Soft Drop Thrust in lepton collisions

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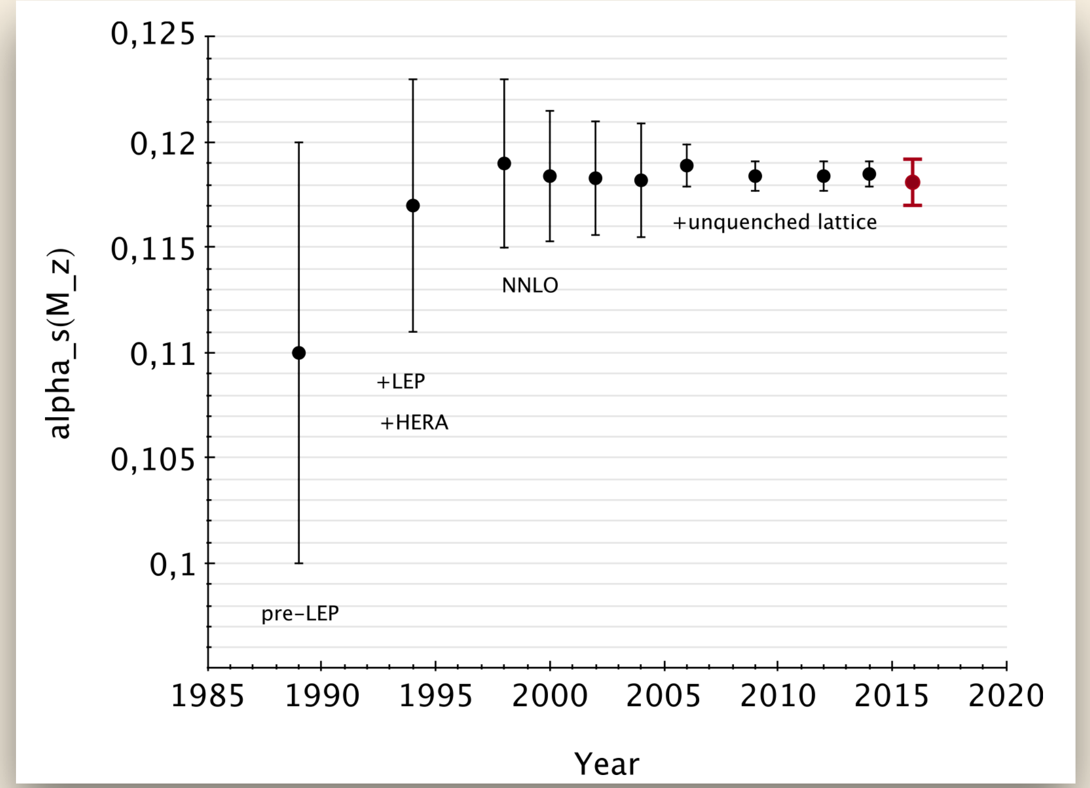
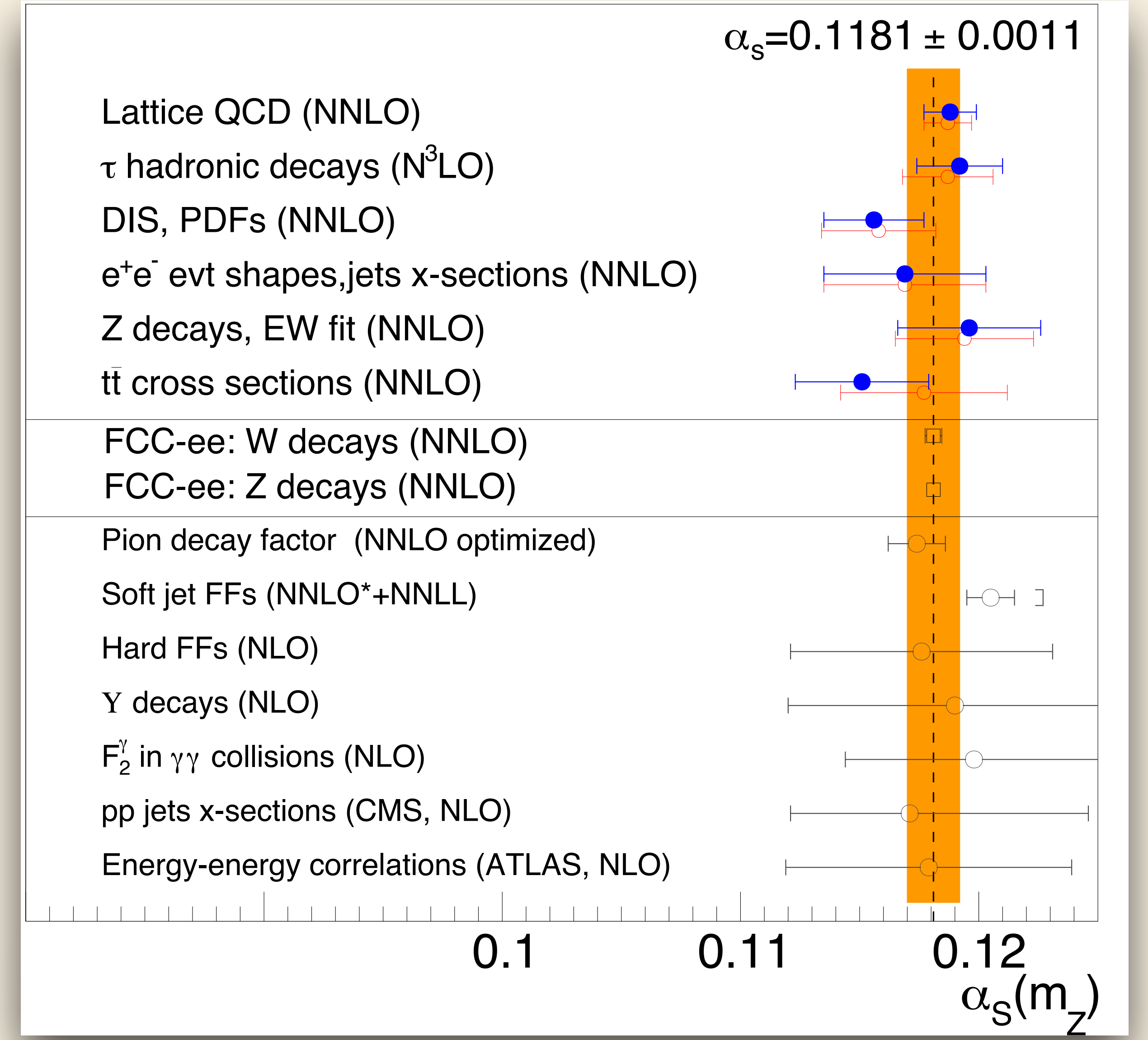
based on arXiv:1603.08927, 1606.03453, 1807.11472 and unpublished results

Why event shapes in lepton collisions?



summary of α_s determinations:



D. d'Enterria, arXiv: 1806.06156

D. d'Enterria and S. Kluth (eds), arXiv: 1907.01435

Why event shapes in lepton collisions?

- e^+e^- event shapes, jets have long been considered ideal for measuring α_s

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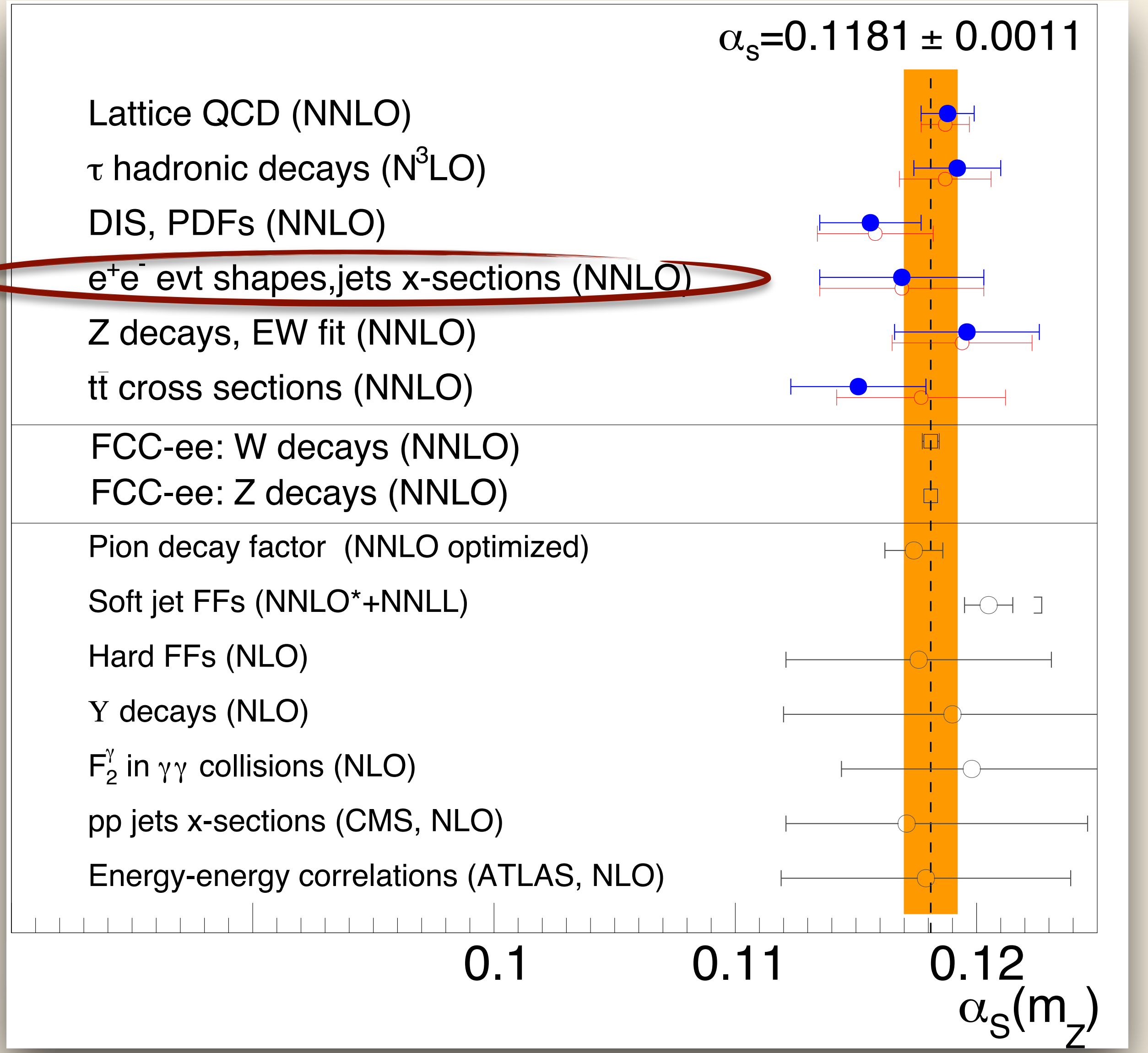

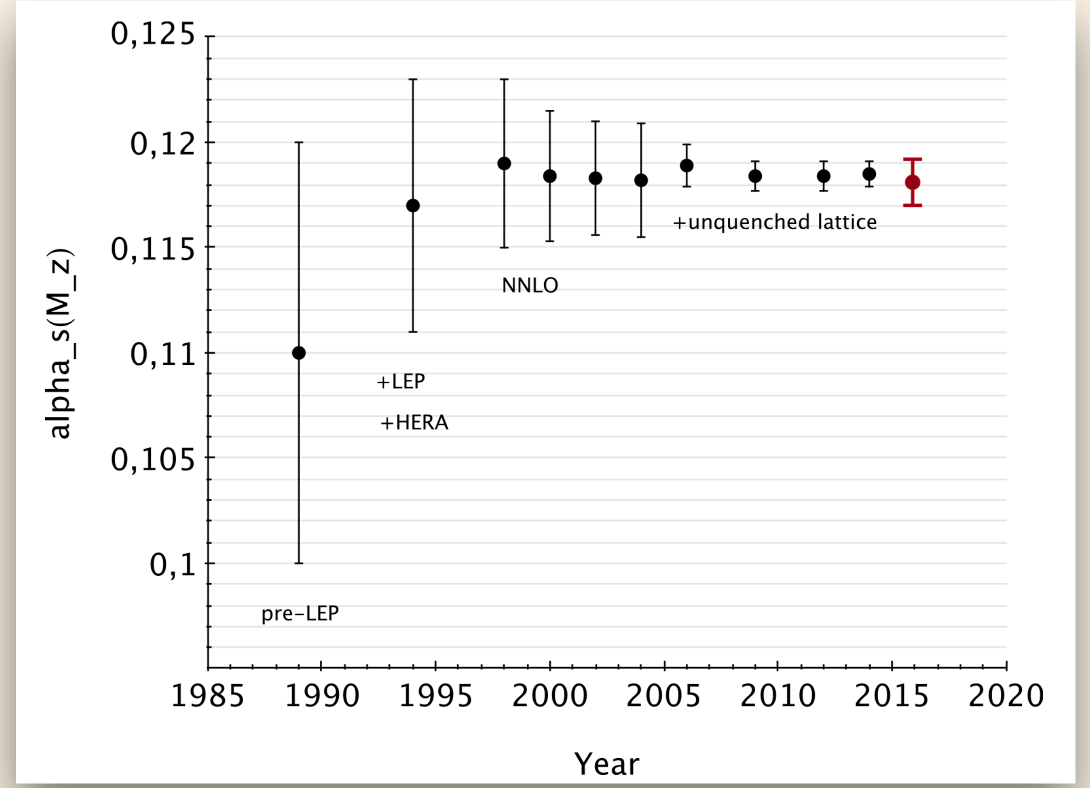

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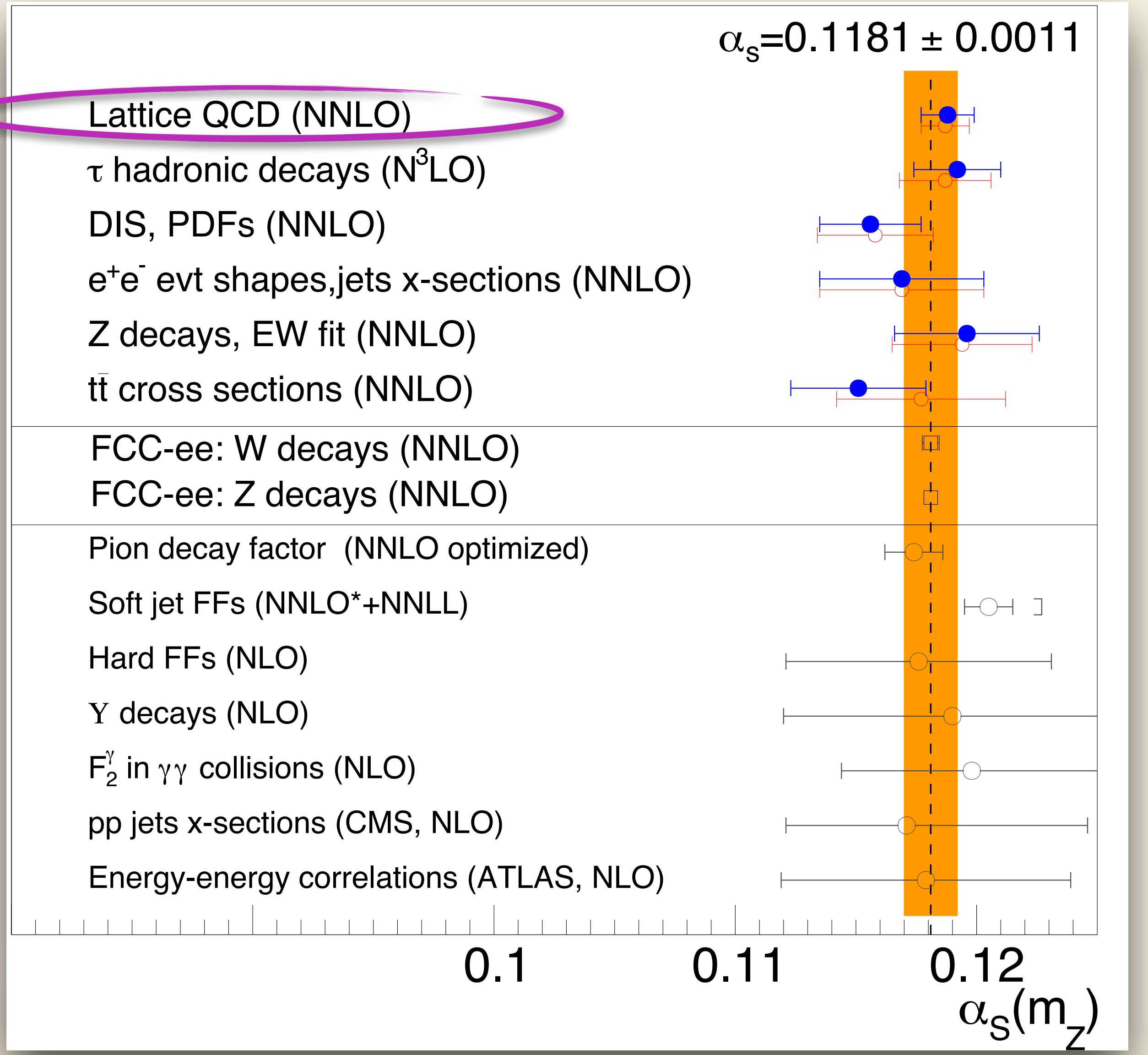

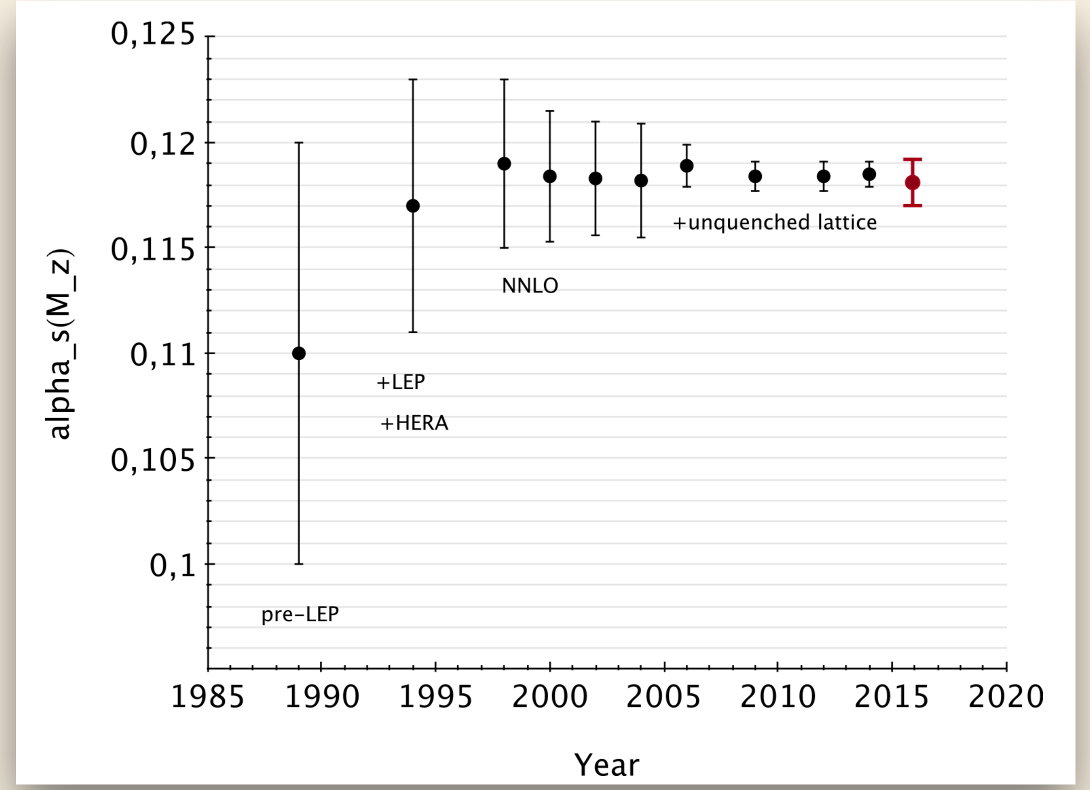

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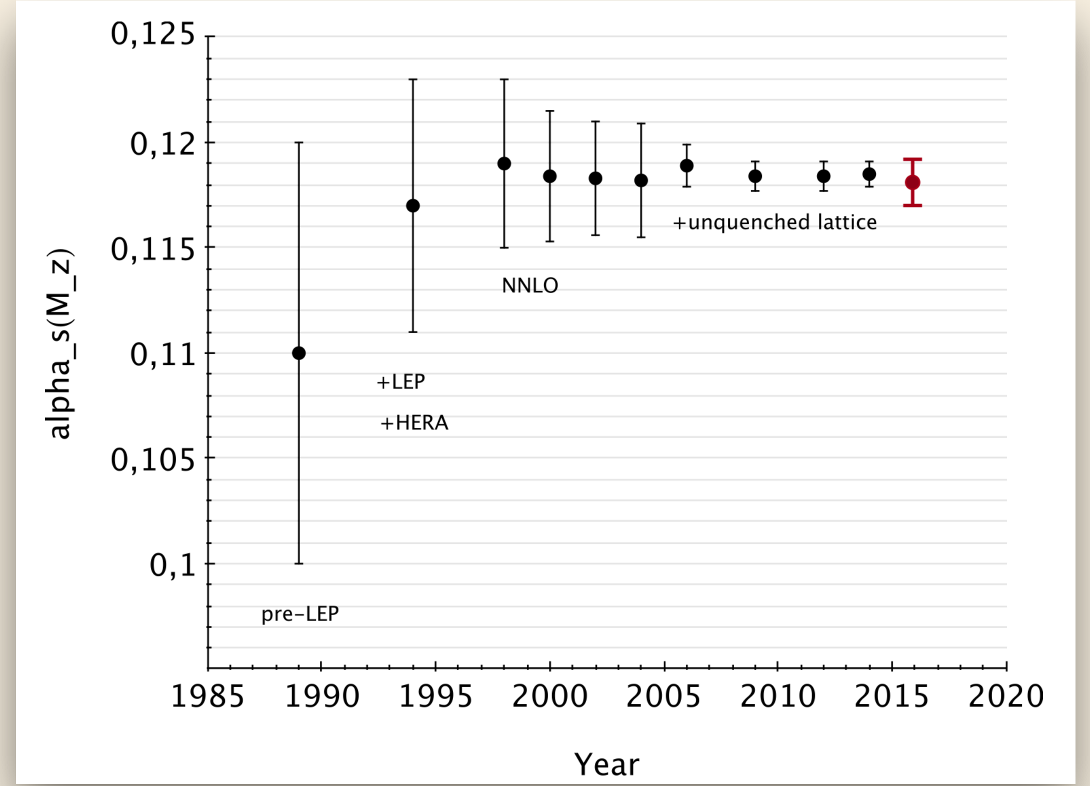
- recent prevailing view: lattice is unbeatable
- yet determination of α_s from experiments remains desirable



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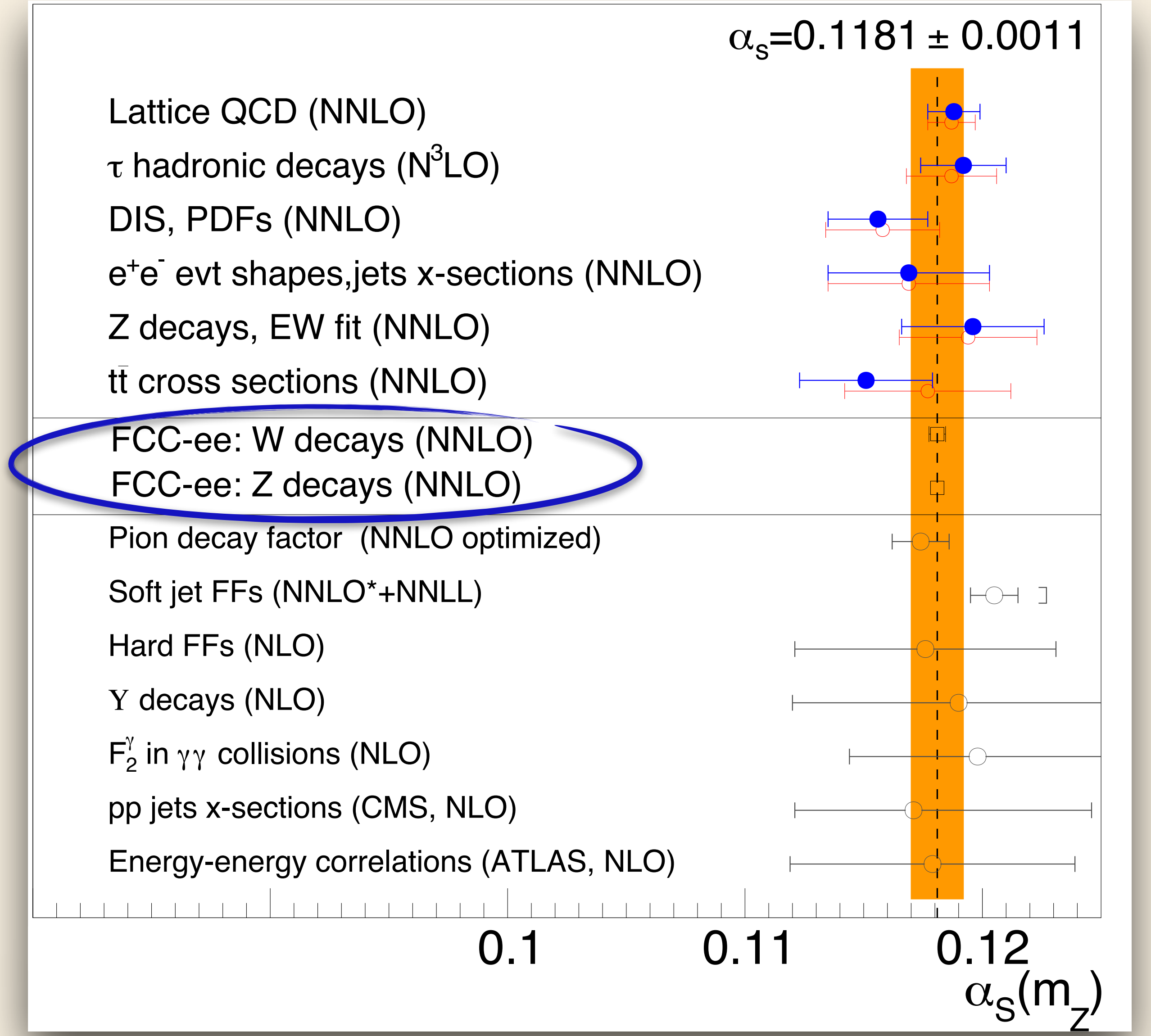

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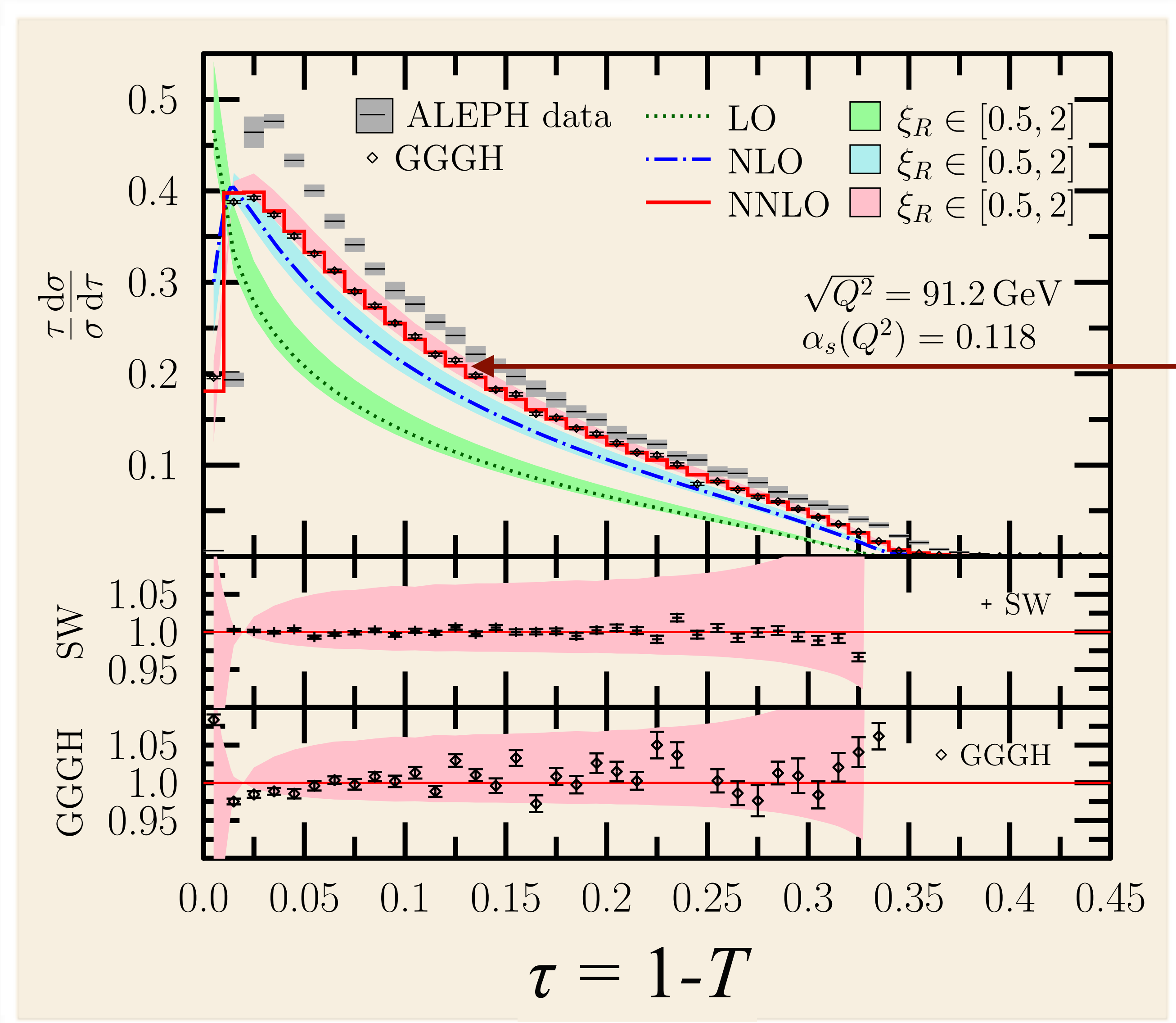
New since LEP

Impact of corrections at NNLO



fixed-order PT is insufficient to describe data

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|} \right)$$

$$\frac{\tau}{\sigma}\frac{d\sigma}{d\tau} = \left(\frac{\alpha_s}{2\pi}\right) A(\tau) + \left(\frac{\alpha_s}{2\pi}\right)^2 B(\tau) + \left(\frac{\alpha_s}{2\pi}\right)^3 C(\tau)$$

A, B and C computed with MCCSM (=Monte Carlo for CoLoRFulNNLO Subtraction Method)

V. Del Duca et al, arXiv:1603.08927

Analytic structure of perturbative expansion

$$\boxed{\frac{\tau}{\sigma}\frac{d\sigma}{d\tau} = \left(\frac{\alpha_s}{2\pi}\right) A(\tau) + \left(\frac{\alpha_s}{2\pi}\right)^2 B(\tau) + \left(\frac{\alpha_s}{2\pi}\right)^3 C(\tau)}$$

$$\begin{aligned}
A(\tau) &= \boxed{A_1 L} + A_0\,, \\
B(\tau) &= B_3 L^3 + \boxed{B_2 L^2} + \boxed{B_1 L} + B_0\,, \\
C(\tau) &= C_5 L^5 + C_4 L^4 + C_3 L^3 + \boxed{C_2 L^2} + C_1 L + C_0 \\
& \quad \vdots \qquad \vdots \qquad \vdots \qquad \vdots
\end{aligned}$$

$$L = -\ln\tau$$

LL NLL N^2LL N^3LL …

for $L \sim 1/\alpha_s$ we need resummation of logarithmic terms at all orders

How to improve?

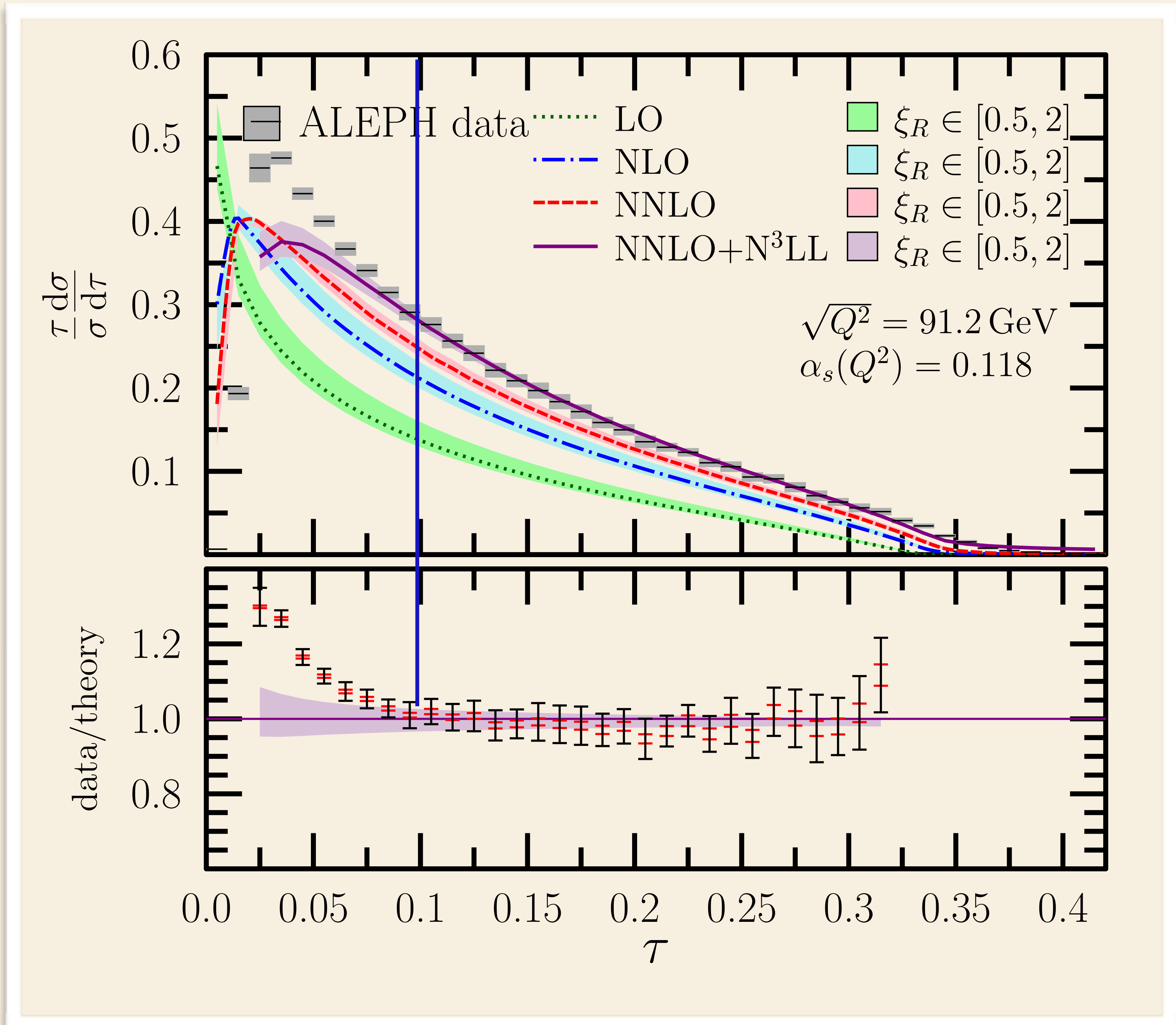
✓ Match to approximate predictions that resum large logarithms of the event shapes

precise predictions are available, e.g.:

– N^3LL for thrust (τ), C-parameter and heavy jet mass (ρ)

– N^2LL for broadenings and EEC

Matching NNLO with N³LL



Works for τ > 0.1, fails in peak regions

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✓ Correct for hadronisation

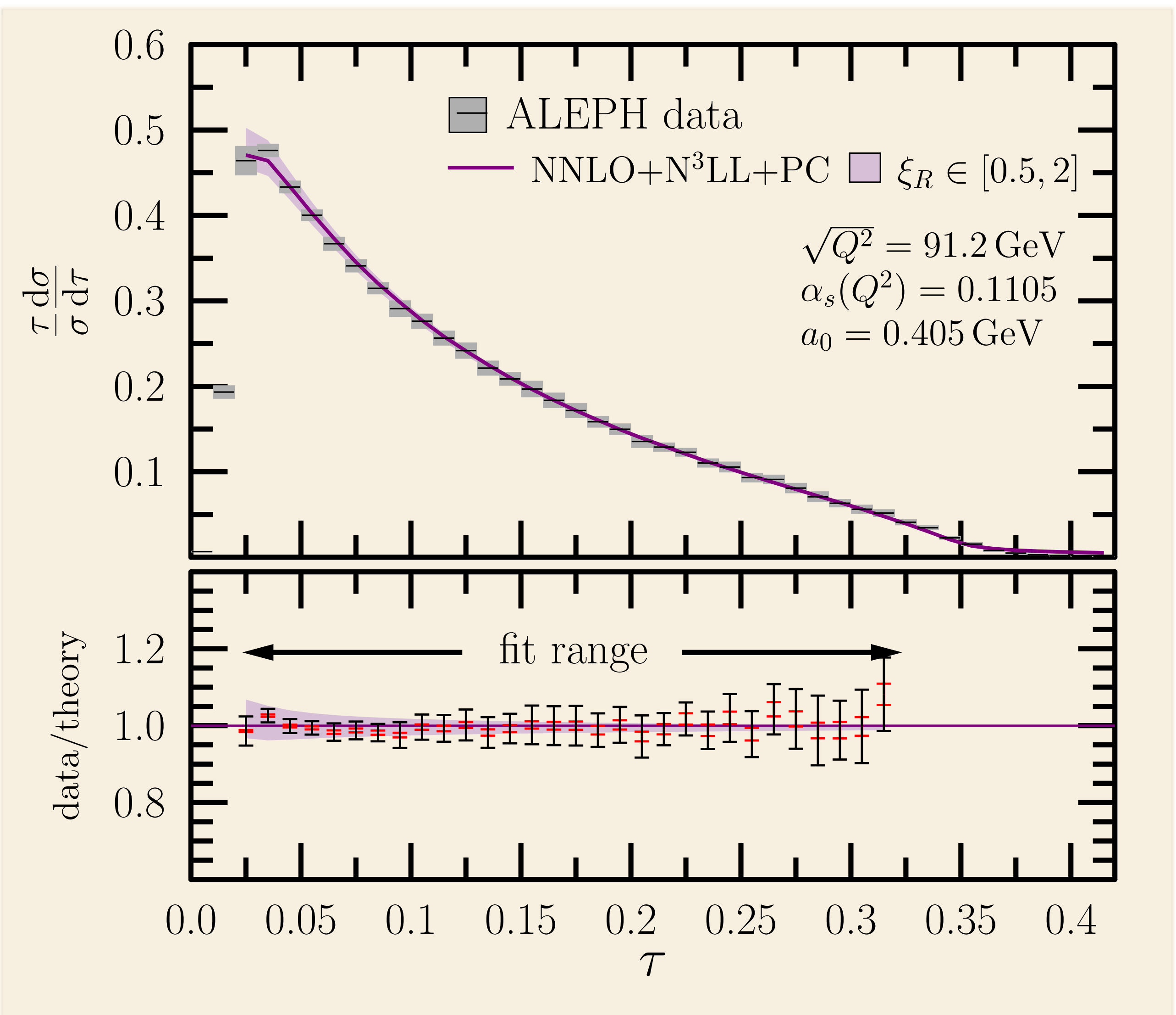
two options:

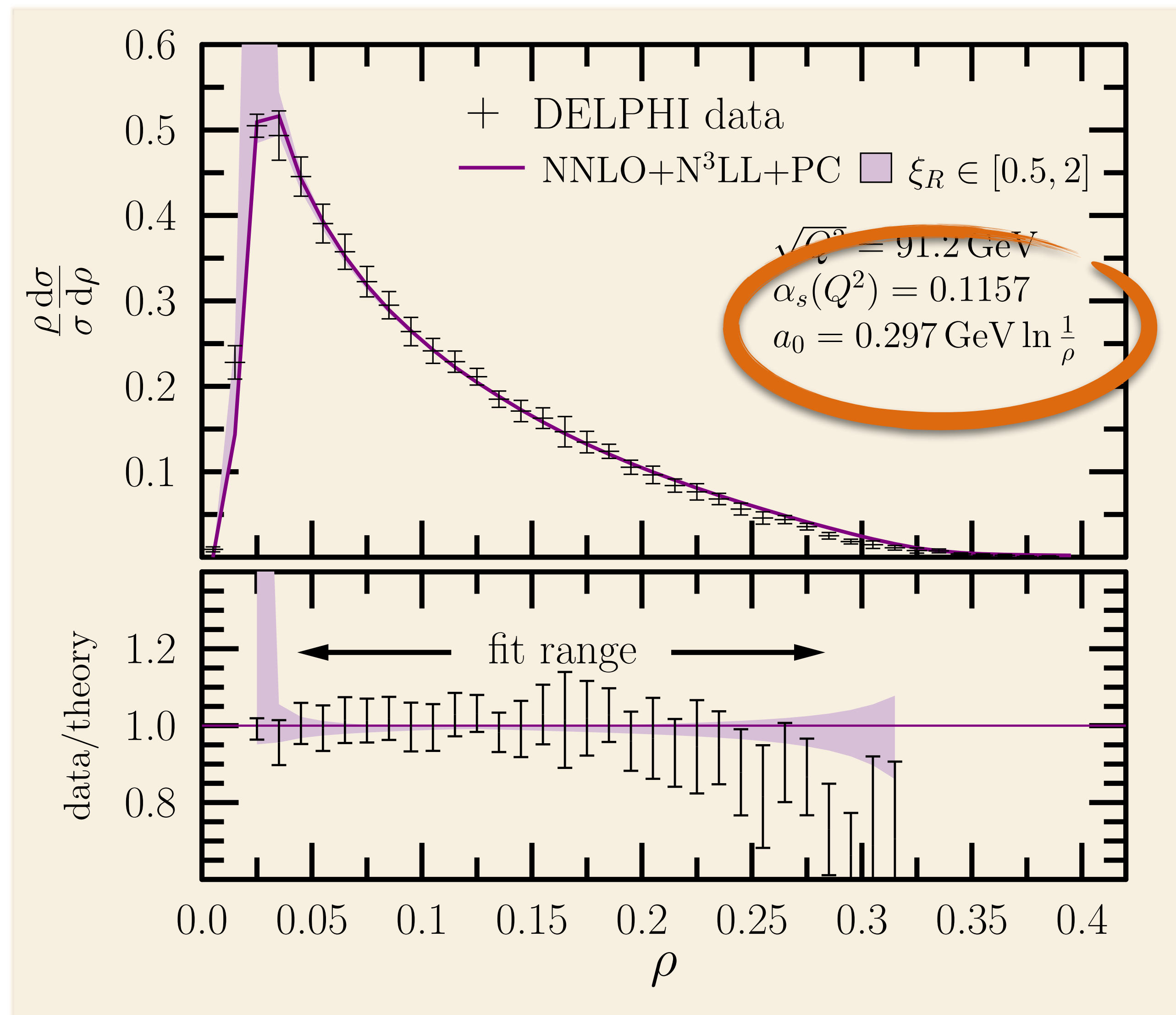
– estimate of hadronisation using modern MC tools

– use analytic model for power corrections

both have their caveats

Fit data on thrust and heavy jet mass with NNLO+N^{3}LL+PC





… does not look universal

How to improve?

✓ Correct for hadronisation, 2nd option:

– estimate of hadronisation using modern MC tools

model dependent

How to improve?

- ✓ Correct for hadronisation, 2nd option:
  - – estimate of hadronisation using modern MC tools
- ✓ Find observable quantities with small perturbative and hadronisation corrections:

motto: "large uncertainty in small quantity is small uncertainty"

How to improve?

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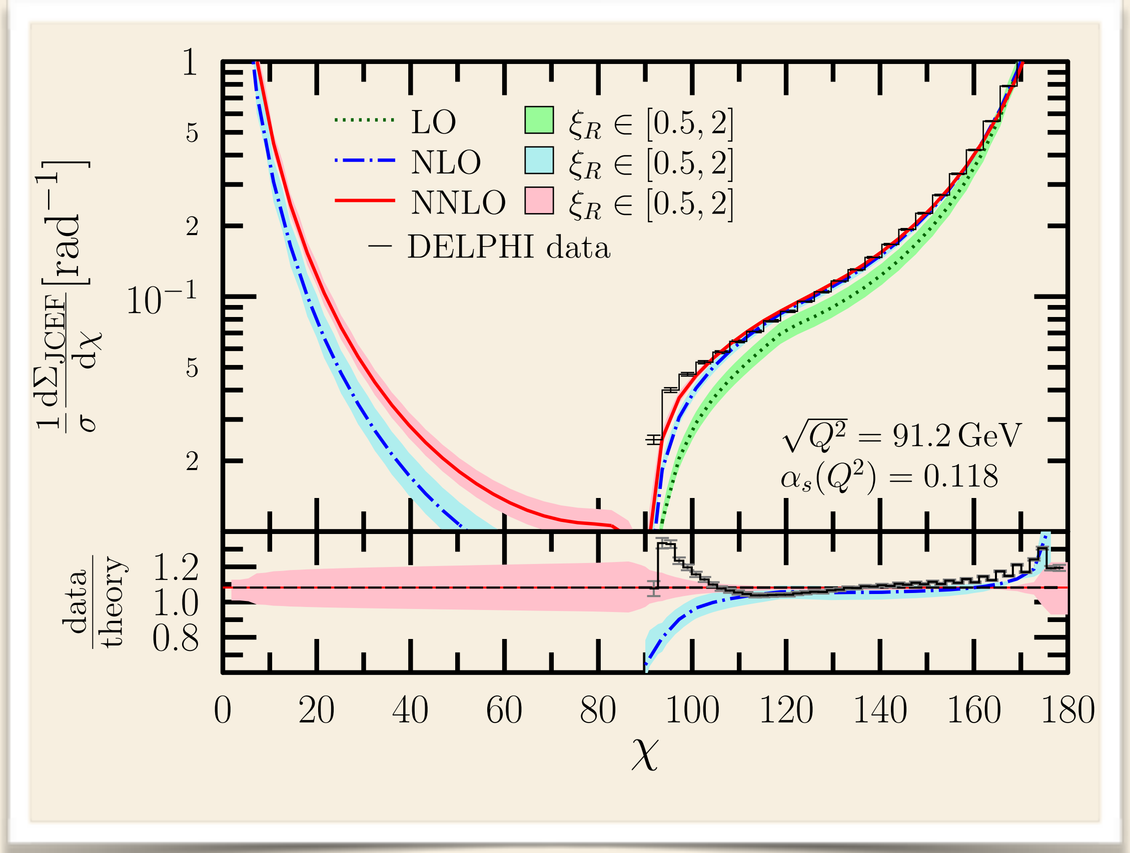
jet cone energy fraction:

$$\frac{\mathrm{d}\Sigma_{\mathrm{JCEF}}}{\mathrm{d}\cos\chi} = \sum_i \int \frac{E_i}{Q} \mathrm{d}\sigma_{e^+e^- \to i+X} \, \delta\left(\cos\chi - \frac{\vec{p}_i \cdot \vec{n}_T}{|\vec{p}_i|}\right)$$



V. Del Duca et al, arXiv:1606.03453

How to improve?

✓ Correct for hadronisation, 2nd option:

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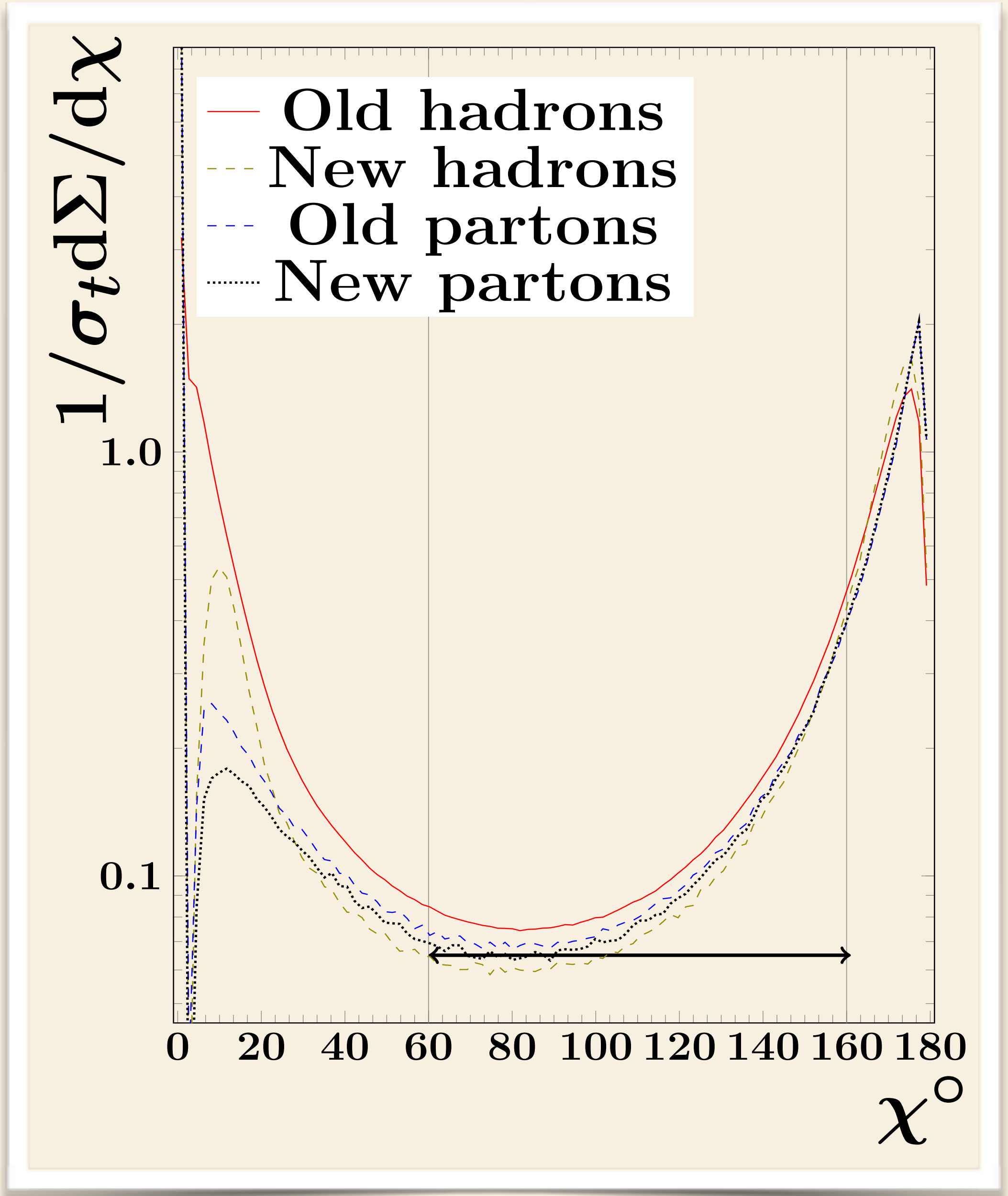
✓ Find observable quantities with small perturbative and hadronisation corrections:

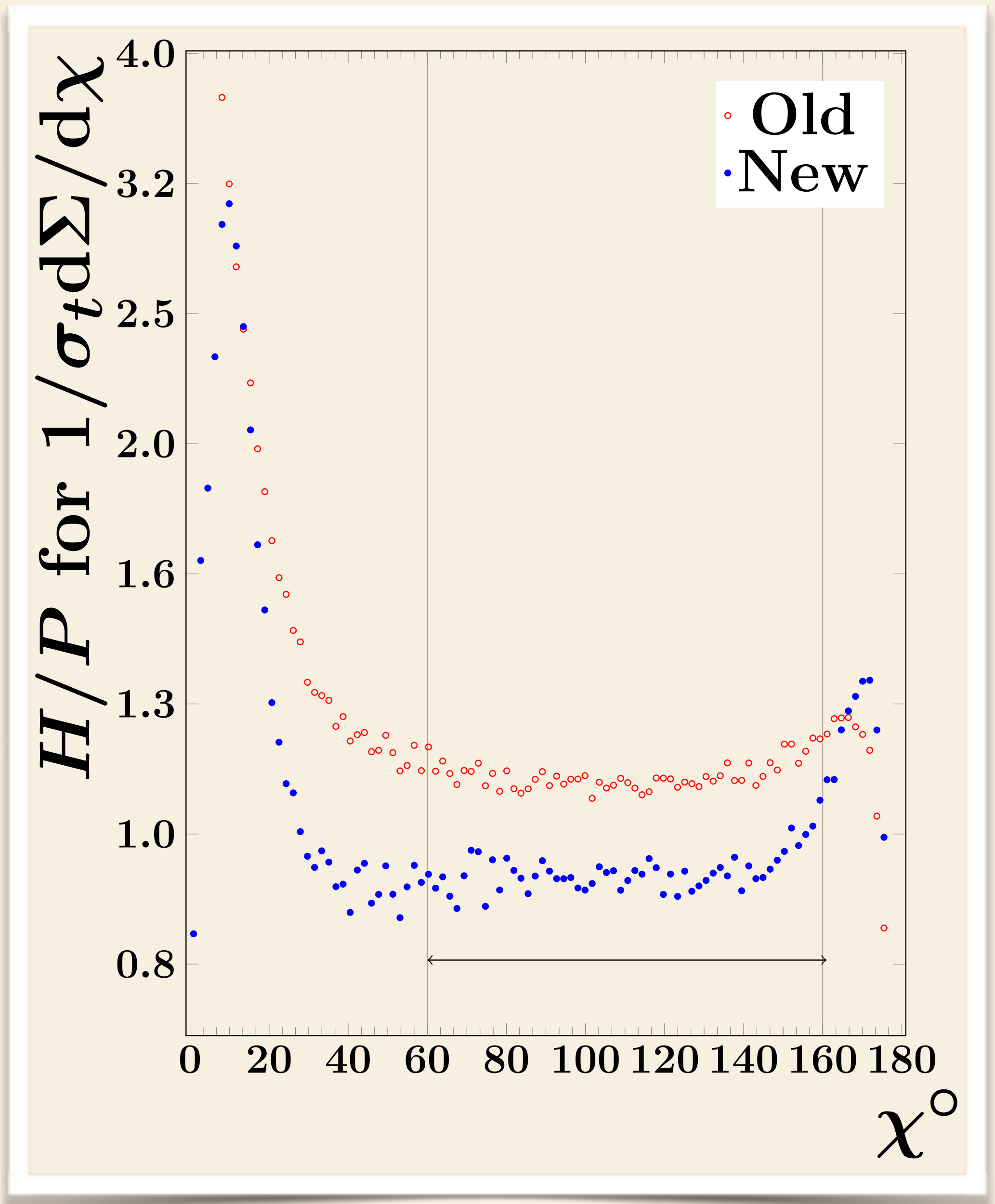
motto: "large uncertainty in small quantity is small uncertainty"

– precluster hadrons and compute shapes from jets

Decamp et al [ALEPH], Phys.Lett. B257 (1991) 479-491

Preclustering reduces hadronization corrections for EEC





Old: without, New: with plecustering (requiring 5 jets)

A. Verbytskyi, private communication

How to improve?

✓ Correct for hadronisation, 2nd option:

– estimate of hadronisation using modern MC tools

✓ Find observable quantities with small perturbative and hadronisation corrections:

motto: "large uncertainty in small quantity is small uncertainty"

– precluster hadrons and compute shapes from jets

– groomed (soft drop) event shapes, designed to reduce contamination from non-perturbative effects

Soft drop event shapes

Soft drop grooming is defined

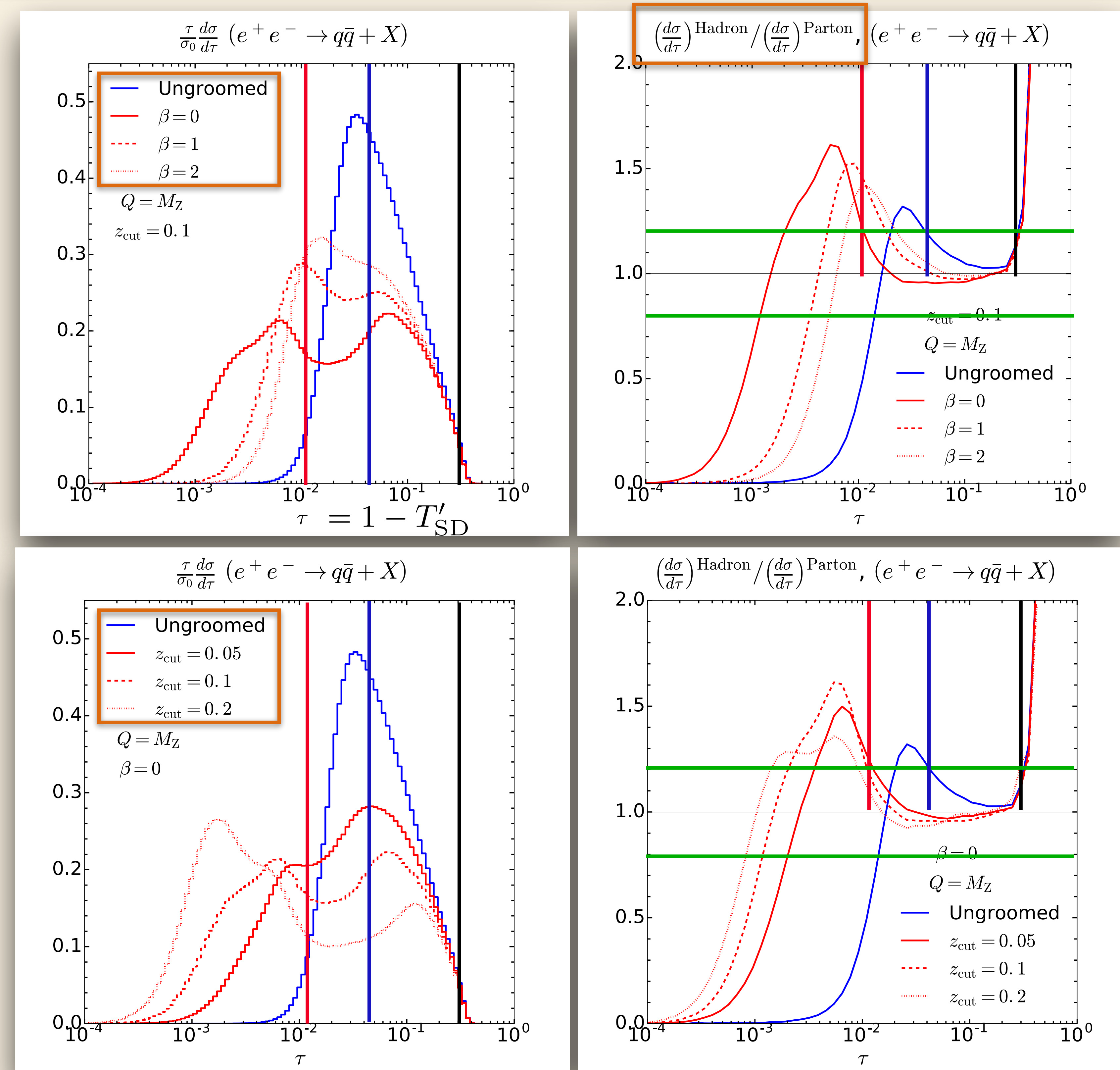
for a jet with radius R using Cambridge-Aachen clustering as:

1. Undo the last step of the clustering for the jet J, and split it into two sub-jets.
2. Check if these sub-jets pass the soft drop condition, which is defined for e^+e^- collisions as:

$$\frac{\min[E_i, E_j]}{E_i + E_j} > z_{\rm cut}(1 - \cos\theta_{ij})^{\beta/2} \quad \text{or} \quad z_{\rm cut}\left(\frac{1-\cos\theta_{ij}}{1-\cos R}\right)^{\beta/2}$$

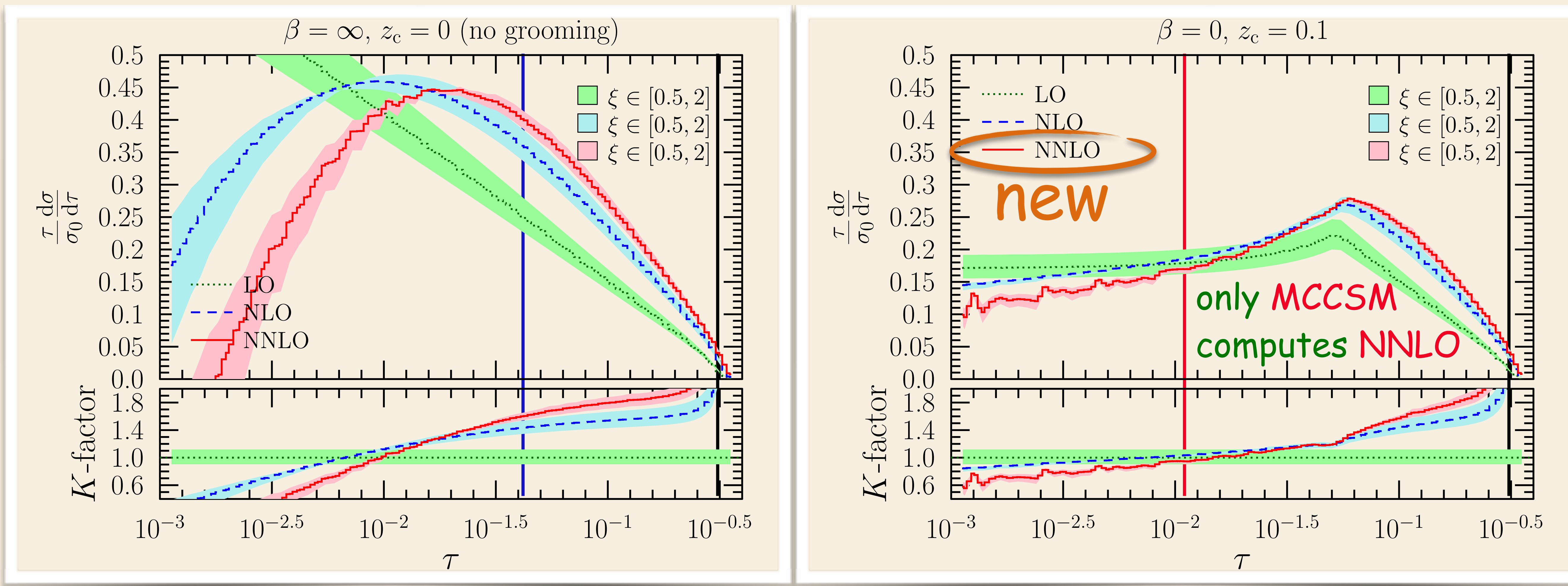
   where E_i and E_j are the energies of the two sub-jets and θ_{ij} is the angle between them.
3. If the splitting fails this condition, the softer sub-jet is dropped and the groomer continues to the next step in the clustering. In other words the jet J is set to be the harder of the two sub-jets.
4. If the splitting passes this condition the procedure ends and the jet J is the soft-drop jet.

Soft drop thrust had. corr. by PYTHIA



J. Baron et al, arXiv: 1803.04719

Soft drop thrust



K-factors are significantly smaller
for soft drop thrust
in the possible fit range

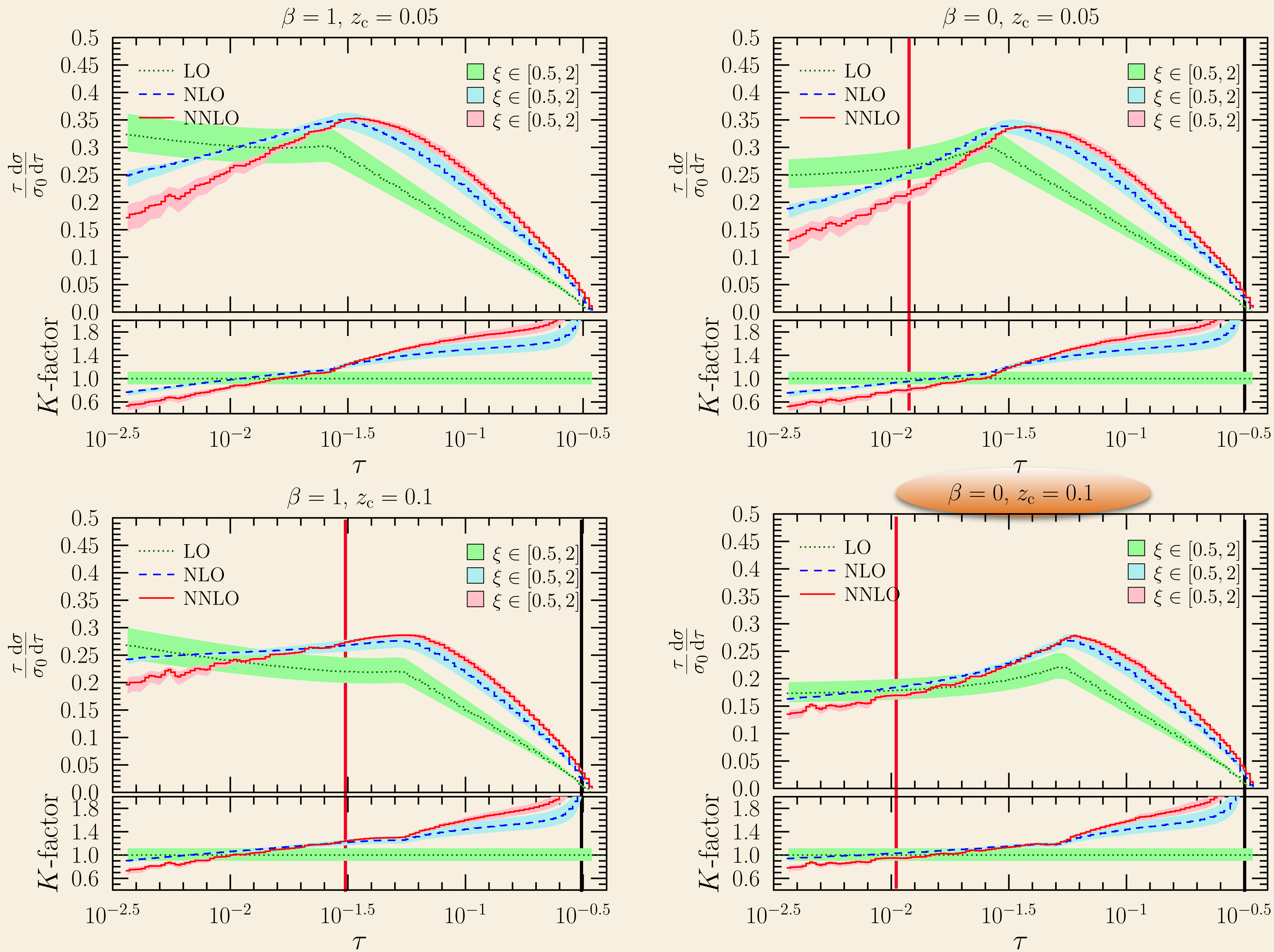
$$K_{\mathrm{NLO}}(\mu) = \frac{d\sigma_{\mathrm{NLO}}(\mu)}{dO} \bigg/ \frac{d\sigma_{\mathrm{LO}}(Q)}{dO}$$

$$K_{\mathrm{NNLO}}(\mu) = \frac{d\sigma_{\mathrm{NNLO}}(\mu)}{dO} \bigg/ \frac{d\sigma_{\mathrm{LO}}(Q)}{dO}$$

expect smaller dependence on renormalization scale

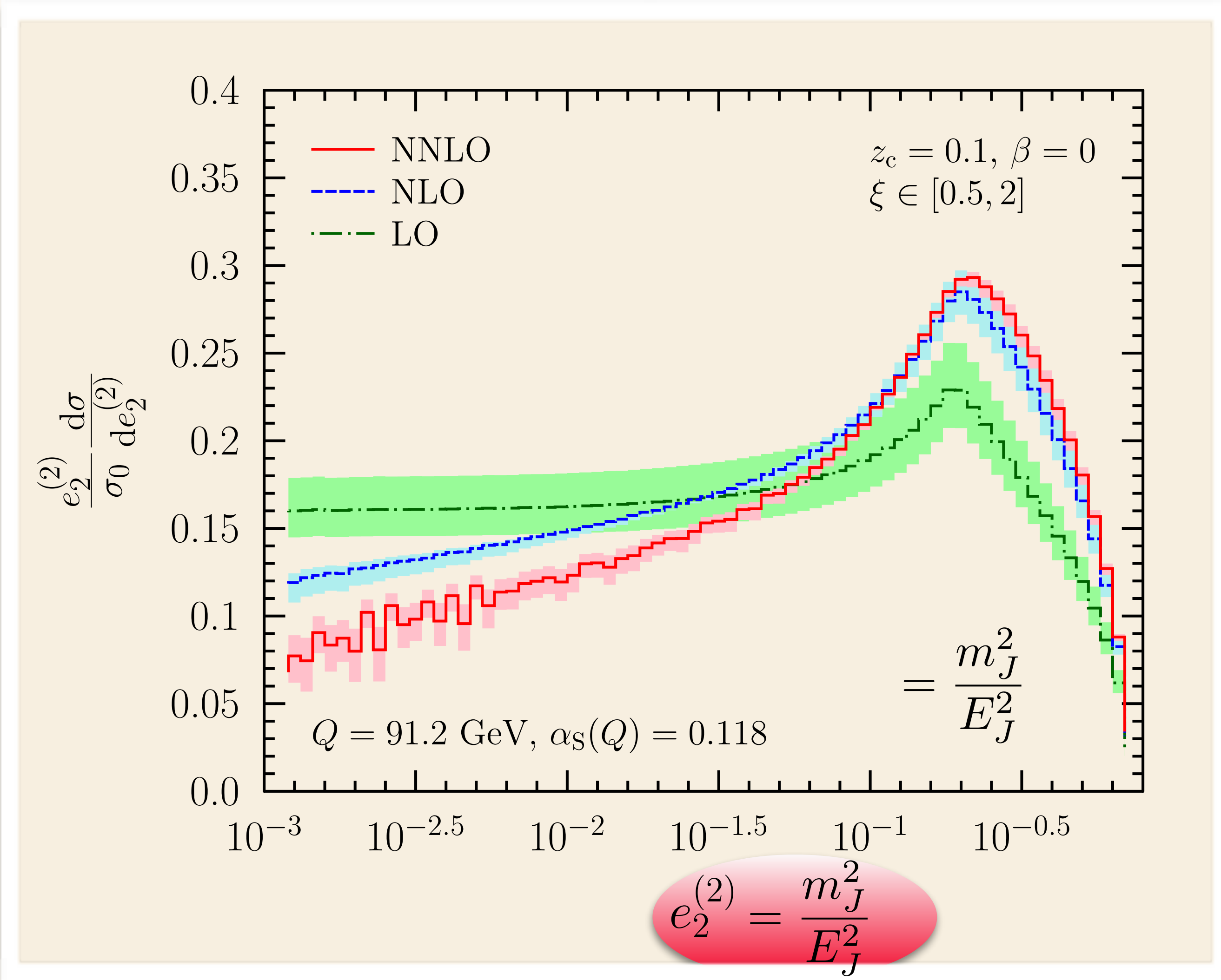
A. Kardos et al, arXiv: 1807.11472

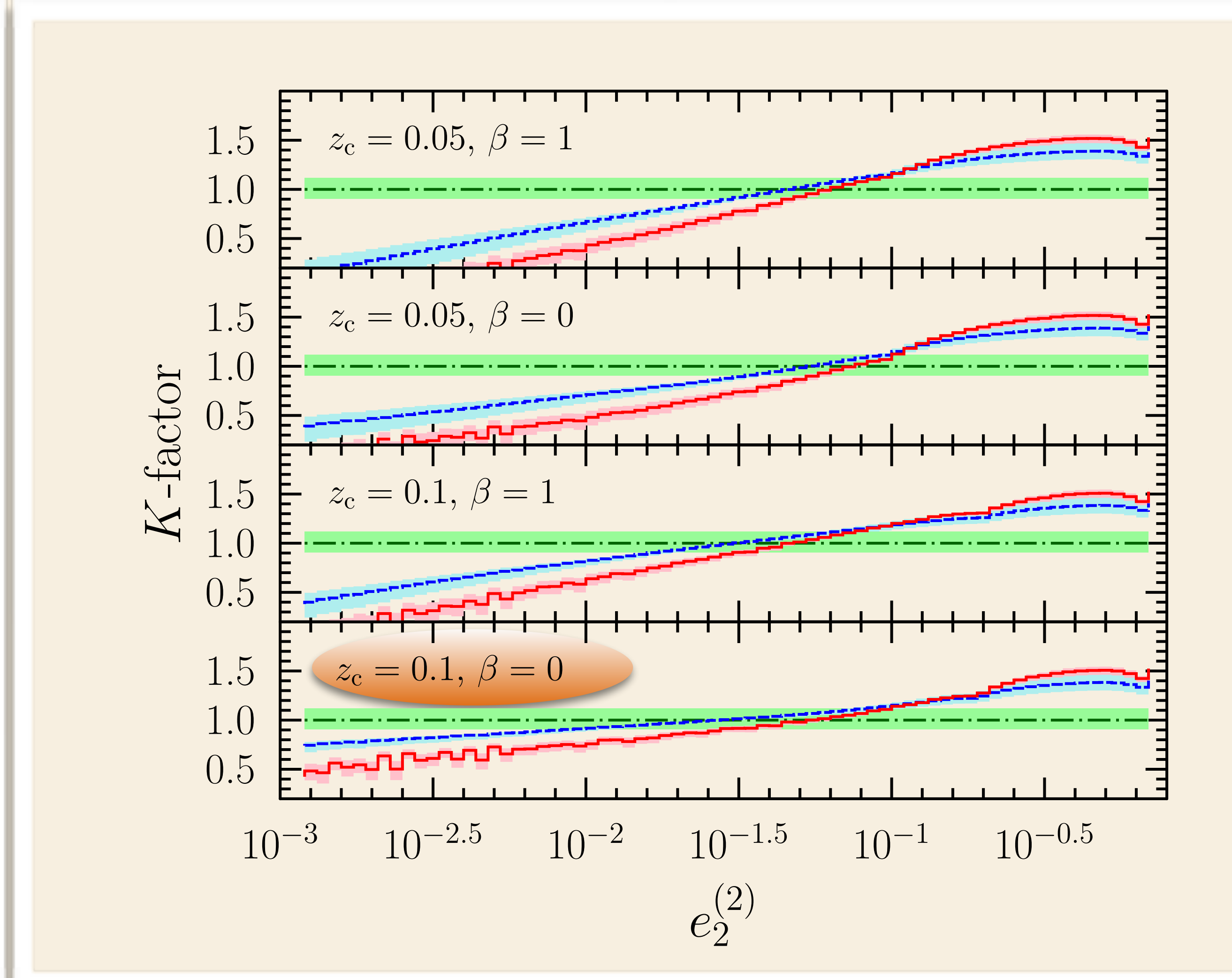
Soft drop thrust: reduced K factors



A. Kardos et al, arXiv: 1807.11472

Soft drop hemisphere mass





cluster an event into exactly two jets, J has larger mass

- similar conclusions for soft drop hemisphere mass
- resummation of large logarithms is in progress (Kardos, Larkoski, ZT)

A. Kardos et al, arXiv: 1807.11472

Conclusions

Conclusions

- ✓ Precise determination of the strong coupling using hadronic final states in electron-positron annihilation requires
  - careful selection of observables (and data — not discussed here)
  - methods to reduce hadronisation corrections
  - estimation of the hadronisation corrections with modern MCs
- ✓ MCCSM was used to compute differential distributions for groomed (soft drop) event shapes:
  - thrust
  - hemisphere invariant mass
  - narrow jet invariant mass (not shown here)
- ✓ Our predictions
  - are stable numerically
  - show better perturbative stability (smaller scale dependence) than un-groomed event shapes
- ✓ Ressummation of soft drop hemisphere mass is in progress

Outlook: prospects for α_s

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry $\sim$ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
ep colliders	$\sim$ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])

J.M. Campbell et al [Snowmass], arXiv: 1310.5189

Determination of strong coupling from e^+e^- data with decreased theoretical uncertainty might be possible