

Toward a helicity resolved parton shower for longitudinally polarized scattering processes

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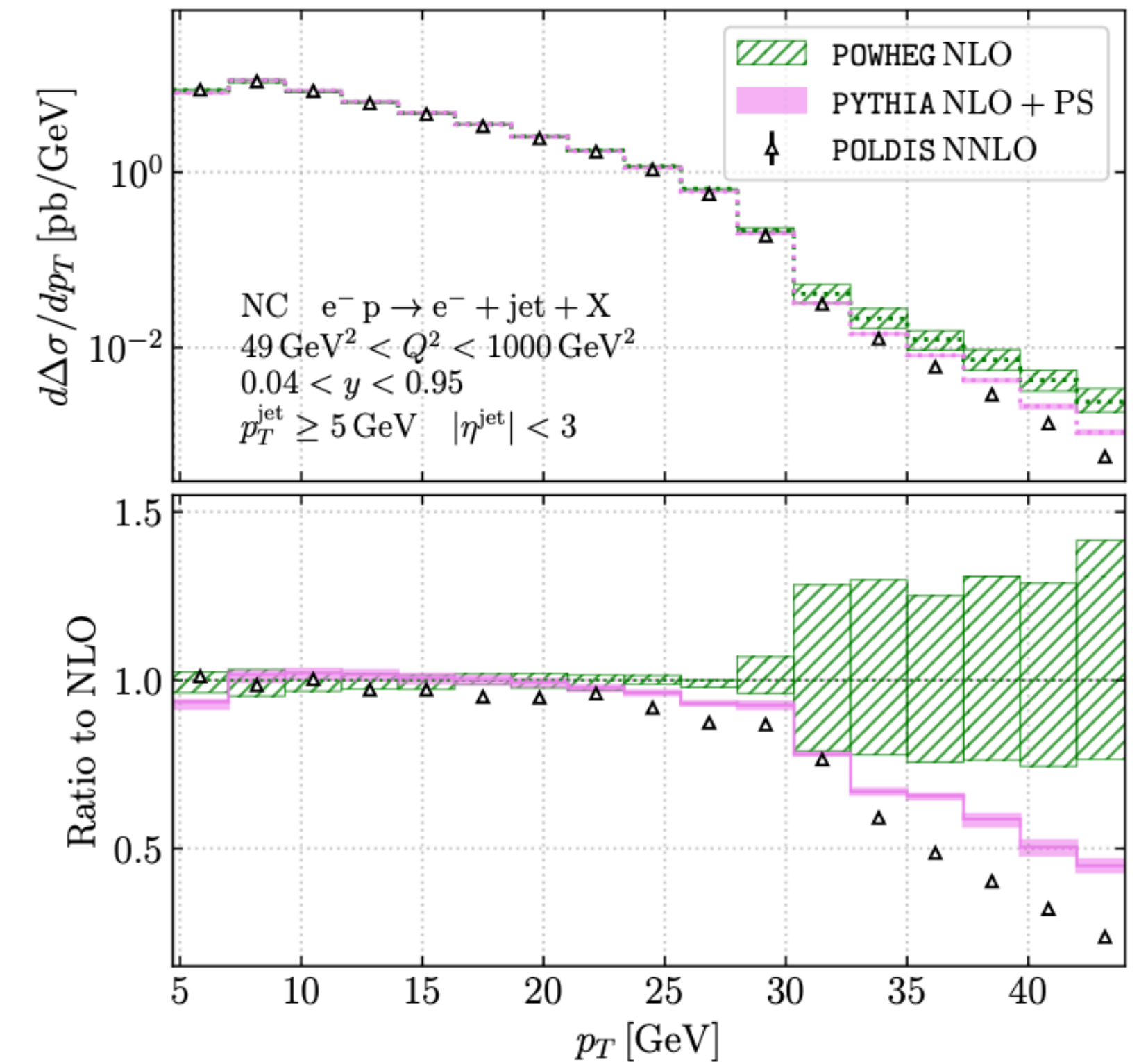
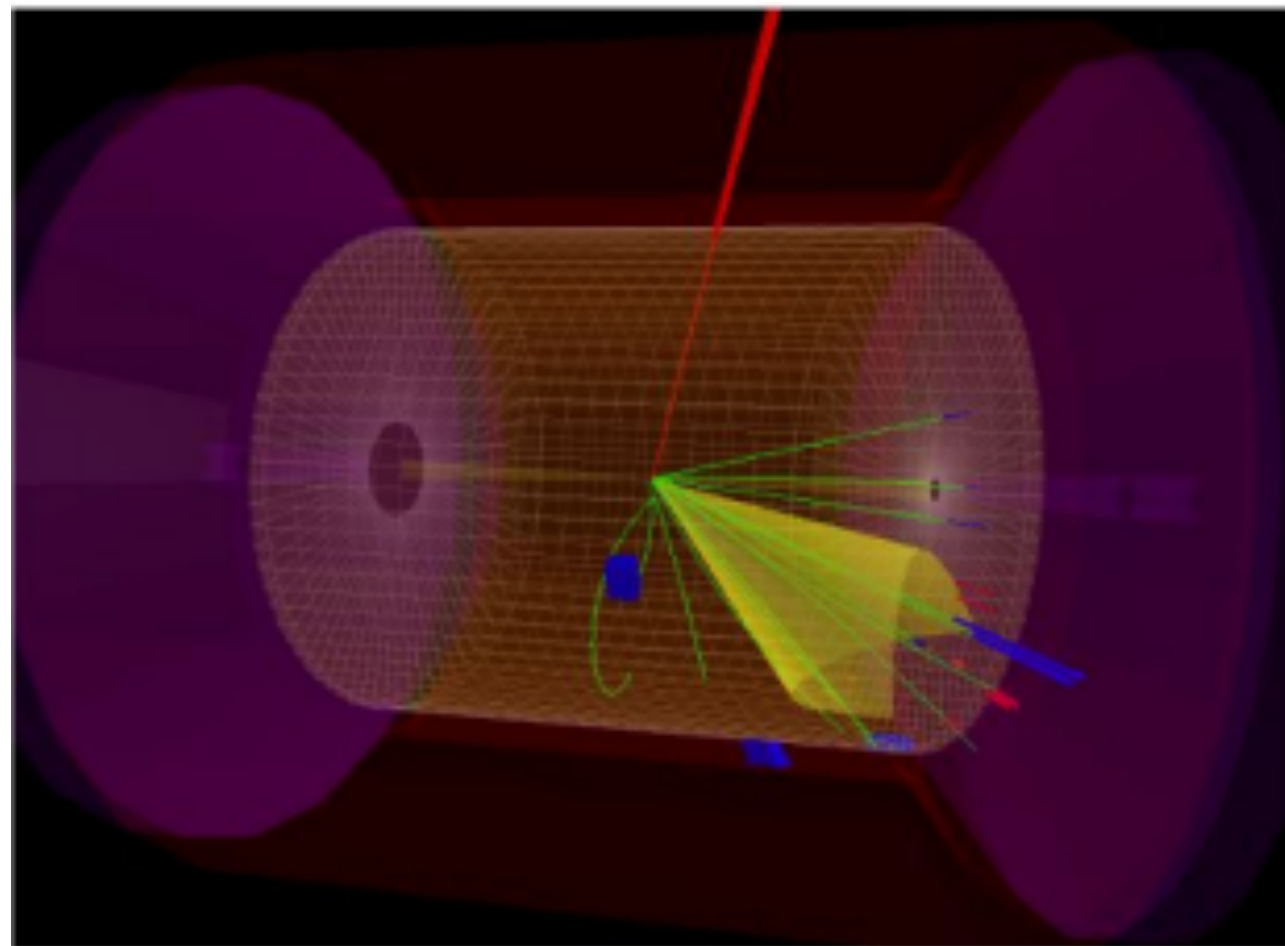


The JETSCAPE Collaboration



Motivation

- Polarized collisions probe differences between beam-spin configurations.
- The measured jets are formed only after QCD radiation, so parton shower effects can modify polarized jet observables.



I. Borsa and B. Jäger, JHEP 07 (2024)

See also: Mankiewicz, Schafer, Veltri '92
Richardson, Webster '18

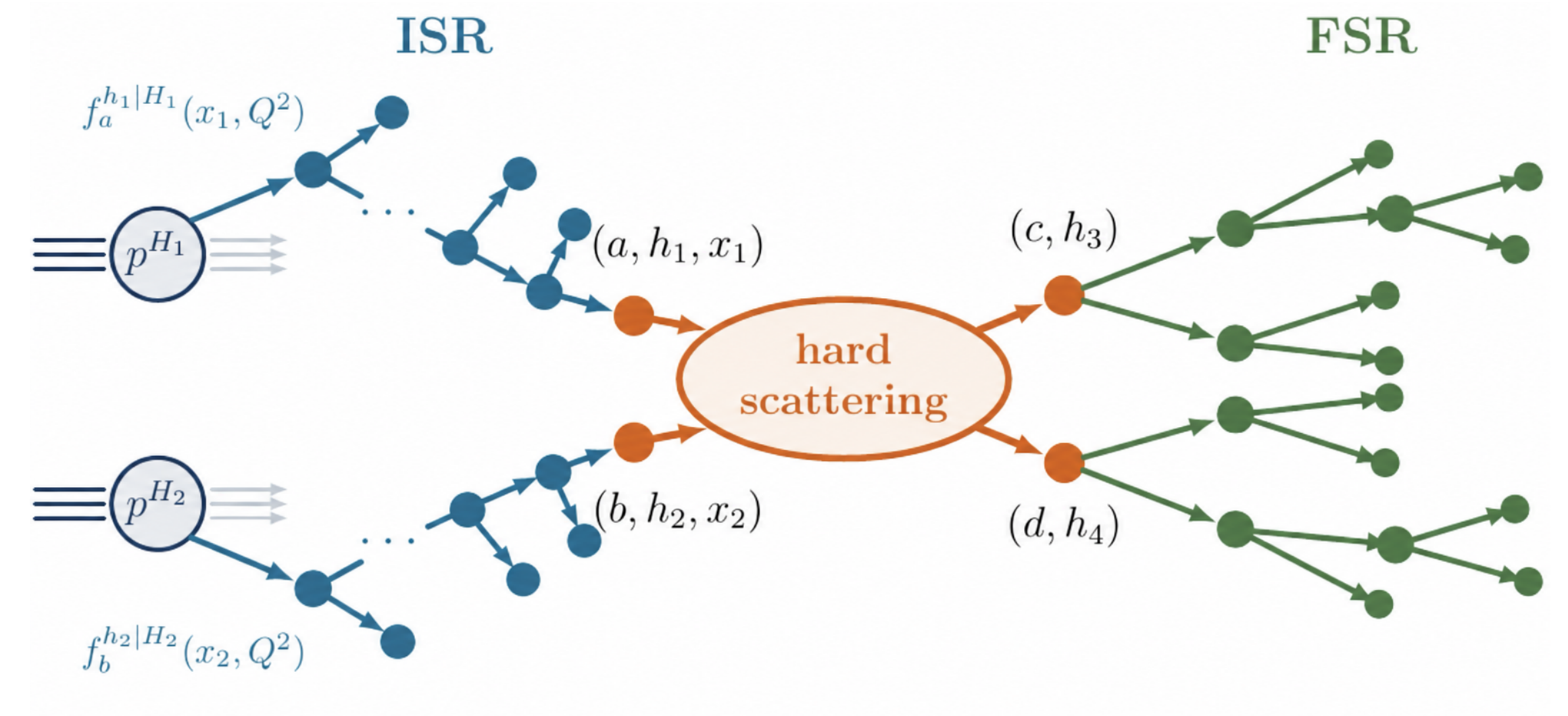
Motivation

- Conventional showers used in polarized predictions are generally helicity-averaged: they generate the radiation without retaining a definite helicity history through the branchings.

Goal: Retain polarization information throughout the shower evolution.

Outline

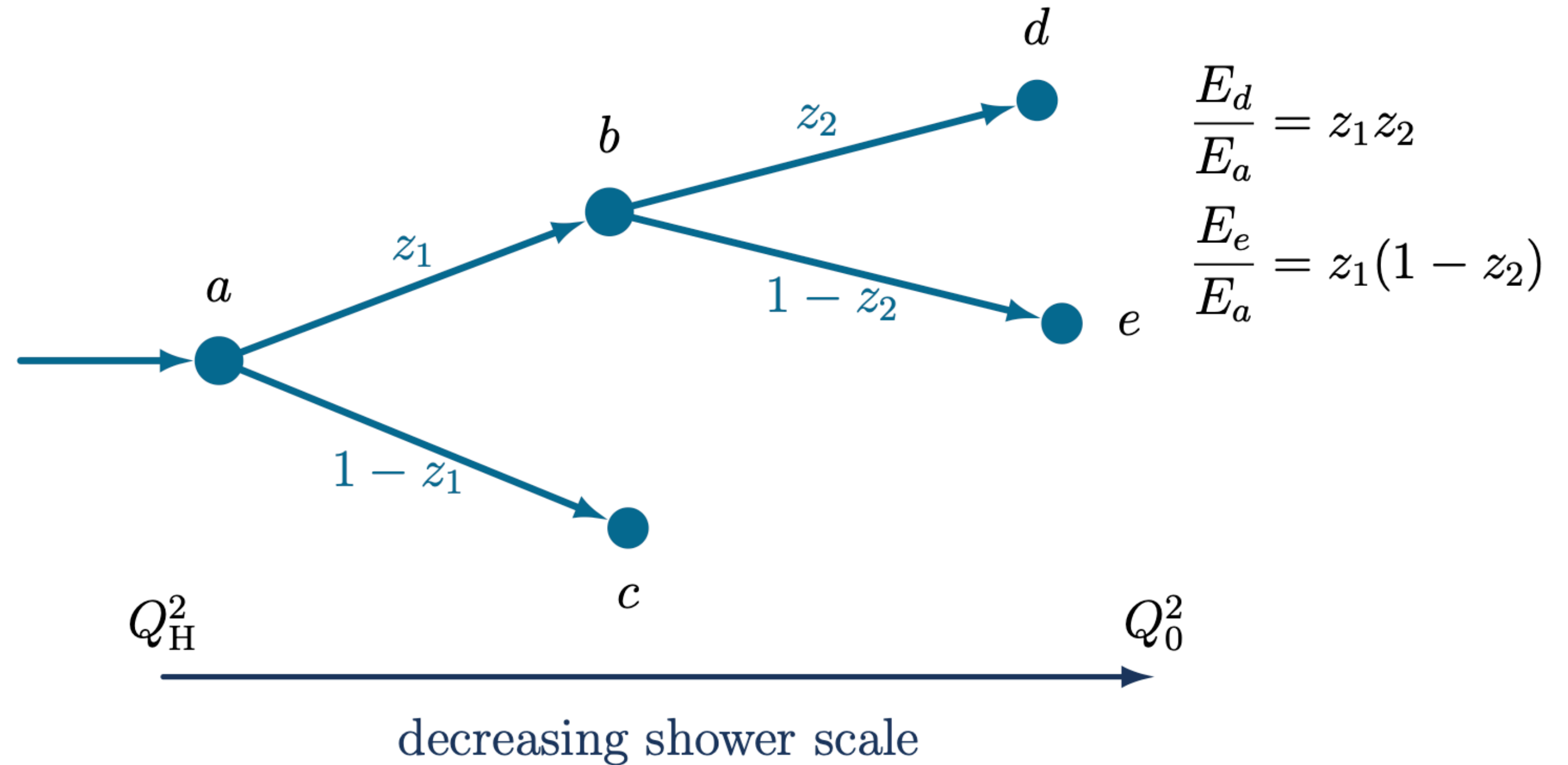
- Overview of the MC Parton Shower
- Final State Shower —with weights
- Final State Shower —with fixed helicity
- Initial State Shower —with fixed helicity
- Complete Shower
- Summary



Overview of the MC Parton Shower

$$d\mathcal{P}_{a \rightarrow bc} = \frac{dQ^2}{Q^2} dz \frac{\alpha_s}{2\pi} P_{a \rightarrow bc}(z)$$

Random branchings



DGLAP Equation:

$$\frac{d}{d \ln Q^2} \begin{pmatrix} D_\Sigma(x, Q^2) \\ D_g(x, Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \begin{pmatrix} P_{qq} & 2N_f P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} D_\Sigma(x, Q^2) \\ D_g(x, Q^2) \end{pmatrix}$$

◆ Can be compared to analytical solution

Overview of the MC Parton Shower

- Sample z and Q^2

$$\Delta_a(Q^2, q^2) = \exp \left[- \sum_c \int_{q^2}^{Q^2} \frac{d\mu^2}{\mu^2} \int dz \frac{\alpha_s}{2\pi} P_{a \rightarrow c}(z) \right]$$

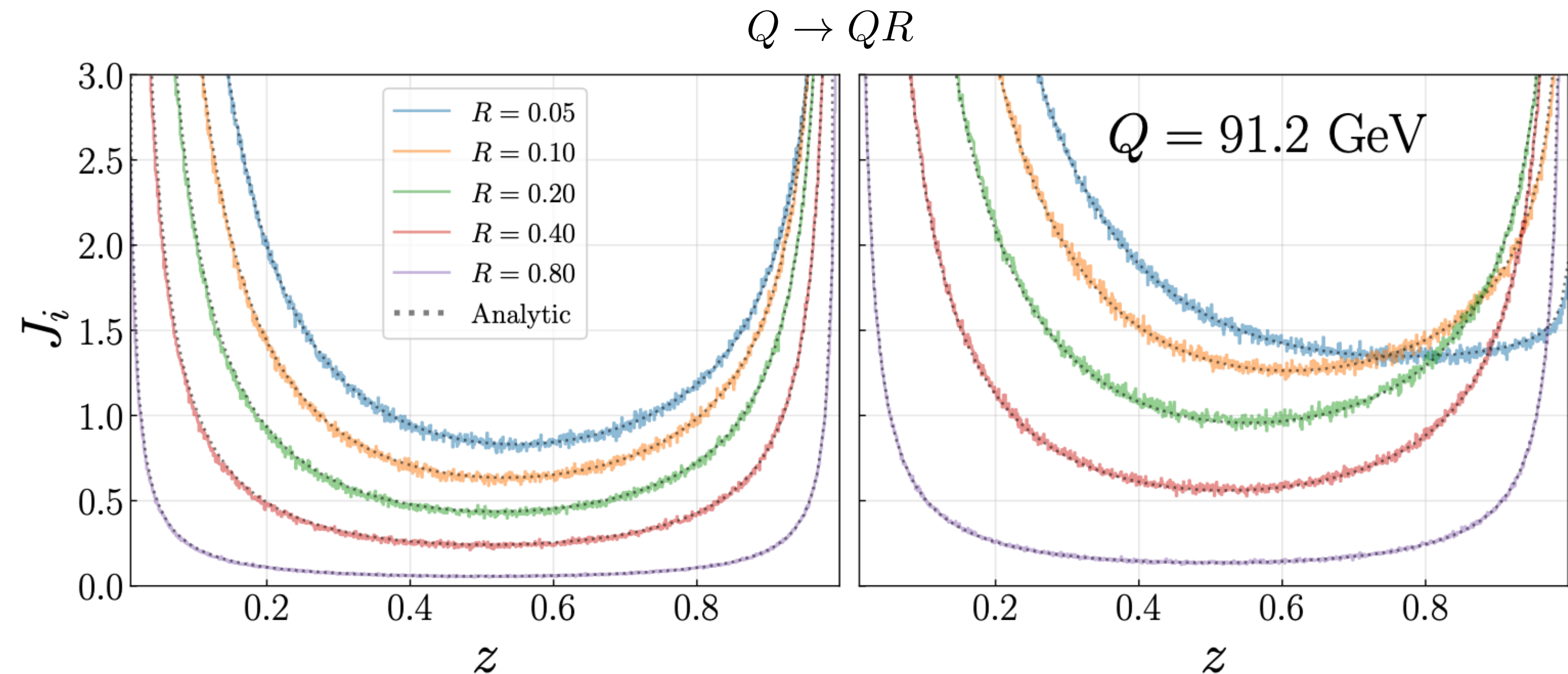
Next branching scale

$$\frac{\int_{\epsilon}^z P(z') dz'}{\int_{\epsilon}^{1-\epsilon} P(z') dz'}$$

Daughter parton's momentum fractions

Shower Cutoff: $z < \epsilon$ or $Q^2 < Q_0^2$

Each parton has: (f, z, θ, ϕ)



D. Neill, F. Ringer and N. Sato, JHEP 07 (2021)

Polarized Parton Shower

- DGLAP Equation

$$\frac{d}{d \ln Q^2} \begin{pmatrix} \Delta D_\Sigma(x, Q^2) \\ \Delta D_g(x, Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \begin{pmatrix} \Delta P_{qq}^{(T)} & 2N_f \Delta P_{gq}^{(T)} \\ \Delta P_{qg}^{(T)} & \Delta P_{gg}^{(T)} \end{pmatrix} \otimes \begin{pmatrix} \Delta D_\Sigma(x, Q^2) \\ \Delta D_g(x, Q^2) \end{pmatrix}$$

D. de Florian, M. Stratmann and W. Vogelsang, Phys. Rev. D 57 (1998)

$$\Delta P_{q \leftarrow q}(z) = C_F \frac{1+z^2}{1-z}, \quad > 0,$$

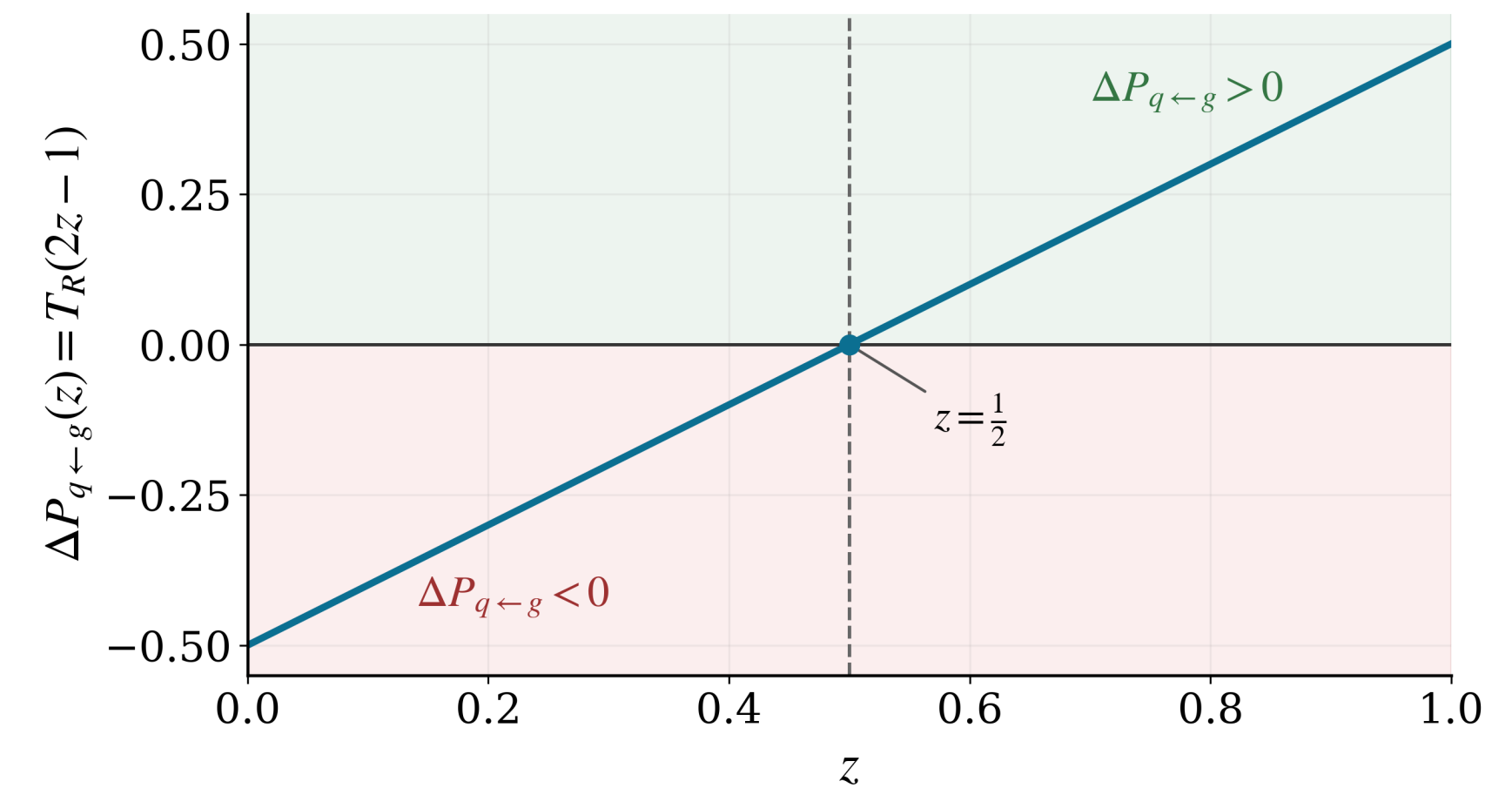
$$\Delta P_{g \leftarrow q}(z) = C_F(2-z), \quad > 0,$$

$$\Delta P_{q \leftarrow g}(z) = T_R(2z-1), \quad \text{changes sign at } z = \frac{1}{2},$$

$$\Delta P_{g \leftarrow g}(z) = 2C_A \left[\frac{1}{1-z} - 2z + 1 \right], \quad > 0$$

- Two possible solutions

- ◆ Use weights
- ◆ Use definite helicity kernels



Polarized Parton Shower — using weights

- Use a proposal kernel that is positive, $|\Delta P(z)|$
- Sample z from $|\Delta P(z)|$ & generate a branching $a \rightarrow b + c$
- Assign weights such that, $w = \frac{Target}{Proposal}$

◆ z sampling weights:

$$w_b = w_a \frac{\Delta P_{b \leftarrow a}(z)}{|\Delta P_{b \leftarrow a}(z)|}$$

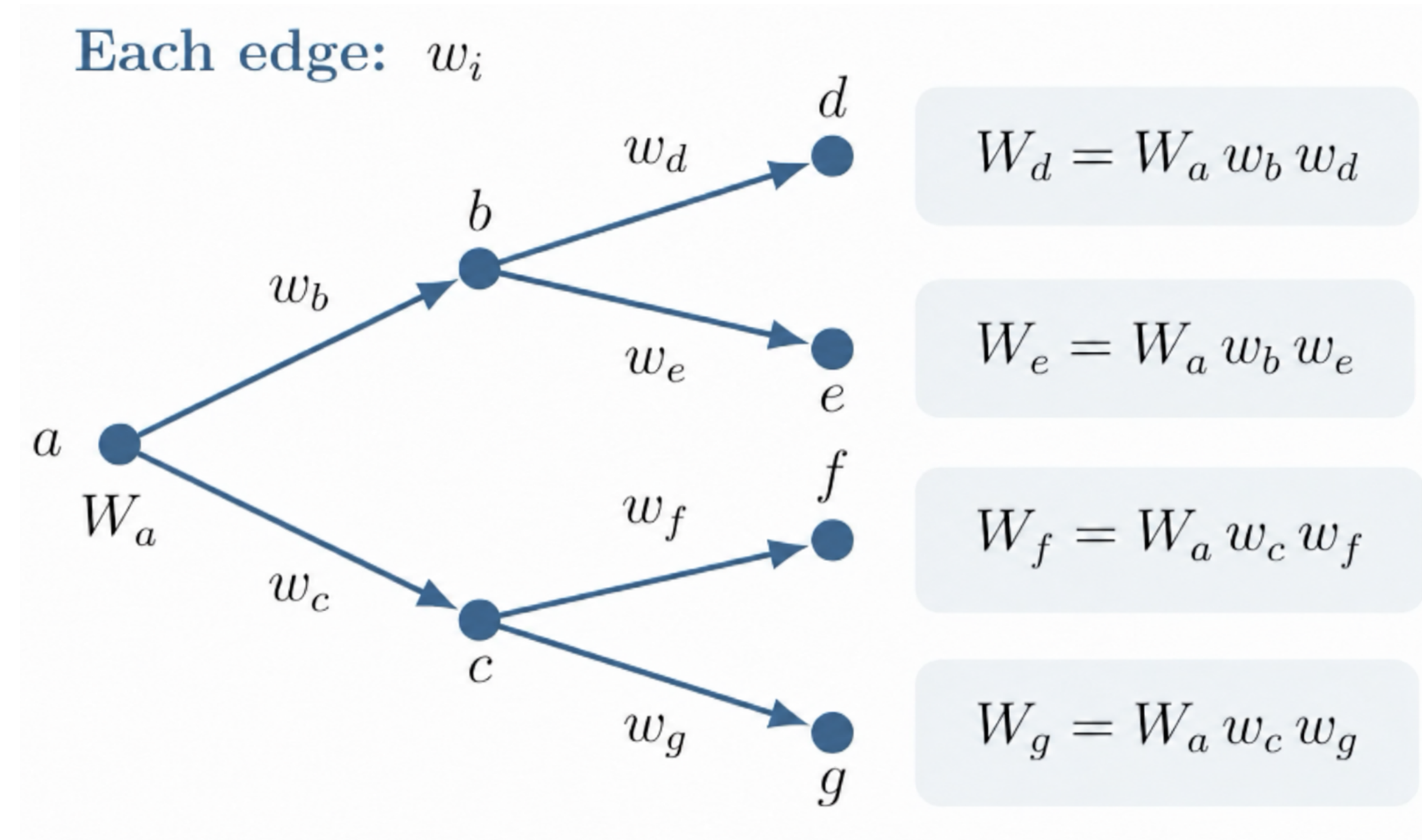
and

$$w_c = w_a \frac{\Delta P_{c \leftarrow a}(1 - z)}{|\Delta P_{c \leftarrow a}(1 - z)|}$$

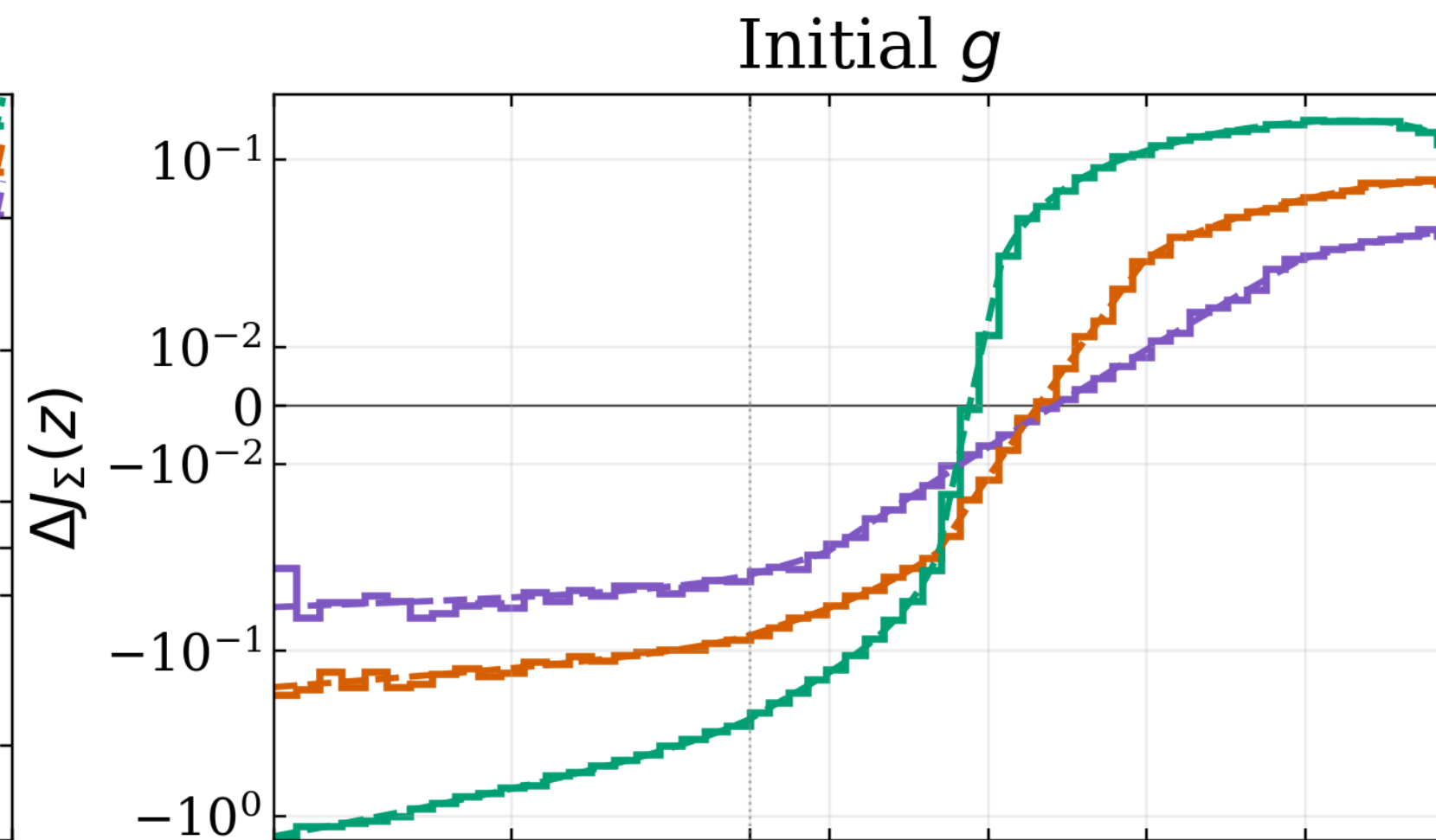
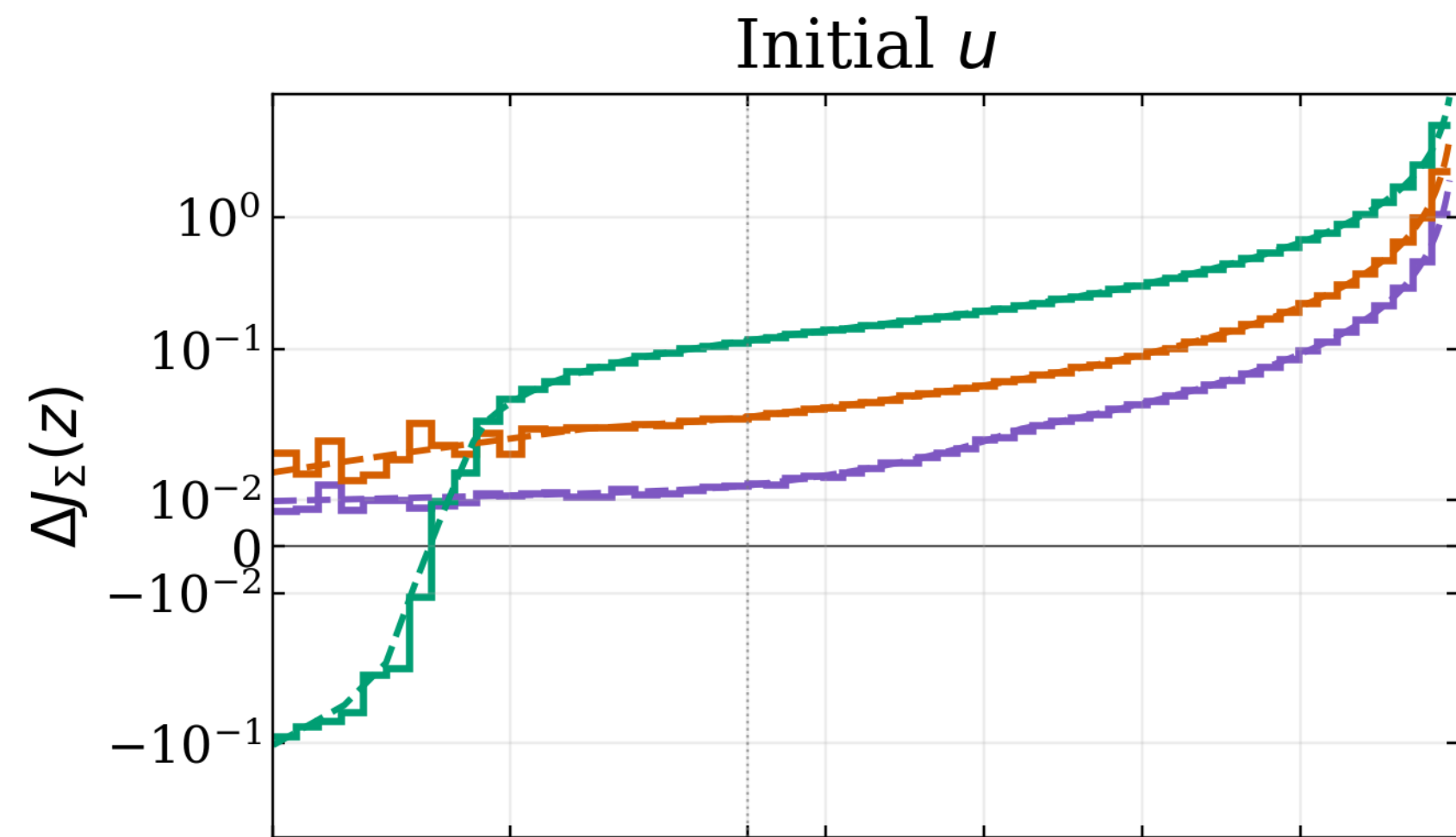
Polarized Parton Shower — using weights

- The weights are multiplied along each branch
- Each parton has: (f, z, w)
- Fill the histogram bins as:

$$\text{Bin content} = \frac{1}{N_{\text{events}}} \sum_{i \in \text{bin}} w_i^{\text{final}}$$



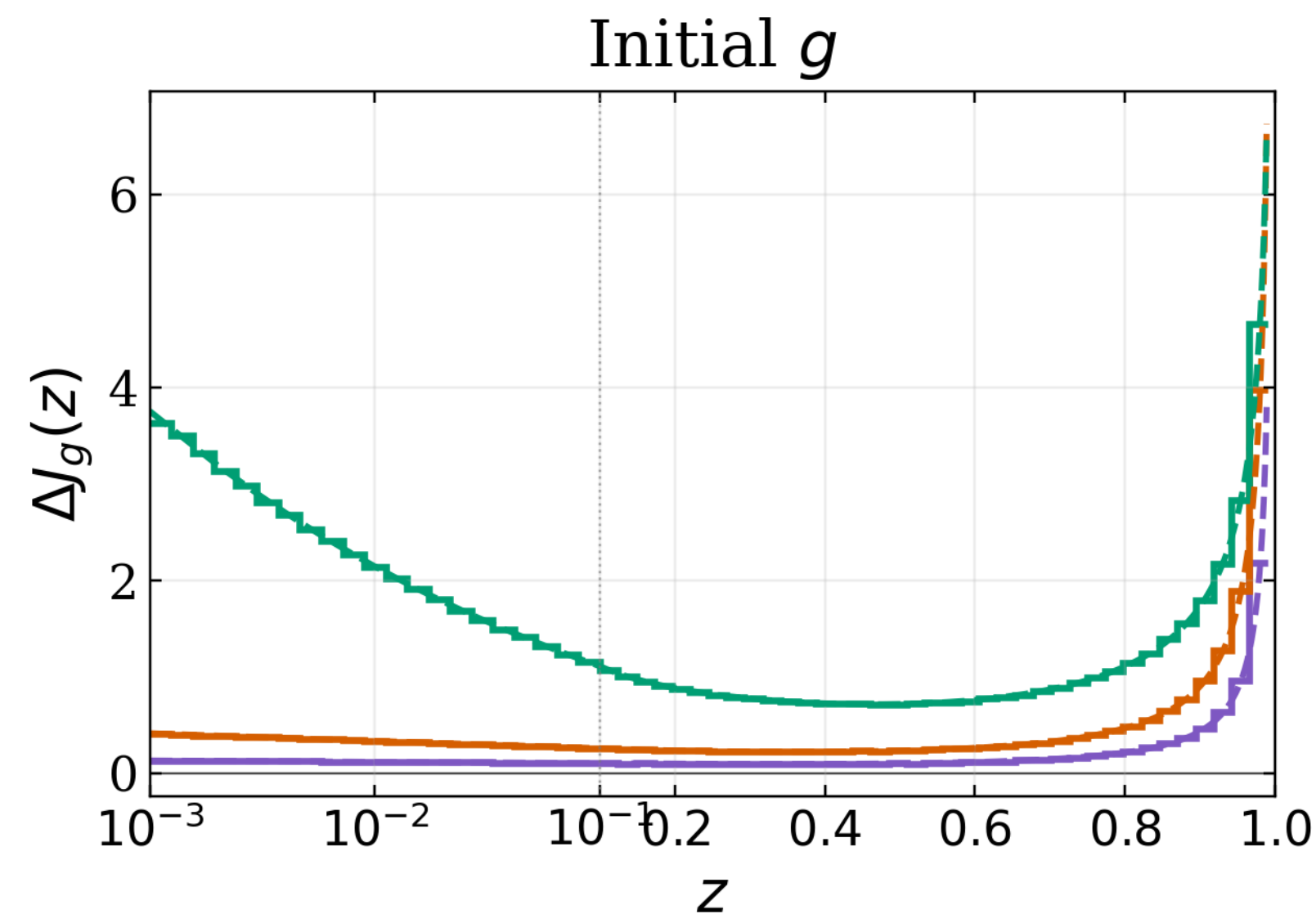
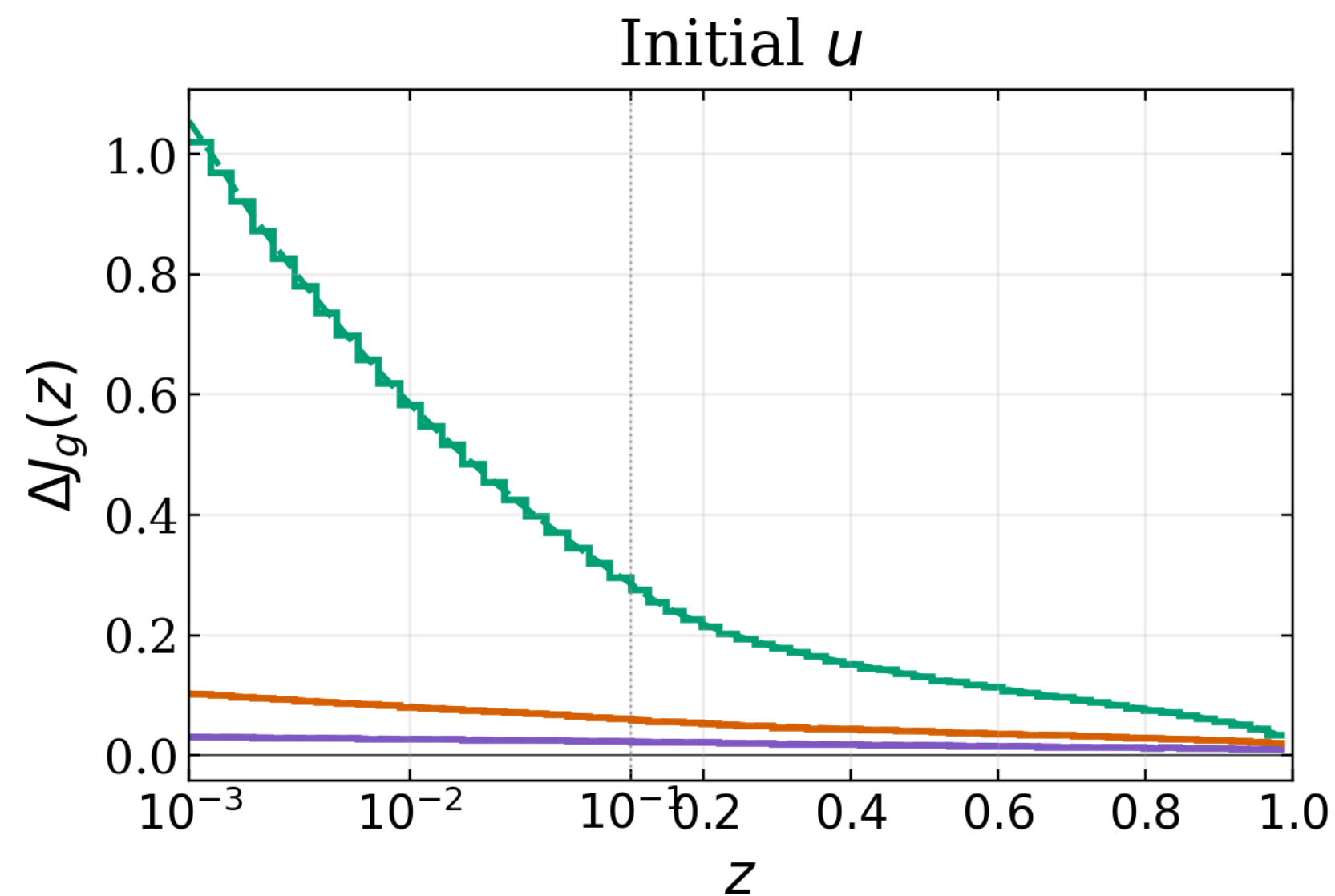
Polarized Parton Shower — using weights



$$Q = 91.2 \text{ GeV} \rightarrow QR$$

logarithmic for $10^{-3} \leq z \leq 0.1$; linear above 0.1

- Weighted shower, $R = 0.8$
- - Mellin, $R = 0.8$
- Weighted shower, $R = 0.6$
- - Mellin, $R = 0.6$
- Weighted shower, $R = 0.2$
- - Mellin, $R = 0.2$

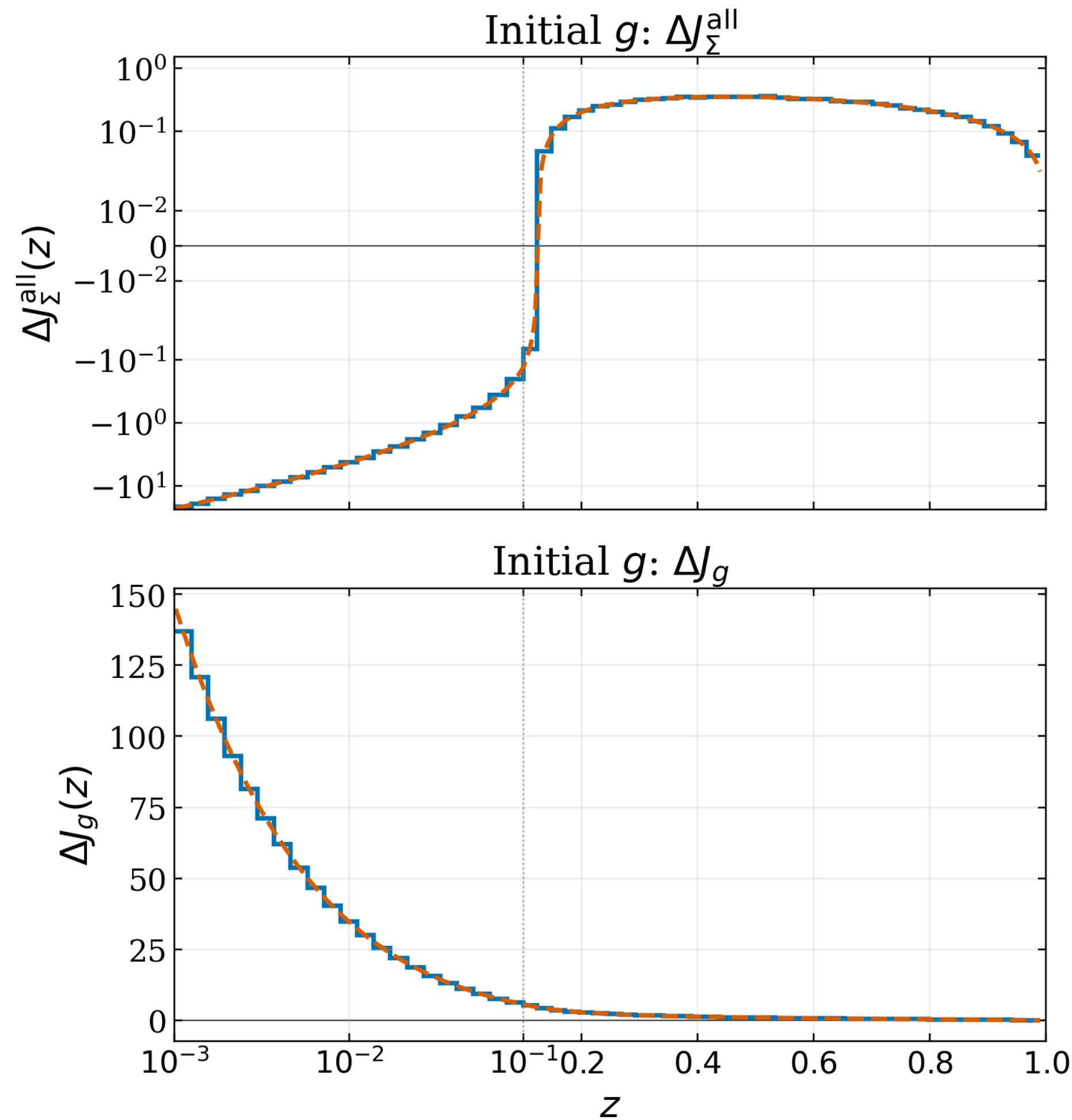
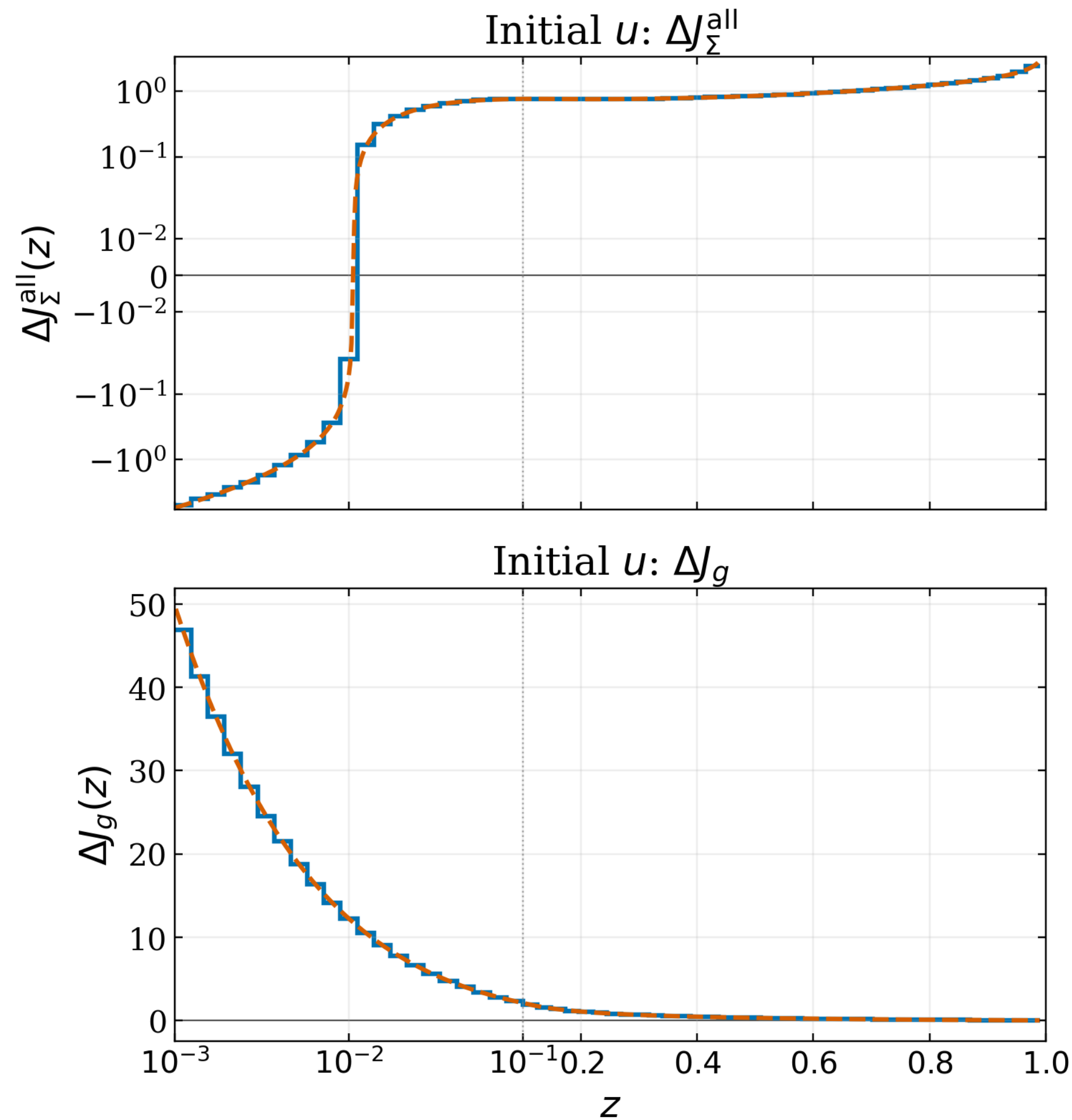


Initial u : 10M showers for $R = 0.2$, 5M for $R = 0.6, 0.8$; initial g : 1M each

Polarized Parton Shower — using weights

— weighted shower (frozen heavy quarks) — piecewise Mellin DGLAP

$Q = 91.2 \text{ GeV} \rightarrow Q_R = 1 \text{ GeV}$, $R = 0.010965$; $N_f: 5 \rightarrow 4 \rightarrow 3$, frozen c, b counted — mixed logarithmic/linear z scale



Could be
extended to NLL!

Polarized Parton Shower — fixed helicity

- Decompose polarized kernel into ordinary helicity kernels

Define, $P^{same} = \frac{P + \Delta P}{2}$ and $P^{flip} = \frac{P - \Delta P}{2}$

Or, $P = P^{same} + P^{flip}$ and $\Delta P = P^{same} - P^{flip}$

- For one flavor channel, we can evolve the helicities separately,

$$\frac{d}{d \ln Q^2} \begin{pmatrix} D_a^+(x, Q^2) \\ D_a^-(x, Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \begin{pmatrix} P^{same} & P^{flip} \\ P^{flip} & P^{same} \end{pmatrix} \otimes \begin{pmatrix} D_a^+(x, Q^2) \\ D_a^-(x, Q^2) \end{pmatrix} \quad D_a^\pm : \text{counts final partons of flavor } a \text{ with } \pm \text{ helicity}$$

For $2N_f + 1$ flavors, we have $4N_f + 2$ components.

Polarized Parton Shower — fixed helicity

$$\frac{d}{d \ln Q^2} \underbrace{(D_a^+ + D_a^-)}_{=D_a} = \frac{\alpha_s}{2\pi} P \otimes (D_a^+ + D_a^-) \implies \text{The sum evolves with } P$$

$$\frac{d}{d \ln Q^2} \underbrace{(D_a^+ - D_a^-)}_{=\Delta D_a} = \frac{\alpha_s}{2\pi} \Delta P \otimes (D_a^+ - D_a^-) \implies \text{The difference evolves with } \Delta P$$

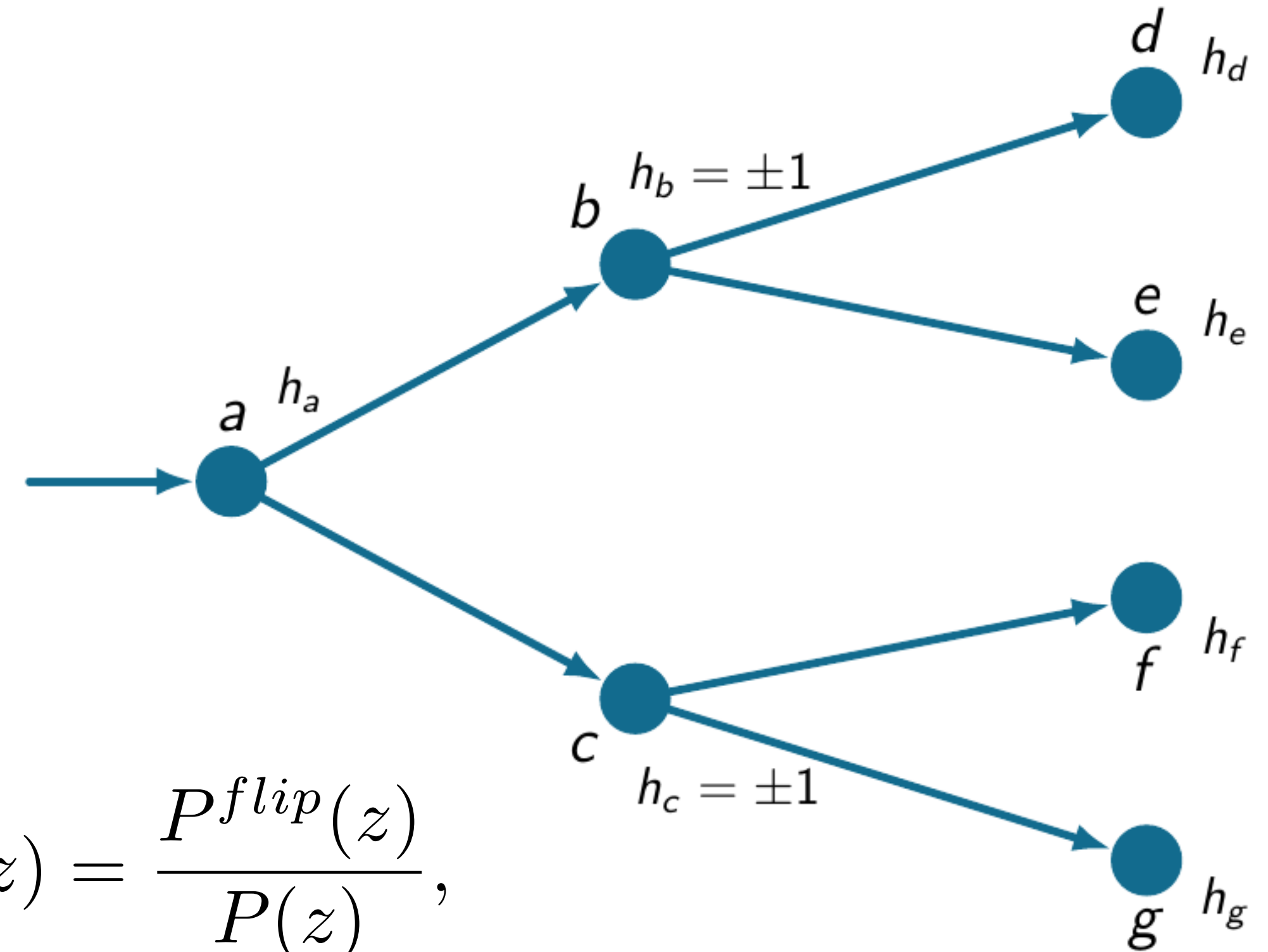
The $(D_a, \Delta D_a)$ basis diagonalizes the evolution, while the $(+/-)$ basis generates definite helicity histories.

Polarized Parton Shower — fixed helicity

- Every parton has: $(f, z, h = \pm 1)$
- Use $P(z)$ for sampling z
- Assign daughter helicity using,

$$\text{Prob}(\text{same} \mid z) = \frac{P^{\text{same}}(z)}{P(z)},$$

$$\text{Prob}(\text{flip} \mid z) = \frac{P^{\text{flip}}(z)}{P(z)},$$

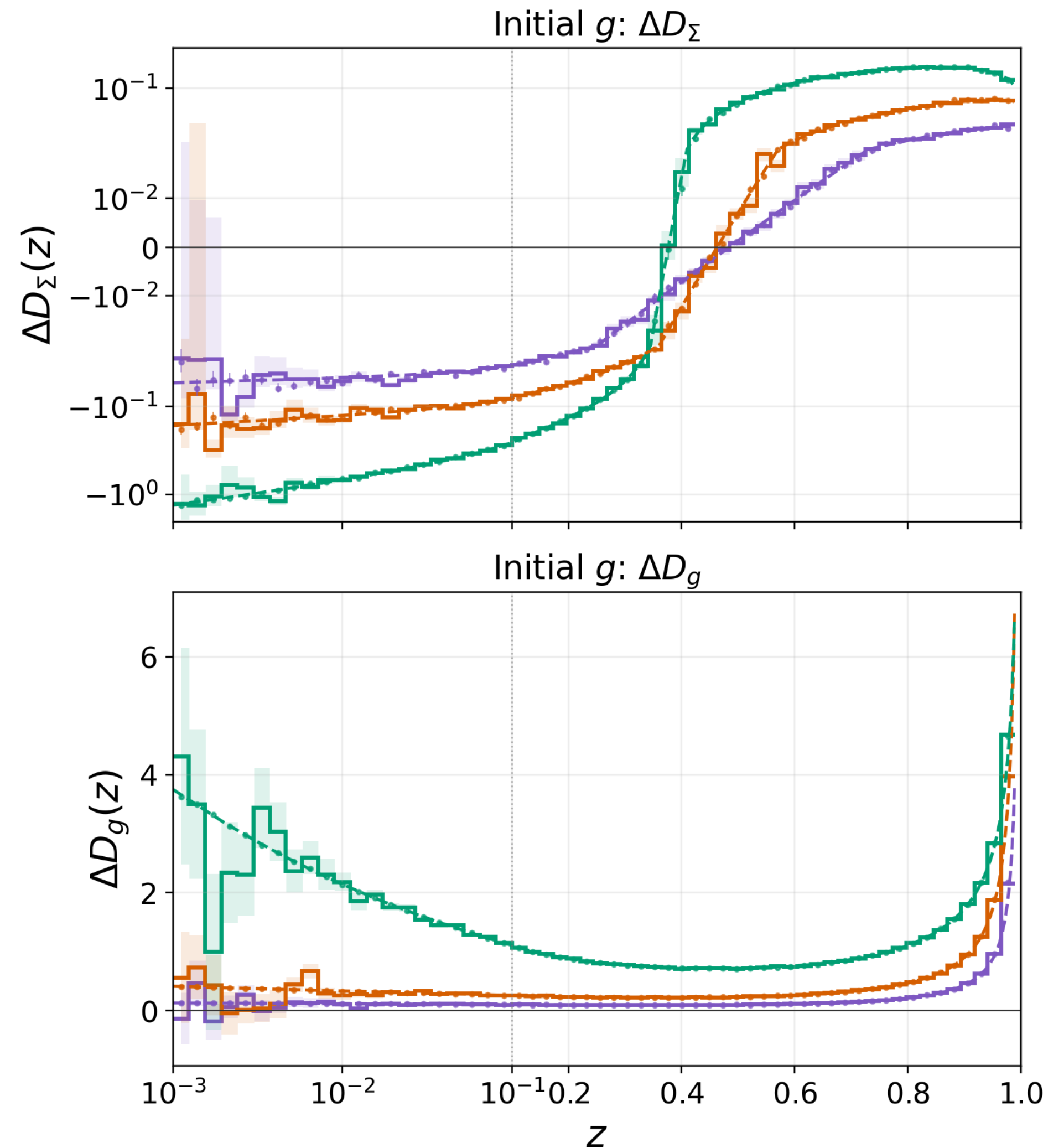
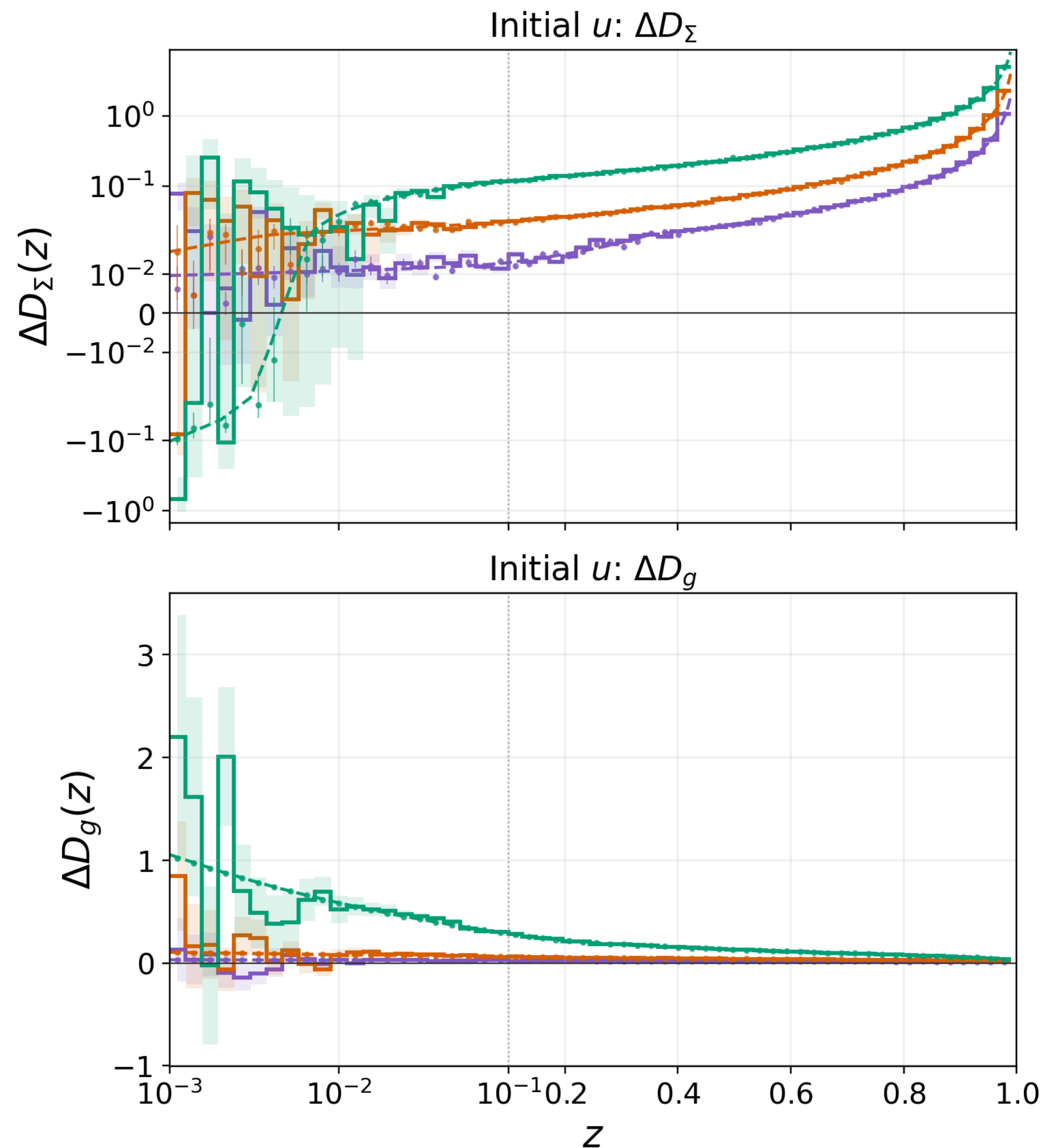


Interpretation

P fixes the total branching rate. ΔP fixes the helicity asymmetry within that rate.

Polarized Parton Shower — fixed helicity

— fixed helicity • weighted ---- Mellin DGLAP — $R = 0.8$ — $R = 0.6$ — $R = 0.2$
 Equal statistics: polarized showers versus Mellin DGLAP with statistical uncertainties — mixed logarithmic/linear z scale



- Fill histogram bins as,

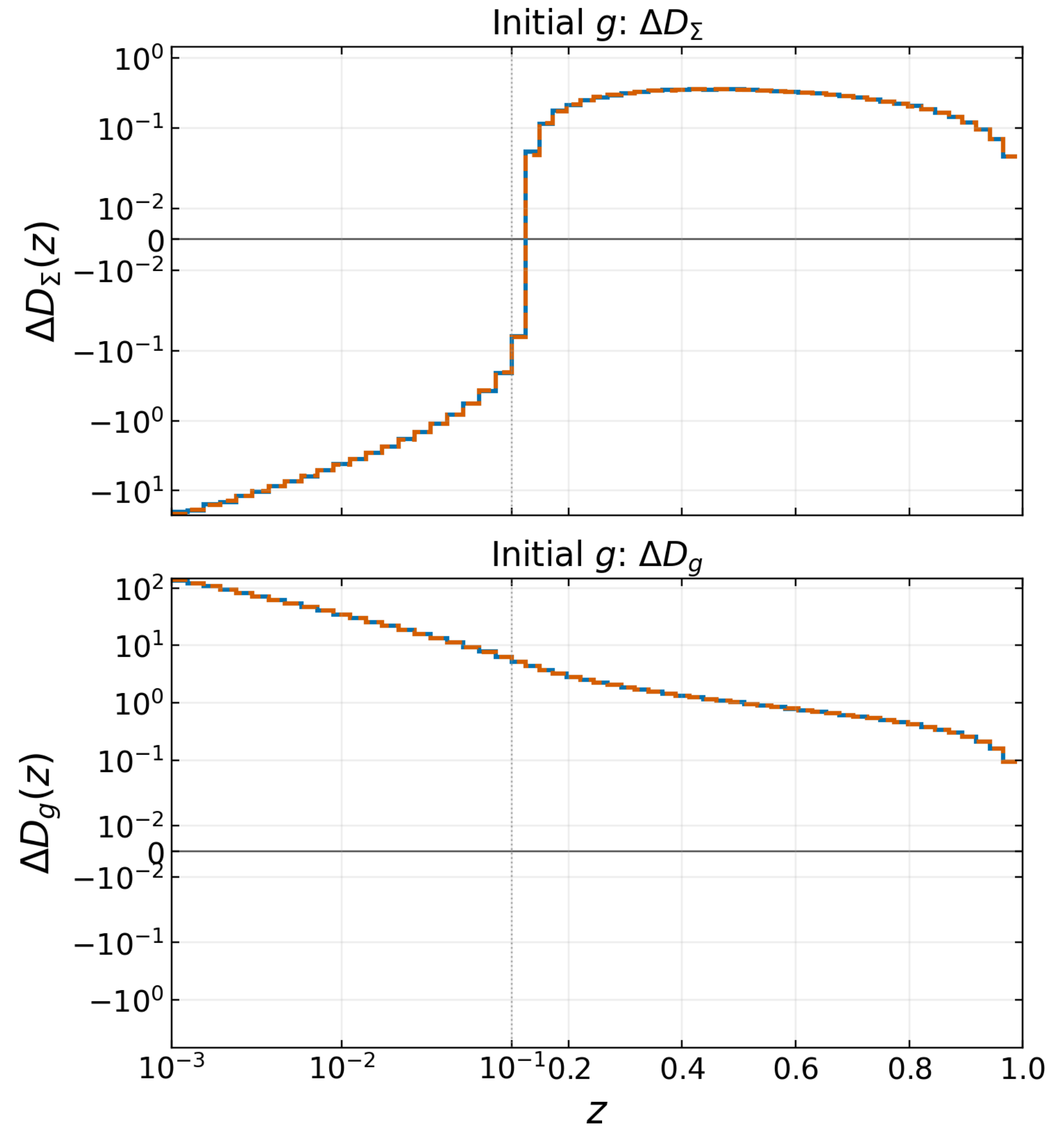
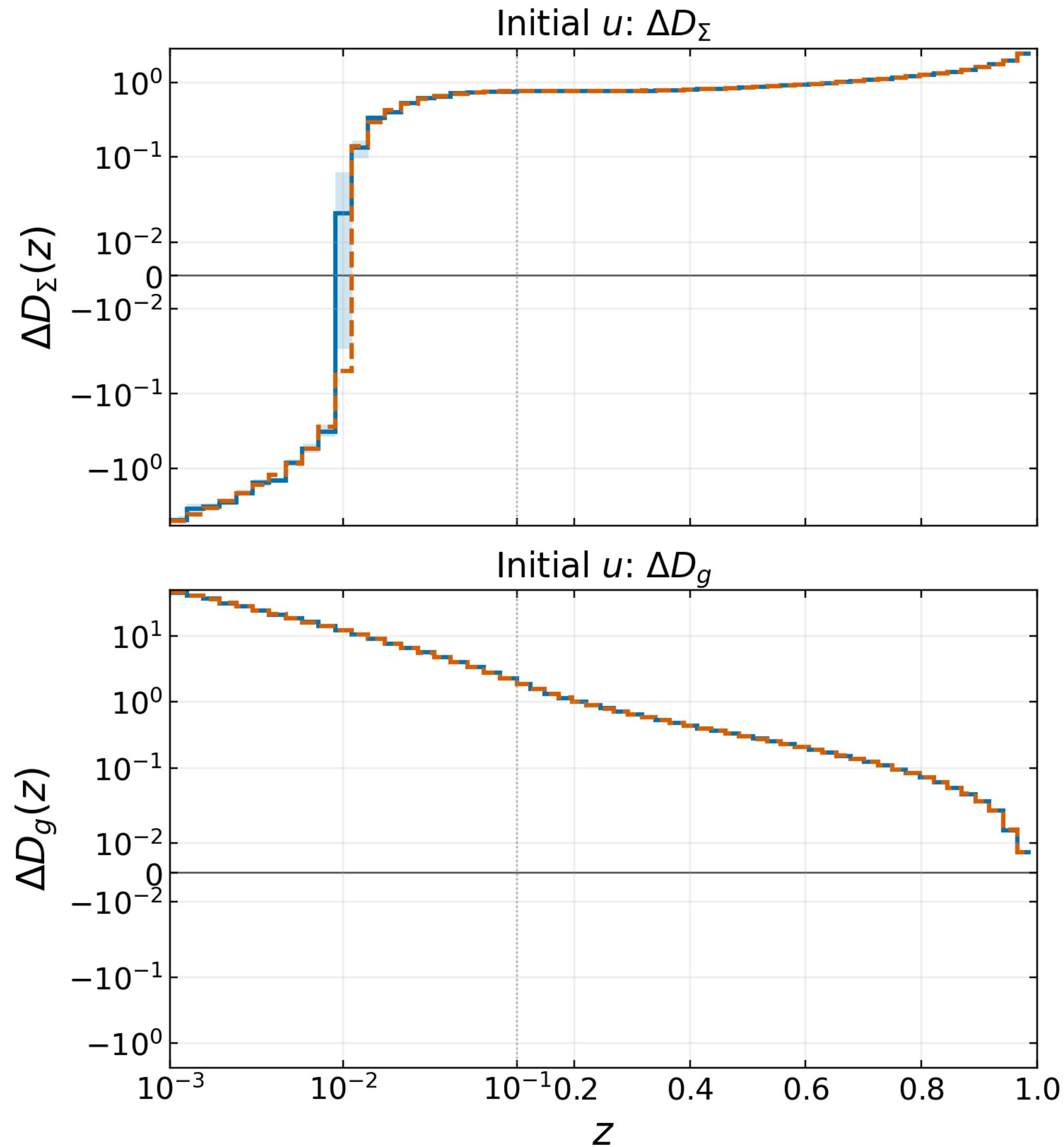
$$\Delta D_{\text{bin}}^{\text{explicit}} = \frac{1}{N_{\text{events}}} \sum_{i \in \text{bin}} h_i,$$

As $z \rightarrow 0$, $D^+(z) \simeq D^-(z)$

Polarized Parton Shower — fixed helicity

— explicit fixed helicity - - - piecewise Mellin DGLAP

$Q = 91.2 \text{ GeV} \rightarrow Q_0 = 1 \text{ GeV}$; $N_f: 5 \rightarrow 4 \rightarrow 3$, seed helicity +1



Initial u : 10,000,000 events; initial g : 10,000,000 events

Polarized Parton Shower — fixed helicity (probabilities)

- Propagate helicity probabilities

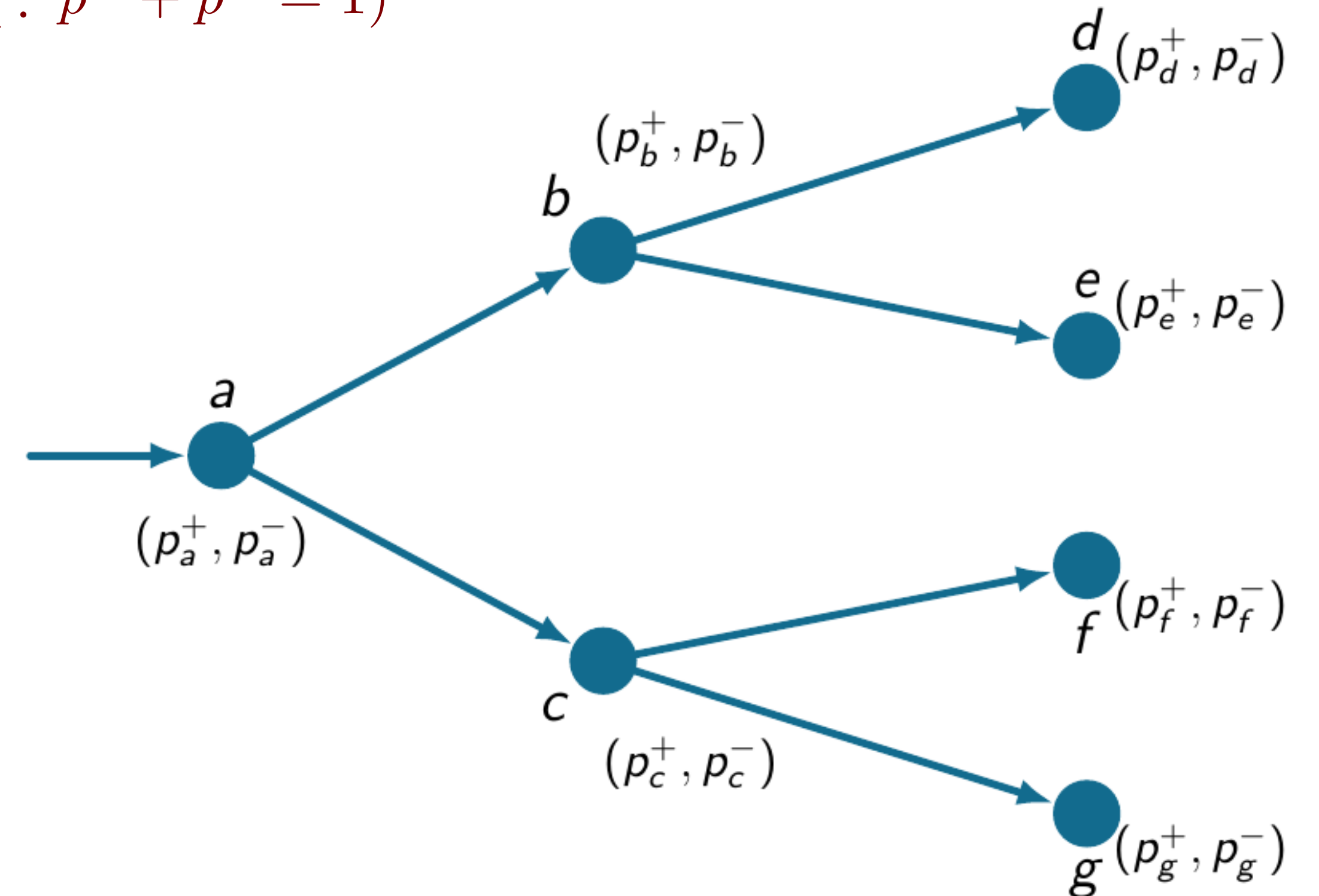
$$p^+ \equiv \text{Prob}(\text{same} \mid z) \quad \text{and} \quad p^- \equiv \text{Prob}(\text{flip} \mid z) \quad (\because p^+ + p^- = 1)$$

$$\text{Explicit: } (p^+, p^-) \xrightarrow{\text{random draw}} h = \pm 1$$

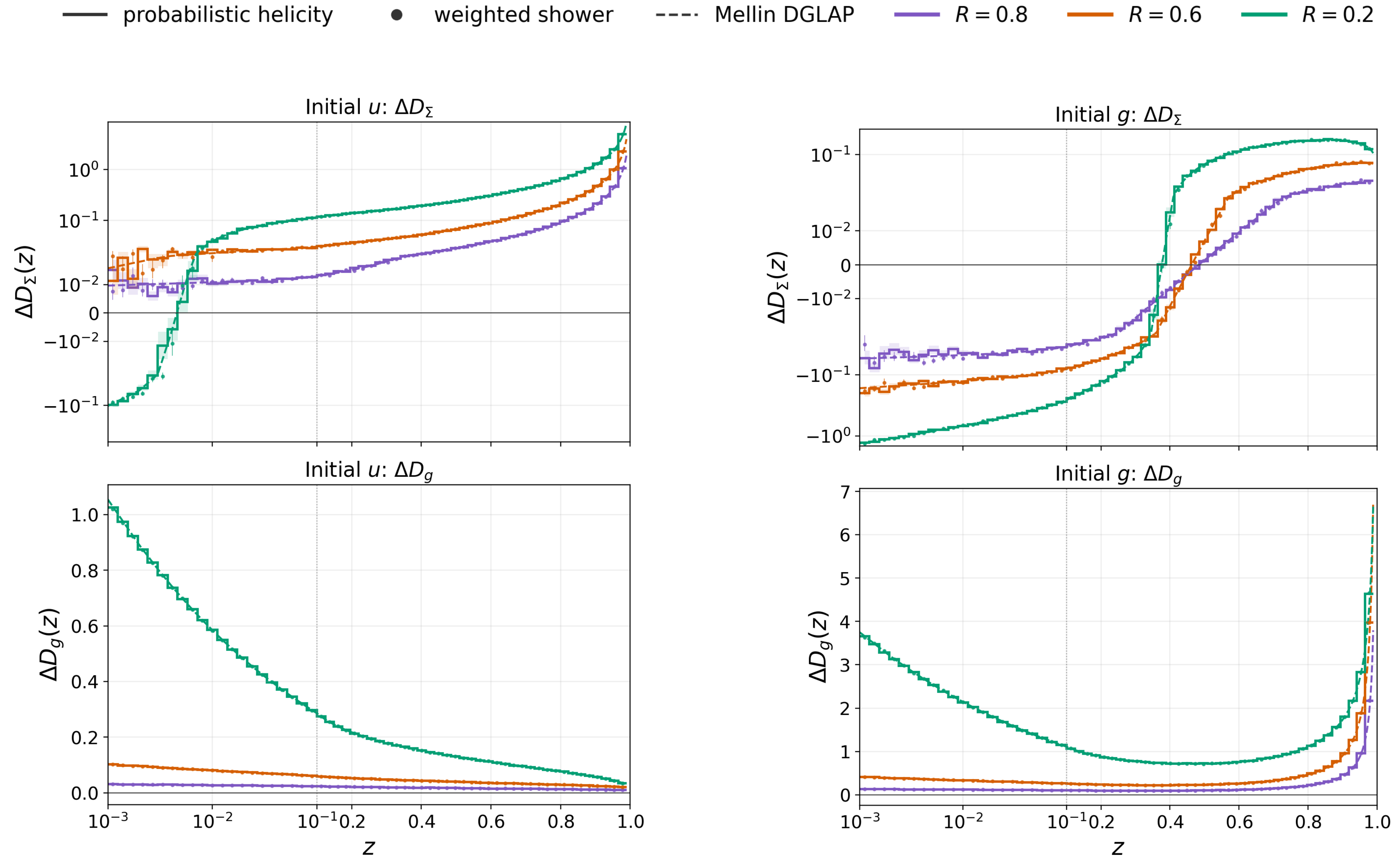
$$\text{Probabilities: } (p^+, p^-) \xrightarrow{\text{no helicity draw}} (p^+, p^-)$$

$$\begin{pmatrix} p_b^+ \\ p_b^- \end{pmatrix} = \frac{1}{P_{b \leftarrow a}(z)} \begin{pmatrix} P_{b \leftarrow a}^{\text{same}}(z) & P_{b \leftarrow a}^{\text{flip}}(z) \\ P_{b \leftarrow a}^{\text{flip}}(z) & P_{b \leftarrow a}^{\text{same}}(z) \end{pmatrix} \begin{pmatrix} p_a^+ \\ p_a^- \end{pmatrix}.$$

$$\Delta D_{\text{bin}}^{\text{prob}} = \frac{1}{N_{\text{events}}} \sum_{i \in \text{bin}} (p_i^+ - p_i^-).$$

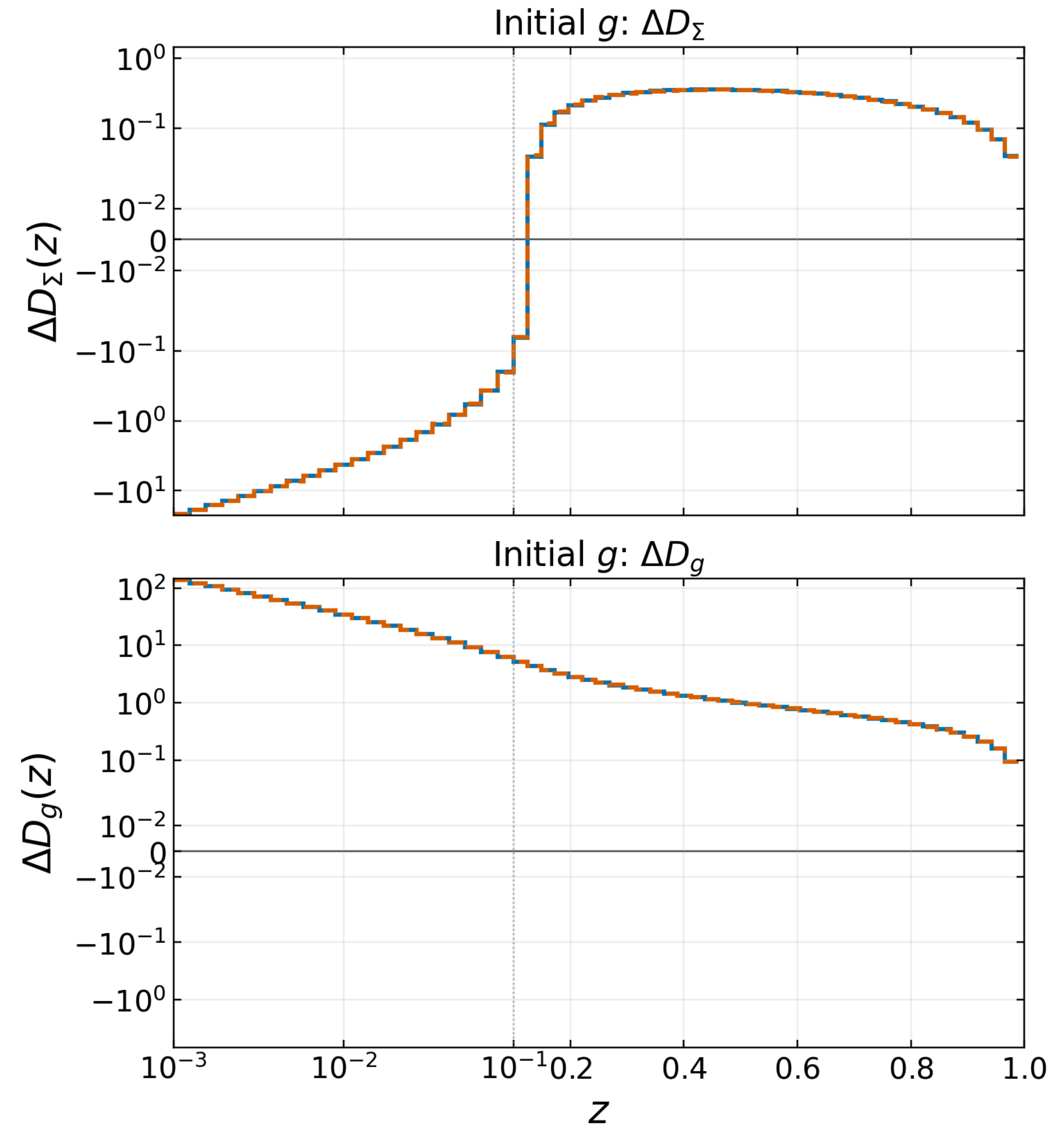
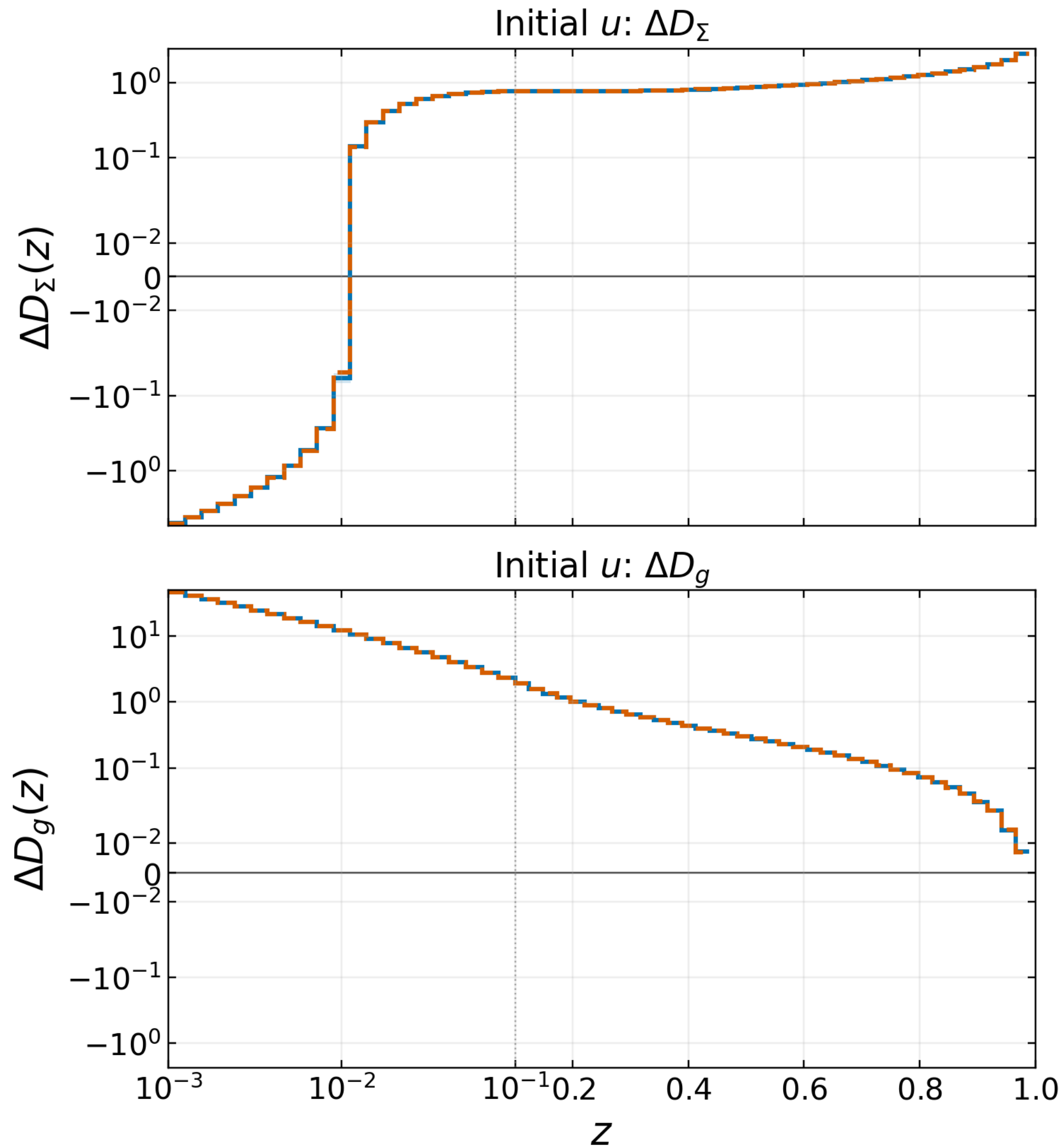


Polarized Parton Shower — fixed helicity (probabilities)



Polarized Parton Shower — fixed helicity (probabilities)

— probabilistic helicity (p_+, p_-) - - - piecewise Mellin DGLAP
 $Q = 91.2 \text{ GeV} \rightarrow Q_0 = 1 \text{ GeV}; N_f: 5 \rightarrow 4 \rightarrow 3, \text{ seed helicity } +1$



Initial u : 10,000,000 events; initial g : 10,000,000 events

Polarized Initial State Parton Shower

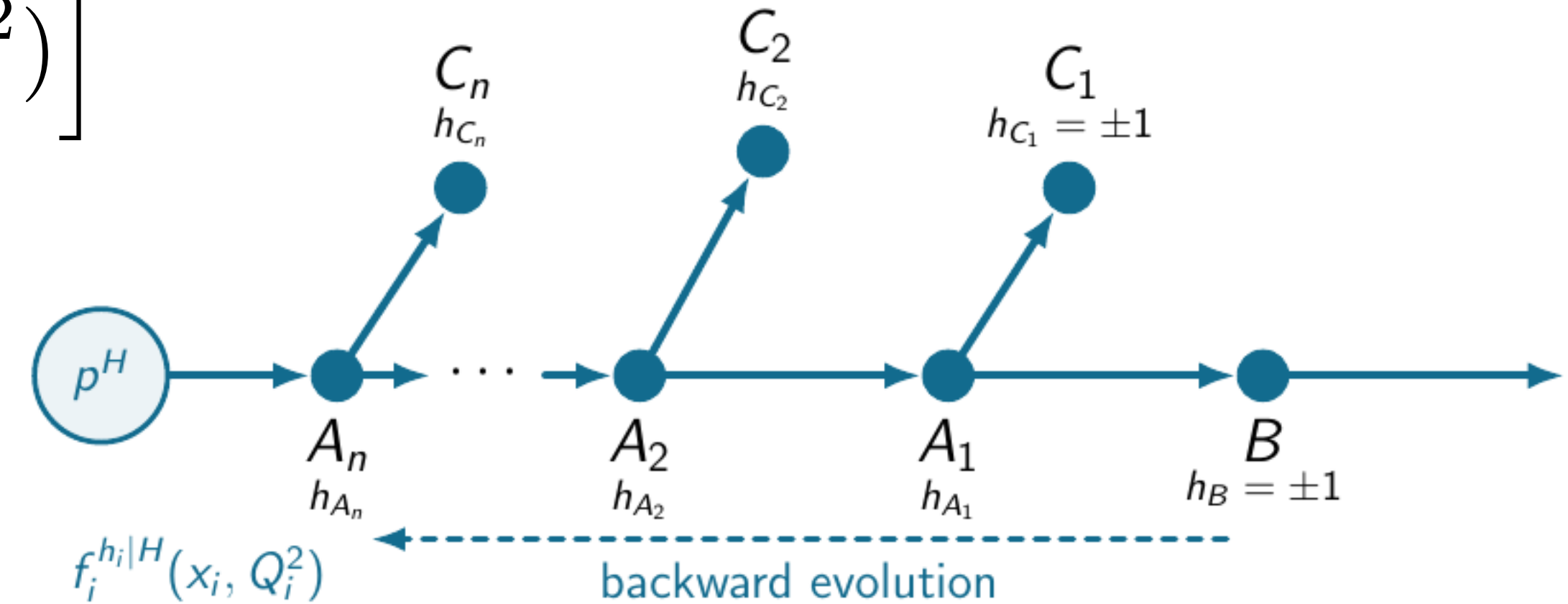
For proton helicity $H = \pm 1$ & parton helicity $h = \pm 1$

$$f_i^{h|H}(x, Q^2) = \frac{1}{2} \left[f_i(x, Q^2) + Hh\Delta f_i(x, Q^2) \right]$$

Define,

$$f_i^+ \equiv f_i^{+1|H} \quad \text{and} \quad f_i^- \equiv f_i^{-1|H}$$

$$\implies f_i = f_i^+ + f_i^- \quad \text{and} \quad \Delta f_i = H(f_i^+ - f_i^-)$$



We use: $f_i(x, Q^2) = f_i^{\text{NNPDF4.0MC LO}}(x, Q^2)$

J. Cruz-Martinez et al., JHEP 09 (2024)

$$\Delta f_i(x, Q^2) = \Delta f_i^{\text{BDSSV24}}(x, Q^2).$$

I. Borsa et al., PRL 133 (2024)

Polarized Initial State Parton Shower

The forward contribution from parent $\left(a, h_a, \frac{x}{z}\right)$ to child (b, h_b, x) is,

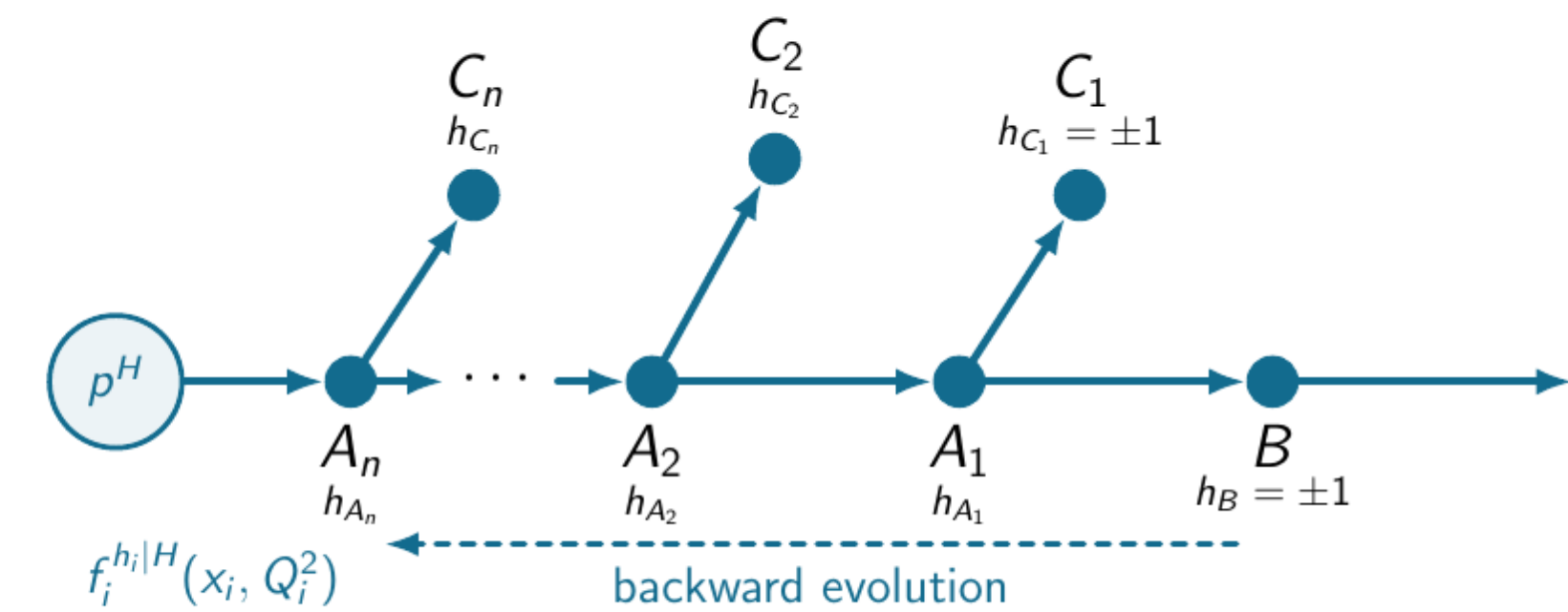
$$d\rho_b^{h_b|H}(x) \sim d\tau dz P_{bh_b \leftarrow ah_a}(z) \rho_a^{h_a|H}(x/z, Q^2),$$

where $\rho_i^{h|H} = x f_i^{h|H}$

Converting forward DGLAP into backward branching probability,

$$d\mathcal{P}_{bh_b \rightarrow ah_a}^H = dz P_{bh_b \leftarrow ah_a}(z) \frac{\rho_a^{h_a|H}(x/z, Q^2)}{\rho_b^{h_b|H}(x, Q^2)}$$

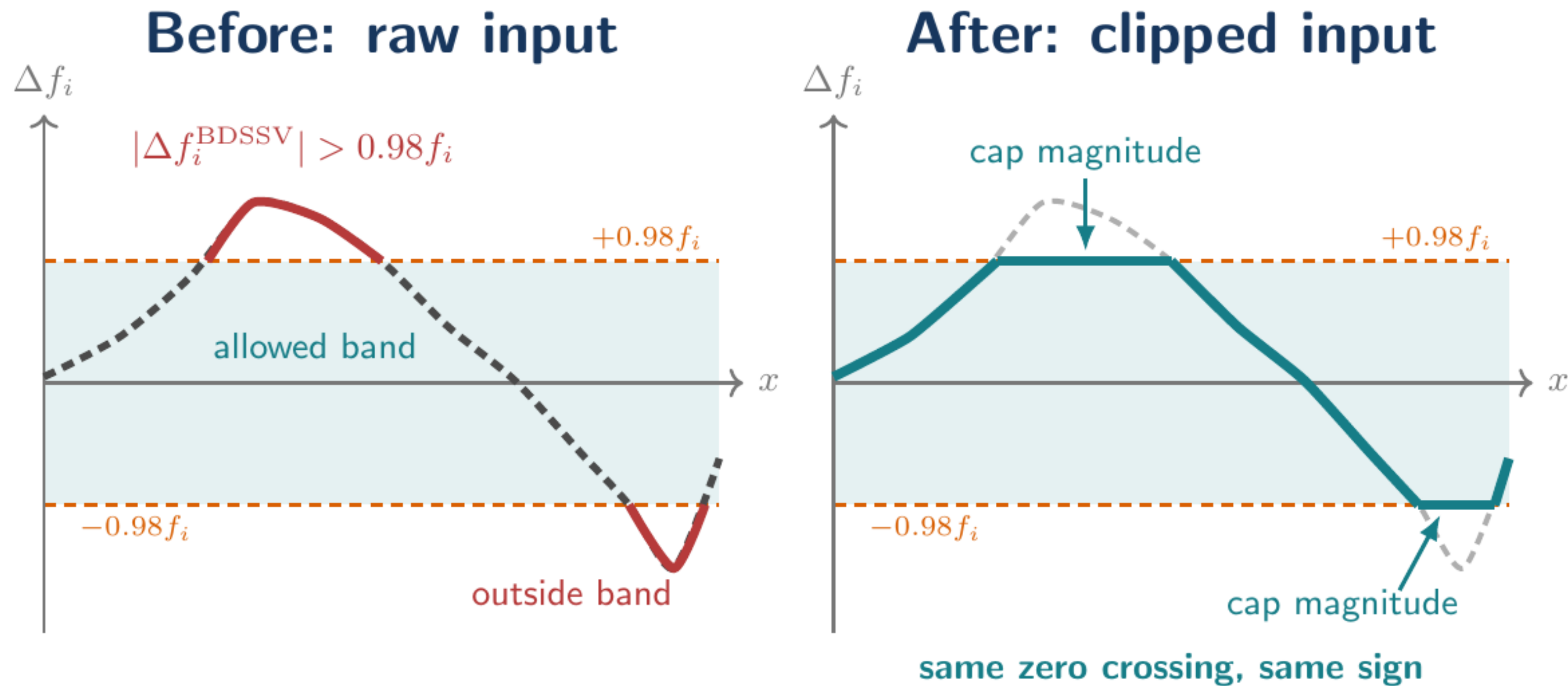
$$\therefore f^\pm > 0 \quad \implies \quad |\Delta f| < f$$



Polarized Initial State Parton Shower

Enforcing $|\Delta f_i| < f_i$,

$$\Delta f_i^{\text{eff}}(x, Q^2) = \text{clip}(\Delta f_i^{\text{BDSSV}24}(x, Q^2), -0.98 f_i^{\text{NNPDF4.0MC LO}}(x, Q^2), +0.98 f_i^{\text{NNPDF4.0MC LO}}(x, Q^2)) .$$

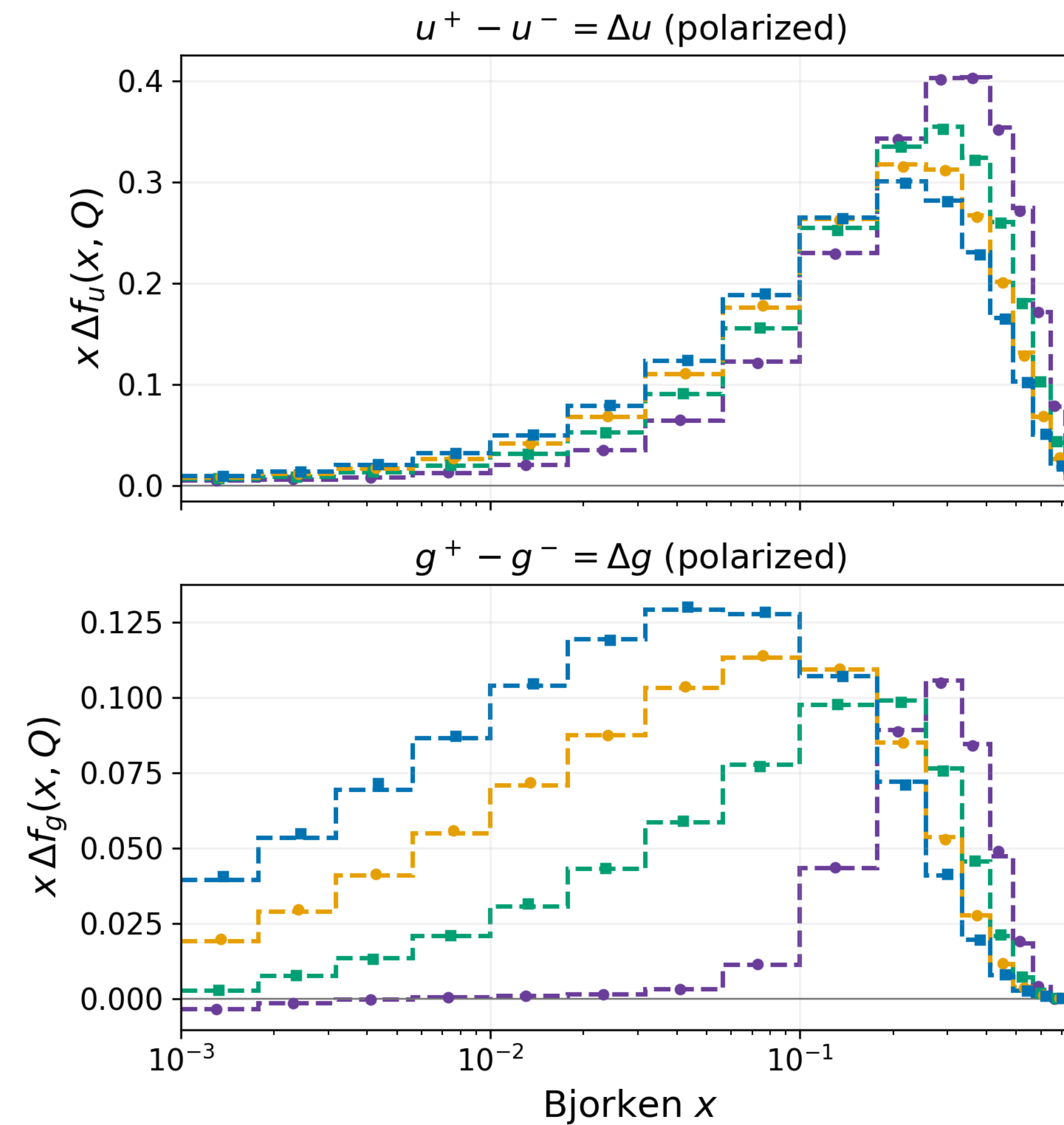
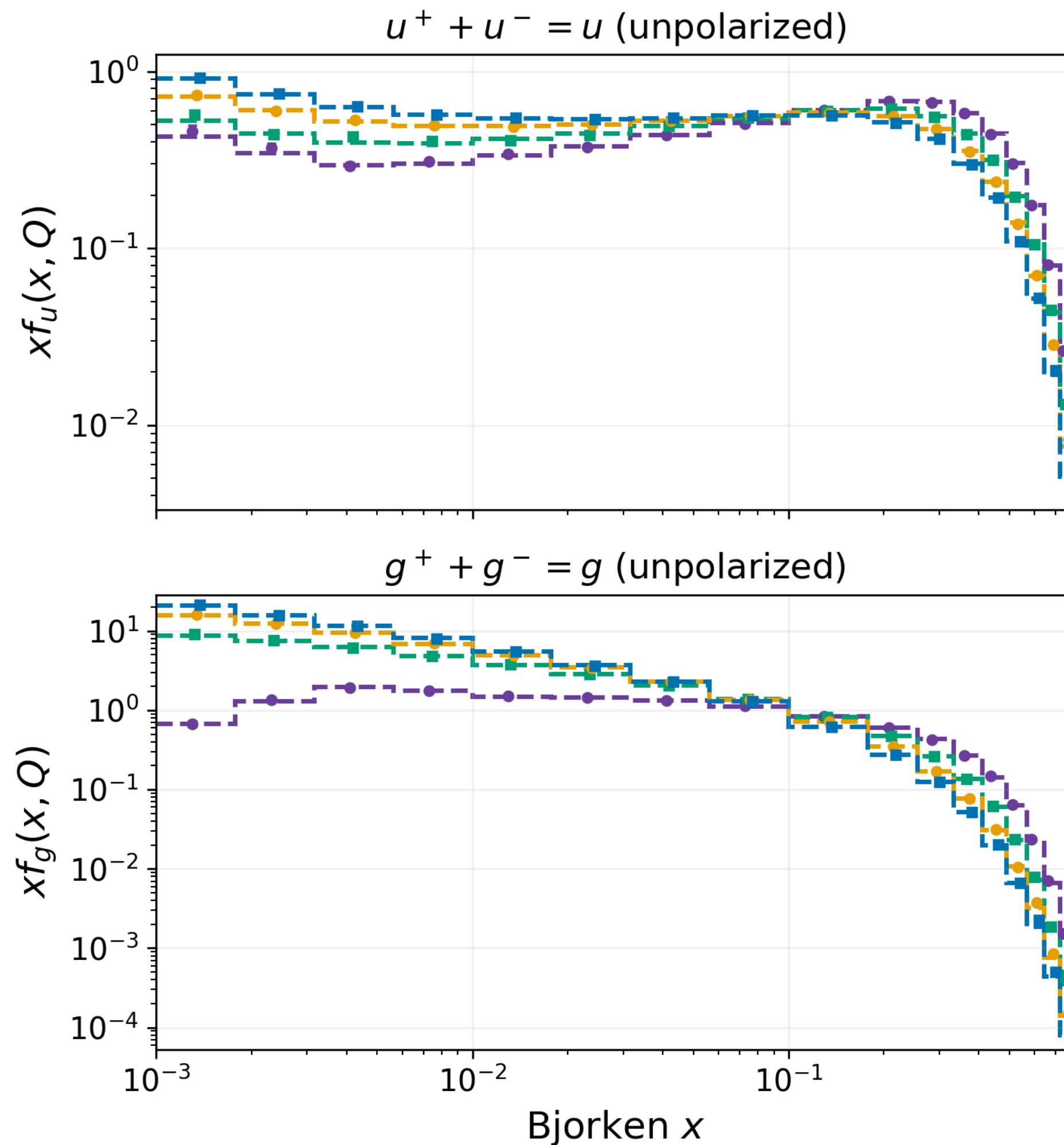


Polarized Initial State Parton Shower

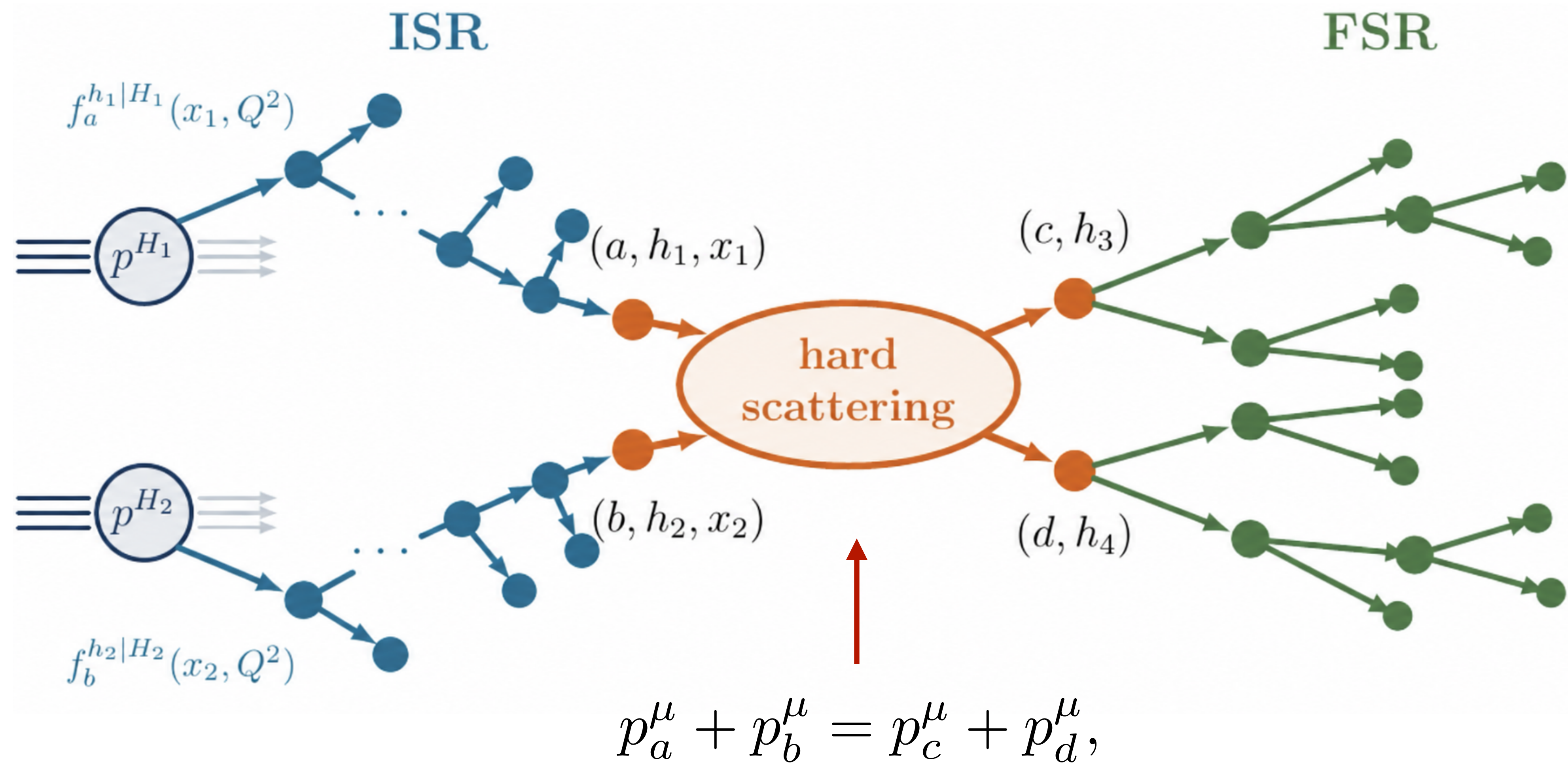
Full-ensemble fixed-helicity backward ISR: $Q_H = 91.2$ GeV $\rightarrow$ lower scales

all flavor/helicity hard states; 2,200,000 histories

$\text{---}\bullet\text{---}$ $Q = 1.01$ GeV $\text{---}\bullet\text{---}$ $Q = 10$ GeV --- independent Mellin DGLAP
 $\text{---}\blacksquare\text{---}$ $Q = 3$ GeV $\text{---}\blacksquare\text{---}$ $Q = 30$ GeV $\bullet$ backward ISR histories



Complete Shower



- pp collision here and can be adapted to the ep collisions at the EIC.

Complete Shower

- Helicity resolved hard process supplies all four correlated helicities and defines the boundary conditions for both showers.

$$d\sigma_{H_1 H_2} \propto \sum_{\substack{a,b,c,d \\ h_1,h_2,h_3,h_4}} f_a^{h_1|H_1}(x_1, Q^2) f_b^{h_2|H_2}(x_2, Q^2) |\mathcal{M}_{h_1 h_2 h_3 h_4}^{ab \rightarrow cd}(\Phi)|^2 d\Phi$$

ISR Boundary conditions:

(a, h_1, x_1)

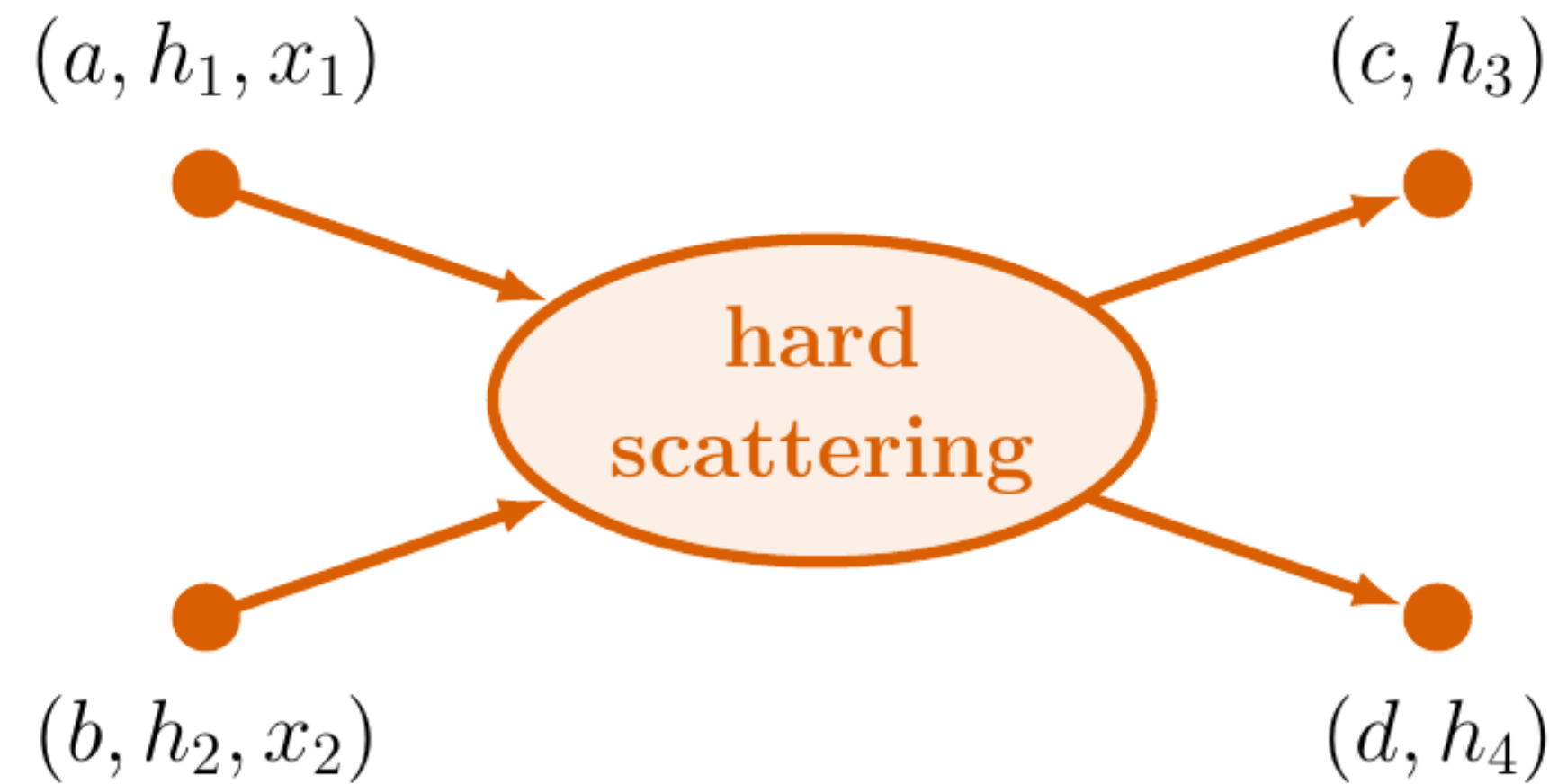


Evolve to
proton 1

(b, h_2, x_2)



Evolve to
proton 2



FSR Roots:

(c, h_3)



Evolve forward
through FSR

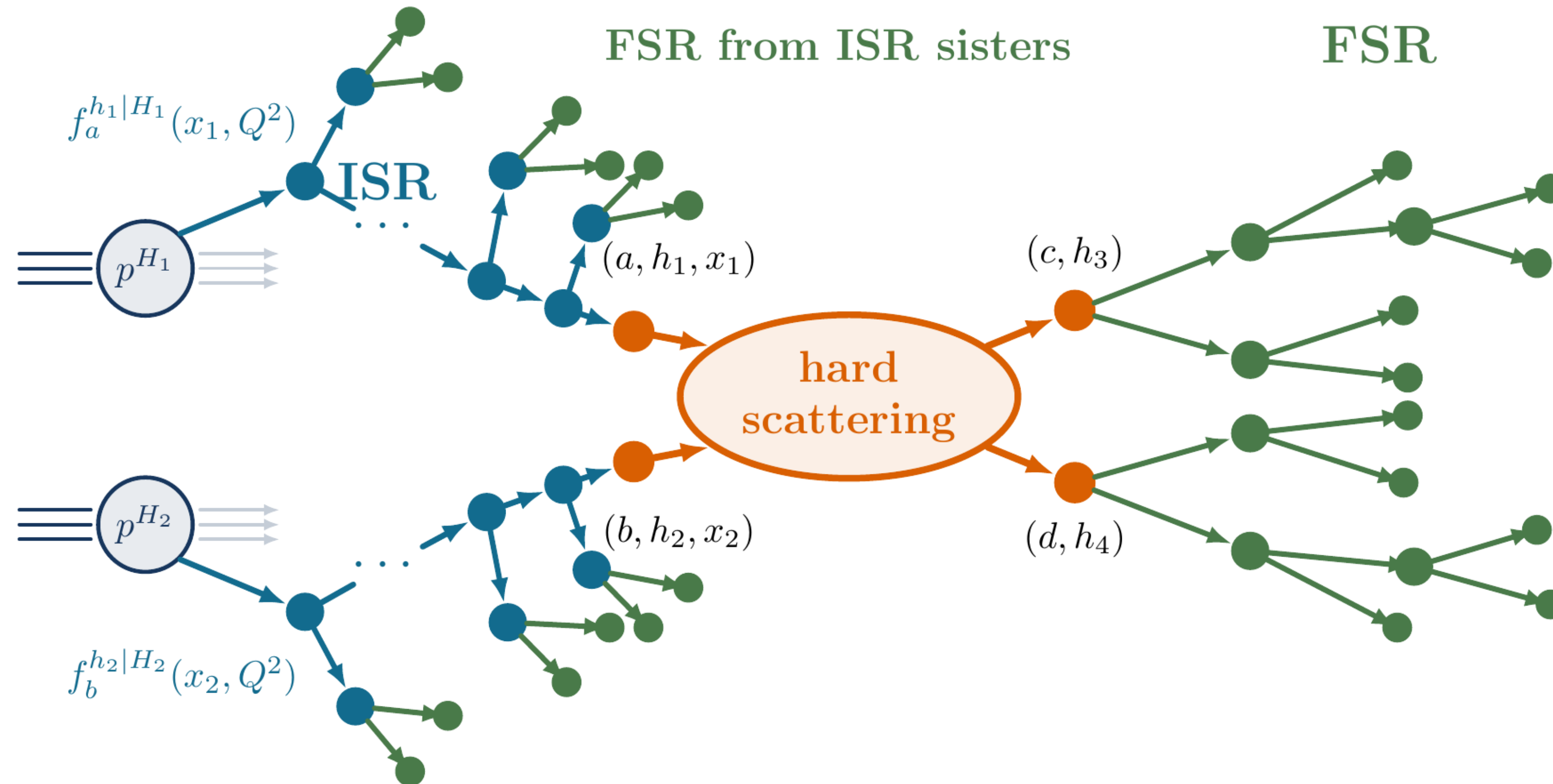
(d, h_4)



Evolve forward
through FSR

Complete Shower

The parent continues backward, while the sister becomes an FSR root.



Final state leaves: FSR from hard outgoing partons + FSR from ISR sisters

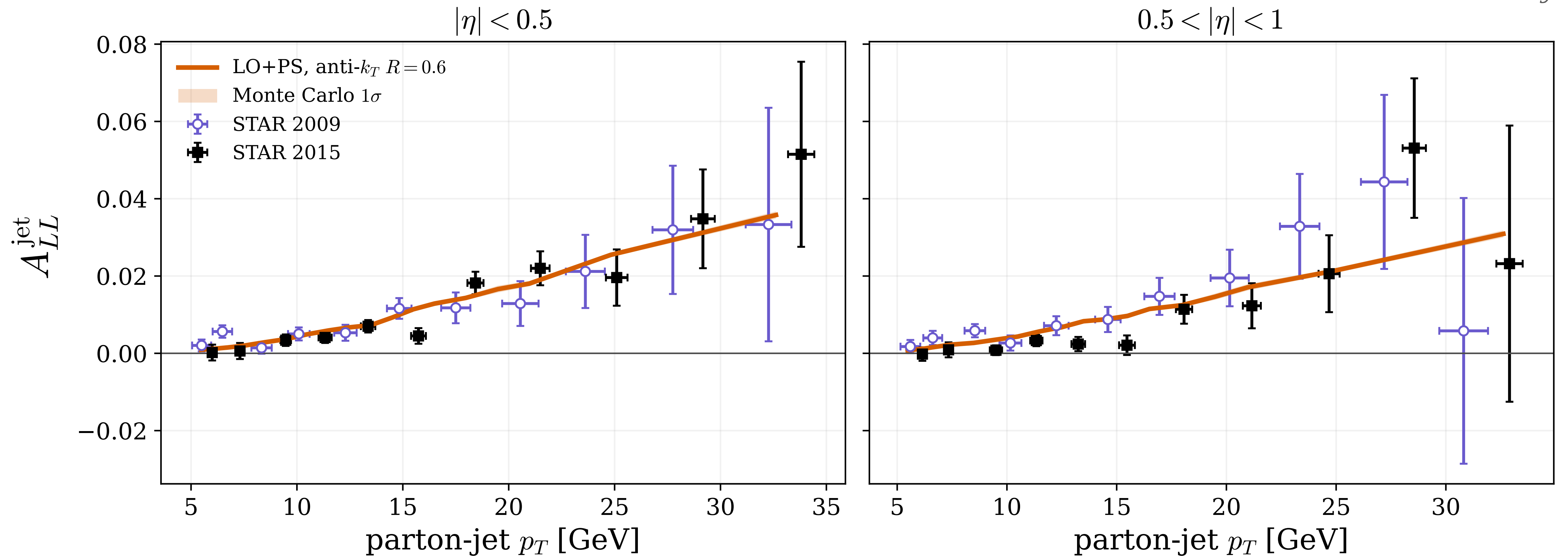
Cluster the final state leaves together into jets with E-scheme anti- k_T .

Complete Shower

Jet spectra, $d\sigma^{++}, d\sigma^{+-} \Rightarrow A_{LL}^{\text{jet}} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$

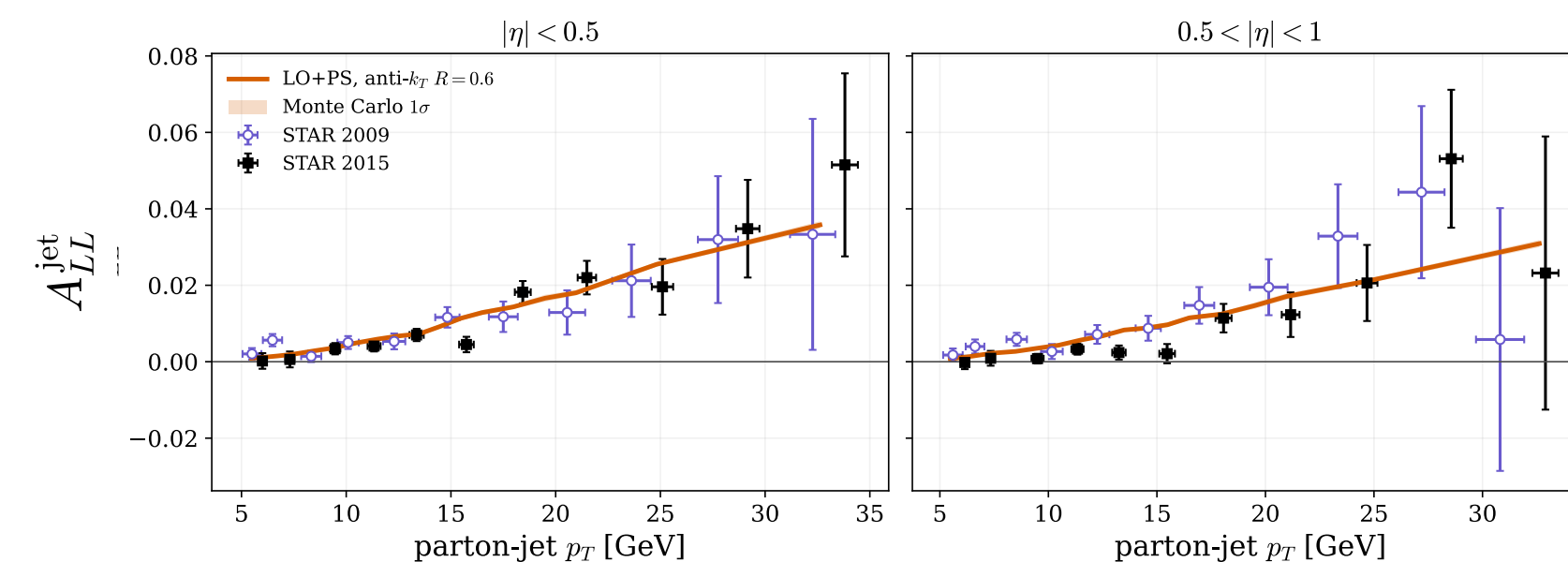
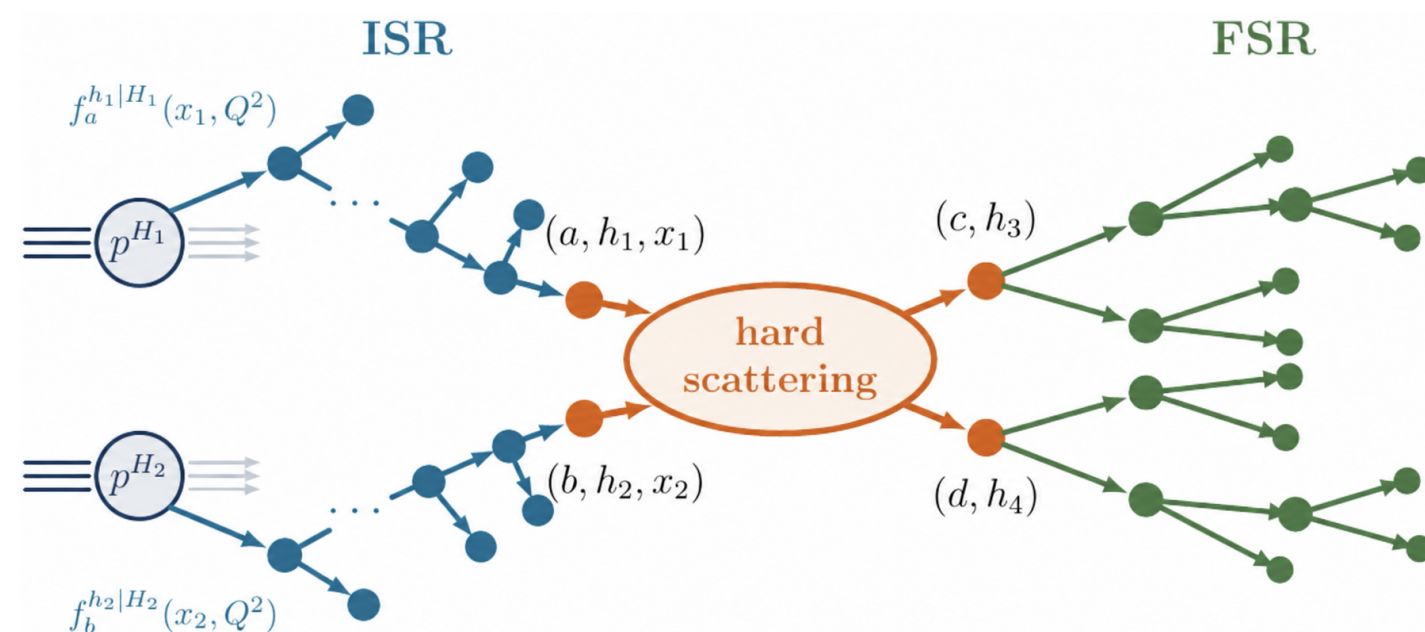
Helicity-resolved $pp \rightarrow \text{jet} + X$ at $\sqrt{s} = 200$ GeV

Preliminary



Conclusion

- A helicity-resolved framework consistently connects the polarized hard process with ISR and FSR.
- Helicity information is propagated through the complete shower history.
- Study which jet observables and kinematic regions are most sensitive to helicity-dependent radiation.
- The framework can be extended toward a more complete and realistic simulation of polarized collision events.



Thank you