Precise determinations of the strong coupling in lepton collisions

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based on

arXiv:1603.08927, 1606.03453, 1708.04093, 1804.09146, 1807.11472, 1902.08158

and unpublished results of ongoing work

FFK-2019, Tihany

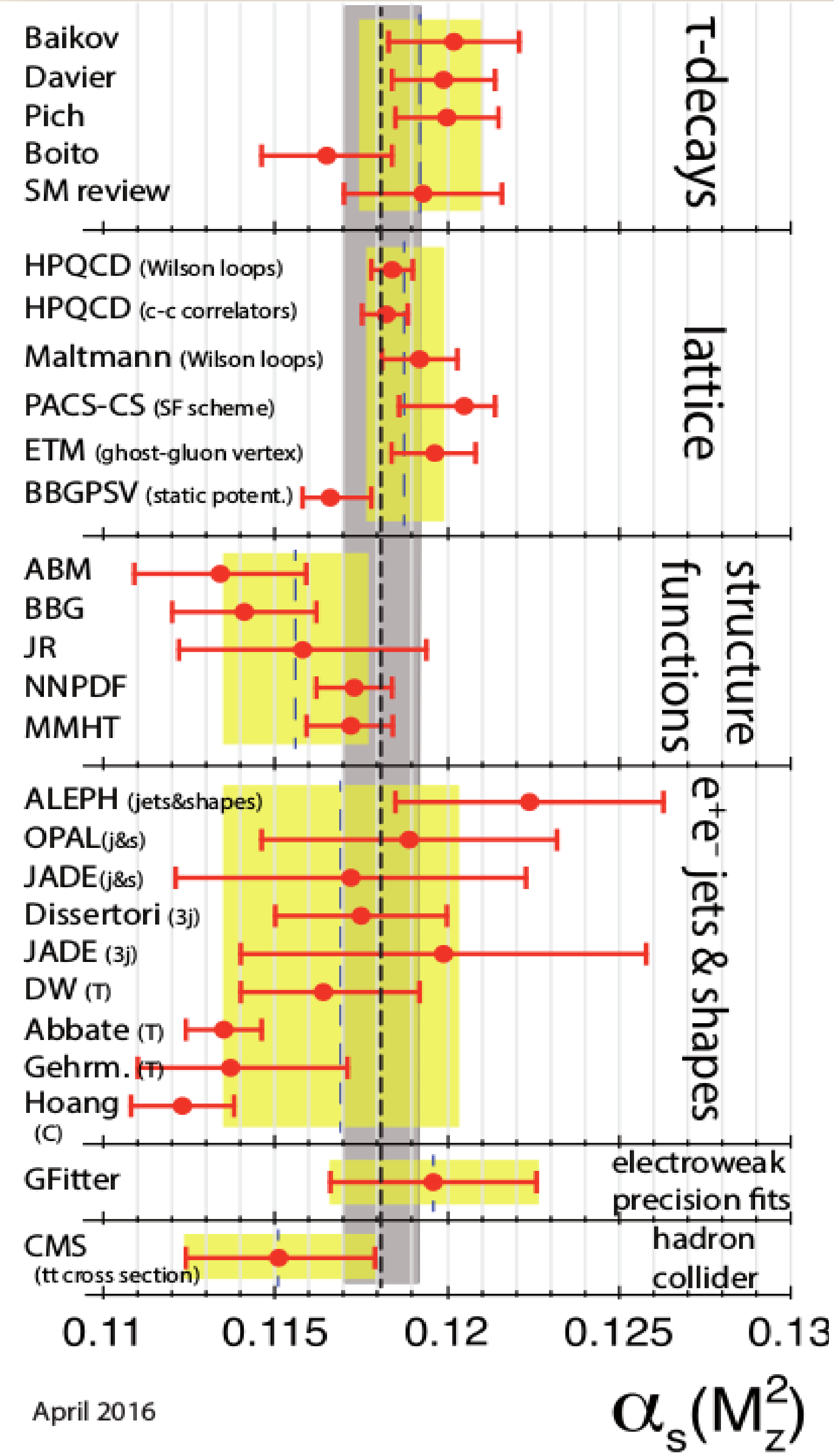
12 June 2019

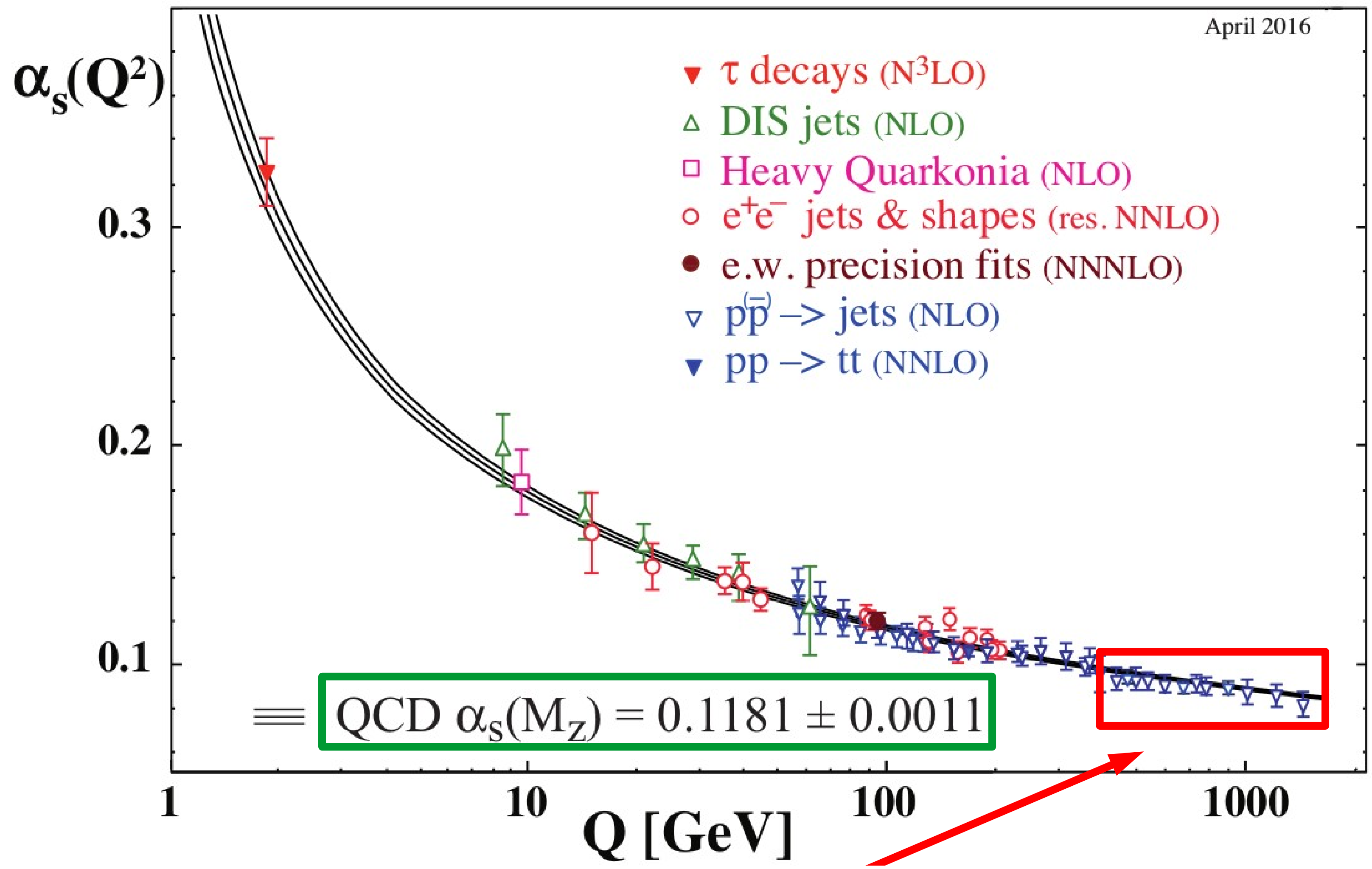
Outline

- Status of the strong coupling
- New measurements of α_s
- Conclusions and Outlook

Status of the strong coupling

PDG 2016 on α_s





not included in average:
LHC data, but only NLO theory

dominated by lattice

$$\frac{\Delta\alpha_S(M_Z)}{\alpha_S(M_Z)} = 0.9\%$$

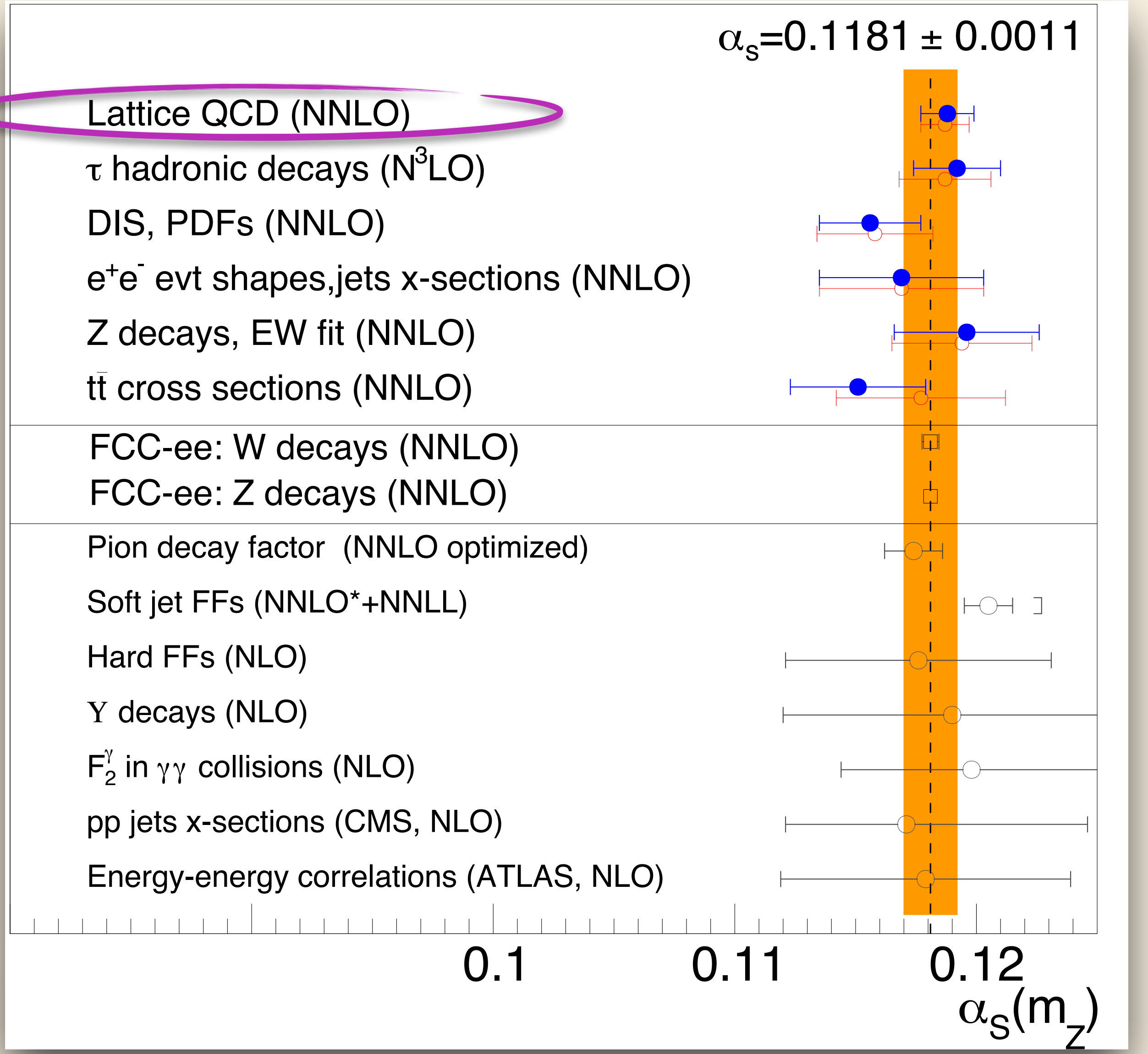
PDG, Chin. Phys. C40 (2016) 100001

PDG 1992: 2.4%

Lattice unbeatable?

- recent prevailing view:

  lattice is unbeatable



D. d'Enterria, arXiv: 1806.06156

Lattice unbeatable?

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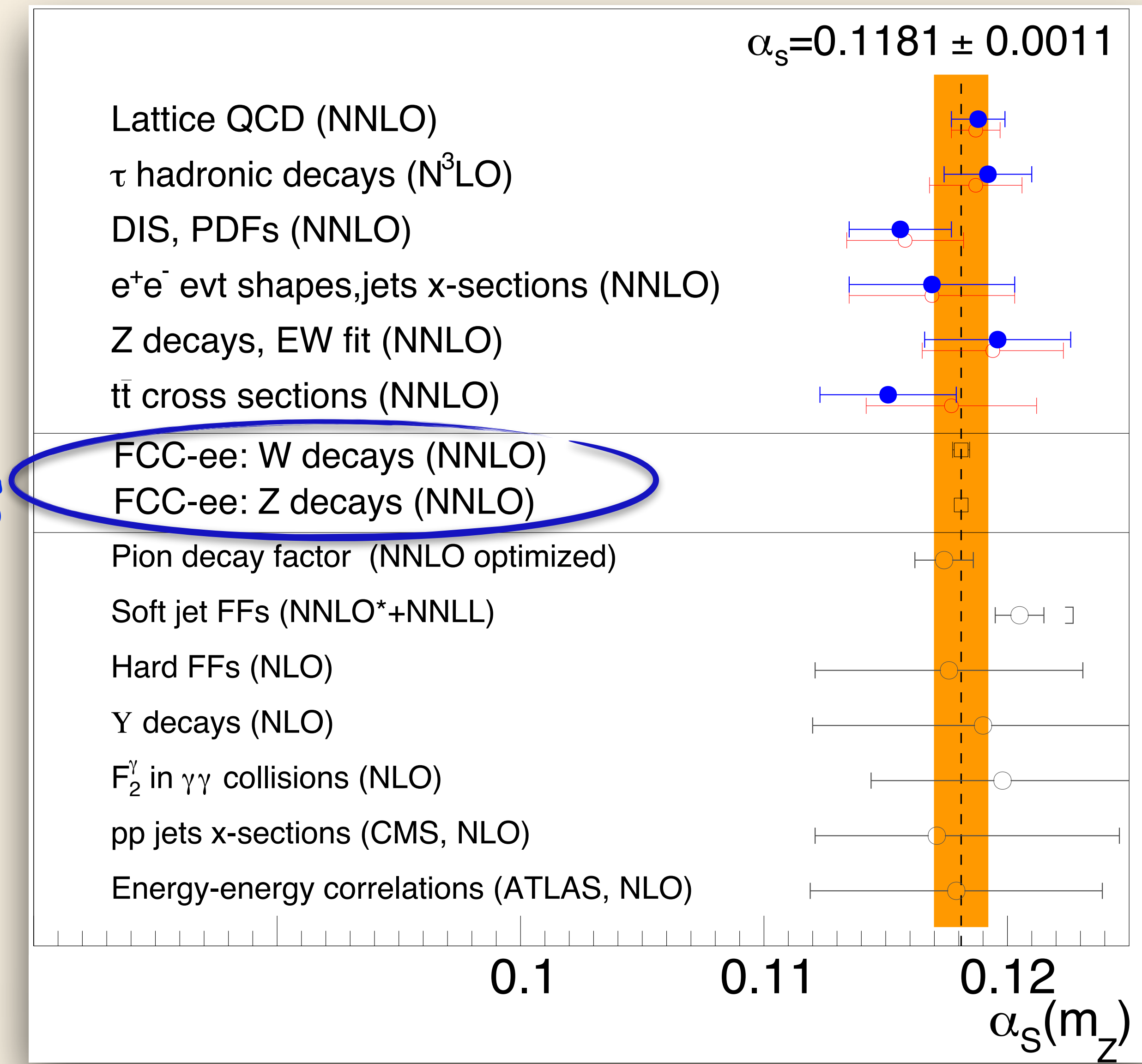
- yet determination of α_s from experiments remains desirable (or at least a fancy)



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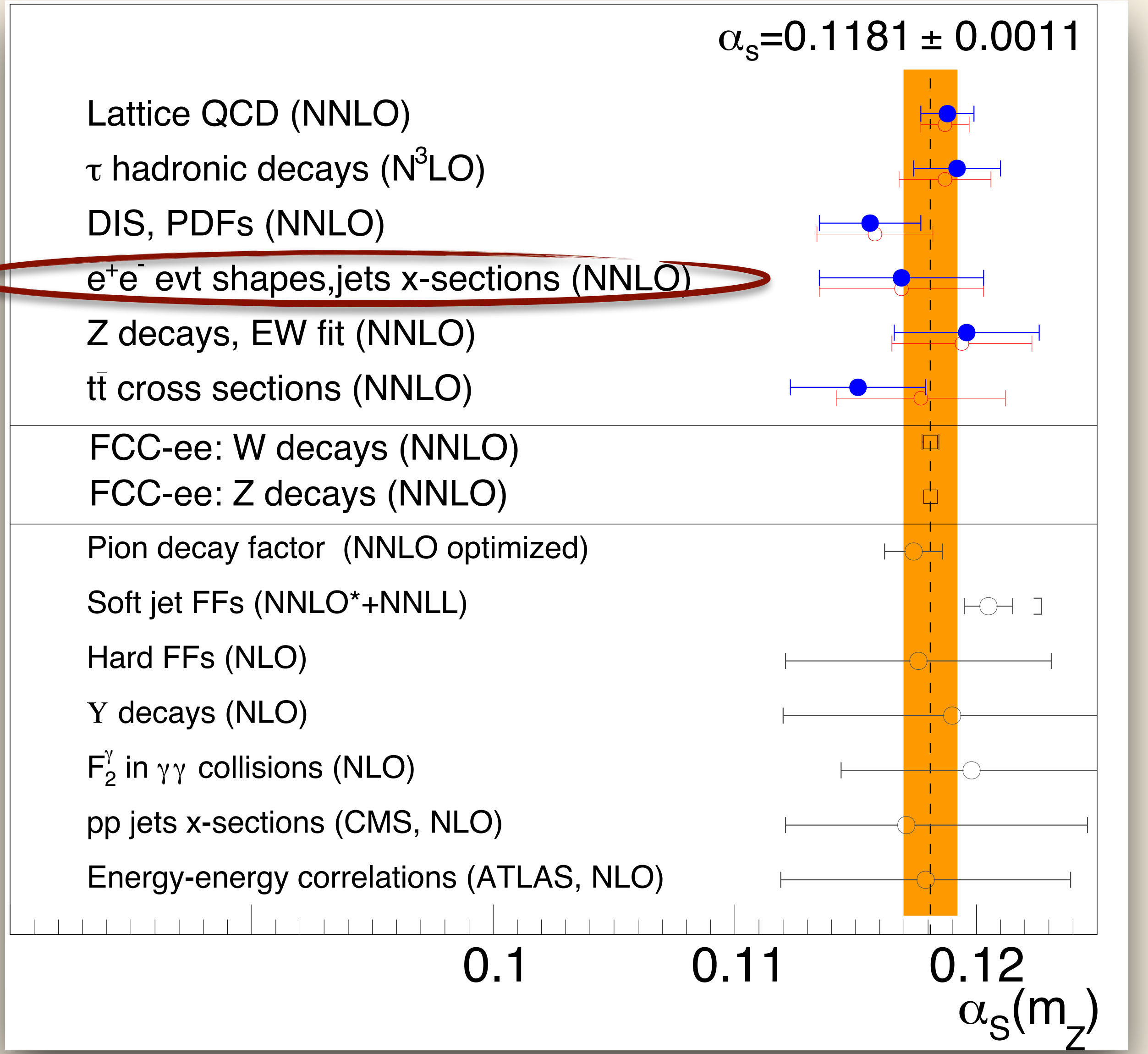
Lattice unbeatable?

- recent prevailing view: lattice is unbeatable
- yet determination of α_s from experiments remains desirable (or at least a fancy)
- e^+e^- event shapes, jets



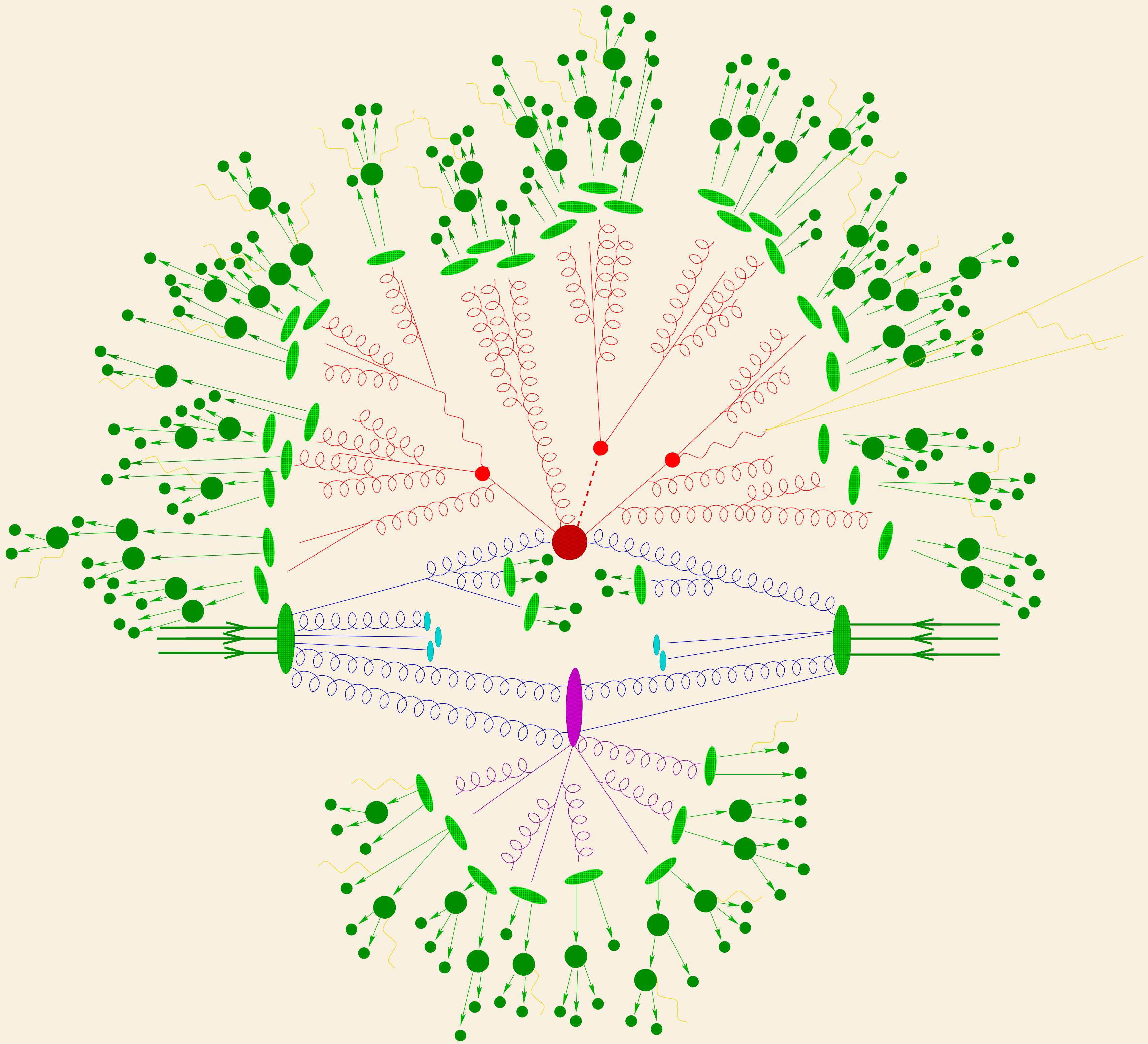
D. d'Enterria, arXiv: 1806.06156

✓ are sensitive to α_s

✓ are measured extensively

✓ can almost be computed from first principles (assuming local parton-hadron duality)

Our picture of a high-energy particle collision



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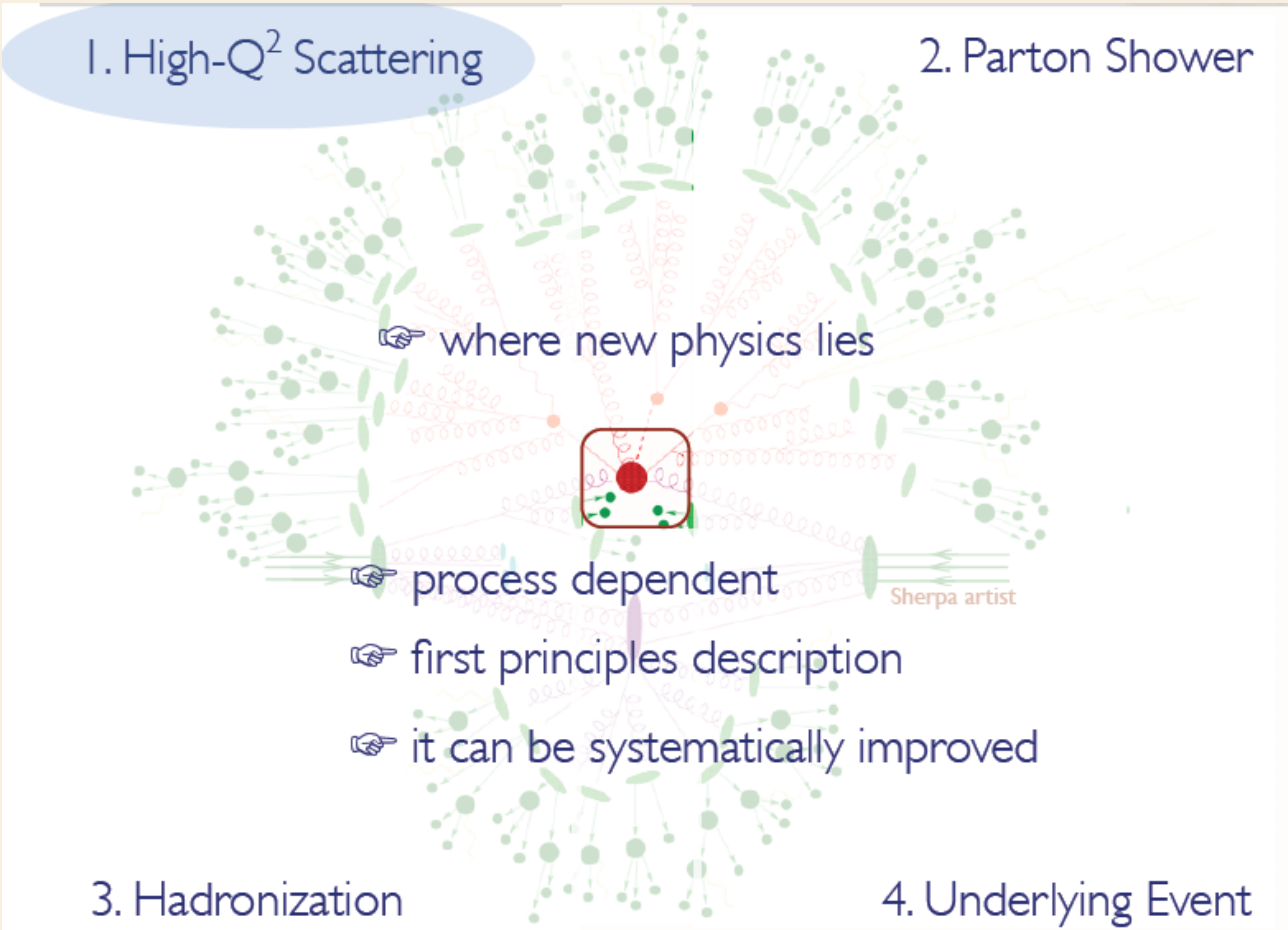

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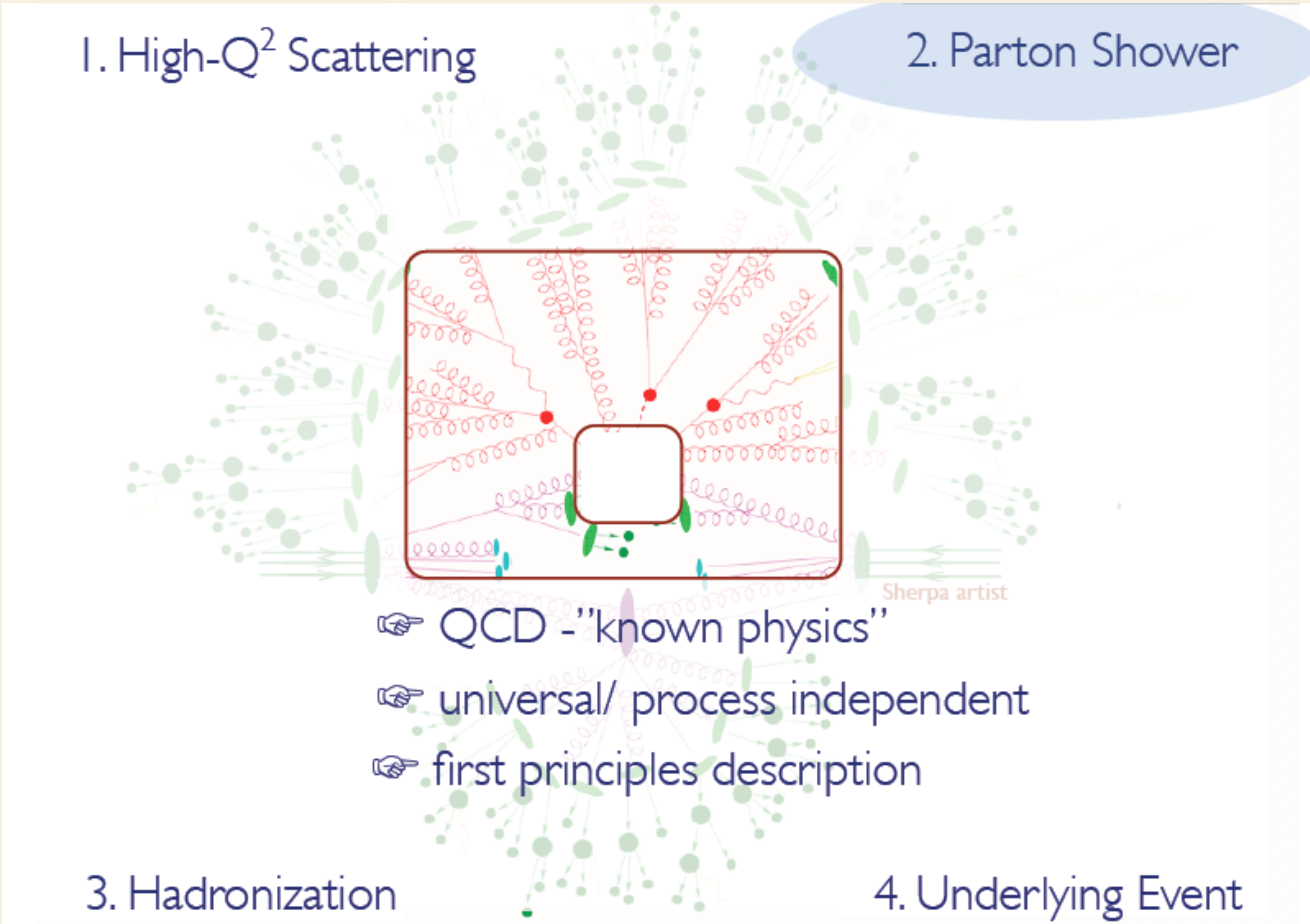

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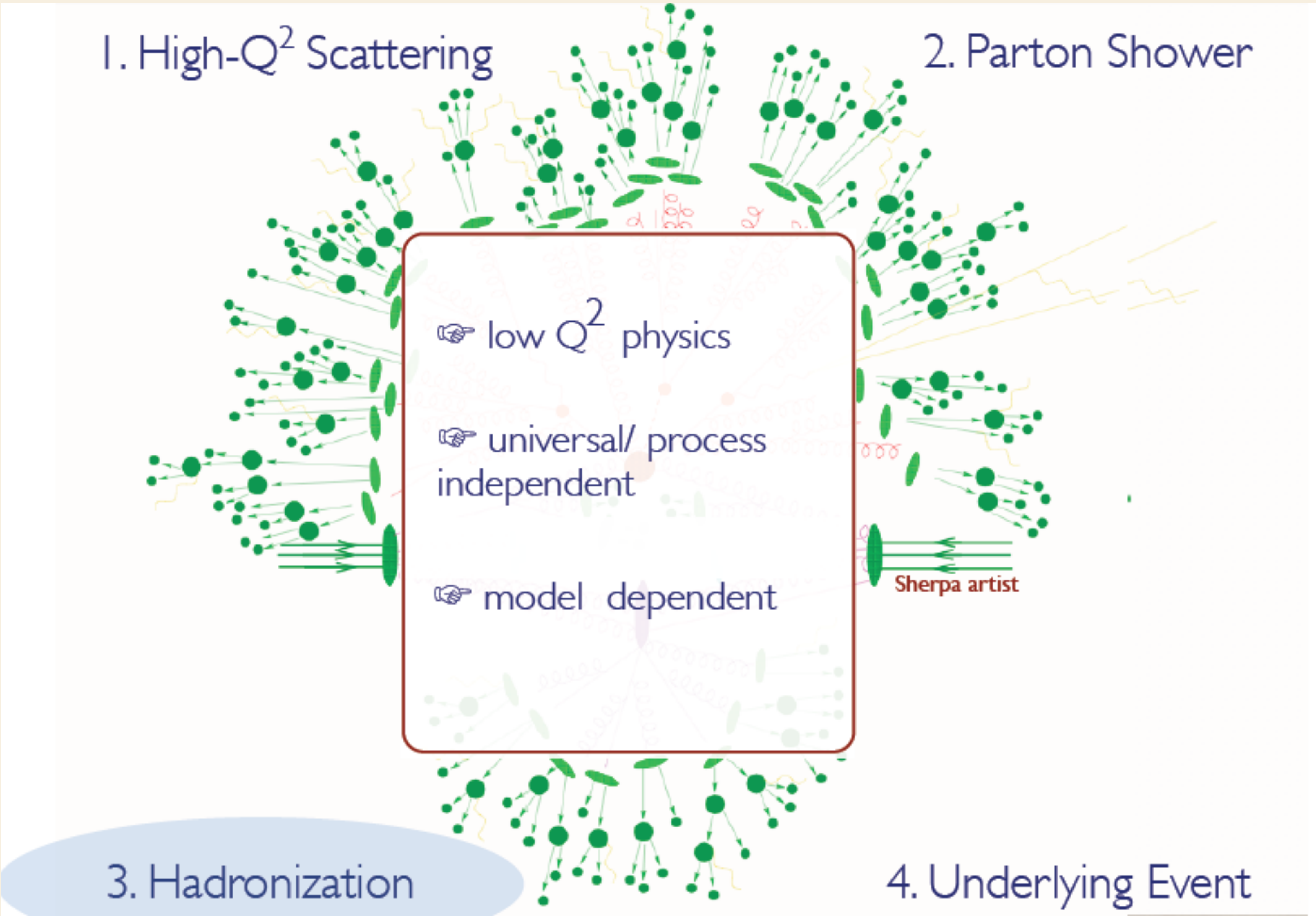

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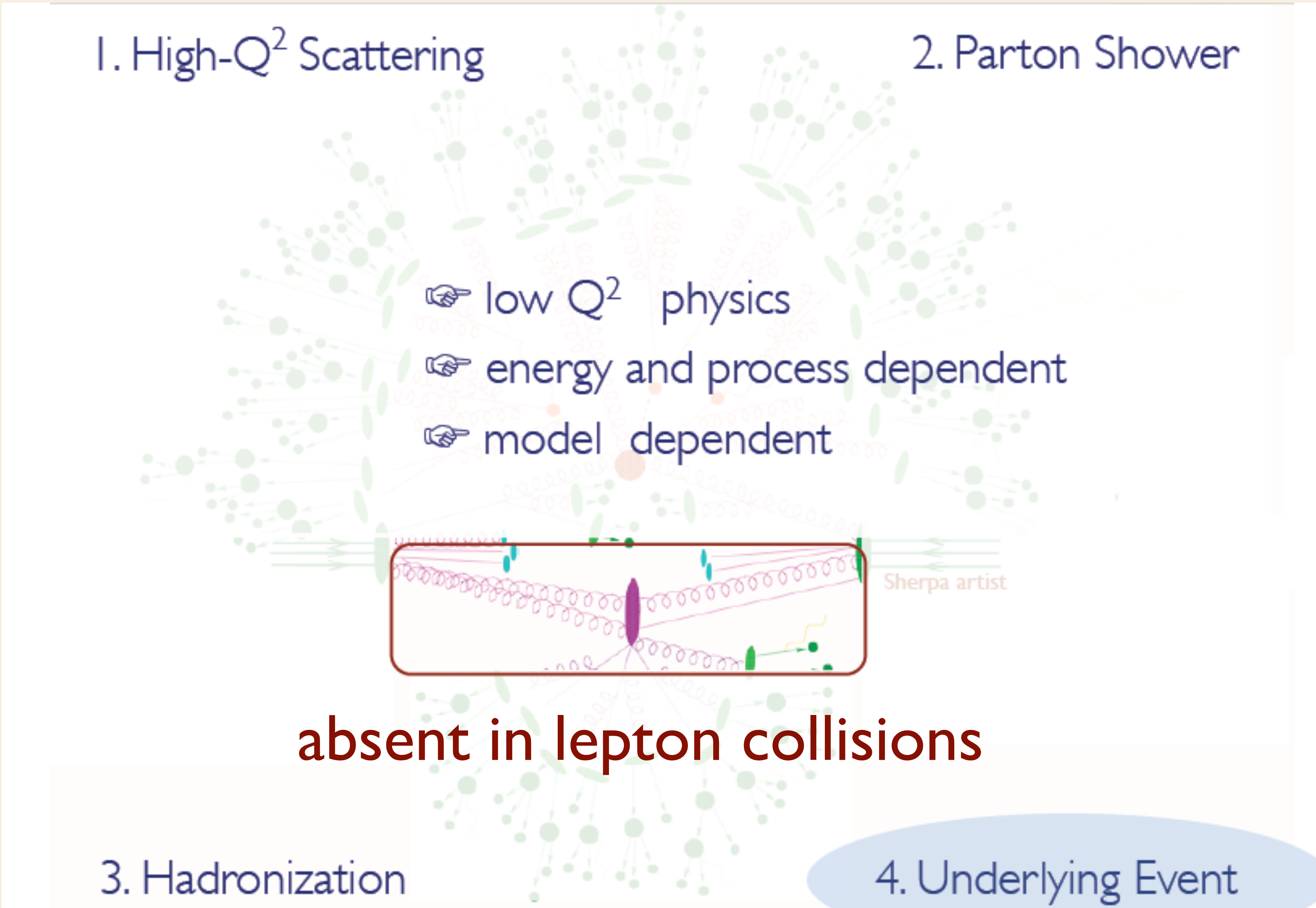
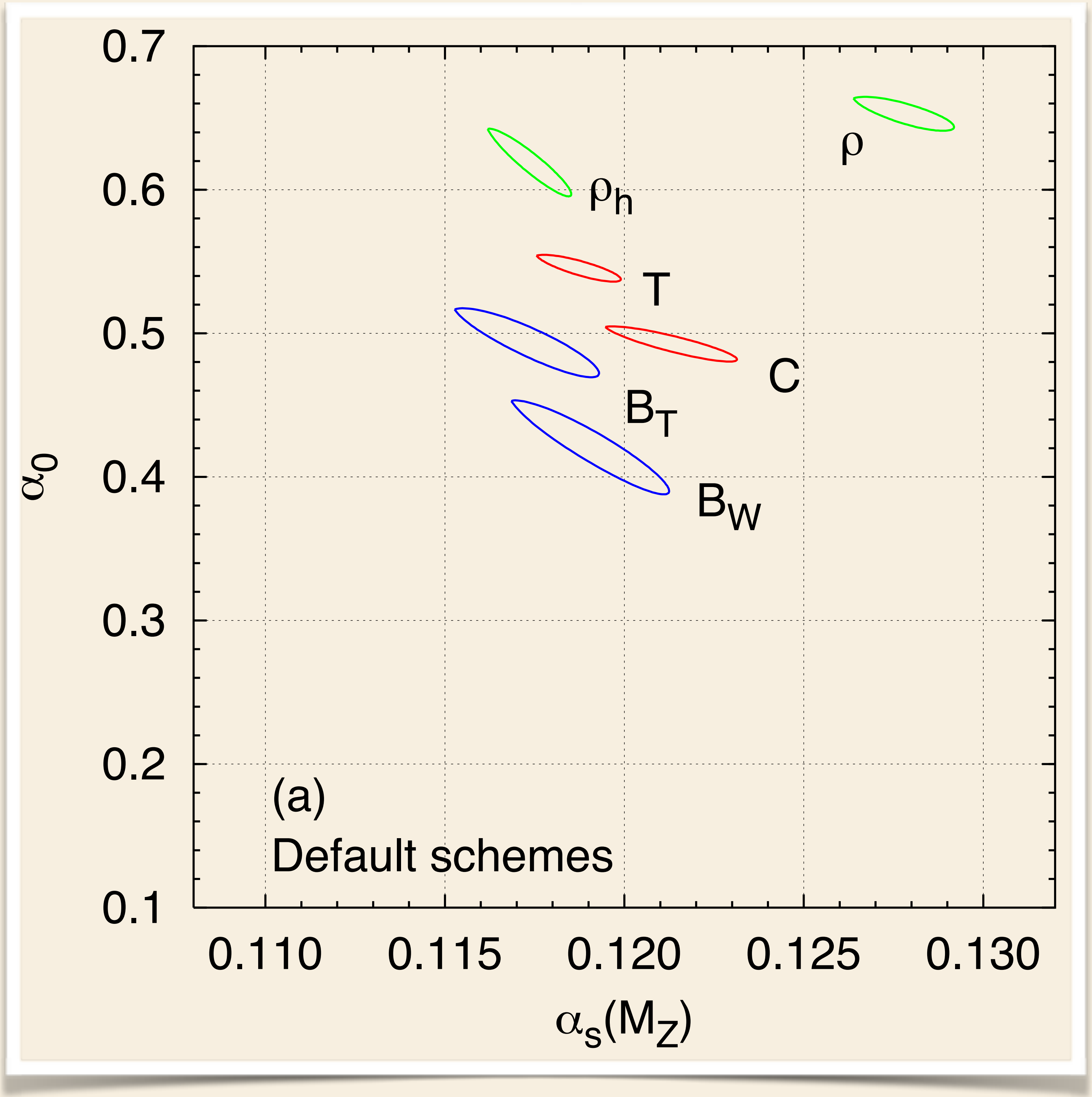
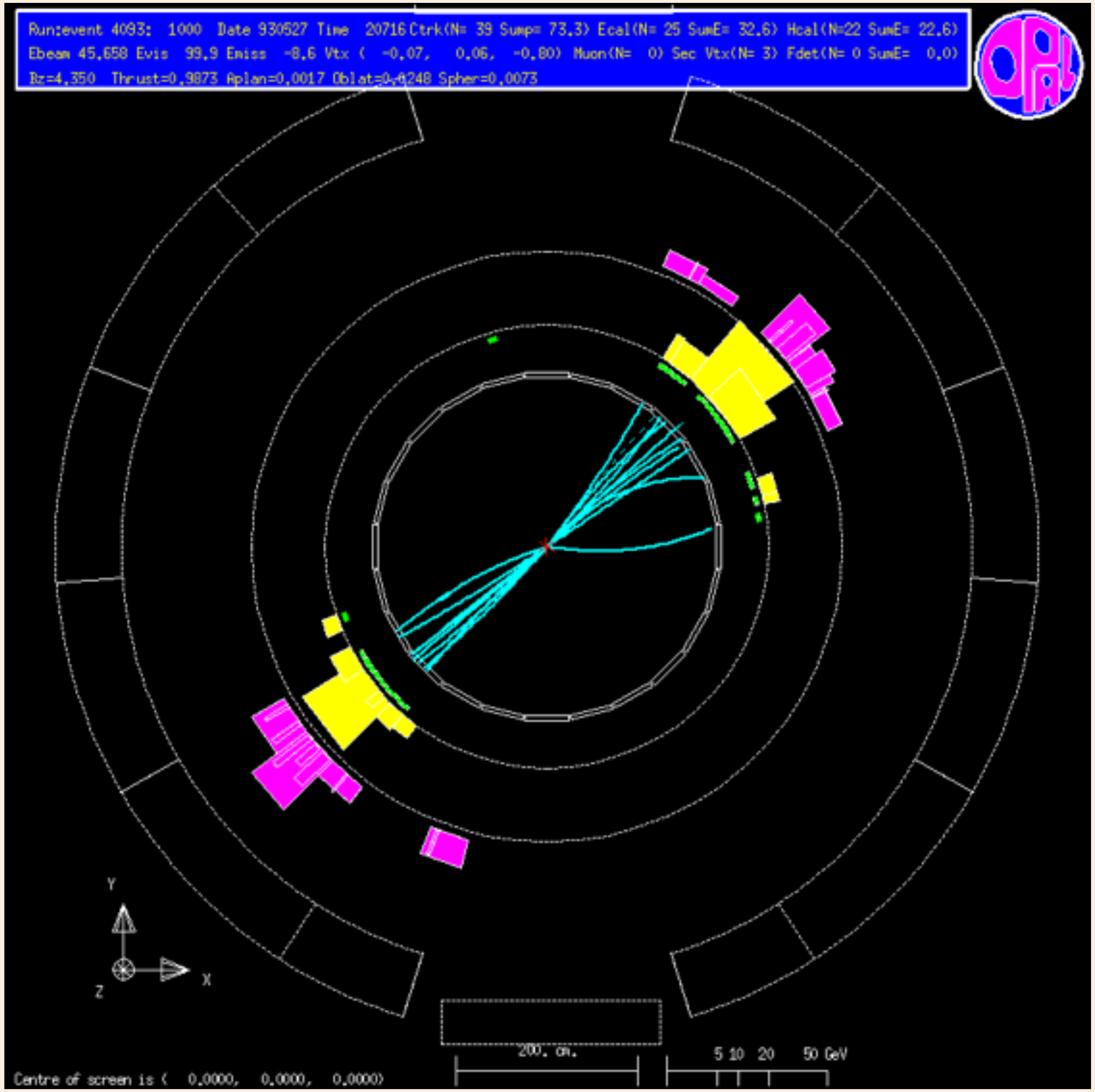


Shapes at NLO+NLL+power corr.+had. mass at LEP



D. Wicke, G. Salam hep-ph/0102343

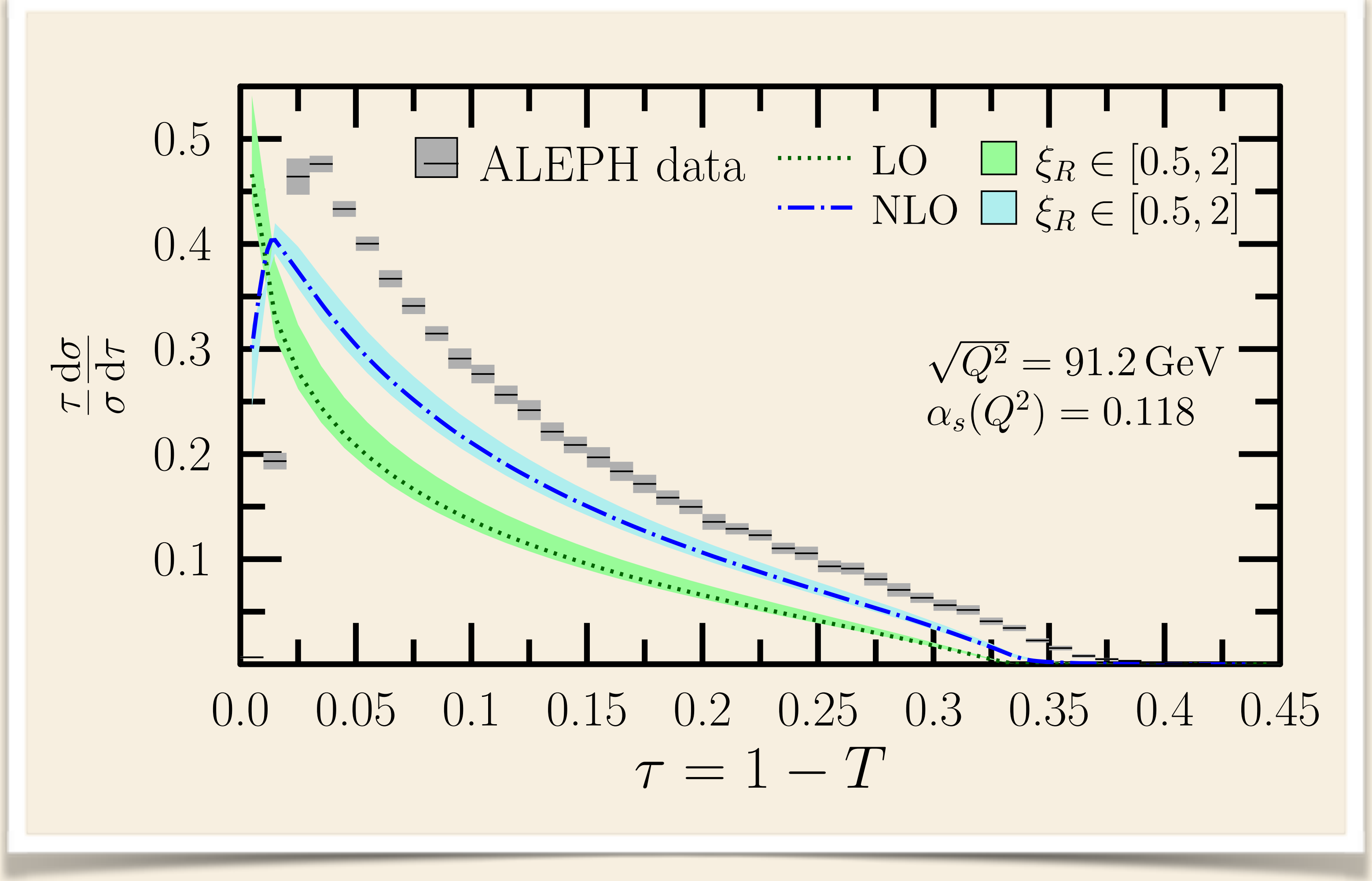
T = thrust: how pencil-like is the event



Three-jet event shapes at LEP

- LO vs. NLO vs. data:

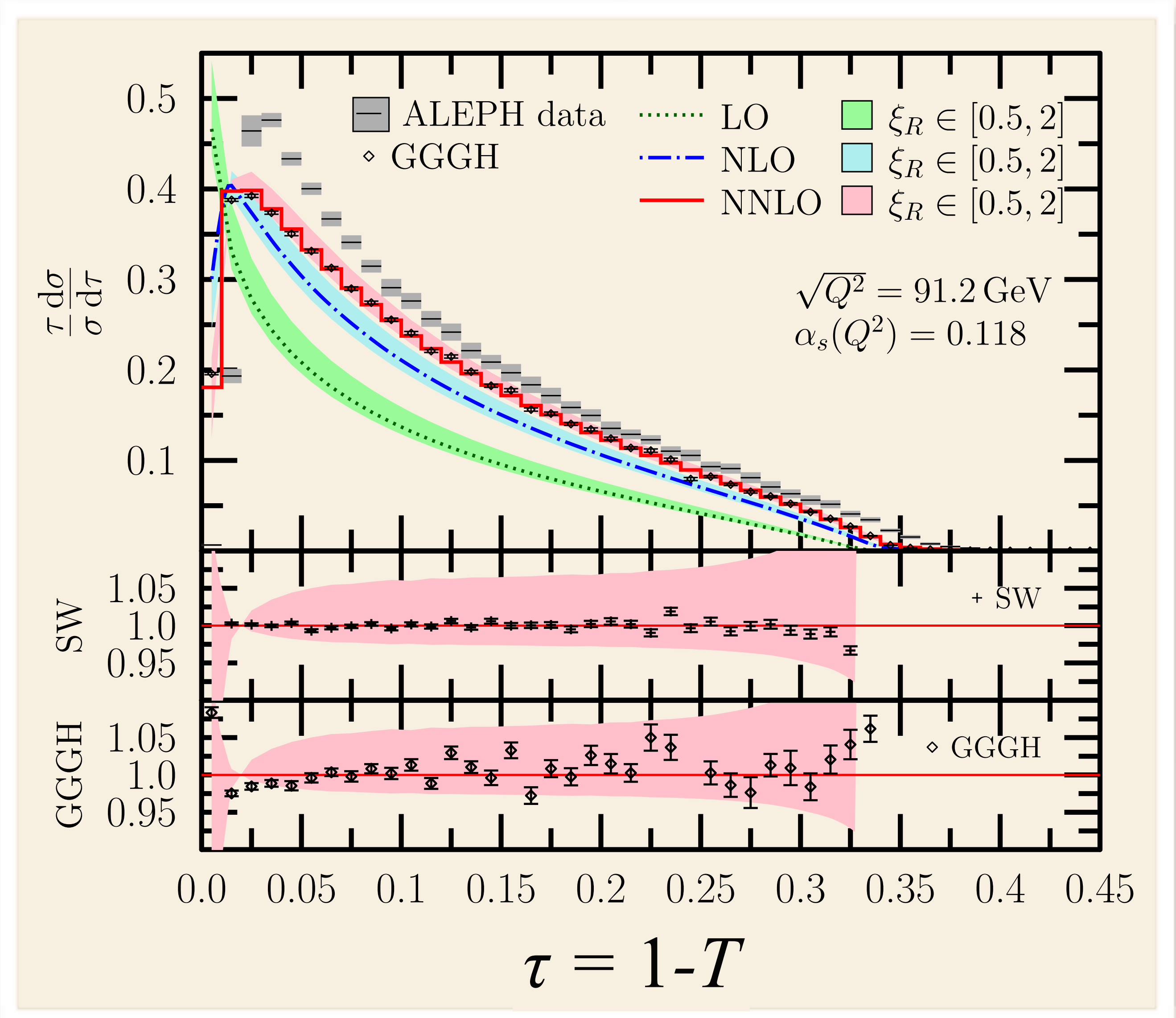
  suffer large perturbative & hadronization corrections



- new since LEP:
  - ✓ NNLO corrections
  - ✓ N^2LL or N^3LL resummation

New measurements of α_s

NNLO is not enough



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

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

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

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

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

$$L = -\ln\tau$$

LL NLL N^2LL N^3LL …

needs resummation of all orders

How to improve?

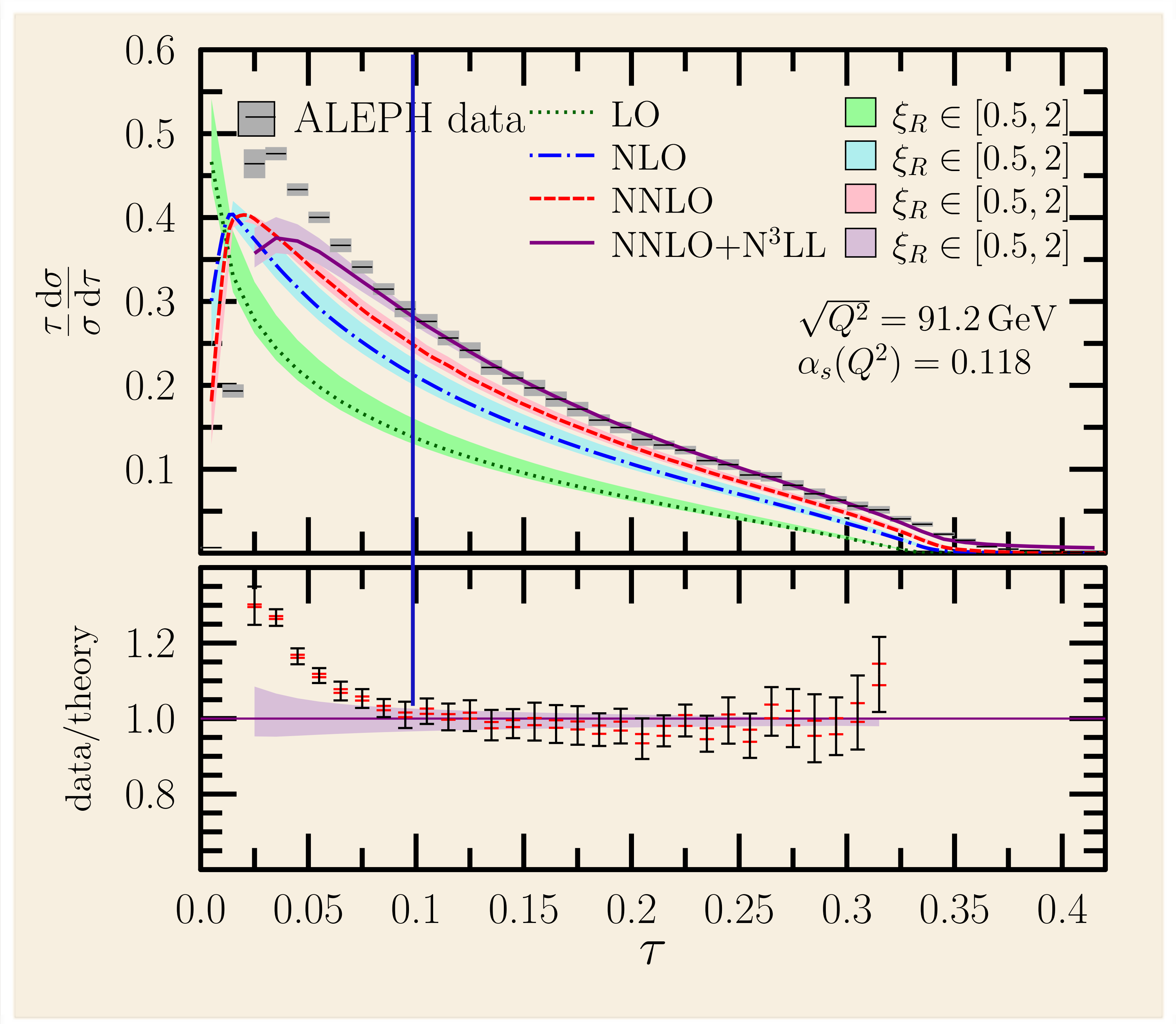
✓ Match to approximate predictions that resum large logarithms of the event shapes

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 N^3LL



Works for τ > 0.1, fails in peak regions

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

✓ Correct for hadronisation

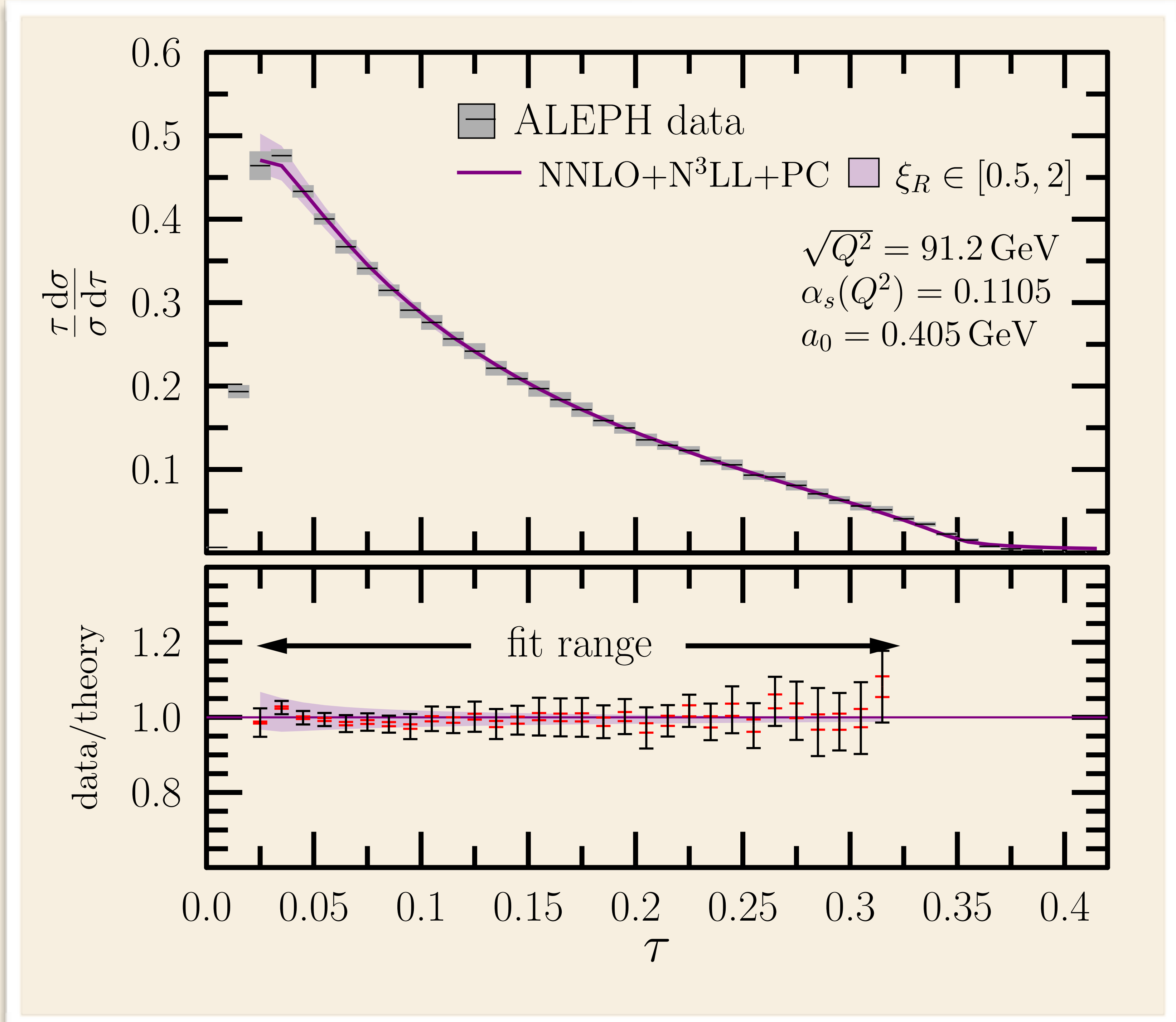
two options:

– estimate of hadronisation using modern MC tools

– use analytic model for power corrections, e.g.:

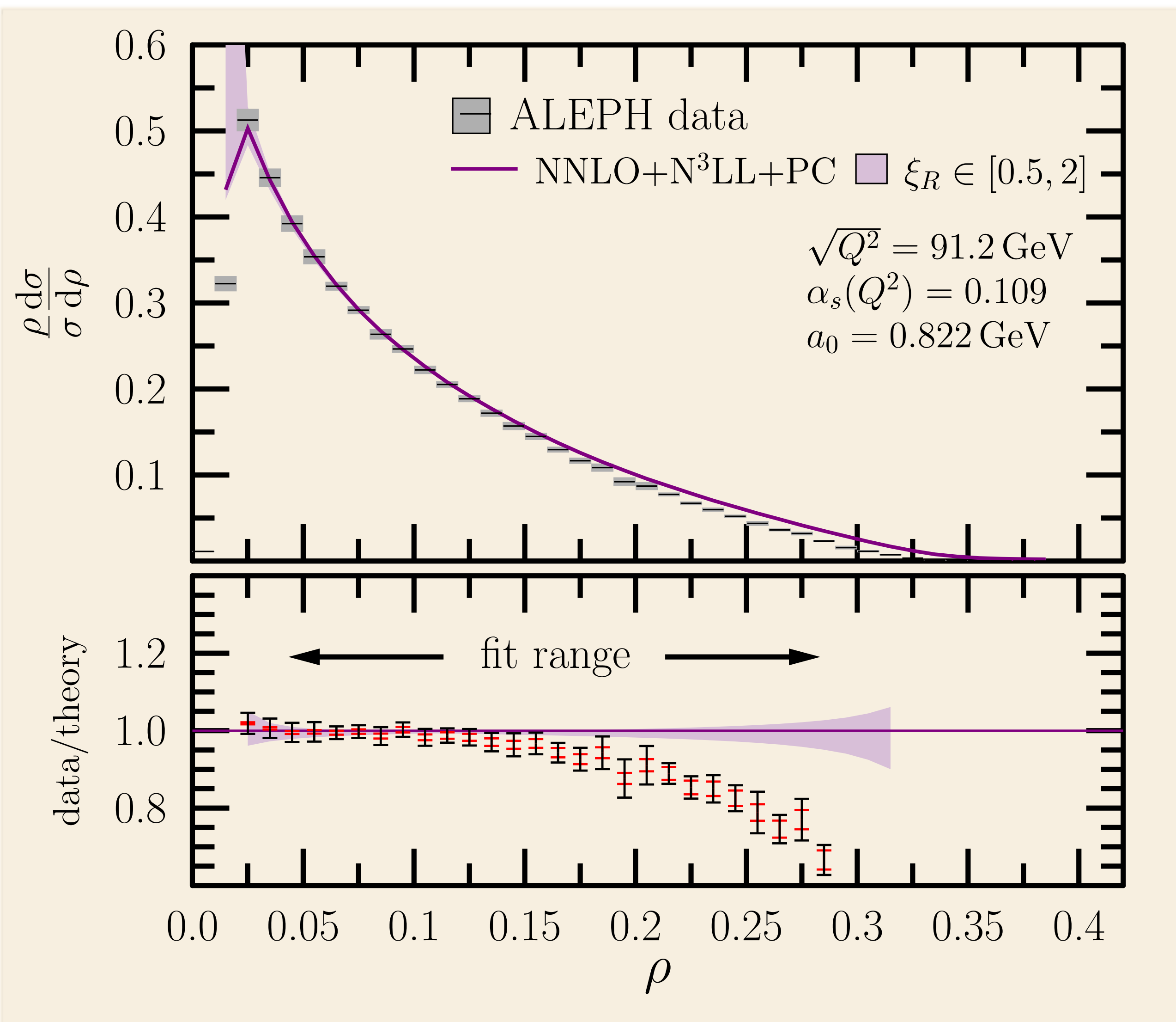
$$\frac{\tau}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\tau}(\tau) \to \frac{\tau}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\tau}(\tau - 2a_0)$$

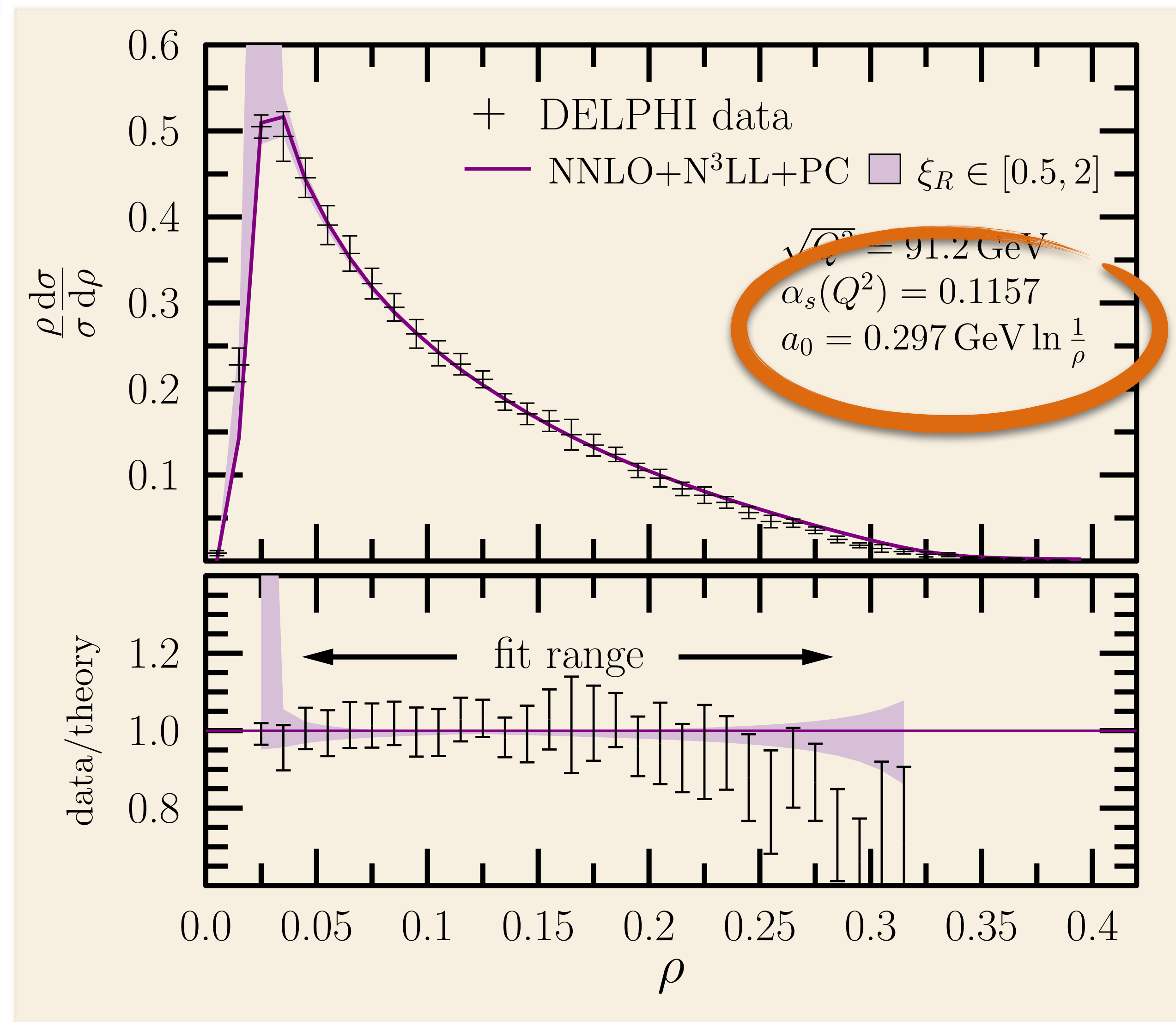
Fit to data with NNLO+N^{3}LL+PC



Works down to the peak, but

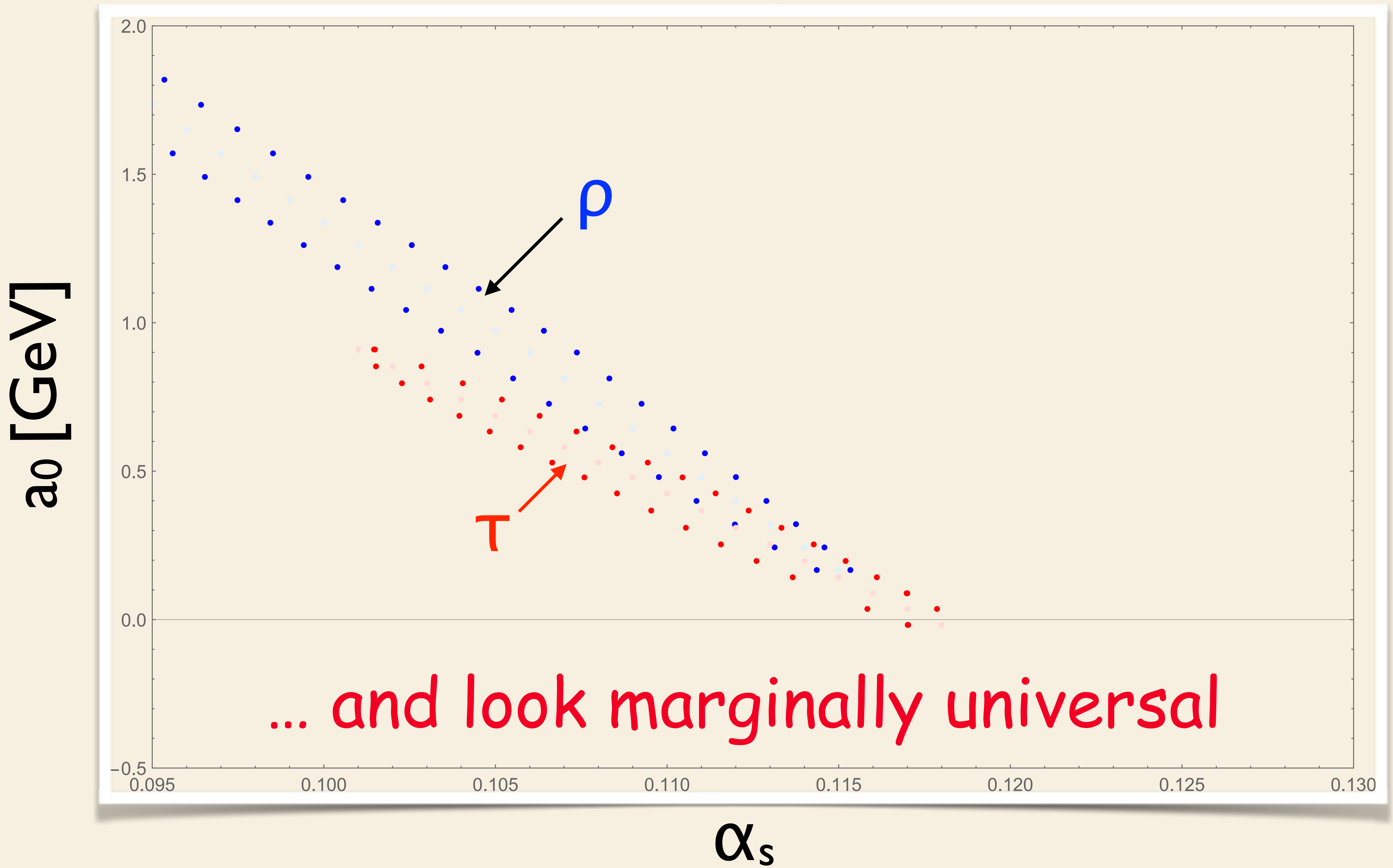
Fit data on heavy jet mass with NNLO+N^{3}LL+PC



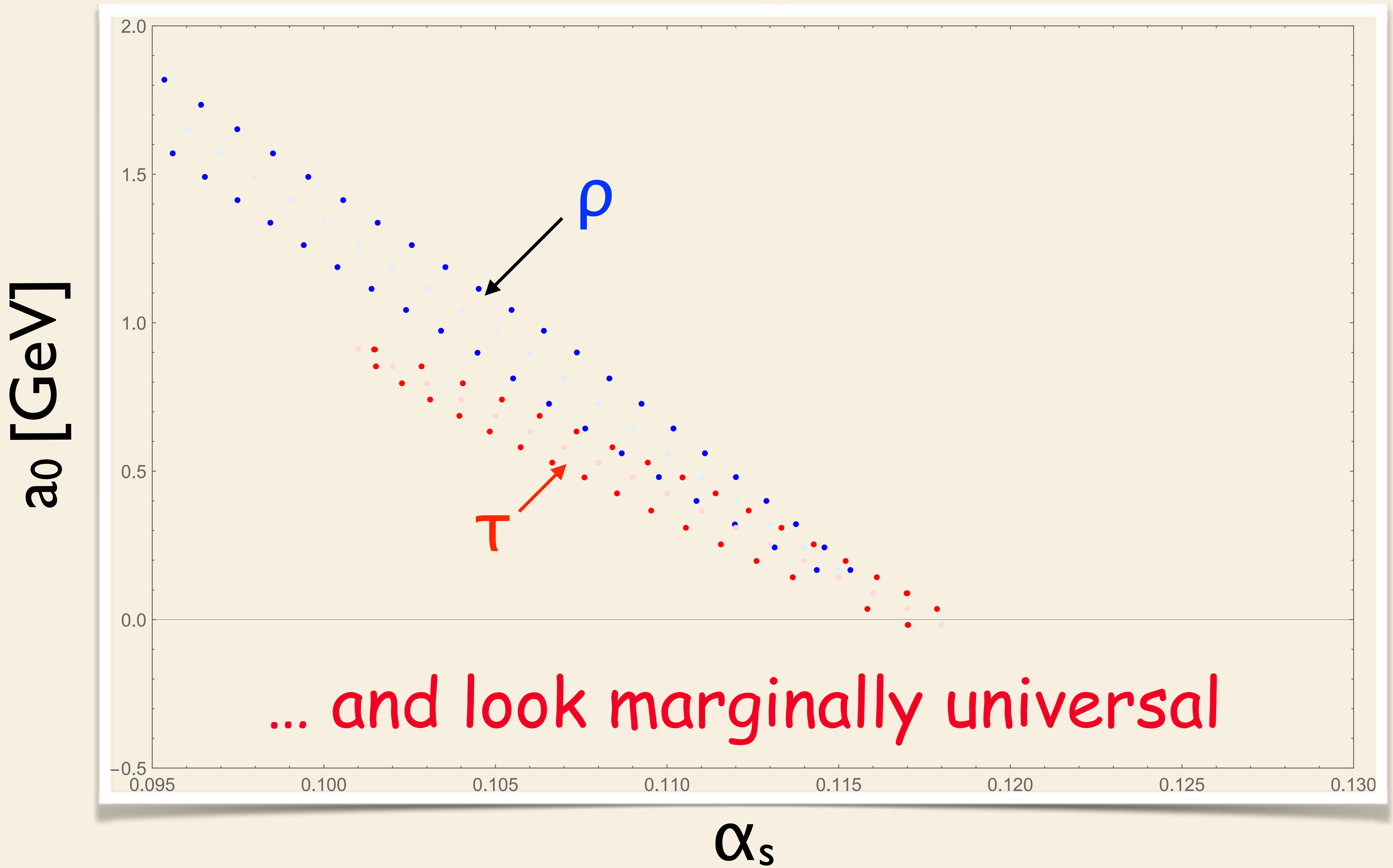


... not as expected

Fit to data with PC

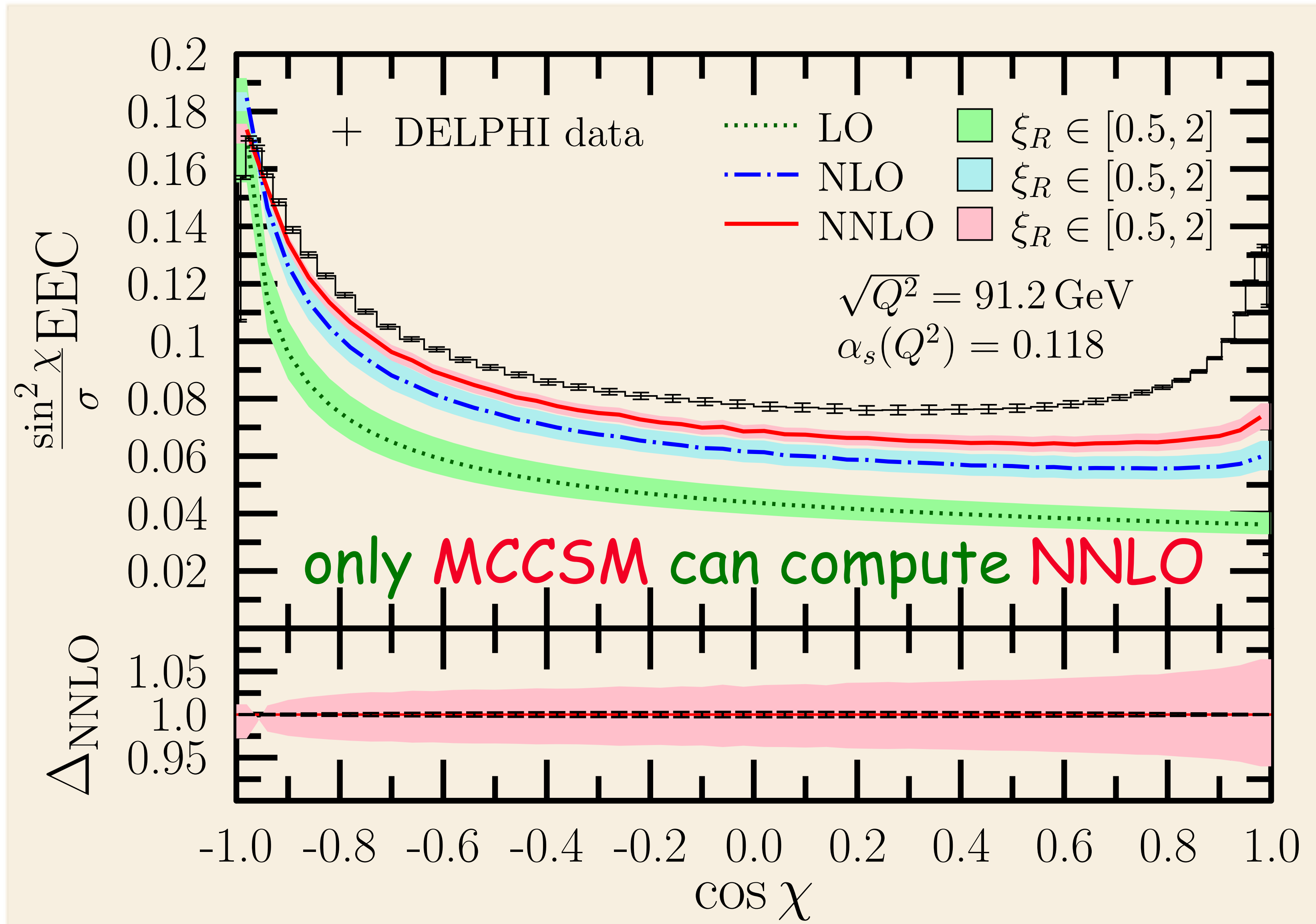


Fit to data with PC



but a_0 and α_s are strongly anticorrelated

EEC @ fixed orders

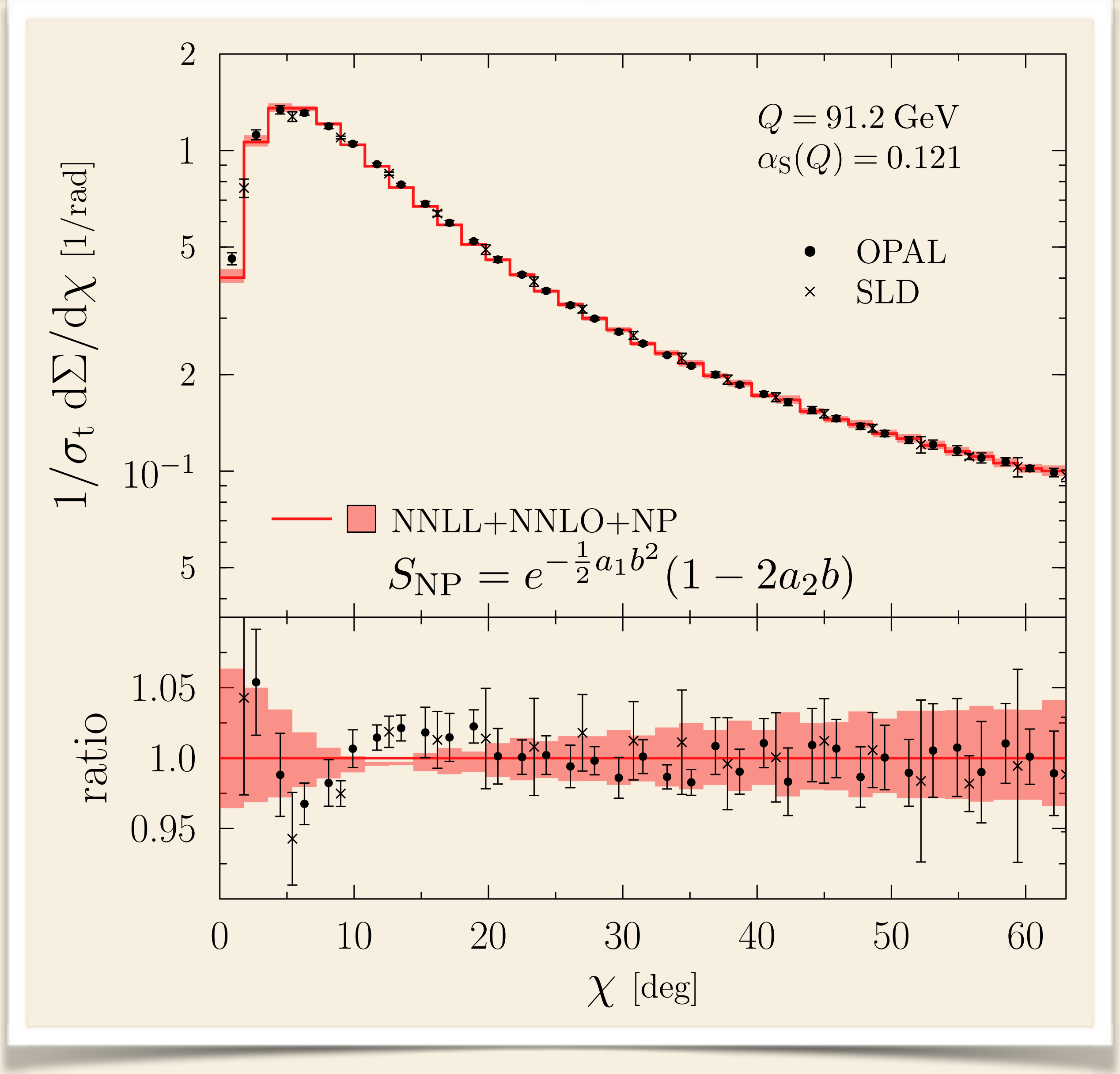


large corrections

$$\mathrm{EEC}(\chi) = \frac{1}{\sigma_{\mathrm{had}}} \sum_{i,j} \int \frac{E_i E_j}{Q^2} \times \mathrm{d}\sigma_{e^+e^- \to i\,j+X}\, \delta(\cos\chi + \cos\theta_{ij})$$

V. Del Duca et al, arXiv:1603.08927

EEC @ NNLO+NNLL+NP

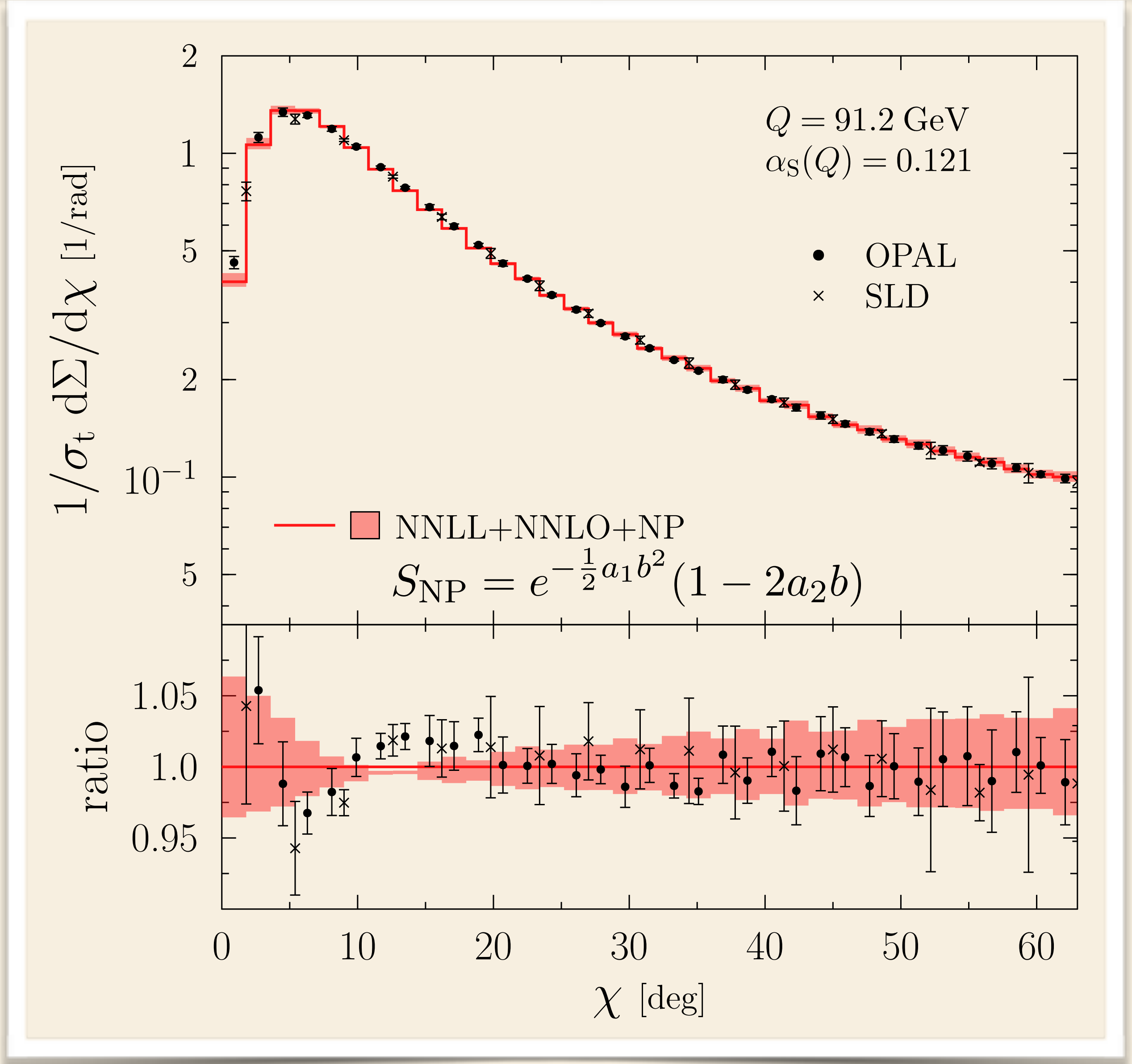


$$\alpha_S(M_Z) = 0.121^{+0.001}_{-0.003} \qquad a_1 = 2.47^{+0.48}_{-2.38}\ \text{GeV}^2 \qquad a_2 = 0.31^{+0.27}_{-0.05}\ \text{GeV}$$

$$\text{corr}(\alpha_S, a_1, a_2) = \begin{pmatrix} 1 & 0.05 & -0.97 \\ 0.05 & 1 & -0.07 \\ -0.97 & -0.07 & 1 \end{pmatrix}$$

Z. Tulipánt et al, arXiv:1708.04093

EEC @ NNLO+NNLL+NP



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☞ parameters are strongly anticorrelated

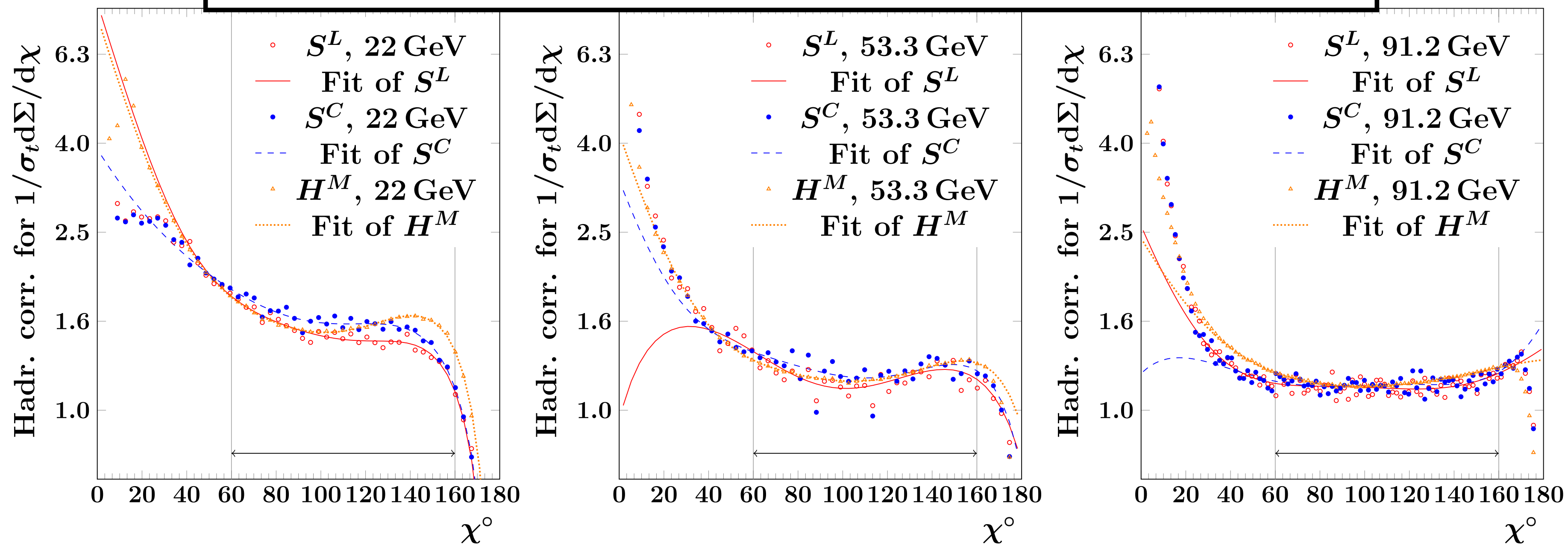
Z. Tulipánt et al, arXiv:1708.04093

How to improve?

✓ Correct for hadronisation, 2nd option:

– estimate of hadronisation using modern MC tools

$$\frac{1}{\sigma_t}\frac{d\Sigma}{d\cos\chi} = \frac{1}{\sigma_t}\int \sum_{i,j} \frac{E_i\, E_j}{Q^2} d\sigma_{e^+e^-\to ij+X}\delta(\cos\chi + \cos\theta_{ij})$$



Hadronization corrections are parametrized using smooth functions to tame statistical fluctuations

Parametrization is valid only in the fit range

Z. Tulipánt et al, arXiv: 1804.09146

Fit results

Global fit at NNLL+NLO:

$\alpha_S(M_Z) = 0.12200 \pm 0.00023(exp.) \pm 0.00113(hadr.) \pm 0.00433(ren.) \pm 0.00293(res.)$

with combined uncertainty: $\alpha_S(M_Z) = 0.12200 \pm 0.00535$

Global fit at NNLL+NNLO:

$\alpha_S(M_Z) = 0.11750 \pm 0.00018(exp.) \pm 0.00102(hadr.) \pm 0.00257(ren.) \pm 0.00078(res.)$

with combined uncertainty: $\alpha_S(M_Z) = 0.11750 \pm 0.00287$

The effect of NNLO on central value is moderate but not negligible, *ren.* uncertainty down by a factor of 2, *res.* uncertainty down by a factor of 3

The overall uncertainty is dominated by theoretical uncertainty (*ren.* and *res.*)

Z. Tulipánt et al, arXiv: 1804.09146

Works better for jet rates

Global fit at NNLL+NNLO:

$$\alpha_s(M_Z) = 0.11881 \pm 0.00063(exp.) \pm 0.00101(hadr.) \pm 0.00045(ren.) \pm 0.00034(res.)$$

with combined uncertainty: $\alpha_s(M_Z) = 0.11881 \pm 0.00131(comb.)$

compared to result using energy-energy correlation:

Global fit at NNLL+NNLO:

$$\alpha_S(M_Z) = 0.11750 \pm 0.00018(exp.) \pm 0.00102(hadr.) \pm 0.00257(ren.) \pm 0.00078(res.)$$

with combined uncertainty: $\alpha_S(M_Z) = 0.11750 \pm 0.00287$

A. Verbitskyi et al, arXiv: 1902.08158

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

New determination based on NNLO+NNLL+non-perturbative corrections from MC simulation gives

$$\alpha_{\rm s}(M_Z) = 0.11881 \pm 0.00131(comb.)$$

with uncertainty competitive with other determinations

Outlook

Outlook: prospects for α_s

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 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	~ 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])

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

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

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”

V. Del Duca et al, arXiv:1606.03453

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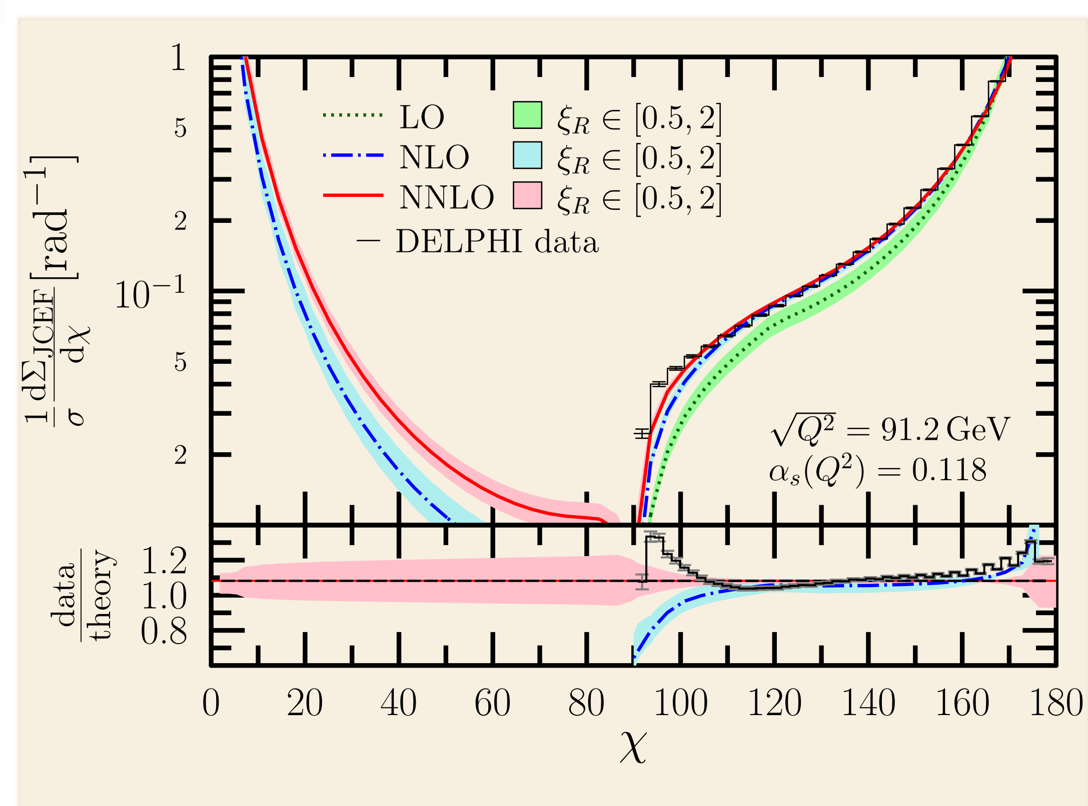
jet cone energy fraction:

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



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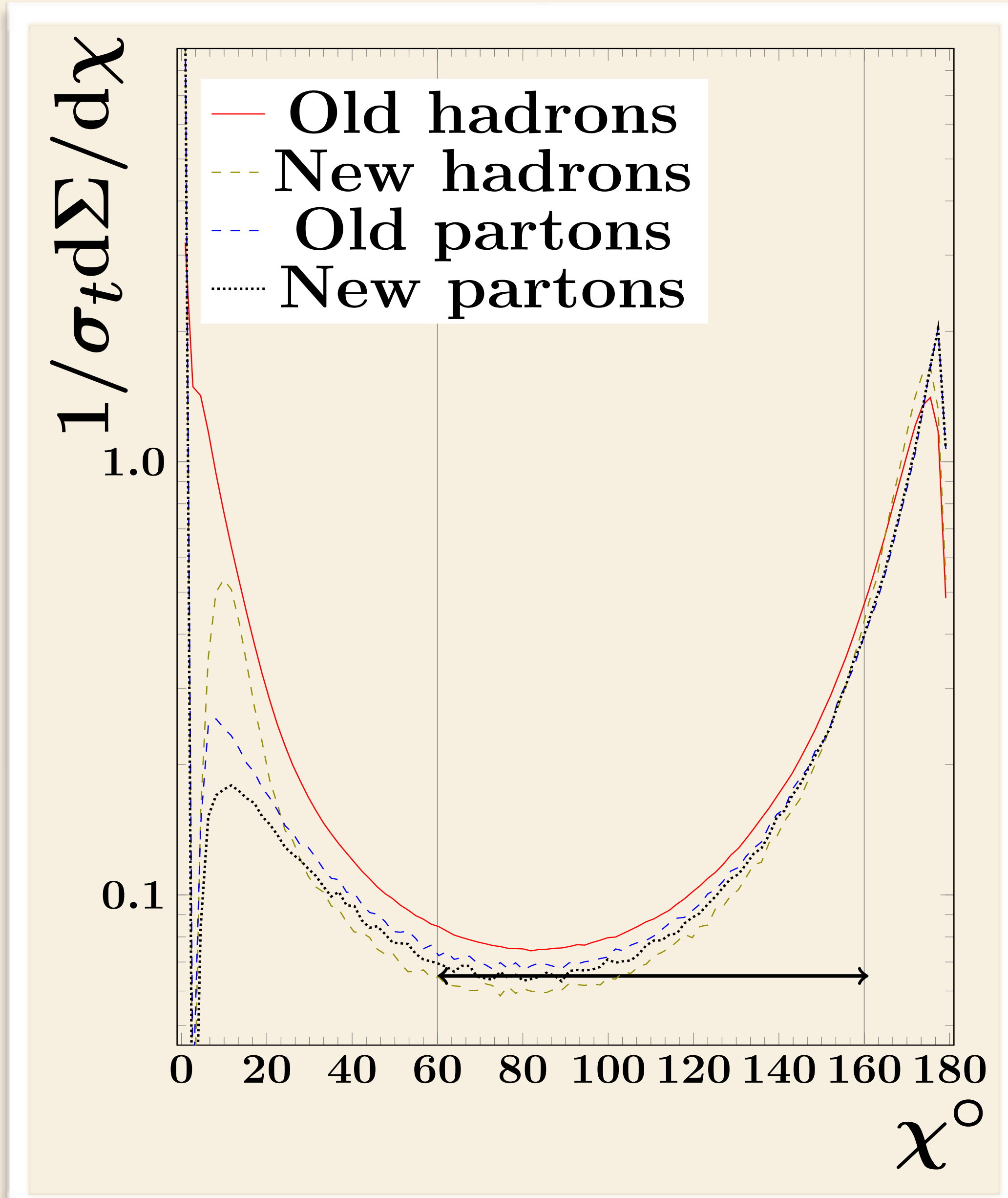
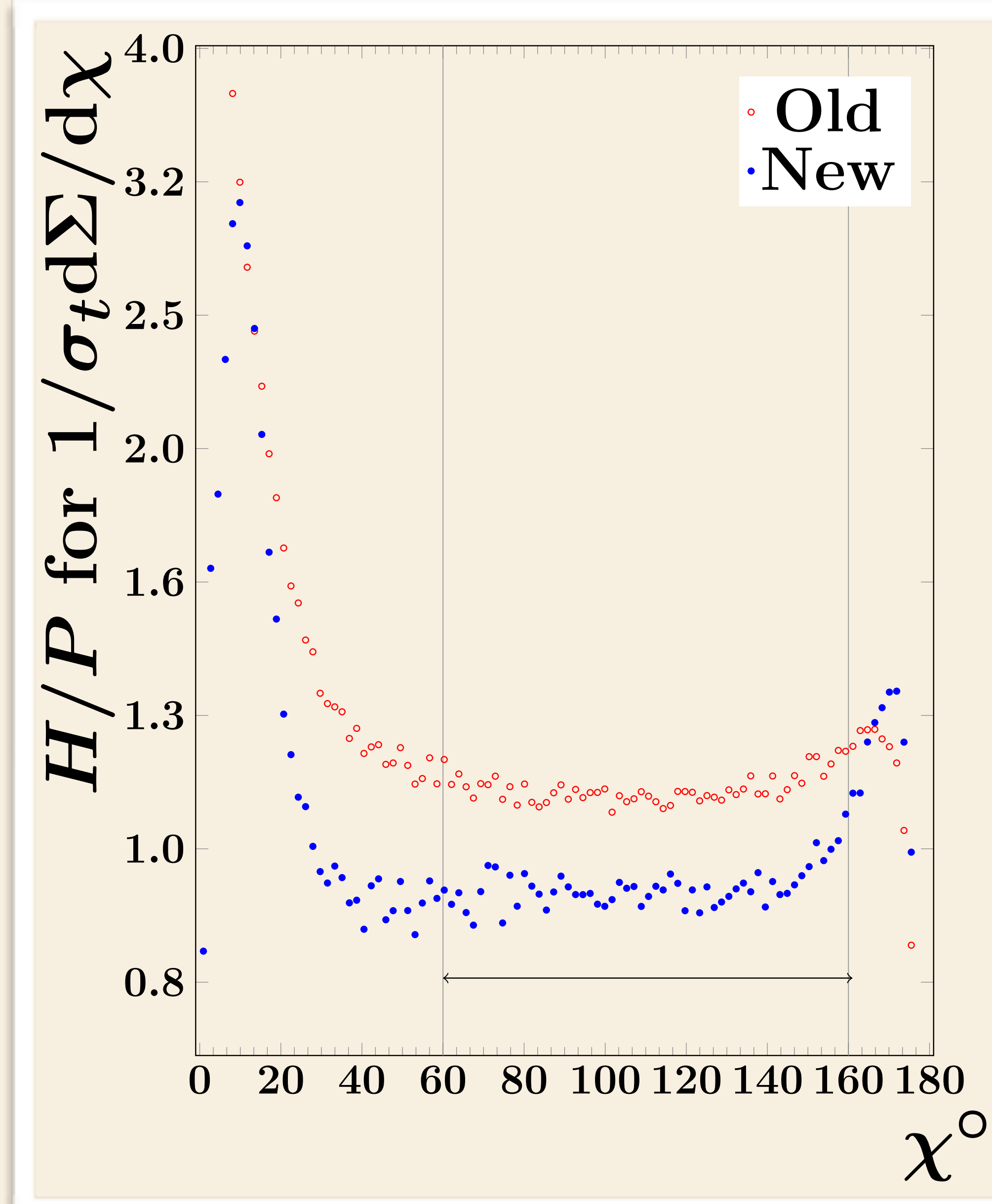
  - precluster hadrons and compute shapes from jets

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

Preclustering reduces hadronization corrections





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

A. Verbytskyi, private communication

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

Work in progress...