Determining the Strong Coupling Constant at NNLO from Jet Observables

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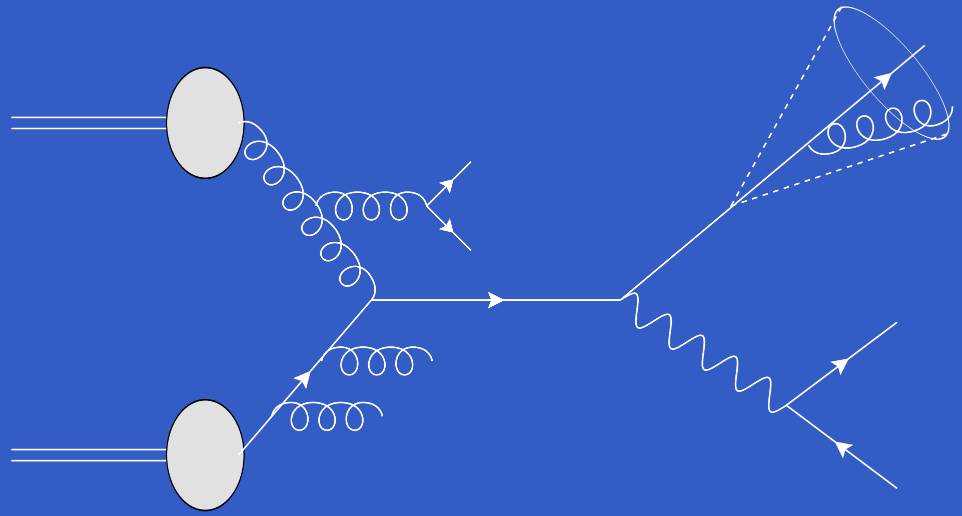
Outline

- Motivation
  - Why study jet observables at NNLO?
  - Jet observables in experiments
    - jet rates
    - event-shape observables
  - Jet observables in theory
- Determinations of α_s
  - α_s from event-shape distributions at NLLA+NNLO
  - α_s from event-shape moments at NNLO
  - α_s from three-jet rates at NNLO
  - Hadronization corrections
- Conclusions

QCD & Jet Observables: why NNLO?

- QCD: very successful theory of strong interactions
- QCD is omnipresent in high energy collisions at many different stages:



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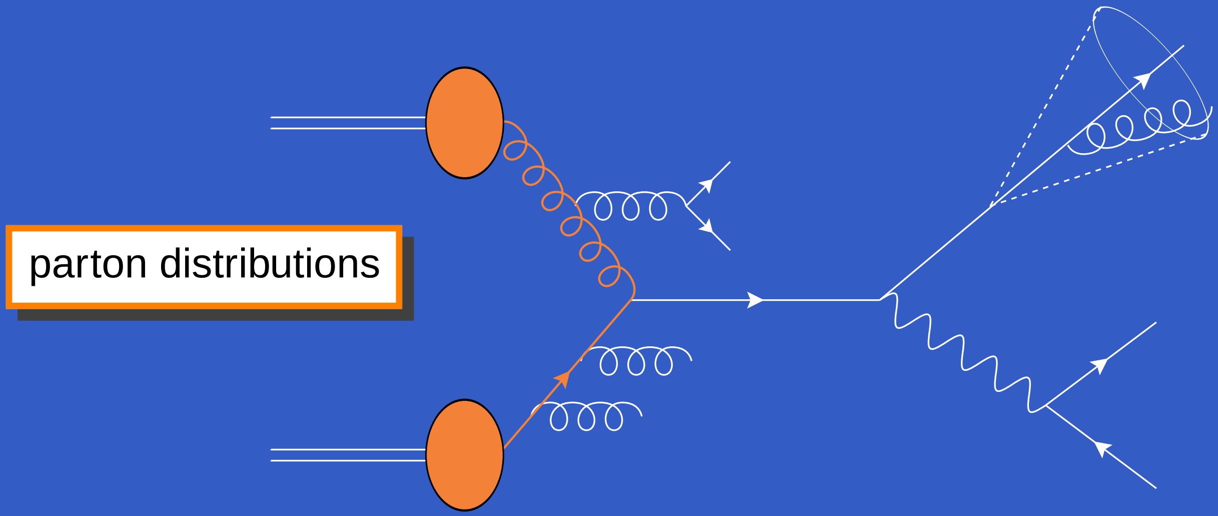

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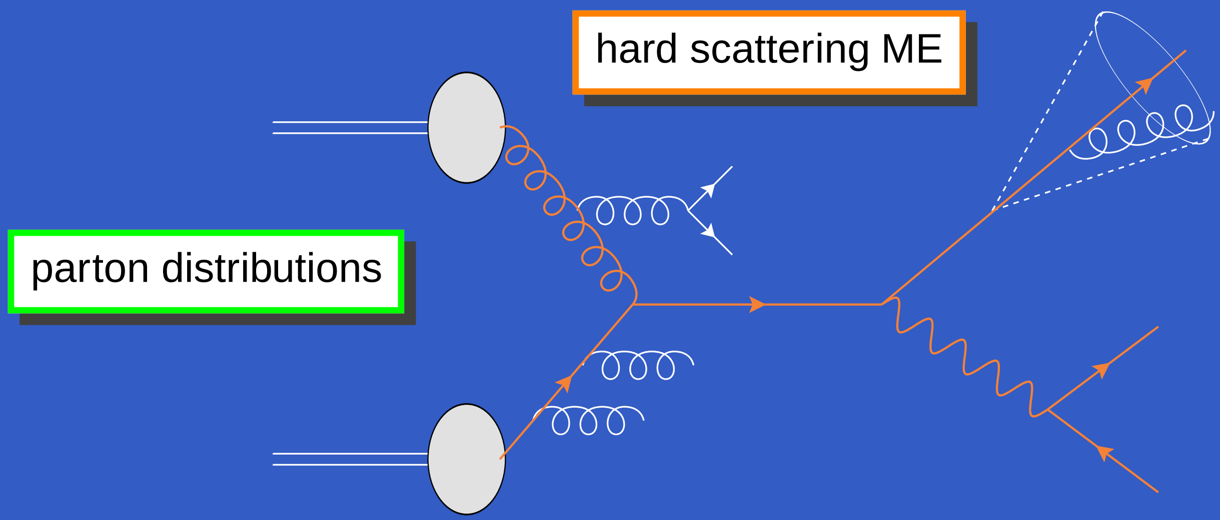

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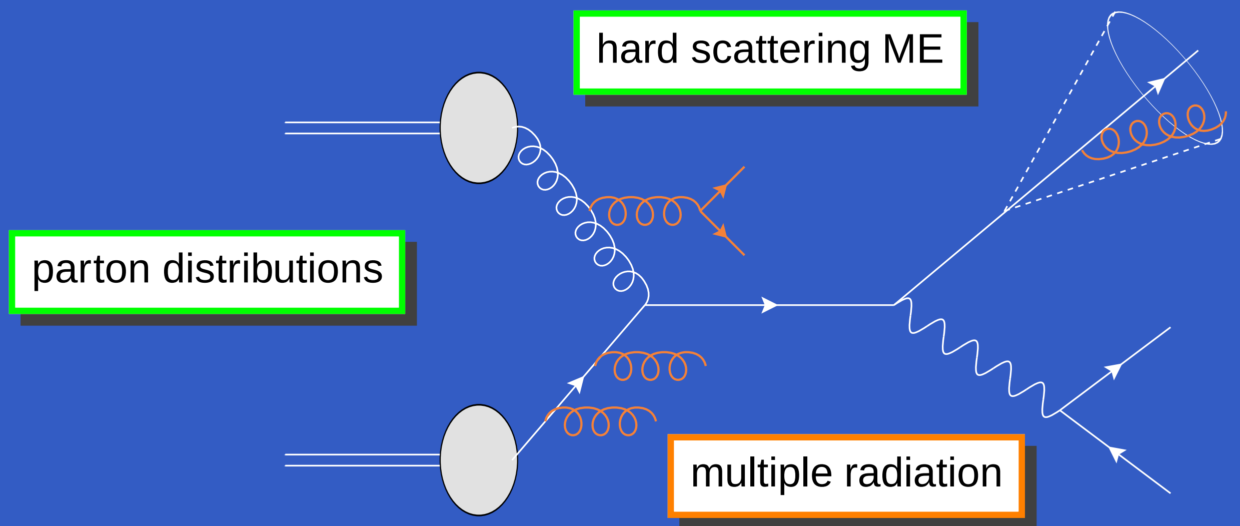

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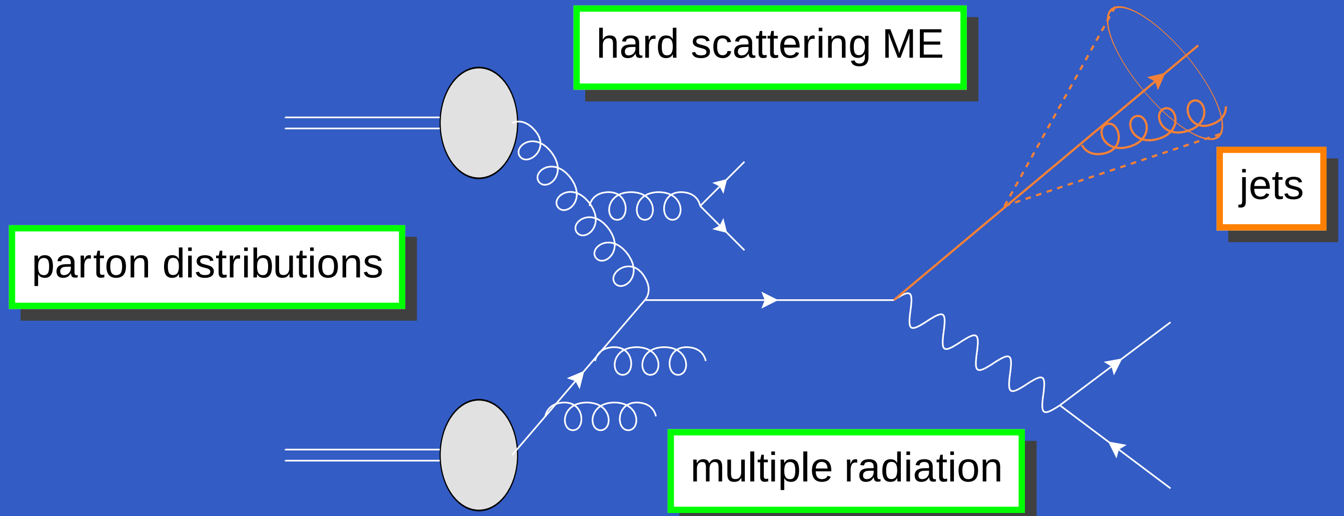

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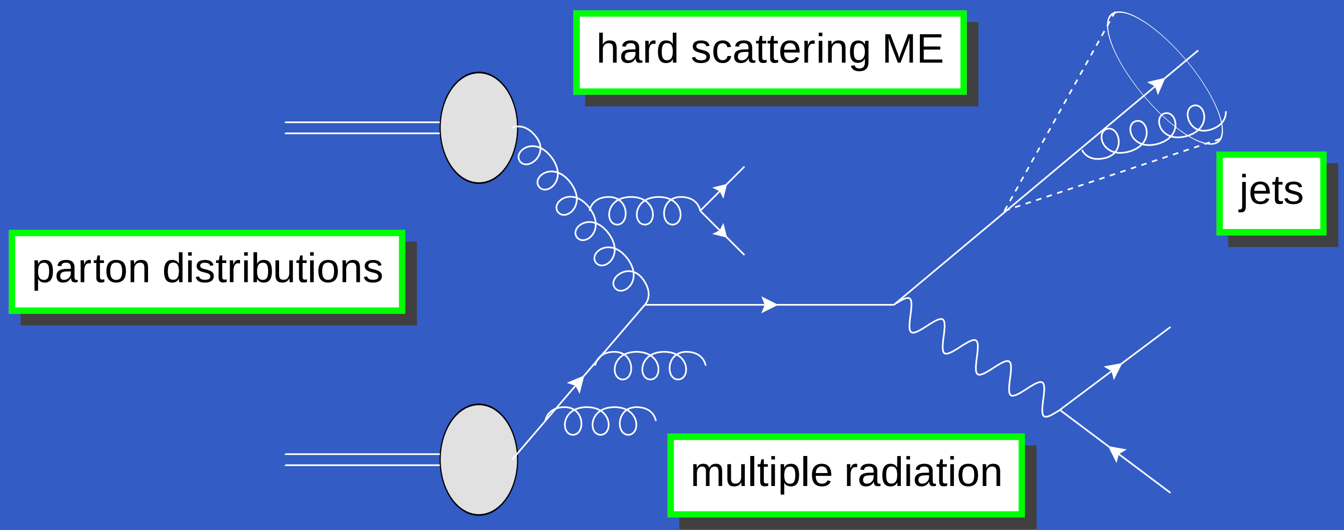
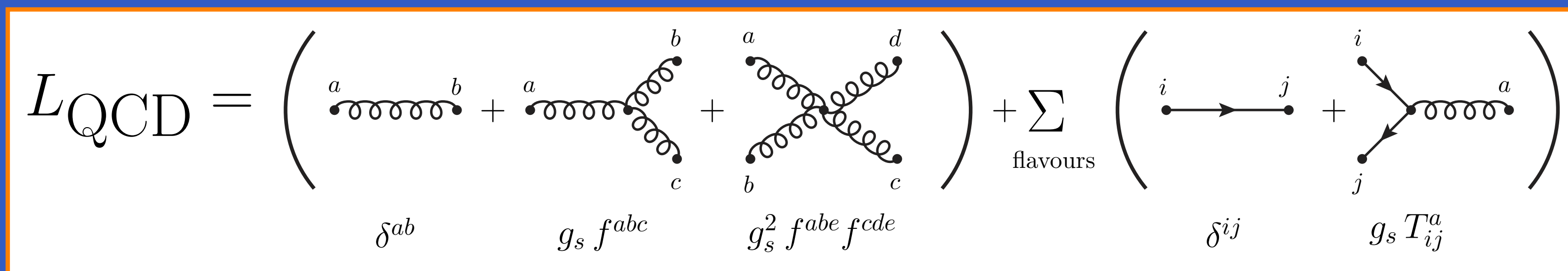


- Need to understand QCD to the highest level of accuracy for
  - interpretation of collider data
  - precision studies: coupling, masses, ...
  - enhance new discovery potential of present collider experiments

Need higher order corrections!

Massless QCD: 1-Parameter Theory

- Apart the quark masses, there is only one free parameter in the QCD lagrangian,



$$\alpha_s \;=\; g_s^2/\,(4\pi)$$

- Can be extracted with good accuracy from e^+e^- data, however
- the value of α_s from LEP data suffers mainly from theoretical scale uncertainty:

$$\alpha_s\,(M_Z) \;=\; 0.1202 \pm 0.0003(\text{stat}) \pm 0.0009(\text{sys}) \pm 0.0013(\text{had}) \pm 0.0047(\text{scale})$$

[LEPQCDWG]

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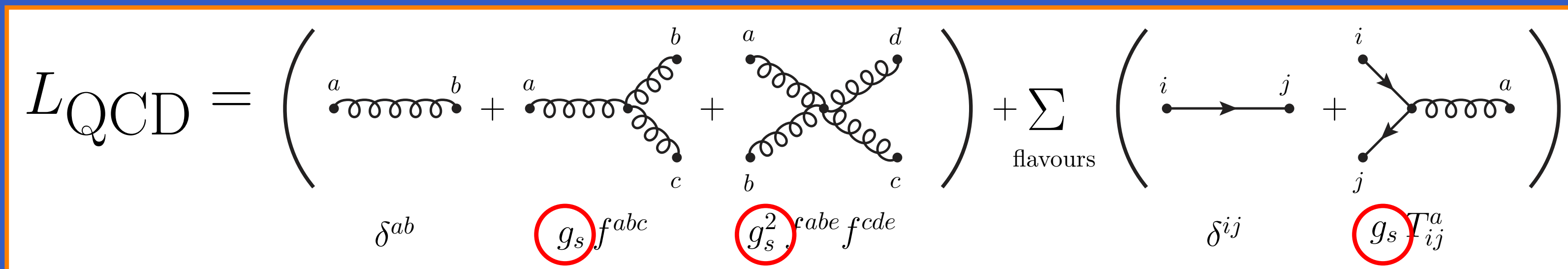

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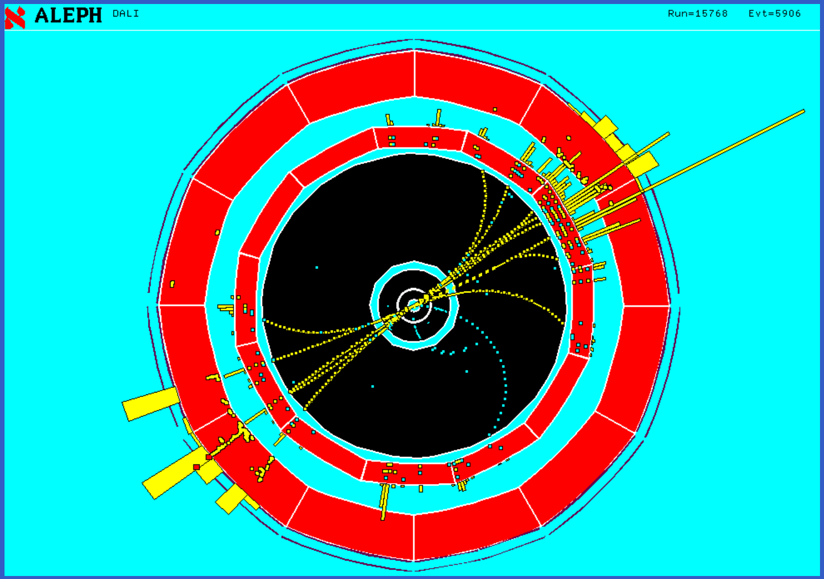
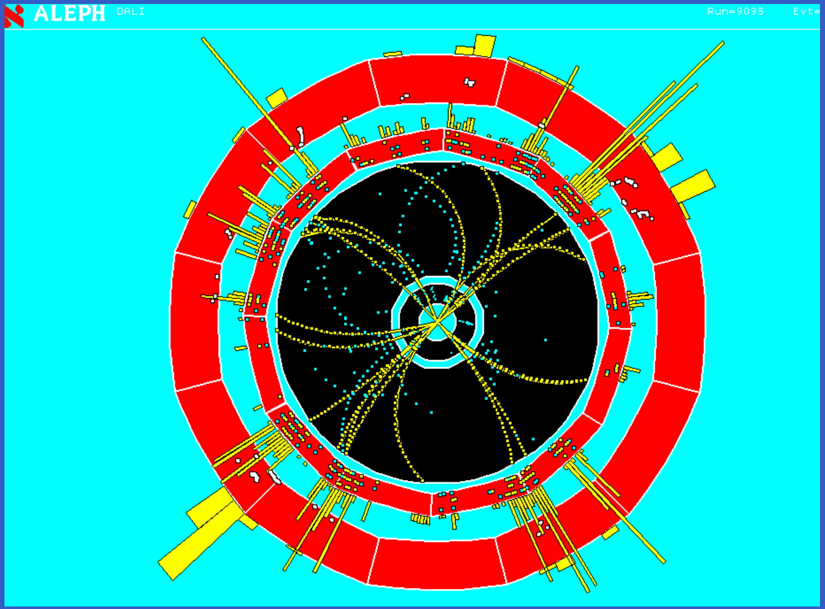
[LEPQCDWG]

Jet Observables in Experiments

- QCD final states visible in form of **JETS**
  - bundle of final-state particles
  - cluster of Hadrons

$\Rightarrow$ Study phenomenology with **JET OBSERVABLES**



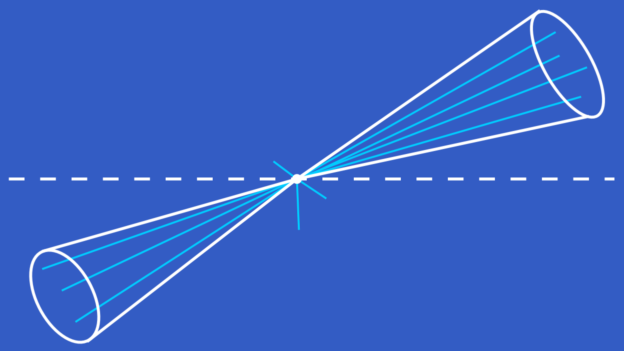


- Possible jet observables
  - number of jets in an event: **jet rates**
  - spatial distribution of particles in an event: **event-shape observables**

Jet Observables in Experiments

- Definition of a jet relies on a jet algorithm,
  - cone algorithms:

    $\rightarrow$ construct stable cones of particles,



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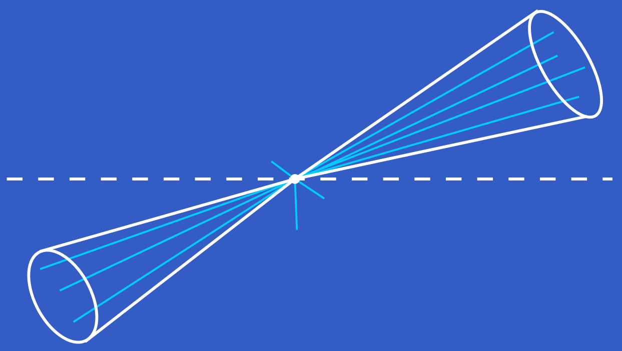
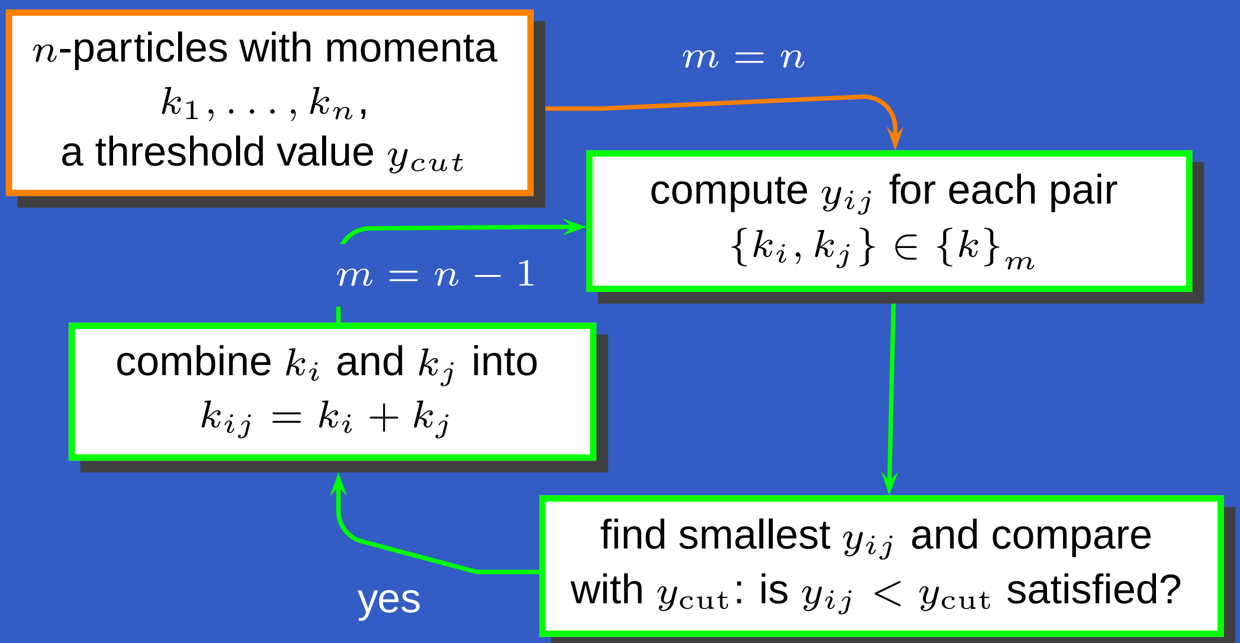
  - recombination algorithms:

    $\rightarrow$ recombination according to distance measure y_{ij} and rec. scheme,



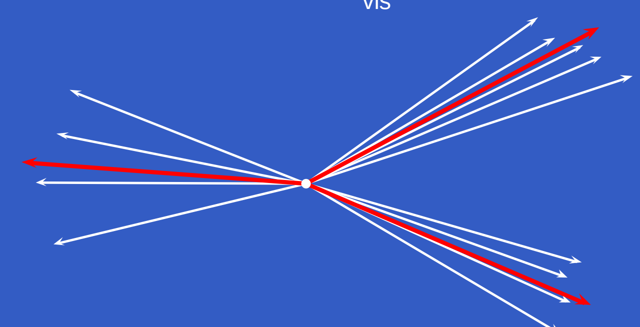


Jade algorithm:

$$y_{ij,J} = \frac{2E_iE_j\left(1-\cos\theta_{ij}\right)}{E^2_{\text{CM}}}$$

Durham algorithm:

$$y_{ij,D} = \frac{2\min\left(E_i^2, E_j^2\right)\left(1-\cos\theta_{ij}\right)}{E^2_{\text{vis}}}$$



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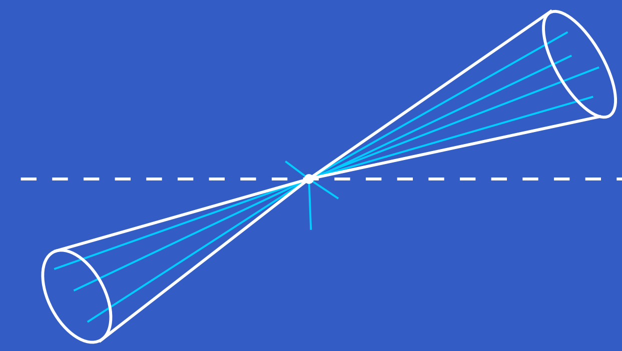

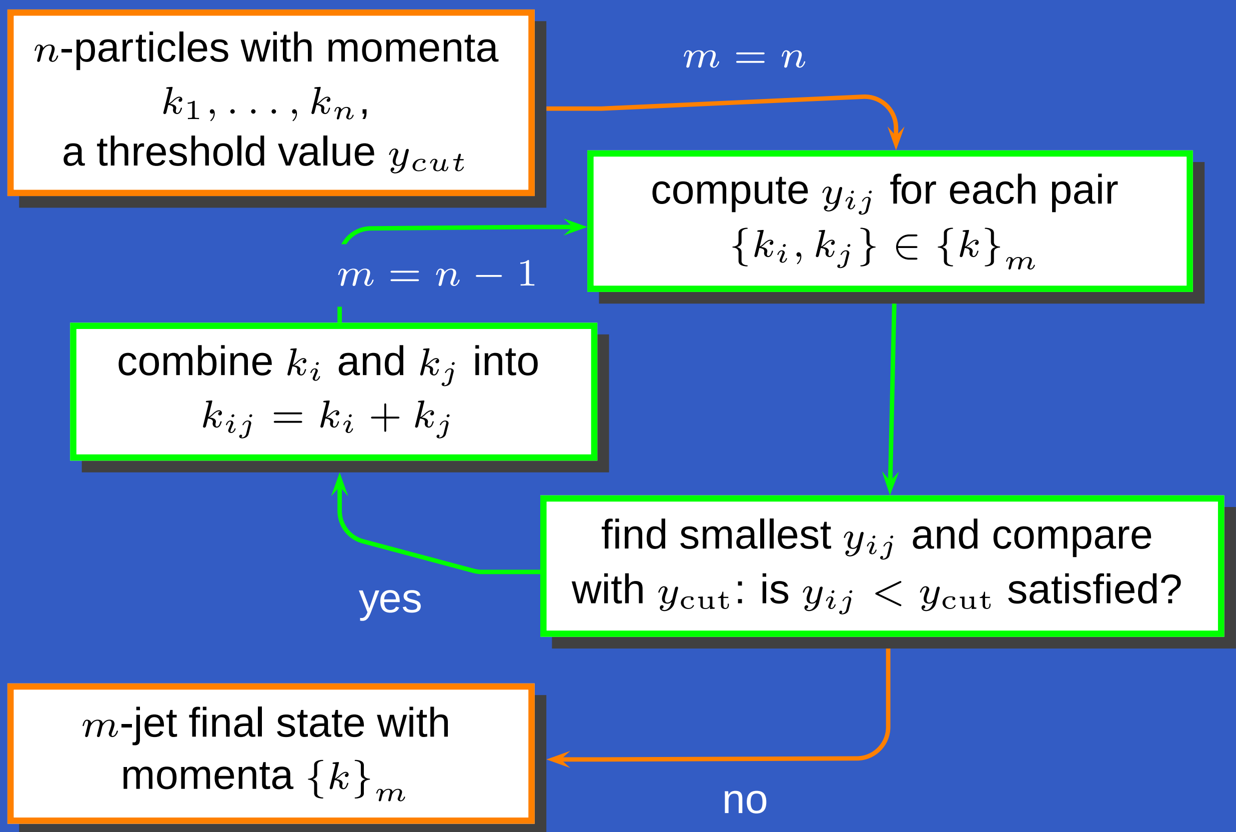

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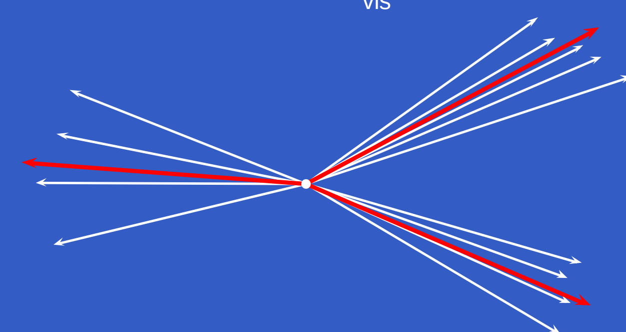


Jet Rates

- Experimental studies based on jet rates:

$$R_n = \frac{n - \text{jet cross section}}{\text{total hadronic cross section}}$$

with $n = 2, 3, 4, 5$.

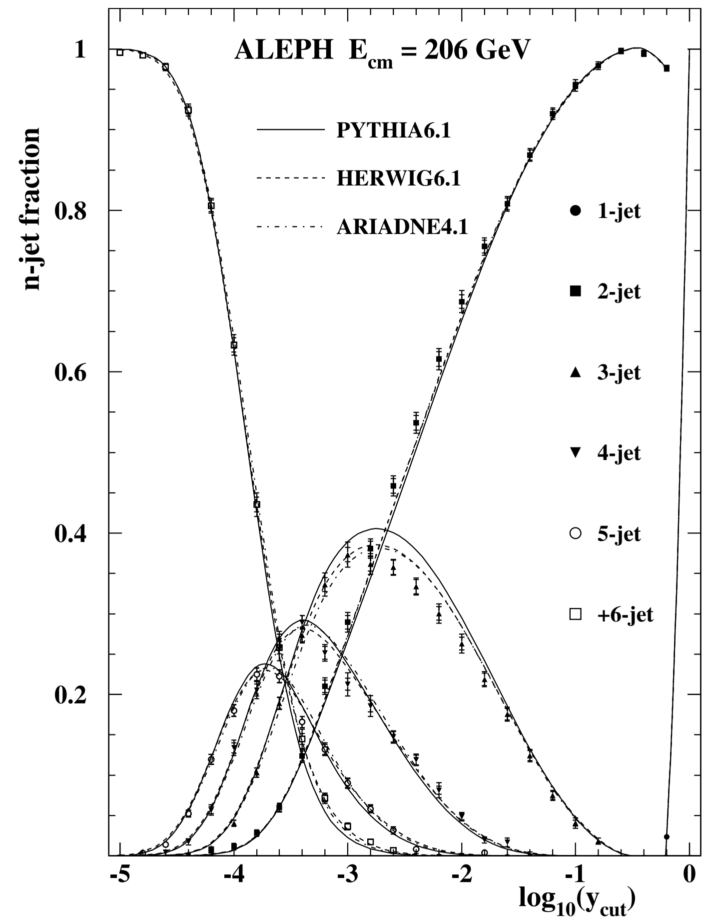


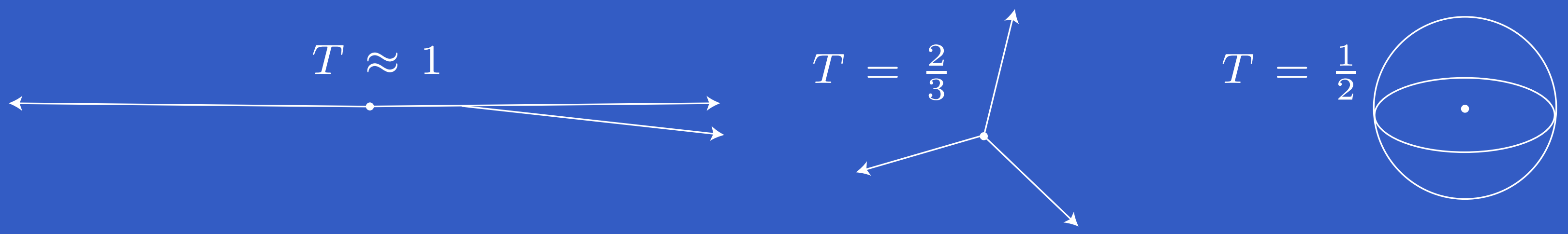
Fig. 7. Measured n-jet fractions for $n = 1, 2, 3, 4, 5$ and $n \geq 6$ and the predictions of Monte Carlo models, at a centre-of-mass energy of 206 GeV

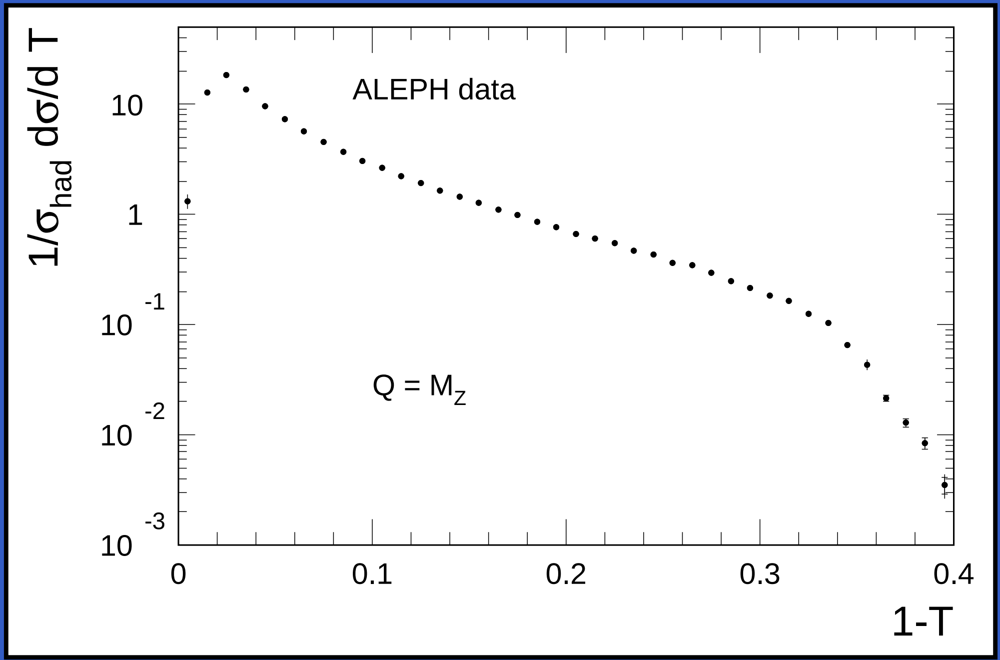
[ALEPH Collaboration, 2004]

Event-Shape Observables

- Parametrize geometrical properties of an event,
- canonical example: Thrust

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$





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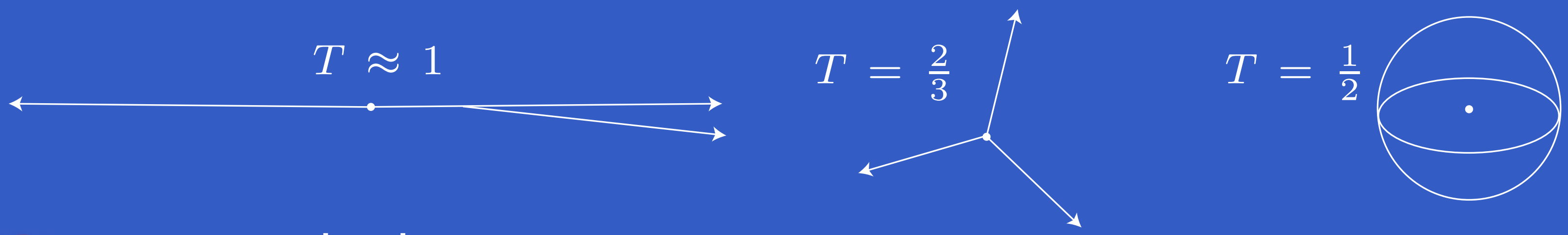


- LEP standard set:
  - Thrust: [Brandt,Farhi]

    $$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$

  - Heavy jet mass: [Clavelli,Wyler]

    $$\rho = \max_i \frac{\left(\sum_{n \in H_i} |\vec{p}_n|\right)^2}{E^2_{\text{tot-vis.}}}$$

  - C-parameter: EV of tensor [Parisi]

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

  - Jet Broadenings: [Rakow,Webber]

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

    $$B_T = B_1 + B_2$$

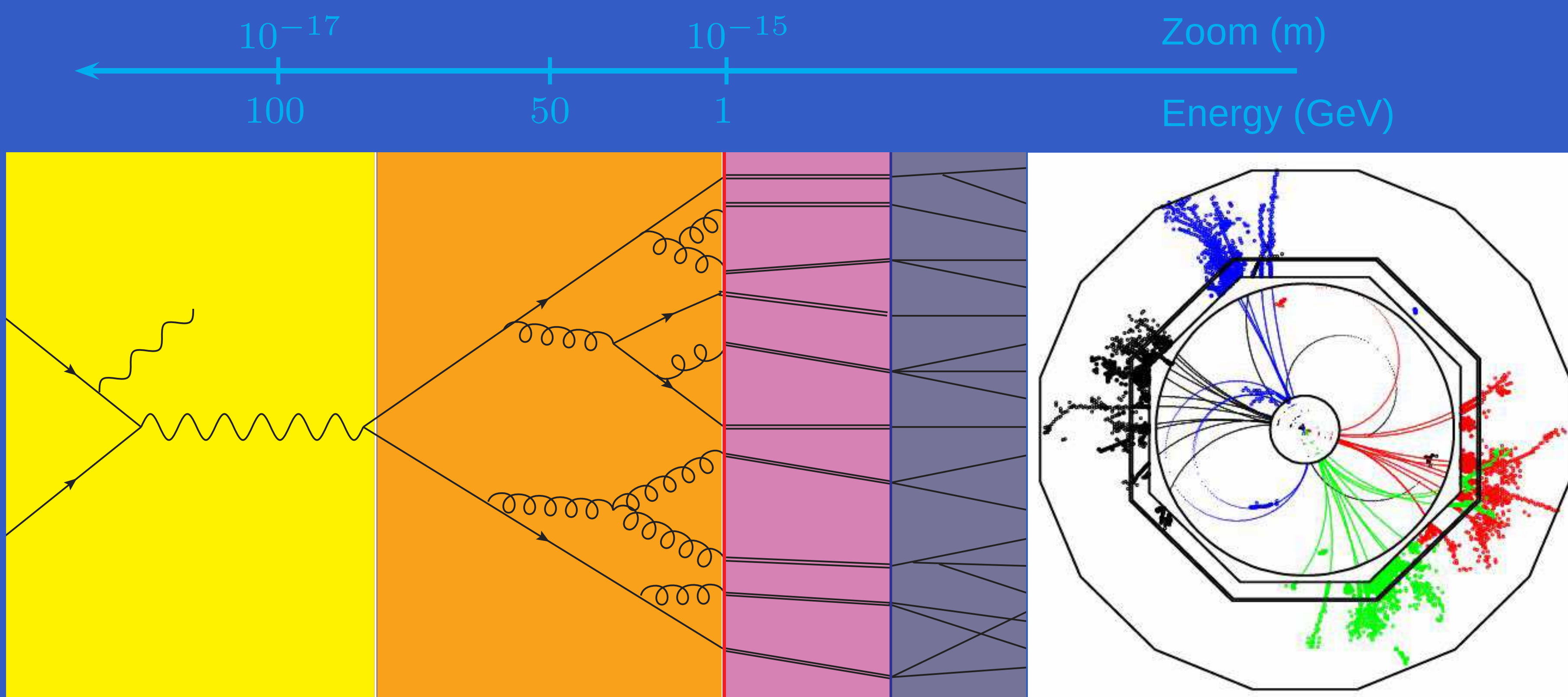
    $$B_W = \max(B_1, B_2)$$

  - Durham $2 \to 3$ jet parameter: Y_3

    [Catani,Dokshitzer,Olsson,Turnock,Webber]

QCD and Jets

- How are Jets of final state particles related to QCD?



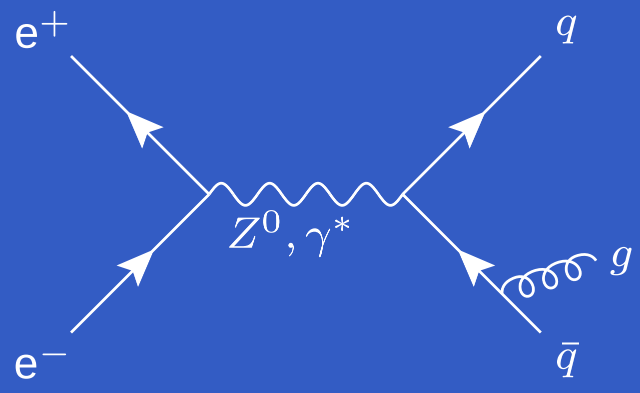
Dynamics described by: parton level | hadron level | detector level

QUARKS AND GLUON | HADRONS | HADRONS

Regime:

PERTURBATIVE QCD | NON-PERTURBATIVE QCD

3 Jets at Leading Order



$$\frac{d\sigma}{dE_g\, d\cos\theta_{\bar{q}g}} \propto \sigma_0 \frac{\alpha_s}{2\pi} \frac{1}{E_g(1-\cos\theta_{\bar{q}g})}$$

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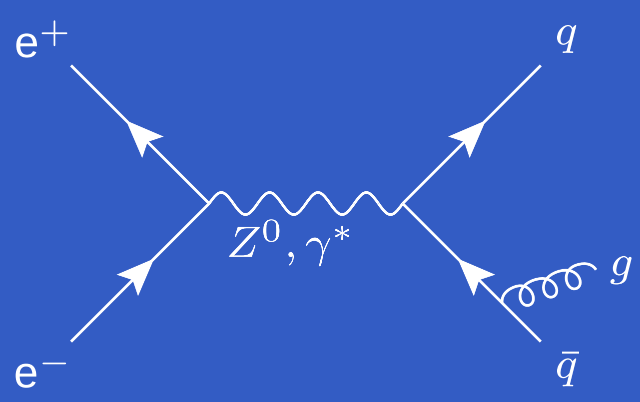

Born cross section for $Z, \gamma \to q\bar{q}$

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Bremsstrahlung:
enhancement for $E_g \to 0$
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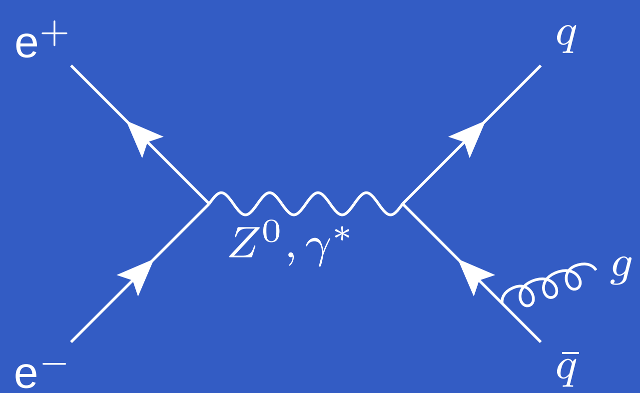

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- Jet rates and event-shape observables:
  - **deviation from 2-jet configuration is proportional to α_s**
  - **enhancement in 2-jet region due to soft and collinear emissions**
  - **suited also for theoretical pQCD since many are IR and collinear safe**

3 Jets at NNLO

- Cross section for event shape y at NNLO described by:
  $\left(y\ :\ \text{event-shape variable},\ \bar{\alpha}_s = \frac{\alpha_s}{2\pi},\ x_\mu = \frac{\mu}{Q}\right)$:

$$\frac{1}{\sigma_{\rm had}}\frac{{\rm d}\sigma}{{\rm d}y}(y,Q,\mu) = \underbrace{\bar{\alpha}_s(\mu)\frac{{\rm d}A}{{\rm d}y}(y)}_{LO} + \underbrace{\bar{\alpha}_s^2(\mu)\frac{{\rm d}B}{{\rm d}y}(y,x_\mu)}_{NLO} + \underbrace{\bar{\alpha}_s^3(\mu)\frac{{\rm d}C}{{\rm d}y}(y,x_\mu)}_{NNLO} + \mathcal{O}(\bar{\alpha}_s^4)\,.$$

LO	$\gamma^* \to q\bar{q}g$	tree level	NNLO	$\gamma^* \to q\bar{q}g$	two loop
				$\gamma^* \to q\bar{q}gg$	one loop
NLO	$\gamma^* \to q\bar{q}g$	one loop		$\gamma^* \to q\bar{q}q\bar{q}$	one loop
	$\gamma^* \to q\bar{q}gg$	tree level		$\gamma^* \to q\bar{q}q\bar{q}g$	tree level
	$\gamma^* \to q\bar{q}q\bar{q}$	tree level		$\gamma^* \to q\bar{q}ggg$	tree level

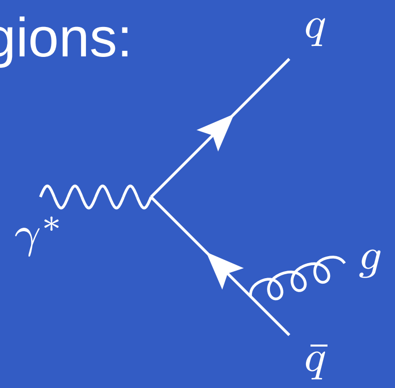
- Need subtraction scheme at NNLO: antenna subtraction

  [Gehrmann, Gehrmann-De Ridder, Glover]

- Coefficient functions $\frac{dA}{dy}$, $\frac{dB}{dy}$, $\frac{dC}{dy}$ are functions of $\log\left(\frac{1}{y}\right)$,

Fixed Order Calculations

- Logarithms are originated from integration over soft and collinear regions:



$$\frac{1}{\sigma_{\rm had}}\frac{{\rm d}\sigma}{{\rm d}y} \propto \sigma_0 \frac{\alpha_s}{2\pi}\frac{1}{E_g\left(1-\cos\theta_{\bar{q}g}\right)}$$

Integral over phase space gives:

$$\frac{d\sigma}{dy} \propto \int \frac{dE_g}{E_g}\frac{d\theta^2_{\bar{q}g}}{\theta^2_{\bar{q}g}}\delta\left(y - y\left(E_g,\theta_{\bar{q}g}\right)\right) \propto \frac{1}{y}\,\log\left(\frac{1}{y}\right)$$

- **They describe the enhancement due to soft and collinear emissions.**
- **In phase space regions where** $\alpha_S \log(1/y) \approx 1 \longrightarrow$ **need resummation.**
- **Matching of fixed order and resummed calculation can be performed.**

Recent Theoretical Progress

- State-of-the-art at LEP times (until 2007):
  - fixed NLO calculations, [Ellis, Ross, Terrano; Kunszt, Nason; Giele, Glover; Catani, Seymour]
  - NLL resummation, [Catani, Trentadue, Turnock, Webber; Banfi, Salam, Zanderighi].

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  - NLL resummation, [Catani, Trentadue, Turnock, Webber; Banfi, Salam, Zanderighi].
- Very important progress in the last three years:
  - for all event-shape observables (in particular LEP standard set):
    - fixed NNLO computation of jet rates and event-shape observables [Gehrmann, Gehrmann-De Ridder, Glover, Heinrich; Weinzierl]
    - matching of NNLO+NLLA [Gehrmann, Stenzel, G.L.]
    - non-perturbative corrections to moments at NNLO [Gehrmann, Jaquier, G.L.]
  - for single event shapes:
    - T: N^3LL resummation in SCET and matching with NNLO, [Becher, Schwartz]
    - T: non-perturbative corrections to NNLO+NLLA distribution, [Davison, Webber]
    - T: power corrections to N^3LL+NNLO, [Abbate, Fickinger, Hoang, Mateu, Steward]
    - MH: N^3LL resummation in SCET and matching with NNLO, [Chien, Schwartz]

Determination of α_S

- Recent works:
  - α_S fit from NNLO and NNLO+NLLA distributions (ALEPH), [Dissertori, Gehrmann-De Ridder, Gehrmann, Glover, Heinrich, G. L., Stenzel.]
  - α_S fit from NNLO and NNLO+NLLA distributions (JADE), [Bethke, Kluth, Pahl, Schieck and JADE Collaboration.]
  - α_S fit using NNLO for moments (JADE/OPAL), [Gehrmann, Jaquier, G. L.]
  - α_S fit with NNLO+NLLA + pc. for T (LEP/PETRA/SLD/AMY), [Davison, Webber]
  - α_S fit with N^3LLA for T (ALEPH), [Becher, Schwartz]
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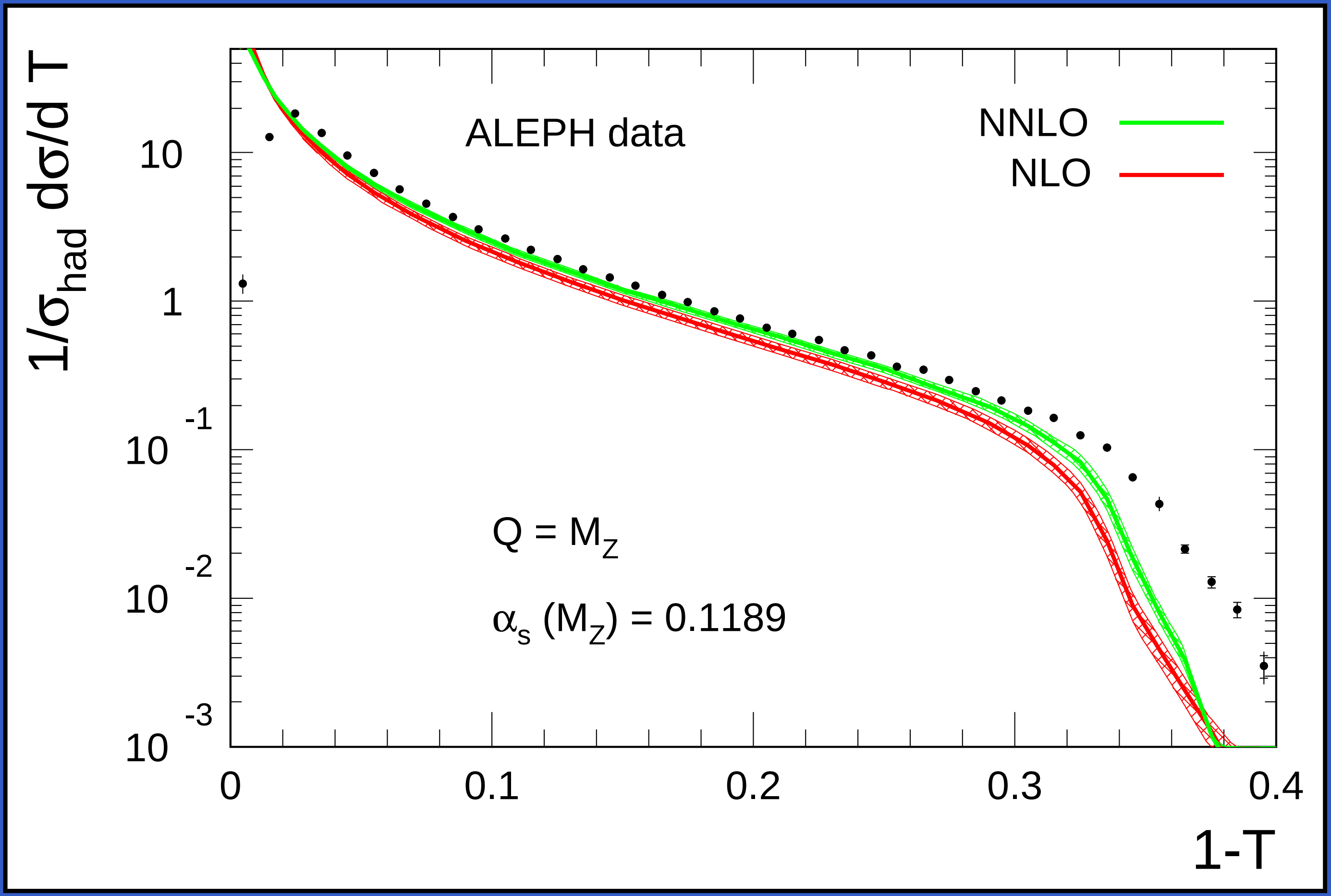
α_s from

Event-Shape Distributions

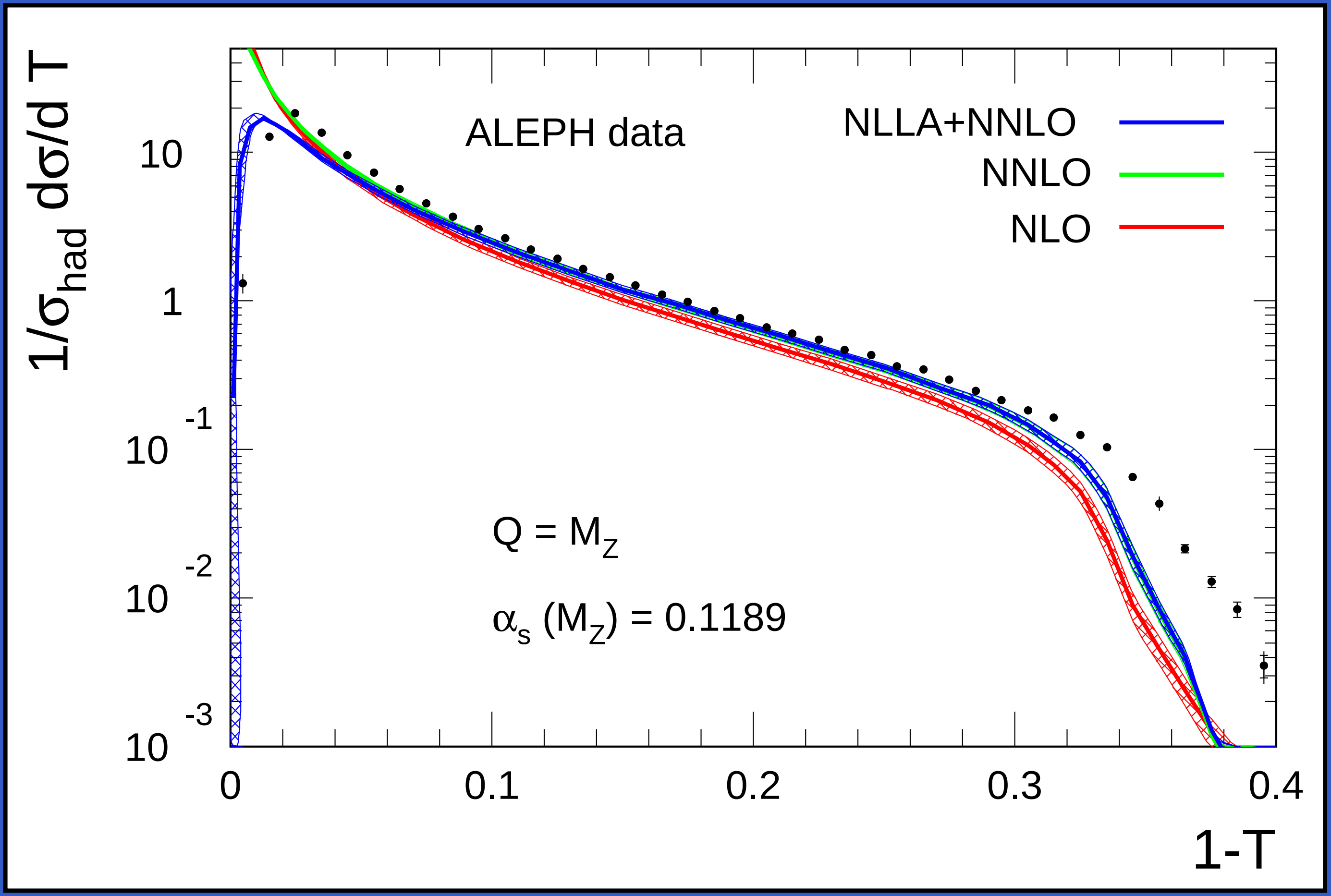
Thrust: Theory vs Data

- NNLO result describes data better than NLO



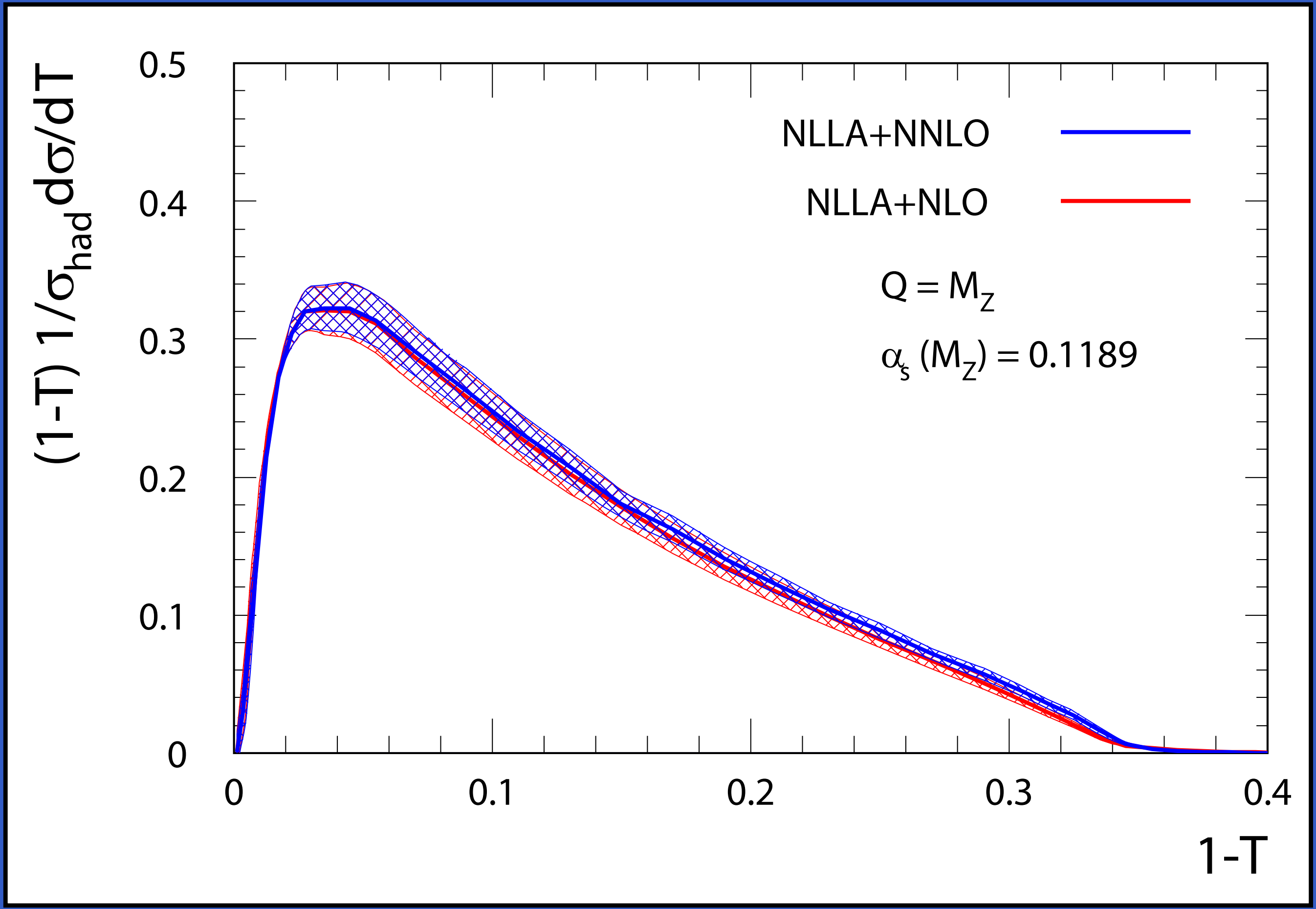
Thrust: Theory vs Data

- Addition of resummation improves description in 2-jet region



Thrust: Theory vs Data

- Scale dependence reduced by 20-40% in 3-jet region



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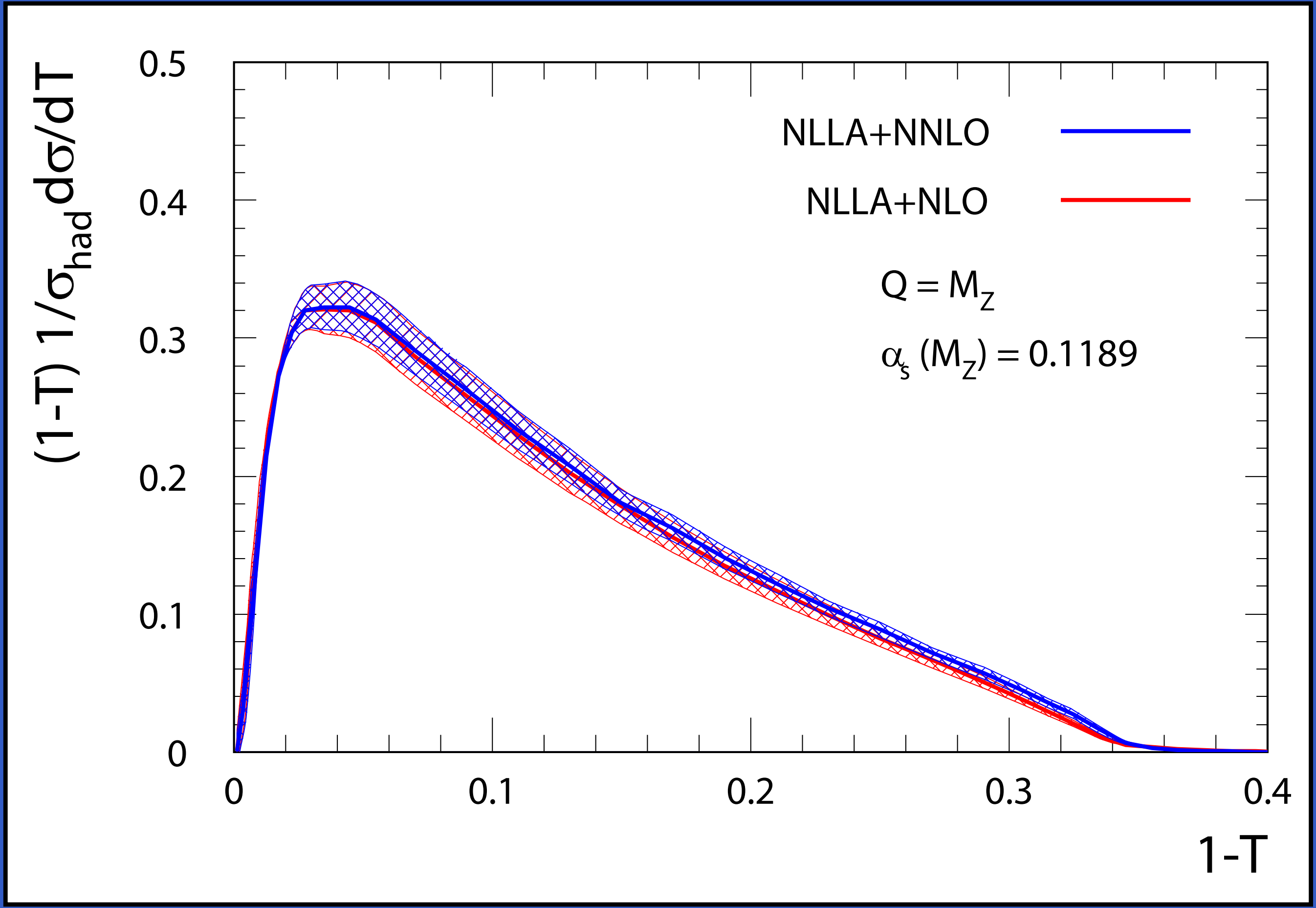
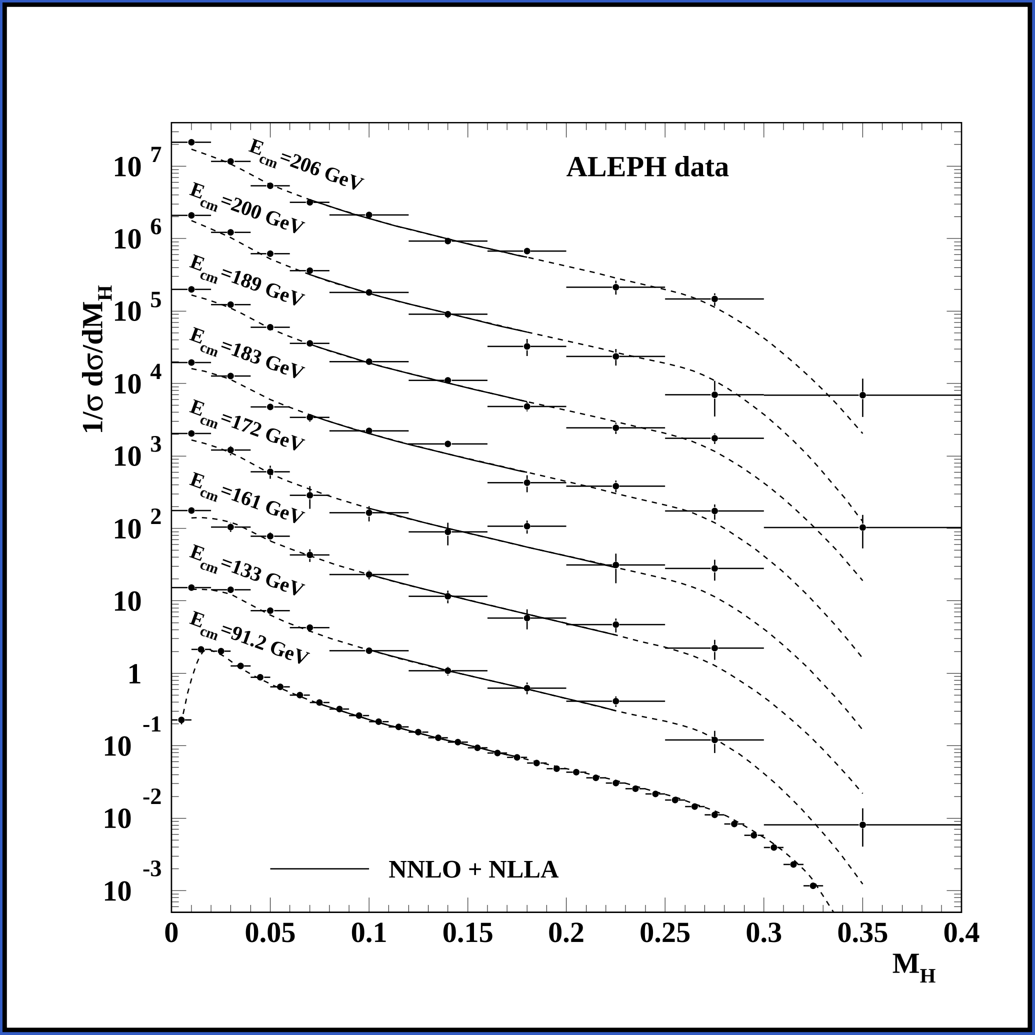


Can perform fit: 6 event-shape observables at 8 different energies

Determination of α_S: NLLA+NNLO fits

- data are fit in the central part of the event shape distribution,
- only statistical uncertainties are included in the χ^2.
- good fit quality (but includes still large statistical uncertainties of C-coefficient)



Uncertainties in α_S from distributions

- Experimental uncertainties:
  - track reconstr., event selection, detector corrections: cut variations or MC
  - background and ISR (LEP2),

  $\sim 1\%$

- Hadronization uncertainties:
  - difference between various models for hadronization:

    Pythia (String frag.), Herwig (Cluster frag.), Ariadne (Dipole + String frag.),

  $\sim 0.7 - 1.5\%$

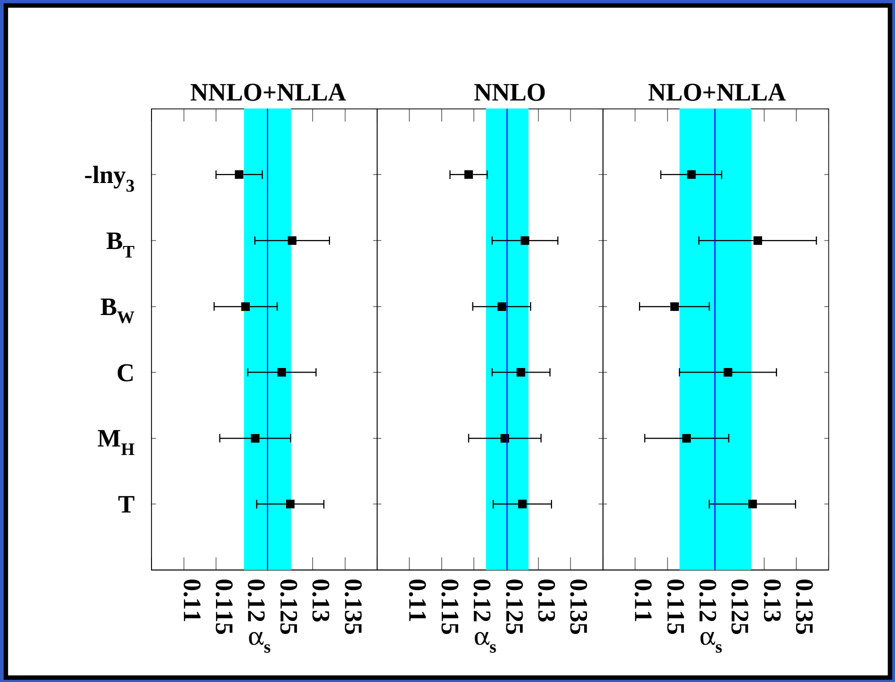
- Theoretical uncertainties (pQCD and resummation):
  - variation of theoretical parameters: $x_\mu, \ldots$
  - uncertainty for b-quark mass correction.

  $\sim 3.5 - 5\%$

- Uncertainty band method to estimate missing higher orders

  [Ford, Jones, Salam, Stenzel, Wicke.]

Extraction of α_s: NNLO+NLLA

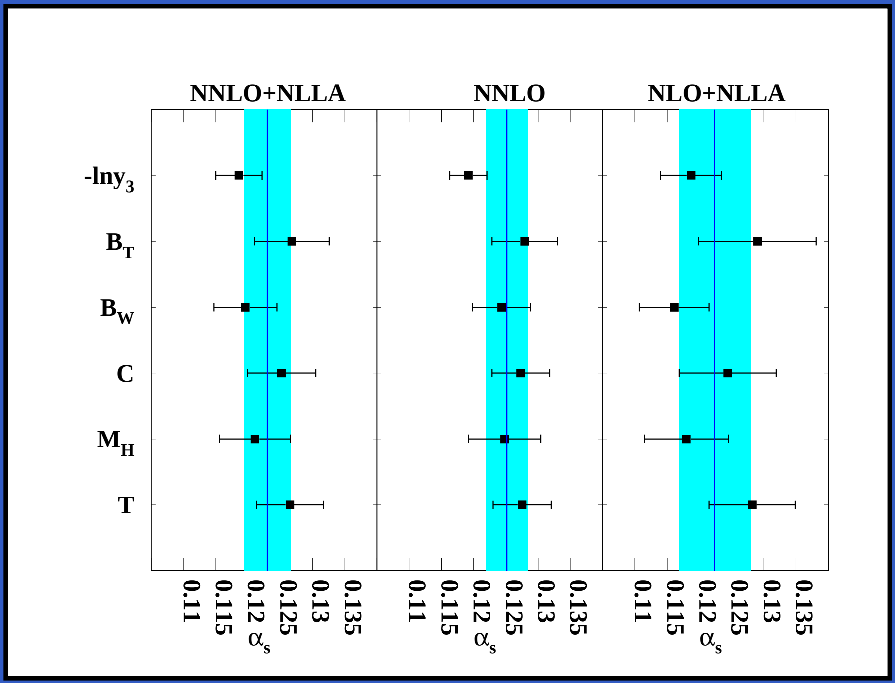


- reduced scatter among variables at NNLO
- reduced scale uncertainty compared to NLO+NLLA
- scale uncertainty increase from NNLO to NNLO+NLLA $\rightarrow$ two-loop running not compensated in resummation

$$\alpha_s\,(M_Z) = 0.1224 \pm 0.0009(\text{stat.}) \pm 0.0009(\text{exp.}) \pm 0.0012(\text{had.}) \pm 0.0035(\text{theo.})$$

- Two classes of observables:
  - T, C-par., B_{tot}: higher fit result $\rightarrow$ sizeable missing higher order
  - -$\ln y_3$, B_w, M_H: lower fit result, $\rightarrow$ good convergence of pert. expansion

Extraction of α_s: NNLO+NLLA



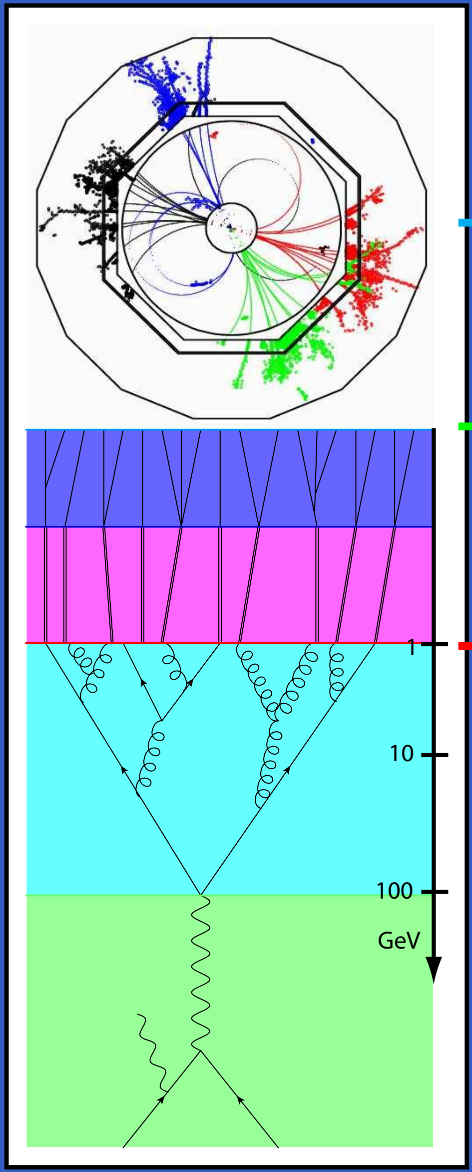
- reduced scatter among variables at NNLO
- reduced scale uncertainty compared to NLO+NLLA
- scale uncertainty increase from NNLO to NNLO+NLLA $\rightarrow$ two-loop running not compensated in resummation

$$\alpha_s(M_Z) = 0.1224 \pm 0.0009(\text{stat.}) \pm 0.0009(\text{exp.}) \pm 0.0012(\text{had.}) \pm 0.0035(\text{theo.})$$

- Two classes of observables:
  - T, C-par., B_{tot}: higher fit result $\rightarrow$ sizeable missing higher order
  - $-\ln y_3$, B_w, M_H: lower fit result, $\rightarrow$ good convergence of pert. expansion

What about hadronization corrections?

Determination of α_s: Hadronization

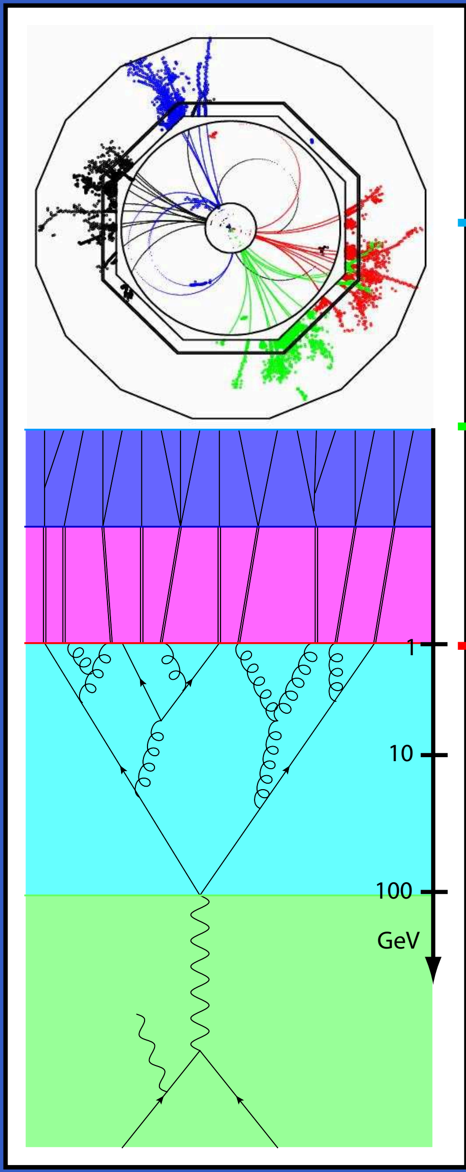


detector level

hadron level

parton level

Determination of α_s: Hadronization



detector level

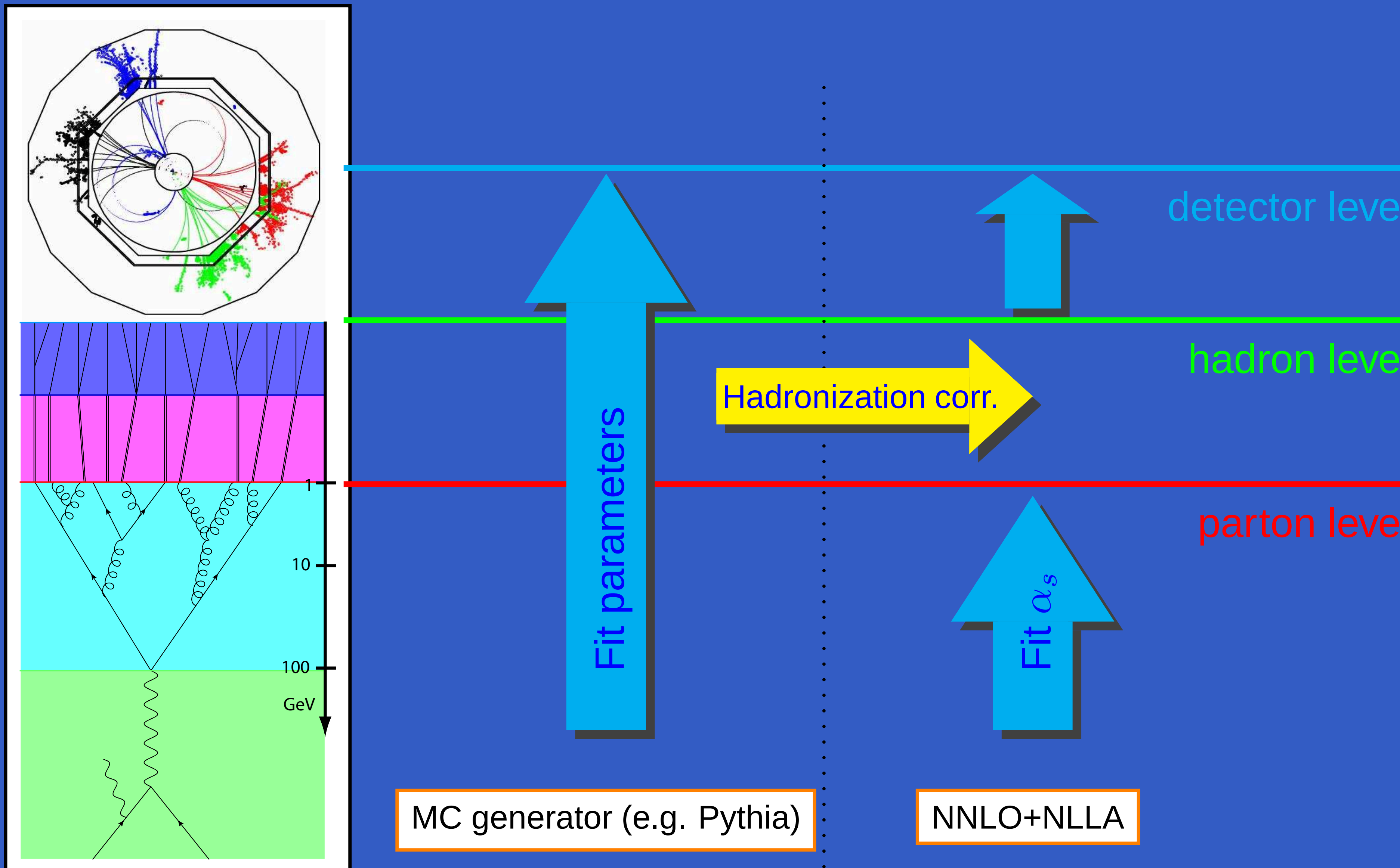
hadron level

parton level

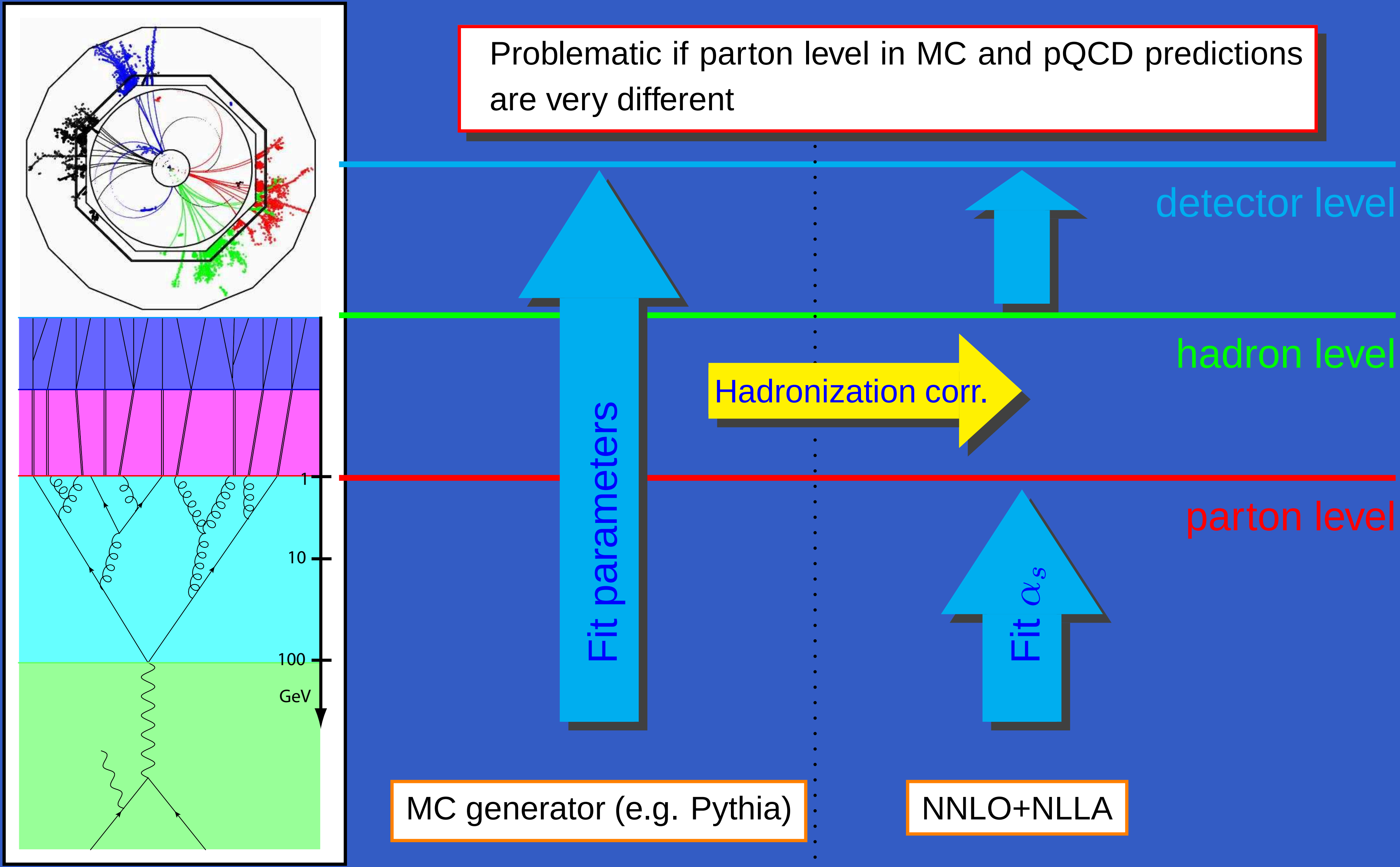
Fit parameters

MC generator (e.g. Pythia)

Determination of α_s: Hadronization

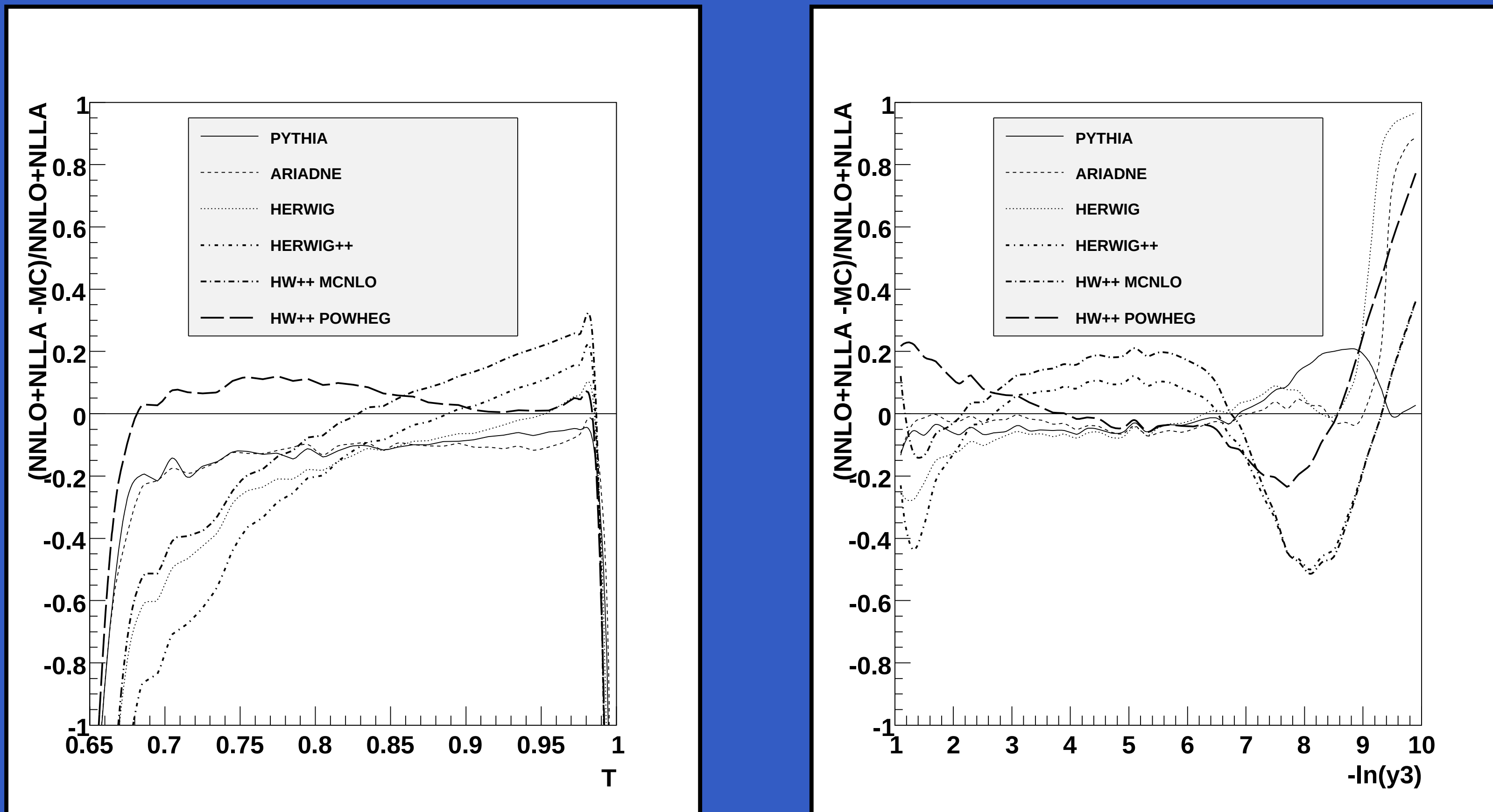


Determination of α_s: Hadronization



Determination of α_s: Hadronization

- Comparison with modern MC generators:



$\alpha_s\,(M_z)$	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
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

Determination of α_s: Hadronization

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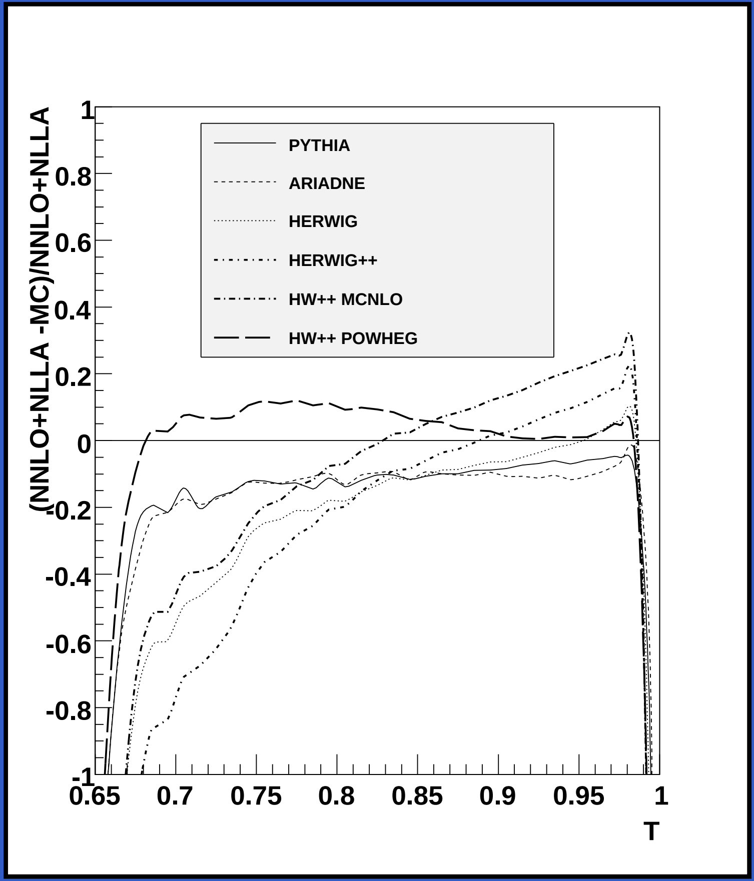
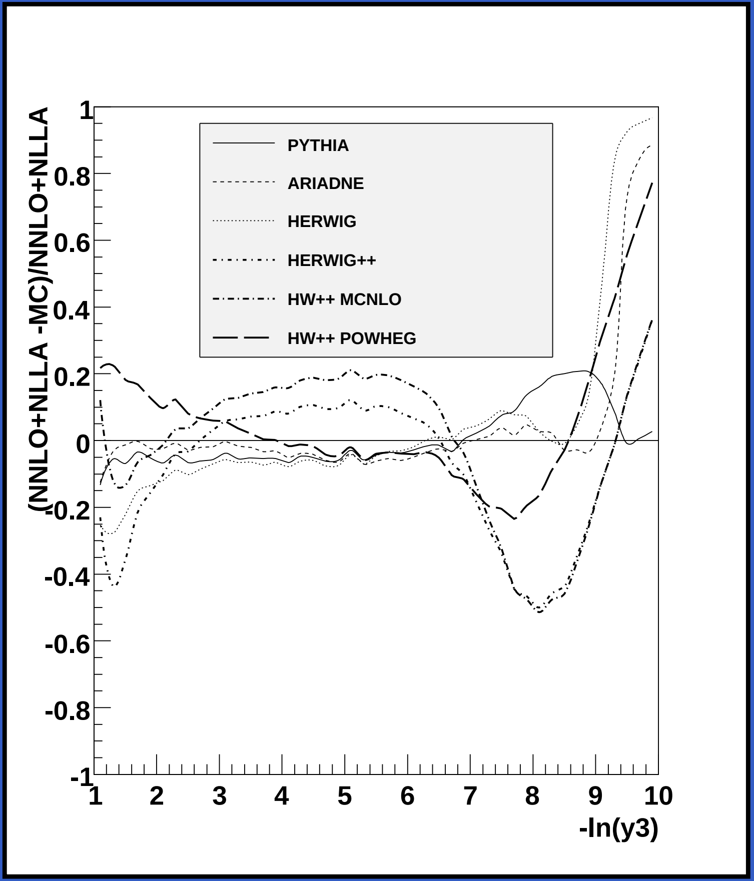




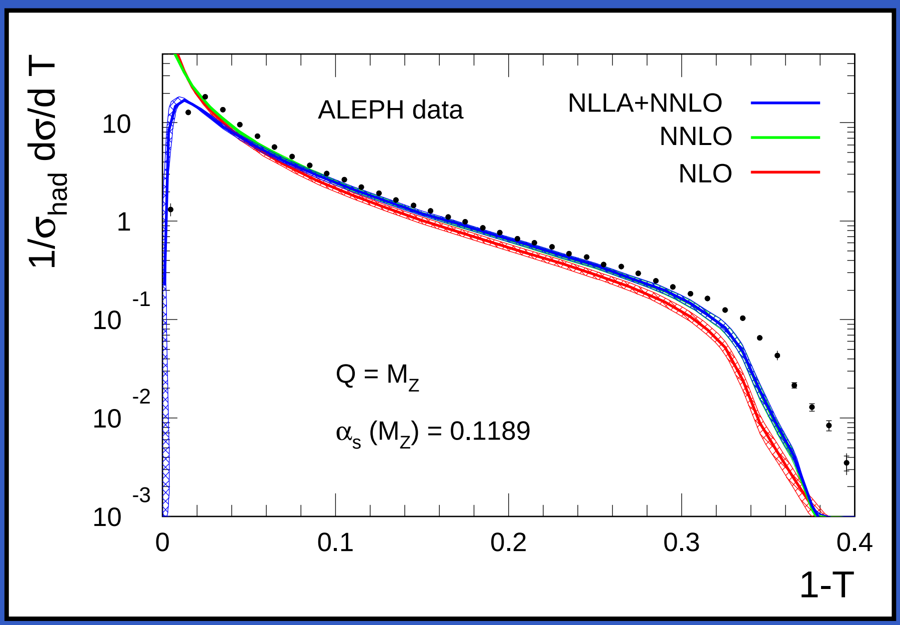
- Thrust: MC parton level prediction larger than in NNLO+NLLA

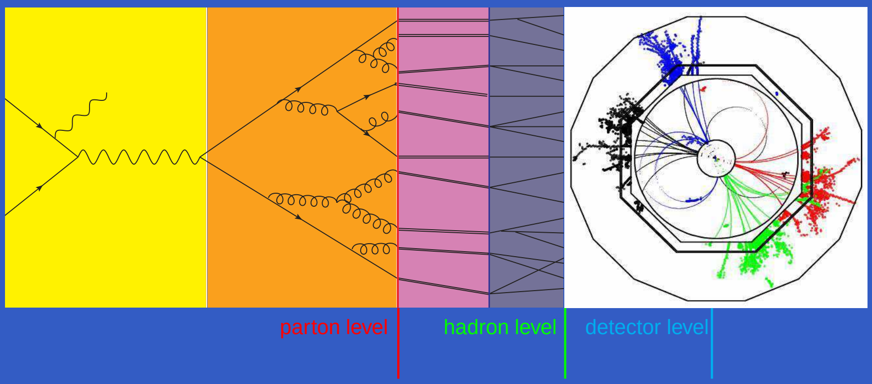
→ Pythia parameters tuned such that missing HO terms are (over-)compensated and hadronization corrections are effectively too small

Hadronization corrections

- NLLA+NNLO results are big improvement in description of data...

  ... however still important differences for $(1-T) \to 0$.





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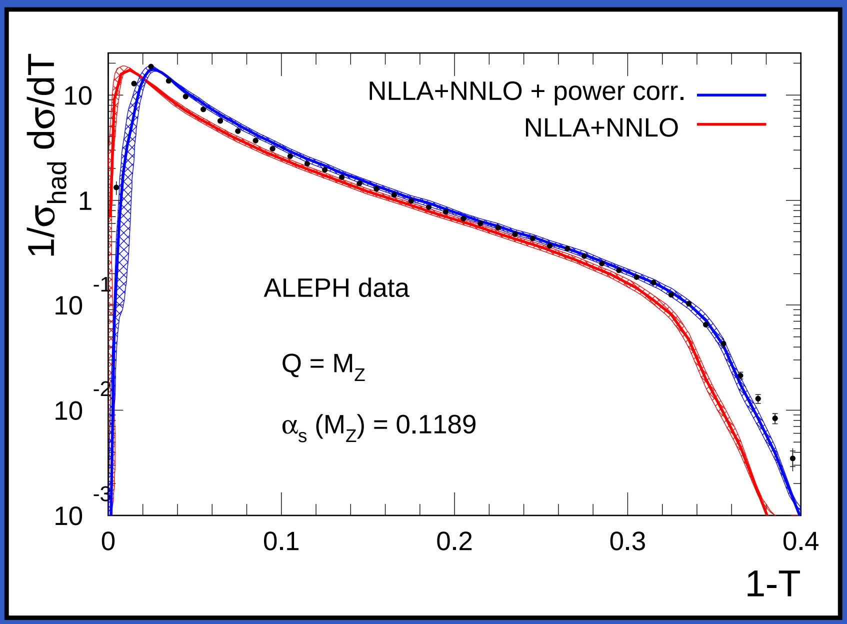

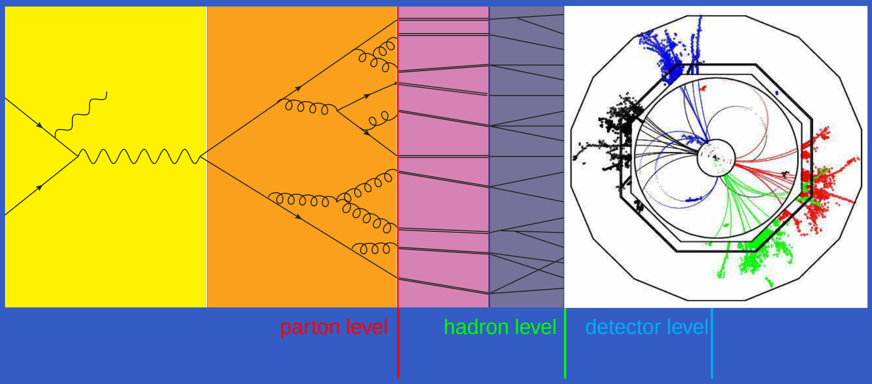

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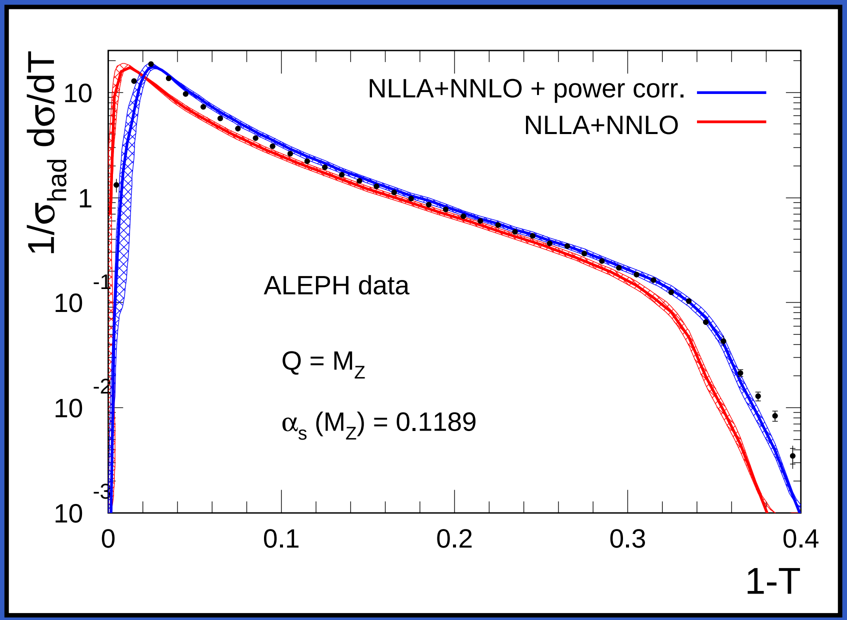
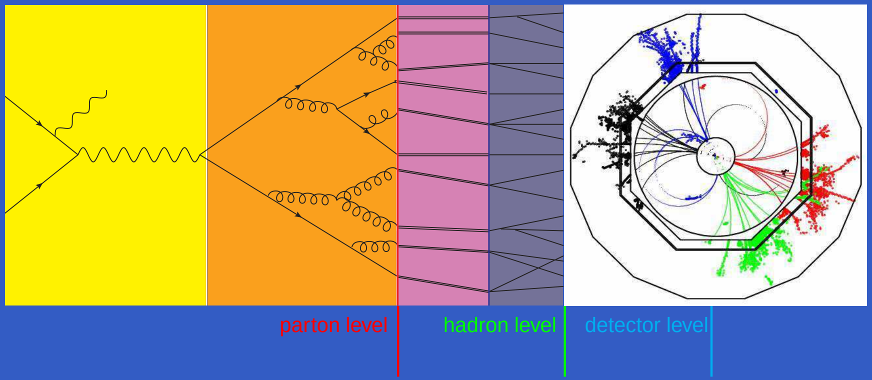




- Distortion caused by hadronization corrections can account for part of the difference,
- however effects of hadronization corrections can be analyzed better by studying moments.

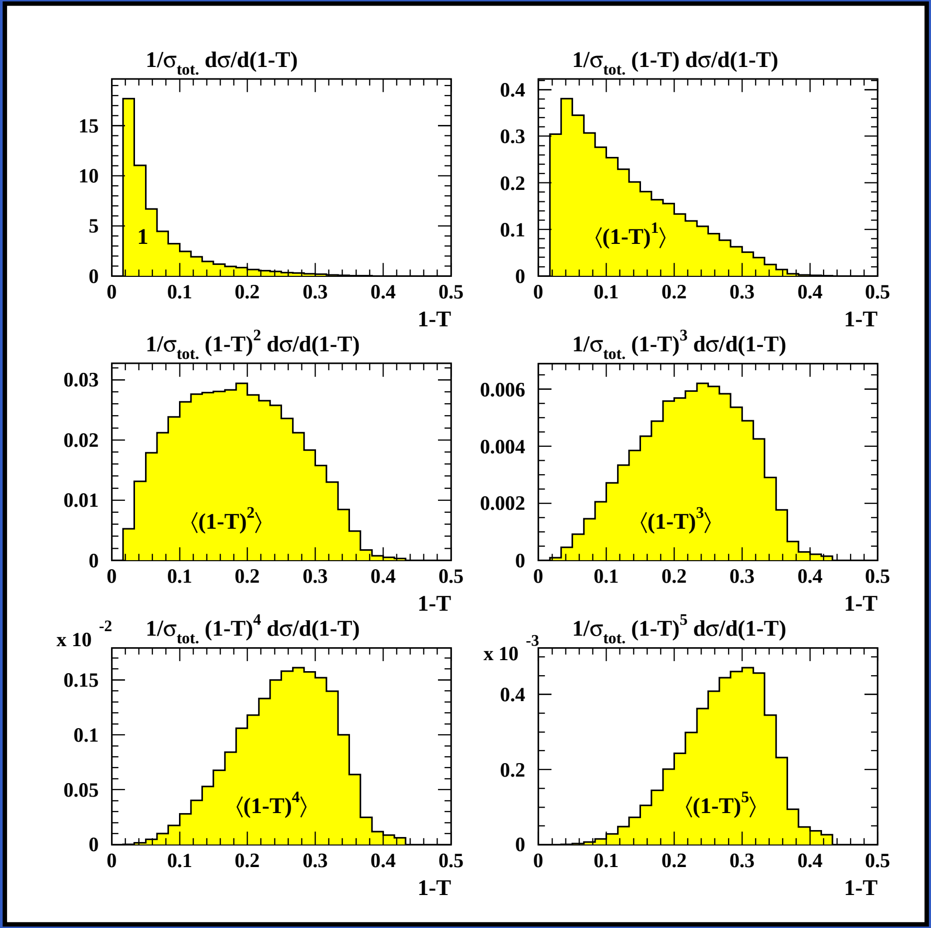
α_s from

Event-Shape Moments

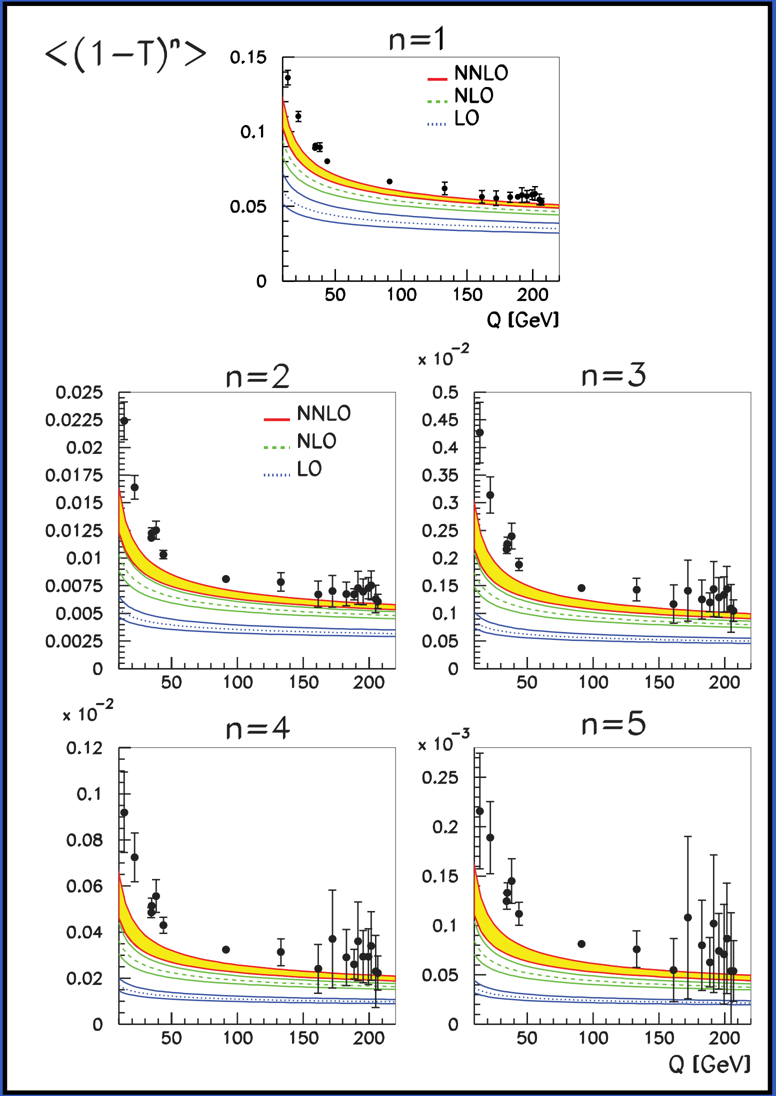
Moments of Event Shapes

- n-th moment of event-shape observable y defined by:

$$\langle y^n \rangle = \frac{1}{\sigma_{\rm had}} \int_0^{y_{\rm max}} y^n \frac{{\rm d}\sigma}{{\rm d}y} {\rm d}y$$



[C. Pahl]



[A.Gehrmann-De Ridder, T. Gehrmann, N. Glover, G. Heinrich]

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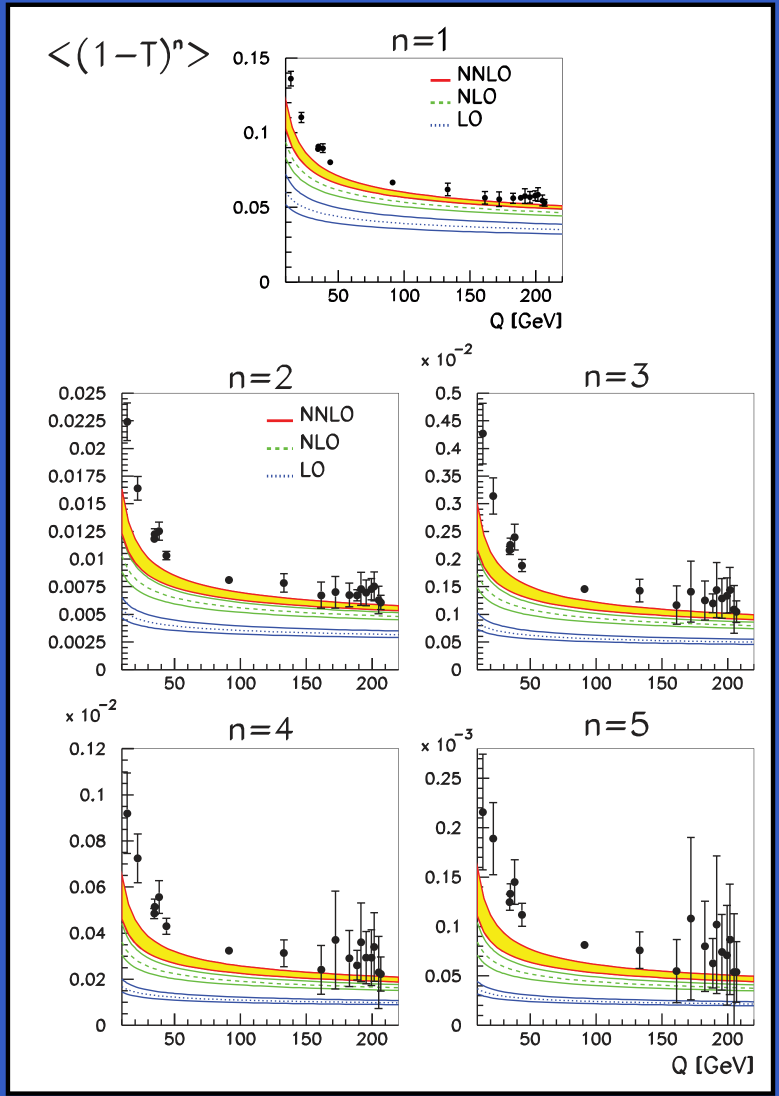


[A.Gehrmann-De Ridder, T. Gehrmann, N. Glover, G. Heinrich]

- Divide perturbative and non-perturbative contributions:

$$\langle y^n \rangle = \langle y^n \rangle_{\mathrm{pt}} + \langle y^n \rangle_{\mathrm{np}} \,,$$

- discrepancy between parton level predictions and data increase with decreasing energy,
- can add non-perturbative corrections either using an analytical modell or a Monte Carlo event generator.

The Dispersive Model

- Idea:
  replace the strong coupling constant below a cut-off scale $\mu_I \approx 2$ GeV by an effective coupling: [J. Dokshitzer, G. Marchesini B. Webber]

$$\frac{1}{\mu_I}\int_0^{\mu_I} dQ\, \alpha_{\text{eff}}(Q^2) = \alpha_0(\mu_I)\,.$$

- Non-perturbative corrections result in a shift of the distribution:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y} = \frac{\mathrm{d}\sigma_{\text{pt}}}{\mathrm{d}y}(y - a_y P) \Rightarrow \langle y^n \rangle = \int_0^{y_{\max}} \mathrm{d}y\,(y + a_y P)^n \frac{1}{\sigma_{\text{tot}}}\frac{\mathrm{d}\sigma_{\text{pt}}}{\mathrm{d}y}(y)\,.$$

- Analytical power correction $P = P(\mu_R)$ extended to NNLO,
  [T. Gehrmann, M. Jaquier, G.L.]

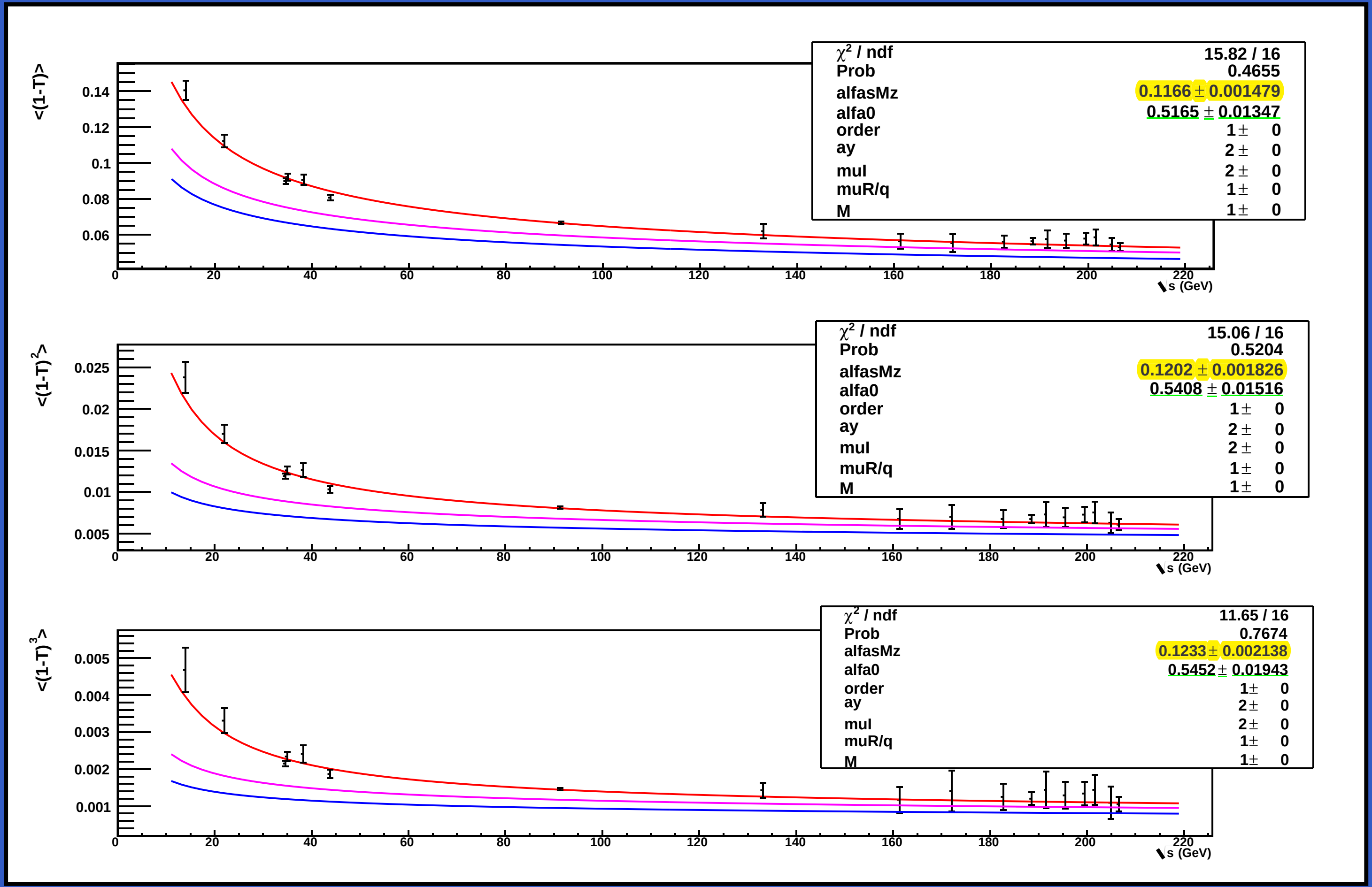
$$P = \frac{4C_F}{\pi^2}\mathcal{M}\left\{\alpha_0 - \left[\alpha_s(\mu_R) + \frac{\beta_0}{\pi}\left(1 + \ln\left(\frac{\mu_R}{\mu_I}\right) + \frac{K}{2\beta_0}\right)\alpha_s^2(\mu_R) + \right.\right.$$

$$\left(2\beta_1\left(1 + \ln\left(\frac{\mu_R}{\mu_I}\right) + \frac{L}{2\beta_1}\right) + 8\beta_0^2\left(1 + \ln\left(\frac{\mu_R}{\mu_I}\right) + \frac{K}{2\beta_0}\right)\right.$$

$$\left.\left.\left. + 4\beta_0^2 \ln\left(\frac{\mu_R}{\mu_I}\right)\left(\ln\left(\frac{\mu_R}{\mu_I}\right) + \frac{K}{\beta_0}\right)\right)\frac{\alpha_s^3(\mu_R)}{4\pi^2}\right]\right\} \times \frac{\mu_I}{Q}.$$

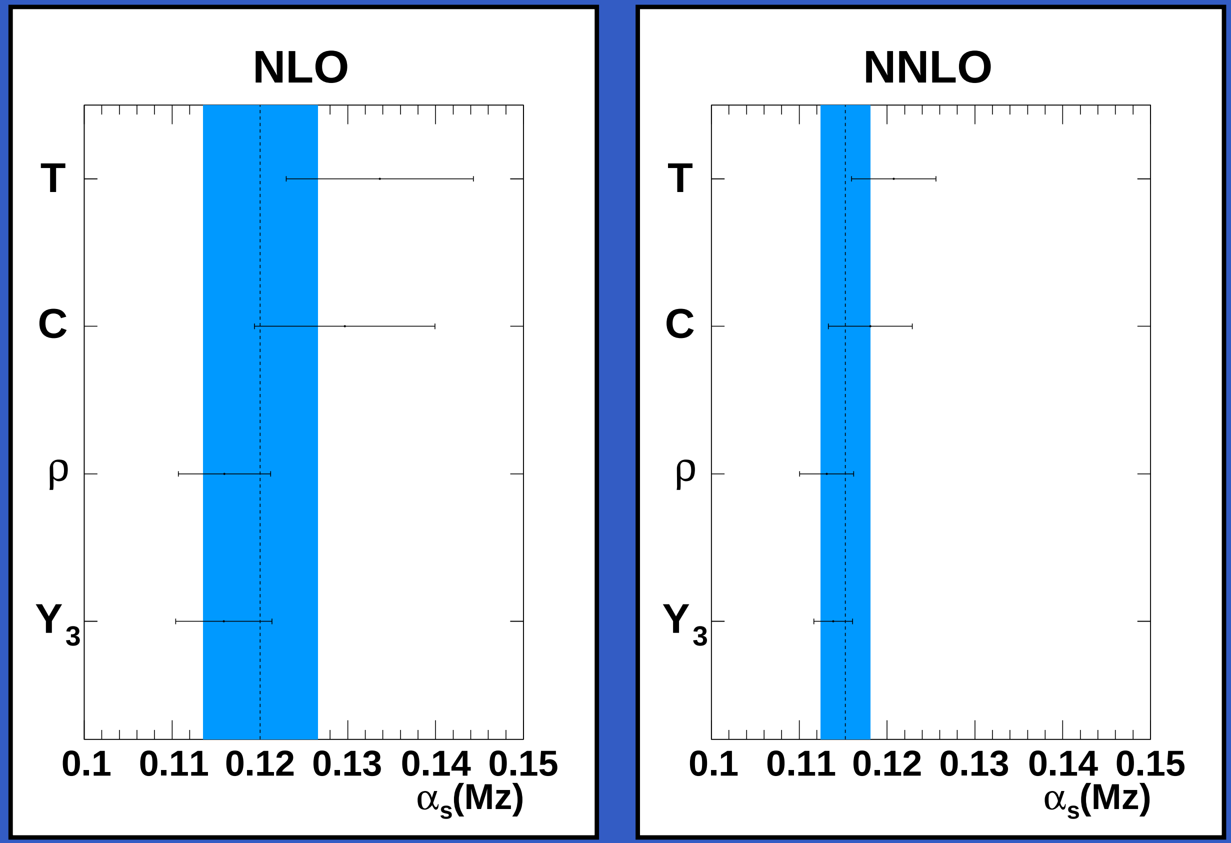
The Dispersive Model

- Fit of α_s and α_0 to JADE and OPAL data for $n = 1, \ldots, 5$:
  - total experimental error used in χ^2,
  - theoretical uncertainty determined by varying μ_R, μ_I and $\mathcal{M}$.



Determination of α_S Using Moments

Result from analytical power corrections:

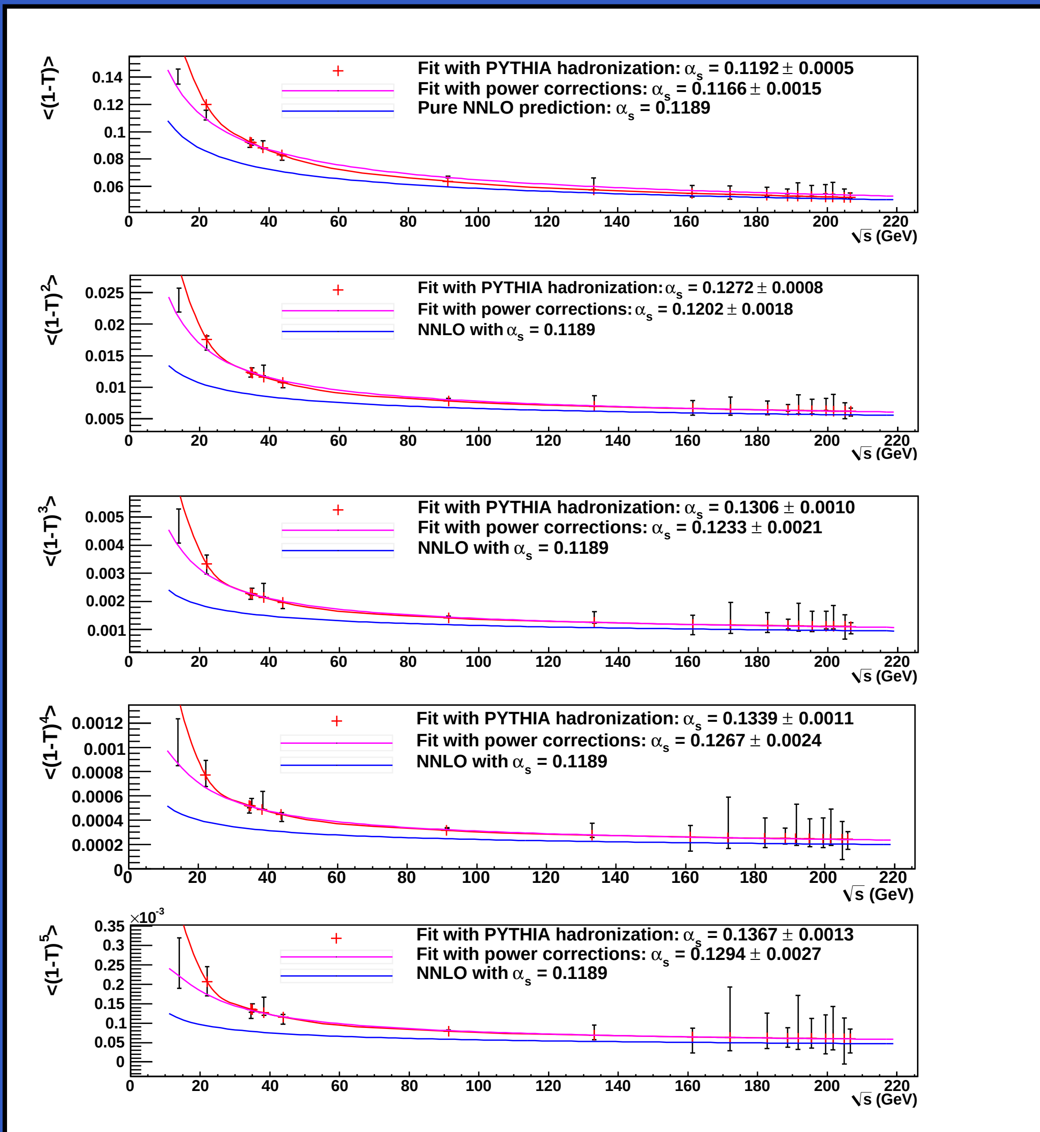


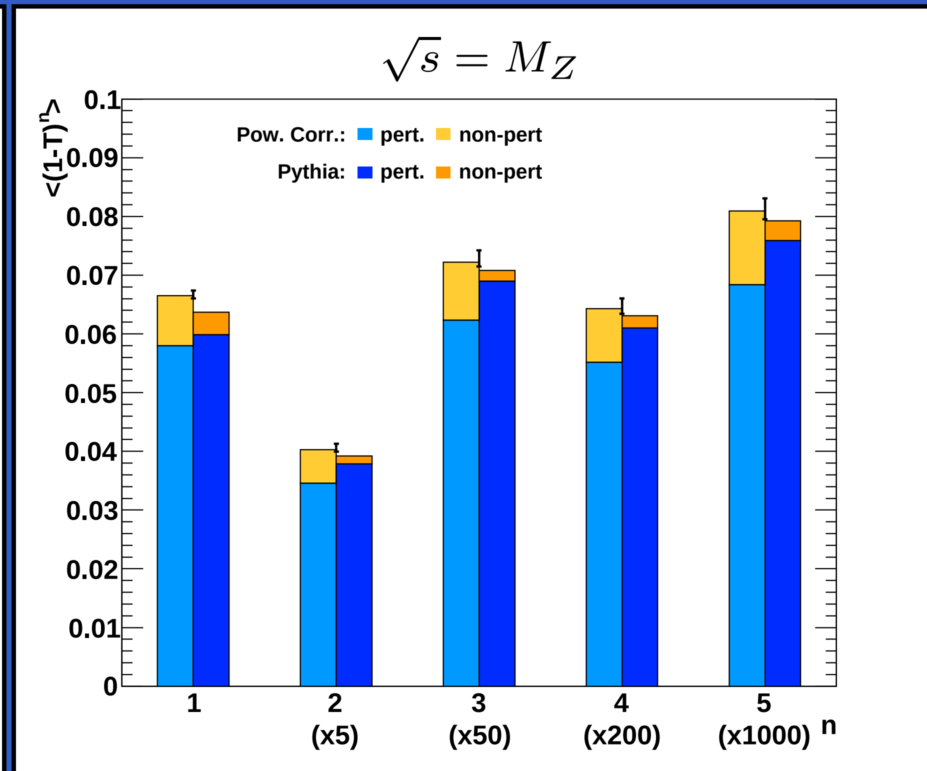
Combined result:

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

Determination of α_S Using Moments

Comparison with Monte Carlo:





- With Monte Carlo:

$\longrightarrow$ smaller hadronization correction

$\longrightarrow$ higher partonic predictions

α_s from

3-jet rates

Determination of α_s using jet rates

- In region $10^{-1} > y_{\rm cut} > 10^{-2}$ only very small hadronization corrections $\rightarrow$ motivates a dedicated extraction of α_s

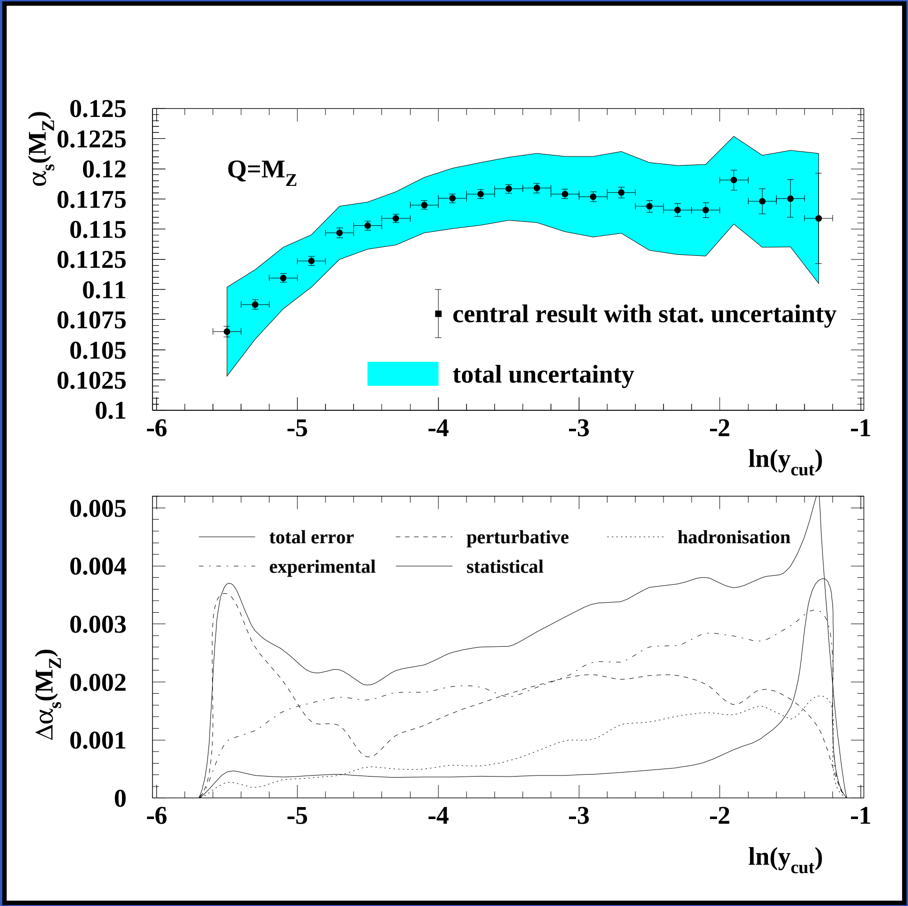
- Separated fits for $-1.3 > \ln(y_{\rm cut}) > -5.1$,
- stability up to $\ln(y_{\rm cut}) = -4.5$,

  (onset of large logarithms beyond),

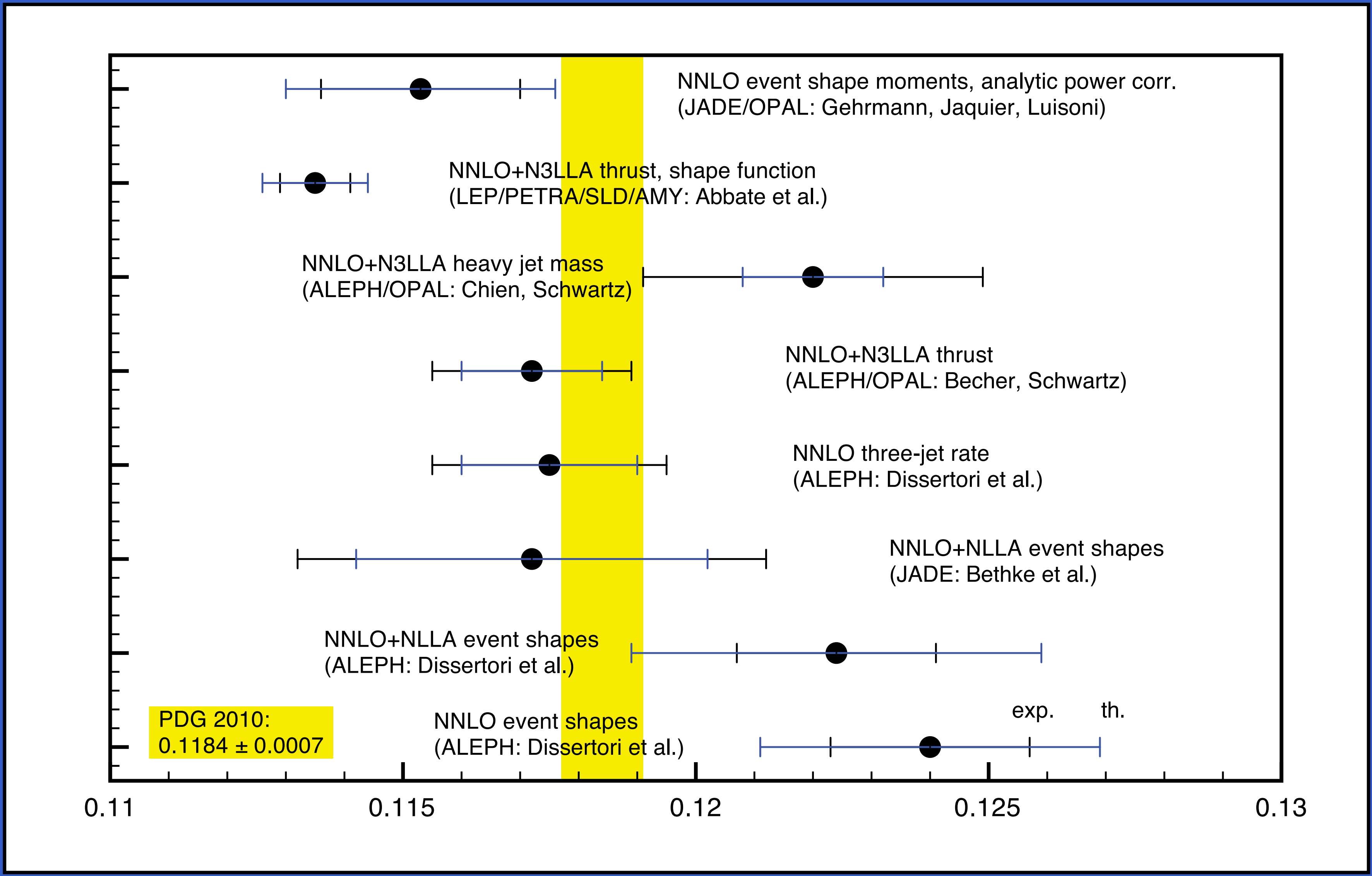
Result at $y_{\rm cut} = 0.02$:

$$\alpha_s(M_Z) = 0.1175 \pm 0.0020(\rm exp) \pm 0.0015(\rm th)$$

- more precise then extractions from event-shape distributions.



α_s from NNLO Jet Observables



Conclusions and Outlook

- New NNLO result on jet observables together with high precision data allow improved extraction of α_s:
  - from NLLA+NNLO event-shape distributions,:

    $$\alpha_s\,(M_Z) = 0.1224 \pm 0.0009(\text{stat.}) \pm 0.0009(\text{exp.}) \pm 0.0012(\text{had.}) \pm 0.0035(\text{theo.})$$

  - from NNLO event-shape moments with analytical power corrections:

    $$\alpha_s\,(M_Z) = 0.1153 \pm 0.0017(\mathrm{exp}) \pm 0.0023(\mathrm{th})$$

  - from NNLO three-jet rate:

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

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  - from NNLO three-jet rate:

    $$\alpha_s\,(M_Z) = 0.1175 \pm 0.0020(\text{exp}) \pm 0.0015(\text{th})$$

- From event-shape analysis some further important observations:
  - combination of NNLO results with hadronization from LO MC not reliable,
  - in LO MC hadronization corrections might be underestimated,
  - further studies in this direction are needed in view of the precision needed at LHC.