Fits of α_s using power corrections in the 3-jet region

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Based on Paolo Nason and GZ 2301.03607

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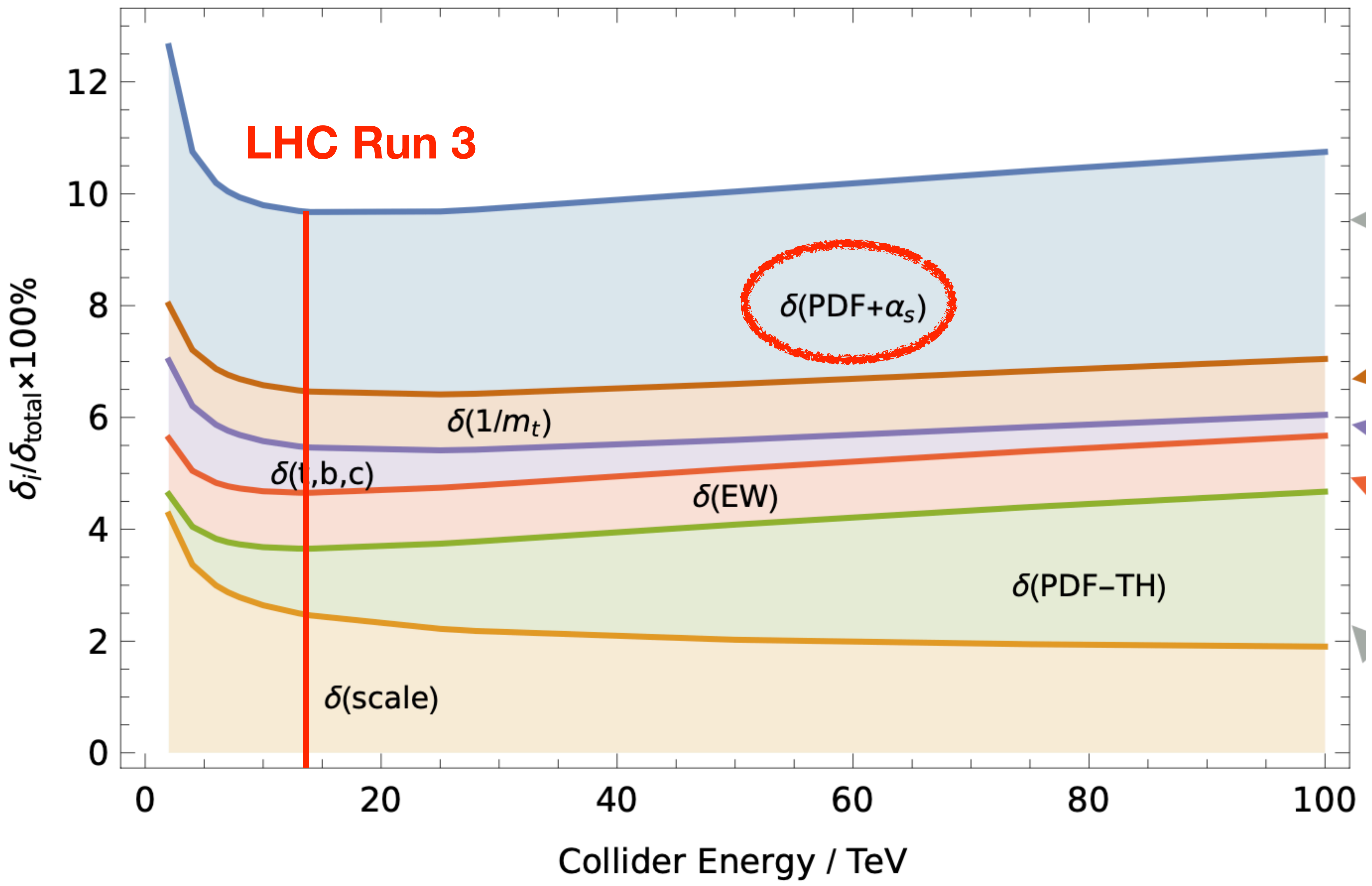
Determination of α_s

Least well-known coupling. Its uncertainty (and the PDF one) affects several precision measurements

<u>Example:</u>

Error budget of Higgs production cross-section via gluon-fusion



Dulat, Lazopoulos, Mistlberger ’18

Determination of α_s

Strong coupling determined by comparing accurate theory predictions with precise measurements for observables sensitive to α_s

Considerations that enter when determining whether an observable is suitable to be used to determine α_s:

- observable's sensitivity to α_s compared to experimental precision (e.g. compare R-ratio with respect to n-jet cross-section)
- accuracy of the prediction (e.g. PDG imposes now at least NNLO accuracy)
- the size of non-perturbative effects
- the scale at which the measurement is performed

The PDG average

Huston, Rabbertz, GZ ’21

Procedure:

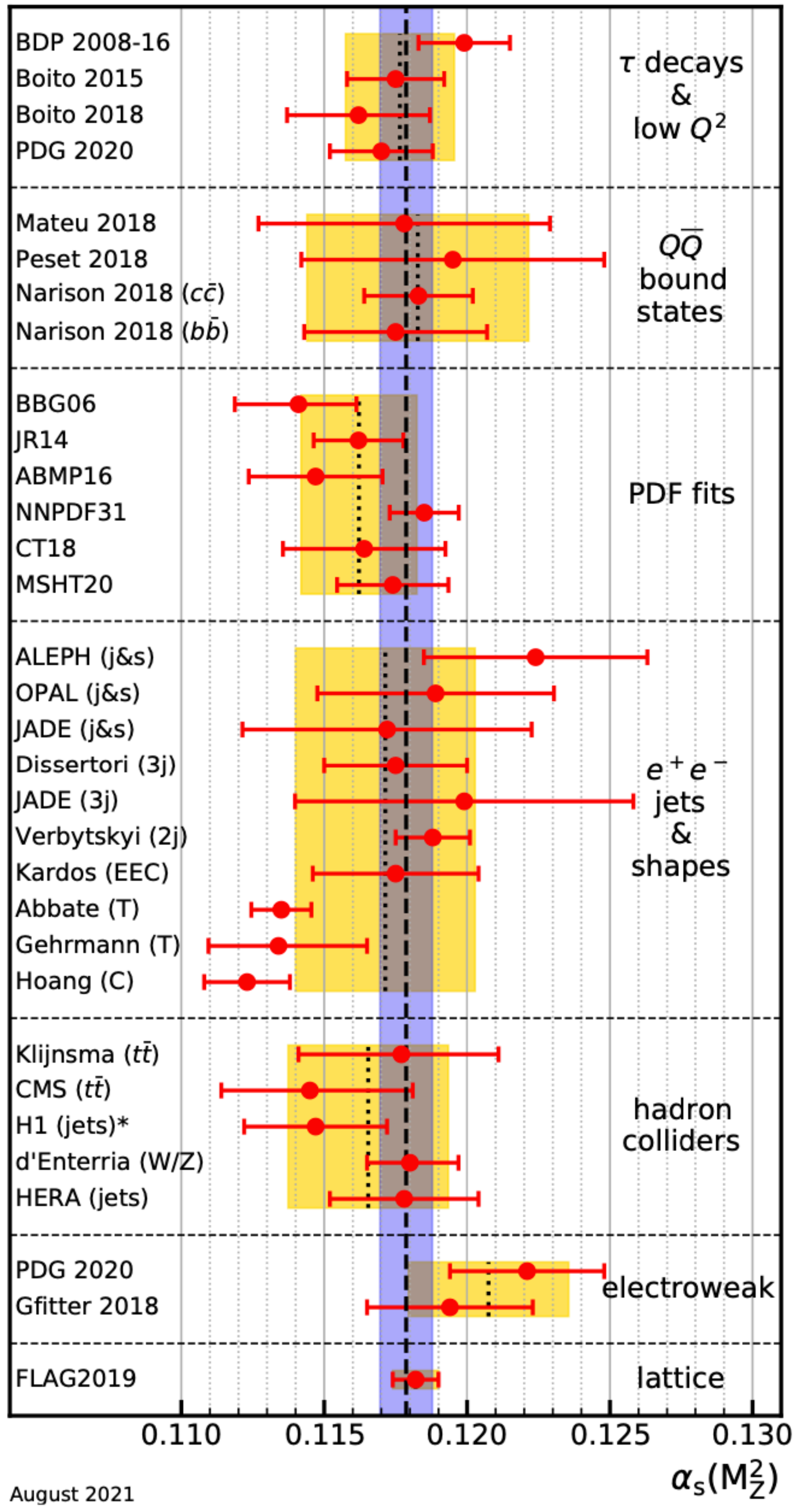
- decide which observables are included
- subdivide observables in categories
- provide an average for each category
- provide an average of all categories

⇒ the PDG average of α_s

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0009$$

$$\alpha_s(M_Z^2) = 0.1182 \pm 0.0008\,, \qquad \text{(lattice)}$$

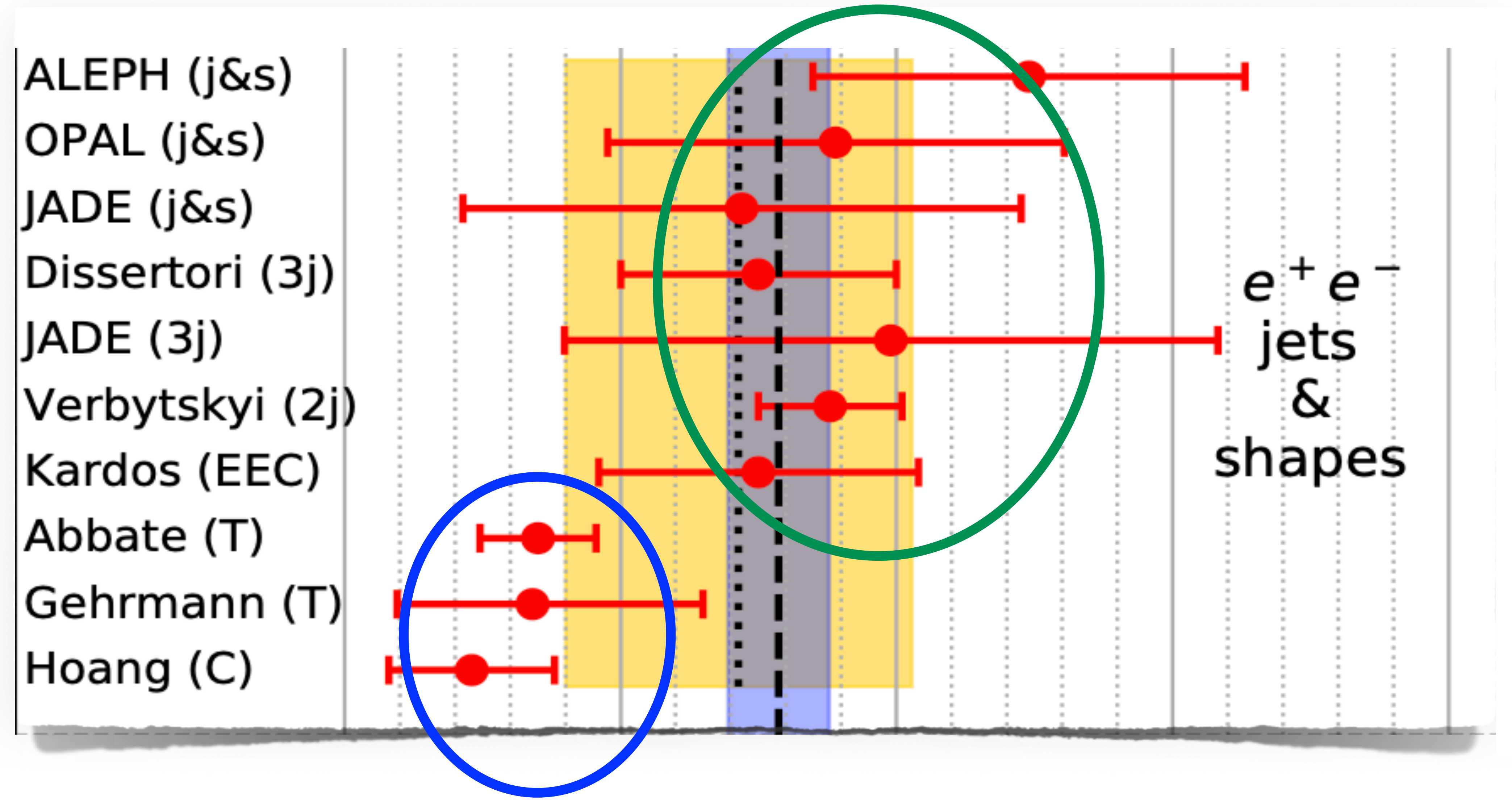
$$\alpha_s(M_Z^2) = 0.1176 \pm 0.0010\,, \qquad \text{(without lattice)}$$



Zooming-in in e^+e^- jet & shapes

<u>“e^+e^-: jet & shapes”:</u>

longstanding discrepancy between α_s determinations based on non-perturbative corrections computed via Monte Carlos and those based on analytic approaches



Definition of the observable

Thrust:

$$T = \max_{\vec{n}_T} \left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}_T|}{\sum_i |\vec{p}_i|} \right) \qquad \tau = 1 - T,$$

C-parameter:

$$\Theta^{\alpha\beta} = \frac{1}{\sum_i |p_i|} \sum_i \frac{p_i^\alpha p_i^\beta}{|\vec{p}_i|}, \qquad \alpha, \beta = 1,2,3$$

$$C = 3 \cdot (\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$$

Durham y3:

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{E_{\text{vis}}^2}$$

Jet masses:

$$M_j^2 = \frac{1}{E_{\text{vis}}^2} \left(\sum_{p_i \in \mathcal{H}_j} p_i \right)^2, \qquad j = 1,2$$

$$M_{\text{H}}^2 = \max\left(M_1^2, M_2^2\right) \qquad M_{\text{D}}^2 = |M_1^2 - M_2^2|$$

Wide broadening:

$$B_j = \frac{\sum_{p_i \in H_j} |\vec{p}_i \times \vec{n}_T|}{2\sum_i |\vec{p}_i|}, \qquad j = 1,2$$

$$B_W = \max\left(B_1, B_2\right)$$

e^+e^- jet & shapes

1. Linear sensitivity to α_s in the 3-jet region 😀

2. NNLO + NNLL (at least) perturbative accuracy through standard resummation techniques or SCET based 😀

Criteria

1. observable's sensitivity to α_s wrt experimental precision
2. accuracy of the prediction
3. the size of non-perturbative effects
4. the scale at which the measurement is performed

4. Measurements performed in a large range of energy scales, from about 35-206 GeV, most precise data at 91.2 GeV 😀

3. Relatively large, Λ/Q linear power corrections 🙁

e^+e^- jet & shapes

Two different approaches to non-perturbative corrections:

- use Shower Monte Carlos hadronization modelss. Often criticised as it does not bear a clean relation to field-theoretical calculations.
- analytic approaches
  - dispersive-like approaches: based on the emission of a very-soft, non-perturbative gluon with an associated non-perturbative coupling α_0

    Dokshitzer, Marchesini, Webber, Salam
  - Factorisation based-approach to split perturbative and non-perturbative (shape-function). Often used in combination with SCET based predictions

    Collins, Soper, Korchemsky, Sterman; Abbate, Bauer, Hoang, Mateu, Schwartz, Stuart, Thaler…

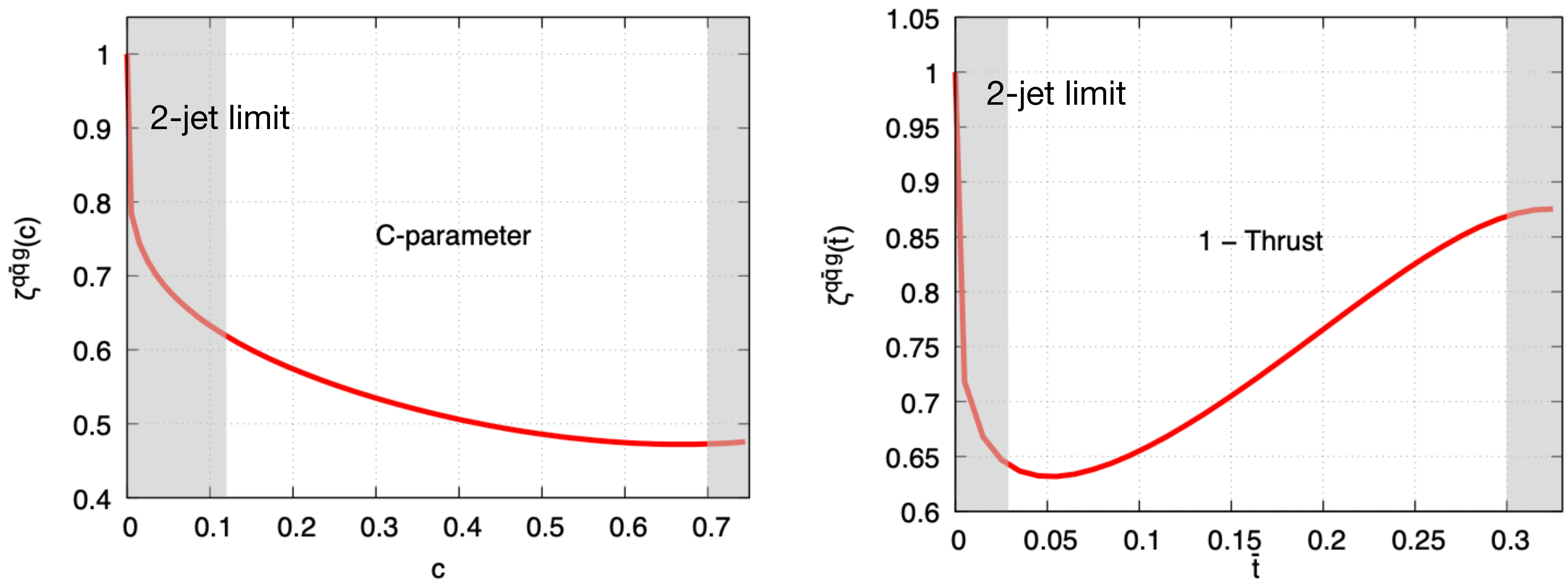
Both analytic approaches calculate non-perturbative corrections in the 2-jet region and apply them also to the 3-jet region

Non-perturbative corrections

Recently, non-perturbative corrections to 3-jet region have been computed for C-parameter and thrust

Caola et al. 2204.02247 (see also Luisoni, Monni, Salam 2012.00622; Caola et al. 2108.00622)

<u>Ratio of full non-perturbative corrections to the 2-jet limit</u>



Does the new calculation of the non-perturbative corrections lift the tension in the determination of α_s from C-parameter and thrust … ?

Are the newly computed corrections preferred by data …?

NP correction in the 3-jet region

Provided an observable is additive wrt to soft gluon emission in the 3-jet region and, after azimuthal integration, the integral in rapidity is convergent, the NP correction can be computed as

$$[\Sigma(v)]_{\mathrm{NP}} = \left\{ \int d\sigma_B(\Phi_B)\delta(v(\Phi_B) - v) \sum_{\mathrm{dip}} \left[-\mathcal{M} \times 4 \frac{\alpha_s C_{\mathrm{dip}}}{2\pi} \frac{1}{Q} \int d\eta \frac{d\phi}{2\pi} h_v(\eta, \phi) \right] \right\} \times I_{\mathrm{NP}}$$

Milan factor: $\mathcal{M} = \frac{3}{64} \frac{(128\pi(1+\log 2) - 35\pi^2)C_{\mathrm{A}} - 10\pi^2 T_R n_F}{11 C_{\mathrm{A}} - 4 T_R n_F},$

C_{dip}: dipole colour charges: $C_{q\bar{q}} = C_{\mathrm{F}} - \frac{C_{\mathrm{A}}}{2}, \qquad C_{qg} = C_{\bar{q}g} = \frac{C_{\mathrm{A}}}{2}$

I_{NP}: non-perturbative universal parameter (can be related to the dispersive parameter α_0)

NP correction in the 3-jet region

The observable dependent part h_V is

$$h_v(\eta,\phi) = \lim_{|l_\perp|\to 0} \frac{1}{|l_\perp|}\left(v(\{P\},l) - v(\{p\})\right)$$

With $\{p\}$ the momenta in the absence of soft radiation and $\{P\}$ the momenta of the hard partons in the presence of a soft massless parton of momentum l

➡the above expression can be computed by taking a gluon l of softness λ, and expanding analytically in λ, keeping only linear terms in λ

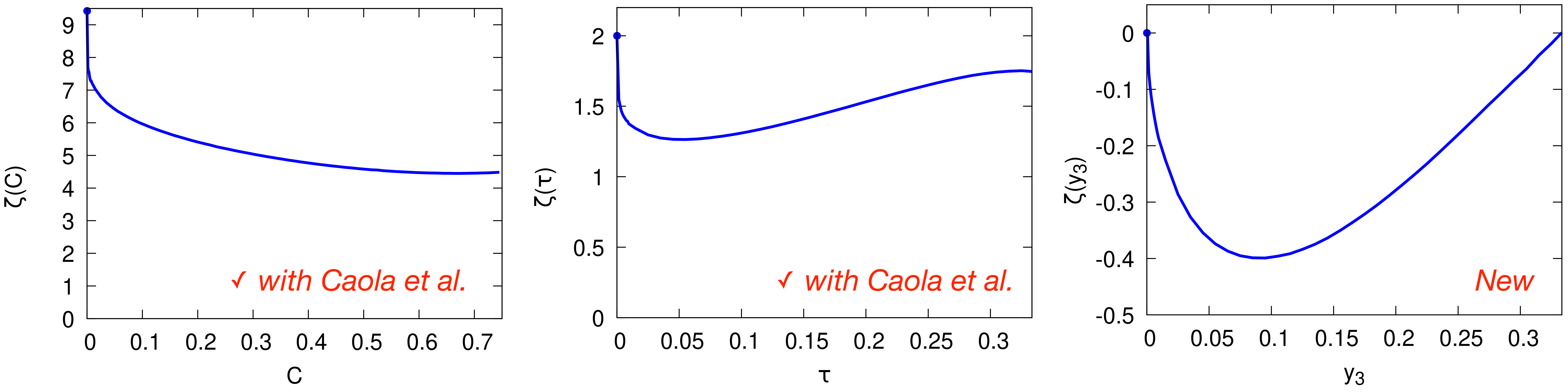
➡or it can be evaluated numerically keeping λ finite, but much smaller than Q

We use the evaluation at finite λ as a check of our results and to estimate the size of quadratic terms

Correction with respect to 2-jet limit

We define

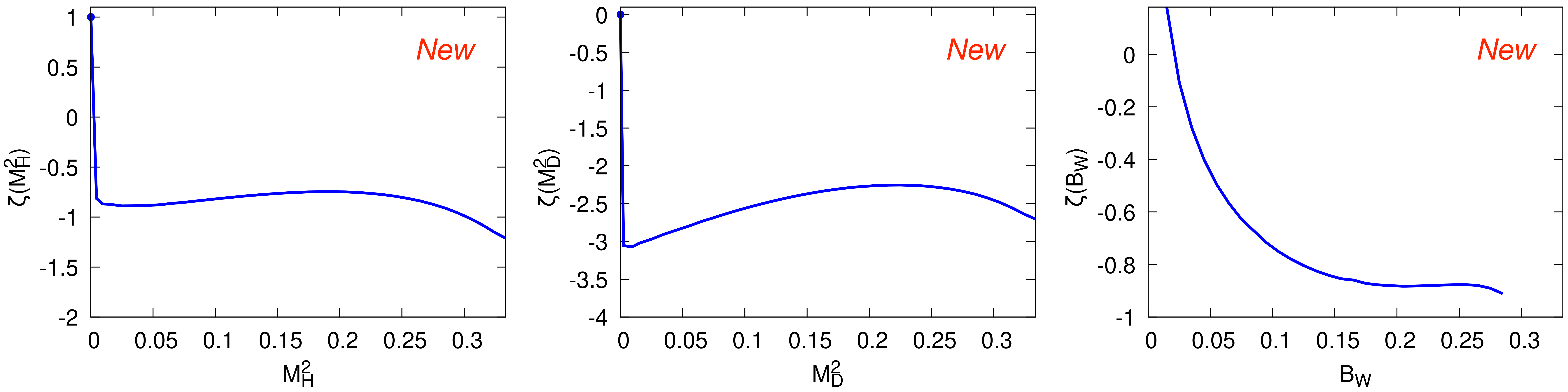
$$\zeta(v) = \left(\frac{d\sigma_B}{dv}\right)^{-1} \left\{ \int d\sigma_B(\Phi_B)\delta(v(\Phi_B) - v) \left[\sum_{\text{dip}} \frac{C_{\text{dip}}}{C_F} \int d\eta \frac{d\phi}{2\pi} h_v(\eta, \phi) \right] \right\}$$



➡y_3 has no linear power corrections in the 2-jet limit

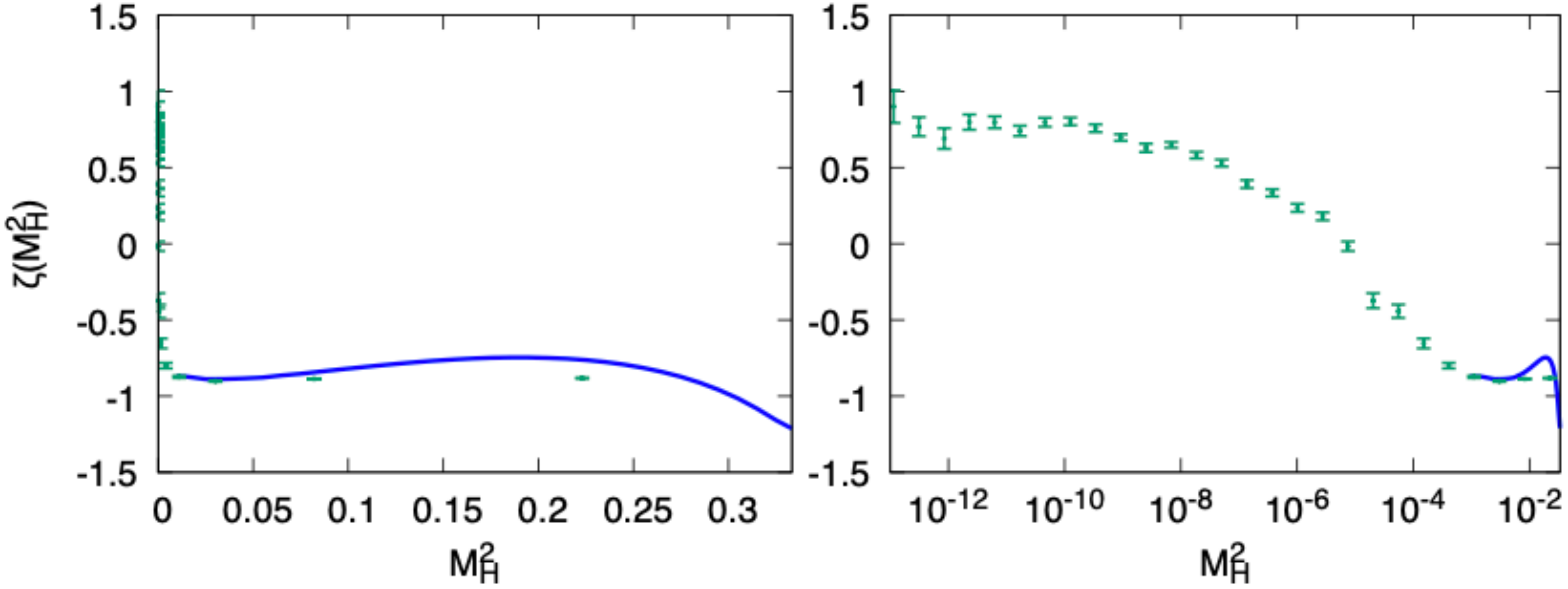
Correction with respect to 2-jet limit

For other observables, the two-jet limit is numerically very difficult to reach since there is an abrupt transition from the 2-jet to the 3-jet



Correction with respect 2-jet limit

We had to resort to quadruple precision to see the transition, for instance of the heavy-jet mass we obtain:



The 2-jet limit must be reached up to single-logs and constant terms, but these are, for some observables, numerically very important

Remarks

- there are clear indications that the 2-jet calculation is not a good approximation the in the 3-jet region, where α_s is fitted (at best it is wrong by a factor of order 1)
- for some observables there is a very abrupt transition from the 2-jet to the 3-jet region. This is an indication that sub-leading logs are numerically very important

➡In the following, we perform fits of α_s limiting ourselves to the three well-behaved observables C, 1-T and y_3 as measured by ALEPH at 91.2 GeV

ALEPH Eur. Phys. J. C 35 (2004) 457–486

Fit

Fit is performed by minimising

$$\chi^2 = \sum_{i,j} \left(\frac{1}{\sigma_{\text{exp}}} \frac{d\sigma_{\text{exp}}(v_i)}{dv_i} - \frac{1}{\sigma_{\text{th}}} \frac{d\sigma_{\text{th}}(v_i)}{dv_i} \right) V_{ij}^{-1} \left(\frac{1}{\sigma_{\text{exp}}} \frac{d\sigma_{\text{exp}}(v_j)}{dv_j} - \frac{1}{\sigma_{\text{th}}} \frac{d\sigma_{\text{th}}(v_j)}{dv_j} \right)$$

with

$$V_{ij} = \delta_{ij}(R_i^2 + T_i^2) + (1 - \delta_{ij}) C_{ij} R_i R_j + \text{Cov}_{ij}^{(\text{Sys})}$$

R_i^2 statistical error

T_i^2 theory error $T_{\text{i}} = \frac{\max(O(Q), O(Q/2), O(Q/4)) - \min(O(Q), O(Q/2), O(Q/4))}{2}$

C_{ij} statistical correlation matrix $C_{ij} = \frac{\frac{N_{ij}}{N} - \frac{N_i N_j}{N^2}}{\sqrt{\frac{N_i}{N} - \frac{N_i^2}{N^2}} \sqrt{\frac{N_j}{N} - \frac{N_j^2}{N^2}}}$

$\text{Cov}_{ij}^{(\text{Sys})}$ covariance matrix of systematic errors

Fit results

Variation	α_s	α_0	χ^2	χ^2/N_{deg}
Default setup	**0.1182**	**0.64**	**7.3**	**0.17**
Renormalization scale $Q/4$	0.1202	0.60	9.1	0.21
Renormalization scale Q	0.1184	0.68	8.7	0.20
NP scheme (b)	0.1198	0.77	7.0	0.16
NP scheme (c)	0.1206	0.80	5.4	0.12
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y_3 clustered	0.1174	0.66	8.2	0.19
C	0.1256	0.48	1.3	0.07
τ	0.1194	0.64	0.8	0.04
y_3	0.1214	1.81	0.2	0.02
C, τ	0.1238	0.51	2.6	0.07

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➡ We use NNLO predictions at scale μ_R = Q/2 and vary the scale up and down by a factor of two

- Antenna-based calculation: A. Gehrmann-De Ridder, T. Gehrmann and E. W. N. Glover, hep-ph/0505111
- ColorFull Subtraction: Del Duca et al 1603.08927, 1606.03453

➡ For the NNLO prediction we rely on the public code EERAD3

Gehrmann-De Ridder, Gehrmann, Glover, Heinrich
0710.0346, 0711.4711, 0802.0813

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Non-perturbative corrections can be included as

- ➡ a shift of the NNLO integrated distribution (scheme “a”)
- ➡ a shift of the LO distribution only (scheme “b”)
- ➡ a shift of the differential distribution (scheme “c”)
- ➡ as in scheme “a” without any estimate of quadratic corrections included in other schemes (scheme “d”)

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Explicitly:

$$\Sigma^{(a)}(v) = \Sigma_{\rm NNLO}(v - \delta v)$$

$$\Sigma^{(b)}_{\rm FULL}(v) = \Sigma_B(v - \delta v) + \Sigma(v) - \Sigma_B(v)$$

$$\Sigma^{(c)}_{\rm FULL}(v) = \Sigma(v) - \delta v \frac{\Sigma_B(v)}{dv}$$

with

$$\delta(v) = \zeta(v) H_{\rm NP} + \left(\tilde{\zeta}(v) \times \frac{Q_0}{\lambda_0} - \zeta(v)\right) \times \frac{Q_0}{\lambda_0} \times H^2_{\rm NP}$$

Estimate of quadratic corrections

$$\Sigma^{(d)}(v) = \Sigma_{\rm NNLO}(v - \delta v)$$

with

$$\delta(v) = \zeta(v) H_{\rm NP}$$

Fit results

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Ambiguity in the event-shape definitions when applied to massive particles. Correct to different schemes using Monte Carlos:

- ➡ E-sheme (our default): make particle massless conserving the energies
- ➡ P-scheme: make particle massless conserving the three-momentum
- ➡ Decay-scheme: decay each massive particle isotropically in its CM frame into two massless particles
- ➡ Standard: do not correct

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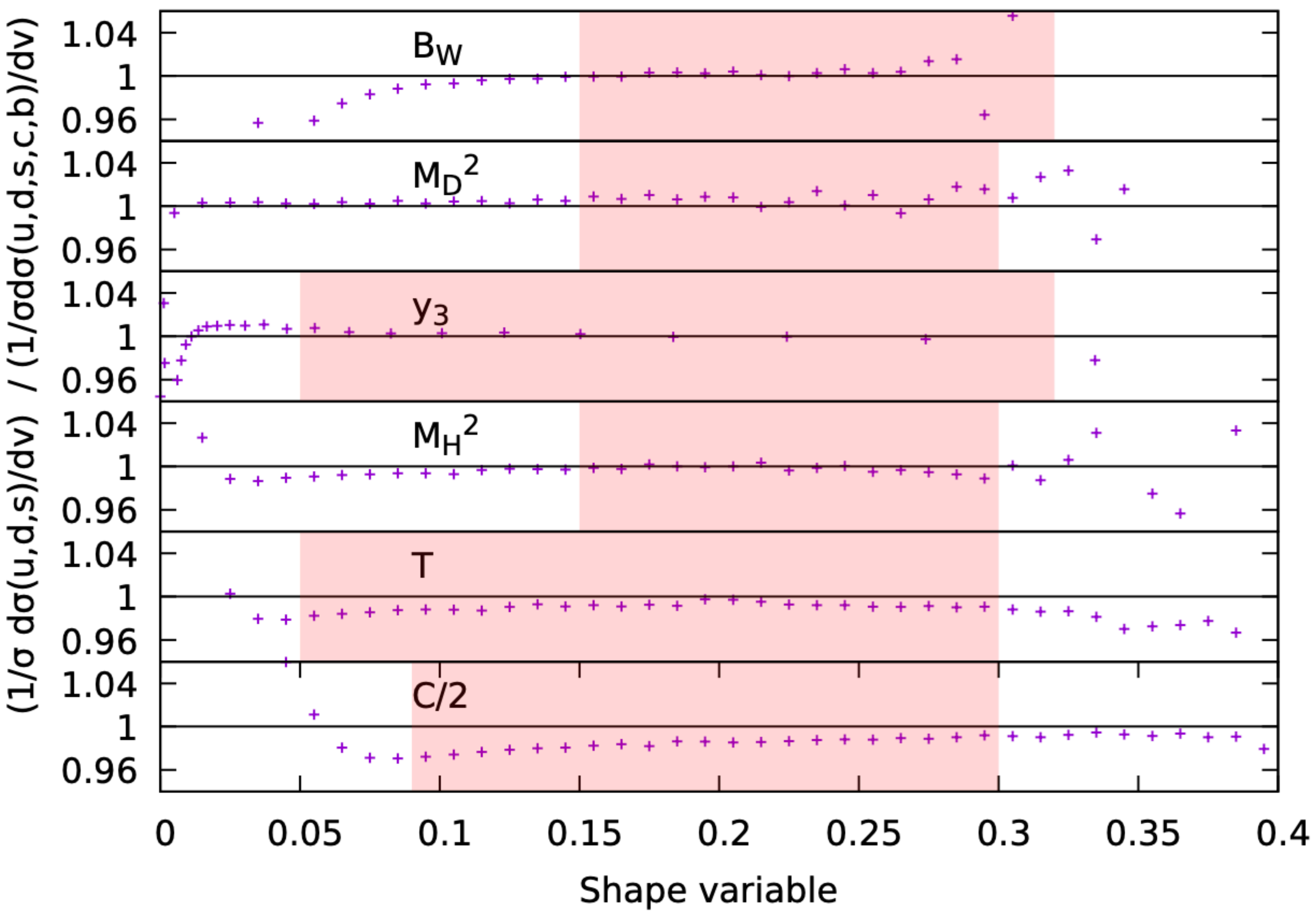
NNLO deals with massless quarks. Use Monte Carlo to correct for massive charm and bottom

$$v_i^{(\rm corr)} = v_i \times \frac{v_i^{{\rm MC},uds}}{v_i^{{\rm MC},udscb}}$$



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As default Monte Carlo for the calculation of the migration matrix for the mass-schemes and heavy-to-light correction we used Pythia 8.

To assess the sensitivity to the Monte Carlo used we also use Herwig 6 and Herwig 7.

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No heavy to light correction	0.1186	0.67	6.8	0.16
Herwig6	0.1180	0.59	15.9	0.36
Herwig7	0.1180	0.60	12.0	0.27
Ranges (2)	0.1174	0.62	12.7	0.23
Ranges (3)	0.1188	0.69	2.7	0.08
Replica method (around average)	0.1192	0.61	7.0	0.16
Replica method (around default)	0.1192	0.61	7.0	0.16
y_3 clustered	0.1174	0.66	8.2	0.19
C	0.1256	0.48	1.3	0.07
τ	0.1194	0.64	0.8	0.04
y_3	0.1214	1.81	0.2	0.02
C, τ	0.1238	0.51	2.6	0.07

Default range fixed to the left of where resummation effects are important.

To assess sensitivity to range by varying the lower edge by a factor 2/3 and 3/2

observable	default	Fit ranges (2)	Fit ranges (3)
C	$[0.25:0.6]$	$[0.17:0.6]$	$[0.375:0.6]$
τ	$[0.1:0.3]$	$[0.067:0.3]$	$[0.15:0.3]$
y_3	$[0.05:0.3]$	$[0.033:0.3]$	$[0.075:0.3]$

Fit results

Variation	α_s	α_0	χ^2	χ^2/N_{deg}
Default setup	**0.1182**	**0.64**	**7.3**	**0.17**
Renormalization scale $Q/4$	0.1202	0.60	9.1	0.21
Renormalization scale Q	0.1184	0.68	8.7	0.20
NP scheme (b)	0.1198	0.77	7.0	0.16
NP scheme (c)	0.1206	0.80	5.4	0.12
NP scheme (d)	0.1194	0.66	5.8	0.13
P-scheme	0.1158	0.62	10.7	0.24
D-scheme	0.1198	0.79	5.7	0.13
Standard scheme	0.1176	0.58	9.2	0.21
No heavy to light correction	0.1186	0.67	6.8	0.16
Herwig6	0.1180	0.59	15.9	0.36
Herwig7	0.1180	0.60	12.0	0.27
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y_3	0.1214	1.81	0.2	0.02
C, τ	0.1238	0.51	2.6	0.07

We implement correlations using a minimum overlap method

$$\text{Cov}_{ij}^{(\text{Sys})} = \delta_{ij} S_i^2 + (1-\delta_{ij}) \min(S_i^2, S_j^2)$$

To assess sensitivity to this, we also use replicas provided to us privately by Hasko Stenzel either around the default central value, or around the average of the replicas

$$\text{Cov}_{ij}^{(\text{Sys})} = \sum_r \left(v_i^{(r)} - \bar{v}_i\right)\left(v_j^{(r)} - \bar{v}_j\right) = N_r\left(\bar{v}_{ij} - \bar{v}_i \bar{v}_j\right)$$

Fit results

Variation	α_s	α_0	χ^2	χ^2/N_{deg}
Default setup	**0.1182**	**0.64**	**7.3**	**0.17**
Renormalization scale $Q/4$	0.1202	0.60	9.1	0.21
Renormalization scale Q	0.1184	0.68	8.7	0.20
NP scheme (b)	0.1198	0.77	7.0	0.16
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P-scheme	0.1158	0.62	10.7	0.24
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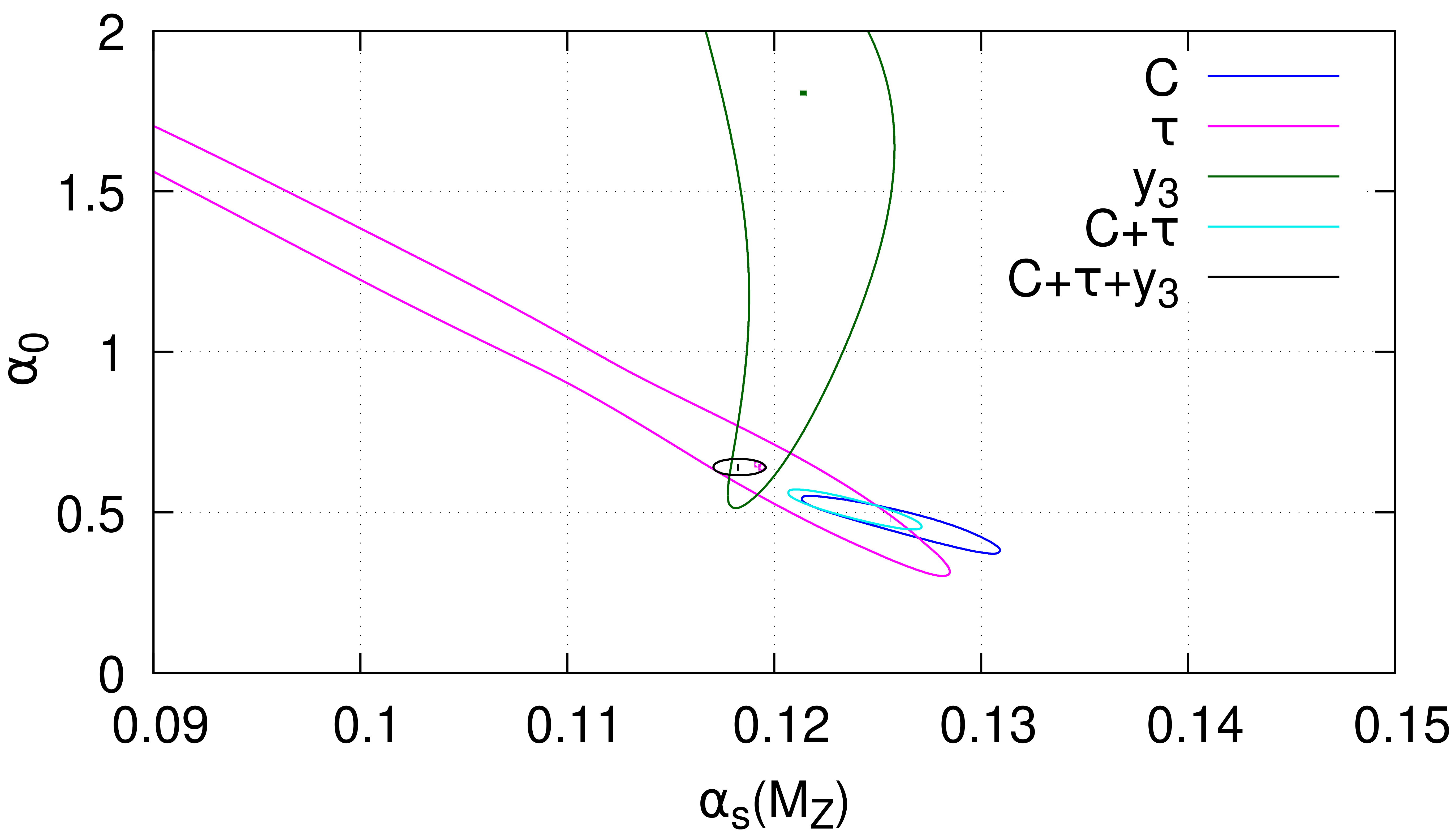
Ranges (3)	0.1188	0.69	2.7	0.08
Replica method (around average)	0.1192	0.61	7.0	0.16
Replica method (around default)	0.1192	0.61	7.0	0.16
y_3 clustered	0.1174	0.66	8.2	0.19
C	0.1256	0.48	1.3	0.07
τ	0.1194	0.64	0.8	0.04
y_3	0.1214	1.81	0.2	0.02
C, τ	0.1238	0.51	2.6	0.07

Even in the 3-jet region y_3 is only additive if one assumes *no clustering* among the two soft partons from gluon splitting. We have computed the non-perturbative correction under this assumption.

To assess the error we also compute it under the assumption that they *always* cluster (corresponding to a massive gluon)

Fit results

Variation	α_s	α_0	χ^2	χ^2/N_{deg}
Default setup	**0.1182**	**0.64**	**7.3**	**0.17**
Renormalization scale $Q/4$	0.1202	0.60	9.1	0.21
Renormalization scale Q	0.1184	0.68	8.7	0.20
NP scheme (b)	0.1198	0.77	7.0	0.16
NP scheme (c)	0.1206	0.80	5.4	0.12
NP scheme (d)	0.1194	0.66	5.8	0.13
P-scheme	0.1158	0.62	10.7	0.24
D-scheme	0.1198	0.79	5.7	0.13
Standard scheme	0.1176	0.58	9.2	0.21
No heavy to light correction	0.1186	0.67	6.8	0.16
Herwig6	0.1180	0.59	15.9	0.36
Herwig7	0.1180	0.60	12.0	0.27
Ranges (2)	0.1174	0.62	12.7	0.23
Ranges (3)	0.1188	0.69	2.7	0.08
Replica method (around average)	0.1192	0.61	7.0	0.16
Replica method (around default)	0.1192	0.61	7.0	0.16
y_3 clustered	0.1174	0.66	8.2	0.19
C	0.1256	0.48	1.3	0.07
τ	0.1194	0.64	0.8	0.04
y_3	0.1214	1.81	0.2	0.02
C, τ	0.1238	0.51	2.6	0.07



Fit results

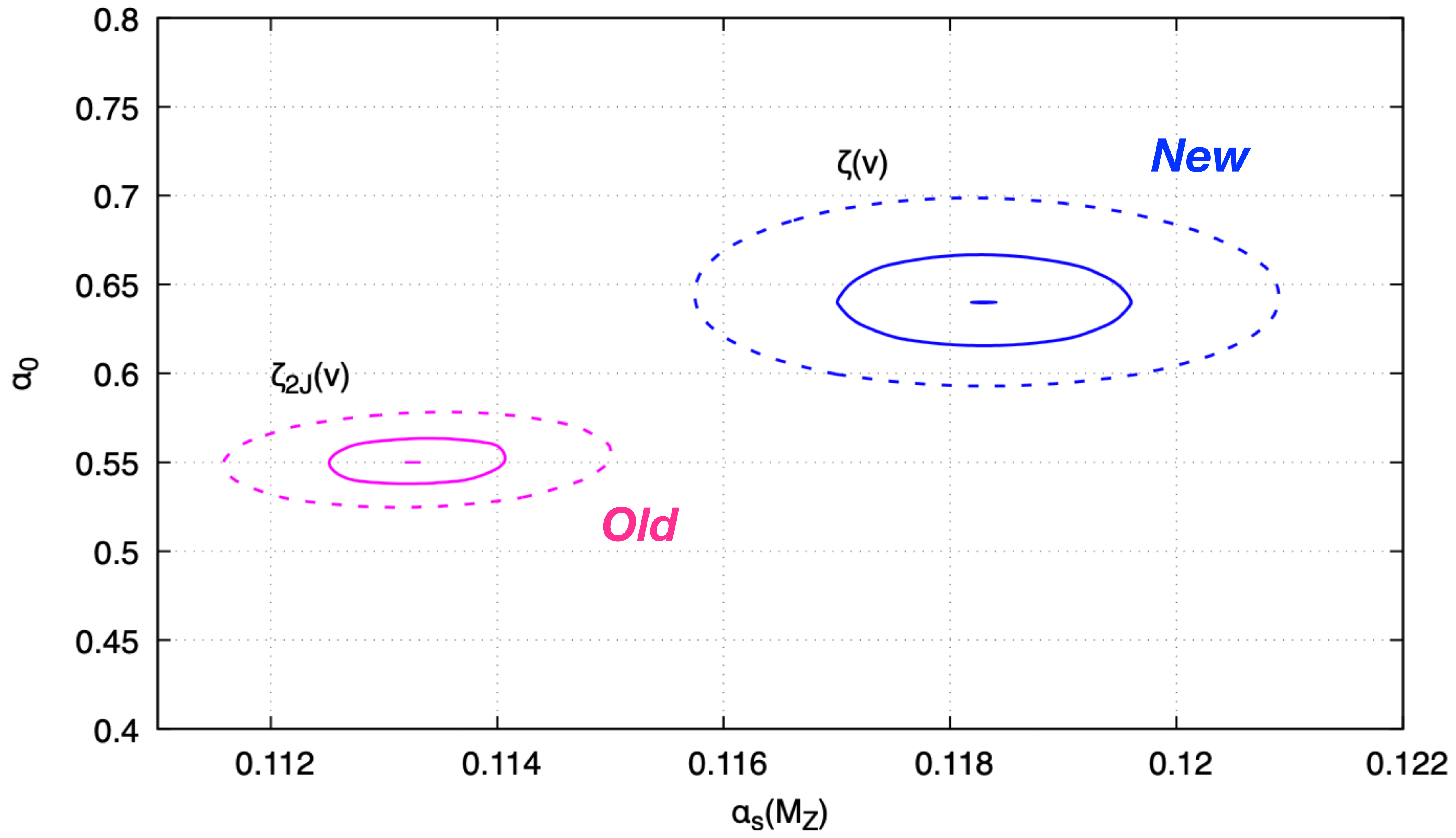
Variation	α_s	α_0	χ^2	χ^2/N_{deg}
Default setup	**0.1182**	**0.64**	**7.3**	**0.17**
Renormalization scale $Q/4$	0.1202	0.60	9.1	0.21
Renormalization scale Q	0.1184	0.68	8.7	0.20
NP scheme (b)	0.1198	0.77	7.0	0.16
NP scheme (c)	0.1206	0.80	5.4	0.12
NP scheme (d)	0.1194	0.66	5.8	0.13
P-scheme	0.1158	0.62	10.7	0.24
D-scheme	0.1198	0.79	5.7	0.13
Standard scheme	0.1176	0.58	9.2	0.21
No heavy to light correction	0.1186	0.67	6.8	0.16
Herwig6	0.1180	0.59	15.9	0.36
Herwig7	0.1180	0.60	12.0	0.27
Ranges (2)	0.1174	0.62	12.7	0.23
Ranges (3)	0.1188	0.69	2.7	0.08
Replica method (around average)	0.1192	0.61	7.0	0.16
Replica method (around default)	0.1192	0.61	7.0	0.16
y_3 clustered	0.1174	0.66	8.2	0.19
C	0.1256	0.48	1.3	0.07
τ	0.1194	0.64	0.8	0.04
y_3	0.1214	1.81	0.2	0.02
C, τ	0.1238	0.51	2.6	0.07

Including LEP II data at 133, 161, 172, 183, 189, 206 GeV does not alter the fit considerably:

$$\alpha_s(M_Z) = 0.1184 \text{ and } \alpha_0 = 0.64,$$

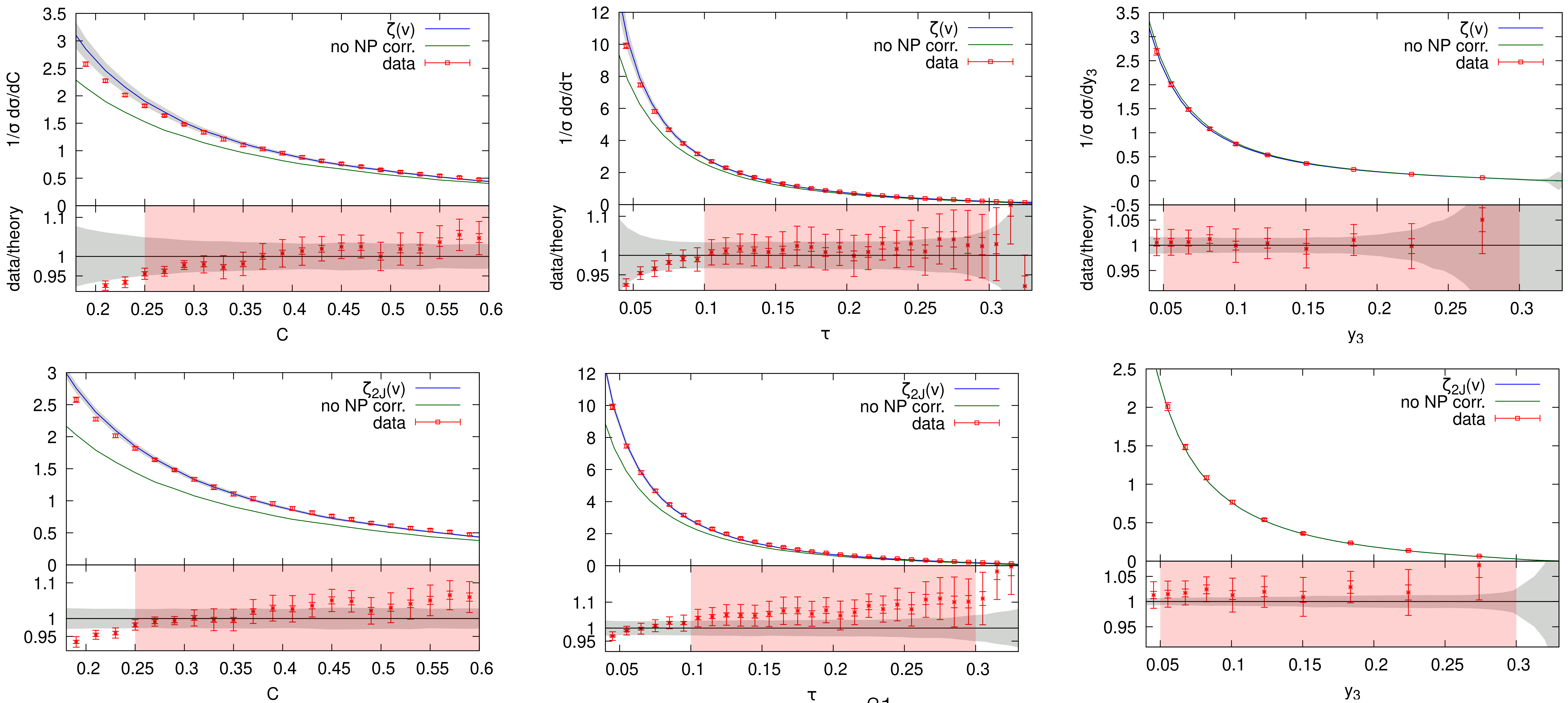
Fit result using 2-jet NP corrections

Variation	α_s	α_0	χ^2	$\chi^2/N_{\rm deg}$
Default setup	0.1132	0.55	15.8	0.36
Renormalization scale $Q/4$	0.1174	0.53	8.5	0.19
Renormalization scale Q	0.1126	0.57	22.0	0.50
NP scheme (b)	0.1126	0.63	25.7	0.58
NP scheme (c)	0.1134	0.72	16.4	0.37
NP scheme (d)	0.1132	0.55	15.8	0.36
P-scheme	0.1108	0.53	21.8	0.50
D-scheme	0.1126	0.66	16.1	0.37
Standard scheme	0.1134	0.51	15.9	0.36
No heavy to light correction	0.1130	0.58	15.9	0.36
`Herwig6`	0.1136	0.51	31.1	0.71
`Herwig7`	0.1136	0.52	21.8	0.49
Ranges (2)	0.1122	0.54	30.0	0.55
Ranges (3)	0.1134	0.58	10.5	0.33
Replica method (around average)	0.1158	0.53	13.4	0.31
Replica method (around default)	0.1160	0.53	13.5	0.31
y_3 clustered	0.1132	0.55	15.8	0.36
C	0.1238	0.45	1.3	0.08
τ	0.1202	0.51	1.2	0.06
y_3	0.1160	–	1.4	0.18
C, τ	0.1222	0.46	2.7	0.08



Quality of the fits

Theory prediction compare to data for observables entering the fits:

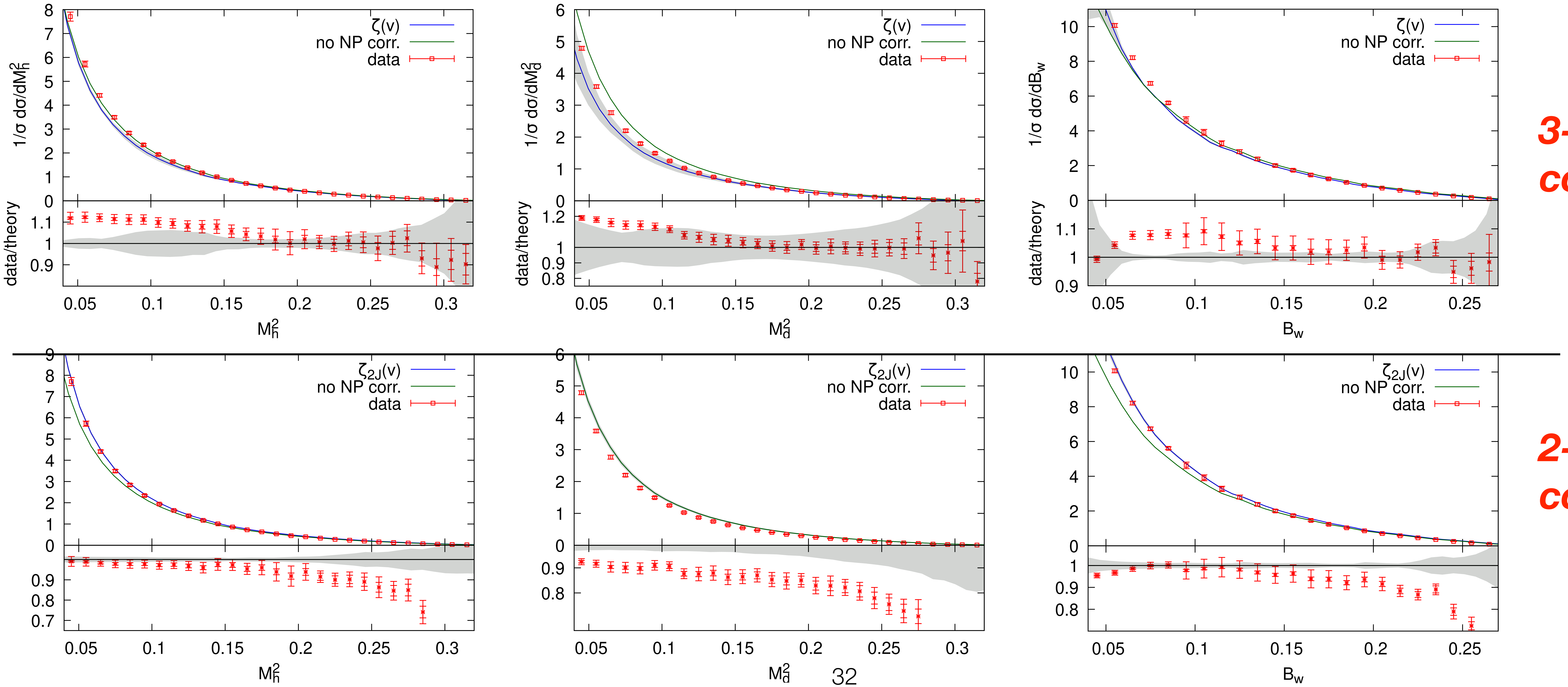


3-jet power corrections 😀

2-jet power corrections 😀

Description of other observables

Description of other observables not entering the fits:



3-jet power corrections

2-jet power corrections

Conclusions

- we computed non-perturbative corrections in the 3-jet region for a number of new observables (M_H, M_D, B_W, y_3) besides the known case of 1-T and C
- for some observables the transition between 2-jet and 3-jet power corrections is very ubrupt
- when limiting the fit to include only "better-behaved" observables, good fits of α_s are obtained
- data seem to prefer the new non-perturbative corrections. In particular "bad" observables not included in the fit can be described well in the 3-jet region only when using the new non-perturbative corrections
- altogether, many effects and uncertainties must be included therefore it seems not feasible to produce results with errors below the percent

Outlook

- Include resummation effects in the fits. Idea would be that the NP shift associated to the two-jet limit is applied to the resummation part and the one to the three-jet limit to the fixed order. Not clear how well this would work in practice
- Find other "well-behaved" observables like 1-T, C, y_3 and fit the strong coupling using these new observables and old LEP data
- See if a hadron-mass scheme is preferred by data. For this, consider enough observables with different behaviour regarding the mass-scheme choice

The board of the High Energy and Particle Physics Division of the European Physics Society solicits nominations for the following prizes:

1. The **High Energy and Particle Physics Prize**, for an outstanding contribution to High Energy Physics in an experimental, theoretical or technological area, will be awarded to one or more persons or to collaboration(s).
2. The **Giuseppe and Vanna Cocconi Prize**, for an outstanding contribution to Particle Astrophysics and Cosmology in the last fifteen years, in an experimental, theoretical or technological area, will be awarded to one or more individuals or to one or more collaborations.
3. The **Young Experimental Physicist Prize**, for outstanding work by one or more early career experimental physicist (maximum of 8 years - excluding career interruptions - of research experience following the PhD) in the field of Particle Physics and/or Particle Astrophysics. Candidates for the prize should have a maximum of 8 years of research experience (excluding career interruptions) following the PhD.
4. The **Gribov Medal**, for outstanding work by an early career researcher (maximum of 8 years - excluding career interruptions - of research experience following the PhD) in Theoretical Particle Physics and/or Field Theory. Candidates for the prize should have a maximum of 8 years of research experience (excluding career interruptions) following the PhD.
5. The **Outreach Prize**, for outstanding achievement in outreach, including education and the promotion of diversity, in connection with High Energy Physics and/or Particle Astrophysics.

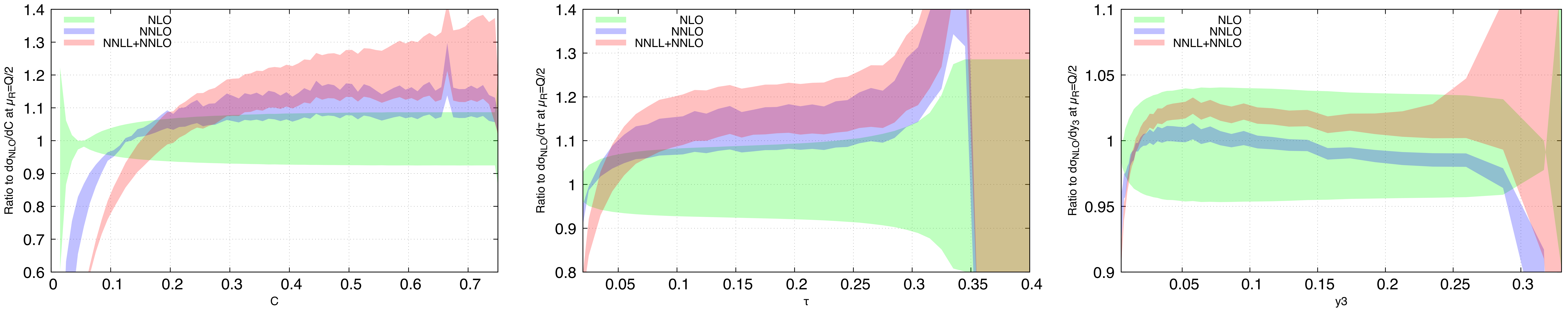
The prizes will be presented at the EPS Conference on High Energy Physics taking place in Hamburg 21-25 August 2023.

Nominations of women and underrepresented minorities are particularly encouraged. All material should be submitted before January 31, 2023 at 12:00pm CET, see https://academicjobsonline.org/ajo/jobs/23868 (see also https://eps-hepp.web.cern.ch/eps-hepp/)

Thank you also for helping in promoting the prizes to the HEP community and actively soliciting quality nominations from colleagues all over the world!!

BACKUP

Impact of resummation



- we limit our fit to the 3-jet region and do not include resummation effects. Our fit range is then to the left of the region where the resummation departs from the NNLO
- it is not clear that including resummation in the 3-jet region correctly approximates higher-order results