

High-precision QCD physics at FCC-ee

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many thanks to Anthony Badea, David d'Enterria,
and Giovanni Stagnitto!



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INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES



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First things first: why QCD in e^+e^- ?

Lepton collider

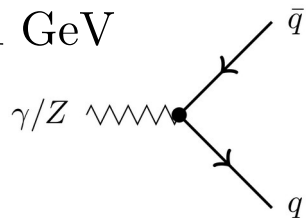
Clean point-like initial state

- no parton-distribution functions
- no pile-up
- no underlying event
- know initial state kinematics
→ constraints on final state
- QCD radiation only in the final state

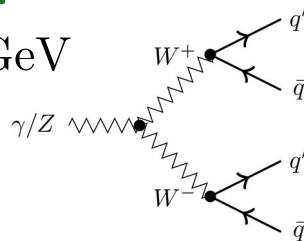
Hadronic final states from EW decays

→ **various flavour channels accessible**

$\sqrt{s} = 91 \text{ GeV}$



$\sqrt{s} = 160 \text{ GeV}$

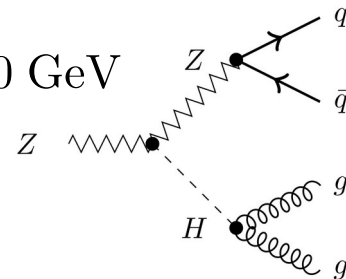


Hadron collider

Non-perturbative input:

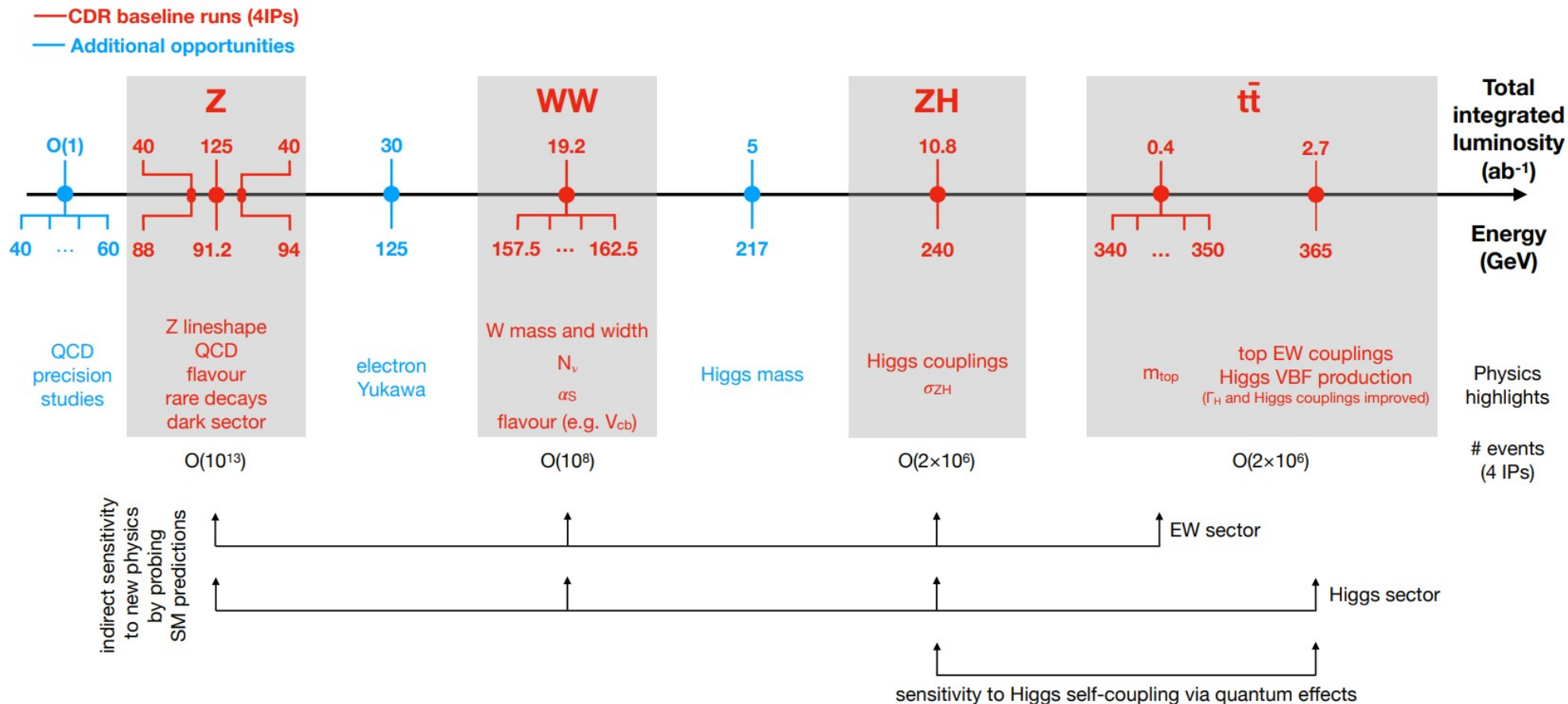
- PDFs
- ISR / color flow from IS/FS
- underlying event + O(100) Pile-up events
- jet energies only %-level accurate
- too messy for pre-mille level precision QCD

$\sqrt{s} = 240 \text{ GeV}$



FCC-ee Physics Runs Ordered by Energy

[2505.00272]



Physics motivation for QCD at FCC-ee

Reason 1: QCD is a systematic for precision EW studies

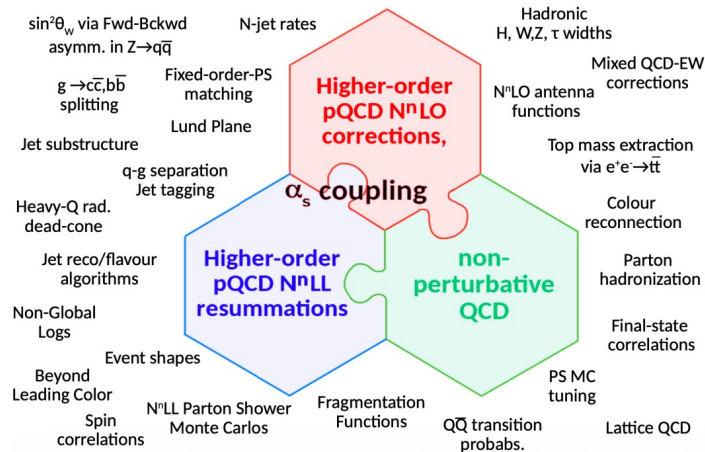
→ the vast majority of Z /W /H/top decays lead to hadronic final states

Decay	BR	#decays @ FCC-ee
Z → hadrons	~70%	$\sim 4 \times 10^{12}$
W → qq'	~67%	$\sim 3 \times 10^8$
H → hadrons	~80%	$\sim 2 \times 10^5$

+ every $t \rightarrow bW$ contains a b-jet

stress-tests of the SM require control of QCD:

- Radiation
- Hadronization
- Colour reconnection
- α_s
- Quark masses



drawing by D. d'Enterria

Physics motivation for QCD at FCC-ee

Reason 2: QCD is a signal

Precision studies of QCD radiation

- $O(10^{12})$ $Z \rightarrow q\bar{q}g$ decays, quark-flavour-tagged
an unparalleled sample to study perturbative and non-perturbative QCD
- Statistical uncertainties $O(10^{-6})$: negligible for most observables
 $\Rightarrow$ FCC-ee will provide the most precise QCD measurements ever

Non-perturbative QCD

- Multiple energy points (Z , WW , ZH , $t\bar{t}$ + options below the Z):
 $\rightarrow$ a built-in lever arm in Q to separate perturbative from non-perturbative physics

Parameter measurements

$\rightarrow \alpha_s(m_Z^2)$ from 0.8% today to the per-mille level

$10^6 \times$ LEP statistics: a new challenge for both experiments and theory

Precision strong coupling determinations

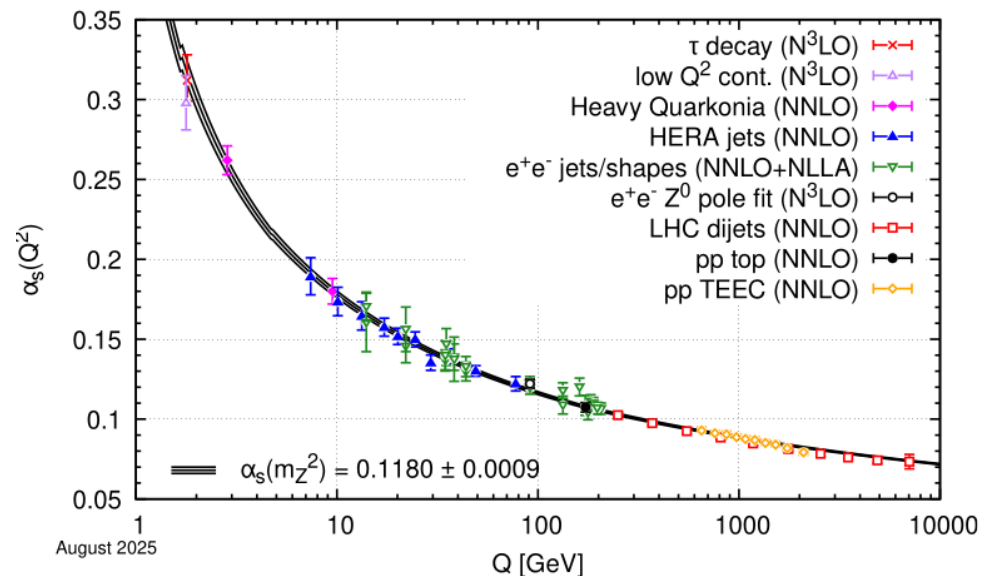
α_s is the only free parameter of QCD

its running beautifully predicted by pQCD

World average (PDG 2025): $\alpha_s(m_Z^2) = 0.1180 \pm 0.0009$

(0.8%) the least precisely known coupling of the SM

(cf. $\alpha_{\text{QED}} : 10^{-10}$; $G_F : 10^{-7}$)

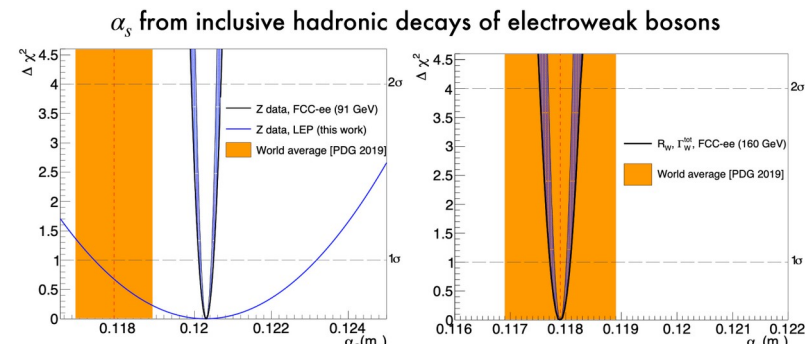


Physics implications of a precise strong coupling

- reduction of parameteric uncertainties: e.g. Higgs width, EW precision fits
- improves bounds set by many BSM searches via SM background predictions
- interpretation of m_t for vacuum stability and GUT-scale extrapolations

Different strong coupling determination methods

Category	present $\alpha_S(m_Z^2) (\times 10^4)$ value $\pm$ uncertainty	FCC-ee Stat. Syst.	Extraction method Theory developments needed
Z hadronic decays	1208 ± 28	0.1 1	Combined $R_\ell^Z, \Gamma_Z, \sigma_{\text{had}}^0$ fit $\mathcal{O}(\alpha_S^5), \mathcal{O}(\alpha^3), \mathcal{O}(\alpha_S, \alpha^3), \mathcal{O}(\alpha_S^2, \alpha^2)$ corr.
W hadronic decays	1070 ± 350	2 2	Combined R_ℓ^W, Γ_W fit $\mathcal{O}(\alpha_S^5), \mathcal{O}(\alpha^2), \mathcal{O}(\alpha^3), \mathcal{O}(\alpha_S, \alpha^3), \mathcal{O}(\alpha_S^2, \alpha^2)$ corr.
τ hadronic decays	1178 ± 19	$\ll 1$ < 10	Combined $\Gamma^{\tau, \text{had}}$ and τ lifetime fit $\mathcal{O}(\alpha_S^5)$, hadronisation corrections
Event shapes & jet rates	1171 ± 31	$\ll 1$ < 10	Combination of event shapes and jet rates $\mathcal{O}(\alpha_S^4)$, hadronisation corrections



All methods are systematic dominated:

- Theory and input variables ($\alpha_{\text{QED}}, m_W, m_Z, |V_{cs}|, |V_{cd}|$)
- QCD and mixed QCDxEW corrections for EW pseudo obs ($\Gamma_Z, R_Z^l, \sigma_{\text{had}}^0$)
- Advantage: non-perturbative effects relatively small (inclusive observables)
- WW channel becomes competitive at FCC-ee
- Scale complementary through tau decays

Challenges: event shapes and alphaS

Long standing puzzle:

some event shape extractions systematically lower then PDG value

[1006.3080] [2412.15164] vs [2301.03607] [2502.01570]

What is the reason? data? Hadronization? PQCD unc.?

→ Open question under active debate. (see Tue's discussion)

EXP example: re-analysis of LEP data

→ **amazing opportunity to test FCC analyses already now!**

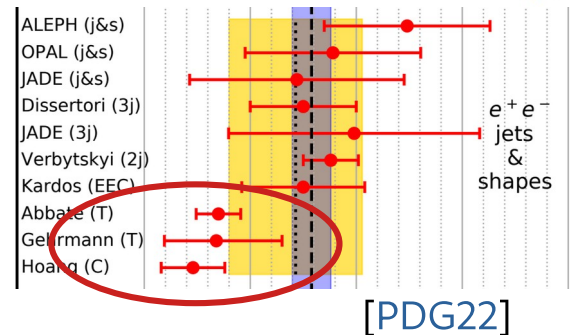
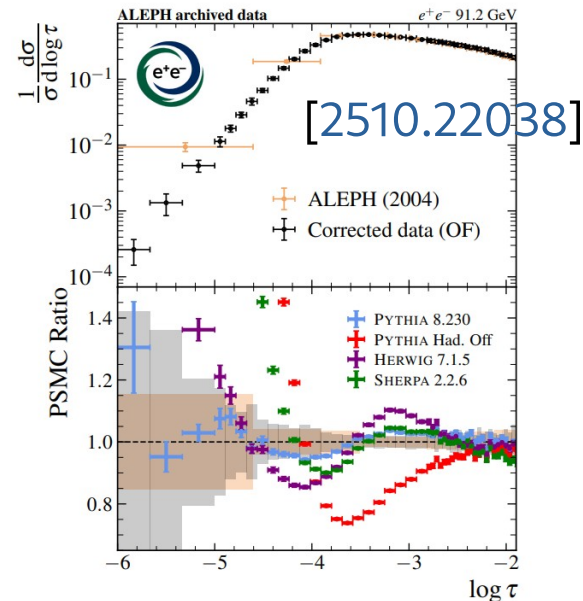
TH example: non-perturbative effects

$$\frac{d\sigma}{dx} \approx \frac{d\sigma^{\text{pert}}}{dx} + \frac{d\sigma^{\text{non-pert}}}{dx} = \frac{d\sigma^{\text{pert}}}{dx} + \Omega(0, x) \frac{\Lambda}{Q} + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$$

different parameterization of linear power corrections

(e.g. dispersive model vs shape functions) lead to different results

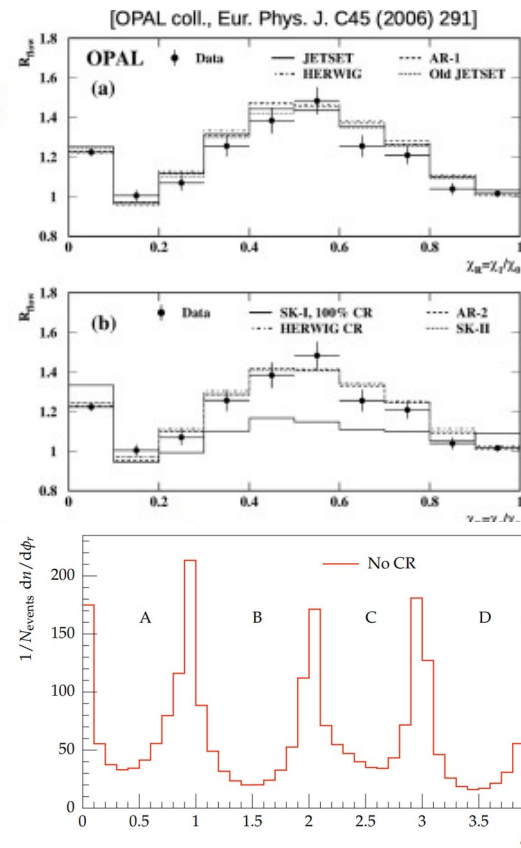
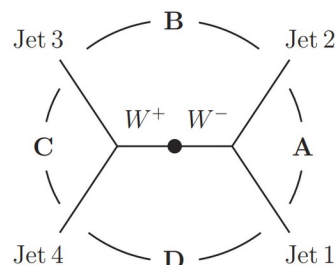
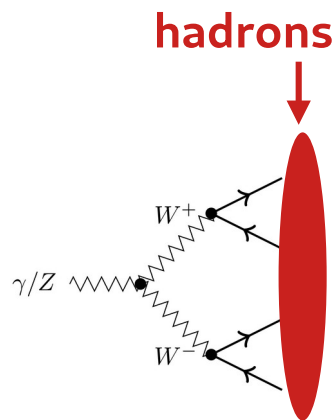
→ **FCC-ee runs at different energy could resolve these issues.**



Challenges: non-perturbative effects in MCs

Example: color reconnections in WW

- doubly hadronic decays allow for color flow between Ws
- implications for color reconnection and hadronization models
- important for m_W measurements from 4q final states
(~ 35 vs 0.4 MeV expected unc.@FCC-ee)
- expect 10^8 fully hadronic WW @ FCC-ee
→ Opportunity to discriminate different models
- also important for top-decays in $e^+e^- \rightarrow t\bar{t}$



[1506.09085]

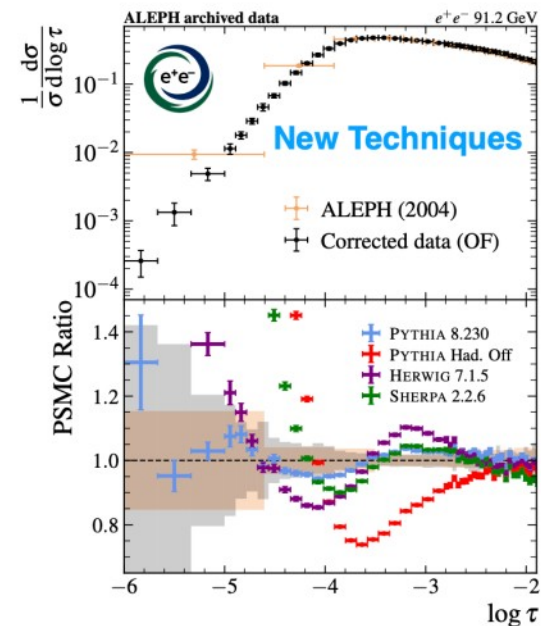
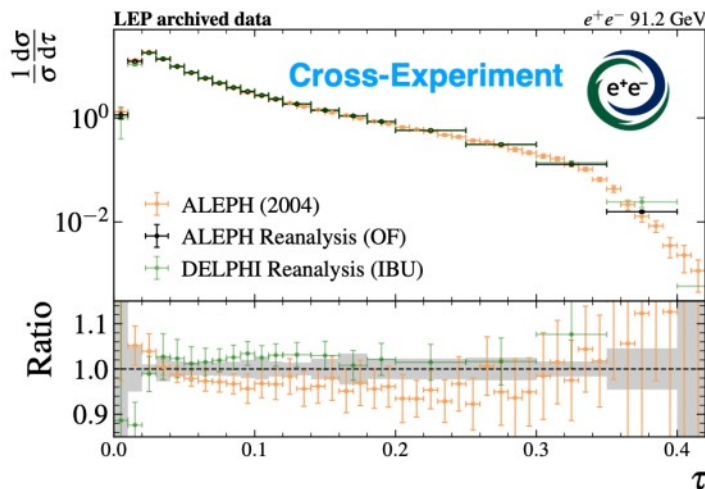
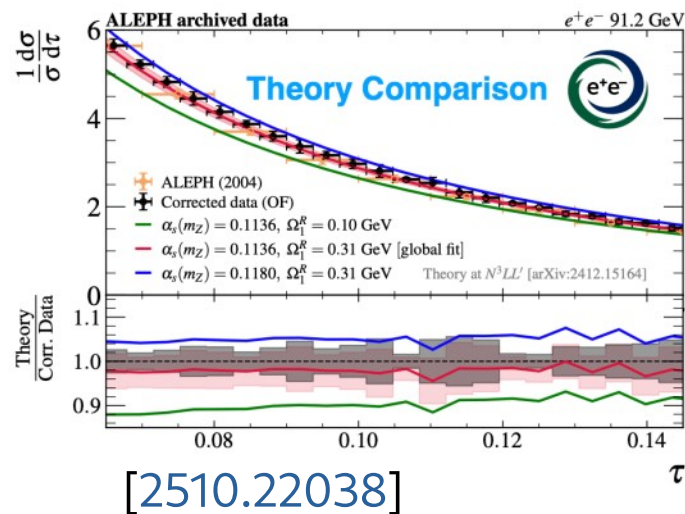
A glimpse into the future: re-analysis of LEP data

e⁺e⁻ alliance: <https://ee-alliance.org>



[see also talk by Yi Chen]

Thrust distribution



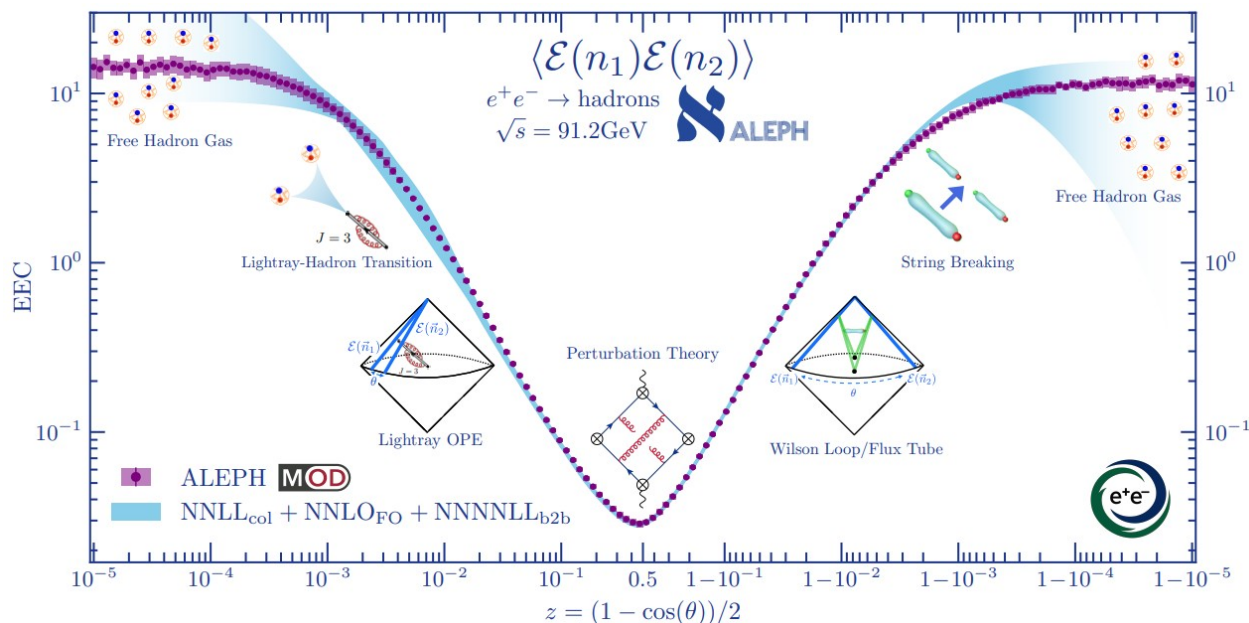
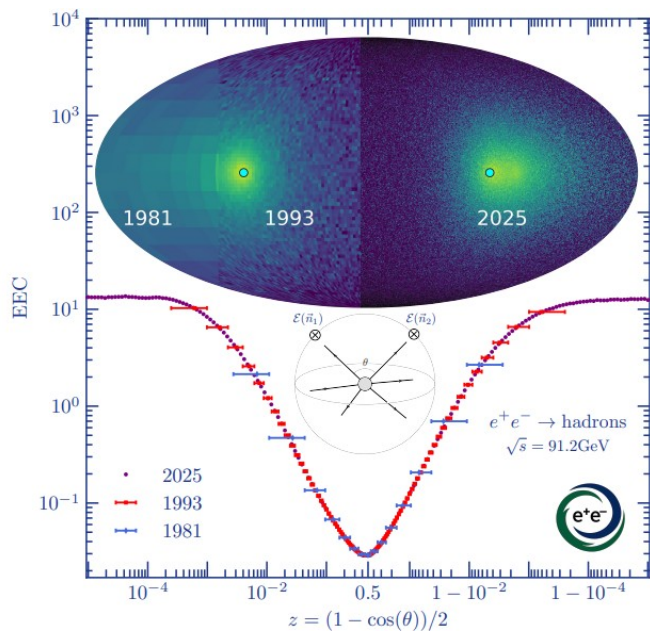
A glimpse into the future: re-analysis of LEP data

[see also Wouter's talk]

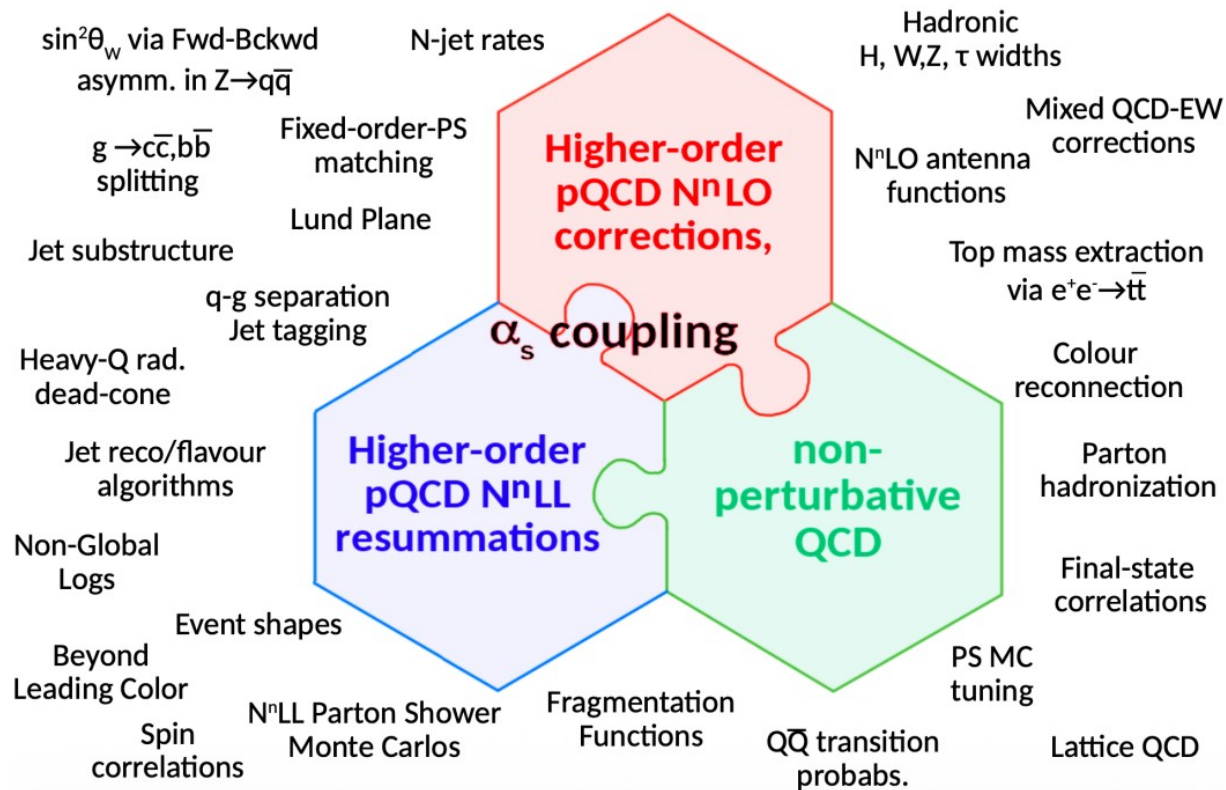
Energy-energy correlators

[2511.00149]

$$\text{EEC}(z) = \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta \left(z - \frac{1 - \cos \theta_{ij}}{2} \right)$$



Summary: FCC-ee is a precision QCD machine



drawing by D. d'Enterria

+ photon induced QCD studies
→ see Peter's talk on Monday

FCC-PED QCD and photon-photon group

Interested? Join the **fcc-ped-physicsgroup-qcd** on <https://groups-portal.web.cern.ch>

Activities (indico category <https://indico.cern.ch/category/5662/>):

- Topical meetings:
 - **just yesterday**: topical meeting on **colour reconnection in ee $\rightarrow$ WW $\rightarrow$ 4q**
 - **Last week of October (26-30)**: meeting on **gamma-gamma physics**
Talks by Savannah Clawson and Peter Meinzinger
 - **Third week of November (16-20)**: meeting on **alphas from event shapes**
talk by Gherardo Vita on Task Force <https://arxiv.org/abs/2609.03002v1>
 - (likely) meeting in December, topic TBD
- Joint Precision, MC, Top, EW, QCD in-person meeting **“Many facets of precision”**
 - **8-12 February**: <https://indico.cern.ch/event/1727272>
 - We will have 1.5 days of discussion on QCD-related topics. We are still drafting the agenda for the QCD sessions. Suggestions for topics are welcome, just let us know.