QCD Working Group Report

Snowmass: Seattle Energy Frontier Workshop, June 30 2013

John Campbell
for the conveners: JC, K. Hatakeyama, J. Huston, F. Petriello

Overview

- Conclusions and much of the material presented here collated from a series of meetings over the course of 2012-13.

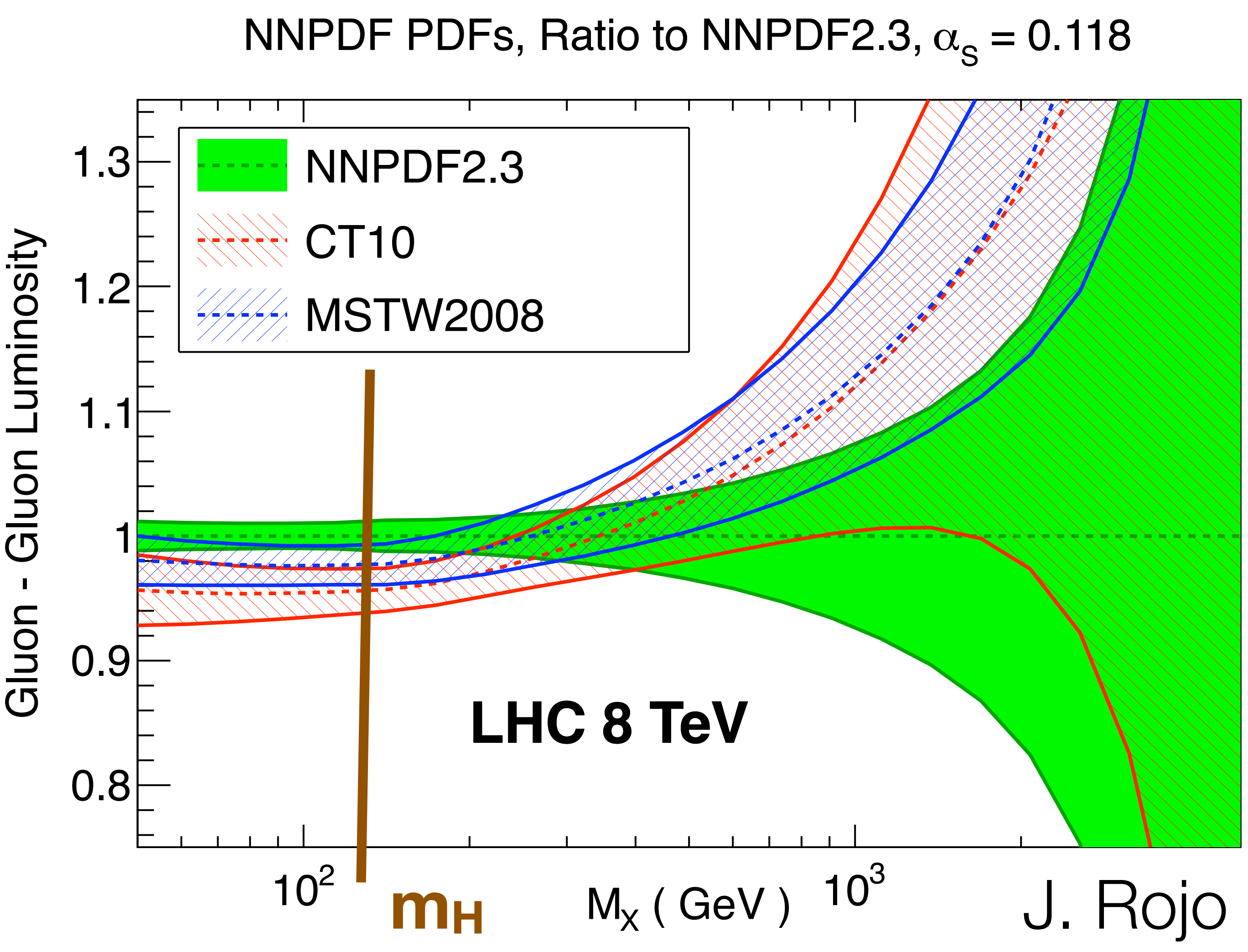
  - Kick-off meeting (Fermilab, October 2012)
  - One-day QCD meeting (Fermilab, January 2013)
  - Energy Frontier meeting (BNL, April 2013)
  - One-day QCD/computing meeting (Loopfest, May 2013)
  - Les Houches “Physics at TeV colliders” (June, 2013)

Themes

- Studies fall into four main themes:
  - Investigations of pdf knowledge and uncertainties.
  - Exploration of phenomenology at (possible) future hadron-collider operating energies (14, 33, 100 TeV).
  - Uncertainties on Higgs+jet cross sections.
  - Potential for improvements in the perturbative description, beyond NLO QCD and including NLO EW.

Current knowledge and uncertainties

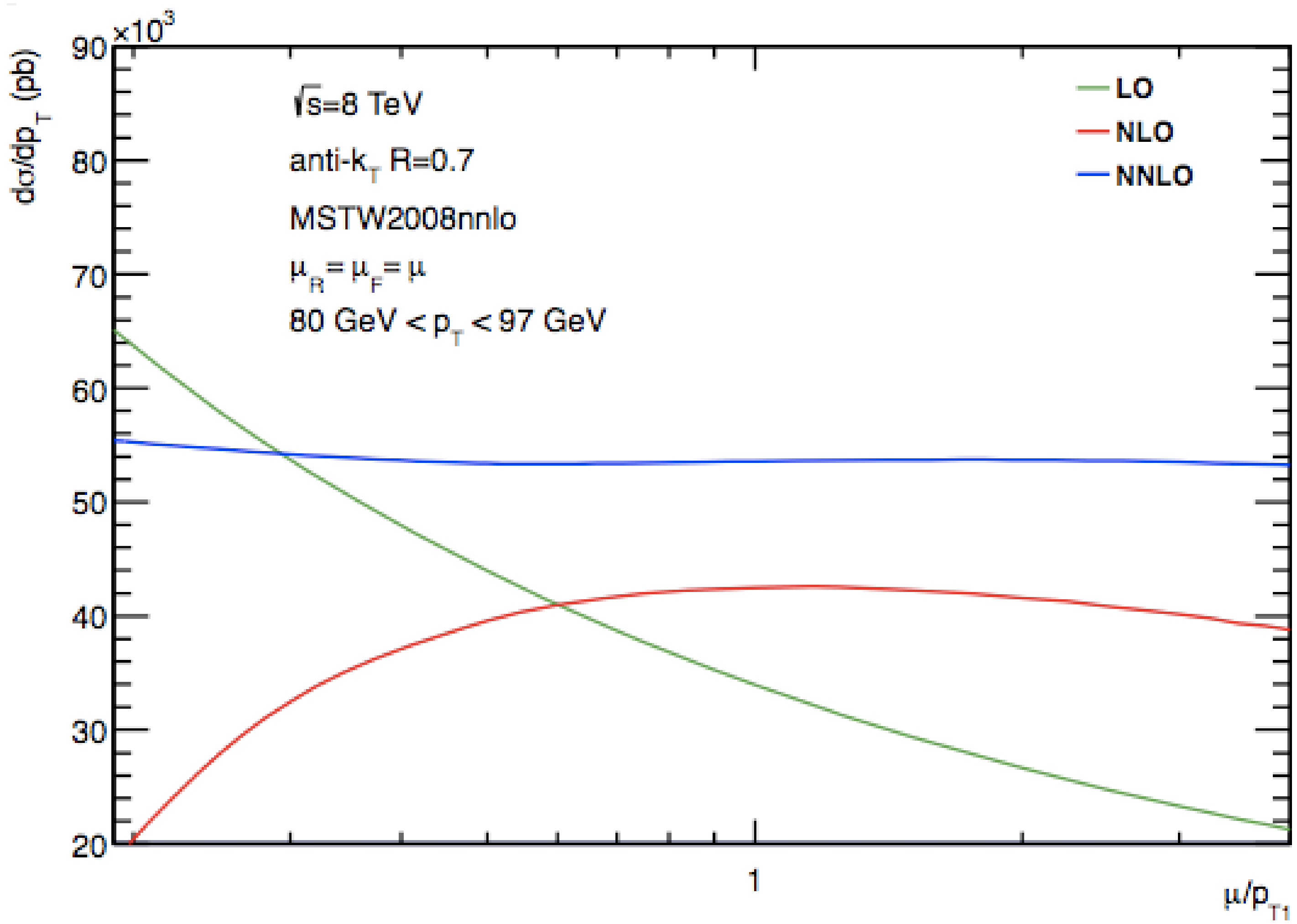
- Central values and uncertainties for the three most widely-used pdf sets - CT10, MSTW08, NNPDF2.3 - generally agree.
- Still room for improvement, particularly in the gluon distribution.
- Potential for reducing the uncertainty in the cross section for Higgs production by gluon fusion.
- Differences mostly due to treatment of fixed-target DIS data.
- Collider-only fits agree better but have larger uncertainties (under investigation for MN).



- Also ongoing: more efficient study of uncertainties (“meta-pdfs”).

Likely improvements from LHC data

- Improved extractions of pdfs will be possible with the advent of suitable NNLO calculations of jet and top-pair differential distributions (~ 1 year).



gluon-only dijet production (Gehrmann de Ridder et al, 2013)

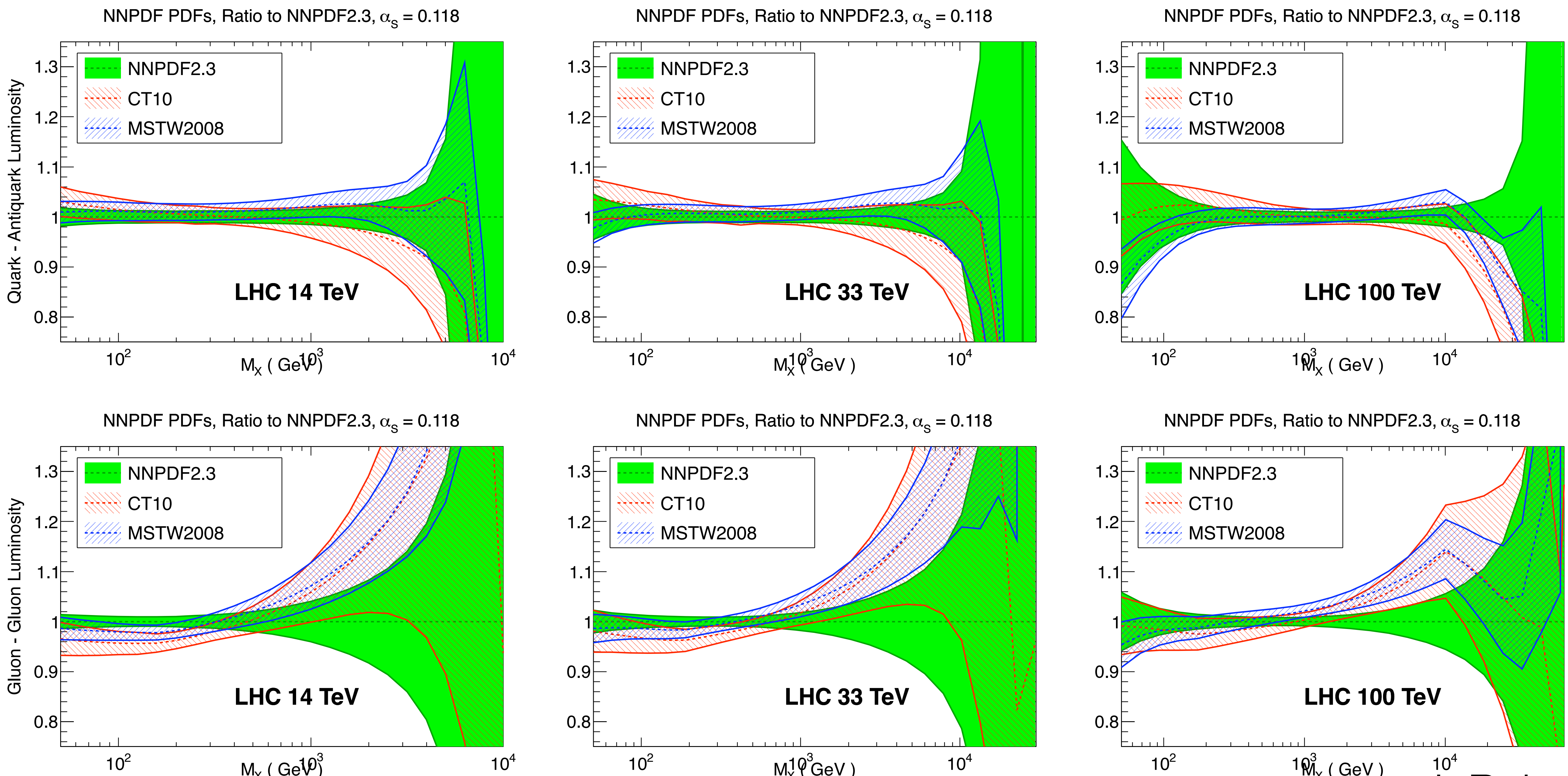
→ still need full (and fast) result for pdf extraction

top pairs at NNLO: will be better with rapidity and mass distributions

- Drell-Yan data also important at high mass, but requires full QCD +EWK corrections; still hard to compete with HERA for quarks.

Luminosity uncertainties at 14TeV+beyond

- Uncertainties for higher energies reasonable for small-moderate *x*.

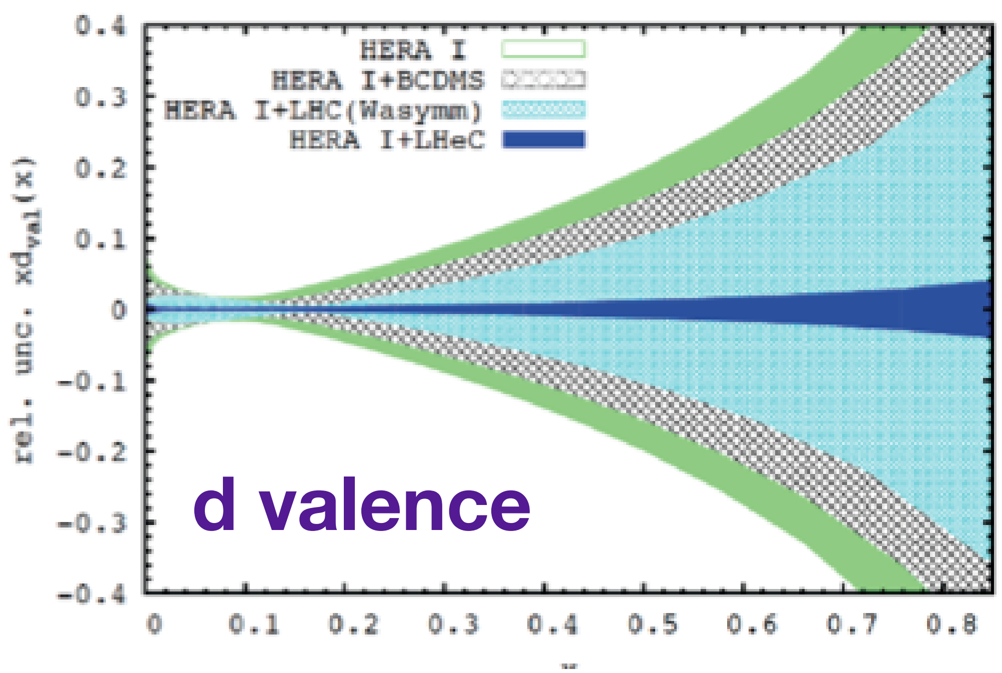


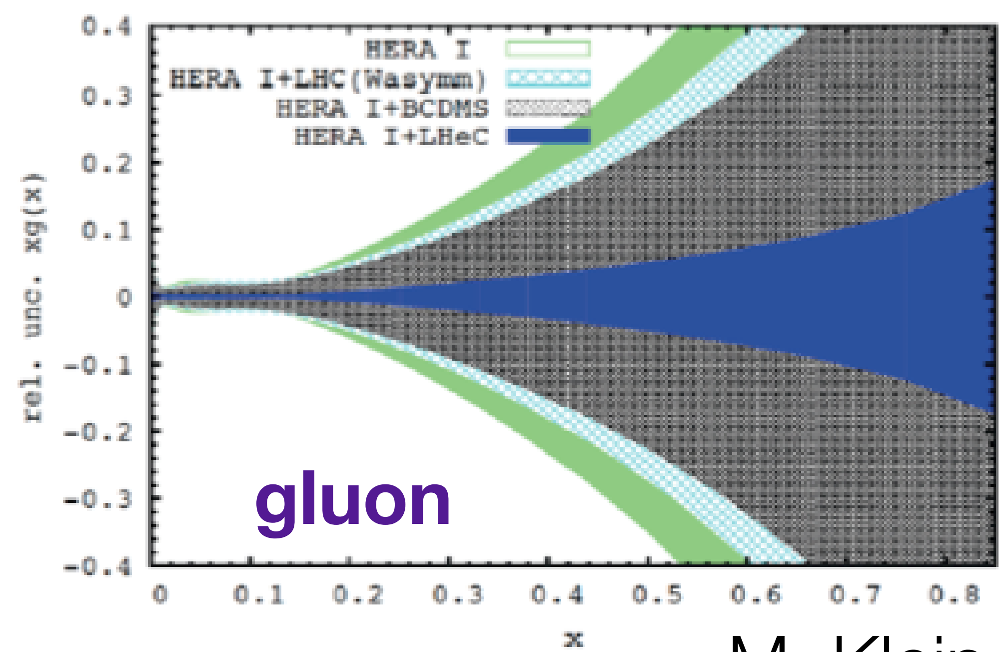
J. Rojo

- Input from LHeC would be useful at small *x* and high *x*.

Improvements from LHeC

- LHeC will allow precision measurement of pdfs over the complete kinematic range needed for 14 TeV and higher energies.





M. Klein

- LHeC also opens the possibility of a measurement of the strong coupling α_s with per mille accuracy.

  → but requires simultaneous advances in theory

case	cut $[Q^2$ (GeV^2)]	α_S	uncertainty	relative precision (%)
HERA only (14p)	$Q^2 > 3.5$	0.11529	0.002238	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.12203	0.000995	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.11680	0.000180	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.11796	0.000199	0.17
LHeC only (14p)	$Q^2 > 20.$	0.11602	0.000292	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11769	0.000132	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.11831	0.000238	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.11839	0.000304	0.26

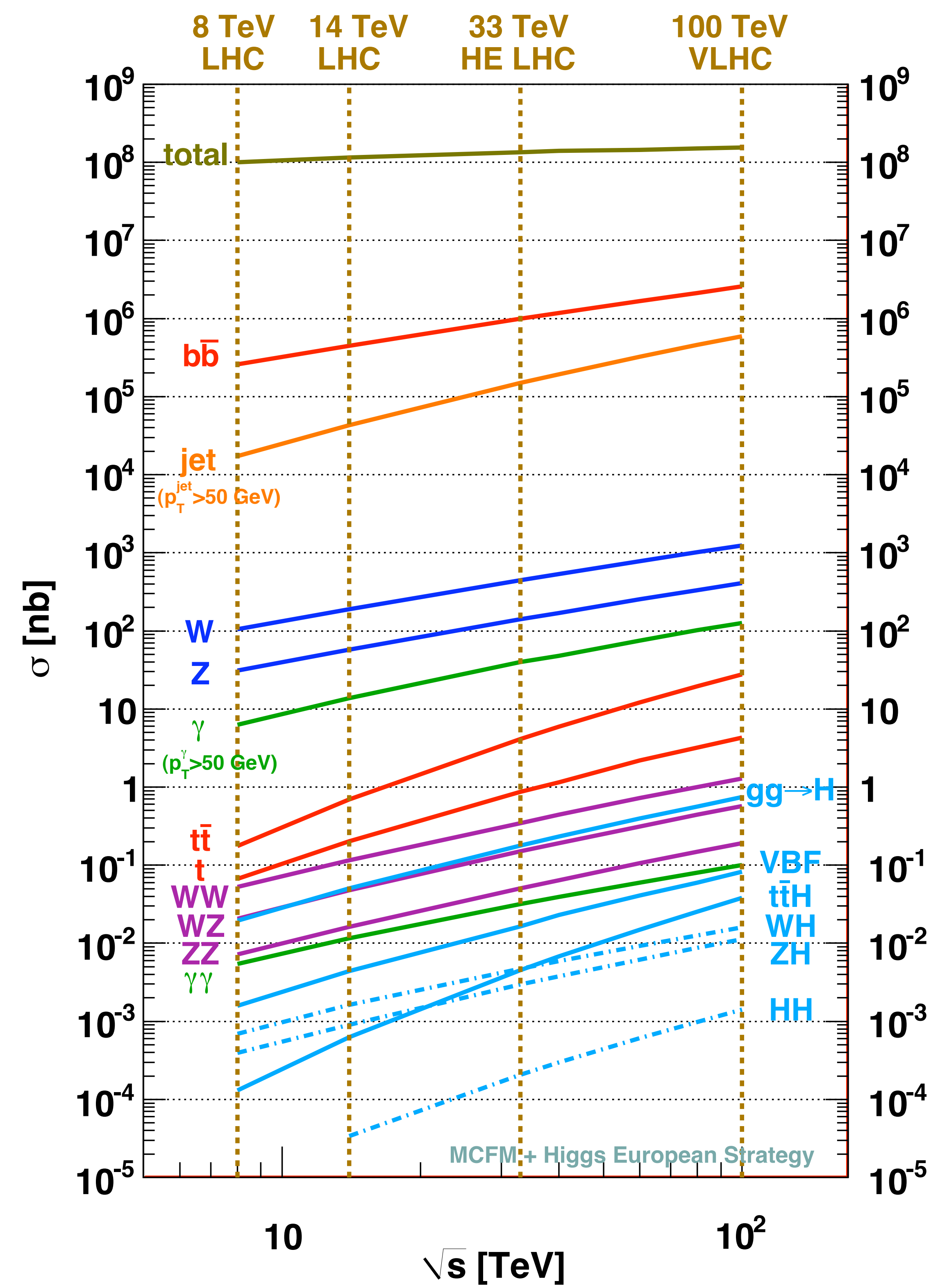
exp. uncertainty reduced by order of magnitude

Cross sections at higher energies

- Most important cross sections are reasonably stable under NLO corrections at higher energies.

33 TeV

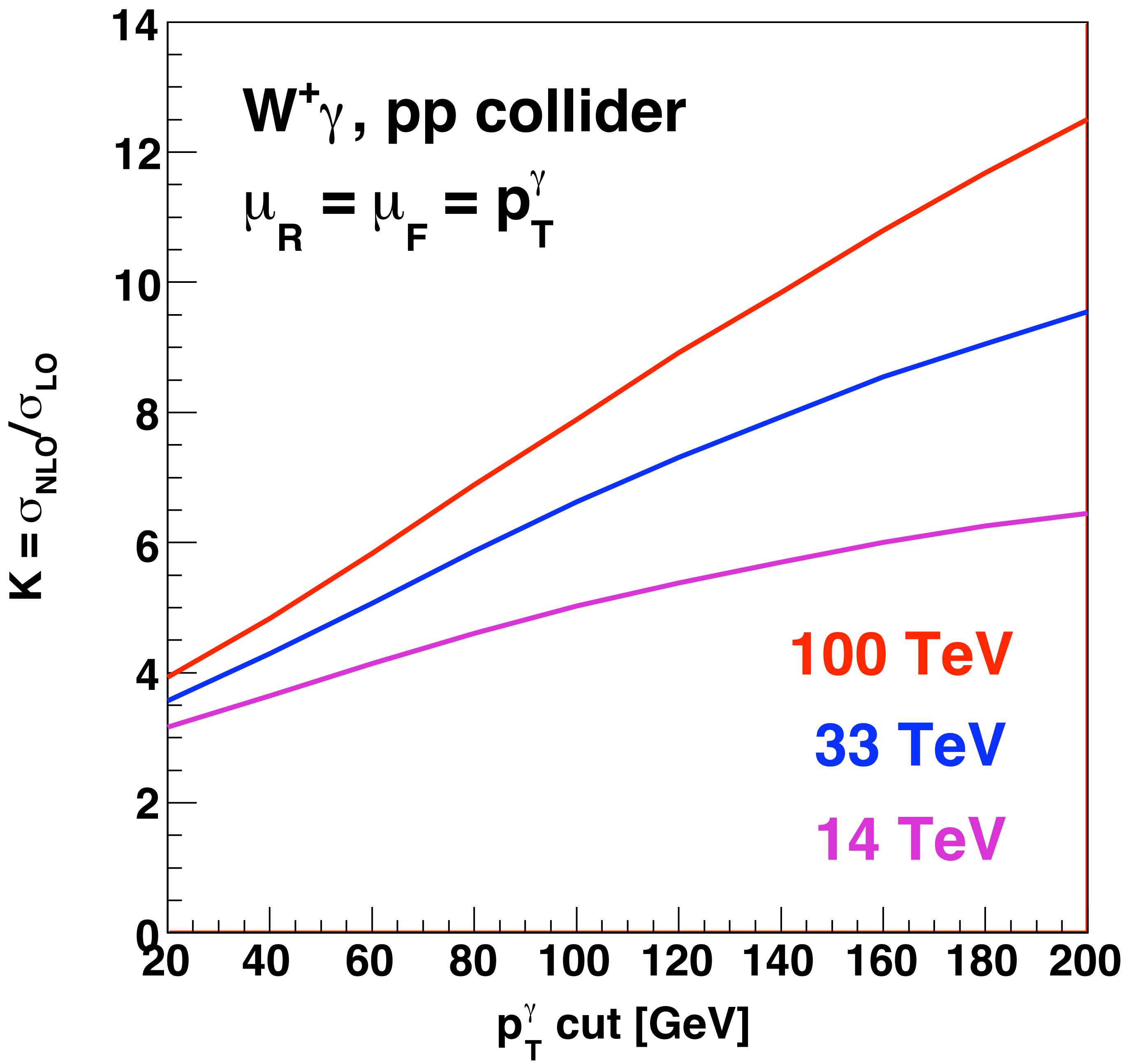
Process	μ_R^2, μ_F^2	σ_{LO} [pb]	σ_{NLO} [pb]	K-factor
W^+j ($p_T^W > 200$ GeV)	$M_W^2 + p_T^{W\,2}$	427	629	1.47
W^-j ($p_T^W > 200$ GeV)	$M_W^2 + p_T^{W\,2}$	291	443	1.52
Z^0j ($p_T^W > 200$ GeV)	$M_Z^2 + p_T^{Z\,2}$	312	460	1.41
γj ($p_T^\gamma > 100$ GeV)	$p_T^{\gamma\,2}$	2690	4030	1.47
$W^+\gamma$ ($p_T^\gamma > 100$ GeV)	$p_T^{\gamma\,2}$	1.90	10.0	5.26
$W^-\gamma$ ($p_T^\gamma > 100$ GeV)	$p_T^{\gamma\,2}$	1.29	7.50	5.81
$Z^0\gamma$ ($p_T^\gamma > 100$ GeV)	$p_T^{\gamma\,2}$	3.66	7.88	2.15
$\gamma\gamma$ (both $p_T^\gamma > 100$ GeV)	$m_{\gamma\gamma}^2$	2.70	3.65	1.35
$\ell^+\ell^-$ ($m_{\ell^+\ell^-} > 150$ GeV)	$m_{\ell^+\ell^-}^2$	20.9	23.6	1.13



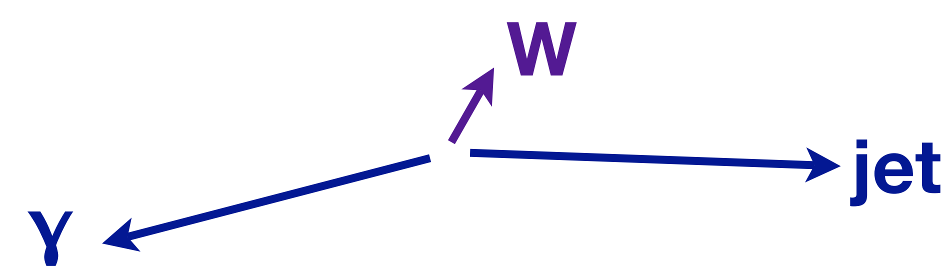
- Some notable exceptions that are understood.
- Scaling of cuts on basic objects assumed (jets, photons).

Lessons from NLO

- Phenomenon of “giant” K-factors well-known - see recent studies by Sapeta & Salam.



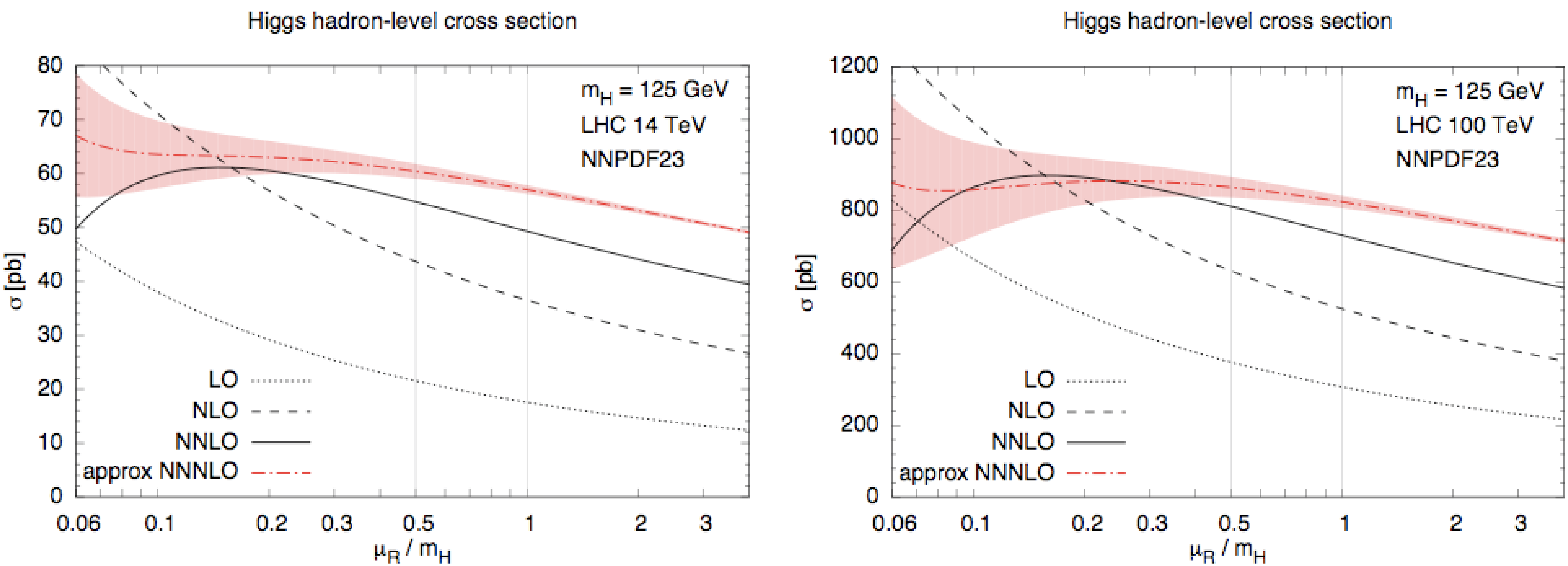
- Caused by new gluon contributions and kinematic configurations.



- Exacerbated by scaling cuts with energy.
- Underlines importance of using latest tools (such as matched samples) where these effects are included.

Improved gg→H cross section

- Approximations to the N³LO gluon fusion Higgs cross section are now available and a full calculation may exist in a few years.

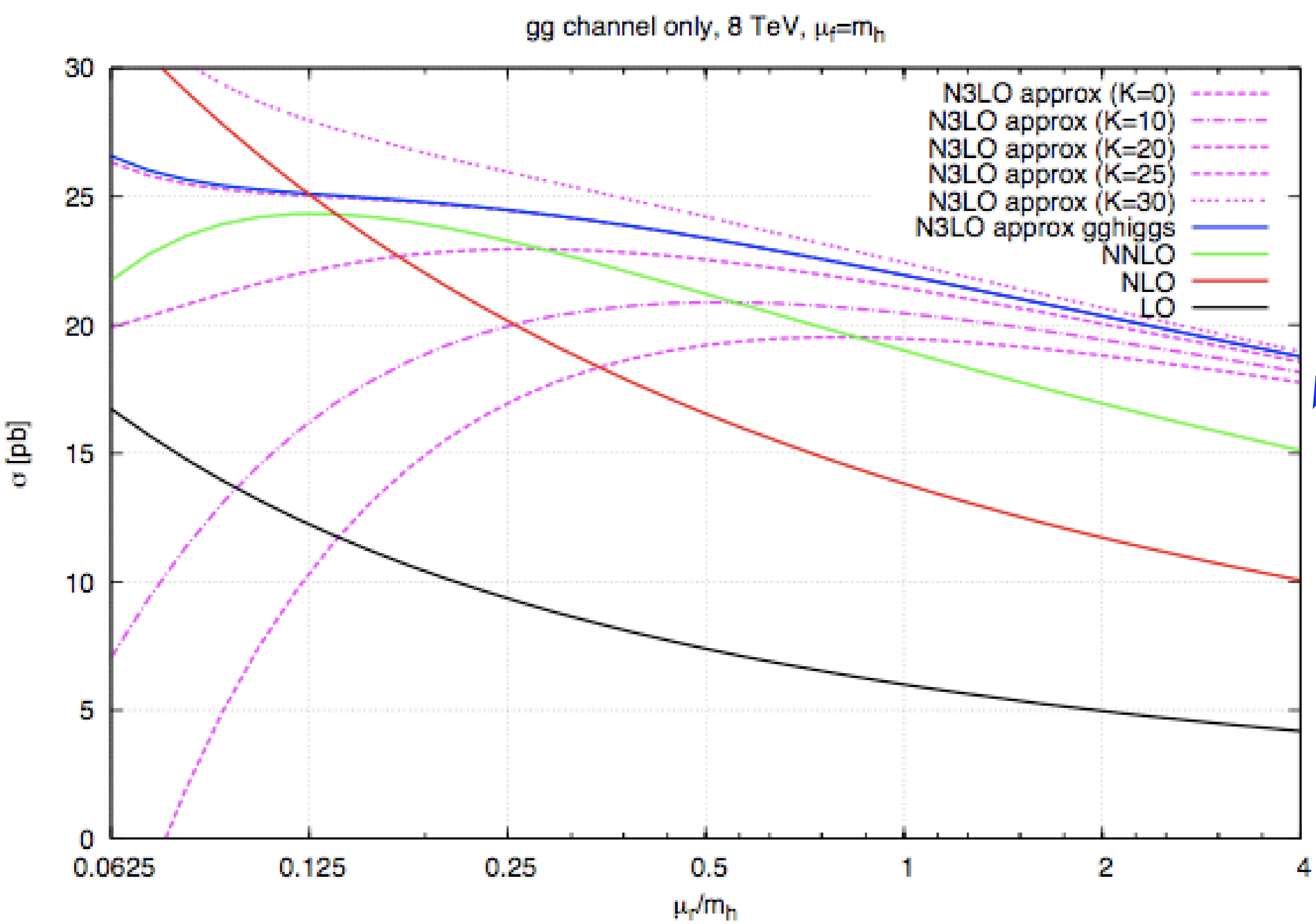


Bonvini et al

- Resumming both soft and BFKL logs leads to greater stability in the cross section, with a similar pattern observed at all energies.

Alternative approximation to N^3LO

- Based on convolution of collinear splitting kernels with lower-order partonic results, to get approximate N^3LO; a step towards a full calculation.
  Buehler and Lazopoulos (2013)



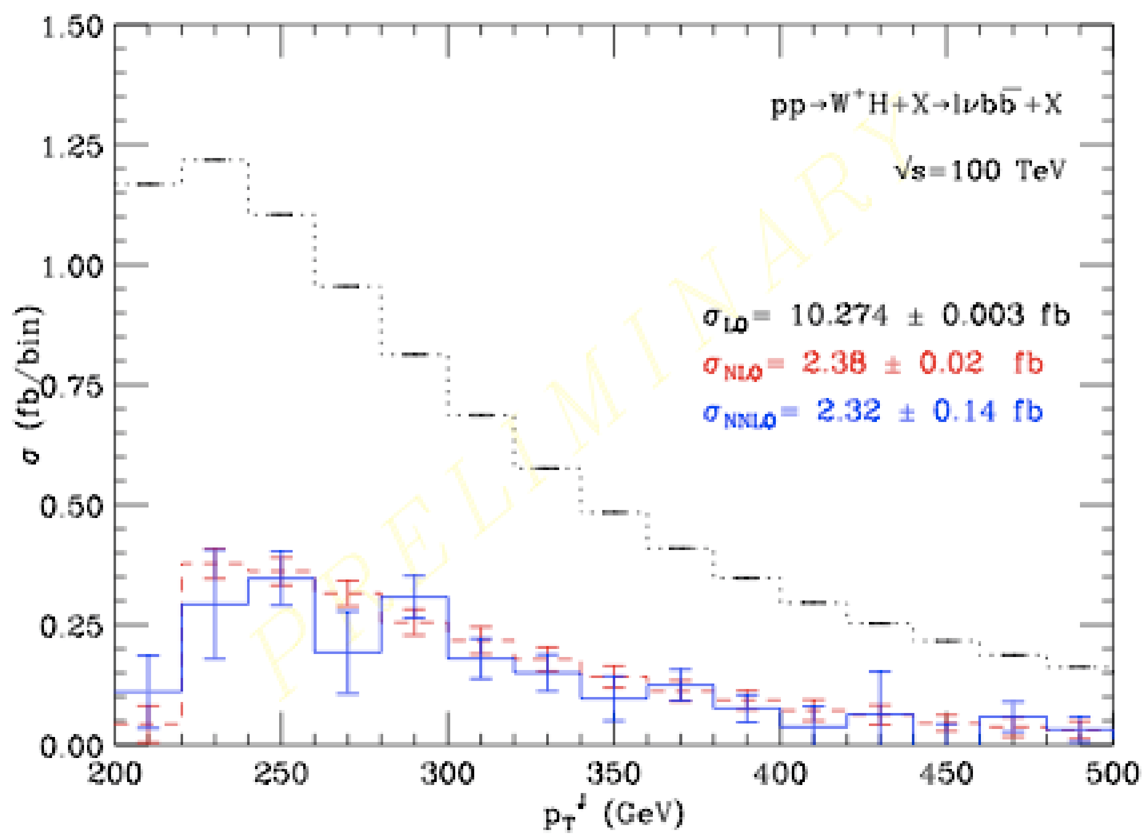
Lack of exact N^3LO parametrized by K

Expect K not much more than 30 (expansion in α_s/π).

K=25 gives very similar results to soft/BFKL resummed result

Other issues

- Typical boost cuts greatly restrict available phase space, affecting perturbative convergence and accuracy of predictions.



Grazzini et al

σ(NLO) ≈ σ(LO) / 4

Resummation should help; studies underway and results may be available soon

- Also under study for MN: improvements in NLO+PS, investigation of importance of BFKL logs in Higgs+jet production at higher energies.

Higgs+jet uncertainties

- A great deal of theoretical work on resumming jet veto logarithms is underway and should lead to a new scheme for estimating uncertainties this year.

Work by different groups

0-jet resummation

- Banfi, Monni, Salam, Zanderighi [1203.5773, 1206.4998]
  - Use QCD NNLL resummation for p_T^H [Bozzi, Catani, Grazzini] plus necessary correction terms to go from p_T^H to $p_T^{\rm jet}$
- Becher, Neubert, Rothen [1205.3806, + updating numerics]
  - Use SCET-II together with "collinear anomaly" treatment to exponentiate rapidity logarithms by hand
- Stewart, FT, Walsh, Zuberi [1206.4312, + to appear]
  - Use SCET-II together with rapidity renormalization group to resum rapidity logs

1-jet resummation

- Liu, Petriello [1210.1906, 1303.4405]
  - Resummation for large $p_{T1}^{\rm jet} \sim m_H$ using SCET-II with rapidity RGE

Frank Tackmann (DESY) | Jet Vetoes/Binning Discussion | 2013-06-06 | 12 / 19

F. Tackmann

Hope for some progress and studies at higher energies by MN

Moving beyond NLO QCD

- A list of the highest-priority higher-order QCD and EW calculations has been compiled.

Process	known	desired	motivation
H	d\sigma @ NNLO QCD d\sigma @ NLO EW finite quark mass effects @ NLO	d\sigma @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H+j	d\sigma @ NNLO QCD (g only) d\sigma @ NLO EW	d\sigma @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H+2j	\sigma_tot(VBF) @ NNLO(DIS) QCD d\sigma(gg) @ NLO QCD d\sigma(VBF) @ NLO EW	d\sigma @ NNLO QCD + NLO EW	H couplings
H+V	d\sigma(V decays) @ NNLO QCD d\sigma @ NLO EW	with H→bb @ same accuracy	H couplings
t\bar tH	d\sigma(stable tops) @ NLO QCD	d\sigma(NWA top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	d\sigma @ LO QCD finite quark mass effects d\sigma @ NLO QCD large m_t limit	d\sigma @ NLO QCD finite quark mass effects d\sigma @ NNLO QCD	Higgs self coupling

Les Houches workshop 2013

Higgs observables here; similar lists for processes involving jets, heavy quarks and vector bosons.

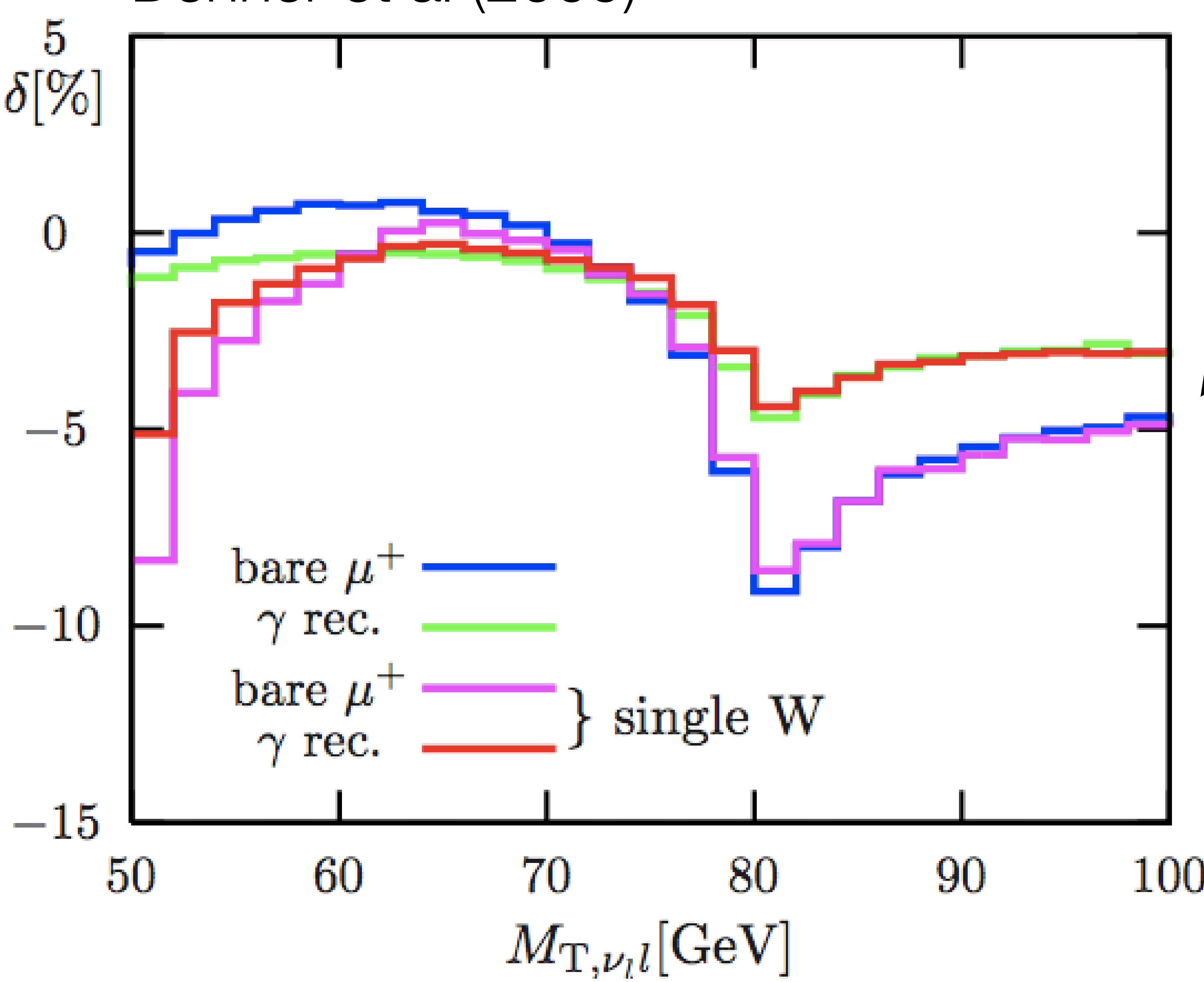
- High priority for:
  - pdfs
  - H bkgs
  - EW structure, TGCs, QGCs
- Key issue: whether QCD and EW corrections factorize or not.

Process	known	desired	motivation
V	d\sigma(lept. V decay) @ NNLO QCD + EW	d\sigma(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V+j	d\sigma(lept. V decay) @ NLO QCD + 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	bkg H → VV TGCs
gg → VV	d\sigma(V decays) @ LO	d\sigma(V decays) @ NLO QCD	bkg to H→VV
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	bgk to VH(→bb)
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'+1jet	d\sigma(V decays) @ NLO QCD	d\sigma(V decays) @ NLO QCD + NLO EW	bkg to H, BSM searches
VV'+2j	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→\gamma \gamma

Factorization of QCD and EW corrections?

- Strong evidence (but not proof) that corrections factorize in gg→H; understood to be due to large threshold corrections.
- Further evidence in W production.

Denner et al (2009)



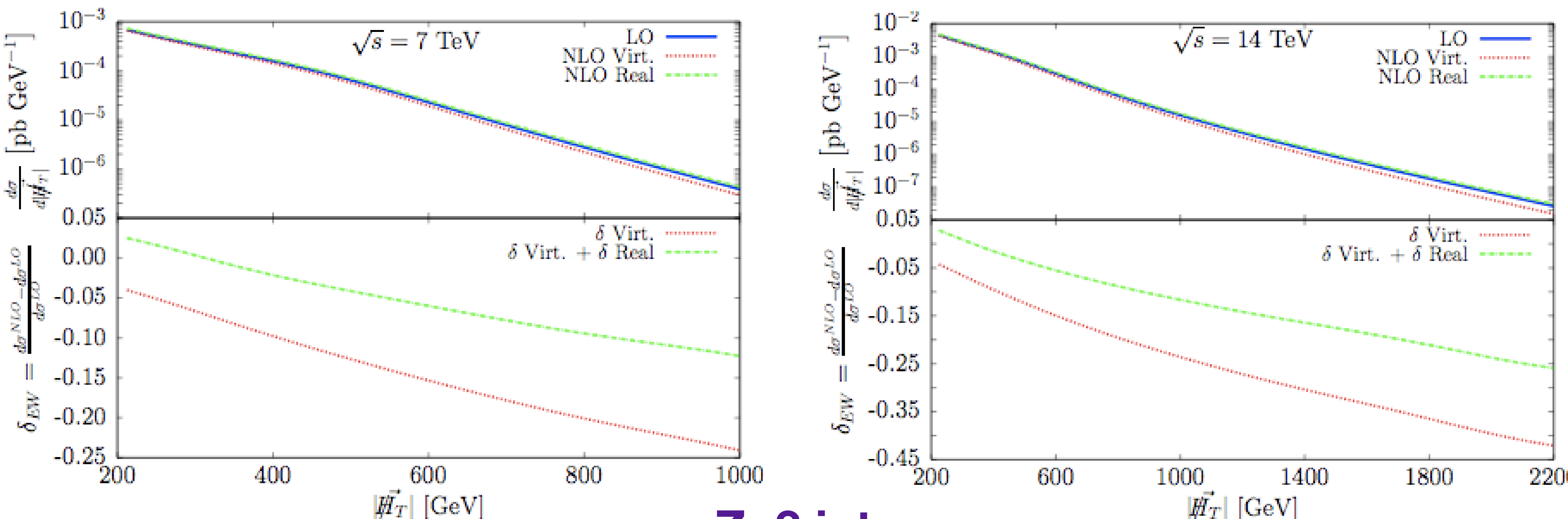
comparison of relative EW corrections in W production (magenta) and W+jet (blue)

corrections almost identical within 20 GeV of resonance → factorization

these two examples may be special, "simple" processes

EW Sudakov logarithms

- In cases where full EW corrections are not known, can appeal to dominance of Sudakov logs when *s* and |*t*| large; the effect of these logs can now be accounted for in ALPGEN.



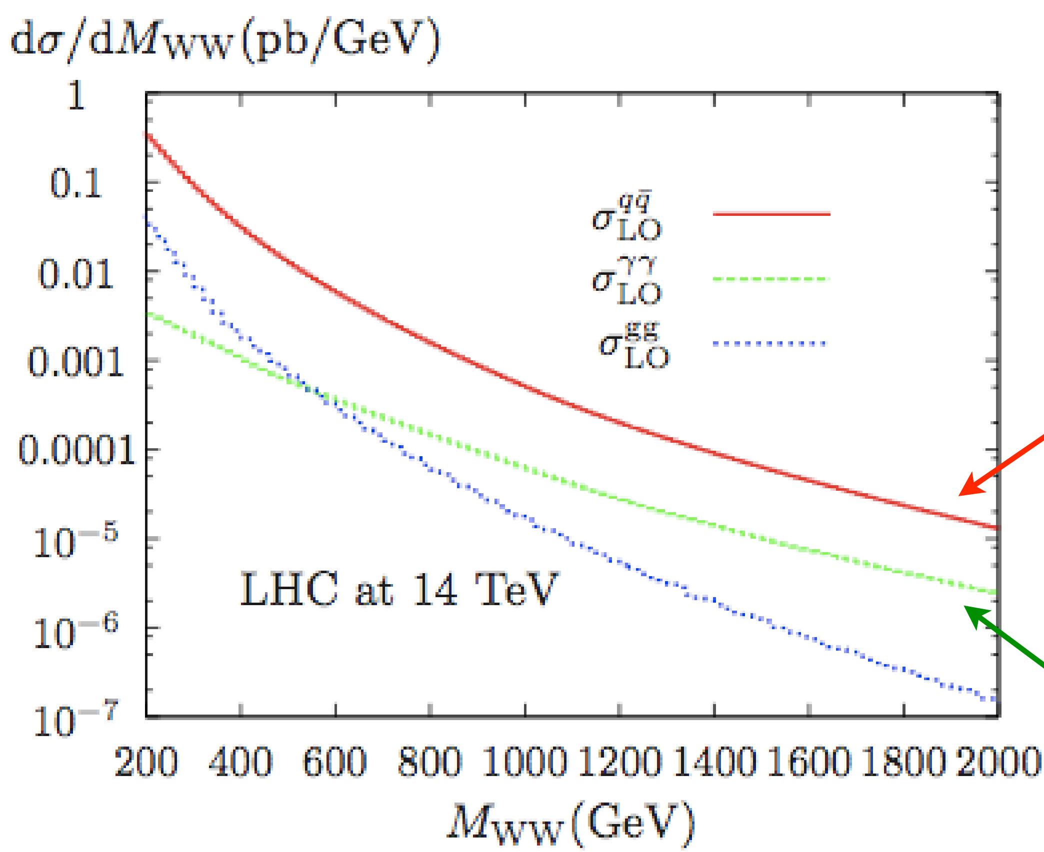
Z+3 jets

Chiesa et al, 2013

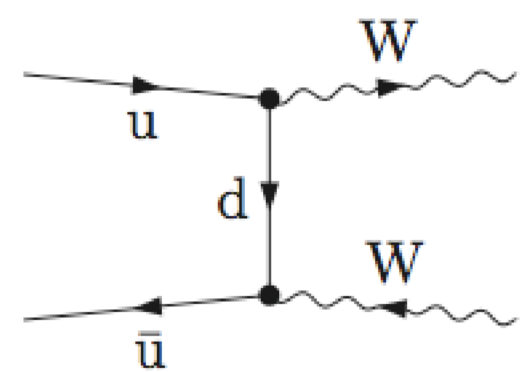
- Effect of these large corrections must be taken into account at higher energies.

Photon pdfs

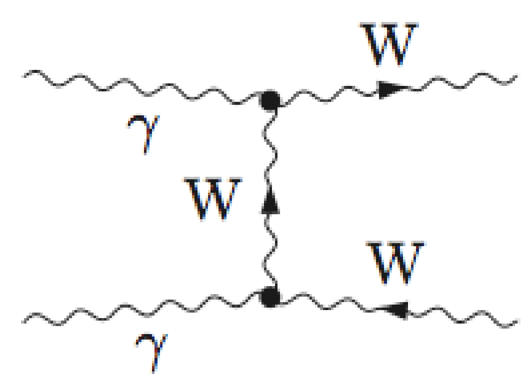
- New pdf sets including photons are being produced by NNPDF and CT for more complete description and for calculating important photon-induced contributions.



Bierweiler et al (2012)



$\hat{\sigma} \sim \log(\hat{s}/m_W^2)/\hat{s}$

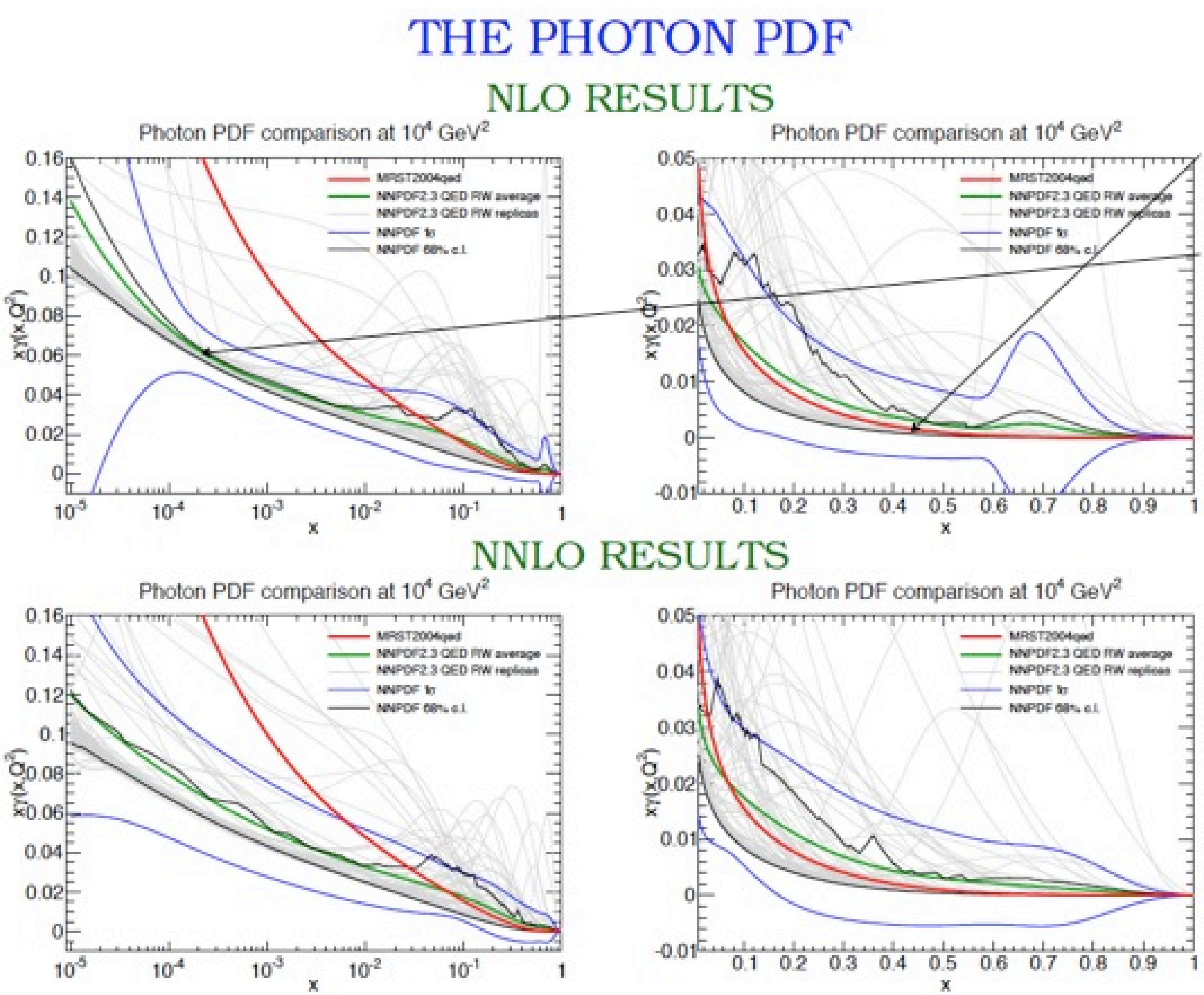


$\hat{\sigma} \sim \mathrm{constant} + 1/\hat{s}$

significant fraction of total WW cross section at large invariant mass

Photon pdf: NNPDF vs MRST

- Important differences found in comparison with (old) MRST set.



Forte, Carrazza

MRST

NNPDF

smaller at low *x* where LHCb data now constrains NNPDF

agreement at large *x* (where impact is largest for WW example)

Between now and MN

- Many studies have yet come to fruition and we hope they will do so over the next few weeks.
- We will hear more about some of them over the next couple of days:
  - Monday afternoon (more detailed update, ongoing studies)
  - Tuesday morning (joint with EW: α_s measurements at e^+e^- colliders, Sudakov logs)
  - Tuesday afternoon (discussion and outlook)