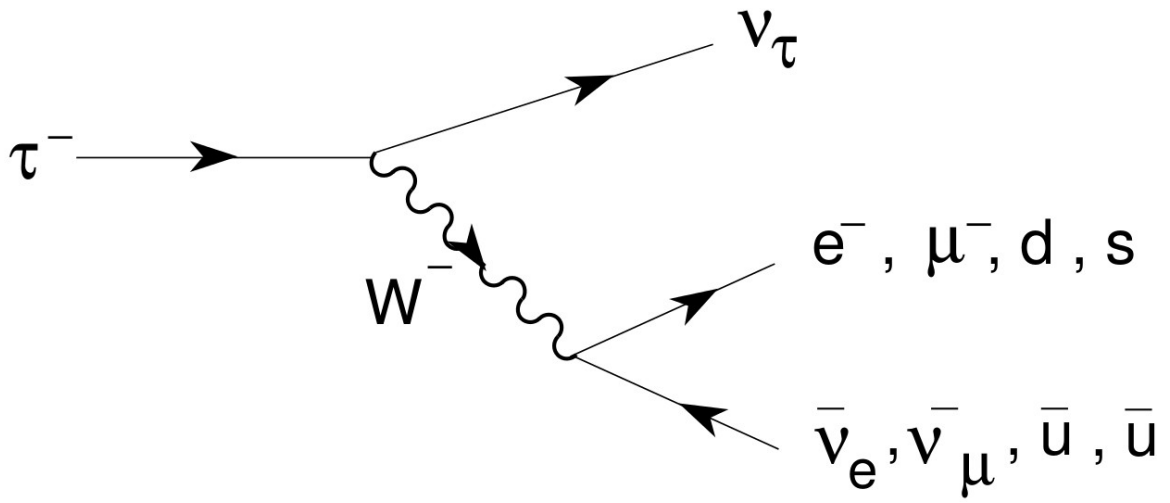
Measurements of α_s in e^+e^- annihilation

Stefan Kluth
MPI für Physik
Föhringer Ring 6
81369 München / Munich
Germany
skluth@mpp.mpg.de
LCWS2016, Morioka, Japan, 08.12.16

Introduction

- Inclusive observables
  - R_{had}, Γ_Z, R_τ, etc
  - No restrictions on final state, QCD is small correction to EW production or decay, experimental systematics
- Semi-inclusive observables
  - Fragmentation functions etc
  - Sensitivity to QCD evolution
- Exclusive observables
  - Jets, event shapes
  - Leading QCD effects, high sensitivity, but complex calculations and impact of experimental and hadronisation effects

Inclusive τ hadronic width



$$R_\tau = \Gamma(\tau^- \to \nu_\tau \text{ hadrons}) / \Gamma(\tau^- \to \nu_\tau \bar{\nu}_e e^-)$$

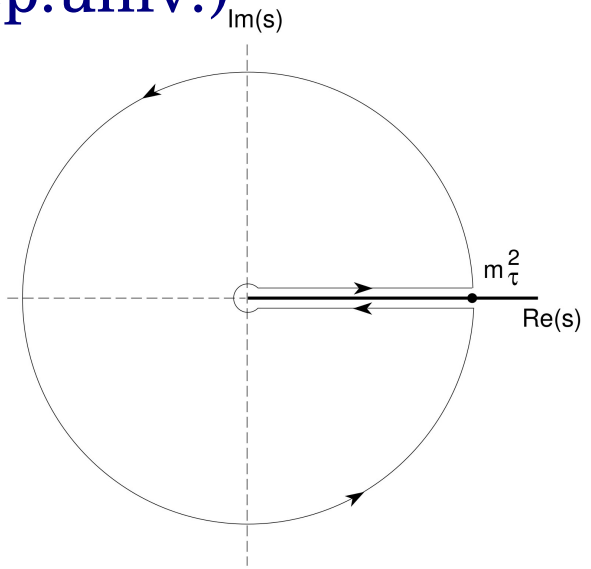
$$R_\tau = (1 - BR_\mu - BR_e) / BR_e = 3.6397 \pm 0.0076 \text{ (lep.univ.)}$$

$$R_{\tau,V+A} = R_\tau - R_{\tau,S} = N_C |V_{ud}|^2 S_{EW} (1 + \delta_{pert} + \delta_{NP})$$

$$R_{\tau,S} = 0.1614 \pm 0.0028$$

$$\delta_{pert} =_{CIPT} \sum_{n=1}^{4} K_n A^{(n)}(\alpha_S)$$

$$=_{FOPT} \sum_{n=1}^{4} r_n a_\tau^n \; ; \; a_\tau^n = \alpha_S(m_\tau^2)/\pi$$



[Prog. Part. Nucl. Phys. 75 (2014) 41]

Inclusive τ hadronic width

Determination of α_S:

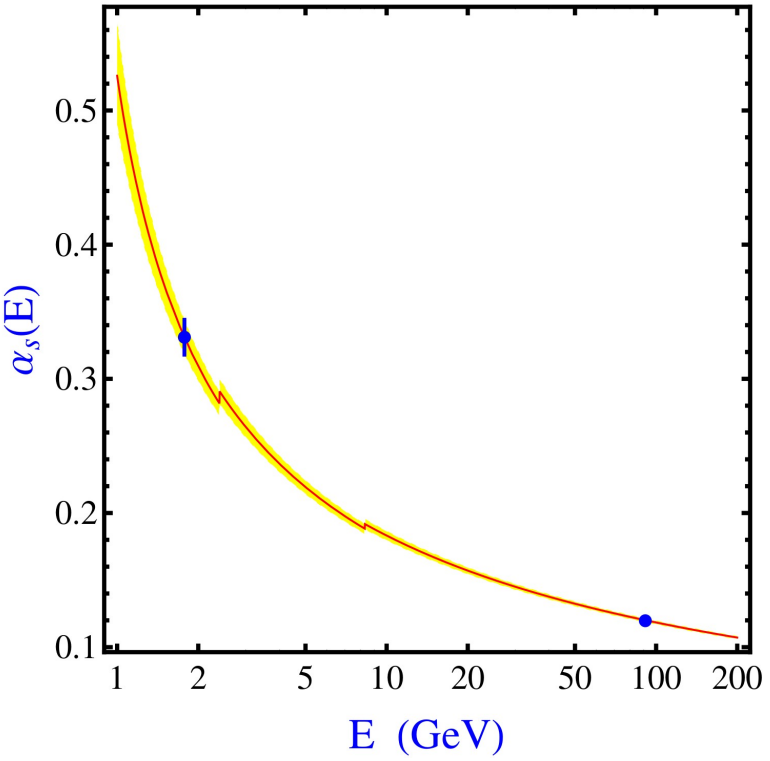
$\alpha_S(m_\tau^2)_{CIPT} = 0.341 \pm 0.013$

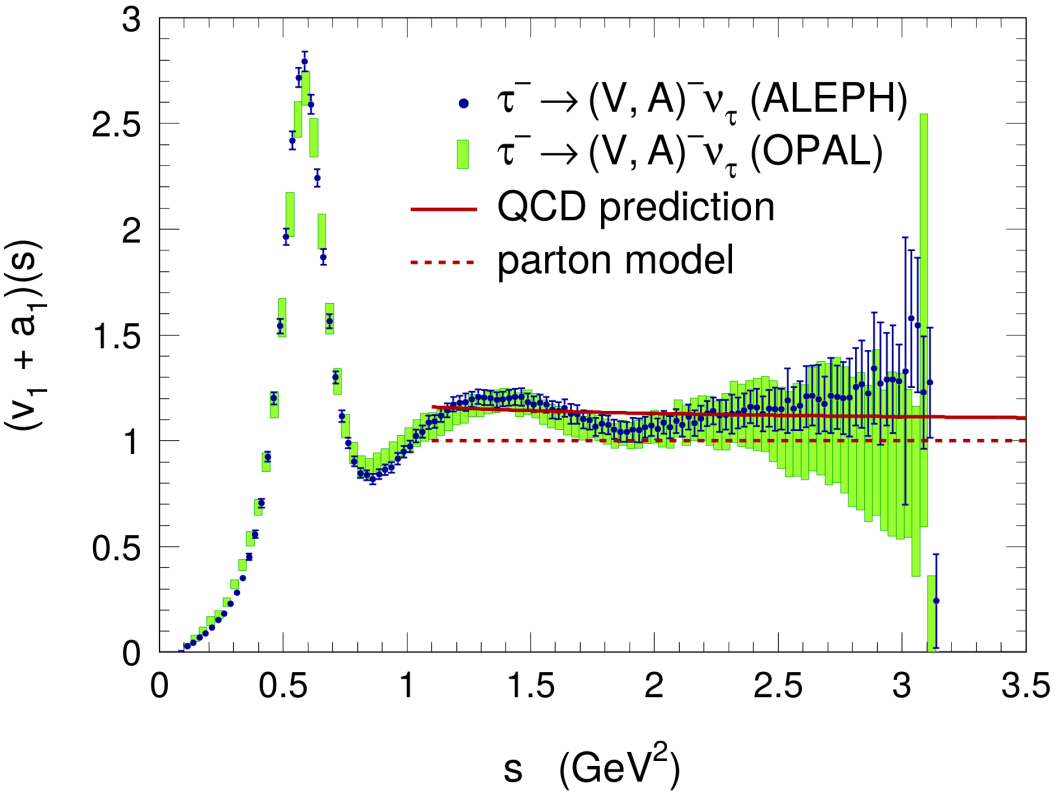
$\alpha_S(m_\tau^2)_{FOPT} = 0.319 \pm 0.014$

$\alpha_S(m_\tau^2)_{comb} = 0.331 \pm 0.013$

$\alpha_S(m_Z^2) = 0.1200 \pm 0.0015$

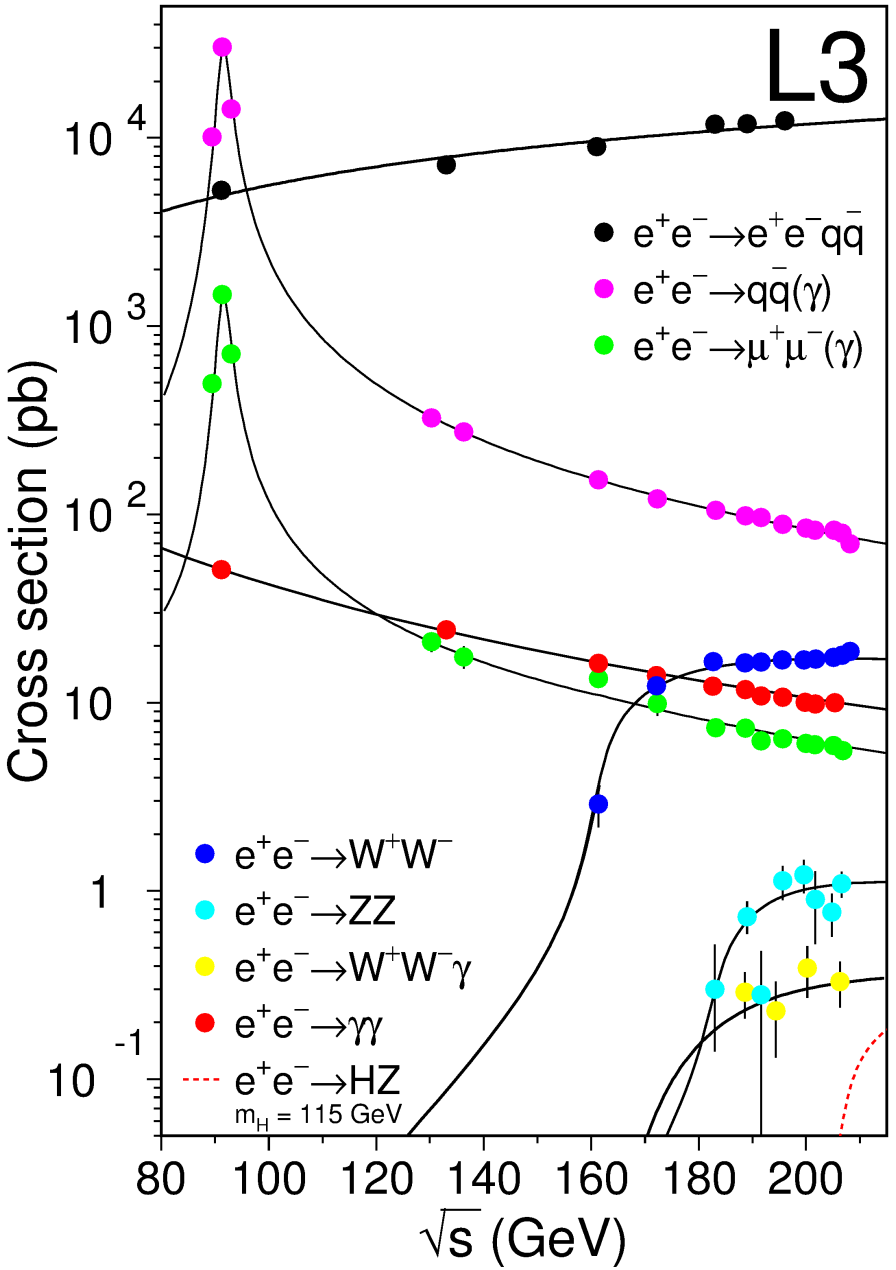
$\delta_{NP} = -0.0059 \pm 0.0014$



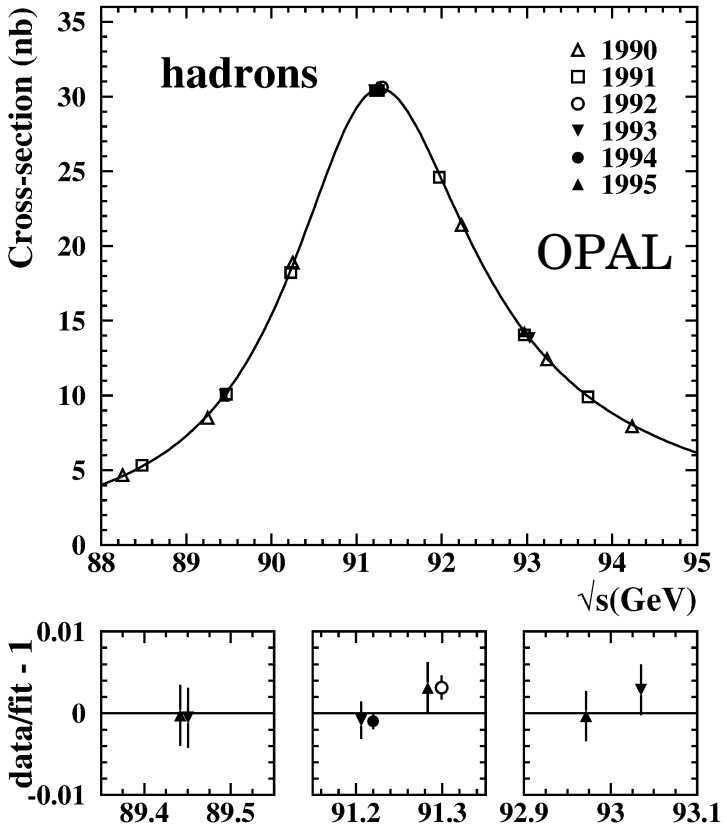


[Prog. Part. Nucl. Phys. 75 (2014) 41; updated error analysis in Mod. Phys. Lett. A31 (2016) 1630032]

EW precision fit

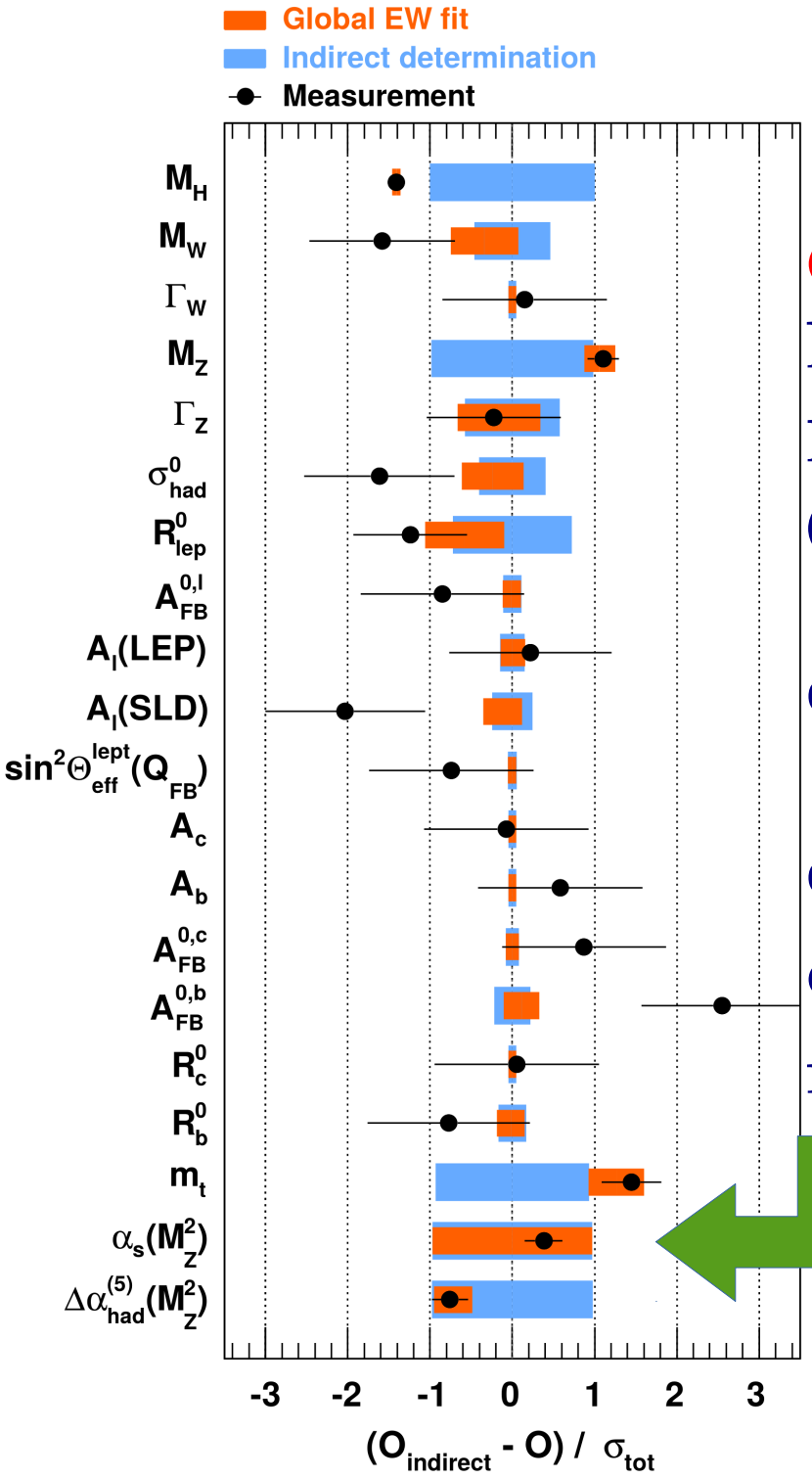


Dominated by had. Z width, but also contributions from QCD corrections to other EW processes with quarks



[Phys. Rept. 532 (2013) 119]

[Eur. Phys. J. C19 (2001) 587]



EW precision fit

QCD corrections to Z partial width, had. Z pole cross section and other parameters e.g. m_W or m_t in NNLO (partially N3LO)

$\alpha_S(m_Z) = 0.1196 \pm 0.0028_{exp.} \pm 0.0009_{theo.}$

α_S is only free parameter w/o corresponding direct measurement (α_S point in plot is world average)

GigaZ!

[Eur. Phys. J. C74 (2014) 3046]

R_{had} at "high" energy

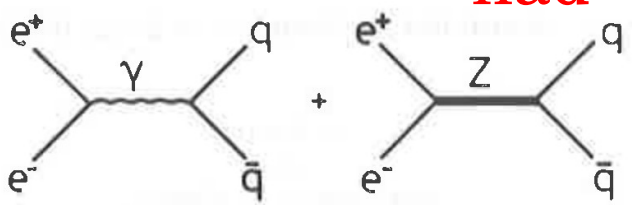


Figure 1: Tree diagrams for $e^+e^- \rightarrow hadrons$

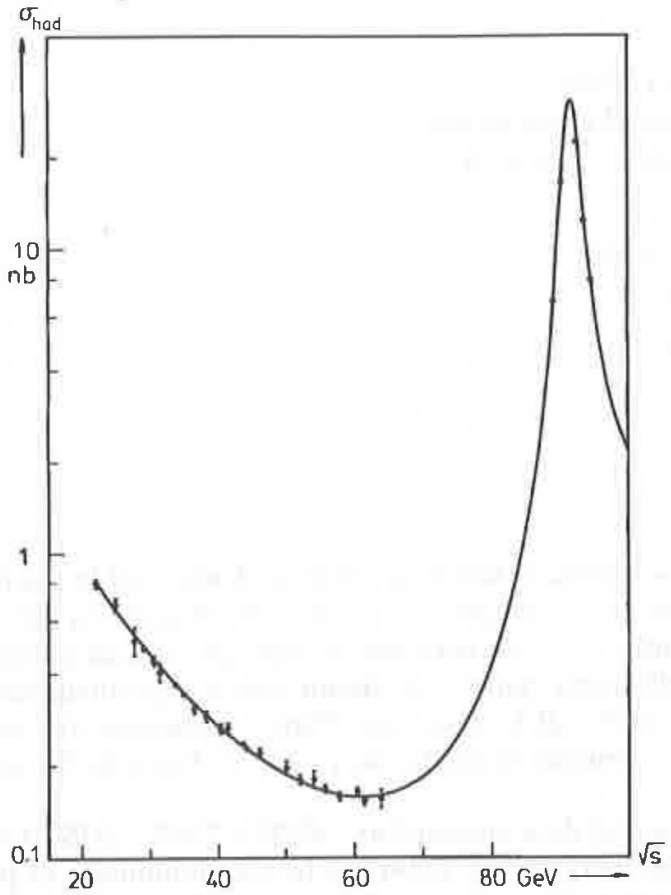
$$R_{had} = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$$
$$= 3\Sigma q_i^2(1 + \alpha_S/\pi + 1.441(\alpha_S/\pi)^2 - 12.8(\alpha_S/\pi)^3)$$

$\sigma(e^+e^- \rightarrow \text{hadrons})$ corrected for EW effects

$\alpha_S(m_Z) = 0.126 \pm 0.022_{exp}$

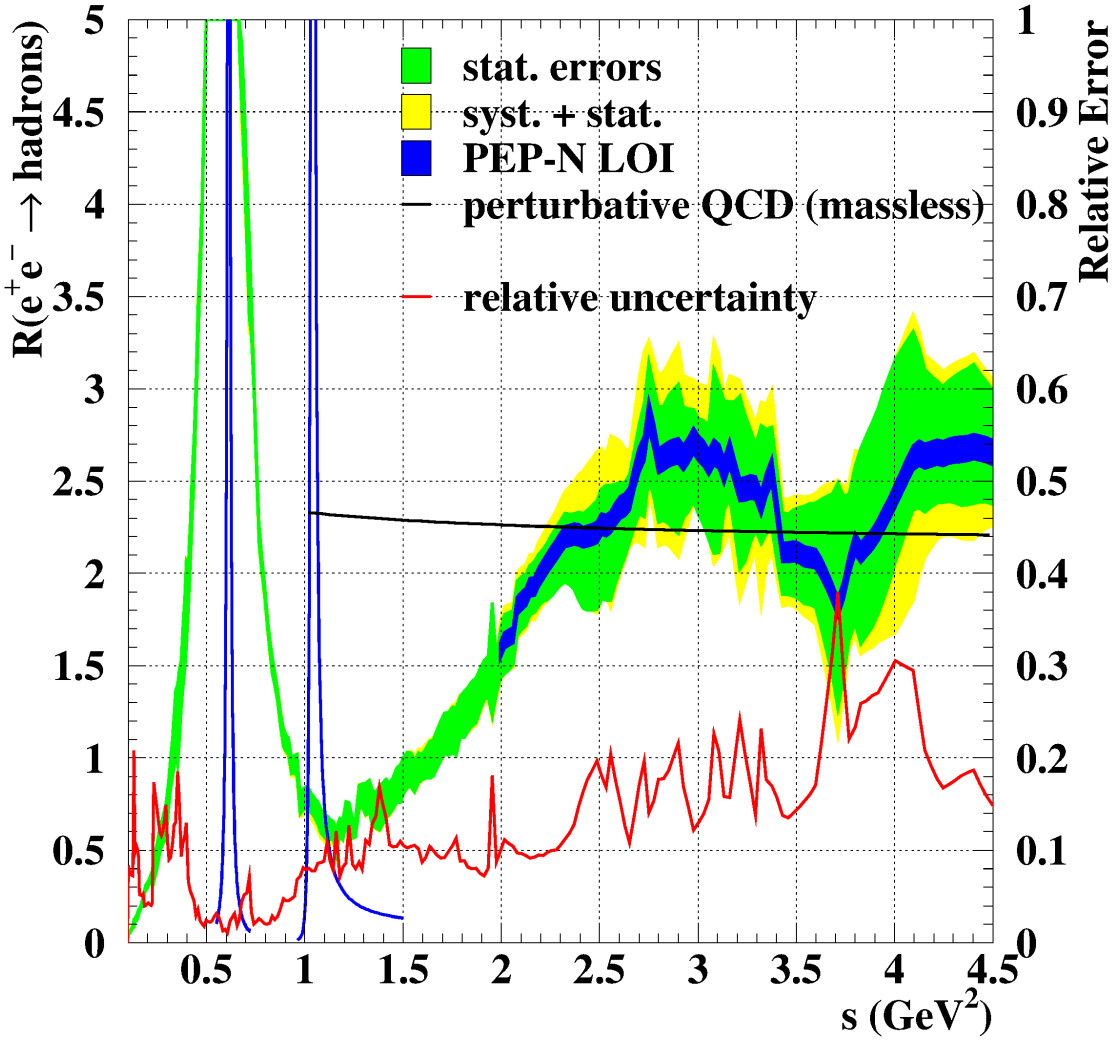
Dominated by statistics (O(10k)) and MC based efficiency corrections

GigaZ ISR and/or low energy runs?



[J. Phys. G 26 (2000) R27; Haidt D, in "Precision tests of the standard electroweak model" ed Langacker P vol 14 of Advanced Series on Directions in High Energy Physics (World Scientific,1995)]

R_{had} at (very) low energy



Prediction for R_{had} at low energies analogous to hadronic τ width in (N)NNLO QCD

Full control over non-pert. effects, but source of syst. errors

Improvement with new data from BaBar, Belle, KLOE ISR programs?

[hep-ex/0106011]

$$\alpha_S(2\ \text{GeV}) = 0.286 \pm 0.031_{exp} \pm 0.015_{theo}$$

$$\alpha_S(m_Z) = 0.117 \pm 0.005_{exp} \pm 0.002_{theo}$$

Fragmentation functions in e^+e^-

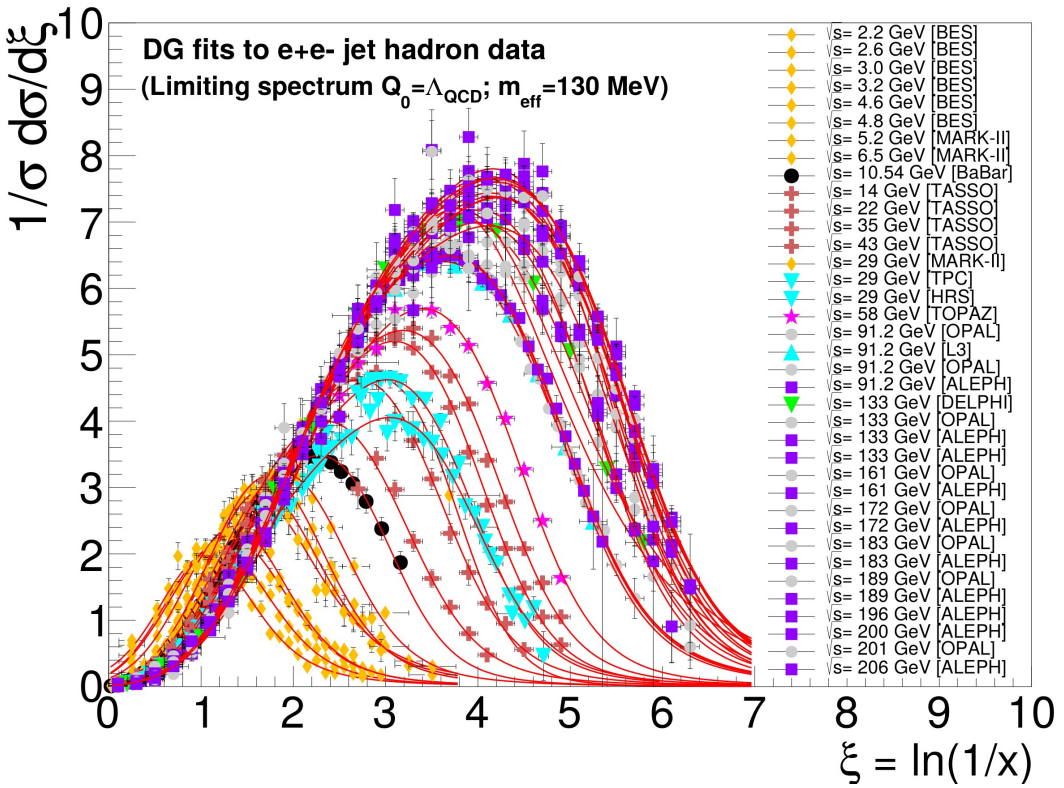
$D_h(\xi,s) = 1/\sigma_{tot} d\sigma(e^+e^- \to h+X)/d\xi$; $\xi = \ln(1x)$ "hump-backed plateau"

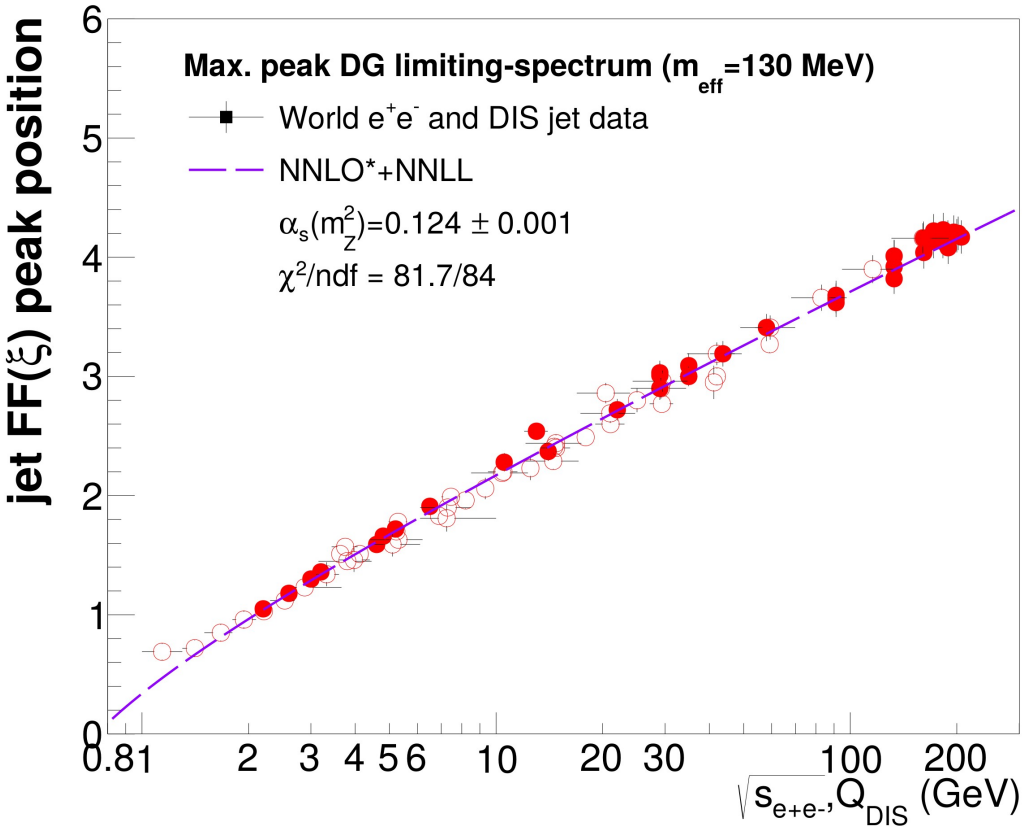
$D_h(\xi,s) = \sum_i \int C_i(z,\alpha_S,s)\, D_i^h(x/z, s)\, dz/z$

Evolution by NNLO*+NNLL QCD

$\alpha_S(m_Z) = 0.1205 \pm 0.0010_{exp} \pm 0.0022_{theo}$

[1505.02624]



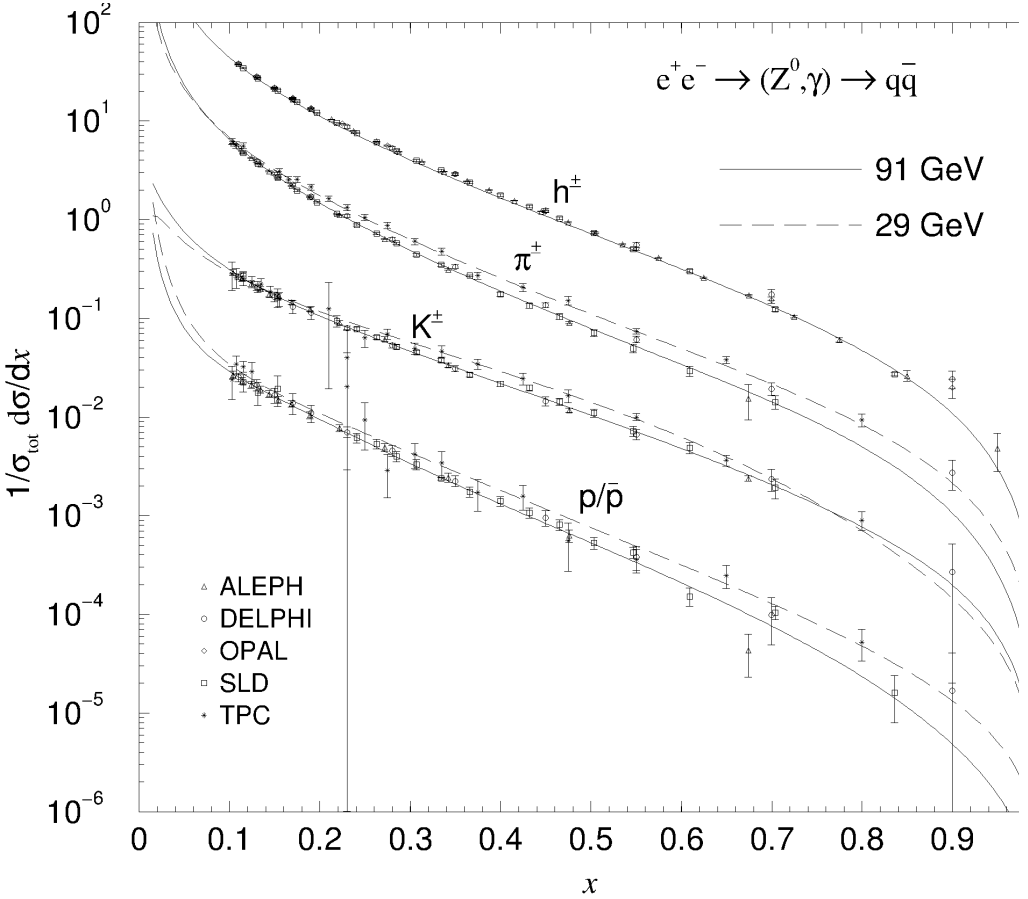


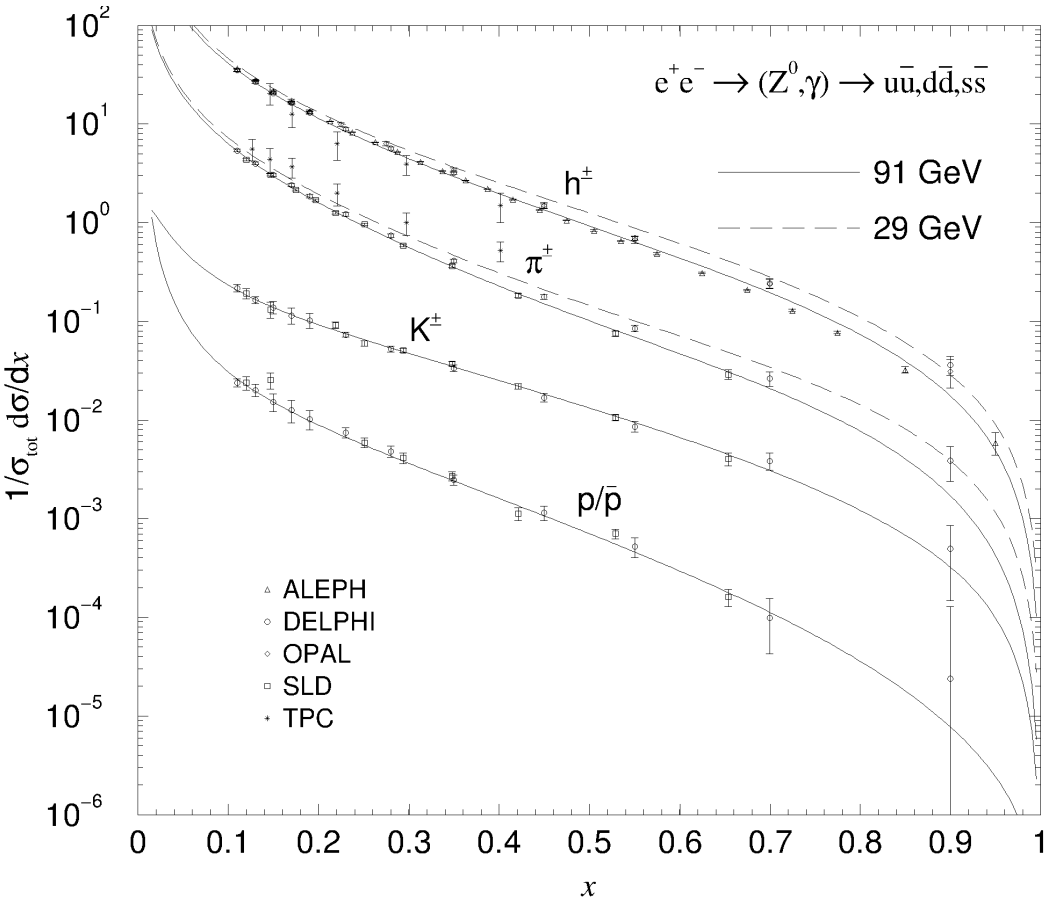
Fragmentation functions in e^+e^-

$d/d\ln(\mu_F) D_h(x,s) = \sum_i \int_x^1 P_{ij}(z,\alpha_S)\, D_i^h(x/z, s)\, dz/z;\ i = u,d,s,c,b,g$

$P_{ij}(z,\alpha_S)$ time-like splitting functions in (N)NLO QCD

$\alpha_S(m_Z) = 0.1176 \pm 0.0060_{exp} \pm 0.0008_{theo}$ GigaZ ISR





[Nucl. Phys. B725 (2005) 181]

σ_L/σ_{tot}

$d^2\sigma/dxdcos\theta = 3/8(1+cos^2\theta)d\sigma_T/dx + 3/4sin^2\theta d\sigma_L/dx + 3/4cos\theta d\sigma_A/dx$

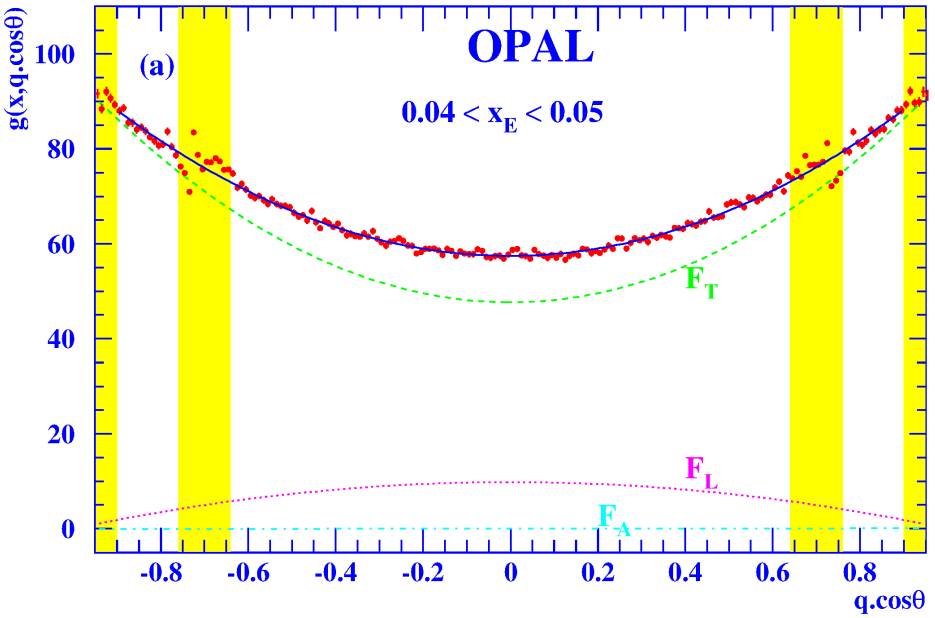
$½ ?_0^{1x} d\sigma_P/dx = \sigma_P$; P = T,L; NLO QCD + JETSET had. corr.,

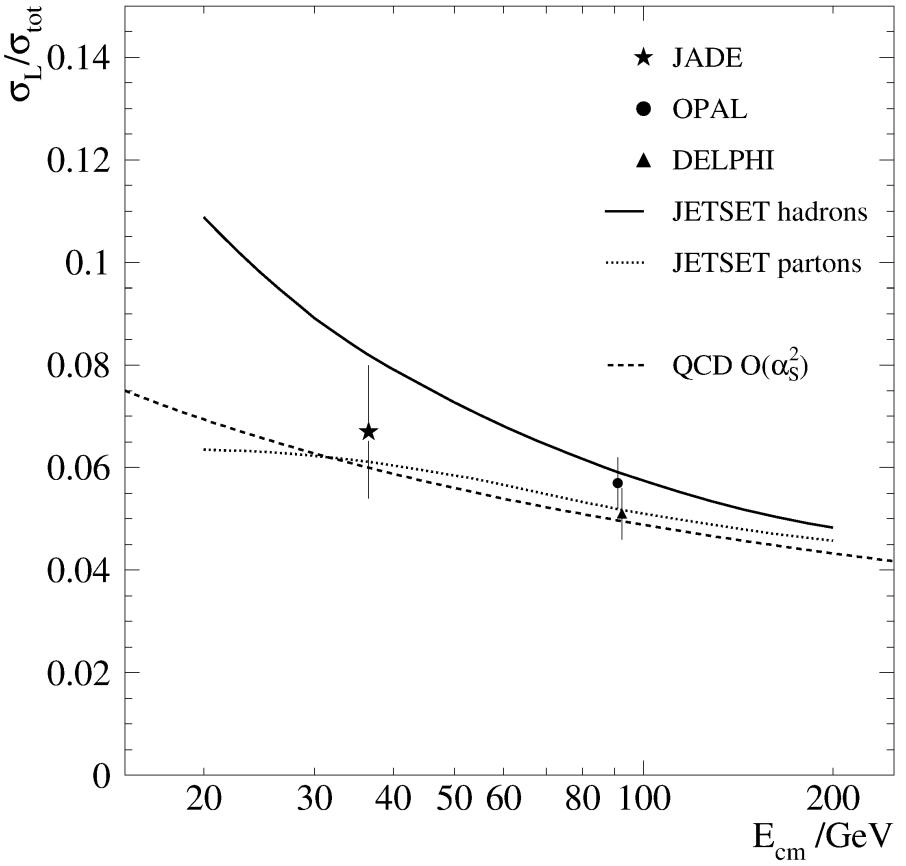
$\alpha_S(m_Z) = 0.1169 \pm 0.0035_{exp} \pm 0.0074_{theo}$

[Rept. Prog. Phys. 69 (2006) 1771]

NNLO should be possible?

GigaZ (ISR)





Quark and gluon jet $\langle n_{ch} \rangle$

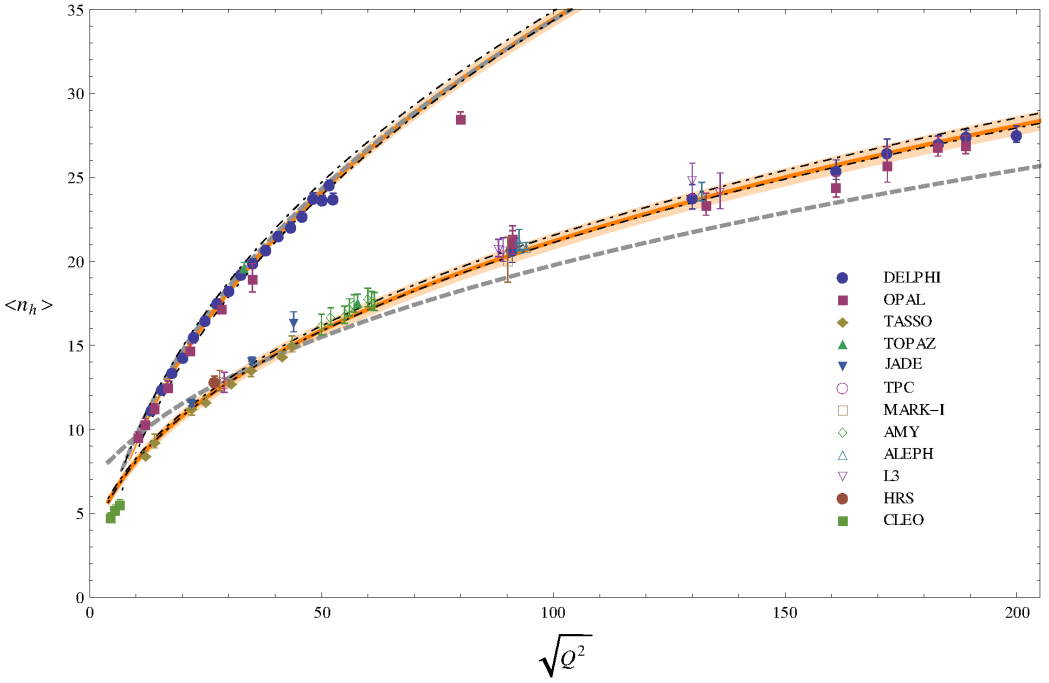
Charged particle multiplicity in quark- or gluon jets

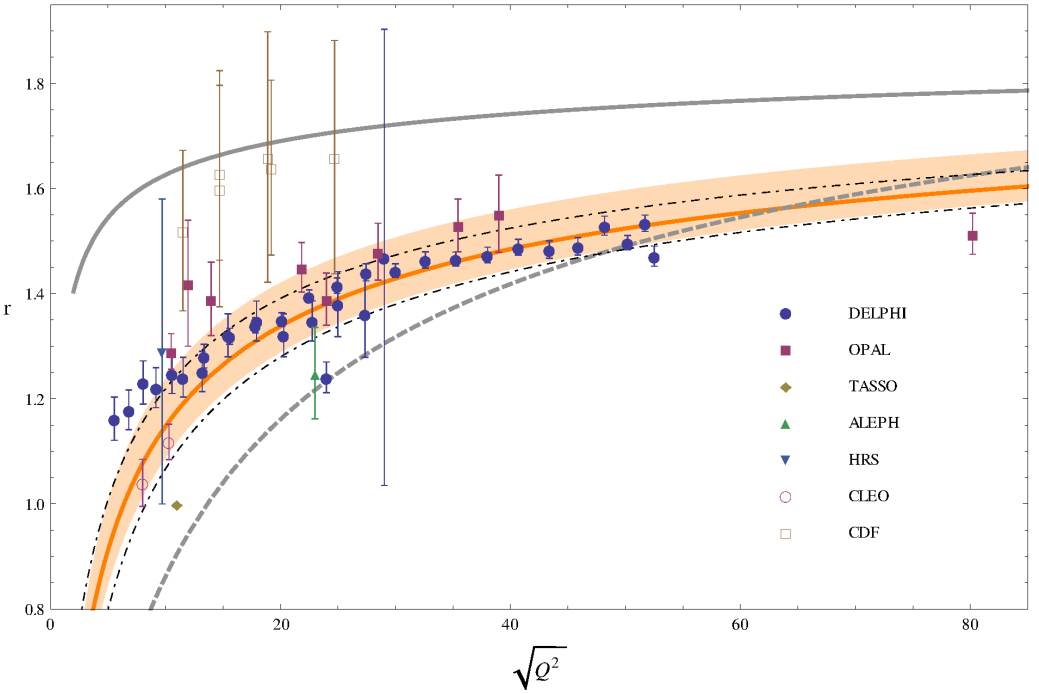
QCD NNLO*+NLO+NNLL prediction in powers of $\sqrt{\alpha_s}$

$\alpha_s(m_Z) = 0.1199 \pm 0.0026_{exp}$

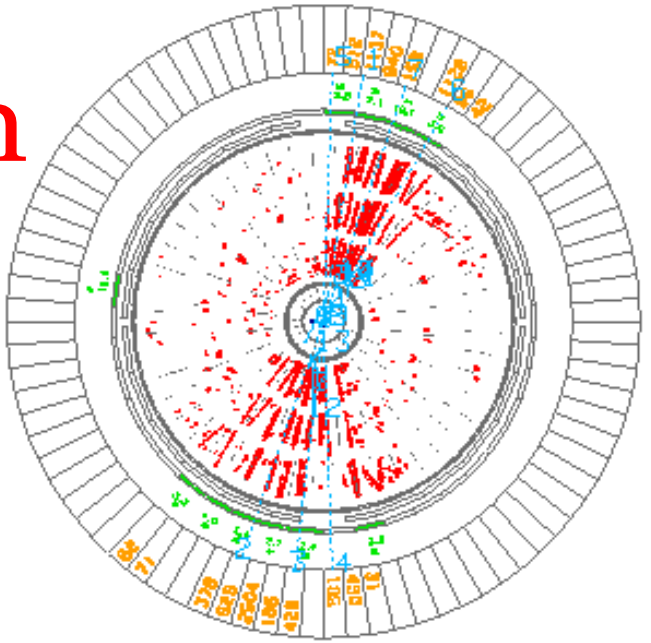
GigaZ, theory improvements?

[Phys.Rev.Lett. 109 (2012) 242002]



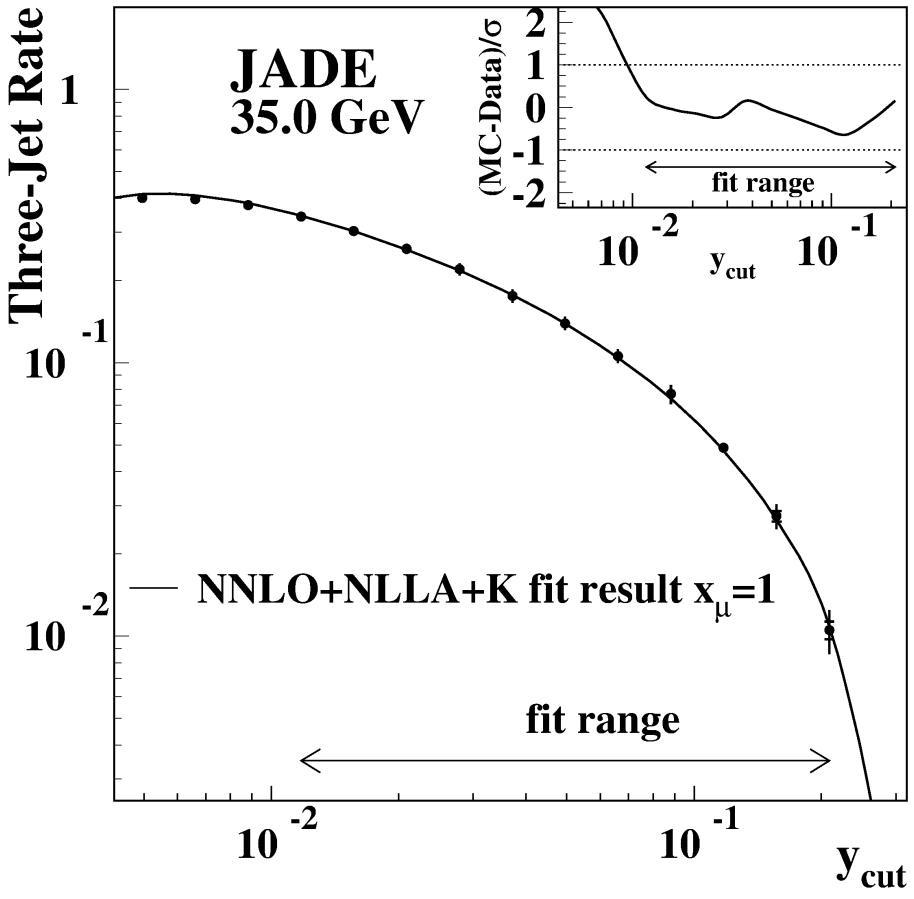


3-jet production

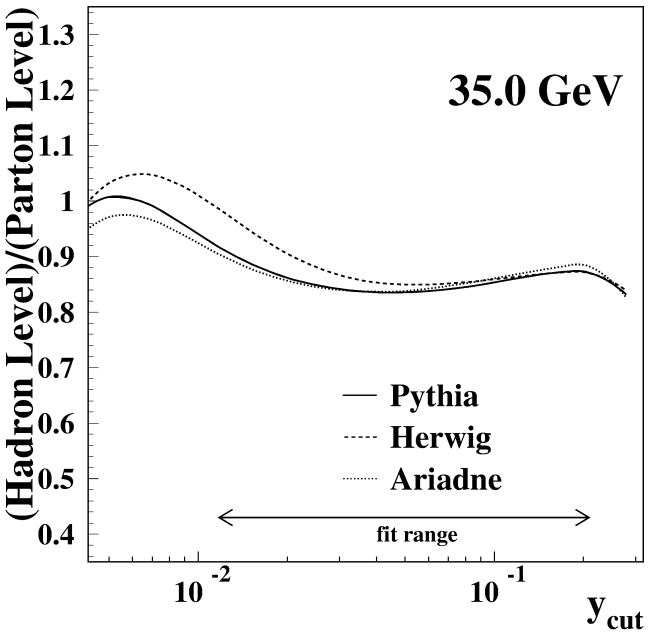


Durham alg.: $y_{ij} = 2\min(E_i,E_j)^2(1-\cos\theta_{ij})/s$,
combine pair w/ smallest y_{ij}, stop when 3 jets

JADE 14, 22, 35, 38, 44 GeV samples



$$\alpha_S(m_Z) = 0.1199 \pm 0.0010_{stat} \pm 0.0021_{exp} \pm 0.0054_{had} \pm 0.0007_{theo}$$



GigaZ ISR

[Eur. Phys. J. C73 (2013) 2332]

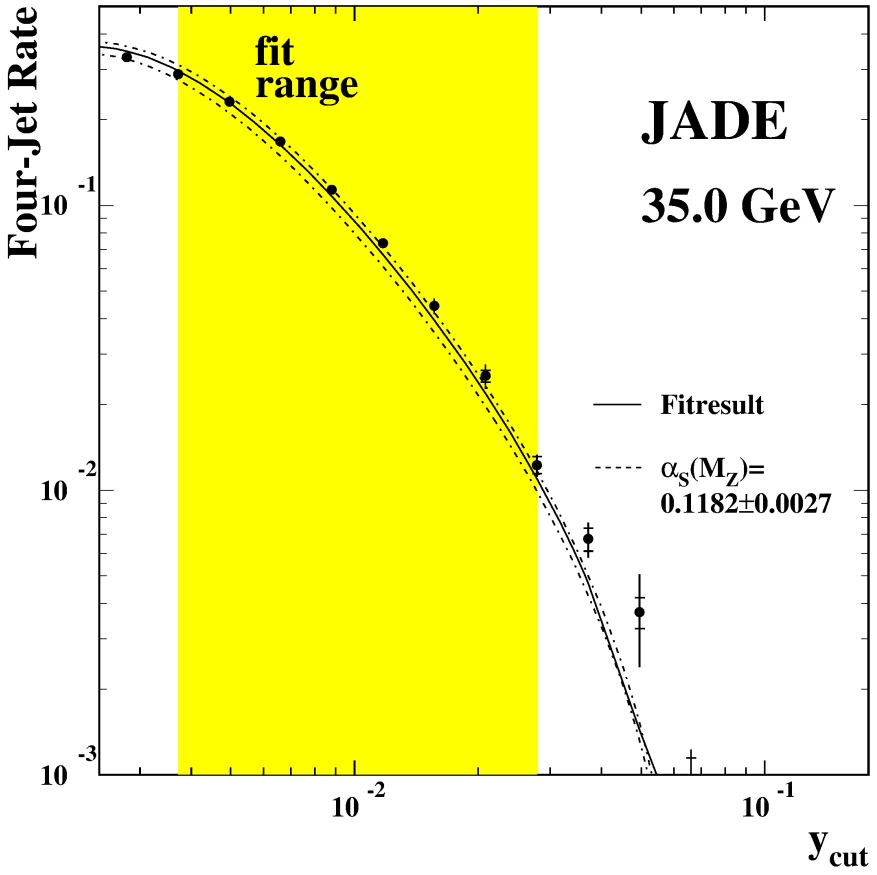
4-jet production

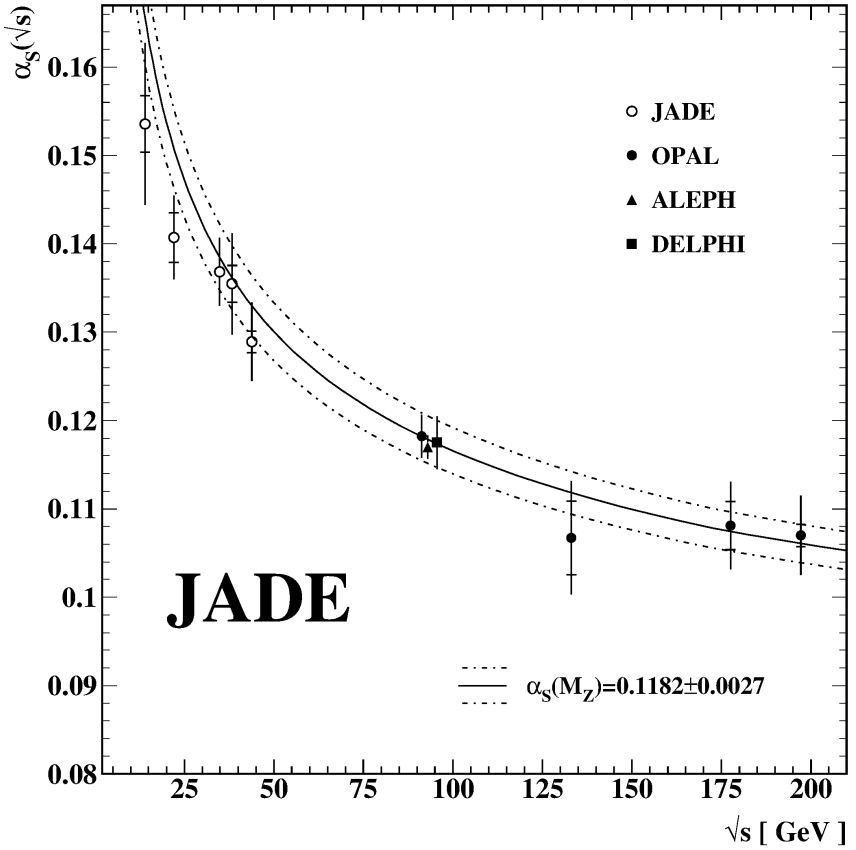
Durham R_4 in NLO QCD: $R_4(y_{cut}) = B(y_{cut})\alpha_S^2 + C(y_{cut})\alpha_S^3$ "+ NLLA"

$\alpha_S(m_Z) = 0.1159 \pm 0.0004_{stat} \pm 0.0012_{exp} \pm 0.0024_{had} \pm 0.0007_{theo}$

GigaZ ISR, improved had. models (MCs)

[Eur. Phys. J. C48 (2006) 3;
Eur. Phys. J. C50 (2007) 769]





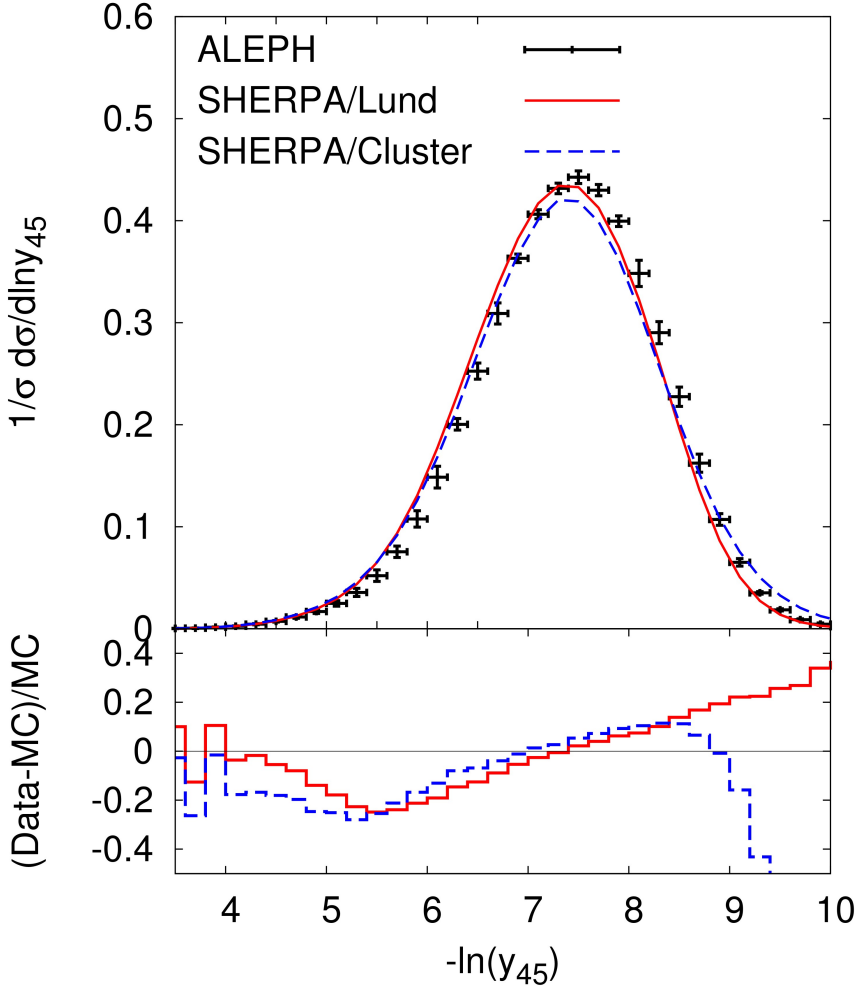
5-jet production

Durham y_{45} in NLO QCD: $1/\sigma d\sigma/dy_{45}(y) = C(y)\alpha_S^3 + D(y)\alpha_S^4$

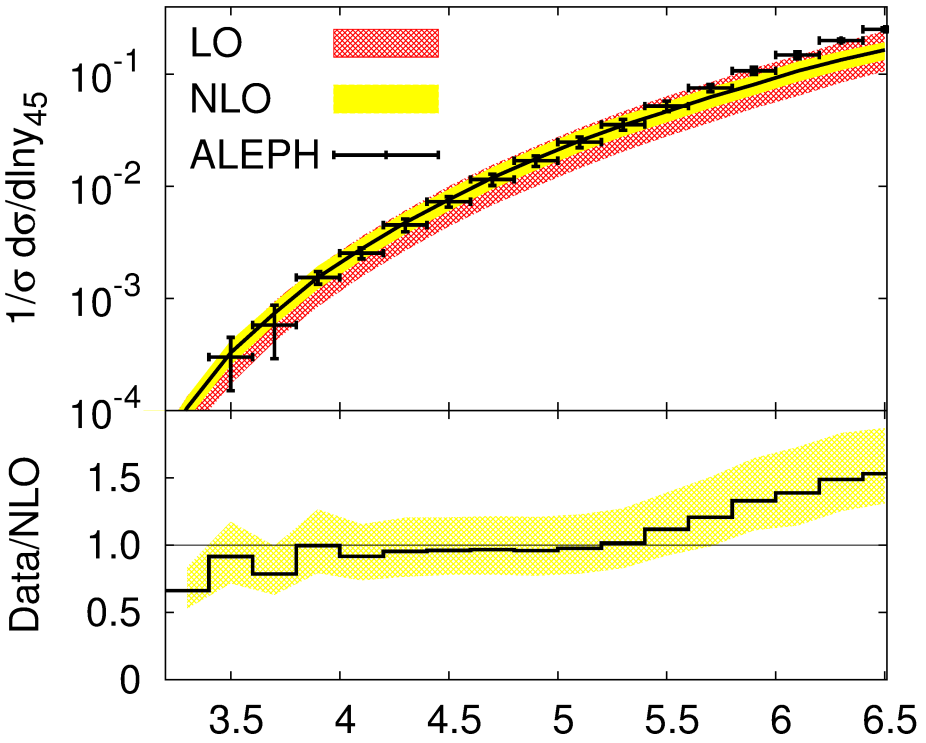
$\alpha_S(m_Z) = 0.1159 \pm 0.0038$ dom. by exp. and theo. errors

Had. corr. from Sherpa (LO multileg ME+PS CKKW)

GigaZ, NNLO?



[JHEP 1011 (2010) 050]



Event shapes

C-parameter: $C = 3/2 \left(\sum_{ij} p_i p_j \sin\theta_{ij} \right) / \left(\sum_i p_i^2 \right)$ particle momenta p_i

NNLO+N3LL'+p.c. QCD prediction based on SCET

LEP, PETRA, SLC data 35 to 207 GeV

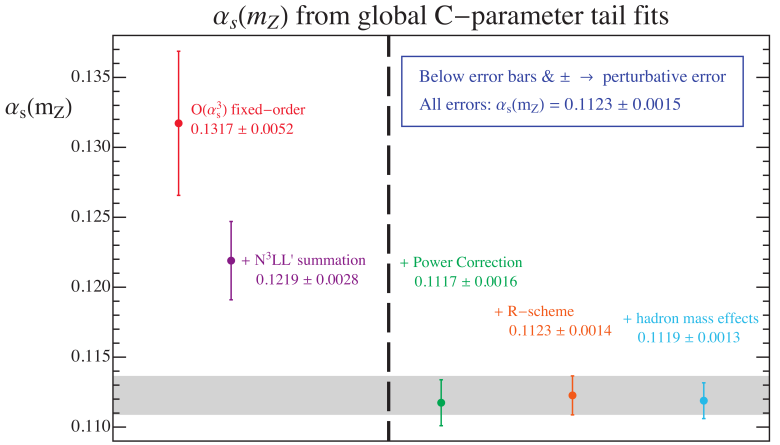
$\alpha_s(m_Z) = 0.1123 \pm 0.0002_{exp} \pm 0.0007_{had} \pm 0.0007_{pert}$ (C-par)

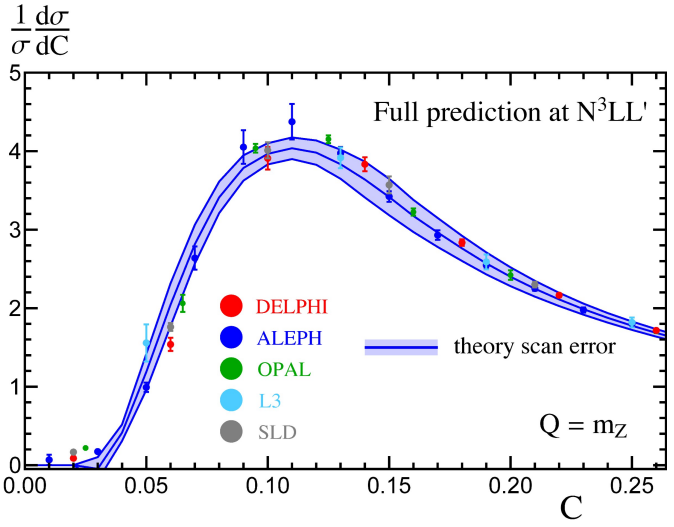
$\alpha_s(m_Z) = 0.1128 \pm 0.0002_{exp}$

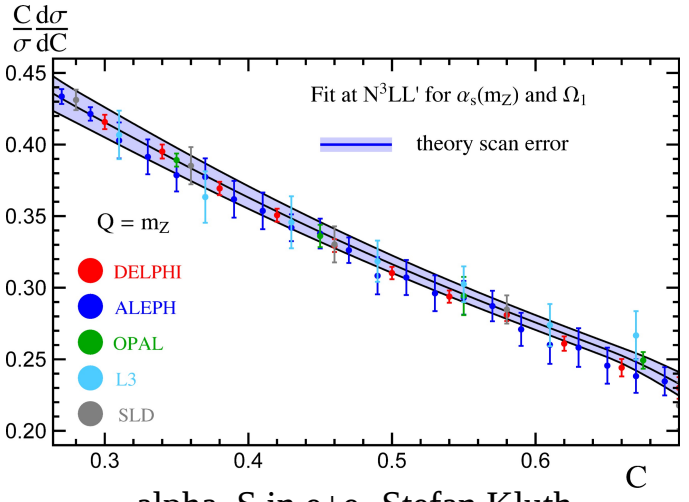
$\pm 0.0005_{had} \pm 0.00011_{pert}$ (Thrust)

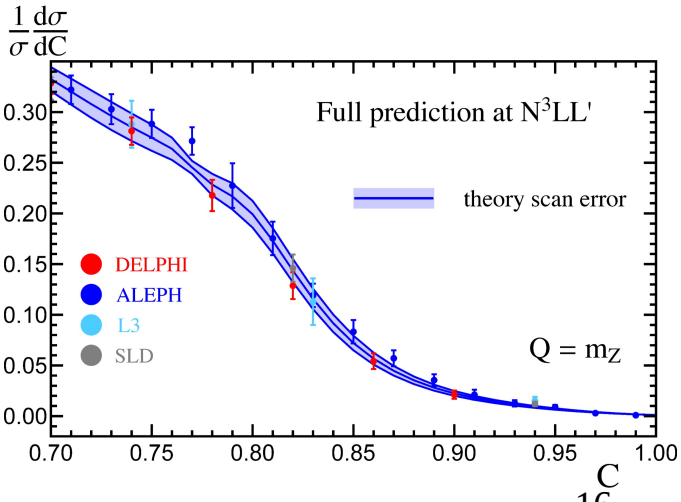
GigaZ, MC based had. corr.?

[Phys. Rev. D91 (2015) 094018]









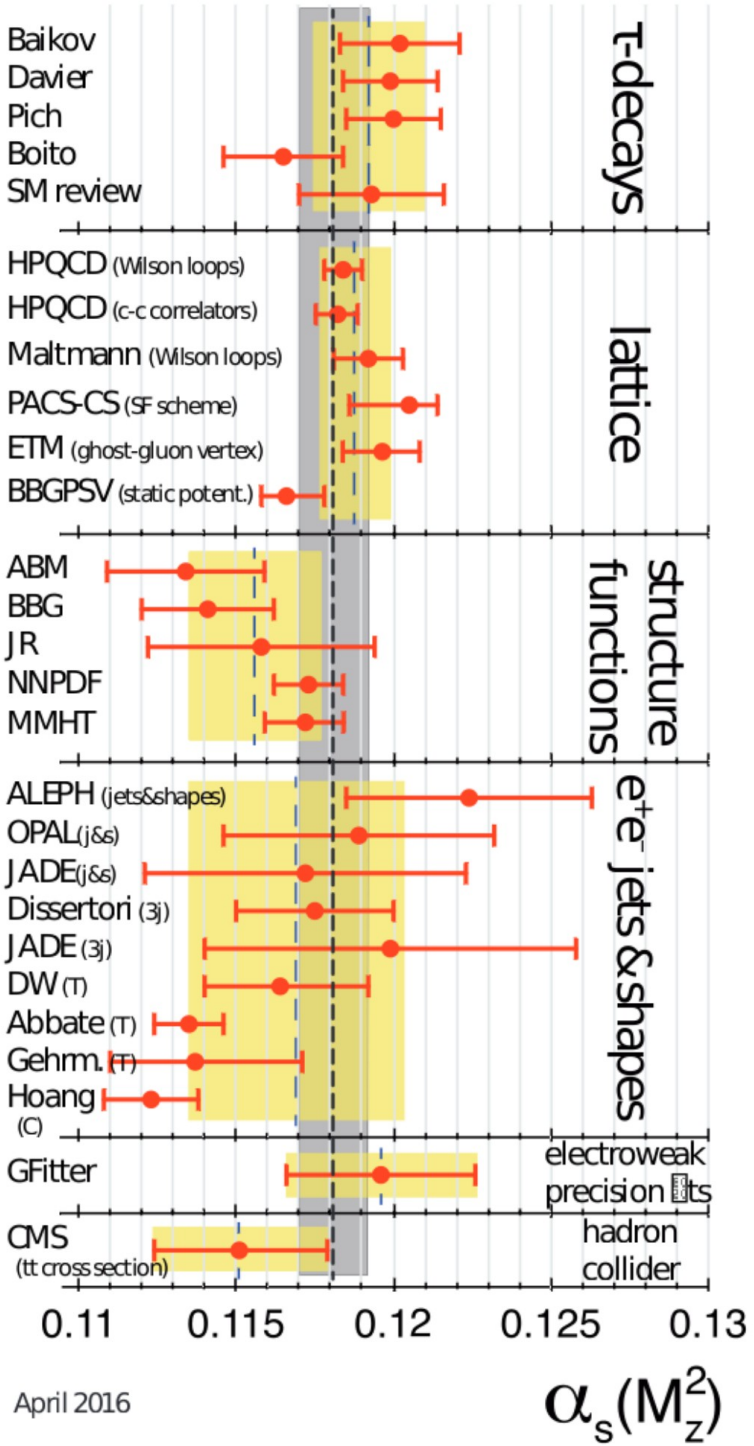
Summary (a la PDG)

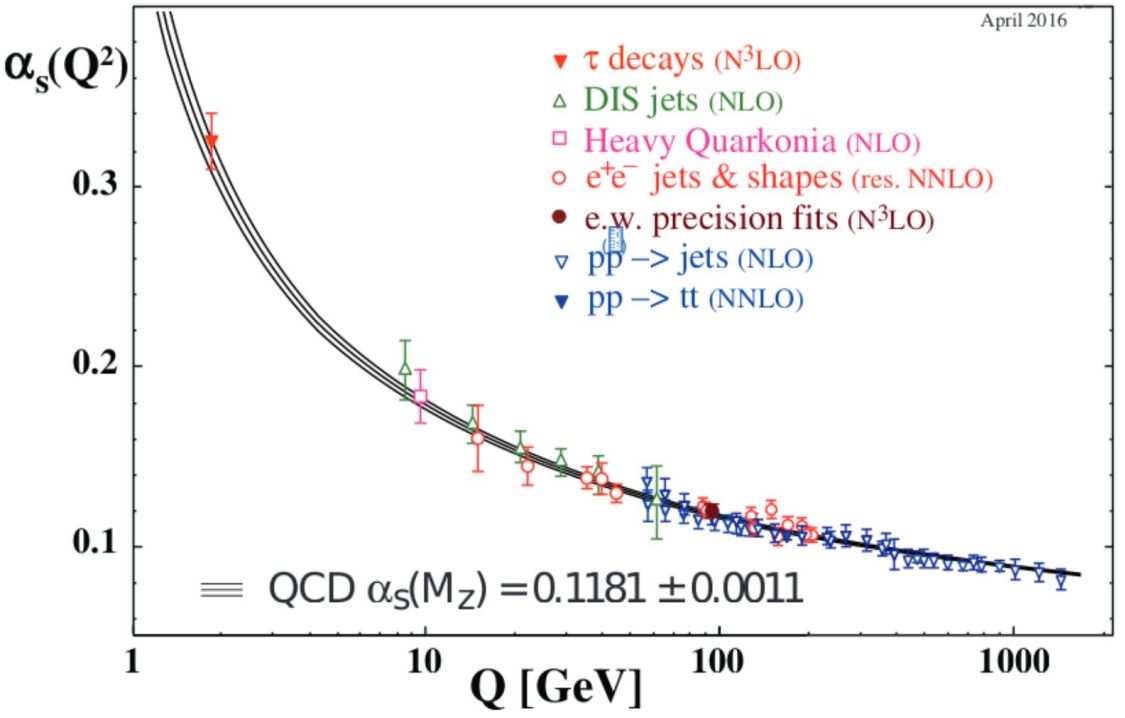
For $e^+e^- \rightarrow$ hadrons unweighted average

$\alpha_s(m_z) = 0.1169 \pm 0.0034$

World average: $\alpha_s(m_z) = 0.1181 \pm 0.0011$

[Chin. Phys. C40 (2016) 100001]





Conclusion

- $\alpha_S(m_Z)$ at below 1% from e^+e^- ?
  - Result from Lattice QCD already there
    - If you believe all of it
  - Best option is EW precision fit → GigaZ
  - Needs confirmation from other methods
    - Semi-incl. FFs, jets+event shapes
- Control / understand non-pert effects
  - Need GigaZ and ISR program
    - Optimize for very low angle ISR γ detection
  - Jets and event shapes at highest energies
    - At 500 GeV had. effects down by factor 5 → error O(0.001), need matching exp. error → control WW bkg