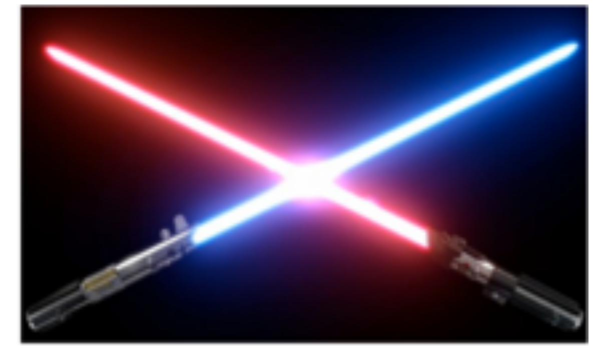
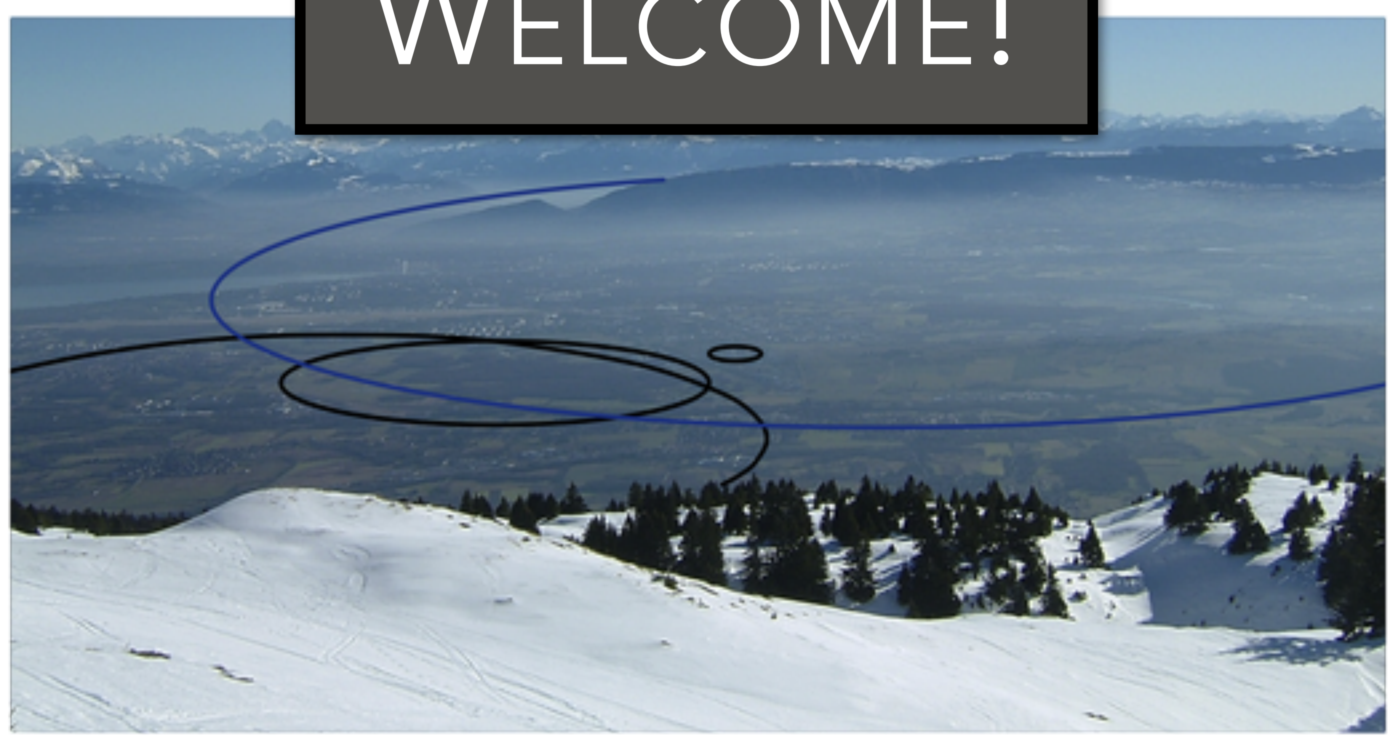
Parton Radiation and Fragmentation from LHC to FCC-ee

FCC-ee WG5: QCD&γγ



WELCOME!



CERN, November 21-22 — 2016

Organisers: D. d'Enterria & P. Skands

Workshop Goals

Survey key QCD measurements at ee colliders & their uses:

- Properties of QCD (elucidate **perturbative** & **non-perturbative** phenomena)
- To inform **EW, Higgs, and other** precision measurements in ee
- To inform the physics modelling at **hadron colliders (→FCC-hh)**
- **Identify unique opportunities** opened by high luminosities (e.g., oku-W, Tera-Z) and energies (e.g., HZ, ttbar) accessible at FCC-ee

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Identify essential detector capabilities (& resolution targets)

So that a complete set of measurements can be done, making good use of the available statistics.

→ **A definitive and complete set** of final-state radiation & fragmentation measurements with very high precision

Decisive demonstrations of high-order / sub-leading perturbative phenomena, and exhaustive exploration of non-perturbative effects

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Provide input for the QCD section of the Conceptual Design Report (CDR) on the FCC-ee physics possibilities.

Contributors are asked to provide **brief summaries** in a proceedings-style writeup to be submitted as a combined single document into arXiv.

Deadline ~ 1 month from end of workshop: before Christmas.

Organisation

Main venue: Filtration Plant (Bldg 222)

Note: Tuesday afternoon sessions in Council Chamber (CC)

Breaks / Refreshment:

Coffee (+ water/juice)
Mornings & Afternoons
(Thanks to the LHC Physics Centre at CERN)

This is an informal meeting; no official reception or dinner.

After the workshop program ends each day (~1740), you are welcome to join in R1 for refreshments and continued discussion

Organisation

	Main Topic(s)	Main Topic(s)
AM Session 1	Fragmentation Functions 1	Heavy Quarks
AM Session 2	Showers & Jets	Event Shapes & Resummations
PM Session 1	Jet Properties	Fragmentation Functions 2
PM Session 2	Particle Correlations	Jets, Showers, & Hadronisation

(+ a few overlaps; reallocations to accommodate constraints, etc)

Some Useful References

arXiv:1602.05043 — Physics at the FCC-ee

$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (WW→H)
$\mathcal{L}$/IP (cm^{-2} s^{-1})	$2.2 \cdot 10^{36}$	$1.1 \cdot 10^{36}$	$3.8 \cdot 10^{35}$	$8.7 \cdot 10^{34}$	$2.1 \cdot 10^{34}$	$2.1 \cdot 10^{34}$
$\mathcal{L}_{\rm int}$ (ab^{-1}/yr/IP)	22	11	3.8	0.87	0.21	0.21
Events/year (4 IPs)	$3.7 \cdot 10^{12}$	$1.2 \cdot 10^{4}$	$6.1 \cdot 10^{7}$	$7.0 \cdot 10^{5}$	$4.2 \cdot 10^{5}$	$2.5 \cdot 10^{4}$
Years needed (4 IPs)	2.5	1.5	1	3	0.5	3

Table 1: Target luminosities, events/year, and years needed to complete the W, Z, H and top-quark programs at FCC-ee. [Note that $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1} corresponds to $\mathcal{L}_{\rm int} = 1$ ab^{-1}/yr for 1 yr = 10^7 s].

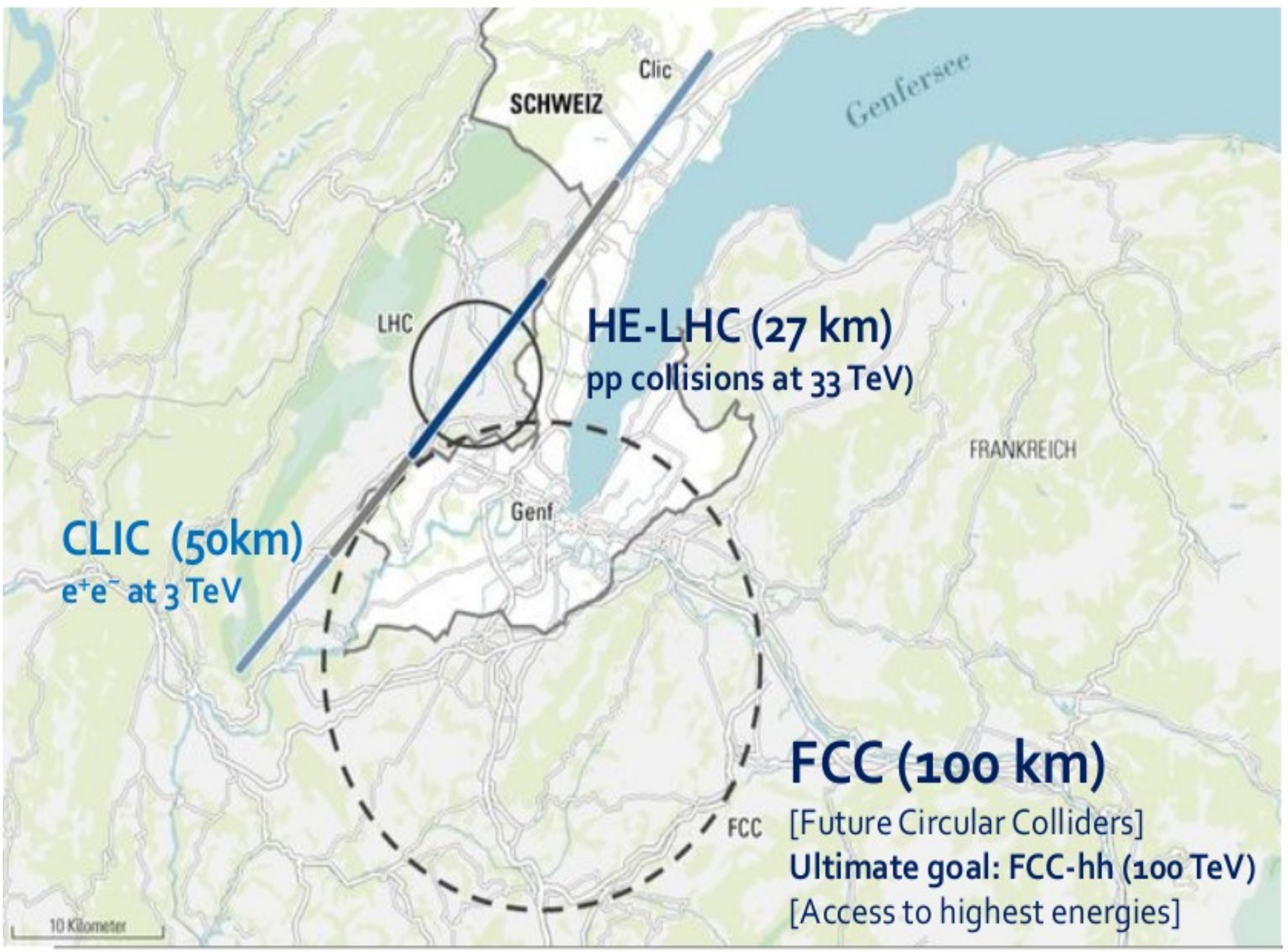
arXiv:1610.06254 — QCD & γγ Studies at FCC-ee (ICHEP poster)

arXiv:1512.05194 — Proceedings, High-Precision α_s Measurements from LHC to FCC-ee (Last year's WG5 workshop writeups)

See also talks from last week's YuriFest Nov 2016

EU HEP long-term perspectives (2040-2060)

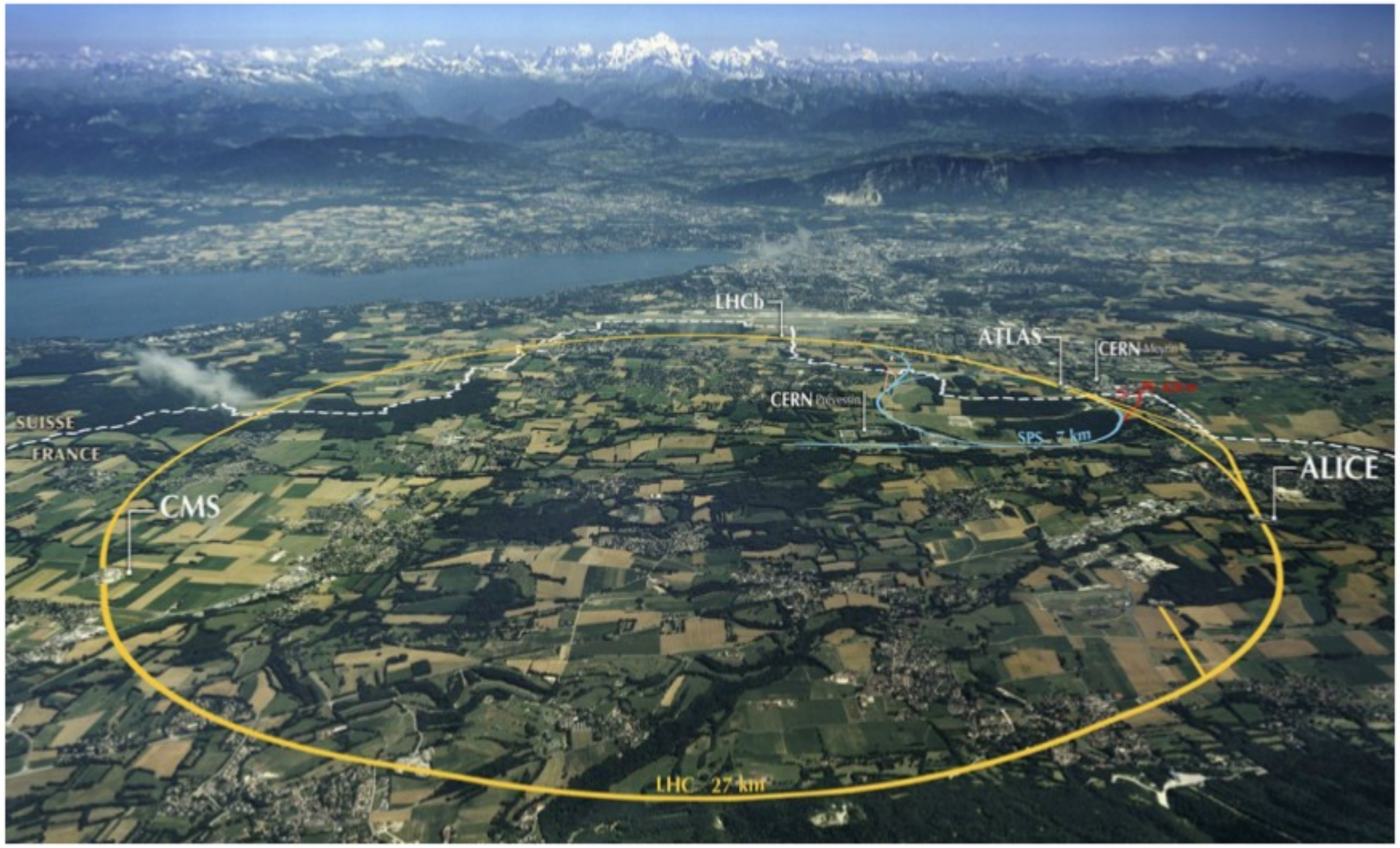
- In May 2013, European Strategy said (very similar statements from US)
  - Perform R&D and design studies for high-energy frontier machines at CERN
    - HE-LHC, a programme for an energy increase to 33 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at $\sqrt{s}$ = 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 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 mid-term perspectives (2030-2040)

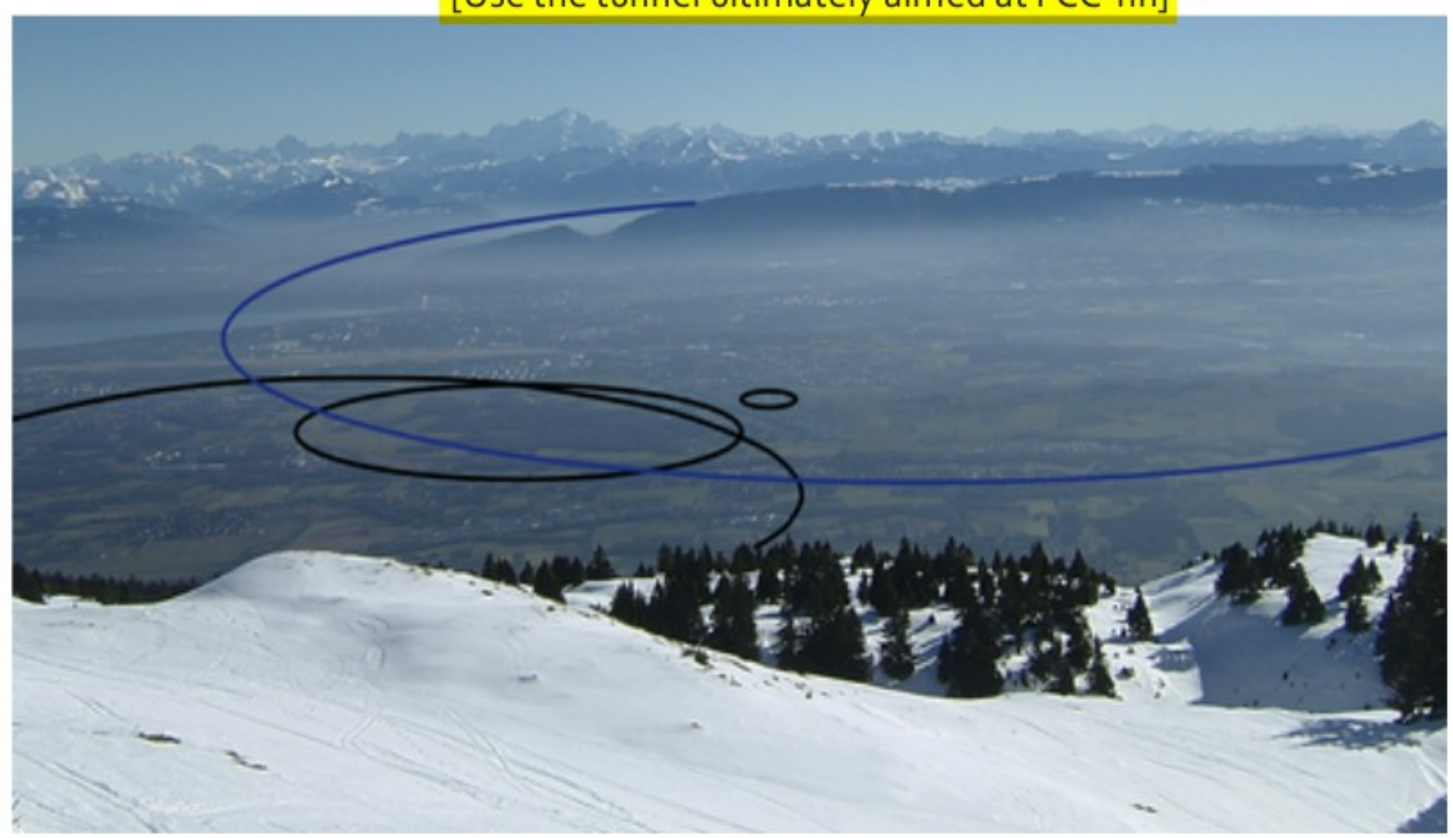
- In May 2013, European Strategy said (very similar statements from US)
  - Acknowledge the strong physics case of e^+e^- colliders with intermediate $\sqrt{s}$

    ➜ 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

- Indirect BSM searches (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

$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (WW→H)
σ	43 nb	290 ab	4 pb	200 fb	0.5 pb	25 fb
$\mathcal{L}$/IP ($cm^{-2}\,s^{-1}$)	$4.3{\cdot}10^{36}$	$2.2{\cdot}10^{36}$	$7.6{\cdot}10^{35}$	$1.8{\cdot}10^{35}$	$5{\cdot}10^{34}$	$5{\cdot}10^{34}$
$\mathcal{L}_{int}$ (ab^{-1}/yr, 2 IPs)	86	45	15	3.5	1.0	1.0
Events/year (2 IPs)	$3.7{\cdot}10^{12}$	$1.3{\cdot}10^{4}$	$6.1{\cdot}10^{7}$	$7.0{\cdot}10^{5}$	$5{\cdot}10^{5}$	$2.5{\cdot}10^{4}$
Years needed (2 IPs)	2.5	1.5	1	3	0.5	3

- Enormous integrated luminosities, extremely “clean” environment with very low backgrounds: Unparalleled opportunities for high-accuracy QCD physics (α_s, jets radiation, jets fragmentation) with direct impact in all SM high-precision tests & BSM searches.

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)	Diboson physics, m_W	H(125) Properties	Top Quark Physics
R. Tenchini F. Piccinini S. Heinemeyer	R. Tenchini F. Piccinini S. Heinemeyer	M. Klute K. Peters	P. Azzi

QCD and γγ Physics	Flavour Physics	New Physics
D. d'Enterria P. Skands	S. Monteil J. Kamenik	M. Pierini C. Rogan A. Weiler

  - Develop the necessary tools

Understand the experimental conditions

Physics Software	Online & Trigger	Exp'tal Environment
C. Bernet B. Hegner	E. Perez C. Leonidopoulos	N. Bacchetta
Common with FCC-hh/eh, Synergies with LHC, LC		Synergy with FCC-hh and Linear Colliders

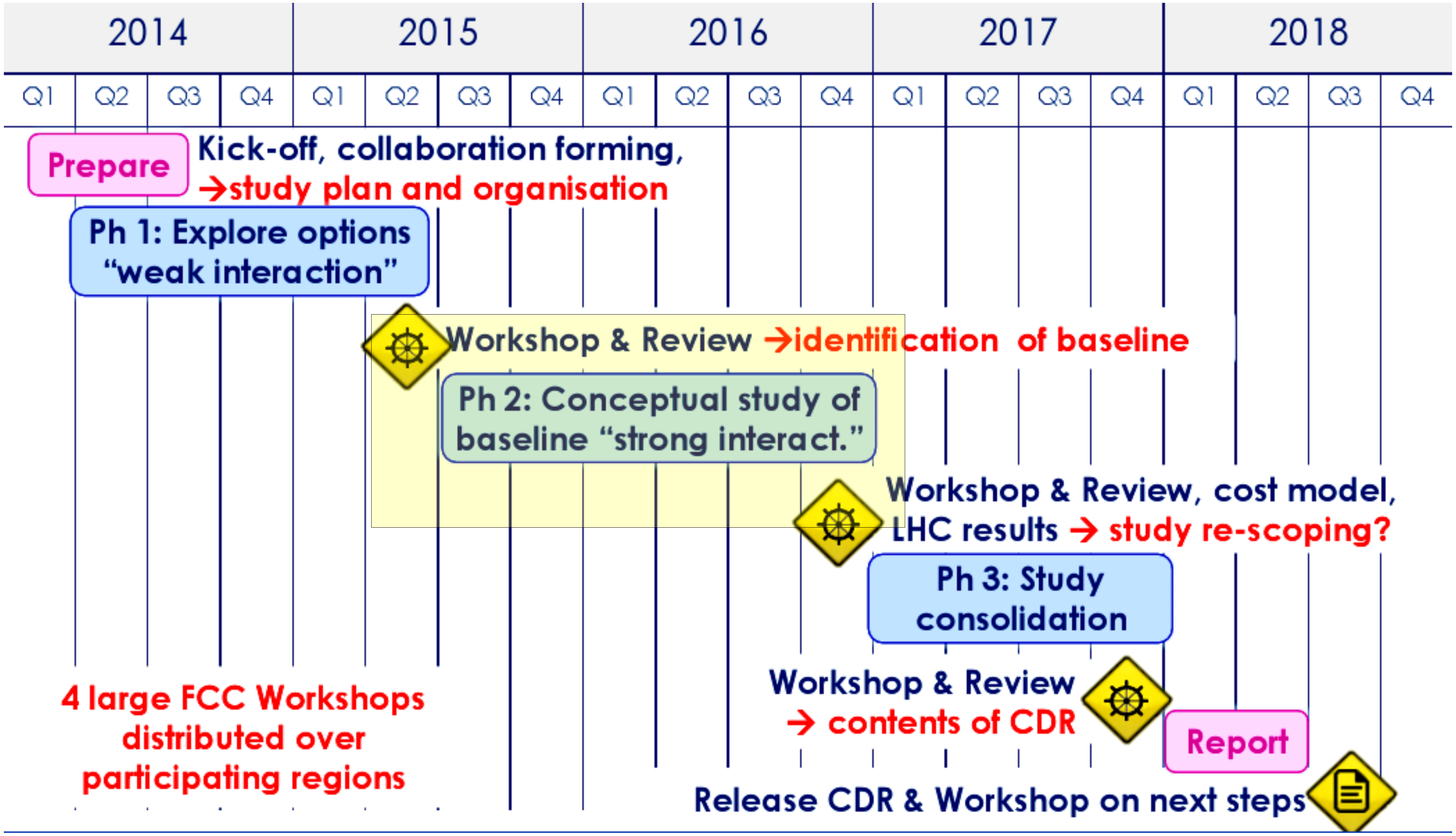
  - Set constraints on the possible detector designs to match statistical precision

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



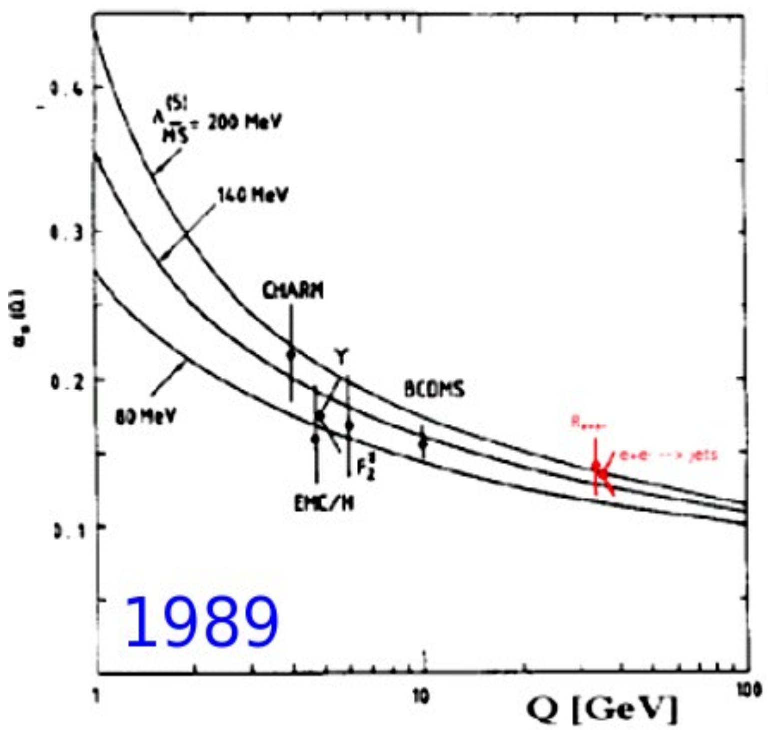
(*) That's why we need your proceedings !

Backup Slides

Determination of the QCD coupling α_s

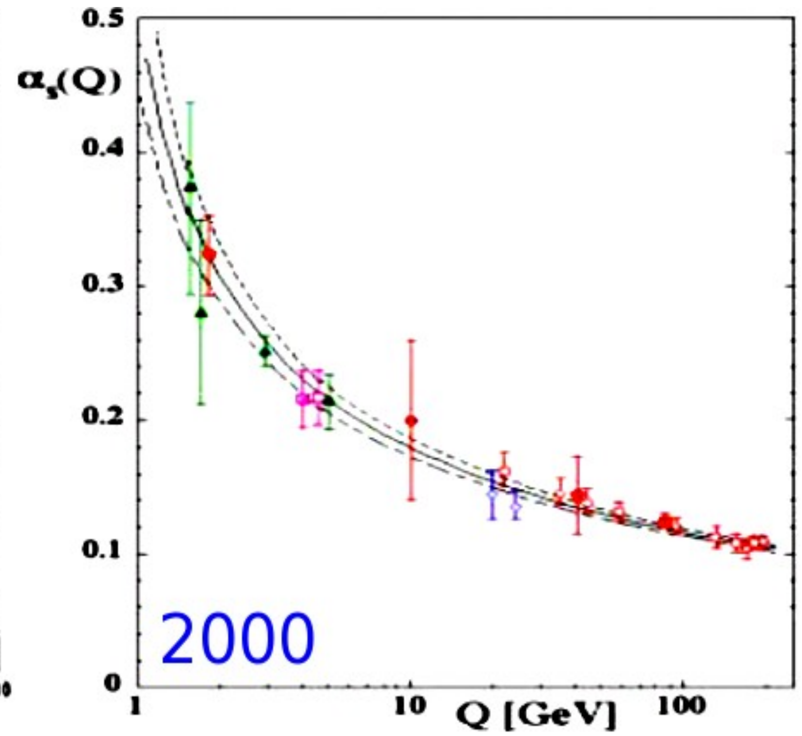
α_s = Single free parameter in QCD (in the $m_q \rightarrow 0$ limit). Determined at a reference scale ($Q=m_Z$). Decreases as $\sim\ln(Q^2/\Lambda^2)$, with $\Lambda\sim0.2$ GeV

- 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.,...).



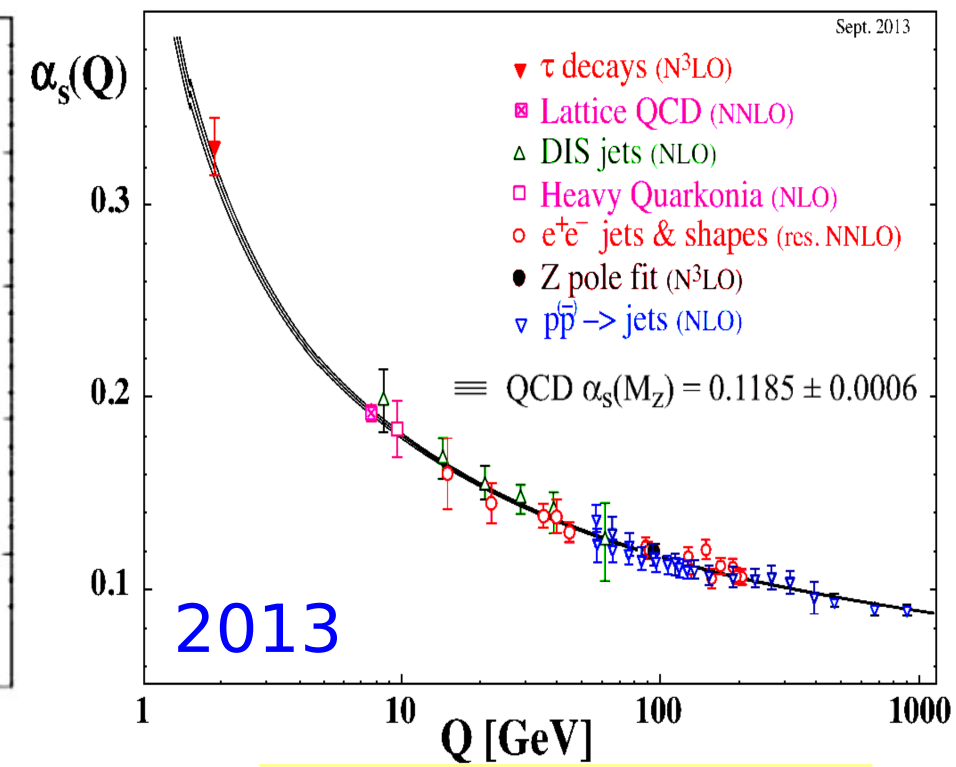
$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

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



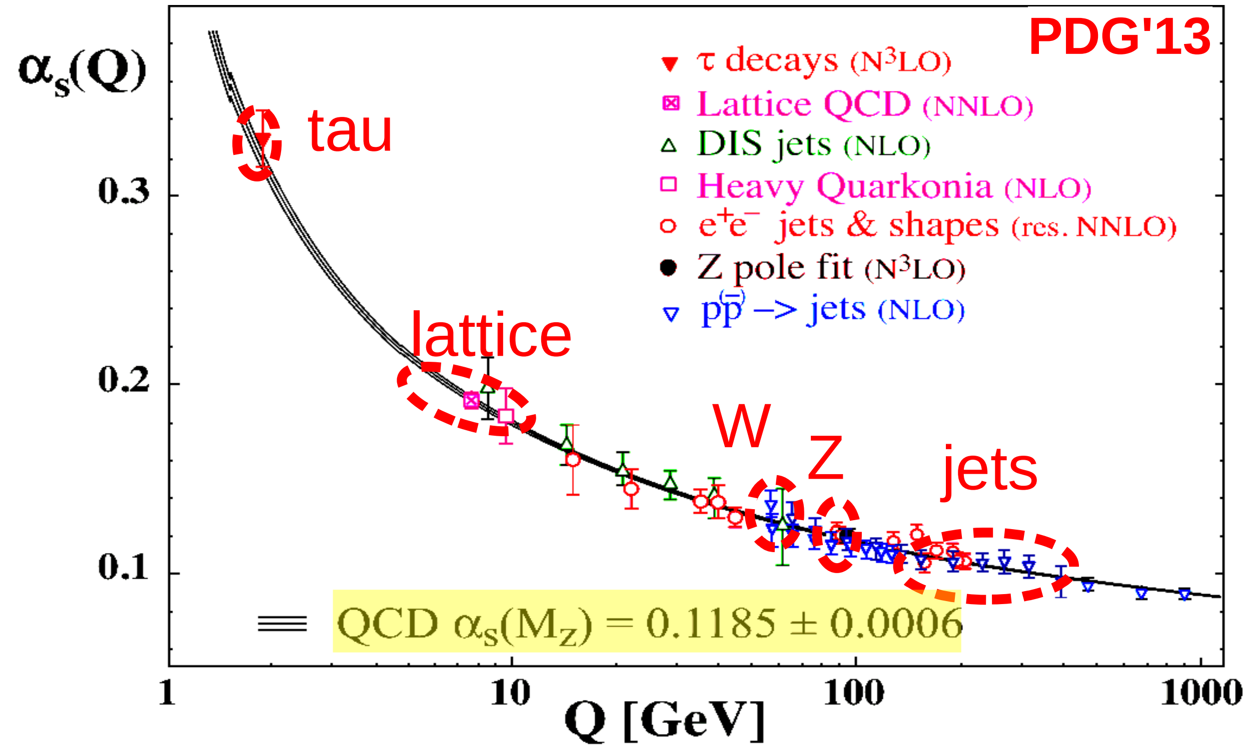
$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (NNLO)

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 $\Lambda\sim0.25$ GeV.

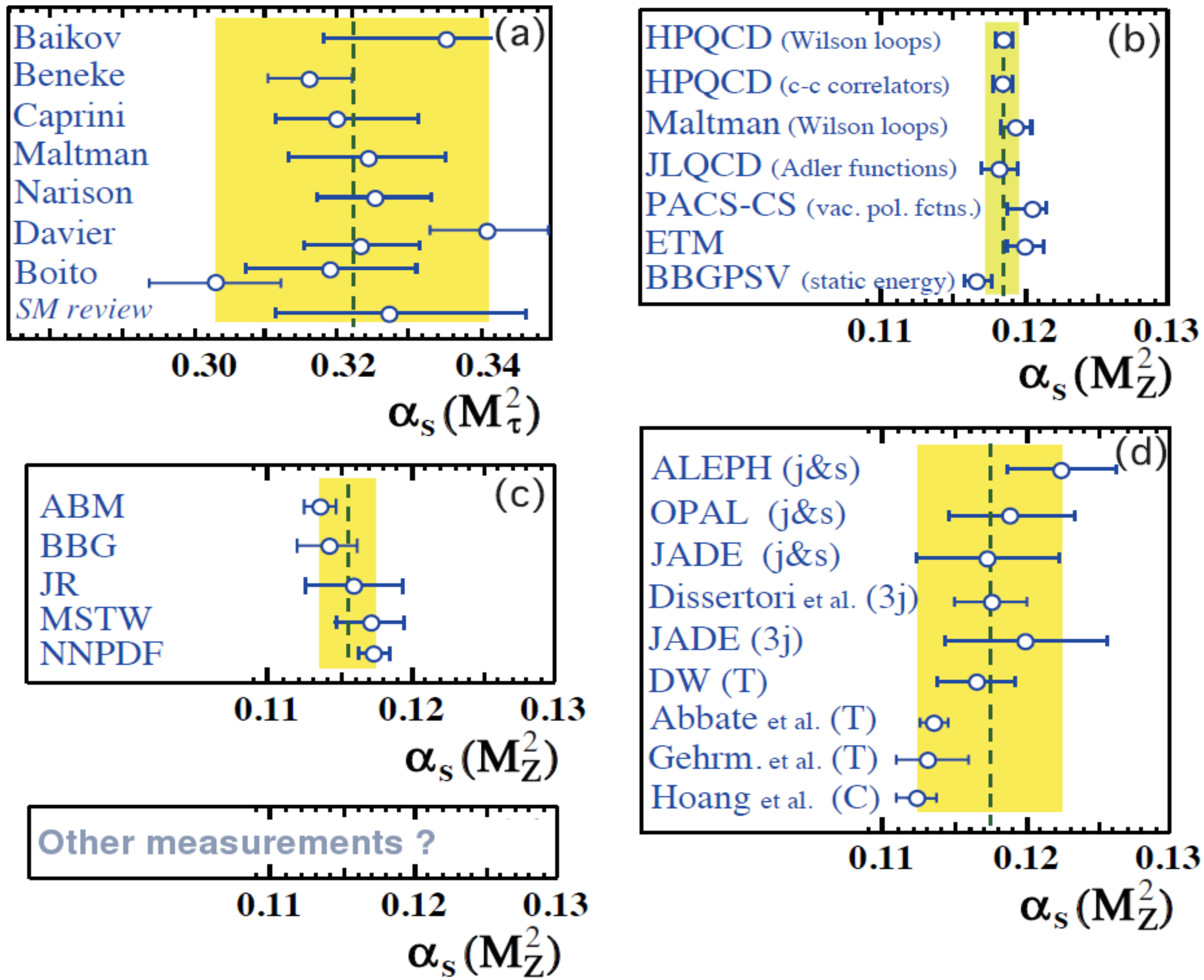


- Measured by comparing various experimental observables to different pQCD predictions:

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