Some thoughts on extracting the strong coupling from the hadr. BR of the W boson at TLEP

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Reminder: hadronic Z decays

ETH Institute for Particle Physics

- See my talk at the TLEP workshop in April 2013
  - precision achievable using the hadr. partial width of the Z
  - precision achievable using hadr. tau decays
- See also TLEP study, arXiv:1308.6176:
  - with a 5×10^{-5} exp. precision expected, an uncert. of ~0.0002 achievable for α_s from hadr. Z decays

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

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

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

pert. scale uncertainty, using latest NNNLO pred:
~0.0002 (absolute uncertainty on α_s),
see arXiv:0801.1821 and 1201.5804

$$\sim \mathcal{O}\left(\frac{m_q^2}{M_Z^2}\right)$$

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

Th. Gehrmann: calculations can be improved if necessary

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

<< 0.0001, no problem

Reminder: hadronic tau decays

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$$R_\tau^{kl} = \int ds \left(1 - \frac{s}{m_\tau^2}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{dR_\tau}{ds} \propto 3\left(1 + \delta_{QCD} + \delta_{NP}\right)$$

approach taken at LEP: fit simultaneously α_s and the non-pert. coefficients, by measuring various moments.

also known at NNNLO

$$\delta_{NP} = \frac{ZERO}{m_\tau^2} + c_4 \cdot \frac{< O_4 >}{m_\tau^4} + c_6 \cdot \frac{< O_6 >}{m_\tau^6} + \cdots$$

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  - the non-perturbative contributions turn out to be (surprisingly) small

    eg. ALEPH: $\delta_{NP} = -0.0059 \pm 0.0014$

    $$\Delta\alpha_s(m_\tau) \approx \pi \cdot \Delta\delta_{NP}$$

  - it would definitely be interesting to measure such moments again, with much improved precision. Eg. an uncertainty on δ_{NP} of < 0.0005

- Regarding the discussion on the control of pert. higher-order contributions, and other theoretical issues:
  - see eg. talk by T. Pich at this workshop

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End <Reminder>

Hadronic W branching ratio

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- See TLEP study, arXiv:1308.6176:

Beyond the measurement of R_ℓ at the Z pole, another interesting possibility for the α_s determination is to use the W hadronic width as measured from W-pair events at and above 161 GeV. The quantity of interest is the branching ratio $B_{\rm had} = \Gamma_{\rm W\to hadrons}/\Gamma_{\rm W}^{\rm tot}$, which can be extracted by measuring the fractions of WW events to the fully leptonic, semi-leptonic and fully hadronic final states:

$$\mathrm{BR}(\mathrm{W}^+\mathrm{W}^- \to \ell^+\nu\ell'^-\bar{\nu}) = (1 - B_{\rm had})^2, \quad (5)$$

$$\mathrm{BR}(\mathrm{W}^+\mathrm{W}^- \to \ell^+\nu \mathrm{q}\bar{\mathrm{q}}') = (1 - B_{\rm had}) \times B_{\rm had}, \quad (6)$$

$$\mathrm{BR}(\mathrm{W}^+\mathrm{W}^- \to \mathrm{q}\bar{\mathrm{q}}'\mathrm{q}''\bar{\mathrm{q}}''') = B_{\rm had}^2. \quad (7)$$

The LEP2 data taken at centre-of-mass energies ranging from 183 to 209 GeV led to $B_{\rm had} = 67.41 \pm 0.27$ [51], a measurement with a 0.4% relative precision. This measurement was limited by WW event statistics of about 4×10^4 events. With over 2×10^8 W pairs expected at TLEP at $\sqrt{s} = 161, 240$ and 350 GeV, it may therefore be possible to reduce the relative uncertainty on $B_{\rm had}$ by a factor ~ 70, down to 5×10^{-5}, and thus the absolute uncertainty on α_s to ± 0.00015.

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Note: from the three measurements above, obviously also possible to extract the hadronic partial width of the W, Γ_h^W

Theoretical predictions for hadr. Γ^W

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- For recent work, see D. Kara, arXiv:1307.7190, and references therein
- or also the PDG review by Erler and Langacker

from D. Kara, arXiv:1307.7190

$$\Gamma_{\text{had}} = \underbrace{\Gamma^{(0)}}_{\text{LO}} + \underbrace{\sum_{i=1}^{4} \Gamma^{(i)}_{\text{QCD}}}_{\text{NLO + HO}} + \underbrace{\Gamma^{(1)}_{\text{EW}}}_{\text{NLO}} + \underbrace{\Gamma^{(2)}_{\text{mixed}}}_{\text{NNLO}}$$

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ignoring EW corrections:

$$\Gamma_h^W = \frac{G_F\, M_W^3}{2\sqrt{2}\pi}\, V\,(1 + \delta_{qcd} + \delta_m + \delta_{np})$$

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same NNNLO exp. has in the Z case, thus pQCD scale uncert. of 0.0002 achievable

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δ_m: should be even less of an issue than for Z, because of the reduced b-contribution

δ_{np}: highly suppressed, as in Z case

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$$V = \sum |V_{qq'}|^2$$

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Extracting α_s from the hadr. W BR

modulo leptonic mass corrections:

$$\Gamma_l^W = \frac{G_F M_W^3}{2\sqrt{2}\pi}$$

Therefore:

$$\Gamma_h^W \approx \Gamma_l^W \, V \left(1 + \frac{\alpha_s(M_W)}{\pi}\right)$$

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~ 26

$\mathcal{O}(1)$

exp. prec:
currently
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Extracting α_s from the hadr. W BR

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attention: this would lead to a **1.5% rel. uncert**. !! But no problem, if 0.5 MeV uncert. is achieved as estimated in the TLEP paper.

Extracting α_s from the hadr. W BR

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So: with current exp. precision it is impossible to extract a precision measurement of α_s.
Even if Γ^W is measured at TLEP at the 10^{-5} level, the CKM knowledge is a show-stopper.

Limiting factors

uncertainty from CKM elements:
(ignoring correlations)

$$\frac{\Delta V}{V} = 2\sqrt{\sum\left(\frac{V_{qq'}}{V}\Delta V_{qq'}\right)^2}$$

taking the numbers from the PDG:

$V_{qq'}$	value	uncert.	rel. [%]	$V_{qq'}/V$
V_{ud}	0.97425	0.00022	0.02	0.47
V_{us}	0.2252	0.0009	0.40	0.11
V_{ub}	0.00415	0.00049	11.8	0.002
V_{cd}	0.230	0.011	4.8	0.11
V_{cs}	1.006	0.023	2.3	0.49
V_{cb}	0.0409	0.0011	2.7	0.02

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Ways out?

- Just assume unitarity, then V=2, and you are done.
- Might be interesting to invest some work in estimating the uncertainty on the most relevant CKM elements, when taking into account all constraints and correlations.
- taking the ratio of the hadr. W BR and the hadr. tau BR doesn't help, because for the tau only V_{ud} counts, which is known to high precision.
- Of course, I cannot exclude other future measurements of V_{cs}, but to a precision at the 0.1 per-mille level, as needed?

Side remarks

obviously, using B(had) instead of the partial width, doesn't alter the problem:

$$\frac{1}{B_h} - 1 \approx \frac{1}{V} \left(1 - \frac{\alpha_s(M_W)}{\pi}\right)$$

Side remarks

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obviously, using B(had) instead of the partial width, doesn't alter the problem:

$$\frac{1}{B_h} - 1 \approx \frac{1}{V} \left(1 - \frac{\alpha_s(M_W)}{\pi}\right)$$

remember the tau case: there is probably interest to constrain better the non-pert. and unknown higher order contributions:

$$R_\tau \approx S_{ew} \left(1 + \frac{\alpha_s(m_\tau)}{\pi} + \delta_{np}\right)$$

$$\Downarrow$$

$$\frac{\Delta\delta_{np}}{\delta_{np}} = \frac{\alpha_s(m_\tau)}{\delta_{np}} \frac{1}{\pi} \frac{\Delta\alpha_s(m_\tau)}{\alpha_s(m_\tau)} \oplus \frac{1}{\delta_{np}} \Delta\left(\frac{R_\tau}{S_{ew}}\right)$$

$$\Downarrow$$

$$\frac{\Delta\delta_{np}}{\delta_{np}} \approx \left(18 \cdot \frac{\Delta\alpha_s(m_\tau)}{\alpha_s(m_\tau)}\right) \oplus \left(167 \cdot \Delta\left(\frac{R_\tau}{S_{ew}}\right)\right)$$

Thus: if α_s constrained at the per-mille level by another measurement, and R_{tau} measured at the sub-per-mille level, then these non-pert. contributions could be constrained at the few % level!

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as long as no independent 0.1 per-mille measurements of V_{cs} are available (or other clever ideas):

Invert the problem indicated here:

(similar idea already used in the past by ALEPH, at LEP2)

$$\frac{\Delta\alpha_s}{\alpha_s} = \frac{\pi}{\alpha_s} \frac{\Gamma_h^W}{\Gamma_l^W\, V} \left(\frac{\Delta\Gamma_h^W}{\Gamma_h^W} \oplus \frac{\Delta V}{V} \right)$$

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- Perform measurements of the hadronic BRs of the Z, the W and Tau at TLEP at the best possible precision, eg. ~ 5×10^{-5}
- Assume that the running of α_s as predicted by QCD is correct at the per-mille level
  - to be studied: exact impact on precision achievable when running to low scales, and passing the charm threshold
- Extract $\alpha_s(M_Z)$ from the hadr. BR of the Z, at precision of ~0.0002, calculate $\alpha_s(M_W)$
- and use this to constrain V = Sum($V^2_{qq'}$) at the **sub per-mille level**!
- Run the $\alpha_s(M_Z)$ extracted above to $\alpha_s(M_{tau})$ and constrain the non-pert. coefficients and possible unknown HO terms to a precision of a few per-cent.
- Thus, a nice overall set of measurements to constrain a number of relevant terms.