High-precision QCD physics at FCC-ee

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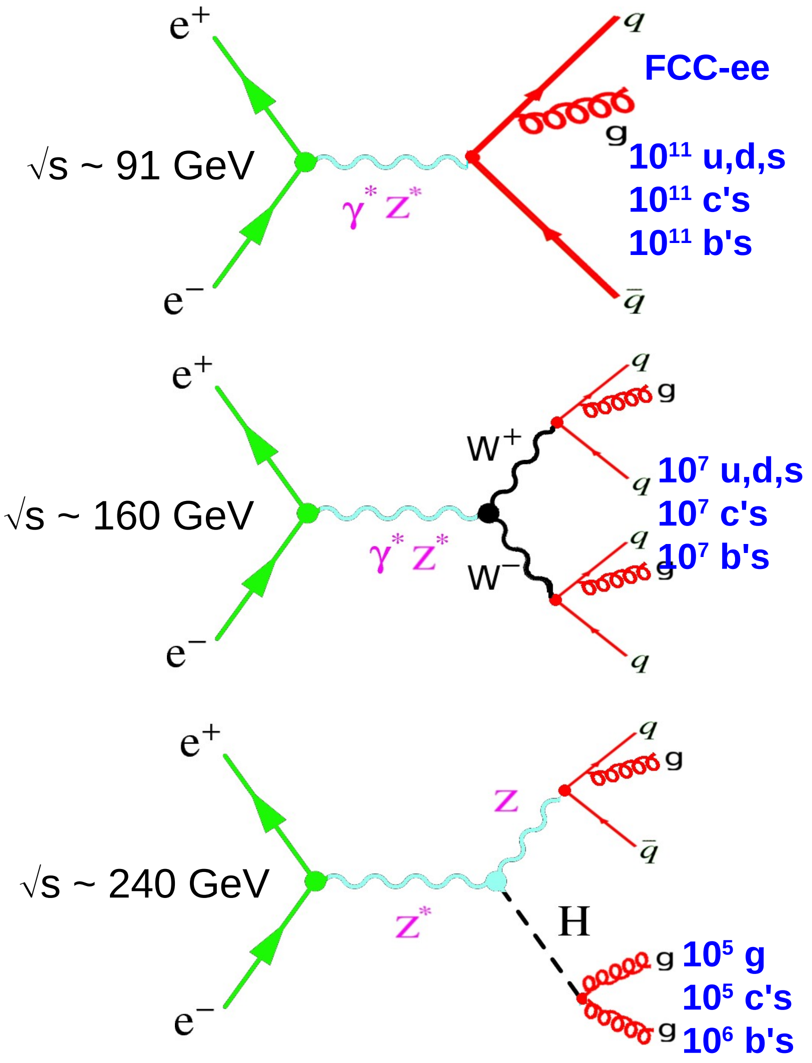
LFC22 workshop
ECT*, Trento, Italy
30/08/2022

QCD, a key ingredient at future colliders

- QCD is crucial for many ee, pp measurements:
- **High-precision α_S:** affects all x-sections & decays (Higgs, top, etc.)
- **N^{n}LO corrections, N^{n}LL resummations:** affects all pQCD x-sections & decays
- **High-precision PDFs:** affects all precision W,Z,H measurements & all searches in pp collisions
- **Heavy-Quark/Light-Quark/Gluon separation (jet substructure, boosted topologies, etc.):** needed for all precision SM measurement & BSM searches with jets in the final jets
- **Semihard QCD (low-x saturation, multiple parton interactions, etc.):** significant pQCD x-sections at FCC-hh
- **Non-perturbative QCD:** affects final states with jets → colour reconnection, parton shower, hadronization, etc.

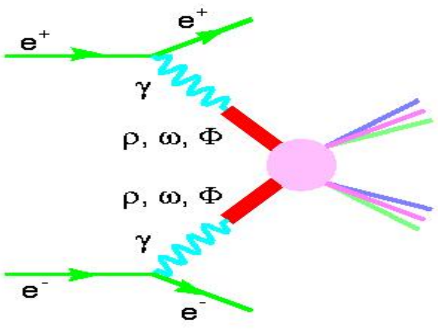
Precision QCD in e^+e^- collisions

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

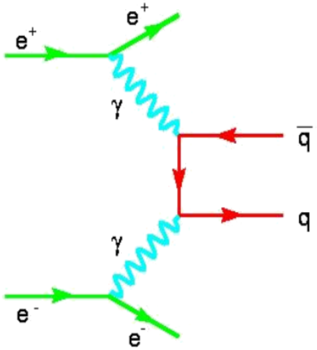


Advantages compared to pp collisions:

- 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



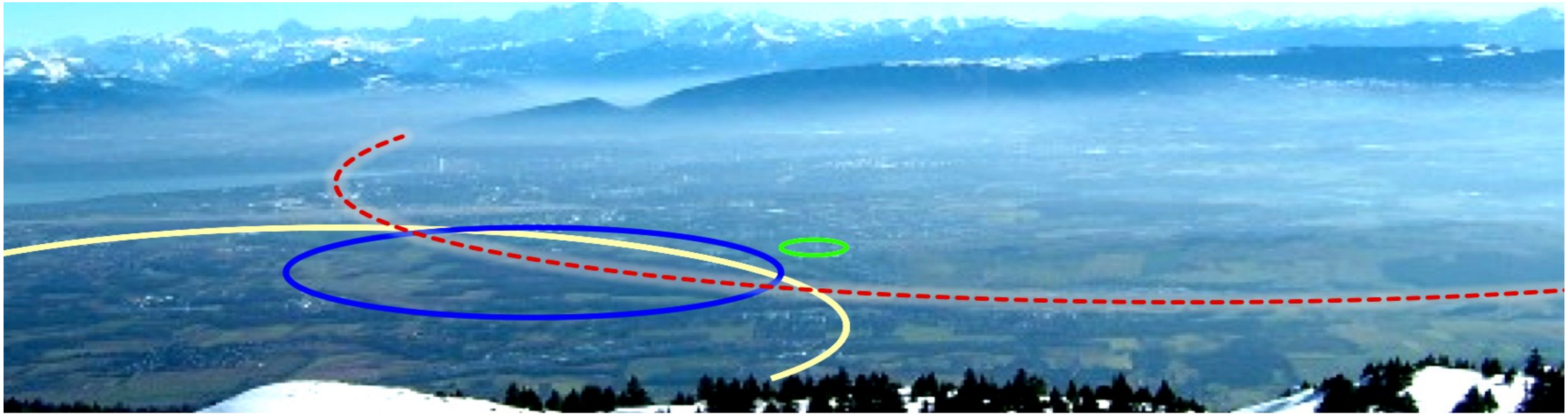
(soft, VDM)

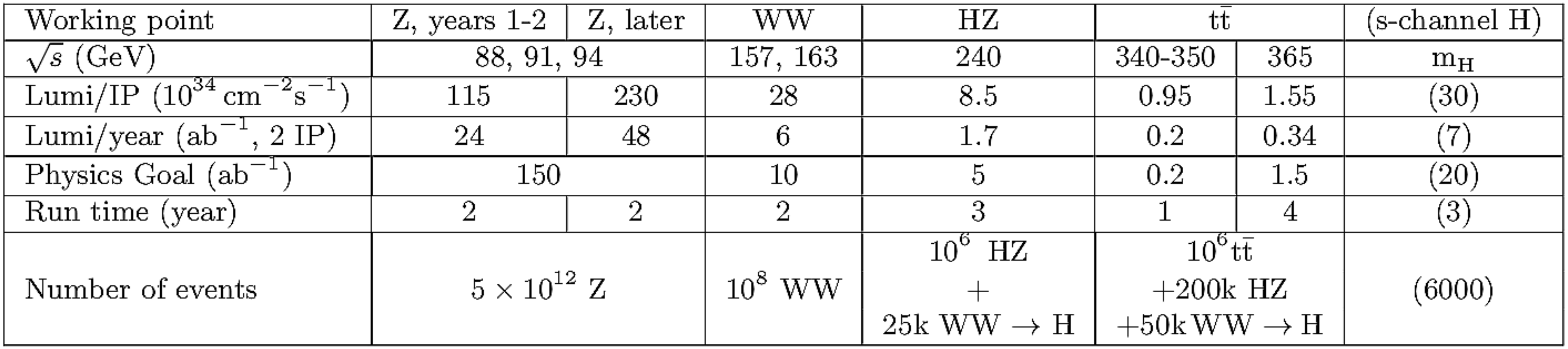


(direct)

CERN FCC-*ee* project

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

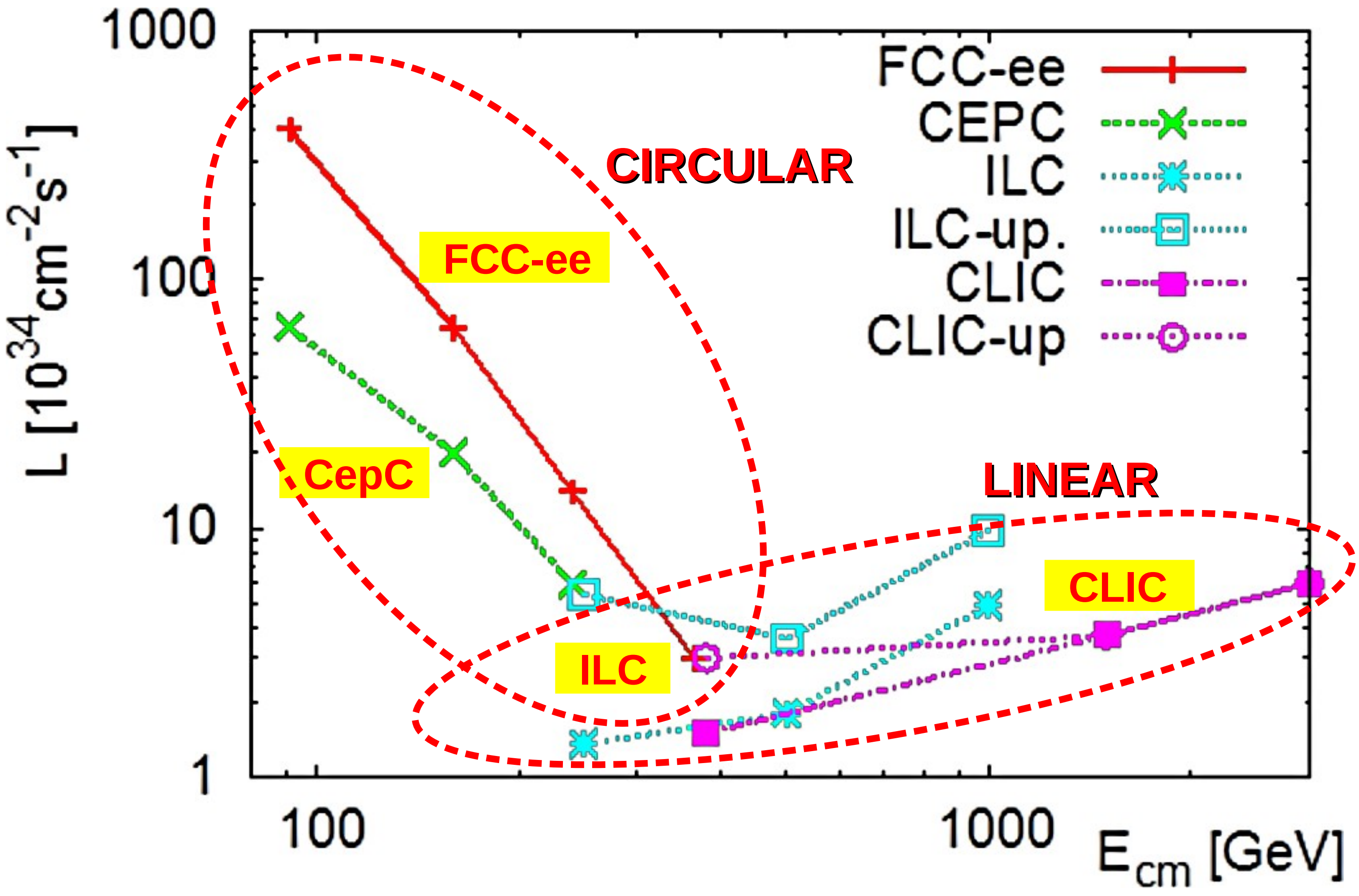




Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365	m_H
Lumi/IP (10^{34} cm^{-2}s^{-1})	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics Goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)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

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

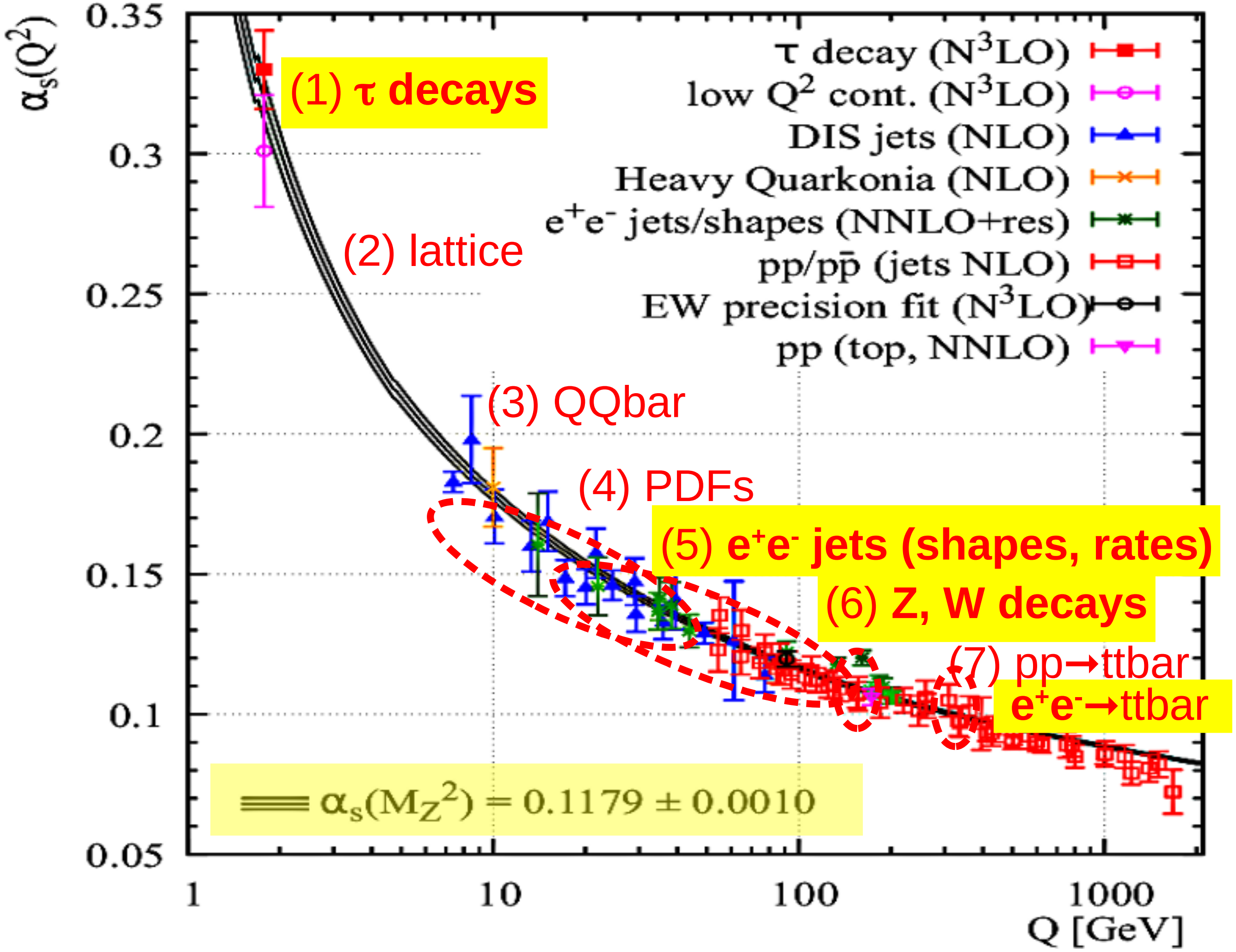
Future e^+e^- colliders under discussion



- FCC-*ee* features luminosities a few time larger than other machines over 90 - 300 GeV
- Negligible statistical uncertainty for Z, W, jets, …, τ data sets

QCD coupling α_S

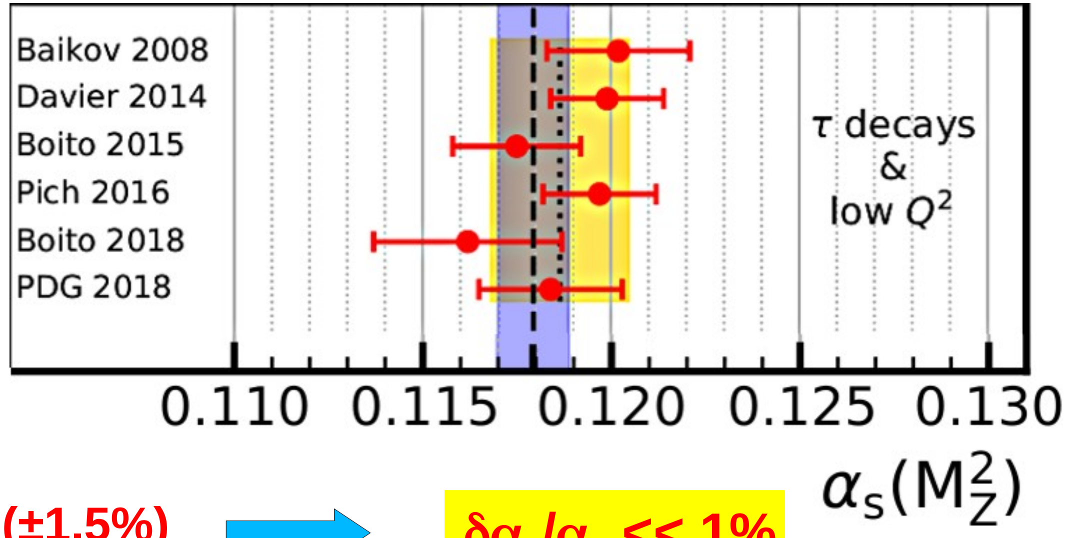
- Currently determined by comparing 7 experimental observables to pQCD NNLO or N^{3}LO predictions, plus global average at the Z pole scale



e$^+$e$^-$ collisions

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\%$**

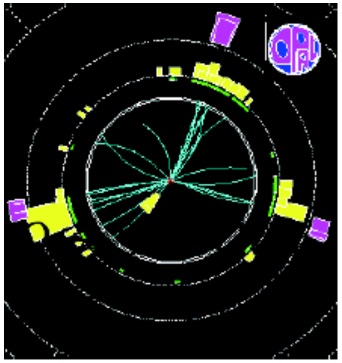
- What next?
  - Theory: better understanding of FOPT vs CIPT differences & need of N^{4}LO
  - Better spectral functions needed (better precision)
  - Higher statistics: $\mathcal{O}(10^{11})$ from $Z \to \tau^+\tau^-$ at FCC-ee(90)
  - Extract the τ width from the ultraprecise measurement of its lifetime

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

- Computed at N^{2,3}LO+N(N)LL accuracy

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

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



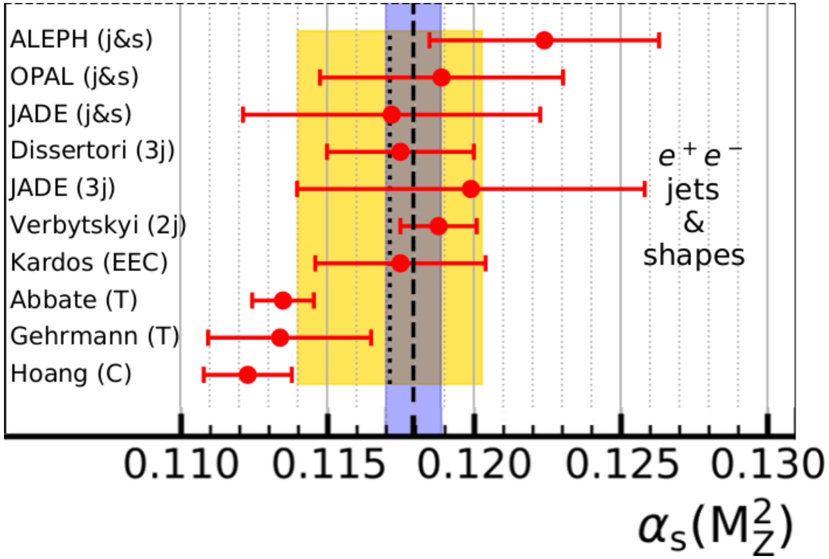
OPAL 3 jet event

- Experimental observables: Thrust, jet shapes, C-parameter, n-jet cross sections

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

- **At FCC-*ee*:**
- Huge Z pole statistics (x10^5 LEP)
- Exquisite systematic precision (stat. uncertainties much smaller)

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

- 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 times better precision than today: $\frac{\delta\alpha_S}{\alpha_S}$ ~ **±0.2% (tot), ±0.1% (exp)**

- The W and Z hadronic widths :

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

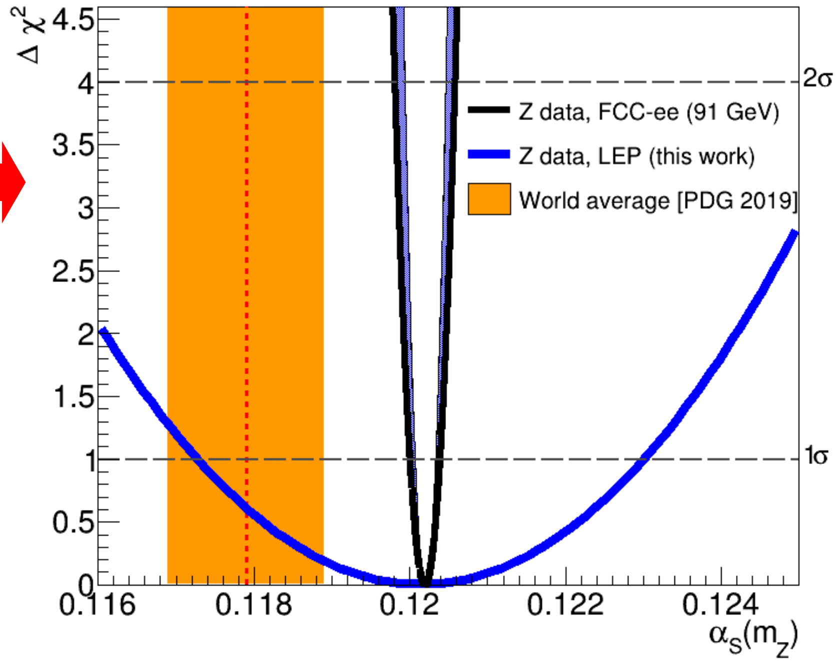
- The ratio of W, Z hadronic-to-leptonic widths :

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

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

$$\sigma_{\rm Z}^{\rm had} = \frac{12\pi}{m_{\rm Z}} \cdot \frac{\Gamma_{\rm Z}^{e}\Gamma_{\rm Z}^{\rm had}}{(\Gamma_{\rm Z}^{\rm tot})^2}$$

2005.04545



$\alpha_s(m_z)$ = 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 :

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

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

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

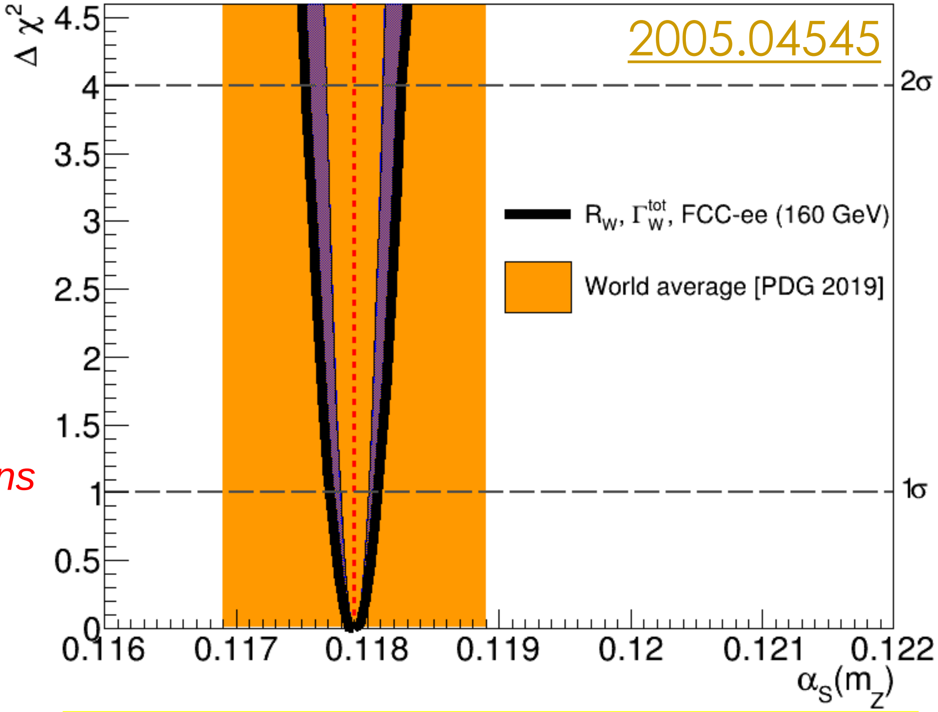
- **At FCC-*ee*:**
- Huge W pole statistics (x10^4 LEP-2)
- Exquisite systematic precision (stat. uncertainties much smaller)

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

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

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

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



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

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

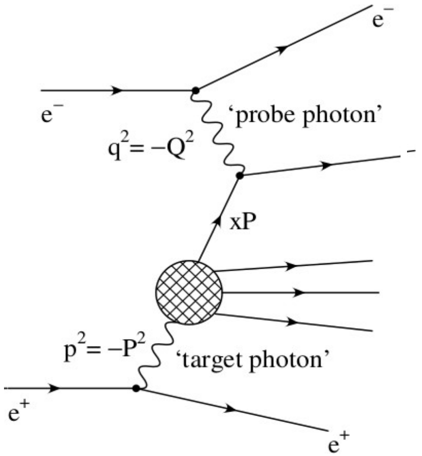
α_S from photon QCD structure function

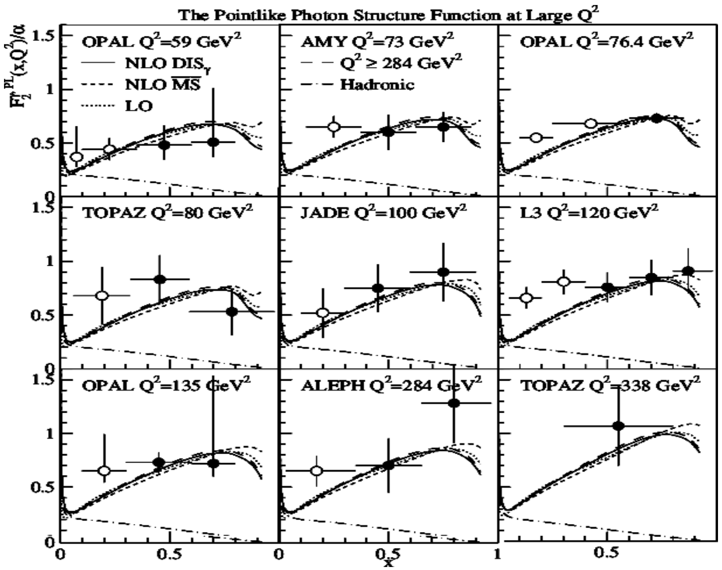
- Computed at NNLO: $\int_0^1 dx F_2^\gamma(x,Q^2,P^2) = \frac{\alpha}{4\pi}\frac{1}{2\beta_0}\left\{\frac{4\pi}{\alpha_s(Q^2)}c_{LO} + c_{NLO} + \frac{\alpha_s(Q^2)}{4\pi}c_{NNLO} + \mathcal{O}(\alpha_s^2)\right\}$
- Poor $F_\gamma^2(x,Q^2)$ experimental measurements
- NLO extraction with large experimental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

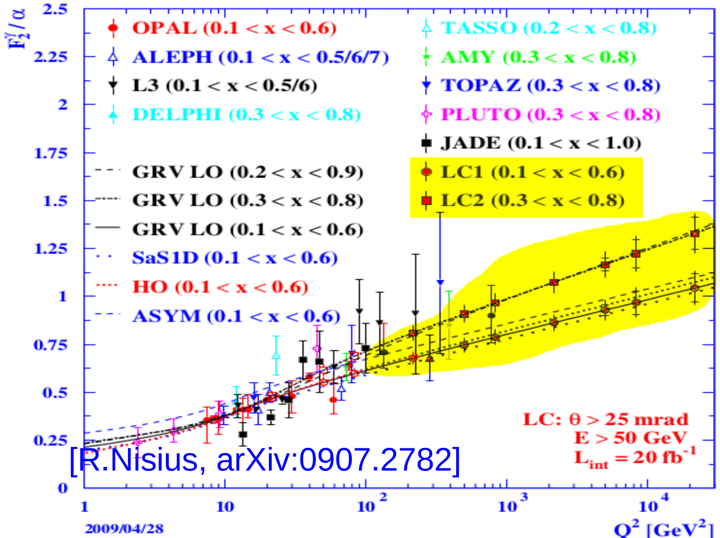
α_s (m$_z$) = 0.1198 ± 0.0054

(±4.5%)

hep-ph/0205069







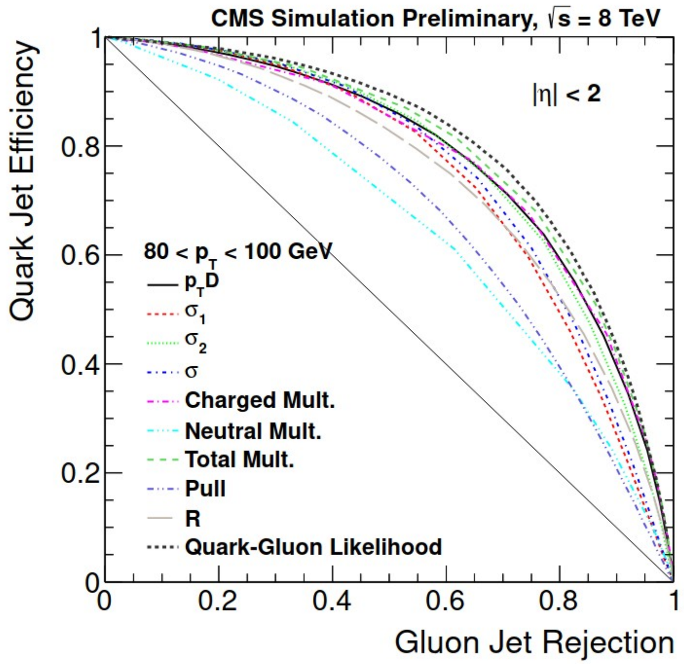
[R.Nisius, arXiv:0907.2782]

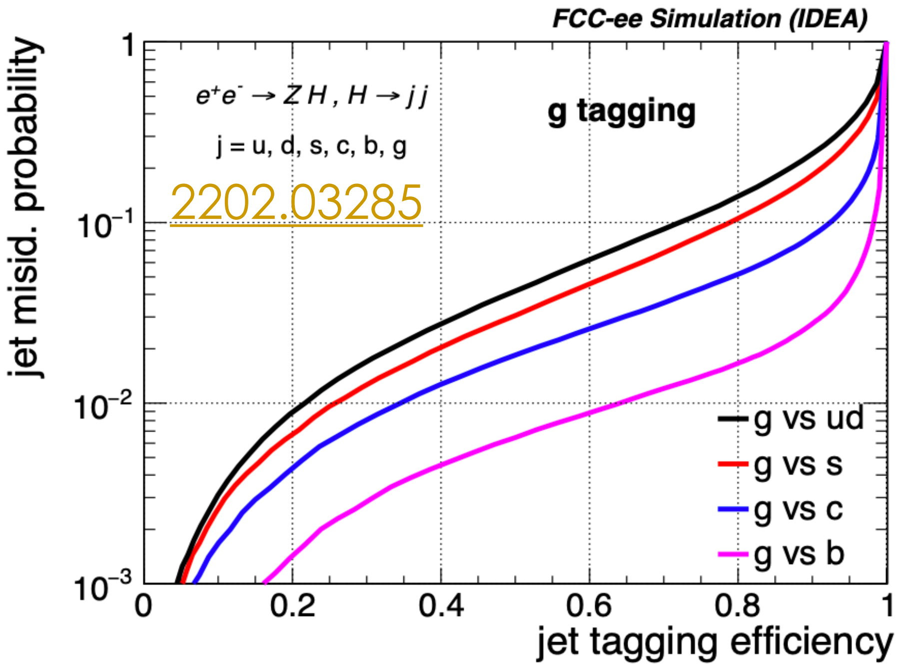
- Future prospects:
  - Fit with NNLO F_γ^2 evolution
  - Better data
  - Dedicated simulation studies (already exist at ILC)
  - Huge $\gamma\gamma$ statistics at FCC-*ee* will lead to $\delta\alpha_S/\alpha_S$ < 1%

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





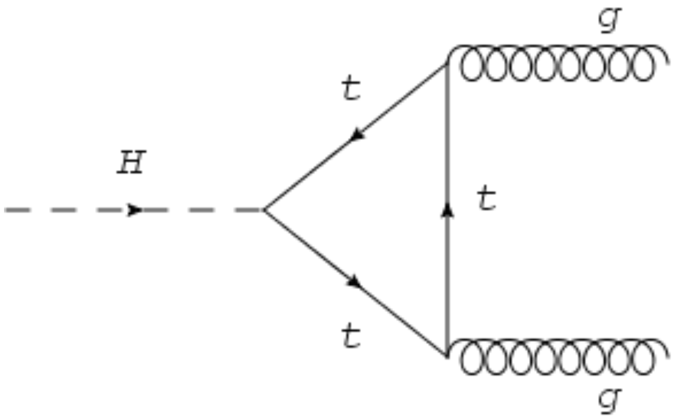
2202.03285

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

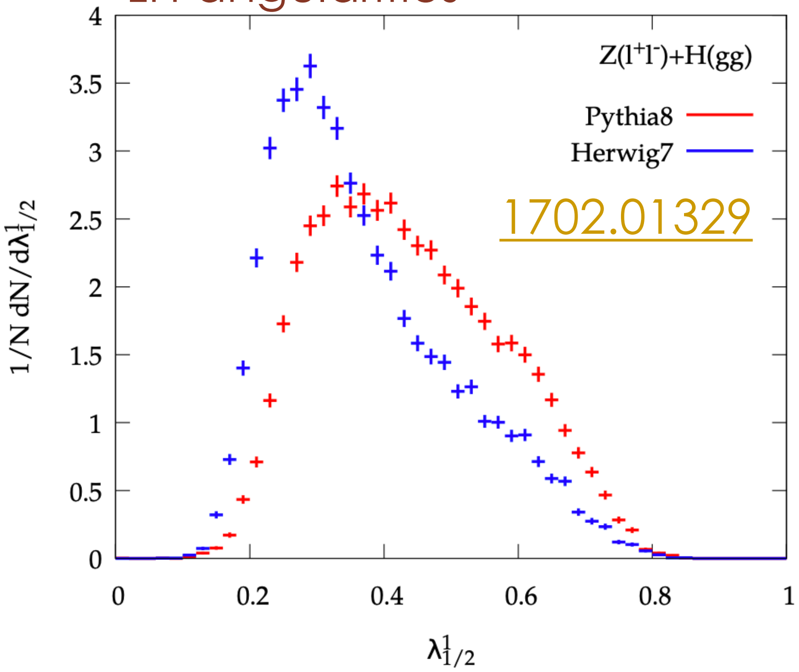
- Exploit FCC-*ee* $H(gg)$ as a pure gluon factory: $H \to gg$ (BR ~ 8% accurately known) provides 120000 extra clean digluon events



- 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

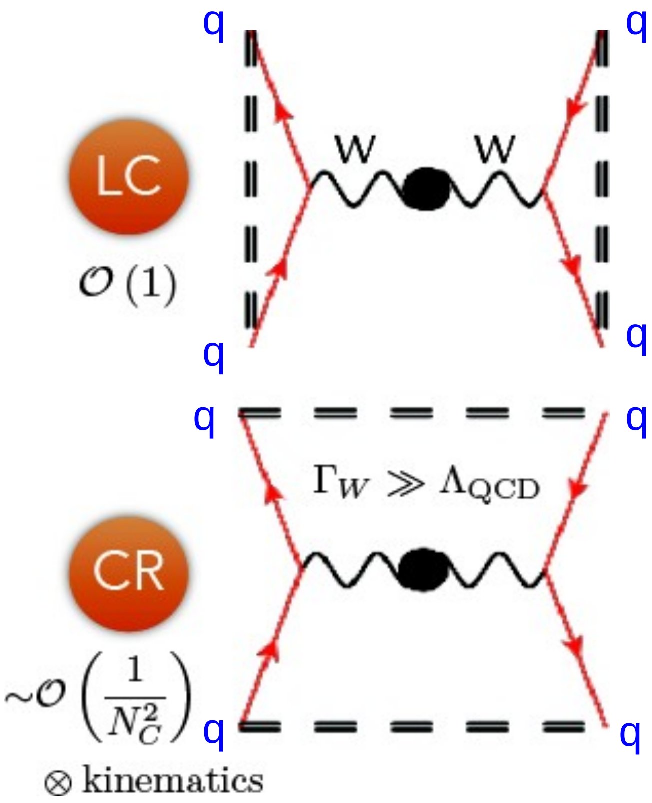
LH angularities



1702.01329

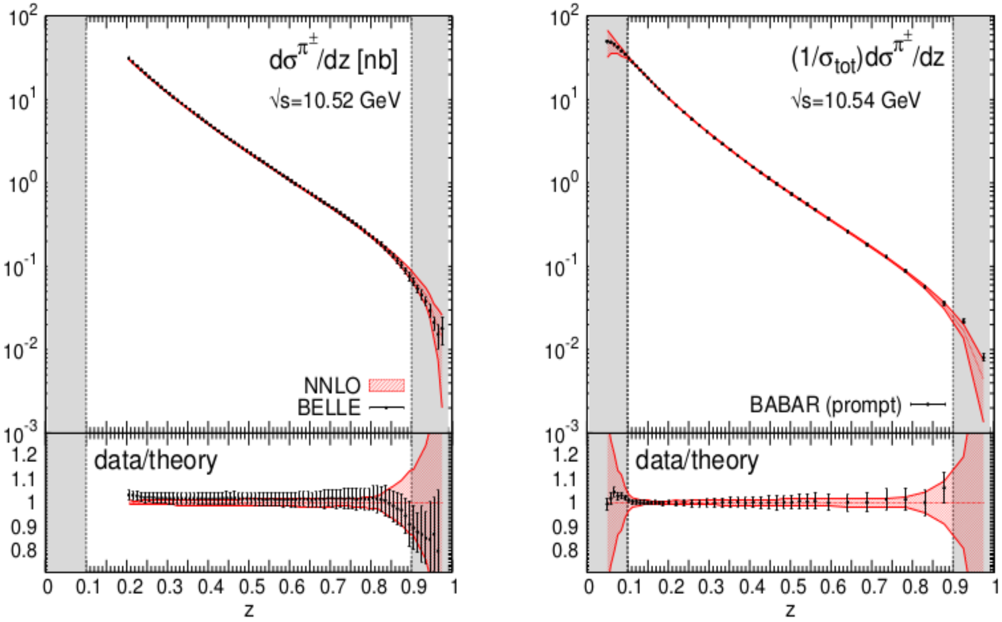
Colour reconnection

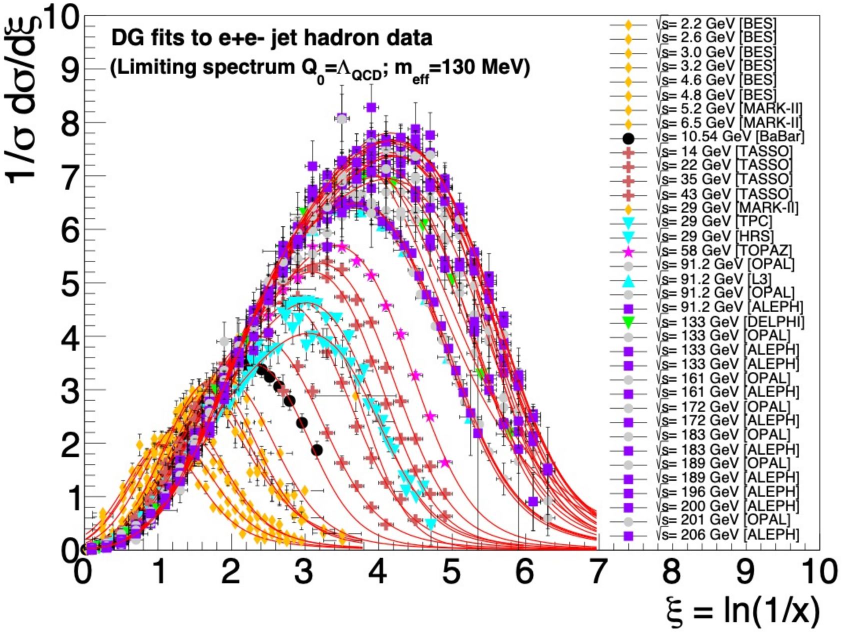
- Colour Reconnection (CR) of partons impacts final state kinematics e.g. shifted angular correlations, invariant mass shifts, etc.
- Exact dynamic poorly understood
- Source of uncertainty in m_W, m_{top}, anomalous Gauge Couplings extractions in multijet final-states
- CR impacts all FCC-*ee* multi-jet final states: $e^+e^- \to WW(4j), H(2j,4j), t\bar{t}, \ldots$
- Combined LEP $e^+e^- \to$ 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



High-precision parton FFs

- Parton-to-hadron fragmentation functions evolution known known at NNLO at high-z and at NNLO*+NNLL at low-z 1702.01329



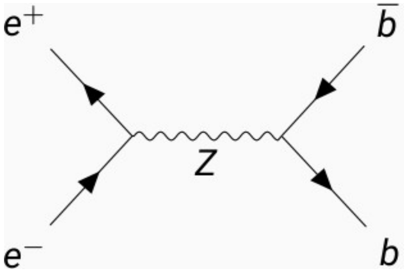


- FCC-*ee* (much broader z range) provides additional QCD coupling extractions, allowing for $\delta\alpha_S < 1\%$

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)

QCD uncertainties on EWK observables

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



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

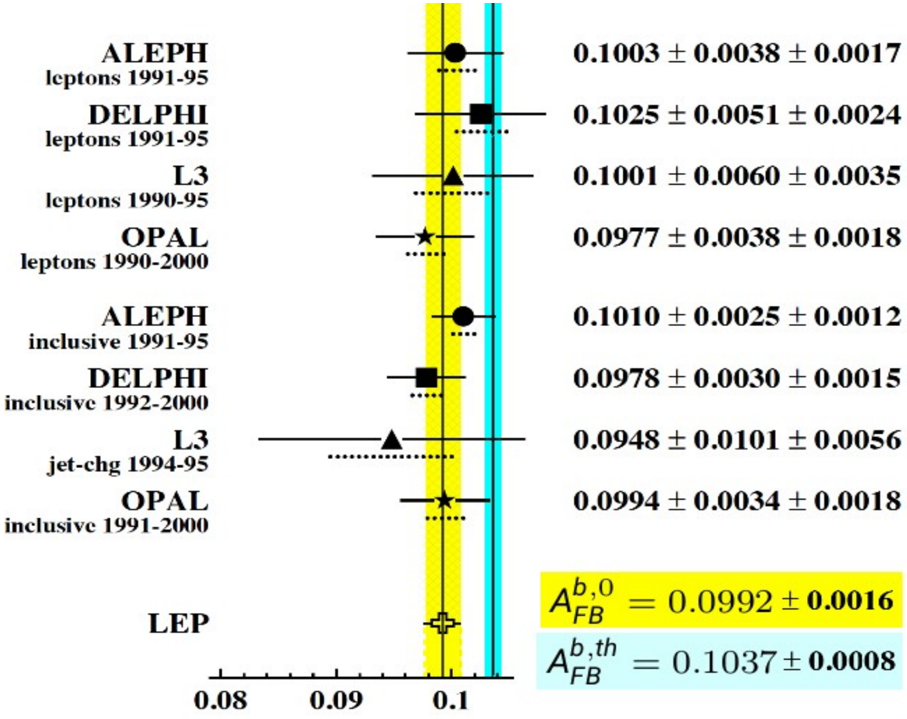
- Experimental EWPOs with the largest discrepancy wrt the SM: 2.8σ

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

$$A_{\rm FB} = \frac{\sigma_{\rm A}}{\sigma_{\rm S}} \propto \frac{-g_{\mu\nu}T^{\mu\nu}}{i\epsilon_{\mu\nu\lambda\rho}\frac{n^{\lambda}Q^{\rho}}{n\cdot Q}T^{\mu\nu}}$$

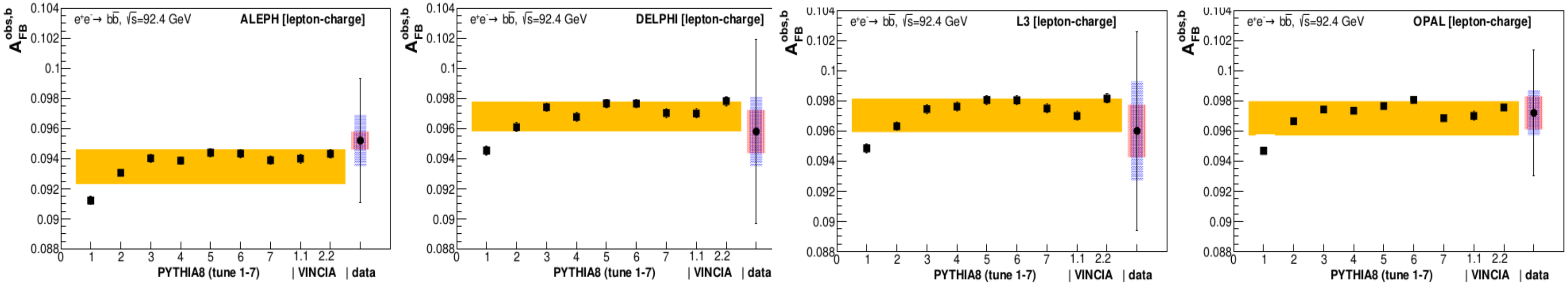
- Total uncertainty: ~1.6%
  - Statistical: 1.5% (~0.05% at FCC-*ee*)
  - Systematics: 0.6% (QCD: 0.4% at FCC-*ee*)

- 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)

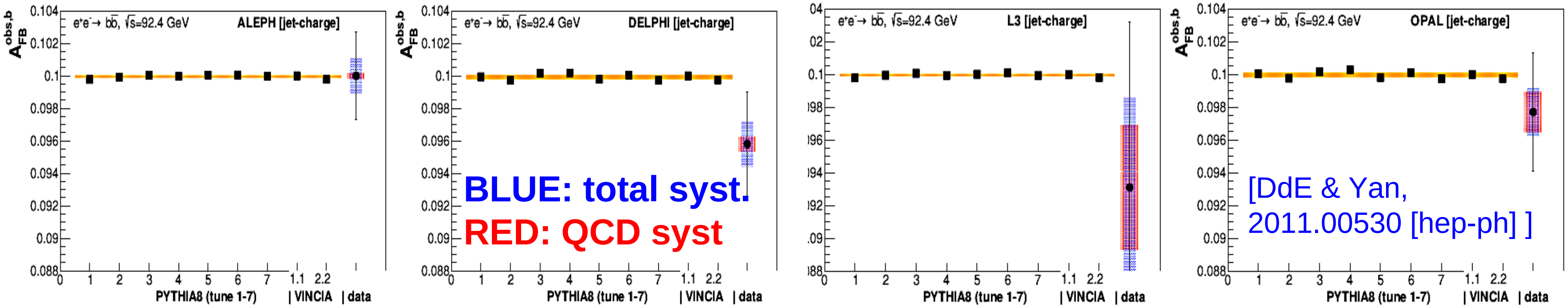


Reduced QCD uncertainties on A_{FB}

- 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.

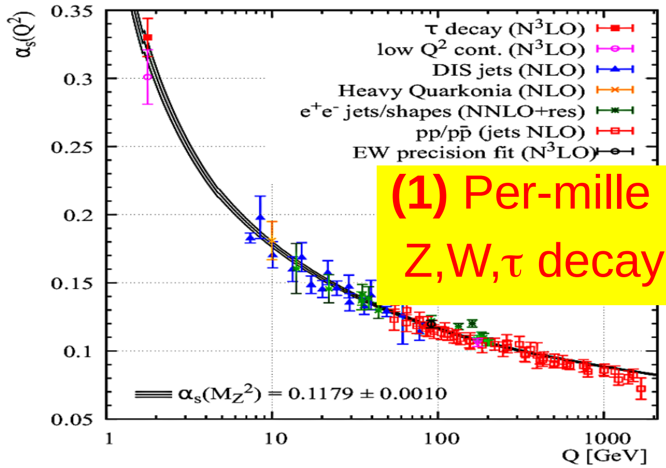
RED: QCD syst

[DdE & Yan, 2011.00530 [hep-ph]]

- 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

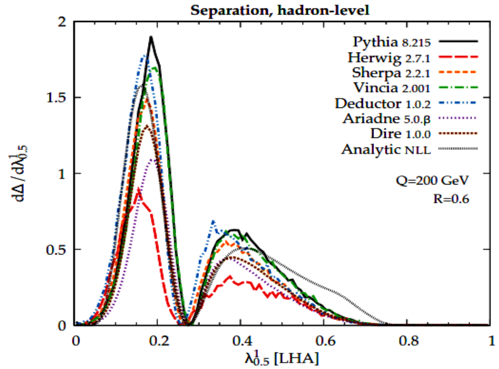
Summary & outlook

- The precision needed to fully exploit all future ee, pp, ep, eA, AA SM and BSM programs requires precise control of pQCD and non-pQCD physics

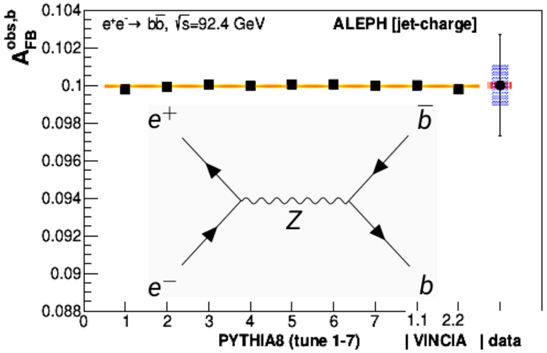


(1) Per-mille α_s via hadronic Z,W,τ decays, evt shapes...

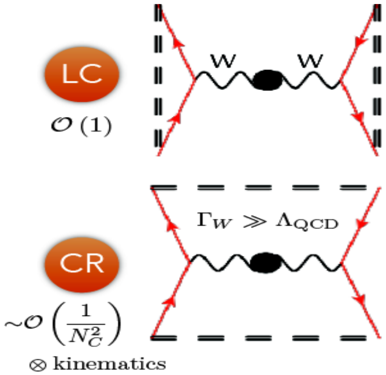
(2) N^{n}LO+N^{n}LL jet structure
Ultimate g/q/Q discrimination



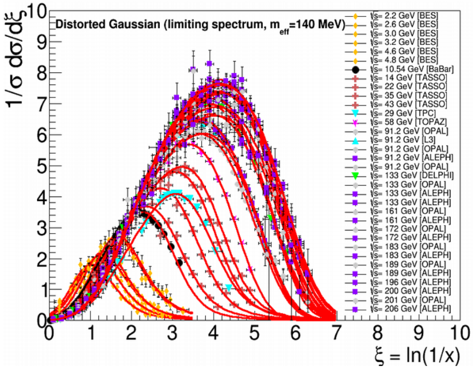
(3) Reduced PS+hadroniz. uncert. of EWPOs

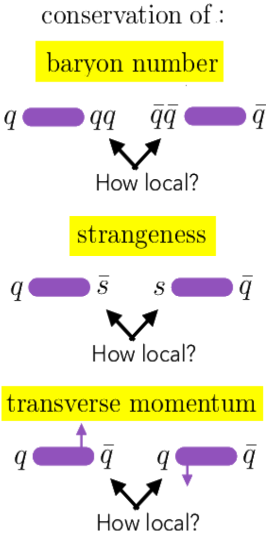


(4) <<1% control of colour reconnection



(5) High-precision hadronization:

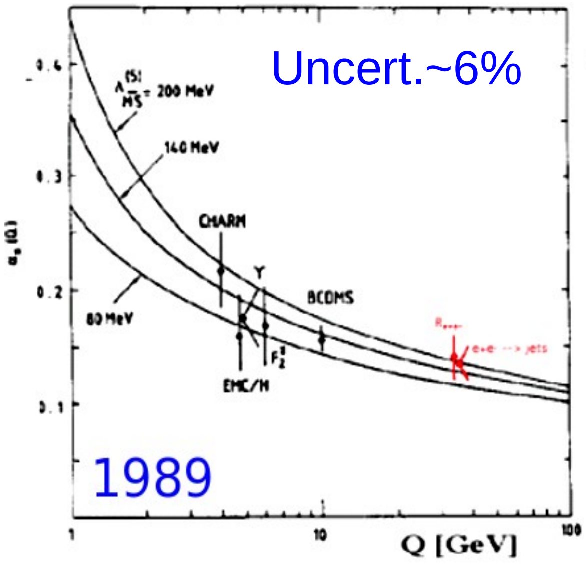



conservation of :
baryon number
How local?
strangeness
How local?
transverse momentum
How local?

Backup Slides

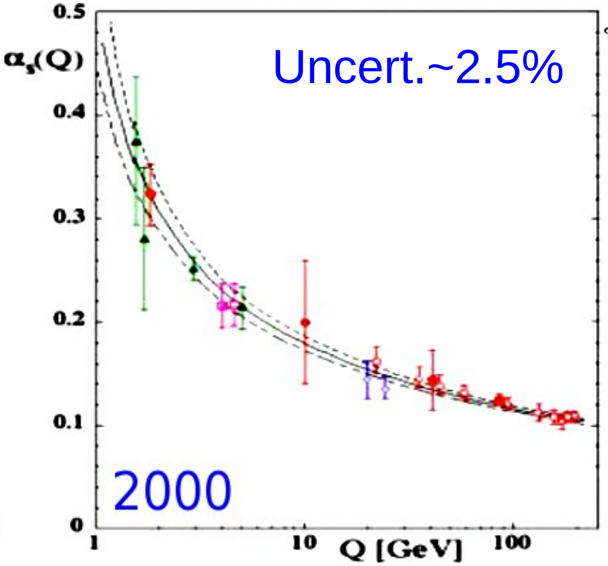
QCD coupling α_S

- Determines strength of the strong interaction between quarks and gluons
- Determined at $Q = m_Z$, decreases as $\alpha_S \sim \ln(Q^2/\Lambda^2)$ with $\Lambda \sim 0.2$ GeV



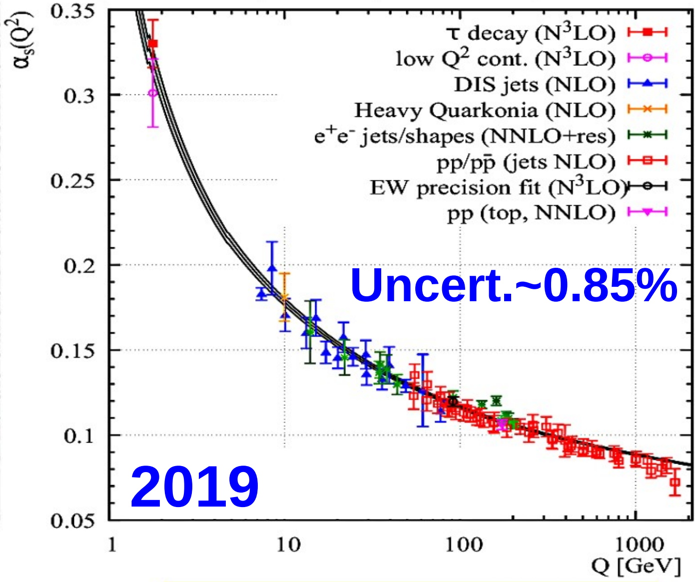
$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

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

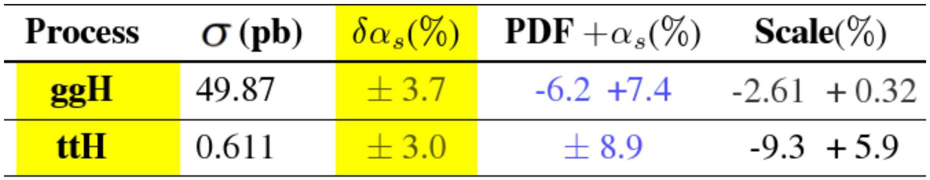


$\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$

- Least precisely known of all interaction couplings!
- $\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_S \sim 10^{-3}$

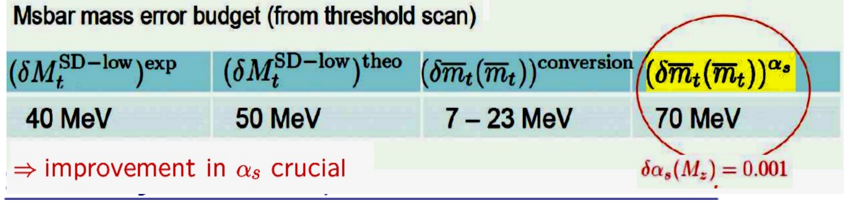
Importance of the QCD coupling α_S

- Impacts all QCD cross sections and decays!



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

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 %

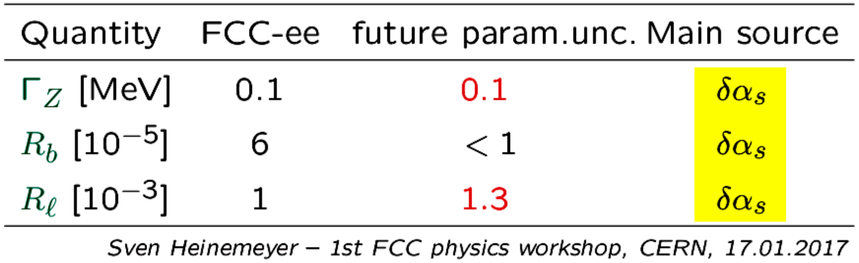


Msbar mass error budget (from threshold scan)

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

$\Rightarrow$ improvement in α_S crucial

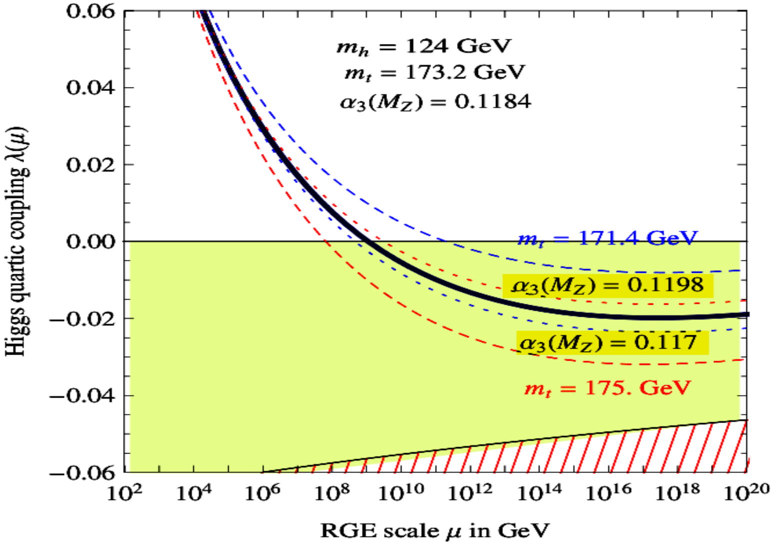
$\delta\alpha_s(M_z) = 0.001$

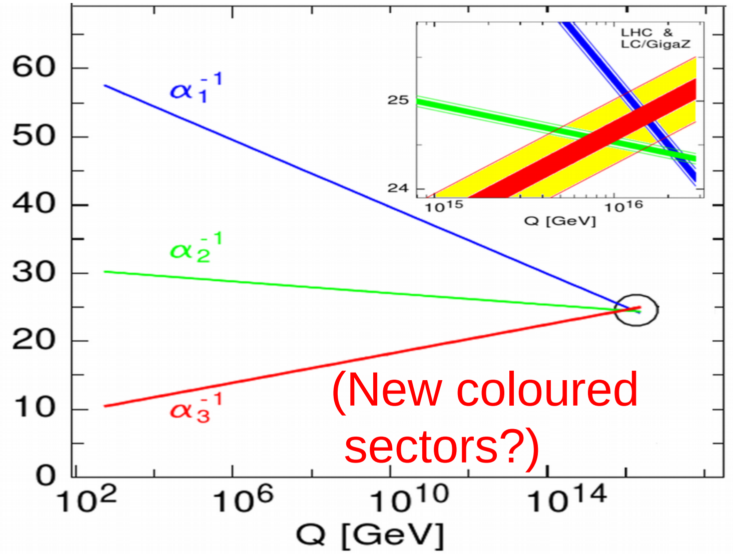


Quantity	FCC-ee	future param.unc.	Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b $[10^{-5}]$	6	< 1	$\delta\alpha_s$
R_ℓ $[10^{-3}]$	1	1.3	$\delta\alpha_s$

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

- Impacts physics approaching Plank scale: EW vacuum stability, GUT, etc.





(New coloured sectors?)

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)	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
$\mathrm{R_W}$	–	$2.1256 \pm 0.0353_{\rm par} \pm 0.0008_{\rm th}$	$2.0812 \pm 0.0007_{\rm par} \pm 0.0008_{\rm th}$	2.069 ± 0.019

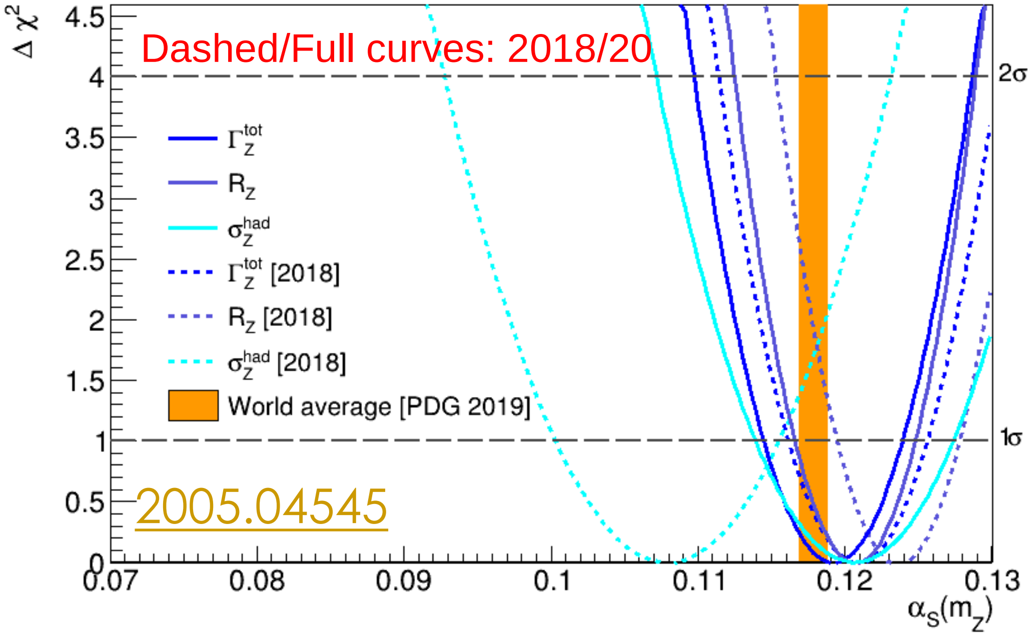
1908.01704

1912.02067

α_S from hadronic Z decays (today)

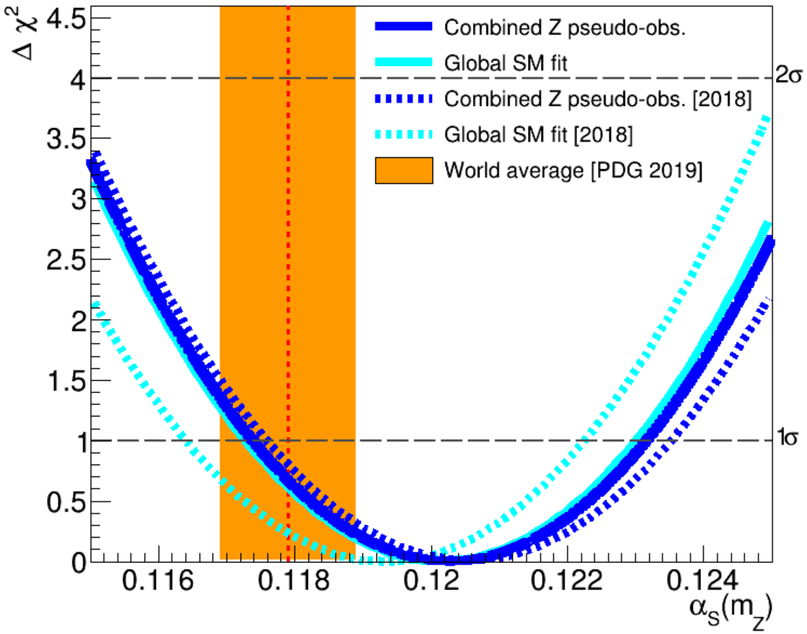
- α_S extracted at N^{3}LO from:
  - Combined fit of 3 Z pseudo observables
  - Full SM fit (with α_S free parameter)

Z boson 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



Dashed/Full curves: 2018/20

2005.04545



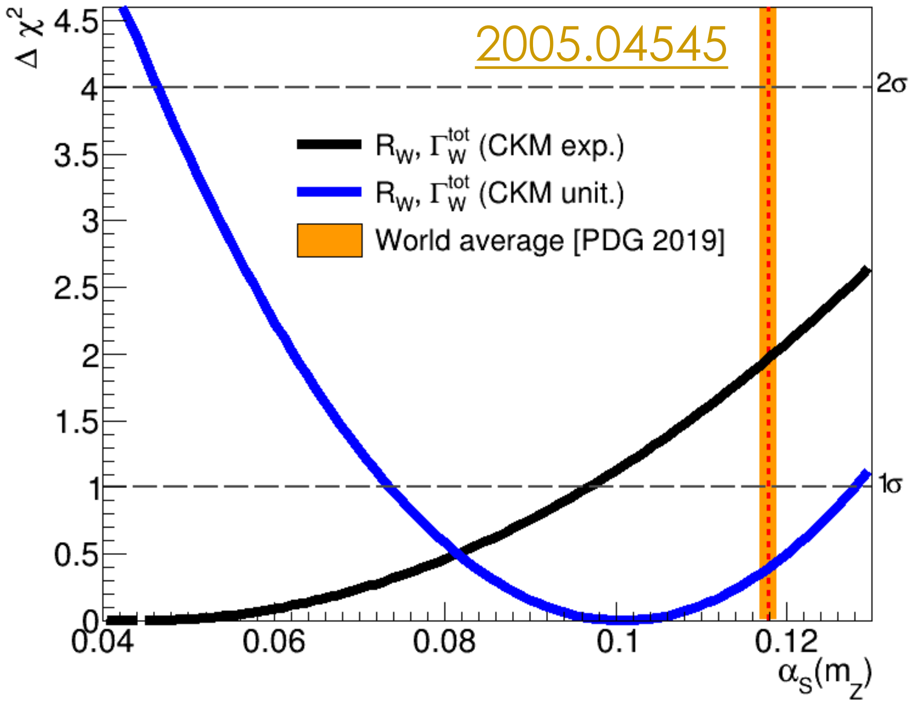
- LEP lumi-bias updates lead to better agreement among Γ_Z, R_Z and σ_Z^{had} extraction: **$\alpha_s(m_z) = 0.1203 \pm 0.0028$ (±2.3%)**
- Unc. updates lead to a better agreement with full fit: **$\alpha_s(m_z) = 0.1202 \pm 0.0028$**

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**

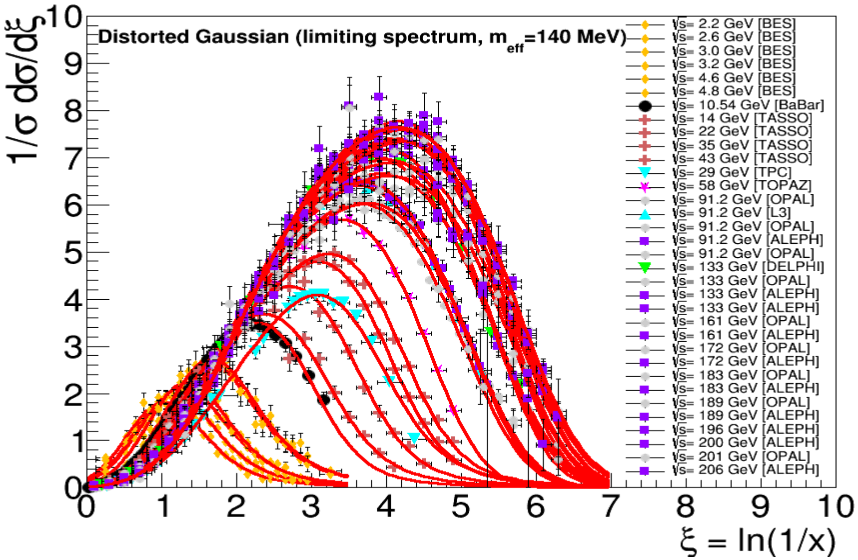


$\alpha_s(m_z) = 0.101 \pm 0.027$ (±27%)

α_S from jet fragmentation

- Soft parton-to-hadron FFS:

1505.02624 – NNLO*+NNLL



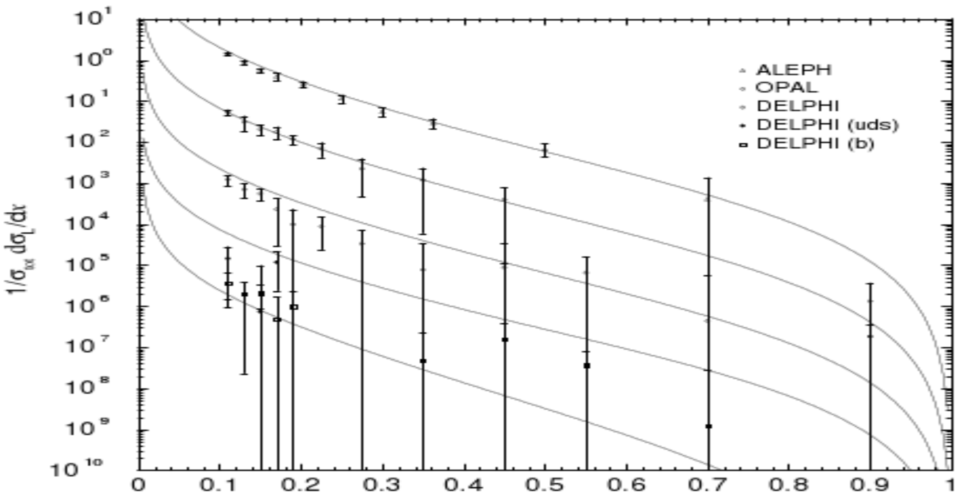
Combined fit of the jet-energy evolution of the FF moments (peak, width, multiplicity, etc.) with α_S as single free parameters

$\alpha_s(m_z)$ = 0.1205 ± 0.0022 (±2%)

(full NNLO corrections missing)

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

$\alpha_s(m_z)$ = 0.1176 ± 0.0055 (±4.7%)



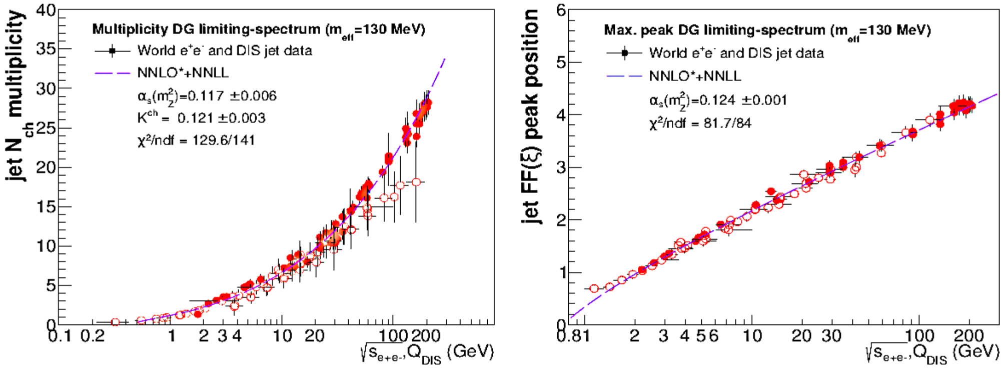


Figure 3: Energy evolution of the charged-hadron multiplicity (left) and of the FF peak position (right) measured in e^+e^- and DIS data fitted to the NNLO*+NNLL predictions. The obtained $\mathscr{K}_{\rm ch}$ normalization constant, individual NNLO* $\alpha_s(m_Z)$ values, and the goodness-of-fit per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

Jet substructure

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

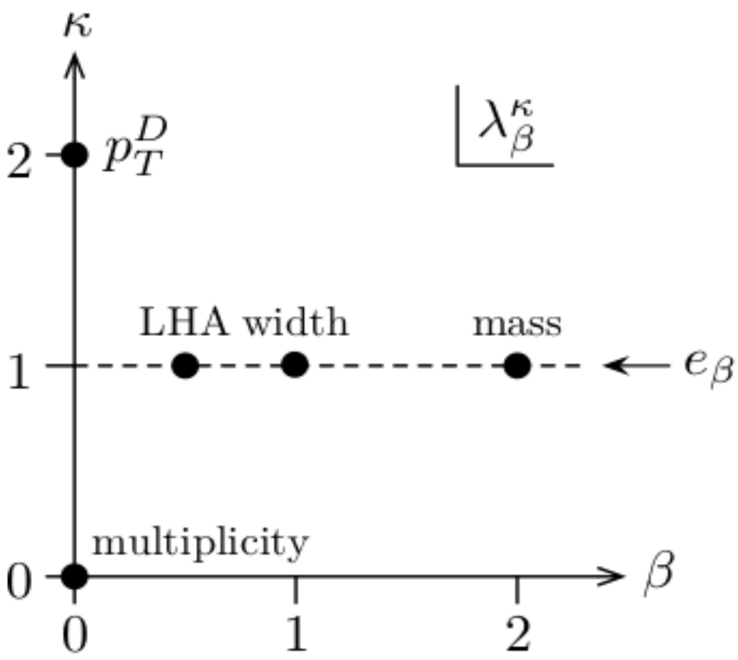
$$\lambda_\beta^\kappa = \sum_{i \in \mathrm{jet}} z_i^\kappa \theta_i^\beta ,$$

(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)

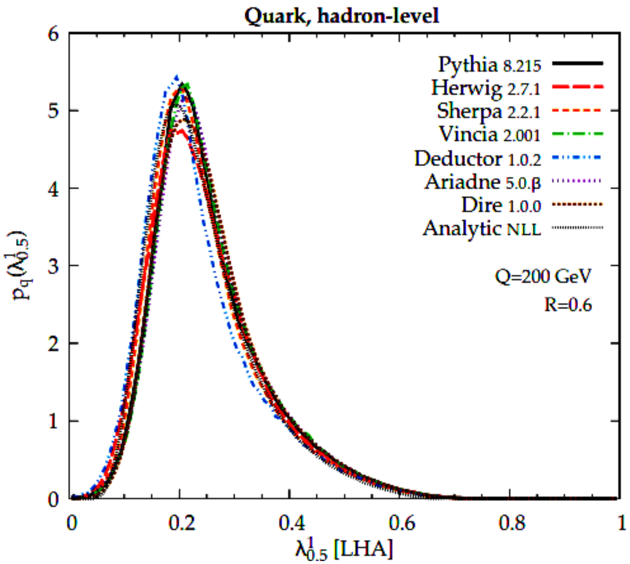


(larger angular weight)

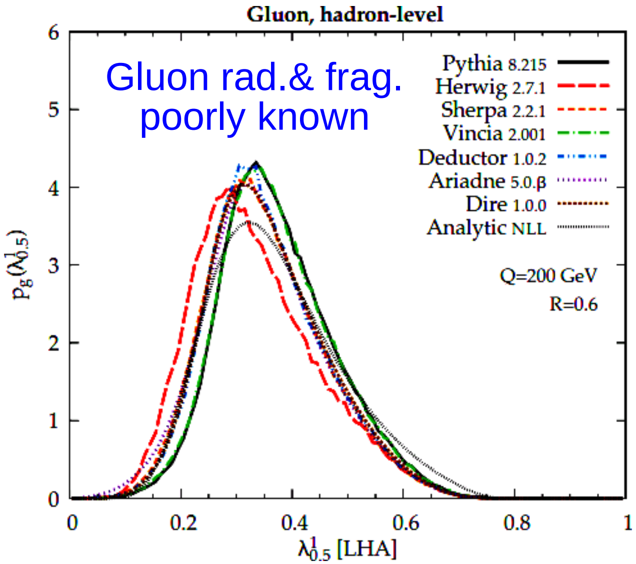
[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

Showering differences in MC generators

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

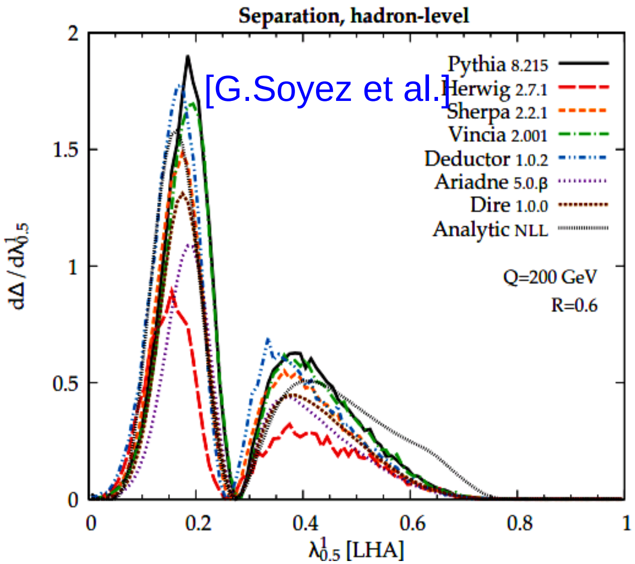


$e^+e^- \to Z \to u\bar{u}$



Gluon rad.& frag. poorly known

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

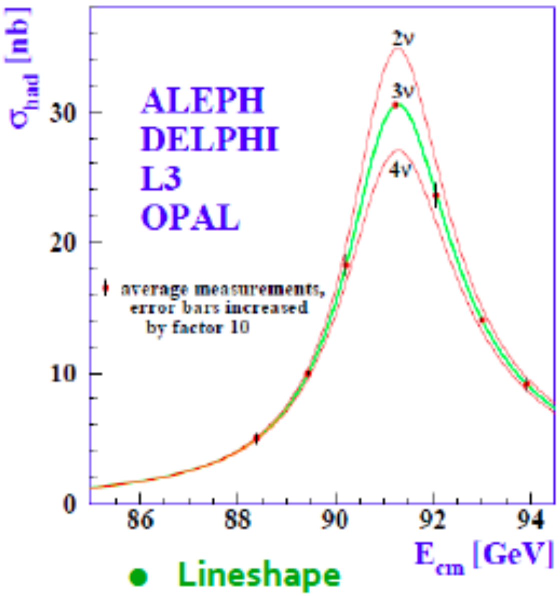


[G.Soyez et al.]

u-quark vs gluon discrimination power

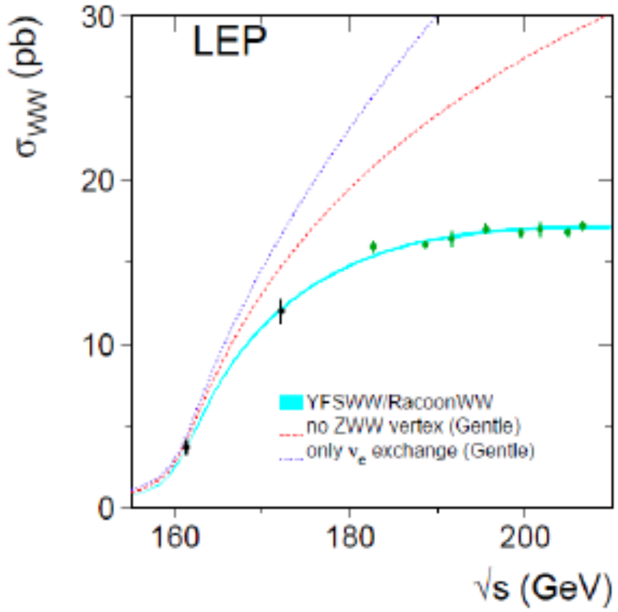
Ultra-precise W,Z and top physics at FCC-*ee*

$\sqrt{s}$=91 GeV, 10^{12} Z's



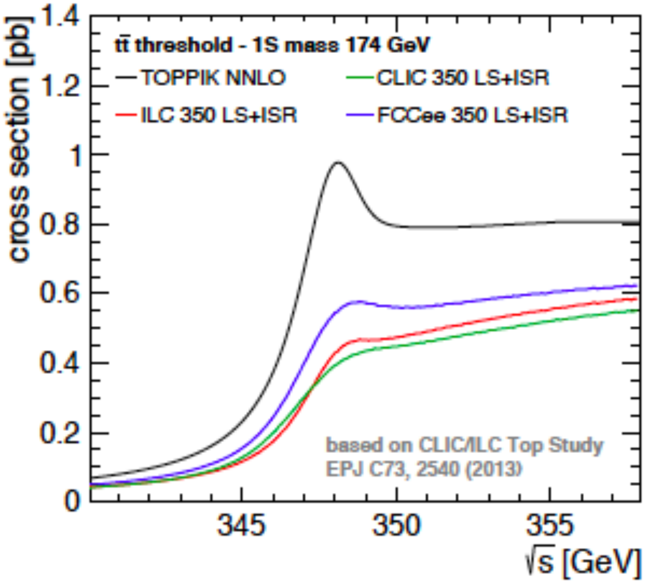
- Lineshape
  - Exquisite E_{beam} (unique!)
  - m_Z, Γ_Z to 10 keV (stat.) 100 keV (syst.)
- Asymmetries
  - $\sin^2\theta_W$ to 5×10^{-6}
- Branching ratios R_l, R_b
  - $\alpha_S(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

$\sqrt{s}$=161 GeV, 10^8 W's



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

$\sqrt{s}$=350 GeV, 10^6 tops

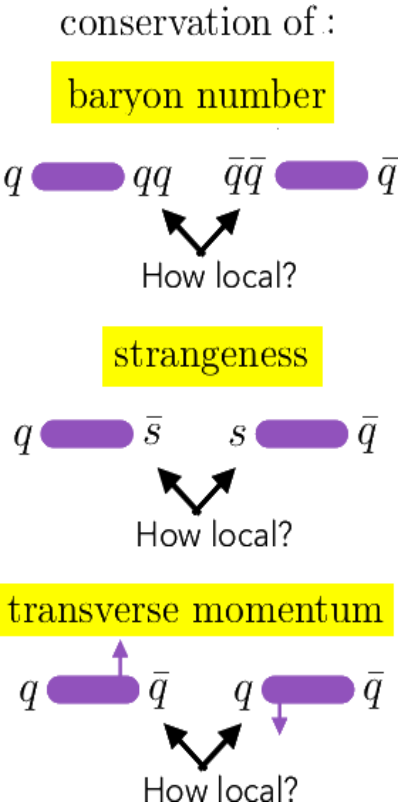


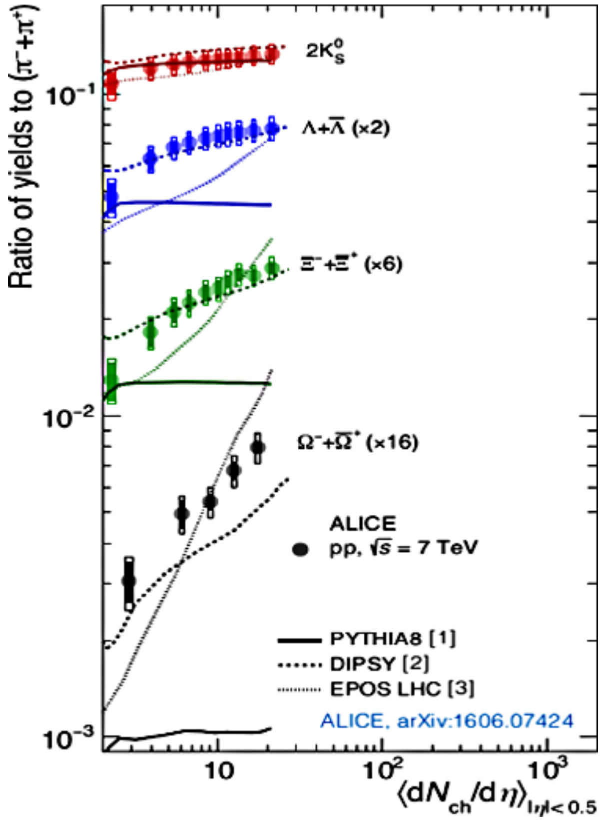
- Threshold scan + 4D fit
  - m_{top} to 10 MeV (stat.) 40 MeV (th.)
  - λ_{top} to 13%
  - EWK couplings to 1–10%

- Mostly thanks to the incredibly huge statistics available!
- Threshold scans with δE_{cm} ~ 0.1, 0.2, 2, 4 MeV (Z, W, H and top-quark)

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.



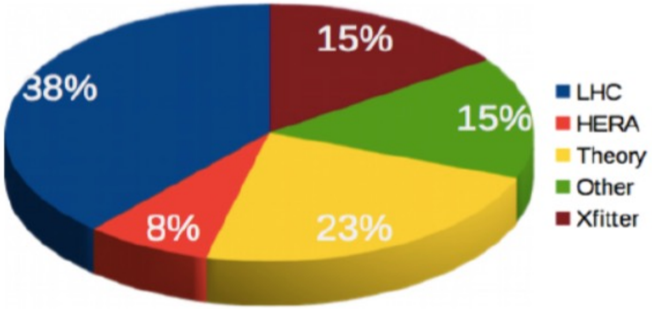


ALICE, arXiv:1606.07424

- 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

The xFitter Project

- The xFitter project (former HERAFitter) is a **unique open-source QCD fit framework**
- GitLab repository (open access to download for everyone)
- This code allows users to:
  - **extract PDFs** from a large variety of data
  - assess the **impact** of **new data on PDFs**
  - check the **consistency** of experimental data
  - test different **theoretical assumptions**



- Several active developers between experimentalists and theorists
- More than 100 publications obtained using xFitter since the beginning of the project
- List of recent analyses by the xFitter Developers' Team:

MORE IN PREPARATION!

Phys.Rev.D 104 (2021) 5, 056019, arXiv:2105.11306	QCD analysis of pion fragmentation functions in the xFitter framework
Phys.Rev.D 102 (2020) 1, 014040, arXiv:2002.02902	Parton Distribution Functions of the Charged Pion Within The xFitter Framework

Pion Fragmentation Functions

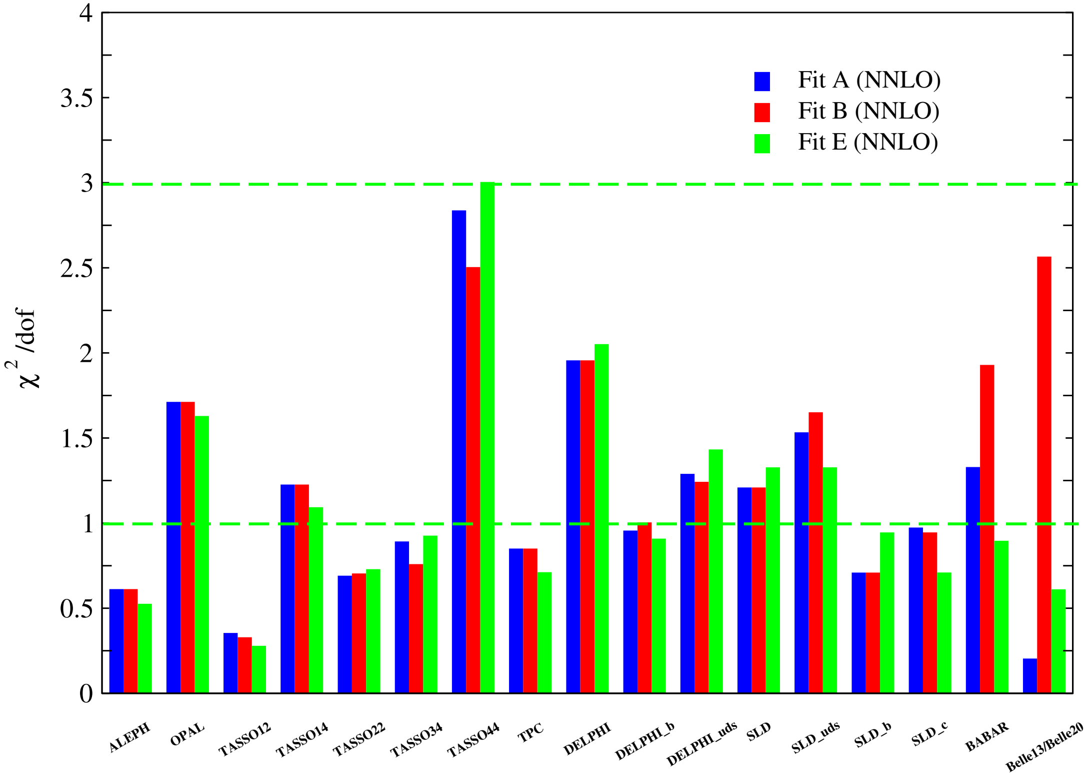
PRD 104 (2021) 5 056019

- To perform the extraction of **pion fragmentation functions** (FFs) from single inclusive electron-positron annihilation (SIA) + BELLE13/20 data
- SIA $e^+e^- \xrightarrow{\gamma^*,Z} \pi^\pm X$ data allow to separate Δq and $\Delta\bar{q}$
- **Parametrization form:** $D_i^{\pi^\pm}(z, Q_0) = \frac{\mathcal{N}_i z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]}{B[2+\alpha_i, \beta_i+1]+\gamma_i B[2+\alpha_i, \beta_i+\delta_i+1]}$
- We assume isospin symmetry $D_u^{\pi^+} = D_{\bar{d}}^{\pi^-}$ and $D_{\bar{u}}^{\pi^+} = D_d^{\pi^-}$
- We assume the charge conjugate $D_i^{\pi^+} = D_{\bar{i}}^{\pi^-}$ for all the flavour component
- We fit the flavour combinations $i = u^+, d^+, s^+, c^+, b^+$ and g
- We parametrise FFs at a starting scale of Q_0^2 = 5 GeV²
- **19 free parameters in total**
- Fitted distributions: $\frac{d\sigma^h}{dz}, \frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dp_h}, \frac{s}{\beta}\frac{d\sigma^h}{dz}, \frac{1}{\beta\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}, \ldots$ ($z = 2E_h/\sqrt{s}$)

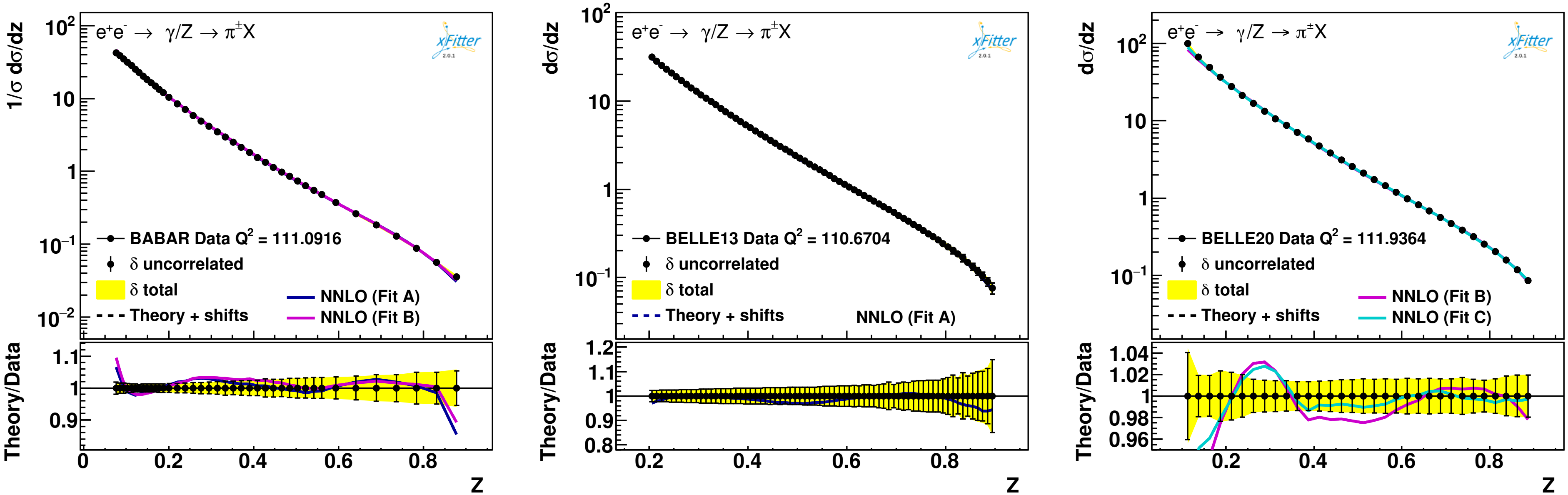
Pion Fragmentation Functions

- Several fits ran:
  - **Fit A** focuses on the impact of BELLE13 data (no BELLE20 data)
  - **Fit B** focuses on the impact of BELLE20 data (no BELLE13 data)
  - **Fit C** focuses on the impact of BELLE20 data without BaBar set (no BELLE13 data)
  - **Fit D** focuses on the impact of low-z BELLE20 data (No BELLE13 and BaBar data) – z > 0.2
  - **Fit E** focuses on the impact of low-z BELLE20 and BaBar data (no BELLE 13 data) – z > 0.2 (BELLE20) and z > 0.1 (BaBar)

- The inclusion of higher-order QCD corrections noticeably improves the quality of our fits
- Fits performed with enhanced tolerance T = $\sqrt{\Delta\chi^2}$= 20
- FFS NLO and NNLO uncertainty bands overlap → perturbative uncertainties are under control (and reasonable choice of T)

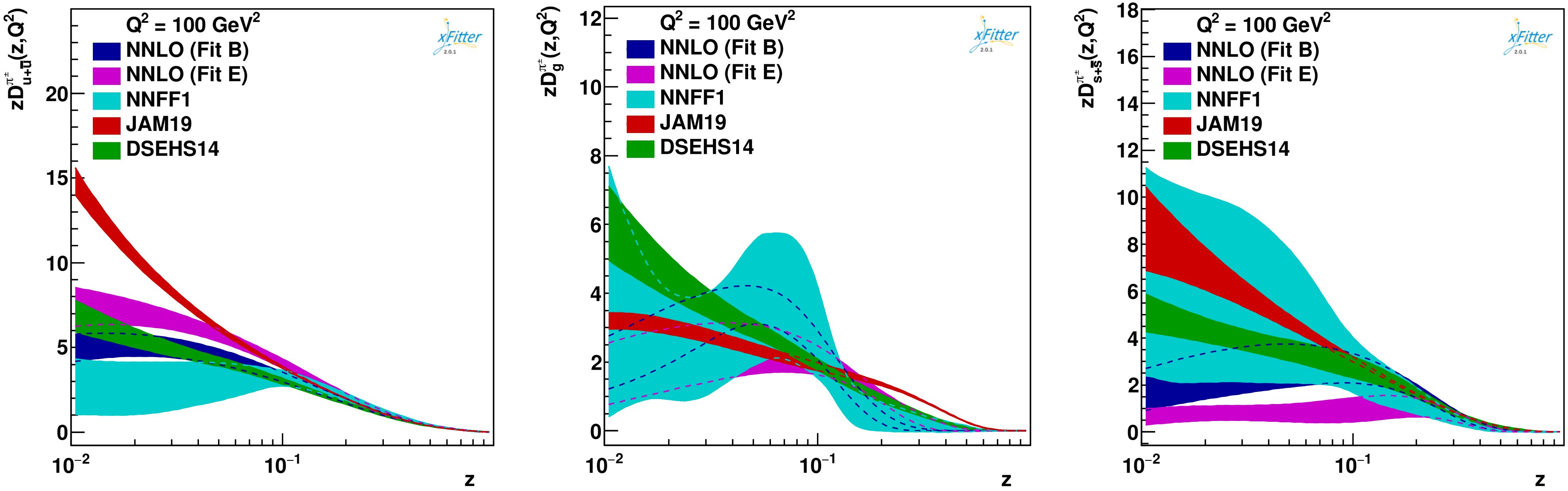


Pion Fragmentation Functions



- Theoretical predictions entirely consistent with the experimental data – partly due to larger uncertainties (BELLE13)
- Fits yield a **good description of the data** **with the exception of the low-z region** (BELLE20 and BaBar)
- **BELLE and BaBar** data sets appear to pull the fit in **opposite directions** - χ^2(Fit B) for BELLE20 is 82/32 vs χ^2(Fit C) for BELLE20 is 32/32
- The effect of excluding low-z data is dramatic - χ^2/dof ~ 1.2 (similar cuts applied in JAM19)

Pion Fragmentation Functions



- Comparison with NNLO NNFF1 and NLO JAM19 and DSEHS14
- **Generally compatible with NNFF1 and DSEHS14 at larger z**, but they differ at low-z (more pronounced for Fit E)
- The **gluon** is generally **compatible with NNFF1** (larger uncertainties)
- FFs generally have a different behaviour as compared to JAM19 – they have much steeper slope at low-z for quarks, with the gluon lying above our curves for intermediate- to larger-z