Discussions on the section for future $\alpha_s$ determinations

Kenichi Hatakeyama (Baylor and CMS/Fermilab LPC) for J. Campbell (FNAL), J. Huston (MSU), F. Petriello (Northwestern) and all contributors

Snowmass Meeting
University of Minnesota
July 31, 2013
Status of the Draft

☐ The current draft as of last night is linked on this indico.

☐ The current section for $\alpha_s$ consists of:

- Future prospects at a $Z$ factory based on the talk by G. Dissertori at the Snowmass EF Seattle meeting
- Potentials at TLEP based on inputs from P. Janot and A. Blondel with a few slides
- A few paragraphs about future prospects at hadron colliders by K.H.
- Future prospects at the LHeC by M. Klein
- Lattice QCD discussions by P. Mackenzie

☐ To do or for discussions:

- Make better connections with other subgroup report.
  - $\alpha_s$ is discussed several times in the Higgs report
- Make a grand table summarizing $\alpha_s$ present and future (many thanks to John for making the first version)?
- Smooth out the texts after having the lattice QCD section
Alphas for Higgs Physics

1.2 Coupling Measurements

For a 126 GeV Standard Model Higgs boson, the parametric uncertainties arise predominantly from the b mass and $\alpha_s$.

1.5: Mass & Total Width Measurements:

The Higgs to bb branching fraction at roughly $58\pm3\%$ is the single largest contribution to the theoretical uncertainty on the total width at this time. With further measurement improvements on $\alpha_s$, precision couplings, and QCD lattice calculations, the Standard Model prediction on the total width will achieve approximately 2% accuracy. The experimental measurement of the Higgs to bb branching fraction in ZH production to sub-percent accuracy will reduce the uncertainty on the Higgs total width prediction to 1%.

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Need to ensure good connections with other subgroups’ reports
### Summary Table?

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

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

- Add the W hadronic width?
- How many ??? can we fill by the end of this meeting?


Backup
Strong Coupling Constant

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

**Recent summary from the PDG**

![Graph showing $\alpha_s$ vs. $M_Z$]

- 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.)

Just learned more about the Lattice determination of $\alpha_s$ (many thanks to P. Mackenzie)

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

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

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α_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**
\[ R_{\text{exp}} = \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \text{leptons})} = R_{\text{EW}} \left( 1 + \delta_{\text{QCD}} + \delta_m + \delta_{np} \right) \]

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

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

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

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

\[ \Delta \frac{\alpha_s}{\alpha_s} \approx \mathcal{O}(\text{few \%}) \cdot \frac{\Delta \delta_m}{\delta_m} \]

Th. Gehrmann: calculations can be improved if necessary

\[ \mathcal{O} \left( \frac{\Lambda^4}{M_Z^4} \right) \ll 0.0001, \text{ no problem} \]

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\[ \frac{\Gamma(Z \rightarrow \text{hadrons})}{\Gamma(Z \rightarrow \text{leptons})} = 20.767 \pm 0.025 \quad (0.12 \% \text{ rel.)} \]

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

\[ \mu = 2^{0.25} \quad M_Z \]

\[ M_H = \frac{900}{100} \quad \text{GeV} \]

\[ M_t = \pm 5 \text{GeV} \]

\[ \pm 0.0002 \quad \text{renormal. schemes} \]

\[ = 0.1226 \pm 0.0058 - 0.0038 \]
\( \alpha_s \) from Incl. Z Decays / Width

- uncertainty because of \( m_H \) gone, \( m_{\text{top}} \) dep. no problem

- pQCD scale uncertainty, from latest NNNLO calculation:
  
  \( \sim 0.0002 \) (absolute uncertainty on \( \alpha_s \)), see arXiv:0801.1821 and 1201.5804

- eg. taking \( \Gamma_Z \): current uncertainty 2.3 MeV

  \( \sim 1.2 \text{ MeV from beam energy} \) (dominating contribution)

  remainder: mostly statistical/experimental

- **so the question is:**
  
  can a future Z factory measure \( \Gamma_Z \) at a precision of \( \sim 0.1 \text{ MeV} \)?

  or \( R \) with an absolute precision of \( \sim 0.001 \)?

- **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.

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From W hadronic width $B_h \equiv \frac{\Gamma_{\text{had}}}{\Gamma_{\text{tot}}} W$

- $WW \rightarrow \ell\nu\ell\nu \ (\text{all } WW) = (1-B_h)^2$.
- $WW \rightarrow \ell\nu qq \ (\text{all } WW) = 2B_h (1-B_h)$.
- $WW \rightarrow qq qq \ (\text{all } WW) = B_h^2$.

Present value at LEP (4x10^4 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 $R_l = \frac{\Gamma_{Z \rightarrow \text{had}}}{\Gamma_l}$

- Present LEP value 20.767 \pm 0.0025 (2x10^7 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.