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On the Status of ! s

Insights and Open Issues

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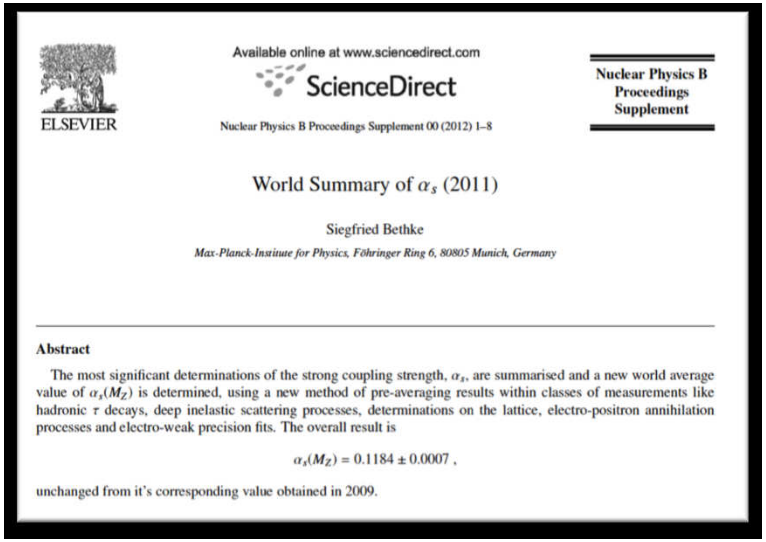
Faculty for Physics
University of Vienna

Content

What this talk it NOT about: World Average of ! $_s$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Nuclear Physics B Proceedings Supplement 00 (2012) 1–8

Nuclear Physics B Proceedings Supplement

World Summary of α_s (2011)

Siegfried Bethke

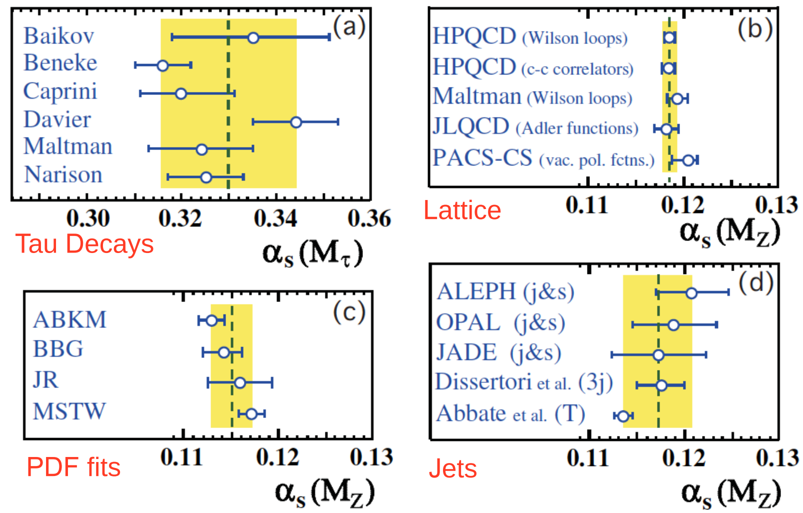
Max-Planck-Insitute for Physics, Föhringer Ring 6, 80805 Munich, Germany

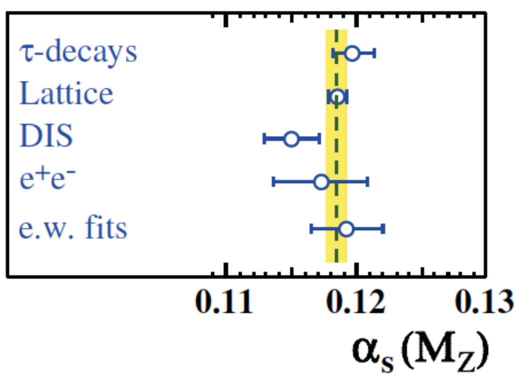
Abstract

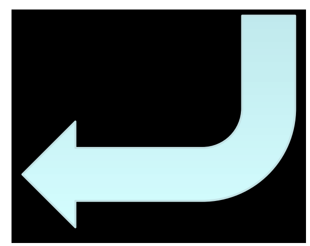
The most significant determinations of the strong coupling strength, α_s, are summarised and a new world average value of $\alpha_s(M_Z)$ is determined, using a new method of pre-averaging results within classes of measurements like hadronic τ decays, deep inelastic scattering processes, determinations on the lattice, electro-positron annihilation processes and electro-weak precision fits. The overall result is

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007\,,$$

unchanged from it's corresponding value obtained in 2009.







$$\alpha_s(m_Z) = 0.1184 \pm 0.0007$$

Content

What this talk it NOT about: World Average of !$_s$

Aims:

- Point out recent developments
- Provide some insight into some tricky points and open issues
- Motivate to push foward precise !$_s$ determinations

This talk attempts to be objective, but certainly won’t !

Apologies to those whose work is not mentioned and missing references !

Some material in this talk taken from presentations given at the Workshop “Precision Measurements of !$_s$” (MPI, Munich, February 9-11, 2012)

Content

- Introduction
- Lattice Simulations
- ! -decays
- Eventshapes and Jet Rates
- DIS
- Conclusions

Strong Coupling: Theory

SU(3) gauge theory:

[redacted]

$$D^{\mu} = \partial^{\mu} + i g_s A^{\mu}$$

$$\alpha_s \equiv \frac{g_s^2}{4\pi}$$

- SU(3) gauge symmetry does not fix strong coupling and quark masses
- QCD parameters are renormalized quantities and NOT physical
- Values are fixed by BSM short-distance physics

Strong Coupling: Theory

RG-evolution:

- Standard scheme: $\overline{\text{MS}}$ defined within dim reg
- 4-loop precision available

$$\frac{\mathrm{d}\alpha_s(\mu)}{\mathrm{d}\ln\mu} = \beta(\alpha_s(\mu)) = -2\,\alpha_s(\mu)\sum_{n=0}^{\infty}\beta_n\left(\frac{\alpha_s(\mu)}{4\pi}\right)^{n+1}$$

$$\begin{aligned}
\beta_0 &= \frac{1}{4}\left[11 - \frac{2}{3}n_f\right] \\
\beta_1 &= \frac{1}{16}\left[102 - \frac{38}{3}n_f\right] \\
\beta_2 &= \frac{1}{64}\left[\frac{2857}{2} - \frac{5033}{18}n_f + \frac{325}{54}n_f^2\right] \\
\beta_3 &= \frac{1}{256}\left[\left(\frac{149753}{6} + 3564\zeta_3\right) - \left(\frac{1078361}{162} + \frac{6508}{27}\zeta_3\right)n_f \right. \\
&\quad \left. + \left(\frac{50065}{162} + \frac{6472}{81}\zeta_3\right)n_f^2 + \frac{1093}{729}n_f^3\right]
\end{aligned}$$

" $_3$: Vermaseren, Larin, v.Ritbergen 1997
Czakon 2004

Decoupling:

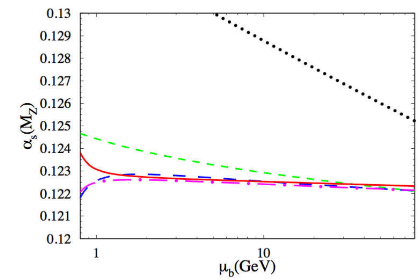
- Defined within an n_f-flavor effective theory
- Massive quarks integrated out
- 4-loop precision available

$$\alpha_s^{(n_f)}(m_h) = \alpha_s^{(n_f+1)}(m_h)\left(1 + \frac{11}{72}\left(\frac{\alpha_s^{(n_f+1)}(m_h)}{\pi}\right)^2 + \ldots\right)$$

Schröder, Steinhauser 2005
Chetyrkin, Kühn, Sturm 2005

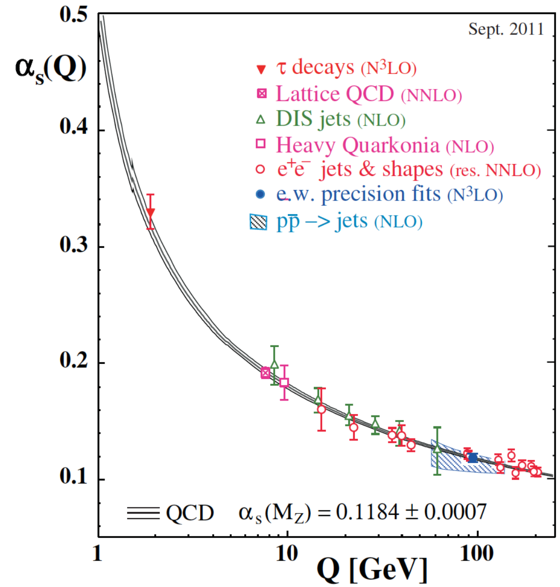
$$\alpha(m_\tau) \longrightarrow \alpha(m_Z): \quad \delta\alpha(m_Z) = \pm 0.0004$$

Theory error smaller than most other uncertainties.



Strong Coupling: Theory

Asymptotic freedom:



- ! $_s$ perturbative only for scales larger than 1 GeV
- Currently we are only capable determining ! $_s$ from processes where perturbation theory dominates.

$\Lambda_{\rm QCD}$:

$$\alpha_s^{(n_f)}(\mu) = \frac{4\pi}{\beta_0^{n_f} \ln(\frac{\mu^2}{\Lambda^2_{\rm QCD}})} + \ldots$$

$$\Lambda^{(5)}_{\overline{MS}} = (213 \pm 8)\ \text{MeV}\ ,$$
$$\Lambda^{(4)}_{\overline{MS}} = (296 \pm 10)\ \text{MeV}$$
$$\Lambda^{(3)}_{\overline{MS}} = (339 \pm 10)\ \text{MeV}$$

- Parameter equivalent to ! $_s$
- Frequently used to as a synonym for the scale of hadronization/confinement in dimensional counting

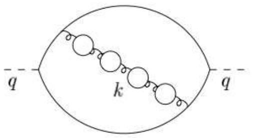
Strong Coupling: Theory

IR-Sensitivity:

$$\alpha_s(k) = \alpha_s(\mu) \sum_{i=0}^{\infty} \left(\frac{\alpha_s(\mu)\beta_0}{4\pi} \right)^i \ln^i \left(\frac{\mu^2}{k^2} \right)$$

- dim reg perturbation theory in gauge theories leads to enhanced sentivity to scales $\mathcal{O}(\Lambda_{\rm QCD})$
- „Renormalons“
- Conceptual origin of the OPE

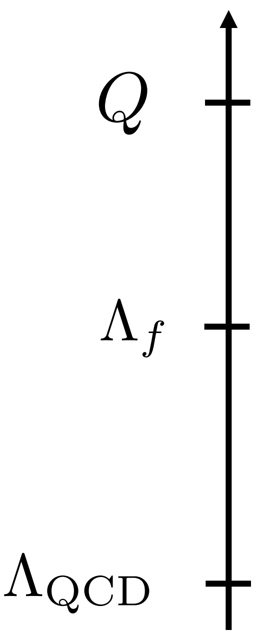
$$\int_0^1 {\rm d}x\, x^{m-1} \ln^n(1/x) \;=\; \frac{n!}{m^{1+n}}$$



Wilson's OPE:

$\Lambda_{\rm QCD} < \Lambda_f < Q$ (cutoff regulator)

$$\sigma = C_0^W(Q,\Lambda^f)\theta_0^W(\Lambda^f) + C_1^W(Q,\Lambda^f)\,\frac{\theta_1^W(\Lambda^f)}{Q^p} + \ldots .$$



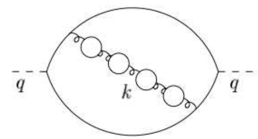
- Cleanest separation of short and long distance contributions
- renormalon-free
- EXTREMELY cumbersome for precision computations

Strong Coupling: Theory

IR-Sensitivity:

$$\alpha_s(k) = \alpha_s(\mu) \sum_{i=0}^{\infty} \left(\frac{\alpha_s(\mu)\beta_0}{4\pi}\right)^i \ln^i\left(\frac{\mu^2}{k^2}\right)$$

- dim reg perturbation theory in gauge theories leads to enhanced sentivity to scales $\mathcal{O}(\Lambda_{\rm QCD})$
- „Renormalons“
- Perturbation theory only valid within OPE



$$\int_0^1 \mathrm{d}x\, x^{m-1} \ln^n(1/x) = \frac{n!}{m^{1+n}}$$

OPE in $\overline{\rm MS}$:

dim. reg. $\quad d = 4 - 2\epsilon$

$$\sigma \sim \mu^{2\epsilon} \int dk^{d-3} \frac{k^{p-1} f(k^2, \Lambda_{\rm QCD}^2)}{(k^2+Q^2)^{p/2}}$$

$$= \mu^{2\epsilon} \int dk^{d-3} \frac{k^{p-1} f(k^2, 0) + \ldots}{(k^2+Q^2)^{p/2}} + \mu^{2\epsilon} \int dk^{d-3}\, k^{p-1} f(k^2, \Lambda_{\rm QCD}) \left[\frac{1}{Q^p} + \ldots\right]$$

$$\sigma = \bar{C}_0(Q,\mu)\bar{\theta}_0(\mu) + \bar{C}_1(Q,\mu)\frac{\bar{\theta}_1(\mu)}{Q^p} + \ldots$$

- High precision calculations manageable
- Renormalons can degrade perturbative behavior
- „Non-perturbative effects“ – and also „Duality Violation“

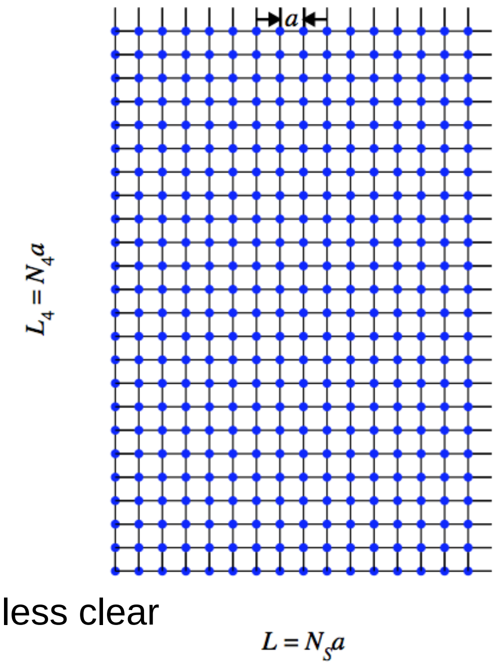
Lattice QCD

- QCD without gauge-fixing and ghosts
- Functional integrals formulated numerically on a finite Euklidean space-time lattice: size $N_s^3 \times N_3 \times a^4$

$$\langle \bullet \rangle = \frac{1}{Z} \int \mathcal{D}U \mathcal{D}\psi \mathcal{D}\bar{\psi} \exp(-S) [\bullet]$$

- Demanding: technical+conceptual implementation of virtual quarks (sea quarks): 4-fold replication on finite lattice

$$\langle \bullet \rangle = \frac{1}{Z} \int \mathcal{D}U \prod_{f=1}^{n_f} \det(\not{D} + m_f) \exp(-S_{\text{gauge}}) [\bullet]$$



- Staggered (4^{th} root of det) — fast numerically, coneptually less clear
  Wilson
  Domain-wall — clean conceptually, expensive

- Large scale separation vs. finite lattice: Effective Theories
  e.g. heavy quark masses: HQET, NRQCD
  Lattice spacing small: Symanzik improved action

- Chiral limit with staggered fermions: considered meaningful, but all results need to be checked with other fermion formulations

- 2(light)+1(strange) fermions: state-of-the-art

Lattice QCD

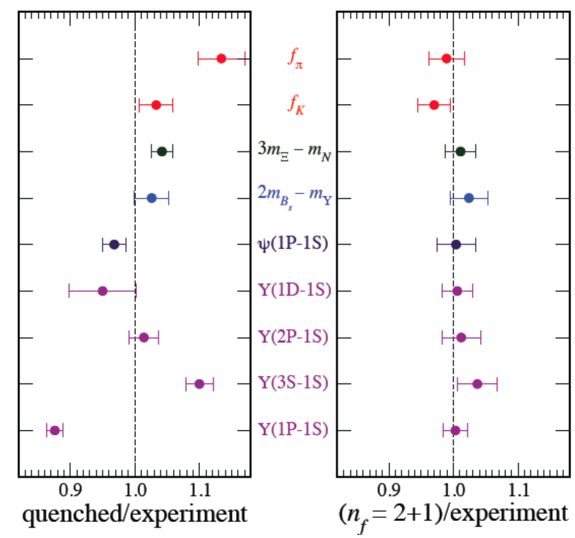
!$_s$-determinations:

- •! tune lattice to observed hadron spectrum

  ➡ fix lattice parameters as fct of a

- •! Compute quantities on the lattice that can also be computed with perturbation theory („lattice replaces experiment")

  - !! small Wilson loops (compare to lattice p.th.)
  - !! Current correlators (lattice + continuum p.th.)
  - !! Adler function (lattice + contiuum p.th.)
  - !! QCD energy in cylinder (lattice p.th.)



$\alpha_{\overline{MS}}^{(n_f=5)}(M_Z)$	R	Q	range	$\mathcal{R}$	sea	Ref.
0.1170(12)			3			[9]
0.1183(8)	Wilson loops	a^{-1}	7	NNLO	2+1 $\sqrt[4]{\text{staggered}}$	[10]
0.1192(11)			7			[11]
0.1174(12)	quarkonium	$2m_c$	1–2	NNLO	2+1 $\sqrt[4]{\text{staggered}}$	[12]
0.1183(7)	correlators	$2m_Q$	3–6	NNLO	2+1 $\sqrt[4]{\text{staggered}}$	[13]
0.1181(3)$^{+14}_{-12}$	Adler function	Q	5	NNLO*	2+1 overlap	[14]
0.1205(8)(5)$^{+0}_{-17}$	"QCD in a can"		80		2+1 Wilson	[15]
0.1000(16)†	aka Schrödinger	L^{-1}	270	asymptotic	2 Wilson	[16]
0.1___(_)	functional		1000		2+1+1 Wilson	[17]

HPQCD

JLQCD

PACS-CS

ALPHA

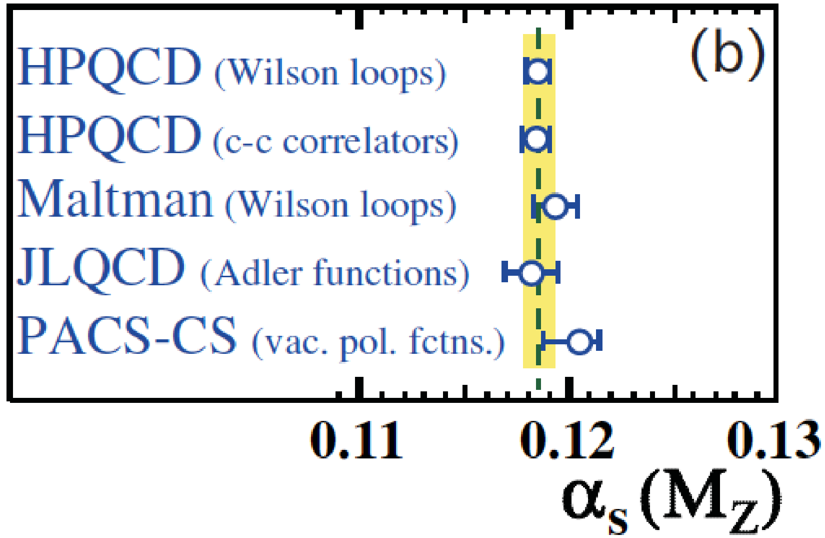
Lattice QCD

! $_s$-determinations:

Results live from their consistency within well-developed methods.

World average dominated by lattice results.

Bethke 2011



Is that it ?

Any reason to go on ? - YES !

(1)! Results should be cross checked (from lattice and other methods)

(2)! Finding the origin of disagreement to other methods motivates dedicated studies

Ability to make precision measurements reflects the true understanding of the method of theory.

" Decay

Total hadronic " width: $R_\tau = \dfrac{\Gamma(\tau \to \nu_\tau + \text{hadrons})}{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}$

Braaten, Narison, Pich 1992

➡ Related to absorptive part of V and AV current correlators

$$R_{\tau,V+A} = N_C\,|V_{ud}|^2\,S_{\rm EW}\,\{1 + \delta_{\rm P} + \delta_{\rm NP}\}$$

non-perturb. corr. (OPE)

$$\delta_{\rm NP} = -0.0059 \pm 0.0014$$

electroweak corr.

$$S_{\rm EW} = 1.0201 \pm 0.0003$$

QCD corrections

O(! s4) : Baikov, Chetyrkin, Kühn 2008

$$\delta_{\rm P} = \sum_{n=1} K_n\,A^{(n)}(\alpha_s) = \sum_{n=1} (K_n + g_n)\,a_\tau^n \equiv \sum_{n=1} r_n\,a_\tau^n \qquad a_\tau \equiv \frac{\alpha_s(m_\tau)}{\pi}$$

Contour-improved (CIPT)

$$A^{(n)}(\alpha_s) = \frac{1}{2\pi i}\oint_{|s|=m_\tau^2} \frac{ds}{s}\left(\frac{\alpha_s(-s)}{\pi}\right)^n \left(1 - 2\frac{s}{m_\tau^2} + 2\frac{s^3}{m_\tau^6} - \frac{s^4}{m_\tau^8}\right)$$

- Resums large " n-logs to all orders
- Improved convergence

Fixed-order (FOPT)

- Treats all corrections on equal footing
- Smaller scale-dependence

" Decay

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- Resums <u>large</u> " $_n$-logs to all orders
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- Well behaved

<u>Fixed-order (FOPT)</u>

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<u>Typical results at O(! $_s$^{4})</u> [lots of literature]

CIPT:

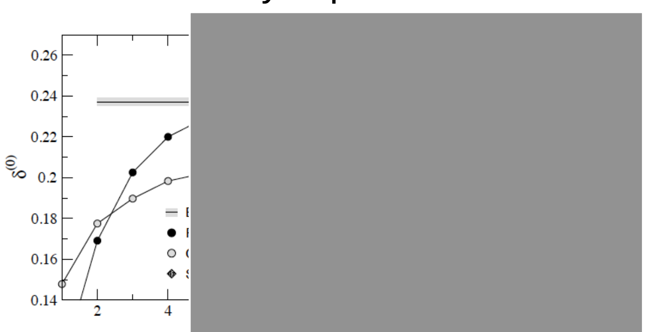
$$\alpha_s(m_\tau) = 0.344 \pm 0.015$$
$$\alpha_s(m_Z) = 0.1210 \pm 0.0015$$

FOPT:

$$\alpha_s(m_\tau) = 0.321 \pm 0.015$$
$$\alpha_s(m_Z) = 0.1185 \pm 0.0015$$

➡ Studies based on models of asymptotic behavior of the perturbative series do not favor any expansion

Beneke, Jamin 2008
Descots-Genon 2010



Beneke, Jamin

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Beneke, Jamin 2008
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➡ Expansion look well, BUT ARE close to being unstable.

Common variation methods unreliable to estimate perturbative error.

What is the theoretical handle that explains the discrepancy ?

" Decay

Duality Violation:

Boito, Cata, Golterman, Jamin, Maltman, Osborne, Peris 2011

➡ m" not sufficiently heavy such that OPE (p.th. + condensates) is justified at very high precision

(resonances not sufficient "smeared" out)

(recall: OPE = expansion in $\Lambda_{\mathrm{QCD}}/m_\tau$)

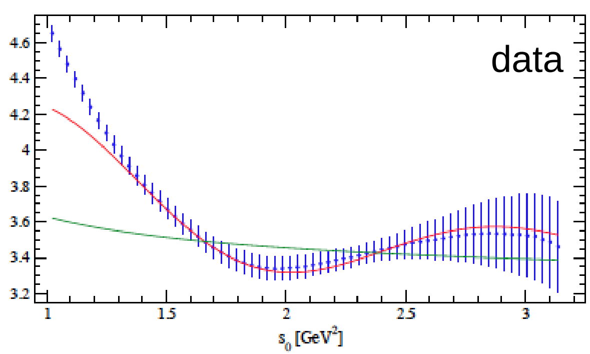
$$\int_0^{s_0} \mathrm{d}s\, w(s)\, \rho^{(1+0)}_{V,A}(s) = \frac{i}{2\pi} \oint_{|s|=s_0} \mathrm{d}s\, w(s)\, \Pi^{(1+0)}_{V,A}(s)$$

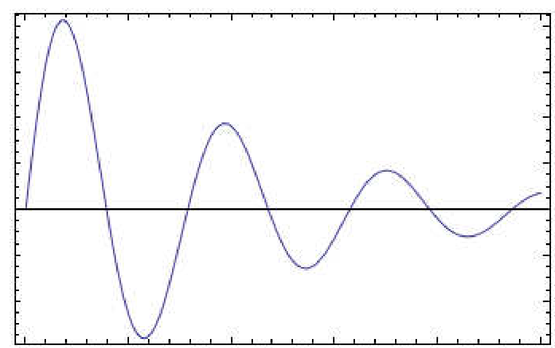
$$\Pi^{(1+0)}_{V,A}(s) = \Pi^{\mathrm{OPE}}_{V,A}(s) + \Delta_{V,A}(s)$$

model (no first principle computation possible) parameters must be fitted

$$\rho^{\mathrm{DV}}_{V,A}(s) = \kappa_{V,A}\, \mathrm{e}^{-\gamma_{V,A} s} \sin(\alpha_{V,A} + \beta_{V,A} s)$$

Behavior of non-perturbative effects in the Minkowskian region

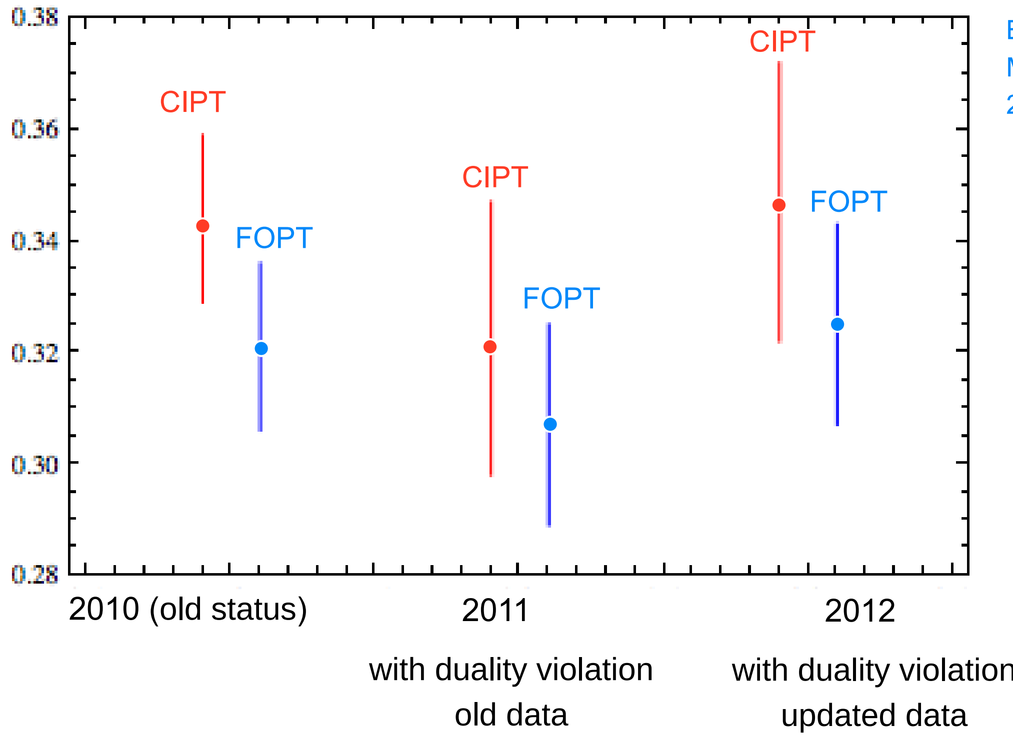




" Decay

Duality Violation:

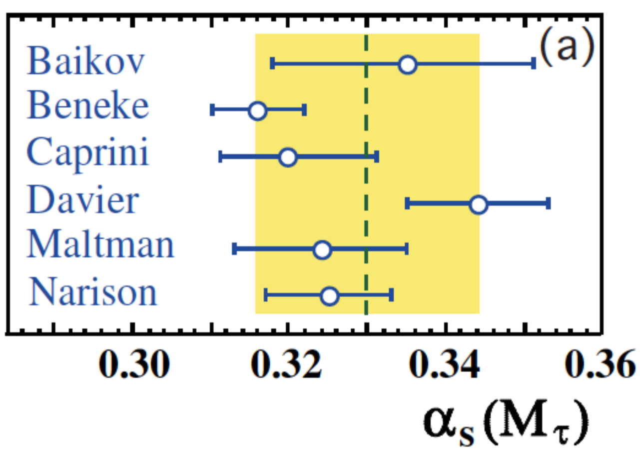
Discrepancy reconciled at the cost of larger errors.



Boito, Cata, Golterman, Jamin, Maltman, Osborne, Peris 2011+2012

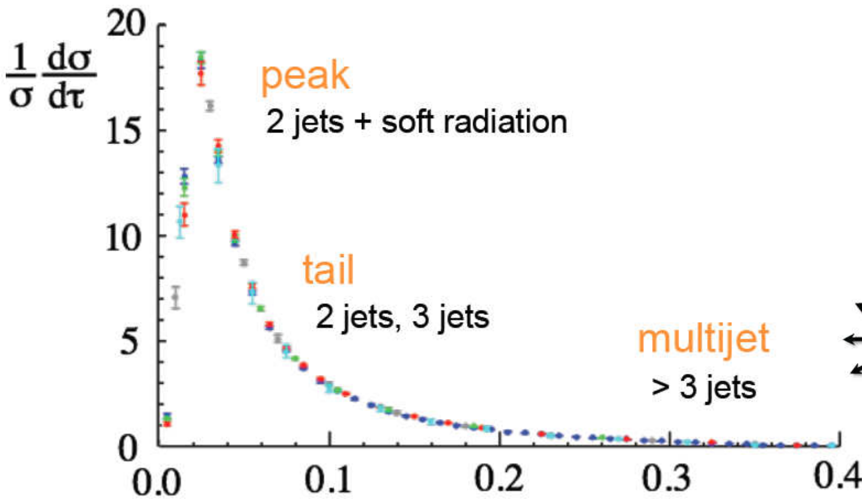
Bethke 2011

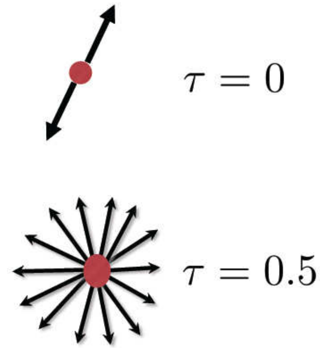
Uncertainties from spread of central values.

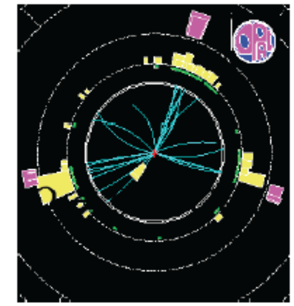


Eventshape Distributions (e+e-)

➡ Single variable measure of global topology properties of hadronic events (primary $q\bar{q}$)
Variable zero for $q\bar{q}$ final state (2 back-to-back zero mass jets)







OPAL 3 jet event

Thrust: $T = \max_{\hat{t}} \frac{\sum_i |\hat{\mathbf{t}} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$ $\quad \tau = 1 - T$

Heavy jet mass $\#_H$: Heavier of the invariant masses of all particle in the 2 hemispheres w.r. to the thrust axis

C-parameter: $C = \frac{3}{2} \frac{\sum_{ij} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$

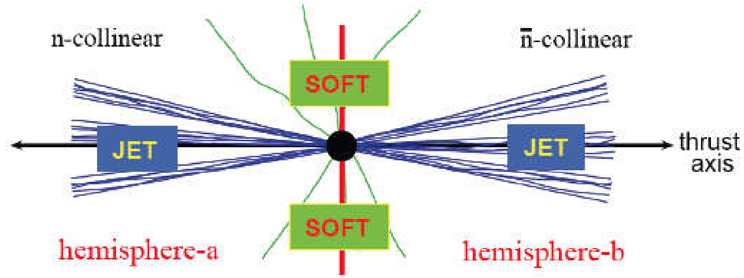
Jet broadening: $B_k = \left(\frac{\sum_{i \in H_k} |\vec{p}_i \times \vec{n}_T|}{2 \sum_i |\vec{p}_i|} \right)$ $\qquad B_T = B_1 + B_2$

y_{23}: Transition value between 2 and 3 jets (Durham jet algorithm)

Eventshape Distributions (e+e-)

➡ Perturbation theory: $\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} \sim \delta(\tau) + \mathcal{O}(\alpha_s)$

$\mathcal{O}(\alpha_s)$ is LO for $\tau > 0$



➡ IR-save & perturbatively inclusive (e.g. thrust)

Korshemski, Sterman

$\mu_h \sim Q$ $\mu_{\rm jet} \sim Q\sqrt{\tau}$ $\mu_{\rm soft} \sim Q\tau \sim \Lambda$

perturbative   perturbative

$\#_H$, C: similar to thrust

B: $\mu_{\rm jet} \sim \mu_{\rm soft}$

➡ High precision era: NNLO, $\mathcal{O}(\alpha_s^3)$ perturbative corrections

partonic Monte-Carlo program

Gehrmann-DeRidder, Gehrmann, Glover, Heinrich 2007

Weinzierl 2009

Eventshape Distributions (e+e-)

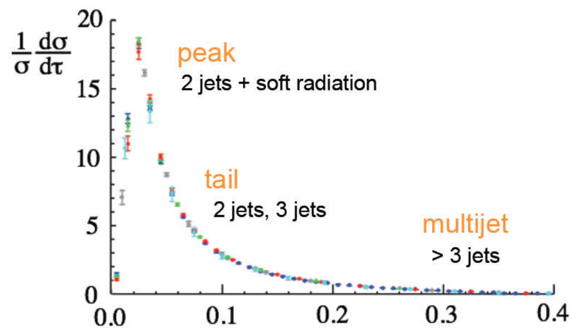
➡ Fixed-Order and log summation:

- •! NNLO (fixed-order)
- •! NNLO + NLL (classic resummation)
- •! NNLO + N[3]LL (SCET factorization)

Catani ea; Dokshitzer ea

} all eventshapes

" , $\#_H$. (B)



➡ Non-perturbative Effects (tail):

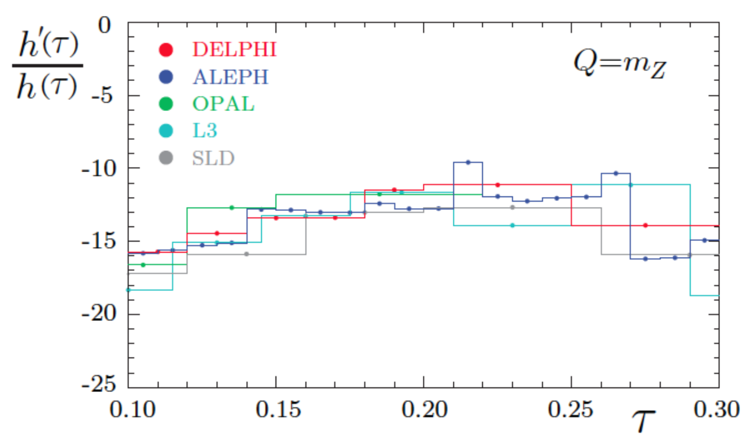
- •! MC: hadron mode – partonic mode
- •! Power corrections from data

<u>Problem of MC-estimate:</u>

- •! Hadronization corrections in MC are not in the scheme needed for calculations based on NNLO corrections (MSbar+dim reg)
- •! MC estimates much too small (tiny ! Few % for ! $_s$)

$$\frac{d\sigma}{d\tau} \sim h(\tau) \to \left(\tau - \frac{2\Lambda}{Q}\right)$$

$$\frac{\delta\alpha_s}{\alpha_s} \sim \frac{2\Lambda}{Q}\,\frac{h'(\tau)}{h(\tau)} \sim 9\%$$

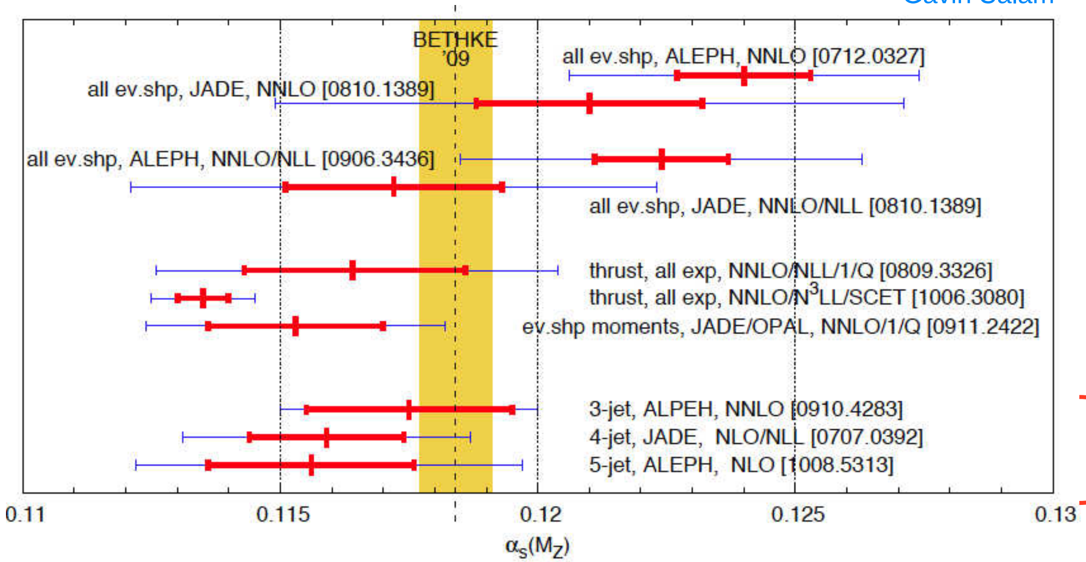


Abbate, Fickinger, Hoang, Mateu, Stewart 2010

Eventshape Distributions (e+e-)

Only 3 NNLO-based analyses left :

Gavin Salam



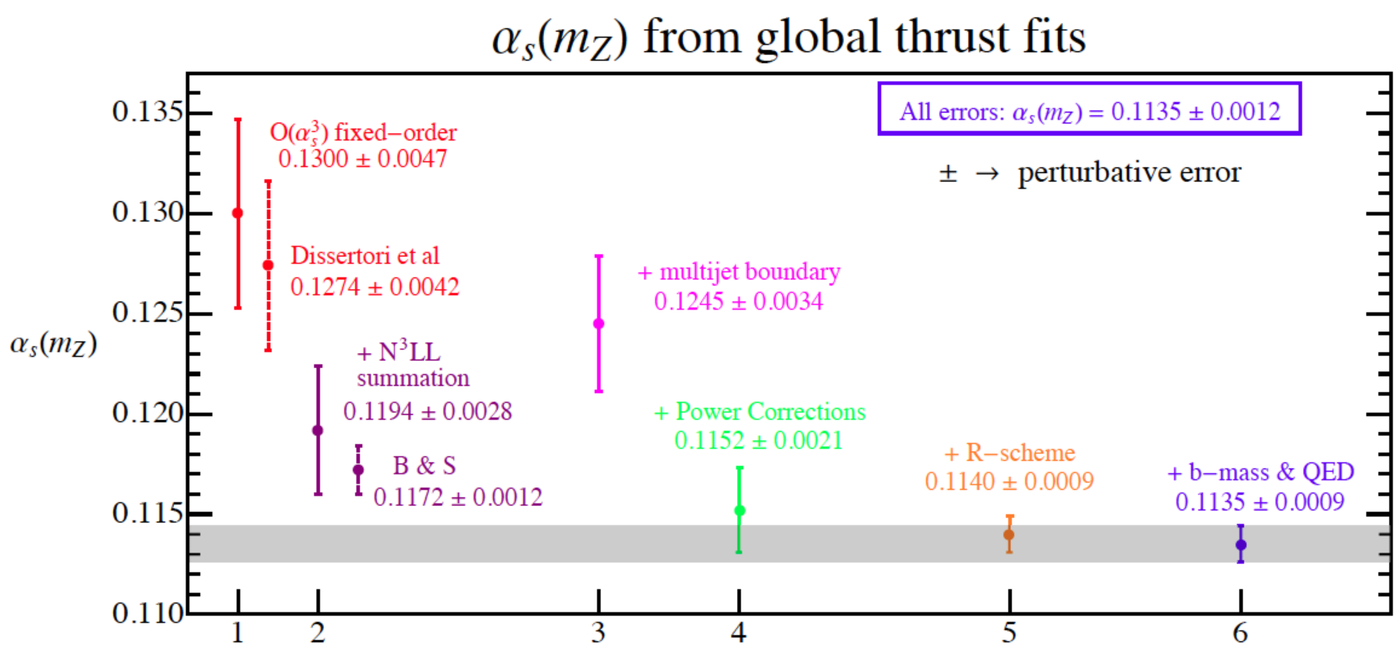
Davison, Webber 2009 (all event shapes_
Abbate, Fickinger, Hoang, Mateu, Stewart 2010 (thrust)
Gehrmann, Jaquier, Luisoni 2010 (all event shapes)

Jet rates

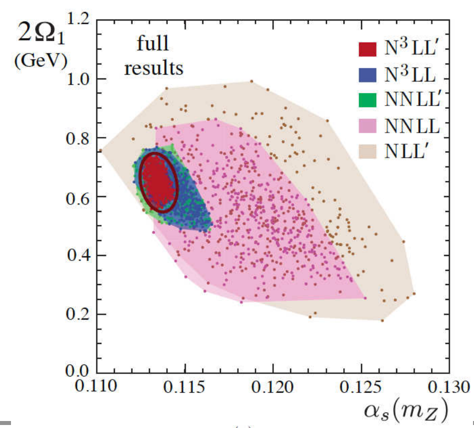
All results for $\alpha_s(m_Z)$ are low !!

Eventshape Distributions (e+e-)

$$\left(\frac{d\sigma}{d\tau}\right)^{\text{sing}}_{\text{part}} \sim \sigma_0\, H(Q,\mu_Q) U_H(Q,\mu_Q,\mu_s) \int d\ell d\ell'\, U_J(Q\tau-\ell-\ell',\mu_Q,\mu_s)\, J_T(Q\ell',\mu_j)\, S_T(\ell-\Delta,\mu_s)$$



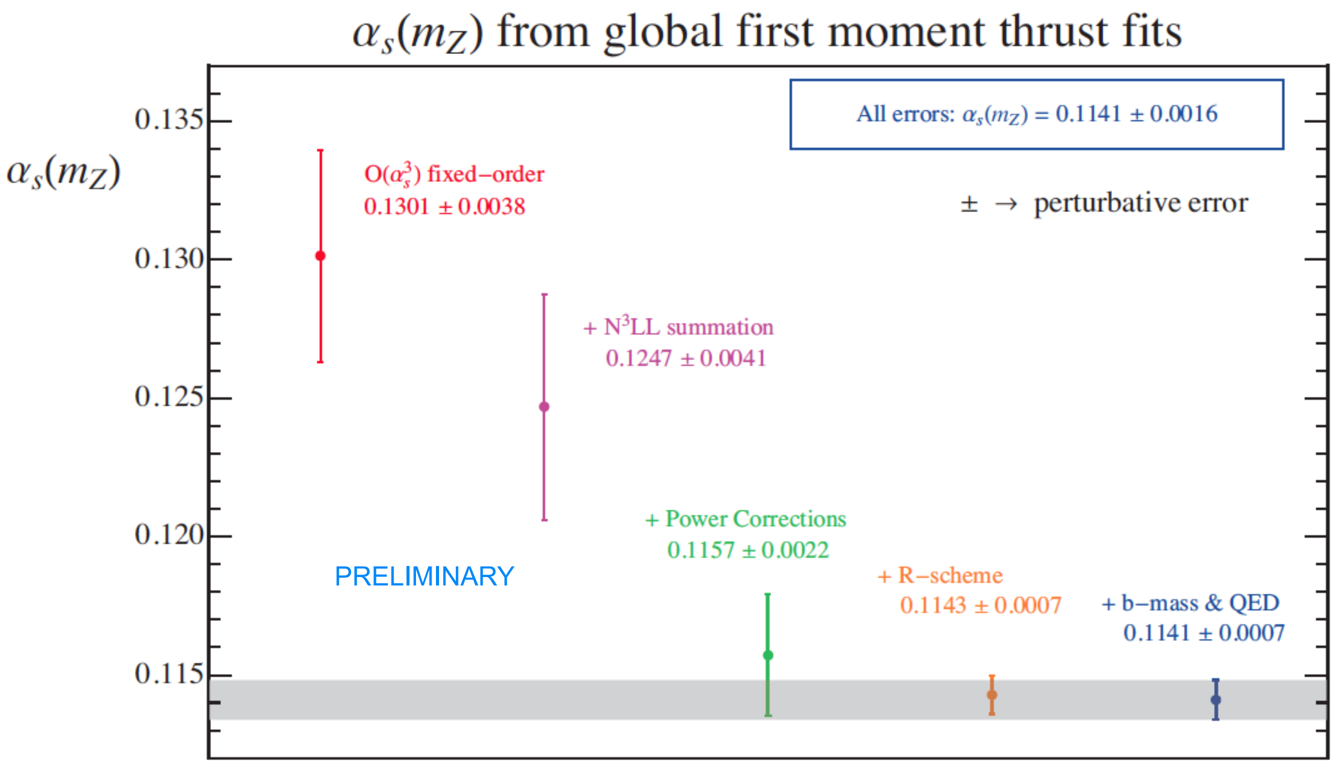
Abbate, Fickinger, Hoang, Mateu, Stewart 2010



- Central values for α_s decrease with order
- Very good convergence

Eventshape Distributions (e+e-)

NEW:



Abbate, Fickinger, Hoang, Mateu, Stewart to appear

- ! SCET analyses for other event shapes needed !

DIS and PDF fits

Alekhin, Blümlein, Moch 2012

	$\alpha_s(M_Z)$	
BBG	$0.1134\ ^{+\ 0.0019}_{-\ 0.0021}$	valence analysis, NNLO [60]
BB	0.1132 ± 0.0022	valence analysis, NNLO [110]
GRS	0.112	valence analysis, NNLO [160]
ABKM	0.1135 ± 0.0014	HQ: FFNS $n_f = 3$ [16]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [16]
JR	0.1124 ± 0.0020	dynamical approach [20]
JR	0.1158 ± 0.0035	standard fit [20]
ABM11	0.1134 ± 0.0011	
MSTW	0.1171 ± 0.0014	[158]
NN21	0.1173 ± 0.0007	[124]
CT10	$0.118 \quad \pm 0.005$	[161]

Table 4.10: Summary of recent NNLO QCD analyses of the DIS world data, supplemented by related measurements using other processes.

•! Central values for #$_s$ decrease NLO to NNLO

•! All below the world average.

Conclusions

- ! Ability to make precise measurements of the strong coupling reflects our understanding and control of QCD in various areas.

- ! High precision measurements and methods claiming very small theoretical uncertainties HAVE TO BE challenged and questioned. Even new and difficult-to-be-answered questions should be asked.

- ! Why do jet observables all seem to give low !$_s$ with NNLO included ?
  What does this mean ?
  Maybe NNNLO helps ?

- ! Eventually: measurements of !$_s$ at the LHC