Measurement of 1-jettiness in deep-inelastic *ep* scattering at HERA

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Technische Universität München,
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Neutral current deep-inelastic scattering

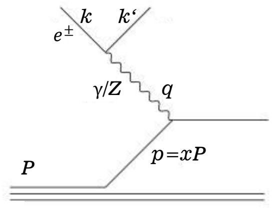
- Process $ep \to e'X$
- Electron or positron scattering

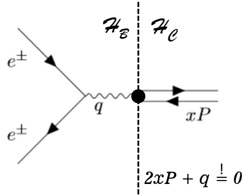
Kinematic variables

- Virtuality of exchanged boson Q^2
  $Q^2 = -q^2 = -(k - k')^2$
- Inelasticity, Bjorken-x and centre-of-mass energy
  $y = \frac{P \cdot q}{P \cdot k} \qquad Q^2 = x_{Bj} \cdot y \cdot s$

Breit frame

- Exchanged boson completely space-like
- Collides head-on with parton (brick-wall frame)





The 1-jettiness event shape observable

1-jettiness

- Axes incoming parton and $q + xP$:

$$\tau_1^b = \frac{2}{Q^2} \sum_{i \in X} \min\{xP \cdot p_i, (q + xP) \cdot p_i\}$$

- Infrared safe and free of non-global logs
- Sensitive to strong coupling α_s and PDFs

DIS thrust normalised to boson axis

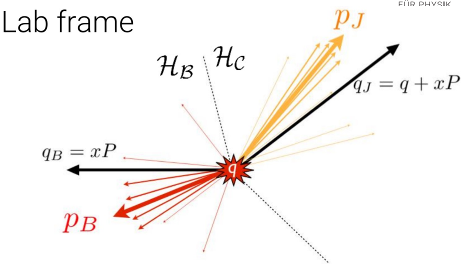
- Normalisation with $Q/2$ of the event:

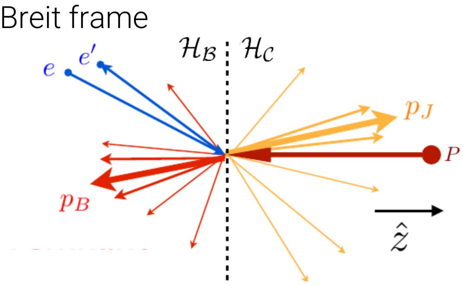
$$\tau_Q = 1 - \frac{2}{Q} \sum_{i \in \mathcal{H}_\mathcal{C}} P_{z,i}^{Breit}$$

- Only particles in the current hemisphere contribute

Equivalence follows from momentum conservation:

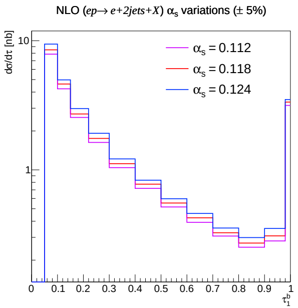
$$\tau_Q = \tau_1^b$$

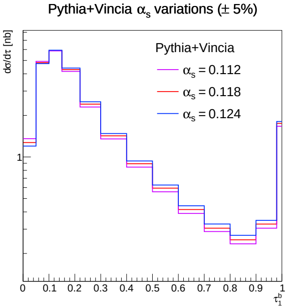




Sketch taken from Kang, Lee, Stewart [Phys.Rev.D 88 (2013) 054004]

Sensitivity of τ_1^b to α_s



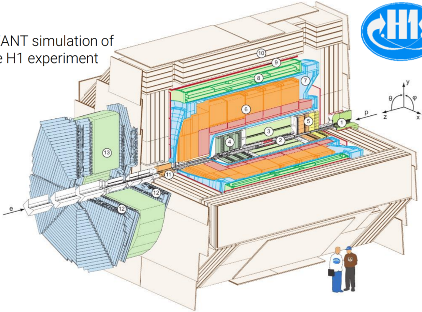


- Plot shows fixed order NLO calculation $ep \to e + 2jets$ for τ_1^b on PARTON LEVEL
- First bin is empty by definition
- Prediction scales linearly with strong coupling α_s

- Plot shows Pythia 8.3 + Vincia prediction for τ_1^b on PARTICLE LEVEL
- High sensitivity in tail region
- No sensitivity in peak region (Born level kinematics)

The H1 detector

GEANT simulation of the H1 experiment



- Integrated luminosity $L = 351.6\ \text{pb}^{-1}$
- Electron and positron runs
- $E_e = 27.6$ GeV, $E_p = 920$ GeV
  $\rightarrow \sqrt{s} = 319$ GeV

- Asymmetric design with trackers, calorimeter, solenoid, muon-chambers, forward & backward detectors
- Trigger requires high-energetic cluster in LAr calorimenter
  $\rightarrow$ electron or hadron
  $\rightarrow$ $> 99\%$ efficient for $y \lessapprox 0.7$
- Particles are reconstructed using a particle flow algorithm
  $\rightarrow$ Combining cluster and track information without double-counting of energy

Data preservation in high energy physics

DPHEP Collaboration and data-preservation

- MPP is among founding institutions in the initiative Data Preservation in High Energy Physics (DPHEP)
- Involved experiments are e.g. JADE, OPAL, H1 and ZEUS

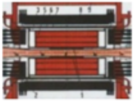
Data preservation has many facets...

- Data (raw, already analysed (n-tuples), simulated (MC))
- Software (Simulation/ reconstruction/ analysis software, analysis workflows,...)
- Documentation (internal/external webpages, technical documentation, int-notes, analysis notes, wiki-pages, code-documentation, ...)
- Keep specific knowledge
  $\Rightarrow$ Best practise: Continue analysing data!

DP at H1

- Total volume at H1 $\approx$ 0.5 PB
- Preservation through modernisation (c.f. D. Britzger's talk in the computing session)

Emerging new interest in HERA data because of EIC (and LHeC)



HERA-II data

- High-Q^2 region: $Q^2 > 150\ \text{GeV}^2$
- Luminosity: $L = 351\ \text{pb}^{-1}$

Signal Monte Carlo models

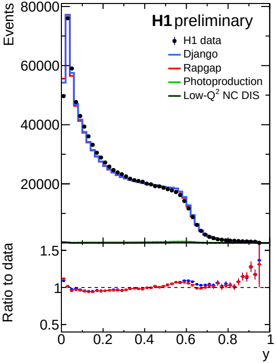
- Rapgap (ME + PS)
- Djangoh (CDM)

Little background in incl. DIS

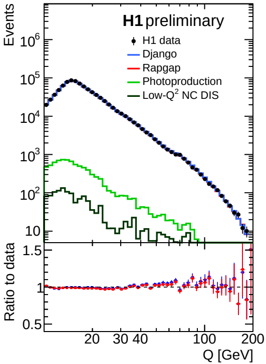
- Photoproduction
- Low-Q^2 NC DIS
- Other sources are negligible (QEDC, CC DIS, di-lepton production)

Reconstruction

- Use the IΣ method $\rightarrow$ Independent of electron ISR



$$y = y_\Sigma = \frac{\Sigma}{\Sigma + E_{e'}(1 - \cos\vartheta_{e'})}$$



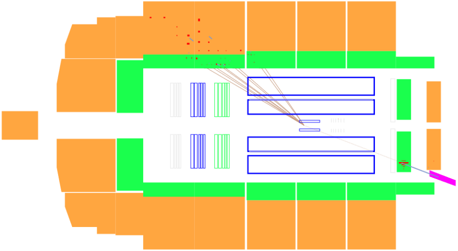
$$Q^2 = Q^2_\Sigma = \frac{E^2_{e'} \sin\vartheta_{e'}}{1 - y_\Sigma}$$

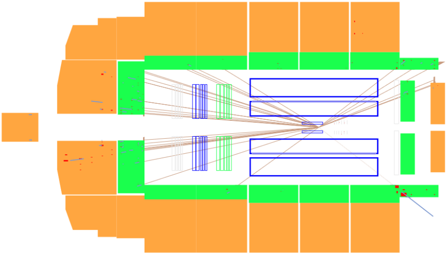
The 1-jettiness event shape observable

1-jettiness

$$\tau_1^b = \frac{2}{Q^2} \sum_{i \in X} \min\{xP \cdot p_i, (q + xP) \cdot p_i\}$$

Visualisation of the 1-jettiness with event displays

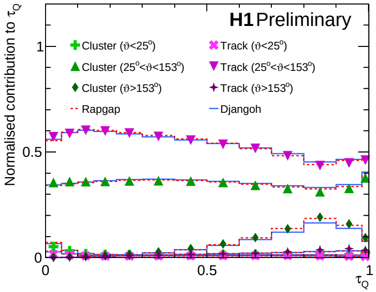


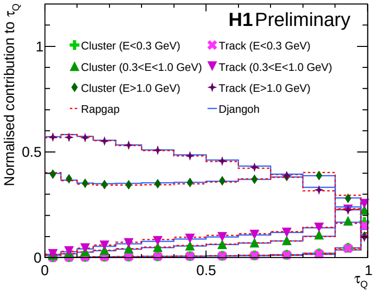


- DIS 1-jet configuration
- Most HFS particles collinear to scattered parton
  $\rightarrow$ Small τ_1^b

- Dijet event
- More and larger contributions to the sum over the HFS
  $\rightarrow$ Large τ_1^b

- All particle candidates in all DIS events contribute $\left(\tau_Q = 1 - \frac{2}{Q}\sum_{i\in\mathcal{H}_\mathcal{C}} P_{z,i}^{Breit}\right)$
- Normalised contribution to τ_Q for different ranges in polar angle ϑ and energy





- Mainly tracks and clusters in the central part of the detector contribute $(25° < \vartheta < 153°)$
- Mainly particles with high energy contribute $(E > 1$ GeV$)$
  $\Rightarrow$ Well measured particles dominate in τ_Q

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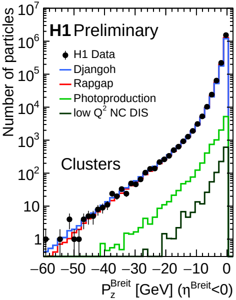
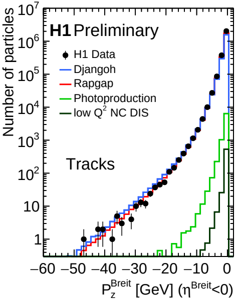
DIS thrust: Sum of longitudinal momenta

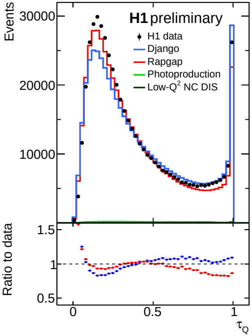
- Longitudinal momentum distribution of single particles in the current hemisphere
- Particles are well modelled by simulation for clusters and tracks





DIS thrust

- $\tau_Q \rightarrow 0$: DIS 1-jet events
- $\tau_Q \rightarrow 1$: Dijet events
- $\tau_Q = 1$: Dijet event, both jets in beam hemisphere



- Reasonable agreement between data and MC
- Full τ_Q range measurable

Purity distribution

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Purity defined as N_{stay} / N_{rec}

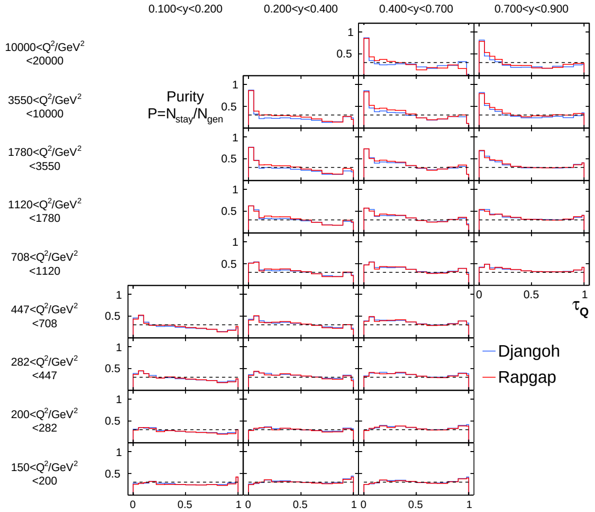
- N_{rec}: Events on detector level in one bin
- N_{stay}: Events that are reconstructed in the same bin they were generated

Purity

- Rapgap and Djangoh behave similarly
- Flat distribution in all y-Q^2 bins
- Purities $> 30\%$ in most bins

From different binnings and 2D migration matrices

- Purity mainly limited by bin-to-bin resolution effects
- Not an effect from limited detector acceptance



Single differential cross section

Measure τ_Q but present cross sections as a function of τ_1^b

1-jettiness cross section

$$\left(\frac{d\sigma}{d\tau_1^b}\right)_i = \frac{N_{data,i} - N_{bkgd,i}}{\Delta_i \cdot L} \cdot c_{\mathrm{QED,i}} \cdot c_{\mathrm{unfold,i}}$$

- Unfolded using bin-by-bin method c_{unfold}
- Corrected for QED radiative effects c_{QED}
- Divide by τ_1^b-bin width Δ_i
- Integrated luminosity $L = 351.6\ \mathrm{pb}^{-1}$

Phase space

- Momentum transfer $150 < Q^2 < 20.000\ \mathrm{GeV}^2$
- Inelasticity $0.2 < y < 0.7$ (single differential)
- Inelasticity $0.1 < y < 0.9$ (triple differential)

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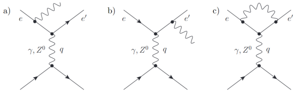
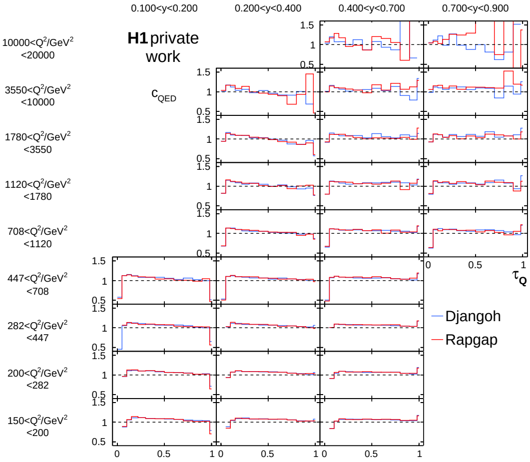
Correct for electron QED radiative effects

- Real emissions of photons (a,b)
- Vertex corrections (c)



- QED processes simulated with HERACLES
- Size of corrections depends on reconstruction method

→ Corrections around 10%
→ Large effect in the first bin



Comparison with MC models

- Djangoh 1.4: Colour-dipole-model
- Rapgap 3.1: ME + parton shower
- Pythia 8.3 + Dire

Dire Parton Shower

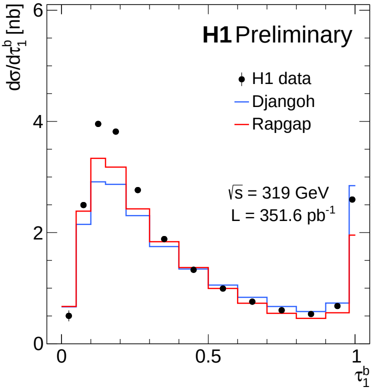
- Dipole-like shower
- Including inclusive NLO DGLAP corrections to the shower evolution

Peak region ($\tau_1^b \lesssim 0.2$)

- Resummation region
- Not well described by the models

Tail region ($\tau_1^b \gtrsim 0.3$)

- Fixed order region ($\mathcal{O}(\alpha_s)$)
- Djangoh and Rapgap perform well
- Pythia+Dire underestimates the data

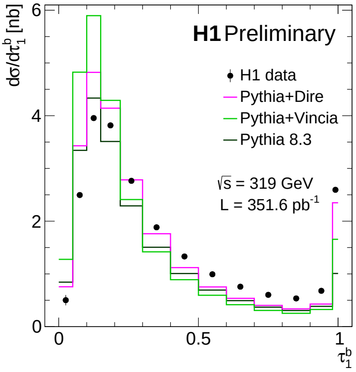


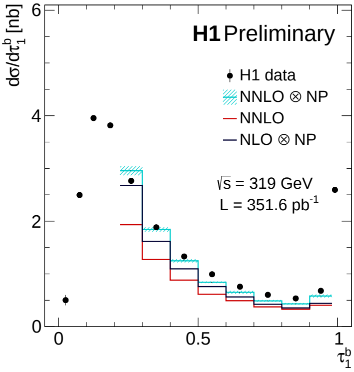
Comparison with parton shower models

- Peak region has strong dependence on different parton showers
- No PS model provides a fully satisfactory description
- 'Pythia default' underestimates $\tau = 1$

$\gamma p \to$2 jets+X NNLO prediction form NNLOJET

- NP corrections from Pythia 8.3 (sizeable)
- NNLO provides a reasonable description of fixed-order region
- NNLO improves over NLO





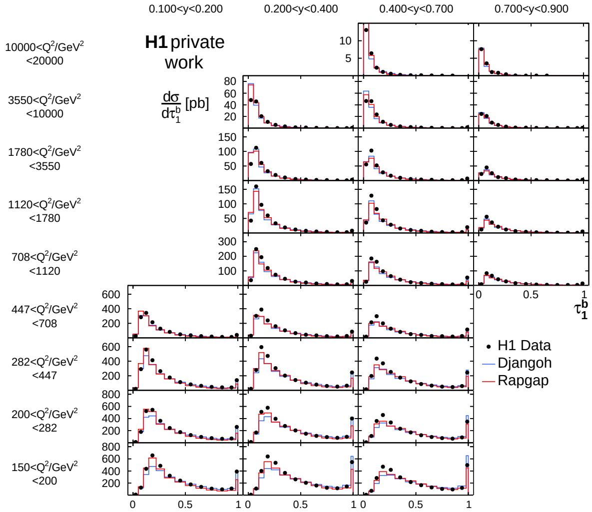
Triple differential cross sections

Large cross section and sizeable data

→ Triple-diff. cross sections as a function of Q^2, y, τ

3D cross sections

- increasing Q^2
  - → Peak moves to lower τ
  - → Tail region lowers
- Increasing y
  - → $\tau = 1$ becomes enhanced

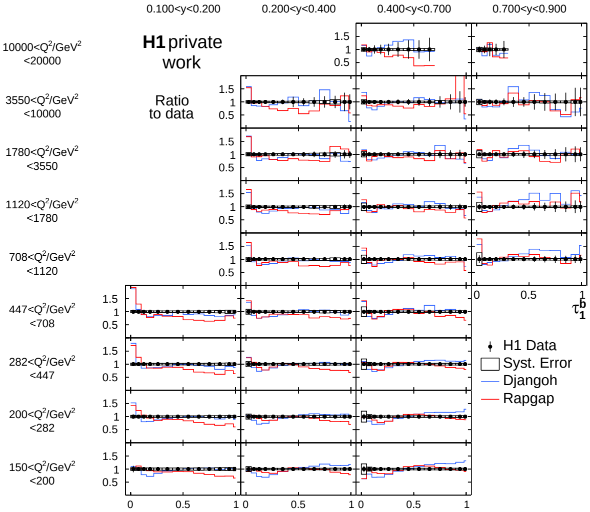


Triple differential cross sections

Ratio to data

- Stat. uncertainties of a few to $O(10\%)$
- Syst. uncertainties are in the range of 5%

$\rightarrow$ 'Classical' MC models perform reasonably well over entire phase space
$\rightarrow$ Pythia+Dire similar to Rapgap at low y, but too large at low τ



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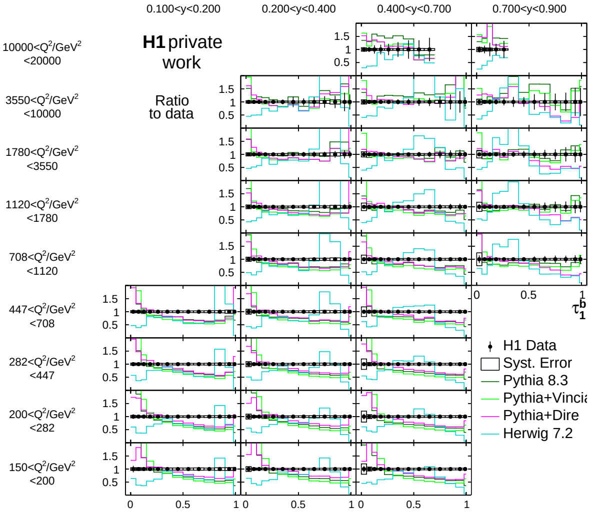
Comparison with further MC models

- Pythia+Vincia
- Pythia w/ default shower

Herwig 7.2

- Often similar to Pythia, but peak region too low (DIS cross section too low)
- Some structure at high τ



Triple differential cross sections

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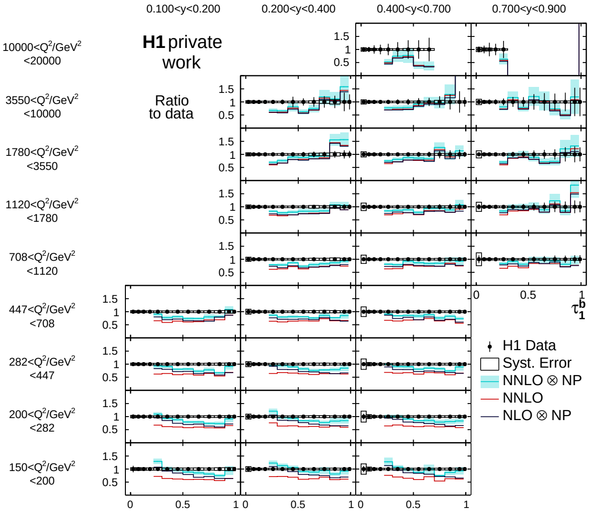
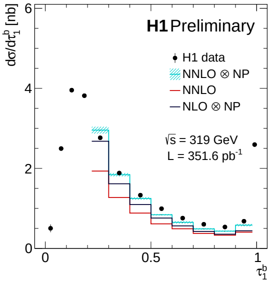
NNLO pQCD (*ep* →2 jets+X)

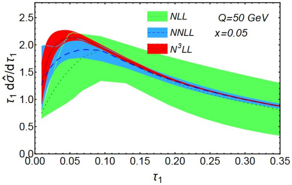
- Reasonable description in entire phase space
- Improved description with increasing Q^2
- Small scale uncertainties

→ Altogether: NNLO improves over NLO but NP corrections are sizeable



- A first measurement of the 1-jettiness event shape observable in NC DIS was presented
  (Analysis team J. Hessler, D. Britzger, S. Lee
  [J. Kretzschmar, E. Elsen])
- 1-jettiness is equivalent to DIS thrust normalised with $Q/2$
  $\rightarrow$ Defined for every NC DIS event
- Classical Monte Carlo provides a good description of the data
- Modern Monte Carlo provides a reasonable description
- NNLO fixed order predictions ($ep \rightarrow 2$ jets) provide good description in the region of validity, but hadronisation corrections are large

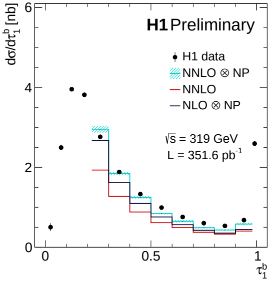


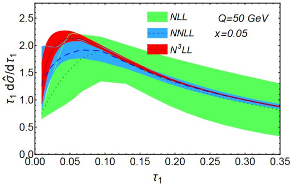


Kang, Lee, Stewart, [PoS DIS2015 (2015) 142]

Outlook

- Apply advanced unfolding methods
- Predictions need to be confronted with data
  - N3LL ([PoS DIS2015 (2015) 142])
  - N3LO (Phys.Lett.B 792 (2019) 182, [1812.06104]
  - NNLO + Power Corrections (Eur.Phys.J.C 79 (2019) 1022 [1909.02760])
  - NNLO+PS (Phys. Rev. D 98, 114013 (2018) [1809.04192]) (UN^{2}LOPS)
  - N3LO+PS (first concepts for N3LO+PS available [arXiv:2106.03206])
- Sensitivity to α_s and PDFs needs to be explored
- Data will become useful for improving (DIS) MC generators
  $\Rightarrow$ Improved parton showers & smaller PDF uncertainties





Kang, Lee, Stewart, [PoS DIS2015 (2015) 142]

[1] Z. Kang, X.Liu, S. Mantry, The 1-Jettiness DIS event shape: NNLL + NLO results, *arXiv:1312.0301v2*, 2014

[2] D. Kang, C. Lee, I. Stewart, Using 1-Jettiness to Measure 2 Jets in DIS 3 Ways, *arXiv:1303.6952v2*, 2013.

[3] D. Kang, DIS Event Shape at N^3LL, https://indico.cern.ch/event/341292/contributions/1739091/attachments/670208/921244/DIS2015-kang.pdf, 2015

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[5] U. Bassler, G. Bernardi, On the Kinematic Reconstruction of Deep Inelastic Scattering at HERA: the Σ Method, *arXiv:hep-ex/9412004v1*, 1994

[6] D. Kang, C. Lee, I. Stewart, Analytic Calculation of 1-Jettiness in DIS at O(α_s), *arXiv:1407.6706v1*, 2014.