Prospects for α_s measurement at CEPC

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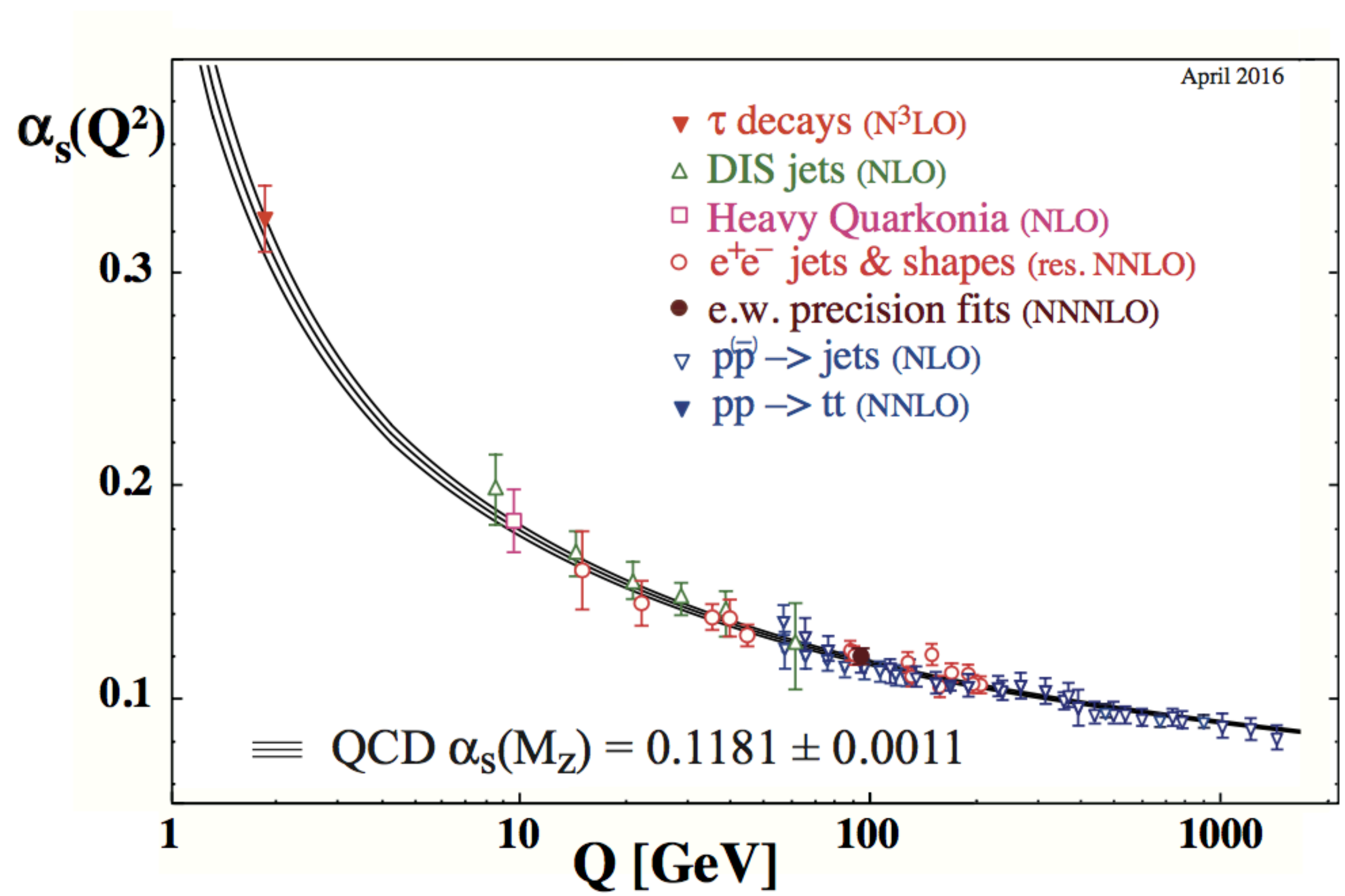
Introduction

- Quantitive description of nature required detailed understanding of QCD
- Strong coupling constant α_s is the most important parameter in QCD
- It's not a physical observable of the theory. It is defined in the context of perturbation theory

Measurement → $O(\alpha_s) = O^{(0)}(\alpha_s) + \alpha_s O^{(1)}(\alpha_s) + \ldots$ → Prediction

- Measurement of α_s in different processes, from GeV (tau decay) to TeV (LHC)
- Beautiful agreement with running predicted by QCD
- Confirmation of asymptotic freedom



Why α_s ?

ggF	W/Z+jets	H+jets	ttbar
$O(\alpha_s^2)$	$O(\alpha_s)$	$O(\alpha_s^3)$	$O(\alpha_s^2)$

- **α_s ~ 0.1 at Z pole: slow convergent perturbation series**
- **Many important processes start at $O(\alpha_s^2)$**

α_s is a major source of uncertainties for Higgs production and decay [Mihaila, 1512.05194]

Channel	M_H[GeV]	$\Delta\alpha_s$	Δm_b	Δm_c
$H \to b\bar{b}$	126	± 0.4 %	± 0.8%	
$H \to c\bar{c}$	126	± 3.9 %		± 2.3 %
$H \to gg$	126	± 4.1 %		

Process	Cross section(pb)	Scale(%)		PDF $+\alpha_s$	$\delta\alpha_s$(%)
ggH	49.87	-2.61	+ 0.32	-6.2 +7.4	± 3.7
VBF	4.15	-0.4	+ 0.8	± 2.5	± 0.7
WH	1.474	-0.6	+ 0.3	± 3.8	± 0.9
ZH	0.863	-1.8	+ 2.7	± 3.7	± 0.9
ttH	0.611	-9.3	+ 5.9	± 8.9	± 3.0

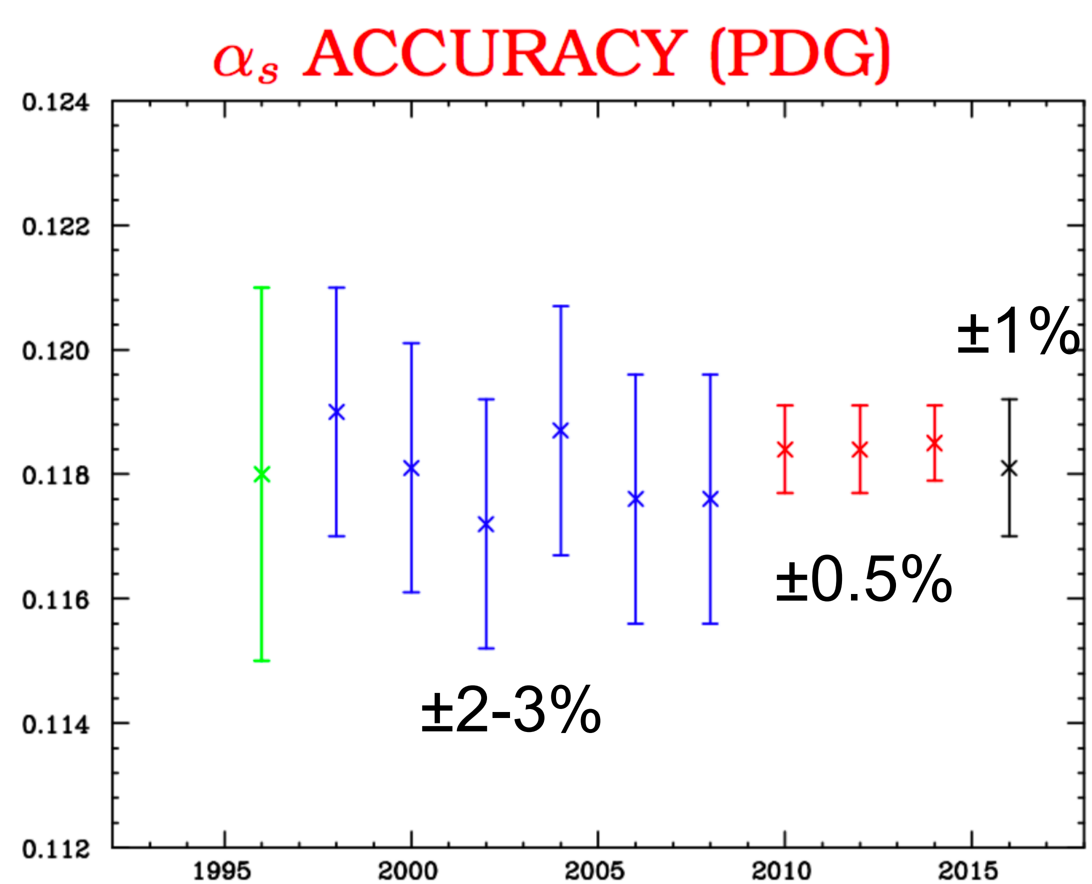
Status of α_s

- **Current world average (PDG 16):** $\alpha_s(M_Z^2) = 0.1181 \pm 0.0011 (\sim 1\%)$
- **Compared with other fundamental constant:**

$$\frac{\delta G_N}{G_N} \simeq 10^{-5} \qquad \frac{\delta G_F}{G_F} \simeq 10^{-8} \qquad \frac{\delta \alpha}{\alpha} \simeq 10^{-10}$$

gravity — weak interaction — QED

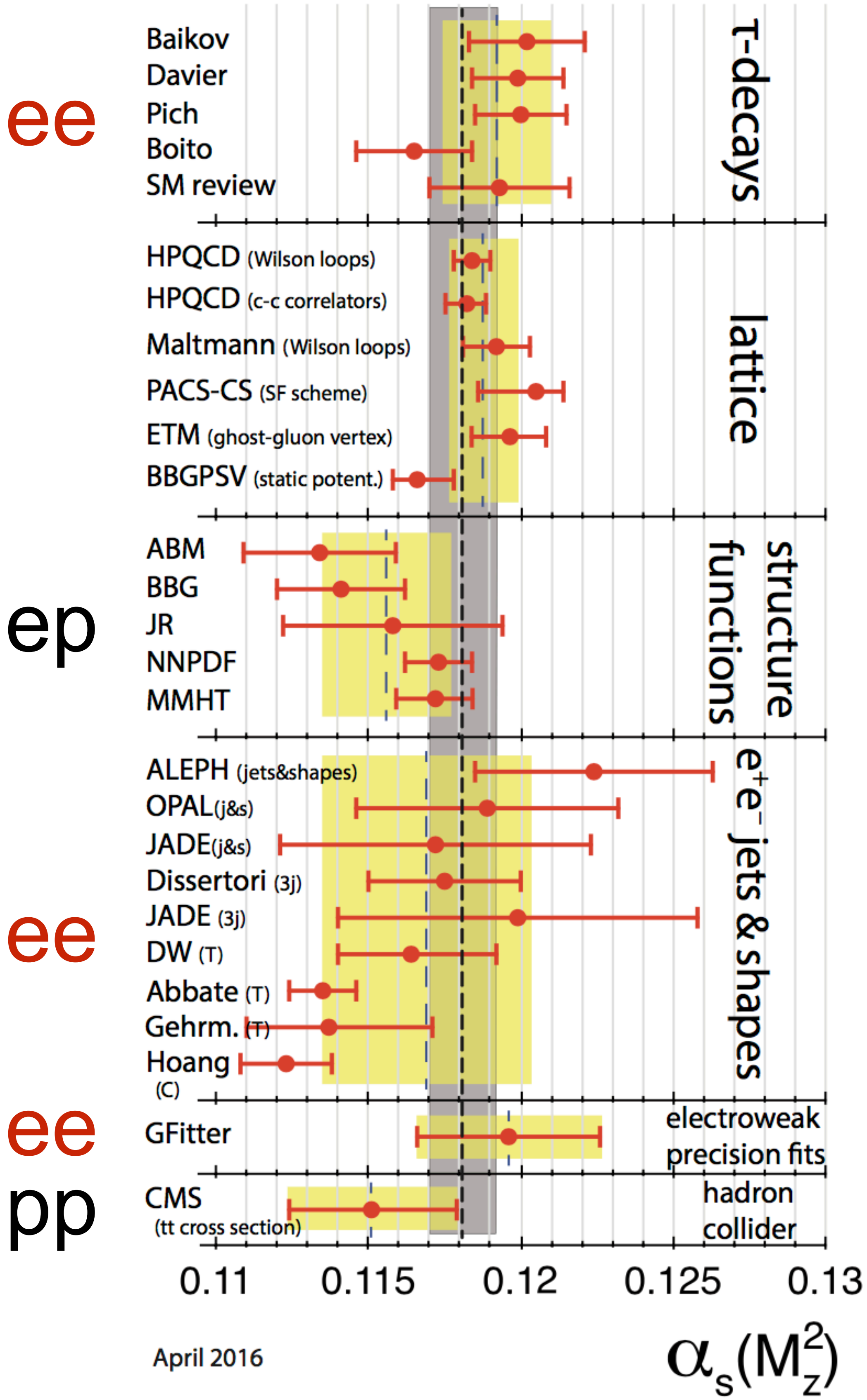
- **α_s is the least determined fundamental interaction constant in nature!**



Surprising lack of progress

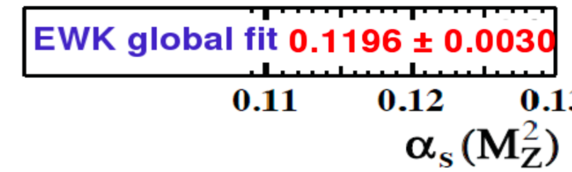
S. Forte, Lattice 2017

Determination of α_s



- What observables to choose for the determination?
  - The observable's sensitivity to α_s as compared to experimental uncertainties
  - The accuracy of perturbative prediction
  - The size of non-perturbative effects
  - The scale at which the measurement is performed
- Currently lattice gives the best determination
  - missing perturbative corrections
  - non-perturbative effects in 3-4 flavor transition
- An independent determination of α_s with <1% uncertainties will be an interesting possibility for future ee collider

α_s from hadronic Z decay



- **α_s through precision measurement of:** $R_l^0 = \frac{\Gamma_{\rm had}}{\Gamma_l}$ $\quad \sigma_0^{\rm had}$ $\quad \Gamma_Z$

$$R_l^0 = \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \text{leptons})} = R_Z^{\rm EW} N_c (1 + \delta_{\rm QCD} + \delta_{\rm m} + \delta_{\rm np})$$

$$\mathcal{O}\left(\frac{m_q^2}{M_Z^2}\right) \quad \mathcal{O}\left(\frac{\Lambda^4}{M_Z^4}\right)$$

LEP (Gfitter) $\quad \alpha_s(M_Z^2) = 0.11196 \pm 0.0028_{\rm exp} \pm 0.0006_{\rm QCD} \pm 0.0006_{\rm EW}$

- **Inclusive, theoretically clean observable. Non-perturbative effects strongly suppressed**
- **Uncertainties dominated by experiment**
- **N3LO QCD known. All theoretical input known to a precision better than exp.**

CEPC super Z factory

10^{11} Z boson

A factor of 70 reduction in statistical uncertainties

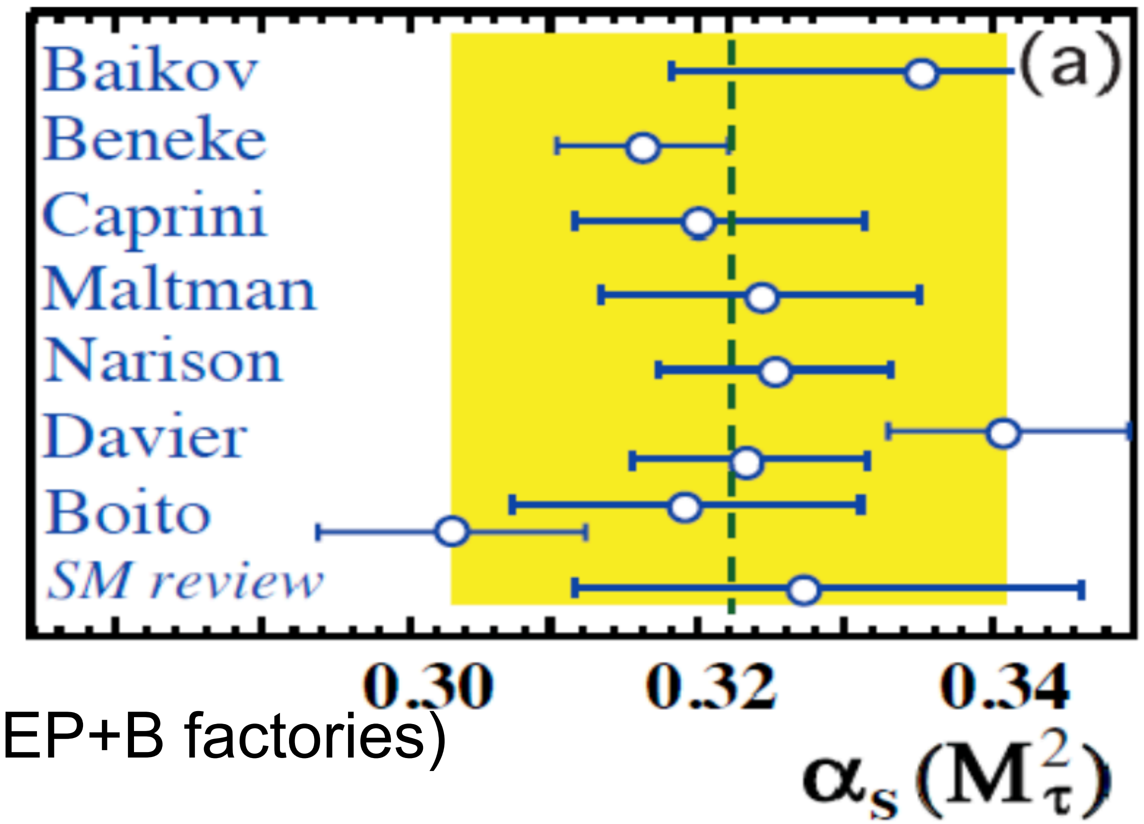
$$\Delta(\alpha_s)_{\rm exp} < 0.5\%$$

$$\Delta(\alpha_s)_{\rm th} < 0.3\%$$

At this level of accuracy, detailed analysis of systematics needed

α_s from hadronic τ decay

$$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\rm EW} N_C (1 + \delta_{\rm QCD} + \delta_{\rm np})$$



Advantage

- Inclusive observable
- α_s extraction at low scale M_τ=1.77GeV
- Absolute error on α_s shrink by an order of magnitude when evolve to Mz

$$\alpha_s(M_Z^2) = 0.1193 \pm 0.0023$$ (2%, LEP+B factories)

- Experimental uncertainties negligible
- Small non-perturbative corrections, consistent with experimental data

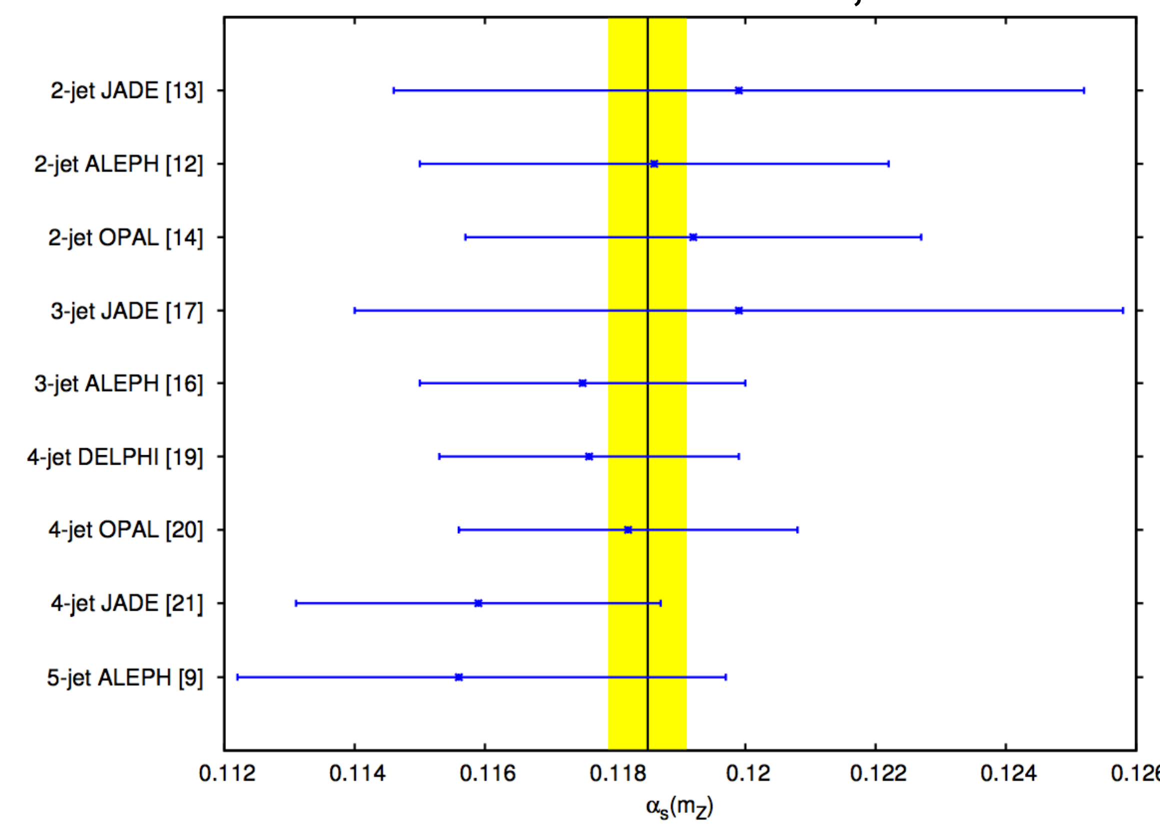
$$\delta_{\rm np} = \frac{\rm ZERO}{m_\tau^2} + c_4 \cdot \frac{\langle O_4 \rangle}{m_\tau^4} + c_6 \cdot \frac{\langle O_6 \rangle}{m_\tau^6} + \cdots$$

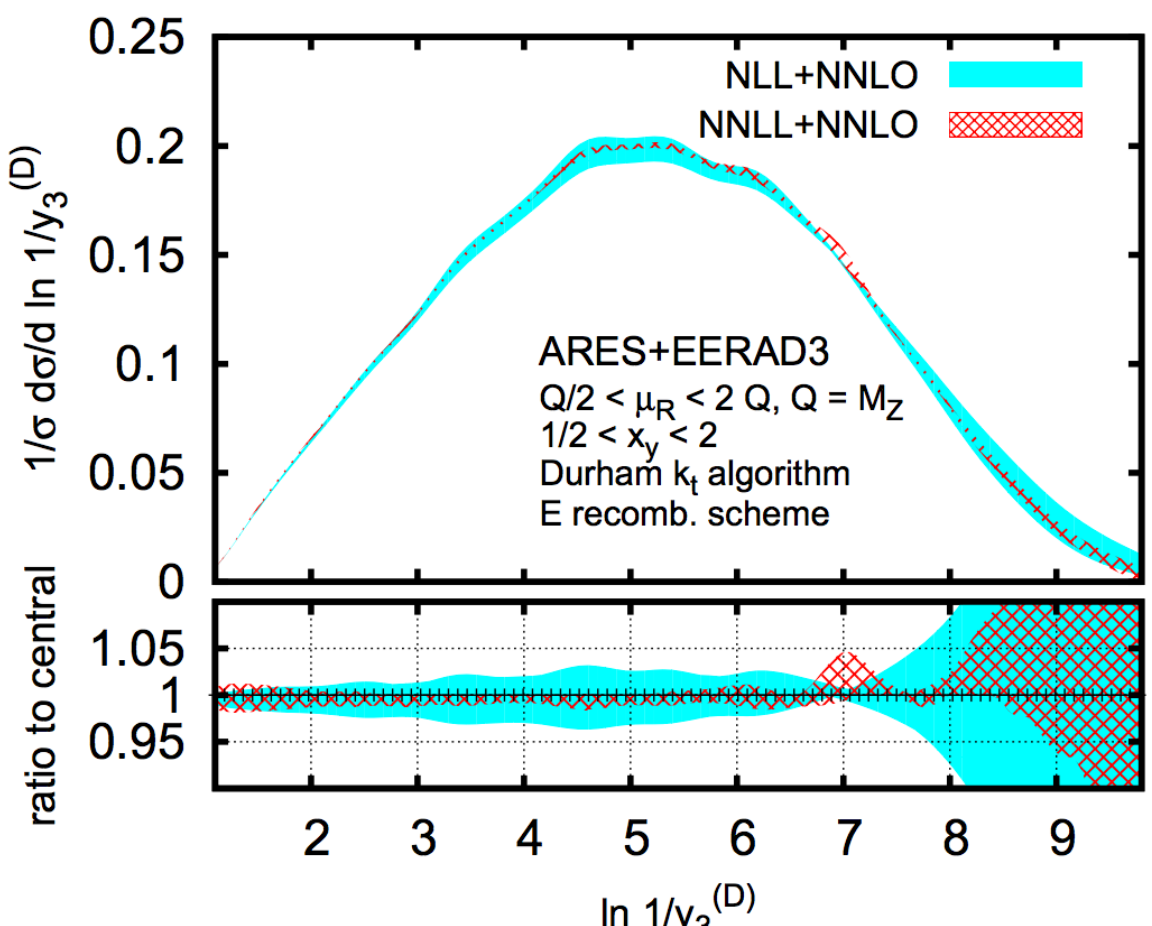
- Main theory uncertainties (~2%) from Fixed Order Perturbation Theory v.s. Contour Improved Perturbation Theory (resumming log of (s/m_τ^2))
- Need N^4LO calculation to clarify

α_s from e+e- jet rates

Banfi, 1512.05194

- event rates: fraction of events having n jets (directly sensitive to α_s)
- No analytic understanding of N.P. corrections. However, parton level MC agrees well with parton shower, indicating N.P. estimate from MC reliable
- Current uncertainties dominated by perturbative scale uncertainties





Banfi, McAslan, Monni, Zanderighi, 2016

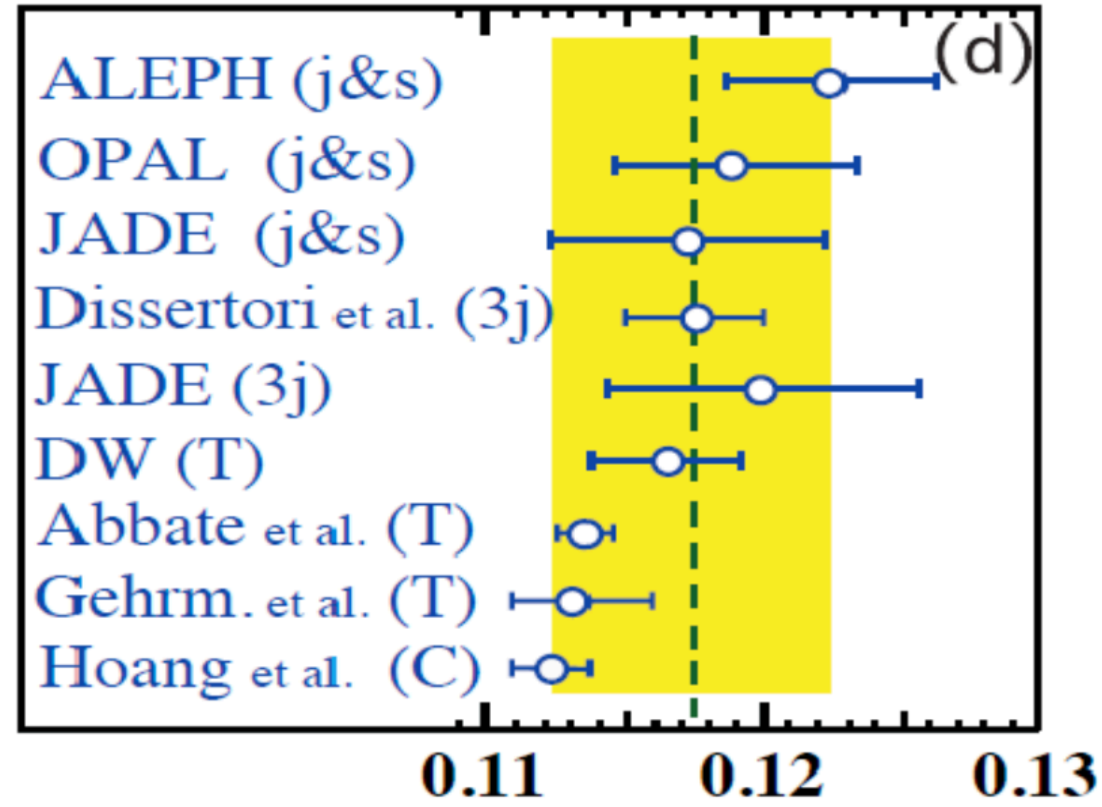
- Recent development in semi-analytic tools make NNLL possible for dijet rate resummation
- significant reduction of scale uncertainties
- Future:
  - NNLO for ≥ 4 jets production and resummation
  - analytic understanding of N.P. effects

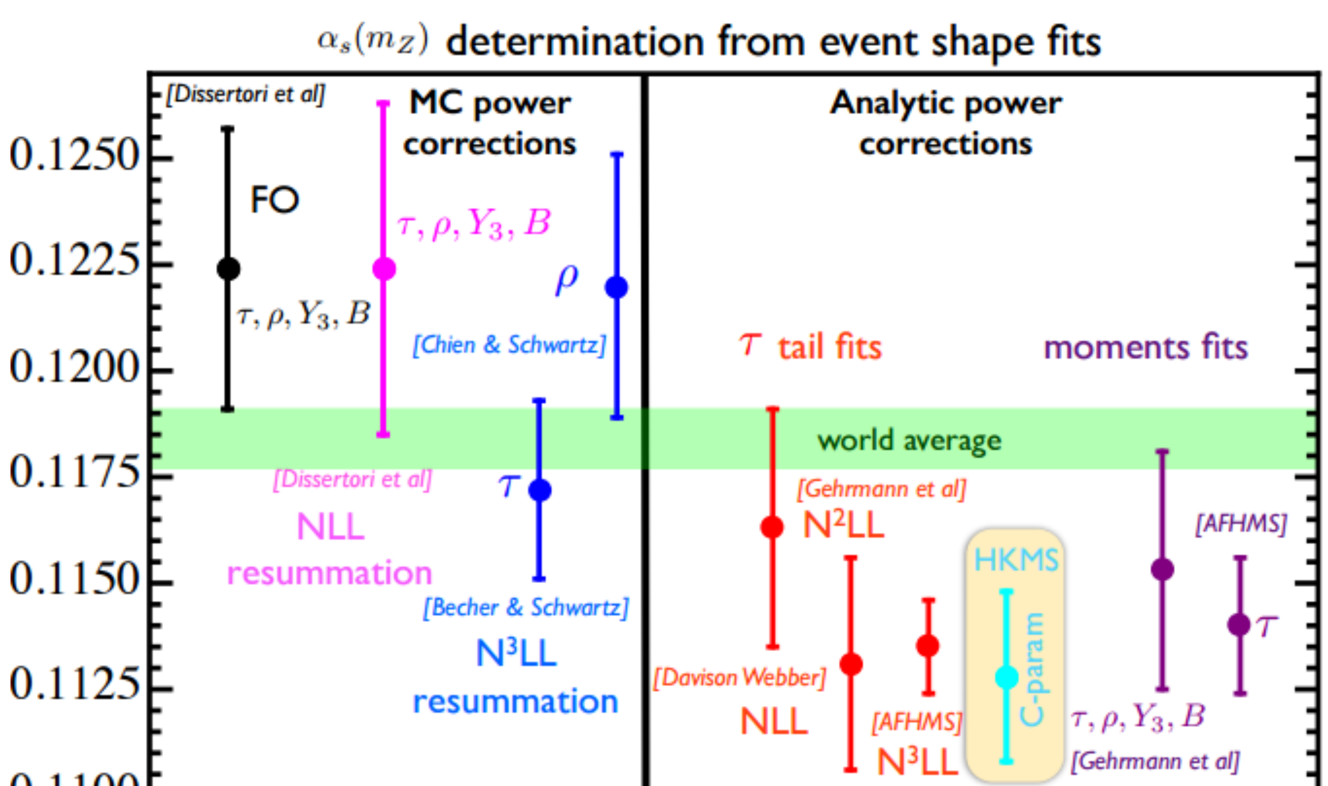
α_s from e+e- event shape: I

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

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

- **Large non-perturbative effects** $\sim \frac{\Lambda}{Q}$





Mateo, 2014

- **Largest theory uncertainties from the treatment of N.P. corrections**
- **Two different approach**
  - **Estimate N.P. effects from MC**
    - mismatch between parton level MC and shower
  - **Analytic parameterization, simultaneous fit of α_s and N.P. parameter**

α_s from e+e- event shape: II

Current best determination from SCET N³LL + NNLO [Hoang, et al]

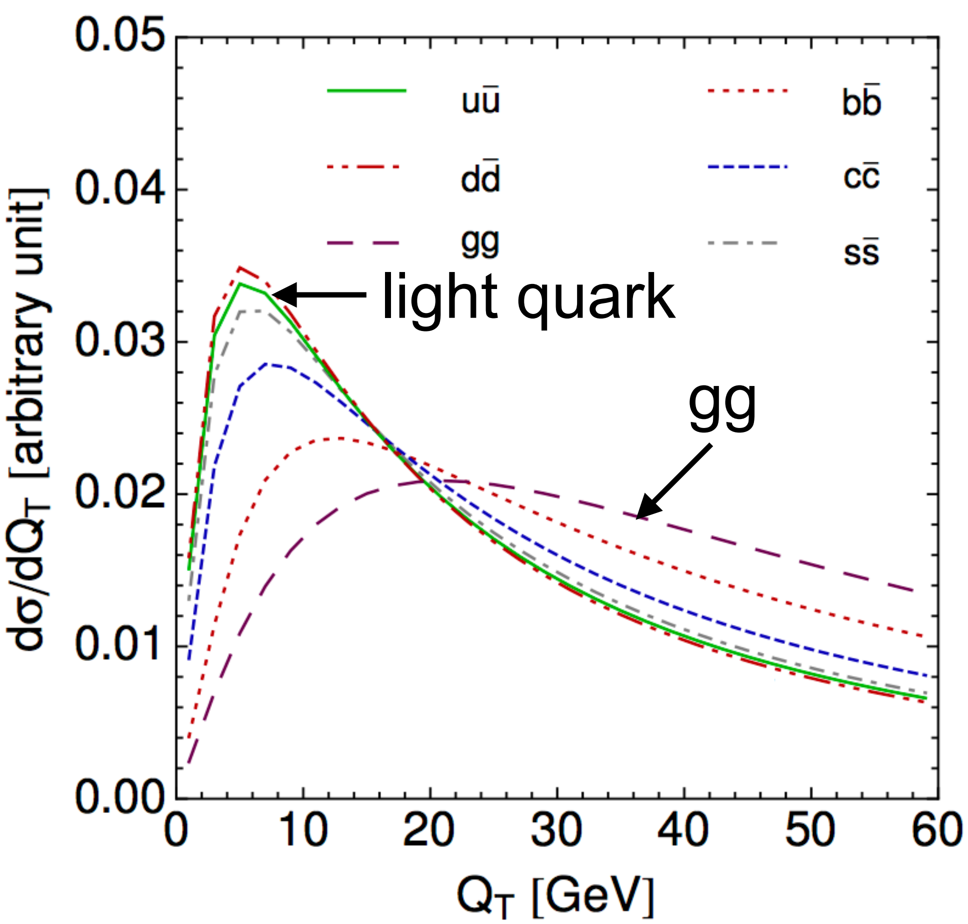
$$\alpha_s(M_Z^2) = 0.1135 \pm 0.0010 \; (\, 0.9\% \,) \quad \text{T}$$

$$\alpha_s(M_Z^2) = 0.1123 \pm 0.0015 \; (\, 1.3\% \,) \quad \text{C Para.}$$

Thrust and C parameter are correlated

Comments (Salam, 2016 KITP)

- **central value too small (4 σ apart from Lattice)**
- **Analytic N.P. modeling valid far a way from 3-jet region, but not too deep into 2-jet region. Not clear how much of LEP data satisfy this requirement**

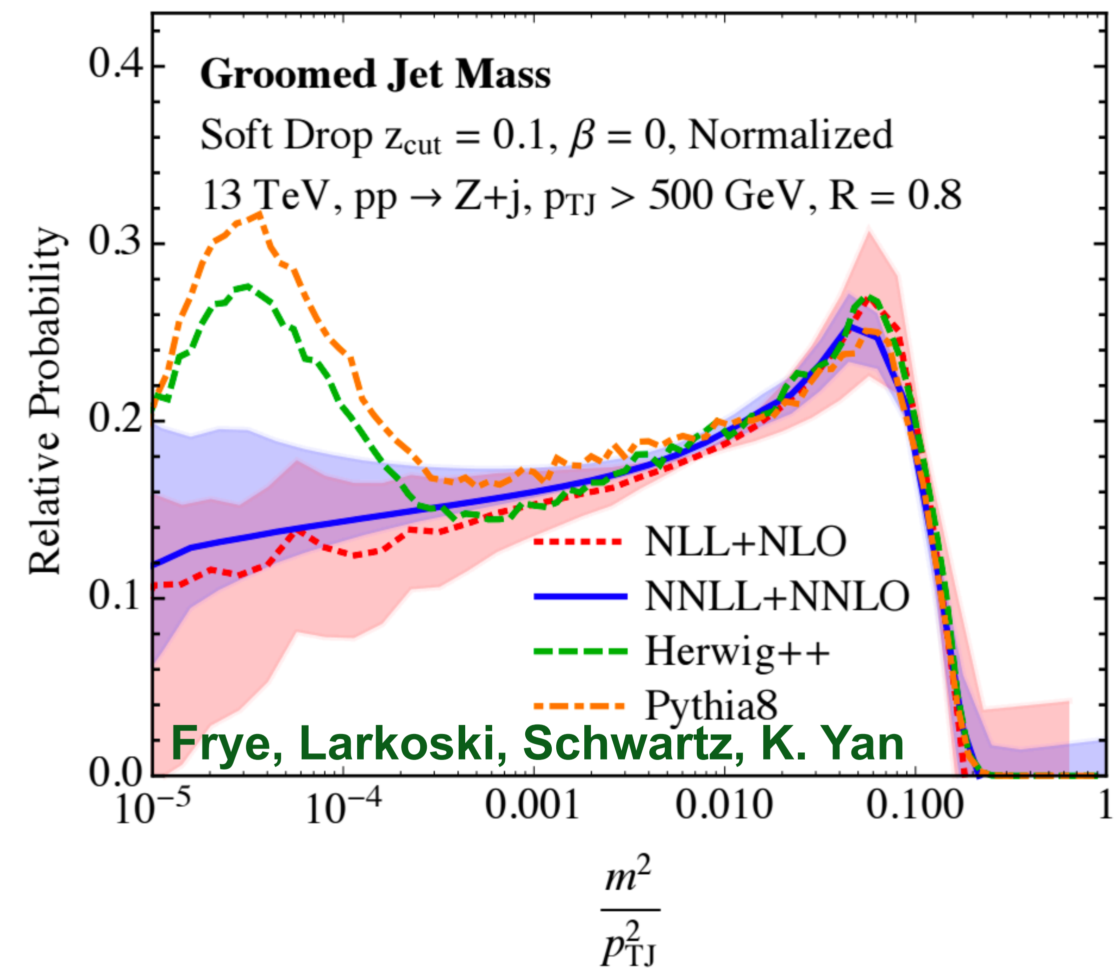


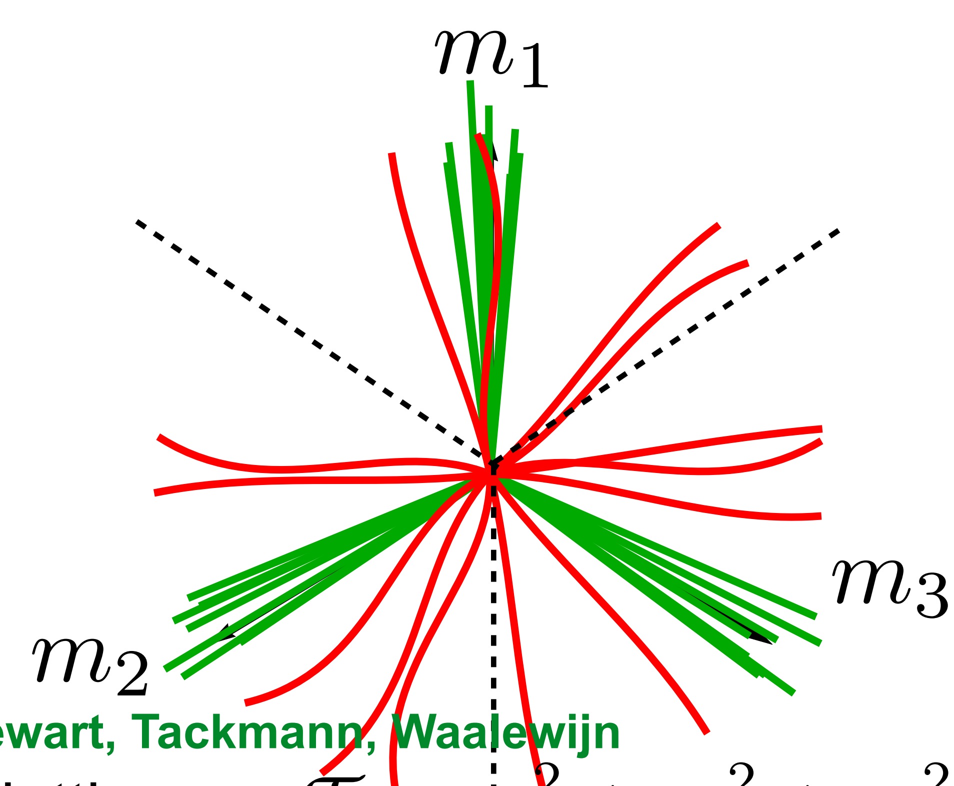
Prospects for CEPC

- **Provide crucial independent data to understand whether small α_s is possible**
- **Increase of Q^2 help reduce N.P. effects**
- **large Q^2 separate 3-jet and 2-jet region, increase the valid region of analytic N.P. modeling**
- **H->gg allows study of gluon event shape for the first time**
- **Theory progress also expected:**
  - **Resummation of Next-to-Leading Power Logs**
  - **Events shape with Λ^2/Q^2 N.P. effects? (e.g., pT like event shape)**

Alternative observables ?

- From discovery tool to precision tool
  - e.g. Soft drop in light jet mass/top mass reconstruction
  - Precision calculation helps asses the robustness + understand the systematics
- Small N.P. effects on the peak, in contrast to thrust or C parameter
  - analytic understanding?
  - Further detailed study required





3-jettiness $\mathcal{T} = m_1^2 + m_2^2 + m_3^2$

- Event shapes with three or more jet (start at α_s^2)
- At CEPC large enough statistics for precision study
- The position of peak logarithmically depends on the sum of parton Casimir (q +q̄ + g ~ 2 (q + q̄))
- Reduce sensitive to N.P. effects / enlarge the valid region for analytic N.P. modeling

Summary for α_s measurement

Preliminary estimate of precision for α_s at CEPC

	Current relative precision (LEP+B fact.)	Future relative precision (CEPC)
Z decay EW fit	expt. $\sim 3\%$ (mostly statistics) theo. $\sim 0.6\%$ (pert. QCD/EW)	expt. $< 0.5\%$ (possible, systematic) theo. $\sim 0.3\%$ (N^{4}LO, almost there)
τ decay	expt. $\sim 0.5\%$ theo. $\sim 2-3\%$ (FOPT v.s. CIPT)	expt. $< 0.2\%$ (possible) theo. $\sim 1\%$ (feasible, N^{4}LO)
jet rates	expt. $\sim 2\%$ (exp.) theo. $\sim 2\%$ (pert. QCD scale)	expt. $< 1\%$ (possible) theo. $< 1\%$ (feasible, NNLO+NNLL)
event shapes	expt. $\sim 1\%$ theo. $\sim 1-3\%$ (analytic v.s. MC N.P.)	expt. $< 1\%$ (possible) theo. $< 1\%$ (feasible, Q^2, NLO+NLL MC)

- **Determination of α_s promising with CEPC super Z/Higgs factory**
  - **Large statistics at Z pole**
  - **increased Q2 to suppressed N.P. effects**
  - **Improvement in theory**
- **Alternative methods for α_s determination**
  - **event shape with soft drop (suppressed N.P. effects)**
  - **≥ 3 jets event shapes (e.g. N-jettiness)**