# QCD Working Group Report

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for J. Campbell (FNAL), J. Huston (MSU), F. Petriello (Northwestern) and all contributors

Seattle Energy Frontier Working Group

*July 3, 2013*

# Overview

- Materials and conclusions we will have in the final white paper report will be collated from a series of meetings held 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)
  - Energy Frontier meeting (Seattle, June-July, 2013)
  - Snowmass on Mississippi (Minneapolis, July-August, 2013)

# Themes

The white paper report will be organized around the following four "themes"

- Investigations of PDF and $\alpha_s$ 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.

See more details in John Campbell's talk on Sunday and in backup

# "Wishlist" for QCD/QED Calculations

| Process | known | desired | motivation |
|---|---|---|---|
| H | d\sigma @ NNLO QCD<br>d\sigma @ NLO EW<br>finite quark mass effects @ NLO | d\sigma @ NNNLO QCD + NLO EW<br>MC@NNLO<br>finite quark mass effects @ NNLO | H branching ratios and couplings |
| H+j | d\sigma @ NNLO QCD (g only)<br>d\sigma @ NLO EW | d\sigma @ NNLO QCD + NLO EW<br>finite quark mass effects @ NLO | H p_T |
| H+2j | \sigma_tot(VBF) @ NNLO(DIS) QCD<br>d\sigma(gg) @ NLO QCD<br>d\sigma(VBF) @ NLO EW | d\sigma @ NNLO QCD + NLO EW | H couplings |
| H+V | d\sigma(V decays) @ NNLO QCD<br>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<br>d\sigma @ NLO QCD large m_t limit | d\sigma @ NLO QCD finite quark mass effects<br>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 (backup)

Vital for improving Higgs coupling determination!

# News from this Meeting

- Monday:
  - Summary report from the Les Houches workshop: J. Huston
  - Cross sections at 14, 33, and 100 TeV pp colliders: J. Campbell
  - Rjet study status: H. Beauchemin

- Tuesday:
  - Alpha_s at an e+e- Z factory: G. Dissertori
  - Sudakov zone at higher energies: K. Mishra

Also, “virtual” contributions from the TLEP community: P. Janot, A. Blondel

# Strong Coupling Constant

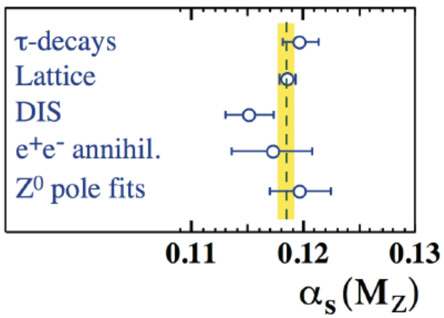
- $\alpha_s$ is the important parameter in QCD and least known coupling constant

Recent summary from the PDG

ETH Institute for Particle Physics

see Bethke, Dissertori, Salam: http://pdg.lbl.gov/2012/reviews/rpp2012-rev-qcd.pdf

G. Dissertori




**current world average:**

$\alpha_S(M_Z) = 0.1184 \pm 0.0007$ (0.6 % rel.)

- central value rather insensitive to choice of input
- uncert. dominated by Lattice results (~0.6% rel.)

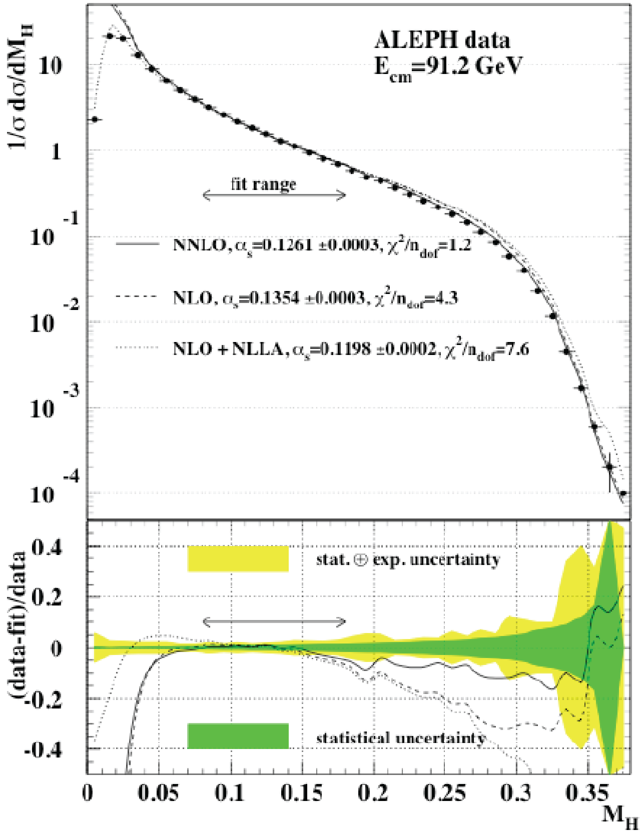
Plan to invite some report on the Lattice determination of $\alpha_s$ in the Minneapolis meeting

How much can we push the collider determination of $\alpha_s$ ?

Set reference to: 0.0001 (abs) or 0.1% (rel)

# $\alpha_s$ from Jet Rates / Event Shape

- "Classical" method, theory known at NNLO+NNLL (NNLO obtained only a few years ago). Current status, typical values:




- Experimental Uncertainties
  - typically ~1% (improvements should be possible)
- Hadronization Uncertainties
  - difference between various models for hadronization,
  - typically around 0.7 - 1.5 %
    - **going well below 1% seems unrealistic**
- Theoretical Uncertainties (pQCD)
  - renormalization scale variation, matching of (N)NLO with resummed calculation, quark mass effects
  - typically 3 - 5 %
    - **going well below 1% seems unrealistic**
  - **my conclusion: this is not the way to go**

G. Dissertori
ETH Zürich

alphas at a Z factory

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# $\alpha_s$ from Incl. Z Decays / Width

- Advantage of inclusive observables:
  - by now known to NNNLO !
  - non-perturbative effects strongly suppressed

$$R_{\text{exp}} = \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \text{leptons})} = R_{EW}\,(1 + \delta_{QCD} + \delta_m + \delta_{np})$$

$$\frac{R_{\text{exp}}}{R_{EW}} = \mathcal{O}(1)$$

$$\sim \mathcal{O}\left(\frac{m_q^2}{M_Z^2}\right) \qquad \frac{\Delta\alpha_s}{\alpha_s} \approx \mathcal{O}(\text{few }\%) \cdot \frac{\Delta\delta_m}{\delta_m}$$

Th. Gehrmann: calculations can be improved if necessary

$$\delta_{QCD} = \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5)$$

$$\mathcal{O}\left(\frac{\Lambda^4}{M_Z^4}\right)$$

<< 0.0001, no problem

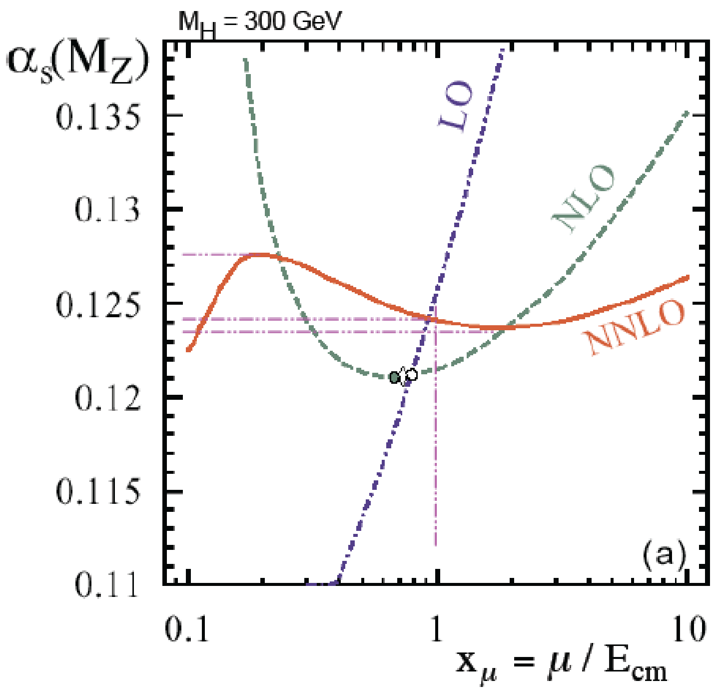
$$c_1 = 1.045 \Rightarrow c_1 \frac{\alpha_s(M_Z)}{\pi} \sim 0.04 = \mathcal{O}(1/25)$$

# $\alpha_s$ from Incl. Z Decays / Width

$$\frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \text{leptons})} = 20.767 \pm 0.025$$ ( 0.12 % rel. )

see next slide

$$\alpha_s(M_Z) = 0.1226 \pm 0.0038 \ \text{exp.}$$ (3.1% rel)




$$^{+0.0028}_{-0.0005} \quad \mu = {}^{2}_{0.25} \ M_Z$$

$$^{+0.0033}_{-0.0} \quad M_H = {}^{900}_{100} \ \text{GeV}$$

$$\pm 0.0002 \quad M_t = \pm 5\text{GeV}$$

$$\pm 0.0002 \quad \text{renormal. schemes}$$

$$= 0.1226 \ {}^{+0.0058}_{-0.0038}$$

# $\alpha_s$ from Incl. Z Decays / Width

- uncertainty because of $m_H$ gone, $m_{top}$ dep. no problem
- pQCD scale uncertainty, from latest NNNLO calculation:
  - ~**0.0002** (absolute uncertainty on $\alpha_s$), see arXiv:0801.1821 and 1201.5804
- eg. taking $\Gamma_Z$: current uncertainty 2.3 MeV
  - ~ 1.2 MeV from beam energy (dominating contribution)
  - remainder: mostly statistical/experimental
  - **so the question is:**
    **can a future Z factory measure $\Gamma_Z$ at a precision of ~ 0.1 MeV ?**
    **or R with an absolute precision of ~0.001 ?**
- **Note: all this is based on the assumption that there are no BSM effects which affect the Z pole observables at this level of precision.**

# Projections(?) from TLEP

A. Blondel and P. Janot

- From W hadronic width $B_h \equiv (\Gamma_{had,} / \Gamma_{tot})_W$
  - WW→ lv lv /(all WW) = $(1-B_h)^{2,}$
  - WW→ lv qq /(all WW) = $2.B_h (1-B_h)$
  - WW→ qq qq /(all WW) = $B_h^2$
  - Present value at LEP ($4\times10^4$ WW events) $B_h = 67.41 \pm 0.27$ %
  - With 0.5 $10^8$ W pairs, and assuming selection efficiency errors scale with statistics, expect reduction of error by factor ~70:

    $\alpha_s(M_W) = 0.11xxx \pm 0.00018$ (reduction by factor 6 w.r.t. present value)
- From Z hadronic width $R_l = \Gamma_{Z\text{->} had} / \Gamma_l$
  - Present LEP value 20.767 ± 0.0025 ($2\times10^7$ Z decays) limited by lepton statistics.
  - With $10^{12}$ Z decays, and assuming selection efficiency errors scale with statistics, expect reduction of error by factor ~200!

    If true, gives enough precision to 0.1% relative uncertainty
  - At this level of precision, many effects not considered now will come into the picture and a more detailed analysis is necessary.

Eagerly waiting for further information/conclusion by Minneapolis.

# EWK Corrections @ High Energies

K. Mishra

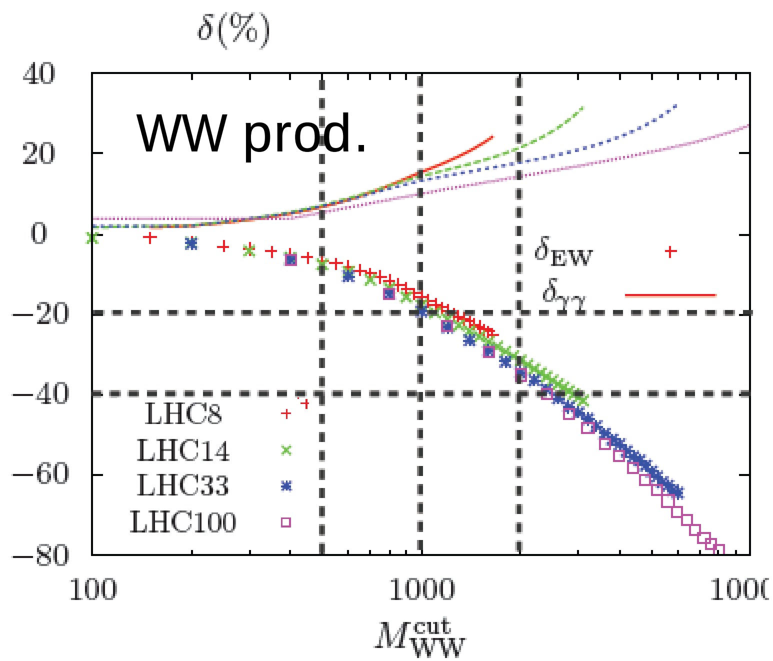
- EWK corrections become more important in higher energy regime
- At the ~TeV scale, they significantly modify production cross section through Sudakov logs of order

$$\alpha_W \ln^2(\mu^2/M_W^2)$$

$= 25^*\alpha_W$ @ $\mu$=1 TeV

This typically exceeds ~10% of LO. The LHC data are entering in this "Sudakov" zone.

- Results for dijets, W, Z, and WW prod. were presented at 14, 33, and 100 TeV.
  - Do not change dramatically with collider energy, but corrections are large in kinematic region accessible at higher energies
  - Will become increasing important at physics at higher energies



# Experimental Contributions

- Rjets: W+jets/Z+jets ratio at HL-LHC, P.H. Beauchemin, E. Meoni
  - high precision and very little dependence on non-perturbative effects (PDF, fragmentation, underlying events)
  - Exclusive jet selection enhance impact of hard radiation for QCD studies
  - Robust against pileup
  - Demonstration of background estimation technique for BSM searches: Z+jets/W+jets is often used for Bkg estimation in Jets+ETmiss searches
  - Eventually look into Wb/Zb, Z(vv)+jets/Z(ll)+jets etc

- Also, expect some projection on inclusive jets at HL-LHC: Ariel Schwartzman, Michael Begel

# From Now To Minnesota

- Write up what we have studied so far!

- Further studies hopefully converge in time for Minnesota
  - $\alpha_s$ from future e+e- colliders / TLEP
  - $\alpha_s$ from Lattice
  - Rjets and inclusive jets prospects at HL-LHC
  - Jet vetoes on Higgs+jets distributions at higher energies [F. Petriello et al.]
  - Investigation of small-x/BFKL effects in W/Z/H+jets [J. Andersen and J. Smillie]
  - Full $O(\alpha*\alpha_s)$ to single-W/Z production in the resonance region (i.e. including real & virtual contributions) [S. Dittmaier et al]: factorization of QCD/EWK correction !?

# Backup

# Summary 1

PDF:

- Current knowledge and uncertainties: central values and uncertainties are in general agreement between the 3 most widely used PDFs, CT10, MSTW08 and NNPDF2.3; there is room for improvement for the gluon distribution, especially in the range for Higgs production through gg fusion; the differences between the groups are mostly due to treatment of fixed target DIS data and is under investigation; collider-only fits are in better agreement but with much larger uncertainties; the use of META-PDFs may serve to greatly simplify theoretical comparisons; more conclusions should be available by Minneapolis
- Likely improvements from LHC data, particularly precision Drell-Yan measurements: the LHC high luminosity jet data, especially after the NNLO jet cross section calculation is completed, will serve as a constraint on the gluon distribution, as will the ttbar rapidity and mass distributions, once that NNLO calculation is available; DY data will also be important but calculation of QCD+EWK corrections is necessary for high mass; for quark distributions, it will be hard to compete with the precision of the HERA data
- PDF luminosities and uncertainties for 14, 33, and 100 TeV: the exercise has been carried out and uncertainties for the higher energies are reasonable for most physics processes, except at low x and high x, where input from an LHeC be useful
- Improvements from an LHeC (including alpha_s): an LHeC will allow precision measurement of PDFs over complete kinematic range needed for 14 TeV and higher energies, plus the possibility of a per mille accuracy on $\alpha_s$

# Summary 2

Cross sections at 14, 33 and 100 TeV:

- MCFM LO, NLO
  - Scale, PDF and alpha_s uncertainties?
  - Comparisons to BFKL predictions a la HEJ

  NLO corrections for processes involving vector bosons and jets should be reasonably stable as the center-of-mass energy increases, as long as the jet threshold increases with the energy, but the K-factors for $W/Z+\gamma$ increase rapidly with increasing energy; more results, including comparisons with HEJ should be available by Minneapolis
- 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

  Conclusions for the above should be available by Minneapolis
- Perturbative series convergence for boosted final states

  Application of typical boost cuts for searches such as WH greatly restricts the phase space such that resummation is necessary for any accurate prediction; relevant resummation studies underway; more information may be available by Minneapolis

# Summary 3

Higgs+jets uncertainties:

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

  a great deal of theoretical work is going on this summer and a new scheme should result in the near future, possibly by the time of Minneapolis

- importance of jet veto logs as a function of energy

  more information should be available by the time of Minneapolis

NLO QCD+NLO EW:

- wishlist? putting current calculations together in one framework

  a new wishlist for NNLO QCD calculations, including 2->3 processes, along with needed electroweak corrections was constructed at Les Houches, and will be discussed at Minneapolis; one of the key aspects is whether the EWK corrections factorize with the higher order QCD corrections; this is known explicitly only for a few processes

- impact of the 'Sudakov zone' as a function of energy; gamma gamma processes

  Sudakov logs can be used as an approximation for the full NLO EW corrections in the Sudakov regime, where s and t are both large; they fail when s is large but t is not; Sudakov log effects can be easily included in Monte Carlos such as ALPGEN; new photon PDFs are coming out from NNPDF and CT; NNPDF indicates that the photon PDF is smaller than MRST2004qed at low x, and similar at high x

# "Wishlist" for QCD/QED Calculations

| 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<br>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<br>d\sigma(stable V) @ NLO EW | d\sigma(V decays) @ NNLO QCD + NLO EW | bkg H → VV<br>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<br>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<br>massive b | d\sigma(lept. V decay) @ NNLO QCD<br>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 |

High priority for:

- pdfs
- H bkgs
- EW structure, TGCs, QGCs

# “Wishlist” for QCD/QED Calculations

| Process | known | desired | details |
|---|---|---|---|
| $t\bar{t}$ | $\sigma_{\rm tot}$ @ NNLO QCD<br>$d\sigma$(top decays) @ NLO QCD<br>$d\sigma$(stable tops) @ NLO EW | $d\sigma$(top decays)<br>@ NNLO QCD + NLO EW | precision top/QCD,<br>gluon PDF, effect of extra<br>radiation at high rapidity,<br>top asymmetries |
| $t\bar{t} + j$ | $d\sigma$(NWA top decays) @ NLO QCD | $d\sigma$(NWA top decays)<br>@ NNLO QCD + NLO EW | precision top/QCD<br>top asymmetries |
| single-top | $d\sigma$(NWA top decays) @ NLO QCD | $d\sigma$(NWA top decays)<br>@ NNLO QCD (t channel) | precision top/QCD, $V_{tb}$ |
| dijet | $d\sigma$ @ NNLO QCD (g only)<br>$d\sigma$ @ NLO weak | $d\sigma$<br>@ NNLO QCD + NLO EW | Obs.: incl. jets, dijet mass<br>$\rightarrow$ PDF fits (gluon at high x)<br>$\rightarrow \alpha_s$<br>CMS http://arxiv.org/abs/1212.6660 |
| 3j | $d\sigma$ @ NLO QCD | $d\sigma$<br>@ NNLO QCD + NLO EW | Obs.: $R3/2$ or similar<br>$\rightarrow \alpha_s$ at high scales<br>dom. uncertainty: scales<br>CMS http://arxiv.org/abs/1304.7498 |
| $\gamma + j$ | $d\sigma$ @ NLO QCD<br>$d\sigma$ @ NLO EW | $d\sigma$ @ NNLO QCD<br>+NLO EW | gluon PDF<br>$\gamma + b$ for bottom PDF |

Table 2: Wishlist part 2 – jets and heay quarks