Spin-sensitive jet observables and their resummation

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Jets and their substructure from LHC data
Online (CERN)

Based on 2103.16526 within the PanScales collaboration with
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Jets at the LHC

- Despite QCD being a *quantum* field theory jets are mostly classical objets
- Can quantify *quantumness* by size of interference at the matrix element level
- In other words if $\mathcal{M}_1\mathcal{M}_1^* \cdots \mathcal{M}_n\mathcal{M}_n^* \sim \prod_{i=1}^n |\mathcal{M}_i|^2$ then quantum effects are negligible[1]
- In fact this is how a typical parton shower treats jet evolution - a set of mostly independent parton splittings
- There are however quantum interference effects present which one can study by peeking inside the jets!
- In this talk I discuss two novel jet-substructure observables that are sensitive to the spin of quarks and gluons $\rightarrow$ angular correlations
- Discuss in the context of e^+e^- but can readily be applied at the LHC

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[1] Cross terms generated through index contractions across matrix elements

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Spin in the past

- At LEP many spin-sensitive jet observables have been measured (eg $\theta^*_{NR}, \chi_{BZ}, \theta_{34}, \Phi^*_{KSW}$)[2], so what is the novelty?
- Almost all jet-angularity observables defined *between* jets and not *inside* jets $\rightarrow$ quantum effects embedded in the hard matrix element, ie not quasi-classical as discussed above
- There exist spin-sensitive two-jet observables like the D-parameter

$$D = \frac{27}{Q^3} \sum_{i<j<k} E_i E_j E_k (1 + 2c_{ij}c_{jk}c_{ik} - c_{ij}^2 - c_{jk}^2 - c_{ik}^2), \qquad c_{ij} = \cos\theta_{ij},$$

- but it has a “trivial” all-order structure given by [Larkoski & Procita (1810.06563)]

$$\frac{d^2\sigma^{\mathrm{NLL}}}{dC\,dD} \approx \frac{d\sigma^{\mathrm{NLL}}}{dC} \frac{d\sigma(C)^{\alpha_s^2}}{dD}.$$

[2] See [Moretti & Stirling (hep-ph/9808429)] for review

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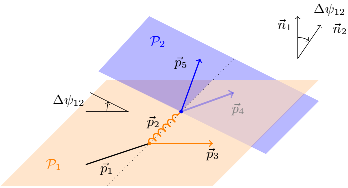
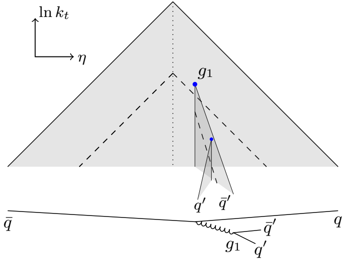
Definition of ψ_{12}



We define ψ_{12} through a Lund jet plane declustering [Dreyer, Salam, Soyez (1807.04758)]. At $\mathcal{O}(\alpha_s^2)$ it is equivalent to the angle between the planes of two successive splittings in the *same* jet.

- (Re-)cluster jet with C/A
- Find highest-k_t branching with $z_1 > z_{1,\mathrm{cut}} \rightarrow$ plane 1
- Follow the softest branch
- Find highest-k_t branching with $z_2 > z_{2,\mathrm{cut}} \rightarrow$ plane 2
- Compute $\Delta\psi$ between two planes



Definition of $\psi_{11'}$

- We define $\psi_{11'}$ similarly through a Lund jet plane declustering. At $\mathcal{O}(\alpha_S^2)$ it is equivalent to the angle between the planes of two splittings in two *distinct* jets.
- Observable EPR-like, ie it correlates two sides of the event that classically do not interact
- No spin correlations unless there is an intermediate gluon. Hence this observable is trivial for a quark initiated jet.

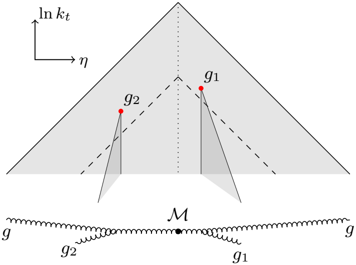
- (Re-)cluster two jets with C/A
- Find highest-k_t branching with $z_1 > z_{1,\text{cut}}$ inside first jet

→ This defines plane 1

- Find highest-k_t branching with $z_{1'} > z_{1',\text{cut}}$ inside second jet

→ This defines plane 1′

- Compute $\Delta\psi$ between two planes



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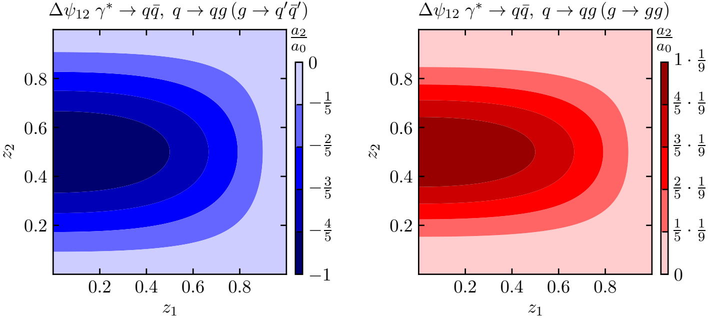
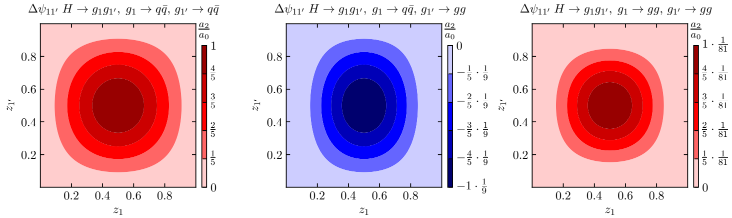
Structure of ψ_{12} in the collinear limit

$$\frac{d\sigma}{d\Delta\psi_{ij}} \propto a_0 \left(1 + \frac{a_2}{a_0}\cos(2\Delta\psi_{ij})\right) \propto \alpha_s^2 L^2$$



- ψ_{12} peaks when the intermediate gluon is soft and the quark-antiquark pair share the energy equally.
- $g \to q\bar{q}$ tends to be out of plane and $g \to gg$ in-plane (ie they tend to cancel).

Structure of $\psi_{11'}$ in the collinear limit



- $\psi_{11'}$ receives contributions from three different channels: 1) both gluons split into a quark-antiquark pair 2) one gluon splits into a quark-antiquark pair 3) both gluons split into gluons.
- The correlations are positive and largest in magnitude in case 1). If one gluon splits into gluons the correlations become negative and suppressed by a factor 1/9.
- If both gluons split into gluons the correlations again become positive, but are now tiny.
- In all cases the correlations are maximal when $z_1 \sim z_{1'} \sim 0.5$

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MicroJets resummation

- In order to resum the two ψ observables we make use of the MircoJets code [Dasgupta, Dreyer, Salam, Soyez (1411.5182, 1602.01110)] which we have extended with the Collins algorithm for spin correlations [Collins Nucl.Phys.B 304 (1988)]
- It is essentially an angular ordered toy shower with evolution variable t

$$t(\theta, p_t) = \int_\theta^1 \frac{d\theta'}{\theta'} \frac{\alpha_s(E\theta')}{\pi} \,,$$

- It resums single logarithmic terms of the the form $(\alpha_S \log(1/\theta))^n$ through DGLAP-style equations (think fragmentation functions)
- Hence it resums the ψ observables at NLL in the strongly ordered limit
- For the next few slides define $\lambda = \alpha_S \log\theta$ to define smallest angle that enters resummation

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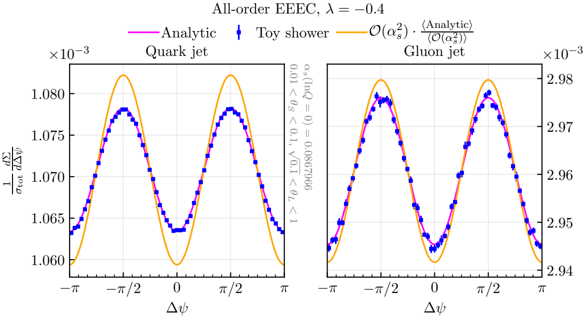
MicroJets validation

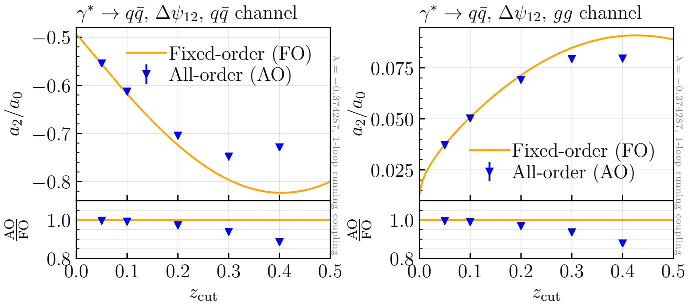
Triple energy correlator recently resummed (see Moult's talk)

$$\frac{1}{\sigma_{\text{tot}}}\frac{d^3\Sigma}{d\Delta\psi d\theta_S d\theta_L} = \left\langle \sum_{i,j,k=1}^{N} \frac{8E_iE_jE_k}{Q^3}\delta\left(\Delta\psi - \phi_{(ij)k}\right)\delta\left(\theta_S - \theta_{ij}\right)\delta\left(\theta_L - \theta_{jk}\right)\right\rangle$$



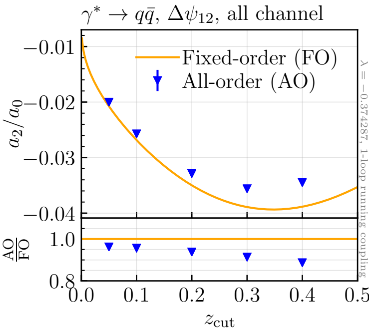
We have perfect agreement between the MicroJets code and the analytical resummation.

Resummed predictions for ψ_{12}



- Here we show a comparison between fixed-order (FO) and all order results for the ψ_{12} observables as a function of a symmetric z_{cut}
- For both channels the resummation tends to reduce the magnitude of the angular modulation
- For moderate z_{cut} the effect is very moderate
- Spin correlations are small in the dominating gluon channel. In order to see the effect one would ideally tag the quarks.

Combined predictions for $nf = 5$



- This becomes particularly clear when one combines all the channels
- Note: Small offset at z_{cut} due to channel with no spin correlation that only contributes to a_0
- Modulation can be enhanced through asymmetric z_{cut} values as can be seen in the below table ($\lambda = -0.5$)

$\frac{a_2}{a_0}$ by flavour channel for 2nd splitting	$g \to q\bar{q}$	$g \to gg$	all
EEEC	-0.36	0.026	-0.008
$\Delta\psi_{12}, z_1, z_2 > 0.1$	-0.61	0.050	-0.025
$\Delta\psi_{12}, z_1 > 0.1, z_2 > 0.3$	-0.81	0.086	-0.042

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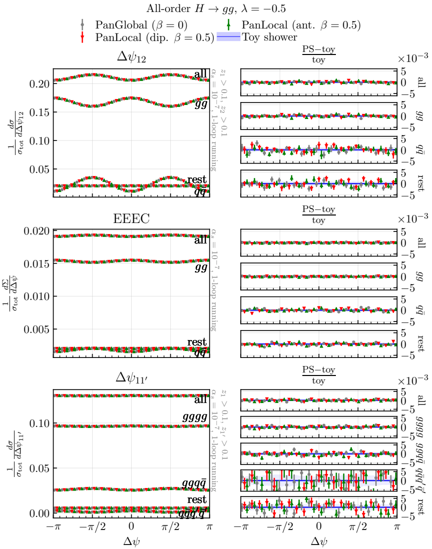
Spin correlations in PanScales



- Observables presented here have been used to validate the PanScales shower framework.
- In strongly ordered collinear limit we get perfect agreement with the resummed predictions.
- Necessary with spin correlations in parton showers if one wants to study angular correlations in realistic setups.
- Spin correlations also implemented in Herwig framework [Richardson & Webster (1807.01955)]

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Outlook and conclusions

- Have introduced and studied two jet-substructure observables sensitive to angular correlations between quarks and gluons
- Enables the study of quantum effects in a quasi-classical regime at colliders
- Still need a thorough phenomenological investigation to establish feasibility
  - Vary z_{cut}
  - Quark masses?
  - Flavour tagging?
  - Non-perturbative effects?
- Currently working on performing resummation analytically rather than through MicroJets

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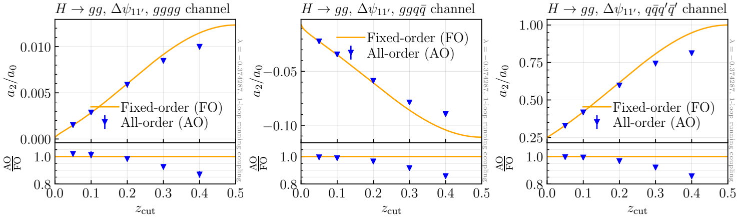
Resummed predictions for $\psi_{11'}$



- Here we show a comparison between fixed-order (FO) and all order results for the $\psi_{11'}$ observables as a function of a symmetric z_{cut}
- For all three channels the resummation tends to reduce the magnitude of the angular modulation
- For moderate z_{cut} the effect is very moderate
- Spin correlations are tiny in the dominating all-gluon channel. In order to see the effect one would ideally tag one or two quarks.

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