Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

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Review of α_s determinations from e+e- annihilation

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Max Planck Institute for Physics
Munich


International Workshop on Future Linear Colliders

LCWS13

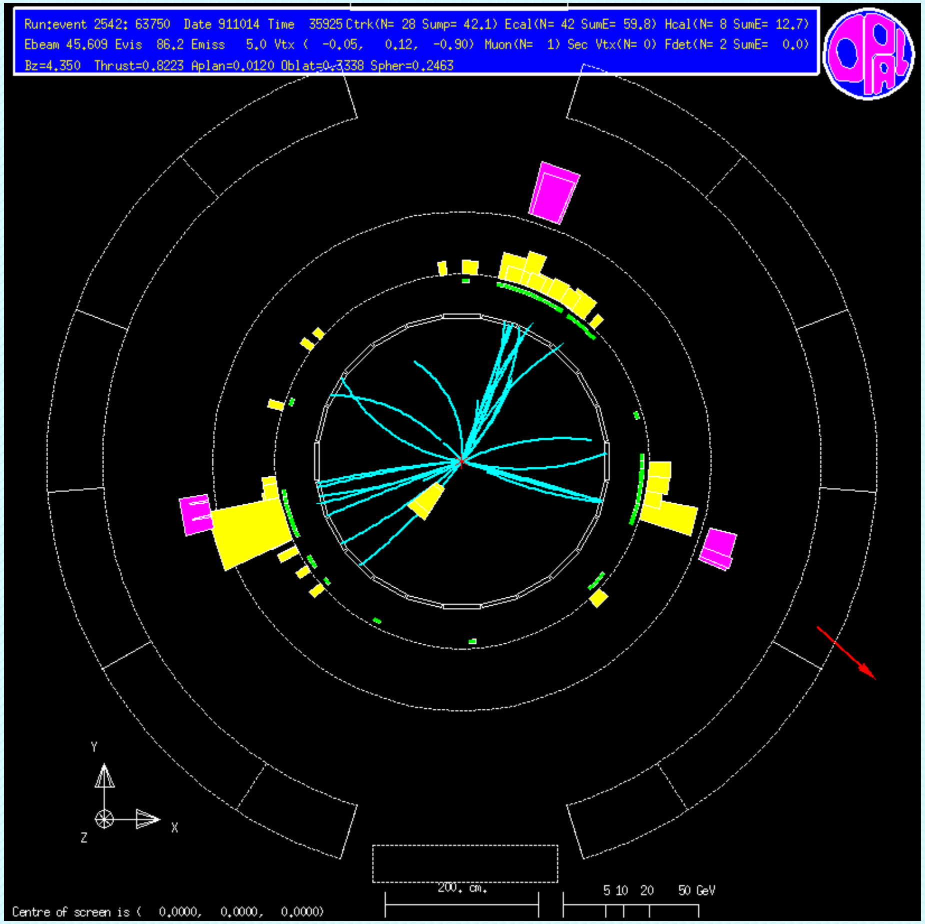
11-15 November 2013, The University of Tokyo

Outline

- Introduction: event shapes in e^+e^- collisions
- α_s from event shapes
- Electroweak corrections and radiative return
- Prospects for the ILC
- Further strong coupling determinations
- Conclusions & Outlook

Introduction: Event Shapes in e^+e^-

- Consider a tipical jet event at LEP:



```
Run:event 2542: 63750  Date 911014  Time   35925 Ctrk(N= 28 Sump= 42.1) Ecal(N= 42 SumE= 59.8) Hcal(N= 8 SumE= 12.7)
Ebeam 45.609 Evis  86.2 Emiss   5.0 Vtx (  -0.05,   0.12,  -0.90) Muon(N=  1) Sec Vtx(N= 0) Fdet(N= 2 SumE=  0.0)
Bz=4.350  Thrust=0.8223 Aplan=0.0120 Oblat=0.3338 Spher=0.2463
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Centre of screen is (   0.0000,   0.0000,   0.0000)
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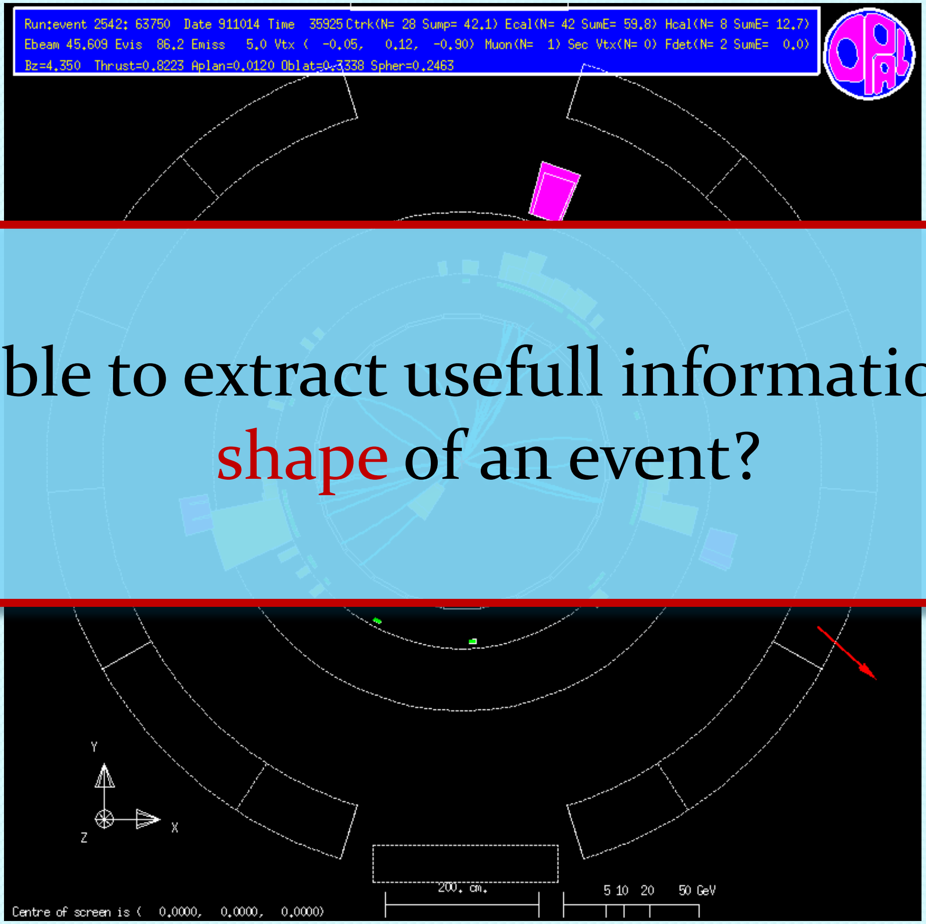

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Is it possible to extract usefull information from the shape of an event?

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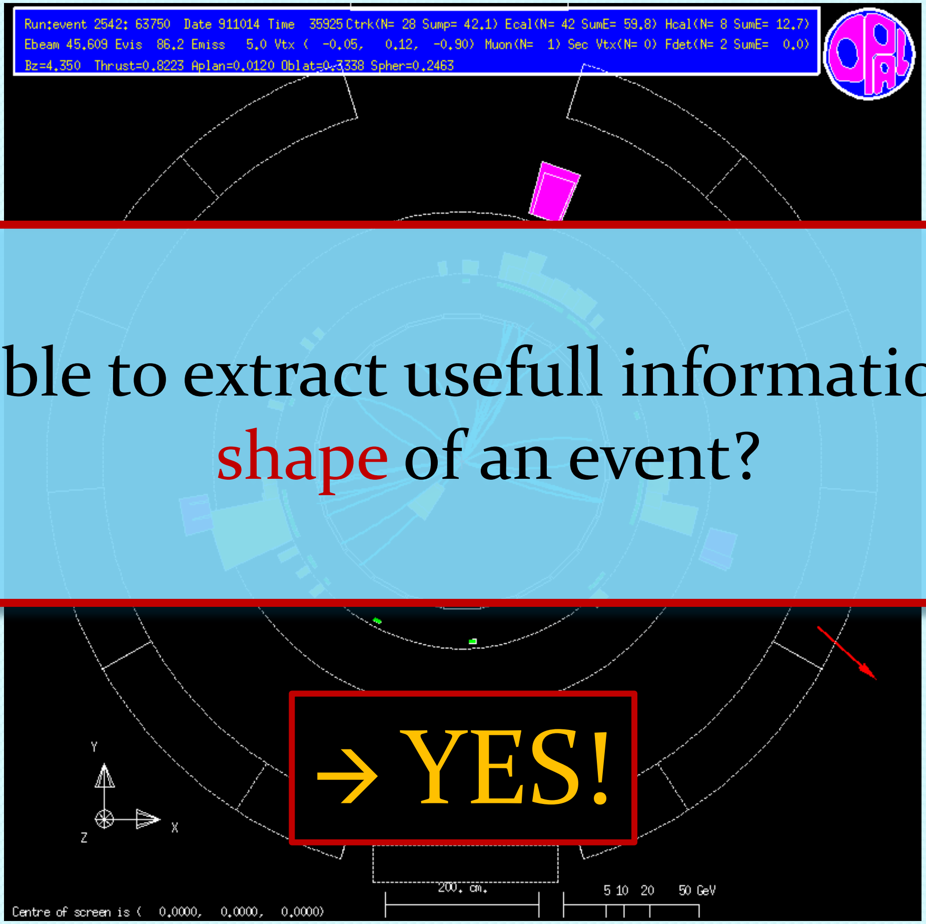

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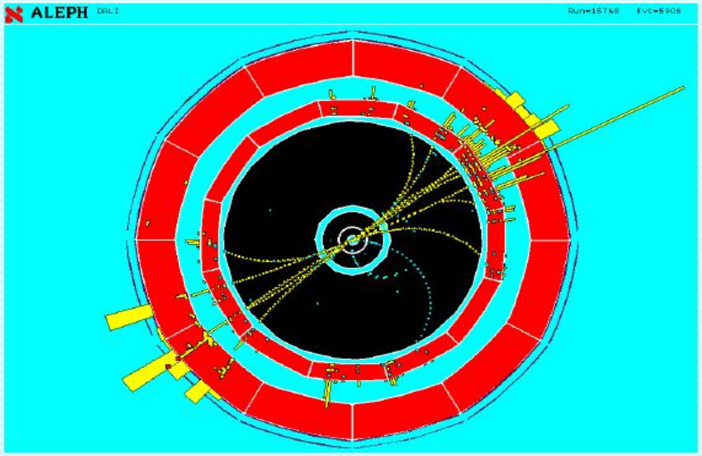
Is it possible to extract usefull information from the shape of an event?

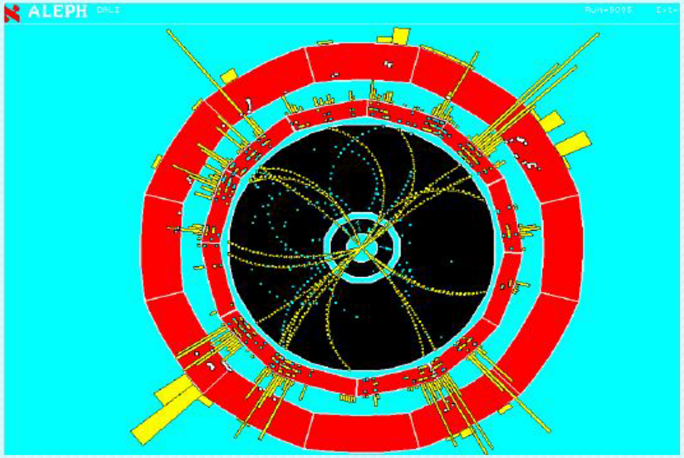
→ YES!

Introduction: Event Shapes in e^+e^-

- Various proposals to measure shape of events finding ways to parametrize the geometry of hadronic final states:
  - Thrust:

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





2-jet events: $T \approx 1$

spherical events: $T \longrightarrow \frac{1}{2}$

smooth transition

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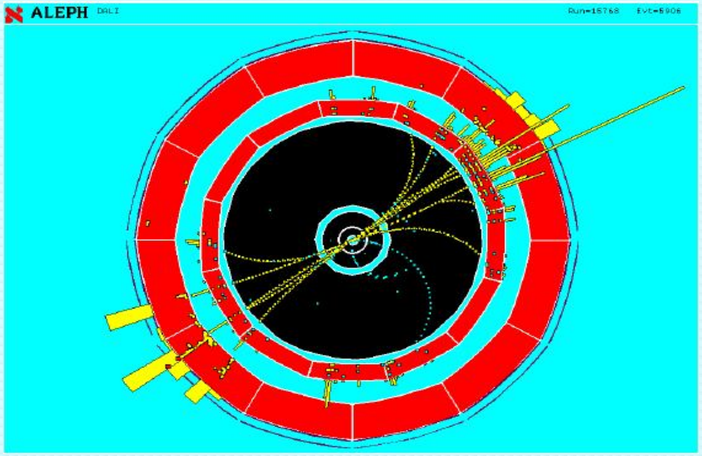

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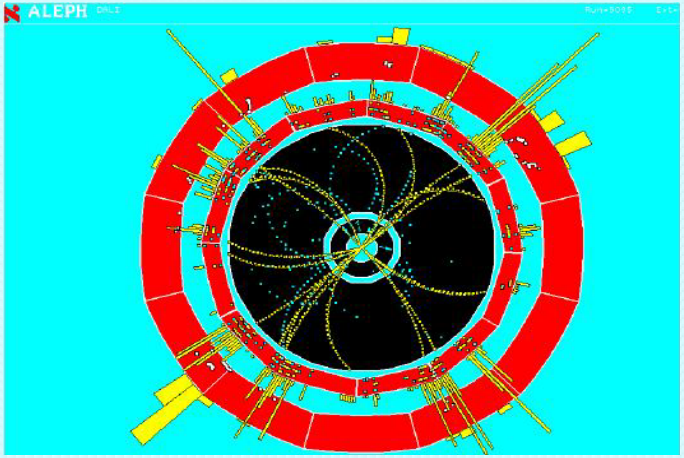

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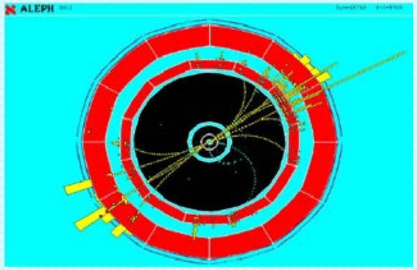

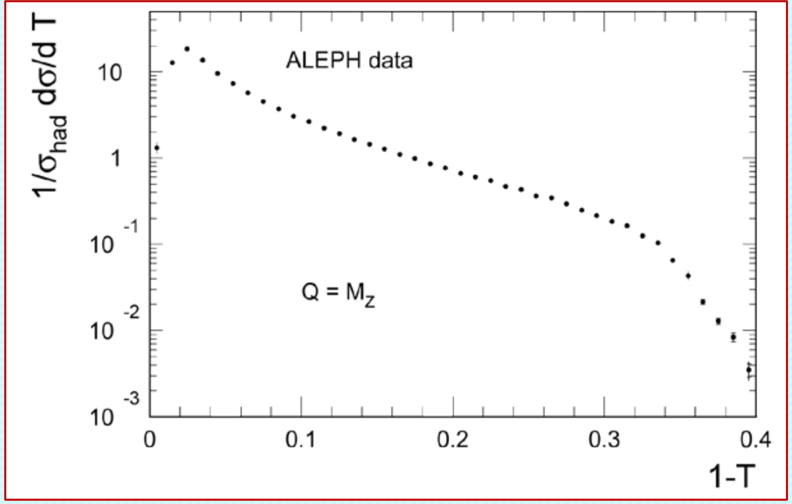

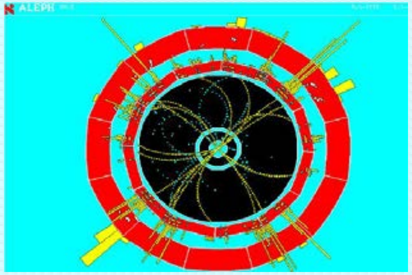

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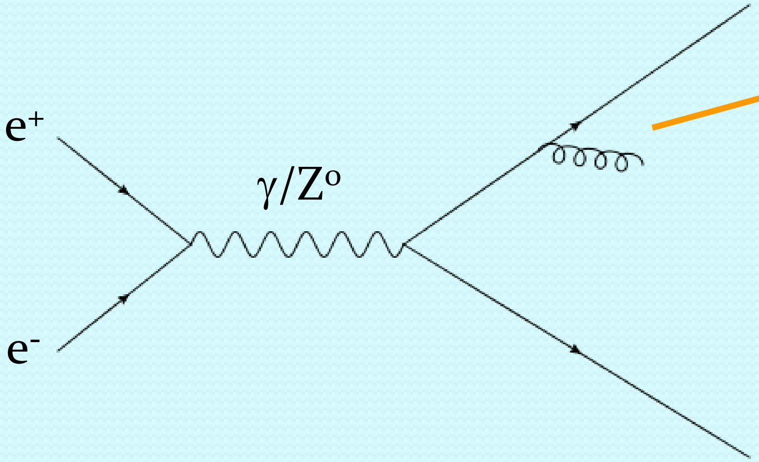

Deviation from 2-jet configuration proportional to α_s

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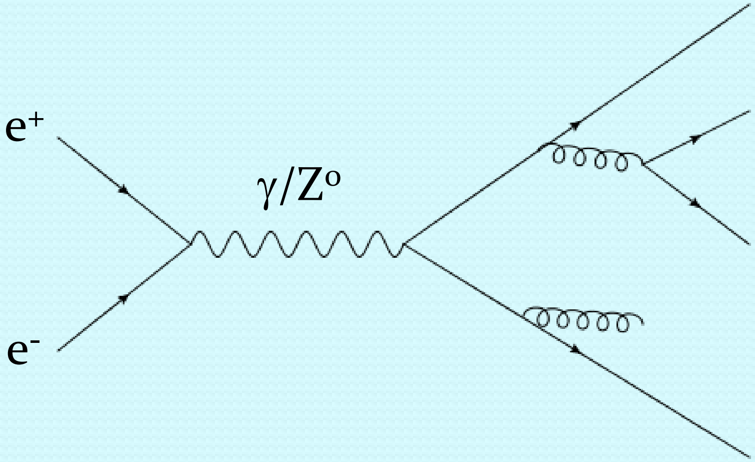

Deviation from 2-jet configuration proportional to α_s

3-jet known at NNLO QCD
4-jet & 5-jet known at NLO QCD

3 jets NLO/NNLO	[Ellis, Ross, Terrano; Kunst, Nason; Giele, Glover; Catani, Seymour] [Gehrmann-De Ridder, Gehrmann, Glover, Heinrich; Weinzierl]
4 jets NLO	[Nagy, Trocsanyi; Signer, Dixon]
5 jets NLO	[Frederix, Frixione, Melnikov, Zanderighi]
first 6-7 jets NLO	[Becker, Goetz, Reuschle, Schwan, Weinzierl]

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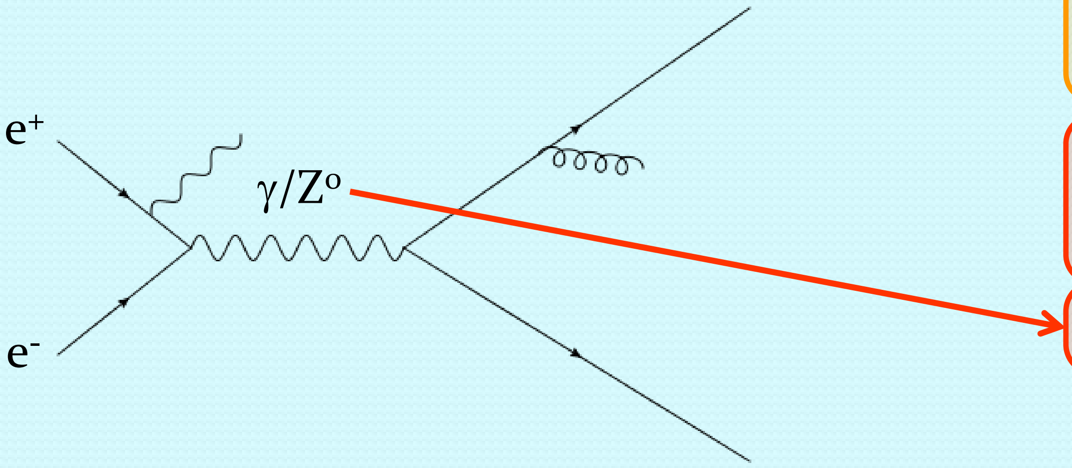

Deviation from 2-jet configuration proportional to α_s

3-jet known at NNLO QCD
4-jet & 5-jet known at NLO QCD

3-jet NLO EW known

3 jets NLO EW [Denner, Dittmaier, Gehrmann, Kurz; Carloni-Calame; Moretti, Piccinini, Ross]

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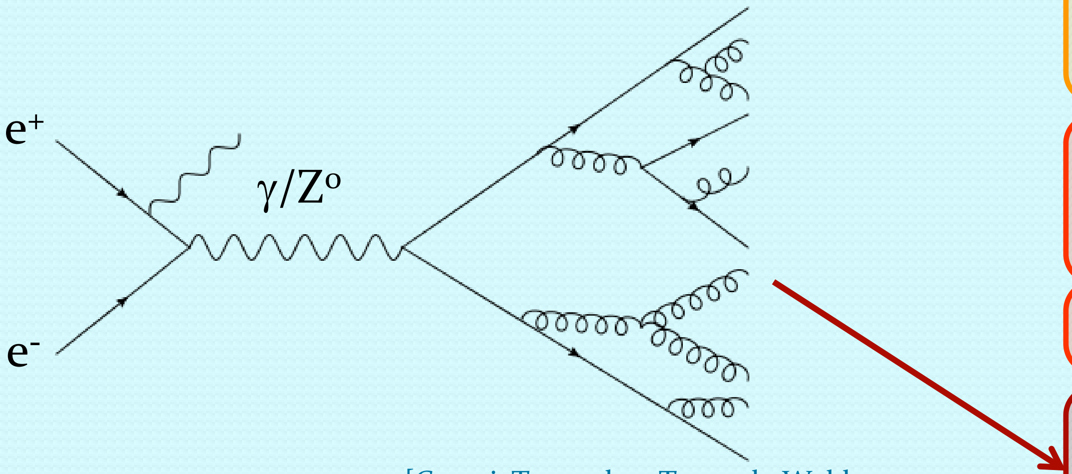

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Resummation at NN(N)L
and matching with fixed order

NLL resummation [Catani, Trentadue, Turnock, Webber; Banfi, Salam, Zanderighi]

NNLO+NLL matching [Gehrmann, GL, Stenzel]

N^3LL/NNLL for Thrust + matching [Becker, Schwartz; Monni, Gehrmann, GL]

N^3LL for M_H + matching [Chien, Schwartz]

NNLL for Broadenings [Becher, Bell, Neubert; Becher, Bell]

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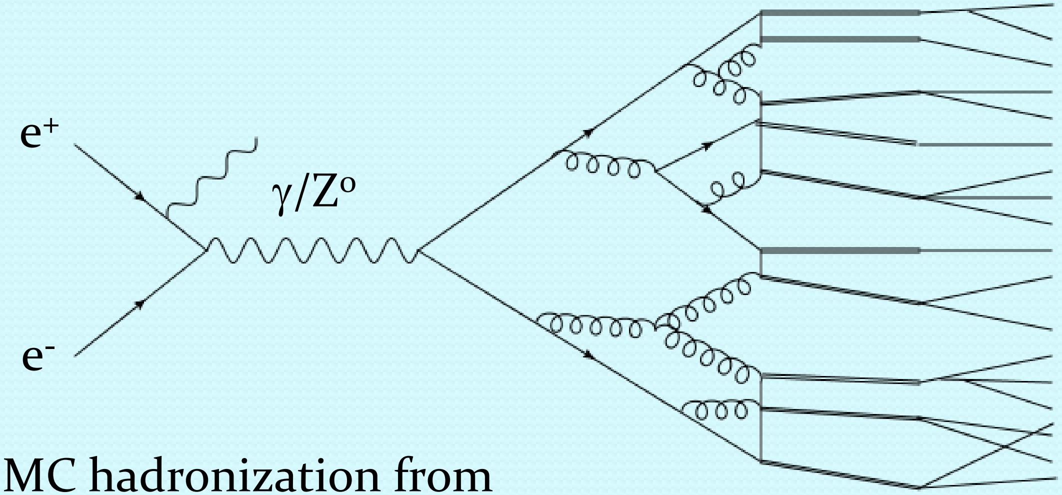

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Resummation at NN(N)L
and matching with fixed order

MC hadronization
Analytical hadronization

MC hadronization from -->Pythia/Herwig/Ariadne	[Sjostrand et al., Corcella et al., Lönnblad]
Analytical dispersive model	[Dokshitzer, Marchesini, Webber; Dokshitzer et al., Davison, Webber; Gehrmann, Monni, GL]
Analytical shape function	[Korchemsky, Sterman, Tafat; Abbate, Fickinger, Hoang, Mateu, Stewart]
Finite mass effects	[Salam, Wicke; Mateu, Stewart, Thaler]

See also V.Mateu's talk

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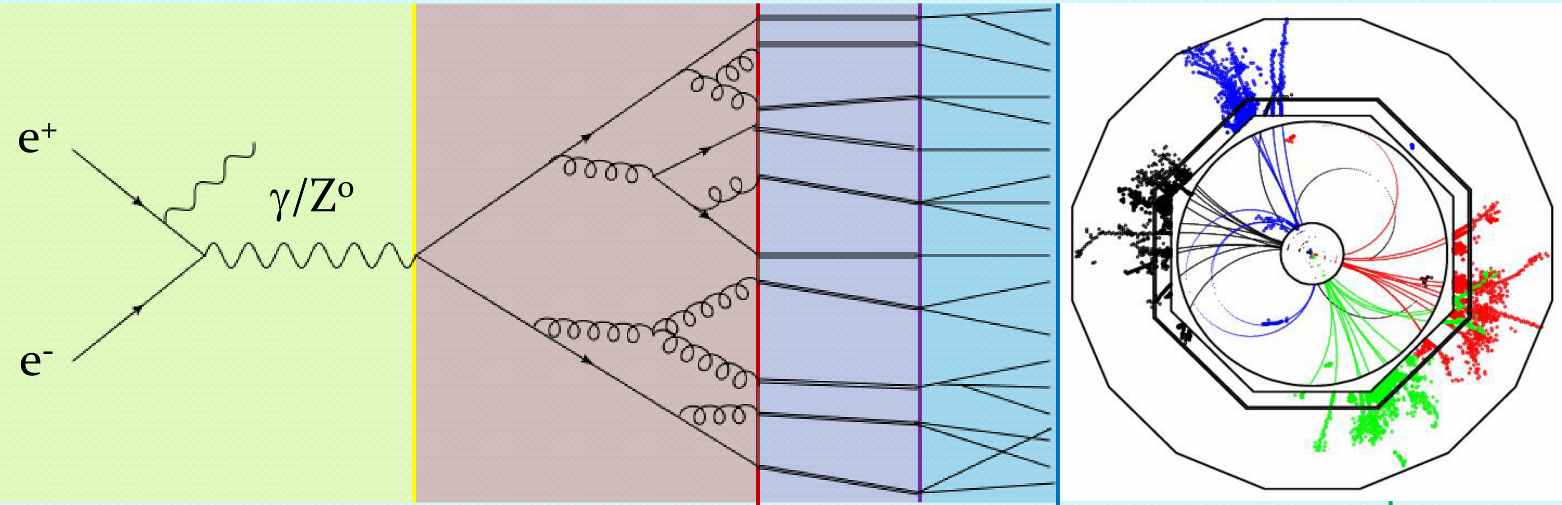

Parton level → | **Hadron level →** | **Detector level →**

← Perturbative regime → | **← Non-Perturbative regime →**

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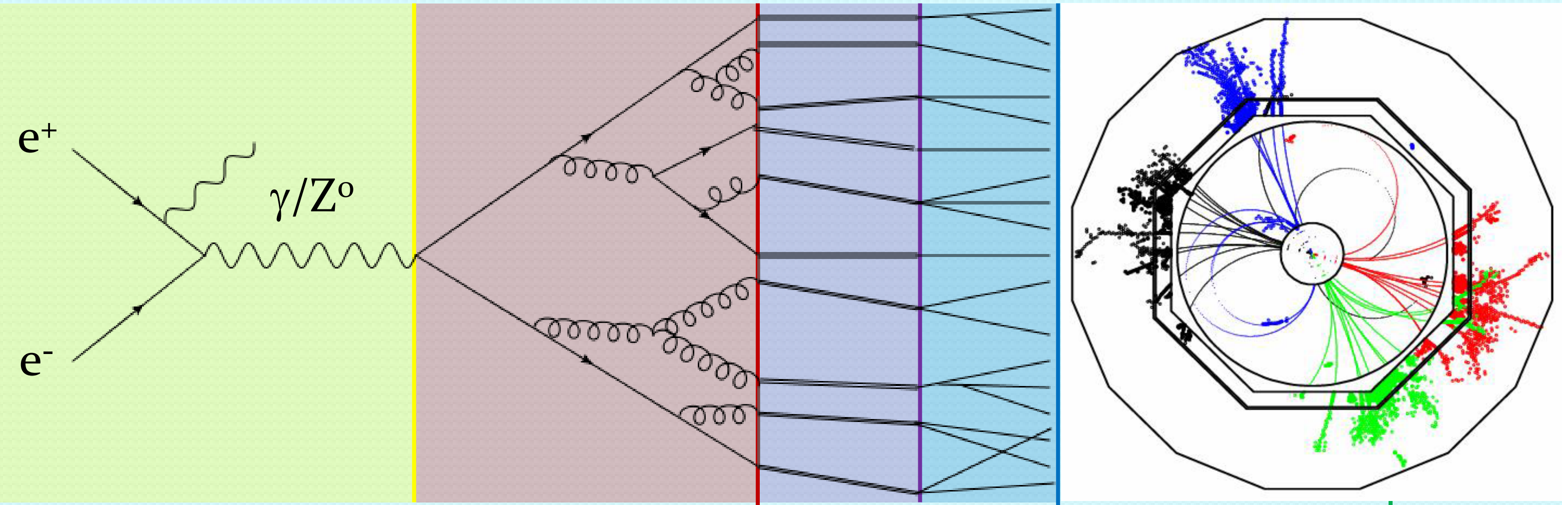


Parton level → **Hadron level →** **Detector level →**

← Perturbative regime → **← Non-Perturbative regime →**

  - Precise extraction of α_s requires precise description of each "step"

Introduction: Event Shapes in e^+e^-

- Further event shapes usually used:
  - Heavy jet mass: $\rho = \frac{1}{E^2_{\text{tot-vis.}}} \max\left(M_L^2, M_R^2\right)$; $M^2_{L/R} = \left(\sum_{n\in H_{L/R}} |\vec{p}_n|\right)^2$
  - Total/Wide Broadenings: $B_i = \frac{\sum_{k\in H_i} |\vec{p}_k \times \vec{n}_T|}{2\sum_j |\vec{p}_j|}$;
    - Total: $B_T = B_1 + B_2$
    - Wide: $B_W = \max\left(B_1, B_2\right)$
  - C-parameter: $\Theta^{\alpha\beta} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{p_i^\alpha p_i^\beta}{|\vec{p}_i|}$ tensor with EV $\lambda_1, \lambda_2, \lambda_3$

$$C = 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1)$$

  - 2 $\longrightarrow$ 3 jet resolution parameter (Durham alg.): Y_3

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

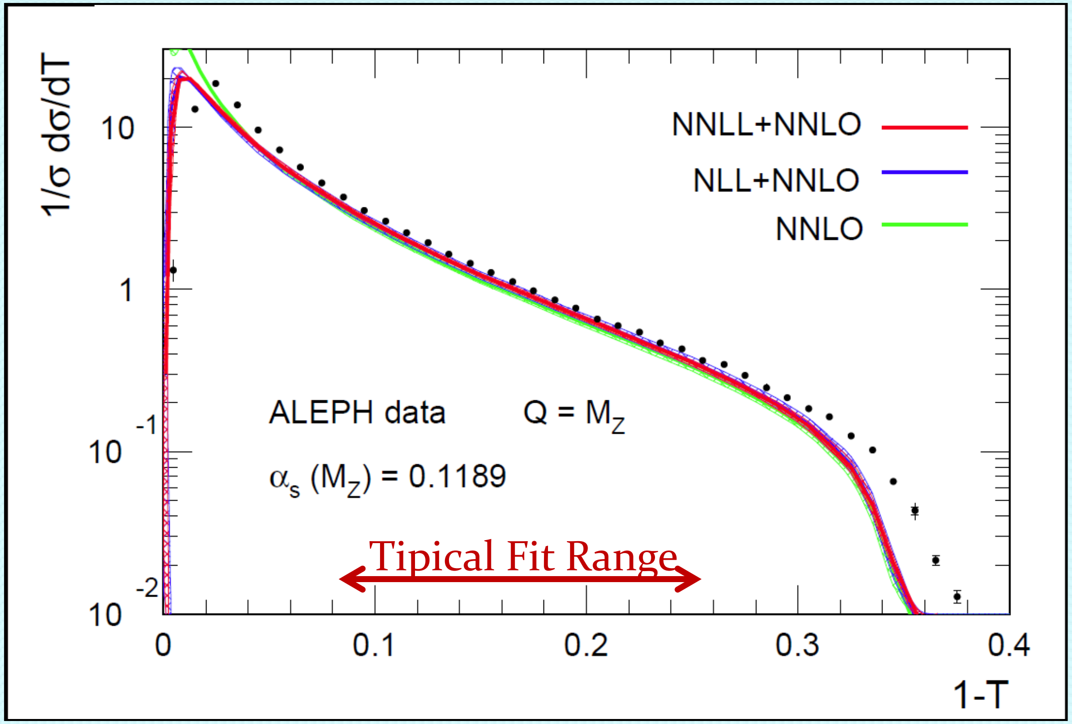
Data sources

- Data on event shapes available at several CM energies and from several experiments:
  - PETRA:
    - TASSO data from 14 to 44 GeV
    - JADE data for 35 and 44 GeV: still maintained and analyzed [Bethke, Kluth, Pahl]
  - TRISTAN:
    - AMY data at 55 GeV
  - SLAC:
    - SLC data at 91.2 GeV
  - LEP:
    - ALEPH / OPAL / DELPHI / L3 data from 91.2 to 207 GeV
    - DELPHI / L3 data with radiated photon and $Q < M_Z$

→ Impact of QED effects in these sets?

Event shapes: theory vs data

- How well are data described by theory predictions?



[Gehrmann, GL, Monni]

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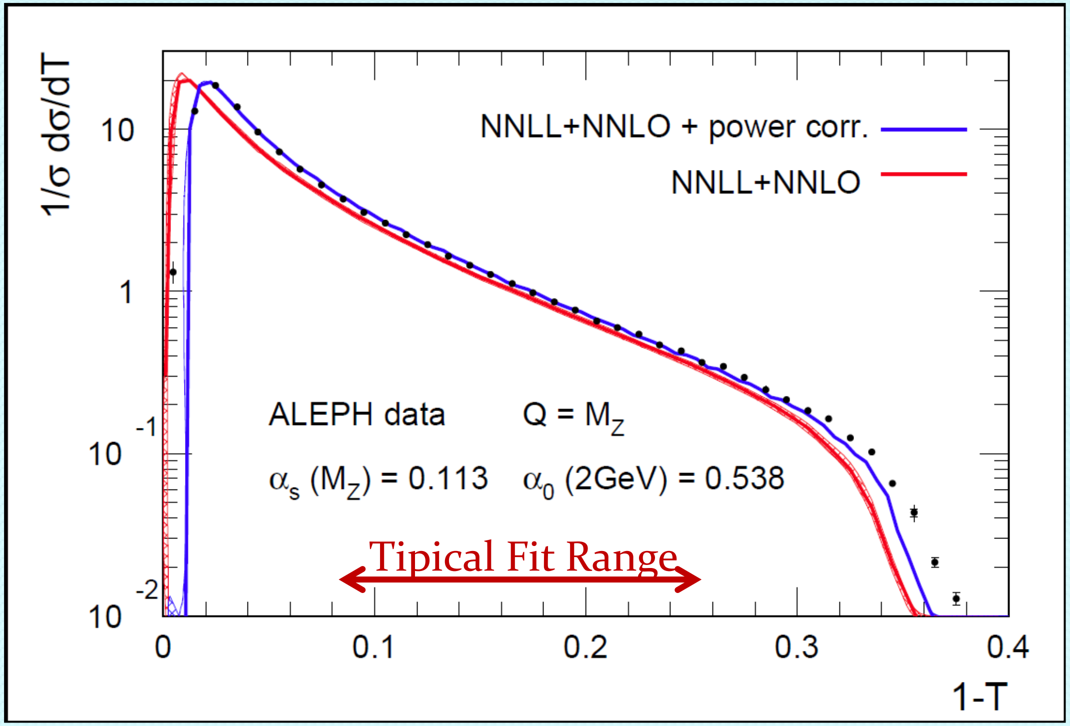

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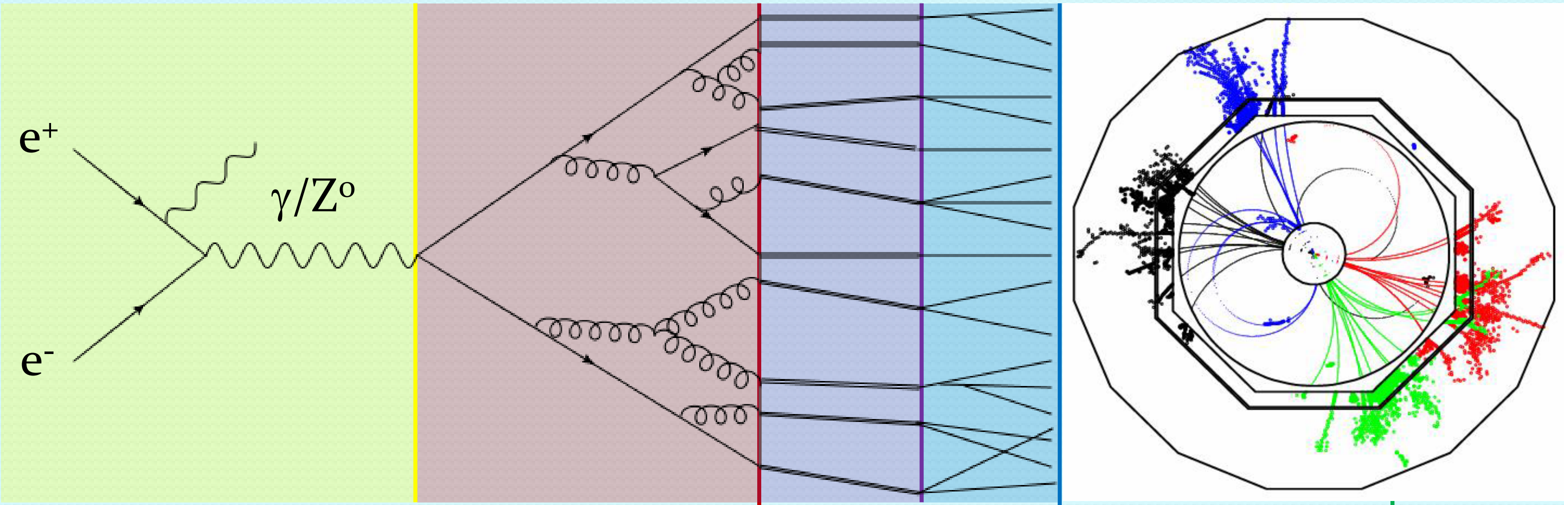
Extracting α_s from data

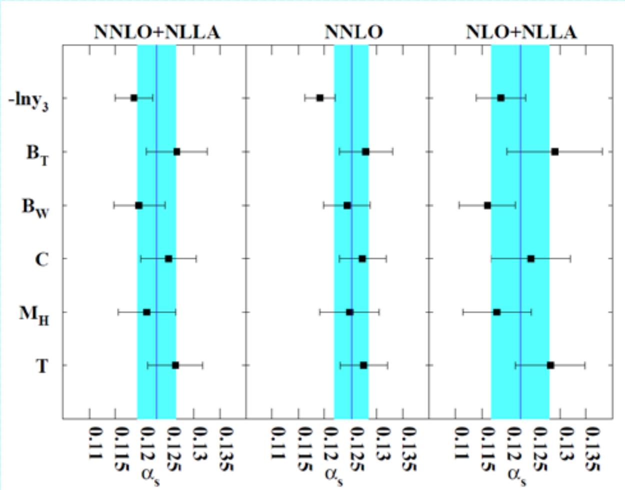


Parton level → **Hadron level →** **Detector level →**

- Main open issues
  - NNLL+NNLO is becoming state-of-the-art for (almost) all observables ✓
  - Analytical vs. Monte Carlo hadronization corrections? ?
  - Which observables and which data sets? ?

NNLO(+NLL) fits to 6 event-shapes

ALEPH data



[Dissertori et al., 0712.0327, 0906.3436]

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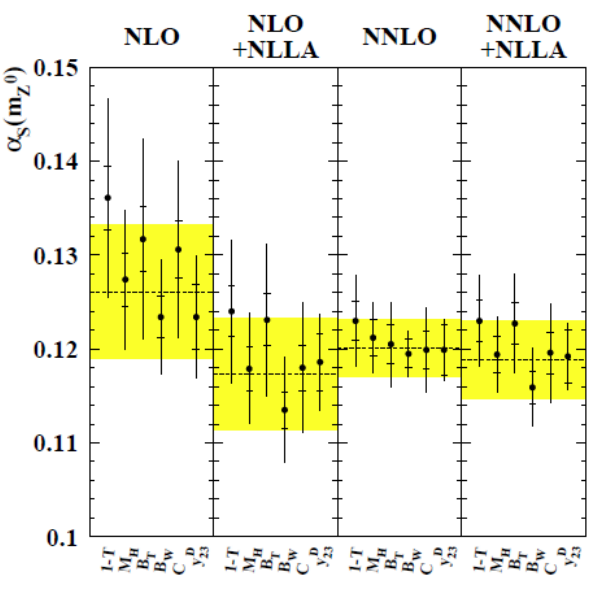
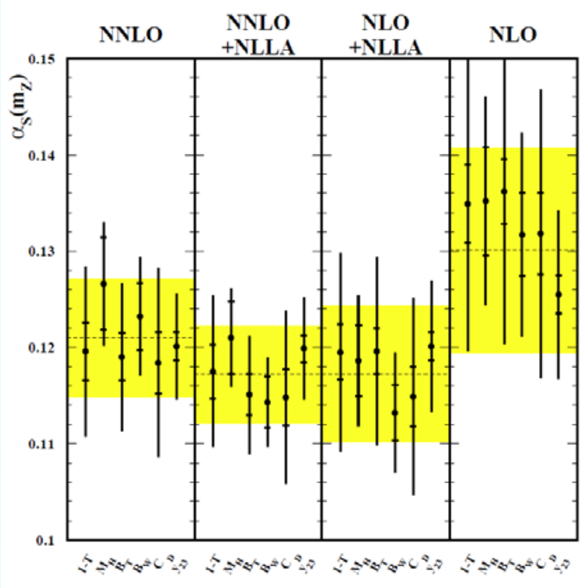


[OPAL Collaboration, 1101.1470]

JADE data



[JADE Collaboration, 0810.1389]

$$\alpha_s(M_Z) = 0.1240 \pm 0.0013 \pm 0.0031$$
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$$\alpha_s(M_Z) = 0.1210 \pm 0.0022 \pm 0.0057$$
$$\alpha_s(M_Z) = 0.1172 \pm 0.0021 \pm 0.0046$$

- From NLO to NNLO: decrease in uncertainties and central value
- From NNLO to NLLA+NNLO: increase in uncertainty
  - → NLLA resummation does not cancel NNLO running of coupling in the matching

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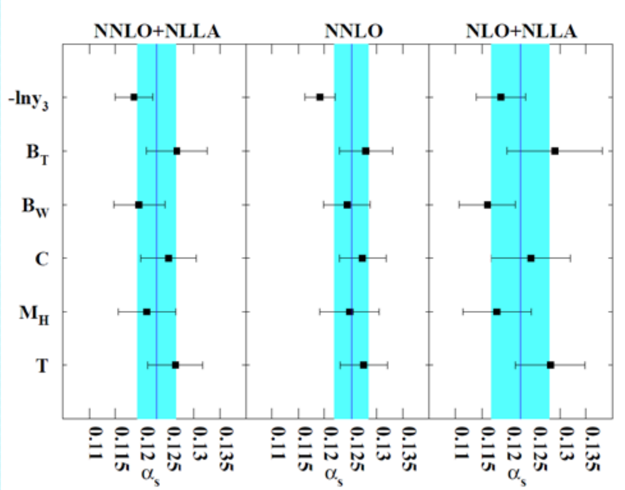

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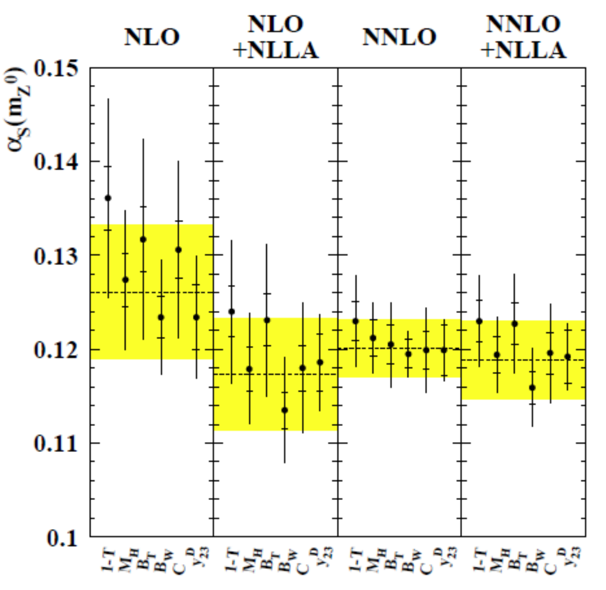

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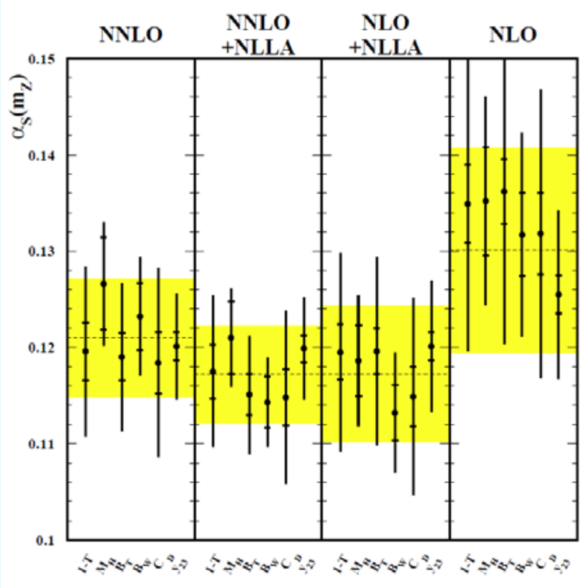

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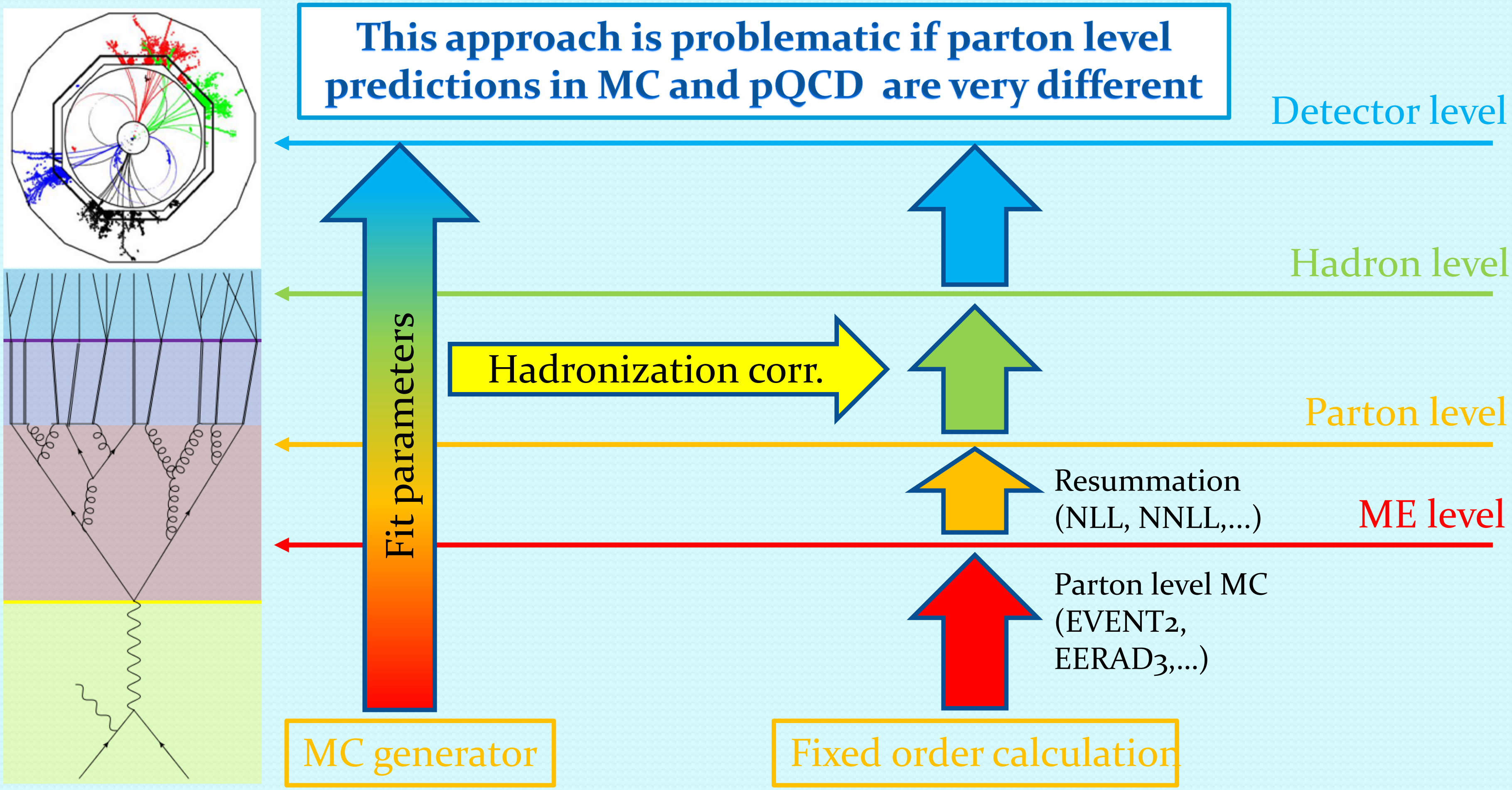
→ Problematic treatment of hadronization corrections

MC hadronization

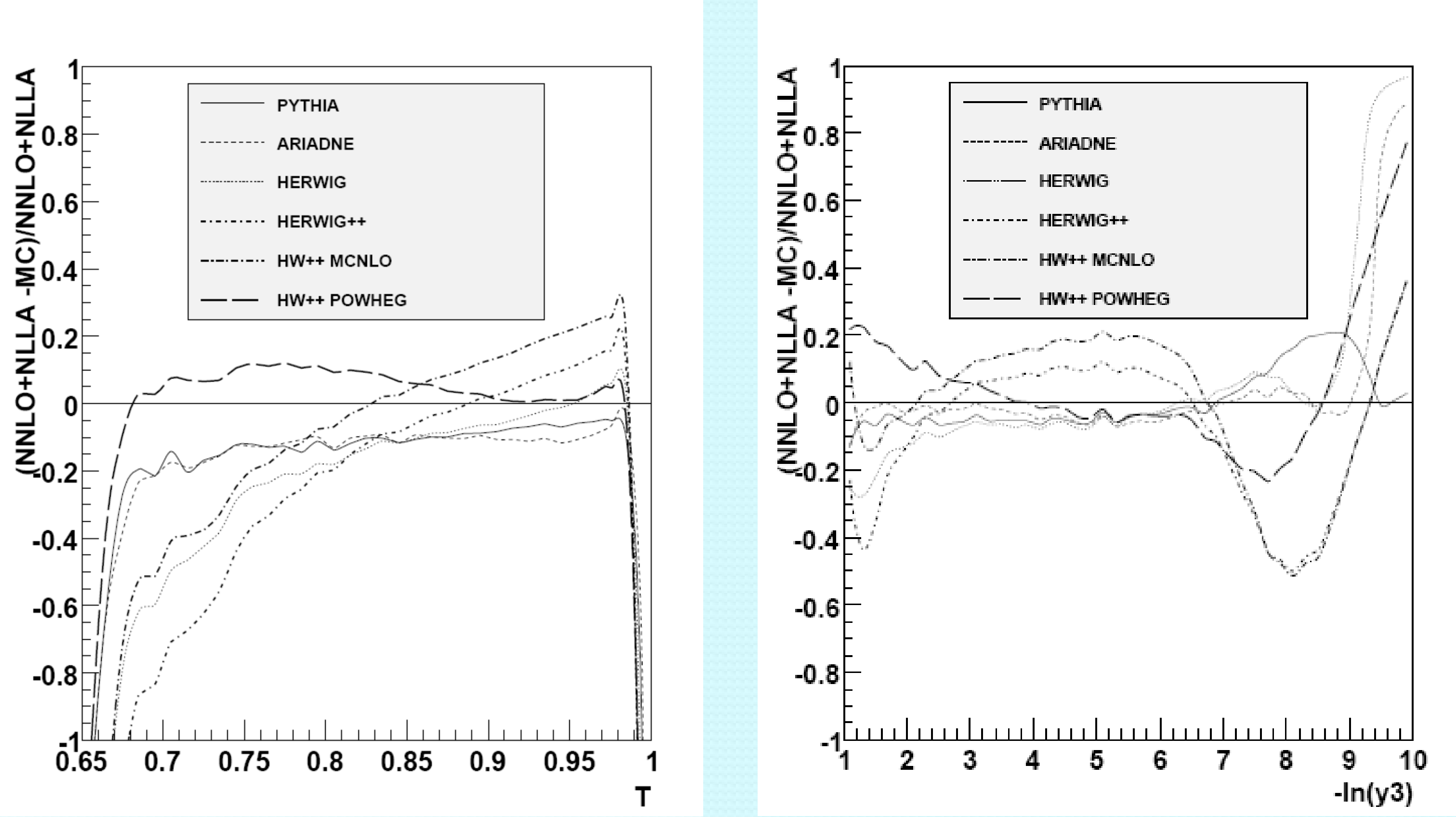


This approach is problematic if parton level predictions in MC and pQCD are very different

Resummation
(NLL, NNLL,...)

Parton level MC
(EVENT2,
EERAD3,...)

MC hadronization



[Dissertori et al.]

- Pythia parameters tuned such that missing higher order terms are over-compensated and hadronization corrections are effectively too small

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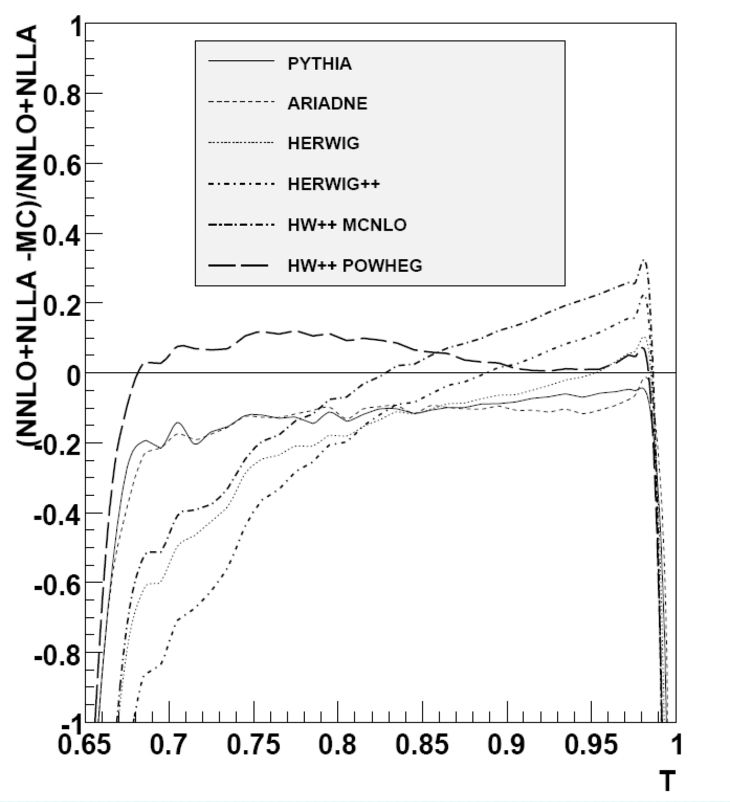
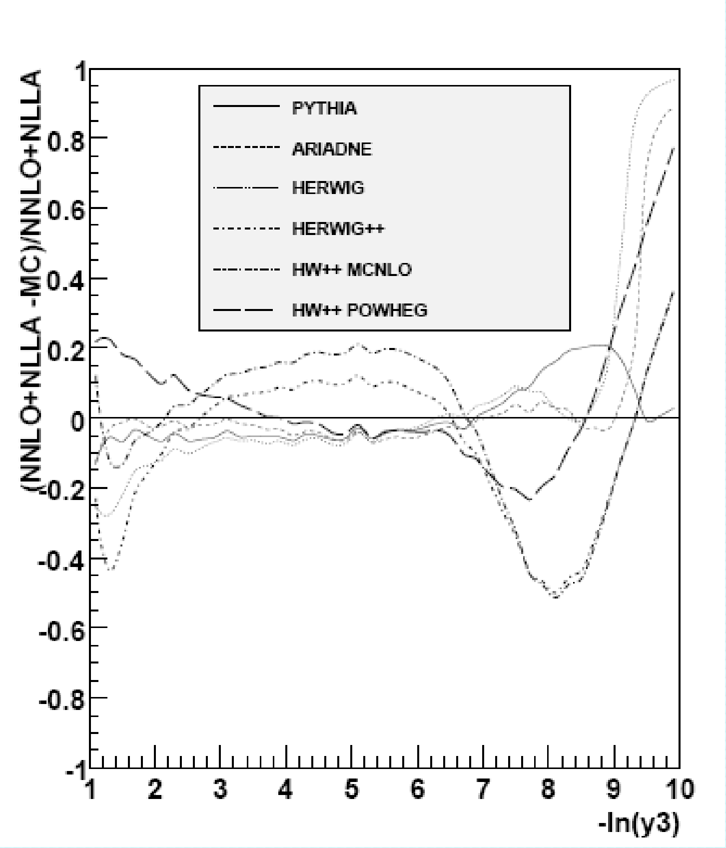
MC hadronization

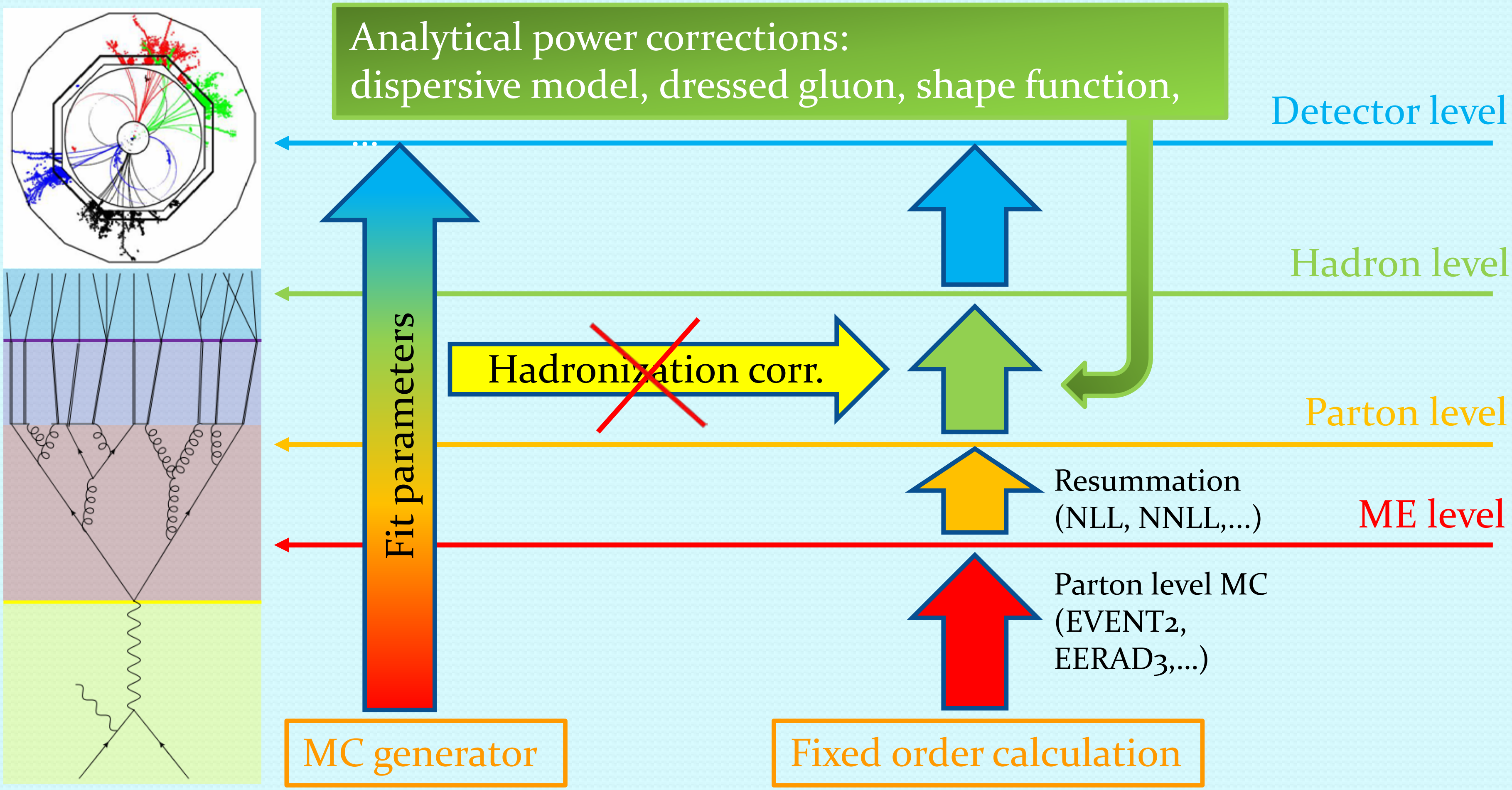




[Dissertori et al.]

$\alpha_s(M_Z)$	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

NNLO(+NLL) global fits



Analytical power corrections:
dispersive model, dressed gluon, shape function, …

Detector level

Hadron level

Parton level

ME level

Fit parameters

~~Hadronization corr.~~

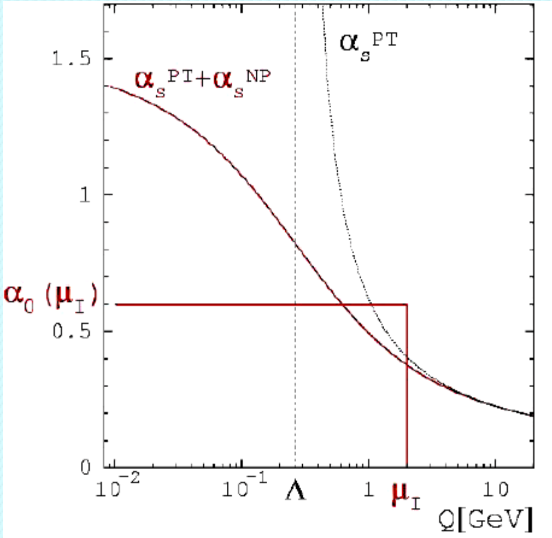
Resummation (NLL, NNLL,…)

Parton level MC (EVENT2, EERAD3,…)

MC generator

Fixed order calculation

Analytical Hadronization Models



- **Dispersive model** [Dokshitzer, Marchesini, Webber; Dokshitzer et al.]
  - NP corrections by means of a physical coupling:

$$\tilde{\alpha}_s(k_\perp^2) = \alpha_s^{\mathrm{PT}}(k_\perp^2) + \alpha_s^{\mathrm{NP}}(k_\perp^2)$$

  - Introduce matching scale μ_I and $\alpha_0(\mu_I) = \frac{1}{\mu_I}\int_0^{\mu_I} dk_\perp \tilde{\alpha}_s(k_\perp^2)$
  - NP correction amounts to a shift:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(y) = \frac{\mathrm{d}\sigma_{\mathrm{pt}}}{\mathrm{d}y}\,(y - a_y\,P)$$

- **Shape function** [Korchemsky, Sterman, Tafat; Abbate, Fickinger, Hoang, Mateu, Stewart]
  - Split soft function into PT and NP contribution:

$$S(\nu, Q) = \int_0^1 \frac{\mathrm{d}\alpha}{\alpha}\left(1 - e^{-\nu\alpha}\right)\left[\int_{\alpha^2 Q^2}^{\alpha Q^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2}\Gamma\left(\alpha_s(k_\perp^2)\right) + B\left(\alpha_s(\alpha Q^2)\right)\right]$$
$$\equiv S_{PT}(\nu, Q, \mu) + S_{NP}(\nu, Q, \mu)$$

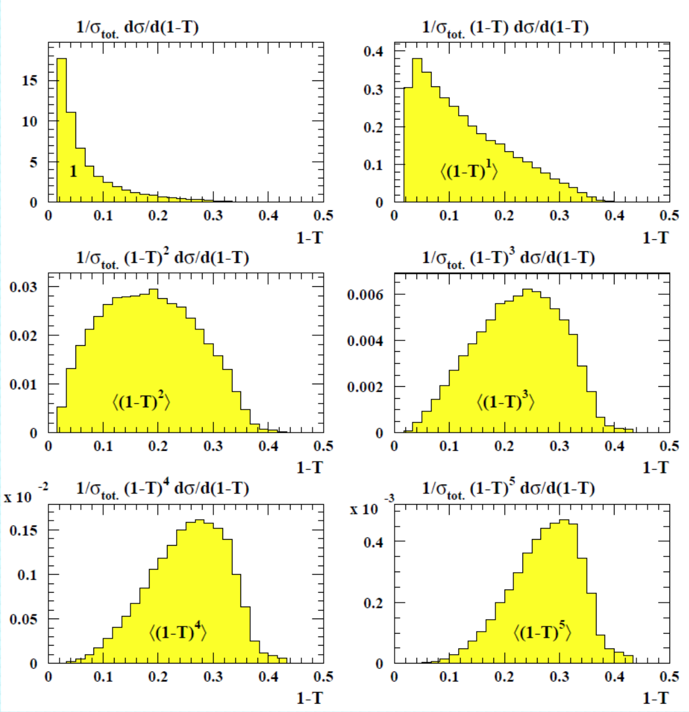
  - Again NP corrections amount to a shift:

$$\frac{\mathrm{d}\sigma_{\mathrm{PT}}(\tau)}{\mathrm{d}\tau} \longrightarrow \frac{\mathrm{d}\sigma_{\mathrm{PT}}(\tau - \lambda_1/Q)}{\mathrm{d}\tau} + \mathcal{O}\left(1/(\tau Q)^2\right) \quad \text{where} \quad \int \mathrm{d}\epsilon\, \epsilon\, f_T(\epsilon; \mu) = \lambda_1$$

α_s from moments

- Alternative to distributions: moments of event shapes

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



[Pahl]

- Higher moments more sensitive to multi-particle region
- Perturbative and non-perturbative contributions additive:

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

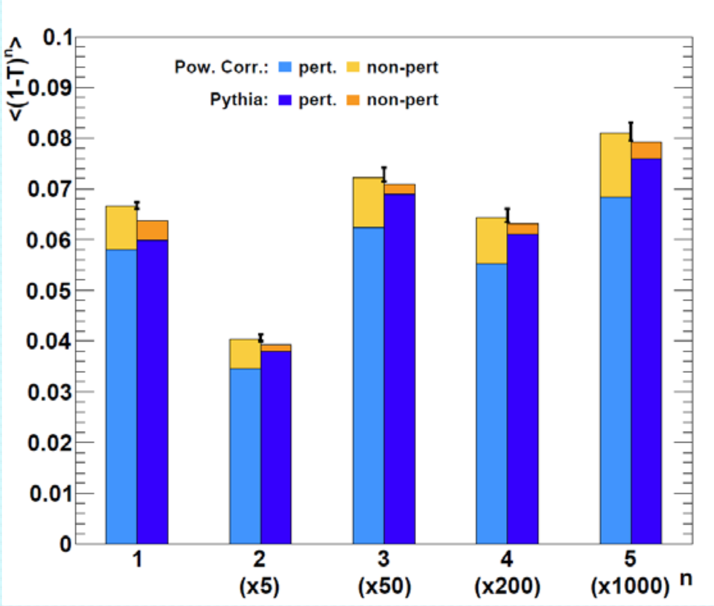
- Can add NP corretions either form Monte Carlo or from analytical description

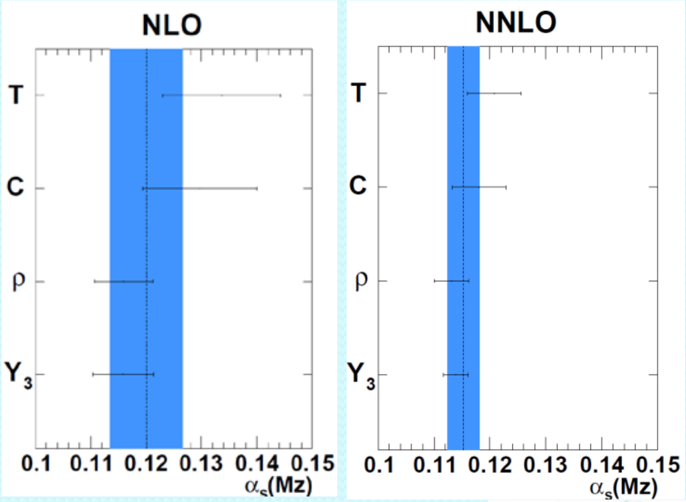
α_s from moments

[Gehrmann, Jaquier, GL, 0911.2422]

- With JADE/OPAL data:
  - Fit to first 5 moments of τ, ρ, C, Y_3
  - Broadenings not included in final average since analytical power correction was not fully extended at NNLO
  - No hadron mass corrections

$$\alpha_s(M_Z) = 0.1153 \pm 0.0017 \pm 0.0023$$
$$\alpha_0(2\text{GeV}) = 0.5132 \pm 0.0115 \pm 0.0381$$

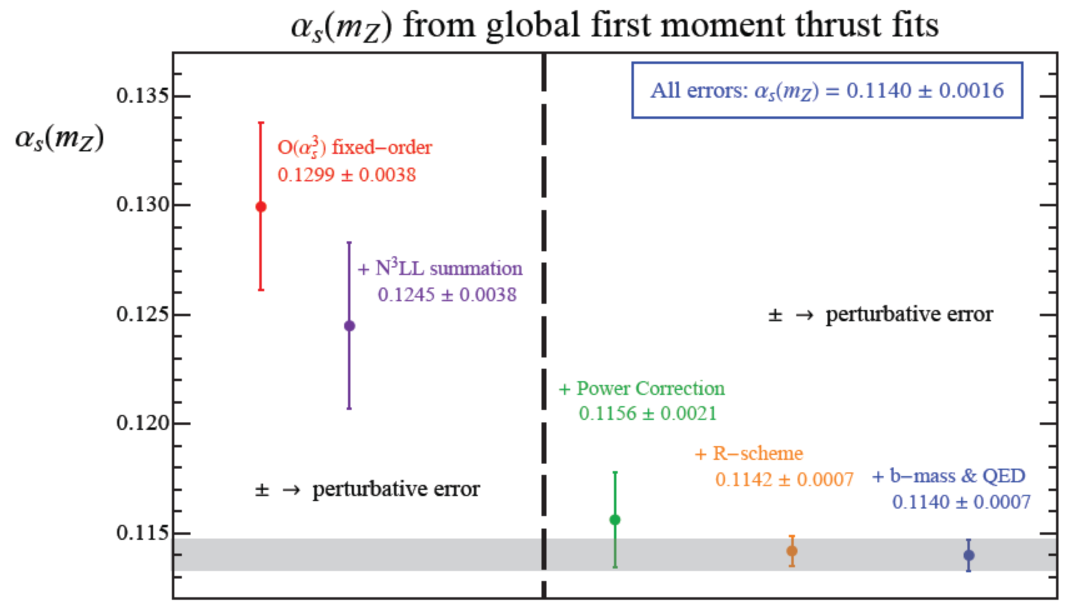


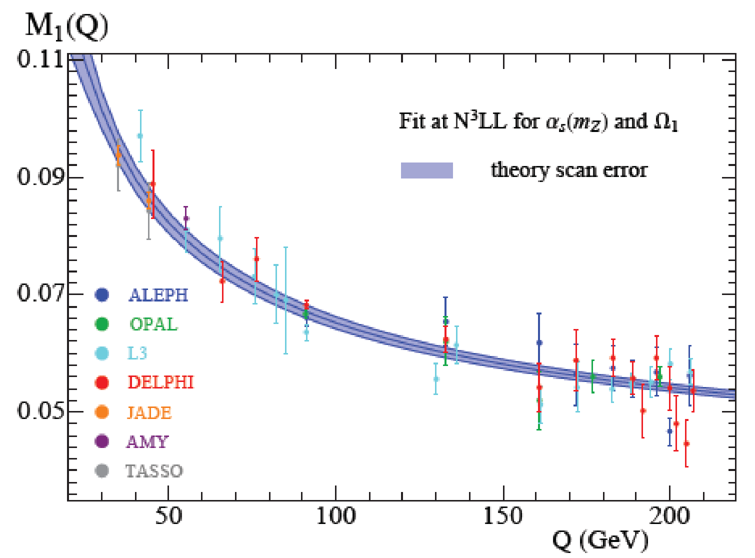


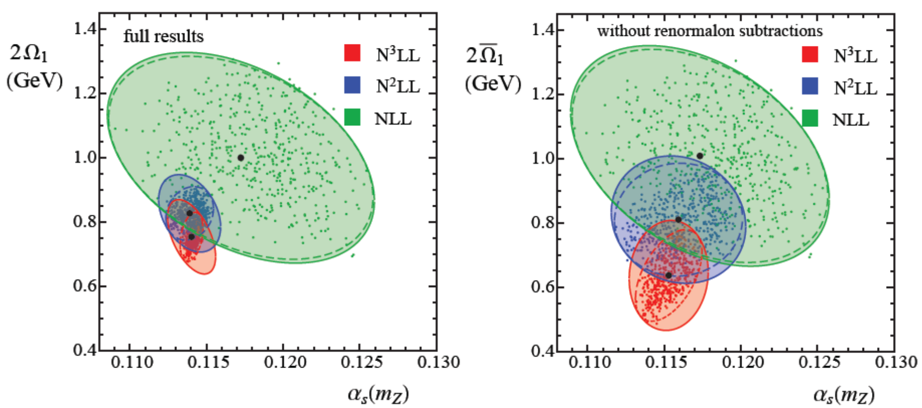
α_s from moments

[Abbate, Fickinger, Hoang, Mateu, Stewart, 1205.5746]

- Global fit for 1st moment of thrust







$$\alpha_s(M_Z) = 0.1141 \pm 0.0004 \pm 0.0016$$

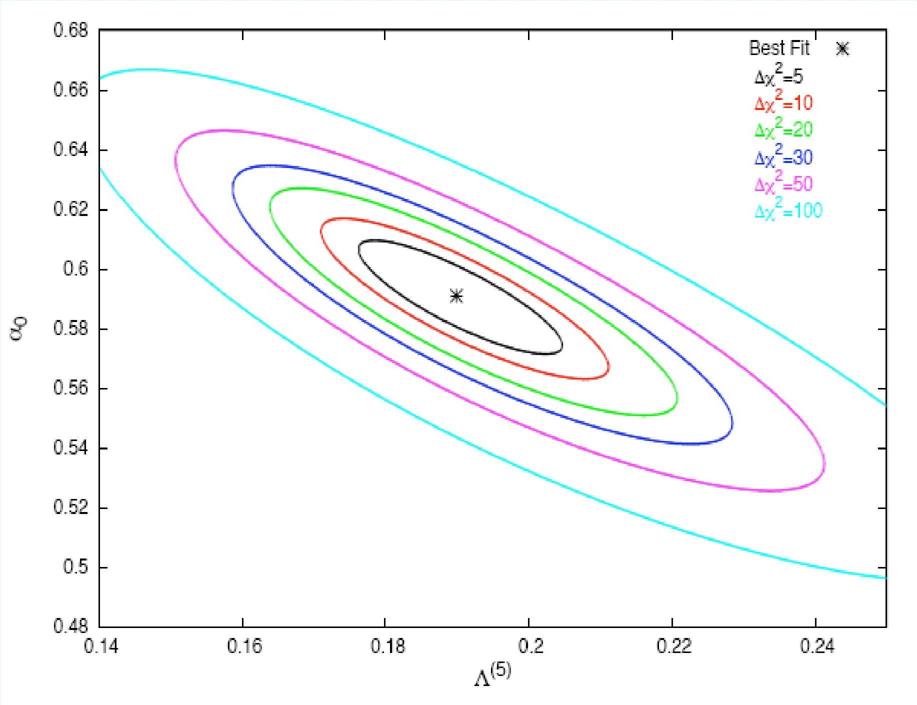
$$\Omega_1 = 0.372 \pm 0.044 \pm 0.039\,\text{GeV}$$

See also V.Mateu's talk

NLL+NNLO+PC with thrust

[Davison, Webber., 0809.3326]

- A first analysis with NNLO thrust distributions:
  - global fit for thrust distributions for energies between 14 GeV and 207 GeV.
  - power corrections within dispersive model
  - scale variation using factor $\sqrt{2}$



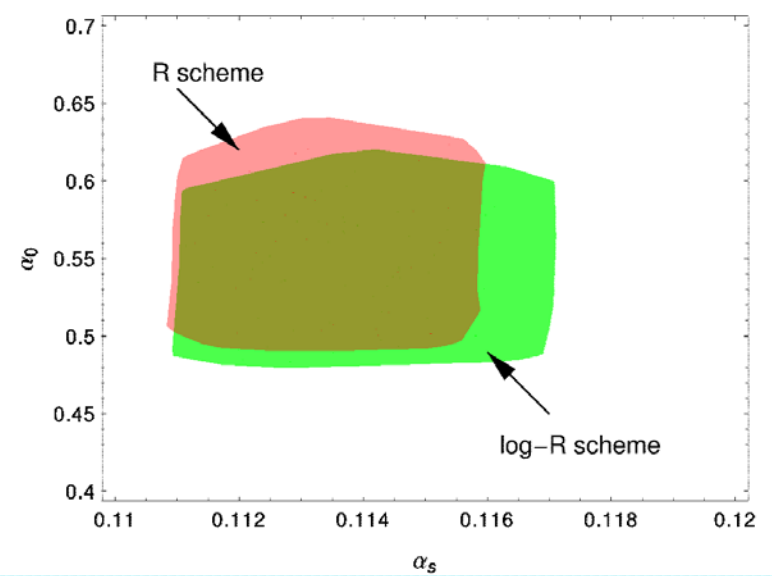
$$\alpha_s(M_Z) = 0.1164^{+0.0028}_{-0.0026}$$

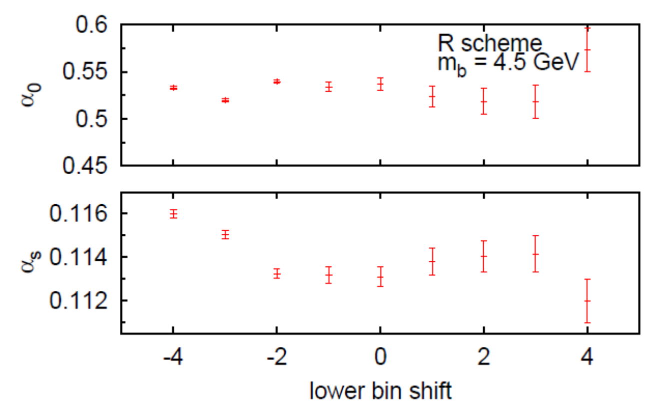
$$\alpha_0(2\text{GeV}) = 0.59 \pm 0.03$$

NNLL+NNLO+PC with thrust

[Gehrmann, GL, Monni, 1210.6945]

- Fit using TASSO/ALEPH/L3 data
  - NP corrections within dispersive model extended to account for NNLL+NNLO corrections
  - b-mass corrections included to NLO
  - Random scan can over theoretical parameters
  - Result stable by varying boundaries:



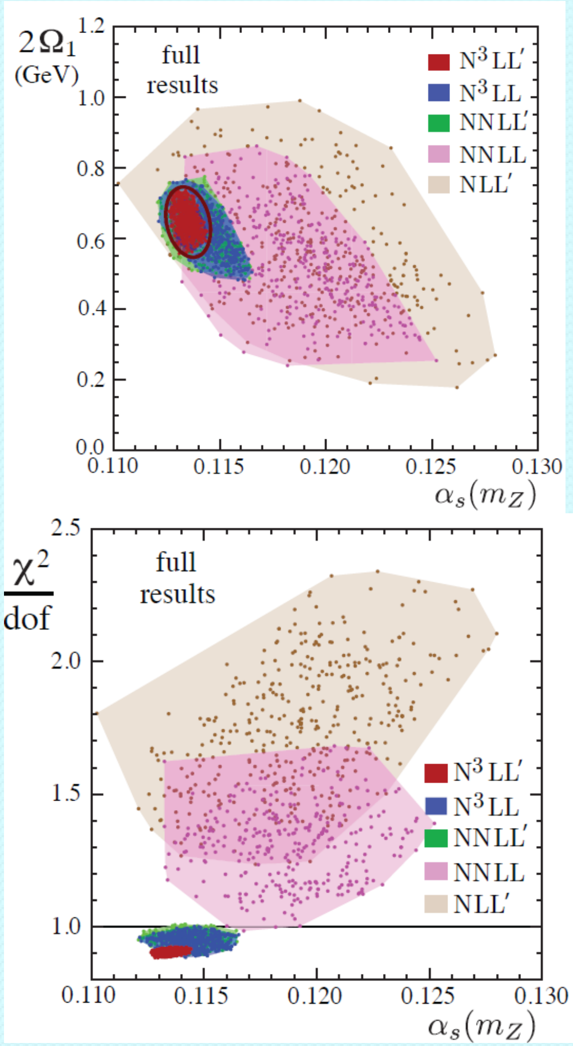


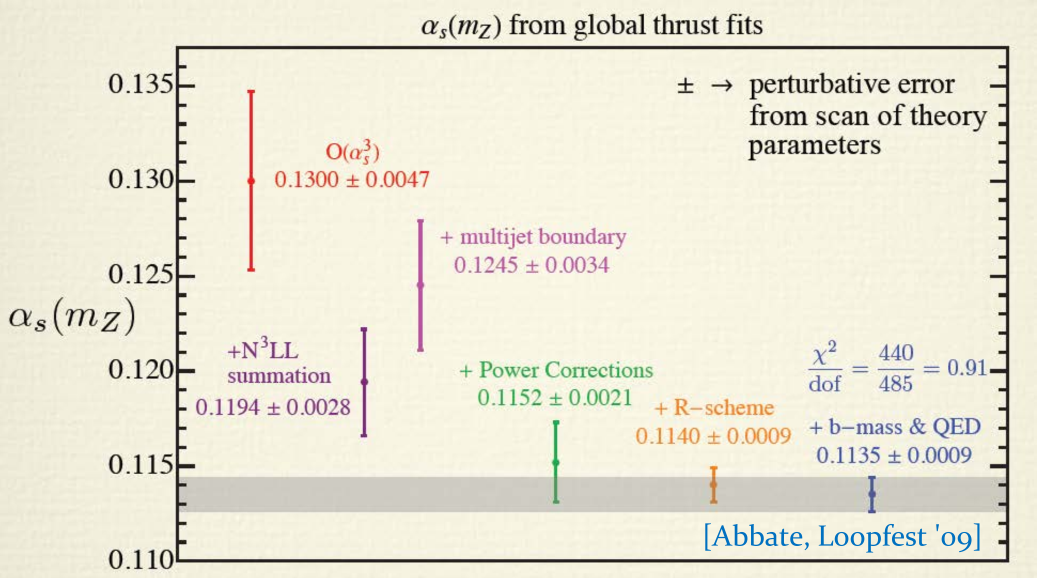
$$\alpha_s(M_Z) = 0.1131^{+0.0028}_{-0.0022}$$
$$\alpha_0(2\text{GeV}) = 0.538^{+0.102}_{-0.047}$$

NN(N)LL+NNLO+PC with thrust (SCET)

[Abbate, Fickinger, Hoang, Mateu, Stewart, 1006.3080]

- Global fit using thrust
  - Analytical hadronization with shape function
  - Renormalon subtraction
  - b-mass corrections and QED corrections





$$\alpha_s(M_Z) = 0.1135 \pm 0.0002 \pm 0.0010$$

$$\Omega_1 = 0.323 \pm 0.009 \pm 0.045\text{GeV}$$

See also V.Mateu's talk

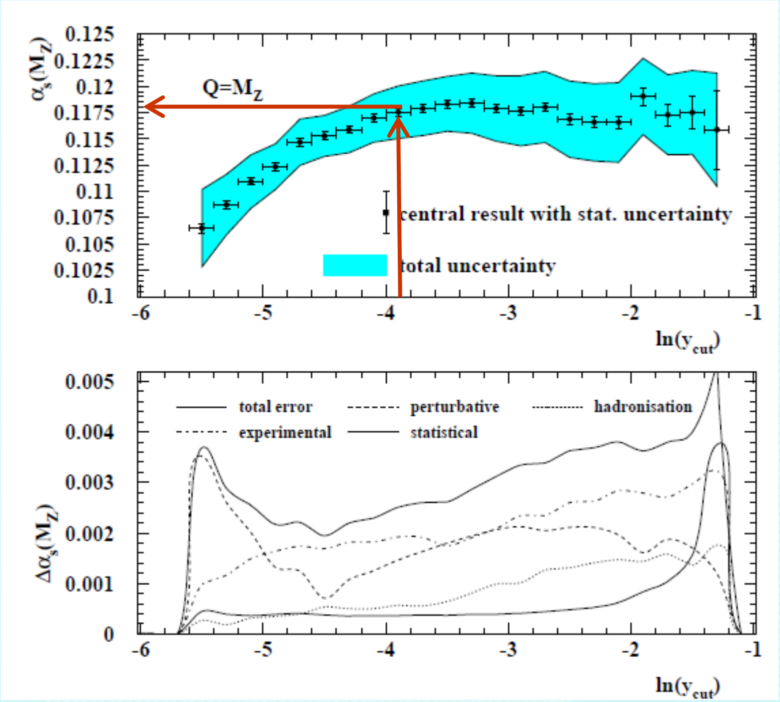
α_s from jet rates

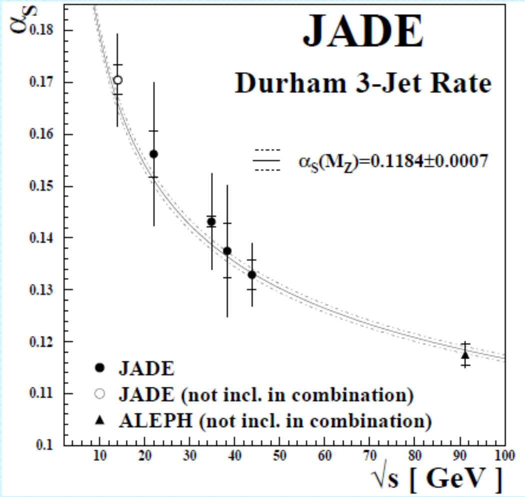
- ith jet rate: $R_i(y_{\mathrm{cut}}) = \frac{\sigma_i(y_{\mathrm{cut}})}{\sigma_{\mathrm{tot}}}$
- From 3-jet rates:
  - ALEPH: [Dissertori et al., 0910.4283]
    - NNLO only
    - Stable up to $\ln(y_{cut}) = -4.5$
    - Small hadronization corrections

$$\boxed{\alpha_s(M_Z) = 0.1175 \pm 0.0020 \pm 0.0015}$$

  - JADE: [Schieck et al., 1205.3714]
    - NNLO+NLLA+K + MC hadronization
    - Impact of resummation important

$$\boxed{\alpha_s(M_Z) = 0.1199 \pm 0.0023 \pm 0.0054}$$



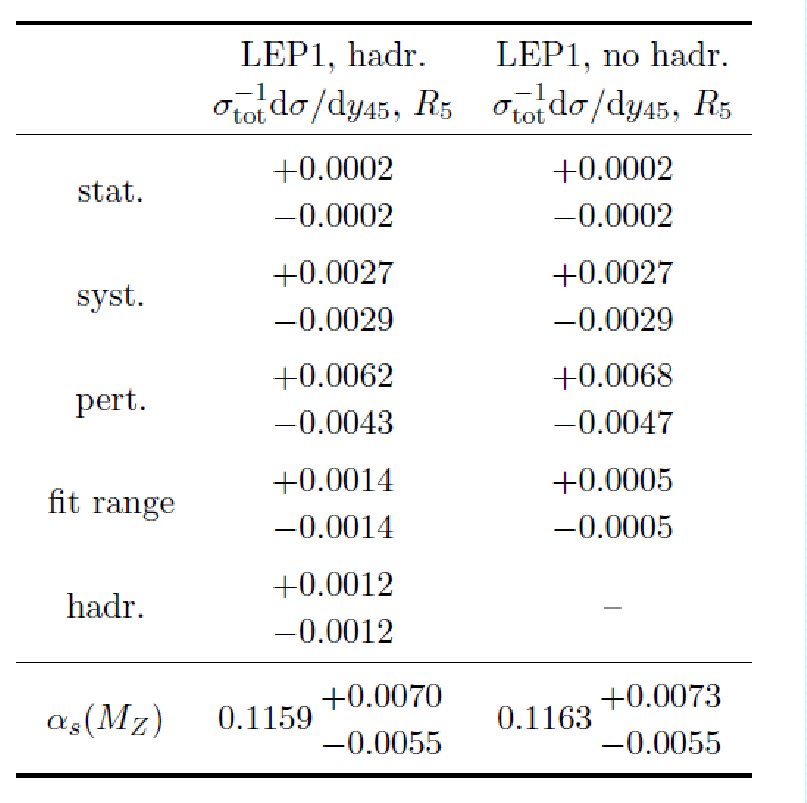


α_s from jet rates

- From 5-jet rates: [Frederix et al., 1008.5313]
  - Using ALEPH data
  - Hadronization corrections estimated with Sherpa

  → small, so **not** included

$$\boxed{\alpha_s(M_Z) = 0.1156^{+0.0041}_{-0.0034}}$$



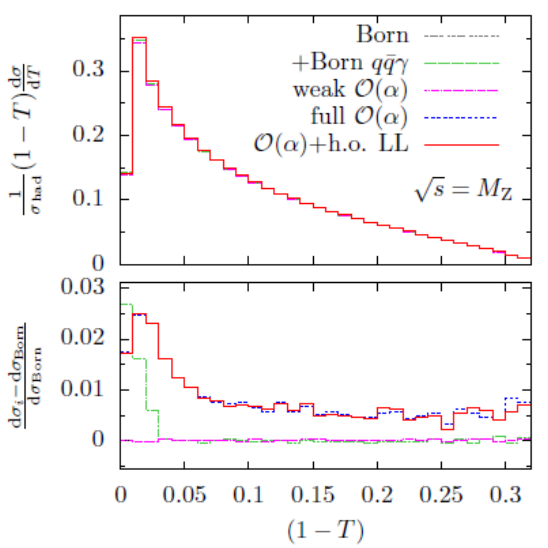
	LEP1, hadr. $\sigma_{\text{tot}}^{-1}\mathrm{d}\sigma/\mathrm{d}y_{45}$, R_5	LEP1, no hadr. $\sigma_{\text{tot}}^{-1}\mathrm{d}\sigma/\mathrm{d}y_{45}$, R_5
stat.	$^{+0.0002}_{-0.0002}$	$^{+0.0002}_{-0.0002}$
syst.	$^{+0.0027}_{-0.0029}$	$^{+0.0027}_{-0.0029}$
pert.	$^{+0.0062}_{-0.0043}$	$^{+0.0068}_{-0.0047}$
fit range	$^{+0.0014}_{-0.0014}$	$^{+0.0005}_{-0.0005}$
hadr.	$^{+0.0012}_{-0.0012}$	–
$\alpha_s(M_Z)$	$0.1159\,^{+0.0070}_{-0.0055}$	$0.1163\,^{+0.0073}_{-0.0055}$

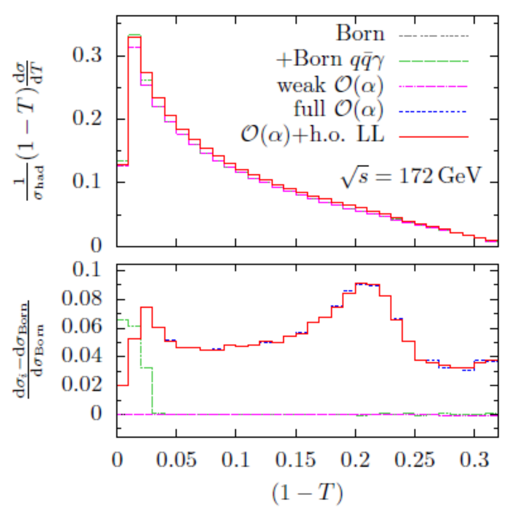
Table 2: Values of the strong coupling constant $\alpha_s(M_Z)$ obtained from fits to ALEPH LEP1 data for $\sigma_{\text{tot}}^{-1}\mathrm{d}\sigma/\mathrm{d}y_{45}$ and R_5. NLO QCD predictions are used. Hadronization corrections are estimated with SHERPA. Default fit ranges are $3.8 \leq -\ln y_{45} \leq 5.2$, and $4.0 \leq -\ln y_{\text{cut}} \leq 5.6$. See the text for details.

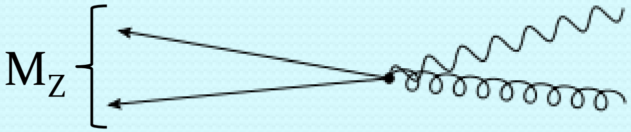
EW corrections & radiative return

[Denner, Dittmaier, Gehrmann, Kurz]

- NLO electroweak effect is potentially as large as NNLO QCD: $\alpha \approx \alpha_s^2$
  - Strong cancellation between event-shape distribution and hadronic cross section
    - ISR cancels
    - Weak loop corrections below per-mille
  - corrections depend on final state photon cuts
  - contribution from photon fragmentation
  - α_s determination with EW corrections non trivial:
    - LEP data corrected for photonic effects
    - At LEP2 radiative return not fully supressed

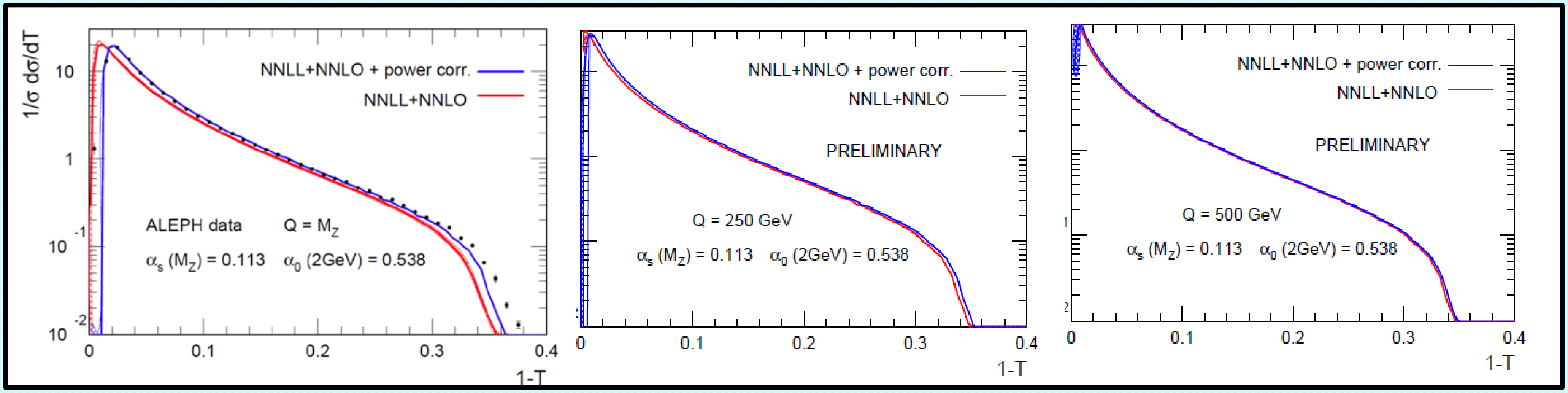




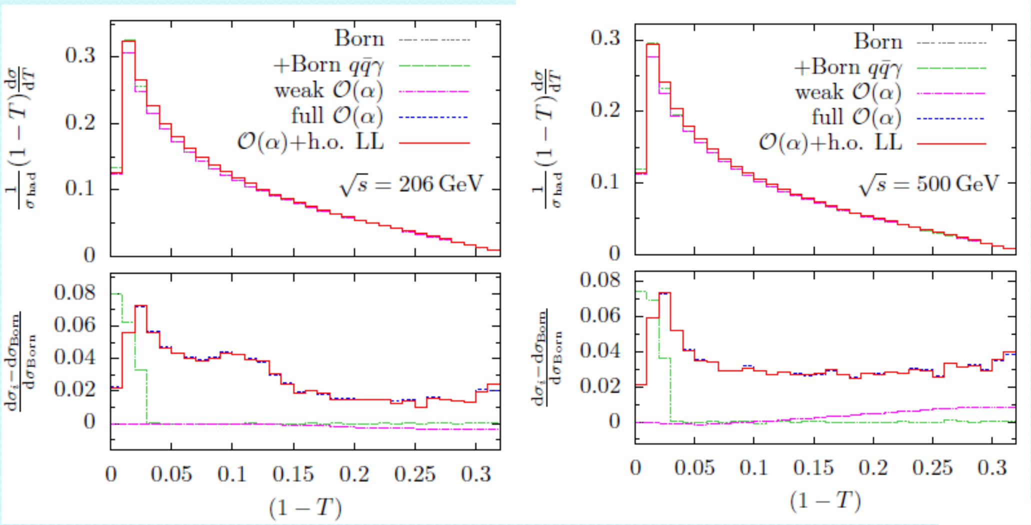


Perspective for ILC

- Hadronization corrections proportional to Q^{-1}:

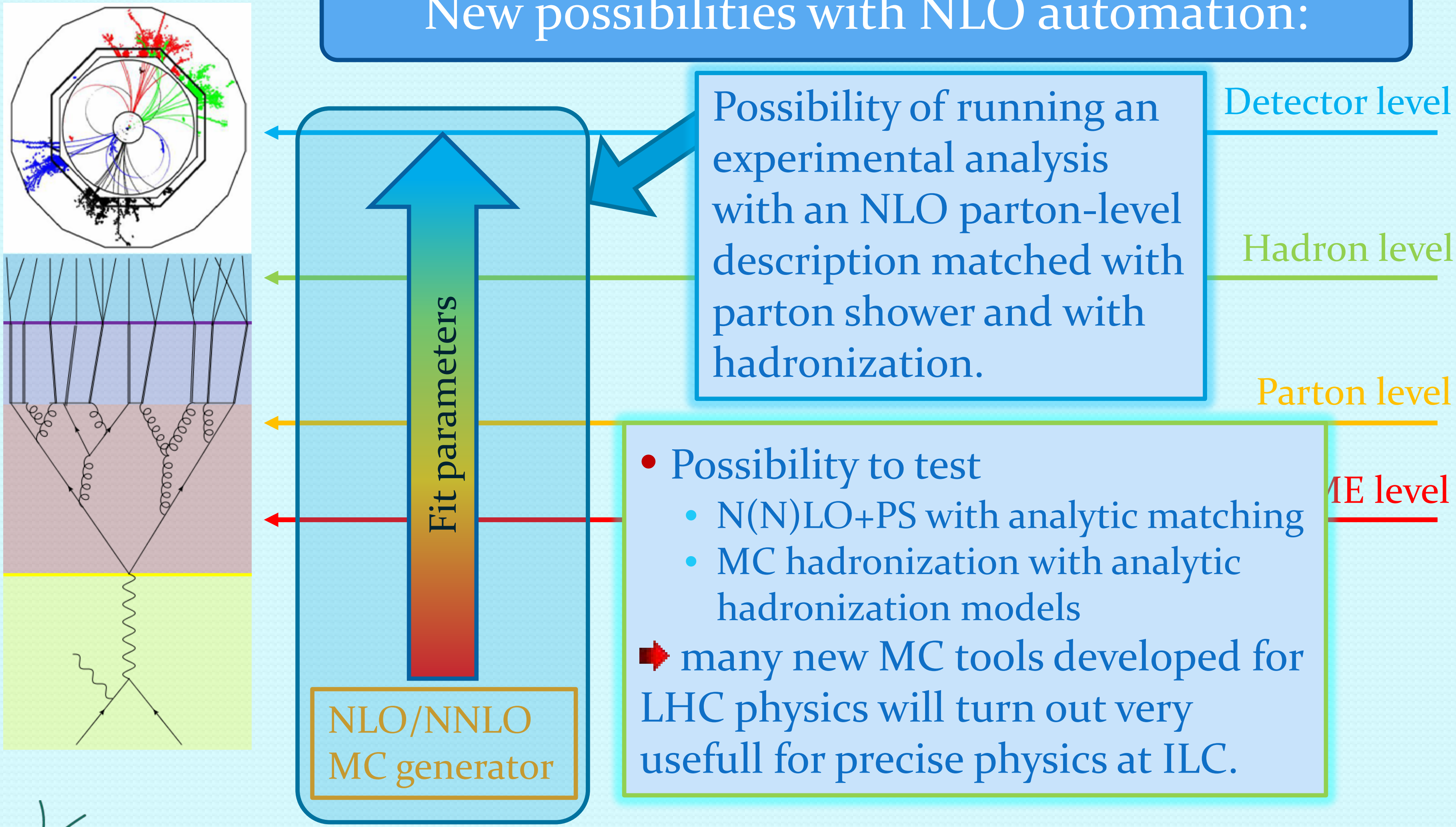


- No Radiative return:



Perspective for ILC

New possibilities with NLO automation:



Possibility of running an experimental analysis with an NLO parton-level description matched with parton shower and with hadronization.

- Possibility to test
  - N(N)LO+PS with analytic matching
  - MC hadronization with analytic hadronization models

➡ many new MC tools developed for LHC physics will turn out very usefull for precise physics at ILC.

Recent fits of the strong coupling

- NNLO/NLL+NNLO with MC hadronization:

1. a/b ALEPH: [Dissertori at al. `07, '09]

$\alpha_s(M_Z)= 0.1240 \pm 0.0013 \pm 0.0031$

$\alpha_s(M_Z)= 0.1224 \pm 0.0013 \pm 0.0037$

2. a/b JADE: [Bethke at al. `08]

$\alpha_s(M_Z)= 0.1210 \pm 0.0022 \pm 0.0057$

$\alpha_s(M_Z)= 0.1172 \pm 0.0021 \pm 0.0046$

3. a/b OPAL: [OPAL collaboration `11]

$\alpha_s(M_Z)= 0.1201 \pm 0.0015 \pm 0.0026$

$\alpha_s(M_Z)= 0.1189 \pm 0.0018 \pm 0.0037$

- NN(N)LL+NNLO without hadronization:

4. ALEPH/OPAL (T): [Becher, Schwartz `08]

$\alpha_s(M_Z)= 0.1172 \pm 0.0013 \pm 0.0017$

5. ALEPH/OPAL (ρ): [Chien, Schwartz `08]

$\alpha_s(M_Z)= 0.1220 \pm 0.0019 \pm 0.0024$

[First error stati+syst., second error theo+had]

- NLL+NNLO with dispersive model:

6. Global fit (T): [Davison, Webber `08]

$\alpha_s(M_Z)= 0.1164^{+0.0028}_{-0.0026} \quad \alpha_0(2\text{GeV}) = 0.59 \pm 0.03$

- NNLL+NNLO with dispersive model

7. Global fit (T): [Gehrmann, GL, Monni. `12]

$\alpha_s(M_Z)= 0.1131^{+0.0028}_{-0.0022} \quad \alpha_0(2\text{GeV}) = 0.538^{+0.102}_{-0.047}$

- NN(N)LL+NNLO with shape function

8. Global fit (T): [Abbate et al. `10]

$\alpha_s(M_Z)= 0.1135 \pm 0.0002 \pm 0.0010$

- Jet rates extraction

9. ALEPH (R_3): no hadronization [Dissertori et al. `10]

$\alpha_s(M_Z)= 0.1175 \pm 0.0020 \pm 0.0015$

10. JADE (R_3): NNLO+NLL [Schieck et al. `12]

$\alpha_s(M_Z)= 0.1199 \pm 0.0023 \pm 0.0054$

11. ALEPH (R_5): [Frederix et al. `10]

$\alpha_s(M_Z)= 0.1156^{+0.0041}_{-0.0034}$

Recent fits of the strong coupling 2

- NNLO moments:

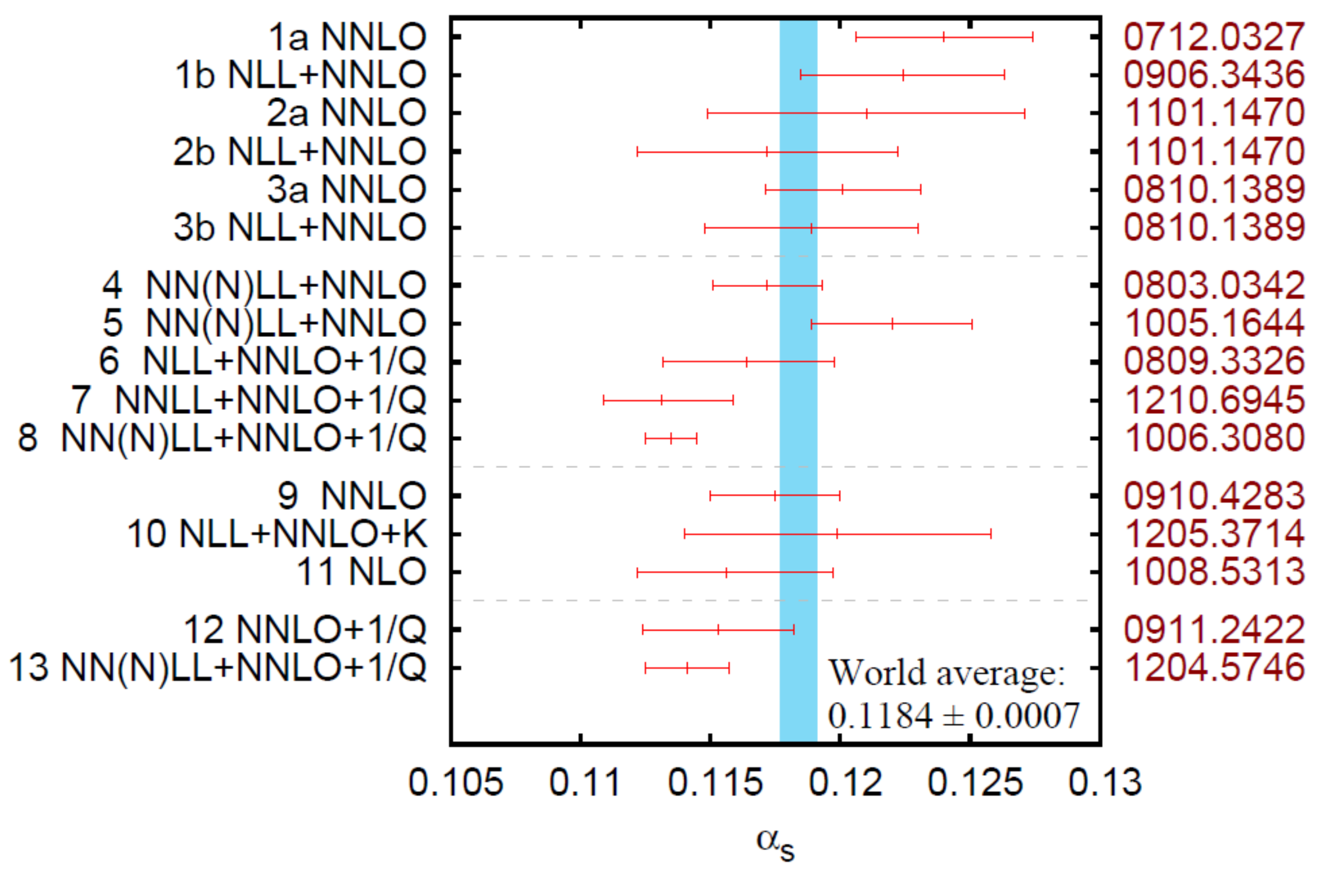
12. ALEPH: [Gehrmann, Jaquier, GL `08]

$\alpha_s(M_Z) = 0.1153 \pm 0.0017 \pm 0.0023$

$\alpha_0(2\text{GeV}) = 0.5132 \pm 0.0115 \pm 0.0381$

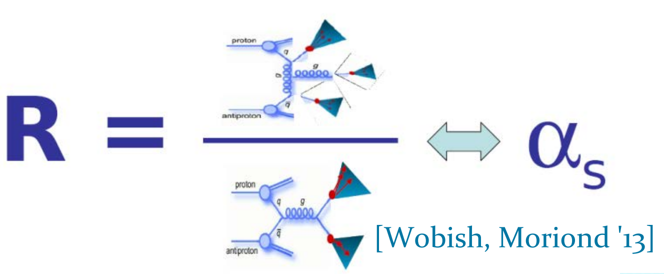
13. Global fit (T): [Abbate et al. `12]

$\alpha_s(M_Z) = 0.1141 \pm 0.0004 \pm 0.0016$

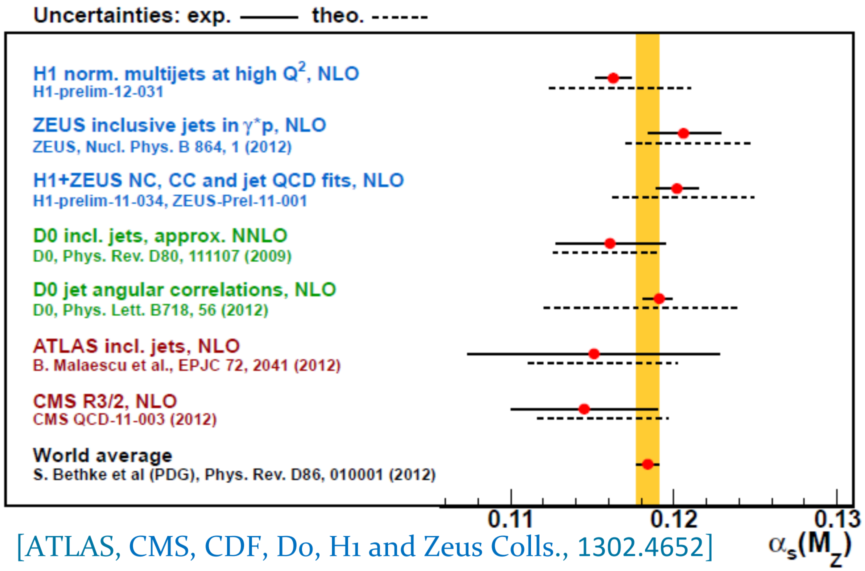


α_s from DIS and Hadron Collider

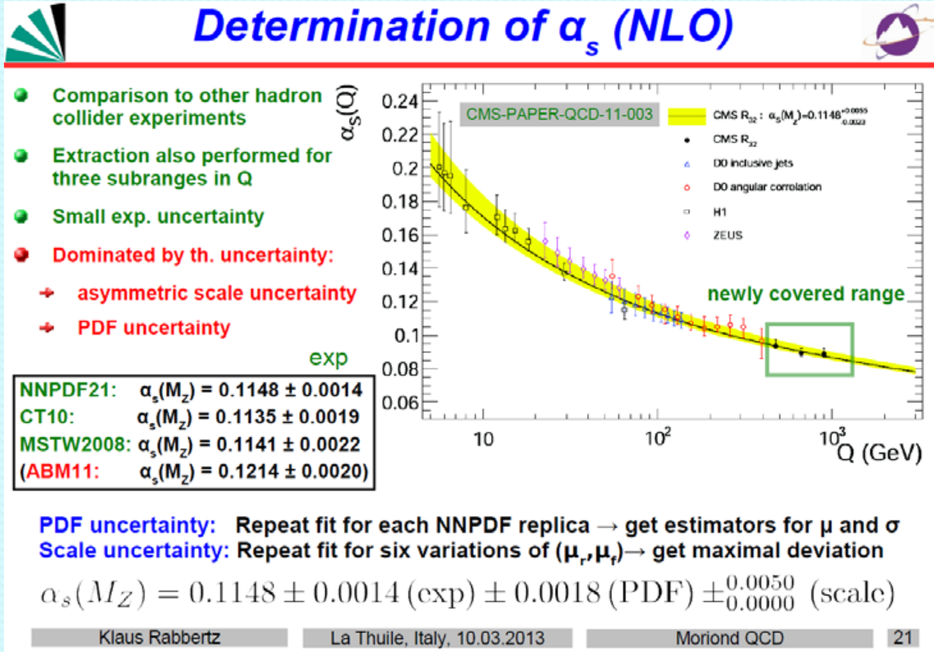
- On their way to precision …
  - From PDF's and jet observables



[Wobish, Moriond '13]



[ATLAS, CMS, CDF, D0, H1 and Zeus Colls., 1302.4652]



Determination of α_s (NLO)

- Comparison to other hadron collider experiments
- Extraction also performed for three subranges in Q
- Small exp. uncertainty
- Dominated by th. uncertainty:
  - asymmetric scale uncertainty
  - PDF uncertainty

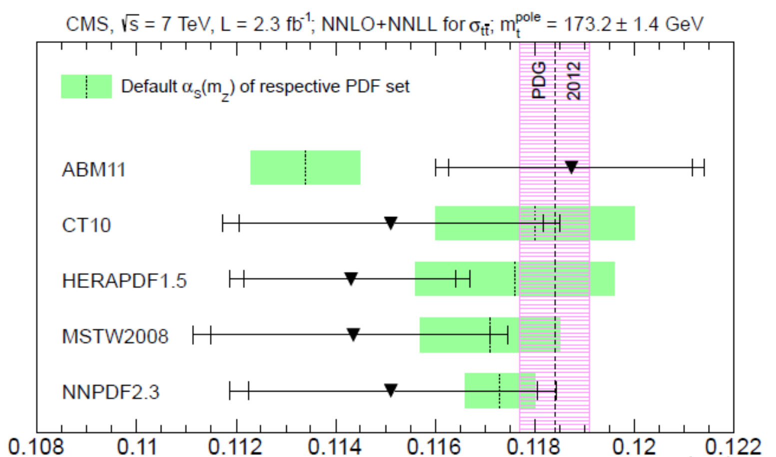
exp

NNPDF21: $\alpha_s(M_Z) = 0.1148 \pm 0.0014$
CT10: $\alpha_s(M_Z) = 0.1135 \pm 0.0019$
MSTW2008: $\alpha_s(M_Z) = 0.1141 \pm 0.0022$
(ABM11: $\alpha_s(M_Z) = 0.1214 \pm 0.0020$)

PDF uncertainty: Repeat fit for each NNPDF replica → get estimators for μ and σ
Scale uncertainty: Repeat fit for six variations of (μ_r, μ_f) → get maximal deviation

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp}) \pm 0.0018\,(\mathrm{PDF}) \pm^{0.0050}_{0.0000}\,(\mathrm{scale})$$

Klaus Rabbertz | La Thuile, Italy, 10.03.2013 | Moriond QCD | 21

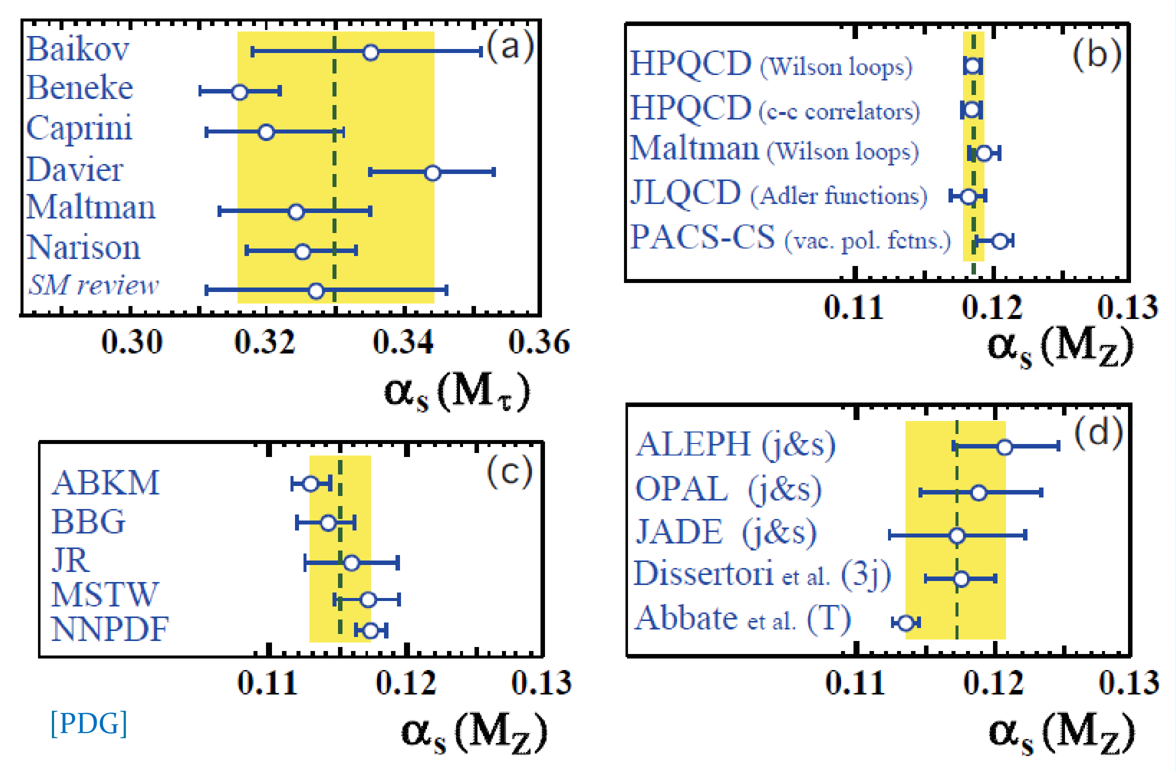


[CMS Coll., 1307.1907]

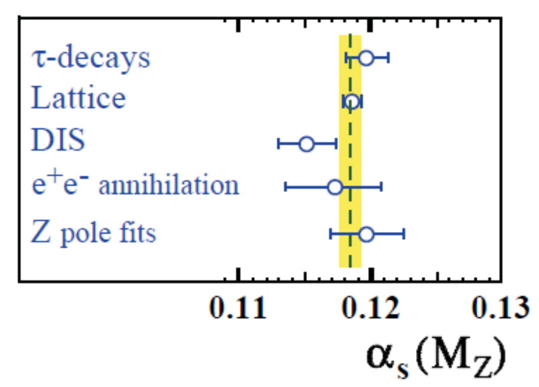
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

von Humboldt
Stiftung / Found

Further determinations of α_s



[PDG]



- Word average: [Bethke, '12]

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$

Conclusions & Outlook

- Many new determinations!!
  - e^+e^- now with NNLL+NNLO

• Fit to full standard set soon?

  - Hadronization corrections are now the challenge

• Further refinement in analytical models?
• What about new MC tools?

    - ILC can help since hadronization corrections get smaller!

  - Learning how to perform precise extractions also from Tevatron and LHC data!

Further new results from different sources are on their way, stay tuned!!