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

CERN, 12th –13th October 2015

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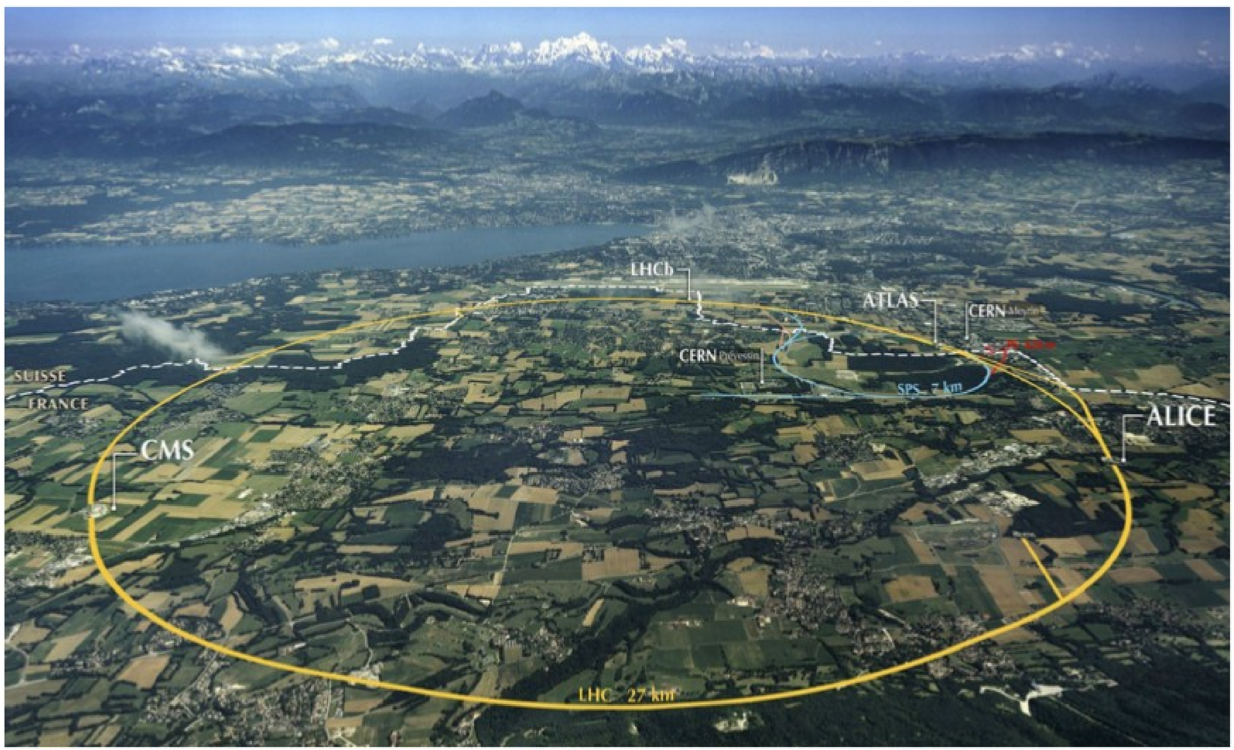
FCC-ee “QCD & γγ Physics” Working Group Conveners

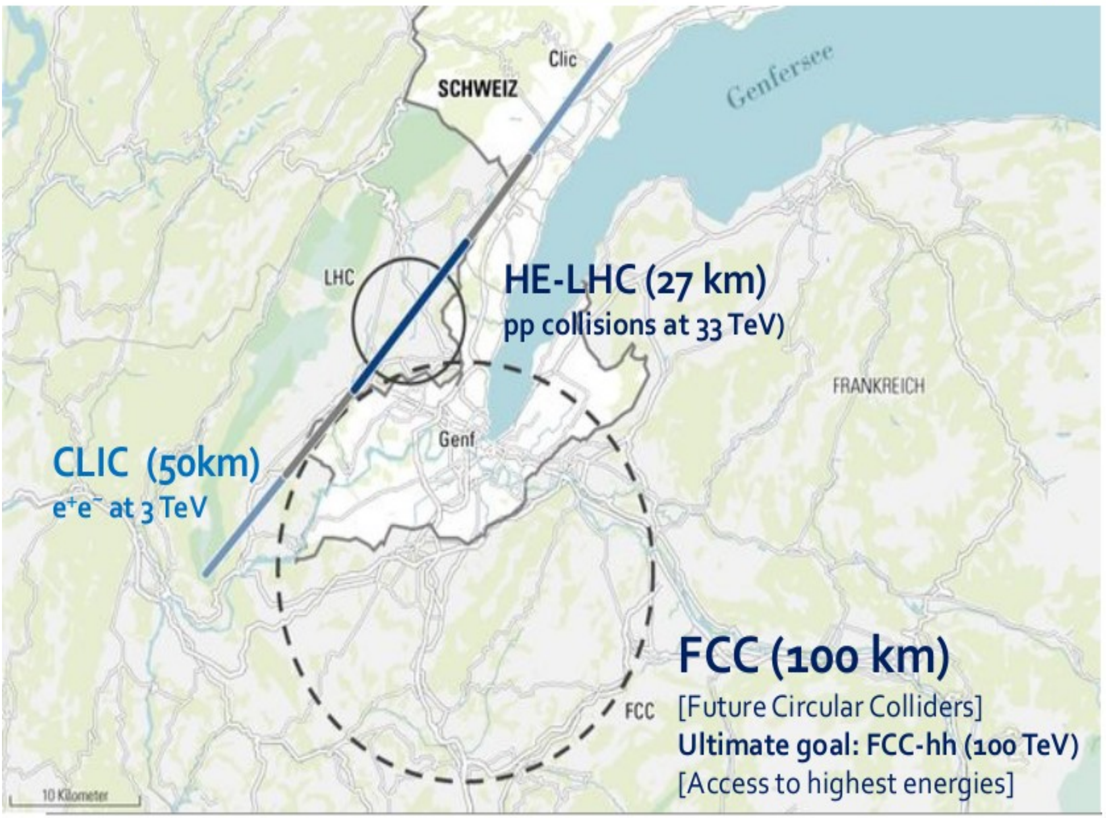
EU HEP short-term perspectives (2020-2030)

- In May 2013, European Strategy said (very similar statements from US)
  - Exploit the full potential of the LHC until ~2030 as the highest priority
    - Get 75-100 fb^{-1} at 13-14 TeV by 2018 (LHC Run2: running)
    - Get ~300 fb^{-1} at 14 TeV by 2022 (LHC Run3: approved)
    - Upgrade machine and detectors to get 3 ab^{-1} at 14 TeV by 2035 (HL-LHC: project)
      - ➡ A first step towards both energy and precision frontier

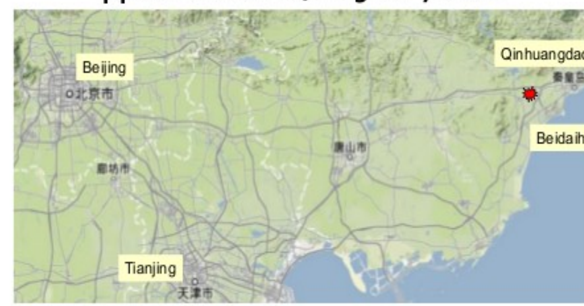


EU HEP long-term perspectives (2040-2060)

- In May 2013, European Strategy said (very similar statements from US)
  - Perform R&D and design studies for high-energy frontier machines at CERN
    - HE-LHC, a programme for an energy increase to 33 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at $\sqrt{s}$ = 100 TeV
    - CLIC, an e^+e^- collider project with $\sqrt{s}$ from 0.3 to 3 TeV



Similar circular projects
(50 or 70km) in China
pp collisions at $\sqrt{s}$ ~ 50 or 70 TeV

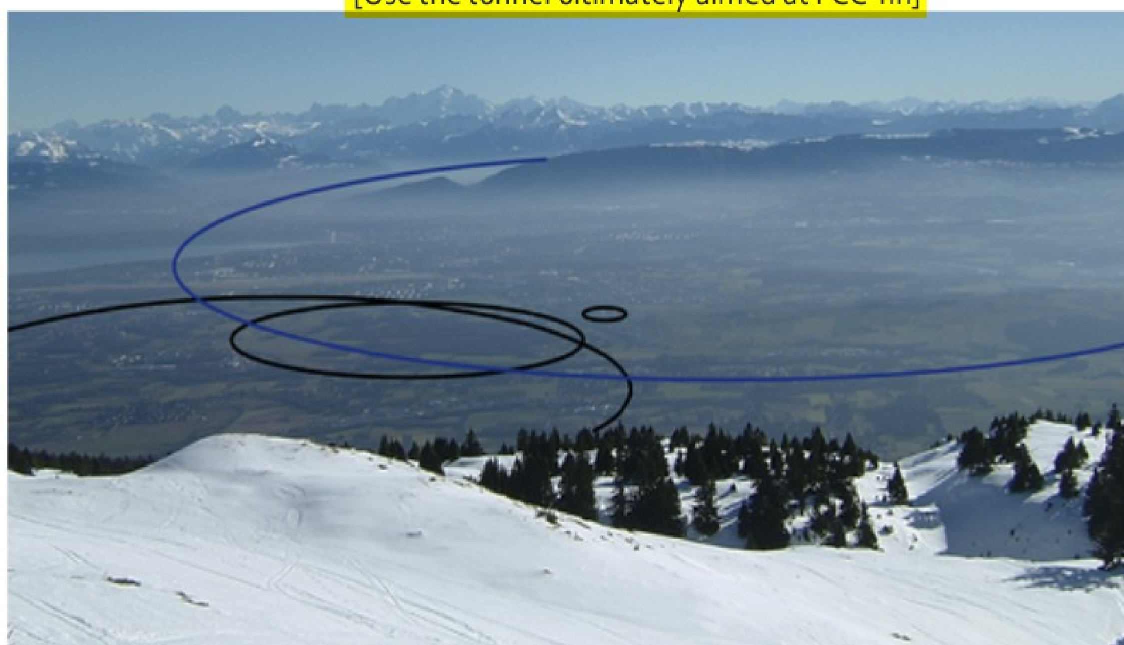


EU HEP mid-term perspectives (2030-2040)

- In May 2013, European Strategy said (very similar statements from US)
  - Acknowledge the strong physics case of e^+e^- colliders with intermediate $\sqrt{s}$
    - ➜ Participate at ILC if Japan govt moves forward with the project.
    - ➜ "***Propose an ambitious post-LHC accelerator project****. CERN should undertake design studies for accelerator projects with emphasis on p-p and e+e- high-energy frontier machines*"

FCC (100 km)

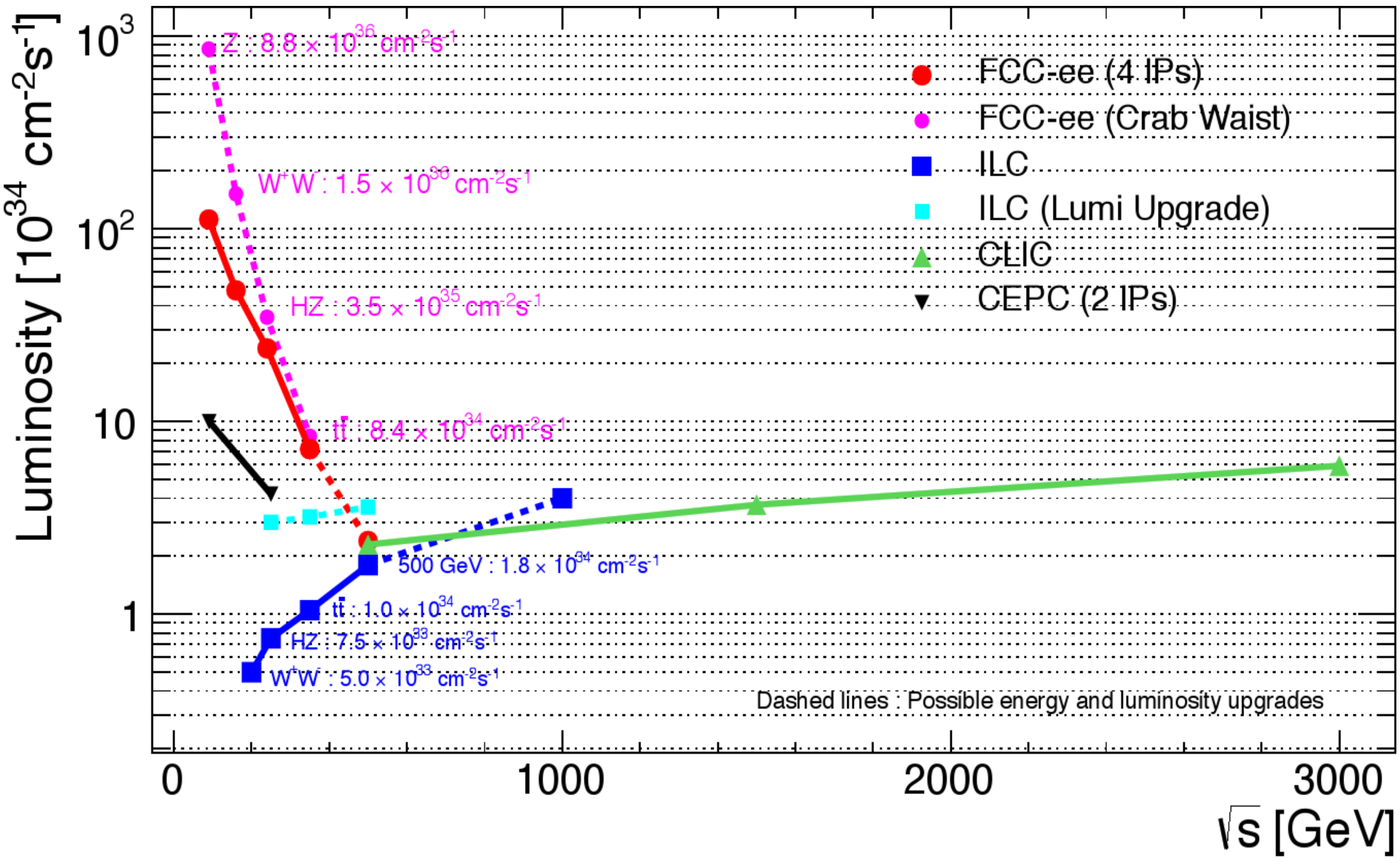
First step: FCC-ee (91-400GeV)
[Use the tunnel ultimately aimed at FCC-hh]



Note: CLIC can also run at $\sqrt{s}$ ~ 350 GeV in ~2035-2040

FCC-ee CERN study project

- <u>Indirect BSM searches</u> (through loops) in high-statistics (multi ab^{-1})
  Z ($\sqrt{s}$=91 GeV), W ($\sqrt{s}$=160 GeV), H ($\sqrt{s}$=240 GeV), top ($\sqrt{s}$=350 GeV)
  high-precision studies (<<0.1% accuracy) in a 80-km circular e^+e^- collider



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

FCC-ee physics programme: Duration

■ 4 IP's and in the crab-waist optics scheme :

$\sqrt{s}$ (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 (tt)	350 (WW→H)
Lumi (ab^{-1}/yr)	86.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}
# years	(0.3) 2.5	1	3	0.5	3
Events@LC (*)	3×10^{9}	2×10^{6}	1.4×10^{5}	10^{5}	3.5×10^{4}
LC @ FCC-ee	1 day	1 week	2 months	3 months	1.5 year

See e.g., arXiV:1506.07830
"ILC Operating Scenarios"

(*) LC = 500 fb^{-1} @ 500 GeV (6 y), 200 fb^{-1} @ 350 GeV (2 y), 500 fb^{-1} @ 250 GeV (5 y)
100 fb^{-1} @ 90 GeV (>3 y), 500 fb^{-1} @ 160 GeV (>5 y)
with ±80% / ±30% polarization for e^-/e^+ beams

>21 years
(1 y = 10^7 s)

■ FCC-ee core physics programme to be completed in 8–10 years

FCC-ee study project structure

- **Lepton studies – Coordinators** A. Blondel, P. Janot **(EXP)** + **J.Ellis,C.Grojean (TH)**
  - Study the properties of the Higgs and other particles with unprecedented precision

EW Physics (Z pole)
R. Tenchini F. Piccinini
S. Heinemeyer

Diboson physics, m_W
R. Tenchini F. Piccinini
S. Heinemeyer

H(125) Properties
M. Klute
K. Peters

Top Quark Physics
P. Azzi

QCD and $\gamma\gamma$ Physics
D. d'Enterria
P. Skands

Flavour Physics
S. Monteil
J. Kamenik

New Physics
M. Pierini C. Rogan
A. Weiler

- Develop the necessary tools

Understand the experimental conditions

Physics Software
C. Bernet
B. Hegner

Common with FCC-hh/eh,
Synergies with LHC, LC

Online & Trigger
E. Perez
C. Leonidopoulos

Exp'tal Environment
N. Bacchetta

Synergy with FCC-hh
and Linear Colliders

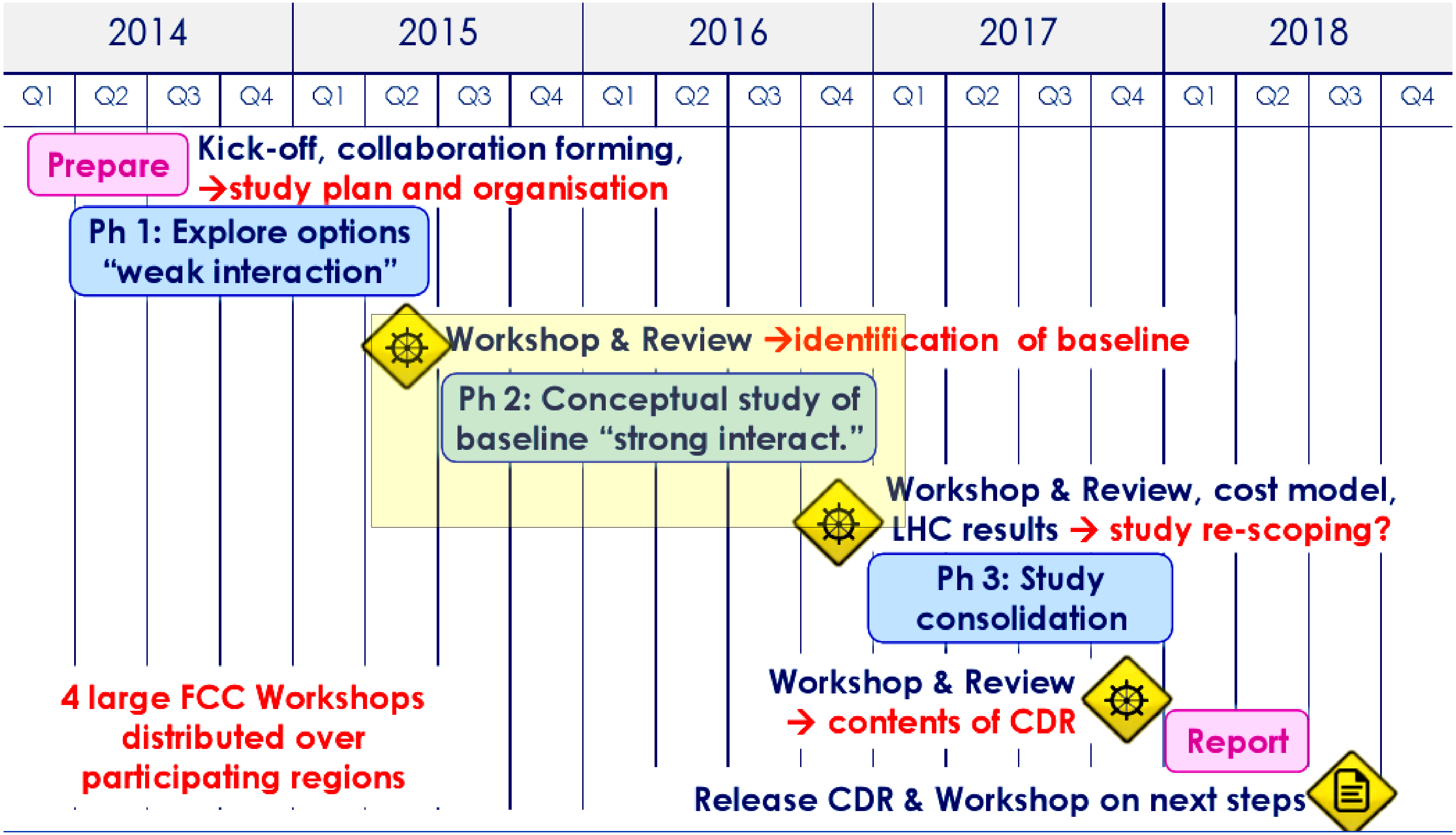
- Set constraints on the possible detector designs to match statistical precision

Detector Designs
A. Cattai
G. Rolandi

Synergy with Linear Collider
detectors and others

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 !

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 ?

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
	alpha_s and physics beyond the Standard Model *TH Conference Room, CERN*	*francesco SANNINO* 14:45 - 15:15
15:00	**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
	alpha_s from pion decay factor *TH Conference Room, CERN*	*Jean-Loic KNEUR* 16:45 - 17:10
17:00	**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		TH Conference Room, CERN	13:30 - 15:00

alpha_s at hadron col...

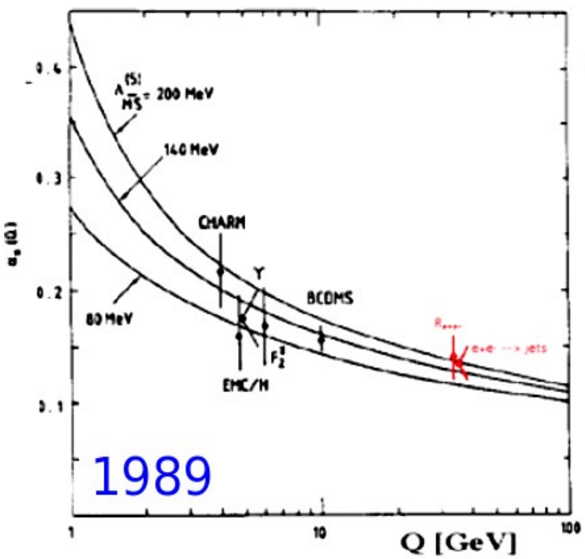
alpha_s from sigma(ttbar) at the LHC	Alexander Dimitrov MITOV	TH Conference Room, CERN	15:00 - 15:25
alpha_s from sigma(ttbar): latest developments	Gavin SALAM	TH Conference Room, CERN	15:25 - 15:45
Future prospects of alpha_s from jets at the LHC at NNLO	Joao PIRES	TH Conference Room, CERN	15:45 - 16:10
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

Backup slides

Determination of the QCD coupling α_s

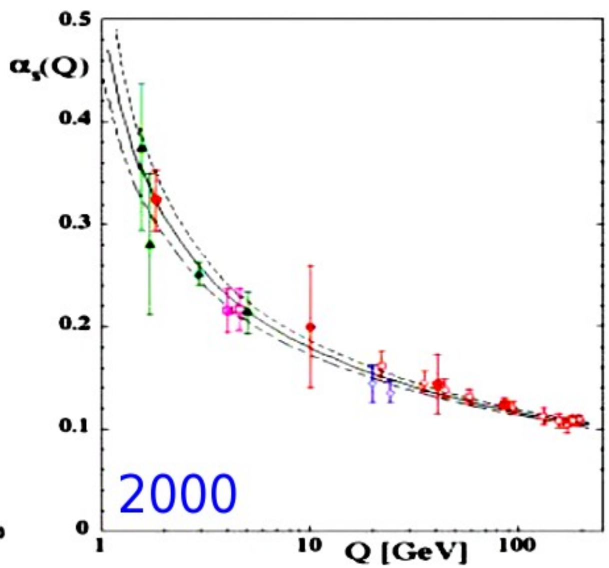
α_s = Single free parameter in QCD (in the $m_q \rightarrow 0$ limit). Determined at a reference scale ($Q=m_Z$). Decreases as $\sim \ln(Q^2/\Lambda^2)$, with $\Lambda \sim 0.2$ GeV

- Least precisely known of all couplings:
  $\delta\alpha \sim 3\cdot10^{-10}$, $\delta G_F \sim 5\cdot10^{-8}$, $\delta G \sim 10^{-5}$, $\delta\alpha_s \sim 5\cdot10^{-3}$
- Impacts all LHC cross-sections.
- Key for SM precision fits (e.g. uncertainties b,c Yukawa).
- BSM physics (GUT, vacuum stab.,...).



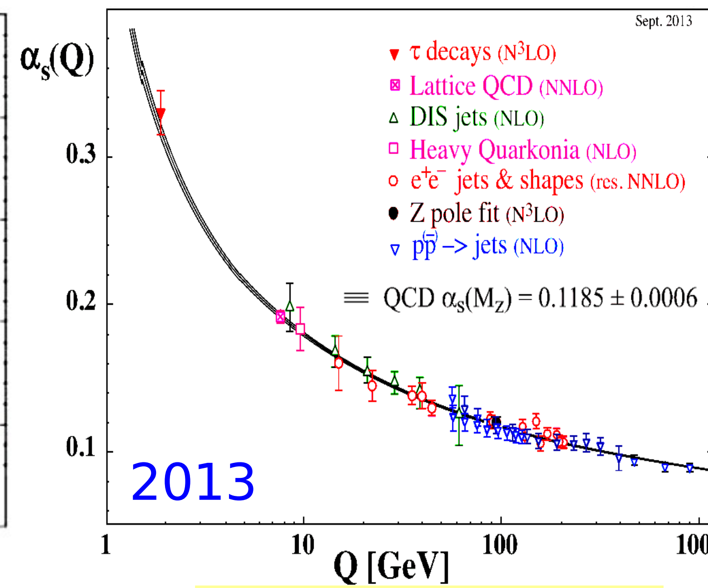
$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

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



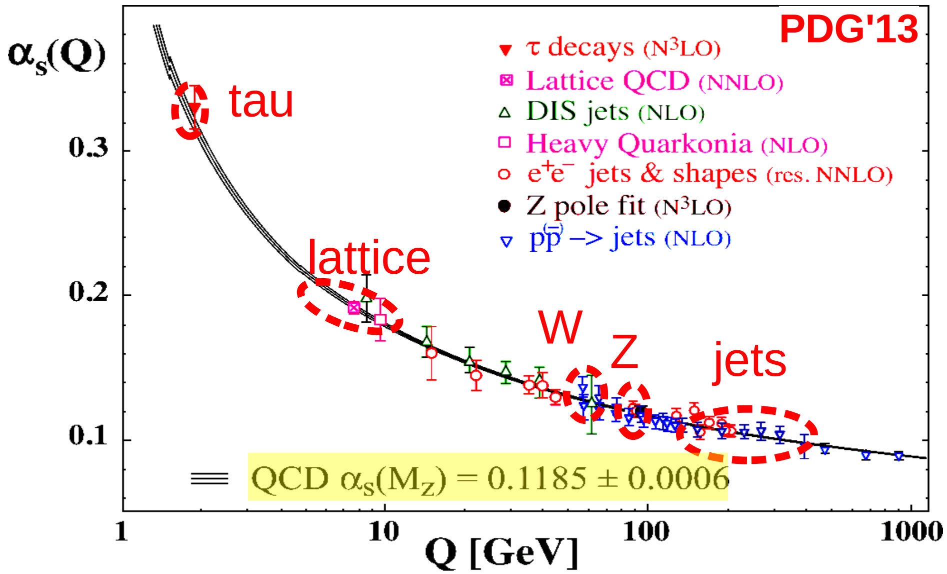
$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (NNLO)

Current PDG uncertainty: ±0.6%

Upcoming 2015 uncertainty: ±1%

Determination of the QCD coupling α_s

α_s = Single free parameter in QCD (in the $m_q \to 0$ limit). Determined at a given ref. scale (e.g. m_Z). Decreases as $\sim\ln(Q^2/\Lambda^2)$, with $\Lambda \sim 0.25$ GeV.

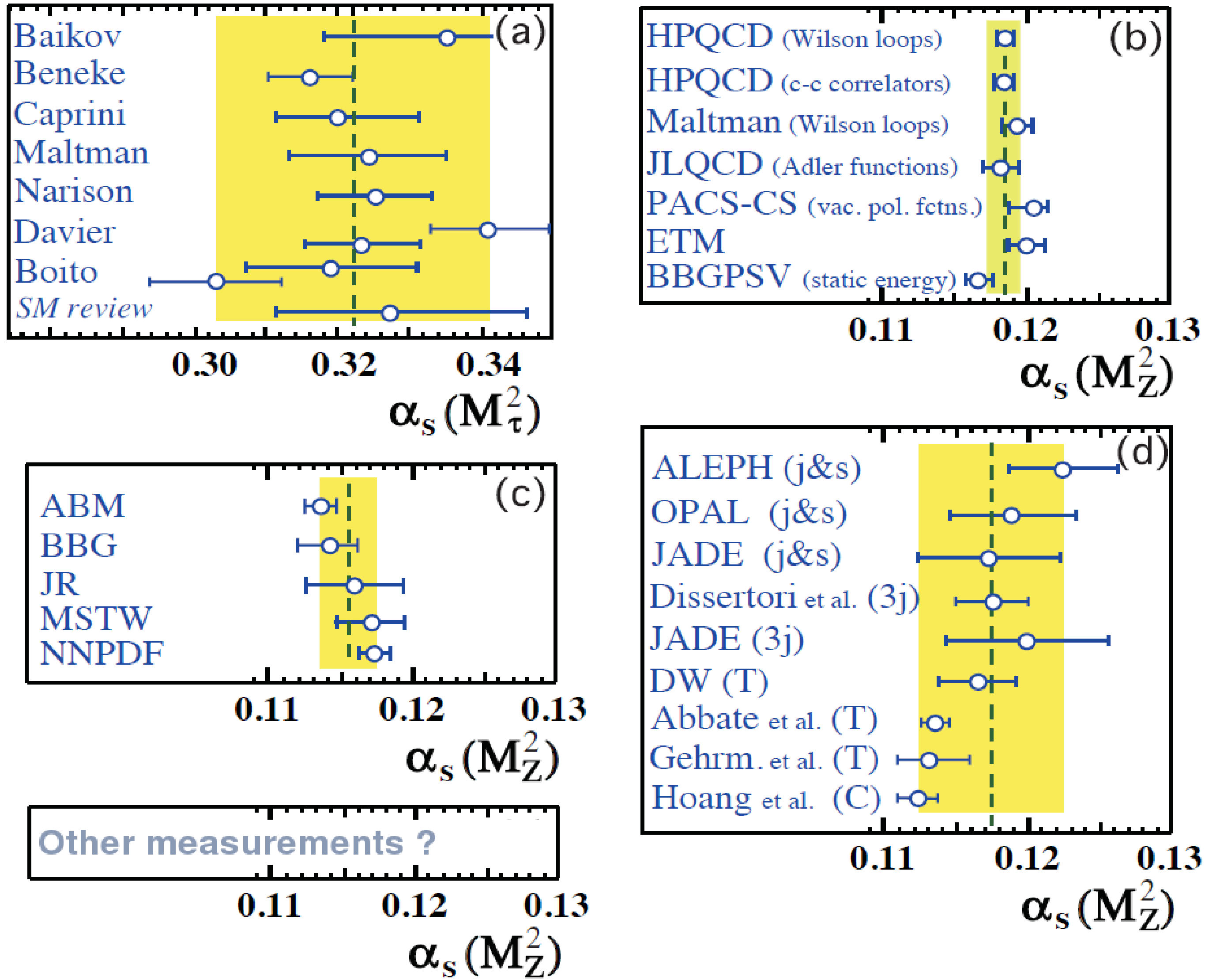


➧ Measured by comparing various experimental observables to different pQCD predictions:

1. Hadronic τ decays: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\rm EW} N_C \left(1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\rm np}\right)$ **(N³LO)**
2. Lattice QCD: Various short-distance quantities: $K^{\rm NP} = K^{\rm PT} = \sum_{i=0}^{n} c_i \alpha_s^i$ **(NNLO)**
3. Hadronic Z decays: $R_Z \equiv \frac{\Gamma(Z \to \rm h)}{\Gamma(Z \to l)} = R_Z^{\rm EW} N_C \left(1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\rm m} + \delta_{\rm np}\right)$ **(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)**

➧ Direct way to reduce α_s world-average uncertainty: Add new independent extractions

Multi-prong determination of α_s coupling



Future determination 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)