QCD and the Strong Force
…greatest hits, and highlights

Joey Huston

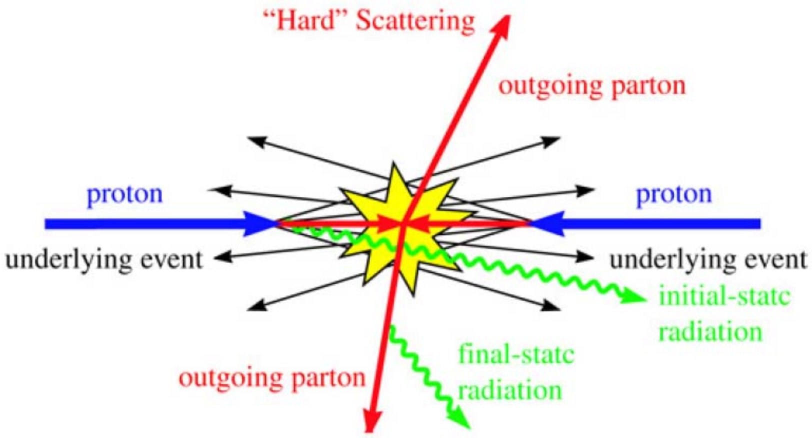
Michigan State University

for the QCD conveners

John Campbell, Ken Hatakeyama, Frank Petriello

QCD

- QCD plays a major role in basically every physics process under discussion in the Snowmass Energy Frontier
- When we talk about precision physics, or discovery physics, we need to understand the role of QCD corrections



- Thus, we have an overlap, and hopefully a synergy, with every physics group in the Energy Frontier
- Most of the work has been done with hadron-hadron colliders, but we will also report on lepton-lepton and lepton-hadron colliders
- Here are some highlights from the QCD report

Higgs Couplings

arXiv:1307:7135, CMS NOTE-13-002

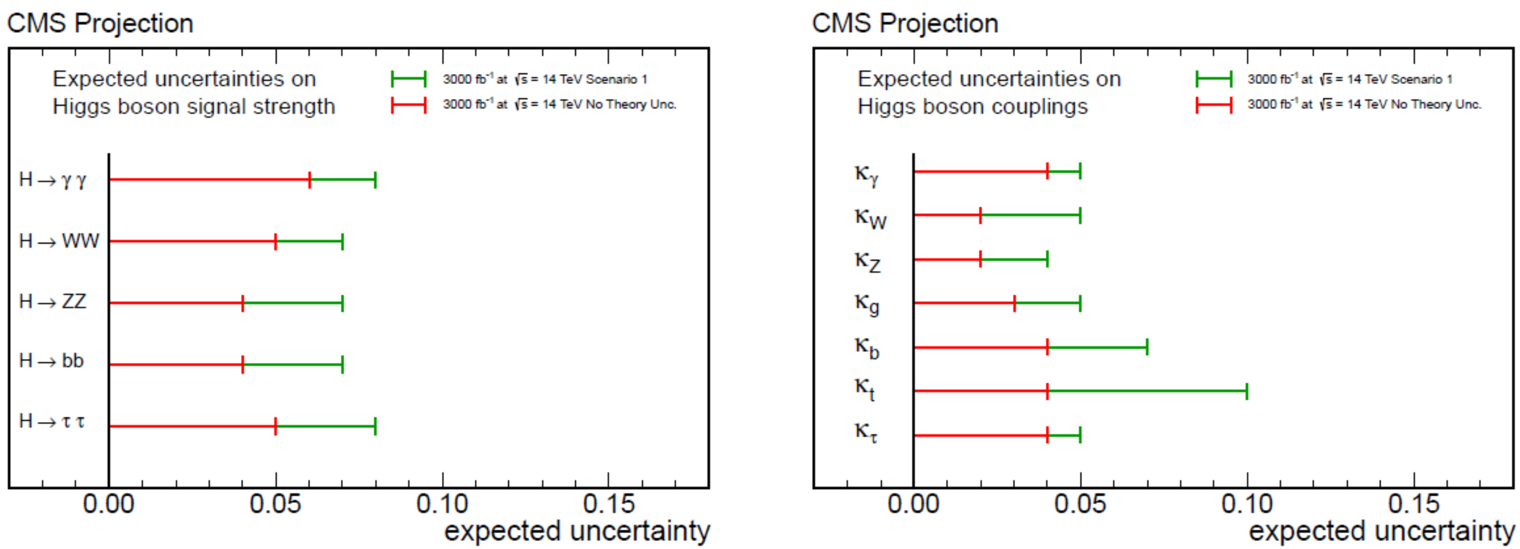


Figure 13: Estimated precision on the signal strengths (left) and coupling modifiers (right). The projections assuming $\sqrt{s} = 14$ TeV, an integrated dataset of 3000 fb^{-1} and Scenario 1 are compared with a projection neglecting theoretical uncertainties.

- QCD scale and PDF uncertainties are key factors for the ultimate Higgs couple determinations at HL-LHC

More details in the Markus Klute's talk tomorrow.

QCD

PDF's

matrix elements

$$\sigma = \sum_{a,b} \int_0^1 \mathrm{d}x_1\, f_{a/A}(x_1,\mu_F^2) \int_0^1 \mathrm{d}x_2\, f_{b/B}(x_2,\mu_F^2) \Bigg\{ \int \mathrm{d}\hat{\sigma}_{ab}^{LO}\,(\alpha_s)\;\Theta_{\mathrm{obs}}^{(m)}$$

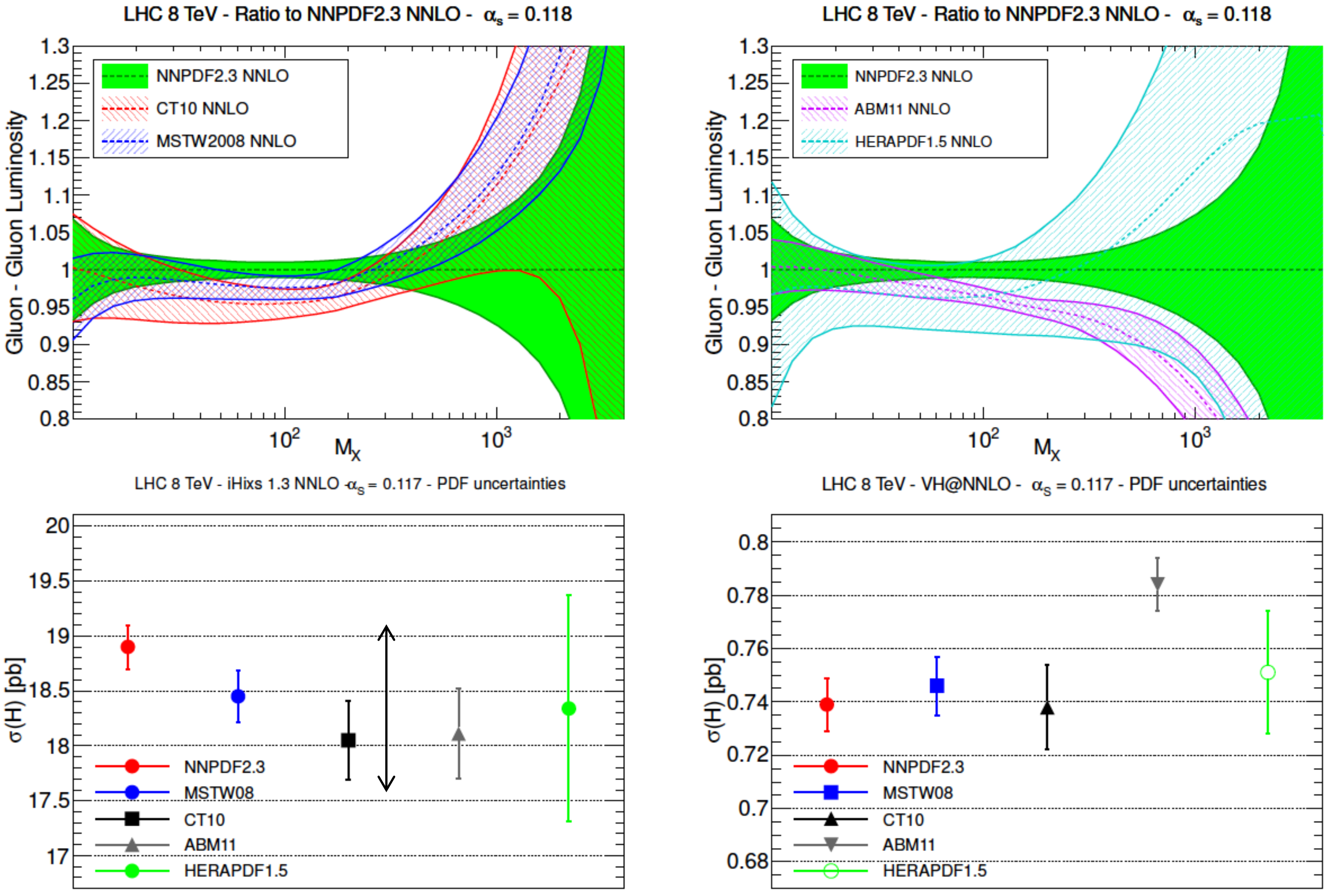
$$+\alpha_s(\mu_R^2)\left[\int \left(\mathrm{d}\hat{\sigma}_{ab}^{V}\,(\alpha_s,\mu_R^2) + \mathrm{d}\hat{\sigma}_{ab}^{C}\,(\alpha_s,\mu_F^2)\right)\,\Theta_{\mathrm{obs}}^{(m)} + \int \mathrm{d}\hat{\sigma}_{ab}^{R}(\alpha_s)\,\Theta_{\mathrm{obs}}^{(m+1)}\right]\Bigg\} + \ldots$$

higher order corrections

jet definitions and observables

We are mostly not so interested in specific observables (e.g. inclusive jet production), but rather in the development of tools that allow us to precisely understand the collider environment, making use of current and future data and of advances in QCD theory

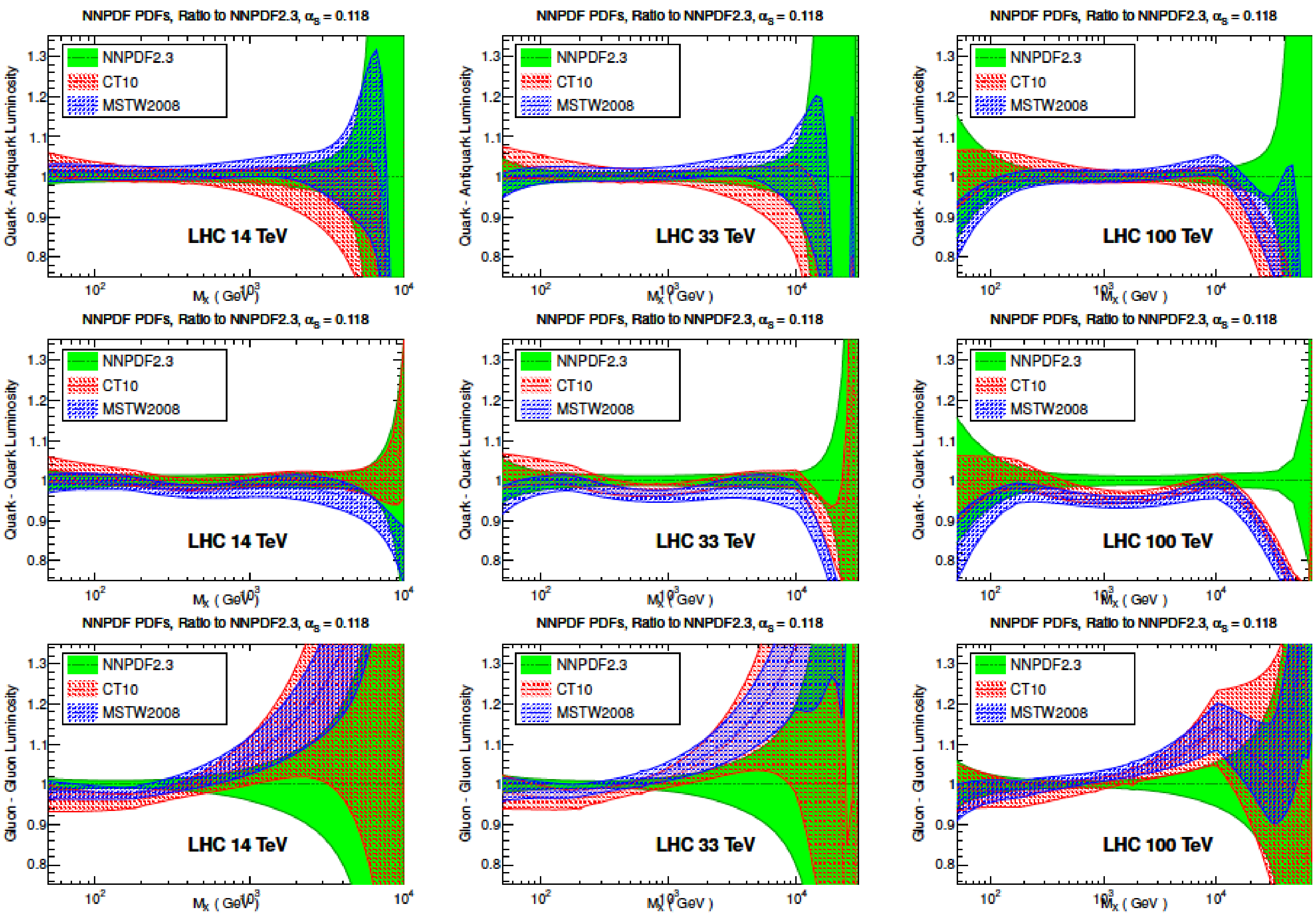
PDFs for the LHC (8 TeV)



ongoing work (Les Houches) to try to improve gg PDF uncertainty in the Higgs range, and thus improve precision of cross section predictions

PDFs at higher energies

PDFs are HERA/fixed target dominated for x<~0.05-0.1; LHC data at 14 TeV offers opportunity for shrinking uncertainties in new physics search range



high masses always a problem, with current uncertainties

low masses become a problem at very high energy colliders

Example: Drell-Yan

What may we have with 100 fb^{-1} …

✓ We may anticipate for 100 fb^{-1} NC and CC DY data over a wide kinematic range of 60 to 1500 GeV with negligible stat. precision (well <0.1%) around the peak region up to 5% at M~ 1 TeV while the systematic uncertainties are expected to be ½ of the present systematic uncertainties, e.g. for NC DY in the range of 0.5% at the peak up to 5% at high masses

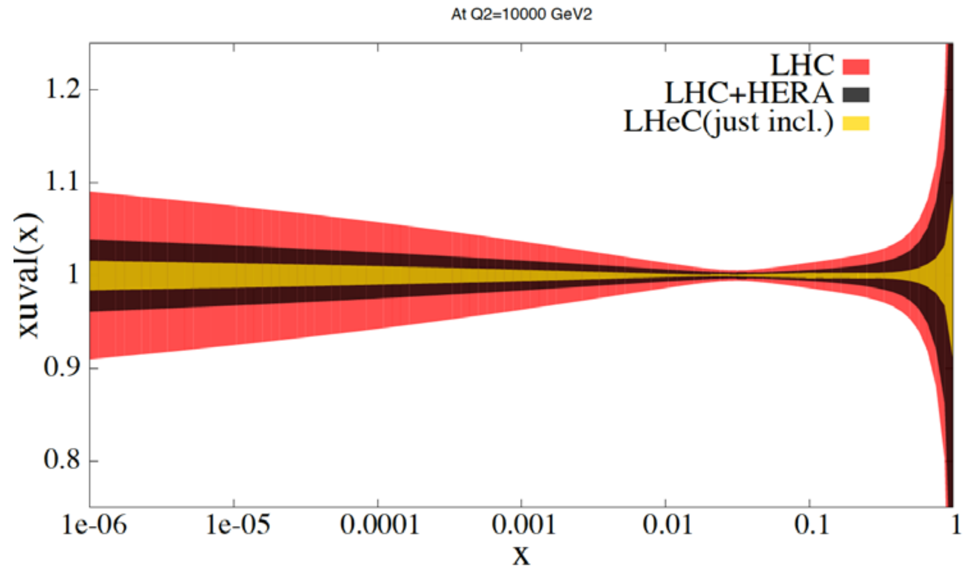
➔ exploring more and more fully the data driven background estimates and the tag and probe based efficiency calculations (significant reduction of stats. component of the systematic uncertainty).

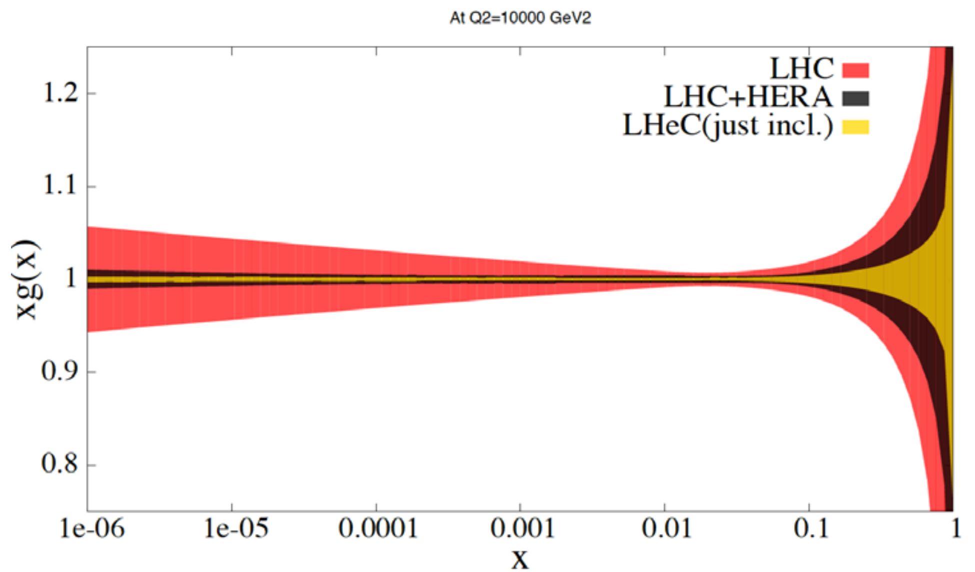
However, with increased statistics, and such small level of systematic uncertainties there may be also NEW effects at the sub-percent level 'discovered'.

Uta Klein

LHC data

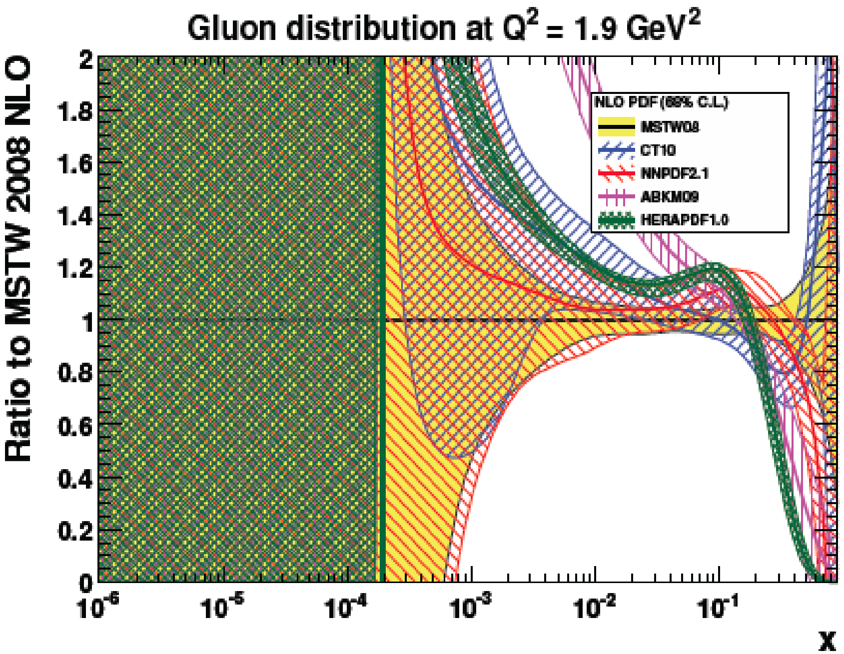
- Use current LHC data in global PDF fits, find no great restraint
  - comes from inclusion of HERA data
- With 100 fb^{-1}, will have precision measurements of DY production from 60 to 1500 GeV, with systematic errors half of the current values, stat errors 5% at high mass
  - Phase 1 (300 fb^{-1}) and phase 2 (3000 fb^{-1}) will provide strong improvement in PDF uncertainties at high mass (BSM search region)

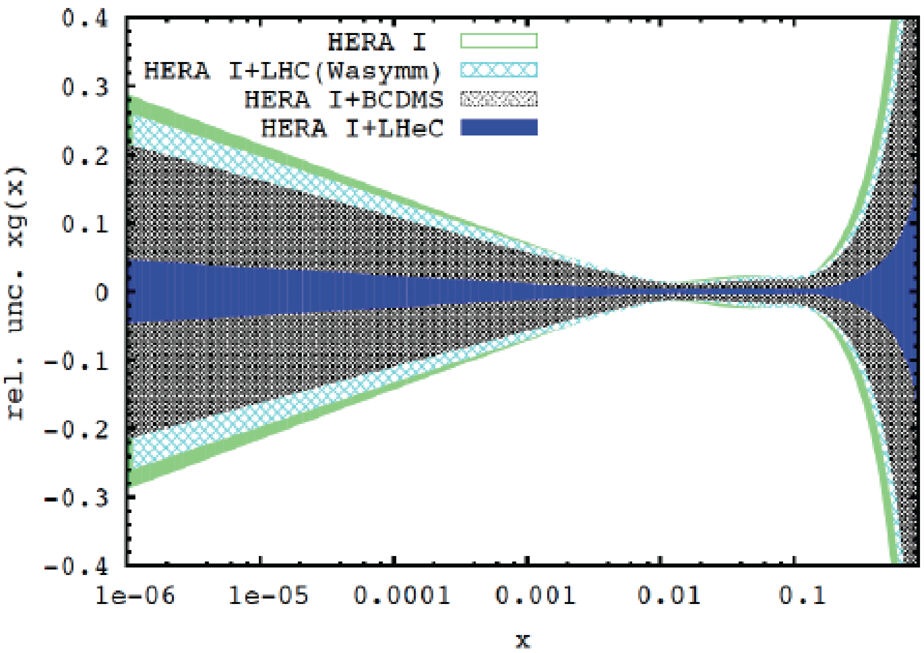




The role of an LHeC

- ep integrated luminosities of several hundred fb^{-1}, Q^2~10^6 GeV^2
- With HERA data, possibility of determining all PDFs in a vastly extended range, and greatly improving precision in currently known range



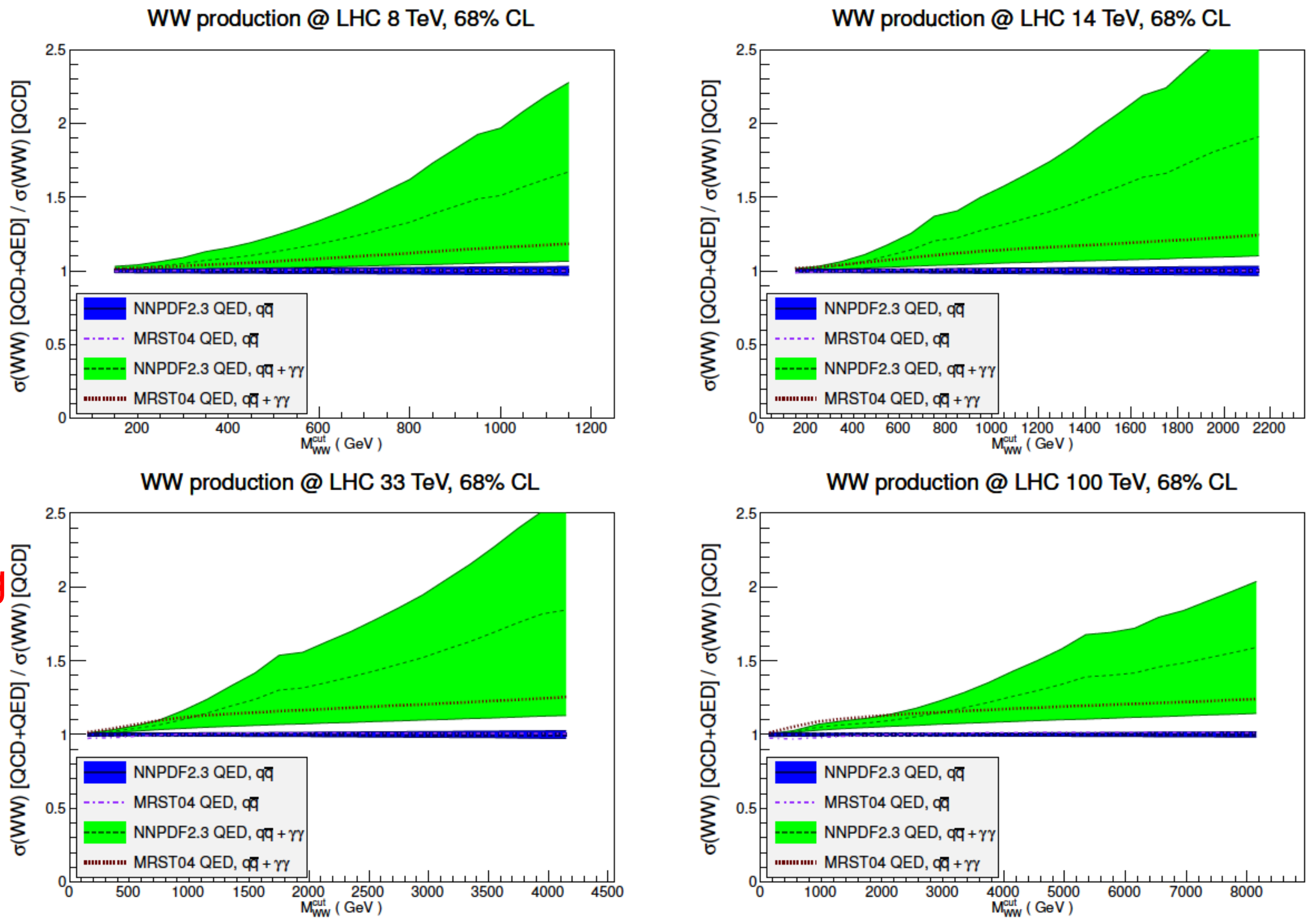


QED-improved PDFs

- Electroweak corrections to parton distributions have important phenomenological implications, in particular for EW production of high mass states

consider production of WW final states including photon-induced production

sizeable production from photon-induced processes,, growing with mass; substantial QED-induced uncertainties in BSM search region

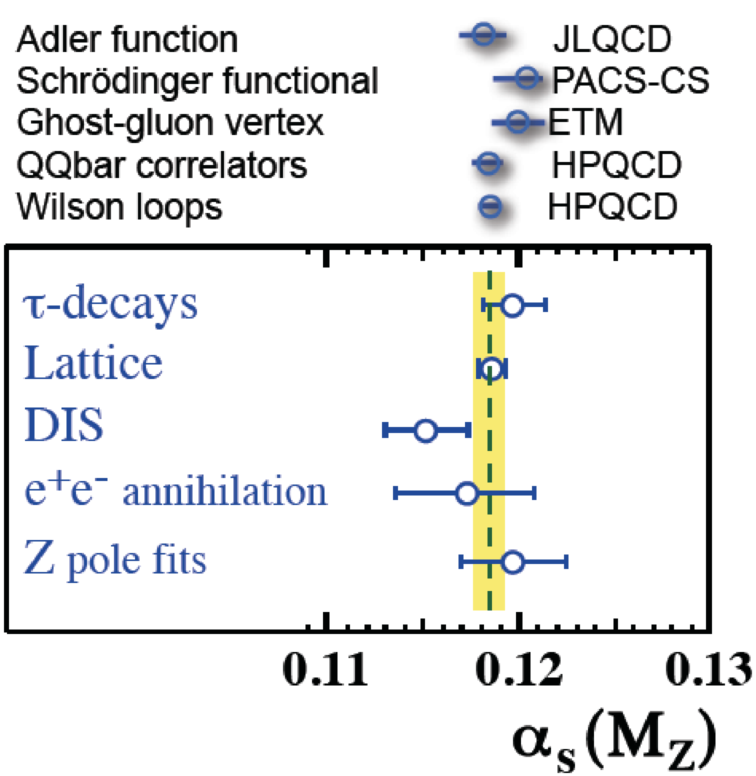


$\alpha_s(m_Z)$

PDG

current world average is 0.1184+/-0.0007; typically use 0.118+/-0.0012

2012, combined the lattice numbers in a weighted average.
It takes a combined error of the most precise of the inputs.



The lattice results (2013) are dominated by the two most precise results from HPQCD, but there are several other lattice results from Europe and Japan, all of which agree with each other and each which is more precise than any non-lattice result.

dominated by lattice results
good to see that different groups with different techniques have similar results

can expect further information from LHC data, but any significant (non-lattice) improvements will come from TLEP or LHeC

see talks on subject on Wed/Fri

$\alpha_s(m_Z)$ Status and Projections

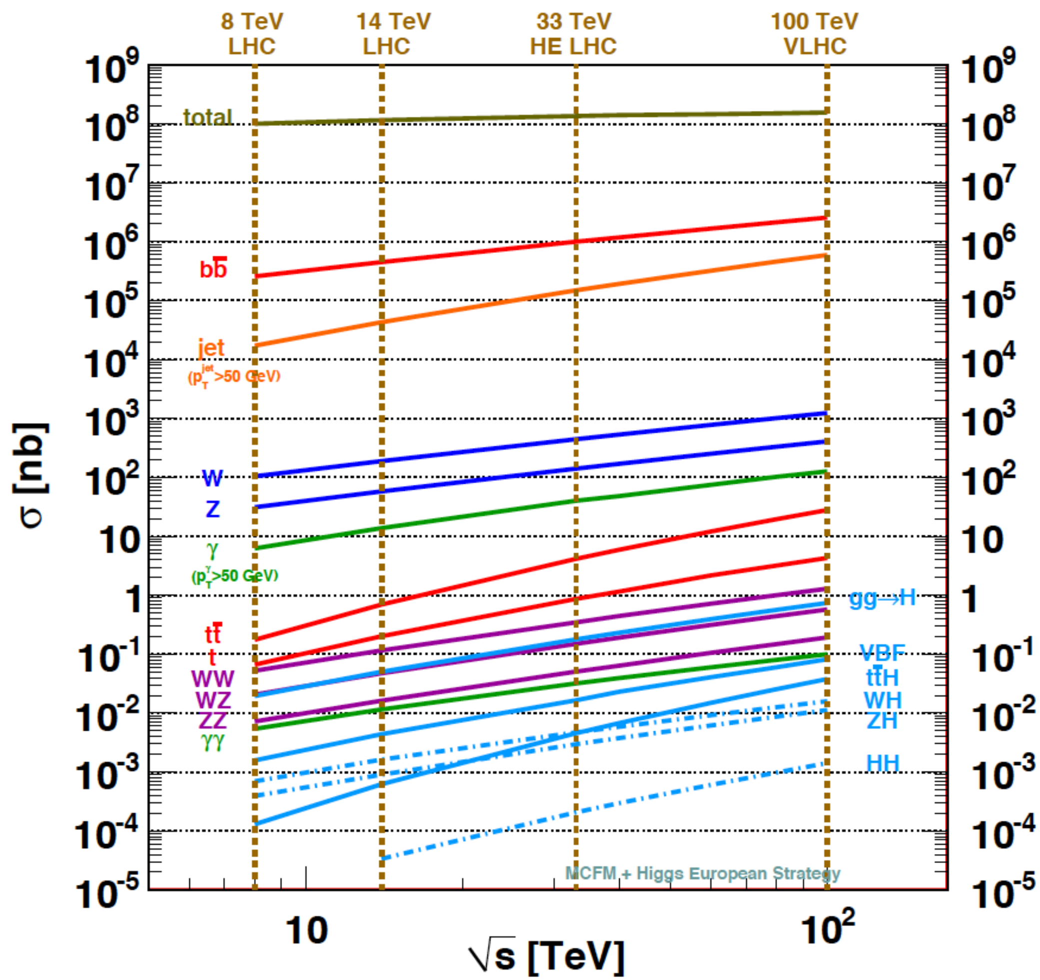
Method	current relative precision	future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry $\sim 3\%$ (NNLO+NLL, n.p. signif.) [1]	? ILC/TLEP $\sim 1\%$? (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [2]	? ILC/TLEP $\sim 0.5\%$? (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [3, 4]	0.1%? (TLEP - GigaZ. ILC?) $\sim 0.2\%$ (N^{4}LO feasible, $\sim$ 10yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [14]	? $\sim 1\%$? (N^{4}LO feasible, $\sim$ 10yrs)
ep colliders	$\sim$ 1-2% (pdf fit dependent) (mostly theory, NNLO) [10, 11, 12, 13]	0.1%? (LHeC + HERA [9]) ? (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [5, 6, 7]	1%? (limited by exp. systematics) (NNLO jets imminent [8])
lattice	$\sim 0.5\%$ (Wilson loops, Adler functions) (limited by accuracy of pert. th.) [15, 16, 17]	$\sim 0.3\%$? (talk by P. Mackenzie)

Table 1: Summary of current uncertainties in extractions of $\alpha_s(M_Z)$ and estimates for future ($\sim$ 10 year) determinations.

All references are in the backup slide.

NLO cross sections vs energy

- Expected growth observed, primarily due to increase of underlying parton luminosities
- Thus processes dominated by gg initial states grow faster than those dominated by qQ initial states
  - thus gg->Higgs and gg->tT grow at roughly the same rate
- NB: double parton scattering (DPS) (for fixed thresholds) becomes more important as the center-of-mass increases



$$\sigma_{XY}^{\rm DPS} \approx \frac{\sigma_X \sigma_Y}{15\ \rm mb}\ . \longrightarrow$$

effective cross section, assumed to be Independent of energy

(gg->)Higgs+jets (at NLO)

- gg initial states like to radiate hard gluons
  - partially due to large color charges
  - partially due to splitting function
- So Higgs production is often accompanied by additional jets; for fixed threshold, this probability increases with center-of-mass energy

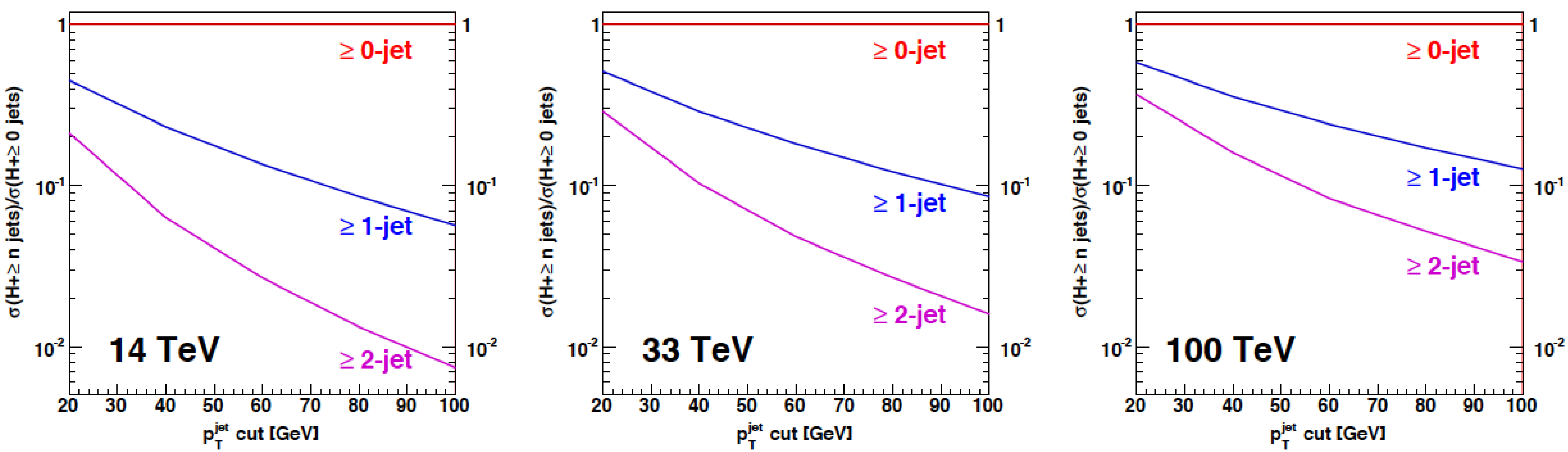
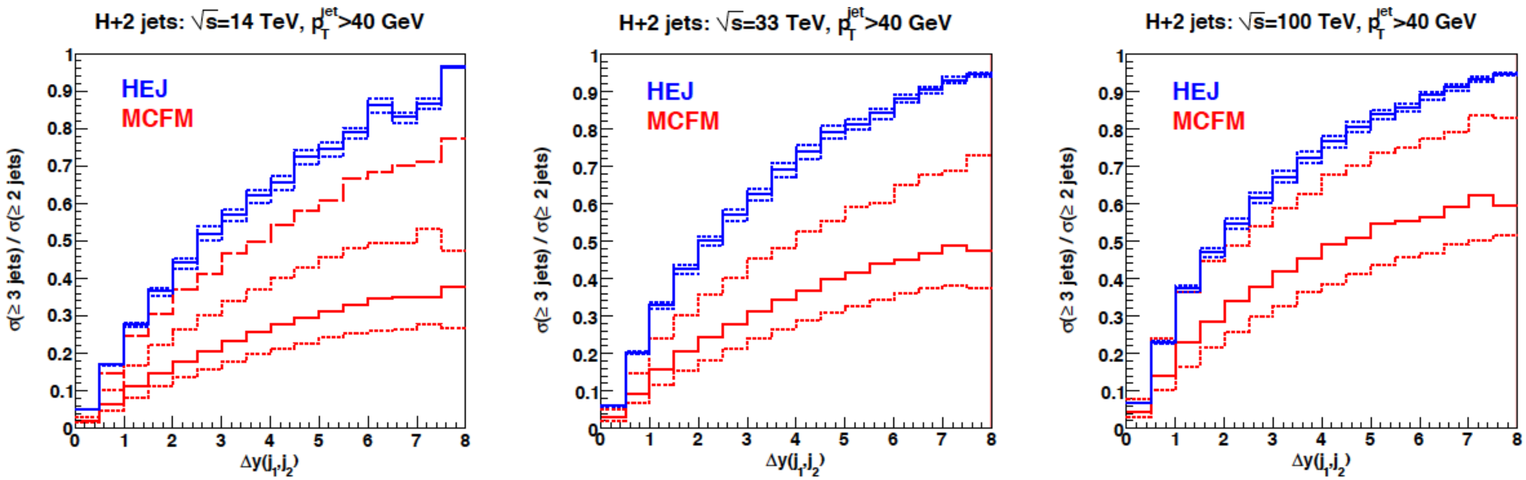
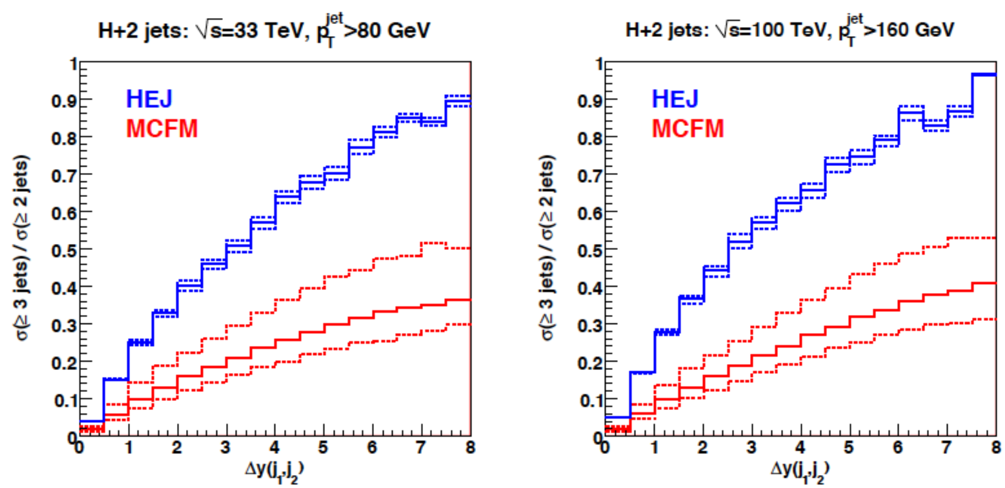


Figure 1-7. *Cross sections for the production of a Higgs boson produced in association with n or more jets, for $n = 0, 1, 2$, normalized to the inclusive Higgs cross section ($n = 0$). Cross sections are shown as a function of the minimum jet p_T and are displayed for a proton-proton collider operating at 14 TeV (left), 33 TeV (center) and 100 TeV (right).*

Higgs+jets



…also expect growth of jet emission with increasing rapidity separation (starting with Higgs + 2 jet final state)



3 jet to 2 jet ratio larger in HEJ than at NLO; effects of additional BFKL type logs

Figure 1-8. *The ratio of number of events that contain at least three jets to the number that contain two jets, as a function of the rapidity difference between the two most widely-separated jets. Predictions are obtained using the NLO calculation of the $H + 2$ jet process and are shown at three operating energies. The jet transverse momentum cut is at 40 GeV (top), or scales with the operating energy (bottom).*

Beyond NNLO

- Full N³LO gg->Higgs cross section perhaps 2 years away
- In the meantime, can construct approximate N³LO cross sections making use of small x ("BFKL") and large x ("Sudakov" or threshold) resummation
- Accurate results can be obtained if maximal use is made of analyticity constraints

The full N^{3}LO Higgs production cross section at the LHC at $\sqrt{s} = 8$ TeV, with $m_H = 125$ GeV was found to be (using the NNPDF2.1 PDF set with $\alpha_s(M_z) = 0.119$)

$$\begin{aligned}
\sigma^{\mathrm{N^3LO}}_{\mathrm{approx}}(\tau, m_H^2) &= \sigma^{(0)}(\tau, m_H^2)\left[\sum_{ij}\left(\delta_{ig}\delta_{jg} + \alpha_s K^{(1)}_{ij} + \alpha_s^2 K^{(2)}_{ij}\right) + \alpha_s^3 K^{(3)}_{gg,\mathrm{approx}}\right] \\
&= \left(22.61 \pm 0.27 + 0.91 \cdot 10^{-2}\bar{g}_{0,3}\right)\ \mathrm{pb} \qquad \text{for } \mu_R = m_H \\
&= \left(24.03 \pm 0.45 + 1.55 \cdot 10^{-2}\bar{g}_{0,3}\right)\ \mathrm{pb} \qquad \text{for } \mu_R = m_H/2,
\end{aligned} \tag{1.5}$$

- These approximate Higgs cross sections were calculated for energies of 7,14, 33 and 100 TeV
  - still significant additional contribution from N³LO
  - better convergence as energy increases
  - scale dependence significantly reduced

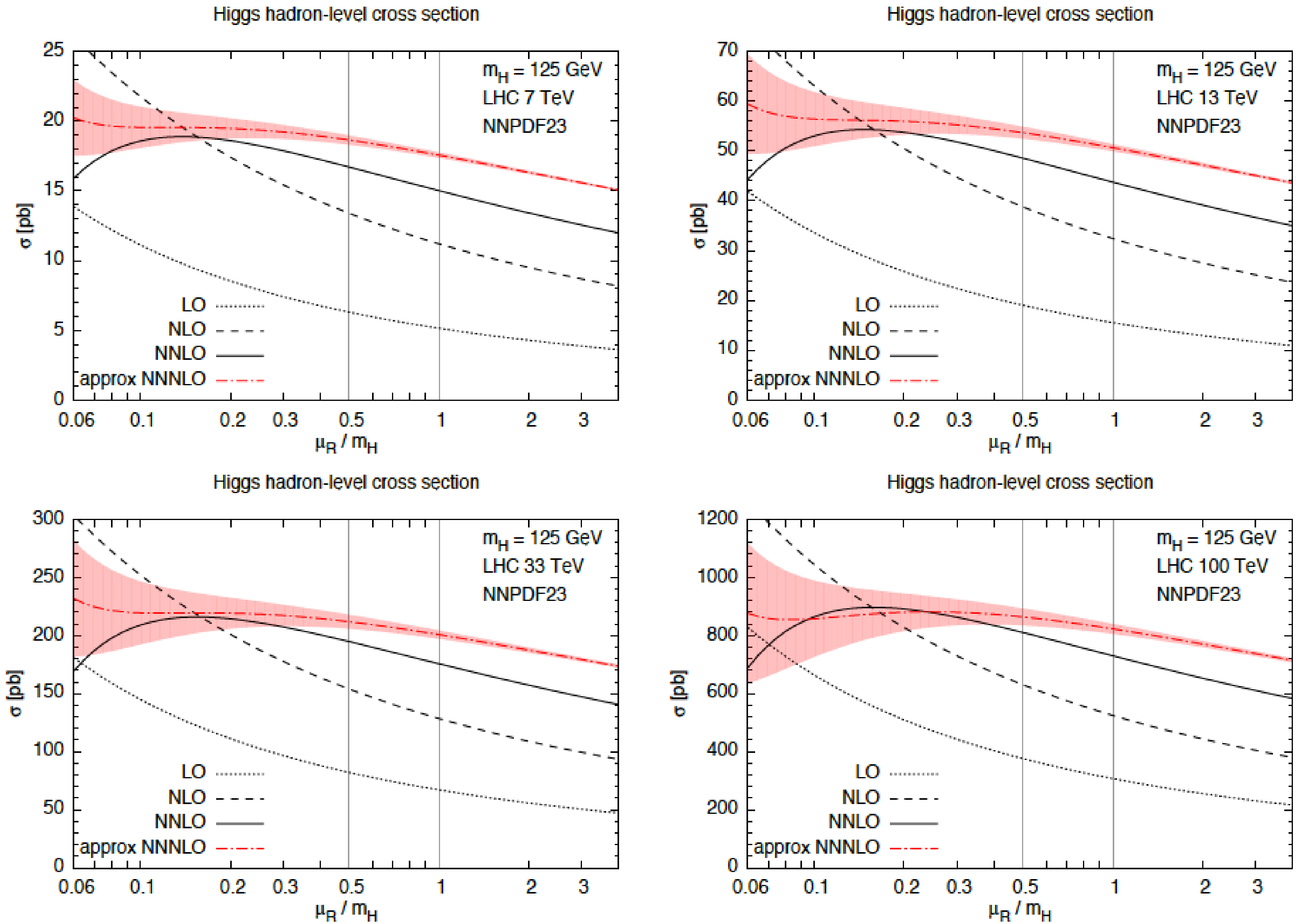


Figure 1-9. *Dependence on the renormalization scale of the LO, NLO, NNLO and approximate N^3LO contribution from the gluon-gluon channel to the total cross section for Higgs production at a proton-proton collider with four different values of the collider energy. The results shown are obtained using the NNPDF2.3 PDF set with $alpha_s(M_z) = 0.118$*

NNLO QCD + NLO EW wishlist

- The Les Houches NLO wishlist was started in 2005
  - purpose was to list important, but doable, calculations at NLO
  - added to in 2007, 2009 and 2011
  - closed in 2013; NLO calculations have become “automatic”
- So, now we have a Les Houches NNLO (+NLO EW) wishlist

Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to$ b$\bar{\mathrm{b}}$ @ same accuracy	H couplings
t$\bar{\mathrm{t}}$H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m_t dependence) dσ @ NLO QCD (infinite m_t limit)	dσ @ NLO QCD (full m_t dependence) dσ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1-1. *Wishlist part 1 – Higgs* (V = W, Z).

NNLO QCD + NLO EW wishlist

- We need to add an additional column regarding the current and expected levels of experimental precision, and why NNLO QCD + NLO EW theoretical precision is needed
  - besides continued employment for theoretical physicists

Process	known	desired	details
$t\bar{t}$	$\sigma_{\rm tot}$ @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
$t\bar{t} + j$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD (t channel)	precision top/QCD, V_{tb}
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: incl. jets, dijet mass $\rightarrow$ PDF fits (gluon at high x) $\rightarrow \alpha_s$
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: $R3/2$ or similar $\rightarrow \alpha_s$ at high scales dom. uncertainty: scales
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma + b$ for bottom PDF

Table 1-2. *Wishlist part 2 – jets and heavy quarks.*

NNLO QCD + NLO EW wishlist

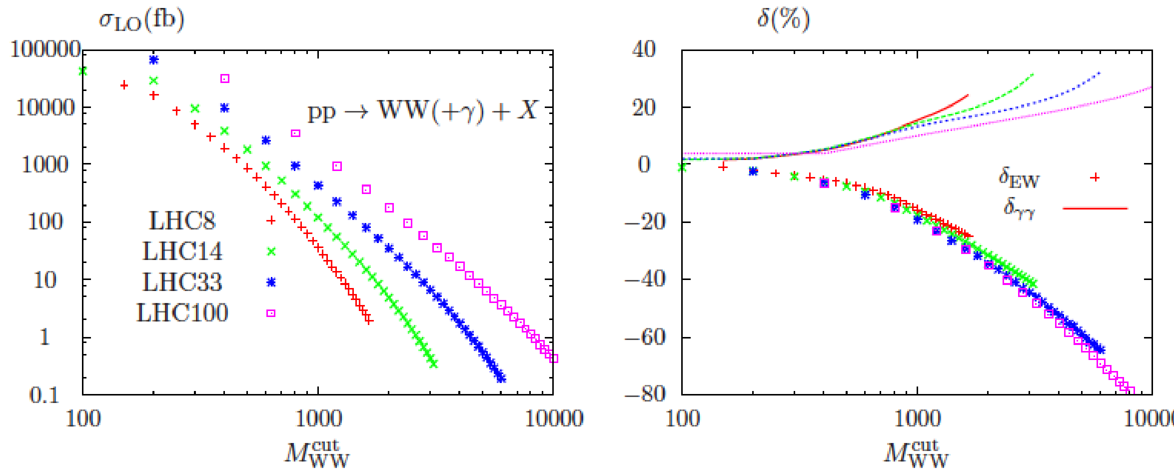
- More details in Les Houches 2013 writeup

Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$V+j$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	$Z+j$ for gluon PDF $W+c$ for strange PDF
$V+jj$	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of $H+jj$ final state
VV'	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$gg \to VV$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$V\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
$Vb\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $VH \to b\bar{b}$
$VV'\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
$VV'V''$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$VV'+j$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
$VV'+jj$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Table 1-3. *Wishlist part 3 – EW gauge bosons ($V = W, Z$).*

Electroweak corrections: Sudakov zone

- When s, |t| are large, and >> m_W, NLO EW high energy logs (Sudakov logs), can be a reasonable approximation for full NLO EW corrections for a process
  - $\alpha_w \ln^2(Q^2/M_W^2)$
- At high masses, corrections can be very large
- Bloch-Nordsiech does not apply



When do we enter the *Sudakov* zone?

Table 1-8. *Are we in the Sudakov zone yet?*

Process	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 33, 100$ TeV
Inclusive jet, dijet	Yes	Yes	Yes
Inclusive W/Z tail	∼ Yes	Yes	Yes
Wγ, Zγ tail ($\ell\nu\gamma, \ell\ell\gamma$)	No	∼ Yes	Yes
W/Z+jets tail	∼ Yes	Yes	Yes
WW leptonic	Close	∼ Yes	Yes
WZ, ZZ leptonic	No	No	Yes
WW, WZ, ZZ semileptonic	∼ Yes	Yes	Yes

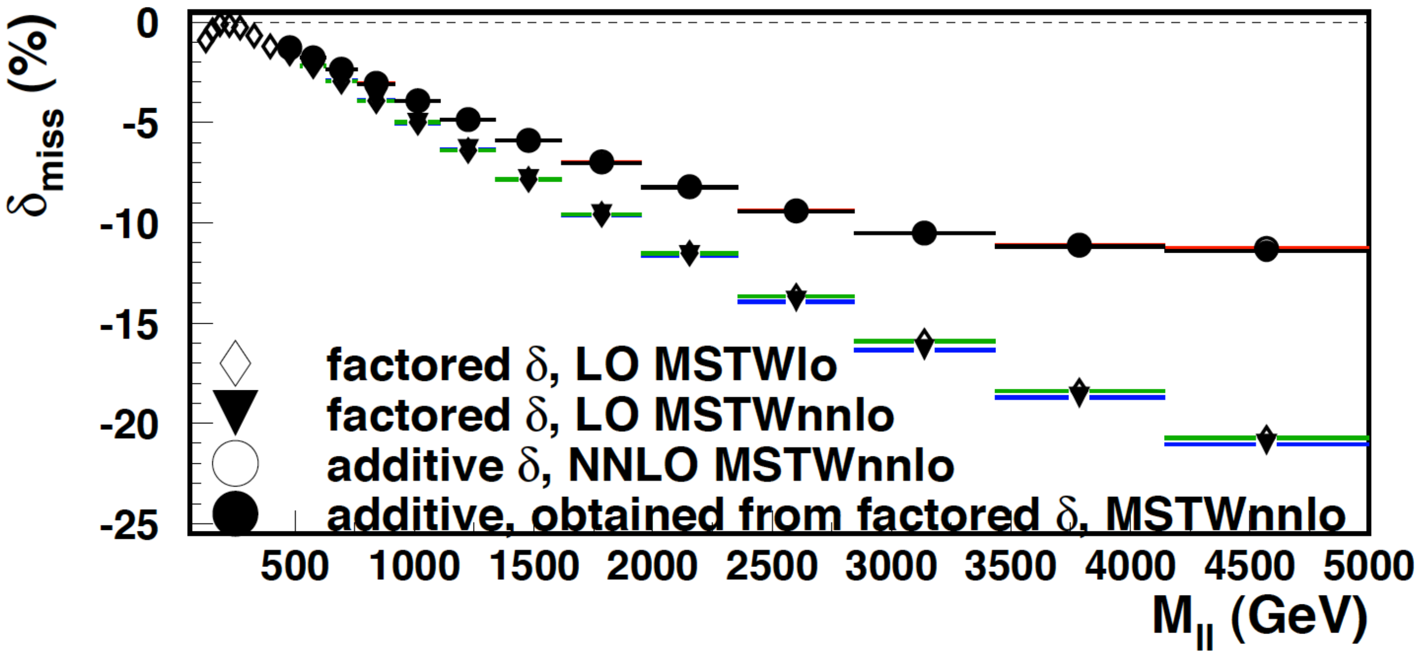
EW and QCD corrections

- Are the corrections additive or multiplicative? Only a complete calculation of the mixed corrections can determine which prescription is appropriate for a process. Only carried out for inclusive Higgs production to date.

$$\sigma_{add} \sim \sigma_0 \left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_{EW})\right],$$

$$\sigma_{mult} \sim \sigma_0 \left[1 + \mathcal{O}(\alpha_s)\right] \times \left[1 + \mathcal{O}(\alpha_{EW})\right]$$

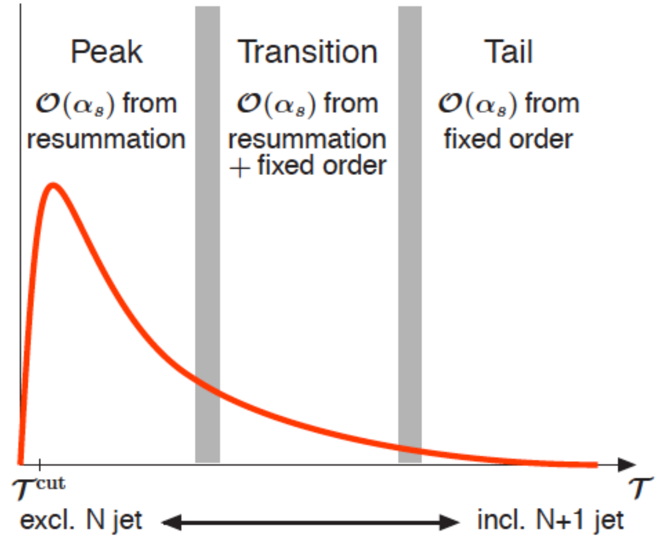
- This ambiguity can have a large impact, even with current data



consider Z' search at 8 TeV

Jet vetoes and exclusive jet binning

- Often necessary (because of differing backgrounds) to veto on additional jets
- Resummation needed to restore precision
- Consider resummation for Higgs+1 jet



at 14 TeV and 33 TeV, resummation improves scale uncertainty, little change in cross section.
at 100 TeV, sizeable increase in cross section

	14 TeV	33 TeV	100 TeV
NLO	$12.48^{+34\%}_{-46\%}$	$40.17^{+54\%}_{-41\%}$	$131.3^{+72\%}_{-98\%}$
NLL′ + NLO	$11.73^{+27\%}_{-27\%}$	$39.71^{+24\%}_{-24\%}$	$166.9^{+22\%}_{-22\%}$
$K_{(\mathrm{NLL'+NLO})\mathrm{NLO}}$	0.940	0.989	1.27

Table 1-9. *Cross section central values and uncertainties for the exclusive Higgs plus one-jet bin for a fixed transverse momentum cut $p_T^{cut} = 30$ GeV. The results are shown in picobarns.*

	14 TeV	33 TeV	100 TeV
NLO	$12.48^{+34\%}_{-46\%}$	$26.90^{+30\%}_{-39\%}$	$91.23^{+38\%}_{-46\%}$
NLL′ + NLO	$11.73^{+27\%}_{-27\%}$	$27.44^{+24\%}_{-24\%}$	$103.0^{+24\%}_{-24\%}$
$K_{(\mathrm{NLL'+NLO})\mathrm{NLO}}$	0.940	1.02	1.13

Table 1-10. *Cross section central values and uncertainties for the exclusive Higgs plus one-jet bin, for the following transverse momentum cuts: $p_T^{cut} = 30$ GeV at 14 TeV, $p_T^{cut} = 60$ GeV at 33 TeV, and $p_T^{cut} = 80$ GeV at 100 TeV . The results are shown in picobarns.*

somewhat tamed by increasing jet p_T cut at higher energies

Schedule for this week

- Wed 8:30-10:00
  - α_s on the lattice P. Mackenzie
  - discussion of future α_s determinations
- Friday 8:30-12:00
  - 8:30-9:30 Discussion (PDFs)/work on report
  - 9:30-10:30 dealing with high pileup A. Schwartzman
  - 10:30-11:30 α_s on the lattice (reprise)
  - 11:30-12:00 meet with Michael and Chip
- Sat
  - 8:30-10:00 discussion (higher order and EW)
  - 10:00-12:00 work on report

Plan to set up Vidyo:

http://vidyoportal.cern.ch/flex.html?roomdirect.html&key=mhrI5BHkDY8A

Backup

Backup

[1] G. Dissertori, A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, G. Heinrich, G. Luisoni and H. Stenzel, JHEP **0908**, 036 (2009) [arXiv:0906.3436 [hep-ph]].

[2] G. Dissertori, A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, G. Heinrich and H. Stenzel, Phys. Rev. Lett. **104**, 072002 (2010) [arXiv:0910.4283 [hep-ph]].

[3] M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Kennedy, R. Kogler, K. Moenig and M. Schott *et al.*, Eur. Phys. J. C **72**, 2205 (2012) [arXiv:1209.2716 [hep-ph]].

[4] P. A. Baikov, K. G. Chetyrkin, J. H. Kuhn and J. Rittinger, Phys. Rev. Lett. **108**, 222003 (2012) [arXiv:1201.5804 [hep-ph]].

[5] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **80**, 111107 (2009) [arXiv:0911.2710 [hep-ex]].

[6] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1307.1907 [hep-ex].

[7] M. Czakon, P. Fiedler and A. Mitov, arXiv:1303.6254 [hep-ph].

[8] A. G. -D. Ridder, T. Gehrmann, E. W. N. Glover and J. Pires, Phys. Rev. Lett. **110**, 162003 (2013) [arXiv:1301.7310 [hep-ph]].

[9] J. L. Abelleira Fernandez *et al.* [LHeC Study Group], J.Phys.G. **39** (2012) 075001.

[10] J. Gao, M. Guzzi, J. Huston, H. -L. Lai, Z. Li, P. Nadolsky, J. Pumplin and D. Stump *et al.*, arXiv:1302.6246 [hep-ph].

[11] S. Alekhin, J. Blumlein and S. Moch, Phys. Rev. D **86**, 054009 (2012) [arXiv:1202.2281 [hep-ph]].

[12] R. D. Ball, V. Bertone, L. Del Debbio, S. Forte, A. Guffanti, J. I. Latorre, S. Lionetti and J. Rojo *et al.*, Phys. Lett. B **707**, 66 (2012) [arXiv:1110.2483 [hep-ph]].

[13] A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt, Eur. Phys. J. C **64**, 653 (2009) [arXiv:0905.3531 [hep-ph]].

[14] P. A. Baikov, K. G. Chetyrkin and J. H. Kuhn, Phys. Rev. Lett. **101**, 012002 (2008) [arXiv:0801.1821 [hep-ph]].

[15] C. McNeile, C. T. H. Davies, E. Follana, K. Hornbostel and G. P. Lepage, Phys. Rev. D **82**, 034512 (2010) [arXiv:1004.4285 [hep-lat]].

[16] E. Shintani, S. Aoki, H. Fukaya, S. Hashimoto, T. Kaneko, T. Onogi and N. Yamada, Phys. Rev. D **82**, 074505 (2010) [arXiv:1002.0371 [hep-lat]].

[17] K. Maltman, D. Leinweber, P. Moran and A. Sternbeck, Phys. Rev. D **78**, 114504 (2008) [arXiv:0807.2020 [hep-lat]].