New analyses of event shapes and the determination of QCD coupling constant in e^+e^- annihilation

贵州民族大学

王声权

第十七届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会
贵阳
2024.07.14

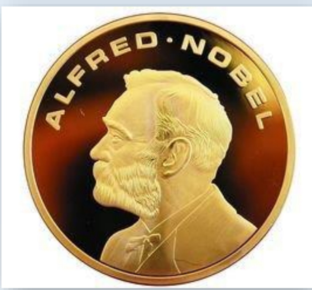
Based on arXiv: 2407.08570; 2112.06212; 1908.00060; 1902.01984
in collaboration with Stanley J. Brodsky, Xing-Gang Wu, Jian-Ming Shen, and Leonardo Di Giustino

Outline

- Introduction for the QCD Running Coupling
- Event shapes at e^+e^- collider
- The determination of QCD coupling constant at LEP
- Summary

Introduction

Quark model
1964(1969)



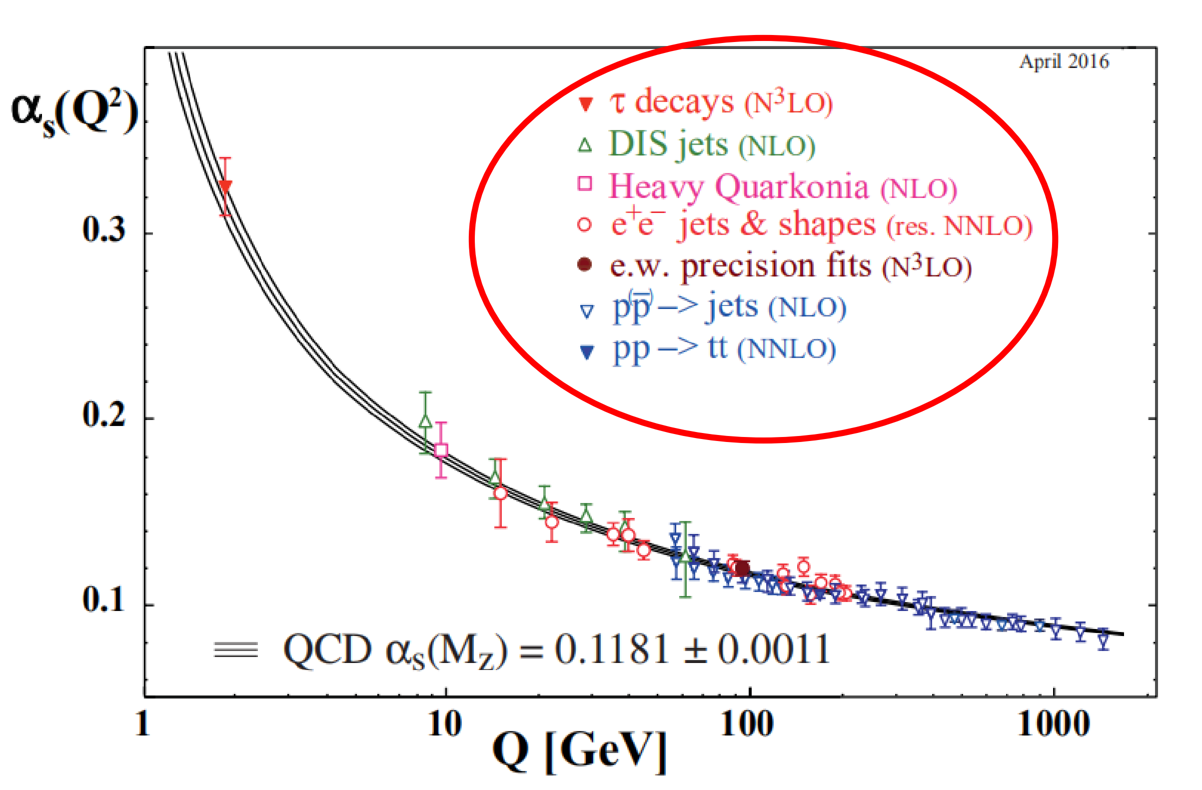
QCD
1973(2004)

默里·盖尔曼(Murray Gell-Mann)

戴维·格罗斯(David J. Gross)
戴维·普利策(H. David Politzer)
弗兰克·维尔泽克(Frank Wilczek)

Introduction

夸克禁闭和渐进自由



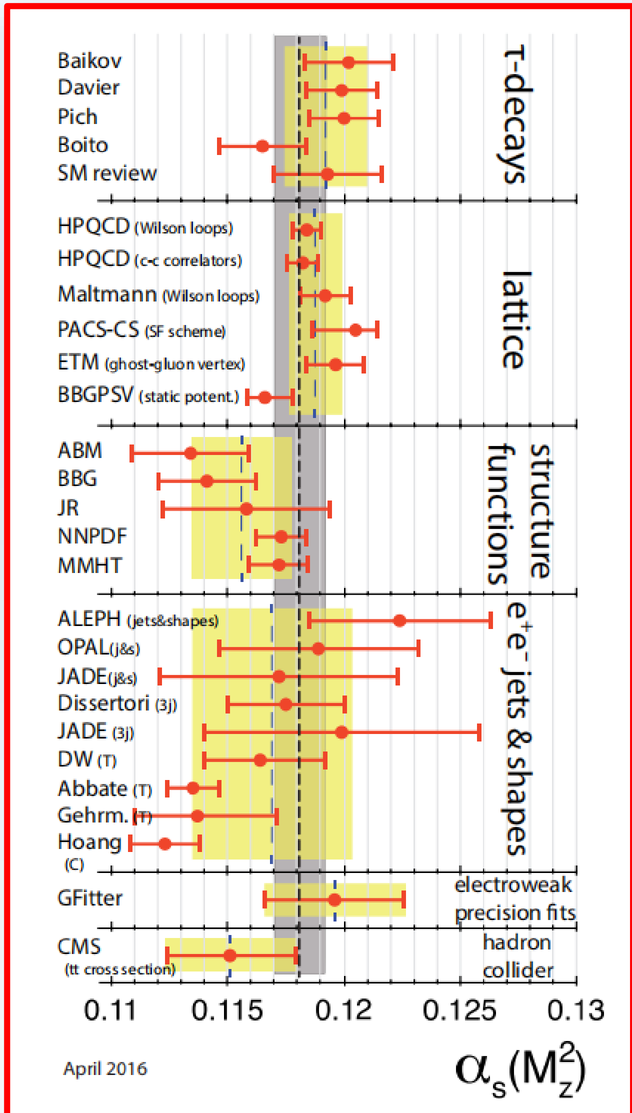
Introduction

Beside the quark masses, the only free parameter in the QCD Lagrangian is the strong coupling constant.

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0011 \quad \text{(w/o } \tau \text{ results; } \chi_0^2/\text{d.o.f.} = 3.3/4),$$
$$\alpha_s(M_Z^2) = 0.1174 \pm 0.0016 \quad \text{(w/o lattice results; } \chi_0^2/\text{d.o.f.} = 2.9/4),$$
$$\alpha_s(M_Z^2) = 0.1185 \pm 0.0013 \quad \text{(w/o DIS results; } \chi_0^2/\text{d.o.f.} = 2.0/4),$$
$$\alpha_s(M_Z^2) = 0.1182 \pm 0.0010 \quad \text{(w/o } e^+e^- \text{ results; } \chi_0^2/\text{d.o.f.} = 3.5/4),$$
$$\alpha_s(M_Z^2) = 0.1184 \pm 0.0012 \quad \text{(w/o hadron collider; } \chi_0^2/\text{d.o.f.} = 2.4/4) \text{ and}$$
$$\alpha_s(M_Z^2) = 0.1180 \pm 0.0010 \quad \text{(w/o e.w. precision fit; } \chi_0^2/\text{d.o.f.} = 3.4/4).$$

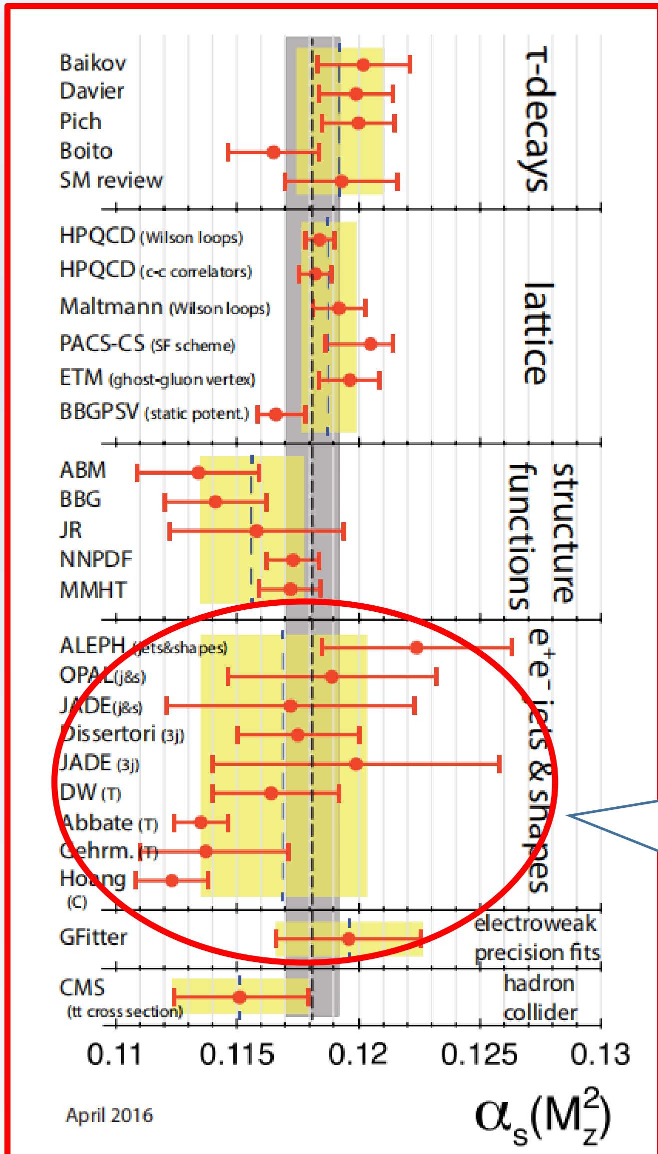
0.8%

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



[Particle Data Group],
Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Event shapes at e^+e^- collider



419. G. Dissertori *et al.*, JHEP **0908**, 036 (2009).
420. G. Abbiendi *et al.*, Eur. Phys. J. **C71**, 1733 (2011).
421. S. Bethke *et al.*, [JADE Collab.], Eur. Phys. J. **C64**, 351 (2009).
422. G. Dissertori *et al.*, Phys. Rev. Lett. **104**, 072002 (2010).
423. J. Schieck *et al.*, Eur. Phys. J. **C73**, 2332 (2013).
424. R.A. Davison and B.R. Webber, Eur. Phys. J. **C59**, 13 (2009).
425. R. Abbate *et al.*, Phys. Rev. **D83**, 074021 (2011).
426. T. Gehrmann *et al.*, Eur. Phys. J. **C73**, 2265 (2013).
427. A.H. Hoang *et al.*, Phys. Rev. **D91**, 094018 (2015).
428. R. Frederix *et al.*, JHEP **1011**, 050 (2010).

- The $a_s(M_Z)$ are plagued by significant scale uncertainty
- Some extracted $a_s(M_Z)$ are deviated from the world average
- non-self-consistent

Event shapes at e^+e^- collider

The method for extracting $a_s(M_Z)$ in e^+e^- collider:

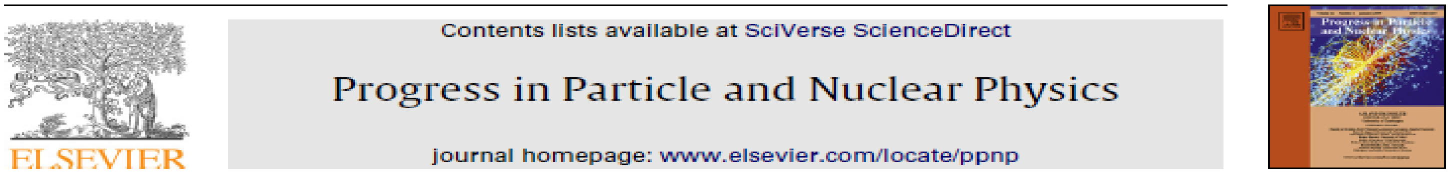
- the renormalization scale is fixed to $Q = \sqrt{s}$
- predictions matched Monte Carlo models to correct for hadronization effects
- based on analytic calculations of non-perturbative and hadronization effects, using methods like power corrections, factorization of soft-collinear effective field theory, dispersive models and low scale QCD effective couplings

We note that there is criticism on both classes of α_s extractions described above: those based on corrections of non-perturbative hadronization effects using QCD-inspired Monte Carlo generators (since the parton level of a Monte Carlo simulation is not defined in a manner equivalent to that of a fixed-order calculation), as well as studies based on non-perturbative analytic calculations, as their systematics have not yet been fully verified. In particular, quoting rather small overall experimental, hadronization and theoretical uncertainties of only 2, 5 and 9 per-mille, respectively [425,427], seems unrealistic and has neither been met nor supported by other authors or groups.

?

[Particle Data Group], Phys. Rev. D98, 030001 (2018)

Principle of Maximum Conformality(PMC)


Contents lists available at SciVerse ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

The renormalization scale-setting problem in QCD

Xing-Gang Wu [a,*], Stanley J. Brodsky [b], Matin Mojaza [b,c]

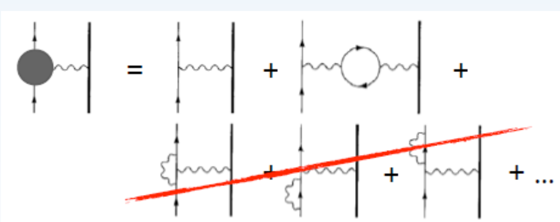
[a] Department of Physics, Chongqing University, Chongqing 401331, PR China

[b] SLAC National Accelerator Laboratory, Stanford University, CA 94039, USA

[c] CP3-Origins, Danish Institute for Advanced Studies, University of Southern Denmark, DK-5230, Denmark

BLM/FAC/PMS

In the case of QED, the renormalization scale can be set unambiguously by using the Gell-Mann-Low method, which automatically sums all vacuum polarization contributions to the photon propagators to all orders.



BLM=> nf-term
BLM method reduces in the Abelian limit to the Gell-Mann-Low method

Quantum Electrodynamics at Small Distances

M. Gell-Mann and F. E. Low
Phys. Rev. **95**, 1300 – Published 1 September 1954

Principle of Maximum Conformality(PMC)

PRL 110, 192001 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Systematic All-Orders Method to Eliminate Renormalization-Scale and Scheme Ambiguities i

Matin M
CP3-Origins, Danish Institute for Advanced Studies, Univ
and SLAC National Accelerator Laboratory, Stan
Stanley J.
SLAC National Accelerator Laboratory, Stanfor
Xing-Ga

PRL 109, 042002 (2012) PHYSICAL REVIEW LETTERS week ending 27 JULY 2012

Scale Ambiguity for Top-Pair Production of Maximum Conformality

and Xing-Gang Wu[1,2,†]
5 Sand Hill Road, Menlo Park, California 94025, USA
sity, Chongqing 401331, People's Republic of China
2012; published 23 July 2012)

ım transfer of the process as the renormalization scale and
ty in the QCD prediction. However, predictions using this

IOP Publishing Reports on Progress in Physics
Rep. Prog. Phys. 78 (2015) 126201 (15pp) doi:10.1088/0034-4885/78/12/126201

Review

Renormalization group invariance and
nalization scale-setting:

ng[1], Hai-Bing Fu[1],
in Mojaza[3]

Feature Story Archive

Taking Some Guesswork Out of High-Energy Physics

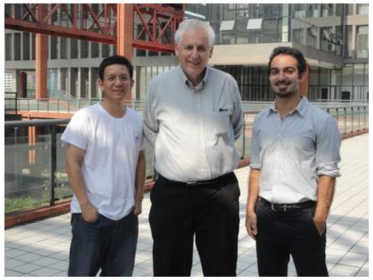
August 6, 2012
by Lori Ann White

SLAC theorist Stan Brodsky and his collaborator Xing-Gang Wu of Chongqing University have just made the lives of high-energy particle theorists the world over a bit easier. They've demonstrated a way to literally take some of the guesswork out of predictions from quantum chromodynamics (QCD). QCD is the theory explaining the behavior of quarks, which in groups of three form protons and neutrons, and gluons, which carry the strong force that "glues" the quarks together.

In the realm of QCD, interactions are the thing. It's not enough to know which quarks make up a particle; just as important is their dynamics: how those quarks bounce off each other and what messages the gluons carry between them as they jostle about. Eavesdropping on quarks is not easy.

To make matters worse, "virtual" particles from the effects of quantum field theory keep popping in and out of existence, changing the discussion. It's as if you're trying to talk to a friend in the midst of a crowd of chatty strangers; snippets of their chatter keep floating over to you and your friend, some from close by – some from farther away – redirecting your train of thought.

SLAC theoretical physicist Stan Brodsky, right, and his colleague, visiting theoretician Xing-Gang Wu, demonstrated the Principle of Maximum Conformality in their current Physical Review Letters... (*Photo by Matt Beardsley*)



(**Click to view larger image.**) **Left to right: Theoretical physicists and collaborators Xing-Gang Wu, Stan Brodsky and Matin Mojaza.** (*Courtesy Matin Mojaza*)

Particle theorists attempt to put the quantum realm under a mathematical microscope. However, the world of subatomic particles operates according to very different rules than our familiar everyday world. Quantum uncertainties take hold. On the scale of quarks and gluons, $E=mc^2$ is not a slogan on a t-shirt, it's the law of the land – if there's a possibility for a particular particle to exist, it, and others, will pop into and out of existence, obscuring what lies under the physicists' calculational lenses.

These "now you see them, now you don't" particles, called virtual particles, give rise to infinite terms in quantum calculations – a big problem for theorists, who must remove the

- Stan and Wu, Phys.Rev.Lett.109,042002(2012)
- Matin, Stan and Wu, Phys.Rev.Lett.110,192001(2013)
- Stan and Wu, Phys.Rev.D85,034038(2012)

- Wu, Stan and Matin, Prog.Part.Nucl.Phys. 72,44(2013)
- Wu, Ma, Wang, Fu, Ma, Stan and Matin, Rep.Prog.Phys. 78, 126201 (2015)
- Wu, Shen, Du, Huang, Wang, Stan, Prog.Part.Nucl.Phys. 108 (2019) 103706

Event shapes at e^+e^- collider

The classic event shapes: the thrust (T), the heavy jet mass (M_H^2/s), the wide and total jet broadenings B_W and B_T, the C-parameter (C)

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

$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2 \theta_{ij}}{\left(\sum_i |\vec{p}_i|\right)^2},$$

Phys. Lett. 12, 57 (1964).
Phys. Rev. Lett. 39, 1587 (1977).

$$M_i^2/s = \frac{1}{E_{\text{vis}}^2} \left(\sum_{k \in H_i} p_k \right)^2$$

Phys. Lett. B 74, 65 (1978).
Phys. Rev. D20, 2759 (1979).

$$\rho \equiv M_H^2/s = \max(M_1^2/s, M_2^2/s)$$

$$B_i = \frac{\sum_{k \in H_i} |\vec{p}_k \times \vec{n}_T|}{2 \sum_k |\vec{p}_k|} .$$

$$B_W = \max(B_1, B_2) ,$$
$$B_T = B_1 + B_2 .$$

Currently, the main obstacle for achieving a precise determination of $a_s(M_Z)$ is not the lack of precise experimental data, especially at Z^0 peak, but the ambiguity of theoretical predictions.

Rep. Prog. Phys. 69, 1771 (2006).

The determination of α_s at LEP

The differential distribution for a event shape:

$$\frac{1}{\sigma_h}\frac{d\sigma}{d\tau} = \bar{A}(\tau)\, a_s(Q) + \bar{B}(\tau)\, a_s^2(Q) + \mathcal{O}(a_s^3).$$

Q = $\sqrt{s}$ using conventional method

$$\frac{1}{\sigma_h}\frac{d\sigma}{d\tau} = \bar{A}(\tau) a_s(\mu_r^{\rm pmc}) + \bar{B}(\tau,\mu_r)_{\rm con} a_s^2(\mu_r^{\rm pmc}) + \mathcal{O}(a_s^3)$$

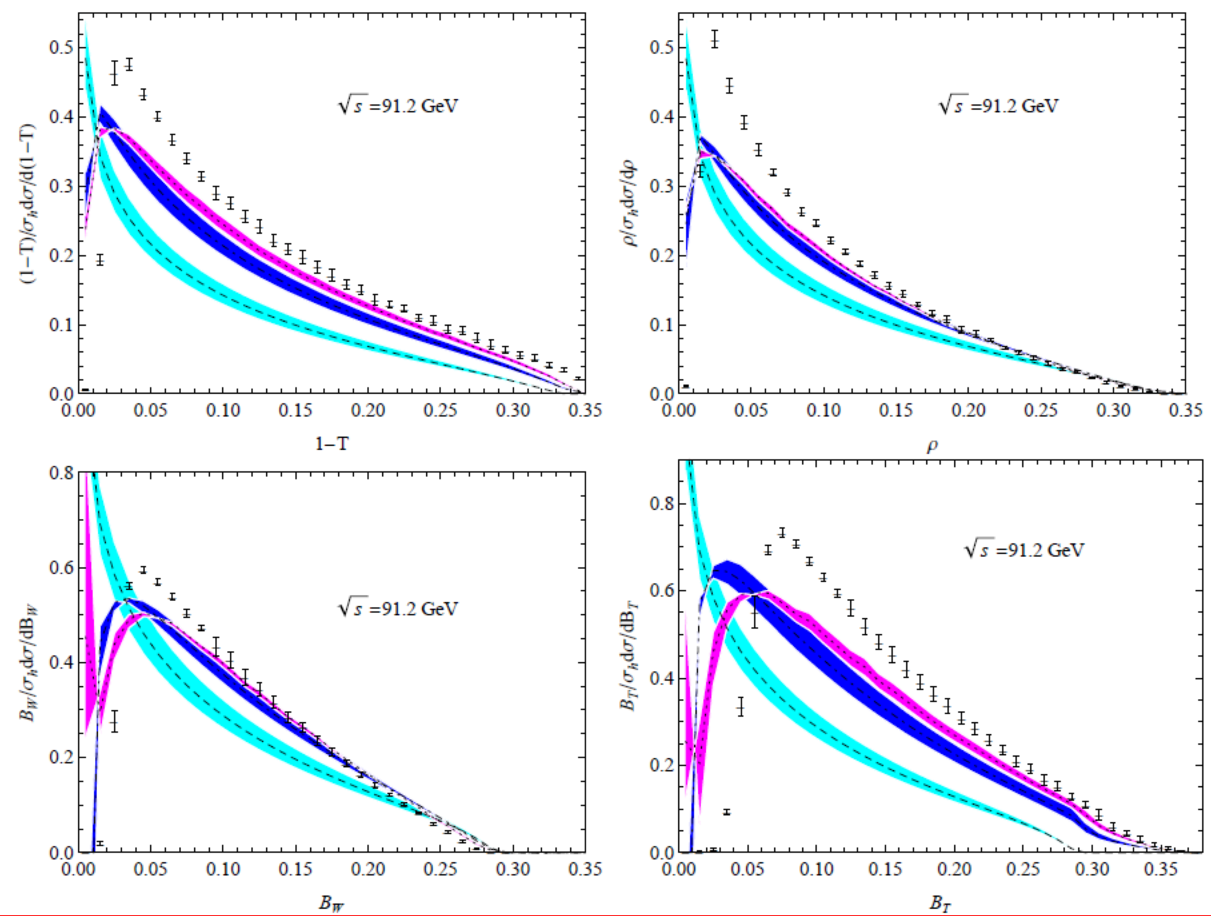
$$\bar{B}(\tau,\mu_r)_{\rm con} = \frac{11 C_A}{4 T_R}\bar{B}(\tau,\mu_r)_{n_f} + \bar{B}(\tau,\mu_r)_{\rm in},$$

$$\mu_r^{\rm pmc} = \mu_r \exp\left[\frac{3\bar{B}(\tau,\mu_r)_{n_f}}{4 T_R \bar{A}(\tau)} + \mathcal{O}(a_s)\right].$$

The determination of α_s at LEP

Conventional results at 91.2 GeV

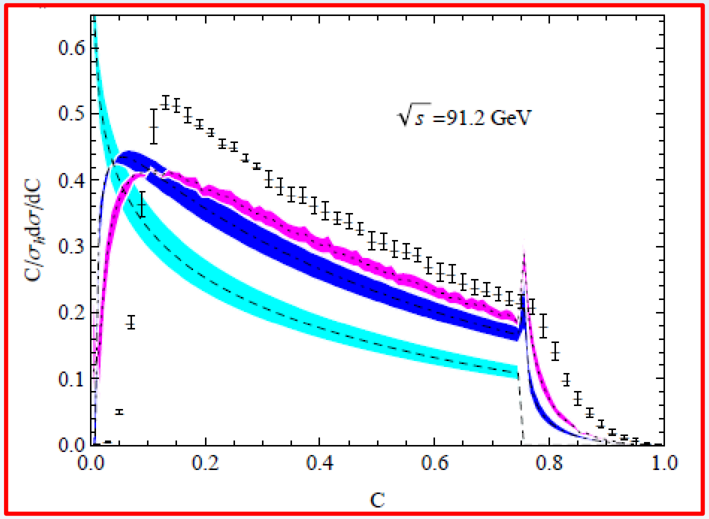
Central values are Q = 91.2 GeV , the errors are [Q/2, 2Q].



Phys. Rev. Lett. 99, 132002
JHEP 0712, 094
Phys.Rev. Lett. 101, 162001
JHEP 0906, 041

The determination of α_s at LEP

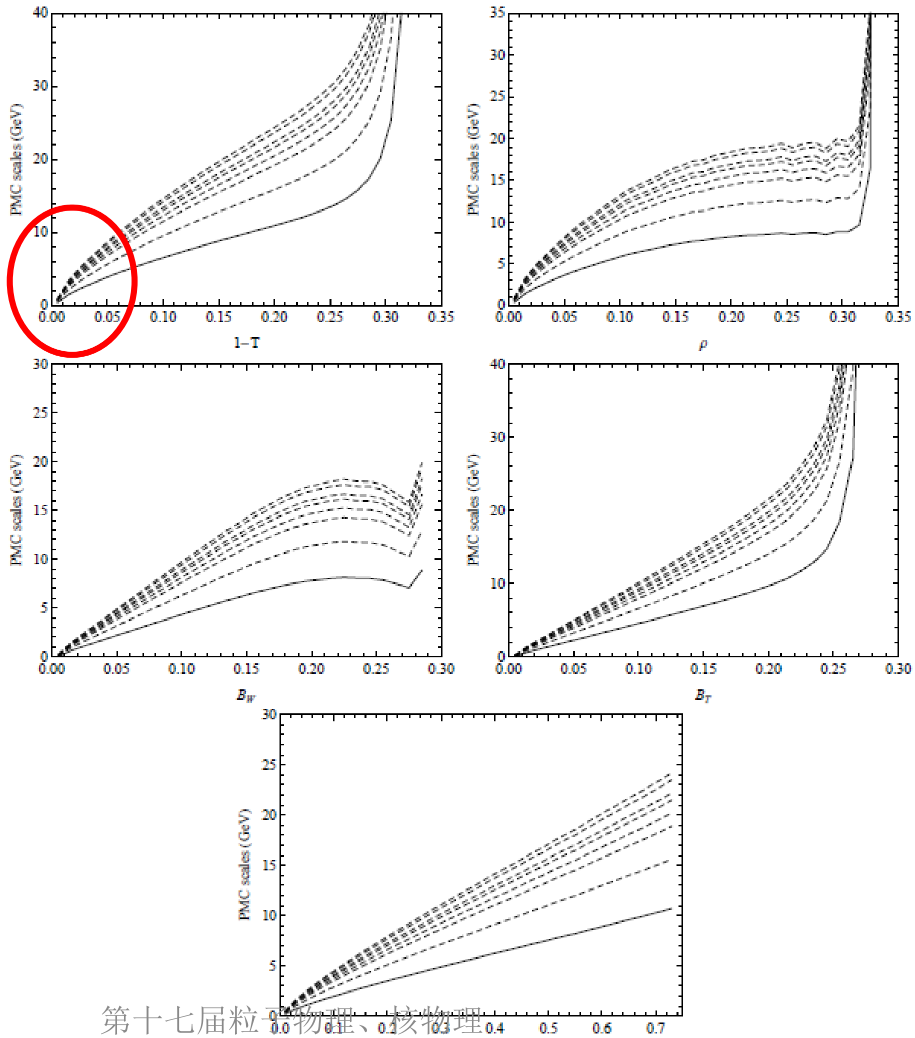
Event shapes using the conventional method:



- The NLO and NNLO are large and the pQCD series shows a slow convergence.
- Estimating the unknown higher order QCD by varying the scale [1/2Q, 2Q] is unreliable.
- The predictions are plagued by scale uncertainty, and even up to NNLO, the predictions do not match the data.
- The extracted coupling constants are deviated from the world average, and are also plagued by scale uncertainty.

The determination of α_s at LEP

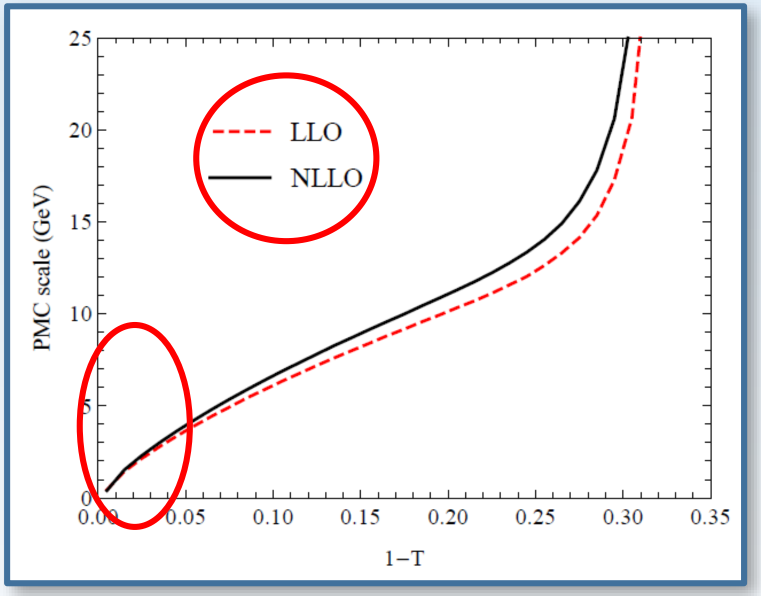
PMC scales:



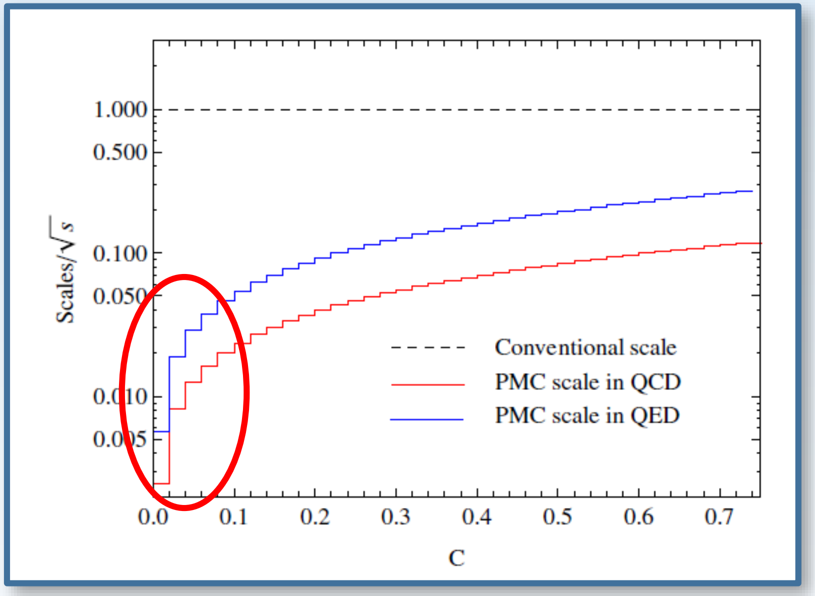
- Remarkably, the PMC scales change dynamically with event shapes;
- The quarks and gluons have soft virtuality near the two-jet region. The PMC scales are very soft in this region, while in the regions away from the two-jet region, the PMC scales are increased, as expected;
- The PMC scales are small in the wide kinematic regions compared to the conventional method \sqrt{s};
- The PMC scales increase with the center-of-mass energy;
- yields the correct physical behavior, and similar behavior are obtained in the SCET theory and other literatures (ZPA 339, 189; EPJC 74, 2896).

The determination of α_s at LEP

T



C

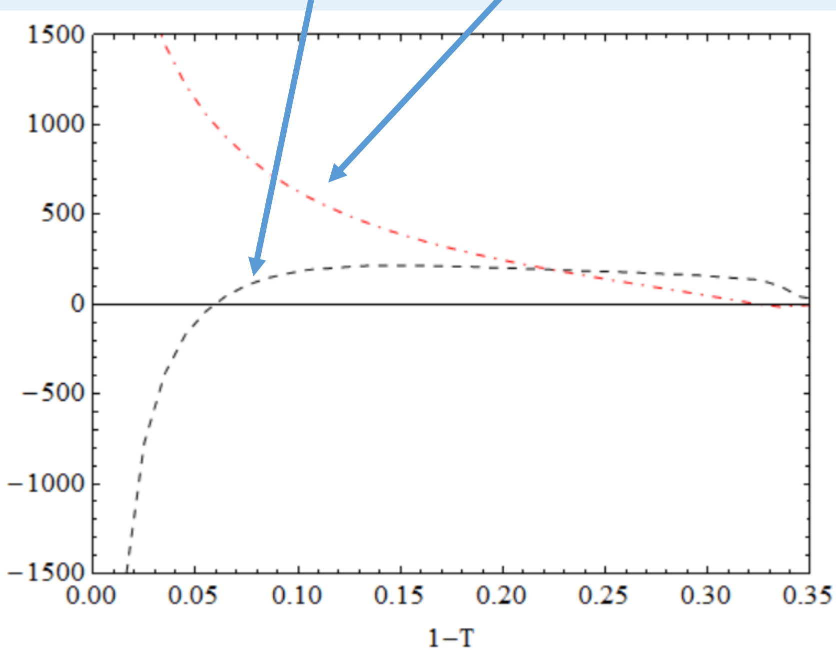


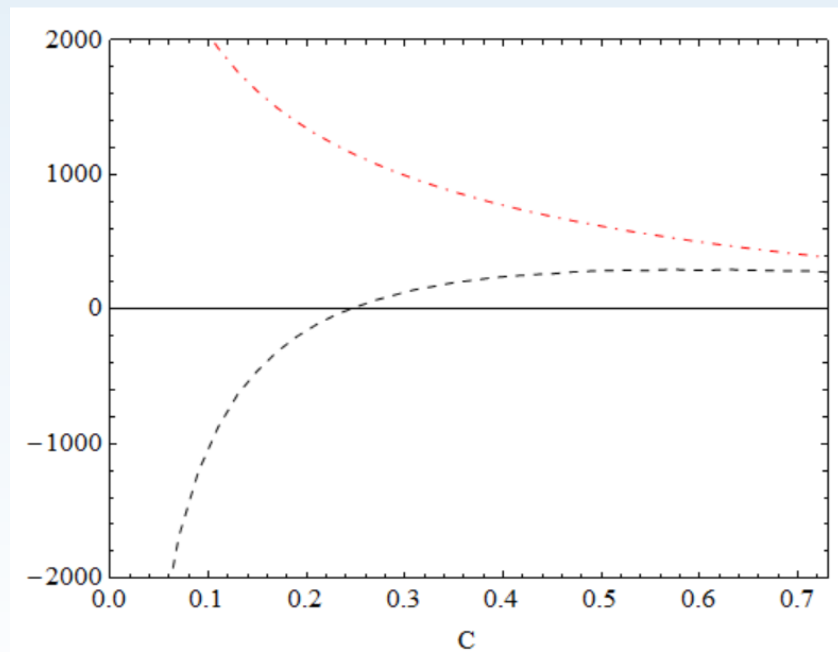
The determination of α_s at LEP

Perturbative coefficients:

$$\bar{B}(y,\mu_r) = \bar{B}(y,\mu_r)_{\rm con} + \bar{B}(y,\mu_r)_{\beta_0} \cdot \beta_0,$$

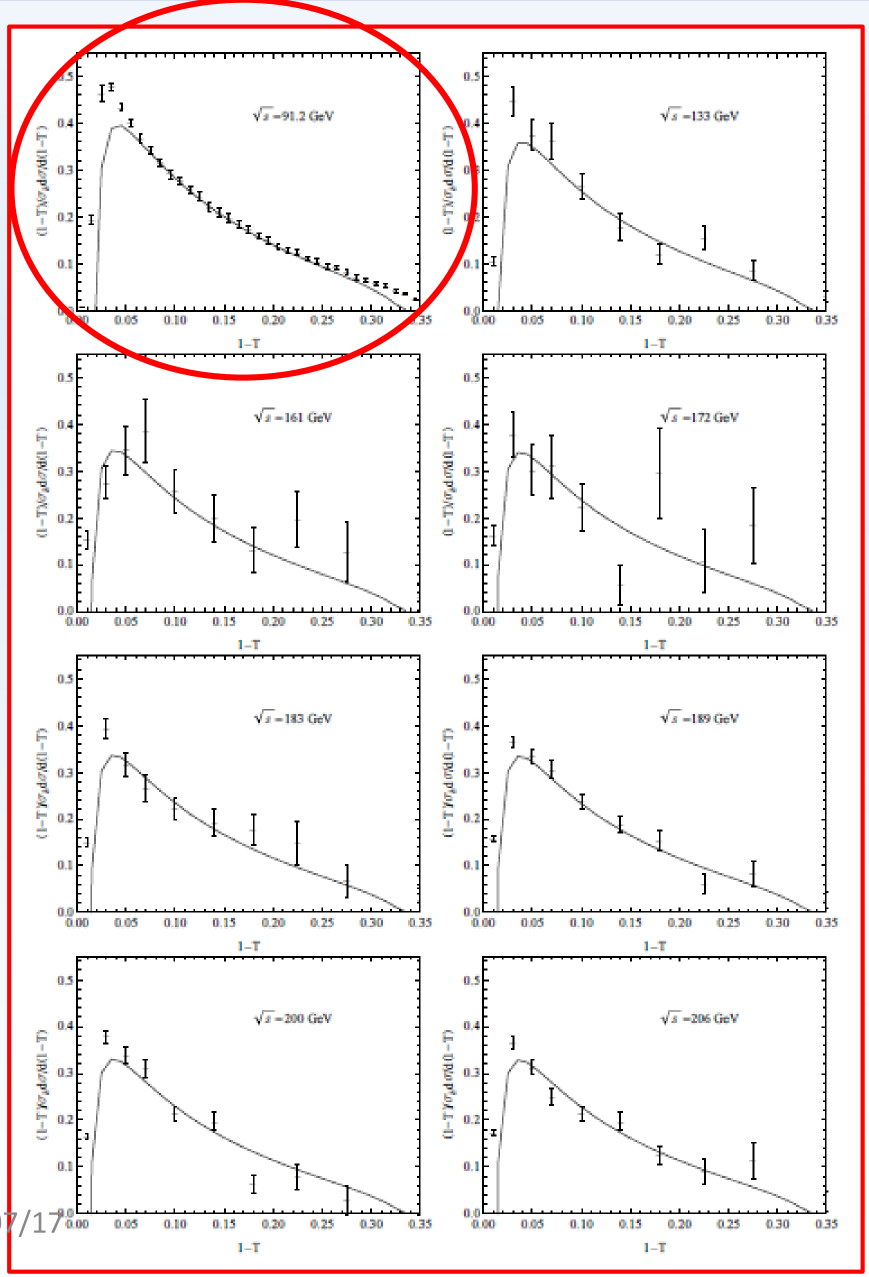
In addition to the PMC scales, the behavior of the PMC conformal coefficients is very different from that of the conventional scale-setting method.



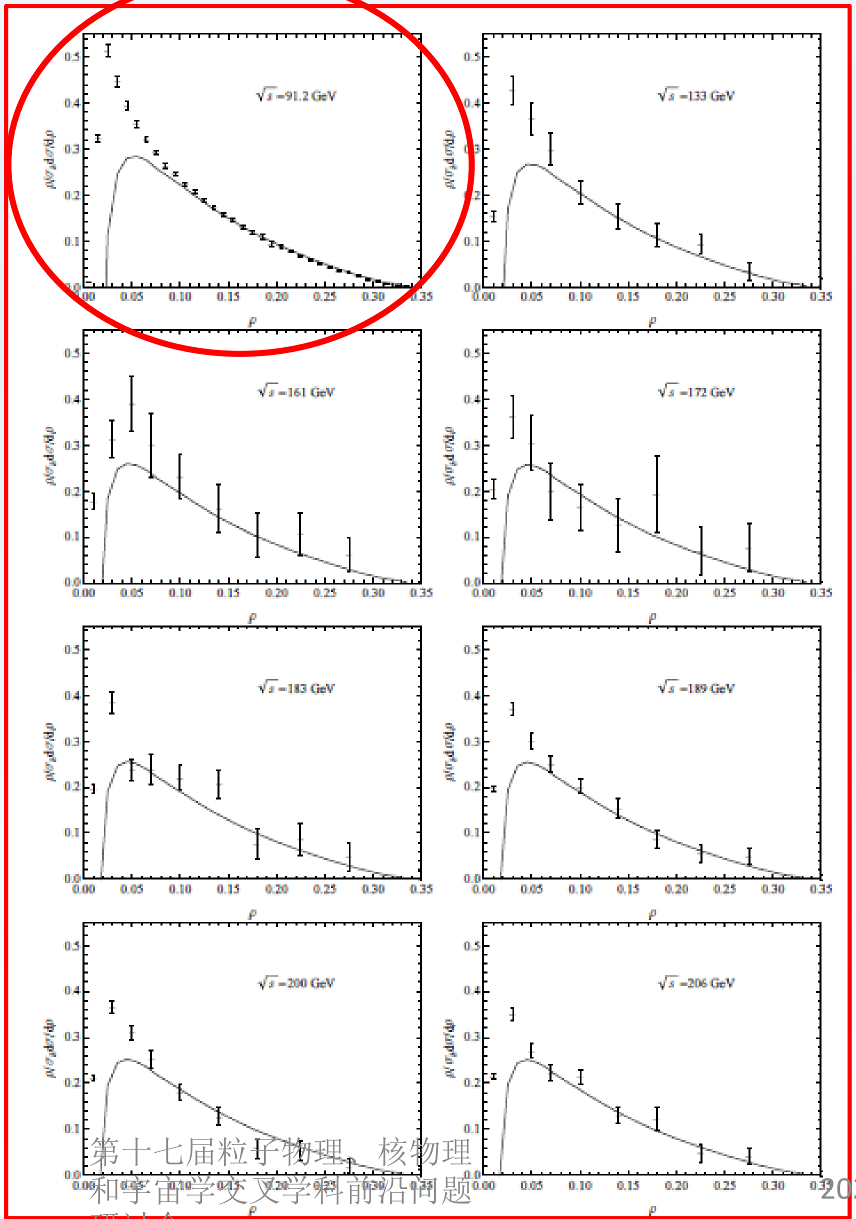


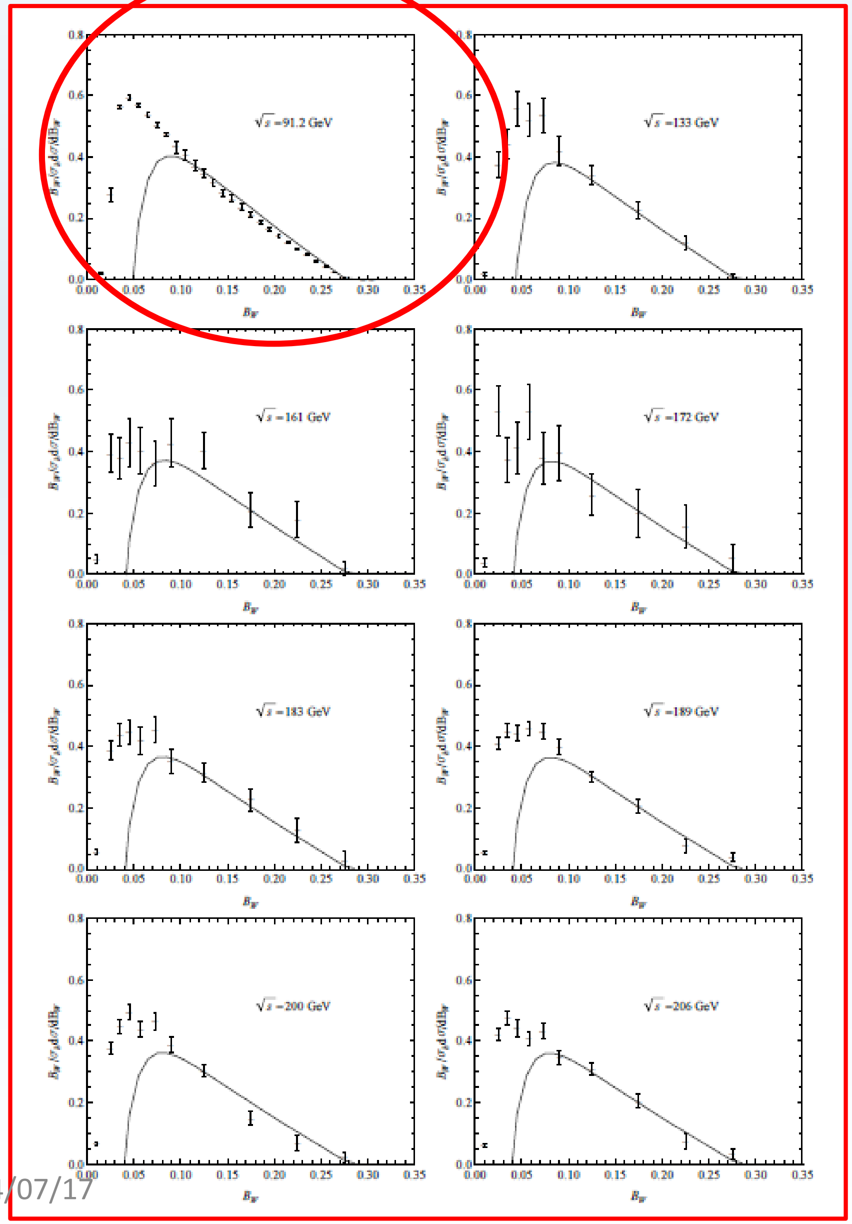
The determination of α_s at LEP

- The resulting PMC predictions are increased in wide kinematic regions compared to the conventional predictions.
- Since the PMC scales are independent of the choice of renormalization scale and the conformal coefficients are also renormalization scale independent, the PMC predictions eliminate the renormalization scale uncertainty.

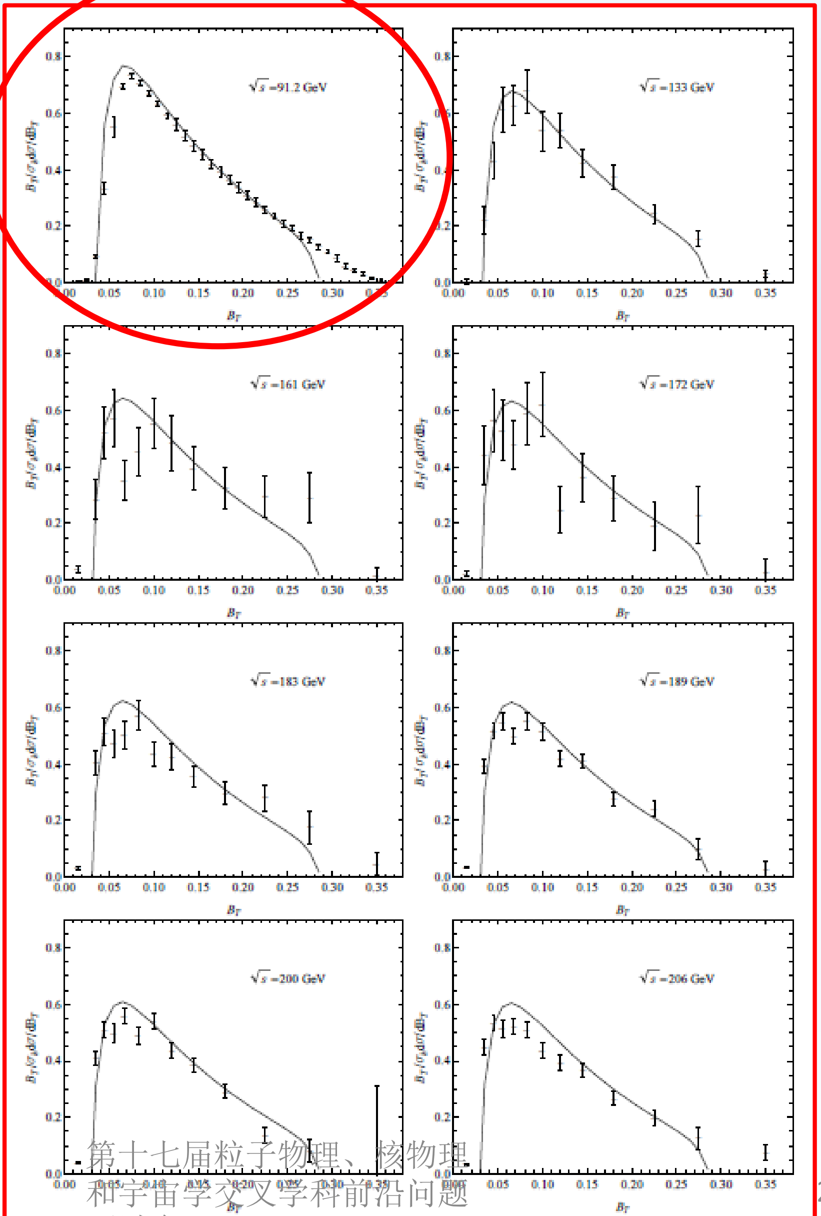


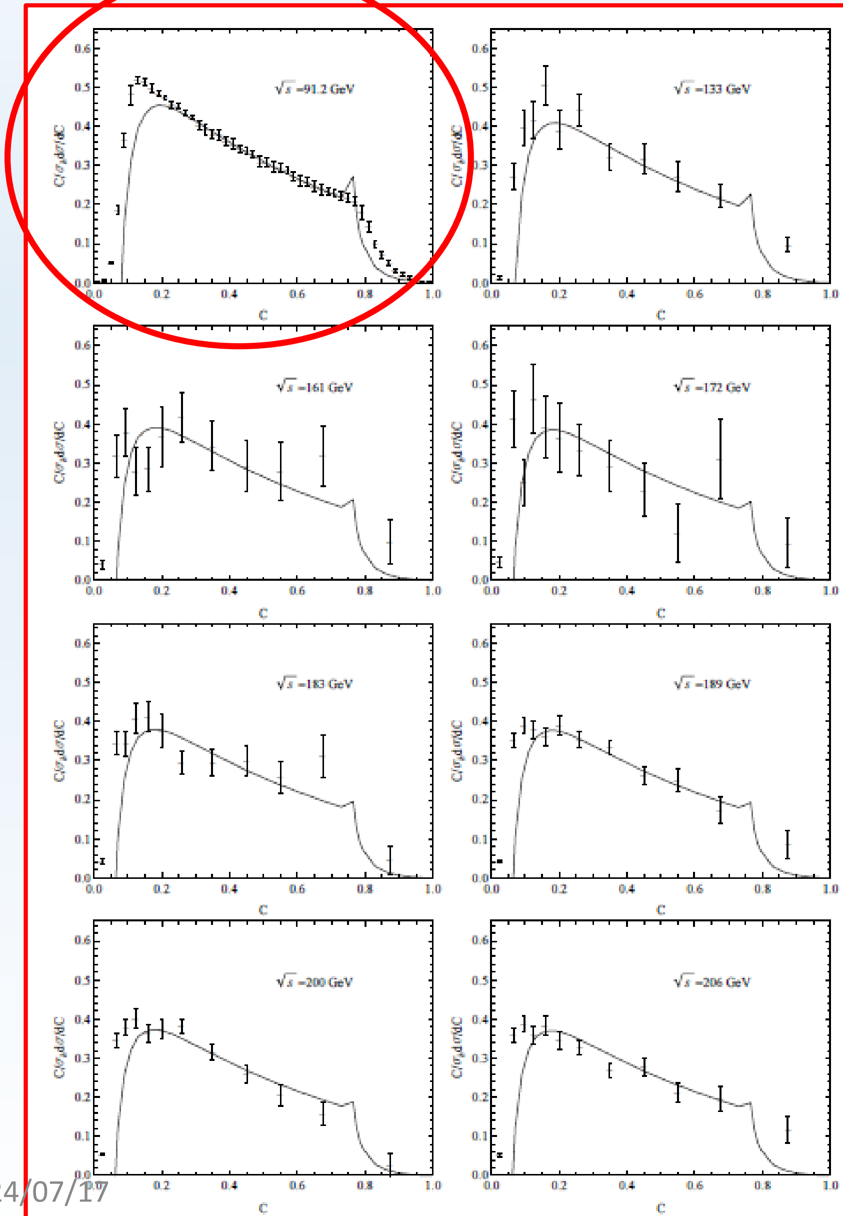
The determination of α_s at LEP





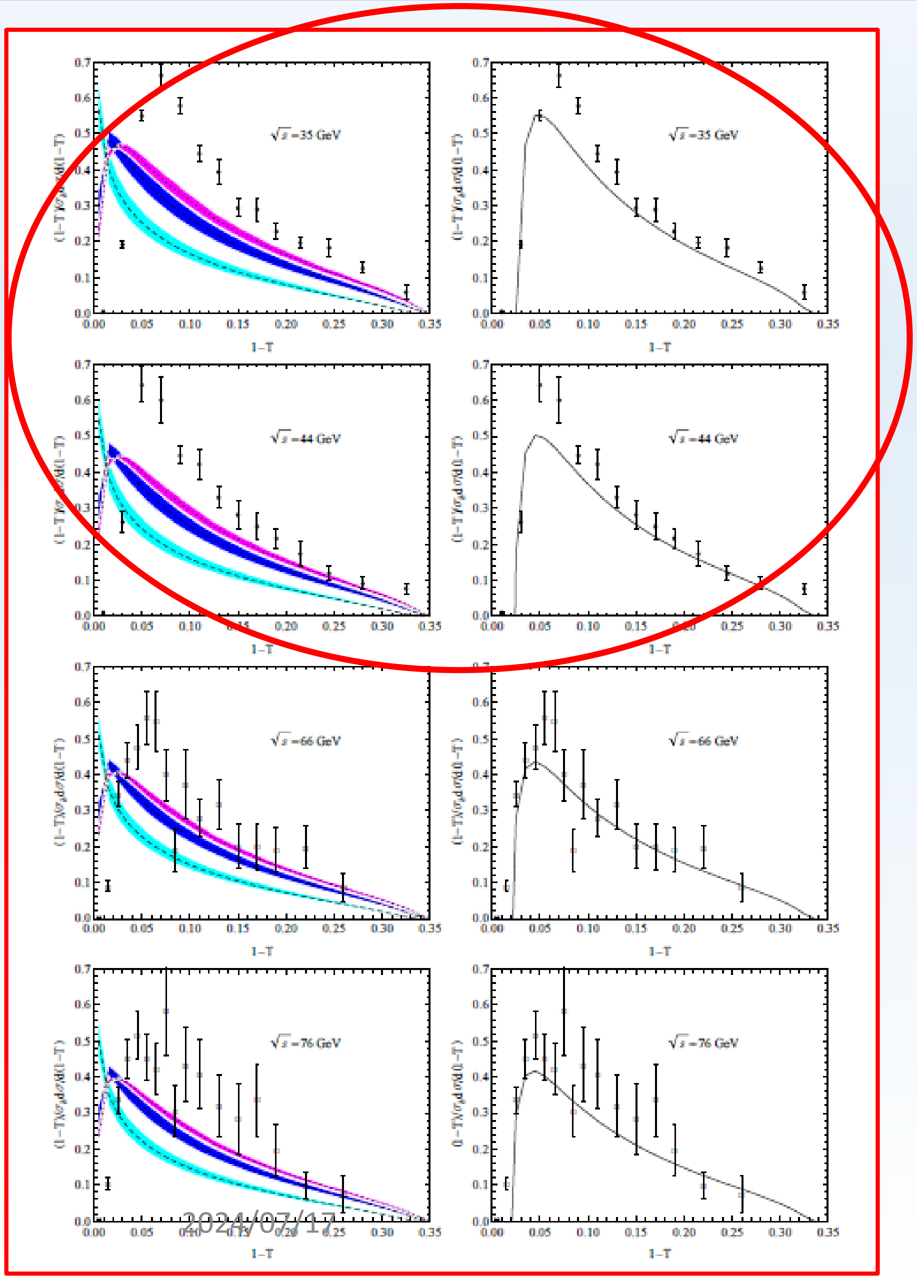
The determination of α_s at LEP



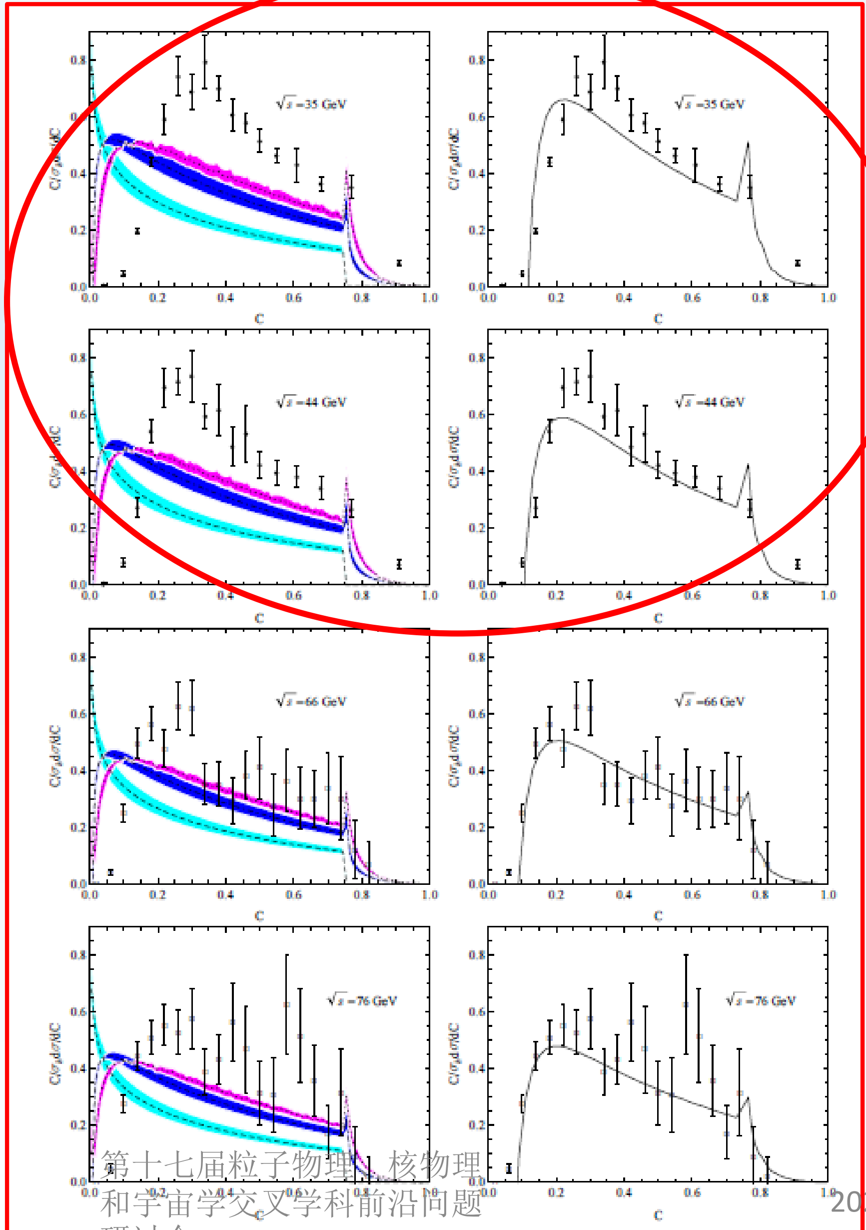


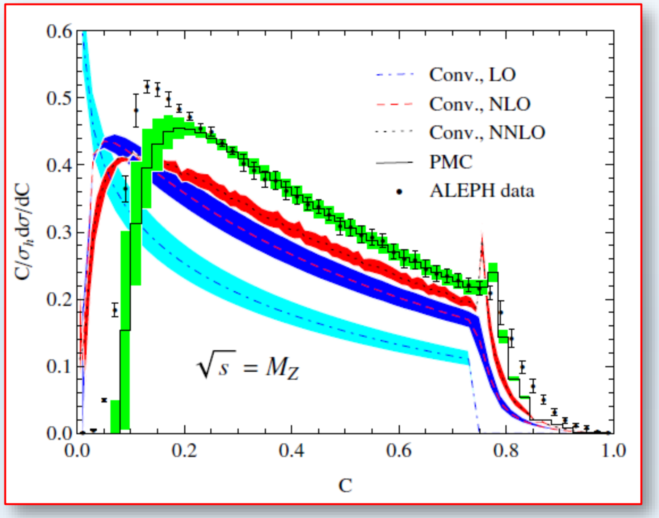
The determination of α_s at LEP

Event shape distributions below *Z0* peak



The determination of α_s at LEP

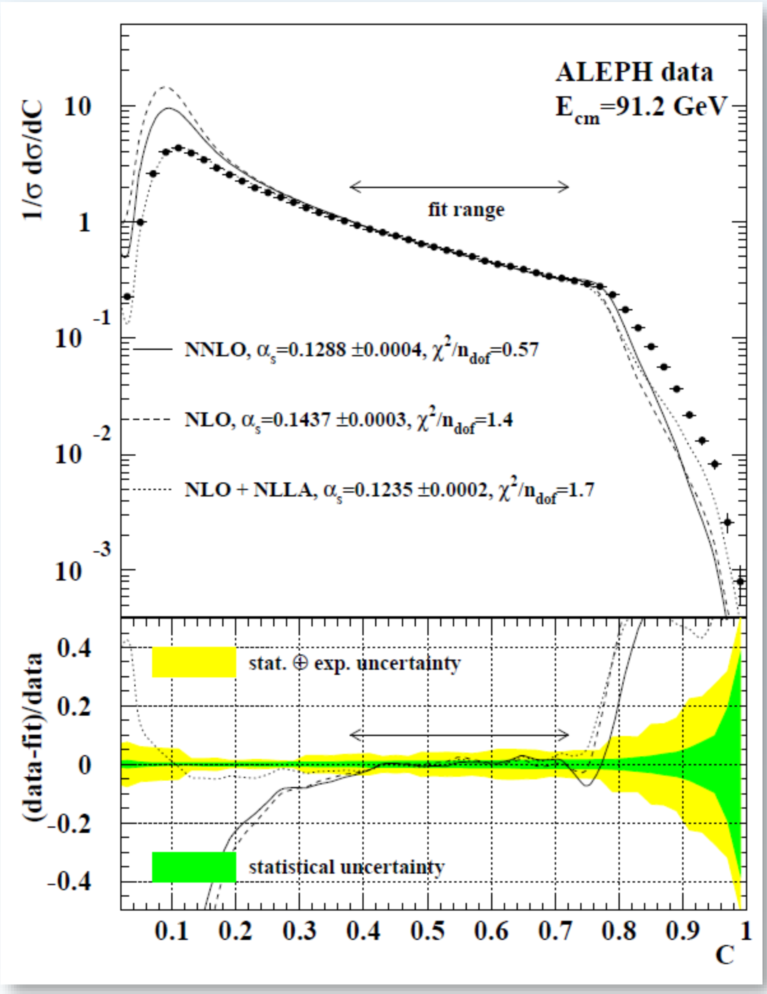




- The PMC predictions are greatly increased in wide kinematic regions, which leads PMC results to be closer to the experimental data.

- There are some deviations near the two-jet and multijet regions, since there are large logarithms that spoil the perturbative regime of the QCD. The resummation of large logarithms is thus required for the PMC results especially near the two-jet regions.

The determination of α_s at LEP



$Q = \sqrt{s} = M_Z$

Conv.

- ✓ One value α_s at scale M_Z is extracted ($\alpha_s(M_Z)$).
- ✓ the fit range of T (C) distribution is narrow.
- ✓ the fit range is arbitrary.
- ✓ different fit range leads to different α_s.

JHEP 0802 (2008) 040

The determination of α_s at LEP

$Q = \sqrt{s} = M_Z$

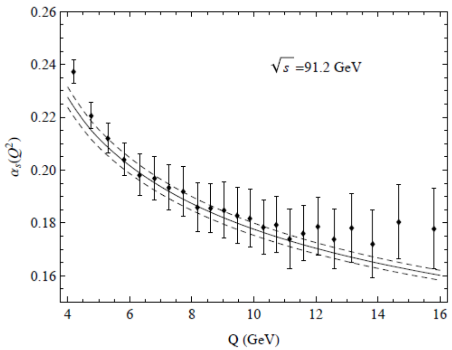


Figure 12. The extracted running coupling $\alpha_s(Q^2)$
paring the PMC predictions with the ALEPH data [
GeV. As a comparison, the solid line is the world av
and two dashed lines represent its uncertainty.

4 < Q < 16 GeV

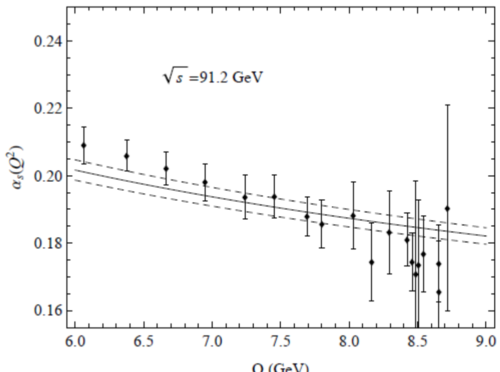


Figure 13. Similar to Fig. (12), but α_s

6 < Q < 9 GeV

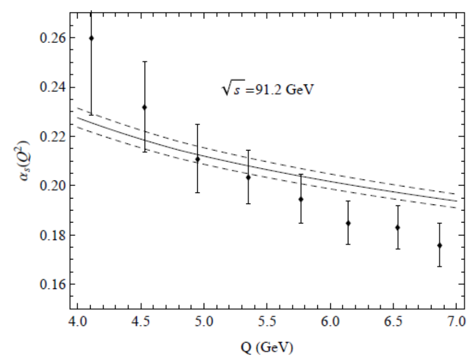


Figure 14. Similar to Fig. (12), but $\alpha_s(Q^2)$ extracted from the wide jet broadening (B_W) distribution.

4 < Q < 7 GeV

The determination of α_s at LEP

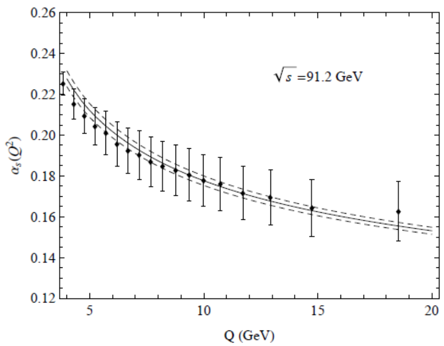


Figure 15. Similar to Fig. (12), but $\alpha_s(Q^2)$ extracted from the total jet broadening (B_T) distribution.

4 < Q < 19 GeV

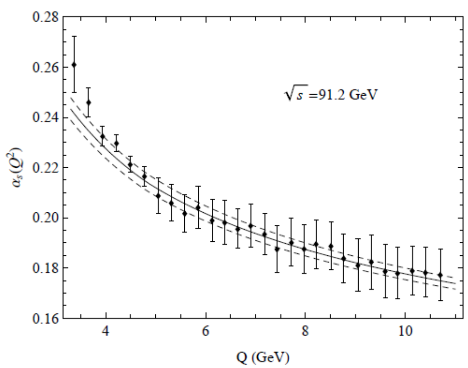


Figure 16. Similar to Fig. (12), but $\alpha_s(Q^2)$ extracted from the C-parameter (C) distribution.

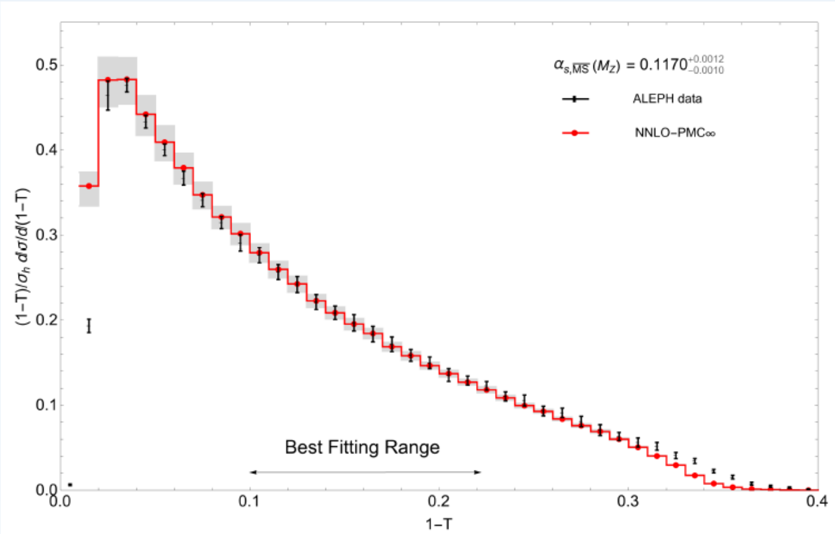
3 < Q < 11 GeV

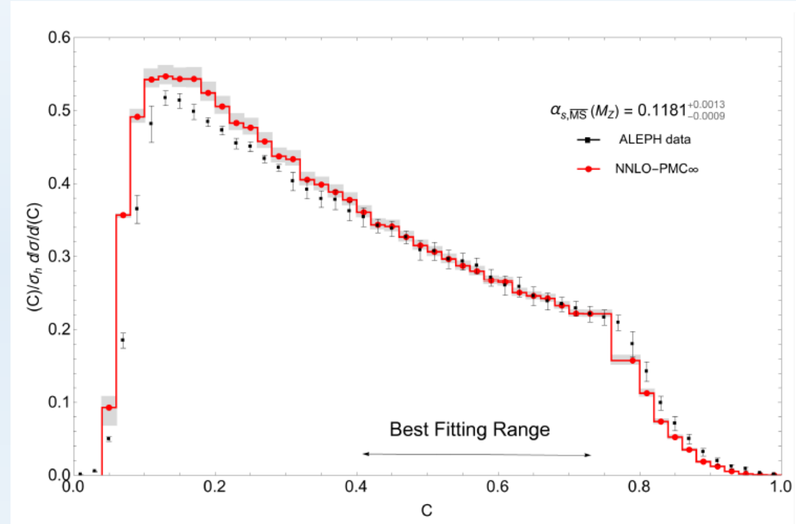
- ✓ The extracted α_s are in agreement with the world average in wide range of Q.
- ✓ The extracted α_s are not plagued by scale uncertainty.
- ✓ Since PMC scale varies with event shapes, we can extract the strong coupling at a wide scale range using the experimental data at single center-of mass-energy.

In QED, the running of the QED coupling at a wide scale range can be determined from events at a single energy

e.g., (OPAL Collaboration), EPJC 45, 1 (2006)

The determination of α_s at LEP





$$\alpha_s(M_Z) = 0.1170^{+0.0007}_{-0.0007}(\text{expt.})^{+0.0010}_{-0.0006}(\text{th.}) = 0.1170^{+0.0012}_{-0.0010},$$

$$\alpha_s(M_Z) = 0.1181^{+0.0006}_{-0.0006}(\text{expt.})^{+0.0011}_{-0.0007}(\text{th.}) = 0.1181^{+0.0013}_{-0.0009},$$

arXiv:2407.08570

The determination of α_s at LEP

the mean value of event shapes,

$$\langle y \rangle = \int_0^{y_0} \frac{y}{\sigma_h} \frac{d\sigma}{dy} dy,$$

- ✓ it involves an integration over the full phase space.
- ✓ it provides an important complement to the differential distributions and to determinate α_s

$$\mu_r^{\rm pmc}|_{\langle 1-T \rangle} = 0.0695\sqrt{s}, \text{ and } \mu_r^{\rm pmc}|_{\langle C \rangle} = 0.0656\sqrt{s},$$

- ✓ PMC scales of differential distribution are also very small.
- ✓ the average of the PMC scale for differential distribution is close to the scale of mean value. self-consistent.

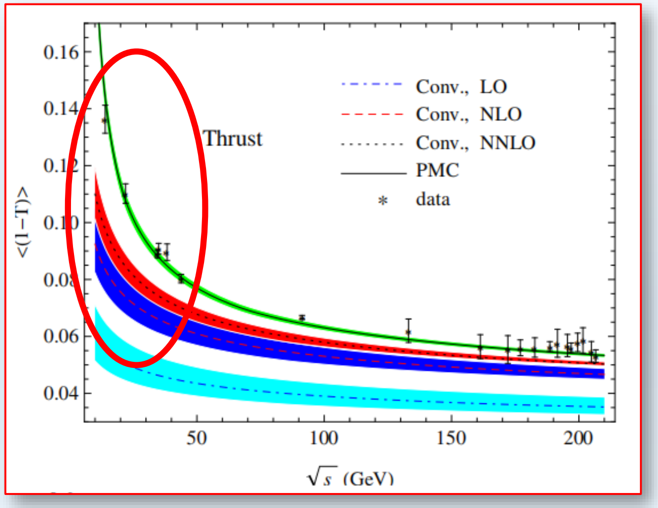
$\mu_r^{\rm pmc} \ll \sqrt{s}$ is also suggested by

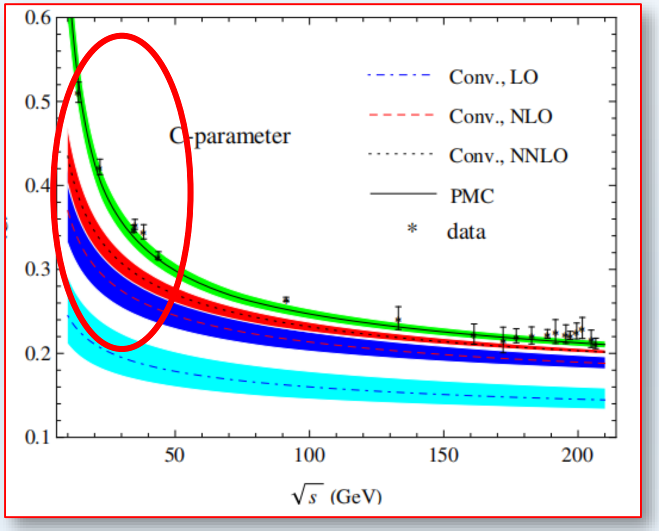
Studies of QCD at e^+e^- centre-of-mass energies between 91 and 209 GeV

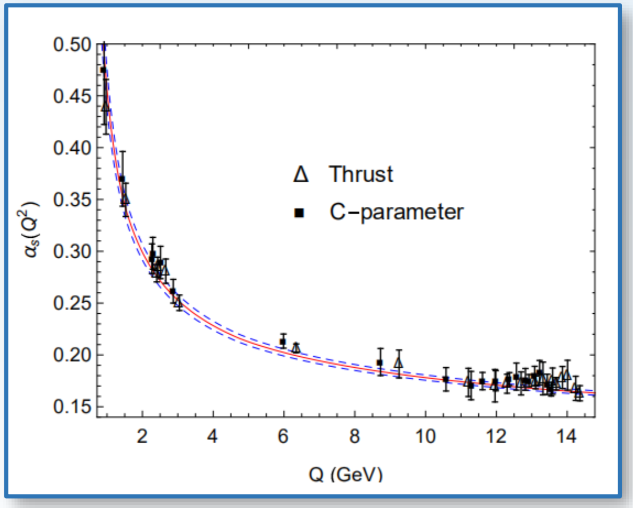
The ALEPH Collaboration

Eur. Phys. J. C 35, 457 – 486 (2004)

The determination of α_s at LEP







The determination of α_s at LEP

$$\alpha_s(M_Z^2) = 0.1185 \pm 0.0011(\text{Exp.}) \pm 0.0005(\text{Theo.}) = 0.1185 \pm 0.0012, \quad (3)$$

T

$$\alpha_s(M_Z^2) = 0.1193^{+0.0009}_{-0.0010}(\text{Exp.})^{+0.0019}_{-0.0016}(\text{Theo.}) = 0.1193^{+0.0021}_{-0.0019}, \quad (4)$$

C

Cited by LHeC and FCC group and PDG

[Particle Data Group], Prog. Theor. Exp. Phys. 2020 (2020), 083C01.

PDG

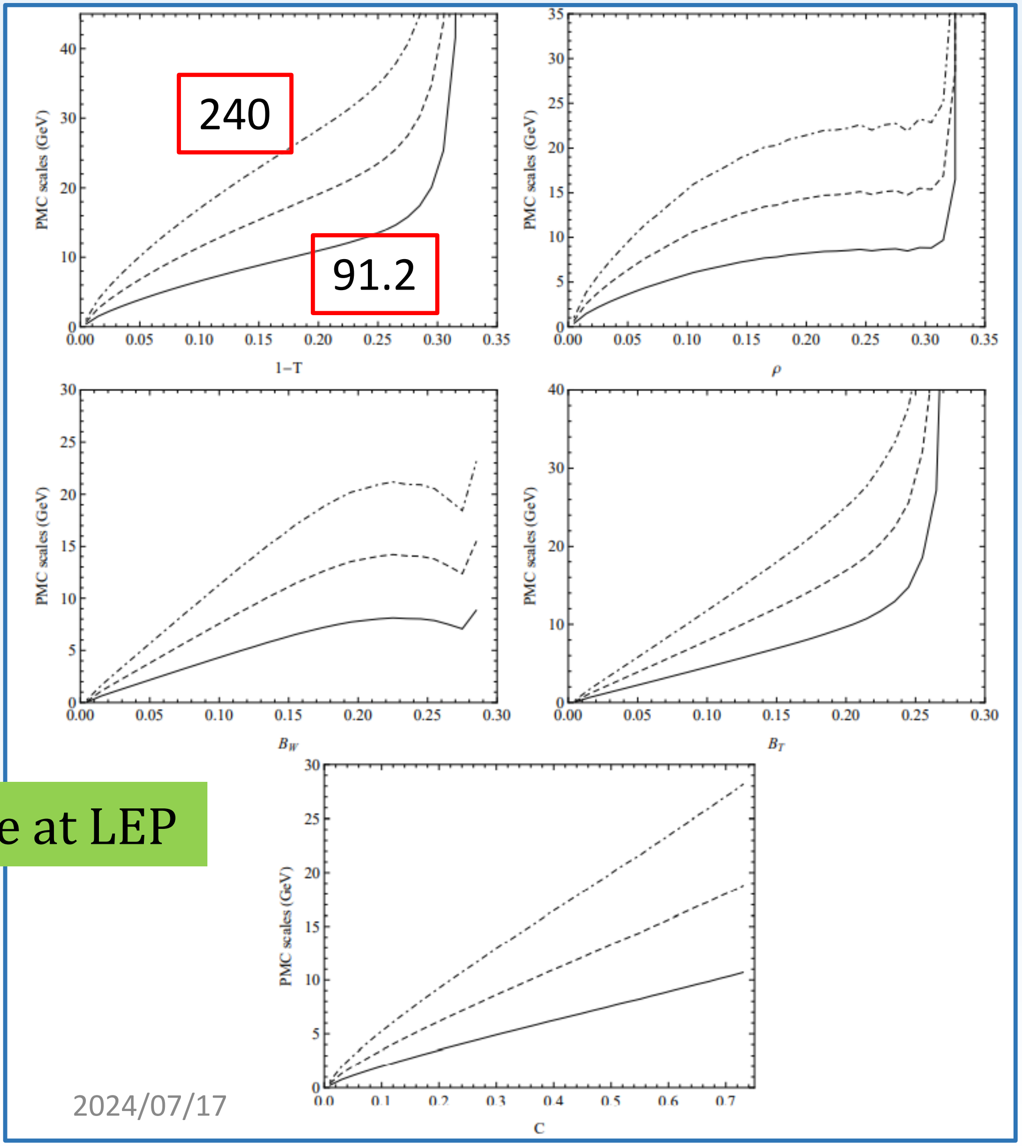
The Large Hadron-Electron Collider at the HL-LHC
LHeC Collaboration and FCC-he Study Group (P. Agostini (Santiago
CERN-ACC-Note-2020-0002, JLAB-ACP-20-3180
e-Print: arXiv:2007.14491 [hep-ex] | PDF

mean value for other event shapes, EEC,

Event shapes at CEPC

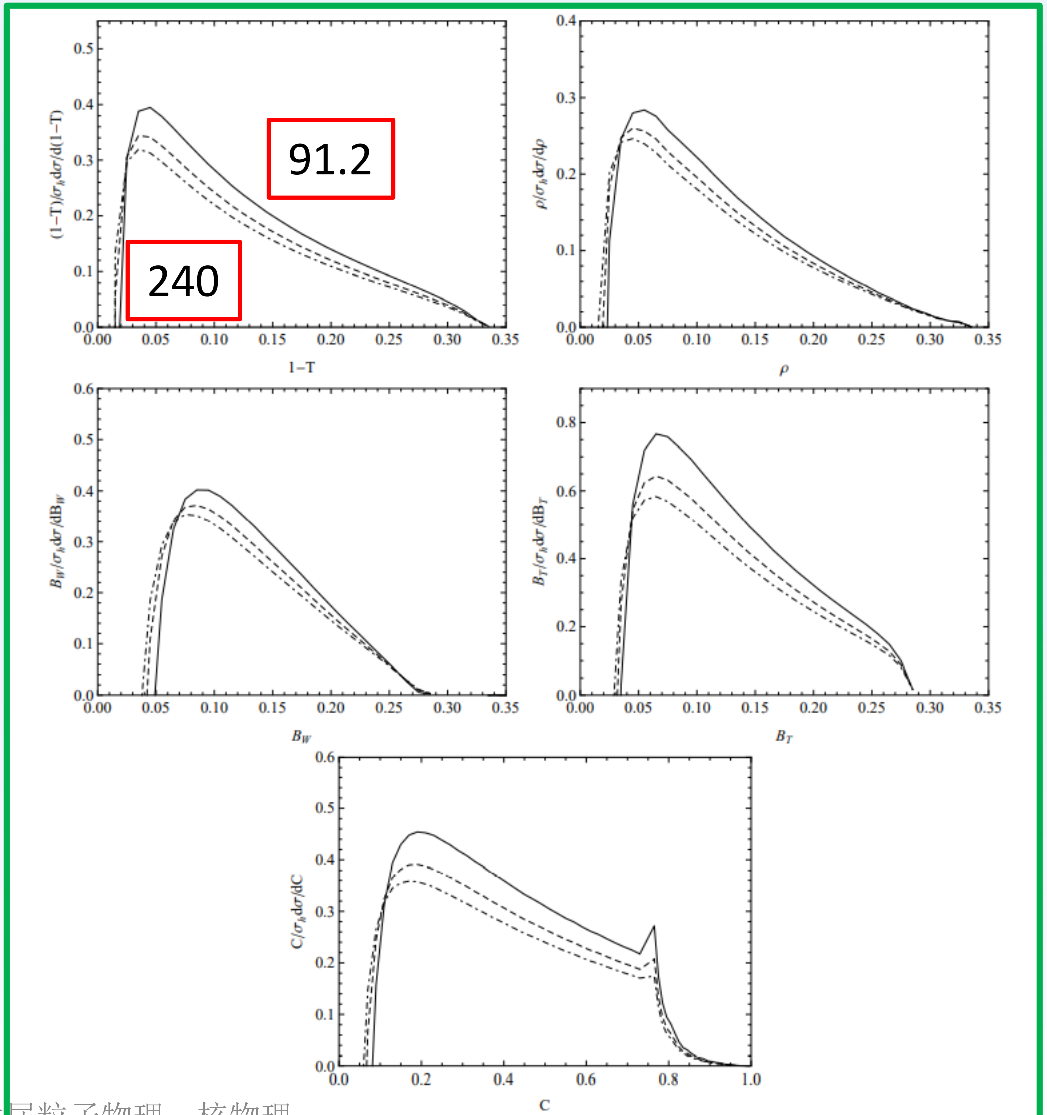
We calculate the classical event shapes at the CEPC at 91.2, 160 and 240 GeV.

PMC scales for event shape observables at CEPC



Similar to the case of the PMC scale at LEP

Event shapes at CEPC



Our precise and scale-independent predictions for event shape observables, and a novel way to verify the running of αs(Q^2) call for the precise measurements at CEPC.

Summary

$$\beta^{\mathcal{R}} = \mu_r^2 \frac{\partial}{\partial \mu_r^2} \left(\frac{\alpha_s^{\mathcal{R}}(\mu_r)}{4\pi} \right) = -\sum_{i=0}^{\infty} \beta_i^{\mathcal{R}} \left(\frac{\alpha_s^{\mathcal{R}}(\mu_r)}{4\pi} \right)^{i+2}$$

- To eliminate the renormalization scheme-and-scale ambiguities
- There is no renormalon divergence in the pQCD series
- The more convergent perturbative series is in general achieved
- A novel method for the precise determination of the QCD running coupling is obtained

thanks