Spin Correlations in the PanScales parton showers and jet observables

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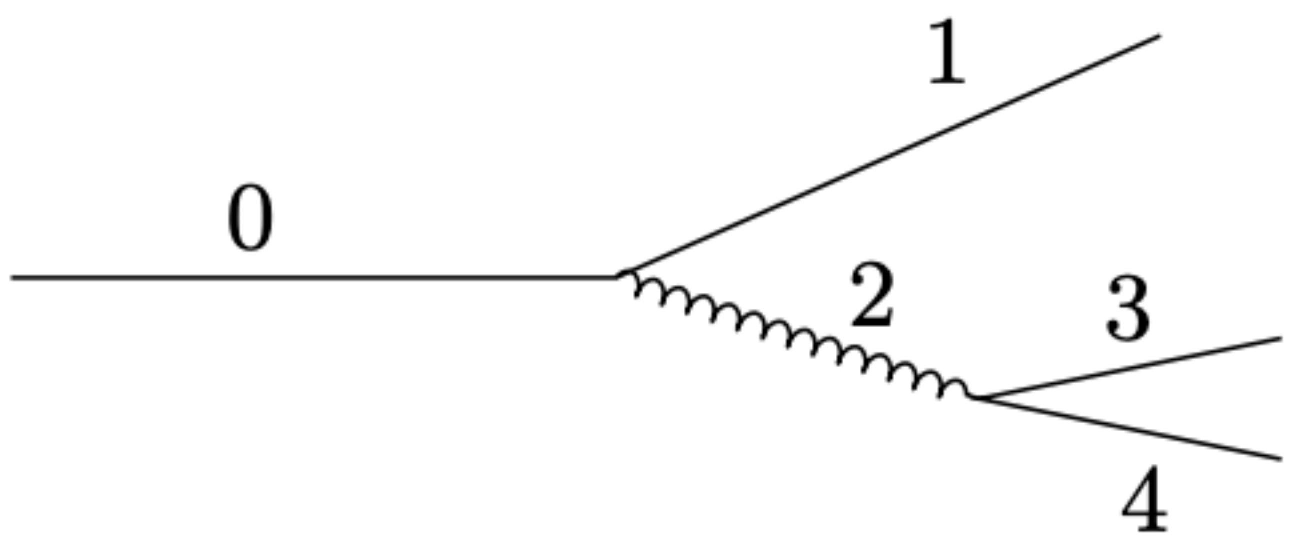
Spin Correlations

PanScales NLL requirement

- Get the ME right for emissions well-separated in Lund plane
- Reproduce NLL resummations of known observables



Spin interference effects

Collinear $\longrightarrow$ $$|M|^2 \propto \mathcal{M}_{0\to 12}^{\lambda_0\lambda_1\lambda_2}\mathcal{M}_{0\to 12}^{*\lambda_0\lambda_1\lambda_2'}\mathcal{M}_{2\to 34}^{\lambda_2\lambda_3\lambda_4}\mathcal{M}_{2\to 34}^{*\lambda_2'\lambda_3\lambda_4}$$

In QCD, spin correlations lead to azimuthal modulation of the form

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

$$\boxed{\begin{array}{c}\ln(\theta_1), \ln(\theta_2) > -|L| \\ \ln(z_1), \ln(z_2) \sim 1\end{array}}$$

Spin Correlations

$$|M|^2 \propto \mathcal{M}_{0\to12}^{\lambda_0\lambda_1\lambda_2}\mathcal{M}_{0\to12}^{*\lambda_0\lambda_1\lambda_2'}\mathcal{M}_{2\to34}^{\lambda_2\lambda_3\lambda_4}\mathcal{M}_{2\to34}^{*\lambda_2'\lambda_3\lambda_4}$$

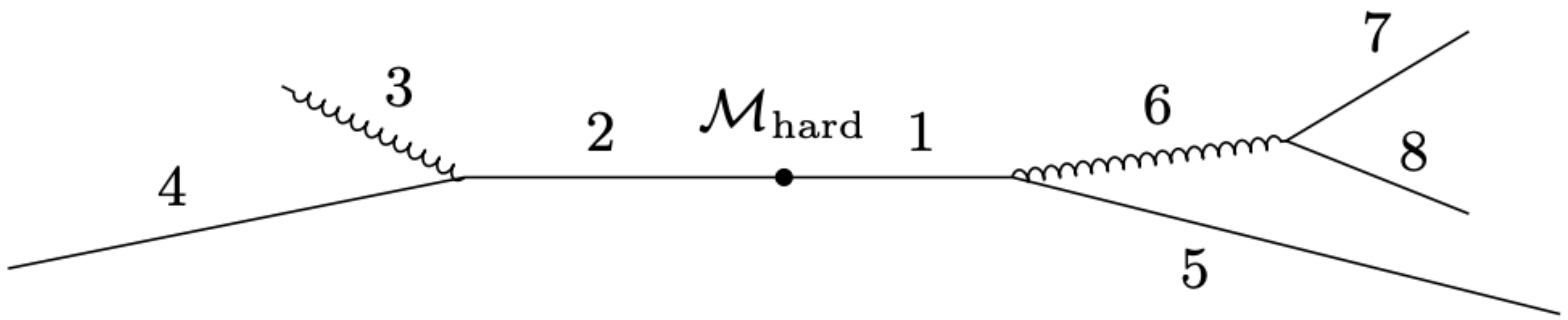
Redoing all spin index contractions at every branching is inefficient

Solution: Collins-Knowles algorithm

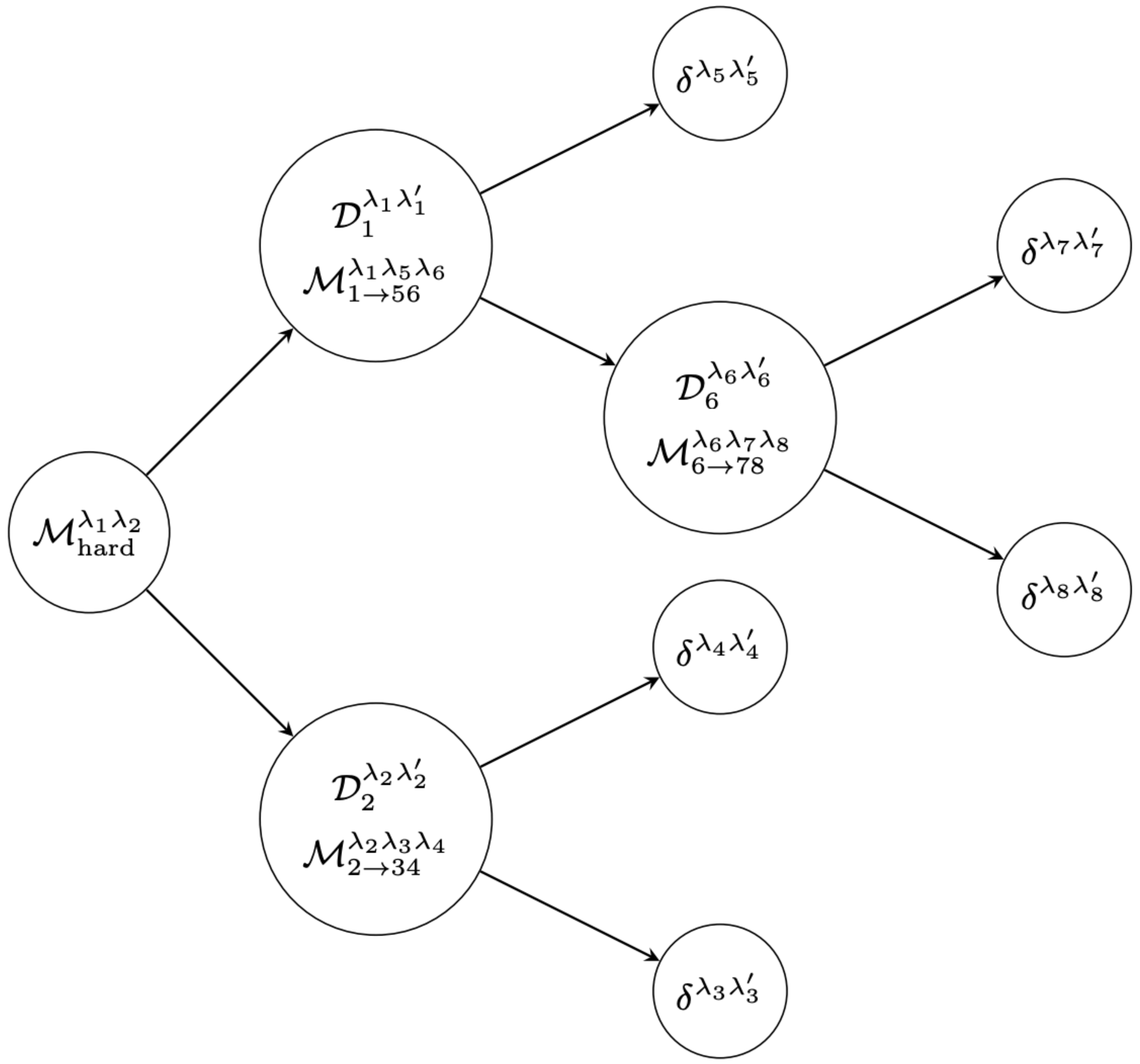
Collins Nucl.Phys.B 304 (1988)

Knowles Nucl.Phys.B 304 (1988)

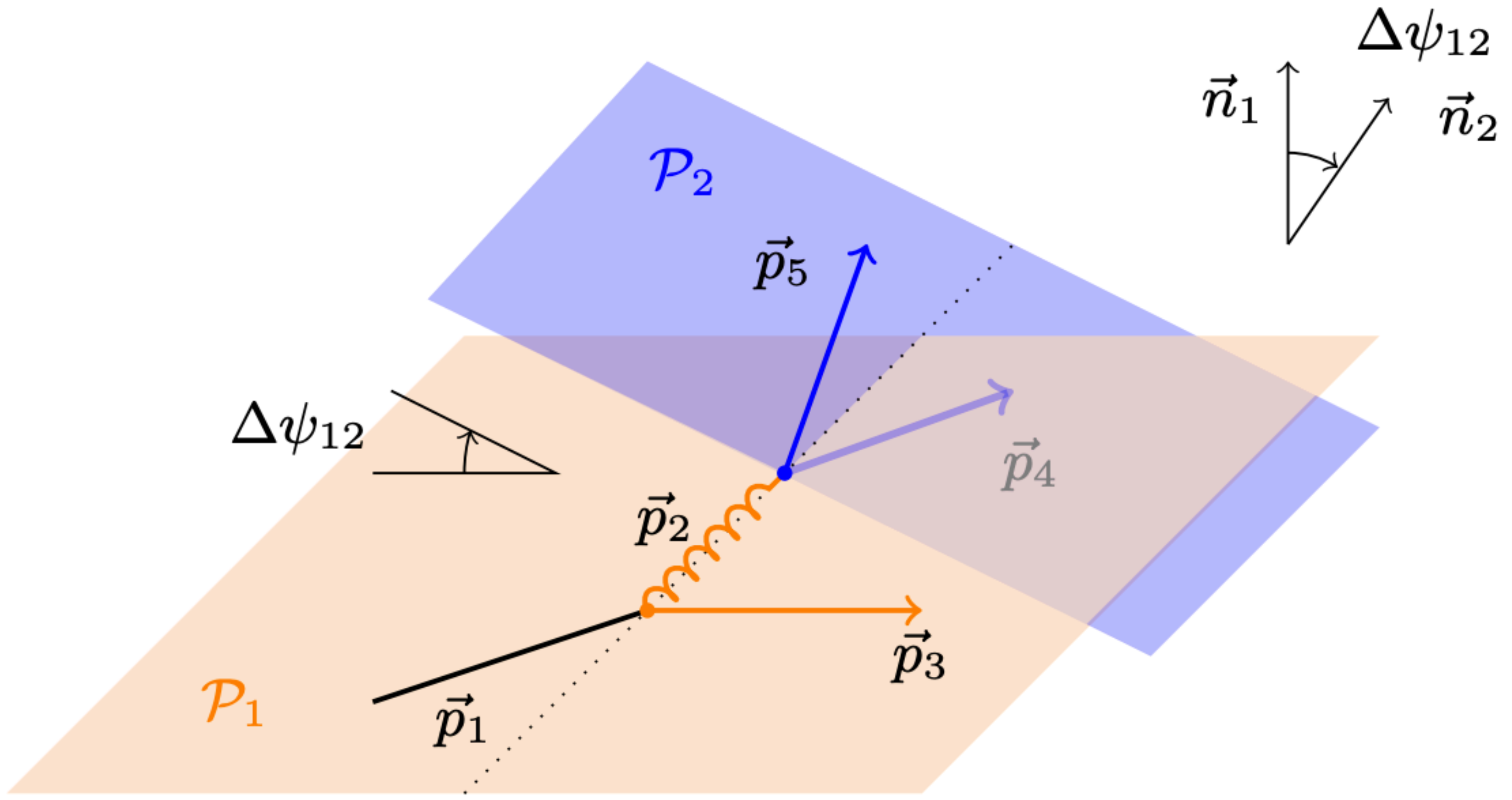
Richardson, Webster Eur.Phys.J.C 80 (2020)



$\rightarrow$



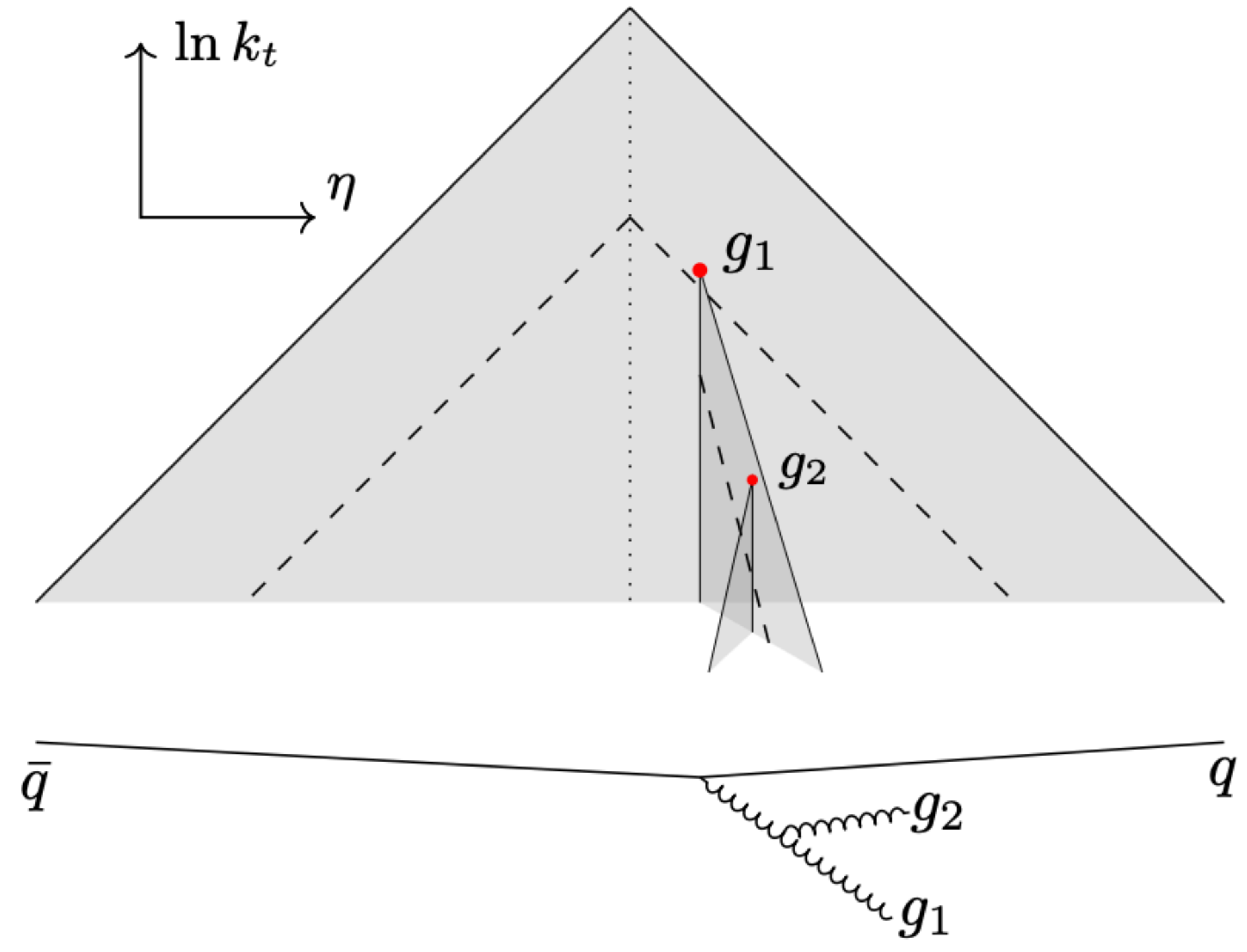
Observables: Lund Declustering



Fixed order:
Angle between the planes of two subsequent branchings

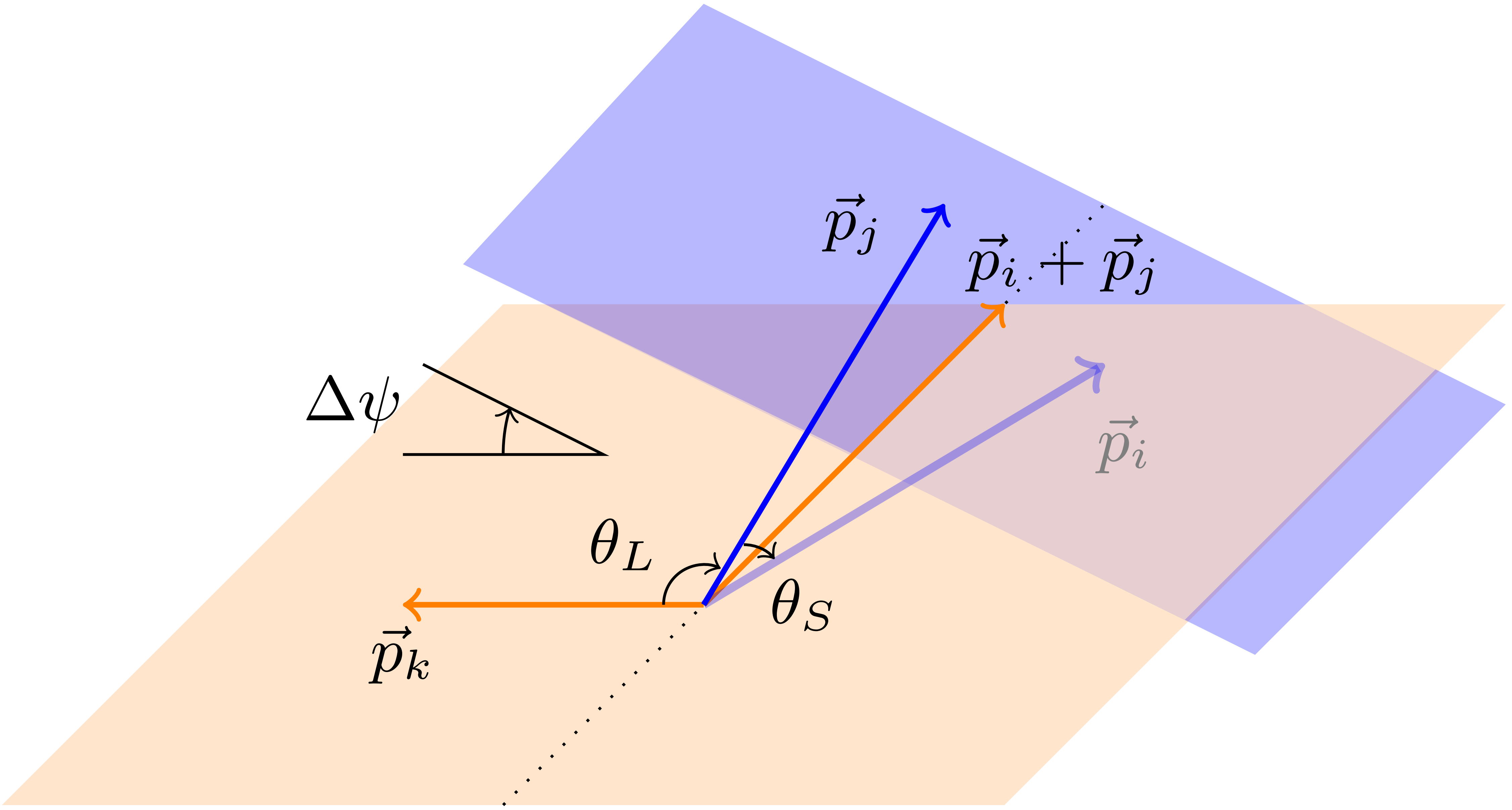
All orders: Lund jet plane Dreyer, Salam, Soyez JHEP 12 (2018) 064

- Decluster with C/A
- Find highest-k_t branching with $z_1 \geq z_{\rm cut}$
- Follow softest branch
- Find highest-k_t branching with $z_2 \geq z_{\rm cut}$
- Compute angle $\Delta\psi_{12}$ between two branching planes



Can also be defined *between* jets: EPR-like observable

Observables: EEEC



Recently resummed Chen, Moult, Zhu Phys. Rev. Lett. 126 (2021)

Energy weight removes soft contributions

Opening angles

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

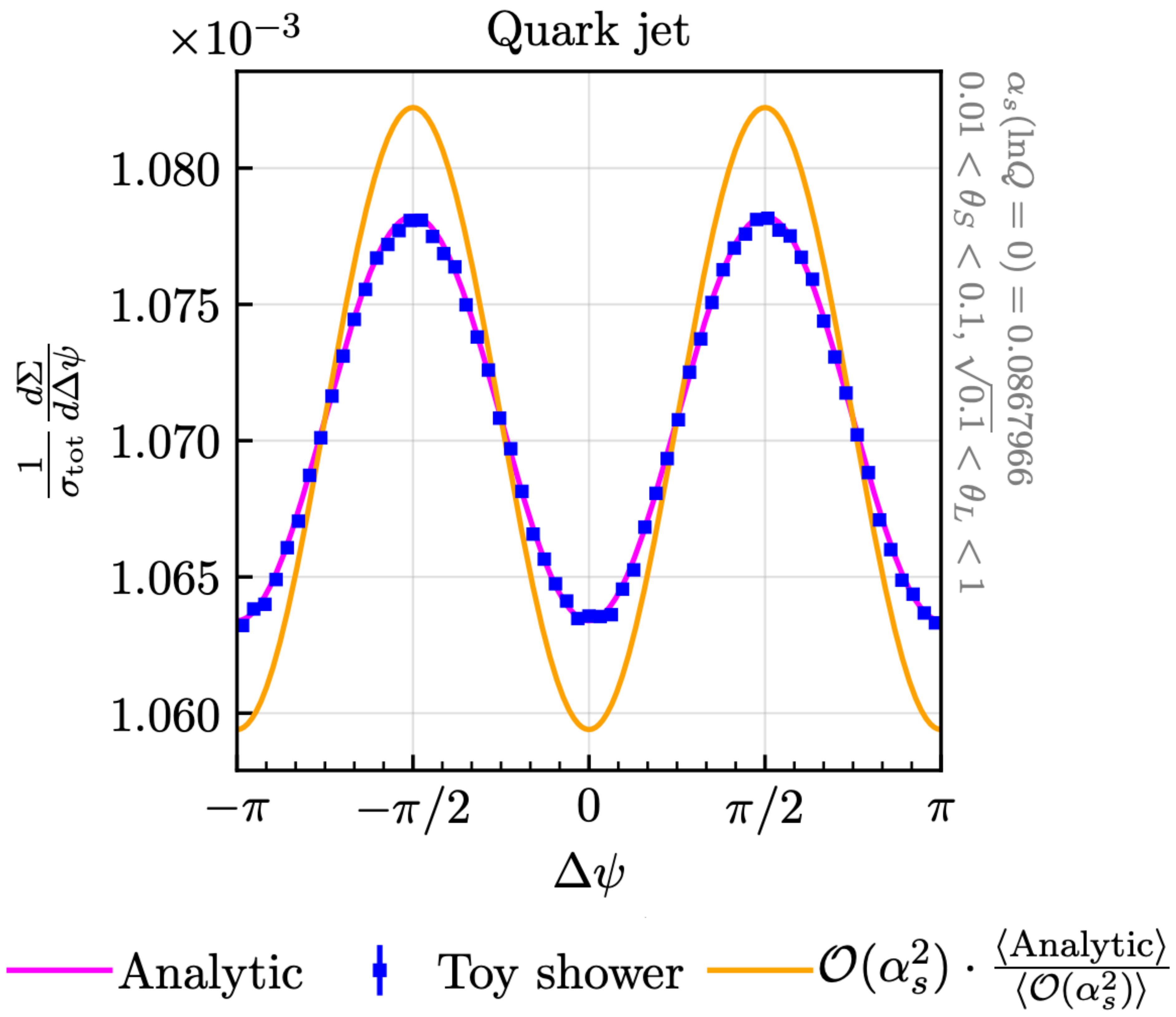
Angle between (p_i, p_j) -plane and $(p_i + p_j, p_k)$ -plane

Effects of resummation

Numerical collinear resummation:
MicroJets (toy shower) + Collins-Knowles

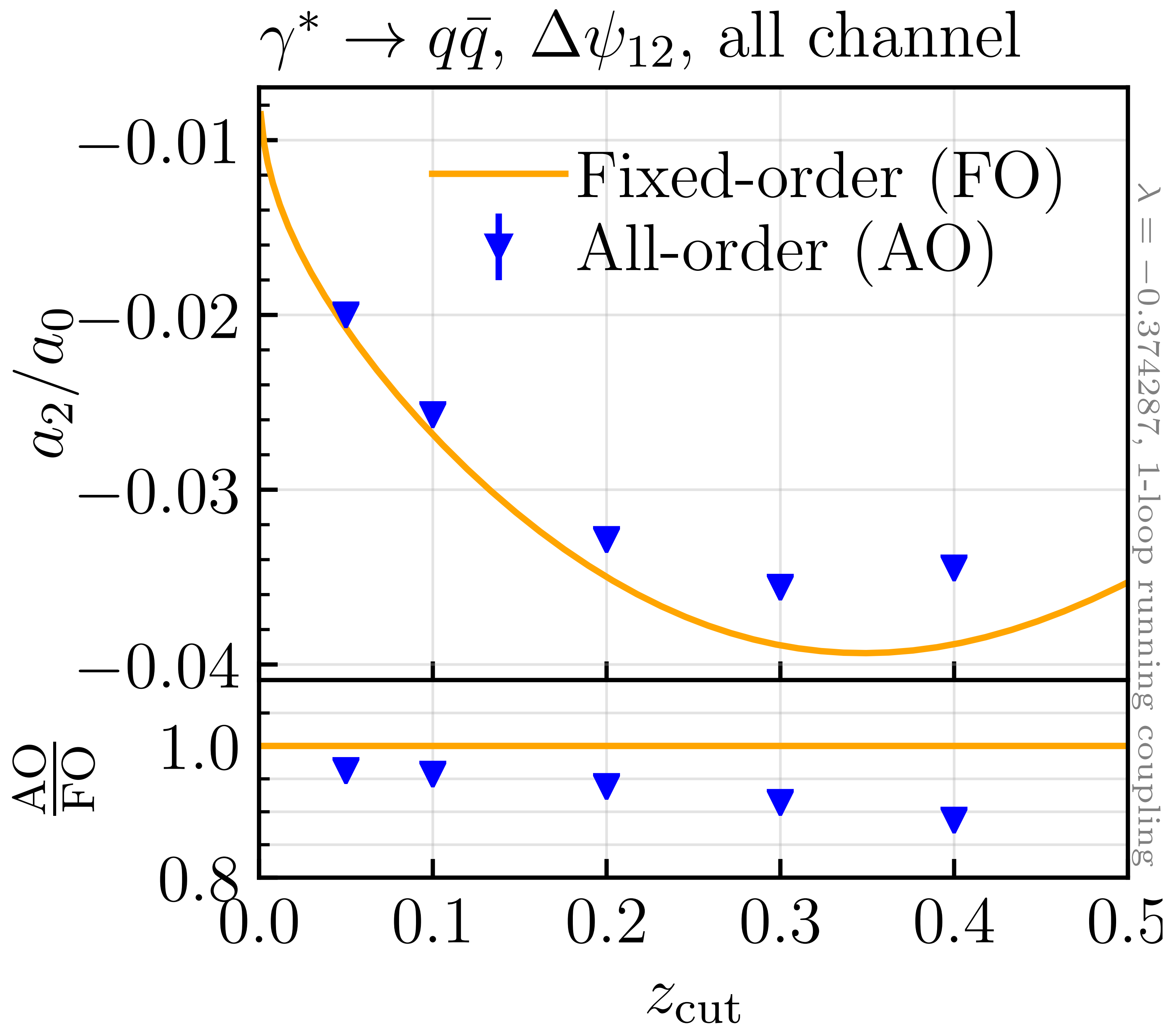
Dasgupta, Dreyer, Salam, Soyez JHEP 04 (2015)
Dasgupta, Dreyer, Salam, Soyez JHEP 06 (2016)

EEEC



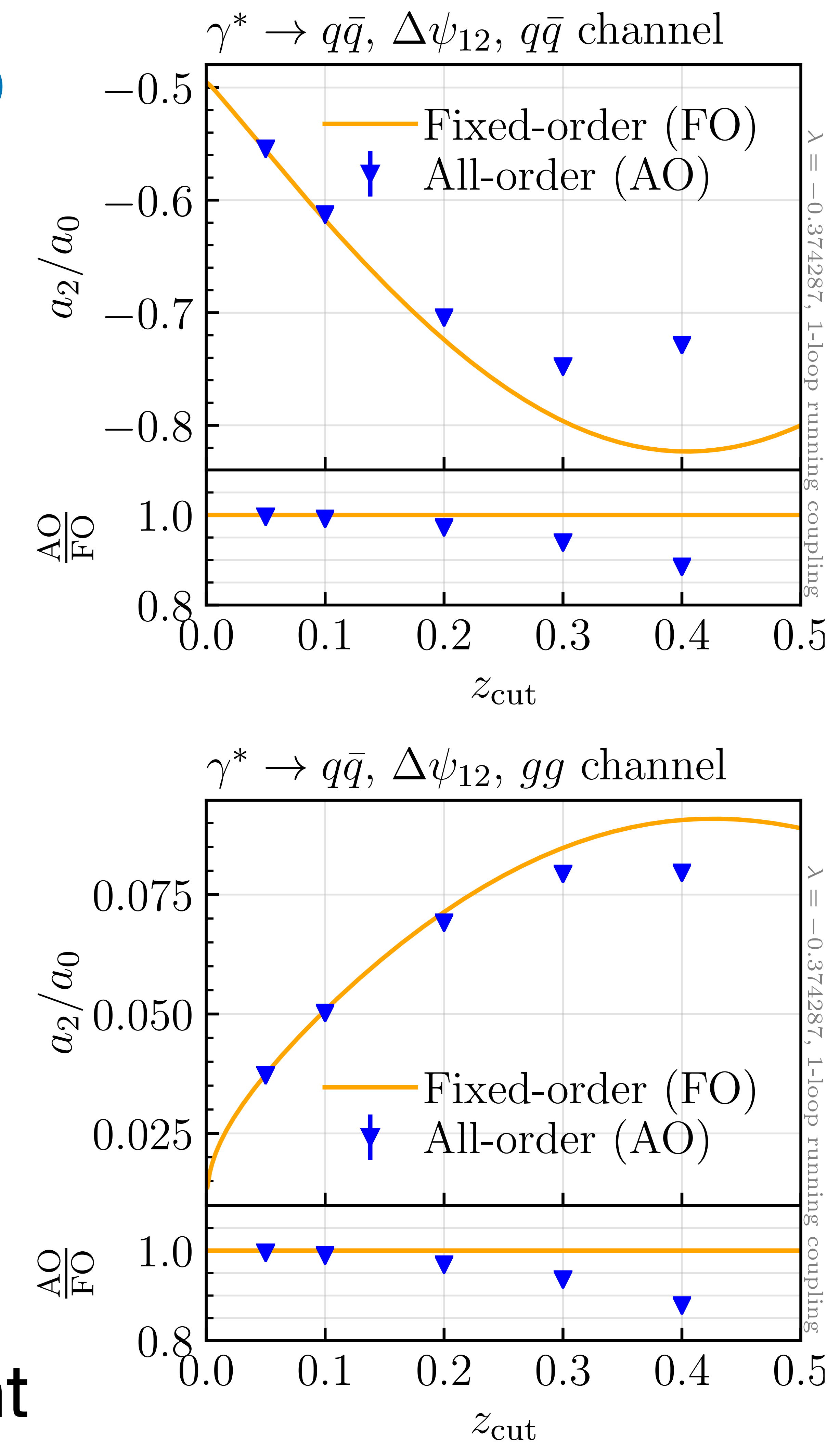
Chen, Moult, Zhu Phys. Rev. Lett. 126 (2021)

$\Delta\Psi_{12}$



$\longrightarrow$ Radiation dilutes spin content

Per channel



All orders: PanScales showers

Comparisons with real showers is technically challenging

Want to send $\alpha_s \to 0$ while keeping $\alpha_s L$ fixed

$\longrightarrow$ Run showers to very small cutoff scale

- Shower stores directional differences in dipoles

  $\longrightarrow$ Avoids large cancellation in dot products

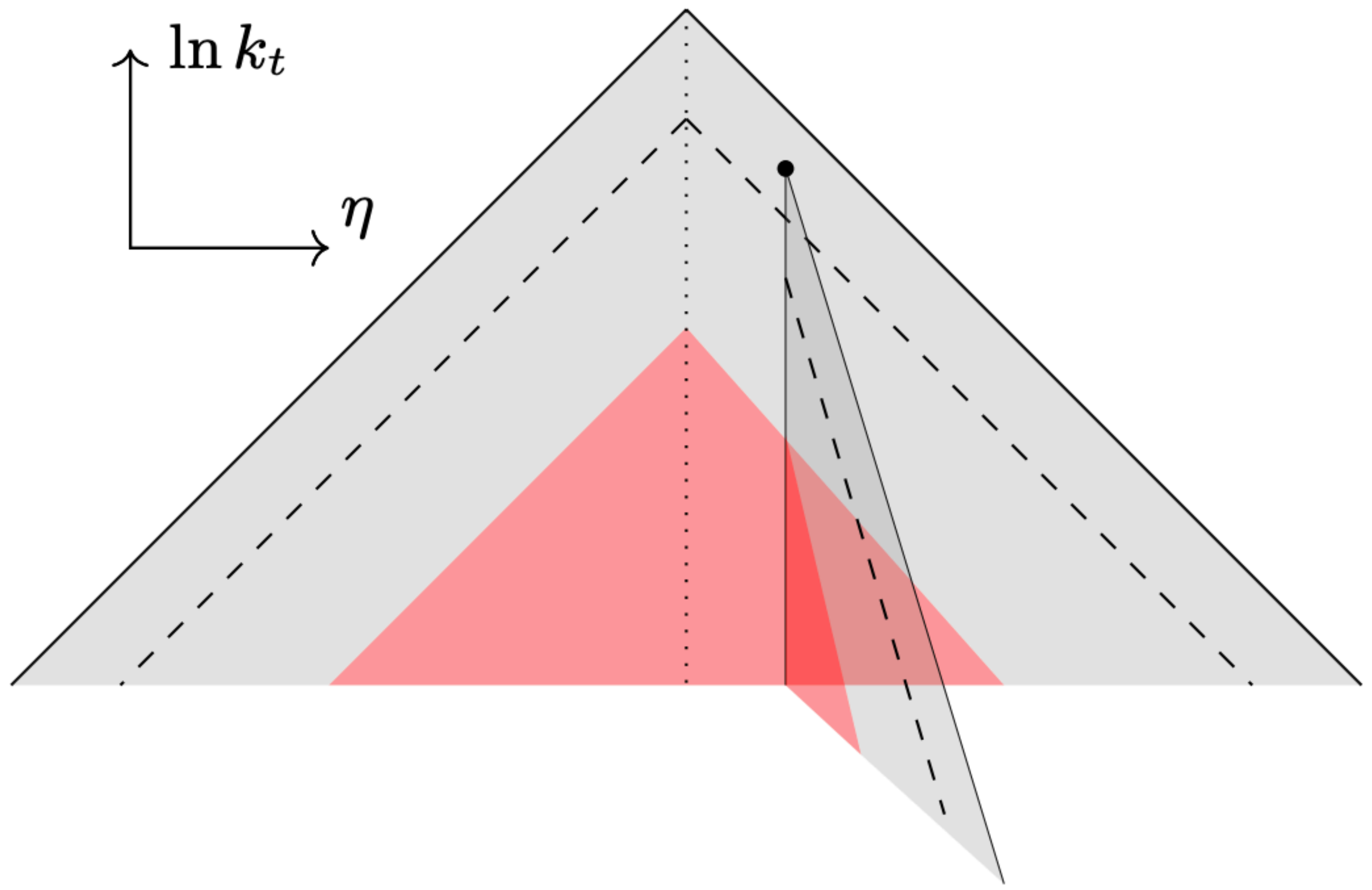
- Dedicated double_exp floating-point type

  $\longrightarrow$ Allows for larger exponent in a double

- Remove soft radiation

  $\longrightarrow$ Avoids multiplicity exploding

  $\longrightarrow$ Thoroughly tested to not alter observable



All orders: PanScales Showers vs. Toy Shower

$\lambda \equiv \alpha_s L = -0.5$

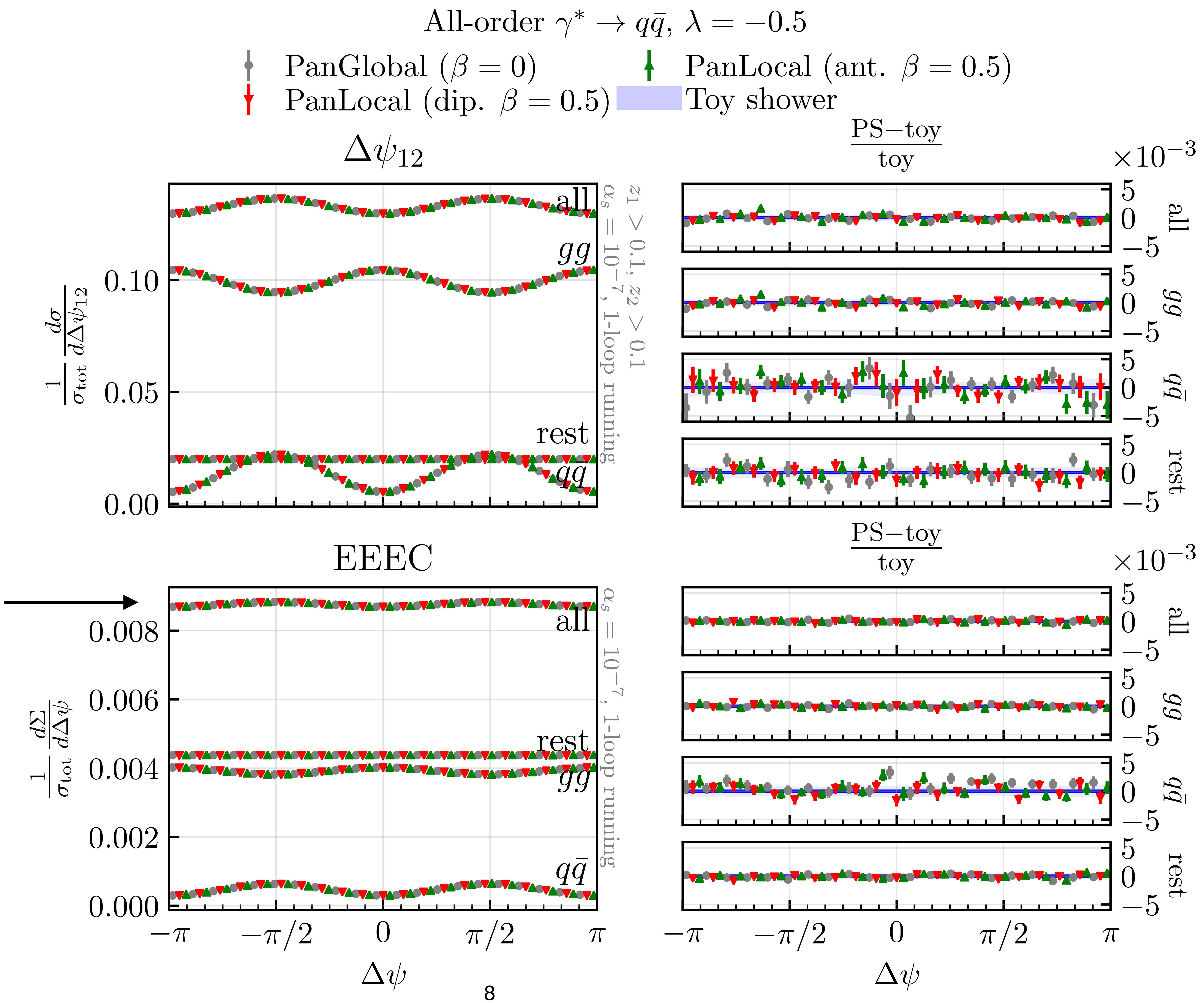
$z_{\text{cut}} = 0.1$

Large cancellations between channels

$\alpha_s \to 0$ limit:

$\alpha_s = 10^{-7}$

$L = -5 \cdot 10^6$



Conclusions & Phenomenology

- Implementation of Collins-Knowles in PanScales showers
- Definition of spin-sensitive observables
- Validation of NLL resummation

Phenomenological considerations

- $\Delta\psi_{12}$ generally has larger relative azimuthal modulation

  $\longrightarrow$ Easier to observe experimentally

- Modulations may be enhanced further by adjusting the value of $z_{\rm cut}$

- There are large cancellations between flavour channels

  $\longrightarrow$ Clear advantage to performing measurements with flavour tagging

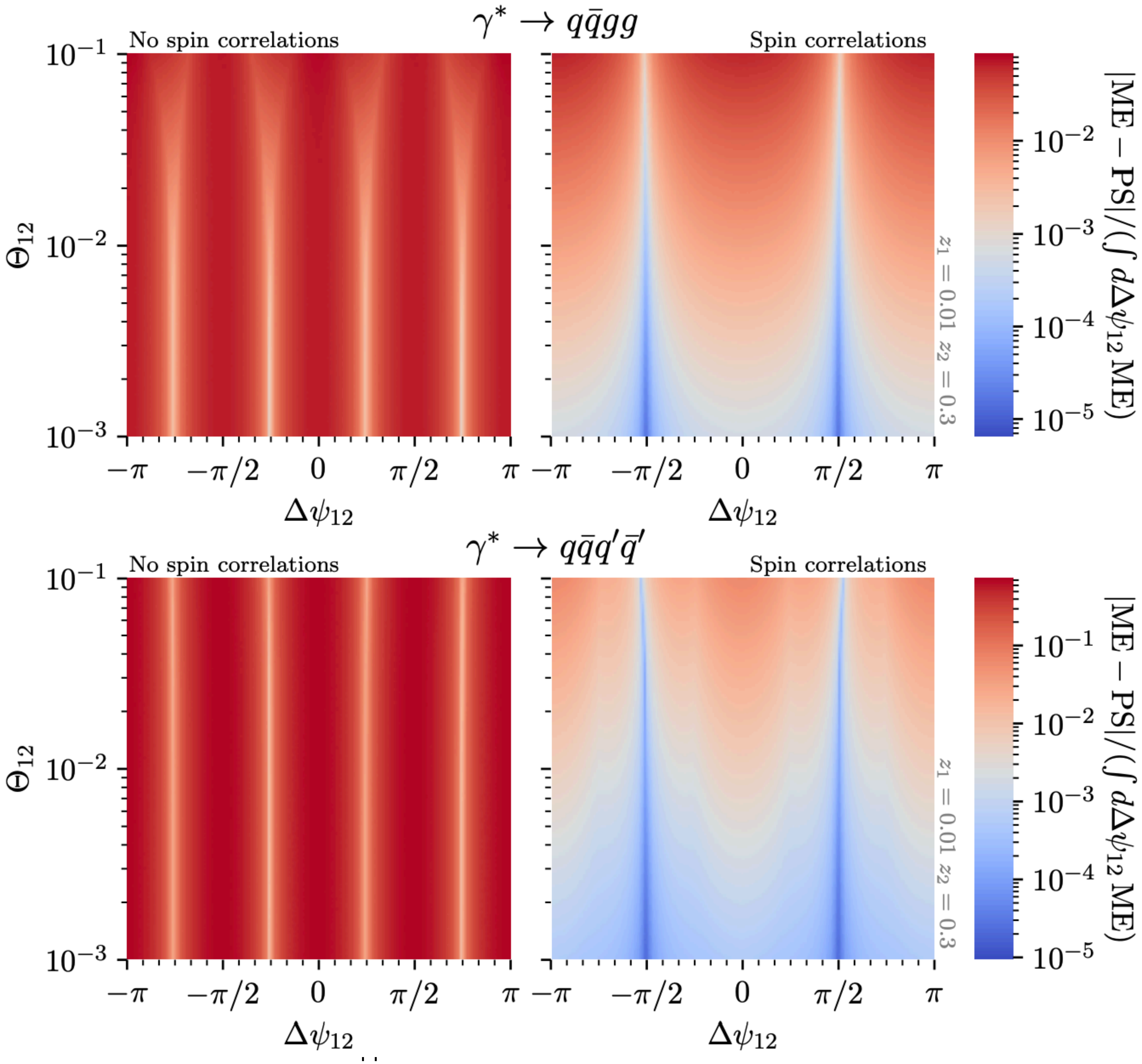
- Many subleading effects at LHC energies
  - Quark masses
  - Recoil effects
  - Non-perturbative corrections

$\lambda = 0.5$	a_2/a_0		
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

Backup

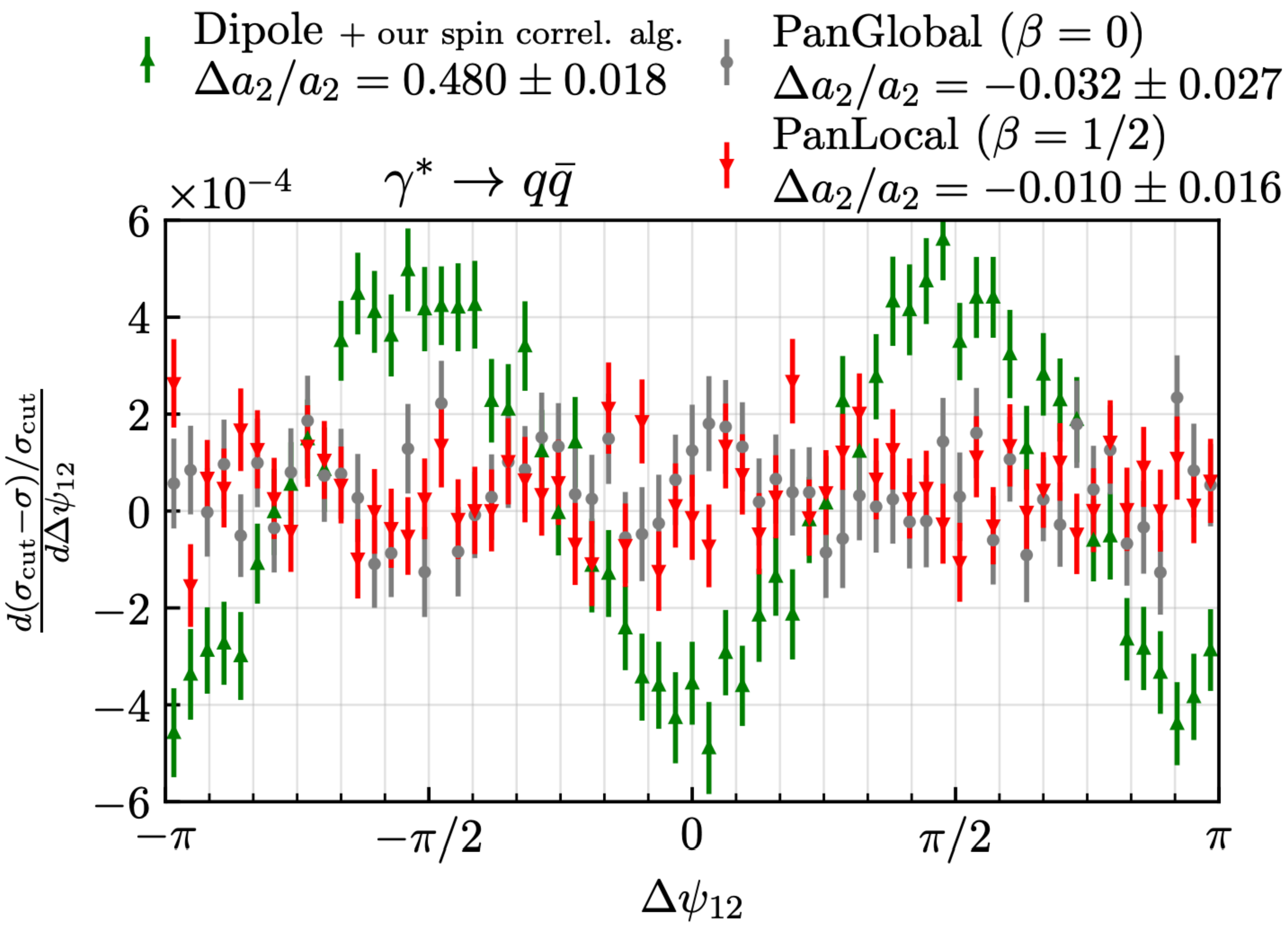
Matrix Element comparison

$$\Theta_{12} = \max(\theta_1, \theta_2/\theta_1)$$
$$z_1 = 0.01$$
$$z_2 = 0.3$$



Removing soft radiation

$$\alpha_s = 0.01$$
$$L = -27.5$$
$$\ln z_{\rm cut}^{\rm PS} = -10$$



Rotational Invariance of Spinor Products