QCD physics at the Future Circular Collider

EU Particle Physics Strategy Update

1st meeting of SM and BSM WG (GT1)

(Virtual), 4th Oct. 2024

David d'Enterria

CERN

FUTURE CIRCULAR COLLIDER

Particle physics at the end of 2024

- Apart from the Higgs discovery, all fundamental questions that motivated the LHC still remain open! *DM, matter-antimatter asymm., EW-Planck hierarchy, ν masses, strong CP problem, DE, cosmol.const, inflation,...*
- World priority is a high-precision Higgs factory to precisely probe the crucial scalar sector of the SM.
- FCC-ee Feasibility Study:
  - Model-indep. Higgs couplings down to 0.1%: Indirect BSM up to $\Lambda \approx 7$ (70) TeV (+EW observ.)
  - Higgs Yukawa couplings to lightest fermions (u,d,s,e,ν?,DM?) Flavor-violating $H \rightarrow qq'$ decays?
- Followed by energy-frontier hadron collider (FCC-hh): H selfcoupling + direct BSM searches up to $\Lambda \approx 100$ TeV

3

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

• ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

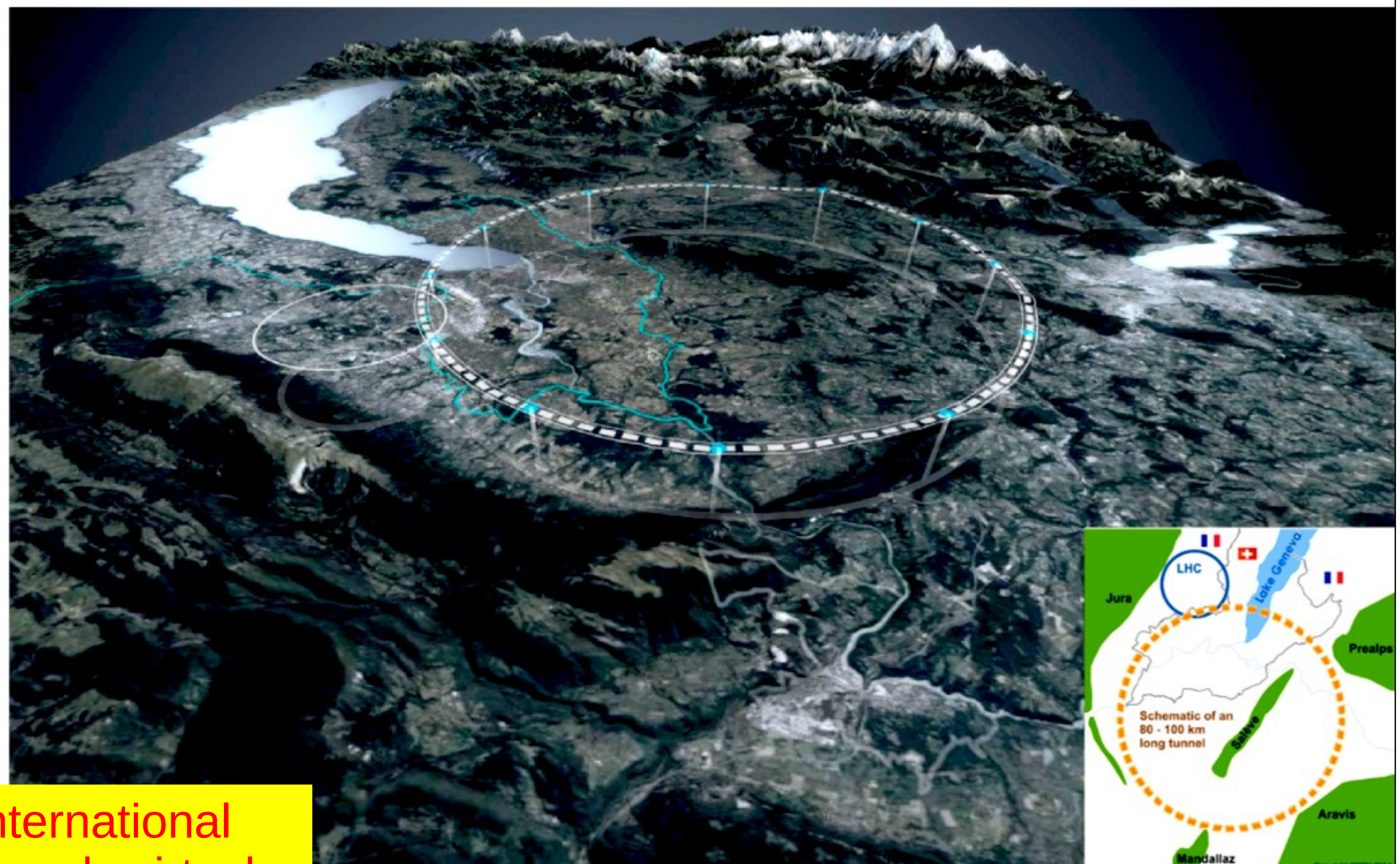
• ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility 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.***

CERN Future Circular Collider (FCC)

- 90.7 km tunnel
- 4 experimental sites
- Deepest shaft 400 m, average 240 m

Two stages

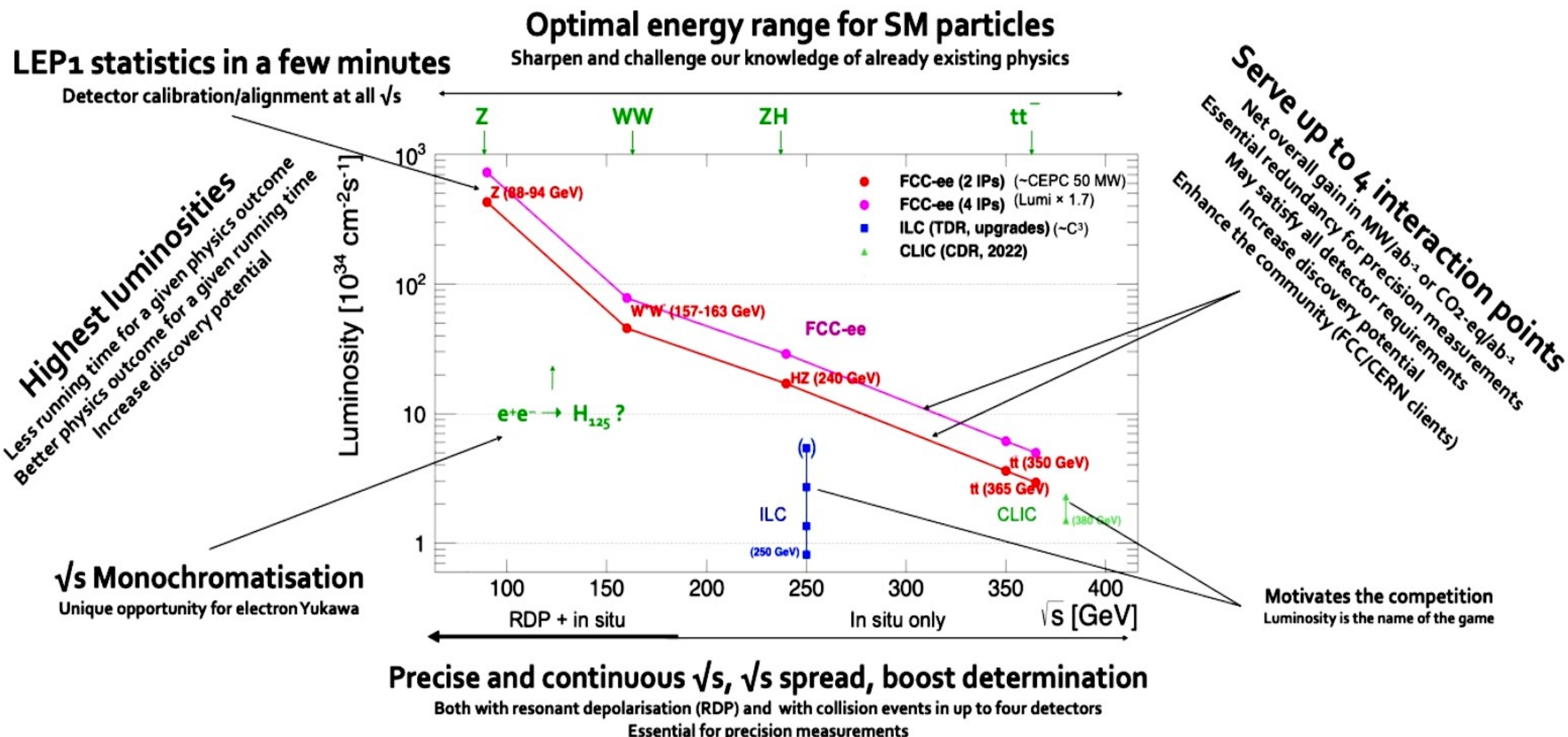
- FCC-ee (~15 years)
- FCC-hh (>20 years)



Exploit world-class international community, facilities, and sci-tech *savoir-faire* accumulated at CERN over the last 70 years!

"I believe FCC is the best project for CERN's future, we need to work together to make it happen"
- Fabiola Gianotti, FCC Week London, 5th June 2023

Impressive FCC-ee luminosities



$6{\cdot}10^{12}$ Z bosons

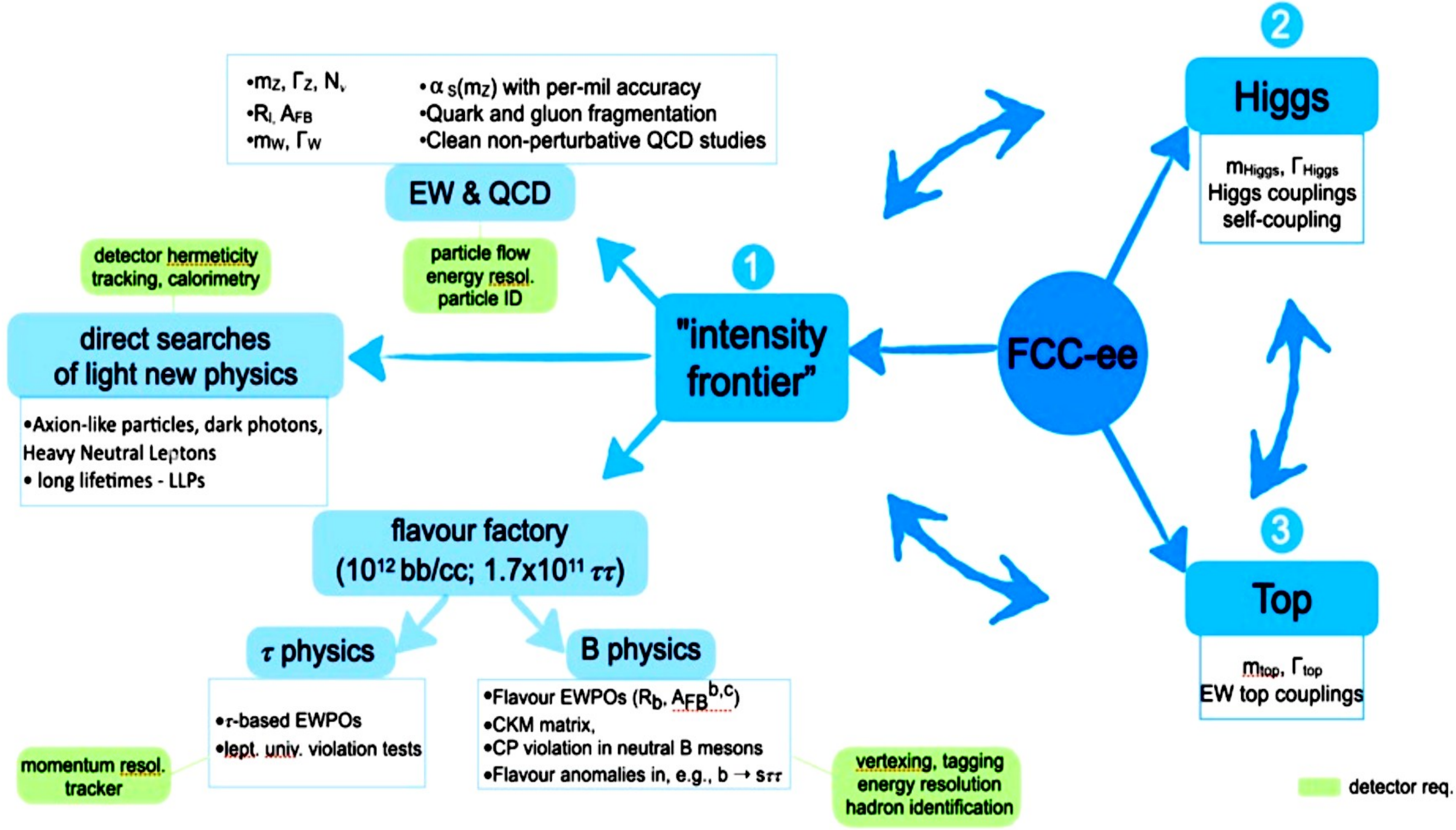
$5{\cdot}10^{8}$ W bosons

$2{\cdot}10^{6}$ Higgs bosons

$4{\cdot}10^{6}$ top quarks

Heaviest SM particles (plus their u,d,s,c,b,g decay jets for QCD studies) probed in pristine conditions...

Very broad FCC-ee physics programme



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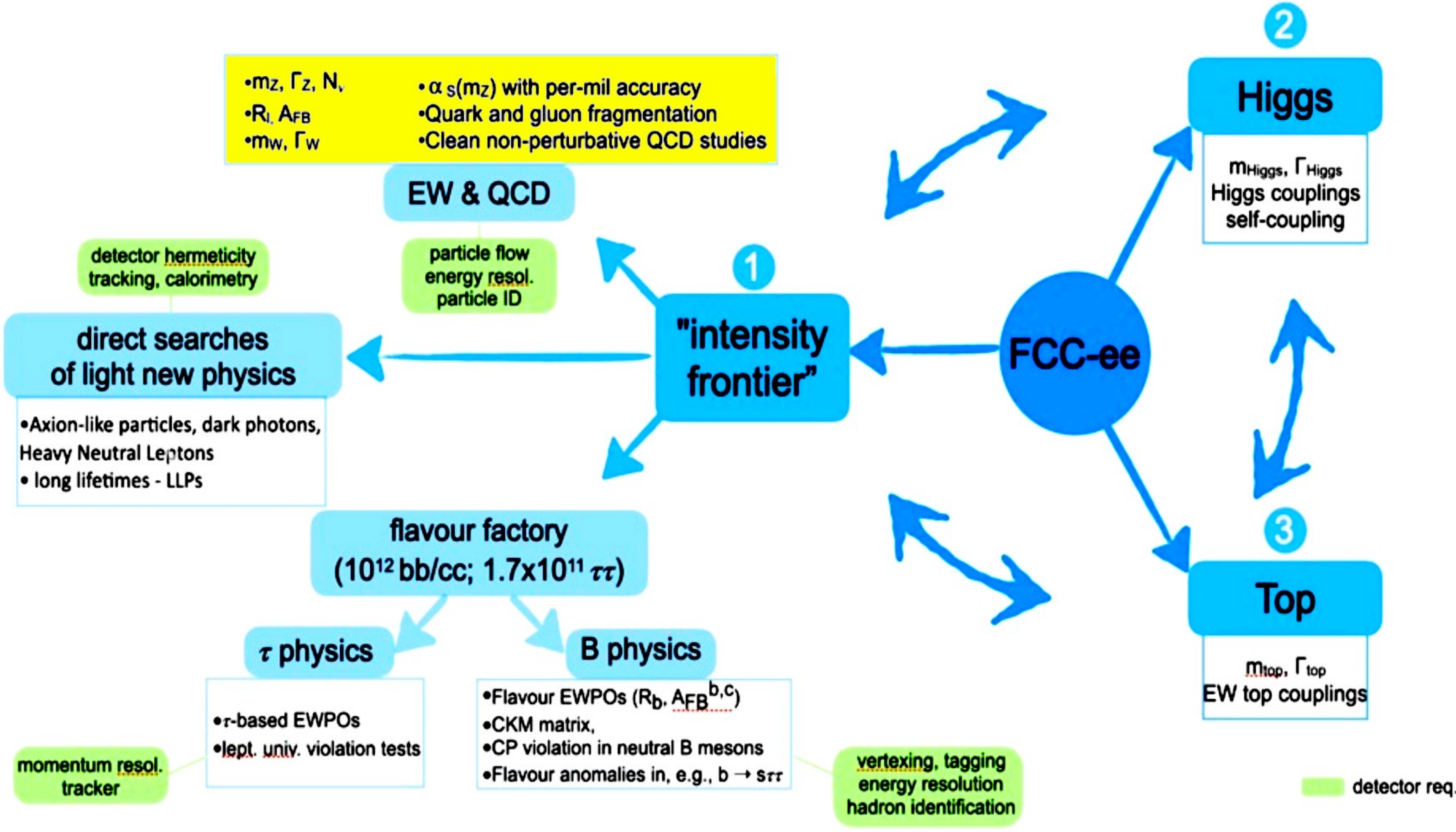


QCD at the core of future e^+e^- colliders

- Though QCD is not per se the driving force for FCC-ee, it is crucial for a huge range of studies:
  - 70–80% of H, Z, W boson decays have fully hadronic final states!

1. Precise α_s determination is needed to accurately & precisely predict all SM x-sections & decay rates (Higgs, top, EWPOs,...)

2. Higher-order (N^nLO, N^nLL) calculations crucial to gain precise control over hadronic final states & jet dynamics.

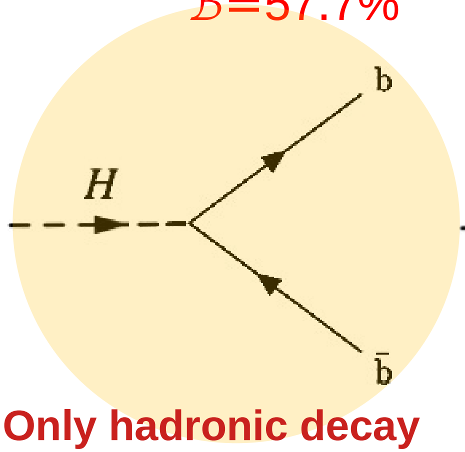
3. Heavy/light quark & gluon separation (flavour tagging, substructure,...) is key for multiple SM measurements (H Yukawas,...) and BSM searches ($X \rightarrow jj$ decays,...).

4. Non-perturbative QCD (hadronisation, colour reconnection,...) impacts studies with hadronic final states: $e^+e^- \rightarrow WW$,ttbar ($\rightarrow$jets), m_W, m_{top} extractions.

QCD at the core of the Higgs e^+e^- programme

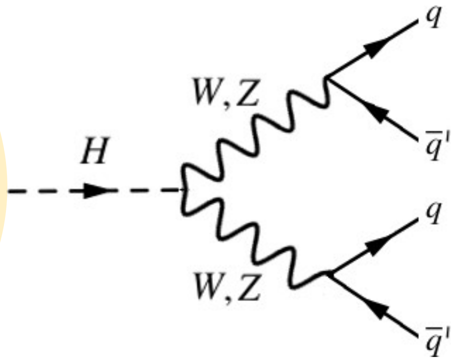
- 80% of the Higgs decays are fully hadronic! (Light Yukawas, FCNC Higgs...)

$\mathcal{B}$=57.7%

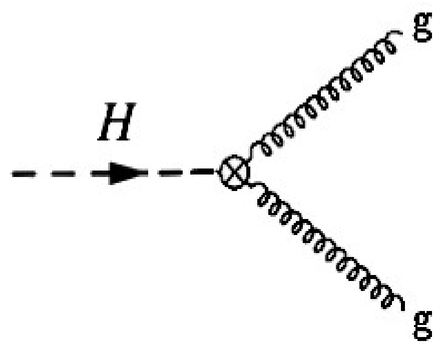


Only hadronic decay channel observed so far!

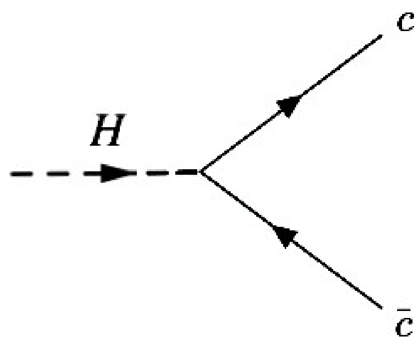
$\mathcal{B}$=11%

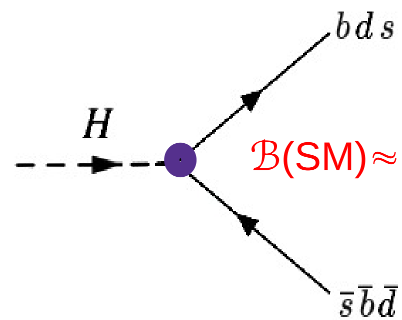


$\mathcal{B}$=8.6%



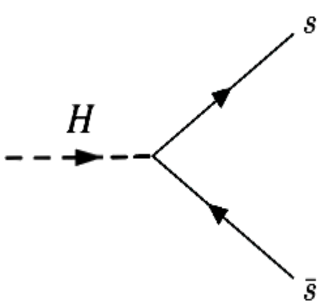
$\mathcal{B}$=2.9%



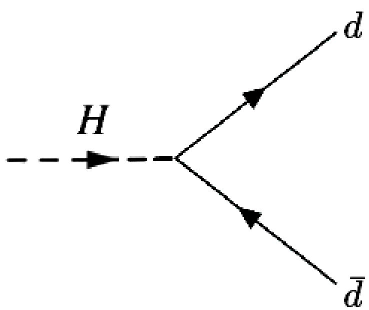


$\mathcal{B}(SM) \approx 10^{-7,-9,-11}$

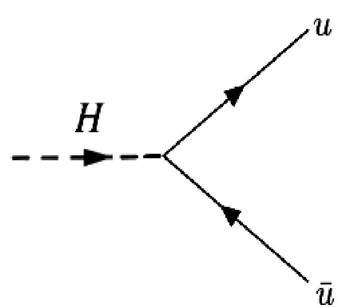
$\mathcal{B}$=0.024%

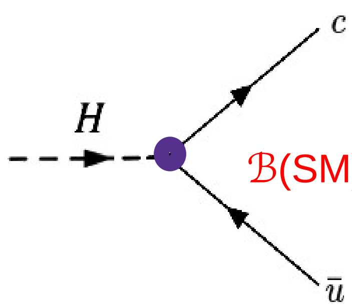


$\mathcal{B}=6\cdot10^{-7}$



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



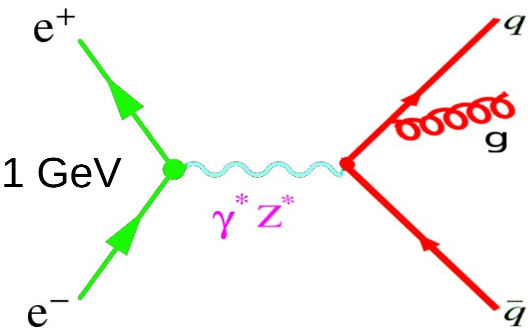


$\mathcal{B}(SM) \approx 10^{-20}$

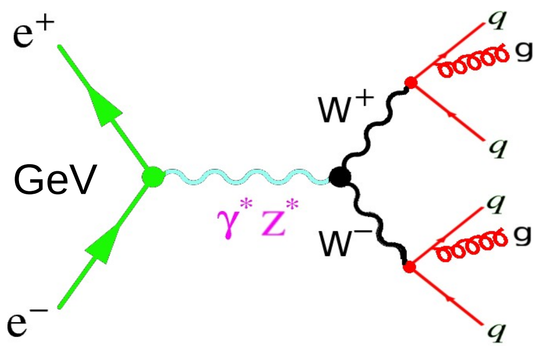
Precision QCD in e^+e^- collisions

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

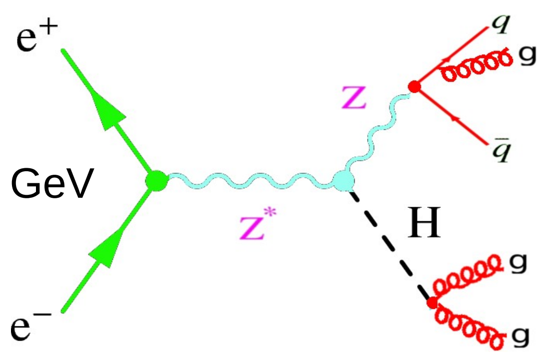
$\sqrt{s}$ = 91 GeV



$\sqrt{s}$ = 160 GeV



$\sqrt{s}$ = 240 GeV



Advantages compared to p-p collisions:

1) QED initial-state with known kinematics

2) Controlled QCD radiation (only in final-state)

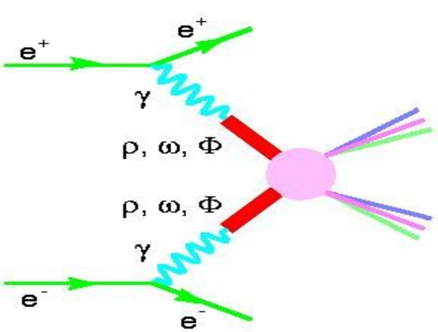
3) Well-defined heavy-Q, quark, gluon jets

4) Smaller non-pQCD uncertainties:

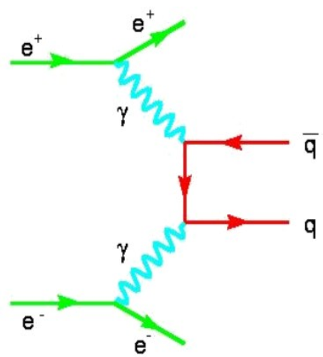
no PDFs, no QCD "underlying event",…

Direct clean parton fragmentation & hadroniz.

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



(soft, VDM)



(direct)

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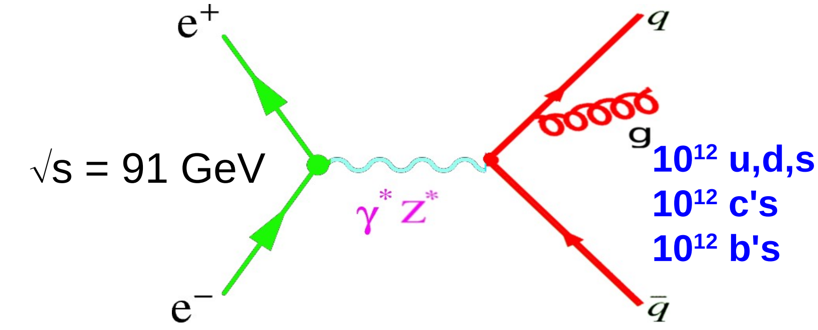

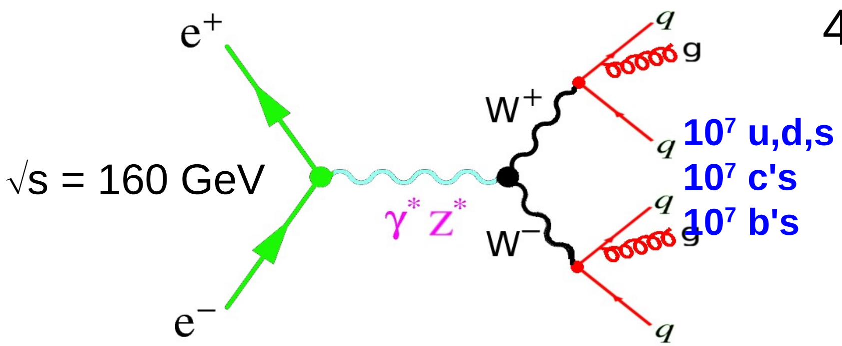

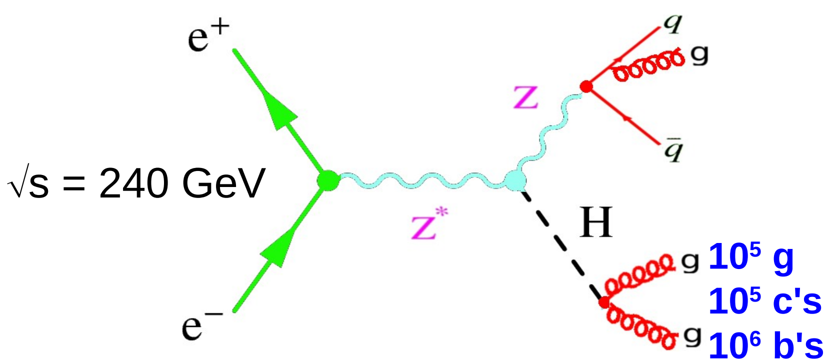

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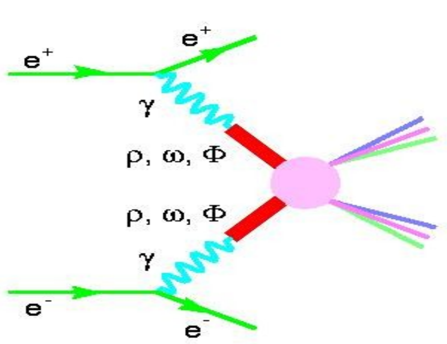

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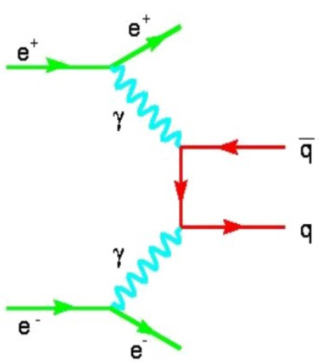


(direct)

Very rich QCD physics at FCC-ee

$\sin^2\theta_W$ via Fwd-Bckwd asymm. in $Z\to q\bar{q}$

N-jet rates

Hadronic H, W, Z, τ widths

Mixed QCD-EW corrections

$g \to c\bar{c}, b\bar{b}$ splitting

Fixed-order-PS matching

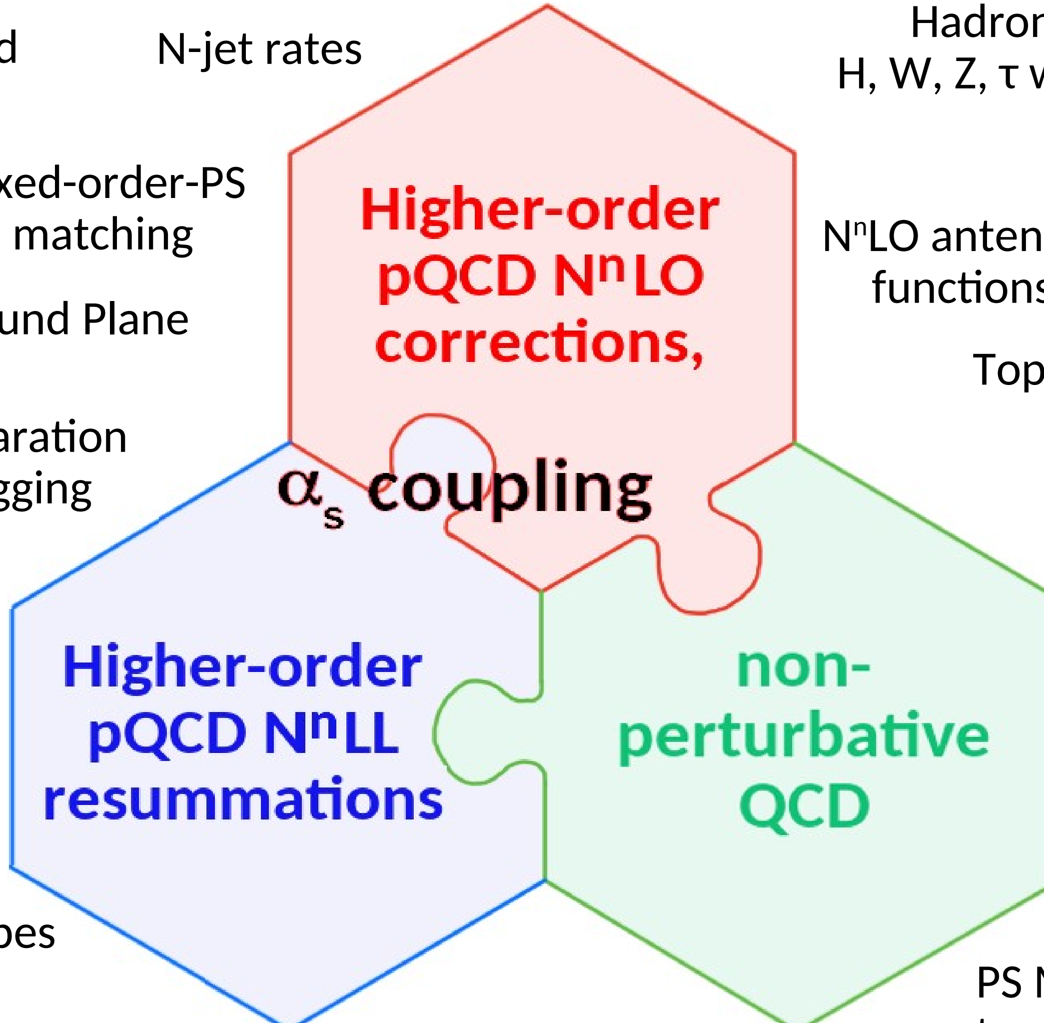
N^nLO antenna functions

Lund Plane

Jet substructure

Top mass extraction via $e^+e^-\to t\bar{t}$

q-g separation
Jet tagging



Heavy-Q rad. dead-cone

Colour reconnection

Jet reco/flavour algorithms

Parton hadronization

Non-Global Logs

Final-state correlations

Event shapes

Beyond Leading Color

PS MC tuning

Spin correlations

N^nLL Parton Shower Monte Carlos

Fragmentation Functions

$Q\bar{Q}$ transition probabs.

Lattice QCD

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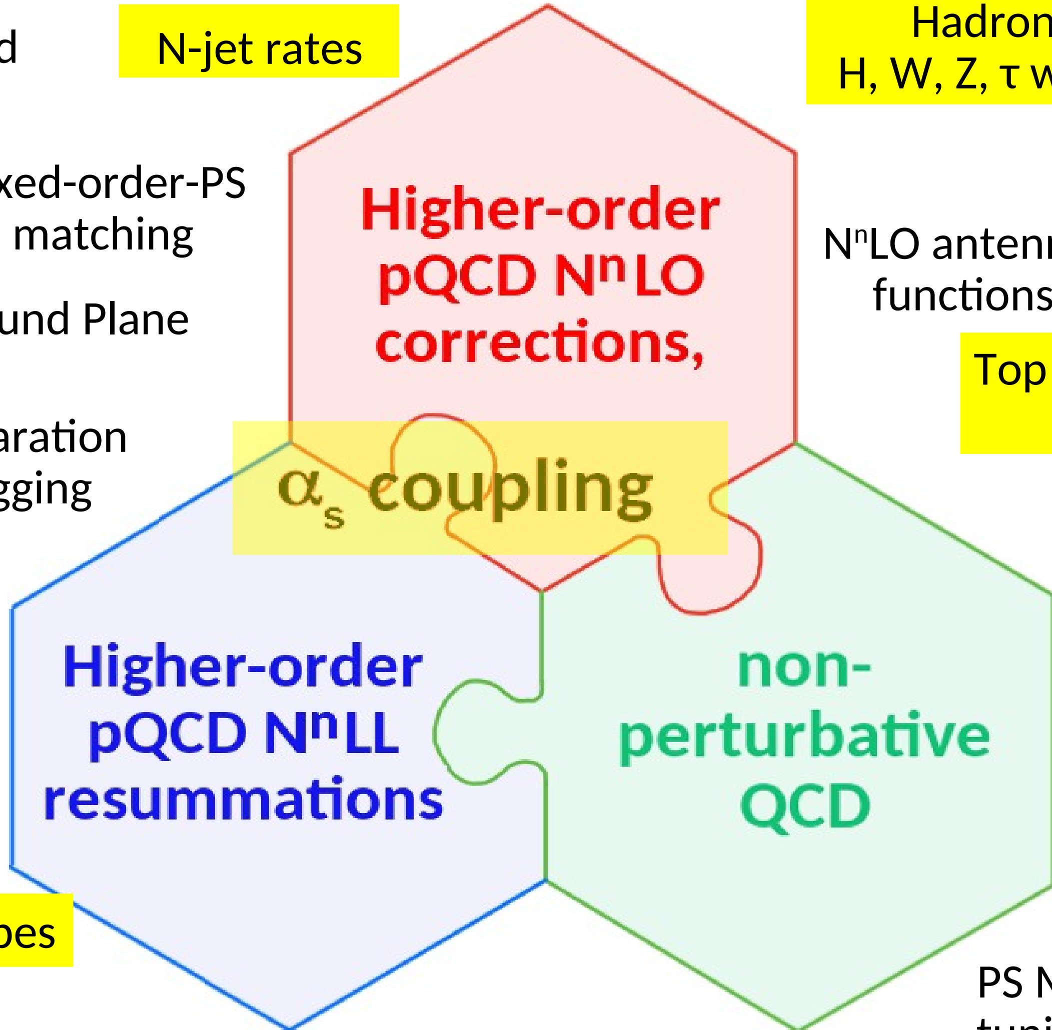

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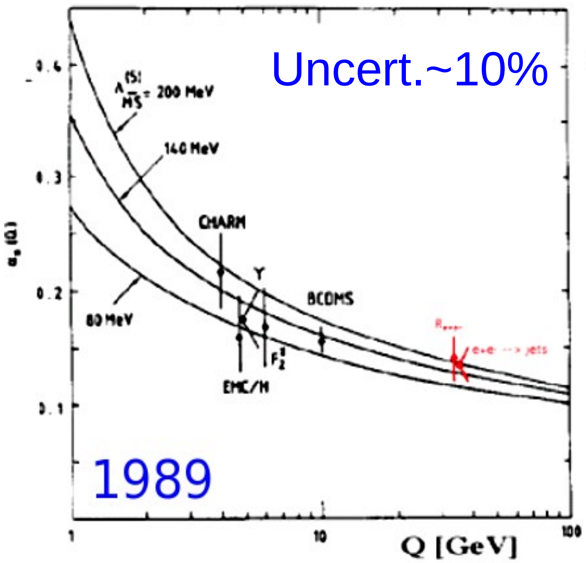
Lattice QCD

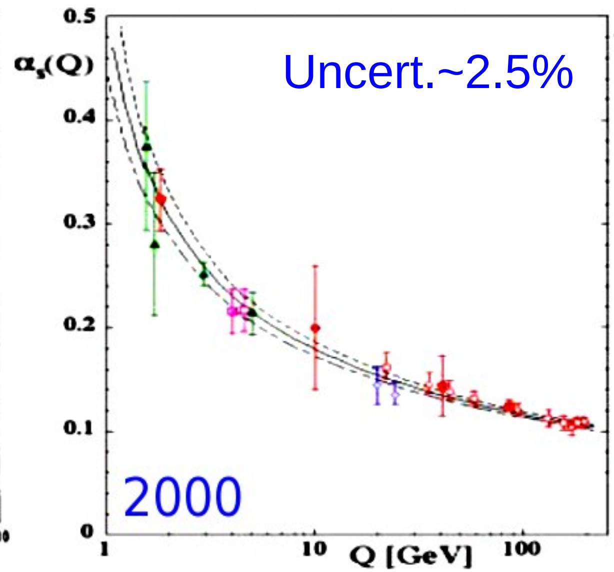
QCD coupling α_s

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



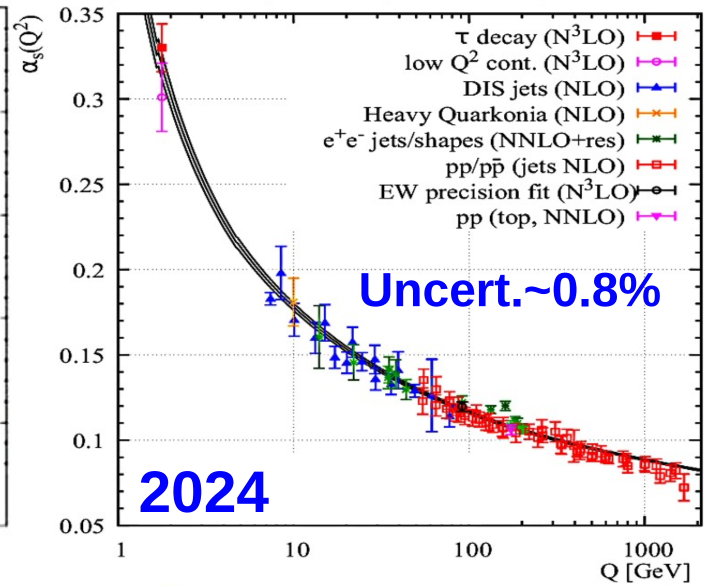
$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

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



$\alpha_s(M_Z) = 0.1180 \pm 0.0011$ **(NNLO)**

➧ Least precisely known of all interaction couplings !

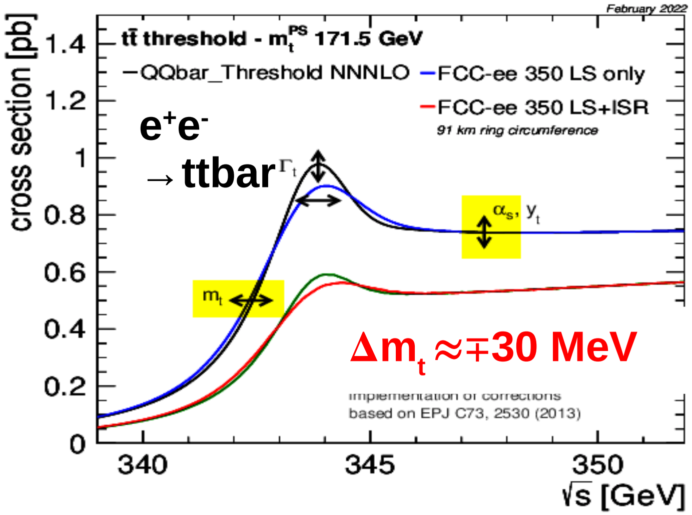
$\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_s \sim 10^{-3}$

α_s impact well beyond QCD

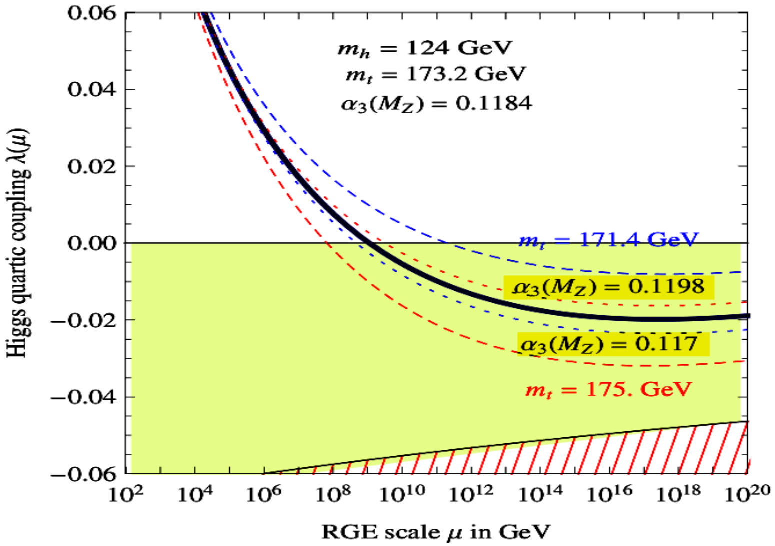
- Parametric uncertainties in multiple precision SM observable calculations:

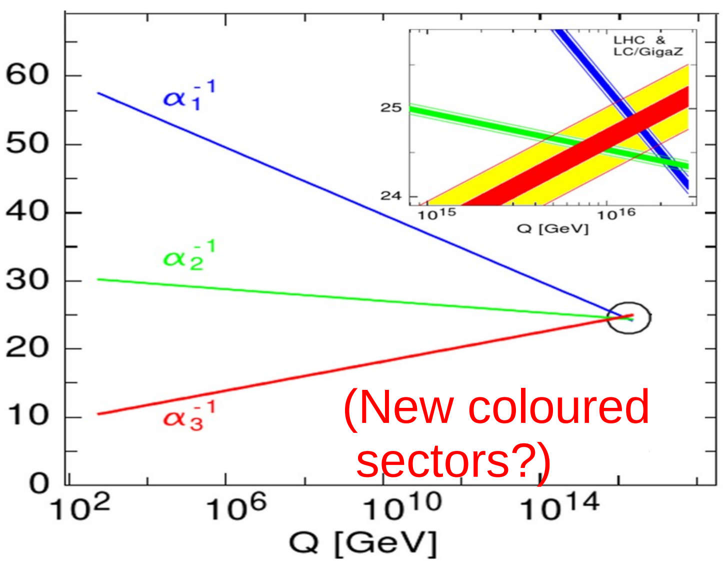
Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	$\pm$ 3.7	-6.2 +7.4	-2.61 + 0.32
ttH	0.611	$\pm$ 3.0	$\pm$ 8.9	-9.3 + 5.9

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



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



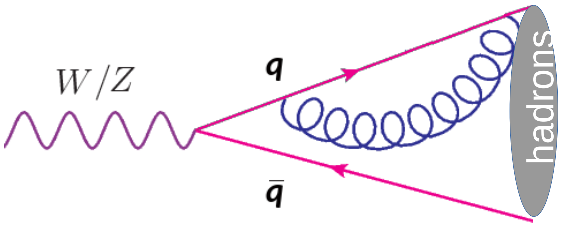


QCD coupling at FCC-ee (Tera-Z)

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

- The W and Z hadronic widths :

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



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

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

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

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

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

[DdE, Jacobsen: arXiv:2005.04545]

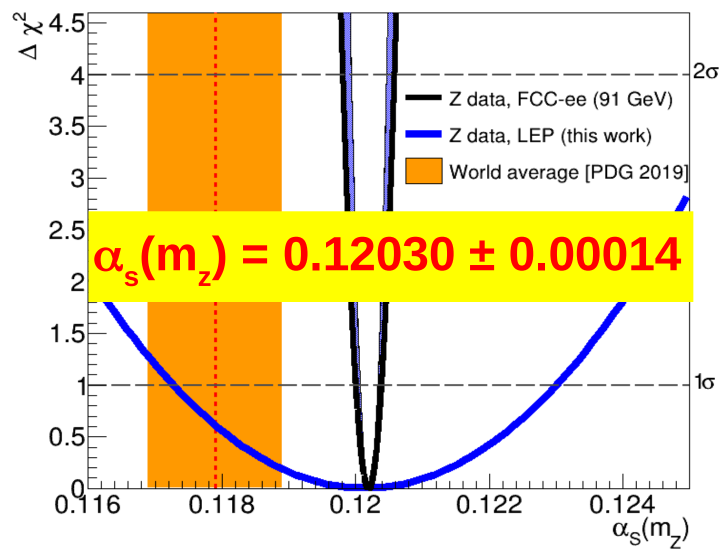
FCC-ee will reach 0.1% precision on $\alpha_s(m_Z)$ ($\times$20 better than LEP results):

– Huge Z pole stats. ($\times 10^5$ LEP):

– Exquisite syst./parametric precision:

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

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



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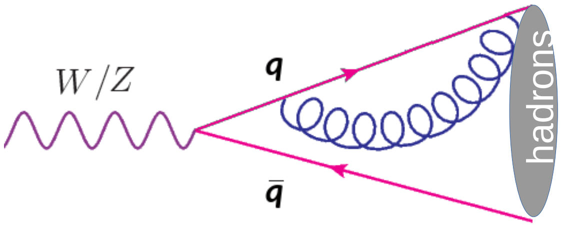


Note: Sensitivity to $\alpha_s(m_Z)$ from O(4%) virtual corrs.

[DdE, Jacobsen: arXiv:2005.04545]

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

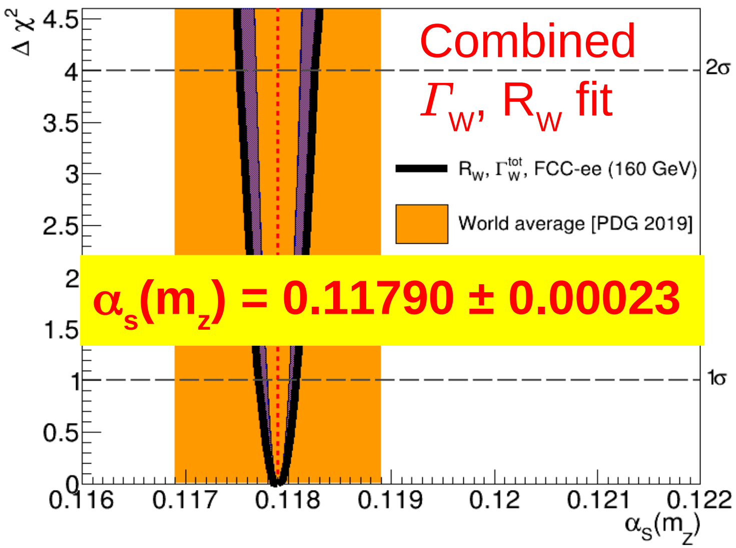
$$\Gamma^{\rm tot}_{\rm W} = 2088.0 \pm 1.2 \text{ MeV}$$

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

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

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

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



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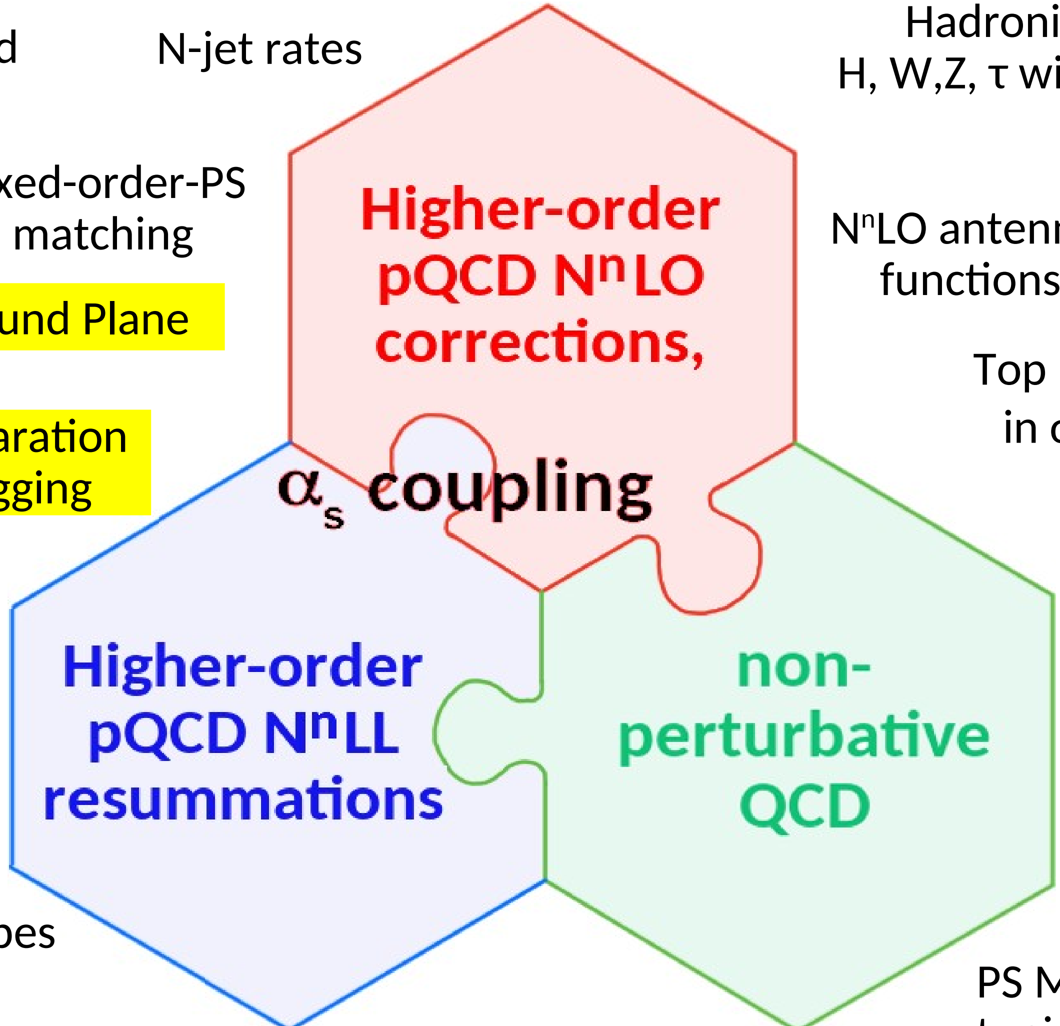

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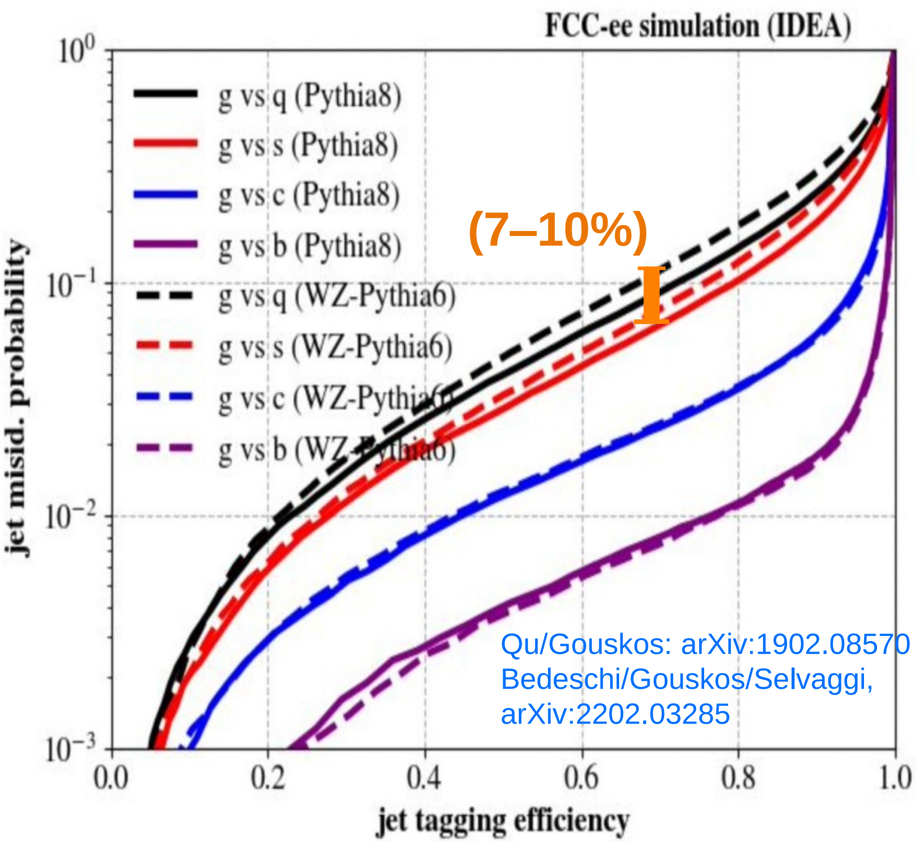
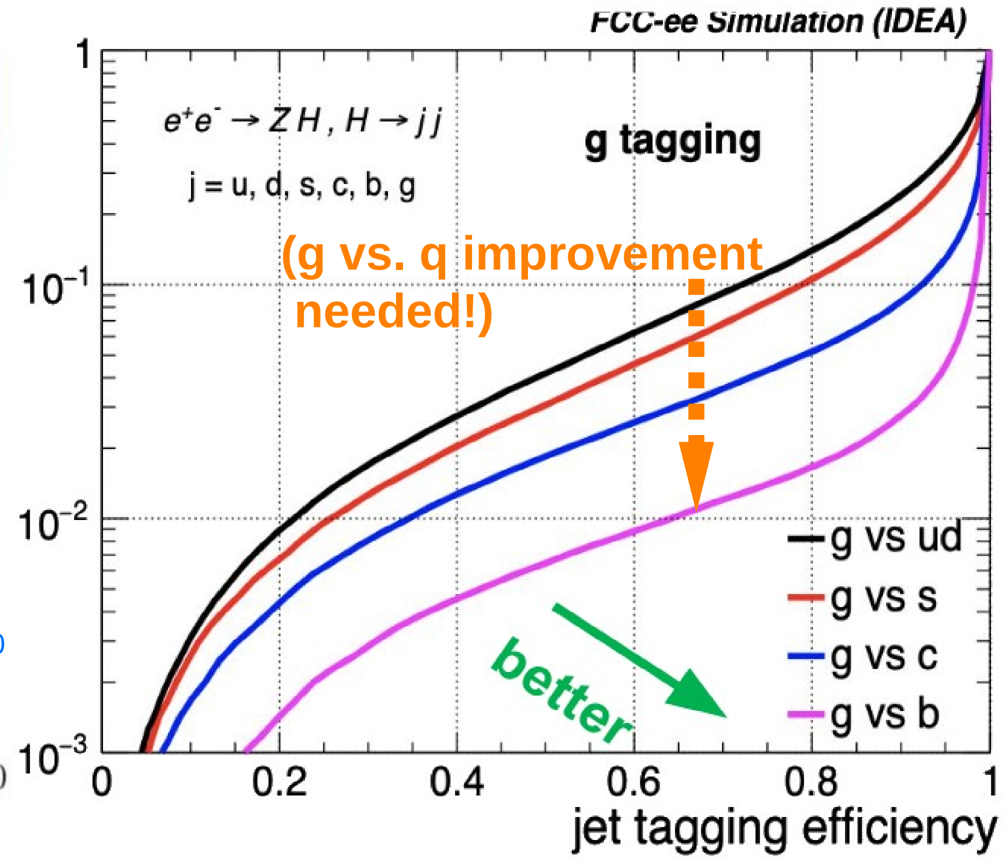
Lattice QCD

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



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

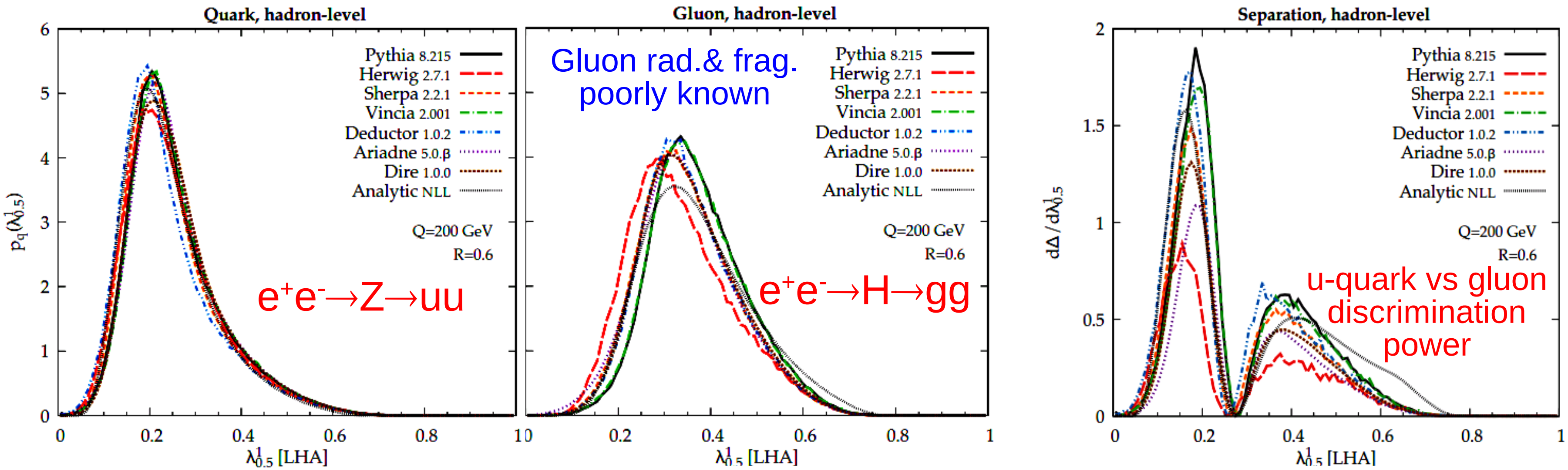


trained on Pythia 8 [solid lines]

- Performance needs to measure e-Yukawa via ee→H(gg) over ee→ Z(qq): ε_g~70%, $\varepsilon_{q\text{-mistag}}$~0.01 (factor x10 improvement). However...

Gluon jets are badly known today

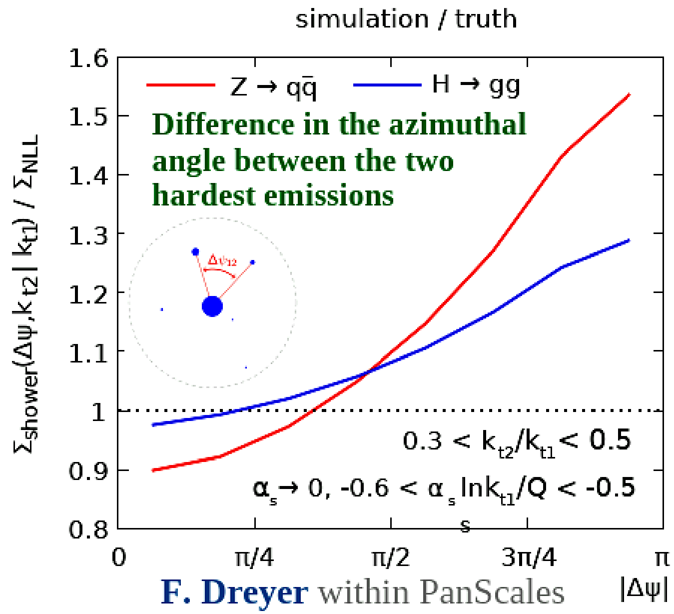
- MC LL parton showers differ vastly on gluon jet substructure properties:



[G.Soyez et al.]

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

- NNLL PS + high-quality e^+e^- gluon jet data/tuning badly needed (orders-of-magn. over LEP data)

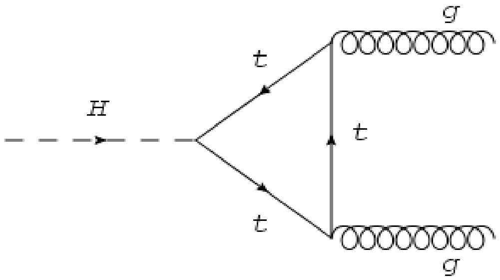


Nonphysical quark/gluon differences in common dipole showers

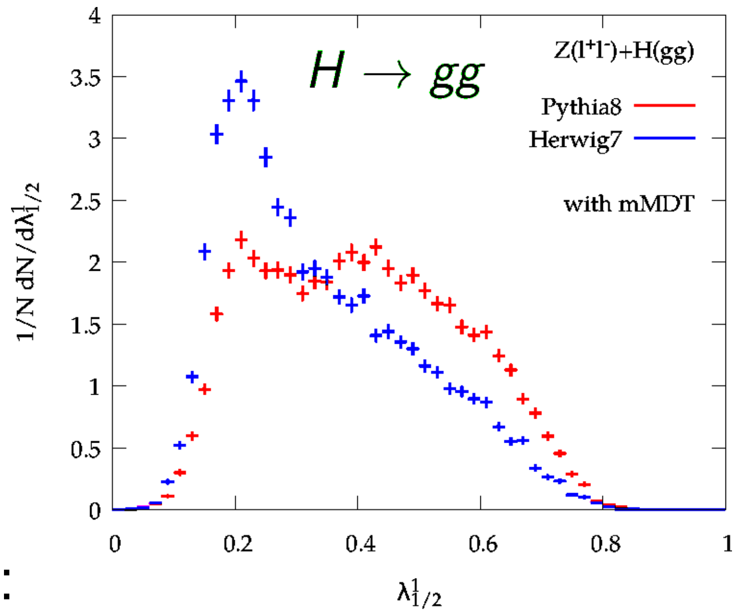
[S.Ferrario-Ravasio et al.]

High-precision g & q jet studies at FCC-ee

- Exploit $\mathcal{O}$(200.000) ee → ZH(gg) at 260 GeV as a "pure gluon" factory: H → gg provides perfectly tagged digluon events.



- Compare to $\mathcal{O}(10^{12})$ Z → qq(g) evts at 91 GeV:
  - 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 ?

Very rich QCD at FCC-ee. Examples:

$\sin^2\theta_W$ via Fwd-Bckwd asymm. in $Z\to q\bar{q}$

N-jet rates

$g\to c\bar{c}, b\bar{b}$ splitting

Fixed-order-PS matching

Lund Plane

Jet substructure

q-g separation
Jet tagging

Heavy-Q rad. dead-cone

Jet reco/flavour algorithms

Non-Global Logs

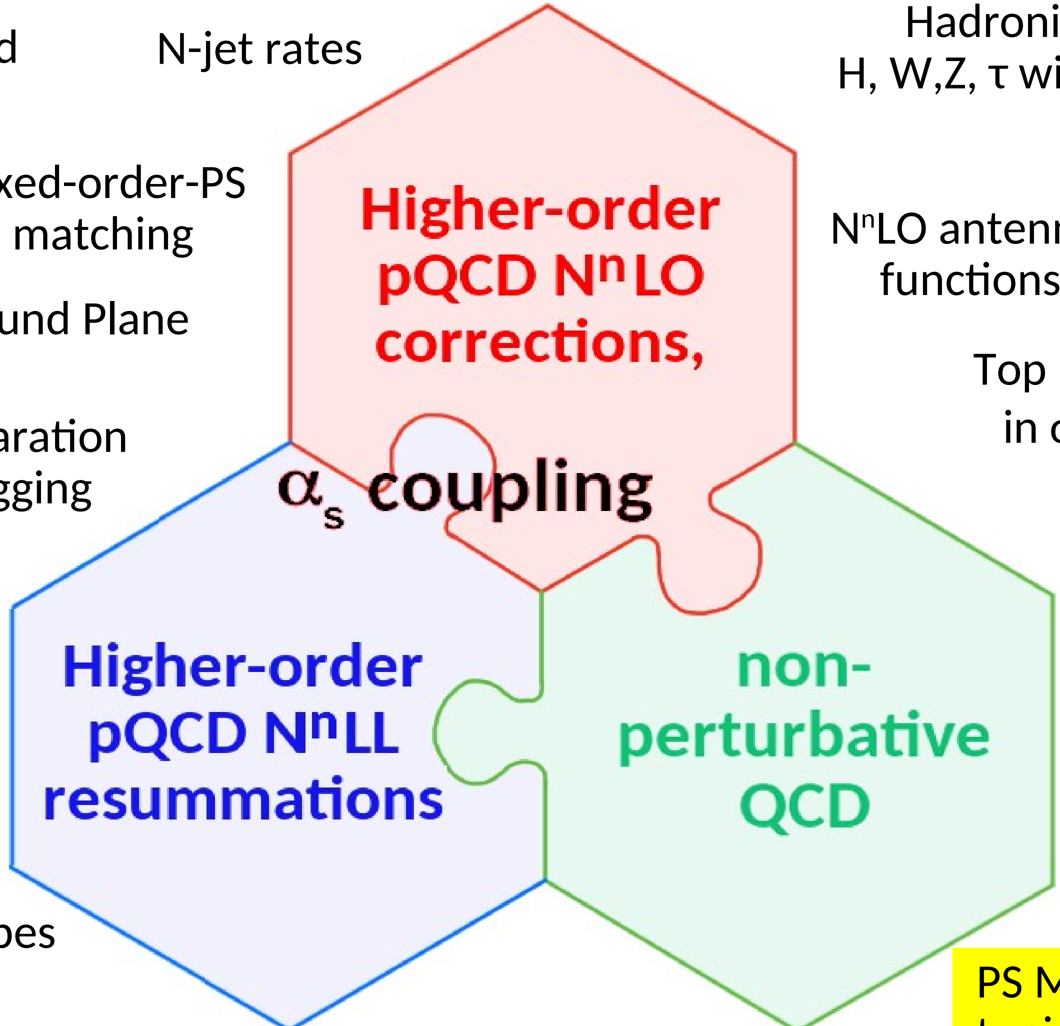
Event shapes

Beyond Leading Color

Spin correlations

N^nLL Parton Shower Monte Carlos

Fragmentation Functions



Hadronic H, W,Z, τ widths

Mixed QCD-EW corrections

N^nLO antenna functions

Top mass corrs. in $\sigma(e^+e^-\to t\bar{t})$

Colour reconnection

Parton hadronization

Final-state correlations

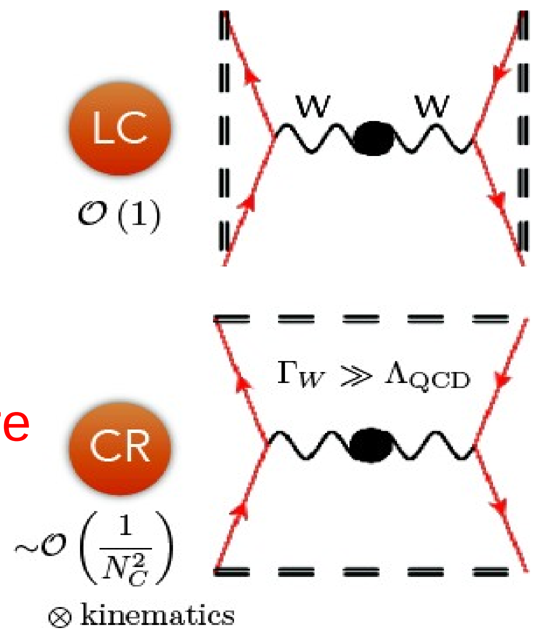
PS MC tuning

$Q\bar{Q}$ transition probabs.

Lattice QCD

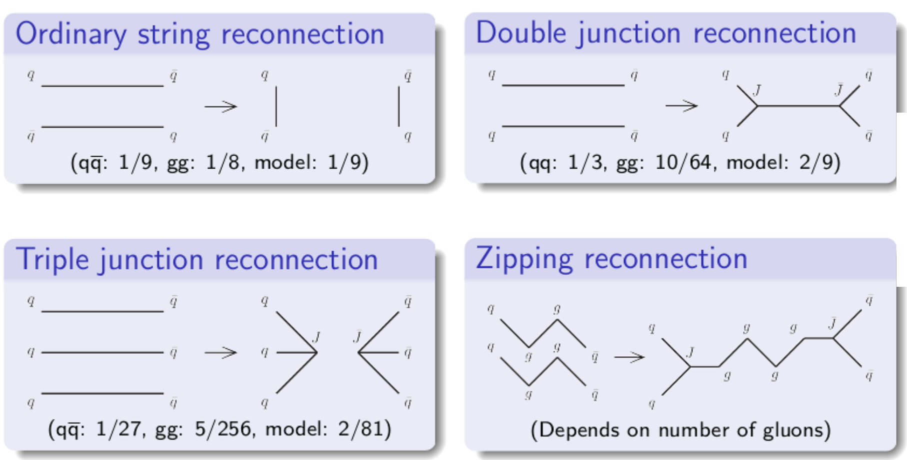
Colour reconnection studies at FCC-ee

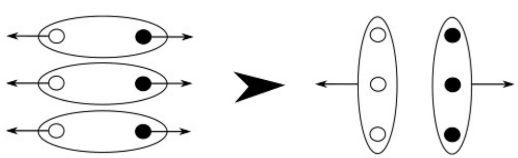
- Colour reconnection among partons is source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states. Especially in pp (MPI cross-talk).
- CR "string drag" effect impacts all FCC-ee multi-jet final-states: $e^+e^- \rightarrow WW(4j)$, H(2j,4j), ttbar,…
  - Shifted masses & angular correlations (CP studies).
  - Combined LEP $e^+e^- \rightarrow WW(4j)$ data best described with 49% CR, 2.2σ away from no-CR.



- Exploit huge stat WW at rest (×10[4] LEP) to measure m_W leptonically & hadronically and constrain CR:

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

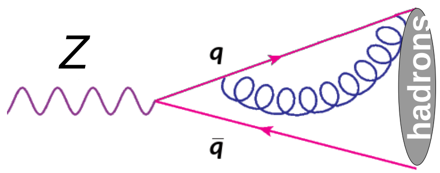


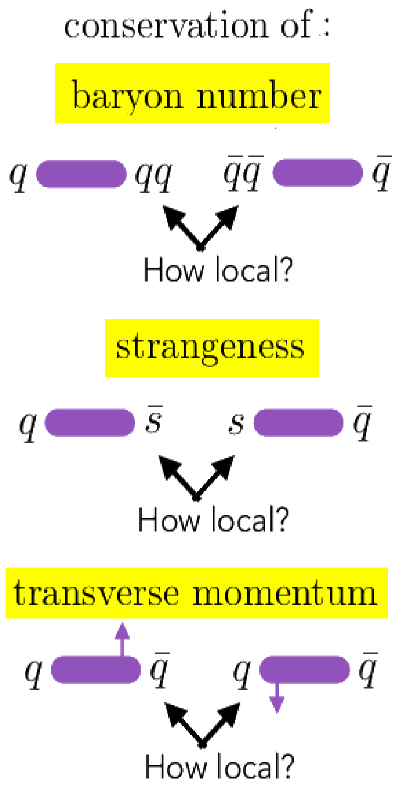


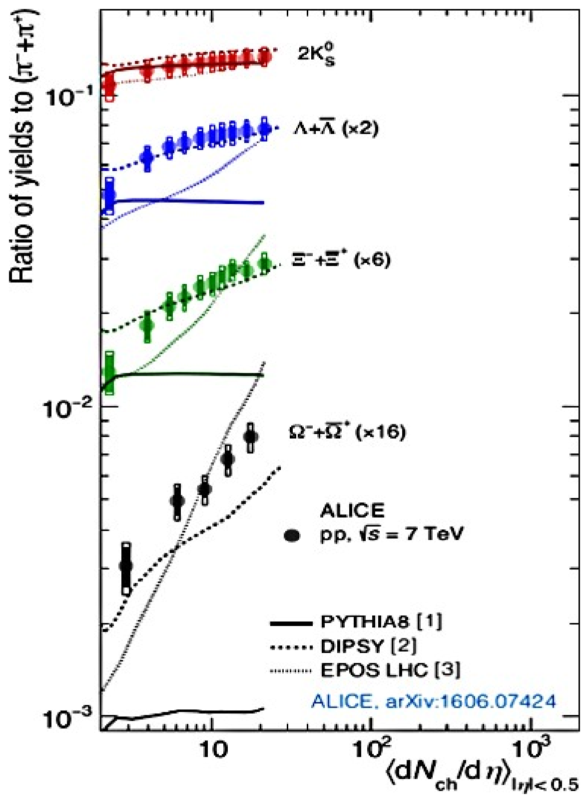
Triple-junction also in HERWIG cluster model. (1710.10906)

Vacuum hadronization studies at FCC-ee

- Precision low-p_T PID hadrons in 10^{12} $e^+e^- \to Z \to$ (10^{14} hadrons) for studies:
  – Baryon & strangeness prod. Colour string dynamics
  – Final-state correlations: space-time, spin (BE, FD)
  – Exotic BR(10^{-12}) bound-states: Onia, multi-quark states, glueballs, ...







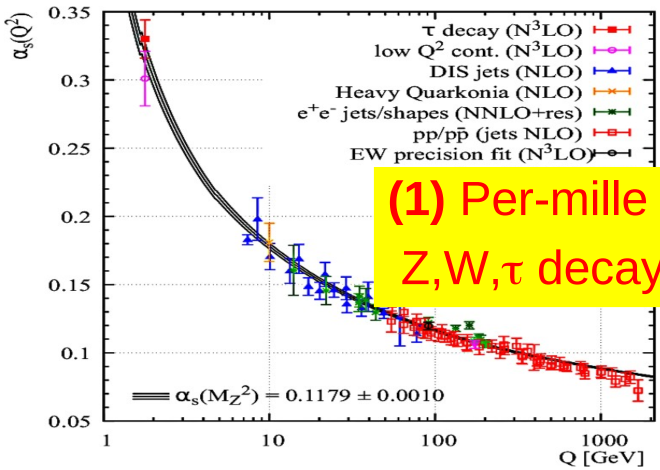
▶ Understand breakdown of universality of parton hadronization with system size observed at LHC.

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

Also e.g. impact ultra-high-energy cosmic-ray MCs (muon puzzle)

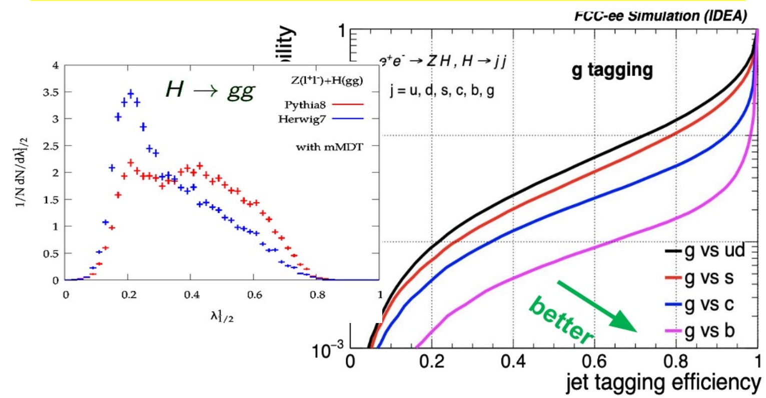
Summary (1): High-precision QCD at FCC-ee

- ☛ 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:

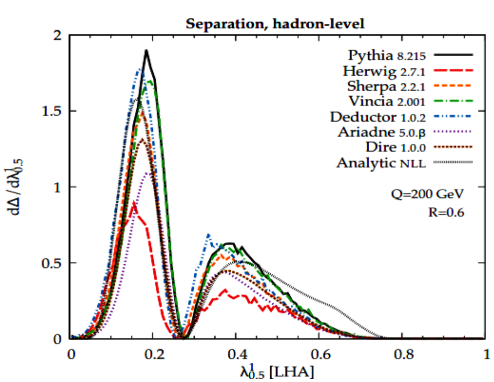


(1) Per-mille α_s via hadronic Z,W,τ decays, evt shapes...

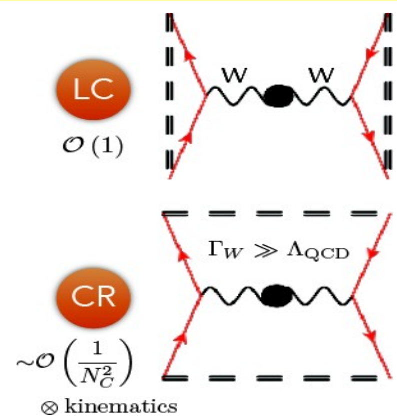
(2) Ultimate g/q/Q discrimination



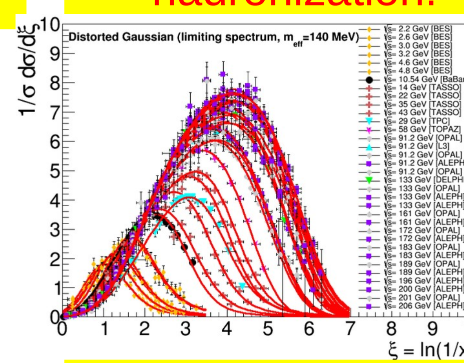
(3) Improved N^{n}LO+N^{n}LL parton showers tuning

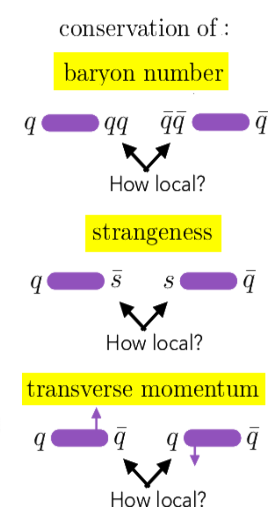


(4) <<1% control of colour reconnection



(5) High-precision hadronization:





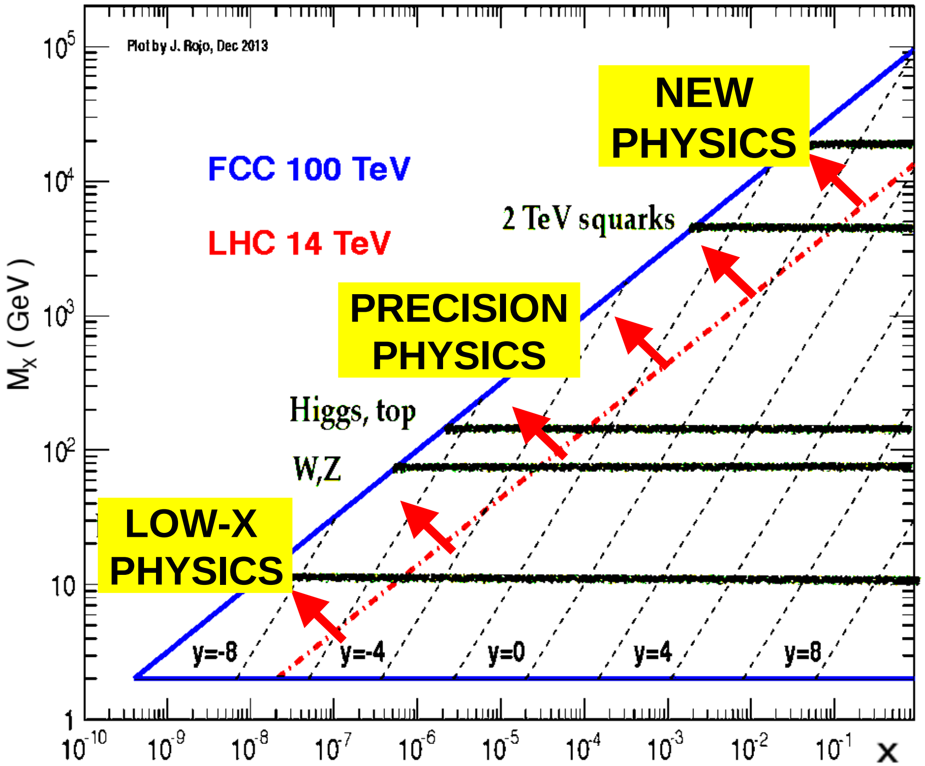
(6) Ultra-rare QCD bound states,...

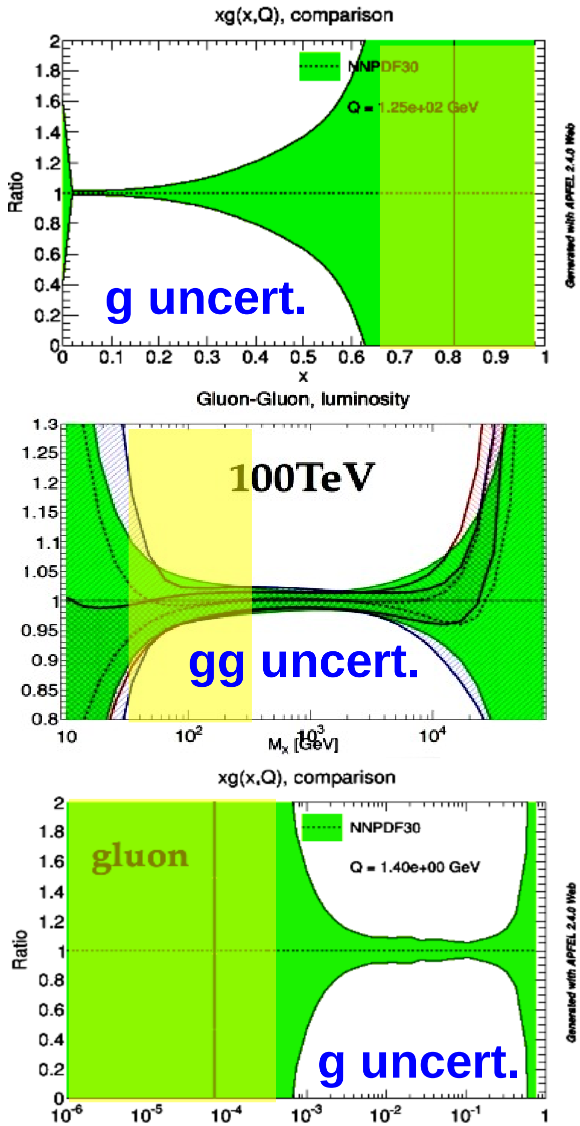
Quick flash on QCD physics topics at FCC-pp…

Parton densities at very-low, low, and high-x

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

(somehow outdated PDF plots)

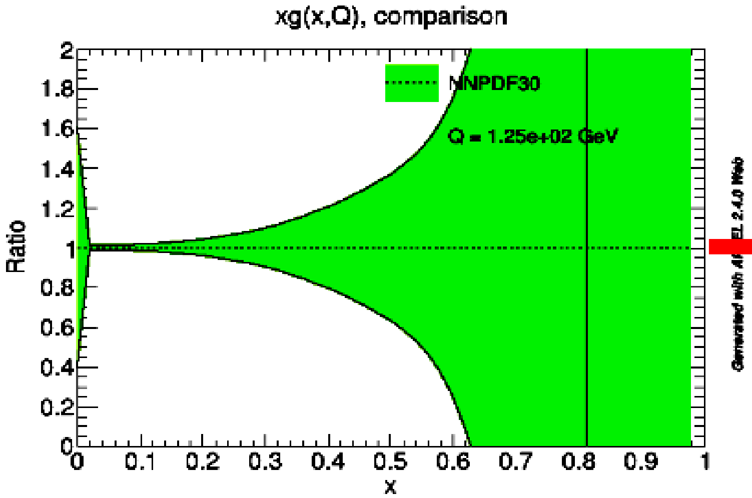


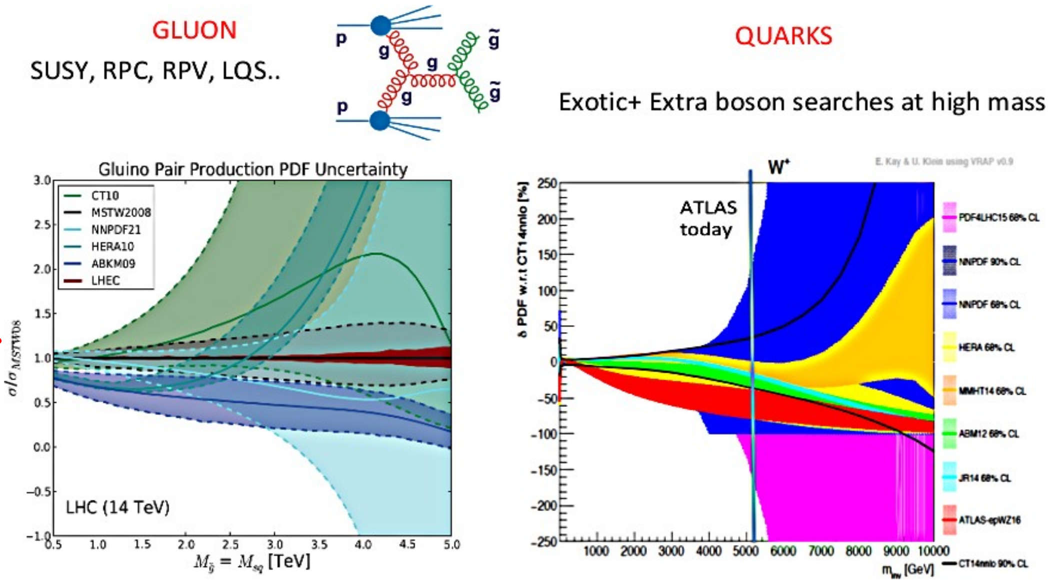


- Z, W, top, photons, jets… to constrain PDFs, as done at LHC
- FCC-ep required to go below O(1%) PDF uncertainties?

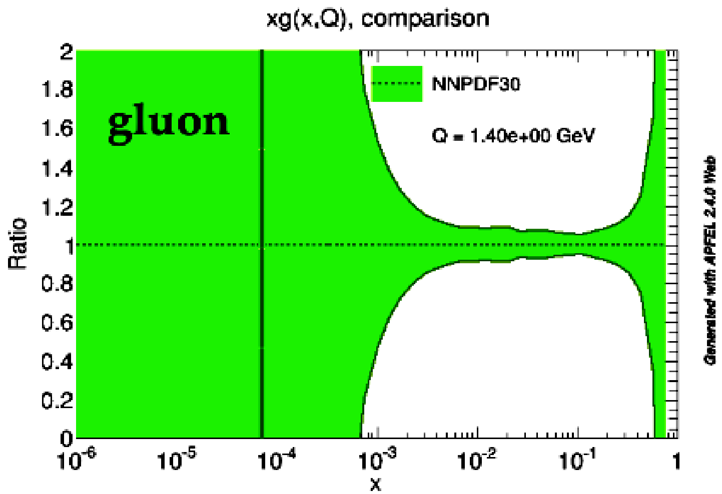
PDFs impact on BSM & precision SM physics

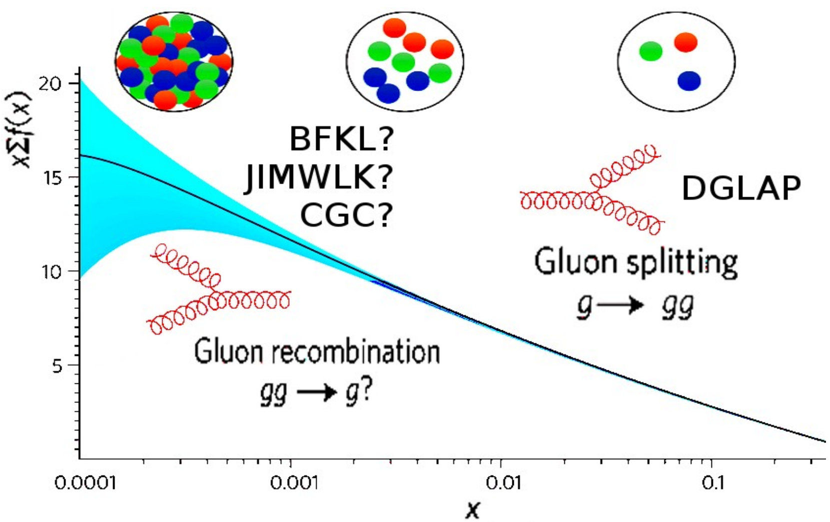
New physics at high-x?





New QCD evolution at low-x?





α_s running at the multi-TeV scale

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

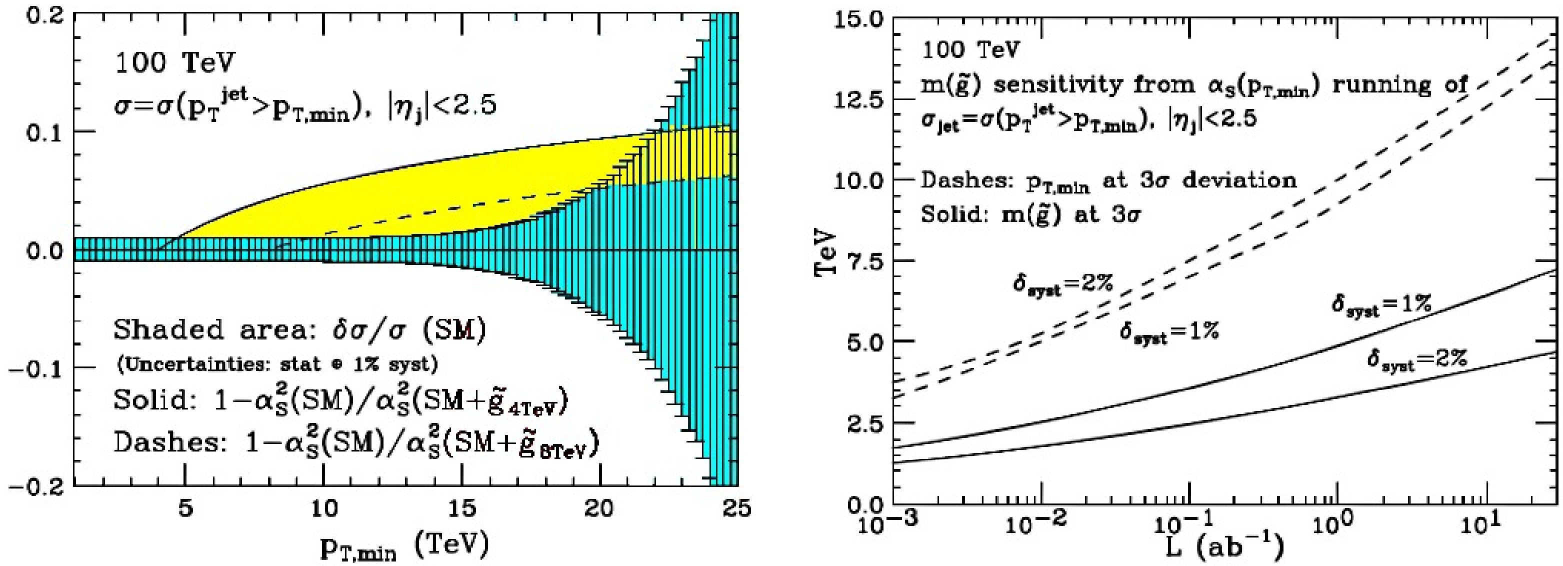
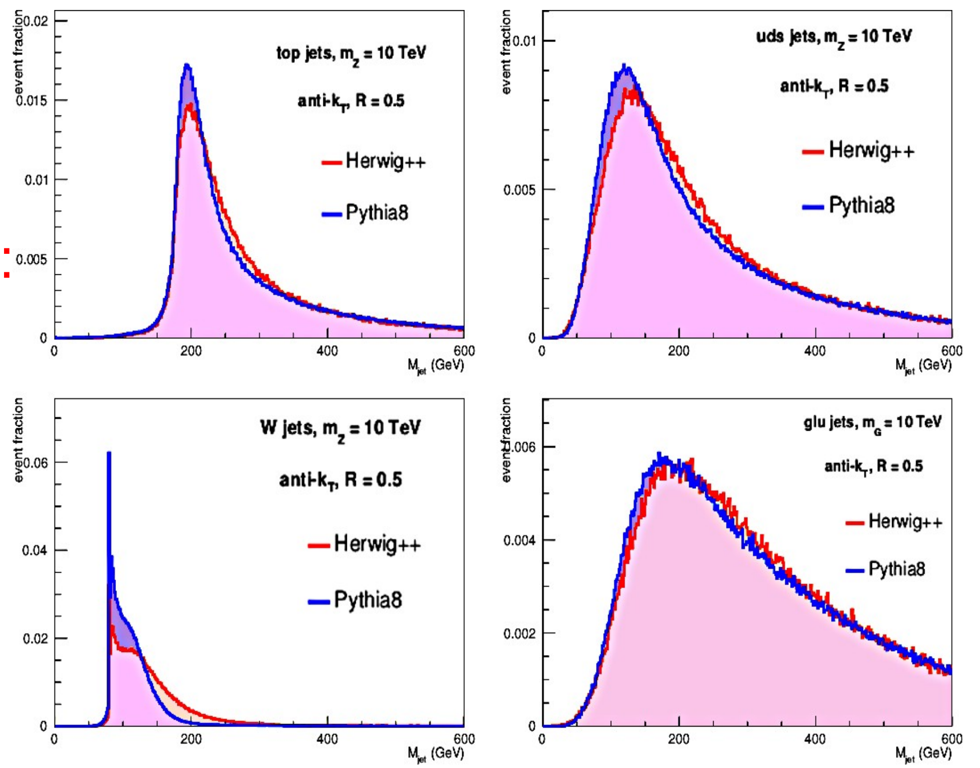


Figure 5.5: Left plot: combined statistical and 1% systematic uncertainties, at 30 ab^{-1}, vs p_T threshold; these are compared to the rate change induced by the presence of 4 or 8 TeV gluinos in the running of α_S. Right plot: the gluino mass that can be probed with a 3σ deviation from the SM jet rate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

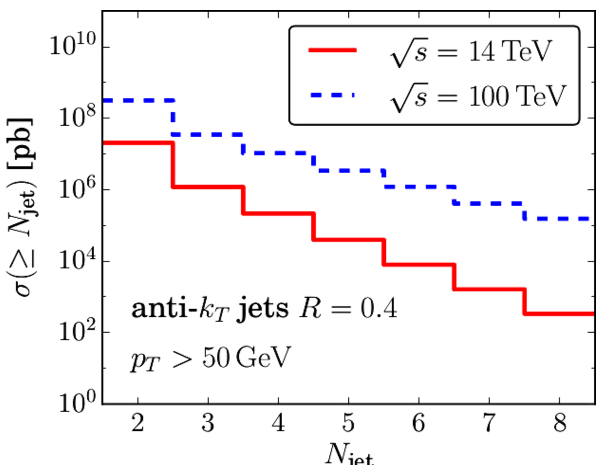
- Jet cross sections with <10% stat. uncert. up to p_T~25 TeV: Sensitivity to e.g. m_g=4–8 GeV gluinos in α_s running
- α_s from PDF fits, advanced jet substructure (LJP), hadronic obs., ...

Highly-boosted jets & multijet events

- Proton-proton collisions at 100 TeV provide unique conditions to produce & study multi-TeV 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) QCD, (BSM?) studies

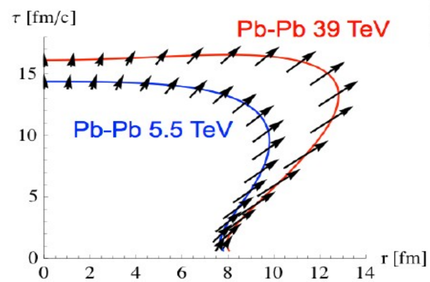


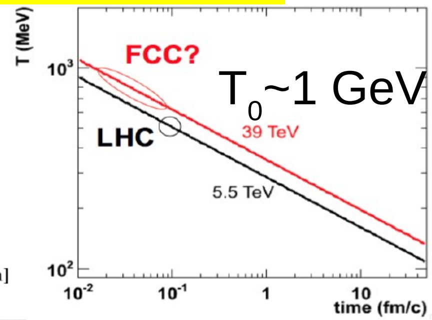
[FCC-pp, arXiv:1607.01831]

Also… Unique many-body QCD with ions

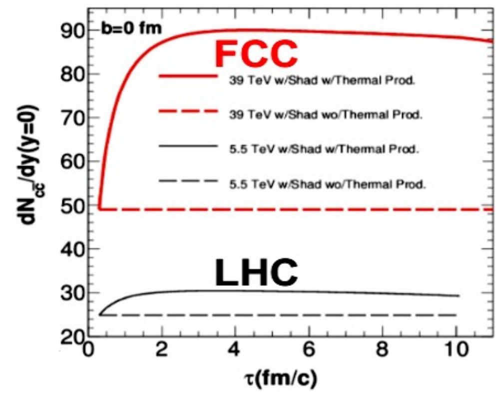
- Unparalleled HI physics with ×7 (39 TeV), ×10 larger $\sqrt{s}$, $\mathcal{L}_{int}$ than LHC:

Energy densities: ~40 GeV/fm³

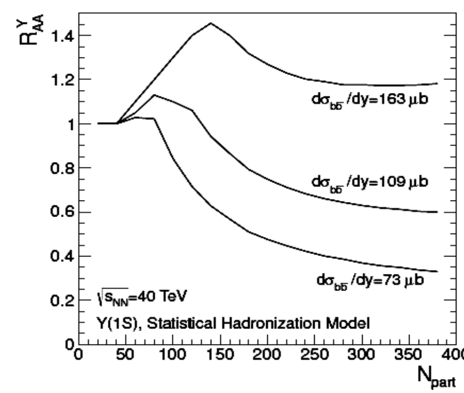


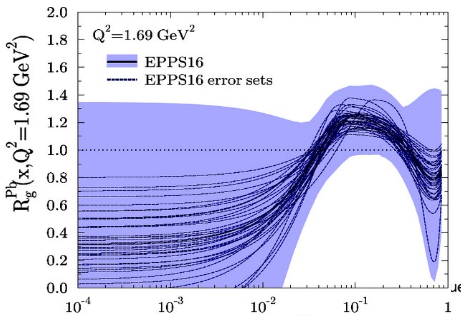


~500 charm pairs in QGP



ϒ(1S) melt.+recomb.?

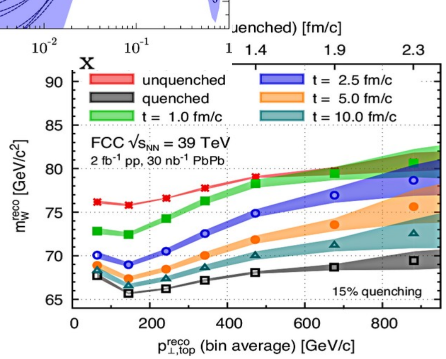


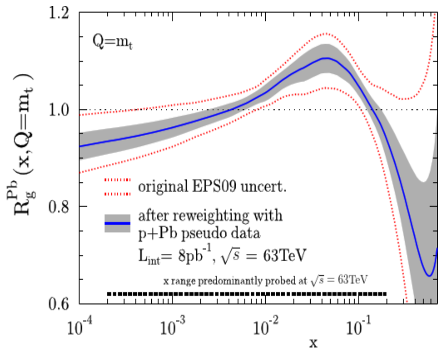


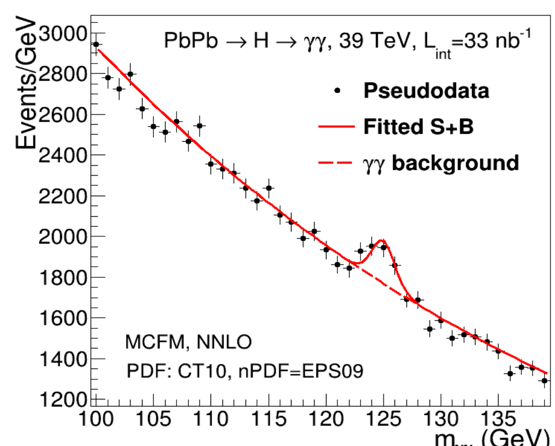
Gluon nPDF saturation down to x~10⁻⁷

See: https://indico.in2p3.fr/event/33460/

Higgs in the QGP





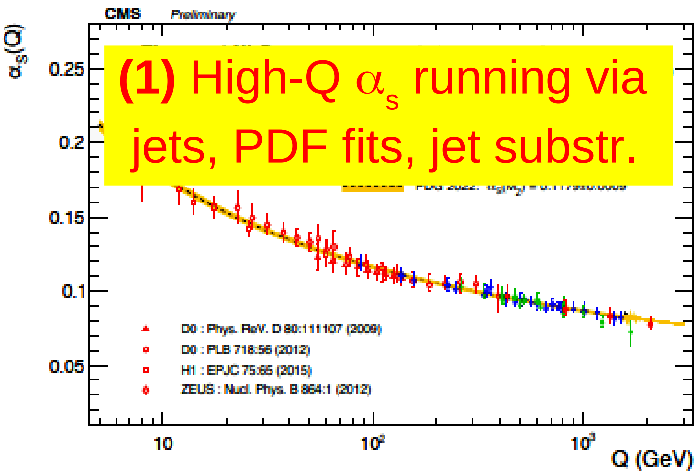


Top quark = Parton rad. "chrono-fmeter" & high-x gluon nPDF probe

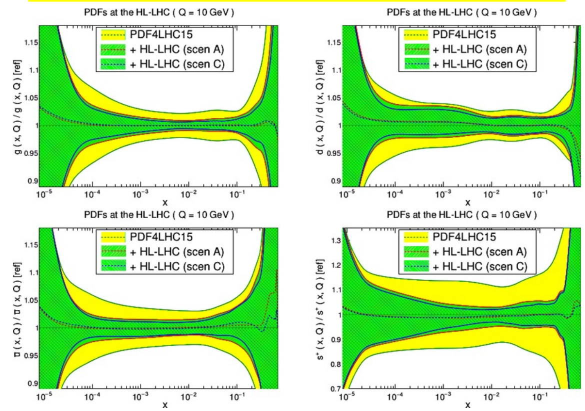
Summary (2): QCD at the FCC-hh

☛ Unique QCD precision and multi-TeV studies at the energy frontier:

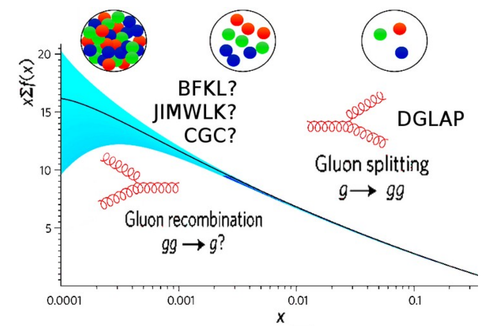
(1) High-Q α_s running via jets, PDF fits, jet substr.



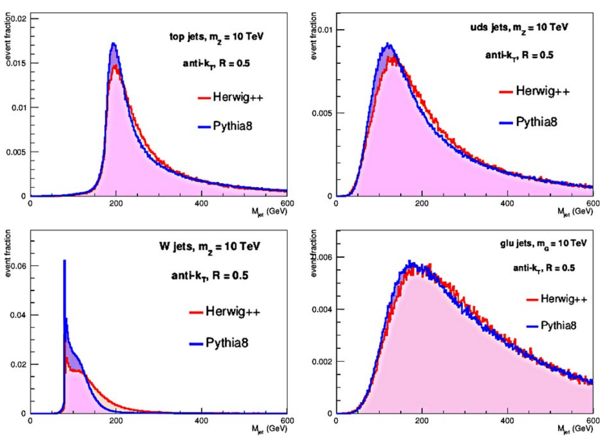
(2) High-precision PDFs



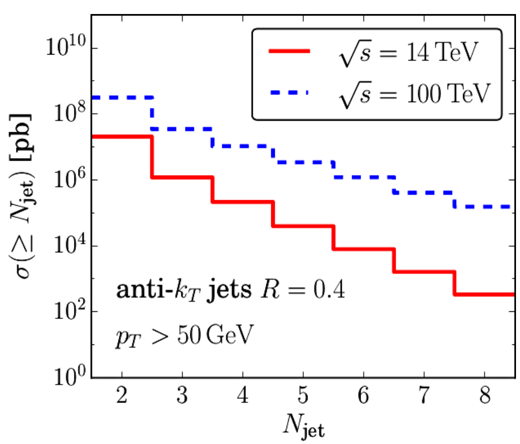
(3) Searches for beyond DGLAP at low x~10^{-7}



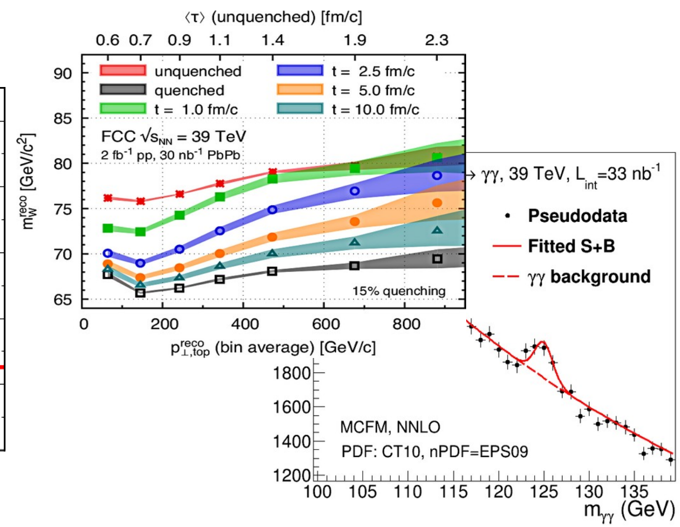
(4) Highly-boosted jets up to $p_T \sim 50$ TeV



(5) Multijets ($N \gg 10$) production



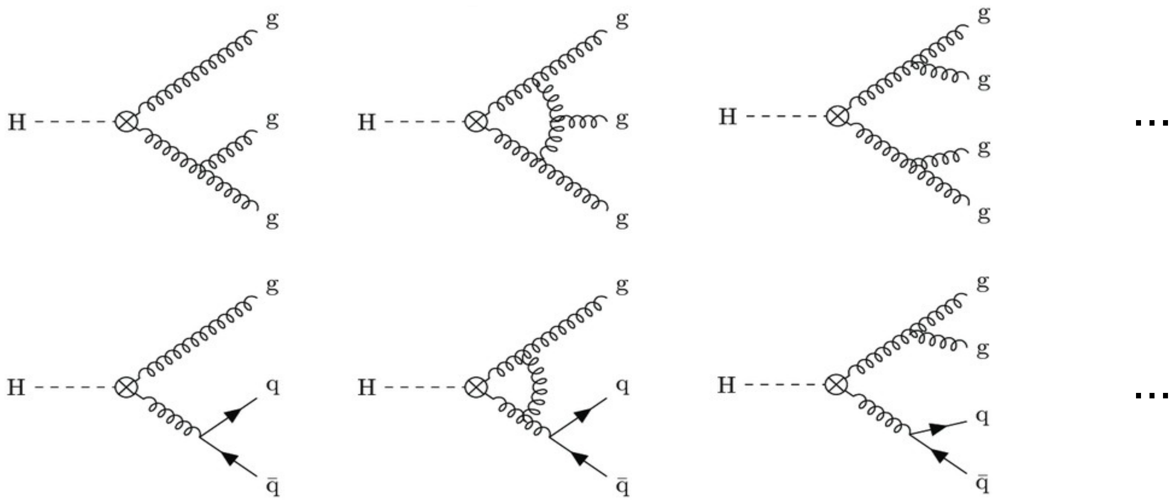
(6) Top and Higgs in the QCD plasma



Back-up slides

Higgs → gg decay and BSM

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



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

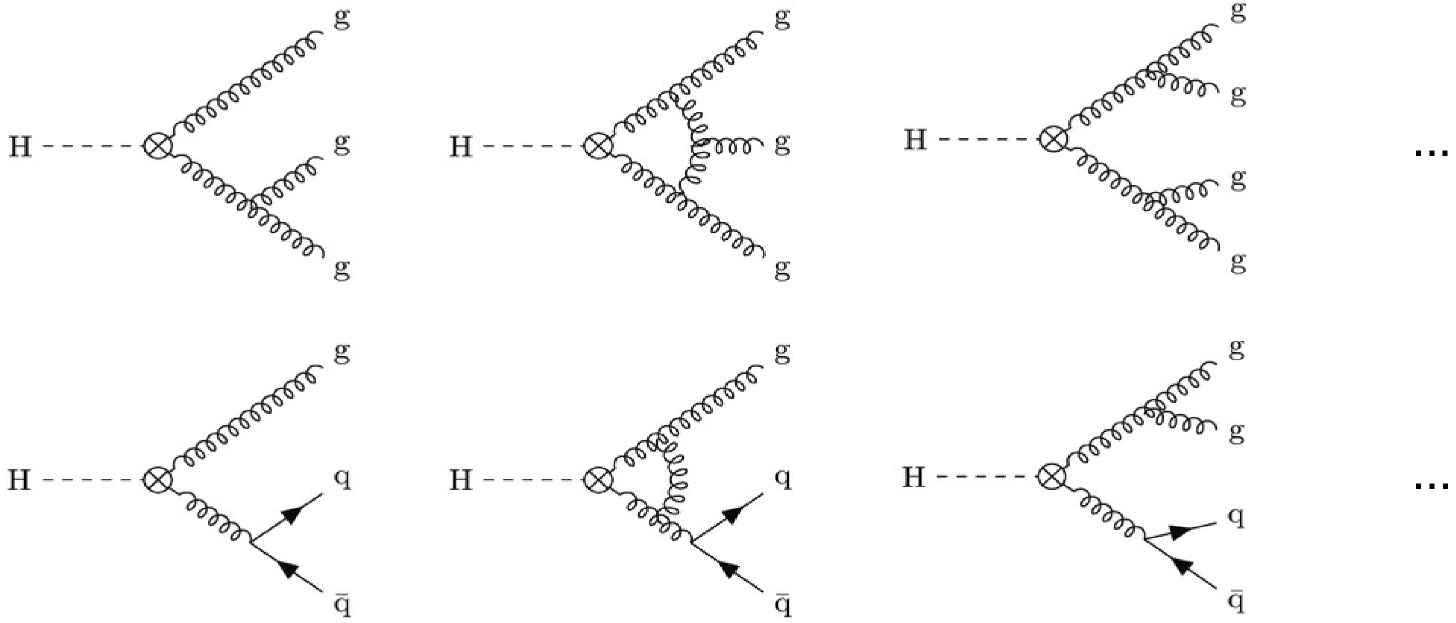
Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings in %

	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

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



Uncertainties: O(3%) TH + O(4%) parametric from $\alpha_s(m_Z)$=0.118±1% (today):

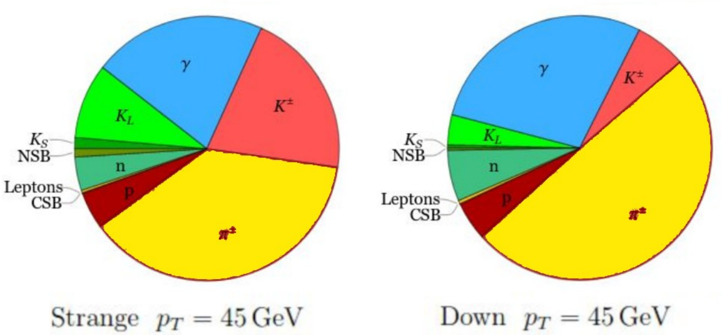
Partial width	intr. QCD	intr. electroweak	total	para. m_q	para. α_s
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	1.4%	0.4%
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	4.0%	0.4%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$< 0.2\%$	3.7%

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

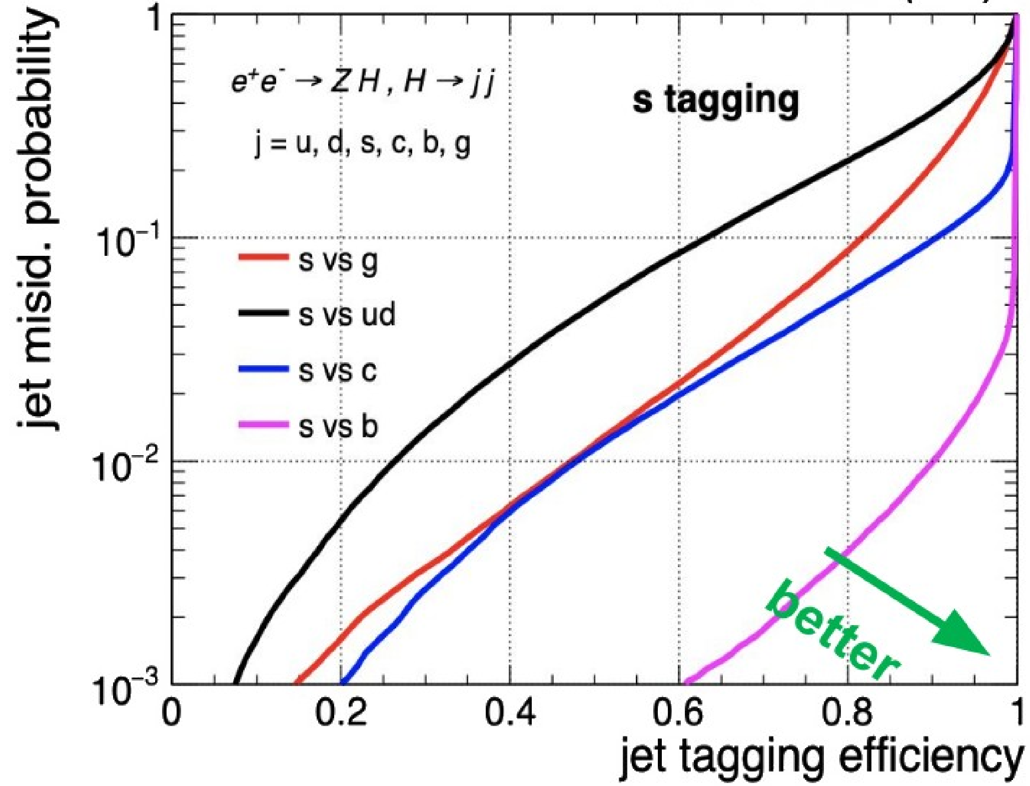
Strange-quark jet tagging at FCC-ee

- 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:



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



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

[O(50) properties/particle]

× [~50-100 particles/jet]

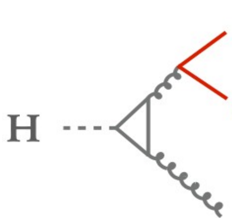
~ O(1000) inputs/jet

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

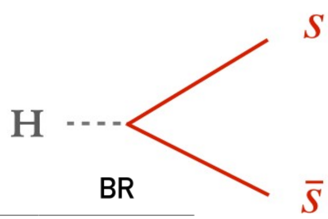
Separating H→ss and H→ gg

- Does the H→ gg(ss) Dalitz decay jeopardize the H→ ss measurement?

Dalitz decay $(\alpha_s^3 y_t^2)$

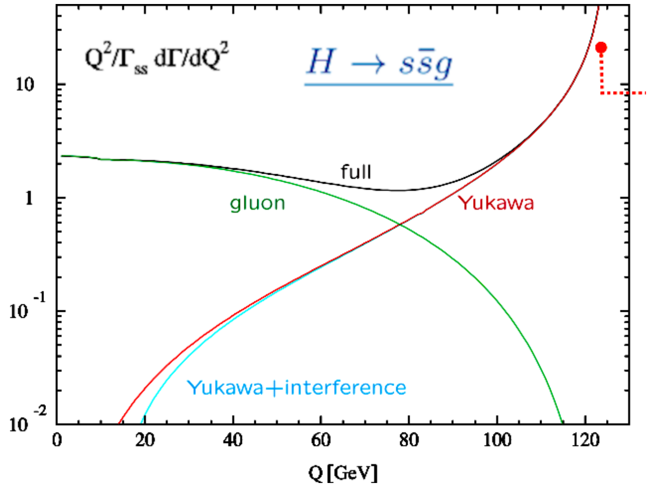


Yukawa decay (y_s^2)



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

Ratio is ~ 400

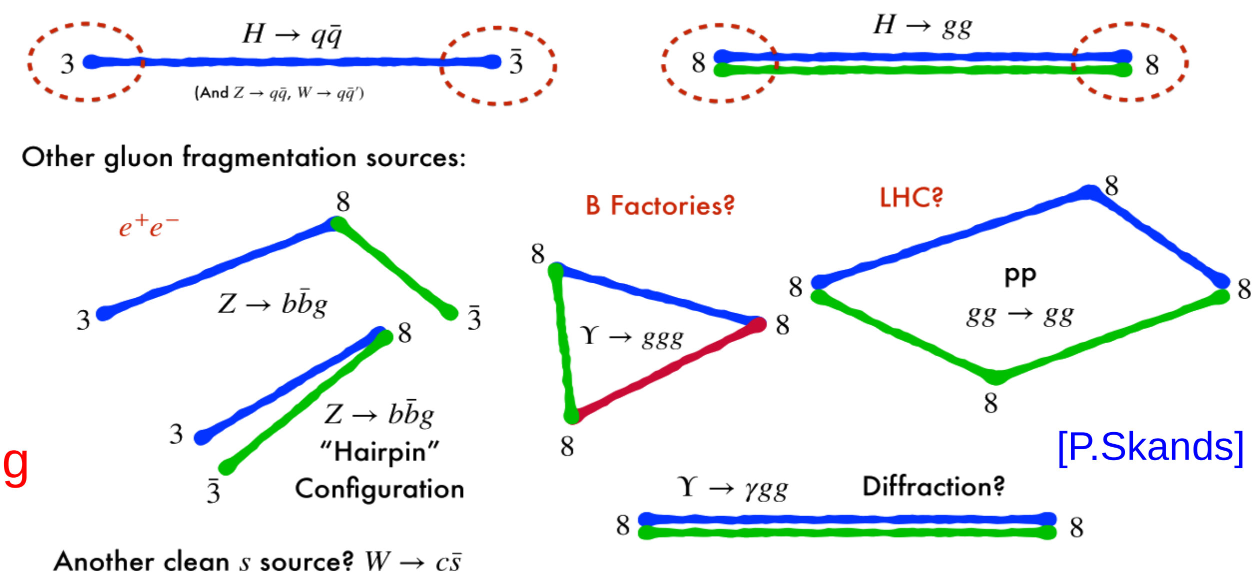


For m_{jj}>100 GeV: Dalitz ssg decays are no bottleneck to the y_s extraction (high mass resum. needed)

[M.Spira; G. Salam]

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

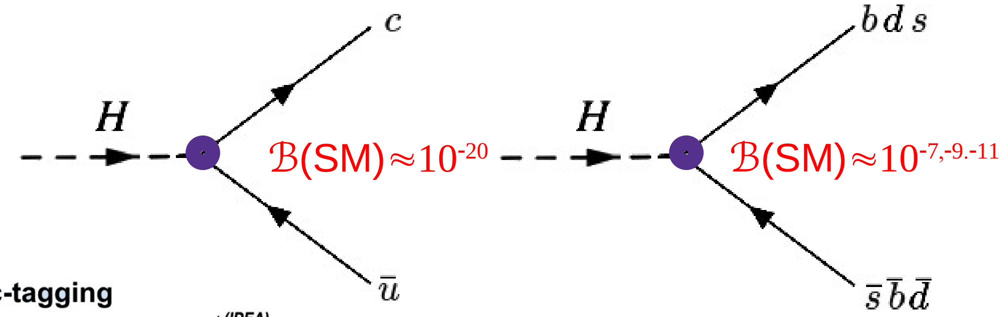
High-precision hadron data (FCC-ee, B-factories?) needed to reliably distinguish leading s, u,d,g fragmentation hadrons



[P.Skands]

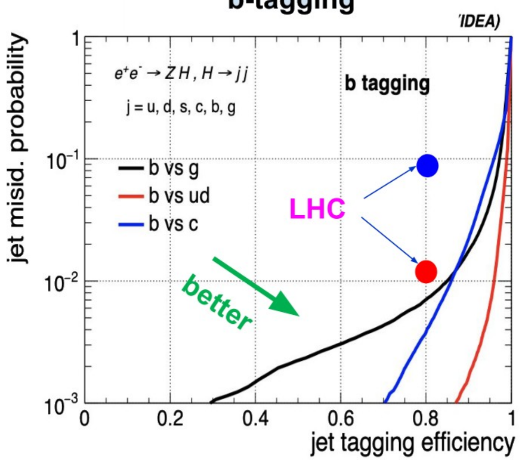
Flavor-violating Higgs decays at FCC-ee

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

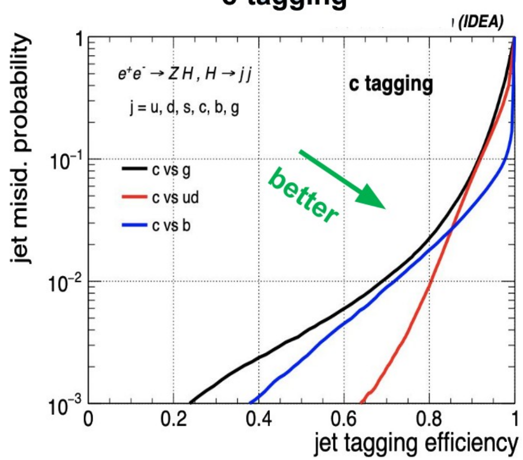


[Kamenik et al. arXiv:2306.17520]

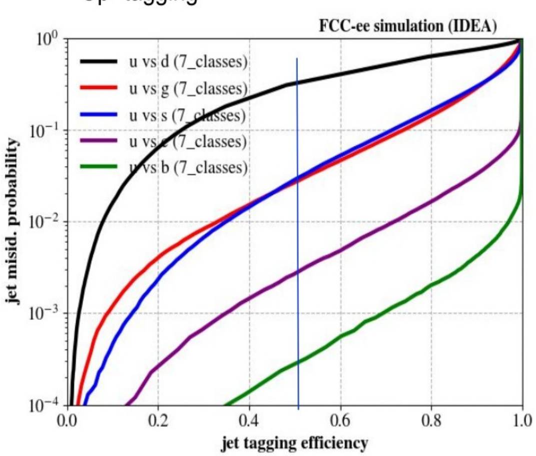
b-tagging



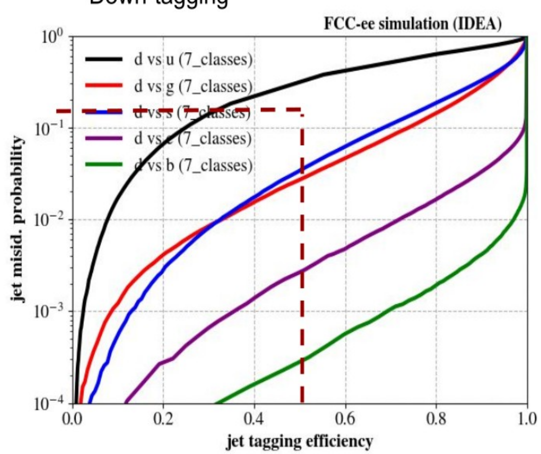
c-tagging



Up -tagging



Down-tagging



– Projected sensitivities:
  $y_{bs,bd,cu} \sim 3{\cdot}10^{-4}$, $y_{sd} \sim 8{\cdot}10^{-4}$
  well beyond current indirect constraints (B_s and D meson oscillations)

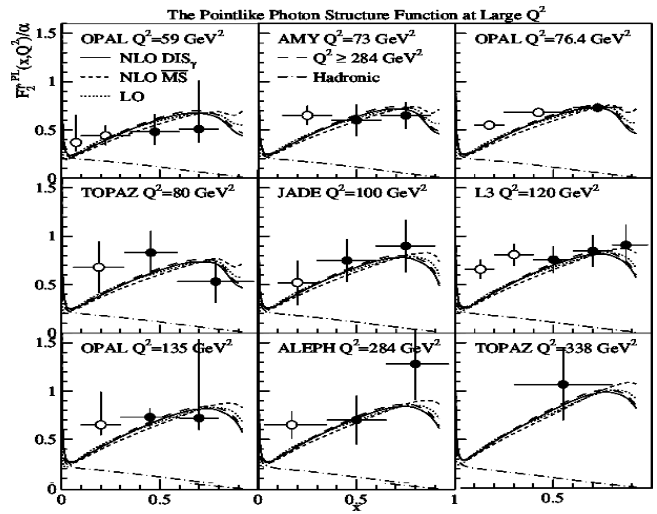
– Expected reach strongly depend on the performance of jet flavor taggers:

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

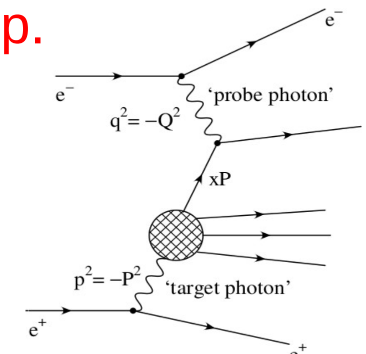
Qu/Gouskos: arXiv:1902.08570
Bedeschi/Gouskos/Selvaggi, arXiv:2202.03285

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:

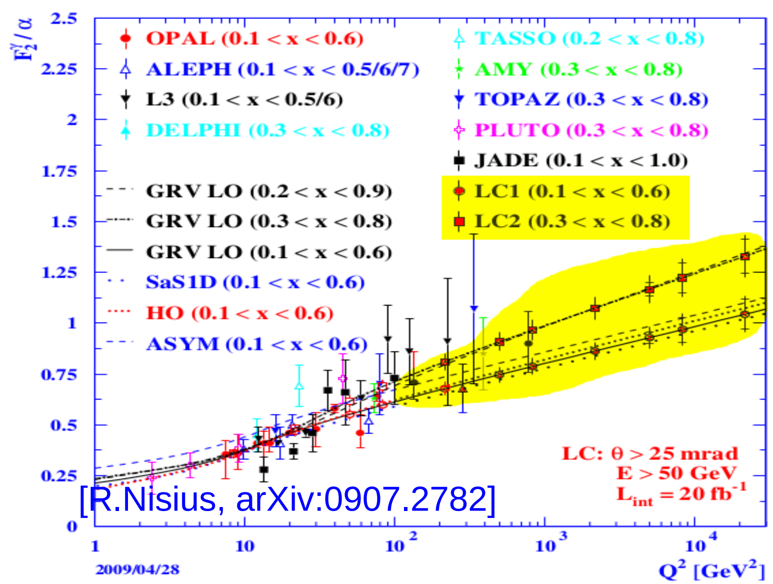


α_s (m$_z$) = 0.1198 ± 0.0054

(±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]

Current & future α_s precision

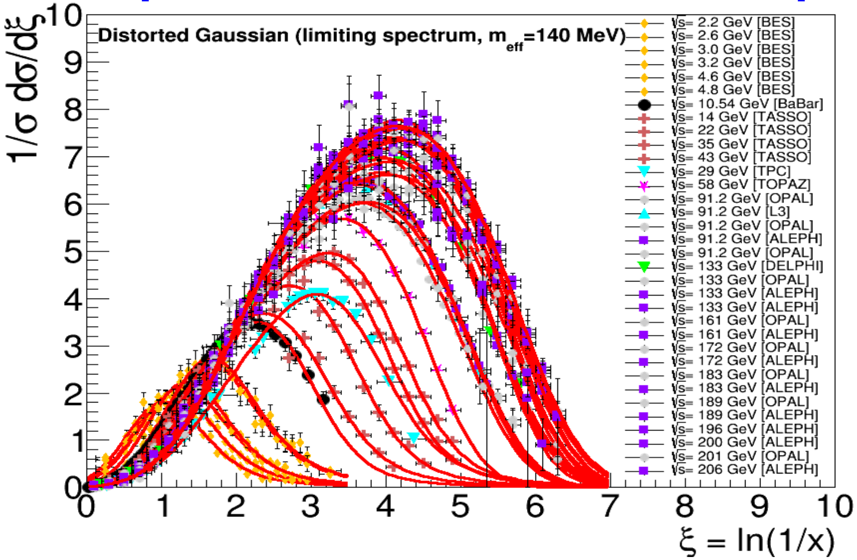
Method	Relative $\alpha_S(m_Z^2)$ uncertainty Current theory & exp. uncertainties sources	Near (long-term) future theory & experimental progress
(1) Lattice	0.7% Finite lattice spacing & stats. $N^{2,3}LO$ pQCD truncation	$\approx$ 0.3% (0.1%) Reduced latt. spacing. Add more observables Add $N^{3,4}LO$,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

- Well-defined exp./th. path towards $\alpha_s(m_z)$ permil precision in coming years

α_s extractions from jet fragmentation (NLO,NNLO*)

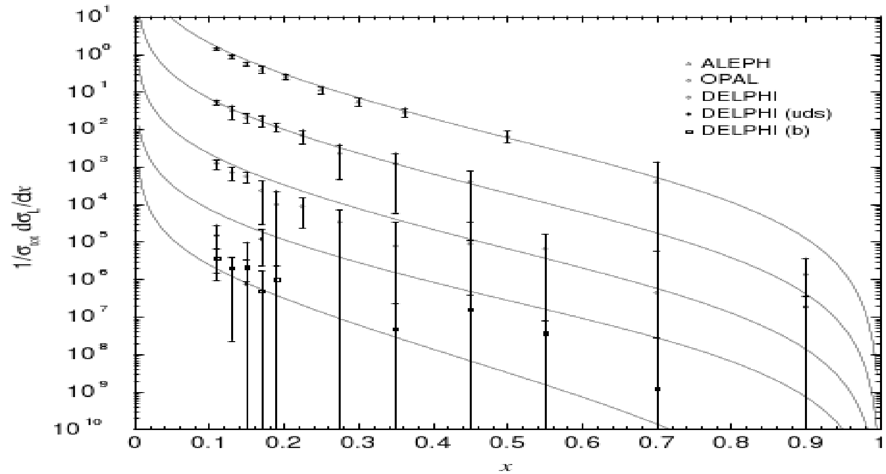
- Soft parton-to-hadron FFs (NNLO*+NNLL):

[D.d'E.,R.Perez-Ramos, arXiv:1505.02624]



- Hard parton-to-hadron FFs (NLO):

$\alpha_s(m_Z) = 0.1176 \pm 0.0055$



[AKK, B. Kniehl et al.,NPB 803(2008)42]

Combined fit of the jet-energy evolution of the FF moments (multiplicity, peak, width,…) with α_s as single free parameter:

$\alpha_s(m_Z) = 0.1205 \pm 0.0022$ (±2%)

(full-NNLO corrections missing)

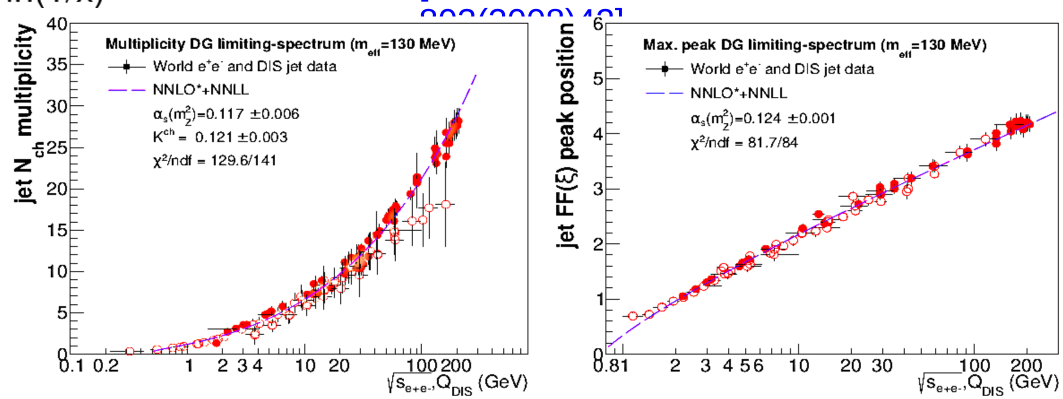


Figure 3: Energy evolution of the charged-hadron multiplicity (left) and of the FF peak position (right) measured in e^+e^- and DIS data fitted to the NNLO*+NNLL predictions. The obtained $\mathcal{K}_{ch}$ normalization constant, individual NNLO* $\alpha_s(m_Z)$ values, and the goodness-of-fit per degree-of-freedom χ^2/ndf.