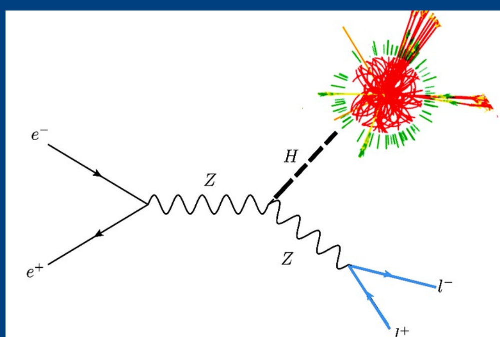
Precision QCD at future colliders

European Strategy for Particle Physics

ESPP Update 2026
Open Symposium
Venice, June 2025



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23-27 JUNE 2025 Lido di Venezia

Precision QCD at future facilities

- Input received: $\mathcal{O}(20)$ future projects

Facility, Experiments	Colliding systems, c.m.s. energy	Timeline	Precision QCD
HL-LHC: ALICE 3, ATLAS & CMS pII, LHCb U2, LHCspin	pp 14 TeV AA 5.5 TeV pA 8.8 TeV	> 2035 (ALICE 3, LHCb U2)	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, m_W
HL-LHC: FPF	LHC collisions, neutrino-nucleon	> 2031	
SPS: NA60+, NA61	pA, AA, 6-17 GeV	> 2030 (NA60+)	
FAIR SIS-100: CBM	pA, AA, 2.5-5 GeV	> 2028	
MUonE	μ(160 GeV)-e	> 2030	g-2 (hadronic)
HIE-ISOLDE upgrades	Radioactive ion beams	> 2029	
KEK: Belle II upg.	ee 10 GeV	> 2035	$\alpha_s(m_\tau^2)$
STCF	ee 2-7 GeV	> 2033	$\alpha_s(m_\tau^2)$
EIC	ep, eA 28-140 GeV	> 2036	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$
LHeC	ep, eA 1.2 TeV	> 2043	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$
FCC	ee 90-365 GeV pp 85 TeV AA 33.5 TeV pA 53.4 TeV	> 2047 > 2074	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, Γ_t, m_W
LCF CLIC	ee 0.25-1 TeV ee 0.38-1.5 TeV	> 2050	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, Γ_t, m_W
LEP3	ee 91-230 GeV	> 2047	$\alpha_s(m_Z^2)$
Muon Collider	$\mu\mu$ 3-10 TeV	> 2050	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$

Plus recent community docs:
α_s(2024), QCD at Belle-II, latt-QCD,...

- Precision benchmarks:

  1) $\alpha_s(m_Z)$ & its Q^2 dependence

  2) QCD & precision top mass (m_{top})

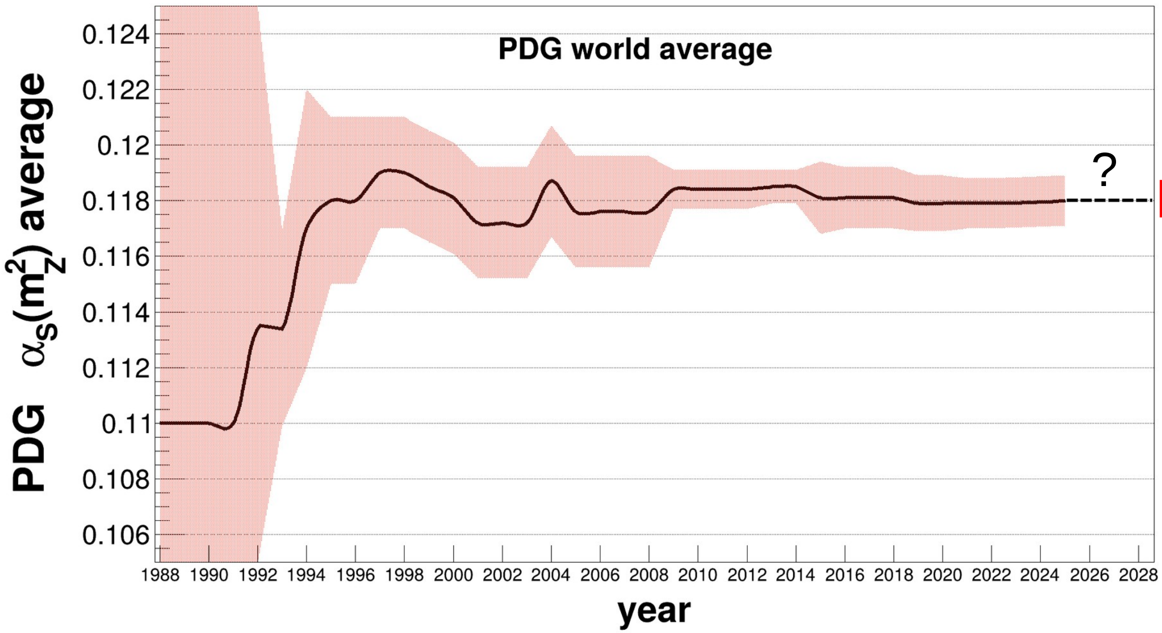
  3) QCD & precision W mass (m_W)

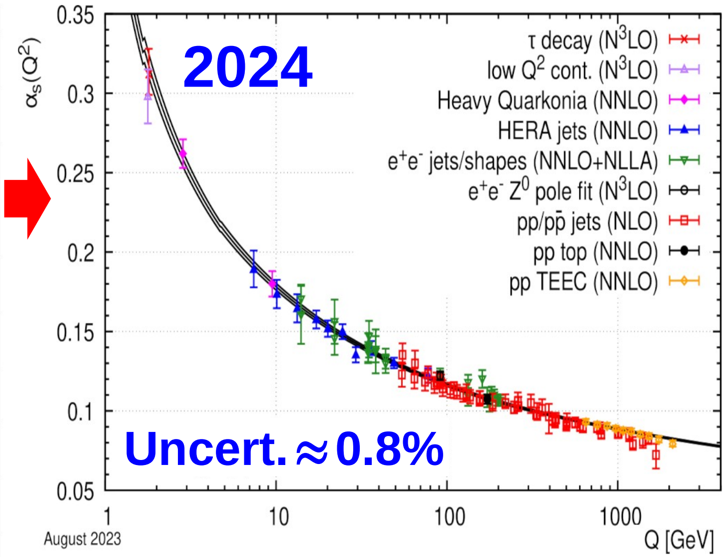
- QCD & Higgs physics

- Theory calculations wish-list:
  pQCD, latt-QCD,
  MC parton-showers

The strong coupling α_s

- Determines strength of the strong interaction among quarks & gluons.
- Single free parameter of QCD in the $m_q = 0$ limit.
- Determined at a ref. scale ($Q=m_Z$), decreases as $\alpha_s \approx \ln(Q^2/\Lambda^2)^{-1}$, $\Lambda \approx 0.2$ GeV





$\alpha_s(m_Z^2) = 0.1180 \pm 0.0009$

➧ Least precisely known of all interaction couplings !

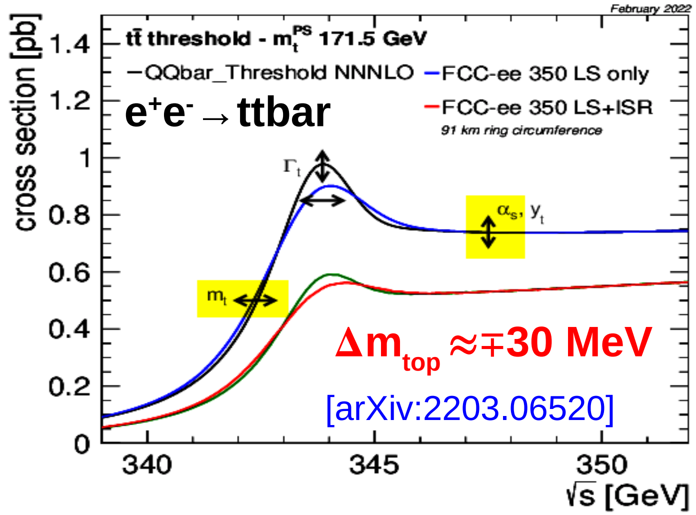
$$\Delta\alpha \approx 10^{-10} \ll \Delta G_F \approx 10^{-7} \ll \Delta G \approx 10^{-4} \ll \Delta\alpha_s \approx 0.8\%$$

α_s impact beyond QCD

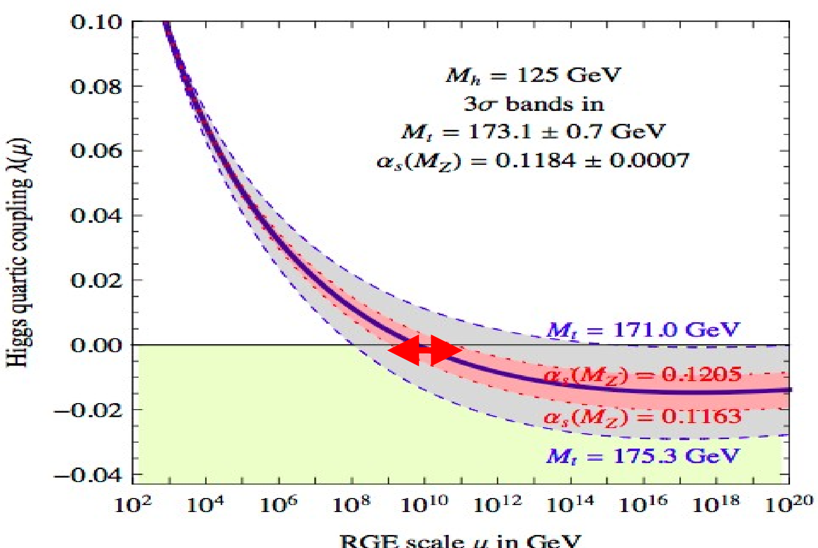
- Parametric uncertainty for key Higgs, EWPO, top quark calculations:

Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 + 0.32
ttH	0.611	± 3.0	± 8.9	-9.3 + 5.9

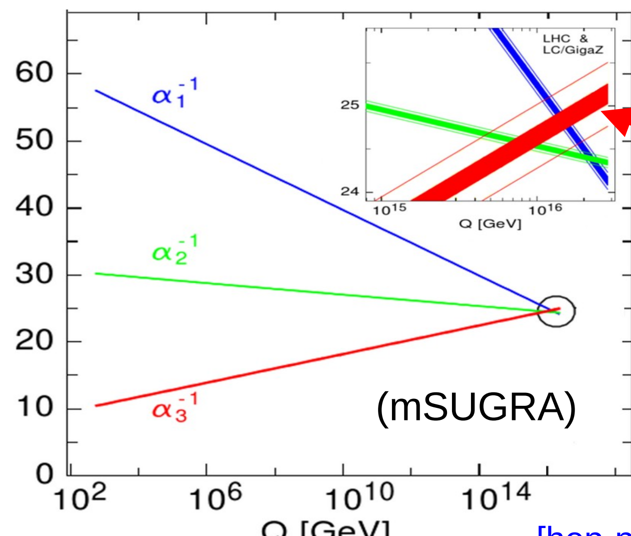
Partial width	intr. QCD	para. m_q	para. α_s
$H \to b\bar{b}$	$\sim 0.2\%$	1.4%	0.4%
$H \to c\bar{c}$	$\sim 0.2\%$	4.0%	0.4%
$H \to gg$	$\sim 3\%$	$< 0.2\%$	3.7%



- Impacts physics approaching Planck scale: EW vacuum stability, GUT:



[arXiv:1112.3022]



$\Delta\alpha_s = \pm 1\%$

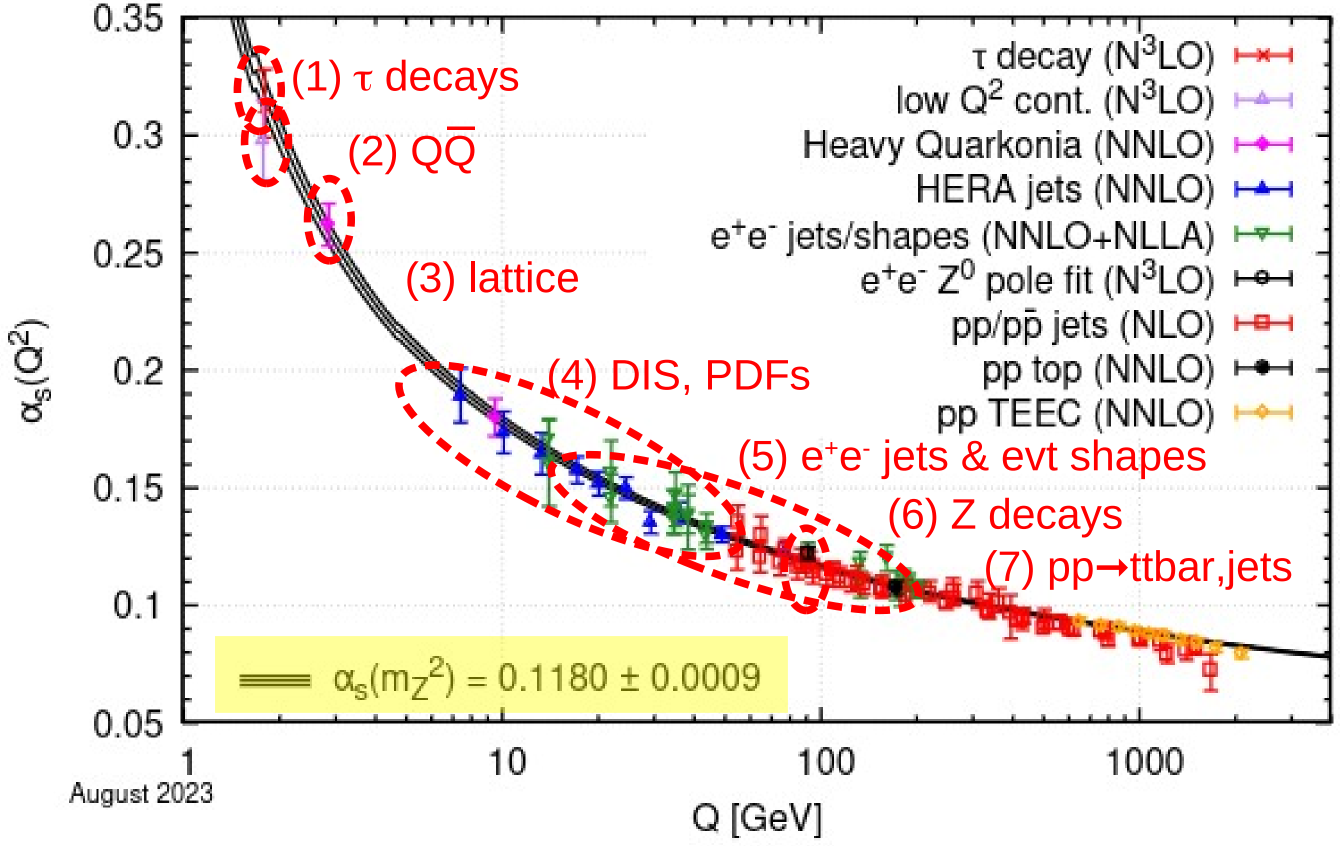
α_s running at high Q:

New coloured sectors?

[hep-ph/0410364]

α_s determination (today)

- Current precision: $\Delta\alpha_s = \pm 0.8\%$
  From combination of 7 experimental observables
  compared to $N^{2,3}LO$ pQCD predictions:



- Running coupling probed at the LHC up to $Q \approx 2$ TeV

QCD coupling at EIC, Belle-II, STCF, LHeC

- α_s extractions at EIC/JLab-22GeV:
  ±1% from inclusive DIS
  ±0.6% from new observables
  (deuteron & spin-dependent SFs):
  ±0.6% from Bjorken SR & pol. PDFs.

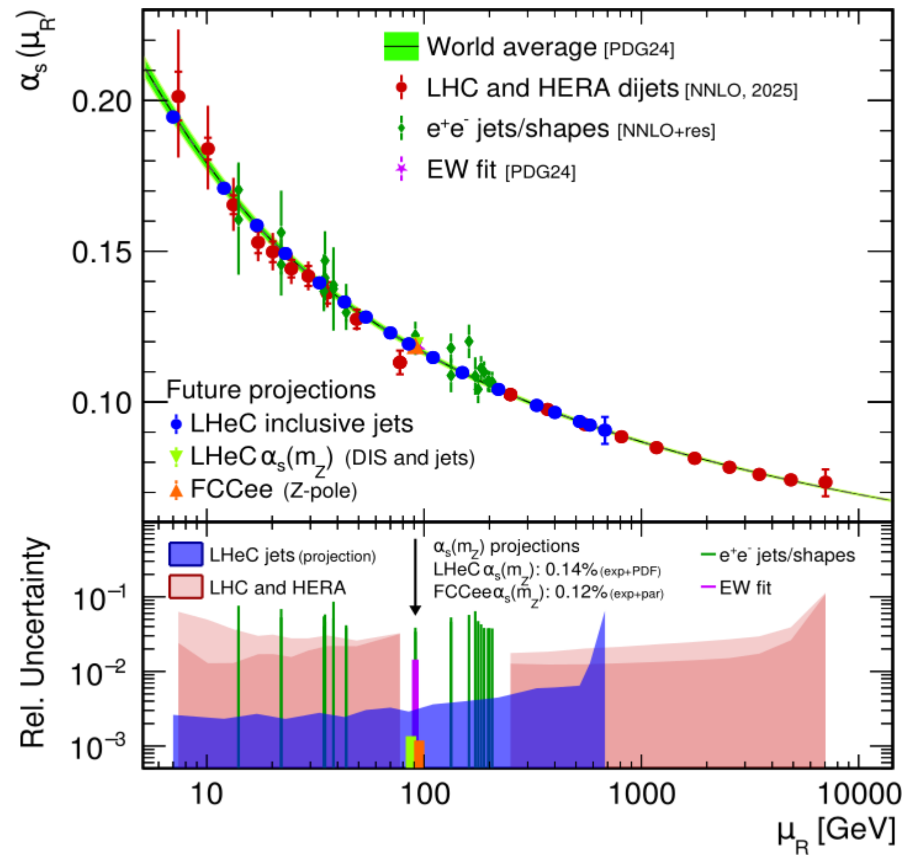
- α_s extractions at Belle-II (Upg):
  (50 billion tau pairs in 50 ab^{-1}):
  Improved tau spectral functions
  ≪1% (stat.) from hadronic tau decays.

  Also possible:
  α_s from R(s) ratio over √s=1–10 GeV
  α_s from event shapes (EECs) & FFs.

- α_s extraction at STCF:

  ≪1% (stat.) from hadronic tau decays

- α_s extractions at LHeC:
  ±0.2% from inclusive DIS fits
  ±0.15% from incl. DIS + jets



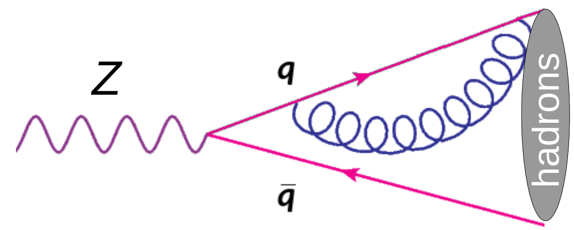
Running Q = 5–500 GeV (jets)

QCD coupling at e⁺e⁻ (LC)

- EW boson pseudoobservables known at N³LO in pQCD:

  - The W and Z hadronic widths :

$$\Gamma^{\rm had}_{\rm W,Z}(Q) = \Gamma^{\rm Born}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm EW} + \delta_{\rm mix} + \delta_{\rm np}\right)$$



  - The ratio of W, Z hadronic-to-leptonic widths :

$$R_{\rm W,Z}(Q) = \frac{\Gamma^{\rm had}_{\rm W,Z}(Q)}{\Gamma^{\rm lep}_{\rm W,Z}(Q)} = R^{\rm EW}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm mix} + \delta_{\rm np}\right)$$

Note: Sensitivity to $\alpha_s(m_Z)$ via $\mathcal{O}$(4%) virtual corrs.

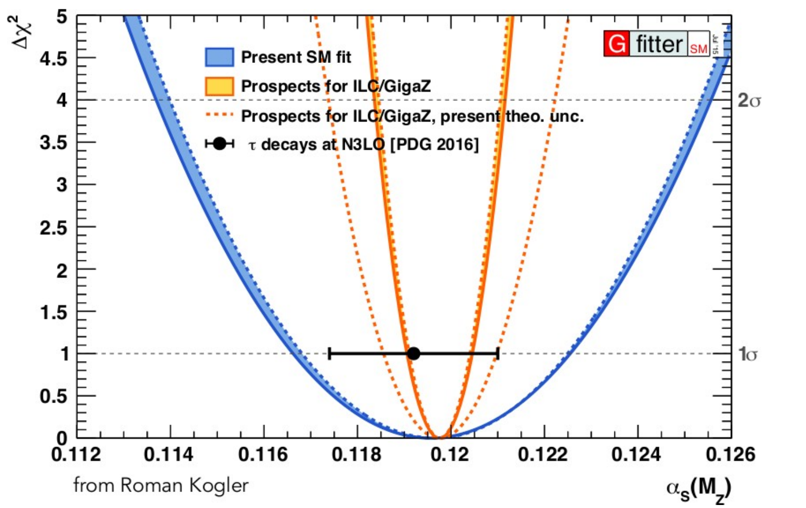
  - In the Z boson case, the hadronic cross section at the resonance peak in e^+e^-:

$$\sigma^{\rm had}_{\rm Z} = \frac{12\pi}{m_{\rm Z}} \cdot \frac{\Gamma^e_{\rm Z}\Gamma^{\rm had}_{\rm Z}}{(\Gamma^{\rm tot}_{\rm Z})^2}$$

arXiv:1512.05194 [hep-ph]

- LC (Giga-Z) will reach 0.6% precision on $\alpha_s(m_Z)$ ($\times$4 better than LEP):
  - Assume Z-pole stats.: 10^9 bosons
  - Other uncertainties (syst., parametric) not considered (but subleading):

$\alpha_s(m_z) = 0.1200 \pm 0.0007$



from Roman Kogler

  - Also from τ hadronic decays, evt. shapes, jet rates: <1%
  - However, LC claim is that α_s should be taken from latt-QCD (±0.1% precision) instead

QCD coupling at e^+e^- (FCC-ee)

- EW boson pseudoobservables known at N^3LO in pQCD:

  - The W and Z hadronic widths :

$$\Gamma^{\rm had}_{\rm W,Z}(Q) = \Gamma^{\rm Born}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm EW} + \delta_{\rm mix} + \delta_{\rm np}\right)$$

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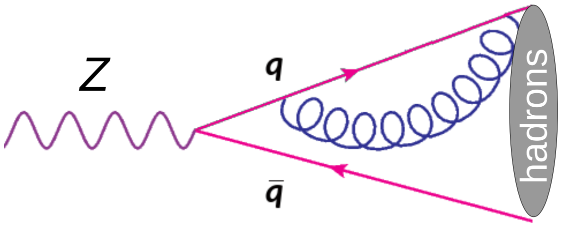


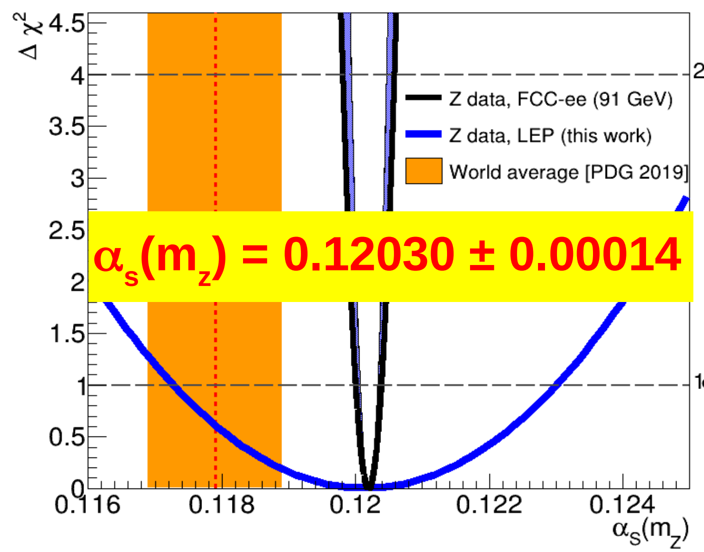
Note: Sensitivity to $\alpha_s(m_Z)$ via $\mathcal{O}$(4%) virtual corrs.

[arXiv:2005.04545]

- FCC-ee will reach 0.1% precision on $\alpha_s(m_Z)$ ($\times$20 better than LEP):
  - Huge Z pole stats. ($\times 10^5$ LEP):
  - Exquisite syst./parametric precision:

$$\begin{array}{ll}
\Delta R_Z = 10^{-3}, & R_Z = 20.7500 \pm 0.0010 \\
\Delta\Gamma^{\rm tot}_Z = 0.1\ {\rm MeV}, & \Gamma^{\rm tot}_Z = 2495.2 \pm 0.1\ {\rm MeV} \\
\Delta\sigma^{\rm had}_Z = 4.0\ {\rm pb}, & \sigma^{\rm had}_Z = 41\,494 \pm 4\,{\rm pb} \\
\hline
\Delta m_Z = 0.1\ {\rm MeV}, & m_Z = 91.18760 \pm 0.00001\ {\rm GeV} \\
\Delta\alpha = 3 \cdot 10^{-5}, & \Delta\alpha^{(5)}_{\rm had}(m_Z) = 0.0275300 \pm 0.0000009
\end{array}$$

  - TH uncertainty needs to be reduced by $\times 4$ from missing α_s^5, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms



QCD coupling at e^+e^- (FCC-ee)

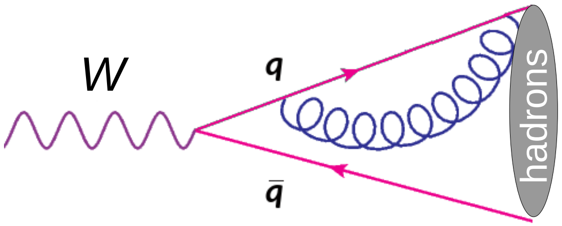
- **EW boson pseudoobservables** known at N^3LO in pQCD:

  - The W and Z hadronic widths :

$$\Gamma^{\rm had}_{\rm W,Z}(Q) = \Gamma^{\rm Born}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm EW} + \delta_{\rm mix} + \delta_{\rm np}\right)$$

  - The ratio of W, Z hadronic-to-leptonic widths :

$$\mathrm{R_{W,Z}}(Q) = \frac{\Gamma^{\rm had}_{\rm W,Z}(Q)}{\Gamma^{\rm lep}_{\rm W,Z}(Q)} = \mathrm{R}^{\rm EW}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm mix} + \delta_{\rm np}\right)$$



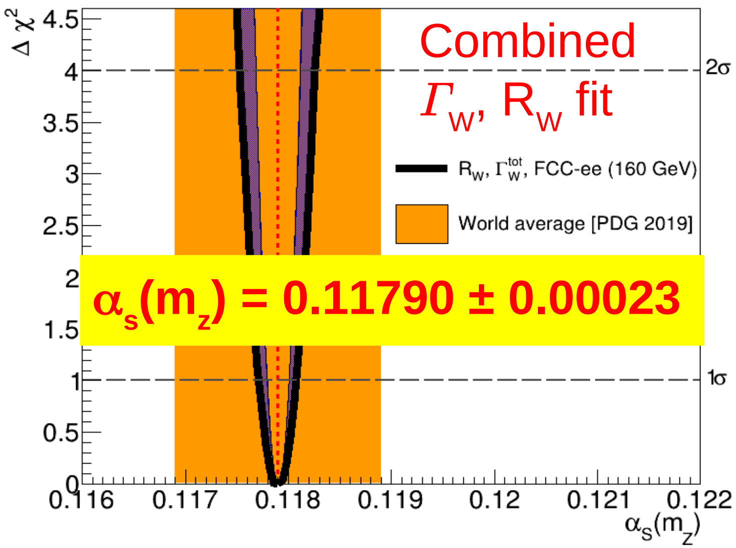
Note: Sensitivity to $\alpha_s(m_Z)$ via $\mathcal{O}$(4%) virtual corrs.

[arXiv:2005.04545]

- FCC-ee will reach 0.2% precision on $\alpha_s(m_W)$ ($\times$300 better than LEP):
  - Huge W pole stats. ($\times 10^4$ LEP-2).
  - Exquisite syst./parametric precision:

$$\Gamma^{\rm tot}_{\rm W} = 2088.0 \pm 1.2\ \mathrm{MeV}$$
$$\mathrm{R_W} = 2.08000 \pm 0.00008$$
$$m_{\rm W} = 80.3800 \pm 0.0005\ \mathrm{GeV}$$
$$|V_{cs}| = 0.97359 \pm 0.00010$$
← $O(10^{12})$ D mesons

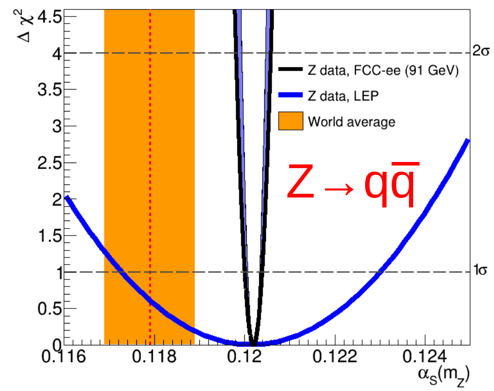
  - TH uncertainty needs to be reduced by $\times$10 from missing α_s^5, α^2, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms

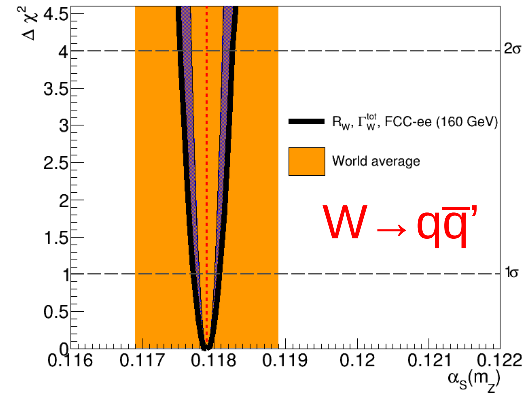


QCD coupling α_s at FCC-ee,hh & LEP3

- α_s extractions at FCC-ee:

  ±0.1% from Z pseudoobservables
  ±0.2% from W hadronic decays
  ≪1% from tau hadronic decays
  ≪1% from evt. shapes & jet rates





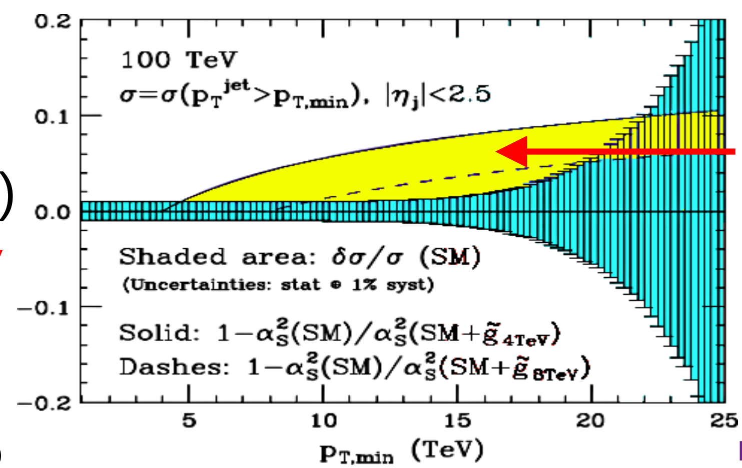
- α_s extractions at LEP3:

  Same physics measurements as FCC-ee modulo smaller samples (×4 less Z) & worse syst. (e.g. beam energy calibration/spread) uncertainties.

  ±0.2% (stat) from Z pseudoobservables
  ±0.9% (stat) from W hadronic decays
  <1% from tau hadr. decays, evt. shapes & jet rates

- α_s extractions at FCC-hh:

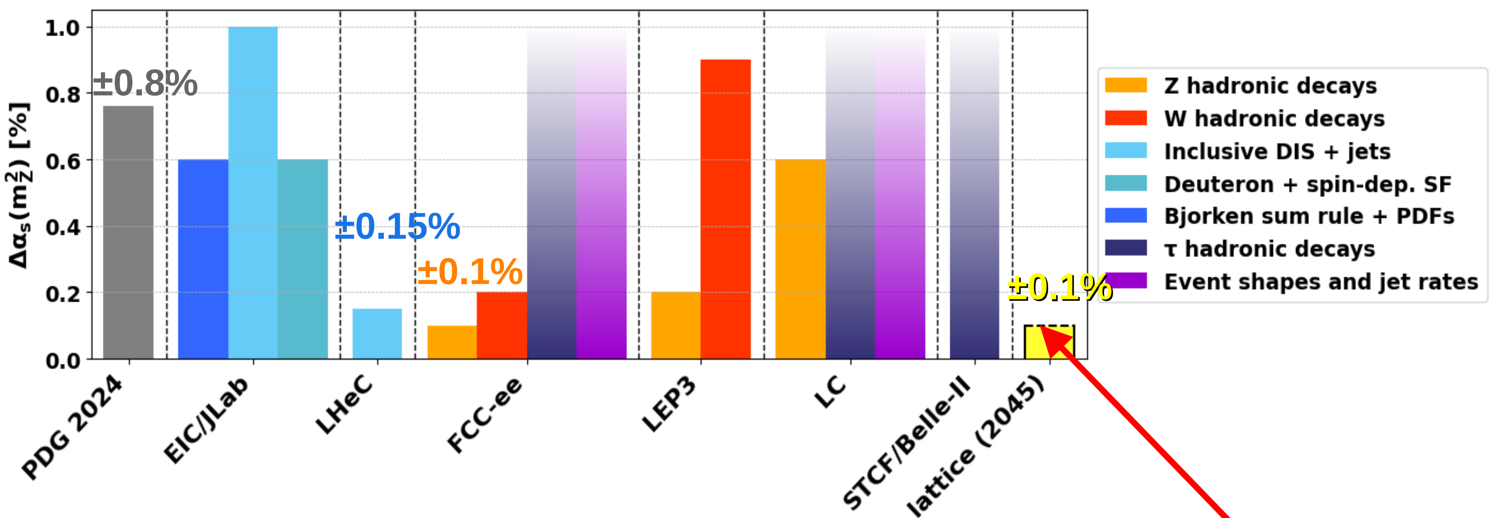
  Test α_s running (asymptotic freedom) with multi-TeV jets up to Q ≈ 50 TeV



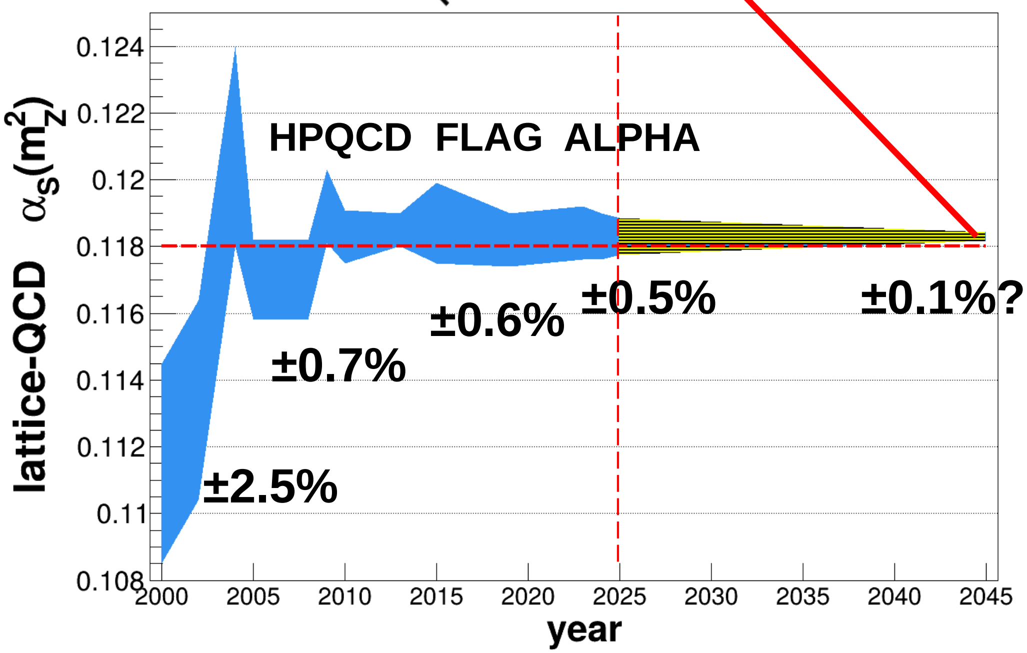
New BSM coloured sectors?

Summary: QCD coupling α_s

- **Forecast** precision at future facilities:

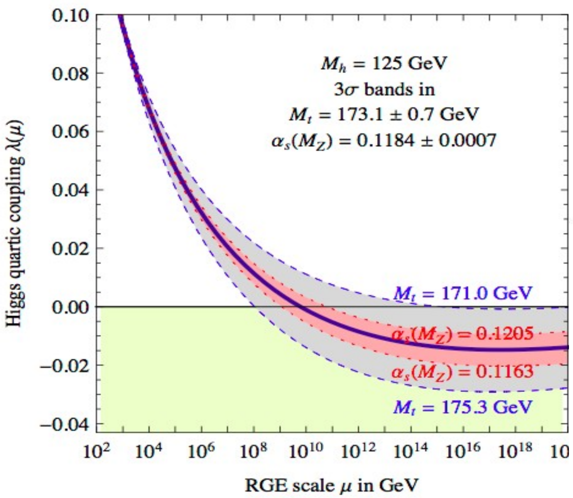


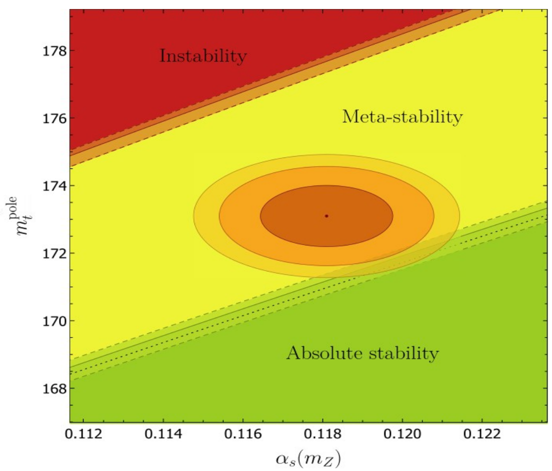
- **Lattice-QCD**:
  - Step-scaling & decoupling are state-of-the-art techniques.
  - Stat. uncert.∝(computing power)^2 reducible by ~1/2 every 10 yrs
  - pQCD observables needed at higher accuracy: α_s^n
  - Syst. uncerts. start playing a role: QED, dynamical charm mass,...

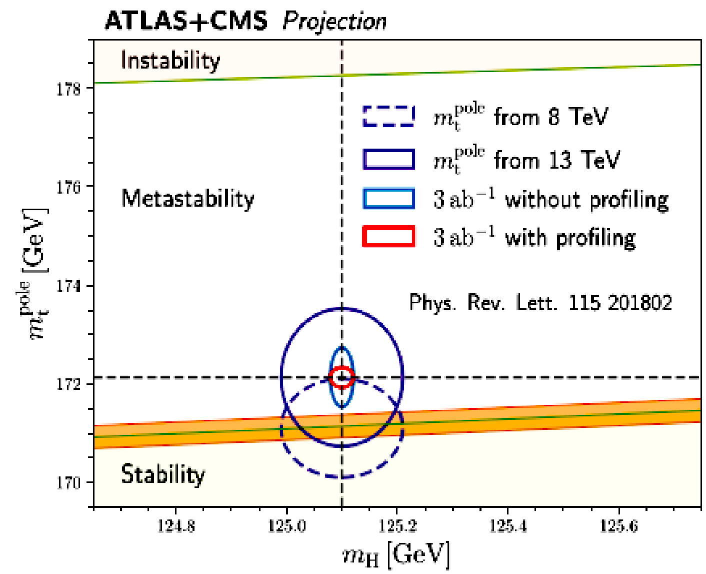


QCD & top quark mass

- Top mass is a key SM parameter, strongly intertwined with QCD:







- p-p collisions (HL-LHC projections):
  - m_{top}(pole) from ttbar+jet x-sections: $\Delta m_{top} \approx \pm200$ MeV
  - m_{top}(MC) from boosted tops: $\Delta m_{top} \approx \pm400$ MeV (theoretical interpretation?)

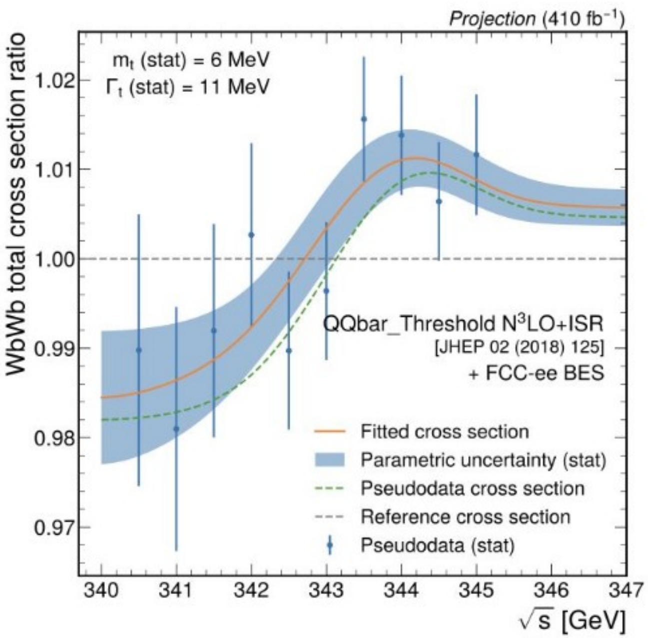
ATLAS+CMS combined uncertainty on the top-quark pole mass [MeV]

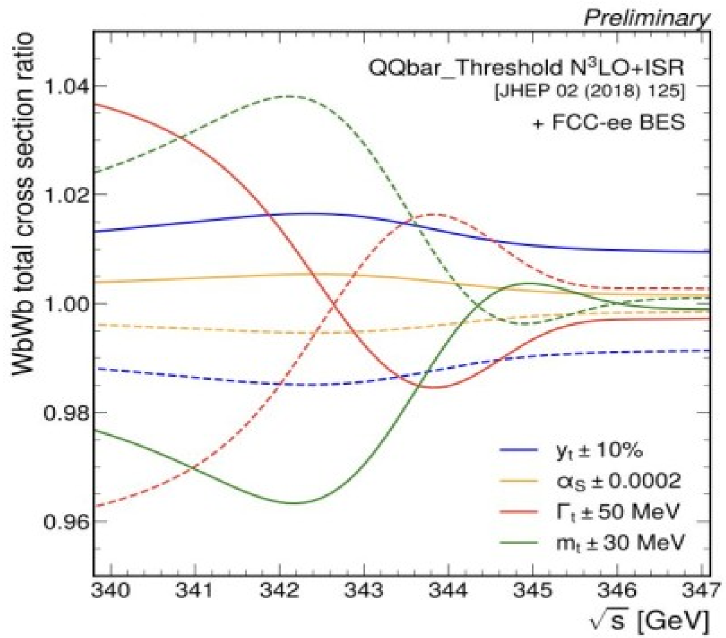
Scenario	*S1* at 2 ab^{-1}	*S2* at 2 ab^{-1}	*S1* at 3 ab^{-1}	*S2* at 3 ab^{-1}
$t\bar{t}$+jet with profiling	400	250	400	200
$t\bar{t}$+jet without profiling	1200	600	1200	600

- Note: HL-LHC/FCC-hh <u>cannot</u> improve m_{top} beyond $\Lambda_{QCD} \approx 200$ MeV
  (e^+e^- machine at $\sqrt{s} \approx 345$ GeV needed to measure it at few-MeV level).

QCD & top quark mass in e^+e^-: FCC-ee

- e^+e^- collisions from threshold scan around √s = 340–345 GeV (FCC-ee): m_{top} precision: $\Delta m_{top} \approx \pm 7$ MeV (exp.), thanks to very good √s control:





Assumed parametric uncertainty:
$\Delta\alpha_s \approx 0.1\%$
$\Delta m_{top} \approx \pm 2$ MeV

[2503.18713 [hep-ph]]

- QCD theory for $\sigma(e^+e^- \to t\bar{t})$ vs. √s at threshold:

$\Delta m_{top} \approx \pm 35$ MeV from N³LO scale uncerts.

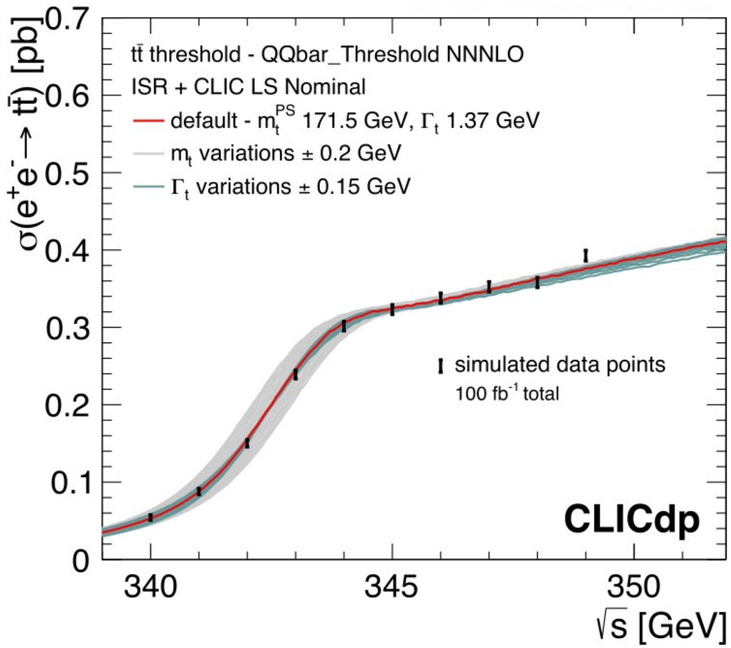
PNRQCD predictions known to N³LO (also including EW+non-resonant effects @ NNLO)

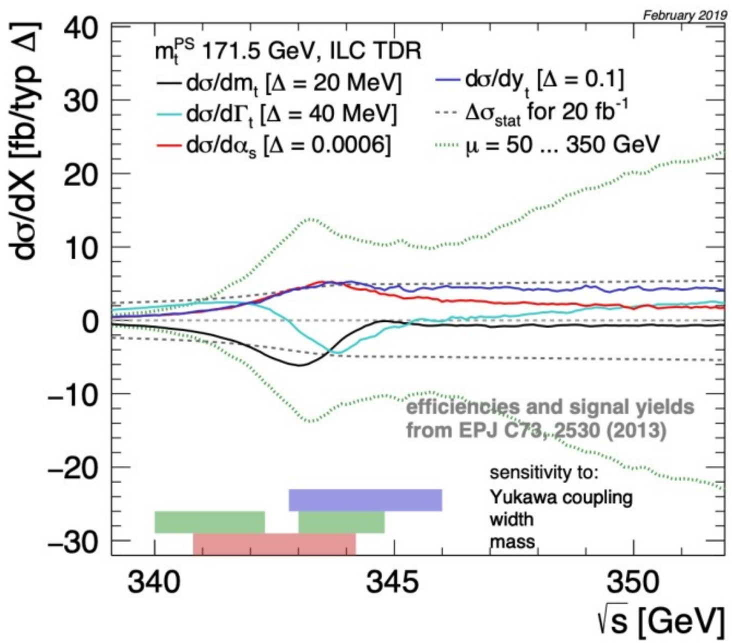
$$R \sim v \sum_k \left(\frac{\alpha_s}{v}\right)^k \cdot \Big\{ \underbrace{1\,(\text{LO})}\; ; \underbrace{\alpha_s, v\,(\text{NLO})}; \underbrace{\alpha_s^2, \alpha_s v, v^2\,(\text{NNLO})}; \underbrace{\alpha_s^3, \alpha_s^2 v, \alpha_s v^2, v^3\,(\text{N3LO})}; \ldots \Big\}$$

[Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser '15]

QCD & top quark mass in e^+e^-: LC

- e^+e^- colls. from threshold scan over $\sqrt{s}$ = 340–350 GeV (CLIC rescaled): m_{top} precision: $\Delta m_{top} \approx \pm 10$ MeV (exp.)





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[JHEP 11 (2019)003]

- QCD theory for $\sigma(e^+e^- \to t\bar{t})$ vs. $\sqrt{s}$ at threshold:

$\Delta m_{top} \approx \pm 35$ MeV from N^{3}LO scale uncerts.

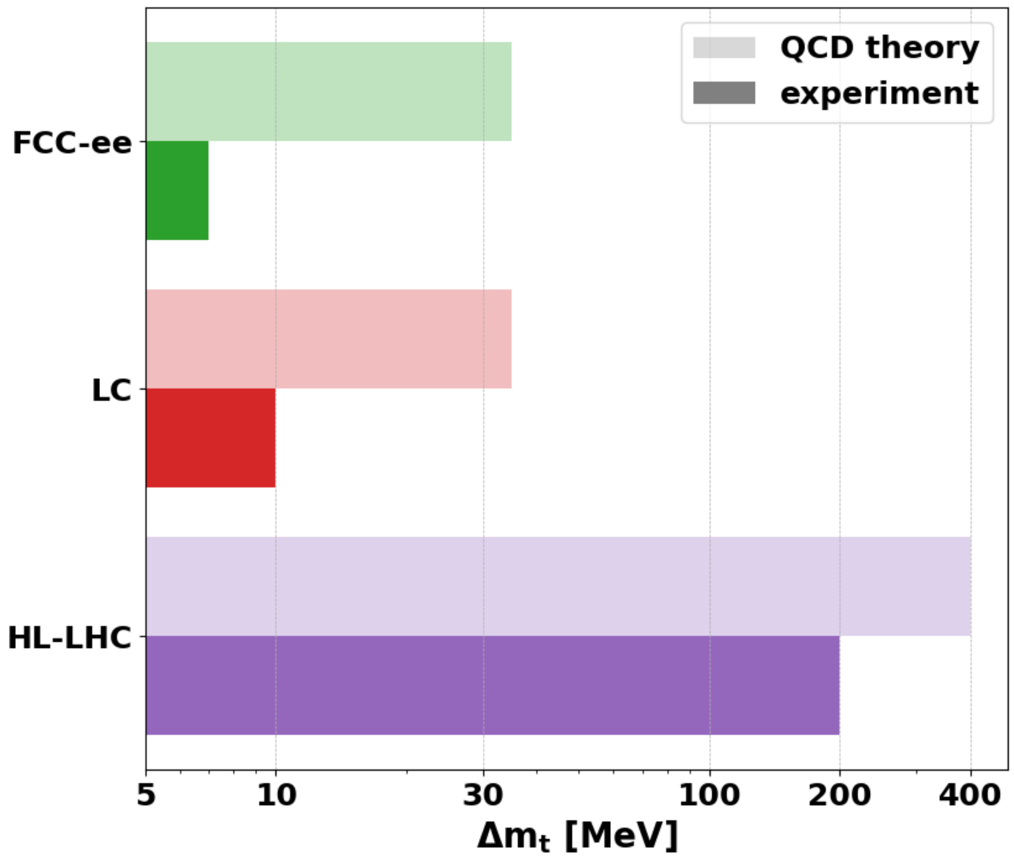
PNRQCD predictions known to N³LO (also including EW+non-resonant effects @ NNLO)

$$R \sim v \sum_k \left(\frac{\alpha_s}{v}\right)^k \cdot \left\{ \underbrace{1\,(\text{LO})} \; ; \underbrace{\alpha_s, v\,(\text{NLO})}; \underbrace{\alpha_s^2, \alpha_s v, v^2\,(\text{NNLO})}; \underbrace{\alpha_s^3, \alpha_s^2 v, \alpha_s v^2, v^3\,(\text{N3LO})}; \ldots \right\}$$

[Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser '15]

Summary: QCD & top quark mass

- Forecast m_{top} precision at future facilities:



- FCC-ee, LC:

  $\Delta m_{top} \approx \pm 7$ MeV (exp.)

  $\Delta m_{top} \approx \pm 10$ MeV (exp.)

  BUT $\Delta m_{top} \approx \pm 35$ MeV from NRQCD uncertainties: Significant (N^4LO) progress needed!

- HL-LHC & FCC-pp:

  At best:

  $\Delta m_{top} \approx \Lambda_{QCD} \approx \pm 200$ MeV

- No high-precision m_{top} possible without parallel QCD theory progress!

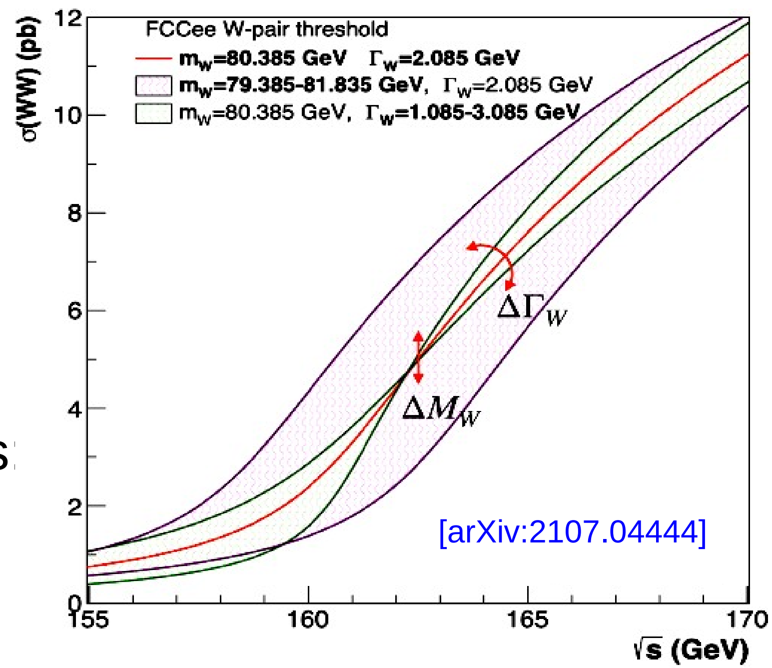
QCD & W boson mass: LH(e)C vs. e^+e^-

- LHC: m_W from p_T^{ℓ}, m_T^{ℓ} (low PU) distribs:
  Best current LHC precision: $\Delta m_W \approx \pm 10$ MeV
  QCD uncertainties (PDFs & low p_T^W): $\Delta m_W \approx \pm 5$ MeV
  Expected HL-LHC: $\Delta m_W \approx \pm 4$ MeV (QCD: ± 3 MeV)

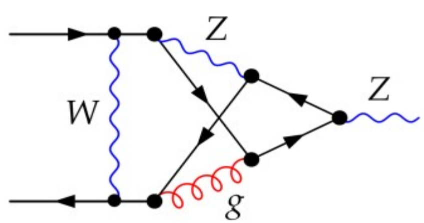
- HL-LHC+LHeC:
  Reduced PDFs+α_s uncerts:
  Expected precision:
  $\Delta m_W \approx \pm 3$MeV (QCD: ± 1 MeV)

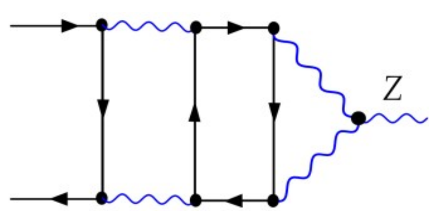
- e^+e^- collisions (FCC-ee, LEP3):
  m_W from $\sigma_{WW}(\sqrt{s})$ scan in $\ell\nu$ decays

  Expected precision:
  FCC-ee: $\Delta m_W \approx \pm 0.4$ MeV (exp)
  LEP3: $\Delta m_W \approx \pm 1.2$ MeV (exp)



- But, significant $\sigma_{WW}(\sqrt{s})$ theory uncertainties:
  $\Delta m_W \approx 3$–5 MeV from missing higher EW & EW⊗QCD corrections in EFT:





$$\Delta m_W(\mathrm{T}) = \left(\frac{d\sigma_{WW}}{dm_W}\right)^{-1} \Delta\sigma_{WW}(\mathrm{T})$$

$$\Delta\sigma_{WW}(\mathrm{T}) < 0.8 \text{ fb}$$

QCD & W boson mass: LH(e)C vs. e^+e^-

- **LHC**: m_W from p_T^ℓ, m_T^ℓ (low PU) distribs:
  Best current LHC precision: $\Delta m_W \approx \pm 10$ MeV
  QCD uncertainties (PDFs & low p_T^W): $\Delta m_W \approx \pm 5$ MeV
  Expected HL-LHC: $\Delta m_W \approx \pm 4$ MeV (QCD: ± 3 MeV)

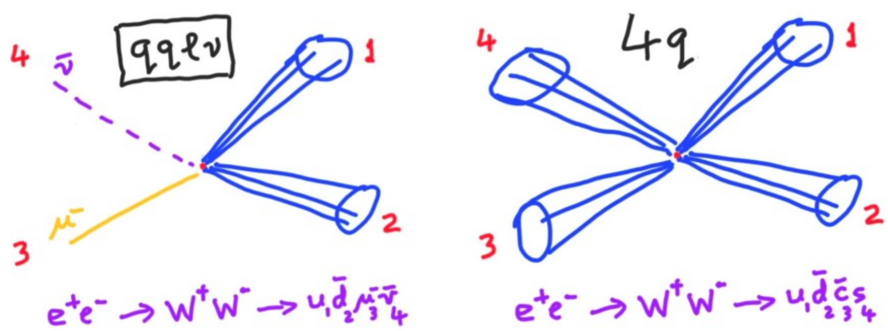
- **HL-LHC+LHeC**:
  Reduced PDFs+α_s uncerts:
  Expected precision:
  $\Delta m_W \approx \pm 3$MeV (QCD: ± 1 MeV)

- e^+e^- collisions (FCC-ee, LEP3, LC):
  m_W from $\sqrt{s}$-constrained kinematic fit of $m_{inv}(jj+\ell\nu)$, $m_{inv}(jj+jj)$ at all $\sqrt{s}$ runs

  Expected precision:
  FCC-ee: $\Delta m_W \approx \pm 0.25$ MeV (exp)
  LC: $\Delta m_W \approx \pm 0.9$ MeV (exp)
  LEP3: $\Delta m_W \approx \pm 0.9$ MeV (exp)

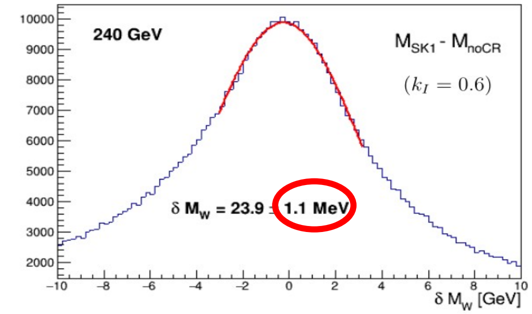
[G. Wilson's talk @ CERN FC workshop 2022]

semi-leptonic $q\bar{q}\ell\nu_\ell$ | fully hadronic $q\bar{q}q\bar{q}$



$6B_\ell B_h = 43.9\%$ | $B_h^2 = 45.4\%$

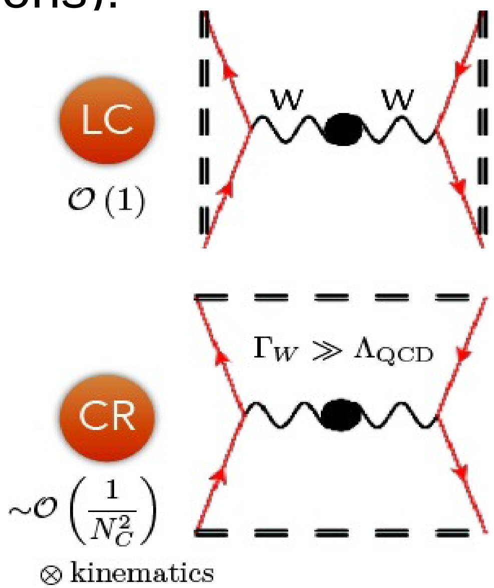
- Significant hadronization uncertainties:
  – In boosted $m_{inv}(jj+\ell\nu)$ at LC: $\Delta m_W \approx \pm 0.9$ MeV
  (much less hadroniz. uncert. in $e^+e^- \to WW$ at rest)
  – In all $m_{inv}(jj+jj)$ analyses: $\Delta m_W \approx \pm 1$ MeV
  (FCC-ee, LC, LEP3) due to Color Reconnection:



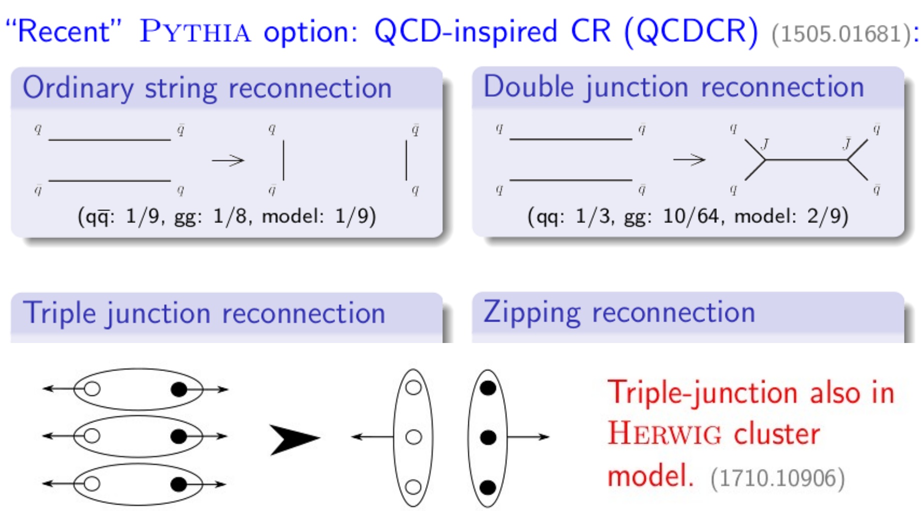
M_W shift due to CR effect, modelled using the SKI scenario

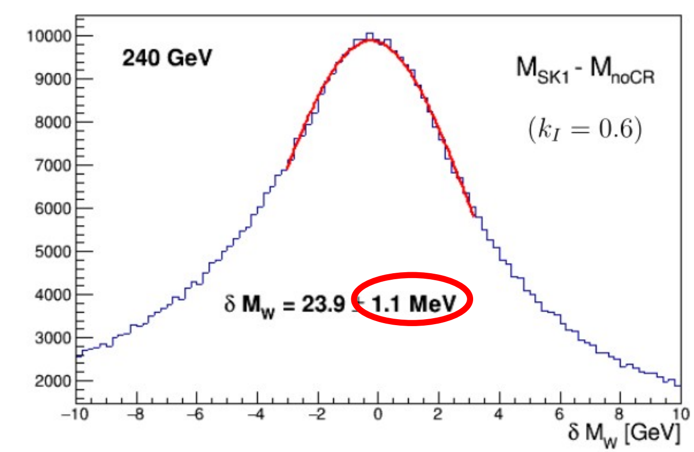
Colour reconnection from m_W in e^+e^-

- Colour reconnection among partons is source of uncertainty in m_W in multijet final states (also m_{top} inv. mass, aGC extractions):
- CR "string drag" impacts $e^+e^- \to WW(4j)$ final state (also $e^+e^- \to$ ttbar, $e^+e^- \to ZZ(4j)$, $H \to 4j$,…):
  - Shifted masses & angular correlations (CP studies).
  - Combined LEP $e^+e^- \to WW(4j)$ data best described with 49% CR, 2.2σ away from no-CR.



- Exploit 10^8 W stats at FCC-ee to measure m_W leptonically & hadronically and constrain CR:

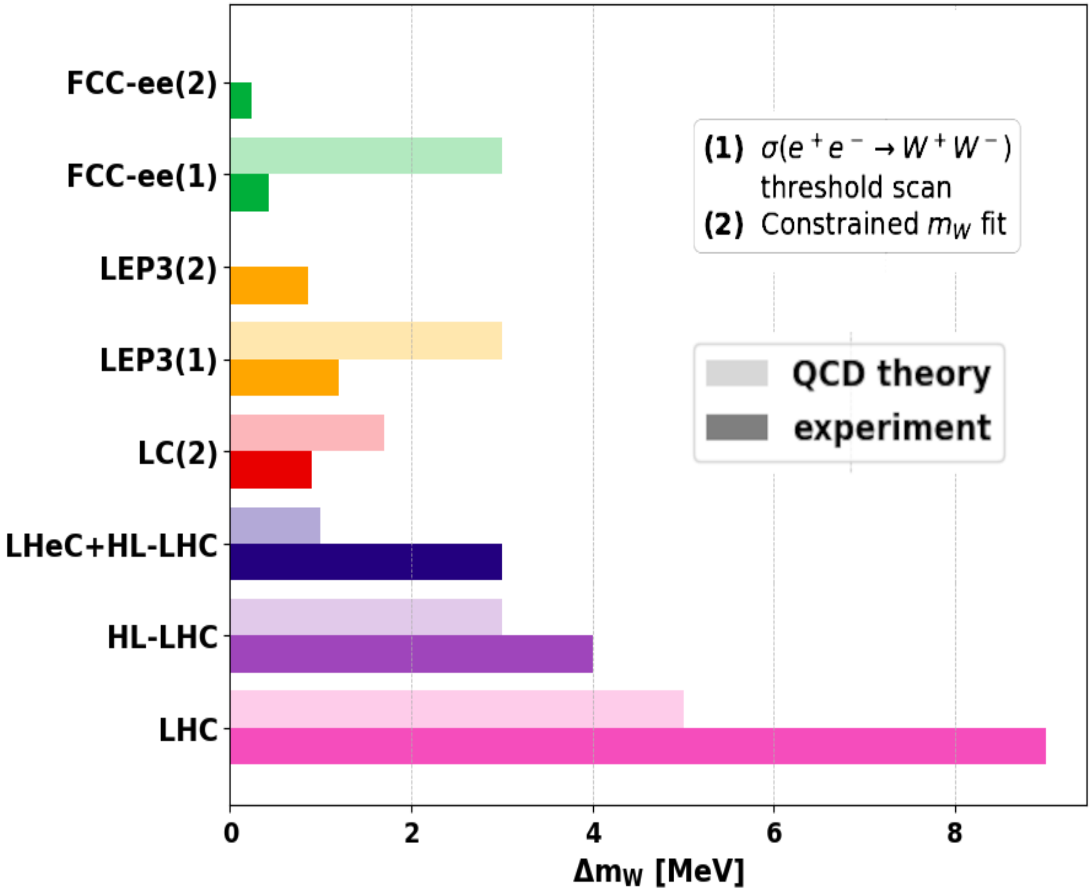




M_W shift due to CR effect, modelled using the SKI scenario

Summary: QCD & W boson mass

- Forecast m_W precision at future facilities:

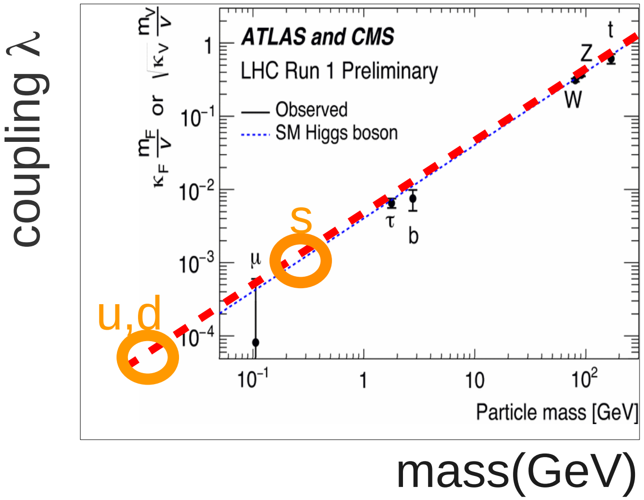


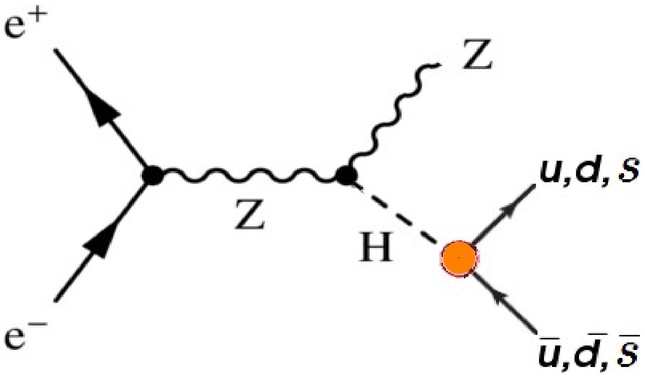
- $\sigma_{WW}(\sqrt{s})$ scan in $\ell\nu$ decays
  - FCC-ee: $\Delta m_W \approx \pm 0.4$ MeV
  - LEP3: $\Delta m_W \approx \pm 1.2$ MeV
  - Theory uncerts. (incl. mixed EW⊗QCD): $\Delta m_W = 3$–5 MeV
- Constrained m_{inv} fit:
  - FCC-ee: $\Delta m_W \approx \pm 0.25$ MeV
  - LC: $\Delta m_W \approx \pm 0.9$ MeV± 1 MeV
  - LEP3: $\Delta m_W \approx \pm 0.9$ MeV
  - QCD (hadronization) uncerts. important for LC (boosted W) & m_{inv}(jj+jj) color reconnect.
- HL-LHC+LHeC:
  - $\Delta m_W \approx \pm 3$ MeV (±1 MeV from PDFs)

- Different high-precision m_W extractions require parallel QCD progress.
- m_W measurements help us understand non-pQCD: Color reconnection

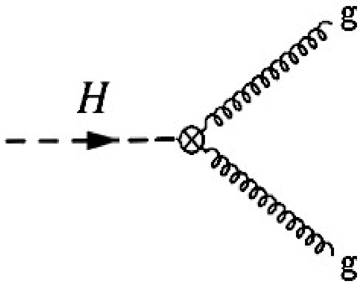
Higgs boson & QCD

- Do the lightest quarks (u,d,s) acquire their masses through their Higgs (Yukawa) couplings?

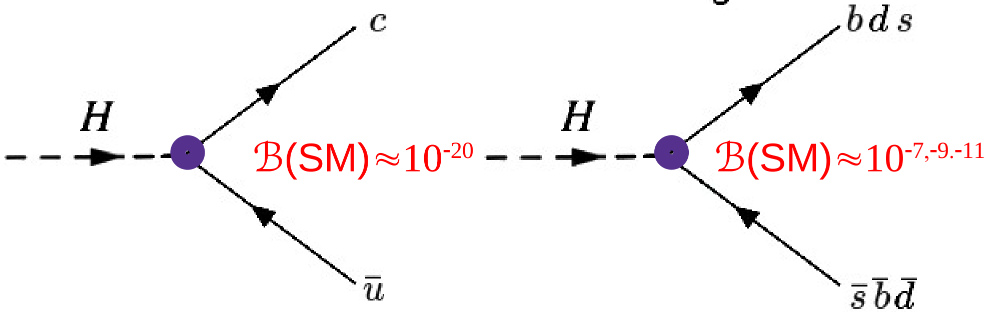




- Does BSM impact (loop-induced) H→gg ?

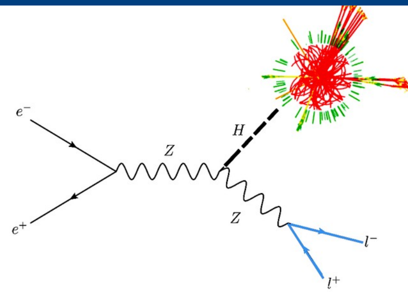


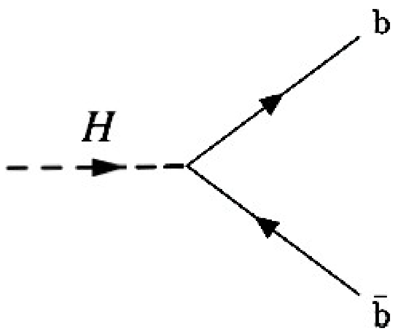
- Does the Higgs boson mediate FCNCs at tree level? H→qq'



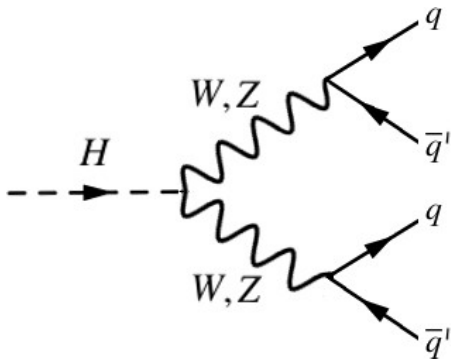
Higgs boson & QCD at e^+e^- colliders

- 80% of the Higgs decays are fully hadronic!

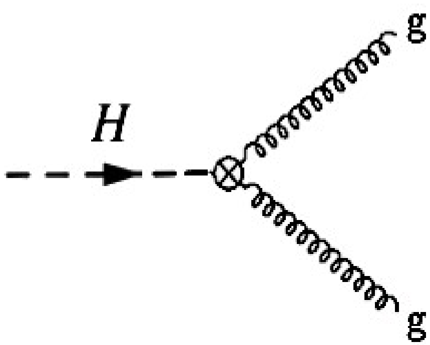




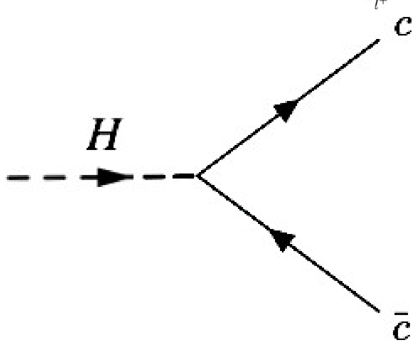
$\mathcal{B}$=57.7%



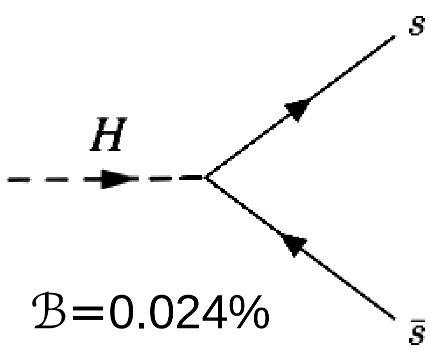
$\mathcal{B}$=11%



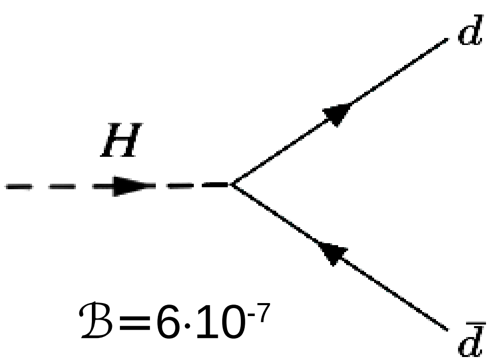
$\mathcal{B}$=8.6%



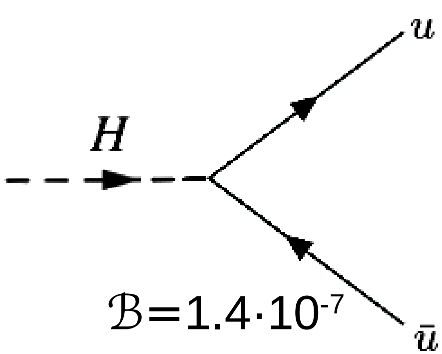
$\mathcal{B}$=2.9%



$\mathcal{B}$=0.024%



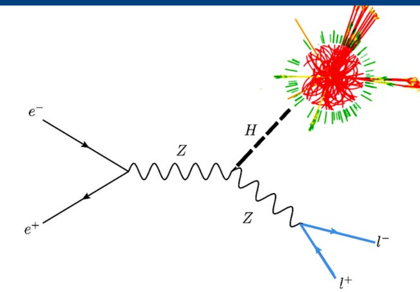
$\mathcal{B}=6\cdot10^{-7}$



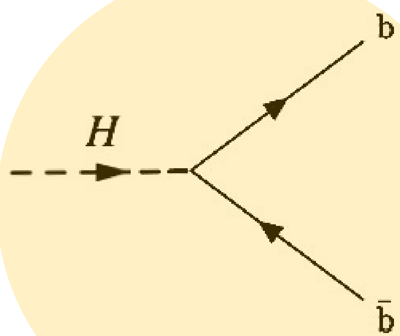
$\mathcal{B}=1.4\cdot10^{-7}$

Higgs boson & QCD at e^+e^- colliders

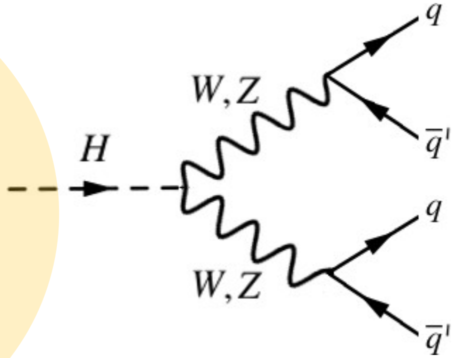
- 80% of the Higgs decays are fully hadronic!



Only hadronic decay channel observed to date!

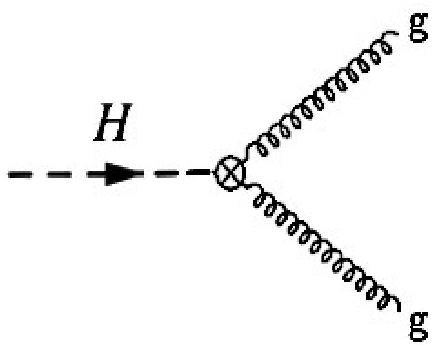


$\mathcal{B}$=57.7%



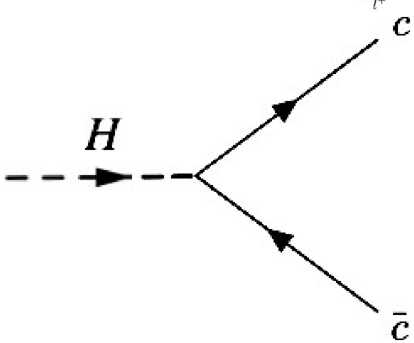
$\mathcal{B}$=11%

N(H) at FCC-ee≈2.e5



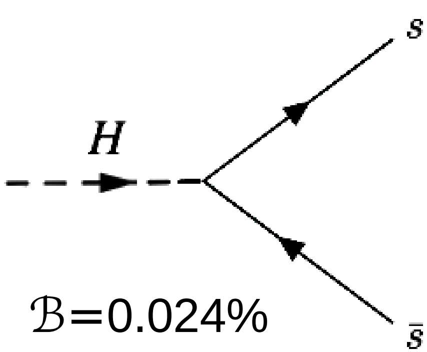
$\mathcal{B}$=8.6%

≈1.5e5 @FCC-ee



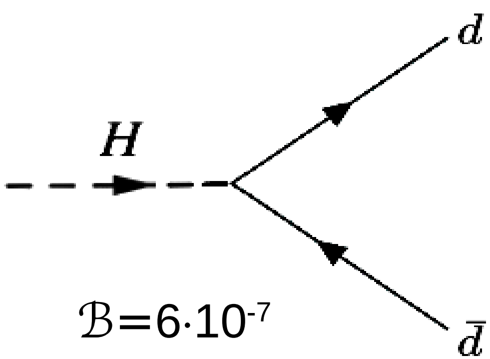
$\mathcal{B}$=2.9%

≈5.e4 @FCC-ee



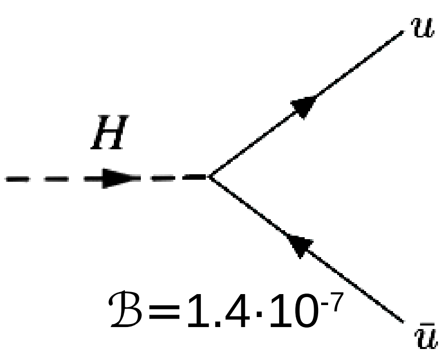
$\mathcal{B}$=0.024%

N(H) at FCC-ee≈400



$\mathcal{B}=6\cdot10^{-7}$

≈1 @FCC-ee



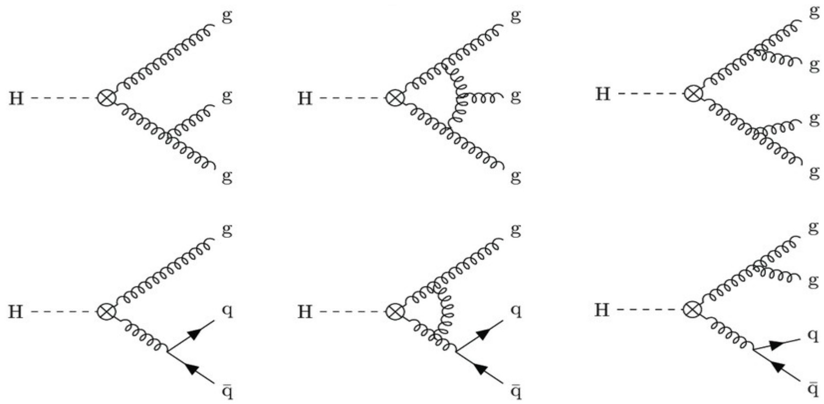
$\mathcal{B}=1.4\cdot10^{-7}$

≈0.3 @FCC-ee

- Significantly improved jet-flavour tagging: Exploit 10^{12} Z→ jj tag-and-probe

Higgs → gg decay & BSM

- H → gg partial width known today theoretically at N^{4}LO (approx) accuracy



Uncertainties today:
$\Delta\mathcal{B}$(H → gg) ≈ ±3% from higher-order corrs.
$\Delta\mathcal{B}$(H → gg) ≈ ±4% from $\Delta\alpha_s(m_Z)$ ≈ 1%

Much larger than $\Delta\kappa_g$ ≈ ±0.7% (FCC-ee)

- Percent deviations on Higgs-gluon (loop-induced) coupling in BSM:

Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings in %

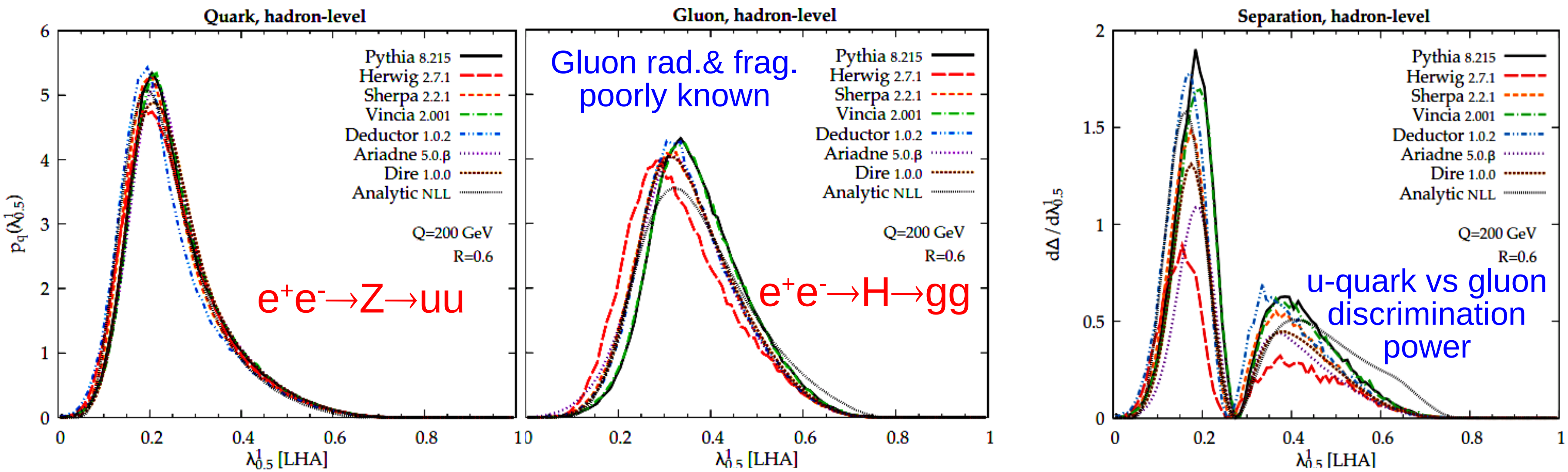
	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	-0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

[arXiv:1708.08912]

- TH work needed to reduce intrinsic uncertainties: Today $\mathcal{O}$(3%) → $\mathcal{O}$(<1%)

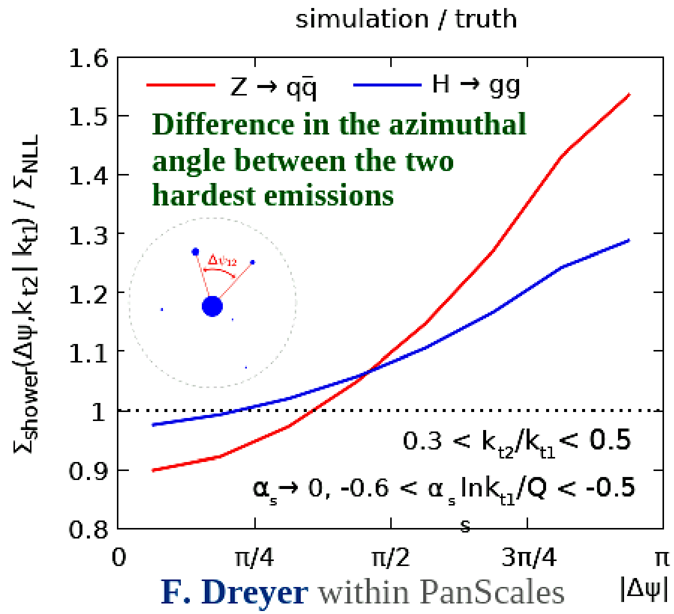
But gluon jets are badly known today

- MC LL parton showers differ vastly on gluon jet substructure properties:



[G.Soyez et al.]

- Unphysical differences in the radiation pattern of q & g jets in LL PS:



Nonphysical quark/gluon differences in common dipole showers

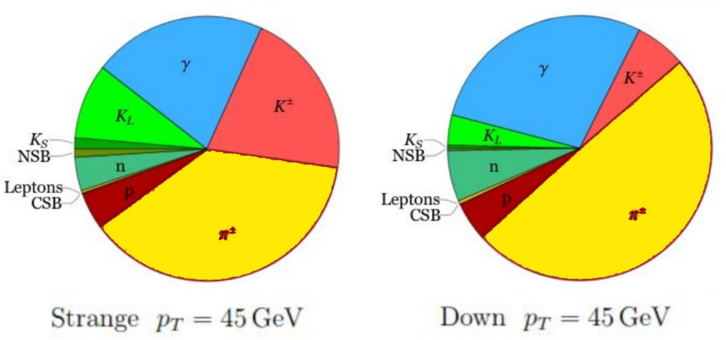
[S.Ferrario-Ravasio et al.]

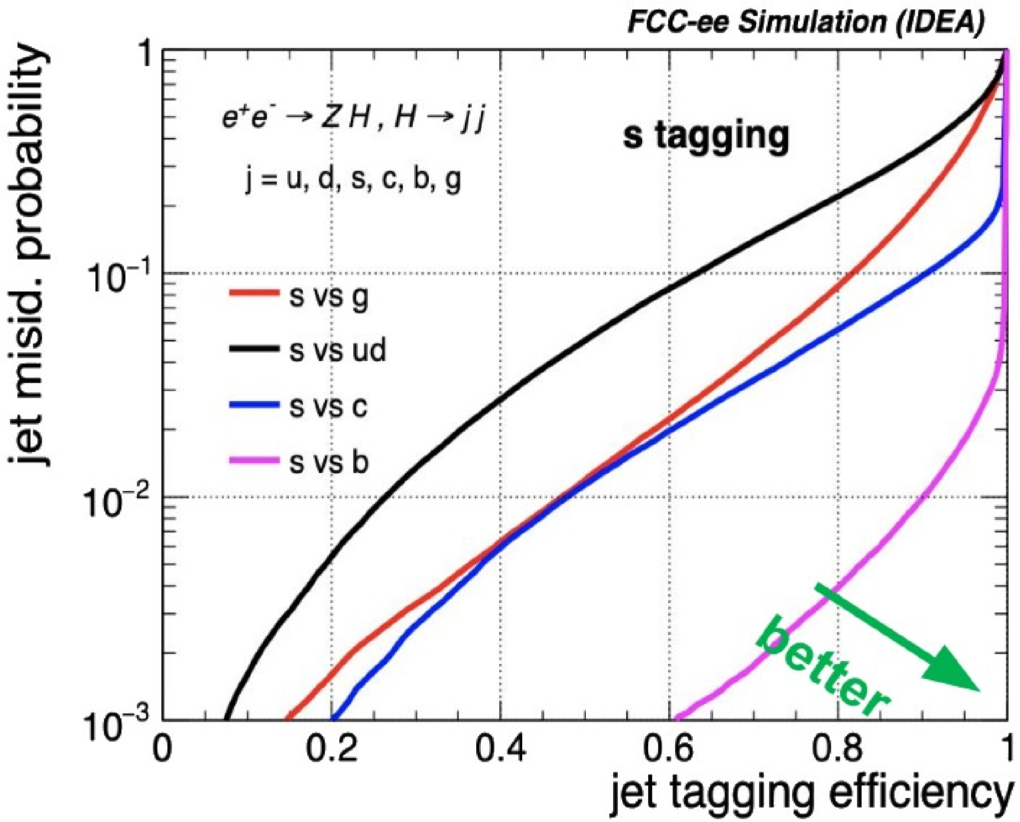
- N^nLL PS + high-quality e^+e^- gluon jet data/tuning badly needed.

Strange Yukawa via H→ss

- FCC-ee will produce $\mathcal{O}$(400) H→ssbar decays. Can one measure y_s?
- ParticleNet jet tagger exploiting hadron PID (via dE/dx, ToF, RICH):

[2003.09517] Momentum weighted fraction:





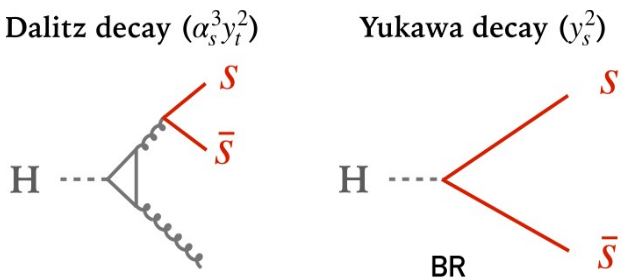
Tagger exploits directly full list of jet constituents (ReconstructedParticles):

[$\mathcal{O}$(50) properties/particle]
× [~50-100 particles/jet]
~ $\mathcal{O}$(1000) inputs/jet

- Analysis e^+e^-→HZ, H→qq with N=2j exclusive jet algorithm:
  Backgds: WW/ZZ/Z, qqH, HWW, HZZ
  Combined jj (Hbb, Hcc, Hss, Hbb) fit yields: H→ss with $\mathcal{O}$(80%) uncertainty

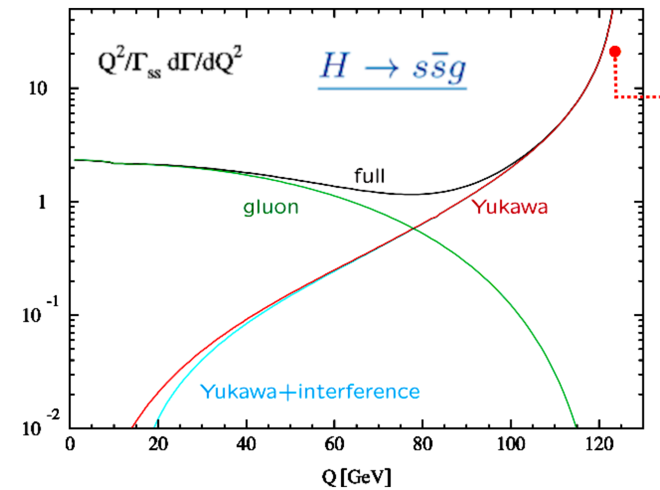
Strange Yukawa via H→ss

- Does the H→g g(ss) “Dalitz” decay jeopardize the H→ss measurement?



	BR
H → gg	8.1×10^{-2}
H → ss	$\sim 2 \times 10^{-4}$

Ratio is ~ 400

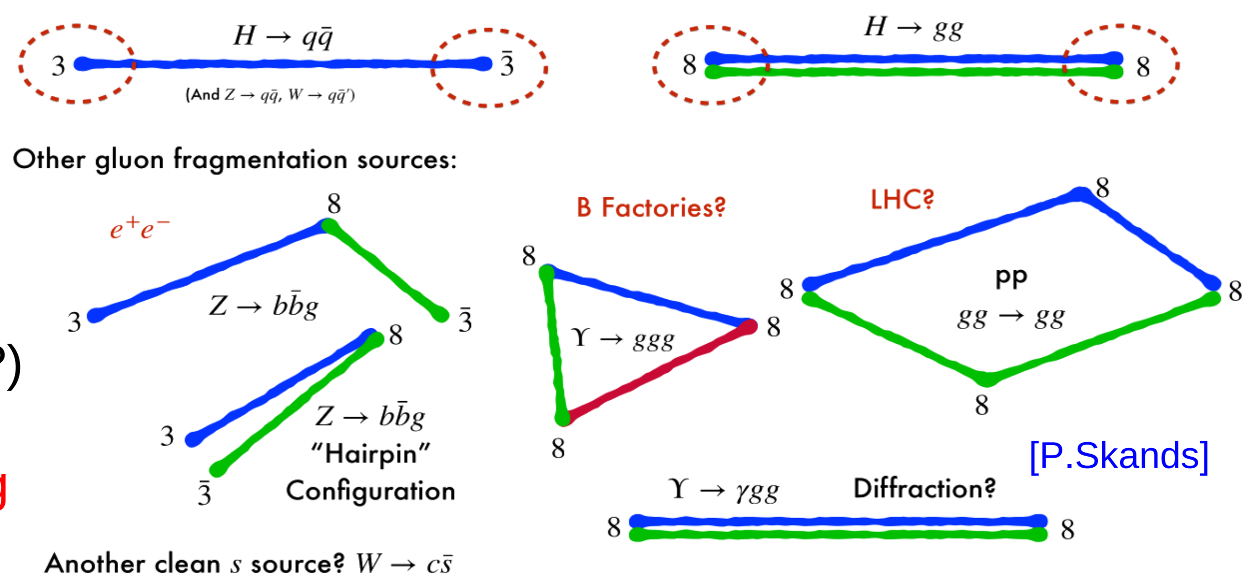


For m_{jj}>100 GeV: Dalitz ssg decays are no bottleneck to the y_s extraction (but high mass resumm. needed)

[M.Spira; G. Salam]

- Need also N^nLL parton showers (matched to N^nLO) and accurate & precise s, g hadronization:

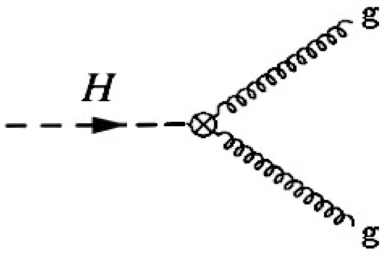
High-precision hadron data (Tera-Z, B-factories?) needed to reliably distinguish leading s,u,d,g fragmentation hadrons



[P.Skands]

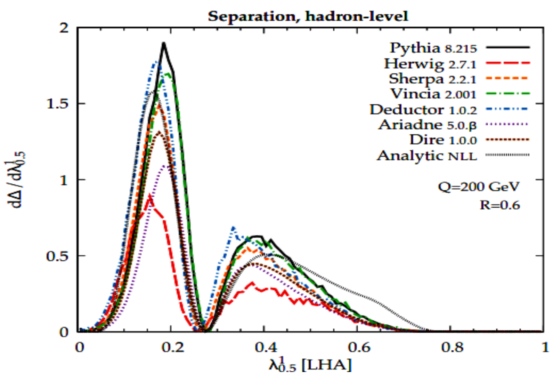
Summary: QCD for Higgs physics

- Precision needed to fully exploit the (B)SM program at Higgs factories requires exquisite control of pQCD & non-pQCD: $\mathcal{B}(H\to \text{had})=80\%$
- 3 key examples:



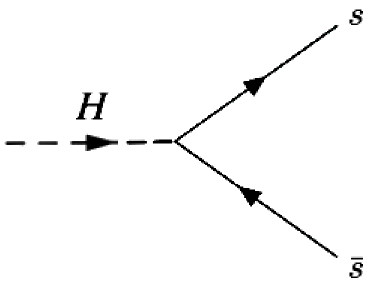
(1) Studying BSM in Higgs-gluon coupling within $\pm$0.7% (exp) requires $\alpha_s(m_Z)$ within $\pm$0.1%:

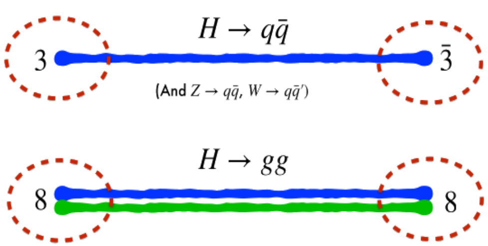
(2) Identifying gluon jets requires significantly improved gluon fragmentation in parton shower (NNLL) MCs:



High-stats data samples to be exploited: $e^+e^-\to Z\to qq(g)$, $e^+e^-\to H(gg)Z$

(3) Observing strange-Yukawa requires significantly improved quark & gluon hadronization:





☛ Dedicated studies of huge/clean hadronic $Z,W\to jj$ samples are key to $H\to jj$ physics.

Theory calculations “wish list”

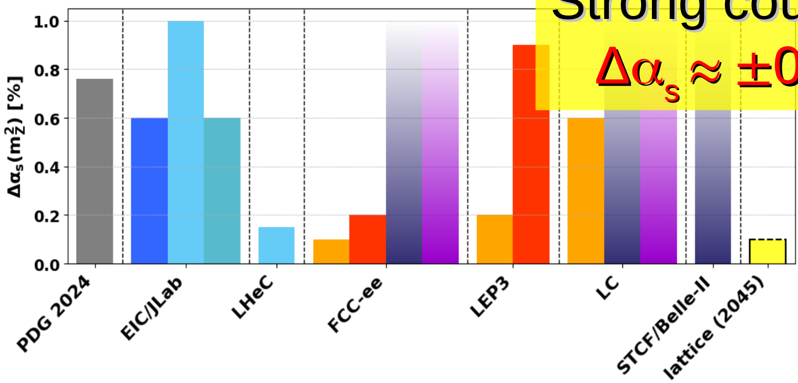
- Summary table for precision-QCD wish-list (pQCD, lattice, MC PS):

	Observable	Missing higher-order & power-suppressed corrections
$\alpha_s(m_Z)$ in e^+e^-	Hadronic Z width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$
	Hadronic W width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$
	Hadronic τ width	$\mathcal{O}(\alpha_s^5)$
	Hadronic event shapes (Z, W, H decays)	N^3LO differential, $N^{3,4}LL$ resummation, power corrections
	Inclusive jet rates	3-jet cross sections at N^3LO, 4-jets at N^2LO, 5-jets at NLO
$\alpha_s(m_Z)$ in latt.	Lattice QCD results	$\mathcal{O}(\alpha_s^6)$ β-function; $\mathcal{O}(\alpha_s^5)$ heavy quark decoupling; $\mathcal{O}(\alpha_s^4)$ static potential
	(α_s extractions; quark masses m_c, m_b)	$\mathcal{O}(\alpha_s^3)$ lattice perturbation theory matching (lattice coupling to $\alpha_s^{\overline{MS}}$ etc.)
m_W, m_{top} in e^+e^-	$\sigma(e^+e^- \to W^+W^-)$ vs. $\sqrt{s}$	EW N^2LO: $\mathcal{O}(\alpha^2)$, Mixed EW-QCD: $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha_s^2\alpha)$
	$\sigma(e^+e^- \to t\bar{t})$ vs. $\sqrt{s}$	NRQCD: $\mathcal{O}(\alpha_s^5)$, Non-resonant: $\mathcal{O}(\alpha_s^5)$,
		$O(\alpha_s^3)$ differential; QED: $\mathcal{O}(\alpha^3)$ at NNLL
QCD in Higgs	$H \to b\bar{b}$ width	N^4LO (massive b-quark); N^4LO differential (massless b-quark)
	$H \to gg$ width	N^5LO (heavy-top limit), N^4LO (massive top)
		N^4LO differential, N^3LO differential (massive top)
e^+e^-,e-p, p-p PS	MC simulations for $e^+e^- \to X$ processes	$N^{2,3}LO$ matched to $N^{2,3}LL$ PS.
		Permille control of non-perturbative QCD effects (hadronization, CR,...)
$\alpha_s(m_Z)$ in DIS	ep $\to$ hadrons (PDF and α_s determination)	$N^{3,4}LO$ evolution equations and inclusive cross sections
	ep $\to$ jets (α_s determination)	N^3LO cross sections

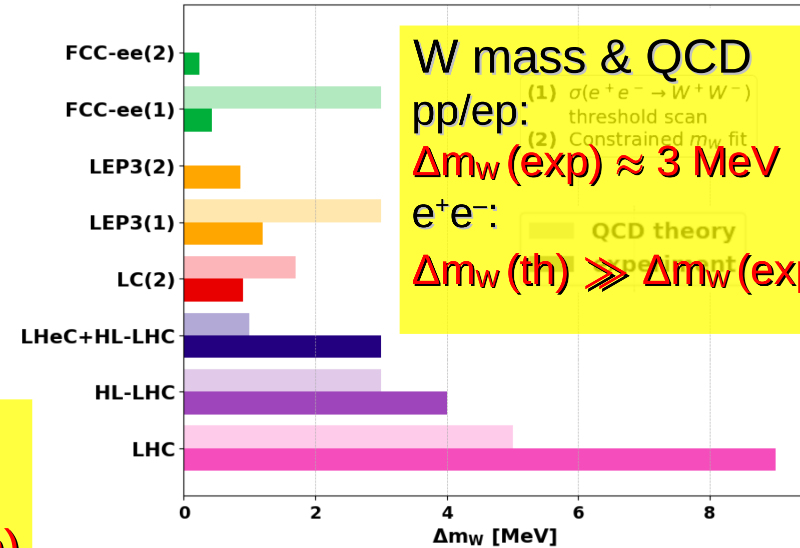
- Future Higgs/EW/top factories (in particular FCC-ee) impose very strong requirements on theory developments to match expected exp. precision.

Summary: Precision QCD at future facilities

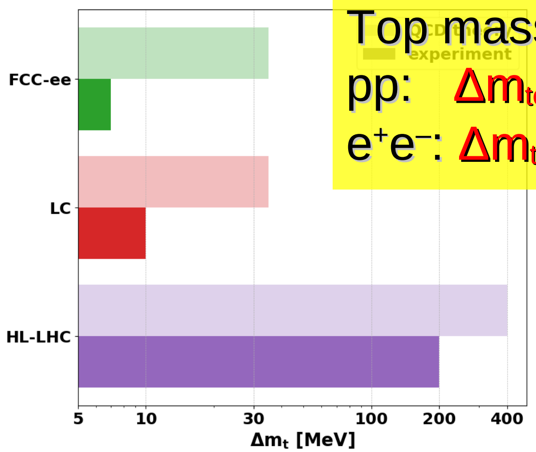
- Precision needed to fully exploit the (B)SM program at Higgs factories requires very precise measurements of pQCD & non-pQCD physics:



Strong coupling
$\Delta\alpha_s \approx \pm 0.1\%$

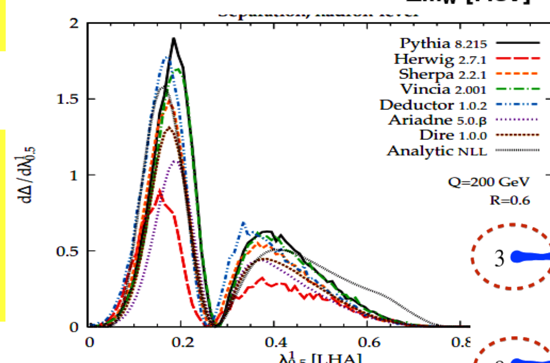


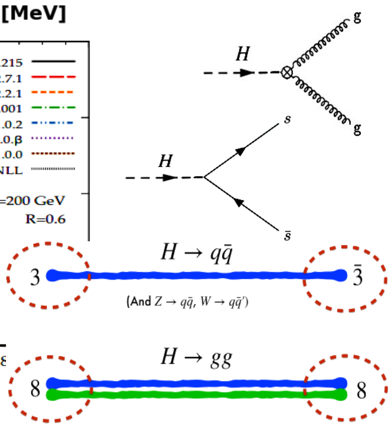
W mass & QCD
pp/ep: Δm_W (exp) ≈ 3 MeV
e^+e^-: Δm_W (th) ≫ Δm_W (exp)



Top mass & QCD
pp: Δm_{top} (exp) ≈ Λ_{QCD}
e^+e^-: Δm_{top} (th) ≈ 5×Δm_{top} (exp)

Higgs & QCD
$N^nLO + N^nLL$ PS + hadronization





☛ Theory (pQCD, latt-QCD, PS MC) progress needed

☛ Exp. QCD studies with huge $e^+e^- \to jj$ samples key to EW, H, top physics.

Backup slides

α_s determination (future)

- Expected improvements:

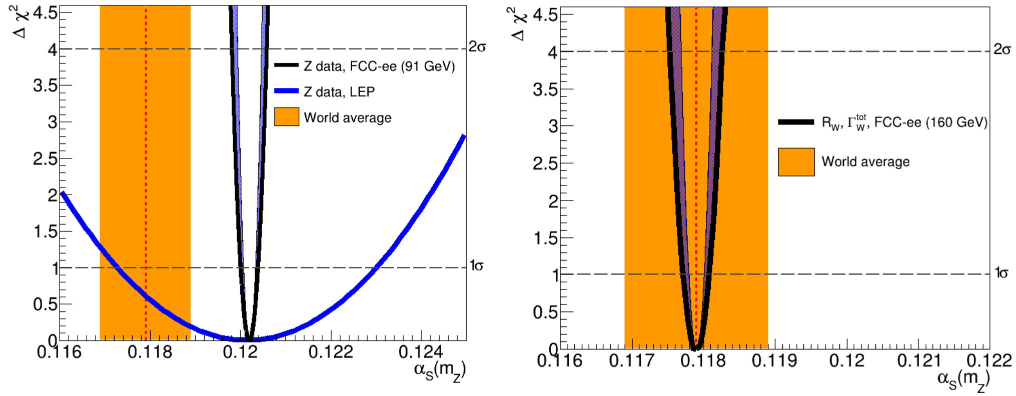
"The strong coupling constant: state of the art and the decade ahead", JPG 51 (2024) 090501

Method	Relative $\alpha_S(m_Z^2)$ uncertainty: Current — theory & exp. uncertainties sources	Relative $\alpha_S(m_Z^2)$ uncertainty: Near (long-term) future — theory & experimental progress
(1) Lattice	0.7% Finite lattice spacing & stats. $N^{2,3}LO$ pQCD truncation	$\approx$ 0.3% (0.1%) Reduced latt. spacing. Add more observables Add $N^{3,4}LO$, active charm (QED effects) Higher renorm. scale via step-scaling to more observ.
(2) τ decays	1.6% N^3LO CIPT vs. FOPT diffs. Limited τ spectral data	$<$ 1.% Add N^4LO terms. Solve CIPT–FOPT diffs. Improved τ spectral functions at Belle II
(3) $Q\overline{Q}$ bound states	3.3% $N^{2,3}LO$ pQCD truncation $m_{c,b}$ uncertainties	$\approx$ 1.5% Add $N^{3,4}LO$ & more ($c\bar{c}$), ($b\bar{b}$) bound states Combined $m_{c,b} + \alpha_S$ fits
(4) DIS & PDF fits	1.7% $N^{2,(3)}LO$ PDF (SF) fits Span of PDF-based results	$\approx$ 1% (0.2%) N^3LO fits. Add new SF fits: $F_2^{p,d}$, g_i (EIC) Better corr. matrices. More PDF data (LHeC/FCC-eh)
(5) e^+e^- jets & evt shapes	2.6% NNLO+$N^{(1,2,3)}LL$ truncation Different NP analytical & PS corrs. Limited datasets w/ old detectors	$\approx$ 1.5% ($<$ 1%) Add $N^{2,3}LO$+N^3LL, power corrections Improved NP corrs. via: NNLL PS, grooming New improved data at B factories (FCC-ee)
(6) Electroweak fits	2.3% N^3LO truncation Small LEP+SLD datasets	($\approx$ 0.1%) N^4LO, reduced param. uncerts. ($m_{W,Z}$, α, CKM) Add W boson. Tera-Z, Oku-W datasets (FCC-ee)
(7) Hadron colliders	2.4% NNLO(+NNLL) truncation, PDF uncerts. Limited data sets ($t\bar{t}$, W, Z, e-p jets)	$\approx$ 1.5% N^3LO+NNLL (for color-singlets), improved PDFs Add more datasets: Z p_T, p-p jets, σ_i/σ_j ratios,...
World average	0.8%	$\approx$ 0.4% (0.1%)

- Precision at HL-LHC time: ±0.4%. At LHeC (incl. DIS+jets): ±0.15%
- Precision after FCC-ee: ±0.1% (Z,W → hadrons pseudoobserv.)
- Running coupling probed up to Q ≈ 40 TeV (FCC-hh)

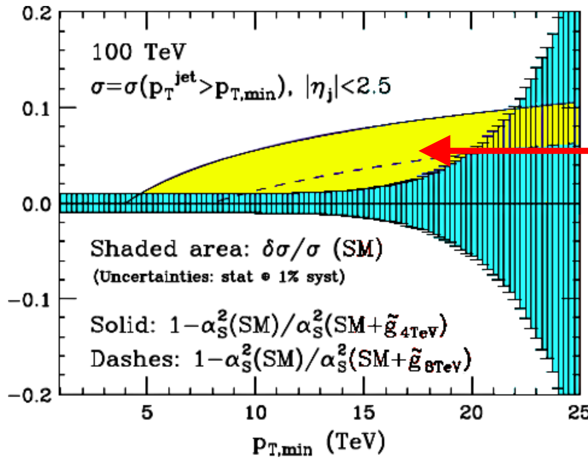
QCD coupling α_s at FCC-ee/FCC-hh/MuColl

- α_s measurements at FCC-ee:
  ±0.1% from Z pseudoobservables
  ±0.2% from W hadronic decays
  ≪1% from tau hadronic decays
  ≪1% from evt. shapes & jet rates



- α_s measurements at FCC-hh:

  Test α_s running (asymptotic freedom) with multi-TeV jets up to Q ≈ 50 TeV

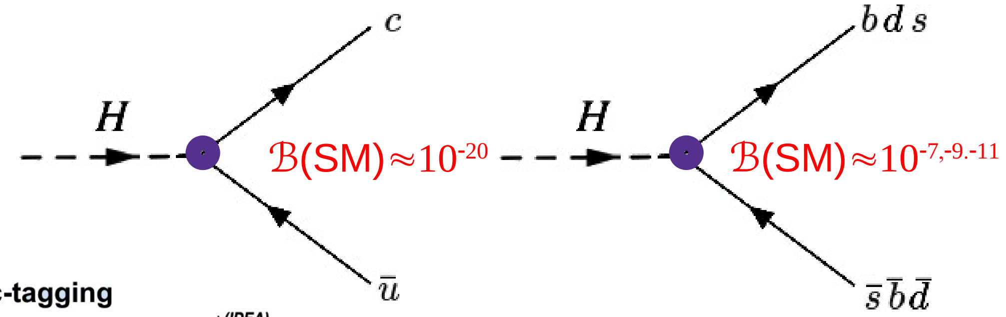


[arXiv:1607.01831]

- α_s measurements at MuColl:
  Running up to Q≈10TeV (EECs)
  Measurements of neutrino SFs at a far-forward detector.

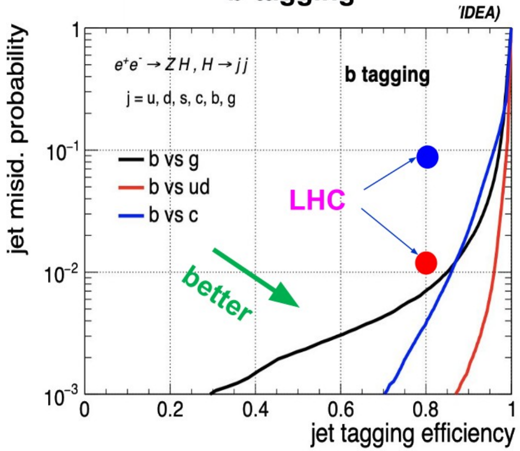
Flavor-violating Higgs decays

- Are there flavour-violating Higgs decays $H \rightarrow qq'$?

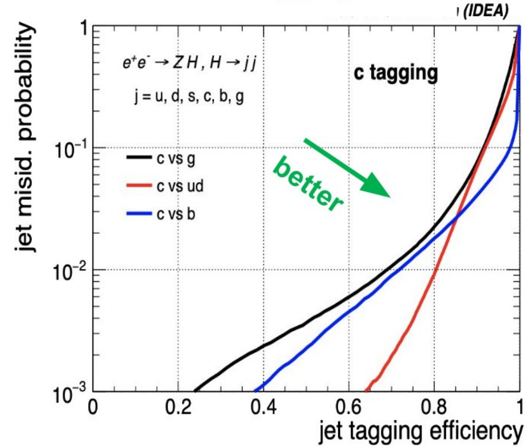


[arXiv:2306.17520]

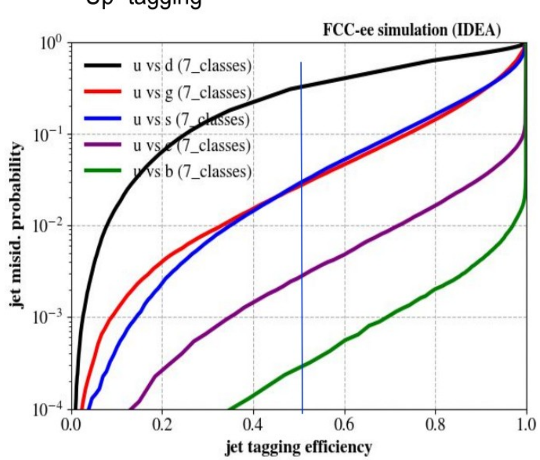
b-tagging



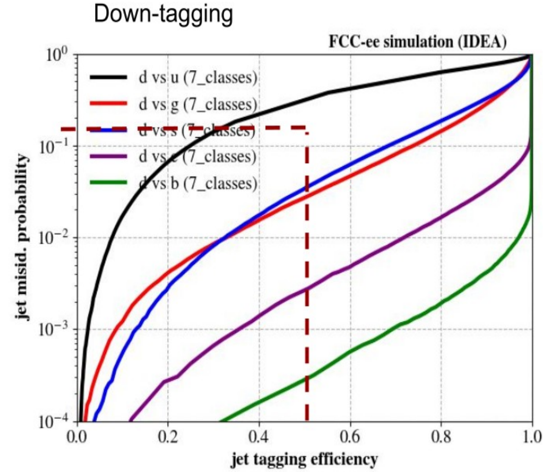
c-tagging



Up -tagging



Down-tagging



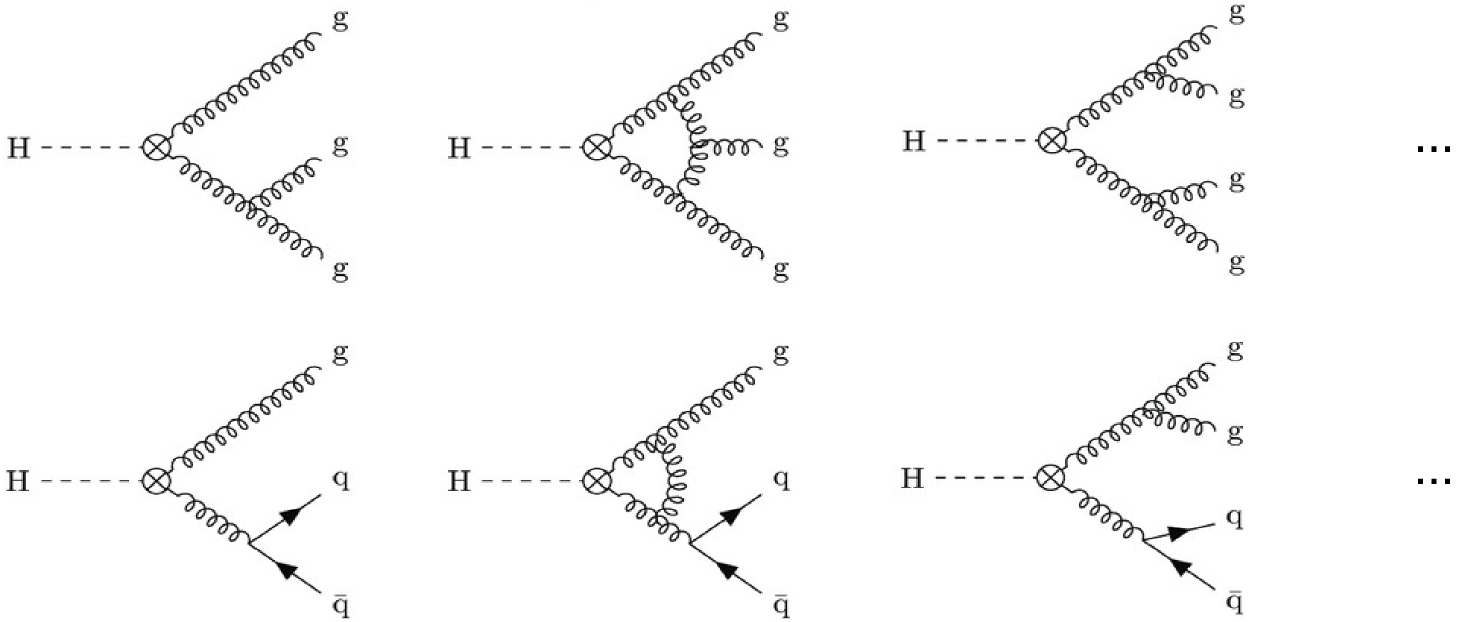
- Projected sensitivities: $y_{bs,bd,cu} \sim 3{\cdot}10^{-4}$, $y_{sd} \sim 8{\cdot}10^{-4}$ well beyond current indirect constraints (B_s and D meson oscillations)
- Expected reach strongly depend on the performance of jet flavor taggers:

  Tunable (tag&probe) with ultra-pure $Z \rightarrow qq$, $W \rightarrow qq'$ samples

arXiv:1902.08570
arXiv:2202.03285

Higgs decays widths & QCD coupling

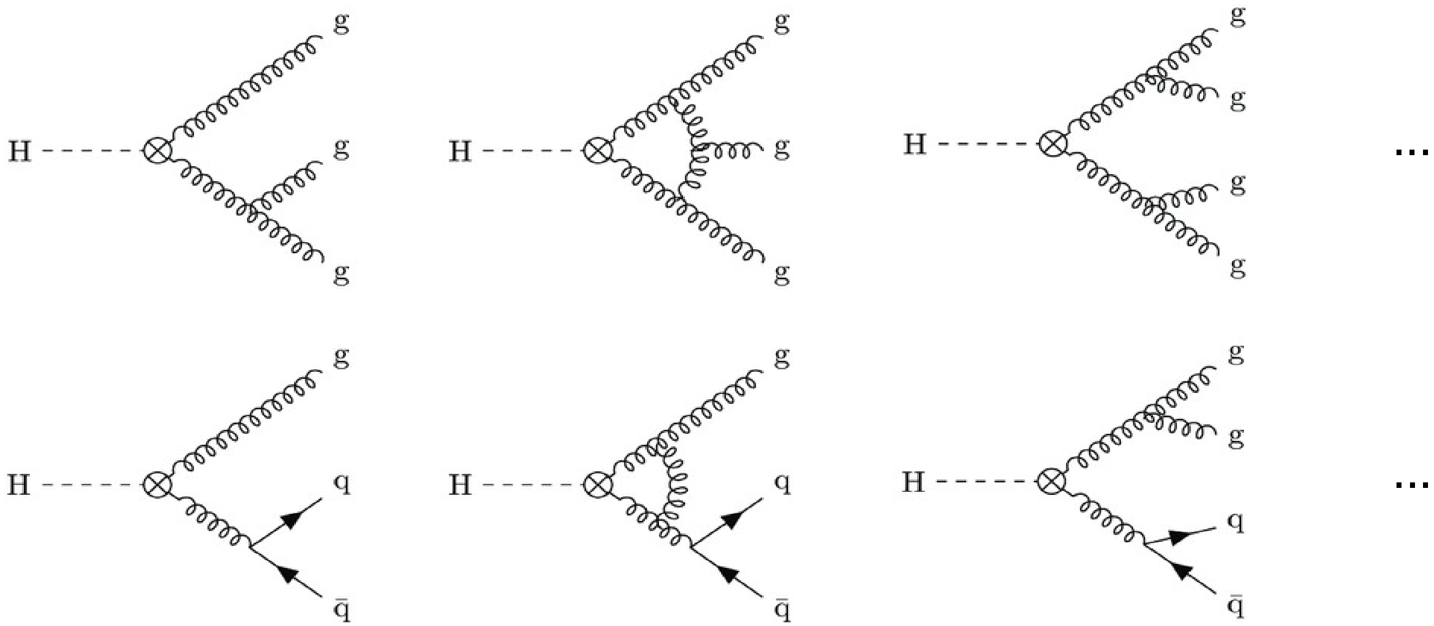
- H→gg partial width known today theoretically at N[4]LO (approx) accuracy



Partial width	intr. QCD	intr. electroweak	total	para. m_q	para. α_s
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	1.4%	0.4%
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	4.0%	0.4%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$< 0.2\%$	3.7%

Higgs decays widths & QCD coupling

- $H \to gg$ partial width known today theoretically at N^4LO (approx) accuracy



- FCC-ee will reduce $\alpha_s(m_Z)$ uncertainties to required κ_g ±0.7% exp. precision

decay	projected intr.	para. m_q	para. α_s	prec. on g^2_{HXX}
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	$\sim 0.8\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	$\sim 1.4\%$
$H \to gg$	$\sim 1\%$		0.5% (0.3%)	$\sim 1.6\%$

TH work needed to reduce intrinsic uncertainties: Today O(3%) → O(<1%)

Precision QCD benchmarks & input docs

- 3 precision-QCD benchmark points defined:

  1) $\alpha_S(m_Z)$ and its Q^2 dependence.
  2) Strong interaction impact on precision measurements of m_{top}
  3) Strong interaction impact on precision measurements of m_W

- 36 ESPPU input docs. associated to precision-QCD received:
  $\mathcal{O}(20)$ with concrete precision-QCD information:

  Low $\sqrt{s}$: MuonE (1), PBC (1), STCF (1)
  DIS machines: DIS-EPPSU (1), LHeC (4)
  H/EW/t factories: ECFA HET Fact. (1), FCC-ee (4), LEP3 (2), LC (1)
  Energy frontier: FCC-hh (2), Muon Collider (2)
  Theory: FORM (1), QIT (1)

- Plus results from recent community reports & experts consultation:

  Belle-II: https://inspirehep.net/literature/2063309, (see A.Vossen, next)
  EIC: https://inspirehep.net/literature/1851258, (see Win Lin, next)
  Lattice QCD:https://inspirehep.net/literature/2053387 (+upcoming feedback)

ECFA HET e+e- factories

- HET e+e- factories:

- At FCC-ee: alpha_s(m_Z) with ±0.1% uncertainty, alpha_s(m_W) with ±0.2%.

- QCD impact on m_W measurement:

NNLO corrections to the W-pair production and W-boson decay processes as well as leading corrections beyond NNLO can be calculated within the EFT approach, and a theory-induced systematic uncertainty below 0.5 MeV on mW from an energy scan near threshold seems feasible. For intermediate and high energies, a full NNLO calculation for W-pair production in the double-pole approximation would be most desirable; a task that should be achievable in the next decade, anticipating further progress at the frontier of loop calculations. Newly developed colour reconnection and hadronisation models should also be considered.

- QCD impact on m_top measurement:

From a detailed assessment of systematic uncertainties, the final precision is expected to be dominated by the scale uncertainties in the N3LO NRQCD prediction, at the level of 20 MeV and 14 MeV at 68% CL for m_t and Gamma_t , respectively, underlining the need for theoretical advancements to fully profit from the physics potential of future e+e- colliders.
The contribution to this uncertainty from alpha_s is 2 MeV, given the assumed 10^-4 precision.

FCC-ee, FCC-hh

- FCC-ee:

- QCD impact on precision Higgs physics.

- QCD impact on m_W measurement:

A theoretical uncertainty of 0.1% in the total cross section for e+e- -> W + W- threshold line-shape translates into a delta mW~1.5 MeV uncertainty. Current state-of-the-art predictions reach delta m_W ~ 3--5 MeV precision, whereas achieving an uncertainty delta m_W < 0.5 MeV will require the calculation of the NNLO EW corrections (currently out of reach), as well as the inclusion of mixed EW-QCD [126] effects and a refined treatment of QED initial-state radiation [127].
Direct m W extraction via the reconstructed invariant mass of W boson decay products needs dedicated studies for a precise assessment. Among the leading theoretical systematics, nonperturbative color-reconnection (CR) effects in the hadronic decays of both W bosons are expected to play a role. The precise m_W extracted from leptonic decays as an input, can be used in lepton + jets and fully hadronic WW decays at FCC-ee will benefit the development and tuning of such CR models.

- QCD impact on m_top measurement:

The final foreseen experimental precision on m top and Gamma_top will be of about 7 and 13 MeV, respectively, dominated by statistical uncertainties (Table 3), whereas missing higher orders in the theoretical predictions amount to 35 (25) MeV on m_top (Gamma_top)
Progress needed include the computation of N4LO corrections in the non-relativistic EFT framework, as well as the description of QED effects at NNLL both in the collinear limit (e.g., ISR [152,153]) and in the soft limit (as discussed in Ref. [154]). Plus N^3LO calculation for the nonresonant channels. The theoretical description of differential distributions, which are central to controlling precisely the effect of experimental cuts., is less accurate than that of the inclusive quantities,and reaches either NLO or NNLO accuracy only for specific observables [155, 156]