Review of strong coupling at FCC-ee

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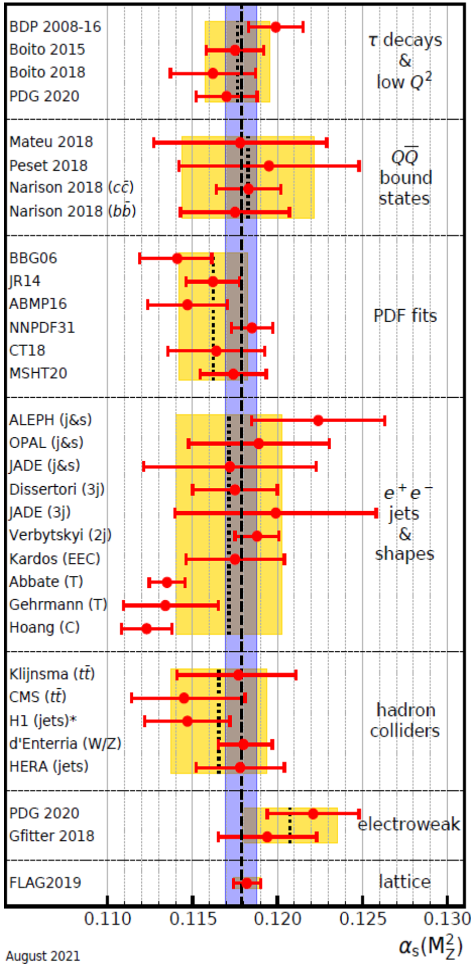
[PDG, PTEP 2020 (2020) 083C01, updated in D. d'Enterria, S. Kluth, G. Zanderighi (eds.), arxiv: 2203.08271]

1 Overview



FCC-ee

FCC-ee

FCC-eh

FCC-ee

FCC-hh

FCC-ee

Summary from "α_S (2022) – Precision measurements of the QCD coupling" at ECT* (Trento) 31.01.-04.02.2022

FCC-ee impact on most categories

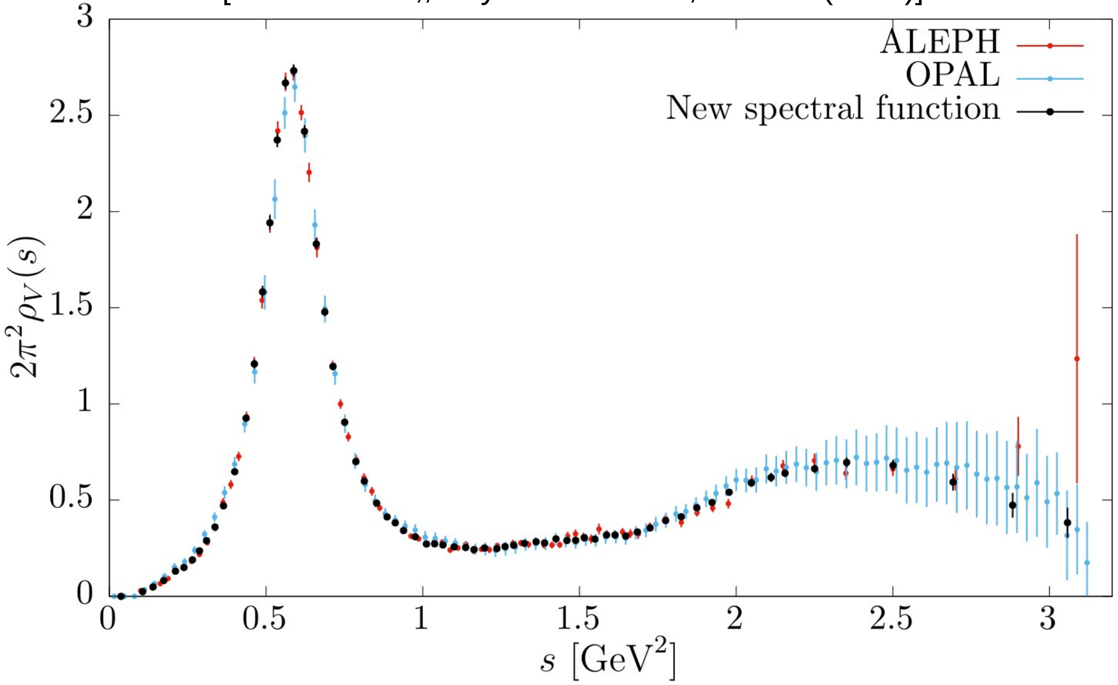
Expect $3 \cdot 10^{12}$ hadronic Z decays ⇒ $6 \cdot 10^{11}$ $Z \rightarrow b\bar{b}$, 10^{11} τ pairs, …

$5 \cdot 10^{8}$ W decays

2 Inclusive: τ decays

Moments of vector (even πs) and axial-vector (odd πs) "spectral functions" with N3LO QCD + np terms ⇒ $\alpha_S(m_\tau)$ ⇒ $\alpha_S(m_Z)$

[D. Boito et al,, Phys. Rev. D 103, 034028 (2021)]



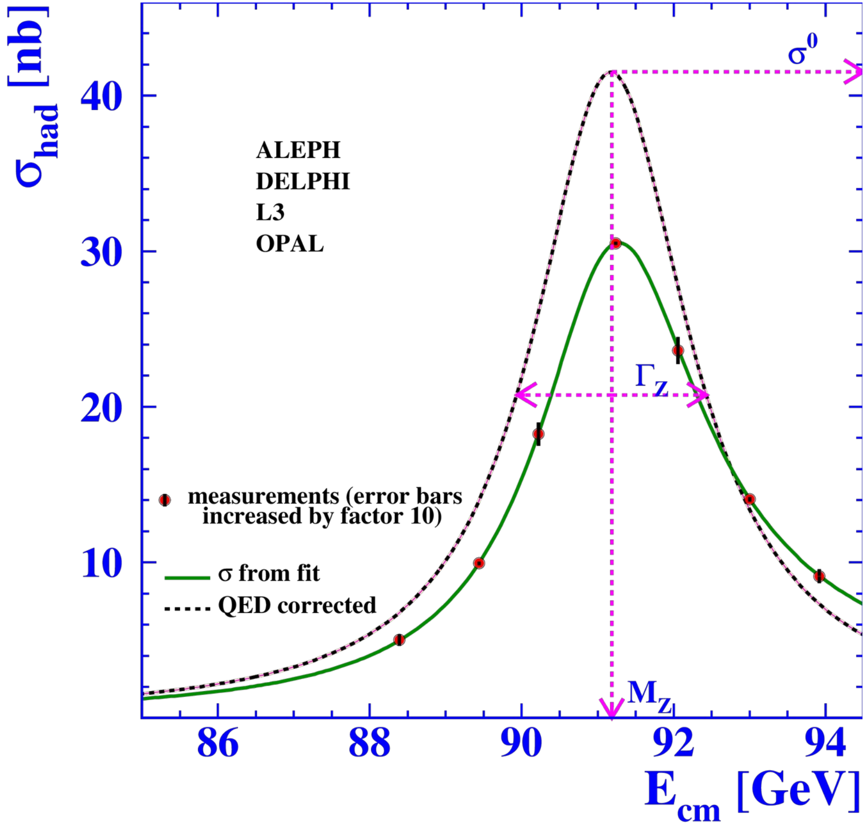
Improved spectral functions: errors at large s, rare and strange τ decays ⇒ better analysis of np effects

[M. A. Benitez-Rathgeb et al., arxiv: 2203.08271]

Theory improvements: FOPT vs CIPT understanding, N4LO calculation ⇒ $\Delta\alpha_S(m_Z) < 1\%$ feasible

2 Inclusive: Z and W decays

[ADLO+S, Phys. Rept. 427 (2006) 257]



SM prediction: $R_l^{Z,W} = \Gamma_{had}/\Gamma_{lep} = R_{EW}(\ 1+\sum a_i(\alpha_S(Q)/\pi)^i + \delta_{EW} + \delta_{mix} + \delta_{np}\ )$

N3LO QCD, 2-loop EW corrections

Γ_{had}, Γ_{lep}, … (EWPO) from mod.ind. fits

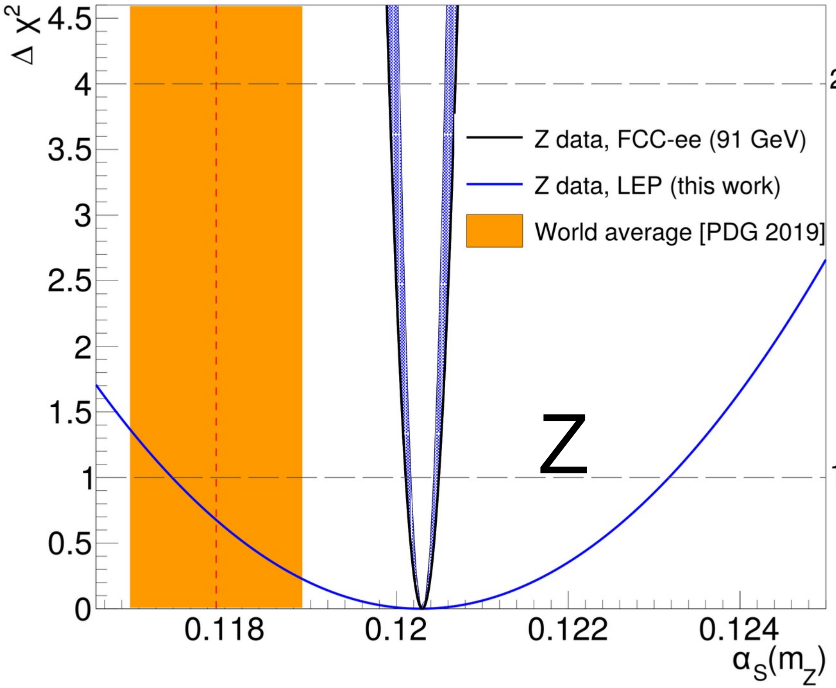
LEP:

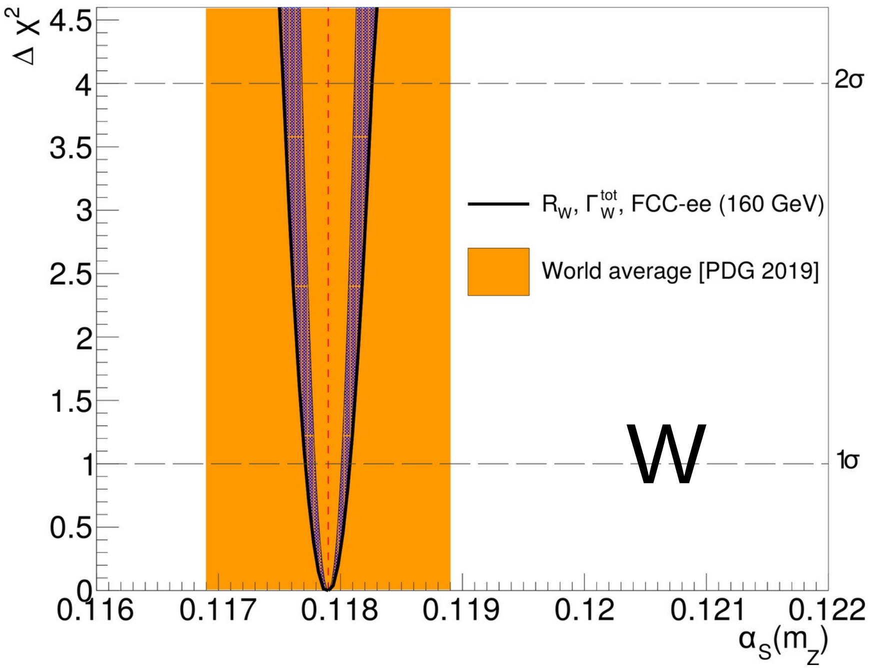
Z: $\alpha_S(m_Z) = 0.120 \pm 0.003_{exp} \pm 0.001_{theo}$

W: $\alpha_S(m_Z) = 0.107 \pm 0.035_{exp} \pm 0.002_{theo}$

[D. d'Enterria, arxiv: 2203.08271]

2 Inclusive: Z and W decays





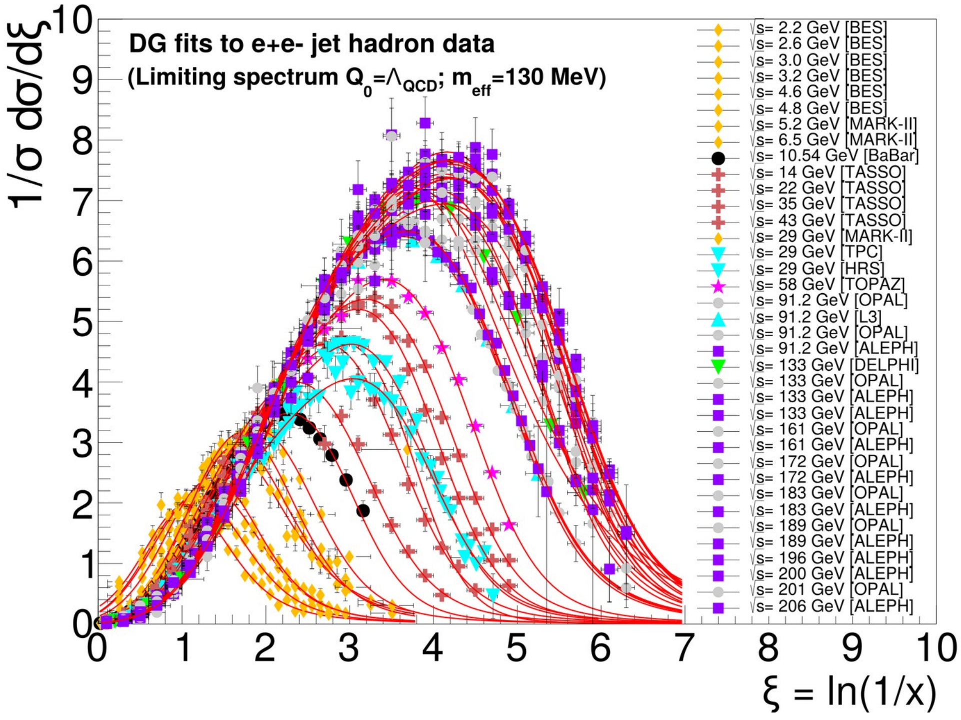
FCC-ee: improved α_{QED}, $|V_{cs}|$, $|V_{cd}|$, m_W; assume N4LO QCD

Z: $\alpha_S(m_Z) = 0.12020 \pm 0.00013_{exp} \pm 0.00005_{par} \pm 0.00022_{theo}$

W: $\alpha_S(m_Z) = 0.11790 \pm 0.00012_{exp} \pm 0.00004_{par} \pm 0.00019_{theo}$

[D. d'Enterria, arxiv: 2203.08271]

3 Semi-inclusive: Soft FFs



Charged hadrons momentum spectra $x = 2E_h/\sqrt{s}$

FF: $D_{a,h}(z,Q)$, $z = p_h/p_a$, $Q = \sqrt{s}$

Distorted Gaussian model:

$D \approx C(\alpha_S(t))\exp(\int^t \gamma(\alpha_S(t'))dt')$

$t = \ln(Q)$, NNLO*+NNLL evolution of $\gamma(\alpha_S(t'))$

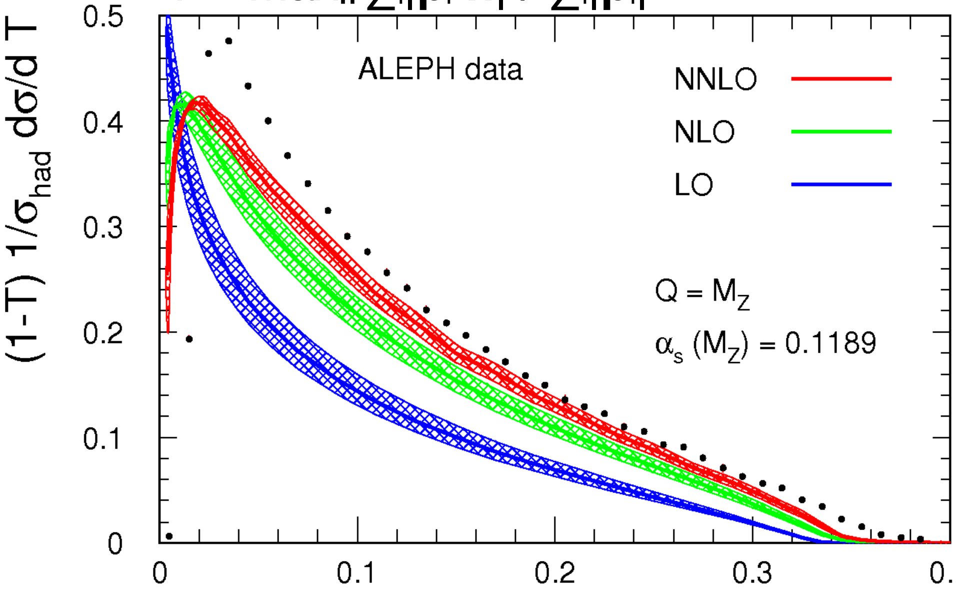
$\alpha_S(m_Z) = 0.121 \pm 0.001_{exp} \pm 0.002_{theo}$

FCC-ee: $\Delta\alpha_{S,exp} < 0.1\%$, full NNLO+NNLL ⇒ $\Delta\alpha_{S,theo} \leq 0.001$?

[R. Perez-Ramos, D. d'Enterria, arxiv: 2203.08271]

4 Exclusive: jets and event shapes

$T = \max_{\mathbf{n}} \sum_i |\mathbf{p}_i \cdot \mathbf{n}| \, / \, \sum_i |\mathbf{p}_i|$



[A. Gehrmann-De Ridder et al., JHEP 12 (2007) 094]

$1/\sigma \, d\sigma/dy = dA/dy \, \alpha_S(Q) + dC/dy \, \alpha_S(Q)^2 + dC/dy \, \alpha_S(Q)^3 + \text{h.o.} + \text{scale} + \text{“}\sigma_{0\rightarrow tot}\text{“}$

NNLO QCD (+resum.) needs np (hadronisation) corr. ~1/Q

MC-based vs analytic models

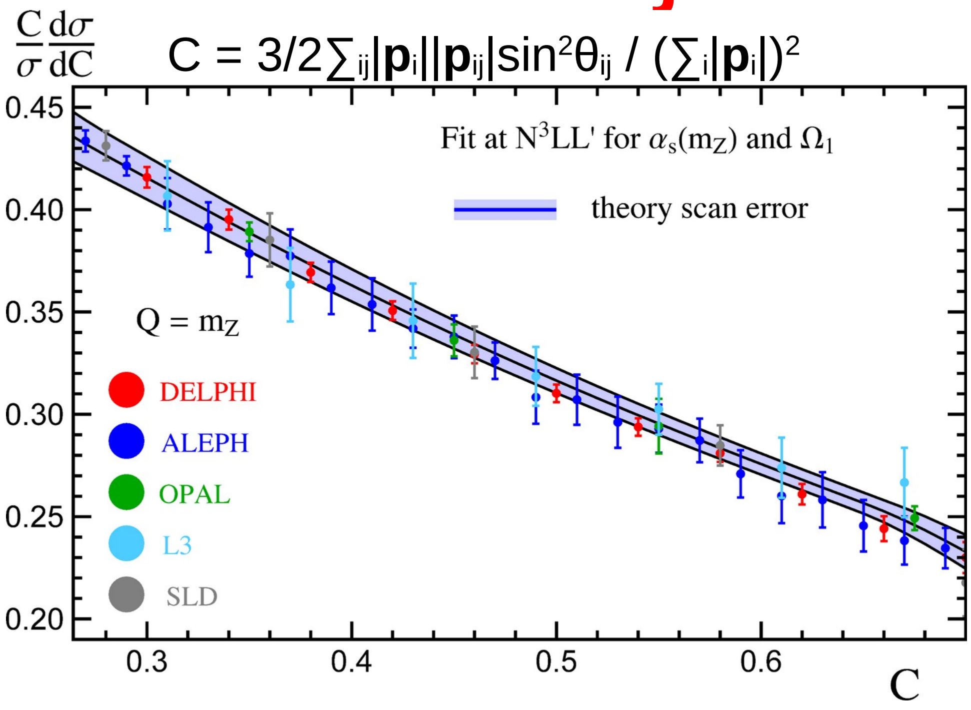
Same structure for other event shapes and for jet production rates

Typical differences MC vs analytic $\Delta\alpha_S(m_Z)_{\text{np-model}} = O(1\%)$

[e.g. A. Hoang et al., Phys. Rev. D91 (2015) 9]

4 Exclusive: jets and event shapes

$C = 3/2 \sum_{ij} |\mathbf{p}_i||\mathbf{p}_{ij}| \sin^2\theta_{ij} / (\sum_i |\mathbf{p}_i|)^2$



Hadronisation unc. within Fitted SCET based model

Significant deviations from world average
$\alpha_S(m_Z) = 0.1179 \pm 0.0009$

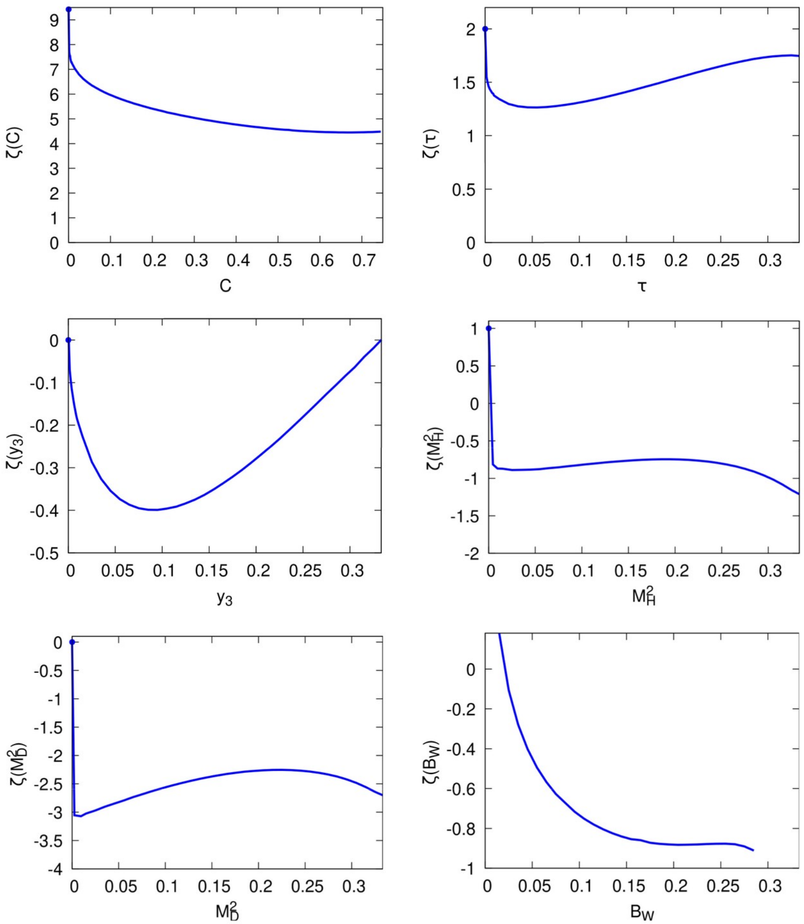
[A. Hoang et al., Phys. Rev. D91 (2015) 9]

NNLO + N3LL' (SCET), LEP/SLD/PETRA/TRISTAN data:

T: $\alpha_S(m_Z) = 0.1134 \pm 0.0002_{exp} \pm 0.0005_{had} \pm 0.0011_{theo}$

C: $\alpha_S(m_Z) = 0.1123 \pm 0.0002_{exp} \pm 0.0007_{had} \pm 0.0014_{theo}$

4 Exclusive: jets and event shapes



[P. Nason, G. Zanderighi, arxiv:2301.03607]

Linear power corrections in large n_f limit in 3-jet region ⇒ constant shift of pert. prediction replaced by observable dependent shift ζ(.)

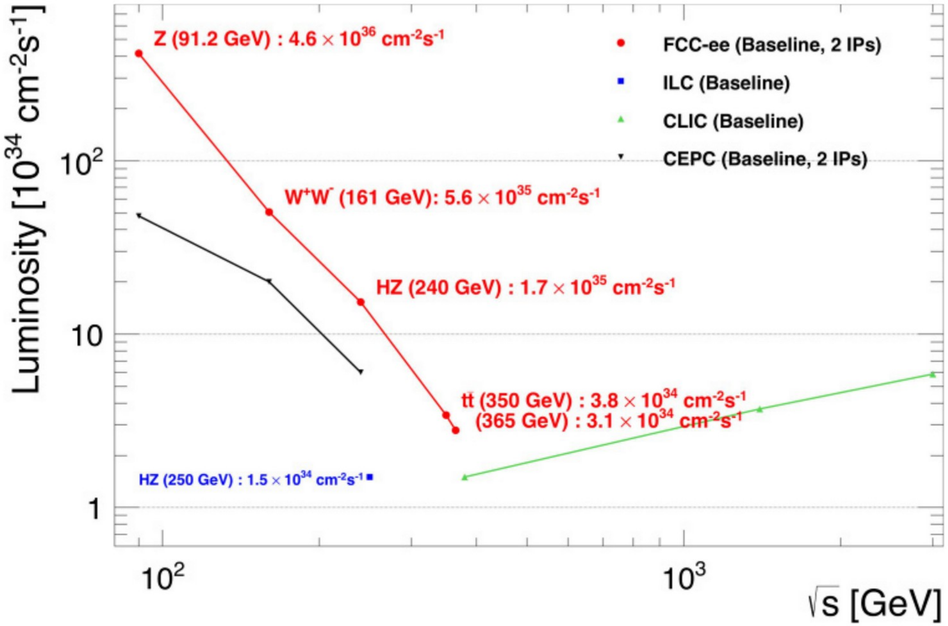
significant $\Delta\alpha_S(m_Z)$ w.r.t. const. shift

See also: new (groomed) observables, NLO+NLL-PS MCs [S. Marzani, D. Reichelt, S. Schumann, G. Soyez, arxiv: 2203.08271]

FCC-ee: $\Delta\alpha_{S,exp} < 0.1\%$, $\Delta\alpha_{S,had} < 1\%$?, $\Delta\alpha_{S,theo} < 1\%$?, $\Delta\alpha_{S,\text{hadron masses}} \approx 1\%$?

5 Bonus track: FCC-ee with $\sqrt{s} < m_Z$

Proposal for Snowmass 2021
Collect 10^9 events with FCC-ee
at $\sqrt{s}$ = 20, 30, 40, … GeV



Benefactors:

MC tuning and soft QCD ⇒ hadronisation systematics

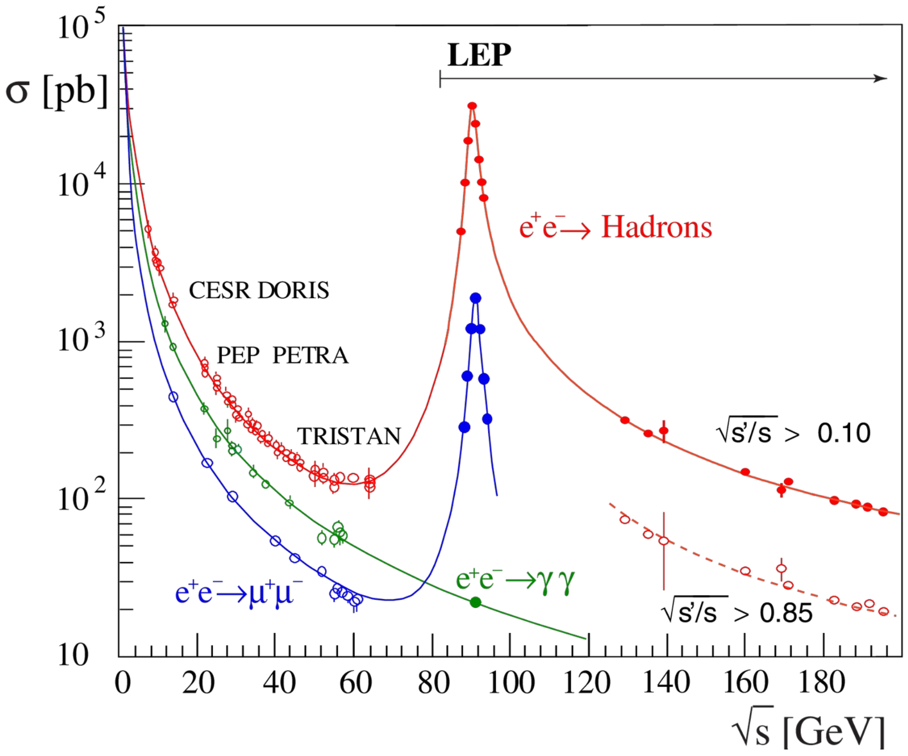
R_l^γ at high precision

FFs: scaling violation, long., transv., asym., soft FFs ξ=ln(1/x), ...

In-situ calibrations?, EW, etc pp

[A. Banfi et al., www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF5_EF4_Andrii_Verbytskyi-208.pdf]

5 R_l^γ at $\sqrt{s} < m_Z$ with FCC-ee



$R_{l\ exp}^\gamma = \sigma(e^+e^- \rightarrow hadrons)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$

$R_{l\ theo}^\gamma = 3\sum_i q_i(1+\alpha_S/\pi+1.441(\alpha_S/\pi)^2+...)$

[A.V. Nesterenko, arxiv: 2203.08271]

$\Delta R_l^\gamma/R_l^\gamma \approx \Delta\alpha_S \Rightarrow \Delta\alpha_{S,stat} \approx 0.0001$ with

$\Delta R_l^\gamma/R_l^\gamma \approx 10^{-4} \Rightarrow O(10^8)$ events

$\Delta R_l^Z/R_l^Z \approx 4\cdot10^{-5}$ FCC-ee, dominated by lepton acceptance $\Rightarrow$ similar for R_l^γ

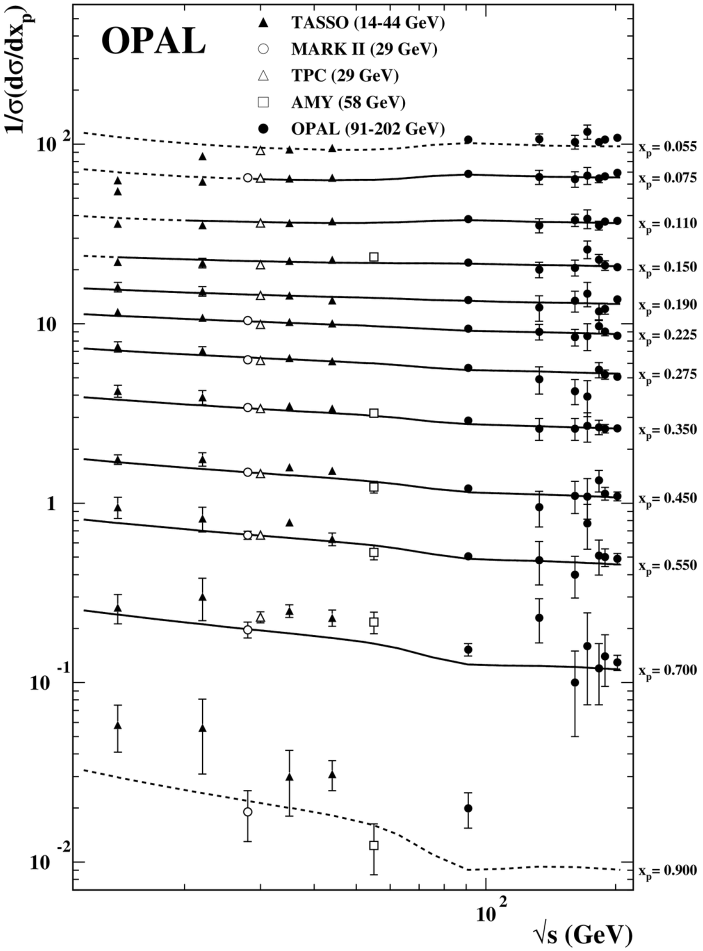
$\Rightarrow \Delta\alpha_{S,exp} \approx 0.0001$

Pure γ couplings, low scale

⇒ less BSM “pollution”

$\Delta\alpha_{S,theo} \approx 0.0002$ as for $R_l^{Z,W}$

5 Scaling violation in hard FFs



Charged hadrons h with scaled momentum $x = 2E_h/\sqrt{s}$ at various $\sqrt{s} = Q$

$1/\sigma d\sigma/dx = \int_0^1 \sum_f C_f(z,\alpha_S(Q)D_f(x/z)\ dz/z$

LEP (ADO) NLO DGLAP analyses: $\alpha_S(m_Z) = 0.1192 \pm 0.0056_{exp} \pm 0.0070_{theo}$

FCC-ee statistics and systematics ⇒ exp. unc. $\Delta\alpha_{S,exp} < 1\%$ (or better?)

Today NNLO DGLAP for proton pdfs ⇒ theo. unc. $\Delta\alpha_{S,theo} \approx 0.001$? (N3LO DGLAP?)

6 Summary

- FCC-ee has great potential for strong coupling
  - From low to high scales
  - Inclusive, semi-inclusive, exclusive processes
- FCC-ee only alternative to Lattice QCD and ep colliders (FCC-eh, LHeC) for $\Delta\alpha_S(m_Z) \approx 0.1\%$
- FCC-ee low energy ($\sqrt{s} < m_Z$) runs promising!

$\Delta\alpha_S(m_Z) = O(0.1\%)$ $\Delta\alpha_S(m_Z) \approx O(1\%)$ $\Delta\alpha_S(m_Z) \geq 1\%$