Precision Test of QCD at CEPC

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Introduction

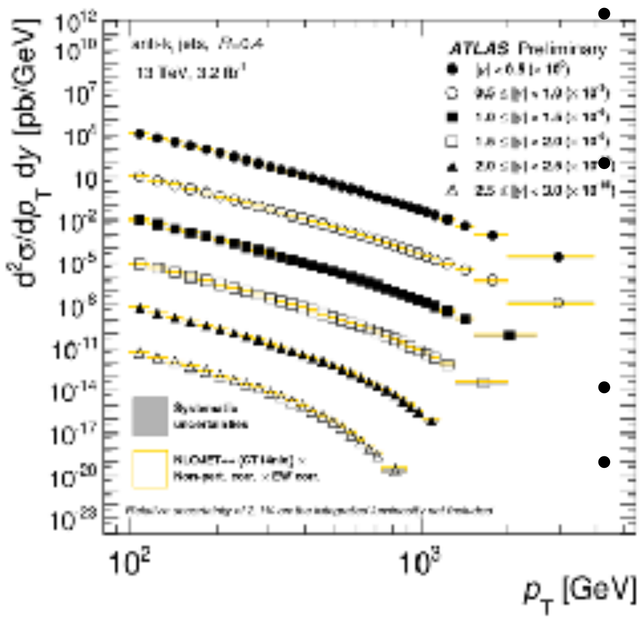
- Strong interaction is responsible for most of the visible mass in our universe.
- The discovery of QCD as the correct theory for strong interaction is a great achievement in the history of human science.
- QCD remains challenging 40 years after discovery: confinement, quark-gluon plasma, phase structure
- Even at high energy where perturbation works, QCD exhibits dramatic phenomena: jet, heavy quark production, partonic structure of proton.
- Accompany by rich theoretical structure: factorization, beautiful structure of amplitudes, connection to N=4 SYM and integrability

From LEP to LHC

CEPC/FCC-ee/ILC

- NLO wishlist completed
- NNLO becomes standard
- NLO event generator
- EFT for jet

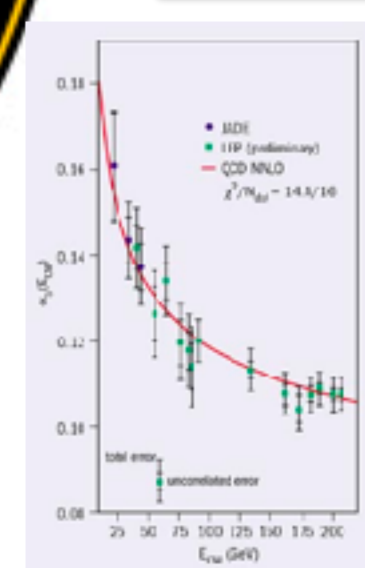
LHC (2009-)



- jet production at highest energy large radiative corrections in higgs production
- substructure of jet
- …

- NLO still rare
- LO event generator

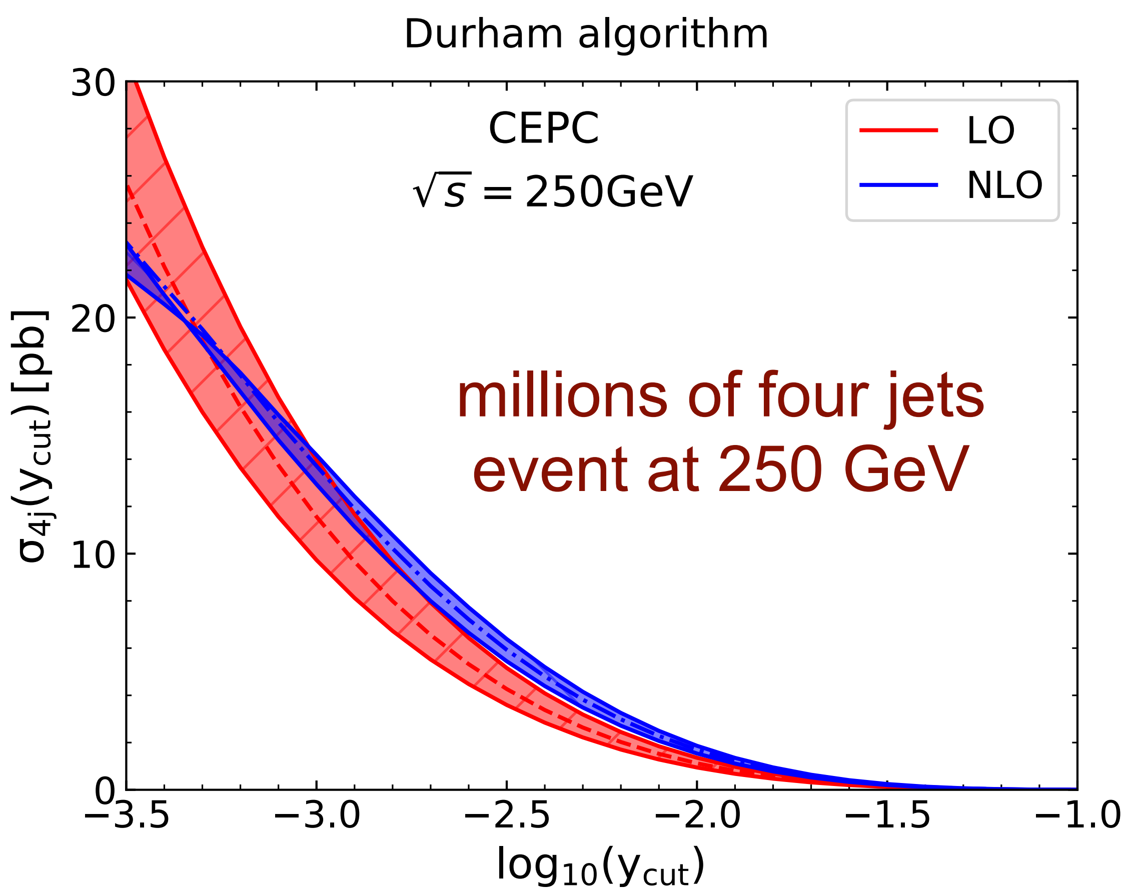
LEP (1989-2000)

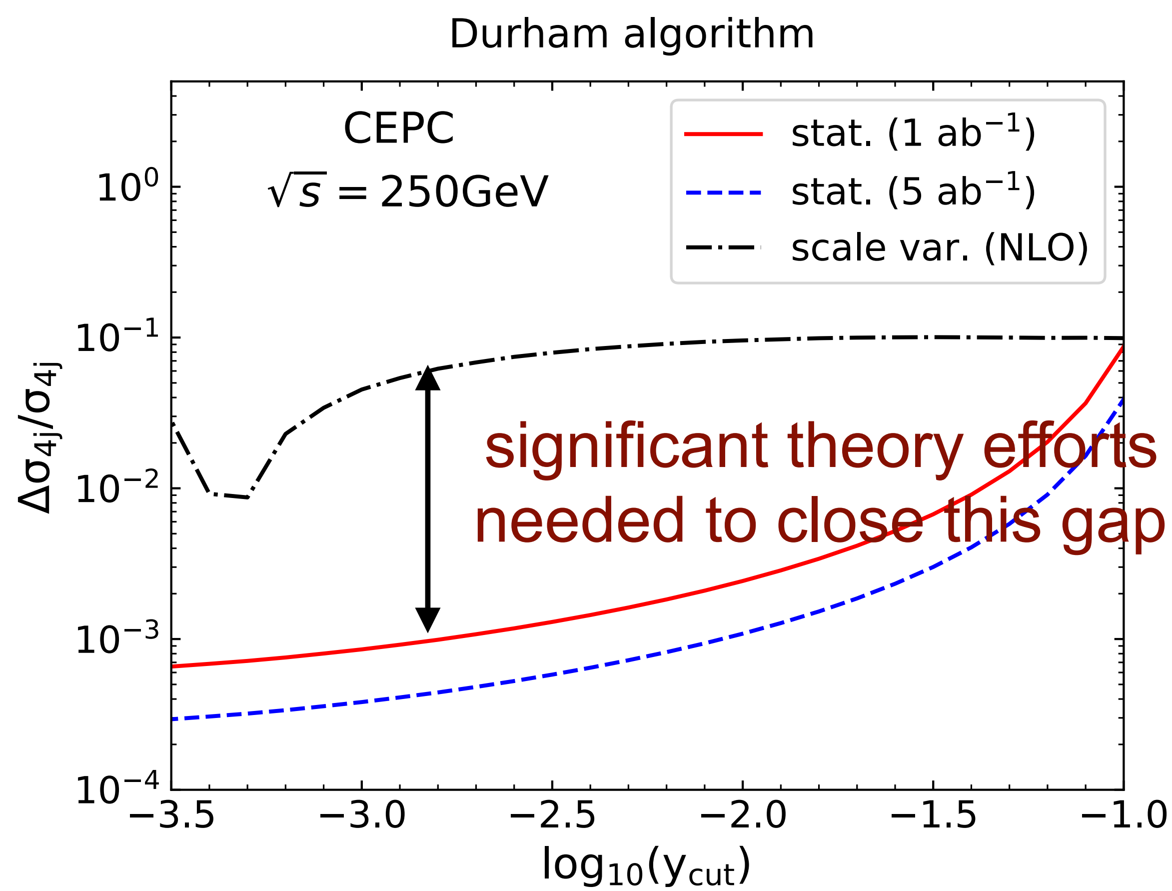


- running of α_s
- precision determination of α_s
- C_A ~ 3.02
- Confirmation of non-abelian interaction
- ……

Why do we need CEPC

- **LEP has already produce fabulous QCD results why a new lepton collider?**
  - **Unprecedented luminosity and high energy, reduced power corrections $1/Q^p$**





- **Isn't LHC already a QCD machine with complicated QCD dynamics at initial and final state?**
  - **Complications in PDFs, multiple scattering, underlying events, final state hadronization, all entangled together**
  - **At lepton collider, only the complications of final-state hadronization presents**

Precision α_s determination

Why α_s ?

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

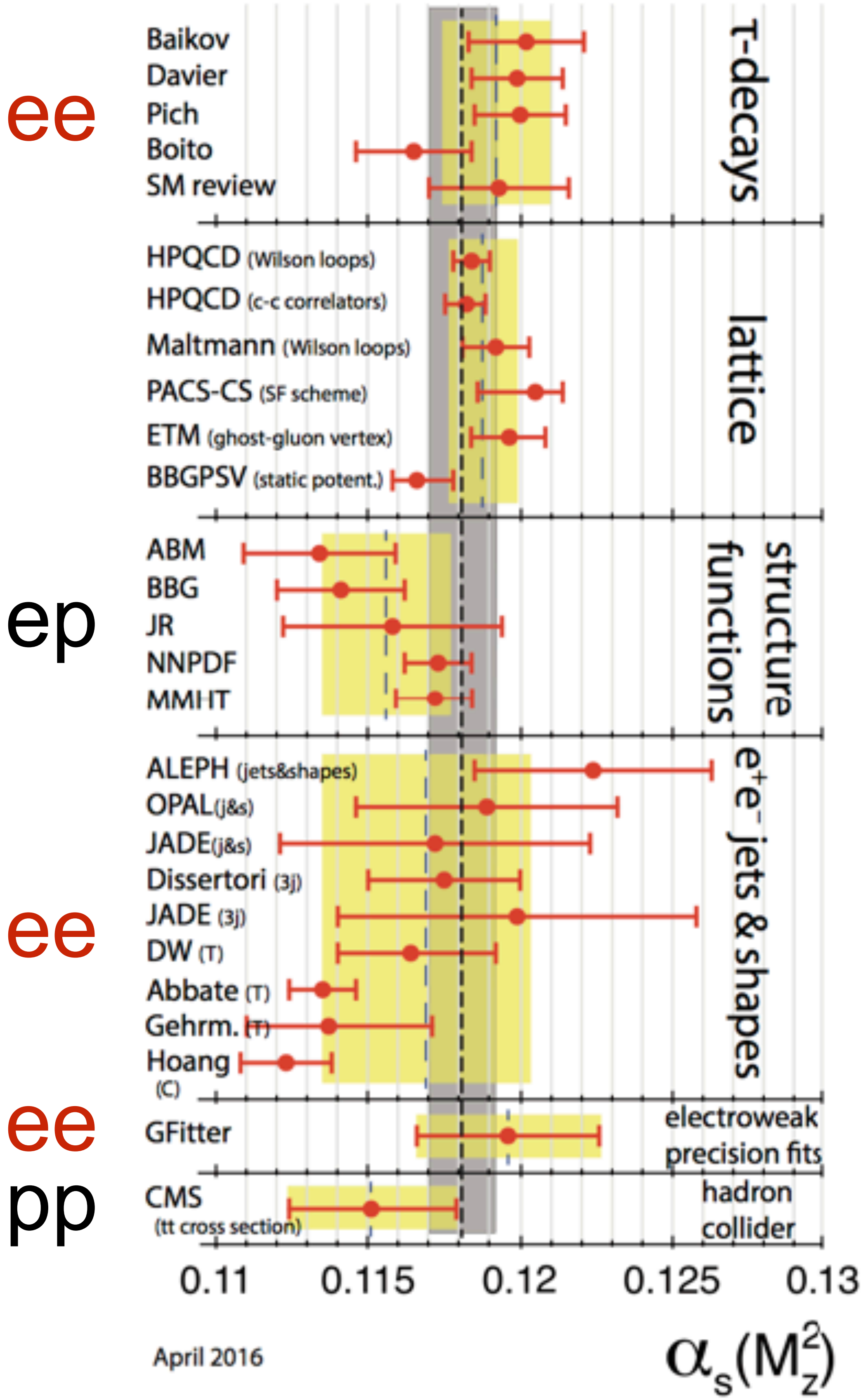
- **α_s ~ 0.1 at Z pole: slow convergent perturbation series**
- **Many important processes start at $O(\alpha_s^2)$**

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 %		

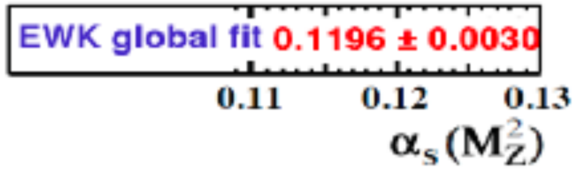
Process	Cross section(pb)	Scale(%)		PDF $+\alpha_s$		$\delta\alpha_s$(%)
ggH	49.87	-2.61	+ 0.32	-6.2	+7.4	± 3.7
VBF	4.15	-0.4	+ 0.8	± 2.5		± 0.7
WH	1.474	-0.6	+ 0.3	± 3.8		± 0.9
ZH	0.863	-1.8	+ 2.7	± 3.7		± 0.9
ttH	0.611	-9.3	+ 5.9	± 8.9		± 3.0

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: $R_l^0 = \frac{\Gamma_{\text{had}}}{\Gamma_l}$ σ_0^{had} Γ_Z

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

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

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

- Inclusive, theoretically clean observable. Non-perturbative effects strongly suppressed
- Uncertainties dominated by experiment
- N3LO QCD known. May need N4LO + higher order mass corrections in the future

CEPC super Z factory

10^{11} Z boson

A factor of 70 reduction in statistical uncertainties

$$\Delta(\alpha_s)_{\text{exp}} < 0.1\%$$

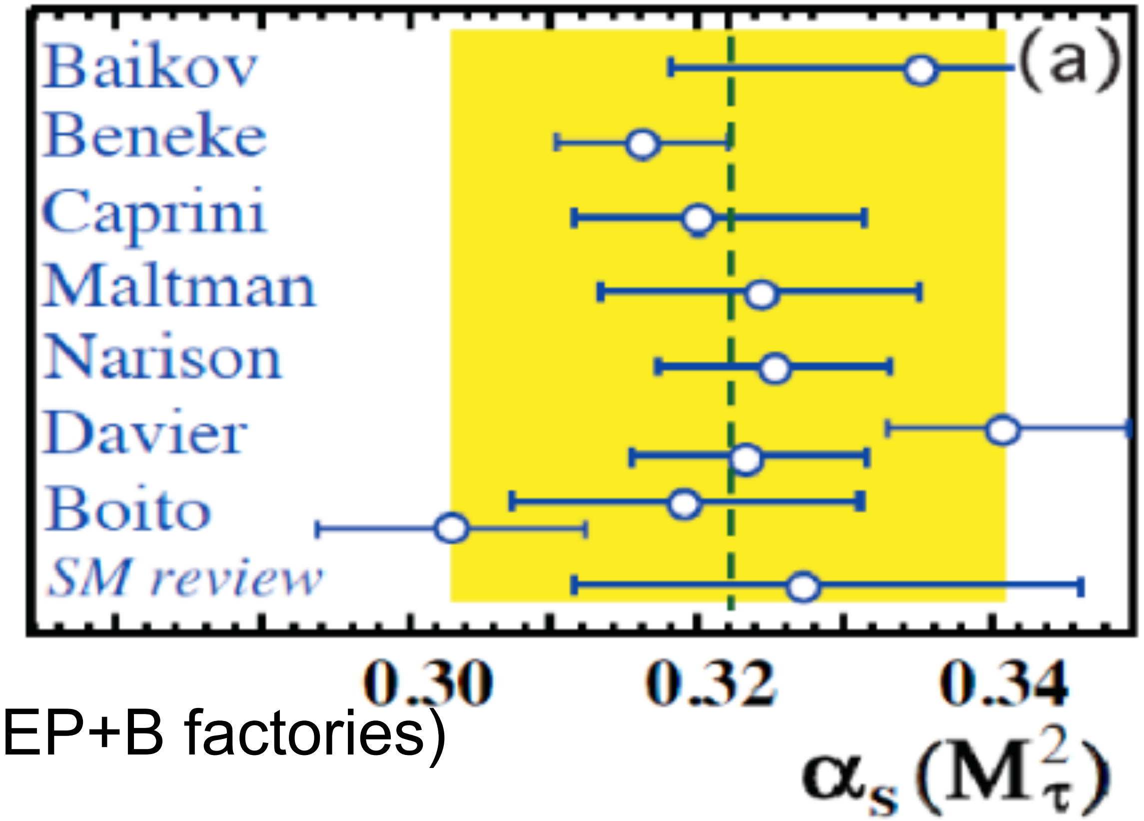
$$\Delta(\alpha_s)_{\text{th}} < 0.3\%$$

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**

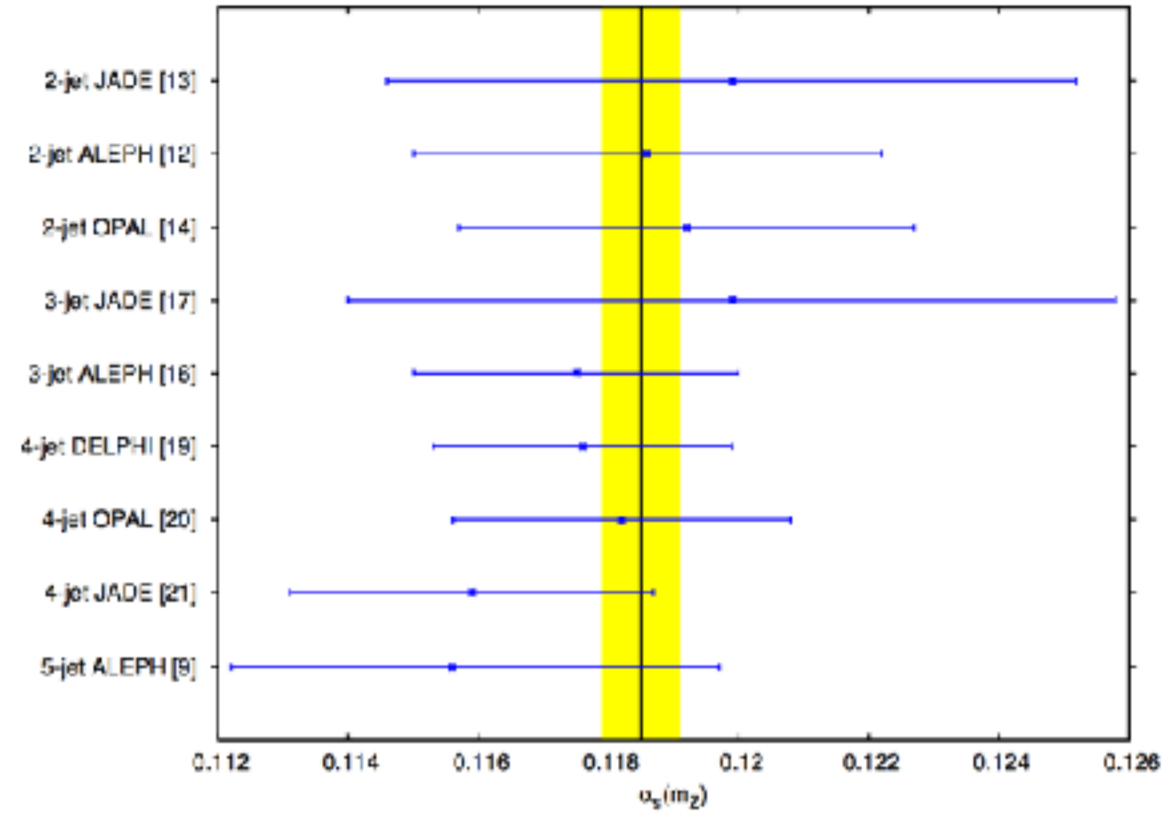
$$\delta_{\rm np} = \frac{\rm ZERO}{m_\tau^2} + c_4 \cdot \frac{\langle O_4 \rangle}{m_\tau^4} + c_6 \cdot \frac{\langle O_6 \rangle}{m_\tau^6} + \cdots$$

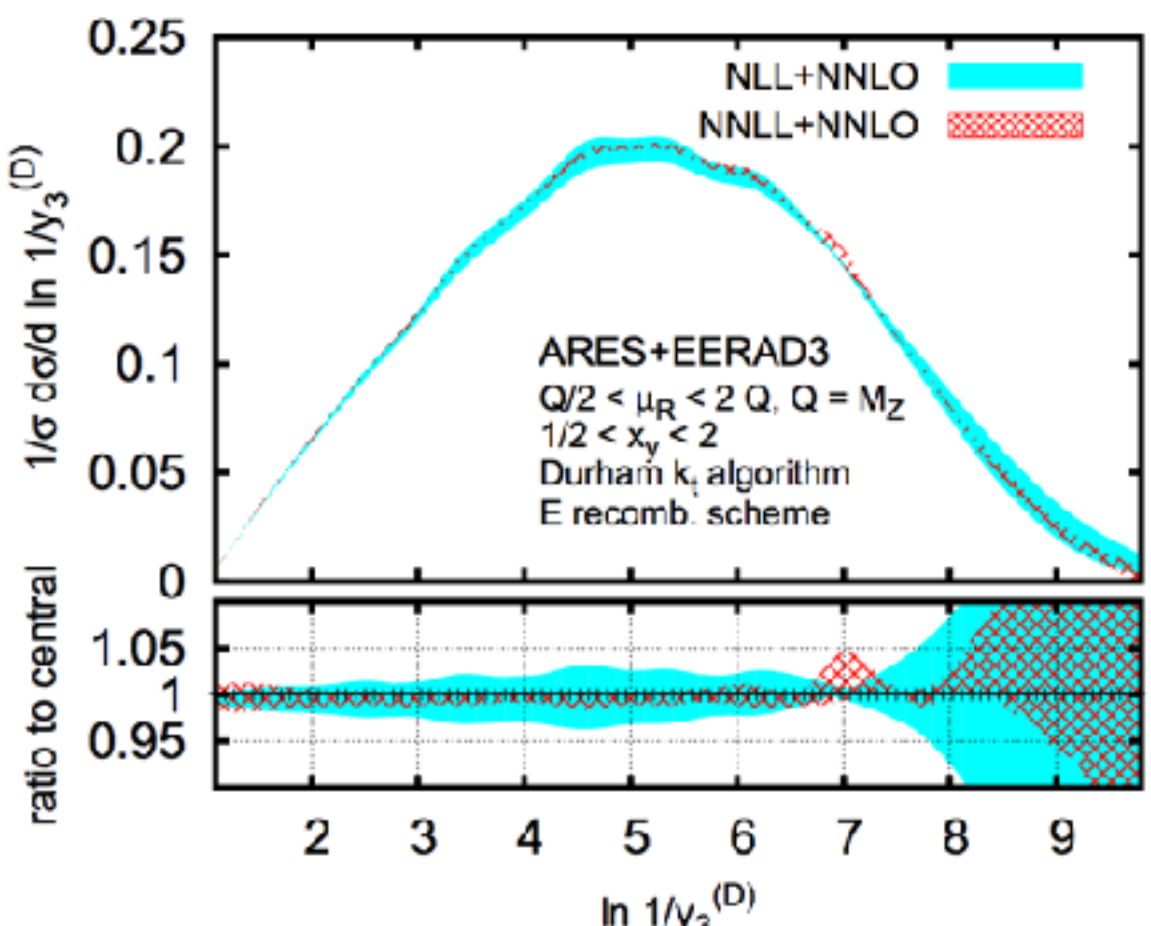
- **Main theory uncertainties (~2%) from Fixed Order Perturbation Theory v.s. Contour Improved Perturbation Theory (resumming log of (s/m_τ^2))**
- **Need N^4LO calculation to clarify**

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





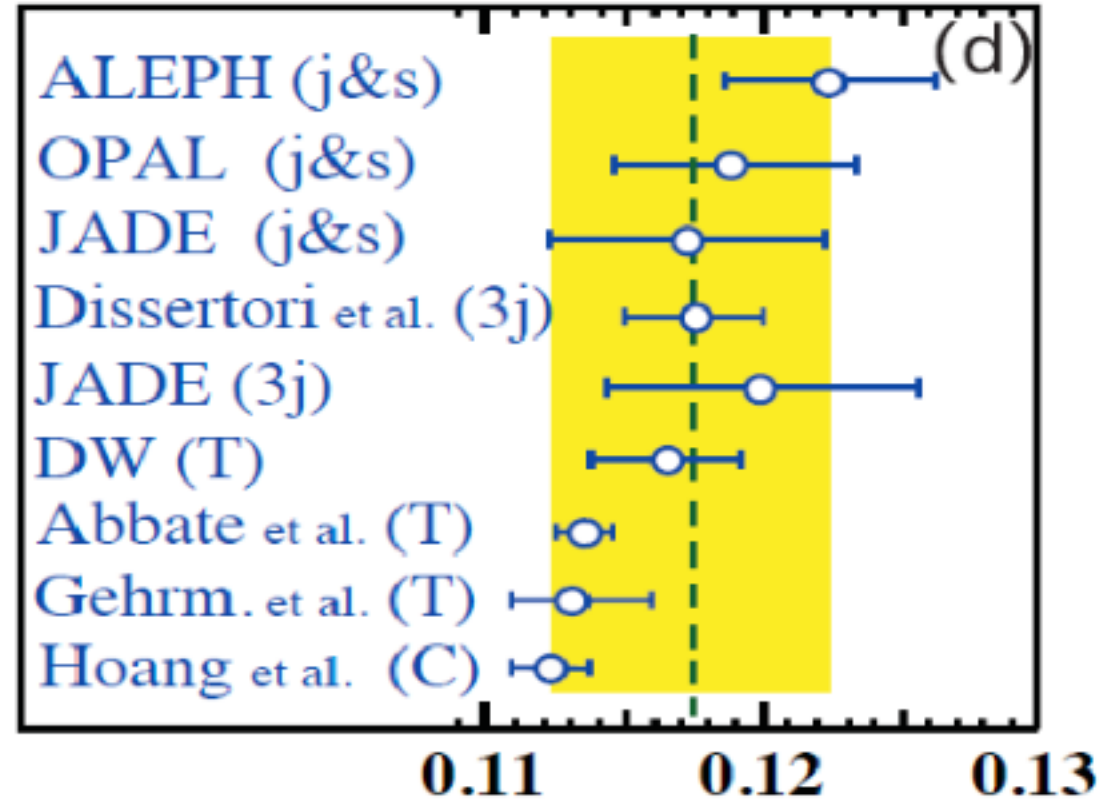
Banfi, McAslan, Monni, Zanderighi, 2016

- 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

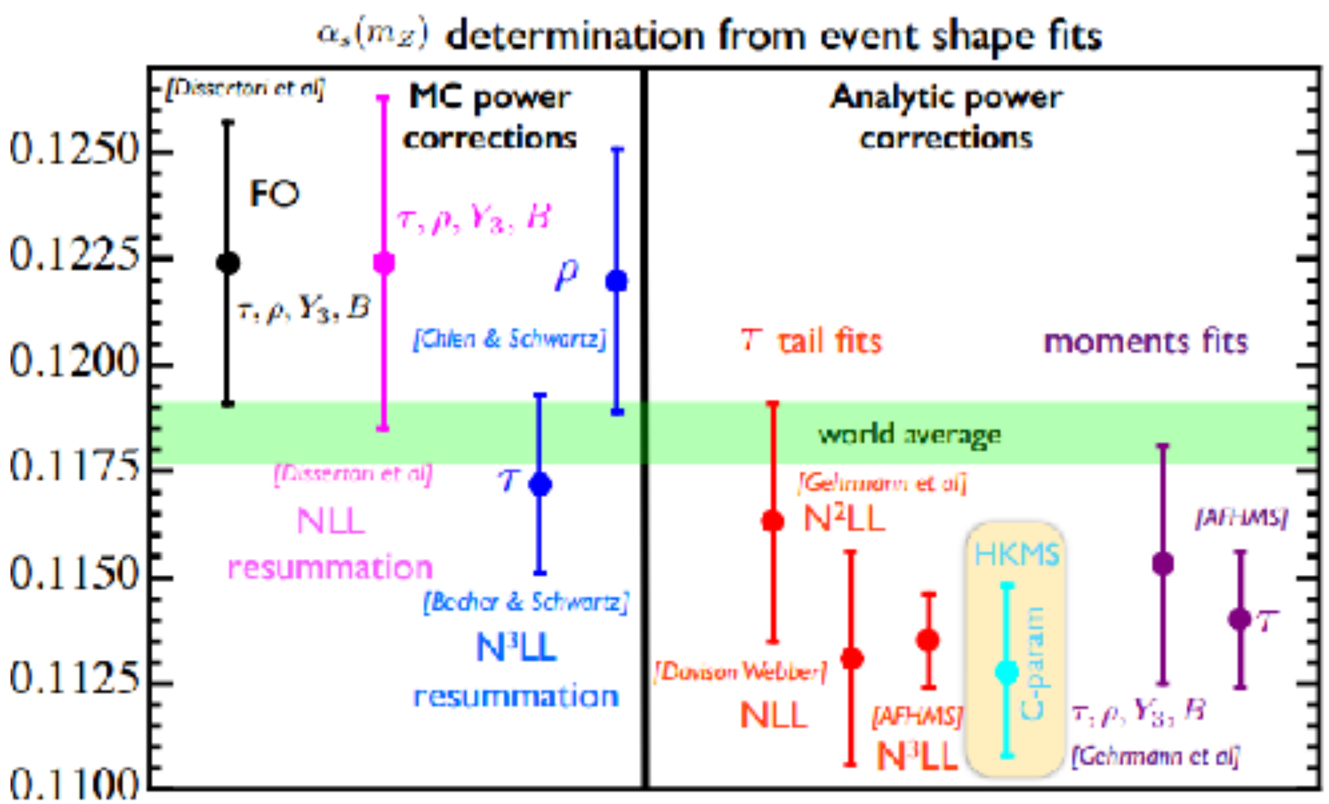
α_s from e+e- event shape

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** $\sim \frac{\Lambda}{Q}$
- **Main reason fro drifting α_s from event shape below world average**



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**

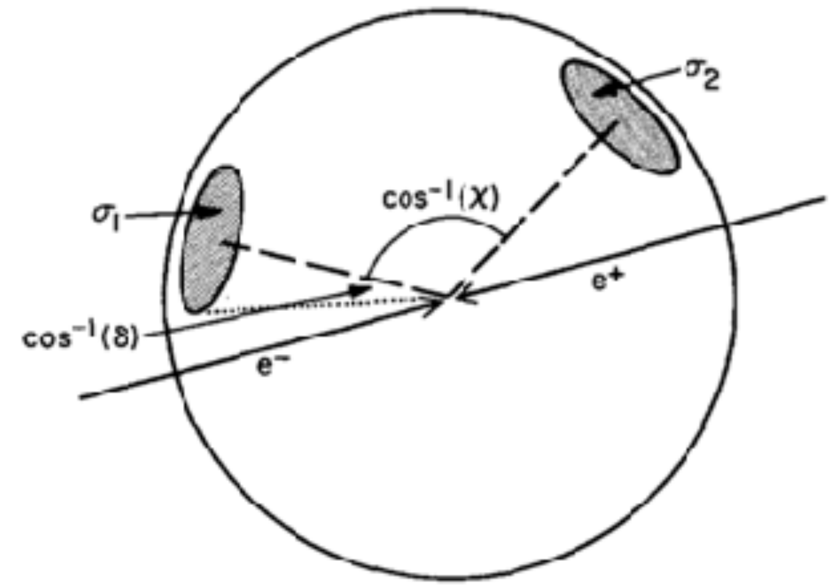
Summary for α_s measurement

	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. $< 0.1\%$ (possible) theo. $\sim 0.3\%$ (N^4LO, 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^4LO)
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 Q^2 to suppressed N.P. effects
- Alternative methods for α_s determination
  - event shape with soft drop (suppressed N.P. effects)
  - ≥ 3 jets event shapes (e.g. N-jettiness)

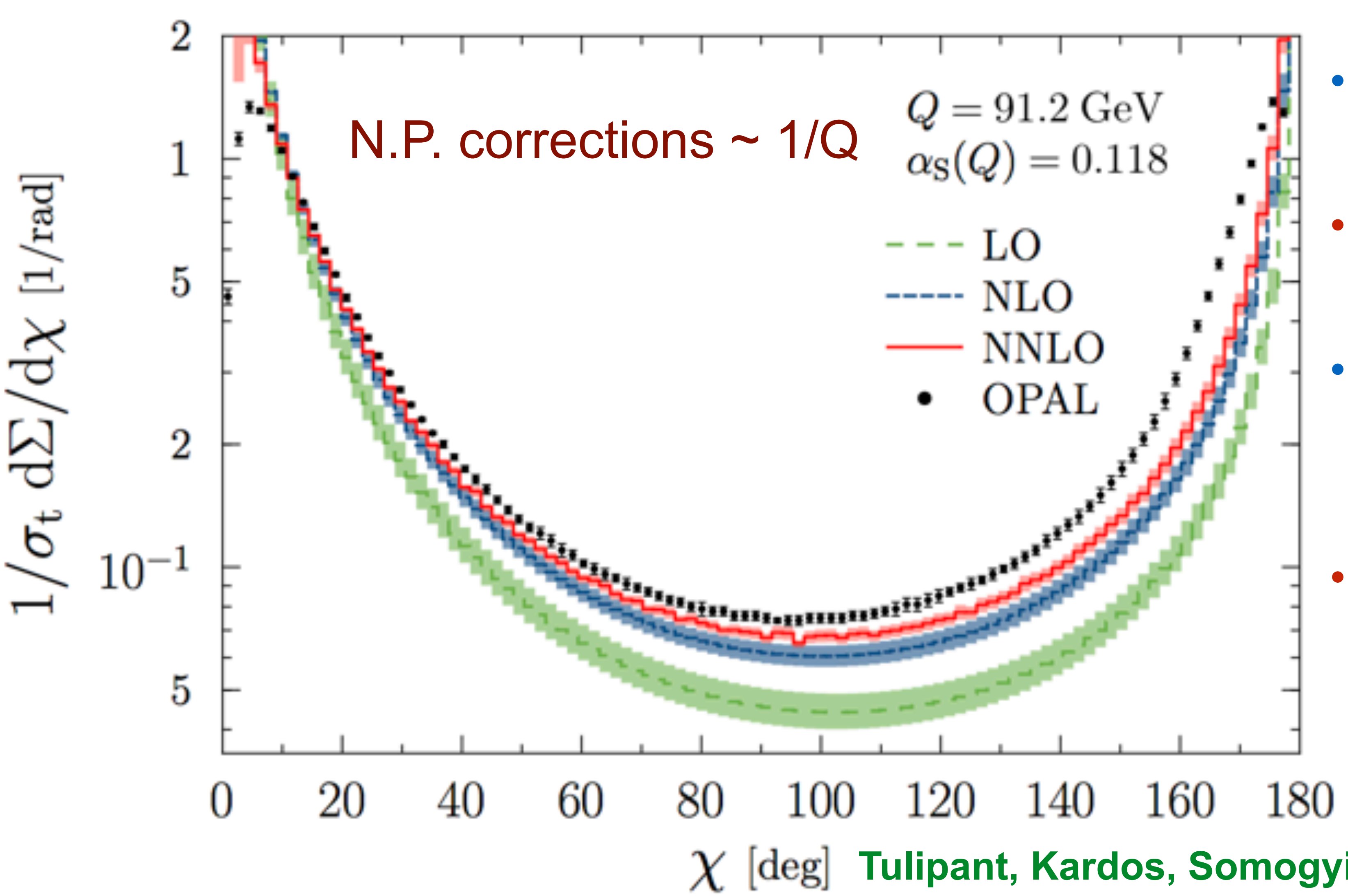
Event shape

Energy-energy correlation



- Measure the two-point energy correlation
- For many years this observable is only known to NLO in QCD. NNLO available only very recently

$$\text{EEC} = \sum_{a,b} \int d\sigma_{V\to a+b+X} \frac{E_a E_b}{Q^2 \sigma_{\text{tot}}} \delta(\cos\theta_{ab} - \cos\chi)$$



Tulipant, Kardos, Somogyi, 2017

- NNLO improve data-theory comparison
- Is the remaining difference really due to N.P. effects?
- At 250 GeV it is expected that the N.P. effects will be reduced to 1/3
- with $5ab^{-1}$ and millions of multi jets events, CEPC will definitely be able to answer the question

Using angularity to disentangle N.P.

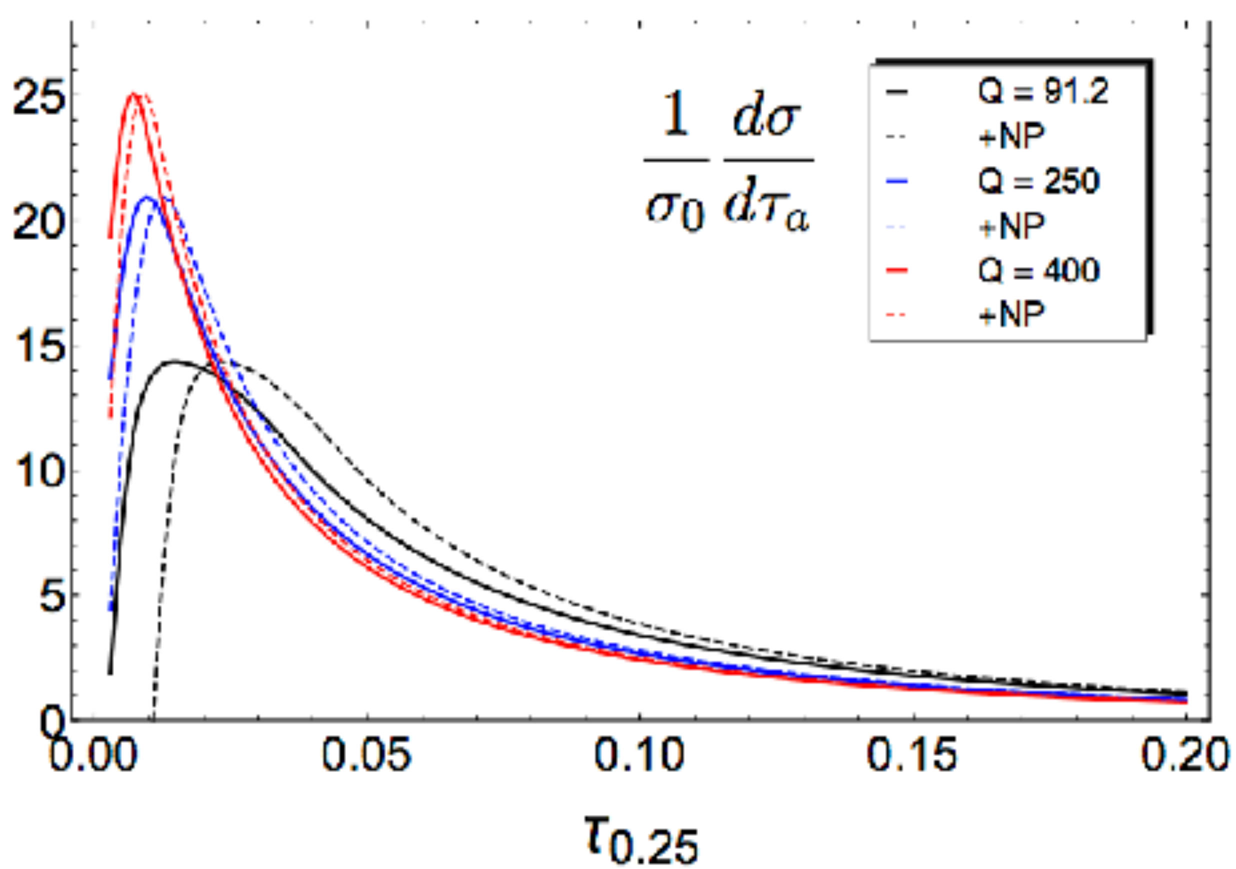
Bell, Lee, Hornig, Talbert, in 1702.01329

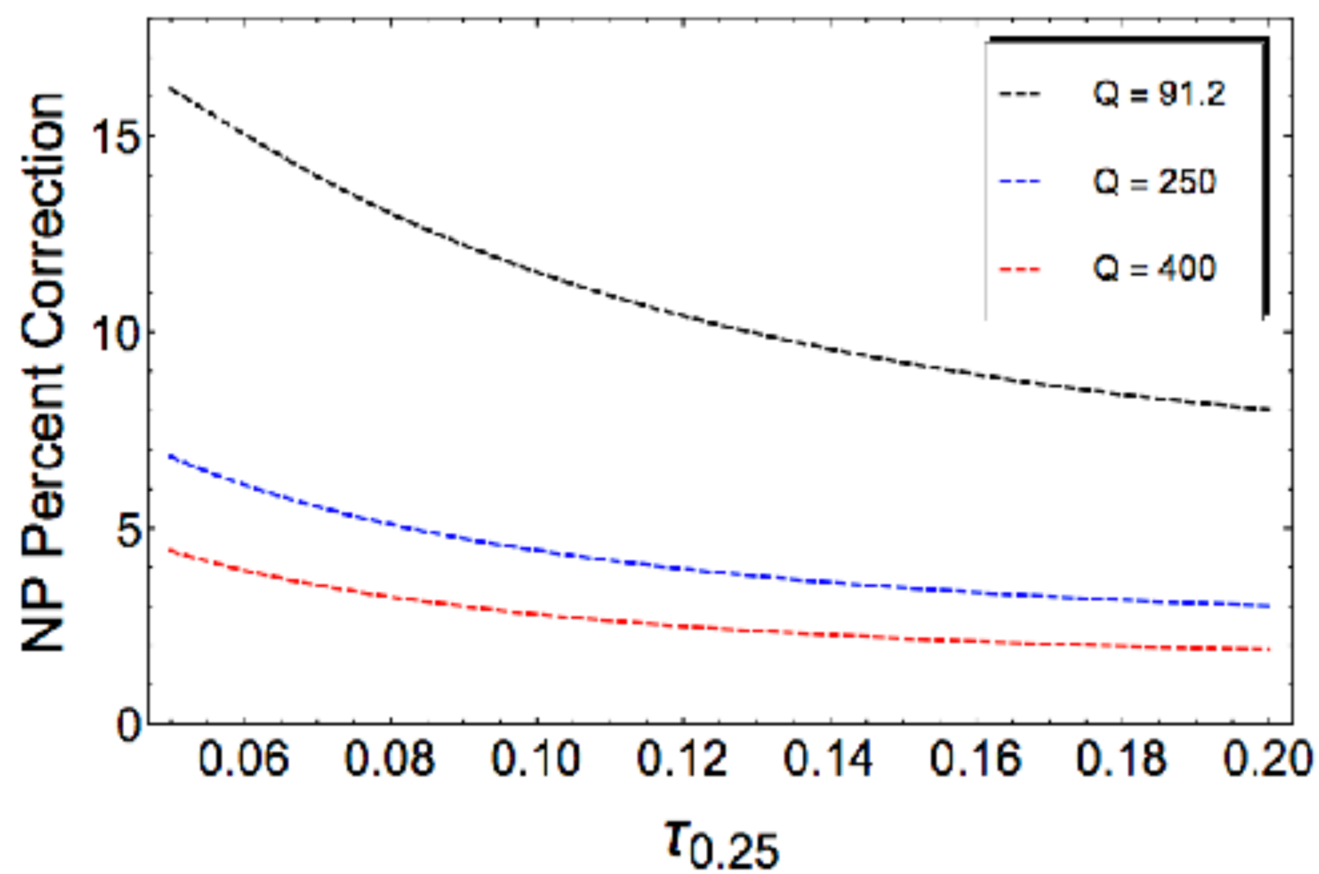
- Angularity is a general event shape interpolate thrust (a=0) and broadening (a=1)

$$\tau_a(X) = \frac{1}{Q}\sum_{i\in X} E_i\,|\sin\theta_i|^a\,(1-|\cos\theta_i|)^{1-a}$$

N.P. $\frac{d\sigma}{d\tau_a}(\tau_a) \xrightarrow[\text{NP}]{} \frac{d\sigma}{d\tau_a}\left(\tau_a - c_{\tau_a}\frac{\mathcal{A}}{Q}\right)$

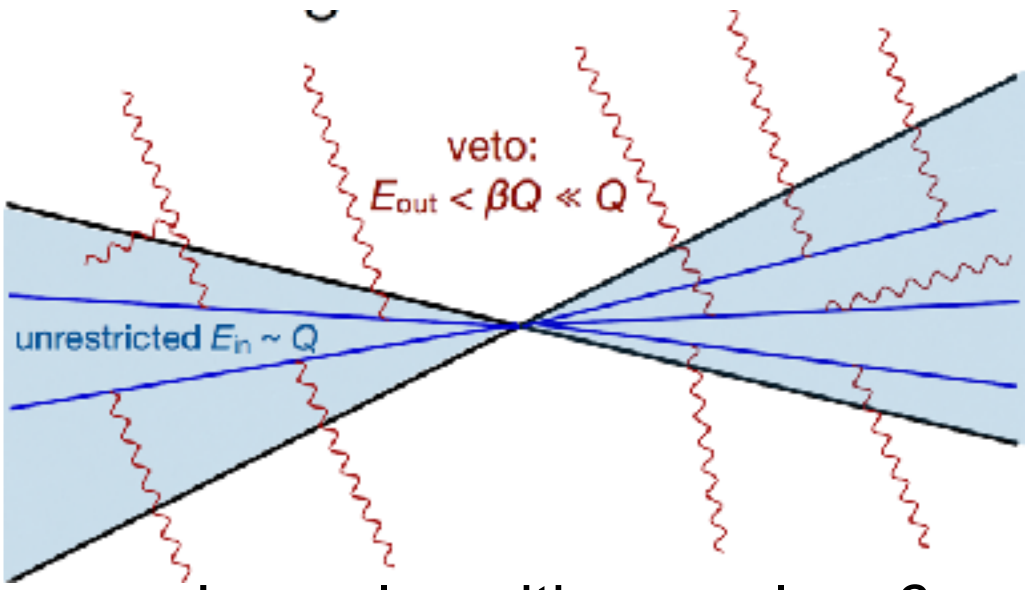
- Varying the parameter a gives additional handle to N.P. effects besides Q
- Increasing Q to 250 GeV also reduce expected N.P. corrections to about 1/3





Non-global logarithms

- Non-global logarithms (Dasgupta, Salam, 2002): observable only sensitive to a portion of phase space. Examples:
  - Sherman-Weinberg jet cross section
  - Light jet mass; narrow jet broadening, jet veto, gaps between jet, jet substructure, ……

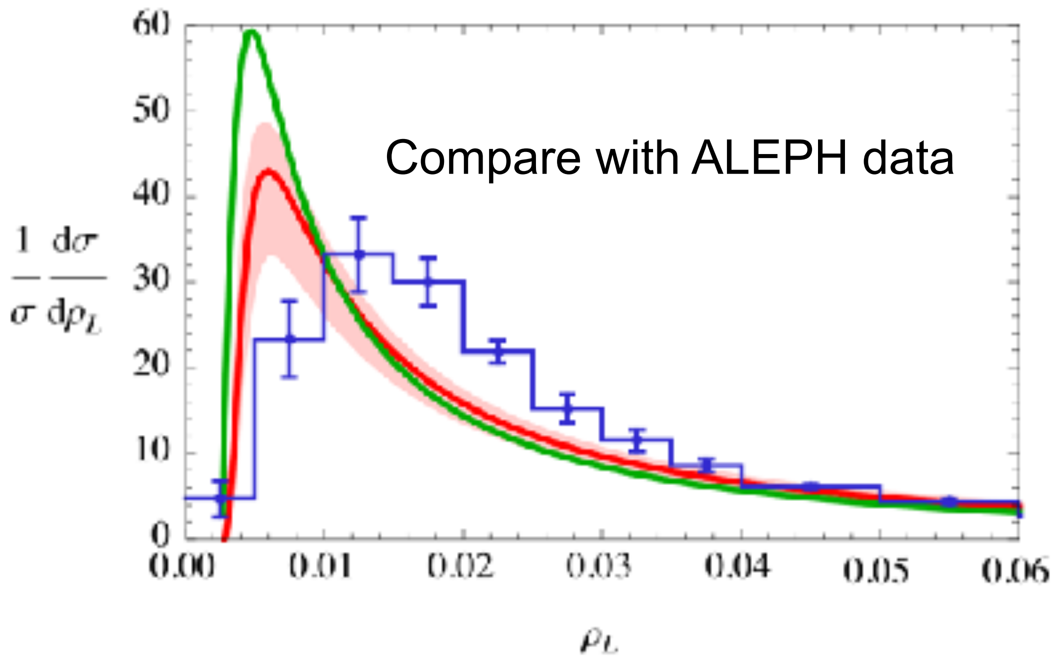


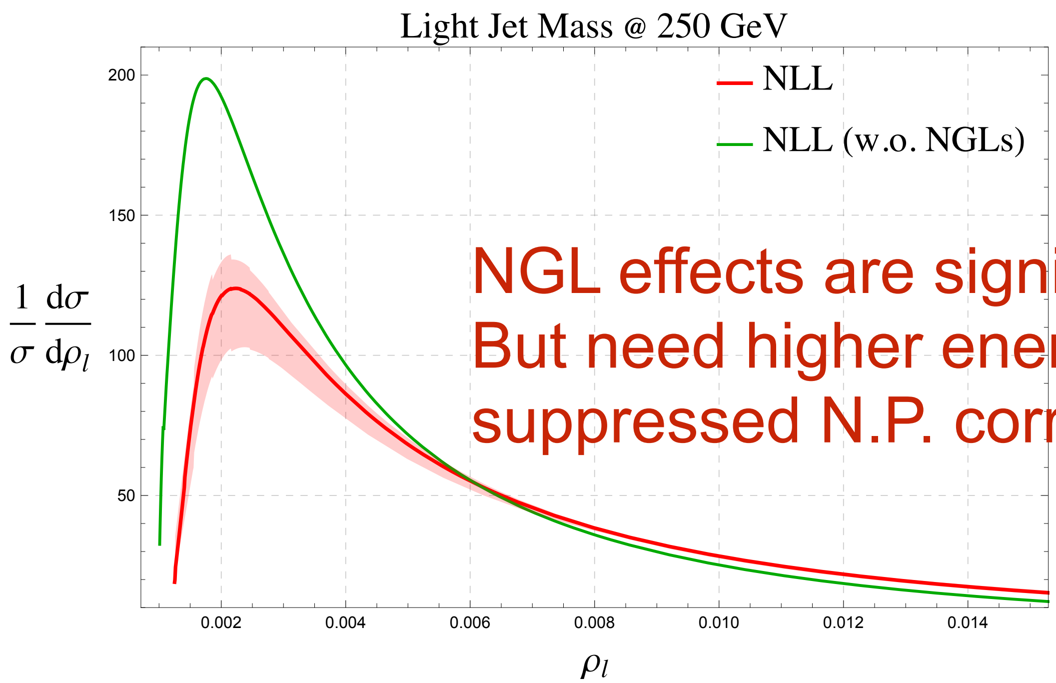
Large logarithms $\alpha_s^n \log^m \beta$ do not exponentiate

BMS equation

$$\partial_L G_{kl}(L) = \int \frac{d\Omega(n_j)}{4\pi} \frac{p_k \cdot p_l}{(p_k \cdot \hat{p}_j)(\hat{p}_j \cdot p_l)} \left[\Theta_{\text{in}}^{n\bar{n}} G_{kj}(L) G_{jl}(L) - G_{kl}(L)\right]$$

- Reduce to BFKL equation in the linear limit. The possibility of observing BFKL dynamics in jet physics is exciting.





NGL effects are significant. But need higher energy to suppressed N.P. corrections

Becher, Pecjak, Shao, 2016

Using event shape to for light quark Yukawa

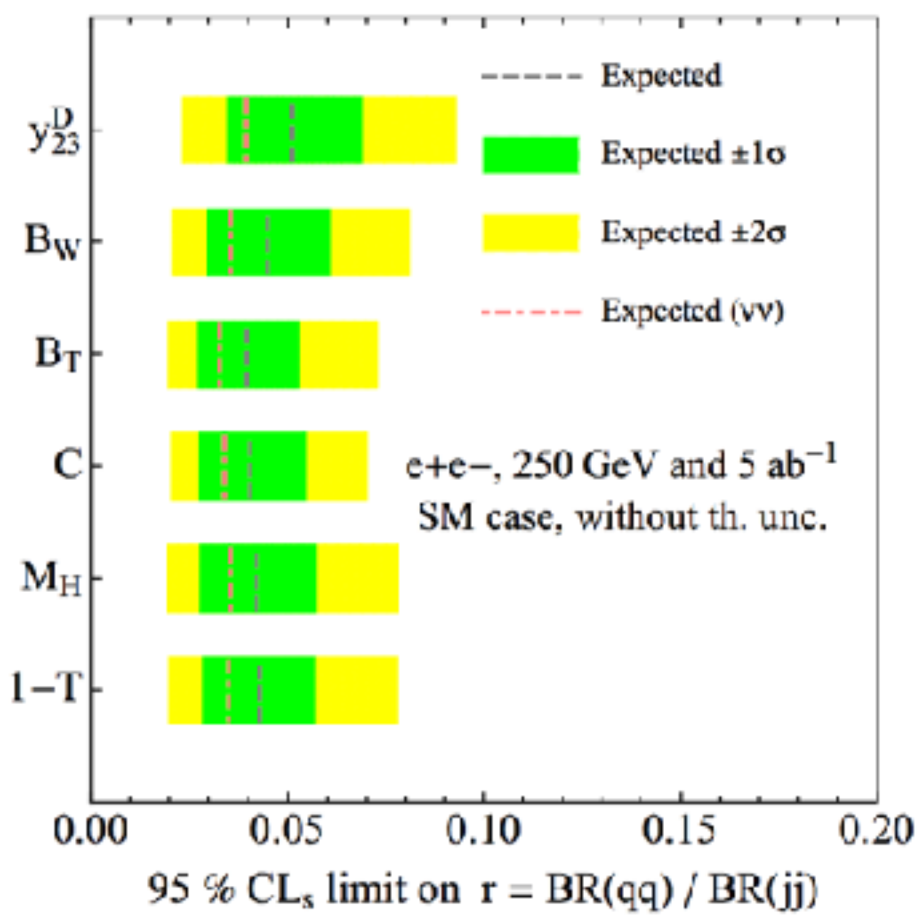
- CEPC will also be unique with clean gg sample from H decay

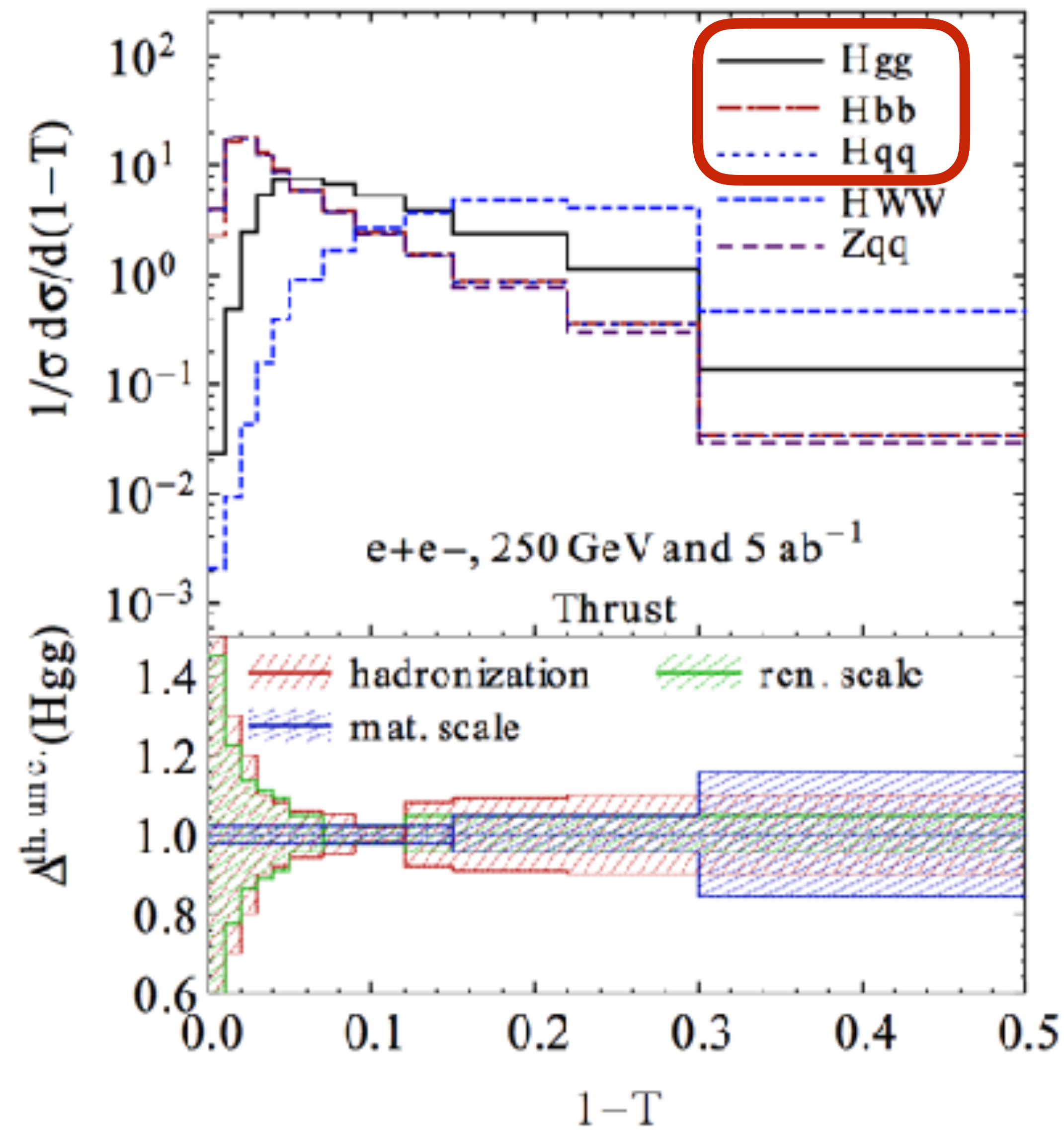
$Z(l^+l^-)H(X)$	gg	$b\bar{b}$	$c\bar{c}$	$WW^*(4h)$	$ZZ^*(4h)$	$q\bar{q}$
BR [%]	8.6	57.7	2.9	9.5	1.3	~ 0.02
N_{event}	6140	41170	2070	6780	930	14

- Difference in event shape distribution for gluon and light quark can be used to constrain Yukawa coupling Jun Gao, 2016

$$d\sigma/d\tau \sim \exp(-C_a L^2)$$

quark C_F
gluon C_A





- In the SM, r = branching ratio of light quark to jets ~ 0
- CEPC can reach a exclusion of about 0.045

$$y_{u,d,s} < 0.082 y_b \ (95\% \ \mathrm{CL}_s)$$

Summary

- precision QCD will benefit a lot from a high luminosity e+e- collider at 240-250 GeV
  - precision alpha_s determination
    - Z-pole global fit expect to give best determination
  - Detailed understanding of power corrections
    - establish or disprove the 1/Q functional form for N.P. corrections
    - observable dependence of N.P. corrections

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Thank you for your attention!