Hard QCD at Higher Orders

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DESY, Zeuthen

– *XIX International Workshop on Deep-Inelastic Scattering and Related Subjects*, Newport News, April 11, 2011 –

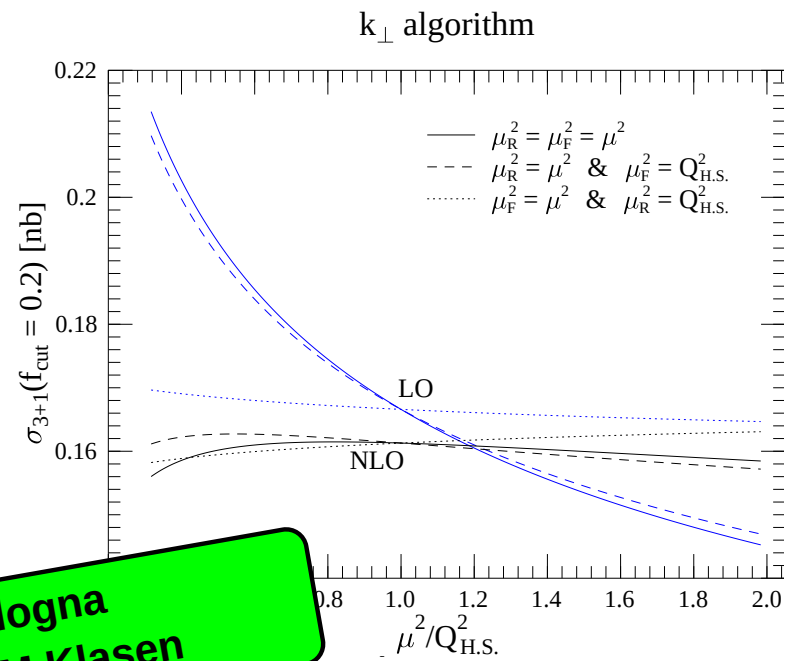
Historical perspective

Perturbative QCD in 2001

- NLO QCD calculations
  - NLOJET++ MC $pp \to 3$jets
    Nagy
- Resummation to (N)LL
  $\text{higher orders} \cap \text{parton shower} = 0$
- NNLO only for DIS structure functions
  - just appeared in 02/2001: Soft and virtual corrections to $pp \to H + X$ at NNLO
    Harlander, Kilgore '01

JETS IN DIS

- New NLO 3-jet calculation NLOJET++ using dipole subtraction method
  $\to$ Z. Nagy, Z. Trocsanyi, IPPP/01/18, hep-ph/0104
- Helicity amplitudes crossed from $e^+e^- \to \gamma^* \to 4$ jets
  $\to$ Z. Bern, L. Dixon, D. Kosower, S. Weinzierl, NPB 489 (1997) 3
  $\to$ J. Campbell, N.Glover, D.Miller, PLB 396 (1997) 257; 409 (1997) 503
  $\to$ Z. Nagy, Z. Trocsanyi, PRD 59 (1999) 014020; E: 62 (2000) 099902
- Agrees with DISASTER++, deviates from DISENT for small x_B and y
- Reduced dependence on scale $Q_{H.S.} = \frac{1}{3}\sum_j E_T^B(j)$



Z. Nagy, Z. Trocsanyi, IPPP/01/18, hep-ph/0104

- Progress in NNLO jet calculations $\to$ talk by T. Gehrmann

DIS 2001 Bologna
plenary talk by M.Klasen

Historical perspective

Parton distributions

- PDFs uncertainties start to appear
- PDF fits from:
  MRST; CTEQ; Botje;
  Alekhin; Giele, Keller, Kosower
- PDFs with NLO evolution only
  - QCD evolution codes with $\mathcal{O}(\text{few}\%)$ differences
  - Les Houches 2001: benchmarks for NNLO QCD evolution accurate to 10^{-5} for $10^{-8} < x < 0.9$
    Salam, Vogt '02

Uncertainties in pdf's

- Global analyses (NLO DGLAP)

  $\sim$ 14 'diverse' experiments $\sim$ 1500 data pts
  $\sim$ 20+ parameters (starting distributions etc.)

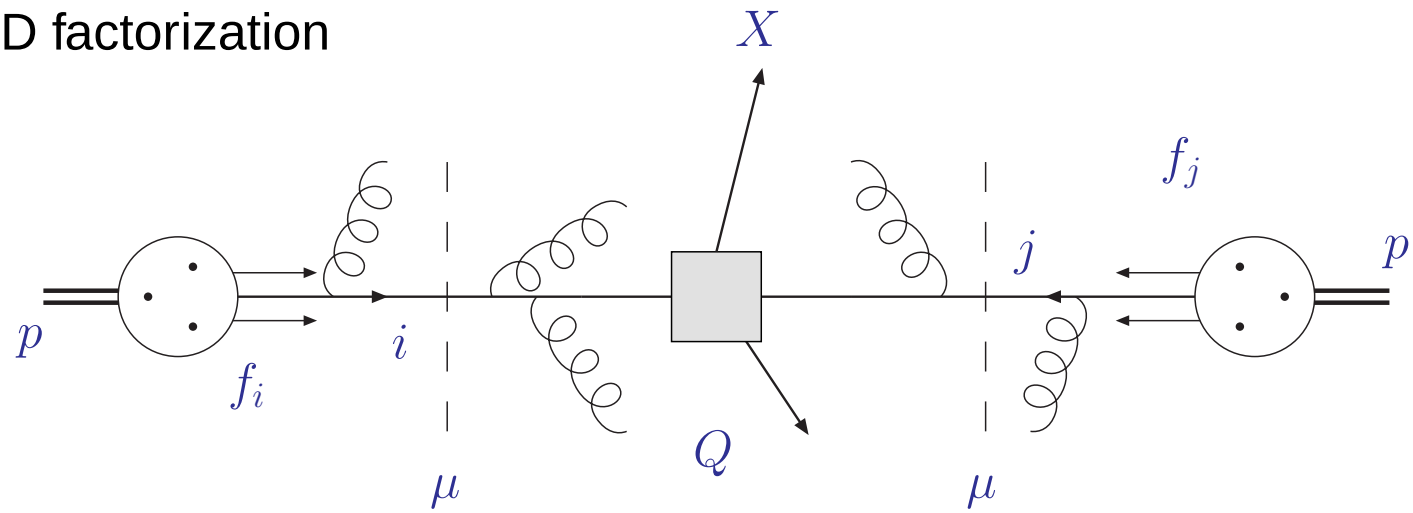
- Sources of uncertainty
  - statistical
  - systematic expt. errors — often not randomly distributed, may depend on theory
  - theory:

    higher order QCD
    choice of factorization and renormalization scales
    resummation corrections $(\ln 1/x, \ldots)$
    power law contributions
    nuclear target corrections
    parametrization of starting distributions
    [illegible] event)

DIS 2001 Bologna
plenary talk by A.Martin

Introduction

- QCD factorization

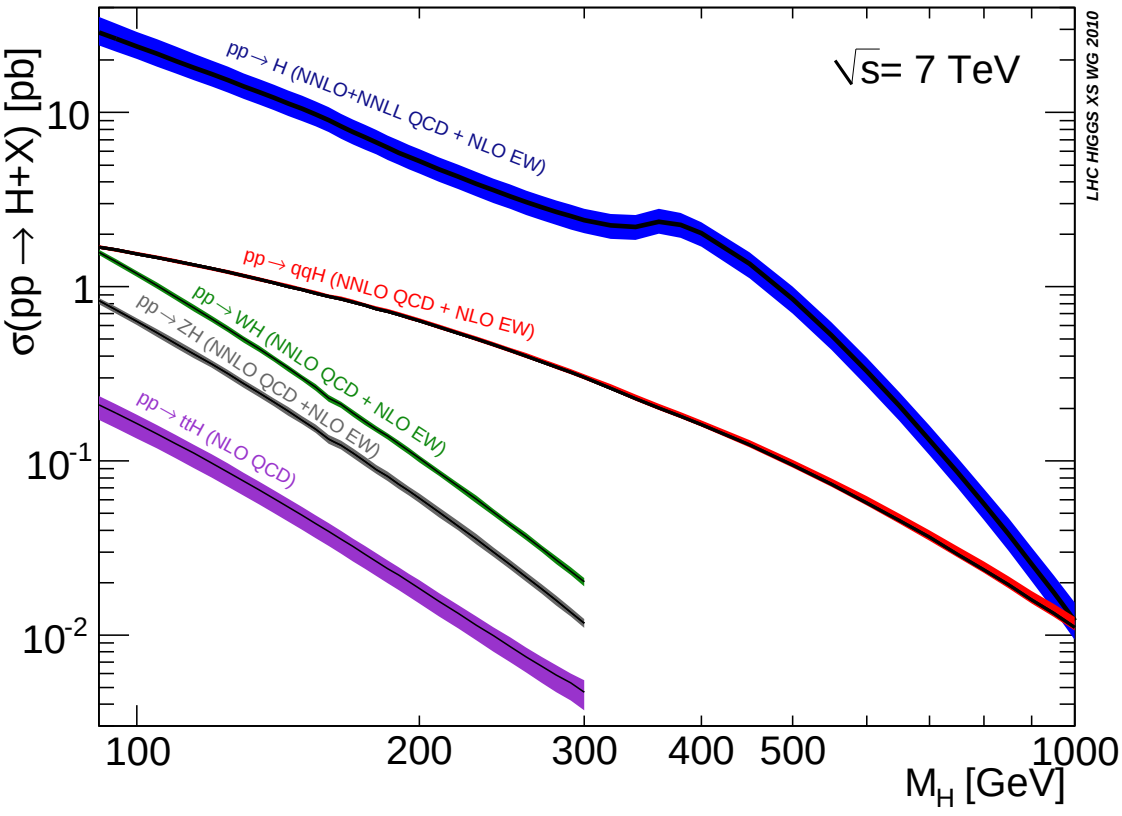


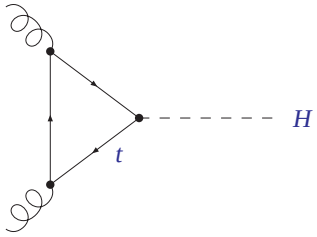
$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - known to NLO, NNLO, . . . ($\mathcal{O}(\text{few}\%)$ theory uncertainty)
- 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, . . .

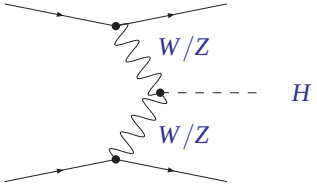
Cross section for Higgs production

- Dominant channels for Higgs boson production LHC Higgs XS WG '10

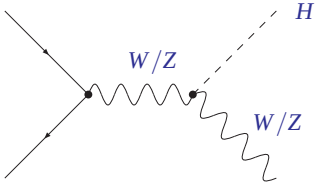




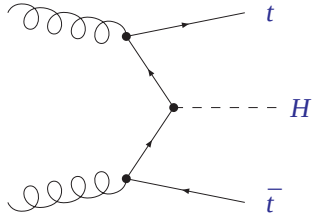
gg-fusion



weak boson fusion

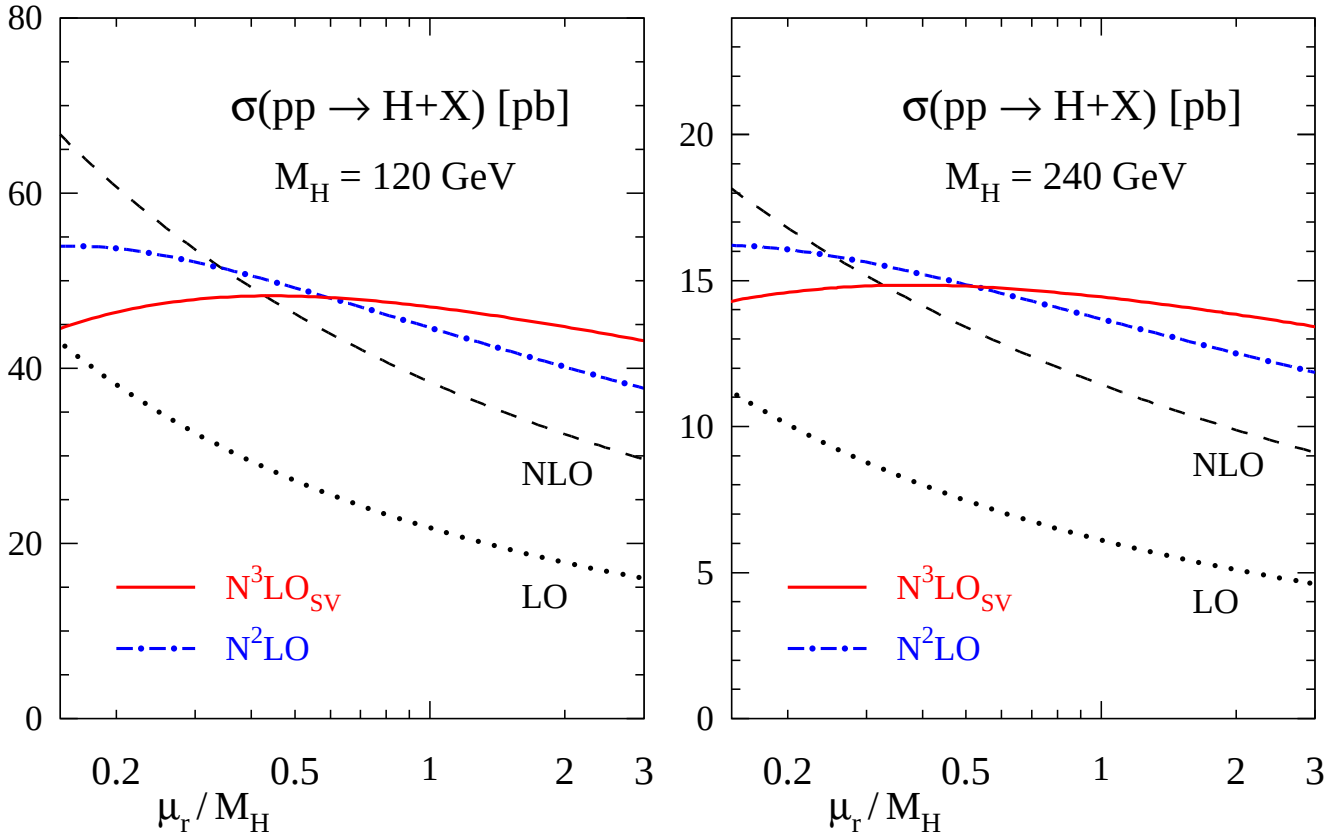


Higgs strahlung



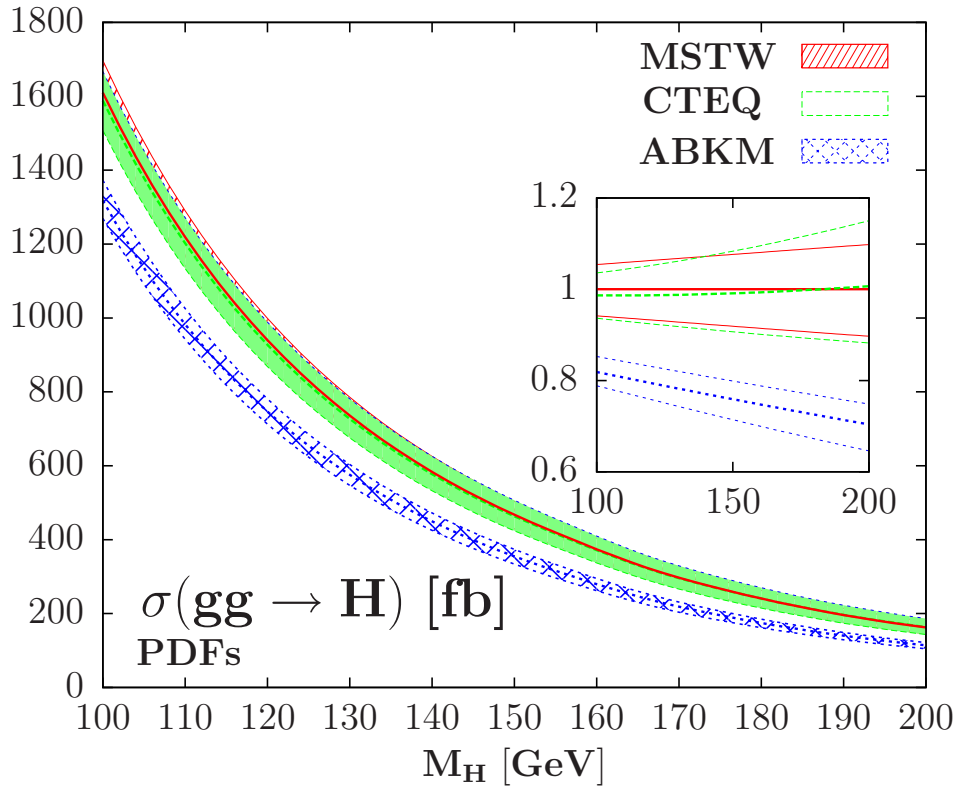
$t\bar{t}H$-channel

Higher-order corrections



- Apparent convergence of perturbative expansion
  - NNLO corrections still large
    Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03
  - improvement through complete soft N^3LO corrections S.M., Vogt '05
    or NNLL resummtion Catani, de Florian, Grazzini, Nason '03, Ahrens et al. '10
- Perturbative stability under renormalizaion scale variation

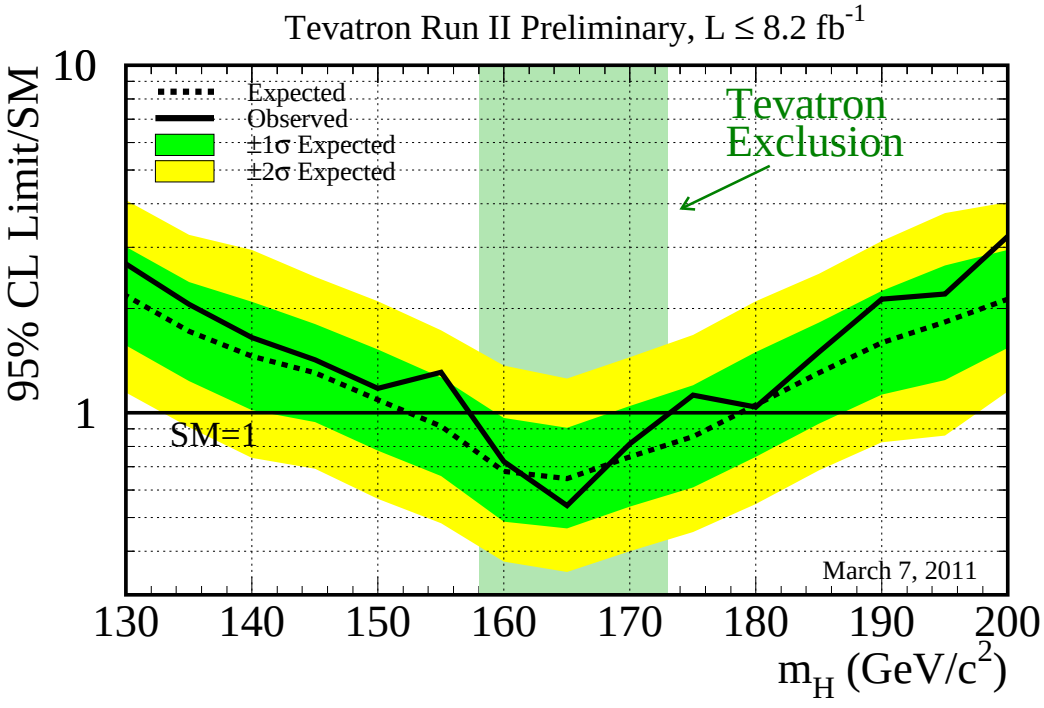
Dependence on parton distributions

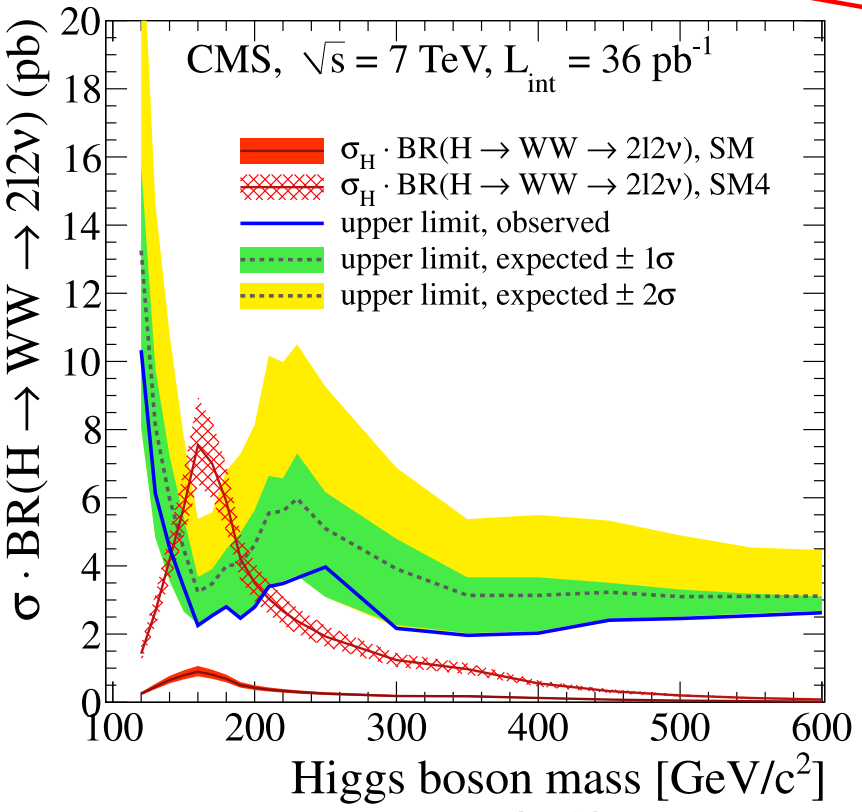


- NNLO cross section $\sigma(gg \to H + X)$ at Tevatron with PDF uncertainties bands at $90\% CL$
  - largest differences in predictions from PDFs and value of α_s
    Baglio, Djouadi '10; Baglio, Djouadi, Ferrag, Godbole '11
  - e.g. at $M_H = 165$ GeV:
    MSTW $+35\%$ higher than ABKM; $+4.0\sigma$ standard deviation

Constraining new physics using Tevatron's Higgs exclusion limit R. Boughezal

Higgs searches at Tevatron and LHC





Tevatron New Phenomena & Higgs Working Group `http://tevnphwg.fnal.gov/` (left)

CMS coll. `arXiv:1102.5429` (right)

- Higgs search driven predominantly by $gg \to H$
  - large perturbative corrections at higher orders enhance signal
  - assumed Higgs signal at Tevatron relies on particular set of PDFs and value of α_s ($\longrightarrow$ MSTW08)

Progress in perturbative QCD

Perturbative QCD at work

- Multiparticle production at NLO
- Precision observables at NNLO
- Infrared struture of QCD
- Resummation

Multiparticle production at NLO

- NLO QCD corrections are essential (important for rates)
  - large K-factors; beyond tree level new parton channels may dominate
  - scale uncertainty; e.g. $pp \to Z(\to \nu\bar{\nu}) + 4$ jets is $\mathcal{O}(\alpha_s^4)$ and $\Delta(\alpha_s^{\rm LO}) \simeq 10\%$ gives $\Delta(\sigma^{\rm LO}) \simeq 40\%$

Why is it difficult ?

- Outline of a generic NLO calculation

Real corrections	Virtual corrections
- subtractions (IR-divergent)	+ subtractions (IR-divergent)

Cancellation of singularities
Finite partonic cross sections
Phase space integration
Convolution with PDFs
Monte Carlo

Tools

- Automation of real emission (based on LO event generators)
  - Dipole subtraction
    SHERPA Gleisberg, Krauss '08; MadDipole Frederix, Greiner, Gehrmann '08;
    TeVJet Seymour, Tevlin '08; AutoDipole Hasegawa, S.M., Uwer '08;
    Helac/Phegas Czakon, Papadopoulos, Worek '09;
  - Residue subtraction
    MadFKS Frederix, Frixione, Maltoni, Stelzer '09
  - Existing NLO packages feature extensive libraries
    MCFM Campbell, Ellis; NLOJET++ Nagy, Trocsanyi

- Automation of virtual corrections
  GOLEM (semi-numerical form factor decomposition)
  Binoth, Guillet, Heinrich, Pilon, Reiter '08
  BlackHat (unitarity and multi-particle cuts)
  Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre '08
  CutTools (reduction at integrand level) Ossola, Papadopoulos, Pittau '07
  Rocket (gen. D-dim. unitarity) Giele, Zanderighi '08
  Samurai (gen. D-dim. unitarity) Mastrolia, Ossola, Reiter, Tramontano '10
  + more packages in development Lazopoulos '09; Giele, Kunszt, Winter '09;
  Melnikov, Schulze '10; Gluza, Kajda, Riemann, Yundin '10; . . .

Tools

- **New**
  combination of virtual (CutTools) and real (MadFKS) contributions into automated NLO package: MadLoop
  Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau ‘11

Amazing progress

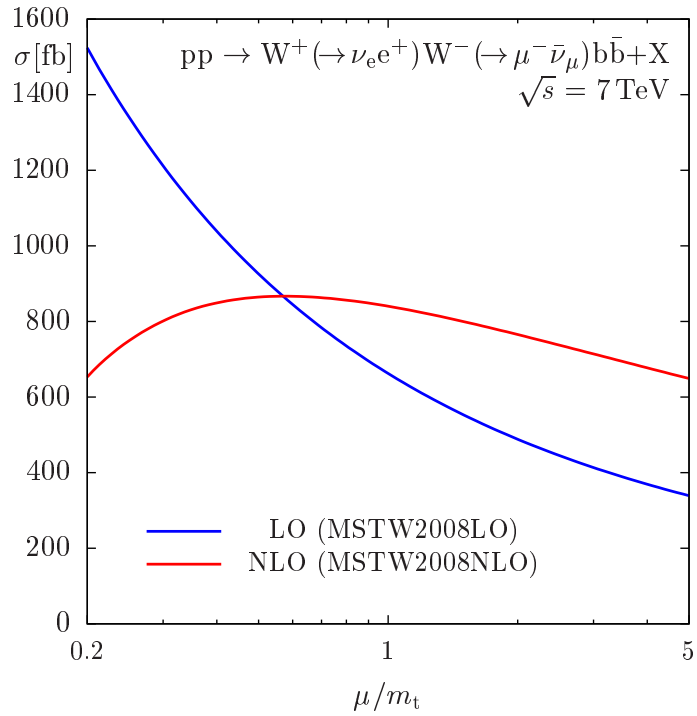
- (Almost) industrial effort to calculate all $2 \to 3$ processes of interest for LHC
- Current frontier $2 \to 4$ ($2 \to 5$) processes
  - $pp \to W^{\pm} + 3$ jets Ellis, Melnikov, Zanderighi '09; Berger, Bern, Dixon et al. '09
  - $pp \to W^{\pm} + 4$ jets Berger, Bern, Dixon et al. '10 $\leftarrow$ **7-pt-functions**
  - $pp \to Z + 3$ jets Berger, Bern, Dixon et al. '09
  - $pp \to t\bar{t}b\bar{b}$ Bredenstein, Denner, Dittmaier, Pozzorini '09; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09
  - $pp \to t\bar{t} + 2$ jets Bevilacqua, Czakon, Papadopoulos, Worek '10
  - $pp \to W^{\pm}W^{\pm} + 2$ jets Melia, Melnikov, Rontsch, Zanderighi '10
  - $pp \to W^{\pm}W^{\pm}b\bar{b}$ Denner, Dittmaier, Kallweit, Pozzorini '10; Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11
  - $pp \to b\bar{b}b\bar{b}$ Binoth, Greiner, Guffanti et al. '09
  - $e^+e^- \to 5$ jets Frederix, Frixione, Melnikov, Zanderighi '10

Recent results

- Cross sections for $pp \to W^+W^-b\bar{b}$ at LO and NLO

  Denner, Dittmaier, Kallweit, Pozzorini '10

  - scale dependence greatly reduced



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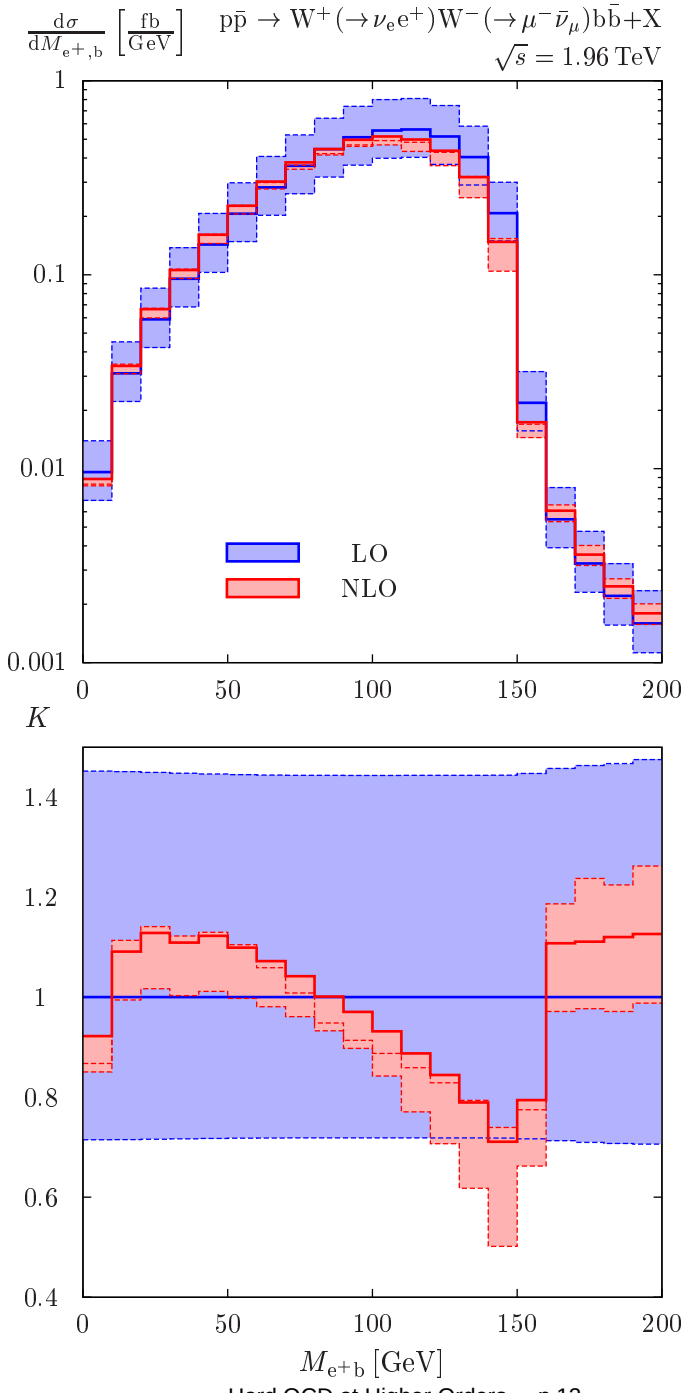
  - K-factors in distributions not uniform (e.g. invariant mass M_{e^+b} of positron–b-jet system



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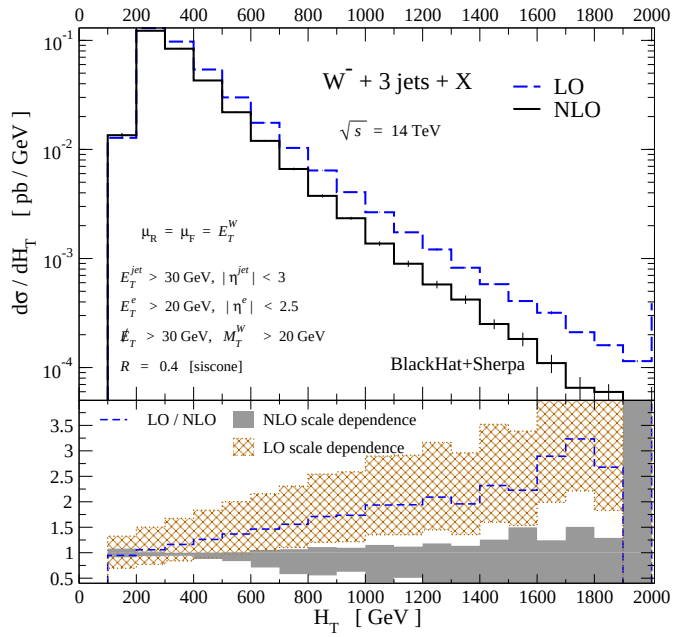
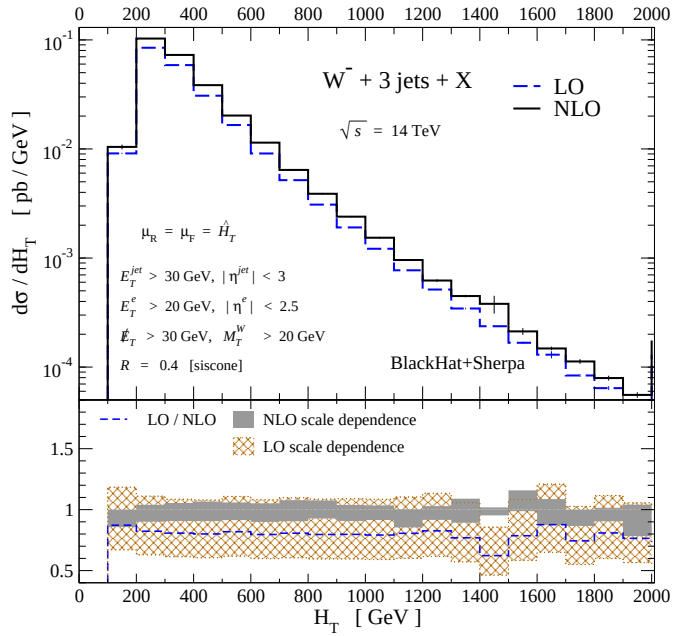
- Distributions for $pp \to W^\pm + 3$ jets

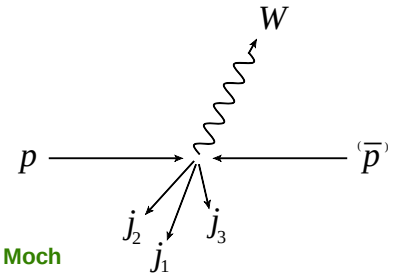
  Berger, Bern, Dixon et al. '09

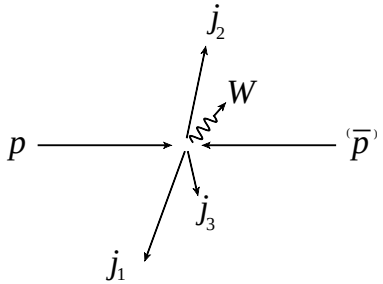
  - issue of scale choice $\mu = E_T^W$ or $\mu = H_T$
  - good convergence with

$$H_T = \sum_{\text{partons}} E_T^{\text{partons}} + E_T^e + E_T^\nu$$









Precision observables at NNLO

- Color-neutral final states
  - productions of gauge bosons $W^{\pm}/Z$ or Higgs
  - fully differential kinematics Anastasiou, Melnikov, Petriello '05; Grazzini '08; Catani, Cieri, Ferrera, de Florian, Grazzini '09 Gavin, Li, Petriello, Quackenbush '10
- Colored (heavy and light)final states
  - NNLO is current frontier of technology
- Di-jets at NNLO
  - impact of jet data on PDFs
  - subtraction formalism Nigel Glover, Pires '10; Boughezal, Gehrmann de Ridder, Ritzmann '10; Anastasiou, F. Herzog, A. Lazopoulos '10; Bolzoni, Somogyi, Trocsanyi '10
- Heavy-quark pair-production at NNLO
  - hadronic $t\bar{t}$-production ($\rightarrow$ much activity)
  - DIS (complicated by additional scale Q^2);
    rely on approximations (threshold, OPE for $Q^2 \gg m^2$)

Computing hadronic cross sections through NNLO R. Boughezal

Three-loop corrections for F_2^{cc} F. Wissbrock

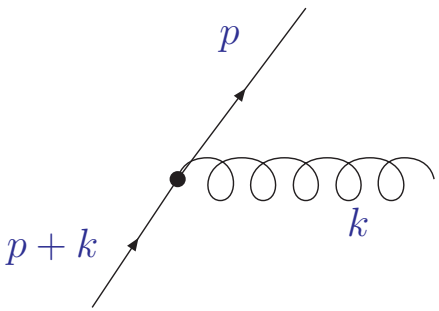
Hadronic top-pair production: theory status

- Two-loop virtual corrections for $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$
  - small-mass limit $m^2 \ll s, t, u$ Czakon, Mitov, S.M. '07
  - complete IR singularities Ferroglia, Neubert, Pecjak, Yang '09
  - analytic results for n_f-terms and leading color Bonciani, Ferroglia, Gehrmann, Maitre, Studerus '08; Bonciani, Ferroglia, Gehrmann, Studerus '09; Bonciani, Ferroglia, Gehrmann, Manteuffel, Studerus '10;
  - numerical result for $q\bar{q} \to t\bar{t}$ Czakon '08
  - one-loop squared terms (NLO $\times$ NLO) Anastasiou, Mert Aybat '08; Kniehl, Merebashvili, Körner, Rogal '08
- Complete one-loop corrections to $t\bar{t}$ in association with jets
  - $t\bar{t} + 1$ jet at NLO Dittmaier, Uwer, Weinzierl '07-'08; Melnikov, Schulze '10
- Real radiation $q\bar{q}/gg \to t\bar{t} + 2$ partons
  - development of subtraction formalism (including hadronic initial states and massive final states) Abelof, Gehrmann-De Ridder, Ritzmann '10; Czakon '11

Phenomenology beyond NLO

Renormalization group evolution of collinear and infrared divergences N. Kidonakis

- Use universal features of soft/collinear regions of phase space
  - double logarithms from singular regions in Feynman diagrams
  - propagator vanishes for: $E_g = 0$, soft θ_{qg} = 0 collinear



$$\frac{1}{(p+k)^2} = \frac{1}{2p\cdot k} = \frac{1}{2E_q E_g(1-\cos\theta_{qg})}$$

$$\alpha_s \int d^4k \frac{1}{(p+k)^2} \longrightarrow \alpha_s \int dE_g \, d\sin\theta_{qg} \, \frac{1}{2E_q E_g(1-\cos\theta_{qg})}$$

$$\longrightarrow \alpha_s \, \ln^2(\ldots)$$

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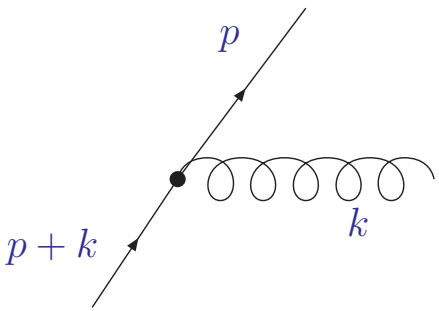

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$$\longrightarrow \alpha_s \ln^2(\dots)$$

Threshold resummation

- All order resummation of large threshold logarithms

  $\alpha_s^n \ln^{2n}(\beta) \longleftrightarrow \alpha_s^n \ln^{2n}(N)$ in heavy-quark velocity $\beta = \sqrt{1-4m^2/s}$
  - resummation in Mellin space (renormalization group equation)
  - long history Kidonakis, Sterman '97; Bonciani, Catani, Mangano, Nason '98; Kidonakis, Laenen, S.M., Vogt '01; ...
- Upshot (see also SCET developments):
  - $\sigma_{ij}^{\text{resummed}} \simeq \exp\left(\alpha_s \ln^2 N\right) + \mathcal{O}(N^{-1}\ln^n N)$

Top-quark phenomenology

Top-quark cross sections and differential distributions N. Kidonakis

- Threshold resummation
  - updates of cross section predictions based on resummation
    S.M., Uwer '08; Cacciari, Frixione, Mangano, Nason, Ridolfi '08; Kidonakis, Vogt '08;
    Beneke, Czakon, Falgari, Mitov, Schwinn '09;
    Ahrens, Ferroglia, Neubert, Pecjak, Yang '10; '11
  - coulomb corrections
    Hagiwara, Sumino, Yokoya '08; Kiyo, Kühn, S.M., Steinhauser, Uwer '08

Global analysis of J/psi production at NLO in NRQCD B. Kniehl

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Resummation

- Matching of NLO calcualtion to parton showers
  $\text{higher orders} \cap \text{parton shower} \neq 0$
- MCNLO Frixione, Webber '06 POWHEG Frixione, Nason, Oleari '07
- General framework: POWHEG box Alioli, Nason, Oleari, Re '10
  - $V + 1$ jet production in POWHEG Alioli, Nason, Oleari, Re '10
  - jet-pair production in POWHEG Alioli, Hamilton, Nason, Oleari, Re '10
  - $t\bar{t} + 1$ jet production with NLO parton showering
    Kardos, Papadopoulos, Trocsanyi '11
- More to come . . .

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Resummation

- Other kinematical regimes
  - small x
  - small $\ln p_T$

Time-like small x resummation for Fragmentation Functions P. Bolzoni

QCD resummation for new variables to study dilepton transverse momentum S. Marzani

The high-energy resummation of rapidity functions S. Marzani

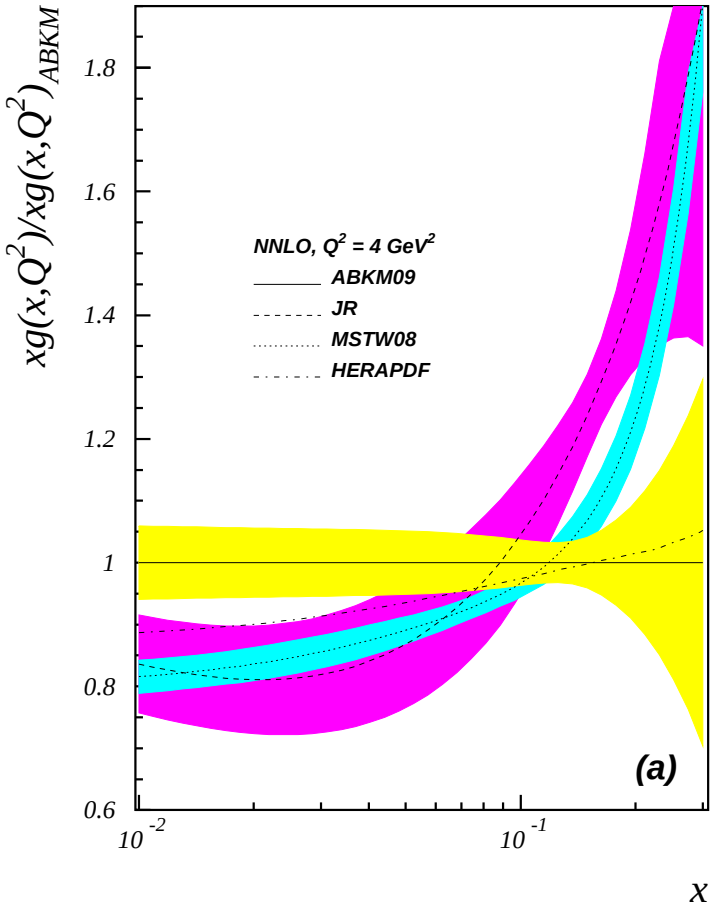
Jet masses and jet shape calculations for the LHC M. Dasgupta

Non-perturbative parameters

Input for collider phenomenology

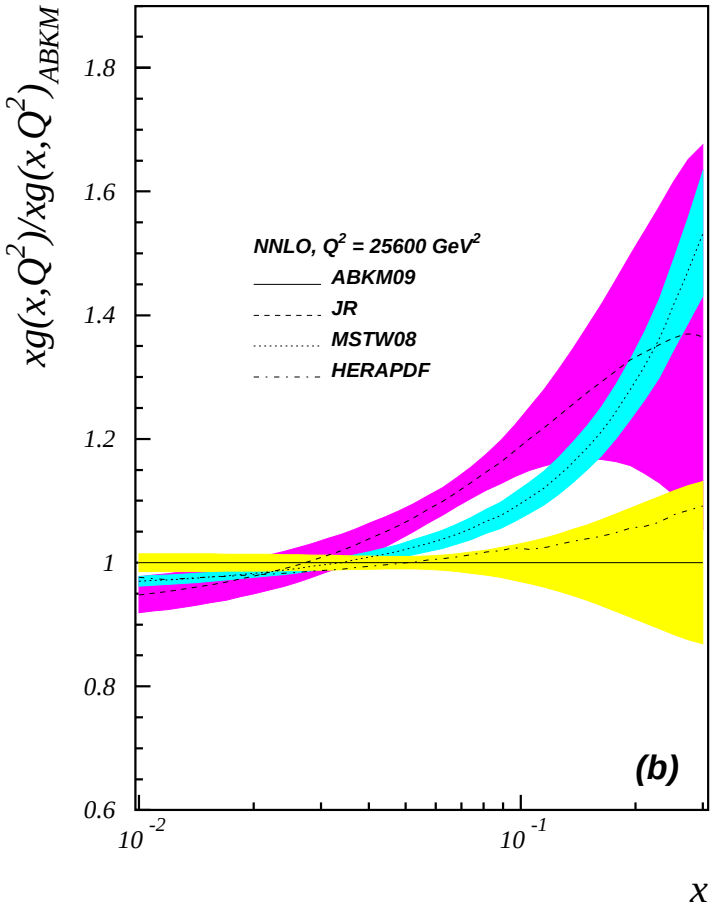
- Parton distribution functions
- Strong coupling constant $\alpha_s(M_Z)$
- Masses of heavy quarks m_c, m_b, m_t

Parton distribution functions



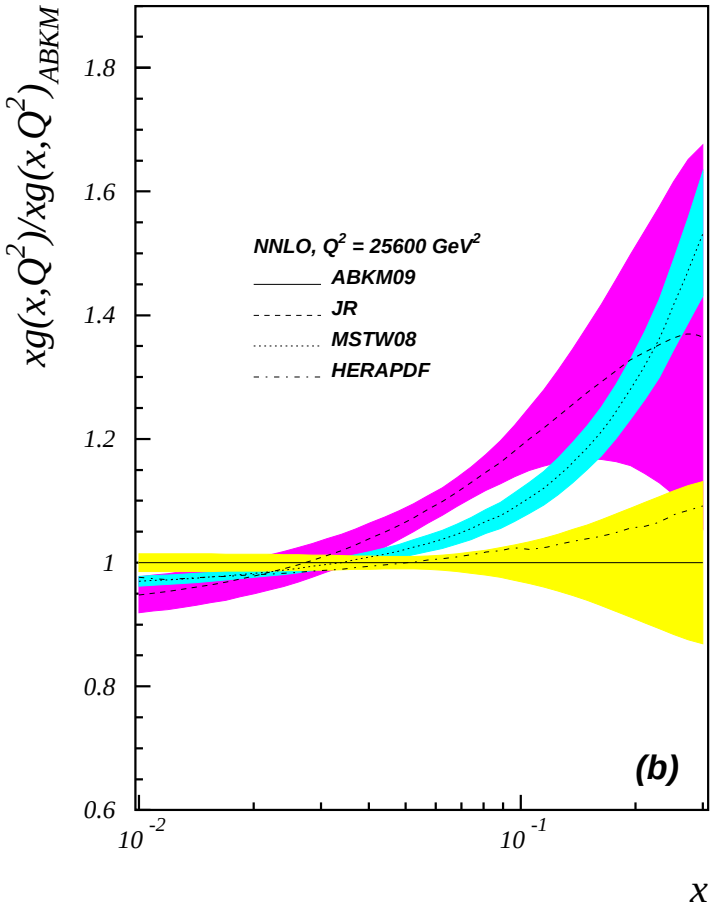
- Gluon distribution at low scales $Q = 2$ GeV
  - comparison from NNLO fits (uncertainties bands at 1σ)
    Alekhin, Blümlein, Jimenez-Delgado, S.M., E. Reya '10

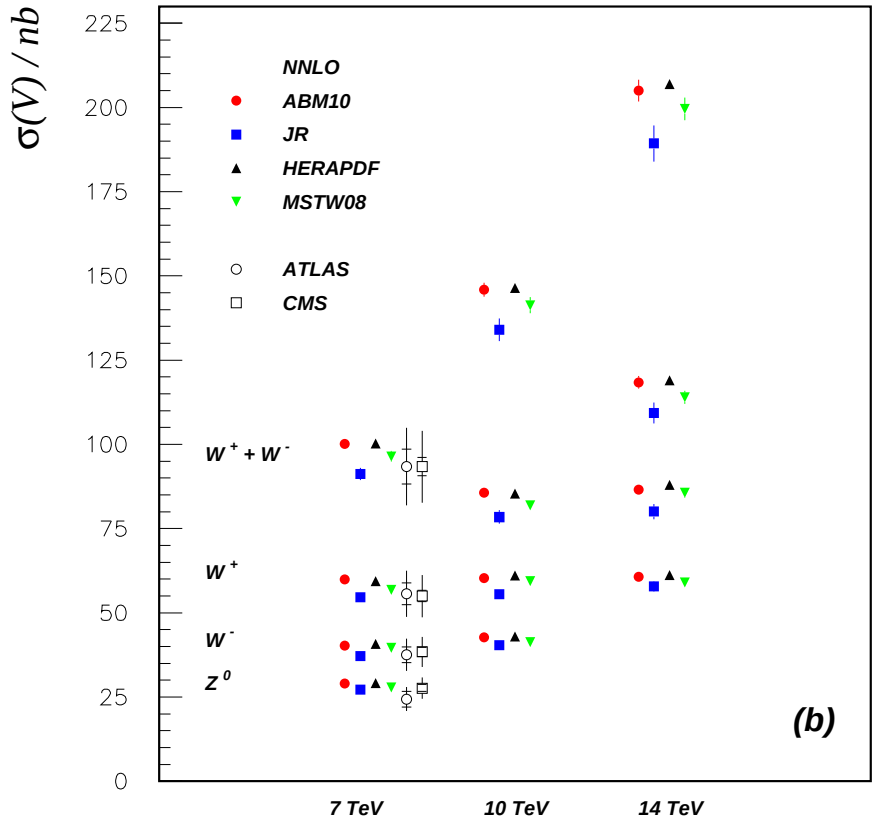
Parton distribution functions



- Gluon distribution at high scales $Q = 160$ GeV
  - comparison from NNLO fits (uncertainties bands at 1σ)
    Alekhin, Blümlein, Jimenez-Delgado, S.M., E. Reya '10

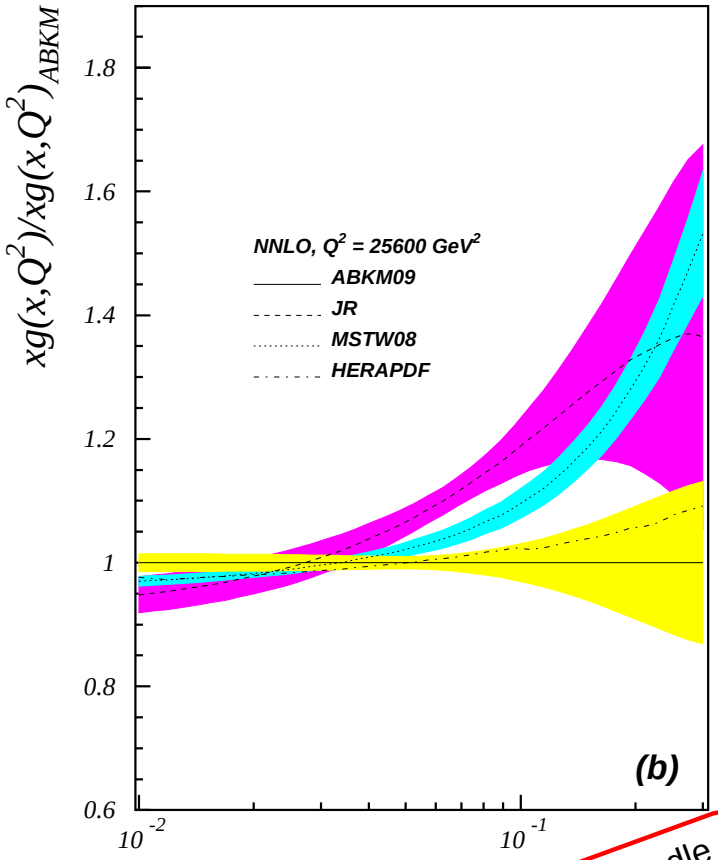
Parton distribution functions

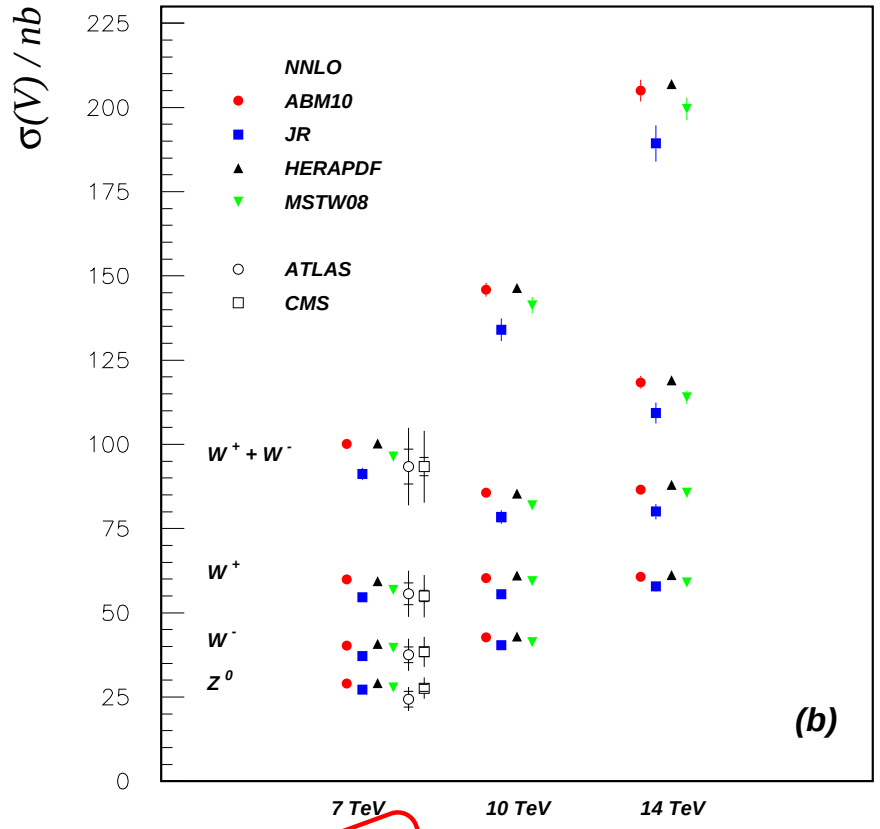




- Gluon distribution at high scales $Q = 160$ GeV
  - comparison from NNLO fits (uncertainties bands at 1σ)
    Alekhin, Blümlein, Jimenez-Delgado, S.M., E. Reya '10
- Implications for Higgs predictions at LHC

Parton distribution functions





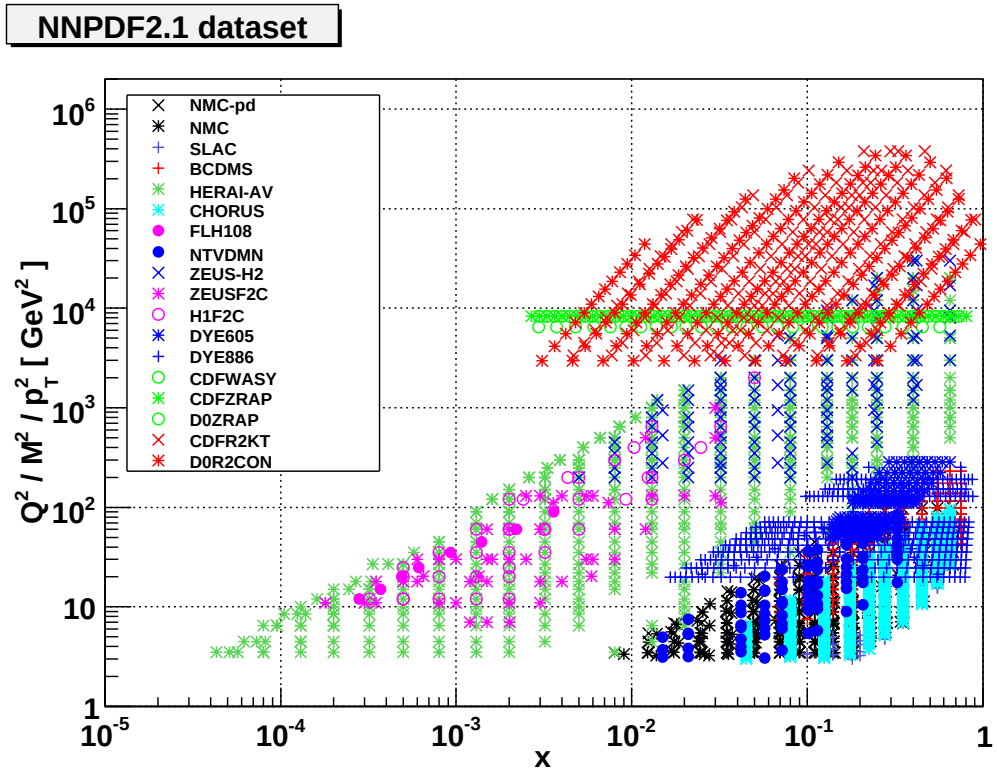
- Gluon di… on scal… V
  … from … certainties … at 1σ)
  …in, Blümlein, … gado, S.M., E…
- Implications for Higgs predictions at LHC

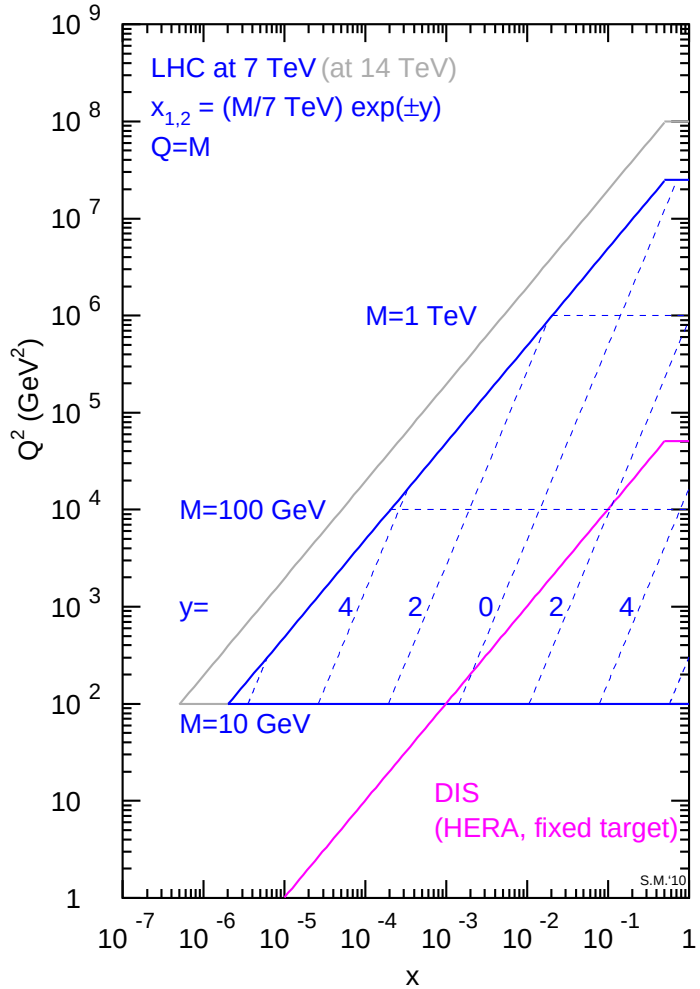
Updated NNLO PDFs and the standard candle processes benchmarking S. Alehkin

CTEQ-TEA: towards an NNLO global PDF analysis P. Nadolsky

Progress in the NNPDF analysis J.Rojo

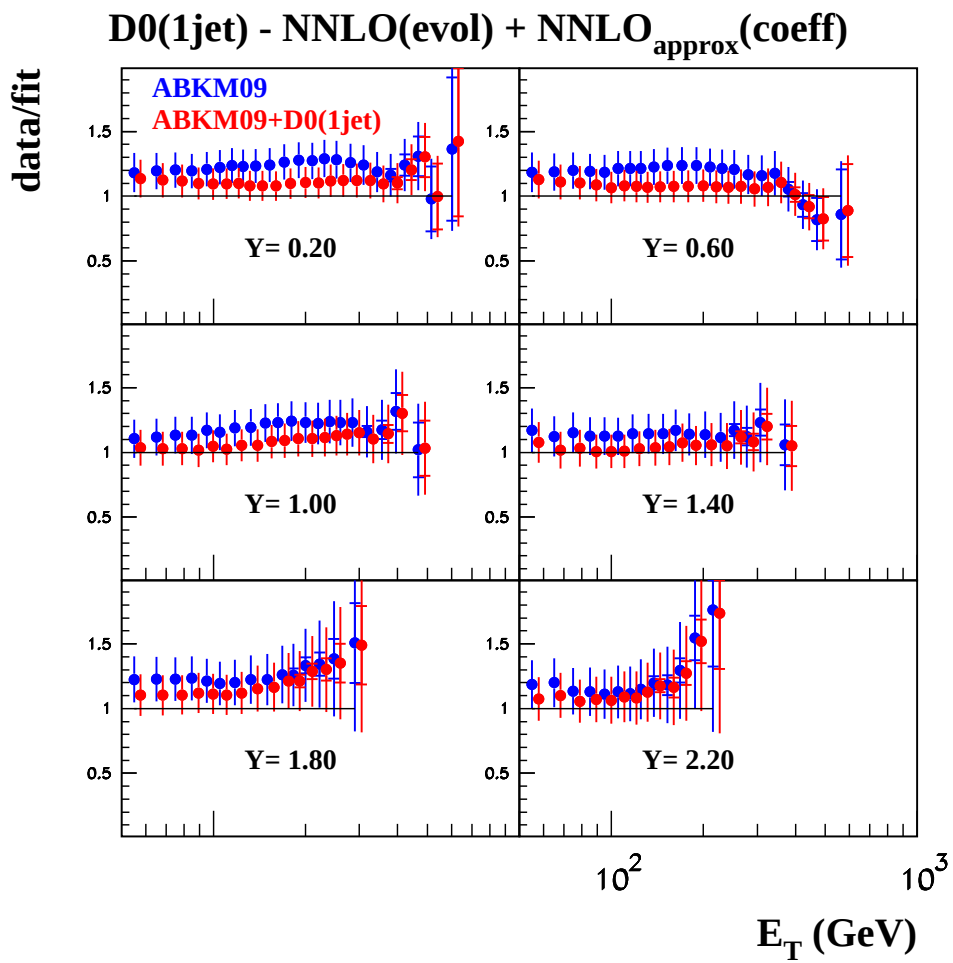
Kinematics

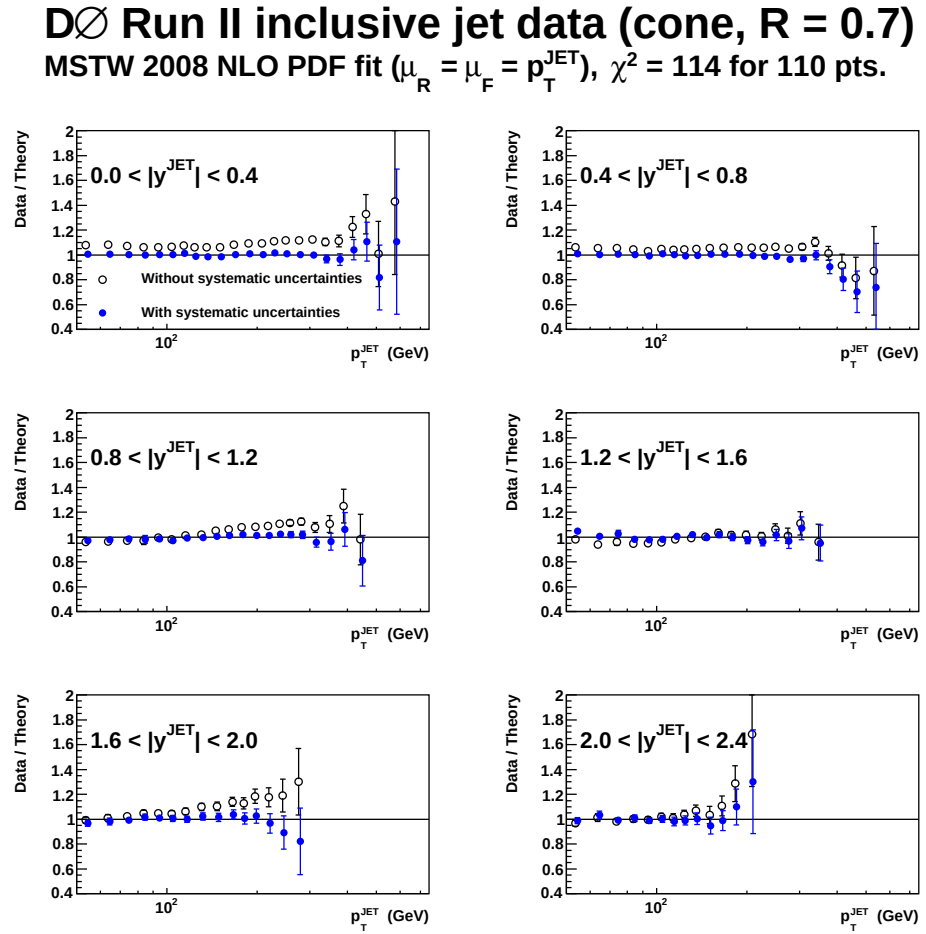




- Kinematics of data used in PDF fits; e.g. NNPDF (left)
- QCD volution of PDFs in Q^2 over three orders from DIS and fixed-target data to LHC energies
  - evolution to NNLO accuracy required

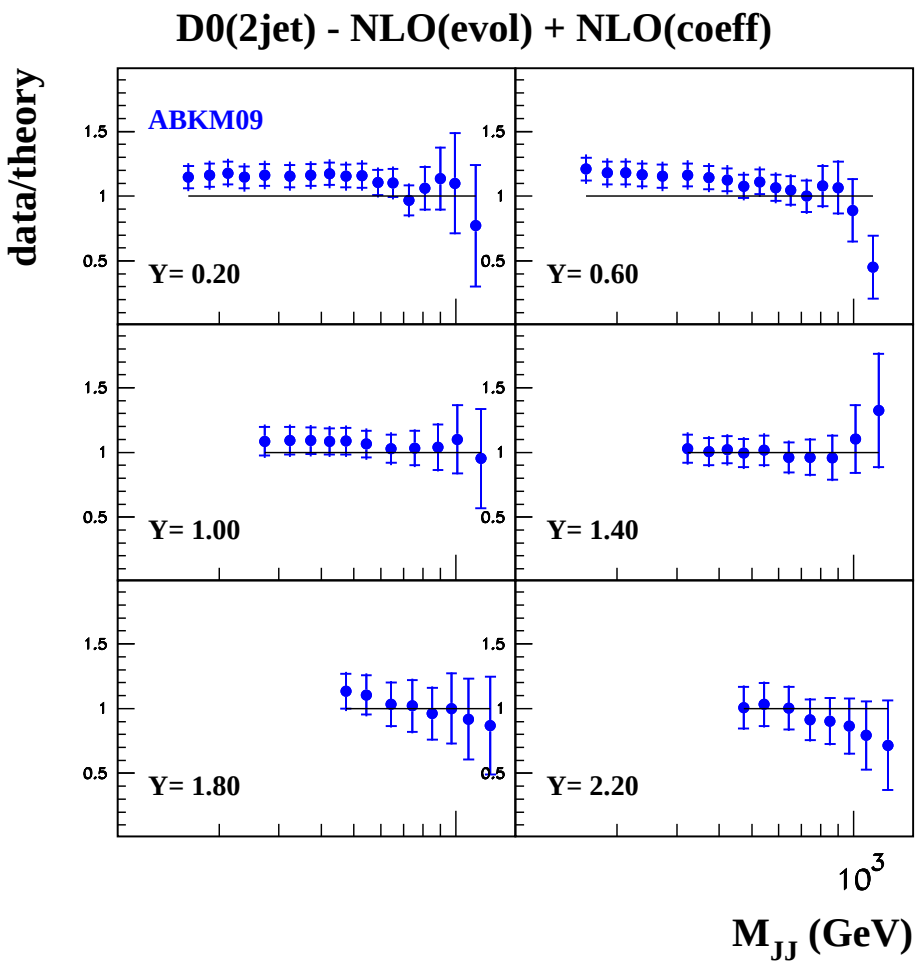
Tevatron jet data (D0) – 1-jet inclusive

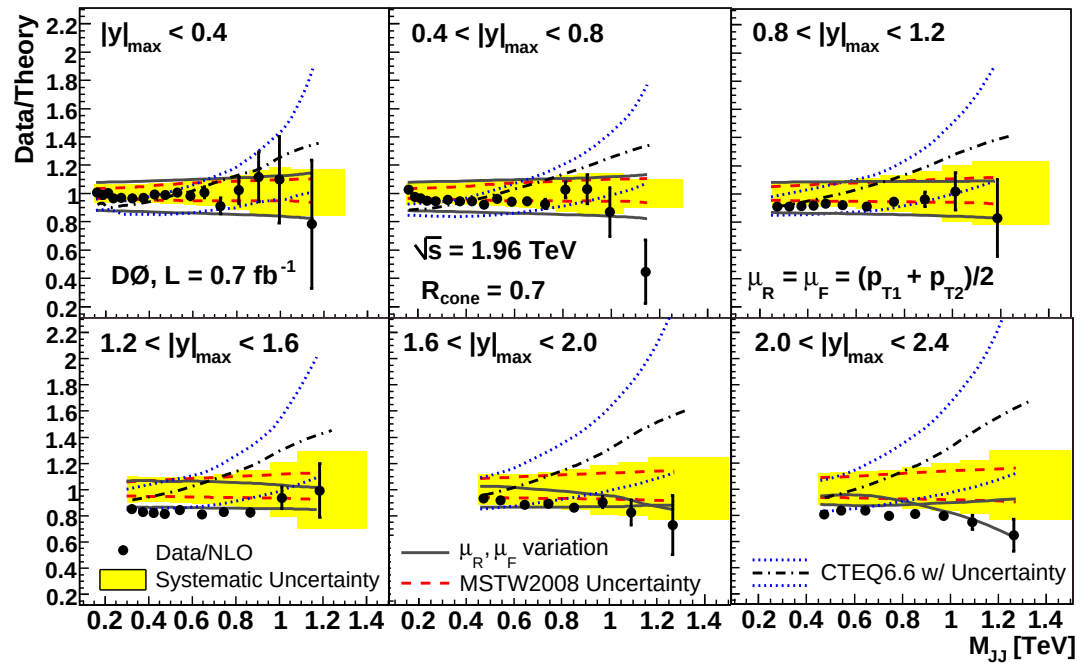




- PDF fits to Tevatron jet data (with NNLO$_{\rm approx}$ corr. Kidonakis, Owens '01) Alekhin, Blümlein, S.M. '11 (left); MSTW `arXiv:0901.0002` (right)
- 3-flavor PDFs for DIS, 5-flavor PDFs for jets, scale $\mu_r = \mu_f = E_T$

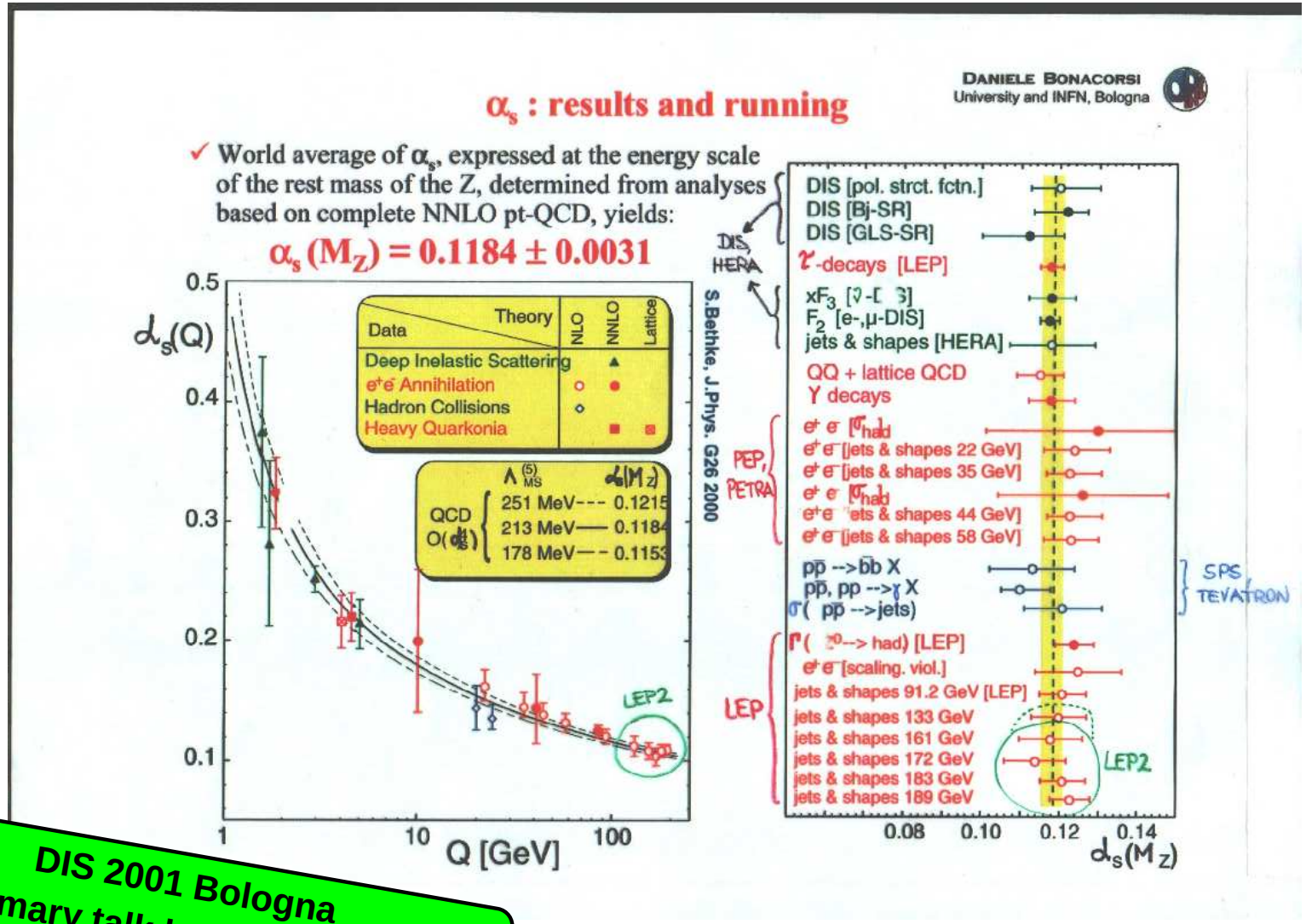
Tevatron jet data (D0) – di-jet invariant mass





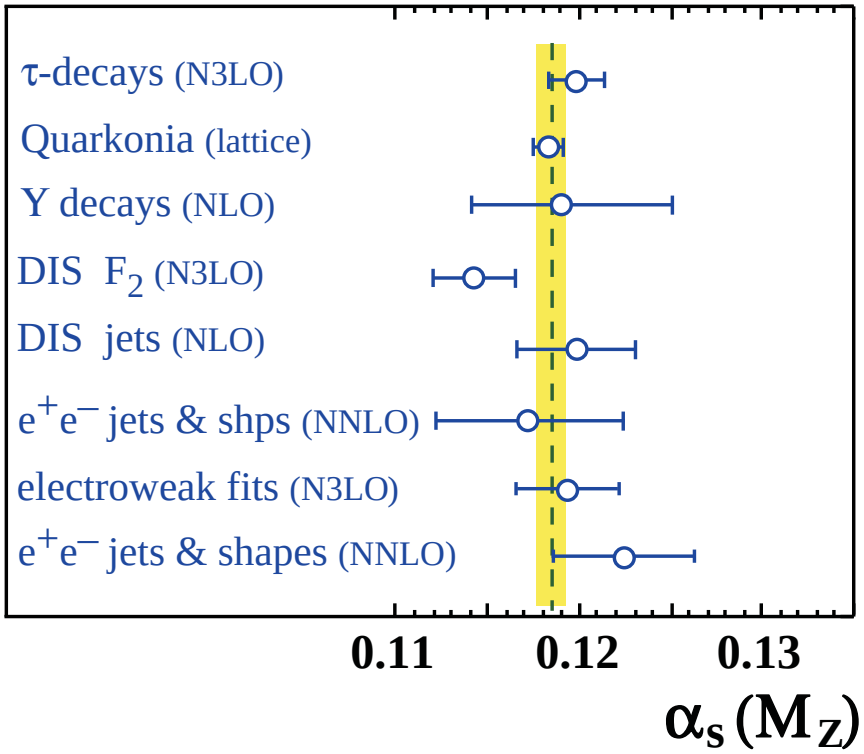
- Predictions for Tevatron di-jet data (no NNLO corrections known)
  Alekhin, Blümlein, S.M. '11 (left); D0 coll. `arXiv:1002.4594` (right)
- Uncertainty due to missing NNLO corrections; scale $\mu_r = \mu_f = M_{JJ}$

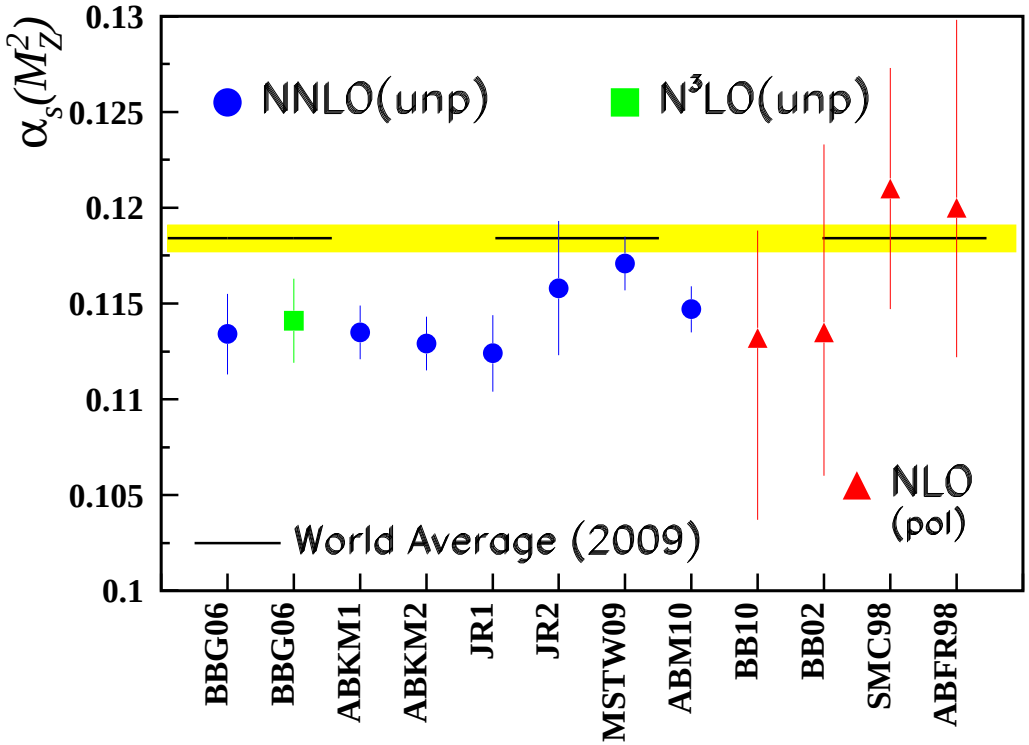
Strong coupling constant



DIS 2001 Bologna
summary talk by M.Fontannaz

Strong coupling constant

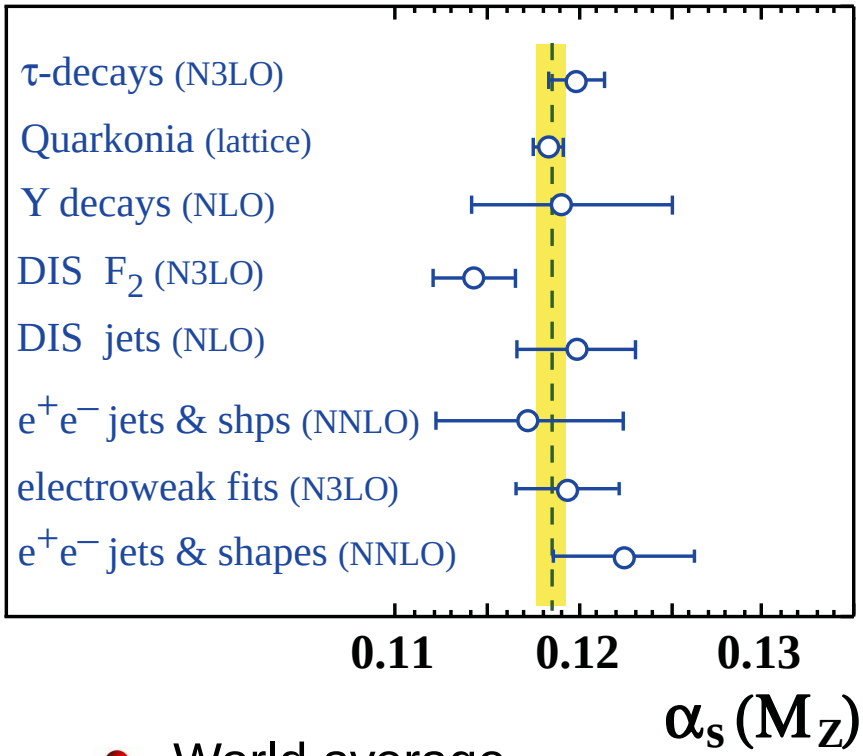


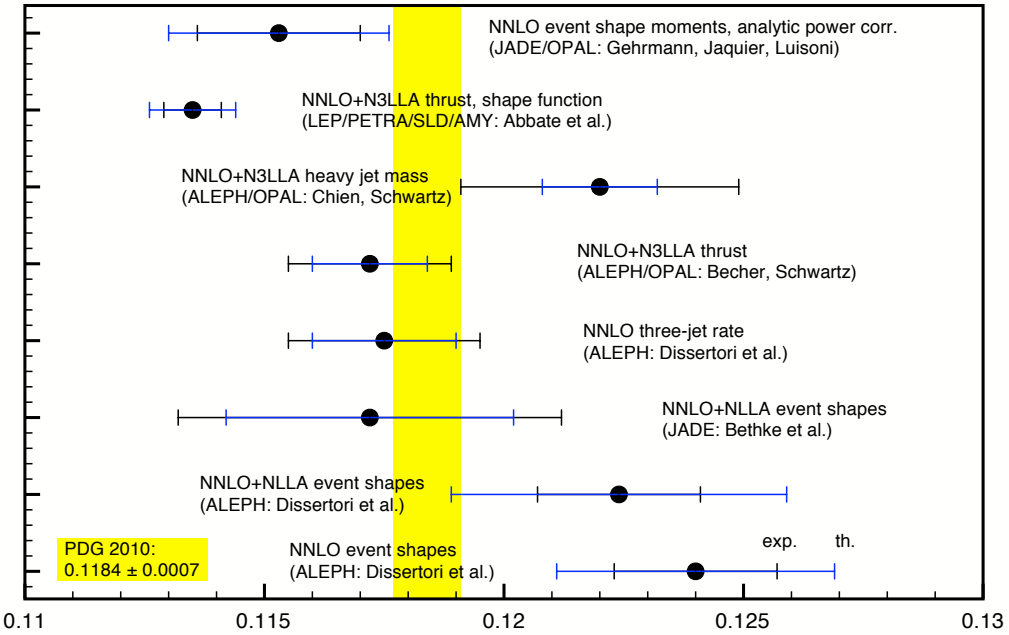


- World average
  $\alpha_s(M_Z) = 0.1184 \pm 0.0007$
  Bethke `arXiv:0908.1135`

- Compilation of $\alpha_s(M_Z)$ values from DIS
  Blümlein, Böttcher `arXiv:1101.0052`
- $\alpha_s(M_Z) = 0.1135 \pm 0.0014$ at NNLO
  ABKM '09

Strong coupling constant





- World average
  $\alpha_s(M_Z) = 0.1184 \pm 0.0007$
  Bethke `arXiv:0908.1135`
- also other determinations:
  $\alpha_s(M_Z) = 0.1161 \pm 0.0045$ (NLO)
  from Tevatron jet data D0 Coll. '10

- Compilation of $\alpha_s(M_Z)$ values from
  $e^+e^- \to 3$ jets Gehrmann '11
- $\alpha_s(M_Z) = 0.1135 \pm 0.0002(\mathrm{exp}) \pm 0.0005(\mathrm{had}) \pm 0.0009(\mathrm{pert})$
  at NNLO + NNLL res.
  Abbate, Fickinger,Hoang, Mateu, Steward '10

Heavy-quark masses

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_{\text{flavors}} \bar{q} \left(\mathrm{i} \not{D} - m_q \right) q \,, \qquad D_\mu = \partial_\mu + \mathrm{i} g_s A_\mu$$

- QCD Lagrangian with formal parameters (no observables)
  - strong coupling $\alpha_s = g_s^2/(4\pi)$
    $\alpha_s \rightarrow$ asymptotic freedom, running coupling ($\overline{MS}$ scheme)
  - quark masses m_q
    $m_q \rightarrow$ pole mass or running mass ($\overline{MS}$ scheme)

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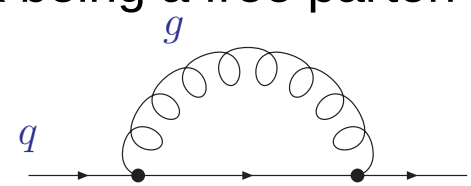
Schemes (in a nut shell)

- Pole mass scheme
  - based on (unphysical) concept of heavy-quark being a free parton

$$\not{p} - m_q - \Sigma(p, m_q)\Big|_{p^2 = m_q^2}$$



  - pole mass measurements are strongly order-dependent
- $\overline{MS}$ mass definition $m(\mu_r)$ realizes running mass
  - short distance mass probes at scale of hard scattering
  - scale dependence greatly reduced

Quark masses in PDF fits

- Choice of value for heavy-quark masses part of uncertainty
- PDF fits assume pole mass scheme for heavy-quarks
  - numerical values systematically lower than those from PDG (2-loop conversion to pole mass)

[GeV]	PDG	ABKM	GJR	HERAPDF	MSTW	CT10	NNPDF2.1
m_c	$1.66\ ^{+0.09}_{-0.15}$	$1.5\ ^{+0.25}_{-0.25}$	1.3	1.4	1.3	1.3	1.41
m_b	$4.79\ ^{+0.19}_{-0.08}$	$4.5\ ^{+0.5}_{-0.5}$	4.2	4.75	4.75	4.75	4.75

Quark masses in PDF fits

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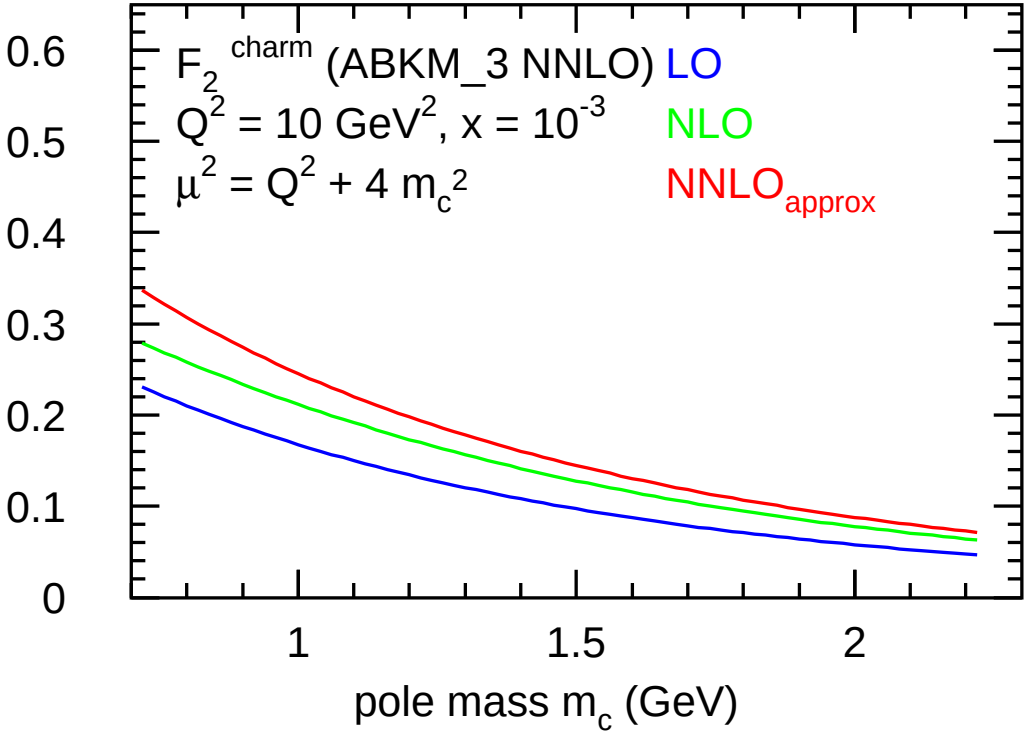
Charm structure function



- Running quark masses in DIS
  - improved convergence
  - reduced scale dependence
- Comparison with pole mass scheme

Quark masses in PDF fits

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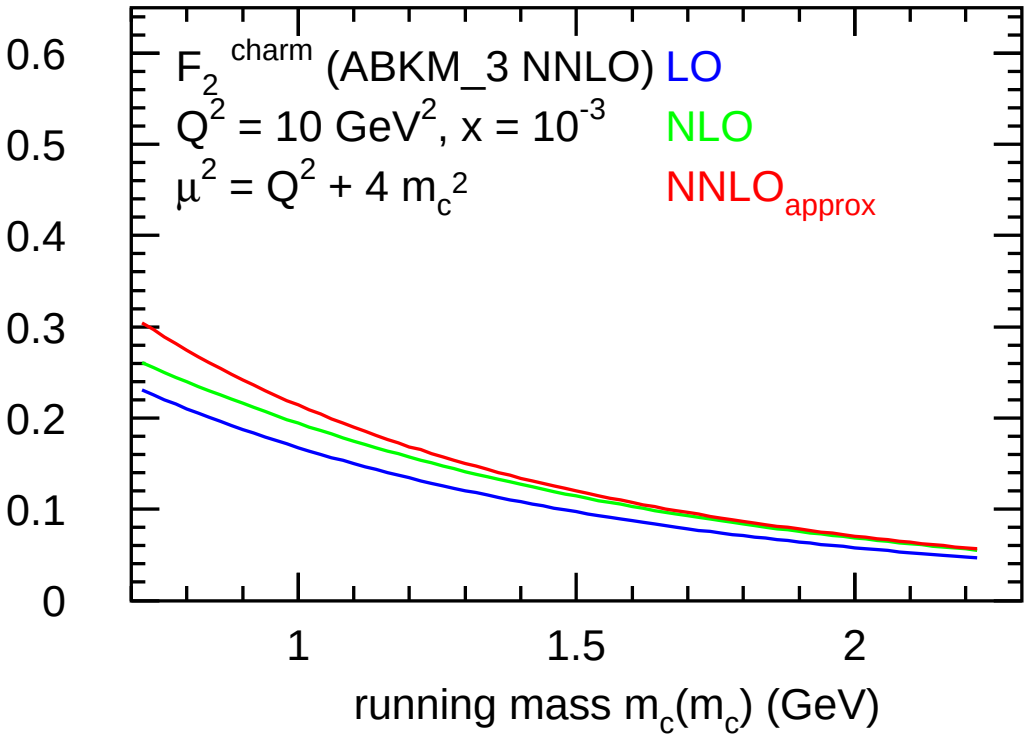
Charm structure function



- Running mass
- Direct determination of $m_c(m_c)$
  Alekhin, S.M. '10

  NLO
  1.26 $\pm$ 0.09 (exp) $\pm$ 0.11 (th) GeV

  $NNLO_{\rm approx}$
  1.01 $\pm$ 0.09 (exp) $\pm$ 0.03 (th) GeV
- PDG quotes running masses:
  $m_c(m_c) = 1.27^{+0.07}_{-0.11}$ GeV
- Implicit $\alpha_s(M_Z)$ dependence in $m_c(m_c)$ determination from QCD sum rules
  Dehnadi, Hoang, Mateu, Zebarjad '11

Related parallel contributions

Running mass definition for DIS S. Alehkin

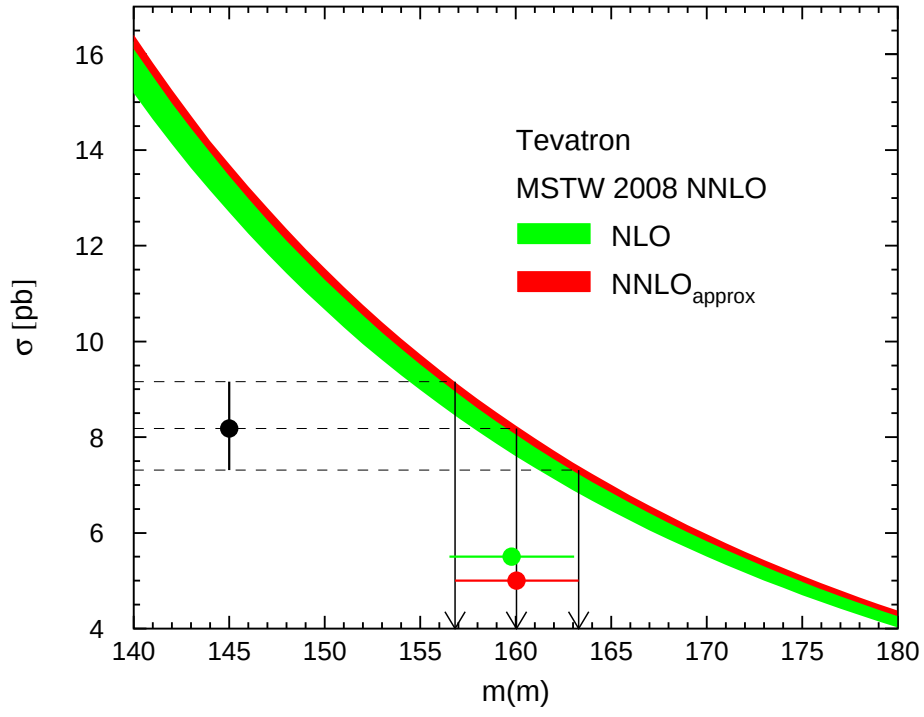
NNLO contributions to heavy-quark scattering in SACOT scheme M. Guzzi

D- and B-hadron production at NLO in the GM-VFN scheme vs. LHC data B. Kniehl

MSTW on HQ R. Thorne

Running top-quark mass

- Direct determination from total cross section Langenfeld, S.M., Uwer '09
  - $\overline{MS}$ mass $\overline{m} = 160.0^{+3.3}_{-3.2}\mathrm{GeV}$
  - conversion to pole mass $m_t = 168.9^{+3.5}_{-3.4}\mathrm{GeV}$
  - world avergage $m_t = 173.3^{+1.1}_{-1.1}\mathrm{GeV}$



Running top-quark mass

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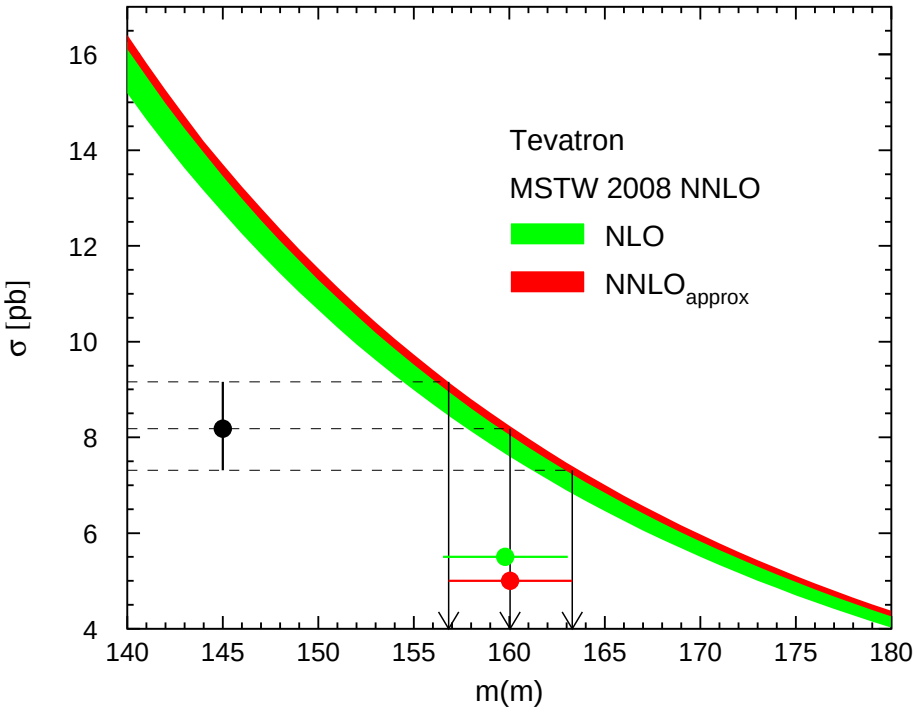
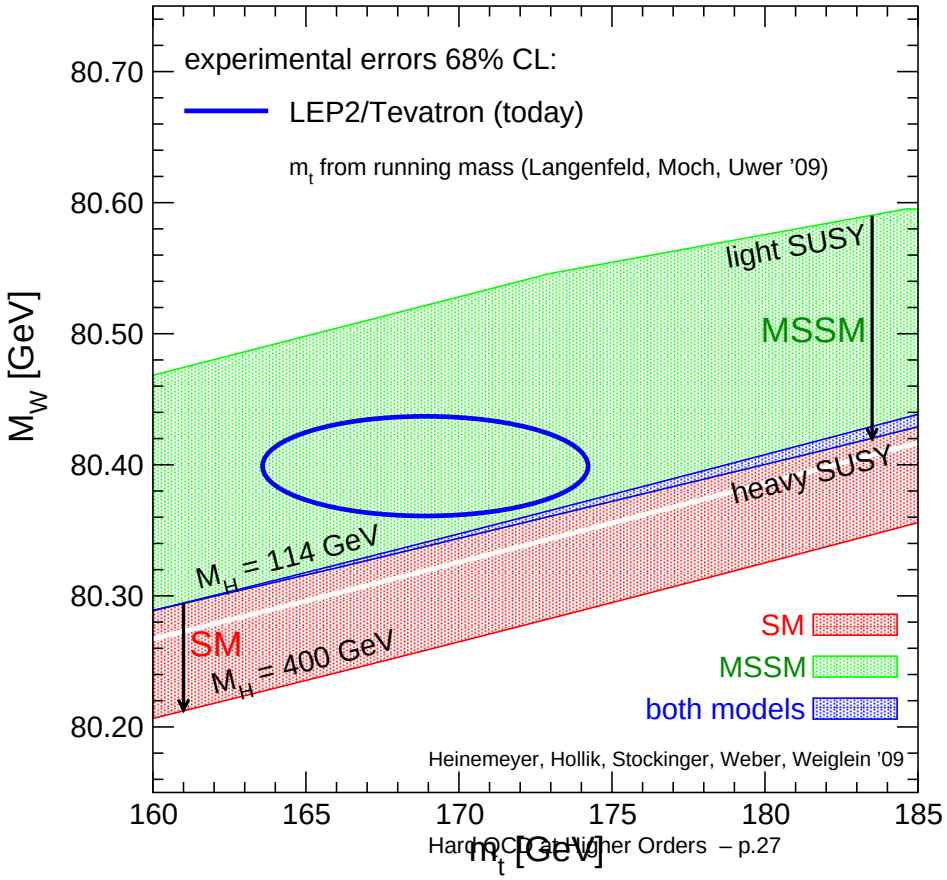
- Implications for indirect Higgs searches
  - constraints on M_H from electroweak precision data





Conclusions

- QCD is mature theory
- Predictions with unprecedented precision

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- Predictions with unprecedented precision

Perturbative calculations

- NLO corrections for large number of multileg processes
- Resummation: merging NLO and parton showers;
  threshold or $\ln p_T$ resummation to NNLL; SCET
- NNLO current frontier in collider phenomenology:
  di-jets, DIS 1-jet inclusive, $t\bar{t}$ hadro-production, etc.

Non-perturbative input

- Parton distributions in the focus: NNLO to become industry standard
- Values of $\alpha_s(M_Z)$: some tension with world average
- heavy quark masses: study of scheme dependence required by precision of experimental data

Acknowledgments

Many thanks

- for discussions on the content of this presentation to

S. Alekhin
J. Blümlein
T. Gehrmann

Apologies

- for incomplete coverage of topics
- for missing valuable references