Physics interplay between FCC-ee & FCC-hh (with a focus on QCD & Higgs)

LFC21 Strong Interactions from QCD to New Strong Dynamics at LHC & Future Colliders

ECT* Trento, Sept 2021

FCC

David d'Enterria (CERN)

Open questions in the SM (1)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ [Gauge interactions: $U(1)_Y$, $SU(2)_L$, $SU(3)_c$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$ [Lepton dynamics]

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- ✘ Dark matter: SM describes only 4% of Universe (visible fermions+bosons): Higgs should couple to any massive dark world.

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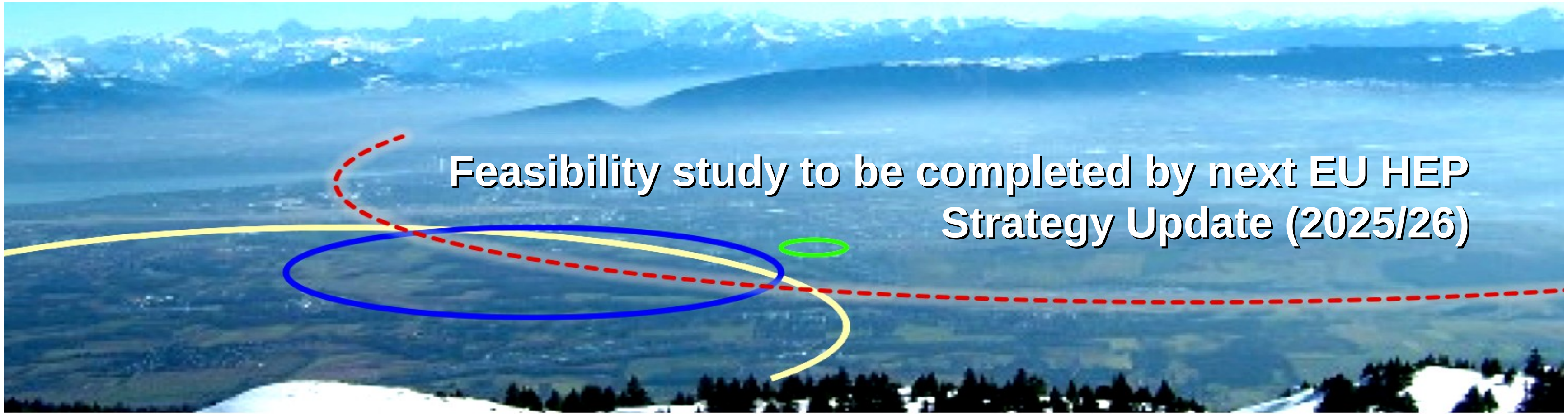
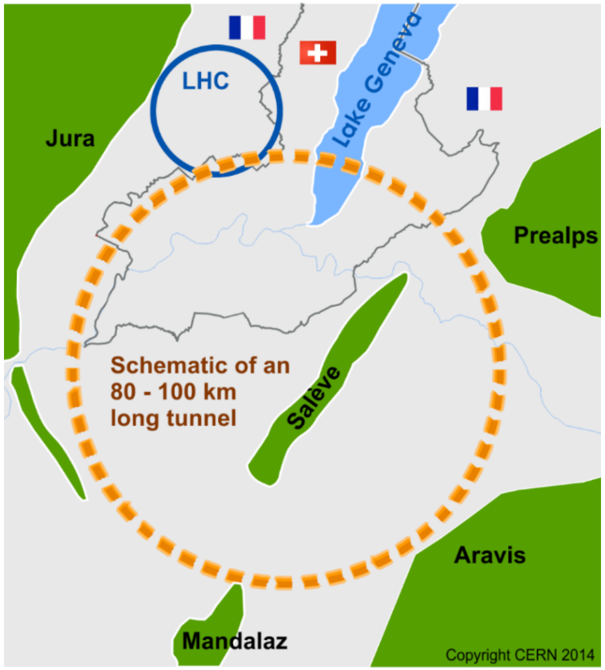
Some/Most(!?) of these questions will NOT be fully answered at the LHC!

CERN Future Circular Collider (FCC) project

- Solving those HEP fundamental problems requires new e^+e^- & pp collider:



- FCC: 100 km ring, Nb_3Sn 16-T magnets, LHC used as injector:
  - pp at $\sqrt{s}$=100 TeV, L~2x10^35, L_{int}=2 ab^{-1}/yr (also pPb, PbPb at $\sqrt{s}$=39–63 TeV)
  - e^+e^- before pp at $\sqrt{s}$=90–350 GeV
    $L_{int} \approx 5\ ab^{-1}$ Higgs factory
    ~1.2 million Higgs in 3+5 years.
    Plus 10^{12} Zs(!), 10^8 Ws(!), $0.5{\cdot}10^6$ tops

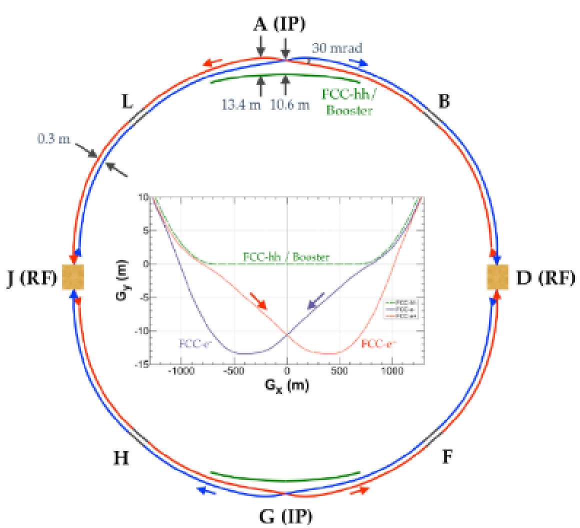


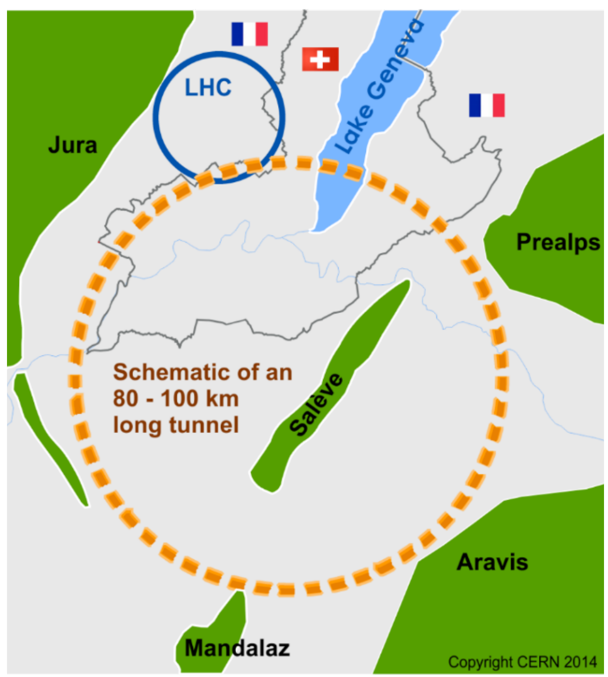
CERN Future Circular Collider

European Strategy for Particle Physics Update (2020) mandate:

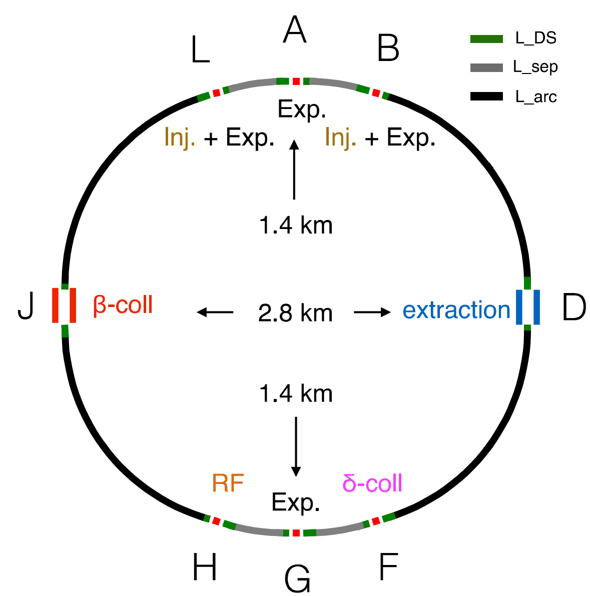
“Europe, together with its international partners, should **investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, and with an electron-positron Higgs and electroweak factory as a possible first stage**. *Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be* **completed on the timescale of the next Strategy update.”**

FCC-ee





FCC-hh



CERN Future Circular Collider

June 2021: FCC Feasibility Study (2021-2025) organization approved unanimously by CERN council.

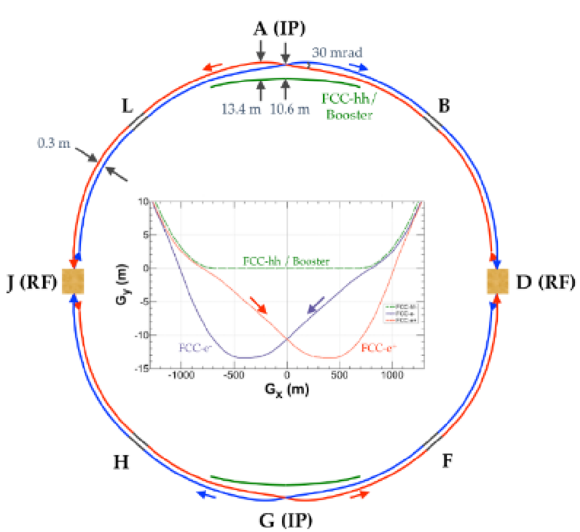
Comprehensive long-term CERN program maximizing physics opportunities:

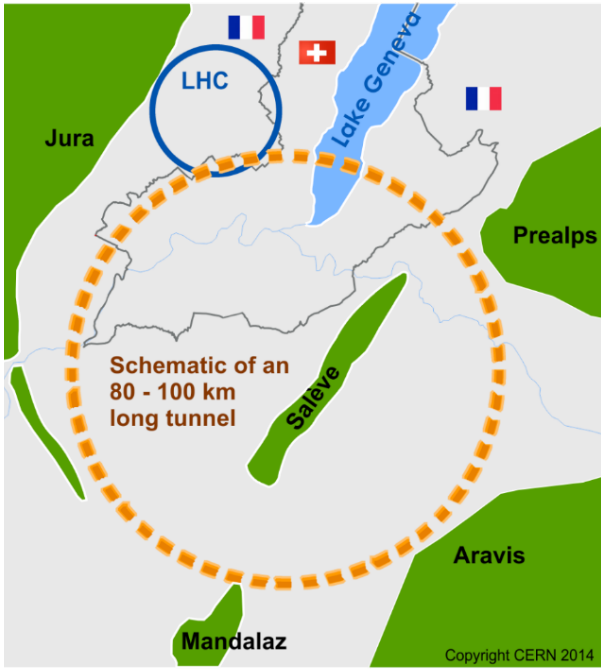
Stage 1 (2040–): FCC-ee (Z, W, H, tt): Higgs, EWK & top factory with highest luminosities.

Stage 2 (2065–): FCC-hh (~100 TeV): Energy frontier machine, with ion & e-h options.

- Complementary physics: Searches via ultraprecise SM tests vs. high mass/p_T searches
- FCC builds upon and exploits CERN's existing lab/infrastructure/know-how.
- Common tunnel, civil engineering and technical infrastructures.
- Integrated project allows seamless HEP continuation after HL-LHC

FCC-ee





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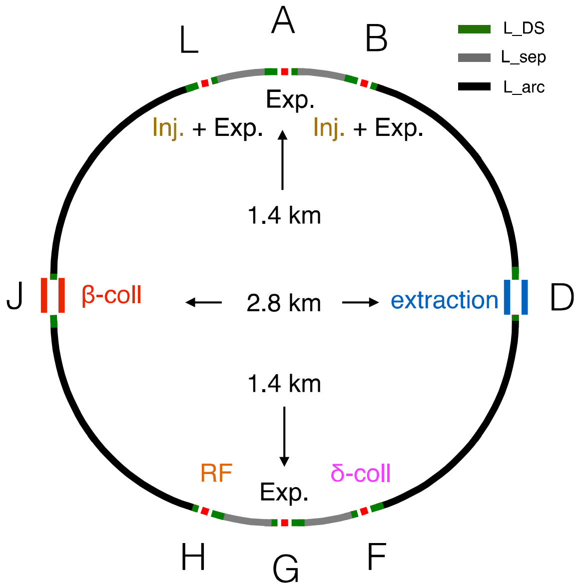
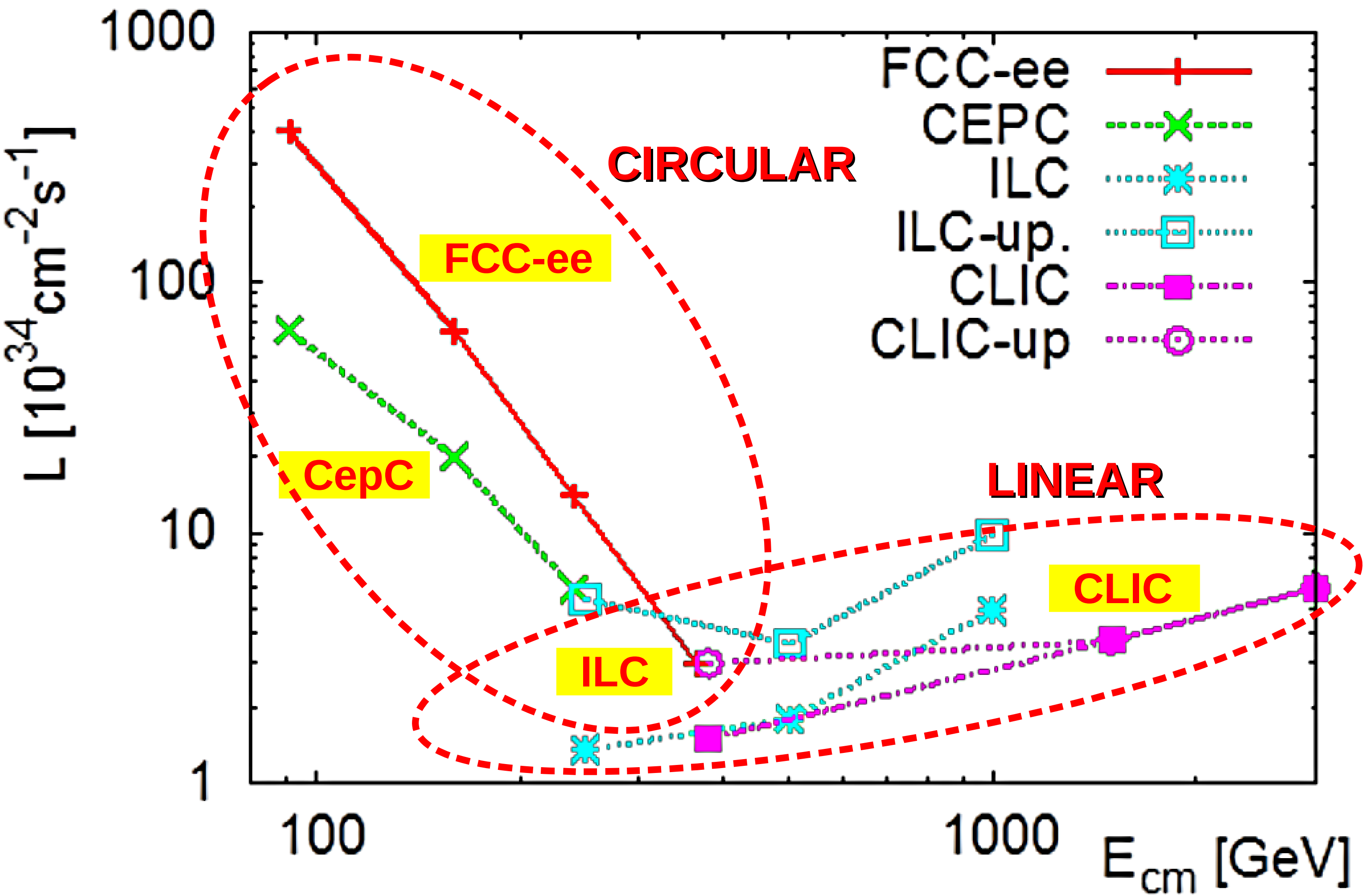


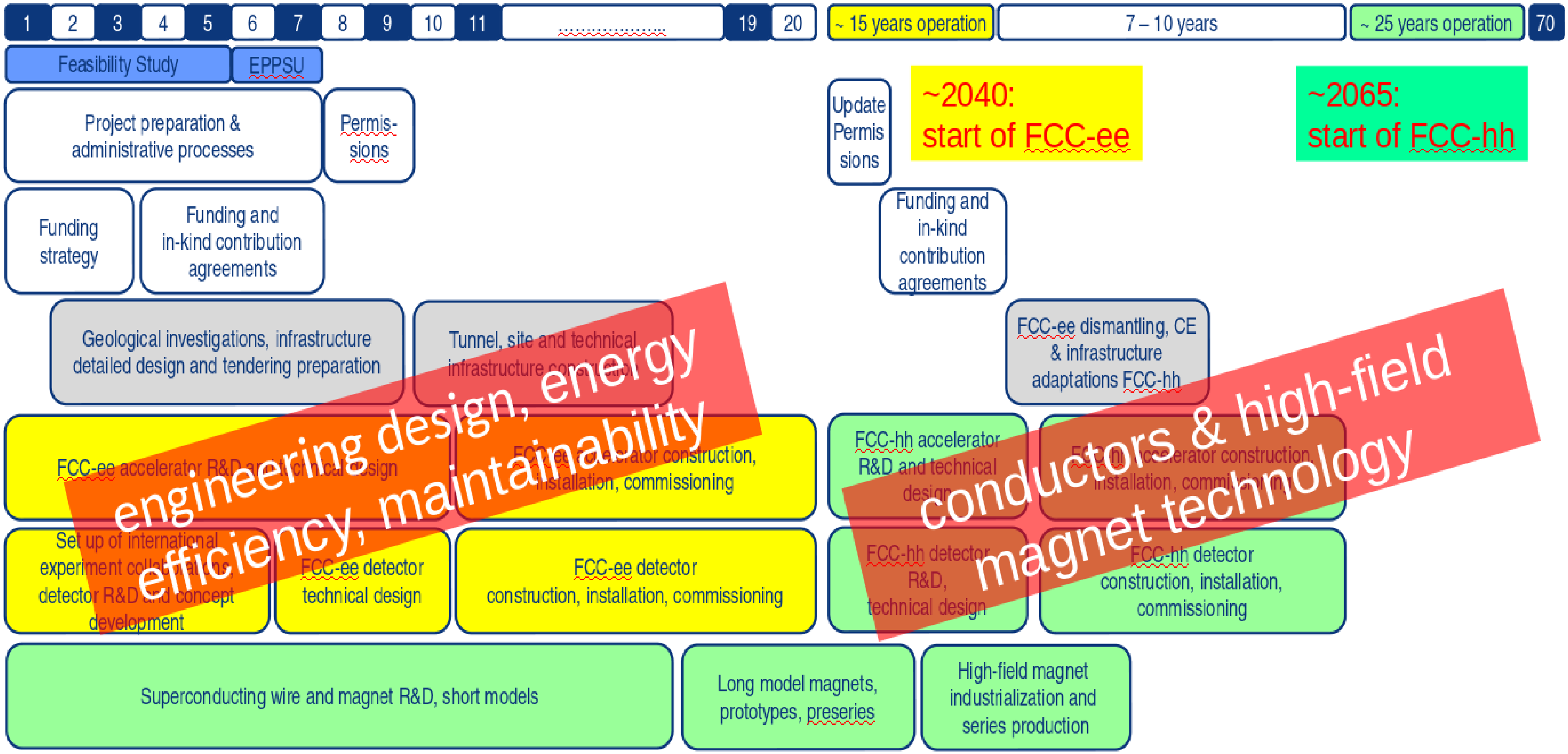
Future e⁺e⁻ colliders luminosities



- FCC-ee features lumis a few times larger than other machines over 90–300 GeV
- FCC-ee: unparalleled Z, W, jets, τ,… data sets: Negligible stat. uncertainties for SM (Higgs, QCD, EWK, flavour,...) and indirect BSM studies

CERN Future Circular Collider schedule

- FCC integrated project technical schedule:



Physics at FCC e^+e^- & pp machines

(1) QCD: α_s coupling

(2) QCD: Parton Distribution Functions

(3) QCD: Jet substructure & flavour tagging

(4) QCD: Non-perturbative regime

(5) Higgs sector

(6) BSM searches

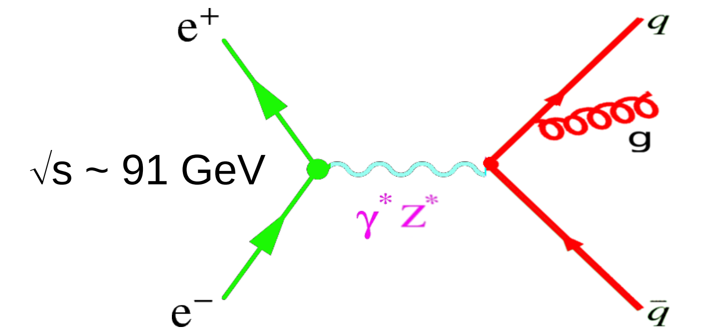
QCD = Key piece at future ee, pp colliders

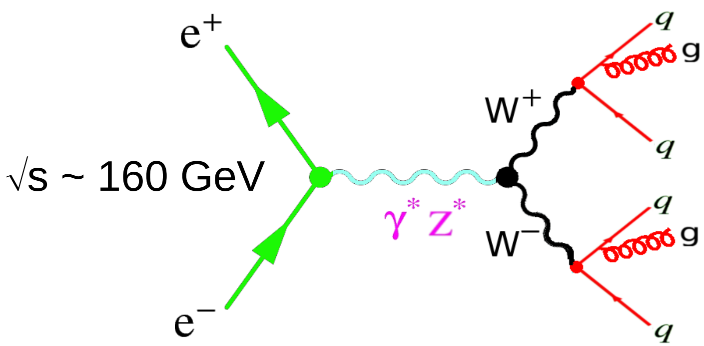
▶ Though QCD is *not per se* the main driving force behind future colliders, QCD is crucial for many pp, ee measurements (signals & backgrounds):

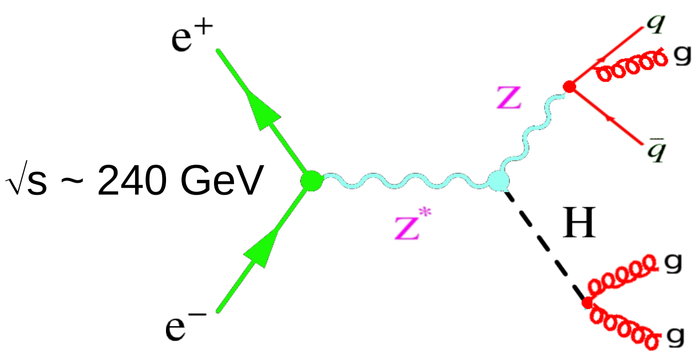
- High-precision α_s: Affects all x-sections & decays (esp. Higgs, top, EWPOs).
- N^nLO corrs., N^nLL resummations: Affects all pQCD x-sections & decays.
- High-precision PDFs: Affects all precision W,Z,H (mid-x) measurements & all searches (high-x) in pp collisions.
- Heavy-Quark/Quark/Gluon separation (jet substructure, boosted topologies..): Needed for all precision SM measurements & BSM searches with final jets.
- Semihard QCD (low-x gluon saturation, multiple hard parton interactions,…): Leading x-sections at FCC-pp (Note: Q_0~10 GeV at 100 TeV).
- Non-perturbative QCD: Affects final-states with jets: Colour reconnection, $e^+e^- \rightarrow$ Z,WW, ttbar $\rightarrow$ 4j,6j... (m_W,m_{top} extractions). Parton hadronization,...

QCD in e⁺e⁻ collisions

- e^+e^- collisions provide an extremely clean environment with fully-controlled initial-state to very precisely probe q,g dynamics:



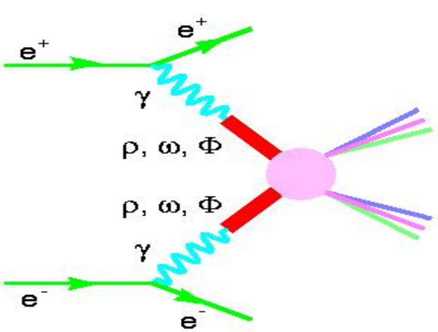




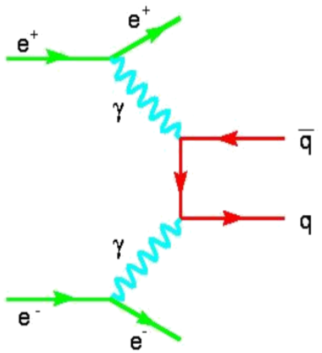
Advantages compared to p-p collisions:

- QED initial-state with known kinematics
- Controlled QCD radiation (only in final-state)
- Well-defined heavy-Q, quark, gluon jets
- Smaller non-pQCD uncertainties:
  no PDFs, no QCD "underlying event",…
  Direct clean parton fragmentation & hadroniz.

- Plus QCD physics in $\gamma\gamma$ (EPA) collisions:



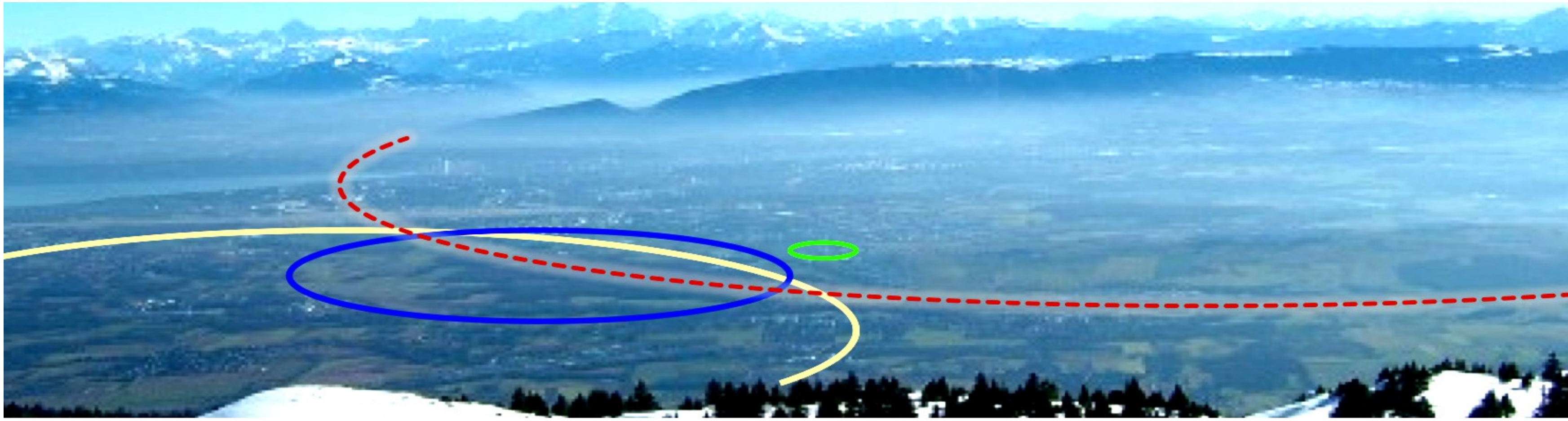
(soft, VDM)



(direct)

Available QCD samples at FCC-ee

- FCC: e^+e^- at $\sqrt{s}$ = 90,(125),160,240,350 GeV provides huge jets data sets



Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365	m_H
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\to$ H	$10^6 t\bar{t}$ +200k HZ +50k WW $\to$ H		(6000)

- Approximate number of QCD jets:

# of light-q jets/year:	$\mathcal{O}(10^{12})$	$\mathcal{O}(10^7)$	$\mathcal{O}(10^5)$	–	$\mathcal{O}(10^8)_{bckgds}$
# of gluon-jets/year:	$\mathcal{O}(10^{11})$	$\mathcal{O}(10^6)$	$\mathcal{O}(10^4)$	$\mathcal{O}(10^3)$	$\mathcal{O}(10^7)_{bckgds}$
# of heavy-Q jets/yr:	$\mathcal{O}(10^{12})$	$\mathcal{O}(10^7)$	$\mathcal{O}(10^5)$	$\mathcal{O}(10^6)$	$\mathcal{O}(10^8)_{bckgds}$

Physics at FCC e^+e^- & pp machines

(1) QCD: α_s coupling

(2) QCD: Parton Distribution Functions

(3) QCD: Jet substructure & flavour tagging

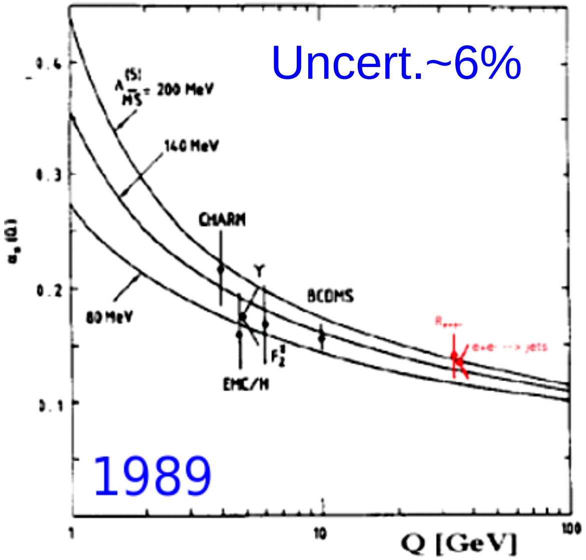
(4) QCD: Non-perturbative regime

(5) Higgs sector

(6) BSM searches

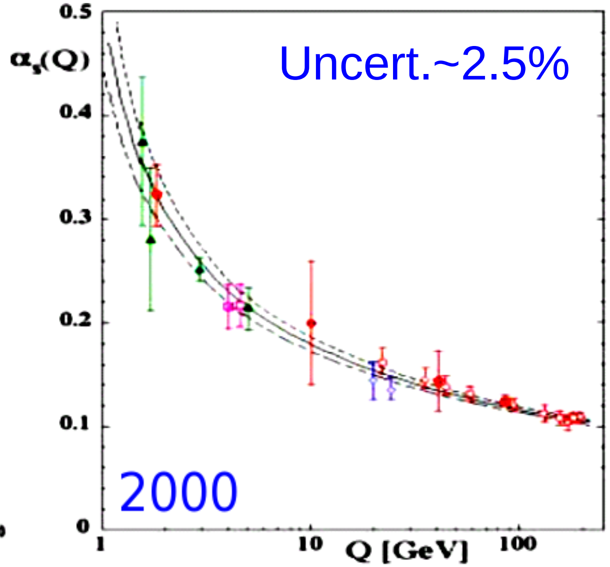
QCD coupling α_s

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



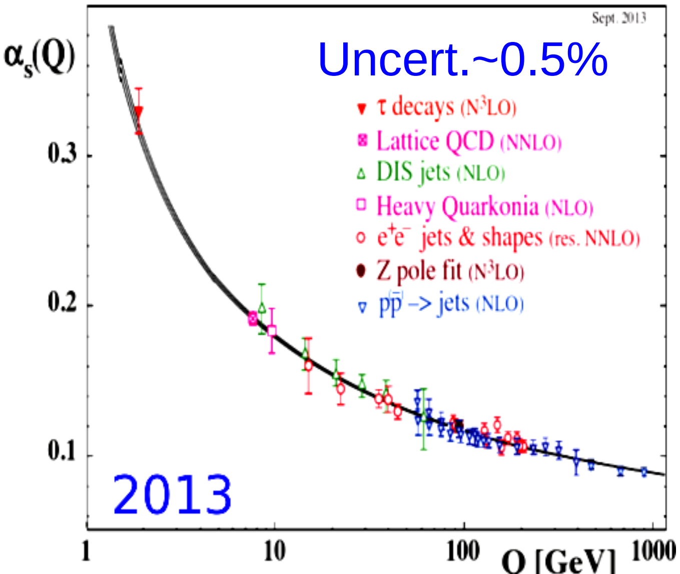
$\alpha_S(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989



$\alpha_S(M_Z) = 0.1184 \pm 0.0031$ (NNLO)

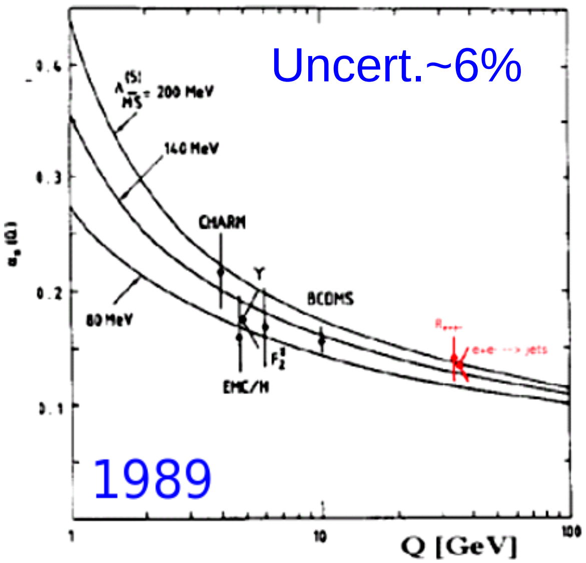
S. B. , J. Phys. G 26, 2000



$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (NNLO)

QCD coupling α_s

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



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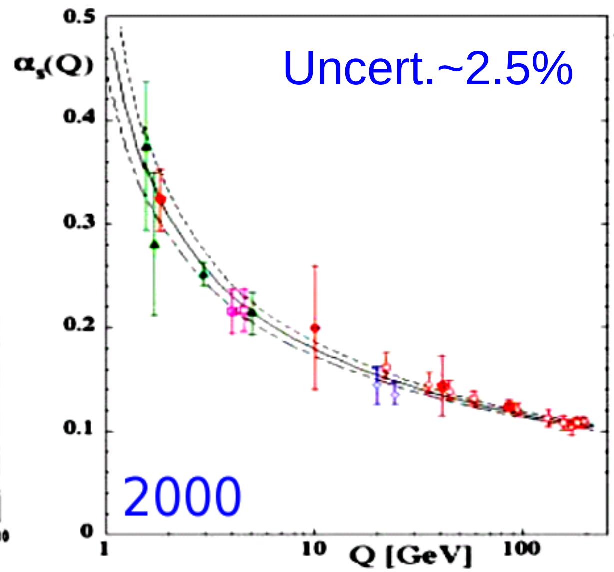

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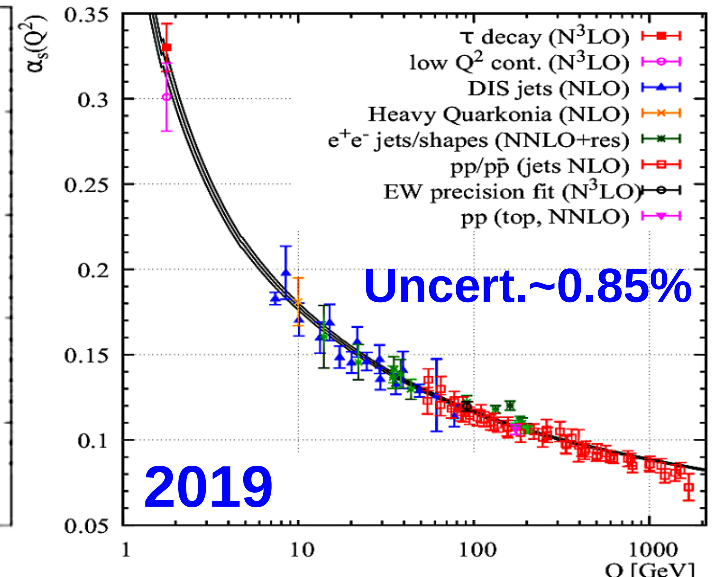


$\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$

- Least precisely known of all interaction couplings !

$$\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_s \sim 10^{-3}$$

Importance of the QCD coupling α_s

➧ Impacts all QCD x-sections & decays (H), precision top & parametric EWPO:

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

Channel	M_H[GeV]	$\delta\alpha_s(\%)$	Δm_b	Δm_c
$H \to c\bar{c}$	126	$\pm$ 7.1	$\pm$ 0.1%	$\pm$ 2.3 %
$H \to gg$	126	$\pm$ 4.1	$\pm$ 0.1%	$\pm$ 0 %

Msbar mass error budget (from threshold scan)

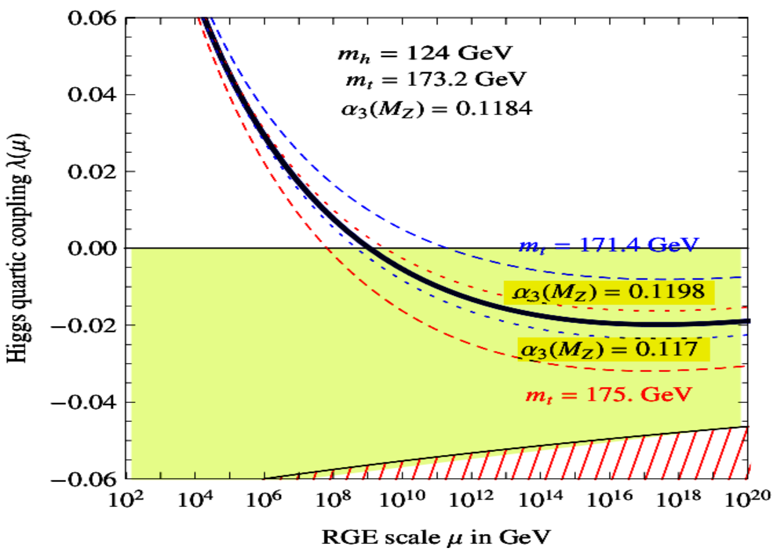
$(\delta M_t^{SD-low})^{exp}$	$(\delta M_t^{SD-low})^{theo}$	$(\delta\overline{m}_t(\overline{m}_t))^{conversion}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

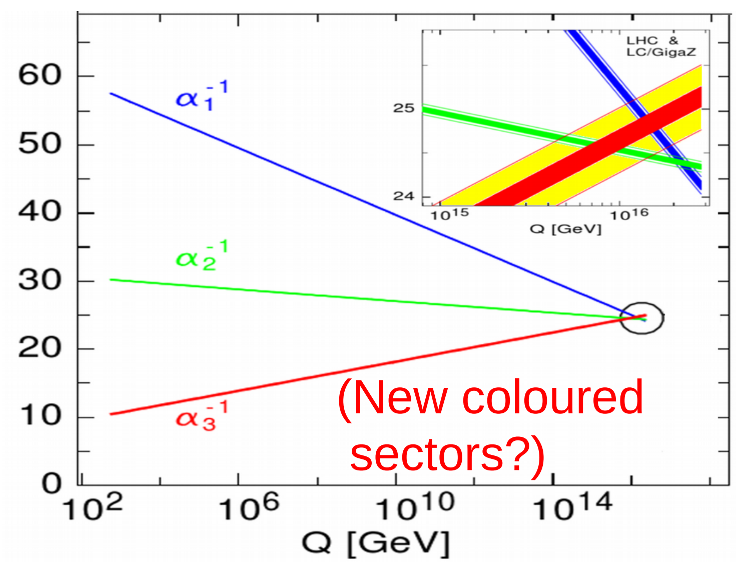
$\Rightarrow$ improvement in α_s crucial $\delta\alpha_s(M_Z) = 0.001$

Quantity	FCC-ee	future param.unc.	Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b [10^{-5}]	6	< 1	$\delta\alpha_s$
R_ℓ [10^{-3}]	1	1.3	$\delta\alpha_s$

Sven Heinemeyer – 1st FCC physics workshop, CERN, 17.01.2017

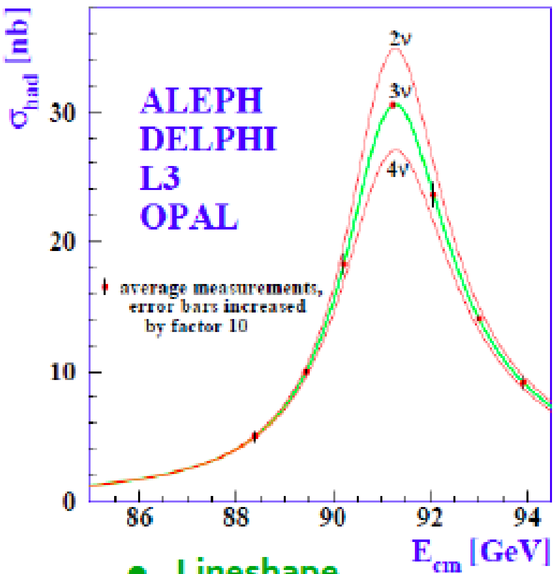
➧ Impacts physics approaching Planck scale: EW vacuum stability, GUT

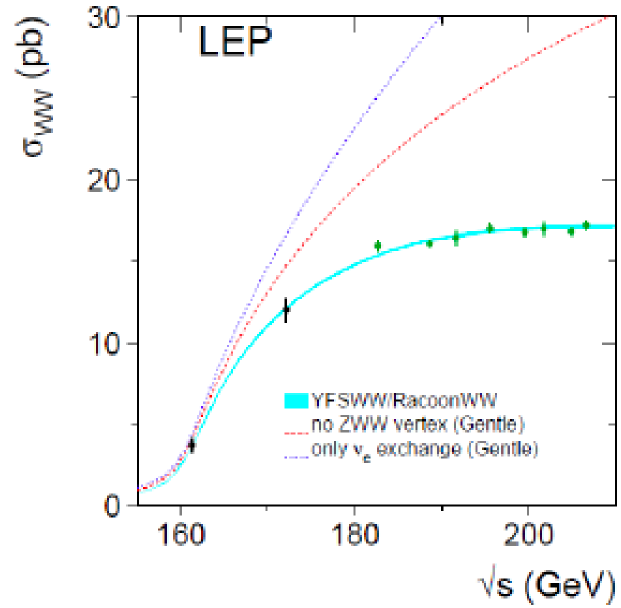


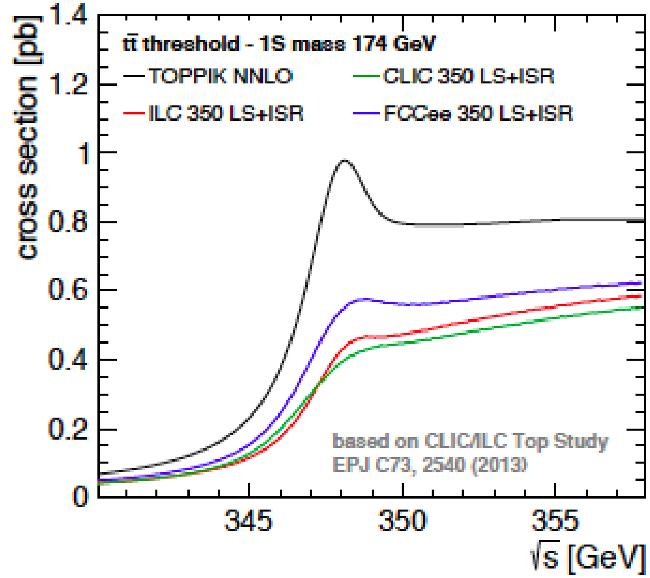


Ultra-precise W, Z, top physics at FCC-ee

$\sqrt{s}$=91 GeV, 10^{12} Z's | **$\sqrt{s}$=161 GeV, 10^{8} W's** | **$\sqrt{s}$=350 GeV, 10^{6} tops**







- Lineshape
  - Exquisite E_{beam} (unique!)
  - m_Z, Γ_Z to 10 keV (stat.) 100 keV (syst.)
- Asymmetries
  - $\sin^2\theta_W$ to 5×10^{-6}
- Branching ratios, R_l, R_b
  - $\alpha_s(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

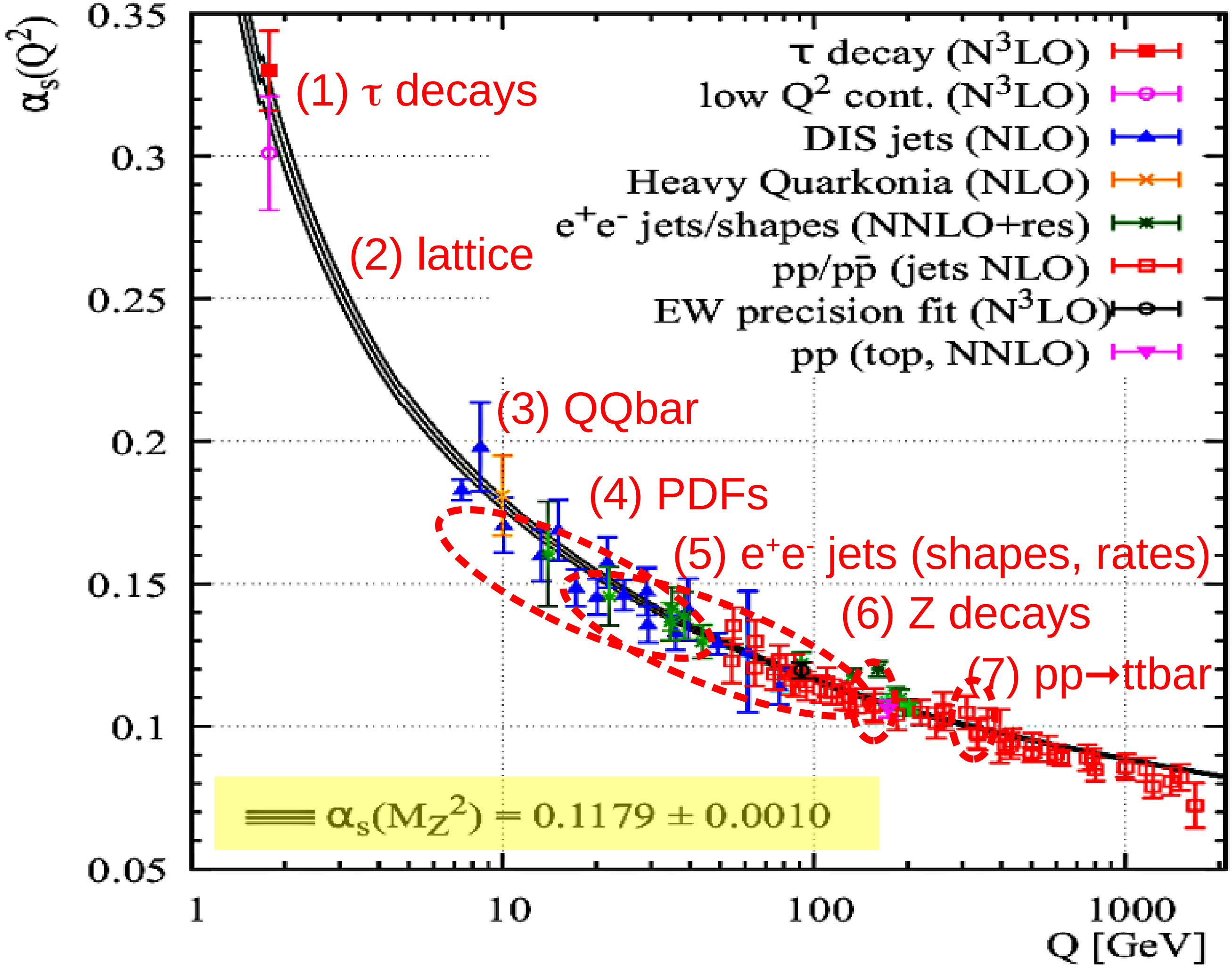
- Threshold scan
  - m_W to 500 keV
- Branching ratios R_l, R_{had}
  - $\alpha_s(m_W)$ to 0.0002
- Radiative returns $e^+e^-\to\gamma Z$ ($Z\to\nu\nu$, $\mu^+\mu^-$)
  - N_ν to 0.001

- Threshold scan + 4D fit
  - m_{top} to 10 MeV (stat.) 40 MeV (th.)
  - λ_{top} to 13%
  - EWK couplings to 1–10%

- Unparalleled Z, W, jets, τ,… data sets: Negligible α_s stat. uncertainties
- Unparalleled syst. uncert.: δE_{cm}(Z,W) ~ 0.1, 0.3 MeV → Very precise $\Gamma_{W,Z}$

World α_s determination (PDG 2019)

- Determined today by comparing 7 experimental observables to pQCD NNLO,N^{3}LO predictions, plus global average at the Z pole scale:



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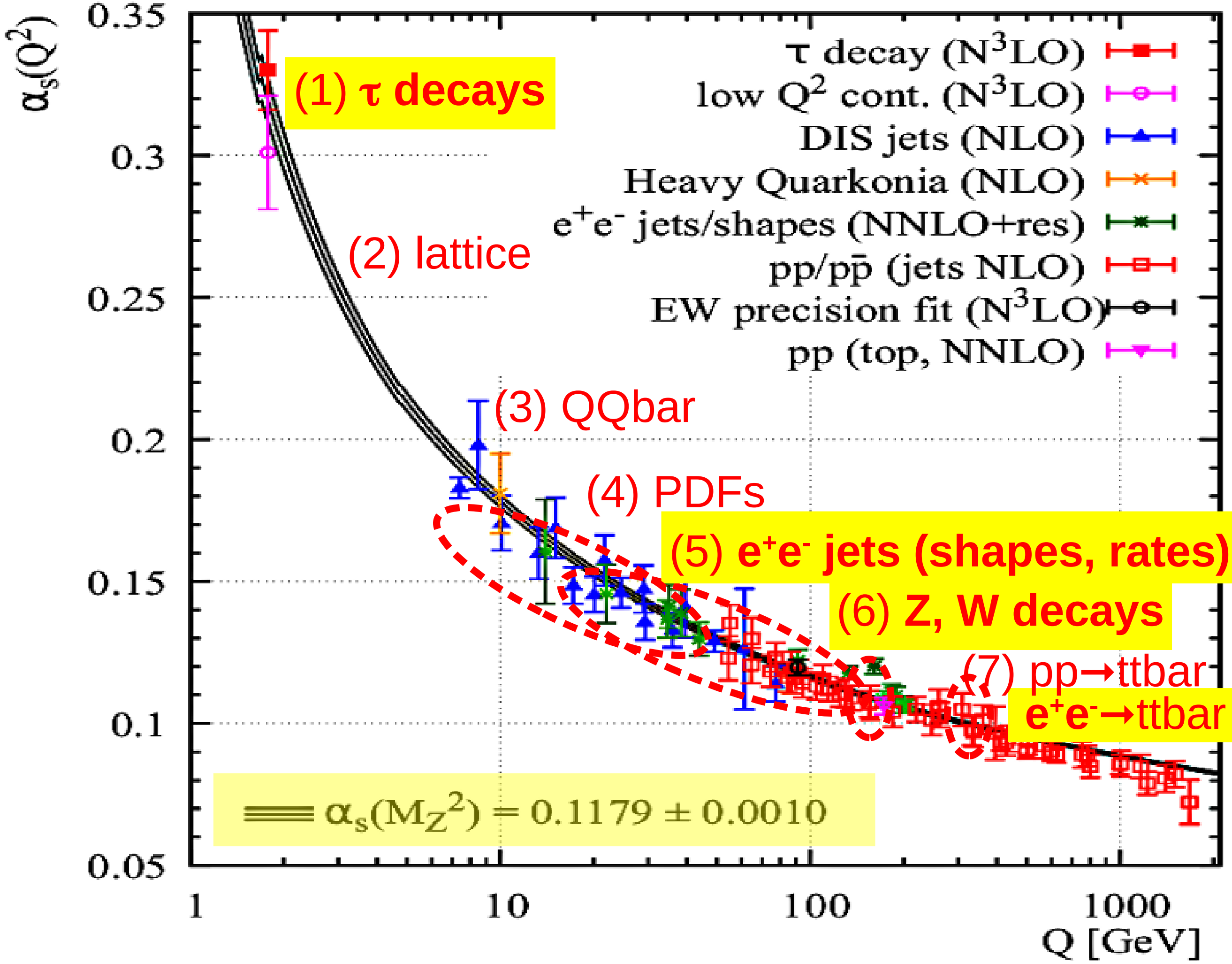
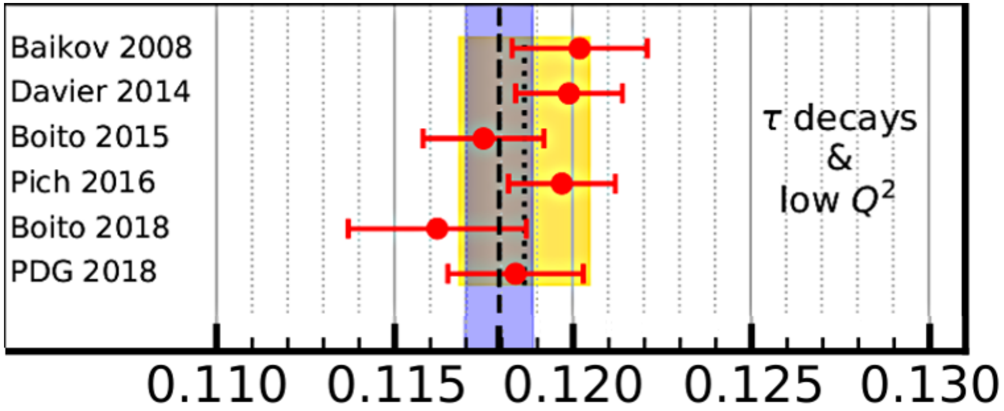


e⁺e⁻ collisions

α_s from hadronic τ-lepton decays

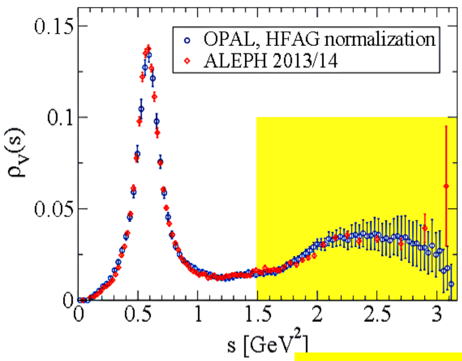
- Computed at N³LO: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\rm EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\rm np})$
- Experimentally: $R_{\tau,exp}$ = 3.4697 ± 0.0080 (±0.23%)
- Various pQCD approaches (FOPT vs CIPT) & treatment of non-pQCD corrections $(\Lambda/m_\tau)^2$ ~2%, yield different results.

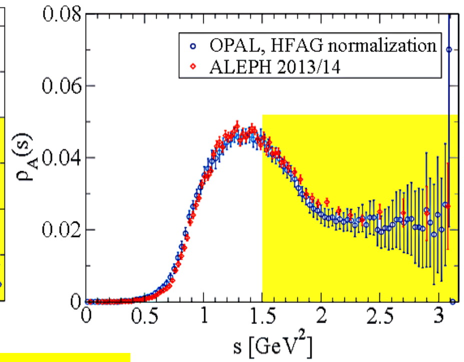


Uncertainty slightly increased: 2013 (±1.3%) → 2019 (±1.5%)

$$\alpha_s(M_Z^2) = 0.1187 \pm 0.0018 \quad (\pm 1.5\%)$$

- Future :
  – Understand FOPT vs CIPT diffs.
  – Better spectral functions needed (high stats & better precision): B-factories (BELLE-II)?
  – High-stats: $\mathcal{O}(10^{11})$ from Z→ττ at FCC-ee(90) : $\delta\alpha_s$ << 1%



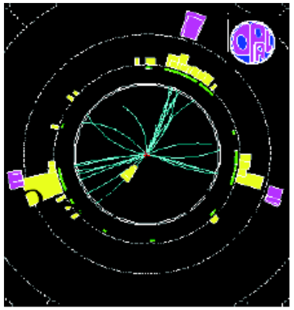


α_s from e⁺e⁻ event shapes & jet rates (today)

- Computed at N^{2,3}LO+N$^{(2)}$LL accuracy.
- Experimentally (LEP):
  Thrust, C-parameter, jet shapes
  n-jet x-sections

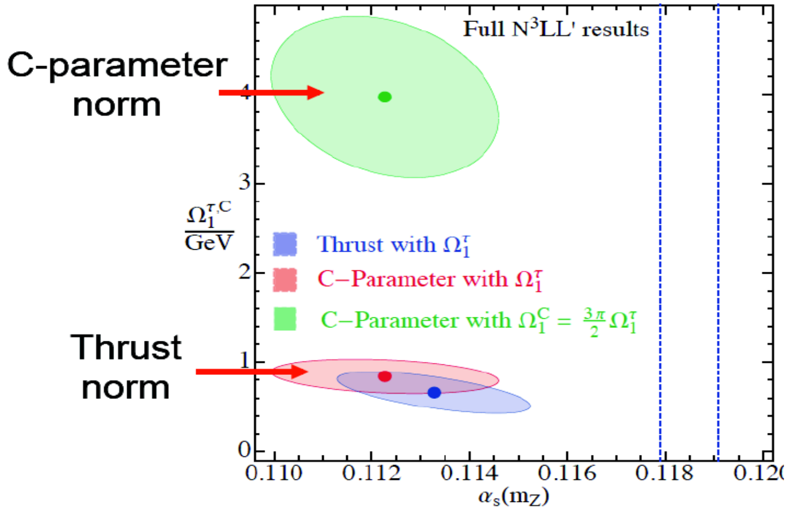
$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

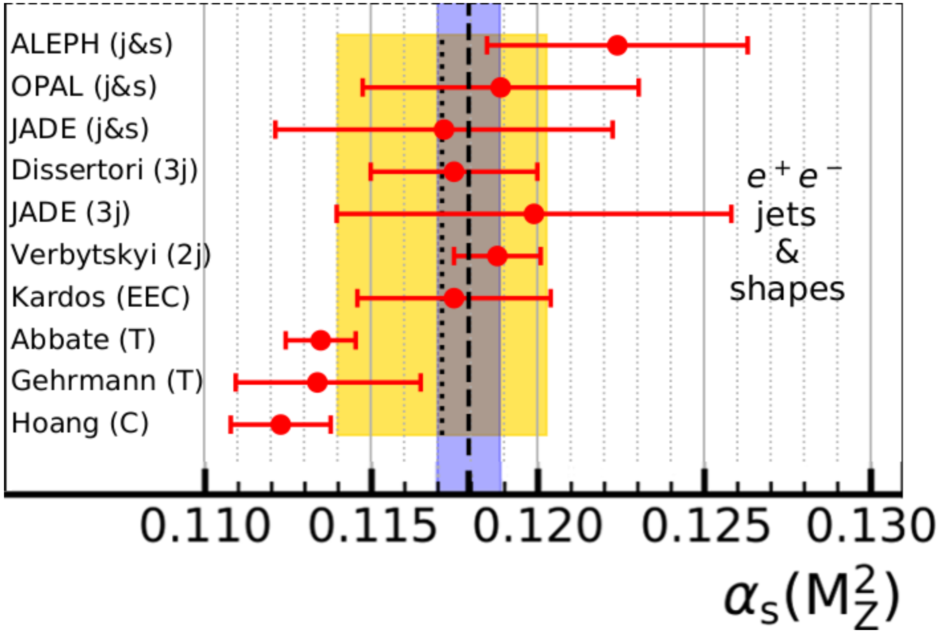
$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$



OPAL 3 jet event

- Results sensitive to non-pQCD (hadronization) accounted for via MCs or analytically:





- Wide span of TH extractions...

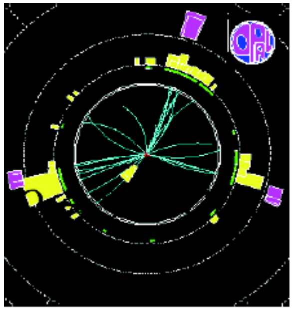
$\alpha_s(M_Z^2) = 0.1171 \pm 0.0031$ **(±2.6%)**

α_s from e^+e^- event shapes & jet rates (FCC-ee)

- Computed at $N^{2,3}LO+N^{(2)}LL$ accuracy.
- Experimentally (LEP):
  Thrust, C-parameter, jet shapes
  3-jet x-sections

$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2 \theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$



OPAL 3 jet event

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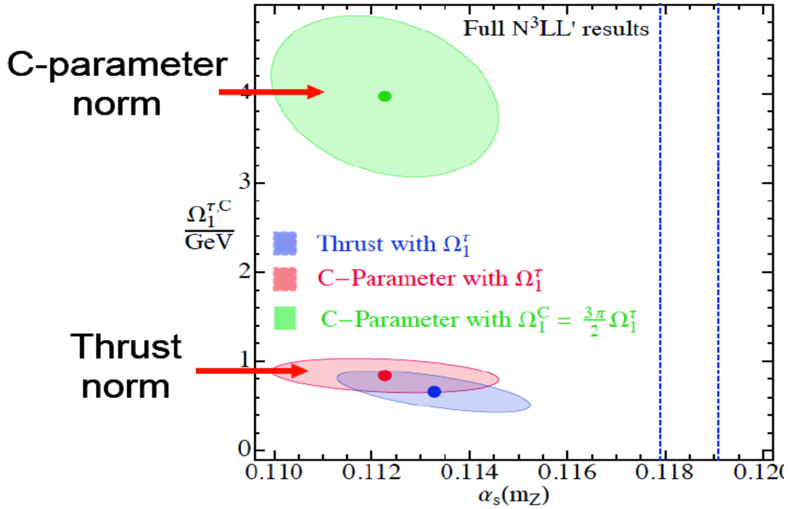
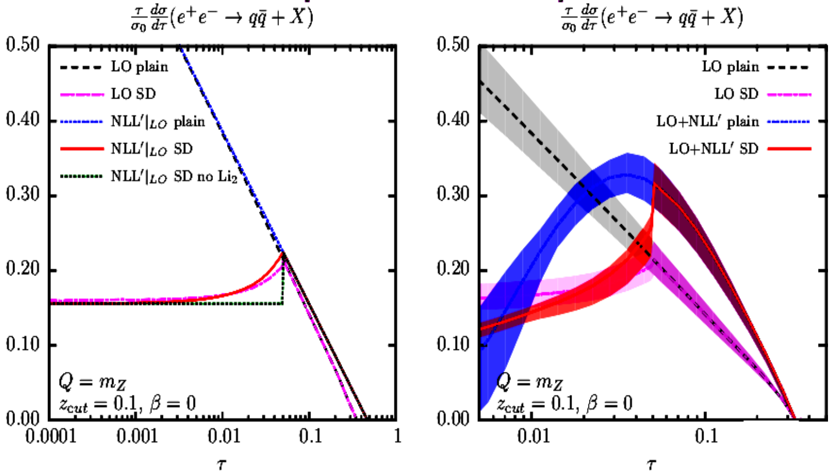


- Modern jet substructure techniques: "Soft drop" can help reduce non-pQCD corrections for thrust:

[Baron, Marzani, VT; '18]



- Future: **$\delta\alpha_s/\alpha_s < 1\%$**

– FCC-ee: Lower-√s (ISR) for shapes, higher-√s for jet rates
– TH: Improved ($N^{2,3}LL$) resummation for rates, hadronization for shapes

Hadronic Z, W decay pseudo-observables

DdE, Jacobsen: arXiv:2005.04545

- Z & W observables theoretically known at N^{3}LO accuracy:

• 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 :

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

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

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

TH uncertainties:
(α^2,α^3 included for Z):
±0.015–0.03% (Z)
±0.015–0.04% (W)

Param. uncerts.:
($m_{Z,W}$, α, $V_{cs,ud}$):
±0.01–0.03% (Z)
±1.1–1.7% (W)
±0.03% (W, CKM unit)

- Measured at LEP with ±0.1–0.3% (Z), ±0.9–2% (W) exp. uncertainties:

	theory			experiment		
	previous	new (this work)	change	previous [6]	new [20, 21]	change
$\Gamma^{\rm tot}_{\rm Z}$ (MeV)	$2494.2 \pm 0.8_{\rm th}$	$2495.2 \pm 0.6_{\rm par} \pm 0.4_{\rm th}$	+0.04%	2495.2 ± 2.3	2495.5 ± 2.3	+0.012%
$R_{\rm Z}$	$20.733 \pm 0.007_{\rm th}$	$20.750 \pm 0.006_{\rm par} \pm 0.006_{\rm th}$	+0.08%	20.767 ± 0.025	20.7666 ± 0.0247	−0.040%
$\sigma^{\rm had}_{\rm Z}$ (pb)	$41\,490 \pm 6_{\rm th}$	$41\,494 \pm 5_{\rm par} \pm 6_{\rm th}$	+0.01%	$41\,540 \pm 37$	$41\,480.2 \pm 32.5$	−0.144%

Recent update of LEP luminosity bias(*) change the Z values by few permil

W boson observables	GFITTER 2.2 (NNLO)	this work (N^{3}LO) (exp. CKM)	this work (N^{3}LO) (CKM unit.)	experiment
$\Gamma^{\rm had}_{\rm W}$ (MeV)	–	$1440.3 \pm 23.9_{\rm par} \pm 0.2_{\rm th}$	$1410.2 \pm 0.8_{\rm par} \pm 0.2_{\rm th}$	1405 ± 29
$\Gamma^{\rm tot}_{\rm W}$ (MeV)	$2091.8 \pm 1.0_{\rm par}$	$2117.9 \pm 23.9_{\rm par} \pm 0.7_{\rm th}$	$2087.9 \pm 1.0_{\rm par} \pm 0.7_{\rm th}$	2085 ± 42
$R_{\rm W}$	–	$2.1256 \pm 0.0353_{\rm par} \pm 0.0008_{\rm th}$	$2.0812 \pm 0.0007_{\rm par} \pm 0.0008_{\rm th}$	2.069 ± 0.019

(*) Voutsinas et al. arXiv:1908.01704, Janot et al. arXiv:1912.02067

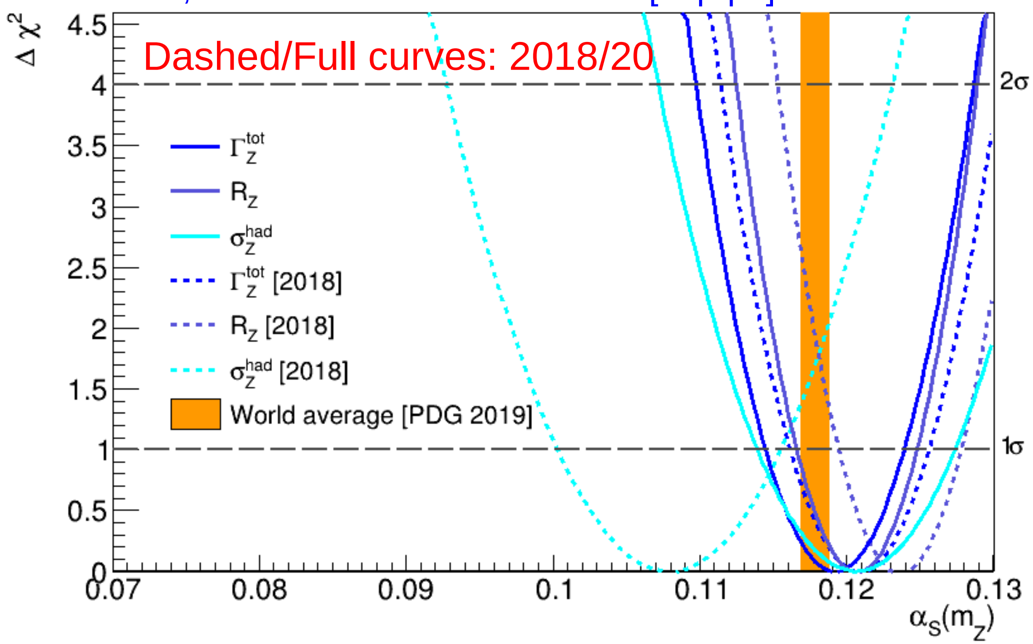
α_s from hadronic Z decays (today)

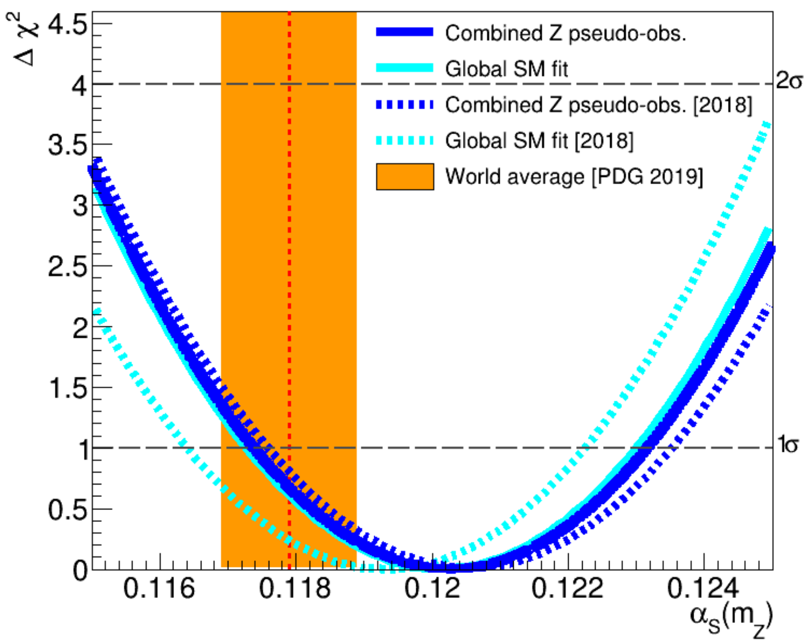
- QCD coupling extracted from:

(i) Combined fit of 3 Z pseudo-observ:
(ii) Full SM fit (with α_s free parameter)

Z boson observable	$\alpha_S(m_Z)$ extraction	uncertainties exp.	param.	theor.
Γ_Z^{tot}	0.1192 ± 0.0047	±0.0046	±0.0005	±0.0008
R_Z	0.1207 ± 0.0041	±0.0041	±0.0001	±0.0009
σ_Z^{had}	0.1206 ± 0.0068	±0.0067	±0.0004	±0.0012
All combined	0.1203 ± 0.0029	±0.0029	±0.0002	±0.0008
Global SM fit	0.1202 ± 0.0028	±0.0028	±0.0002	±0.0008

DdE, Jacobsen: arXiv:2005.04545 [hep-ph]





- LEP lumi-bias updates lead to much better agreement among Γ_Z, R_Z, σ_0 extractions:
- Improved **$\alpha_s(m_Z) = 0.1203 \pm 0.0028$ (±2.3%)**

PDG'19: $\alpha_s(m_Z) = 0.1205 \pm 0.0030$ (±2.5%)

- EXP/TH updates lead to better agreement with full SM fit:
- **$\alpha_s(m_Z) = 0.1202 \pm 0.0028$**

PDG'19: $\alpha_s(m_Z) = 0.1194 \pm 0.0029$

α_s from hadronic Z decays (FCC-ee)

- QCD coupling extracted from:

(i) Combined fit of 3 Z pseudo-observ:
(ii) Full SM fit (with α_s free parameter)

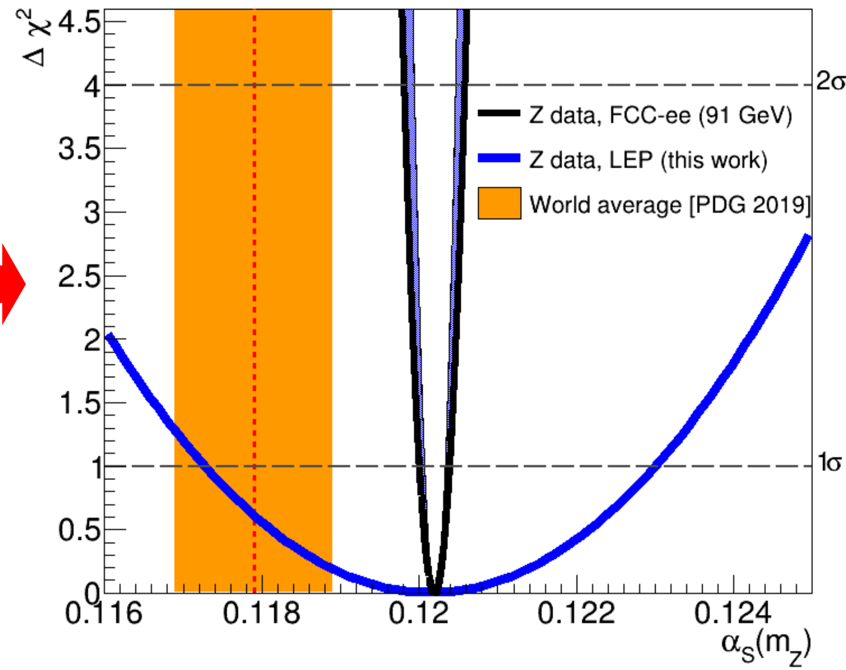
Z boson observable	$\alpha_S(m_Z)$ extraction	uncertainties exp.	param.	theor.
All combined	0.1203 ± 0.0029	± 0.0029	± 0.0002	± 0.0008
Global SM fit	0.1202 ± 0.0028	± 0.0028	± 0.0002	± 0.0008
All combined (FCC-ee)	0.12030 ± 0.00026	± 0.00013	± 0.00005	± 0.00022
Global SM fit (FCC-ee)	0.12020 ± 0.00026	± 0.00013	± 0.00005	± 0.00022

- FCC-ee:
  - Huge Z pole stats. ($\times 10^5$ LEP):
  - Exquisite systematic/parametric precision (stat. uncert. negligible):

$$\Delta R_Z = 10^{-3}, \quad R_Z = 20.7500 \pm 0.0010$$
$$\Delta\Gamma_Z^{tot} = 0.1 \text{ MeV}, \quad \Gamma_Z^{tot} = 2495.2 \pm 0.1 \text{ MeV}$$
$$\Delta\sigma_Z^{had} = 4.0 \text{ pb}, \quad \sigma_Z^{had} = 41\,494 \pm 4 \text{ pb}$$
$$\Delta m_Z = 0.1 \text{ MeV}, \quad m_Z = 91.18760 \pm 0.00001 \text{ GeV}$$
$$\Delta\alpha = 3 \cdot 10^{-5}, \quad \Delta\alpha_{had}^{(5)}(m_Z) = 0.0275300 \pm 0.0000009$$

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

DdE, Jacobsen: arXiv:2005.04545 [hep-ph]



- 10 times better precision than today:
  $\delta\alpha_s/\alpha_s \sim \pm 0.2\%$ (tot), $\pm 0.1\%$ (exp)
  Strong (B)SM consistency test.

$\alpha_s(m_Z) = 0.12030 \pm 0.00028$ ($\pm 0.2\%$)

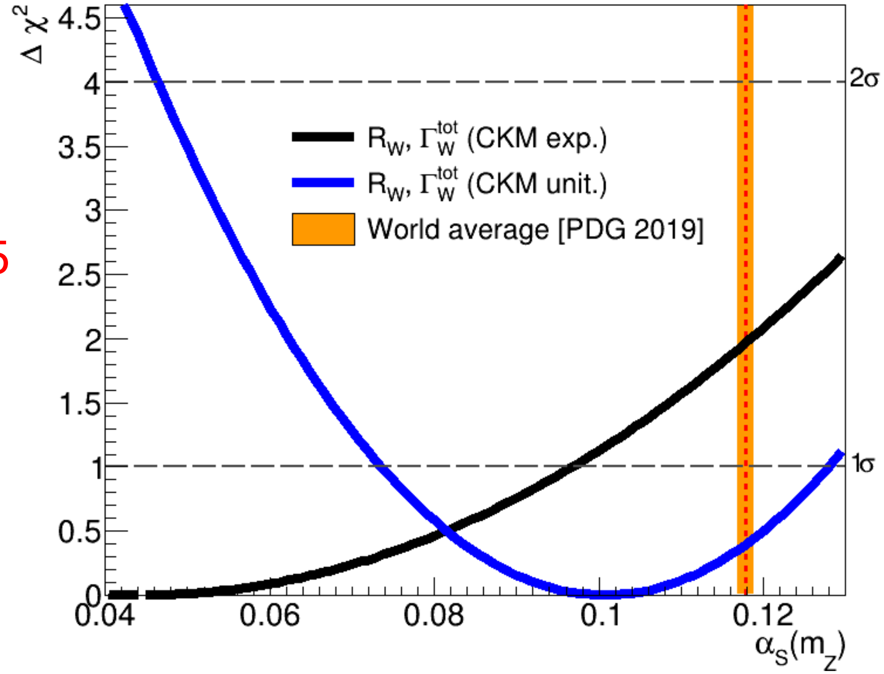
α_s from hadronic W decays (today)

- QCD coupling extracted from new N³LO fit of combined Γ_W, R_W pseudo-observ.:

W boson	$\alpha_S(m_Z)$	uncertainties		
observables	extraction	exp.	param.	theor.
Γ_W^{tot}, R_W (exp. CKM)	0.044 ± 0.052	± 0.024	± 0.047	(± 0.0014)
Γ_W^{tot}, R_W (CKM unit.)	0.101 ± 0.027	± 0.027	(± 0.0002)	(± 0.0016)
Γ_W^{tot}, R_W (FCC-ee, CKM unit.)	0.11790 ± 0.00023	± 0.00012	± 0.00004	± 0.00019

DdE, Jacobsen: arXiv:2005.04545 [hep-ph]

- Very imprecise extraction:
  - Large propagated parametric uncert. from poor V_{cs} exp. precision (±2%): QCD coupling unconstrained: 0.04±0.05
  - Imposing CKM unitarity: large exp. uncertainties from Γ_W, R_W (0.9–2%): QCD extracted with ~27% precision
  - Propagated TH uncertainty much smaller today: ~1.5%



$\alpha_s(m_z) = 0.101 \pm 0.027$ (±27%)

α_s from hadronic W decays (FCC-ee)

- QCD coupling extracted from new N^{3}LO fit of combined Γ_W, R_W pseudo-observ.:

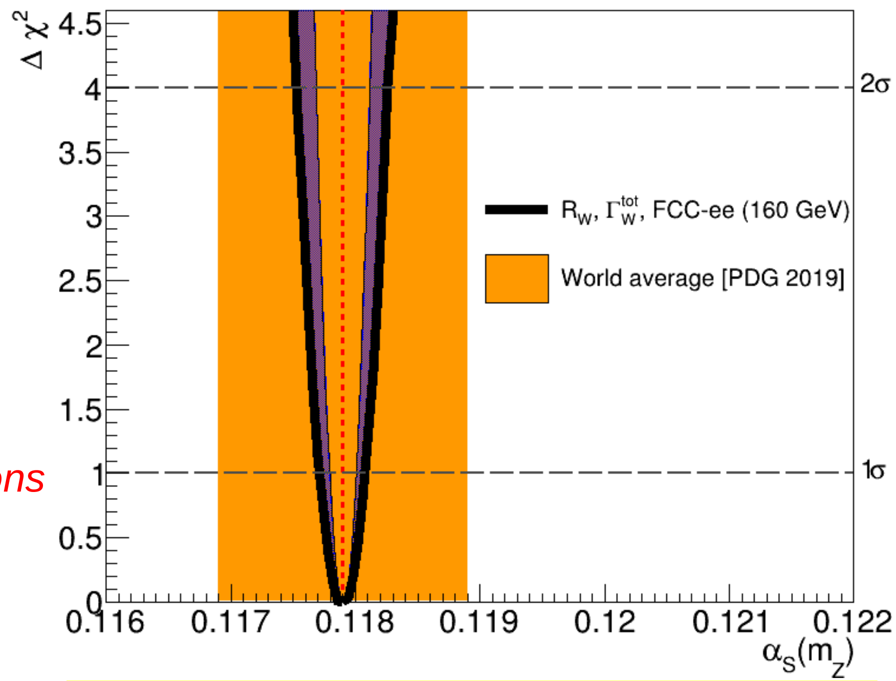
W boson observables	$\alpha_S(m_Z)$ extraction	uncertainties exp.	param.	theor.
Γ_W^{tot}, R_W (exp. CKM)	0.044 ± 0.052	± 0.024	± 0.047	(± 0.0014)
Γ_W^{tot}, R_W (CKM unit.)	0.101 ± 0.027	± 0.027	(± 0.0002)	(± 0.0016)
Γ_W^{tot}, R_W (FCC-ee, CKM unit.)	0.11790 ± 0.00023	± 0.00012	± 0.00004	± 0.00019

- FCC-ee extraction:
  - Huge W pole stats. ($\times 10^4$ LEP-2).
  - Exquisite syst./parametric precision:

$$\Gamma_W^{tot} = 2088.0 \pm 1.2 \text{ MeV}$$
$$R_W = 2.08000 \pm 0.00008$$
$$m_W = 80.3800 \pm 0.0005 \text{ GeV}$$
$$|V_{cs}| = 0.97359 \pm 0.00010$$ ← *O(10^{12}) D mesons*

  - TH uncertainty reduced by $\times 10$ after computing missing α_s^5, α^2, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms

DdE, Jacobsen: arXiv:2005.04545 [hep-ph]

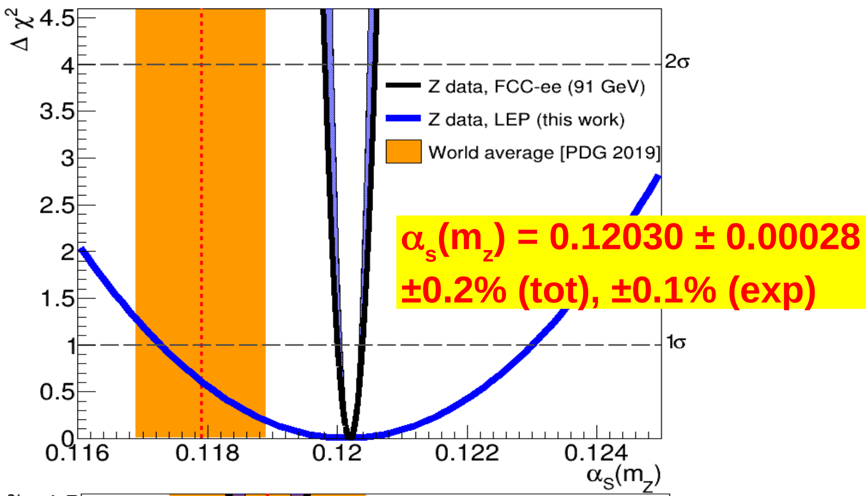


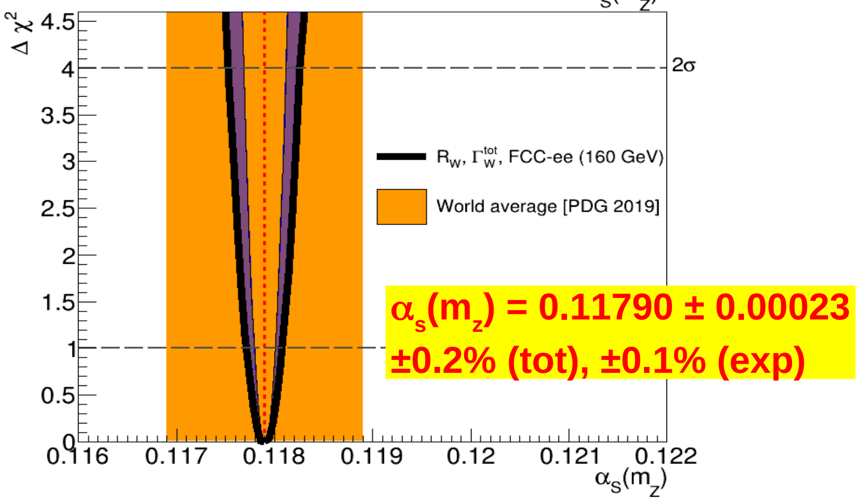
$\alpha_s(m_z) = 0.11790 \pm 0.00023$ ($\pm 0.2\%$)

Partial summary: α_s at FCC-ee

- World-average QCD coupling at $N^{2,3}LO$ today:
  - *Determined from 7 observables with combined ±0.85% uncertainty: Least well-known gauge coupling.*
  - *Impacts all LHC QCD x-sections & decays.*
  - *Role beyond SM: GUT, EWK vacuum stability, New colored sectors?*
- Uncerts. for e^+e^- extractions today:
  - τ decays: ±1.5% (mostly non-pQCD)
  - Shapes, jets: ±2.6% (mostly non-pQCD)
  - Z pseudo-observ.: ±2.5% (mostly exp.)
- New Z, W extractions:
  - Z boson: New fit with high-order EW corrections + updated LEP data: ±2.3%, ±0.6%, (exp., th.) uncerts.
  - W boson: New N^3LO fit to Γ_W, R_W ~47%,~27% (param., exp.) uncerts.

- 0.1% uncertainty only possible with a machine like FCC-e^+e^-





What are the detector design improvements needed to bring propagated syst. uncert. on W,Z pseudo-observ. below 0.1% ?

α_s running at the multi-TeV scale (FCC-pp)

- Jets from pp collisions above LHC energies provide the only known means to test asymptotic freedom & new coloured sectors above ~3 TeV:

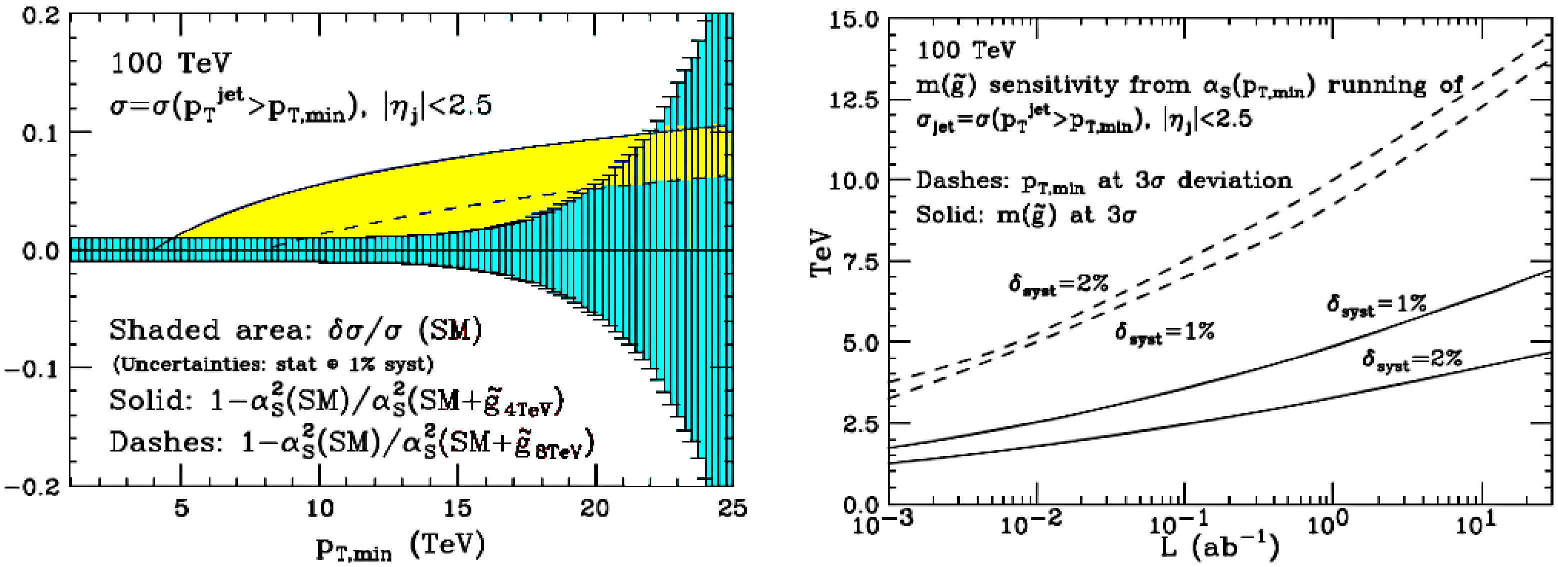


Figure 5.5: Left plot: combined statistical and 1% systematic uncertainties, at 30 ab^{-1}, vs p_T threshold; these are compared to the rate change induced by the presence of 4 or 8 TeV gluinos in the running of α_S. Right plot: the gluino mass that can be probed with a 3σ deviation from the SM jet rate (solid line), and the p_T scale at which the corresponding deviation is detected.

- FCC-pp: – Jet cross sections with <10% stat. uncert. up to p_T~25 TeV
  – Sensitivity to m_g=4–8 GeV gluinos in α_s running.

Physics at FCC e^+e^- & pp machines

(1) QCD: α_s coupling

(2) QCD: Parton Distribution Functions

(3) QCD: Jet substructure & flavour tagging

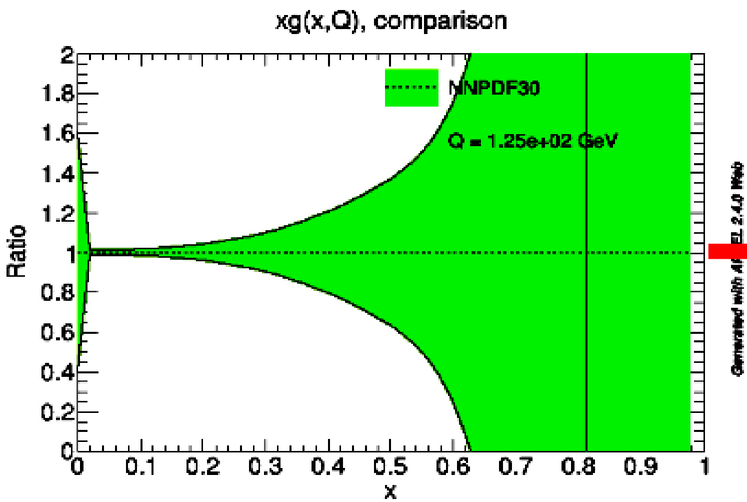
(4) QCD: Non-perturbative regime

(5) Higgs sector

(6) BSM searches

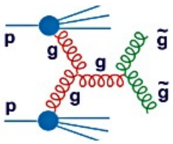
PDFs impact on new BSM / QCD physics

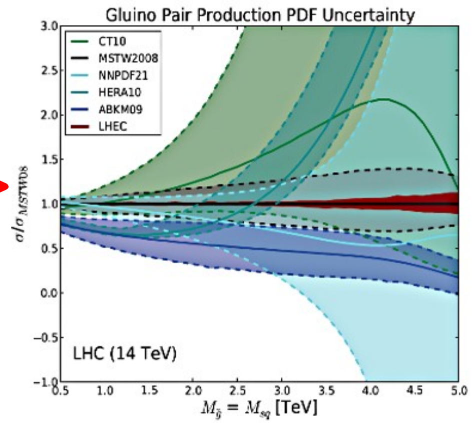
New physics at high-x?



GLUON

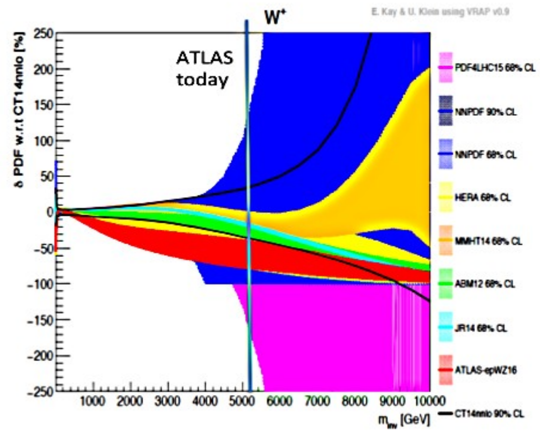
SUSY, RPC, RPV, LQS..



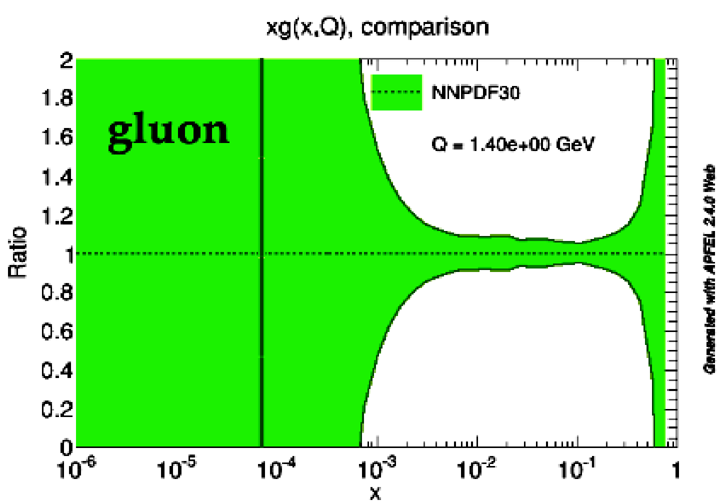


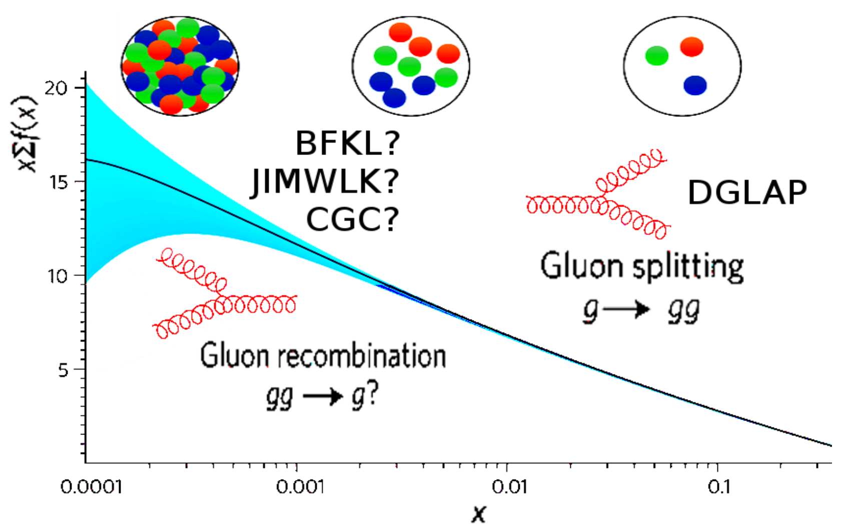
QUARKS

Exotic+ Extra boson searches at high mass



New QCD evolution at low-x?

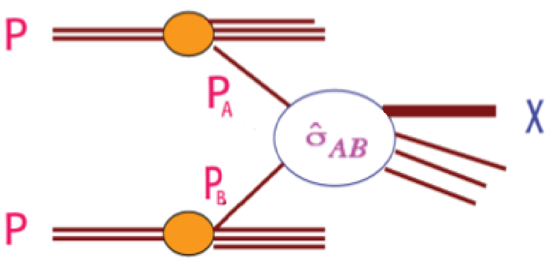


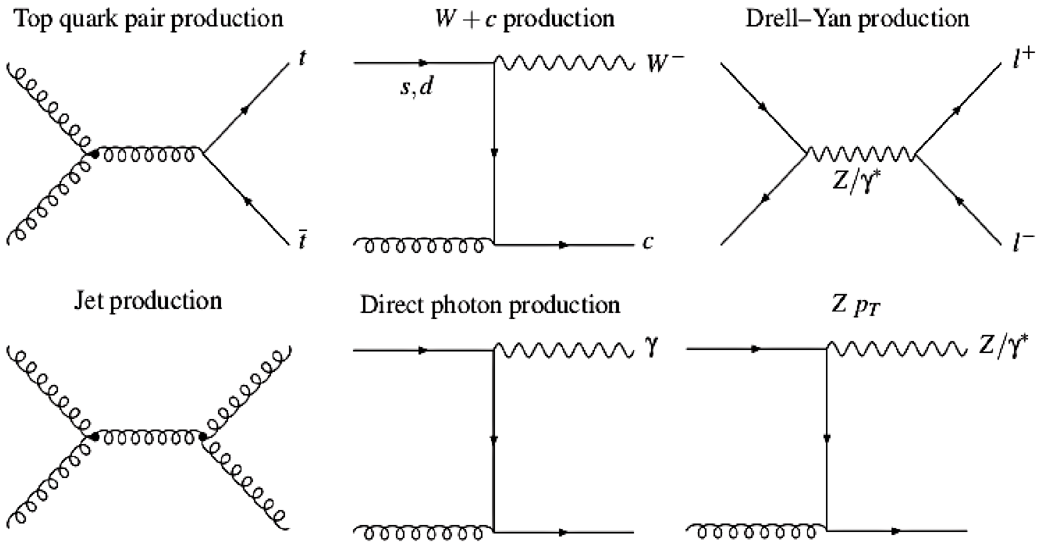


Improved PDFs with p-p data (today)

- 6 partonic processes in pp at the LHC have provided key PDF constraints:

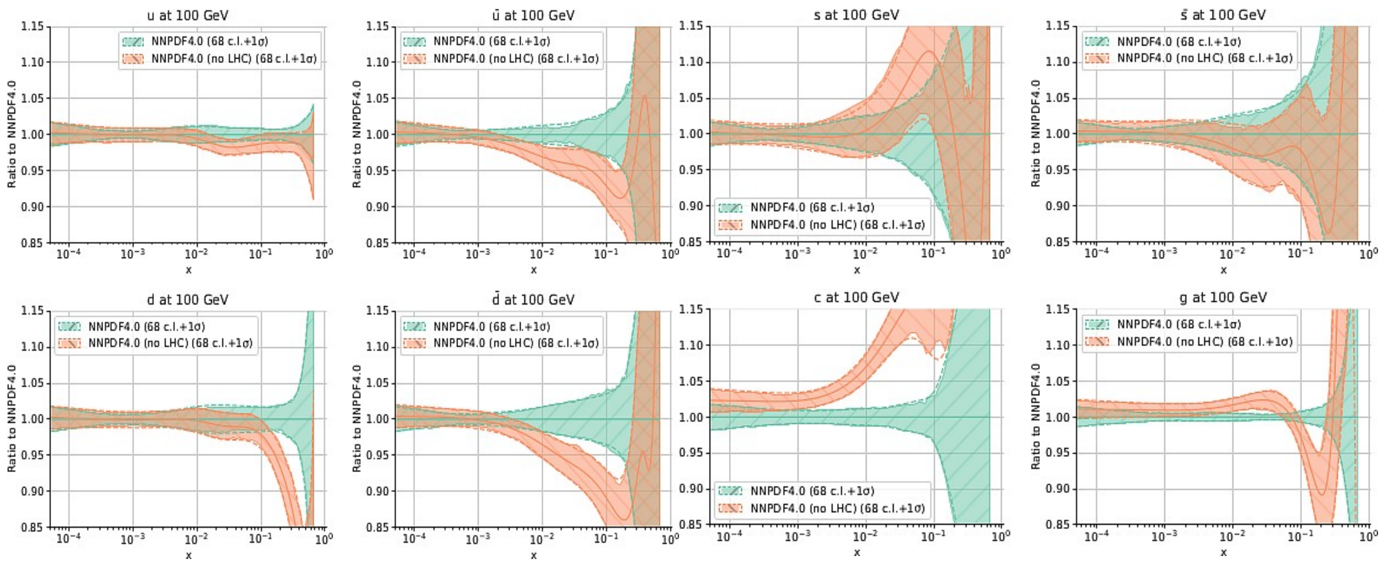
$\sigma = \hat{\sigma} \otimes \text{PDF}$





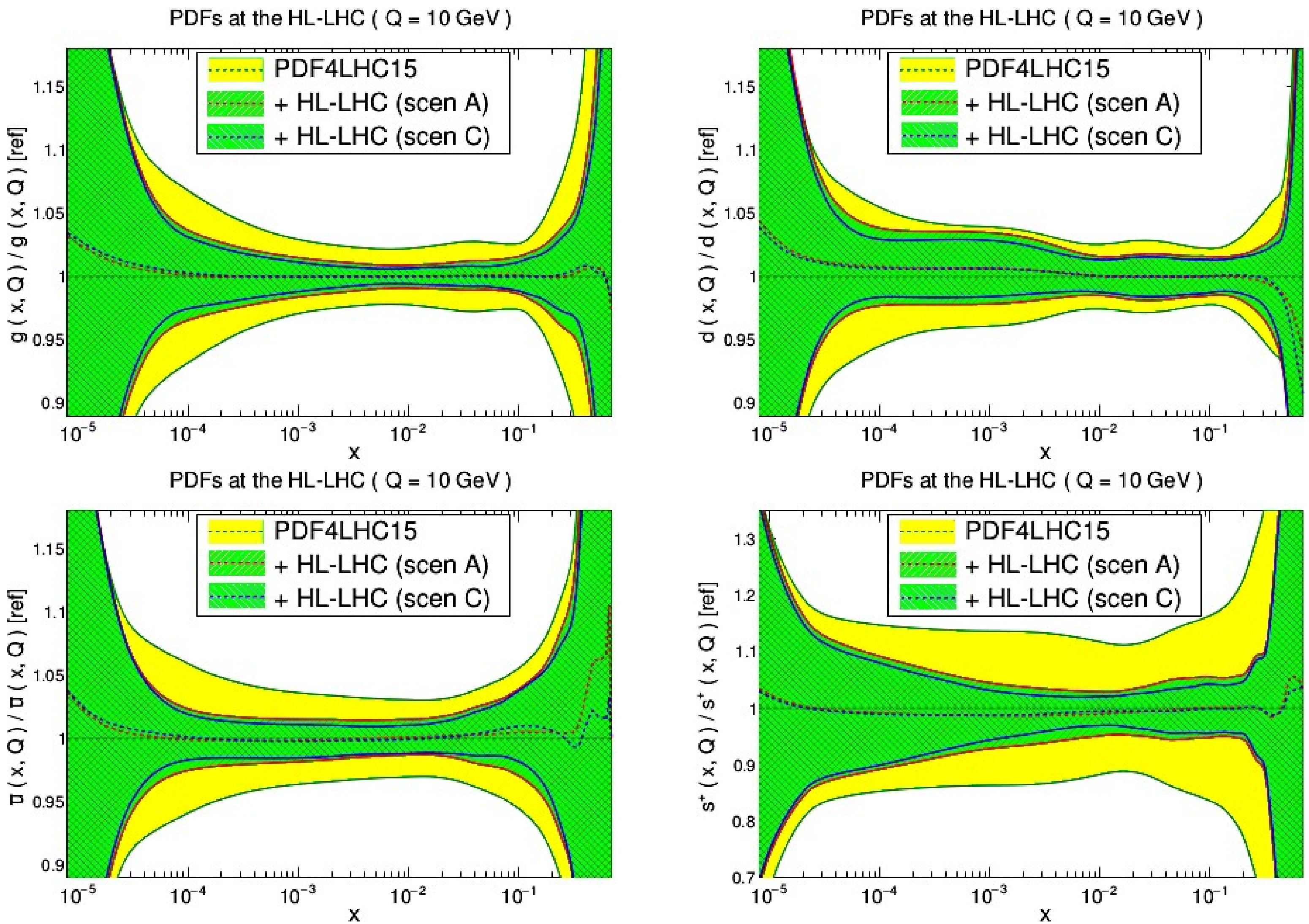
- Updated NNLO PDFs using LHC Run-II data:

At high-x, 10–15% change (plus ~50% reduced uncerts.) for all partons except u-quark



NNPDF4.0: arXiv:2109.02653

Improved PDFs with pp data (HL-LHC)

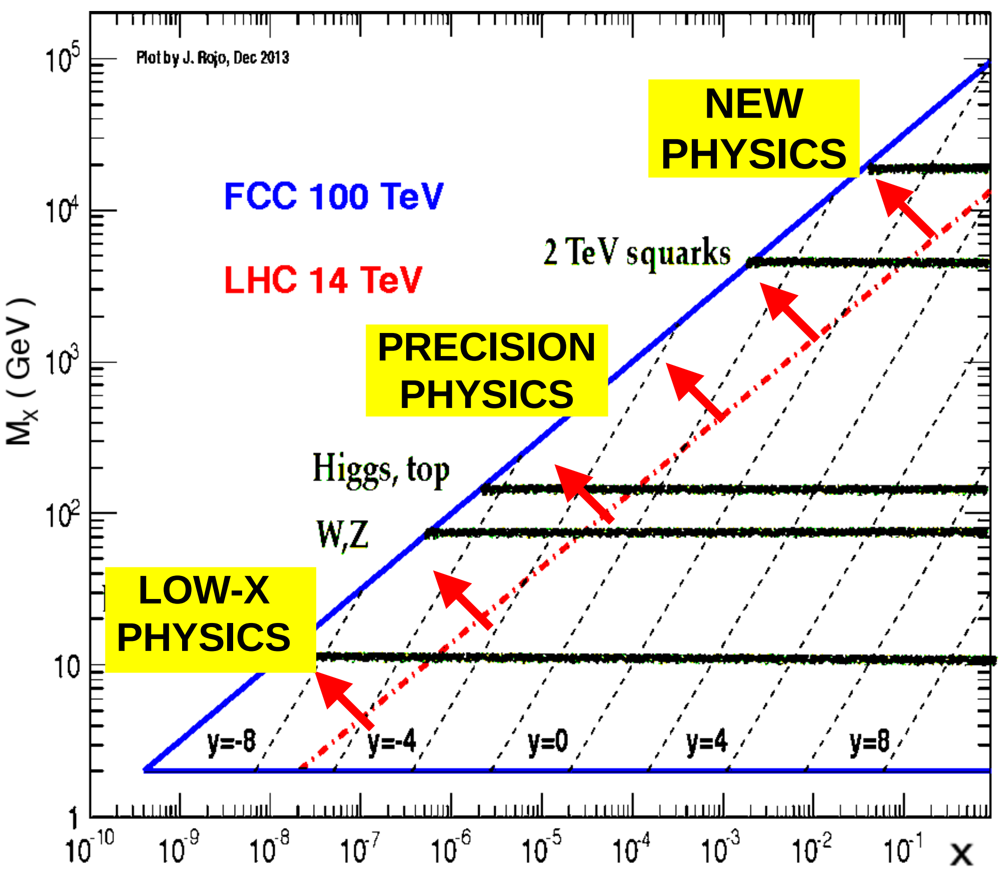


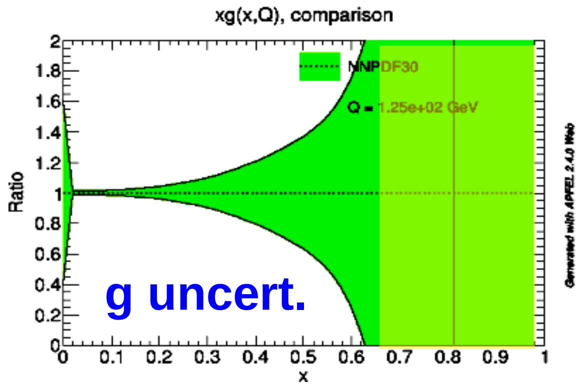
[R.A. Khalek et al. arXiv:1810.03639]

- Significant (factor ~2) PDF uncertainty reduction (with little dependence on projected systematics). But not at very low-,high-x...

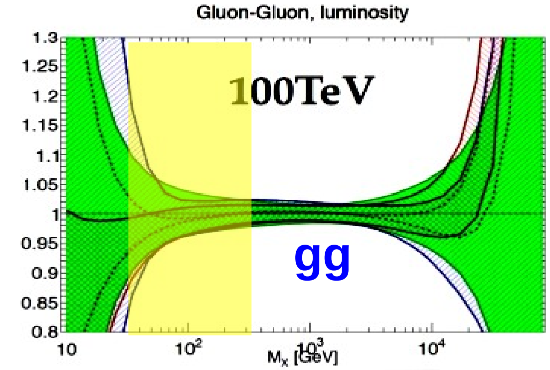
PDFs needs for FCC-pp

- Still large PDF uncertainties in pp at 100 TeV in key (x,Q^2) regions:

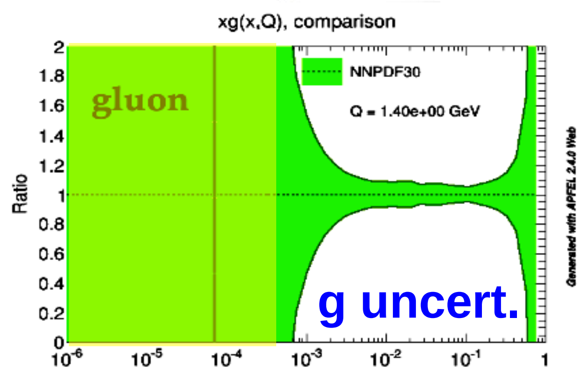




High-x



Mid-x



Low-x

- FCC-ep required to reach <1% uncertainty for σ(W,Z,H) at FCC-pp, or FCC-pp data themselves will suffice?

Physics at FCC e^+e^- & pp machines

(1) QCD: α_s coupling

(2) QCD: Parton Distribution Functions

(3) QCD: Jet substructure & flavour tagging

(4) QCD: Non-perturbative regime

(5) Higgs sector

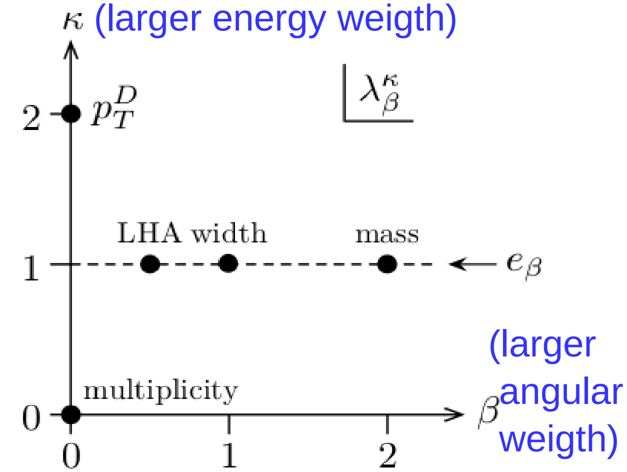
(6) BSM searches

Precise jet substructure & flavour tagging

- State-of-the-art jet substructure studies based on angularities:

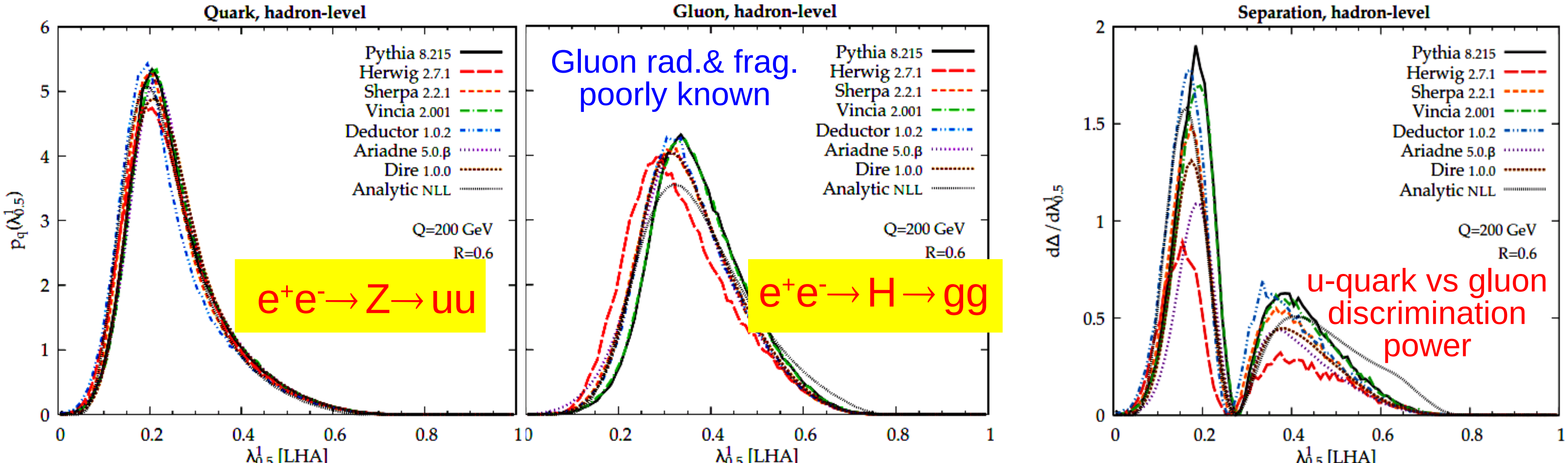
$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta ,$$

(normalized $E^n \times \theta^n$ products)



[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

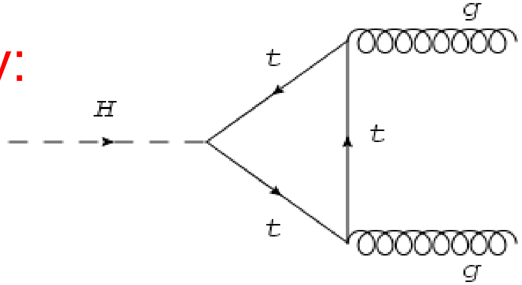
- "Sudakov"-safe variables of jet constituents: multiplicity, LHA, width/broadening, mass/thrust, C-parameter,...
- k=1: IRC-safe computable (N^nLO+N^nLL) via SCET (but uncertainties from non-pQCD effects)
- MC parton showers differ on gluon (less so quark) radiation patterns:



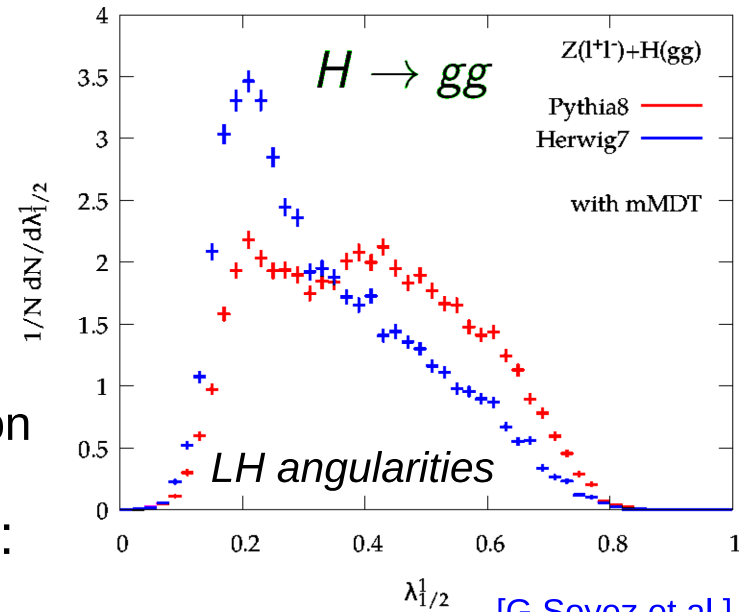
[G.Soyez et al.]

High-precision gluon & quark jet studies (FCC-ee)

- Exploit FCC-ee H(gg) as a ”pure gluon” factory: H→gg (BR~8% accurately known) provides O(100.000) extra-clean digluon events.



- Multiple handles to study gluon radiation & g-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 resolution

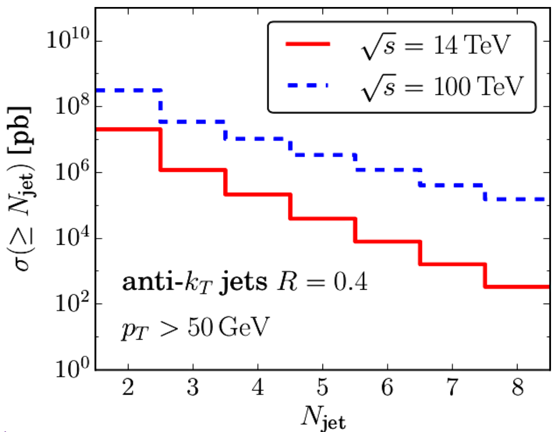


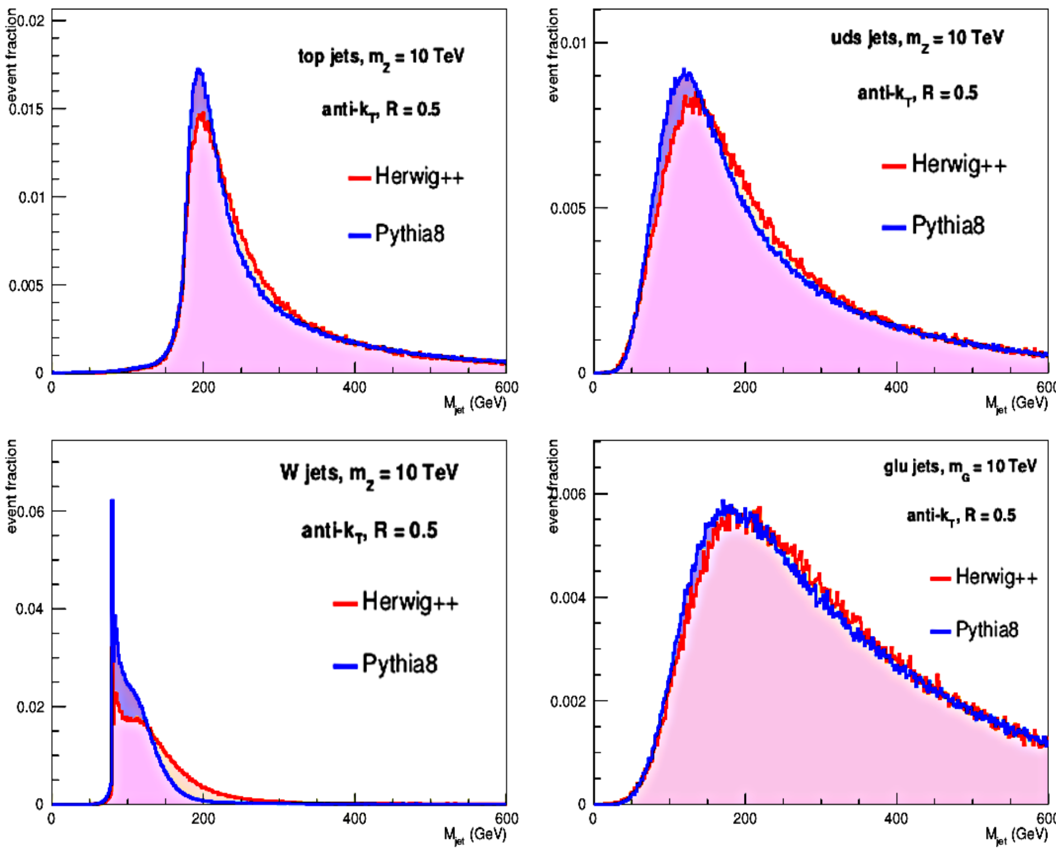
[G.Soyez et al.]

- Multiple high-precision analyses at hand:
  – BSM: Improve q/g/Q discrimination tools
  – pQCD: Check N^nLO antenna functions. High-precision QCD coupling.
  – non-pQCD: Gluon fragmentation: Octet neutralization? (zero-charge gluon jet with rap gaps). Colour reconnection? Glueballs ? Leading η's,baryons?

Highly-boosted jets, multijets (FCC-pp)

- Proton-proton collisions at 100 TeV provide unique conditions to produce & study highly-boosted objects: top, W, Z, H, R_{BSM}(jj),... Resolving small angular dijet sep. $\Delta R \approx 2M(jj)/p_T(j)$.
- Jet substructure: key to separate dijets from QCD & (un)coloured resonance decays, e.g. $R_{10\text{-}TeV} \rightarrow$ tt,qq,gg,WW
- Diffs. in MC generators for quark vs. gluon jets (& jet radius).
- Also unique multijet (N>>10) BSM, QCD studies





[FCC-pp, arXiv:1607.01831]

Physics at FCC e^+e^- & pp machines

(1) QCD: α_s coupling

(2) QCD: Parton Distribution Functions

(3) QCD: Jet substructure & flavour tagging

(4) QCD: Non-perturbative regime

(5) Higgs sector

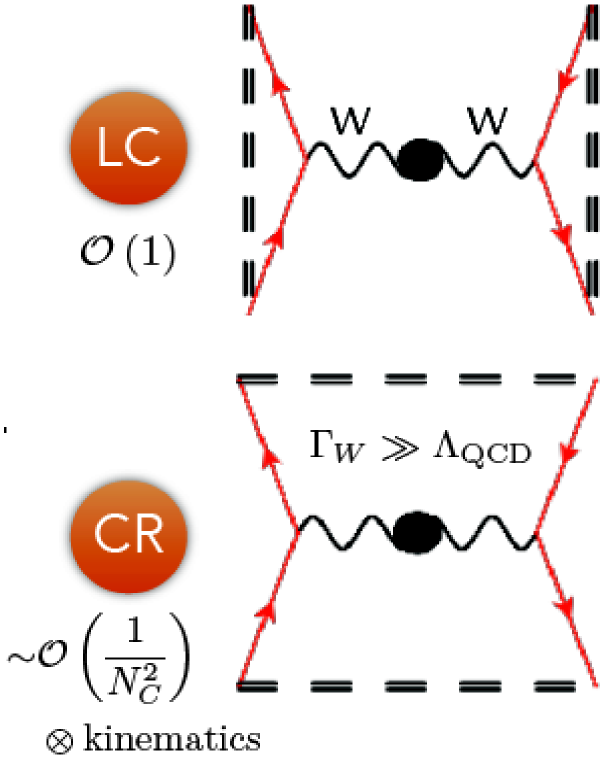
(6) BSM searches

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).

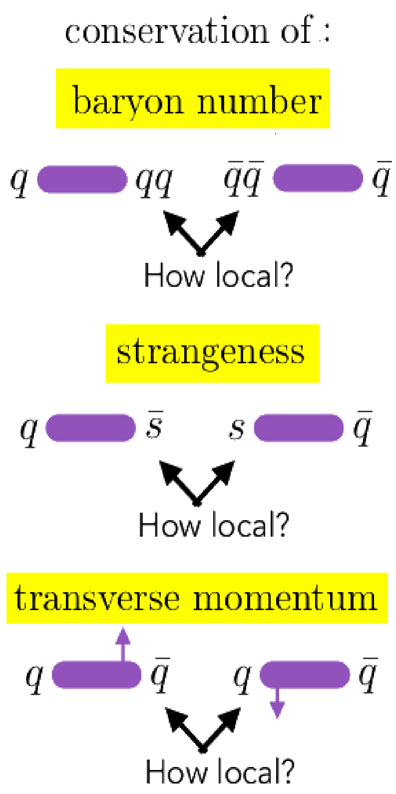
  - CR impacts all FCC-ee multi-jet final-states (potentially shifted angular correlations):
    – $e^+e^- \rightarrow WW(4j)$, Z(4j), ttbar,
    – H(2j,4j) CP studies,…
    – String-drag effect on W mass
    (Hinted at LEP: No-CR excluded at 99% CL).

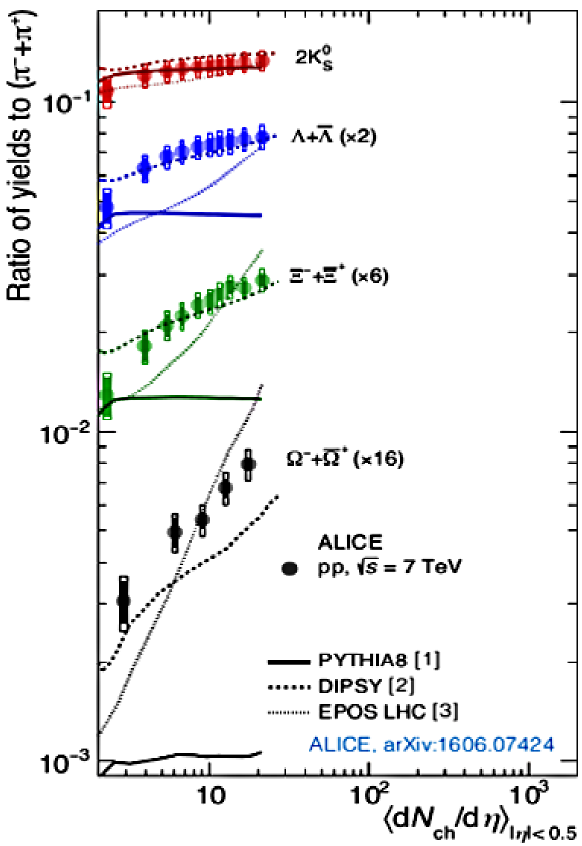
  - Exploit huge W stats ($\times 10^4$ LEP) to "turn the m_W measurement around": Determine m_W leptonically and constrain CR in hadronic WW: Colour reconnection controlled to <1%



Other non-pQCD phenomena

- High-precision low-p_T PID hadrons in e^+e^-,pp for detailed studies:
  - – Baryon & strangeness production. Colour string dynamics.
  - – Final-state correlations (spin: BE, FD; momenta; space)
  - – Bound state formation: Onia, multi-quark states, glueballs, ...



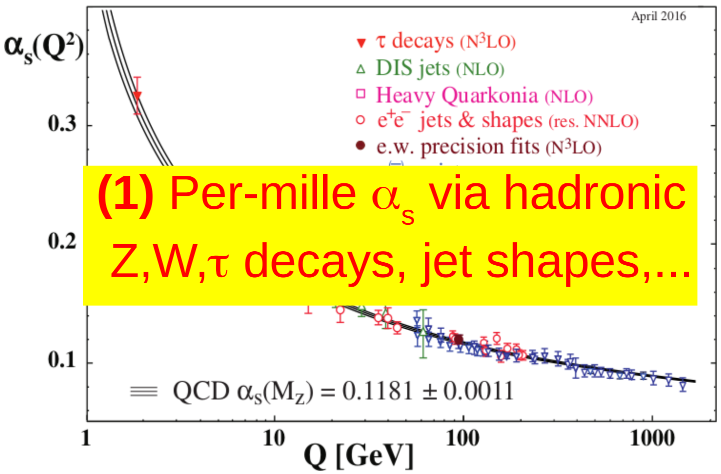


- ▶ Understand breakdown of universality of parton hadronization observed at LHC.

- Baseline vacuum e^+e^- studies for high-density QCD in small & large systems.

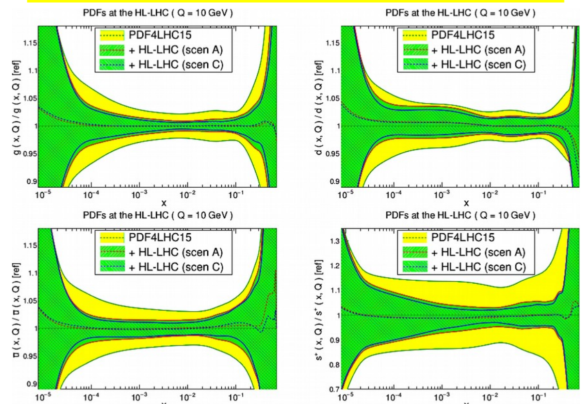
Partial summary: QCD at FCC-ee & FCC-pp

- ☛ The precision needed to fully exploit all future ee/pp/ep/eA/AA SM & BSM programs requires exquisite control of pQCD & non-pQCD physics.
- ☛ Unique QCD precision studies accessible at FCC-ee, FCC-pp:

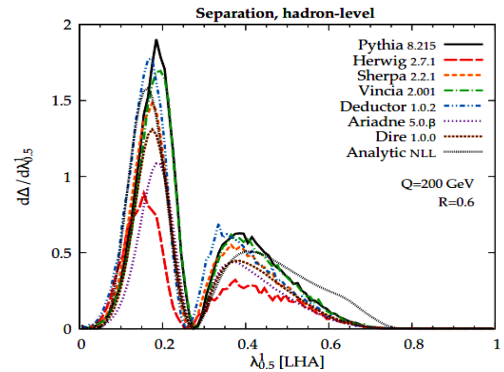


(1) Per-mille α_s via hadronic Z,W,τ decays, jet shapes,...

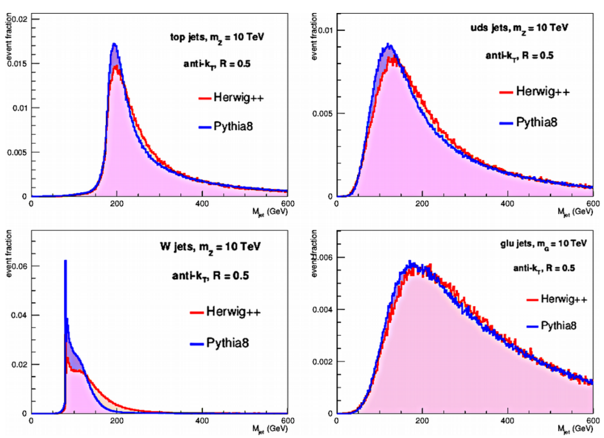
(2) High-precision PDFs



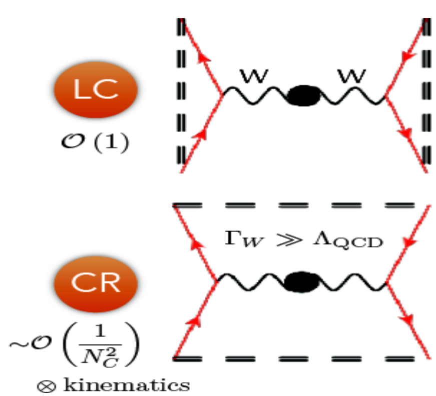
(3) N^nLO+N^nLL jet struct. High g/q/Q discrimination



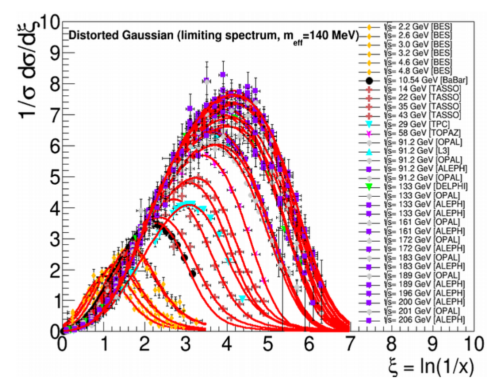
(4) Unique studies of highly-boosted dijet & multijets

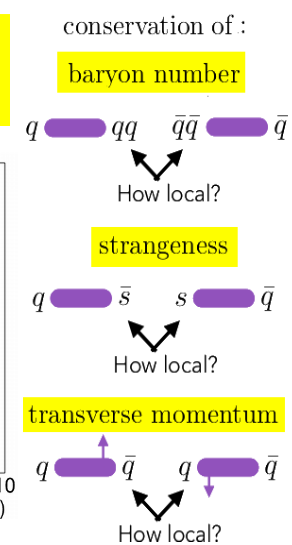


(5) <1% control of colour reconnection



(6) High-precision hadronization:





Physics at FCC e^+e^- & pp machines

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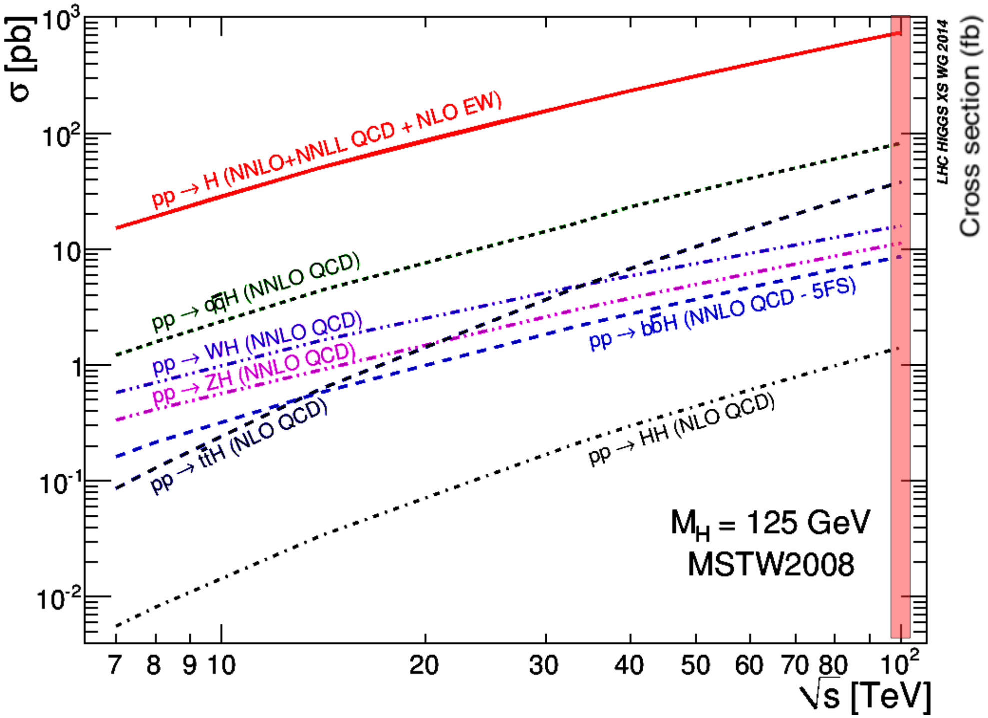
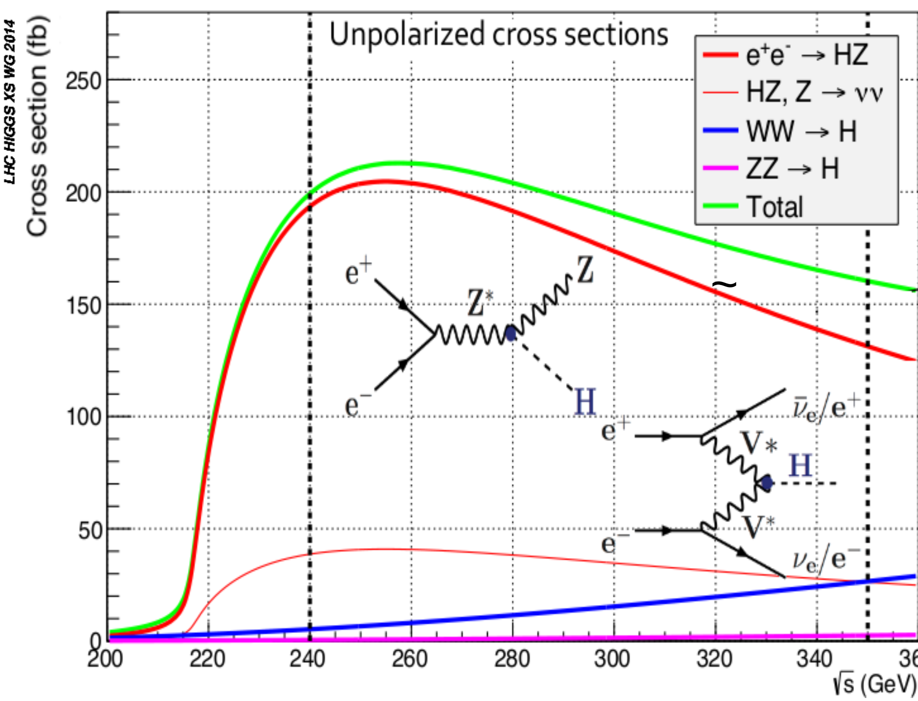
Higgs physics at FCC-pp & FCC-ee

- Huge number of Higgs expected: $2\cdot10^{10}$ (FCC-pp), $1.2\cdot10^{6}$ (FCC-ee)

$\sigma(pp\rightarrow H+X) \approx 0.9$ nb (ttH/HH/HHH access) $\sigma(e^+e^-\rightarrow H+X)\approx 200$ fb (low bckgd, no pileup)





	gg→H	VBF	WH	ZH	ttH	HH
σ_{100} [pb]	802	69	16	11	32	1.9
σ_{100}/σ_{14}	x17	x16	x10	x11	x52	x40

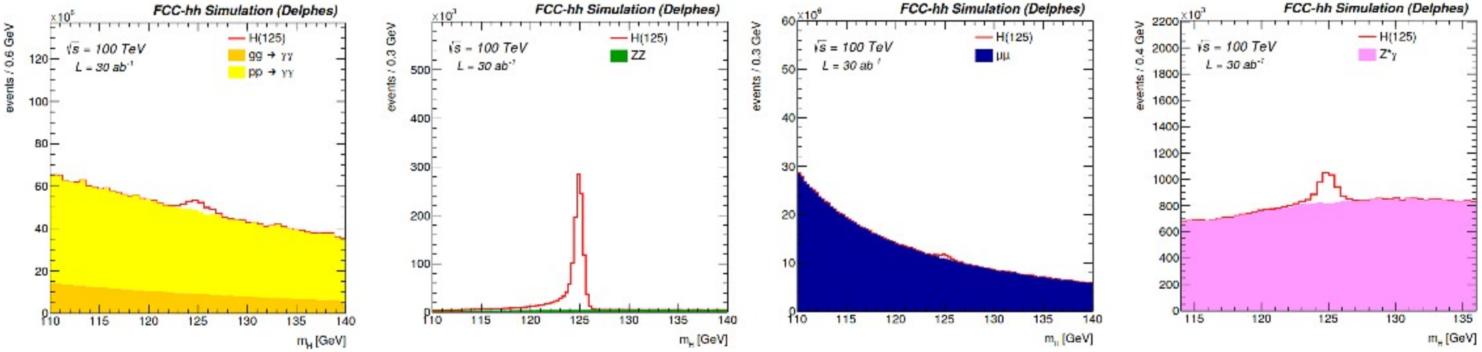
Total Integrated Luminosity (ab^{-1})	5
Number of Higgs bosons from $e^+e^-\rightarrow HZ$	1,200,000
Number of Higgs bosons from boson fusion	50,000

- H couplings (down to 0.2%), rare & BSM decays, and H self-coupling

Rare & invisible Higgs decays (FCC-pp)

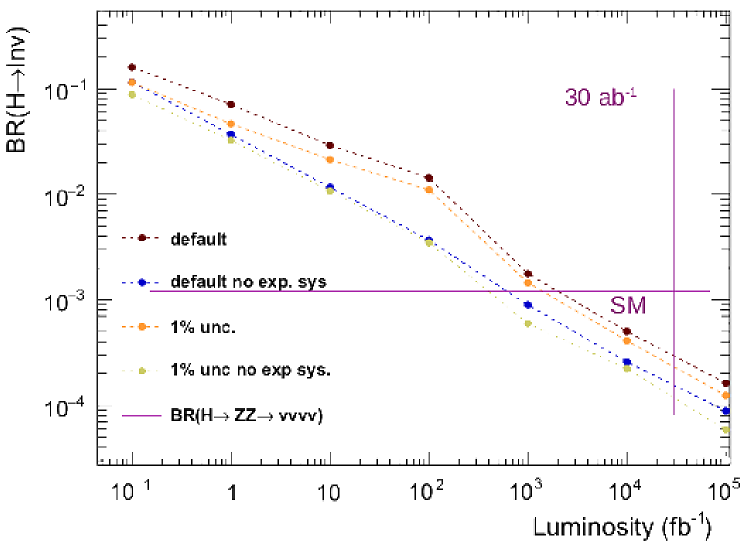
CERN-ACC-2018-0045

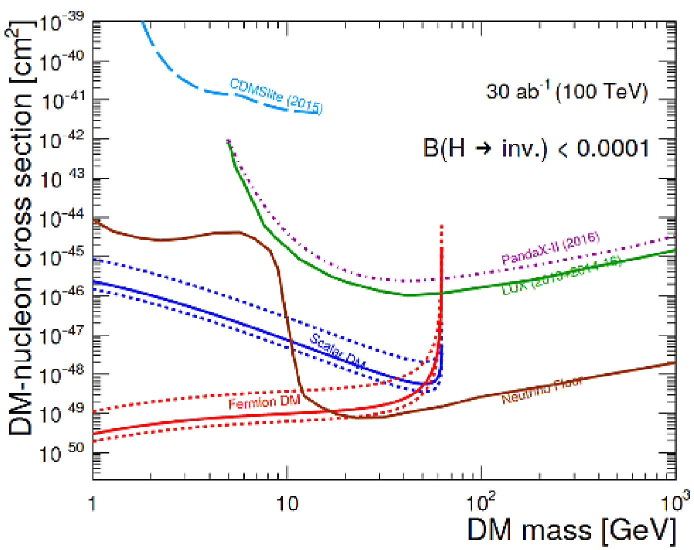
- Complementary measurements of H→γγ, H→ZZ→4ℓ, H→μμ, H→Zγ→ℓℓγ



BRs precision: 1–2%

- H + large E_T^{miss} BR(H→inv) from precise fit the E_T^{miss} spectrum
  - background p_T spectrum from Z→νν constrained to the % level
  - ultimate precision: BR(H→inv) < 2.5 10^{-4} • SM (BR(H→4ν) = 0.11%) reached with ~1 ab^{-1}

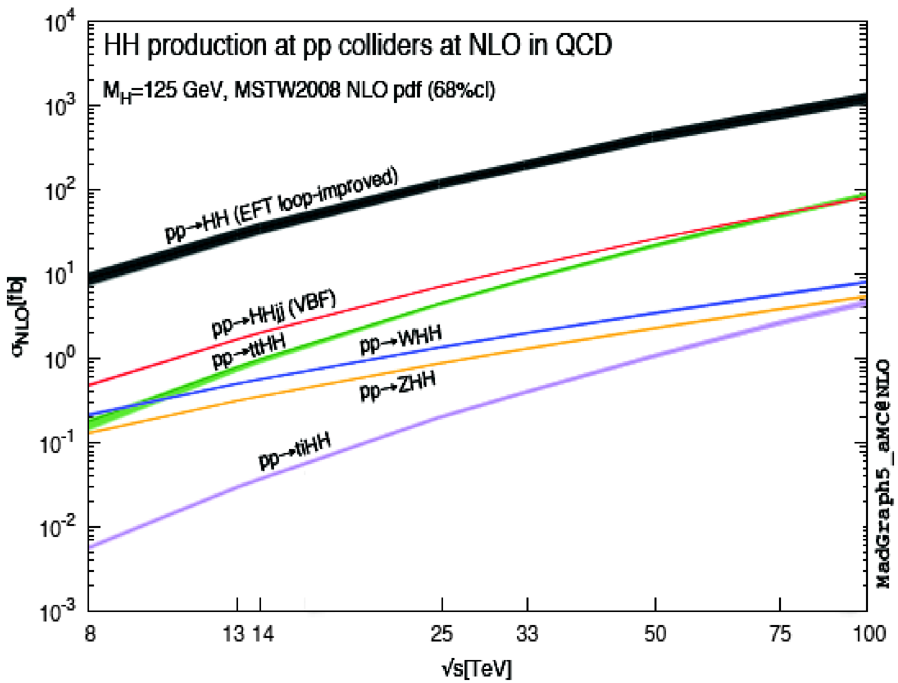




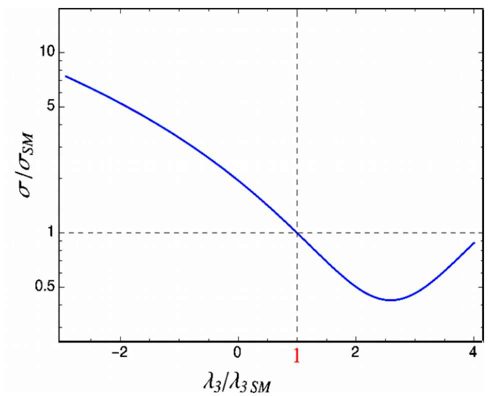
Higgs self-couplings (λ_3,λ_4) at FCC-pp

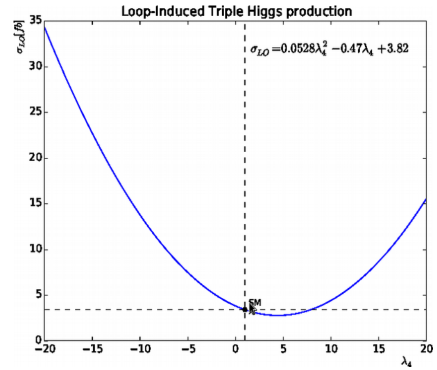
[R. Contino et al., arXiv:1606.09408]

- Double (triple) Higgs cross section ≈ 1.9 pb (5 fb)



But various diagrams contribute to σ_{HH},σ_{HHH}: ~diluted sensitivity to λ_3, λ_4





process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

- bb(bb)ɣɣ most sensitive channel:
  Critical flavor-tagging performances.

- Precisions on coupling:
  Trilinear (g_{HH})~ 3–6%
  Quartic (g_{HHH}) mildly constrained: 2σ

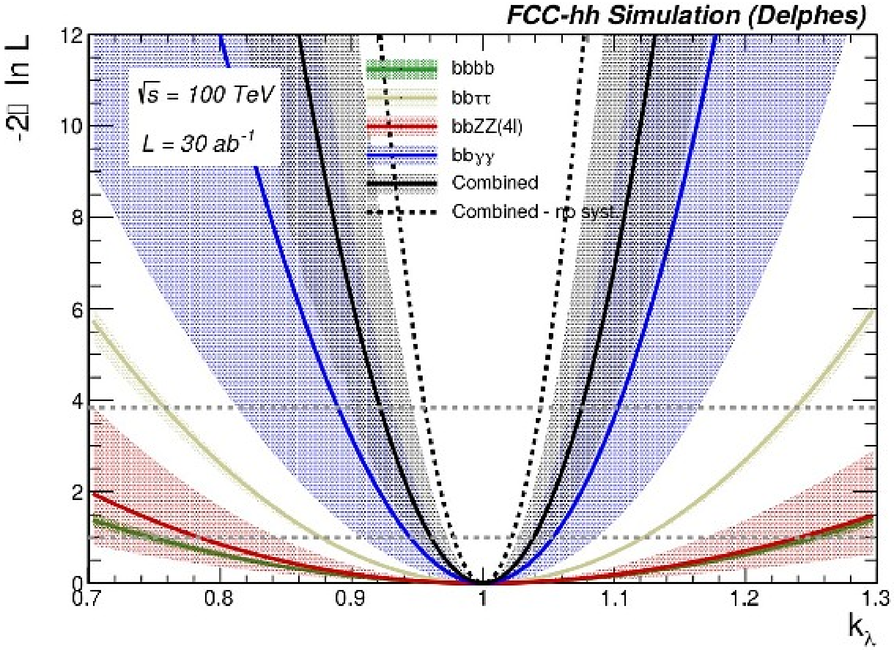
Higgs self-couplings (λ_3,λ_4) at FCC-pp

- 1D maximum likelihood fits of the BDT discriminants

  68% CL uncertainty on κ_λ:

bbγγ	bbττ	bbbb	combined
3.5-8.5%	12-13%	24-26%	2.9-5.5%

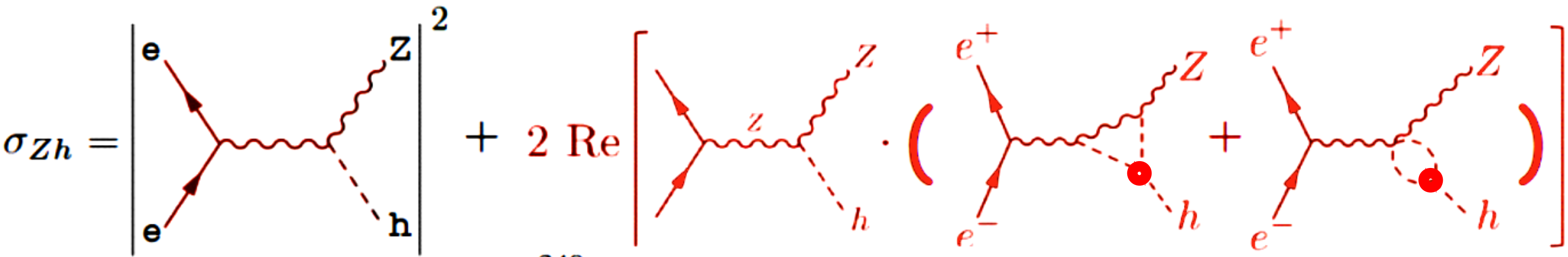
  – driven by the $b\bar{b}\gamma\gamma$ channel, limited by systematics



- A few remarks:
  – small impact of (eg QCD) background relies on the fact that the data will help to constrain the normalisations
  – precision achievable only if good measurements of other couplings: 1% uncertainty on $y_t \Rightarrow$ 5% uncertainty on κ_λ
  – uncertainty on σ_{HH}: 0.5%-1.5% (~5% today): needs at least one order beyond NLO with full top-mass dependence, possibly beyond N^{3}LO in the infinite top-mass limit
- Evolution with luminosity:
  – 10% precision achievable with 3 ab^{-1} of data, ie a 3-5 year early run

Higgs self-coupling (λ_3) at FCC-ee

- Higgs trilinear indirectly constrained through loop corrections to σ(H+Z):



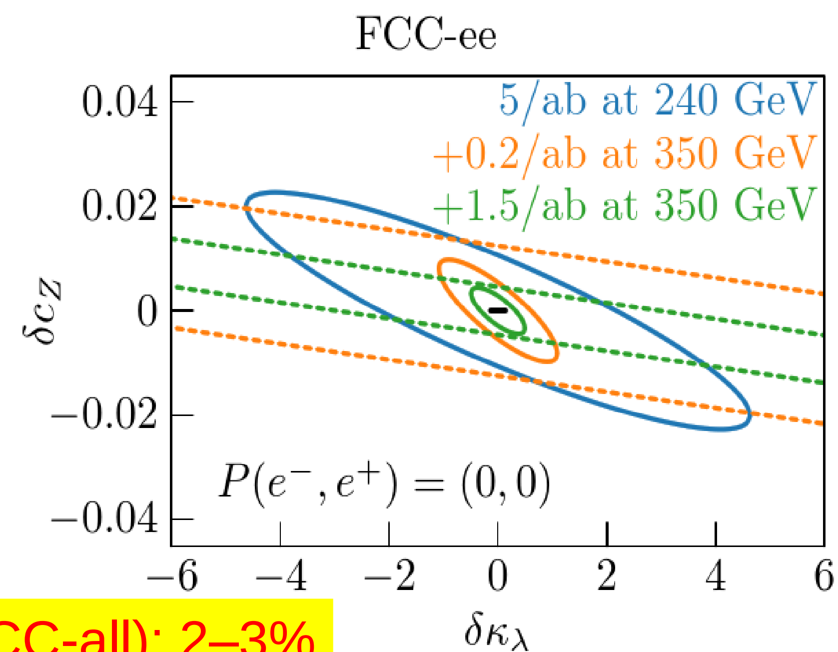
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

[M. McCullough, 2014]

Self-coupling correction δ_h: energy-dependent
δ_Z: energy-independent (distinguishable).

- Tiny effect, but visible thanks to extreme (0.4%) precision on σ_{ZH} coupling reachable at FCC-ee.

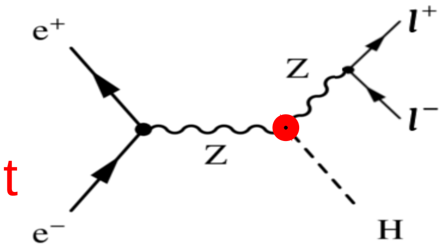
- Indirect limits on trilinear λ coupling at ~40% level combining 240+350GeV



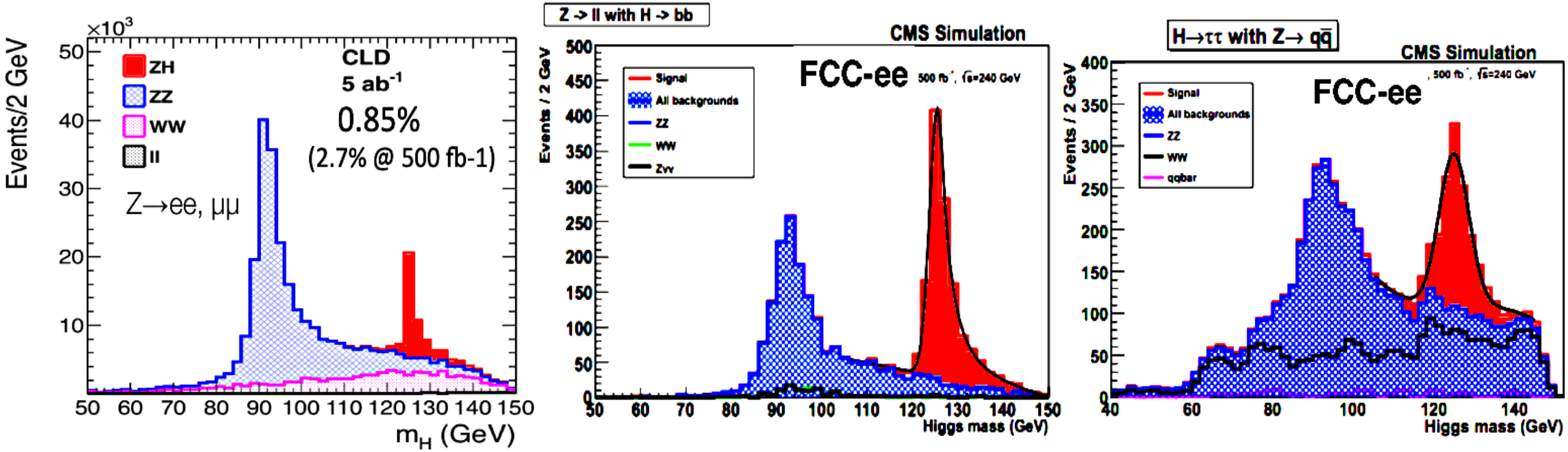
- Final Higgs self-coupling precision (FCC-all): 2–3%

Precision H couplings, width, mass (FCC-ee)

- Recoil method in H-Z(ll) unique to lepton collider: reconstruct H 4-mom. independent of H decay mode.
- High-precision (0.4%) σ_{ZH} provides model-independent g_Z coupling: $\sigma(ee \to ZH) \propto g_Z^2$, with ±0.2% uncert.



$$m^2_{\rm recoil} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}}$$



- Total width (Γ_H) with ~1% precision by combining σ(ZH) and BR(H→ZZ):

$$\sigma(ee \to ZH) BR(H \to ZZ) \propto \frac{g^4_{HZZ}}{\Gamma} \Rightarrow \Gamma$$

- Rest of Yukawa from other decays: $\sigma(ee \to ZH) BR(H \to XX) \propto \frac{g^2_{HZZ} g^2_{HXX}}{\Gamma} \Rightarrow g^2_{HXX}$

Precision Higgs couplings (FCC-ee,FCC-pp)

- FCC-ee provides ×2–20 improvement in couplings uncertainties w.r.t. (model-dependent) HL-LHC expectations (2–5%):

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95
g_{HHH} (%)	50.	44./33. 27./24.	2-3$^{(*)}$
Γ_H (%)	SM	1.1	0.91
BR_{inv} (%)	1.9	0.19	0.024
BR_{EXO} (%)	SM (0.0)	1.1	1

ee,ep (g_{HZZ} to $g_{H\tau\tau}$)

hh ($g_{H\mu\mu}$ to g_{HHH})

ee (Γ_H), hh (BR_{inv}), ee (BR_{EXO})

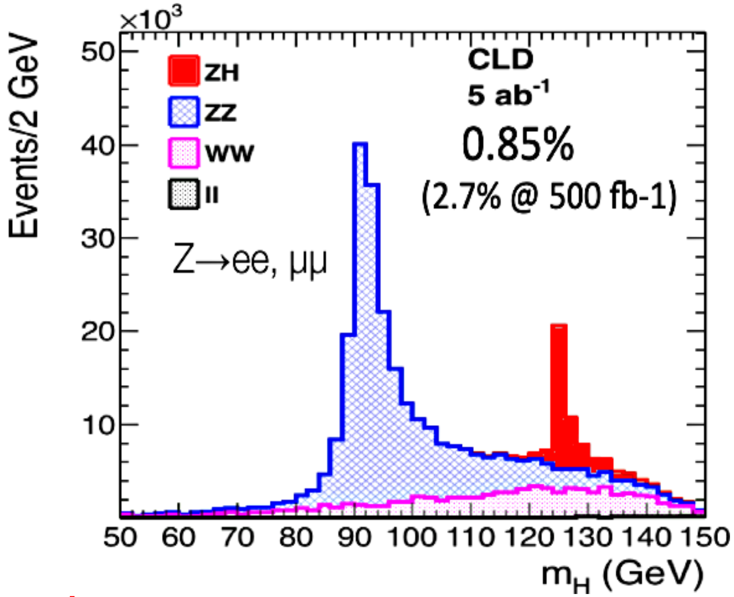
- Most precise g_{ZZ} ≈0.17% coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{HXX}/g^{SM}_{HXX})/5\%}$ > 6 TeV

Few-MeV m_H mass determination (FCC-ee)

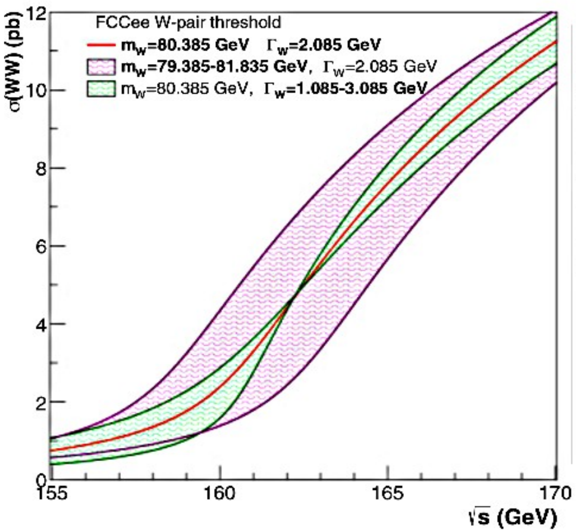
- $e^+e^- \to H\ Z(l^+l^-)$ recoil method: allows Higgs mass reconstruction with $\delta m_H = 8$ MeV in $Z \to \mu^+\mu^-$

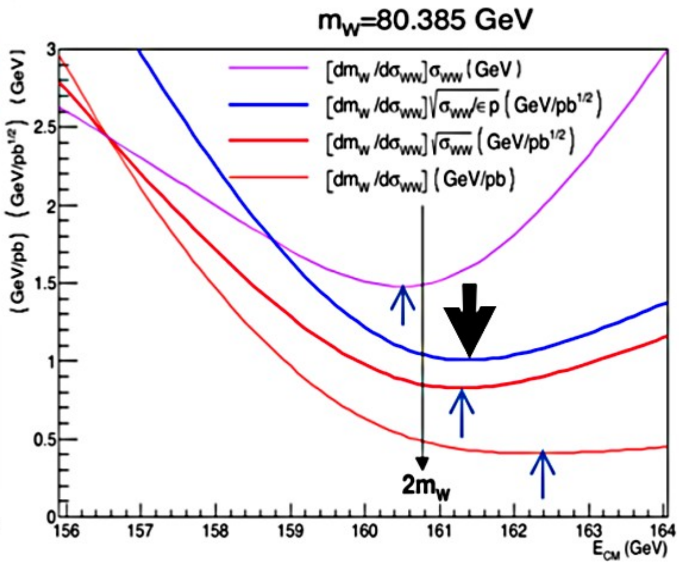
$$m^2_{\text{recoil}} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$

($\delta m_H = \pm 5$ MeV adding other decays)



- Can m_H be accurately reconstructed via σ(HZ) line shape scan? Like done for m_W via $e^+e^- \to W^+W^-$...





With 7/ab @ 162.6 GeV:
δm_W(stat)= ±0.5 MeV

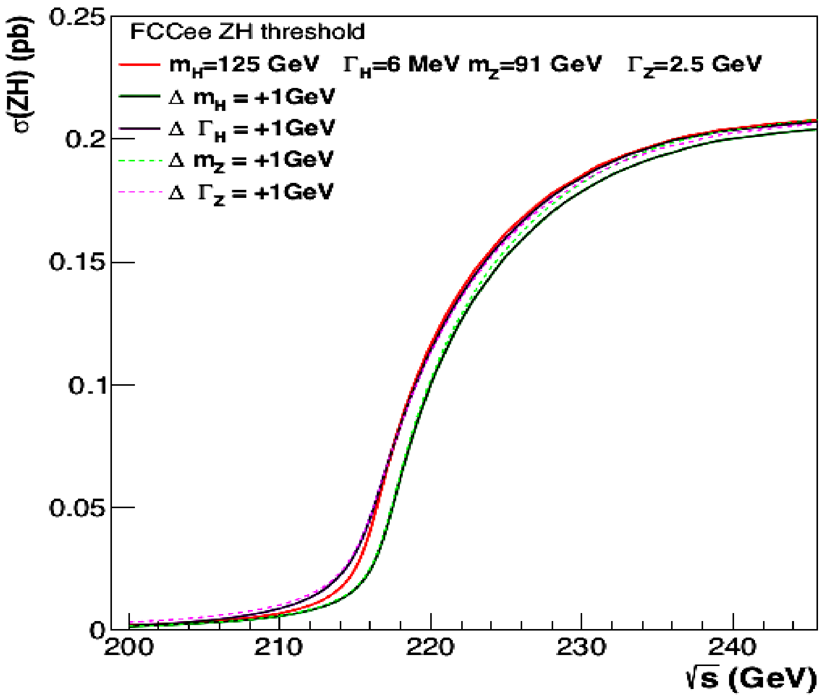
Need systematics control:

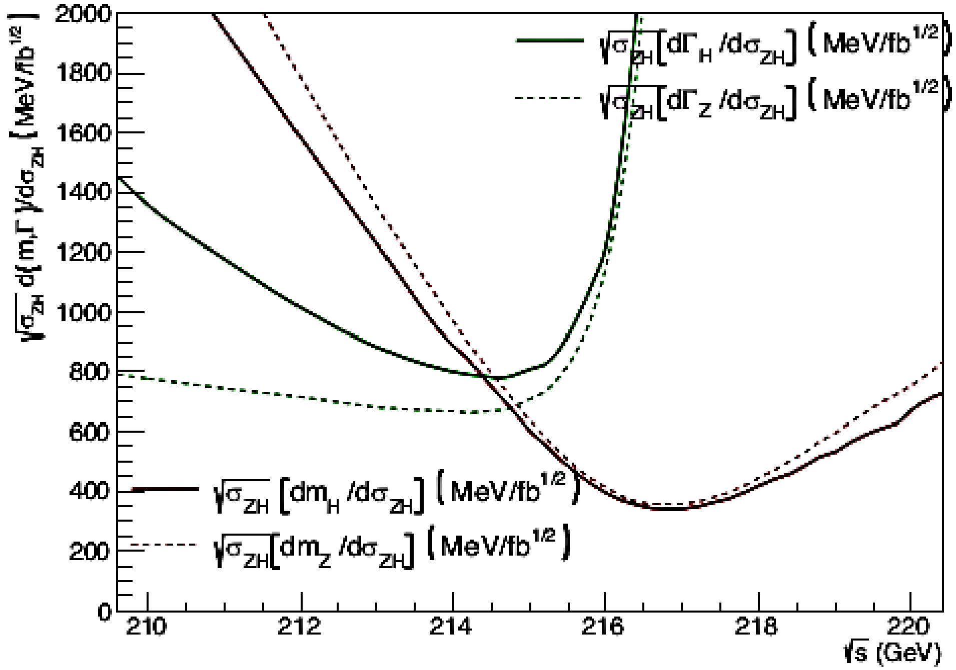
- δE_{beam}<0.5 MeV ($6\cdot10^{-6}$)
- $\delta\varepsilon/\varepsilon$, $\delta L/L < 2\cdot10^{-4}$)
- $\delta\sigma_B$ <1 fb ($2\cdot10^{-3}$)

[arXiv:1703.01626 arXiv:1909.12245]

Few-MeV m_H mass determination (FCC-ee)

- Can m_H be accurately reconstructed via σ(HZ) line shape scan?
- Preliminary MG5@NLO studies (Paolo Azzurri):





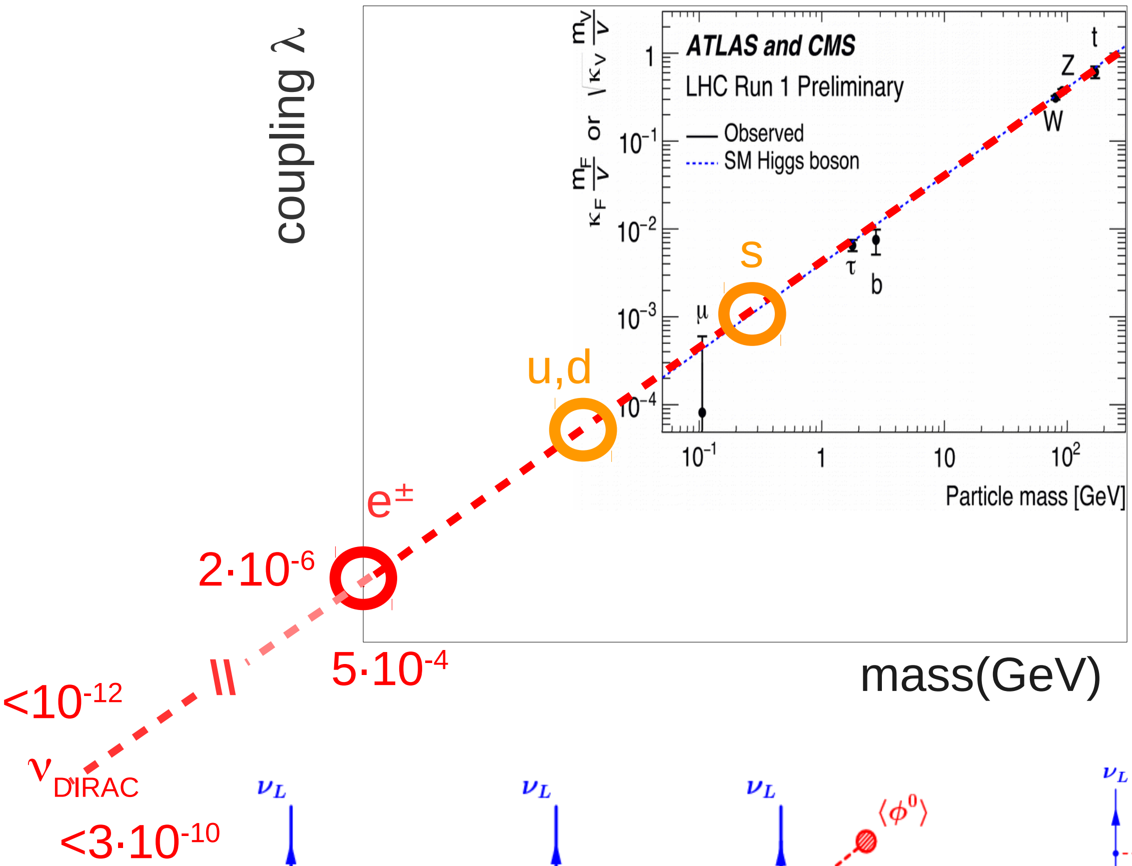
- Optimal data-taking point for min Δm_H(stat): $\sqrt{s} \simeq mZ+mH-0.2 \simeq 217$ GeV
- **$\sqrt{\sigma_{ZH}}(dm_H/d\sigma_{ZH})_{min}$=350 MeV/$\sqrt{fb}$** With 5/ab @ 217 GeV: $\delta m_H = \pm 5$ MeV

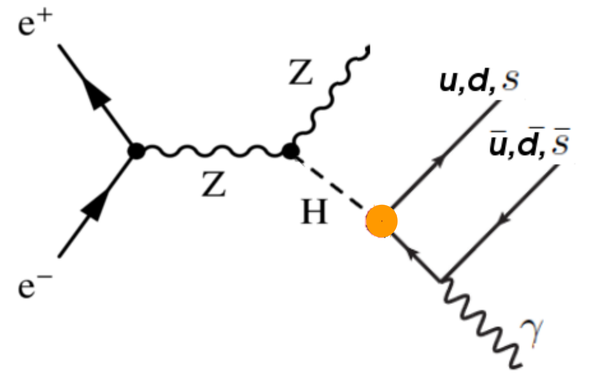
  Need systematics control: $\delta E_{beam} < 5$ MeV ($5\cdot 10^{-5}$), $\delta\varepsilon/\varepsilon$, $\delta L/L < 10^{-3}$, $\delta\sigma_B < 0.1$ fb ($\sim 10^{-3}$)

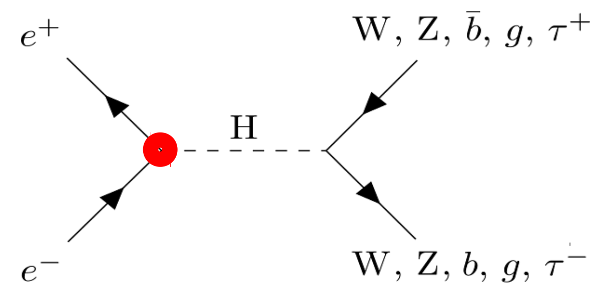
- Combining threshold HZ x-section with m_{HZ}(recoil) should give: $\delta m_H = \pm 3.5$ MeV

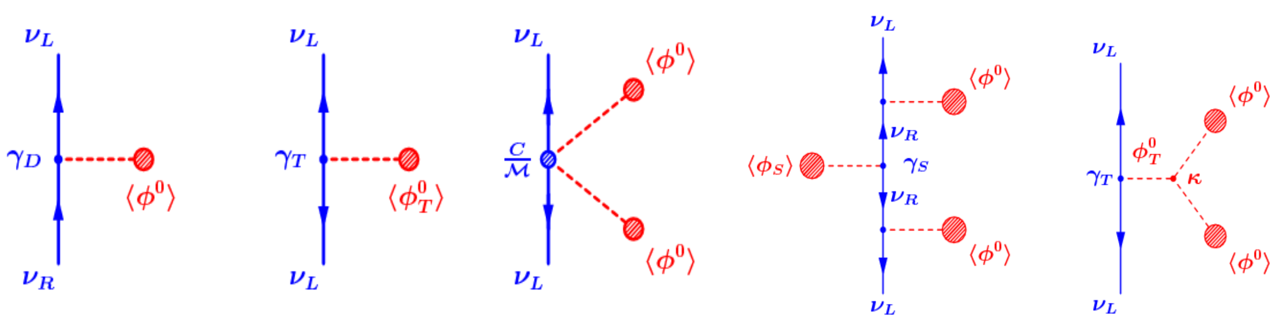
Generation of lightest fermion (u,d,s,ν's) masses?

- LHC can only access 3rd (plus few 2nd)-gen. Yukawas. What about the rest?



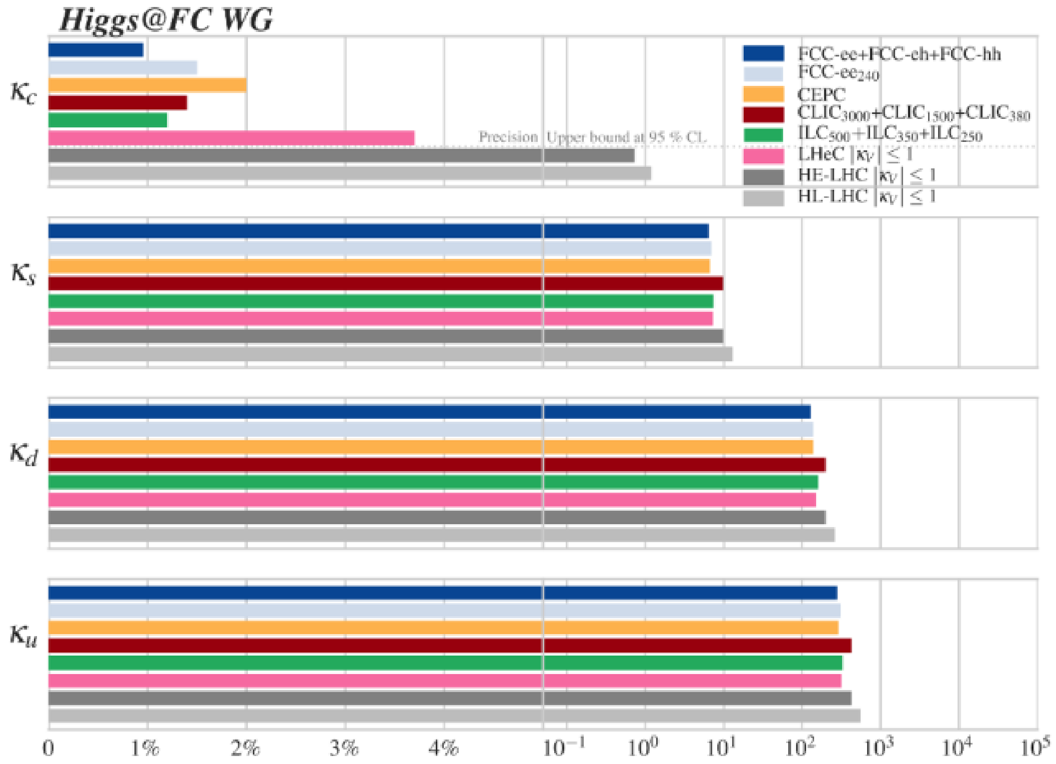






Light quarks Yukawas (FCC-pp, FCC-ee)

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

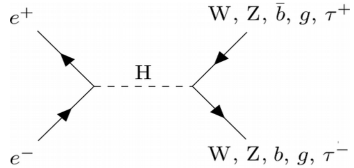


Limits from exclusive $H \rightarrow VM(\rho,\omega\phi)+\gamma$ decays ($BR \sim 10^{-6}$) to be studied/added

- 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%

e Yukawa via s-channel $e^+e^- \to H$ (FCC-ee)

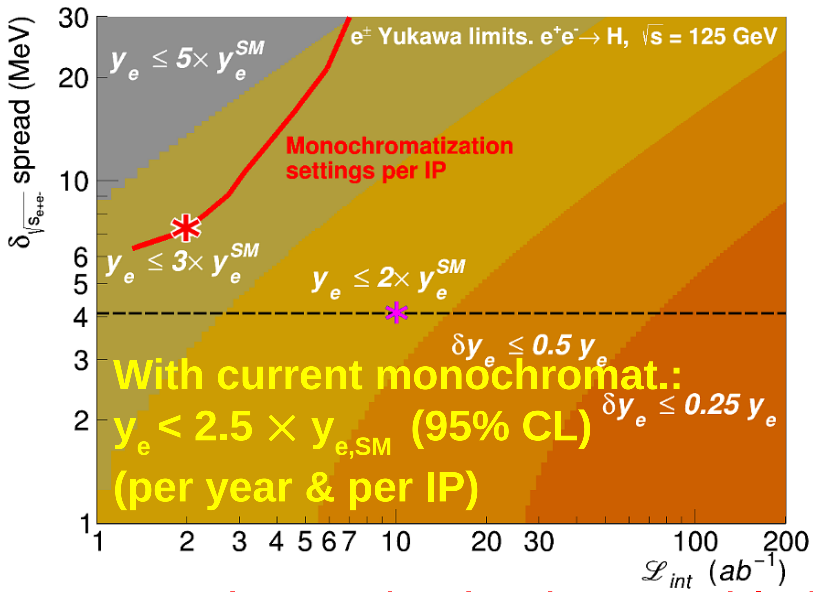
- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125.00 GeV):



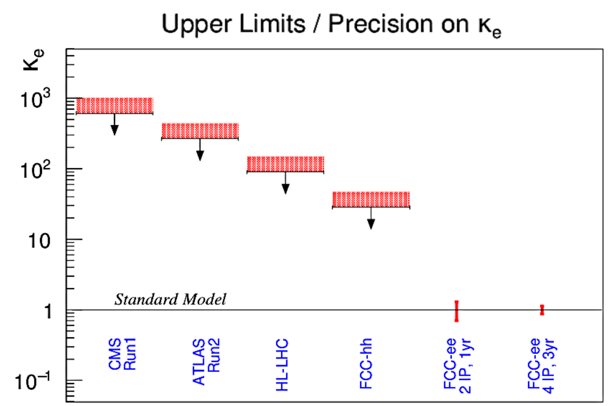
$\sigma(e^+e^- \to H)_{B\text{-}W}$ = 1.64 fb

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

- Prerequisite: Higgs mass extraction δm_H = O(3 MeV) via HZ @ 240,217 GeV
- Generator-level study for signal + backgrounds for 10 decay channels:
  Most significant channels: H→gg (for light-q mistag ~1%), H→WW*→l+jets



For 10 ab^{-1} & $\sqrt{s}_{spread} = \Gamma_H$: Signif ≈ 1.3σ



- Monochromatization improvable beyond ($\sqrt{s}_{spread}$, $\mathscr{L}_{int}$)≈(7 MeV, 2 ab^{-1})?
- Fundamental unique physics accessible:
  → Electron Yukawa coupling: Limits ×100 (×30) better than HL-LHC (FCC-hh)
  → BSM scale affecting e$^\pm$ Yukawa pushed up to Λ_{BSM} > 110 TeV

Physics at FCC e^+e^- & pp machines

(1) <u>QCD</u>: α_s coupling

(2) <u>QCD</u>: Parton Distribution Functions

(3) <u>QCD</u>: Jet substructure & flavour tagging

(4) <u>QCD</u>: Non-perturbative regime

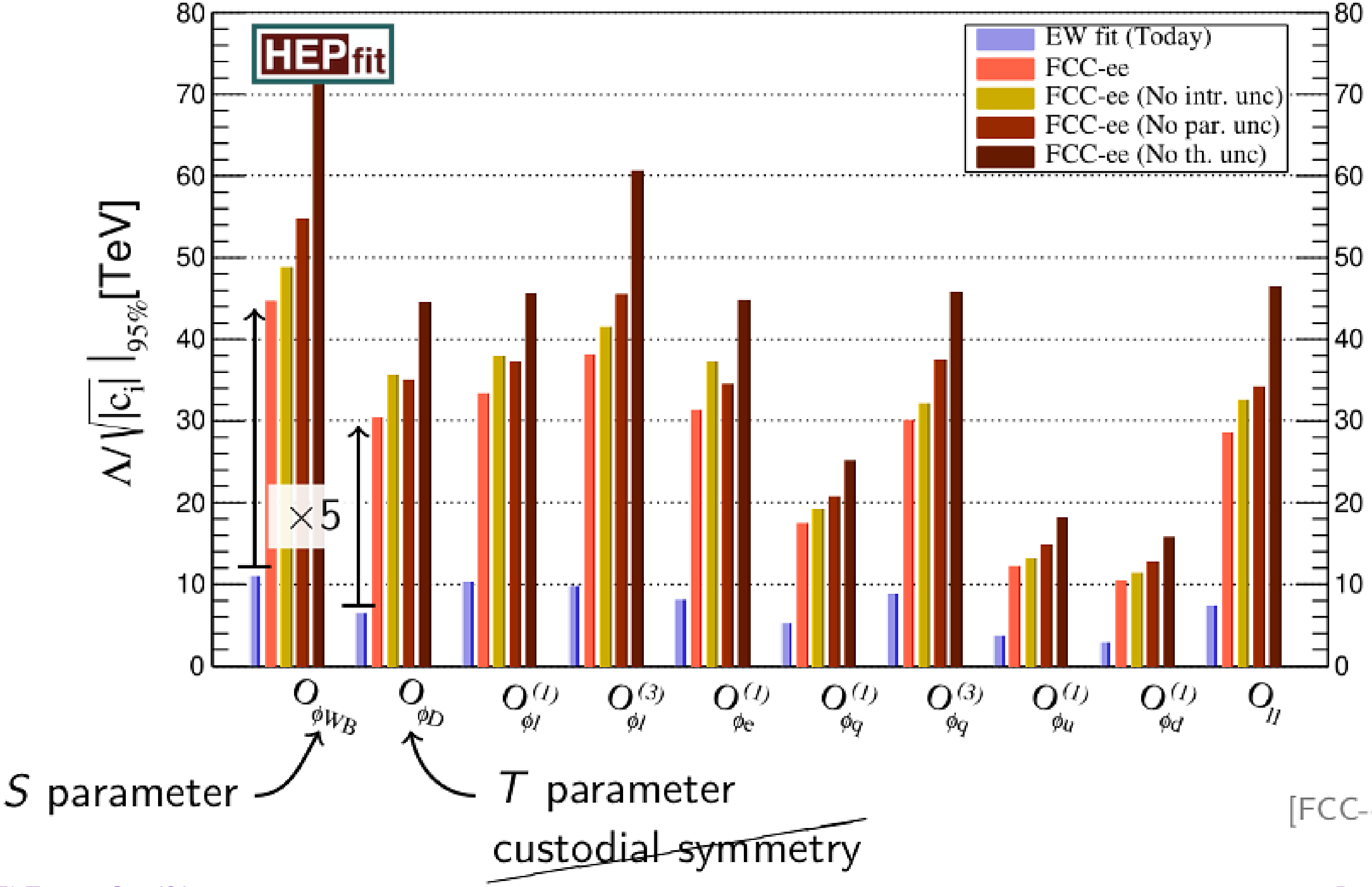
(5) Higgs sector

(6) BSM searches

Indirect BSM searches (EW coupled) at FCC-ee

- Indirect EW-coupled new physics EFT limits pushed up to O(50 TeV) thanks to ultraprecise EWPO measurements in e^+e^- collisions with 10^{12} Z's and 10^8 W's:

$(m_Z, \Gamma_Z, A_{FB}, R_x, \alpha(m_Z), m_W, m_t, \text{etc.})$

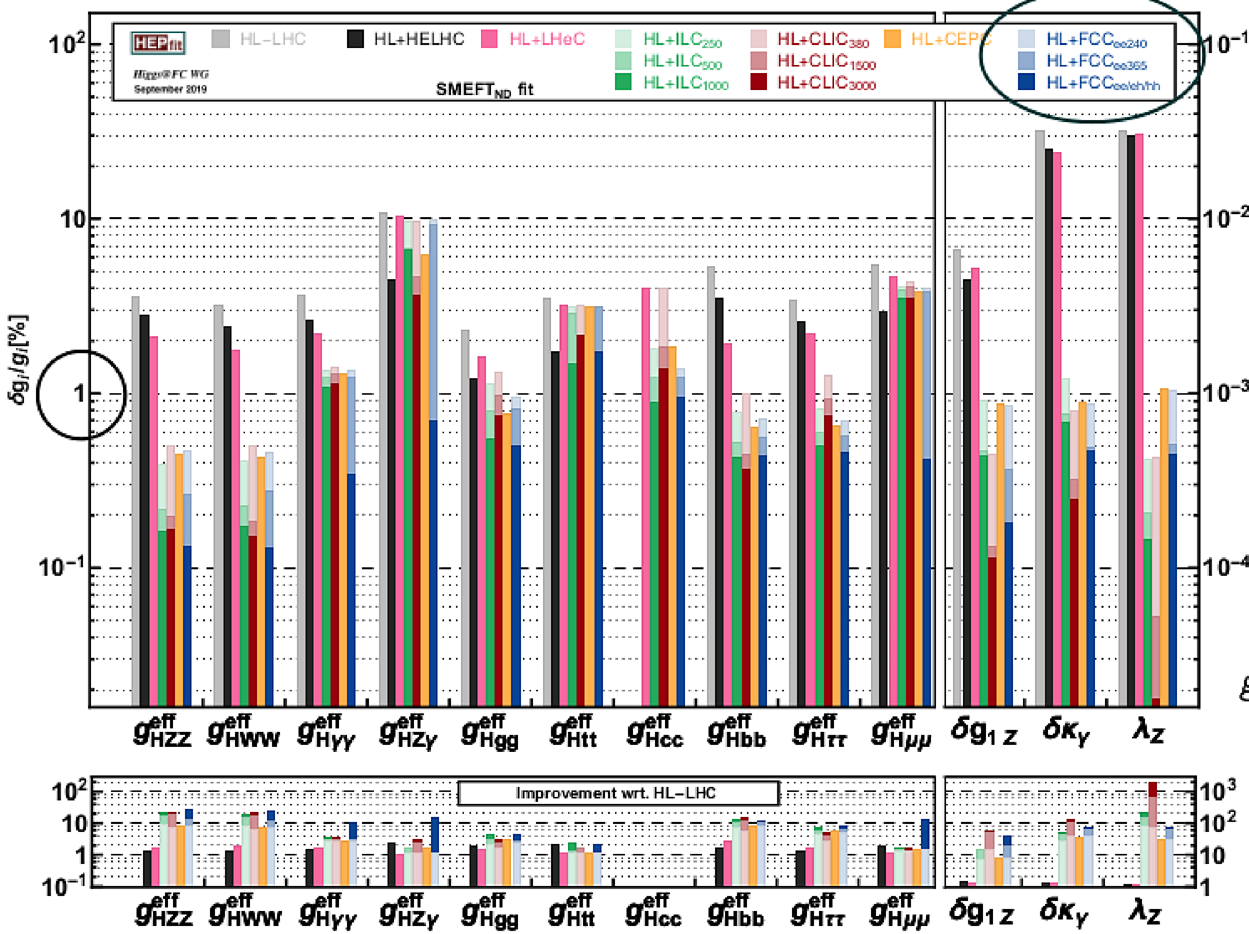


[FCC-ee CDR]

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 permil level:

[Higgs@FC '19]

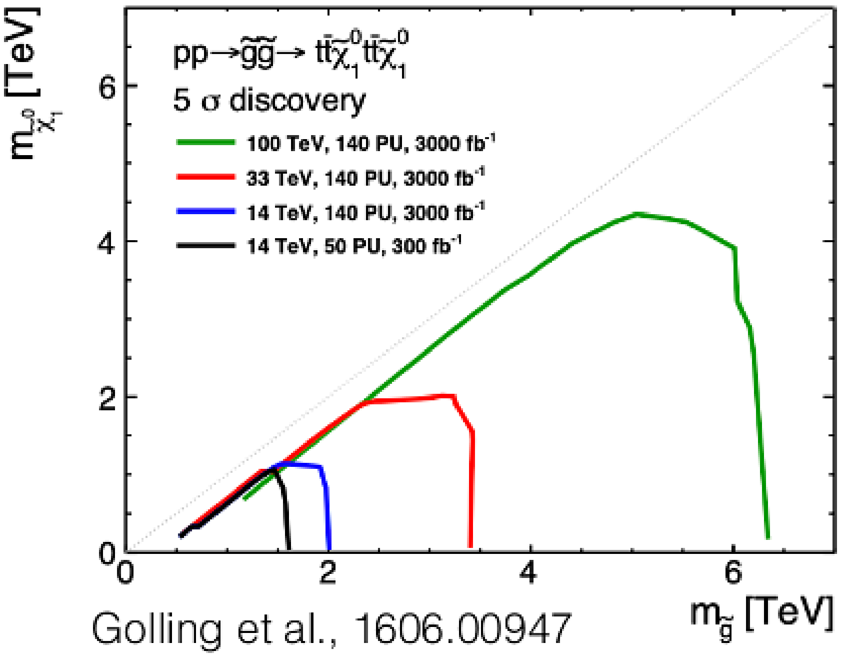


[Ellis,You '15]
[Ellis et al '17]
[de Blas et al '16]
[GD et al '17]
[Barklow et al '17]
[Barklow et al '17]
[Di Vita et al '17]
[Chiu et al '17]
[de Blas et al '19]

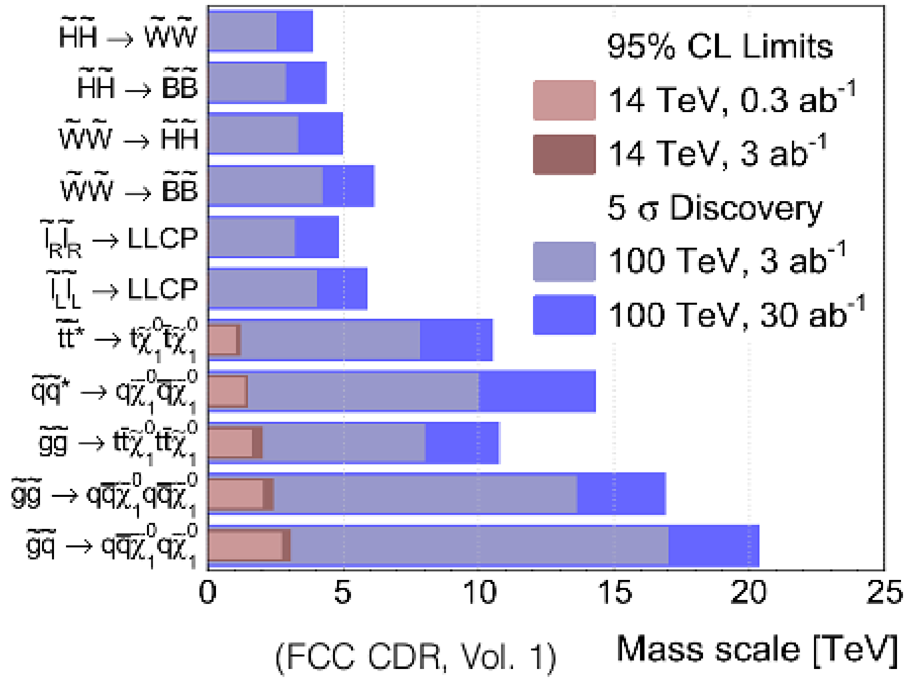
$$g^{\rm eff}_{HXX} \equiv \sqrt{\frac{\Gamma_{H\to XX}}{\Gamma^{\rm SM}_{H\to XX}}}$$

Direct BSM searches at FCC-hh

- Direct heavy-mass reach (e.g. SUSY) in p-p at 100 TeV is x(5-10) times LHC:



Golling et al., 1606.00947

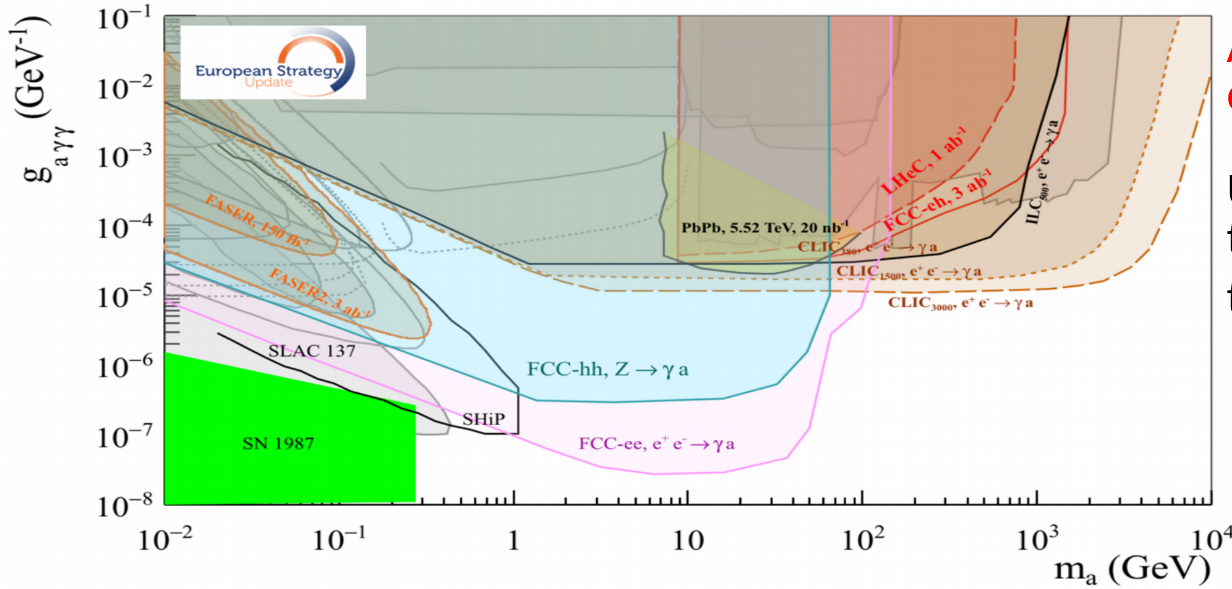


(FCC CDR, Vol. 1)

ε	High-scale mediation	Low-scale mediation
stop	$5\times10^{-5}\left(\frac{10\ \text{TeV}}{m_{\tilde{t}}}\right)^2$	$2\times10^{-3}\left(\frac{10\ \text{TeV}}{m_{\tilde{t}}}\right)^2$
gluino	$7\times10^{-6}\left(\frac{17\ \text{TeV}}{m_{\tilde{g}}}\right)^2$	$6\times10^{-3}\left(\frac{17\ \text{TeV}}{m_{\tilde{g}}}\right)^2$

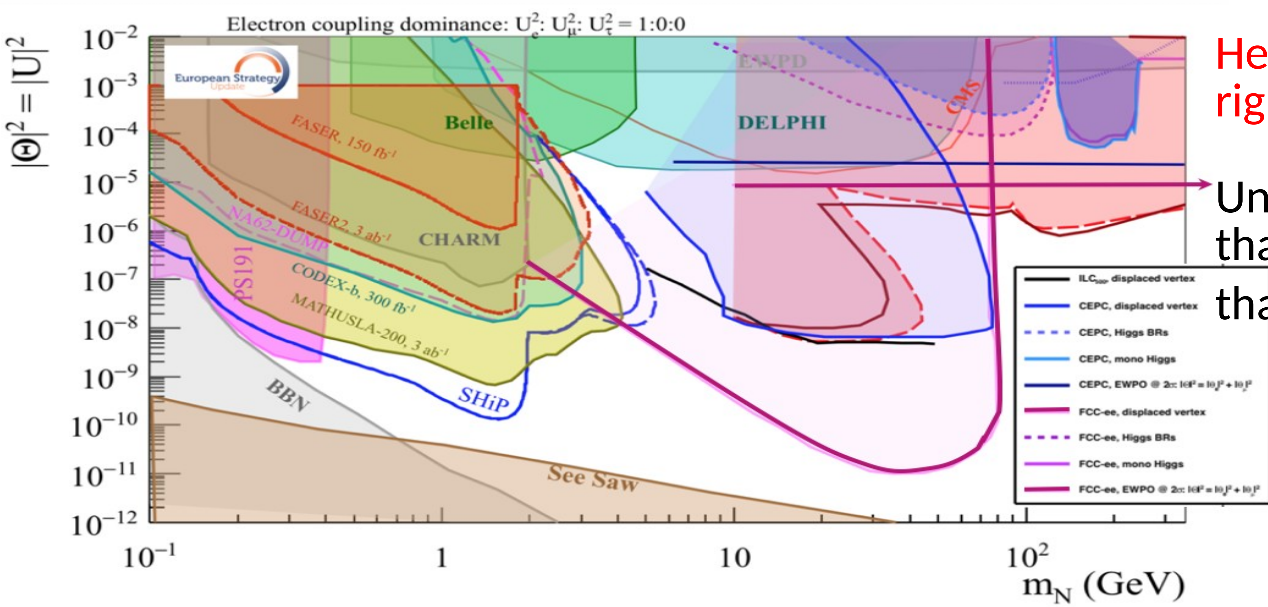
source: European Strategy briefing book

Direct BSM searches at FCC-ee: FIPs



Axion-like particles (ALPs), dilatons,...

Unique limits (up to x10^3 better than today) over m_a=1–100 GeV thanks to 10^{12} Z decays.

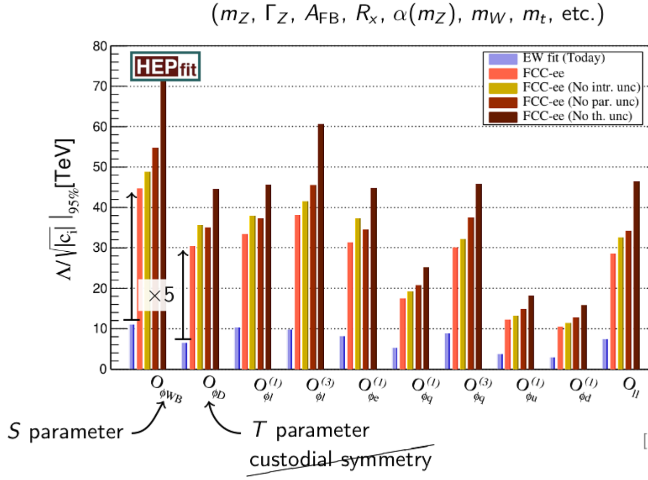


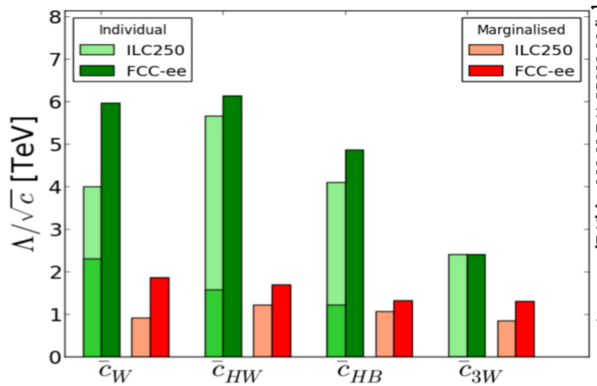
Heavy-neutral leptons (HNLs), right-handed (sterile) neutrinos,...

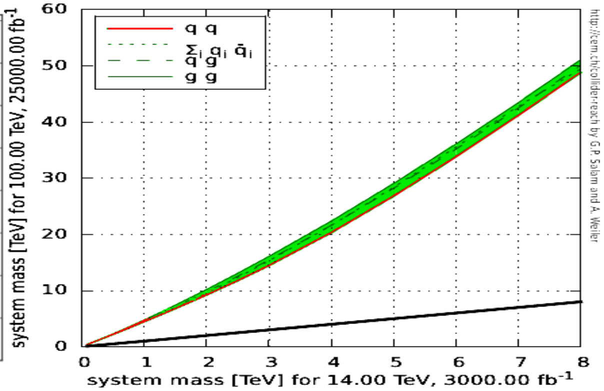
Unique limits (up to x10^3 better than today) over m_a=5–100 GeV thanks to 10^{12} Z decays.

Summary

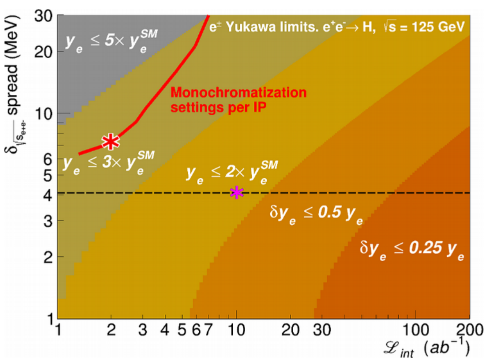
- FCC provides unparalleled c.m. energies (100 TeV) & lumis (20, 150 ab^{-1}) in p-p and e^+e^- colls. to address many HEP fundamental open problems.
- High-precision Z, W, H, top studies (FCC-ee) & high-mass (FCC-pp) allow setting direct/indirect constraints on BSM up to $\Lambda \gtrsim$ 50 TeV

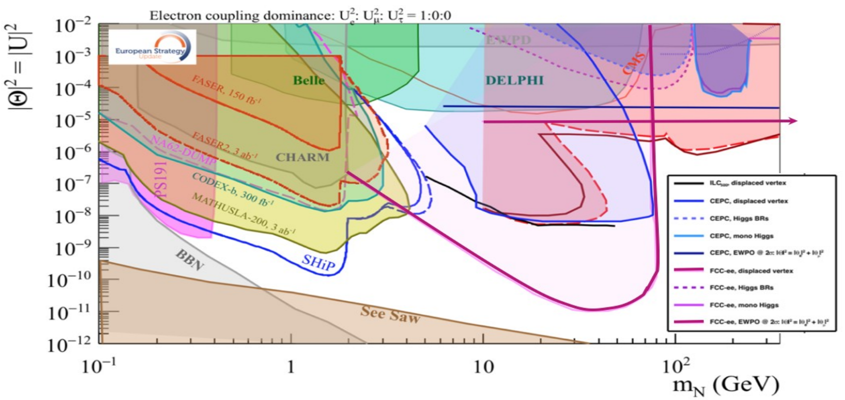


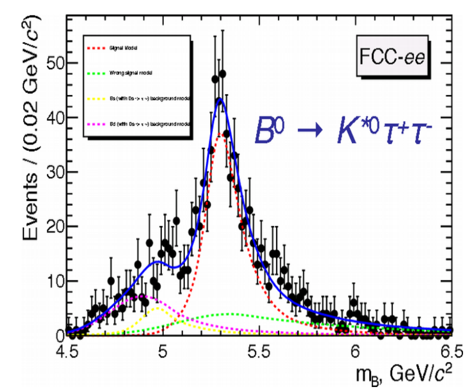




- Plus: 1st gen. Yukawas, right-handed ν's, dark matter, QCD, flavour, ...



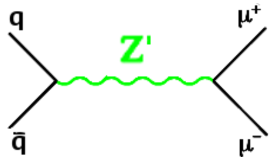




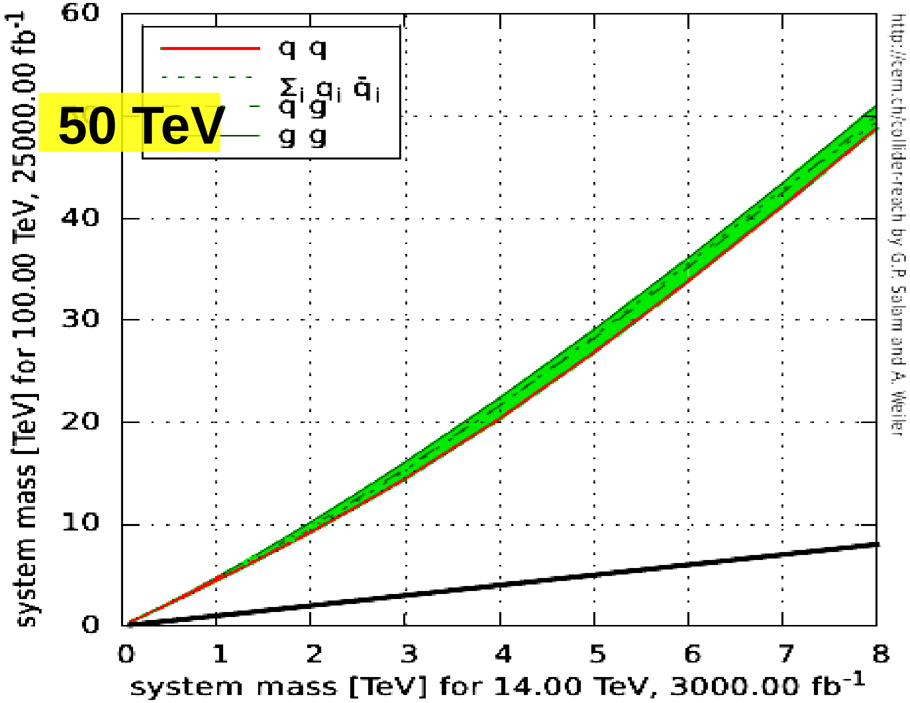
Backup slides

BSM physics reach at FCC

- FCC-pp: Direct production of new heavy particles up to ~50 TeV (~8 TeV at LHC):

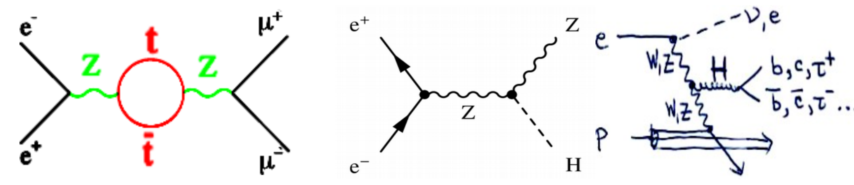


Parton-parton masses: FCC vs. LHC

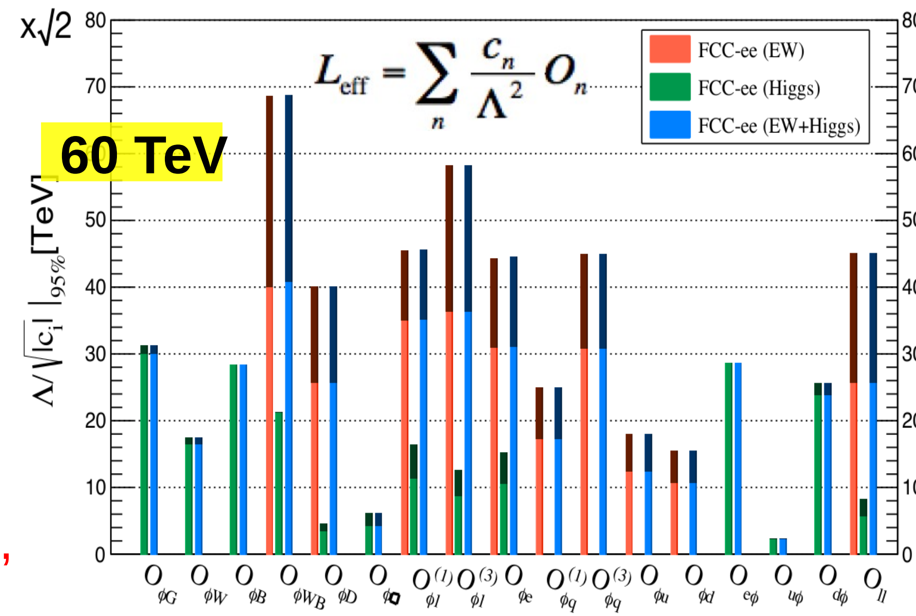


- Plus many more: Higgs self-coupling, TeV-p_T W,Z,H,t; WW scatt., DM,...

- FCC-ee,eh: Indirect sensitivity to virtual corrections up to ~60 TeV (~3 TeV at LEP for EWK sector):

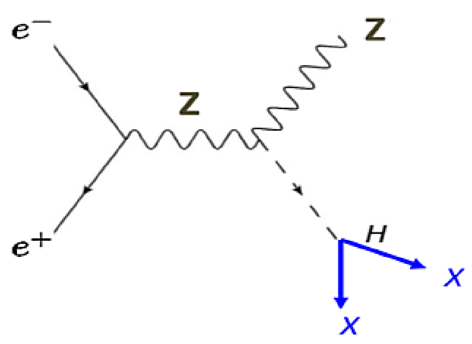


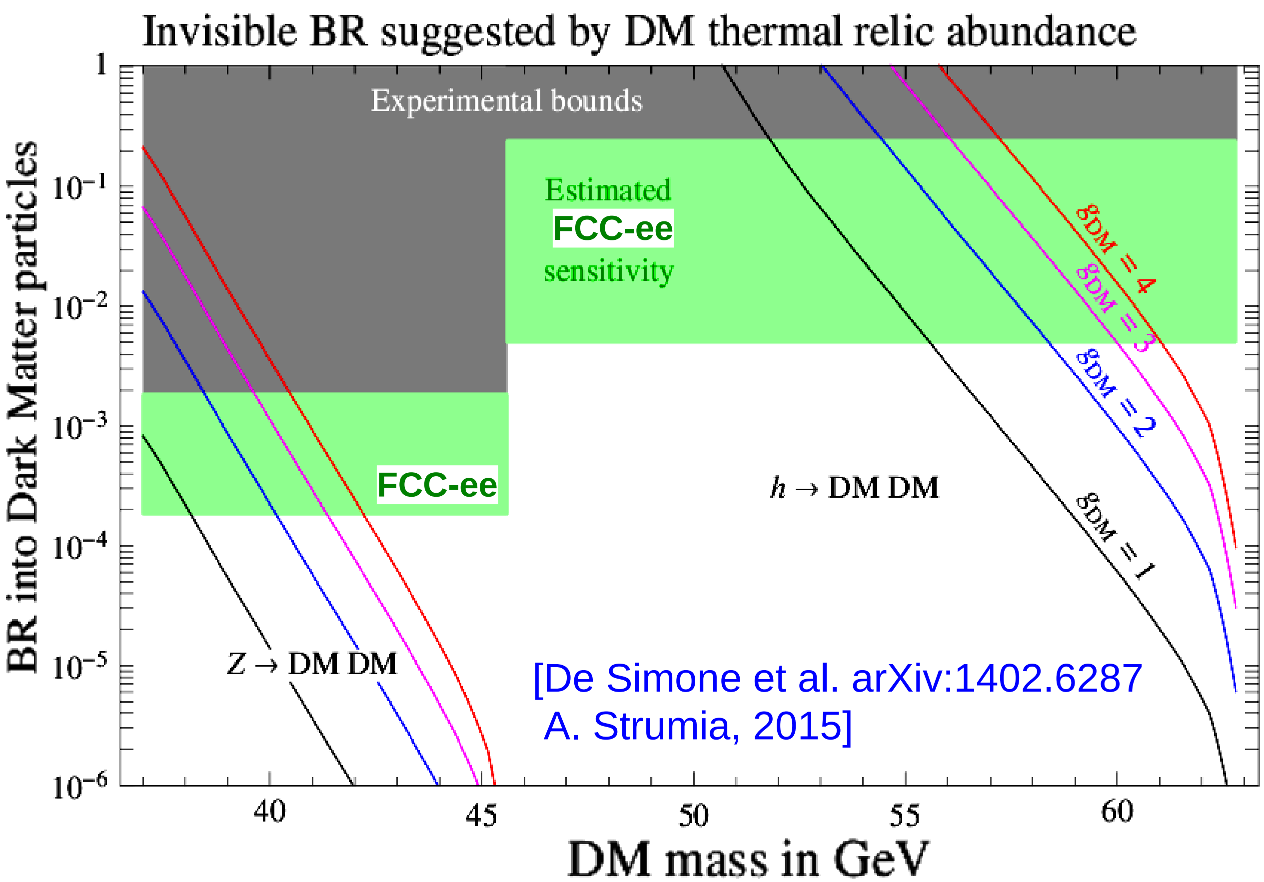
SM-EFT limits from EWK ($\delta X<10^{-5}$) and Higgs ($\delta g_H<1\%$) observables uncertainties:



Direct BSM searches at FCC-ee: DM via H,Z decays

- DM freeze-out fixes $\sigma v \approx 3\ 10^{-26} cm^3/s$. If m_{DM} is just below $m_{Z,H}/2$, DM freeze-out dominated by resonant Z,H exchange, fixing $\Gamma_{Z,H}$.





- Precision ($<10^{-3}$ and $<10^{-1}$) measurements of invisible Z & H widths are best collider option to test any $m_{DM}<m_{Z,H}/2$ that couples via SM mediators.

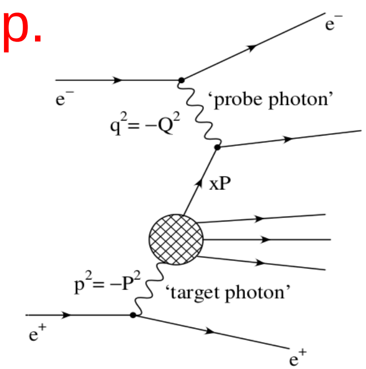
α_s from photon QCD structure function (NLO)

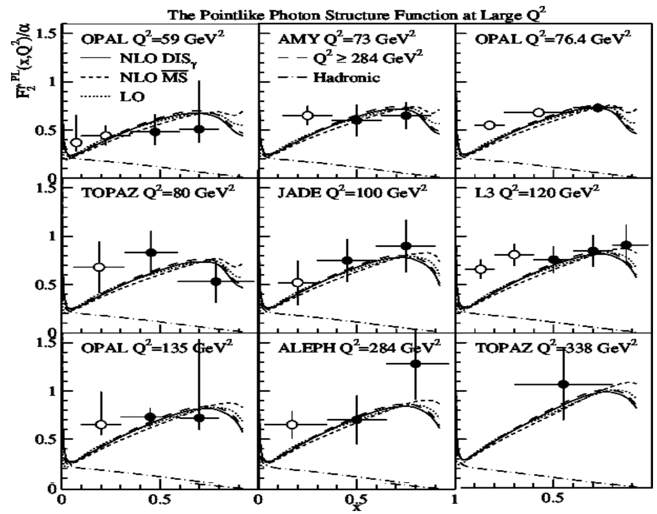
- Computed at NNLO: $$\int_0^1 dx F_2^{\gamma}(x,Q^2,P^2) = \frac{\alpha}{4\pi}\frac{1}{2\beta_0}\left\{\frac{4\pi}{\alpha_s(Q^2)}c_{LO} + c_{NLO} + \frac{\alpha_s(Q^2)}{4\pi}c_{NNLO} + \mathcal{O}(\alpha_s^2)\right\}$$
- Poor $F^2_{\gamma}(x,Q^2)$ experimental measurements:
- Extraction (NLO) with large exp. uncertainties today:

α_s (m$_z$) = 0.1198 ± 0.0054

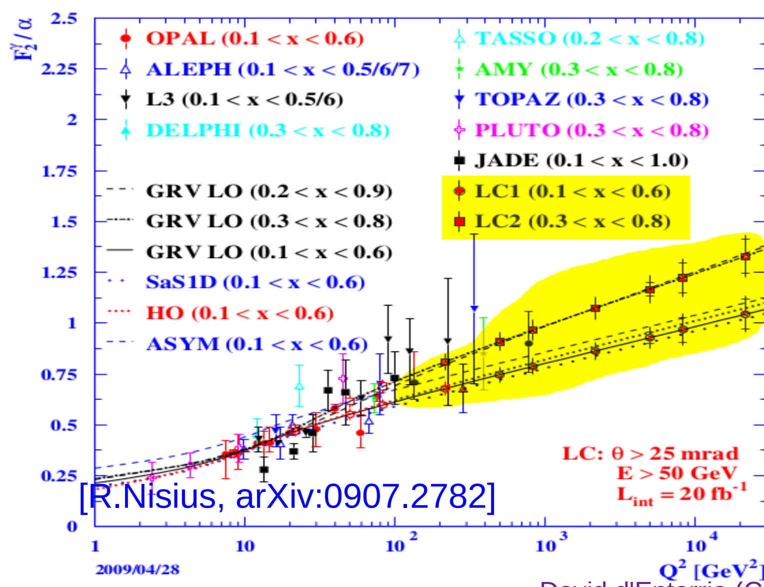
(±4.5%)

[M.Klasen et al. PRL89 (2002)122004]





- Future prospects:
  - Fit with NNLO F^2_{γ} evolution (ongoing)
  - Better data badly needed: Belle-II ?
  - Dedicated simul. studies at ILC exist:
  - Huge $\gamma\gamma$ (EPA) stats at FCC-ee will lead to: **$\delta\alpha_s/\alpha_s$ < 1%**

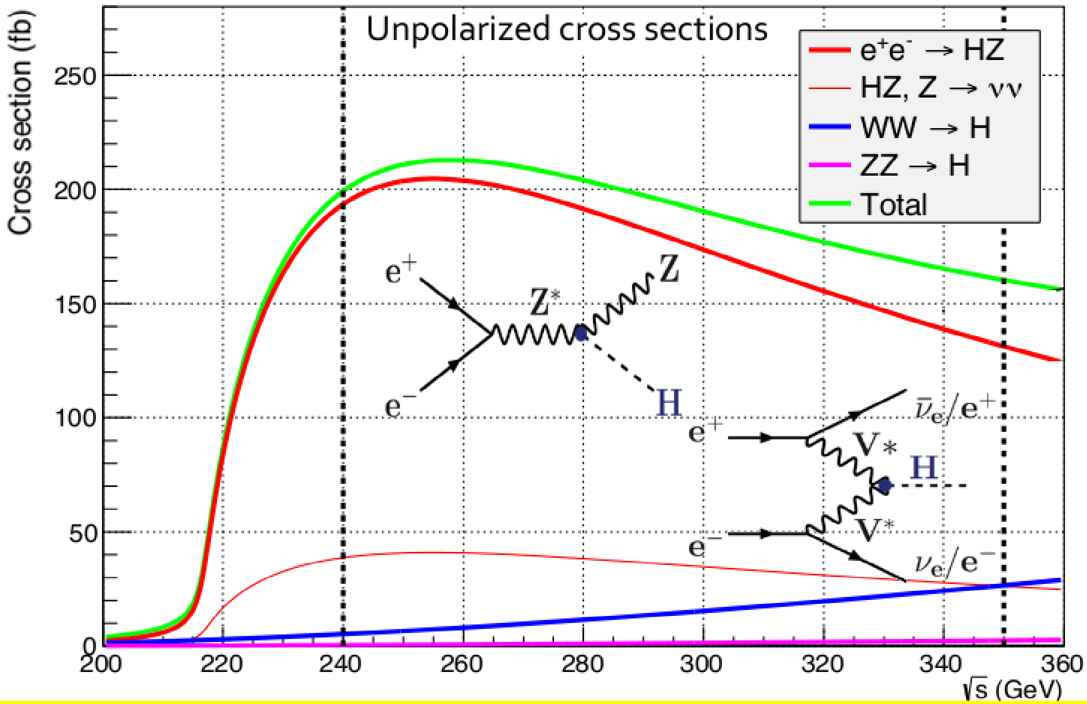


[R.Nisius, arXiv:0907.2782]

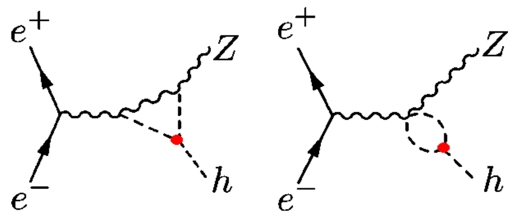
FCC-ee = Higgs boson factory

- Higgs cross sections: $\sigma(e^+e^- \to H+X) \approx 200$ (HZ)+ 50 (VBF) fb
- 1.2M Higgs bosons produced:
  - Small & very well controlled backgrounds (S/B~10^{-2}–10^{-3})
  - Extra-clean environment w/o pileup:

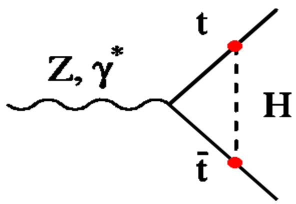
	5/ab @ 240 GeV	0.2/ab @ 350 GeV 1.5/ab @ 365 GeV
# Higgs from HZ	1,000,000	200,000
# Higgs from VBF	25,000	50,000



(sensitivity to self-coupling)



(sensitivity to top y_t)

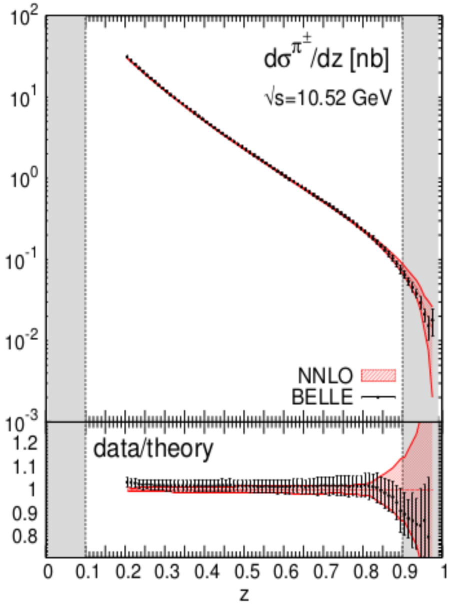


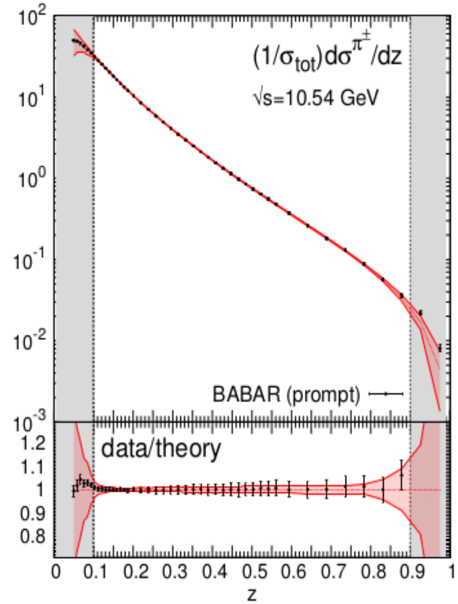
- Access to precise (down to 0.15%) Higgs couplings & rare & BSM decays

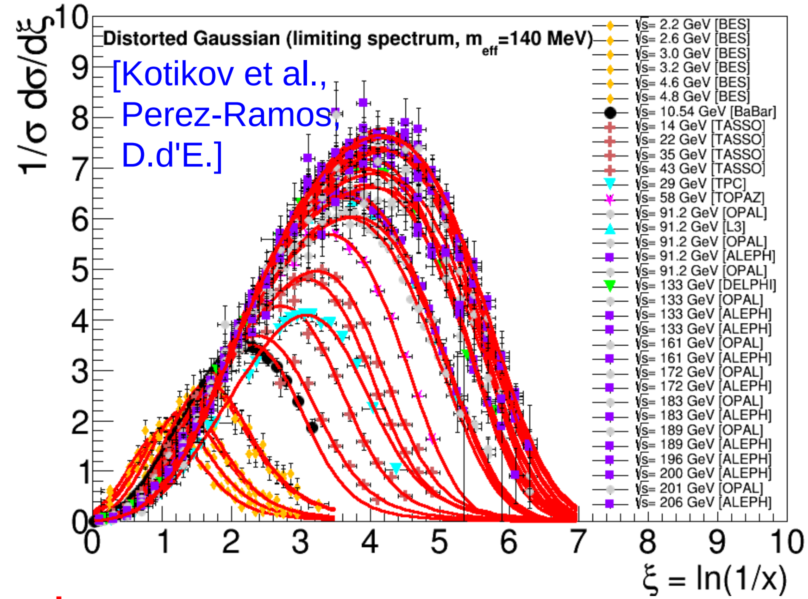
High-precision parton FFs (FCC-ee)

- Parton-to-hadron fragment. functions evolution known at NNLO at high-z & at NNLO*+NNLL at low-z:

[D.Anderle et al., A.Vossen et al., B.Kniehl et al., V.Bertone et al., N.Sato et al., D.deFlorian et al.,...]







provide additional QCD coupling extractions:

Method	Current $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment state-of-the-art)	Future $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment progress)
soft FFs	$1.8\%_{th} \oplus 0.7\%_{exp} \approx 2\%$ (NNLO* only (+NNLL), npQCD small)	$0.7\%_{th} \oplus 0.7\%_{exp} \approx 1\%$ (∼2 yrs), $<1\%$ (FCC-ee) (NNLO+NNLL. More precise e^+e^- data: 90–350 GeV)
hard FFs	$1\%_{th} \oplus 5\%_{exp} \approx 5\%$ (NLO only. LEP data only)	$0.7\%_{th} \oplus 2\%_{exp} \approx 2\%$ (+B-factories), $<1\%$ (FCC-ee) (NNLO. More precise e^+e^- data)

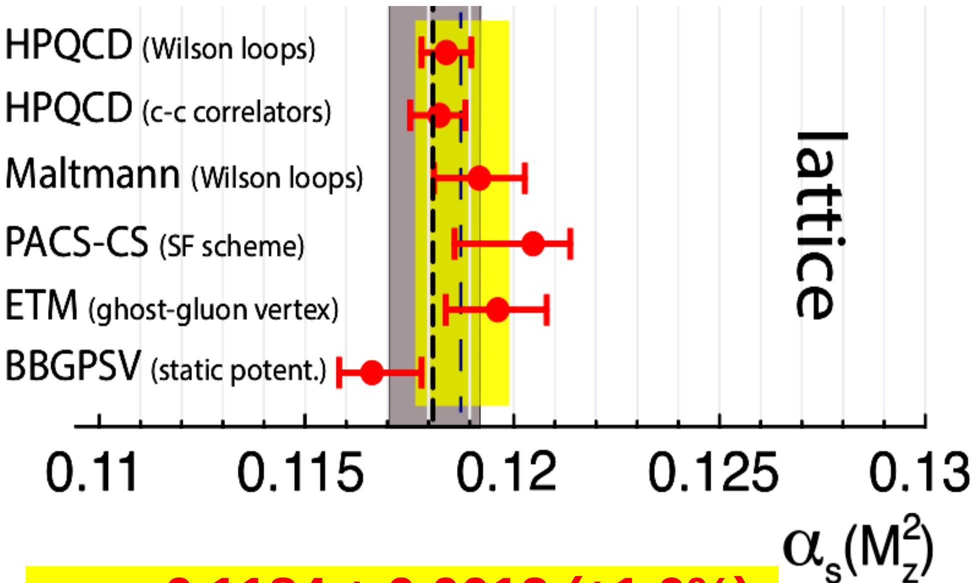
- FCC-ee (much broader z range) allows for α_s extraction with **$\delta\alpha_s < 1\%$**

α_s from lattice QCD

- Comparison of short-distance quantities (Wilson loops, q static potential, vacuum polariz.,...) computed at NNLO in pQCD, to lattice QCD "data":

$$K^{\mathrm{NP}} = K^{\mathrm{PT}} = \sum_{i=0}^{n} c_i \alpha_s^i$$

[FLAG Collab. http://itpwiki.unibe.ch/flag]



- Currently, it's extraction with smallest uncertainties: ±1% (lattice spacing & statistics).

  Extracted value depends on observables:

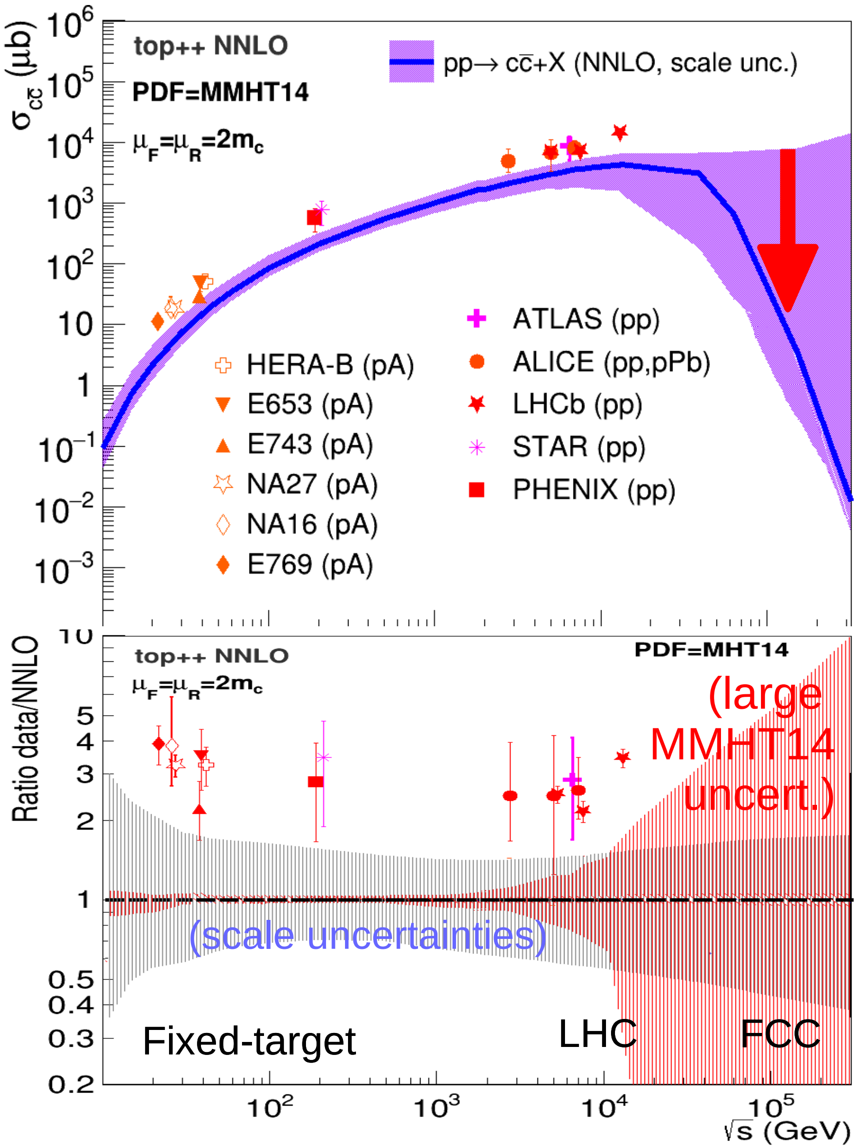
  Uncertainty increased: 2013 (±0.4%) → 2017 (±1.0%)

α_s = 0.1184 ± 0.0012 (±1.0%)

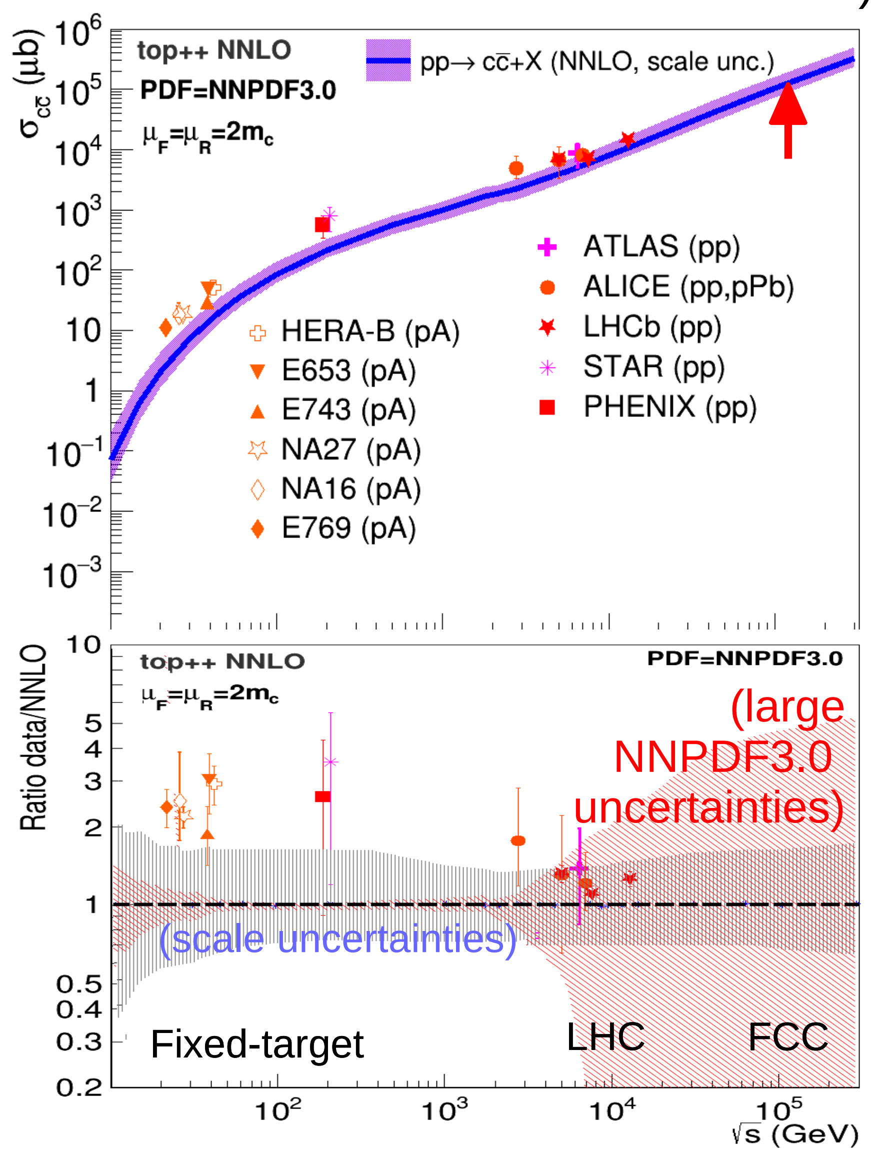
- Future prospects:
  - Uncertainty in α_s could be halved with (much) better numerical data.
  - Reaching ±0.1% requires 4th-loop perturbation theory (~10 years?)

Heavy-quark production (FCC-pp)

- Charm: Data ×2.5 theory (negative gluon at very low x, √s>30 TeV)

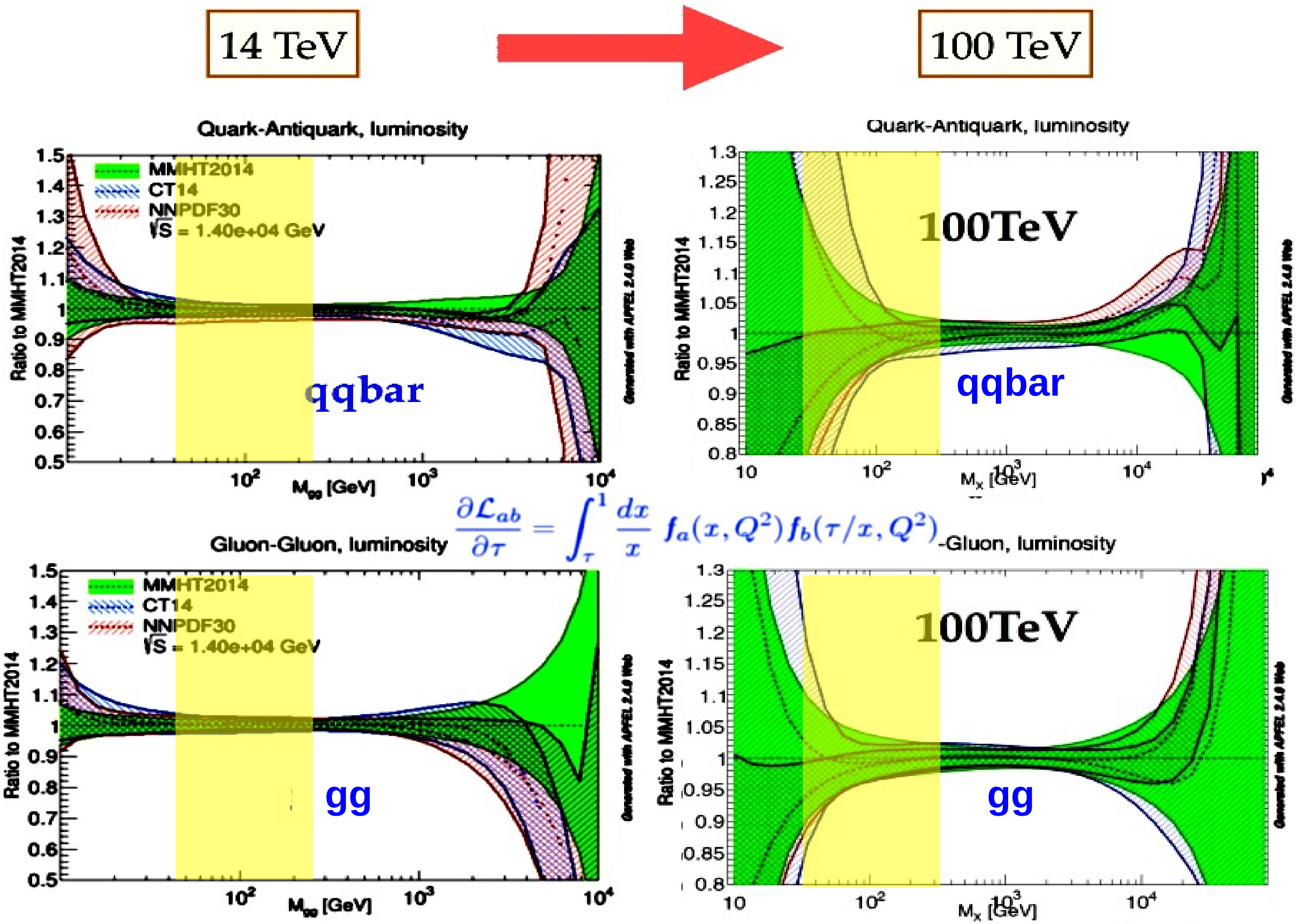


- Charm: Data ×2 theory (agreement within uncert. but "kink" at √s>10 TeV)



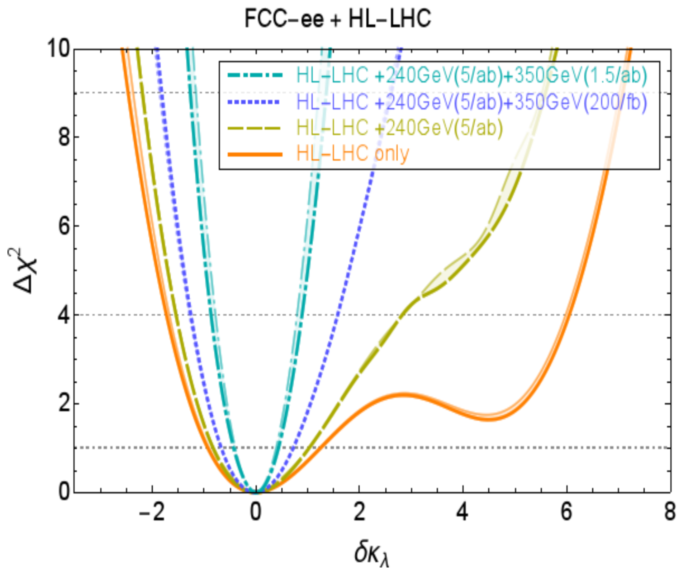
Parton lumis at FCC "precision" region

- "Precision" region at FCC-pp: **5–7%** PDF uncertainty for σ(W,Z,H)

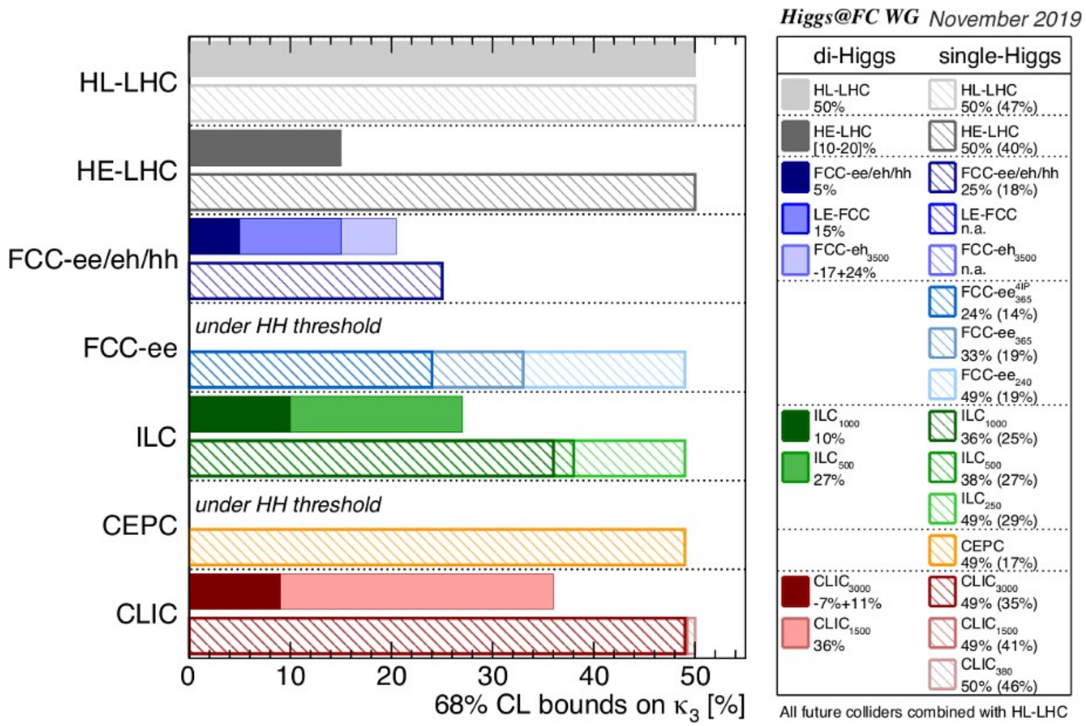


$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_{\tau}^{1} \frac{dx}{x} f_a(x, Q^2) f_b(\tau/x, Q^2)$$

Higgs self-coupling (λ_3) at FCC-ee

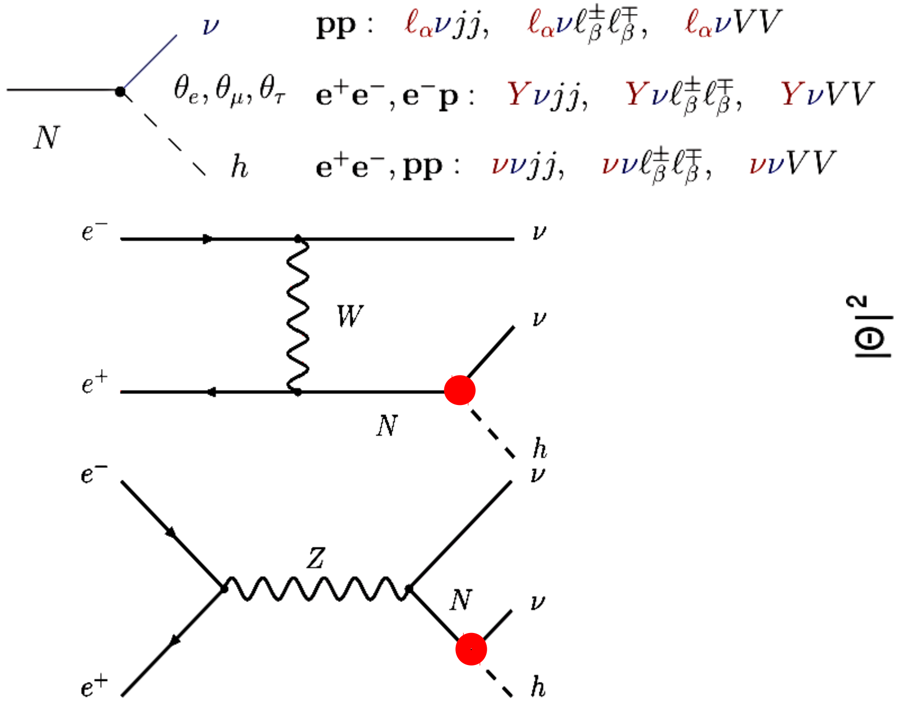


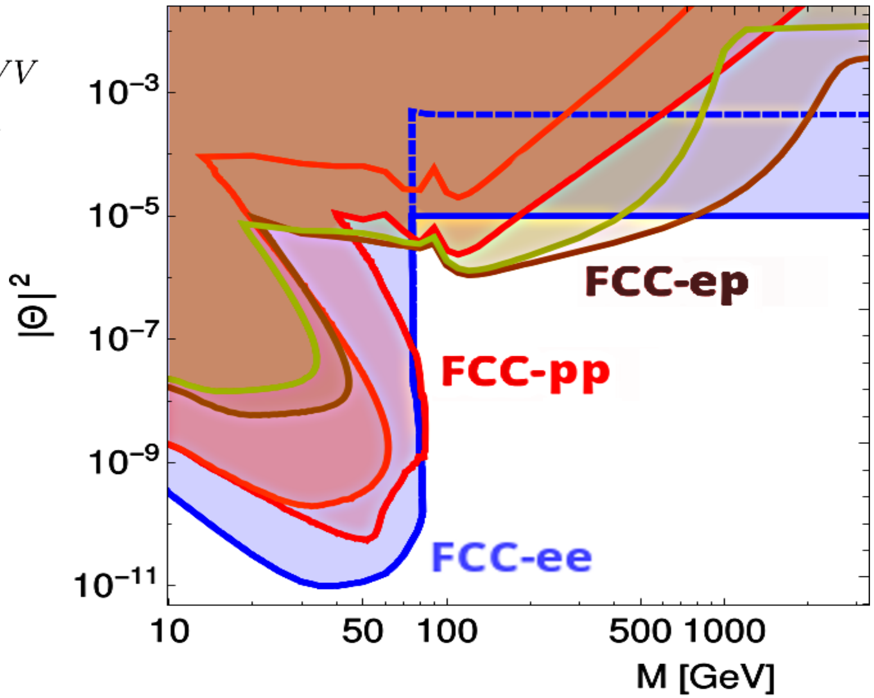
- Higgs self-coupling constrained to within ~40%.
- Addition of FCC-ee 240+350GeV Higgs cross section solves 2nd minimum on λ from HL-LHC data alone.
- Final Higgs self-coupling precision (FCC-all): 2–3%



Higgs coupling to neutrinos (FCC-ee,hh)

- Low-mass seesaw scenario with sterile ν (N_i) that mix with the SM ν with O(1) Yukawa couplings & EW-scale masses.
- N_i decay to Higgs+ν. Exp. signature: mono-Higgs(jj+ME).





(Also via invisible $H \rightarrow N_i\nu$ decays for $m_N < m_H$)

[Antusch, Cazzato, Fischer, IJMPA 32 (2017)1750078]

- With Z (EWPO), sensitivity down to active-sterile mix $|\theta|^2 \sim 10^{-11}$ for $m_N > 10$ GeV