QCD and top phenomena at future colliders

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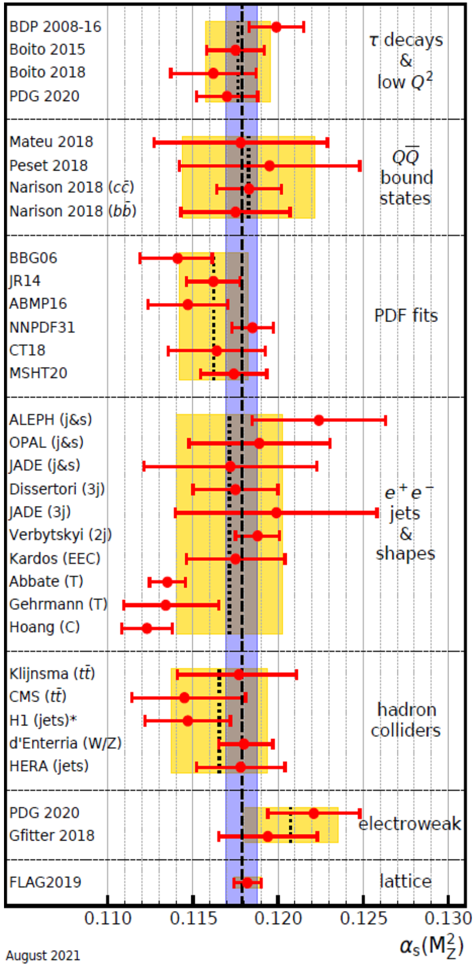
25.04.23

1 Introduction

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



FCC-ee

FCC-ee

FCC-eh
LHeC

FCC-ee

FCC-hh

FCC-ee

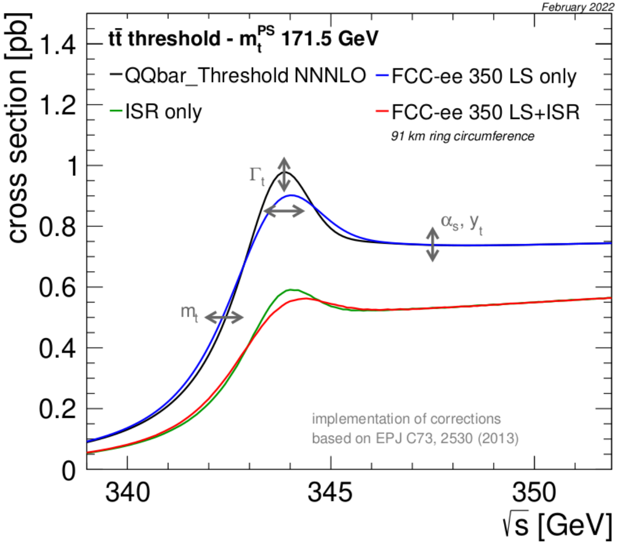
Summary from “α_S (2022) – Precision measurements of the QCD coupling” at ECT* (Trento) 31.01.-04.02.2022

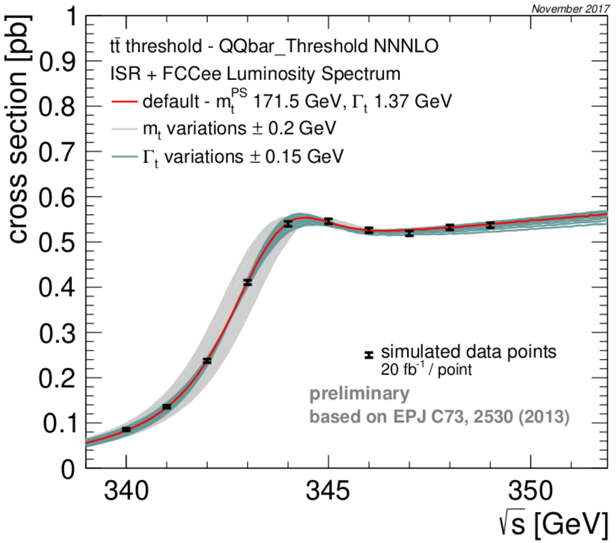
FCC-ee impact on most categories
Expect $3{\cdot}10^{12}$ hadronic Z decays ⇒ $6{\cdot}10^{11}$ $Z \to b\bar{b}$, 10^{11} τ pairs, …
$5{\cdot}10^{8}$ W decays, 10^{6} $t\bar{t}$ on threshold

FCC-hh, FCC-eh (LHeC)

2 Top quark properties in e^+e^-

Threshold scan: ~10^6 $t\bar{t}$ events, ultimate measurement of m_t and Γ_t





[FCC coll., Eur. Phys. J. C79 (2019) 474, arxiv: 2209.11267]

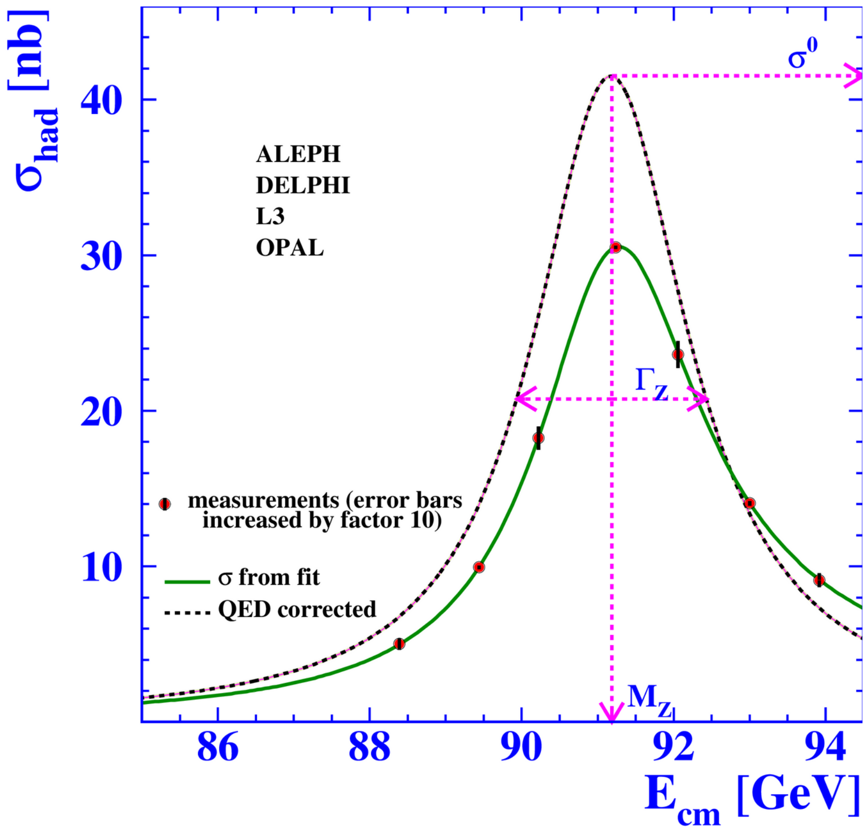
$m_t = (\ 171.5 \pm 0.017_{stat} \pm 0.007_{cms} \pm 0.005_{\alpha S} \pm 0.040_{theo}\ )$ GeV

$\Gamma_t = (\ 1.37 \pm 0.045_{stat} \pm 0.003_{cms} \pm 0.005_{\alpha S} \pm 0.040_{theo}\ )$ GeV

$\Delta\alpha_S(m_Z) \approx 0.0002$ needed, unambigous theo. definition of m_t

3 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

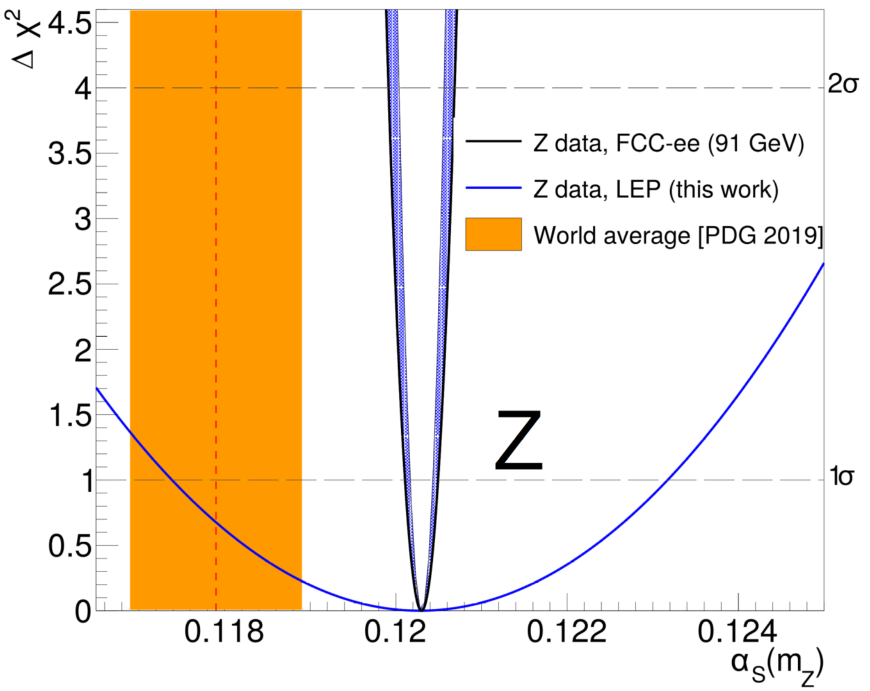
LEP:

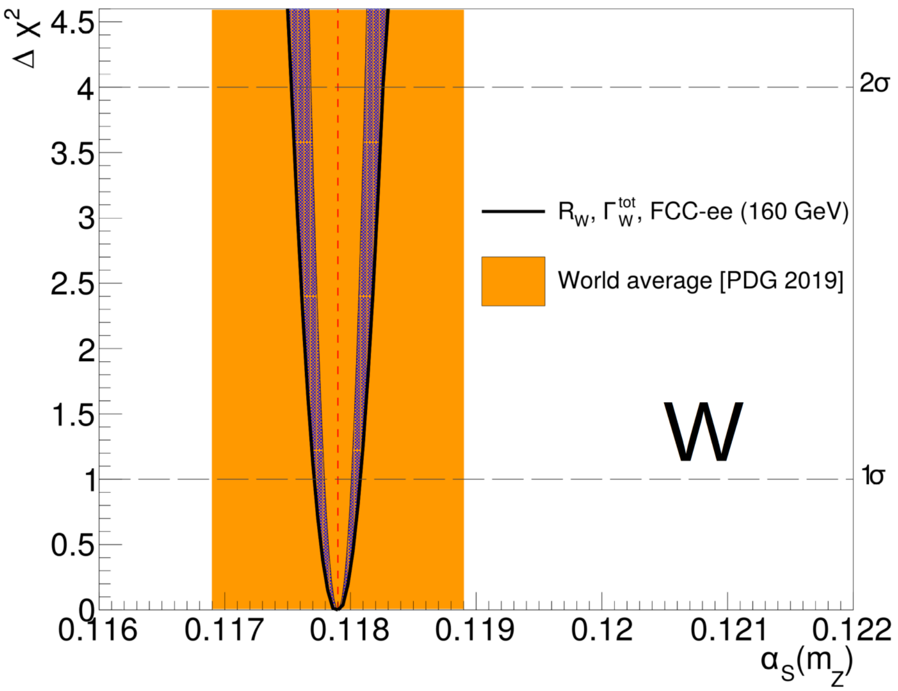
Z: $\alpha_S(m_Z) = 0.120 \pm 0.003_{exp} \pm 0.001_{theo}$

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

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

3 Z and W decays





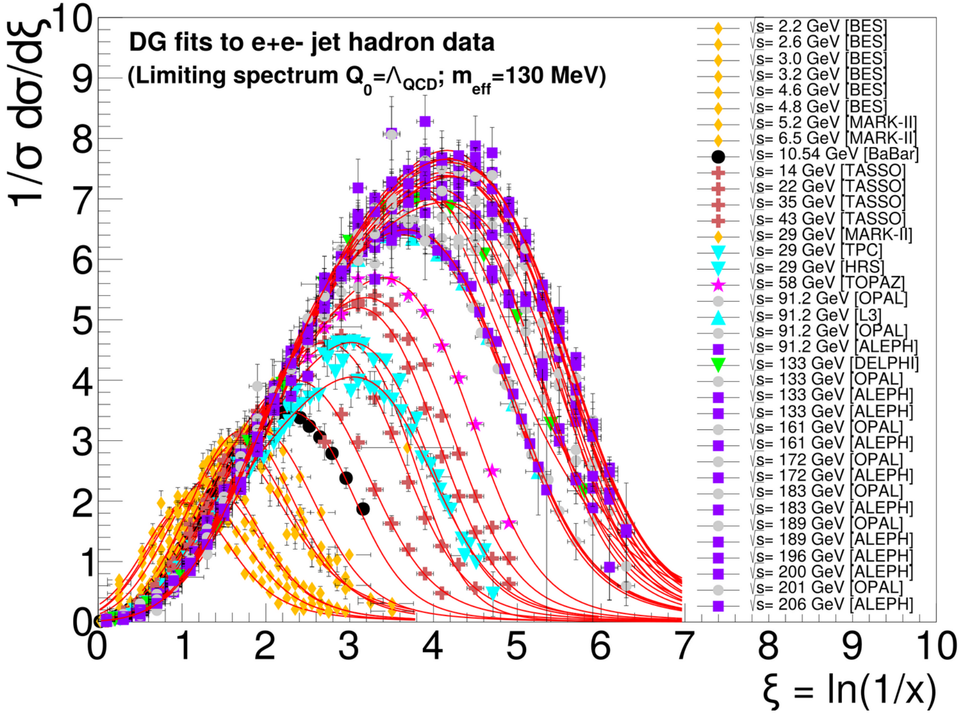
FCC-ee: improved α_{QED}, $|V_{cs}|$, $|V_{cd}|$, m_W; assume N4LO QCD

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, in arxiv: 2203.08271]

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

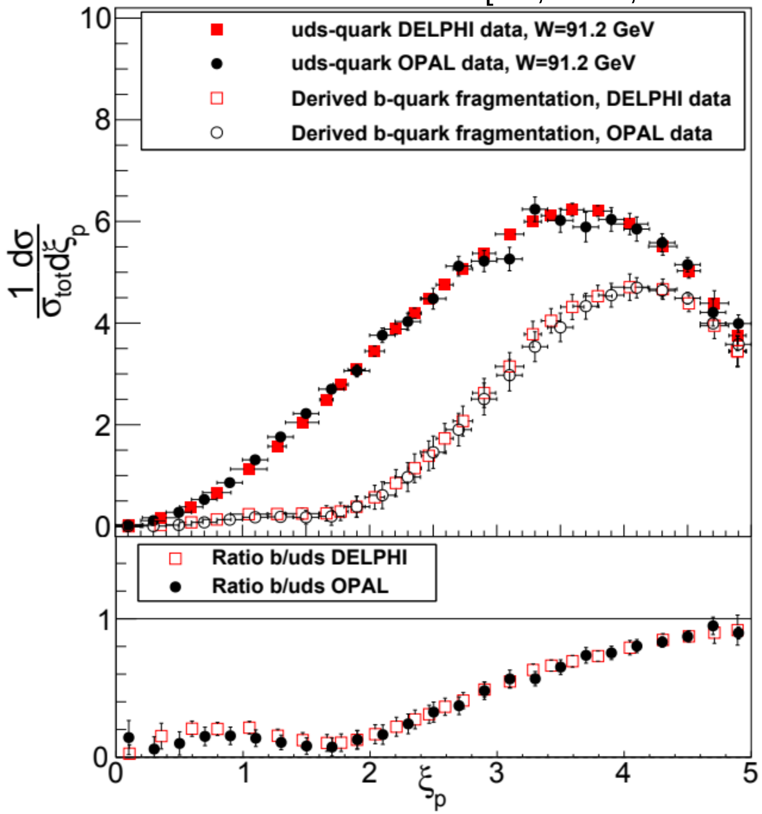
With c, b, (t) tags: study heavy quark fragmentation

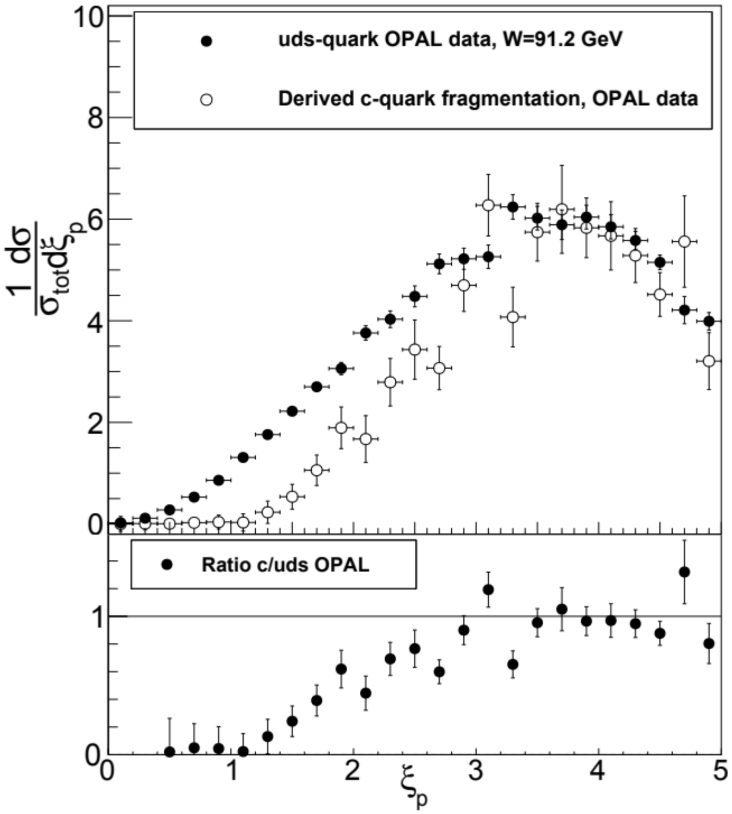
[R. Perez-Ramos, D. d'Enterria, arxiv: 2203.08271]

4 Soft FFs in e^+e^-

Heavy quark Q fragmentation: dead cone effect

[SK, Ochs, Perez Ramos, arxiv: 2303.13343]





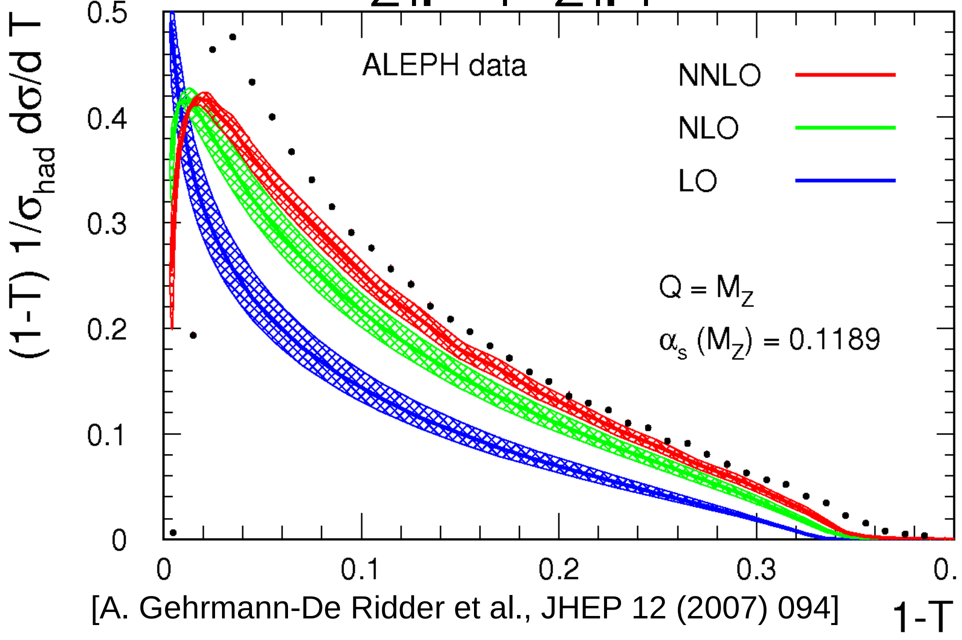
Frag'n of Q with $v_Q/c < 1$ different from light q

Q jet modelling
Q tagging

Future e^+e^-: Reduced stat. and exp. errors

5 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]

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

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

MC-based vs analytic models

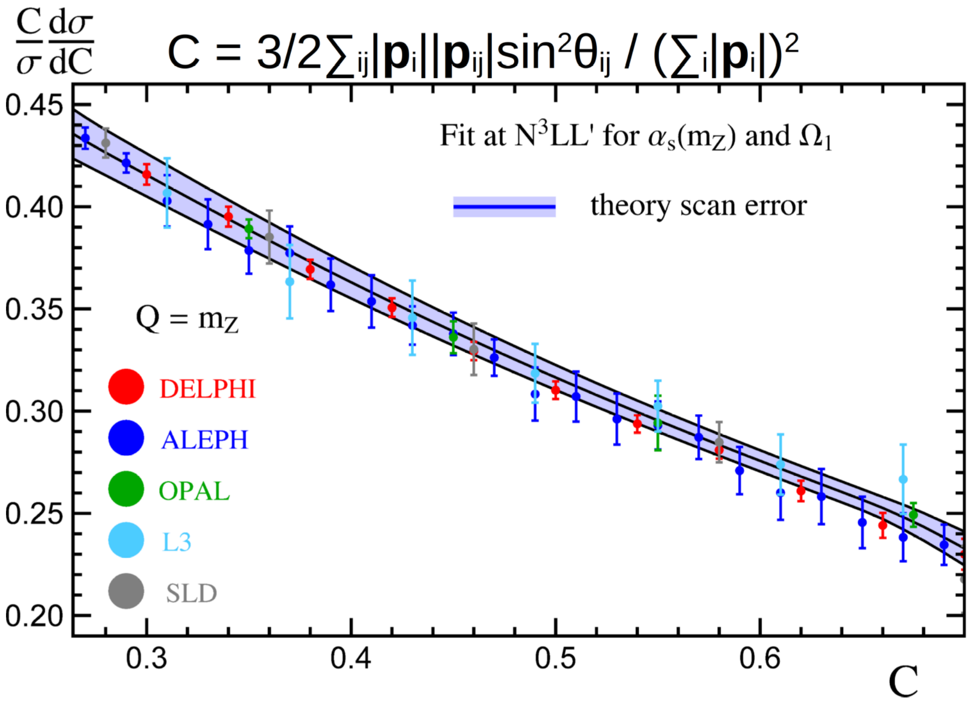
Typical differences MC vs analytic $\Delta\alpha_S(m_Z)_{\text{np-model}} = O(1\%)$

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

Same structure for other event shapes and for jet production rates

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

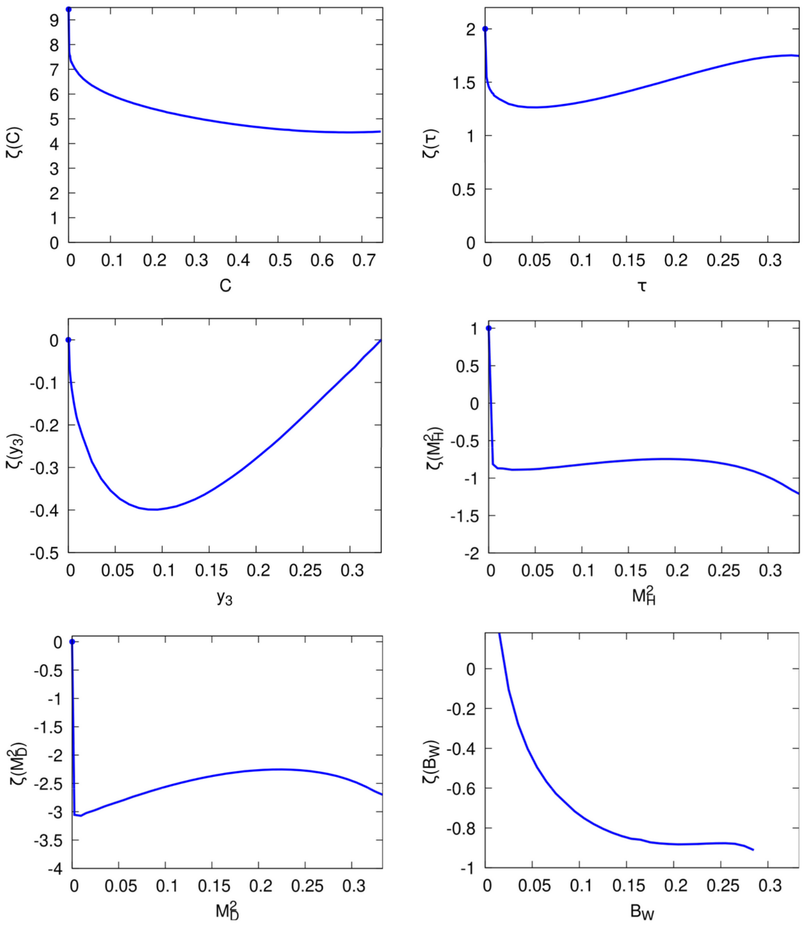
[A. Hoang et al., Phys. Rev. D91 (2015) 9]

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

5 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(.)

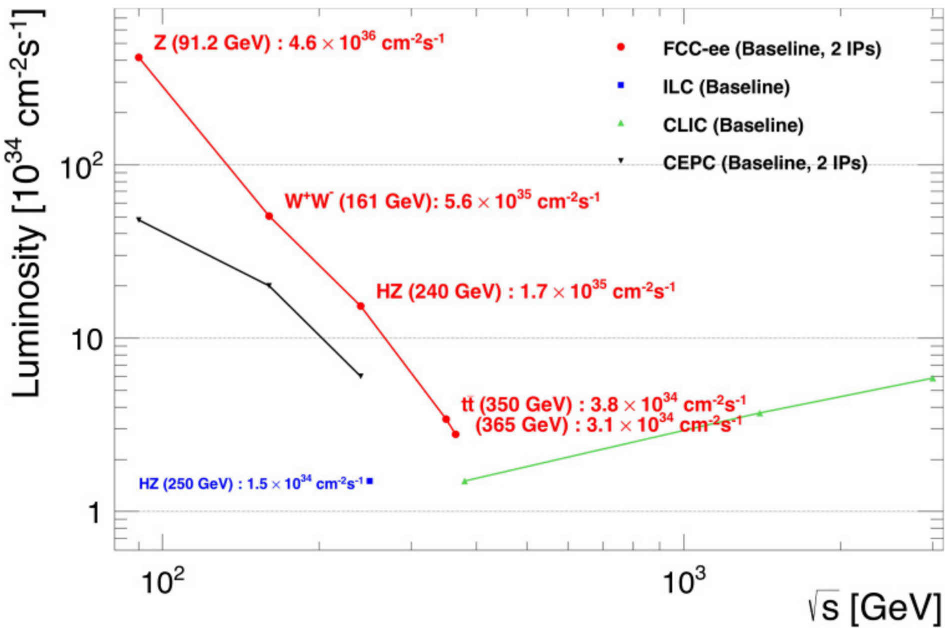
significant $\Delta\alpha_S(m_Z)$ w.r.t. const. shift

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%?, $\Delta\alpha_{S,hadron\ masses}$ ≈ 1%?

6 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 (→1.3) ⇒ hadronisation systematics

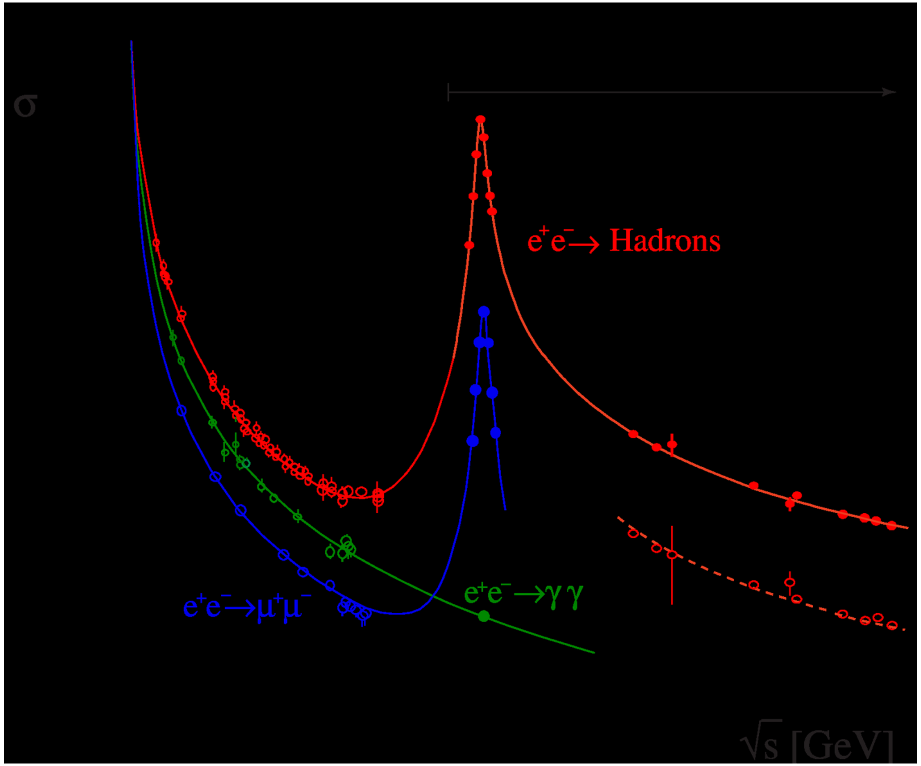
R_l^γ at high precision

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]

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



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

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

[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 ⇒ similar for R_l^γ

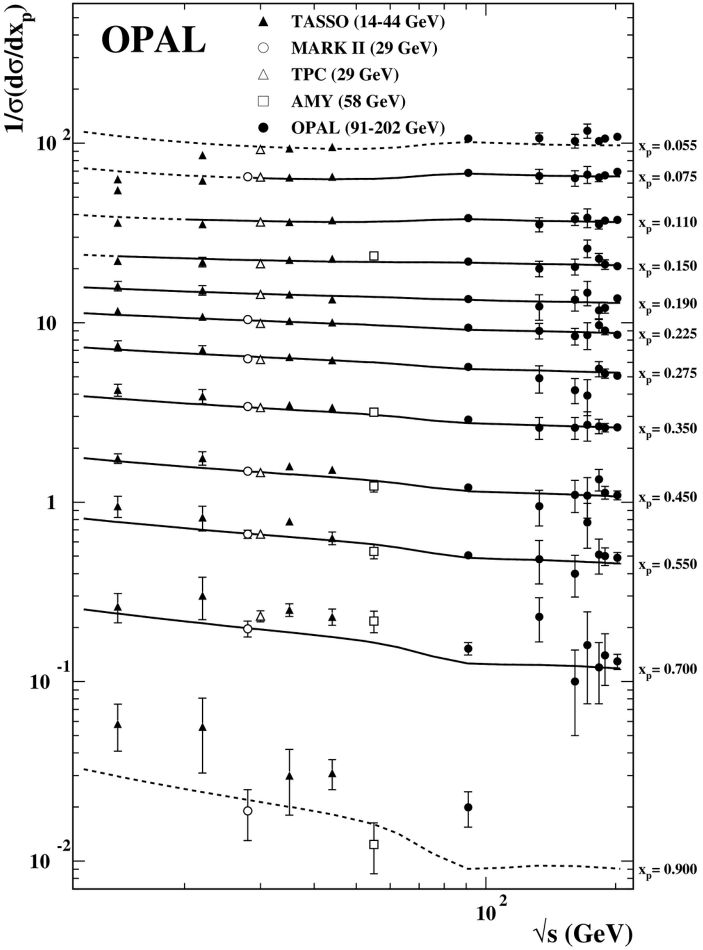
⇒ $\Delta\alpha_{S,exp} \approx 0.0001$

Pure γ couplings, low scale

⇒ less BSM “pollution”

$\Delta\alpha_{S,theo} \approx 0.0002$ as for $R_l^{Z,W}$ (→1.2)

7 Scaling violation in hard FFs



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

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

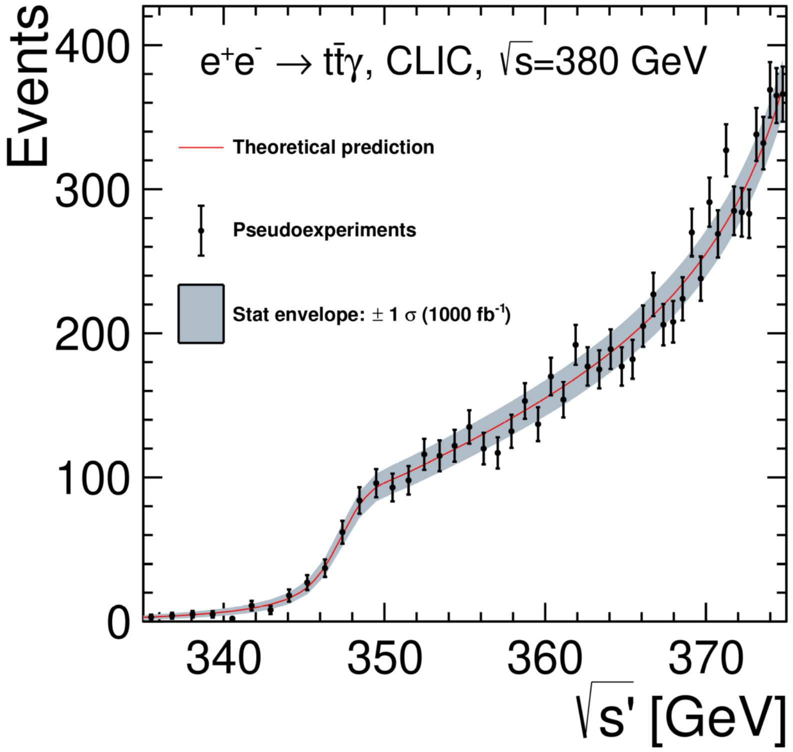
LEP (ADO) NLO DGLAP analyses:
$\alpha_S(m_Z) = 0.1192 \pm 0.0056_{exp} \pm 0.0070_{theo}$

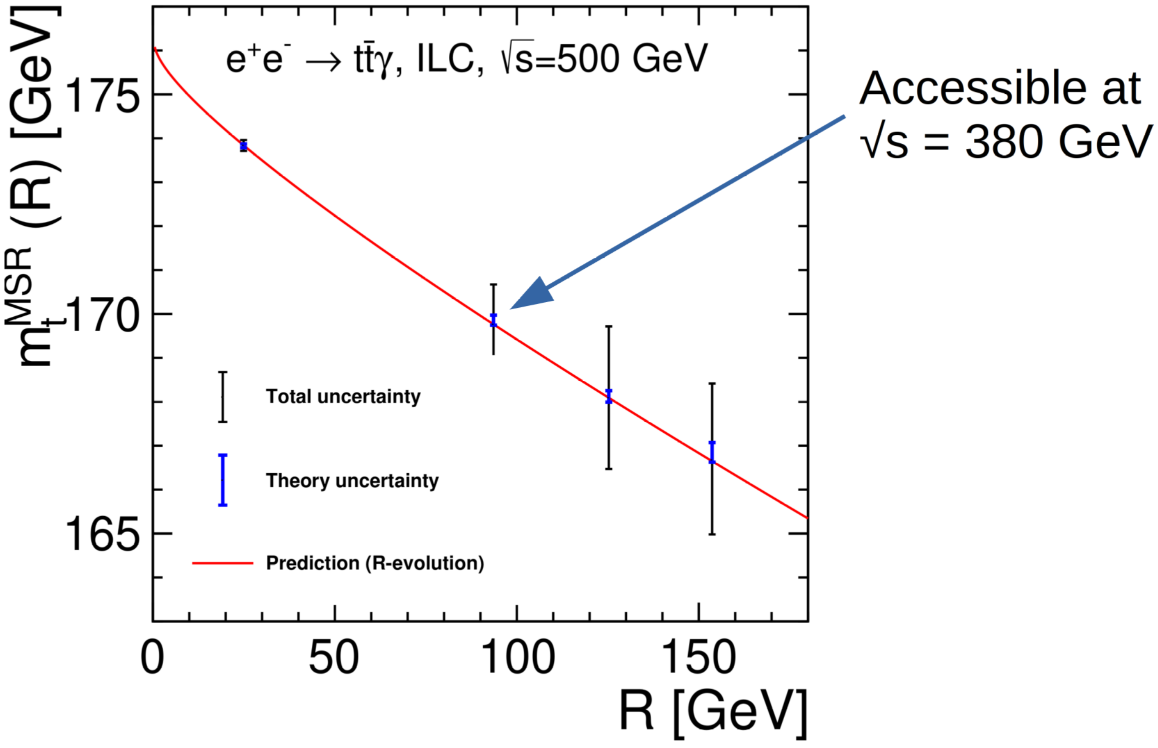
FCC-ee statistics and systematics ⇒ exp. unc. $\Delta\alpha_{S,exp} < 1\%$ (or better? $\sqrt{s} < m_Z$?)

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

8 Quark mass running: top

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

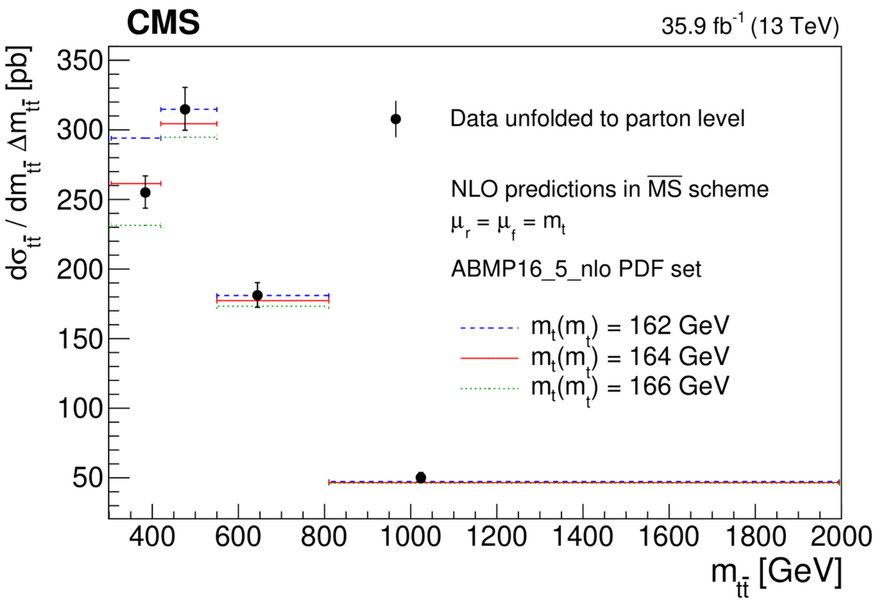


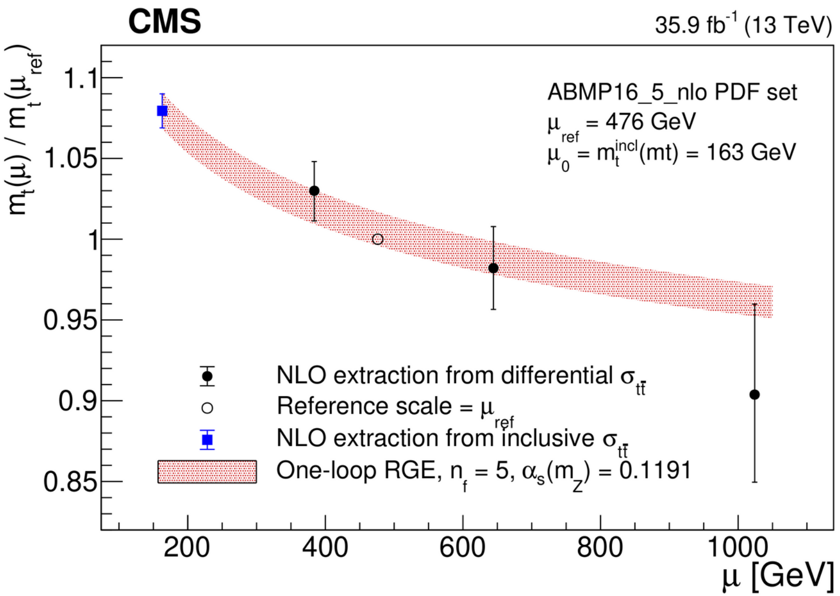


[M. Boronat et al, Phys. Lett. B804 (2020) 135353]

8 Quark mass running: top

Measure $d\sigma/dm_{t\bar{t}}$ in pp collisions: $m_{t\bar{t}}^2 = 2m_t^2 + 2(E_t E_{\bar{t}} - \mathbf{p}_t \cdot \mathbf{p}_{\bar{t}})$



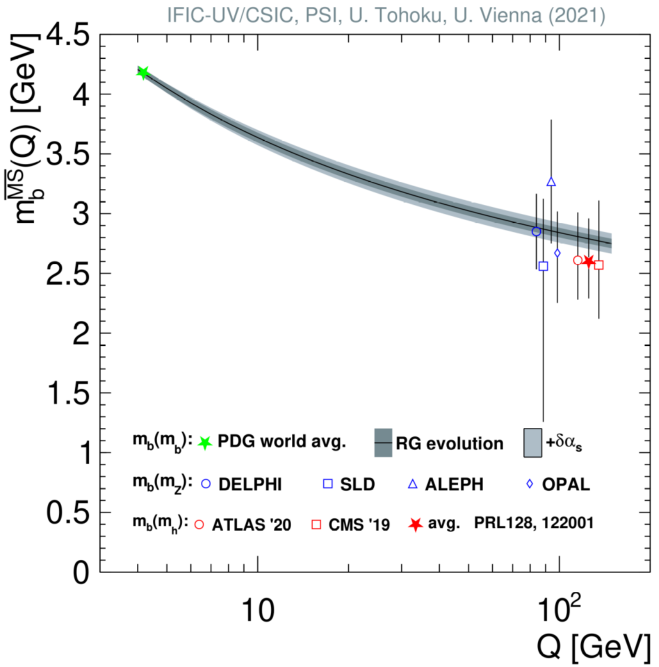


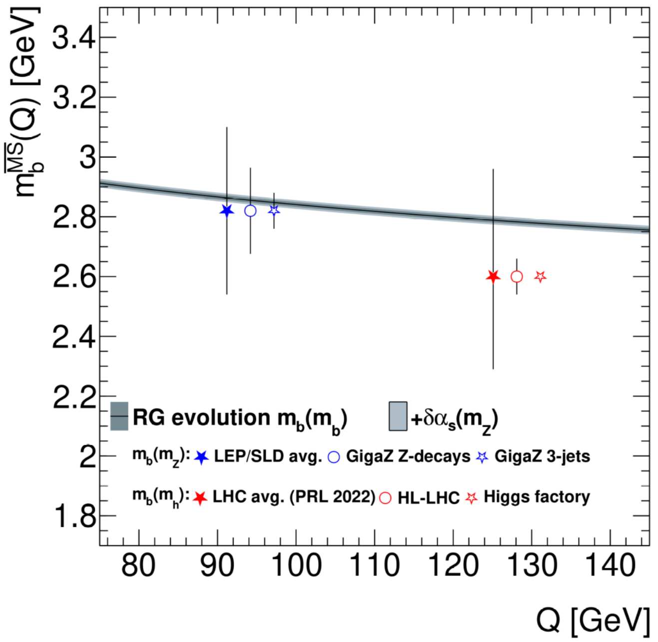
Expect much larger $m_{t\bar{t}}$ reach with FCC-hh

[CMS, Phys. Lett. B803 (2020) 135263]

8 Quark mass running: b

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



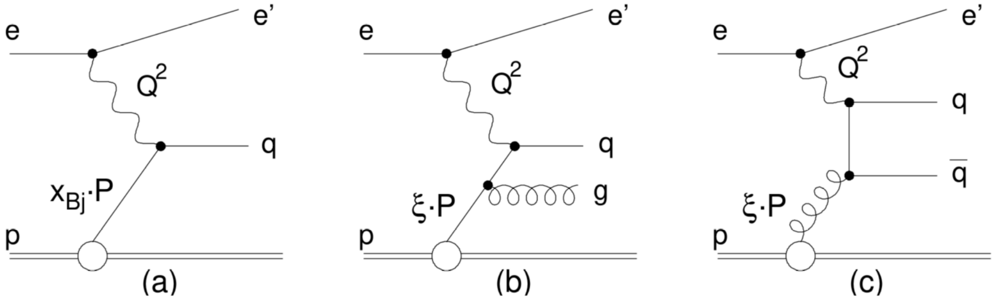


[J. Aparisi et al, arxiv: 2203.16994]

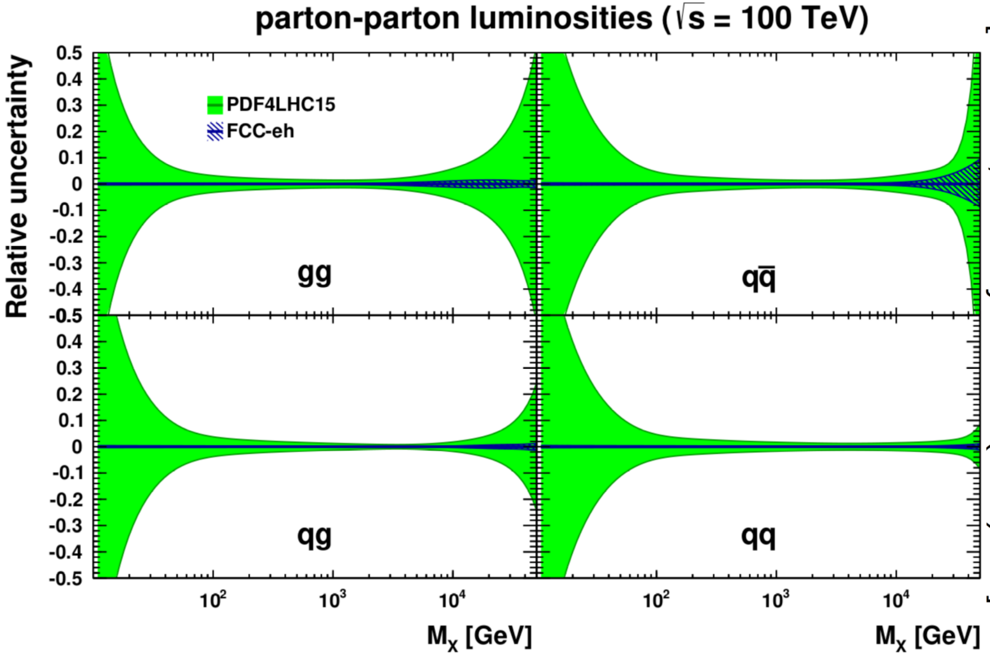
SM Yukawa $y_b = m_b/(\sqrt{2}vev_H) \Rightarrow y_b$ or m_b from $H \to b\bar{b}$

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

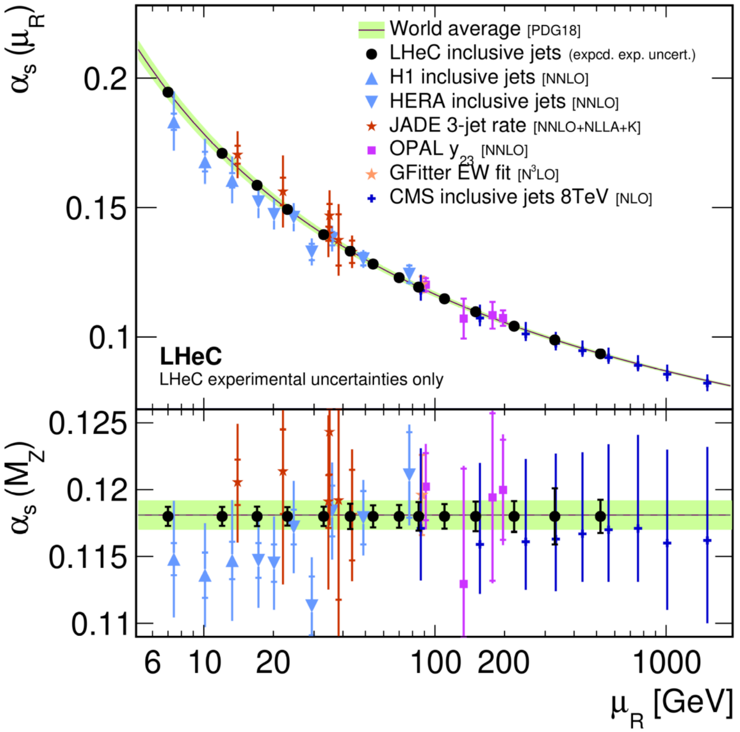
9 eP colliders: LHeC and FCC-eh



	E_p [TeV]	E_e [GeV]	$\sqrt{s}$ [TeV]
LHeC:	7	50/60	1.2/1.3
FCC-eh:	50	60	3.5

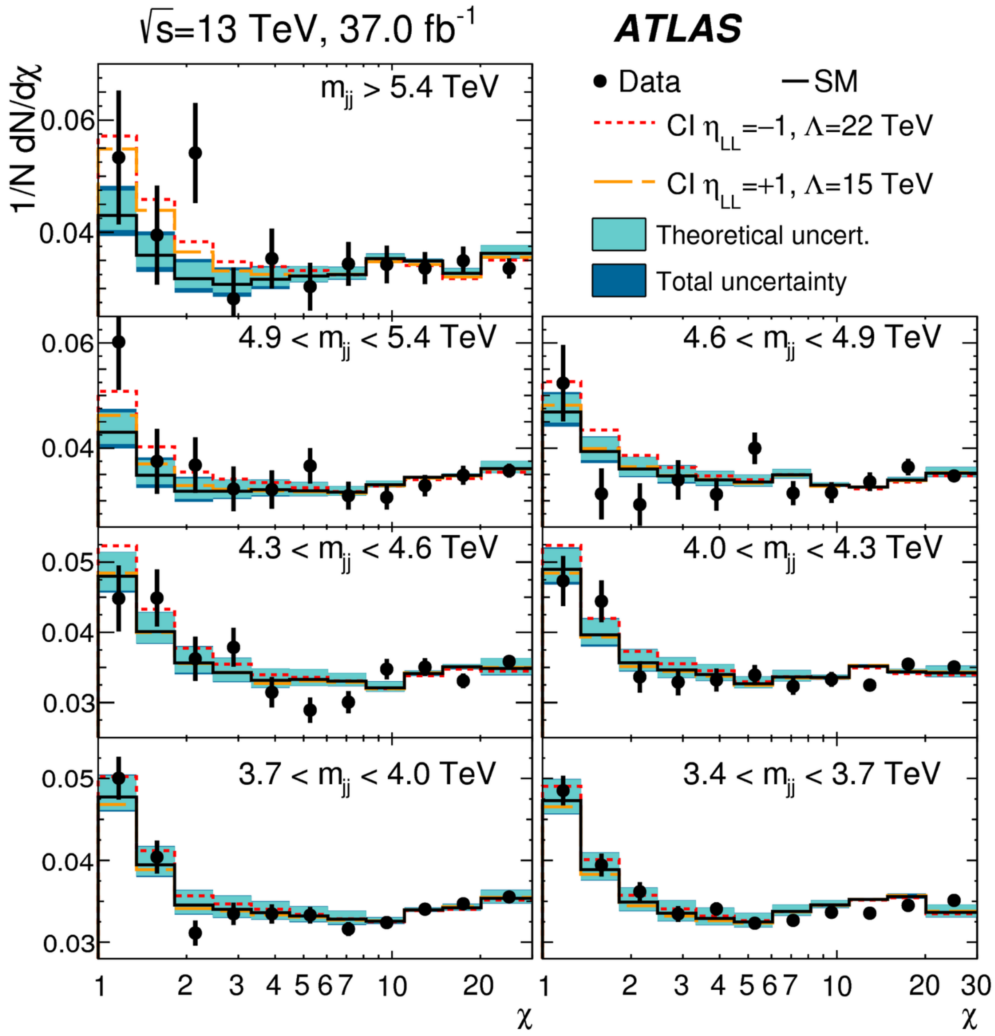


[FCC coll., Eur. Phys. J. C79 (2019) 474]



[LHeC, FCC-eh, J. Phys. G48 (2021) 110501]

10 Di-jets in pp



Anti-k_t jets R=0.4

$p_{t,jet1}$ > 440 GeV, $p_{t,jet2}$ > 60 GeV

$\chi = \cot^2(\theta^*/2) \approx e^{(\eta 1 - \eta 2)}$

Expect much larger m_{jj} reach at HL-LHC and FCC-hh (≈50 TeV)

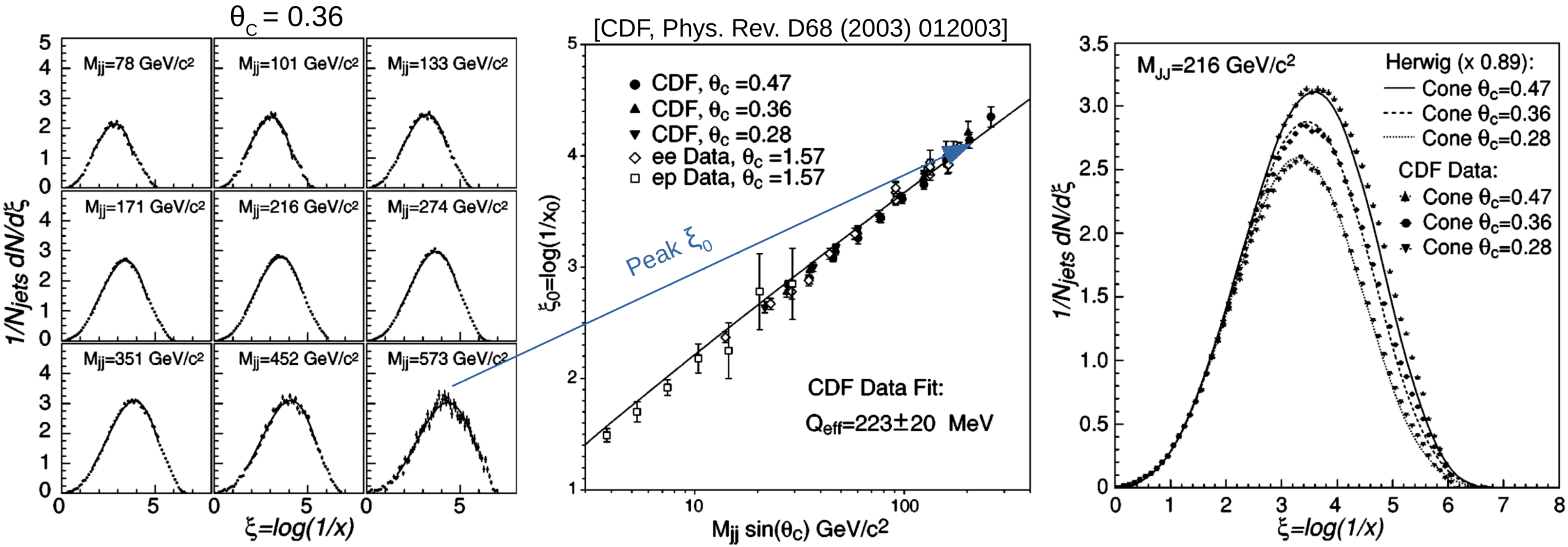
Searches, but also (absence of) quark substructure

[ATLAS, Phys. Rev. D96, 052004 (2017)]

10 Di-jets in pp fragmentation

CDF cone jets R = 0.28, 0.36, 0.47, $x = p/E_{jet}$, $\xi = \log(1/x)$

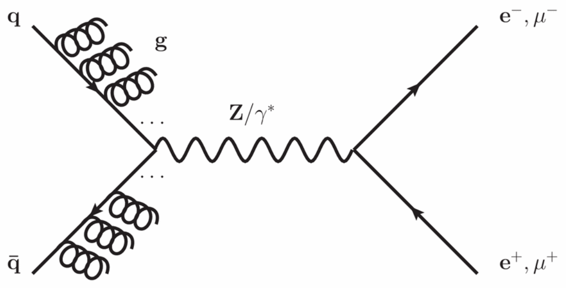
$p\bar{p}$ at 1.8 TeV, select balanced central di-jet events



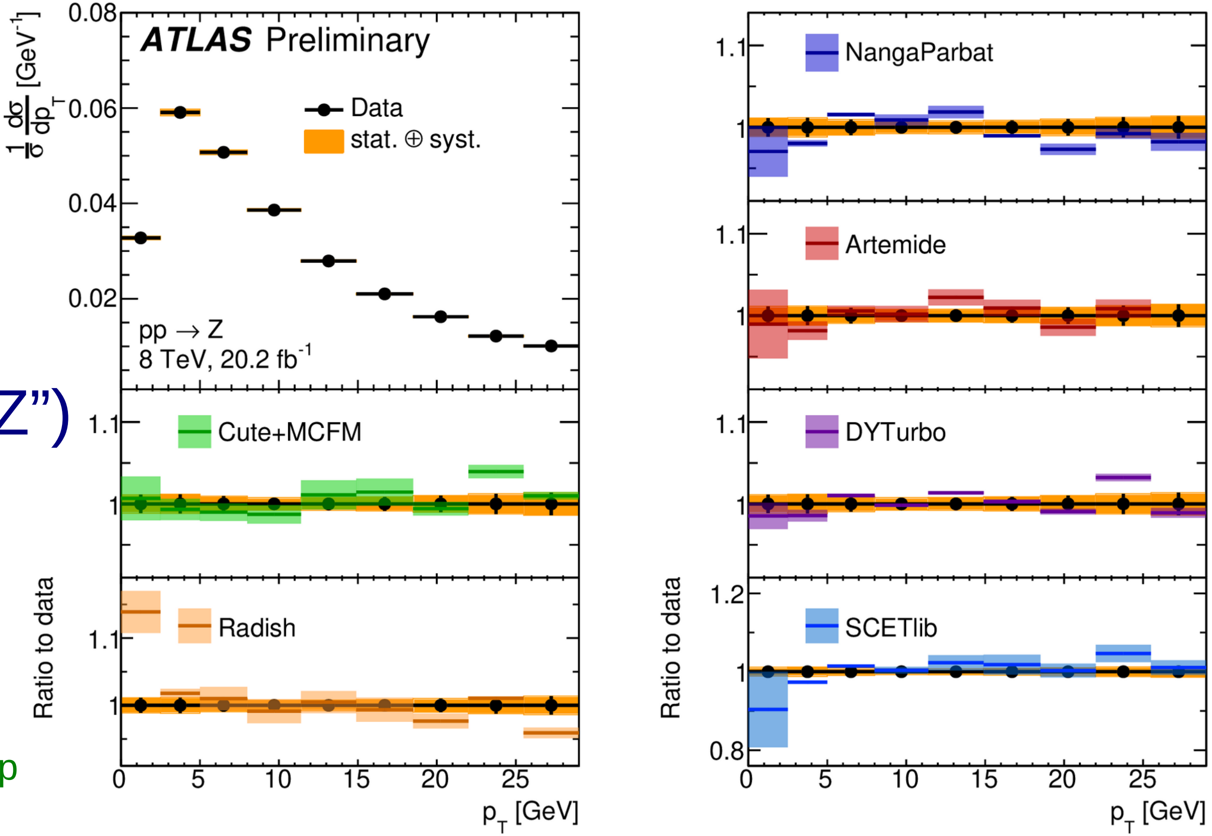
QCD MLLA* fit, probe of MC PS+had., $m_{jj} \approx 50$ TeV at FCC-hh

11 Drell-Yan in pp

Lepton pairs $m_{l\bar{l}} \approx m_Z$ in pp



[ATLAS-CONF-2023-013/15]

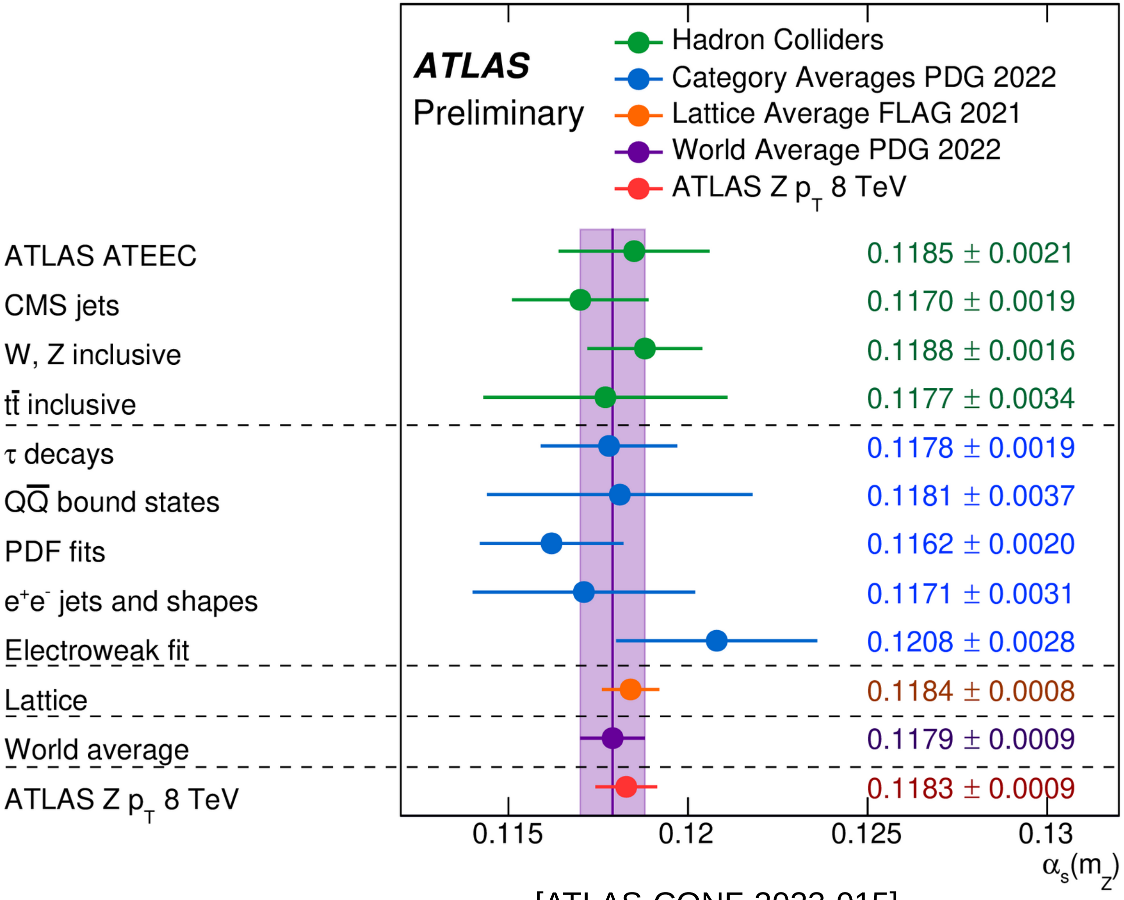


p_t spectrum of $l\bar{l}$ system ("Z") sensitive to $\alpha_S(m_Z)$

N3LO+N3LL result:

$\alpha_S(m_Z) = 0.1178 \pm 0.0004_{exp} \pm 0.0005_{pdf} \pm 0.0007_{scale}$

12 Summary



[ATLAS-CONF-2023-015]

Future $\Delta\alpha_S(m_Z)$ estimates

|
|
| 1.5% (theory,pdfs)
|

<1% (theory, spec.func.)

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]

12 Summary

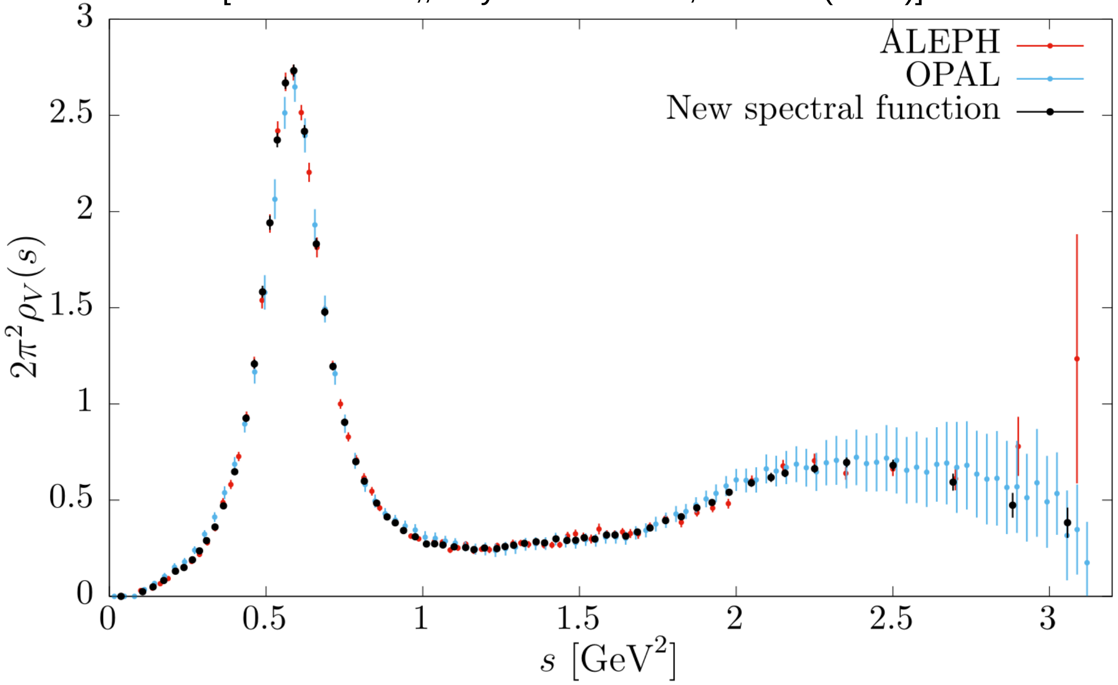
- FCC et al great potential for QCD
  - Running strong coupling and quark masses
- FCC et al ultimate top quark measurements
- FCC-ee, ep colliders (FCC-eh, LHeC) and Lattice QCD for $\Delta\alpha_S(m_Z) \approx 0.1\%$
- FCC-ee low energy ($\sqrt{s} < m_Z$) runs promising!

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

1.2 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., in arxiv: 2203.08271]

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

m_top: ee: top → ttbar threshold scan, top event shapes, etc
Hh: X + leptons, boosted top jets, groomed top jets

Gamma_top: ee: threshold scan

3.3 single top