REVISITING STRONG-COUPLING DETERMINATIONS FROM EVENT SHAPES

[GUIDO BELL]

based on: GB, C. Lee, Y. Makris, J. Talbert, B. Yan, 2311.03990.

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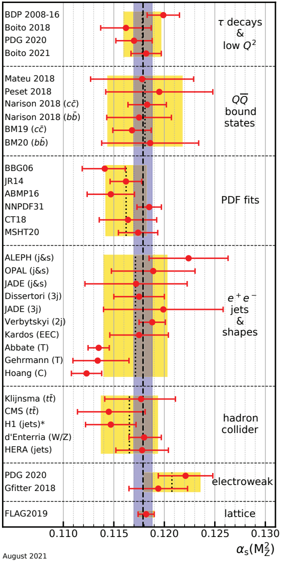
Introduction

- α_s is a fundamental SM parameter
- α_s enters every precision study in particle physics

PDG 2021 world average

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



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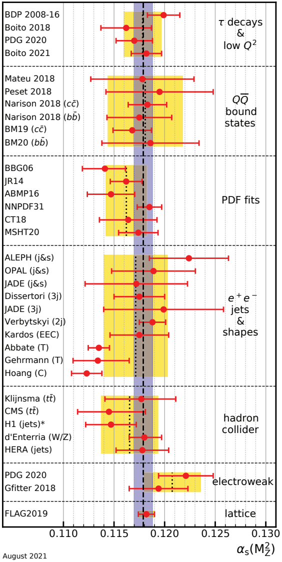
Thrust [Abbate, Fickinger, Hoang, Mateu, Stewart 10]

$$\alpha_s(M_Z) = 0.1135 \pm 0.0011$$

C-parameter [Hoang, Kolodrubetz, Mateu, Stewart 15]

$$\alpha_s(M_Z) = 0.1123 \pm 0.0015$$

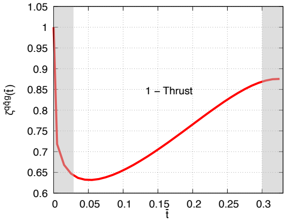
$\Rightarrow$ "3σ anomaly"



New developments

Recent studies focused on non-perturbative effects from 3-jet configurations

- C-parameter in the symmetric 3-jet limit [Luisoni, Monni, Salam 20]
- general renormalon analysis [Caola, Ferrario Ravasio, Limatola, Melnikov, Nason 21; + Ozcelik 22]



effective shift parameter

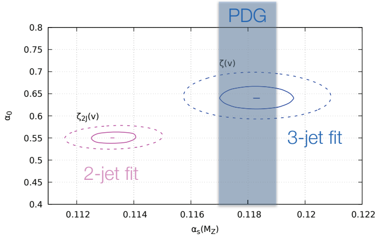
$$\frac{d\sigma}{de}(e) \xrightarrow{\text{NP}} \frac{d\sigma}{de}\left(e - \zeta(e)\frac{\Lambda}{Q}\right)$$

- ▷ renormalon-type (massive gluon) computation starting from $q\bar{q}\gamma$ final state
- ▷ reconstructs QCD result as a sum over colour dipoles

$\Rightarrow$ first (model-dependent) estimate of 3-jet power corrections

New developments

Novel 3-jet power corrections have been implemented in α_s fit [Nason, Zanderighi 23]



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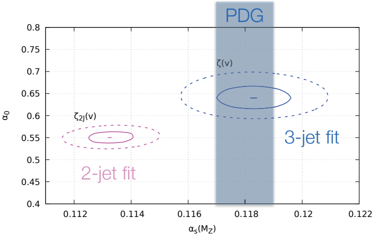

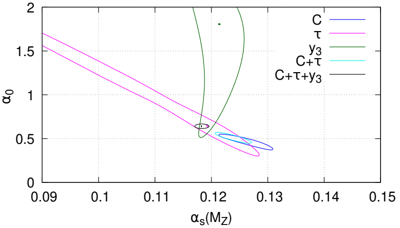

- fit to ALPEH data with $Q = M_Z$ only
- fit does not include resummation
- universality of non-perturbative corrections unclear (in particular for y_3)

$\Rightarrow$ conclusions are premature

Our approach

Focus on 2-jet predictions that are theoretically well established

- SCET-based α_s extractions were performed by a single group

Thrust at N^3LL with Power Corrections and a Precision Global Fit for $\alpha_s(m_Z)$ Riccardo Abbate,[1] Michael Fickinger,[2] André H. Hoang,[3] Vicent Mateu,[3] and Iain W. Stewart[1]	2010
A Precise Determination of α_s from the C-parameter Distribution André H. Hoang,[1,2] Daniel W. Kolodrubetz,[3] Vicent Mateu,[1] and Iain W. Stewart[3]	2015

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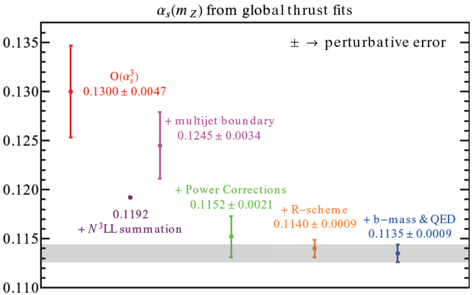

[talk by V. Mateu@α_s workshop 2011]

Main Focus:

- renormalon schemes
- perturbative scale choices

$\Rightarrow$ we do not aim at a competetive α_s extraction in this work!

OUTLINE

PERTURBATIVE TREATMENT

RESUMMATION

MATCHING TO FIXED-ORDER

PROFILE FUNCTIONS

NON-PERTURBATIVE TREATMENT

GAPPED SHAPE FUNCTION

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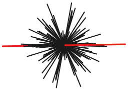
- RESULTS

Thrust

Event shapes assign a number to the geometric distribution of hadrons

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

$\tau \approx 0$



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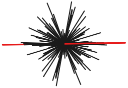


$\tau \approx 0.5$

Standard exercise to calculate $\mathcal{O}(\alpha_s)$ distribution

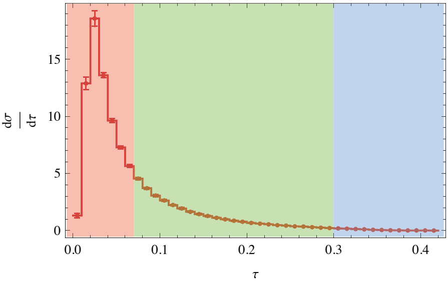
$$\frac{1}{\sigma_B}\frac{d\sigma}{d\tau} = \delta(\tau) + \frac{\alpha_s C_F}{2\pi}\left\{ \left(\frac{\pi^2}{3} - 1\right)\delta(\tau) - \frac{3(1-3\tau)(1+\tau)}{\tau_+} - \frac{2(2-3\tau+3\tau^2)}{(1-\tau)}\left(\left[\frac{\ln\tau}{\tau}\right]_+ - \frac{\ln(1-2\tau)}{\tau}\right)\right\}$$

$$= \delta(\tau) + \frac{\alpha_s C_F}{2\pi}\left\{ \left(\frac{\pi^2}{3} - 1\right)\delta(\tau) - \frac{3}{\tau_+} - 4\left[\frac{\ln\tau}{\tau}\right]_+ + \text{non-singular terms}\right\}$$

Overall structure

Thrust distribution

$$\frac{1}{\sigma_B}\frac{d\sigma}{d\tau} = \delta(\tau) + \frac{\alpha_s C_F}{2\pi}\left\{\left(\frac{\pi^2}{3}-1\right)\delta(\tau) - \frac{3}{\tau_+} - 4\left[\frac{\ln\tau}{\tau}\right]_+ + \text{non-singular}\right\} + \mathcal{O}(\alpha_s^2)$$



peak region

- very sensitive to non-perturbative effects

tail region

- resummation of singular corrections

far-tail region

- fixed-order QCD, but few events

Singular contribution

For $\tau \to 0$ all emissions are collinear or soft

$$\frac{1}{\sigma_B}\frac{d\sigma}{d\tau} \simeq H(Q,\mu) \int d\tau_n \, d\tau_{\bar{n}} \, d\tau_s \; J(\sqrt{\tau_n}Q,\mu) \; J(\sqrt{\tau_{\bar{n}}}Q,\mu) \; S(\tau_s Q,\mu) \; \delta(\tau - \tau_n - \tau_{\bar{n}} - \tau_s)$$

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$H(Q,\mu)$: square of on-shell vector form factor

- known to 4-loop [Lee, von Manteuffel, Schabinger, Smirnov, Smirnov, Steinhauser 22]

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$J(\sqrt{\tau_n} Q,\mu)$: inclusive quark jet function

- known to 3-loop [Brüser, Liu, Stahlhofen 18; Banerjee, Dhania, Ravindran 18]

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$S(\tau_s Q,\mu)$: thrust soft function

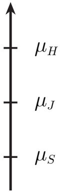
- known to 2-loop [Kelley, Schwartz, Schabinger, Zhu 11; Gehrmann, Luisoni, Monni 11]
- 3-loop computation on-going [Baranowski, Delto, Melnikov, Wang 22; + Pikelner 24; Chen, Feng, Jia, Liu 22]

Resummation

Resum singular corrections to all orders using RG techniques

$$\frac{d}{d\ln\mu} H(Q,\mu) = \left[2\Gamma_{\rm cusp}(\alpha_s)\ \ln\frac{Q^2}{\mu^2} + \gamma_H(\alpha_s)\right] H(Q,\mu)$$

$$\Rightarrow\ H(Q,\mu) = H(Q,\mu_H)\ U_H(\mu_H,\mu)$$



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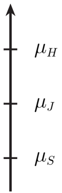


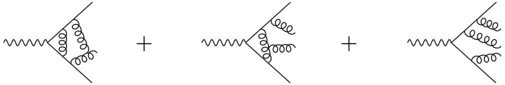
All ingredients for N^{3}LL$'$ resummation are known, except for 3-loop soft constant

$$c_{\tilde{S}}^3 = \begin{cases} -19988 \pm 5440 & \texttt{EERAD3} \\ 691 \pm 1000 & \text{Padé} \end{cases}$$

$\Rightarrow$ `EERAD3` is our default choice, but we also study the impact of switching to Padé

Non-singular contribution

Thrust distribution is known to $\mathcal{O}(\alpha_s^3)$ [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich 07; Weinzierl 09]



$\Rightarrow$ implemented in public `EERAD3` generator [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich 14]

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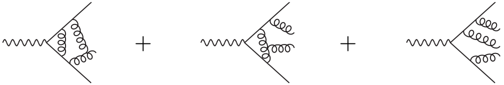

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Combine singular and non-singular contributions

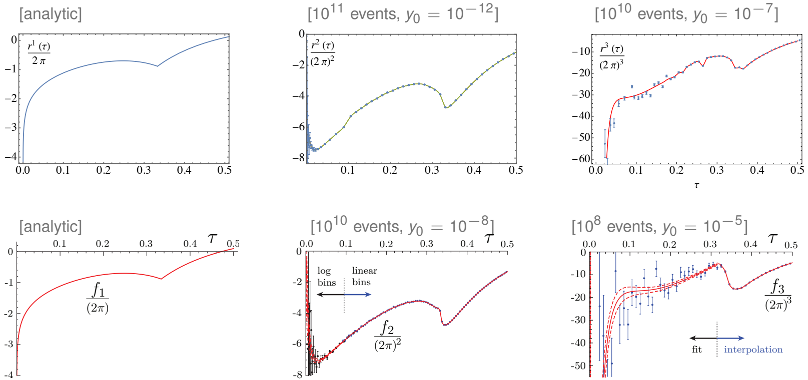
$$\sigma_c^{PT}(\tau) = \frac{\sigma_{c,\text{sing}}(\tau;\mu_H,\mu_J,\mu_S)}{\sigma_0} + \frac{\alpha_s(\mu_{ns})}{2\pi}\, r_c^1(\tau) + \left(\frac{\alpha_s(\mu_{ns})}{2\pi}\right)^2 \left\{ r_c^2(\tau) + \beta_0\, r_c^1(\tau) \ln\frac{\mu_{ns}}{Q} \right\}$$

$$+ \left(\frac{\alpha_s(\mu_{ns})}{2\pi}\right)^3 \left\{ r_c^3(\tau) + 2\beta_0\, r_c^2(\tau) \ln\frac{\mu_{ns}}{Q} + r_c^1(\tau)\left(\frac{\beta_1}{2}\ln\frac{\mu_{ns}}{Q} + \beta_0^2 \ln^2\frac{\mu_{ns}}{Q}\right) \right\}$$

$\Rightarrow$ need to determine remainder functions $r_c^i(\tau)$

Remainder functions

Compare our extraction with 2010 analysis from Abbate et al



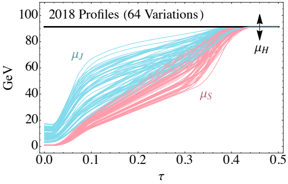
- ▶ high-statistics runs reveal that `EERAD3` is unstable for small τ values

$\Rightarrow$ use $N^3LL' + \mathcal{O}(\alpha_s^2)$ predictions for the α_s fits

Profile functions

Perturbative prediction depends on four dynamical scales: $\mu_H, \mu_J, \mu_S, \mu_{ns}$

$\Rightarrow$ use scale variation to estimate higher-order corrections in all sectors of the calculation



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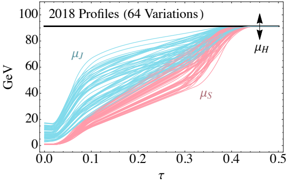

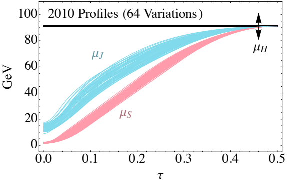

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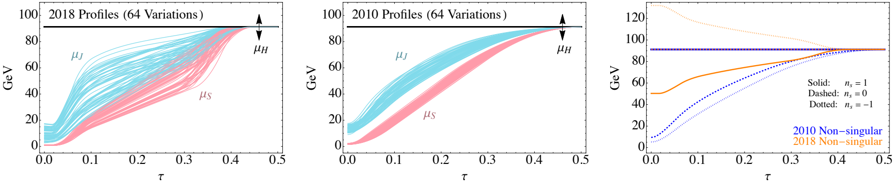

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- 2018 scales are more conservative than the 2010 scales used by Abbate et al
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- variations of μ_{ns} try to account for missing logs in $\mathcal{O}(\tau)$ suppressed terms

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Non-perturbative effects

Dijet factorisation theorem relies on SCET-1 scale hierachy $\mu_H \gg \mu_J \gg \mu_S$

Peak region: $\mu_S \sim \Lambda_{\text{QCD}}$

- fully non-perturbative shape function

$\Rightarrow$ theoretical prediction becomes very model dependent

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Peak region: $\mu_S \sim \Lambda_{\rm QCD}$

- fully non-perturbative shape function

$\Rightarrow$ theoretical prediction becomes very model dependent

Tail region: $\mu_S \gg \Lambda_{\rm QCD}$

- OPE of soft function

$$S(k) = \frac{1}{N_c} \mathrm{Tr}\, \langle \Omega | S_{\bar{n}}^\dagger S_n \, \delta\Big(k - \int d\eta \, e^{-|\eta|} \, \mathcal{E}_T(\eta)\Big) S_n^\dagger S_{\bar{n}} | \Omega \rangle = \delta(k) - 2\Omega_1 \, \delta'(k) + \dots$$

$\Rightarrow$ translates into a shift of the perturbative distribution [Lee, Sterman 06]

$$\boxed{\frac{d\sigma}{d\tau}(\tau) \xrightarrow{\rm NP} \frac{d\sigma}{d\tau}\Big(\tau - \frac{2\Omega_1}{Q}\Big)}$$

$$\Omega_1 = \frac{1}{N_c} \mathrm{Tr}\, \langle \Omega | S_{\bar{n}}^\dagger S_n \, \mathcal{E}_T(0) \, S_n^\dagger S_{\bar{n}} | \Omega \rangle$$

Gapped shape function

Specific implementation of non-perturbative effects [Korchemsky, Sterman 99; Hoang, Stewart 07]

$$S(k,\mu_S) = \int dk' \; \underbrace{S_{PT}(k-k',\mu_S)}_{\text{perturbative soft function}} \; \underbrace{f_{\text{mod}}(k'-2\overline{\Delta})}_{\text{shape-function model}}$$

- gap parameter $\overline{\Delta}$ models minimal soft momentum of hadronic final state

$\Rightarrow$ convolution with perturbative cross section yields shift

$$2\overline{\Omega}_1 = 2\overline{\Delta} + \int dk\, k\, f_{\text{mod}}(k)$$

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$$2\overline{\Omega}_1 = 2\overline{\Delta} + \int dk\, k\, f_{\text{mod}}(k)$$

S_{PT} and $\overline{\Delta}$ suffer from renormalon ambiguities in the $\overline{\text{MS}}$ scheme [Hoang, Stewart 07]

$\Rightarrow$ switch to a renormalon-free scheme

Renormalon subtraction

Redefine gap parameter

$$\overline{\Delta} = \underbrace{\Delta(\mu_\delta, \mu_R)}_{\text{renormalon free}} + \underbrace{\delta(\mu_\delta, \mu_R)}_{\text{cancels renormalon ambiguity of } S_{PT}}$$

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Class of schemes that is free of leading soft renormalon [Bachu, Hoang, Mateu, Pathak, Stewart 20]

$$\frac{d^n}{d(\ln\nu)^n} \ln\left[\widetilde{S}_{PT}(\nu, \mu_\delta)\, e^{-2\nu\delta(\mu_\delta,\mu_R)}\right]_{\nu=\xi/\mu_R} = 0$$

- derivative rank $n \geq 0$
- reference scale μ_δ
- subtraction scale μ_R
- overall normalisation $\xi = \mathcal{O}(1)$

$\Rightarrow$ different choices of $\{n, \xi, \mu_\delta, \mu_R\}$ define different renormalon subtraction schemes

R-gap scheme

Used in 2010 and 2015 analyses

R Scheme: $\{n, \xi, \mu_\delta, \mu_R\} = \{1, e^{-\gamma_E}, \mu_S, R\}$

- additional profile for subtraction scale μ_R

$$\mu_R(\tau) = R(\tau) \equiv \begin{cases} R_0 + \mu_1 \tau + \mu_2 \tau^2 & \tau \leq t_1 \quad \text{(peak region)} \\ \mu_S(\tau) & \tau \geq t_1 \quad \text{(tail and far-tail)} \end{cases}$$

Dependence on μ_δ and μ_R is controlled by RGE

$$\frac{d}{d\ln\mu_\delta}\,\Delta(\mu_\delta,\mu_R) = -\frac{d}{d\ln\mu_\delta}\,\delta(\mu_\delta,\mu_R) \equiv \gamma_\Delta\left[\alpha_s(\mu_\delta)\right]$$

$$\frac{d}{d\mu_R}\,\Delta(\mu_R,\mu_R) = -\frac{d}{d\mu_R}\,\delta(\mu_R,\mu_R) \equiv -\gamma_R\left[\alpha_s(\mu_R)\right]$$

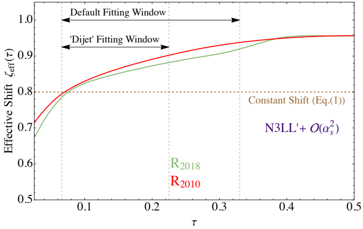
"R evolution"

[Hoang, Jain, Scimemi, Stewart 08]

R-gap scheme

Effective shift of perturbative distribution

$$\zeta_{\text{eff}}(\tau) \equiv \int dk\, k\, e^{-2\delta(\mu_\delta,\mu_R)\frac{d}{dk}}\, f_{\text{mod}}\big(k - 2\Delta(\mu_\delta,\mu_R)\big)$$



R evolution induces a larger shift

for larger values of τ

$\Rightarrow$ can one find a scheme in which the growth of the shift is mitigated?

R* scheme

We propose a closely related scheme

R⋆ Scheme: $\{n, \xi, \mu_\delta, \mu_R\} = \{1, e^{-\gamma_E}, R^\star, R^\star\}$

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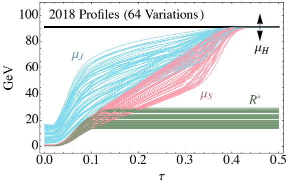

- no logarithms in $\frac{\mu_\delta}{\mu_R}$
- subtractions must be reexpanded in $\alpha_s(\mu_S)$

$\Rightarrow$ logarithms in $\frac{\mu_S}{\mu_\delta}$ only arise at $\mathcal{O}(\alpha_s^3)$

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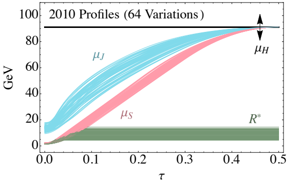

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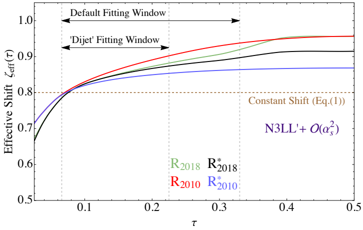
R^* scheme

Effective shift of perturbative distribution

$$\zeta_{\text{eff}}(\tau) \equiv \int dk\, k\, e^{-2\delta(\mu_\delta,\mu_R)\frac{d}{dk}}\, f_{\text{mod}}\big(k - 2\Delta(\mu_\delta,\mu_R)\big)$$

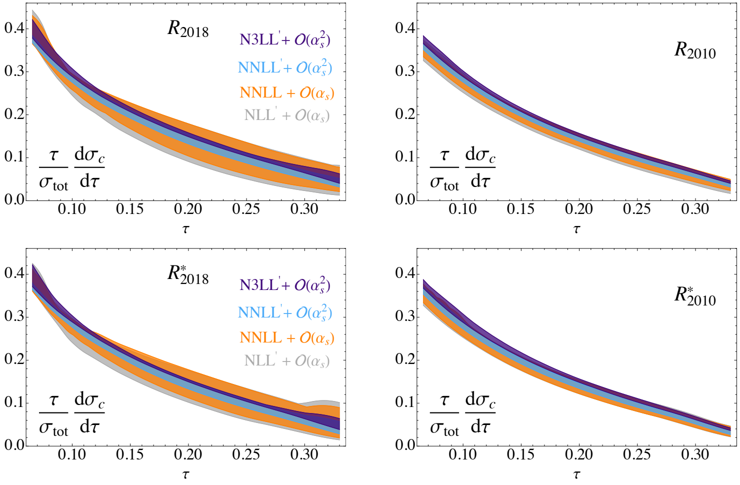


- effective shift flattened as desired
- corresponds to $\lesssim$ 10% modification of dominant power correction

$\Rightarrow$ the scheme is not necessarily preferred, but it allows us to verify if the predictions are stable under a variation of the renormalon scheme

Differential distributions

We compare two renormalon schemes (R,R*) for two profile scale choices (2018,2010)



[$Q = m_Z$, $\alpha_s(m_Z) = 0.11$, $\Omega_1(R_\Delta, R_\Delta) = 0.4$ GeV, $R_\Delta = 1.5$ GeV]

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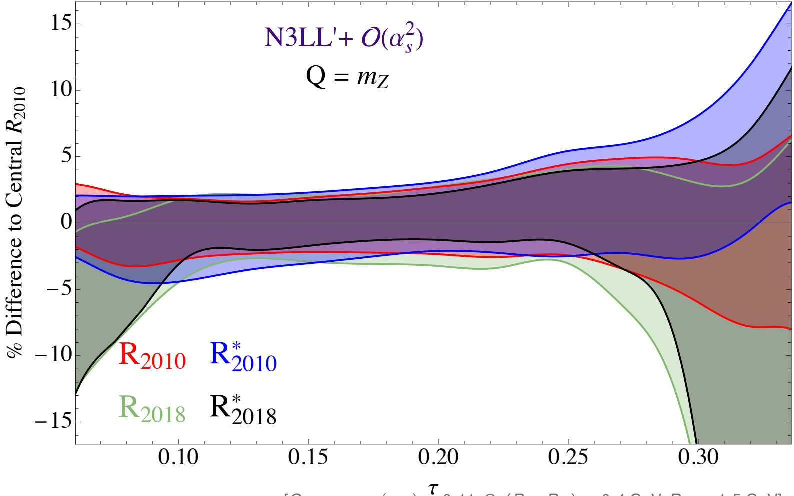


[$Q = m_Z$, $\alpha_s(m_Z) = 0.11$, $\Omega_1(R_\Delta, R_\Delta) = 0.4$ GeV, $R_\Delta = 1.5$ GeV]

OUTLINE

PERTURBATIVE TREATMENT

- RESUMMATION
- MATCHING TO FIXED-ORDER
- PROFILE FUNCTIONS

NON-PERTURBATIVE TREATMENT

- GAPPED SHAPE FUNCTION
- RENORMALON SCHEMES

α_s FITS

- EXTRACTION METHOD
- RESULTS

Extraction method

We perform a χ^2 analysis at the level of binned distributions

$$\chi^2 \equiv \sum_{i,j} \Delta_i \, V_{ij}^{-1} \Delta_j \qquad\qquad \Delta_i \equiv \frac{1}{\sigma}\frac{d\sigma}{d\tau}(\tau_i)\Big|^{\exp} - \frac{1}{\sigma}\frac{d\sigma}{d\tau}(\tau_i)\Big|^{\text{th}}$$

- theory bins from cumulative distribution according to midpoint prescription

$$\frac{1}{\sigma}\frac{d\sigma}{d\tau}(\tau_i)\Big|^{\text{th}}_{\text{MP}} \equiv \frac{1}{\sigma_{tot}} \frac{\sigma_c\big(\tau_2, \mu_a(\overline{\tau})\big) - \sigma_c\big(\tau_1, \mu_a(\overline{\tau})\big)}{\tau_2 - \tau_1} \qquad\qquad \overline{\tau} = \frac{\tau_1 + \tau_2}{2}$$

- correlation of systematic experimental uncertainties estimated via minimal overlap model

$$V_{ij}\big|_{\text{MOM}} = \big(e_i^{\text{stat}}\big)^2 \delta_{ij} + \min\big(e_i^{\text{sys}}, e_j^{\text{sys}}\big)^2$$

- theoretical uncertainties estimated from a random scan of $\mathcal{O}(1000)$ profile parameters

$\Rightarrow$ parametrised by an error ellipse $K_{\text{theory}} = \begin{pmatrix} \sigma_\alpha^2 & \rho_{\alpha\Omega}\,\sigma_\alpha\sigma_\Omega \\ \rho_{\alpha\Omega}\,\sigma_\alpha\sigma_\Omega & \sigma_\Omega^2 \end{pmatrix}$

Experimental data

52 datasets with varying center-of-mass energies

ALEPH	91.2, 133, 161, 172, 183, 189, 200, 206
DELPHI	45, 66, 76, 91.2, 133, 161, 172, 183, 189, 192, 196, 200, 202, 205, 207
JADE	35, 44
L3	41.4, 55.3, 65.4, 75.7, 82.3, 85.1, 91.2, 130.1, 136.1, 161.3, 172.3, 182.8, 188.6, 194.4, 200, 206.2
OPAL	91, 133, 161, 172, 177, 183, 189, 197
SLD	91.2
TASSO	35, 44

Two fit windows

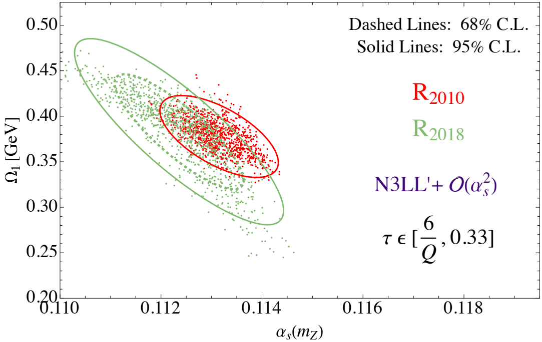
- default $6/Q \leq \tau \leq 0.33$ 488 bins
- reduced $6/Q \leq \tau \leq 0.225$ 371 bins

Two fit parameters

- $\alpha_s \equiv \alpha_s(m_Z)$
- $\Omega_1 \equiv \Omega_1(R_\Delta, R_\Delta)$ with $R_\Delta = 1.5$ GeV

Results

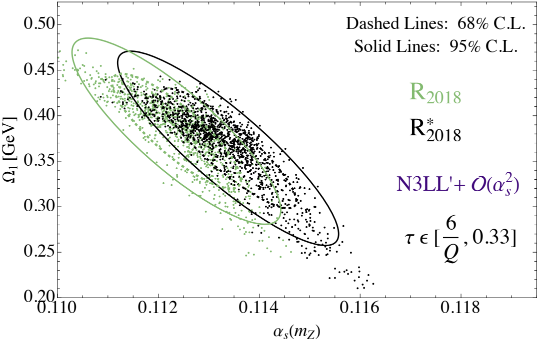
R scheme with different profile scale choices



- R_{2010} setup closest to Abbate et al
- confirm low α_s value
- R_{2018} has significantly larger uncertainties

Results

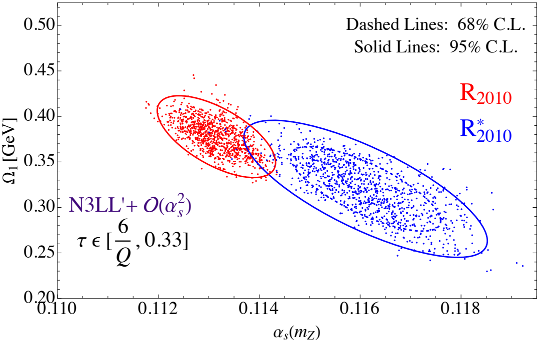
2018 scales for different renormalon schemes



- note that Ω_1 is a scheme-dependent quantity
- α_s drifts mildly to larger values of α_s

Results

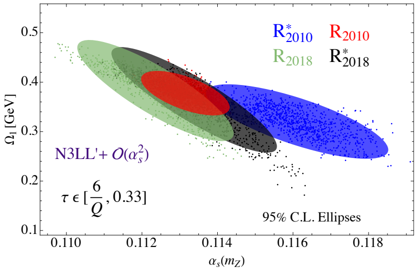
2010 scales for different renormalon schemes

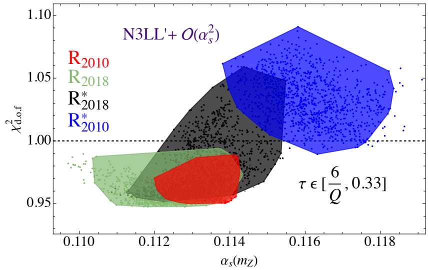


- note that Ω_1 is a scheme-dependent quantity
- scheme change has a much larger impact for 2010 scales
- related to lower value of t_1

Fit quality

All schemes provide good fits to the data



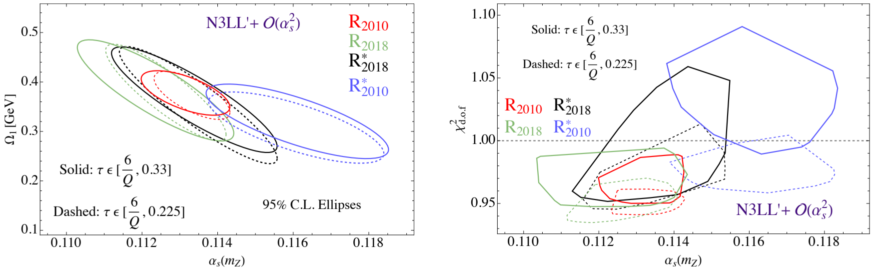


- R^*_{2010} slightly less preferred than the others
- spread of $\{\alpha_s, \Omega_1\}$ values much larger than R_{2010} ellipse would suggest

$\Rightarrow$ sign of additional systematic theory uncertainties?

Reduced fit window

Compare with fits that concentrate more on dijet events



- only mild effect on the extracted $\{\alpha_s, \Omega_1\}$ values
- universal trend towards lower χ^2_{dof} values among all schemes

$\Rightarrow$ may reduce uncertainties from uncontrolled extrapolation into 3-jet region

Comparison to prior analyses

Our setup is similar but not identical to the 2010 and 2015 analyses

- we use $\mathrm{N^3LL'} + \mathcal{O}(\alpha_s^2)$ predictions instead of $\mathrm{N^3LL'} + \mathcal{O}(\alpha_s^3)$
- we use a very different numerical value for $c_{\tilde{S}}^3$
- we do not account for bottom and hadron masses or QED effects
- we use a slightly different method for calculating binned distributions
- we use a slightly different fit method

⇒ all these points are unrelated to the main concern of our analysis

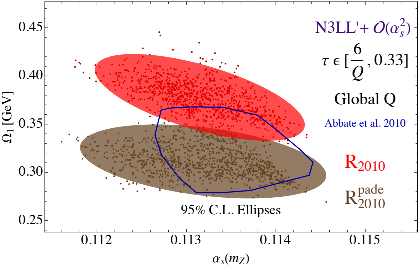
(renormalon schemes and profile scale choices)

⇒ in fact our analysis represents the first independent confirmation of the prior analyses!

Impact of $c_{\tilde{S}}^3$

Compare extractions that use two different values of the 3-loop soft constant

$$c_{\tilde{S}}^3 = \begin{cases} -19988 \pm 5440 & \texttt{EERAD3} \\ 691 \pm 1000 & \text{Padé} \end{cases}$$



- ▶ minor impact on α_s
- ▶ noticeable downward shift for Ω_1

⇒ brings our extraction into even better agreement with Abbate et al

Conclusions

We revisited α_s determinations based on global thrust data

- our analysis represents the first independent confirmation of the previous analyses
- we find that the extractions are very sensitive to scheme and scale choices

  $\Rightarrow$ view this as a signal of systematic theory uncertainties
- fits that are based on dijet events show a better fit quality

  $\Rightarrow$ propose to perform fits that are more focussed on this region
- further progress possible on perturbative side

  $\Rightarrow$ $\mathcal{O}(\alpha_s^3)$ remainder function, 3-loop soft constant $c_{\tilde{S}}^3$, resummation of $\mathcal{O}(\tau)$ corrections

Backup slides