THEORETICAL PROGRESS ON EVENT SHAPES AND FITS TO α_s

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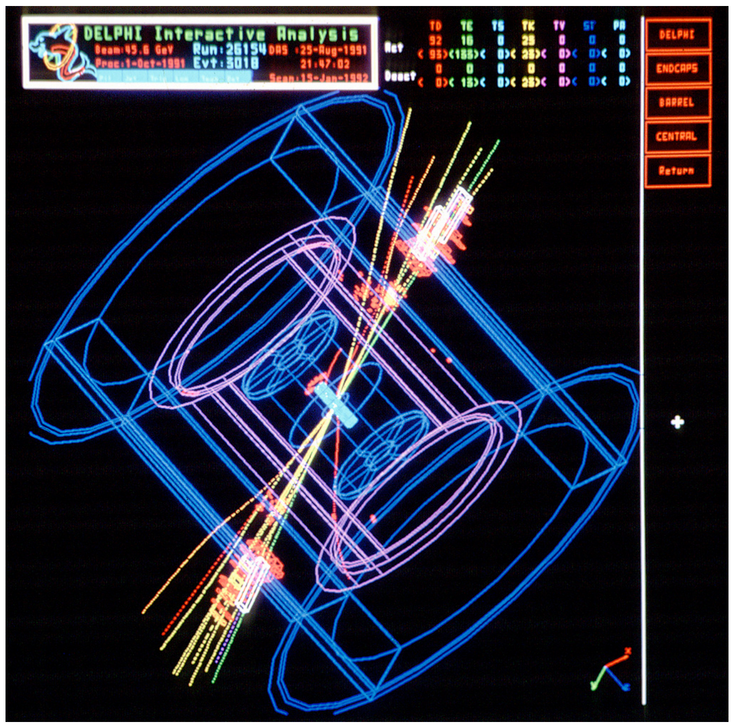
A biased perspective from an Effective Field Theorist...

OUTLINE

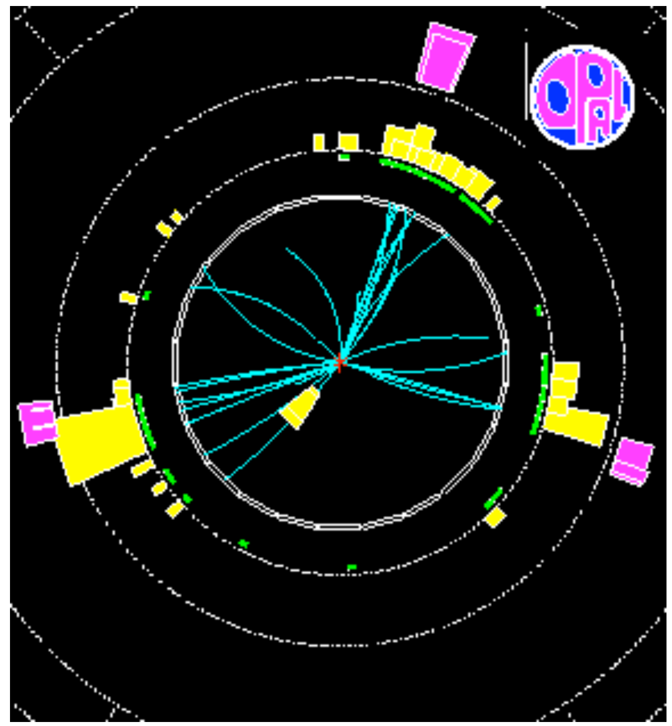
- Introduction
- Fixed order computations
- Resummation
- Power corrections
- Nonsingular terms and mass effects
- Comparison to data and fits
- Summary

INTRODUCTION

Event Shapes $e^+ e^- \to \text{jets}$



DELPHI 2-jet event

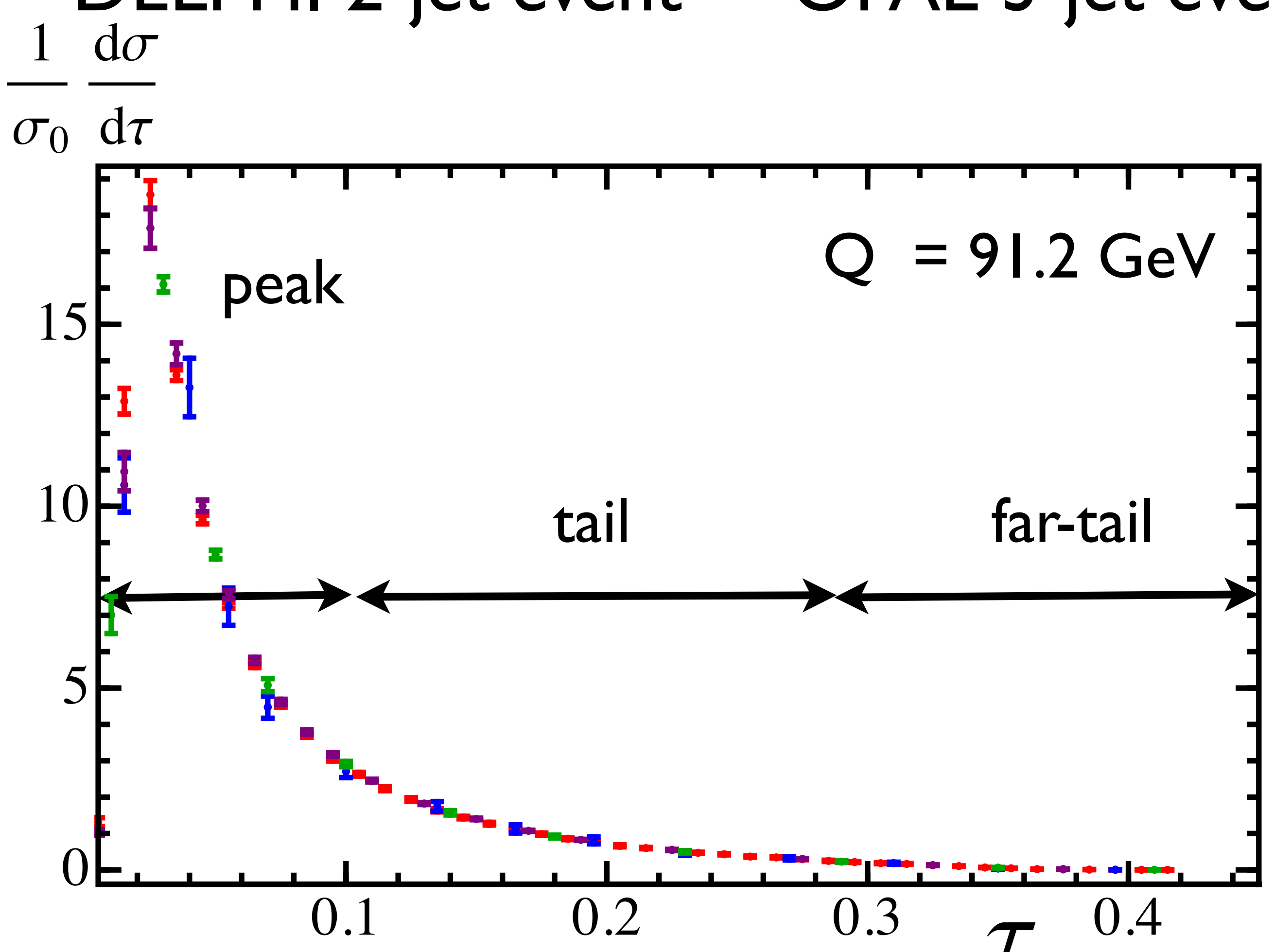


OPAL 3-jet event

Event shapes characterize in a geometrical way the distribution of hadrons in the final state

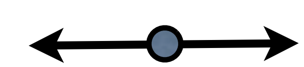
Thrust is the most commonly studied event shape variable

$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

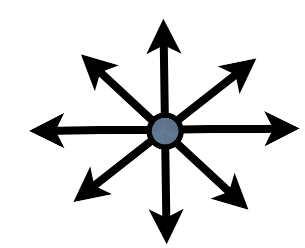


They are theoretically **more friendly than a Jet algorithm**

dijet $\tau = 0$



spherical $\tau = \frac{1}{2}$



Continuous transition from 2-jet to 3-jet, ... multi-jet events

Most common Event shapes

- **Thrust** $$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum |\vec{p}_i\,|}$$ *[E. Farhi]*

- **Angularities** $$\tau_{(a)} = \frac{1}{Q} \sum_i E_i \,(\sin\theta_i)^a (1 - |\cos\theta_i|)^{1-a}$$ *[Berger, Kucs, Sterman]*

- **Jet Masses** $$\rho_\pm = \frac{1}{Q^2} \Big(\sum_{i \in \pm} p_i \Big)^2$$ *[Clavelli]* *[Chandramohan Clavelli]*

- **Jet Broadening** $$B = \frac{\sum_i |\vec{p}_i \times \vec{n}|}{\sum_i |\vec{p}_i|}$$ *[Catani, Turnock, Webber]*

- **C-parameter** $$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2(\theta_{ij})}{(\sum_i |\vec{p}_i|)^2}$$ *[Parisi]* *[Donoghue, Low, Pi]*

Most common Event shapes

- **Thrust** $$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum |\vec{p}_i|}$$
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2-jet event shapes

$e \to 0$

$\updownarrow$

dijet configuration

Most common Event shapes

- Thrust $$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum |\vec{p}_i\,|}$$

- Angularities $$\tau_{(a)} = \frac{1}{Q} \sum_i E_i \, (\sin\theta_i)^a (1 - |\cos\theta_i|)^{1-a}$$

Depend on a continuous parameter

- Jet Masses $$\rho_\pm = \frac{1}{Q^2} \Big(\sum_{i \in \pm} p_i \Big)^2$$

- Jet Broadening $$B = \frac{\sum_i |\vec{p}_i \times \vec{n}|}{\sum_i |\vec{p}_i|}$$

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

Most common Event shapes

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- Jet Masses $$\rho_{\pm} = \frac{1}{Q^2} \Big(\sum_{i \in \pm} p_i \Big)^2$$
- Jet Broadening $$B = \frac{\sum_i |\vec{p}_i \times \vec{n}|}{\sum_i |\vec{p}_i|}$$ Recoil sensitive
- C-parameter $$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2(\theta_{ij})}{(\sum_i |\vec{p}_i|)^2}$$

Most common Event shapes

- Thrust $$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum |\vec{p}_i\,|}$$
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- Jet Broadening $$B = \frac{\sum_i |\vec{p}_i \times \vec{n}|}{\sum_i |\vec{p}_i|}$$

Necessitate minimization procedure

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

Most common Event shapes

Other event shapes include

- Thrust major
- Thrust minor
- Spherocity
- D-parameter
- Energy-Energy correlation
- y_{23}
- ...

Most common Event shapes

Other event shapes include

- Thrust major
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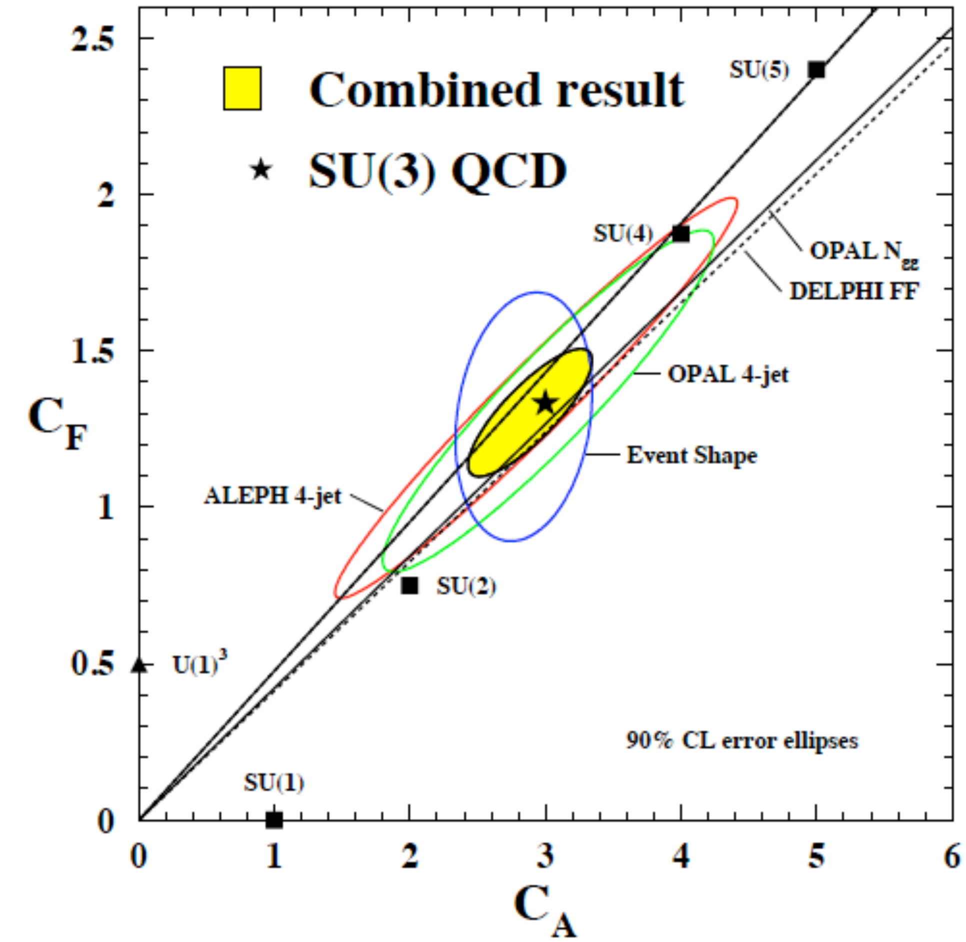
- ...

3-jet event shapes

Applications of event shapes

Measurements of QCD color factors

figure taken from *[Kluth hep-ex/0603011]*

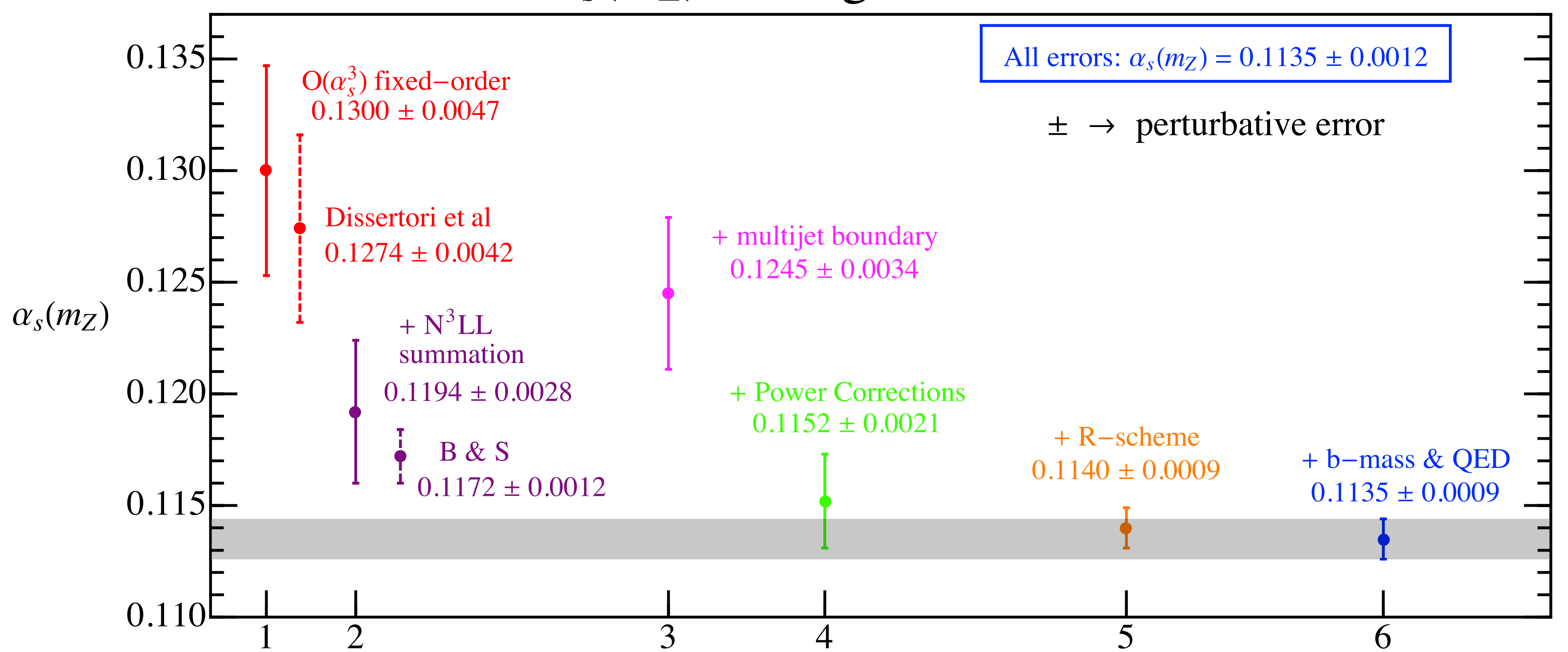


Determination of $\alpha_s(m_Z)$

[Abbate, Fickinger, VM, Stewart]

arXiv:1006.3080
arXiv:1204.5746

$\alpha_s(m_Z)$ from global thrust fits



FIXED ORDER PREDICTIONS

Fixed order predictions

1-loop: Analytic or one numeric integral

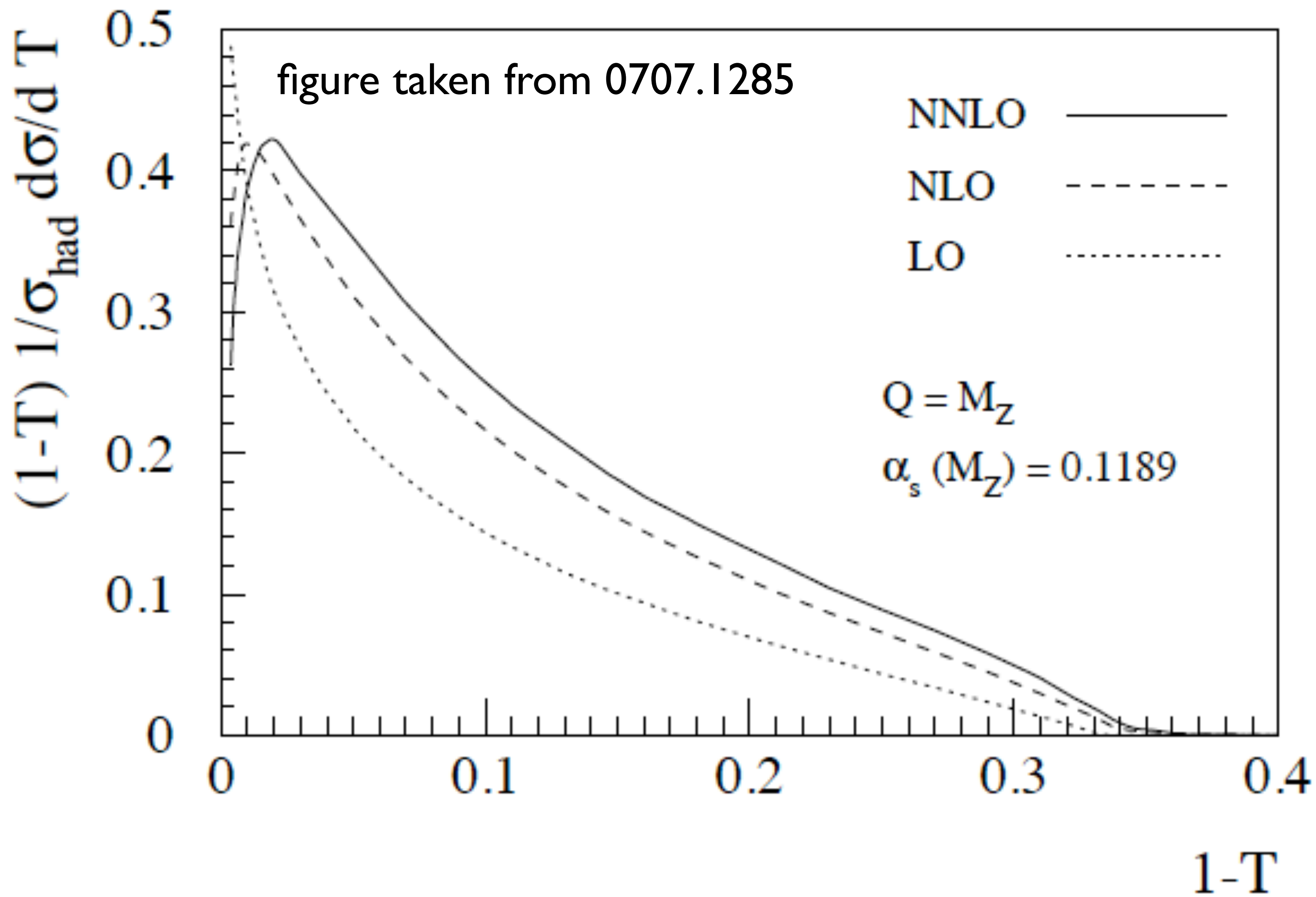
[Ellis, Ross, Terrano 1980]

2-loop: Numerical, delicate virtual-real IR cancellation

Event 2 [Catani, Seymour 1996]

3-loop: Numerical, delicate virtual-real IR cancellation

Mercutio [Weinzierl 2008]
EERAD 3 [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich 2007]



RESUMMATION

Resummation or large logarithms

Event shapes are not inclusive quantities

Incomplete IR cancellation generate large logs at small e

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau} = -\frac{2\alpha_s}{3\pi}\frac{1}{\tau}\Big(3 + 4\lg\tau + \dots\Big)$$

Invalidate perturbative expression for small τ

One has to reorganize the entire expansion by considering $\alpha_s \lg(e) \sim \mathcal{O}(1)$

Counting more clear in the exponent of cumulant distribution

$$\Sigma(e_c) \equiv \int_0^{e_c} de \frac{1}{\sigma_0}\frac{d\sigma}{de}$$

$$\log\Sigma(e_c) = \lg e \sum_{i=0}\Big(\alpha_s \log e\Big)^{i+1} + \sum_{i=0}\Big(\alpha_s \log e\Big)^{i+1} + \alpha_s \sum_{i=0}\Big(\alpha_s \log e\Big)^{i} + \alpha_s^2 \sum_{i=0}\Big(\alpha_s \log e\Big)^{i}$$

LL NLL NNLL N^3LL

+ terms which are not singular as $e \to 0$

Classic approach to resummation

Based on coherent branching formalism

[Catani, Trentadue Turnock, Webber]

$$\Sigma(e) = C(\alpha_s)\Sigma(\alpha_s, e) + D(\alpha_s, e)$$

matching condition (→ $C(\alpha_s)$)

resummed singular logs (→ $\Sigma(\alpha_s, e)$)

nonsingular terms (→ $D(\alpha_s, e)$)

$$C(\alpha_s) = 1 + \sum_i C_i \alpha_s^i$$

$$\Sigma(\alpha_s, e) = \lg e \sum_{i=0} \Big(\alpha_s \log e\Big)^{i+1} + \sum_{i=0} \Big(\alpha_s \log e\Big)^{i+1} + \alpha_s \sum_{i=0} \Big(\alpha_s \log e\Big)^{i}$$

Except for EEC, classic resummation at most NLL

CAESAR, automated tool for semianalitic NLL resummation

[Banfi, Salam, Zanderighi, 2003-04]

Effective Field Theory Approach

(Will focus on SCET but CSS is equivalent)

Soft-Collinear Effective Theory (SCET)

[Bauer, Fleming, Luke]
[Bauer, Fleming, Pirjol, Stewart]
...

- Designed to study highly energetic particles far off-shell
- Initially used for B decays, also useful for jet physics
- Modal theory (fields are decomposed in sub-fields)
- Complicated non-local theory (plenty of Wilson lines)
- Easy to proof factorization, resummation via RGE

Factorization theorem

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}e} = H_Q \times J_e \otimes S_e + \mathcal{O}\left(e^0, \frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$

[Bauer, Lee, Fleming, Sterman]
[Berger, Kuks, Sterman]

Universal Wilson Coefficient — Jet function — Soft function — Nonsingular terms, power corrections

Calculable in perturbation theory

Perturbative and nonperturbative components

Effective Field Theory Approach

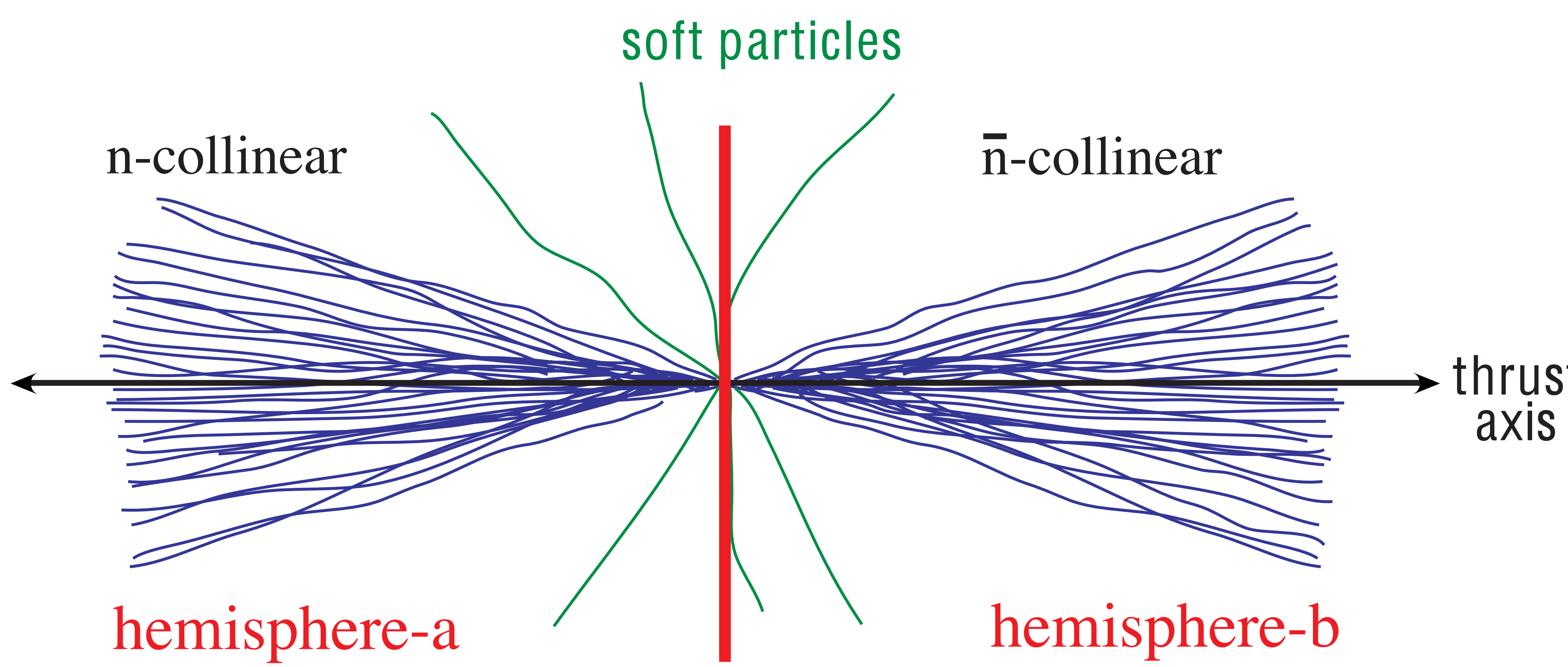
(Will focus on SCET but CSS is equivalent)

$$\frac{1}{\sigma_0}\frac{d\sigma}{de} = H_Q \times J_e \otimes S_e + \mathcal{O}\left(e^0, \frac{\Lambda_{QCD}}{Q}\right)$$

[Bauer, Lee, Fleming, Sterman]

[Berger, Kuks, Sterman]

Theorem only valid for non-recoil sensitive event shapes: exclude jet broadening



Resummation of large logs is achieved through renormalization group evolution for each separate matrix element

Effective Field Theory Approach

(Will focus on SCET but CSS is equivalent)

$$\frac{1}{\sigma_0}\frac{d\sigma}{de} = H_Q \times J_e \otimes S_e + \mathcal{O}\left(e^0, \frac{\Lambda_{QCD}}{Q}\right)$$

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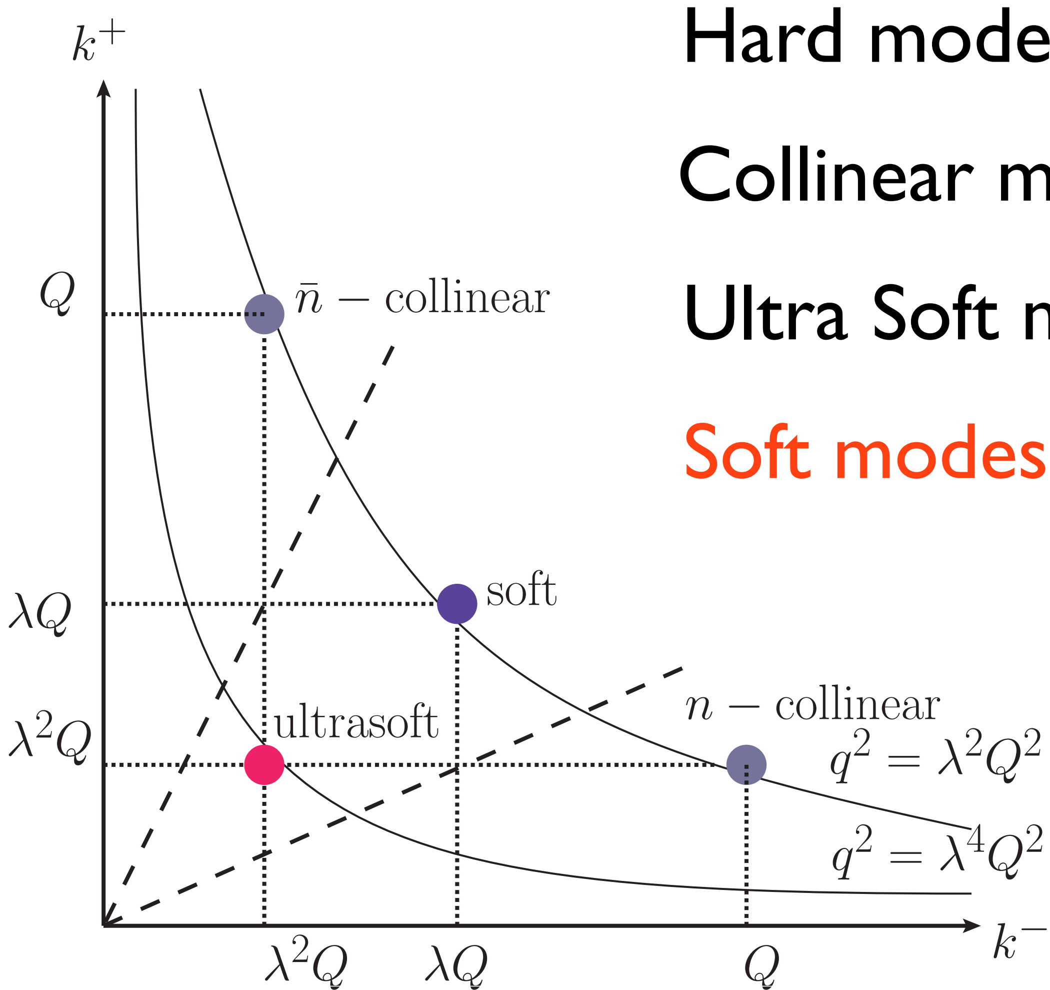


Hard modes integrated out, Hard function $q^2 \sim Q^2$

Collinear modes make up Jet function $q^2 \sim Q^2\lambda^2$

Ultra Soft modes make up Soft function $q^2 \sim Q^2\lambda^4$

Soft modes do not play a role in $SCET_I$ $q^2 \sim Q^2\lambda^2$

Effective Field Theory Approach

(Will focus on SCET but CSS is equivalent)

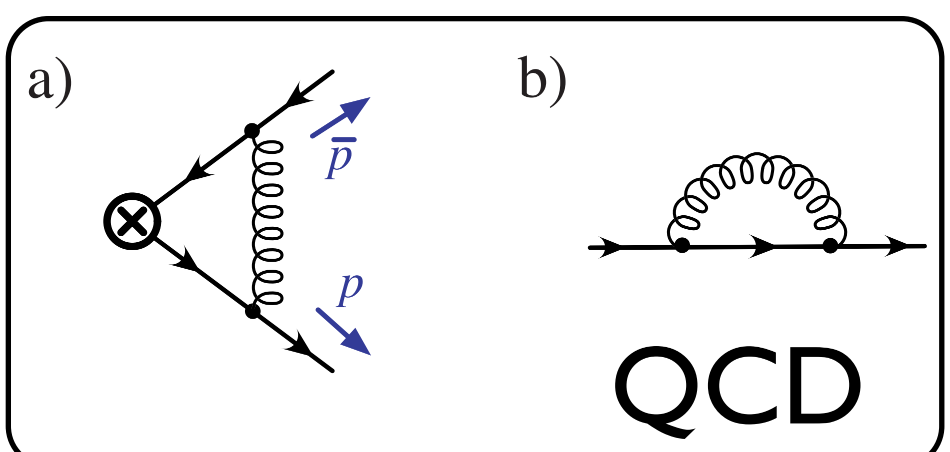
$$\frac{1}{\sigma_0}\frac{d\sigma}{de} = H_Q \times J_e \otimes S_e + \mathcal{O}\left(e^0, \frac{\Lambda_{\rm QCD}}{Q}\right)$$

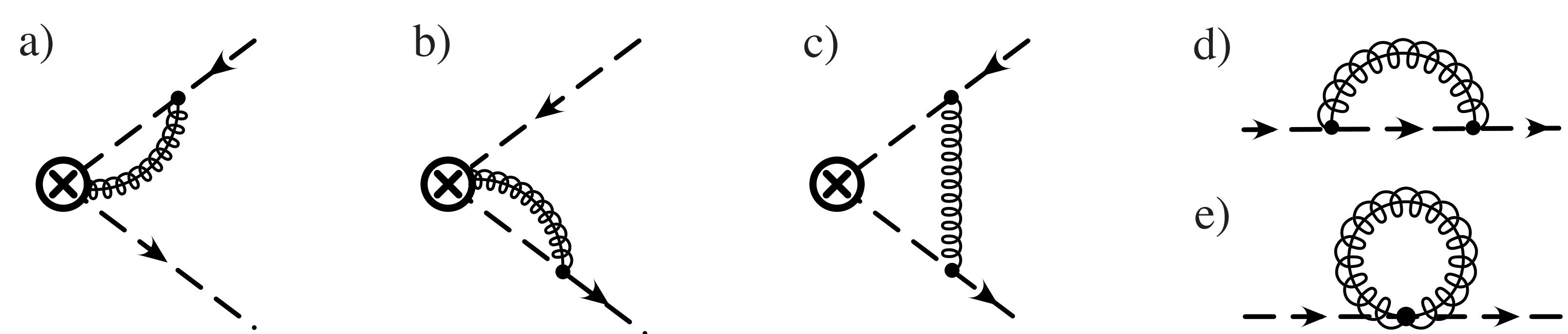
[Bauer, Lee, Fleming, Sterman]

[Berger, Kuks, Sterman]

Theorem only valid for non-recoil sensitive event shapes: exclude jet broadening

H_Q:
- Purely perturbative
- Matching SCET to QCD
- Same for all event shapes
- Known at 3 loops *[Baikov et at]*
- Anomalous dimension known at 3-loops *[Moch et al]* *[Lee et al]*





SCET

Effective Field Theory Approach

(Will focus on SCET but CSS is equivalent)

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}e} = H_Q \times J_e \otimes S_e + \mathcal{O}\left(e^0, \frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$

[Bauer, Lee, Fleming, Sterman]

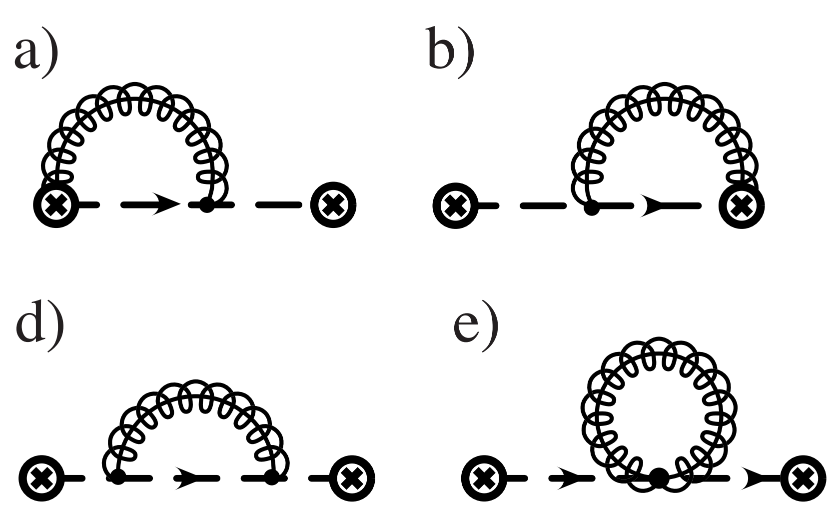
[Berger, Kuks, Sterman]

Theorem only valid for non-recoil sensitive event shapes: exclude jet broadening

J_e

- Purely perturbative
- Evolution of produced jets
- Same for thrust, Jet masses, C-parameter
- Known at 2 loops, logs known at 3-loops *[Becher & Neubert]*
- Anomalous dimension known at 3-loops *[Moch, Vermaressen & Vogt]*

} Except angularities, EEC



Effective Field Theory Approach

(Will focus on SCET but CSS is equivalent)

$$\frac{1}{\sigma_0}\frac{d\sigma}{de} = H_Q \times J_e \otimes S_e + \mathcal{O}\left(e^0, \frac{\Lambda_{\rm QCD}}{Q}\right)$$

[Bauer, Lee, Fleming, Sterman]
[Berger, Kuks, Sterman]

Theorem only valid for non-recoil sensitive event shapes: exclude jet broadening

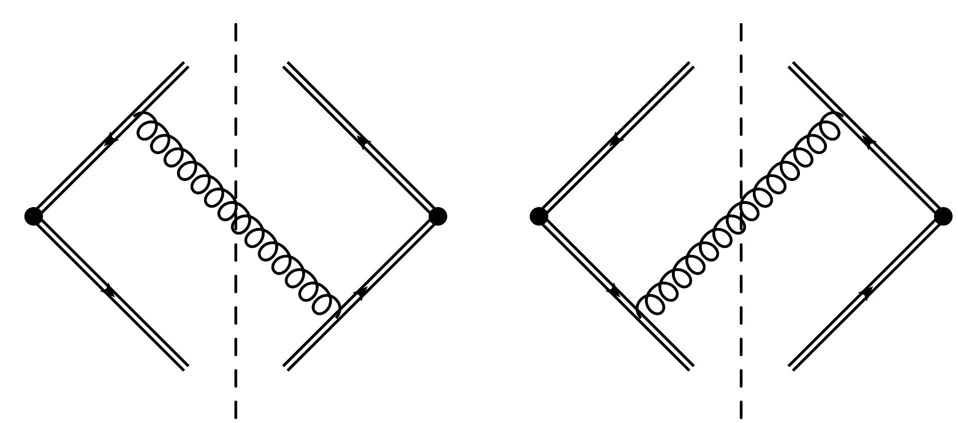
S_e:
- Can factorize perturbative effects
- Soft radiation effects
- Same for thrust and Jet masses *[Hornig et al][Monni et al][Kelley et al]*
- Known at 2 loops, logs known at 3-loops
- Anomalous dimension known at 3-loops

(Except angularities, C-parameter, EEC)

$$S_e = \hat{S}_e \otimes F_e$$

perturbative — **perturbative** & nonperturbative

[VM,Thaler, Stewart]

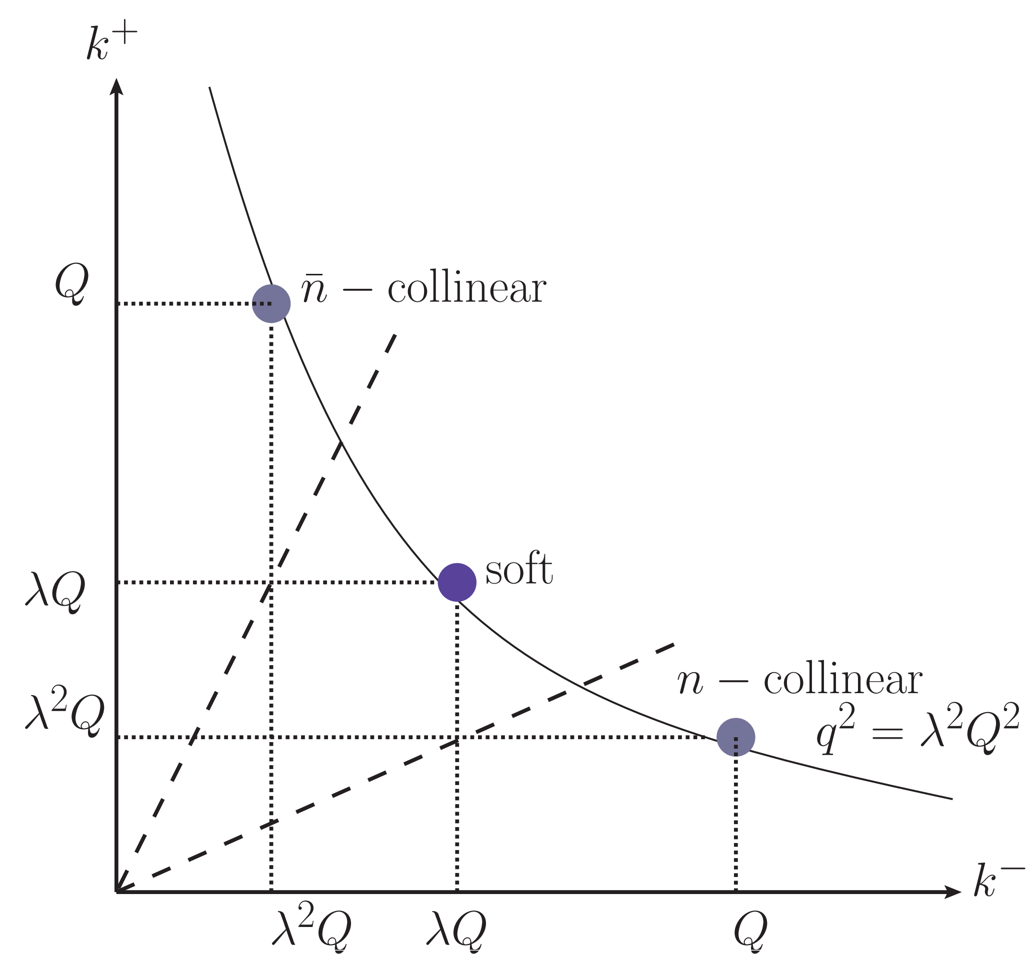


Jet Broadening

First studied in the classic approach	*[Catani, Turnock, Webber]*		LL
	[Dokshitzer, Lucenti, Marchesini, Salam]		NLL
Recently also from SCET approach	*[Becher, Bell, Neubert]*	collinear anomaly	NLL
	[Chiu, Jain, Neil, Rothstein]	rapidity renormalization	NLL
	[Becher, Bell]	collinear anomaly	NNLL

Requires SCET_{II} treatment, since collinear and soft modes live on the same mass shell

Jet and Soft functions have rapidity divergences which **cancel in the product**



Jet Broadening

[Becher, Bell, Neubert]

$$J_{B_L} \otimes J_{B_R} \otimes S_B = P(Q^2, B_L, B_R)$$

Rapidity divergent

Rapidity finite

Q-dependence in P exponentiates

This exponentiation sums up large singular logs

[Chiu, Jain, Neil, Rothstein]

Regularize Jet and soft function with a rapidity regulator, introduced directly in SCET

$$W_n = \sum_{\text{perms}} \exp\left[-\frac{g w^2}{\bar{n}\cdot\mathcal{P}} \frac{|\bar{n}\cdot\mathcal{P}_g|^{-\eta}}{\nu^{-\eta}} \bar{n}\cdot A_n \right]$$

$$S_n = \sum_{\text{perms}} \exp\left[-\frac{g w}{n\cdot\mathcal{P}} \frac{|2\,\mathcal{P}_{g3}|^{-\eta/2}}{\nu^{-\eta/2}} n\cdot A_n \right]$$

New regularization induces new type of running for soft and jet. Large singular logs summed up via **Renormalization Group Equation**

Ingredients for a resummed calculation

	cusp	non-cusp	matching	$\beta[\alpha_s]$
LL	1	-	tree	1
NLL	2	1	tree	2
NNLL	3	2	1	3
N^3LL	4^{pade}	3	2	4
NLL'	2	1	1	2
$NNLL'$	3	2	2	3
N^3LL'	4^{pade}	3	3	4

NLL results
- Any event shape using CAESAR *[Banfi, Salam, Zanderighi]*
- Jet Broadening *[Becher, Bell, Neubert]* *[Chiu, Jain, Neil, Rothstein]*

N^2LL results
- Energy-Energy Correlation *[De Florian, Grazzini]*
- Jet Broadening *[Becher, Bell]*

N^3LL results
- Thrust *[Becher, Schwartz] [Abatte, Fickinger, Hoang, VM, Stewart]*
- Heavy Jet Mass *[Chien, Schwartz]* *[Hoang, VM, Schwartz, Stewart, w.i.p.]*
- C-parameter *[Kolodrubetz, VM, Stewart, w.i.p.]*

POWER CORRECTIONS

Approaches to Power Corrections

- Monte Carlo Generators

Pythia, Ariadne, Herwig, Powheg, ...

Use hadronization models

Hard to separate perturvative vs nonperturbative effects

- Renormalon based

Effective coupling model *[Dokshitzer & Webber]*
Dressed gluon *[Gardi & Gruenberg]*

Residual model dependence

- Shape functions

Factorization based *[Korchemski, Sterman, Tafat]*
SCET based *[Hoang & Stewart; Lee & Sterman]*

Derived directly from QCD
Operator definition
Systematically improvable

Approaches to Power Corrections

- Monte Carlo Generators

Pythia, Ariadne, Herwig, Powheg, ...

Use hadronization models

Hard to separate perturvative vs nonperturbative effects

Use of MC to estimate power corrections to event shape distributions is not appropriate for high-precision studies which include high-order perturbative corrections

Mixes LL parton shower (and shower IR cuttoff) with multiloop computations and higher order resummation (with dim-reg IR cuttoff)

Shower tunned mainly at the Z-pole only

For high-precision studies at a linear collider one would need a MC with **more perturbative input** and tunned to several values of c.o.m. energy

Dispersive approach

[Dokshitzer & Webber]

Assume that α_s is replace by an effective coupling below certain cutoff μ_I

Subtract from perturbation theory contributions at scales below μ_I

It is believed that this procedure removes all renormalons

Initial approach relied on one gluon exchange

The Milan factor accounts for two-gluon exchange *[Dokshitzer, Webber Salam]*

It predicts that leading power correction is universal up to a calculable coefficient

Effect on first moment

$$\langle e \rangle = \langle e \rangle_{\mathrm{PT}} + c_e \frac{\mathcal{P}}{Q}$$

Effect on distributions

$$\frac{\mathrm{d}\sigma}{\mathrm{d}e} = \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}e}\left(e - c_e \frac{\mathcal{P}}{Q}\right)$$

c_e = universality constant

(more on this later)

$$\mathcal{P} = \frac{4C_F}{\pi^2}\mathcal{M}\frac{\mu_I}{Q}\left\{\alpha_0(\mu_I) - \alpha_s(\mu_R) - \beta_0\frac{\alpha_s^2}{2\pi}\left(\ln\frac{\mu_R}{\mu_I} + \frac{K}{\beta_0} + 1\right)\right\}$$

Milan Factor $\simeq 1.49$

Shape function approach

[Korchemsky & Sterman]
[Korchemsky & Tafat]

Soft function is convolution of perturbative soft function and shape function

$$S_e = \hat{S}_e \otimes F_e$$

perturbative — **perturbative** & nonperturbative

[VM, Thaler, Stewart]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}e} = \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}e} \otimes F_e$$

Non pert. distribution is convolution of pert. distribution with shape function
This is valid on the peak of the distribution as well

Effect on moments
$$\langle e^n \rangle = \sum_{i=0}^{n} \binom{n}{i} \langle e^i \rangle_{\mathrm{PT}} \frac{\Omega^e_{n-i}}{Q^{n-i}}$$
[Korchemsky & Tafat]
[Abatte, Fickinger, Hoang, VM, Stewart]

Effect on distributions
$$\frac{\mathrm{d}\sigma}{\mathrm{d}e} = \sum_{i=0}^{\infty} \frac{(-1)^i}{i!} \frac{\Omega^e_i}{Q^i} \frac{\mathrm{d}^i}{\mathrm{d}e^i} \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}e}$$
[Korchemsky & Sterman]

Massless universality
$$\Omega^e_1 = c_e\, \Omega^\rho_1$$
[Lee & Sterman]

Shape function approach

[Korchemsky & Sterman]
[Korchemsky & Tafat]

The leading $u = \frac{1}{2}$ renormalon in Ω_1 can be removed by appropriate subtractions

$$\hat{\sigma}_e(x) \to \tilde{\sigma}_e(x) = \hat{\sigma}_e(x)\, e^{-ix\,\delta_e(R,\mu)/Q}$$

[Hoang & Kluth]

$$\delta_e(R,\mu) = \frac{c_e}{c_{e'}}\, R e^{\gamma_E} \frac{\mathrm{d}}{\mathrm{d}\ln(ix)} \ln S^{\mathrm{pert}}_{e'}(x,\mu)\Big|_{x=(iRe^{\gamma_E})^{-1}}$$

[VM, Thaler, Stewart]

Renormalon inside

$$\Omega_1^e(R,\mu) \equiv \Omega_1^e(\mu) - \delta_e(R,\mu)$$

Renormalon free

Massless predictions for universality

Thrust	$\tau = 1 - \max_{\vec{n}} \frac{\sum_i \lvert\vec{p}_i \cdot \vec{n}\rvert}{\sum \lvert\vec{p}_i\rvert}$	$c_\tau = 2$
Two-Jetiness	$\tau_2 = 1 - \max_{\vec{n}} \frac{\sum_i \lvert\vec{p}_i \cdot \vec{n}\rvert}{Q}$	$c_{\tau_2} = 2$
C-parameter	$C = \frac{3}{2} \frac{\sum_{i,j} \lvert\vec{p}_i\rvert\lvert\vec{p}_j\rvert \sin^2(\theta_{ij})}{(\sum_i \lvert\vec{p}_i\rvert)^2}$	$c_C = 3\pi$
Angularities	$\tau_{(a)} = \frac{1}{Q} \sum_i E_i \,(\sin\theta_i)^a (1 - \lvert\cos\theta_i\rvert)^{1-a}$	$c_{\tau_{(a)}} = \frac{2}{1-a}$
Jet Masses	$\rho_\pm = \frac{1}{Q^2} \Big(\sum_{i \in \pm} p_i \Big)^2$	$c_\rho = 1$

Hadron Mass Effects on Power Corrections

[Salam & Wicke]

$$\Omega_1 \to \Omega_1 + K \left(\log \frac{Q}{\Lambda} \right)^{\frac{4C_A}{\beta_0}}$$

- Use the flux tube model (later refined with QCD effects)
- Predict that hadron masses break universality
- Find a privileged scheme (E-scheme) which preserves universality
- Predict that hadron multiplicity translates into log(Q) effects on power corrections.

[VM, Thaler, Stewart]

$$\gamma^{\Omega_1} = -\frac{\alpha_s C_A}{\pi} \log(1 - r^2)$$

- Use SCET, first principle computation
- Confirm that mass breaks universality
- Find sets of universality classes with same power correction
- Compute anomalous dimension of Ω_1
- Compute matching for thrust of the OPE

It appears that these running effects have small effect on α_s determinations, but can increase the error

NONSINGULAR TERMS AND MASS EFFECTS

Nonsingular terms

These terms are suppressed in the peak, but important in tail and O(1) in far tail

Factorization and resummation for nonsingular never worked out → Can be included in fixed order

In far tail resummation has to be turned off, since logs are no longer large

Modify logs to switch off resummation *[Jones, Ford, Salam, Stenzel, Wicke]*

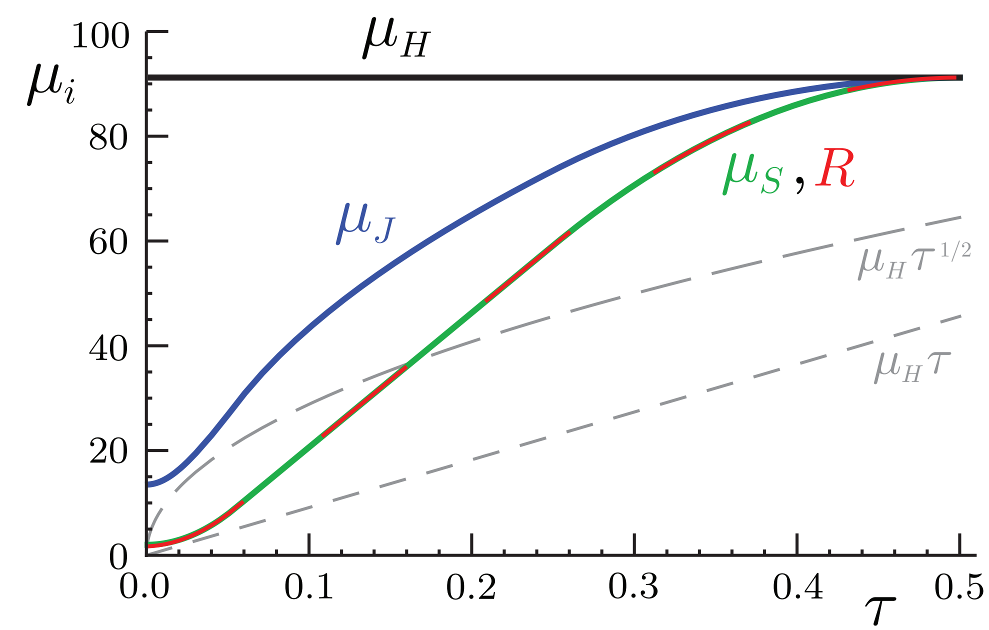
Modified log(R) matching scheme

$$\log\left[\Sigma(\tau_{\max})\right] = \frac{1}{\sigma}\frac{d\sigma}{d\tau}\bigg|_{\tau=\tau_{\max}} = 0$$

$$L \longrightarrow L' = \frac{1}{p}\log\left(\left(\frac{1}{\tau}\right)^p - \left(\frac{1}{\tau_{\max}}\right)^p + 1\right)$$

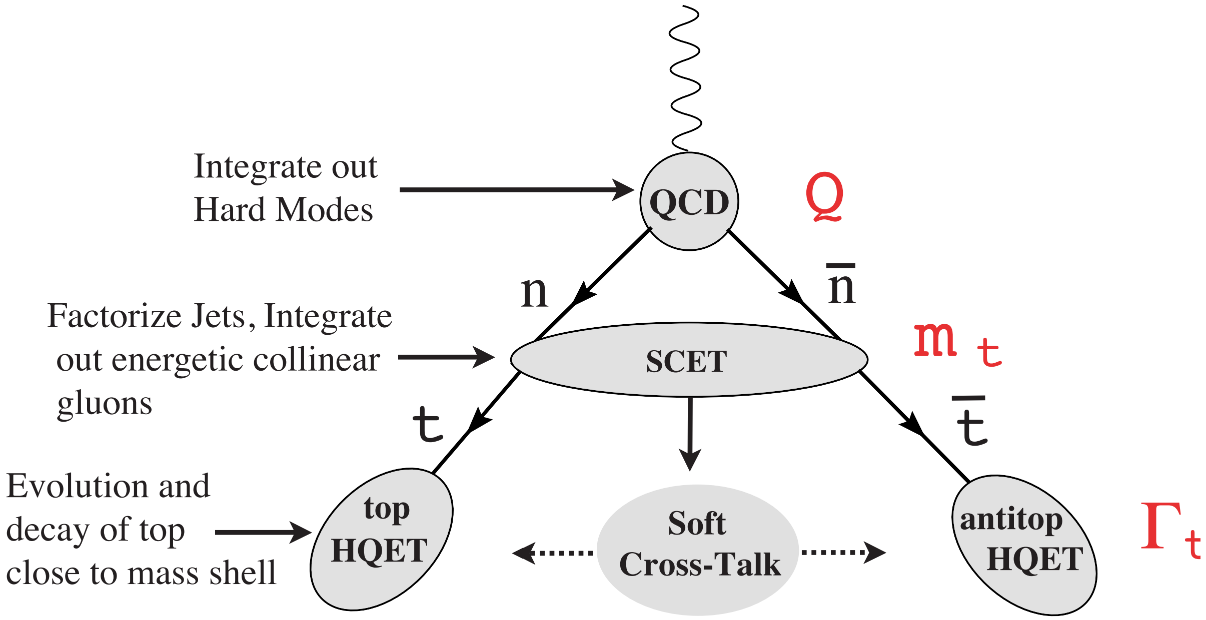
Merge all scales in far tail with profile functions

[Abbate, Fickinger, Hoang, VM, Stewart]



Quark mass effects on event shapes

[Fleming, Hoang, Mantry, Stewart]



Production of very energetic top quarks
Resummation of logs at N^{2}LL
Only Jet function modified at this order
Considers decay of top quark
Designed to measure top mass at ILC

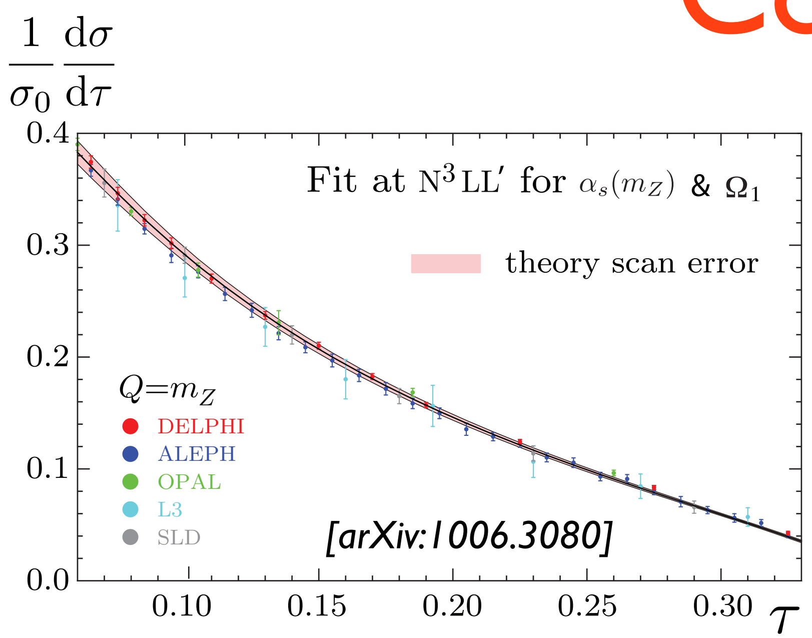
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_t^2\,\mathrm{d}M_{\bar t}^2}\right)_{\rm hemi} = \sigma_0\, H_Q(Q,\mu_Q,\mu_m) H_m\Big(m,\frac{Q}{m},\mu_m,\mu\Big) \times \int \mathrm{d}\ell^+ \mathrm{d}\ell^- B_+\Big(\hat s_t - \frac{Q\ell^+}{m},\Gamma,\mu\Big)\, B_-\Big(\hat s_{\bar t} - \frac{Q\ell^-}{m},\Gamma,\mu\Big) S_{\rm hemi}(\ell^+,\ell^-,\mu)$$

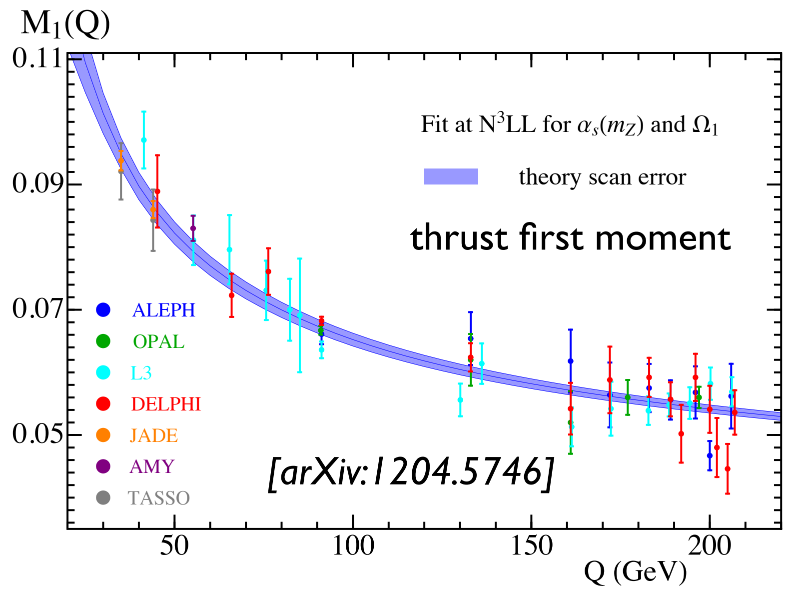
[Abbate, Fickinger, Hoang, VM, Stewart]

Applied top results to include bottom mass corrections to thrust
Included non-singular contribution
Included renormalon subtraction

COMPARISONS TO DATA AND FITS

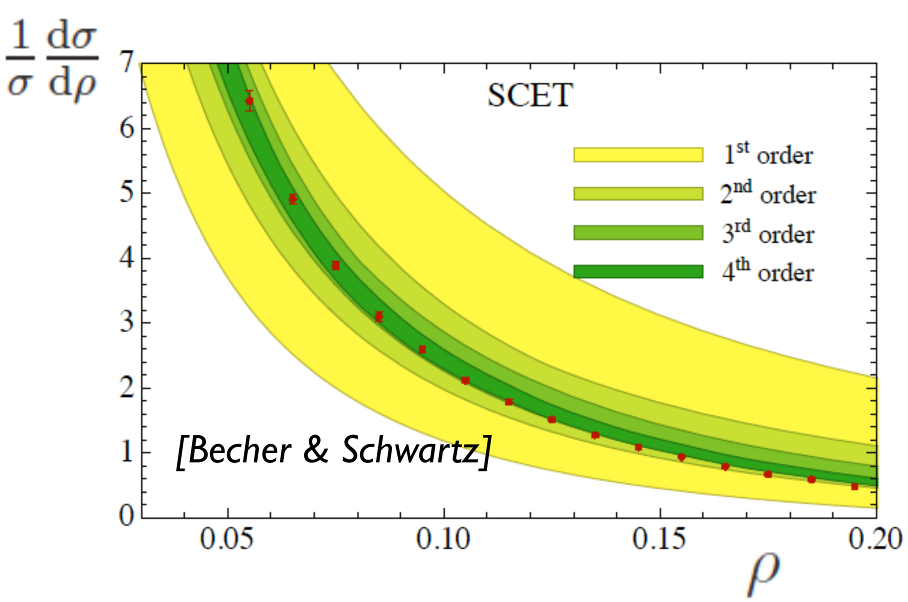
Comparisons to data

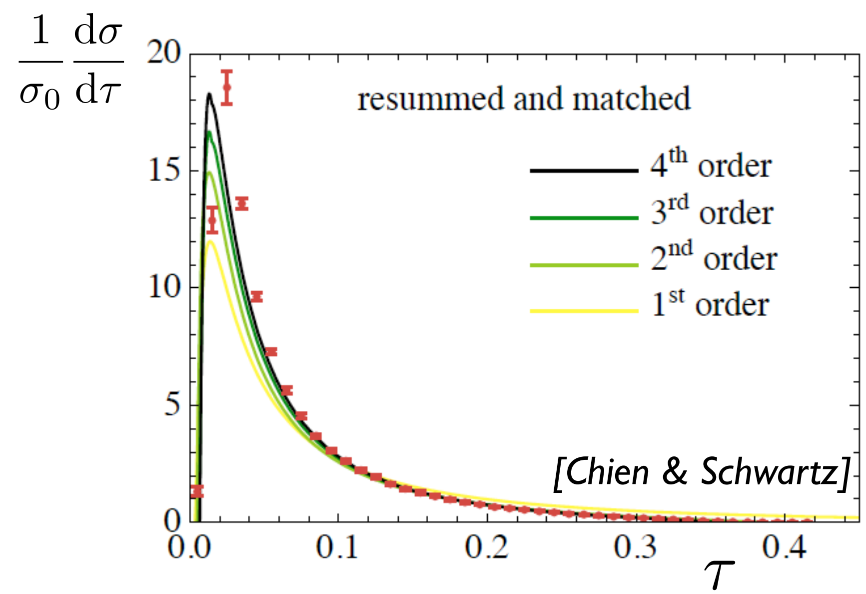




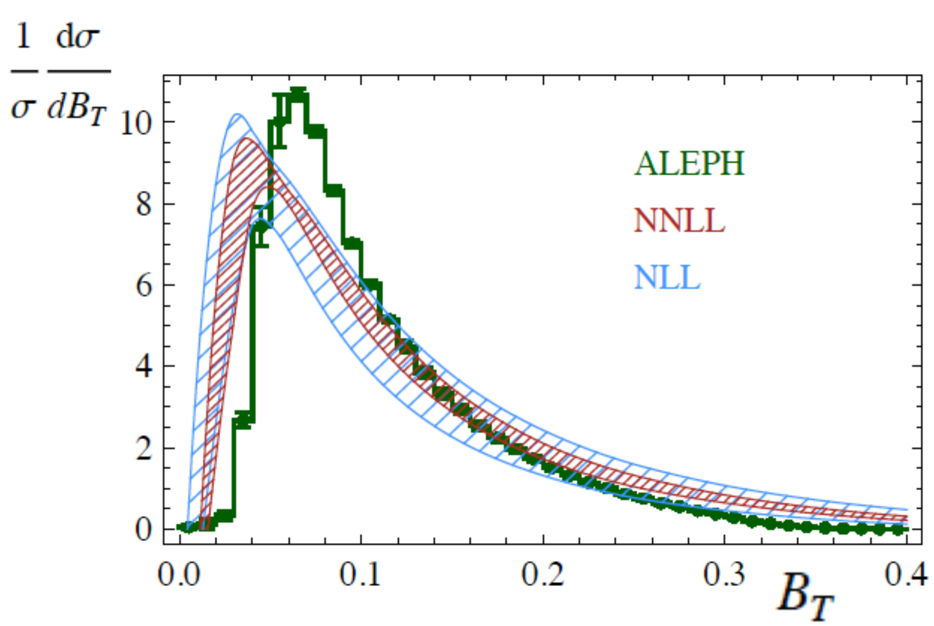
N^{3}LL, with power corrections

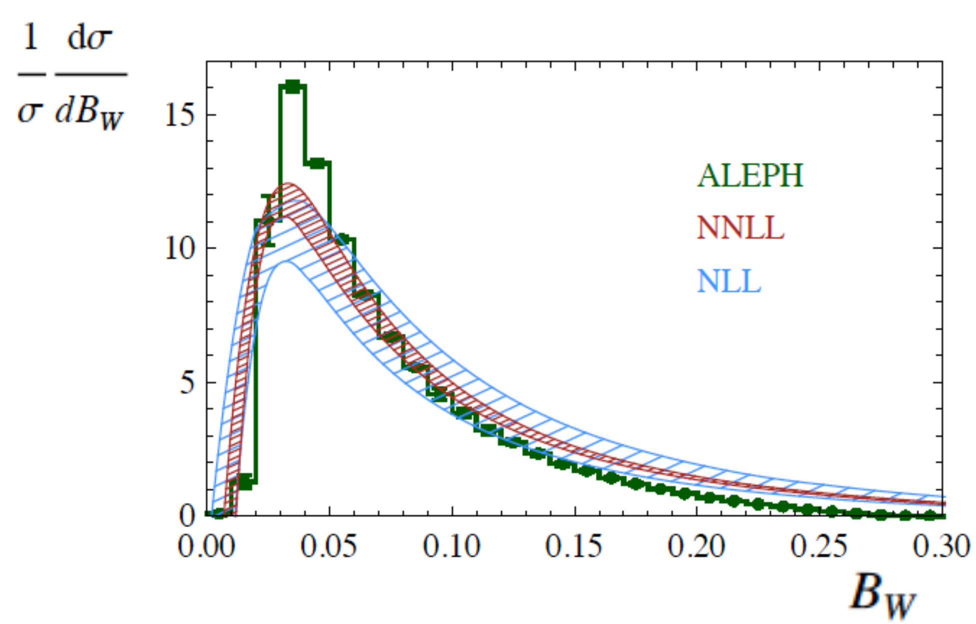
[Abatte, Fickinger, Hoang, VM, Stewart]





N^{3}LL, no power corrections, singular + nonsingular



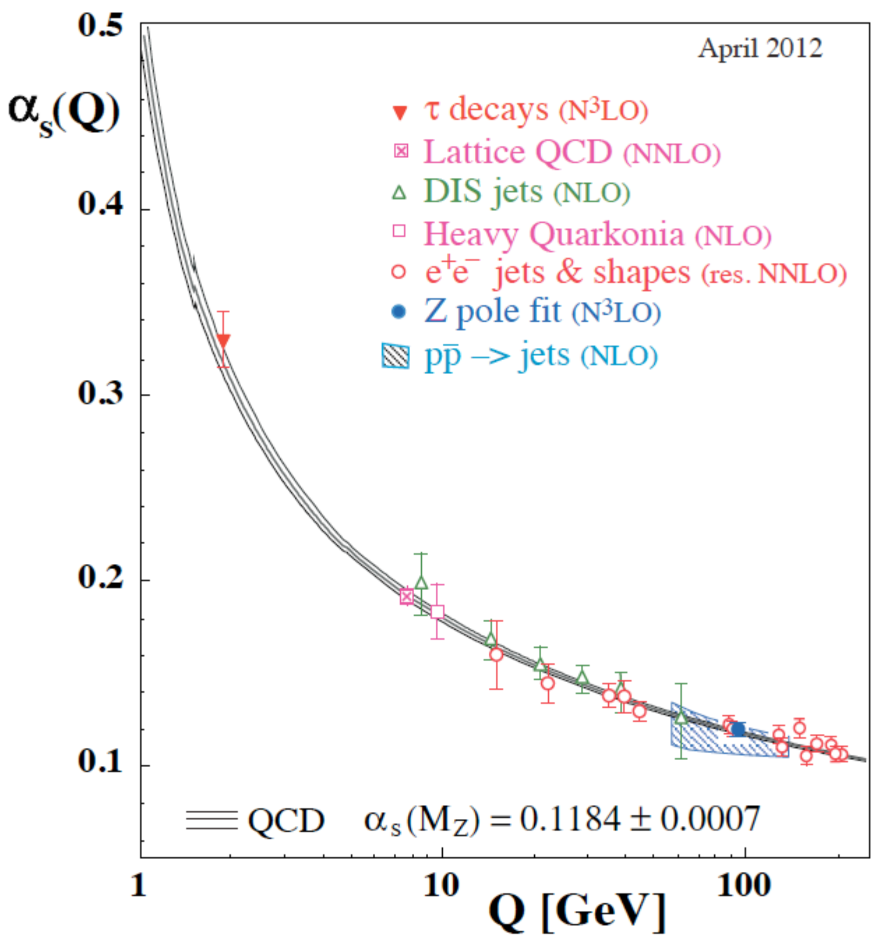


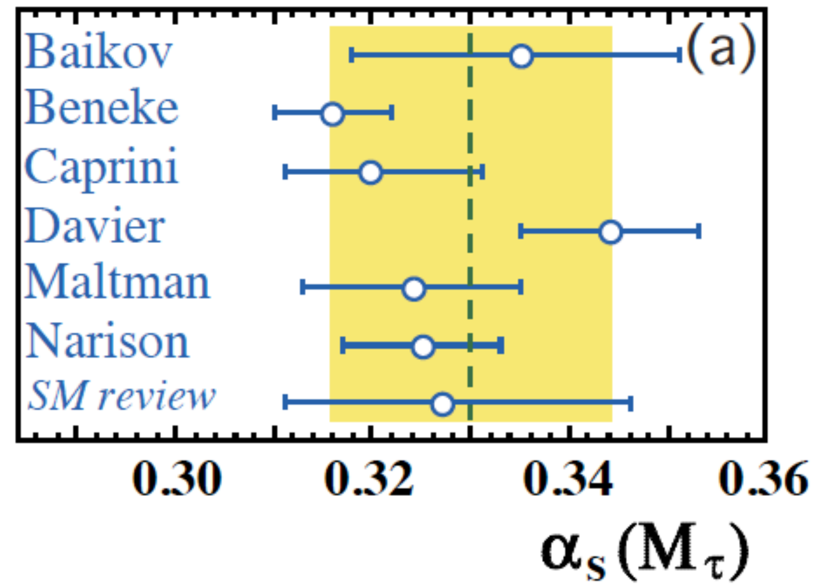
N^{2}LL, no power corrections, only singular

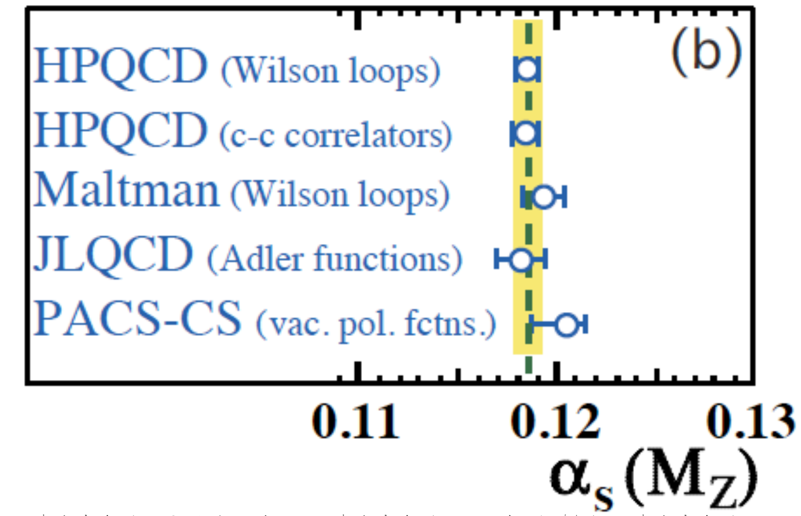
[Becher & Bell]

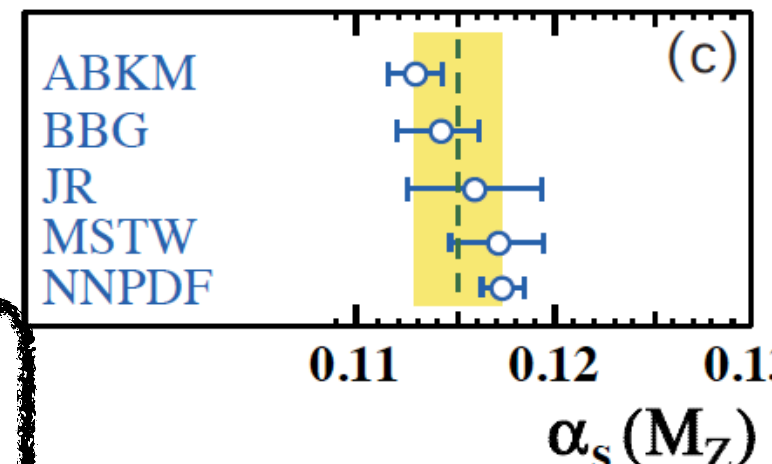
α_s determination: world average

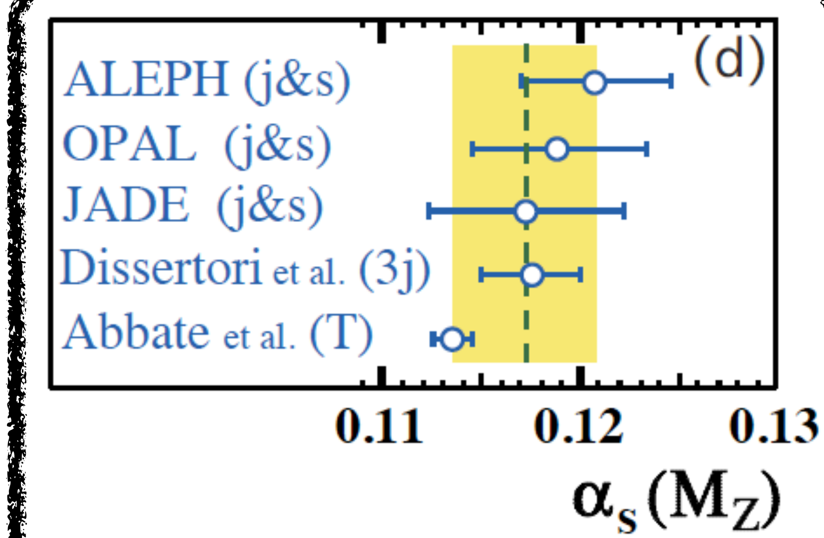
Figures taken from PDG





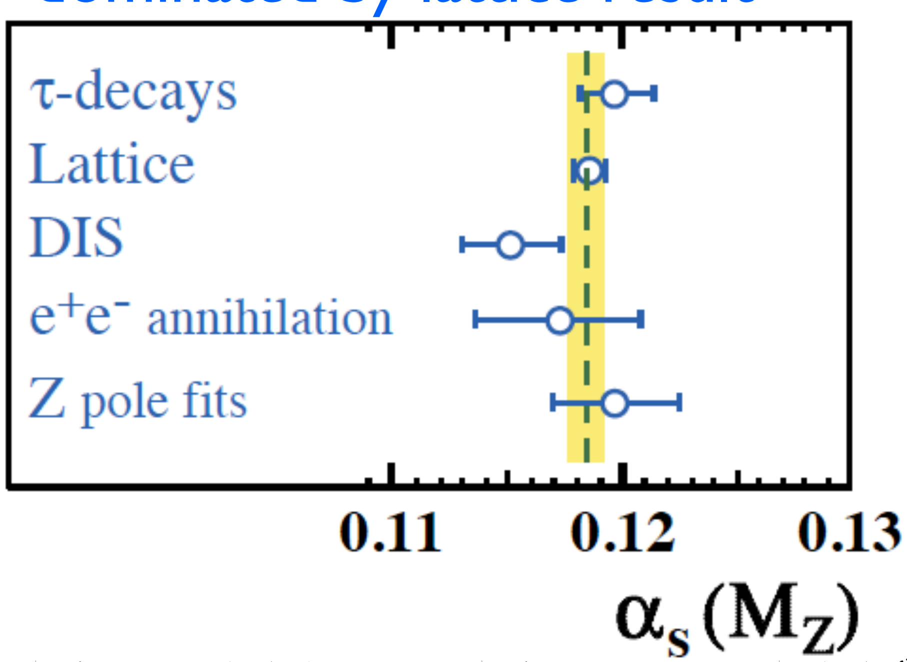






High-precision event shape determinations washed out from average

World average completely dominated by lattice result



many details in review arXiv: 1110.0016

Determinations are first averaged within a given process

The various averages are later combined together for the final average

Experimental data

Facility	Location	$\sqrt{s}$ [GeV]	Experiments
ACO [84]	LAL Orsay	≈ 1	M3N [85, 86]
ADONE [87]	INFN Frascati	$1-3$	Boson [88], $\mu\pi$ [89], $\gamma\gamma$ [90], $\gamma\gamma 2$ [91], MEA [92]
VEPP-2 [93]	Novosibirsk	$1-1.5$	VEPP-2 [93]
CEA [94]	Cambridge, MA	4	BOLD [95]
SPEAR [96]	SLAC Stanford	$2-8$	SLAC-LBL [97, 98], MARK I [99], MARK II [100]
PEP [101]	SLAC Stanford	29	MARK II [102], HRS [103], TPC/2γ [104, 105], MAC [106]
DORIS [107, 108]	DESY Hamburg	$3-11$	PLUTO [109], DASP [110, 111], LENA [112], DH(HM) [113, 114]
CESR [115]	Cornell, Ithaka	$10-11$	CLEO [116, 117], CUSB [118, 119]
PETRA [120]	DESY Hamburg	$12-47$	CELLO [121], JADE [122], MARK J [123], PLUTO [109], TASSO [110, 124]
TRISTAN [125]	KEK Tsukuba	$50-64$	TOPAZ [126], VENUS [127], AMY [128]
SLC [129]	SLAC Stanford	≈ 91	MARK II [102], SLD [130]
LEP [131]	CERN Geneva	$88-209$	ALEPH [132, 133], DELPHI [134, 135], L3 [136], OPAL [137]

Table taken from *[Kluth 2003]*

At each value of Q one expects to find a distribution for each event shapes plus moments of the distribution

Really a lot of data!!!

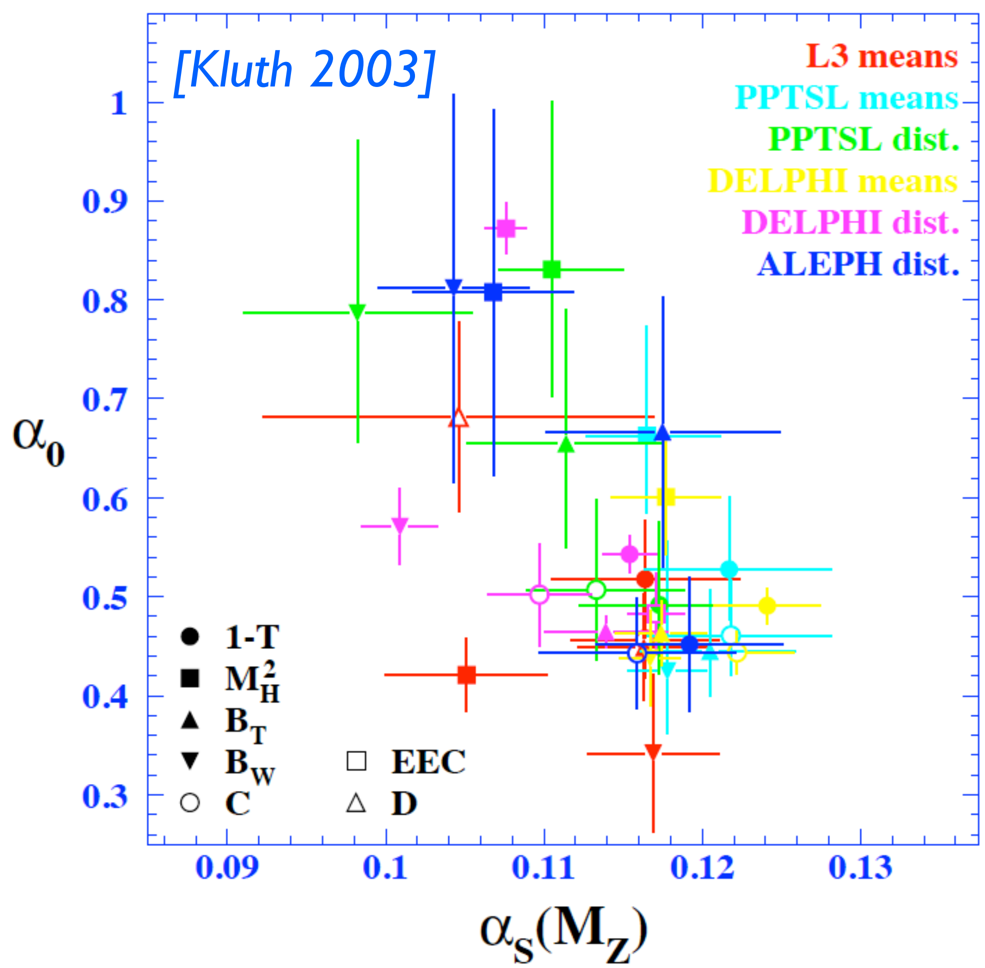
Small Q, not used

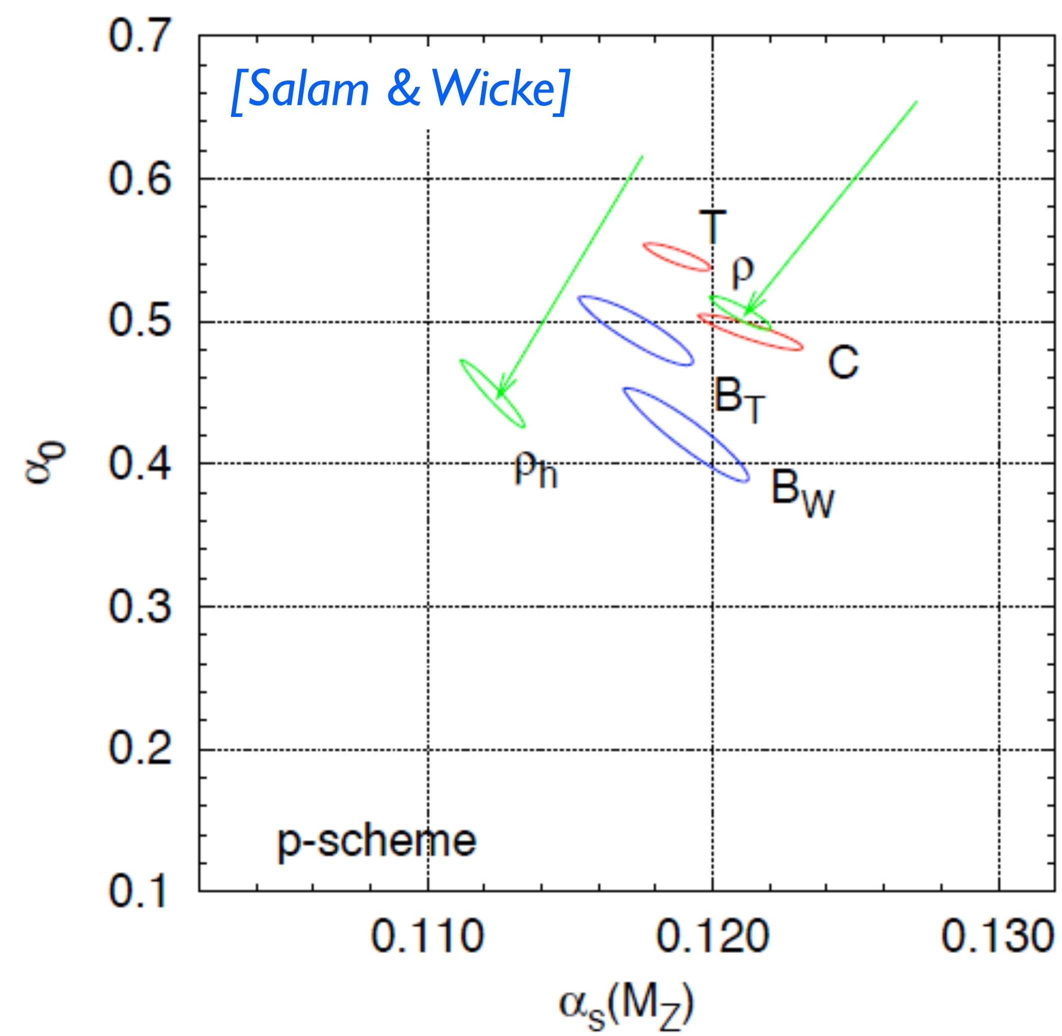
α_s determination: tests of universality

These tests have been so far done in the dispersive approach model

They mainly use the first moment of the distributions

Mainly two loop studies only





Distributions and moments

N²LL predictions only

Two loop predictions only

Does not account for hadron mass effects

First moments only

N²LL predictions only

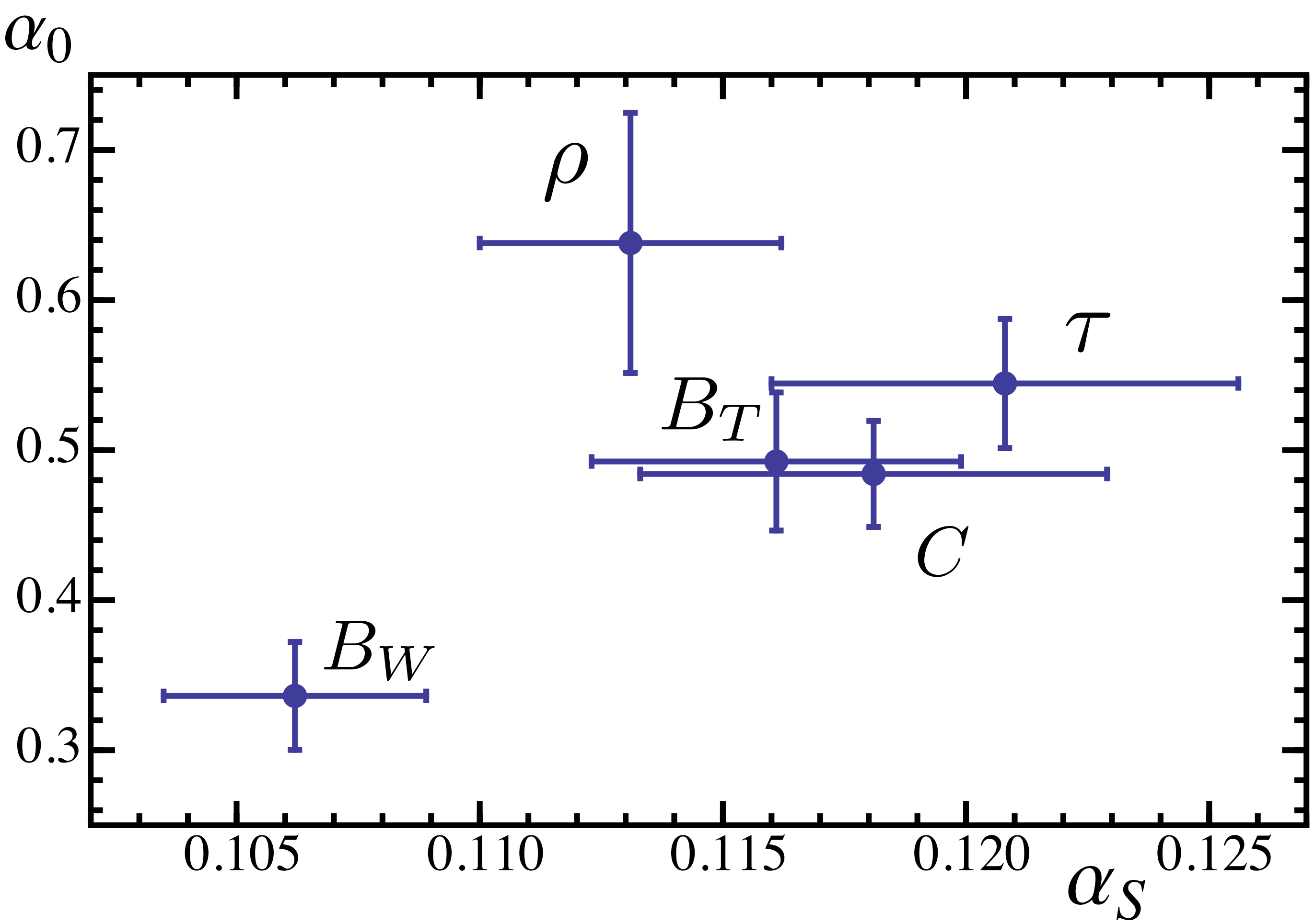
Converts all event shapes to p-scheme

approximate universality

α_s determination: tests of universality

[Gehrmann, Jaquier, Luissoni]

Only universality study with 3-loop input
They use first five moments
Did not take into account hadron mass effects



Y_3 has no $\frac{1}{Q}$ power correction $\quad \alpha_s(m_Z) = 0.1139 \pm 0.0022$

α_s determination: tests of universality

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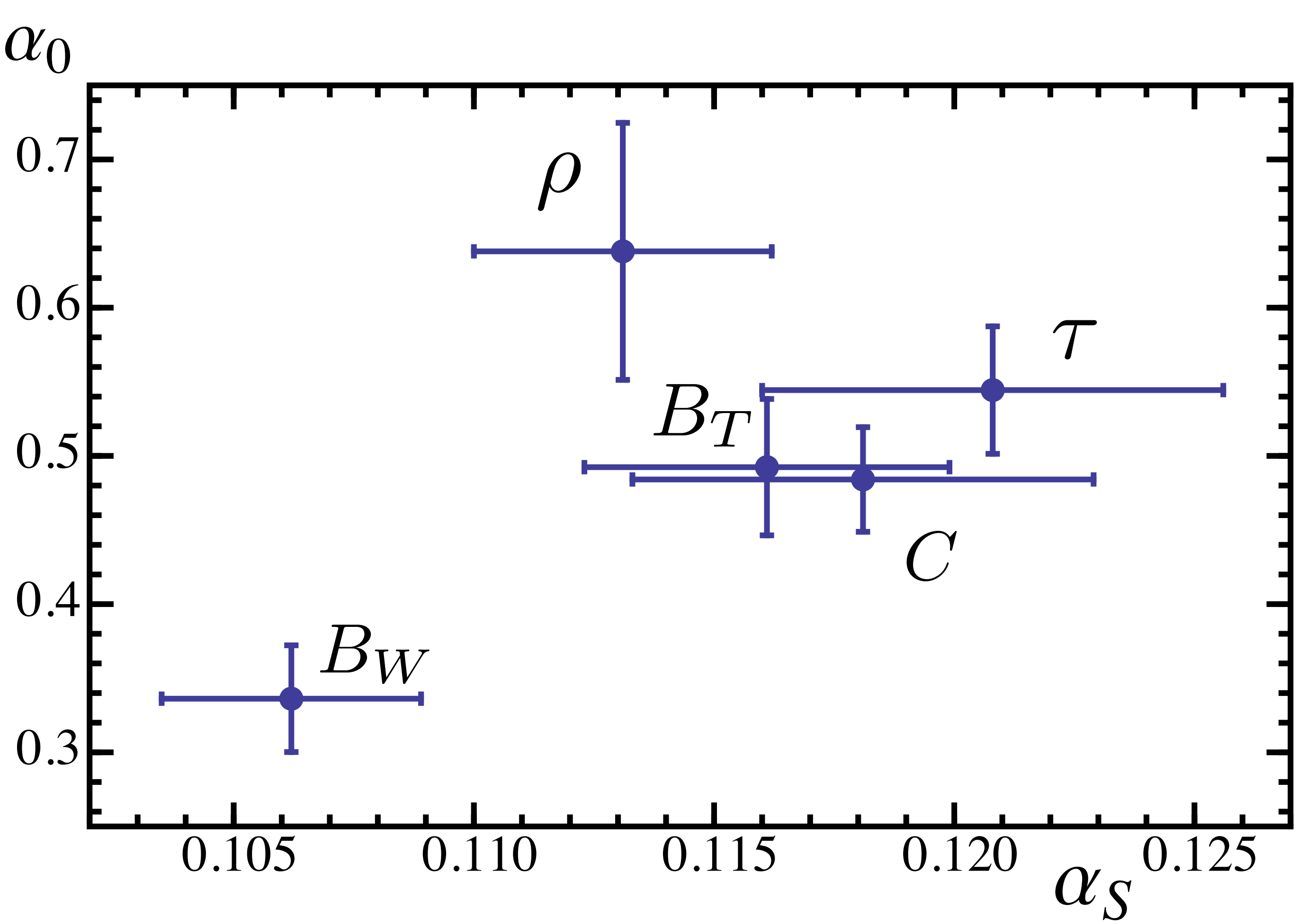

For final average exclude B_W and B_T

$$\alpha_s(m_Z) = 0.1153 \pm 0.0028$$

Y_3 has no $\frac{1}{Q}$ power correction $\quad \alpha_s(m_Z) = 0.1139 \pm 0.0022$

α_s determination: tests of universality

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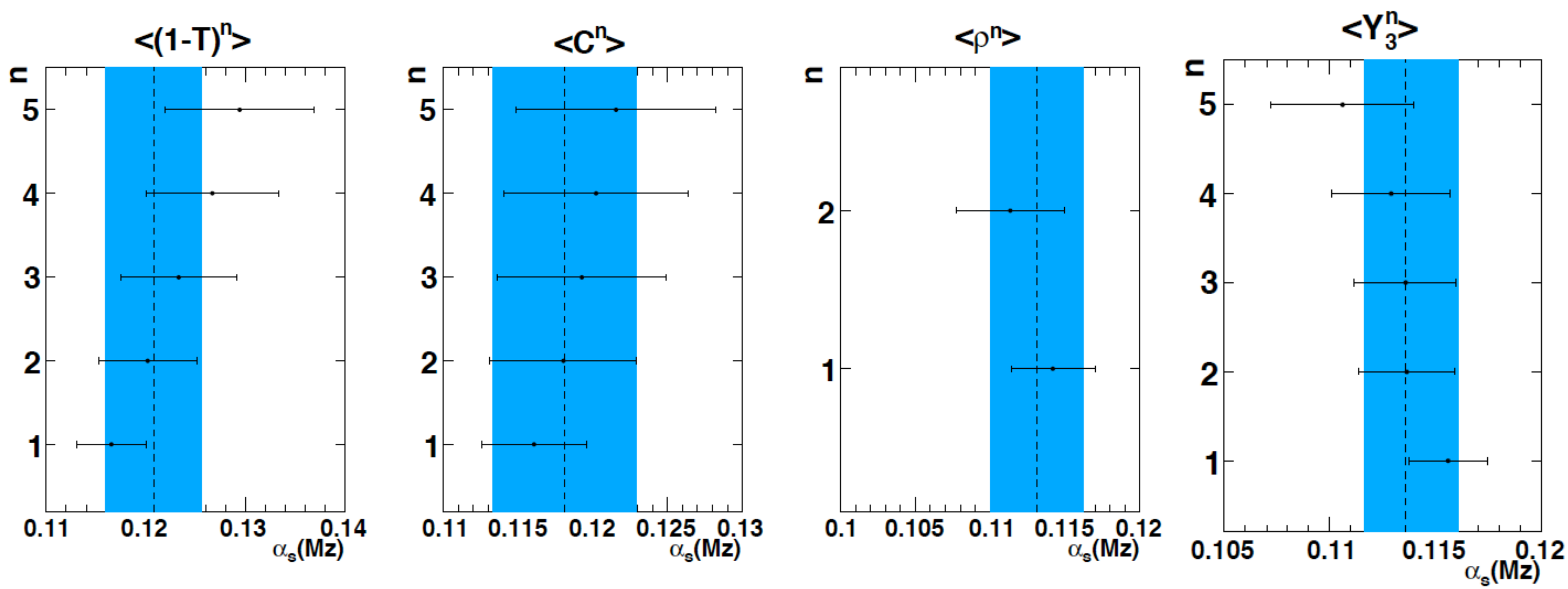
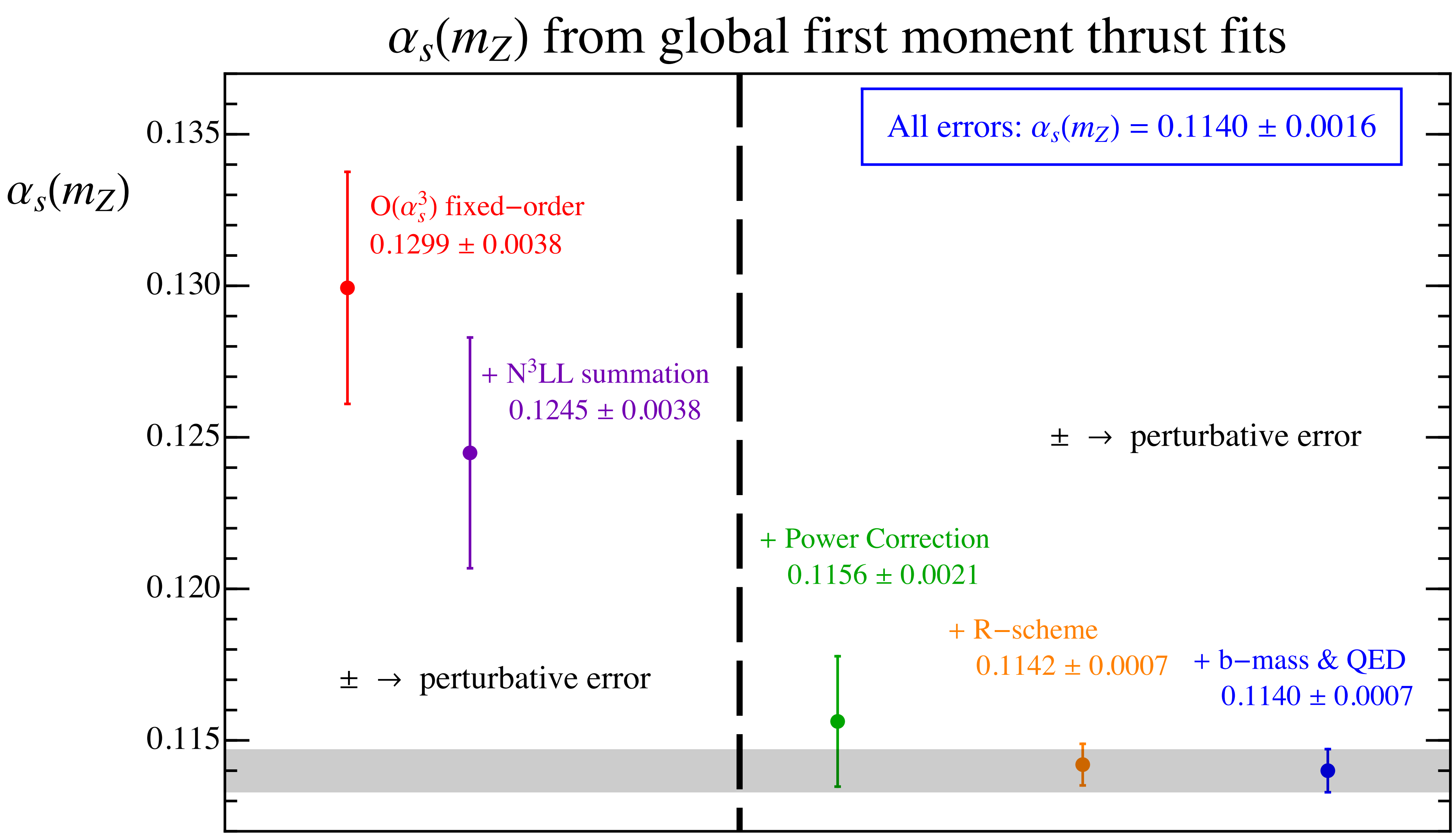


strong dependence of $\alpha_s(m_Z)$ on n

α_s determination: moment fits

[Abbate, Fickinger, Hoang, VM, Stewart]

Only first moment of thrust
Used N^{3}LL code, with power corrections and renormalon subtraction
Different levels of theoretical sophistication



α_s determination: moment fits

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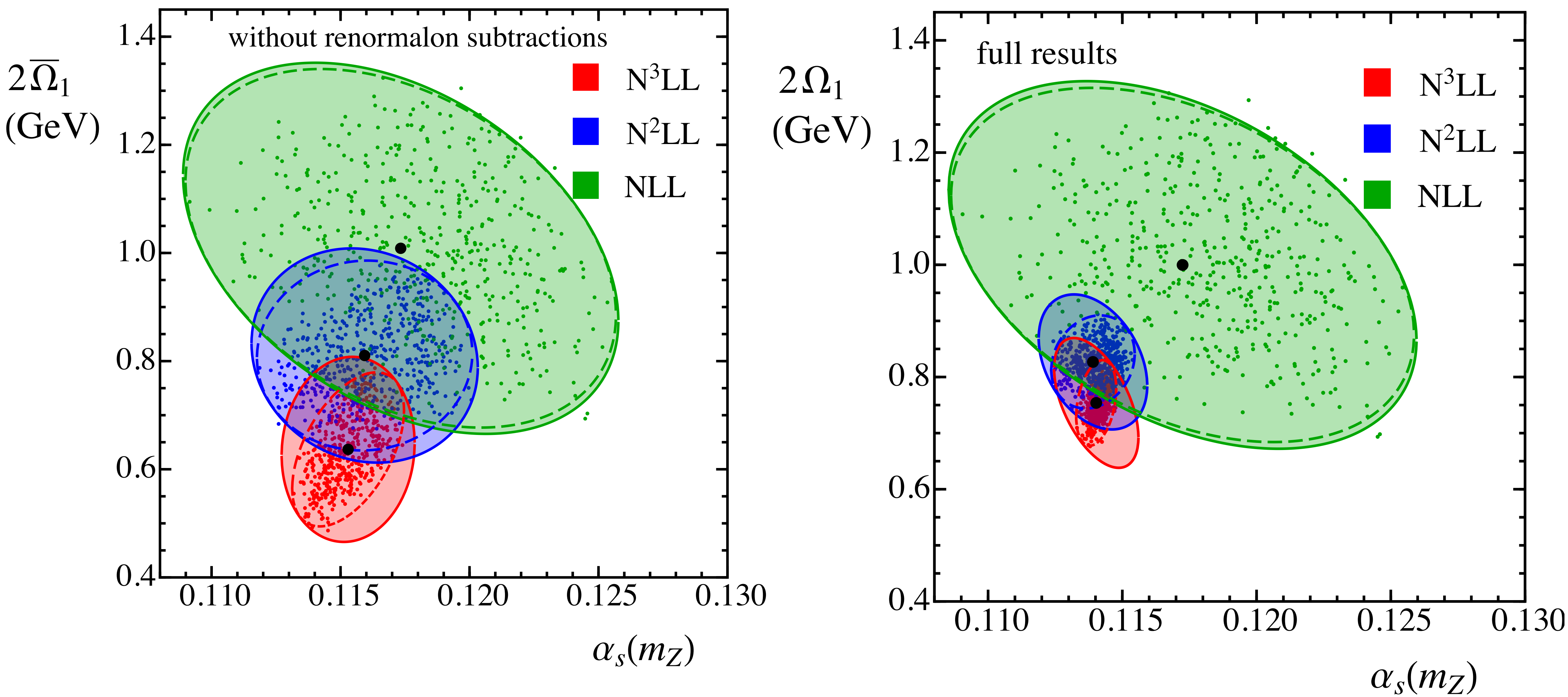
Different levels of theoretical sophistication
Significant error reduction when renormalon is removed

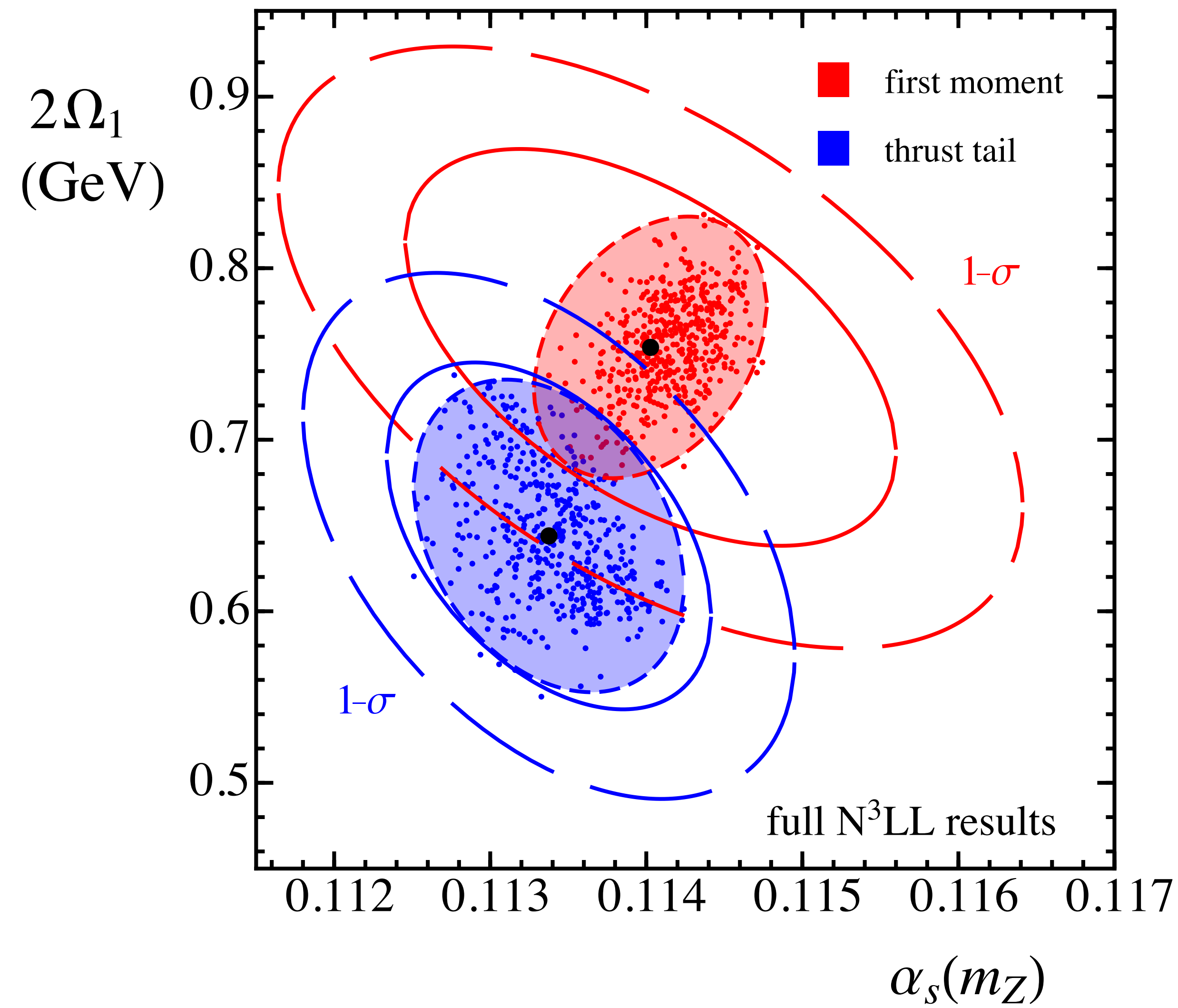


α_s determination: moment fits

[Abbate, Fickinger, Hoang, VM, Stewart]

Only first moment of thrust
Used N^{3}LL code, with power corrections and renormalon subtraction
Different levels of theoretical sophistication
Significant error reduction when renormalon is removed

Good agreement with tail fits



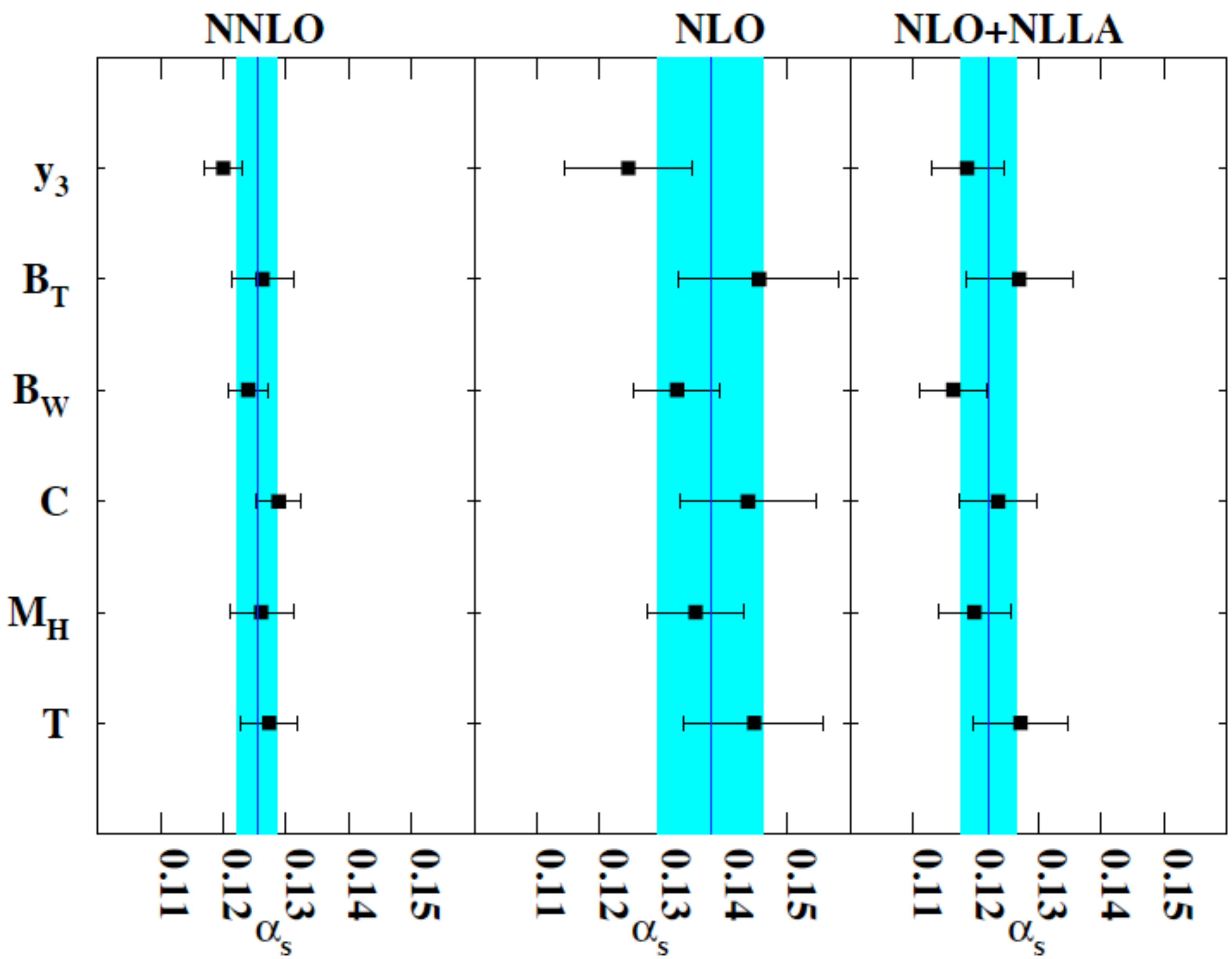
α_s determination: tail fits

Only consider analysis with 3-loop input

[Dissertori et al 0712.0327]

- Does not include resummation
- Fits to LEP data
- Q by Q fits
- Many event shapes
- Power corrections from MC

$$\alpha_s(m_Z) = 0.1224 \pm 0.0033$$



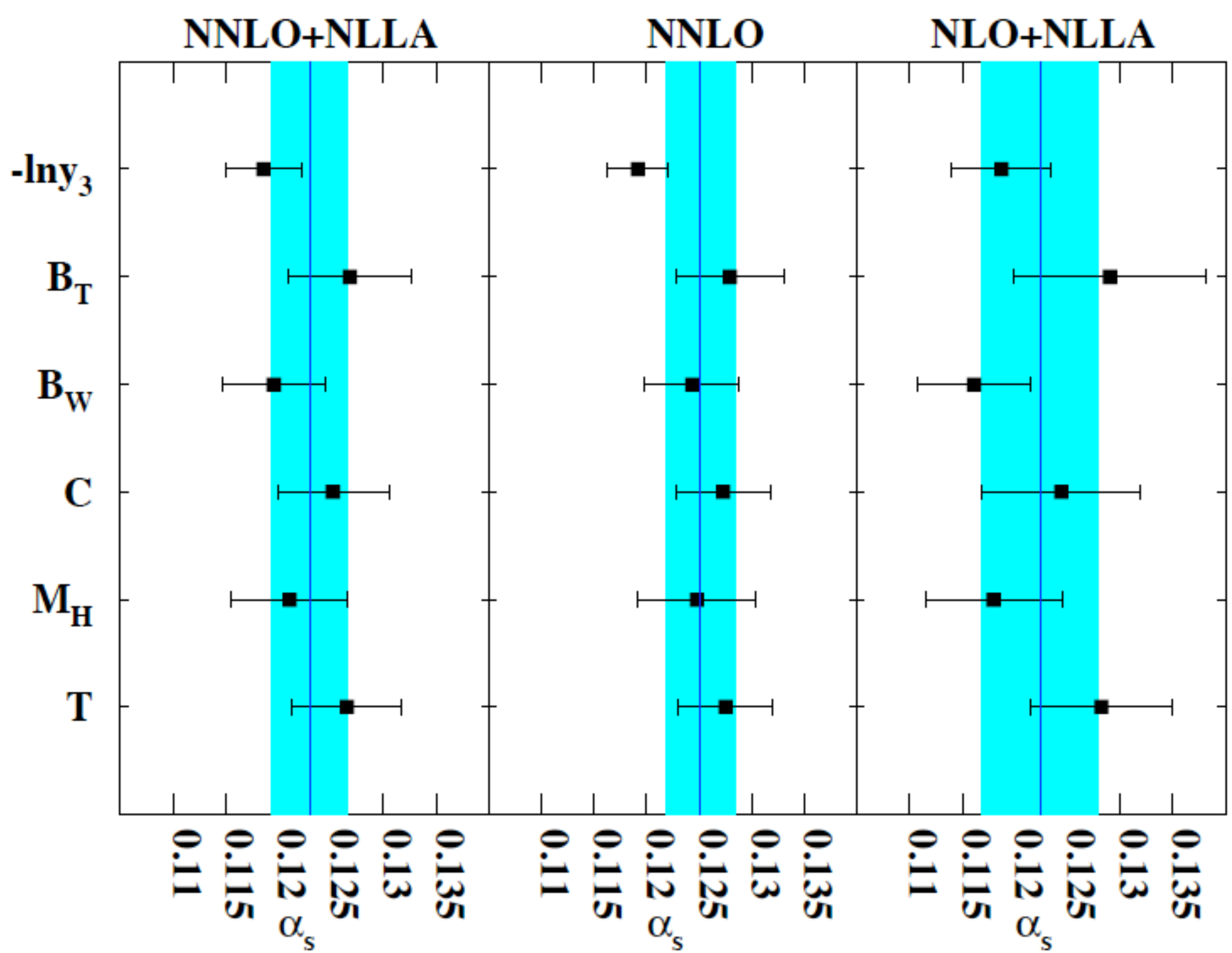
α_s determination: tail fits

Only consider analysis with 3-loop input

[Dissertori et al 0906.3436]

- NLL resummation
- Fits to LEP data
- Q by Q fits
- Many event shapes
- Power corrections from MC

$$\alpha_s(m_Z) = 0.1224 \pm 0.0039$$



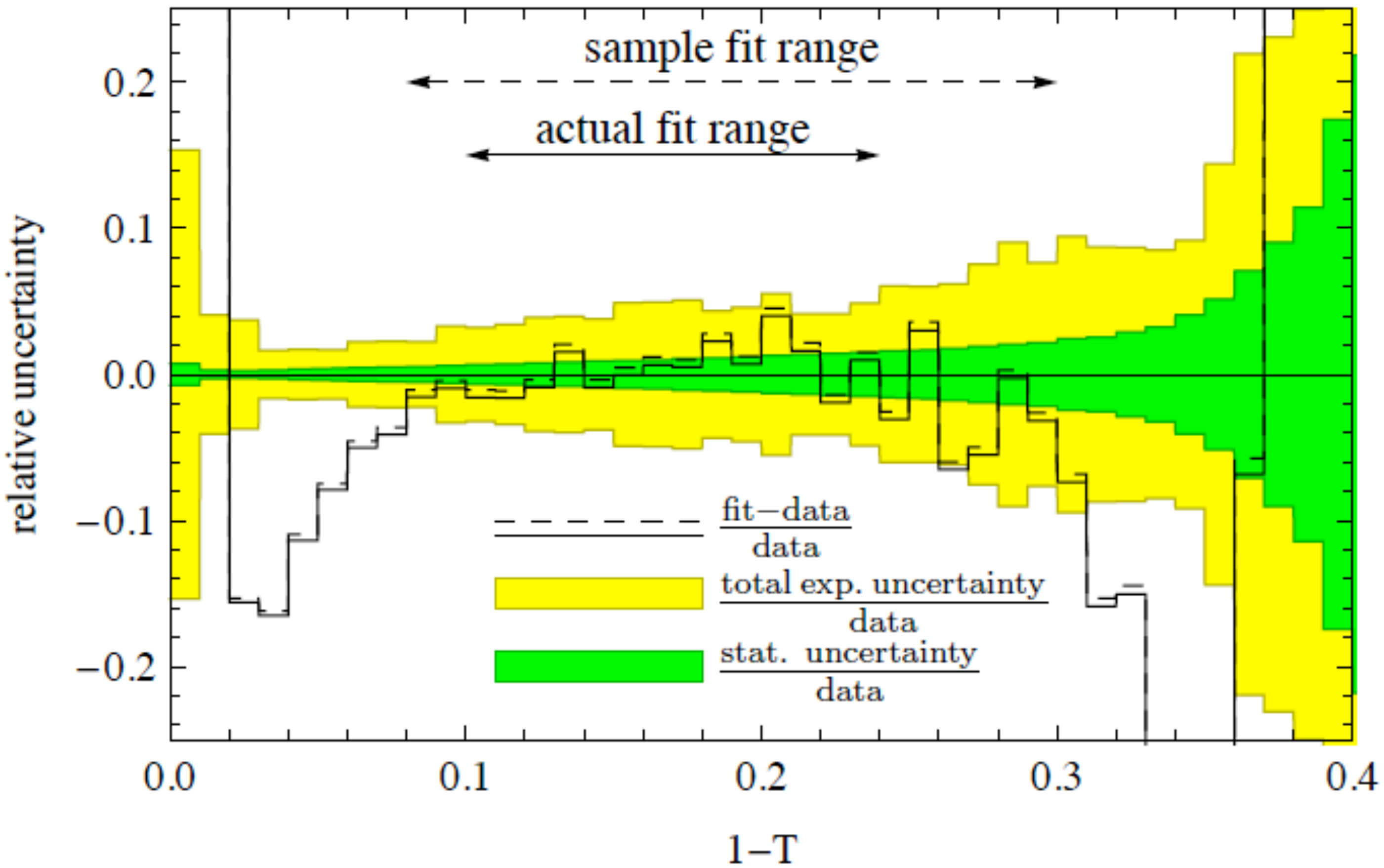
α_s determination: tail fits

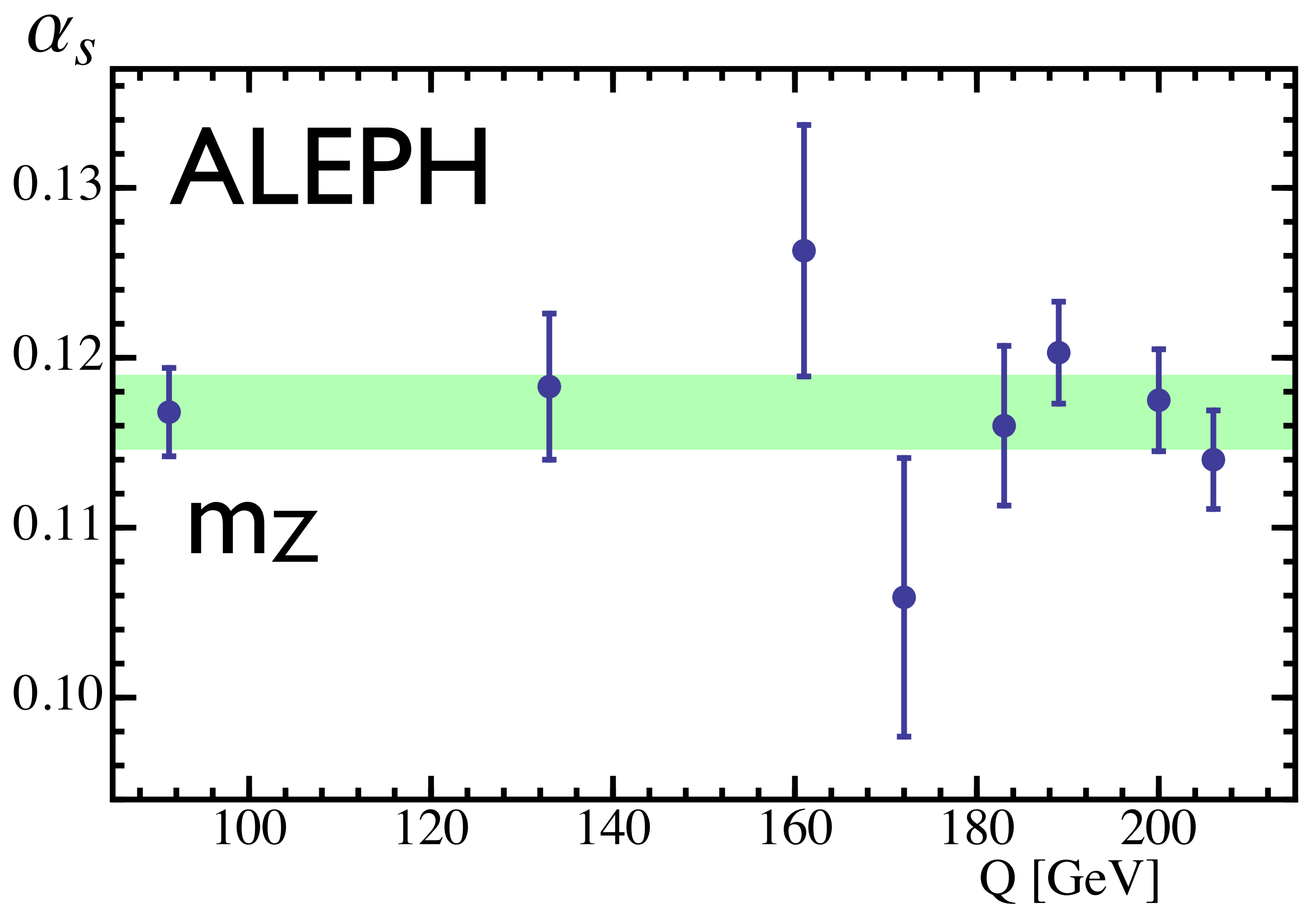
Only consider analysis with 3-loop input

[Becher & Schwartz 0803.0342]

- N^3LL resummation
- Fits to ALEPH and OPAL data
- Q by Q fits
- Thrust
- Power corrections from MC

$$\alpha_s(m_Z) = 0.1172 \pm 0.0021$$



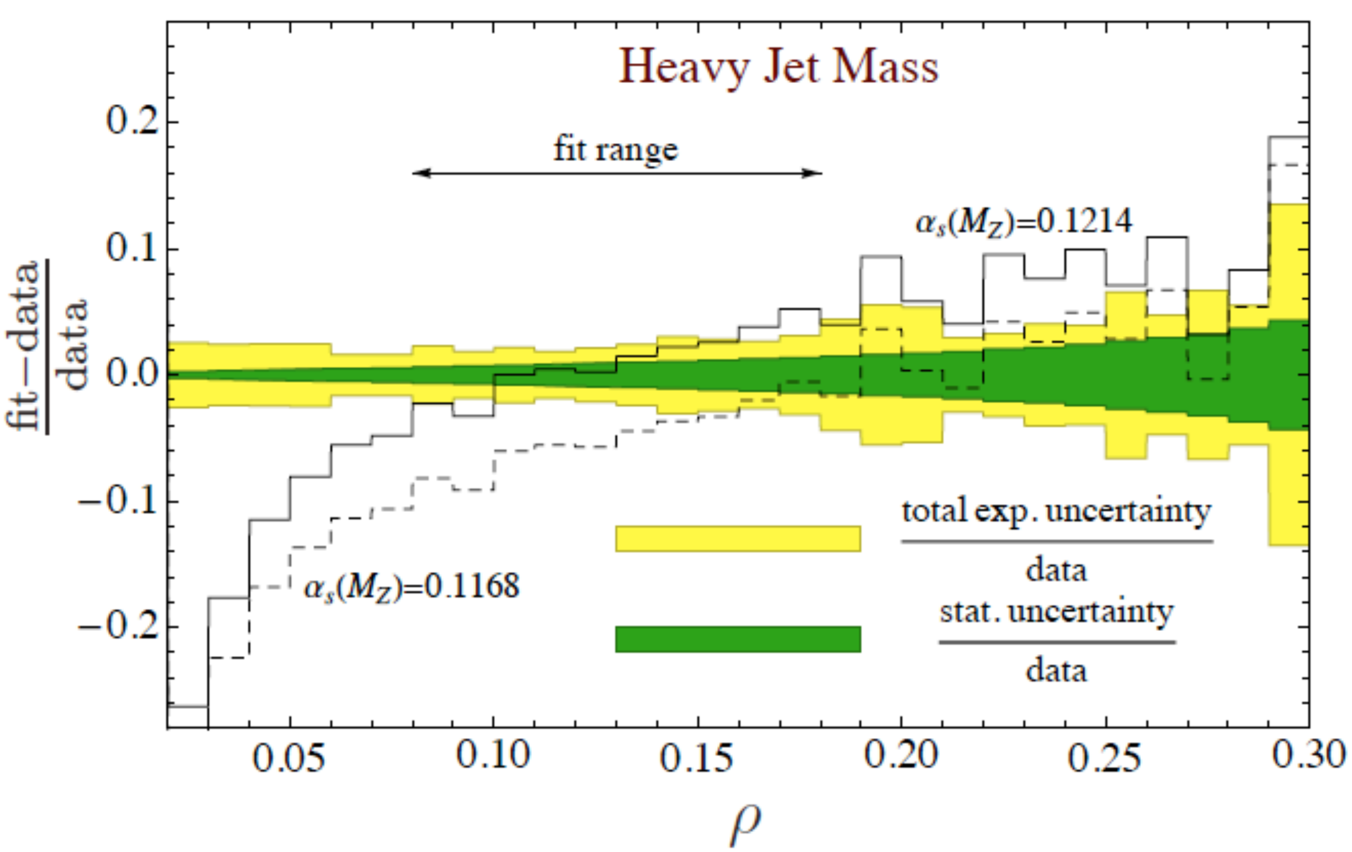


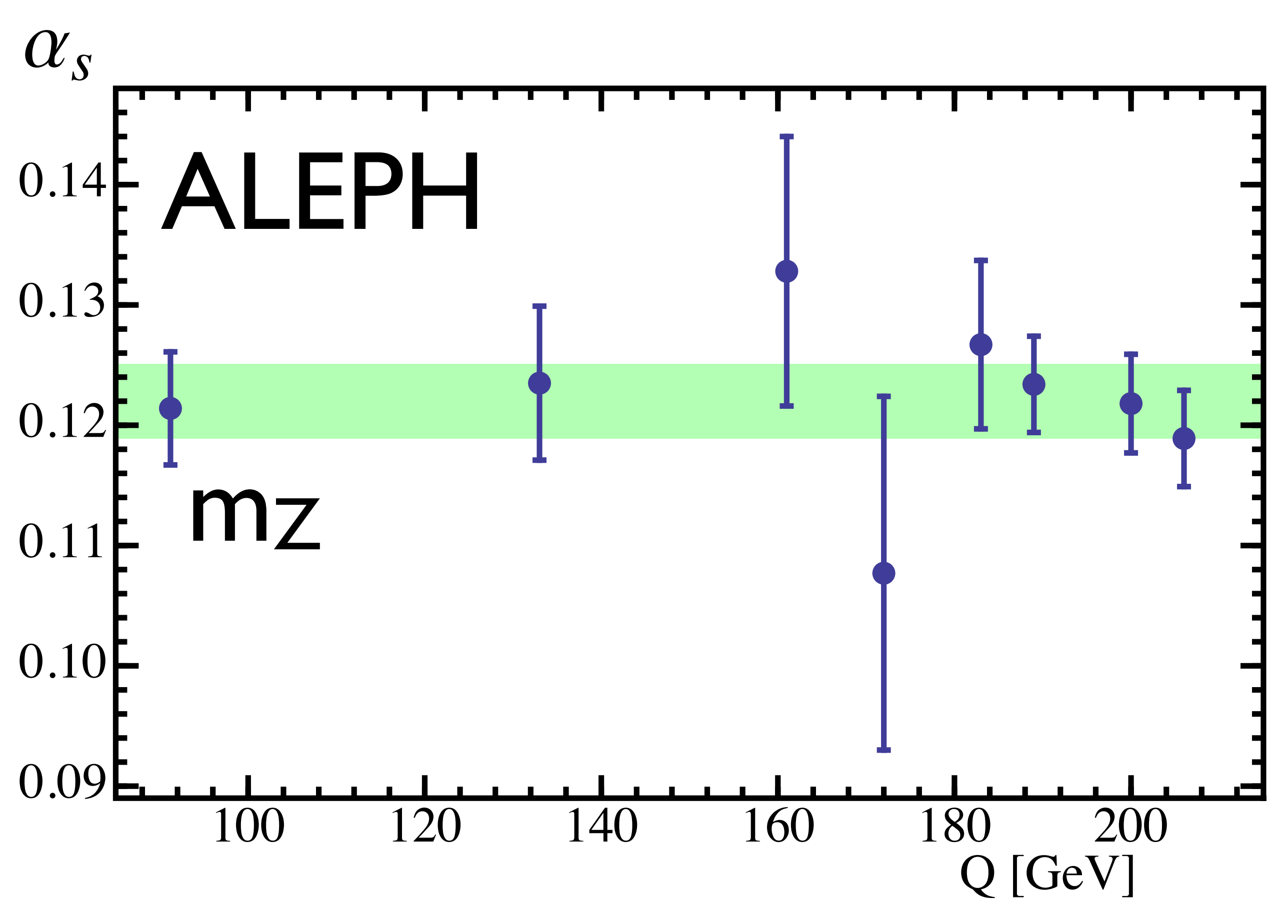
α_s determination: tail fits

Only consider analysis with 3-loop input

[Chien & Schwartz 0803.0342]
- N^{3}LL resummation
- Fits to ALEPH data
- Q by Q fits
- HJM
- Power corrections from MC

$$\alpha_s(m_Z) = 0.1220 \pm 0.0031$$





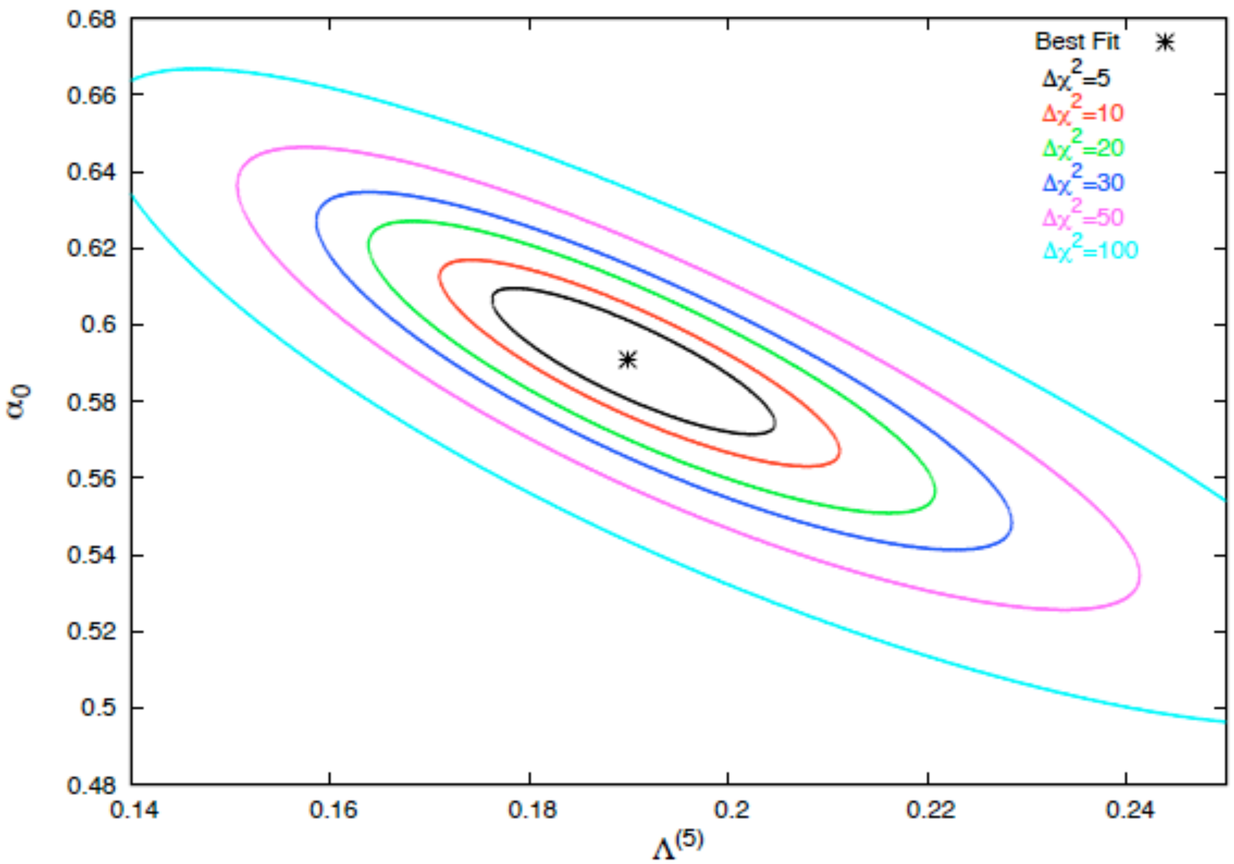
α_s determination: tail fits

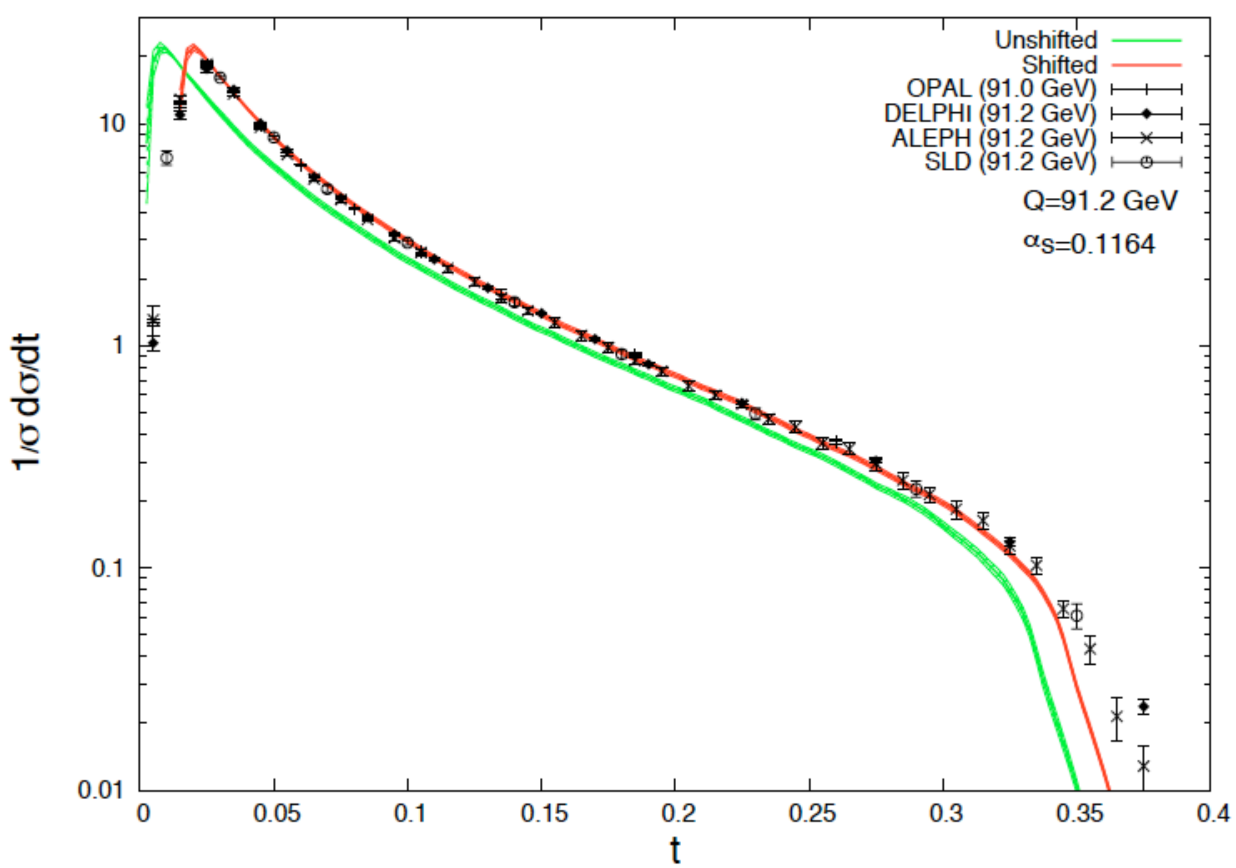
Only consider analysis with 3-loop input

[Davidson & Webber 0809.3326]

- N²LL resummation
- Fits to many Q values, global fit
- Thrust
- Power corrections from dispersive model

$$\alpha_s(m_Z) = 0.1163 \pm 0.0028$$





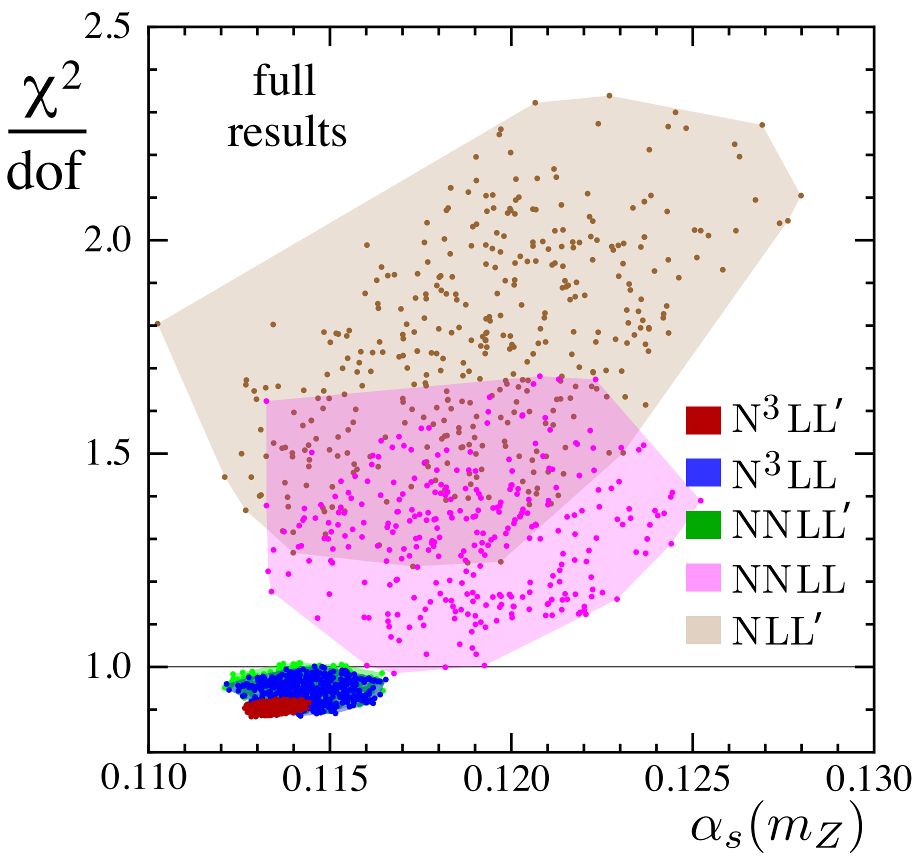
α_s determination: tail fits

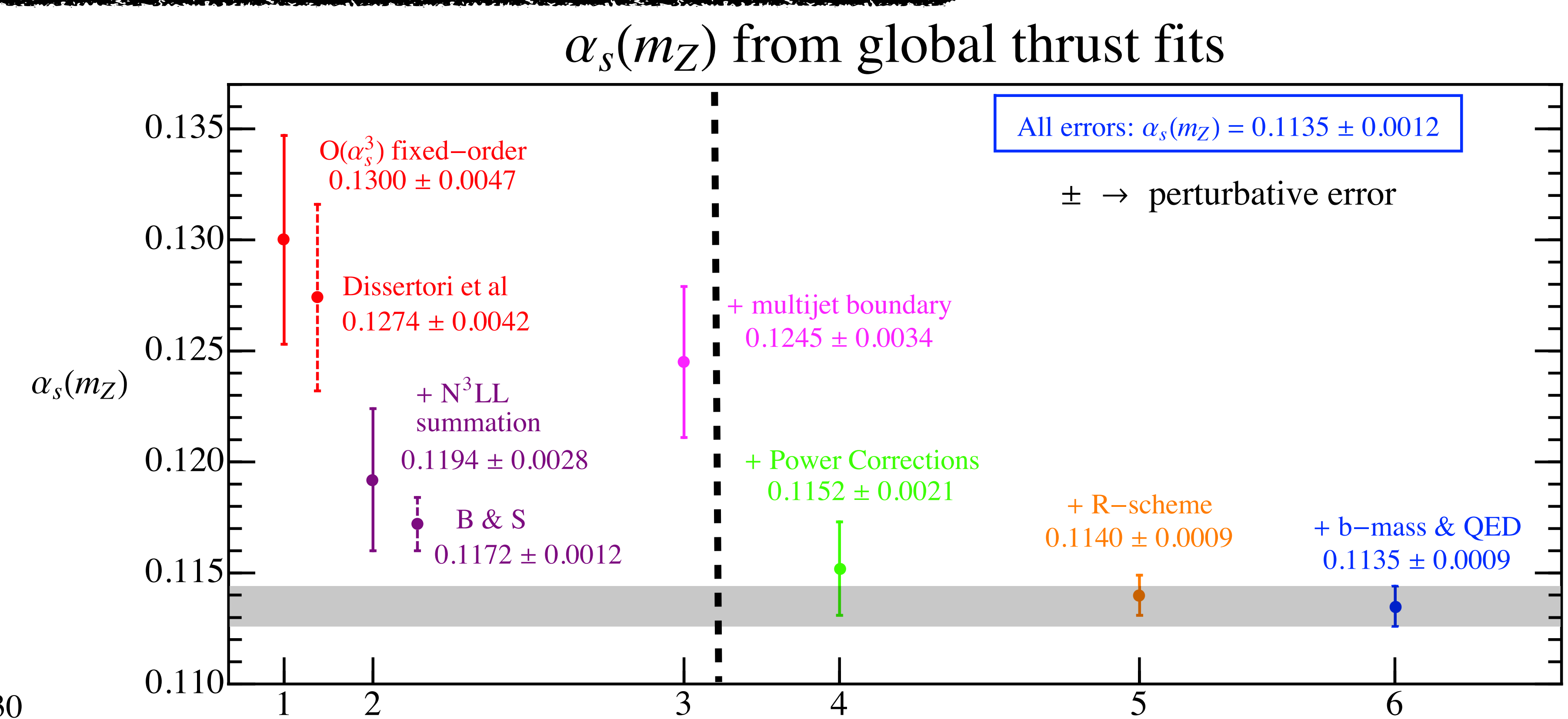
Only consider analysis with 3-loop input

[Abbate, Fickinger, Hoang, VM Stewart 1006.3080]

- N³LL resummation
- Fits to Q > 34 GeV, global fit
- Thrust
- Power corrections OPE
- QED and mass effects
- Renormalon subtraction

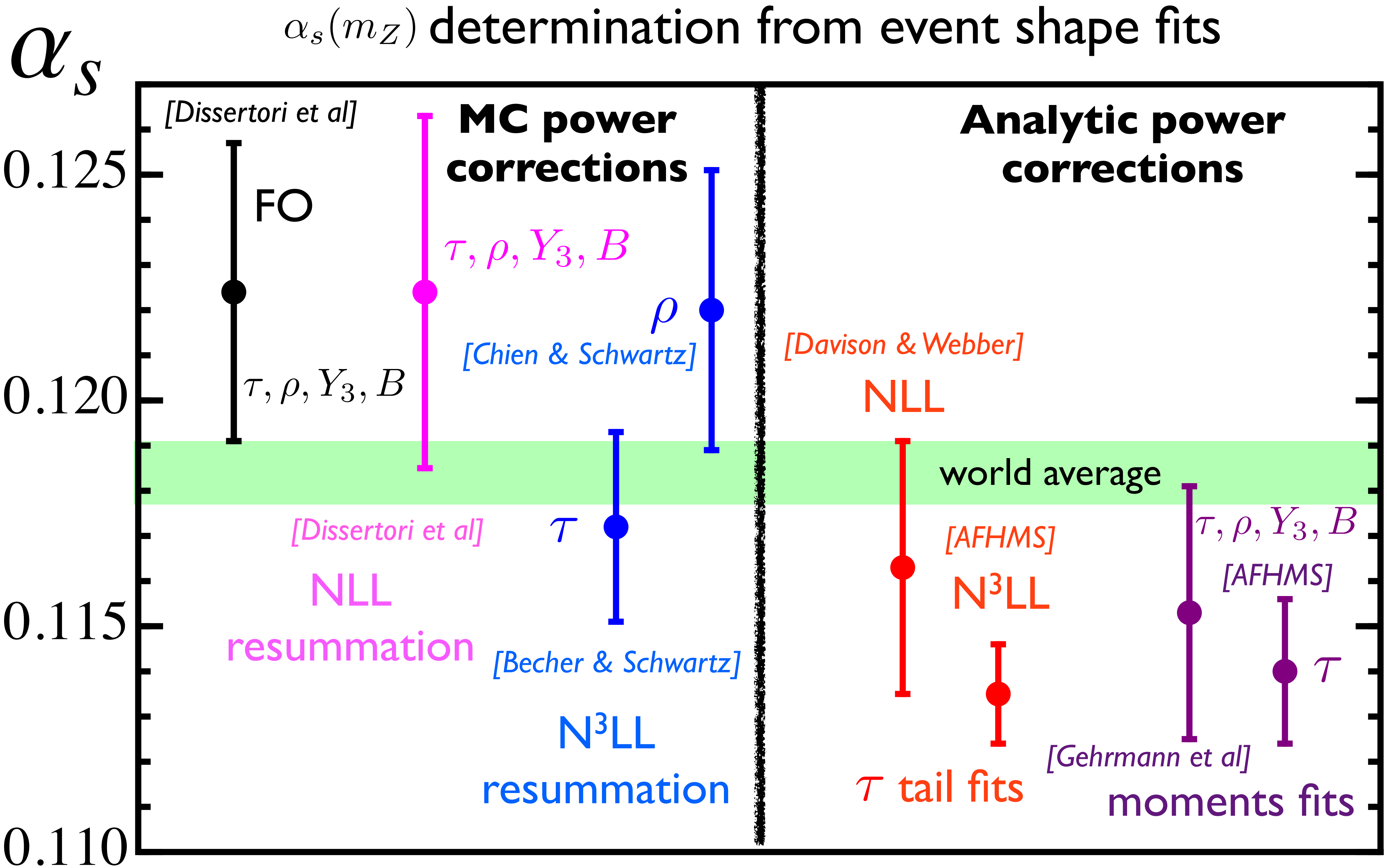
$$\alpha_s(m_Z) = 0.1135 \pm 0.0011$$





α_s determination: compendium

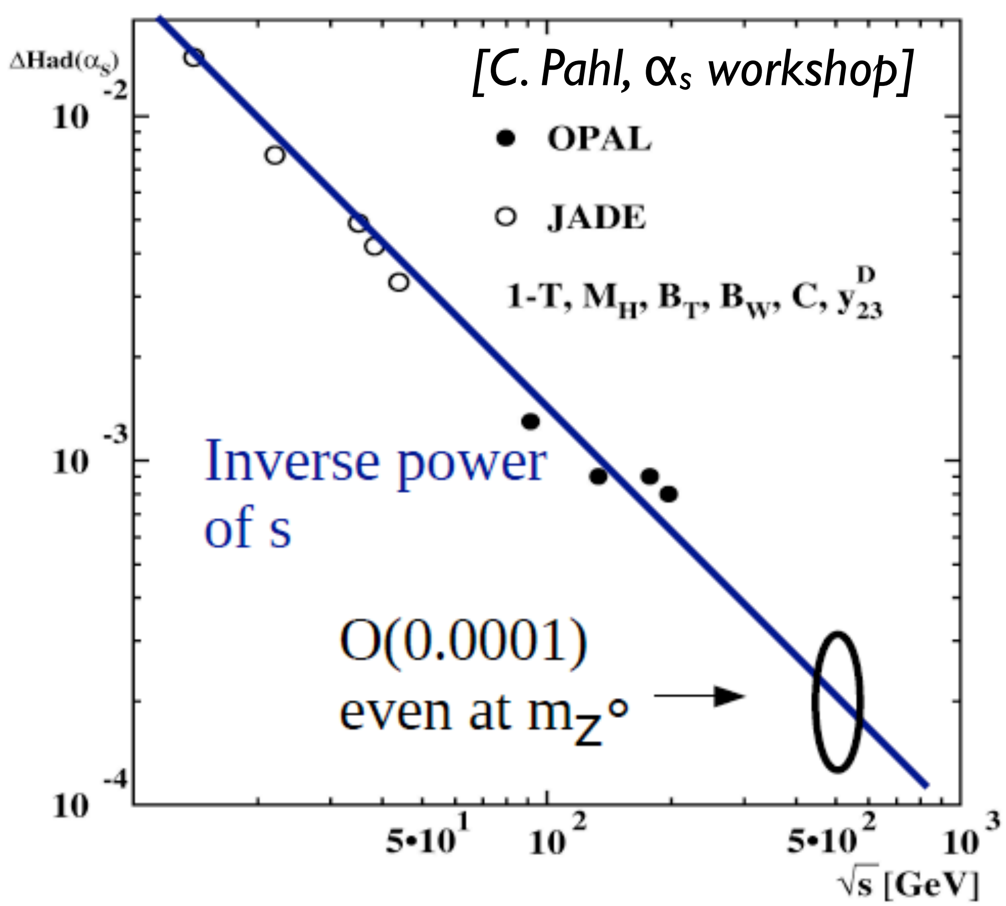
Only consider analysis with 3-loop input



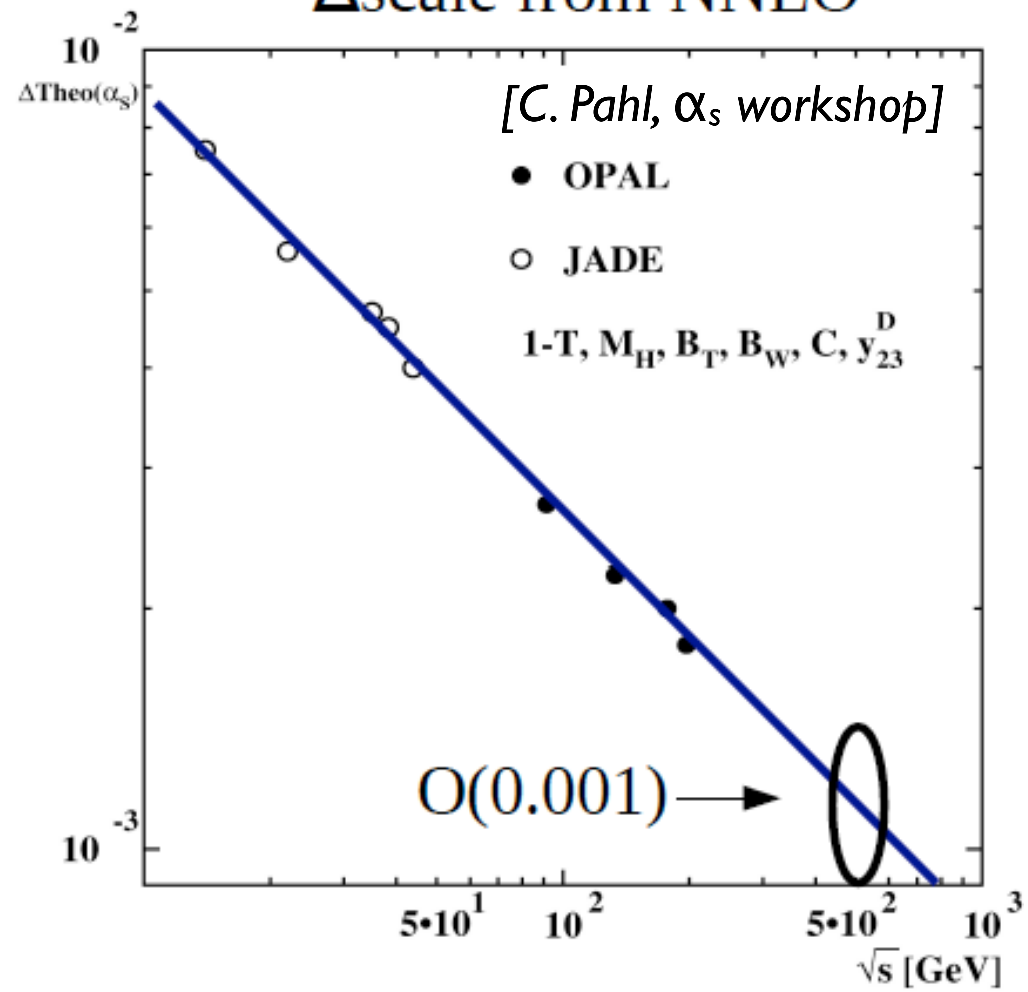
PROSPECTS FOR ILC-CLIC

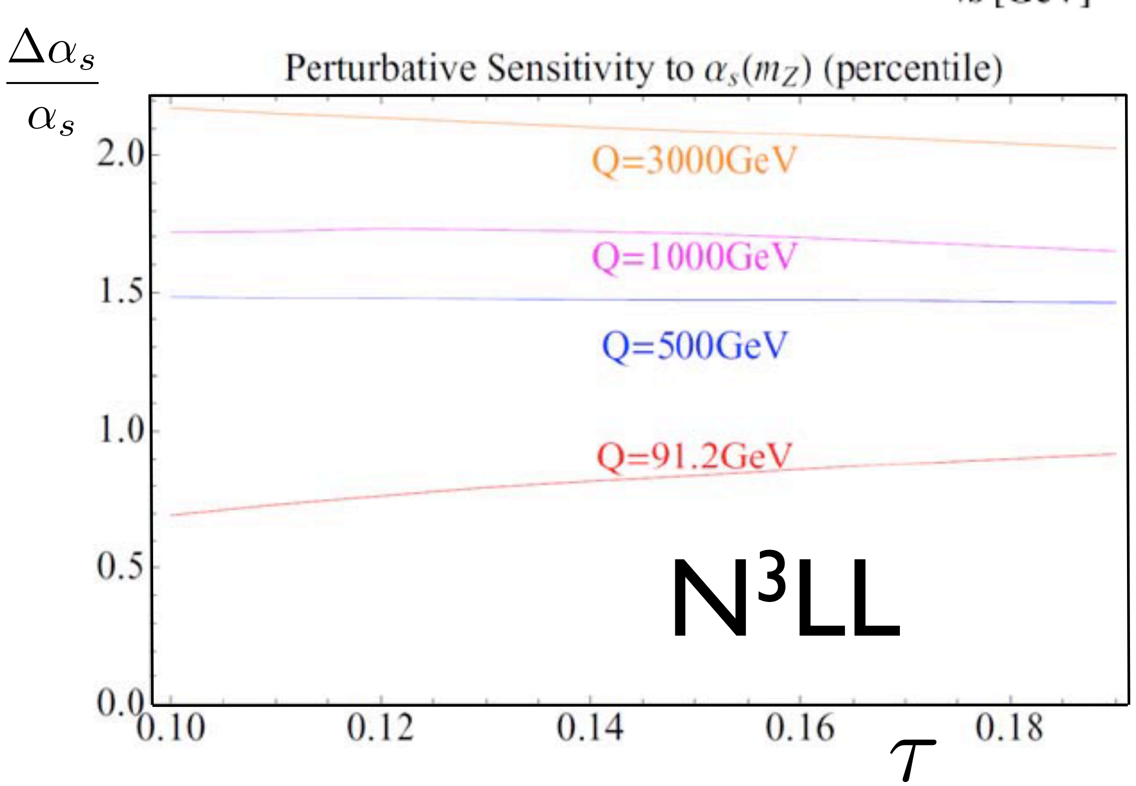
Prospects for ILC-CLIC

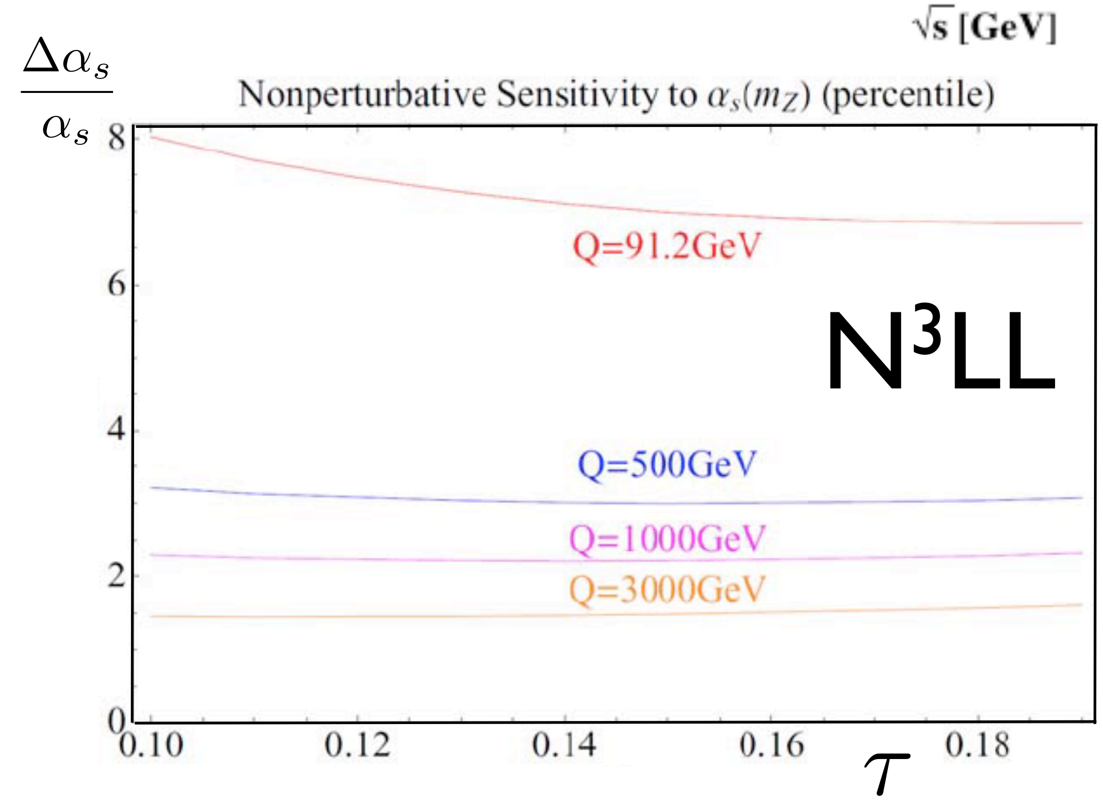
Δhad from NNLO+NLLA



Δscale from NNLO







CONCLUSIONS

CONCLUSIONS

- Huge amount of high-quality event-shape data
- Significant theoretical progress: fixed order, resummation, power corrections, etc...
- High precision α_s determination, low central value...
- Negligible power corrections at ILC-CLIC energies. Possibility to measure top quark mass.
- Looking forward to ILC and CLIC data !!!