QCD physics at FCC-ee

An overview of
FCC: QCD physics, D. d'Enterria, P. F. Monni (eds.)
sub. to European Strategy for Particle Physics – 2026 update
indico.cern.ch/event/1439855/contributions/6461624/

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"Among all forms of mistake,
prophecy is the most gratuitous."
George Eliot, Middlemarch

Introduction

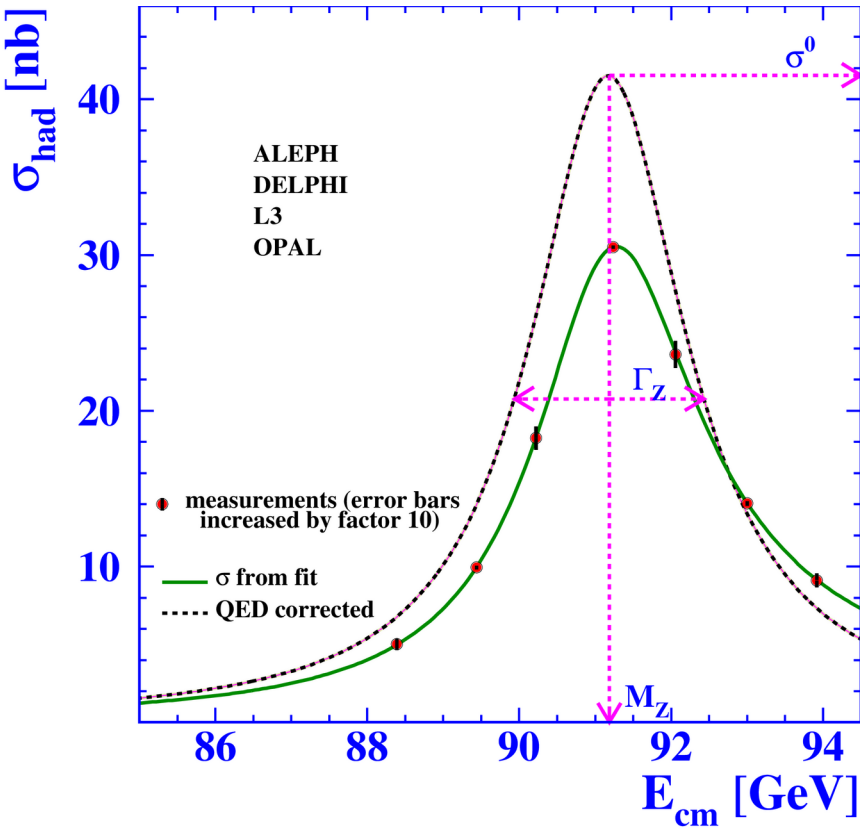
FCC-ee running strategy: very large $e^+e^- \to (Z/\gamma)^* \to q\bar{q}$ samples at all energy points

Run	Z	WW	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
time (years)	4	2	3	1	4
$\mathcal{L}_{\text{int}}$ (ab^{-1})	205	19.2	10.8	0.42	2.70
$e^+e^- \to Z$, WW, ZH, $t\bar{t}$					
N_{evts} (Z, W, H, top)	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH	2×10^6 $t\bar{t}$	
N_{evts} (HFS decays)	4.2×10^{12}	1.1×10^8	1.2×10^6	0.9×10^6	
N_{partons} (HFS decays)	≥ 2	≥ 4	≥ 4	≥ 6	
E_{j} (max. jet scale probed)	45 GeV	40 GeV	45, 65 GeV	125 GeV	
$e^+e^- \to Z^{(*)} \to q\bar{q}$					
σ	32.5 nb	40 pb	13.5 pb	5.3 pb	
N_{evts} (HFS)	4.2×10^{12}	7.7×10^8	1.5×10^8	1.7×10^7	
E_{j} (max. jet scale probed)	45 GeV	80 GeV	120 GeV	180 GeV	

Selection of $e^+e^- \to (Z/\gamma)^* \to q\bar{q}$ at $\sqrt{s} > m_Z$ must suppress "radiative return" and "4(6)-fermion production"

Z and W hadronic width

[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

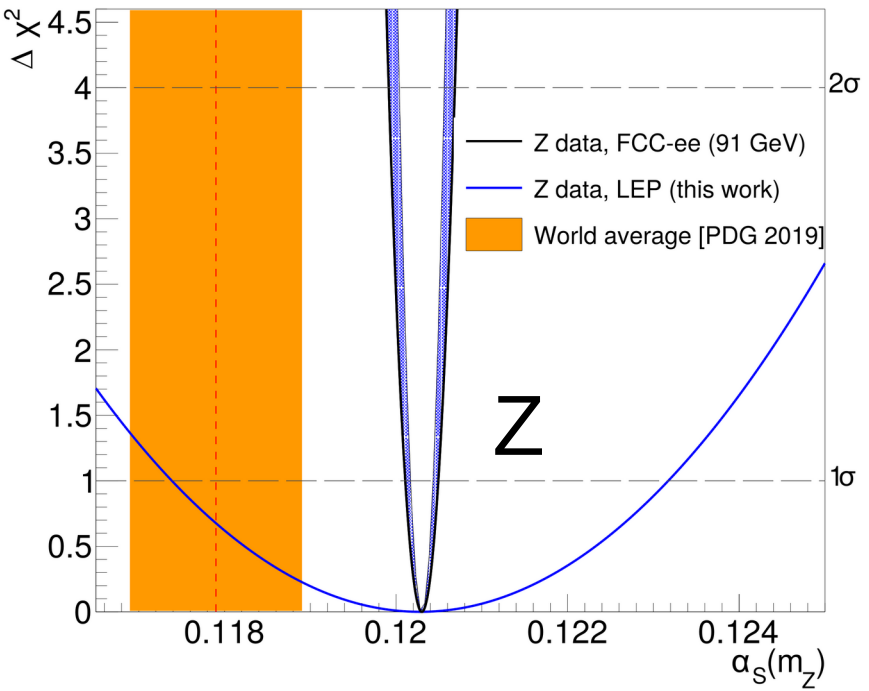
LEP:

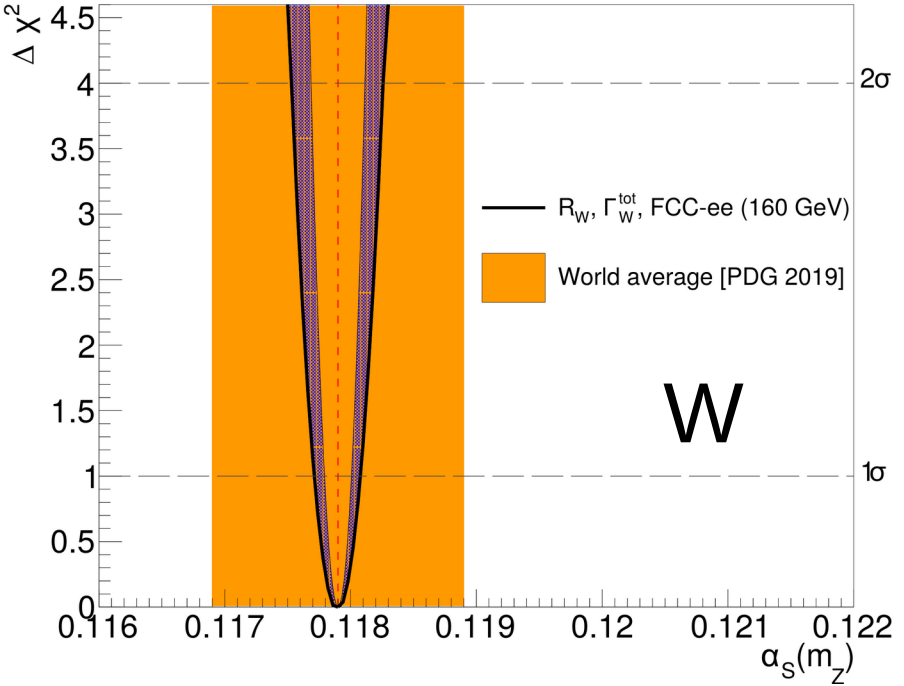
Z: $\alpha_S(m_Z) = 0.120 \pm 0.003_{exp} \pm 0.001_{theo}$

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 hadronic width





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

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

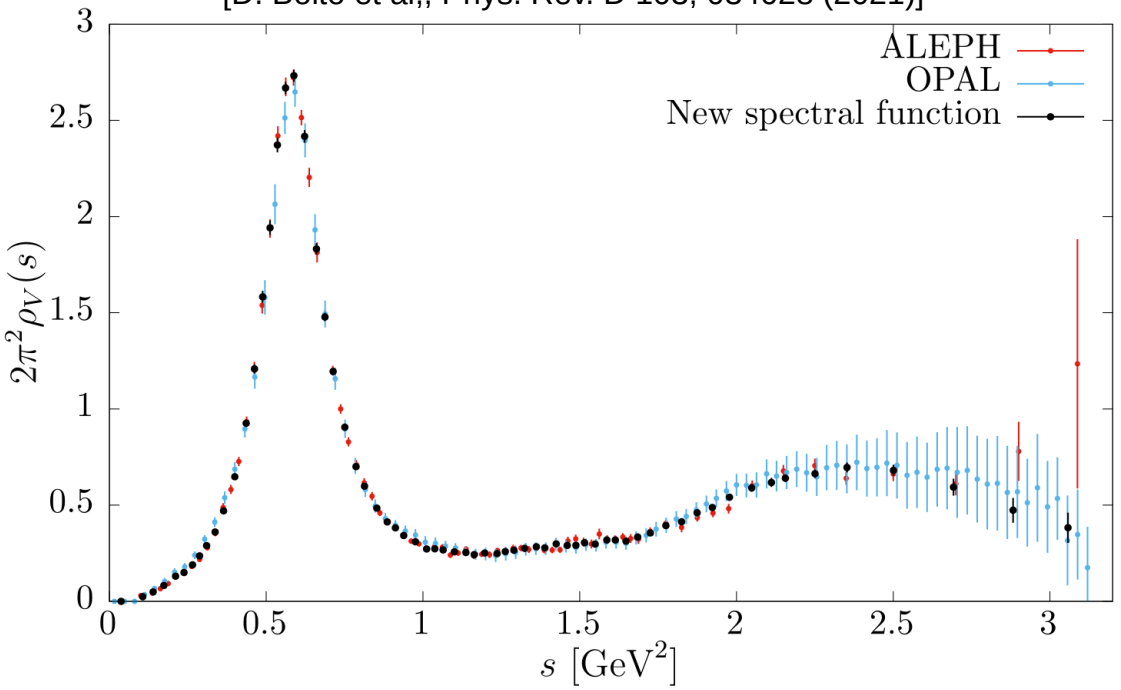
W: $\alpha_S(m_Z) = 0.11790 \pm 0.00012_{exp} \pm 0.00004_{par} \pm 0.00019_{theo}$

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

τ decays

$\Gamma_\tau^{(ud)} = F_{EW}\,(1 + \alpha_s(m_\tau)/\pi + \ldots + \delta_{NP}\,)$, δ_{NP} from moments of vector (even πs) and axial-vector (odd πs) "spectral functions" ⇒ $\alpha_S(m_\tau) \Rightarrow \alpha_S(m_Z)$

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



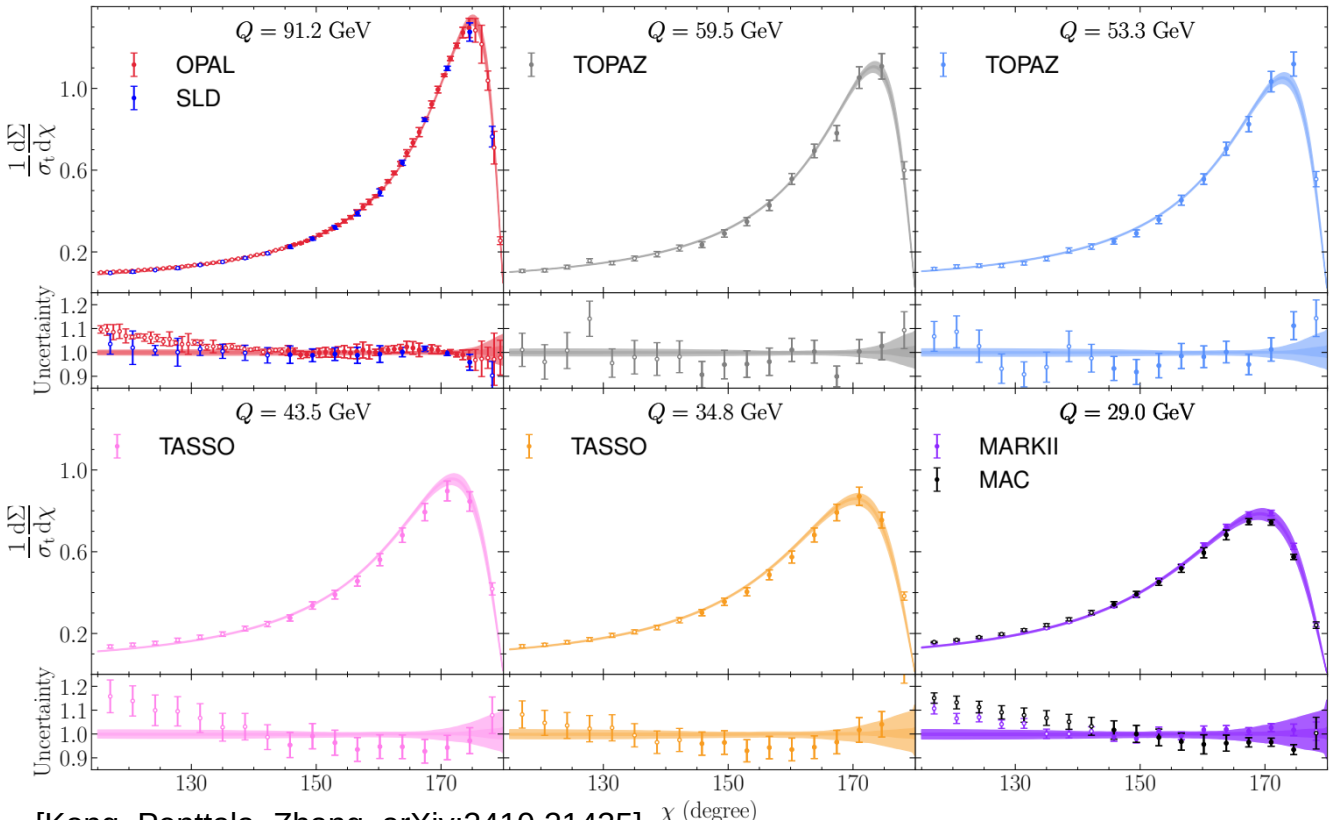
$4{\cdot}10^{11}$ τ at FCC-ee ⇒ improved spectral functions, τ_τ, rare and strange τ decays ⇒ better analysis of np effects

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

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

Semi-inclusive EECs

$$d\Sigma/d\chi = 1/(\Delta\chi N) \int_{bin} \Sigma_{events} \Sigma_{ij} E_i E_j/s \; \delta(\chi' - \theta_{ij}) \, d\chi'$$



[Kong, Penttala, Zhang, arXiv:2410.21435]

EEC is energy weighted distribution of angles between particle pairs

QCD NNLO+N3LL resum.

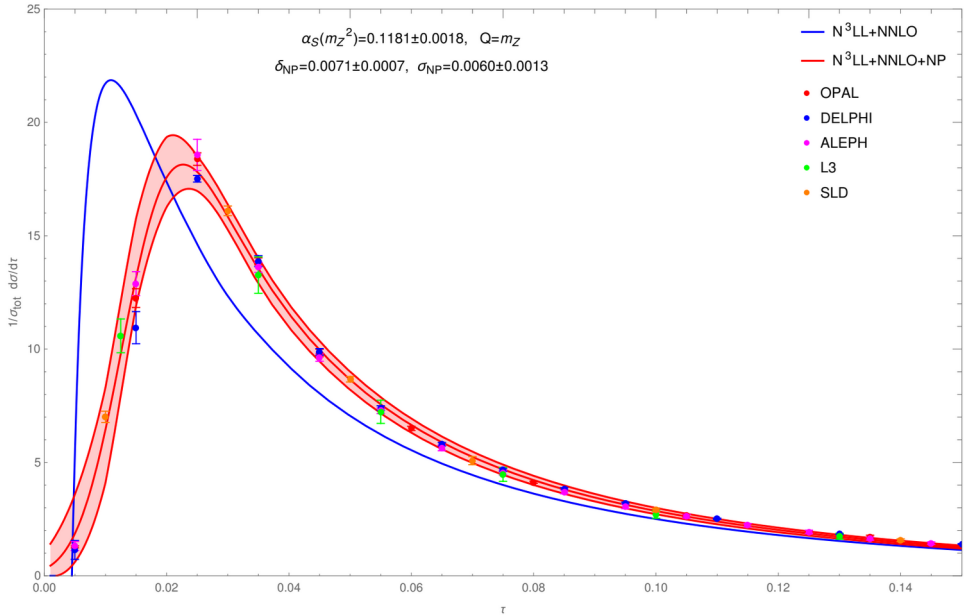
np effects from TMD factorisation in N3LL

$\alpha_s(m_Z) = 0.1193 \pm 0.0009_{exp} \pm 0.0011_{theo}$

Potential for $\Delta\alpha_s(m_Z) < 1\%$ at FCC-ee

Thrust event shape

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



Similar structure for other event shapes and for jet production rates [U.G. Aglietti et al, arXiv:2502.01570]

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

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

Laplace (vs physical space) resum.:

$\alpha_s(m_z) = 0.1181 \pm 0.0018$

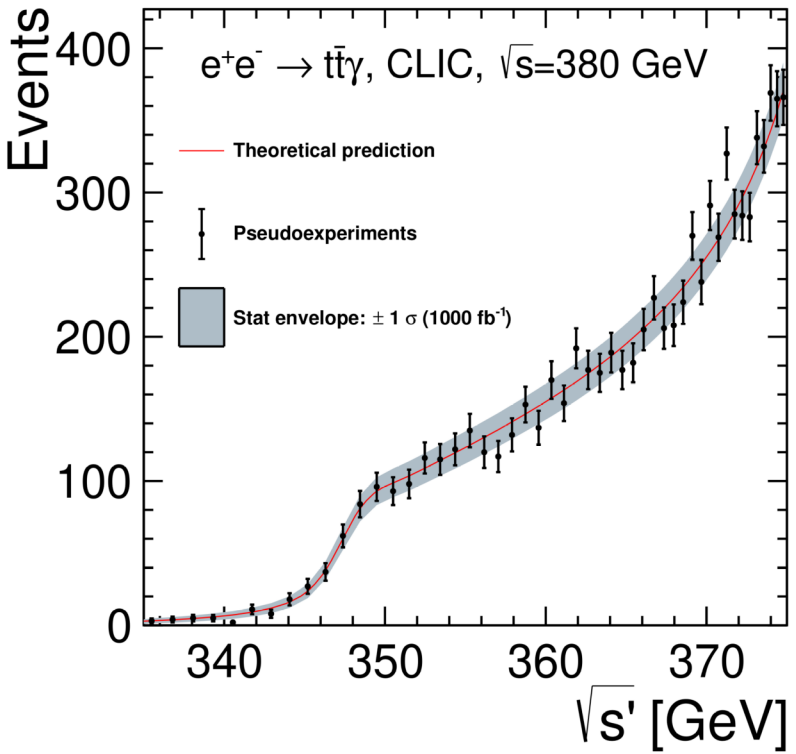
[e.g. A. Hoang et al., Phys. Rev. D91 (2015) 094018]

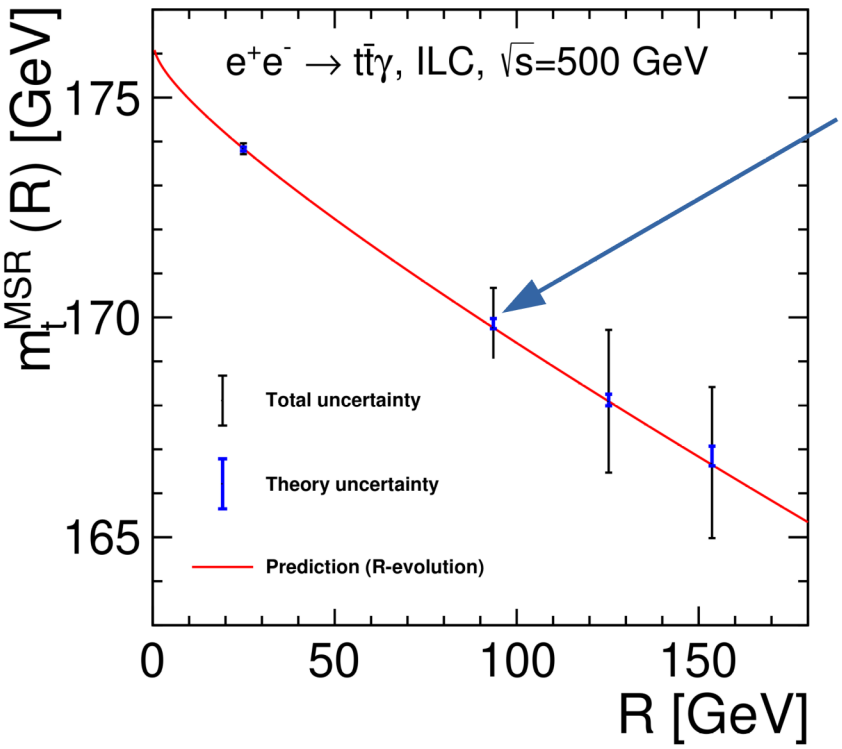
Current differences MC vs analytic

$\Delta\alpha_s(m_z)_{\text{np-model}} = O(1\%) \Rightarrow$ needs study

Quark mass running: top

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





Corresponds to CLIC
√s = 380 GeV

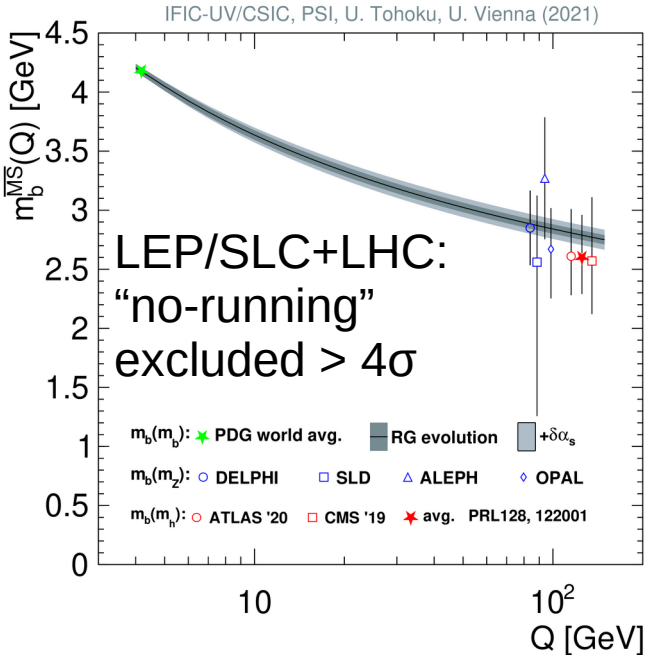
Expect similar sensitivity at FCC-ee
√s = 365 GeV

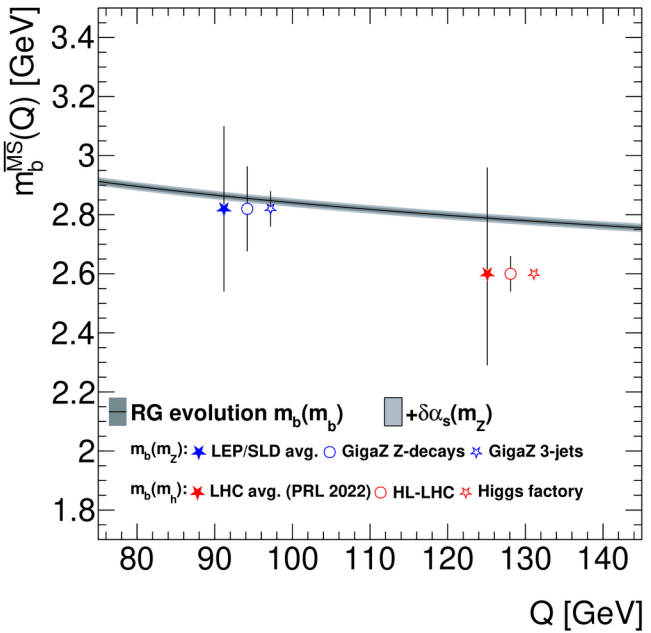
[M. Boronat et al, Phys. Lett. B804 (2020) 135353]

Quark mass running: b

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

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





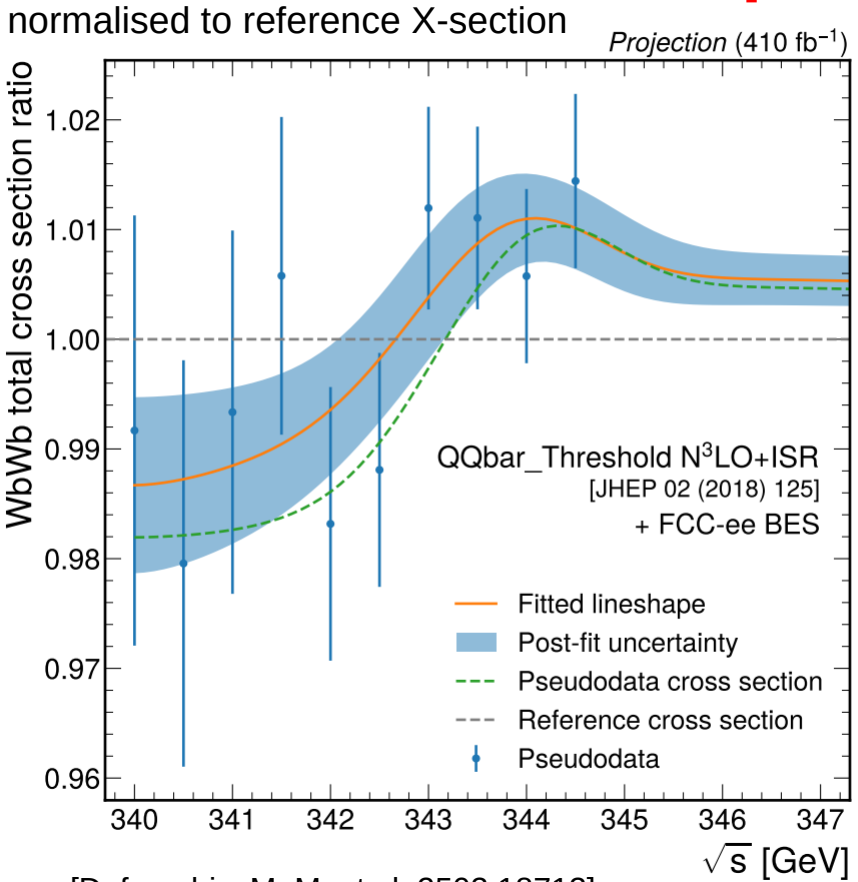
[J. Aparisi et al, arxiv: 2203.16994 and refs]

GigaZ → TeraZ (Z peak runs) at FCC-ee

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

"GigaZ (TeraZ) 3-jets" needs NNLO for $e^+e^- \to b\bar{b}$+jet

Top quark mass



[Defranchis, M. M. et al, 2503.18713]

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

$m_t = (171.5 \pm 0.004_{exp} \pm 0.001_{cms} \pm 0.002_{\alpha S} \pm 0.004_{yt} \pm 0.035_{theo})$ GeV

$\Gamma_t = (1.33 \pm 0.010_{exp} \pm 0.002_{cms} \pm 0.002_{\alpha S} \pm 0.004_{yt} \pm 0.025_{theo})$ GeV

$\Delta\alpha_S(m_Z) \approx 0.0001$, $\Delta y_t \approx 3\%$,

N4LO NR-QCD needed (herculean task)

NNLL QED corrections needed

QCD in WW: m_W

LEP m_W uncertainties direct reconstruction

Source	Systematic Uncertainty in MeV			
	on m_W			on Γ_W
	$q\bar{q}\ell\nu_\ell$	$q\bar{q}q\bar{q}$	Combined	
ISR/FSR	8	5	7	6
Hadronisation	13	19	14	40
Detector effects	10	8	9	23
LEP energy	9	9	9	5
Colour reconnection	–	35	8	27
Bose-Einstein Correlations	–	7	2	3
Other	3	10	3	12
Total systematic	21	44	22	55
Statistical	30	40	25	63
Statistical in absence of systematics	30	31	22	48
Total	36	59	34	83

[ADLO, Phys.Rept. 532 (2013) 119-244]

FCC-ee (12/ab)

m_W Γ_W

“lepton+jets”

$e^+e^- \to W^+W^- \to q\bar{q}l\nu_l$

QCD!

“all jets”

$e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$

0.5 ?

QCD!

FCC-ee WW threshold scan:

$\Delta m_{W,stat}$ = 0.5 MeV

0.5 1.2

$\Delta\Gamma_{W,stat}$ = 1.2 MeV

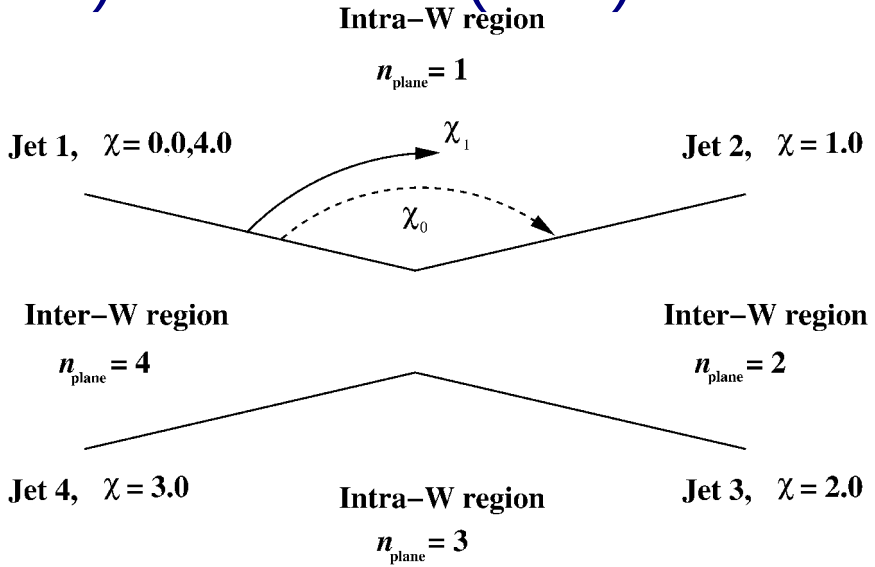
Needs NNLO EW (herculean task), EW-QCD and QED corrections

Colour Reconnection in WW

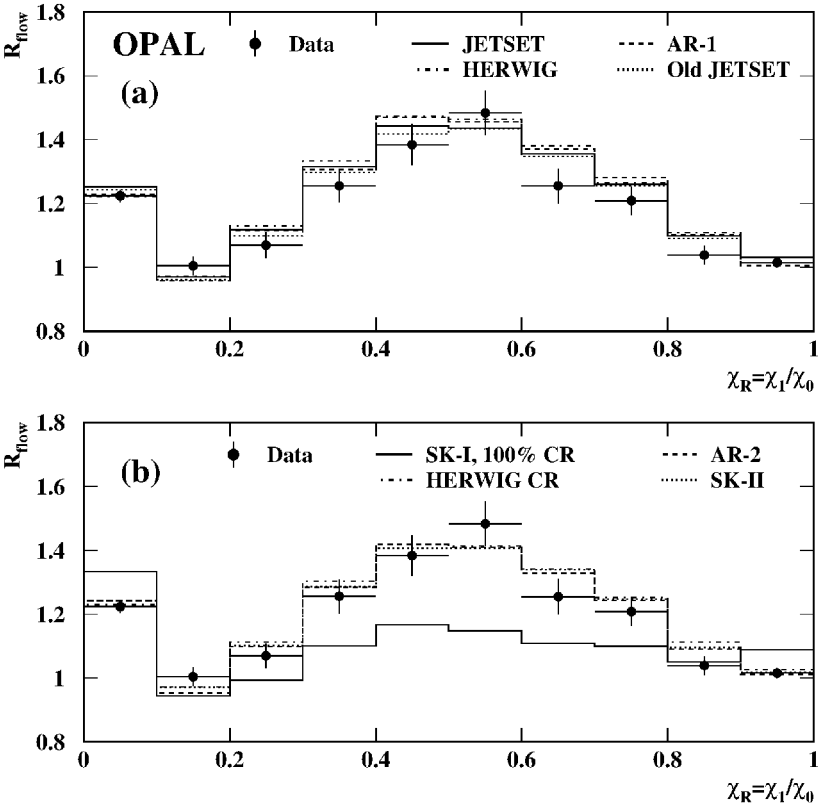
CR effects: $\Delta m_{W,CR} = \pm 8$ MeV (LEP),

$\Delta m_{t,CR} = \pm 40$ MeV (LHC), ZH(jets), ...

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



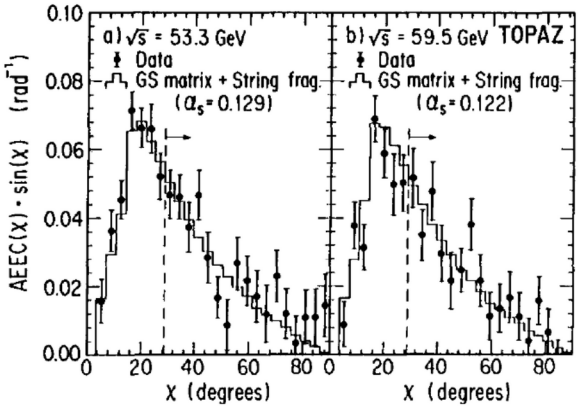
[OPAL coll., Eur. Phys. J. C45 (2006) 291]

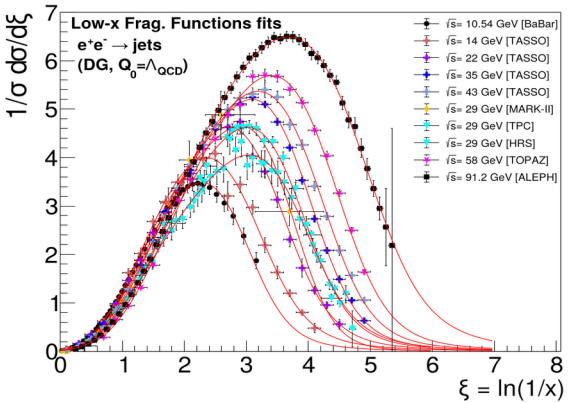


FCC-ee: > 10^4·LEP hadronic W pairs, smaller exptl. systematics

FCC-ee low energy $\sqrt{s} < m_Z$

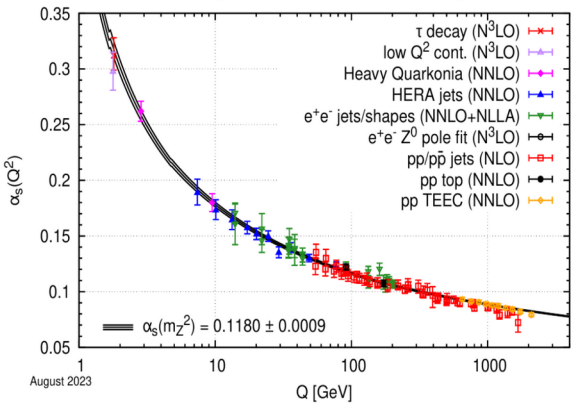
Hard vs soft QCD, Hadronisation

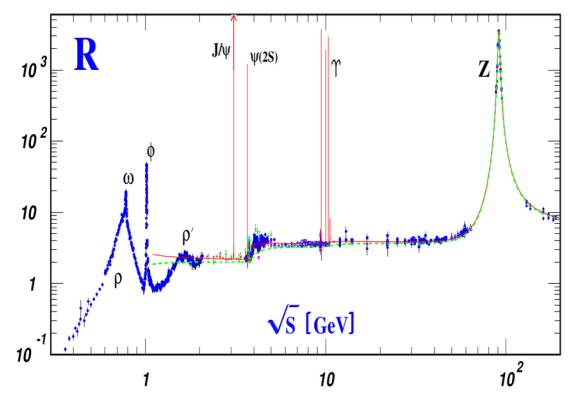




Fragmentation, QCD, MCs, Hadronisation

$\alpha_s(Q)$ event shapes, jets, FFs, EECs, Hadronisation





R = σ(hadrons)/ σ($\mu^+\mu^-$)

α_s(20-40 GeV) at 0.1%?

[Back-up Document to FCC: QCD physics, arXiv:2503.23855]

Bonus EWPOs: A_{FB} $e^+e^- \to f\bar{f} \Rightarrow \sin^2(\theta_W)(Q)$

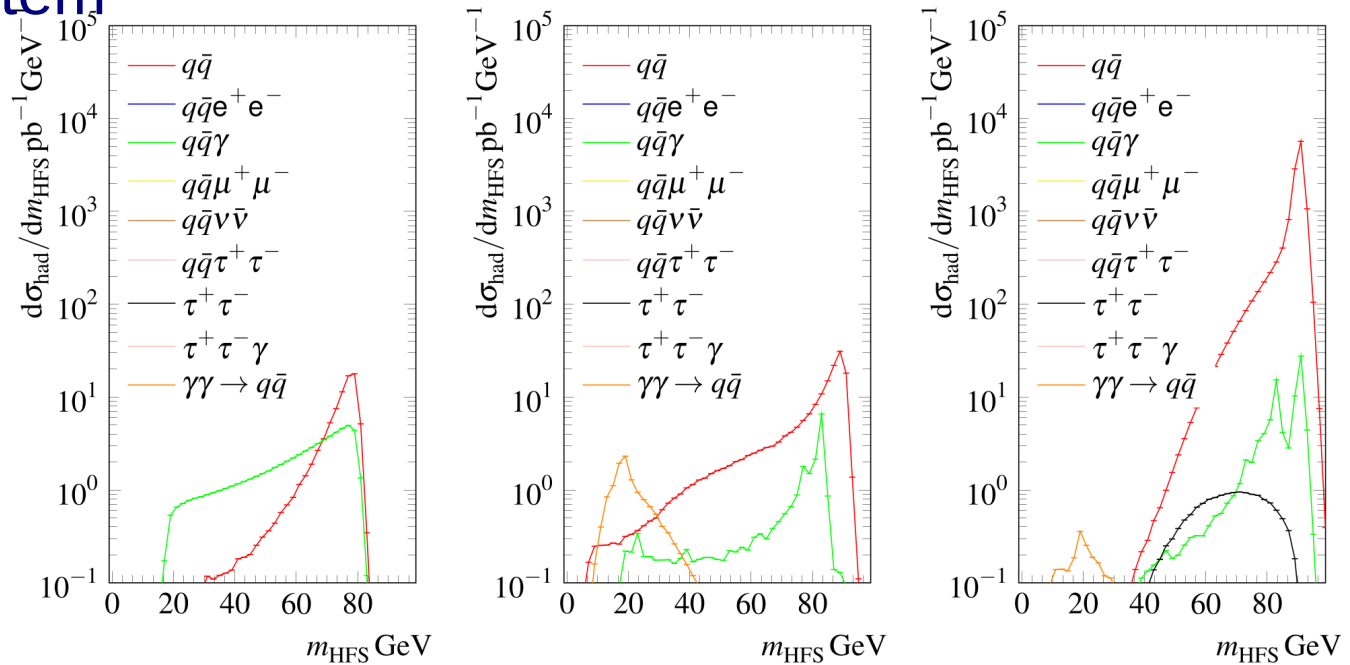
Low energy $\sqrt{s} < m_Z$

"Tagged"
$E_{vis} \approx m_Z$, isolated photon,
4-mom balance of 2 jets
+ photon system

"Untagged"
$E_{vis} \approx 2E_{beam} - \Sigma p_{vis,z}$

"No ISR/FSR"
$E_{vis} \approx 2E_{beam}$

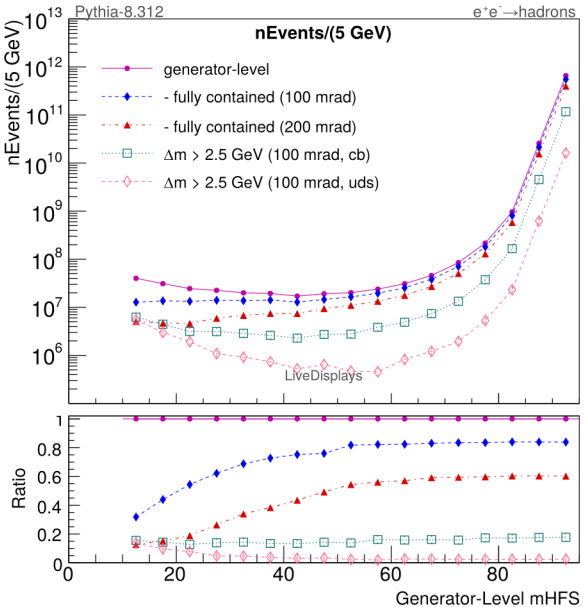
[Back-up Document to FCC: QCD physics, arXiv:2503.23855]

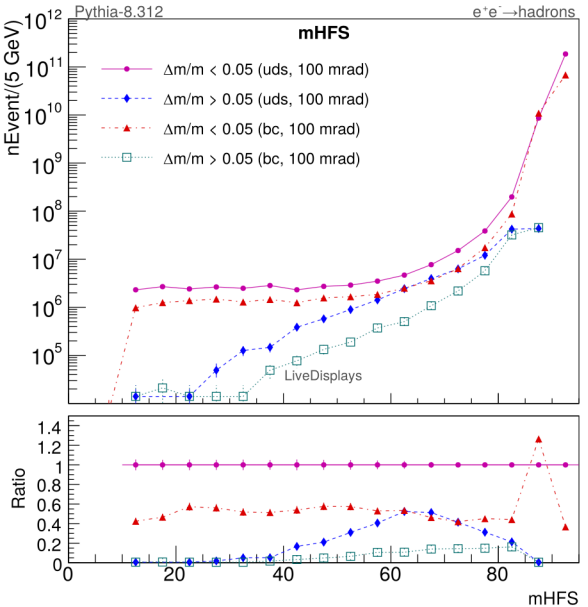


Low energy $\sqrt{s} < m_Z$

Acceptance low at √s' < 20 GeV due to boost

[Back-up Document to FCC: QCD physics, arXiv:2503.23855]





Acceptance similar for uds and cb

Δm/m>0.05: not well reconstructed

Possible add-on to FCC-ee run strategy

Run	Z pole (ISR events)	40-GeV	60-GeV	$e^+e^- \to H$
$\sqrt{s}$	88, 91, 94 GeV	40 GeV	60 GeV	125 GeV
time	4 years	1 month	1 month	3 years
$\mathcal{L}_{int}$ (ab^{-1})	205	3.5	6.2	≈100
$\sigma(e^+e^- \to q\bar{q})$	Depending on ISR selection criteria [7]	289 pb	162 pb	104 pb
$\sqrt{s_{had}}$	20–80 GeV	40 GeV	60 GeV	125 GeV
N_{evts} (HFS)	$\mathcal{O}(10^9)$	$\mathcal{O}(10^9)$	$\mathcal{O}(10^9)$	$\mathcal{O}(10^{10})$
E_j (max. jet scale probed)	10–40 GeV	20 GeV	30 GeV	62 GeV

Low-√s data with ISR/FSR give access to lower √s' < 20 GeV

Summary

- Outtakes (apologies): QCD in H decays, parton showers, ...
- FCC-ee will be a dream lab for QCD
  - $\alpha_s(m_Z)$ at ‰ level at small and large scales
  - soft QCD, parton showers, heavy flavour, etc
- Some FCC-ee SM measurements (m_W, m_t, …) limited by soft and hard QCD uncertainties
  - need dedicated FCC-ee studies and herculean theory efforts
- FCC-ee low energy runs and ISR program
  - enable soft QCD studies, validate MCs, small √s' scale precision measurements