Spin correlations in parton showers and jet observables

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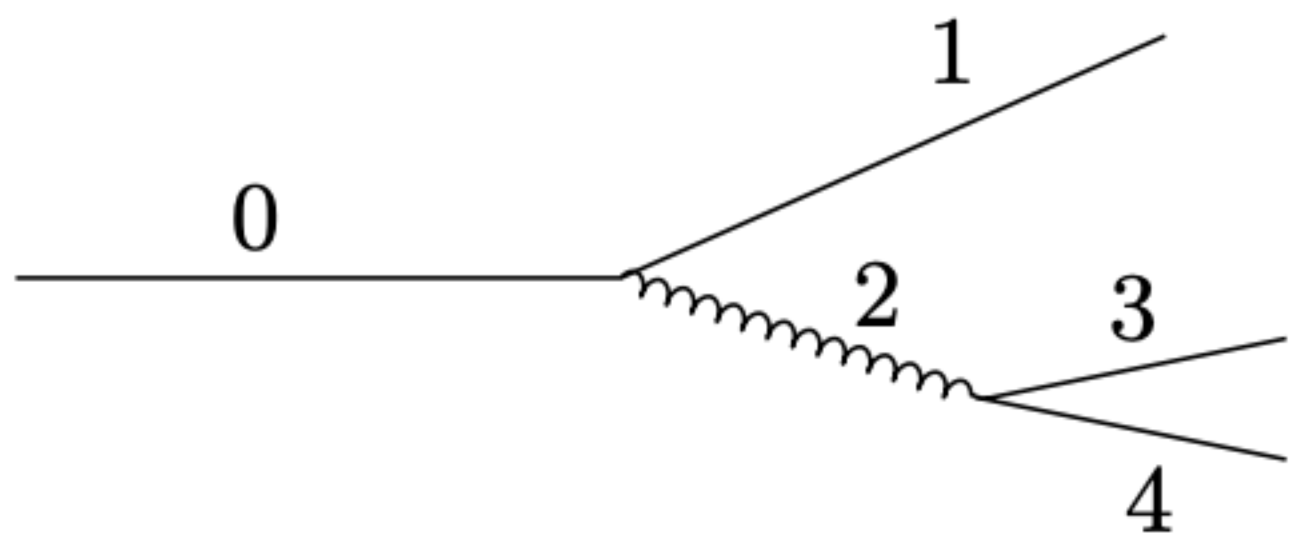
2103.16526

European Research Council
Established by the European Commission

Collinear Spin Correlations in Jets

Jet modelling through parton showers is mostly classical

Quantum interference effects do however appear, in the form of spin correlations



Spin interference effects

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

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

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

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

Spin in Monte Carlo

Matrix element $\longrightarrow$ Spin-sensitive observables at LEP:

$D, \theta^*_{\mathrm{NR}}, \chi_{\mathrm{BZ}}, \theta_{34}, \Phi^*_{\mathrm{KSW}}$

Talk by Stefan

$\uparrow$

Spin-sensitive observables *between* jets or *inside* jets

$\downarrow$

Parton shower $\longrightarrow$

- Lund plane density
- Energy correlators
- Machine learning
- ….

Talk by Benjamin

- Spin correlations are *crucial* for NLL accuracy in parton showers
- MC serves as input for ML models $\longrightarrow$ need to incorporate spin effects correctly

This talk:

- Implementation of spin correlations in the PanScales showers
- Definition of some new spin-sensitive jet-substructure observables
- Validation of PanScales showers to NLL accuracy in those (collinear) observables

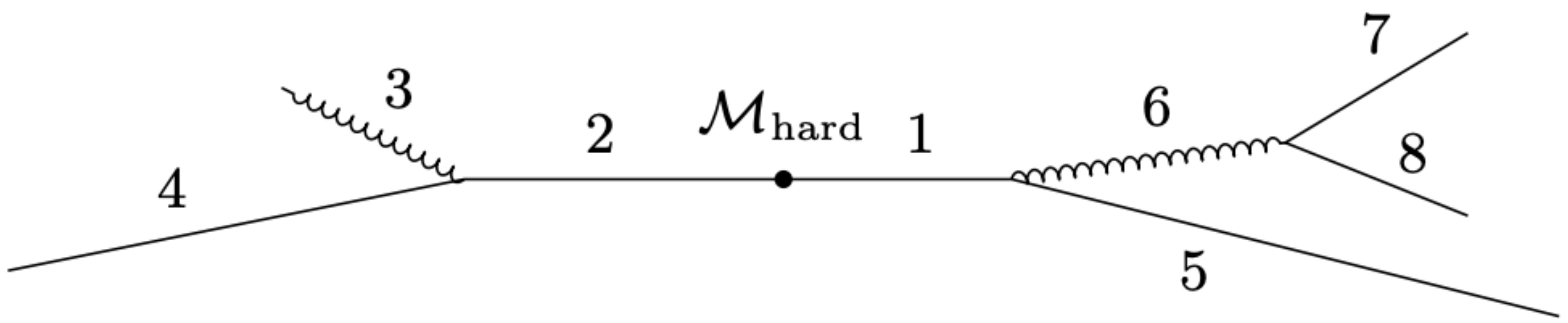
Spin in Parton Showers

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

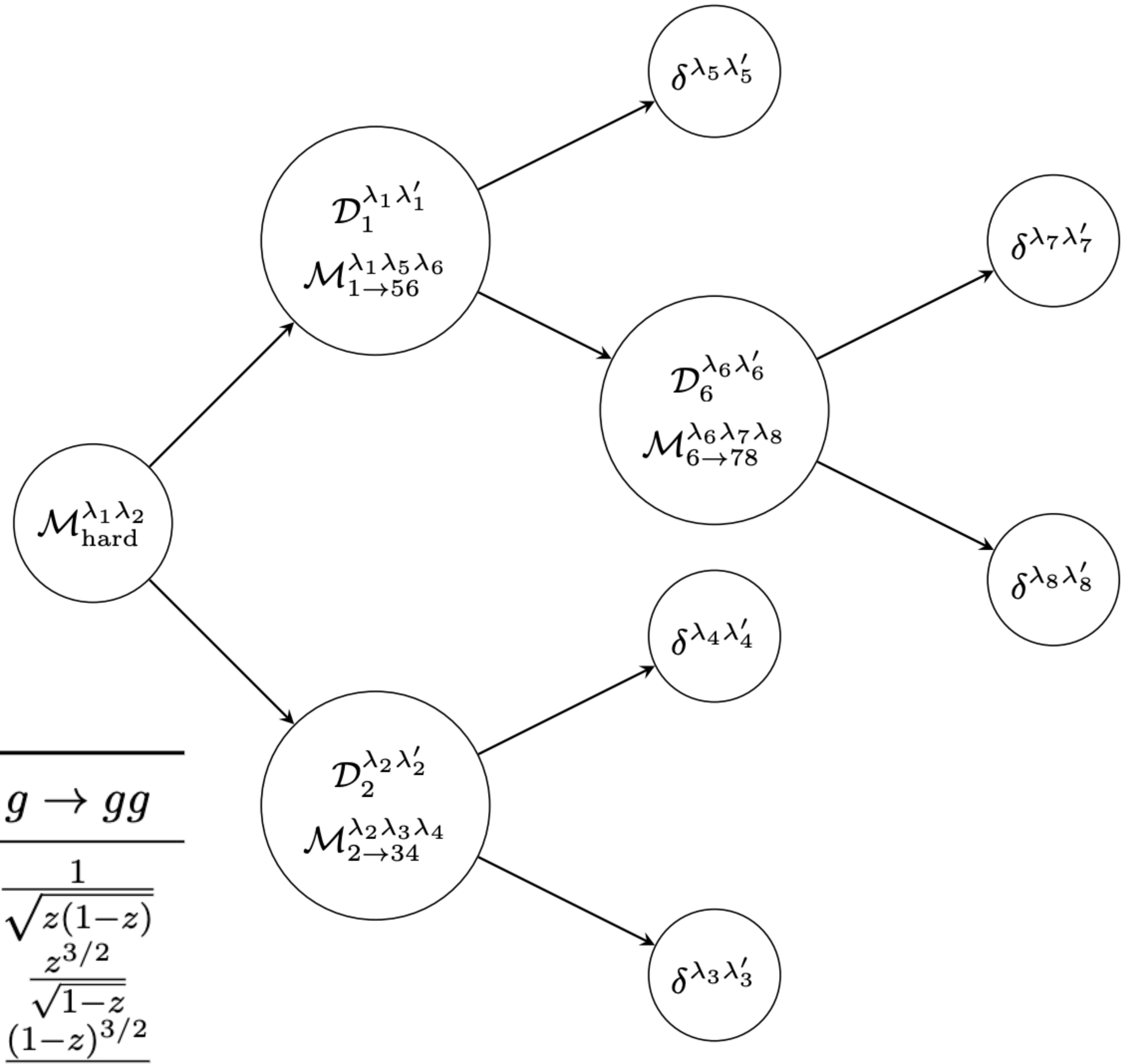
- Store the intermediate tensor with free spin indices $\longrightarrow$ 2^N indices
- Redo the whole calculation at every branching $\longrightarrow$ inefficient

Solution: Collins-Knowles algorithm

Collins Nucl.Phys.B 304 (1988)
Knowles Nucl.Phys.B 304 (1988)
Richardson, Webster Eur.Phys.J.C 80 (2020)



$\longrightarrow$



Caveat in dipole showers:

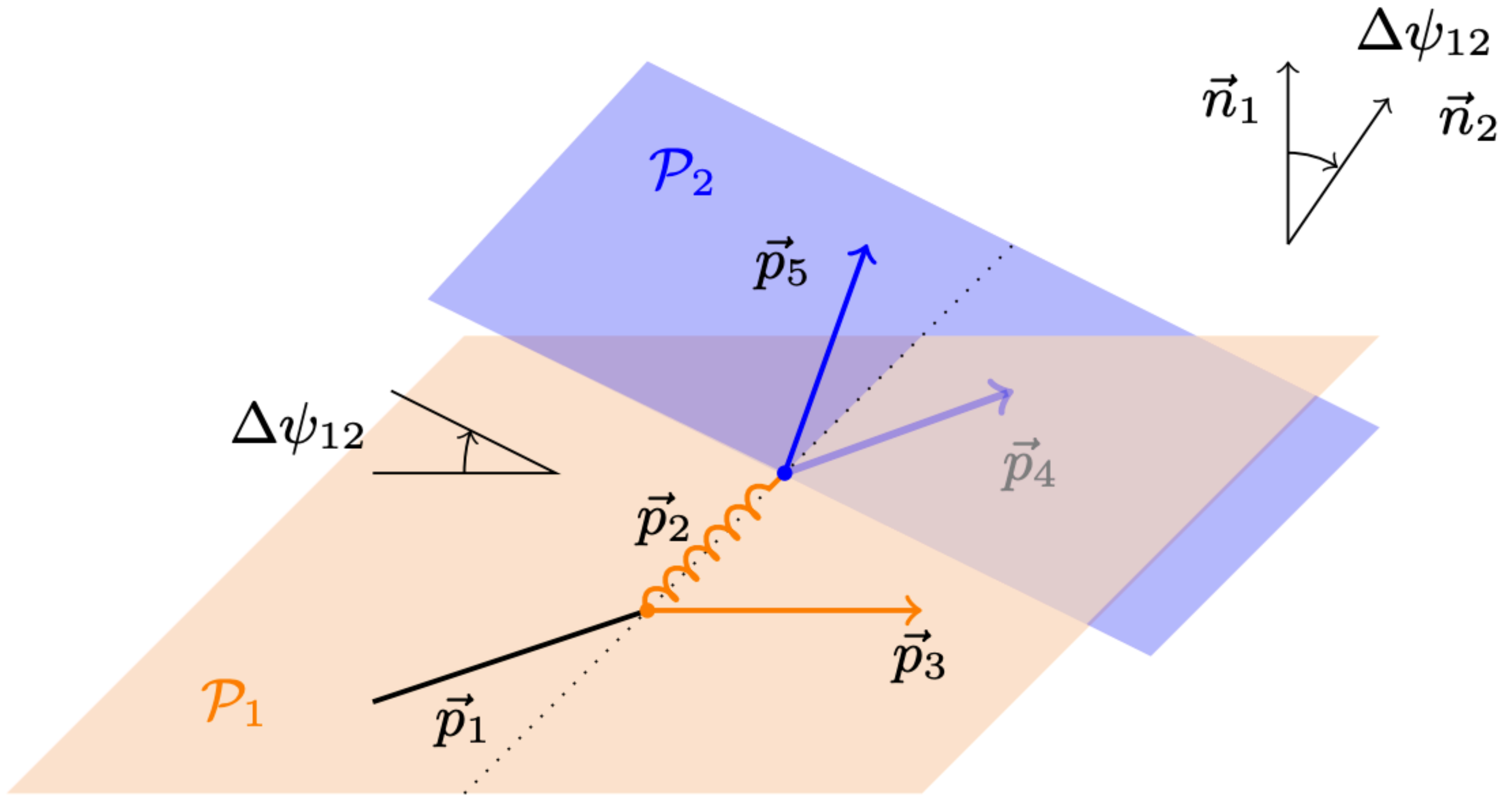
Shower azimuth $\neq$ collinear azimuth

$\longrightarrow$ Boost-invariant branching amplitudes

λ_a	λ_b	λ_c	$q\to qg$	$g\to q\bar{q}$	$g\to gg$
λ	λ	λ	$\frac{1}{\sqrt{1-z}}$	0	$\frac{1}{\sqrt{z(1-z)}}$
λ	λ	$-\lambda$	$\frac{z}{\sqrt{1-z}}$	$-z$	$\frac{z^{3/2}}{\sqrt{1-z}}$
λ	$-\lambda$	λ	0	$1-z$	$\frac{(1-z)^{3/2}}{\sqrt{z}}$
λ	$-\lambda$	$-\lambda$	0	0	0

$$\mathcal{M}_{a\to bc}^{\lambda_a\lambda_b\lambda_c} = \frac{1}{\sqrt{2}}\frac{g_s}{p_b\cdot p_c}\mathcal{F}_{a\to bc}^{\lambda_a\lambda_b\lambda_c}(z)S_\tau(p_b,p_c) \longrightarrow$$ Spinor products

Observables: $\Delta\psi_{12}$

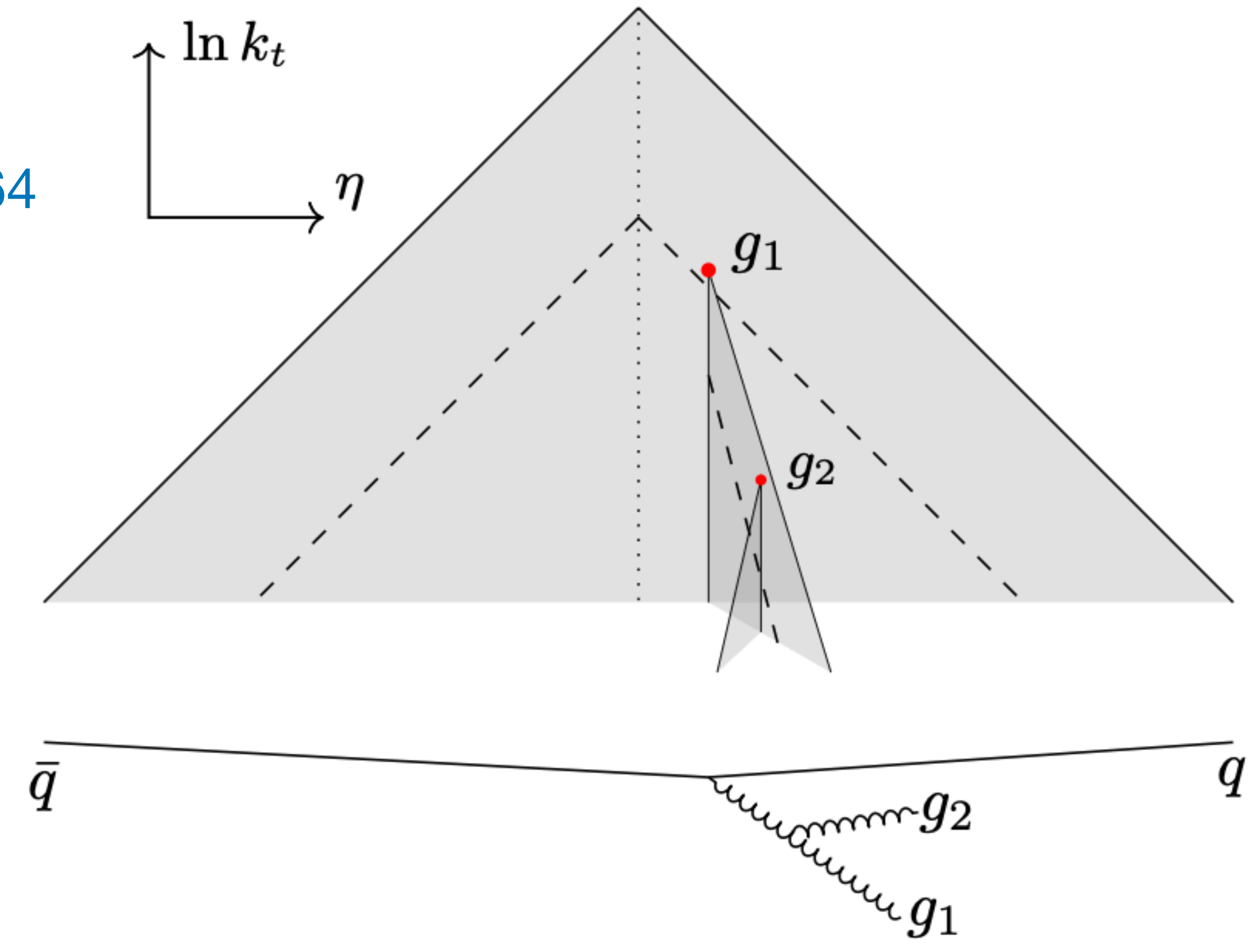


Fixed order:
Angle between the planes of two subsequent branchings

All orders: Lund plane declustering

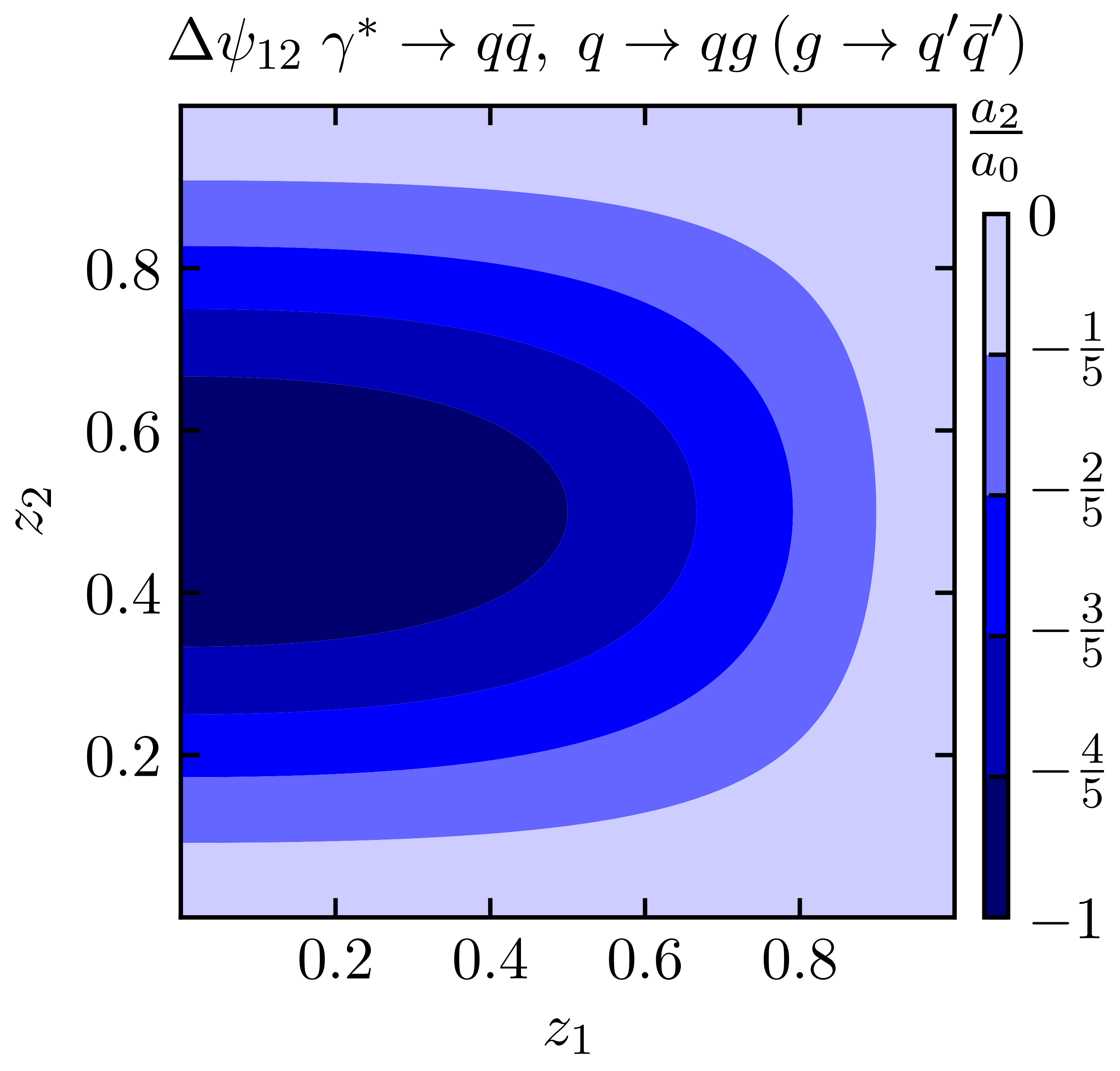
Dreyer, Salam, Soyez JHEP 12 (2018) 064

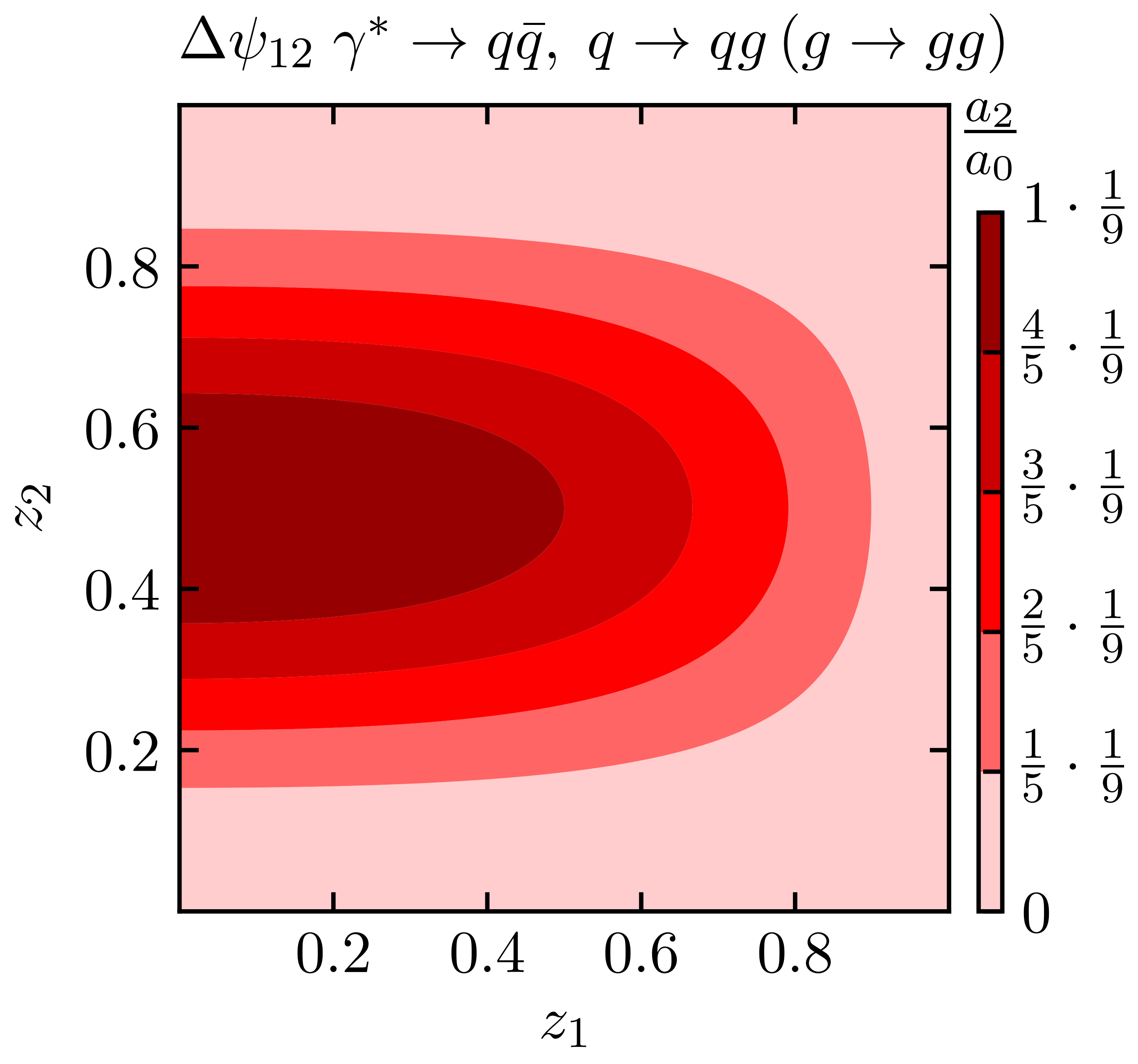
- Decluster with C/A
- Find highest-k_t branching with $z_1 \geq z_{\rm cut}$
- Follow softest branch
- Find highest-k_t branching with $z_2 \geq z_{\rm cut}$
- Compute angle $\Delta\psi_{12}$ between two branching planes



$\Delta\psi_{12}$ at Fixed-order

$$\frac{d\sigma}{d\Delta\psi_{12}} \propto a_0 \left(1 + \frac{a_2}{a_0}\cos(2\Delta\Psi_{12})\right) \propto \alpha_s^2 L^2$$



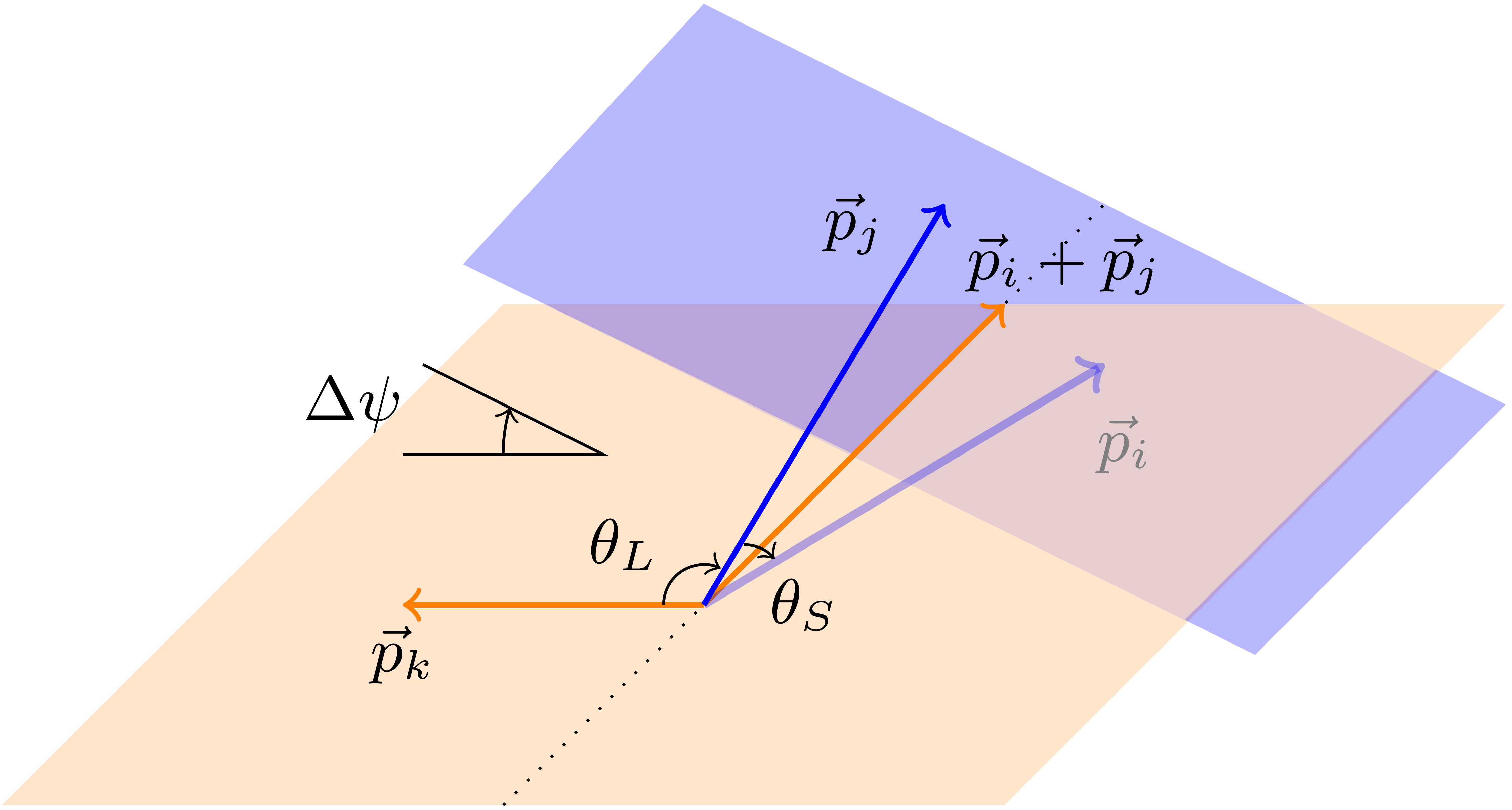


- Large cancellations between channels
- Peaks for soft intermediate gluons, balanced second branching

Observables: EEEC

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

$\longrightarrow$ Talk by Hua Xing



Energy weight removes soft contributions

Opening angles

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

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

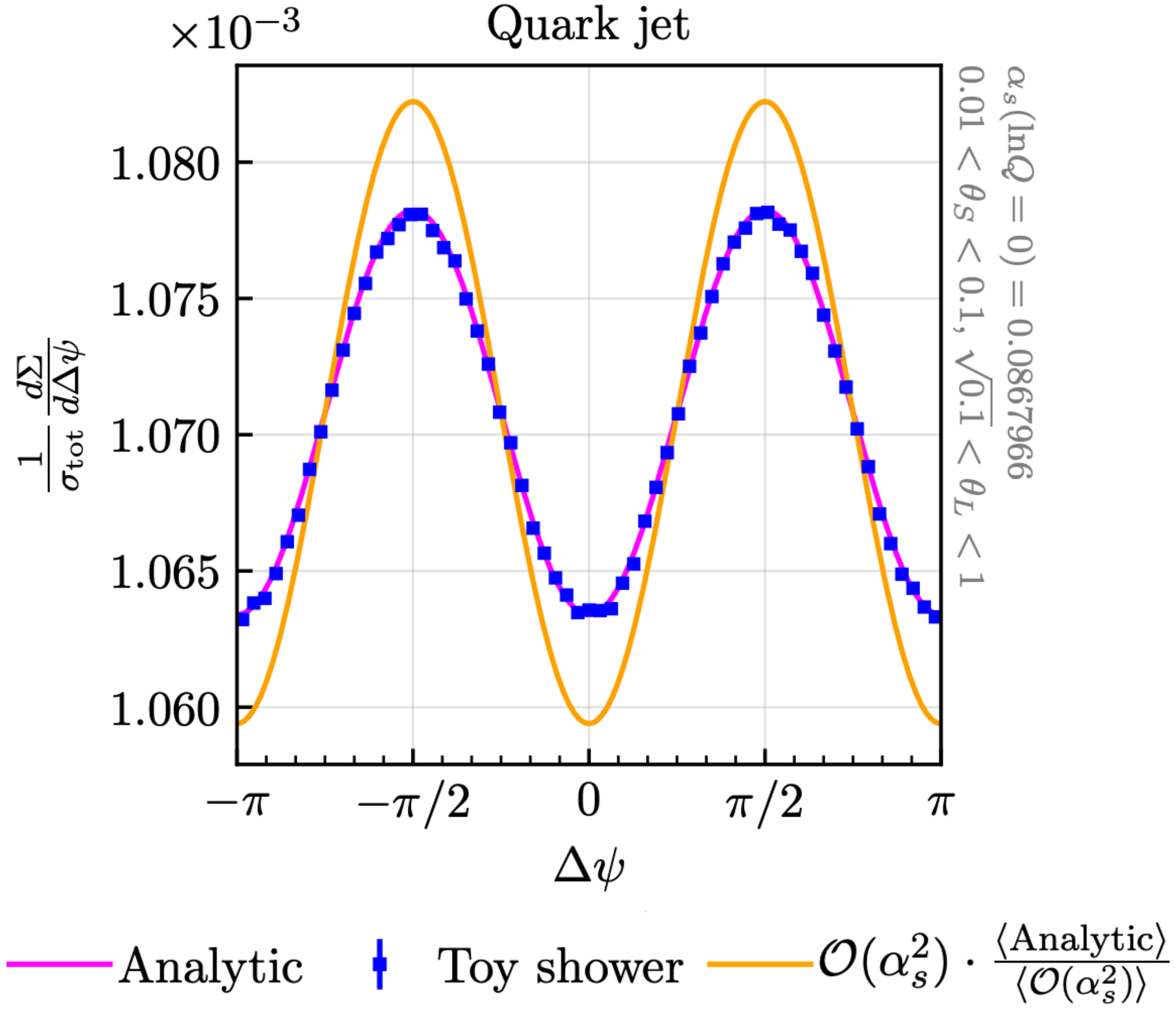
Effects of Resummation

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

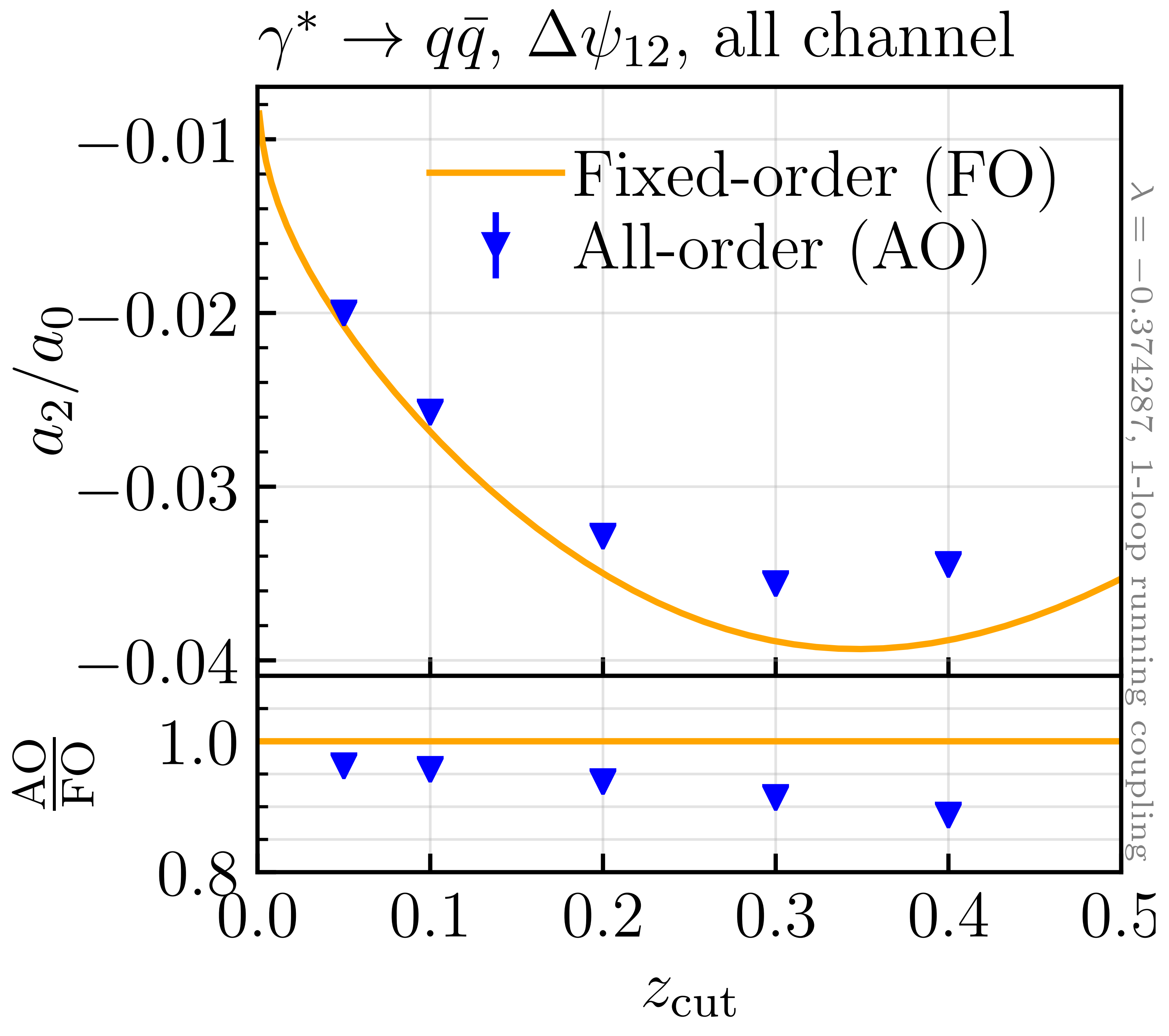
Dasgupta, Dreyer, Salam, Soyez JHEP 04 (2015)

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

EEEC

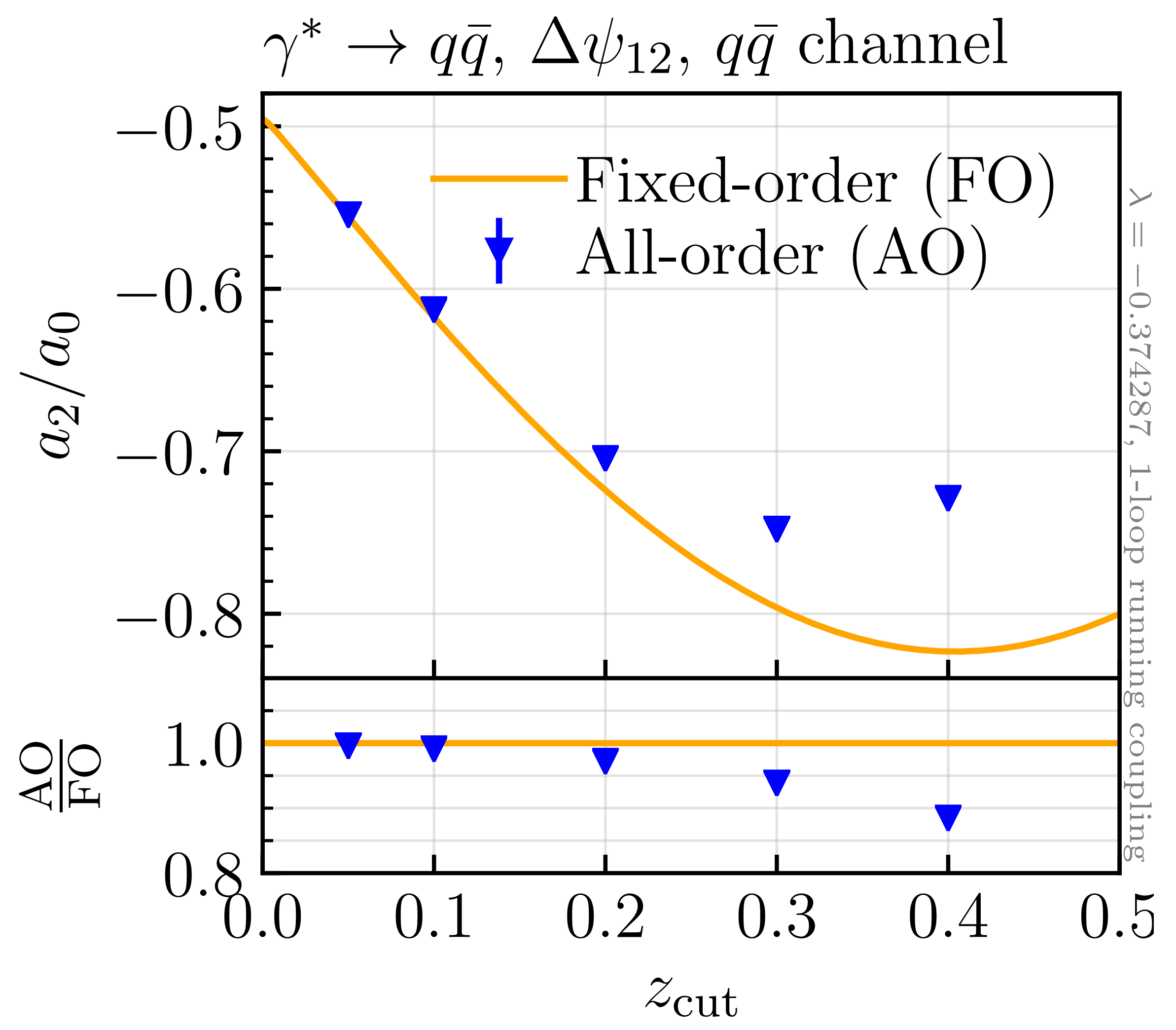


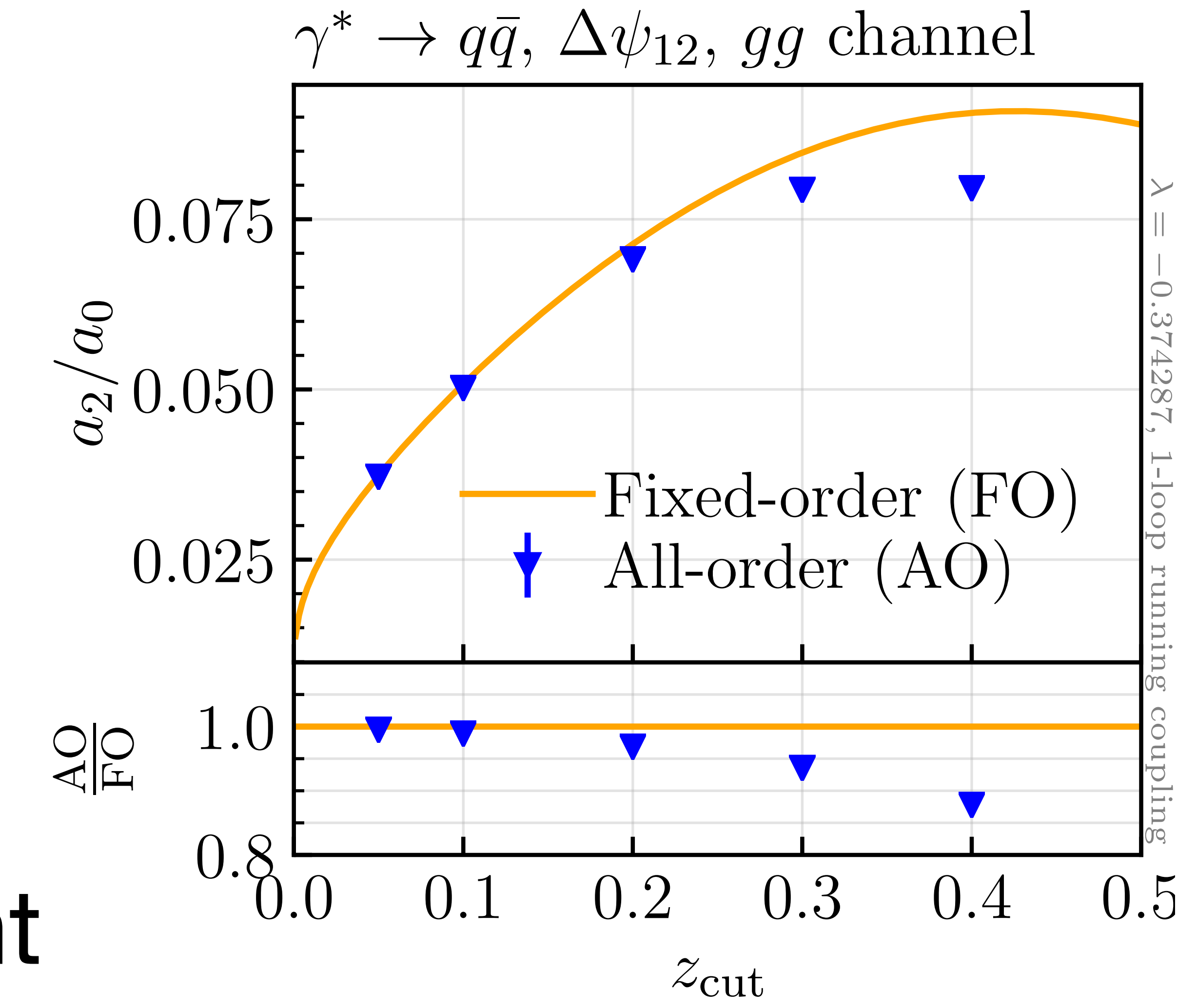
$\Delta\Psi_{12}$



$\longrightarrow$ Radiation dilutes spin content

Per channel





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

PanScales Showers vs. Toy Shower

Testing NLL accuracy of a full-fledged shower

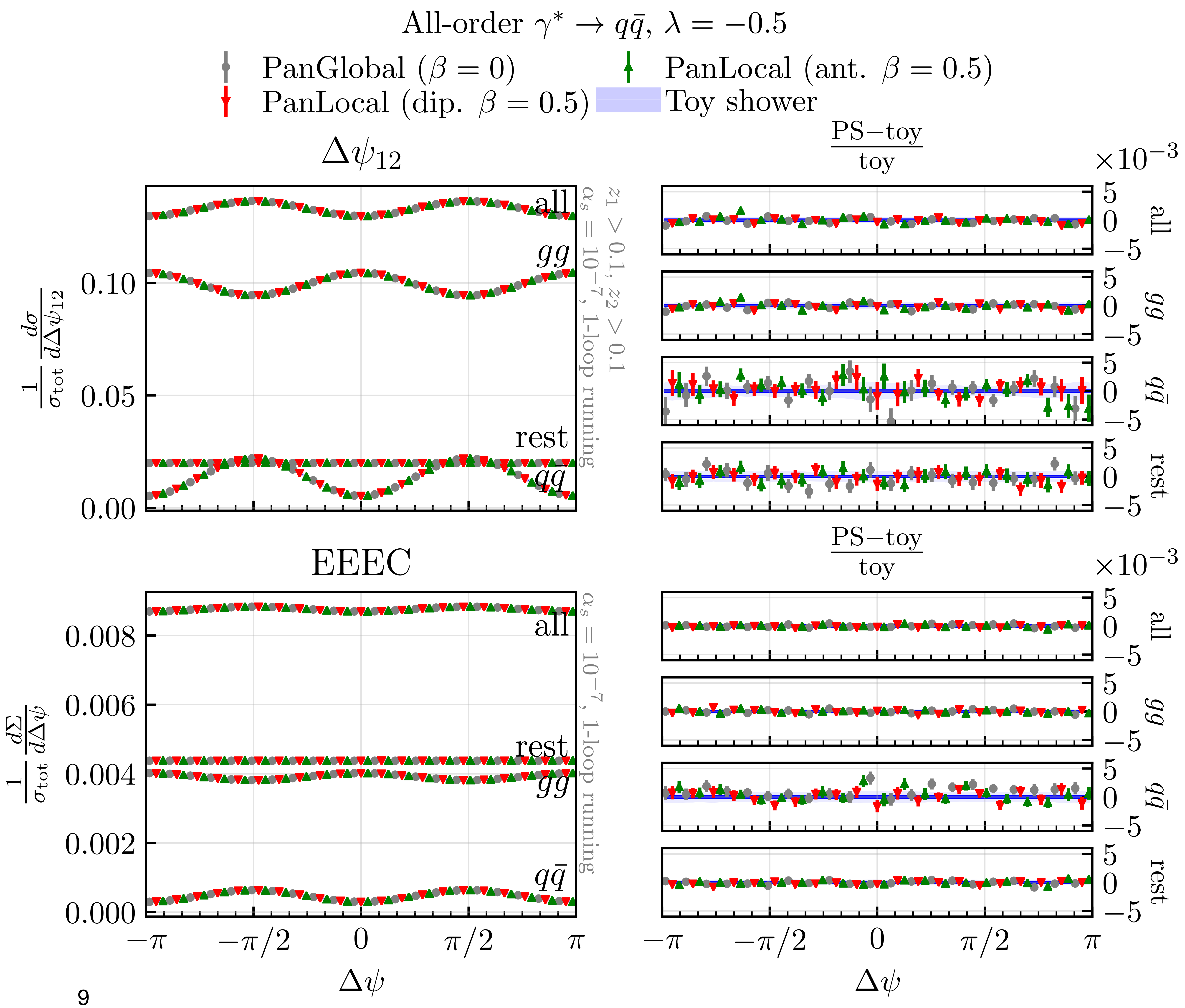
$$\frac{d\sigma}{d\psi} \propto \exp\left[\alpha_s^{-1} g_1(\alpha_s L) + g_2(\alpha_s L) + \mathcal{O}(\alpha_s^n L^{n-1})\right]$$

LL NLL Higher order

Isolate NLL by taking the $\alpha_s \to 0$ limit

at fixed $\lambda \equiv \alpha_s L$

$$\boxed{\begin{aligned} \alpha_s &= 10^{-7} \\ L &= -5 \cdot 10^6 \\ \lambda \equiv \alpha_s L &= -0.5 \\ z_{\text{cut}} &= 0.1 \end{aligned}}$$



Phenomenological Considerations

$\lambda = 0.5$		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

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

  $\longrightarrow$ Easier to observe experimentally
- Modulations may be enhanced further by adjusting the value of z_{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

$\longrightarrow$ Requires a comprehensive phenomenological study

Spin in the Soft Limit (preliminary)

The Collins-Knowles algorithm was originally designed collinear branchings only
$\longrightarrow$ Spin correlations also appear in the soft limit

Solution: correct the branching amplitudes to also be accurate in the soft limit

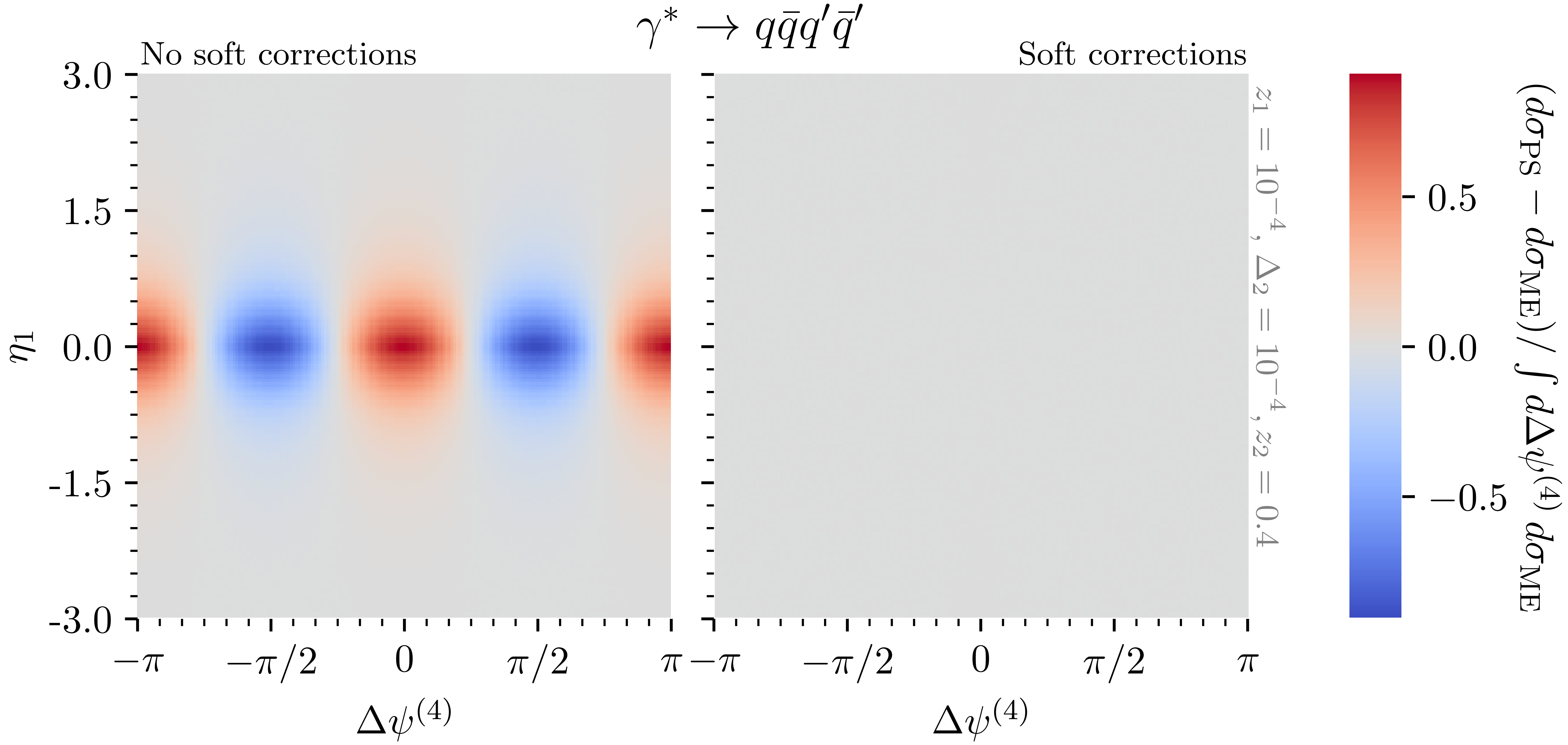
$$q \to qg: \quad \mathcal{M}^{\lambda,\lambda,\lambda}_{\tilde{i}\to ik} = \frac{g_s}{\sqrt{2}}\frac{1}{\sqrt{z}}\frac{S_{-\lambda}(p_i,p_j)}{S_{-\lambda}(p_i,p_k)S_{-\lambda}(p_j,p_k)}$$

$$\mathcal{M}^{\lambda,\lambda,-\lambda}_{\tilde{i}\to ik} = \frac{g_s}{\sqrt{2}}\sqrt{z}\frac{S_{\lambda}(p_i,p_j)}{S_{\lambda}(p_i,p_k)S_{\lambda}(p_j,p_k)},$$

$$\mathcal{M}^{\lambda,\lambda,\lambda}_{\tilde{i}\to ik} = \frac{g_s}{\sqrt{2}}\frac{1}{z}\frac{S_{-\lambda}(p_i,p_j)}{S_{-\lambda}(p_i,p_k)S_{-\lambda}(p_j,p_k)}$$

$$g \to gg: \quad \mathcal{M}^{\lambda,\lambda,-\lambda}_{\tilde{i}\to ik} = \frac{g_s}{\sqrt{2}}z\frac{S_{\lambda}(p_i,p_j)}{S_{\lambda}(p_i,p_k)S_{\lambda}(p_j,p_k)}$$

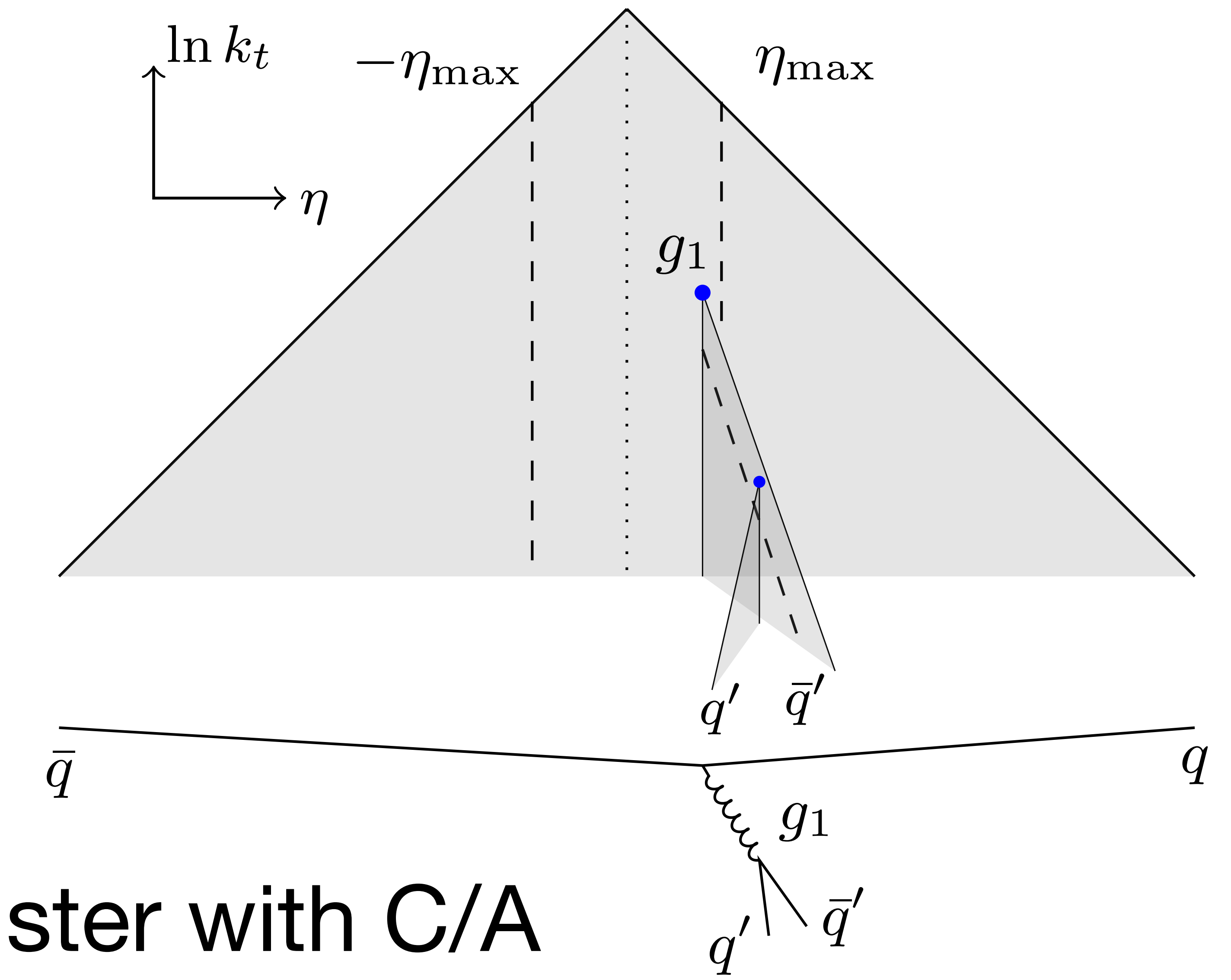
$$\mathcal{M}^{\lambda,-\lambda,\lambda}_{\tilde{i}\to ik} = -\frac{g_s}{\sqrt{2}}\frac{(1-z)^{3/2}}{\sqrt{z}}\frac{1}{S_{\lambda}(p_i,p_k)},$$



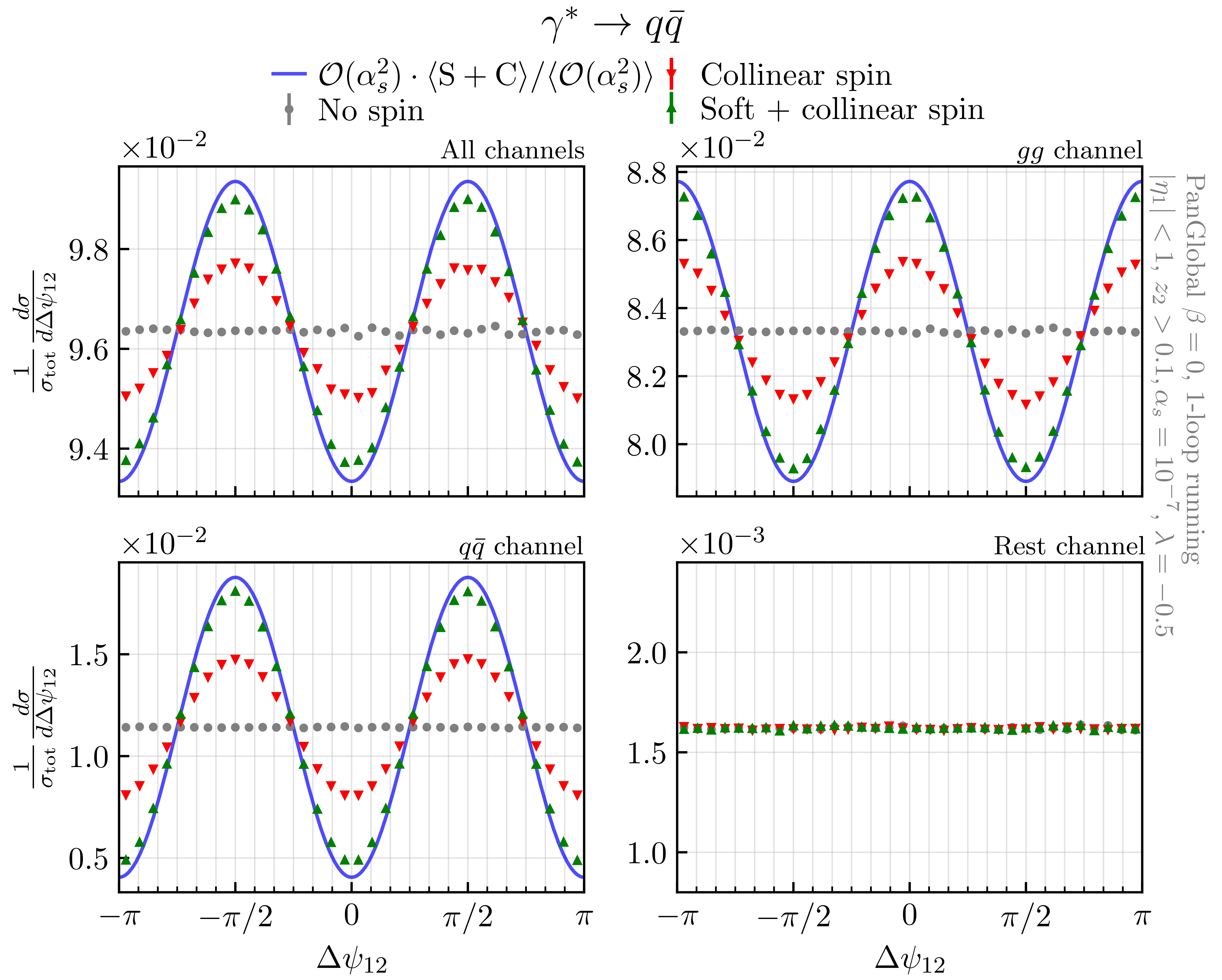
Observables: $\Delta\psi_{12}^{\text{slice}}$ (preliminary)

Currently no known resummed observables sensitive to soft spin effects

$\longrightarrow$ Adapt $\Delta\psi_{12}$



- Decluster with C/A
- Find highest-k_t branching with soft branch with $|\eta| < \eta_{\max}$ and hard branch with $|\eta| > \eta_{\max}$
- Follow softest branch
- Find highest-k_t branching with $z_2 \geq z_{\text{cut}}$
- Compute angle $\Delta\psi_{12}^{\text{slice}}$ between two branching planes



Conclusions

- Implementation of Collins-Knowles in PanScales showers
- New jet-substructure observables sensitive to spin interference effects
- Validate (collinear) NLL resummation within the PanScales showers
- More detailed phenomenological study required

  $\rightarrow$ Subleading effects, parametric sensitivity, etc…

Backup

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

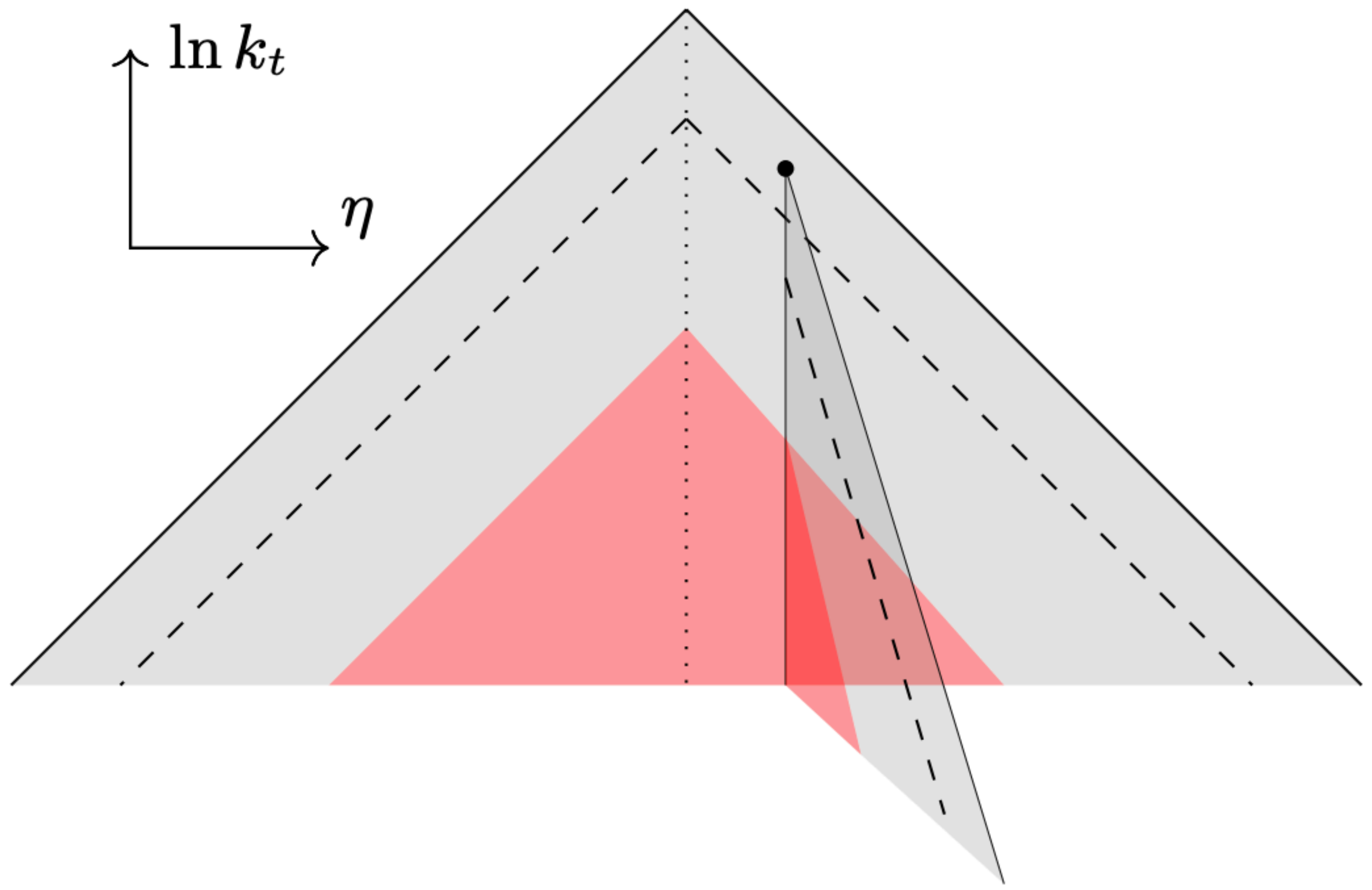
- Dedicated double_exp floating-point type

  $\longrightarrow$ Allows for larger exponent in a double

- Remove soft radiation

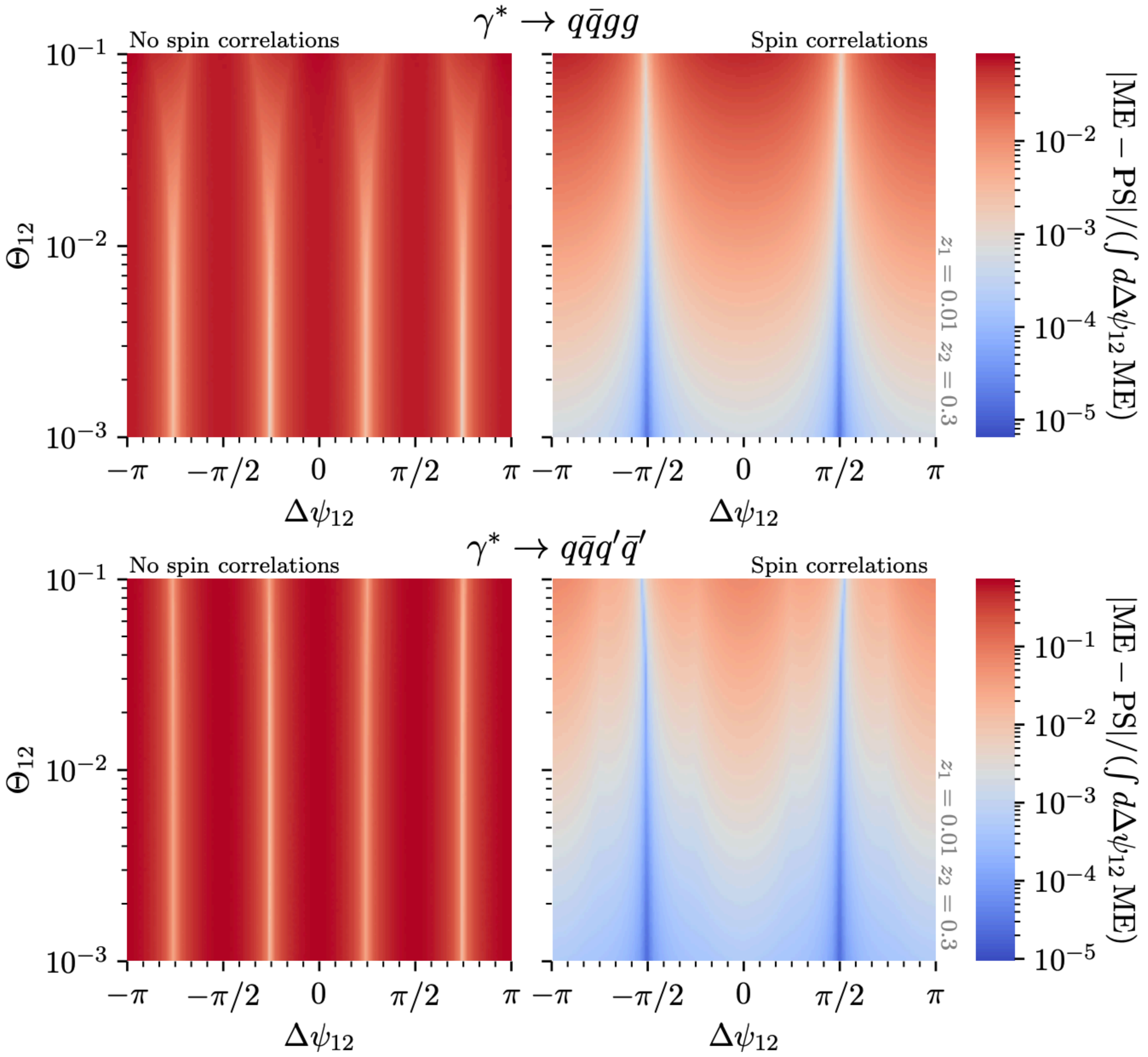
  $\longrightarrow$ Avoids multiplicity exploding

  $\longrightarrow$ Thoroughly tested to not alter observable



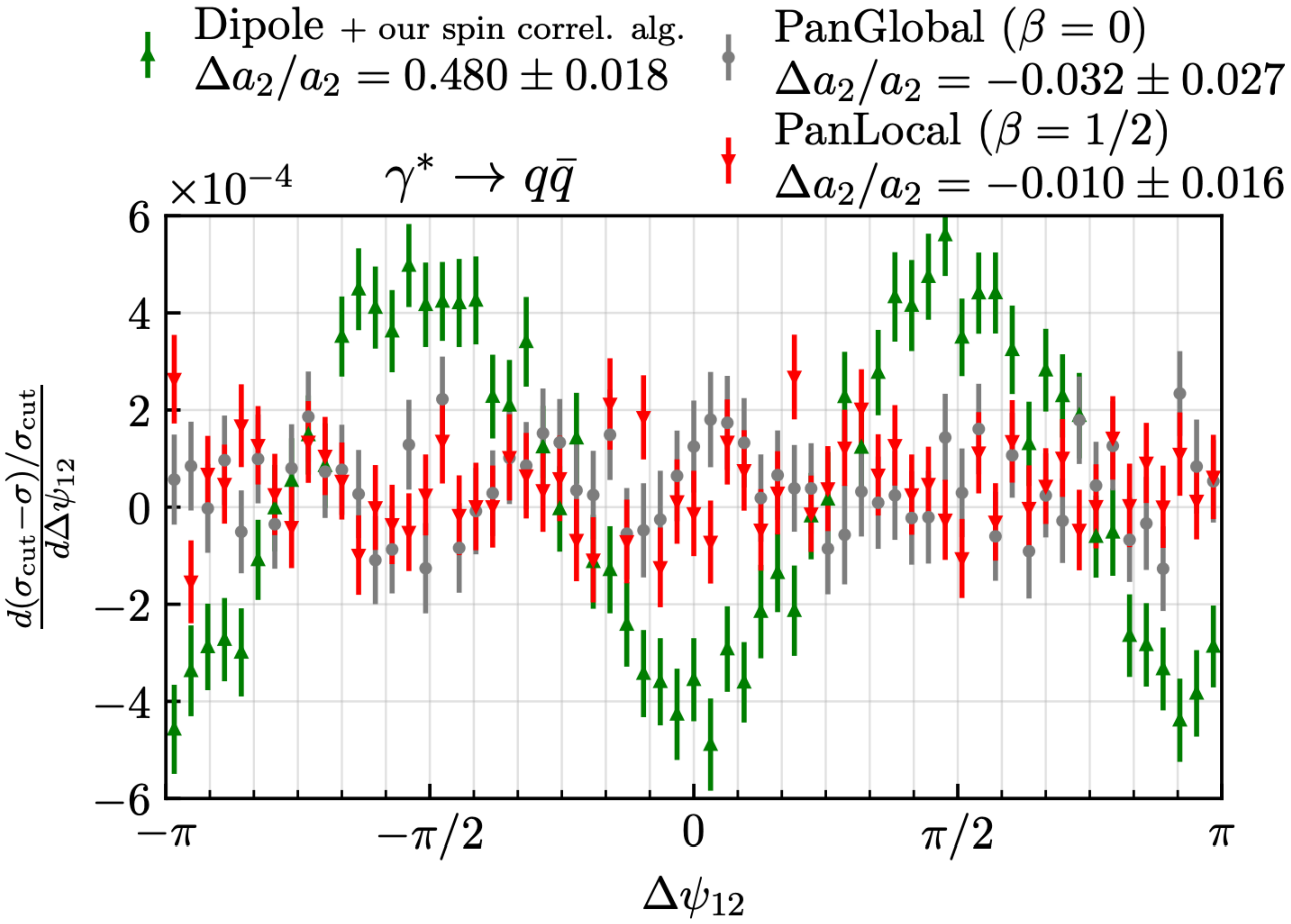
Matrix Element Comparison

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



Removing Soft Radiation

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



Rotational Invariance of Spinor Products