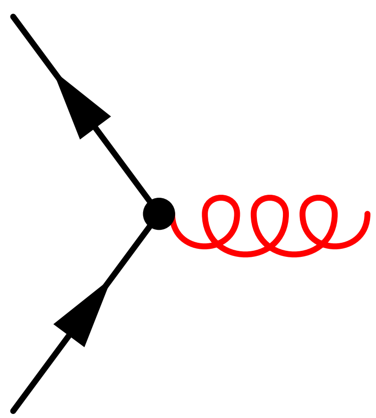
Precision QCD Study at Future e+e- Colliders

Hua Xing Zhu
Massachusetts Institute of Technology

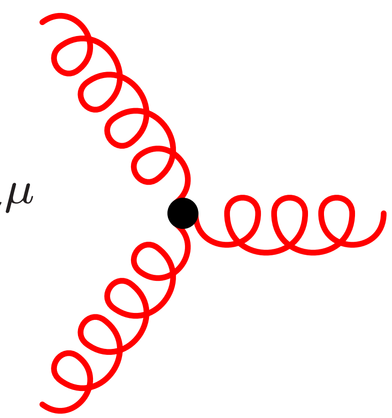
IAS program on High Energy Physics
HKUST Jockey Club, Institute for Advance Study
Jan. 23, 2017

Motivation

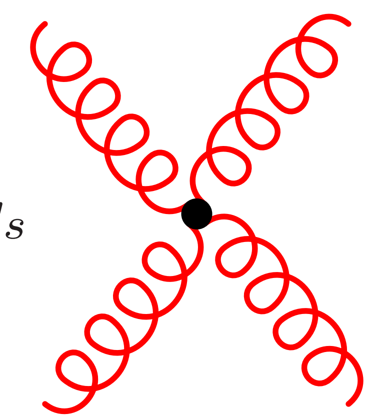
- QCD is a non-abelian Yang-Mills theory with very rich phenomena:
  - Asymptote freedom, confinement, jet formation, quark gluon plasma, color superconductivity …
- Yet it's definition is simple:



$= -i g_s t^a \gamma^\mu$



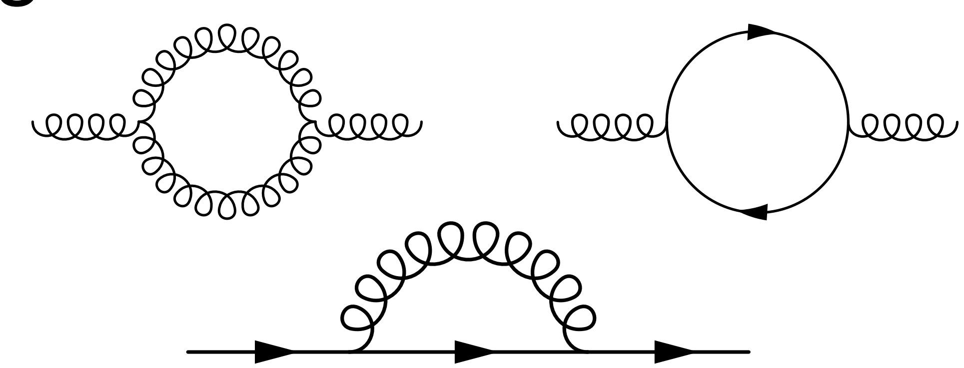
$\propto g_s$



$\propto g_s^2$

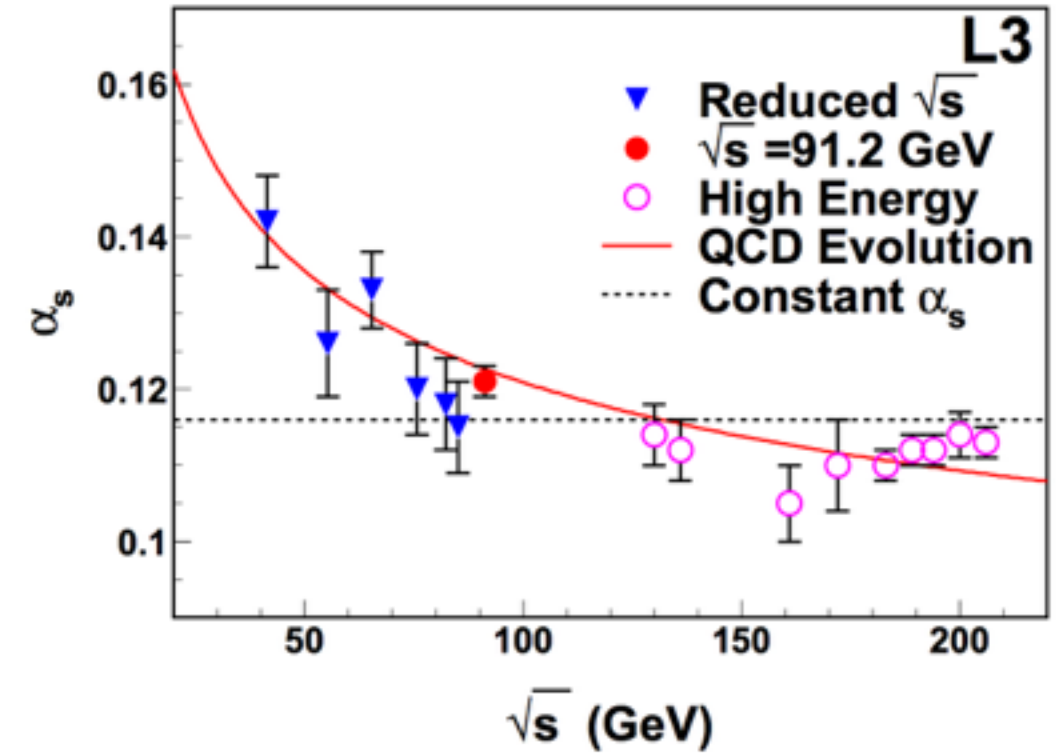
$$\sim C_F = \frac{4}{3} \qquad\qquad \sim C_A = 3$$

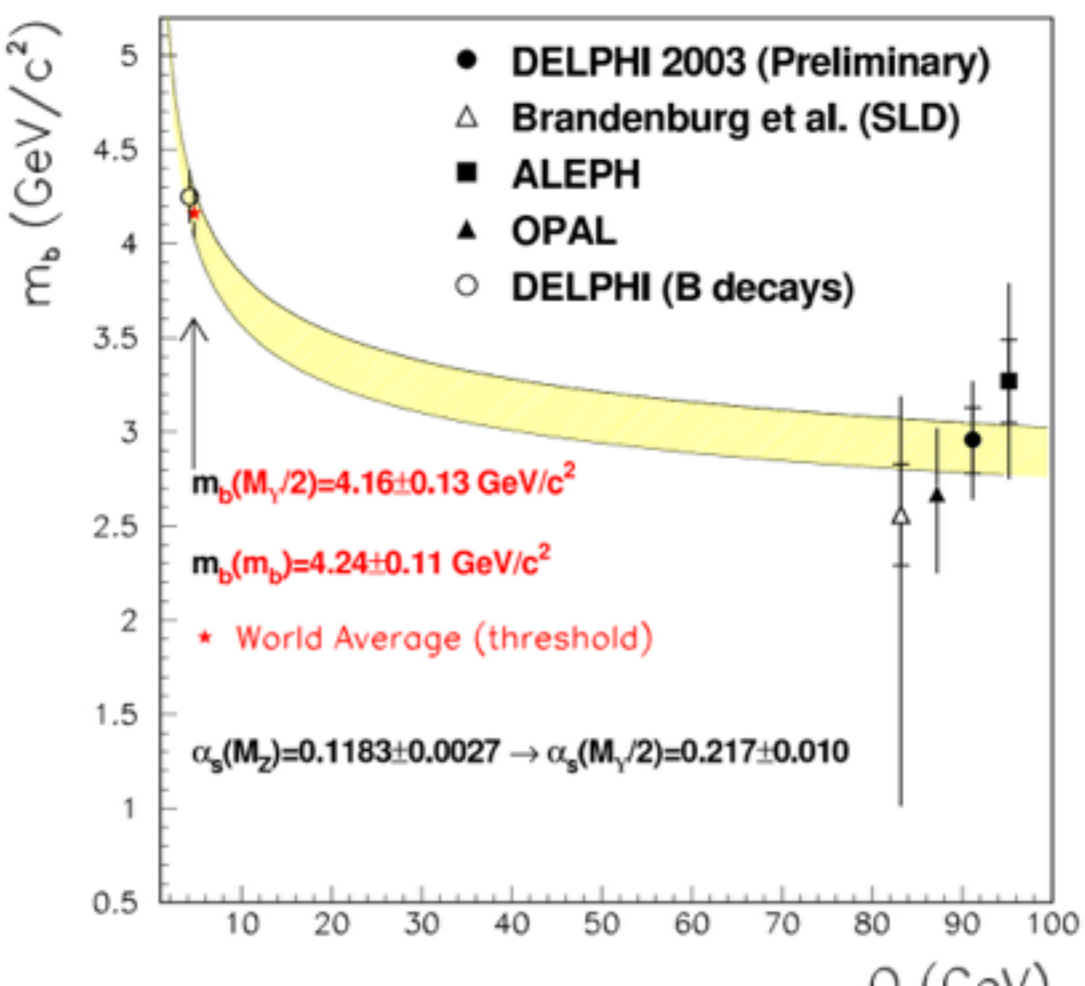
- For example, the non-abelian gauge interaction leads to
  - running of strong coupling
  - running of heavy quark mass

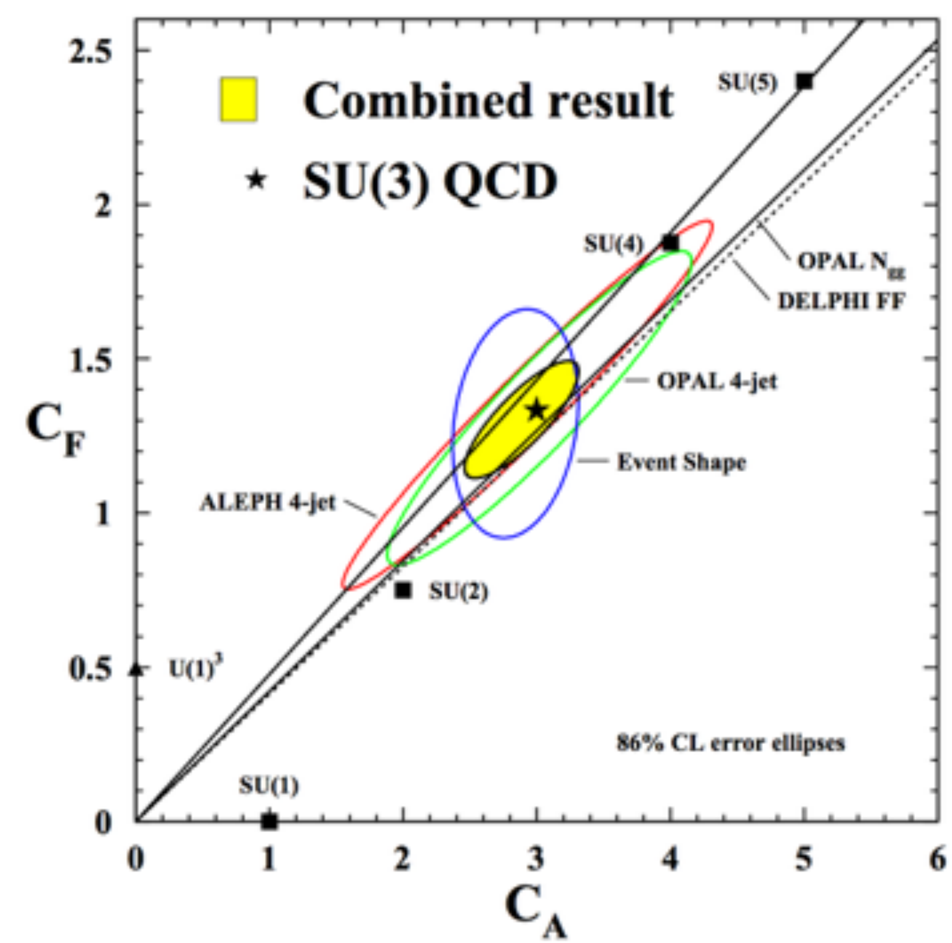


Legacy of LEP from 14 to 209 GeV

- QCD as the correct theory of strong interaction undoubtedly established from many different measurements at LEP:
  - Running of α_s through event shapes and jet rates measurement
  - Running of b-quark mass through 3-jet rate in b-quark event
  - Combined Fits of QCD gauge structure constant







QCD at future e+e- study

- While e+e- collider is not a QCD machine, it has unique advantage over hadron colliders for understanding QCD at a more precise level
  - Fixed initial state energy
  - Absent of underlying events
- A future e+e- machine will support a rich program of precision QCD study
  - More precision in α_s measurement
  - Understanding of non-global observable
  - Finer structure of multi-jet events
  - Testing models of hadronization
  - Monte-Carlo Tuning
  - Fragmentation function
  - Interplay with EW, Higgs, BSM
  - ……

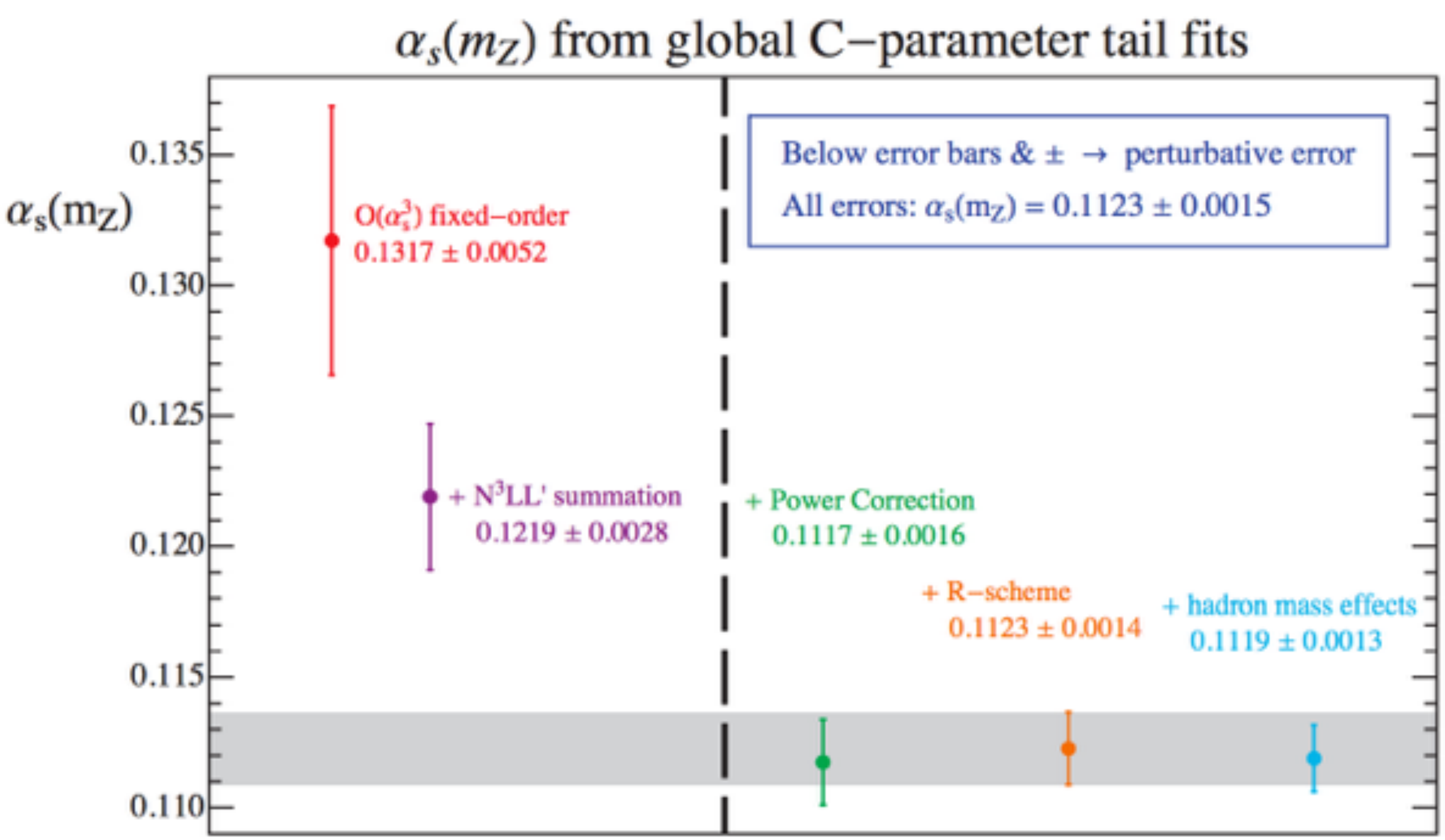
QCD at future e+e- study

- While e+e- collider is not a QCD machine, it has unique advantage over hadron colliders for understanding QCD at a more precise level
  - Fixed initial state energy
  - Absent of underlying events
- A future e+e- machine will support a rich program of precision QCD study
  - More precision in α_s measurement
  - Understanding of non-global observable
  - Finer structure of multi-jet events
  - Testing models of hadronization
  - Monte-Carlo Tuning
  - Fragmentation function
  - Interplay with EW, Higgs, BSM
  - ……

Event shape

- Remarkable theoretical progress over the last decade for event shape calculation. The state of the arts:
  - NNLO QCD + NLO EW for e+e- to 3 jets
- N3LL resummation for thrust, heavy jet mass, C parameter form Soft-Collinear Effective Theory

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

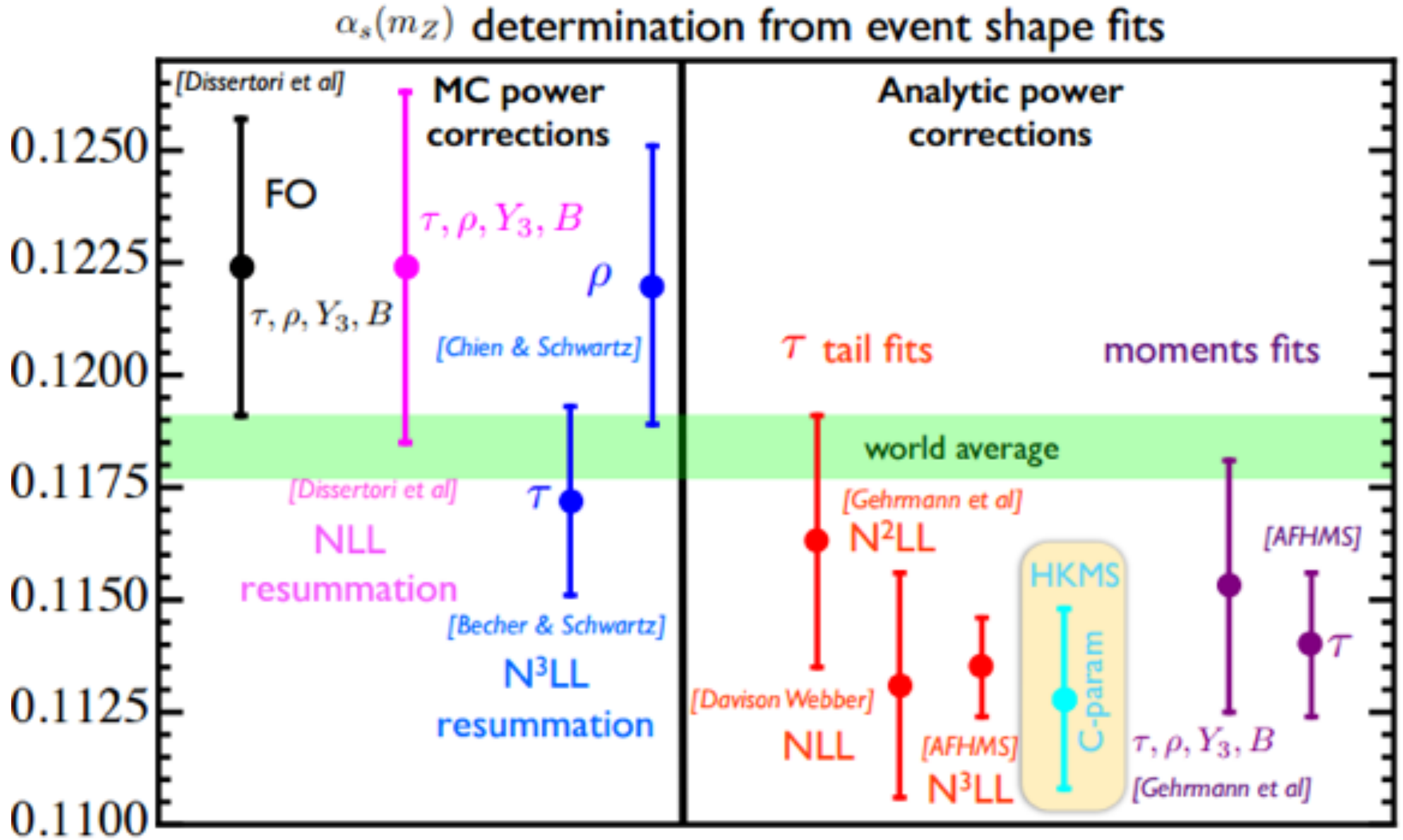


$$\alpha_s(m_Z) = 0.1123 \pm 0.0002_{\rm exp} \pm 0.0007_{\rm hadr} \pm 0.0014_{\rm pert}$$

- Simultaneous fit of α_s and non-perturbative corrections (Analytic power corrections). Consistent between thrust, heavy jet mass and C parameter
- The biggest effect is the -8% corrections when adding the non-perturbative fit corrections

Hoang, Kolodrubetz, Mateu, Stewart, 2015

Issue with nonperturbative modeling



Mateu, ICHEP 2014

- MC power corrections: estimate NP effects from difference of hadron and parton level MC
- Significant difference between MC power corrections and analytic power corrections
- While α_s fit using MC power corrections tend to agree better with world average, one should be careful that MC use LO matrix in its prediction
- Future e+e- collider with different/higher energy will be important to address this issue

Next-to-Leading Power logs in event shape

$$\frac{d\sigma}{d\tau} \sim \frac{\ln^m \tau}{\tau}(\text{Leading Power}) \;+\ln^m \tau(\text{Next-to-Leading Power}) \;+\ldots$$

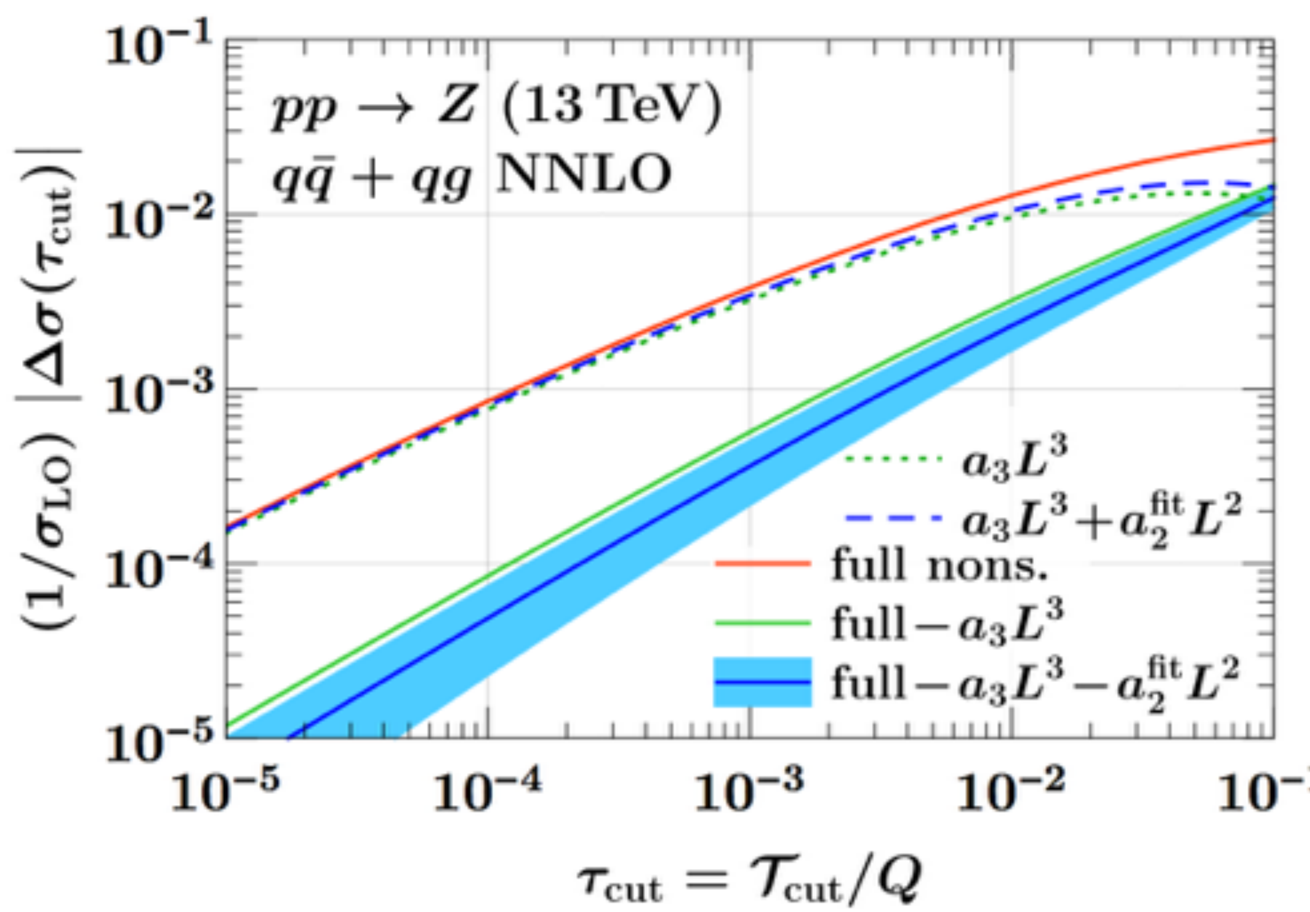
- While the leading power large logarithms are under good control, the subleading power logarithms are far from understood
- Recently the full set of operators for NLP corrections have been obtained in SCET

[Kolodrubetz, Moult, Stewart, 16]; Feige, Kolodrubetz, Moult, Stewart, forthcoming]

- First O(α_s^2) analytic result for leading logarithms at NLP for thrust

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma^{(2,2)}}{\mathrm{d}\tau} = \left[-32C_F^2 + 8C_F(C_F+C_A)\right]\ln^3\tau$$
$$= 8C_F(C_A-3C_F)\ln^3\tau\,.$$

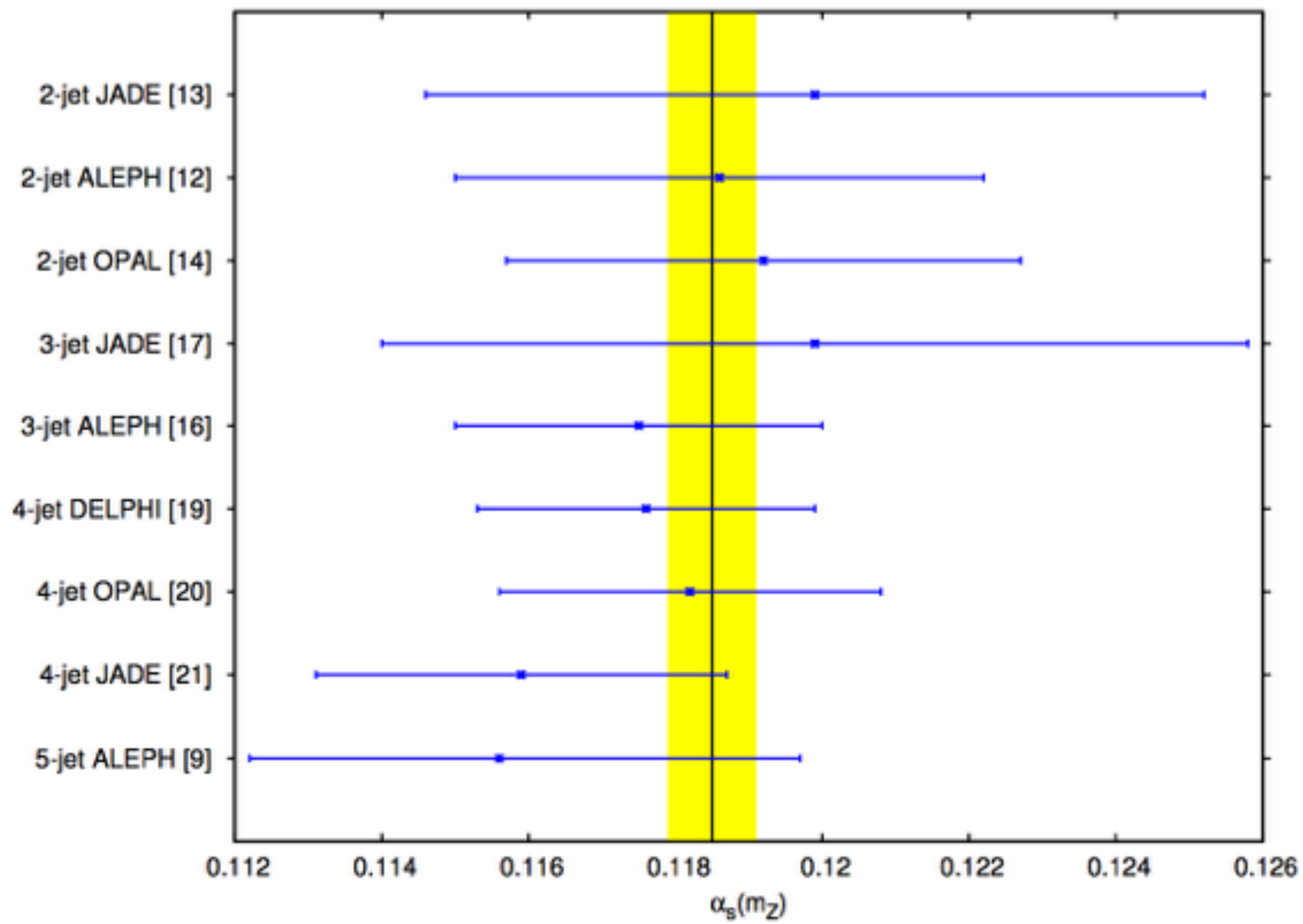
- (Right Fig.) Comparison of analytic and numerical NLP log for beam thrust at hadron collider
- Resummation of NLP logarithms may be important to further reduced theoretical uncertainties in event shape fit



Lorena, Moult, Tackmann, Stewart, HXZ, 2016

Jet rates extraction: NNLO frontier

- The fixed order revolution in the past decade make extraction of five-jet rate at NLO and three-jet rate at NNLO possible
- For jet rates, parton level MC predictions agree well with pQCD calculation, indicating that MC power corrections gives sensible estimate
- Dominant theoretical uncertainties from scale variations: call for NNLO/N3LO calculation and resummation

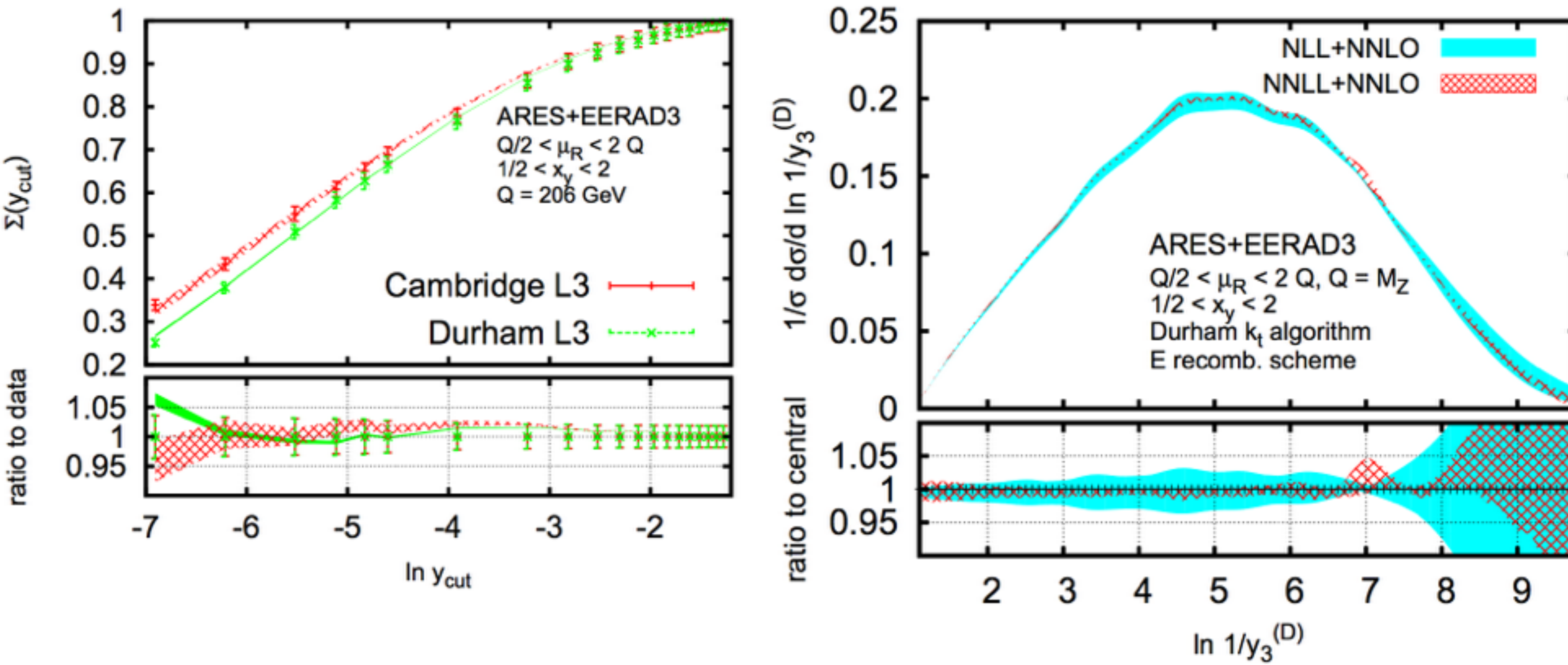


High-precision αs measurements from LHC to FCC-ee, 1512.05194

Resummation two-jet rate

- For a long time two-jet rate can only be resumed at NLL accuracy
- Recent progress: resumming two-jet rate at NNLL with ARES method

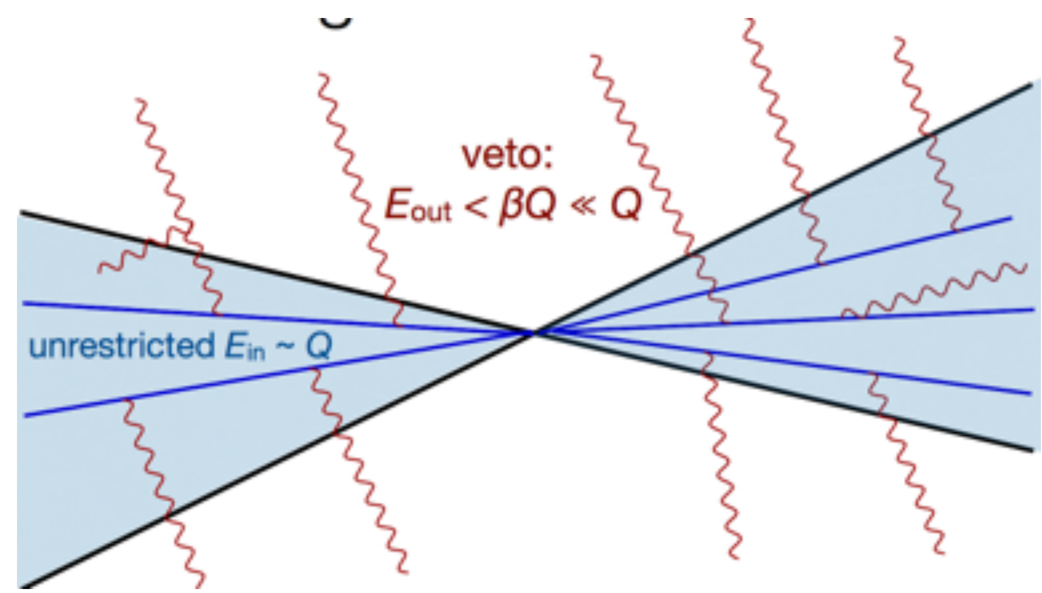
Banfi, McAslan, Monni, Zanderighi, 2016



- NNLL resummation leads to sizable reduction of scale uncertainties for two-jet rate with Durham algorithm. Promising for precision determination of α_s.

Towards better understand of non-global logarithms

- Non-global logarithms (**Dasgupta, Salam, 2002**): observable only sensitive to a portion of phase space. Example: Sterman-Weinberg jet cross section



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

- Many more exmaples:
  - light-jet mass, narrow jet broadening,exclusive jet mass, jet veto, gaps between jet, jet substructure, isolated photon

First reason why they are interesting!

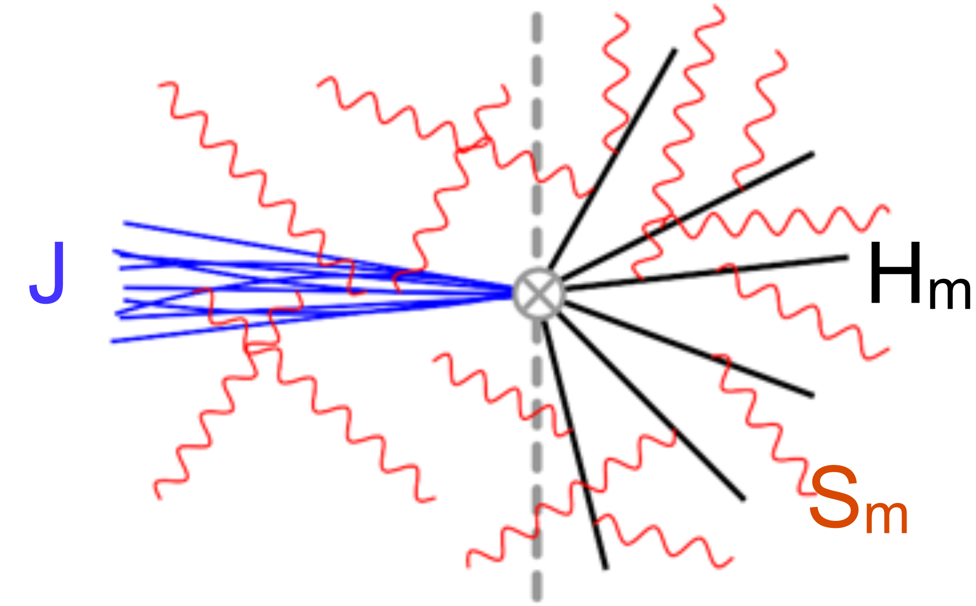
- Leading non-global logarithms at large Nc govern by non-linear evolution equation (Banfi, Marchesini, Smye, 2002)

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

- If Θ_{in}=1, this reduced to the famous Balitsky/Korchegov equation. **The possibility of observing BFKL dynamics in jet physics is another reason why they are interesting.** e+e- collider provides the cleanest environment for discover
- Significant renew interests since 2010: Banfi, Becher, Caron-Huot, Chien, Delenda, Dusgupta, Hagiwara, Hatta, Hornig, Kelley, Khelifa-Kerfa, Larkoski, Lee, Lorena, Moult, Neill, Neubert, Pecjak, Schabinger, Schwartz, Shao, Spannowsky, Stewart, Ueda, von Manteuffel, Walsh, HXZ, Zuberi …

First result for an realistic observable: light jet mass

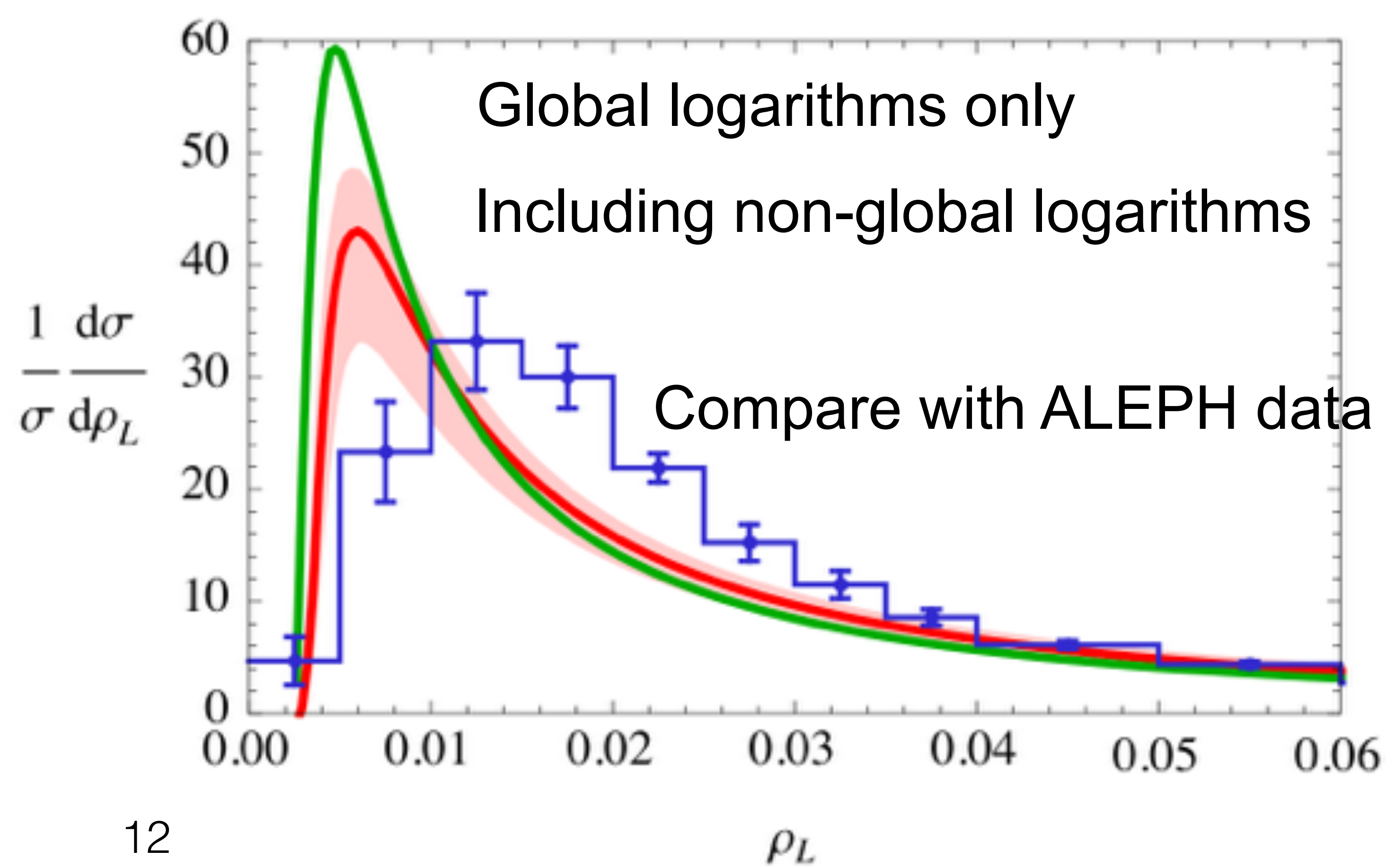
Becher, Pecjak, Shao, 2016



- Highly non-trivial "factorization" theorem
- Infinite many soft operator S_m, mixed under renormalization
- Non-trivial convolution between soft and hard function

$$\sigma(M_L^2) \sim \int_0^\infty d\omega_L \, J(M_L^2 - Q\omega_L) \otimes \sum_{m=1}^{\infty} \langle \boldsymbol{\mathcal{H}}_m^i(\{n\}, Q) \otimes \boldsymbol{\mathcal{S}}_m(\{n\}, \omega_L) \rangle$$

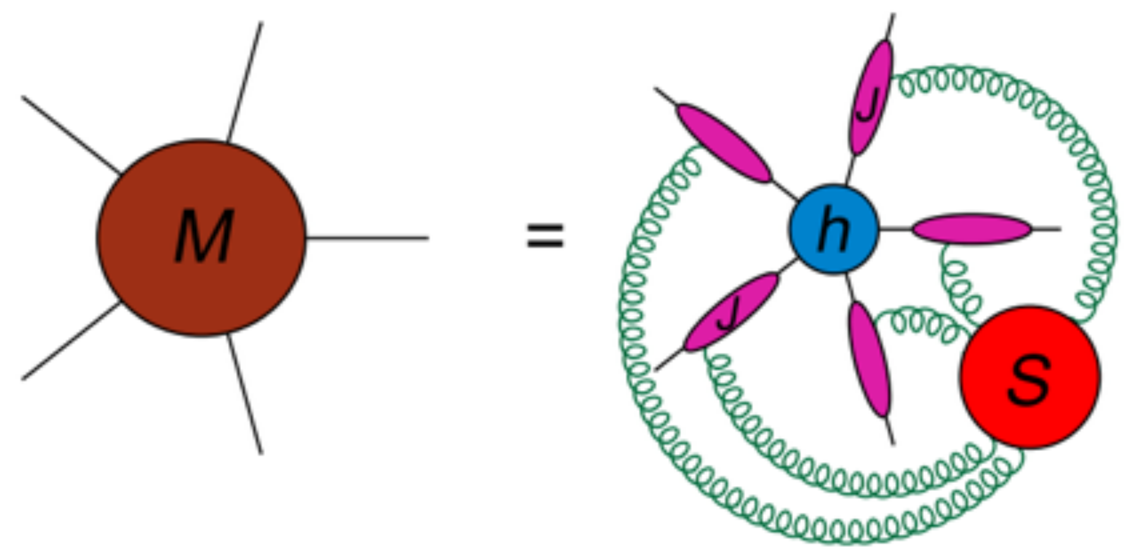
- Including non-global logarithms leads to better agreement with data
- Substantial non-perturbative corrections expected based on experience with heavy jet mass: shift the peak



Revealing the finer structure of QCD amplitudes

- Scattering amplitudes: the most perfect microscopic structures in the universe (**Dixon, 1105.0771**)

Infrared singularities of n-particle on-shell scattering amplitudes factorize into a hard function, n collinear jet function, and a soft function which depends only on the four velocity of the jets.



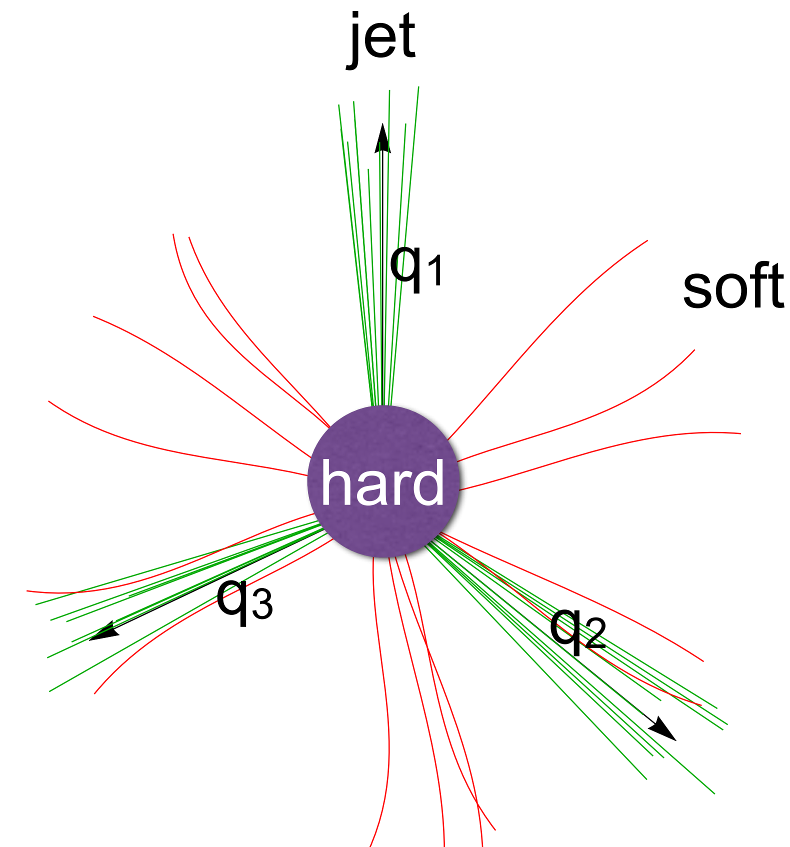
- For a two-jet event at e+e-, $Q \to p_1 p_2$, the structure is trivial $((\mu^2/2p_1 \cdot p_2)^{n\varepsilon})$
- It's only from three or more jets events $Q \to p_1 p_2 p_3 \ldots$ that one can see the non-trivial structures through the Lorentz invariants constructed from $p_1 p_2 p_3 \ldots$
- Early resummation study on three-jet event shape: thrust minor, D parameter. **[Banfi, Dokshitzer, Marchesini, Zanderighi, 2001]**
- A general N-jet event shape: N-jettiness (**Tackmann, Waalewijn, Stewart, 2009**)

3-jettiness in e+e-

- The simplest example having non-trivial structure is 3-jettiness in e+e- collider

$$\tau \equiv \sum_k \min_{\{q_i\}} \frac{2q_i \cdot p_k}{Q^2}$$

$$\sum_i^3 q_i^\mu = (Q,0,0,0) \qquad q_i^2 = 0$$

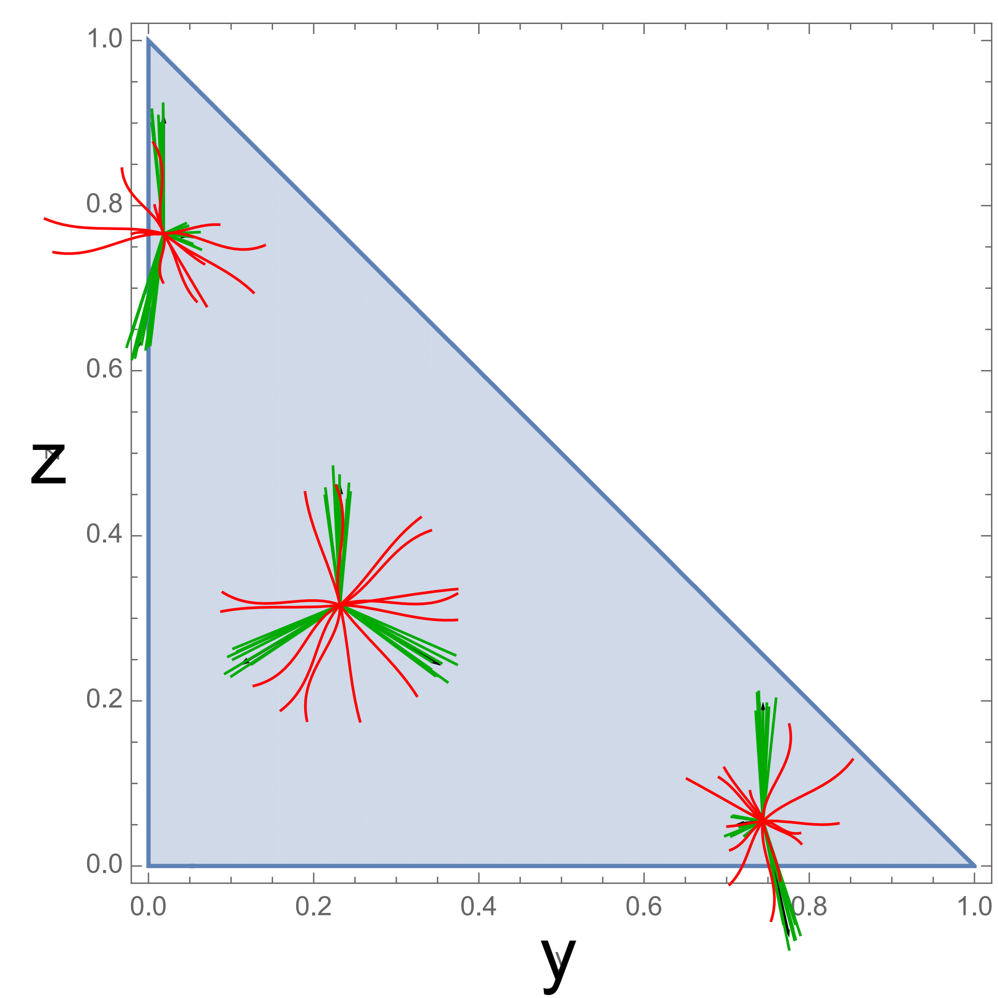


$$\frac{d\sigma}{d\tau} \sim H \cdot J_1 \otimes J_2 \otimes J_3 \otimes S$$

- The born configuration has only three parsons in the final state, and 3-jettiness vanishes
- The born configuration can be parameterized by two dimensionless variable ranged from 0 to 1

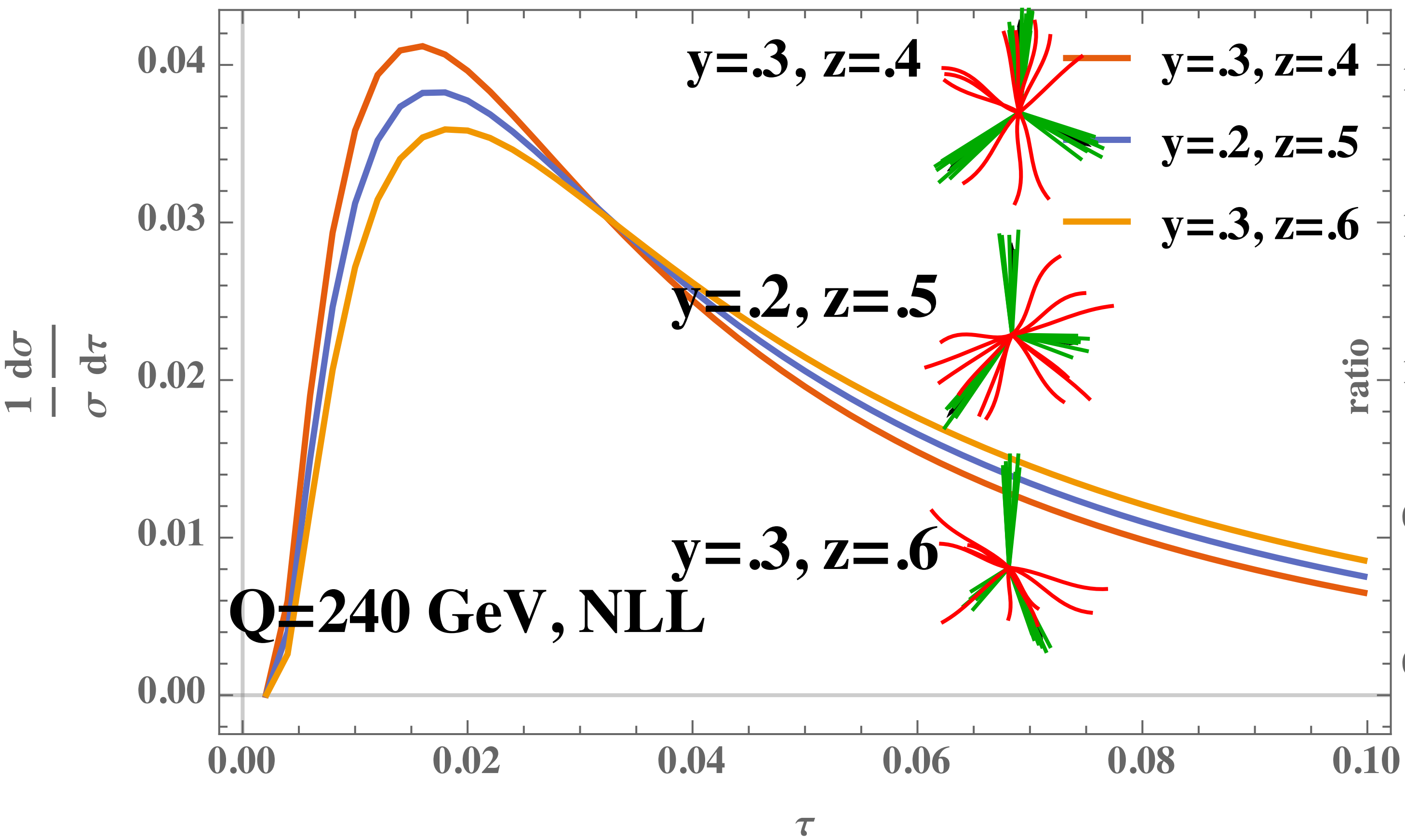
$$y = \frac{q_1 \cdot q_3}{Q^2}, \qquad z = \frac{q_2 \cdot q_3}{Q^2}$$

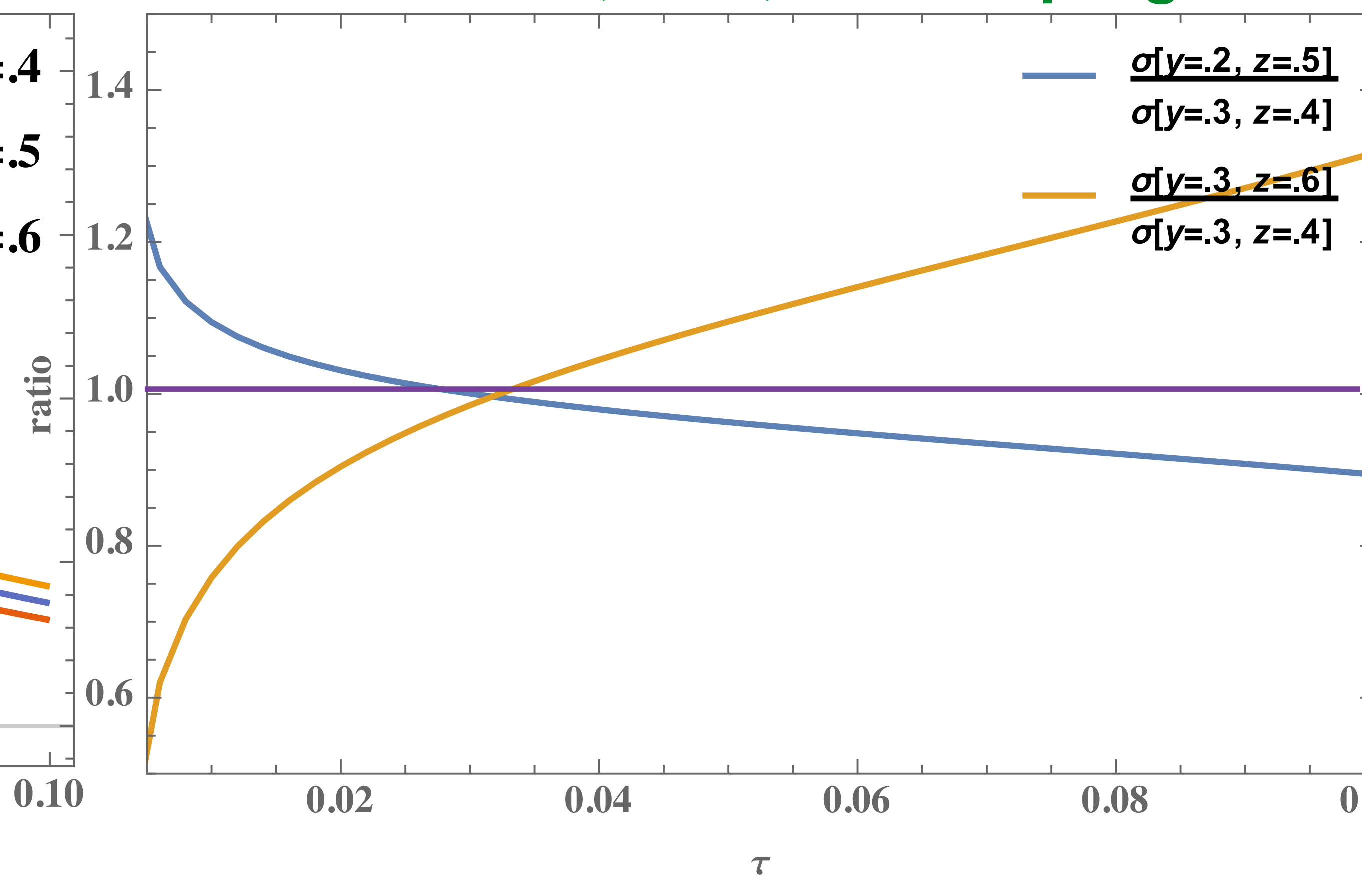
- The event is dijet like in the boundary of y-z triangle



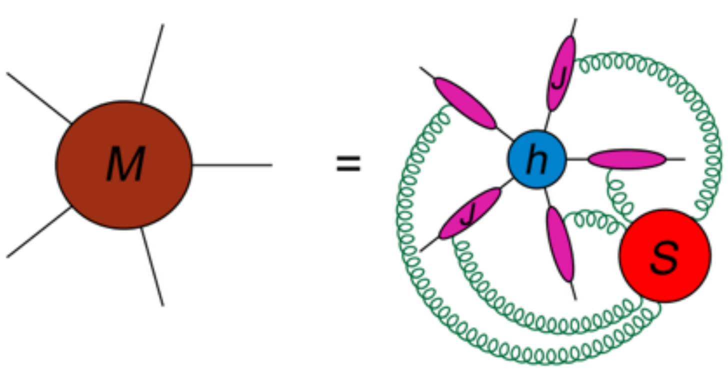
Seeing the IR structure of QCD amplitudes

J. Gao, HXZ, work in progress

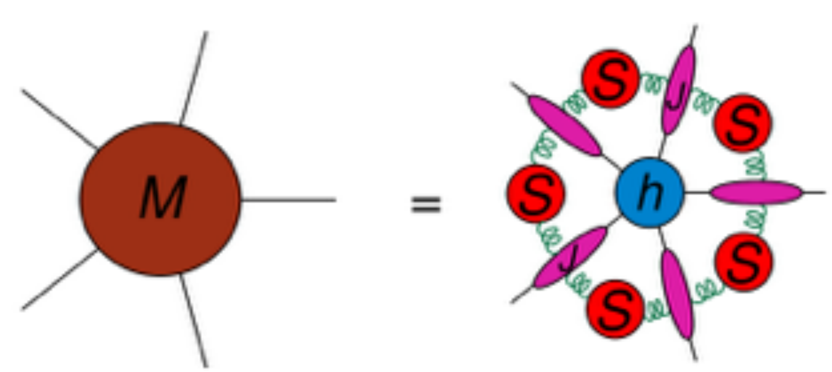




- NLL 3-jettiness distribution for different born configuration, and ratio to Benz configuration, assuming 100% quark-gluon discrimination
- At Leading log, the normalized cross section is insensitive to the shape of born configuration.
- At NLL, the born sensitivities enter through large angle soft gluon radiation

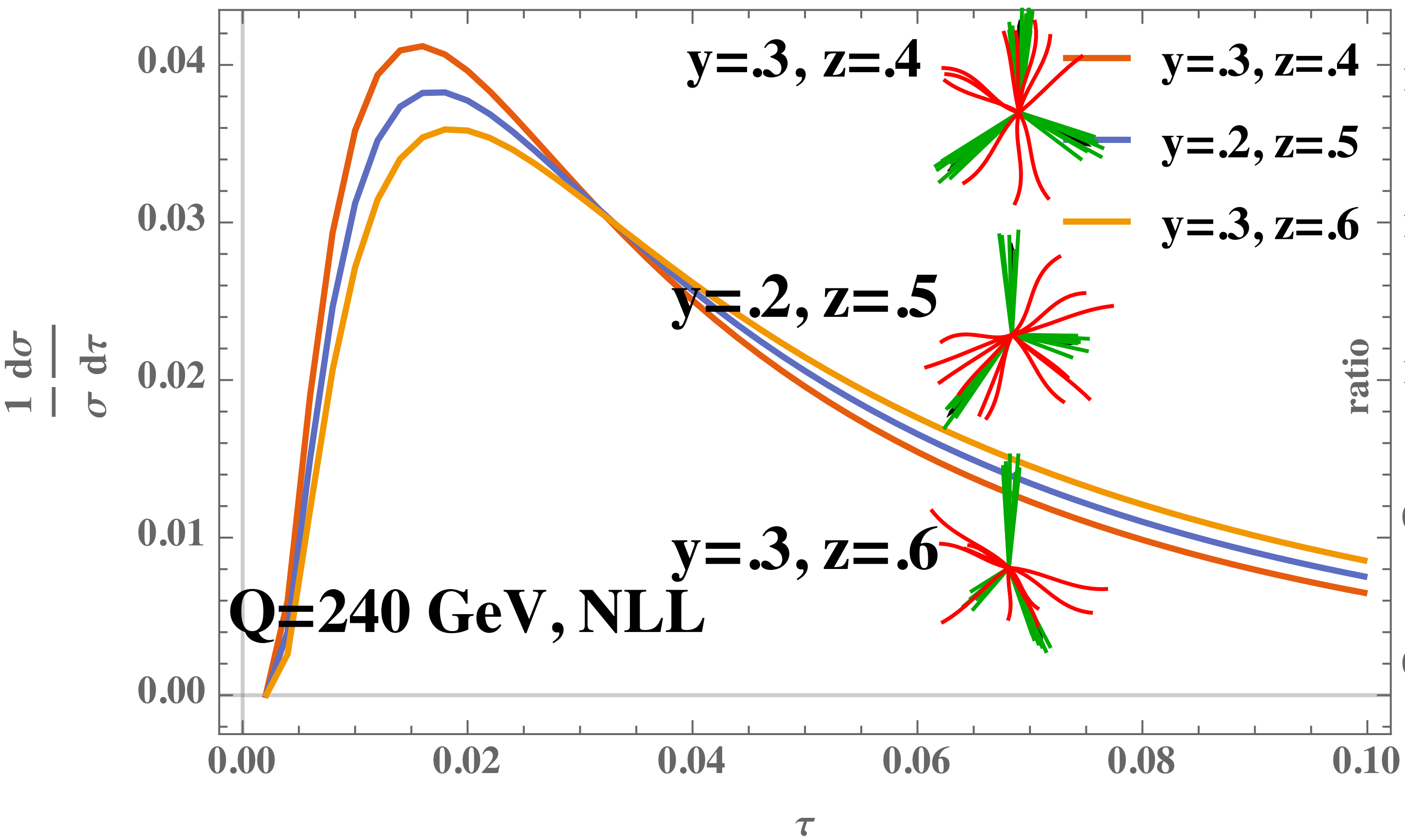


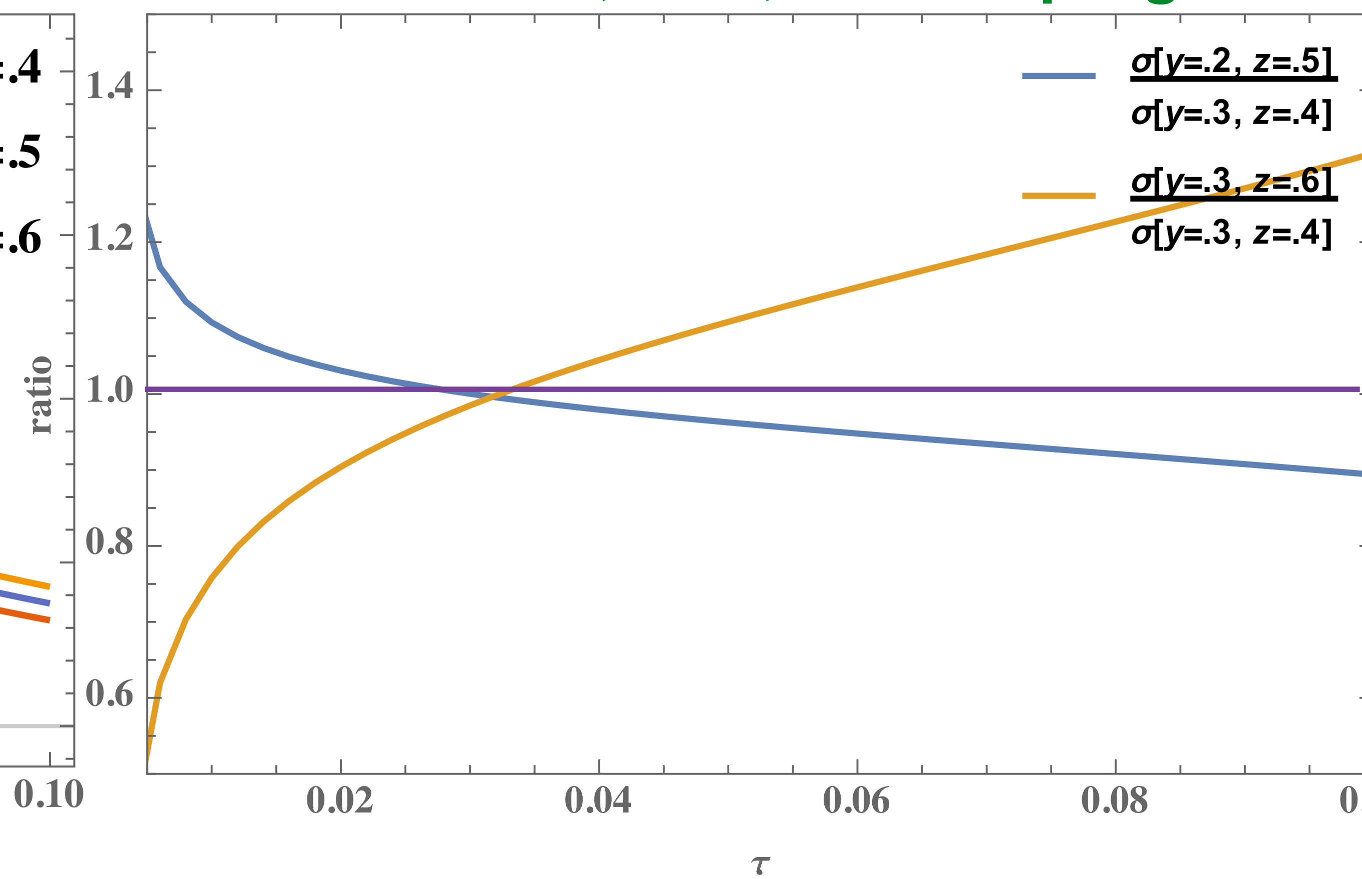
Soft correlation become dipole-like at one and two loop due to conformal symmetry in the IR



Seeing the IR structure of QCD amplitudes

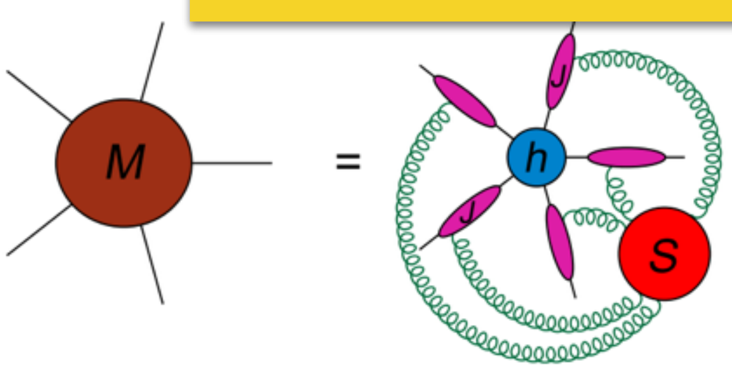
J. Gao, HXZ, work in progress



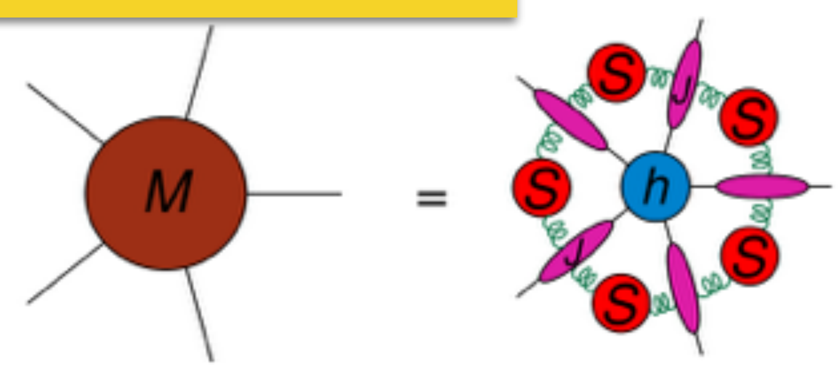


- NLL 3-jettiness distribution for different born configuration, and ratio to Benz configuration, assuming 100% quark-gluon discrimination
- At L... born conf...
- At N...

Measuring the deviation from 1 will be a direct proof of the non-trivial IR dynamics, and will be useful to constraint Monte-Carlo tools



Soft correlation become dipole-like at one and two loop due to conformal symmetry in the IR



Summary

- I have talked about a number of theoretical QCD topics in e+e- colliders that is closest to my heart
  - Precision determination of α_s from event shape and jet rates
  - Non-global observables
  - More differential observables that can test the finer structure of QCD
- The field is healthy: a lot of interesting unsolved problems; is evolving: new observables/techniques to be and will be invented to help us understanding our real world QFT at colliders. Stay tuned.

Thank you for your attention!