FUTURE CIRCULAR COLLIDER

# High precision QCD physics at FCC-ee

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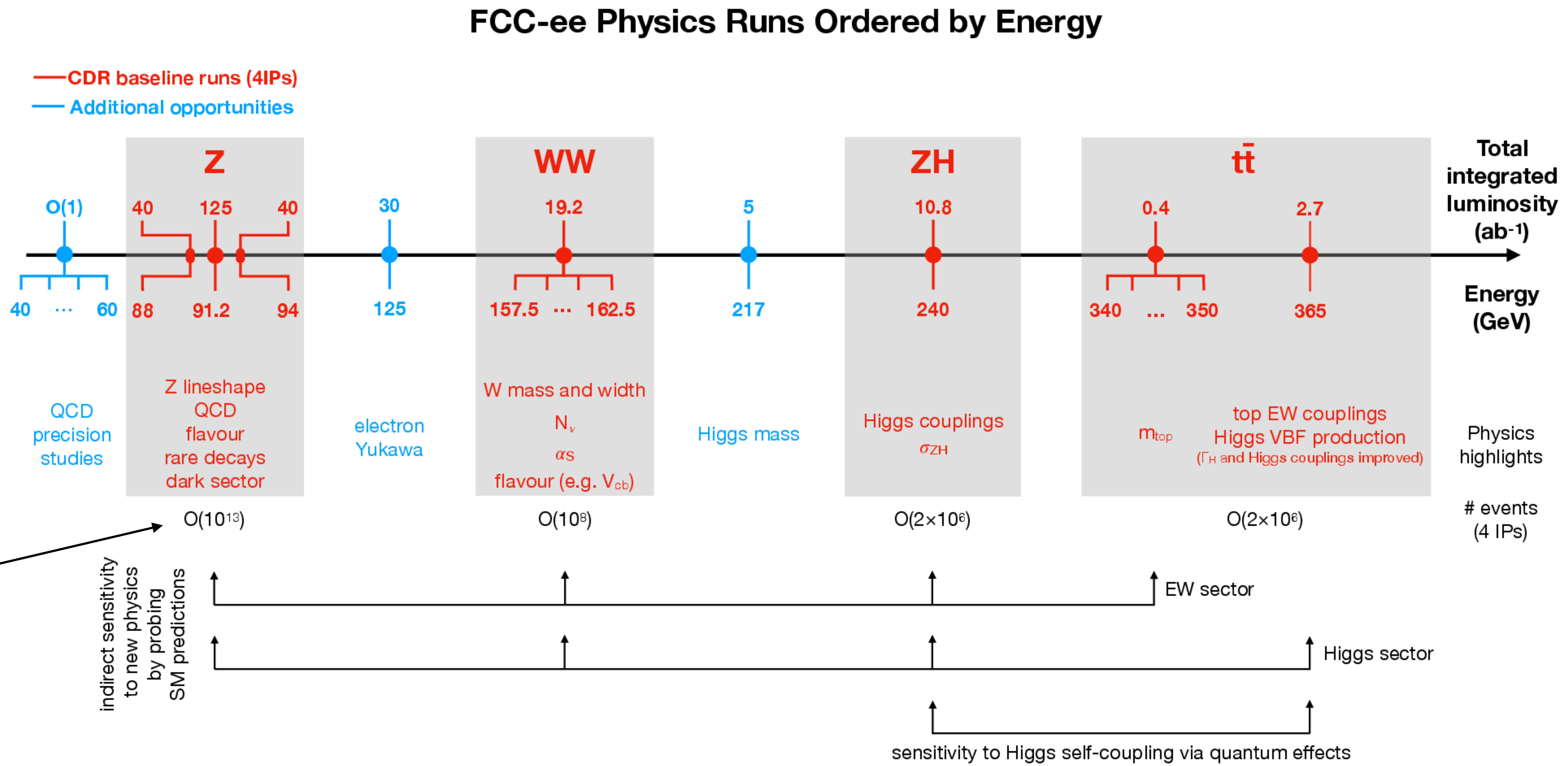
LPNHE PARIS

SORBONNE UNIVERSITÉ

# FCC-ee overview

- 91km circumference, $e^+e^-$ collisions at 4 IP, **ambitious physics program**




$10^6 \times$ LEP

# QCD at FCC-ee

## What is needed

- **Precise understanding of strong interaction** crucial to exploit broad range of SM measurement and BSM searches
  - **Precise determination of** $\alpha_S$: prediction of all ee XS and decays
  - **Accurate pQCD calculation** (NxLO, NxLL): prediction precision, extraction of SM quantities from data
  - **Heavy/light quark/gluon separation**: ex: Higgs Yukawa couplings to q and g
  - **NP dynamics** (colour reconnection, hadronisation): impact all hadronic final states

## What the FCC-ee offers

- **Very high luminosity** across **wide range of energy scales**
- **Clean, controlled, well-defined setup:**
  - No PDF, no MPI, no beam remnants; uncoloured initial state
    → Kinematically constrained initial and final states
  - QCD radiations only in final state
  - Well separated jets, well defined parton flavour

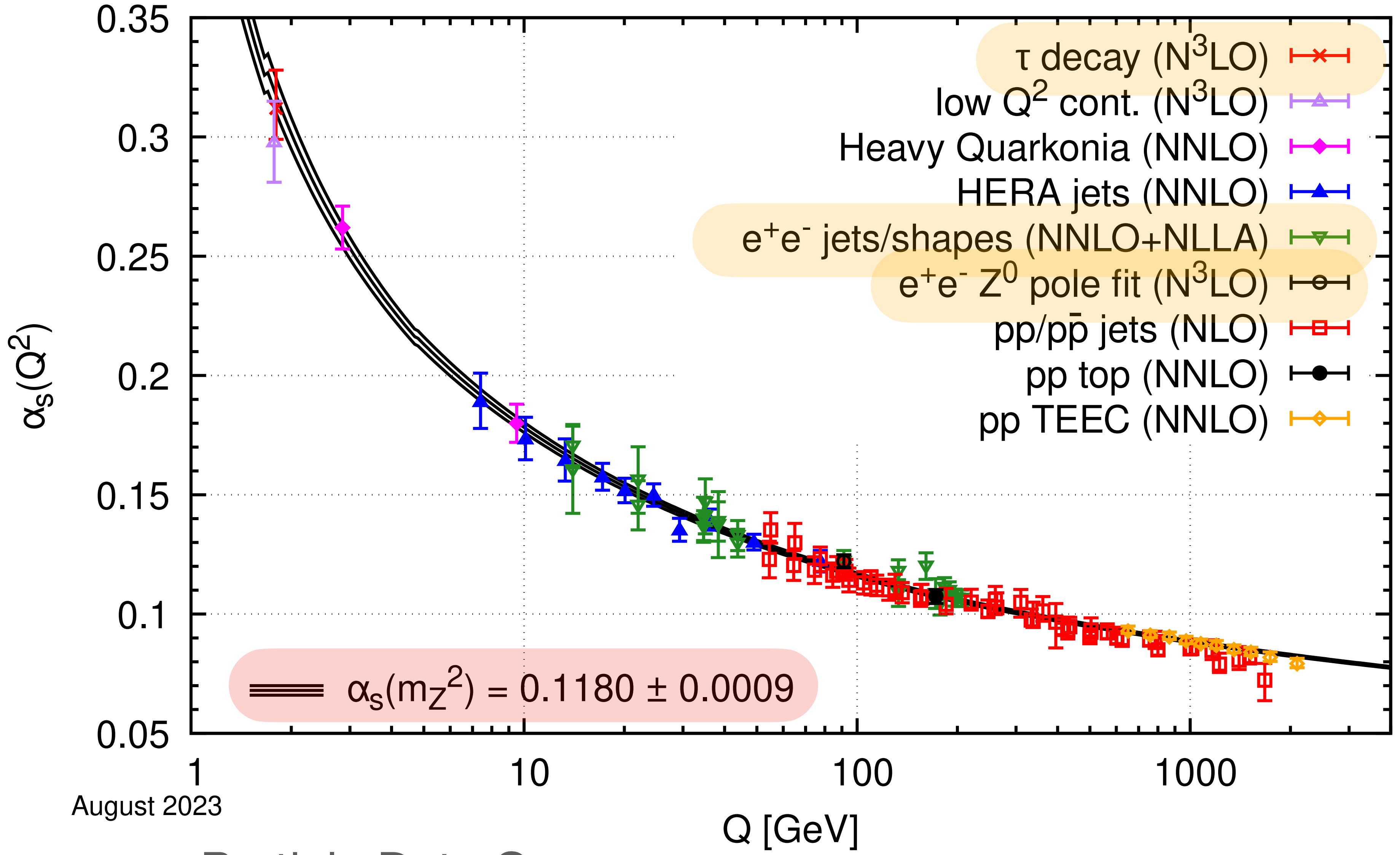
→ Enables **very high-precision measurements**

# Outline

- **$\alpha_S$ determination at FCC-ee**
  - From Z, W, $\tau$ hadronic decays
- **Studies of parton radiation and jet properties**
  - Jet tagging
  - Jet substructure
- **Non-perturbative QCD**
  - Colour reconnection
  - Hadronisation

# $\alpha_S$ determination

- Least precisely known coupling, limits the accuracy of QCD predictions
- Current world average determined with **0.8% uncertainty** from combination of several measurements, **some of them from ee collisions**
- At FCC-ee: extraction from **Z, W, $\tau$ hadronic decays, event shapes and jet rates**



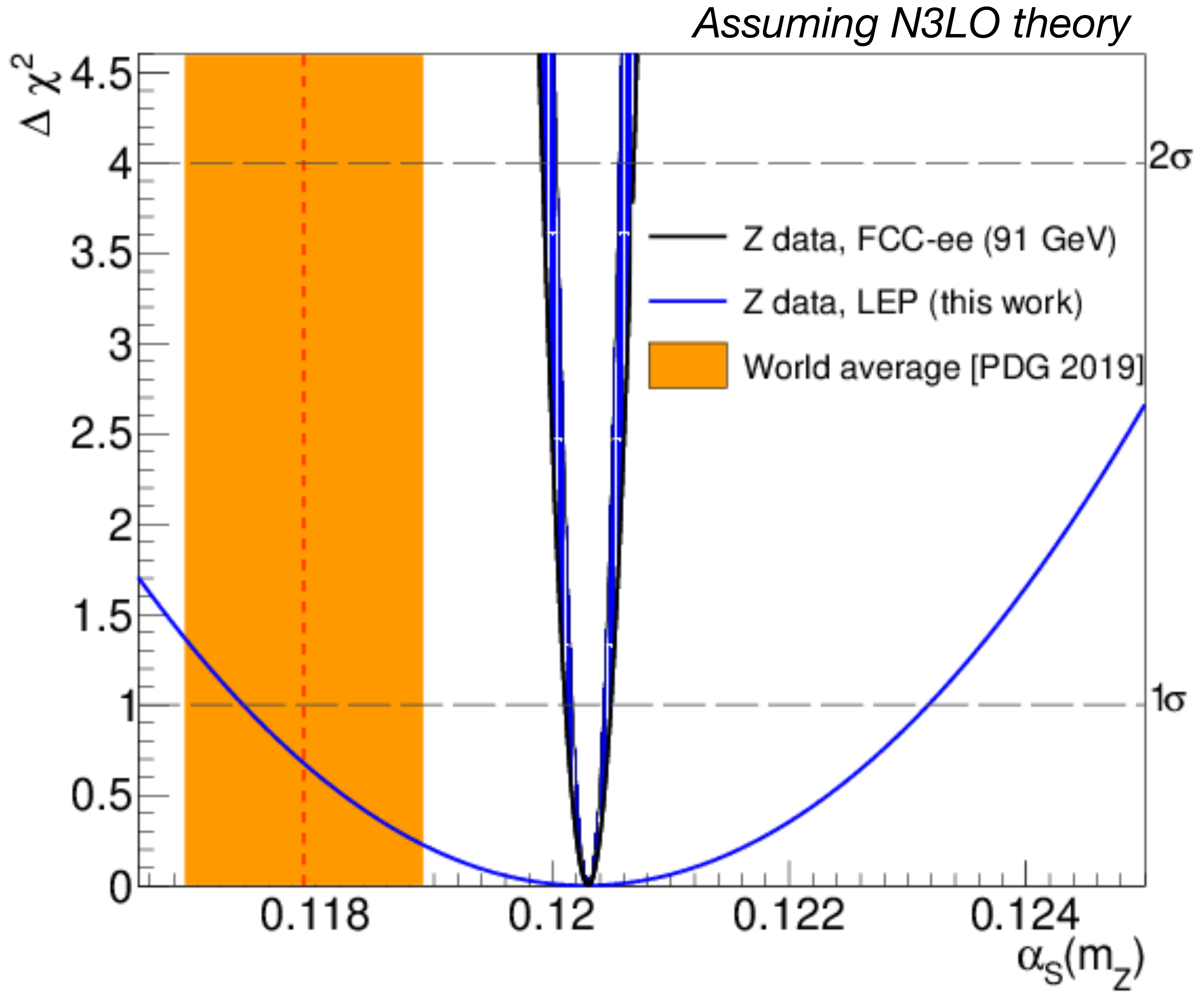

Particle Data Group

| Category | present $\alpha_S(m_Z^2)$ ($\times 10^4$) value $\pm$ uncertainty | FCC-ee Stat. | FCC-ee Syst. | Extraction method / Theory developments needed |
|---|---|---|---|---|
| Z hadronic decays | 1 208 $\pm$ 28 | 0.1 | 1 | Combined $R_\ell^Z$, $\Gamma_Z$, $\sigma^0_{had}$ fit<br>$\mathcal{O}(\alpha_S^5)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_S, \alpha^3)$, $\mathcal{O}(\alpha_S^2, \alpha^2)$ corrs. |
| W hadronic decays | 1 070 $\pm$ 350 | 2 | 2 | Combined $R_\ell^W$, $\Gamma_W$ fit<br>$\mathcal{O}(\alpha_S^5)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_S, \alpha^3)$, $\mathcal{O}(\alpha_S^2, \alpha^2)$ corrs. |
| $\tau$ hadronic decays | 1 178 $\pm$ 19 | $\ll$1 | <10 | Combined $\Gamma^{\tau,had}$ and τ lifetime fit<br>$\mathcal{O}(\alpha_S^5)$, hadronisation corrections |
| Event shapes & jet rates | 1 171 $\pm$ 31 | $\ll$1 | <10 | Combination of event shapes and jet rates<br>$\mathcal{O}(\alpha_S^4)$, hadronisation corrections |

QCD at FCC-ee, 2025

# $\alpha_S$ from Z hadronic decays

- **Combined fit at N3LO** of Z boson total width $\Gamma_Z$ ratio of hadronic/leptonic branching fraction $R_l^Z$ total hadronic XS at the resonance peak $\sigma_{had}^0$
- Benefit from **precise measurements, very high accuracy for theoretical prediction** (suppressed NP effects thanks to large energy scale)




Projected reduction of fit uncertainty, 2005.04545

| Observable | present value | ± | uncert. | FCC-ee **Stat.** | FCC-ee Syst. | Measurement method(s) leading uncertainty |
|---|---|---|---|---|---|---|
| $m_Z$ (keV) | 91 187 600 | ± | 2000 | **4** | 100 | Z lineshape scan<br>Beam energy calibration |
| $\Gamma_Z$ (keV) | 2 495 500 | ± | 2300 | **4** | 12 | Z lineshape scan<br>Beam energy calibration |
| $R_\ell^Z$ ($\times10^3$) | 20 767 | ± | 25 | **0.05** | 0.05 | Ratio of hadronic to leptonic decays<br>Acceptance for leptons |
| $\sigma^0_{had}$ ($\times10^3$) (nb) | 41 480.2 | ± | 32.5 | **0.03** | 0.8 | Peak hadronic cross section<br>Luminosity measurement |

QCD physics at FCC-ee, 2025

**Total exp unc on $\alpha_S$ ~0.1%**

Theory calculations needed with **factors of x4** better precision ($\alpha_S^5, \alpha^3, \alpha_S\alpha^3, \alpha\alpha_S^2$ corrections)

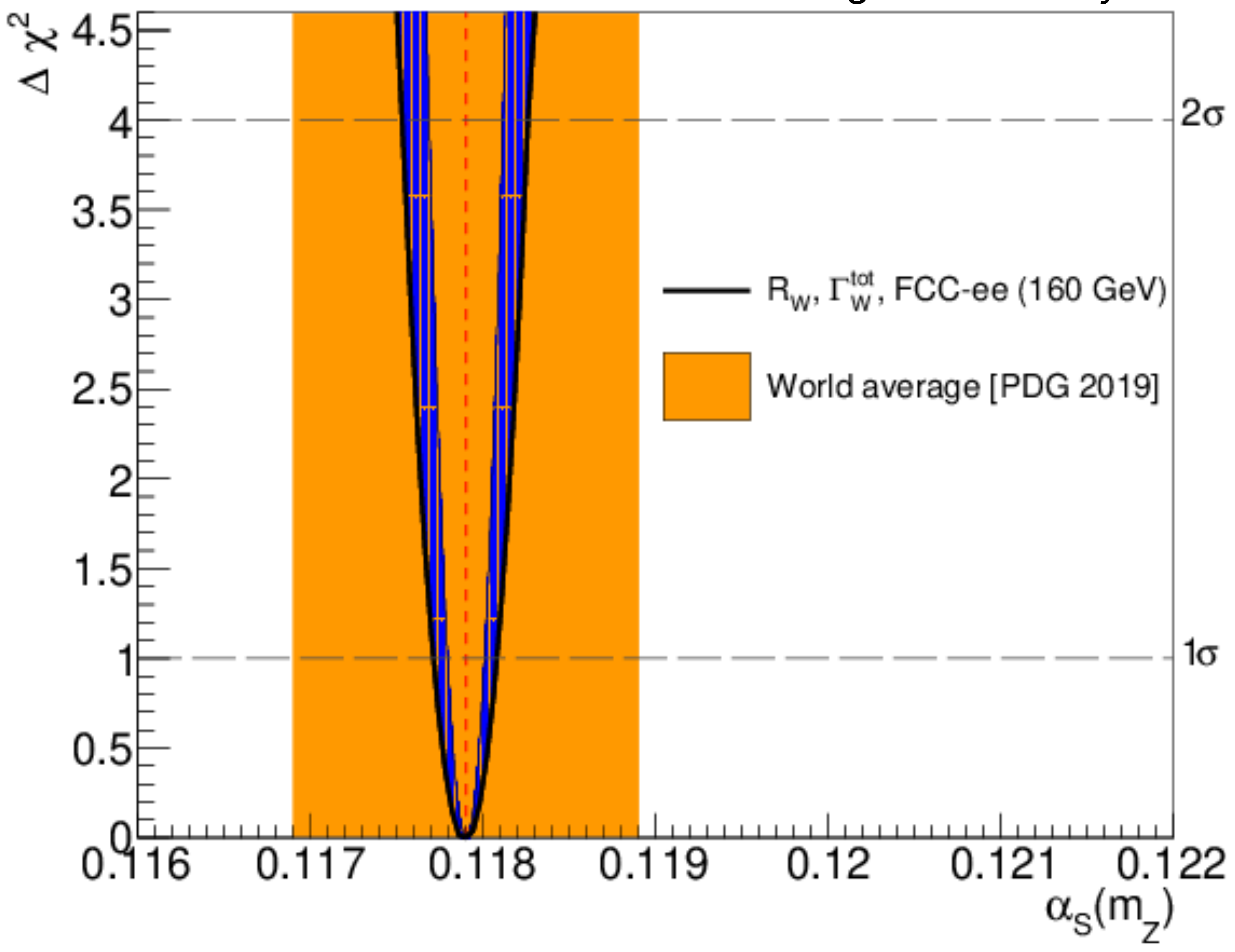
# $\alpha_S$ from W hadronic decays

- **Combined fit at N3LO** of W boson total width $\Gamma_W$ ratio of hadronic/leptonic branching fraction $R_l^W$
- Benefit from **precise measurements**, **very high accuracy for theoretical prediction** (suppressed NP effects thanks to large energy scale)

| Observable | value | present ± | uncert. | FCC-ee Stat. | FCC-ee Syst. | Measurement method(s) leading uncertainty |
|---|---|---|---|---|---|---|
| $m_W$ (MeV) | 80 360.2 | ± | 9.9 | **0.18** | 0.16 | WW threshold scan and $m_{inv}$ in W decays EW theory uncertainties dominate |
| $\Gamma_W$ (MeV) | 2 085 | ± | 42 | **0.27** | 0.2 | WW threshold scan and $m_{inv}$ in W decays EW theory uncertainties dominate |
| $\mathcal{B}(W \to \ell\nu_\ell)$ (%) | 10.86 | ± | 0.09 | **0.001** | 0.001 | W decays EW theory uncertainties dominate |

QCD physics at FCC-ee, 2025

*Assuming N3LO theory*



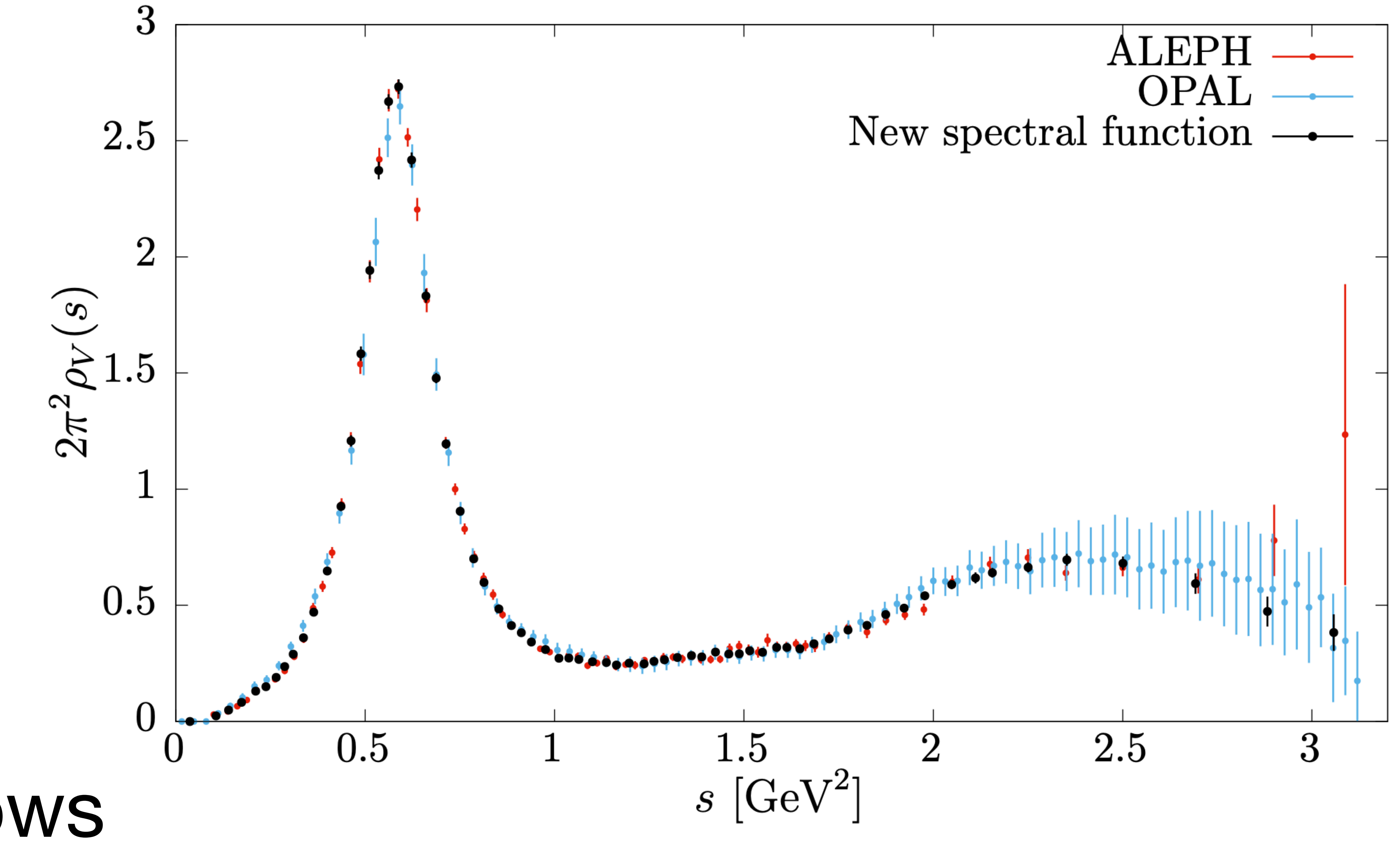

*Projected fit uncertainty, 2005.04545*

**Total exp unc on $\alpha_S$ ~0.2%**

Theory calculations needed with **factors of x10** better precision ($\alpha_S^5, \alpha^2, \alpha^3, \alpha_S\alpha^3, \alpha_S^2\alpha^2$ corrections)

# $\alpha_S$ from $\tau$ hadronic decays

- $\alpha_S(m_\tau)$ **from N4LO fit** to hadronic/leptonic branching fraction $R_\tau$ and $\tau$ **lifetime** using **spectral functions** and FESR, evolved to $\alpha_S(m_Z)$ via RGE




D. Boito et al, Phys Rev D 103, 034028 (2021)

- Large sample of $\tau$ decay ($4 \times 10^{11}$ at the Z pole) allows for **x50-500 improvement in the statistical uncertainty**

- **Total unc on $\alpha_S$ <1% achievable** (to be exactly quantified)

- Particularly strong **test of $\alpha_S$ running at low energy**

- **Theory open questions:** difference between different pQCD approach (**FOPT vs CIPT**), treatment of NP effects

# Studies of parton radiation and jet properties

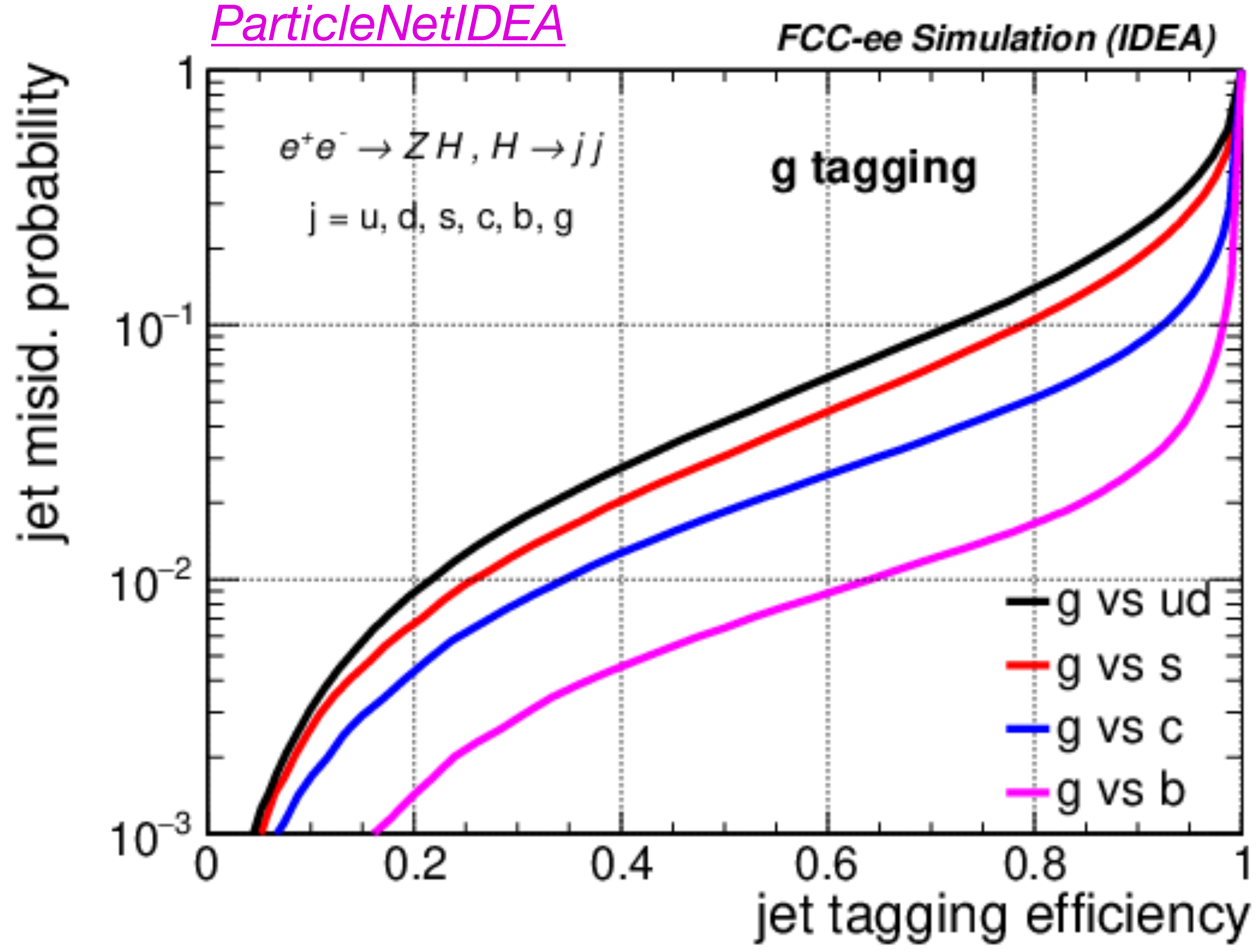
## Motivations

- Necessary for efficient **reconstruction** and **identification** of hadronic final states:
  - Precise **SM measurements** (Higgs coupling measurements, especially to b, c, gluons)
  - Precise **BSM searches**
- Benefit from **large statistics** (~$10^{13}$ Z decays, ~70% hadronic final states) and **clean environment** at FCC-ee
- Many opportunities:
  - **Jet flavour tagging** (including quark/gluon discrimination)
  - **High-precision gluon & quark jet studies** (allows MC tuning)
  - **Jet substructure** (access to parton shower evolution, hadronisation)

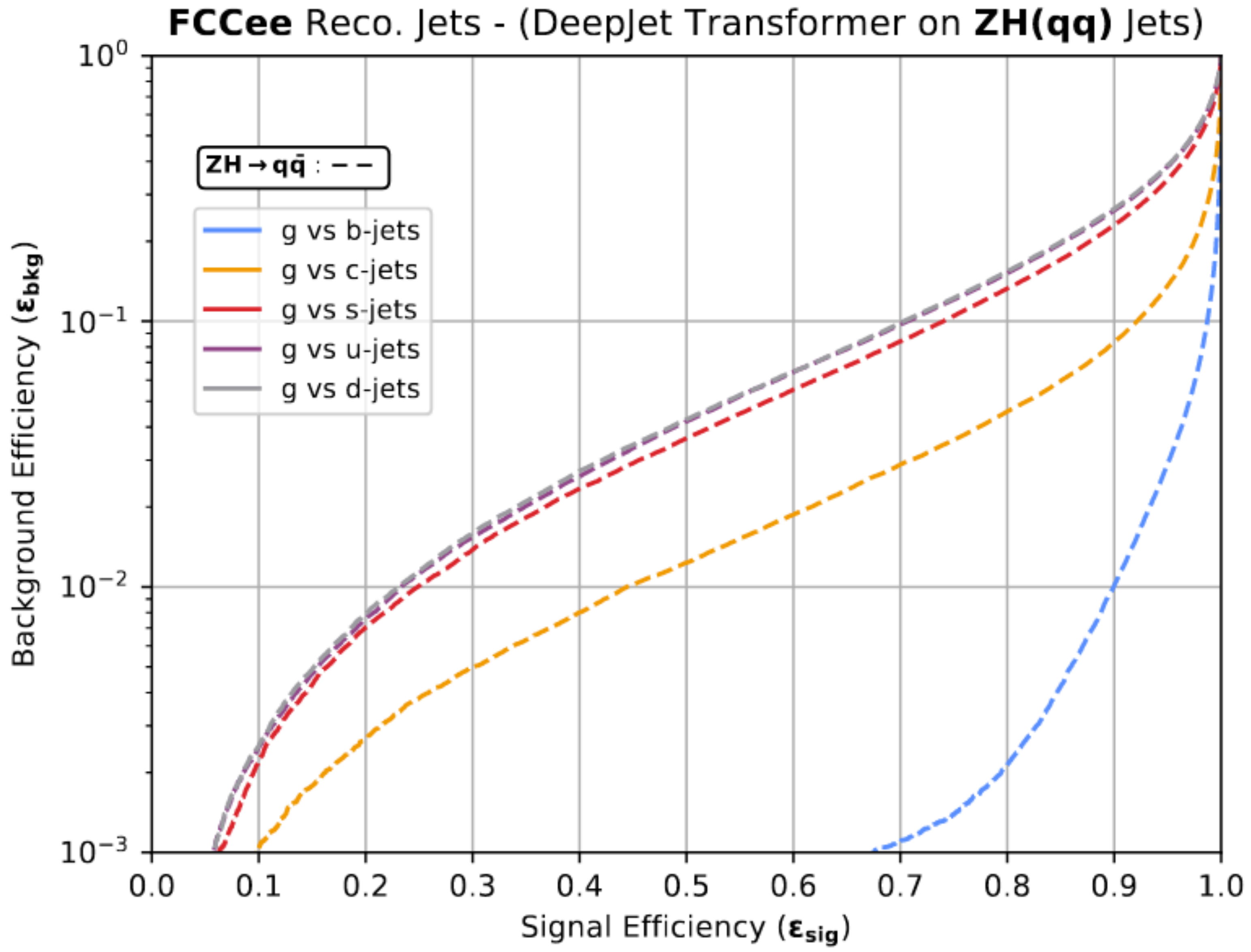
# Jet flavour tagging

- Based on **different properties of jets originating from various sources**
- **Quark/Gluon discrimination**: amount of radiation, spin correlations in subjet locations, $p_T$-weighted jet charge
- Recent **ML-based approaches** use low-level information, new jet representations, PID
  - In the context of **FCC-ee**: **ParticleNetIDEA**, **DeepJetTransformer**…
  - Good performances, rejection of ud jets more challenging due to similar hadron composition
    *Unclear how much gluon discrimination can be trusted (low-stats gluon-tagged jet samples at LEP)…*

ParticleNetIDEA




DeepJetTransformer

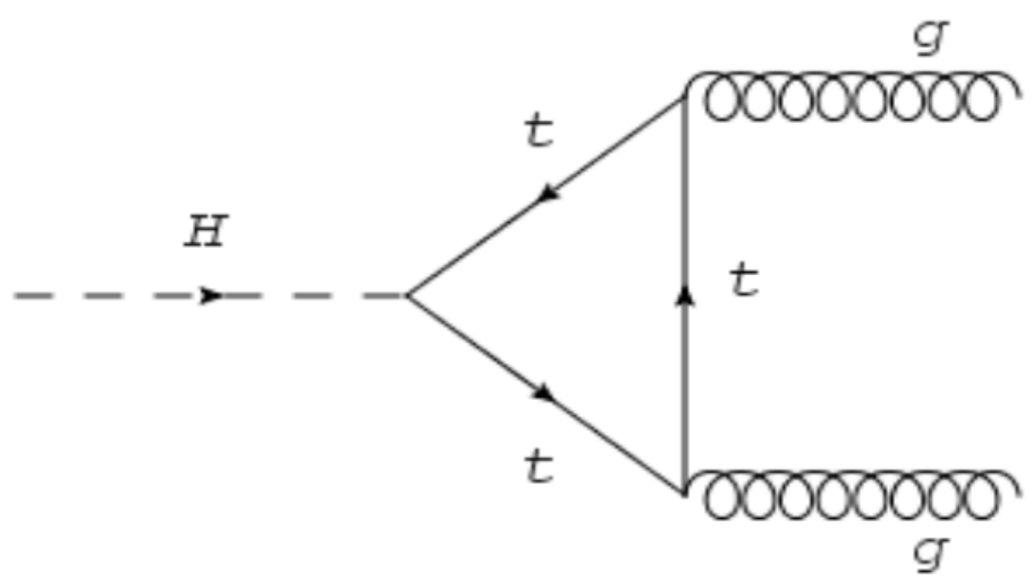


# High-precision gluon & quark jet studies

- Poorly known gluon radiation and fragmentation leads to **large discrepancy between MC generators** for gluon jets (Existing MC tuning relies mostly on **quark-enriched samples**)

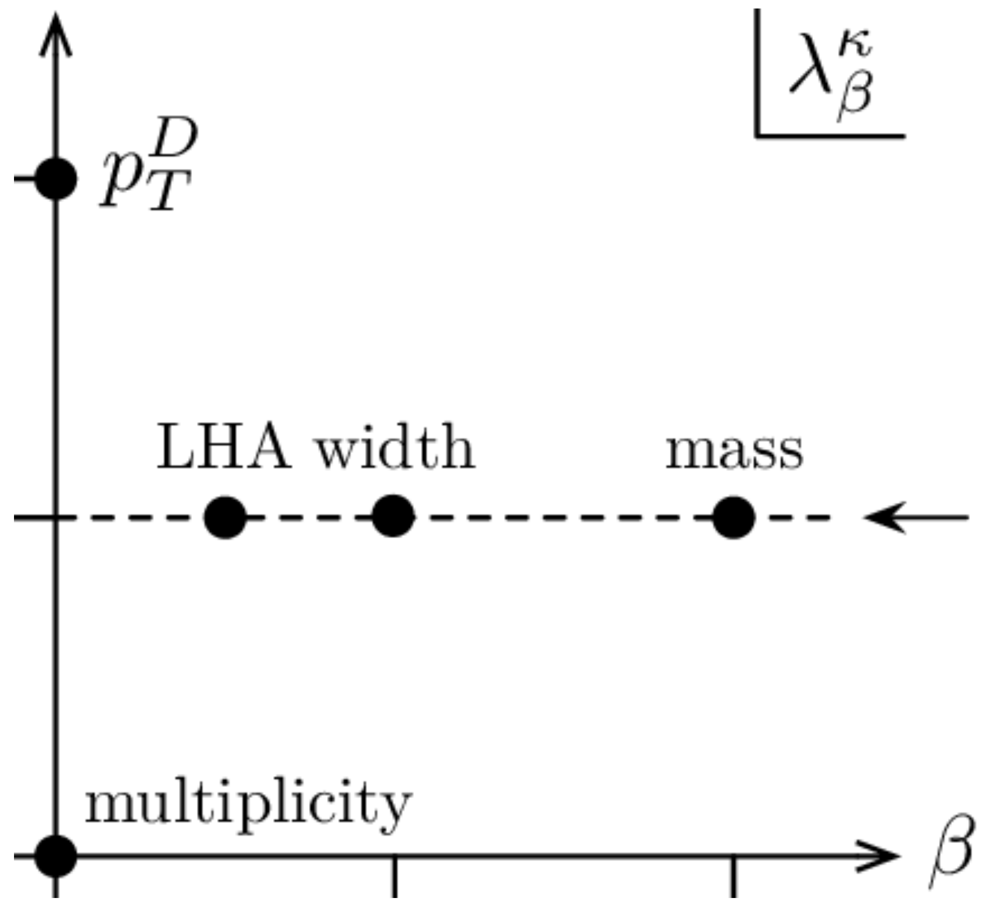
- FCC-ee exploited as a **pure gluon factory**:
  - $H \to gg$ (8% BR, 120k extra-clean di-gluon events) vs $Z \to qq$ $(10^{10}$ events)
  - $Z \to bbg$ (g in one hemisphere recoiling against 2 b-jets in the other)

- Multiple high-precision analyses:
  - **q/g discrimination** (training on pure samples)
  - **Non-pQCD** (gluon fragmentation, colour reconnection…)
  - **pQCD** (NNLL PS tuning, *jet substructure*)



# Jet substructure

$$\lambda^{\kappa}_{\beta} = \sum_{i \in jet} z_i^{\kappa} \theta_i^{\beta}$$




- Sensitivity to parton shower and hadronisation mechanisms
- **Angularities** (LHA: $\kappa = 1, \beta = 1/2$), Lund Jet Plane, C-parameter…

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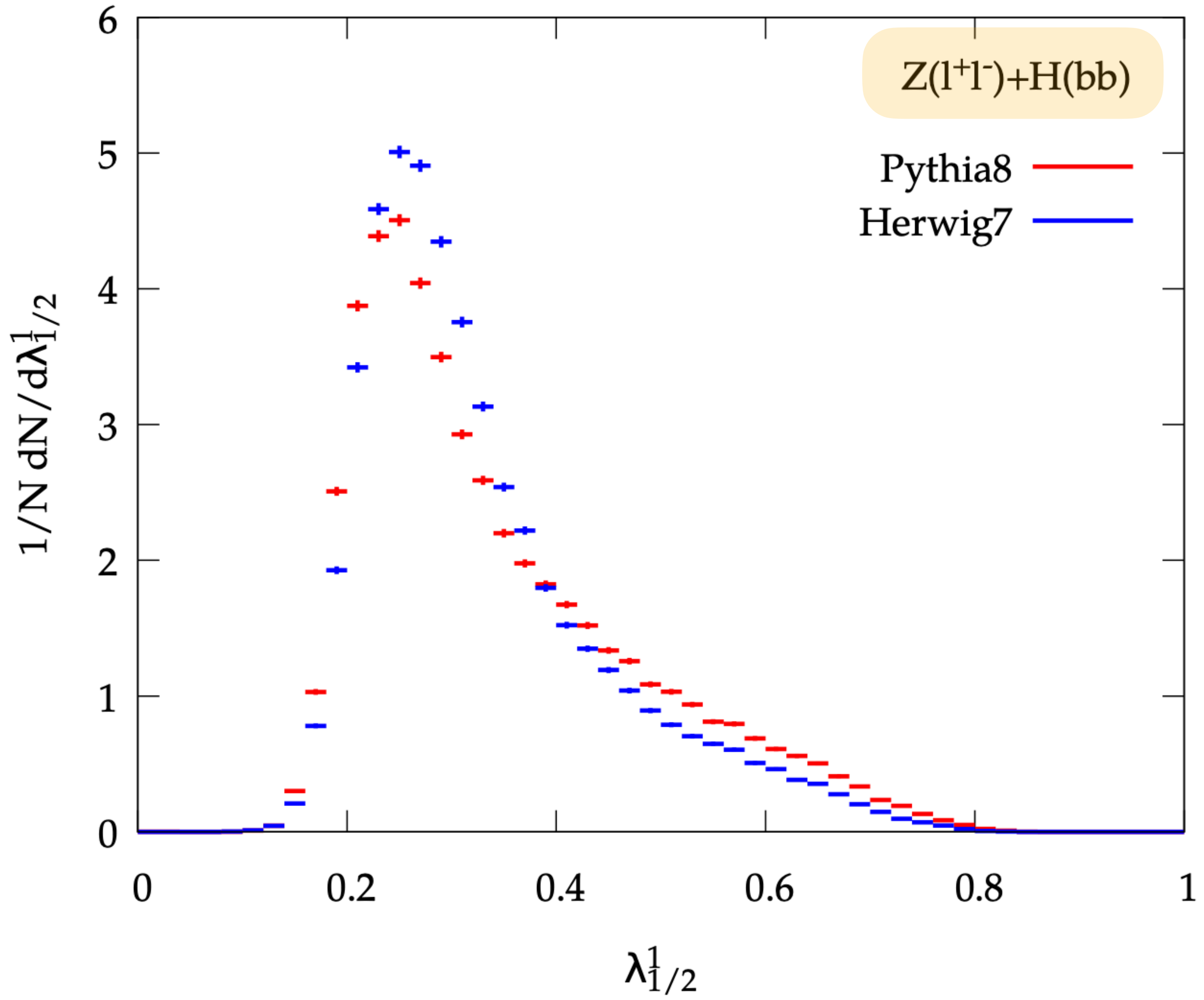
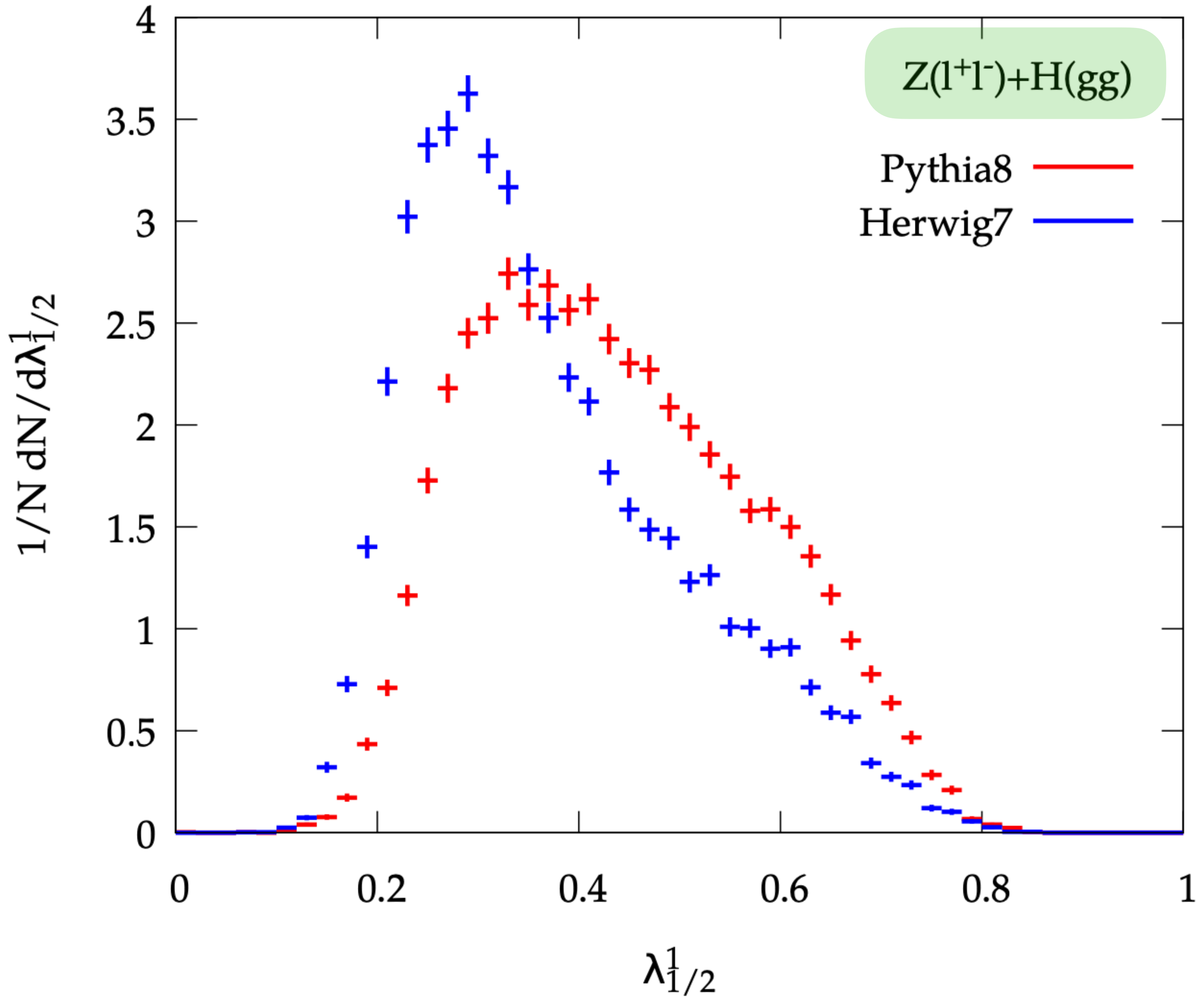



Decent agreement




Larger discrepancy

→ **improved MC tuning** (new constraints on PS generators)

→ **better understanding of showering and hadronisation**

# Non-perturbative QCD phenomena

## Motivations

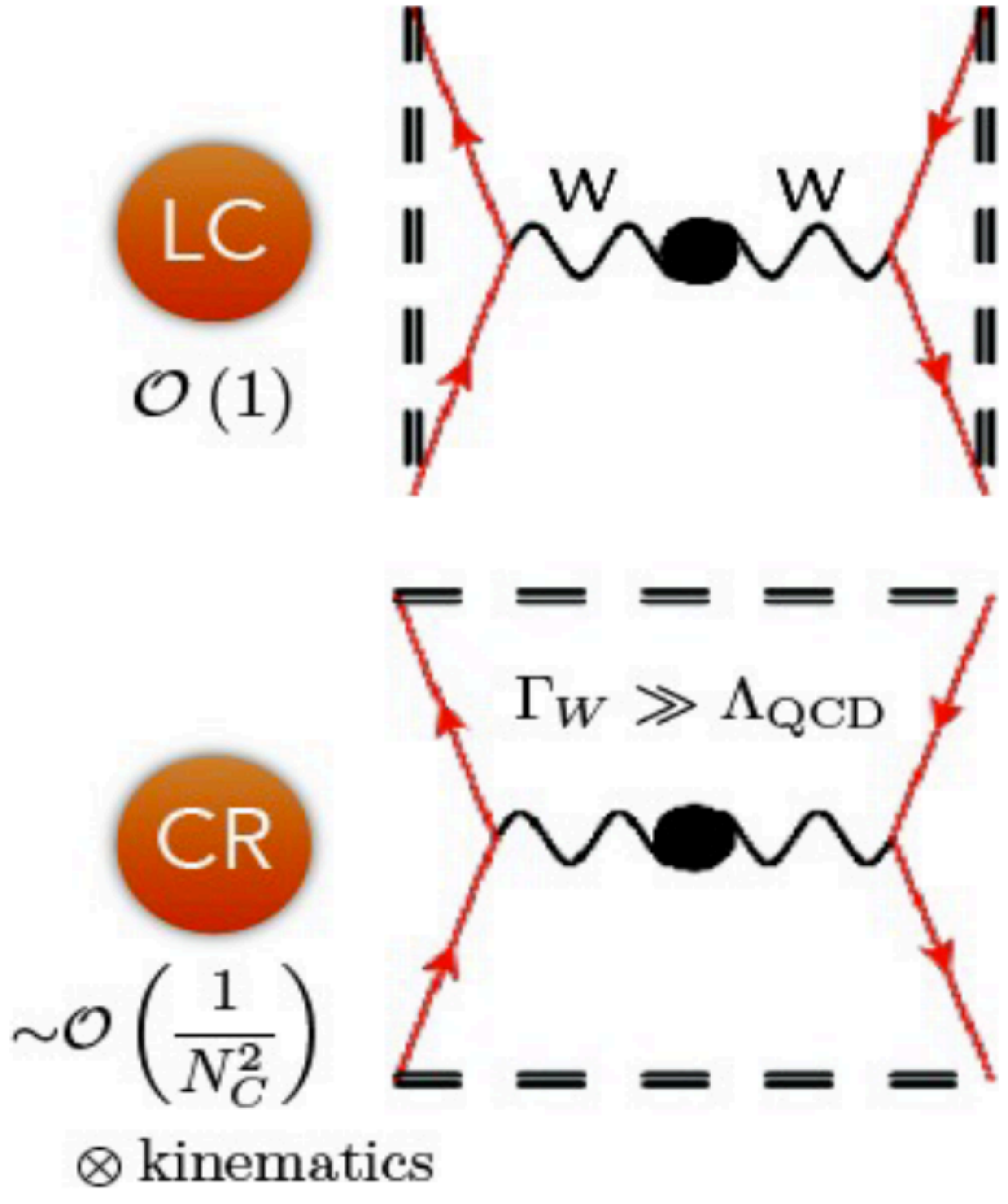
- Not calculable from first principle, rely on **phenomenological models** tuned to experimental data

- Underlying dynamics poorly understood, **impact all hadronic final states**

→ Non-perturbative corrections/modelling uncertainties can be **non-negligible** in precision SM measurements and BSM searches

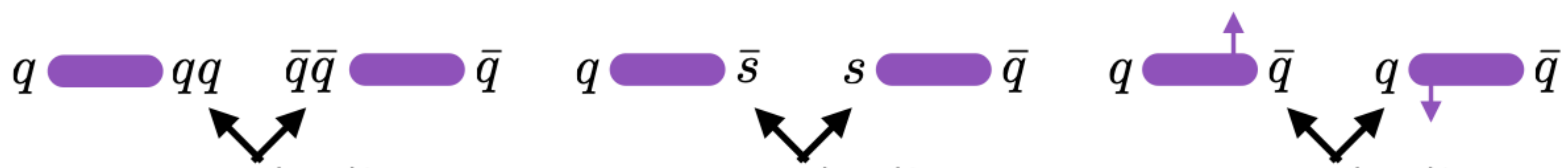
- Non-perturbative QCD studies at FCC-ee enabled by **huge statistics**, **exquisite precision**, **very clean environment** (no MPI, no UE)

# Colour reconnection (CR)




- Affects jet shapes/multiplicities, final state kinematics, UE, hadronisation modelling…
- Source of uncertainty e.g. in $m_W$:
  $\Delta m_{W,CR} = \pm 1$ MeV
- **String drag effect** impacts all FCC-ee multi-jet final states: **shifted masses and angular correlations** (hinted at LEP for fully hadronic W decays)
- Exploit **huge WW stat** $(10^8$ events), **no MPI** and **reduced experimental systematics**
  → **Constrain CR** from $m_W$ measurement in leptonic and hadronic decay
  → Target precision **below 1%**

# Hadronisation




- Multitude of hadronisation studies enabled by **precise charged hadrons PID** at FCC-ee:
  - **Colour string dynamics** (baryon and strangeness number conservation, transverse momentum conservation)
  - **Final-state correlations** (spin, momentum)
  - **Exotic bound states** (quarkonia, glueball, multi-quark states)
  - **Breakdown of universality of parton hadronisation with system size** observed by ALICE (possibly linked to collective or colour reconnection effects)

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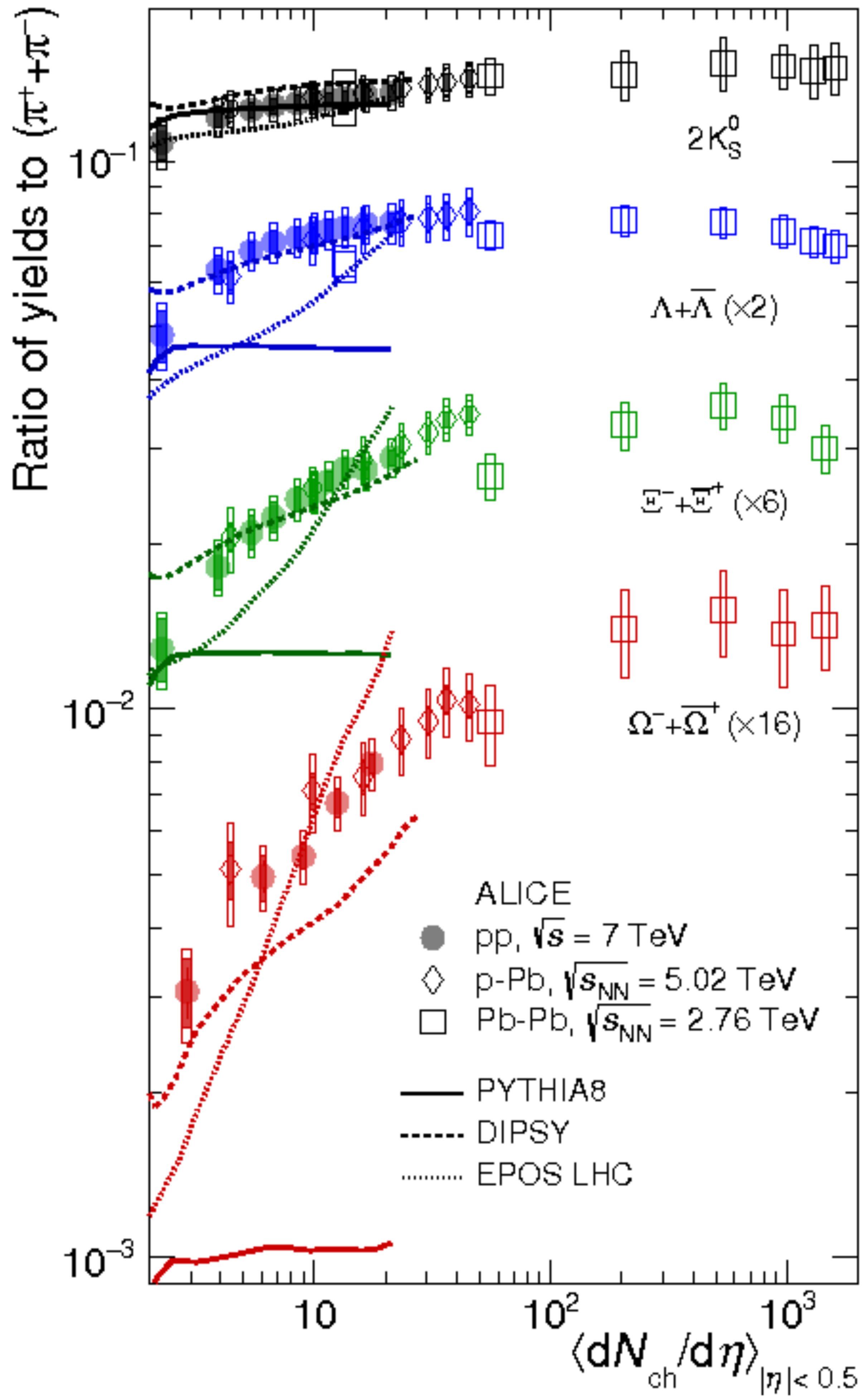



"significant enhancement of strange to non-strange hadron production is observed with increasing particle multiplicity in pp collisions"

# Summary

- The precision needed to fully exploit broad range SM and BSM programs requires precise control of **QCD physics**
- **FCC-ee** dream lab for **QCD**
  - $\alpha_S(m_Z)$ **at ‰ level**, precision measurement of $\alpha_S$ running
  - Better understanding of **perturbative and non-perturbative QCD** (parton shower, color reconnection, hadronisation, heavy flavour, etc)
  - *Low centre-of-mass energy runs further enable soft QCD studies, MC validation, precision measurements*
- Some FCC-ee SM measurement currently limited by QCD uncertainties
  → **require dedicated studies and huge theory effort**

# Thank you for your attention!

# Backup

# $\alpha_S$ from event shapes & jet rates

- Extractions based on **fitting accurate theoretical prediction to experimental data**, using various observables, datasets, perturbative calculation, hadronisation models
- Example: thrust, C-parameter, energy-energy correlators, n-jet cross sections…
- Discrepancy between different measurements → future measurements at FCC-ee will shed light onto these tensions + insight into accurate modelling of NP effects
- Alternative: observables with reduced sensitivity to hadronisation → jet substructure variable (**Lund Jet Plane, soft-drop thrust**), ratio of jet cross sections ($R_{3/2}$)

$$T = 1 - \max_n \frac{\sum_i |p_i \cdot n|}{\sum_i |p_i|}$$

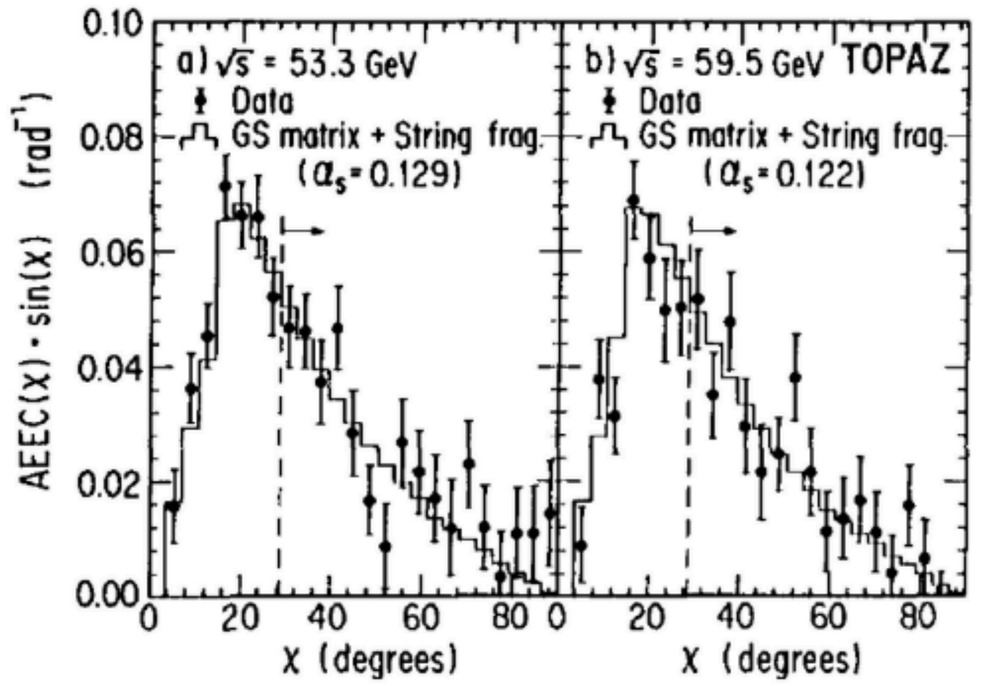
$$C = \frac{3}{2} \frac{\sum_{i,j} |p_i||p_j| \sin^2(\theta_{i,j})}{(\sum_i |p_i|)^2}$$

$$R_{3/2} = \sigma_{\geq 3j} / \sigma_{\geq 2j}$$

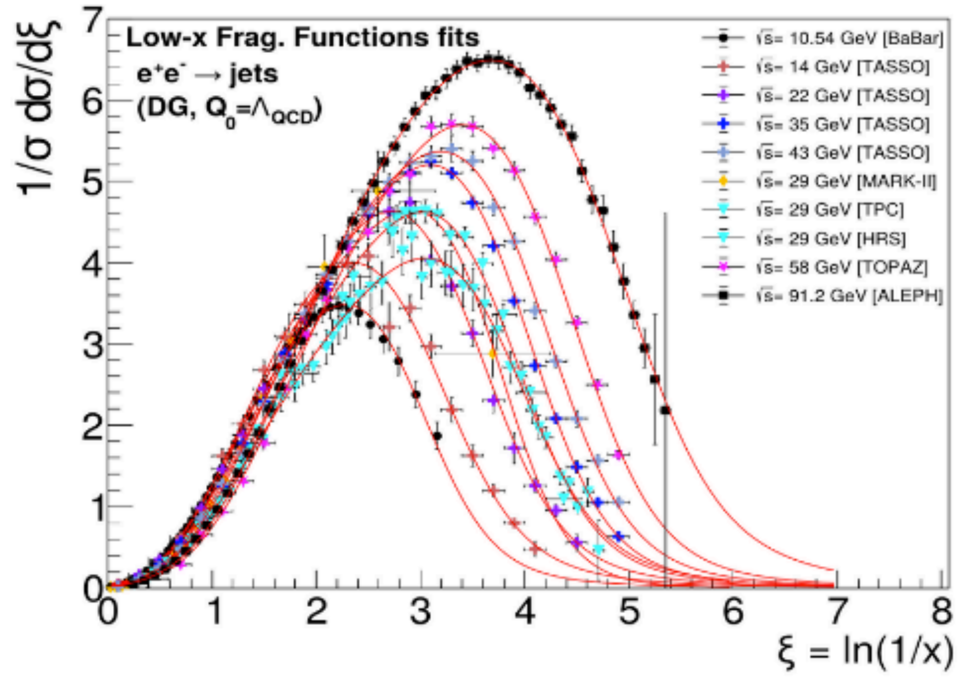
# Opportunities at low √s

- Different strategies for low √s:
  - Taking advantage of hard QED radiation (**ISR/FSR**) during the Z run (~$10^9$ events for several energy ranges)
  - Short (one-month long) **dedicated low-√s runs** would provide $10^9$ hadronic events at each low-CM-energy point
- Can be exploited for **precision QCD measurements**
- Can be used to disentangle more effectively the **effect of hadronisation corrections**:

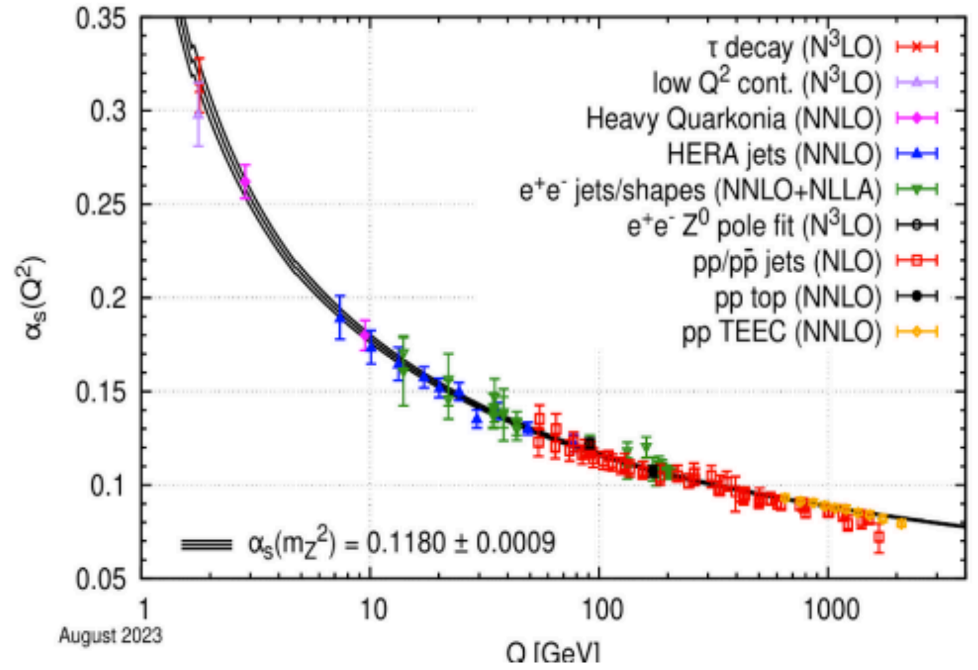
$$d\sigma \sim d\sigma^{(P)} + d\sigma^{(NP)} \qquad d\sigma^{(NP)} \sim \Omega(v)\left(\frac{\Lambda_{QCD}}{\sqrt{s_{had}}}\right) + \mathcal{O}\left(\frac{\Lambda^2_{QCD}}{s_{had}}\right)$$



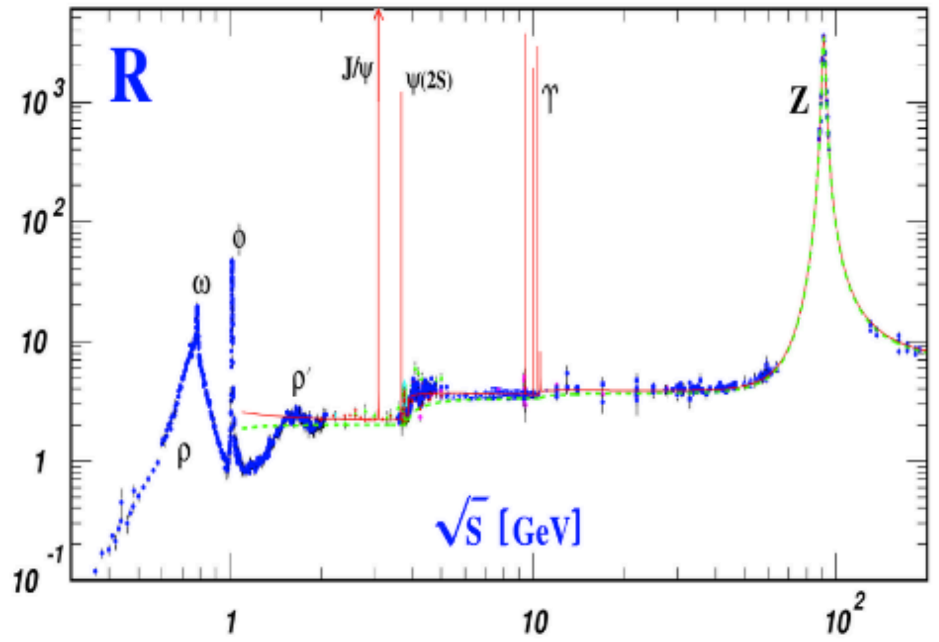

EEC, hard vs soft radiation




Fragmentation functions




$\alpha_S(Q)$




$$R = \frac{\sigma(\text{hadrons})}{\sigma(\mu^+\mu^-)}$$