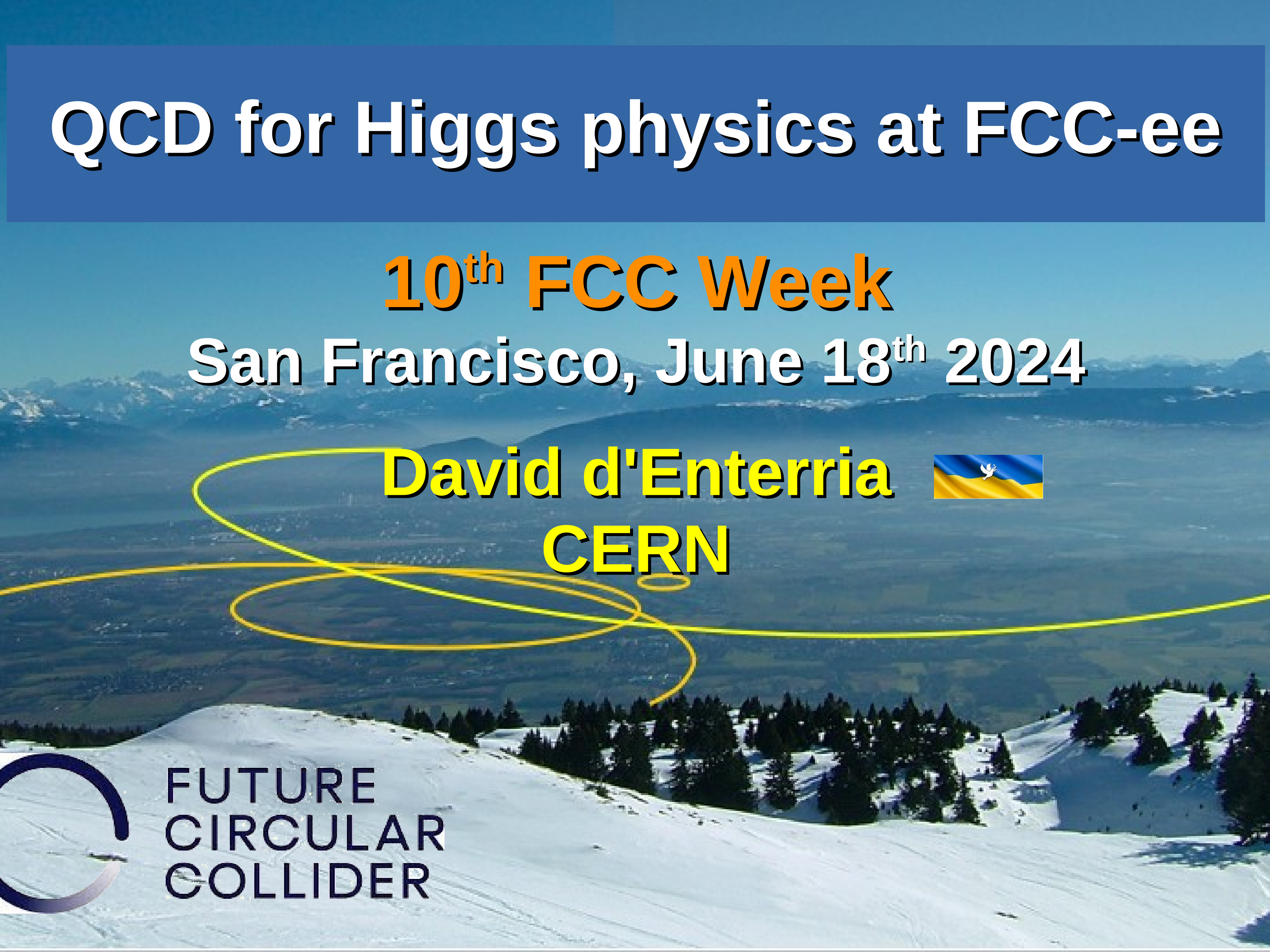
QCD for Higgs physics at FCC-ee



10th FCC Week

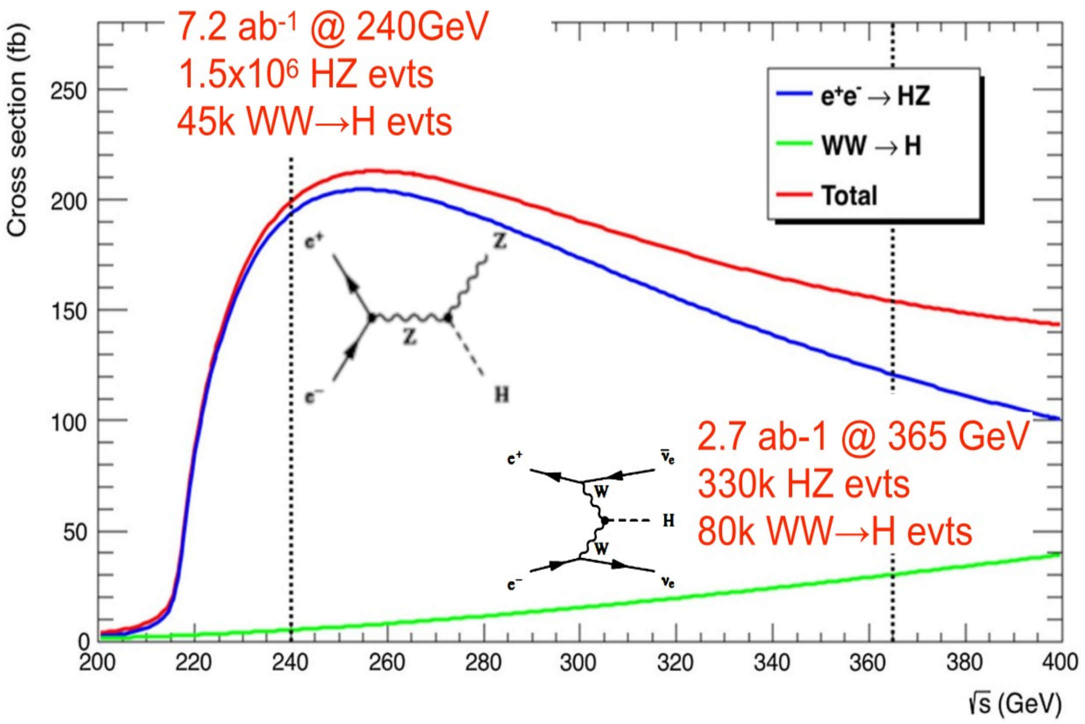
San Francisco, June 18th 2024

David d'Enterria
CERN

FUTURE
CIRCULAR
COLLIDER

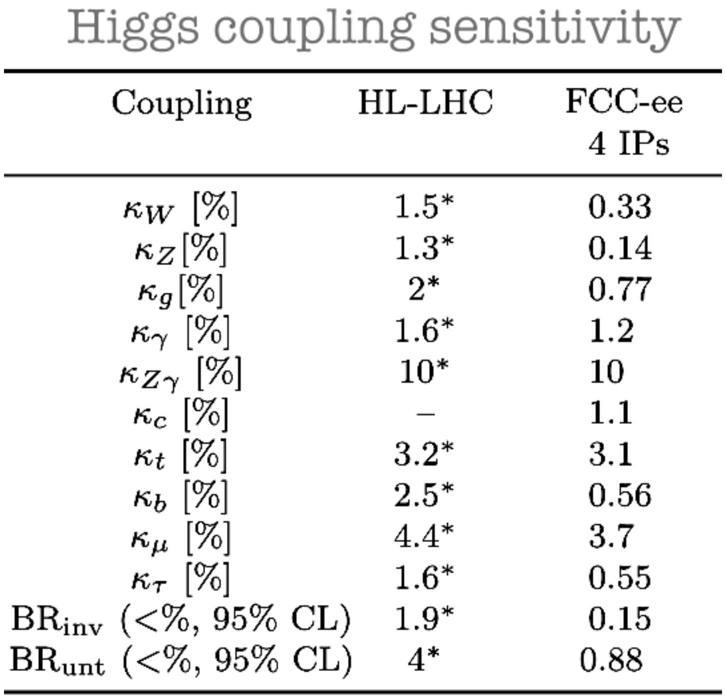
Higgs boson at the FCC-ee (I)

- Central goal of FCC-ee: Model-independent measurements of Higgs couplings & width with <1% precision via measurements at 2 c.m. energies:



7.2 ab^{-1} @ 240GeV
1.5x10^6 HZ evts
45k WW→H evts

2.7 ab-1 @ 365 GeV
330k HZ evts
80k WW→H evts



Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee 4 IPs
κ_W [%]	1.5*	0.33
κ_Z [%]	1.3*	0.14
κ_g [%]	2*	0.77
κ_γ [%]	1.6*	1.2
$\kappa_{Z\gamma}$ [%]	10*	10
κ_c [%]	–	1.1
κ_t [%]	3.2*	3.1
κ_b [%]	2.5*	0.56
κ_μ [%]	4.4*	3.7
κ_τ [%]	1.6*	0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	0.88

- Improvement factor up to ×10 compared to HL-LHC.
- Sensitivity to scalar-coupled BSM physics (SMEFT):

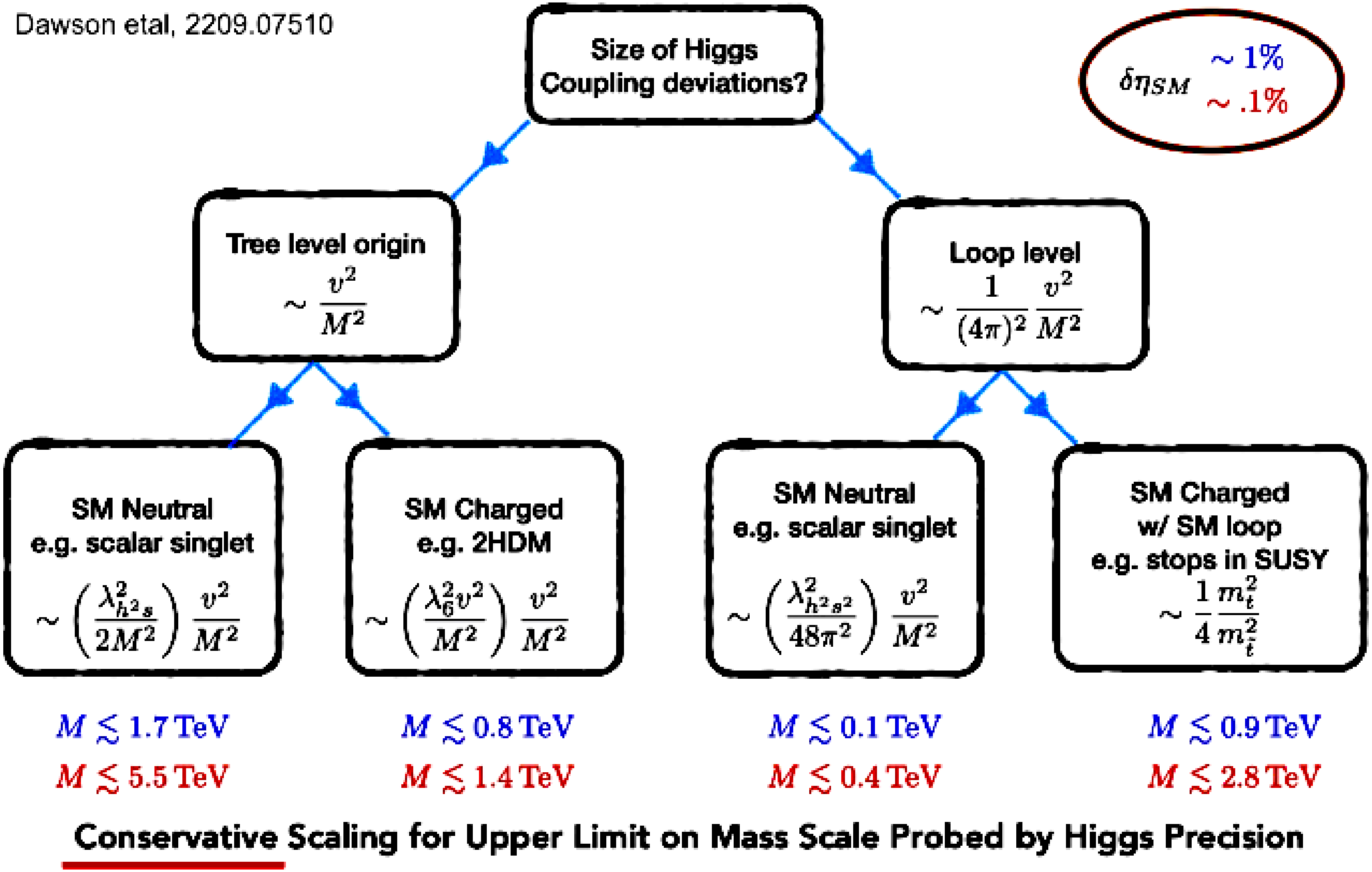
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} \qquad \Lambda \gtrsim (1\,\mathrm{TeV}) / \sqrt{(\delta \mathrm{g_{HXX}} / \mathrm{g^{SM}_{HXX}})/5\%}$$

> 6 TeV

Precisely probing the Higgs boson properties

- Mass scales O(0.4-5.5 TeV) probed in a wide range of BSM models

Dawson etal, 2209.07510



Size of Higgs Coupling deviations?

$\delta\eta_{SM}$ $\sim 1\%$ / $\sim .1\%$

Tree level origin $\sim \frac{v^2}{M^2}$

Loop level $\sim \frac{1}{(4\pi)^2}\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2 s}}{2M^2}\right)\frac{v^2}{M^2}$

$M \lesssim 1.7\,\text{TeV}$

$M \lesssim 5.5\,\text{TeV}$

SM Charged e.g. 2HDM $\sim \left(\frac{\lambda^2_6 v^2}{M^2}\right)\frac{v^2}{M^2}$

$M \lesssim 0.8\,\text{TeV}$

$M \lesssim 1.4\,\text{TeV}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2 s^2}}{48\pi^2}\right)\frac{v^2}{M^2}$

$M \lesssim 0.1\,\text{TeV}$

$M \lesssim 0.4\,\text{TeV}$

SM Charged w/ SM loop e.g. stops in SUSY $\sim \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}}^2}$

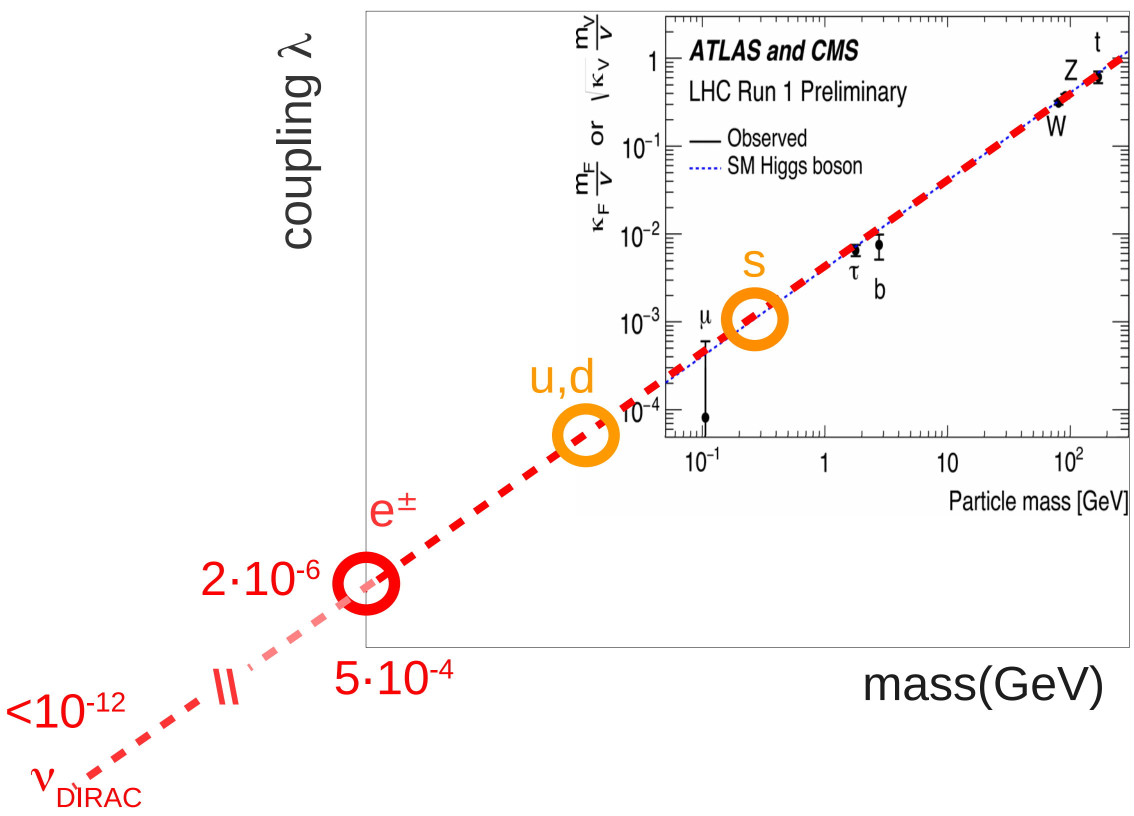
$M \lesssim 0.9\,\text{TeV}$

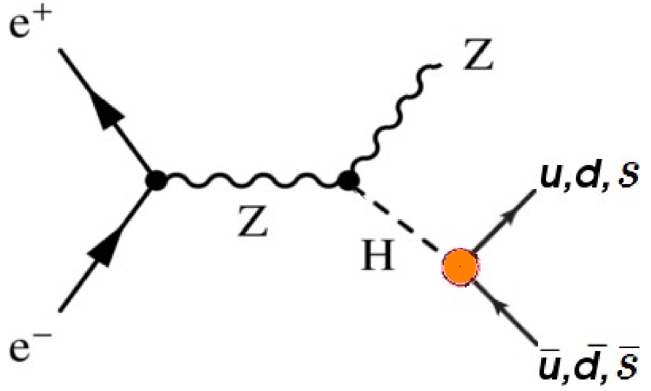
$M \lesssim 2.8\,\text{TeV}$

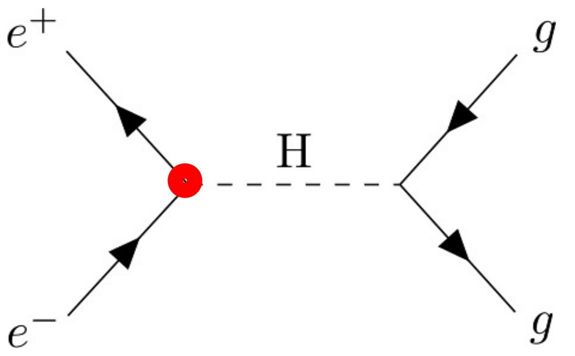
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

Higgs boson at the FCC-ee (II)

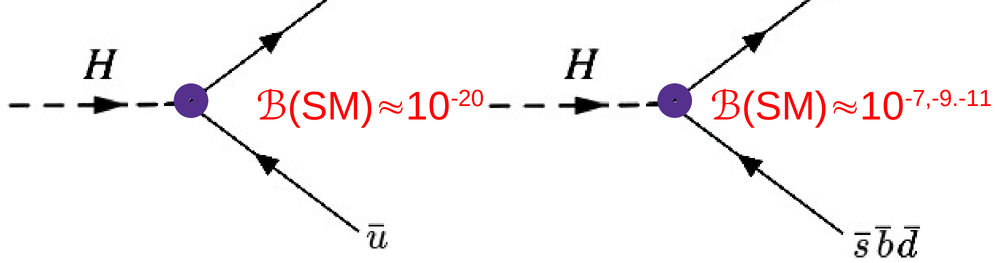
- Do the lightest fermions (u,d,s,e) acquire their masses through their Higgs (Yukawa) couplings?







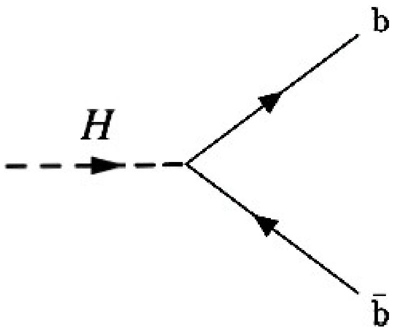
- Does the Higgs boson mediate H → qq' FCNCs at tree level?



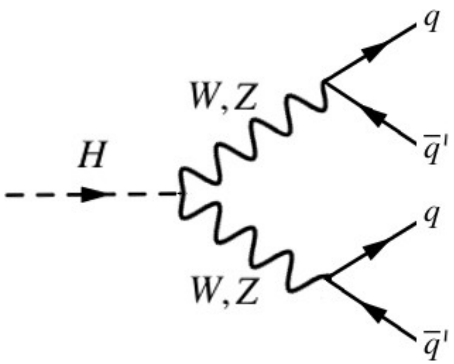
QCD at the core of Higgs physics programme

- 80% of the Higgs decays are fully hadronic!

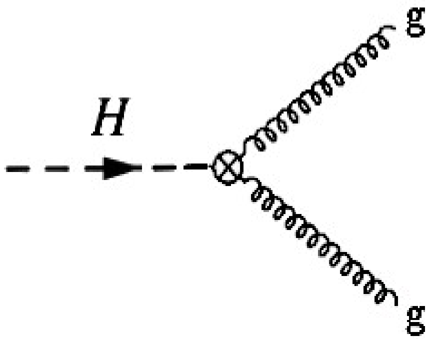
$\mathcal{B}=57.7\%$



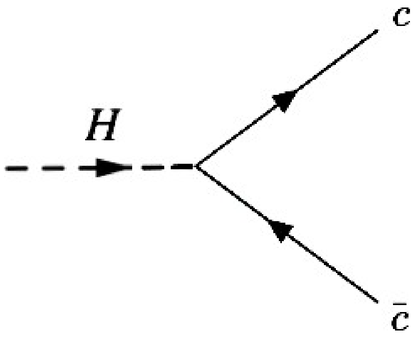
$\mathcal{B}=11\%$



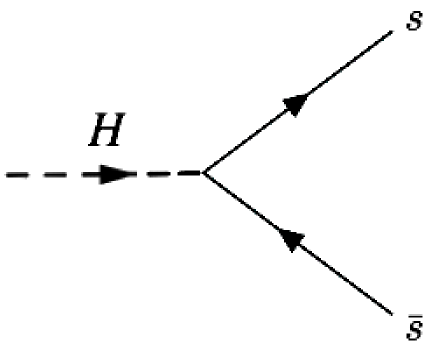
$\mathcal{B}=8.6\%$



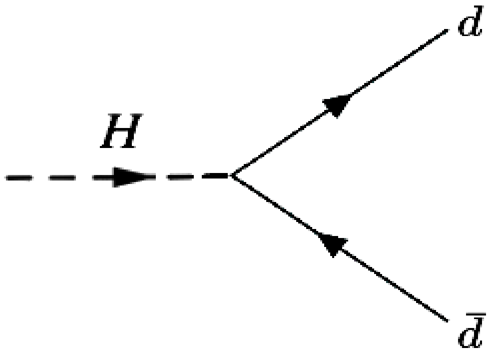
$\mathcal{B}=2.9\%$



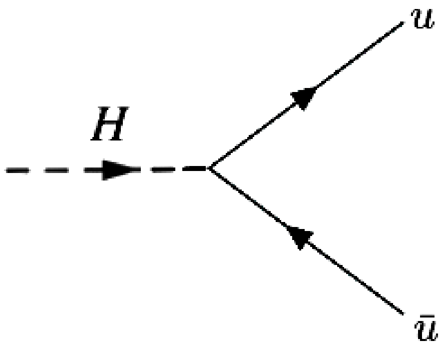
$\mathcal{B}=0.024\%$



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



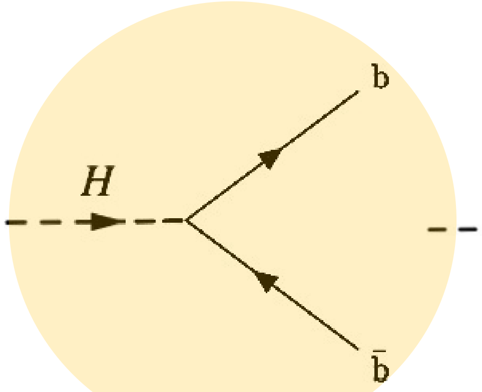
$\mathcal{B}=1.4\cdot10^{-7}$



QCD at the core of Higgs physics programme

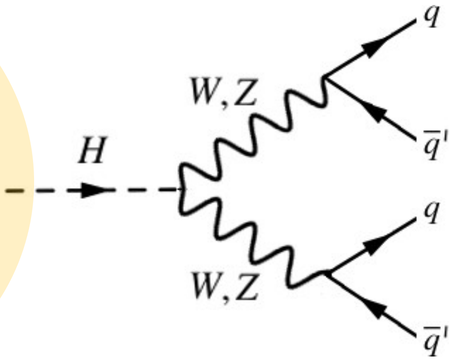
- 80% of the Higgs decays are fully hadronic. Most of them unseen to date!

$\mathcal{B}=57.7\%$

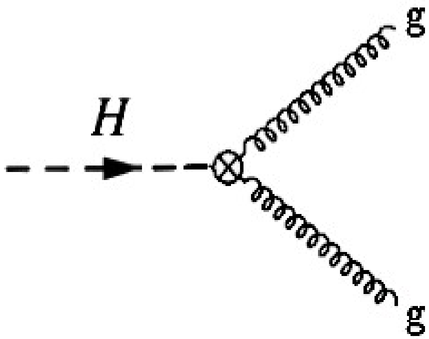


Only hadronic decay channel observed so far!

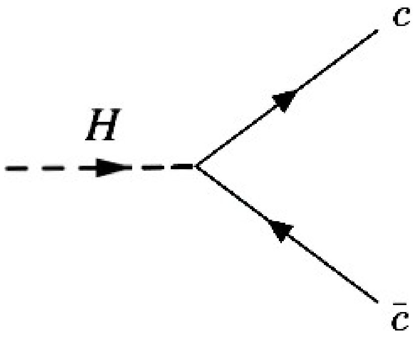
$\mathcal{B}=11\%$



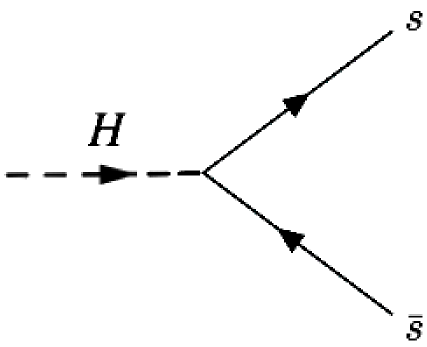
$\mathcal{B}=8.6\%$



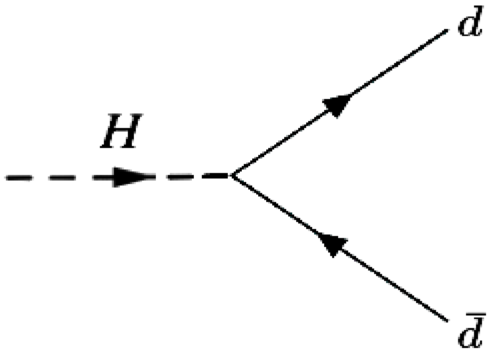
$\mathcal{B}=2.9\%$



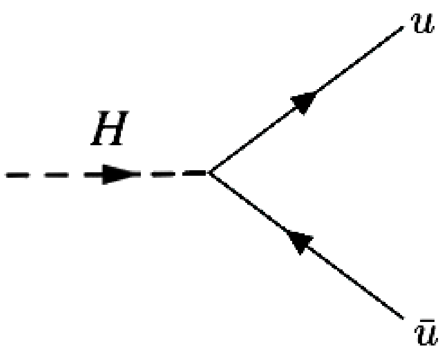
$\mathcal{B}=0.024\%$



$\mathcal{B}=6{\cdot}10^{-7}$



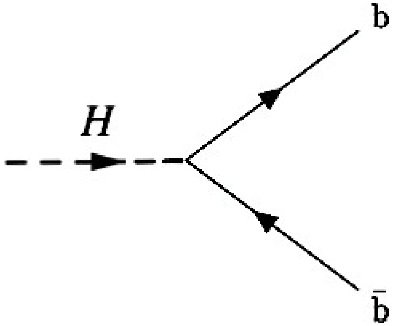
$\mathcal{B}=1.4{\cdot}10^{-7}$



QCD at the core of Higgs physics programme

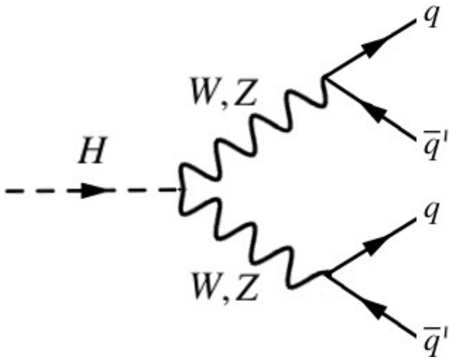
- 80% of the Higgs decays are fully hadronic. Mostly measurable at FCC-ee!

$\mathcal{B}=57.7\%$



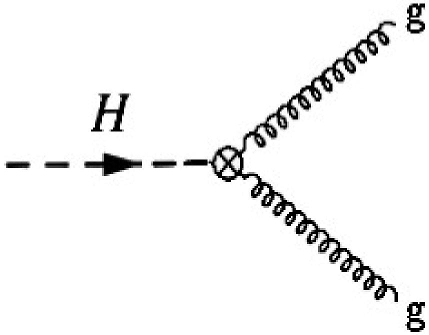
N(H)≈1.e6 @FCC-ee

$\mathcal{B}=11\%$



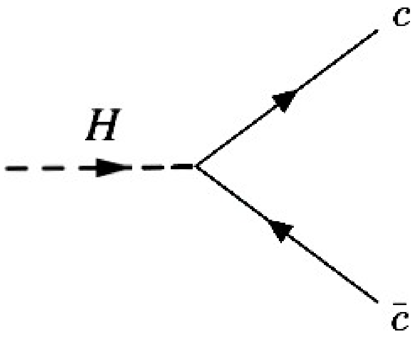
N(H)≈2.e5 @FCC-ee

$\mathcal{B}=8.6\%$



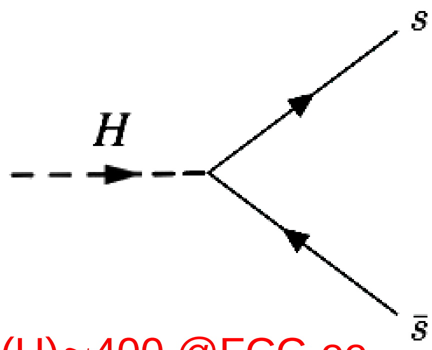
N(H)≈1.5e5 @FCC-ee

$\mathcal{B}=2.9\%$



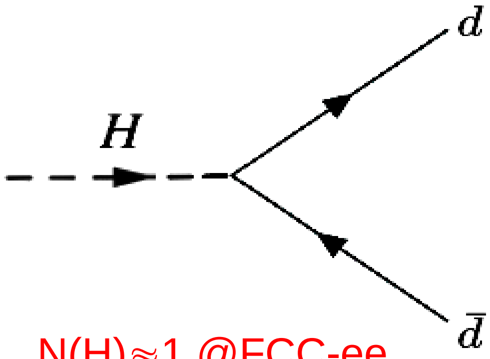
N(H)≈5.e4 @FCC-ee

$\mathcal{B}=0.024\%$



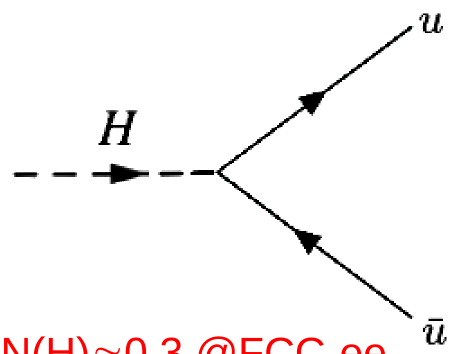
N(H)≈400 @FCC-ee

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



N(H)≈1 @FCC-ee

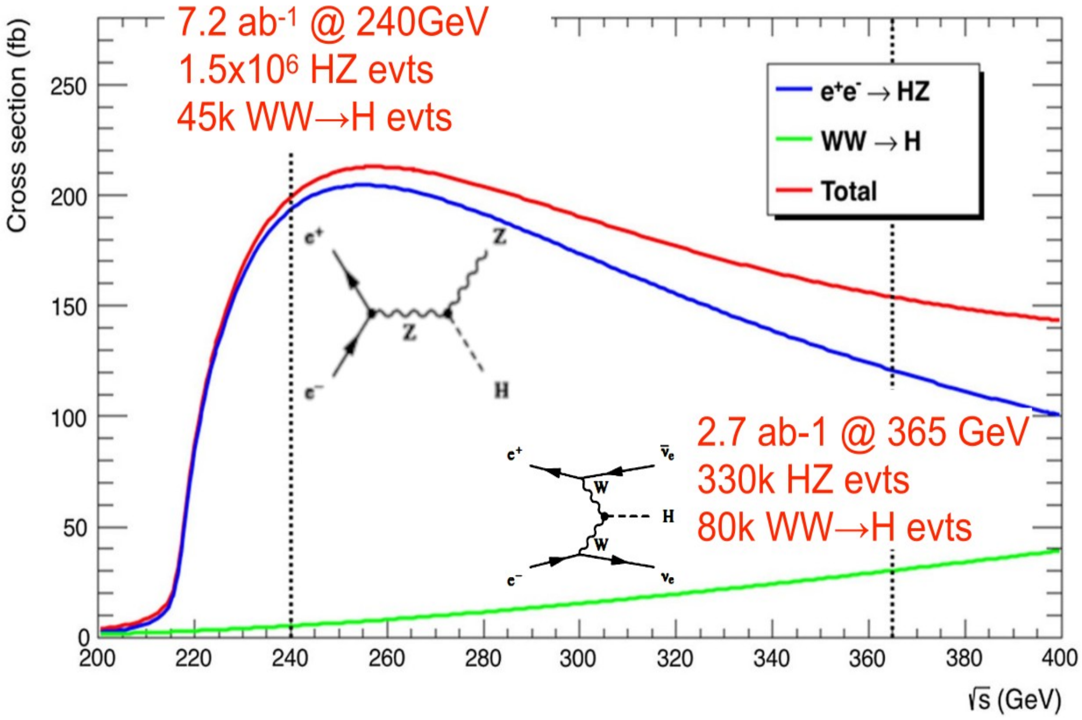
$\mathcal{B}=1.4\cdot10^{-7}$

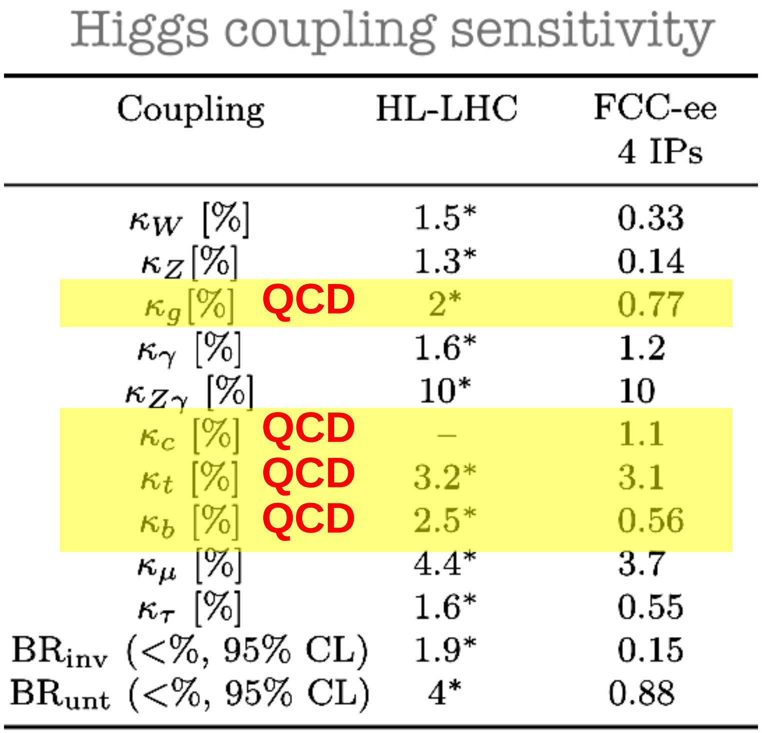


N(H)≈0.3 @FCC-ee

Higgs boson at the FCC-ee (I)

- Central goal of FCC-ee: Model-independent measurements of Higgs couplings & width with <1% precision via measurements at 2 c.m. energies:





Higgs coupling sensitivity

Coupling		HL-LHC	FCC-ee 4 IPs
κ_W [%]		1.5*	0.33
κ_Z [%]		1.3*	0.14
κ_g [%]	**QCD**	2*	0.77
κ_γ [%]		1.6*	1.2
$\kappa_{Z\gamma}$ [%]		10*	10
κ_c [%]	**QCD**	–	1.1
κ_t [%]	**QCD**	3.2*	3.1
κ_b [%]	**QCD**	2.5*	0.56
κ_μ [%]		4.4*	3.7
κ_τ [%]		1.6*	0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)		1.9*	0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)		4*	0.88

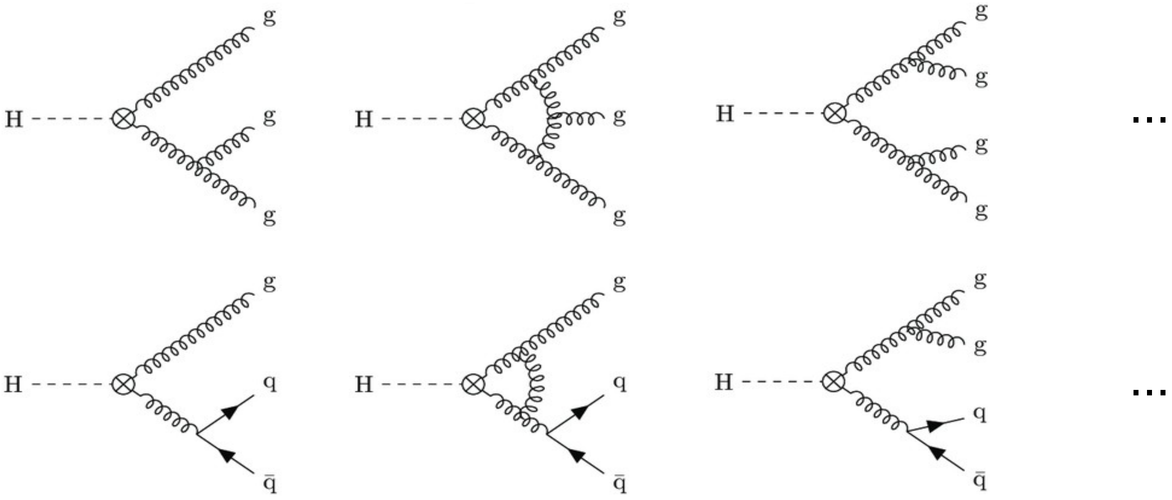
- Improvement factor up to ×10 compared to HL-LHC.
- Sensitivity to scalar-coupled BSM physics (SMEFT):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} \qquad \Lambda \gtrsim (1\,\mathrm{TeV}) / \sqrt{(\delta g_{\mathrm{HXX}} / g_{\mathrm{HXX}}^{\mathrm{SM}})/5\%}$$

> 6 TeV

Higgs → gg decay and BSM

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



- Percent deviations on Higgs-gluon coupling in BSM models:

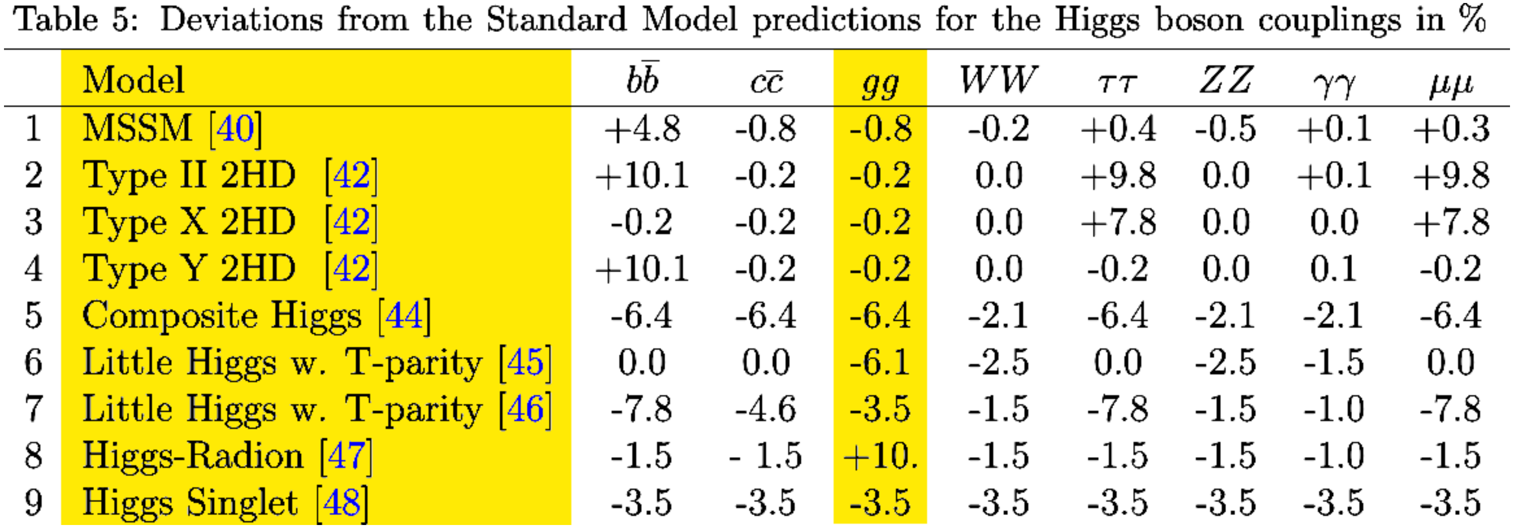


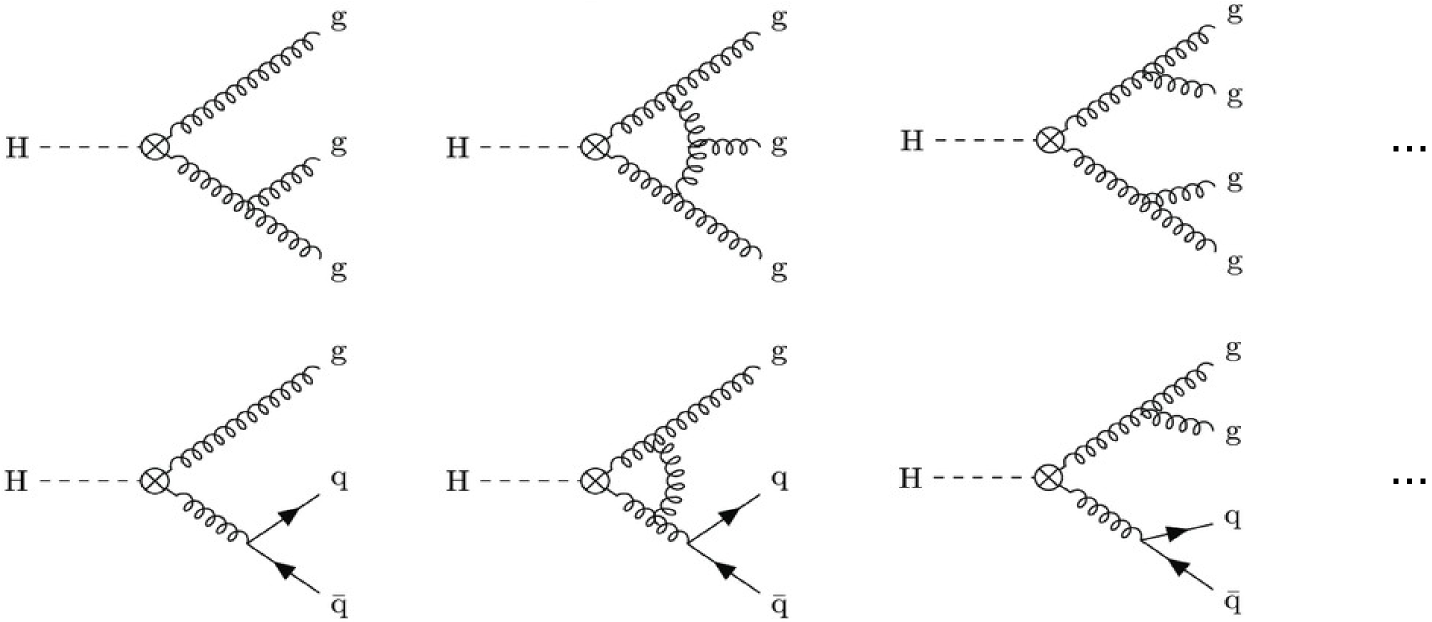
Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings in %

	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

[T. Barklow et al. arXiv:1708.08912]

Higgs decays widths & QCD coupling

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



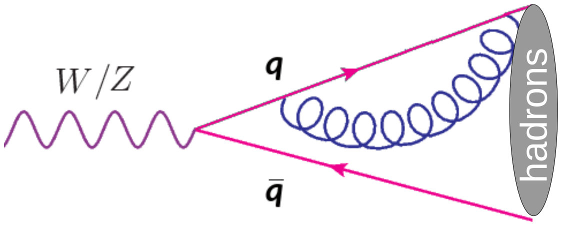
Uncertainties: O(3%) TH + O(4%) parametric from $\alpha_s(m_Z)=0.118\pm1\%$ (today):

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%

- FCC-ee will need a much more precise $\alpha_s(m_Z)$ to constrain κ_g at ±0.7% (exp)

QCD coupling at FCC-ee (Tera-Z)

- EW boson pseudoobservables known at N^{3}LO 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 :

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

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

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

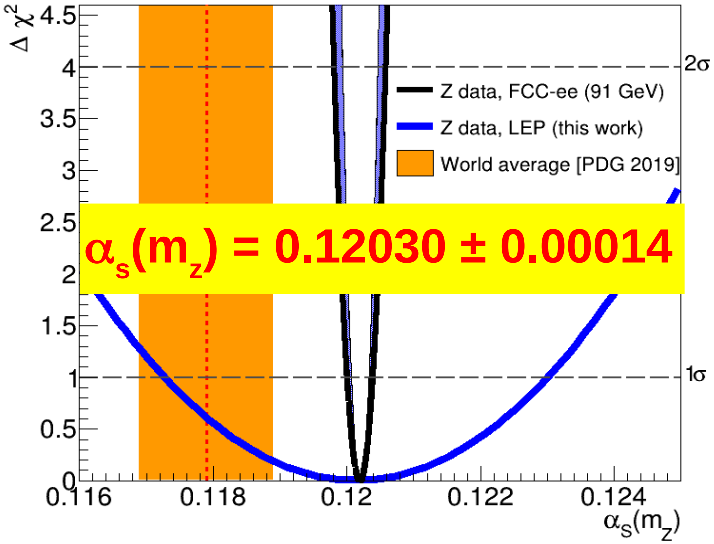
Note: Sensitivity to $\alpha_s(m_Z)$ from O(4%) virtual corrs.

[DdE, Jacobsen: arXiv:2005.04545]

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

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

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



$\alpha_s(m_z)$ = 0.12030 ± 0.00014

QCD coupling at FCC-ee (Oku-W)

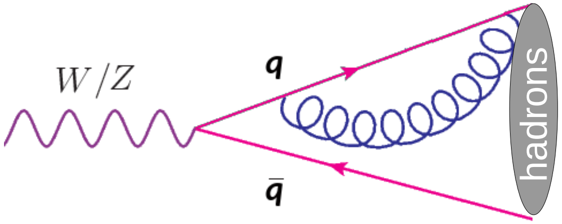
- EW boson pseudoobservables known at N^{3}LO in pQCD:

- 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 $\alpha_s(m_Z)$ from O(4%) virtual corrs.

[DdE, Jacobsen: arXiv:2005.04545]

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

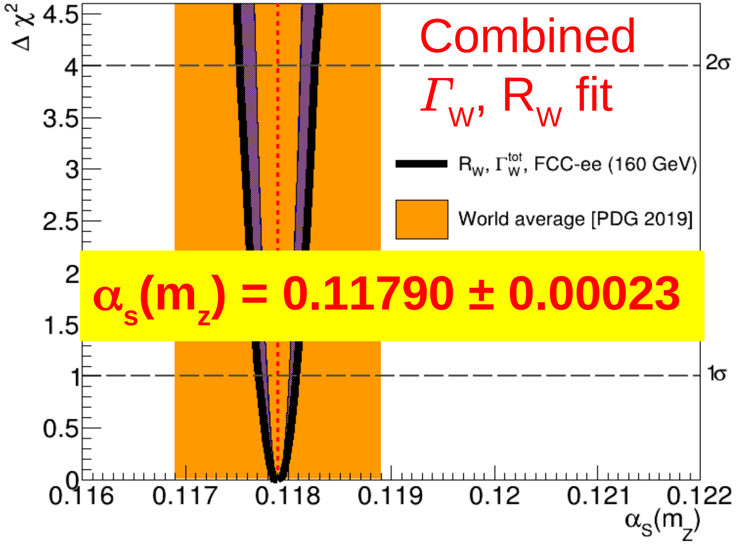
$$\Gamma^{\rm tot}_{\rm W} = 2088.0 \pm 1.2 \text{ MeV}$$

$$R_{\rm W} = 2.08000 \pm 0.00008$$

$$m_{\rm W} = 80.3800 \pm 0.0005 \text{ GeV}$$

$$|V_{cs}| = 0.97359 \pm 0.00010$$ ← O(10^{12}) D mesons

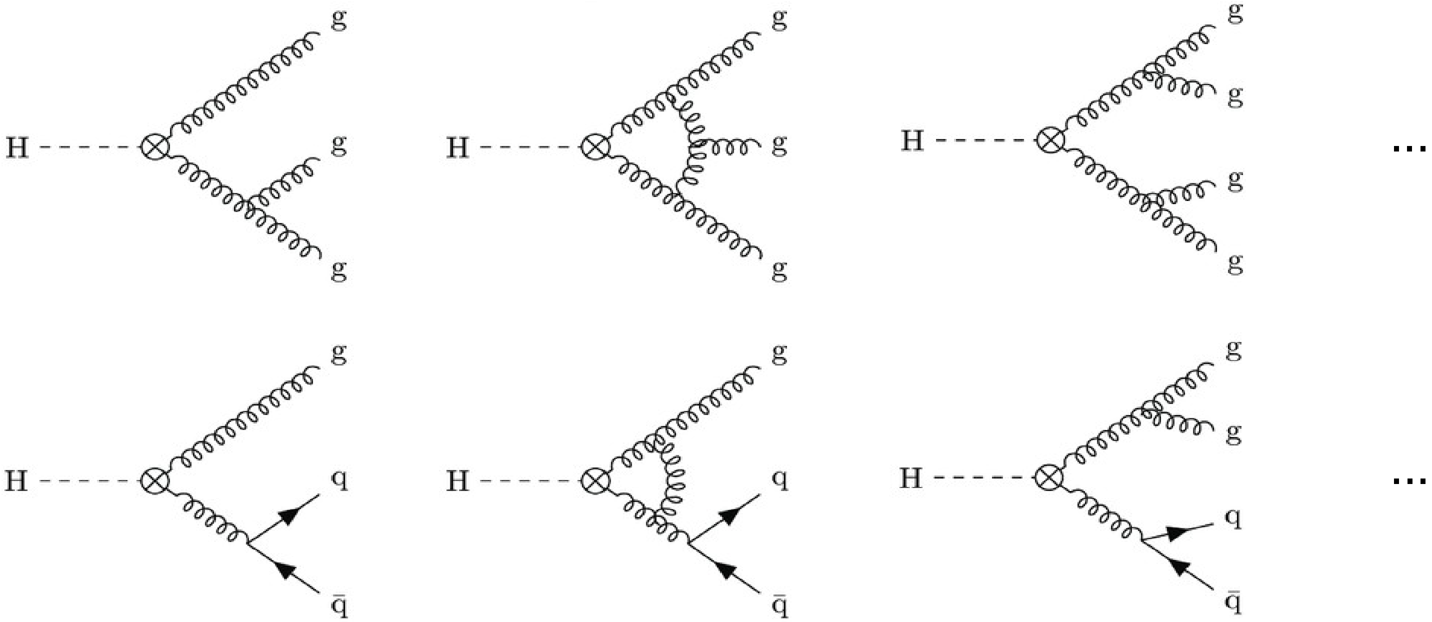
  - – TH uncertainty to be reduced by ×10 from missing α_s^5, α^2, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms


Combined Γ_W, R_W fit

$\alpha_s(m_z) = 0.11790 \pm 0.00023$

Higgs decays widths & QCD coupling

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



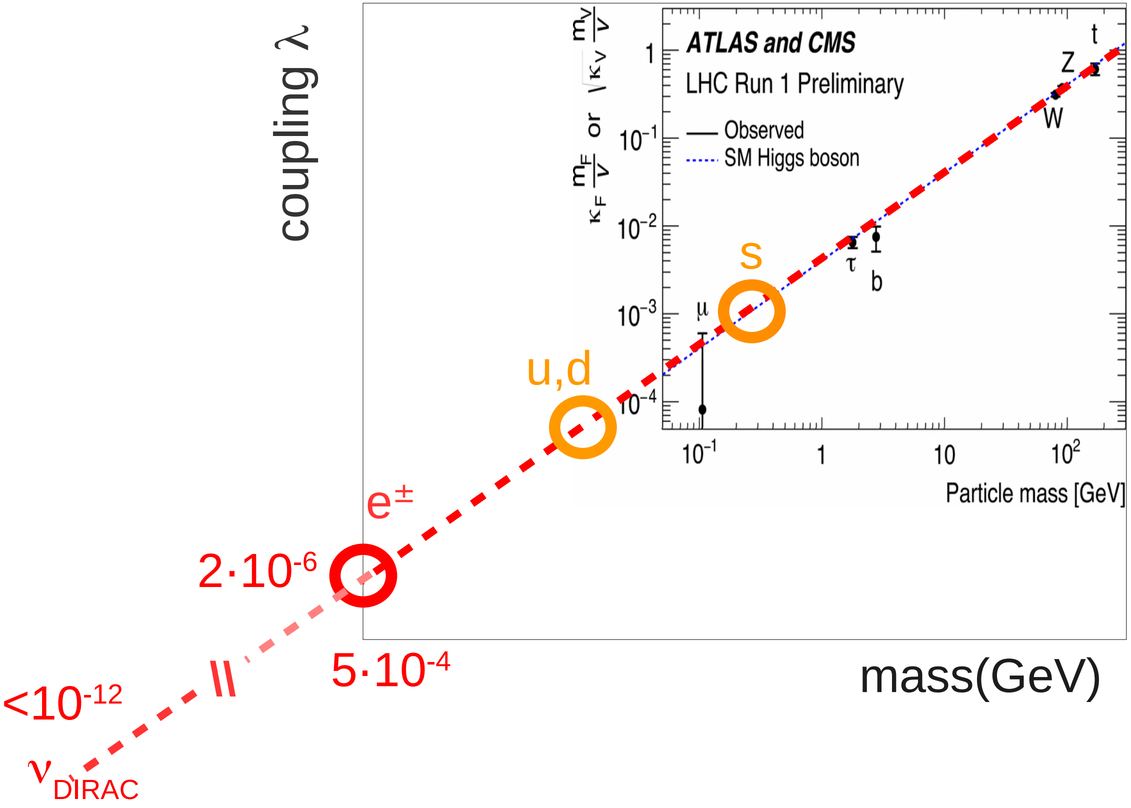
- FCC-ee will reduce $\alpha_s(m_Z)$ uncertainties to required κ_g ±0.7% exp. precision

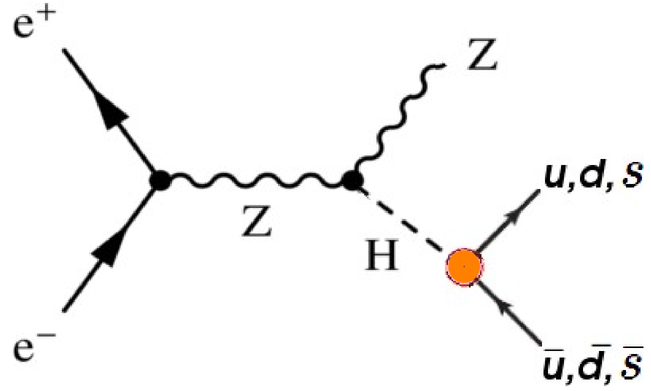
decay	projected intr.	para. m_q	para. α_s	prec. on g^2_{HXX}
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	$\sim 0.8\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	$\sim 1.4\%$
$H \to gg$	$\sim 1\%$		0.5% (0.3%)	$\sim 1.6\%$

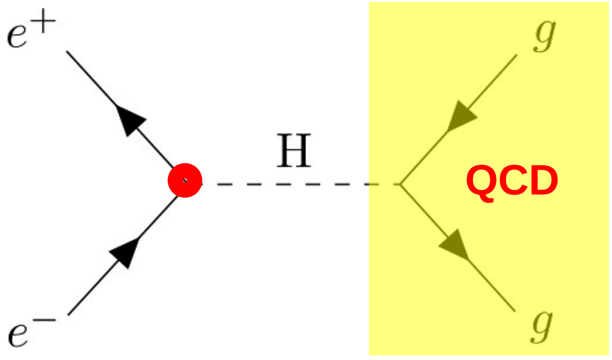
TH work needed to reduce intrinsic uncertainties: Today O(3%) → O(<1%)

Higgs boson at the FCC-ee (II)

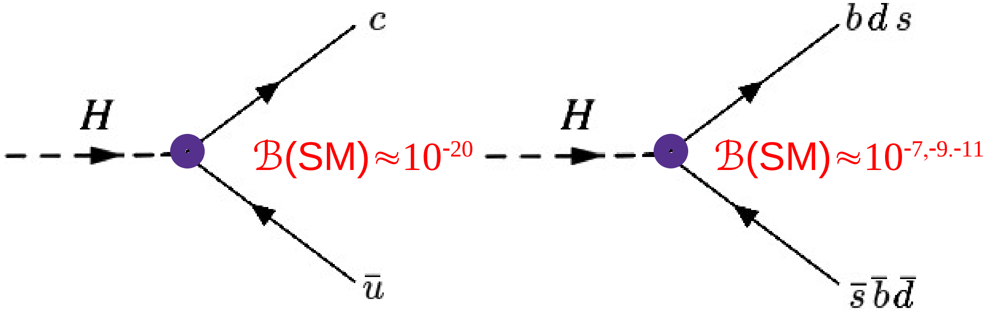
- Do the lightest fermions (u,d,s,e) acquire their masses through their Higgs (Yukawa) couplings?





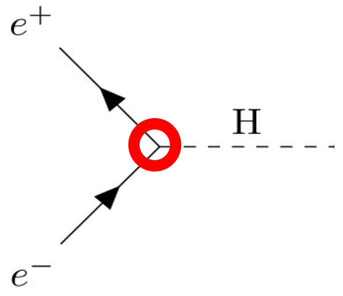


- Does the Higgs boson mediate H → qq' FCNCs at tree level?



Electron Yukawa via s-channel $e^+e^- \to H$

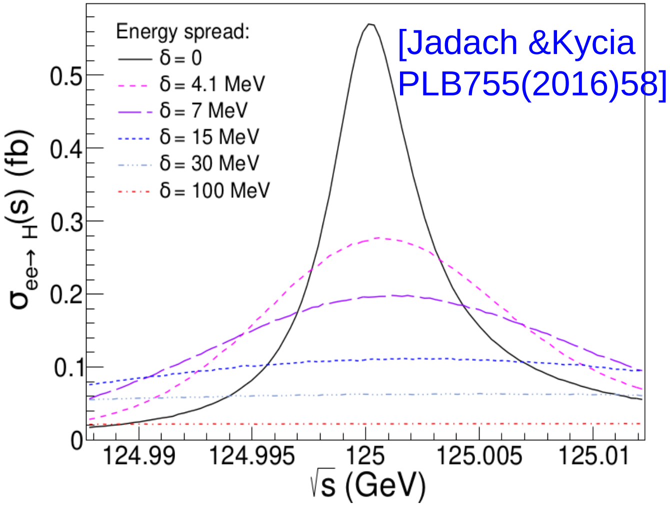
- Resonant s-channel Higgs production at FCC-ee (√s = 125.000 GeV):



Unique possibility to probe e-H
(decay $\mathcal{B}=5\cdot 10^{-9}$ is hopeless...)

$$\sigma(e^+e^-\to H) = \frac{4\pi\Gamma_H^2 Br(H\to e^+e^-)}{(\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2} = 1.64\text{ fb}$$

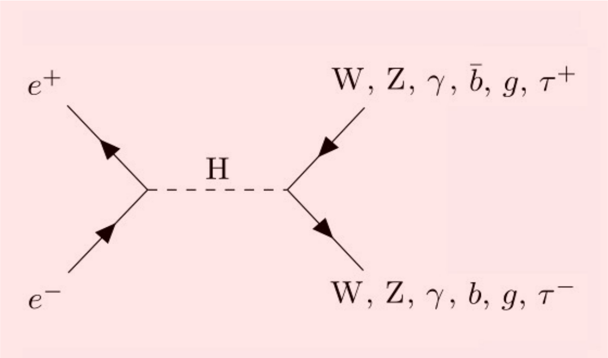
$\sigma(e^+e^-\to H)_{\rm spread}$ = 280 ab ISR + $\sqrt{s}_{\rm spread}$ (=Γ_H = 4.2 MeV)

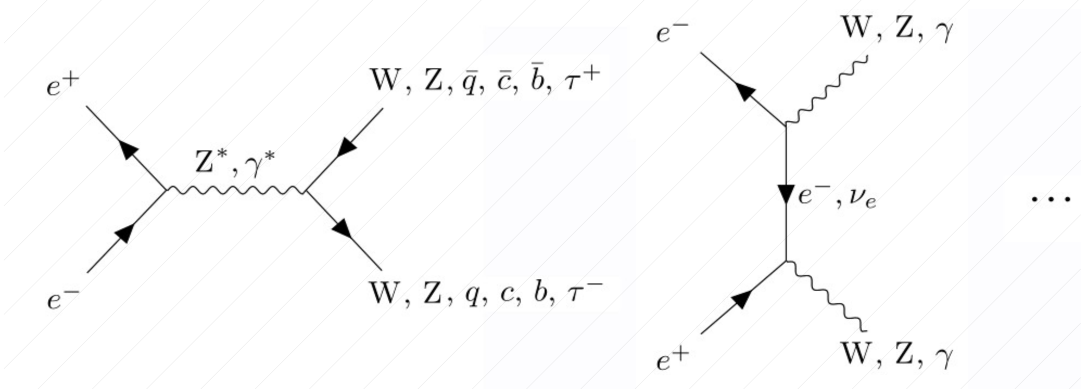


[Jadach &Kycia PLB755(2016)58]

- Very-rare counting experiment over 10 decay channels. S/B ~ 10^{-3}-10^{-7} !

BACKGROUNDS (s-channel Z*/γ*, all t-channels)





- MVA with $\mathcal{O}(50)$ variables for kinematical properties of each single, pair, (n-wise combinations) of physics objects, global event vars., MELA vars.,...

Most significant channel: $e^+e^- \to H(gg) \to jj$

- No e^+e^- background can generate 2 true gluon jets !

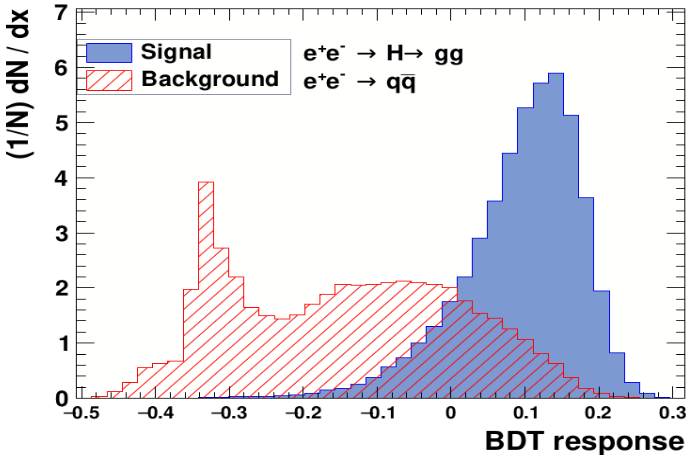
[DdE,Poldaru/Wojcik arXiv:2107.02686]

- Analysis performances assumed:

  2 gluon-tagged jets (with 70% effic. each)
  u,d,s mistagging rate: ~1%

  Challenging, but not impossible (see next)

  Retains 50% of $\sigma(H \to gg)$ = 24 ab signal



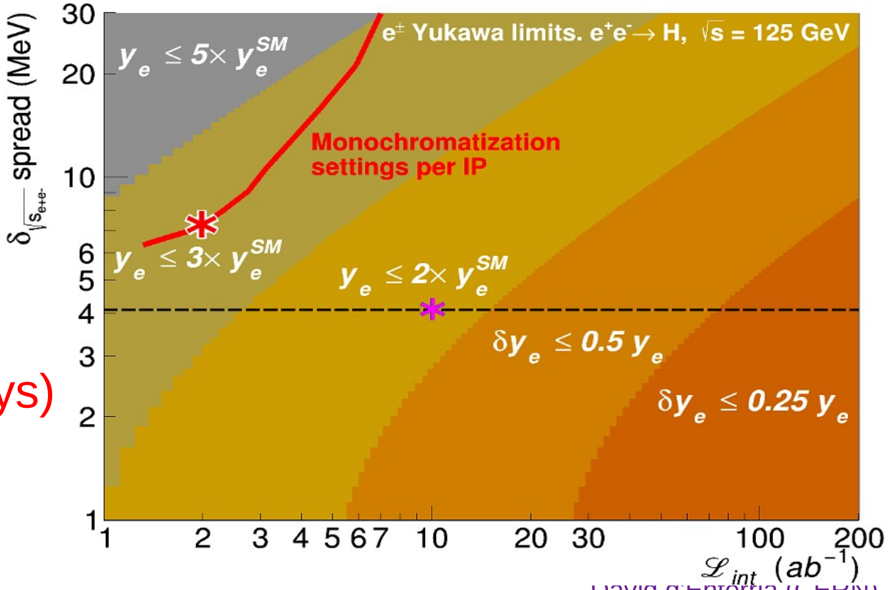
- BDT MVA result (removing jet vars. potentially already used in g-uds discrimination):

  Signal reduction ~50%
  Backgd. reduction: x17

- For $\mathcal{L}_{int}$=10 ab^{-1} :

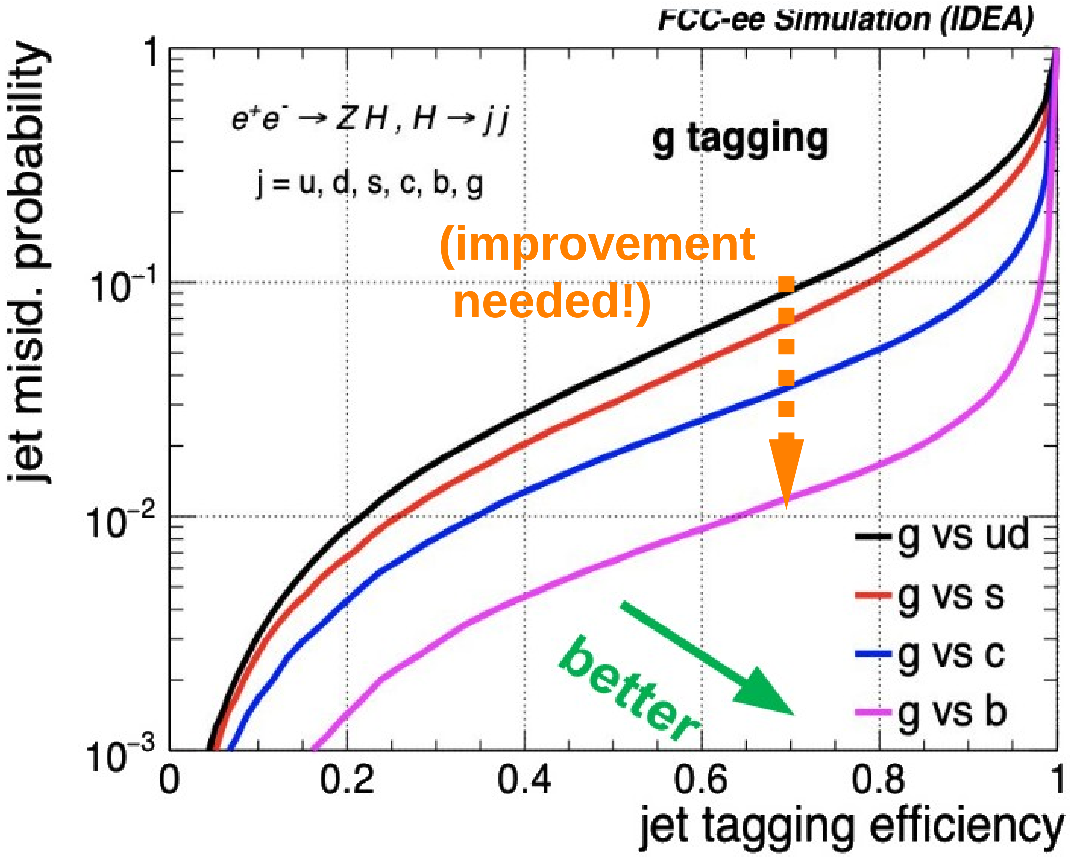
  $S/\sqrt{B} = 55/\sqrt{2500} \approx 1.1$
  Significance $\approx$ 1.1σ (1.3σ, other decays)

  With current best monochromatization:
  $y_e < 2.5 \times y_{e,SM}$ (95% CL) per year & per IP



Gluon jet tagging at FCC-ee

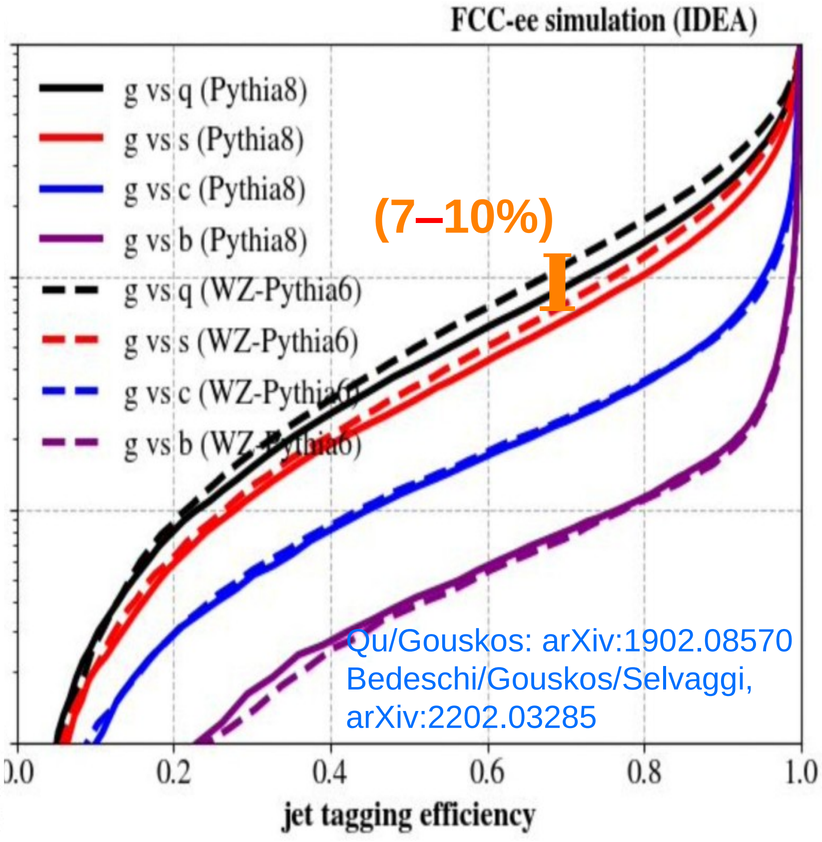
- Current state-of-the-art GNN ParticleNet (+IDEA): ε_g~70%, $\varepsilon_{q\text{-mistag}}$~0.07–0.1



(improvement needed!)

better

trained on Pythia 8 [solid lines]



(7–10%)

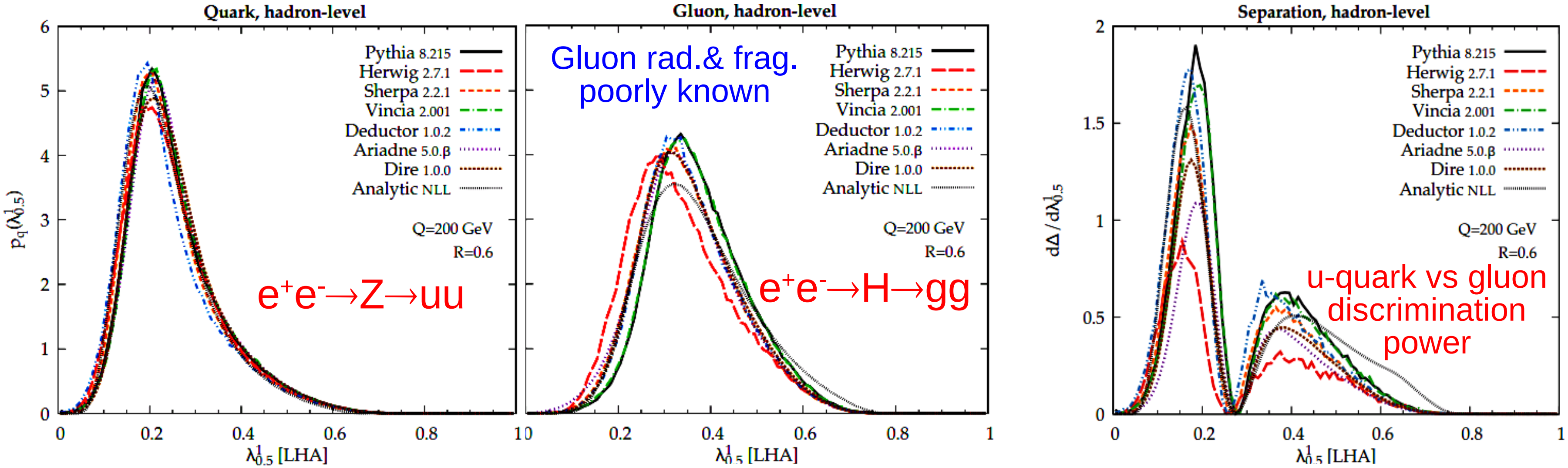
Qu/Gouskos: arXiv:1902.08570
Bedeschi/Gouskos/Selvaggi, arXiv:2202.03285

tested on Pythia 8 [solid lines]
tested on WZ-Pythia6 [dashed lines]

- To approach the e-Yukawa, we need: ε_g~70%, $\varepsilon_{q\text{-mistag}}$~0.01 (factor x10 improvement). However...

But gluon jets are badly known today

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



Gluon rad.& frag. poorly known

$e^+e^- \to Z \to uu$

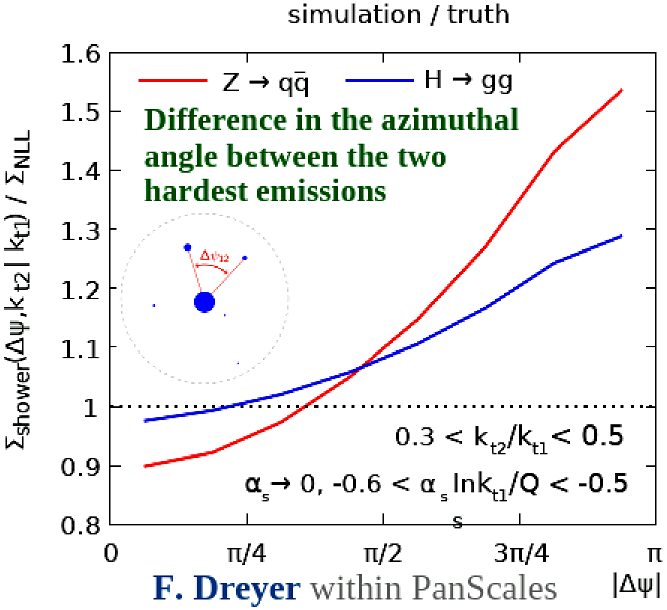
$e^+e^- \to H \to gg$

u-quark vs gluon discrimination power

[G.Soyez et al.]

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

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



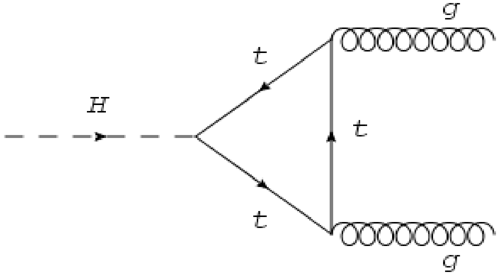
Difference in the azimuthal angle between the two hardest emissions

F. Dreyer within PanScales

Nonphysical quark/gluon differences in common dipole showers

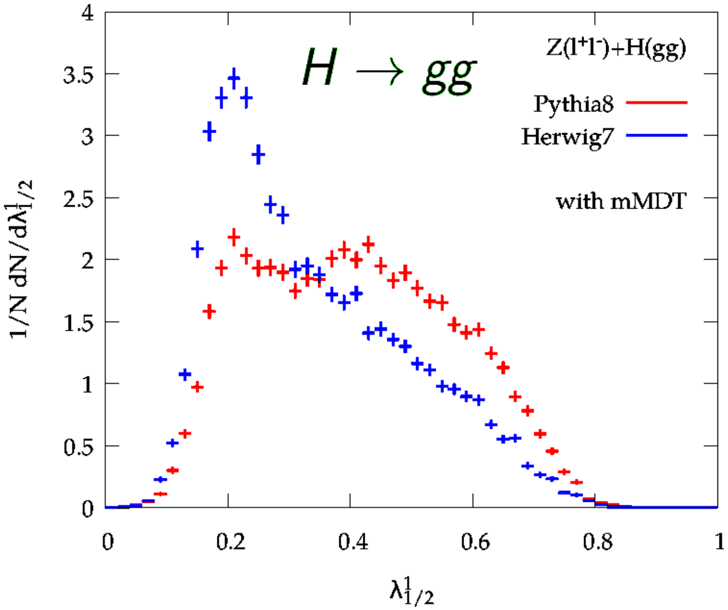
[S.Ferrario-Ravasio et al.]

FCC-ee for high-precision gluon jet studies



- Exploit FCC-ee H(gg) as a "pure gluon" factory: H → gg provides $\mathcal{O}$(150.000) extra-clean digluon events.

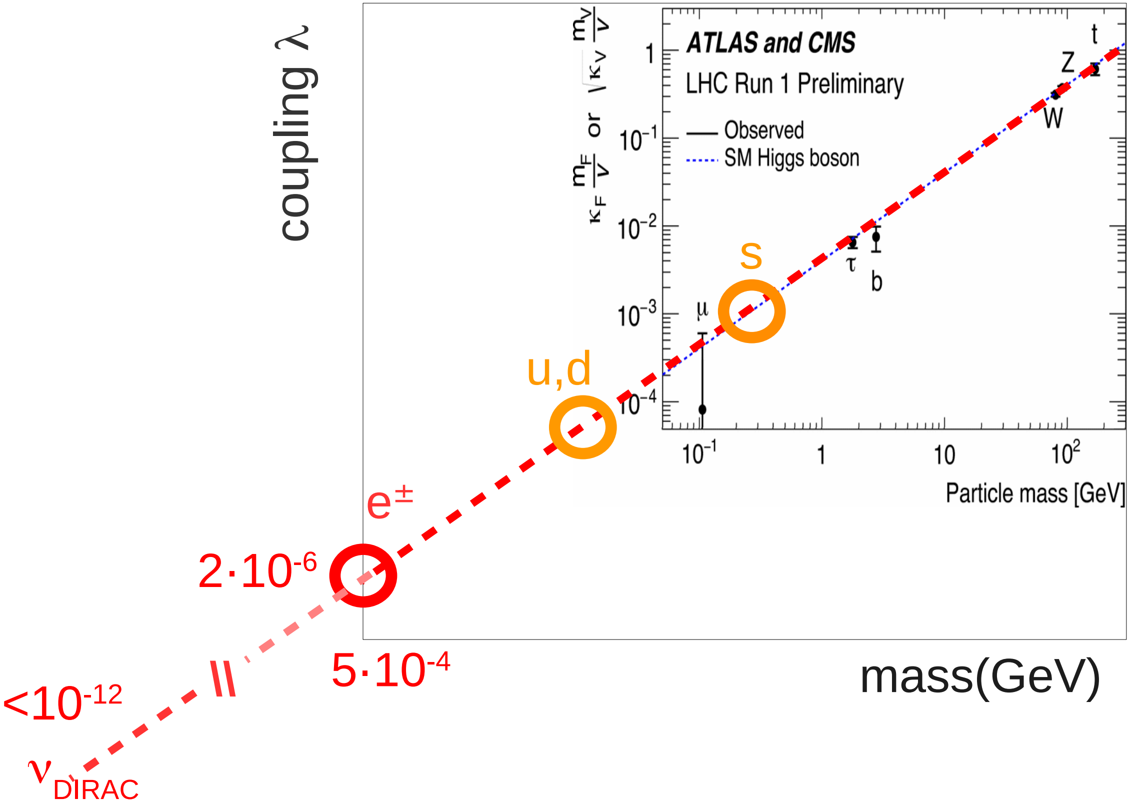
- Compare to Z → qq(g): Multiple handles to study g rad./jet properties:
  - Gluon vs. quark via H → gg vs. Z → qq (Profit from excellent g,b separation)
  - Gluon vs. quark via Z → bbg vs. Z → qq(g) (g in one hemisphere recoiling against 2-b-jets in the other).
  - Vary E_{jet} range via ISR: $e^+e^- \to Z^*,\gamma^* \to jj(\gamma)$
  - Vary jet radius: small-R down to calo resol

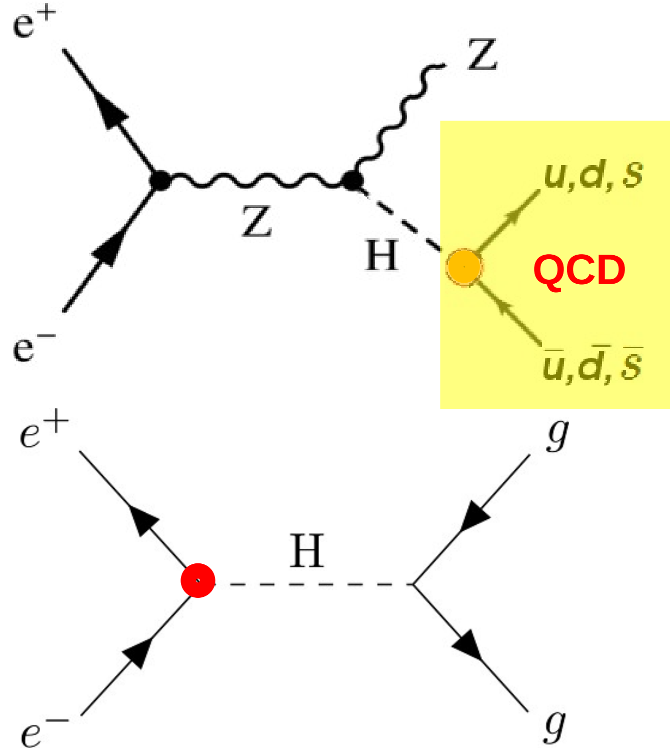


- Multiple high-precision analyses at hand
  – Jet tagging: ML training on <u>pure</u> samples: Improve q/g/Q discrimination
  – pQCD: Improve/retune NNLL parton showers, Lund Plane, jet substructure...
  – non-pQCD: Improved gluon hadronization: Leading η's ? Baryon junctions ? Octet neutralization? Colour reconnection? Glueballs ?

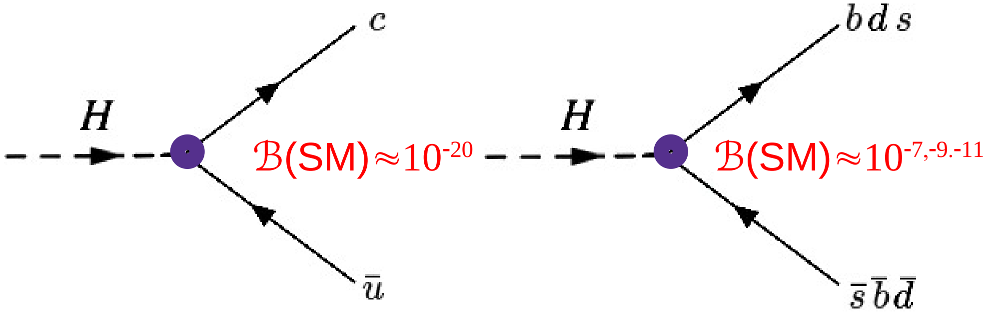
Higgs boson at the FCC-ee (II)

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





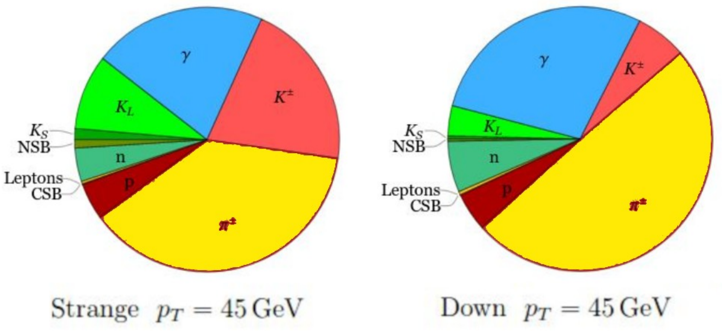
- Does the Higgs boson mediate FCNCs at tree level? $H\to qq'$



Strange-quark jet tagging at FCC-ee

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

[2003.09517] Momentum weighted fraction:



Strange $p_T = 45\,\text{GeV}$ Down $p_T = 45\,\text{GeV}$

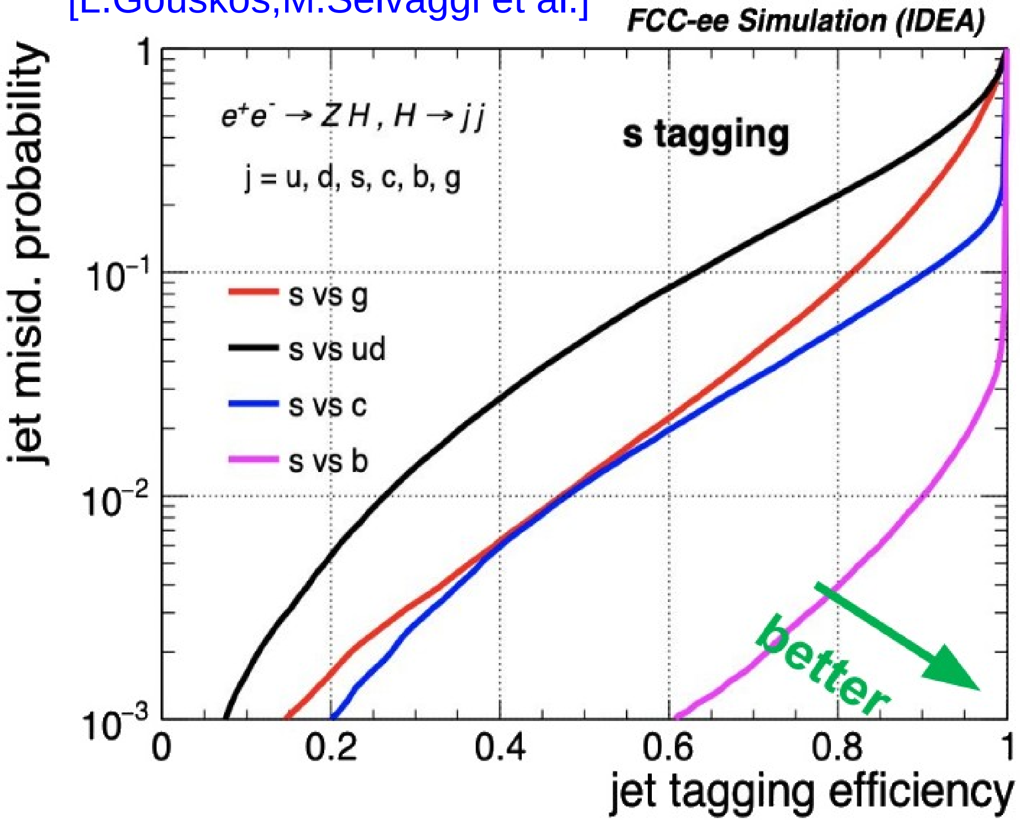
Tagger exploits directly full list of jet constituents (ReconstructedParticles):

[O(50) properties/particle]

× [~50-100 particles/jet]

~ O(1000) inputs/jet

[L.Gouskos,M.Selvaggi et al.]



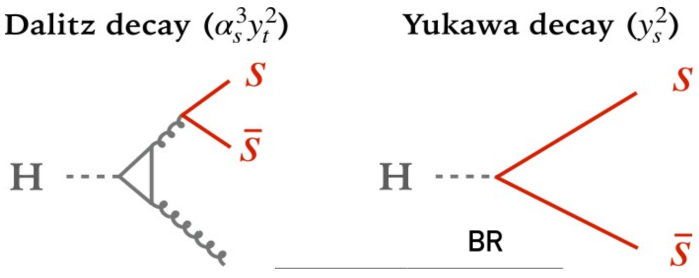
- Analysis e^+e^- → HZ, H → qq with N=2j exclusive jet algorithm:

  Backgds: WW/ZZ/Z, qqH, HWW, HZZ [Details in L.Gouskos talk]

  Combined jj (Hbb, Hcc, Hss, Hbb) fit yields: H → ss with O(80%) uncertainty

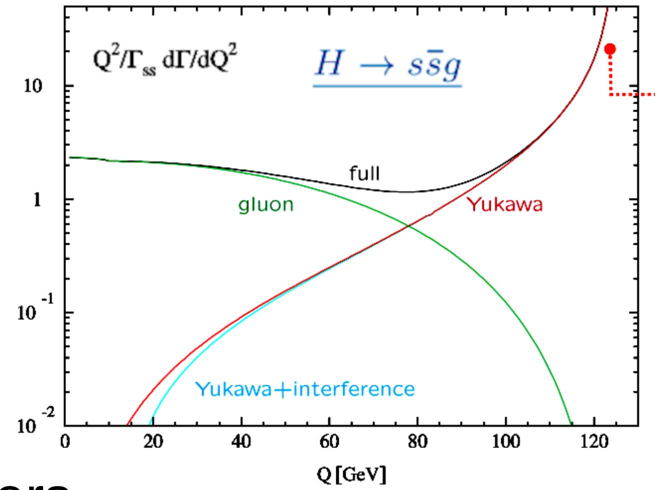
Separating H→ ss and H→ gg

- Does the H→ gg(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

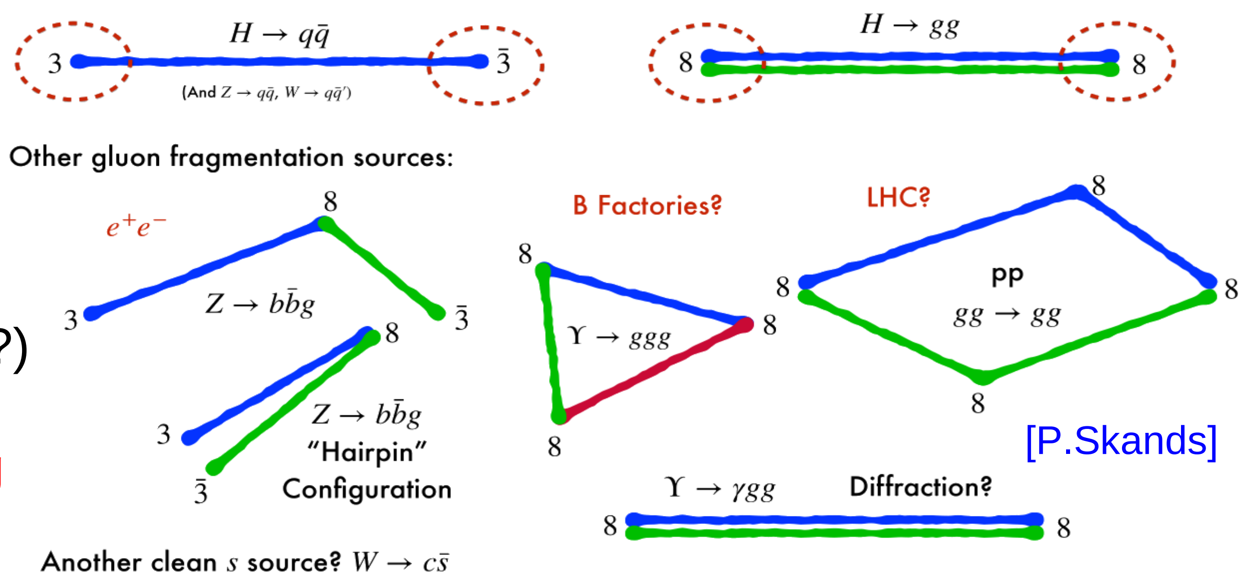


For m_{jj}>100 GeV: Dalitz ssg decays are no bottleneck to the y_s extraction (high mass resum. needed)

[M.Spira; G. Salam]

- Need also NNLL parton showers (matched to NNLO) and accurate/precise s, g (string, cluster) hadronization:

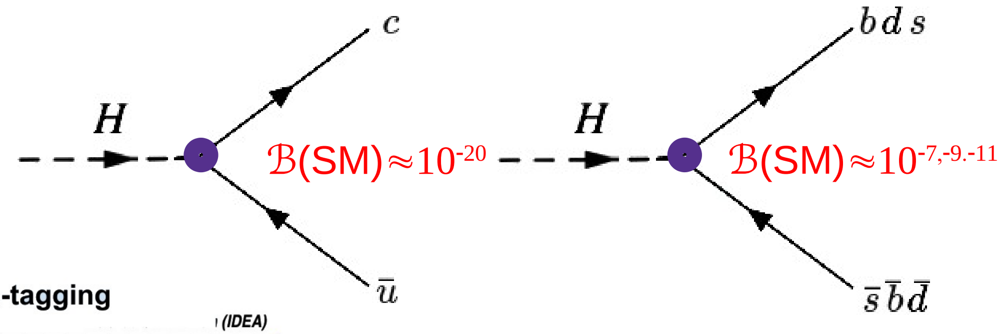
High-precision hadron data (FCC-ee, B-factories?) needed to reliably distinguish leading s, u,d,g fragmentation hadrons



[P.Skands]

Flavor-violating Higgs decays at FCC-ee

- Are there flavour-violating Higgs decays H → qq' ?



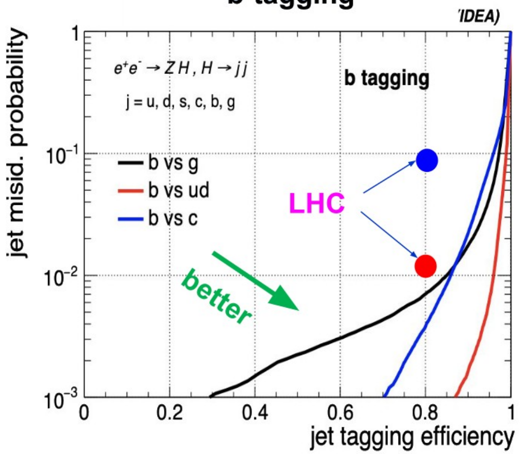
[Kamenik et al. arXiv:2306.17520]

– Projected sensitivities: $y_{bs,bd,cu} \sim 3\cdot10^{-4}$, $y_{sd} \sim 8\cdot10^{-4}$ well beyond current indirect constraints (B_s and D meson oscillations)

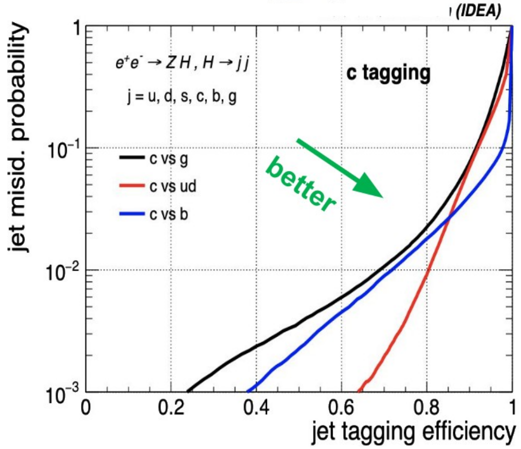
– Expected reach strongly depend on the performance of jet flavor taggers:

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

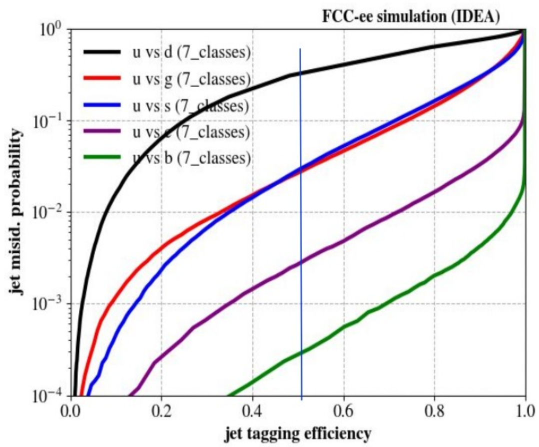
b-tagging



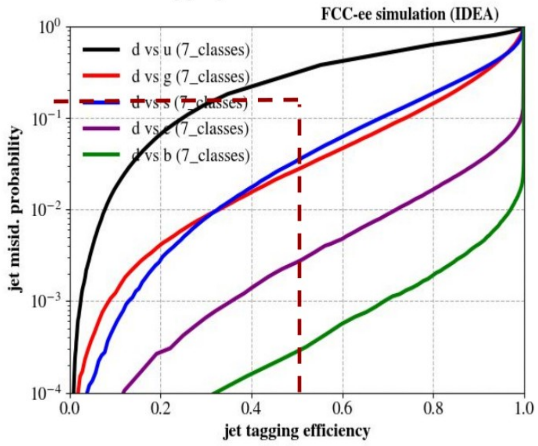
c-tagging



Up -tagging



Down-tagging



Qu/Gouskos: arXiv:1902.08570
Bedeschi/Gouskos/Selvaggi, arXiv:2202.03285

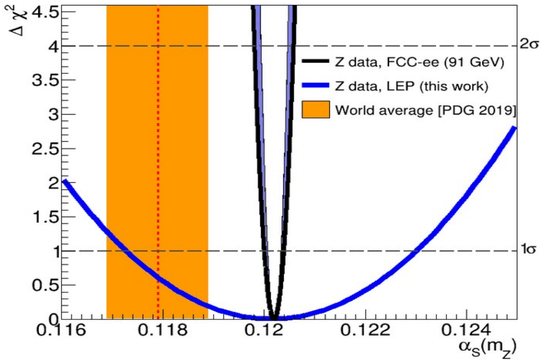
Summary: QCD for Higgs physics at FCC-ee

☛ Precision needed to fully exploit the (B)SM Higgs programme at FCC-ee ($\mathcal{B}$=(H → had)=80%) requires exquisite control of pQCD & non-pQCD physics

☛ 4 key examples presented:

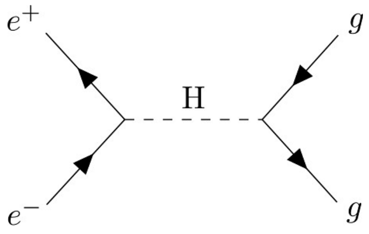
(1) Studying Higgs-gluon coupling within
±0.7% (exp) requires $\alpha_s(m_Z)$ within ±0.1%:

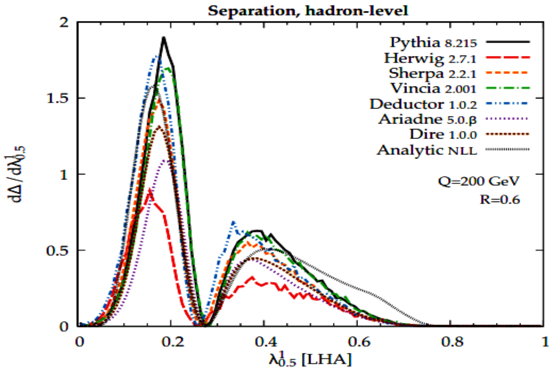
Reachable via hadronic Z,W decays (TeraZ,OkuW)



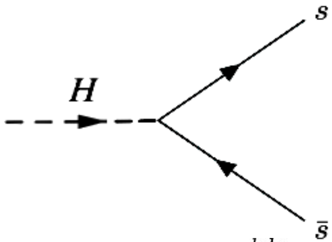
(2) Constraining e-Yukawa via
ee → H → gg requires 1% light-q vs. gluon mistagging:

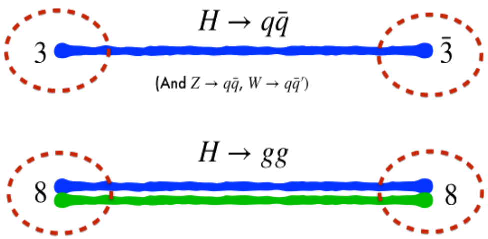
Detailed study of ee → H(gg)Z,
ee → Z → qq(g) required.



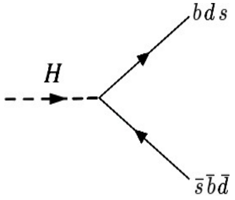


(3) Observing strange-Yukawa requires
requires improved q,g parton shower & hadronization:





(4) Best H → qq' searches available, but
require state-of-the-art Q,q jet taggers

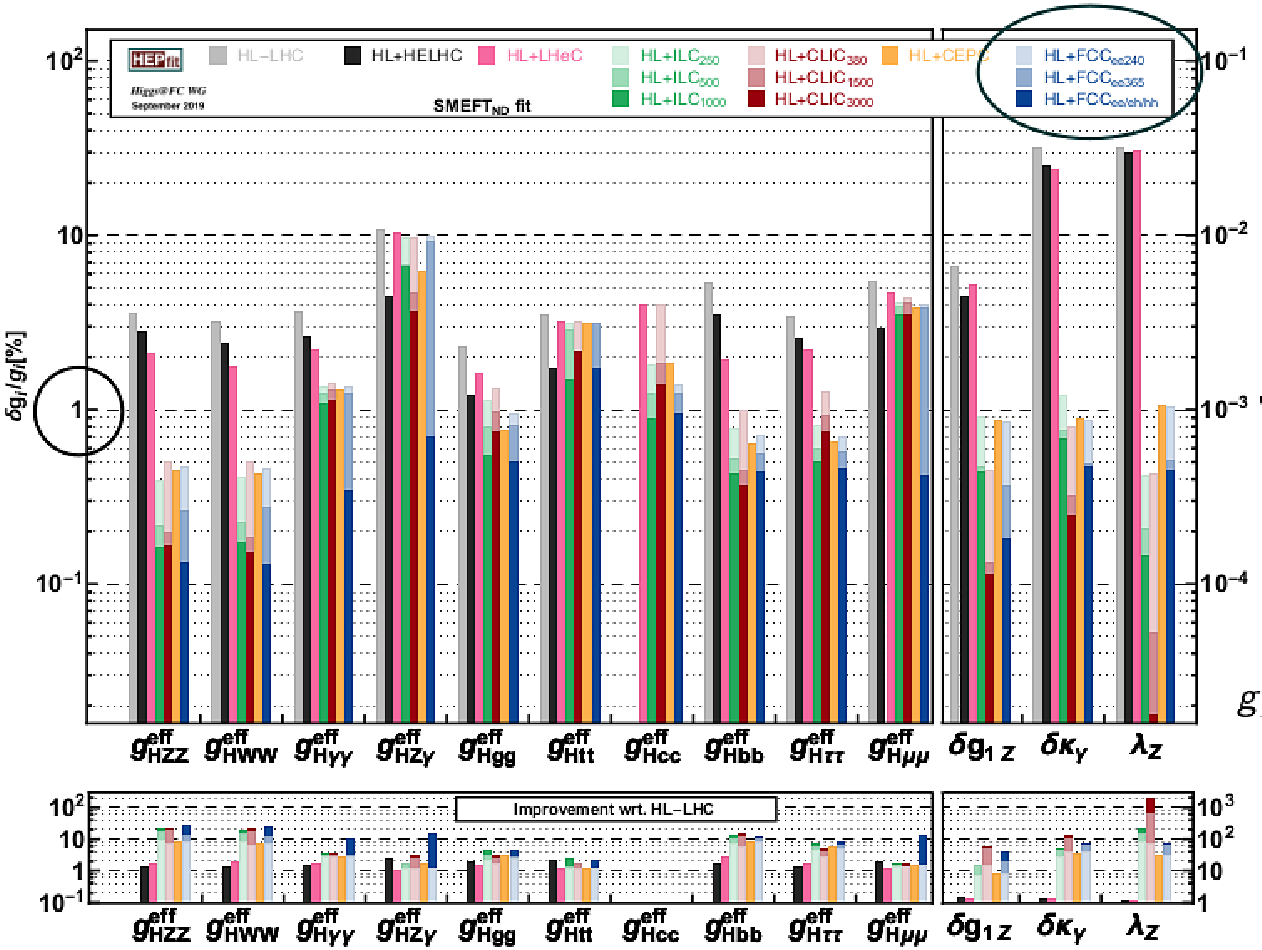


Backup slides

Indirect BSM searches (Higgs coupled) at FCC

- Indirect scalar-coupled new physics EFT limits pushed up to O(6 TeV) thanks to precision H partial widths down to the permil level:

[Higgs@FC '19]

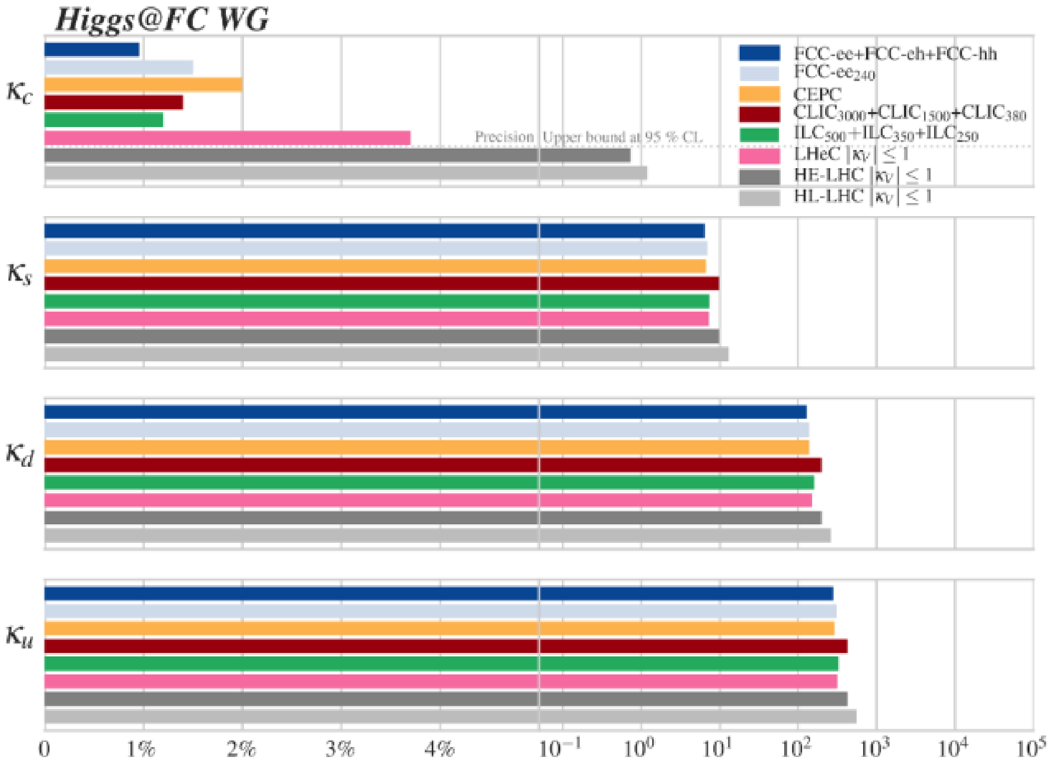


[Ellis,You '15]
[Ellis et al '17]
[de Blas et al '16]
[GD et al '17]
[Barklow et al '17]
[Barklow et al '17]
[Di Vita et al '17]
[Chiu et al '17]
[de Blas et al '19]

$$g^{eff}_{HXX} \equiv \sqrt{\frac{\Gamma_{H\to XX}}{\Gamma^{SM}_{H\to XX}}}$$

Light quarks Yukawas (FCC-pp, FCC-ee)

- Constraints on light Yukawa obtained from the upper limits on BR to all untagged particles, using global fits in κ framework

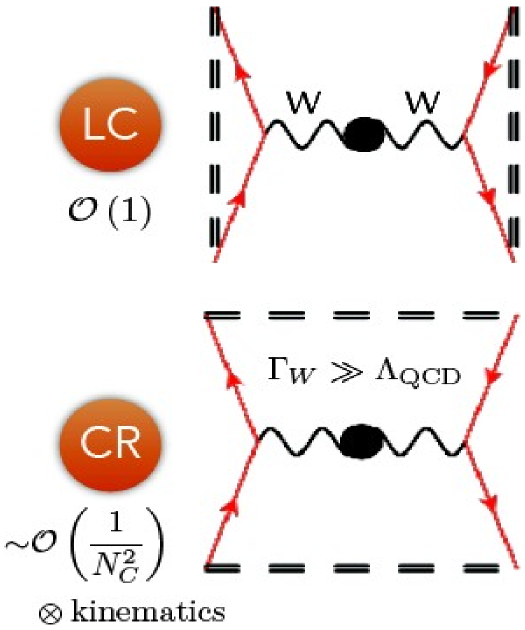


Limits from exclusive
$H \rightarrow VM(\rho,\omega\phi)+\gamma$
decays (BR$\sim10^{-6}$)
to be studied/added

- FCC-ee+eh+hh:
  - first generation: 95% CL limits $\kappa_u < 280$, $\kappa_d < 130$
  - second generation: 95% CL limit $\kappa_s < 6.4$, κ_c measured with precision of <1%

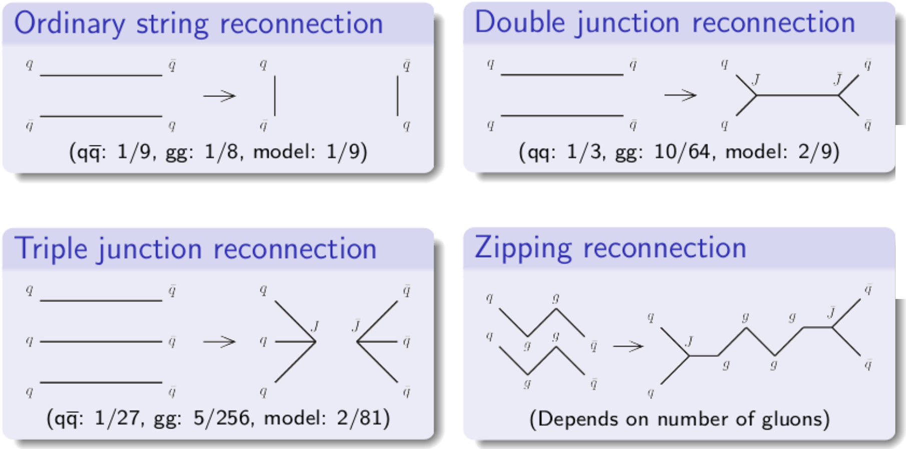
Non-pQCD example: Colour reconnection

- Colour reconnection among partons is source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states. Especially in pp (MPI cross-talk).
- CR "string drag" effect impacts all FCC-ee multi-jet final-states: $e^+e^- \to WW(4j)$, H(2j,4j), ttbar,…
  - – 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 huge W stats (×10^4 LEP) to measure m_W leptonically & hadronically and constrain CR:

"Recent" PYTHIA option: QCD-inspired CR (QCDCR) (1505.01681):



Ordinary string reconnection

($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection

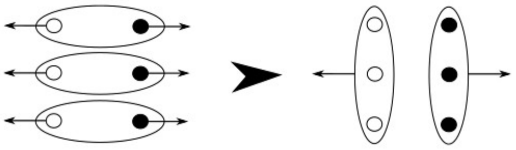
($q\bar{q}$: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection

($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

(Depends on number of gluons)



Triple-junction also in HERWIG cluster model. (1710.10906)