QCD and the Strong Force

Joey Huston

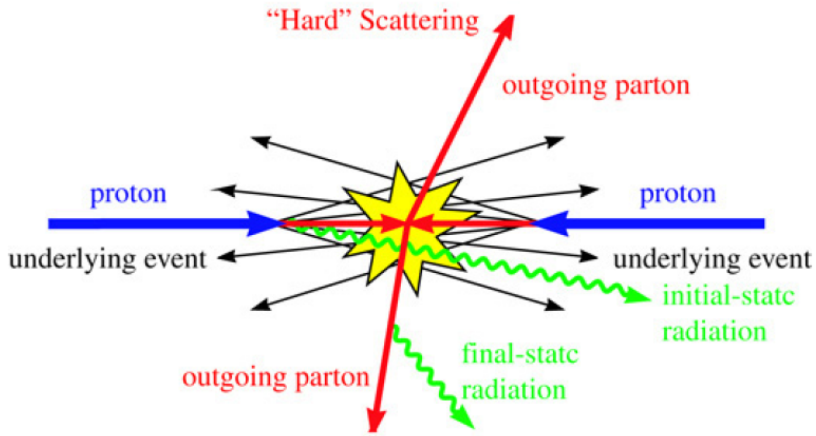
Michigan State University

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 workshop
- 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 this workshop
- We have tried to exploit this synergy at the BNL meeting by having only joint sessions, with EWK, Higgs, top and QCD computing
  - we can talk to ourselves anytime
- Thus, there may be an overlap in slides, but hey I'm going first…

Charge

- The charge for the QCD group (like every other group) is to determine the
  1. current state of the art
  2. what is likely/priority for the next 5 years?
  3. what is likely/priority for longer time scale (20 years)?
- Of course a) is the easiest, b) is less so and parts of c) are in the realm of pure speculation
- We have broken down each question into a series of more definite sub-issues that should be addressed. For details, see my talk at the kickoff meeting at Fermilab.
- This talk will concentrate on issues discussed in this meeting, as well as those that have developed over the course of the last 6 months, both in Snowmass QCD meetings/discussion as well as in (pre-)Les Houches work

…keeping in mind not only the LHC, but…

A. hadron colliders

1. *LHC 13 TeV, 300/fb , spacing: 25 ns (50 ns), pileup: 19 (38) events/crossing*
2. *LHC 13 TeV, 3000/fb (HL-LHC) , spacing: 25 ns, pileup: 95 events/crossing*
3. *LHC 30 TeV, 3000/fb (HE-LHC) , spacing: 50 ns, pileup: 225 events/crossing*
4. *VHE-LHC 100 TeV, 3000/fb, spacing: 50 ns, pileup: 263 events/crossing*
5. *VLHC at 100 TeV, 1000/fb , spacing: 19 ns, pileup: 40 events/crossing*

future machines, especially hadron colliders

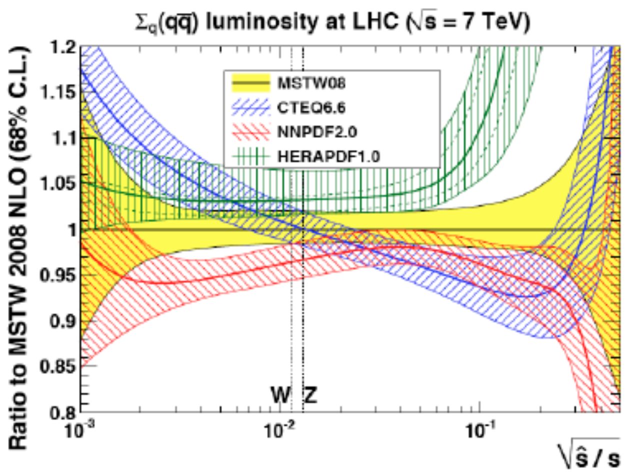
…sorry, not much work on linear colliders so far

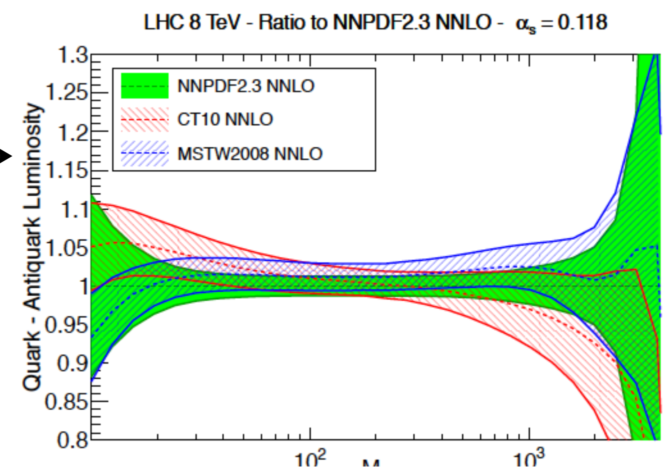
unitarity

pileup numbers are the average number of interactions per crossing at the peak luminosity, as explained

PDFs

- I gave a talk at this meeting on ‘PDFs for the LHC’ reporting specifically on some new benchmark results at NNLO (arXiv:1211.5142)



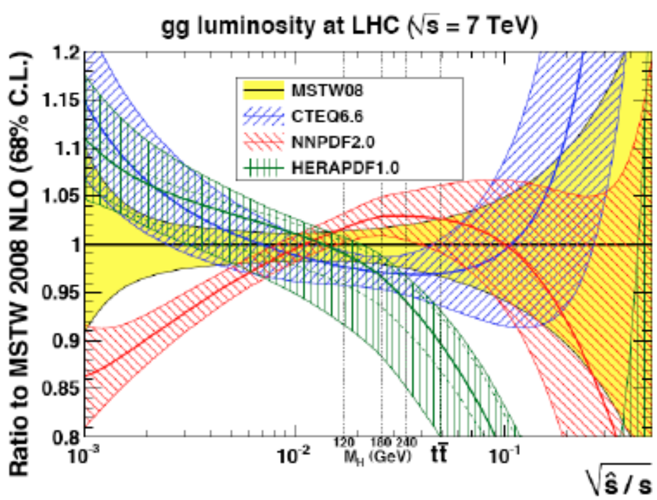


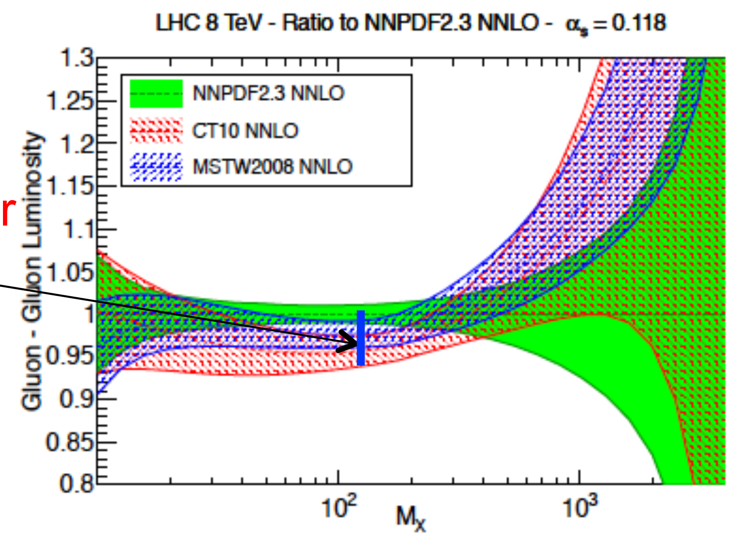
improvements from 2010 to 2012…

…and from NLO to NNLO

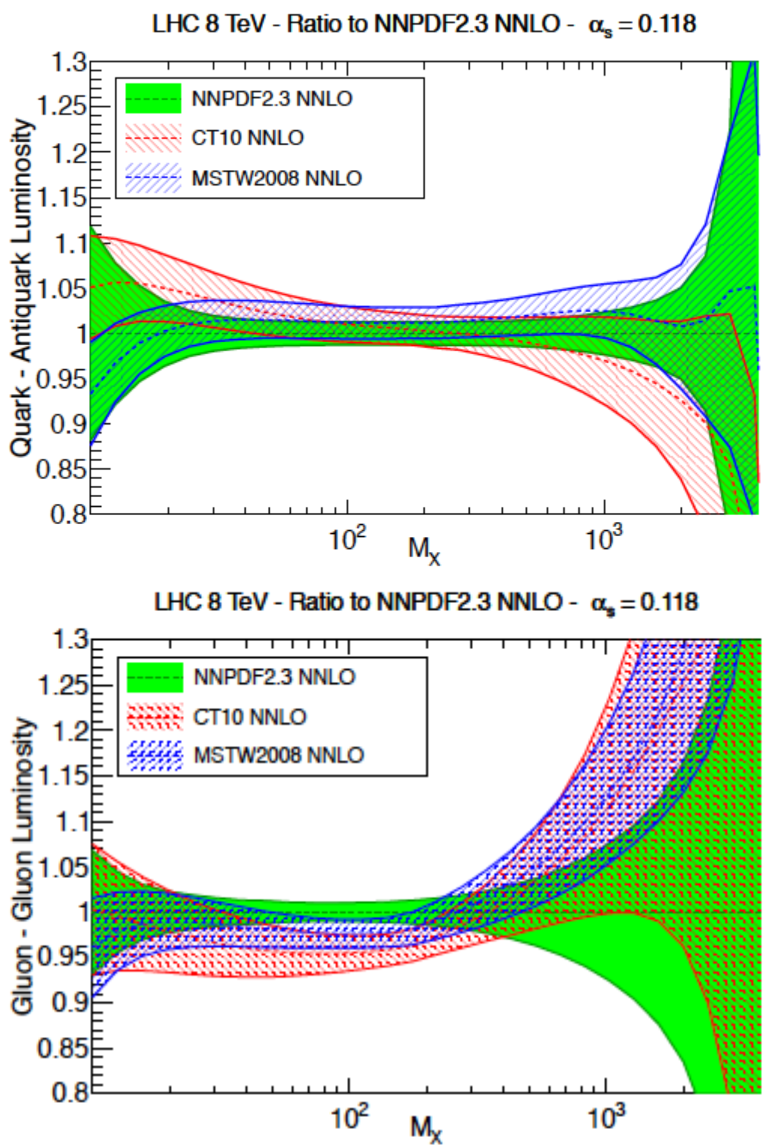
so Higgs PDF uncertainty under good control

α_s uncertainty still +/-0.002



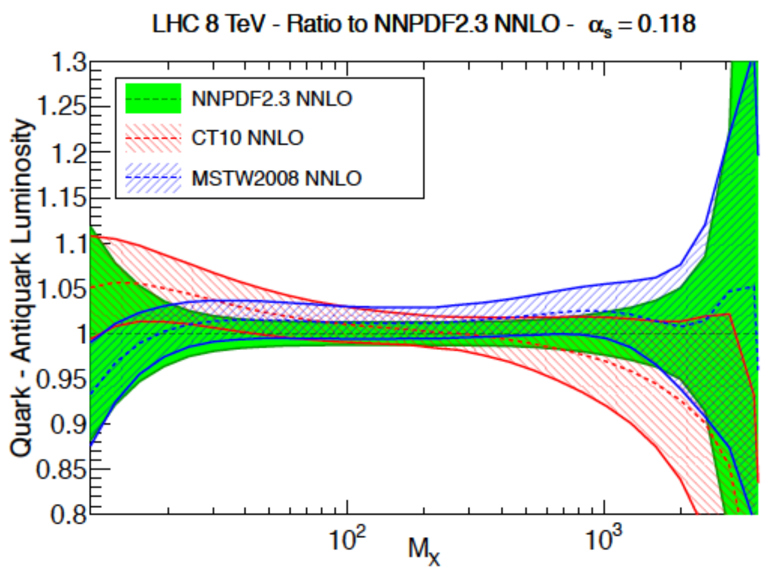


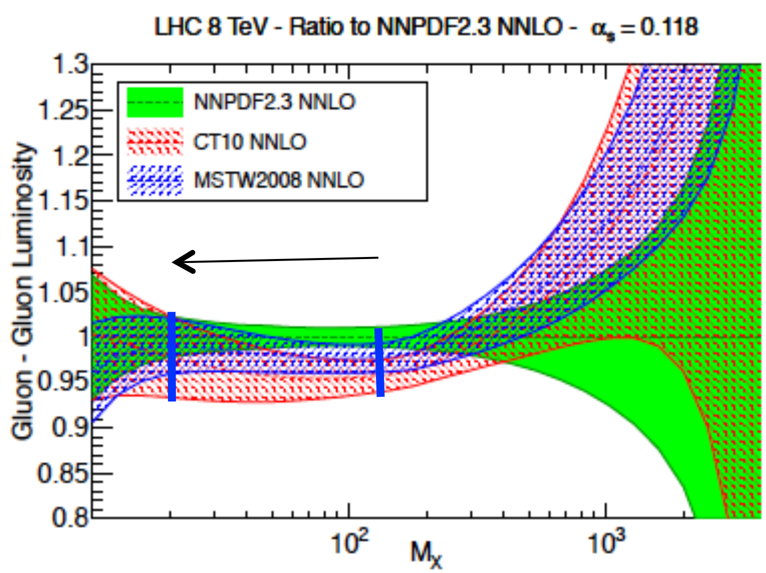
PDFs



- But what about at high mass?
- Are we going to believe a 50% excess at multi-TeV dijet masses, especially if we believe that it's produced by a gg initial state?
- These are 68% CL PDF errors
- We assume that we can extrapolate from 68% to 90%CL (CT PDF uncertainties actually performed at 90%CL)
- What about non-Gaussian behavior going to 95%, 98%?
- CT can use Lagrange Multiplier technique to look at this; NNPDF can use their Monte Carlo approach
- This is something we will do for the Snowmass report

PDFs



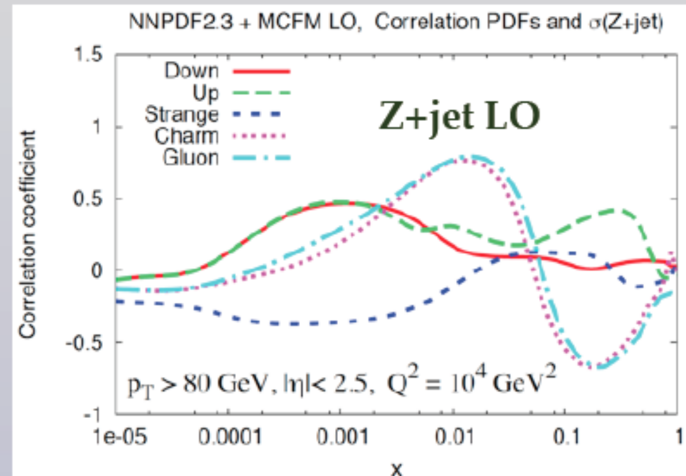


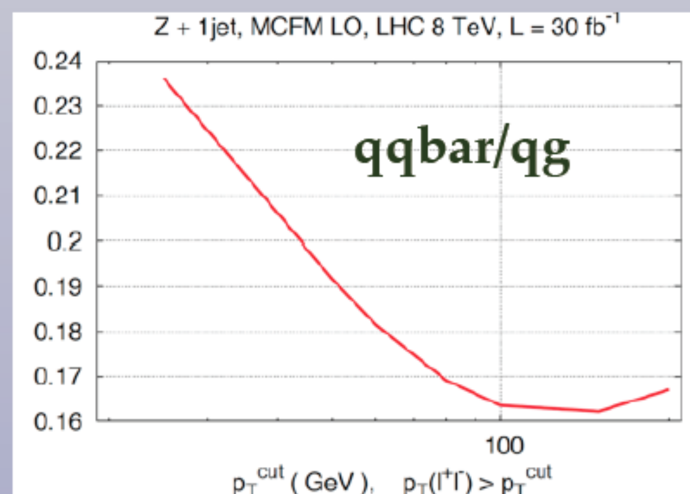
- What about uncertainties for higher energies
  - 13 TeV
  - 33 TeV
  - 100 TeV
- To first order, can just rescale horizontal axis for the plots to the left
  - but uncertainties do decrease with increasing Q^2
- So this is an approximation of the gg uncertainty for gg->Higgs (125 GeV) at 33 TeV
- We can calculate exactly the uncertainties for the different energies
- This is something we will do for the Snowmass writeup

Using LHC data to improve PDF precision

New avenues to the gluon (I)

- In global PDF fits, the **gluon** is directly constrained by **jet data** only (and HERA at small-x)
- Jets are NLO with **large scale uncertainties** (though NNLO close, **arxiv:1301.7310**), and experimental errors substantial because of the **JES**
- Given the crucial role of the gluon for LHC physics, **complementary LHC observables directly sensitive the gluon** would be beneficial
- One possibility is **Z/W boson production at large pT** (in association with jets). Cross section > 80% **dominated by gluon-quark scattering** (ISR of extra jets gluon dominated)
- The measurement can be only with leptons (double differential in pT and rapidity), thus with **very small systematic errors**
- Statistical errors will be negligible
- This measurement will be equivalent to **measuring the partonic luminosity relevant for gg > H**





correlated systematic error information crucial

…and the experimental precision achieved for tT production at the LHC, plus the completion of the NNLO tT cross section means that top production is an important PDF benchmark

…but we need NNLO tT differential cross sections for full exploitation

Uta Klein: 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'.

…no real improvement in α_s uncertainty, though, IMHO

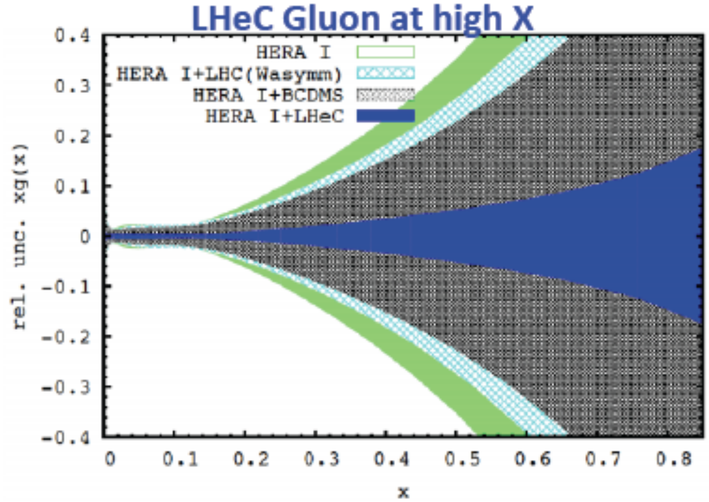
Do we need an LHeC?

PDFs at the LHeC

- PDFs are essential for precision physics at the LHC :
  - **one of the main theory uncertainties in Higgs production**
  - Measurements at high pT, high invariant masses, sensitive to new physics effects, have significant PDF uncertainties (high x)

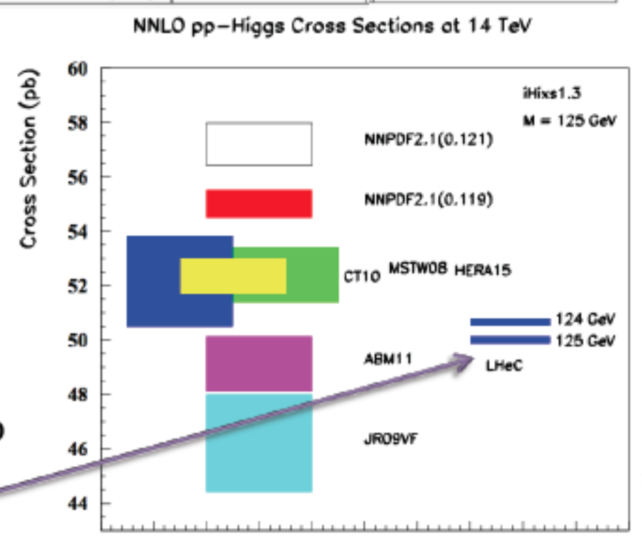
- LHeC could provide a complete PDF set with precise gluon, valence at high x, as well as strong coupling

LHeC Gluon at high X



LHeC promises per mille accuracy on alphas!

case	cut $[Q^2$ in GeV$^2]$	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26



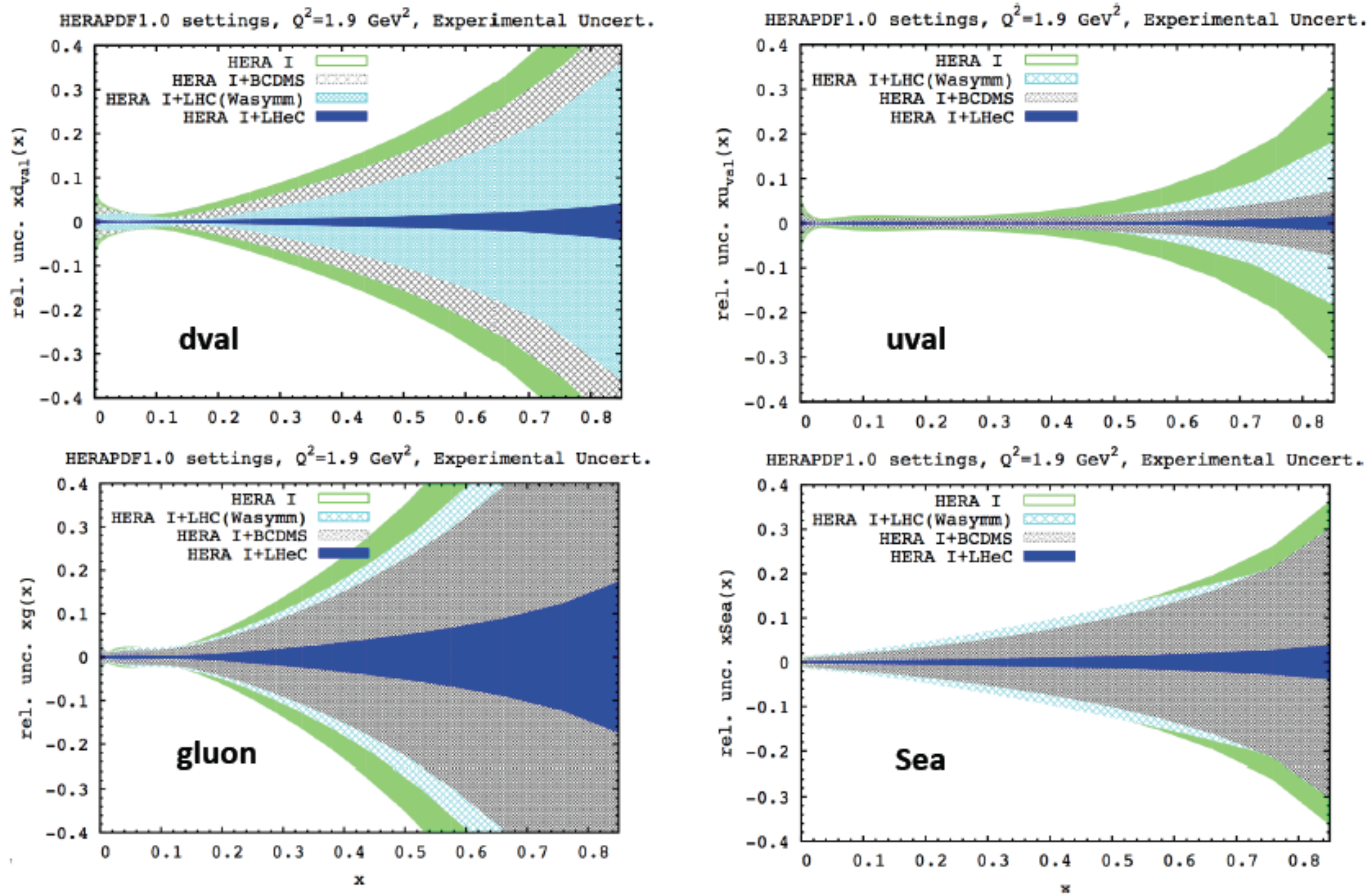
At the LHeC , Higgs is cleanly produced via ZZ or WW fusion, complementary to the dominant gg fusion at pp

- precision from LHeC can add a significant constraint on MH

Voica Radescu (see also Max Klein at https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=226756)

Impact of LHeC on PDFs: zoom on high x

* Experimental uncertainties are shown at the starting scale $Q^2=1.9$ GeV^2



- Les Houches NLO wishlist, started in 2005, and incremented in 2007 and 2009 was officially closed in 2011, since all of the calculations on the list were complete, and there are no technical impediments towards calculations of new final states, either with dedicated or semi-automatic calculations
- Note that dedicated calculations can be factors of 10 faster than semi-automatic

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [27, 28]; Campbell/Ellis/Zanderighi [29]. ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [30] WZ jet, $W\gamma$ jet completed by Campanario et al. [31, 32]
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [33]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [34, 35] Interference QCD-EW in VBF channel [36, 37]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [38] and WWZ by Hankele/Zeppenfeld [39], see also Binoth/Ossola/Papadopoulos/Pittau [40] VBFNLO [41, 42] meanwhile also contains $WWW, ZZW, ZZZ, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma, W\gamma\gamma j$ [43, 44, 45, 46, 47, 21]
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [48, 49] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [50]
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa [51] and Rocket [52] collaborations Z+3jets by Blackhat/Sherpa [53]
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek [54, 55]
7. $pp \to VV\,b\bar{b}$,	Pozzorini et al. [25], Bevilacqua et al. [23]
8. $pp \to VV$+2jets	W^+W^++2jets [56], W^+W^-+2jets [57, 58], VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [59, 60, 61]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al. [62, 63]
NLO calculations added to list in 2009	
10. $pp \to V$ + 4 jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets [22], Z+4jets [20] see also HEJ [64] for $W + n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier [11]
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
also completed: $pp \to W\gamma\gamma$ jet	Campanario/Englert/Rauch/Zeppenfeld [21]
$pp \to$ 4 jets	Blackhat/Sherpa [19]

Table 1: The updated experimenter's wishlist for LHC processes

For Snowmass report

- Calculate cross sections (LO and NLO, and in some cases NNLO) and uncertainties for a number of benchmark cross sections for higher energy pp accelerators
- Use MCFM for starters

What's next for the Les Houches NLO wishlist?

- Nothing: I've retired the NLO wishlist
- It's being replaced by a NNLO wishlist plus a wishlist for EW corrections for hard processes

Below we construct a table of calculations needed at the LHC, and which are feasible within the next few years. Certainly, results for inclusive cross sections at NNLO will be easier to achieve than differential distributions, but most groups are working towards a partonic Monte Carlo program capable of producing fully differential distributions for measured observables.

- $t\bar{t}$ production: done
  needed for accurate background estimates, top mass measurement, top quark asymmetry (which is zero at tree level, so NLO is the leading non-vanishing order for this observable, and a discrepancy of theory predictions with Tevatron data needs to be understood). Several groups are already well on the way to complete NNLO results for $t\bar{t}$ production [84, 85, 86, 87].
- W^+W^- production:
  importand background to Higgs search. At the LHC, $gg \to WW$ is the dominant subprocess, but $gg \to WW$ is a loop-induced process, such that two loops need to be calculated to get a reliable estimate of the cross section. Advances towards the full two-loop result are reported in [88, 89].
- inclusive jet/dijet production: gg done; full by end of year?
  NNLO parton distribution function (PDF) fits are starting to become the norm for predictions and comparisons at the LHC. Paramount in these global fits is the use of inclusive jet production to tie down the behavior of the gluon distribution, especially at high x. However, while the other essential processes used in the global fitting are known to NNLO, the inclusive jet production cross section is only known at NLO. Thus, it is crucial for precision predictions for the LHC for the NNLO corrections for this process to be calculated, and to be available for inclusion in the global PDF fits. First results for the real-virtual and double real corrections to gluon scattering can be found in [90, 91].

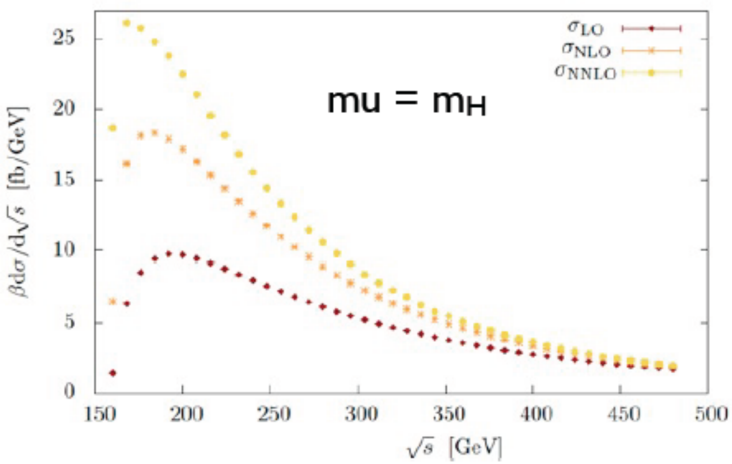
NNLO wishlist: continued

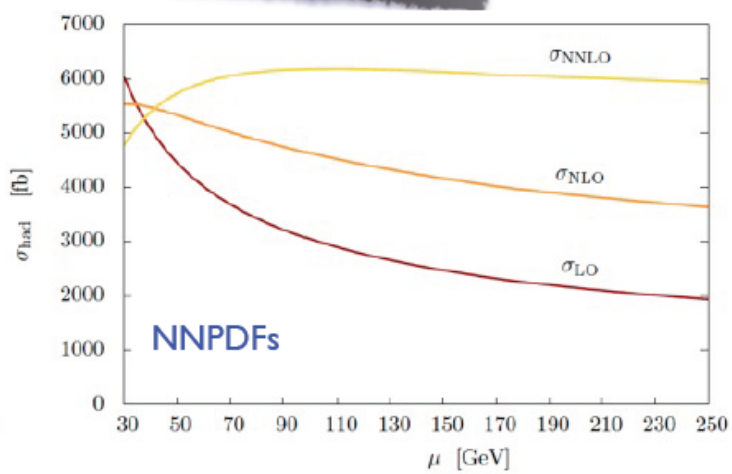
- V+1 jet production: <2 years
  $W/Z/\gamma$ + jet production form the signal channels (and backgrounds) for many key physics processes, for both SM and BSM. In addition, they also serve as calibration tools for the jet energy scale and for the crucial understanding of the missing transverse energy resolution. The two-loop amplitudes for this process are known [92, 93], therefore it can be calculated once the parts involving unresolved real radiation are available.
- V+γ production: by end of year?
  important signal/background processes for Higgs and New Physics searches. The two-loop helicity amplitudes for $q\bar{q} \to W^{\pm}\gamma$ and $q\bar{q} \to Z^{0}\gamma$ recently have become available [94].
- Higgs+1 jet production: gg done; full by end of year?
  As mentioned previously, events in many of the experimental Higgs analyses are separated by the number of additional jets accompanying the Higgs boson. In many searches, the Higgs + 0 jet and Higgs + 1 jet bins contribute approximately equally to the sensitivity. It is thus necessary to have the same theoretical accuracy for the Higgs + 1 jet cross section as already exists for the inclusive Higgs cross section, i.e. NNLO. The two-Loop QCD Corrections to the Helicity Amplitudes for $H \to 3$ partons are already available [95].

Radja Boughezal

arXiv:1303.4405

H+jet @ NNLO: gg-channel





$$\sigma_{LO}(pp \to Hj) = 2713^{+1216}_{-776} \text{ fb},$$
$$\sigma_{NLO}(pp \to Hj) = 4377^{+760}_{-738} \text{ fb},$$
$$\sigma_{NNLO}(pp \to Hj) = 6177^{-204}_{+242} \text{ fb}.$$

$\sigma_{NLO}/\sigma_{LO} = 1.6$

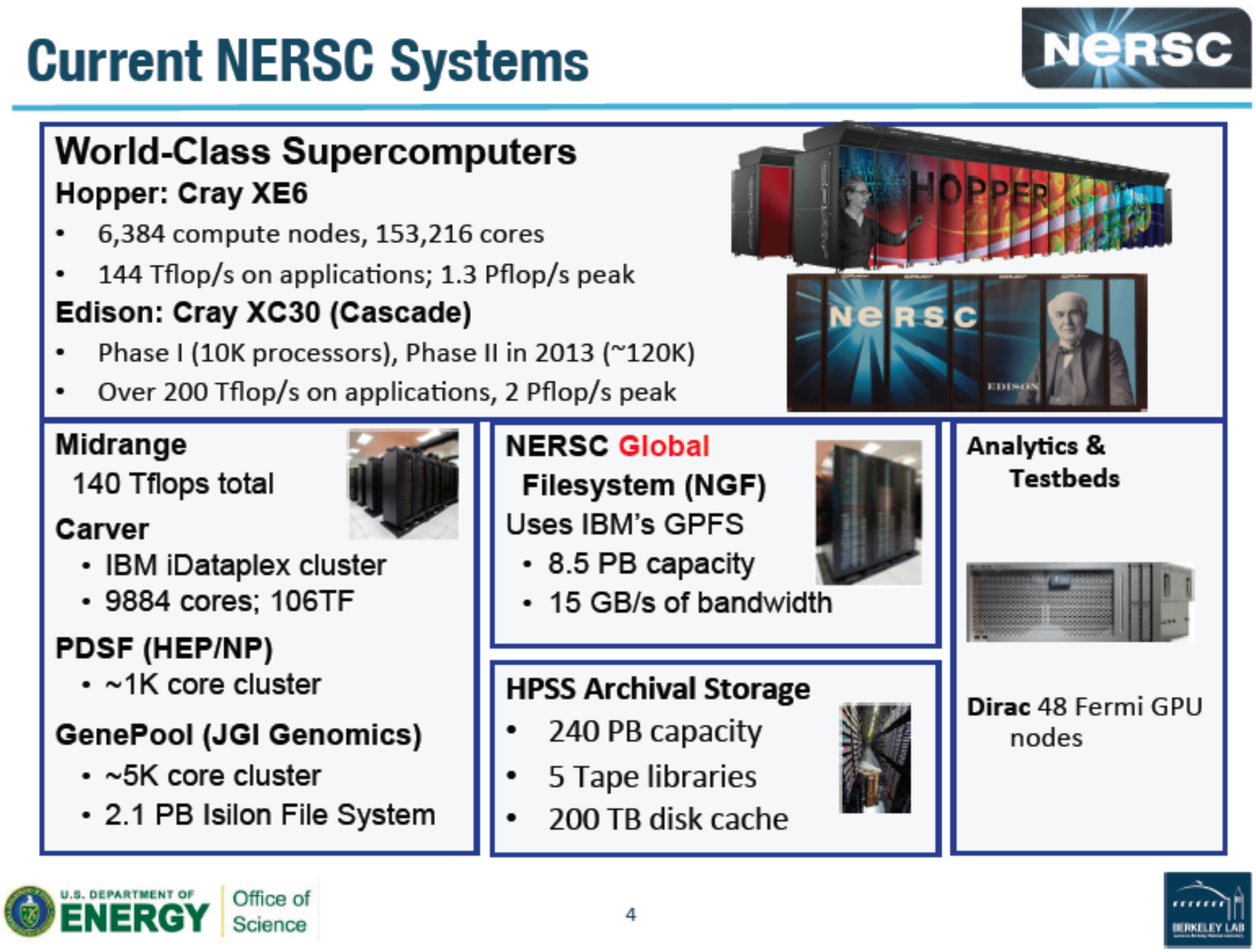
$\sigma_{NNLO}/\sigma_{NLO} = 1.3$

so sizeable increase of cross section in going to NNLO

clear implications for Higgs+jets studies going on by ATLAS and CMS

what can we guess for Higgs + 2 jets?

Richard Gerber



higher order calculations very CPU-intensive

we're not making as much use of existing HPC resources as we could

Higgs+jets (binned cross sections)

Uncertainties

Jianming Qian

Scale uncertainties of cross sections in exclusive jet bins are calculated

- assuming uncertainties of inclusive jet cross sections

  $\varepsilon_{\geq 0}, \quad \varepsilon_{\geq 1}, \quad \varepsilon_{\geq 2}$

  are independent (Stewardt and Tackmann: Phys. Rev. D85 (2012) 034011)

- and propagated from the following equations

  $$\sigma_0 = \sigma_{\geq 0} - \sigma_{\geq 1}; \quad \sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}; \quad \sigma_2 = \sigma_{\geq 2}$$

The actual implementation is described in the joint ATLAS/CMS note:
ATL-PHYS-PUB-2011-818

Procedure for the LHC Higgs boson search combination in summer 2011

(LHC Higgs Combination Group Report)

The ATLAS and CMS collaboration and the Higgs Combination group

July 20, 2011

since cross sections are uncorrelated, add in quadrature

125 GeV at 8 TeV with ATLAS jet selection

jet bin (n)	jet fraction (f_n)	Uncertainties Inclusive ($\epsilon_{\geq n}$)	Uncertainties Exclusive (ϵ_n)
$n = 0$	0.614	0.078	0.170
$n = 1$	0.267	0.202	0.370
$n = 2$	0.119	0.697	0.697

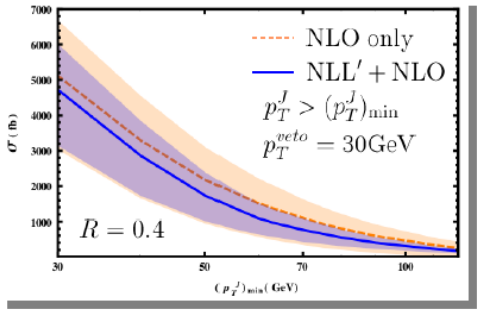
(Uncertainties are symmetrized in the implementation)

uncertainties for exclusive (fixed order) cross sections can be much larger than for inclusive cross sections

Higgs+jets (binned cross sections)

Progress Xiaohui Liu

- Numerical consequence
  - Higgs + 1j
    - Entire Spectrum
      - Conservative error estimation
      - Up to 25% reduction in the uncertainty



resummation for Higgs + 0 jet and for Higgs + 1 jet has lead to sizeable reduction in scale uncertainty

m_H (GeV)	p_T^{veto} (GeV)	$\sigma_{\rm NLO}$ (pb)	$\sigma_{\rm NLL'+NLO}$ (pb)	$f^{1j}_{\rm NLO}$	$f^{1j}_{\rm NLL'+NLO}$
124	25	$5.92^{+35\%}_{-46\%}$	$5.62^{+29\%}_{-30\%}$	$0.299^{+38\%}_{-49\%}$	$0.283^{+33\%}_{-34\%}$
125	25	$5.85^{+34\%}_{-46\%}$	$5.55^{+29\%}_{-30\%}$	$0.300^{+37\%}_{-49\%}$	$0.284^{+33\%}_{-33\%}$
126	25	$5.75^{+35\%}_{-46\%}$	$5.47^{+30\%}_{-30\%}$	$0.300^{+38\%}_{-49\%}$	$0.284^{+34\%}_{-33\%}$
124	30	$5.25^{+31\%}_{-41\%}$	$4.83^{+29\%}_{-29\%}$	$0.265^{+35\%}_{-43\%}$	$0.244^{+33\%}_{-33\%}$
125	30	$5.19^{+32\%}_{-41\%}$	$4.77^{+30\%}_{-29\%}$	$0.266^{+35\%}_{-43\%}$	$0.244^{+33\%}_{-33\%}$
126	30	$5.12^{+32\%}_{-41\%}$	$4.72^{+30\%}_{-29\%}$	$0.266^{+35\%}_{-43\%}$	$0.246^{+33\%}_{-32\%}$

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XL and Petriello'12, XL and Petriello'13

ımmary

- Formalism to understanding jet bin cross section has been established (not only Higgs)
- More reliable prediction and reduced theory uncertainty
- Error estimation should be revised using the resummed results for higgs + 0j and higgs +1j
- Fine tuning work worth probing (higher accuracy, log(R) issue, non-global logs, etc..)

we need to revisit the formulation of the uncertainties for binned jet Higgs cross sections

this is a task for Snowmass/ Les Houches ←

also investigate jet veto effects for higher energy accelerators

NLO ME+PS

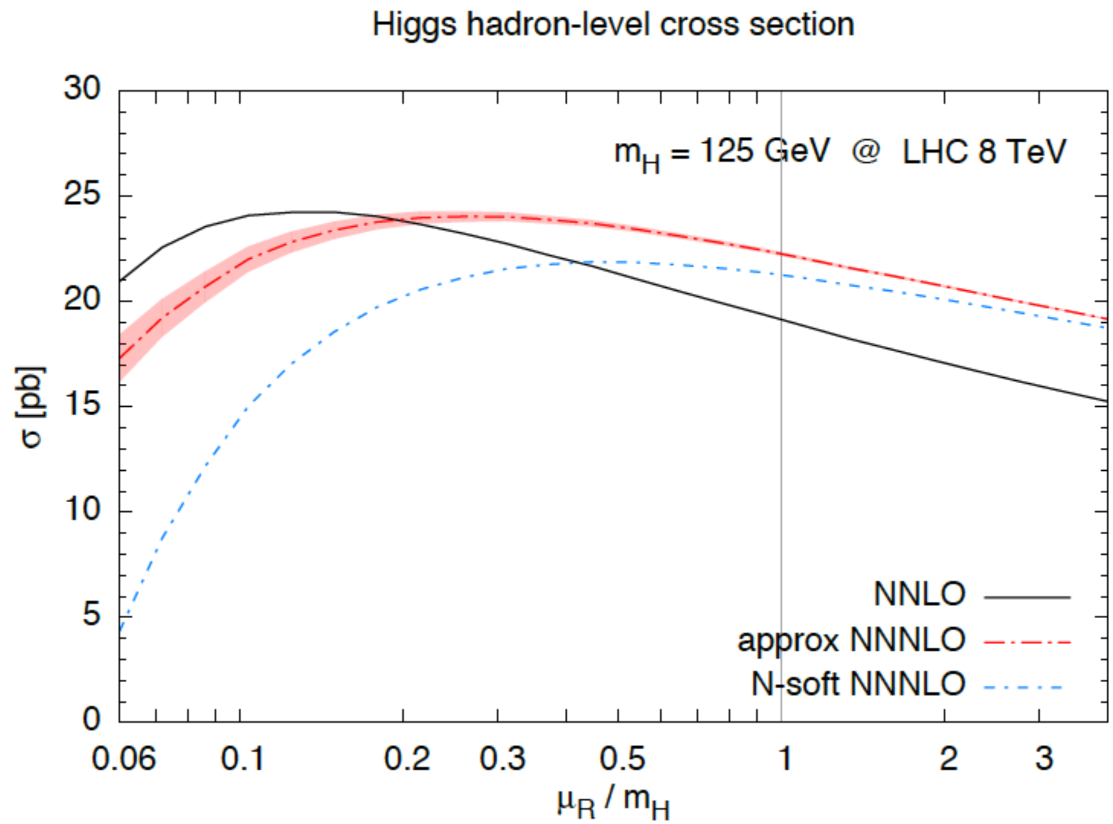
- There are several frameworks now, such as Sherpa and aMC@NLO, in which multiple jets can be included at NLO, with additional jets at LO, with additional additional jets via the parton shower
- For example, Higgs + 0, 1 and 2 jets at NLO, with up to 3 additional jets at LO (matrix element) in Sherpa
- The result is a MC dataset similar to what is seen in the data, with a NLO(+NLL) accuracy
- This is a good framework to try to further understand Higgs cross sections plus their uncertainties
- Snowmass + Les Houches project->do the above

Beyond NNLO

- Note the considerable flattening of the scale uncertainty at approximate NNNLO
- Note also the importance of including BFKL logs in addition to soft logs
- Note also that the net result is an increase in the (gg->) Higgs cross section that we currently use for our comparisons
- Snowmass+Les Houches project: investigate effects of BKFL logs in resummation for the higher energy accelerators, plus the explicit expected effects of BFKL logs in hard scattering processes, a la HEJ, compared to fixed order predictions for multi-jet final states, such as from Blackhat+Sherpa

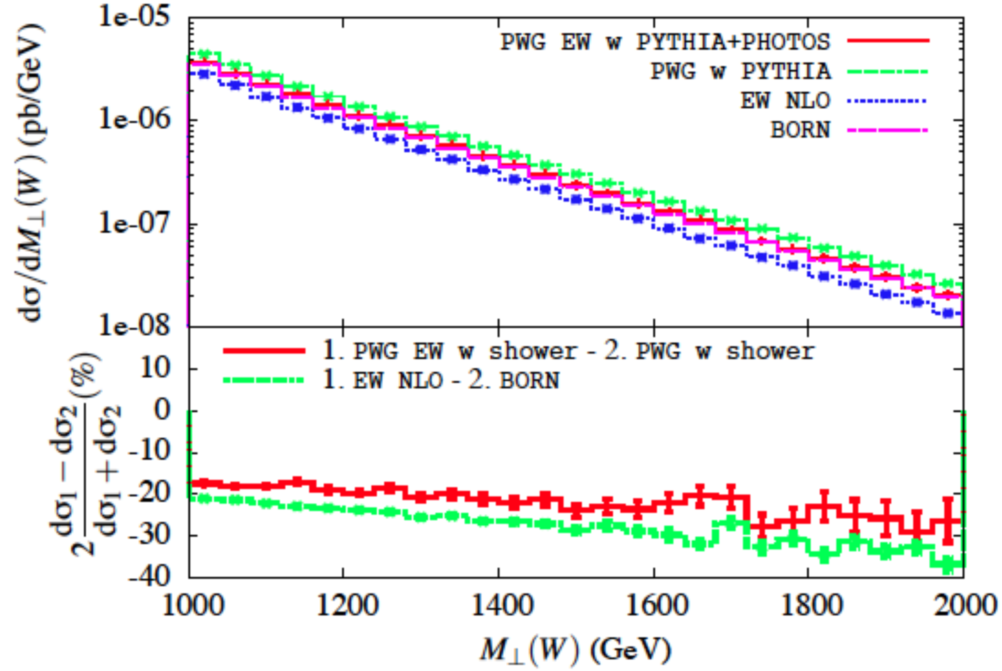
Plot produced by Marco Bonvini

Paper==‘Higgs production in gluon fusion beyond NNLO’, R. Ball et al; arXiv:1303.3590



QCD+EWK

- How well do we know the DY cross section for a mass of 2 TeV?
- Would we recognize a real deviation from SM, say a broad resonance, if we saw it?



Brookhaven, Ap

Uta Klein

A wish list for discussion & studies

.. some tasks are already under study also in LPCC and EW experimental and theory WG's

- ❖ Numerical stability of NNLO and NLO calculations, e.g. issues related to choice of symmetric p_T cuts, intrinsic integration settings, and the case of fine bins and high precision (→ smaller than exp. uncertainties, so <0.5% per bin), etc.
- ➔ "optimal" choice (and documentation) of EW parameters and SM inputs
- ➔ high precision (<0.1% per bin) "APPLgrids at NNLO" .. ?
- ❖ Precision evaluation of missing HO EW (ISR, interferences, weak) corrections and QED FSR modelling; application of missing HO EW corrections and remaining systematics
- ❖ Uncertainties due to further missing HO QCD effects as usually estimated by "scale uncertainties" → realistic prescription for NNLO (CPU time!)
- ❖ Improved modelling of p_T(W,Z) : implementation of resummation into NLO MC models (but e.g also control of resummation scale)
- ❖ Improved modelling and measurement proposals for non-resonant photon-induced dilepton productions, but also for the NLO gamma-p induced dilepton and W productions
- ❖ Improved modelling of real W and Z radiation beyond LO approach outlined by U.Baur, arXiv:hep-ph/0611241

QCD+EWK effects

A. Vicini: there has been a great deal of progress in the last few years, but all of the separate pieces have not been put together in a common framework, allowing a 'best' estimate of cross sections and uncertainties

Perturbative expansion of the Drell-Yan cross section

$$\sigma_{tot} = \sigma_0 + \boxed{\alpha_s \sigma_{\alpha_s} + \alpha_s^2 \sigma_{\alpha_s^2}} + \dots$$
$$+ \boxed{\alpha \sigma_\alpha} + \boxed{\alpha^2 \sigma_{\alpha^2}} + \dots$$
$$+ \boxed{\alpha\alpha_s \, \sigma_{\alpha\alpha_s}} + \alpha\alpha_s^2 \, \sigma_{\alpha\alpha_s^2} + \dots$$

Fixed order corrections exactly evaluated and available in simulation codes
Subsets of corrections partially evaluated or approximated

O(α²)
- EW Sudakov logs J.Kühn, A.Kulesza, S.Pozzorini, M.Schulze, Nucl.Phys.B797:27-77,2008, Phys.Lett.B651:160-165,2007, Nucl
- QED LL
- QED NLL (approximated)
- additional light pairs (approximated)

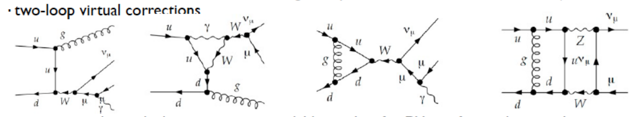
O(αα_s)
- EW corrections to ffbar+jet production
- QCD corrections to ffbar+gamma production

A.Denner, S.Dittmaier, T.Kasprzik, A.Mueck, arXiv:0909.39

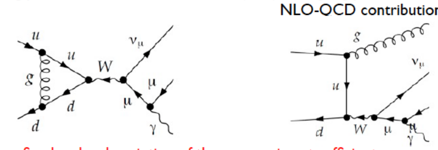
Mixed QCDxEW corrections the Drell-Yan cross section

$\sigma_{tot} = \sigma_0 + \alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2} + \dots + \alpha\sigma_\alpha + \alpha^2\sigma_{\alpha^2} + \dots + \boxed{\alpha\alpha_s\,\sigma_{\alpha\alpha_s}} + \alpha\alpha_s^2\,\sigma_{\alpha\alpha_s^2} + \dots$

- The first mixed QCDxEW corrections include different contributions:
  - emission of two real additional partons (one photon + one gluon/quark)
  - emission of one real additional parton (one photon with QCD virtual corrections, one gluon/quark with EW virtual corrections)
  - two-loop virtual corrections



- an exact complete calculation is not yet available, neither for DY nor for single gauge boson production
  W.B. Kilgore, C. Sturm, arXiv:1107.4798
- The bulk of the mixed QCDxEW corrections, relevant for a precision MW measurement, is factorized in QCD and EW contributions:
  (leading-log part of final state QED radiation) X (leading-log part of initial state QCD radiation || NLO-QCD contribution to the K-factor)



In any case, a fixed order description of the process is not sufficient...

Alessandro Vicini - University of Milano   Brookhaven, April 4th 2013

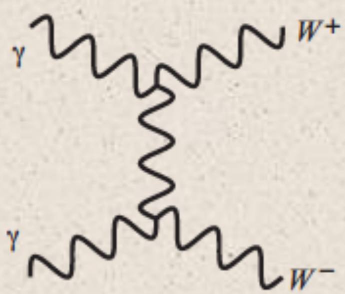
9

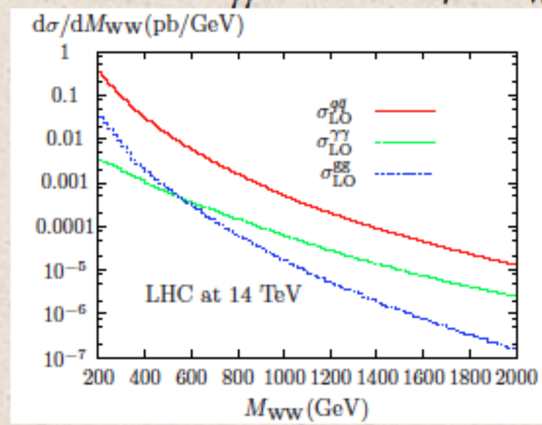
Les Houches project: put those pieces together

Photon PDFs: Carl Schmidt

2) Photon induced processes can be kinematically enhanced.

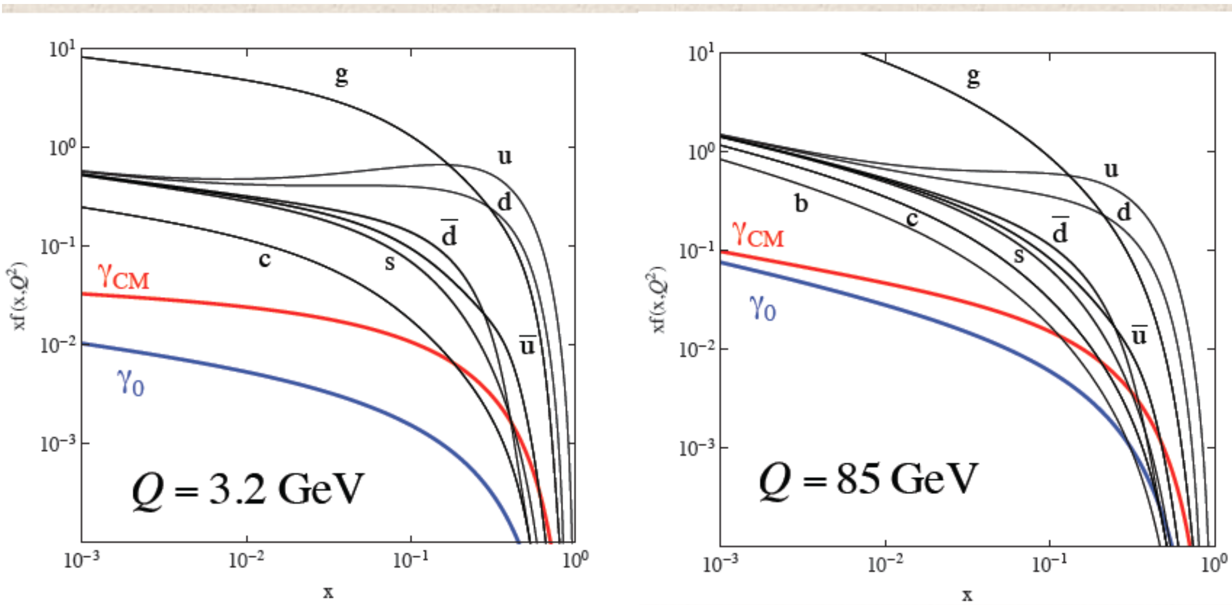
$\gamma\gamma \rightarrow W^+W^-$ asymptotically $\hat{\sigma}_{\gamma\gamma} \approx 8\pi\alpha^2/M_W^2$





significant fraction of high mass WW pairs from γγ, even after kinematic cuts

Bierweiler et al., JHEP 1211 (2012) 093



photon PDFs can be larger than anti-quarks at high x

the LHC (and higher energy machines) is a γγ factory

Snowmass+Les Houches project: investigate this

The future looks bright

- …but the future also looks busy
- Given the schedule presented, much of this work needs to be done before Les Houches (June 3-23)
- We'll be calling you
- But much of it will also be done at Les Houches and after
- And if it doesn't make it into the Snowmass report, it will make it into the Les Houches proceedings
  - ~Feb 2014
- Our next meeting will be after Loopfest on May 16 (Florida State)
- I'll also try to organize a meeting from Les Houches

Snowmass outline

(1) PDF's

(a) current knowledge and uncertainties

(b) likely improvements from LHC data, particularly precision Drell-Yan measurements

(c)PDF luminosities and uncertainties for 14, 33 and 100 TeV

(d) improvements from an LHeC (including alpha_s)

(2) Cross sections at 14, 33 and 100 TeV

(a)MCFM LO, NLO

-what cross sections to choose?

-what differential distributions to show?

-scale, PDF and alpha_s uncertainties?

-comparisons to BFKL predictions a la HEJ

(b)NLO, NNLO and beyond

-NLO extrapolation to higher parton multiplicities

-improvements in NLO+PS, a la CKKW->comparisons

-Higgs(+jets) cross sections as function of energy

-importance of BFKL logs as a function of energy

c)perturbative series convergence for boosted final states

(3) Higgs+jets uncertainties

(a)resummation of jet veto logs->pointing to a new scheme for Higgs+jets uncertainties?

(b)importance of jet veto logs as a function of energy

(4) NLO QCD+NLO EW

(a)wishlist? putting current calculations together in one framework

(b)impact of the 'Sudakov zone' as a function of energy; gamma gamma processes

Les Houches worklist

1) Higgs-related

a) PDF uncertainties for gluon-gluon fusion

-trace differences between CTEQ, MSTW and NNPDF to see if uncertainty can be reduced

b) acceptances and uncertainties of acceptances for Higgs (gg->Higgs->WW/ZZ)

c) Higgs+jets cross sections

-comparisons of @MC@NLO, Powheg MINLO, MEPS@NLO, HEJ, etc

-comparisons of W/Z+jets with above (+LoopSim) as a testbed

-revisit tag jets: hadronization uncertainties for high rapidity jets

d) Higgs+jets uncertainties

-new scheme for jet veto uncertainties using Higgs+0, Higgs+1 jet resummation calculations

-comparison of Higgs+0 jet resummation results

2) PDFs

a) impact of LHC data, current and future

b) impact of/need for an LHeC

c) combination of PDF sets

d) impact of NNLO jet calculations

3) (N)NLO QCD + (N)NLO EWK

a) wishlist of calculations->Stefan says he will prepare a review of what current exists-

b) study of the 'Sudakov Zone', ~1 TeV

c) PDFs with QED corrections, photon PDFs, gamma-gamma processes

4) Data vs Theory

a) making more use of Rivet

b) dressed leptons: what is the best way of making comparisons between data and theory

c) more sophisticated looks at analyses with background subtractions

d) MPI->try to constrain jet content of UE

5) Also

a) handling top decays in processes like tTH, tTbB and tTjj

Sign up

- To keep up to date on the ongoing work and/or to participate in the writeup
- Send an email to listserv@slac.stanford.edu with
  - snowmass-qcd or
  - snowmass-ewk
  - in the subject line and body (I forget which one is needed so do both)

Slides from October meeting

QCD and the Strong Force

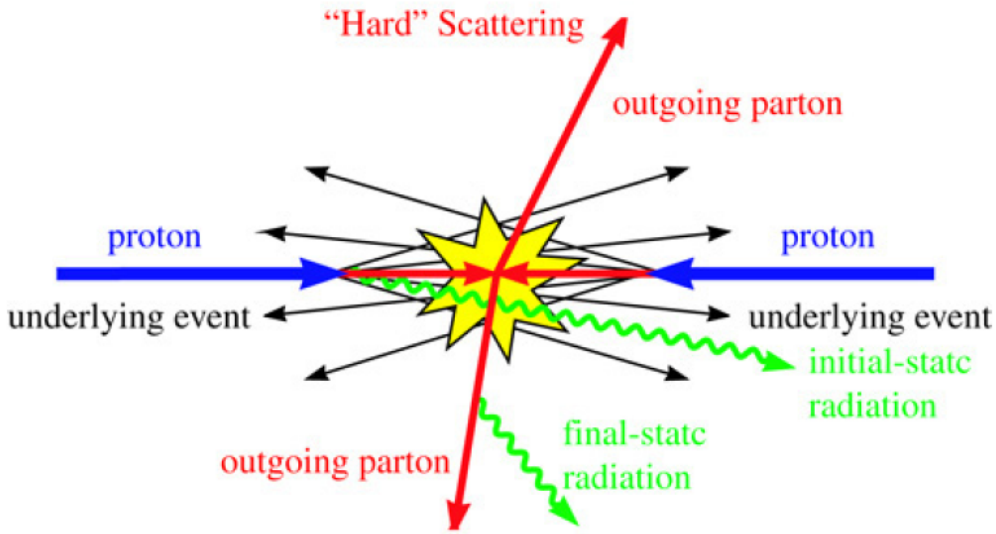
Joey Huston
Michigan State University

for the QCD conveners

John Campbell, Ken Hatakeyama,
Frank Petriello

QCD

- QCD plays a major role in basically every physics process under discussion in this workshop
- 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 this workshop
- For example, part of our session tonight will be jointly with the EWK group, given the interplay between QCD and EWK corrections for precision measurements

Charge

- The charge for the QCD group (like every other group) is to determine the
  1. current state of the art
  2. what is likely/priority for the next 5 years?
  3. what is likely/priority for longer time scale (20 years)?
- Of course a) is the easiest, b) is less so and parts of c) are in the realm of pure speculation
- We have broken down each question into a series of more definite sub-issues that should be addressed. For each issue, we include a discussion of the current status and outlook, some possible projects, and overlap/synergy with the other physics groups.

Question 1a

- What are the prospects for future higher order calculations at NLO and matched with parton showers? What subtleties remain to be understood for precision measurements?
- Techniques in calculation of pQCD cross sections have reached the point where any reasonable cross section can be calculated in a finite time. The current limit is 2->6 (W+5 jets, ttbar with decays).
- Many existing calculations can also be recycled; 4 jet cross section has been used to calculate photon+3 jets and diphoton+2 jets
- See extra slides

Question 1a

- There remain open questions as to the best scale choice (and uncertainty) for complex multi-parton calculations, since a variety of physical scales may appear in the calculation
- There are now attempts, such as MINLO, to choose nodal scales (plus appropriate Sudakov factors) in NLO multi-parton calculations that may shed light on this issue

- Projects
  - collate cross section predictions where a choice of an optimal scale and range of uncertainty is not obvious (example: tTbB)
  - study effect of application of MINLO procedure to these (and other) calculations
  - where does this uncertainty cause problems for experimenters?

Question 1a

- There have also been great advances in the inclusion of NLO multi-parton matrix elements in parton shower Monte Carlos, in a semi-automatic manner
- We expect that any future NLO calculation can be straightforwardly implemented in a parton shower Monte Carlo
- There have also been developments in addition of NLO parton states of different multiplicities, without double- or under-counting, in such a manner that theoretical final states can be generated similar to what is measured in the data, i.e. an inclusive Higgs sample where the 1 and 2 jet final states are described at NLO, and higher multiplicities are described at LO

- Projects
  - detailed comparisons of predictions from different approaches for combining NLO+PS (Powheg, MENLOPS, aMC@NLO) for key physical processes (such as inclusive jet production)
  - compare multi-parton NLO PS predictions (MEPS@NLO for the moment) to fixed order predictions, to NLO PS predictions and to data
    - W+jets
    - Higgs+jets

Question 1b

- Once we have the NLO and NNLO calculations, how do we (experimentalists) use them?
- If a theoretical calculation is done, but it can not be used by any experimentalists, does it make a sound? Or create a citation?
- We need public programs and/or public ntuples
- Oftentimes, the program is too complex to be run by non-authors
- In that case, ROOT ntuples may be the best solution
  - see for example experience with Blackhat+Sherpa ntuples
- Computing and storage are an issue both for the authors of these programs and for the users
  - overlap with computing group

- Projects
  - study of B+S ntuple structure; questions of universality/possible improvements

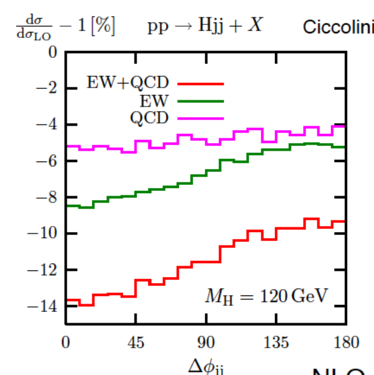
Question 1c

- Survey of the importance of EWK corrections. Do we need an EWK wishlist similar to the now-defunct NLO QCD one
- Where are combined QCD-EWK corrections important?
- Projects:
  - NLO (QCD+) EWK wishlist
- Overlap
  - EWK group

- See for example the workshop on EWK Corrections to Hard QCD Processes at the IPPP at Durham (Sep 24-26)
- See http://www.ippp.dur.ac.uk/Workshops/12/EW_LHC
- See also www.pa.msu.edu/~huston/atlas/ippp_ewk_summary.pdf

example: azimuthal angle between tagging jets

Ciccolini,Dittmaier, Krämer [hep-ph/0306234]



NLO QCD corrections rather flat
NLO EW corrections distort shape

Question 1d

- The frontier for NNLO is 2->2 processes
- What processes do we need calculated?
- What is the timescale?
- Projects:
  - NNLO wishlist (build on Les Houches wishlist; see extra slides)
- To date, most NNLO calculations are 2->1 (W/Z/Higgs)
- Multiple NNLO calculations containing colorless final states (diphoton production, W+Higgs production) have recently been completed
- Several partonic channels contributing to tt at NNLO have been completed and full result is expected soon
- Work is proceeding on dijets, W/Z+jet, Higgs+jet

Question 1e

- What are the prospects for including NNLO effects in a parton shower? To what extent are any physics analyses limited by the choice of either NLO+PS or NNLO?
- Are measurements constraining subtle effects (recoil strategies, etc) in parton showering and/or NLO +PS calculations?
  - a la the ttbar symmetry at the Tevatron
- A program/technique including NNLO QCD matrix elements in a parton shower Monte Carlo will not be forthcoming in the near future, but in principle, there is nothing that prevents such a development.
- Note that the parton showers themselves are still at LL/NLL. What limitations does this result in?
- Projects
  - do we need a parton shower that is fully NLL?
  - what is needed in parton showering to fully model what is observed in the data?

Question 2a

- Can jet analyses be repeated with different (infra-red safe) jet algorithms and/or jet sizes?

- Both major LHC experiments are using the antikT algorithm (which is good) but different jet sizes (which is bad). Physics analyses can be automated to the extent that there is no reason not to carry them out with several jet sizes and/or several jet algorithms. Each algorithm/size may illustrate different aspects of the underlying physics.

Question 2b

- Can jet substructure, in particular for boosted systems, be put to wider use in other physics analyses?

- There has been a great deal of attention given to jet substructure, especially for boosted systems. These tools can also be put to use for most physics analyses, again to try to understand the underlying physics better.
- Projects
  - catalog general substructure tools/ frameworks, a la FastJet or SpartyJet. What tools are missing?
- Overlaps
  - top, bsm,Higgs

Question 2c

- At what future luminosities might existing jet algorithms cease to be robust? What techniques may be introduced to stabilize them?

- The antikT algorithm, and the accompanying techniques, have worked well at the LHC,even with current luminosities resulting in >=30 additional events per crossing. Studies need to be carried out to see at what pileup rates, existing jet algorithms may cease to be robust, and better clustering techniques may need to be developed.
- Projects:
  - how do the existing jet substructure tools perform at high pileup rates (say nPU=100) and what kind of further developments may be necessary?
- Overlaps
  - top, BSM, Higgs

Question 2d

- Can particle flow techniques be taken advantage of in future jet algorithms?

- Both ATLAS and CMS have used particle flow techniques to improve the jet energy scale determination. Such techniques are considered as crucial for future linear collider experiments, and it may be that new jet algorithms can be developed to take advantage of the commensurate granular resolution inherent in such techiques.
- Projects:
  - how might jet reconstruction be improved given highly granular readout?

Question 2e

- Can event shapes such as jettiness be useful in future measurements, and should the experimental collaborations study their implementation at the LHC?
- There has already been some work by ATLAS and CMS, but this is an area that needs to be developed further
- Projects:
  - develop it further

Question 3a

- What impact will LHC data have on PDFs?
- Projects:
  - what is the ultimate precision/limitations of collider-only PDFs?

- There has been a great deal of work on understanding PDF predictions and uncertainties at the LHC, in particular by the PDF4LHC working group.
- The DIS data, including both HERA and fixed target are the dominant ‘deciders’ in global fits. Collider cross sections, however, are often directly sensitive to the gluon distribution in a way that DIS data is not. As the statistical and systematic errors improve, the use of LHC data in global fits will accelerate. It is crucial that correlated systematic error information be published for all of this data.

Question 3b

- How much better might an eLHC constrain PDFs? Is the improved precision necessary?
- Projects:
  - what physics processes need the PDF precision that such a machine could provide? Are new fixed target measurements necessary as well?
- The LHC probes PDFs in ranges outside of direct investigation possible in HERA. This will become even more true with higher running energies for the LHC, or a possible successor. An eLHC will serve to directly determine PDFs in this new kinematic regime.
- The information provided will be superior to that determined by the inclusion of collider data in the PDF fits, but it should be investigated how necessary that increased precision might be.

Question 3b+

- What are the prospects for improving the theoretical description of PDFs?
- How important is a good knowledge of the photon PDF?
- What does having a negative gluon imply?
- For example, including QED corrections in the evolution, or even moving beyond NNLO. (See Durham EWK workshop for discussion of QED effects in PDFs.)
- Projects:
  - evaluate importance of QED/EWK corrections for PDFs.
- Overlap
  - EWK group

Question 3c

- What are the prospects for improved measurements of α_s at the LHC and future colliders?
- Measuring α_s, and its running, is one of the most fundamental of QCD tests
- Projects:
  - what are the sensitivities of α_s measurements at the LHC and at future accelerators?

Question 4a

- In what situations do we need better resummation techniques? Can we envisage future experimental measurements where severe phase space restrictions will be required?
- Resummation techniques have greatly improved in recent years, for a variety of kinematic variables. What is needed, perhaps, is a catalog of situations where a better resummation formalism/ technique is needed.
- Projects:
  - catalog of situations where improvements in resummation are needed.

Question 4b

- To what extent do current formalisms to resum large logarithms in jet-binned cross sections agree? Can we envisage more flexible resummation formalisms to handle more complicated observables?
- Projects:
  - catalog measurements where jet vetoing/binning might be necessary, and estimate the possible effects on the uncertainty

- Often it is necessary to apply jet vetoes/binning in a physics measurement, and thus in the corresponding theoretical QCD calculation. For example, the Higgs production process is known to NNLO, but the application of jet vetoes/binning can significantly increase the size of the uncertainty over that of the inclusive cross section.
- There are now techniques to resum the effects of the vetoes, but it is not clear how the current techniques can be applied to the complex phase space that results from the application of jet algorithms.
- See extra slides
- Overlaps: Higgs

Question 5

- Are there gaps in our understanding of diffractive and hard diffractive physics?

- There are two main directions: (1) diffraction and forward physics as a means to study unresolved issues of QCD and to search for and to investigate any manifestations of new physics and (2) diffraction as a way to study soft physics.
- For (1): one can study Higgs and BSM physics with forward proton tagging. This can serve as a spin-parity analyser/filter, allow for the measurement of the Higgs branching ratio into bottom quark pairs, and allow tests of CP violation in the Higgs sector. For heavier Higgs, it will also be possible to measure the Higgs width. One can also study the spin-parity assignments for any new quarkonium-type states.

Question 5 (cont)

- Projects:
  - how well can we predict/ measure processes such as diffractive Higgs production? How does the photon-photon flux in a pp machine compare to that in a future linear collider? For what future physics topics would such measurements be useful?
- Overlaps
  - Higgs
- At the LHC, and any future high energy colliders, there will be a large photon-photon flux, which can be used to produce a number of final states, including WW production, and light charginos. (See Durham EWK workshop.)
- For (2): one can continue the study of the violation of factorization for diffractive scattering at ep and pp machines, measure dijet properties for a sample of pure gluon jets, and in general study hard diffractive production of a number of final states.

Question 6

- How hampered are we by our limited understanding of non-perturbative physics?
- Projects:
  - understand sensitivity of top mass definition to non-perturbative effects
- This includes both effects such as jet fragmentation as well as the multiple parton interactions that make up the bulk of the underlying event. Another issue is the definition of kinematic quantities that have been treated in a classical sense to date, but for which increased precision requires a better theoretical basis; perhaps foremost among these is the measurement of the top mass to both the current precision and to the improved precision that will be possible with further LHC running and at future machines.

Snow-Houches

- Many of these issues have been addressed in the Les Houches workshops which have taken place since 1999
  - witness the many Les Houches accords
  - the next workshop will be before the Minneapolis meeting (June 3-23 2013)

+

==Snow-Houches

- We will try to coordinate some of the common work between the two

Evening session

- 7:30-9:00 West Wing WH10W
  - last half-hour with EWK group
  - ReadyTalk: 9343617 Passcode: 7907
  - Evo: Universe CPM2012-Energy Frontier HE5-QCD
- See also pQCD computing session 1:15 PM
  - Nu's Room WH12X

Extra slides

- Les Houches NLO wishlist, started in 2005, and incremented in 2007 and 2009 was officially closed in 2011, since all of the calculations on the list were complete, and there are no technical impediments towards calculations of new final states, either with dedicated or semi-automatic calculations
- Note that dedicated calculations can be factors of 10 faster than semi-automatic

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [27, 28]; Campbell/Ellis/Zanderighi [29]. ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [30] WZ jet, $W\gamma$ jet completed by Campanario et al. [31, 32]
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [33]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [34, 35] Interference QCD-EW in VBF channel [36, 37]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [38] and WWZ by Hankele/Zeppenfeld [39], see also Binoth/Ossola/Papadopoulos/Pittau [40] VBFNLO [41, 42] meanwhile also contains $WWW, ZZW, ZZZ, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma, W\gamma\gamma j$ [43, 44, 45, 46, 47, 21]
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [48, 49] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [50]
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa [51] and Rocket [52] collaborations Z+3jets by Blackhat/Sherpa [53]
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek [54, 55]
7. $pp \to VV\,b\bar{b}$,	Pozzorini et al.[25],Bevilacqua et al.[23]
8. $pp \to VV$+2jets	W^+W^++2jets [56], W^+W^-+2jets [57, 58], VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [59, 60, 61]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al. [62, 63]
NLO calculations added to list in 2009	
10. $pp \to V+4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets [22], Z+4jets [20] see also HEJ [64] for $W + n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier [11]
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
also completed:	
$pp \to W\gamma\gamma$ jet	Campanario/Englert/Rauch/Zeppenfeld [21]
$pp \to 4$ jets	Blackhat/Sherpa [19]

Table 1: The updated experimenter's wishlist for LHC processes

Last to be calculated

- a 4 top final state

Constraining BSM Physics at the LHC: Four top final states with NLO accuracy in perturbative QCD

G. Bevilacqua[a] **and M. Worek**[b]

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[b] *Theoretische Physik, Fachbereich C, Bergische Universität Wuppertal, Gauss Str. 20, D-42097 Wuppertal, Germany*

E-mail: bevilacqua@physik.rwth-aachen.de, worek@physik.uni-wuppertal.de

ABSTRACT: Many theories, from Supersymmetry to models of Strong Electroweak Symmetry Breaking, look at the production of four top quarks as an interesting channel to evidentiate signals of new physics beyond the Standard Model. The production of four-top final states requires large partonic energies, above the $4m_t$ threshold, that are available at the CERN Large Hadron Collider and will become more and more accessible with increasing energy and luminosity of the proton beams. A good theoretical control on the Standard Model background is a fundamental prerequisite for a correct interpretation of the possible signals of new physics that may arise in this channel. In this paper we report on the calculation of the next-to-leading order QCD corrections to the Standard Model process $pp \to t\bar{t}t\bar{t} + X$. As it is customary for such studies, we present results for both integrated and differential cross sections. A judicious choice of a dynamical scale allows us to obtain nearly constant $\mathcal{K}$-factors in most distributions.

KEYWORDS: NLO Computations, Heavy Quark Physics, Standard Model, Beyond Standard Model

WUB/12-12, TTK-12-22

ROOT ntuples

- More complex to use than MCFM
  - no manual for example
  - and you don't produce the events yourself
- ntuples produced separately by Blackhat + Sherpa for →
  - so TB's of disk space
- No jet clustering has been performed; that's up to the user
  - a difference from MCFM, where the program has to be re-run for each jet size/algorithm
- What algorithms/jet sizes that can be run depends on how the files were generated
  - i.e. whether the right counter-events are present
- For the files on the right at 7 TeV (for W^+ + 3 jets), one can use kT, antikT, siscone (f=0.75) for jet sizes of 0.4, 0.5, 0.6 and 0.7

- bornLO (stands alone for pure LO comparisons; not to be added with other contributions below)
  - 20 files, 5M events/file, 780 MB/file
- Born
  - 18 files, 5M events/file, 750 MB/file
- loop-lc (leading color loop corrections)
  - 398 files, 100K events/file, 19 MB/file
- loop-fmlc (needed for full color loop corrections)
  - 399 files, 15K events/file, 3 MB/file
- real (real emission terms)
  - 169 files, 2.5 M event/file, 5 GB/file
- vsub (subtraction terms)
  - 18 files, 10M events/file, 2.8 GB/file

Jet Clustering

- For jet clustering, we use SpartyJet, and store the jet results in SJ ntuples
  - and they tend to be big since we store the results for multiple jet algorithms/ sizes
- Then we friend the Blackhat +Sherpa ntuples with the SpartyJet ntuples producing analysis ntuples (histograms with cuts) for each of the event categories
- Add all event category histograms together to get the plots of relevant physical observables

http://projects.hepforge.org/spartyjet/

arXiv:1201.3617 (manual)

SpartyJet is a set of software tools for jet finding and analysis, built around the FastJet library of jet algorithms. SpartyJet provides four key extensions to FastJet: a simple Python interface to most FastJet features, a powerful framework for building up modular analyses, extensive input file handling capabilities, and a graphical

Reweighting

can reweight each event to new

- -PDF
- -factorization scale
- -renormalization scale
- -α_s (tied to the relevant PDFs)

based on weights stored in ntuple (and linking with LHAPDF)

so, for example, the events were generated with CTEQ6, and were re-weighted to CTEQ6.6

2.1 Born and real contributions

The new weight is given by

$$w = \mathbf{me\_wgt2} \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F) F(\mathbf{id2}, \mathbf{x2}, \mu_F) \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \tag{1}$$

with μ_F the new factorization scale, μ_R the new factorization scale, f the new PDF, α_s the correponding running coupling and n the number of strong coupling (the number of jets n_j for the born contribution and $n_j + 1$ for the real contribution). If the factorization scale is not changed, one can simplify the computation (and save the pdf function call):

$$w = \mathbf{weight2} \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \tag{2}$$

2.2 Virtual contribution

The virtal contribution is treated like the real and born contribution, but the matrix element has a dependence on the renormalization scale parametrized using the additional weights **usr_wgts**.

$$w = m \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F) F(\mathbf{id2}, \mathbf{x2}, \mu_F) \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \tag{3}$$

$$m = \mathbf{me\_wgt2} + l\,\mathbf{usr\_wgts}[0] + \frac{l^2}{2} \mathbf{usr\_wgts}[1] \tag{4}$$

$$l = \log\left(\frac{\mu_R^2}{\mathbf{ren\_scale}^2}\right) \tag{5}$$

Reweighting, cont.

2.3 Integrated subtraction

The computation of the new weight for the integrated subtraction is the most complicated. The ROOT file has 16 additional weights to make this possible.

$$w = m\frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \quad (6)$$

$$m = \mathbf{me\_wgt2} \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F) f(\mathbf{id2}, \mathbf{x2}, \mu_F) \quad (7)$$

$$+ \left(f_a^1\omega_1 + f_a^2\omega_2 + f_a^3\omega_3 + f_a^4\omega_4\right) F_b(x_b) \quad (8)$$

$$+ \left(F_b^1\omega_5 + F_b^2\omega_6 + F_b^3\omega_7 + F_b^4\omega_8\right) f_a(x_a) \quad (9)$$

$$\omega_i = \mathbf{usr\_wgts}[i-1] + \mathbf{usr\_wgts}[i+7] \log\left(\frac{\mu_R^2}{\mathbf{ren\_scale}^2}\right) \quad (10)$$

9

complex: carry both single and double logs

where

$$f_a^1 = \begin{cases} a = \text{quark} & : \quad f_a(x_a, \mu_F) \\ a = \text{gluon} & : \quad \sum_{\text{quarks}} f_q(x_a, \mu_F) \end{cases} \quad (11)$$

$$f_a^2 = \begin{cases} a = \text{quark} & : \quad \frac{f_a(x_a/x'_a, \mu_F)}{x'_a} \\ a = \text{gluon} & : \quad \sum_{\text{quarks}} \frac{f_q(x_a/x'_a, \mu_F)}{x'_a} \end{cases} \quad (12)$$

$$f_a^3 = f_g(x_a, \mu_F) \quad (13)$$

$$f_a^4 = \frac{f_g(x_a/x'_a, \mu_F)}{x'_a} \quad (14)$$

we run into the sum over quarks and antiquarks again

and $n = n_j + 1$.

PDF Errors

Better than what is done in MCFM (as far as disk space is concerned); PDF errors are generated on-the-fly through calls to LHAPDF. But then don't store information for individual eigenvectors.

```
void BlackhatAnalysis::GetPdfErrors(const std::vector<Double_t> x,
                                    const Double_t f_c,
                                    const std::vector<int> flav,
                                    Double_t Q,
                                    bool shiftUp,
                                    Double_t &delta)
{
    Double_t f_p,f_m;
    // Loop over all eigenvectors
    for(int e=1;e<=m_nEigen;e++)
    {
        LHAPDF::initPDF(2, 2*e-1); // init positive shift pdf
        LHAPDF::initPDF(3, 2*e); // init negative shift pdf
        //std::cout << "Eigenvector " << e << std::endl;
        f_p = LHAPDF::xfx(2,x[0],Q,flav[0])/x[0]*LHAPDF::xfx(2,x[1],Q,flav[1])/x[1];
        f_m = LHAPDF::xfx(3,x[0],Q,flav[0])/x[0]*LHAPDF::xfx(3,x[1],Q,flav[1])/x[1];
        if(shiftUp) // if positive pdf shift
            delta += pow(std::max(std::max(f_p-f_c,f_m-f_c),0.0),2);
        else // if negative pdf shift
            delta += pow(std::max(std::max(f_c-f_p,f_c-f_m),0.0),2);
    }
    delta = sqrt(delta);
    if(!shiftUp) delta *= -1.0;
    //std::cout << "Total delta: " << delta << std::endl;
}
```

$$\Delta X^+_{\max} = \sqrt{\sum_{i=1}^{N}[\max(X_i^+ - X_0, X_i^- - X_0, 0)]^2},$$

$$\Delta X^-_{\max} = \sqrt{\sum_{i=1}^{N}[\max(X_0 - X_i^+, X_0 - X_i^-, 0)]^2}.$$

Branches in ntuple

branch name	type	Notes
id	I	id of the event. Real events and their associated counterterms share the same id. This allows for the correct treatment of statistical errors.
nparticle	I	number of particles in the final state
px	F[nparticle]	array of the x components of the final state particles
py	F[nparticle]	array of the y components of the final state particles
pz	F[nparticle]	array of the z components of the final state particles
E	F[nparticle]	array of the energy components of the final state particles
alphas	D	$alpha_s$ value used for this event
kf	I	PDG codes of the final state particles
weight	D	weight of the event
weight2	D	weight of the event to be used to treat the statistical errors correctly in the real part
me_wgt	D	matrix element weight, the same as weight but without pdf factors
me_wgt2	D	matrix element weight, the same as weight2 but without pdf factors
x1	D	fraction of the hadron momentum carried by the first incoming parton
x2	D	fraction of the hadron momentum carried by the second incoming parton
x1p	D	second momentum fraction used in the integrated real part
x2p	D	second momentum fraction used in the integrated real part
id1	I	PDG code of the firt incoming parton
id2	I	PDG code of the second incoming parton
fac_scale	D	factorization scale used
ren_scale	D	renormalization scale used
nuwgt	I	number of additional weights
usr_wgts	D[nuwgt]	additional weights needed to change the scale

What's next for the Les Houches NLO wishlist?

- Nothing: I'm retiring the NLO wishlist
- It's being replaced by a NNLO wishlist plus a wishlist for EW corrections for hard processes

Below we construct a table of calculations needed at the LHC, and which are feasible within the next few years. Certainly, results for inclusive cross sections at NNLO will be easier to achieve than differential distributions, but most groups are working towards a partonic Monte Carlo program capable of producing fully differential distributions for measured observables.

- $t\bar{t}$ production:
  needed for accurate background estimates, top mass measurement, top quark asymmetry (which is zero at tree level, so NLO is the leading non-vanishing order for this observable, and a discrepancy of theory predictions with Tevatron data needs to be understood). Several groups are already well on the way to complete NNLO results for $t\bar{t}$ production [84, 85, 86, 87].
- W^+W^- production:
  importand background to Higgs search. At the LHC, $gg \to WW$ is the dominant subprocess, but $gg \to WW$ is a loop-induced process, such that two loops need to be calculated to get a reliable estimate of the cross section. Advances towards the full two-loop result are reported in [88, 89].
- inclusive jet/dijet production:
  NNLO parton distribution function (PDF) fits are starting to become the norm for predictions and comparisons at the LHC. Paramount in these global fits is the use of inclusive jet production to tie down the behavior of the gluon distribution, especially at high x. However, while the other essential processes used in the global fitting are known to NNLO, the inclusive jet production cross section is only known at NLO. Thus, it is crucial for precision predictions for the LHC for the NNLO corrections for this process to be calculated, and to be available for inclusion in the global PDF fits. First results for the real-virtual and double real corrections to gluon scattering can be found in [90, 91].

NNLO wishlist: continued

- V+1 jet production:
  $W/Z/\gamma$ + jet production form the signal channels (and backgrounds) for many key physics processes, for both SM and BSM. In addition, they also serve as calibration tools for the jet energy scale and for the crucial understanding of the missing transverse energy resolution. The two-loop amplitudes for this process are known [92, 93], therefore it can be calculated once the parts involving unresolved real radiation are available.
- V+γ production:
  important signal/background processes for Higgs and New Physics searches. The two-loop helicity amplitudes for $q\bar{q} \to W^{\pm}\gamma$ and $q\bar{q} \to Z^{0}\gamma$ recently have become available [94].
- Higgs+1 jet production:
  As mentioned previously, events in many of the experimental Higgs analyses are separated by the number of additional jets accompanying the Higgs boson. In many searches, the Higgs + 0 jet and Higgs + 1 jet bins contribute approximately equally to the sensitivity. It is thus necessary to have the same theoretical accuracy for the Higgs + 1 jet cross section as already exists for the inclusive Higgs cross section, i.e. NNLO. The two-Loop QCD Corrections to the Helicity Amplitudes for $H \to 3$ partons are already available [95].

Jet vetos and scale dependence: WWjet

- Often, we cut on the presence of an extra jet
- This can have the impact of improving the signal to background ratio
  - …and it may appear that the scale dependence is improved
- However, in the cases I know about, the scale dependence was *anomalous* at NLO without the jet veto, indicating the presence of uncancelled logs
- The apparent improvement in scale dependence may be illusory

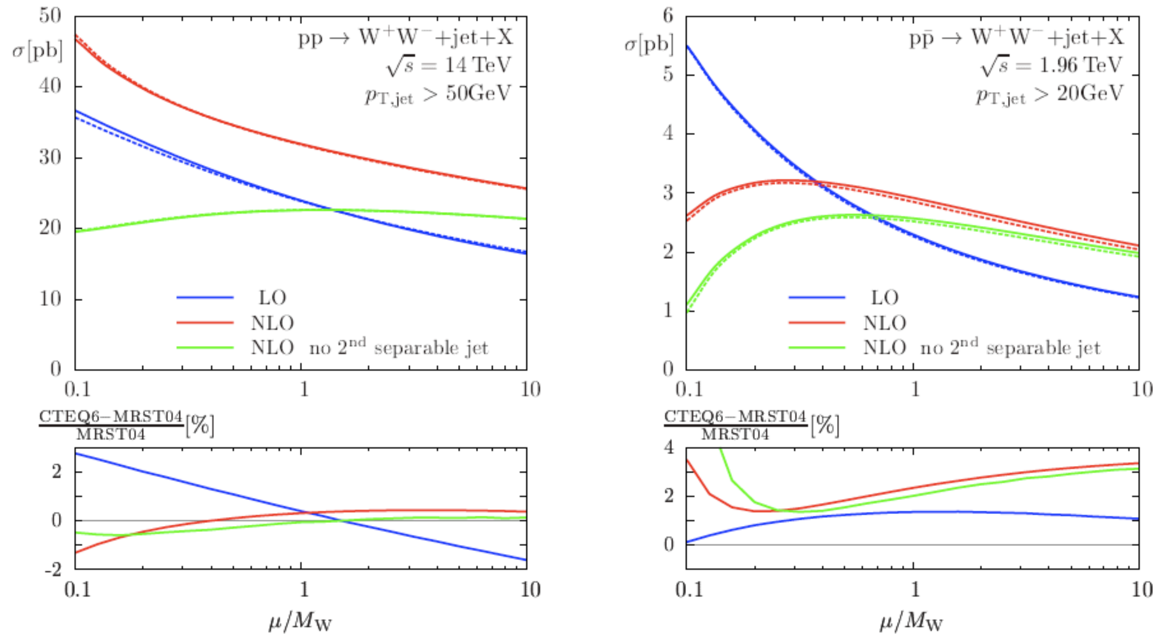
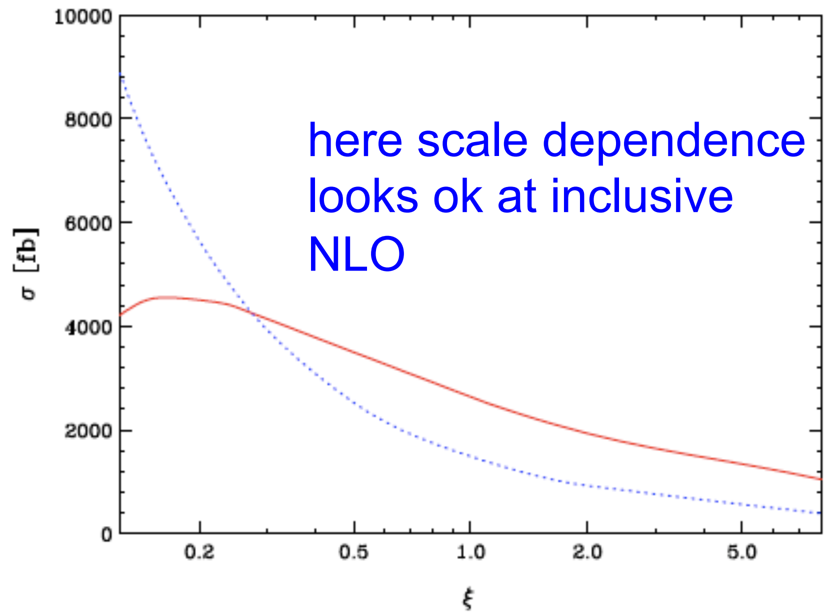


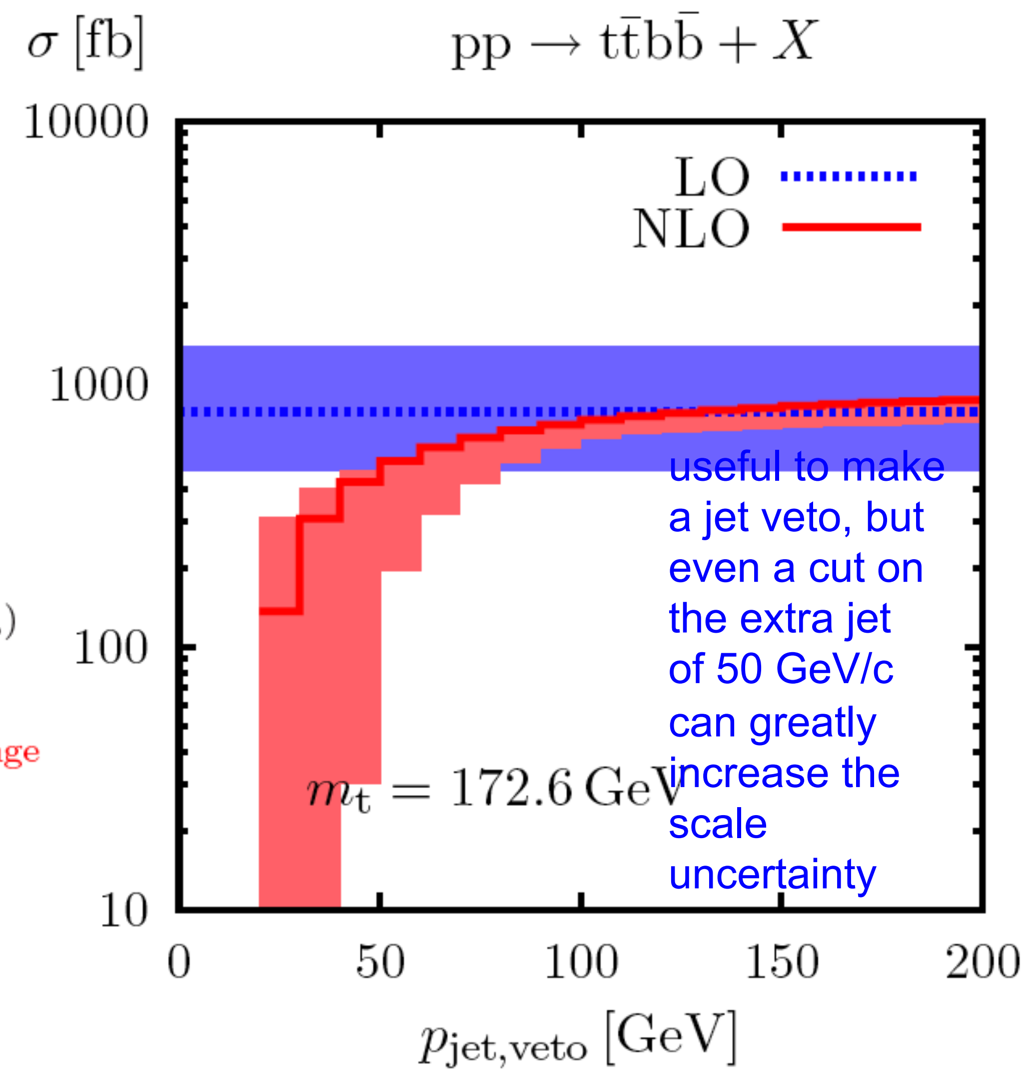
Figure 11: Comparison of WW+jet production cross sections in the LHC setup with $p_{T,\text{jet}} > 50$ GeV and for Tevatron with $p_{T,\text{jet}} > 20$ GeV: The straight lines show the results calculated with the five-flavour PDFs of CTEQ6, the dashed lines those calculated with the four-flavour PDFs of MRST2004F4. Contributions from external bottom (anti-)quarks are omitted, as described in Section 2.2.

Consider tTbB



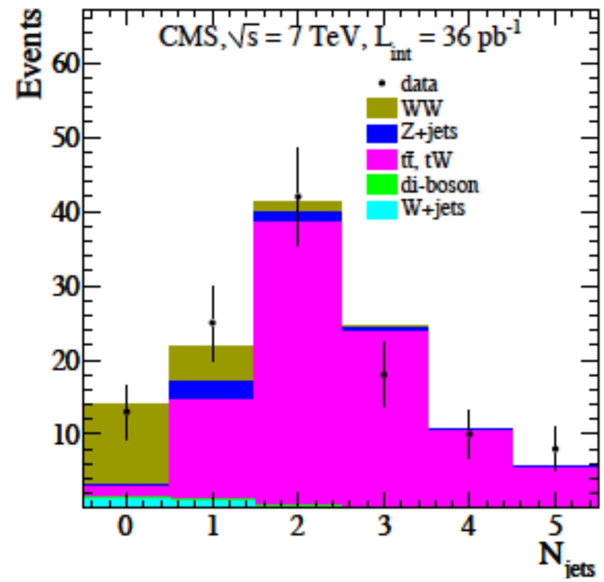
Perturbative instability for small $p_{\mathrm{jet,veto}}$

- veto ⇒ negative contribution $-\alpha_s^5 \ln^2(Q_0/p_{\mathrm{jet,veto}})$
- IR log dramatically enhances NLO uncertainty
- $p_{\mathrm{jet,veto}} < 40\,\mathrm{GeV}$ ⇒ NLO-band enters $K < 0$ range
  NLO prediction completely unrealiable!



Uncertainties in the face of jet vetos/bins

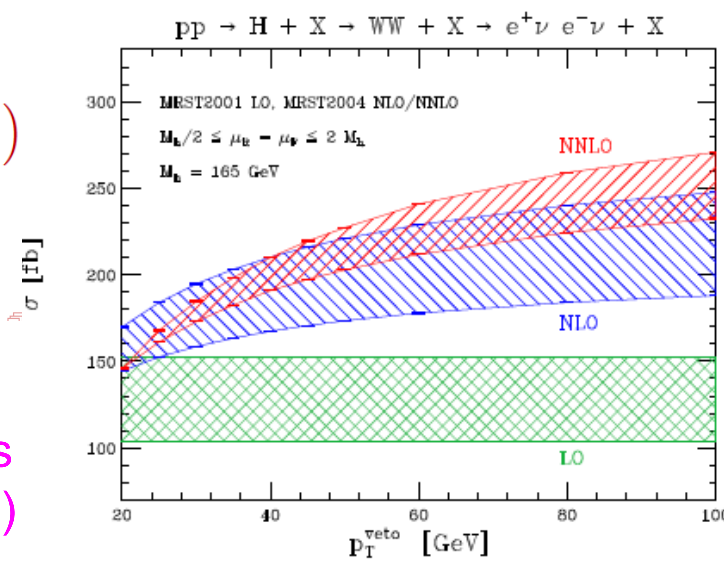
- For Higgs searches (with decays into WW*), important to divide sample into separate jet bins
  - backgrounds are different
  - physics is different (VBF shows up in 2 jet bin)
- If I calculate the scale uncertainties naively, I get the following



- Common scale variation for jet bins, e.g. for the Tevatron

$$\frac{\Delta\sigma}{\sigma} = \underbrace{66.5\% \times \begin{pmatrix}+5\% \\ -9\%\end{pmatrix}}_{\text{0 jets}} + \underbrace{28.6\% \times \begin{pmatrix}+24\% \\ -22\%\end{pmatrix}}_{\text{1 jet}} + \underbrace{4.9\% \times \begin{pmatrix}+78\% \\ -41\%\end{pmatrix}}_{\geq \text{2 jets}} = \begin{pmatrix}+14\% \\ -14\%\end{pmatrix}$$

- *Smaller* uncertainty in 0-jet bin than in inclusive cross section



- Note that fixed order expansion gets unstable at low p_T^{veto}

Sudakov double logs $\ln^2(p_T^{cut}/m_H)$

Perturbative Structure of Jet Cross Sections

$$\sigma_{\rm total} = \underbrace{\int_0^{p_T^{\rm cut}} dp_T \frac{d\sigma}{dp_T}}_{\sigma_0(p_T^{\rm cut})} + \underbrace{\int_{p_T^{\rm cut}}^{\infty} dp_T \frac{d\sigma}{dp_T}}_{\sigma_{\geq 1}(p_T^{\rm cut})}$$

$$\sigma_{\rm total} = 1 + \alpha_s + \alpha_s^2 + \cdots$$

$$\sigma_{\geq 1}(p_T^{\rm cut}) = \alpha_s(L^2 + L) + \alpha_s^2(L^4 + L^3 + L^2 + L) + \cdots$$

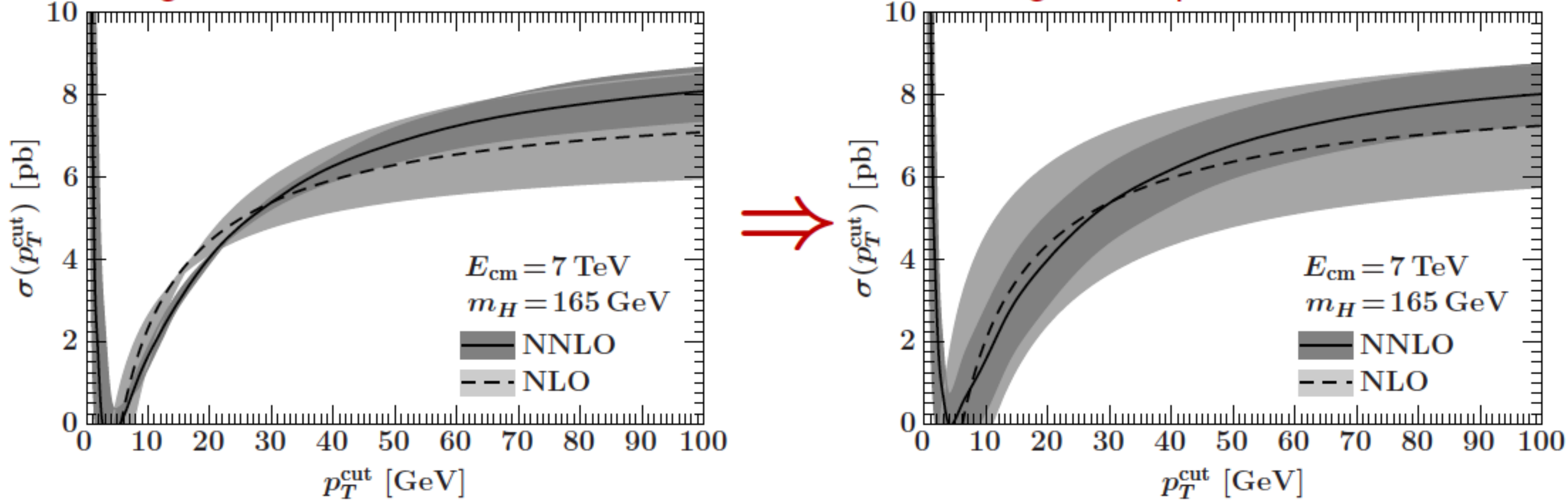
$$\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p_T^{\rm cut})$$
$$= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + L) + \alpha_s^2(L^4 + \cdots) + \cdots\right]$$

- Perturbative series in $\sigma_{\rm total}$ and $\sigma_{\geq 1}(p_T^{\rm cut})$ have different structures and are unrelated
- Apparent small uncertainties in $\sigma_0(p_T^{\rm cut})$ arise from cancellation between two series with large corrections

…should treat perturbation series for $\sigma_{>=0\rm jets}$, $\sigma_{>=1\rm\ jet}$, $\sigma_{>=2\rm\ jets}$ as independent with uncorrelated systematic errors (i.e, add in quadrature)

Realistic Fixed-Order Scale Uncertainties

Using naive scale variation for σ_0 ⟹ Using above procedure for σ_0



- Uncertainties reproduce naive scale variation at large cut values
- Larger uncertainties at small cut values → take into account presence of large logarithmic corrections

e.g. at LHC with $p_T^{\rm cut} = 30\,\mathrm{GeV}$

method	$\frac{\Delta\sigma_{\rm total}}{\sigma_{\rm total}}$	$\frac{\Delta\sigma_0}{\sigma_0}$	$\frac{\Delta\sigma_1}{\sigma_1}$	$\frac{\Delta\sigma_{\geq 2}}{\sigma_{\geq 2}}$
naive	10%	5%	14%	45%
new	10%	17%	29%	45%