Precise determination of α_S and FFs at future lepton colliders

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Workshop on FCC-ee and Lepton Colliders
LNF, Italy
23/01/2025

Università di Roma Tor Vergata

Istituto Nazionale di Fisica Nucleare

FCC

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 asymmetry, EW-Planck hierarchy, strong CP problem, υ masses, …
- World priority is a **high-precision Higgs factory** to precisely probe the crucial scalar sector of the SM
- FCC-ee Feasibility Study:
  - Model-independent Higgs couplings down to 0.1%
  - Indirect BSM up to $\Lambda \approx 7\ (70)$ TeV (+ EW observables)
  - Higgs Yukawa couplings to lightest fermions (u, d, s, e, υ?, DM?)
  - Flavour-violating $H \rightarrow qq'$ decays?
- Followed by energy-frontier **hadron collider (FCC-hh)**: Higgs self-couplings + direct BSM searches up to $\Lambda \approx 100$ TeV

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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.

Impressive FCC-ee luminosities

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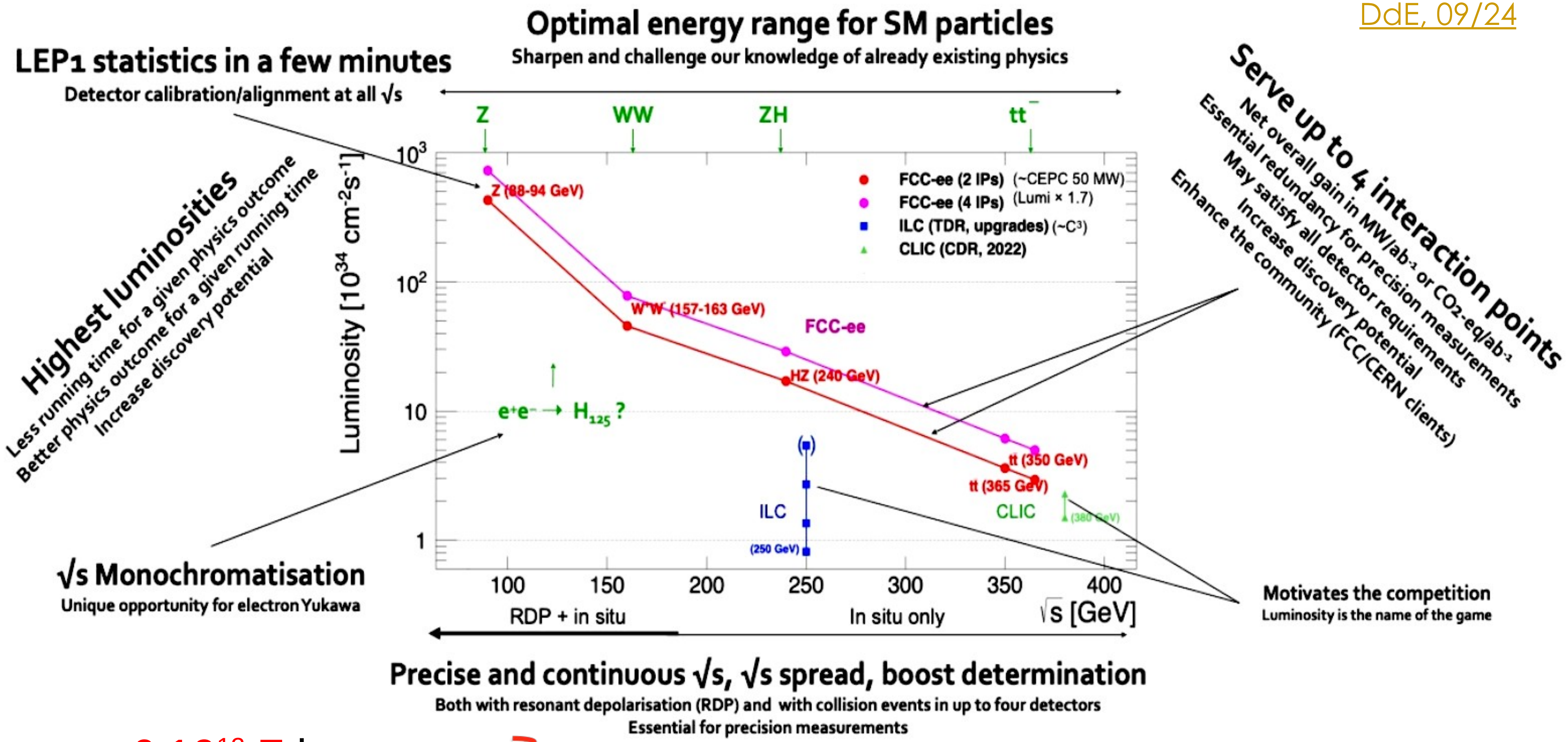


Optimal energy range for SM particles
Sharpen and challenge our knowledge of already existing physics

LEP1 statistics in a few minutes
Detector calibration/alignment at all √s

Highest luminosities
Less running time for a given physics outcome
Better physics outcome for a given running time
Increase discovery potential

Serve up to 4 interaction points
Net overall gain in MW/ab^{-1} or CO2-eq/ab^{-1}
Essential redundancy for precision measurements
May satisfy all detector requirements
Increase discovery potential
Enhance the community (FCC/CERN clients)

√s Monochromatisation
Unique opportunity for electron Yukawa

Motivates the competition
Luminosity is the name of the game

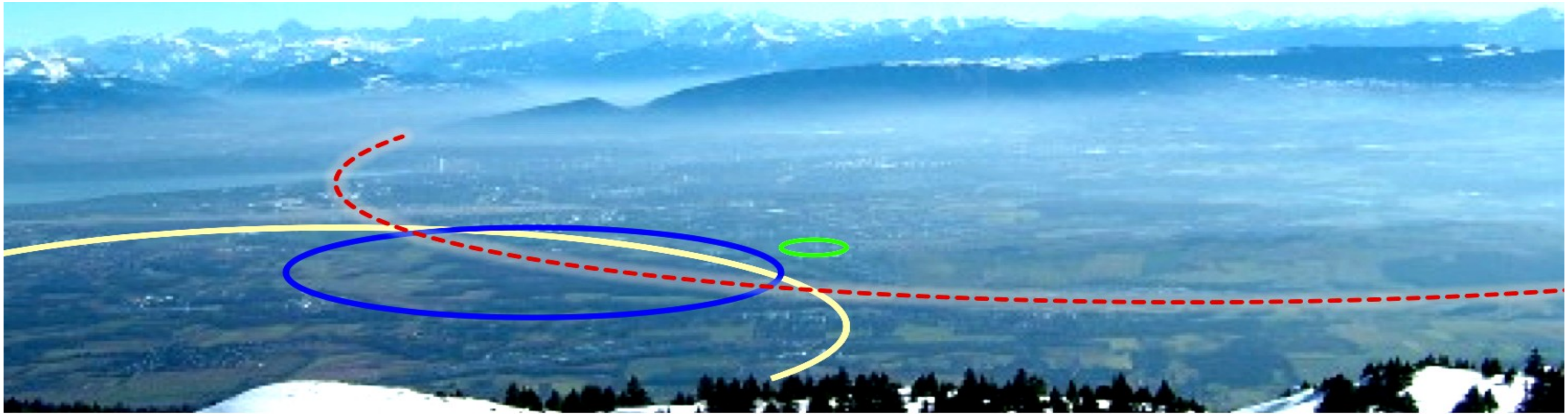
Precise and continuous √s, √s spread, boost determination
Both with resonant depolarisation (RDP) and with collision events in up to four detectors
Essential for precision measurements

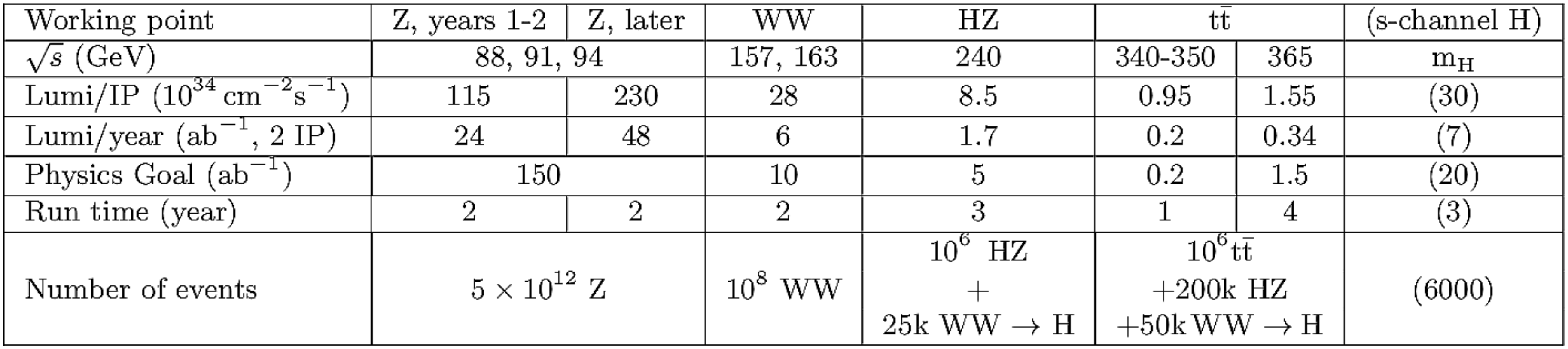
- $6 \cdot 10^{12}$ Z bosons
- $5 \cdot 10^{8}$ W bosons
- $2 \cdot 10^{6}$ Higgs bosons
- $4 \cdot 10^{6}$ top quarks

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

CERN FCC-ee project

- e^+e^- operation before pp at $\sqrt{s}$ = 90, (125), 160, 240 and 350 GeV





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 $\rightarrow$ H	$10^6\,t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H		(6000)

- State-of-the-art detectors + exquisite control of the beam energy → **tiny systematic uncertainties (10^{-5})**

QCD, a key ingredient at future e^+e^- colliders

- Though QCD is not per-se the driving force for the FCC-ee, it is crucial for a huge range of studies
- 70-80% of H, Z and W boson decays have fully hadronic final state!
- **Precise α_s determination** needed to accurately and precisely predict all SM cross-sections and decay rates
- **Higher-order (N^nLO, N^nLL) calculations** crucial to gain precise control over hadronic final states and jet dynamics
- **Heavy/light quark and gluon separation** (flavour tagging, substructure, etc.) is key for multiple SM measurements (Higgs Yukawas, etc.) and BSM searches i.e. X → jj decays, …
- **Non-perturbative QCD** (hadronisation, colour reconnection, …) impacts all the studies with hadronic final states: $e^+e^- \to WW$, $t\bar{t}$ (→ jets), m_W, m_{top}, etc.

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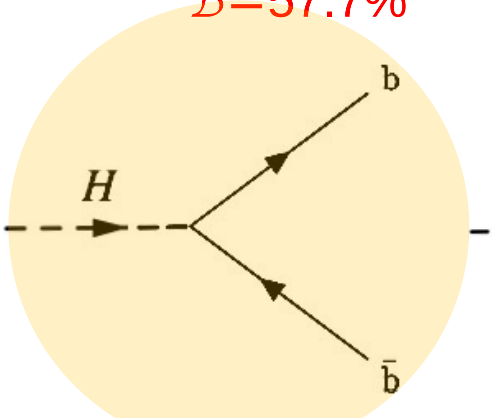
QCD at the core of the Higgs e$^+$e$^-$ program

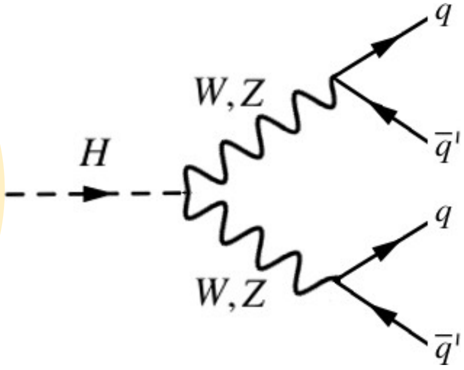
- 80% of of the Higgs decays are fully hadronic! Light Yukawas, FCNC Higgs, …

$\mathcal{B}=57.7\%$

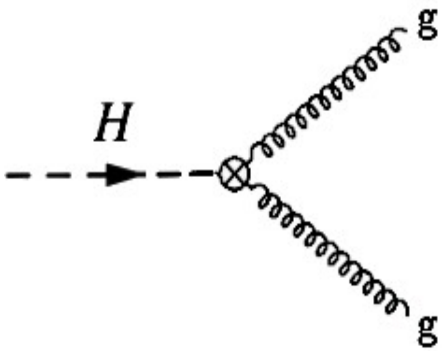


Only hadronic decay channel observed so far!

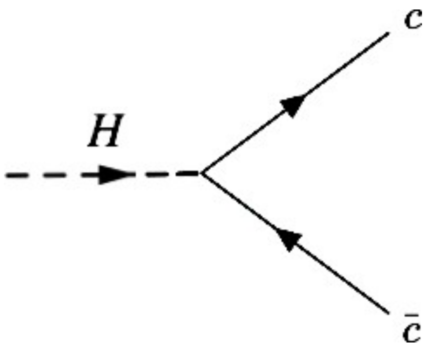
$\mathcal{B}=11\%$

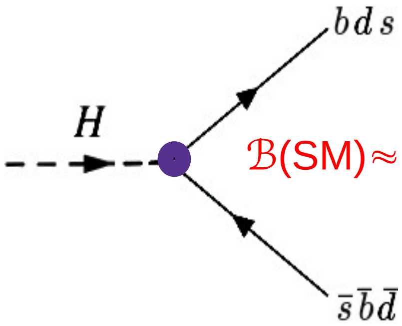


$\mathcal{B}=8.6\%$



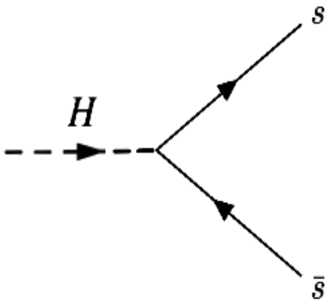
$\mathcal{B}=2.9\%$



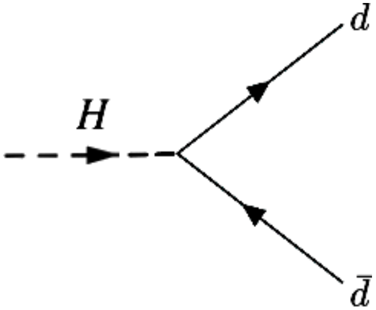


$\mathcal{B}(\mathrm{SM})\approx10^{-7,-9.-11}$

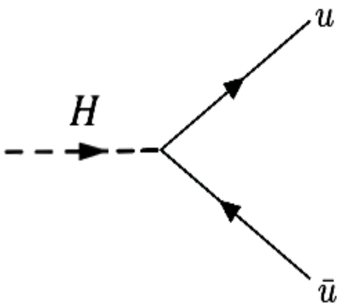
$\mathcal{B}=0.024\%$

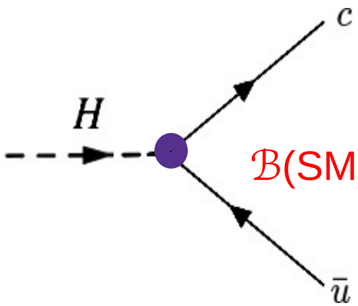


$\mathcal{B}=6\cdot10^{-7}$



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





$\mathcal{B}(\mathrm{SM})\approx10^{-20}$

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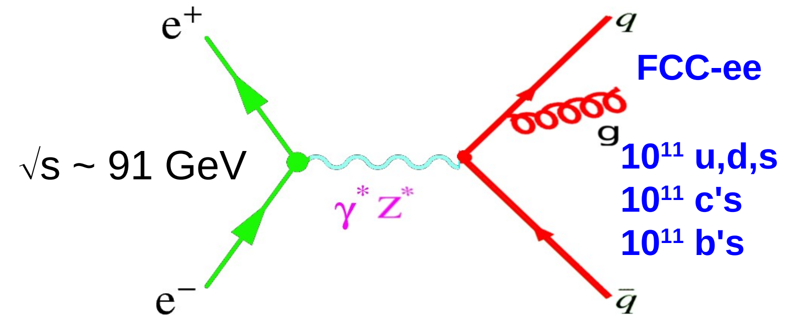
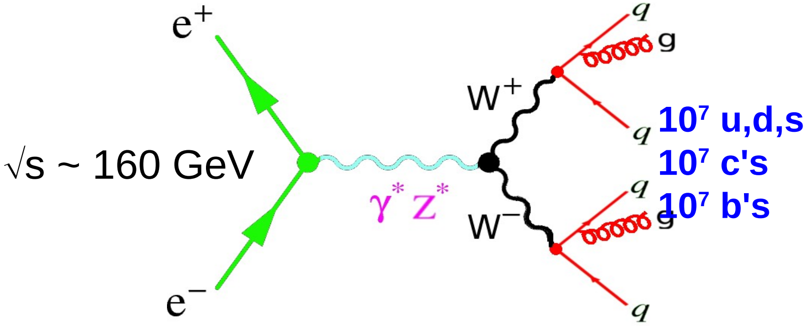
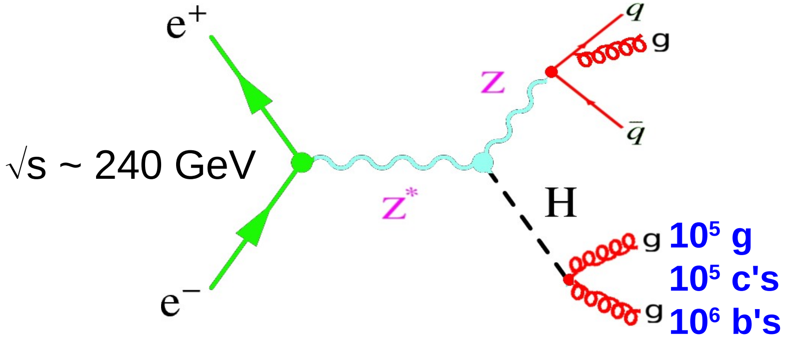
Precision QCD in e^+e^- collisions

- e^+e^- collisions provide an **extremely clean environment** with fully-controlled initial state to probe quark and gluons dynamics very precisely

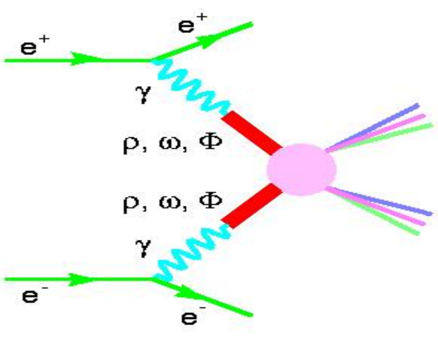




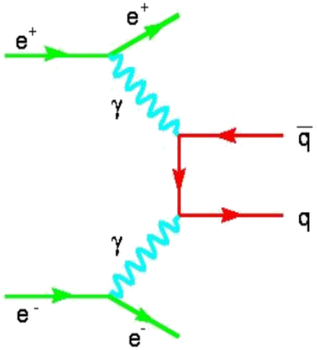


Advantages compared to pp collisions:

- QED initial state with known kinematics
- Controlled QCD radiation (final state)
- Well-defined quarks and gluon jets
- Smaller non-pQCD uncertainties (no PDFs, no QCD underlying events, etc.)
- Direct clean parton fragmentation and hadronization
- QCD physics in $\gamma\gamma$ collisions



(soft, VDM)



(direct)

Very rich QCD physics at FCC-ee

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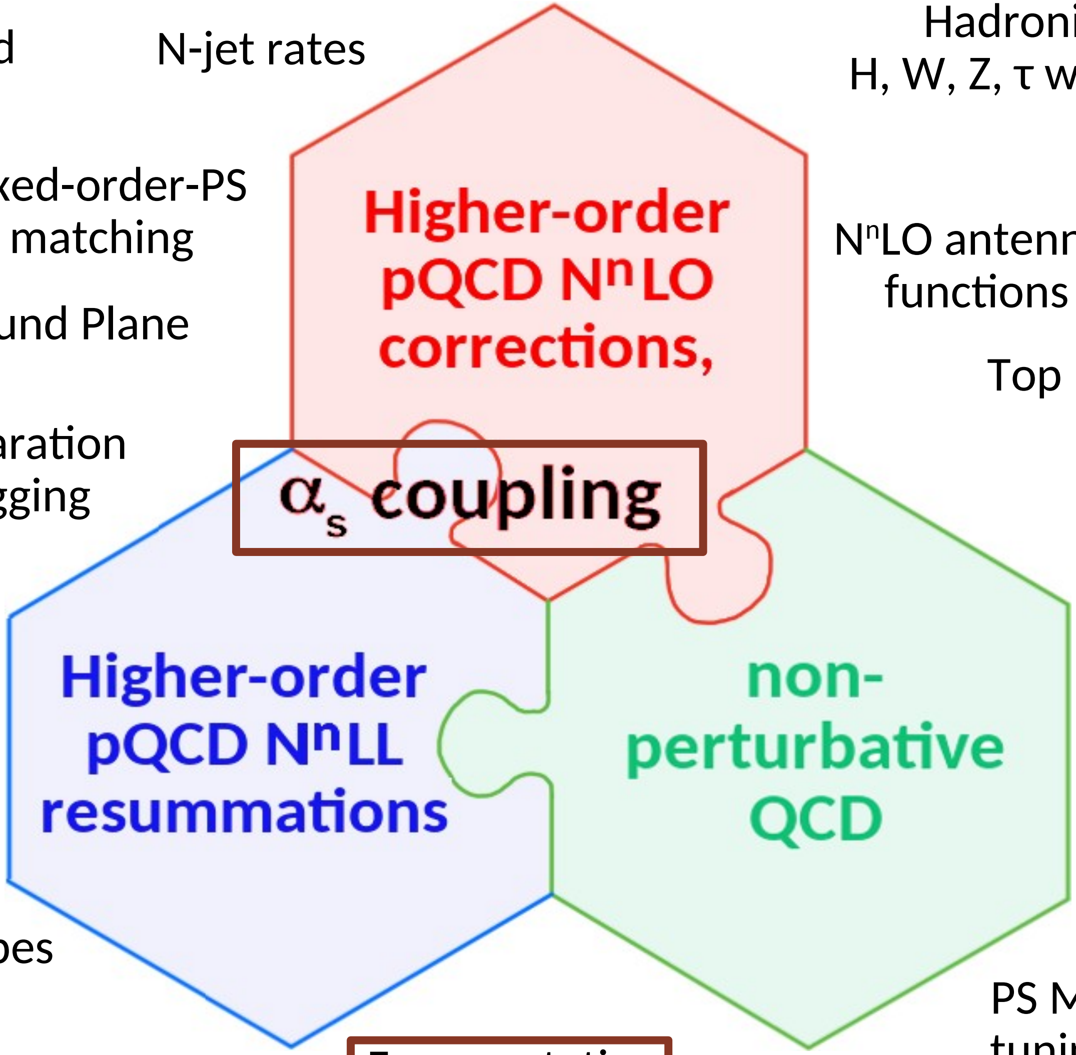

Higher-order pQCD $\mathrm{N^nLO}$ corrections,

α_s coupling

Higher-order pQCD $\mathrm{N^nLL}$ resummations

non-perturbative QCD

$\sin^2\theta_W$ 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

$\mathrm{N^nLL}$ Parton Shower Monte Carlos

Fragmentation Functions

$Q\bar{Q}$ transition probabs.

Hadronic H, W, Z, τ widths

Mixed QCD-EW corrections

$\mathrm{N^nLO}$ antenna functions

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

Colour reconnection

Parton hadronization

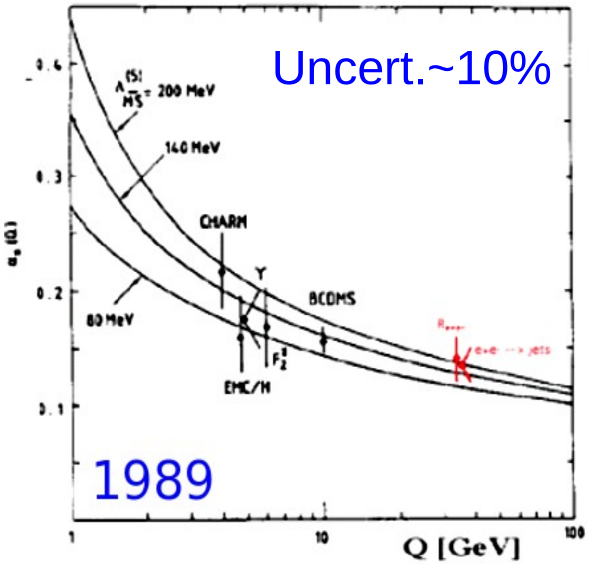
Final-state correlations

PS MC tuning

Lattice QCD

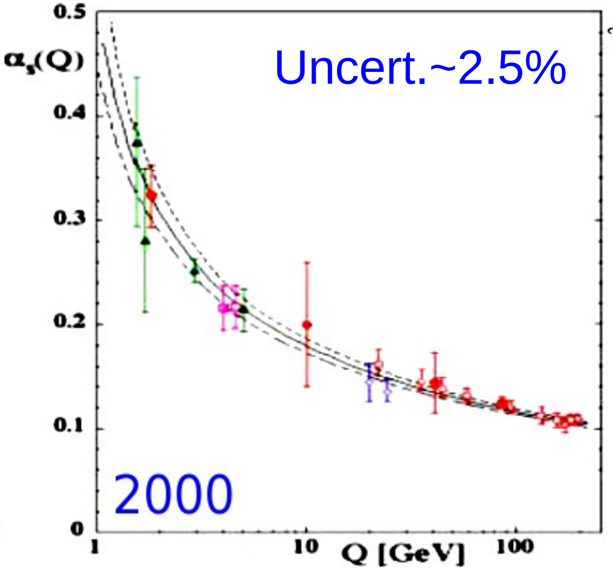
QCD coupling α_s

- Determines strength of the strong interaction between quarks and gluons
- **Single free parameter of QCD** in the $m_q = 0$ limit
- Determined at $Q = m_Z$, decreases as $\alpha_s \sim \ln(Q^2/\Lambda^2)$ with $\Lambda \sim 0.2$ GeV



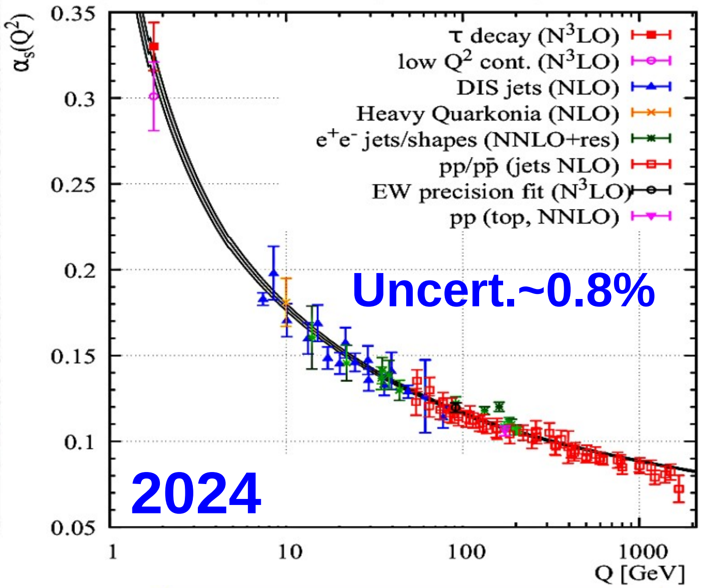
$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

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



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

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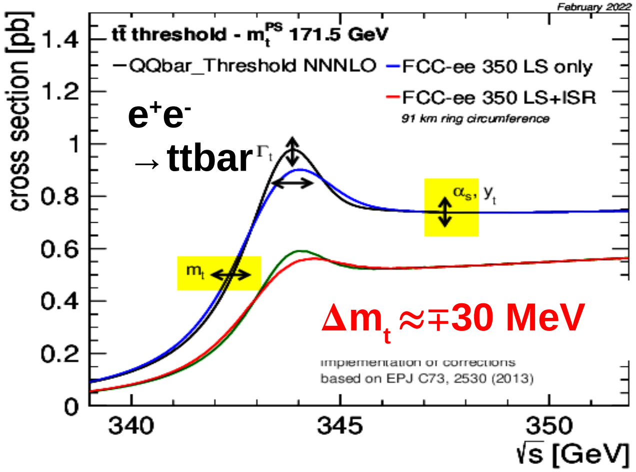
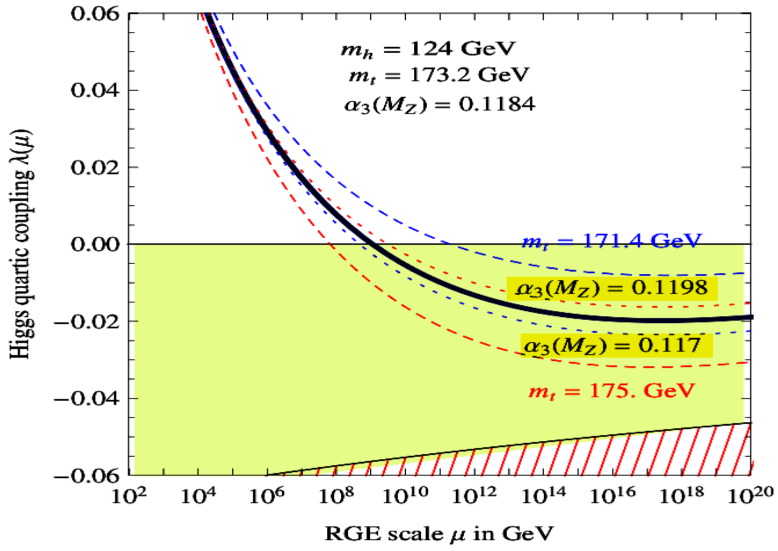
- Parametric uncertainties in multiple precision SM observable calculations:

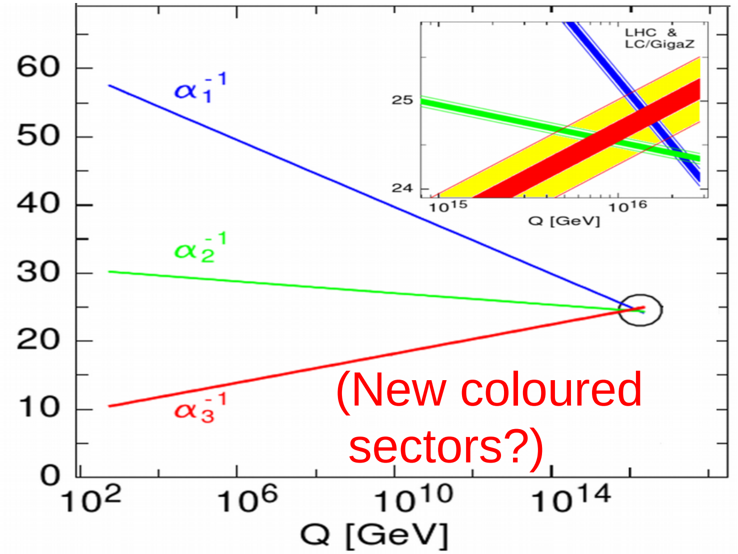
Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 +0.32
ttH	0.611	± 3.0	$\pm$ 8.9	-9.3 +5.9

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 Plank scale: EW vacuum stability, GUT, etc.

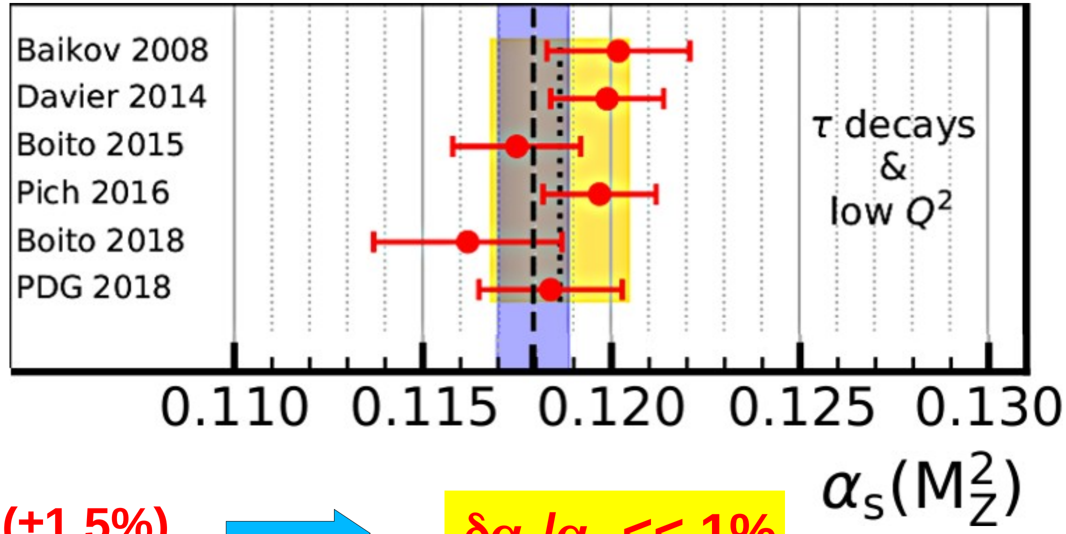




(New coloured sectors?)

α_S from hadronic τ-lepton decays

- Computed at N^{3}LO: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C \left(1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\text{np}}\right)$
- Experimentally we have $R_{\tau,exp} = 3.4697 \pm 0.0080$ ($\pm 0.23\%$)
- Various pQCD approaches (Fixed Order Perturbation Theory - FOPT - vs Contour Improved Perturbation Theory – CIPT) and treatment of non-pQCD corrections yield different results



$\alpha_s(m_z) = 0.1187 \pm 0.0018$ ($\pm 1.5\%$) → **$\delta\alpha_s/\alpha_s \ll 1\%$**

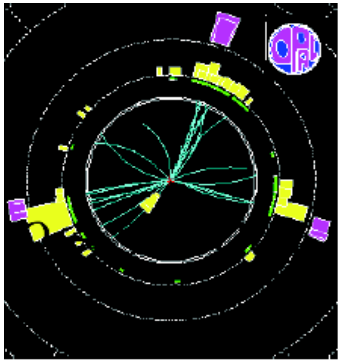
- What next?
  - Theory: better understanding of FOPT vs CIPT differences & need of N^{4}LO
  - Better spectral functions needed (better precision)
  - Higher statistics: $\mathcal{O}(10^{11})$ from $Z \to \tau^+\tau^-$ at FCC-ee(90)
  - Extract the τ width from the ultraprecise measurement of its lifetime

α_S from e^+e^- event shapes and jet rates

- Computed at N^{2,3}LO+N(N)LL accuracy
- Experimental observables: Thrust, jet shapes, C-parameter, n-jet cross sections

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

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

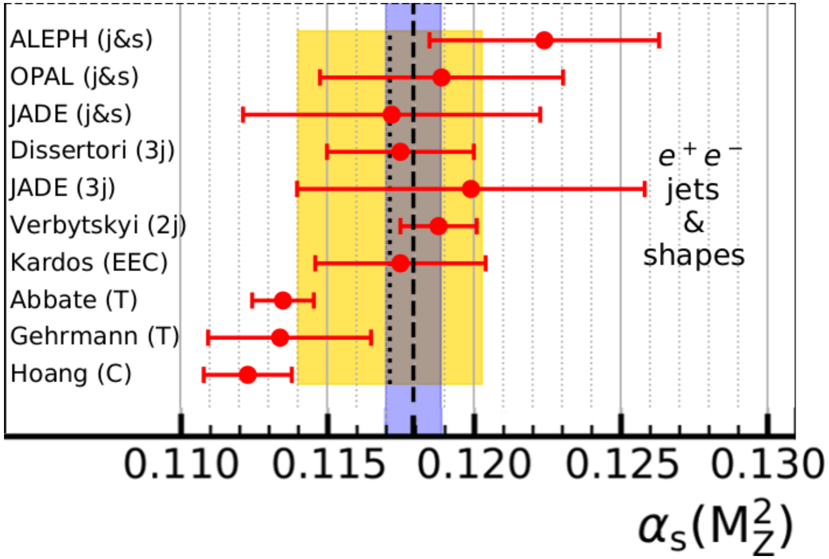


OPAL 3 jet event

- Results sensitive to non-pQCD e.g. hadronization accounted for via MCs or analytically

$\alpha_s(m_z)$ = 0.1171 ± 0.027 (±2.6%)

$\delta\alpha_s/\alpha_s < 1\%$



- What next?
  - FCC-ee: Lower $\sqrt{s}$ (ISR) for shapes, higher $\sqrt{s}$ for jet rates
  - Theory: Improved NN(N)LL resummed calculations for rates, hadronization for shapes

α_s from hadronic Z decays (FCC-*ee*)

- α_s extracted at N³LO from:
  - Combined fit of 3 Z pseudo-observables
  - Full SM fit (with α_s free parameter)

- The W and Z hadronic widths :

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

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

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

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

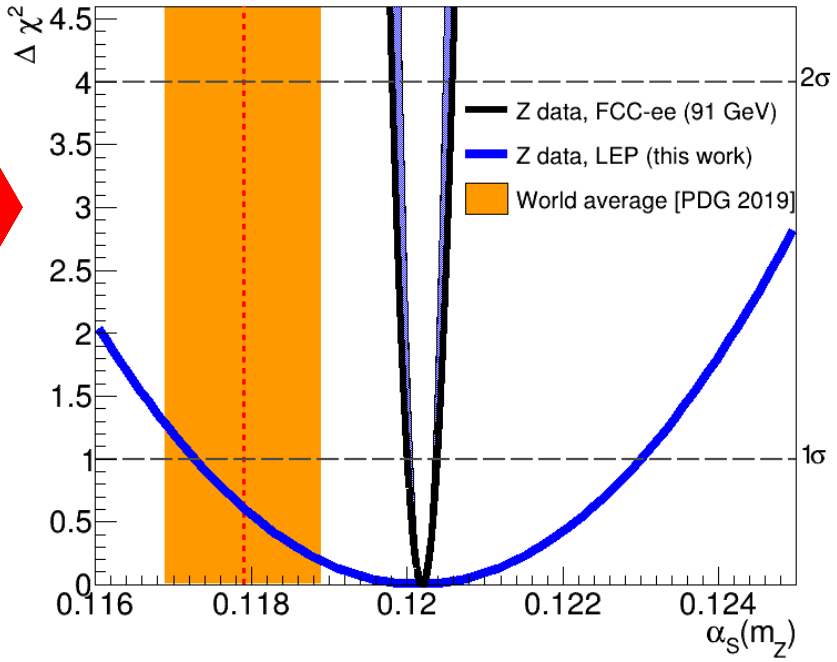
$$\sigma^{\rm had}_{\rm Z} = \frac{12\pi}{m_{\rm Z}} \cdot \frac{\Gamma^e_{\rm Z}\Gamma^{\rm had}_{\rm Z}}{(\Gamma^{\rm tot}_{\rm Z})^2}$$

2005.04545

- **At FCC-ee:**
- Huge Z pole statistics (x10⁵ LEP)
- Exquisite systematic precision (stat. uncertainties much smaller)

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

- Theory uncertainties reduced by a factor of 4 computing missing α_s^5, α^3, $\alpha\alpha_s^2$ and $\alpha^2\alpha_s$ terms
- 20 times better precision than today: $\frac{\delta\alpha_s}{\alpha_s}$ ~ **±0.2% (tot), ±0.1% (exp)**



$\alpha_s(m_z)$ = 0.12030 ± 0.00014 (±0.1%)

α_s from hadronic W decays (FCC-*ee*)

- α_s extracted from N^{3}LO fit of combined Γ_W, R_W W pseudo-observables:

- The W and Z hadronic widths :

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

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

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

- **At FCC-ee:**
- Huge W pole statistics (x10^4 LEP-2)
- Exquisite systematic precision (stat. uncertainties much smaller)

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

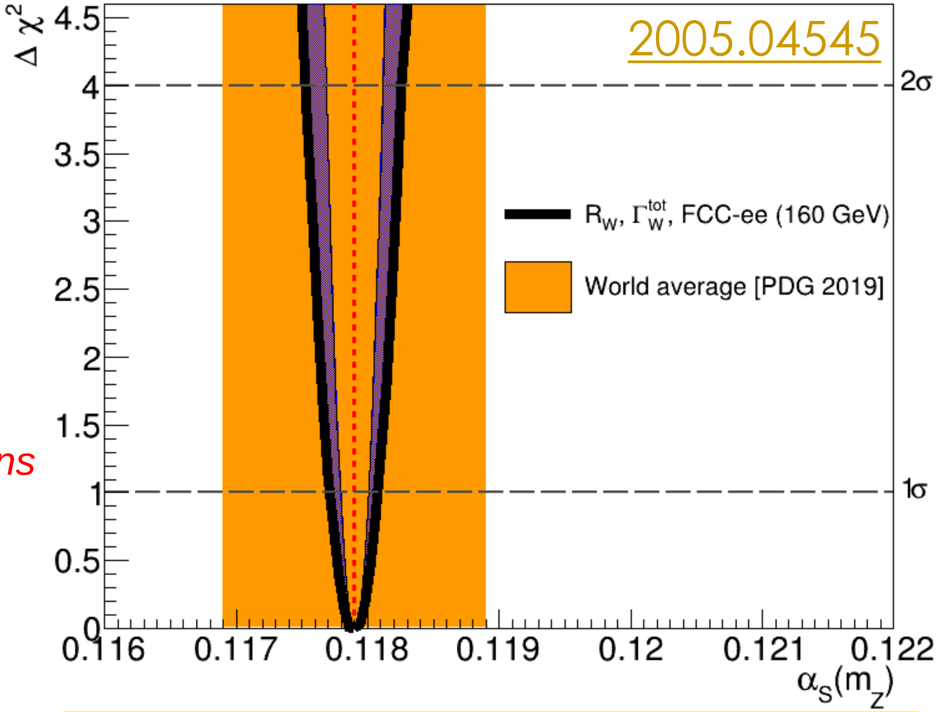
$$\mathrm{R_W} = 2.08000 \pm 0.00008$$

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

$$|V_{cs}| = 0.97359 \pm 0.00010$$

← *O(10^{12}) D mesons*

- Theory uncertainties reduced by a factor of 10 computing missing $\alpha_s^5, \alpha^2, \alpha^3, \alpha\alpha_s^2$ and $\alpha^2\alpha_s$ terms
- 150 times better precision than today!



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

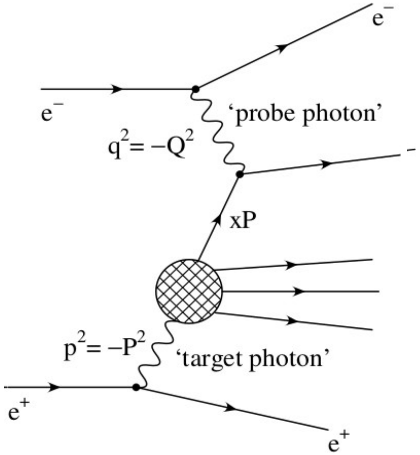
α_s from photon QCD structure function

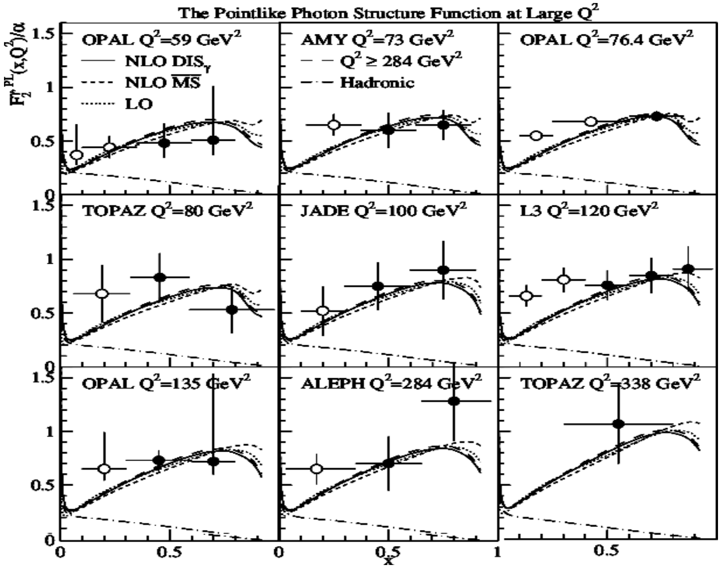
- Computed at NNLO: $\int_0^1 dx F_2^\gamma(x,Q^2,P^2) = \frac{\alpha}{4\pi}\frac{1}{2\beta_0}\left\{\frac{4\pi}{\alpha_s(Q^2)}c_{LO} + c_{NLO} + \frac{\alpha_s(Q^2)}{4\pi}c_{NNLO} + \mathcal{O}(\alpha_s^2)\right\}$
- Poor $F_\gamma^2(x,Q^2)$ experimental measurements
- NLO extraction with large experimental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

$\alpha_s(m_z)$ = 0.1198 ± 0.0054

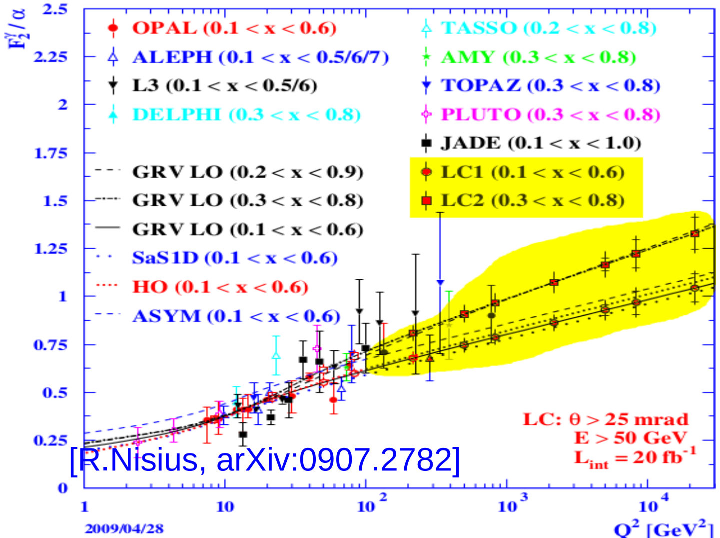
(±4.5%)

hep-ph/0205069





- **Future prospects:**
  - Fit with NNLO F_γ^2 evolution
  - Better data
  - Dedicated simulation studies (already exist at ILC)
  - Huge $\gamma\gamma$ statistics at FCC-*ee* will lead to $\delta\alpha_s/\alpha_s$ < 1%

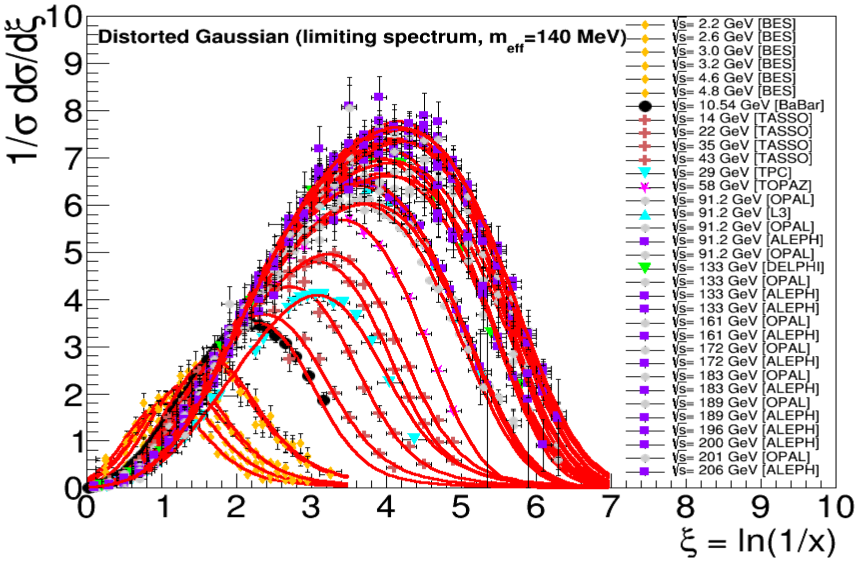


[R.Nisius, arXiv:0907.2782]

α_S from jet fragmentation

- Soft parton-to-hadron FFS:

1505.02624 – NNLO*+NNLL



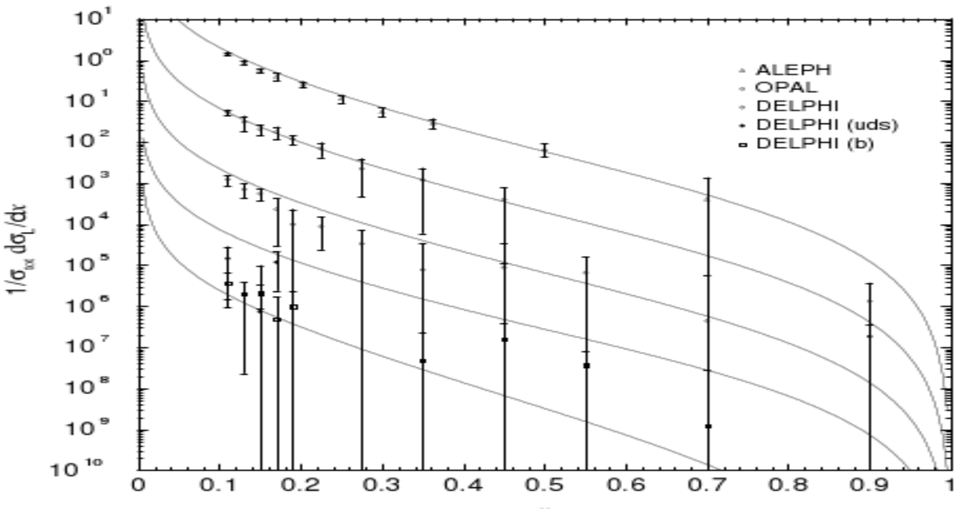
Combined fit of the jet-energy evolution of the FF moments (peak, width, multiplicity, etc.) with α_S as single free parameters

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

(full NNLO corrections missing)

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

$\alpha_s(m_Z) = 0.1176 \pm 0.0055$ (±4.7%)



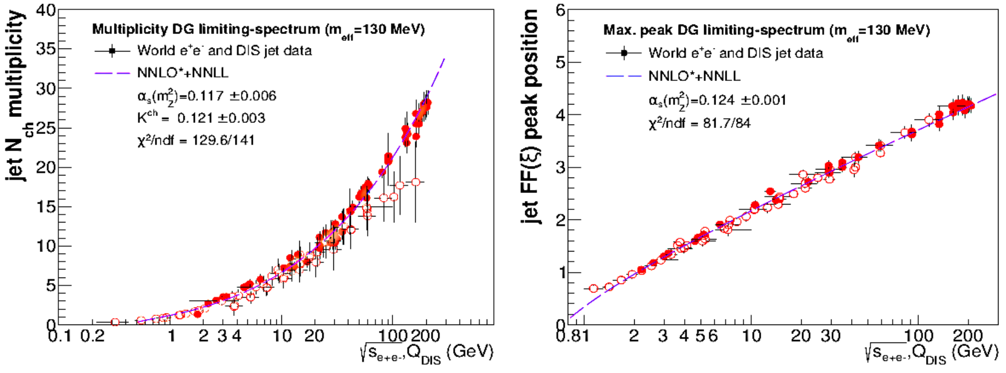


Figure 3: Energy evolution of the charged-hadron multiplicity (left) and of the FF peak position (right) measured in e^+e^- and DIS data fitted to the NNLO*+NNLL predictions. The obtained $\mathcal{K}_{ch}$ normalization constant, individual NNLO* $\alpha_s(m_Z)$ values, and the goodness-of-fit per degree-of-freedom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

High-precision parton FFs at FCC-ee

- Parton-to-hadron fragmentation functions evolution known at NNLO at high-z and at NNLO*+NNLL at low-z

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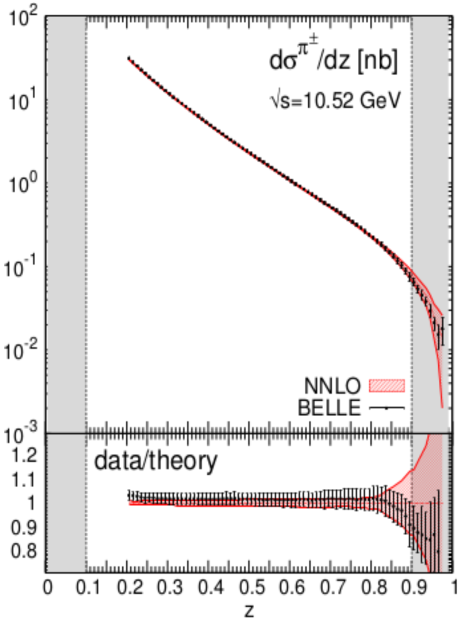
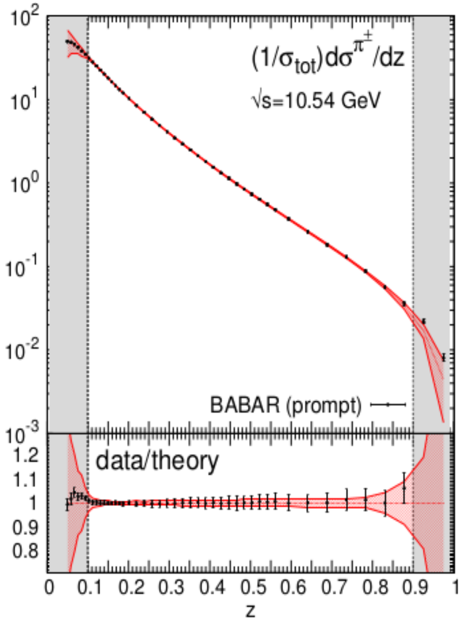
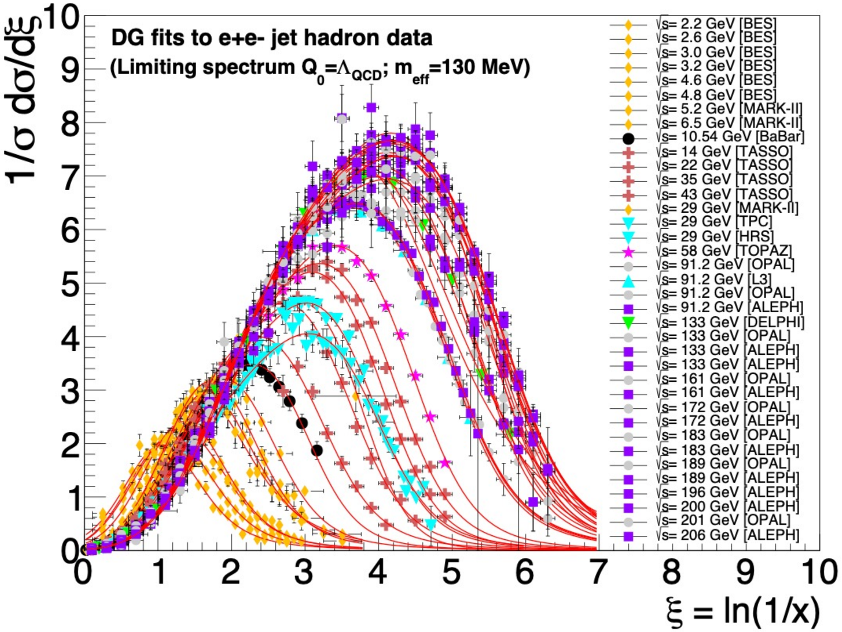


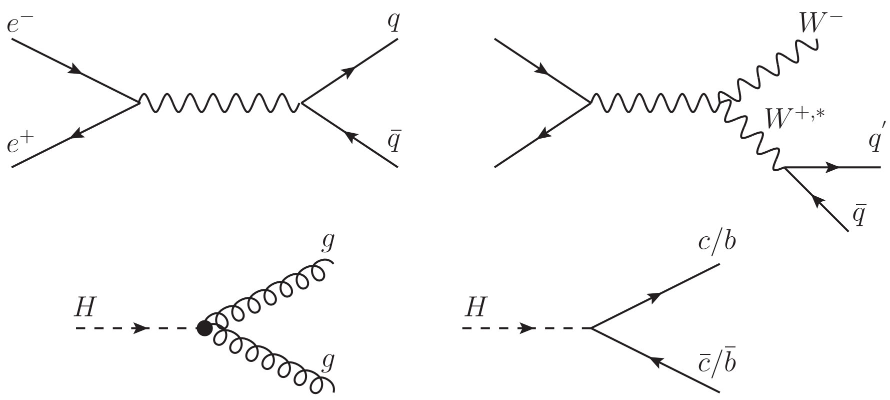




- FCC-*ee* (much broader z range) provides additional QCD coupling extractions, allowing for $\delta\alpha_S$ < 1%

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)

Opportunities with future lepton colliders



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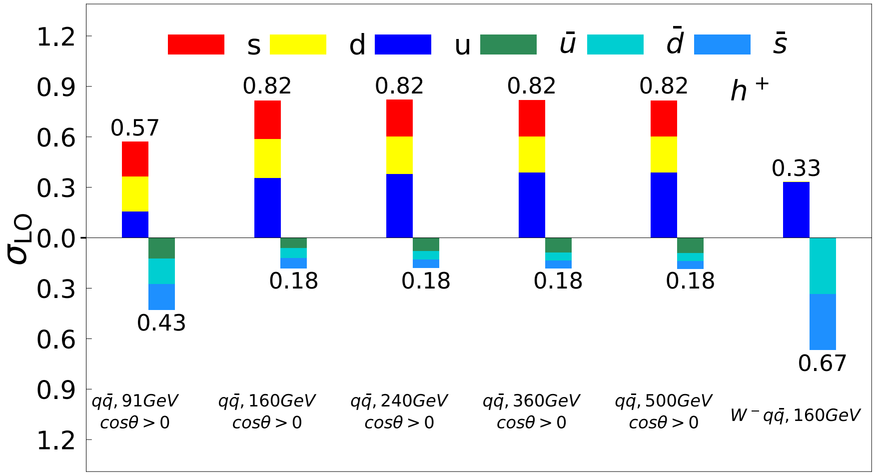
FFs–sensitive processes



LO cross section for various light quarks and antiquarks production

- Producing $q\bar{q}$ samples at various energies with kinematic cuts is crucial for light quark flavour and charge separation
- Heavy quark enriched samples and gluon samples from Higgs boson hadronic decays
- Further quark flavour and charge separation from W boson production with hadronic decays

Parton FFs at future lepton colliders

- High luminosity and high energies of future lepton colliders open new opportunities for precision determination of FFs

Proposed hadron multiplicity measurements from annihilation to quarks

2407.10059

Proposed hadron multiplicity measurements from decays of W and Higgs bosons

e^+e^- annihilation

$\sqrt{s}$ (GeV)	luminosity (ab^{-1})			final state	kinematic cuts	hadrons	N_{pt}
	CEPC	FCC-*ee*	ILC				
91.2	60	150	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	132
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	65
160	4.2	-	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	168
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	83
161	-	10	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	168
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	83
240	13	5	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	186
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	92
250	-	-	2	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	186
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	92
350	-	0.2	0.2	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	98
360	0.65	-	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	98
365	-	1.5	-	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	98
500	-	-	4	$q\bar{q}$	$\cos(\theta) > 0$	$h^{+,-}$	198
				$c\bar{c}/b\bar{b}$	-	$h^\pm$	98

W boson decay channels

$\sqrt{s}$ (GeV)	# events (million)			final state	kinematic cuts	hadrons	N_{pt}
	CEPC	FCC-*ee*	ILC				
80.419	116	68	62	$W^-W^{+*} \to W^-q\bar{q}$	-	$h^{+,-}$	120
	58	34	31	$W^-W^{+*} \to W^-c\bar{s}$			

Higgs boson decay channels

$\sqrt{s}$ (GeV)	# events (million)			final state	kinematic cuts	hadrons	N_{pt}
	CEPC	FCC-*ee*	ILC				
125	0.23	0.09	0.07	gg	-	$h^\pm$	77
	0.08	0.03	0.02	$c\bar{c}$			
	1.53	0.59	0.47	$b\bar{b}$			

- Joint determination of FFs to charged pion, kaon and proton **at NLO**

- Strong selection criteria on kinematics to ensure validity of leading-twist factorisation and perturbative calculations ($z > 0.01$, $E_h > 4$ GeV)

Projection for constraints on FFS

- Pseudo-data on the proposed measurements are constructed using NPC23 FFs as truth theory

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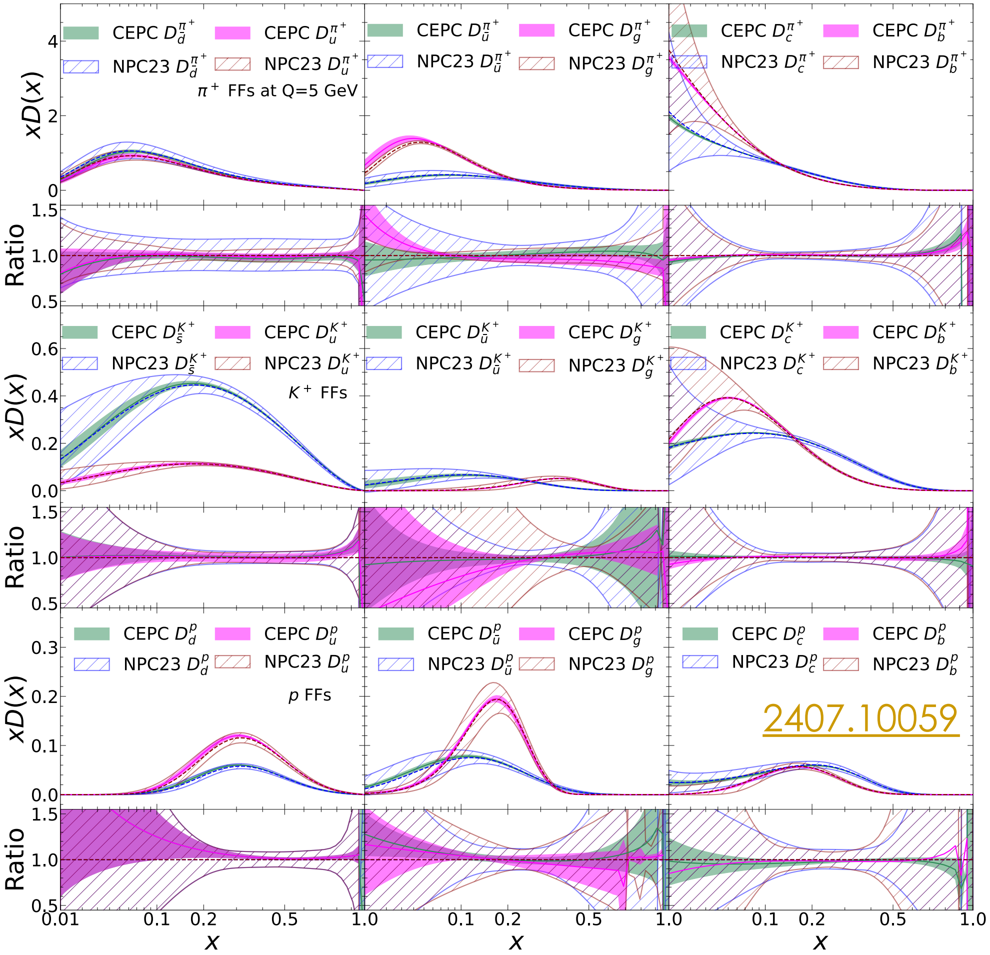
- Fits to FFs at NLO in QCD carried out with data solely from future e^+e^- colliders



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- Assuming same (un-)correlated systematic uncertainties as SLD measurements
- Statistical errors calculated based on prescribed luminosities
- Fits using NPC23 fitting framework
- Theoretical uncertainties from NLO scale variations included
- Best-fit agrees well with the truth FFs
- **Uncertainties greatly reduced taking CEPC as an example**

Projection for constraints on FFS

- Pseudo-data on the proposed measurements are constructed using NPC23 FFs as truth theory

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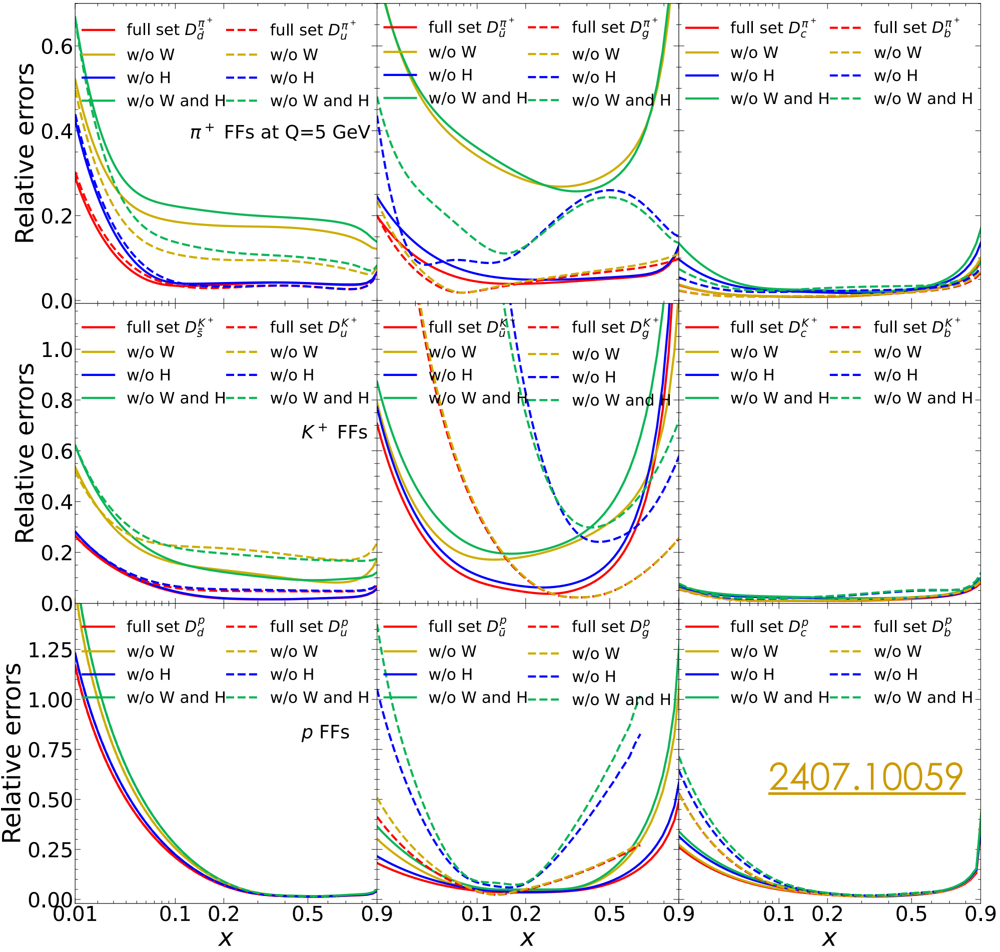
- Fits to FFs at NLO in QCD carried out with data solely from future e^+e^- colliders



2407.10059

- Assuming same (un-)correlated systematic uncertainties as SLD measurements
- Statistical errors calculated based on prescribed luminosities
- Fits using NPC23 fitting framework
- W boson data essential for **quark flavour separation**
- Similarly Higgs boson data for constaring **gluon FFs**

Projection for constraints on FFS

- ➢ Pseudo-data on the proposed measurements are constructed using NPC23 FFs as truth theory

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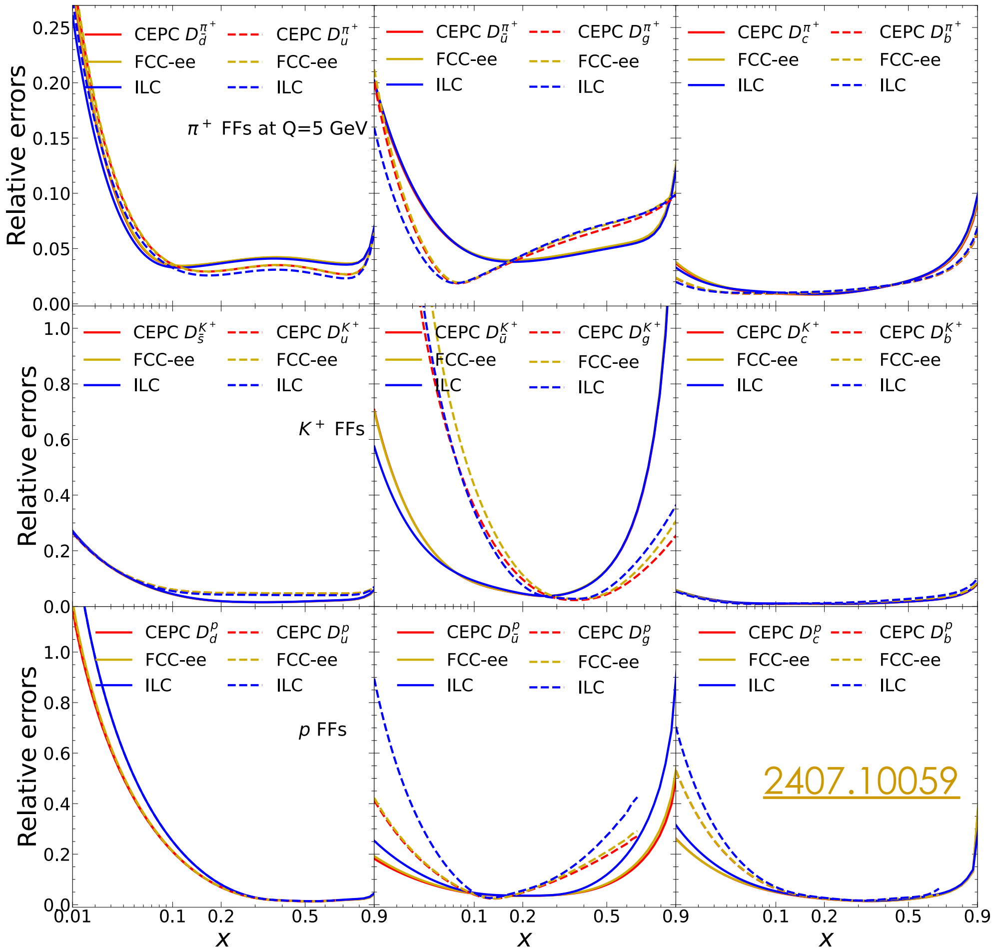
- ➢ Fits to FFs at NLO in QCD carried out with data solely from future e⁺e⁻ colliders



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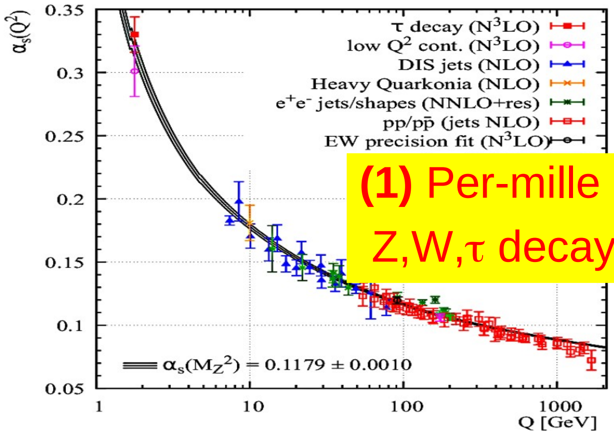
- ➢ Assuming same (un-)correlated systematic uncertainties as SLD measurements
- ➢ Statistical errors calculated based on prescribed luminosities
- ➢ Fits using NPC23 fitting framework
- ➢ **ILC, FCC-ee and CEPC give quite similar results** except in regions limited by statistics

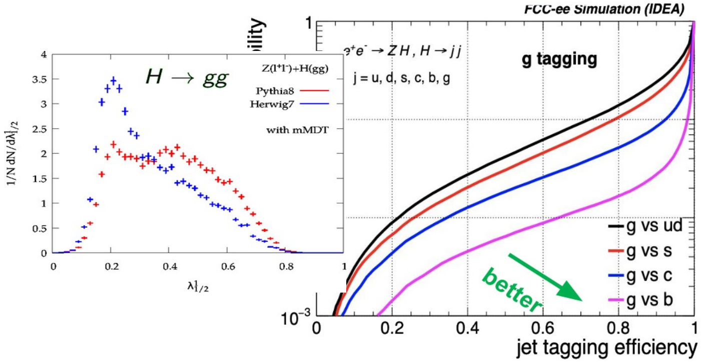
Summary & outlook

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

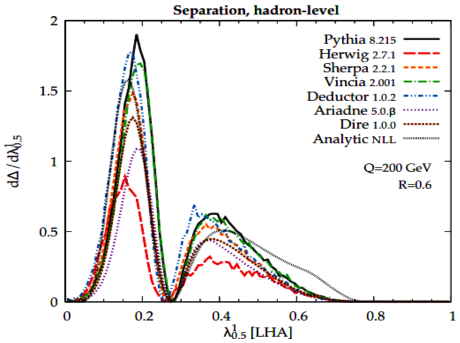


(1) Per-mille α_s via hadronic Z,W,τ decays, evt shapes...

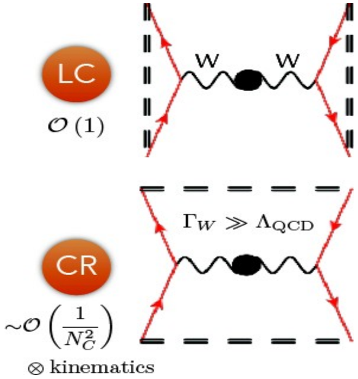
(2) Ultimate g/q/Q discrimination



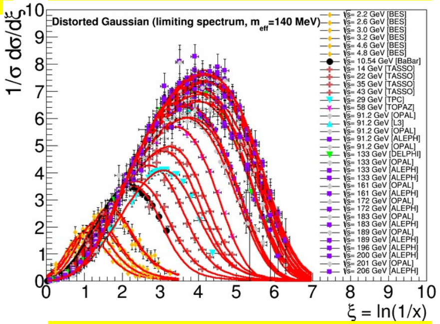
(3) Improved NⁿLO+NⁿLL parton showers tuning

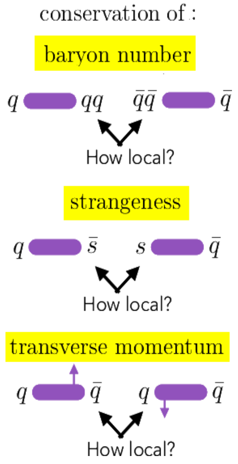


(4) <<1% control of colour reconnection



(5) High-precision hadronization:



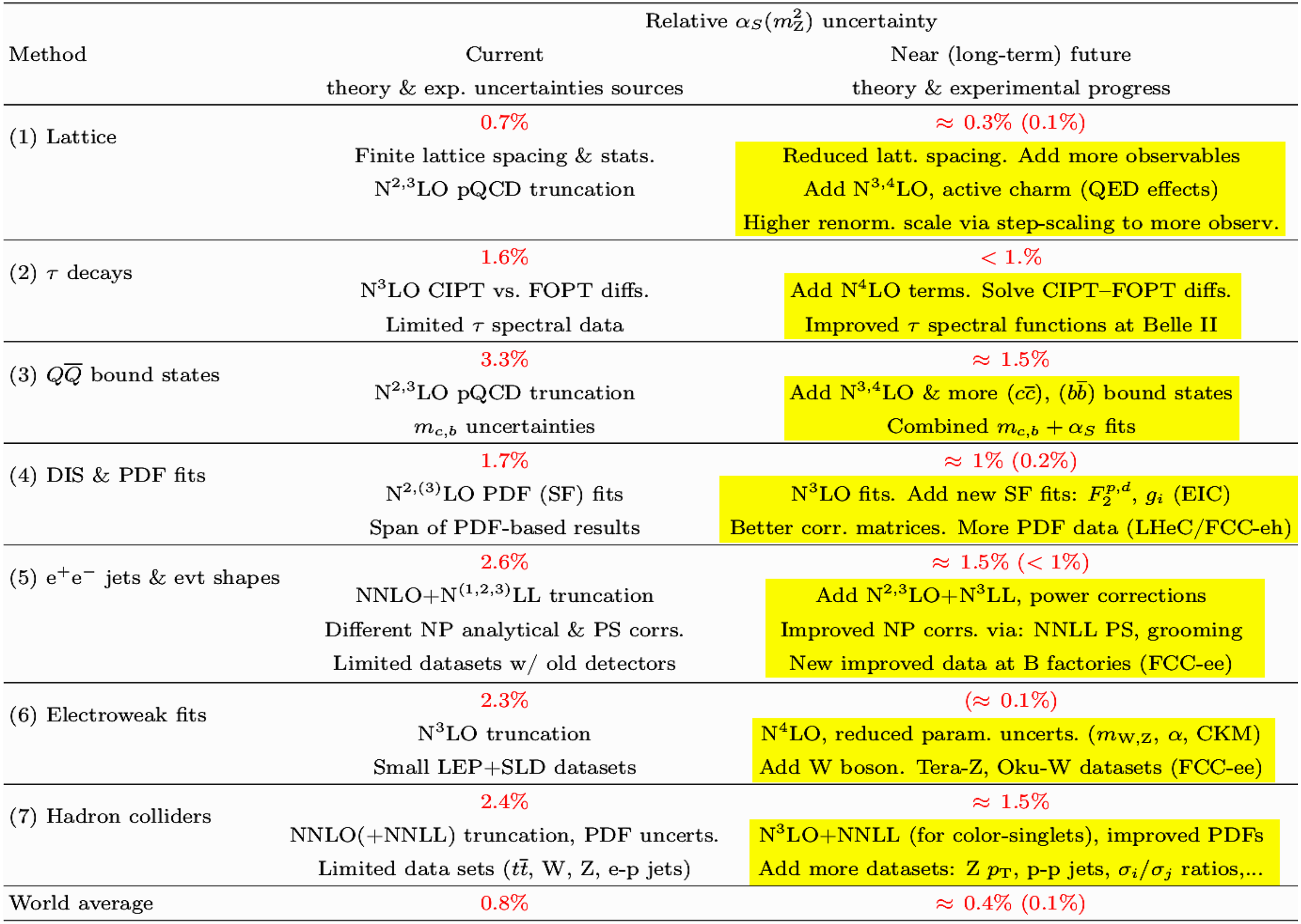


(6) Ultra-rare QCD bound states,...

Backup Slides

Current anf future α_s precision

- Well-defined exp./th. path towards $\alpha_s(m_Z)$ per-mill precision in coming years



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%)

α_S from hadronic W/Z decays

- W and Z 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 :

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

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

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

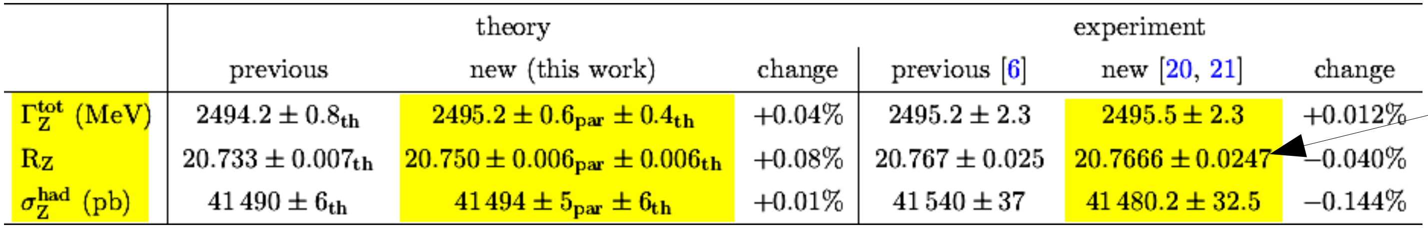
Theory unc. (α^2, α^3 included for Z):

±0.015-0.03% (Z)
±0.015-0.04% (W)

Param. unc. ($m_{W,Z}$, α, $V_{cs,ud}$):

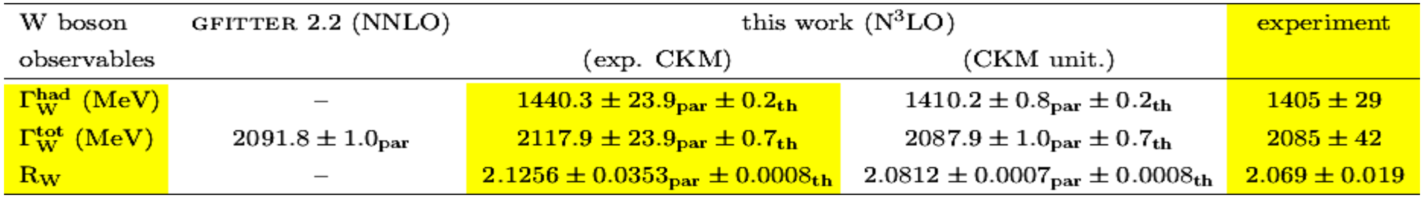
±0.01-0.03% (Z)
±1.1-1.7% (W)

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



	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%
$\mathrm{R_Z}$	$20.733 \pm 0.007_{\rm th}$	$20.750 \pm 0.006_{\rm par} \pm 0.006_{\rm th}$	+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



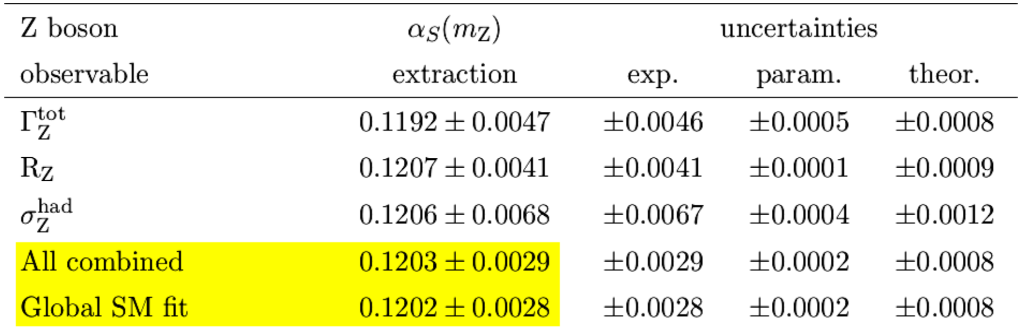
W boson observables	GFITTER 2.2 (NNLO)	this work (N^{3}LO) (exp. CKM)	(CKM unit.)	experiment
$\Gamma^{\rm had}_{\rm W}$ (MeV)	–	$1440.3 \pm 23.9_{\rm par} \pm 0.2_{\rm th}$	$1410.2 \pm 0.8_{\rm par} \pm 0.2_{\rm th}$	1405 ± 29
$\Gamma^{\rm tot}_{\rm W}$ (MeV)	$2091.8 \pm 1.0_{\rm par}$	$2117.9 \pm 23.9_{\rm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

1908.01704

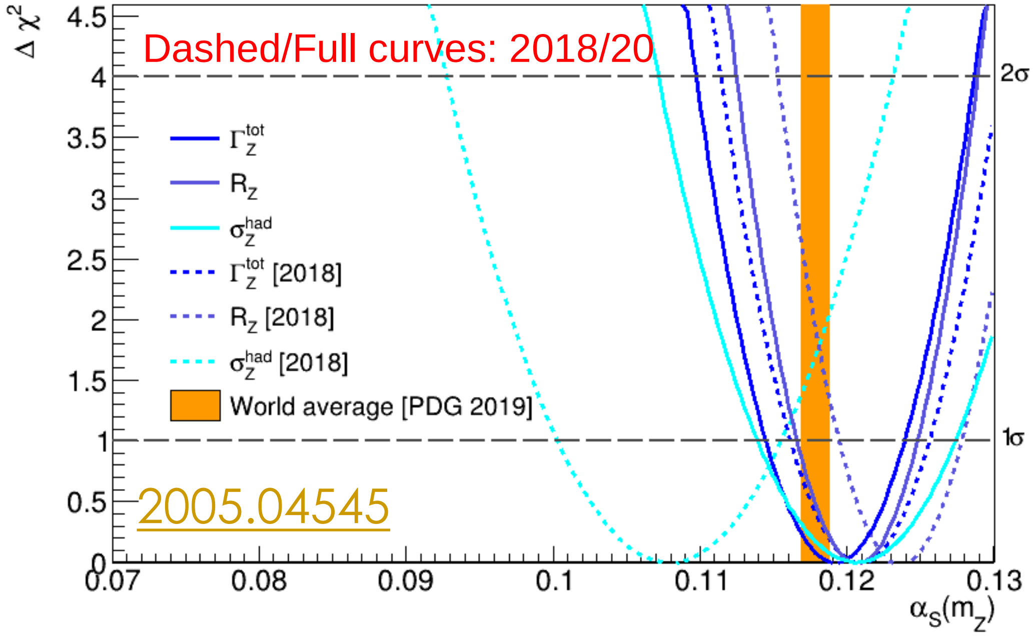
1912.02067

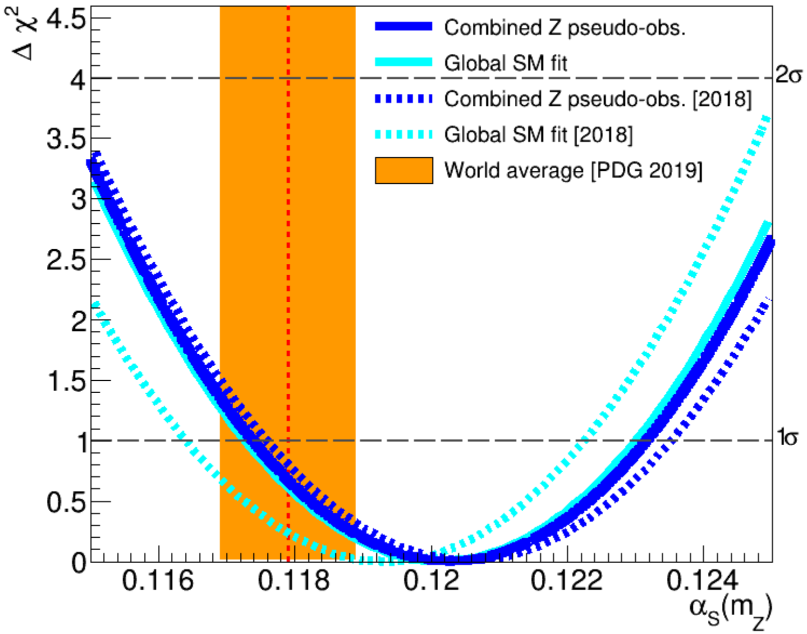
α_S from hadronic Z decays (today)

- α_S extracted at N^{3}LO from:
  - Combined fit of 3 Z pseudo observables
  - Full SM fit (with α_S free parameter)



Z boson	$\alpha_S(m_Z)$	uncertainties		
observable	extraction	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





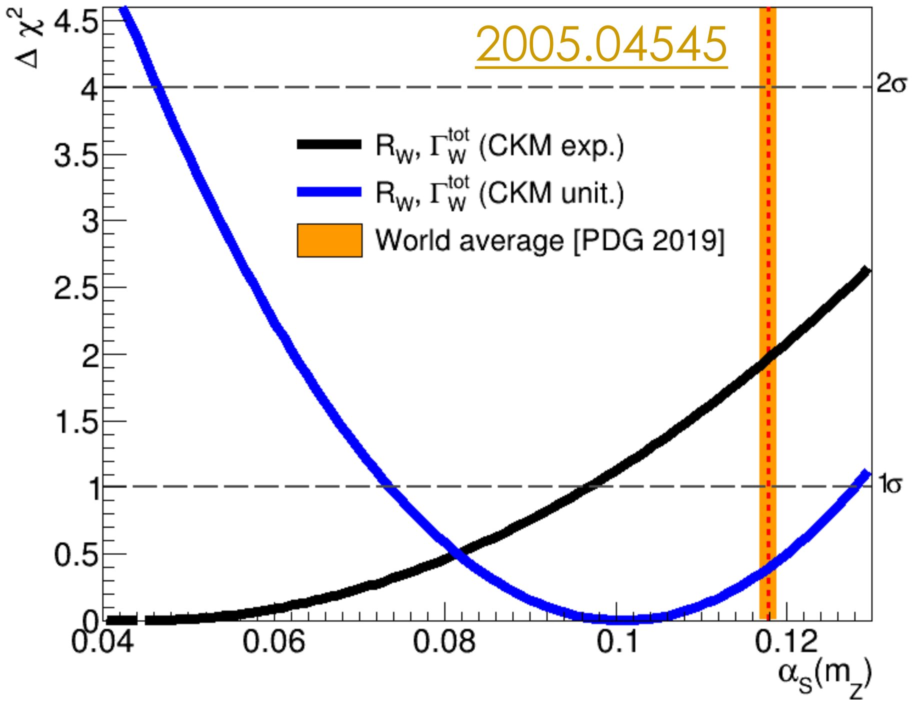
- LEP lumi-bias updates lead to better agreement among Γ_Z, R_Z and σ_Z^{had} extraction: **$\alpha_s(m_z) = 0.1203 \pm 0.0028$ (±2.3%)**
- Unc. updates lead to a better agreement with full fit: **$\alpha_s(m_z) = 0.1202 \pm 0.0028$**

α_S from hadronic W decays (today)

- QCD coupling extracted from new N^{3}LO combined fit of Γ_W and R_W:

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

- Large propagated parametric uncertainties from poor V_{cs} (±2%)
- Imposing CKM unitary: large experimental uncertainties from Γ_W and R_W (0.9-2%)
- Propagated theory uncertainties (1.5%)
- Very imprecise extraction! QCD coupling constant extracted with **27% precision**

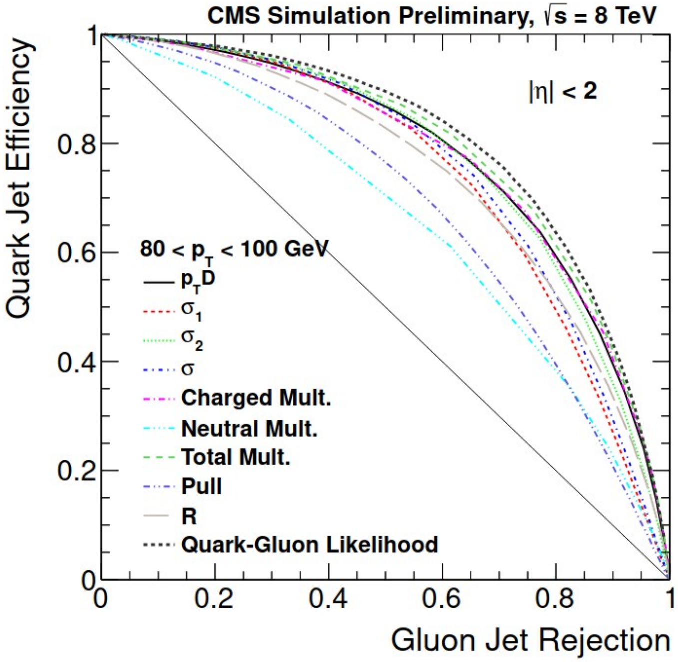


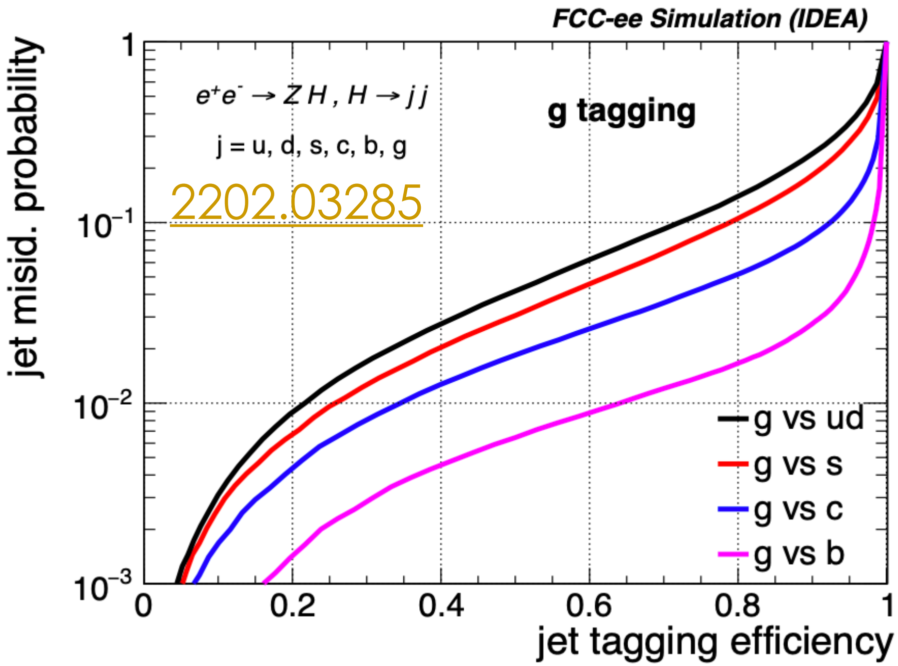
$\alpha_s(m_z) = 0.101 \pm 0.027$ (±27%)

Quark-gluon discrimination

1409.3072

- Exciting but challenging prospects in pp collisions
  - Enhance quark signal at hadron colliders
- Several handles exist to separate quark and gluons: 1211.7038
  - Gluons radiate more
  - Spin correlations in subjet location
  - p_T - weighted jet charge





2202.03285

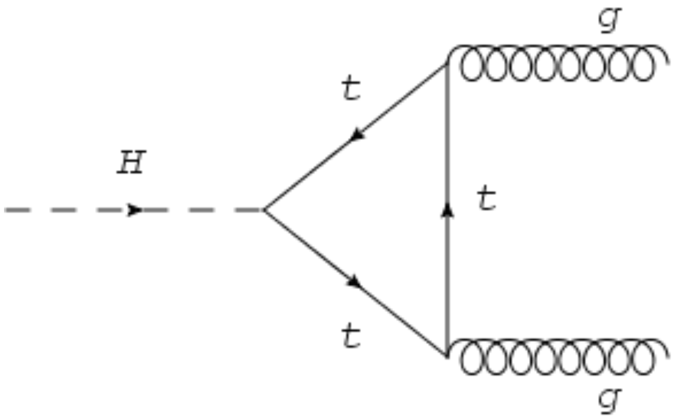
Machine Learning (ML) approaches have already found success!

Rejection of ud jets is the most challenging, due to similar particle displacement and nature

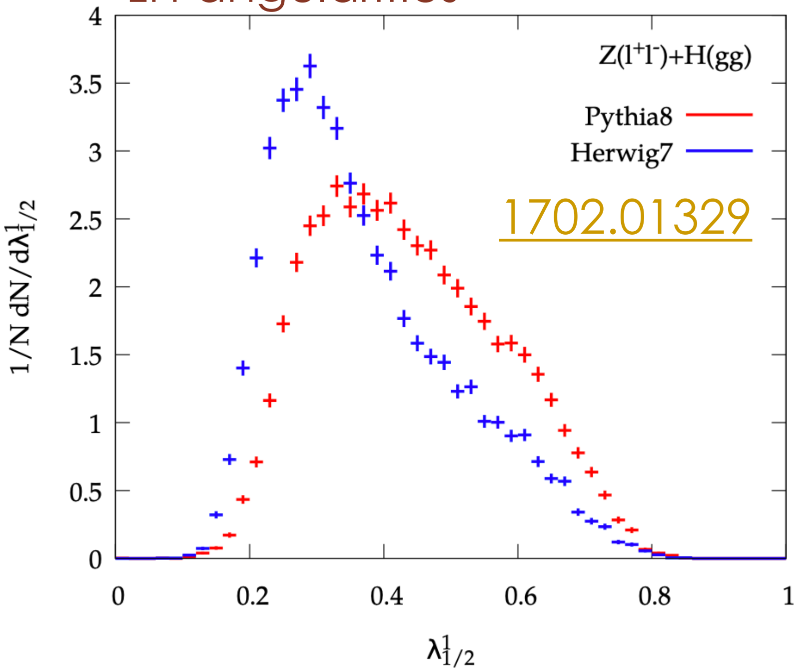
High-precision gluon and quark jet studies

- Exploit FCC-ee $H(gg)$ as a pure gluon factory: $H \to gg$ (BR ~ 8% accurately known) provides 120000 extra clean digluon events
- Multiple handles to study gluon radiation and gluon-jet properties:
  - Gluon vs. quark via $H \to gg$ vs $Z \to q\bar{q}$
  - Gluon vs. quark via $Z \to b\bar{b}g$ vs $Z \to q\bar{q}$
- Multiple high-precision analyses possible:
  - Access to light-quark Higgs Yukawa couplings
  - BSM: Improve q/g/Q discrimination tools
  - pQCD: High-precision QCD coupling
  - non-pQCD: Gluon fragmentation, colour reconnection

Improved MC tuning

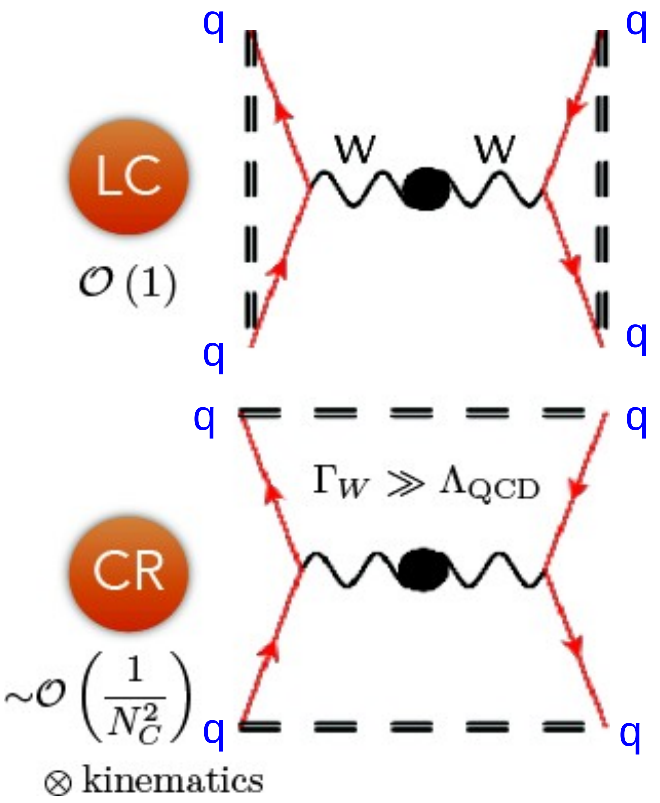


LH angularities



Colour reconnection

- Colour Reconnection (CR) of partons impacts final state kinematics e.g. shifted angular correlations, invariant mass shifts, etc.
- Exact dynamic poorly understood
- Source of uncertainty in m_W, m_{top}, anomalous Gauge Couplings extractions in multijet final-states
- CR impacts all FCC-*ee* multi-jet final states: $e^+e^- \rightarrow WW(4j), H(2j,4j), t\bar{t}, \ldots$
- Combined LEP e^+e^- → WW(4j) data best described with 49% CR, 2.2σ away from no-CR
- String-drag effect on W mass (hinted at LEP)
- Exploit huge W stats (x10^4 LEP) to measure m_W leptonically & hadronically and constrain CR



Jet substructure

- Need for state-of art jet substructure studies based on angularities

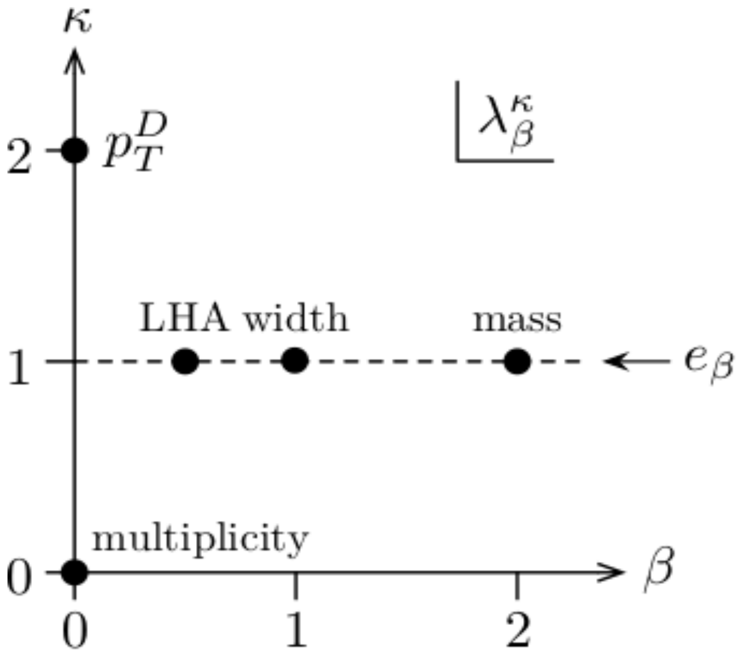
$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta ,$$

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

- 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)

(larger energy weight)

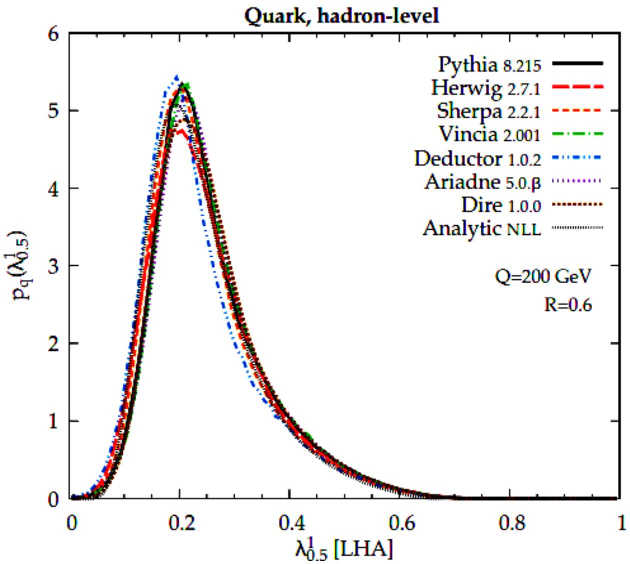


(larger angular weight)

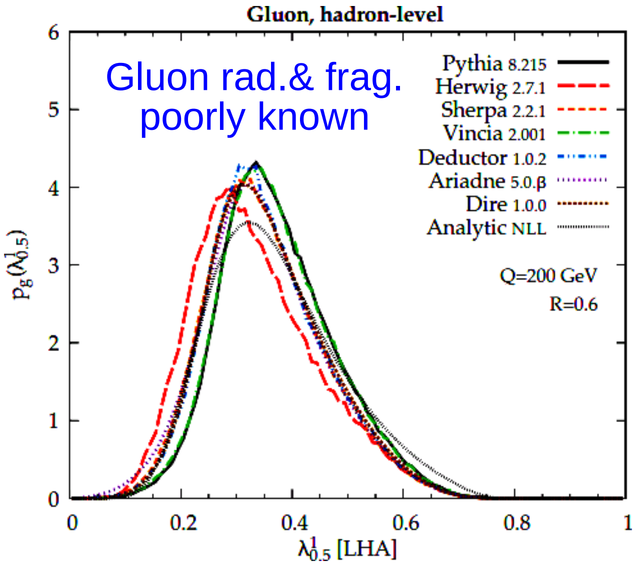
[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

Showering differences in MC generators

- Les Houches Angularity (LHA) is angularity with k = 1 and $\beta = 0.5$
- Not directly measured at LEP
- MC parton showers differ on gluon (less on quark) radiation patterns

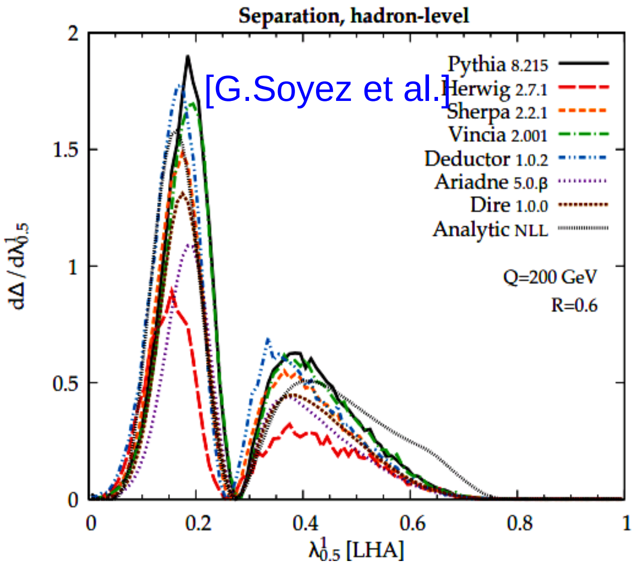


$e^+e^- \rightarrow Z \rightarrow u\bar{u}$



Gluon rad.& frag. poorly known

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

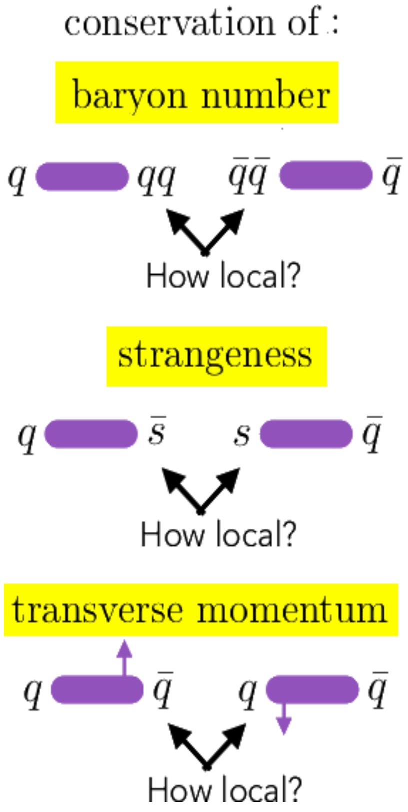


[G.Soyez et al.]

u-quark vs gluon discrimination power

Detailed hadronization studies

- High-precision low-p_T PID hadrons in e^+e^- required for detailed studies:
  - Baryon & strangeness production
  - Colour string dynamics
  - Final-state correlations (spin: Bose-Einstein, Fermi-Dirac; momenta, etc.)
  - Bound state formation: Onia, multi-quark states, etc.


conservation of :

baryon number

q qq $\bar{q}\bar{q}$ $\bar{q}$

How local?

strangeness

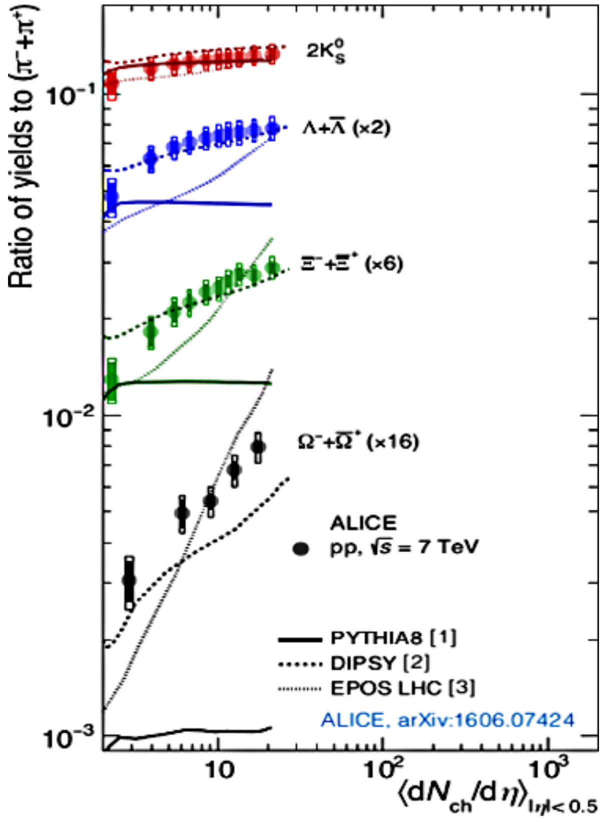
q $\bar{s}$ s $\bar{q}$

How local?

transverse momentum

q $\bar{q}$ q $\bar{q}$

How local?



ALICE, arXiv:1606.07424

- Understand breakdown of universality of parton hadronization with system size observed at the LHC
- Baseline vacuum e^+e^-: studies for high density QCD in small and large systems
- Also impact e.g. ultra-high energy cosmic MCs

QCD uncertainties on EWK observables

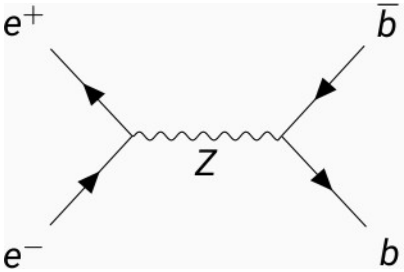
- With x10^5 more Z's than LEP, EWK observables at FCC-*ee* will be dominated by systematics (QCD)

- $e^+e^- \rightarrow b\bar{b}$ forward-backward asymmetry at LEP

- Experimental EWPOs with the largest discrepancy wrt the SM: 2.8σ

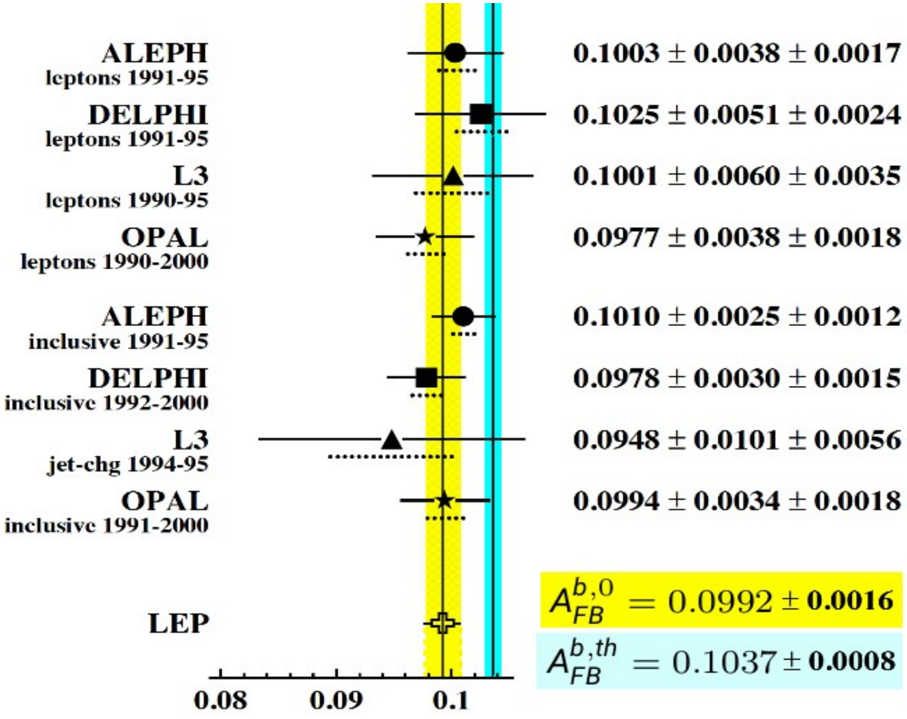
- Total uncertainty: ~1.6%
  - Statistical: 1.5% (~0.05% at FCC-*ee*)
  - Systematics: 0.6% (QCD: 0.4% at FCC-*ee*)

- QCD effects on $A_{FB}^{0,b}$:
  - Gluon splitting
  - Smearing of b-jet/thrust axis
  - b- and c-quark radiation and fragmentation (B/D hadron decay models)



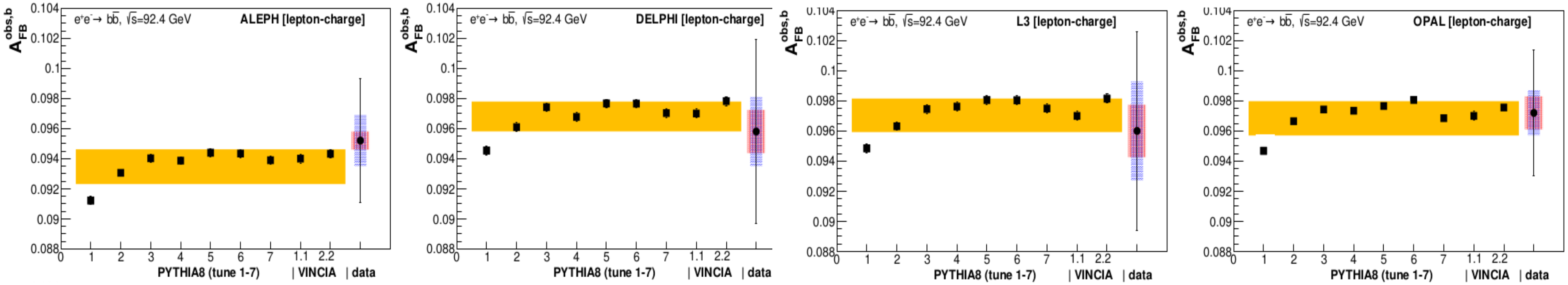
$$A_{FB}^{b} = \frac{N_F - N_B}{N_F + N_B}$$

$$A_{FB} = \frac{\sigma_A}{\sigma_S} \propto \frac{-g_{\mu\nu}T^{\mu\nu}}{i\epsilon_{\mu\nu\lambda\rho}\frac{n^\lambda Q^\rho}{n\cdot Q}T^{\mu\nu}}$$

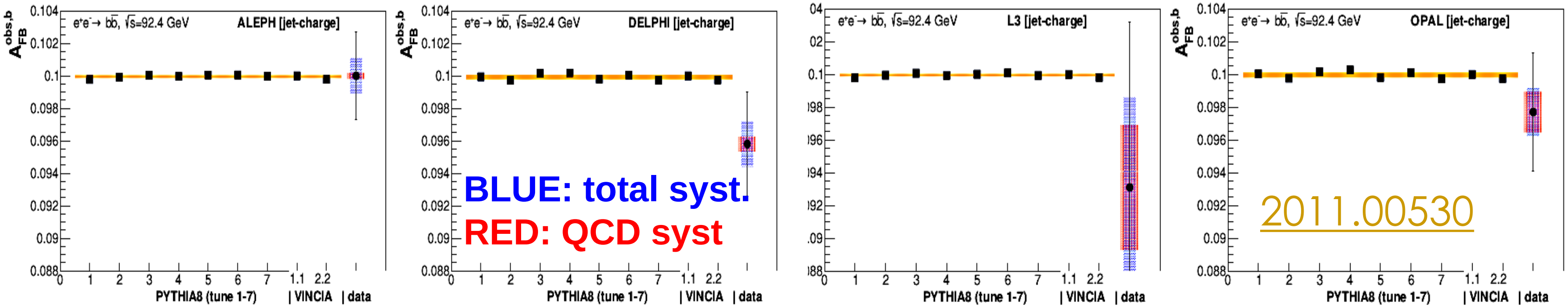


Reduced QCD uncertainties on A_{FB}

- QCD uncertainties recomputed from Pythia8.226 and VINCIA2.2
- $e^+e^- \rightarrow b\bar{b}$ A_{FB} asymmetry for lepton-based analyses:



- $e^+e^- \rightarrow b\bar{b}$ A_{FB} asymmetry for jet-charged-based analyses:



BLUE: total syst.

RED: QCD syst

2011.00530

- 2020 vs 1998 PS + hadronization uncertainties halved: 0.7% (lepton-based) and ~0.3% (jet-charged-based analyses)
- FCC data needed to reduce PS & non-pQCD systematic uncertainties