Workshop on high-precision α_s measurements: from LHC to FCC-ee

CERN, 12th –13th October 2015

D. d'Enterria (CERN)

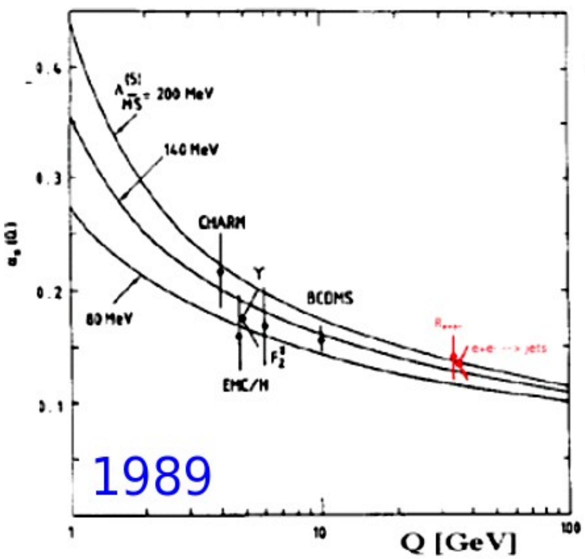
FCC-ee "QCD & $\gamma\gamma$ Physics" Working Group Conveners

Goals of the α_s workshop

- What is the current state-of-the-art of each one of the α_s determination methods, from the theoretical and experimental perspective?
- What is the current size of the theoretical (missing higher orders, electroweak corrections, power corrections, hadronization corrections,...) and experimental uncertainties associated to each measurement?
- What is the expected α_s uncertainty in 10 years from now thanks to the ongoing (or expected) theoretical developments, plus O(1 ab^{-1}) collected p-p data at 14 TeV at the LHC ?
- What are the improvements expected to be brought about by e^+e^- collisions at the FCC-ee with 10^{12} Z bosons and jets, and 10^8 W bosons and τ leptons collected ?
- What are the systematic errors that the FCC-ee detectors should target in order to match the expected statistical precision, or where that is not possible, what are the important theoretical targets that should be met or exceeded ?

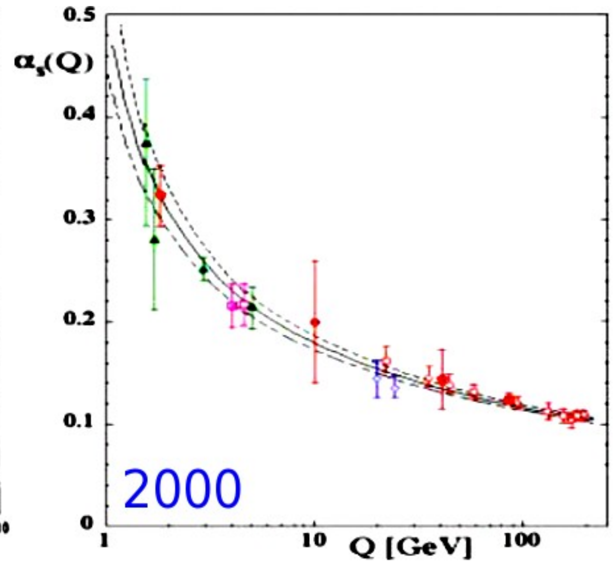
Importance of the QCD coupling α_s

α_s = Single free parameter in QCD (in the $m_q \to 0$ limit). Determined at a reference scale ($Q=m_Z$). Decreases as $\sim\ln(Q^2/\Lambda^2)$, with $\Lambda\sim0.2$ GeV



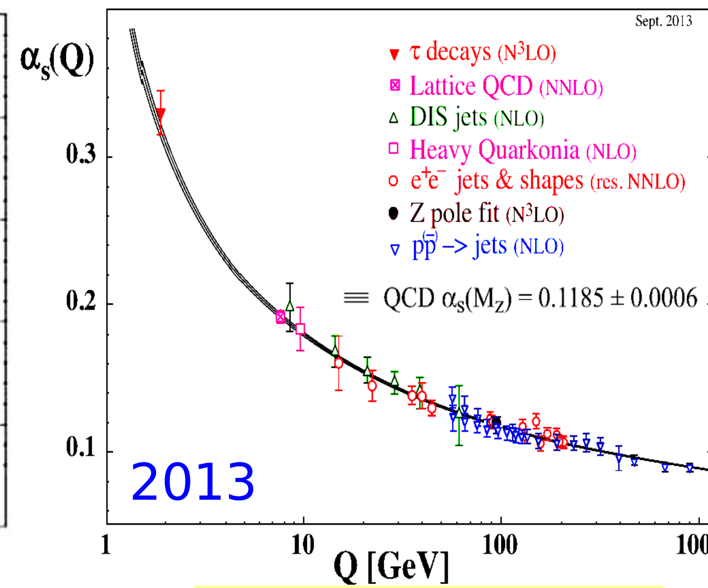
$\alpha_S(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989



$\alpha_S(M_Z) = 0.1184 \pm 0.0031$ (NNLO)

S. B. , J. Phys. G 26, 2000



$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (NNLO)

Current PDG uncertainty: ±0.5%

- Least precisely known of all couplings !

  $\delta\alpha \sim 3\cdot10^{-10}$, $\delta G_F \sim 5\cdot10^{-8}$, $\delta G \sim 10^{-5}$, $\delta\alpha_s \sim 5\cdot10^{-3}$

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- Impacts all LHC cross-sections.

Uncertainties (update of [LHC HXSWG 2013] for $\sqrt{s} = 14$ TeV)

Process	Cross section(pb)	Scale(%)		$\delta\alpha_s$(%)	PDF $+\alpha_s$(%)
ggH	49.87	-2.61	+0.32	± 3.7	-6.2 +7.4
VBF	4.15	-0.4	+0.8	± 0.7	± 2.5
WH	1.474	-0.6	+0.3	± 0.9	± 3.8
ZH	0.863	-1.8	+2.7	± 0.9	± 3.7
ttH	0.611	-9.3	+5.9	± 3.0	± 8.9

[L. Mihaila]

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- Impacts all LHC cross-sections.
- Key for SM precision fits (e.g. Higgs b,c,g BRs uncertainties and associated Yukawas).

Parametric Uncertainties (from [LHC HXSWG 2013])

Channel	M_H [GeV]	$\Delta\alpha_s$	Δm_b	Δm_c
$H \to b\bar{b}$	126	$\pm$ 0.4 %	$\pm$ 0.8%	$\pm$ 0 %
$H \to c\bar{c}$	126	$\pm$ 7.1 %	$\pm$ 0.1%	$\pm$ 2.3 %
$H \to gg$	126	$\pm$ 4.1 %	$\pm$ 0.1%	$\pm$ 0 %

[L. Mihaila]

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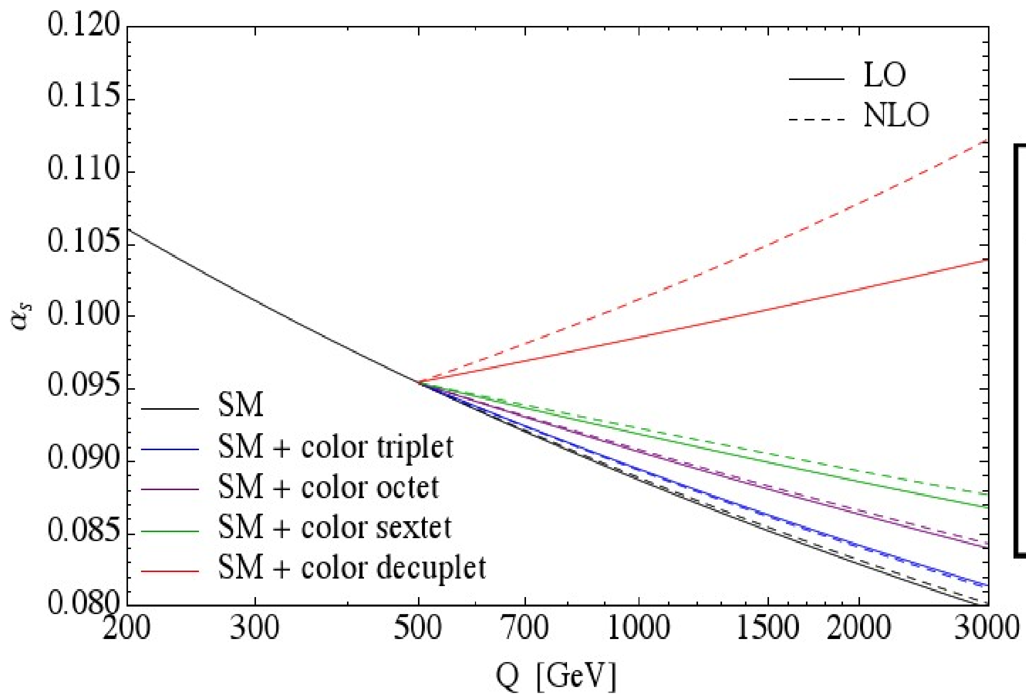
- Key for SM precision fits (e.g. Higgs b,c,g BRs uncertainties).
- BSM physics (e.g. new colored sector).



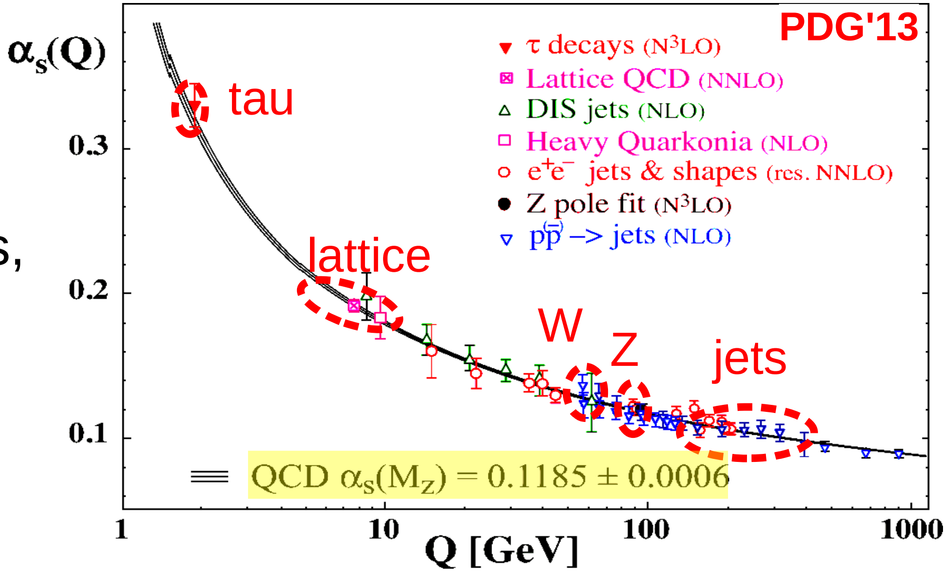
95% CL mass exclusions bounds

color content	$n_{\rm eff}$	m_X in GeV
Gluino	3	280
Dirac sextet	5	410
MSSM	6	450
Dirac decuplet	15	620

[F. Sannino]

Determination of the QCD coupling α_s

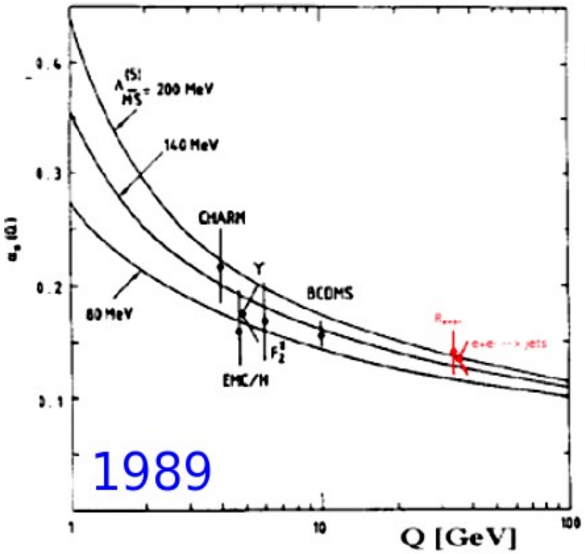
- Measured by comparing various experimental observables to different pQCD NNLO predictions, and performing a global average for its value at the Z pole scale.



1. Hadronic τ decays: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\text{np}})$ **(N³LO)**
2. Lattice QCD: Various short-distance quantities: $K^{\text{NP}} = K^{\text{PT}} = \sum_{i=0}^{n} c_i \alpha_s^i$ **(NNLO)**
3. Hadronic Z decays: $R_Z \equiv \frac{\Gamma(Z \to \text{h})}{\Gamma(Z \to l)} = R_Z^{\text{EW}} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\text{m}} + \delta_{\text{np}})$ **(N³LO)**
4. DIS had. observables: PDFs, σ(jet): $\frac{\partial}{\partial \ln Q^2} D_i^h(x,Q^2) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_S}{4\pi} P_{ji}\left(\frac{x}{z}, Q^2\right) D_j^h(z,Q^2)$ **(NLO,NNLO)**
5. e⁺e⁻ had. observables: Event-shapes, jet rates: $\frac{1}{\sigma}\frac{d\sigma}{dY} = \frac{dA}{dY}\hat{\alpha}_S + \frac{dB}{dY}\hat{\alpha}_S^2 + \frac{dC}{dY}\hat{\alpha}_S^3$ **(NNLO)**
6. Other hadronic observables: σ(ttbar),σ(jets) in p-p, $Q\bar{Q}$ rad. decays **(NLO,NNLO)**

- Other extractions: W decay, e-p jet γ-production, π decay, FFs (hard,soft), F_2^γ,...

Determination of the QCD coupling α_s



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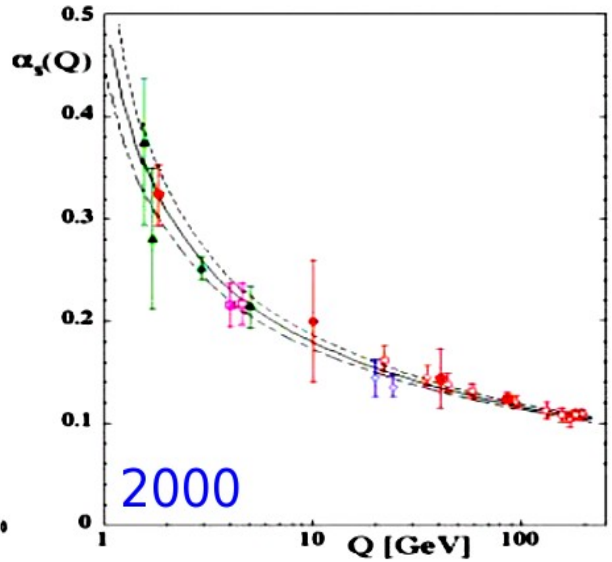

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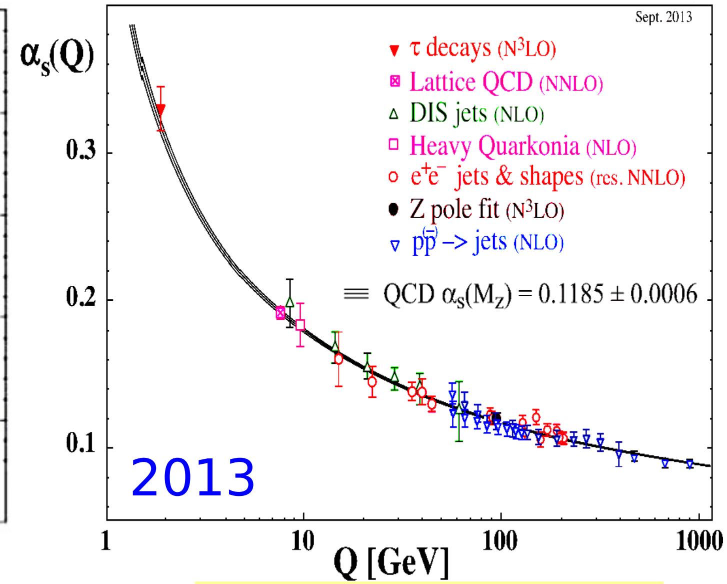

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[S. Bethke]

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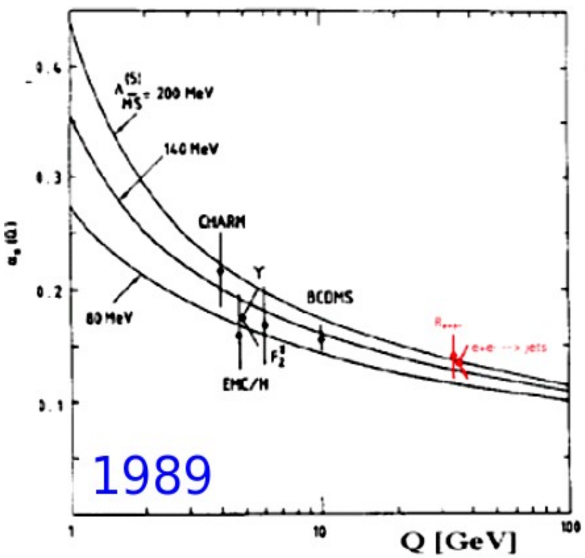

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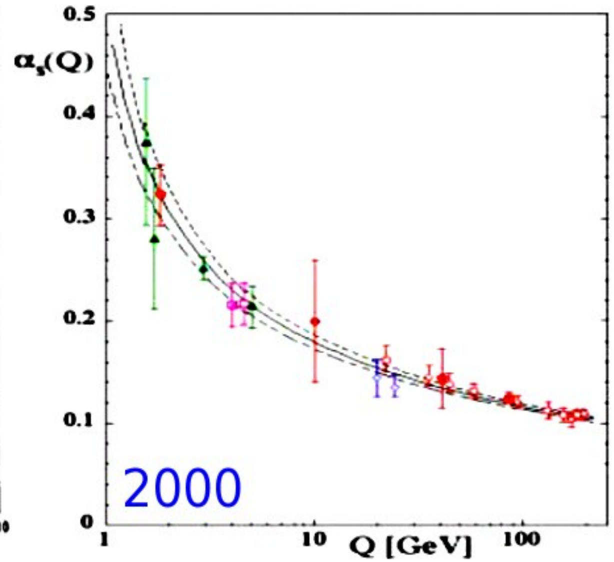

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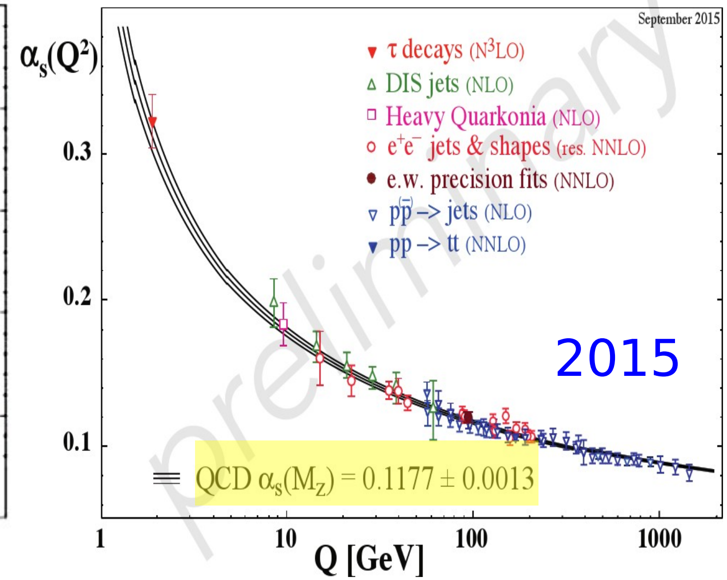
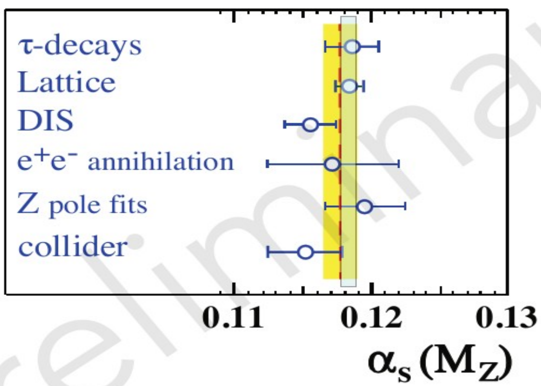


Upcoming 2015 uncertainty: ±1.1%



- decreased weight (increased error) of lattice results
- decreased central value from τ-decays
- result from new class (hadron collider, ttbar x-section), with only one published result, however known to be systematically low

$\alpha_s(M_Z) = 0.1177 \pm 0.0013$

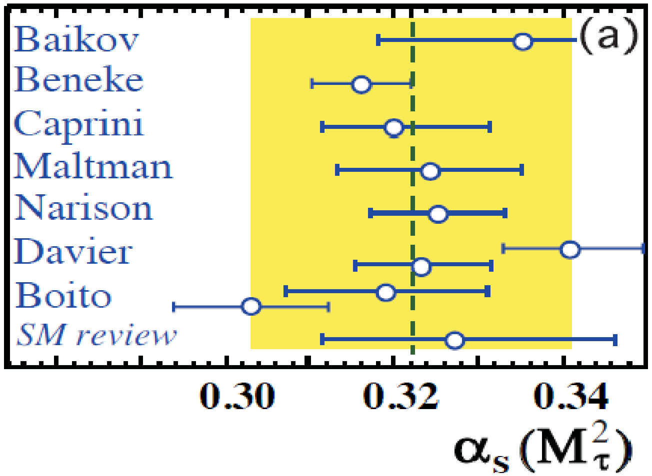
without lattice: $\alpha_s(M_Z) = 0.1170 \pm 0.0018$

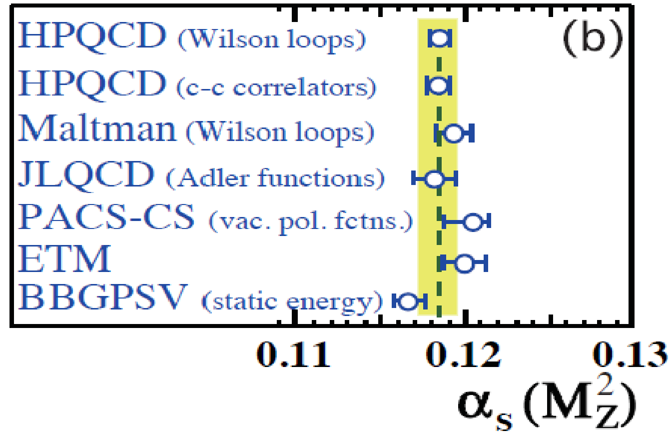
w/2013 RPP lattice: $\alpha_s(M_Z) = 0.1183 \pm 0.0006$

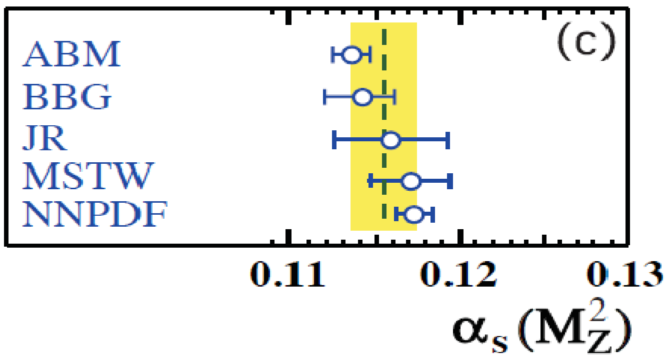
[S. Bethke]

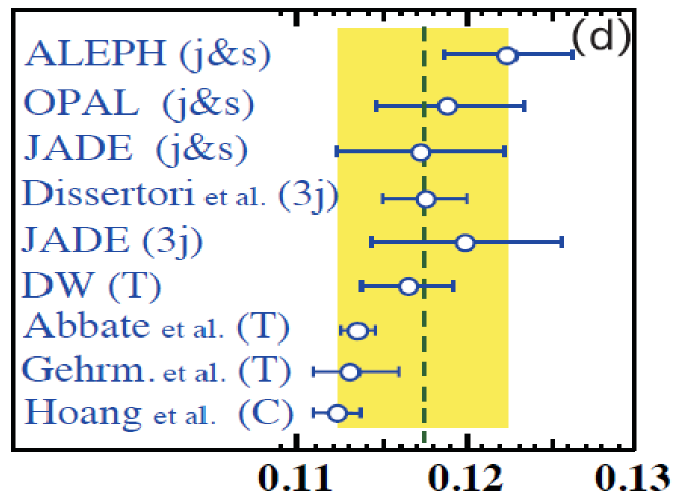
Multi-prong determination of α_s coupling

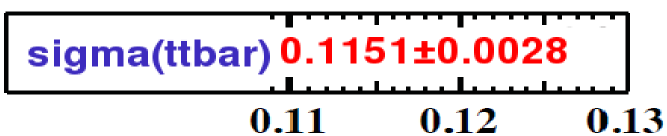
[S. Bethke]

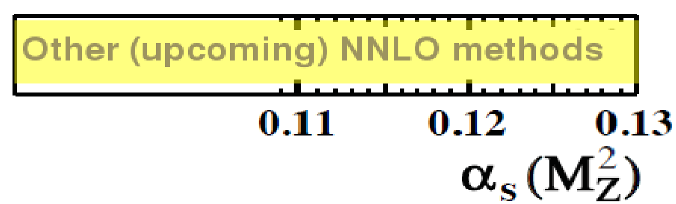


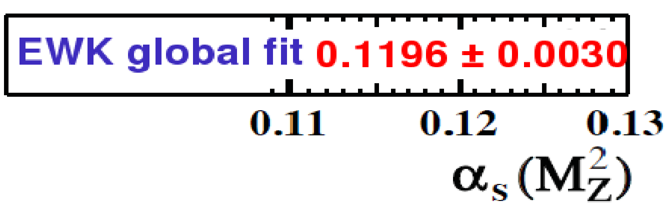






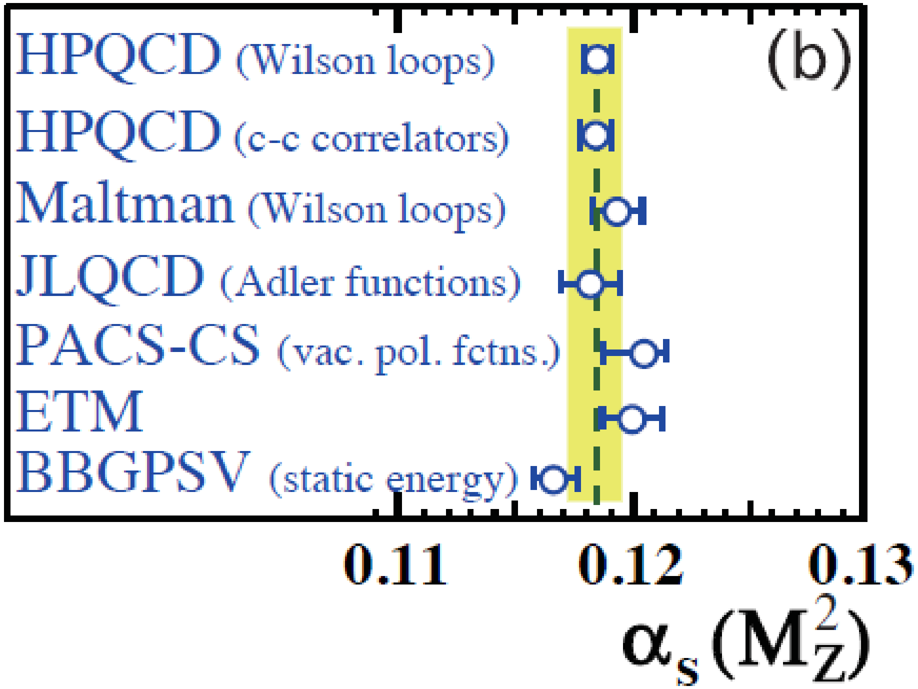






α_s from lattice QCD

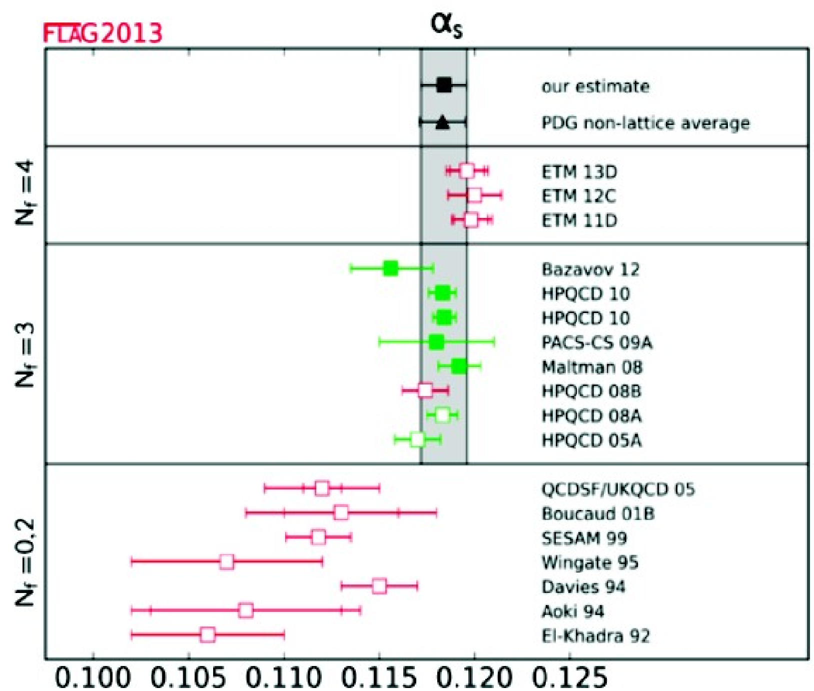
α_s = 0.1184 ± 0.0012 (±1.0%)



[P. Mackenzie]
[X. Garcia i Tormo]

- Currently the extraction with smallest uncertainties: ~1%
- Latt-QCD community-agreed combination:

FLAG review of lattice results (2013)



Prospects:

- Uncertainty in α_s could be halved with (much) better numerical data.
- It could be cut to ~0.1% with a 4th loop of perturbation theory (10 years work)

α_s from pion, Υ decays

α_s = 0.1174±0.0017 (±1.5%)

[J.L.Kneur]

$$F_\pi^2(pert)_{\overline{MS}} = N_c \frac{m^2}{2\pi^2}\left[-L + \frac{\alpha_S}{4\pi}(8L^2 + \frac{4}{3}L + \frac{1}{6}) + (\frac{\alpha_S}{4\pi})^2[f_{30}(n_f)L^3 + f_{31}(n_f)L + f_{32}(n_f)L + f_{33}(n_f)] + \mathcal{O}(\alpha_S^3)\right]$$

$$L \equiv \ln\frac{m}{\mu},\ n_f = 2(3)$$

$$\overline{\alpha}_S(m_Z) = 0.1174^{+.0010}_{-.0005}(\text{rgopt th}) \pm .0010|_{(F_\pi/F_0)} \pm .0005_{evol}$$

Issues:

- pion decay factor too low scale for pQCD?, optimization approach,...
- Intriguing agreement with world average.

[J. Soto]

$$R_\gamma \equiv \frac{\Gamma(\Upsilon(1S)\to\gamma X)}{\Gamma(\Upsilon(1S)\to X)} = \frac{36}{5}\frac{e_b^2\alpha}{\alpha_s}\frac{N}{D},$$

$$N, D = 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(v^2) + \mathcal{O}(\frac{v^4}{\alpha_s})$$
$$+\mathcal{O}(\alpha_s{}^2) + \mathcal{O}(\alpha_s v^2) + \mathcal{O}(\alpha_s\frac{v^4}{\alpha_s}) + \mathcal{O}(v^4) + \mathcal{O}(\frac{v^6}{\alpha_s})$$

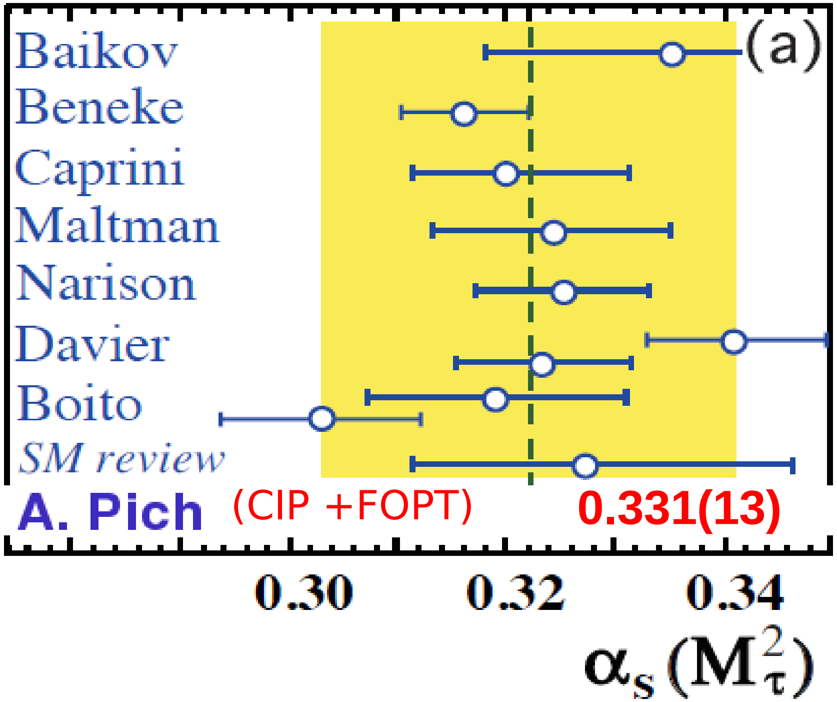
α_s(NLO)= 0.1190±0.007 (±6%)

- A NNLO extraction of α_s appears feasible in the coming years, the key ingredients being:
  - More precise data for the $\Upsilon(1S)$ photon spectrum (and total hadronic width)
  - Non-trivial higher order perturbative calculations

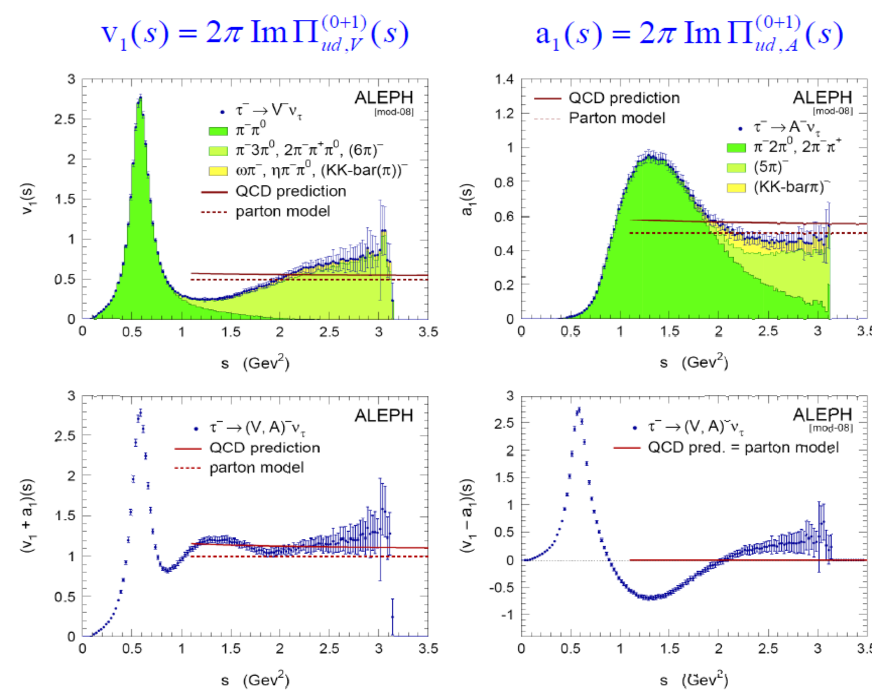
α_s from τ-lepton decays

α_s = 0.1187 ± 0.0023 (±1.9%)

[A. Pich]



- Different theoretical approaches for pQCD and non-pQCD contributions under discussion
- tau community-agreed α_s combination needed



Prospects:

- Better data (high stats & precision) in particular spectral functions needed: BF, FCC-ee
- Better understanding of higher pQCD orders

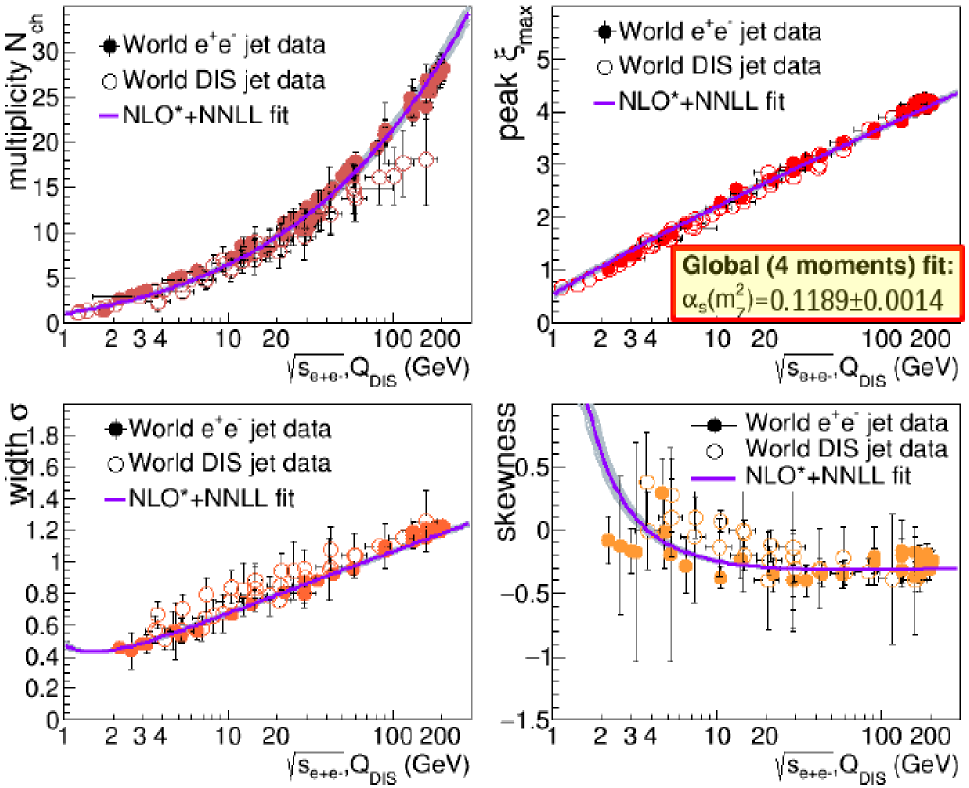
α_s from soft,hard parton-to-hadron FFs

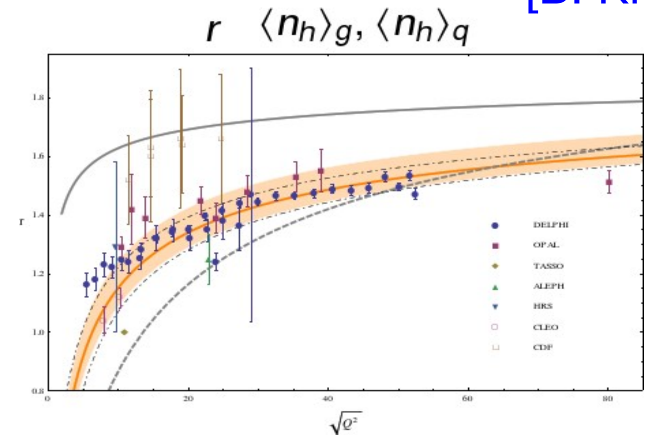
[R.Perez-Ramos]

[B. Kniehl]

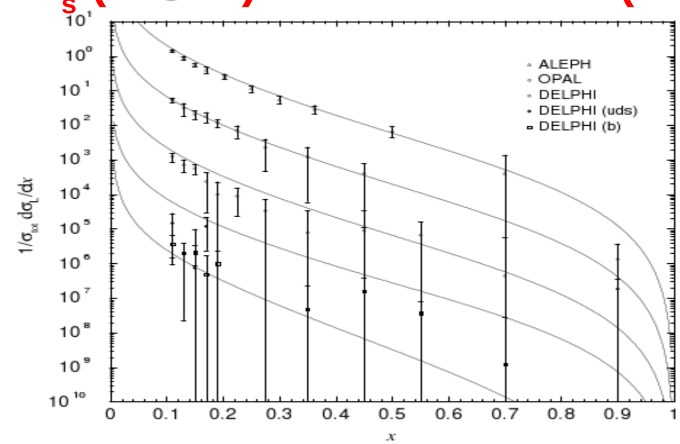
α_s (NNLO*+NNLL)=0.1205±0.0010$^{+0.0022}$(±2%)

- Combined global fit of e$^+$e$^-$&DIS data to NLO*+NNLL:





α_s (NNLO)=0.1199±0.0044 (±3.6%)



α_s (NLO)=0.1176±0.0055±0.0008 (±4.7%)

Prospects:

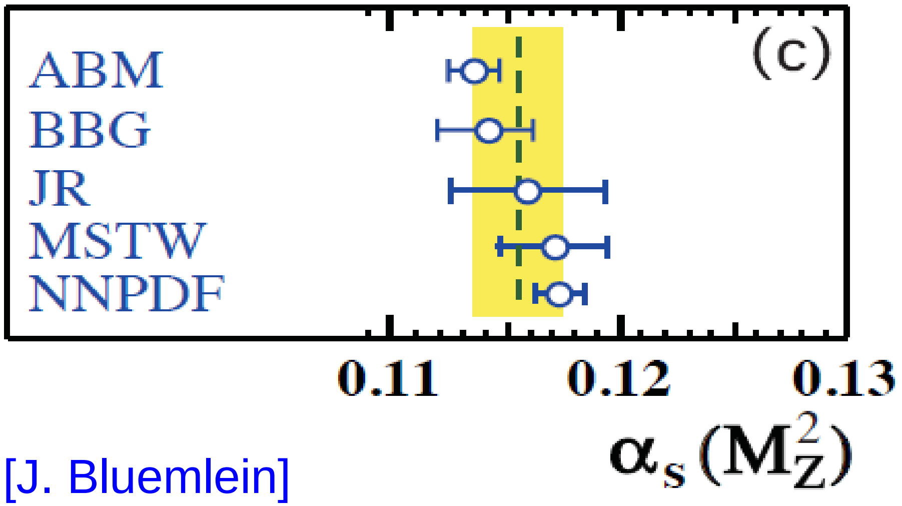
- Soft FFs: Full-NNLO for all FF moments.

Prospects:

- Hard FFs: Upcoming NNLO fit

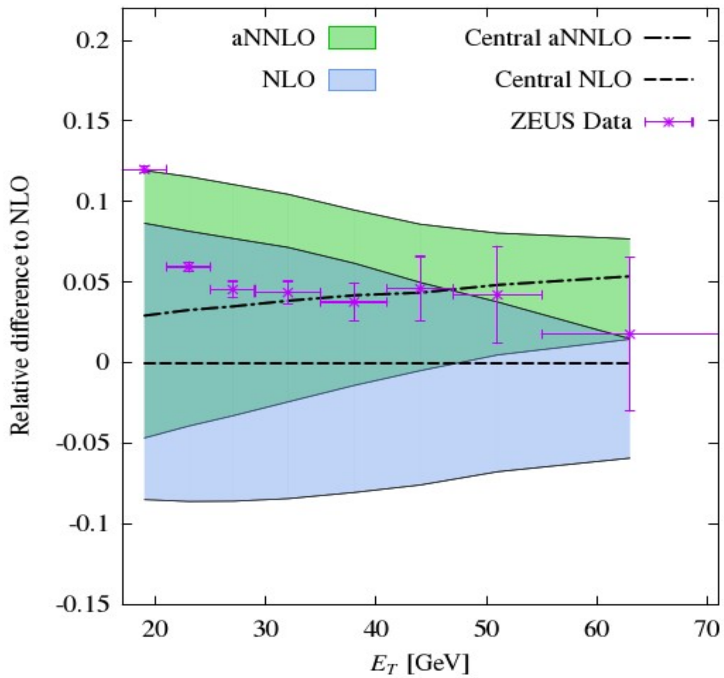
α_s from e-p: PDFs, jets in DIS/γ-production

α_s = 0.1154±0.0020 (±1.7%)



[J. Bluemlein]

[M. Klasen]



- N³LO DIS analysis yields : $\alpha_s(M_Z^2) = 0.1141 \pm 0.0021$
- Correct NNLO anlyses require the fit of $d^2\sigma/dxdQ^2$ and the correct description of $F_L, F_2^{c\bar{c}}$.
- Consistent α_s and m_c fits are mandatory.
- Next important analysis: inclusion of the LHC jet data in complete NNLO fits.

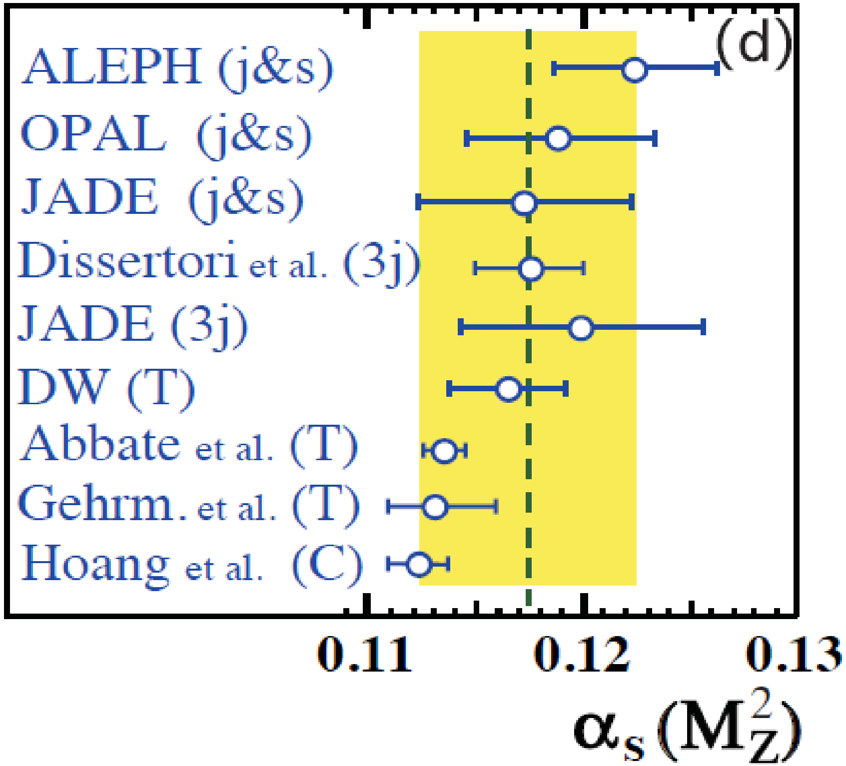
α_s (NNLO*)=0.1120±0.002(exp) ±0.003(th) (±4.0%)

Prospects:
- ➧ Complete full-NNLO for jets
- ➧ Compute F_2^γ at NNLO

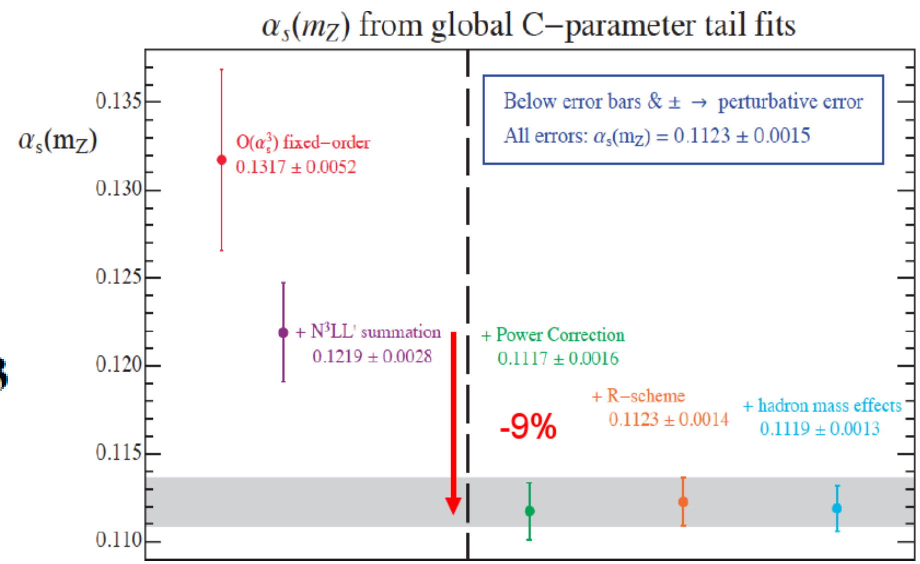
α_s from e^+e^- event shapes, jet rates

$\alpha_s = 0.1174 \pm 0.0051$ (±4.3%)

[S. Kluth] [A. Hoang] [A. Banfi]



- Main issue for α_s extractions: non-pQCD uncertainties dominate (hadronization, power corrections). Corrections via MCs or via analytical calculations.



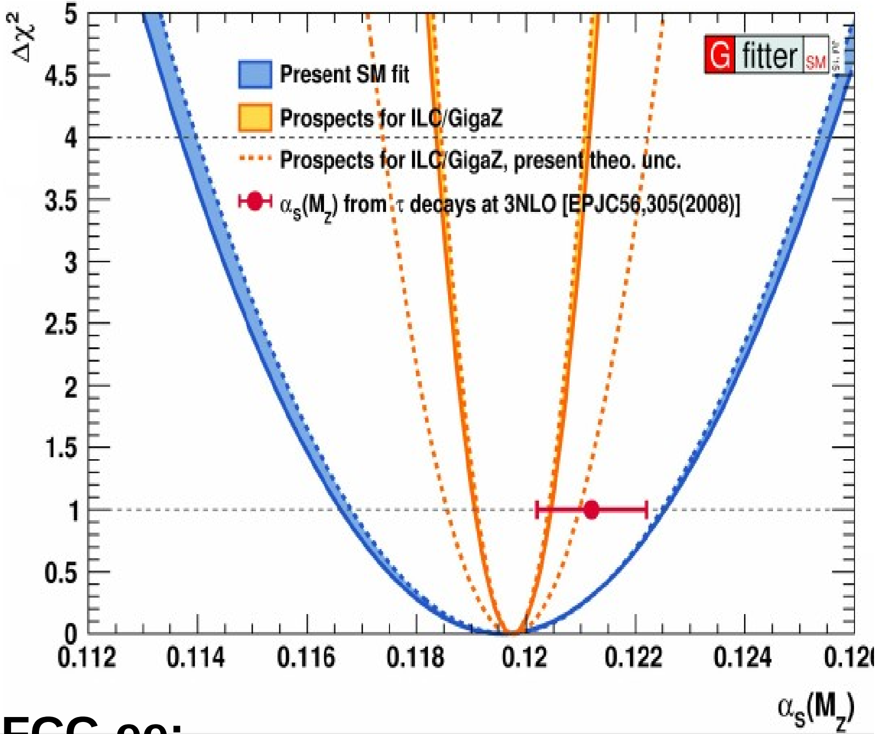
Prospects:

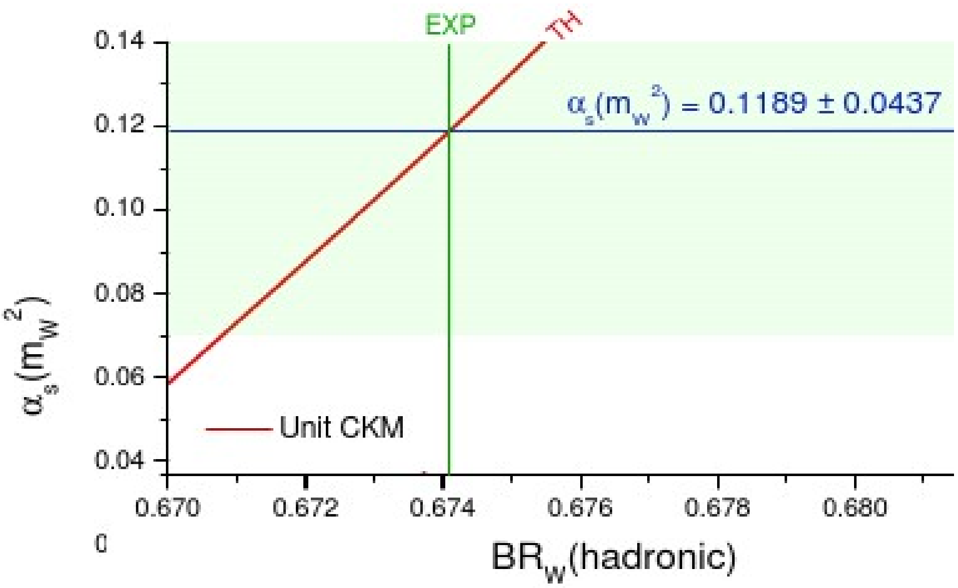
- Event shapes require lower-√s data. Jet rates require higher-√s e+e- data
- Jet rates with improved resummation: NLL for 2-jet rates, NLL for 3-jet rates

α_s from Z and W decays

[K. Monig] [J. Kuehn] [M. Srebre]

α_s = 0.1196 ± 0.0030 (±2.5%)





	$\alpha_s(m_W^2)$	$\Delta\alpha_s(m_W^2)$
Today (Unit CKM)	$0.1189 \pm 0.0004_{\rm param.} \pm 0.0433_{\rm exp.}$	±37%
LHC (Unit CKM)	$0.1208 \pm 0.0004_{\rm param.} \pm 0.0271_{\rm exp.}$	±23%
FCC-ee	$0.1208 \pm 0.0004_{\rm exp.}$	±0.3%

FCC-ee:

$$\Delta\alpha_s = 0.00015_{\rm exp} \oplus 0.00023_{\rm QCD} \oplus 0.00025_{\rm EW}$$
$$= 0.00035$$ (QCD almost there with errors from J.K.)

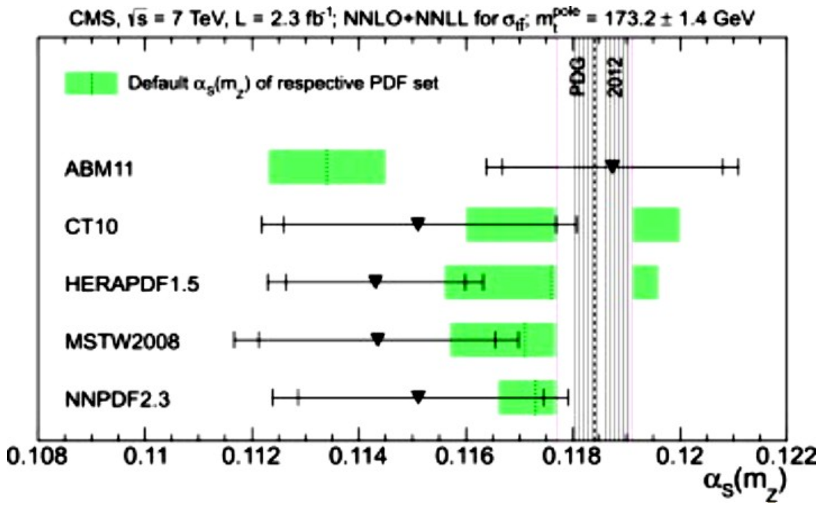
Prospects:

- Huge Z,W stats at FCC-ee will represent a big step forward: $\Delta\alpha_s$ < 0.3%
- R-ratio at B-factories? Upcoming beta function at 5 loops. α_s from Higgs→hadrons

α_s from top-pair, jets p-p cross sections

$\alpha_s = 0.1151 \pm 0.0028$ (±2.5%)

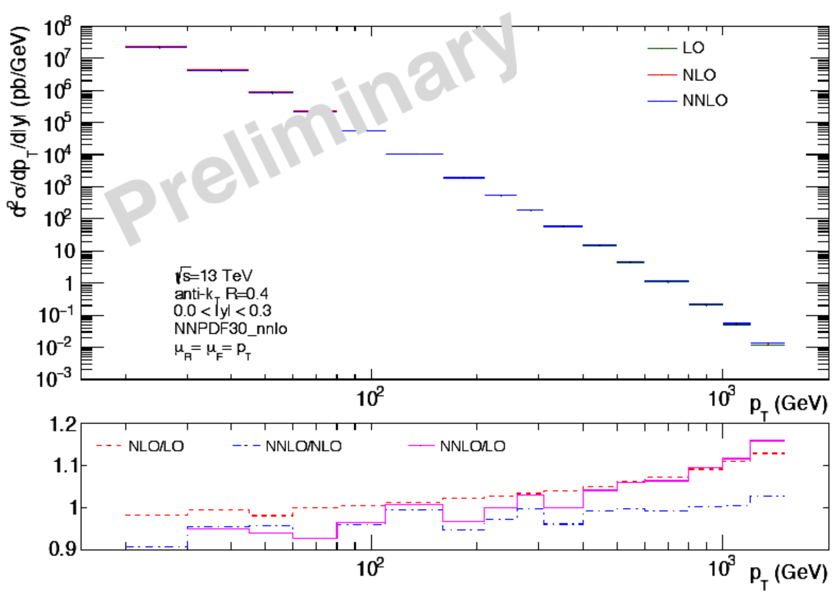
[A. Mitov], [G.Salam]



Top-pair issues:

- Total vs differential x-sections, MC modeling, NNLO+NNLL vs. NNLO relevant scale, top mass PDF selection (or global fit with DIS?)
- Updated experimental x-sections will increase extracted αs to 0.1187–0.1201

[J.Pires]



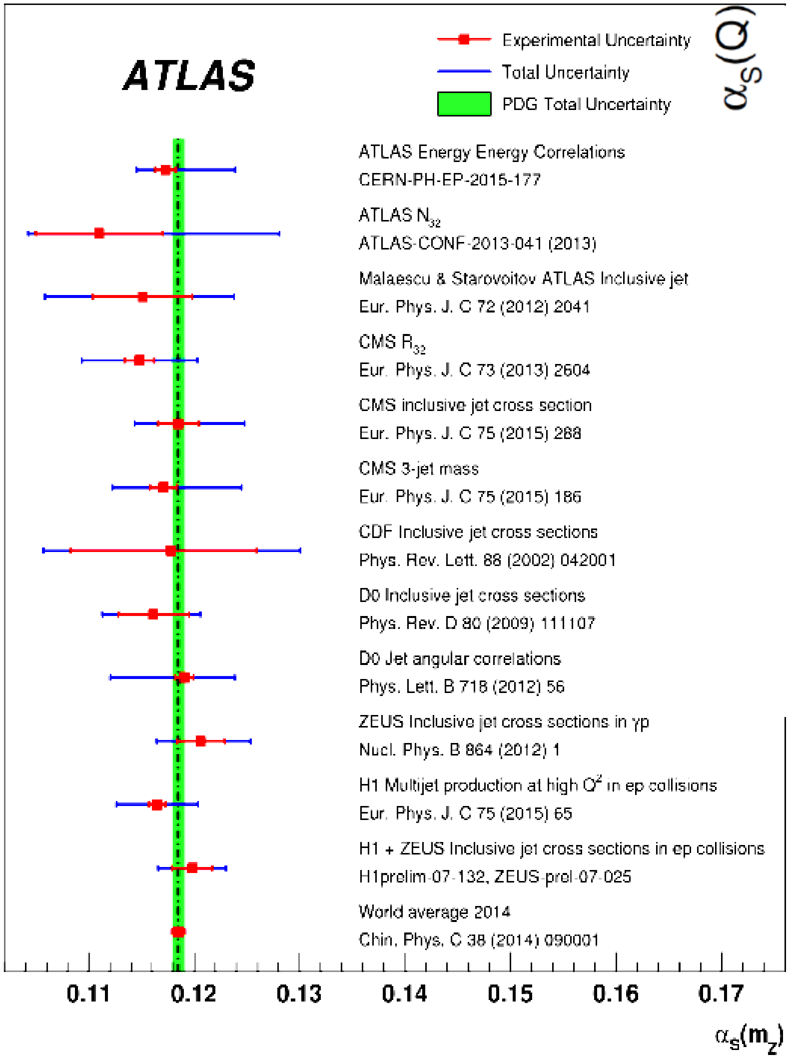
moderate corrections of -10% that rise to 1% at high-p_T with respect to NLO

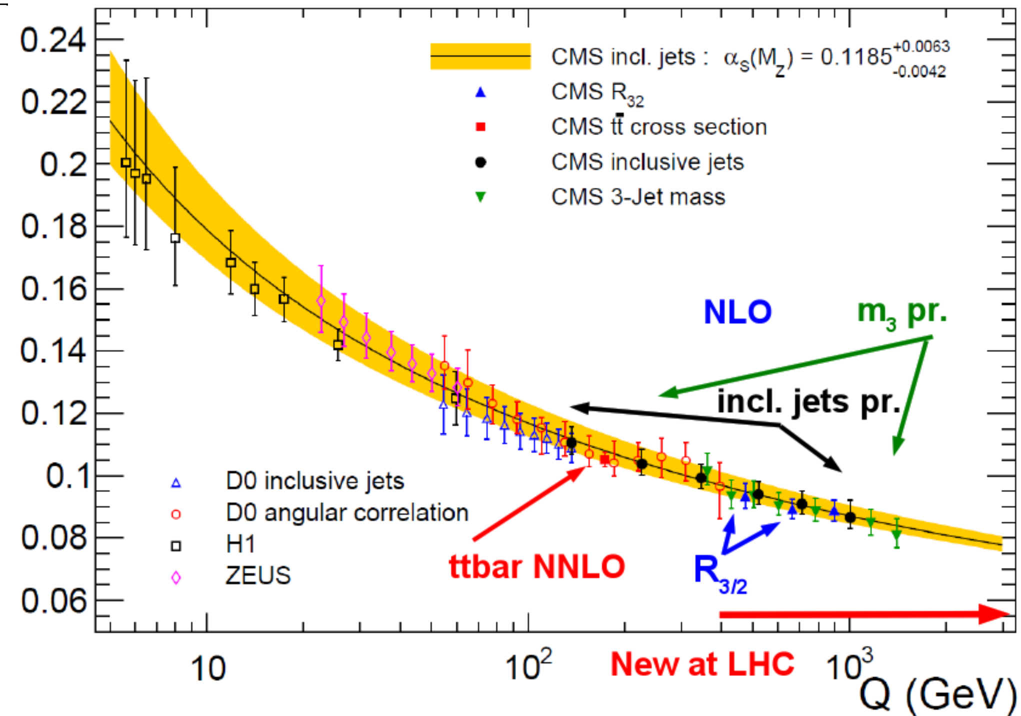
- NNLO jet cross sections will have a large impact in many αs extractions: PDFs, FFs, jets in DIS/photoprod.,...
- NNLO changes x-section by -10%,+1% Reduced scale uncertainty
- Final NNLO result within months. Important pQCD breakthrough!

α_s coupling from LHC (ATLAS, CMS)

[B. Malaescu]

[K. Rabbertz]

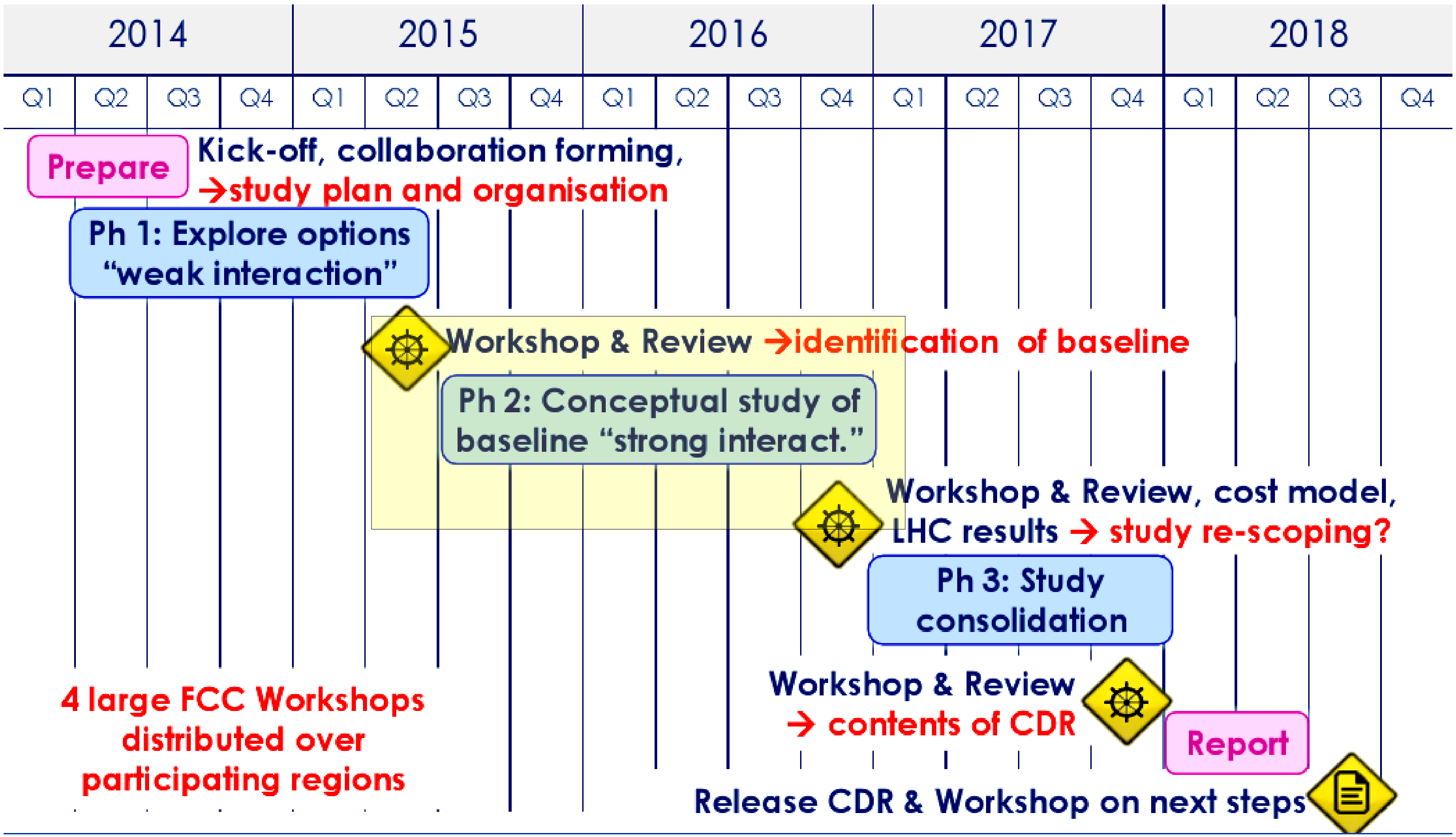




- 1st time asymptotic freedom tested at TeV's
- Novel high-precision as extractions thanks to NNLO x-sections: top-quark &(upcoming)jets.
- Attention to be paid to correlation matrix.

Towards FCC-ee Conceptual Design Report

- Dedicated physics workshops & associated writeups(*) for intermediate physics report in route towards FCC-ee CDR



(*) That's why we need your proceedings !

Workshop Proceedings

Workshop on high-precision alpha_s measurements: from LHC to FCC-ee

12-13 October 2015
CERN
Europe/Zurich timezone

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Proceedings

Template for the proceedings (1-4 pages per contribution): https://indico.cern.ch/event/392530/attachments/1167733/1687079/alphas_lhc_fcc-ee_proceeds.pdf

Source files: https://indico.cern.ch/event/392530/attachments/1167733/1687078/alphas_lhc_fcc-ee_proceeds.tar.gz

To compile, simply do:

> tar -zxvf alphas_lhc_fcc-ee_proceeds.tar.gz

> modify your file MyName.in

> pdflatex alphas_lhc_fcc-ee_proceeds.tex

Once you are done, please send us your file MyName.in (plus figures, if any) via email.

Deadline for contributions: 30 october 2015

Thanks to everybody for your excellent results/presentations !

Backup slides

FCC-ee high-precision SM physics

- Experimental uncertainties mostly of systematic origin
  - So far, mostly conservatively estimated based on LEP experience
  - Work ahead to establish more solid numbers

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g -> bb
N_ν	Peak	2.984 ± 0.008	0.00004	0.004	Lumi meast.
$A_{FB}^{\mu\mu}$	Peak	0.0171 ± 0.0010	0.000004	<0.00001	E_{beam} meast.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.000001	0.00015	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 1	QED corr.
N_ν	Radiative return e^+e^- -> γZ(inv)	2.92 ± 0.05 2.984 ± 0.008	0.0008	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	0.00015	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)

Generally better by factor ≥ 25

- Theoretical developments needed to match expected experimental uncertainties

Future determinations of α_s coupling

Snowmass'13, arXiv:1310.5189

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.)	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate)	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small)	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, ~ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small)	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, ~ 10 yrs)

Organization of the α_s workshop (Monday)

- 4 broad sessions. 20' per talk + 5' for discussion (extended if needed).

14:00	**Presentation / Goals of the workshop** *TH Conference Room, CERN*	*David D'ENTERRIA et al.* 14:00 - 14:10
	World Summary of alpha_s (2015) *TH Conference Room, CERN*	*Siegfried BETHKE* 14:10 - 14:45
15:00	**alpha_s and physics beyond the Standard Model** *TH Conference Room, CERN*	*francesco SANNINO* 14:45 - 15:15
	Impact of alpha_s on Higgs prod. & decay uncertainties *TH Conference Room, CERN*	*Luminita MIHAILA* 15:15 - 15:40
	Coffee break *TH Conference Room, CERN*	15:40 - 16:00
	alpha_s at low scales	
16:00	**alpha_s from lattice QCD** *TH Conference Room, CERN*	*paul MACKENZIE* 16:00 - 16:25
	Determination of αs from the QCD static energy *TH Conference Room, CERN*	*Xavier GARCIA TORMO* 16:25 - 16:45
17:00	**alpha_s from pion decay factor** *TH Conference Room, CERN*	*Jean-Loic KNEUR* 16:45 - 17:10
	alpha_s from hadronic tau decays *TH Conference Room, CERN*	*Antonio PICH et al.* 17:10 - 17:35
	alpha_s from hadronic quarkonia decays *TH Conference Room, CERN*	*Soto i Riera JOAN* 17:35 - 18:00
18:00	**alpha_s from soft parton-to-hadron FFs** *TH Conference Room, CERN*	*Redamy PEREZ-RAMOS et al.* 18:00 - 18:20

Organization of the α_s workshop (Tuesday)

- 4 broad sessions. 20' per talk + 5' for discussion (extended if needed).

alpha_s at high scales

alpha_s from DIS (PDFs) :	*Johannes BLUEMLEIN*	*TH Conference Room, CERN*	09:30 - 09:55
alpha_s from DIS (jets, photoproduction)	*Michael KLASEN*	*TH Conference Room, CERN*	09:55 - 10:20
alpha_s from scaling violations of hard parton-to-hadron FFs	*Prof. Bernd KNIEHL*	*TH Conference Room, CERN*	10:20 - 10:45
alpha_s from e+e- event shapes	*Stefan KLUTH et al.*	*TH Conference Room, CERN*	10:45 - 11:10
Coffee break		*TH Conference Room, CERN*	11:10 - 11:25
alpha_s from e+e- C-parameter event shape	*Andre HOANG*	*TH Conference Room, CERN*	11:25 - 11:50
alpha_s from e+e- jet cross sections	*Andrea BANFI*	*TH Conference Room, CERN*	11:50 - 12:15
alpha_s from hadronic Z decays and from the full electroweak fit	*Klaus MONIG*	*TH Conference Room, CERN*	12:15 - 12:40
alpha_s from hadronic W decays	*Matej SREBRE et al.*	*TH Conference Room, CERN*	12:40 - 13:05
alpha_s from sigma(e+e--->hadrons)	*Johann KUEHN*	*TH Conference Room, CERN*	13:05 - 13:30
Lunch break			

Lunch break		*TH Conference Room, CERN*	13:30 - 15:00

alpha_s at hadron col...

alpha_s from sigma(ttbar) at the LHC	*Alexander Dimitrov MITOV*	*TH Conference Room, CERN*	15:00 - 15:25
alpha_s from sigma(ttbar): latest developments	*Gavin SALAM*	*TH Conference Room, CERN*	15:25 - 15:45
Future prospects of alpha_s from jets at the LHC at NNLO	*Joao PIRES*	*TH Conference Room, CERN*	15:45 - 16:10
Coffee break		*TH Conference Room, CERN*	16:10 - 16:30
alpha_s determinations from ATLAS (status & plans)	*Bogdan MALAESCU*	*TH Conference Room, CERN*	16:30 - 16:55
alpha_s determinations from CMS (status & plans)	*Klaus RABBERTZ*	*TH Conference Room, CERN*	16:55 - 17:20
Conclusions (FCC-ee Yellow Report preparation)		*TH Conference Room, CERN*	17:20 - 18:00