Precision QCD at future e^+e^- colliders (mostly FCC-ee)

Intl Workshop on the high-energy Circular e-e+ Collider (CEPC)

Shanghai/Virtual, Oct. 2020

David d'Enterria

(CERN)

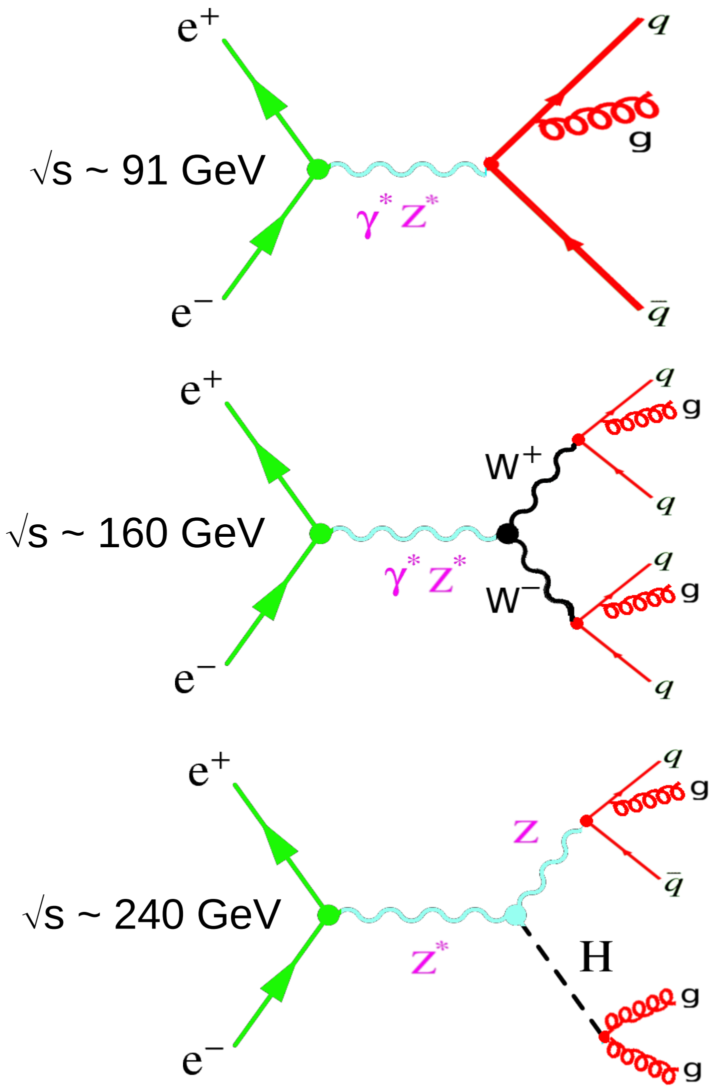
QCD = Key piece at future ee, pp colliders

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

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

Precision QCD in e^+e^- collisions

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



Advantages compared to p-p collisions:

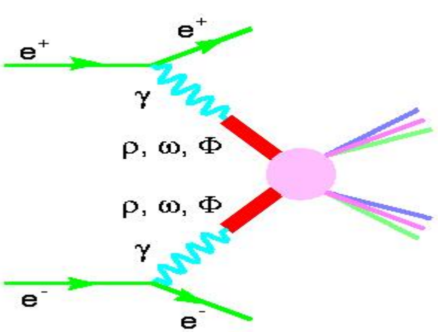
– QED initial-state with known kinematics

– Controlled QCD radiation (only in final-state)

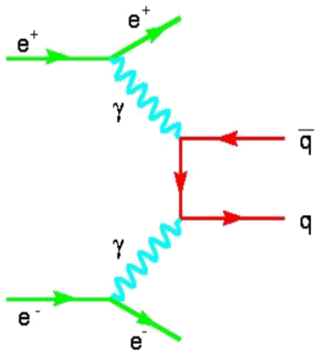
– Well-defined heavy-Q, quark, gluon jets

– Smaller non-pQCD uncertainties:
no PDFs, no QCD "underlying event",…
Direct clean parton fragmentation & hadroniz.

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



(soft, VDM)



(direct)

Precision QCD in e^+e^- collisions (FCC-ee)

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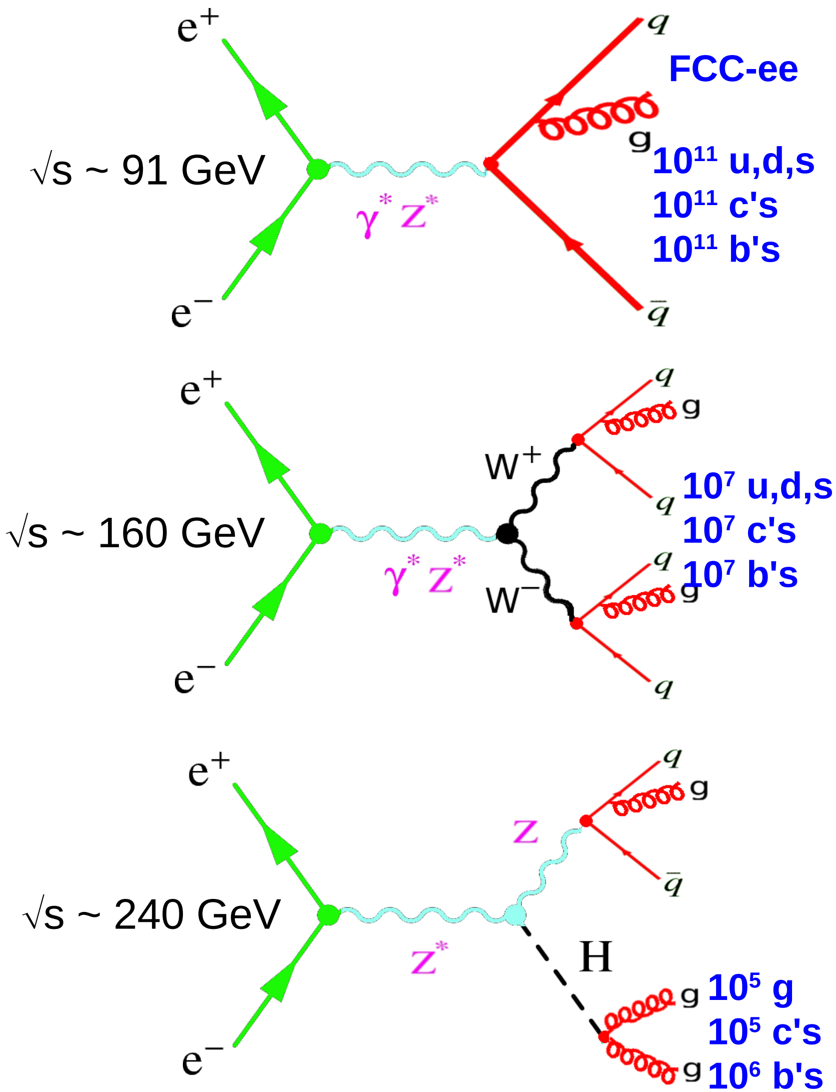

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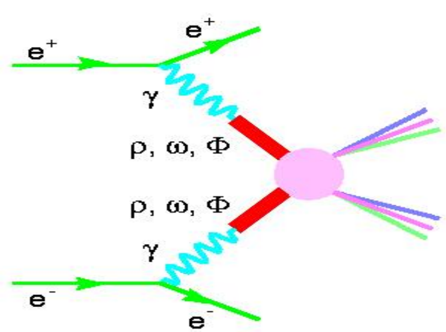

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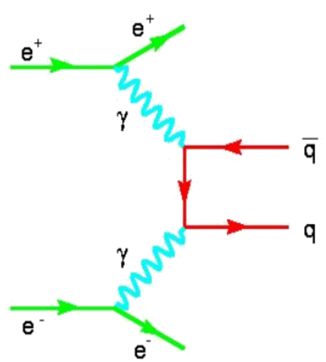
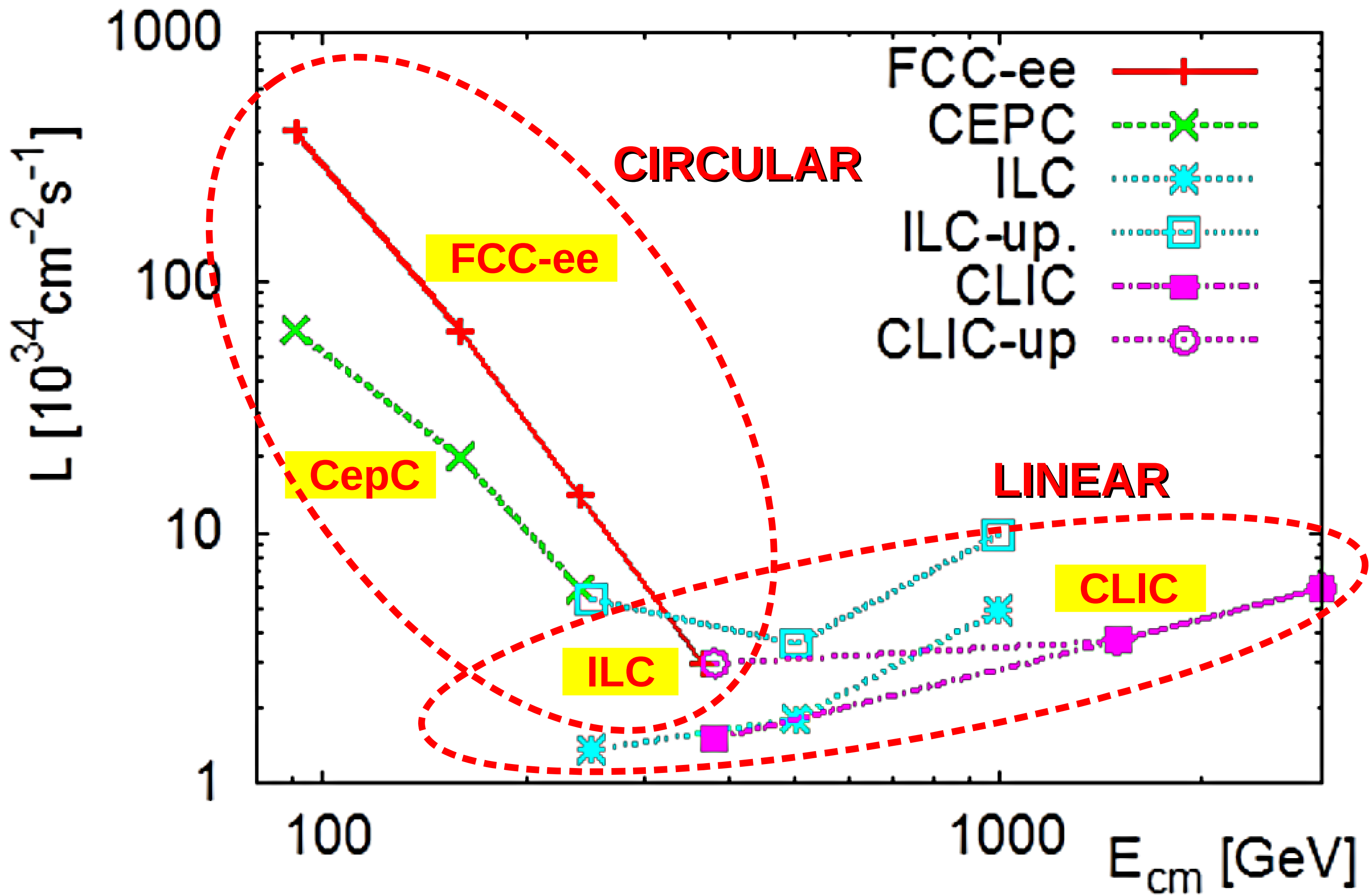


(direct)

Future e^+e^- colliders under discussion



- FCC-ee features lumis a few times larger than other machines over 90–300 GeV
- Unparalleled Z, W, jets, τ,... data sets: Negligible stat. uncertainties

QCD physics at future e^+e^- machines

(1) QCD coupling

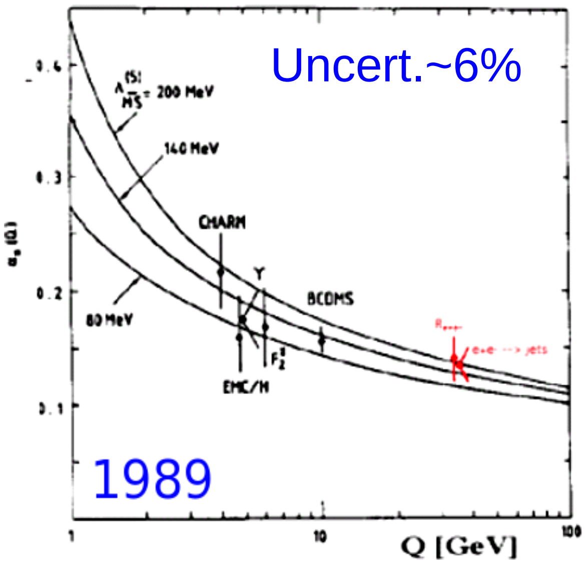
(2) Jet substructure & flavour tagging

(3) Parton shower & Non-perturbative QCD

NOTE: Only UNIQUE QCD measurements, inaccessible at any current machine, are covered.

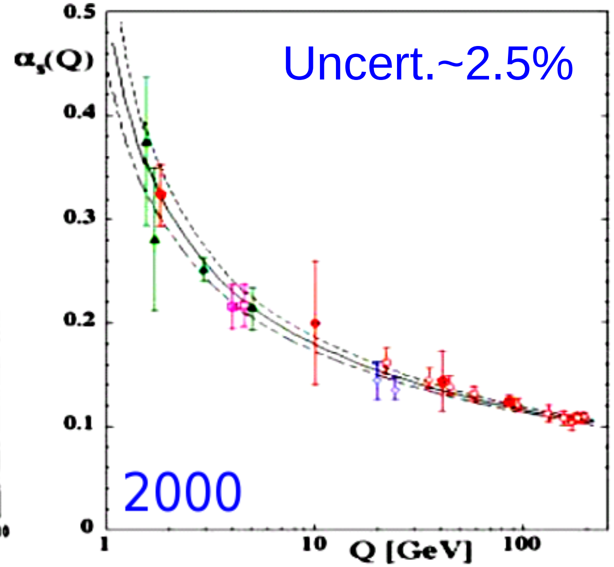
QCD coupling α_s

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



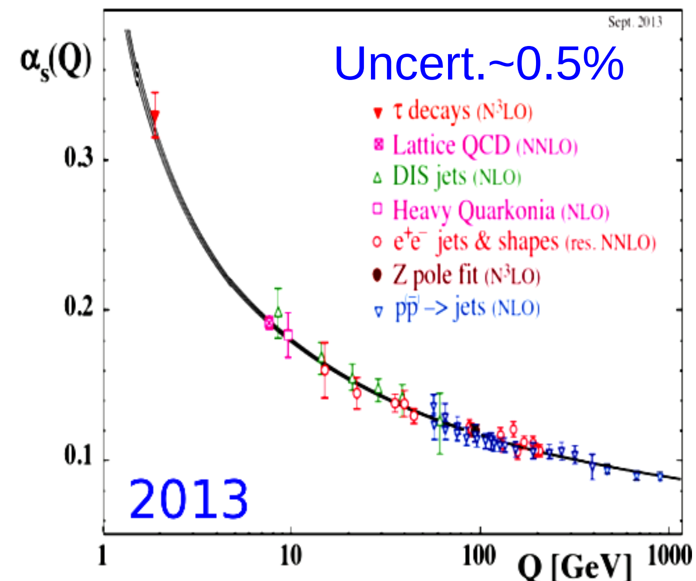
$\alpha_S(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

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



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

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



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

QCD coupling α_s

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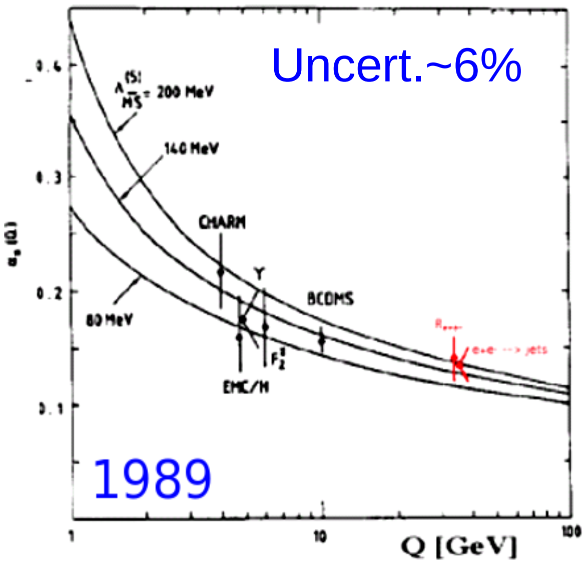

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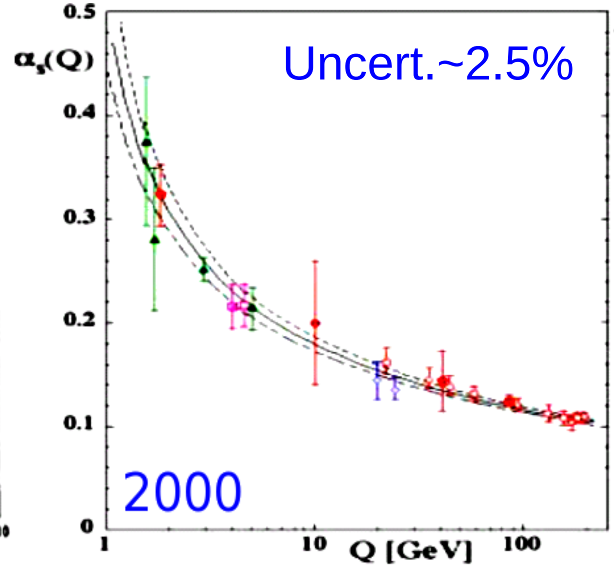

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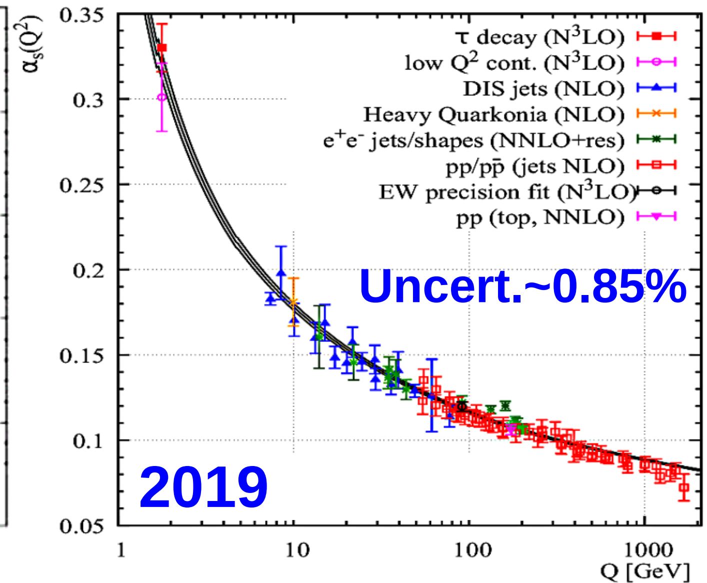


$\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$

- Least precisely known of all interaction couplings !

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

Importance of the QCD coupling α_s

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

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

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

Msbar mass error budget (from threshold scan)

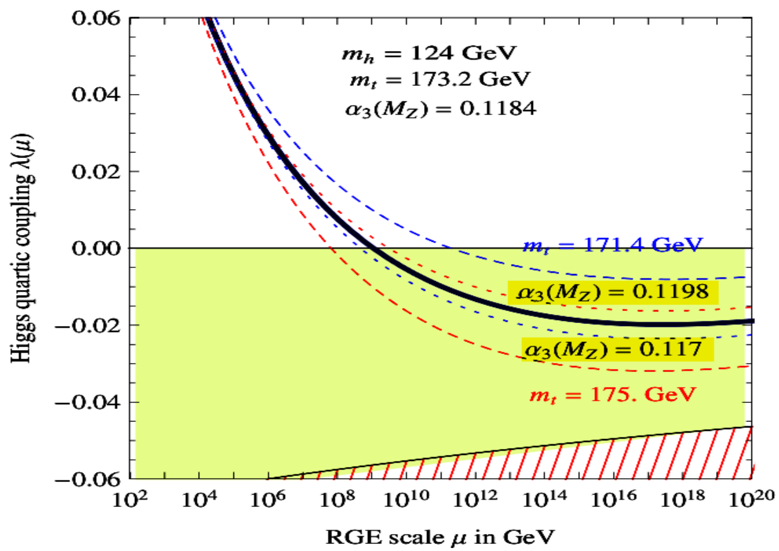
$(\delta M_t^{SD-low})^{exp}$	$(\delta M_t^{SD-low})^{theo}$	$(\delta\overline{m}_t(\overline{m}_t))^{conversion}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

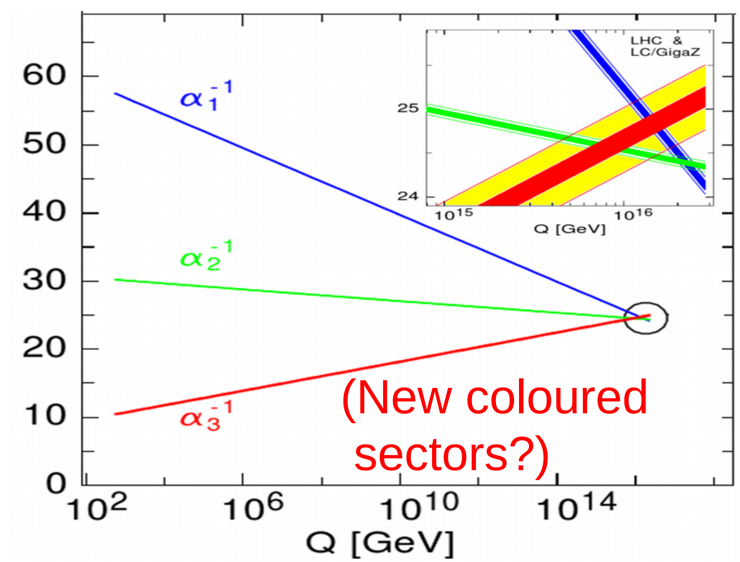
$\Rightarrow$ improvement in α_s crucial $\delta\alpha_s(M_Z) = 0.001$

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

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

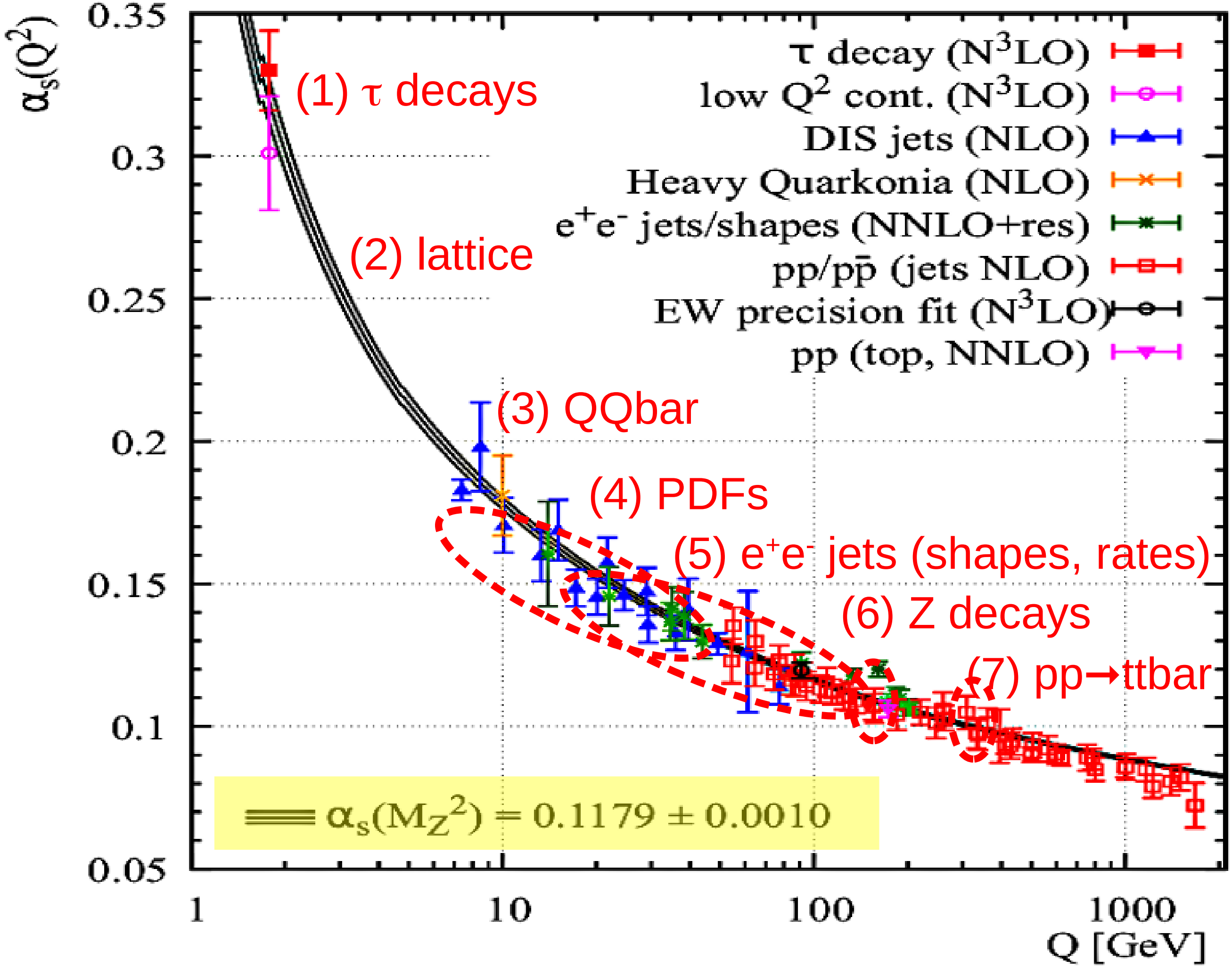
- Impacts physics approaching Planck scale: EW vacuum stability, GUT





World α_s determination (PDG 2019)

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



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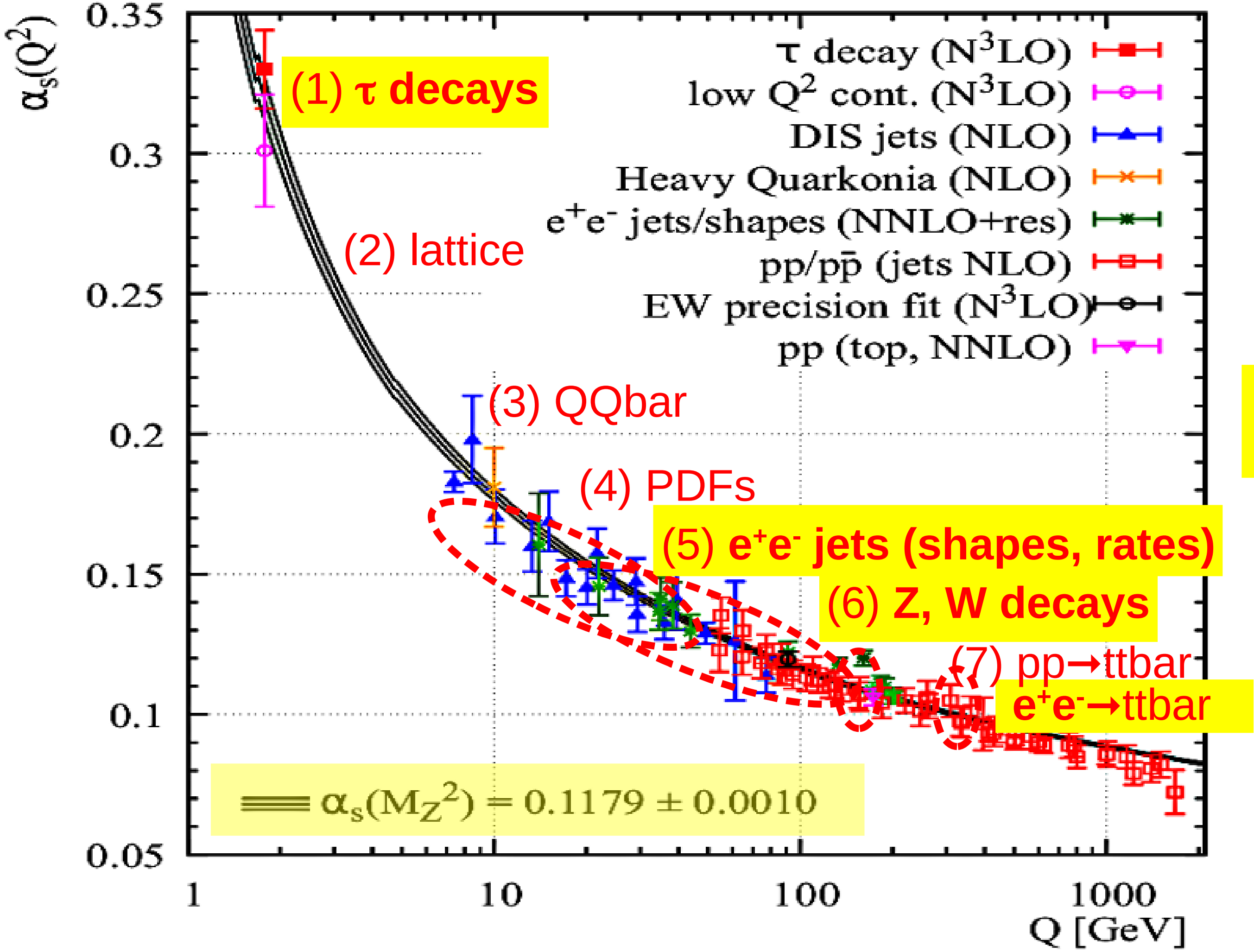
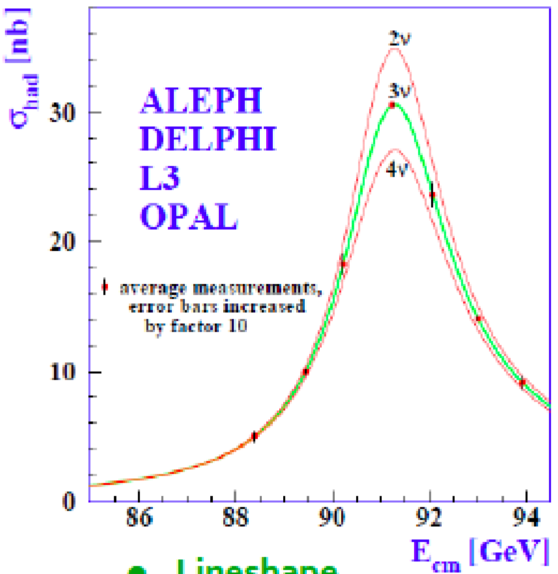
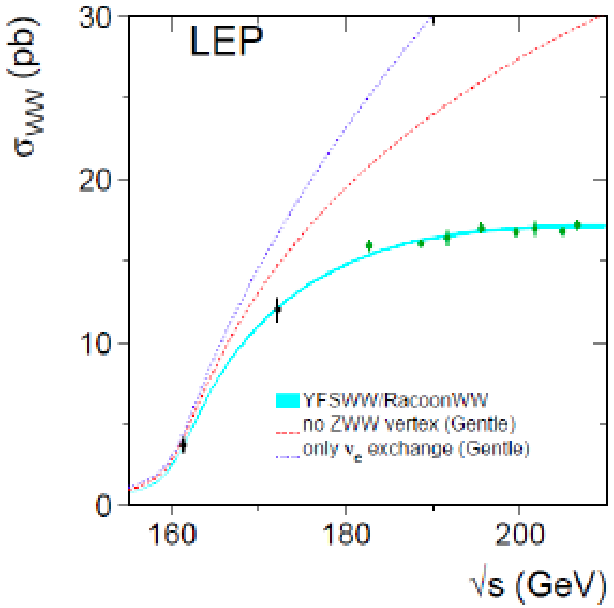


Ultra-precise W, Z, top physics at FCC-ee

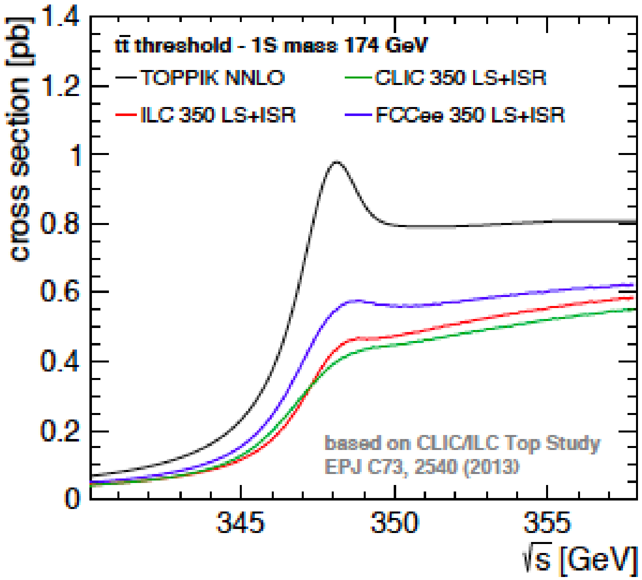
$\sqrt{s}$=91 GeV, 10^{12} Z's | **$\sqrt{s}$=161 GeV, 10^8 W's** | **$\sqrt{s}$=350 GeV, 10^6 tops**



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



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



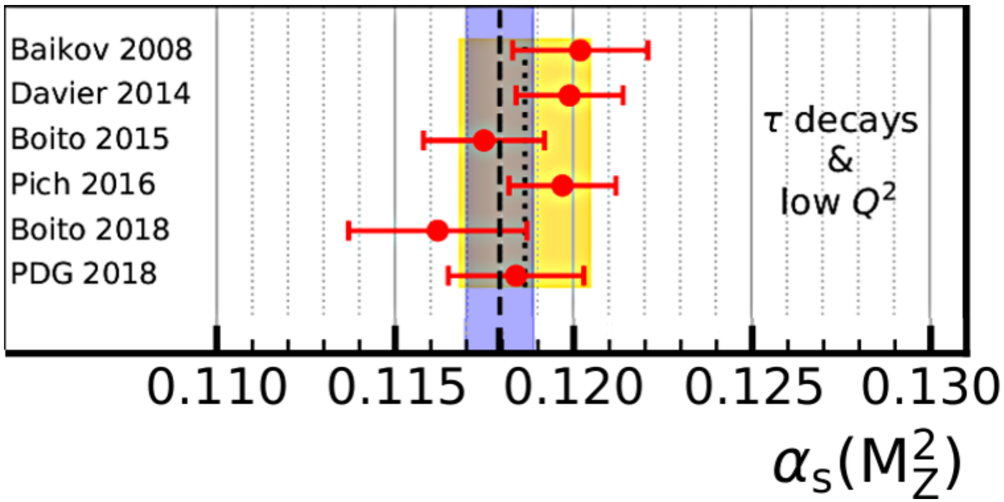
- Threshold scan + 4D fit
  - m_{top} to 10 MeV (stat.) 40 MeV (th.)
  - λ_{top} to 13%
  - EWK couplings to 1–10%

- Mostly thanks to: (i) Huge statistics
  (ii) Threshold scans with δE_{cm} ~ 0.1, 0.3, 2., 4. MeV (Z,W,H,t)

α_s from hadronic τ-lepton decays

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

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



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

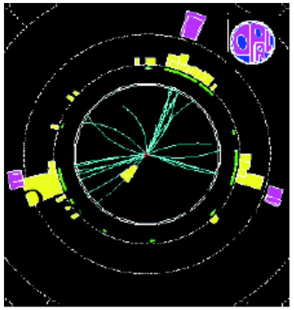
- <u>Future</u> :
  - TH: Better understanding of FOPT vs CIPT differences.
  - Better spectral functions needed (high stats & better precision): B-factories (BELLE-II)?
  - High-stats: $\mathcal{O}(10^{11})$ from Z→ττ at FCC-ee(90) : **$\delta\alpha_s/\alpha_s$ << 1%**

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

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

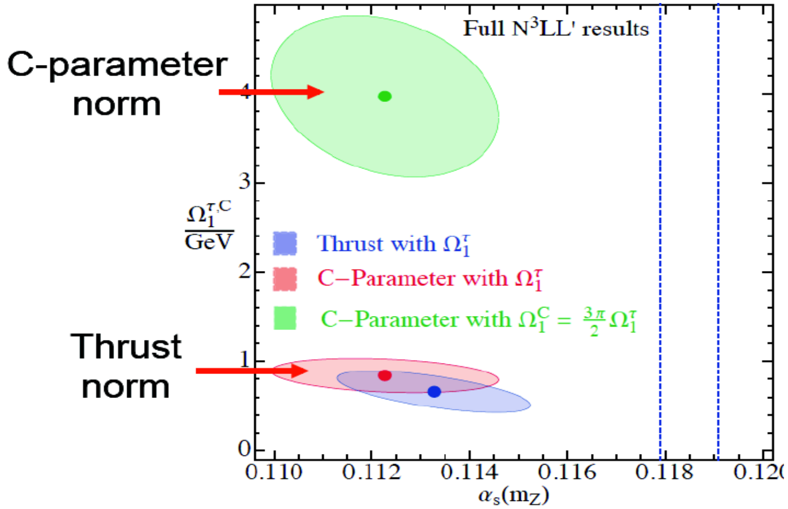
$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

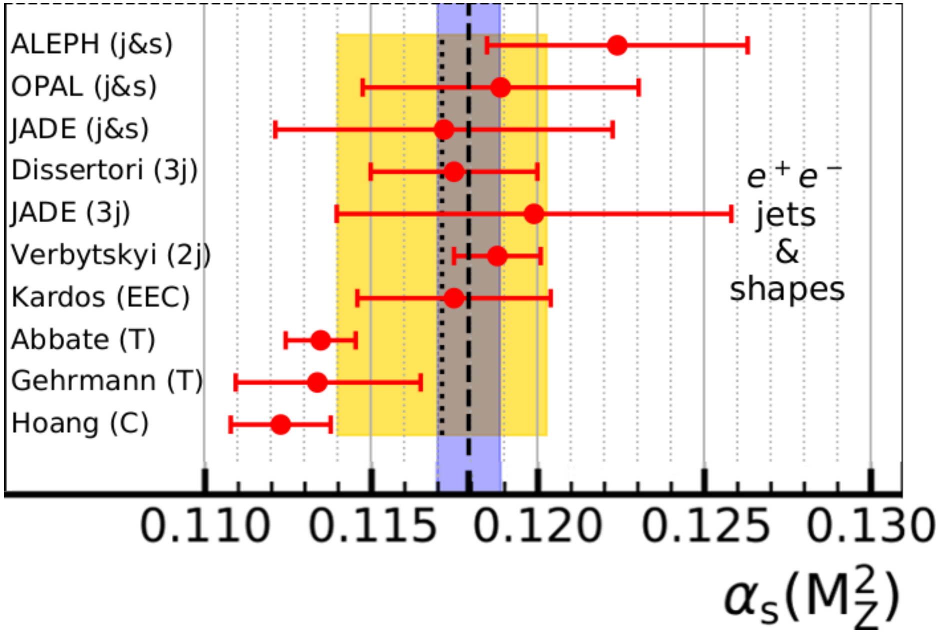
$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2 \theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$



OPAL 3 jet event

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





- Wide span of TH extractions...

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

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

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

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

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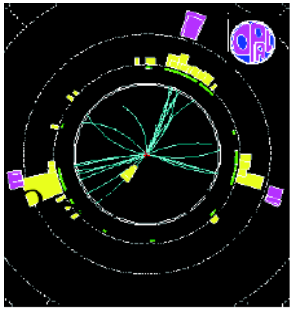

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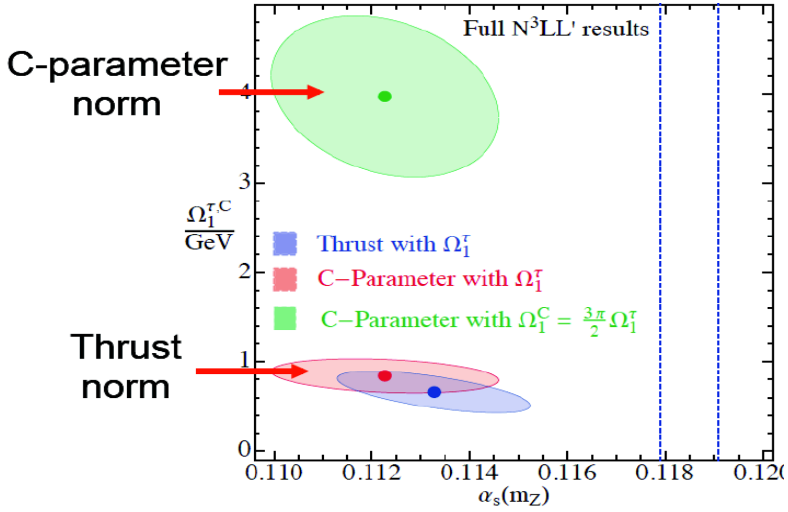
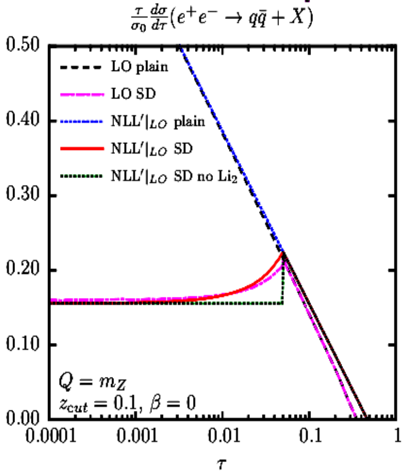
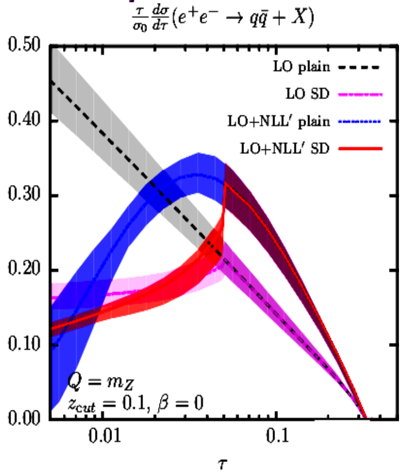


- Modern jet substructure techniques: "Soft drop" can help reduce non-pQCD corrections for thrust:

[Baron, Marzani, VT; '18]





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

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

α_s from hadronic Z, W decays

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

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

- The W and Z hadronic widths :

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

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

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

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

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

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

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

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

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

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

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

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

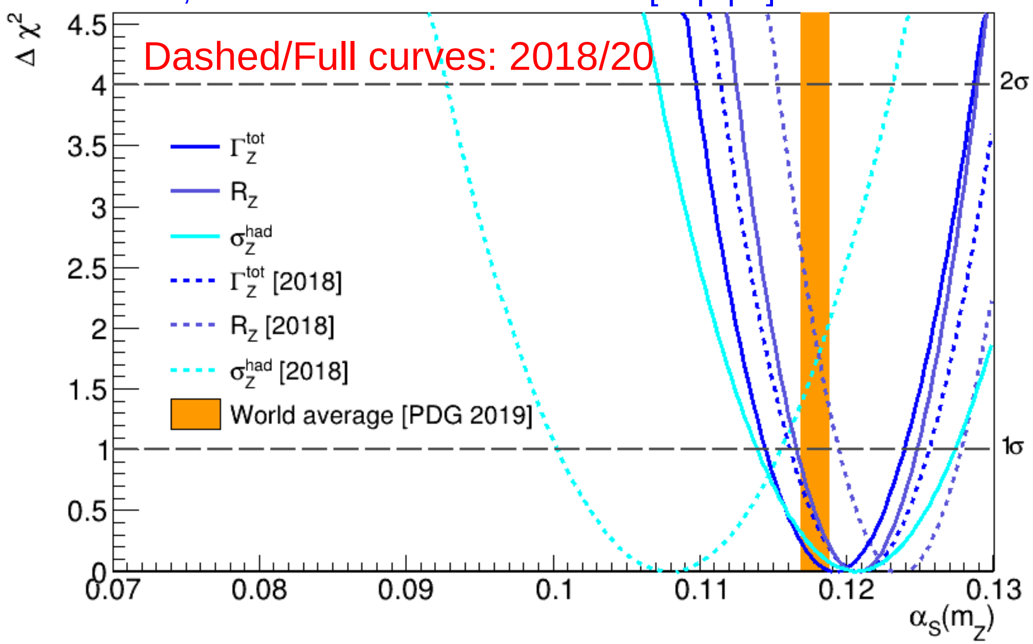
α_s from hadronic Z decays (today)

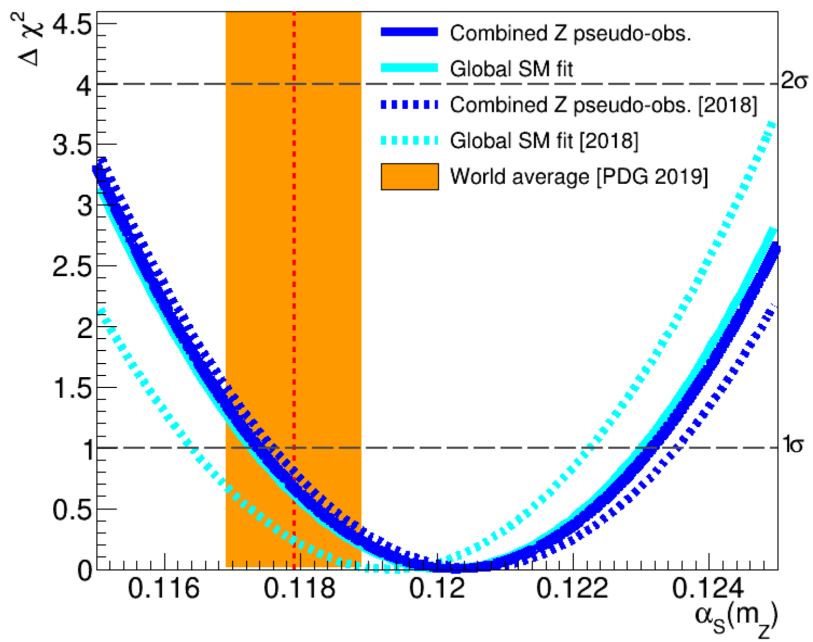
- QCD coupling extracted from:

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

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

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





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

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

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

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

α_s from hadronic Z decays (FCC-ee)

- QCD coupling extracted from:

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

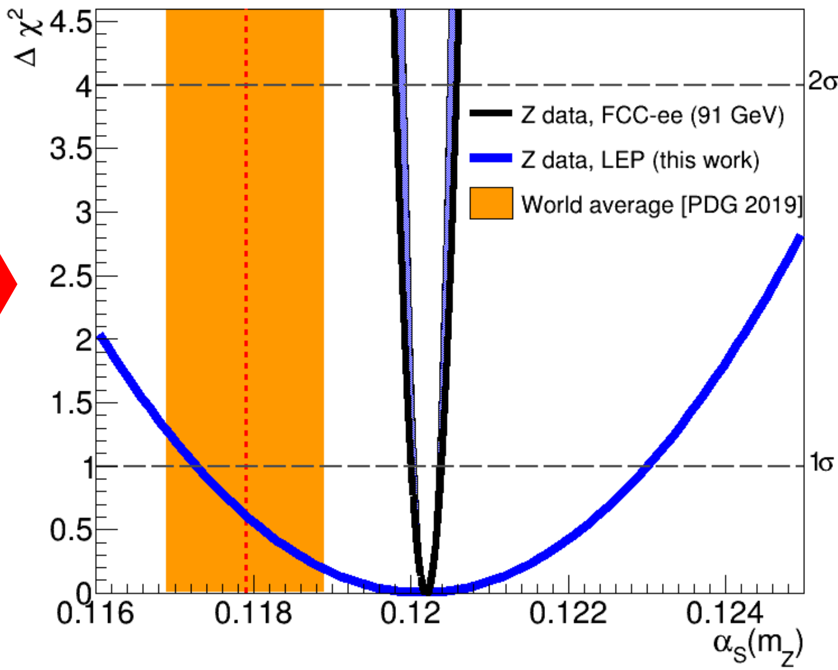
Z boson observable	$\alpha_S(m_Z)$ extraction	uncertainties exp.	param.	theor.
All combined	0.1203 ± 0.0029	± 0.0029	± 0.0002	± 0.0008
Global SM fit	0.1202 ± 0.0028	± 0.0028	± 0.0002	± 0.0008
All combined (FCC-ee)	0.12030 ± 0.00026	± 0.00013	± 0.00005	± 0.00022
Global SM fit (FCC-ee)	0.12020 ± 0.00026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

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

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

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

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



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

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

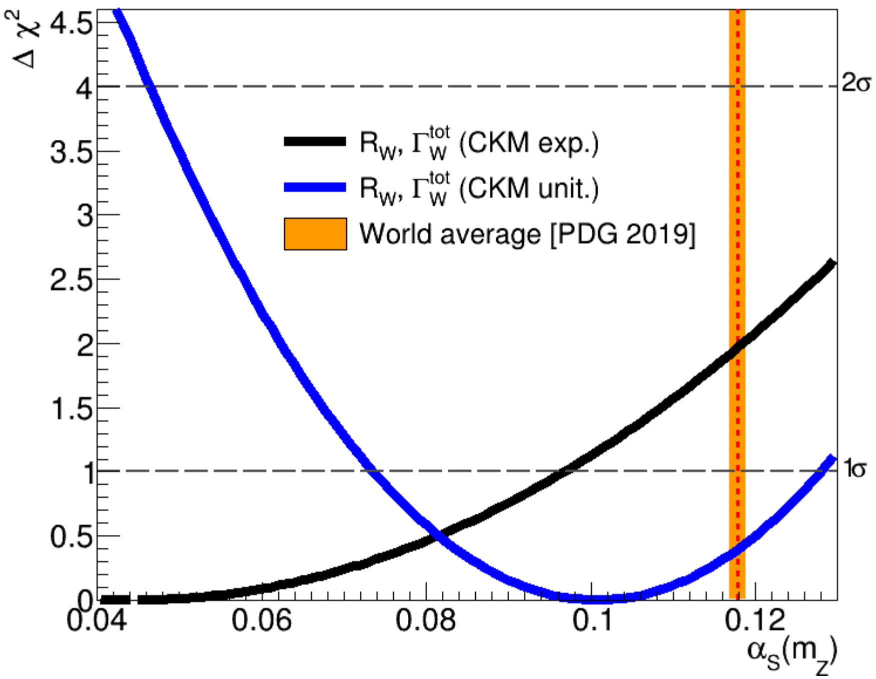
α_s from hadronic W decays (today)

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

W boson 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

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

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



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

α_s from hadronic W decays (FCC-ee)

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

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

- FCC-ee extraction:

– Huge W pole stats. ($\times 10^4$ LEP-2).

– Exquisite syst./parametric precision:

$$\Gamma_W^{tot} = 2088.0 \pm 1.2 \text{ MeV}$$

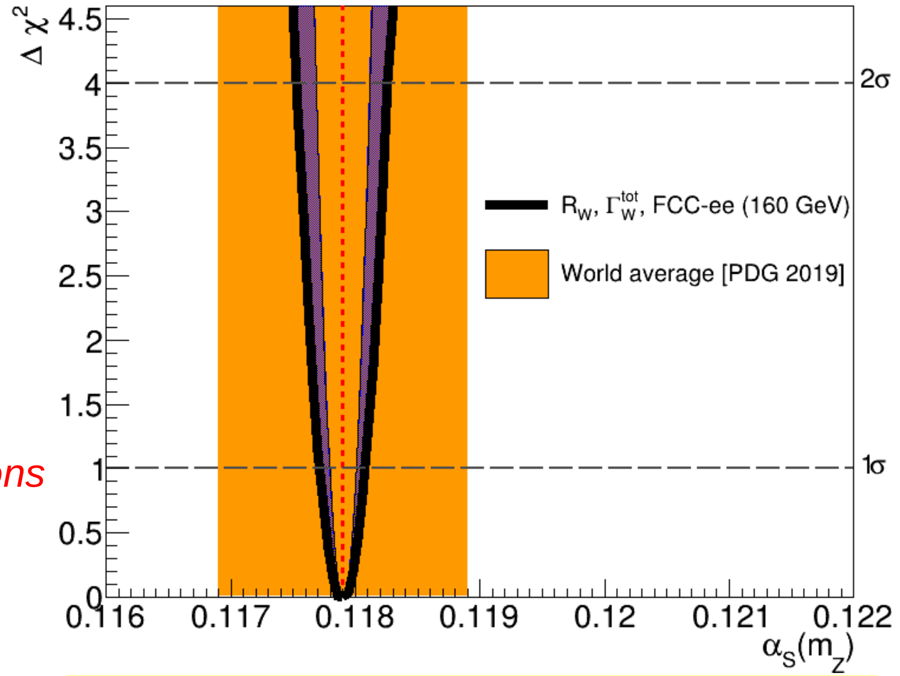
$$R_W = 2.08000 \pm 0.00008$$

$$m_W = 80.3800 \pm 0.0005 \text{ GeV}$$

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

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

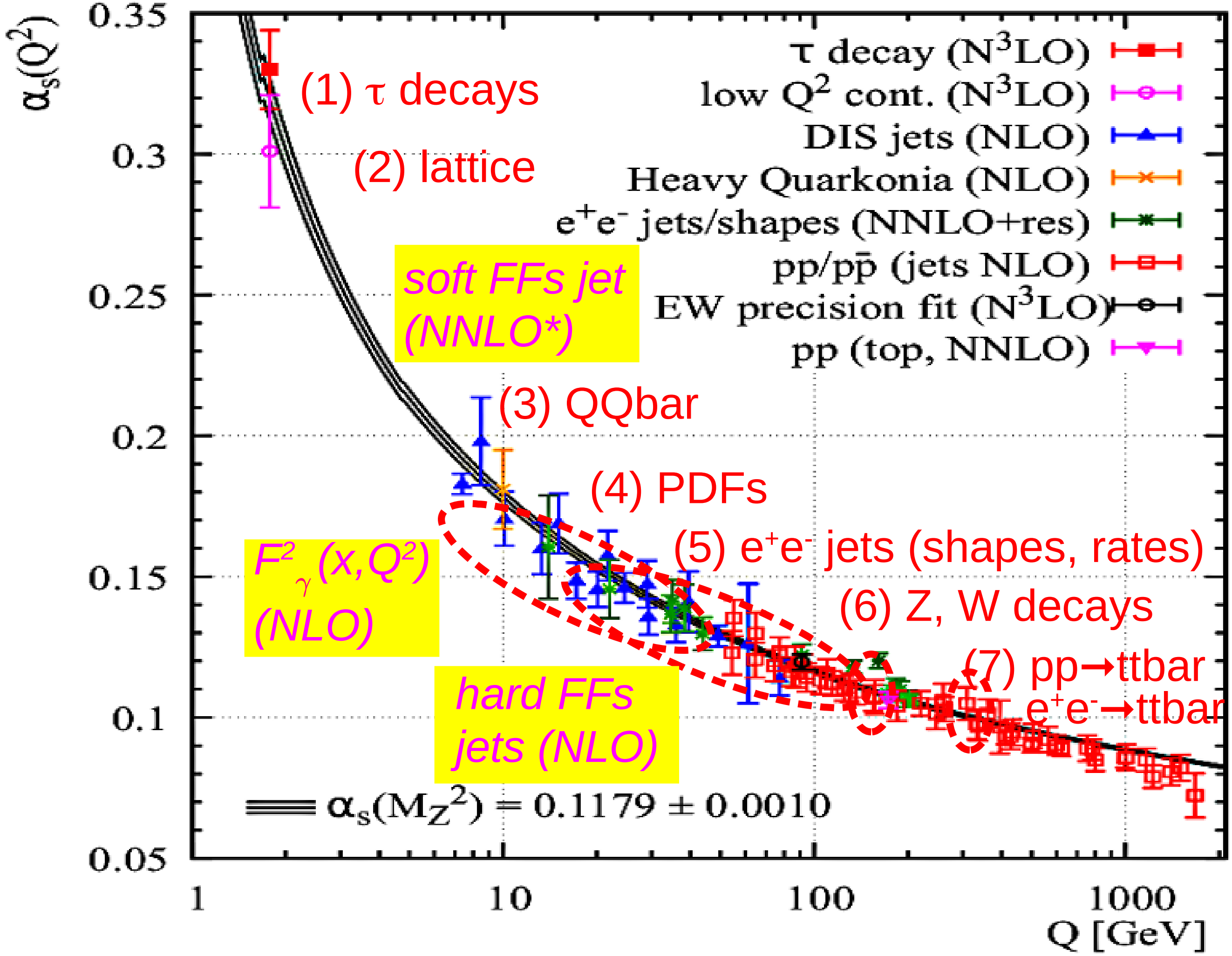
DdE, Jacobsen: arXiv:2005.04545 [hep-ph]



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

Other α_s extractions (not *yet* in world average)

- There are few other classes of e^+e^- observables, computed today at lower accuracy (NLO, NNLO*), that can be used to extract the QCD coupling:



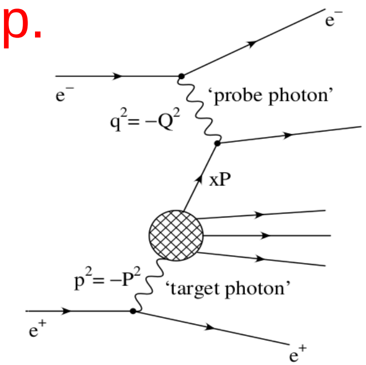
α_s from photon QCD structure function (NLO)

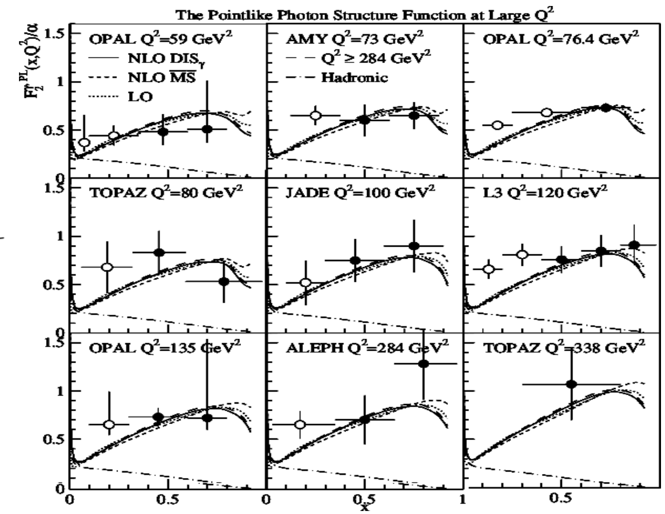
- Computed at NNLO: $\int_0^1 dx F_2^{\gamma}(x,Q^2,P^2) = \frac{\alpha}{4\pi}\frac{1}{2\beta_0}\left\{\frac{4\pi}{\alpha_s(Q^2)}c_{LO} + c_{NLO} + \frac{\alpha_s(Q^2)}{4\pi}c_{NNLO} + \mathcal{O}(\alpha_s^2)\right\}$
- Poor $F^2_{\gamma}(x,Q^2)$ experimental measurements:
- Extraction (NLO) with large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

$\alpha_s(m_z) = 0.1198 \pm 0.0054$

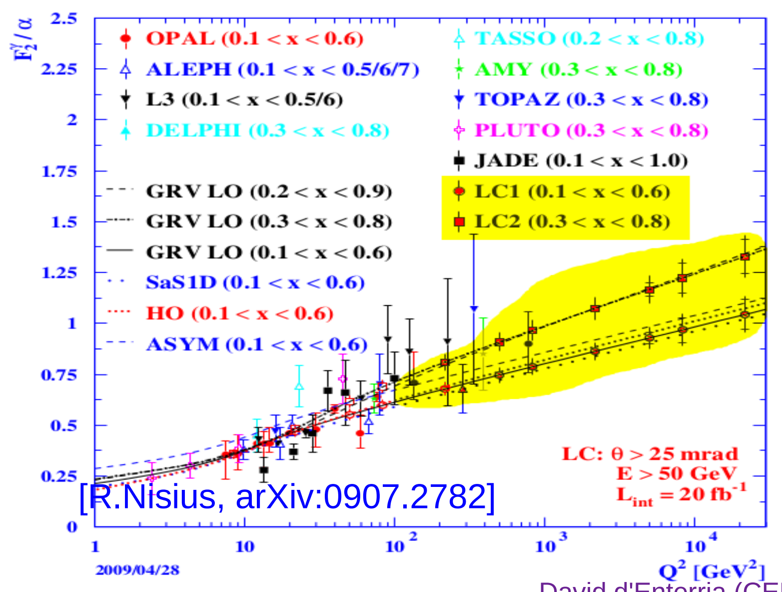
($\pm$4.5%)

[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%

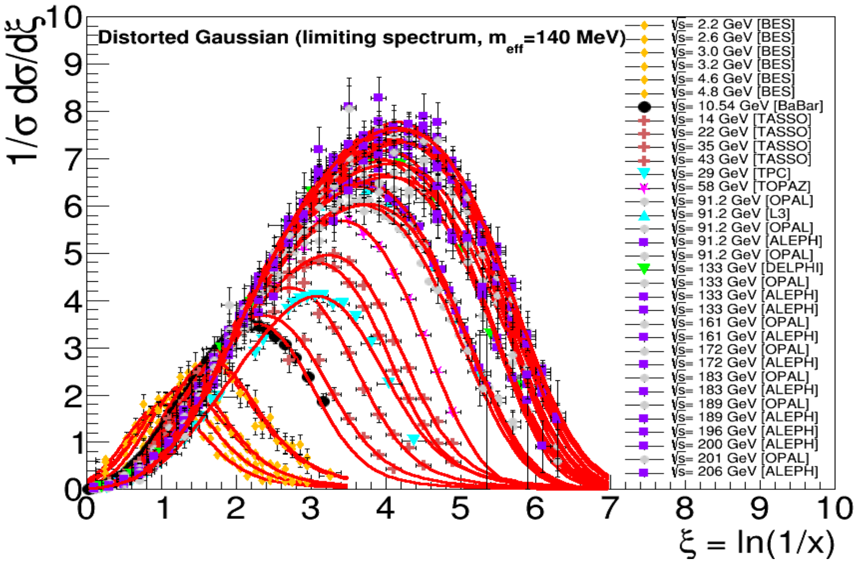


[R.Nisius, arXiv:0907.2782]

α_s extractions from jet fragmentation (NLO,NNLO*)

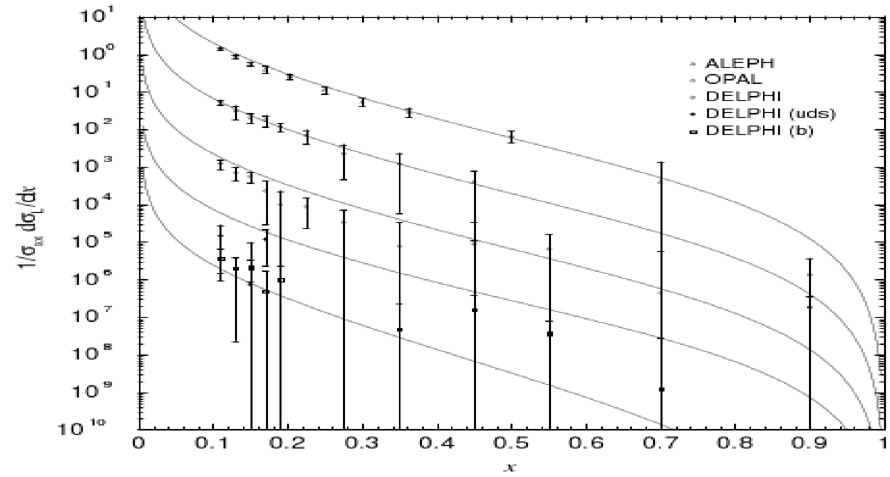
- Soft parton-to-hadron FFs (NNLO*+NNLL):

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



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

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



[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)

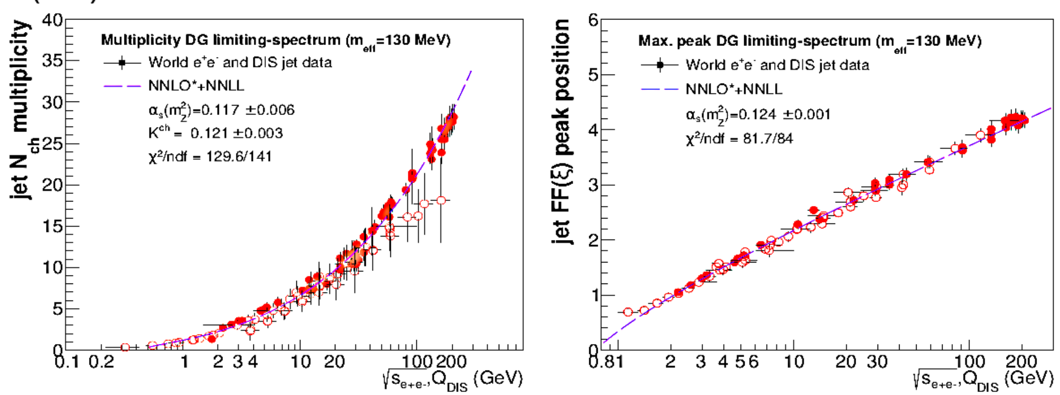
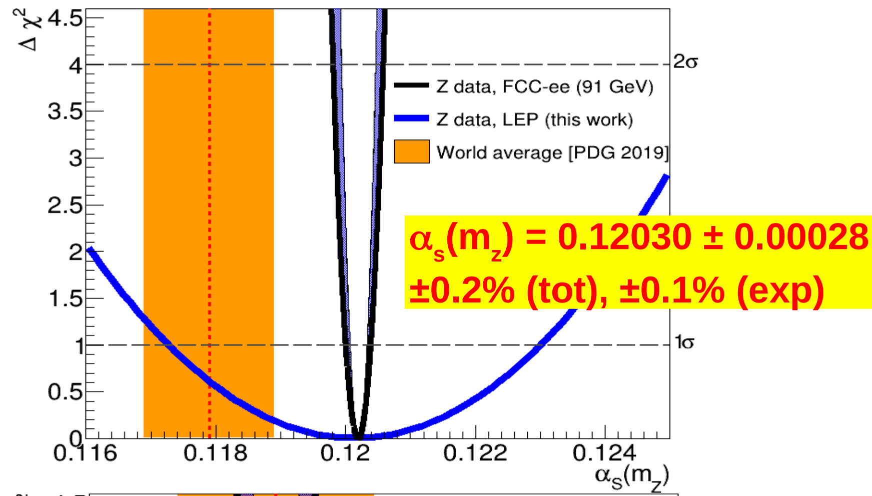


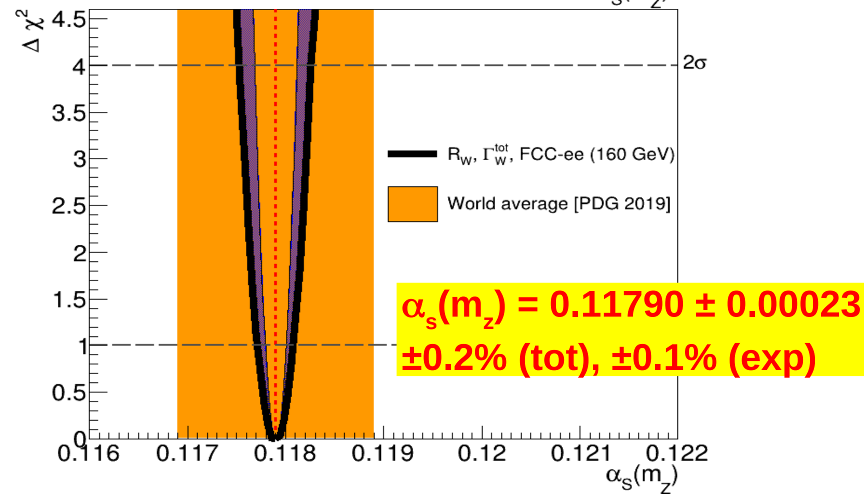
Figure 3: Energy evolution of the charged-hadron multiplicity (left) and of the FF peak position (right) measured in e^+e^- and DIS data fitted to the NNLO*+NNLL predictions. The obtained $\mathcal{K}_{ch}$ normalization constant, individual NNLO* $\alpha_s(m_Z)$ values, and the goodness-of-fit per degree-of-freedom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

α_s at future e^+e^- colliders (summary)

- World-average QCD coupling at $N^{2,3}LO$ today:
  - *Determined from 7 observables with combined 0.85% uncertainty (least well-known gauge coupling).*
  - *Impacts all LHC QCD x-sections & decays.*
  - *Role beyond SM: GUT, EWK vacuum stability, New colored sectors?*
- e^+e^- extractions:
  - Hadronic tau decays: ±1% TH
  - Event shapes, jet rates: ±1% TH
  - Z&W pseudo-observ.: ±0.1% TH
- State-of-the-art Z, W extractions:
  - Z boson: New fit with high-order EW corrections + updated LEP data: ~2.3% (exp.) uncertainty today.
  - W boson: New N^3LO fit to Γ_W, R_W ~27% (exp.) uncertainty today.

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





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

QCD physics at future e^+e^- machines

(1) QCD coupling

(2) Jet substructure & flavour tagging

(3) Parton shower & Non-perturbative QCD

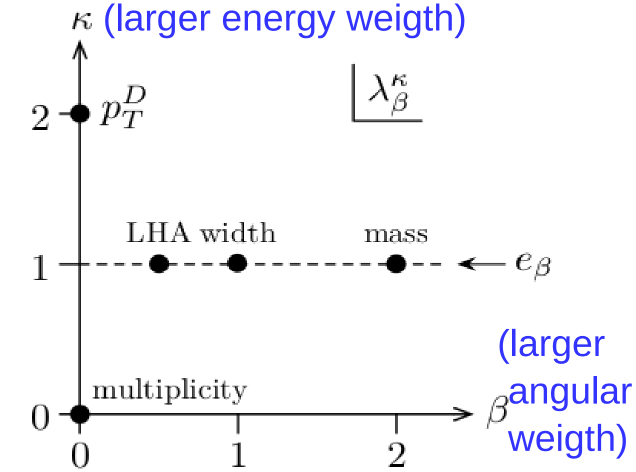
NOTE: Only UNIQUE QCD measurements, inaccessible at any current machine, are covered.

Jet substructure & flavour tagging

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

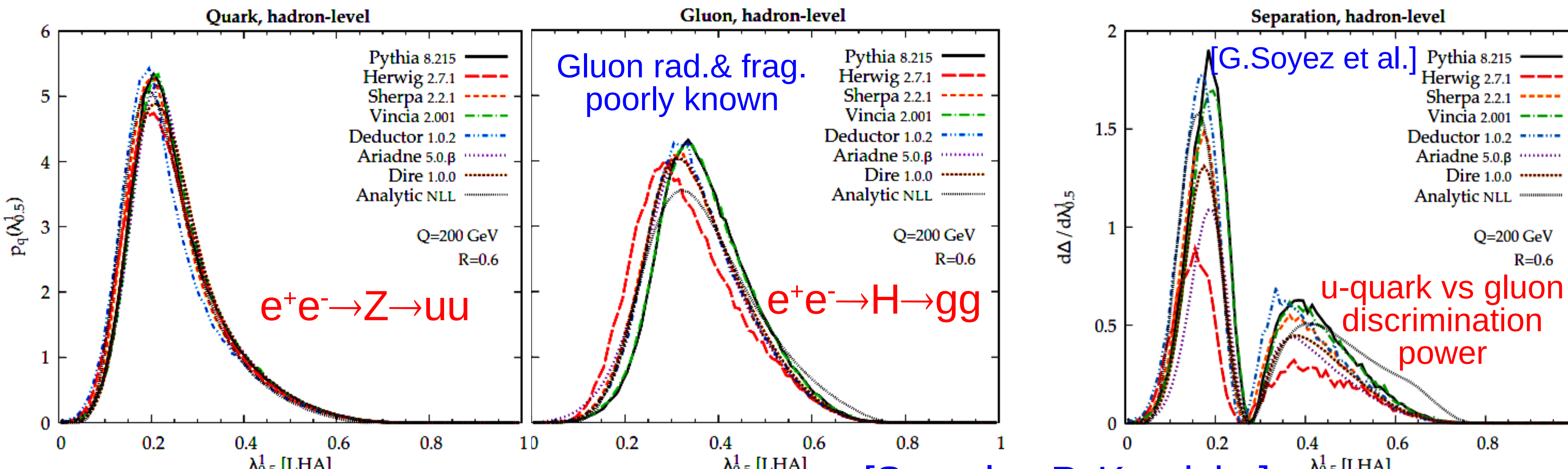
$$\lambda_\beta^\kappa = \sum_{i\in \text{jet}} z_i^\kappa \theta_i^\beta ,$$

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



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

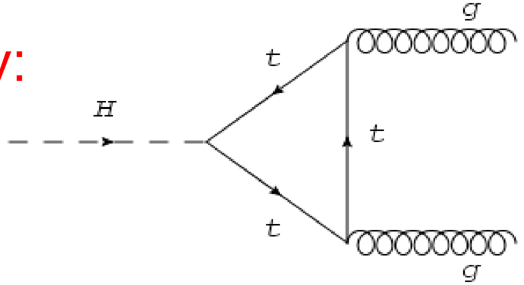
- "Sudakov"-safe variables of jet constituents: multiplicity, LHA, width/broadening, mass/thrust, C-parameter,...
- k=1: IRC-safe computable (N^nLO+N^nLL) via SCET (but uncertainties from non-pQCD effects)
- MC parton showers differ on gluon (less so quark) radiation patterns:



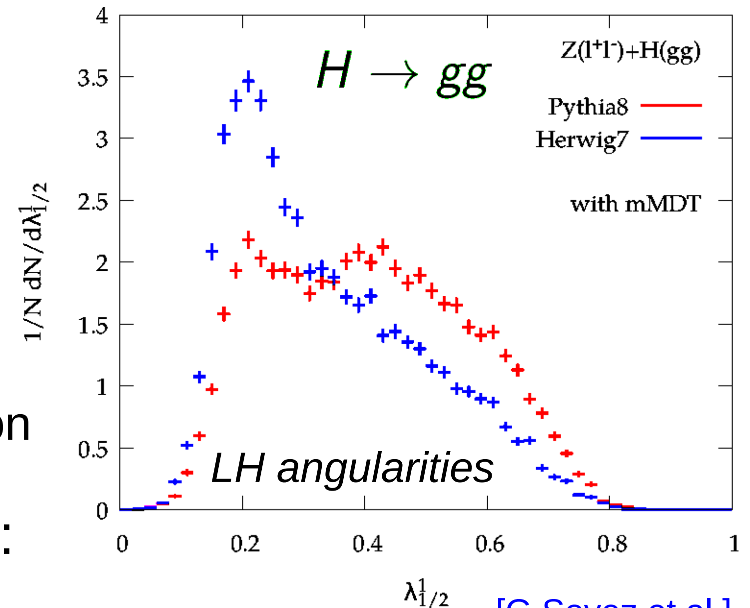
[See also P. Komiske]

High-precision gluon & quark jet studies

- Exploit FCC-ee H(gg) as a "pure gluon" factory: H→gg (BR~8% accurately known) provides 120.000 extra-clean digluon events.



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



[G.Soyez et al.]

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

[See also P. Komiske]

QCD physics at future e^+e^- machines

(1) QCD coupling

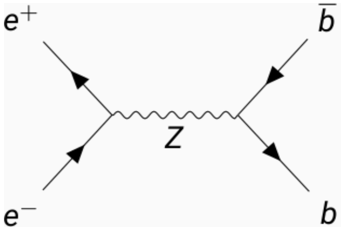
(2) Jet substructure & flavour tagging

(3) Parton shower & Non-perturbative QCD

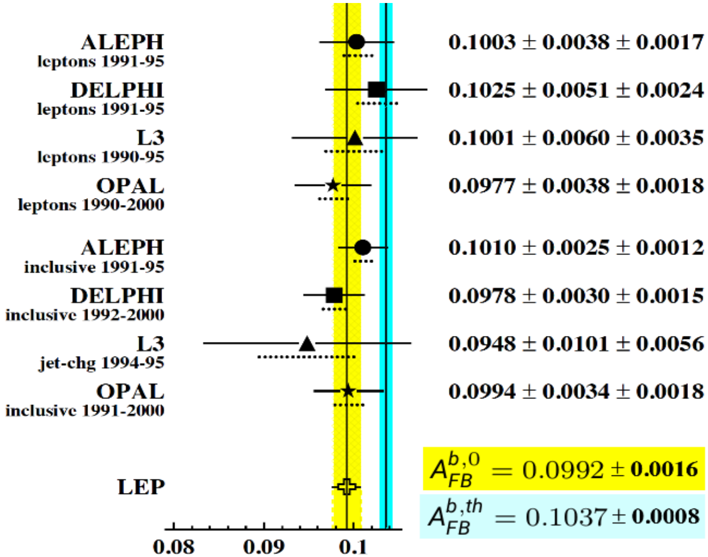
NOTE: Only UNIQUE QCD measurements, inaccessible at any current machine, are covered.

QCD uncertainties on EWK observables

- With $\times 10^5$ more Z's than LEP, EWK uncertainties at FCC-ee will be dominated by syst. (QCD). Example: $e^+e^- \rightarrow b\bar{b}$ forward–backward asymmetry
  - – 8 measurements at LEP: 4 lepton-based, 4 jet-charge-based
  - – Exp. observable with largest discrepancy today wrt. the SM: 2.8σ



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

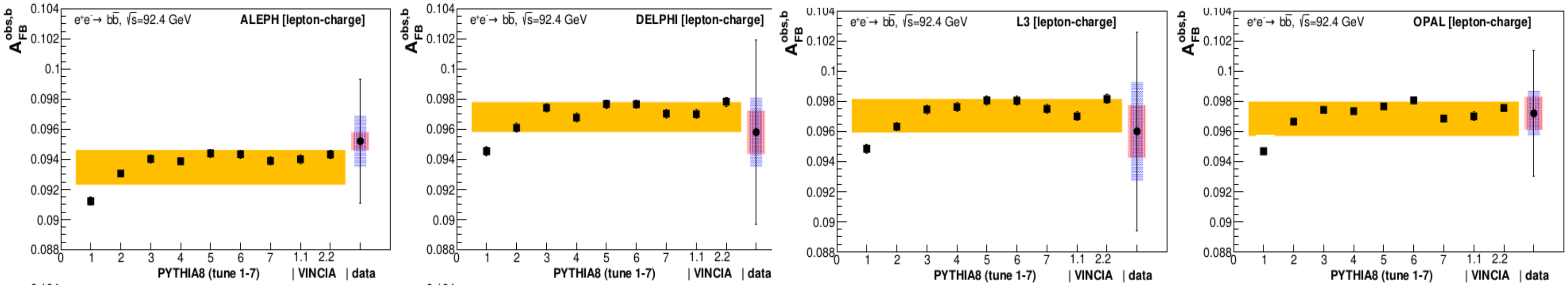


- Exp. Uncertainties: ~1.6%
  - – Statistical: ±1.5% (~0.05% at FCC-ee)
  - – Systematics: ±0.6% (QCD-related: ±0.4%)
- QCD effects on $A_{FB}^{0,b}$ (depending strongly on exp. selection procedure):
  - – Gluon splitting (TH control: α_s^2 corrections)
  - – Smearing of b-jet/thrust axis
  - – b and c radiation & fragmentation. B and D decay models.

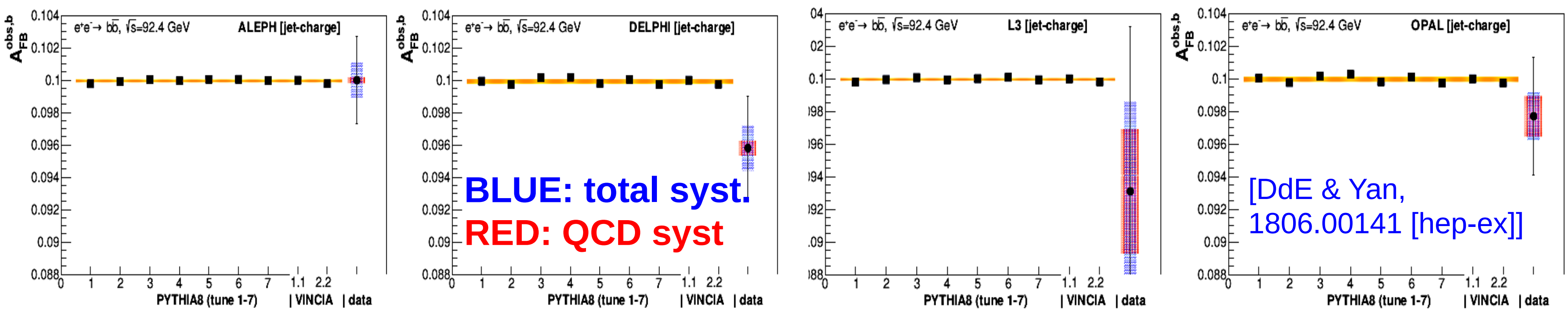
  [Uncertanties estimated by Abbaneo et al., EPJC 4 (1998)]
- We have revisited the impact of QCD effects on $A_{FB}^{0,b}$ implementing original analyses in up-to-date retuned parton-shower+hadronization MCs

Reduced QCD uncertainties on A_{FB} at Z pole

- QCD uncertainties recomputed from PYTHIA8.226 (7 tunes) & VINCIA2.2
- $e^+e^- \to bb$ forward–backward asymmetry for lepton-based analyses:



- $e^+e^- \to bb$ forward–backward asymmetry for jet-charge-based analyses:



BLUE: total syst.
RED: QCD syst

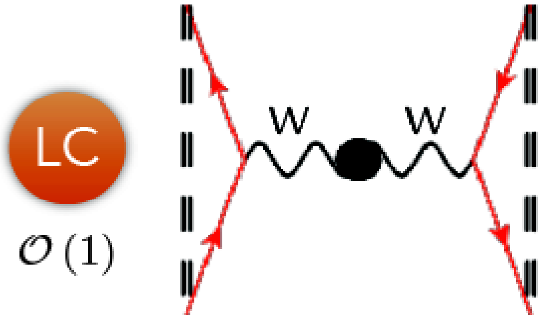
[DdE & Yan, 1806.00141 [hep-ex]]

- 2020 vs. 1998 parton shower+hadronization uncertainties:
  – Lepton-based: Consistent for ALEPH, slightly smaller for DELPHI, L3, OPAL.
  – Jet-charge-based: Much smaller for all experiments.
- Improved PS & non-pQCD tunes w/ e^+e^- data needed to reduce syst. uncert.

Colour reconnection

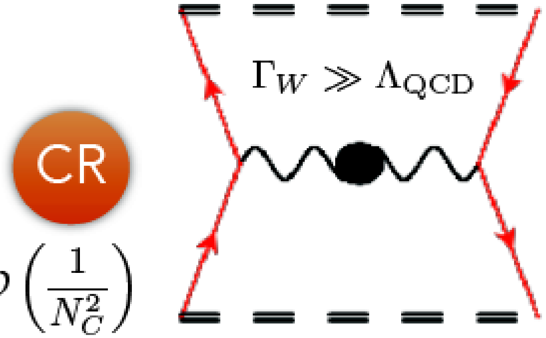
- Colour reconnection among partons is source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states. Especially in pp (MPI cross-talk).

  - CR impacts all FCC-ee multi-jet final-states (potentially shifted angular correlations): $e^+e^- \to WW(4j)$, Z(4j), ttbar, H(2j,4j) CP studies,… String-drag effect on W mass (hinted at LEP).



$\mathcal{O}(1)$

  - Exploit huge W stats (×10^4 LEP) to measure m_W leptonically & hadronically and constrain CR in hadronic WW.



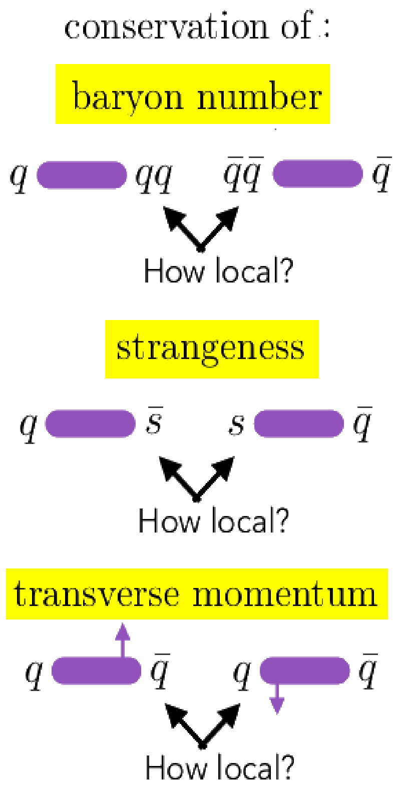
$\sim\mathcal{O}\left(\frac{1}{N_C^2}\right)$

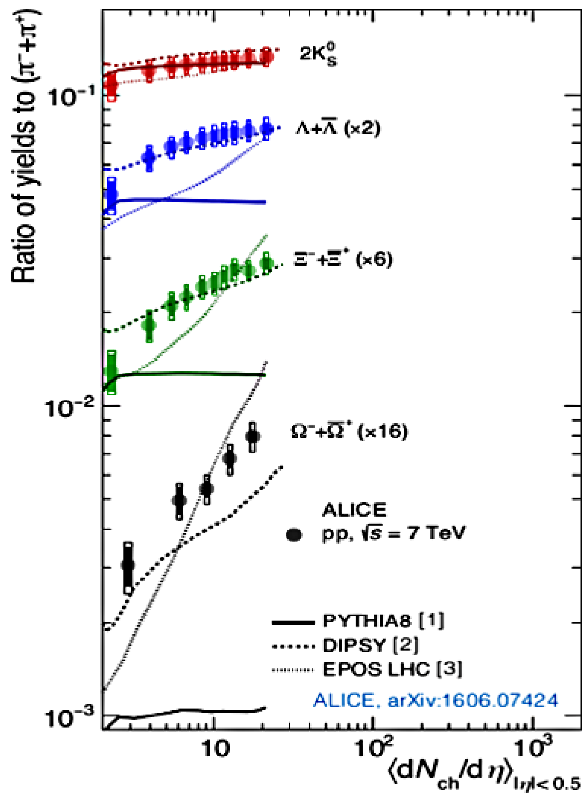
$\otimes$ kinematics

[See also P. Skands slides]

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: BoseEinstein, FermiDirac; momenta; space)
  - Bound state formation: Onia, multi-quark states, glueballs, ...





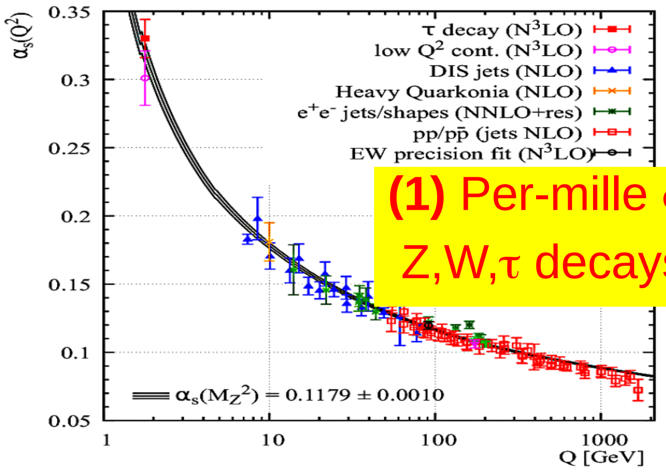
- ▶ Understand breakdown of universality of parton hadronization observed at LHC.

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

[See also P. Skands slides]

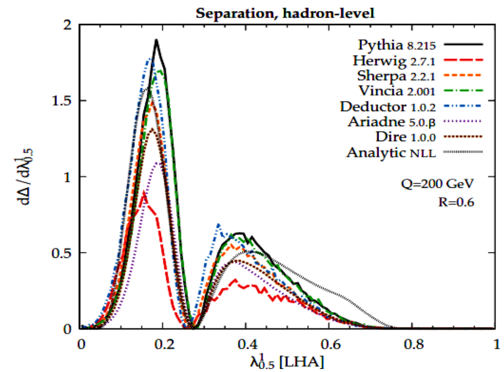
Summary: QCD at future e^+e^- colliders

- ☛ 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 (CEPC, ILC):

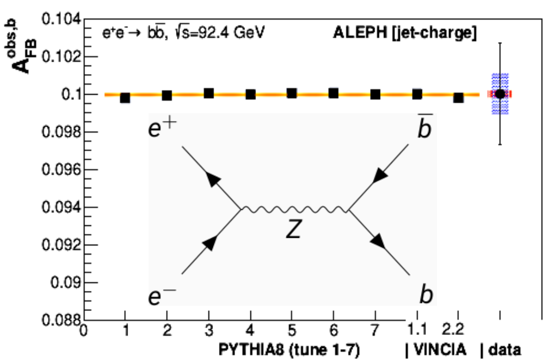


(1) Per-mille α_s via hadronic Z,W,τ decays, evt shapes...

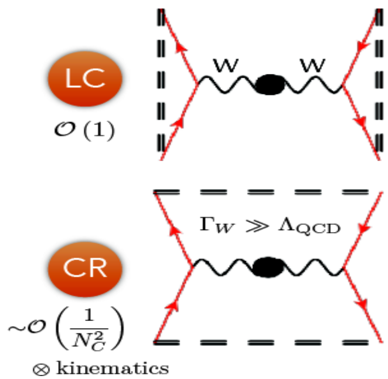
(2) N^{n}LO+N^{n}LL jet structure High g/q/Q discrimination



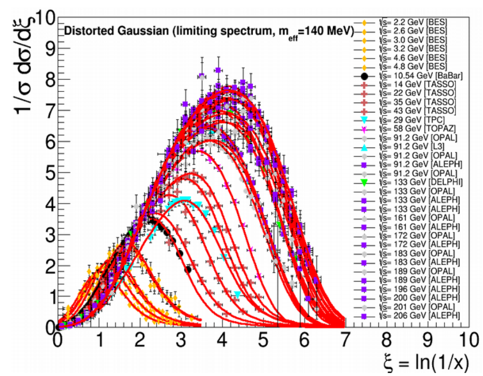
(3) Reduced PS+hadroniz. uncert. of EWK observ.

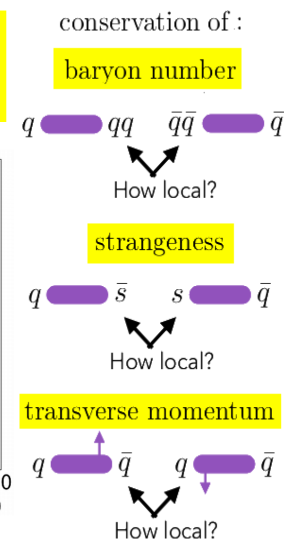


(4) <1% control of colour reconnection



(5) High-precision hadronization:

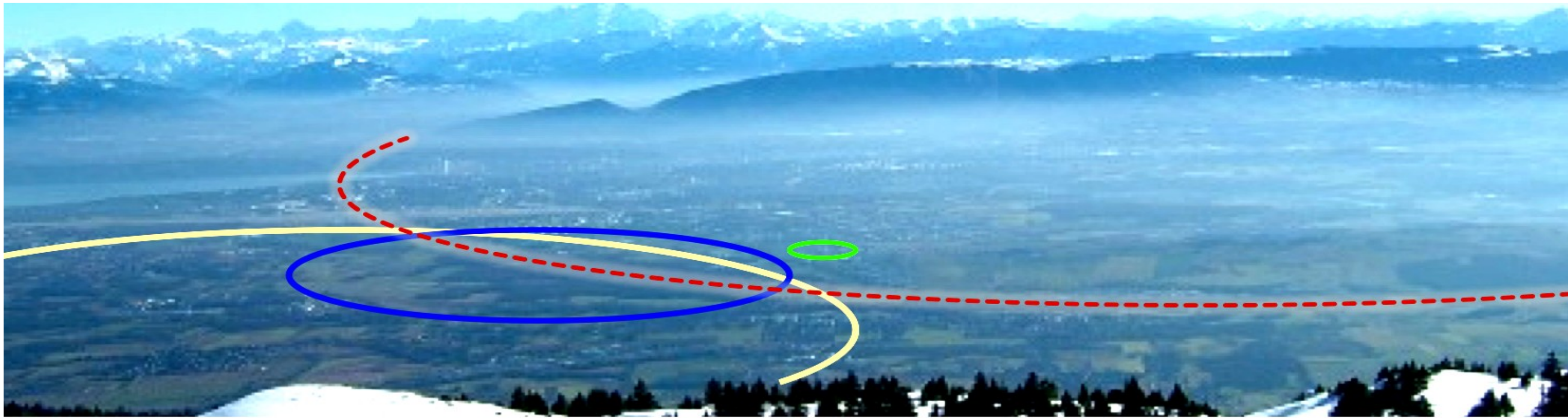




Backup slides

CERN FCC-ee project

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

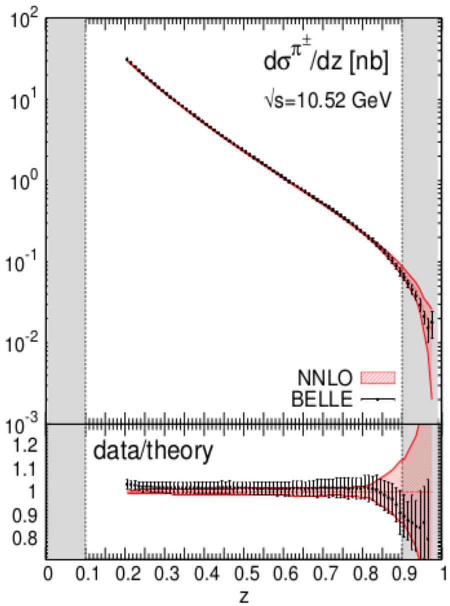


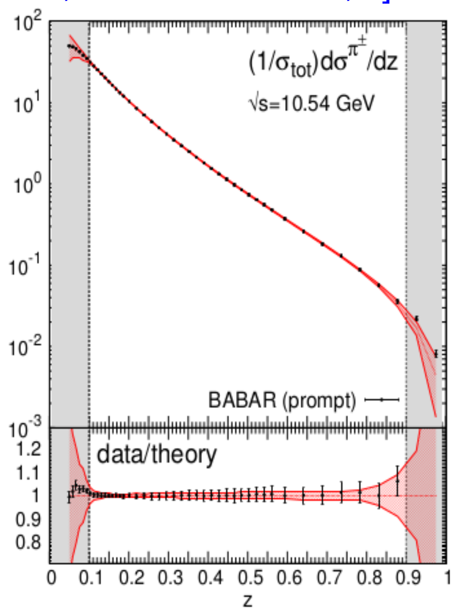
$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (WW→H)
σ	43 nb	290 ab	4 pb	200 fb	0.5 pb	25 fb
$\mathcal{L}$/IP (cm^{-2} s^{-1})	10^{36}	$5{\cdot}10^{35}$	10^{35}	$7\cdot10^{34}$	$1.5{\cdot}10^{34}$	$1.5{\cdot}10^{34}$
$\mathcal{L}_{\rm int}$ (ab^{-1}/yr, 2 IPs)	50	10	8	1.8	0.5	0.35
Events/year (2 IPs)	10^{12}	$3{\cdot}10^{3}$	$3{\cdot}10^{7}$	$3\cdot10^{5}$	$2.5{\cdot}10^{5}$	10^{4}
Years needed (2 IPs)	4	1.5	1	3	0.5	4
# of light-q jets/year:	$\mathcal{O}(10^{12})$	–	$\mathcal{O}(10^{7})$	$\mathcal{O}(10^{5})$	–	–
# of gluon-jets/year:	$\mathcal{O}(10^{11})$	$\mathcal{O}(10^{2})$	$\mathcal{O}(10^{6})$	$\mathcal{O}(10^{4})$	–	$\mathcal{O}(10^{3})$
# of heavy-Q jets/yr:	$\mathcal{O}(10^{12})$	$\mathcal{O}(10^{3})$	$\mathcal{O}(10^{7})$	$\mathcal{O}(10^{5})$	$\mathcal{O}(10^{5})$	$\mathcal{O}(10^{4})$

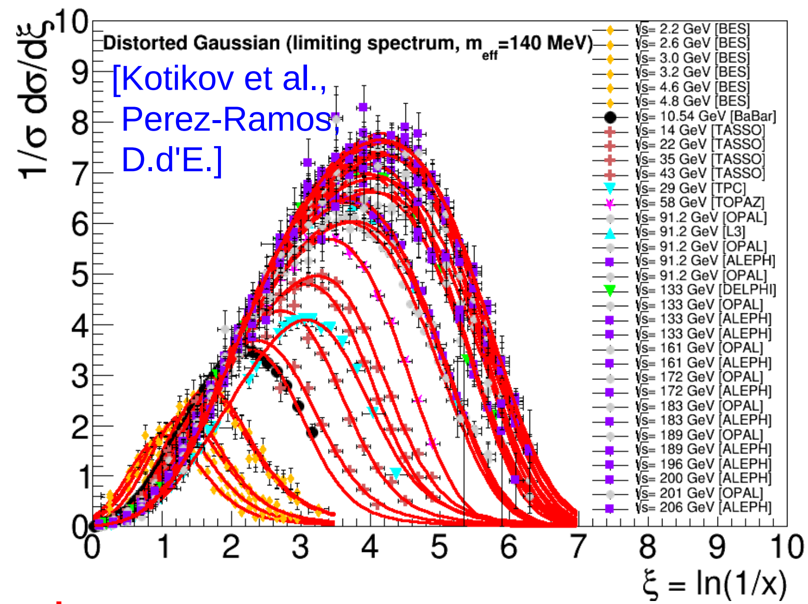
High-precision parton FFs

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

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







provide additional QCD coupling extractions:

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

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