α_s at NNLO(+NLLA) from (mainly) ALEPH data

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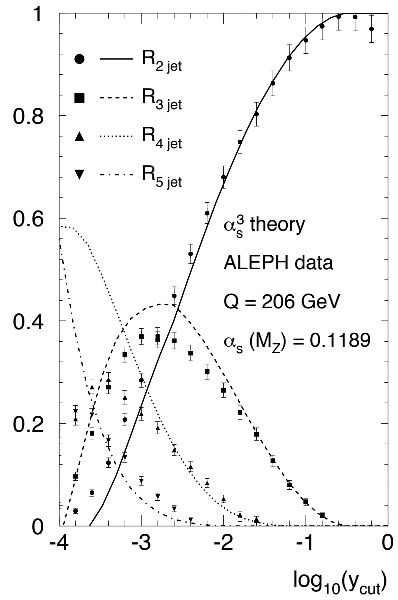
Workshop on 'Precision Measurements of α_s', MPI Munich, 9-11 February 2011

Jets and event shapes

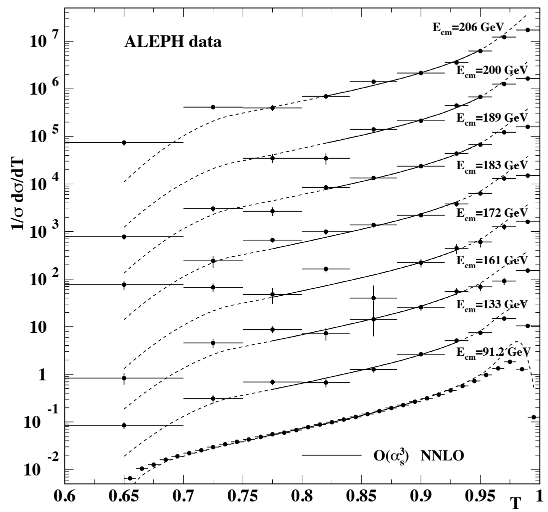
- Jets: direct signature of quark and gluon production
  - defined through jet algorithm (distance measure)
  - e.g. Durham algorithm

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



- Event shapes: measure of event geometry
  - standard set
    - thrust T
    - heavy jet mass M_H ($\rho = M_H^2/s$)
    - C-parameter
    - wide and total broadening: B_W, B_T
    - 2→3 jet transition parameter Y_3

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

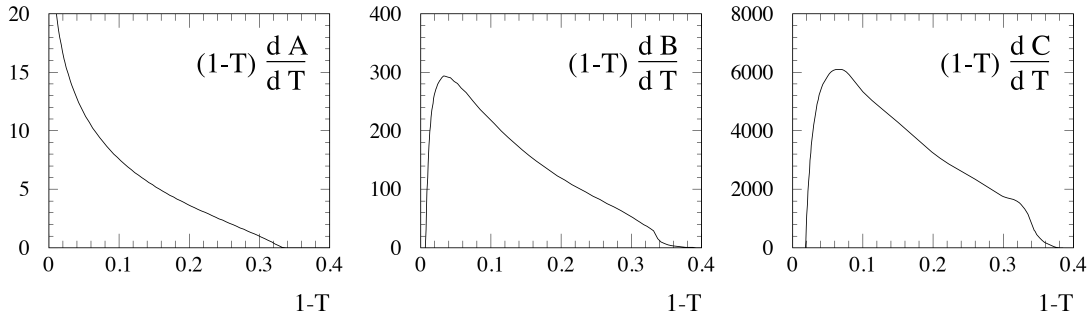


$e^+e^- \to$ 3 jets and event shapes

- perturbative expansion in α_s to NNLO

$$\frac{1}{\sigma_{\mathrm{had}}}\frac{\mathrm{d}\sigma}{\mathrm{d}y}(s,\mu^2,y) = \left(\frac{\alpha_s(\mu)}{2\pi}\right)\frac{\mathrm{d}\bar{A}}{\mathrm{d}y} + \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2\left(\frac{\mathrm{d}\bar{B}}{\mathrm{d}y} + \frac{\mathrm{d}\bar{A}}{\mathrm{d}y}\beta_0\log\frac{\mu^2}{s}\right)$$
$$+\left(\frac{\alpha_s(\mu)}{2\pi}\right)^3\left(\frac{\mathrm{d}\bar{C}}{\mathrm{d}y} + 2\frac{\mathrm{d}\bar{B}}{\mathrm{d}y}\beta_0\log\frac{\mu^2}{s} + \frac{\mathrm{d}\bar{A}}{\mathrm{d}y}\left(\beta_0^2\log^2\frac{\mu^2}{s} + \beta_1\log\frac{\mu^2}{s}\right)\right)$$

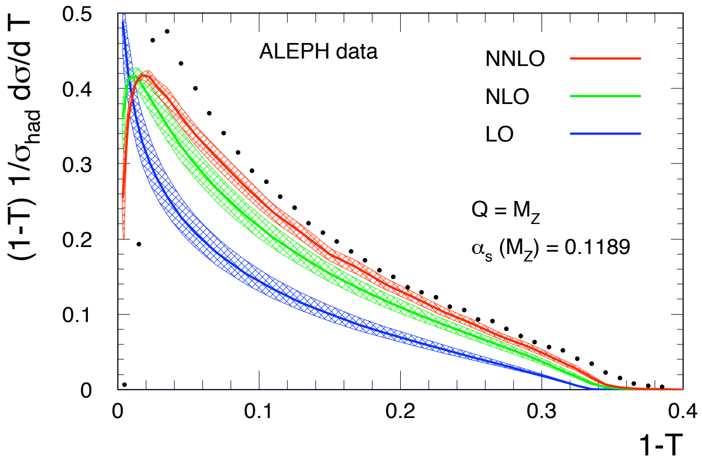
- dimensionless coefficients computed using parton-level event generator
  (A. Gehrmann-De Ridder, E.W.N. Glover, G. Heinrich, TG; S. Weinzierl)

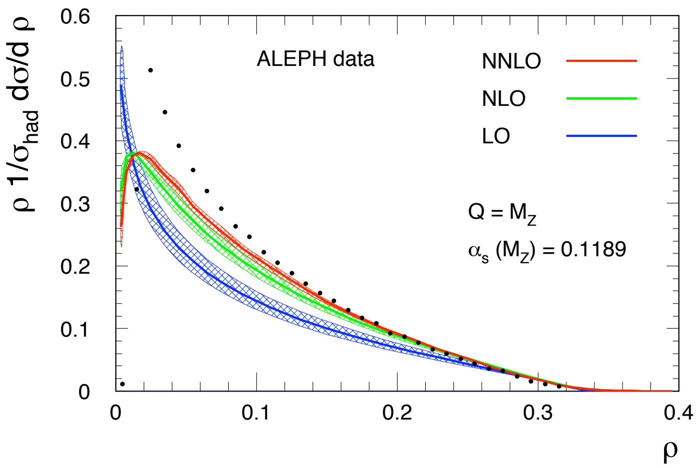


- calculation based on antenna subtraction at NNLO
  (A. Gehrmann-De Ridder, E.W.N. Glover, TG)

$e^+e^- \rightarrow 3$ jets and event shapes

- NNLO results: thrust and M_H

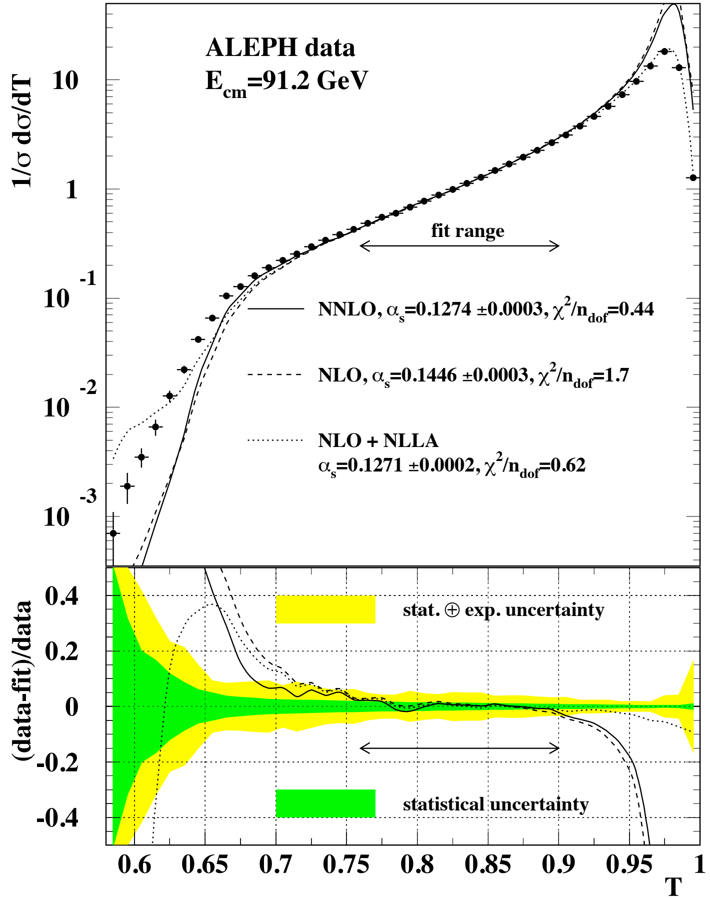




- NNLO effects differ between variables
  - large corrections: T, C, B_T
  - small corrections: M_H, B_W, Y_3
- reduction of scale dependence
- better agreement with data
- two-jet limit: poor convergence of perturbative expansion: need resummation
- before comparing with data
  - include quark mass effects
    (P. Nason, C. Oleari; W. Bernreuther, A. Brandenburg, P. Uwer; G. Rodrigo, A. Santamaria)
  - include hadronization effects
    (HERWIG, PYTHIA, ARIADNE)

α_s from event shapes at NNLO

- fit to six event shapes
  - including NLO mass terms
  - including hadronization
  - restrict to 3 jet region
- data: LEP and LEP2 ALEPH
- better consistency among different shape variables
- reduction of theory error



α_s = 0.1240±0.0008(stat)±0.0010(exp)±0.0011(had)±0.0029(th)

(G. Dissertori, A. Gehrmann-De Ridder, E.W.N. Glover, G. Heinrich, H. Stenzel, TG)

cf. OPAL: α_s = 0.1201±0.0008(stat)±0.0013(exp)±0.0010(had)±0.0024(th)

(OPAL Collaboration)

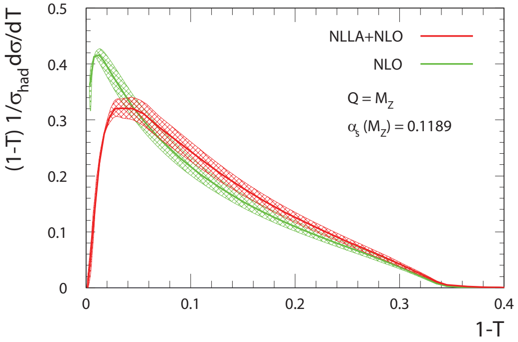
Resummation of event shapes

- fixed order perturbative expansion fails in two-jet limit y→0
- resummation of large logarithms on integrated distribution

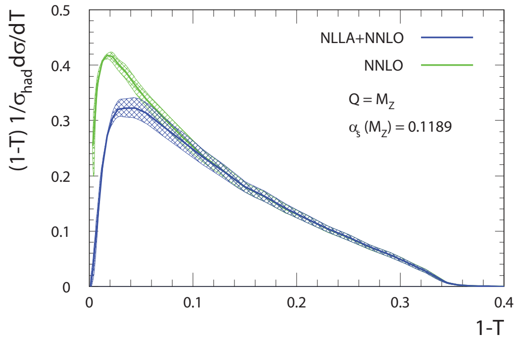
$$R(y,Q,\mu) \equiv \frac{1}{\sigma_{\text{had}}} \int_0^y \frac{d\sigma(x,Q,\mu)}{dx} dx. \qquad R(y,Q,\mu) = 1 + \mathcal{A}(y)\,\bar{\alpha}_s(\mu) + \mathcal{B}(y,x_\mu)\,\bar{\alpha}_s^2(\mu) + \mathcal{C}(y,x_\mu)\,\bar{\alpha}_s^3(\mu)$$

- structure of large logarithms: exponentiation, leading, next-to-leading, ...

$\bar{\alpha}_s\mathcal{A}(y)$	$\bar{\alpha}_s L$	$\bar{\alpha}_s L^2$				
$\bar{\alpha}_s^2\mathcal{B}(y,x_\mu)$	$\bar{\alpha}_s^2 L$	$\bar{\alpha}_s^2 L^2$	$\bar{\alpha}_s^2 L^3$	$\bar{\alpha}_s^2 L^4$		
$\bar{\alpha}_s^3\mathcal{C}(y,x_\mu)$	$\bar{\alpha}_s^3 L$	$\bar{\alpha}_s^3 L^2$	$\bar{\alpha}_s^3 L^3$	$\bar{\alpha}_s^3 L^4$	$\bar{\alpha}_s^3 L^5$	$\bar{\alpha}_s^3 L^6$

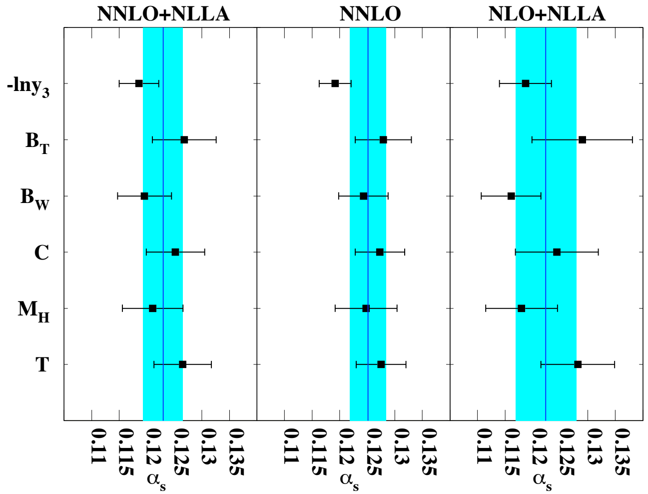


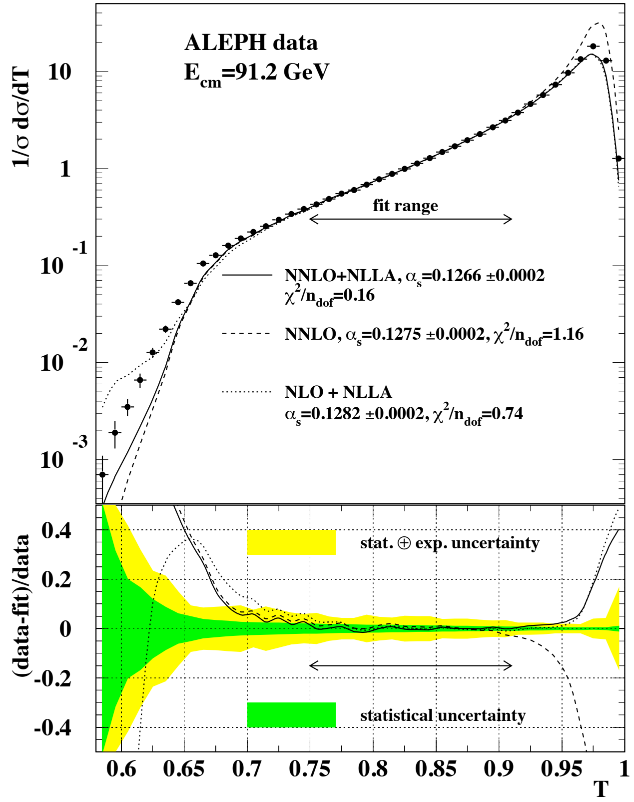
- NLLA resummation available for all event shapes
  (S. Catani, L. Trentadue, G. Turnock, B. Webber)
- matched onto NNLO: remove double counting
  (G. Luisoni, H. Stenzel, TG)



α_s from event shapes at NNLO+NLLA

- fit to six event shapes
  - including NLO mass terms
  - including hadronization
  - enlarged fit range
- data: LEP and LEP2 ALEPH





(G. Dissertori, A. Gehrmann-De Ridder, E.W.N. Glover, G. Heinrich, G. Luisoni, H. Stenzel, TG)

α_s = 0.1224±0.0009(stat)±0.0009(exp)±0.0012(had)±0.0035(th)

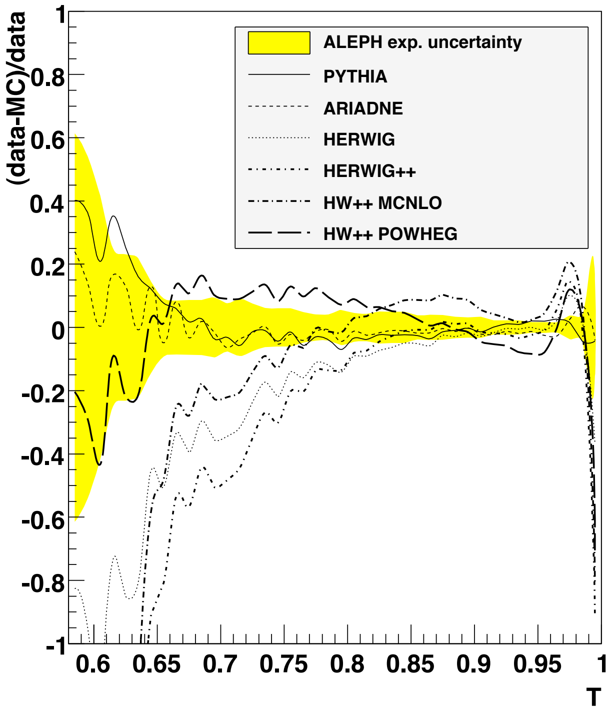
JADE: α_s = 0.1172±0.0006(stat)±0.0040(syst)±0.0030(th) (S. Bethke, S. Kluth, C. Pahl, C. Schieck)

OPAL: α_s = 0.1189±0.0008(stat)±0.0016(exp)±0.0010(had)±0.0036(th) (OPAL Collaboration)

α_s from event shapes at NNLO+NLLA

- systematic uncertainty: hadronization correction
  - modeled by parton level vs. hadron level Monte Carlo generators
    - PYTHIA (default), HERWIG, ARIADNE (estimate systematic error)
- compare with modern generators
    - HERWIG++ (and MC@NLO or POWHEG)
- spread much larger

$\alpha_s(M_Z)$	T	C	M_H	B_W	B_T	$-\ln y_3$
PYTHIA	0.1266	0.1252	0.1211	0.1196	0.1268	0.1186
χ^2/N_{dof}	0.16	0.47	4.4	4.4	0.84	1.89
ARIADNE	0.1285	0.1268	0.1234	0.1212	0.1258	0.1202
χ^2/N_{dof}	0.96	0.52	2.5	3.1	2.15	1.41
HERWIG	0.1256	0.1242	0.1253	0.1203	0.1258	0.1203
χ^2/N_{dof}	0.5	0.65	4.4	2.0	2.15	0.8
HW++	0.1242	0.1228	0.1299	0.1212	0.1238	0.1168
χ^2/N_{dof}	6.6	3.2	3.3	1.33	2.65	0.56
HW++ MCNLO	0.1234	0.1220	0.1292	0.1220	0.1232	0.1175
χ^2/N_{dof}	10.7	4.2	2.2	1.1	5.7	0.69
HW++ POWHEG	0.1189	0.1179	0.1236	0.1169	0.1224	0.1142
χ^2/N_{dof}	1.46	2.55	3.8	3.9	1.54	0.56



- all generators extensively tuned to LEP data
- hadronization models may correct for other shortcomings of generators

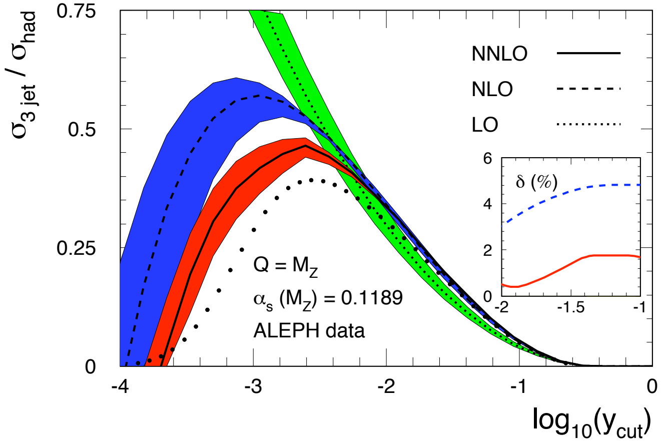
Hadronization corrections

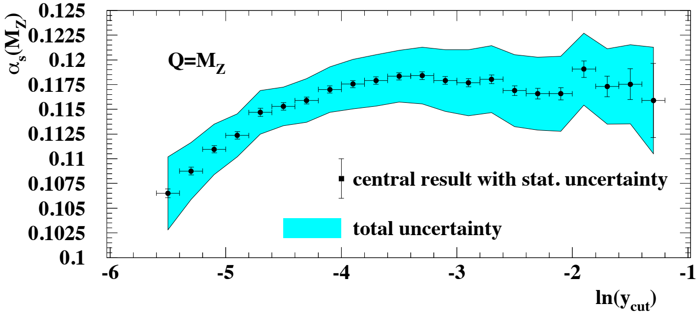
- limiting precision of studies of jet and event shape data
- possible solutions:
  - select observables insensitive to hadronization (jet rates)
    - three-jet rate at NNLO
      (G. Dissertori, A. Gehrmann-De Ridder, E.W.N. Glover, G. Heinrich, H. Stenzel, TG)
  - postulate parton-hadron duality: no hadronization corrections
    - T and M_H at NNLO+N^3LLA (T. Becher, Y.T. Chien, M. Schwartz)
  - use analytic hadronization models
    - shape function
      - T at NNLO+N^3LLA (R. Abbate, M. Fickinger, A. Hoang, V. Mateu, I.W. Stewart)
    - dispersive model
      - T at NNLO+NLLA (R. Davison, B. Webber)
      - moments of event shapes at NNLO (G. Luisoni, M. Jaquier, TG)

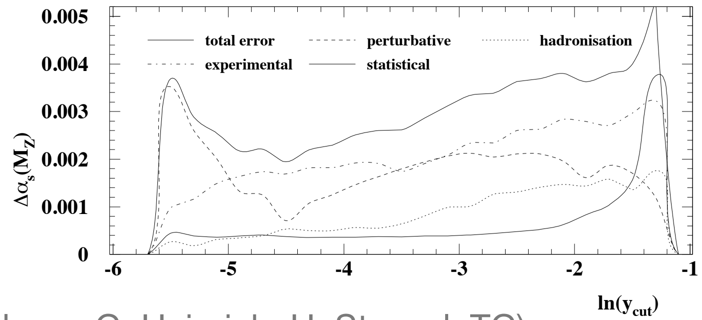
α_s from three-jet rate at NNLO

- NNLO corrections small
  - stable perturbative prediction
  - resummation not needed
  - theory error below 2%
- hadronization corrections
  - much smaller than for event shapes
  - good agreement between all generators
- data with different jet resolution correlated
  - fit at $y_{cut} = 0.02$
  - consistent results with other resolution

$$\alpha_s = 0.1175 \pm 0.0020(\mathrm{exp}) \pm 0.0015(\mathrm{th})$$



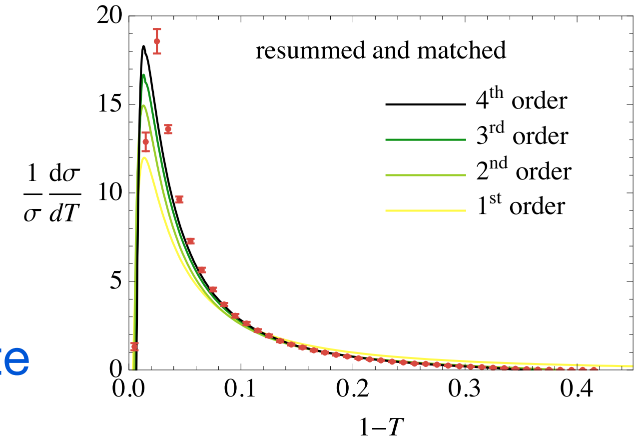




(G. Dissertori, A. Gehrmann-De Ridder, E.W.N. Glover, G. Heinrich, H. Stenzel, TG)

α_S from T and M_H at NNLO+N^{3}LLA

- Soft-collinear effective theory (SCET): hard, collinear and soft modes
  - provides framework for jet observables in two-jet limit
  - allows systematic resummation beyond NLLA
  - results (matched onto NNLO)
    - T at N^{3}LLA (T. Becher, M. Schwartz; R. Abbate, M. Fickinger, A. Hoang, V. Mateu, I.W. Stewart)
    - M_H at N^{3}LLA (Y.T. Chien, M. Schwartz)
- estimate hadronization corrections
  - from Monte Carlo generators
  - from simple shape function model
- use magnitude of corrections only as error estimate

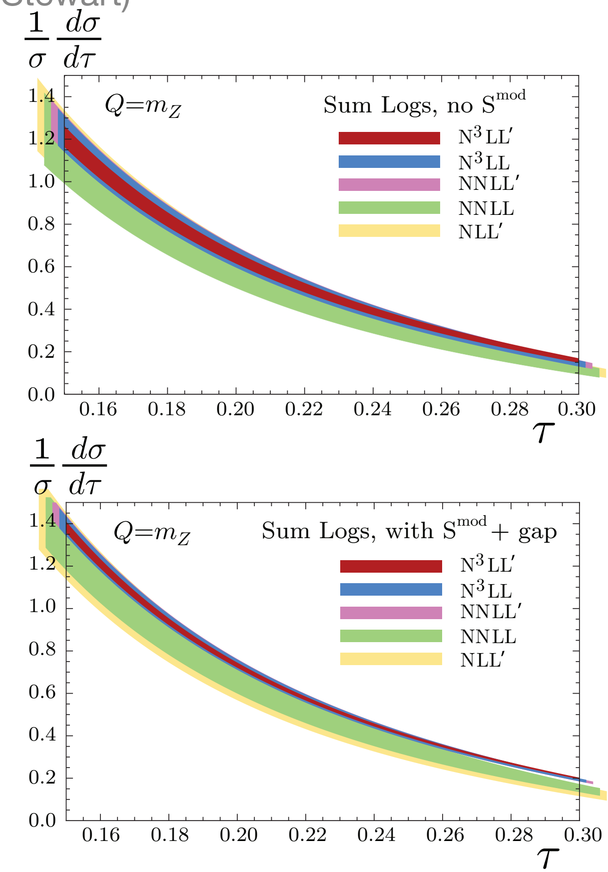


T: α_S = 0.1172±0.0010(stat)±0.0008(sys)±0.0012(had)±0.0012(th) (T. Becher, M. Schwartz)

M_H: α_S = 0.1220±0.0014(stat)±0.0013(sys)±0.0022(had)±0.0012(th) (Y.T. Chien, M. Schwartz)

α_s from T at NNLO+N^{3}LLA

- SCET formalism allows to ascribe soft effects to shape function
- systematic matching of perturbative and non-perturbative contribution (absent in Monte Carlo simulations): renormalon subtraction
- study includes (R. Abbate, M. Fickinger, A. Hoang, V. Mateu, I.W. Stewart)
  - resummation to N^{3}LLA, matched onto NNLO
  - quark mass effects in resummation
  - photonic radiation in resummation
  - hadronization corrections from shape function

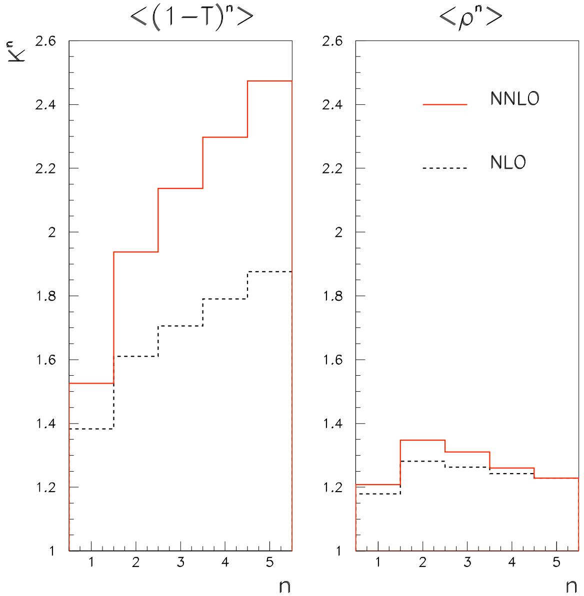


α_s = 0.1135±0.0002(exp)±0.0005(had)±0.0009(th)

Event shape moments

- Moments sample kinematic region of event shape distribution
- power corrections additive

$$\langle y^n \rangle = \frac{1}{\sigma_{\text{had}}} \int_0^{y_{\max}} y^n \frac{d\sigma}{dy} dy \approx \int_0^{y_{\max}} dy (y + a_y P)^n \frac{1}{\sigma_{\text{had}}} \frac{d\sigma_{\text{pt}}}{dy}(y)$$

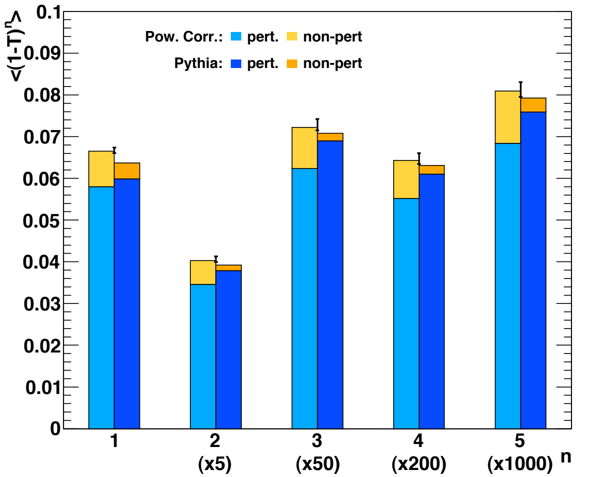


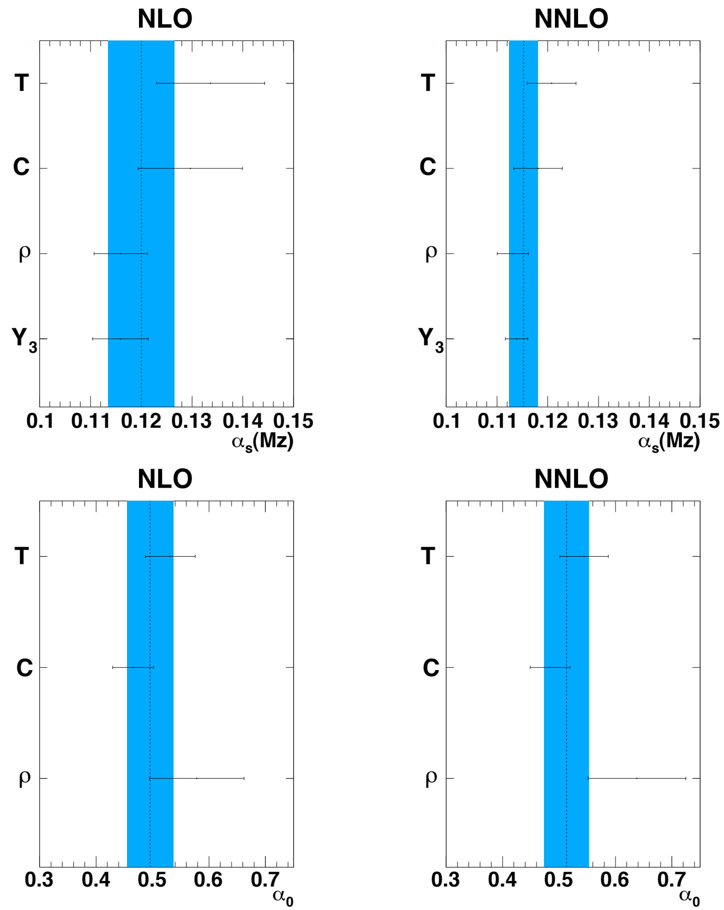
- perturbative contribution known to NNLO
  (A. Gehrmann-De Ridder, E.W.N. Glover, G. Heinrich, TG; S. Weinzierl)
- inclusive observable:no resummation
- dispersive model for power correction (based on renormalons)
  - replace QCD coupling by effective coupling α_0 below scale μ_I = 2 GeV
- extend dispersive model to NNLO (M. Jaquier, G. Luisoni, TG)

$$P = \frac{4C_F}{\pi^2}\mathcal{M}\left\{\alpha_0 - \left[\alpha_s(\mu_R) + \frac{\beta_0}{\pi}\left(1+\ln\left(\frac{\mu_R}{\mu_I}\right)+\frac{K}{2\beta_0}\right)\alpha_s^2(\mu_R) + \left(2\beta_1\left(1+\ln\left(\frac{\mu_R}{\mu_I}\right)+\frac{L}{2\beta_1}\right)+8\beta_0^2\left(1+\ln\left(\frac{\mu_R}{\mu_I}\right)+\frac{K}{2\beta_0}\right)\right.\right.\right.$$
$$\left.\left.\left. + 4\beta_0^2 \ln\left(\frac{\mu_R}{\mu_I}\right)\left(\ln\left(\frac{\mu_R}{\mu_I}\right)+\frac{K}{\beta_0}\right)\right)\frac{\alpha_s^3(\mu_R)}{4\pi^2}\right]\right\} \times \frac{\mu_I}{Q}$$

α_s from event shape moments at NNLO

- simultaneous fit of α_s and α_0 to event shape moments from JADE and OPAL
  - including full correlations (C. Pahl)
  - exclude jet broadenings (unknown recoil corrections)
- good consistency among observables
- substantial difference to PYTHIA hadronization





$$\alpha_s = 0.1153 \pm 0.0017(\mathrm{exp}) \pm 0.0023(\mathrm{th})$$
$$\alpha_0 = 0.5132 \pm 0.0115(\mathrm{exp}) \pm 0.0381(\mathrm{th})$$

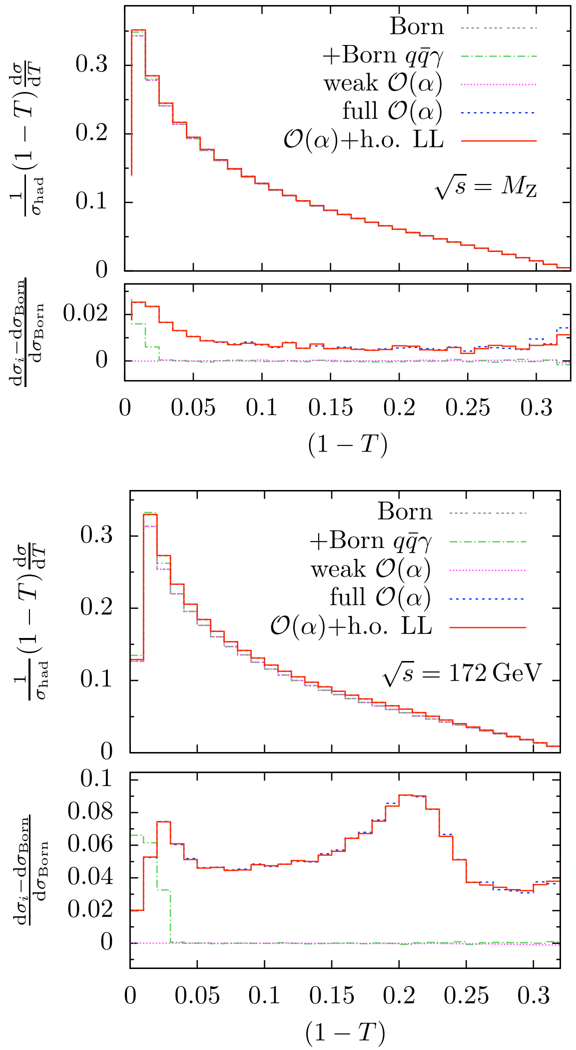
(M. Jaquier, G. Luisoni, TG)

- study of thrust distribution (R. Davison, B. Webber)

$\alpha_s = 0.1167 \pm 0.0028(\mathrm{th})$ $\alpha_0 = 0.59 \pm 0.03$

Outlook: Electroweak corrections

- NLO electroweak effects potentially as large as NNLO QCD: $\alpha \simeq \alpha_s^2$
- strong cancellations between event shape distribution and hadronic cross section
  - initial state radiation
  - weak loop corrections
- depend on final state photon cuts
- contribution from photon fragmentation
- LEP2: radiative return not fully suppressed
- LEP data were corrected for photonic effects
  - comparison non-trivial



(A. Denner, S. Dittmaier, C. Kurz, TG)

Summary

- NNLO corrections to jet observables allow precision physics studies on LEP data
  - new determinations of α_s
  - combination with resummation
  - revisit hadronization corrections
- hadronization is currently limiting precision
  - Monte Carlo models appear inappropriate
  - analytic models under intensive development