Spin correlations in parton showers and jet observables

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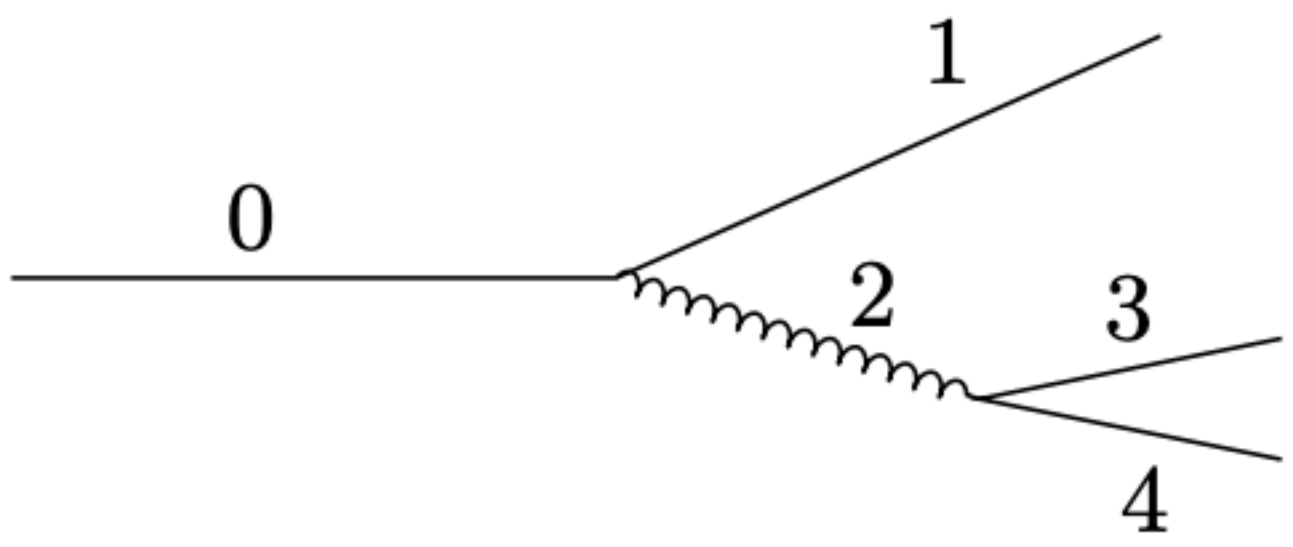
Collinear Spin Correlations in Jets

Jet modelling through parton showers is mostly classical

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



Collinear $\longrightarrow$

Spin interference effects

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

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

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

$$\ln(\theta_1), \ln(\theta_2) > -|L|$$
$$\ln(z_1), \ln(z_2) \sim 1$$

Spin in Monte Carlo

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

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

Talk by Stefan

↑

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

↓

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

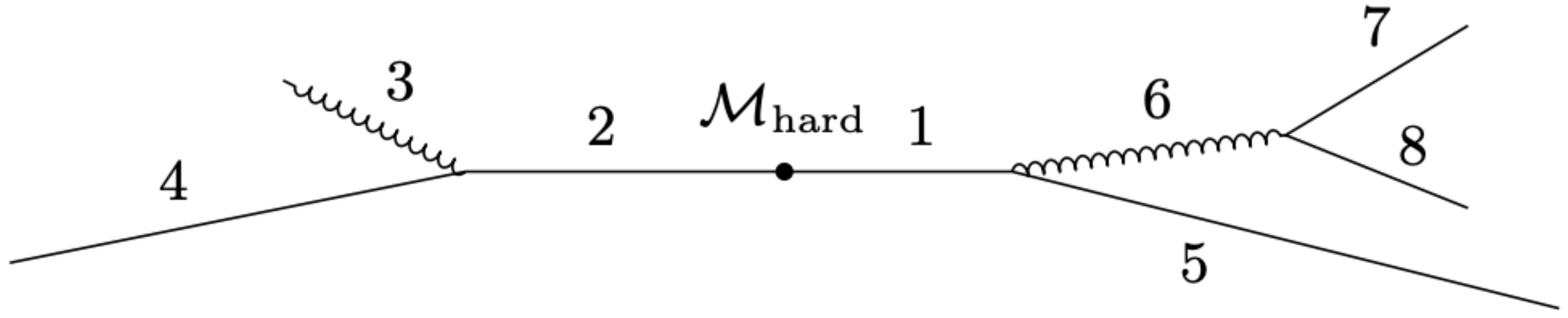
Spin in Parton Showers

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

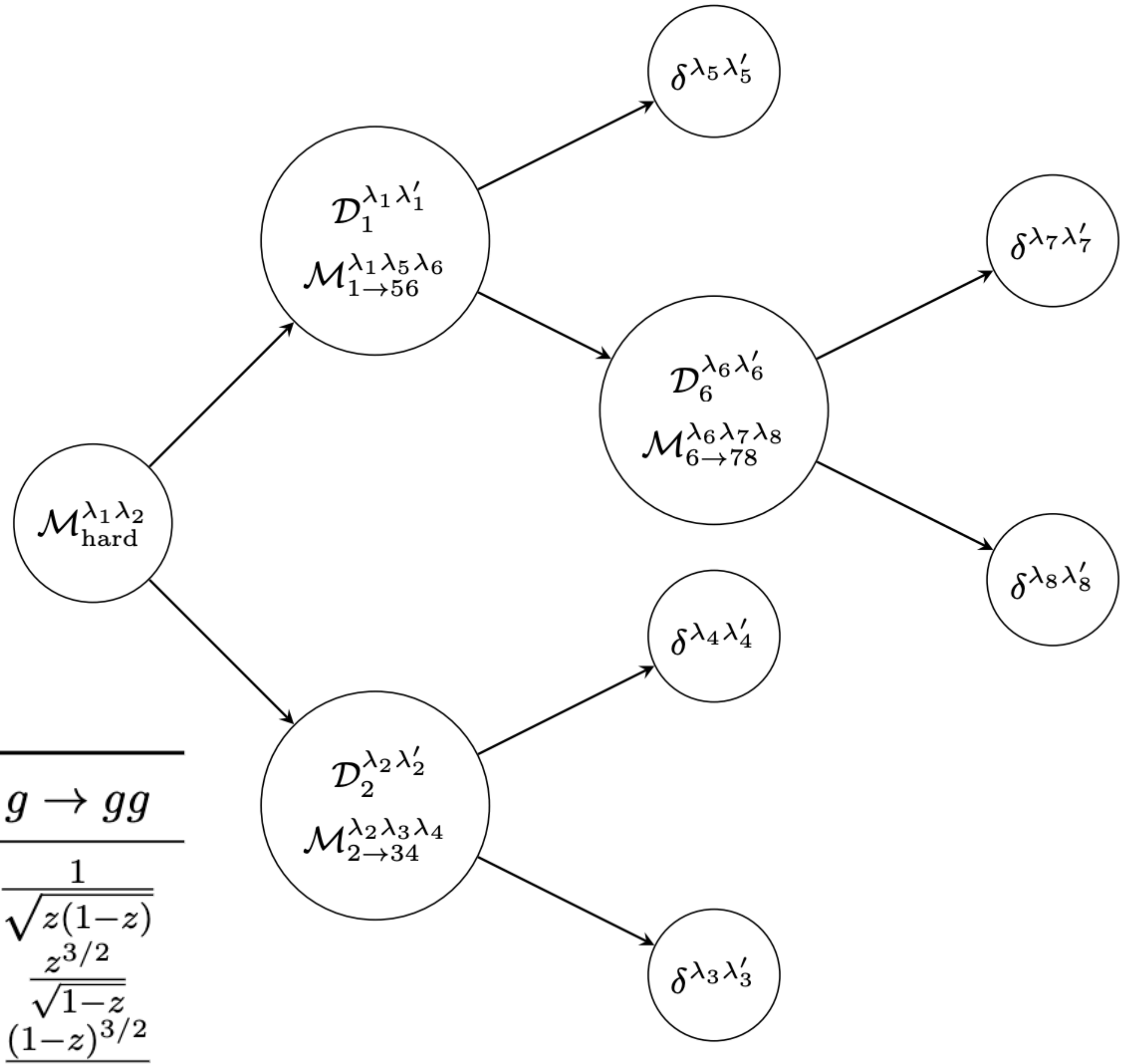
- Store the intermediate tensor with free spin indices $\longrightarrow$ 2^N indices
- Redo the whole calculation at every branching $\longrightarrow$ inefficient

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:

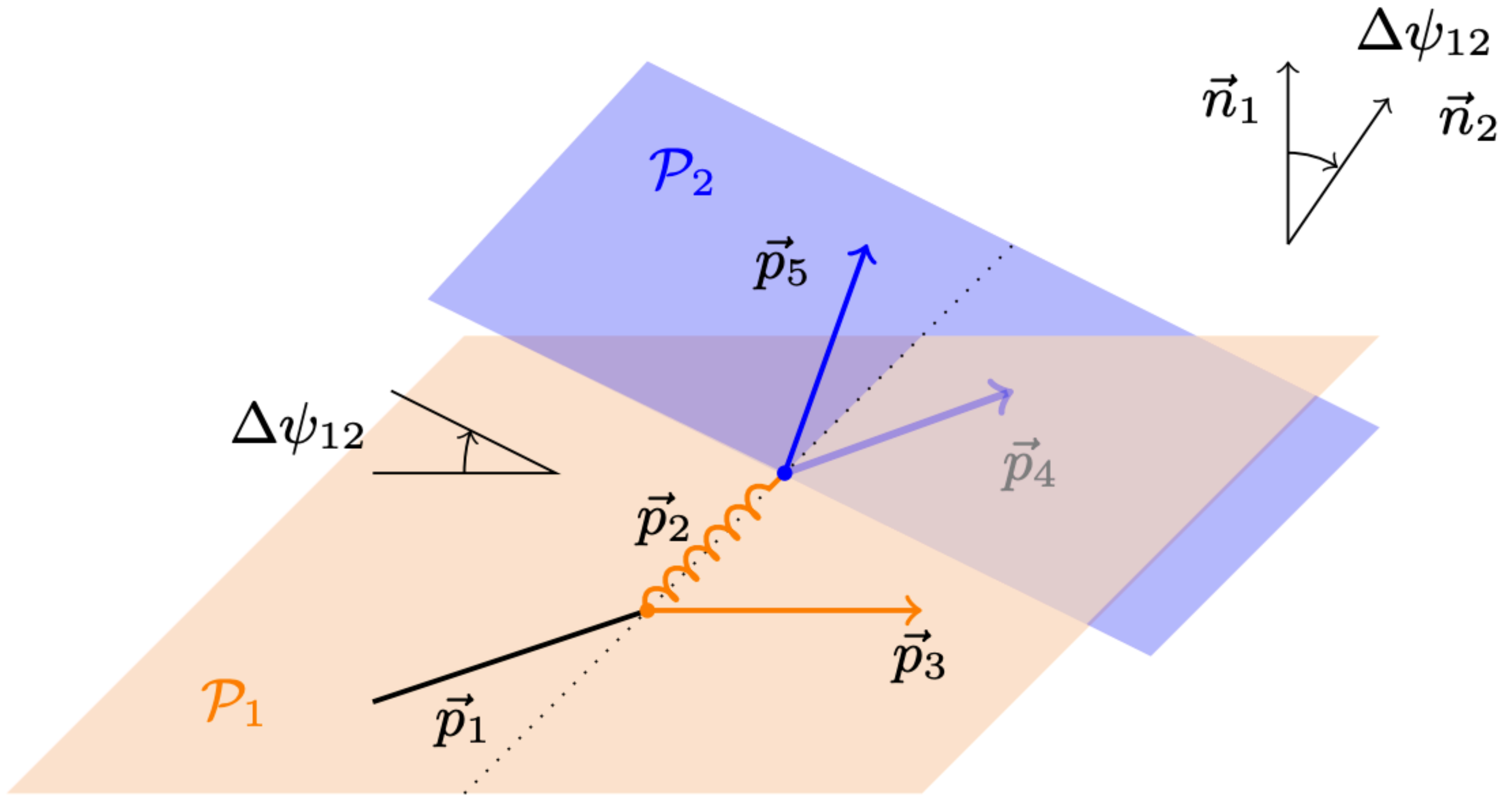
Shower azimuth $\neq$ collinear azimuth

$\longrightarrow$ 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

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

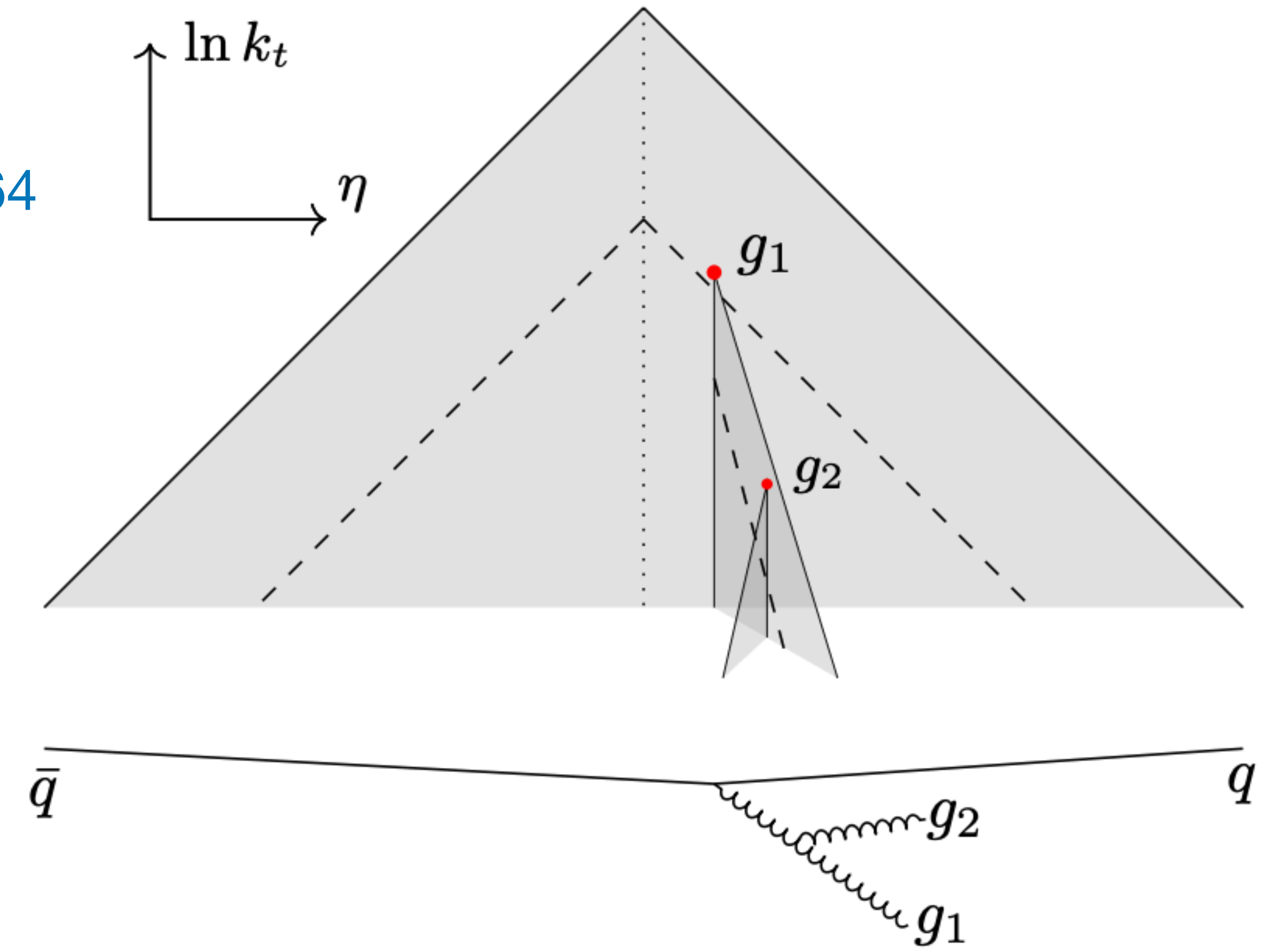
Observables: $\Delta\psi_{12}$



Fixed order:
Angle between the planes of two subsequent branchings

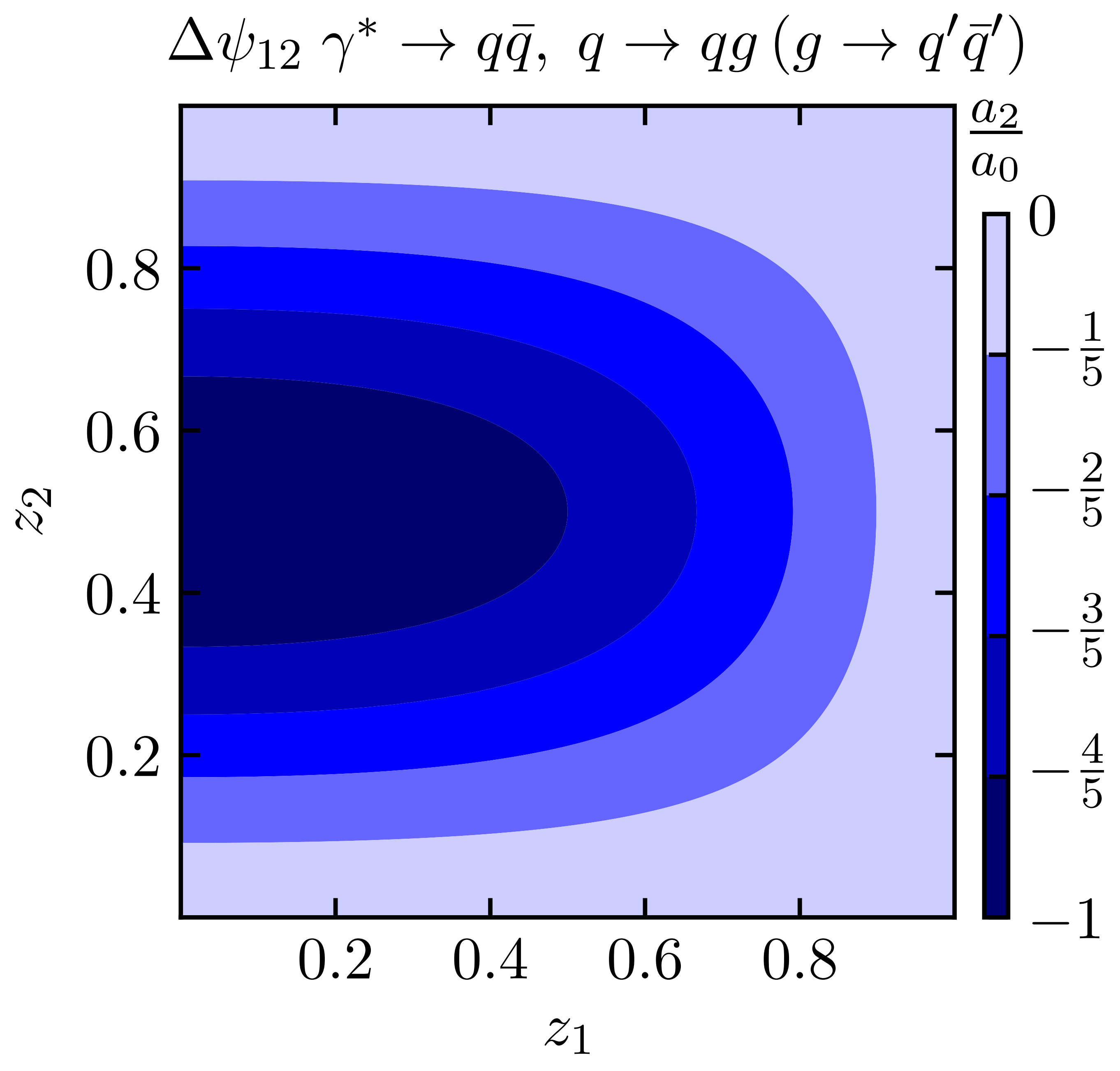
All orders: Lund plane declustering Dreyer, Salam, Soyez JHEP 12 (2018) 064

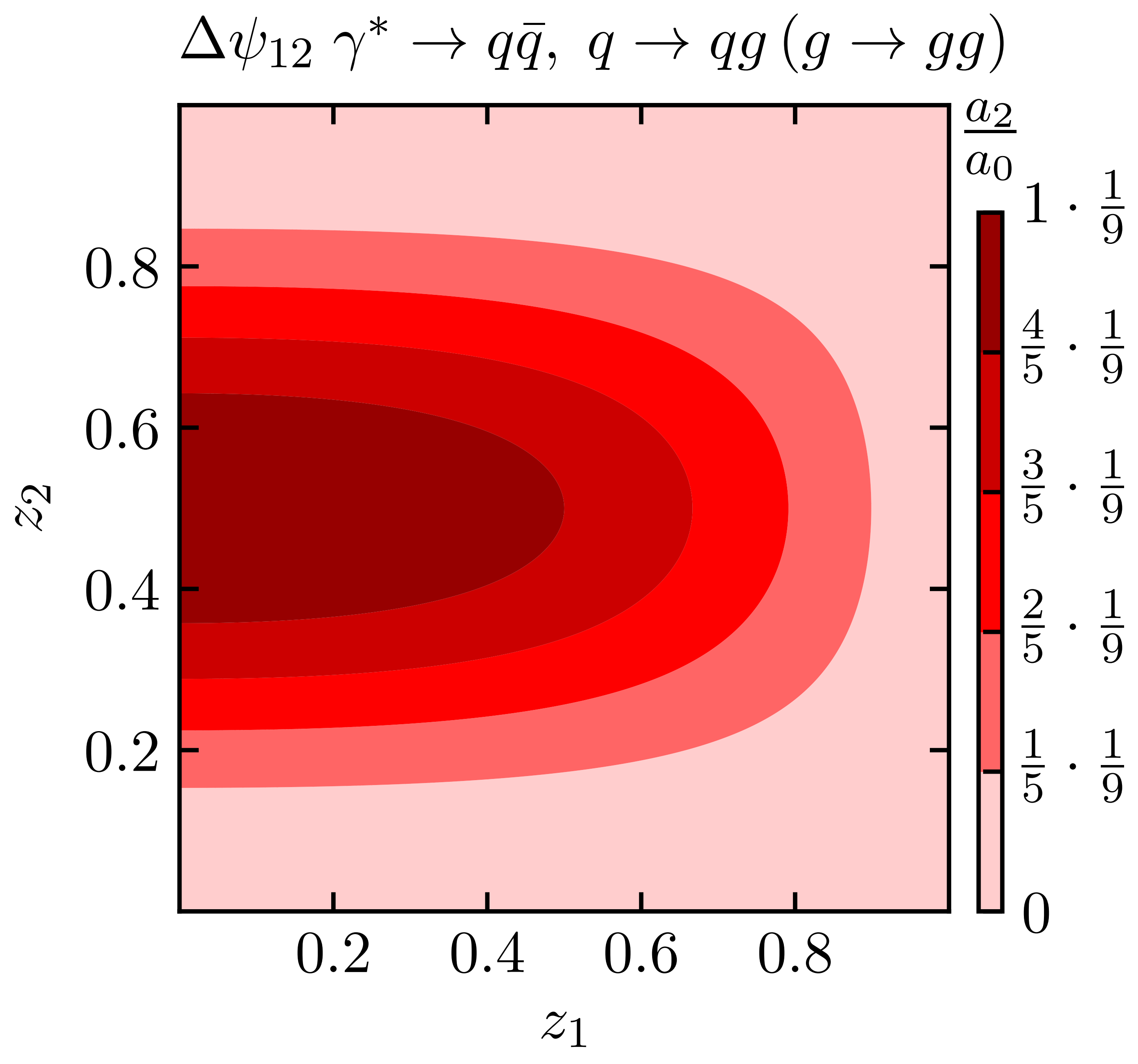
- Decluster with C/A
- Find highest-k_t branching with $z_1 \geq z_{\text{cut}}$
- Follow softest branch
- Find highest-k_t branching with $z_2 \geq z_{\text{cut}}$
- Compute angle $\Delta\psi_{12}$ between two branching planes



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

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



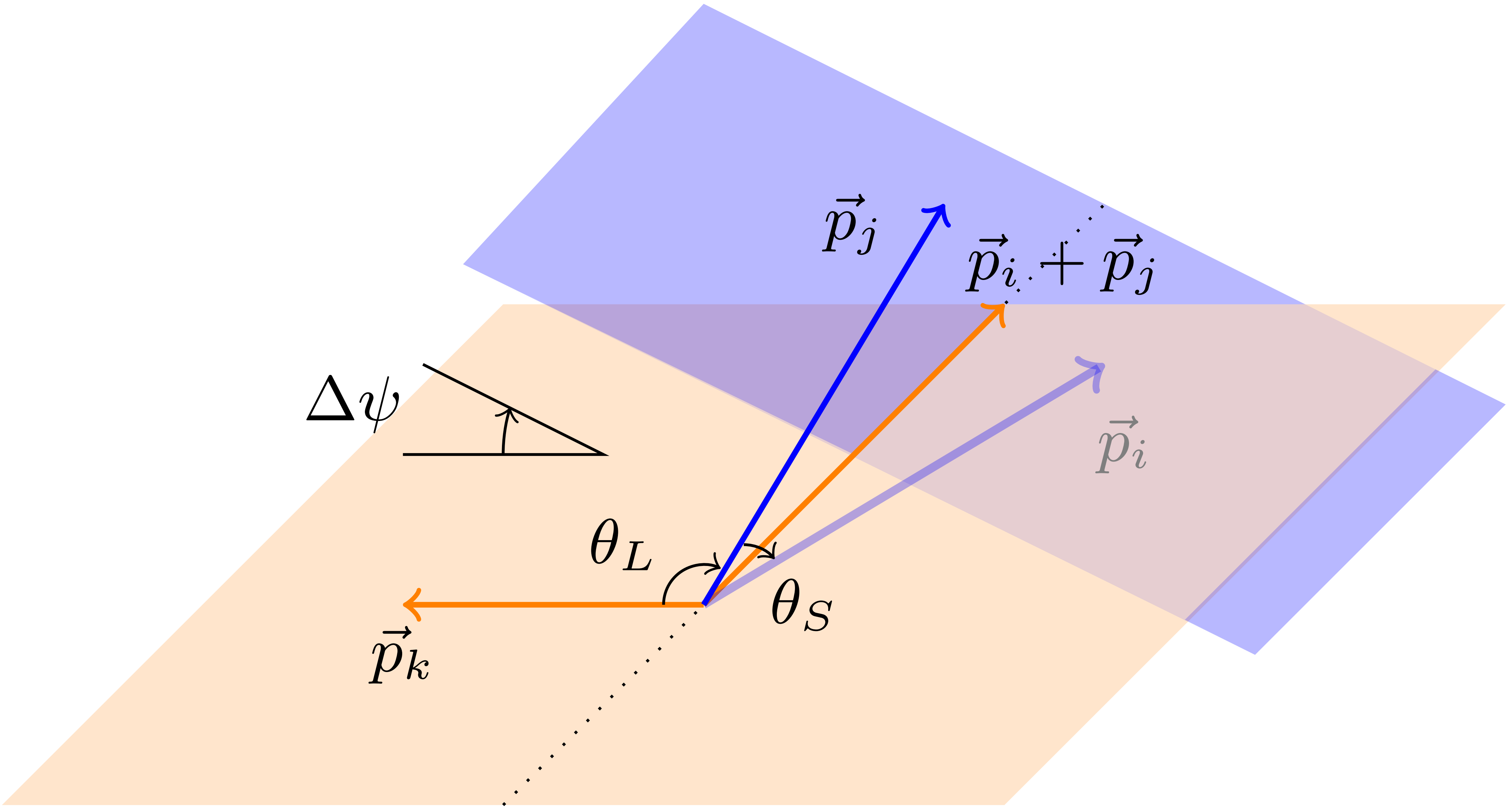


- Large cancellations between channels
- Peaks for soft intermediate gluons, balanced second branching

Observables: EEEC

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

→ Talk by Hua Xing



Energy weight removes soft contributions

Opening angles

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

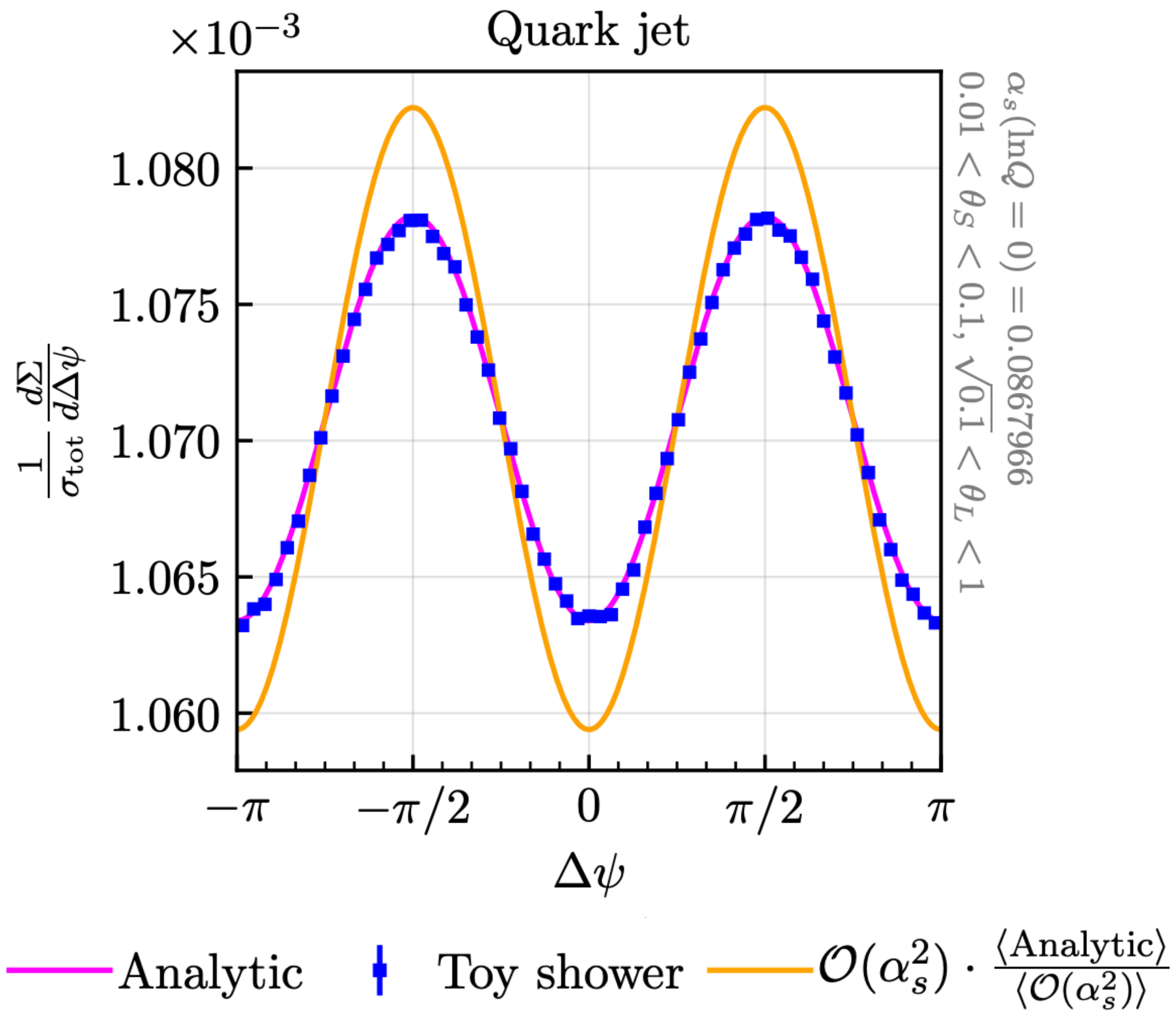
Angle between (p_i, p_j) -plane and $(p_i + p_j, p_k)$ -plane

Effects of Resummation

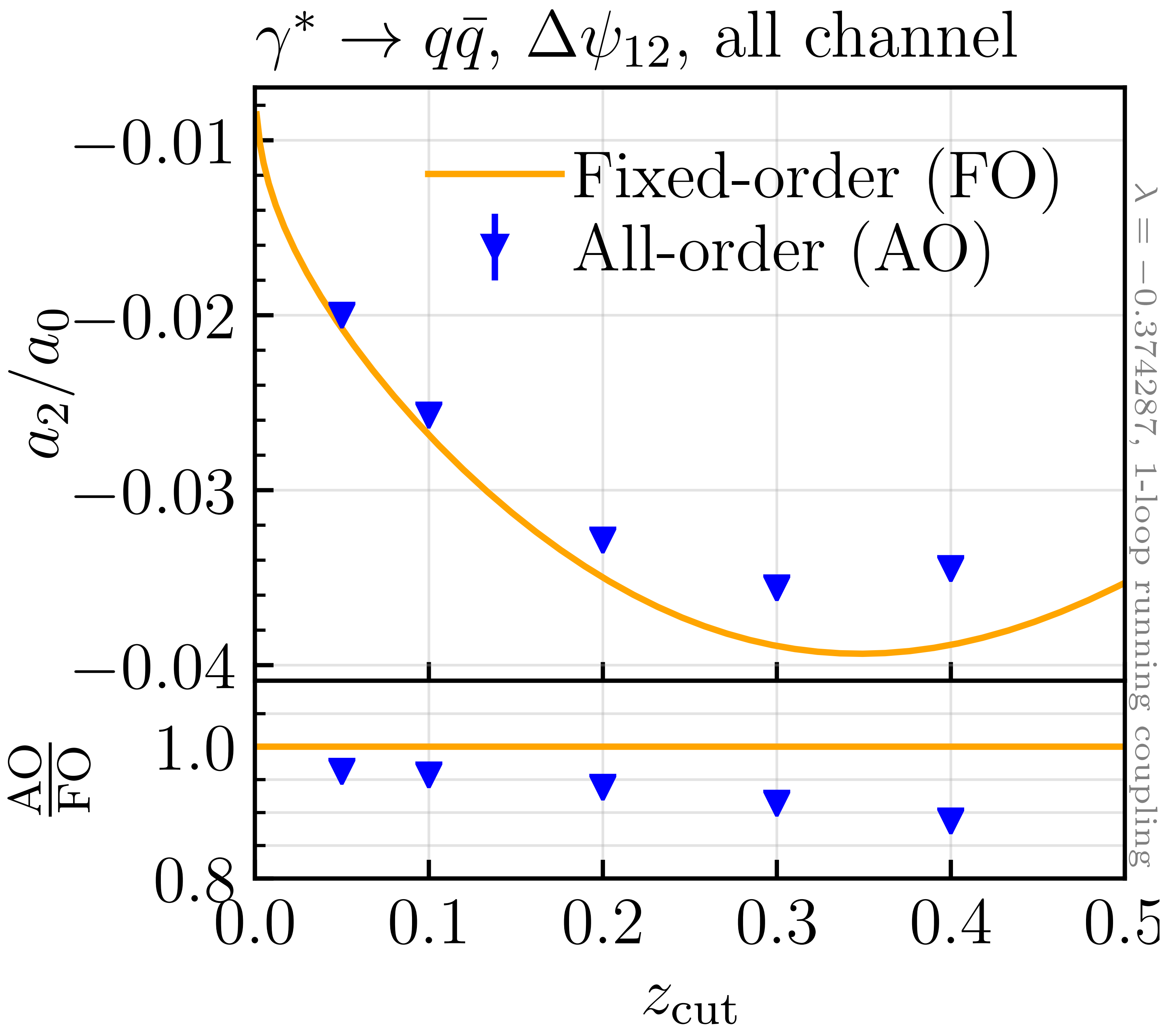
Numerical collinear resummation:
MicroJets (toy shower) + Collins-Knowles

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

EEEC

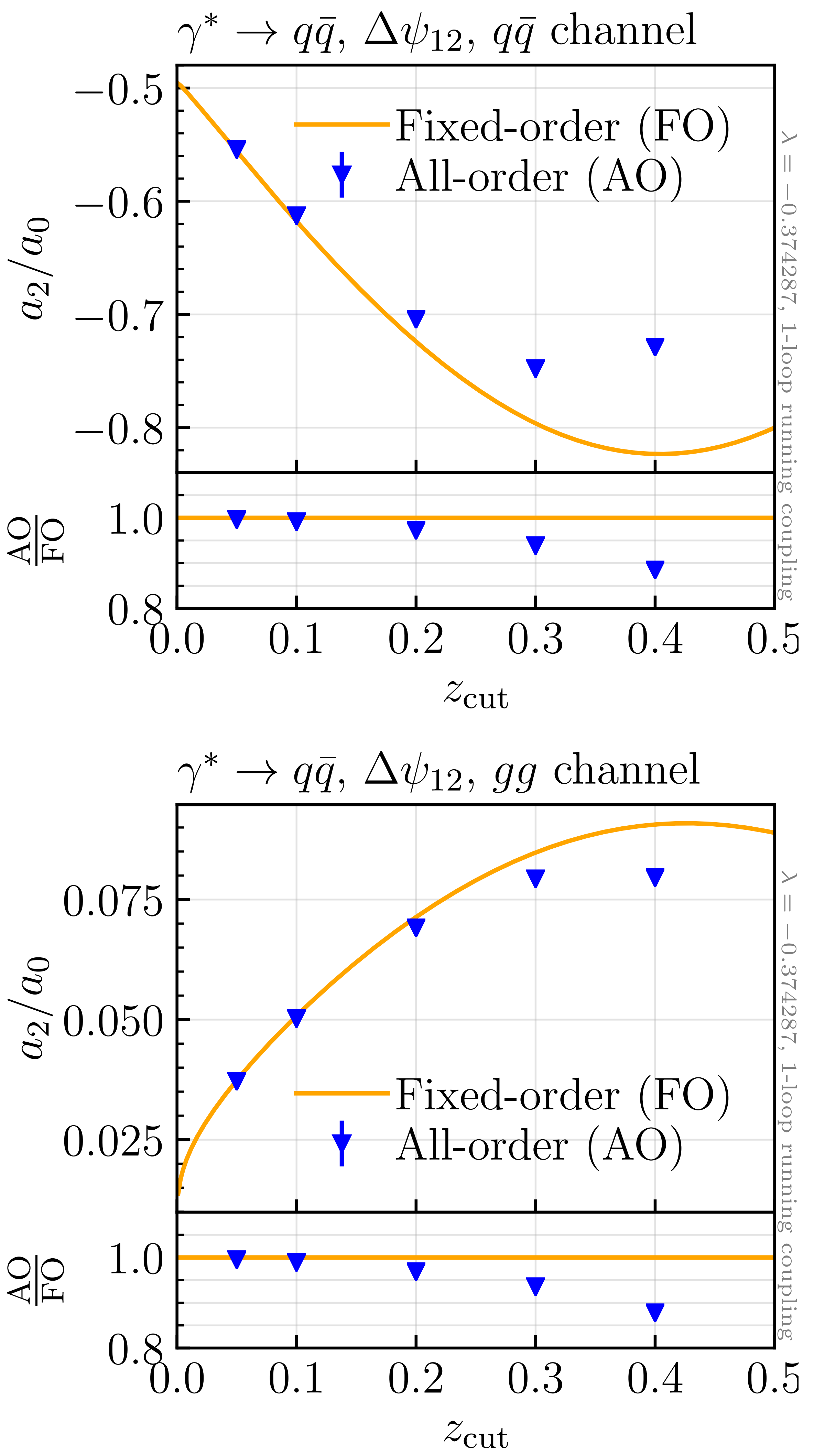


$\Delta\Psi_{12}$



→ Radiation dilutes spin content

Per channel



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

PanScales Showers vs. Toy Shower

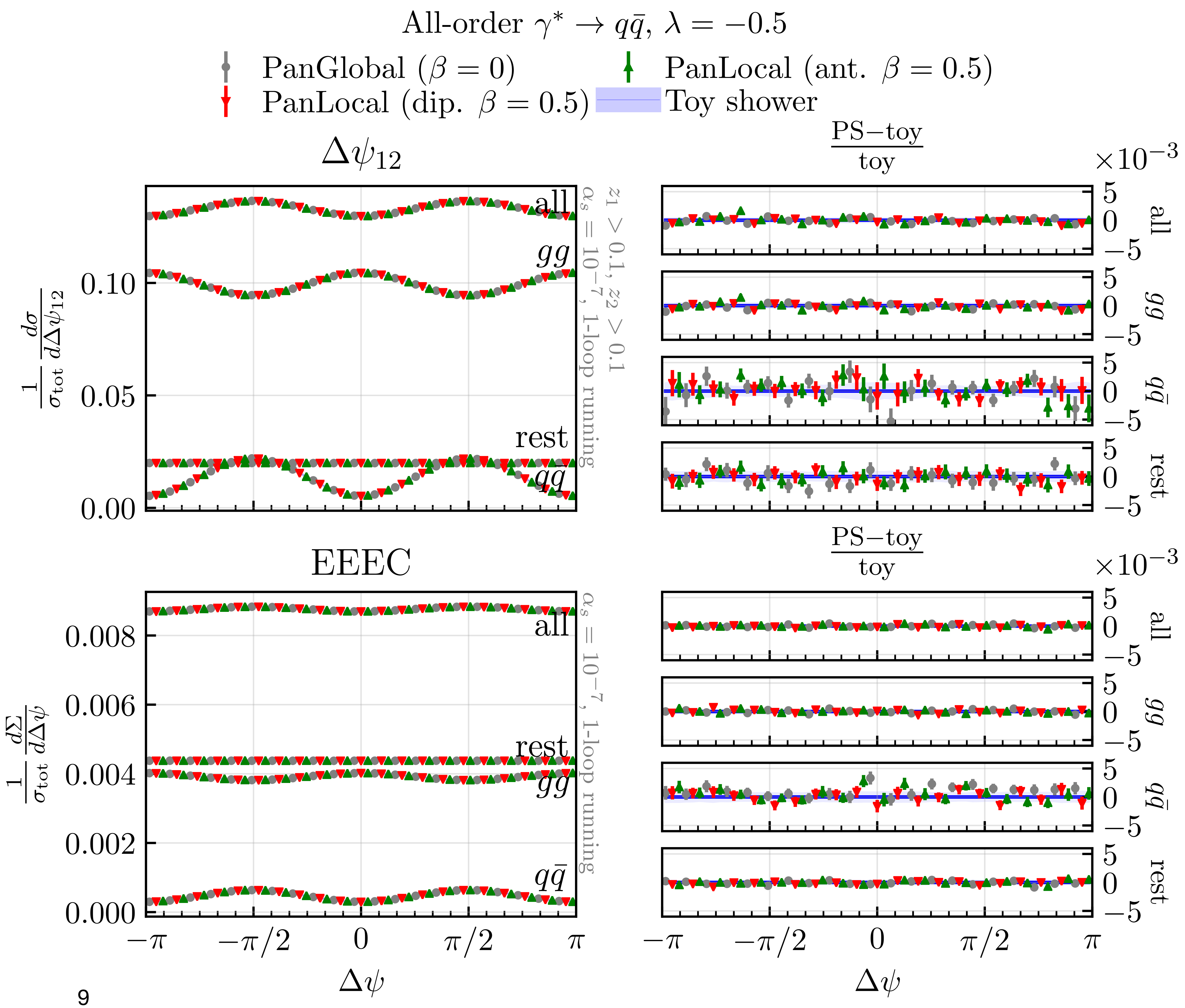
Testing NLL accuracy of a full-fledged shower

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

↓ LL ↓ NLL ↓ Higher order

Isolate NLL by taking the $\alpha_s \to 0$ limit at fixed $\lambda \equiv \alpha_s L$

$$\alpha_s = 10^{-7}$$
$$L = -5 \cdot 10^6$$
$$\lambda \equiv \alpha_s L = -0.5$$
$$z_{\rm cut} = 0.1$$



UCL

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_{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

$\lambda = 0.5$	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

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

$q \to qg:$

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

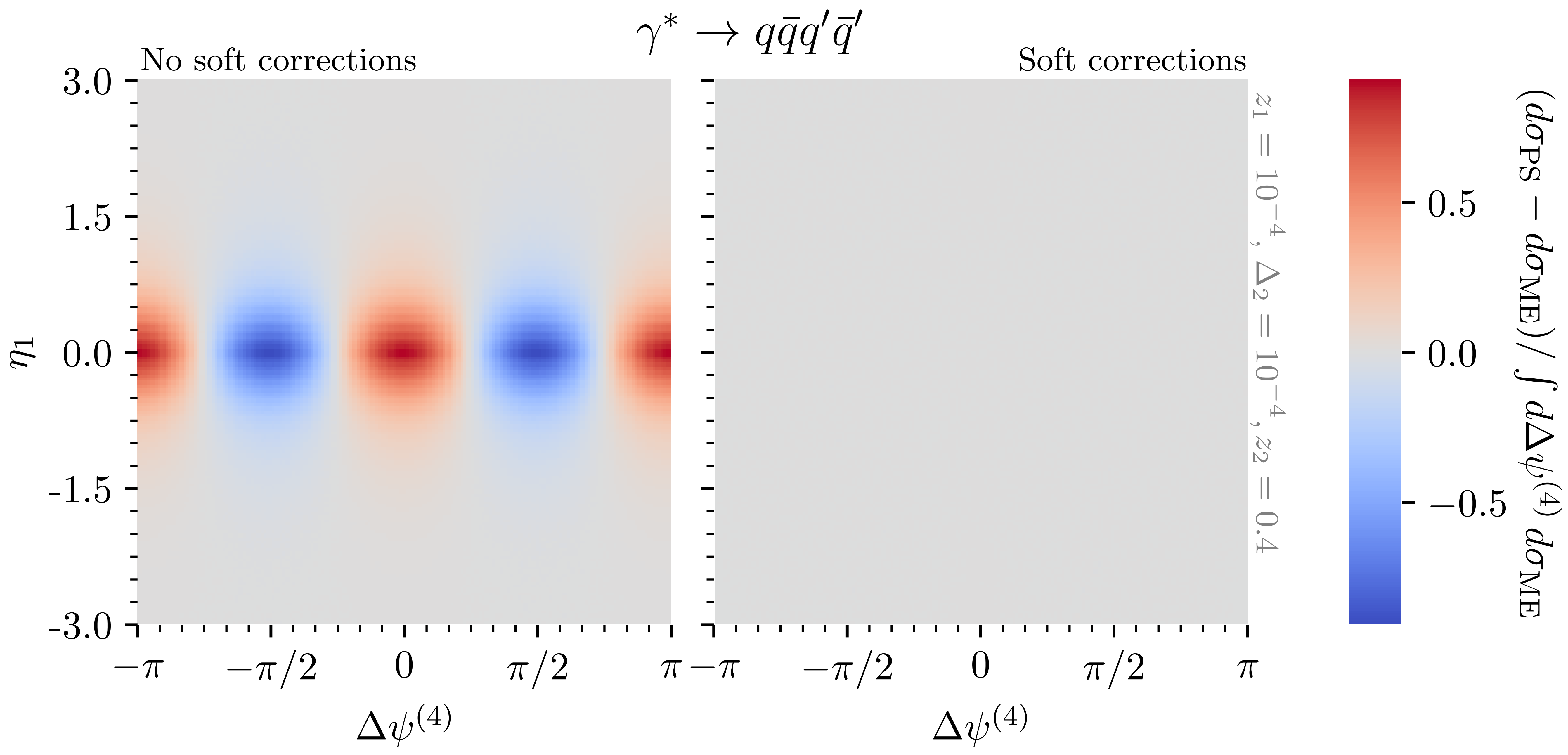
$$\mathcal{M}^{\lambda,\lambda,-\lambda}_{\tilde{i}\to ik} = \frac{g_s}{\sqrt{2}}\sqrt{z}\frac{S_{\lambda}(p_i,p_j)}{S_{\lambda}(p_i,p_k)S_{\lambda}(p_j,p_k)},$$

$g \to gg:$

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

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

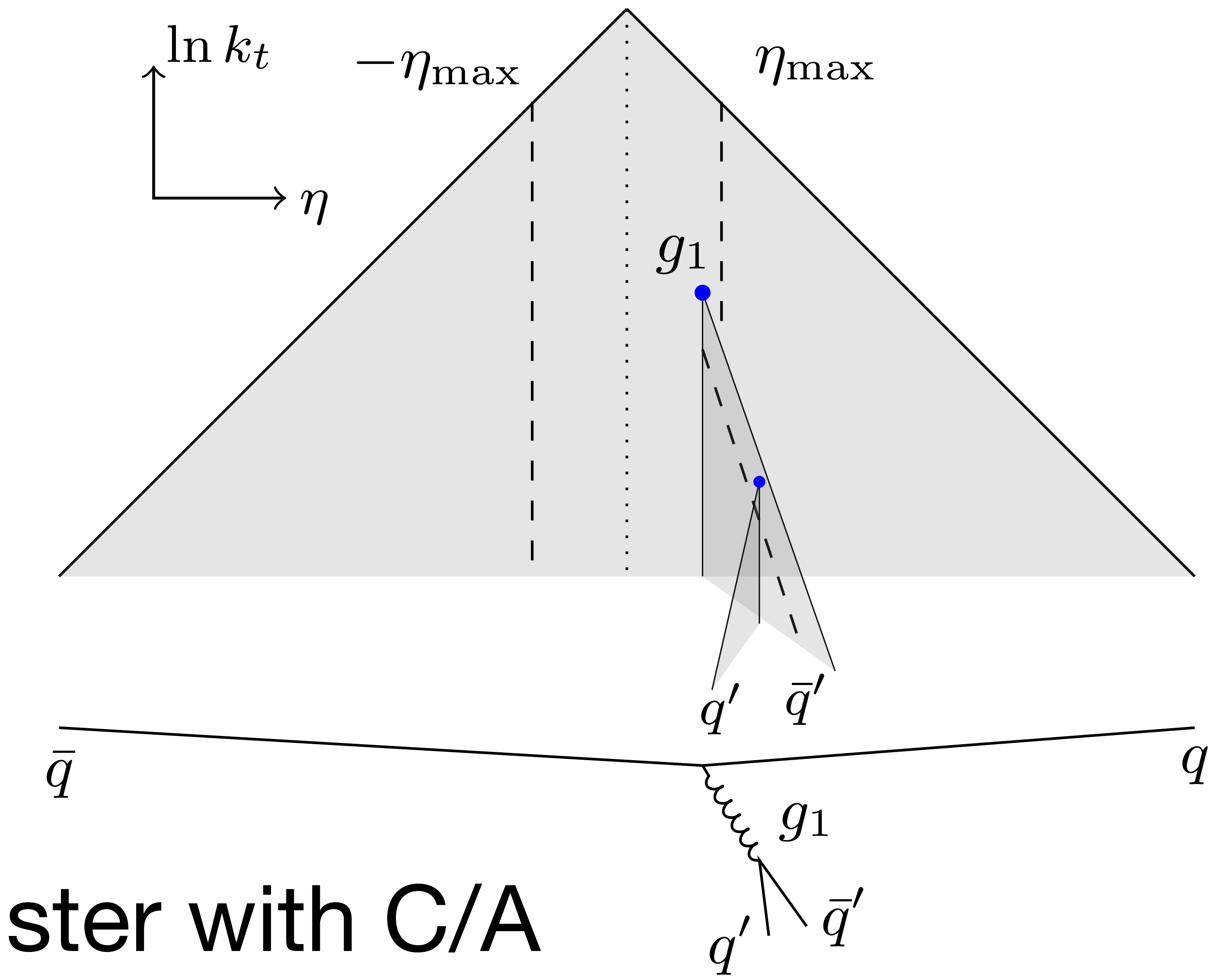
$$\mathcal{M}^{\lambda,-\lambda,\lambda}_{\tilde{i}\to ik} = -\frac{g_s}{\sqrt{2}}\frac{(1-z)^{3/2}}{\sqrt{z}}\frac{1}{S_{\lambda}(p_i,p_k)},$$



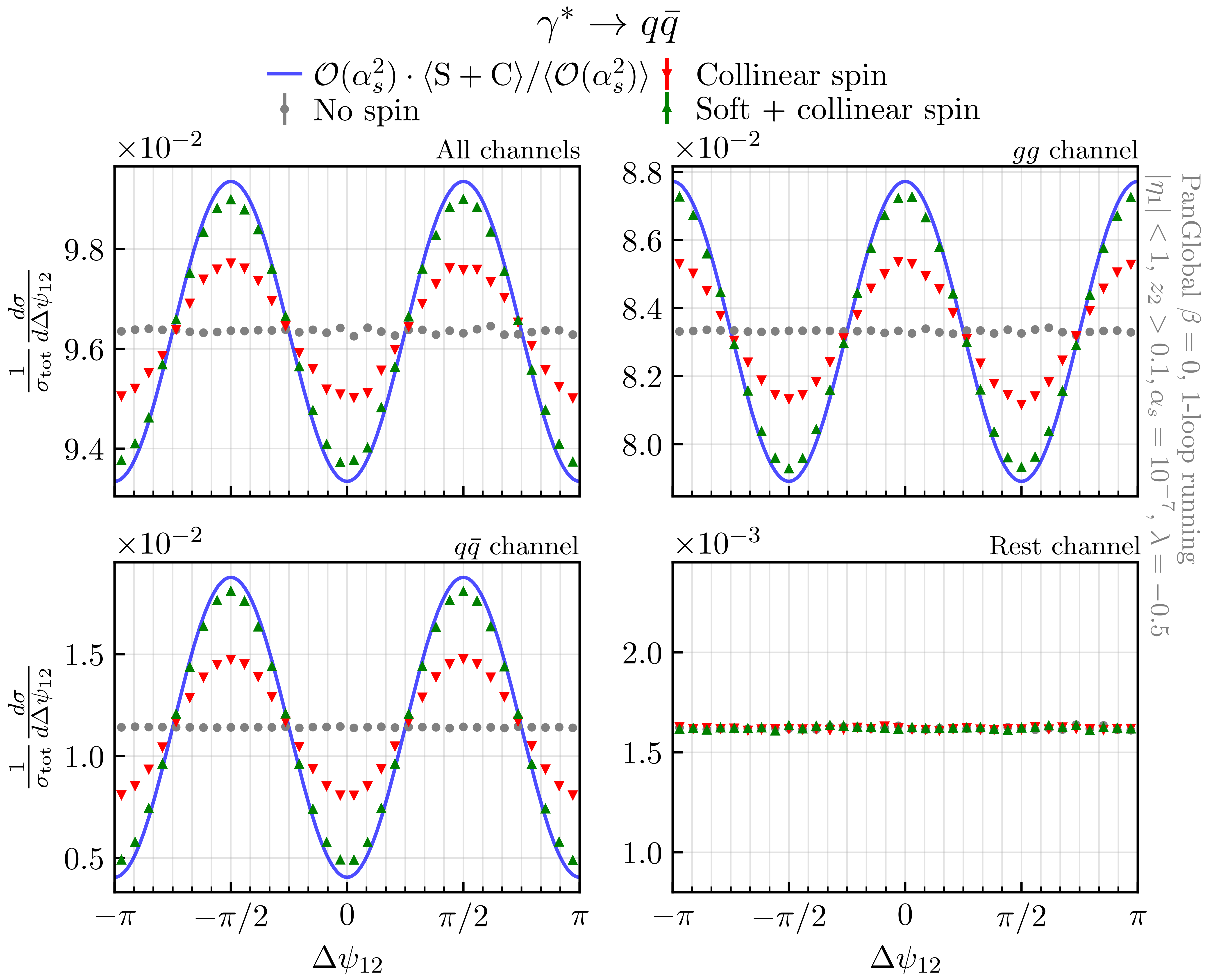
Observables: $\Delta\psi_{12}^{\text{slice}}$ (preliminary)

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

  → 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

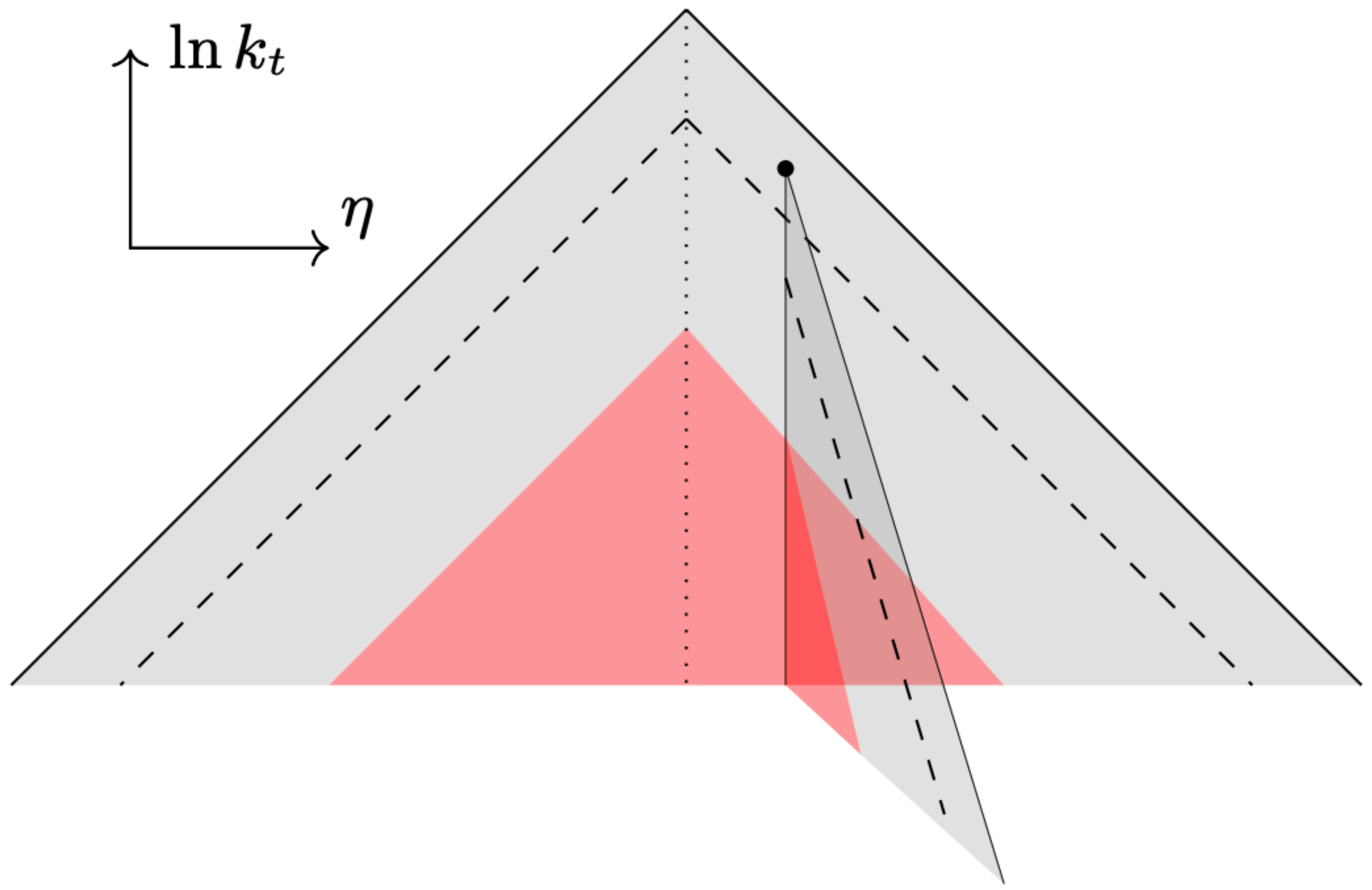
- Dedicated double_exp floating-point type

  $\longrightarrow$ Allows for larger exponent in a double

- Remove soft radiation

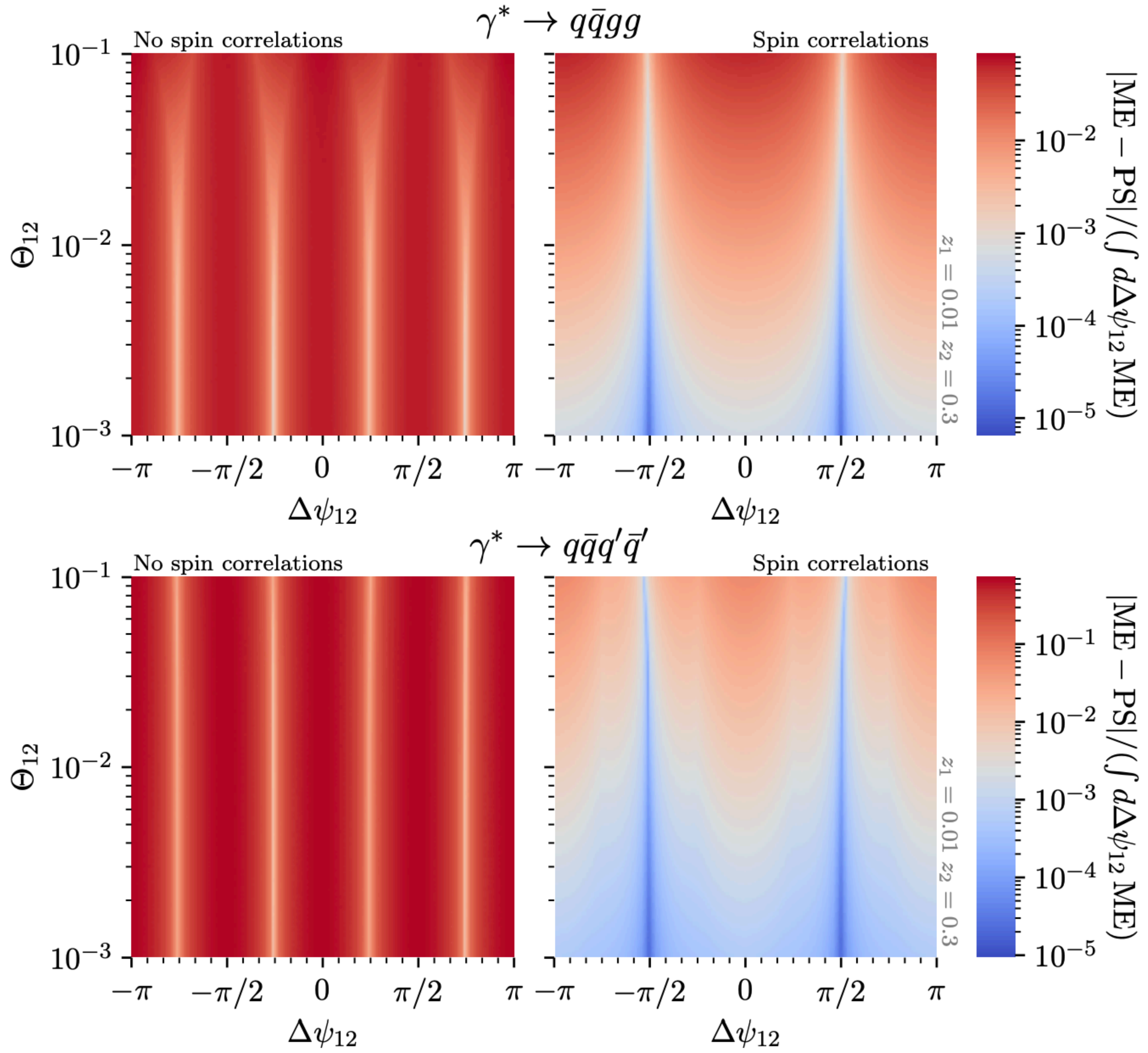
  $\longrightarrow$ Avoids multiplicity exploding

  $\longrightarrow$ Thoroughly tested to not alter observable



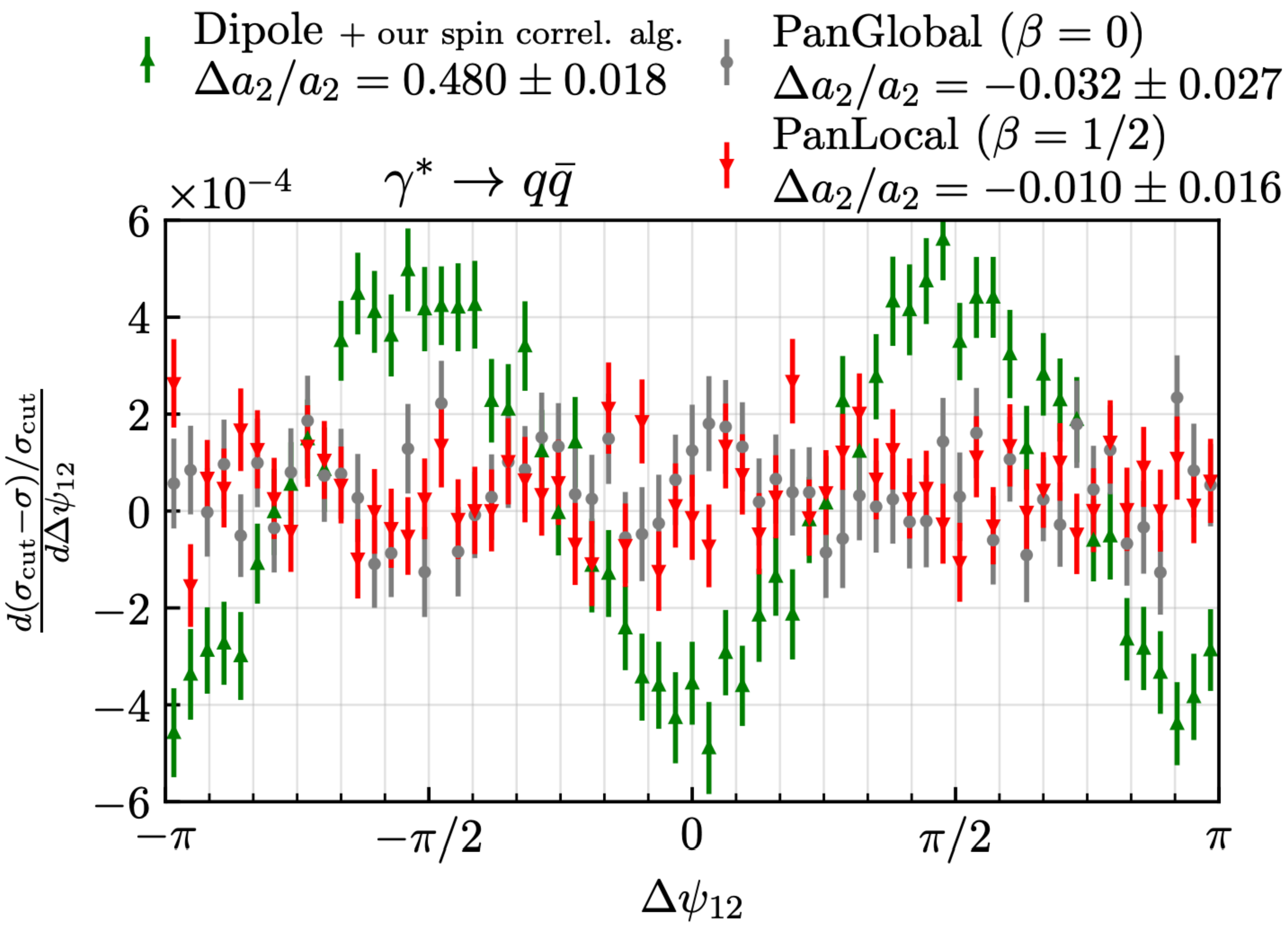
Matrix Element Comparison

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



Removing Soft Radiation

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



Rotational Invariance of Spinor Products