High-precision QCD physics at FCC-ee

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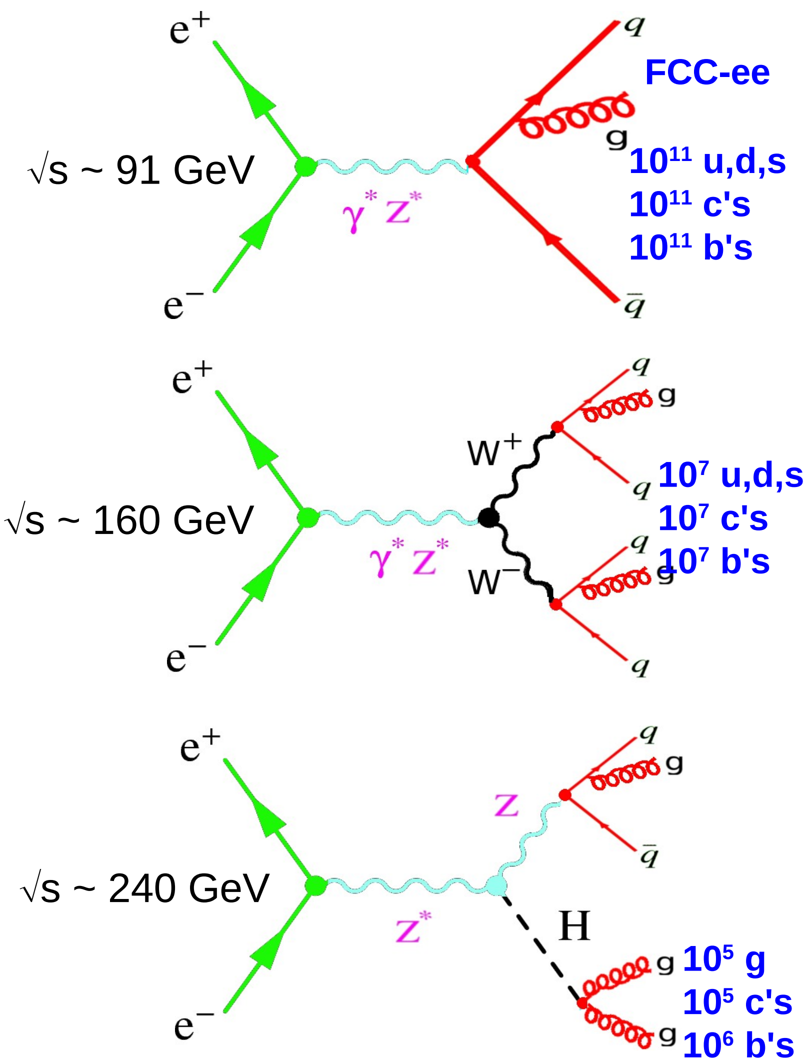
QCD, a key ingredient at future colliders

- QCD is crucial for many ee, pp measurements:
- **High-precision α_S:** affects all x-sections & decays (Higgs, top, etc.)
- **N^{n}LO corrections, N^{n}LL resummations:** affects all pQCD x-sections & decays
- **High-precision PDFs:** affects all precision W,Z,H measurements & all searches in pp collisions
- **Heavy-Quark/Light-Quark/Gluon separation (jet substructure, boosted topologies, etc.):** needed for all precision SM measurement &BSM searches with jets in the final jets
- **Semihard QCD (low-x saturation, multiple parton interactions, etc.):** significant pQCD x-sections at FCC-hh
- **Non-perturbative QCD:** affects final states with jets → colour reconnection, parton hadronization, etc.

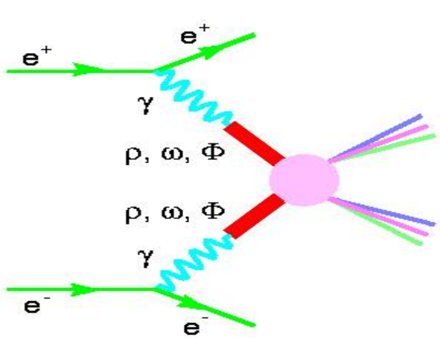
Precision QCD in e^+e^- collisions

- e^+e^- collisions provide an extremely clean environment with fully-controlled initial state to probe quark and gluons dynamics very precisely

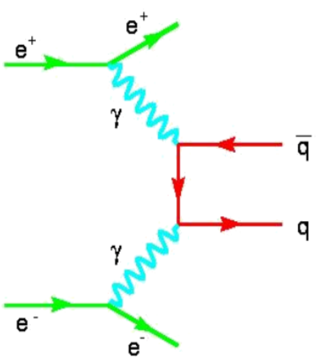


Advantages compared to pp collisions:

- QED initial state with known kinematics
- Controlled QCD radiation (final state)
- Well-defined quarks and gluon jets
- Smaller non-pQCD uncertainties (no PDFs, no QCD underlying events, etc.)
- Direct clean parton fragmentation and hadronization
- QCD physics in $\gamma\gamma$ collisions



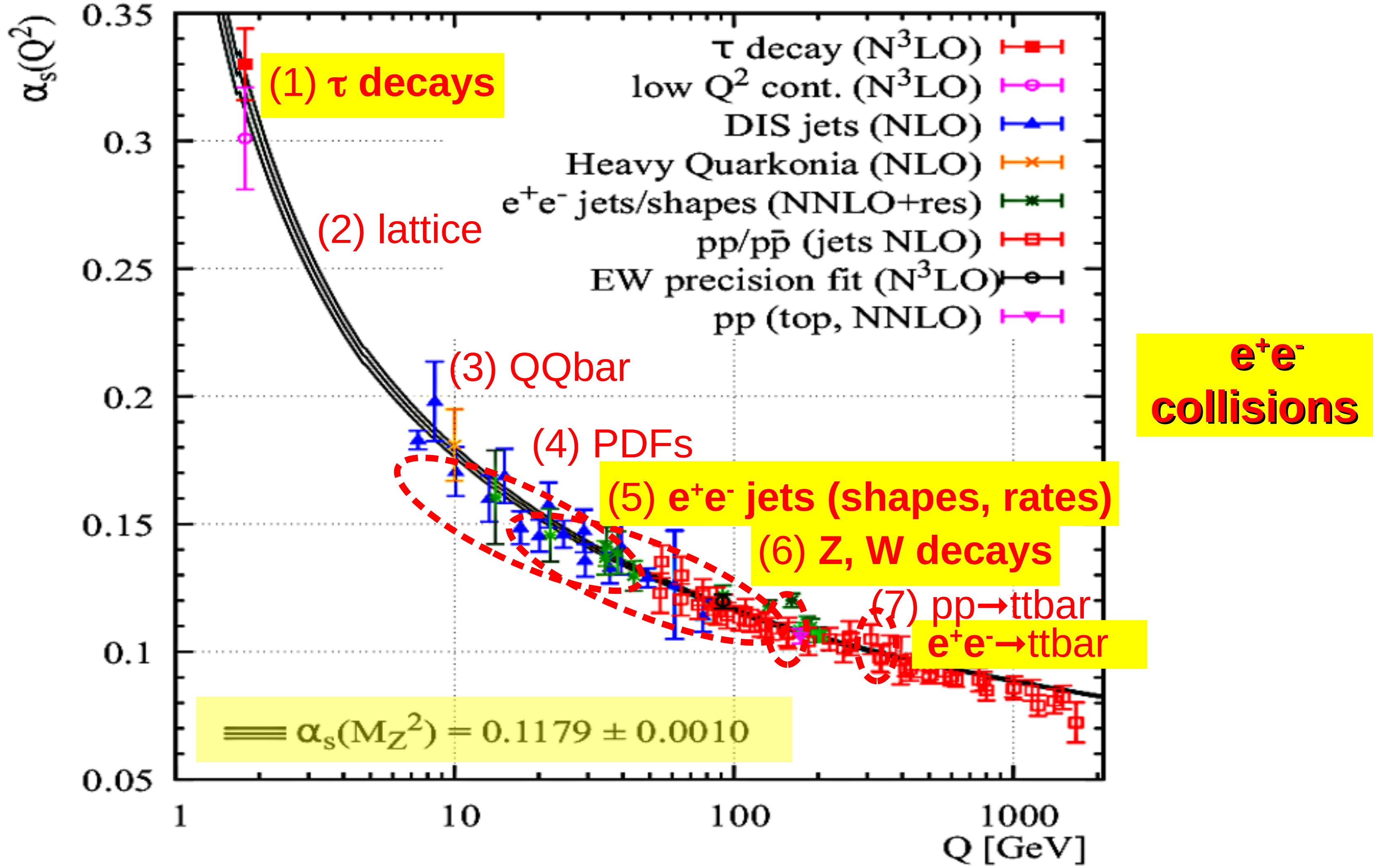
(soft, VDM)



(direct)

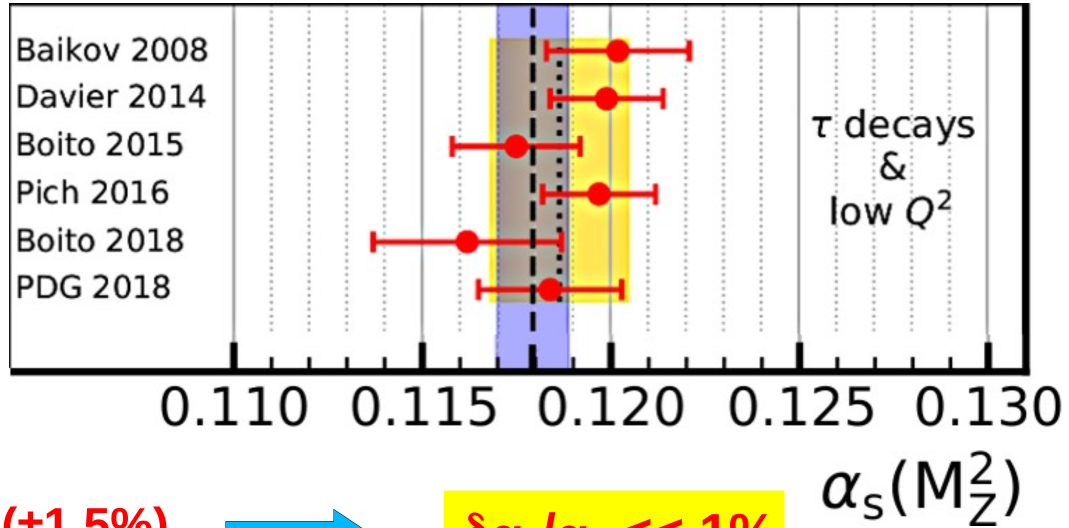
QCD coupling α_S

- Currently determined by comparing 7 experimental observables to pQCD NNLO or N³LO predictions, plus global average at the Z pole scale



α_S from hadronic τ-lepton decays

- Computed at N³LO: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\text{np}})$
- Experimentally we have $R_{\tau,exp} = 3.4697 \pm 0.0080$ ($\pm$0.23%)
- Various pQCD approaches (Fixed Order Perturbation Theory - FOPT - vs Contour Improved Perturbation Theory – CIPT) and treatment of non-pQCD corrections yield different results



$\alpha_s(m_z) = 0.1187 \pm 0.0018$ (±1.5%) → **$\delta\alpha_s/\alpha_s \ll 1\%$**

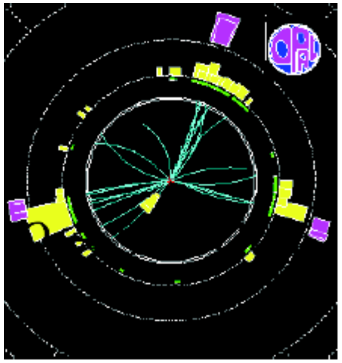
- What next?
  - Theory: better understanding of FOPT vs CIPT differences & need of N⁴LO
  - Better spectral functions needed (better precision)
  - Higher statistics: $\mathcal{O}(10^{11})$ from $Z \to \tau^+\tau^-$ at FCC-ee(90)
  - Extract the τ width from the ultraprecise measurement of its lifetime

α_S from e^+e^- event shapes and jet rates

- Computed at N^2,3LO+N(N)LL accuracy

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

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



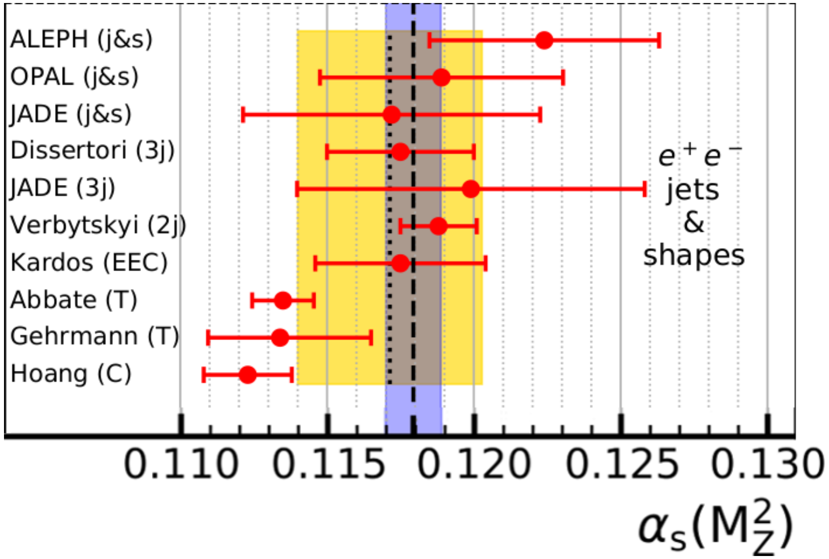
OPAL 3 jet event

- Experimental observables: Thrust, jet shapes, C-parameter, n-jet cross sections

- Results sensitive to non-pQCD e.g. hadronization accounted for via MCs or analytically

$\alpha_s(m_z) = 0.1171 \pm 0.027$ (±2.6%)

$\delta\alpha_s/\alpha_s < 1\%$



- What next?
  - FCC-e^+e^-: Lower $\sqrt{s}$ (ISR) for shapes, higher $\sqrt{s}$ for jet rates
  - Theory: Improved NN(N)LL resummed calculations for rates, hadronization for shapes

α_S from hadronic Z decays (FCC-*ee*)

- α_S extracted at N³LO from:
  - Combined fit of 3 Z pseudo observables
  - Full SM fit (with α_S free parameter)

- The W and Z hadronic widths :

$$\Gamma^{\rm had}_{\rm W,Z}(Q) = \Gamma^{\rm Born}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm EW} + \delta_{\rm mix} + \delta_{\rm np}\right)$$

- The ratio of W, Z hadronic-to-leptonic widths :

$$\mathrm{R_{W,Z}}(Q) = \frac{\Gamma^{\rm had}_{\rm W,Z}(Q)}{\Gamma^{\rm lep}_{\rm W,Z}(Q)} = \mathrm{R^{EW}_{W,Z}}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm mix} + \delta_{\rm np}\right)$$

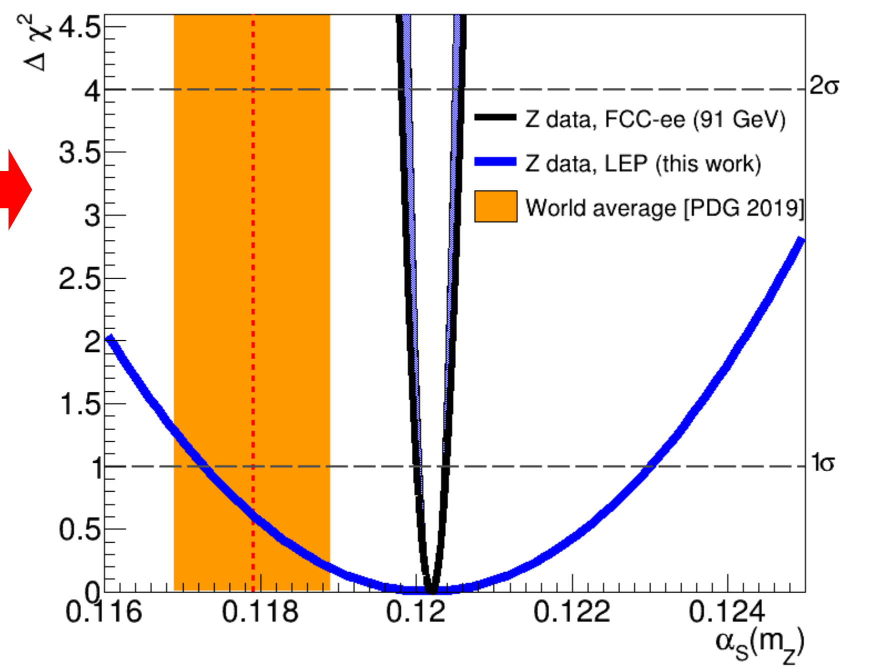
- In the Z boson case, the hadronic cross section at the resonance peak in e^+e^-:

$$\sigma^{\rm had}_{\rm Z} = \frac{12\pi}{m_{\rm Z}} \cdot \frac{\Gamma^e_{\rm Z}\Gamma^{\rm had}_{\rm Z}}{(\Gamma^{\rm tot}_{\rm Z})^2}$$

2005.04545

- **At FCC-*ee*:**
- Huge Z pole statistics (x10⁵ LEP)
- Exquisite systematic precision (stat. uncertainties much smaller)

$$\begin{array}{ll}
\Delta \mathrm{R_Z} = 10^{-3}, & \mathrm{R_Z} = 20.7500 \pm 0.0010 \\
\Delta\Gamma^{\rm tot}_{\rm Z} = 0.1\ \mathrm{MeV}, & \Gamma^{\rm tot}_{\rm Z} = 2495.2 \pm 0.1\ \mathrm{MeV} \\
\Delta\sigma^{\rm had}_{\rm Z} = 4.0\ \mathrm{pb}, & \sigma^{\rm had}_{\rm Z} = 41\,494 \pm 4\ \mathrm{pb} \\
\hline
\Delta m_{\rm Z} = 0.1\ \mathrm{MeV}, & m_{\rm Z} = 91.18760 \pm 0.00001\ \mathrm{GeV} \\
\Delta\alpha = 3\cdot 10^{-5}, & \Delta\alpha^{(5)}_{\rm had}(m_{\rm Z}) = 0.0275300 \pm 0.0000009
\end{array}$$



- Theory uncertainties reduced by a factor of 4 computing missing α_S^5, α^3, $\alpha\alpha_S^2$ and $\alpha^2\alpha_S$ terms
- 20 times times better precision than today: $\frac{\delta\alpha_S}{\alpha_S}$ **~ ±0.2% (tot), ±0.1% (exp)**

$\alpha_s(m_z)$ = 0.12030 ± 0.00014 (±0.1%)

α_S from hadronic W decays (FCC-*ee*)

- α_S extracted from N³LO fit of combined Γ_W, R_W W pseudo observables:

• The W and Z hadronic widths :

$$\Gamma^{\rm had}_{\rm W,Z}(Q) = \Gamma^{\rm Born}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm EW} + \delta_{\rm mix} + \delta_{\rm np}\right)$$

• The ratio of W, Z hadronic-to-leptonic widths :

$$\mathrm{R_{W,Z}}(Q) = \frac{\Gamma^{\rm had}_{\rm W,Z}(Q)}{\Gamma^{\rm lep}_{\rm W,Z}(Q)} = \mathrm{R^{EW}_{W,Z}}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm mix} + \delta_{\rm np}\right)$$

- **At FCC-*ee*:**
- Huge W pole statistics (x10⁴ LEP-2)
- Exquisite systematic precision (stat. uncertainties much smaller)

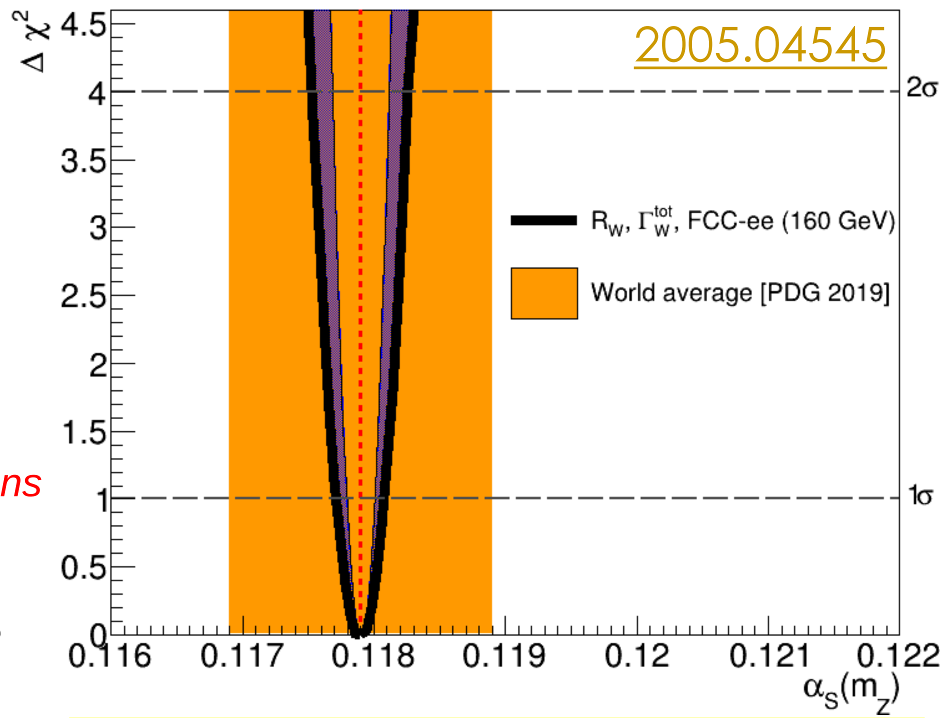
$$\Gamma^{\rm tot}_{\rm W} = 2088.0 \pm 1.2 \text{ MeV}$$

$$\mathrm{R_W} = 2.08000 \pm 0.00008$$

$$m_{\rm W} = 80.3800 \pm 0.0005 \text{ GeV}$$

$$|V_{cs}| = 0.97359 \pm 0.00010$$ *← O(10¹²) D mesons*

- Theory uncertainties reduced by a factor of 10 computing missing α_S^5, α^2, $\alpha^3, \alpha\alpha_S^2$ and $\alpha^2\alpha_S$ terms
- 150 times times better precision than today!

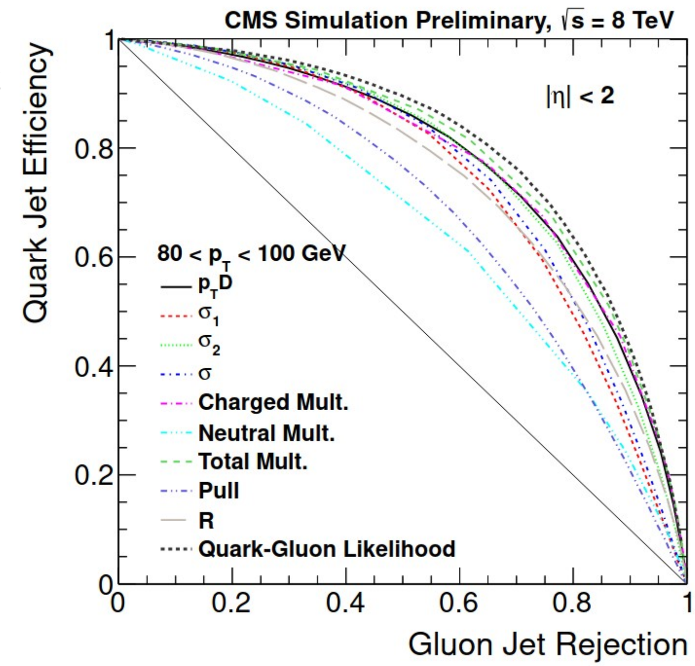


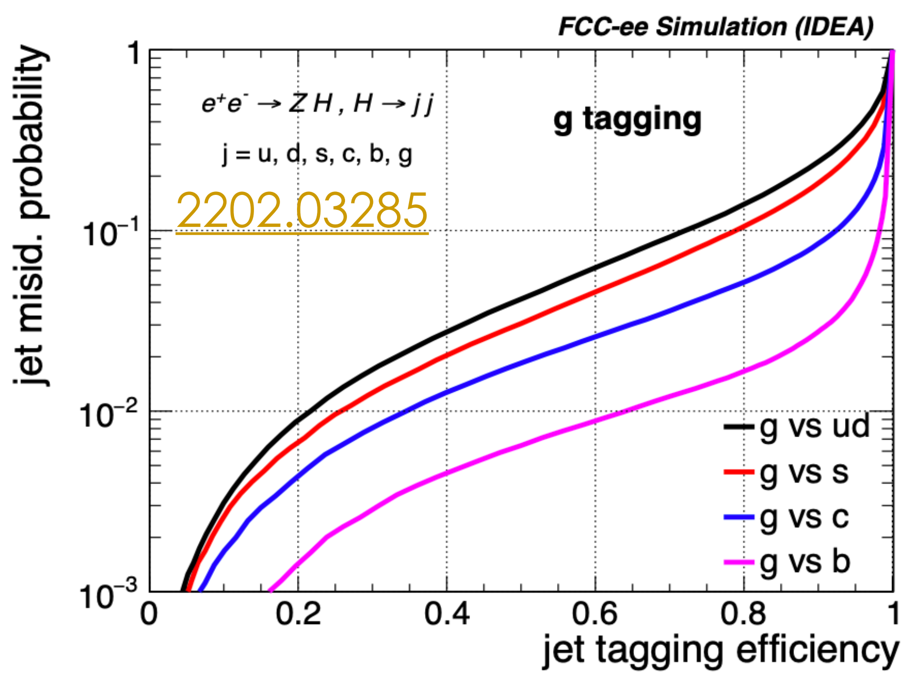
$\alpha_s(m_z)$ = 0.11790 ± 0.00023 (±0.2%)

Quark-gluon discrimination

1409.3072

- Exciting but challenging prospects in pp collisions
  - Enhance quark signal at hadron colliders
- Several handles exist to separate quark and gluons: 1211.7038
  - Gluons radiate more
  - Spin correlations in subjet location
  - p_T - weighted jet charge



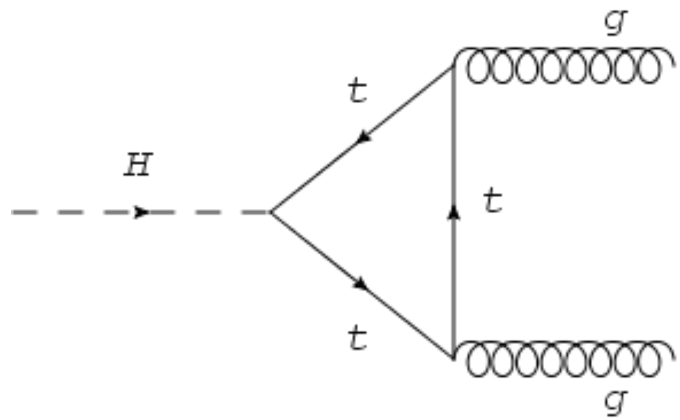


Machine Learning (ML) approaches have already found success!

Rejection of ud jets is the most challenging, due to similar particle displacement and nature

High-precision gluon and quark jet studies

- Exploit FCC-ee $H(gg)$ as a pure gluon factory: $H \to gg$ (BR ~ 8% accurately known) provides 120000 extra clean digluon events

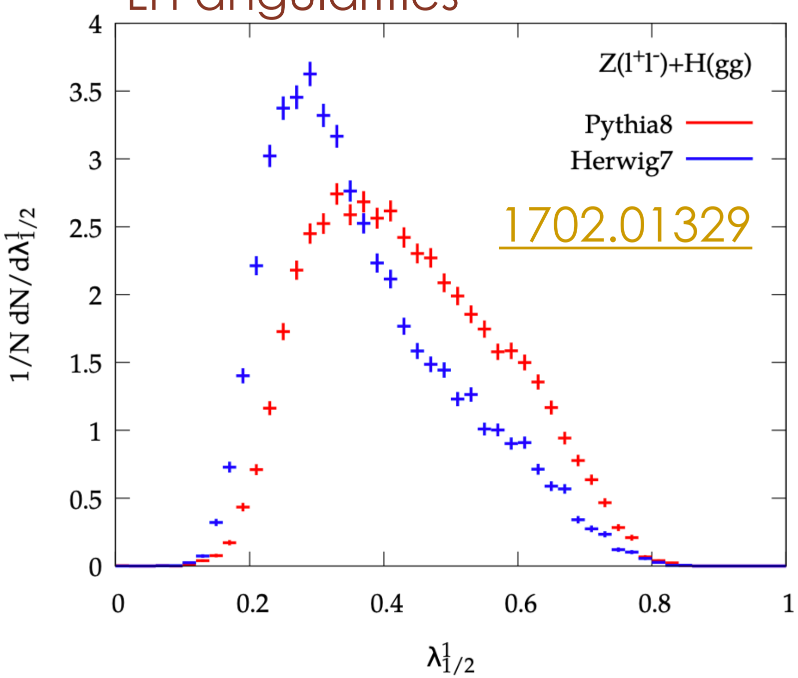


- Multiple handles to study gluon radiation and gluon-jet properties:
  - Gluon vs. quark via $H \to gg$ vs $Z \to q\bar{q}$
  - Gluon vs. quark via $Z \to b\bar{b}g$ vs $Z \to q\bar{q}$

- Multiple high-precision analyses possible:
  - Access to light-quark Higgs Yukawa couplings
  - BSM: Improve q/g/Q discrimination tools
  - pQCD: High-precision QCD coupling
  - non-pQCD: Gluon fragmentation, colour reconnection

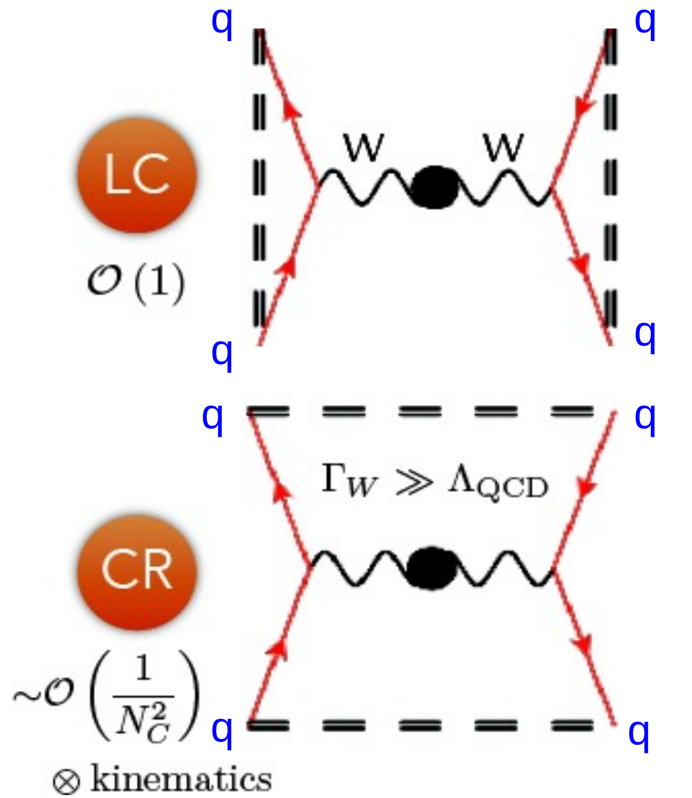
Improved MC tuning

LH angularities



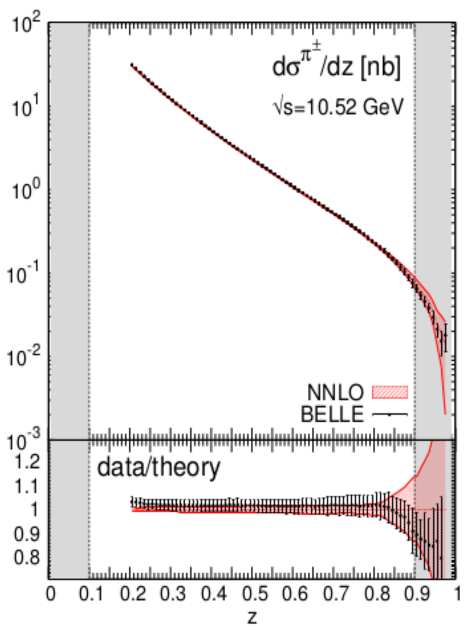
Colour reconnection

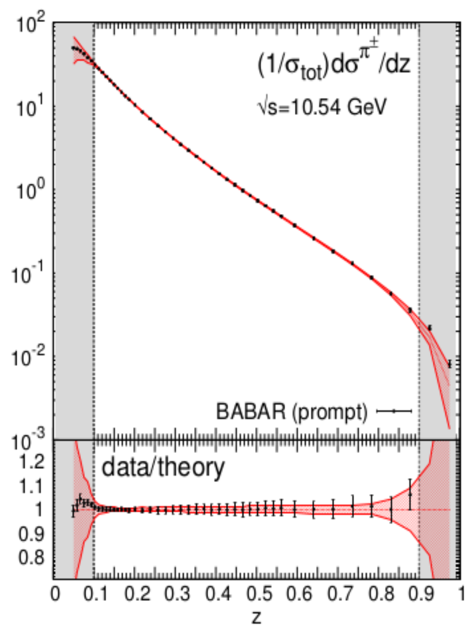
- Colour Reconnection (CR) of partons impacts final state kinematics e.g. shifted angular correlations, invariant mass shifts, etc.
- Exact dynamic poorly understood
- Source of uncertainty in m_W, m_{top}, anomalous Gauge Couplings extractions in multijet final-states
- CR impacts all FCC-*ee* multi-jet final states: $e^+e^- \rightarrow WW(4j), H(2j, 4j), t\bar{t}, \ldots$
- Combined LEP $e^+e^- \rightarrow$ WW(4j) data best described with 49% CR, 2.2σ away from no-CR
- String-drag effect on W mass (hinted at LEP)
- Exploit huge W stats (x10^4 LEP) to measure m_W leptonically & hadronically and constrain CR

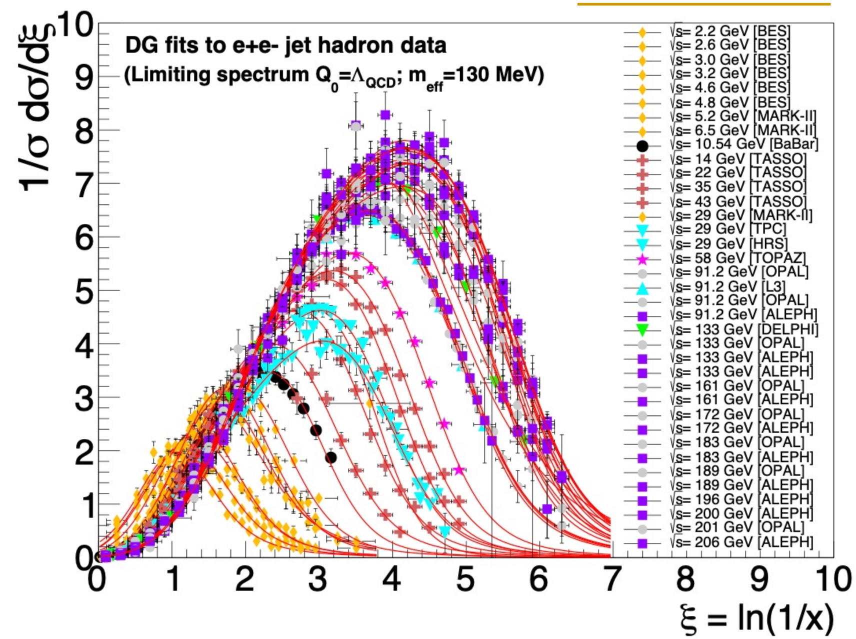


High-precision parton FFs

- Parton-to-hadron fragmentation functions evolution known known at NNLO at high-z and at NNLO*+NNLL at low-z [1702.01329]



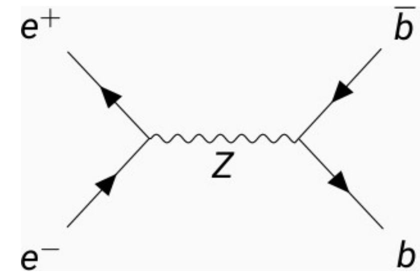




- FCC-*ee* (much broader z range) provides additional QCD coupling extractions, allowing for $\delta\alpha_S$ < 1%

Method	Current $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment state-of-the-art)	Future $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment progress)
soft FFs	$1.8\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 2\%$ (NNLO* only (+NNLL), npQCD small)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ (∼2 yrs), <1% (FCC-ee) (NNLO+NNLL. More precise e^+e^- data: 90–350 GeV)
hard FFs	$1\%_{\rm th} \oplus 5\%_{\rm exp} \approx 5\%$ (NLO only. LEP data only)	$0.7\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2\%$ (+B-factories), <1% (FCC-ee) (NNLO. More precise e^+e^- data)

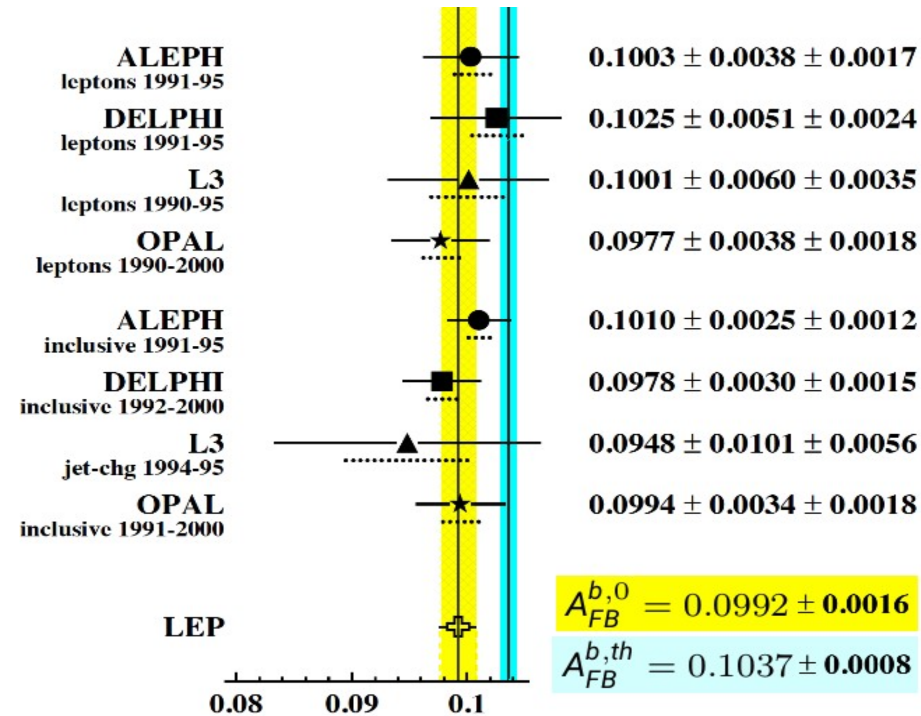
QCD uncertainties on EWK observables



- With x10^5 more Z's than LEP, EWK observables at FCC-ee will be dominated by systematics (QCD)
- $e^+e^- \to b\bar{b}$ forward-backward asymmetry at LEP
- Experimental EWPOs with the largest discrepancy wrt the SM: 2.8σ

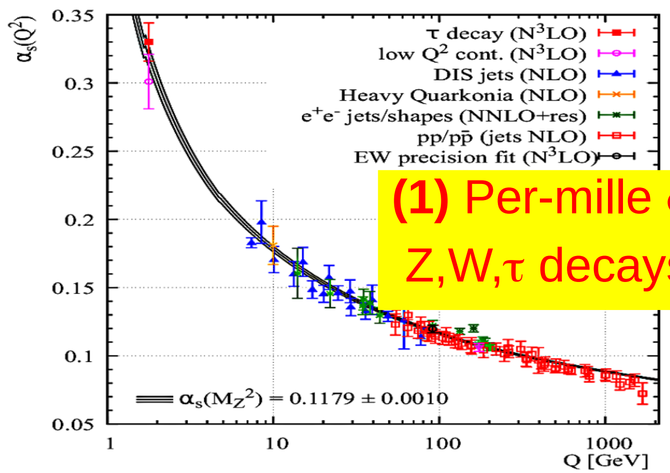
$$A^b_{FB} = \frac{N_F - N_B}{N_F + N_B} \qquad A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{A}}}{\sigma_{\mathrm{S}}} \propto \frac{-g_{\mu\nu}T^{\mu\nu}}{i\epsilon_{\mu\nu\lambda\rho}\frac{n^\lambda Q^\rho}{n\cdot Q}T^{\mu\nu}}$$

- Total uncertainty: ~1.6%
  - Statistical: 1.5% (~0.05% at FCC-ee)
  - Systematics: 0.6% (QCD: 0.4% at FCC-ee)
- QCD effects on $A^{0,b}_{FB}$:
  - Gluon splitting
  - Smearing of b-jet/thrust axis
  - b- and c-quark radiation and fragmentation (B/D hadron decay models)



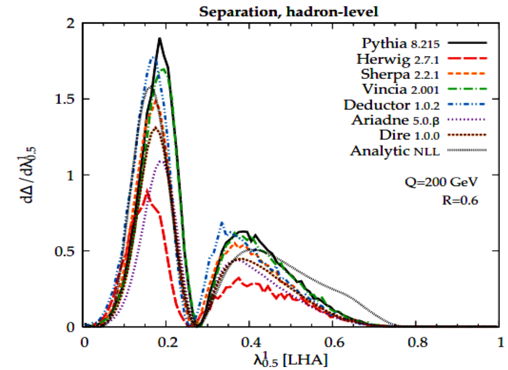
Summary & outlook

➢ The precision needed to fully exploit all future ee, pp, ep, eA, AA SM and BSM programs requires precise control of pQCD and non-pQCD physics

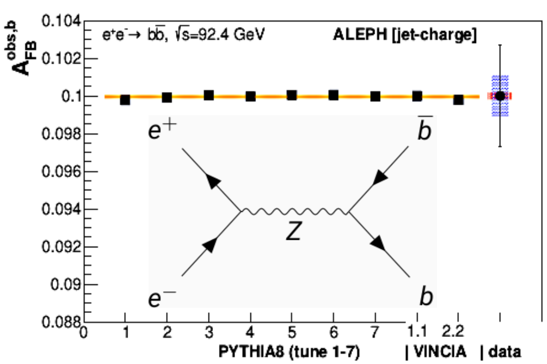


(1) Per-mille α_s via hadronic Z,W,τ decays, evt shapes...

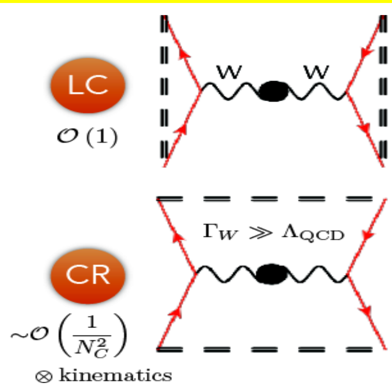
(2) N^{n}LO+N^{n}LL jet structure
Ultimate g/q/Q discrimination



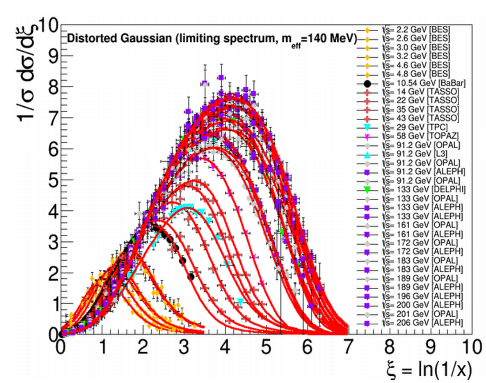
(3) Reduced PS+hadroniz. uncert. of EWPOs

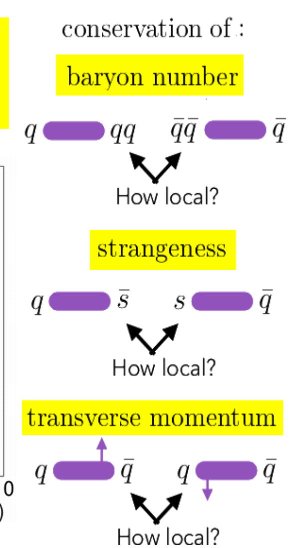


(4) <<1% control of colour reconnection



(5) High-precision hadronization:

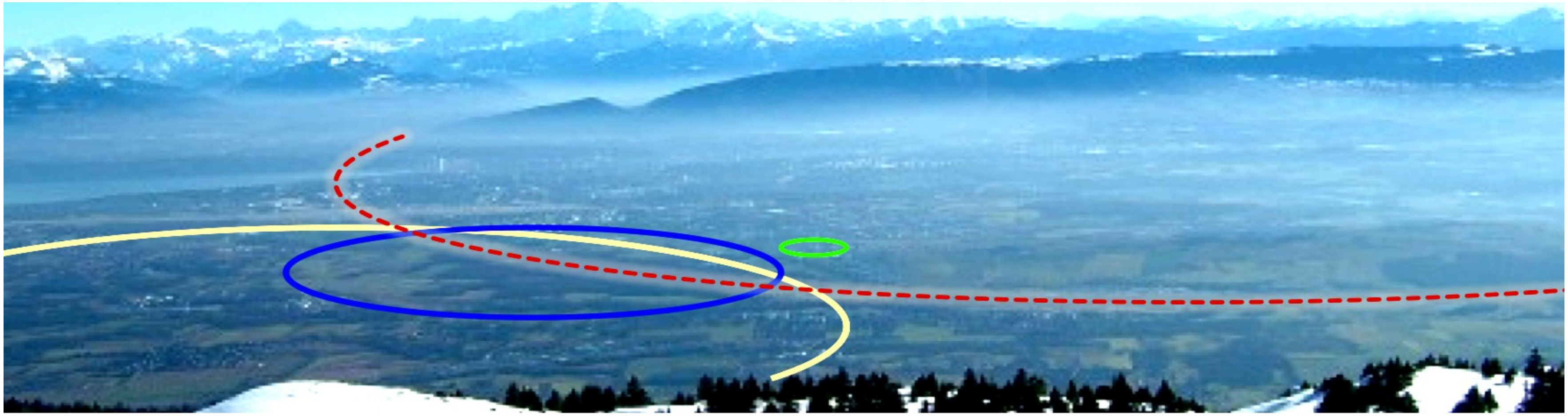




Backup Slides

CERN FCC-*ee* project

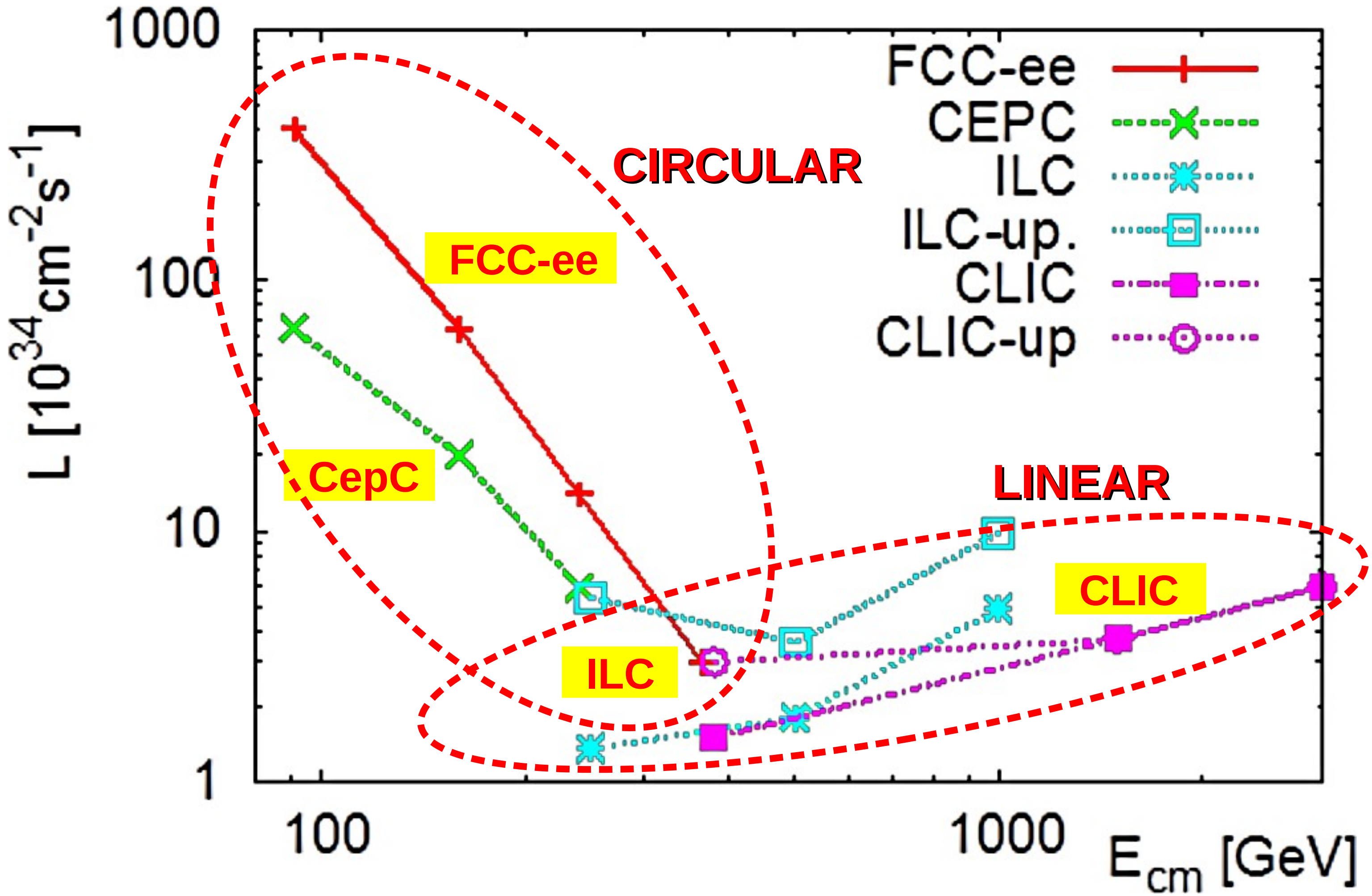
- e^+e^- operation before pp at $\sqrt{s}$ = 90, (125), 160, 240 and 350 GeV



Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365	m_H
Lumi/IP (10^{34} cm^{-2}s^{-1})	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics Goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\rightarrow$ H	$10^6 t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H		(6000)

# of light-q jets/year:	**O(10^{12})**	O(10^7)	O(10^5)	–	O(10^8)
# of gluon-jets/year:	O(10^{11})	O(10^6)	**O(10^4)**	–	O(10^6)
# of heavy-Q jets/yr:	O(10^{12})	O(10^7)	O(10^5)	**O(10^6)**	O(10^8)

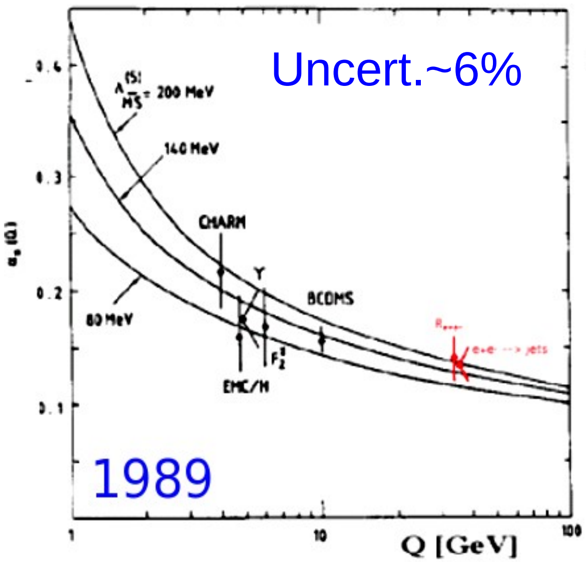
Future e^+e^- colliders under discussion

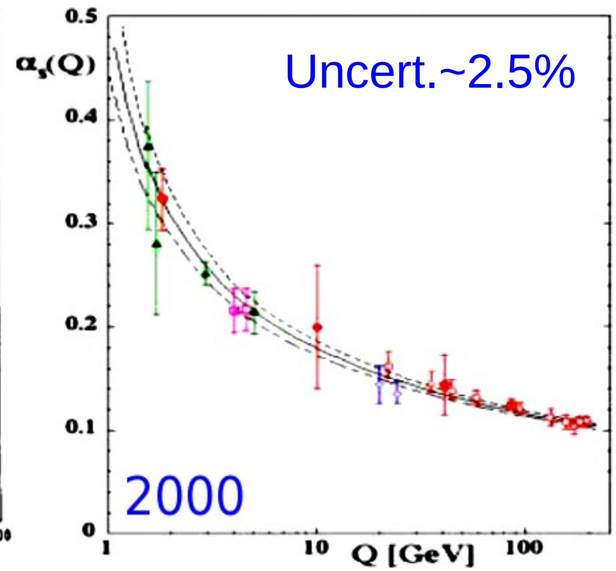


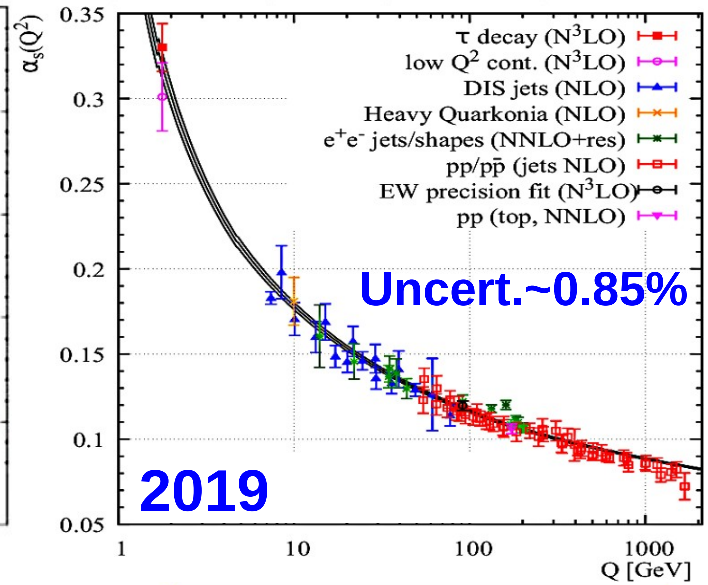
- FCC-*ee* features luminosities a few time larger than other machines over 90 - 300 GeV
- Negligible statistical uncertainty for Z, W, jets, …, τ data sets

QCD coupling α_S

- Determines strength of the strong interaction between quarks and gluons
- Determined at $Q = m_Z$, decreases as $\alpha_S \sim \ln(Q^2/\Lambda^2)$ with $\Lambda \sim 0.2$ 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

$\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$

- 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 cross sections and decays!

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

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

Msbar mass error budget (from threshold scan)

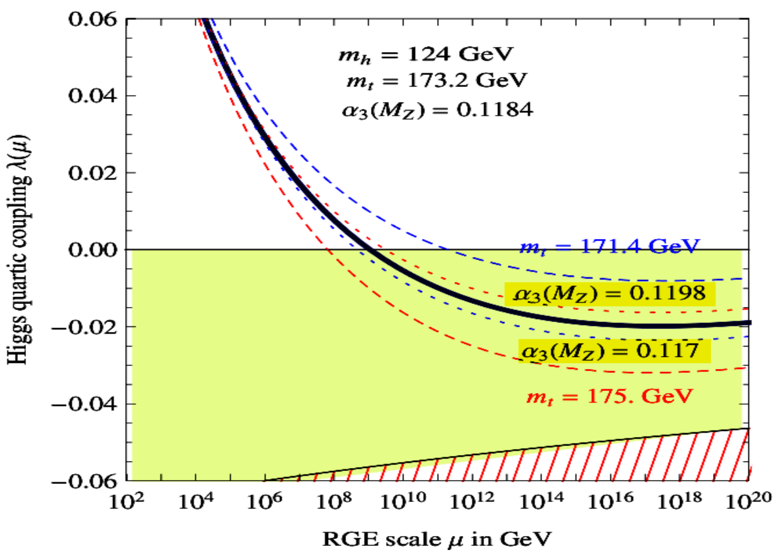
$(\delta M_t^{\rm SD-low})^{\rm exp}$	$(\delta M_t^{\rm SD-low})^{\rm theo}$	$(\delta\overline{m}_t(\overline{m}_t))^{\rm conversion}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

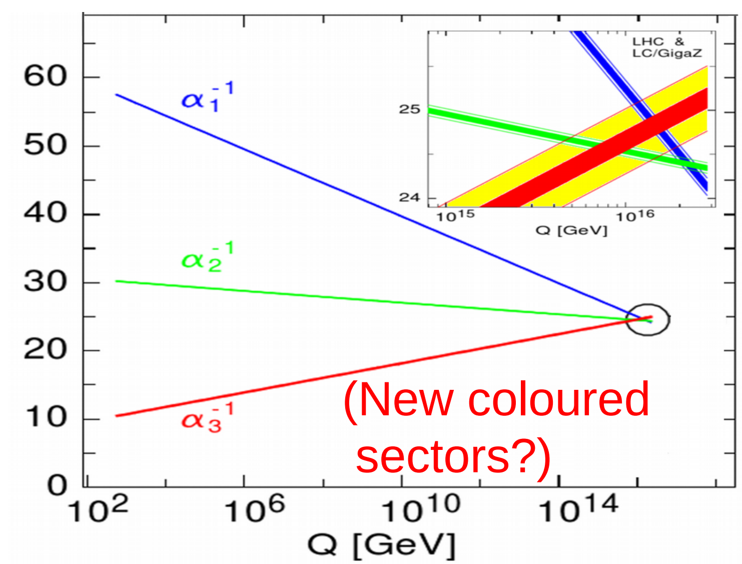
$\Rightarrow$ improvement in α_s crucial $\delta\alpha_s(M_z) = 0.001$

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 Plank scale: EW vacuum stability, GUT, etc.





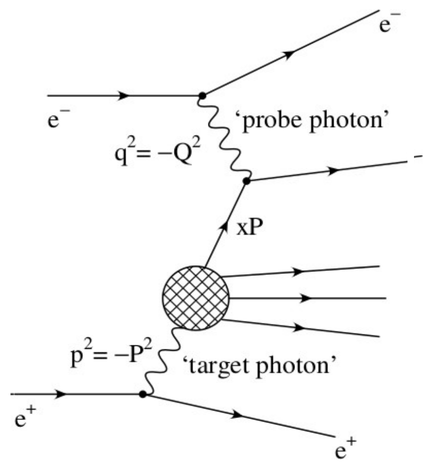
α_S from photon QCD structure function

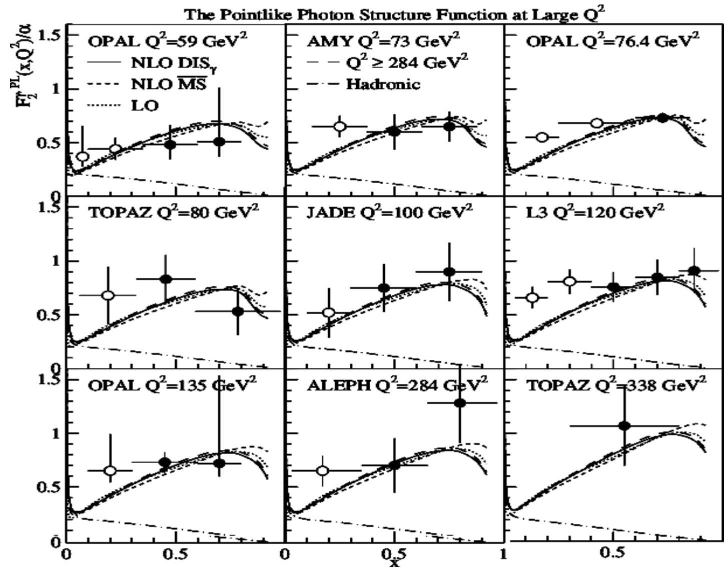
- Computed at NNLO: $\int_0^1 dx F_2^{\gamma}(x, Q^2, P^2) = \frac{\alpha}{4\pi}\frac{1}{2\beta_0}\left\{\frac{4\pi}{\alpha_s(Q^2)}c_{LO} + c_{NLO} + \boxed{\frac{\alpha_s(Q^2)}{4\pi}c_{NNLO}} + \mathcal{O}(\alpha_s^2)\right\}$
- Poor $F_\gamma^2(x, Q^2)$ experimental measurements
- NLO extraction with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

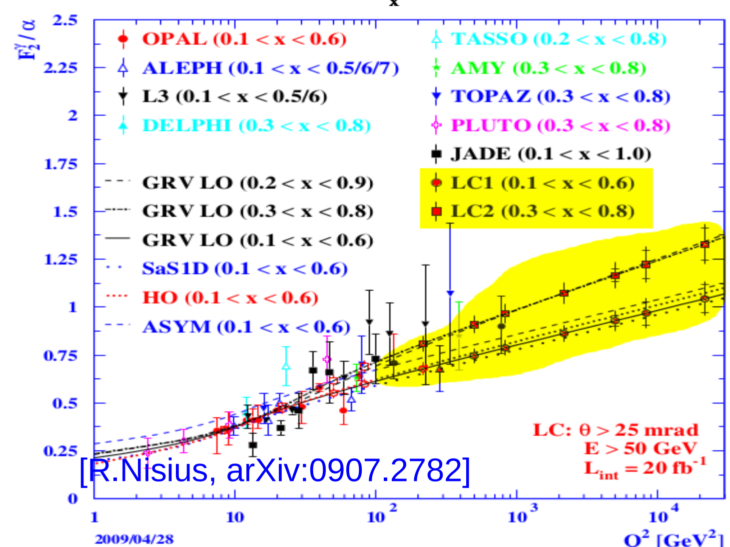
α_s (m$_z$) = 0.1198 ± 0.0054

(±4.5%)

hep-ph/0205069





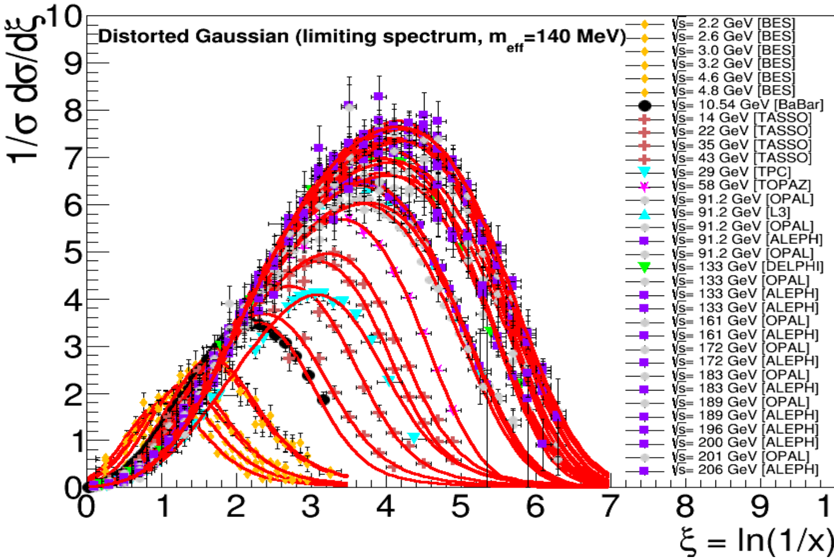


- Future prospects:
  - Fit with NNLO F_γ^2 evolution
  - Better data
  - Dedicated simulation studies (already exist at ILC)
  - Huge $\gamma\gamma$ statistics at FCC-ee will lead to $\delta\alpha_S/\alpha_S < 1\%$

α_S from jet fragmentation

➢ Soft parton-to-hadron FFS:

1505.02624 – NNLO*+NNLL



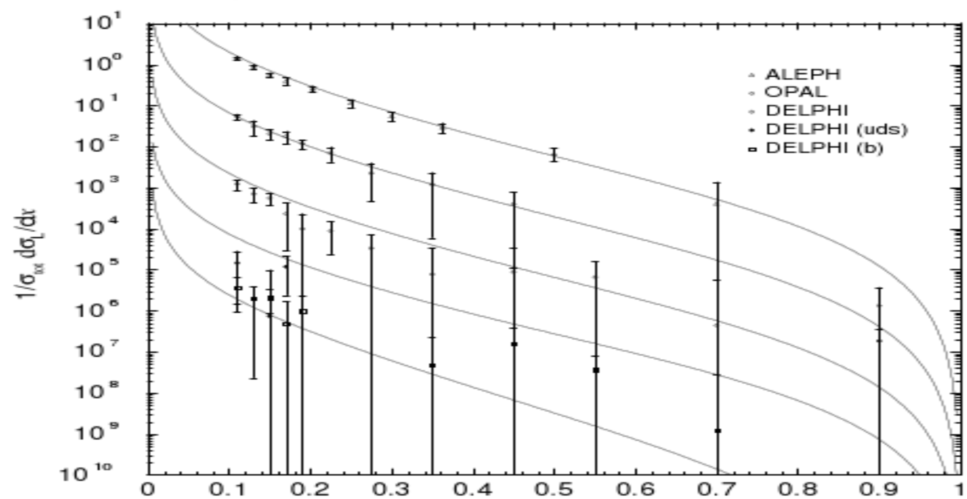
Combined fit of the jet-energy evolution of the FF moments (peak, width, multiplicity, etc.) with α_S as single free parameters

$\alpha_s(m_Z) = 0.1205 \pm 0.0022$ (±2%)

(full NNLO corrections missing)

➢ Hard parton-to-hadron FFS (NLO):

$\alpha_s(m_Z) = 0.1176 \pm 0.0055$ (±4.7%)



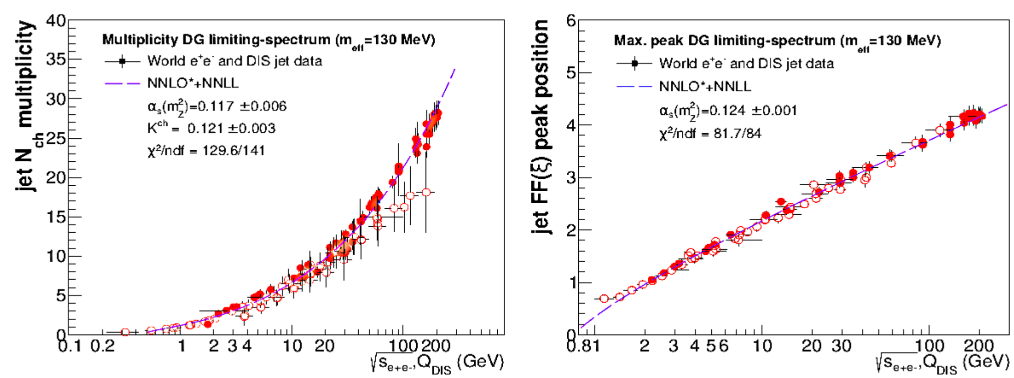


Figure 3: Energy evolution of the charged-hadron multiplicity (left) and of the FF peak position (right) measured in e^+e^- and DIS data fitted to the NNLO*+NNLL predictions. The obtained $\mathcal{K}_{ch}$ normalization constant, individual NNLO* $\alpha_s(m_Z)$ values, and the goodness-of-fit per degree-of-freedom χ^2/ndf.

Jet substructure

- Need for state-of art jet substructure studies based on angularities

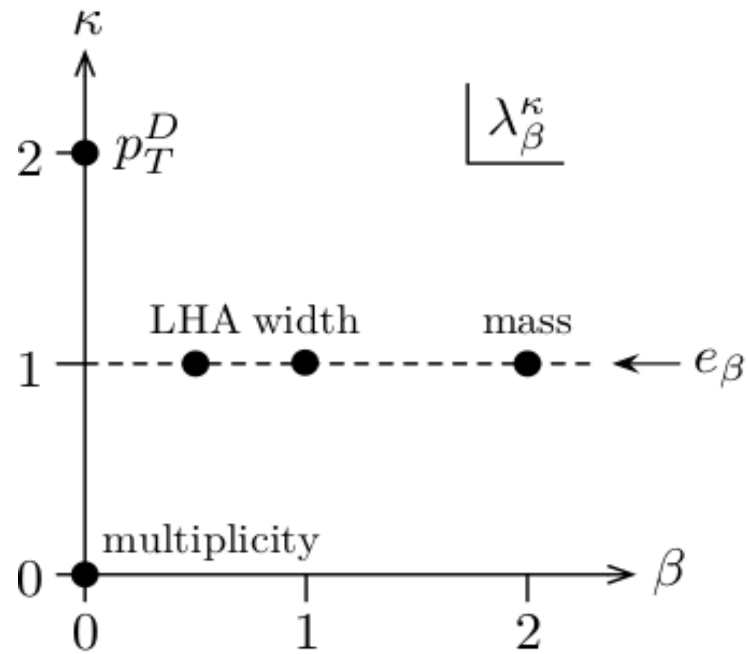
$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta ,$$

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

- Variables of jet constituents: multiplicity, LHA, width/broadening, mass/thrust, C-parameter, …

- k=1: IRC-safe computable (N^nLO + N^nLL) via SCET (but uncertainties from non-pQCD effects)

(larger energy weight)

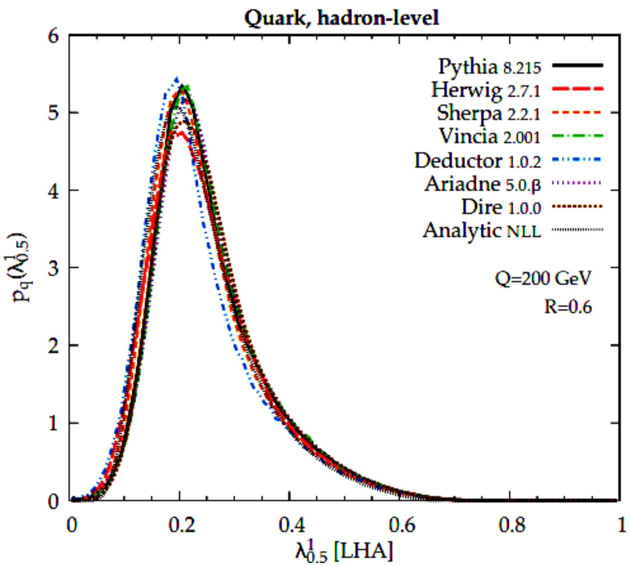


(larger angular weight)

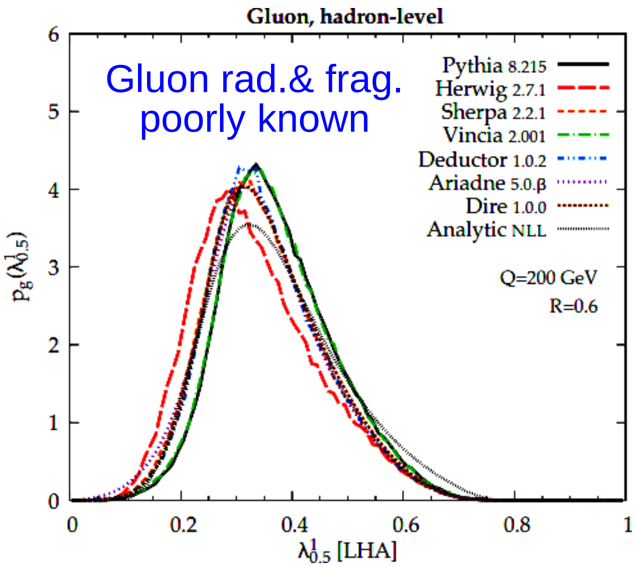
[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

Showering differences in MC generators

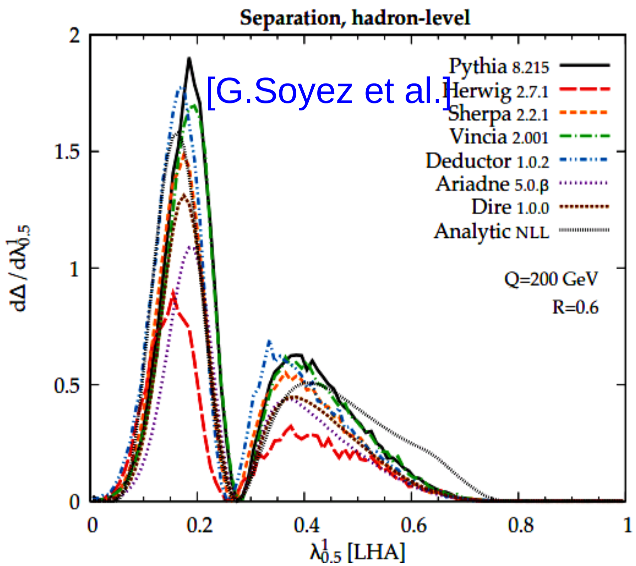
- Les Houches Angularity (LHA) is angularity with k = 1 and β = 0.5
- Not directly measured at LEP
- MC parton showers differ on gluon (less on quark) radiation patterns



$e^+e^- \to Z \to u\bar{u}$



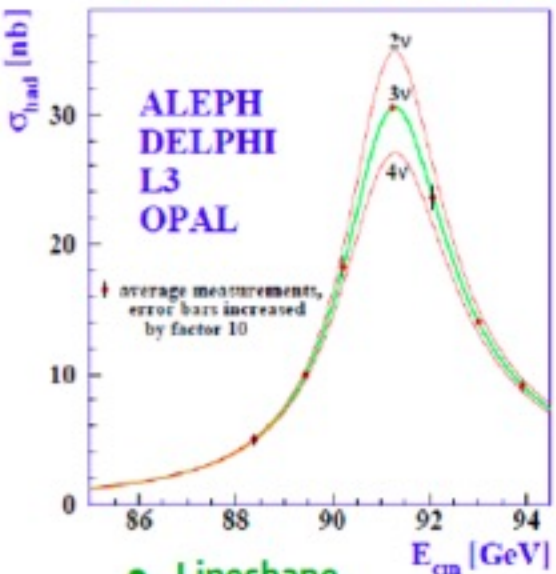
$e^+e^- \to H \to gg$



u-quark vs gluon discrimination power

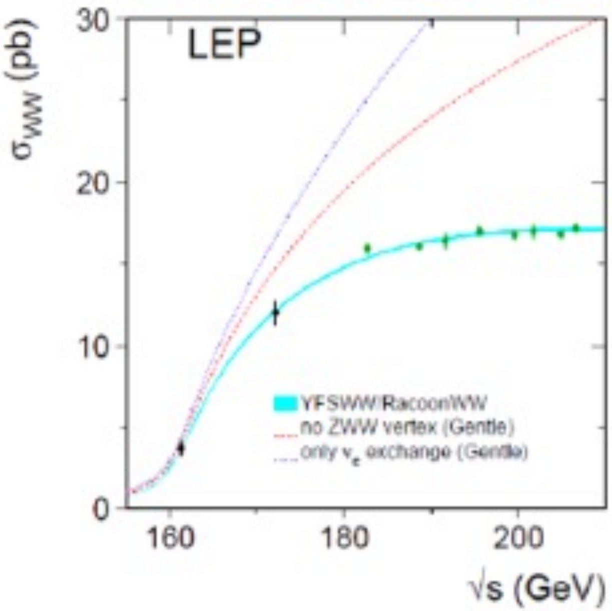
Ultra-precise W,Z and top physics at FCC-*ee*

$\sqrt{s}$=91 GeV, 10^{12} Z's



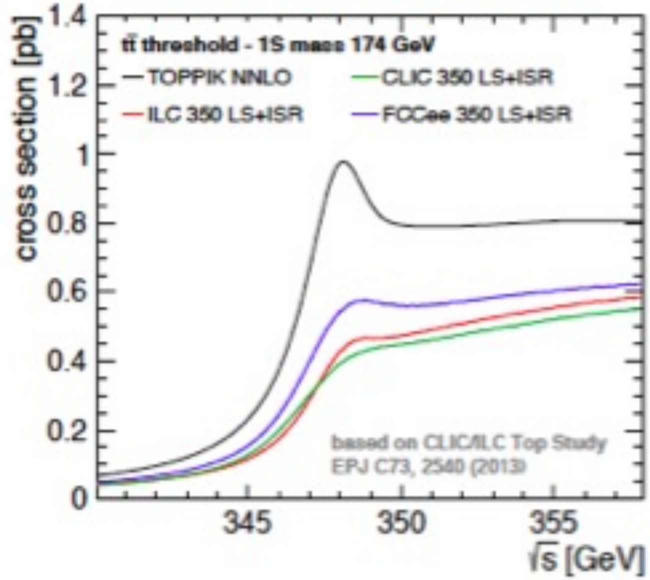
- Lineshape
  - ➨ Exquisite E_{beam} (unique!)
  - ➨ m_Z, Γ_Z to 10 keV (stat.) 100 keV (syst.)
- Asymmetries
  - ➨ $\sin^2\theta_W$ to 5×10^{-6}
- Branching ratios, R_l, R_b
  - ➨ $\alpha_S(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

$\sqrt{s}$=161 GeV, 10^8 W's



- Threshold scan
  - ➨ m_W to 500 keV
- Branching ratios R_l, R_{had}
  - ➨ $\alpha_S(m_W)$ to 0.0002
- Radiative returns $e^+e^-\to\gamma Z$ ($Z\to\nu\nu$, $\mu^+\mu^-$)
  - ➨ N_ν to 0.001

$\sqrt{s}$=350 GeV, 10^6 tops

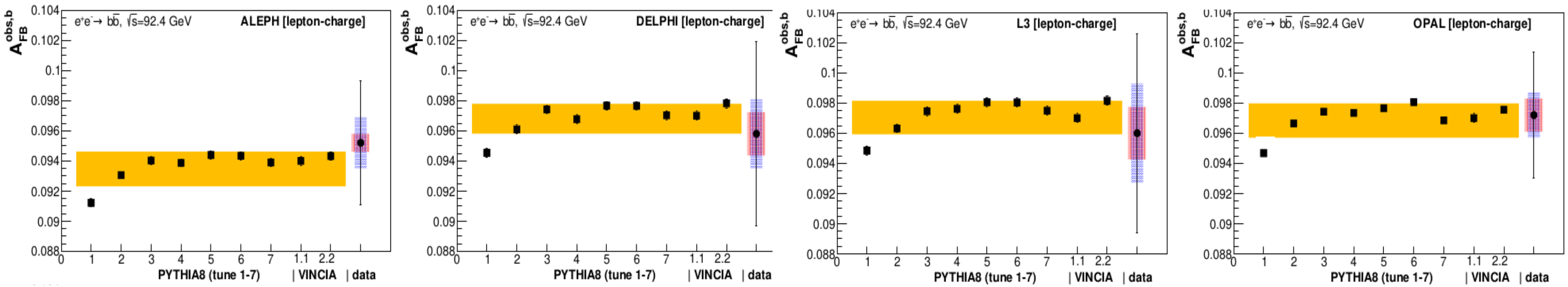


- Threshold scan + 4D fit
  - ➨ m_{top} to 10 MeV (stat.) 40 MeV (th.)
  - ➨ λ_{top} to 13%
  - + EWK couplings to 1–10%

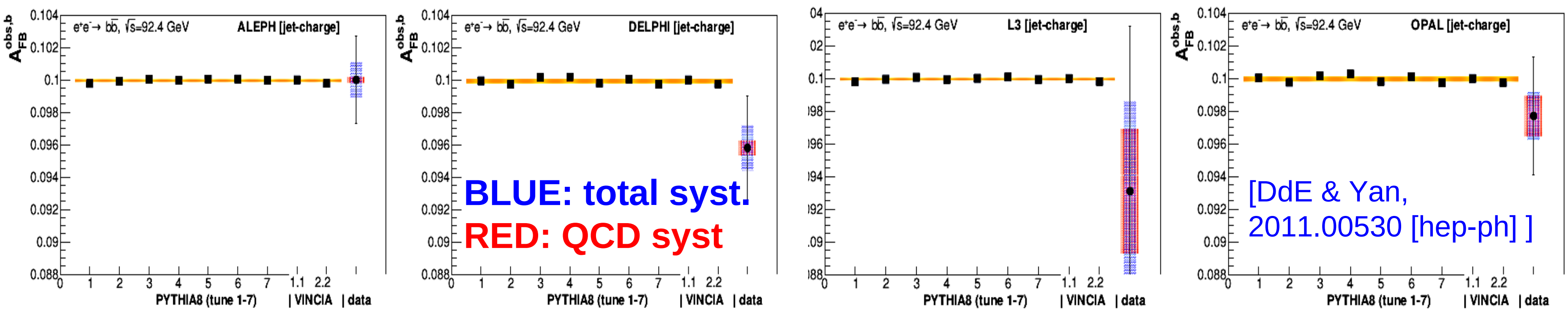
➢ Mostly thanks to the incredibly huge statistics available!

Reduced QCD uncertainties on A_{FB}

- QCD uncertainties recomputed from Pythia8.226 and VINCIA2.2
- $e^+e^- \to b\bar{b}$ A_{FB} asymmetry for lepton-based analyses:



- $e^+e^- \to b\bar{b}$ A_{FB} asymmetry for jet-charged-based analyses:



- Much smaller uncertainties exhibited by jet-charged-based analyses
- Improved PS & non-pQCD tunes w. e^+e^- data needed to reduce syst. uncert.