Improved strong coupling measurements at TLEP?

some personal thoughts, plus input from discussion

with Th. Gehrmann (UZH)

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April 2013

Recent summary from the PDG

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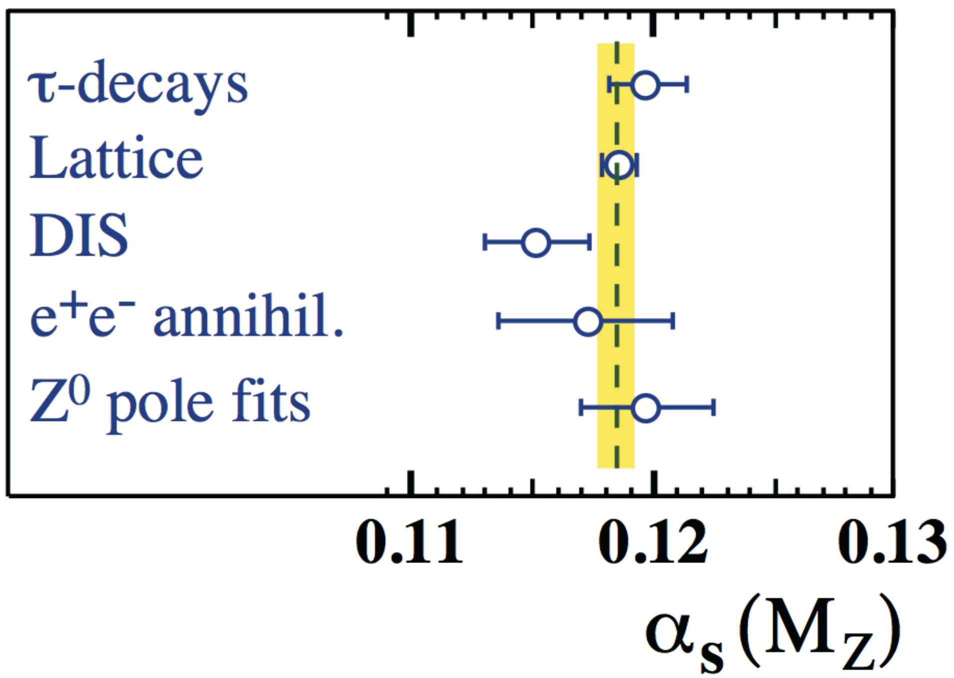
see Bethke, Dissertori, Salam: http://pdg.lbl.gov/2012/reviews/rpp2012-rev-qcd.pdf



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.)

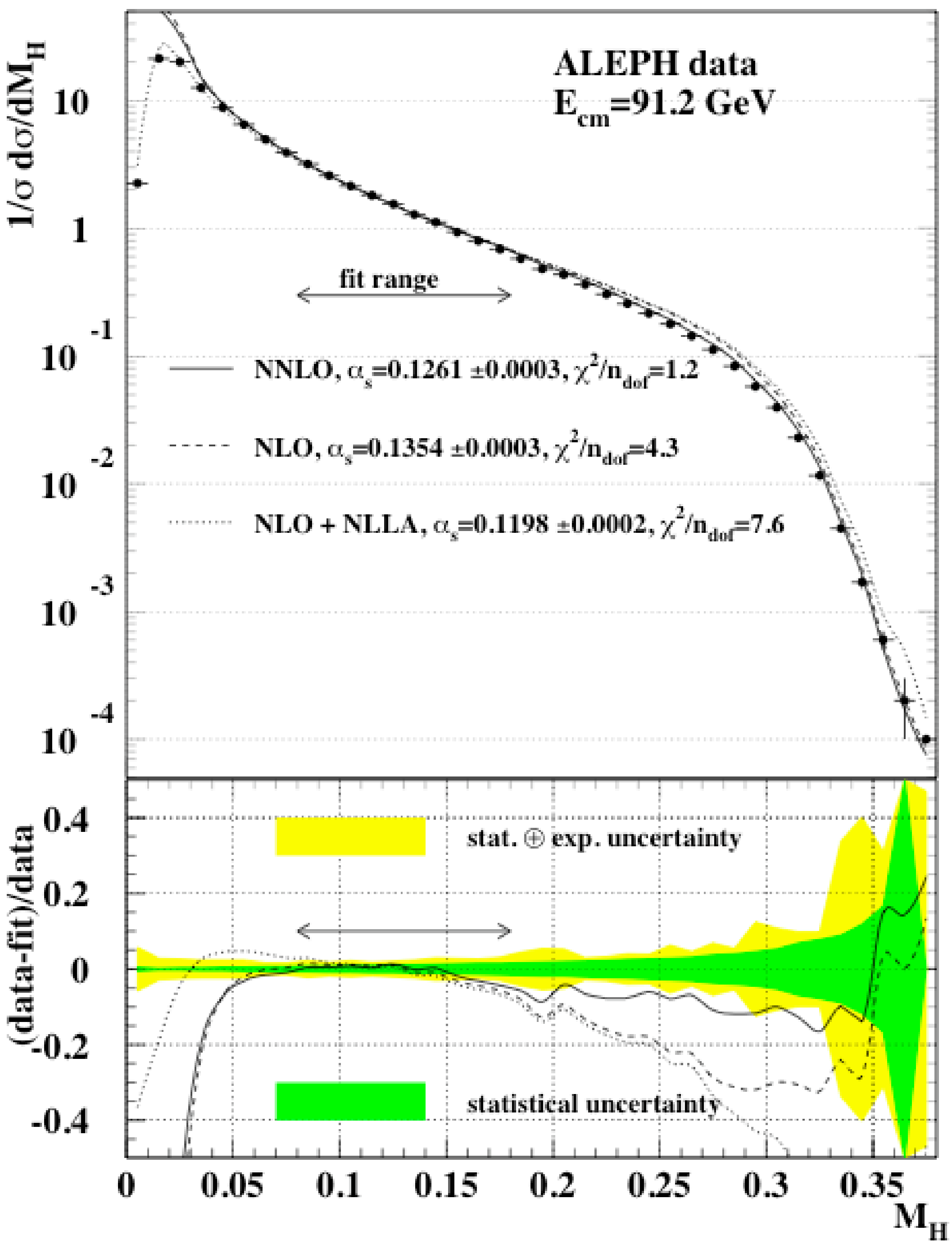
Question:
what is interesting (or realistic) goal to take as reference for this discussion?

Let's choose: **0.0001 (abs) or ~0.1 % (rel)**

Also: let's focus at Z peak measurements, in order to have an independent $\alpha_S(M_Z)$ as input, eg., for m_{top} determination at ttbar threshold.

Jet rates, event shapes

- "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**

α_s from inclusive Z decays

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

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

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

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

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

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

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

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

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

<< 0.0001, no problem

Example (using NNLO)

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

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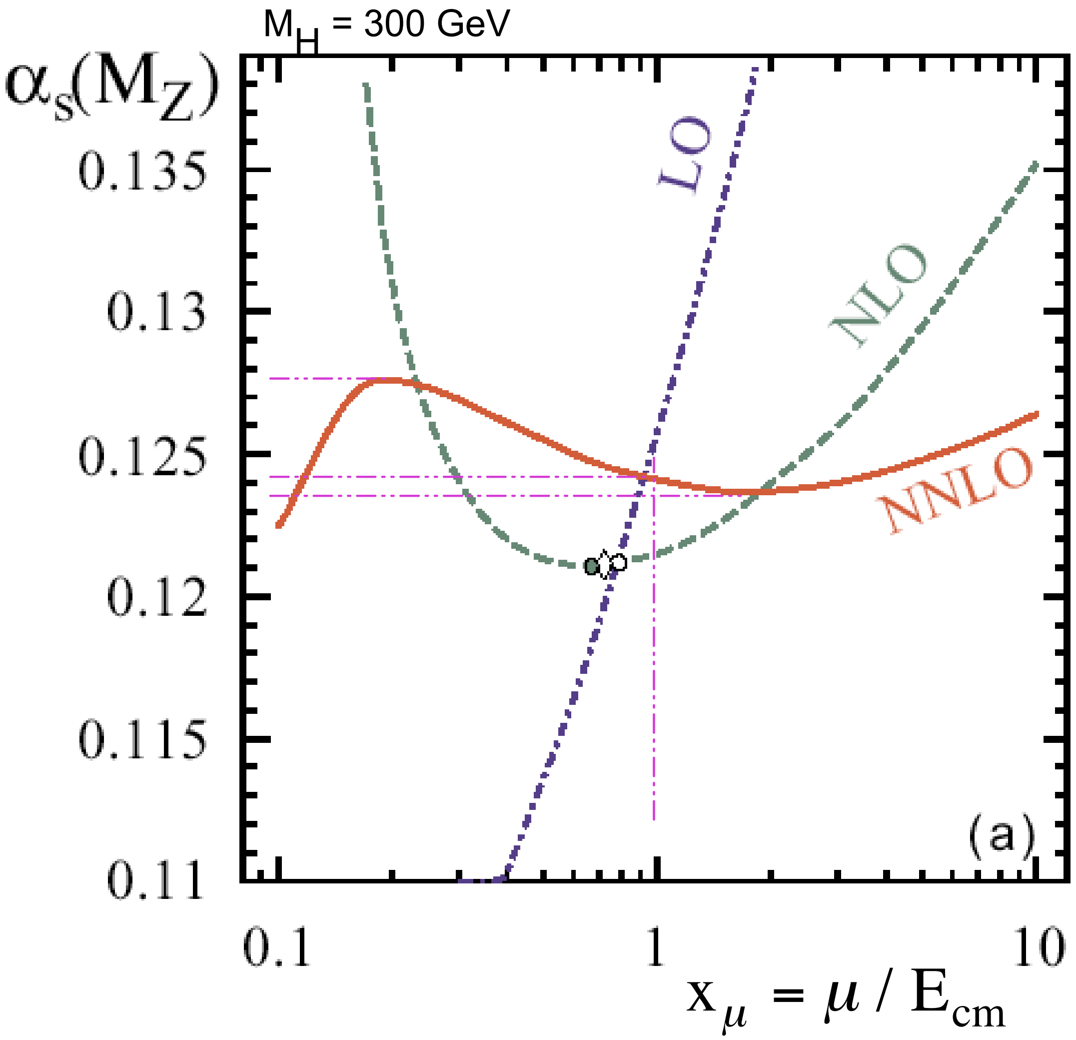
see next slide

$$\alpha_s(M_Z) = 0.1226 \pm 0.0038 \;\; \text{exp.}$$



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

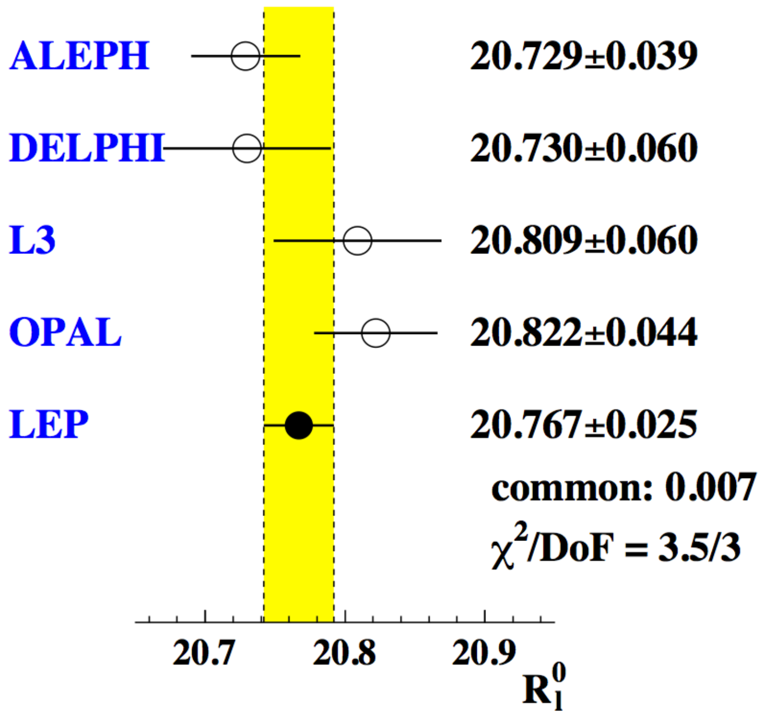
$$^{+0.0033}_{-0.0} \quad M_H = {}^{900}_{100}\ \text{GeV}$$

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

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

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

Latest results from LEP EW group



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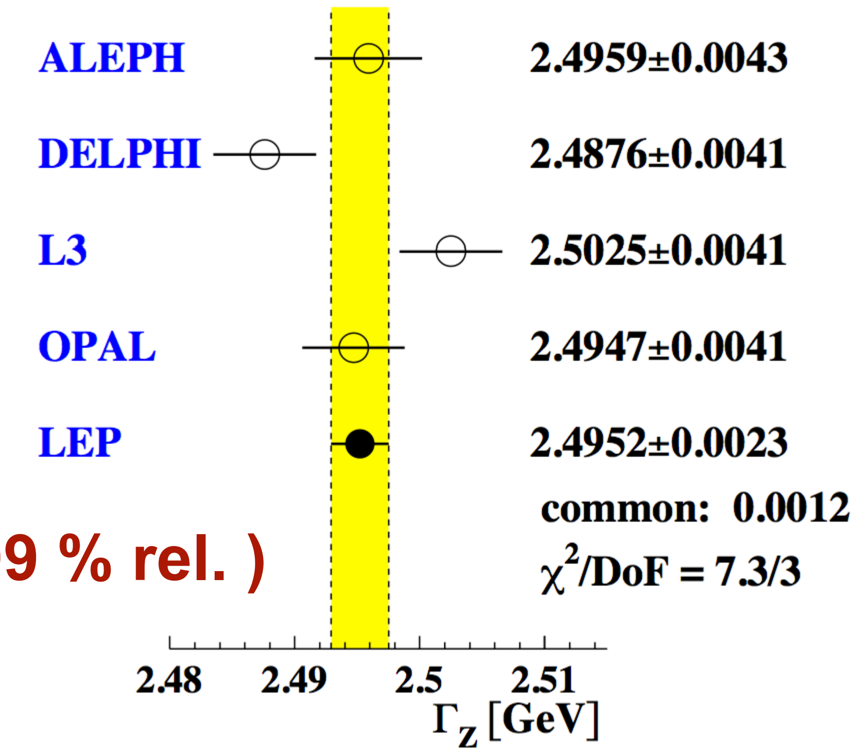

(0.09 % rel.)

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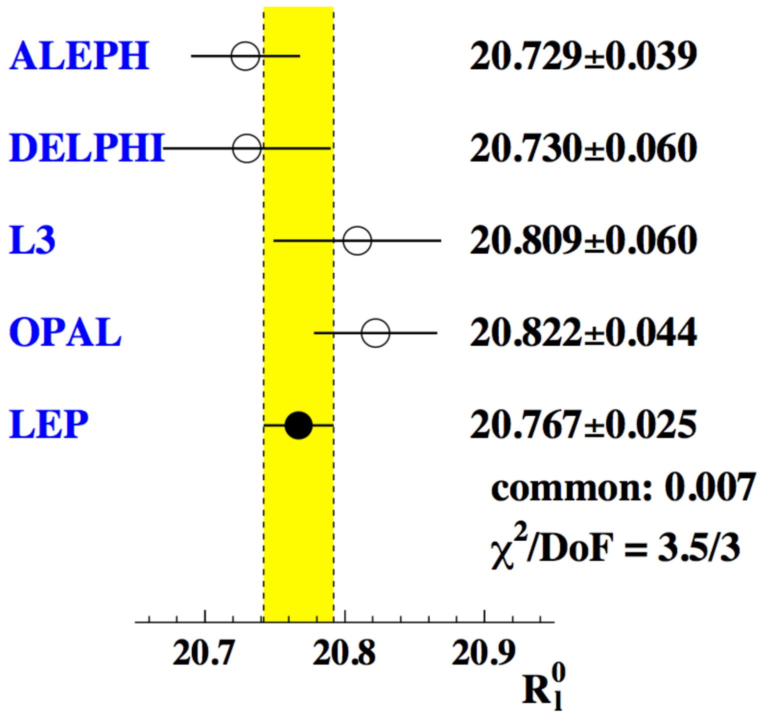

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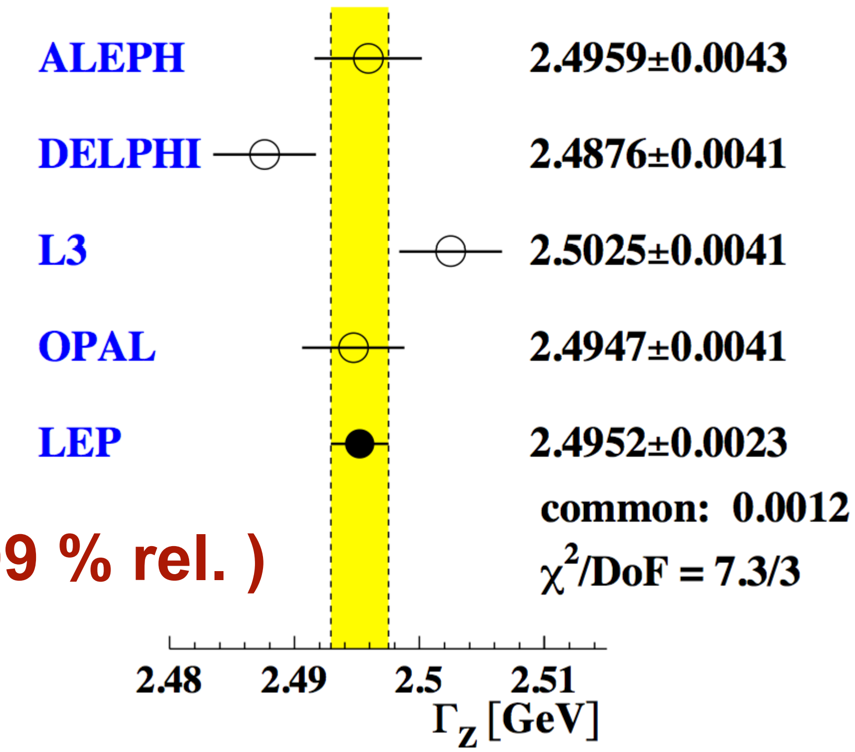

(0.09 % rel.)

Source	δ	Γ_Z [MeV]	σ^0_{had} [nb]	R^0_ℓ	R^0_b	ρ_ℓ	$\sin^2\theta^{lept}_{eff}$	m_W [MeV]
$\Delta\alpha^{(5)}_{had}(m^2_Z)$	0.00035	0.3	0.001	0.002	0.00001	—	0.00012	6
$\alpha_S(m^2_Z)$	0.003	1.6	0.015	0.020	—	—	0.00001	2
m_Z	2.1 MeV	0.2	0.002	—	—	—	0.00002	3
m_t	4.3 GeV	1.0	0.003	0.002	0.00016	0.0004	0.00014	26
$\log_{10}(m_H/\text{GeV})$	0.2	1.3	0.001	0.004	0.00002	0.0003	0.00022	28
Theory		0.1	0.001	0.001	0.00002	—	0.00005	4
Experiment		2.3	0.037	0.025	0.00065	0.0010	0.00016	34

from slide 4:

$$\frac{\Delta\alpha_s}{\alpha_s} \approx 25 \cdot \frac{\Delta R_{\exp}}{R_{\exp}}$$

thus: for a rel. prec. of ~0.1% on α_s we need rel. exp. prec. ~25 times better !!

So summarizing

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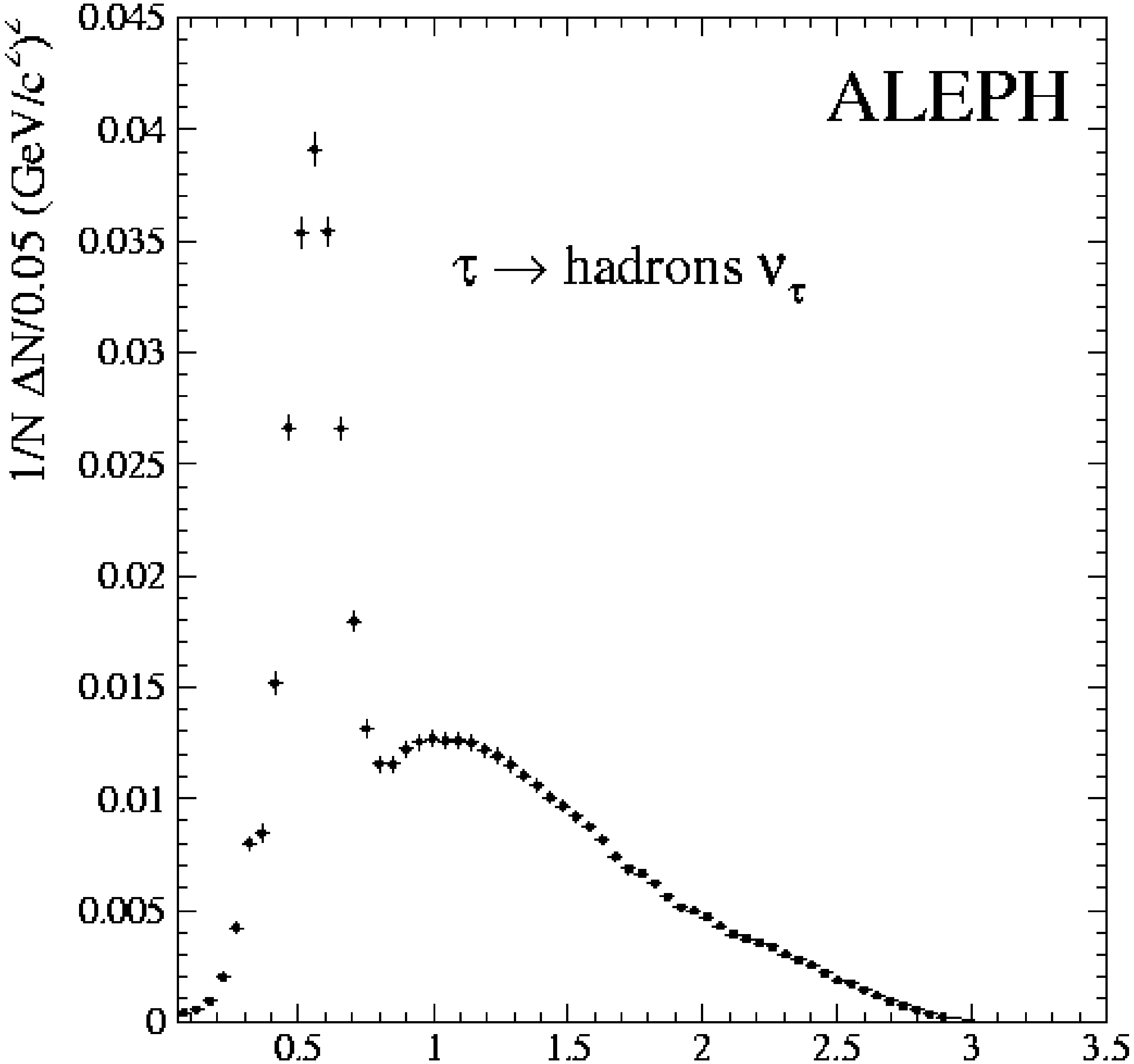
- uncertainty because of m_H gone, m_{top} dep. no problem
- pQCD scale uncertainty, from latest NNNLO calculation:
  - ~**0.0002** (absolute uncertainty on α_s), see arXiv:0801.1821 and 1201.5804
- eg. taking Γ_Z: current uncertainty 2.3 MeV
  - ~ 1.2 MeV from beam energy (dominating contribution)
  - remainder: mostly statistical/experimental
  - **so the question is:**
    can TLEP measure Γ_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.**

R_τ: τ hadronic BR



s [GeV²]

s = (invariant mass)² of hadronic decay products

in principle even more inclusive than R at the Z pole, since integrating over hadronic inv. mass spectrum

$$R_\tau = \frac{1}{\pi}\int_0^{m_\tau^2} \frac{ds}{m_\tau^2}\left(1-\frac{s}{m_\tau^2}\right)^2 Im\Pi_\tau(s)$$

interesting "advantage": "shrinking" of uncertainty just due to running of α_s :

$$\alpha_s(m_\tau) = 0.3285 \pm 0.018 \quad \textbf{(5.5 \% rel.)}$$

$$\alpha_s(m_Z) = 0.1194 \pm 0.0021 \quad \textbf{(1.8 \% rel.)}$$

The Beauty of a Moment...

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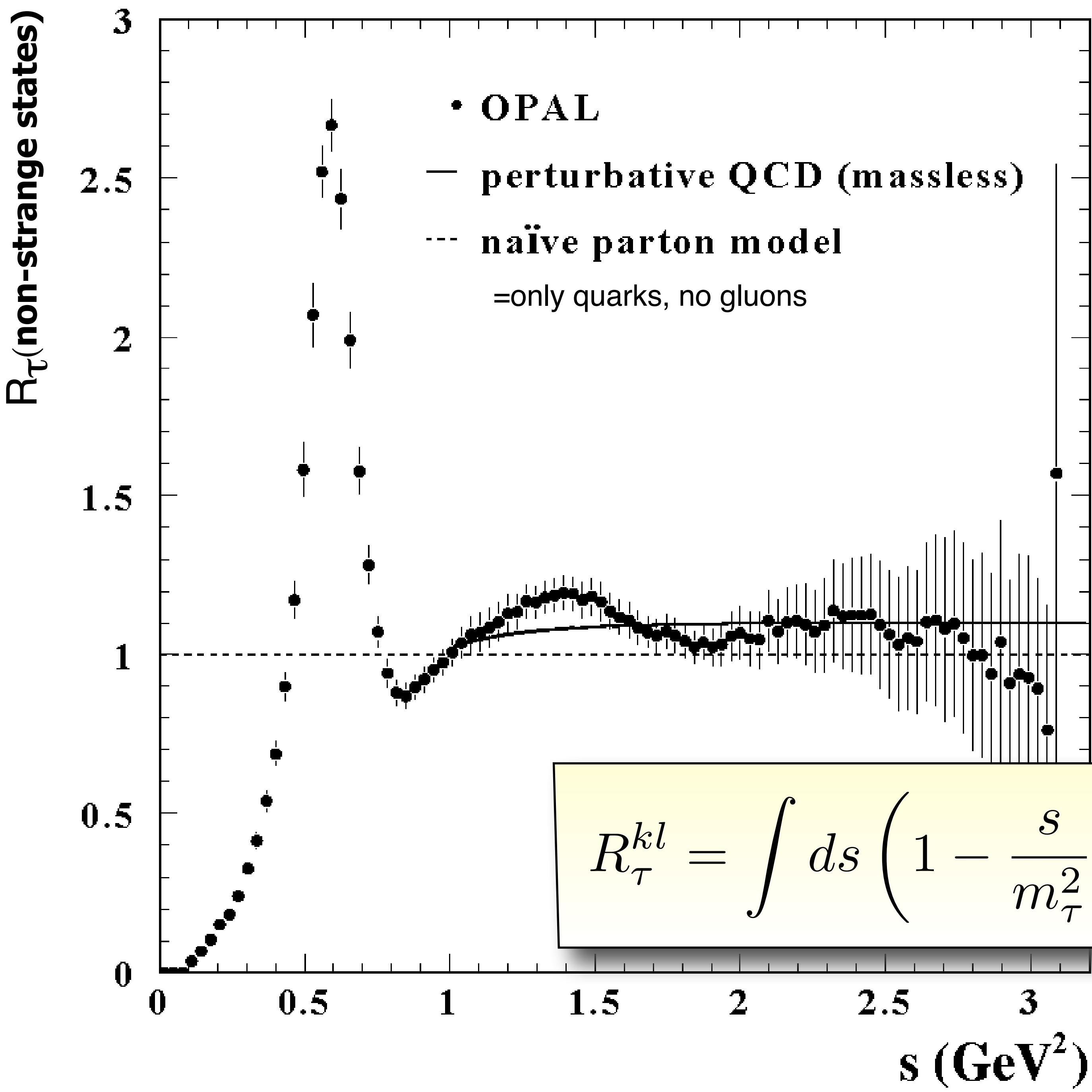
Without phase space factor and taking moments, in order to average out resonances:



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

opinions vary about the importance of this “ZERO”, see eg. Altarelli, arXiv: 1303.6065

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

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

also known at NNNLO

α_s at the Tau Scale

- From moments-measurements at LEP:
  - the non-perturbative contributions turn out to be (surprisingly) small

    eg. ALEPH: δ_{NP} = - 0.0059 ± 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
- But:
  - various methods of estimating higher-order terms (see eg. Altarelli:1303.6065, or Pich:1303.2262) differ by >~ 5 % for $\alpha_s(m_{tau})$, ie. leading to >~ 1% at the Z mass scale.
  - Seems difficult (impossible?) to improve on this?

Conclusion

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- Jet-or event-shape based measurements, as well as using tau decays:
  seems difficult (impossible?) to go well below the 1% rel. uncertainty.

- EWK observables at the Z pole, such as hadronic width (branching ratio):
  this could be interesting to be further investigated.