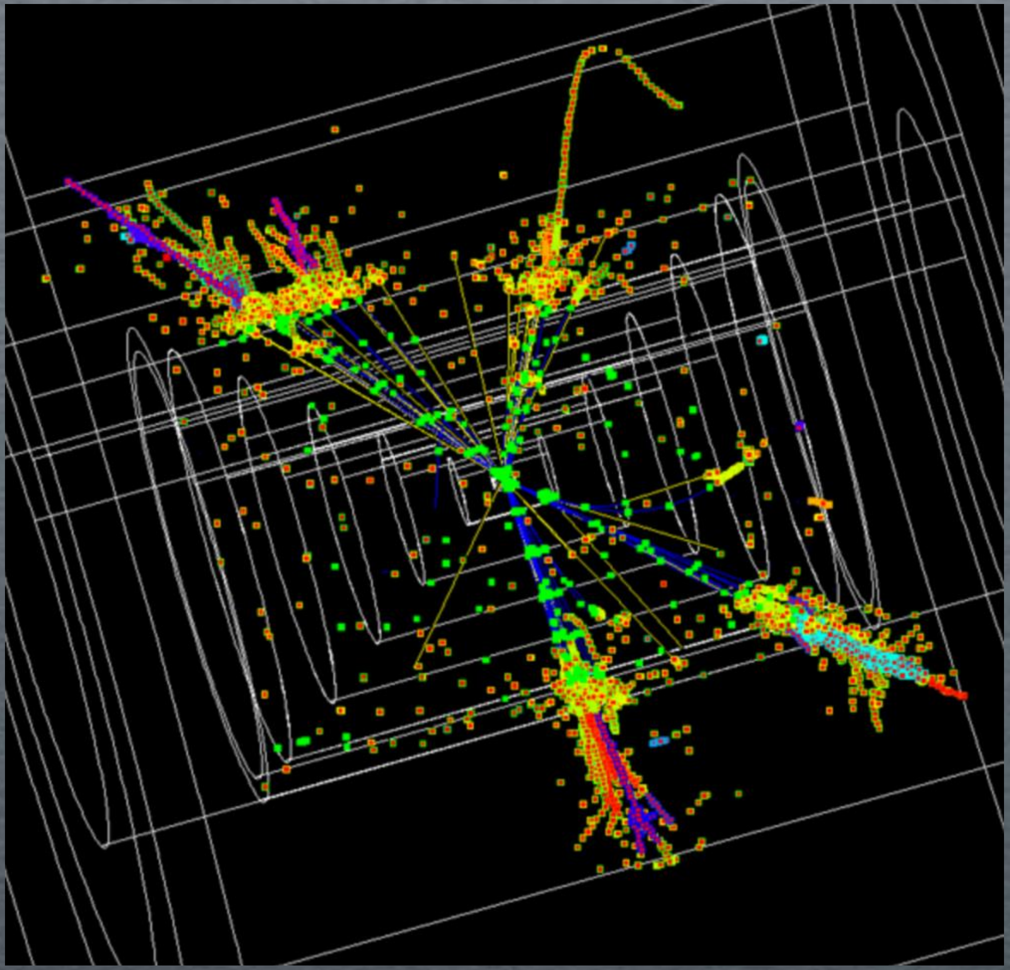
QCD precision measurements using novel techniques



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Muon Collider Physics and Detector Workshop - 4 June 2021

Outline

Personal selection of theoretically intriguing problems, whose solution would greatly benefit from a high-energy lepton collider

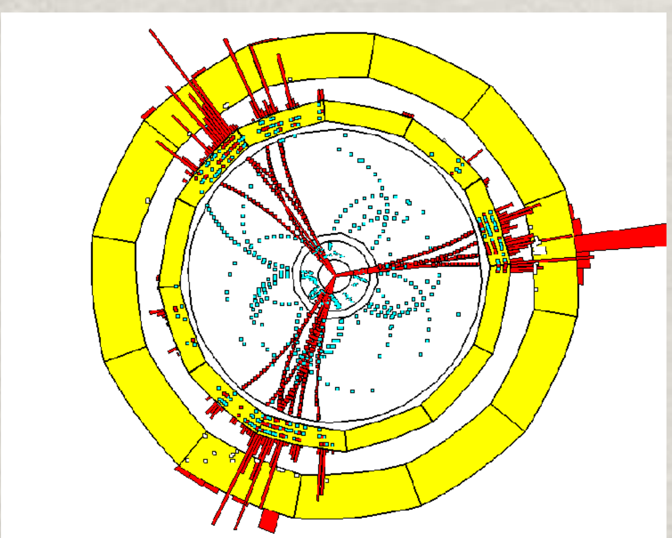
- Hadronisation corrections in event-shape and jet rates
- Hadronic decays of heavy objects (jet substructure)
- Top mass determination from boosted tops

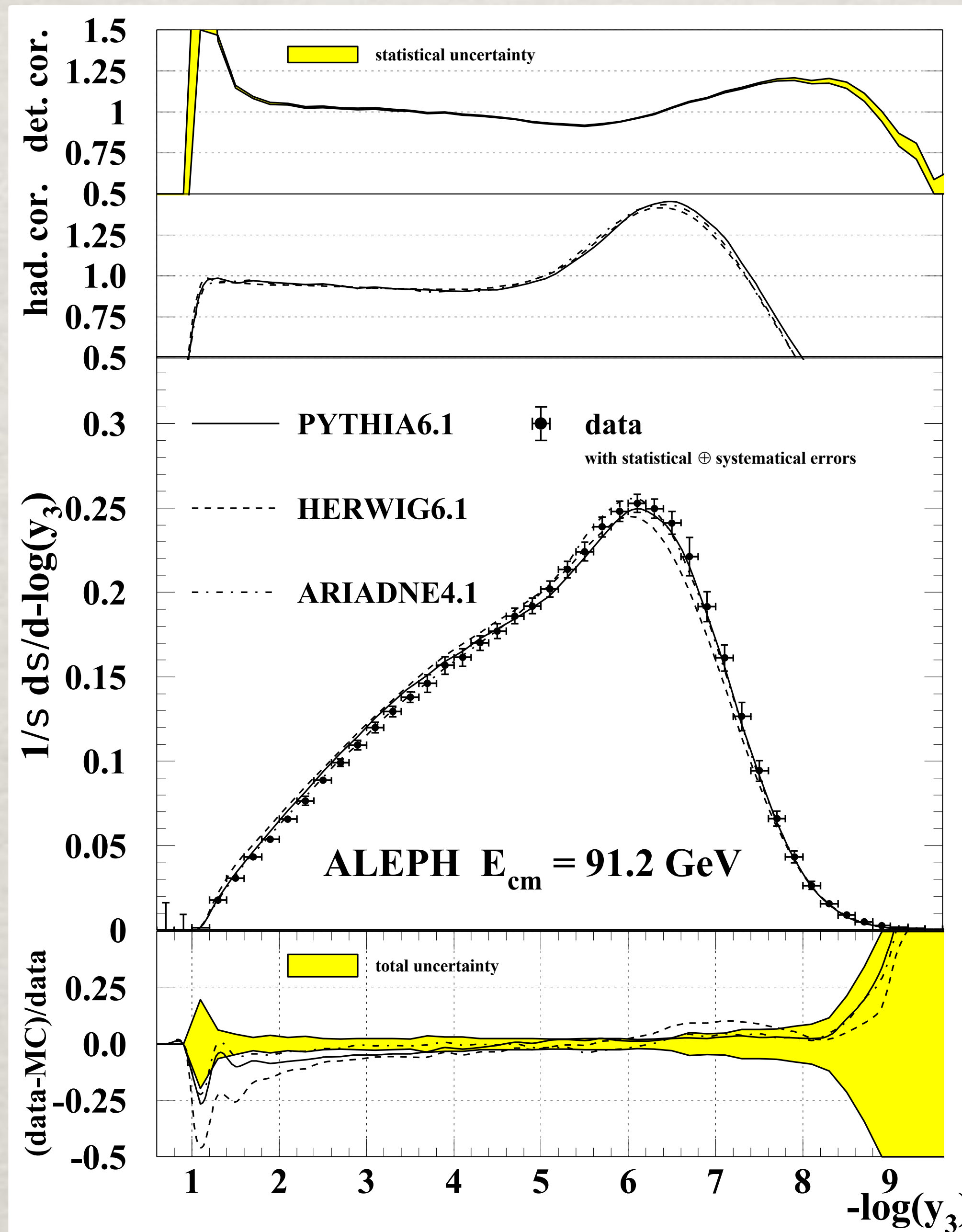
Ultimately, our success is solving those problems will be reflected in more accurate measurements of the short-distance parameters of QCD, the strong coupling and the top mass

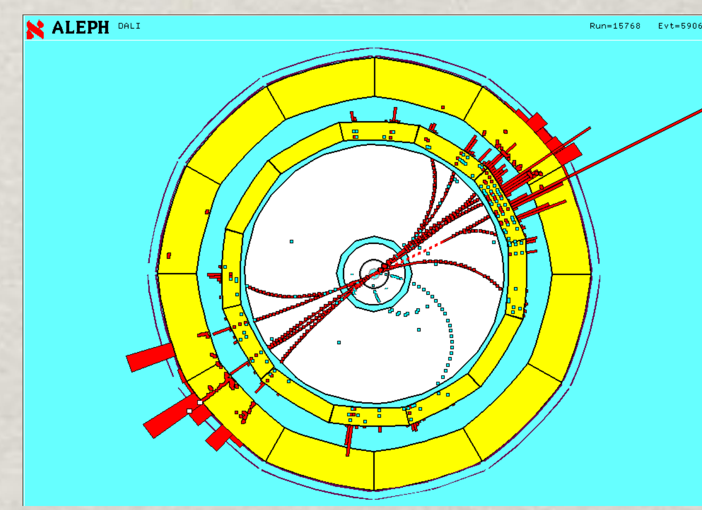
Hadronisation

Jet observables in QCD

- Jet observables (e.g. event-shape distributions and jet rates) are powerful probes of QCD dynamics from high to low scales







$$\sim \underbrace{\alpha_s}_{\text{LO}} + \underbrace{\alpha_s^2}_{\text{NLO}} + \underbrace{\alpha_s^3}_{\text{NNLO}} \ldots$$

$$\sim \exp\left[\underbrace{Lg_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\text{NNLL}} + \ldots\right]$$

Strong coupling with jets

- Jet observables constitute an important means of determination of the strong coupling
- Currently, tension between determinations with different jet observables

Two-jet rate (NNLL+NNLO)

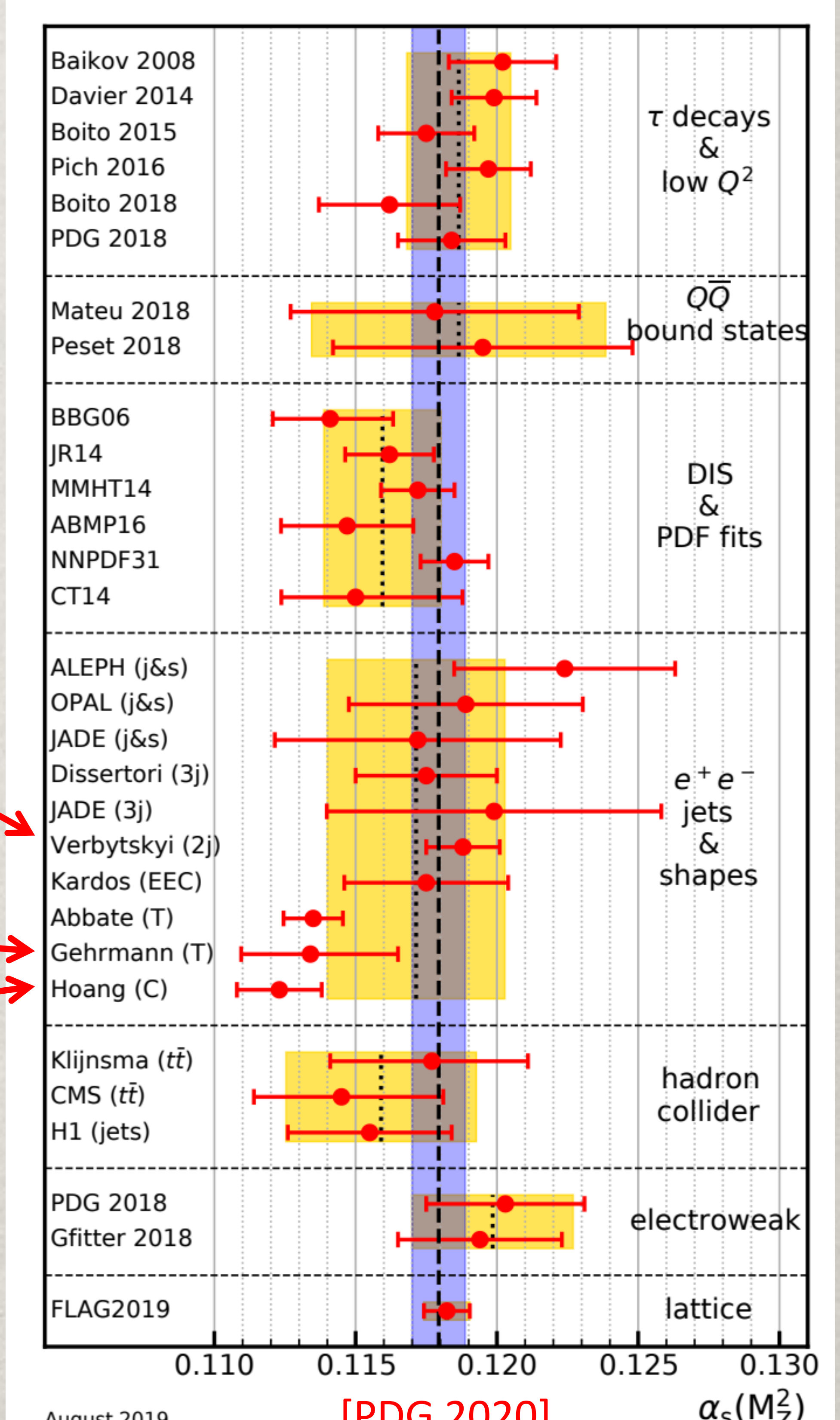
$$\alpha_s(M_Z) = 0.1188 \pm 0.0013$$

Thrust and C-parameter ((N)NNLL+NNLO)

$$\alpha_s(M_Z) = 0.1137^{+0.0034}_{-0.0027}$$

$$\alpha_s(M_Z) = 0.1123 \pm 0.0015$$

- What is the main difference between various approaches?



[PDG 2020]

Progress in PT calculations

The last ten years have been characterised by an impressive progress in perturbative calculations for jet observables

- NNLO calculation of $e^+e^- \to 3\,\mathrm{jets}$

  [Gehrmann-De Ridder Gehrmann Glover Heinrich 0711.4711]

- (N)NNLL resummation of factorisable observables (e.g. thrust, broadening) in SCET

  [Becher Schwartz 0803.0342]

  [Becher Bell 1210.0580]

  [Hoang Kolodubrez Mateu Stewart 1501.04111]

- General NNLL resummation of event shapes in e^+e^- annihilation with the ARES method

  [AB Monni McAslan Zanderighi 1412.2126]

  [AB El-Menoufi Monni 1807.11487]

- First-ever NNLL resummation of a jet-rate with ARES

  [AB Monni McAslan Zanderighi 1607.03111]

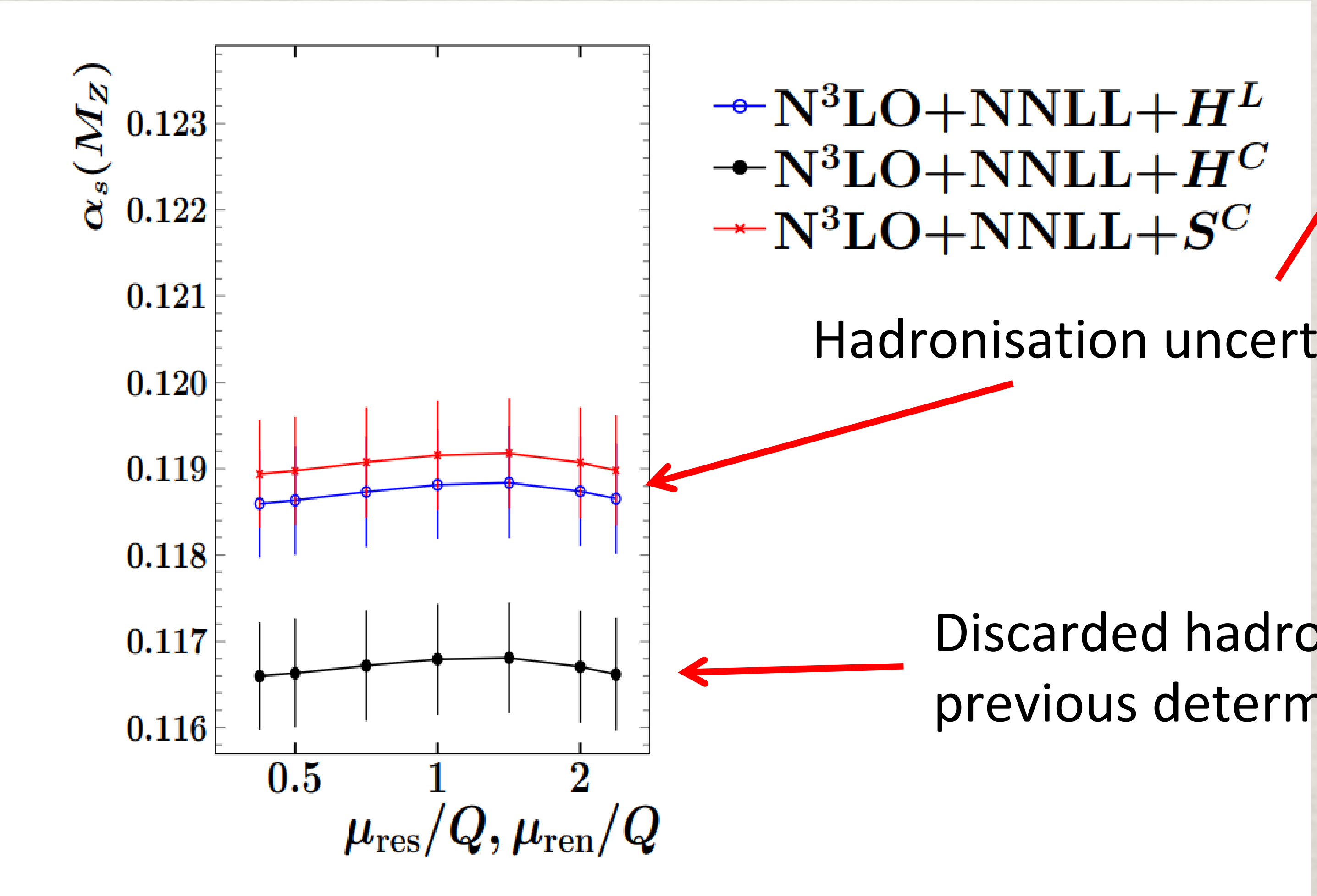
Given this precision, the relevant question is how to estimate non-perturbative corrections due to hadronisation

Hadronisation corrections

- In the two-jet rate analysis, hadronisation corrections using Monte Carlo event generators, as the ratio between hadron- and parton-level results

[Verbytskyi et al 1902.08158]

$$\alpha_s(M_Z) = 0.1188 \pm 0.0009(\text{stat}) \pm 0.0009(\text{exp}) \pm 0.0010(\text{had}) \pm 0.0006(\text{theo})$$



Perturbative QCD uncertainty

Hadronisation uncertainty

Discarded hadronization model, not an issue in previous determinations due to larger PT uncertainty

- This approach is sensible as long as perturbative QCD uncertainties dominate, but now it's hadronization the main source of uncertainty!

Leading hadronisation effects

- Central hadrons with momenta ~1GeV give rise to shift of perturbative distributions of jet observables

[Dokshitzer Webber hep-ph/9704298]

Average over PT configurations

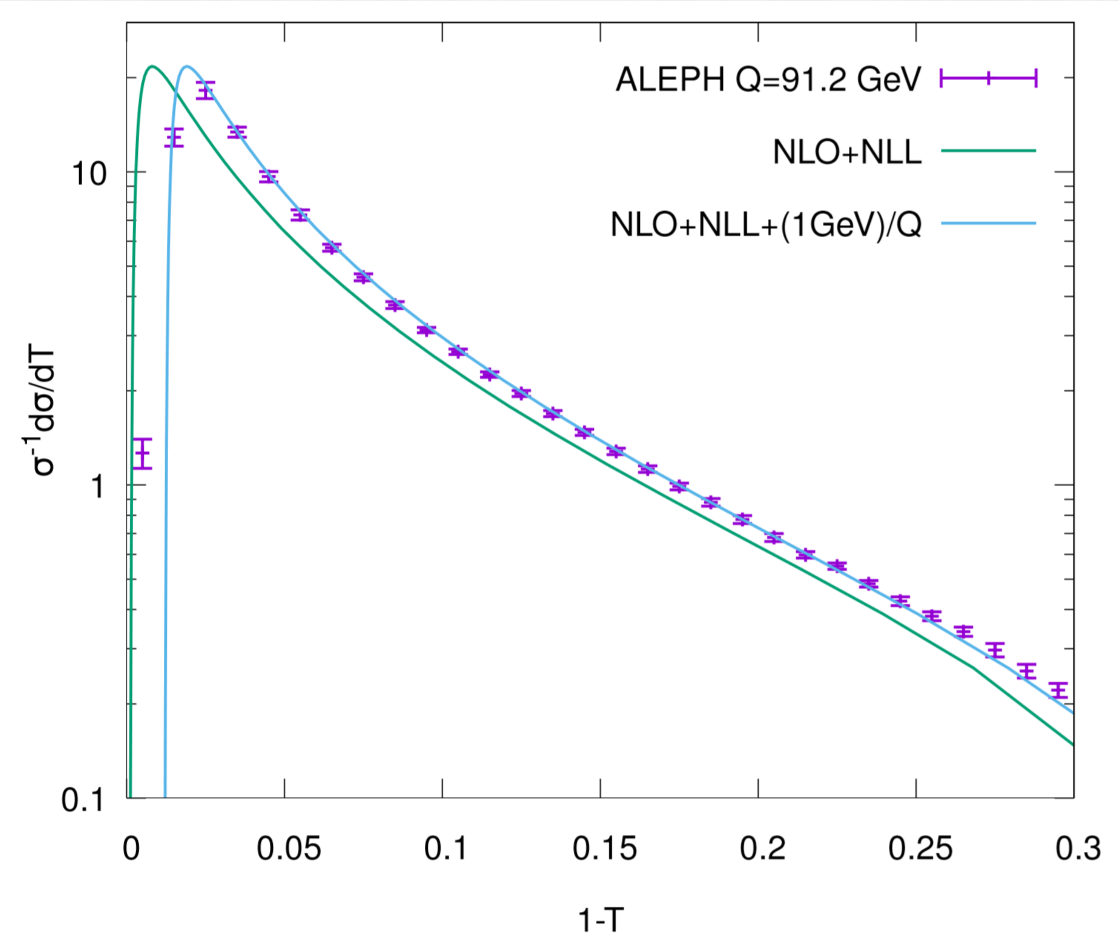
$$\text{shift} = \frac{\langle k_t \rangle_{\text{NP}}}{Q} \langle c_V \rangle_{\text{PT}}$$

$$\langle k_t \rangle_{\text{NP}} \equiv \int dk_t \sum_h \phi_h(k_t) \sim 1\,\text{GeV}$$

$$\langle c_V \rangle_{\text{PT}} \equiv \int d\eta \frac{d\phi}{2\pi} f_V(\eta, \phi)$$

Universal (?) NP parameter

Observable dependent but calculable



Simultaneous PT-NP fits

- Most accurate determinations of α_s with thrust and C-parameter arise from simultaneous fits of 1/Q hadronisation corrections

Thrust (NNLL+NNLO)

[Gehrmann Luisoni Monni 1210.6945]

C-parameter (NNNLL+NNLO)

[Hoang Kolodubrez Mateu Stewart 1501.04111]

$$\alpha_s(M_Z) = 0.1137^{+0.0034}_{-0.0027} \qquad \alpha_s(M_Z) = 0.1123 \pm 0.0015$$

$$\alpha_0(2\,\mathrm{GeV}) = 0.524^{+0.096}_{-0.044} \quad \sim \langle k_t \rangle_{\mathrm{NP}} \sim \quad \Omega_1 = 0.421 \pm 0.063\,\mathrm{GeV}$$

- Such fits give values of the strong coupling below the world average, and errors of different size despite similar accuracy of PT predictions

Both Monte-Carlo and analytic determinations of hadronisation corrections are challenged by the precision of perturbative QCD calculations

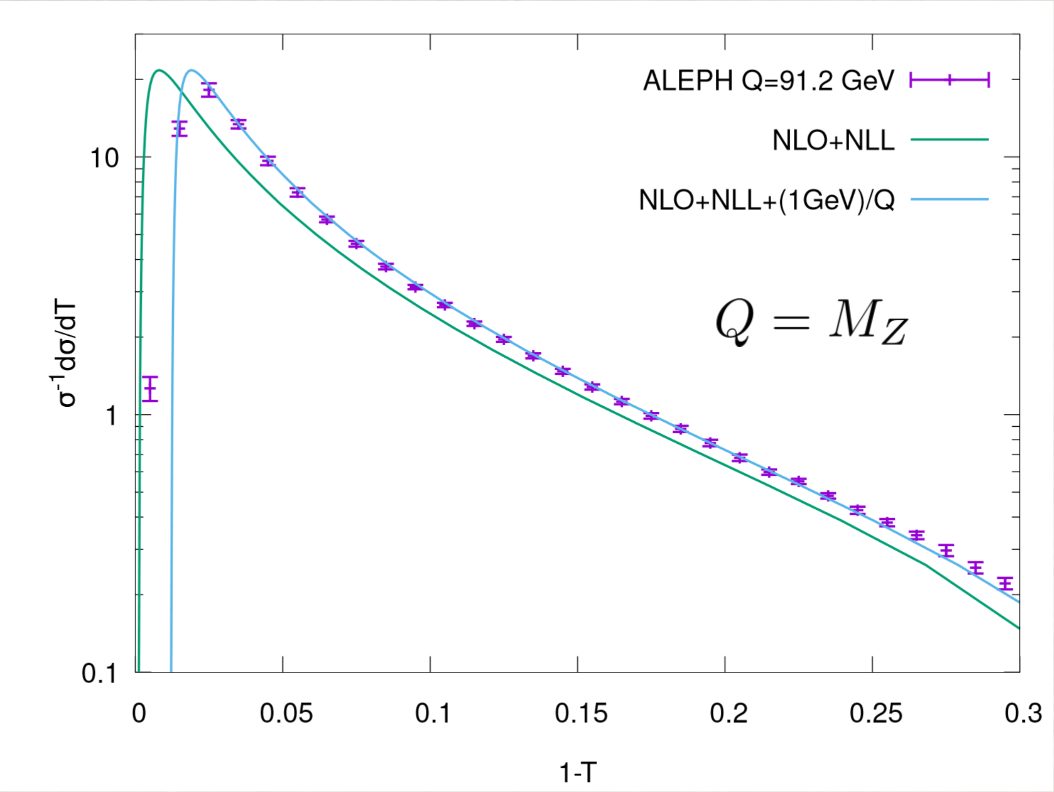
- Monte Carlo event generators have the correct kinematics, but predictions are too dependent on the hadronisation model

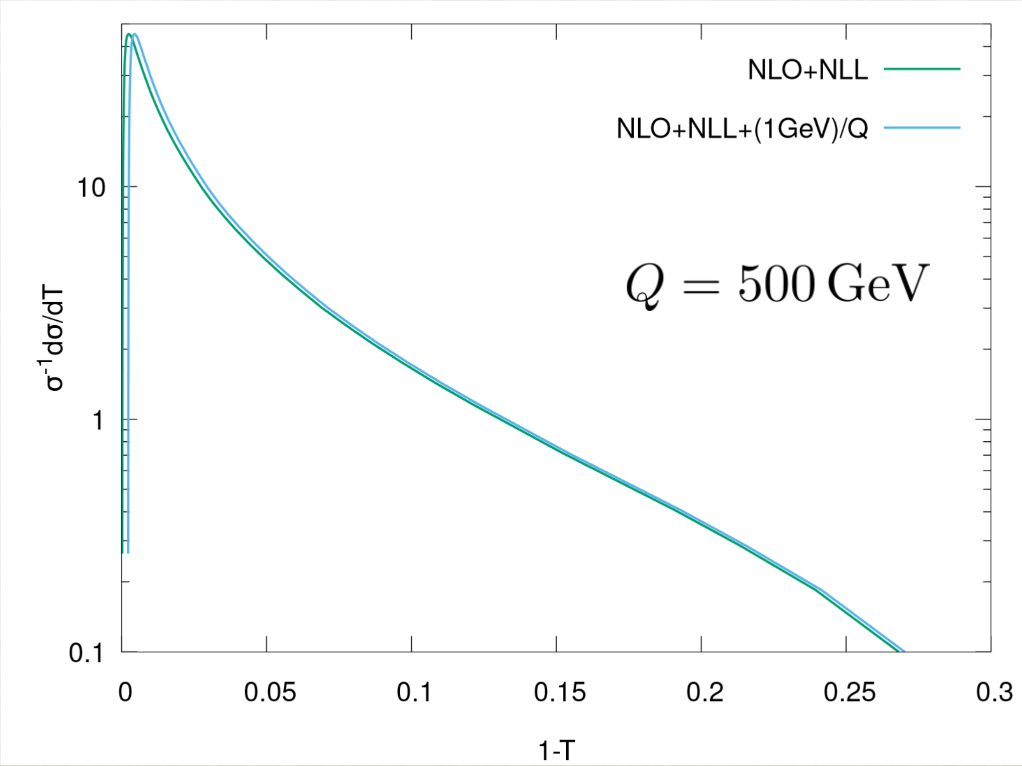
- The shift model of leading hadronisation corrections is an oversimplification in the fit region, neglected effect give an extra 3-4% uncertainty

[Luisoni Monni Salam 2012.00622]

Hadronisation at future colliders

- At future lepton colliders, hadronisation corrections to two-jet observables will be way smaller than at LEP1 ⇒ 1 jet ~ 1 parton





Two-fold advantage for fits of the strong coupling

- Monte-Carlo hadronisation corrections will have a reduced impact in the error on α_s ⇒ perturbative uncertainties (now ~0.1%) dominant
- Negligible impact of subleading hadronisation corrections ⇒ more reliable determination of NP parameter(s) of leading 1/Q corrections

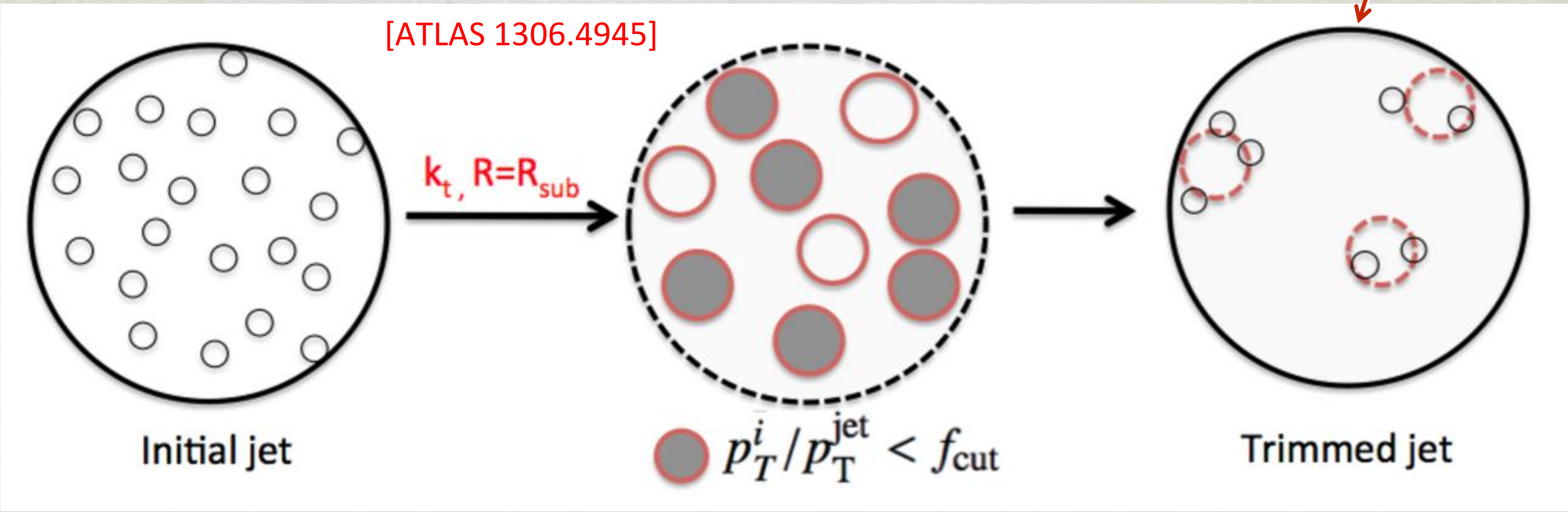
Jet substructure

Boosted objects

- Both HL-LHC and future colliders will produce boosted heavy objects, whose decay products fall in the same jet (e.g. boosted Higgs or tops)

[Butterworth Davison Rubin Salam 0802.2470]

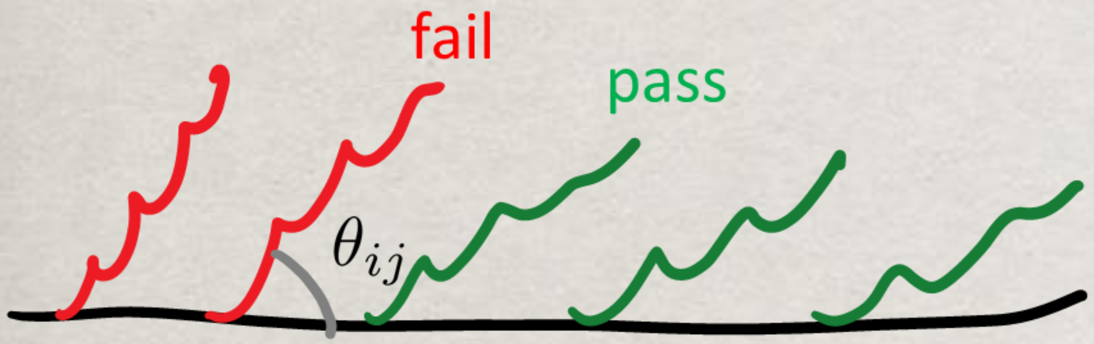
hadronic top candidate



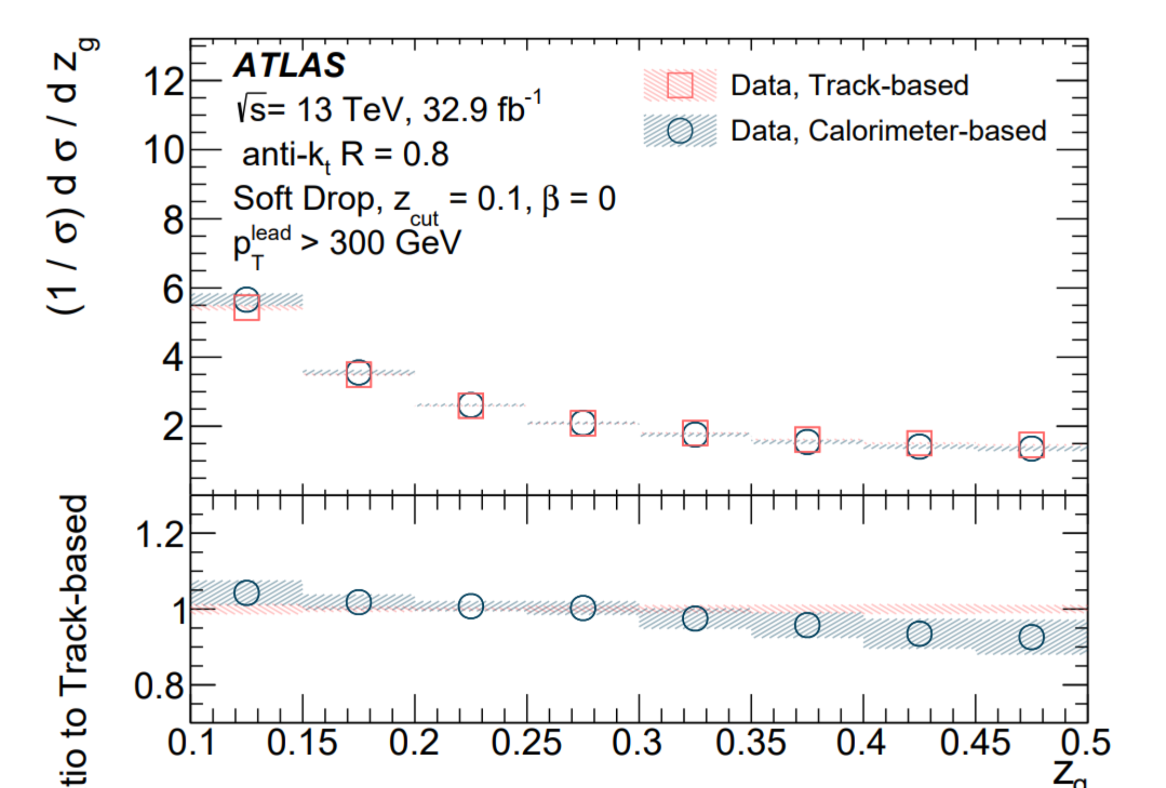
- Key feature of boosted object taggers are groomers, procedures that clean jets from soft constituents irrelevant for mass reconstruction

The Soft-drop groomer

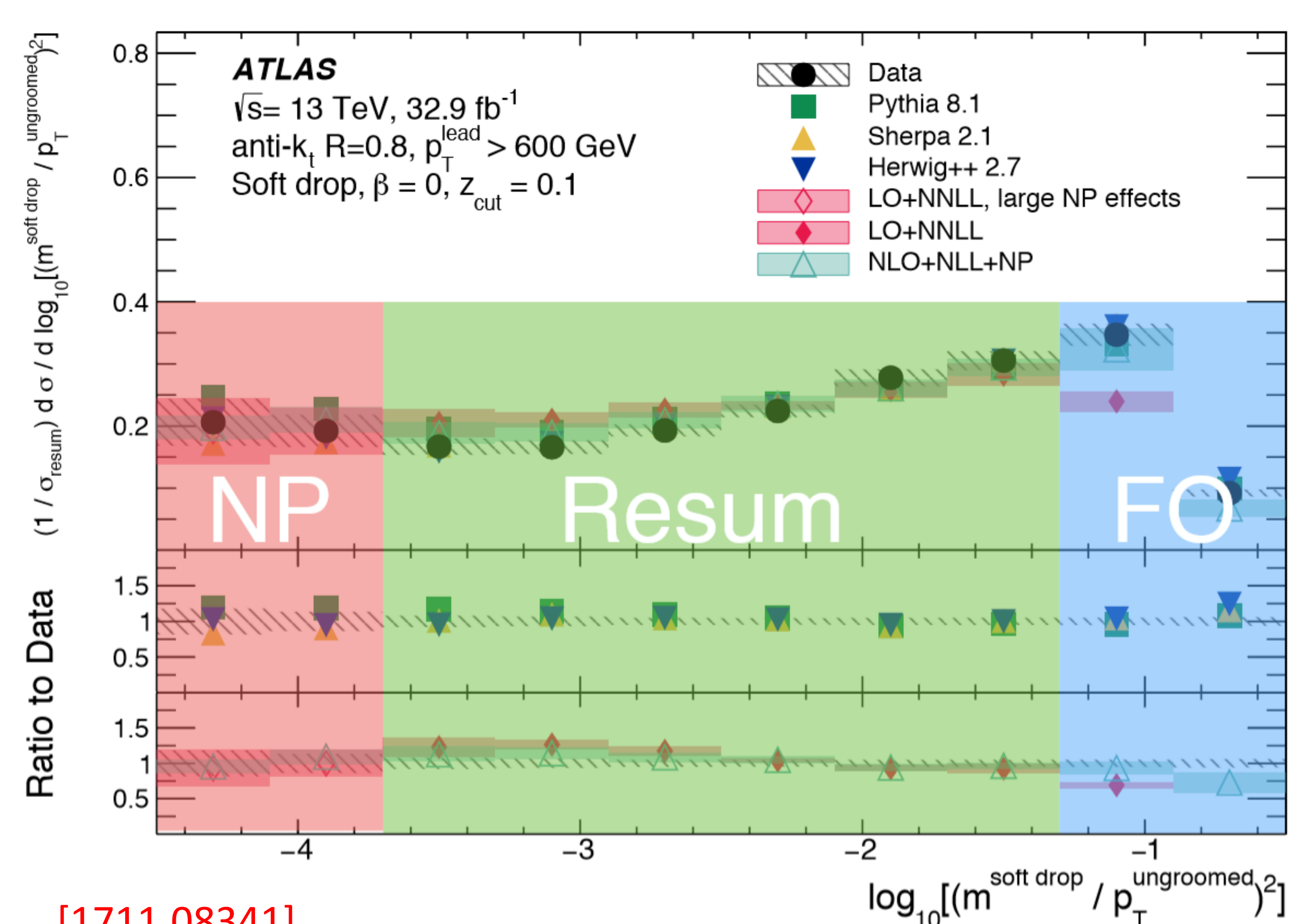
- The most established groomer is the soft-drop, which allows the calculation of distribution in the mass of a jet at high accuracy ⇒ reliable analytical modelling of tagger performance [Larkoski Marzani Soyez Thaler 1402.0007]



$$z_g \equiv \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{\theta_{ij}}{R}\right)^{\beta}$$



[1912.09837]

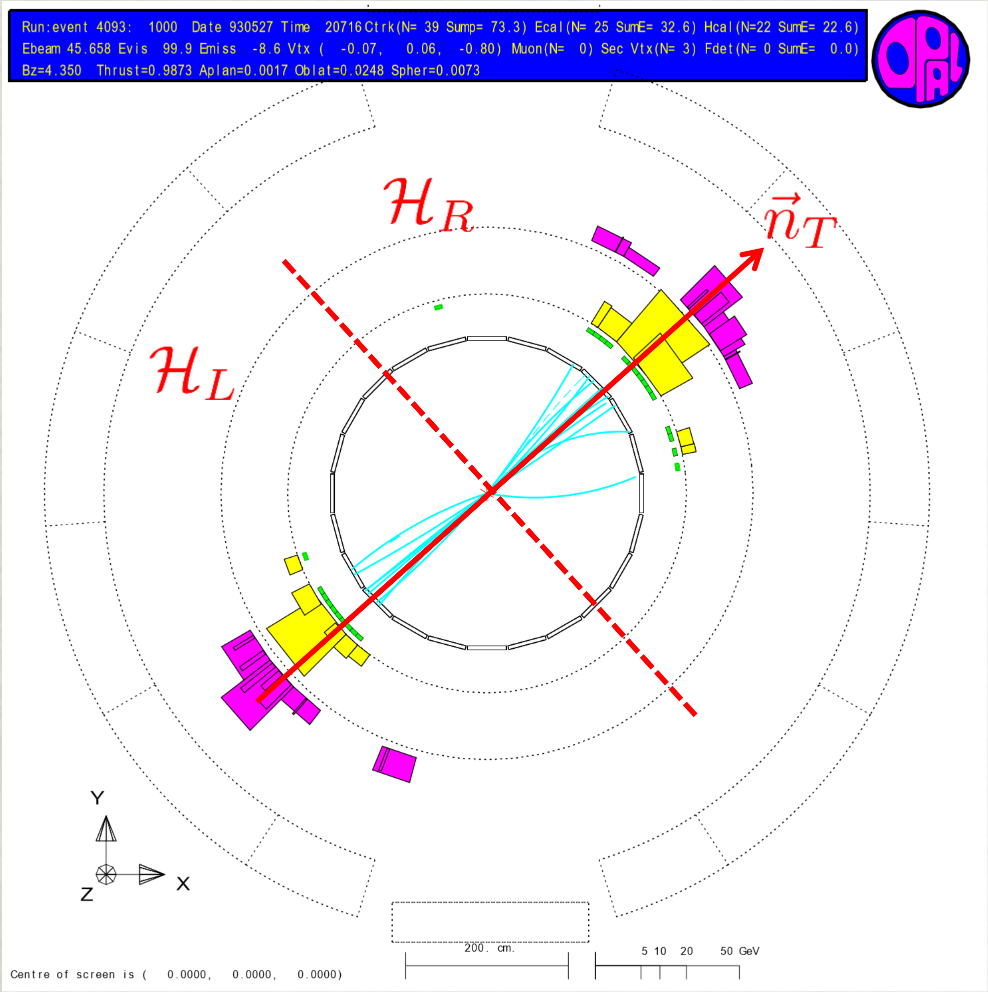


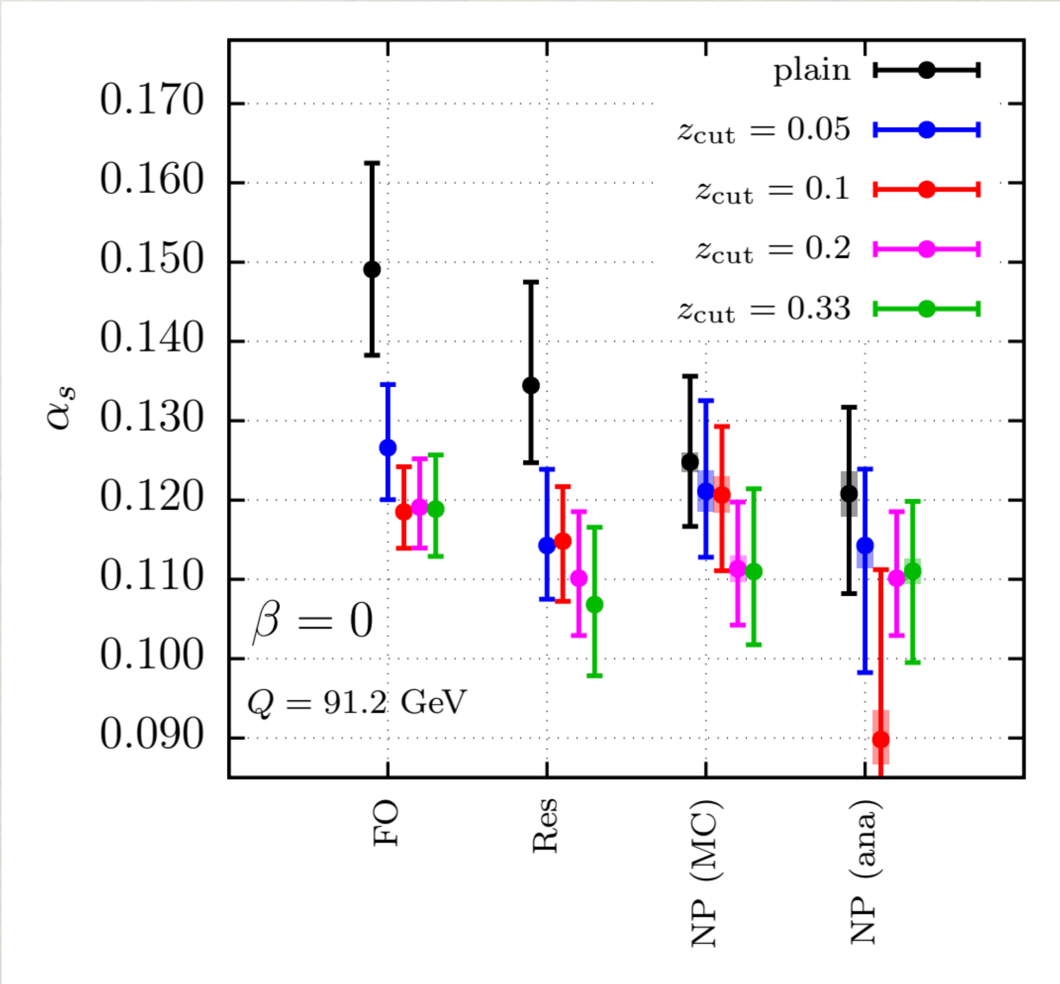
[1711.08341]

Grooming for precision

- Grooming procedures can be applied to jet observables in to reduce the impact of hadronisation corrections
- Example: soft-drop thrust, computed on hadrons that survive a soft-drop procedure

[Marzani Reichelt Schumann Theeuwes 1906.10504]

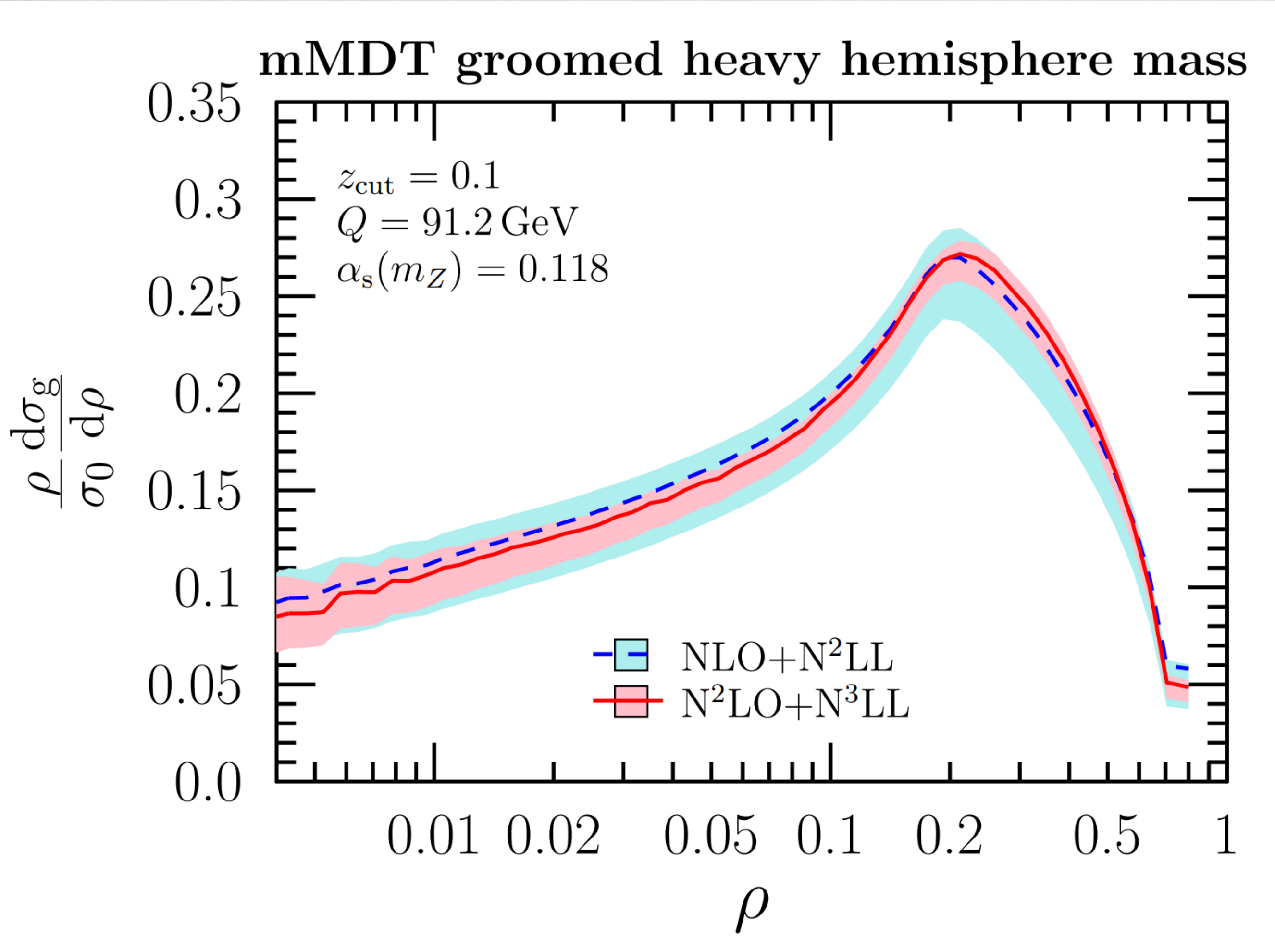


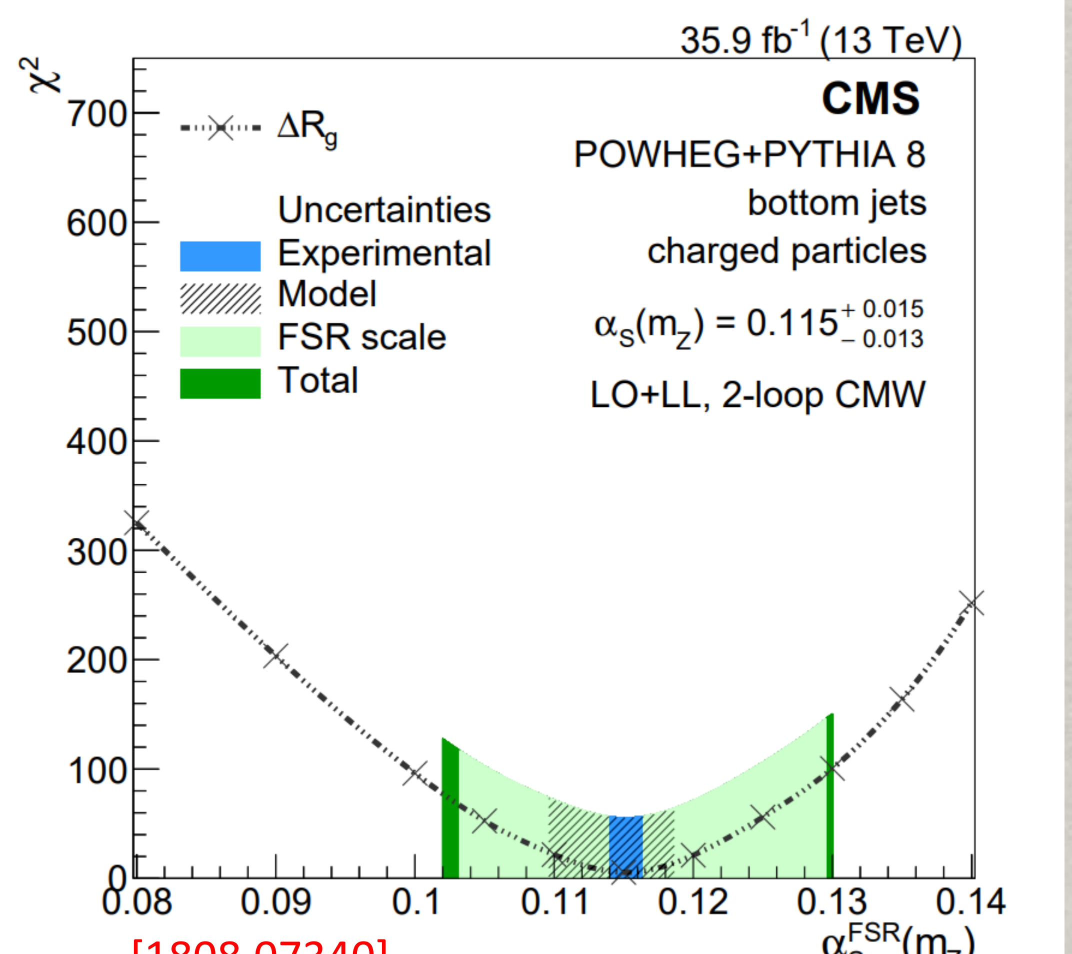


- Problem: at LEP1 not enough jet constituents survive grooming ⇒clear gain from raising the collider energy

A NEW PRECISION ERA?

- Due to the cleaner environment, lepton colliders can be used as a laboratory for precisions studies of jet substructure
- The distribution in $\rho \equiv m_{\text{jet}}^2/Q^2$ can be computed at very high accuracy in the region $m_{\text{jet}}^2 \ll z_{\text{cut}} Q^2 \ll Q^2$ [Kardos Larkoski Trocsanyi 2002.00942, 2002.05730]





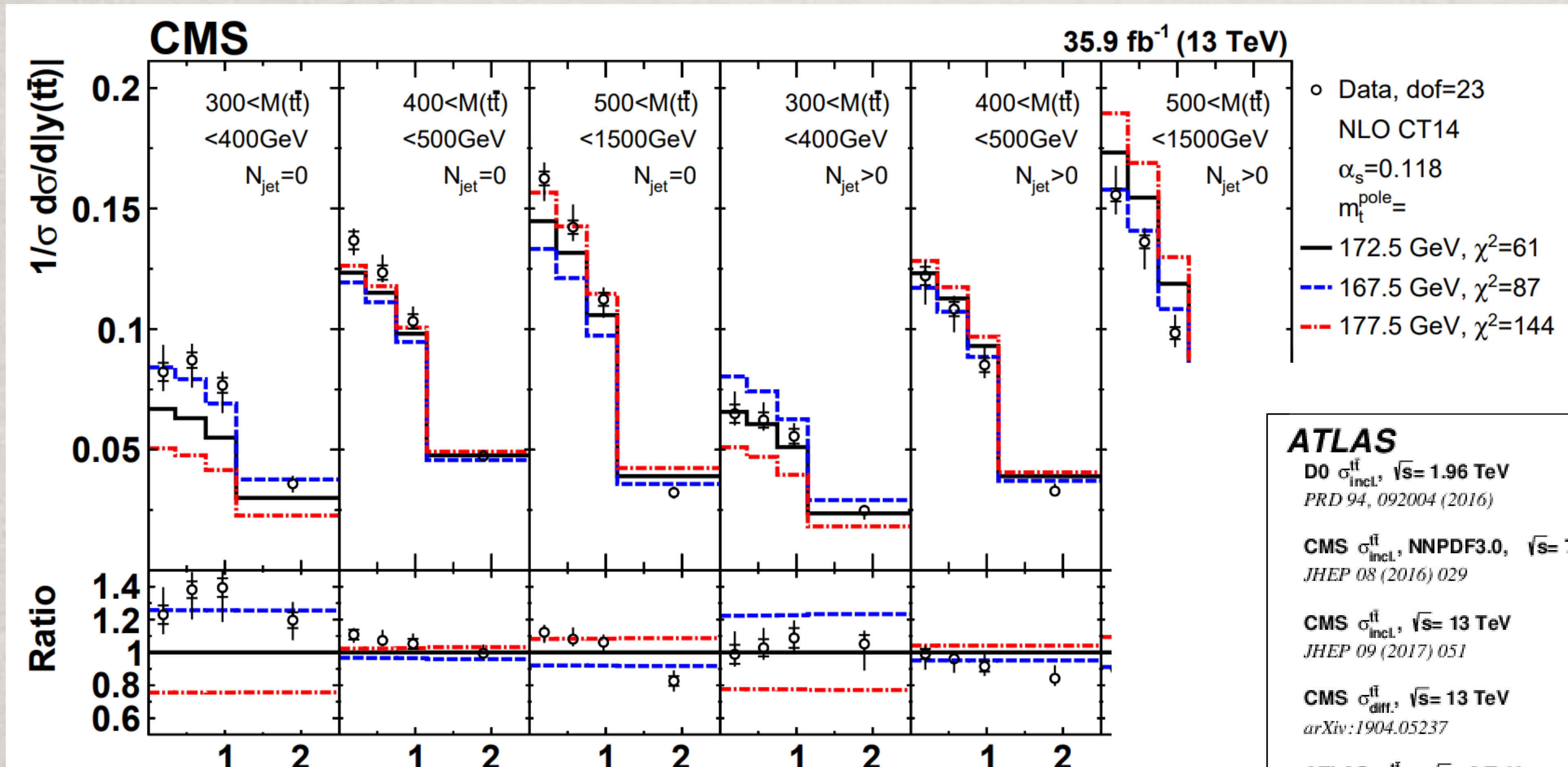
[1808.07340]

- Preliminary studies at the LHC show feasibility of extraction of the strong coupling using jet-substructure observables

Top mass

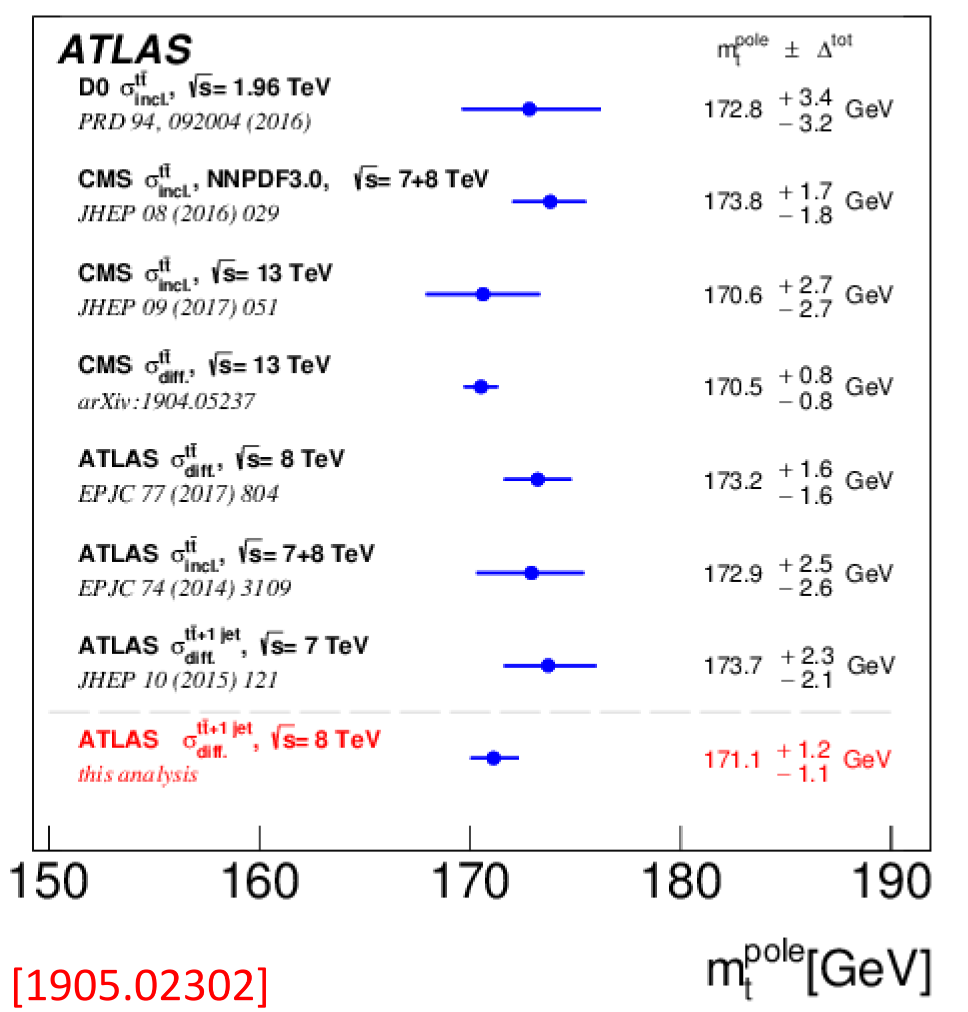
Top-mass measurements

- At the LHC, the extraction of the top mass is now obtained by comparing suitable distributions to precise theoretical predictions



[1904.05237]

- Can exploit lepton colliders to push the error in the top mass below 1GeV?

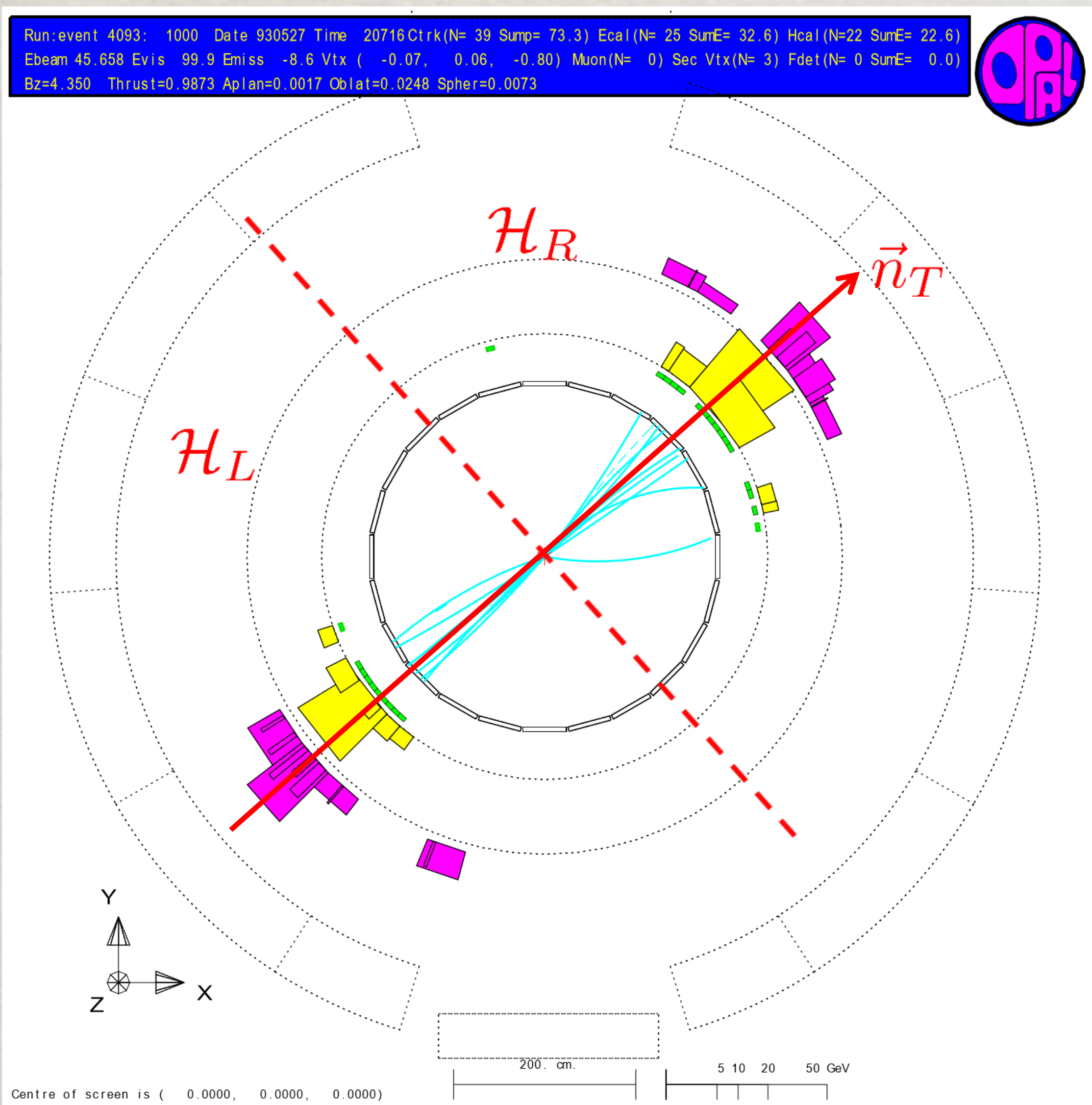


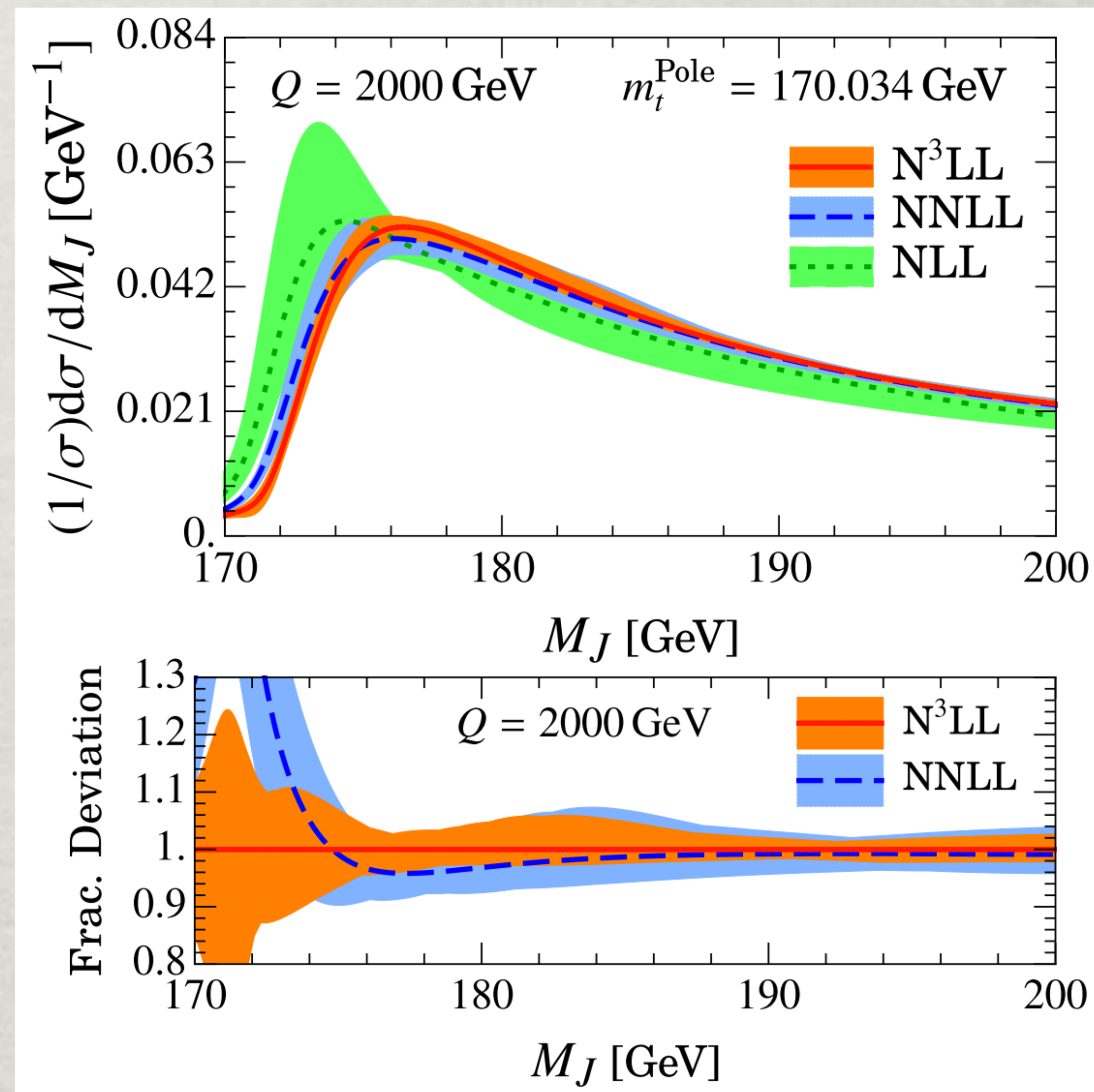
[1905.02302]

Boosted top mass

- At lepton colliders, one can consider the peak in the distribution of the total mass of two hemisphere in boosted top-antitop events

[Fleming Hoang Mantry Stewart hep-ph/0703207]





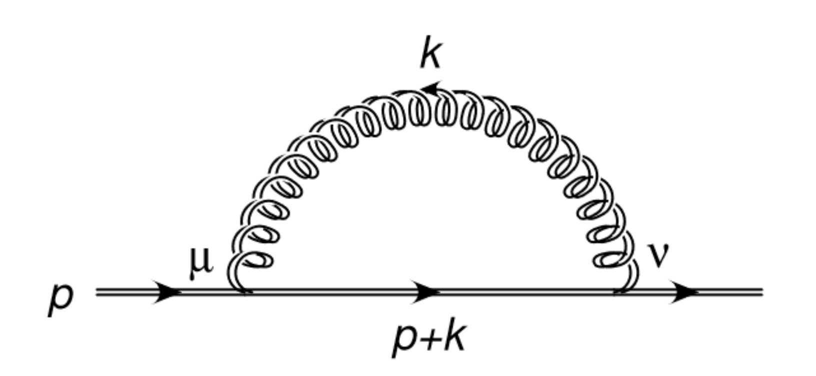
[Bachu et al 2012.12304]

- Uncertainties below 1 GeV $\Rightarrow$ sensitivity to precise definition of top mass

Top-mass renormalons

- It is well known that the top pole mass is related to a short-distance mass (e.g. $\overline{\text{MS}}$) through a divergent PT series (renormalon)

[Ravasio Nason Oleari 1810.10931]



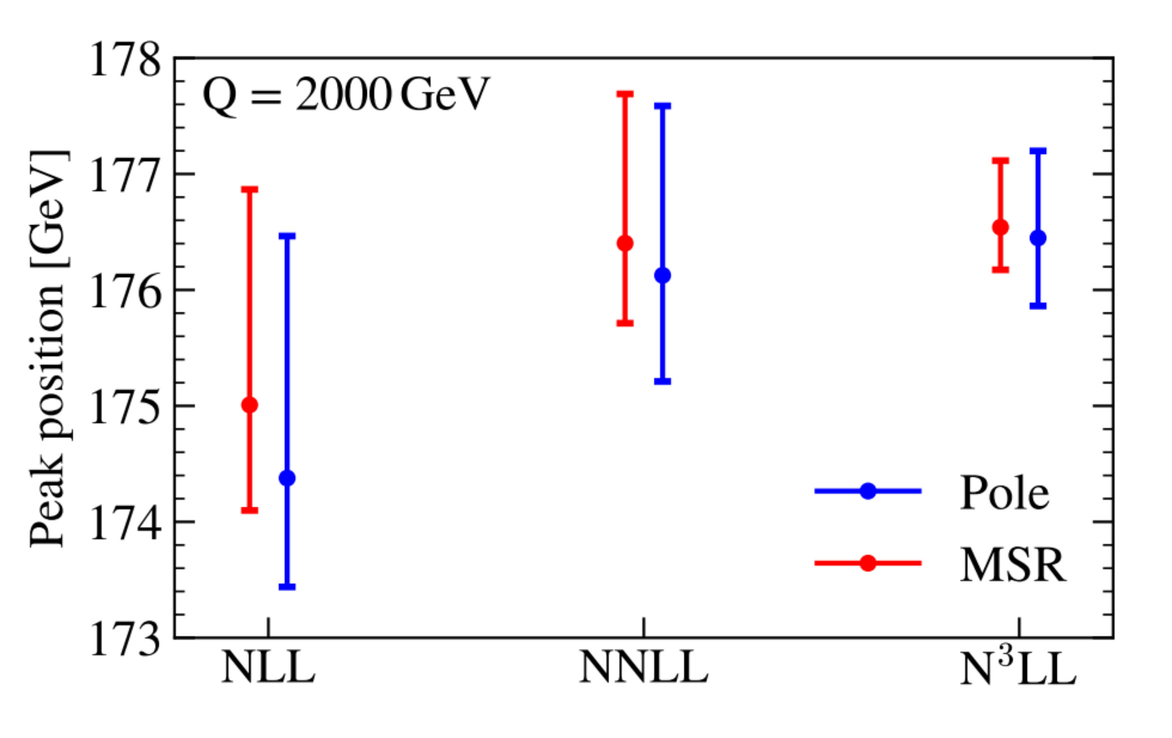
$$\bar{m}(\mu) = m_{\text{pole}} - \alpha_s \frac{C_F}{2} \lambda + \mathcal{O}(\alpha_s^2 (\alpha_s \beta_0)^n)$$

gluon mass, triggers the divergence

- This divergence reflect the sensitivity of the pole mass to NP physics

- Solution: use a suitable short-distance mass (MSR) free from renormalons [Hoang et al 1704.01580]

- Consistent extraction of the top mass with an uncertainty below 1 GeV [Bachu et al 2012.12304]



Concluding remarks

Future lepton colliders offer the possibility to answer a number of general theoretical questions in QCD and beyond

- Smaller hadronisation corrections pave the way to very precise determination of the strong coupling with jet observables
- Boosted object techniques could be used to devise novel observables for precision studies
- New observables for precision determination of the top mass could push its accuracy below 1GeV

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Thank you for your attention!