QCD needs for e^+e^- precision physics

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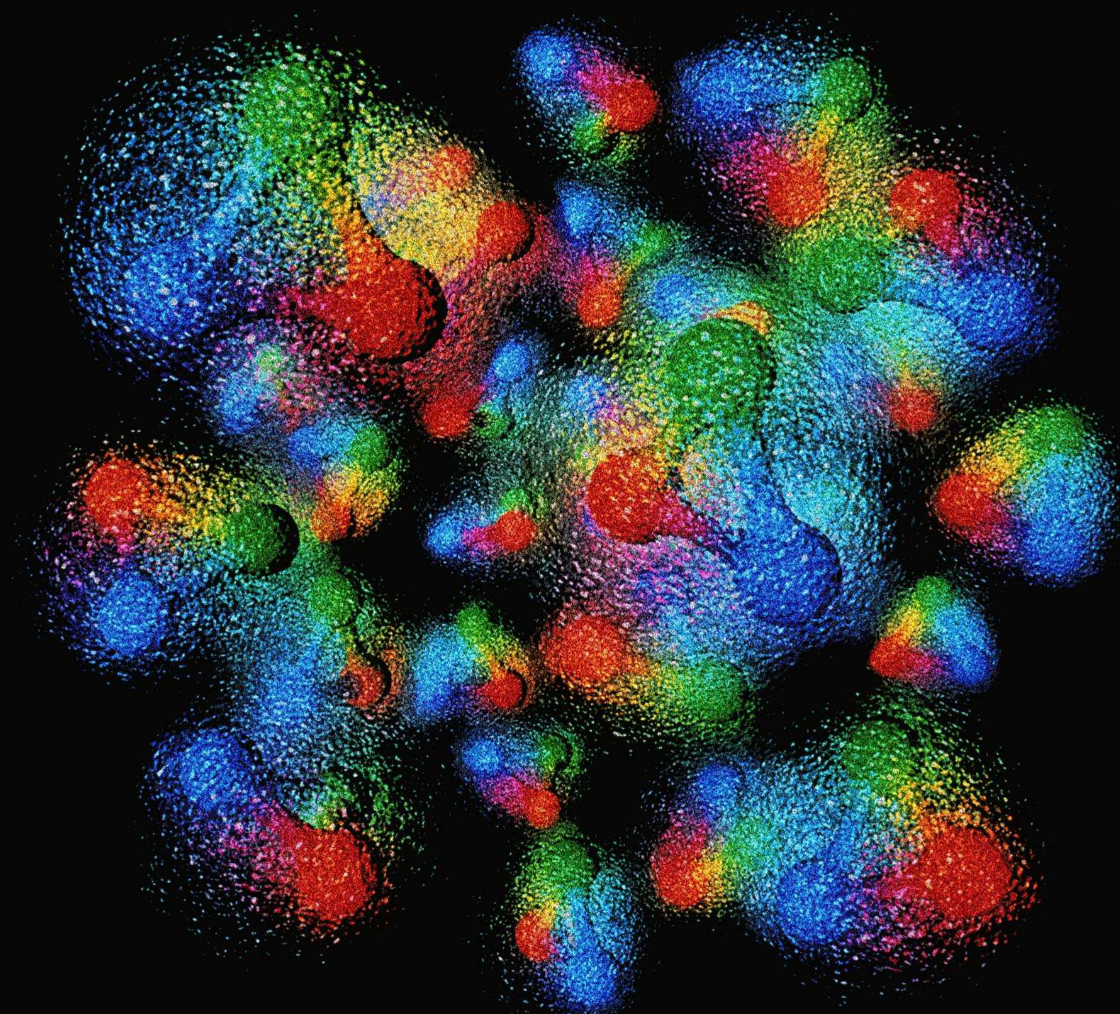


Need for theory input

- Comparison of EWPOs with SM to **probe new physics**
  $\longrightarrow$ multi-loop (mostly electroweak) corrections in full SM

- Extraction of EWPOs (**pseudo-observables**) from **real observables**
  $\longrightarrow$ backgrounds (in full SM), QED/QCD, MC tools

- "Other" eletroweak parameters (**"input" parameters**)
  $\longrightarrow$ m_{t}, α_{s}, etc. extracted from other processes

Z-pole observables

- Deconvolution of initial-state QED radiation:

  $$\sigma[e^+e^- \to f\bar{f}] = \mathcal{R}_{\text{ini}}(s,s') \otimes \sigma_{\text{hard}}(s')$$

  Soft photons (resummed) + collinear photons

  Exclusive description: MC tools

- Subtraction of γ-exchange, γ–Z interference, box contributions:

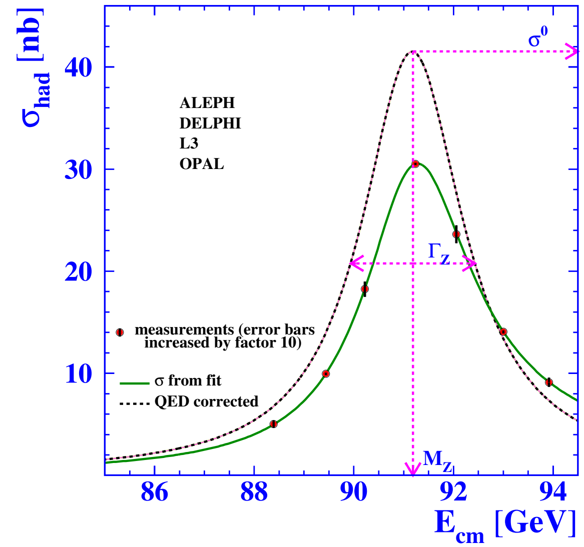
  $$\sigma_{\text{hard}} = \sigma_Z + \underbrace{\sigma_\gamma + \sigma_{\gamma Z} + \sigma_{\text{box}}}$$

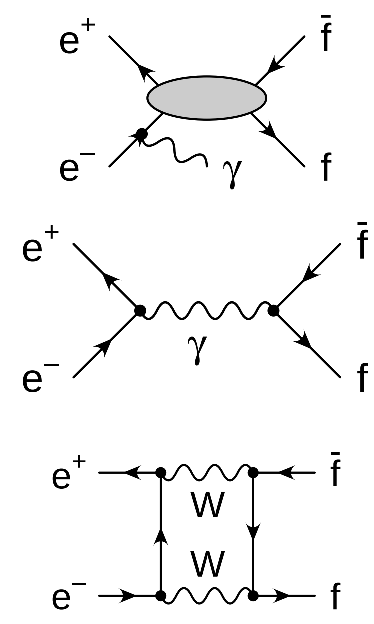
- Z-pole contribution:

  computed in SM

  $$\sigma_Z = \frac{R}{(s-\overline{M}_Z^2)^2 + \overline{M}_Z^2\Gamma_Z^2} + \sigma_{\text{non-res}}$$

LEP EWWG '05

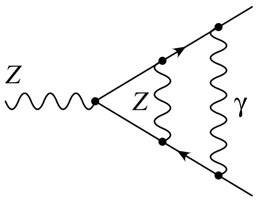


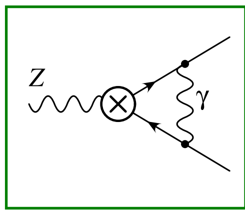


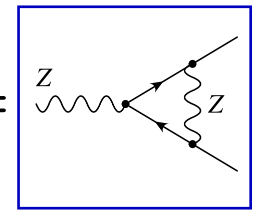
Z decay

Factorization of massive and QED/QCD FSR:

$$\overline{\Gamma}_f \approx \frac{N_c \overline{M}_Z}{12\pi}\left[\left(\mathcal{R}_V^f |g_V^f|^2 + \mathcal{R}_A^f |g_A^f|^2\right)\frac{1}{1+\mathrm{Re}\,\Sigma'_Z}\right]_{s=\overline{M}_Z^2}$$



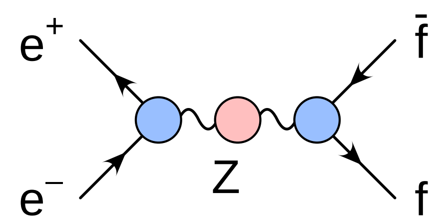
$=$


$+$ finite, with $\otimes =$


$\mathcal{R}_V^f,\ \mathcal{R}_A^f$: Final-state QED/QCD radiation;
known to $\mathcal{O}(\alpha_s^4)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha\alpha_s)$

Kataev '92
Chetyrkin, Kühn, Kwiatkowski '96
Baikov, Chetyrkin, Kühn, Rittinger '12

g_V^f, g_A^f, Σ'_Z: Electroweak corrections



Z decay

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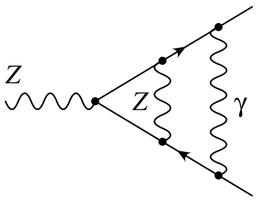

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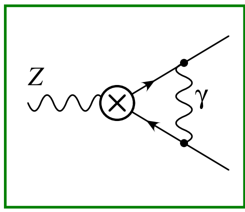
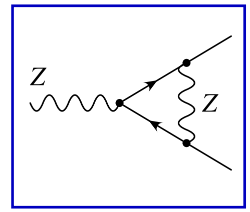
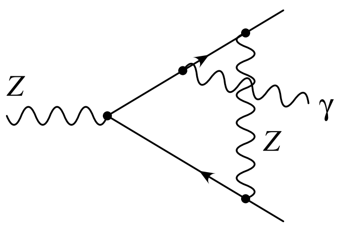


+ finite, with $\otimes$ =


Additional non-factorizable contributions, e.g.



$\rightarrow$ Known at $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ Czarnecki, Kühn ’96
Harlander, Seidensticker, Steinhauser ’98

$\rightarrow$ Currently not known at $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha\alpha_{\mathrm{s}}^2)$, etc.

$\rightarrow$ $\mathcal{O}(0.01\%)$ uncertainty on Γ_{Z}, σ_{Z}, maybe larger for A_{b}

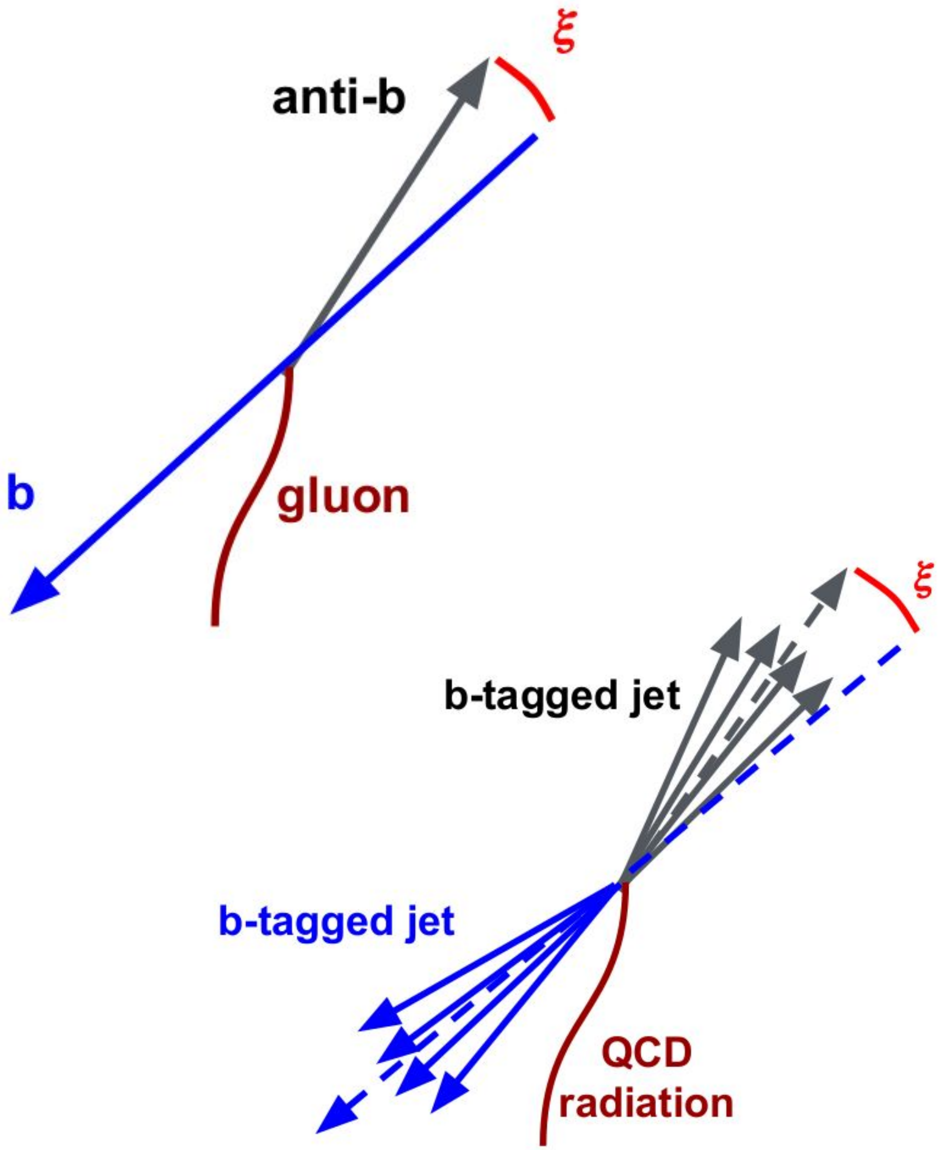
$\rightarrow$ How to account for in MC simulations?

Forward-backward asymmetry for heavy quarks

- Measurement of $A_{\mathrm{FB}}^{b,c}$ requires
  - $b/\bar{b}$ ($c/\bar{c}$) discrimination
  - Measurement of b (c) angle
- Mismatch between observed and parton-level b (c) angle due to QCD radiation (requires accurate modeling)
- Contamination from gluon splitting $g \to bb$ ($g \to cc$)
- Impact of hadronization/fragmentation
  (need more precise models and fragmentation functions)

A_{FB}(b/c)

arXiv:2010.08604



- New developments for A_{FB}(b/c): QCD corrections and uncertainties can be reduced significantly using acollinearity (ξ) cuts ⇒ important reduction in systematics, but how much ?
- Further improvements expected from better heavy flavor tagging capabilities and a more accurate measurement of the heavy quark flight direction
- **More sophisticated b/c tagging techniques => minimal charm/light background effects**
- **g->QQ splitting: huge control samples, smaller effect with back-to-back configuration and double tagging**
- Note that all these measurements can be done with exclusive decays. A Tera-Z facility will provide ≈10^8 B^+ exclusive decays

“missing” pieces: gluon fragmentation (1)

- $g\to Q\bar{Q}$ splitting tricky in parton showers

  (no soft enhancement, coll. divergence shielded by masses)

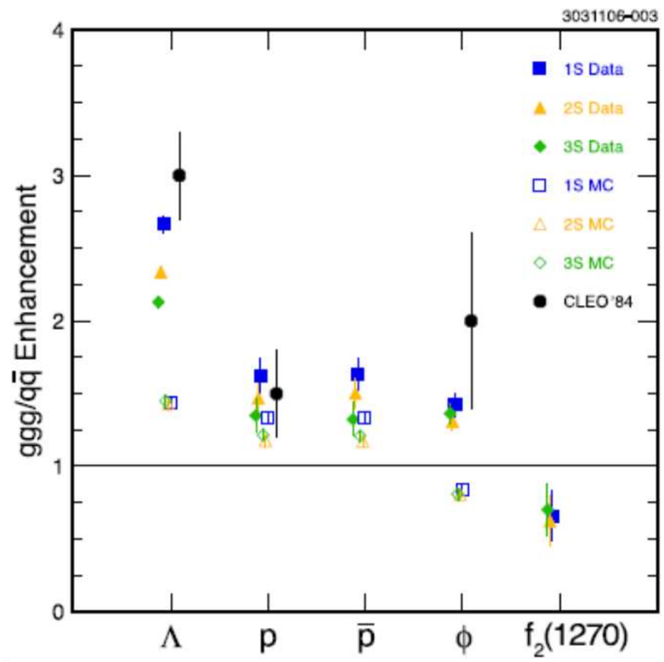
  - HF production is perturbative process
  - analyse $4b$ and $2b2c$ final states
    combine two softest equal flavour HFs into “gluon” and measure the $g\to Q\bar{Q}$ splitting function
    will yield information about shower evolution parameter and correct scale definition for α_S

"missing" pieces: gluon fragmentation (2)

- e^-e^+ (like LEP) dominated by quark jets:
  $\longrightarrow$ questionable handle on details of gluon fragmentation

(examples: enhanced diquark-popping? (leading) baryons? realisation of LPHD in gluons?)

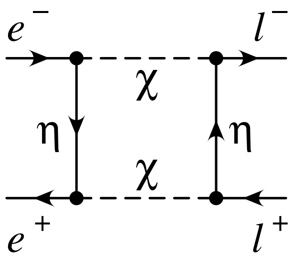
- measurement strategy:
  - "Mercedes star" with two id'd heavy quark jets $\longrightarrow$ third jet is gluon jet
  - jet-shape measurements: sub-jettiness & friends
  - hadron yields inside jet
  - leading hadron identity/x_p
  - di-baryon/di-strange correlations inside jet



$ee \to ff$ above Z pole

With $\mathcal{O}(\mathrm{ab}^{-1})$ at $\sqrt{s} \sim 161$ GeV and $\sqrt{s} \sim 240$ GeV:

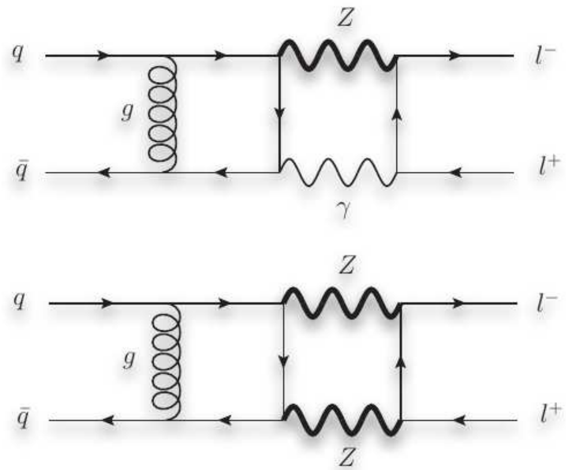
- $< 10^{-3}$ precision for $\sigma[e^+e^- \to f\bar{f}]$ (similar for A_{FB})
- sensitivity to new physics, e.g. Z' bosons or lepto-philic DM



- NNLO corrections for full process $e^+e^- \to f\bar{f}$ needed (+ partial higher orders)

Leading missing contribution: Mixed QCD×EW corrections
$\to$ related to QCD×EW corrections for $pp \to \ell^+\ell^-$

Buonocore et al. '21
Bonciani et al. '21
Buccioni et al. '22



Comparison of EWPOs with theory

- To probe new physics, compare EWPOs with SM theory predictions
- Need to take theory error into account:

	Current exp.	Current th.[†]	CEPC	FCC-ee
M_W [MeV]	15	4 *	0.5	0.4
Γ_Z [MeV]	2.3	0.4	0.1	0.1
$R_\ell = \Gamma_Z^\mathrm{had}/\Gamma_Z^\ell$ [10^{-3}]	25	5	2	1
$R_b = \Gamma_Z^b/\Gamma_Z^\mathrm{had}$ [10^{-5}]	66	10	4.3	$<$6
$\sin^2\theta^\ell_\mathrm{eff}$ [10^{-5}]	16	4.5	$<$1	0.5

* computed from G_μ † full NNLO and leading NNNLO

- Theory error estimate is not well defined, ideally $\Delta_\mathrm{th} \ll \Delta_\mathrm{exp}$
- Common methods:
  - Count prefactors (α, N_c, N_f, ...)
  - Extrapolation of perturbative series
  - Renormalization scale dependence
  - Renormalization scheme dependence

Projected theory uncertainties

- To probe new physics, compare EWPOs with SM theory predictions
- Need to take theory error into account:

	Current exp.	Future th.[†]	CEPC	FCC-ee
M_W [MeV]	15	1 *	0.5	0.4
Γ_Z [MeV]	2.3	0.1	0.1	0.1
$R_\ell = \Gamma_Z^{\text{had}}/\Gamma_Z^\ell$ $[10^{-3}]$	25	1.5	2	1
$R_b = \Gamma_Z^b/\Gamma_Z^{\text{had}}$ $[10^{-5}]$	66	5	4.3	<6
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	16	1.5	<1	0.5

* computed from G_μ

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2)$, leading 4-loop

(N_f^n = at least n closed fermion loops)

most challenging for $Z \to q\bar{q}$

SM predictions for Higgs decays

hgg: [CEPC: 2.4%, FCC-ee: 1.6%]

- $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$ (in large m_t-limit) QCD corrections — Baikov, Chetyrkin '06; Schreck, Steinhauser '07
- $\mathcal{O}(\alpha)$ EW — Aglietti, Bonciani, Degrassi, Vicini '04; Degrassi, Maltoni '04

Theory error (dominated by QCD): $\Delta_{\text{th}} \approx 3\%$
With $\mathcal{O}(\alpha_s^4)$ in large m_t-limit (4-loop massless QCD diags.): $\Delta_{\text{th}} \approx 1\%$

Parametric error: $\delta\alpha_s = 0.001 \rightarrow \Delta_{\text{par}} \approx 3\%$
$\delta\alpha_s = 0.0001 \rightarrow \Delta_{\text{par}} \approx 0.3\%$

Parametric uncertainties

Impact of input parameter uncertainties on SM prediction
for precision observables:

Snowmass EF EWK report ’22

	ILC-GigaZ	FCC-ee	Param. error scen. 1	Param. error scen. 2
M_W [MeV]	2.5	0.4	2.8	0.6
Γ_Z [MeV]	0.12	$<$0.1	0.3	0.1
R_ℓ [10^{-3}]	6	1	3.2	1.3
$\sin^2\theta^\ell_\mathrm{eff}$ [10^{-5}]	1	0.5	3.2	1.3
$\Gamma_{h\to bb}$ [%]	2	1.3	1.4	0.6
$\Gamma_{h\to WW}$ [%]	2	0.8	0.2	0.1
$\Gamma_{h\to gg}$ [%]	2.6	1.8	1.5	0.6

Parametric inputs:

	scen. 1	scen. 2
δm_t [MeV]	300	50
δm_b [MeV]	30	13
δM_Z [MeV]	0.8	0.1
δM_H [MeV]	20	10
$\delta\alpha_\mathrm{s}$ [10^{-3}]	0.5	0.2
$\delta(\Delta\alpha)$ [10^{-4}]	1	0.3

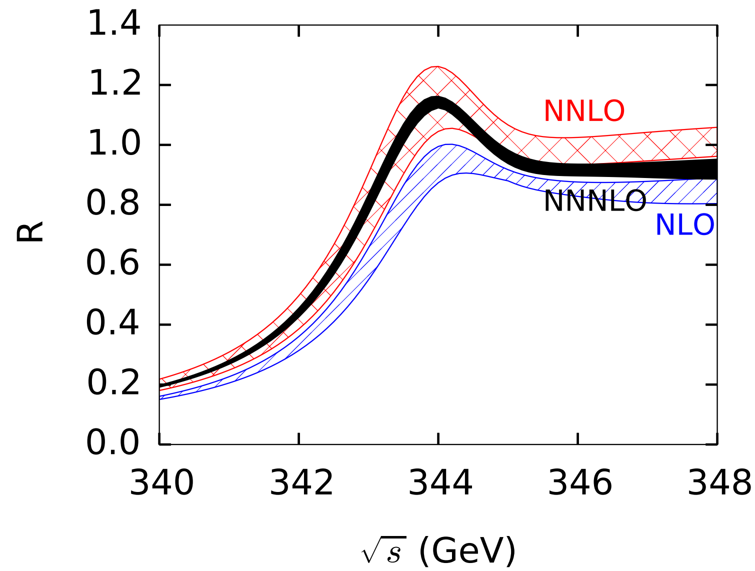
Reviews: 1906.05379, 2012.11642

- m_t: From $e^+e^- \to t\bar{t}$ at $\sqrt{s} \sim 350$ GeV

today:

$$\delta m_t^{\overline{\mathrm{MS}}} = [\quad]_{\mathrm{exp}} \oplus [50\ \mathrm{MeV}]_{\mathrm{QCD}} \oplus [10\ \mathrm{MeV}]_{\mathrm{mass\ def.}} \oplus [70\ \mathrm{MeV}]_{\alpha_s}$$

$$> 100\ \mathrm{MeV}$$



Beneke et al. '15

Fermion masses

Reviews: 1906.05379, 2012.11642

- m_t: From $e^+e^- \to t\bar{t}$ at $\sqrt{s} \sim 350$ GeV

today:	**future:**	
$\delta m_t^{\overline{\rm MS}} = [\quad]_{\rm exp}$	$[20\text{ MeV}]_{\rm exp}$	
$\oplus\,[50\text{ MeV}]_{\rm QCD}$	$\oplus\,[30\text{ MeV}]_{\rm QCD}$	(resumm., N^{4}LO ??)
$\oplus\,[10\text{ MeV}]_{\text{mass def.}}$	$\oplus\,[10\text{ MeV}]_{\text{mass def.}}$	
$\oplus\,[70\text{ MeV}]_{\alpha_s}$	$\oplus\,[15\text{ MeV}]_{\alpha_s}$	($\delta\alpha_s \lesssim 0.0002$)
> 100 MeV	$\lesssim 50$ MeV	

Fermion masses

Reviews: 1906.05379, 2012.11642

- m_t: From $e^+e^- \to t\bar{t}$ at $\sqrt{s} \sim 350$ GeV

today:	**future:**	
$\delta m_t^{\overline{\text{MS}}} = [\quad]_{\text{exp}}$	$[20\ \text{MeV}]_{\text{exp}}$	
$\oplus\ [50\ \text{MeV}]_{\text{QCD}}$	$\oplus\ [30\ \text{MeV}]_{\text{QCD}}$	(resumm., N^{4}LO ??)
$\oplus\ [10\ \text{MeV}]_{\text{mass def.}}$	$\oplus\ [10\ \text{MeV}]_{\text{mass def.}}$	
$\oplus\ [70\ \text{MeV}]_{\alpha_s}$	$\oplus\ [15\ \text{MeV}]_{\alpha_s}$	($\delta\alpha_s \lesssim 0.0002$)
> 100 MeV	$\lesssim 50$ MeV	

- $m_b,\ m_c$: From quarkonia spectra using Lattice QCD

  $\delta m_b^{\overline{\text{MS}}} \sim 30$ MeV, $\delta m_c^{\overline{\text{MS}}} \sim 25$ MeV — LHC HXSWG '16

  $\to$ estimated improvements $\delta m_b^{\overline{\text{MS}}} \sim 13$ MeV, $\delta m_c^{\overline{\text{MS}}} \sim 7$ MeV

  Lepage, Mackenzie, Peskin '14

Strong coupling

- α_s: d'Enterria et al., Snowmass '22
  - Most precise determination using Lattice QCD:

    $\alpha_s = 0.1184 \pm 0.0006$ HPQCD '10

    $\alpha_s = 0.1185 \pm 0.0008$ ALPHA '17

    $\alpha_s = 0.1179 \pm 0.0015$ Takaura et al. '18

    $\alpha_s = 0.1172 \pm 0.0011$ Zafeiropoulos et al. '19

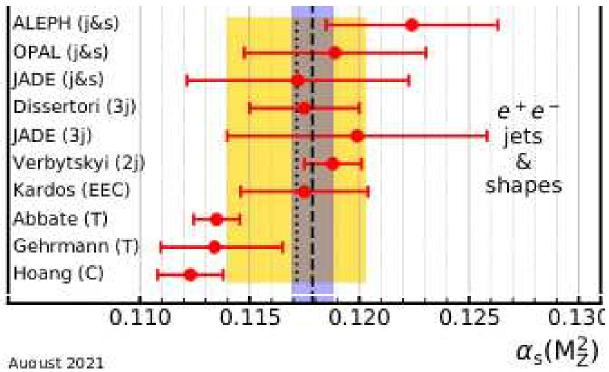
    $\rightarrow$ future improvements: $\delta\alpha_s < 0.0005$

  - e^+e^- event shapes: $\alpha_s \sim 0.113 ... 0.119$

    $\rightarrow$ Large non-pertubative power corrections

    $\rightarrow$ Improvement with better observables (jet ratios, groomed thrust, ...)?

PDG '21



  - Hadronic τ decays: $\alpha_s = 0.119 \pm 0.002$ PDG '18

    $\rightarrow$ Non-perturbative uncertainties in OPE and from duality violation

    Pich '14; Boito et al. '15,18

Strong coupling

- α_s:
  - Electroweak precision ($R_\ell = \Gamma_Z^{\rm had}/\Gamma_Z^\ell$):
    $\alpha_s = 0.120 \pm 0.003$ PDG '18

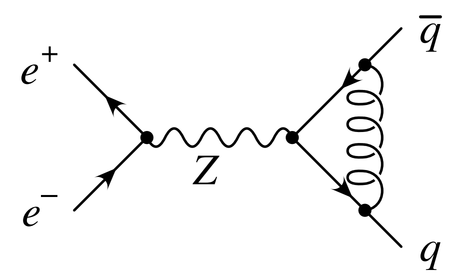
    $\rightarrow$ No (negligible) non-perturbative QCD effects

    FCC-ee: $\delta R_\ell \sim 0.001$

    $\Rightarrow \quad \delta\alpha_s \sim 0.00015$

    Theory input: N^{3}LO EW corr. + leading N^{4}LO
    to keep $\delta_{\rm th} R_\ell \lesssim \delta_{\rm exp} R_\ell$

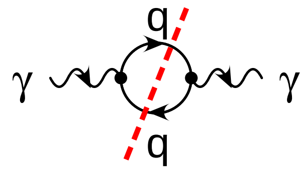
    Caviat: R_ℓ could be affected by new physics



Electromagnetic coupling

- $\Delta\alpha \equiv 1 - \frac{\alpha(0)}{\alpha(M_Z)} \approx 0.059 = 0.0315_{\text{lept}} + 0.0276_{\text{had}}$

a) $\Delta\alpha_{\text{had}}$ from $e^+e^- \to$ had. using dispersion relation

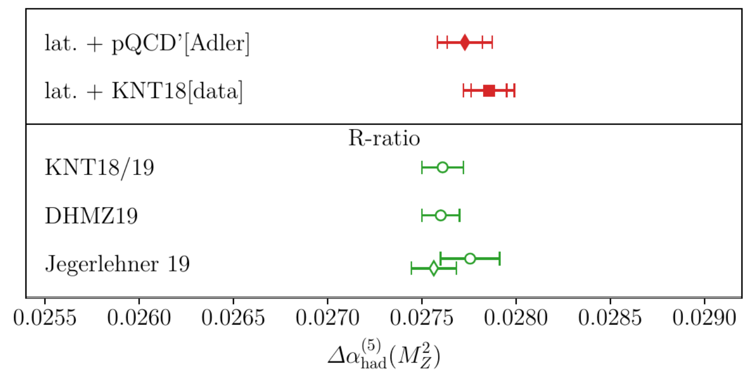


$\to$ Current precision $\sim 10^{-4}$

Davier et al. '19; Jegerlehner '19; Keshavarzi, Nomura, Teubner '19

b) $\Delta\alpha_{\text{had}}$ from Lattice QCD (challenging but much progress)

Burger et al. '15
Cè et al. '22



Future improvements for methods (a) and (b):

- More precise exp./lattice data
- Full 4-loop pQCD for R-ratio / Adler function (for $|Q^2| \gg \Lambda_{\text{QCD}}$)
- More precise inputs for m_b, m_c, α_s

$\to \delta(\Delta\alpha_{\text{had}}) \lesssim 5 \times 10^{-5}$ likely achievable

Jegerlehner '19

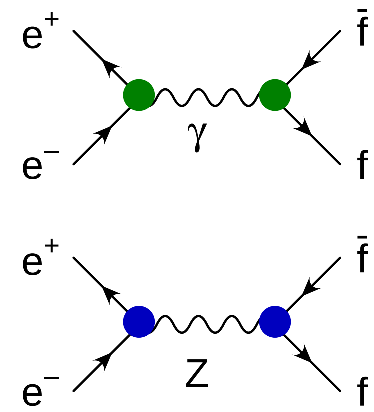
Electromagnetic coupling

- $\Delta\alpha \equiv 1 - \frac{\alpha(0)}{\alpha(M_Z)} \approx 0.059 = 0.0315_{\text{lept}} + 0.0276_{\text{had}}$

  c) Direct det. of $\Delta\alpha_{\text{had}}$ from $e^+e^- \to \mu^+\mu^-$ off the Z peak   Janot '15

  $$|\mathcal{M}_{ij}|^2 \propto |g_i^\ell|^2 |g_j^\ell|^2 + (s - M_Z^2)\,\alpha(M_Z)|g_{i,j}^\ell|^2 + \ldots$$

  ↑ determined from Z pole



  $\to$ Use $A_{\text{FB}}^{\mu\mu}$ at $\sqrt{s_1} \sim 88$ GeV and $\sqrt{s_2} \sim 95$ GeV to reduce systematics

  $\to$ $\delta(\Delta\alpha_{\text{had}}) \sim 3 \times 10^{-5}$ for $\mathcal{L}_{\text{int}} = 85$ ab^{-1}

  $\to$ Requires 2/3-loop corrections for $e^+e^- \to \mu^+\mu^-$

Summary

- **QCD effects are important for precision measurements at future e^+e^- colliders:**
  - Perturbative fixed-order corrections (in particular for hadronic final states)
  - Parton shower (resummation)
  - Hadronization effects

- **Need high-fidelity Monte-Carlo tools for analysis of:**
  - hadronization/fragmentation functions
  - flavor tagging (contamination from gluon splitting)
  - acceptance and selection efficiency/purity
  - color reconnection

- Improved determinations of **input parameters** require advances in **perturbative** and **non-perturbative** theory tools

Backup slides