QCD at future e^+e^- colliders

DIS 2017

Birmingham, 5th April 2017

David d'Enterria (CERN)

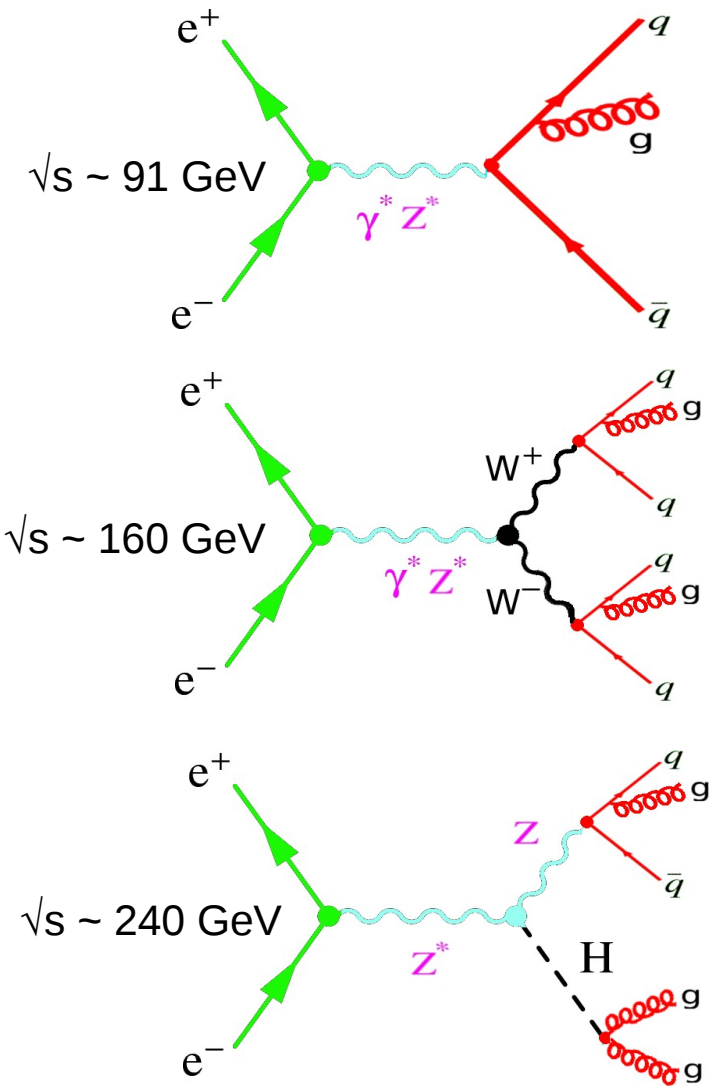
Mostly based on FCC-ee studies published as: arXiv:1702.01329, arXiv:1512.05194

Proceedings, Parton Radiation and Fragmentation from LHC to FCC-ee : CERN, Geneva, Switzerland, November 22-23, 2016
David d'Enterria (ed.) (CERN), Peter Z. Skands (ed.) (Monash U.).
Feb 4, 2017. 181 pp. COEPP-MN-17-1
Conference: C16-11-21.1 Contributions
e-Print: arXiv:1702.01329 **[hep-ph]** | PDF

Proceedings, High-Precision α_s Measurements from LHC to FCC-ee : CERN, Geneva, Switzerland, October 2-13, 2015
David d'Enterria (ed.) (CERN) *et al.*. Dec 16, 2015. 135 pp.
CERN-PH-TH-2015-299, COEPP-MN-15-13, FERMILAB-CONF-15-610-T
Conference: C15-10-12.1 Contributions
e-Print: arXiv:1512.05194 **[hep-ph]** | PDF

QCD physics in e^+e^- collisions

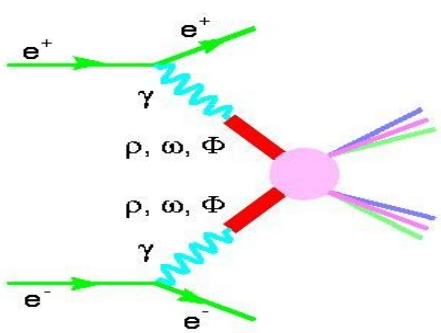
- e^+e^- collisions provide an extremely clean environment with fully-controlled initial-state to highly precisely probe q,g dynamics:



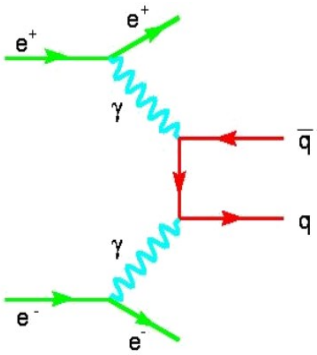
Advantages compared to p-p collisions:

- Electroweak initial-state with known kinematics
- No QCD "underlying event"
- Smaller QCD radiation (only in final-state)
- Smaller non-pQCD uncertainties (no PDFs)

- Plus QCD physics in $\gamma\gamma$ (EPA) collisions:



(soft, VDM)



(direct)

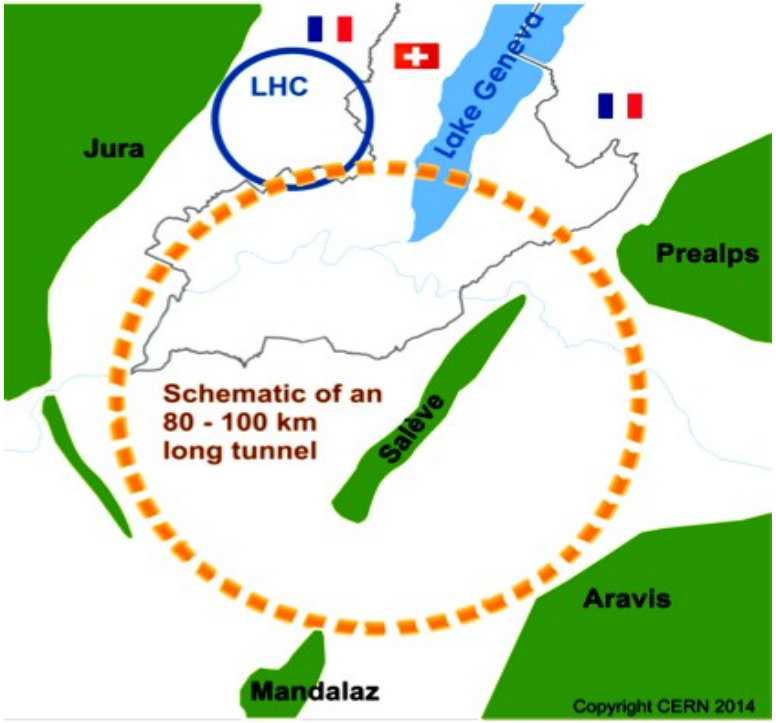
EU HEP mid-term perspectives (2030-2040)

- Indirect new physics searches: Higher-precision/lumi e^+e^- colliders.
- 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 in ILC if Japan government moves forward with the project
    - In the context of the FCC, perform accelerator R&D and design studies
      - ➡ In view of a high-luminosity, high-energy, circular e^+e^- collider as a first step

FCC (100 km)

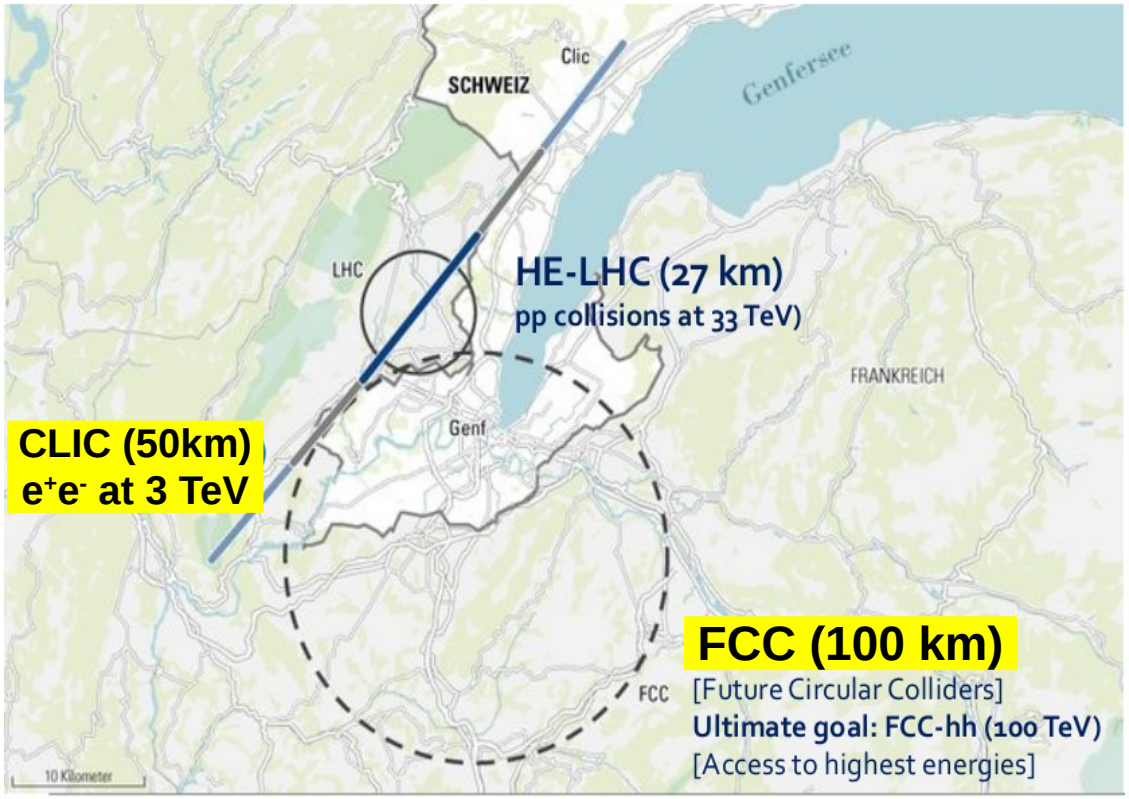
First step: FCC-ee (91-400GeV)

[Use the tunnel ultimately aimed at FCC-hh]

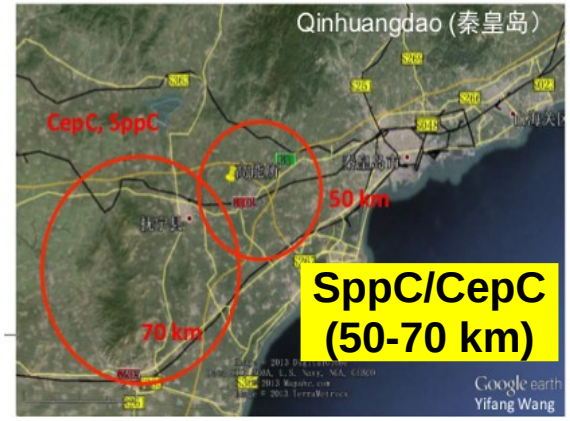


EU HEP long-term perspectives (2040-2060)

- Direct new physics searches: Higher-energy colliders.
- 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

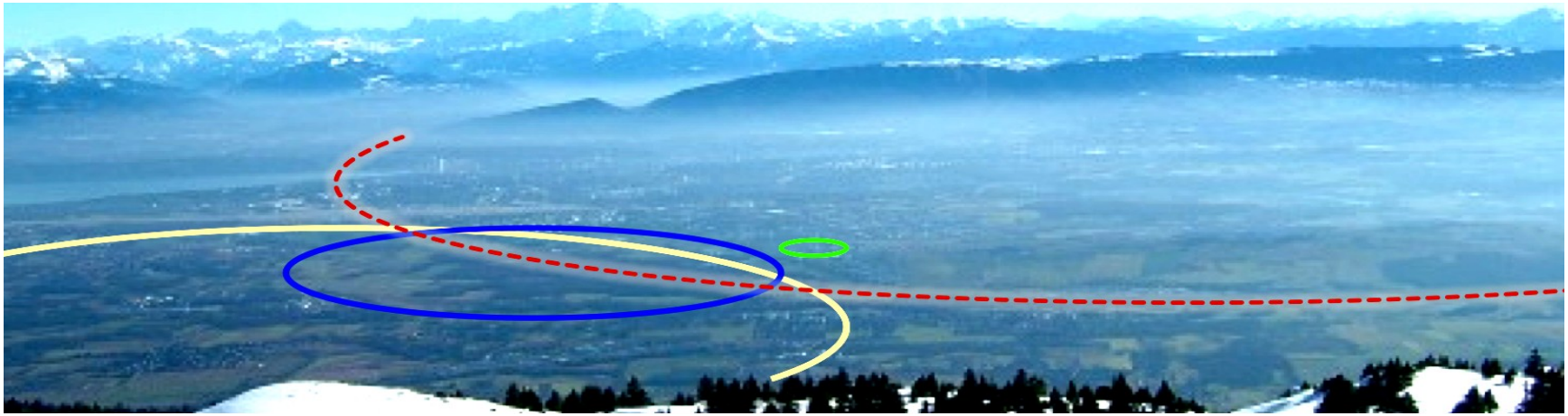


Similar circular projects (50 or 70km) in China
pp collisions at $\sqrt{s}$ ~ 50 or 70 TeV

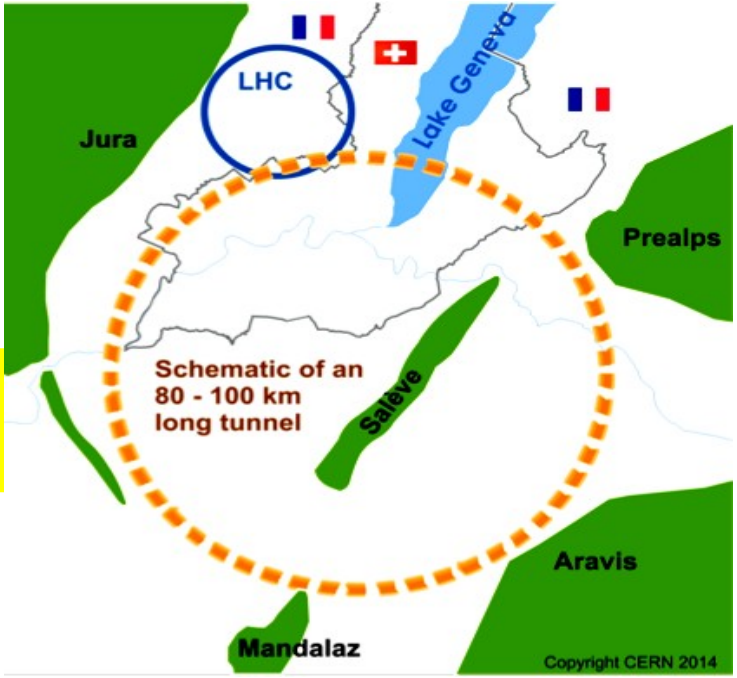


CERN Future Circular Collider (FCC) project

- FCC European Design Study, ongoing CDR (expected by mid 2018)

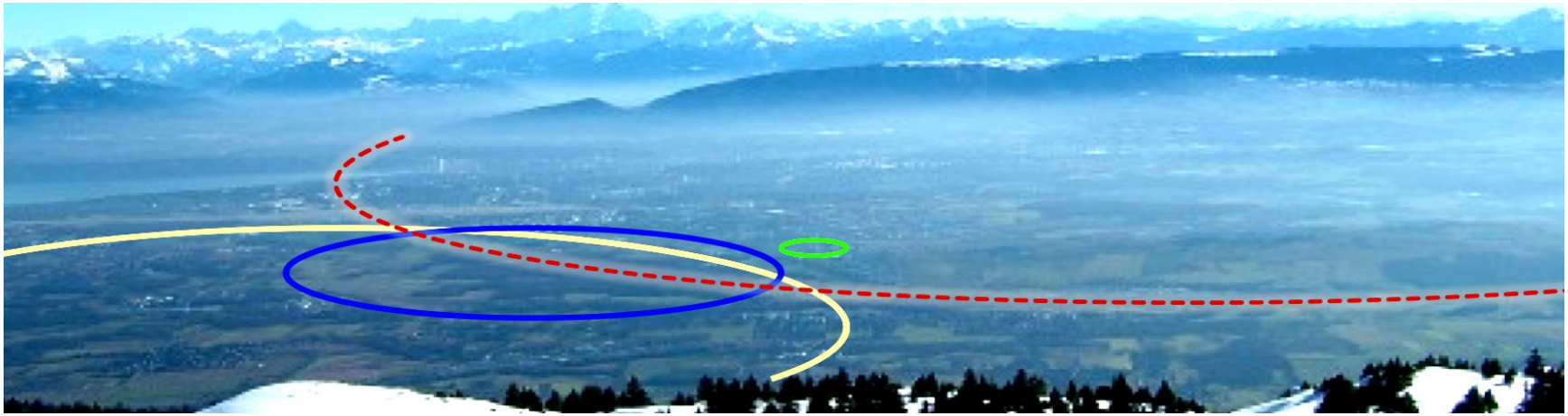


- 100 km ring, Nb_3Sn 16 T magnets, LHC used as injector:
  - pp at $\sqrt{s}$=100 TeV, L~2×10^{35}, L_{int} ~ 1 ab^{-1}/yr (also pPb & PbPb at $\sqrt{s}$=39–63 TeV)
  - e^+e^- option (before pp) at $\sqrt{s}$=90–350 GeV L~10^{35}–$4\cdot10^{36}$, L_{int}=1–90 ab^{-1}/yr for H, Z
  - e-h option at $\sqrt{s}$=3.5 TeV, L~10^{34} L_{int} ~ 0.1 ab^{-1}/yr. (also e-Pb at $\sqrt{s}$~1–3 TeV)



CERN FCC-ee project

- FCC European Design Study, ongoing CDR (expected by mid 2018)



- e^+e^- option (before pp) at √s = **90**, 125, 160, **240**, 350 GeV

$\sqrt{s}$ (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
# of light-q jets/year:	$\mathcal{O}(10^{12})$	–	$\mathcal{O}(10^{7})$	$\mathcal{O}(10^{6})$	–	–
# of gluon-jets/year:	$\mathcal{O}(10^{11})$	$\mathcal{O}(10^{3})$	$\mathcal{O}(10^{6})$	$\mathcal{O}(10^{5})$	–	$\mathcal{O}(10^{3})$
# of heavy-Q jets/yr:	$\mathcal{O}(10^{12})$	$\mathcal{O}(10^{4})$	$\mathcal{O}(10^{7})$	$\mathcal{O}(10^{6})$	$\mathcal{O}(10^{5})$	$\mathcal{O}(10^{4})$

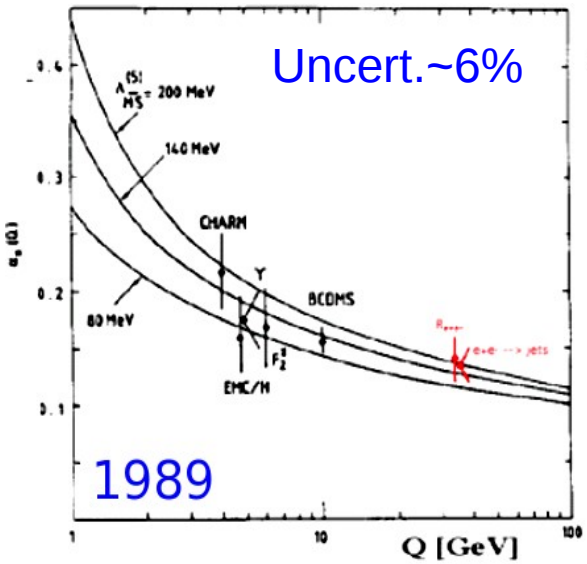
QCD = crucial SM sector at future e^+e^- colliders

- Though QCD is *not per se* the main driving force behind e^+e^- machines, QCD is crucial for many measurements (signals & backgrounds):
  - High-precision α_s: Affects SM fits/tests, all hadronic decays,...
  - N^nLO corrs., N^nLL resummations: Needed for all precise QCD final states
  - Heavy-Quark/Quark/Gluon separation, subjet structure, boosted topologies,...: Needed for all precision measurements & searches with final jets.
  - Non-perturbative QCD: Colour reconnection affects e^+e^- jetty final-states: $e^+e^- \to WW \to 4j$, $Z \to 4j$, $t\bar{t}$ (m_{top} extraction)
  - …
- I will cover a few of the ongoing dedicated QCD studies:
  - FCC (ee): Multiple studies under investigation.
    (SppC/CEPC: Similar possibilities as FCC:not investigated, also lower lumi)
  - ILC (GigaZ option): α_s determination.
  - CLIC: photon-photon QCD physics (e.g. γ structure function).

  (There exist a few possibilities at Belle-II and other low-$\sqrt{s}$ e^+e^- machines)

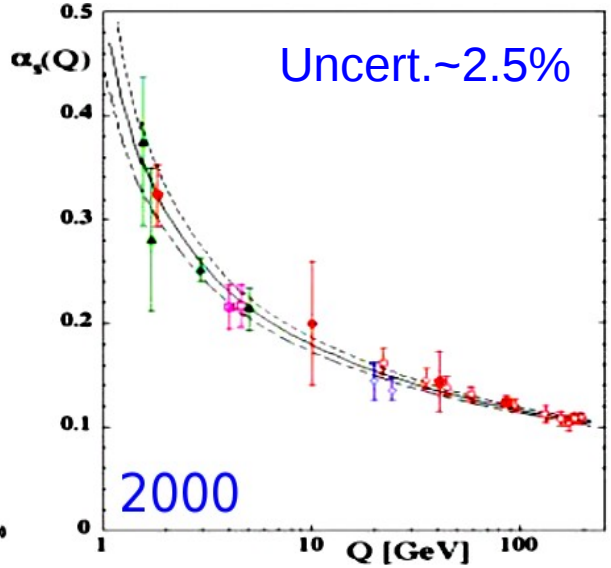
QCD coupling α_s

- Determines strength of the strong interaction between quarks & gluons.
- Single free parameter in QCD in the $m_q \to 0$ limit.
- Determined at a ref. scale ($Q=m_Z$), decreases as $\alpha_s \sim \ln(Q^2/\Lambda^2)^{-1}$, $\Lambda \sim 0.2$ GeV



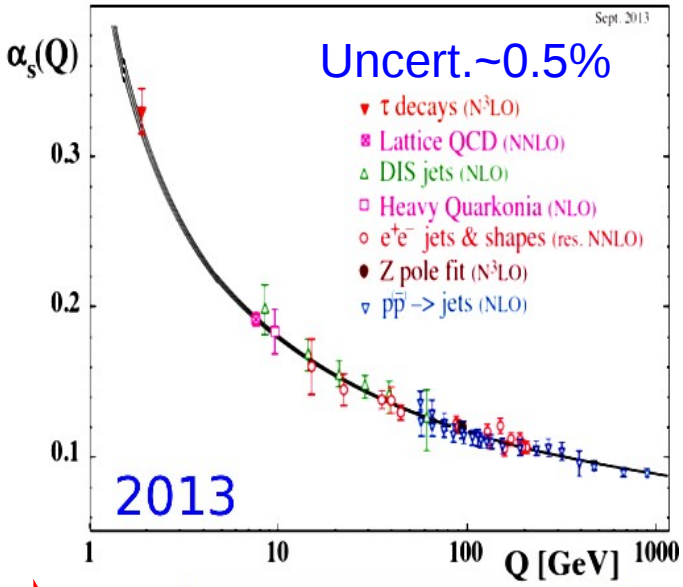
$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

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



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

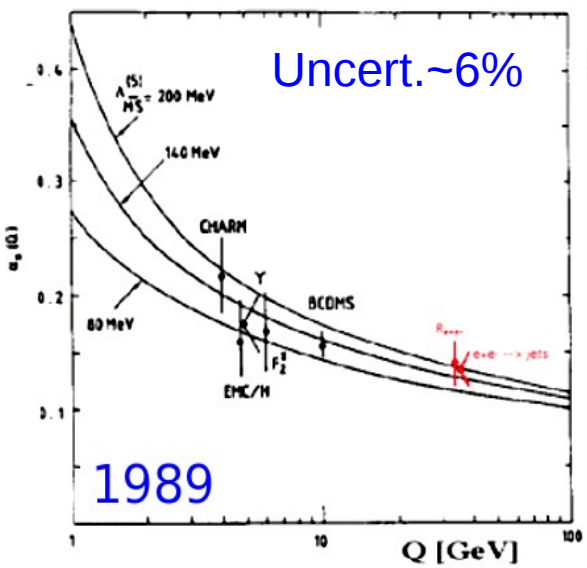
S. B. , J. Phys. G 26, 2000

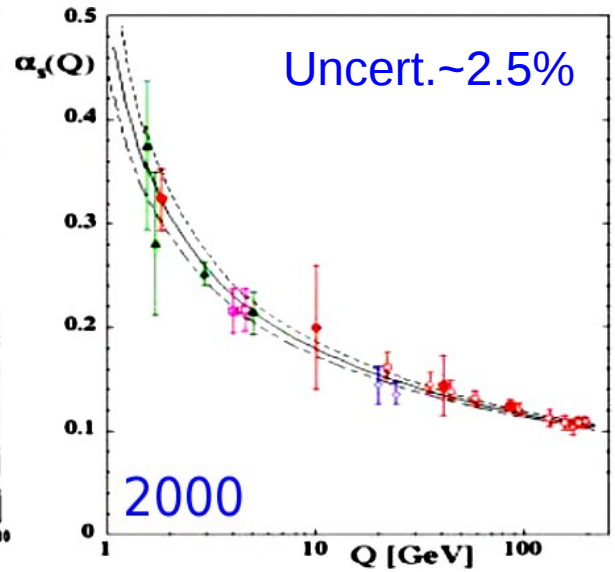


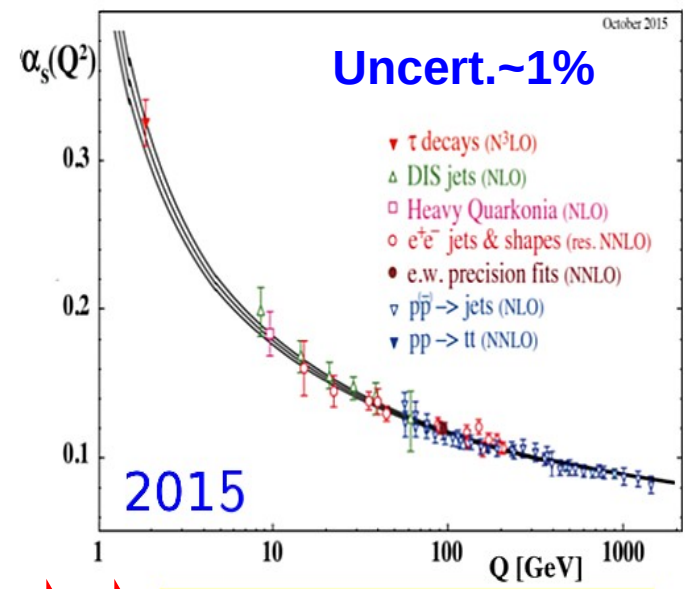
$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (NNLO)

QCD coupling α_s

- Determines strength of the strong interaction between quarks & gluons.
- Single free parameter in QCD in the $m_q \to 0$ limit.
- Determined at a ref. scale ($Q=m_Z$), decreases as $\alpha_s \sim \ln(Q^2/\Lambda^2)^{-1}$, $\Lambda \sim 0.2$ GeV







$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO) → $\alpha_s(M_Z) = 0.1184 \pm 0.0031$ (NNLO) → $\alpha_s(M_Z) = 0.1181 \pm 0.0013$ **(NNLO)**

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

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

- Least precisely known of all interaction couplings !

$$\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_s \sim 10^{-3}$$

Importance of the QCD coupling α_s

- Impacts all QCD x-sections & decays (H), precision top & parametric EWPO:

Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	$\pm$ 3.7	-6.2 +7.4	-2.61 + 0.32
ttH	0.611	$\pm$ 3.0	$\pm$ 8.9	-9.3 + 5.9

Channel	M_H[GeV]	$\delta\alpha_s(\%)$	Δm_b	Δm_c
$H \to c\bar{c}$	126	$\pm$ 7.1	$\pm$ 0.1%	$\pm$ 2.3 %
$H \to gg$	126	$\pm$ 4.1	$\pm$ 0.1%	$\pm$ 0 %

Msbar mass error budget (from threshold scan)

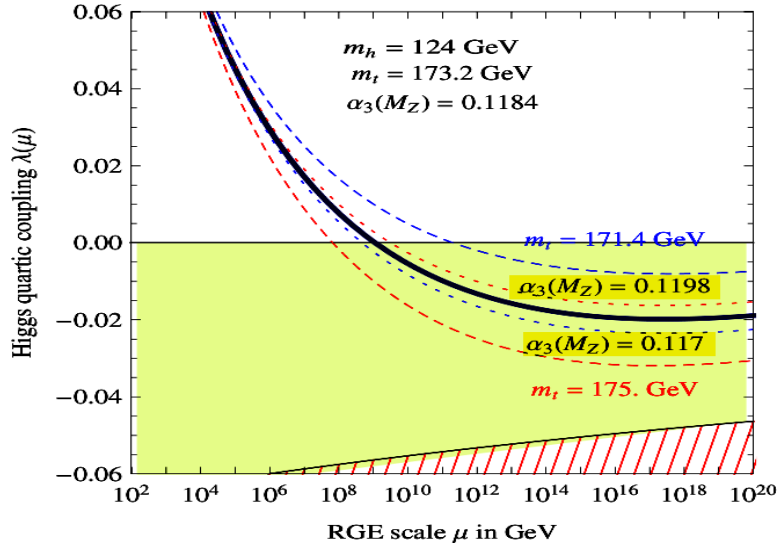
$(\delta M_t^{SD-low})^{exp}$	$(\delta M_t^{SD-low})^{theo}$	$(\delta\overline{m}_t(\overline{m}_t))^{conversion}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

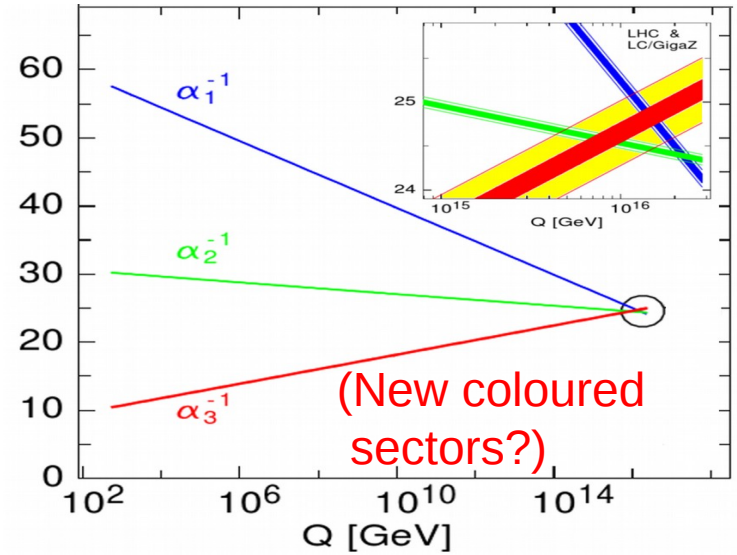
$\Rightarrow$ improvement in α_s crucial $\delta\alpha_s(M_z) = 0.001$

Quantity	FCC-ee	future	param.unc. Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b [10^{-5}]	6	< 1	$\delta\alpha_s$
R_ℓ [10^{-3}]	1	1.3	$\delta\alpha_s$

Sven Heinemeyer – 1st FCC physics workshop, CERN, 17.01.2017

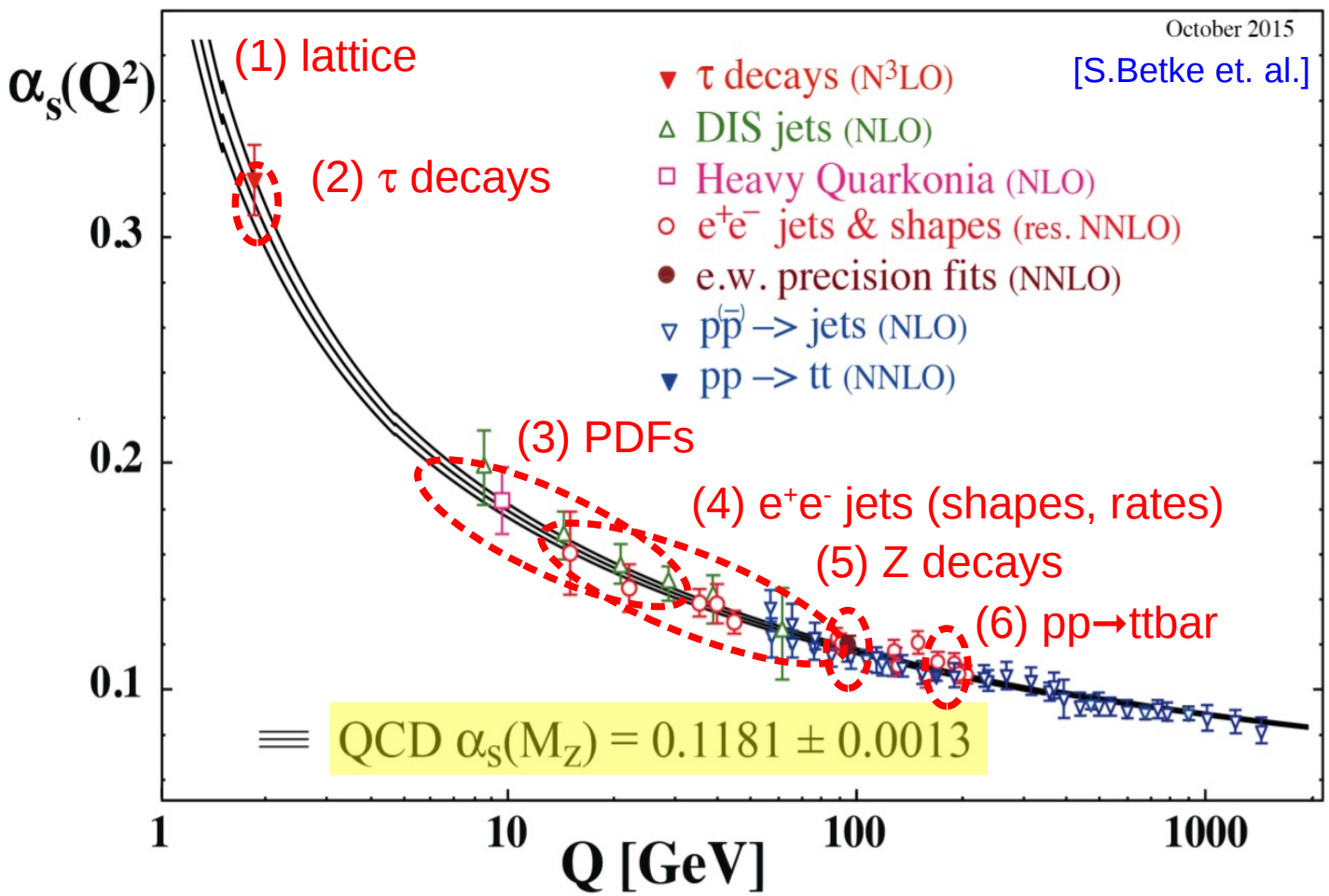
- Impacts physics approaching Planck scale: EW vacuum stability, GUT





World α_s determination (PDG 2016)

- Determined today by comparing 6 experimental observables to pQCD NNLO,N^{3}LO predictions, plus global average at the Z pole scale:



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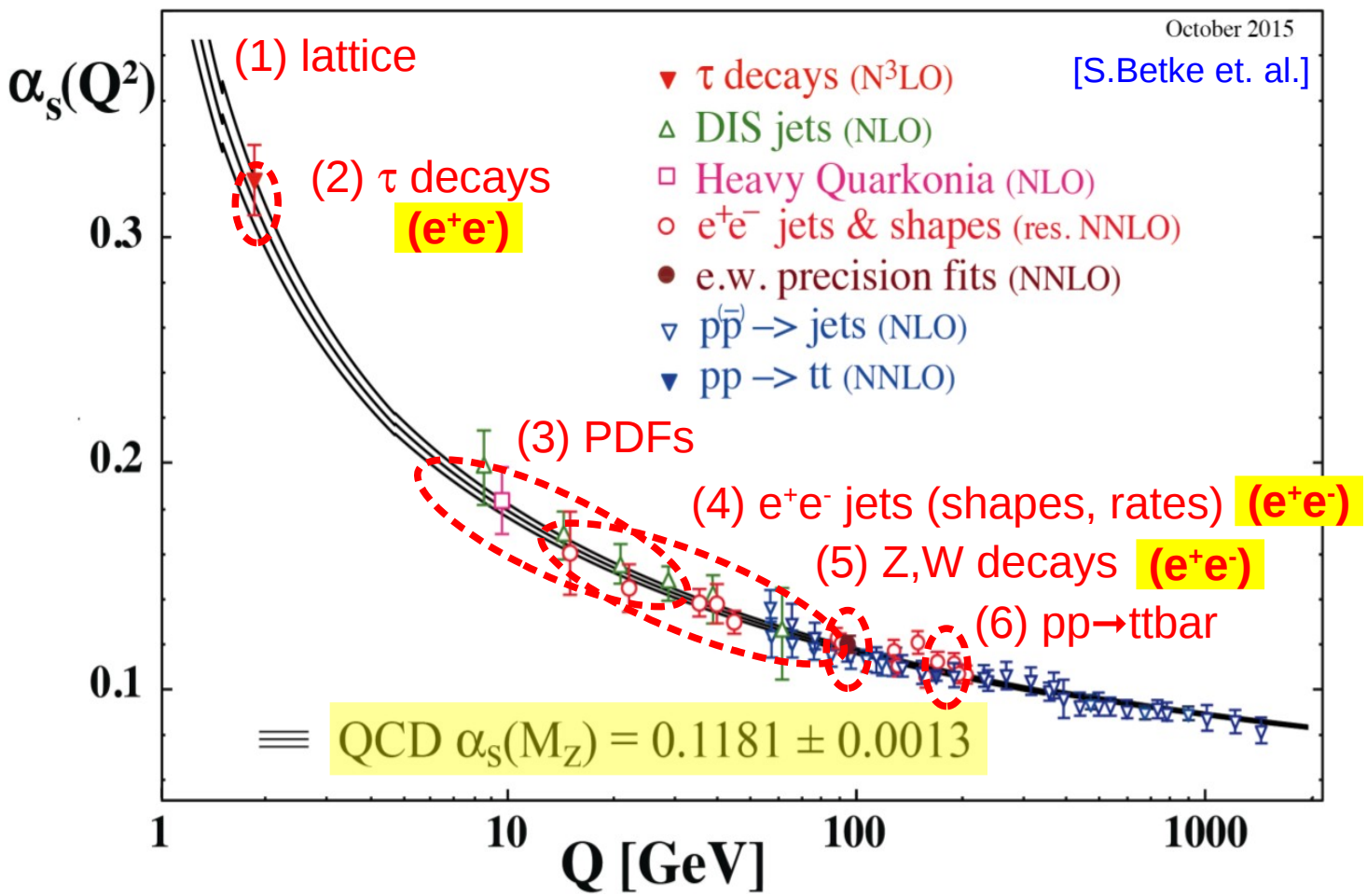
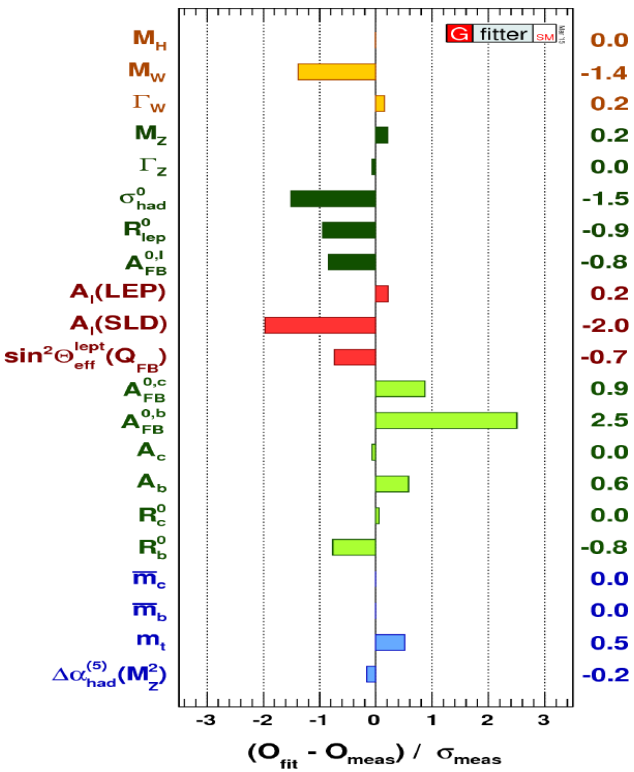
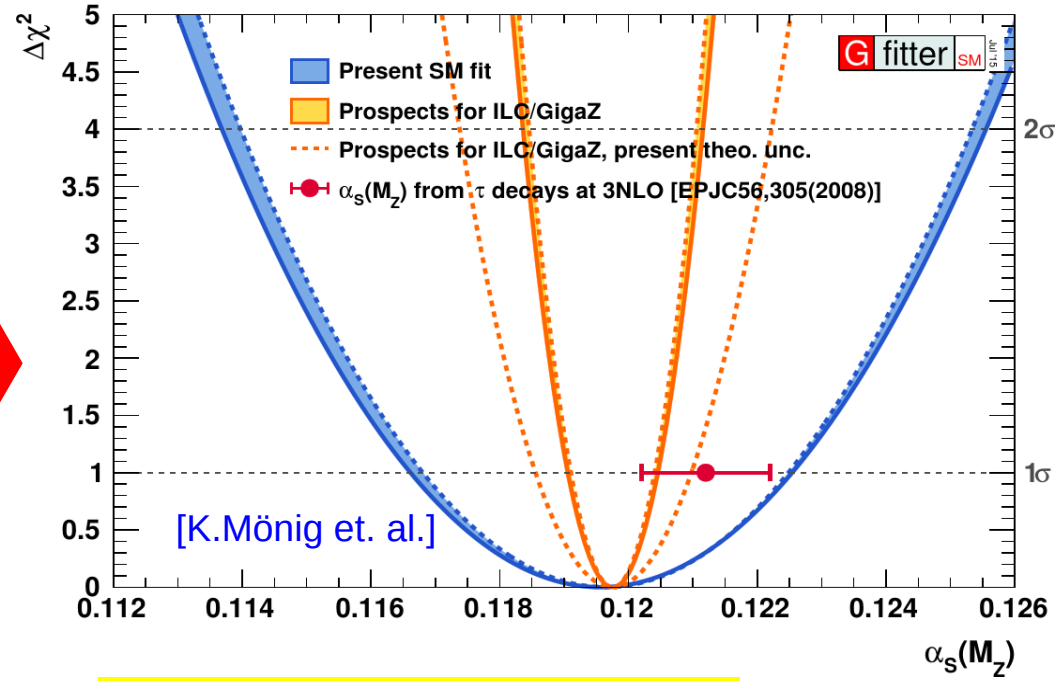


α_s via hadronic Z decays

- Computed at N³LO: $R_Z \equiv \frac{\Gamma(Z\to \mathrm{h})}{\Gamma(Z\to l)} = R_Z^{\mathrm{EW}} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\mathrm{m}} + \delta_{\mathrm{np}})$
- LEP: Γ_Z = 2.4952±0.0023 GeV (±0.1%), $R_\ell^0 = \frac{\Gamma_{\mathrm{had}}}{\Gamma_\ell}$, $\sigma_{\mathrm{had}}^0 = \frac{12\pi}{m_Z}\frac{\Gamma_e\Gamma_{\mathrm{had}}}{\Gamma_Z^2}$, $\sigma_\ell^0 = \frac{12\pi}{m_Z}\frac{\Gamma_\ell^2}{\Gamma_Z^2}$

After Higgs discovery, α_s can be directly determined from full fit of SM:





$\alpha_s(M_Z)$ = 0.1196 ± 0.0030 (±2.5%)

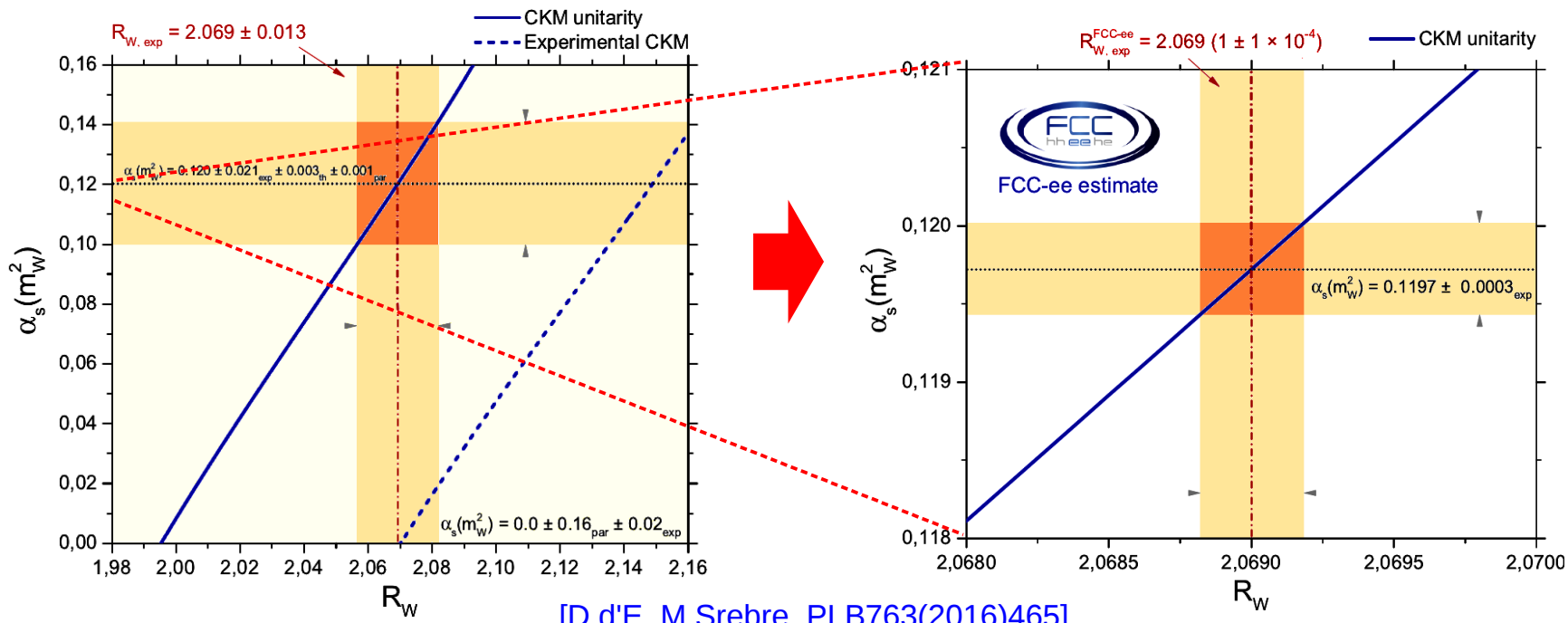
- FCC-ee: – Z stats (×10⁵ LEP) will lead to: **$\delta\alpha_s$ < 0.2%**
  – TH uncertainties: $\sin^2\theta_{eff}$, m_W, m_{top}

α_s via hadronic W decays

- Computed at $N^{2,3}LO$: $\Gamma_{W,had} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_s}{\pi}\right)^k + \delta_{electroweak}(\alpha) + \delta_{mixed}(\alpha\alpha_s)\right]$
- LEP: Γ_W = 1405±29 MeV (±2%), BR_W = 0.6741±0.0027 (±0.4%)

  Extraction with large exp. & parametric (CKM V_{cs}) uncertainties today:

$\alpha_s(M_z) = 0.117 \pm 0.040$ **(±35%)**



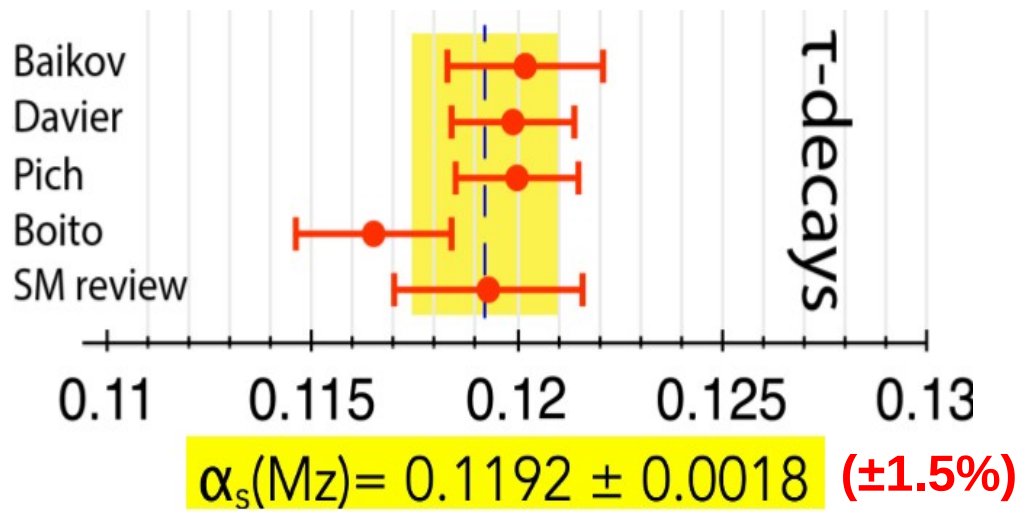
[D.d'E, M.Srebre, PLB763(2016)465]

- FCC-ee: – Huge W stats (×10^4 LEP) will lead to: **$\delta\alpha_s$ < 0.3%**
  – TH uncertainty: $|\delta V_{cs}|$ to be significantly improved (10^{-4})

α_s from hadronic τ-lepton decays

- Computed at N^{3}LO: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\rm EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\rm np})$
- Experimentally: $R_{\tau,\rm exp}$ = 3.4697 ± 0.0080 (±0.23%)
- Various pQCD approaches (FOPT vs CIPT) & treatment of non-pQCD contributions, yield different results.

  Uncertainty slightly increased: 2013 (±1.3%) → 2015 (±1.5%)



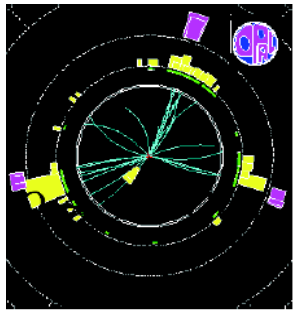
- Future prospects:
  - Better understanding of FOPT vs CIPT differences.
  - Better spectral functions needed (high stats & better precision): B-factories (BELLE-II)
  - High-stats: $\mathcal{O}(10^{11})$ from Z($\tau\tau$) at FCC-ee(90) (less Giga-Z): $\delta\alpha_s < 1\%$

α_s via e^+e^- jet event shapes & rates

- Computed at $N^{2,3}LO+N^{(2)}LL$ accuracy.
- LEP data for thrust, C-parameter, jet shapes, 3-jet x-sections

$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

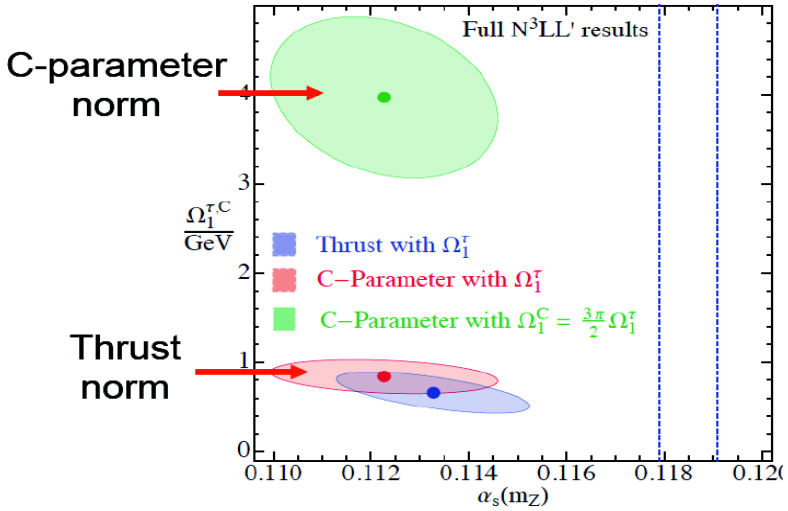
$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$

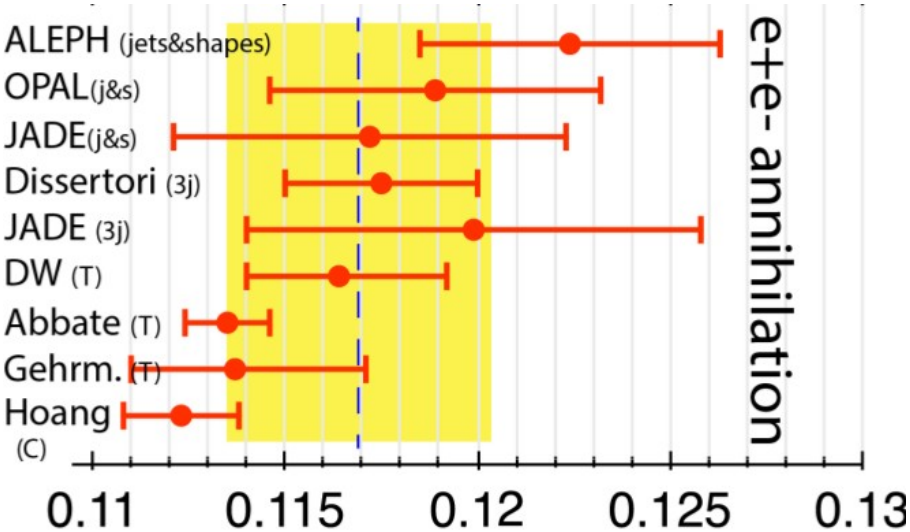


OPAL 3 jet event

Results sensitive to non-pQCD (hadronization) accounted for via MCs or analytically:

[S.Kluth et al., A.Hoang et. al.]





$\alpha_s(M_Z) = 0.1169 \pm 0.0034$ **(±2.9%)**

- FCC-ee:
  - Higher-√s data needed for rates (lower-√s for shapes): **$\delta\alpha_s < 1\%$**
  - TH uncert.: Jet rates with improved (NNLL or N^3LL) resummation

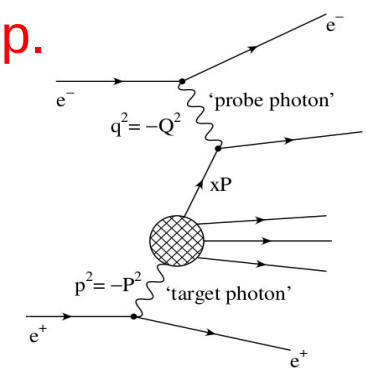
α_s from γ QCD structure function

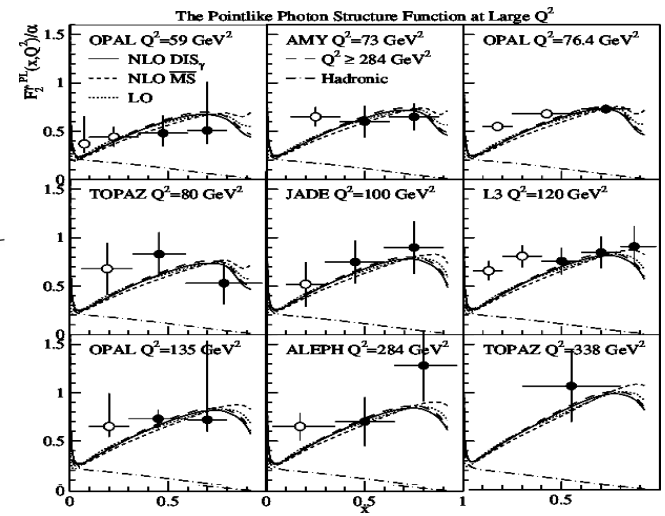
- Computed at NNLO: $$\int_0^1 dx F_2^\gamma(x,Q^2,P^2) = \frac{\alpha}{4\pi}\frac{1}{2\beta_0}\left\{\frac{4\pi}{\alpha_s(Q^2)}c_{LO} + c_{NLO} + \frac{\alpha_s(Q^2)}{4\pi}c_{NNLO} + \mathcal{O}(\alpha_s^2)\right\}$$
- Poor $F^2_\gamma(x,Q^2)$ experimental measurements:
- Extraction (NLO) with large exp. uncertainties today:

$$\alpha_s(M_z) = 0.1198 \pm 0.0054$$

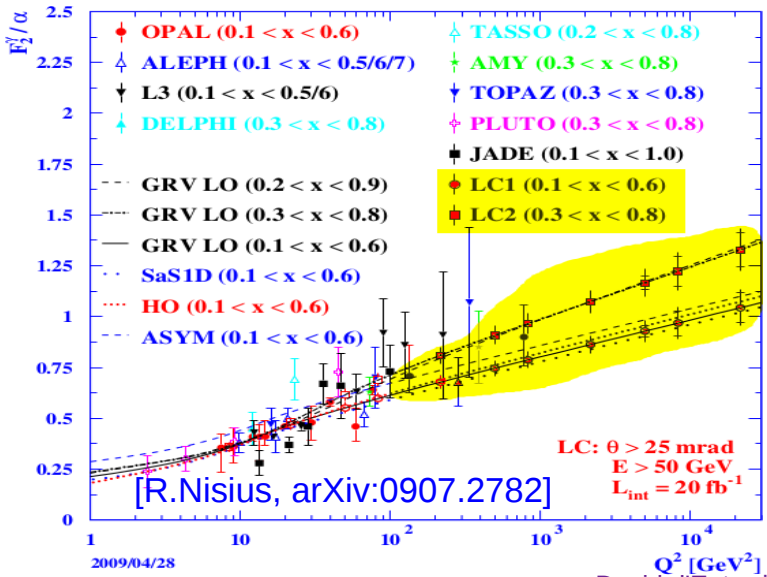
(±4.5%)

[M.Klasen et al. PRL89 (2002)122004]





- Future prospects:
  - Better data badly needed.
  - Belle-II ?
  - Dedicated studies at ILC exist:
  - Huge $\gamma\gamma$ (EPA) stats at FCC-ee will lead to: $\delta\alpha_s < 1\%$

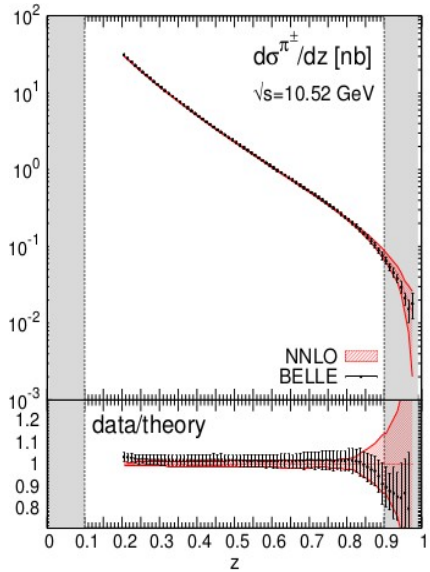


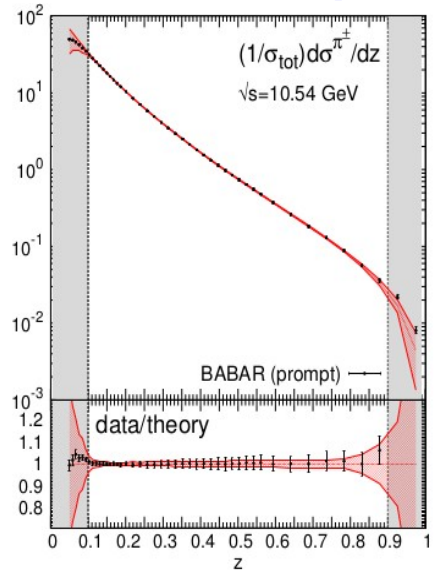
[R.Nisius, arXiv:0907.2782]

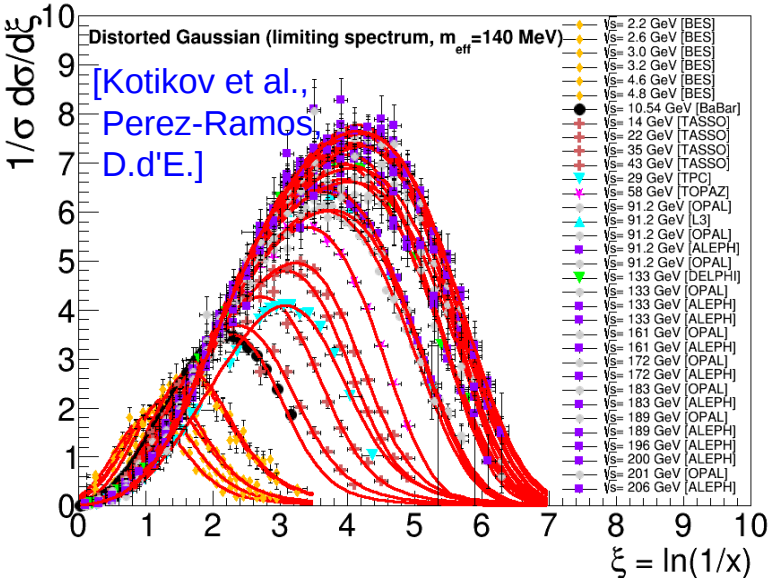
High-precision parton FFs & hadronization

- Parton-to-hadron fragmentation functions known at NNLO at high-z & at NNLO*+NNLL at low-z:

[D.Anderle et al., A.Vossen et al., B.Kniehl et al., V.Bertone et al., N.Sato et al., D.deFlorian et al.,...]

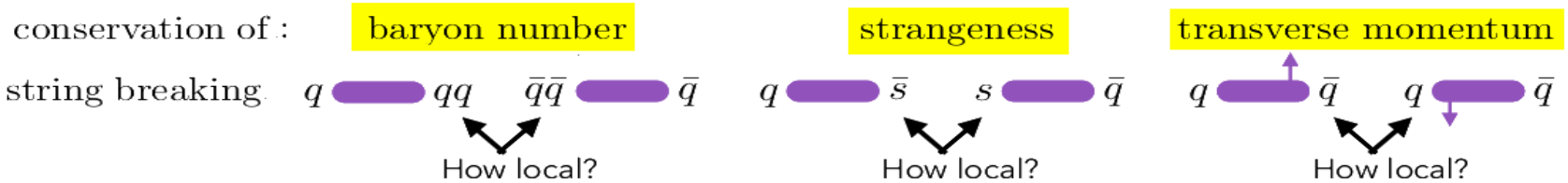






➧ FCC-ee (much broader z range) allow for α_s extraction with **$\delta\alpha_s$ < 1%**

- High-precision PID'd hadrons allow for detailed non-pQCD studies: baryon & strangeness production, Bose-Einstein and Fermi-Dirac final-state correlations, colour string dynamics (spin effects, helix,...):

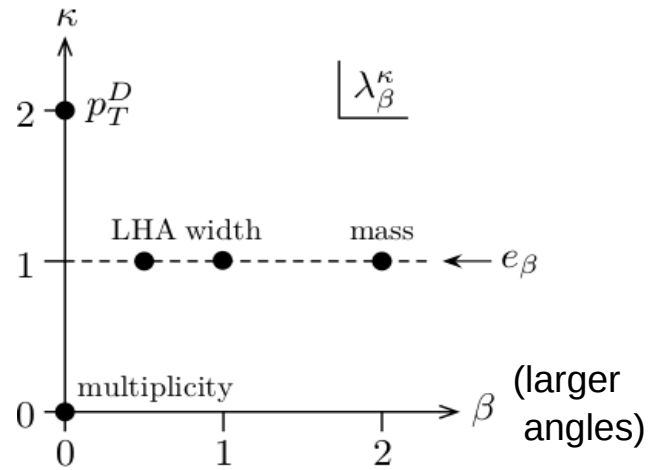


High-precision jet substructure (angularities)

- State-of-the-art jet substructure studies based on IR-safe angularities variables: jet multiplicity, mass, shapes (thrust, C-param., broadening),... Computable (N^nLO+N^nLL) via SCET (clean data needed to control non-pQCD corrs.)

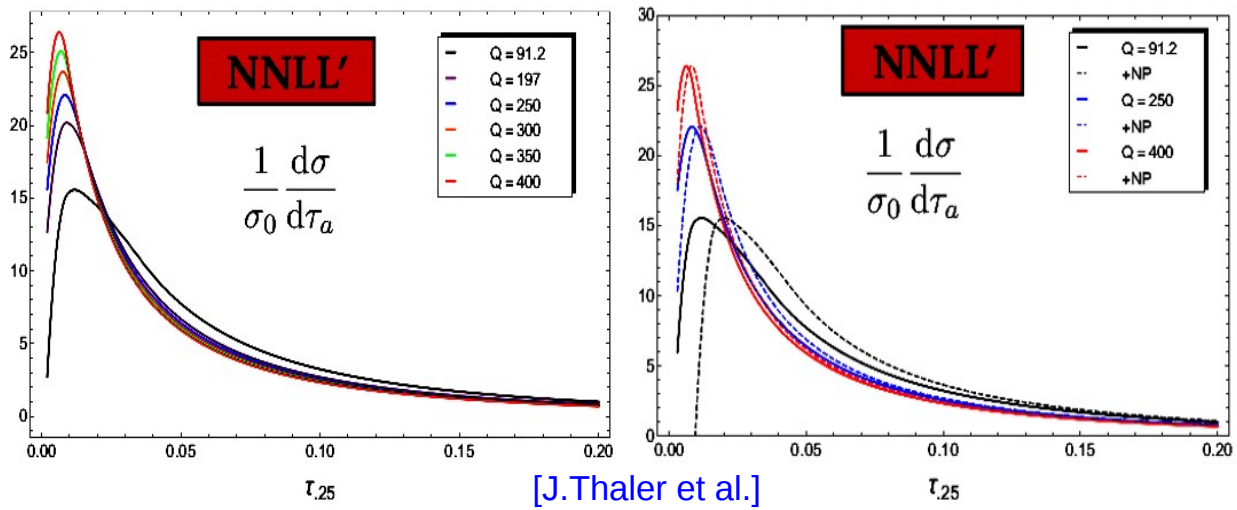
$$\lambda_\alpha^\kappa = \frac{1}{E_{\rm jet}^\kappa R^\alpha} \sum_{i\in{\rm jet}} E_i^\kappa \Delta R_i^\alpha$$

(normalized $E^n \times \theta^n$ products)

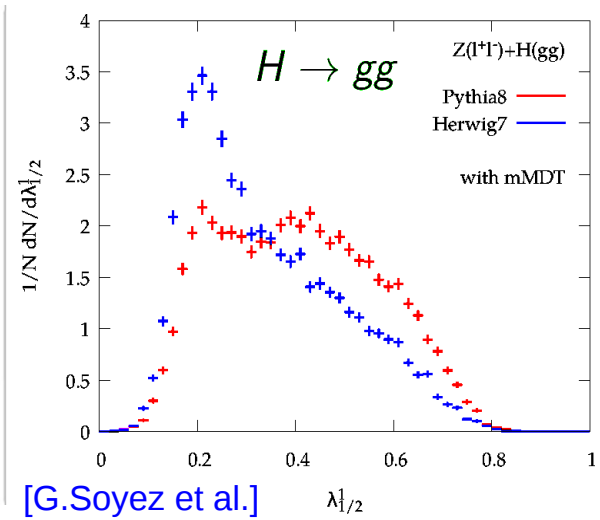


[Larkoski, Salam, Thaler, 13]
[Larkoski, Thaler, Waalewijn, 14]

- High-stats & high-precision (clean) jet structure at FCC-ee energies:



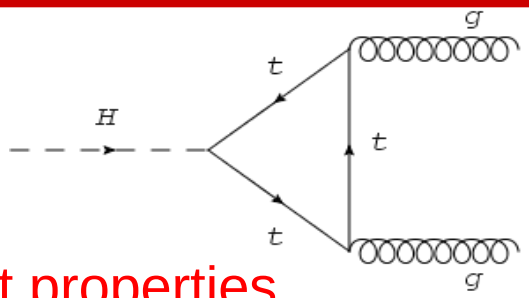
[J.Thaler et al.]



[G.Soyez et al.]

High-precision g-jet studies via $e^+e^- \to H(gg)+X$

- FCC-ee H(gg) is a "pure gluon" factory:
  $H \to gg$ (BR~10% accurately know) provides O(200.000) extra-clean digluon events:
  - ➧ High-precision study of gluon radiation & g-jet properties



G. Soyez, K. Hamacher, G. Rauco, S. Tokar, Y. Sakaki

Handles to split degeneracies

H→gg vs Z→qq

Rely on good **H→gg vs H→bb** separation; mandated by Higgs studies requirements anyway?

Z→bbg vs Z→qq(g)

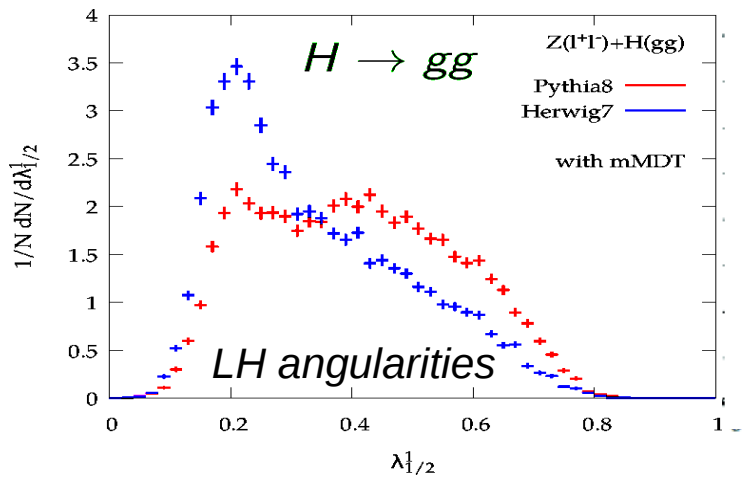
g in one hemisphere recoils against two b-jets in other hemisphere: **b tagging**

Vary jet radius: small-R → calo resolution

(R ~ 0.1 also useful for jet substructure)

Vary E_{CM} range : below m_Z : radiative events → **forward** boosted

(also useful for FFs & general scaling studies);
Scaling is **slow**, logarithmic → large lever arm



- Check N^nLO antenna functions
- Improve q/g/Q discrim.tools (BSM)
- Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
- Colour reconnection? Glueballs ?
- Leading η's,baryons in g jets?

Colour reconnection in multi-jet final states

- Colour reconnection among partons in e^+e^- = Source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states: $e^+e^- \to WW(4j)$, $Z(4j)$, tt
- Use e^+e^- leptonic final-states to learn about CR:

At LEP 2: hot topic (by QCD standards): **'string drag' effect on W mass**

Non-zero effect convincingly demonstrated at LEP-2

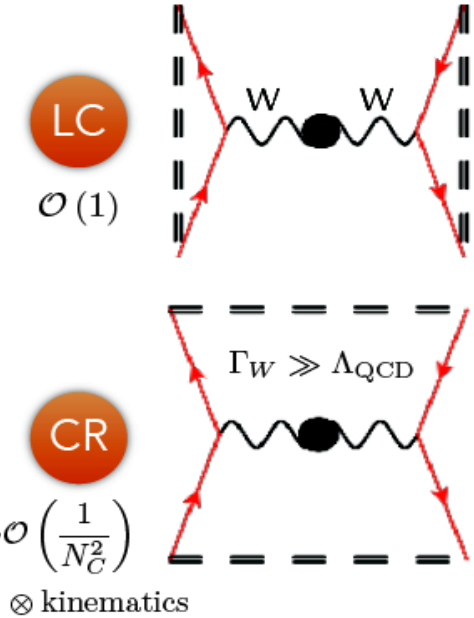
No-CR excluded at 99.5% CL [Phys.Rept. 532 (2013) 119]

But not much detailed (differential) information

Thousand times more WW at FCC-ee

Sjöstrand: turn the W mass problem around; use huge sample of semi-leptonic events to measure m_W

→ use as constraint to measure CR in hadronic WW



Has become even hotter topic at LHC

It appears jet universality is under heavy attack.
Fundamental to understanding & modeling hadronisation

Follow-up studies now underway at LHC.

T. Sjöstrand, W. Metzger, S. Kluth, C. Bierlich

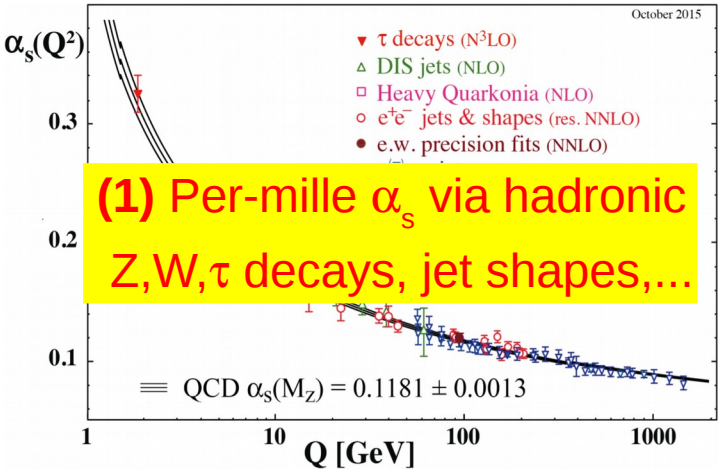
High-stats ee → other side of story

Also relevant in (hadronic) ee→tt, and Z→4 jets

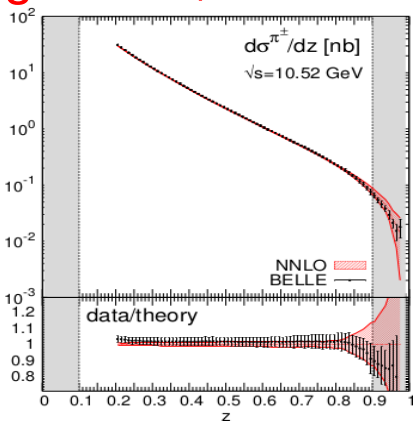
+ Overlaps → interactions?
increased tensions (strangeness)?
breakdown of string picture?

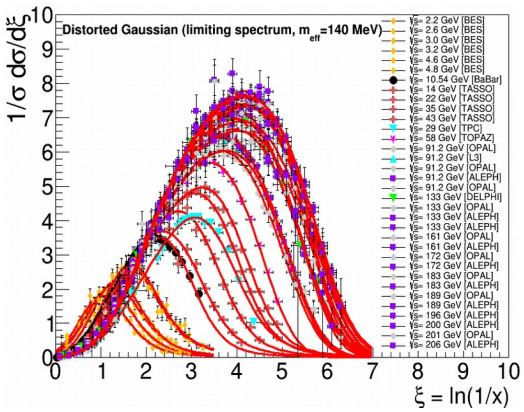
Summary

- The precision required to fully exploit the future ee/pp/ep/eA/AA SM & BSM programs requires exquisite control of (n)pQCD, accessible thanks to multiple, unique, high-stats, clean e^+e^- measurements:



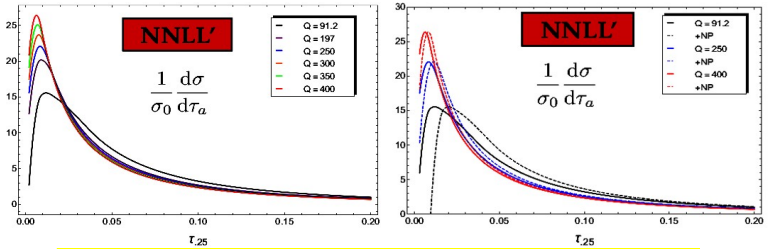
(1) Per-mille α_s via hadronic Z,W,τ decays, jet shapes,...

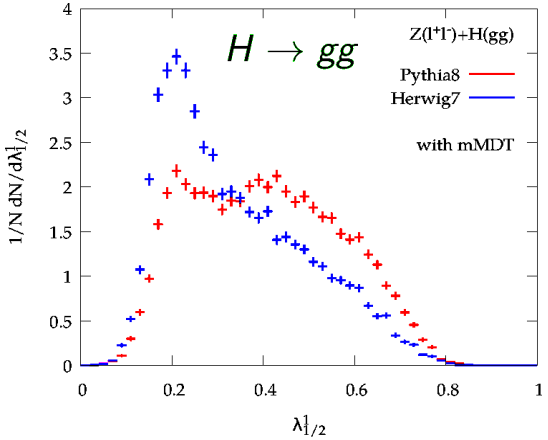


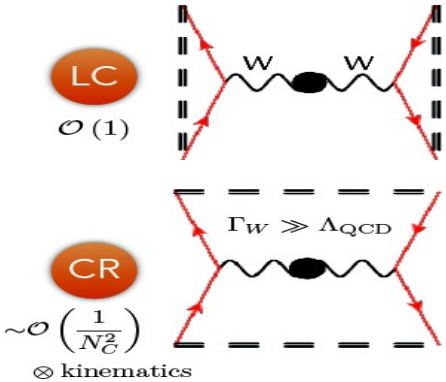


(2) Fragmentation functions at N^nLO+N^nLL

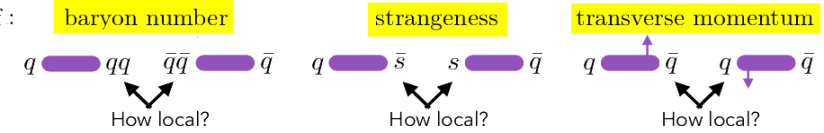
(3) N^nLO+N^nLL jet angularities







(5) High-precision non-pQCD: s, B prod., final-state corrs.,...



(4) High-precision g/q/Q discrimination

(6) <1% control of colour reconnection

Backup slides