High-precision QCD physics at FCC-ee

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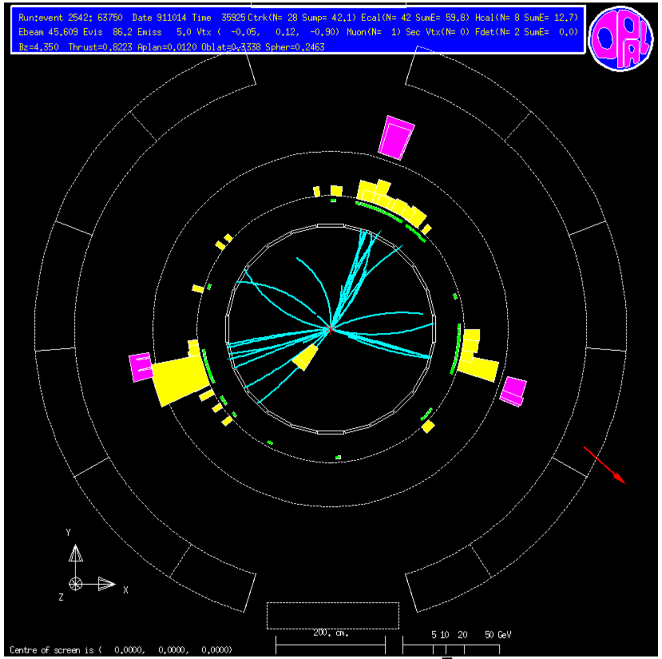
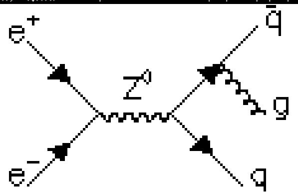
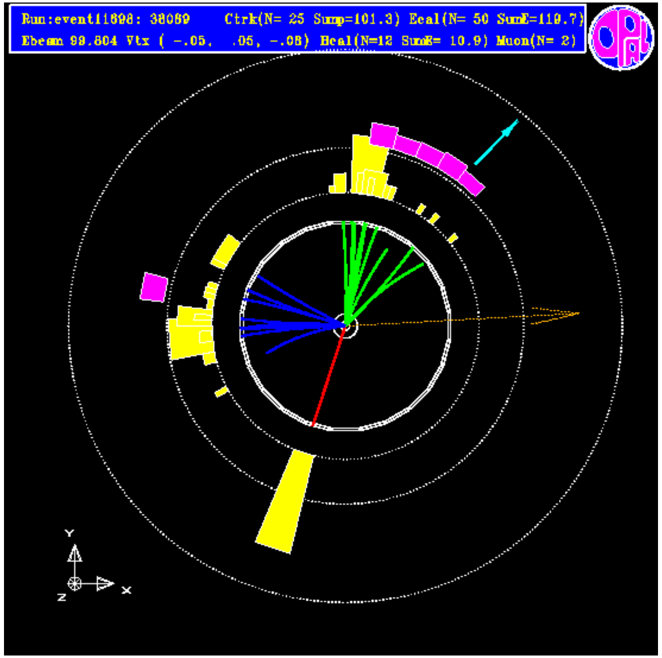
High precision QCD in e^+e^-

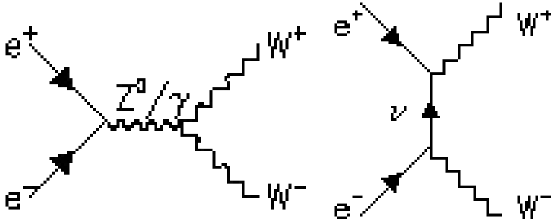
$e^+e^- \rightarrow q\bar{q}g$



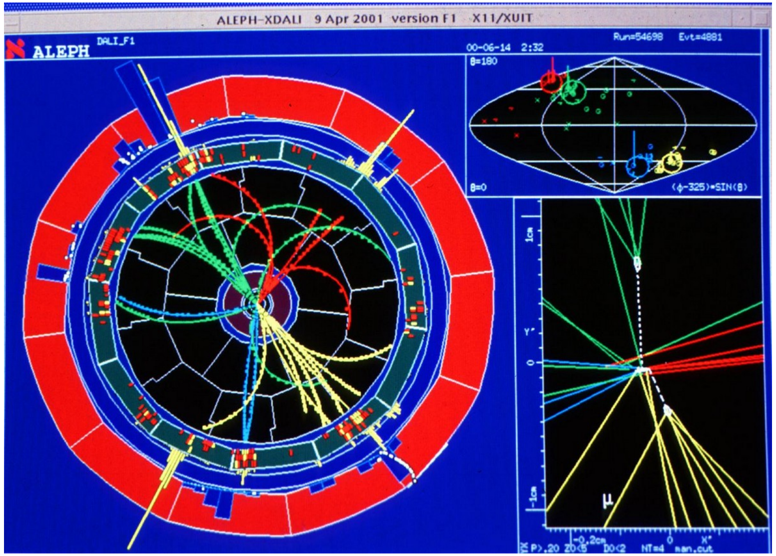


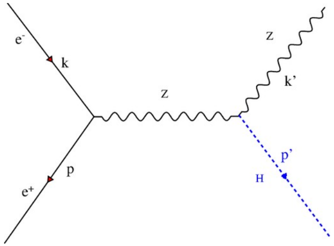
$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}e\nu_e$



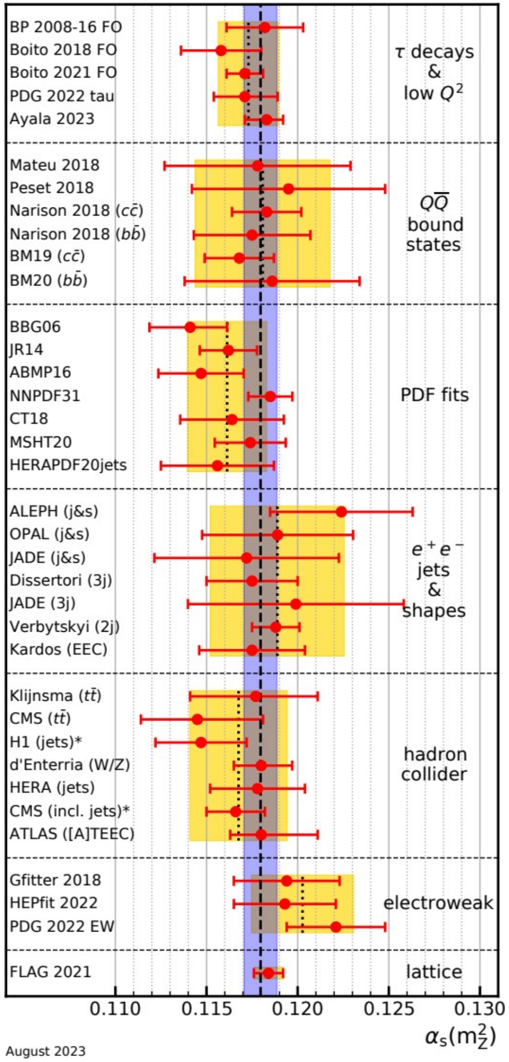


$e^+e^- \rightarrow$
$b\bar{b}$ (115 GeV) $q\bar{q}$ ($\sim m_Z$)





[Huston, Rabbertz, Zanderighi, in PDG coll., arXiv: 2312.14015]



Overview

FCC-ee

PDG QCD update 2023, based on

FCC-ee

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

LHeC
FCC-eh

FCC-ee

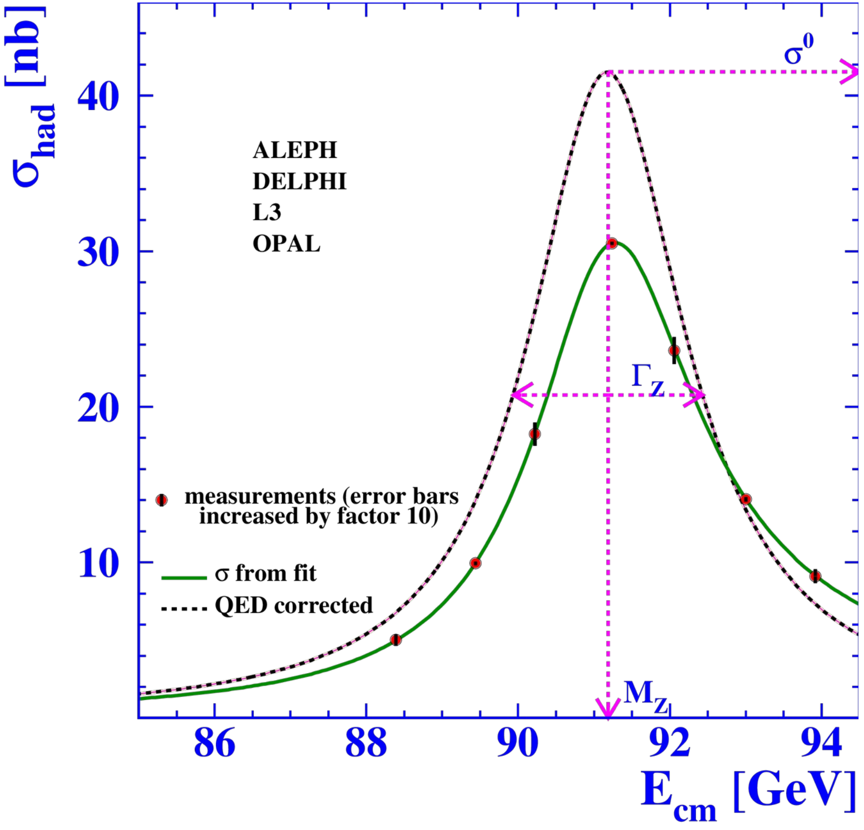
FCC-ee impact on most categories

LHeC
FCC-hh
FCC-eh
FCC-ee

Expect $3{\cdot}10^{12}$ hadronic Z decays ⇒ $6{\cdot}10^{11}$ Z→$b\bar{b}$, 10^{11} lepton pairs (e,μ,τ), $5{\cdot}10^{8}$ W decays, 10^{6} $t\bar{t}$ on threshold, O(10^{5}) H→gg, ...

Z and W decays in e^+e^-

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



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

N3LO QCD, 2-loop EW corrections

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

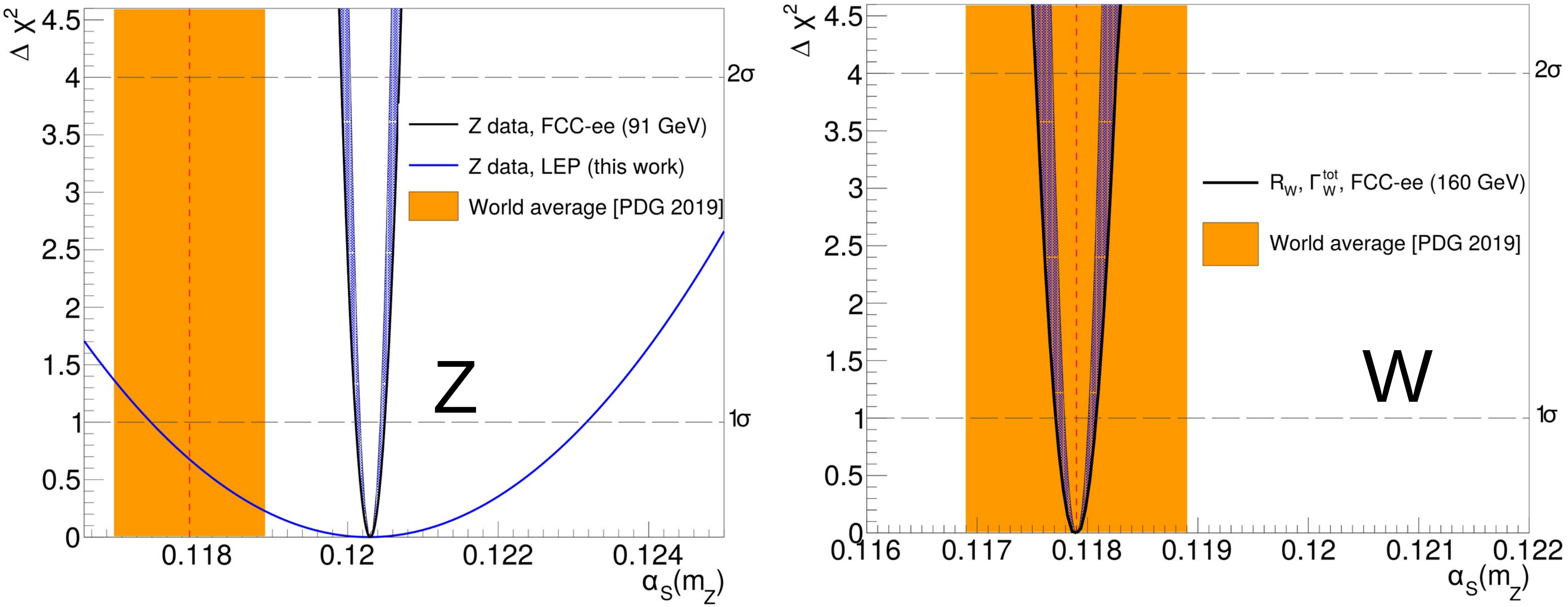
LEP:

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, in arxiv: 2203.08271]

Z and W decays in e^+e^-



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

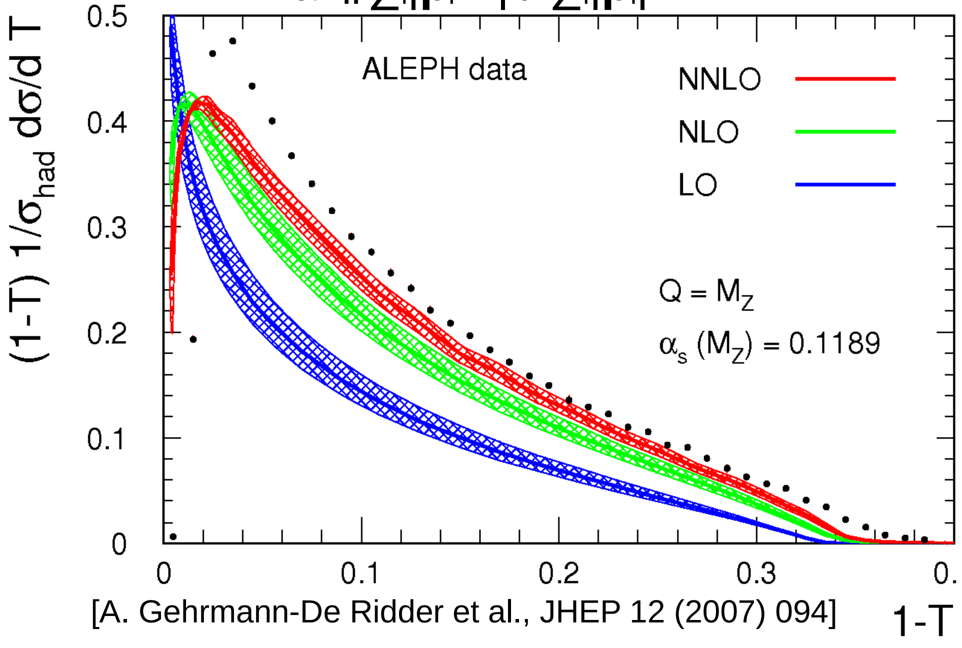
Z: $\alpha_S(m_Z) = 0.12020 \pm 0.00013_{exp} \pm 0.00005_{par} \pm 0.00022_{theo}$

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

[D. d'Enterria, in arxiv: 2203.08271]

Jets and event shapes in e^+e^-

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



[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

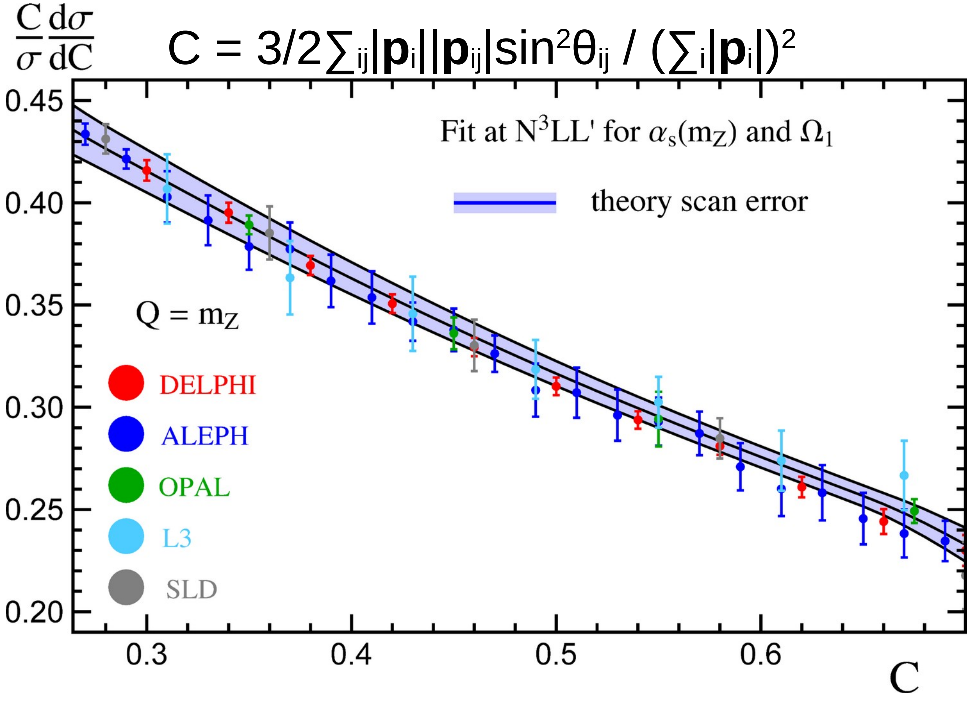
Same structure for other event shapes and for jet production rates

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) 094018]

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
$\alpha_S(m_Z) = 0.1179 \pm 0.0009$

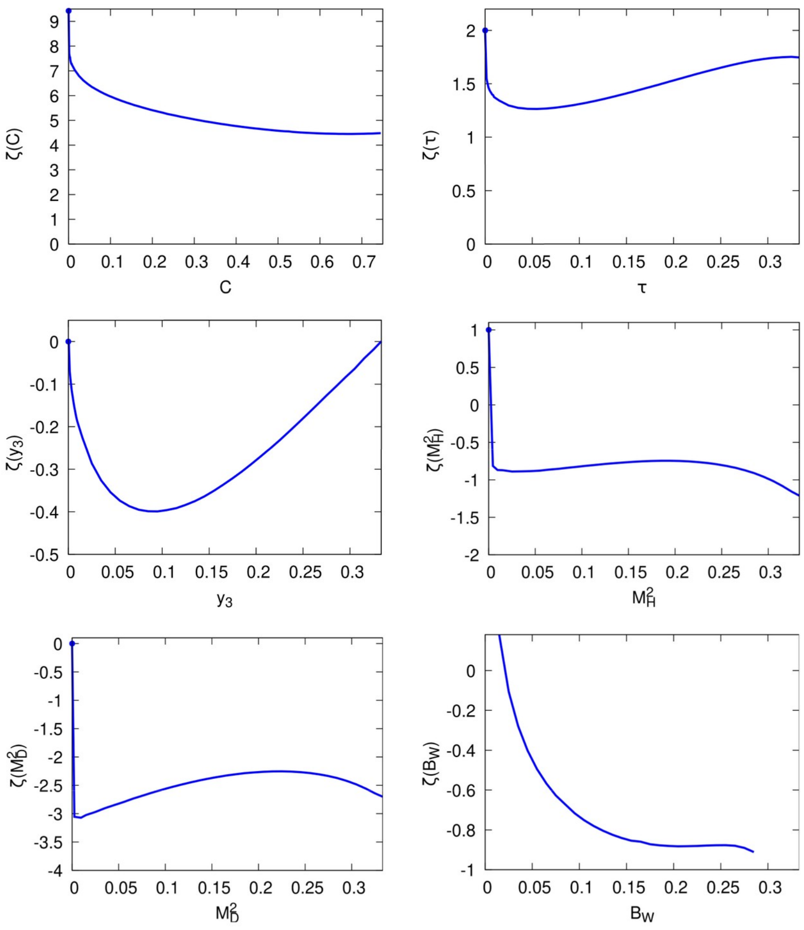
[A. Hoang et al., Phys. Rev. D91 (2015) 094018]

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

Jets and event shapes



[P. Nason, G. Zanderighi, JHEP 06 (2023) 058]

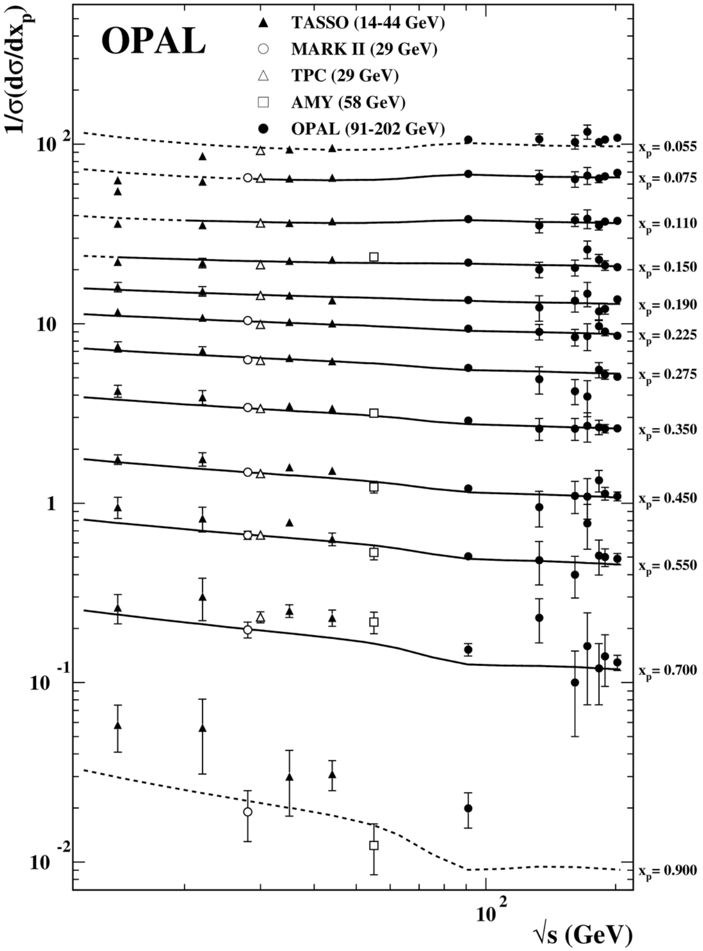
Linear power corrections in large n_f limit in 3-jet region ⇒ constant shift of pert. prediction replaced by observable dependent shift ζ(.)

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

Scaling violation in hard FFs



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

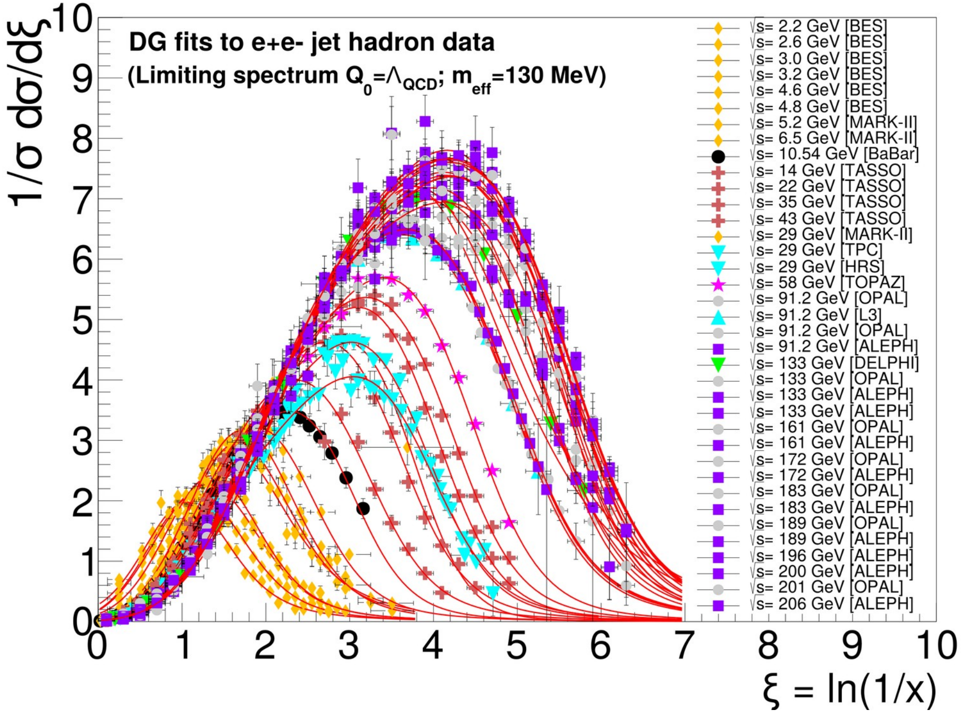
$$1/\sigma d\sigma/dx = \int_0^1 \sum_f C_f(z,\alpha_S(Q)D_f(x/z)\, dz/z$$

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? $\sqrt{s} < m_Z$?)

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

Soft FFs in e^+e^-



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 $\Rightarrow$ $\Delta\alpha_{S,theo} \leq 0.001$?

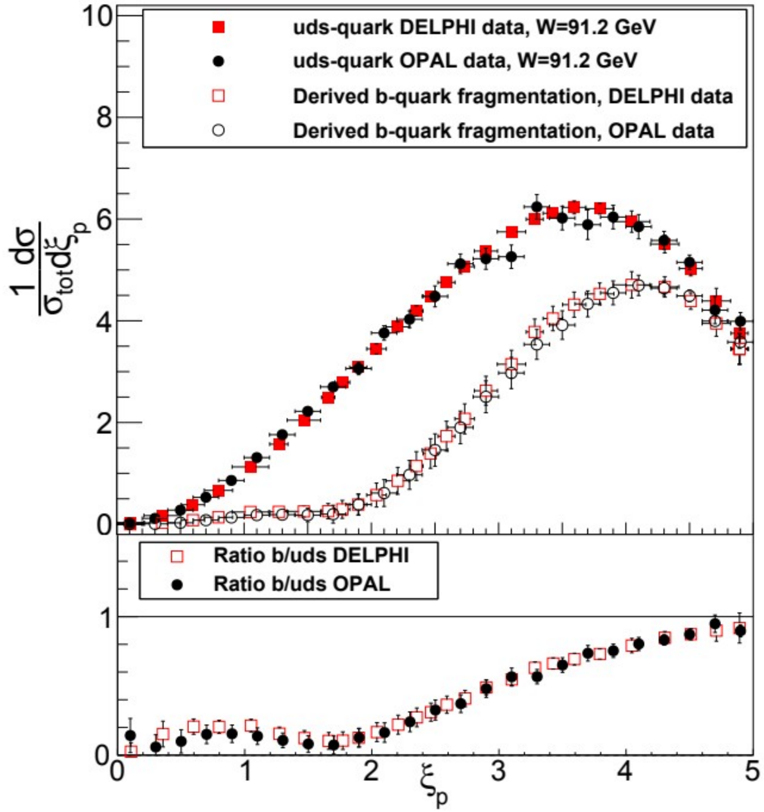
With c, b, (t) tags: study heavy quark fragmentation

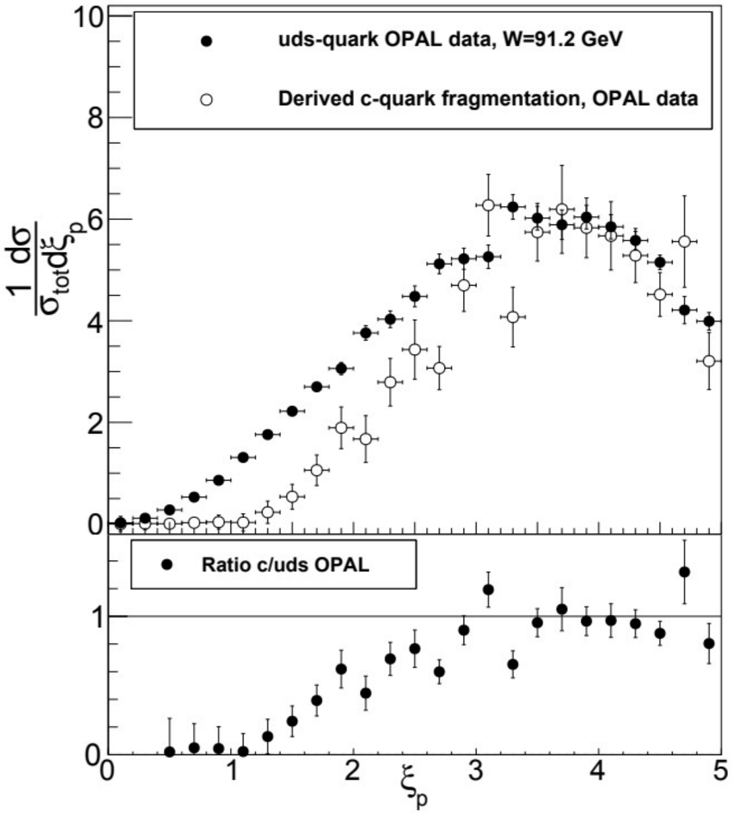
[R. Perez-Ramos, D. d'Enterria, arxiv: 2203.08271]

Soft FFs in e^+e^-: dead cone effect

Study heavy quark Q scaled momentum dist'n

[SK, Ochs, Perez Ramos, Phys. Rev. D107 (2023) 094039]





Frag'n of Q with $v_Q/c < 1$ different from light q

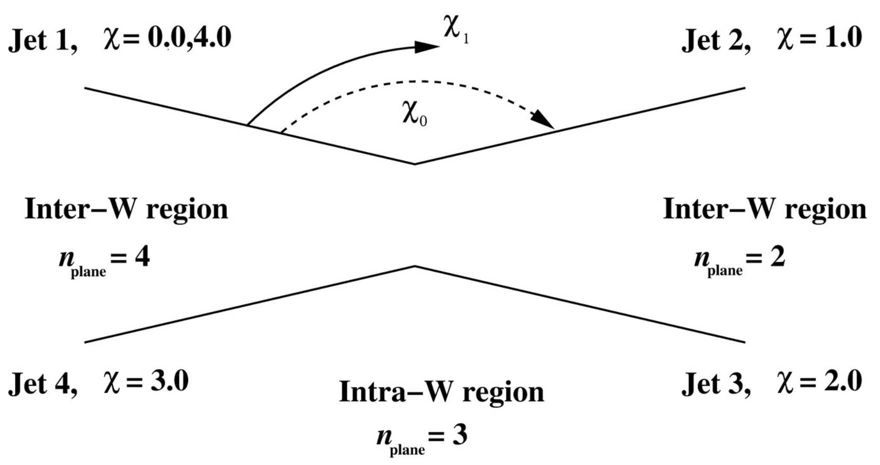
Q jet modelling
Q tagging
m_Q?

Future e^+e^-:
Reduced stat. and exp. errors
$\sqrt{s}$ dependence

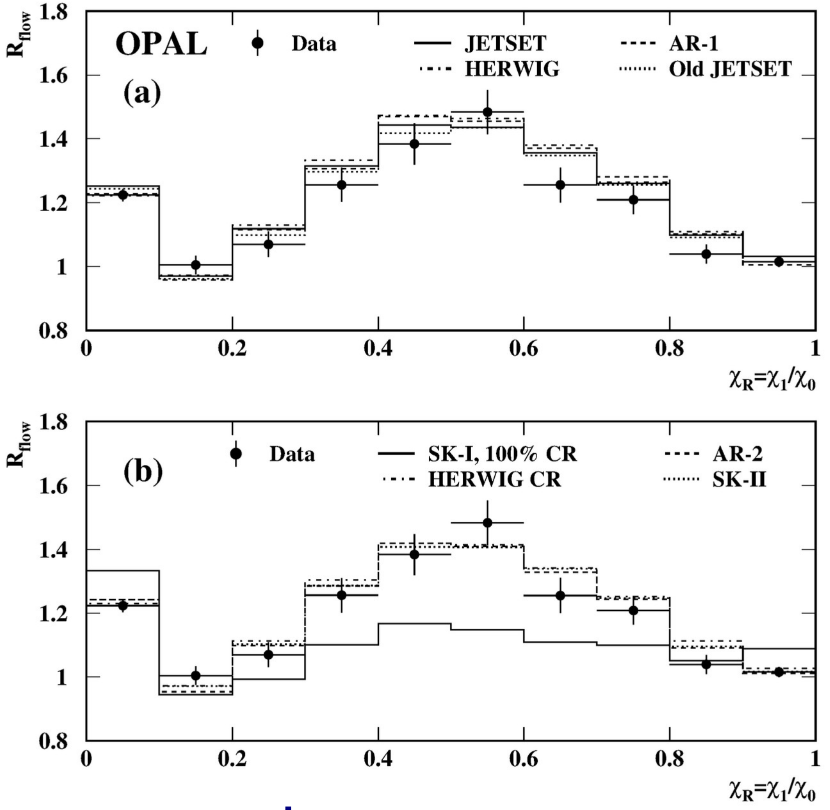
Colour Reconnection in W pairs

CR effects on m_W (±xxMeV), m_t (±xxMeV), ZH(jets), ...

Ratio of charged particle flow in planes within (intra) or between (inter) Ws



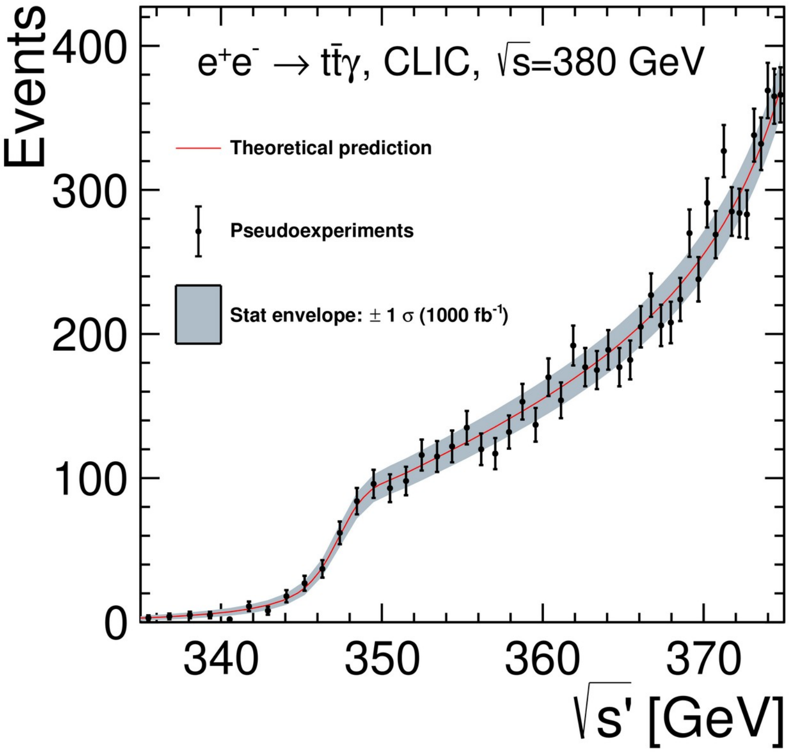
[OPAL coll., Eur. Phys. J. C45 (2006) 291]

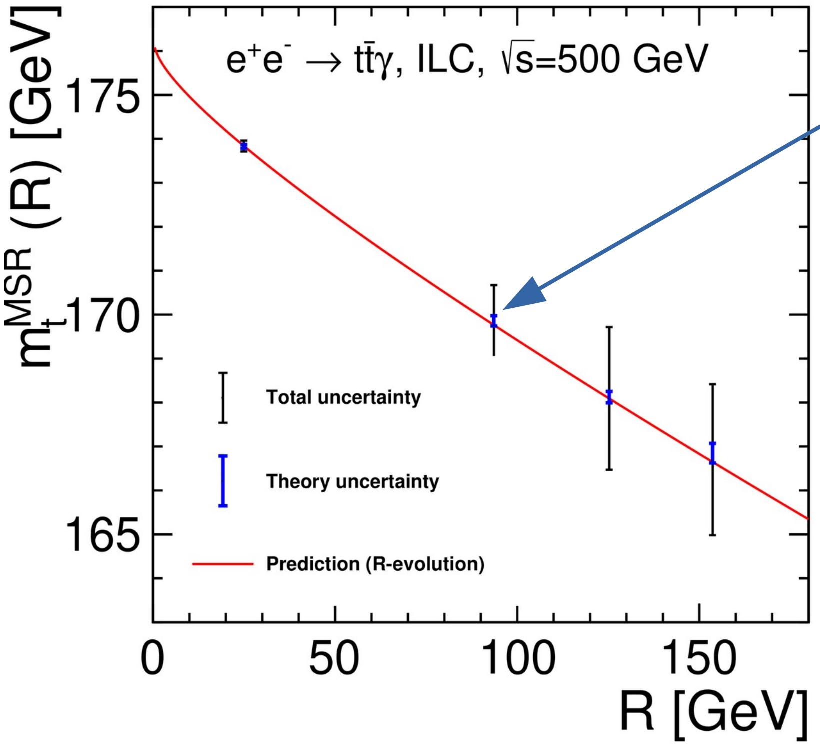


FCC-ee: 10^4·LEP W pairs, smaller exptl. systematics

Quark mass running: top

$e^+e^- \rightarrow t\bar{t}\gamma$ to access $m_t(s')$ at production: $s' = s(1-2E_\gamma/\sqrt{s})$





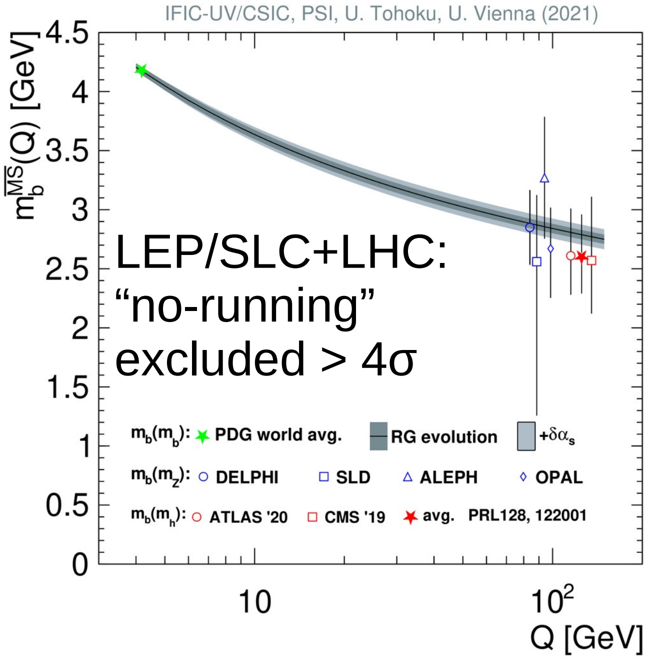
Accessible at $\sqrt{s}$ = 380 GeV

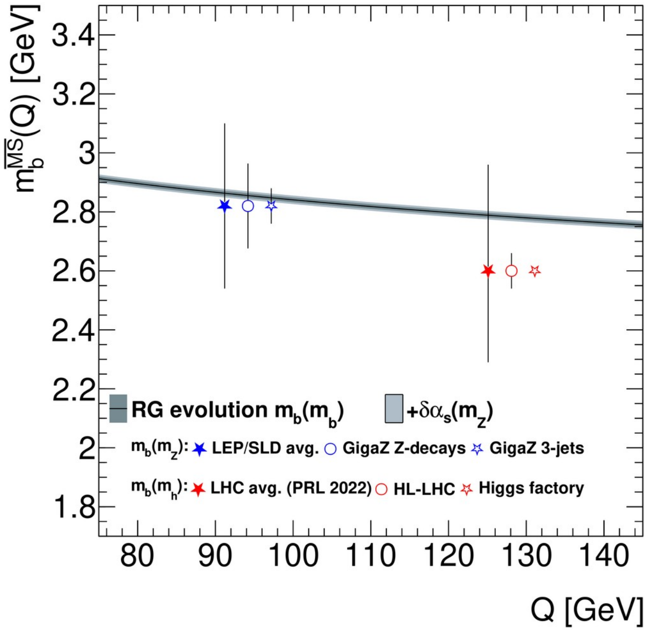
[M. Boronat et al, Phys. Lett. B804 (2020) 135353]

Quark mass running: b

$e^+e^- \to Z \to b\bar{b}$(+jet): $R_{0,b} = \Gamma_{Z\to b\bar{b}}/\Gamma_{Z\to had} \sim (m_b/m_Z)^2$,

$R_3^{(b)}/R_3^{(light)} \sim (m_b/m_Z)^2/y_{cut}$; $pp \to H(H \to b\bar{b}, ZZ) + X$, $\Gamma_{H\to b\bar{b}}/\Gamma_{H\to ZZ} \sim m_b^2$





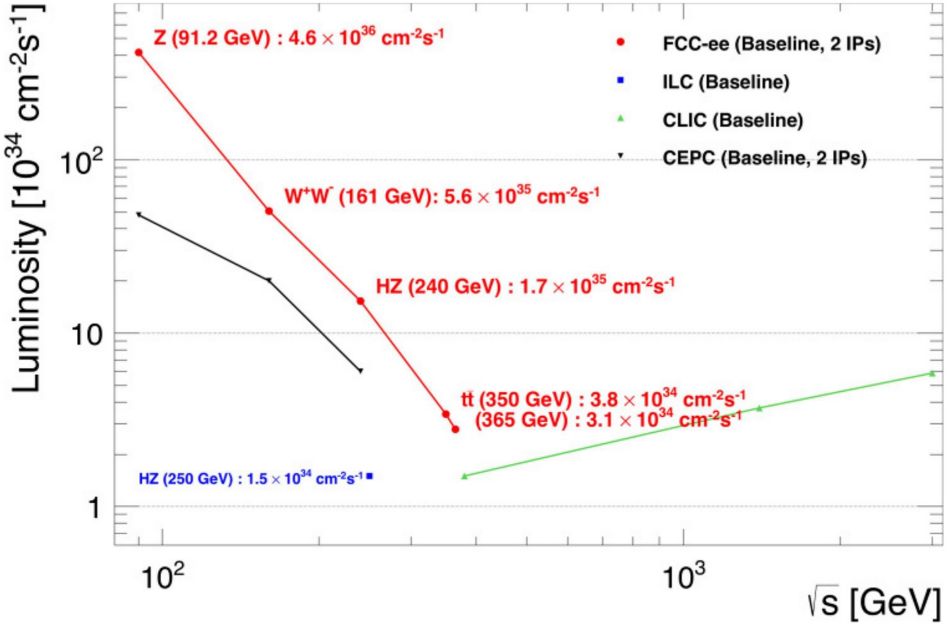
[J. Aparisi et al, arxiv: 2203.16994 and refs]

SM Yukawa $y_b = m_b/(\sqrt{2}vev_H) \Rightarrow y_b$ *or* m_b from $H \to b\bar{b}$

Extrapolation of “GigaZ 3-jets” needs NNLO for $e^+e^- \to b\bar{b}$+jet

FCC-ee with $\sqrt{s} < m_Z$

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



Or consider ISR events on Z peak

Benefactors:

MC tuning and soft QCD

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

R_l^γ and $\alpha_S(m_Z)$ at high precision?

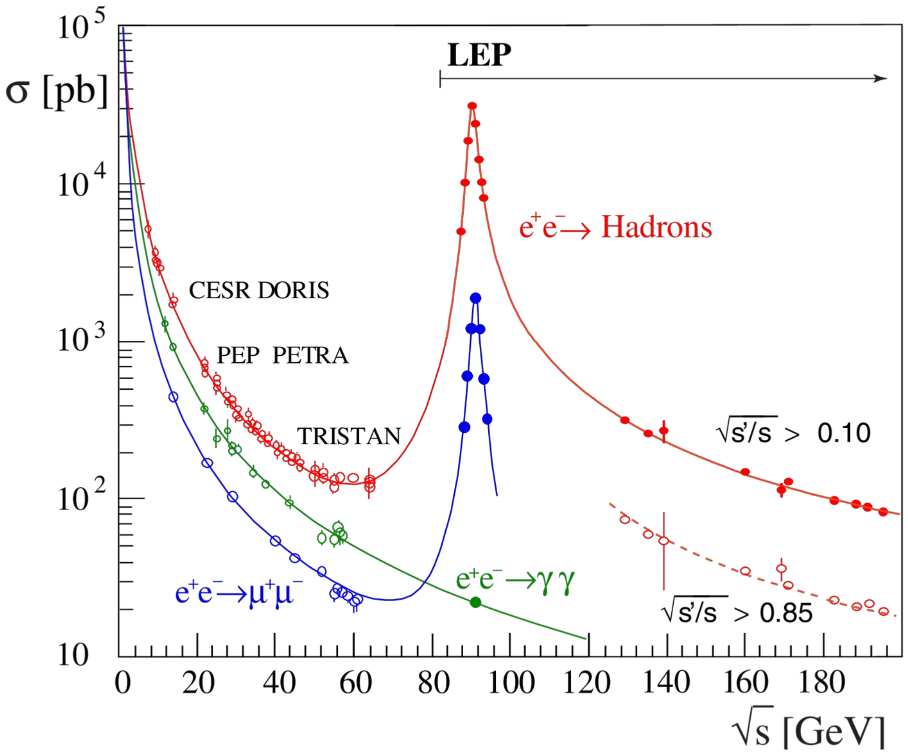
$\sin^2\theta_W(\sqrt{s})$ from $A_{FB}^{(l,q)}(\sqrt{s})$?

$m_{b(c)}(\sqrt{s})$?

In-situ calibrations?, EW, etc pp

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

R_l^γ at $\sqrt{s} < m_Z$ with FCC-ee



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

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

[A.V. Nesterenko, in 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

[FCC coll., Eur. Phys. J. C79 (2019) 474]

$\Delta R_l^Z/R_l^Z \approx 5 \cdot 10^{-5}$ FCC-ee, dominated by lepton acceptance $\Rightarrow$ similar for R_l^γ

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

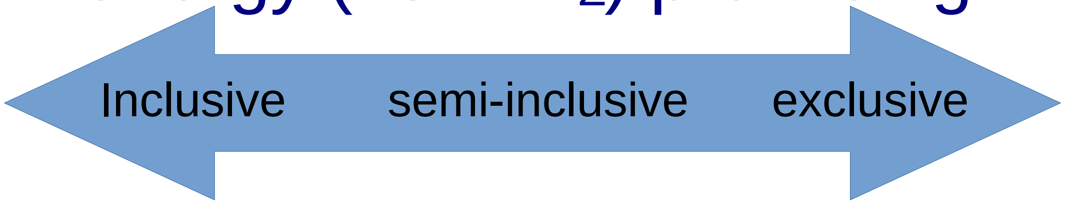
Pure γ couplings, low scale

⇒ less BSM "pollution"

$\Delta\alpha_{S,theo} \approx 0.0002$ as for $R_l^{Z,W}$ (pg3)

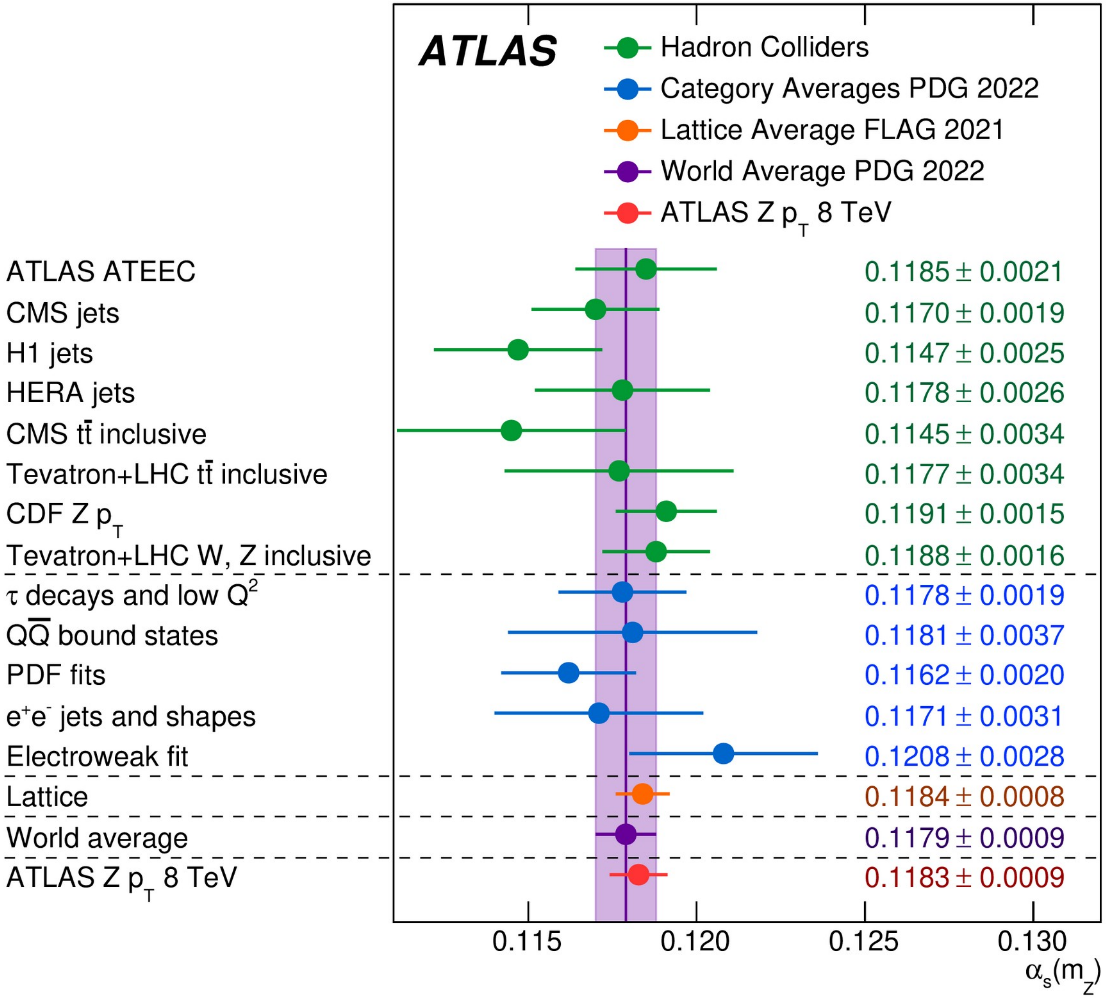
Summary / Outlook

- FCC-ee et al great potential for QCD
  - Running strong coupling and quark masses
  - q and g properties (FFs, subjets, ML training)
  - Non-pert. QCD: power corr., colour recon., MC models, ...
- FCC-ee, ep colliders (FCC-eh, LHeC) and Lattice QCD for $\Delta\alpha_S(m_Z) \approx 0.1\%$
- FCC-ee low energy ($\sqrt{s} < m_Z$) promising!



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

Summary



[ATLAS-STDM-2023-01, arXiv: 2309.1298]

Future $\Delta\alpha_S(m_Z)$ estimates

- 1.5% (theory,pdfs)
- <1% (theory, spectral functions)
- 1.5% (theory)
- 0.2% (future ep pdfs)
- 1% (theory)
- 0.1% (future ee)
- 0.1% (theory)
- <1% (theory,pdfs)

[D. d'Enterria, S. Kluth, G. Zanderighi (eds.), arxiv: 2203.08271]