QCD and top physics: current status and prospects from the experiment side

On behalf of ATLAS and CMS collaborations

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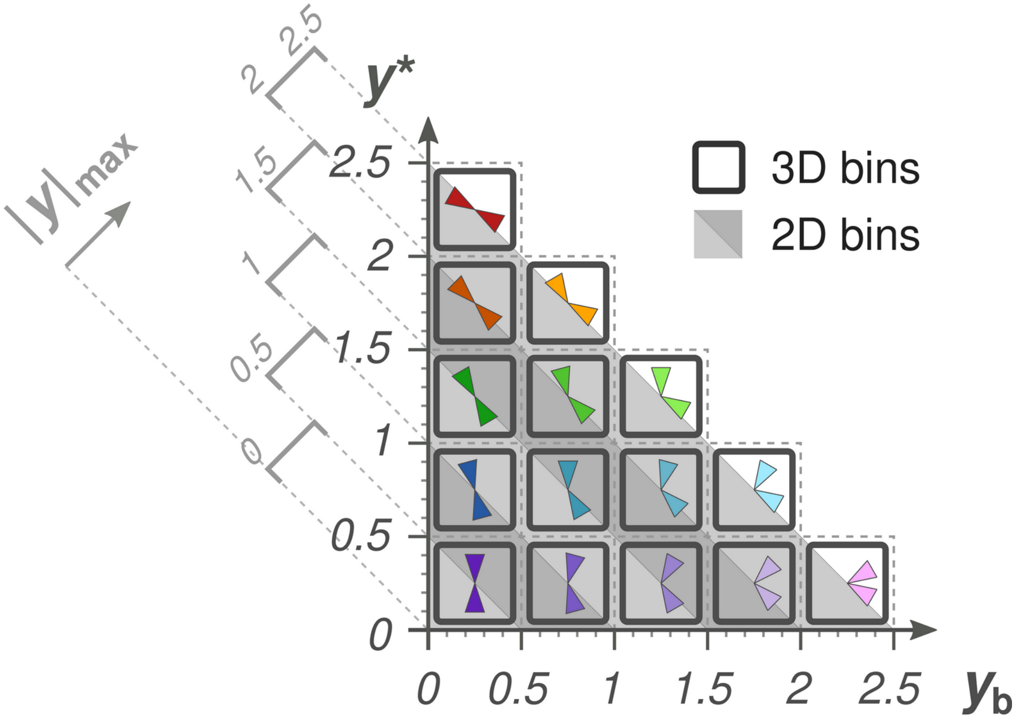
EISA workshop on future colliders 2024
20 May 2024, Mon Repos, Corfu

Present
QCD at LHC
top at LHC
Future
QCD at future colliders
top (b) at future colliders
Summary

Highly selective based on personal prejudices about the future
“Prediction is very difficult especially if it's about the future” (Niels Bohr)

CMS di-jets 13 TeV: concepts

anti-k_t jets R = 0.4 or 0.8, $p_{t,1} > 100$ GeV, $p_{t,2} > 50$ GeV, $|y| < 3$



[CMS coll., CMS-SMP-21-008, arXiv: 2312.16669]

Variables:

y_{max} is y of jet closer to beam

$y^* = ½ |y_1 - y_2|$, $y_b = ½ |y_1 + y_2|$

$\langle p_T \rangle_{1,2} = ½ (p_{T,1} + p_{T,2})$

$m_{1,2}$ is m_{inv} of di-jet system

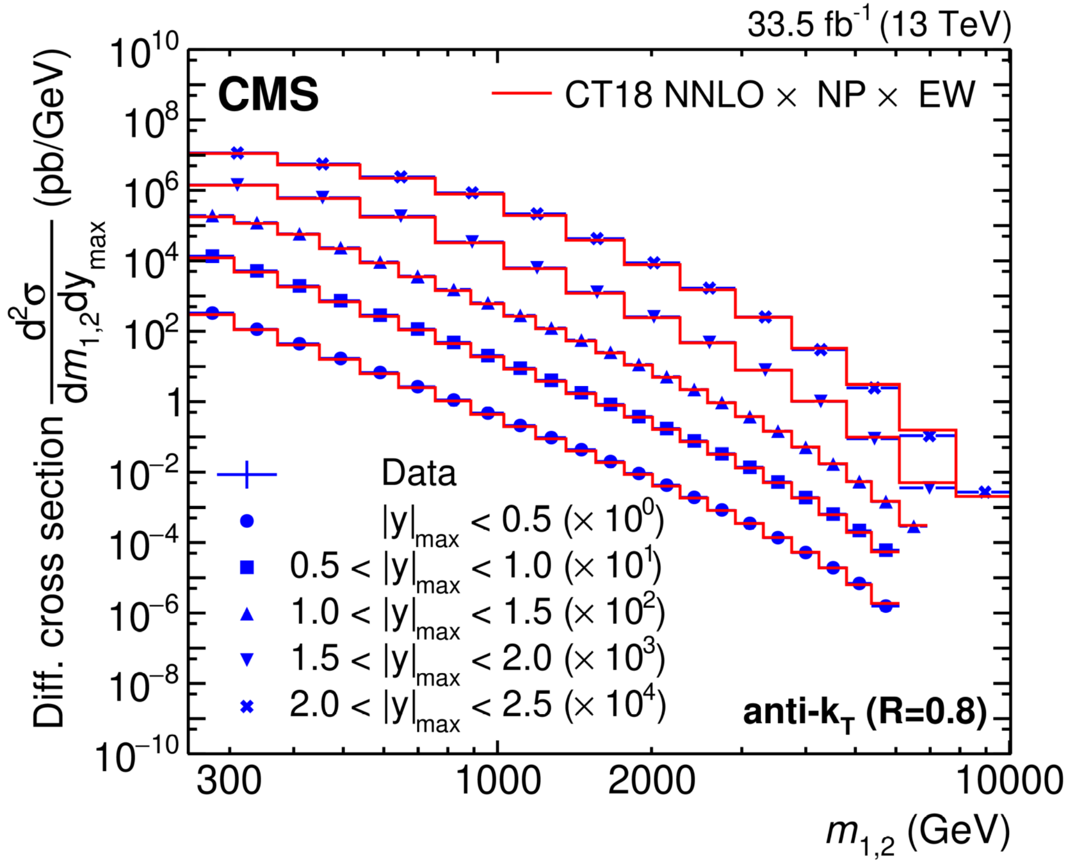
Measurements:

$d^2\sigma/(dm_{1,2}dy_{max})$

$d^3\sigma/(dy^*dy_bdm_{1,2})$

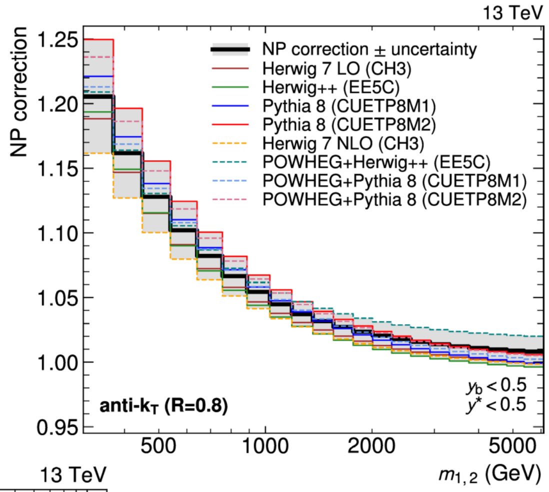
$d^3\sigma/(dy^*dy_bd\langle p_T \rangle_{1,2})$

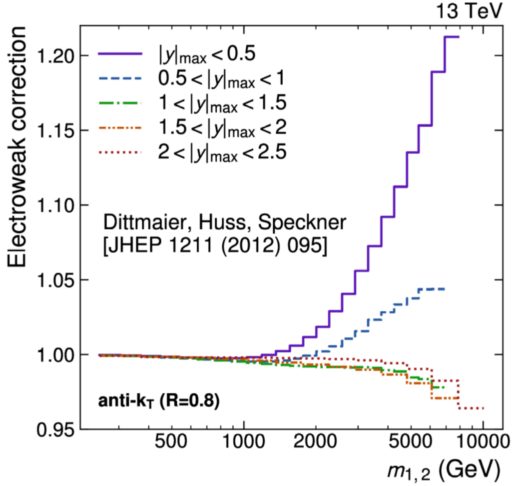
CMS di-jets 13 TeV: measurements



Total errors O(10%) or less

R = 0.8: NP corrections large for small $m_{1,2}$, smaller for R=0.4



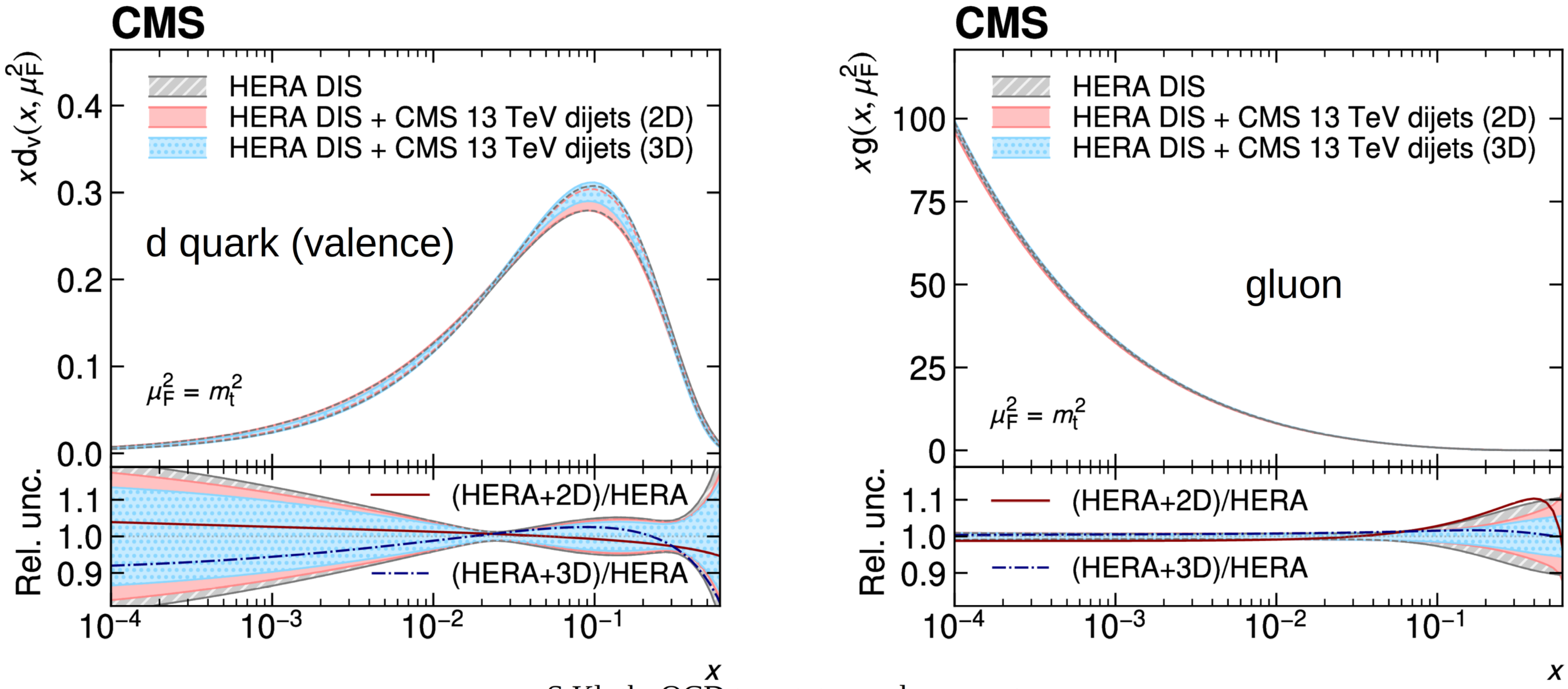


EW corrections significant for $m_{1,2}$ > 1000 GeV

CMS di-jets 13 TeV: pdf fit

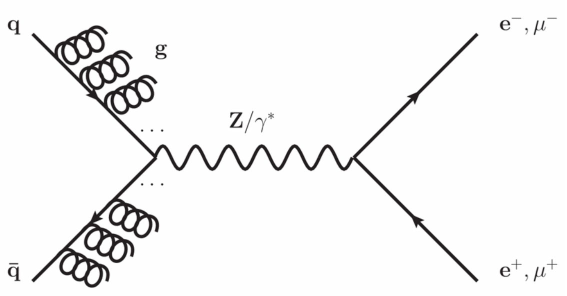
HERAPDF and CMS R=0.8 di-jet 2D/3D, NNLO* (leading colour)

$\alpha_s(m_Z) = 0.1179 \pm 0.0019$ (HERAPDF+2D)

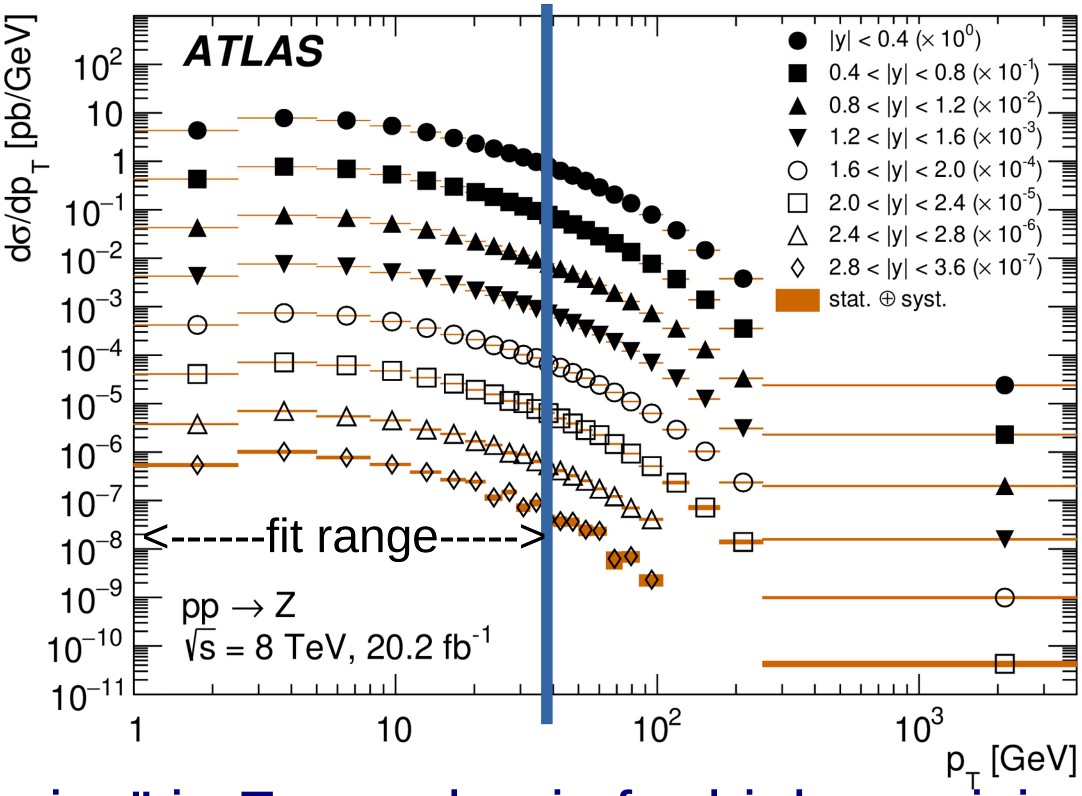


ATLAS NC Drell-Yan 8 TeV

$pp \rightarrow l\bar{l} + X$ with $m_{l\bar{l}} \approx m_Z$



[ATLAS coll., Eur. Phys. J. C 84 (2024) 315]



In Collins-Soper frame

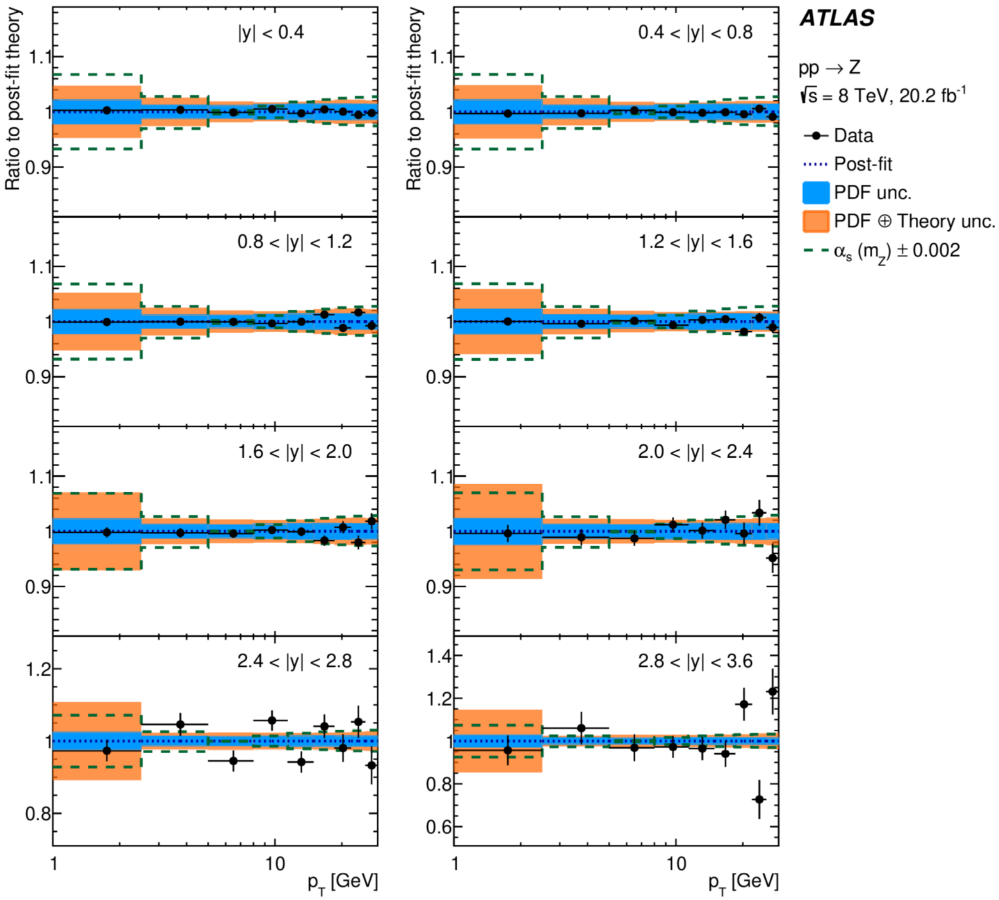
$d\sigma^5/(dp_t dy dm_{l\bar{l}} d\cos\theta_l d\Phi_l) \sim$

$d\sigma^3/(dp_t dy dm_{l\bar{l}} F(\theta_l,\Phi_l,A_i))$

$i=1,\ldots,7$

Z decay and production “factorise” in Z cms, basis for high precision QCD analysis

ATLAS NC Drell-Yan 8 TeV



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

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

N3LO+N4LLa result (DYTURBO):

$\alpha_S(m_Z) = 0.1178 \pm 0.0004_{exp} \pm 0.0005_{pdf} \pm 0.0004_{scale} \pm 0.0005_{other} = 0.1178 \pm 0.0009_{tot}$

PDF parametrisation vs fit, non-pert model checked carefully

Best $\alpha_S(m_Z)$ besides Lattice QCD!

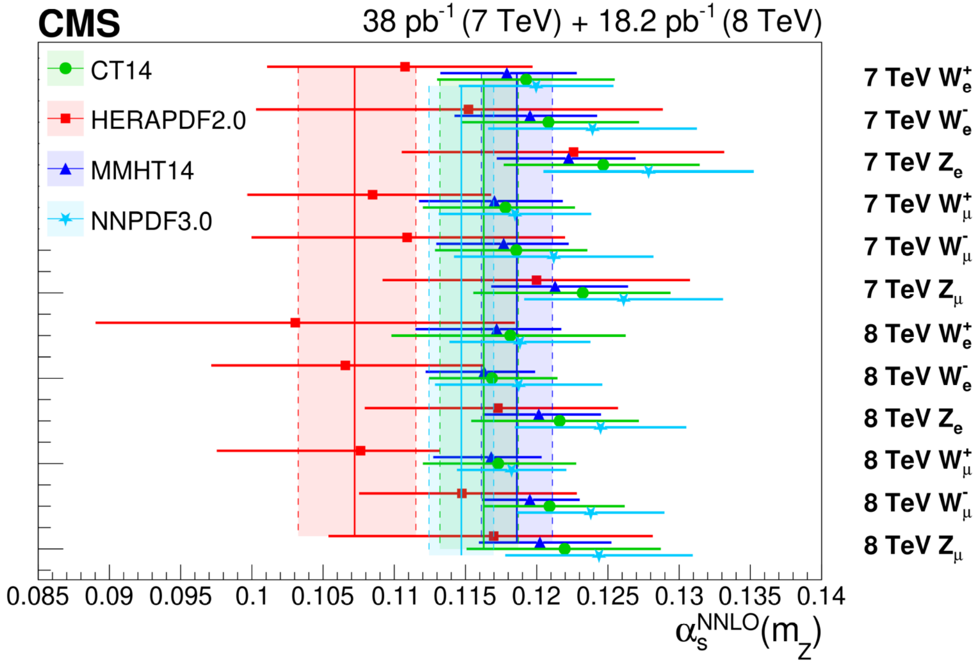
CMS incl. W/Z production

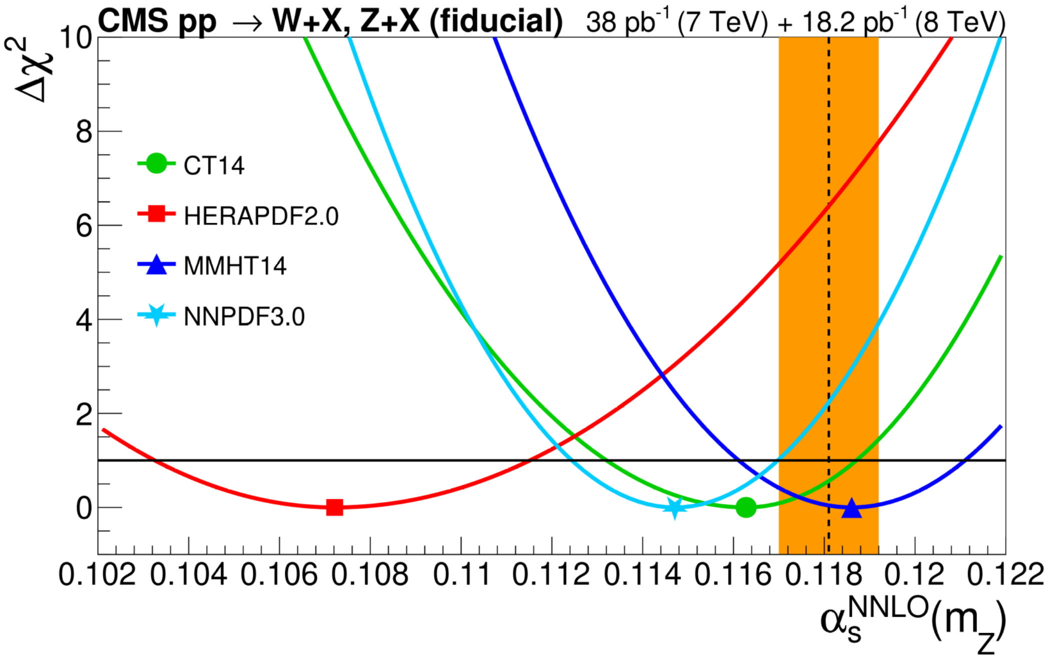
pp → W/Z + X fid. cross sections, NNLO QCD (N3LO today)

$\alpha_s(m_Z) = 0.1186 \pm 0.0003_{stat} \pm 0.0018_{lumi} \pm 0.0009_{syst}$
$\pm 0.0013_{PDF} \pm 0.0007_{scale}$ (MMHT14)

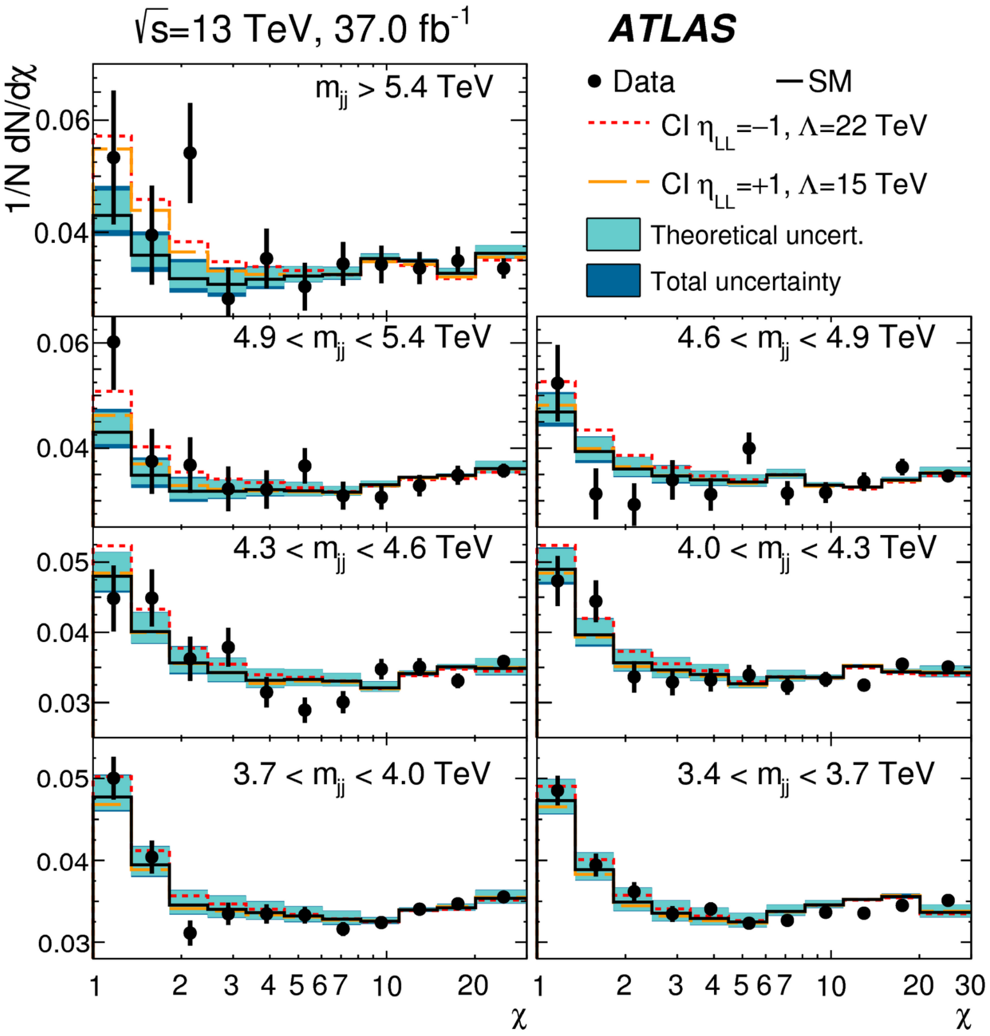
$\alpha_s(m_Z) = 0.1175 \pm 0.0027$ (MMHT14+CT14)

[CMS coll., JHEP 06 (2020) 018]





ATLAS Di-jets angular correlation



Anti-k_t jets R=0.4

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

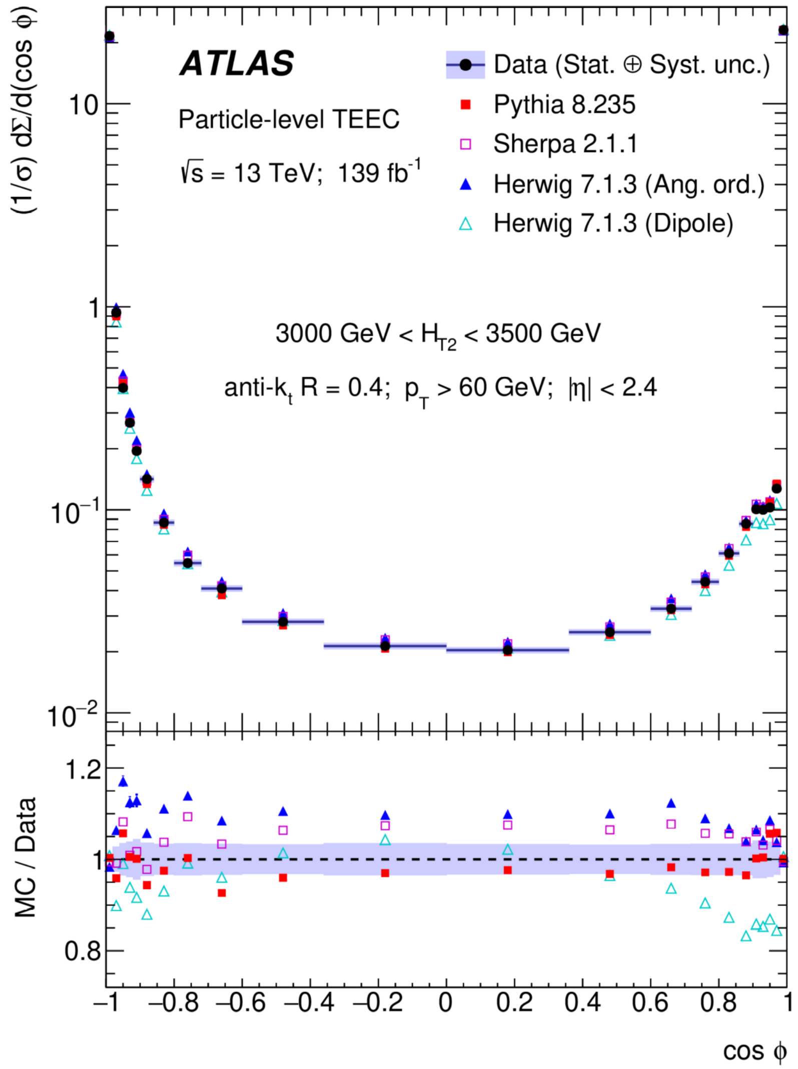
$\chi = \cot^2(\theta^*/2) \approx e^{(y1-y2)}$

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

Searches, but also (absence of) quark substructure

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

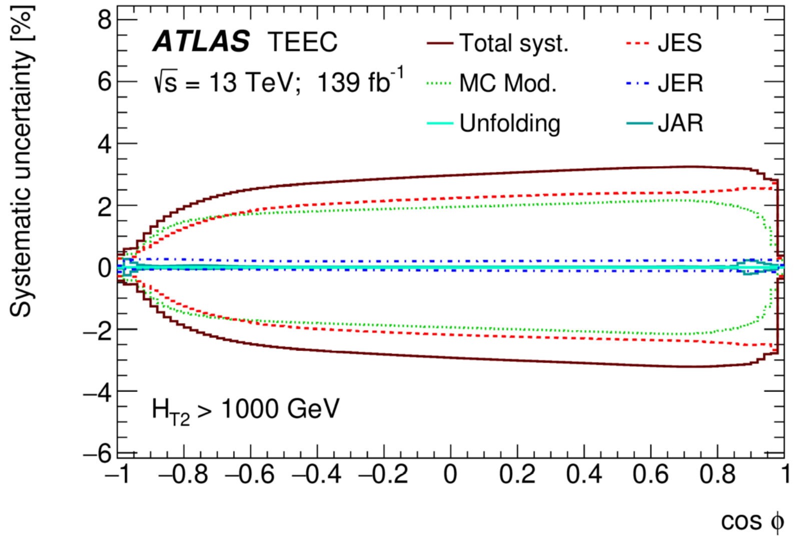
ATLAS TEEC 13 TeV



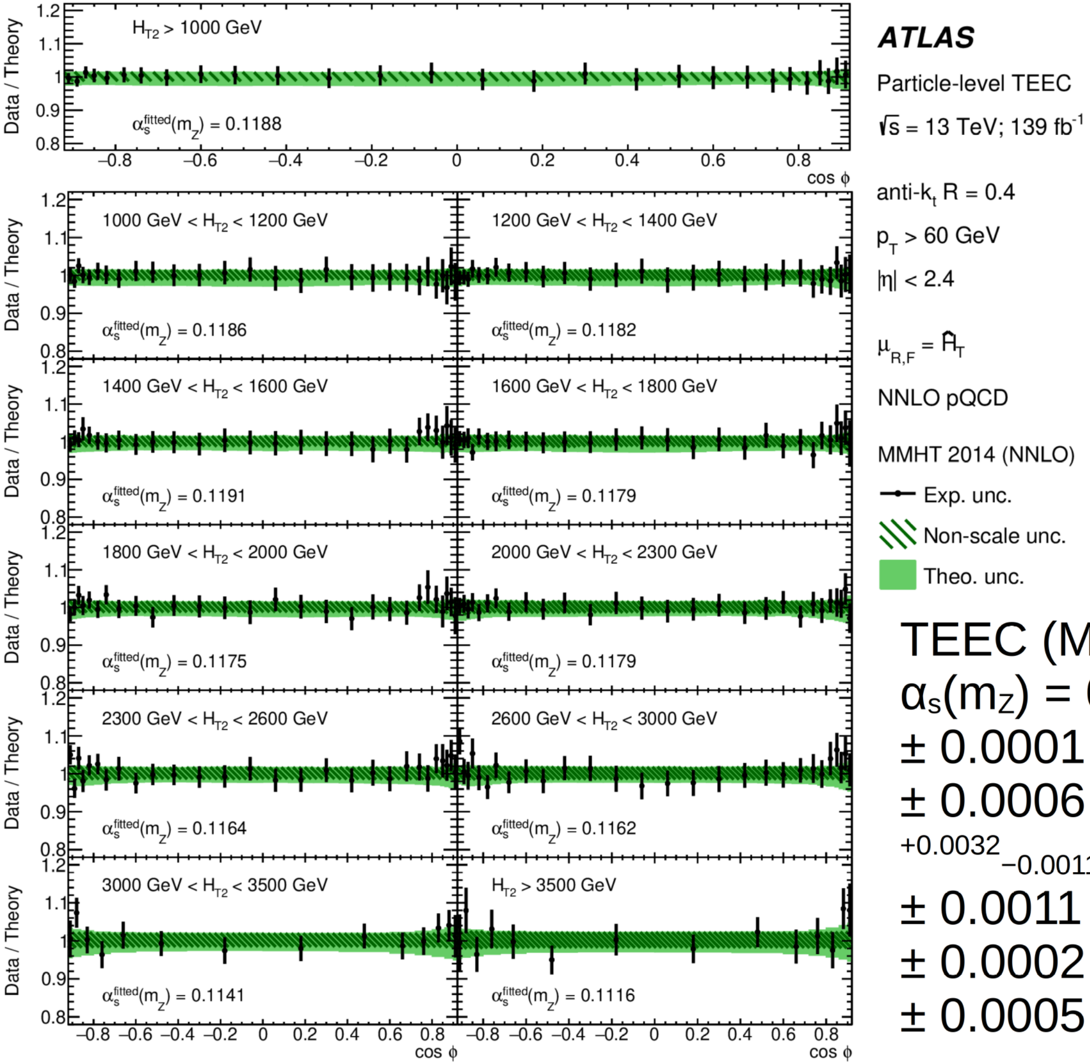
[ATLAS coll., JHEP 07 (2023) 85]

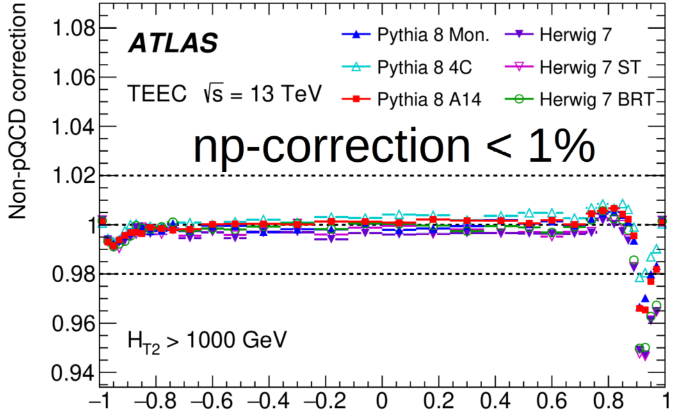
Anti-k_t R=0.4 jets, p_t > 60 GeV (460 GeV jet trigger), $H_{T2} = p_{t,1}+p_{t,2} > 1000$ GeV

$1/\sigma\, d\sigma^{TEEC}/d\cos\Phi =$
$1/N \sum_{events} \sum_{jets} E_{t,i} E_{t,j} / (\sum_{jets} E_{t,i}) \delta(\cos\Phi_{ij} - \cos\Phi)$

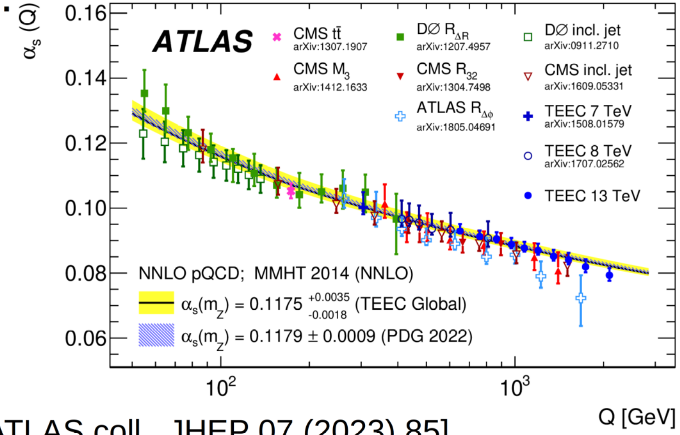


ATLAS TEEC 13 TeV





TEEC (MMHT14):
$\alpha_s(m_Z) = 0.1175$
± 0.0001 (stat.)
± 0.0006 (exp.)
$^{+0.0032}_{-0.0011}$ (scale)
± 0.0011 (PDF)
± 0.0002 (np)
± 0.0005 (unf.)

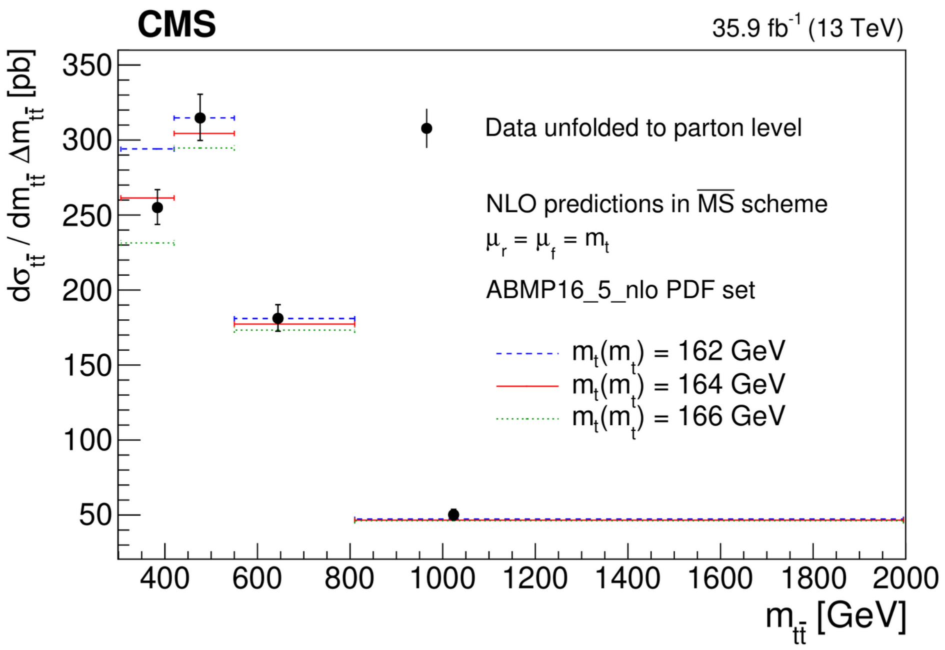


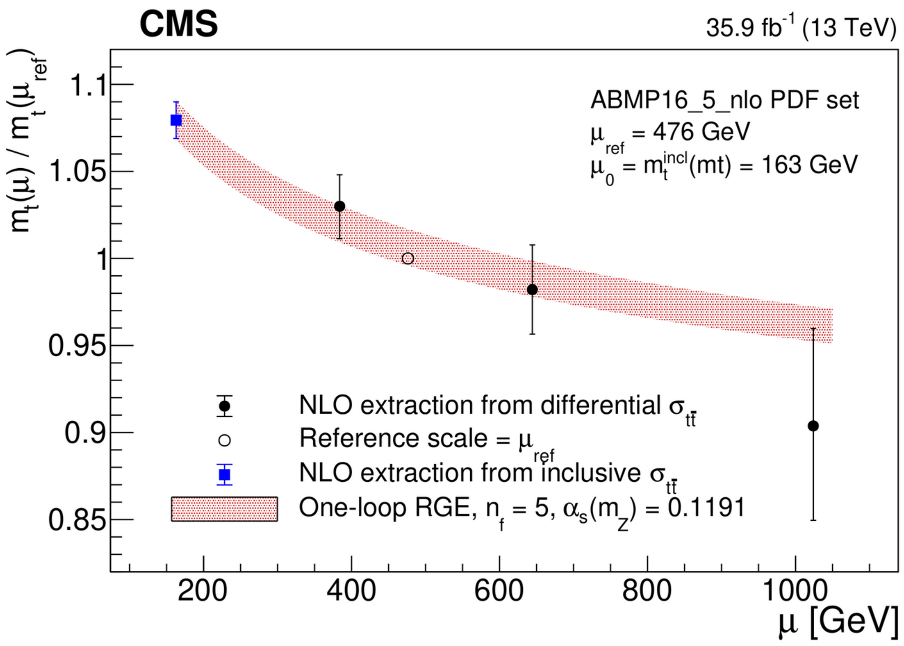
[ATLAS coll., JHEP 07 (2023) 85]

CMS m_t running 13 TeV

Measure $d\sigma/dm_{t\bar{t}}$ in $pp \to b\bar{b}l\bar{\nu}_l\bar{l}\nu_l$ (di-lepton), $m_{t\bar{t}}^2 = 2m_t^2 + 2(E_t E_{\bar{t}} - \mathbf{p}_t \cdot \mathbf{p}_{\bar{t}})$

"no running" excluded at 2.1σ (>95% CL)



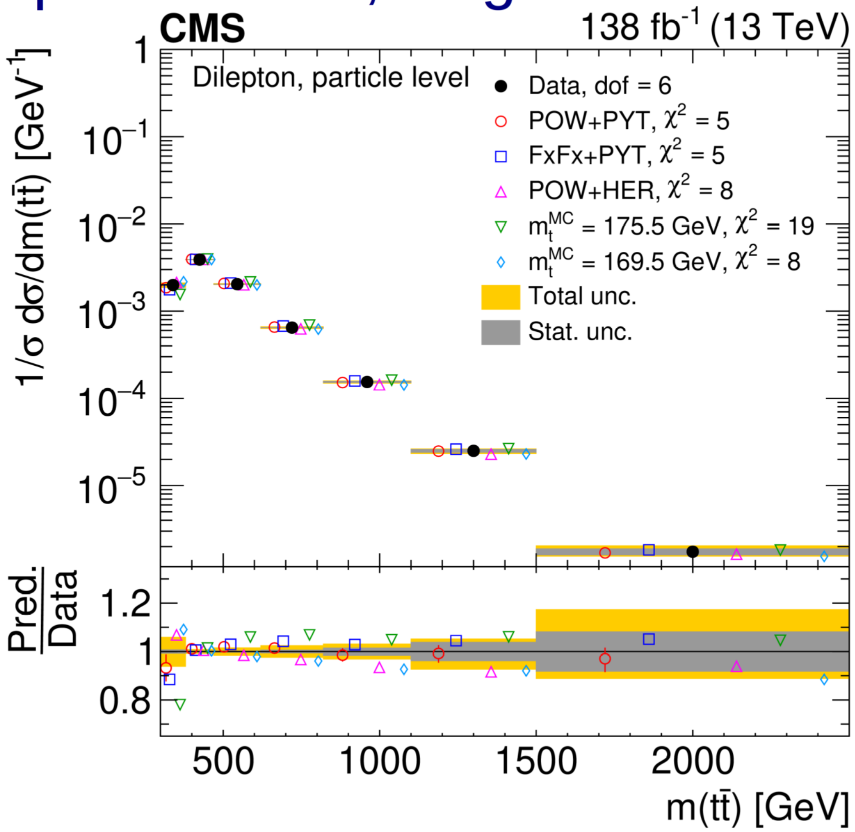


Expect much larger $m_{t\bar{t}}$ reach with FCC-hh

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

CMS $t\bar{t}$ distributions 13 TeV

Di-lepton selection with additional jets, > 100 distributions particle / parton level, single / multi-differential (normalised) cross sections



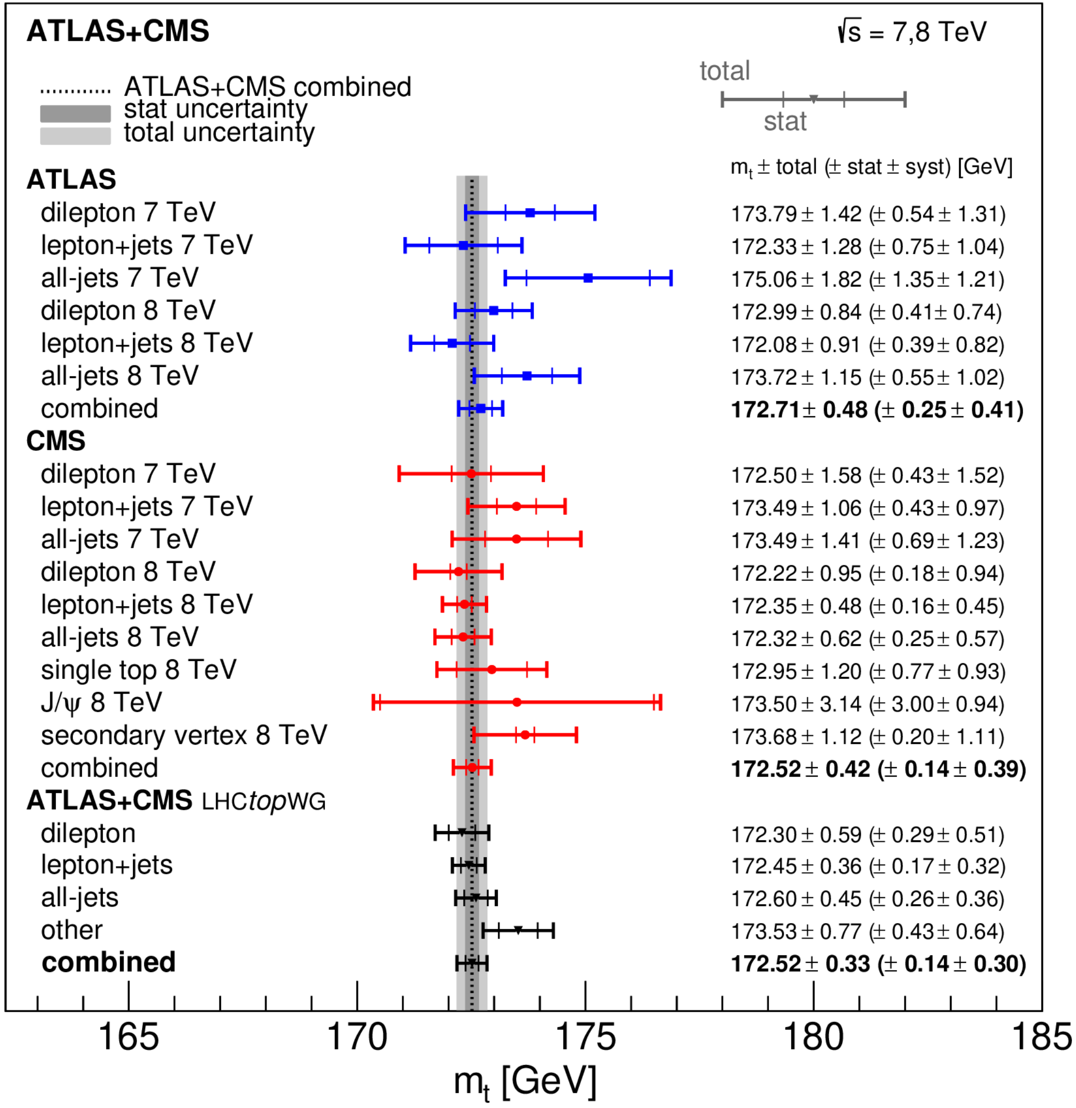
Test MC models for top physics

Test SM (QCD) theory, potential for precisiontop properties measurements

Good agreement with single-differential predictions, some problems with multi-differential

[CMS coll., CMS-TOP-20-006, sub. to JHEP]

$m_{t\bar{t}}$ reach extended to 2.5 TeV



ATLAS+CMS m_t combination

Combination with BLUE method (χ^2 with covariance matrix)

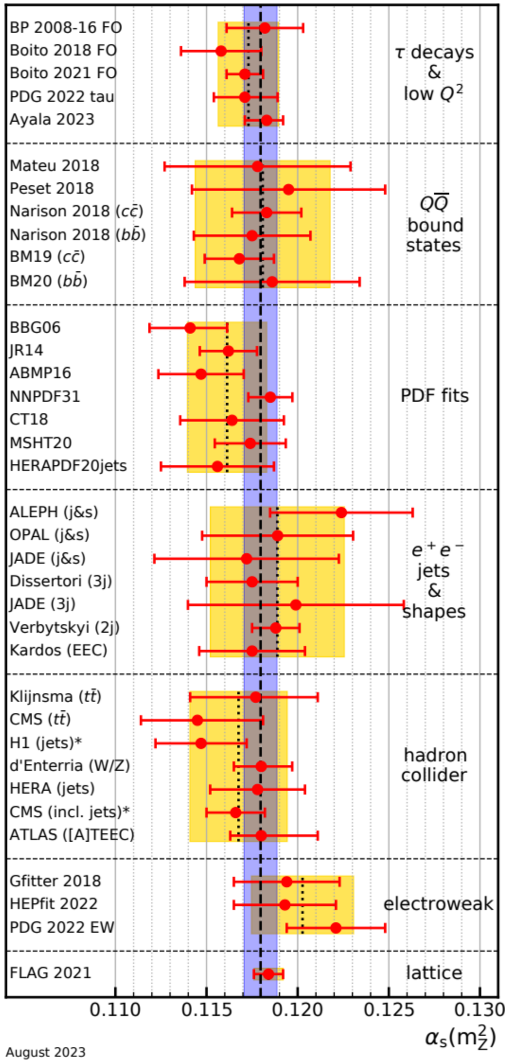
Careful evaluation of correlations within and between experiments for all systematics

b-JES largest syst. (180 MeV), then b-tag (90 MeV)

$\Delta m_t \approx 0.2\%$! Major achievement of LHC

[ATLAS-TOPQ-2019-13, CMS-TOP-22-001]

[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)

LHeC
FCC-eh 31.01.-04.02.2022

FCC-ee impact on most categories

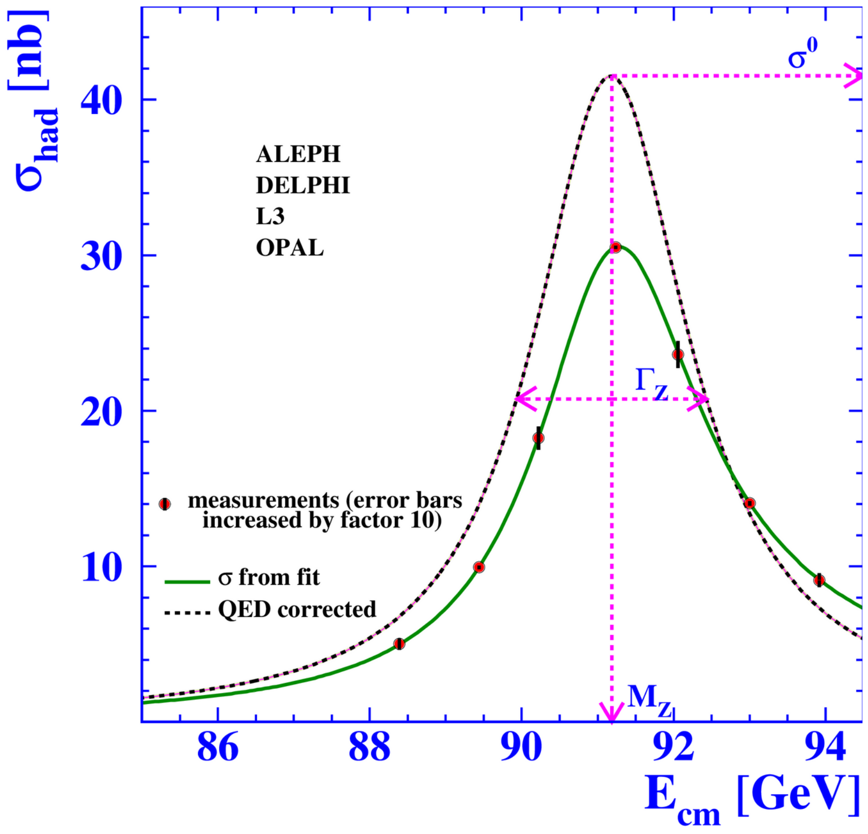
FCC-ee Expect $3{\cdot}10^{12}$ hadronic Z decays ⇒ $6{\cdot}10^{11}$ $Z \rightarrow b\bar{b}$, 10^{11} τ pairs, …

LHeC
FCC-hh
FCC-eh $5{\cdot}10^{8}$ W decays, 10^{6} $t\bar{t}$ on threshold

FCC-ee LHeC, FCC-hh, FCC-eh

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

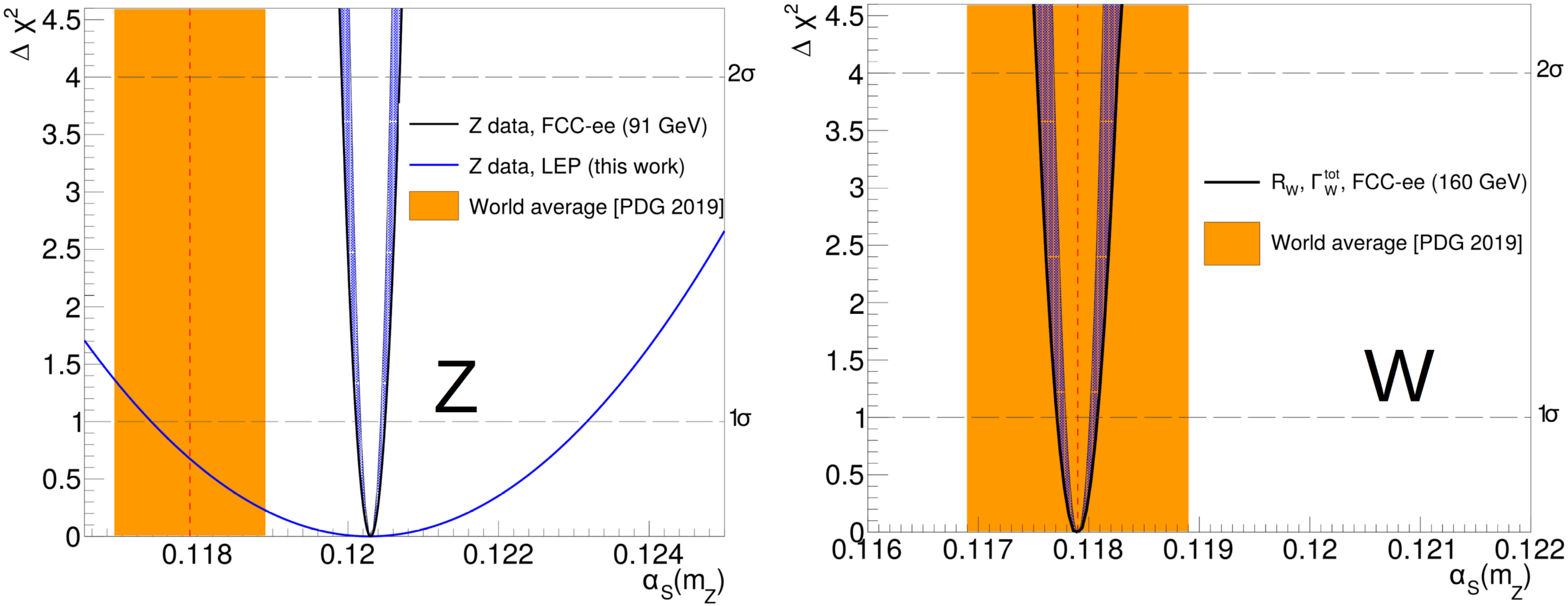
LEP:

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^-



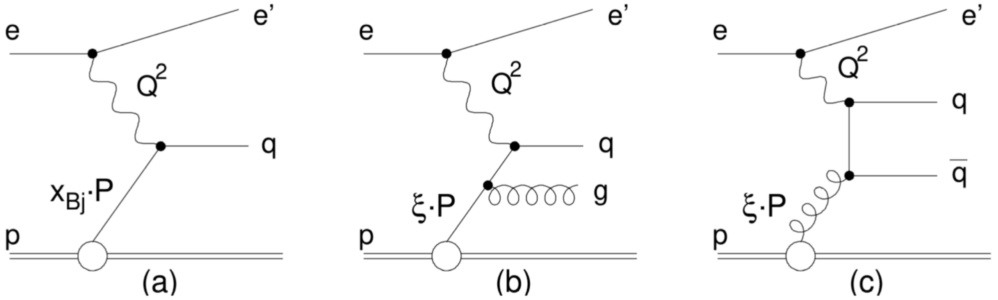
FCC-ee: improved α_{QED}, $|V_{cs}|$, $|V_{cd}|$, m_W; assume N4LO QCD

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

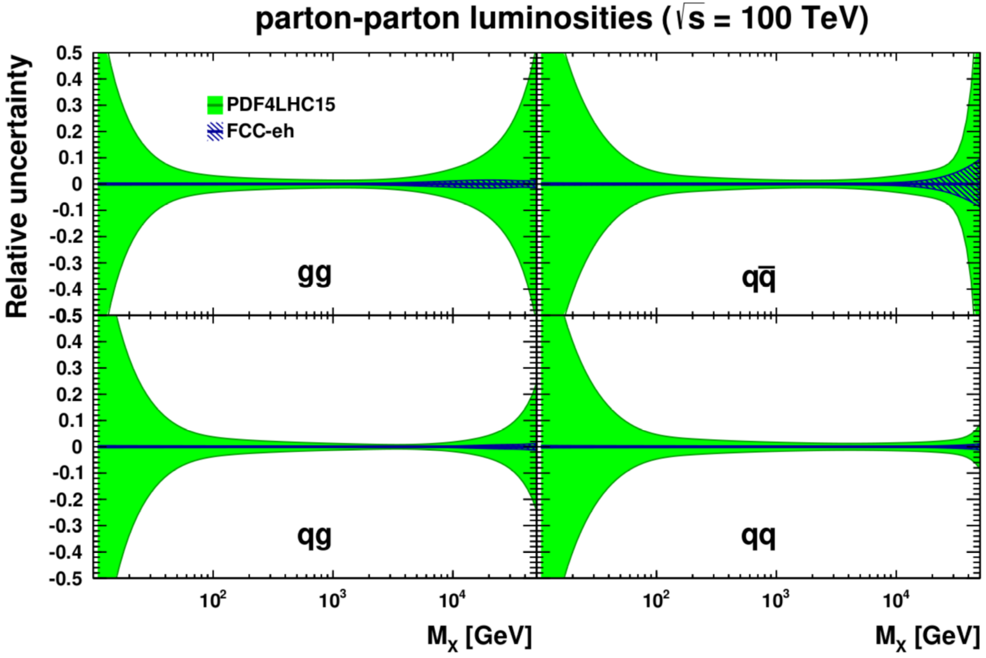
W: $\alpha_S(m_Z) = 0.11790 \pm 0.00012_{exp} \pm 0.00004_{par} \pm 0.00019_{theo}$

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

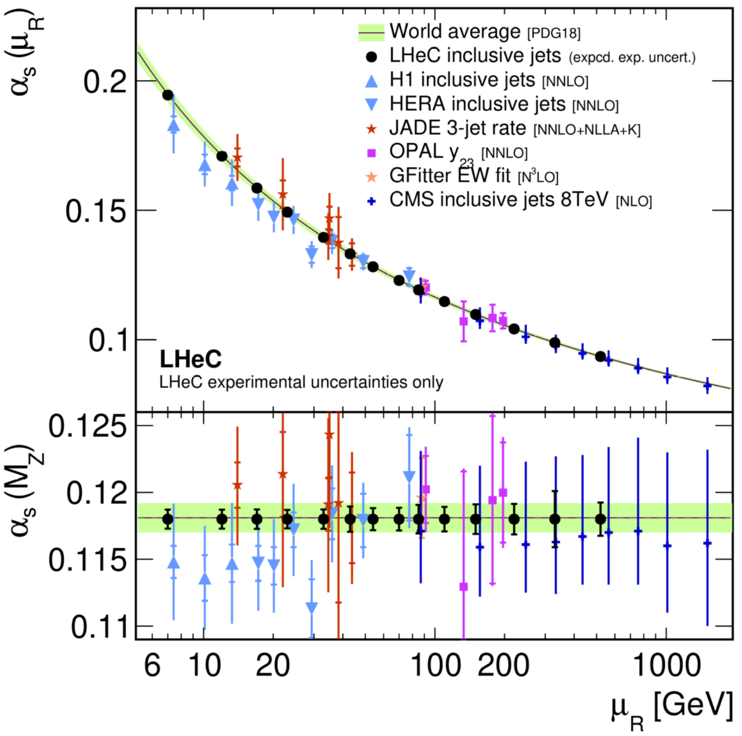
eP colliders: LHeC and FCC-eh



	E_p [TeV]	E_e [GeV]	√s [TeV]
LHeC:	7	50/60	1.2/1.3
FCC-eh:	50	60	3.5



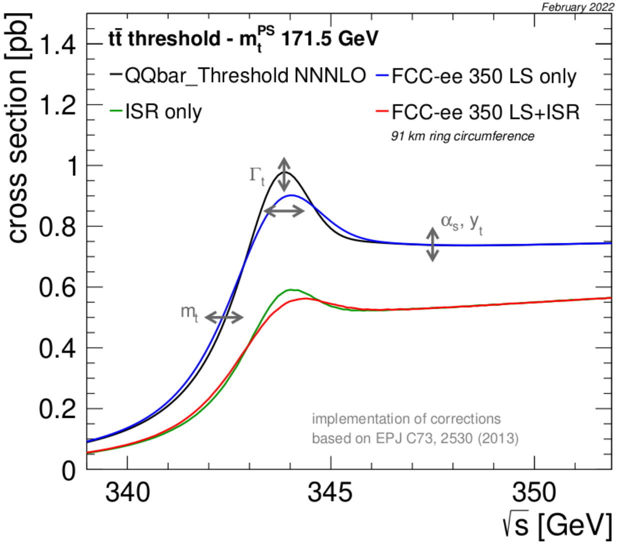
[FCC coll., Eur. Phys. J. C79 (2019) 474]

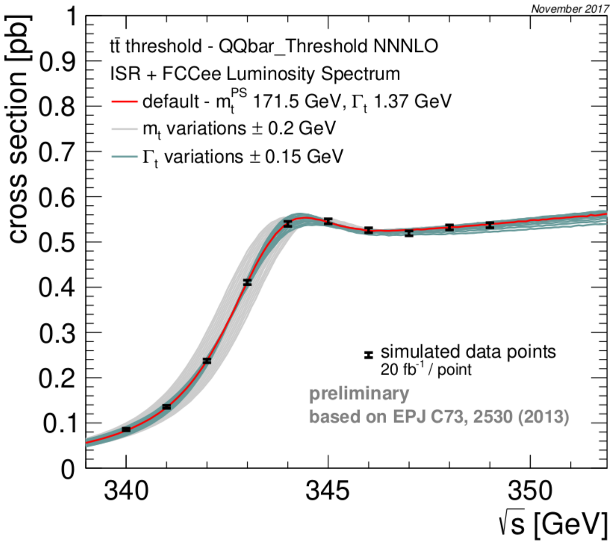


[LHeC, FCC-eh, J. Phys. G48 (2021) 110501]

Top quark properties in e^+e^-

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





Low sensitivity to top Yukawa cplg y_t:

$\Delta m_t^{(yt)} \approx 0.005$ GeV

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

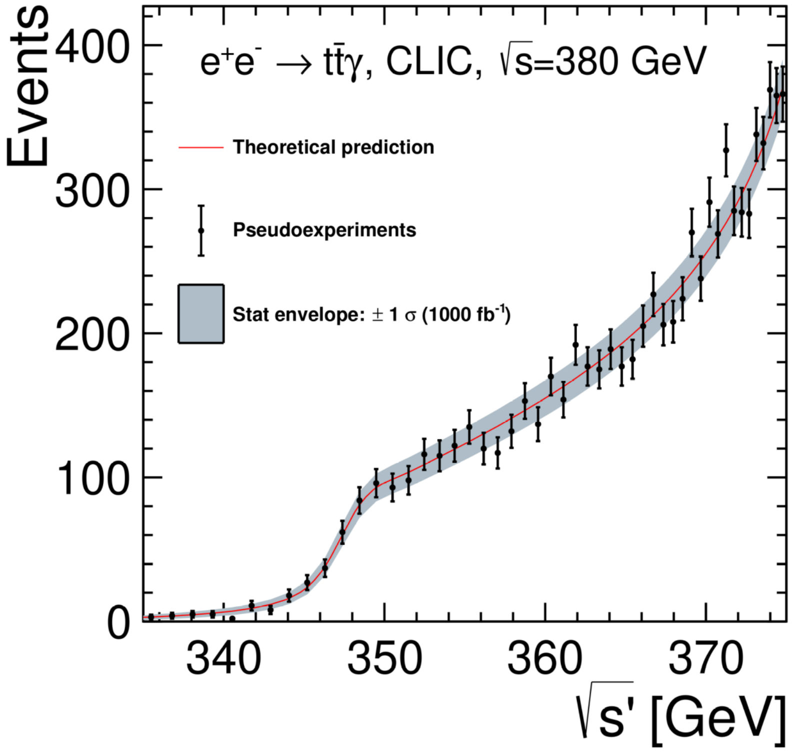
$m_t = (\,\mathit{171.5} \pm 0.017_{stat} \pm 0.003_{cms} \pm 0.005_{\alpha S} \pm 0.040_{theo}\,)$ GeV

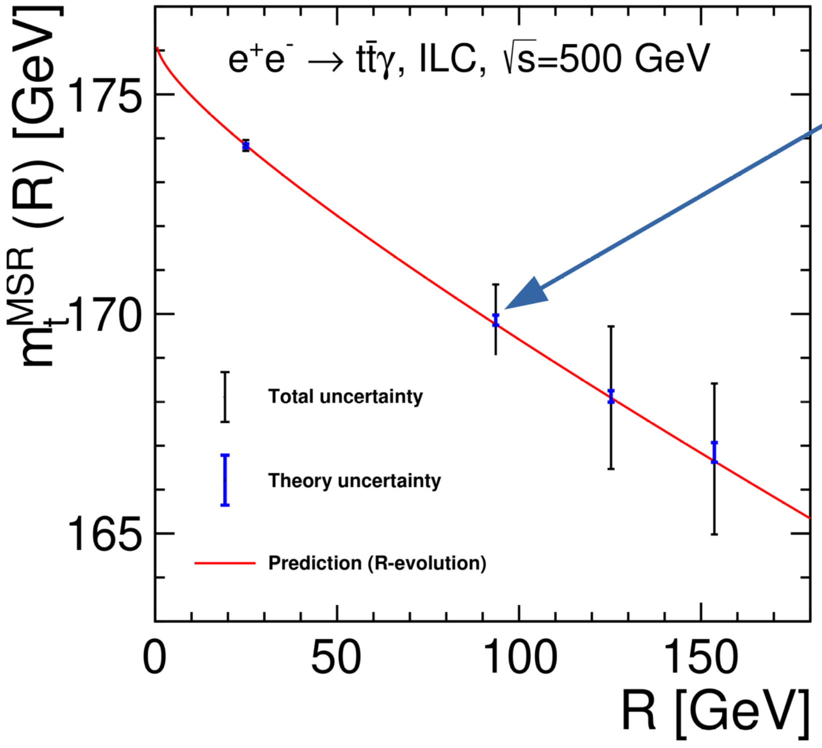
$\Gamma_t = (\,\mathit{1.37} \pm 0.045_{stat} \pm 0.003(?)_{cms} \pm 0.005(?)_{\alpha S} \pm 0.040_{theo}\,)$ GeV

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

Quark mass running: top

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





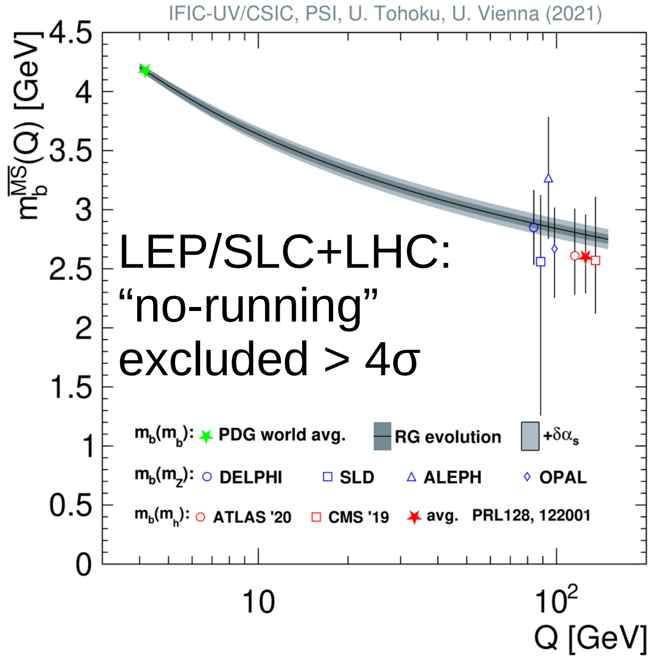
Accessible at $\sqrt{s}$ = 380 GeV

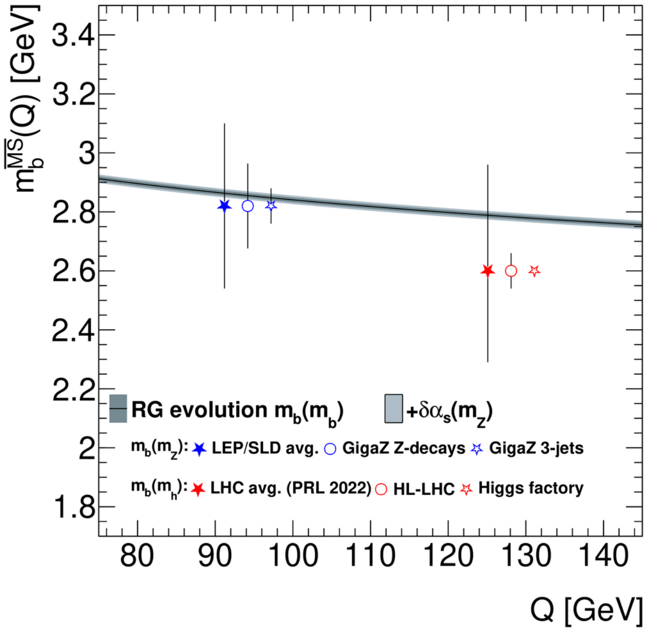
[M. Boronat et al, Phys. Lett. B804 (2020) 135353]

Quark mass running: b

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

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



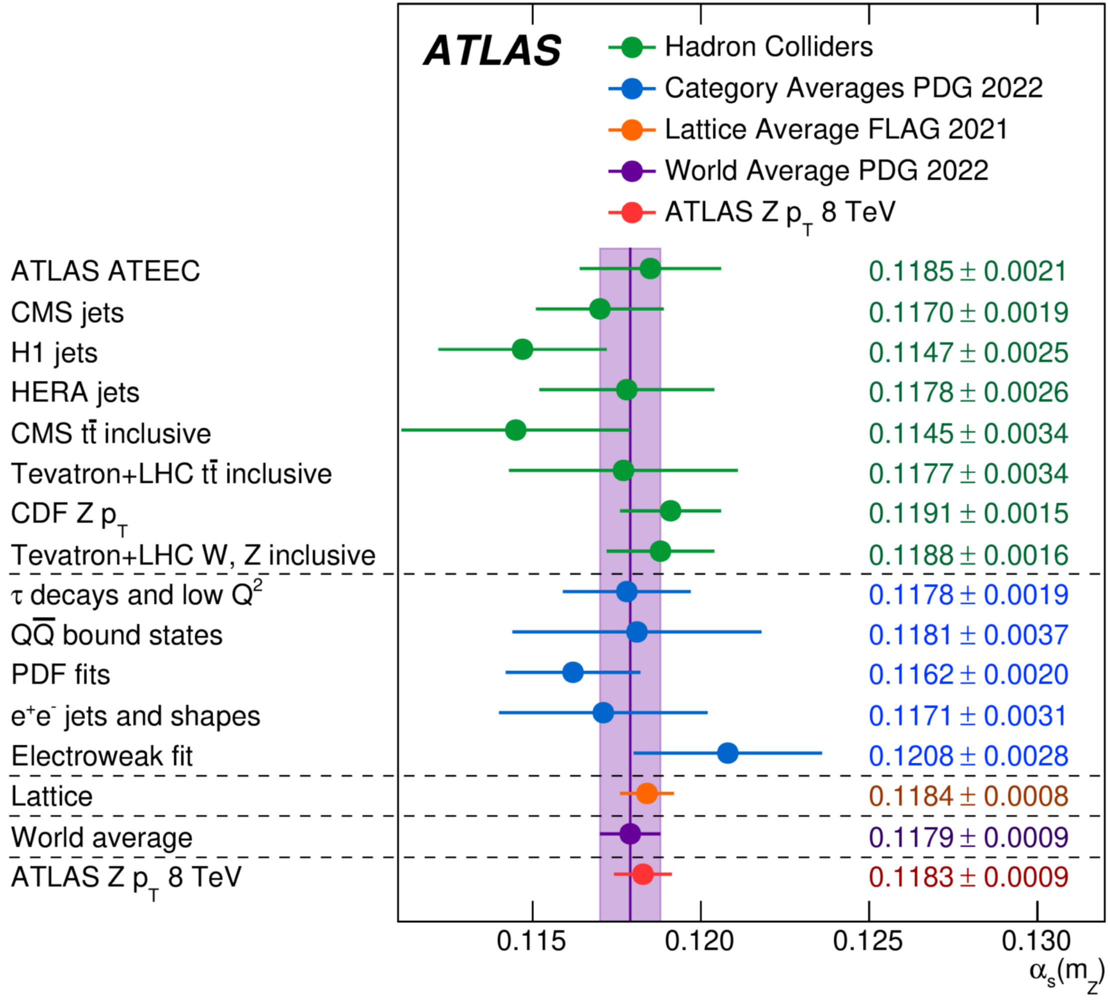


[J. Aparisi et al, arxiv: 2203.16994 and refs]

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

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

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]

Summary

- FCC-ee/eh/hh 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 $\Delta\alpha_S(m_Z) \approx 0.1\%$

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