prospects of jet measurements for PDF determinations

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Universität Hamburg

CMS workshop *QCD studies with jets at Run II*, Geneva, Jan 28, 2016

Based on work done in collaboration with:

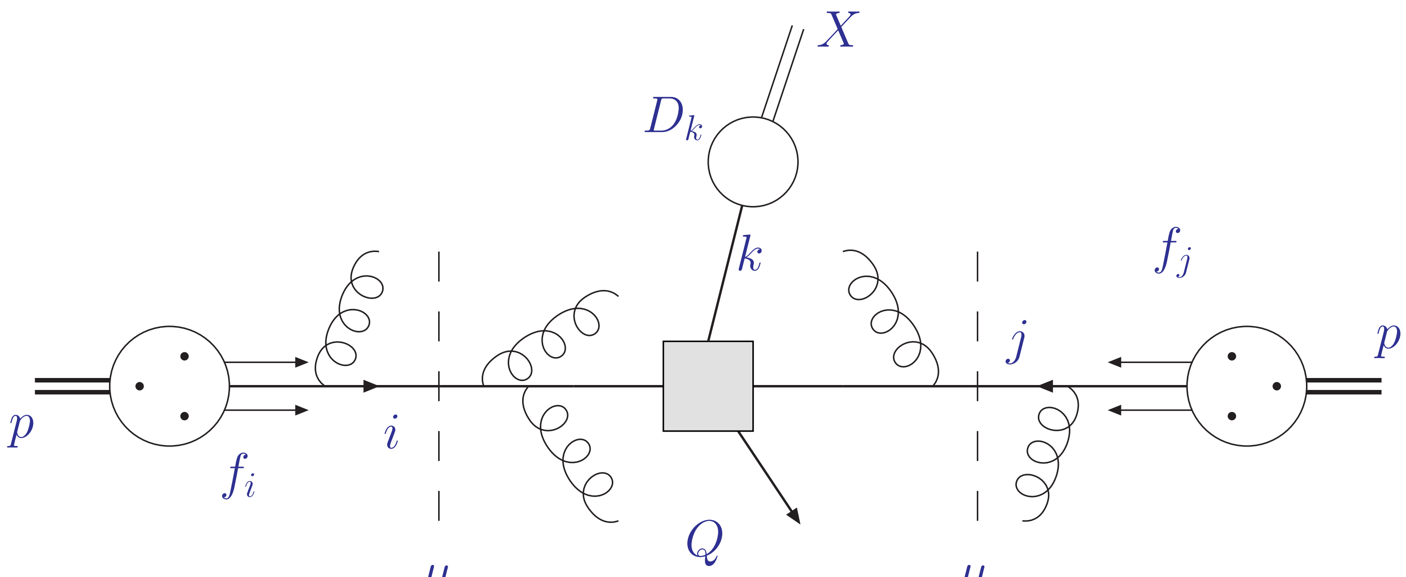
- *Iso-spin asymmetry of quark distributions and implications for single top-quark production at the LHC*
  S. Alekhin, J. Blümlein, S. M. and R. Plačakytė arXiv:1508.07923

- *Determination of Strange Sea Quark Distributions from Fixed-target and Collider Data*
  S. Alekhin, J. Blümlein, L. Caminada, K. Lipka, K. Lohwasser, S. M., R. Petti, and R. Plačakytė arXiv:1404.6469

- *The ABM parton distributions tuned to LHC data*
  S. Alekhin, J. Blümlein and S. M. arXiv:1310.3059

- Many more papers of ABM and friends . . .
  2008 – ...

QCD factorization



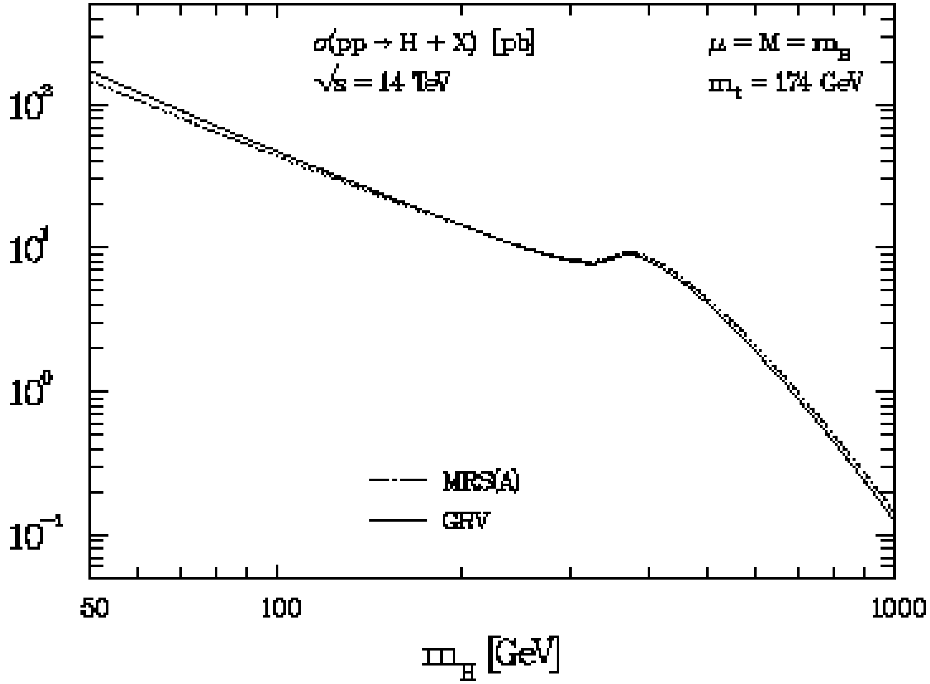
$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Factorization at scale μ
  - separation of sensitivity to dynamics from long and short distances
- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - cross section $\hat{\sigma}_{ij\to k}$ for parton types i, j and hadronic final state X
- Non-perturbative parameters: parton distribution functions f_i, strong coupling α_s, particle masses m_X
  - known from global fits to exp. data, lattice computations, . . .

Higgs boson production

Higgs cross section (1995)

NLO QCD corrections



MRS(A): Martin, Roberts and Stirling, Phys. Rev. D50 (1994) 6734

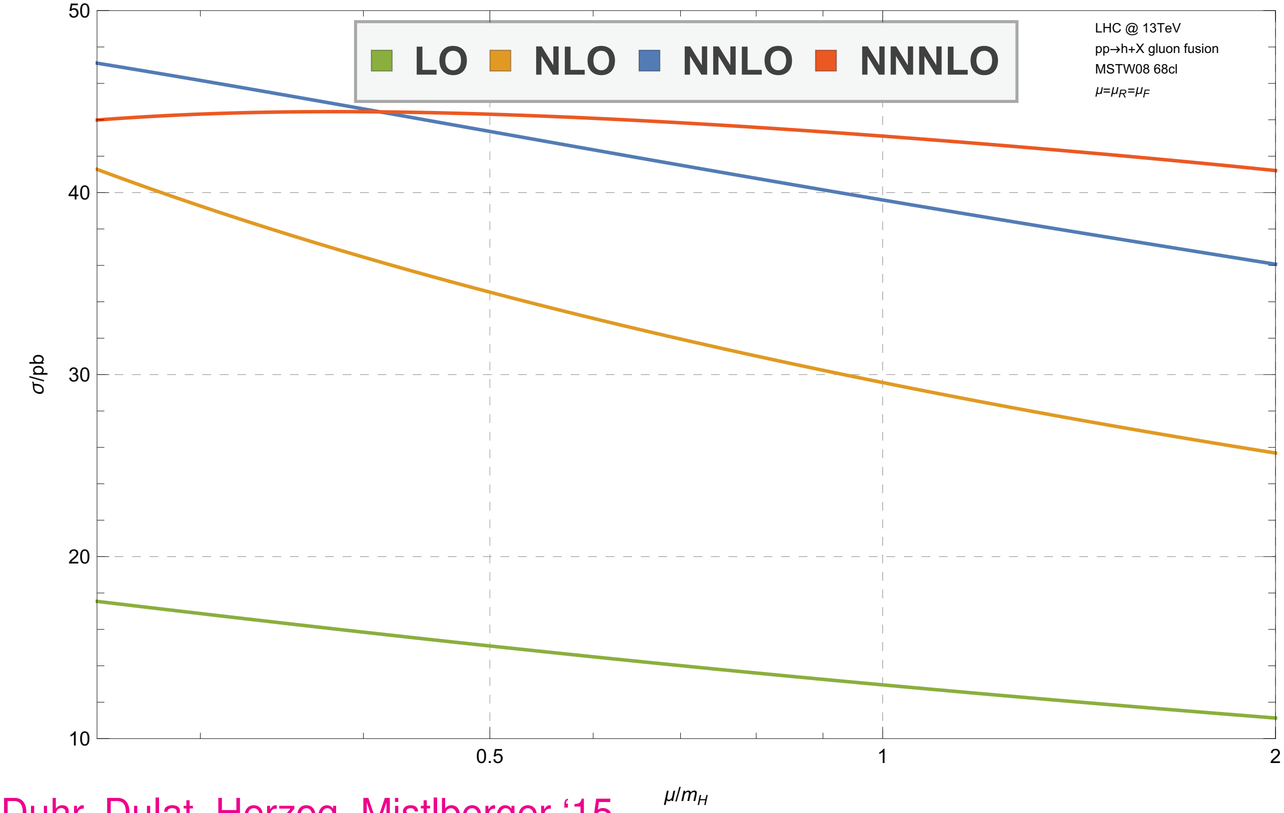
GRV: Glück, Reya and Vogt, Z. Phys. C53 (1992) 127

One of the main uncertainties *in the prediction of the Higgs production cross section is due to the* **gluon density**. *[. . .] Adopting a set of representative parton distributions [. . .], we find a* **variation of about 7%** *between the maximum and minimum values of the cross section for Higgs masses above* $\sim$ *100 GeV.*

Spira, Djouadi, Graudenz, Zerwas (1995)
hep-ph/9504378

Higgs cross section (2016)

Exact N^{3}LO QCD corrections



Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15

- Apparent convergence of perturbative expansion
- Scale dependence of exact N^{3}LO prediction with residual uncertainty 3%
- Minimal sensitivity at scale $\mu = m_H/2$

Dependence of cross section on parton luminosity

- Cross section $\sigma(H)$ at NNLO with uncertainties: $\sigma(H) + \Delta\sigma(\mathrm{PDF} + \alpha_\mathrm{s})$ for $m_H = 125.0$ GeV at $\sqrt{s} = 13$ TeV with $\mu_R = \mu_F = m_H$ and nominal α_s

ABM12 Alekhin, Blümlein, S.M. '13	39.80 ± 0.84 pb
CJ12 (NLO) Owens, Accardi, Melnitchouk '12	$41.94\,^{+\,0.16}_{-\,0.12}$ pb
CT14 Dulat et al. '15	$42.33\,^{+\,1.43}_{-\,1.68}$ pb
HERAPDF2.0 H1+Zeus Coll.	$42.62\,^{+\,0.35}_{-\,0.43}$ pb
JR14 (dyn) Jimenez-Delgado, Reya '14	38.01 ± 0.34 pb
MMHT14 Martin, Motylinski, Harland-Lang, Thorne '14	$42.36\,^{+\,0.56}_{-\,0.78}$ pb
NNPDF3.0 Ball et al. '14	42.59 ± 0.80 pb
PDF4LHC15 Butterworth et al. '15	42.42 ± 0.78 pb

- Large spread for predictions from different PDFs $\sigma(H) = 38.0 \ldots 42.6$ pb
- PDF and α_s differences between sets amount to up to 11%
  - significantly larger than residual theory uncertainty due to N^{3}LO QCD corrections

How to explain the differences ?

Parton content of the proton

Data in global PDF fits

Data sets considered in ABM12 analysis

- Analysis of world data for deep-inelastic scattering and fixed-target data for Drell-Yan process
  - inclusive DIS data HERA, BCDMS, NMC, SLAC $(NDP = 2699)$
  - semi-inclusive DIS charm production data HERA $(NDP = 52)$
  - Drell-Yan data (fixed target) E-605, E-866 $(NDP = 158)$
  - neutrino-nucleon DIS (di-muon data) CCFR/NuTeV $(NDP = 178)$
  - LHC data for $W^{\pm}$- and Z-boson production ATLAS, CMS, LHCb $(NDP = 60)$

Iterative cycle of PDF fits

i) check of compatibility of new data set with available world data

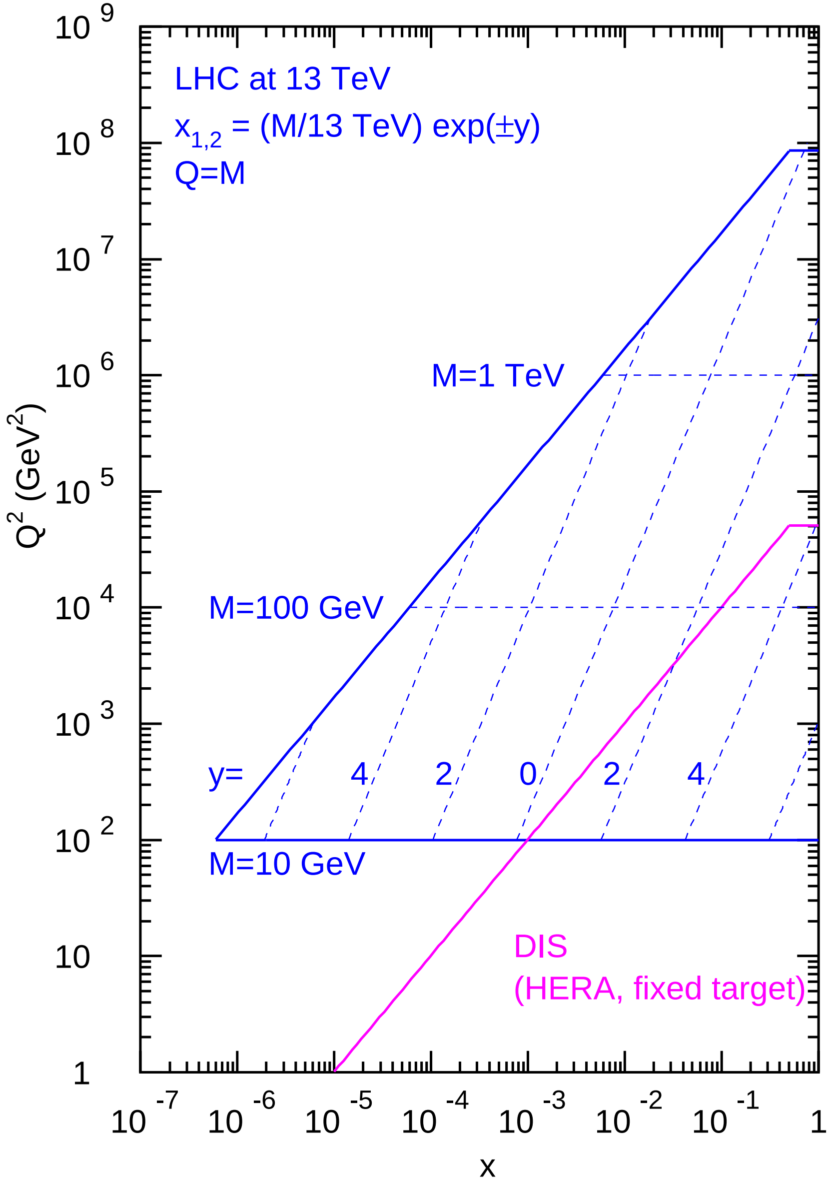
ii) study of potential constraints due to addition of new data set to fit

iii) perform high precision measurement of the non-perturbative parameters

- parton distributions
- strong coupling $\alpha_s(M_Z)$
- heavy quark masses

Parton kinematics at LHC

- Information on proton structure depends on kinematic coverage

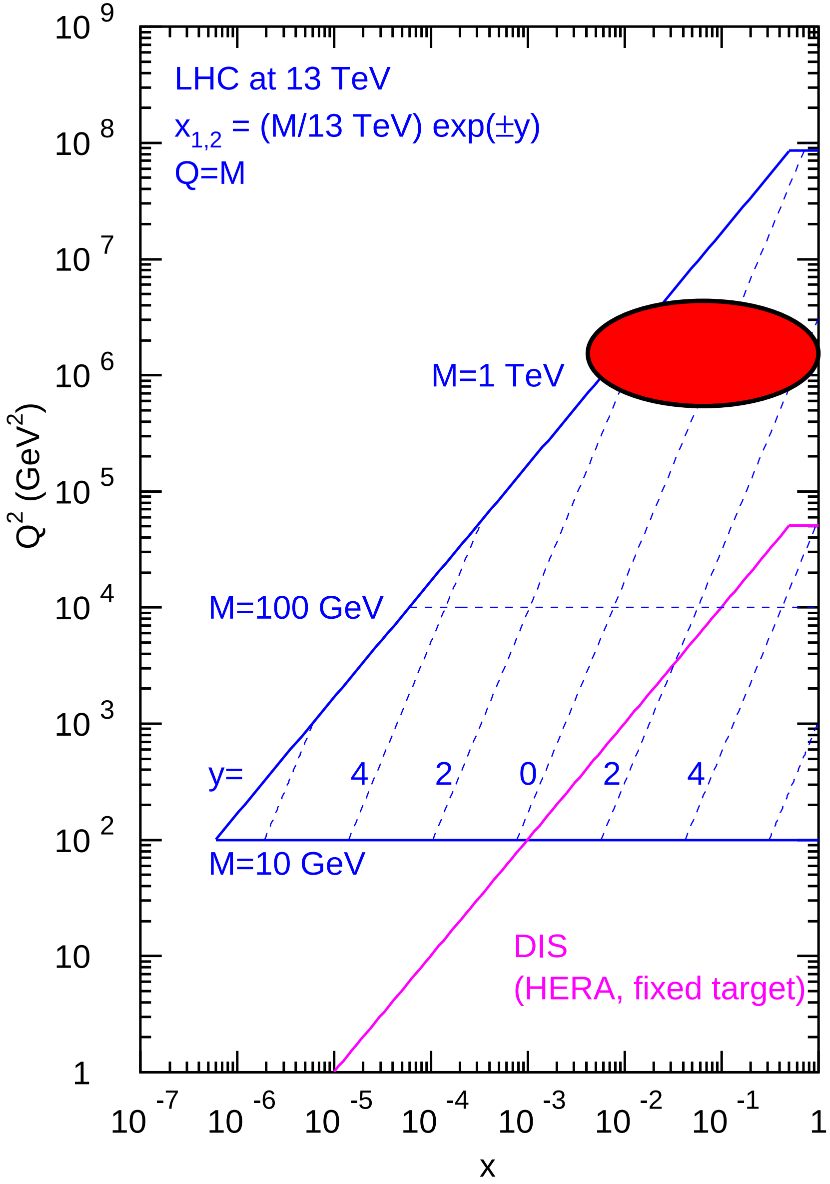


- LHC run II at $\sqrt{s}$ = 13 TeV
  - parton kinematics well covered by HERA and fixed target experiments
- Parton kinematics with $x_{1,2} = M/\sqrt{S}\mathrm{e}^{\pm y}$
  - forward rapidities sensitive to small-x
- Cross section depends on convolution of parton distributions
  - small-x part of f_i and large-x PDFs f_j

$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \left[\ldots\right]$$

Parton kinematics at LHC

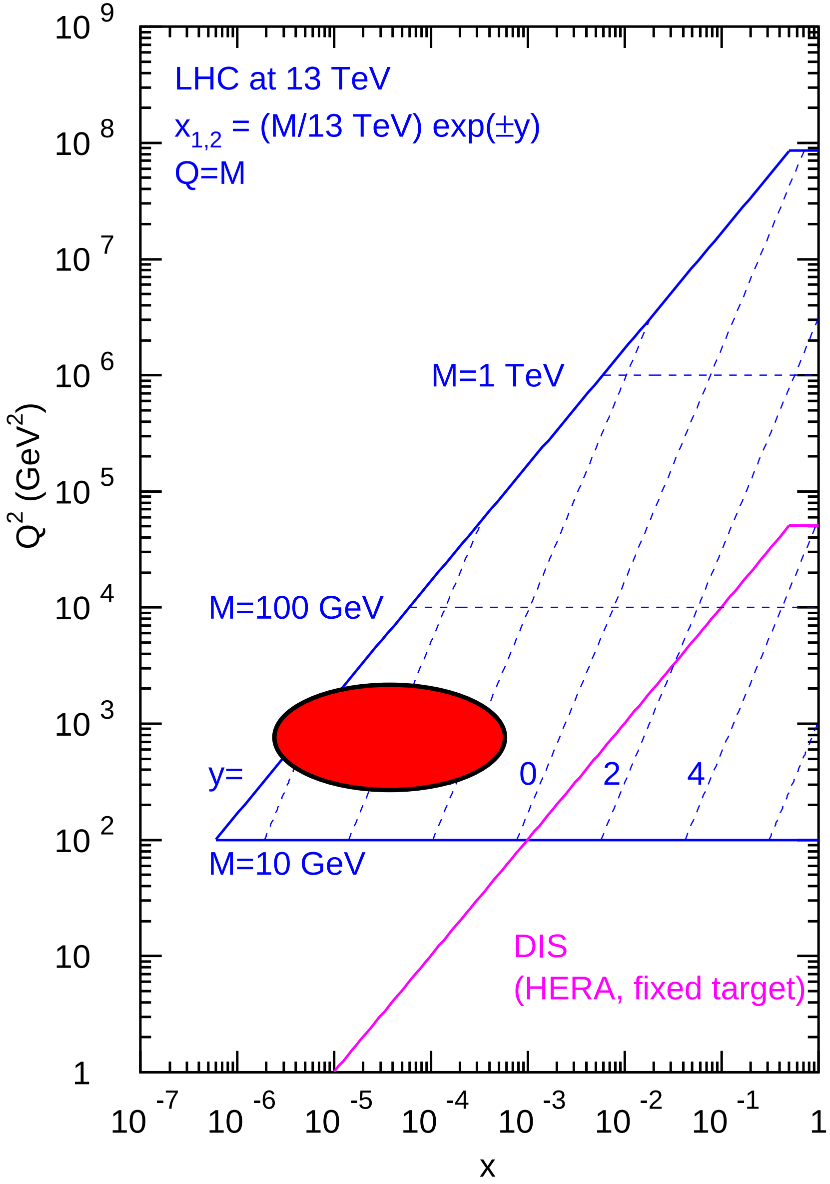
- Information on proton structure depends on kinematic coverage



- Interesting regions
  - hard high-p_T jets, gluon PDF at medium to large x and α_s in TeV region

Parton kinematics at LHC

- Information on proton structure depends on kinematic coverage



- Interesting regions
  - forward jets probe small x gluon PDF at low scales

Theory considerations in PDF fits

Theory considerations

- Strictly NNLO QCD for determination of PDFs and α_s
- Consistent scheme for treatment of heavy quarks
  - $\overline{\mathrm{MS}}$-scheme for quark masses and α_s
  - fixed-flavor number scheme for $n_f = 3, 4, 5$
- Consistent theory description for consistent data sets
  - low scale DIS data with account of higher twist
- Full account of error correlations

Interplay with perturbation theory

- Accuracy of determination driven by precision of theory predictions
- Non-perturbative parameters sensitive to
  - radiative corrections at higher orders
  - chosen scheme (e.g. ($\overline{MS}$ scheme)
  - renormalization and factorization scales μ_R, μ_F
  - . . .

Benchmark measurements

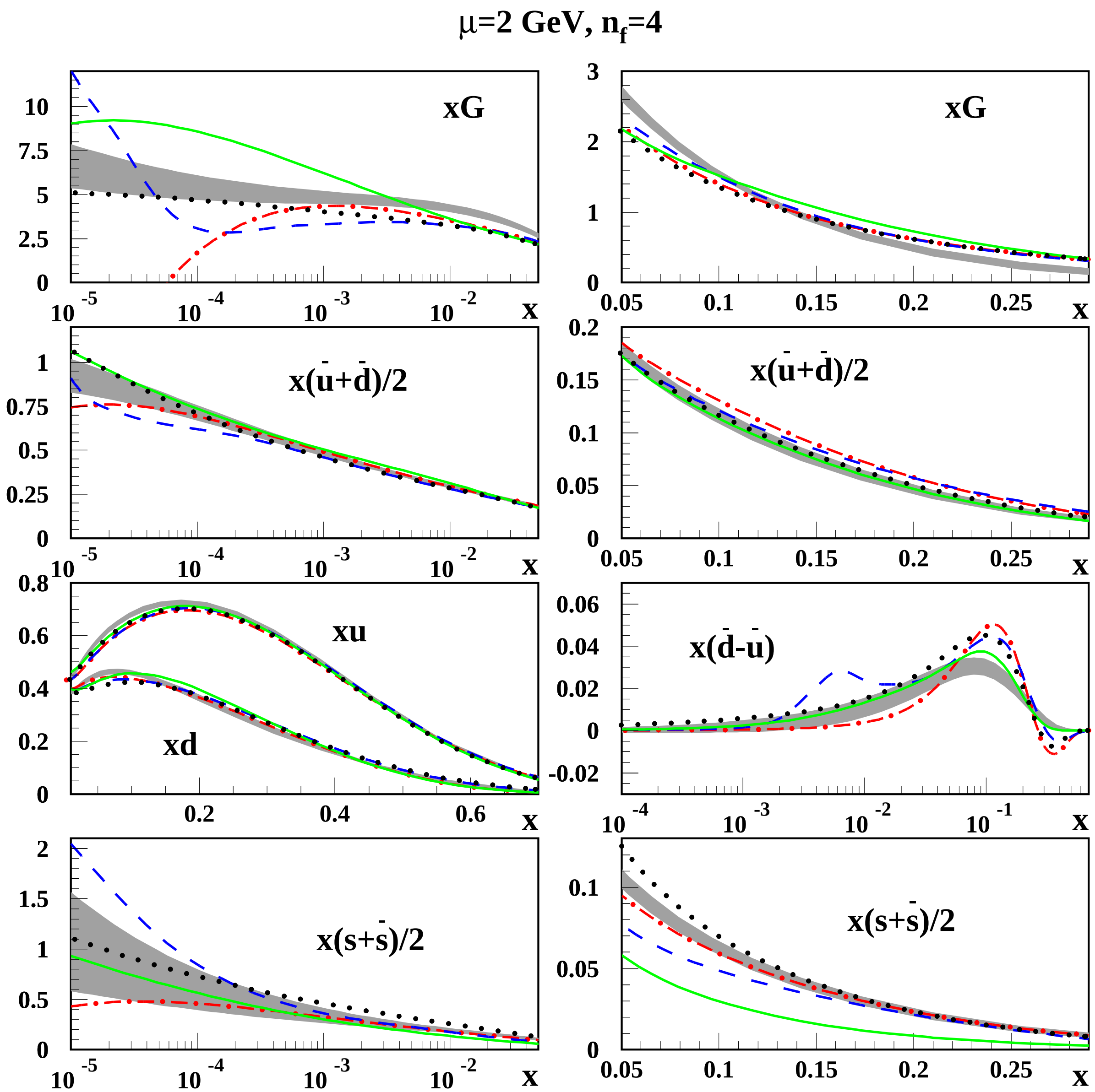
DIS

- Structure functions for neutral and charged current known to $\mathcal{O}(\alpha_s^3)$
  S.M, Vermaseren, Vogt '04–'08
  - F_2, F_3, known N^{3}LO, F_L known NNLO
- Heavy-quark structure functions
  - asymptotic NNLO terms at large $Q^2 \gg m^2$ Bierenbaum, Blümlein, Klein '09; Behring, Bierenbaum, Blümlein, De Freitas, Klein, Wissbrock '14
  - approximate NNLO expressions for neutral and charged current
    Lo Presti, Kawamura, S.M., Vogt '12, Blümlein, A. Hasselhuhn, and T. Pfoh '14

LHC

- Complete NNLO QCD corrections available for
  - $W^{\pm}$- and Z-boson production
    Hamberg, van Neerven, Matsuura '91; Harlander, Kilgore '02
  - hadro-production of top-quark pairs Czakon, Fiedler, Mitov '13
  - single top-quark production (t-channel) Brucherseifer, Caola, Melnikov '14

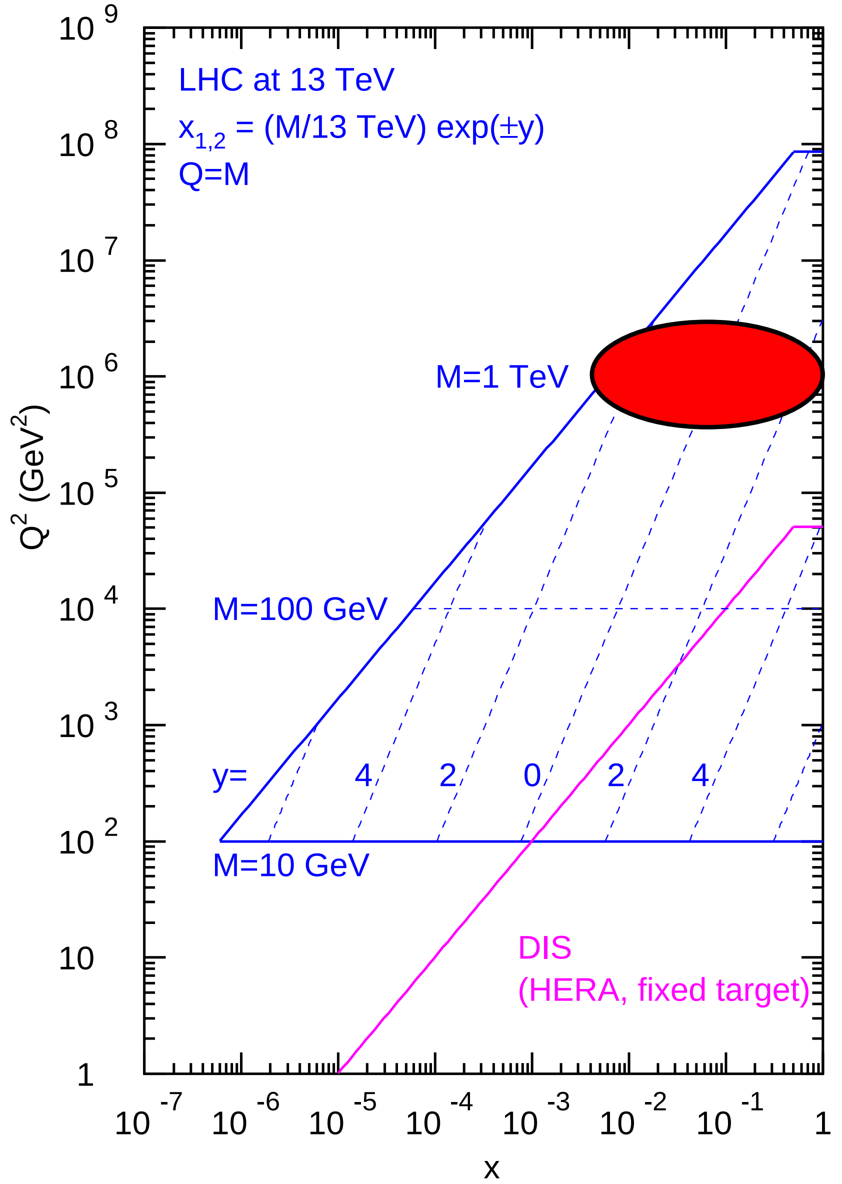
Parton distributions tuned to LHC data



- 1σ band for ABM12 PDFs (NNLO, 4-flavors) at $\mu = 2$ GeV
  Alekhin, Blümlein, S.M.'13
- comparison with:
  JR09 (solid lines),
  MSTW (dashed dots),
  NN23 (dashes) and
  CT10 (dots)
- Some interesting observations to be made ...

Heavy quarks in deep-inelastic scattering

Parton kinematics at LHC



Treatment of heavy-quarks

Light quarks

- Neglect "light quark" masses $m_u, m_d \ll \Lambda_{QCD}$ and $m_s < \Lambda_{QCD}$ in hard scattering process
  - scale-dependent u, d, s, g PDFs from mass singularities

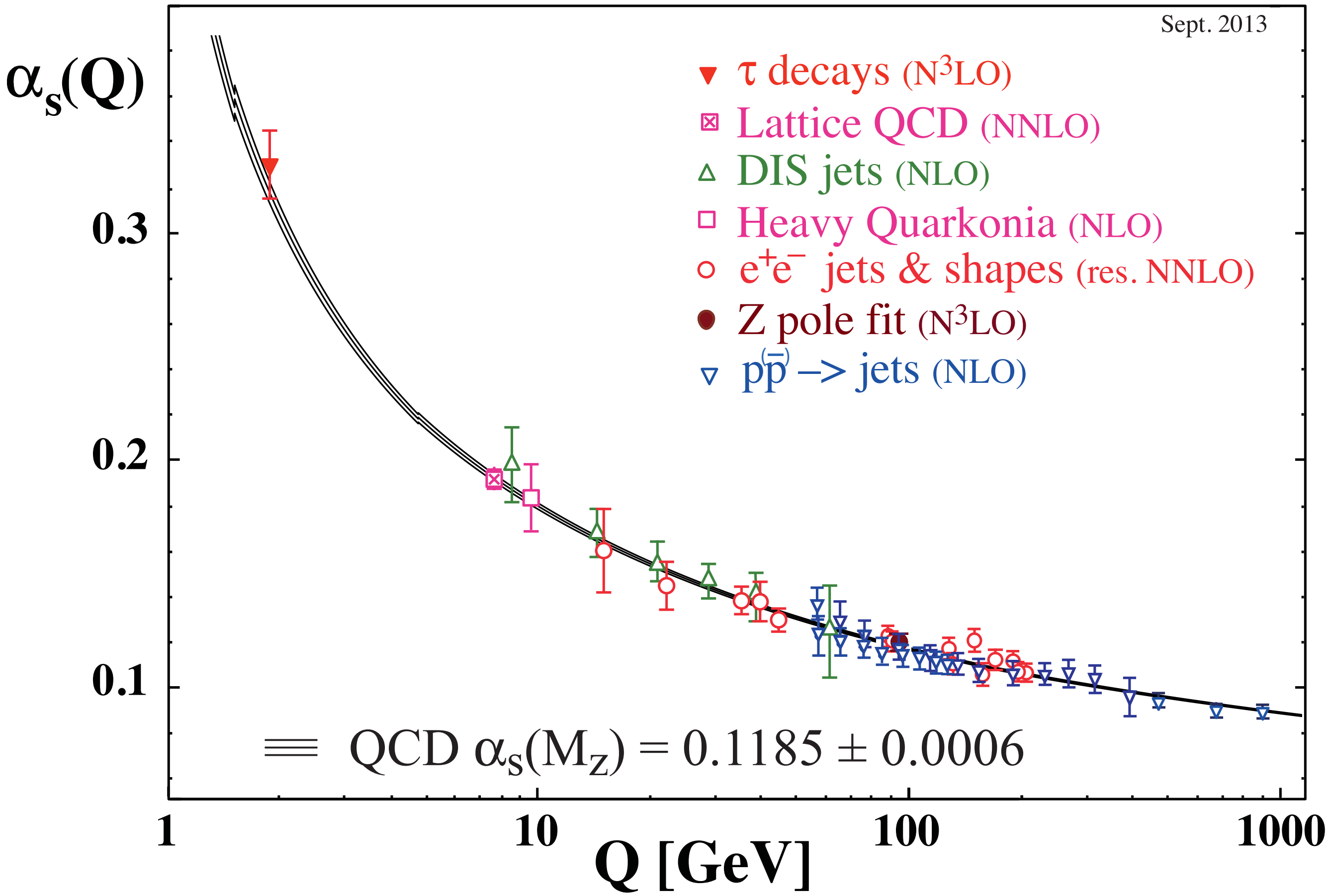
Heavy quarks

- No mass singularities for $m_c, m_b, m_t \gg \Lambda_{QCD}$, no (evolving) PDFs
  - c and b PDFs for $Q \ggg m_c, m_b$ generated perturbatively
  - matching of two distinct theories
    $\longrightarrow n_f$ light flavors + heavy quark of mass m at low scales
    $\longrightarrow n_f + 1$ light flavors at high scales

Strong coupling with flavor thresholds

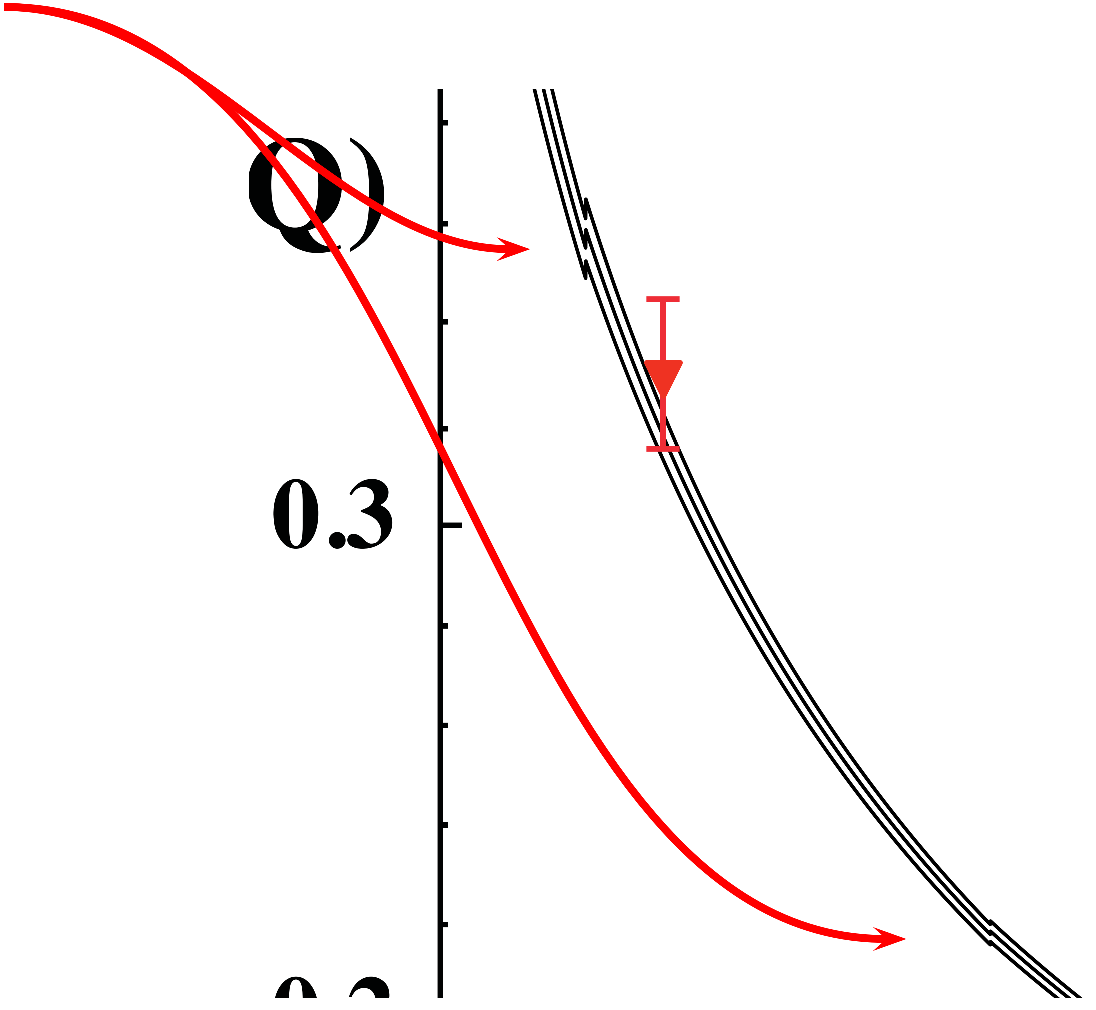
- Solution of QCD β-function for $\alpha_s^{n_l} \longrightarrow \alpha_s^{(n_l+n_h)}$
  - discontinuities for $n_f = 3 \rightarrow n_f = 4 \rightarrow n_f = 5$
- Big picture

Bethke for PDG 2014



Strong coupling with flavor thresholds

- Solution of QCD β-function for $\alpha_s^{n_l} \longrightarrow \alpha_s^{(n_l+n_h)}$
  - discontinuities for $n_f = 3 \rightarrow n_f = 4 \rightarrow n_f = 5$
- Zoom

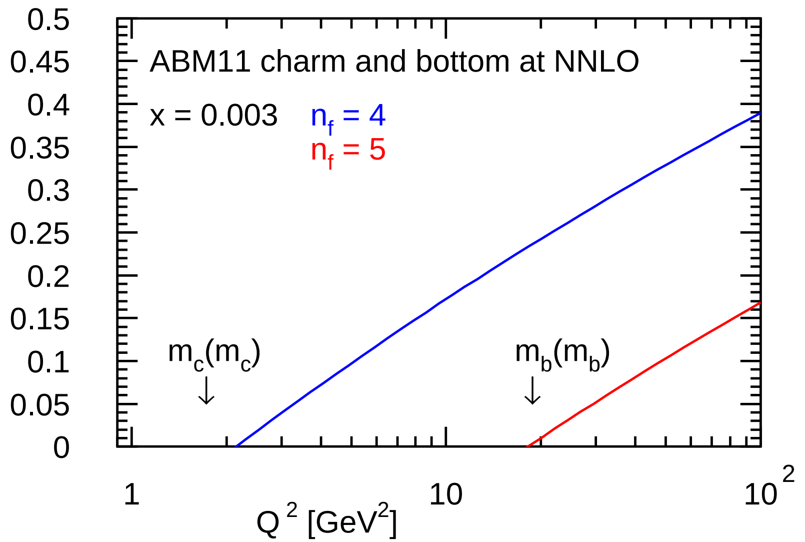


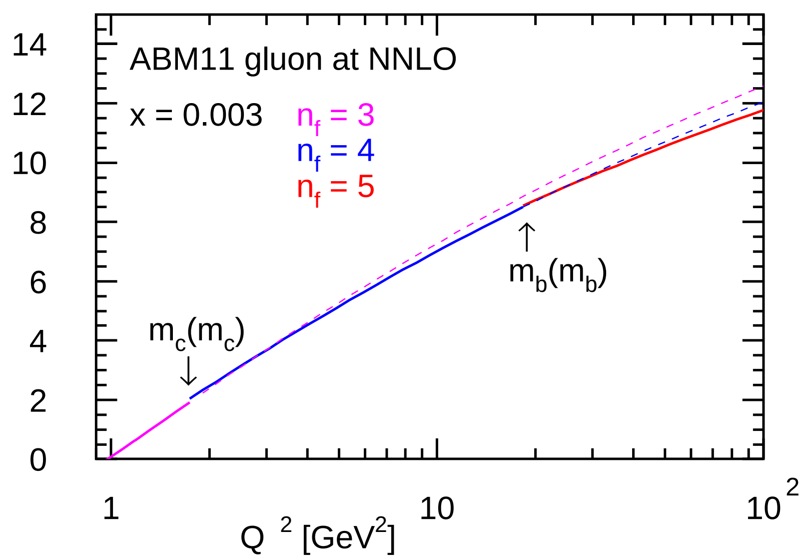
PDFs with flavor thresholds

- Generate heavy-quark PDFs $h^{(n_f+1)}$ from light-flavor PDFs
  - heavy-quark operator matrix elements (OMEs) A_{ji} at three loops
    Bierenbaum, Blümlein, Klein '09; Ablinger, Behring, Blümlein, De Freitas, von Manteuffel, Schneider '14

$$h^{(n_f+1)}(x,\mu) + \bar{h}^{(n_f+1)}(x,\mu) = A_{hq}(x) \otimes \Sigma^{(n_f)}(x,\mu) + A_{hq}(x) \otimes g^{(n_f)}(x,\mu)$$

  - likewise light-quark PDFs $l_i^{(n_f)} \to l_i^{(n_f+1)}$ and gluon and the quark singlet PDFs $(\Sigma^{(n_f)}, g^{(n_f)}) \to (\Sigma^{(n_f+1)}, g^{(n_f+1)})$
- Solution of evolution equations between thresholds for $n_f \longrightarrow (n_f+1)$ with fixed $n_f = 3 \to n_f = 4 \to n_f = 5$





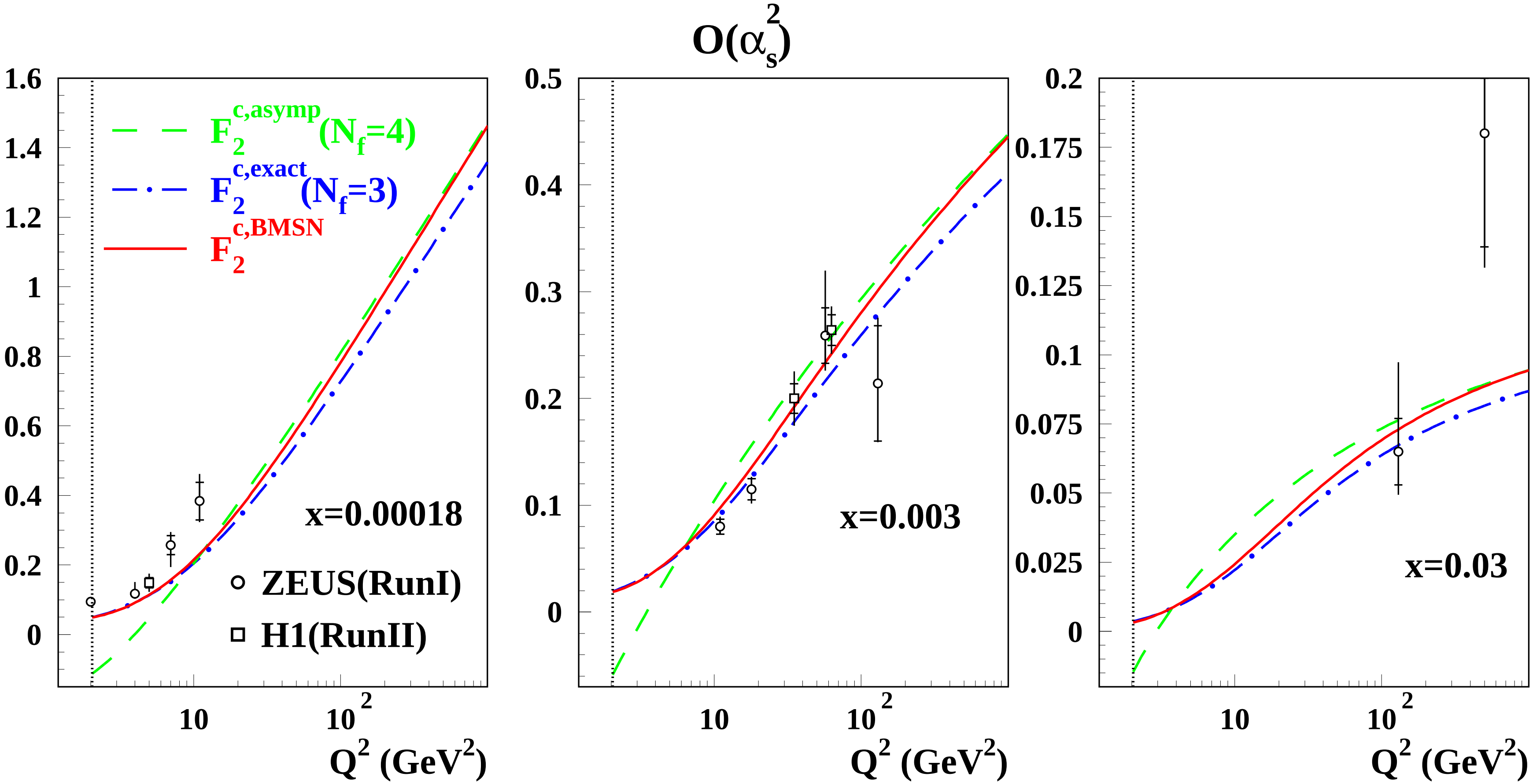
Cross sections with flavor thresholds

Fixed flavor number scheme (FFNS) ("do nothing")

- Cross section with massive quarks at scales $Q \not\gg m_c$
  - top-quark hadro-production ($t\bar{t}$ pairs, single top in 4FS or 5FS, . . .]
- F_2^c at HERA with u, d, s, g partons and massive charm coeff. fcts.
  - complete NLO predictions Laenen, Riemersma, Smith, van Neerven '92
  - approximations at NNLO Bierenbaum, Blümlein, Klein '09; Lo Presti, Kawamura, S.M., Vogt '12; Behring, Bierenbaum, Blümlein, De Freitas, Klein, Wissbrock '14

Variable flavor number scheme (VFNS) ("match something")

- (Smooth) matching of two distinct theories:
  n_f light + heavy quark at low scales $\longrightarrow n_f + 1$ light flavors at high scales
  - Higgs boson production in $b\bar{b}$-annihilation ("Santander matching" Harlander, Krämer, Schumacher '11)
- F_2^c at HERA with ACOT Aivazis, Collins, Olness, Tung '94, BMSN Buza, Matiounine, Smith, van Neerven '98, RT Thorne, Roberts '98, FONNL Forte, Laenen, Nason, Rojo '10
  - model assumptions in matching conditions
  - details of implementation matter in global fits

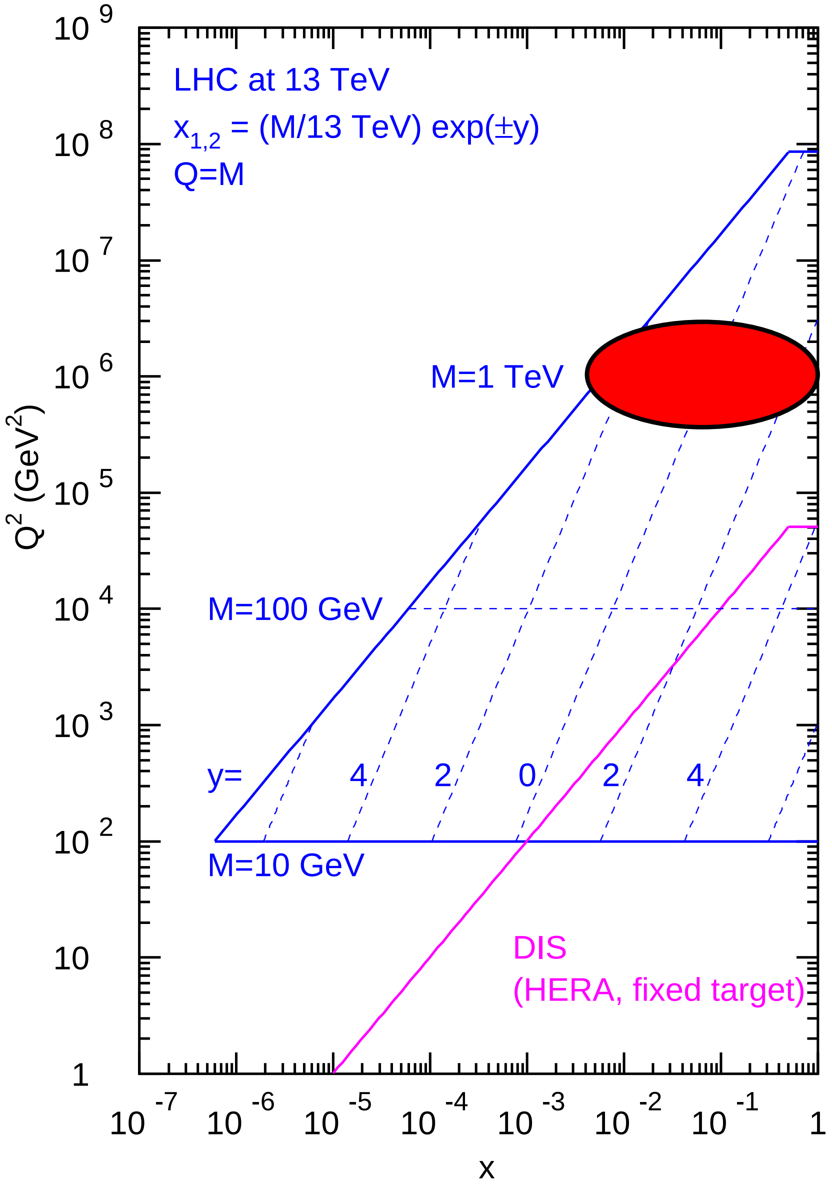


Alekhin, Blümlein, Klein, S.M. '09

- F_2^c in different schemes compared to H1- and ZEUS-data
  - GMVFN scheme in BMSN prescription (solid lines)
  - 3-flavor scheme (dash-dotted lines)
  - 4-flavor scheme (dashed lines)
  - charm-quark mass $m_c = 1.43$ GeV (vertical dotted line)

Threshold logarithms at large p_T

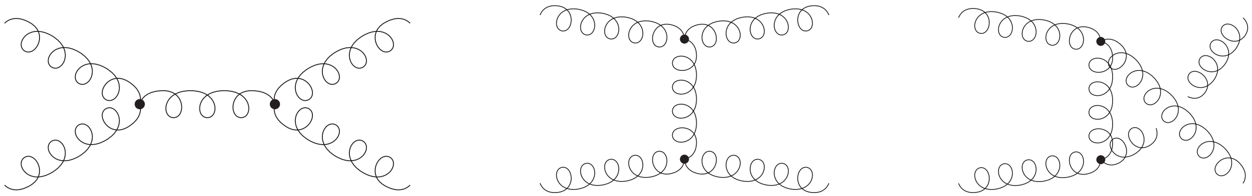
Parton kinematics at LHC



Jet hadro-production at NNLO

Status of QCD theory for jet cross sections

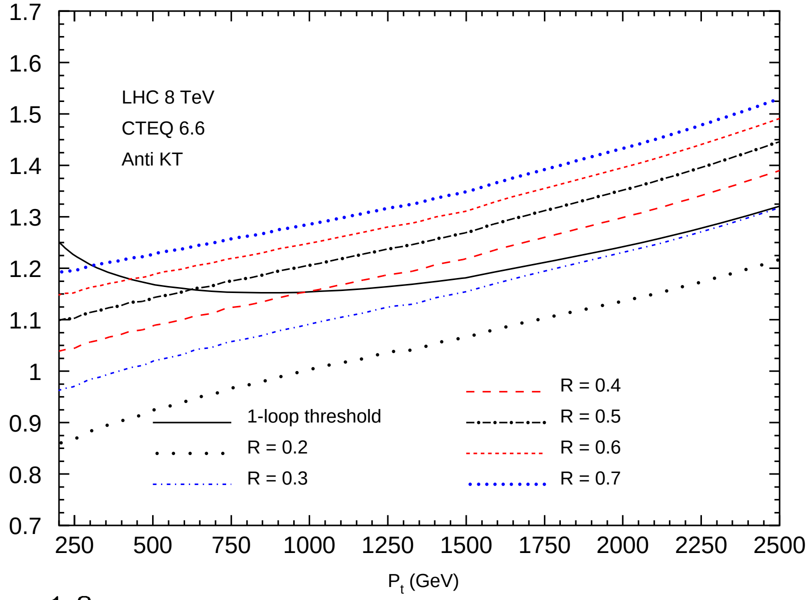
- Hadro-production of jets (single jet inclusive, di-jets)
  - NLO known since long
  - partial results at NNLO (purely gluonic contributions)
    Currie, Gehrmann-De Ridder, Glover, Pires, '13

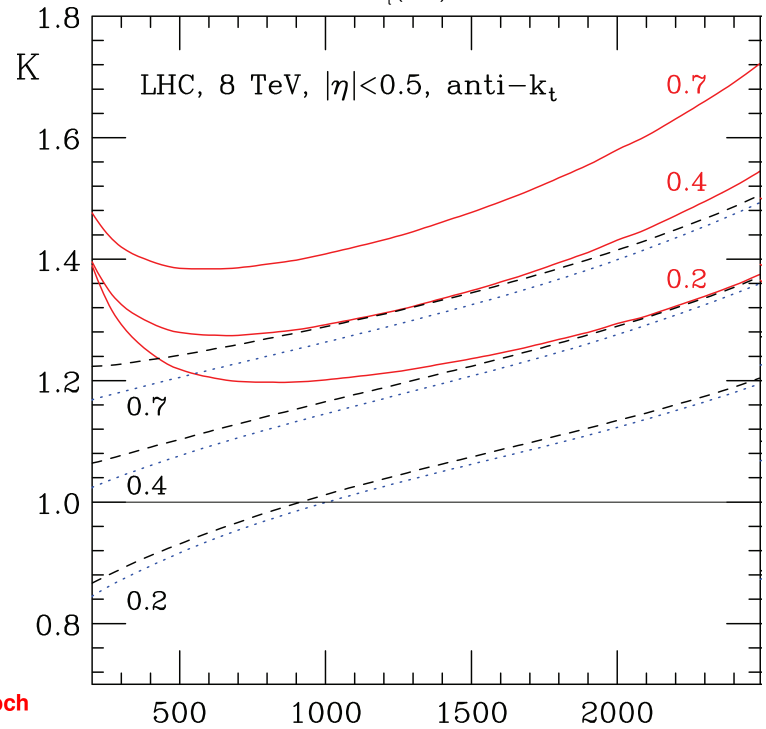


Threshold logarithms

- One-jet inclusive jets hadro-production $P + P(\bar{P}) \to J(R) + X(s_4)$
  - large threshold corrections of type $\alpha_s^l \, [\ln^{2l-1}(s_4/p_T^2)/s_4]_+$ from soft/collinear gluon radiation Kidonakis, Owens '00
  - $\ln R$ dependence on jet's cone size R in small cone approximation
    de Florian, Vogelsang '07
- Threshold approximation needs to account for Sudakov logarithms $\ln(p_T^2/s)$ and $\ln R$ terms $\longrightarrow$ numerically of similar magnitude

Threshold logarithms at NNLO



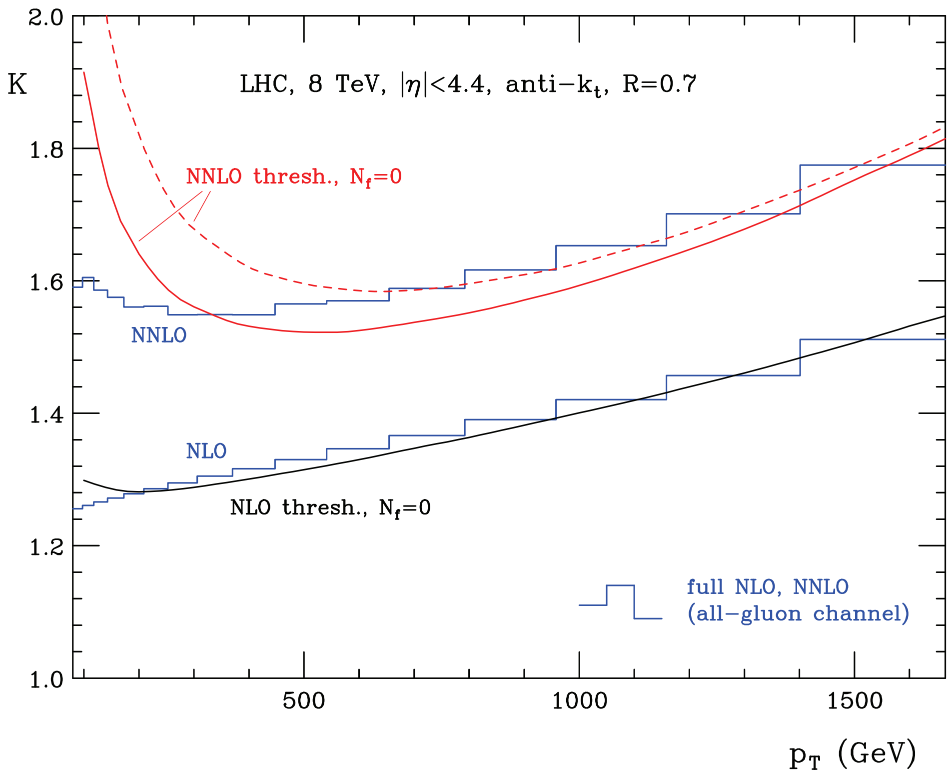


- threshold logarithms alone (w/o $\ln R$) at NLO fail to describe exact results
  Kumar, Moch '13

- cone size dependence $\ln R$ numerically important
- $\ln R$ terms improve agreement between exact result and threshold approximation at NLO de Florian, Hinderer, Mukherjee, Ringer, Vogelsang '13

Jet hadro-production at NNLO

- Nice match at NNLO
  - threshold approximation de Florian, Hinderer, Mukherjee, Ringer, Werner Vogelsang '13
  - exact NNLO (purely gluonic) computation Currie, Gehrmann-De Ridder, Glover, Pires '13



- in principle ready for applications in PDF analyses or experimental analyses of jet data Carrazza, Pires '14

Strong coupling constant

Strong coupling constant (1992)

	$\alpha_s(\mathrm{M_Z^2})$
R_τ	$0.117\,{}^{+\,0.010}_{-\,0.016}$
DIS	0.112 ± 0.007
Υ Decays	0.110 ± 0.010
$R_{e^+e^-}(s < 62\text{GeV})$	0.140 ± 0.020
$p\overline{p} \to W + jets$	0.121 ± 0.024
$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to l\bar{l})$	0.132 ± 0.012
Jets at LEP	0.122 ± 0.009
Average	0.118 ± 0.007

G. Altarelli (1992)
in *QCD - 20 Years Later,*
CERN-TH-6623-92

Essential facts

- World average 1992 $\alpha_s(M_Z) = 0.118 \pm 0.007$
- Central value at NLO QCD
  - still right, but for very different reasons
- Error at NLO QCD
  - now down to $\sim 0.0050 - 0.0040$ (theory scale uncertainty)

Strong coupling constant (2016)

Measurements at NNLO

- Values of $\alpha_s(M_Z)$ at NNLO from PDF fits

SY	0.1166 ± 0.013	F_2^{ep}	Santiago, Yndurain '01
	0.1153 ± 0.063	$xF_3^{\nu N}$ (heavy nucl.)	
A02	0.1143 ± 0.013	DIS	Alekhin '01
MRST03	0.1153 ± 0.0020		Martin, Roberts, Stirling, Thorne '03
BBG	$0.1134\ ^{+\,0.0019}_{-\,0.0021}$	valence analysis, NNLO	Blümlein, Böttcher, Guffanti '06
GRS	0.112	valence analysis, NNLO	Glück, Reya, Schuck '06
A06	0.1128 ± 0.015		Alekhin '06
JR08	0.1128 ± 0.0010	dynamical approach	Jimenez-Delgado, Reya '08
	0.1162 ± 0.0006	including NLO jets	
ABKM09	0.1135 ± 0.0014	HQ: FFNS $n_f = 3$	Alekhin, Blümlein, Klein, S.M. '09
	0.1129 ± 0.0014	HQ: BSMN	
MSTW	0.1171 ± 0.0014		Martin, Stirling, Thorne, Watt '09
Thorne	0.1136	[DIS+DY, HT*] (2013)	Thorne '13
ABM11_J	$0.1134 \ldots 0.1149\ \pm 0.0012$	Tevatron jets (NLO) incl.	Alekhin, Blümlein, S.M. '11
NN21	0.1173 ± 0.0007	(+ heavy nucl.)	NNPDF '11
ABM12	0.1133 ± 0.0011		Alekhin, Blümlein, S.M. '13
	0.1132 ± 0.0011	(without jets)	
CT10	0.1140	(without jets)	Gao et al. '13
CT14	$0.1150\ ^{+\,0.0060}_{-\,0.0040}$	$\Delta\chi^2 > 1$ (+ heavy nucl.)	Dulat et al. '15
MMHT	0.1172 ± 0.0013	(+ heavy nucl.)	Martin, Motylinski, Harland-Lang, Thorne '15

Strong coupling constant (2016)

Other measurements of α_s at NNLO

- Values of $\alpha_s(M_Z)$ at NNLO from measurements at colliders

3-jet rate	0.1175 ± 0.0025	Dissertori et al. 2009	arXiv:0910.4283
e^+e^- thrust	$0.1131\ ^{+\,0.0028}_{-\,0.0022}$	Gehrmann et al.	arXiv:1210.6945
e^+e^- thrust	0.1140 ± 0.0015	Abbate et al.	arXiv:1204.5746
C-parameter	0.1123 ± 0.0013	Hoang et al.	arXiv:1501.04111
CMS	0.1151 ± 0.0033	$t\bar{t}$	arXiv:1307.1907
NLO Jets ATLAS	$0.111\ ^{+\,0.0017}_{-\,0.0007}$		arXiv:1312.5694
NLO Jets CMS	0.1148 ± 0.0055		arXiv:1312.5694

Differences in α_s determinations

Why α_s values from MSTW and NNPDF are large

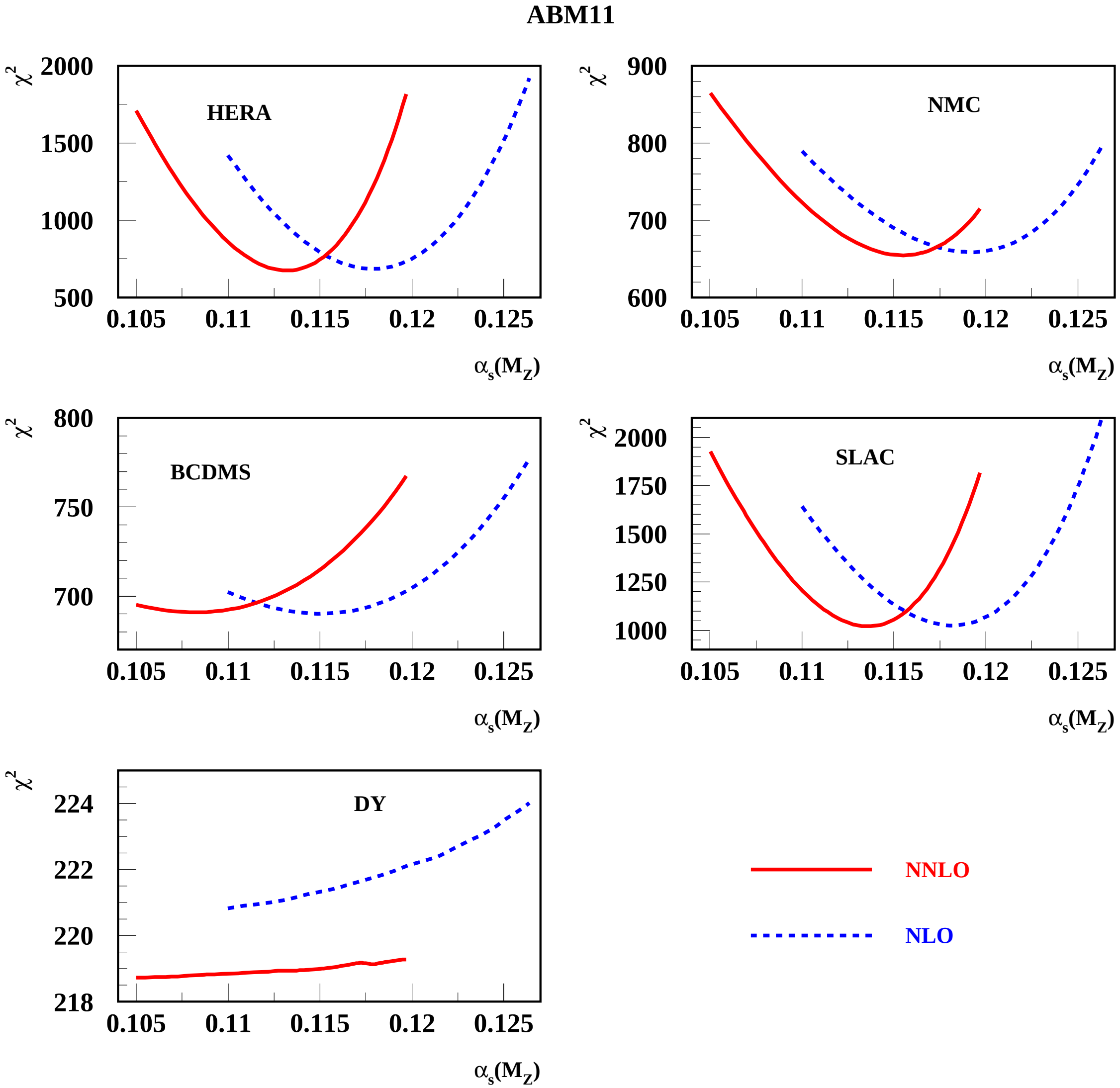
- Differences result from different physics models and analysis procedures
  - target mass corrections (powers of nucleon mass M_N^2/Q^2)
  - higher twist $F_2^{\rm ht} = F_2 + ht^{(4)}(x)/Q^2 + ht^{(6)}(x)/Q^4 + \dots$
  - error correlations
- Hadroproduction of jets known NLO only
  - strictly speaking $\alpha_s(M_Z)$ value only NLO (systematically larger)

	α_s	NNLO	target mass corr.	higher twist	error correl.
ABM12	0.1132 ± 0.0011	**yes**	**yes**	**yes**	**yes**
NNPDF21	0.1173 ± 0.0007	**(yes)**	**yes**	**no**	**yes**
MSTW	0.1171 ± 0.0014	**(yes)**	**no**	**no**	**no**
MMHT	0.1172 ± 0.0013	**(yes)**	**no**	**no**	–

- Effects for differences are understood
  - variants of ABM with no higher twist etc. reproduce larger α_s values
    Alekhin, Blümlein, S.M. '11

Zooming in on ABM

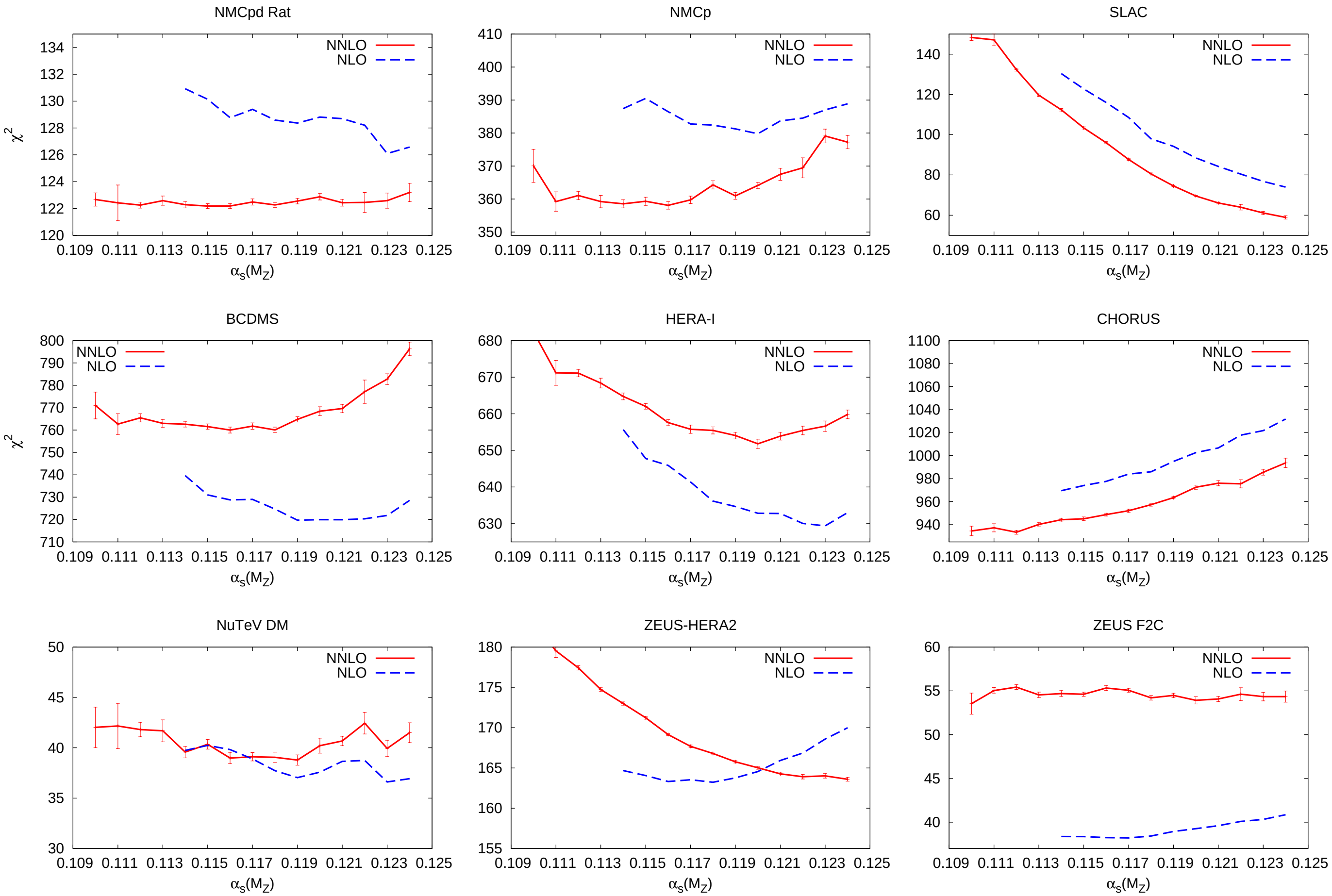
α_s *from DIS and PDFs*



- Profile of χ^2 for different data sets in ABM11 PDF fit Alekhin, Blümlein, S.M. '12

Zooming in on NNPDF

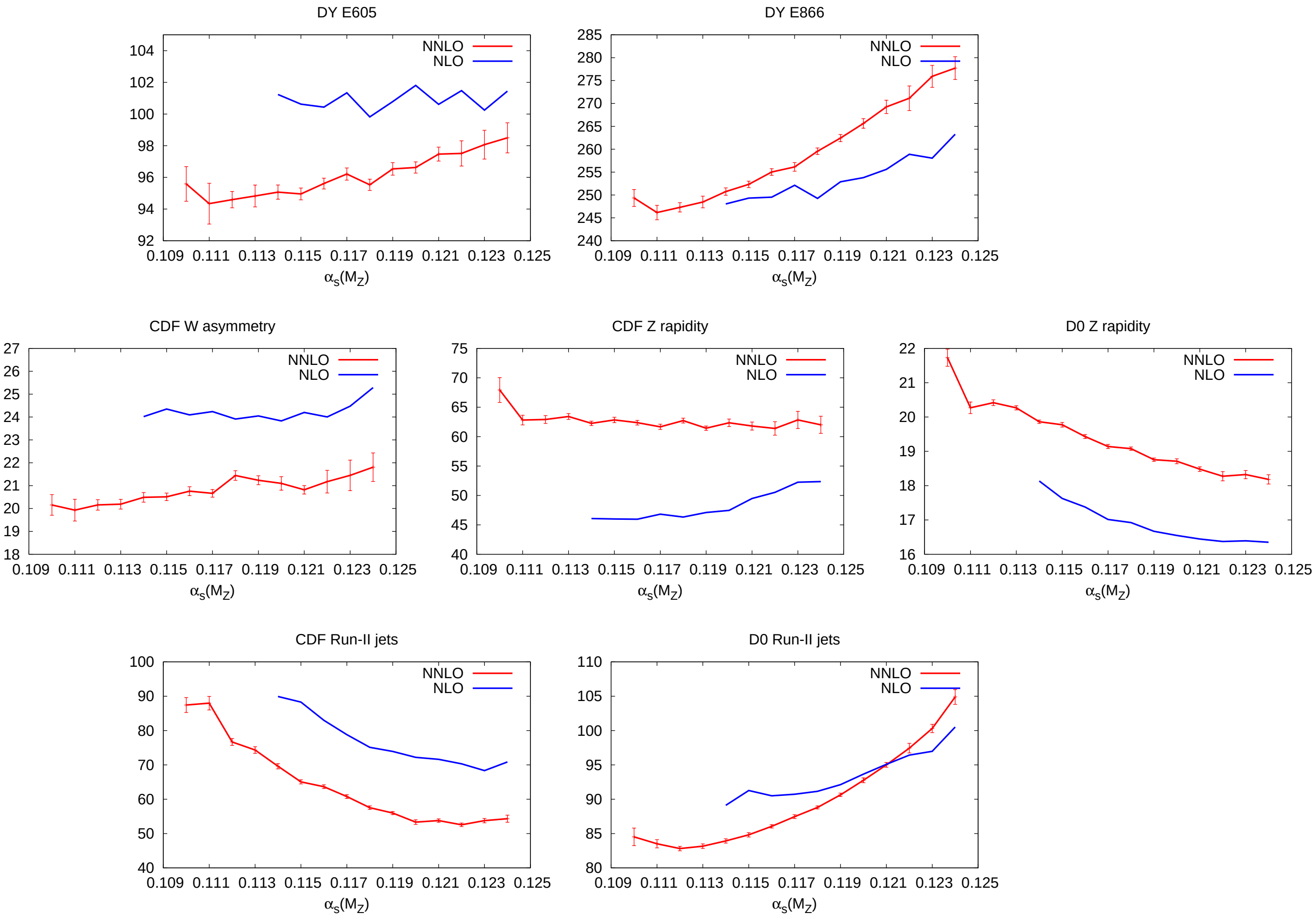
α_s from DIS and PDFs



- Profile of χ^2 for different data sets in NNPDF21 fit Ball et al. '11

Zooming in on NNPDF

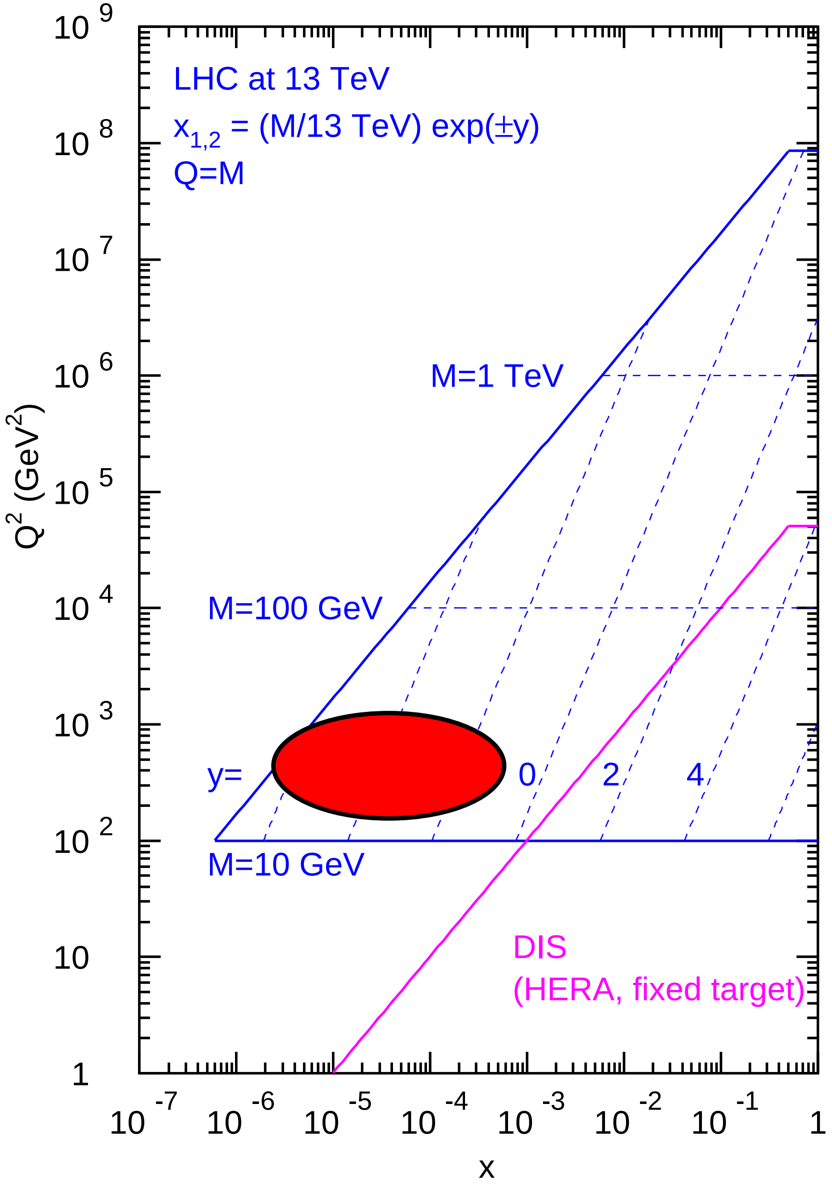
α_s *from DIS and PDFs*



- Profile of χ^2 for different data sets in NNPDF21 fit Ball et al. '11

Forward region

Parton kinematics at LHC



Gluon PDF at small x

Facts

- Gluon PDF at small-x
  - fits yield $xg(x) \simeq x^a$ with $a \simeq -0.2$
  - kinematic coverage of data down to $x \simeq 10^{-5}$

Issues

- Extrapolation of gluon PDF towards smaller x
  - some PDFs feature large uncertainities for extrapolation to unmeasured regions $\longrightarrow$ this invalidates predictive potential
- Some PDFs predict negative gluon PDF at small-x and low scales
  - unphysical feature as consequence of modelling in variable flavor number schemes applied
  - large differences between gluon PDFs fitted at NLO and NNLO

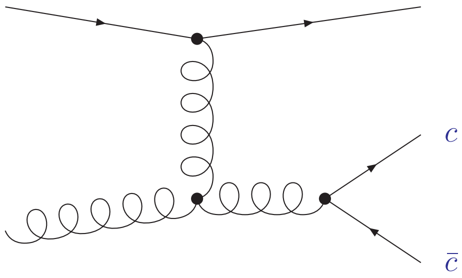
Challenge

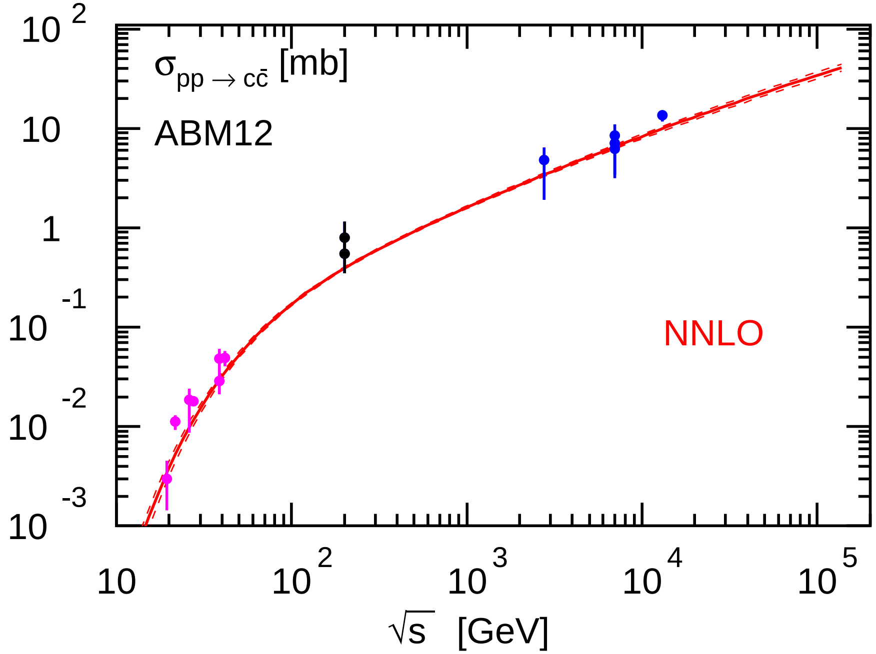
- Test of pertubative QCD in forward region (large rapidities)

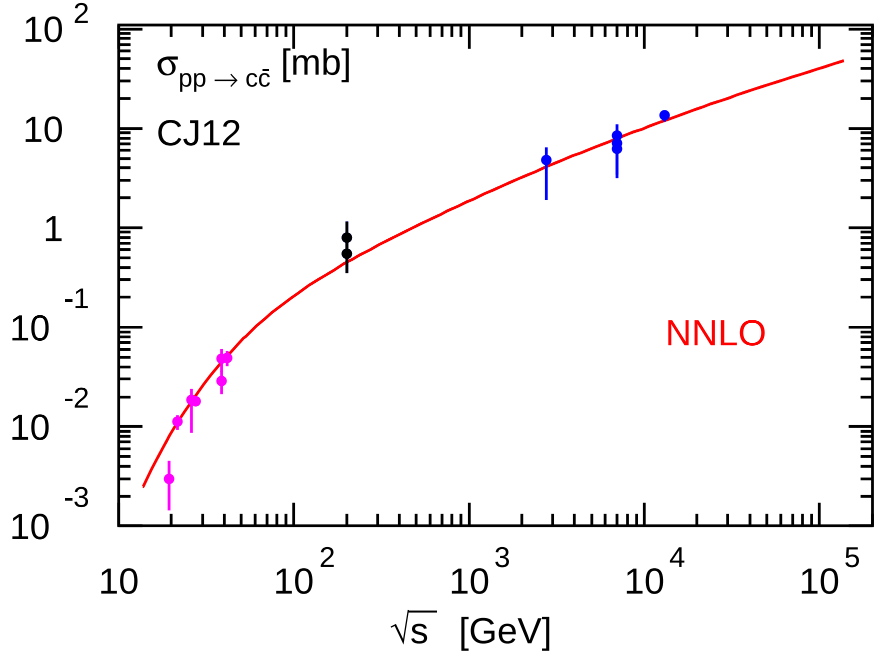
Charm-quark hadro-production at NNLO

Diagnostic tool

- Charm-quark hadro-production at high energies
  - quark-gluon parton luminositiy dominates



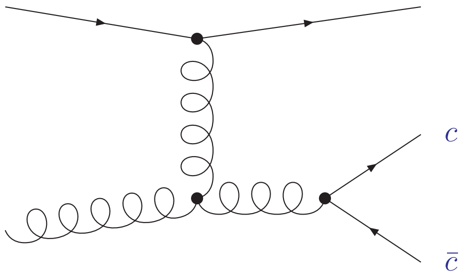


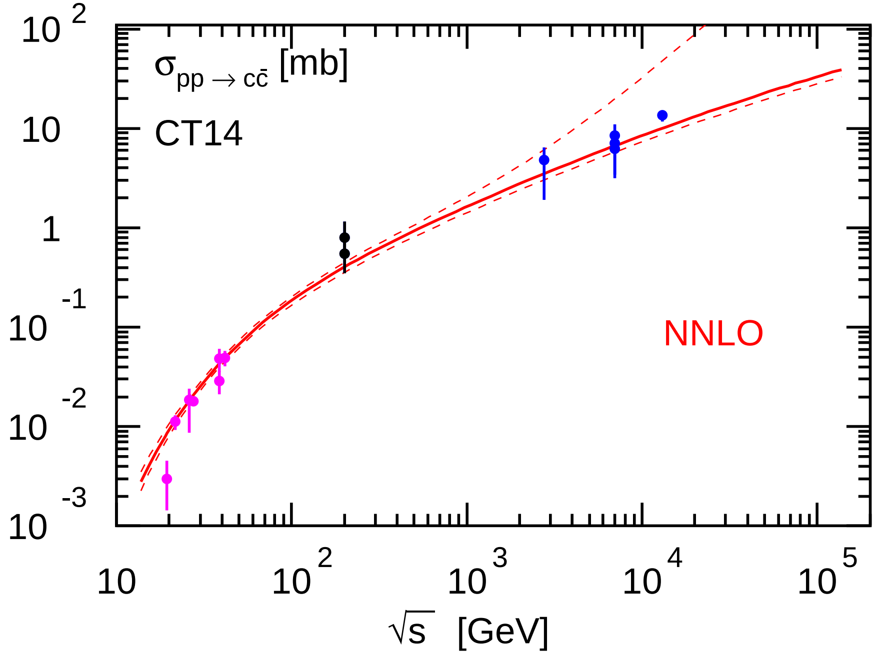


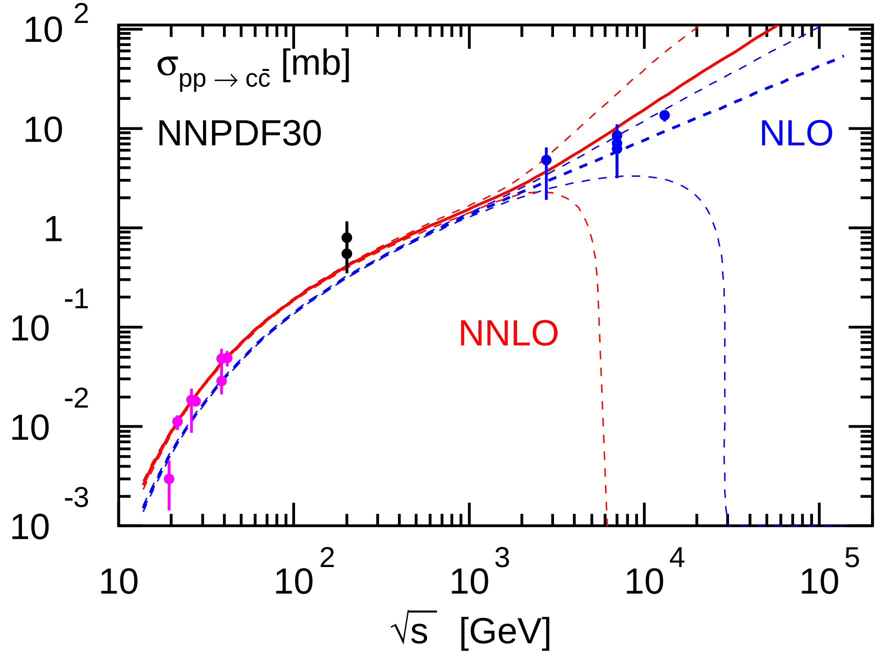
Charm-quark hadro-production at NNLO

Diagnostic tool

- Charm-quark hadro-production at high energies
  - quark-gluon parton luminositiy dominates







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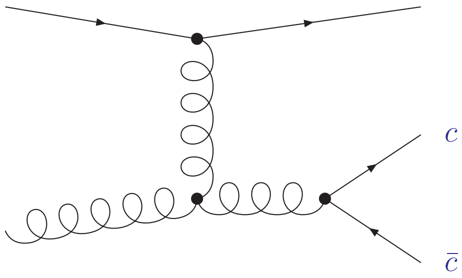

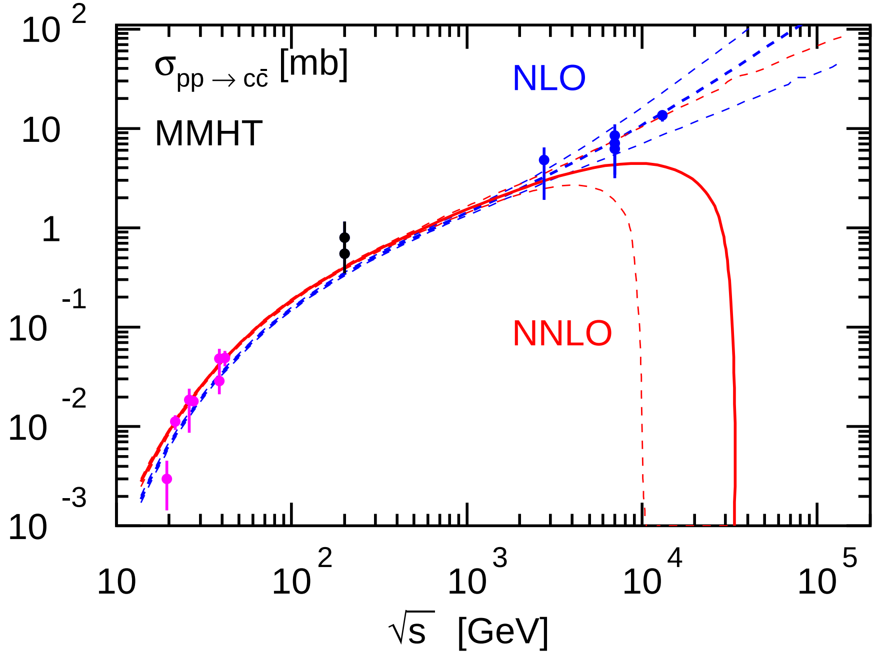

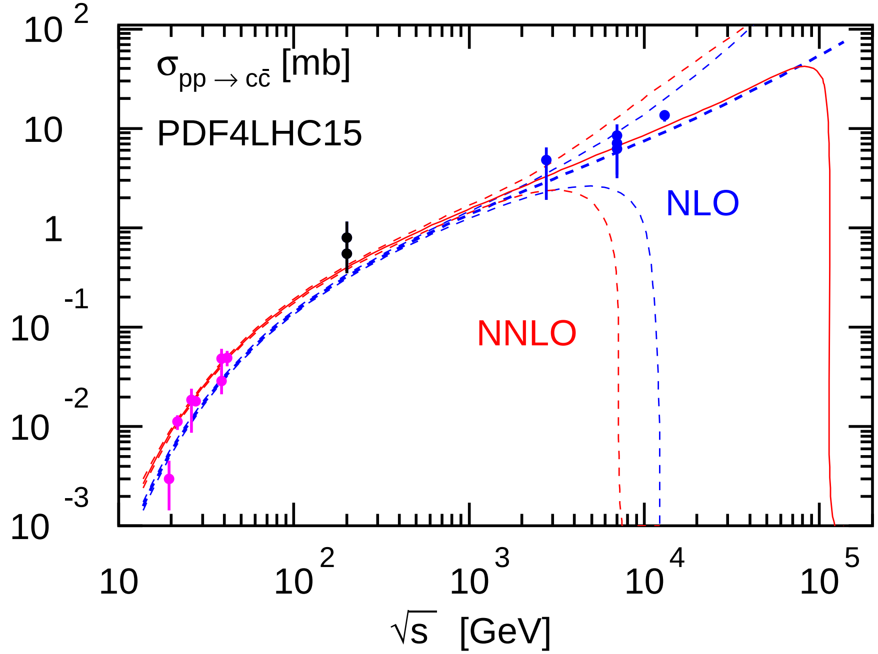

Summary

Prospects of jet measurements for PDF determinations

High p_T

- High p_T jet data allow for precision determinations of . . .

  . . . strong coupling constant $\alpha_s(M_Z)$

  . . . gluon PDF at medium to large-x
- Precision of $\lesssim 1\%$ makes theoretical predictions at NNLO in QCD mandatory

Forward region

- Jet data from forward region . . .

  . . . test perturbative QCD at small-x

  . . . rule out negative gluon PDF at small-x

  . . . test perturbative QCD at small-x
- Because of large spread in PDFs theoretical predictions at NLO in QCD suffice