

HERWIG 7 Developments for the Electron-Ion Collider

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The Plan

🌀 **Part I:** A Brief Introduction to **HERWIG 7**

→ Recent & upcoming features.

🌀 **Part II:** **HERWIG 7** for the **EIC**,

→ Photoproduction & Polarized Scattering.

🌀 **Conclusions & Outlook**

Part I: A Brief Introduction to **HERWIG 7**



HERWIG = Hadron Emission Reactions With Interfering Gluons.

 **HERWIG 5.1** [Marchesini et al., Comput. Phys. Commun. 67 (1992) 465–508.]

FORTRAN; final version: 6.521 [March 11th, 2013]

Features: Angular-ordered parton shower $\oplus$ cluster hadronization model.

 **Rewritten** in C++ $\rightarrow$ **HERWIG++** [Gieseke, Ribon, Seymour, Stephens, Webber, hep-ph/0311208],

based on **ThePEG** = Toolkit for High Energy Physics Event Generation [Lönnblad].

 HERWIG++ 3.0 was released as **HERWIG 7.0**.

Latest stable version $\rightarrow$ **7.3.0** (December 2023), **7.4.0** forthcoming!

New HERWIG 7 physics manual out! [arXiv:2512.16645].



HERWIG 7 Feature Overview

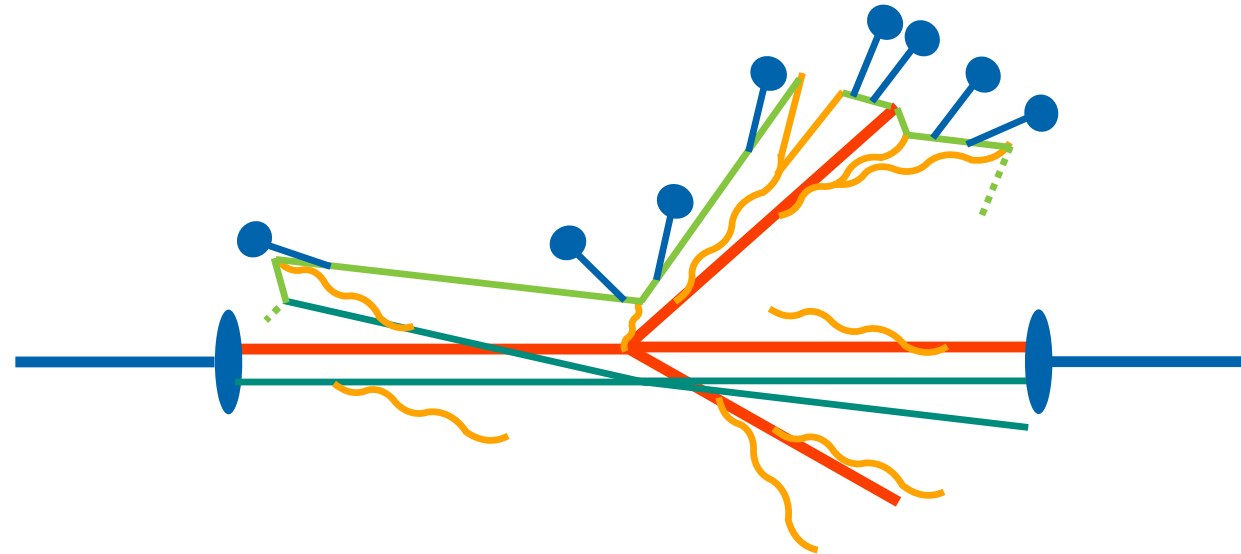
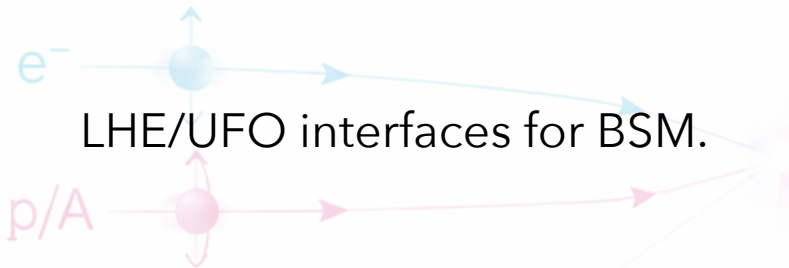
Angular-ordered parton shower & Dipole shower
[with **spin correlations!**],

Automated NLO matching/NLO multijet merging
[& FxFx merging with MG5_aMC],

Cluster and string hadronization models,

Eikonal MPI model, Colour-reconnection model,

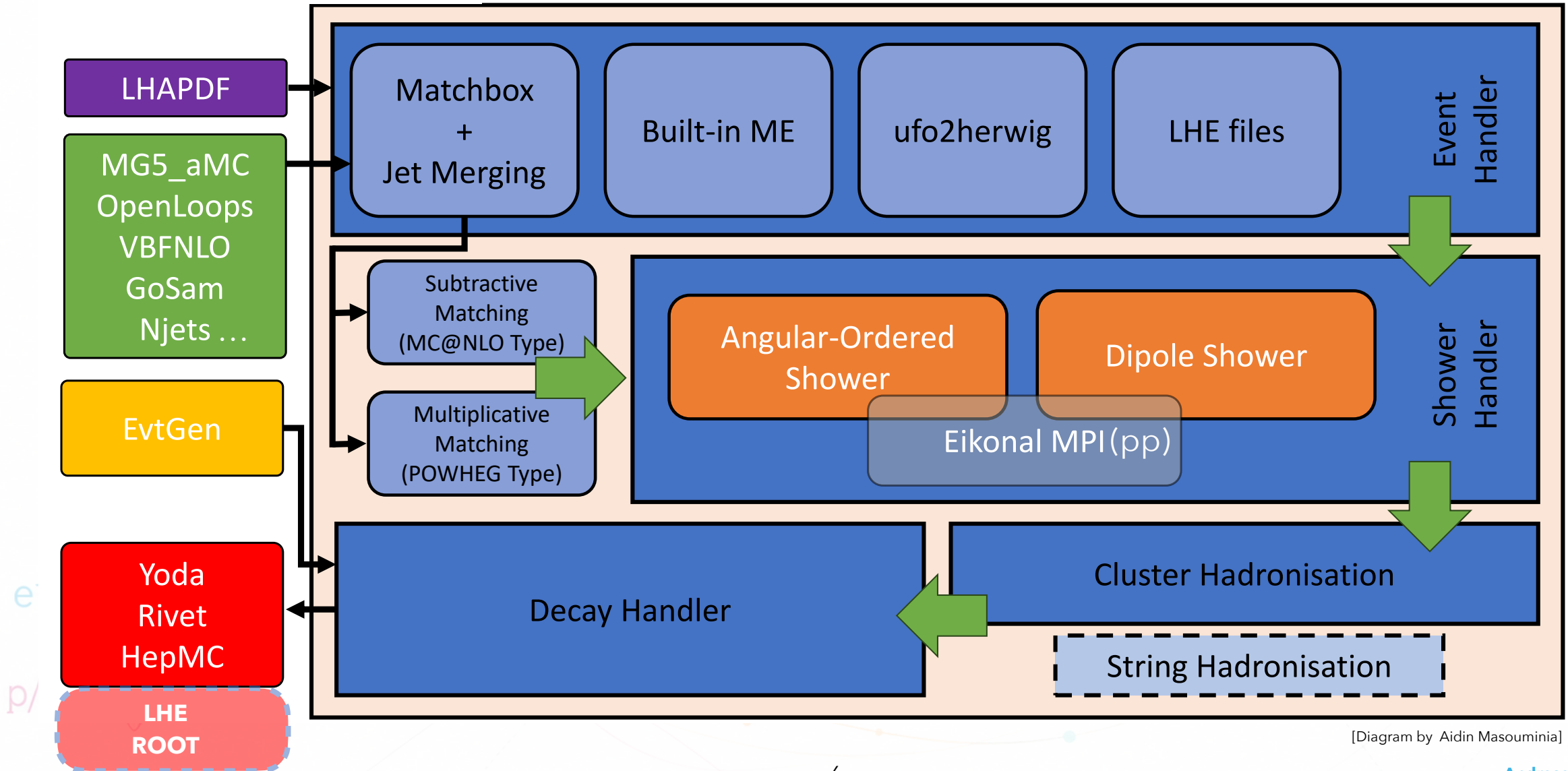
LHE/UFO interfaces for BSM.



[Diagram by Simon Plätzer]

Under the Hood

HERWIG 7



[Diagram by Aidin Masouminia]

Recent and Upcoming HERWIG 7 Developments

EW parton shower improvements. [Masouminia, Richardson, arXiv:2108.10817, arXiv:2602.19927],

Generalized (BSM) parton showers [Darvishi, Masouminia, Richardson, to appear],

Dark showers [Kulkarni, Masouminia, Plätzer, Stafford, arXiv:2408.10044],

Quarkonium parton shower [Masouminia, Richardson, arXiv:2508.06307],

Tune of interleaving parameters against coherence-sensitive observables in QCD+QED+EW parton shower: [Masouminia, Seymour, Sule, to appear],

NLL parton shower [Forshaw, Holguin, Plätzer, arXiv:2003.06400, Holguin, Plätzer, Seymour, Sule, arXiv:2605.02622],

Spin correlations in the parton shower with polarized beams [Masouminia, AP, Richardson, arXiv:2606.23845, Baldonado, Masouminia, AP, Richardson, to appear].

“Blob” Matrix Elements/Non-trivial vacua → EW Sphalerons & QCD Instantons [AP, Plätzer, Sakurai, arXiv:1910.04761, Cormier, Jin, Kirchgaesser, AP, Plätzer, in progress].

KrkNLO matching for single- and diboson production [Sarmah, Siódmok, Whitehead, arXiv:2511.16605].

String hadronization in HERWIG 7 [Divisova, Myska, Sarmah, Siódmok, arXiv:2509.02348],

New cluster model developments [Plätzer, arXiv:2204.06956, Hoang, Jin, Plätzer, Samitz, arXiv:2404.09856, Gieseke, Kiebacher, Plätzer, Friedigkeit, arXiv:2505.14542],

Hadronization and decays of excited hadrons on HQET [Masouminia, Richardson, arXiv:2312.02757].

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String Hadronization in HERWIG 7

[Divisova, Myska, Sarmah, Siódmok, arXiv:2509.02348]

- 🎯 **PYTHIA hadronization: Lund string model** → interaction between colour-charged quarks as a colour flux tube → a relativistic **string**.
- 🎯 **HERWIG/SHERPA: Cluster model** → colour-connected partons combine into colour-singlet groups → **clusters**.
- 🎯 Advantages & disadvantages:

String	Cluster
👍 very predictive framework for how space-time motion & breakup translate into energy-momentum distribution of hadrons	👎 less dynamical space-time picture
👎 many parameters related to flavour properties	👍 more predictive flavour composition



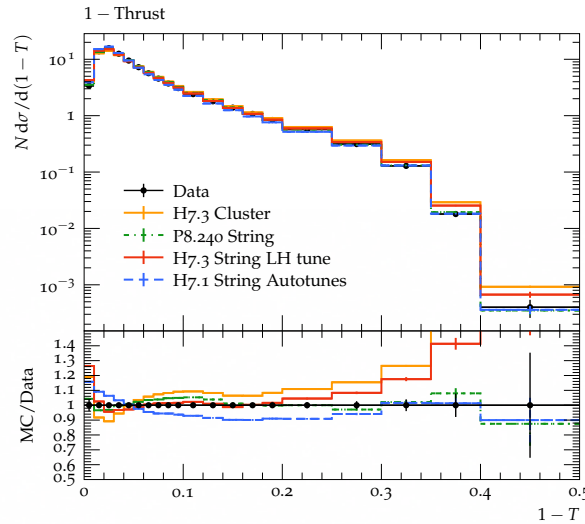
String Hadronization in HERWIG 7

[Divisova, Myska, Sarmah, Siódmok, arXiv:2509.02348]

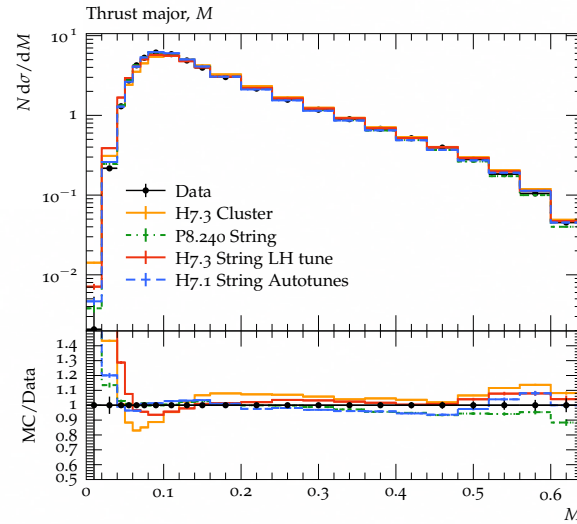


String model via TheP8I; new LH tune planned for **HERWIG 7.4**.

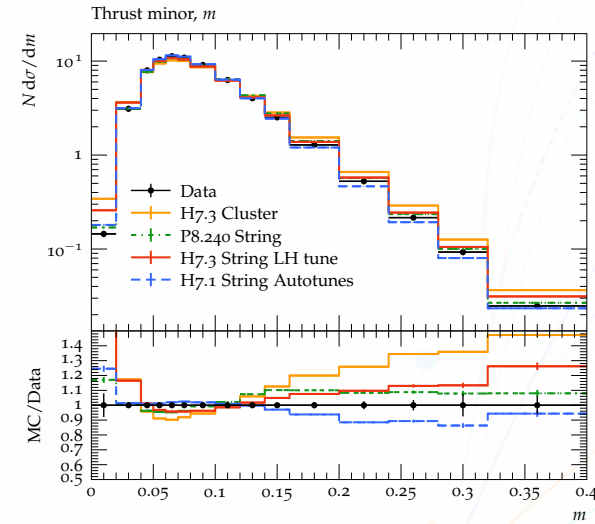
DELPHI



(a) Thrust, $1 - T$

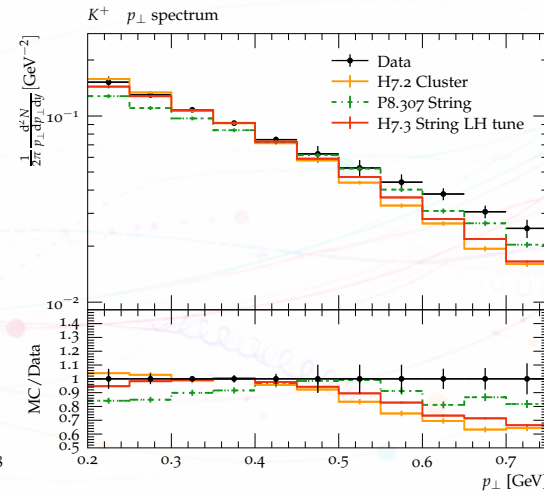
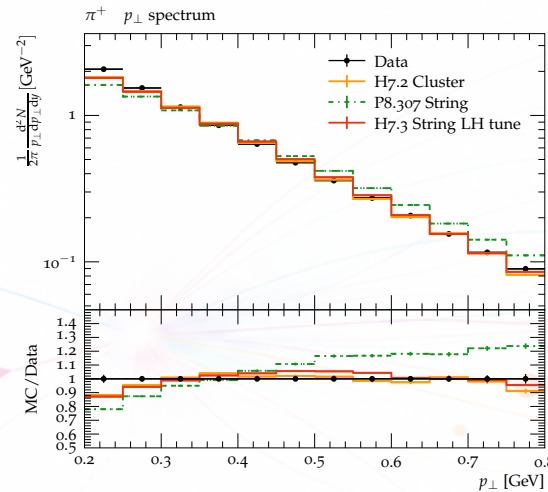
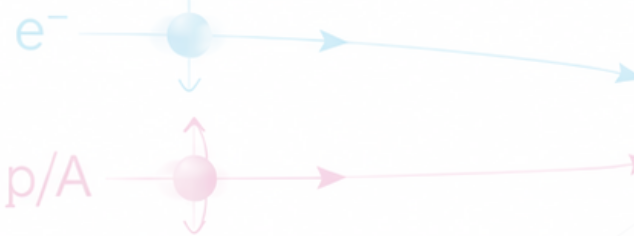


(b) Thrust Major, M



(c) Thrust Minor, m

STAR



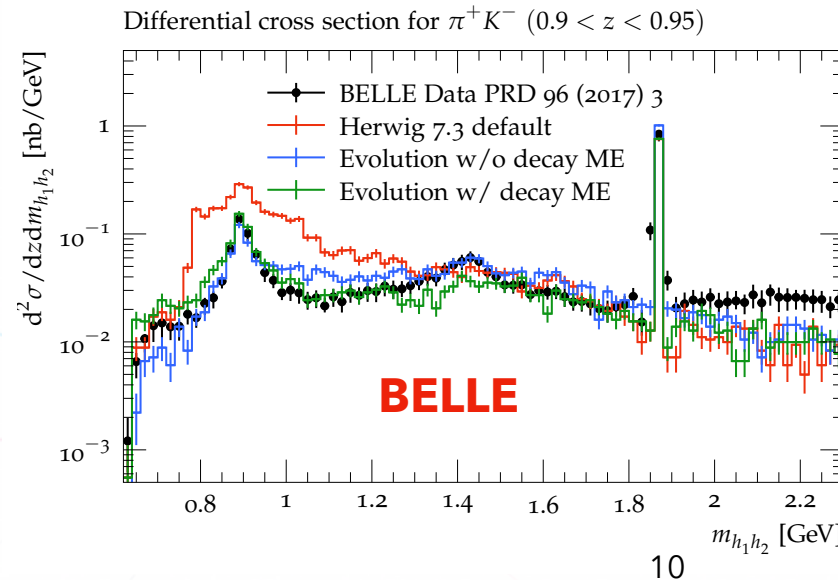
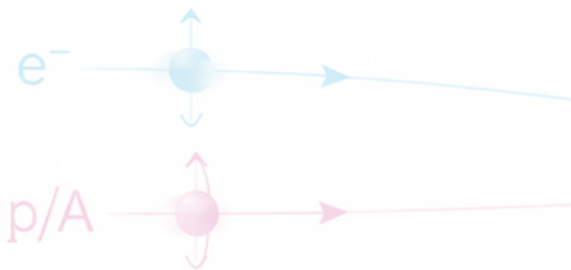
New Cluster Model Developments

[Plätzer, arXiv:2204.06956, Hoang, Jin, Plätzer, Samitz, arXiv:2404.09856, Gieseke, Kiebach, Plätzer, Priedigkeit, arXiv:2505.14542]

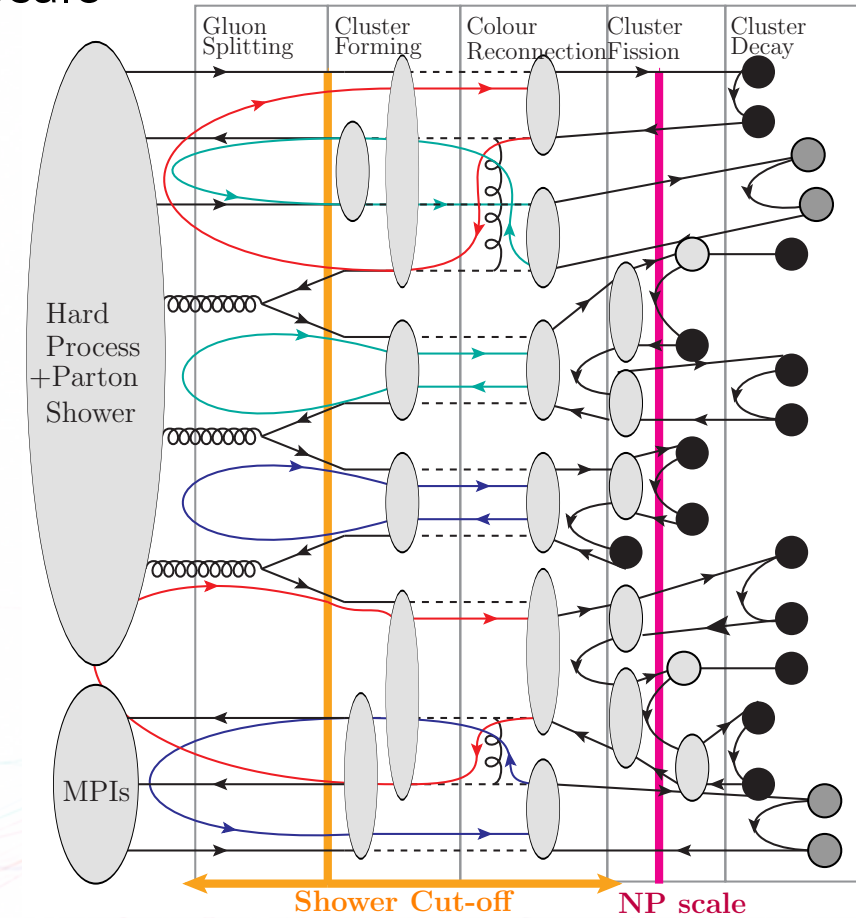
IR colour evolution motivates viewing **cluster fission** as a low-scale perturbative process.

New developments:

- cluster fission as a factorized partonic process.
- ME-inspired sampling for cluster masses & decay angles.
- Clear separation between cluster fission (perturbative) & cluster decay.

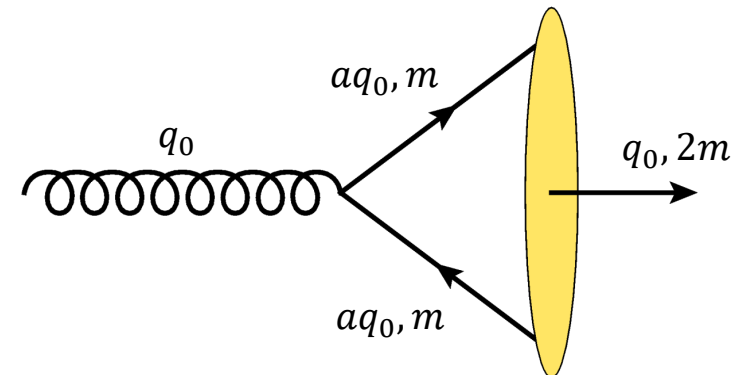
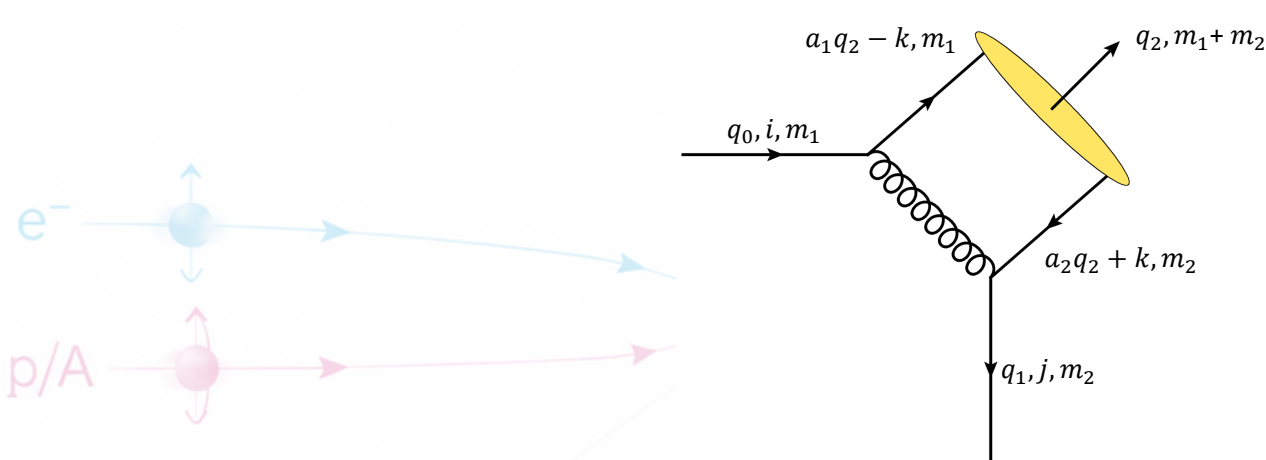


* clusters with $M > 3\text{--}4 \text{ GeV}$
fission (CF) → then light clusters decay into hadrons (CD).



Quarkonium Parton Shower

- 🎯 **Quarkonia:** flavour-neutral heavy $Q\bar{Q}$ bound states.
- 🎯 **Rich spectroscopy** $\rightarrow$ stringent tests of QCD, including **spin dependence** & effects of gluon exchange.
- 🎯 **Challenge:** interplay between perturbative & non-perturbative dynamics.
- 🎯 **NRQCD** (heavy-quark velocity $\ll 1$) $\rightarrow$ short-distance coefficients computed perturbatively, long-distance matrix elements encode hadronization.
- 🎯 Process-independent **quarkonium parton shower** in **HERWIG 7**, e.g.: [Masouminia, Richardson, arXiv:2508.06307]

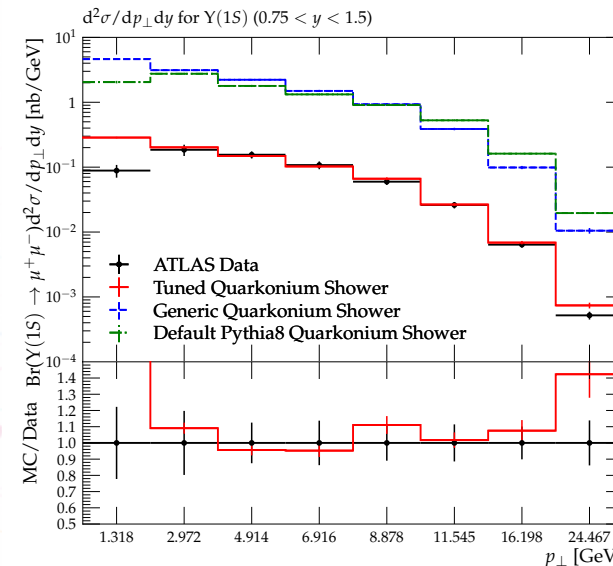
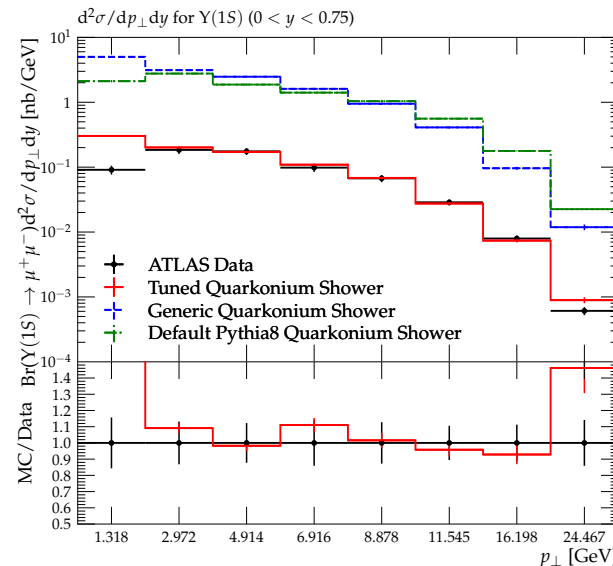
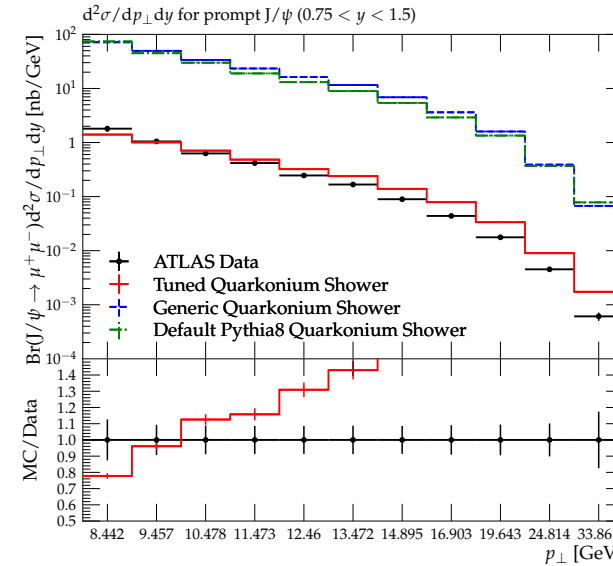
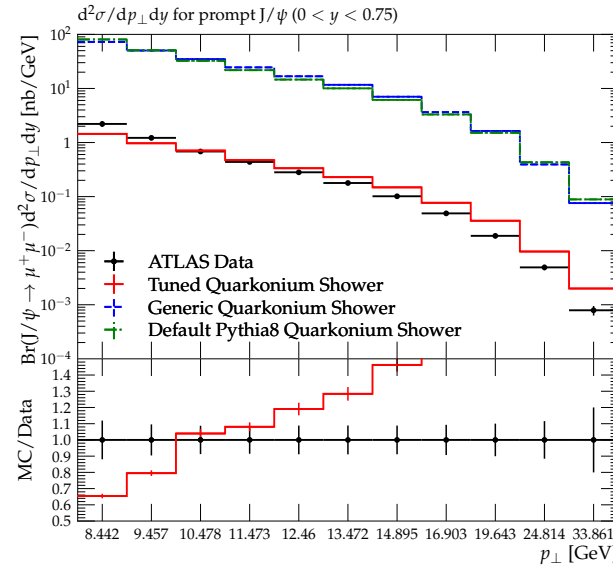


Quarkonium Parton Shower

[Masouminia, Richardson, arXiv:2508.06307]

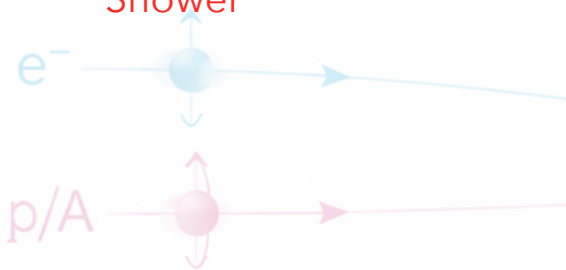
Prompt production of J/ψ and Υ states.

ATLAS data compared with **PYTHIA 8**, the default **HERWIG 7** shower and the tuned **HERWIG 7** Quarkonium Shower



Improves description of observables, in the intermediate – high- p_T regimes.

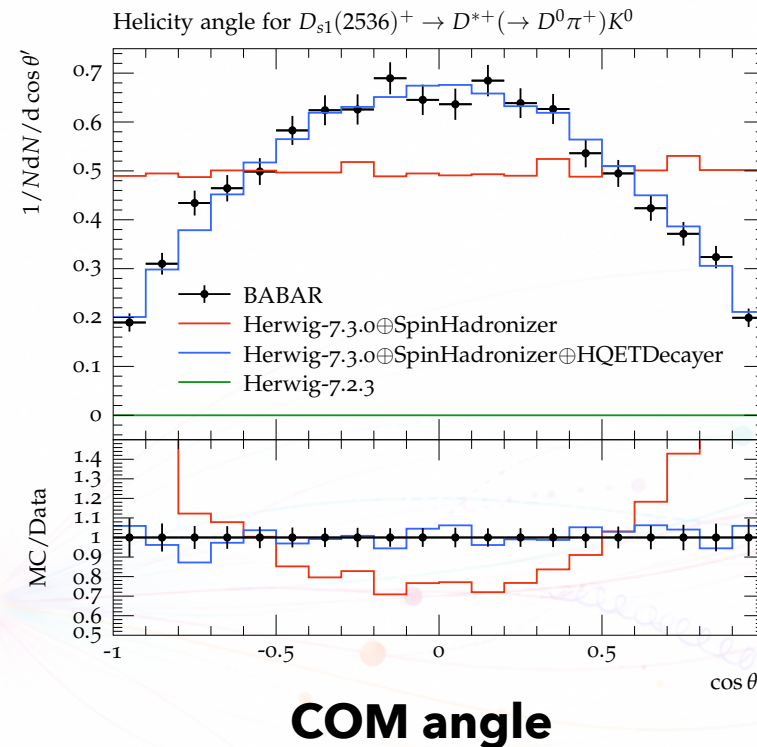
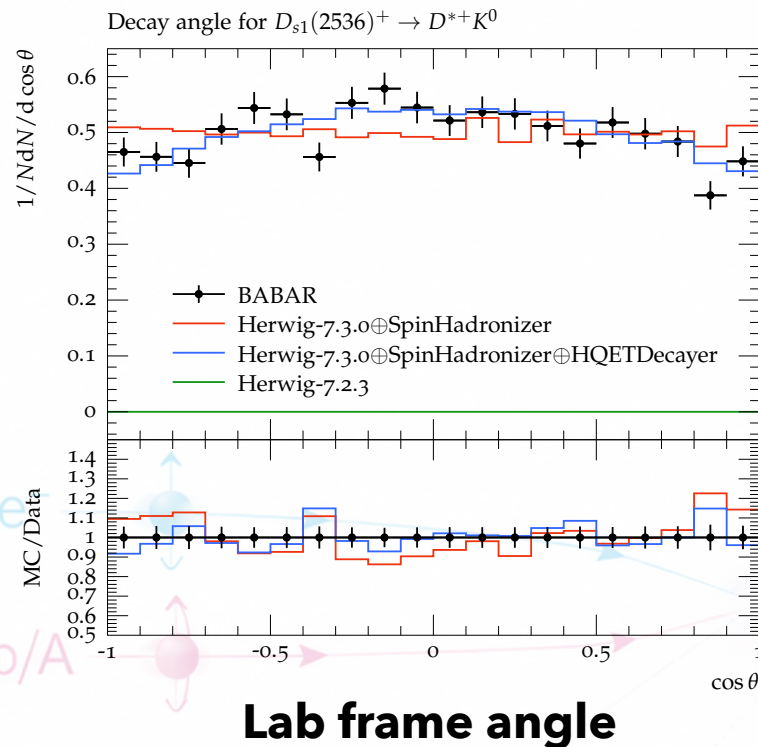
Quarkonium parton shower planned for HERWIG 7.4.



Hadronization & Excited Hadron Decay in HQET

[Masouminia, Richardson, arXiv:2312.02757]

- Pass heavy-quark polarization from the shower to hadronization,
➔ account for **net polarization observed in excited mesons & heavy baryons**.
- Heavy Quark Effective Theory + spin-flavour symmetry.



Data from: Lees et al. [**BaBar**],
Phys. Rev. D 83 (2011), 072003.

Part II: HERWIG 7 for the EIC



Jet Photoproduction at the EIC: Sizeable Generator Spread

HERWIG, PYTHIA, SHERPA comparison for jet photoproduction

[Helenius, Meizinger, Plätzer, P. Richardson, arXiv:2406.08026] → Direct & Resolved production at LEP/HERA/EIC.

EIC predictions (examples):

→ **Large higher-order effects:** SHERPA MC@NLO increases the rate by ~50% relative to LO.

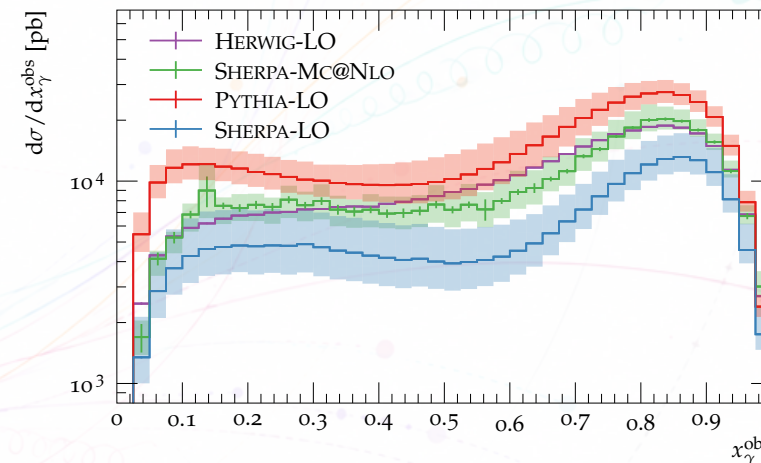
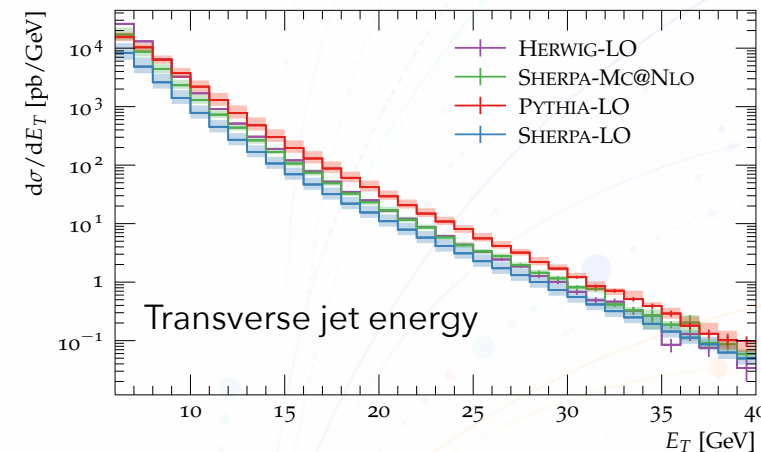
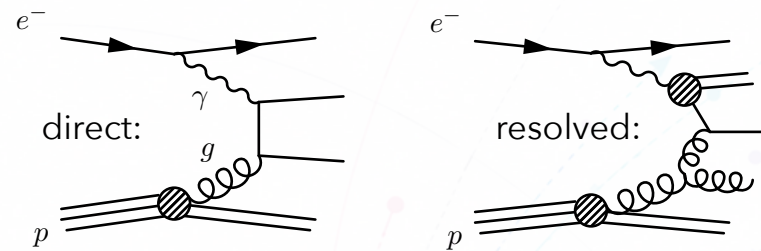
→ **Required:** Modern photon PDFs & better-constrained resolved-photon MPI + shower modeling.

HERWIG 7 TO-DOs:

Complete NLO+PS photoproduction in Matchbox.

Extend MPI from pp to resolved photons.

Improve photon-remnant and event-record handling.



$x_\gamma^{\text{obs}} \simeq 1$: direct-enriched; lower x_γ^{obs} : resolved-enriched.

Why Polarized Scattering?

🌀 Schematically: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g \rightarrow$ Where does proton spin come from?

Goal: constrain quark & gluon helicity contributions to proton spin.

🌀 Fixed-target **DIS/SIDIS** & polarized pp at **RHIC** provide **complementary** constraints.

🌀 **EIC** extends measurements to **high precision & much lower x** , especially for sea quarks and gluons.

➡ Realistic simulations of polarized final states **require** generators that propagate polarization through the **hard process and the parton shower**.

🌀 **Scope here:** **longitudinal polarization** and **collinear helicity** PDFs.



Spin Correlations in Parton Showers: A Short Review



Original spin-density matrix algorithm → **Collins & Knowles**, originally in **HERWIG 5.1**. [Collins, Nucl. Phys. B304,

794 (1988), Knowles, Nucl. Phys. B304, 767 (1988), Knowles, Comput. Phys. Commun. 58, 271 (1990), Knowles, Nucl. Phys. B310, 571 (1988)]

- Extended to heavy-particle production/decay [Richardson, hep-ph/0110108].
- In **HERWIG 7** since version **7.2**, angular-ordered + dipole showers [Richardson, Webster, arXiv:1807.01955].
- More recently in **PanScales**: also accounts for leading- N_c spin correlations in soft emissions [Hamilton,

Medves, Salam, Scyboz, Soye, arXiv:2011.10054, van Beekveld, Ferrario Ravasio, Salam, Soto-Ontoso, Soye, Verheyen, arXiv:2205.02237].



Alternatives exist:

 **Pythia** → no spin-density evolution, uses an azimuthal-modulation prescription [Cabouat, Sjöstrand, arXiv:1710.00391].

 **Sherpa/Alaric** → current-based polarization algorithm [Höche, Hoppe, Reichelt, arXiv:2508.19018].

 **VINCIA** implements $2 \rightarrow 3$ antenna functions, helicities sampled at every shower step [Larkoski, Lopez-Villarejo,

Skands, arXiv:1301.0933, Fischer, Lifson, Skands, arXiv:1708.01736].

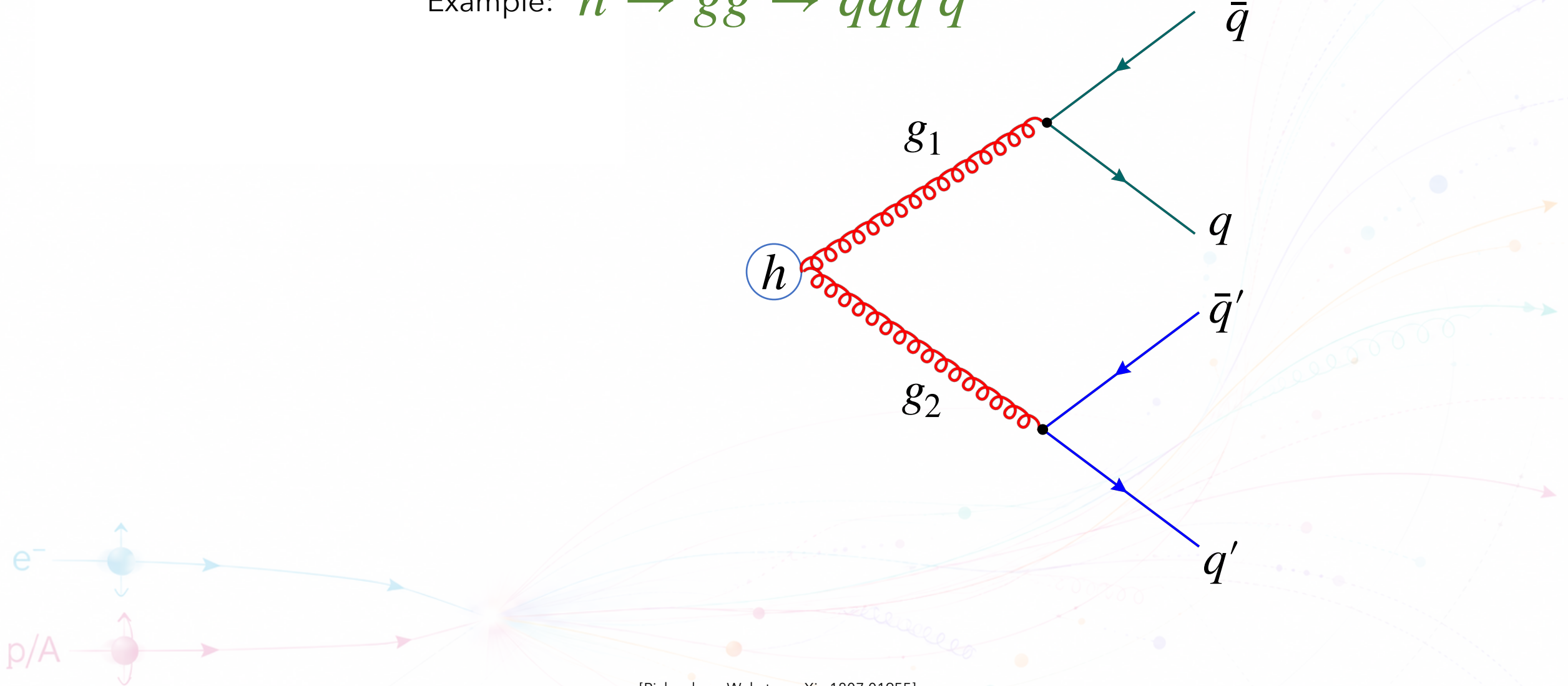
 Amplitude-level evolution ideas **could** incorporate spin correlations [Forshaw, Holguin, Plätzer, arXiv:1905.08686 & arXiv:2003.06400,

Plätzer, Sjöstrand, arXiv:2204.03258, Nagy, Soper, arXiv:0706.0017, Z. Nagy, D. Soper, arXiv:0805.0216].

[*See CMS study using HERWIG vs. PYTHIA: arXiv:2603.03689]

HERWIG 7: Spin Correlations via Collins & Knowles

Example: $h \rightarrow gg \rightarrow q\bar{q}q'\bar{q}'$

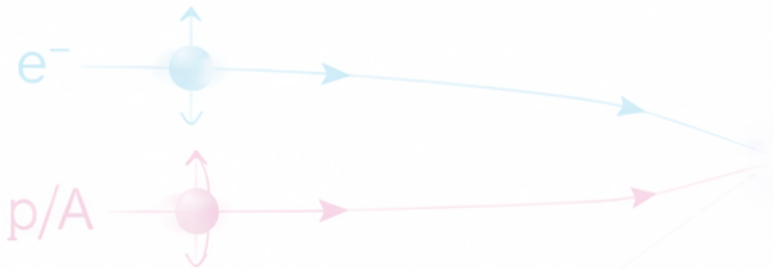
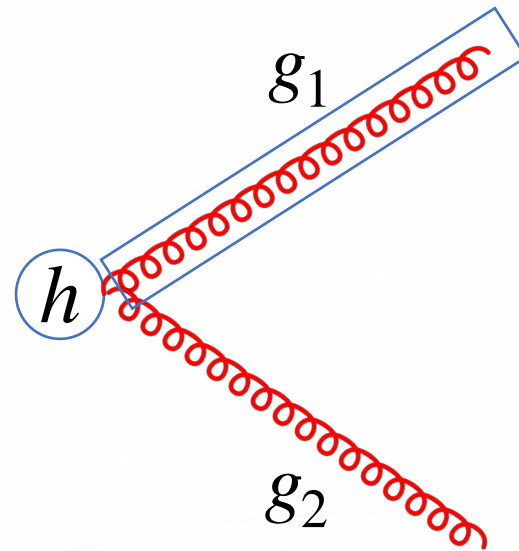


[Richardson, Webster, arXiv:1807.01955]

HERWIG 7: Spin Correlations via Collins & Knowles

Example: $h \rightarrow gg \rightarrow q\bar{q}q'\bar{q}'$

Step 1: generate momenta for $h \rightarrow gg$ using the full matrix element.



[Richardson, Webster, arXiv:1807.01955]

HERWIG 7: Spin Correlations via Collins & Knowles

Example: $h \rightarrow gg \rightarrow q\bar{q}q'\bar{q}'$

Step 2: Select one gluon at random and **calculate the spin-density matrix** for subsequent evolution:

$$\rho_{g1}^{\lambda_{g1}\lambda'_{g1}} = \frac{1}{N} \mathcal{M}_{h \rightarrow gg}^{\lambda_{g1}\lambda_{g2}} \left(\mathcal{M}_{h \rightarrow gg}^{\lambda'_{g1}\lambda_{g2}} \right)^*$$

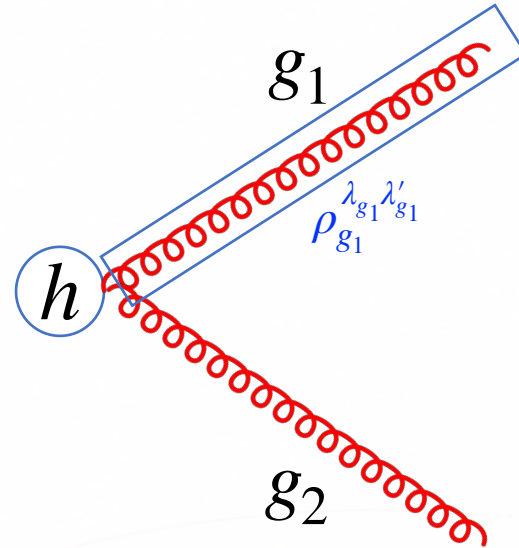
$\lambda_{g1}, \lambda'_{g1}$: polarizations of the first gluon.

λ_{g2} : polarization of the second gluon,

$\mathcal{M}_{h \rightarrow gg}^{xy}$: helicity amplitudes for $h \rightarrow gg$,

N : norm factor such that $\text{Tr } \rho_{g1} = 1$.

[Einstein summation over λ_{g2}]



HERWIG 7: Spin Correlations via Collins & Knowles

Example: $h \rightarrow gg \rightarrow q\bar{q}q'\bar{q}'$

Step 3: Generate parton shower branching; its azimuth depends on the **spin-density matrix**!

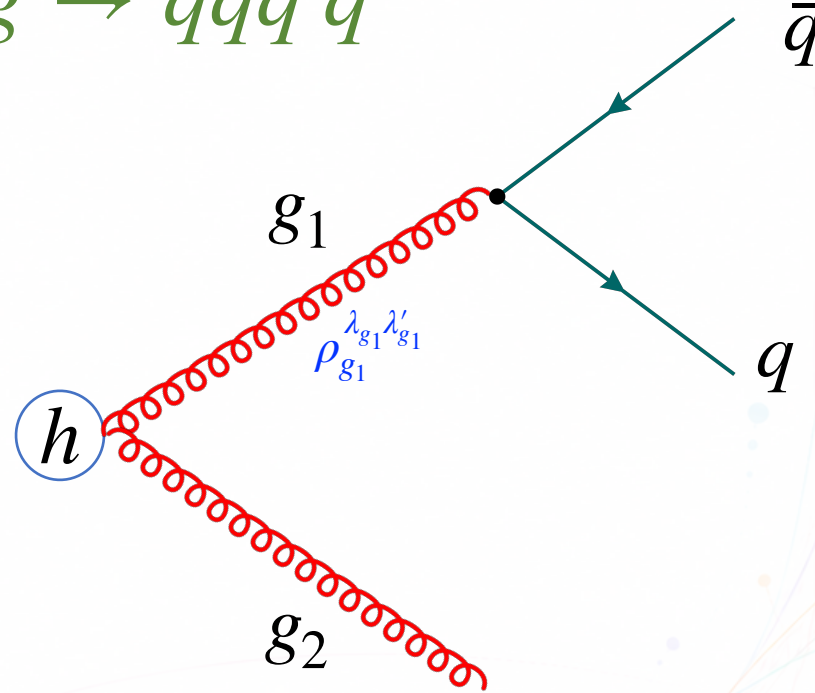
Generated according to the distribution:

$$\rho_{g_1}^{\lambda_{g_1}\lambda'_{g_1}} \mathcal{M}_{g \rightarrow q\bar{q}}^{\lambda_{g_1}\lambda_q\lambda_{\bar{q}}} \left(\mathcal{M}_{g \rightarrow q\bar{q}}^{\lambda'_{g_1}\lambda_q\lambda_{\bar{q}}} \right)^*$$

$\lambda_q, \lambda_{\bar{q}}$: helicities of quark, antiquark.

$\mathcal{M}_{g \rightarrow q\bar{q}}^{xyz}$: helicity amplitudes for $g \rightarrow q\bar{q}$.

$\sum_{\lambda_{g_1}, \lambda'_{g_1}}$ [Einstein summation over $\lambda_{g_1}, \lambda'_{g_1}$]



[Richardson, Webster, arXiv:1807.01955]

HERWIG 7: Spin Correlations via Collins & Knowles

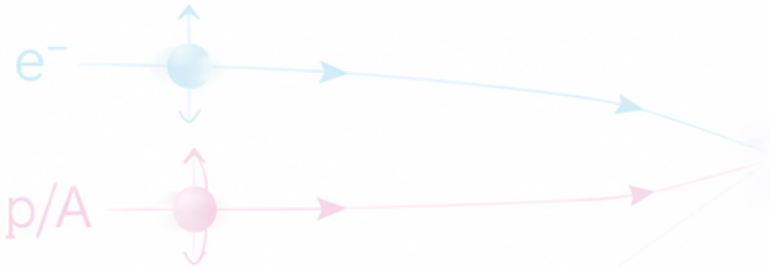
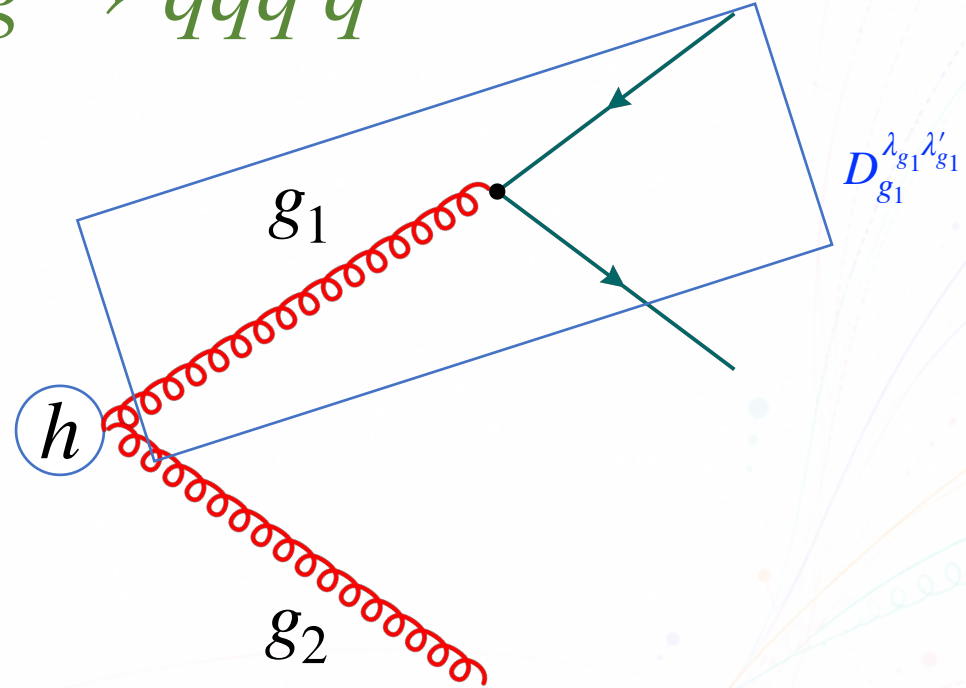
Example: $h \rightarrow gg \rightarrow q\bar{q}q'\bar{q}'$

Step 4: Construct the **decay matrix** D for gluon 1.
If no further emissions:

$$D_{g_1}^{\lambda_{g_1}\lambda'_{g_1}} = \frac{1}{N} \mathcal{M}_{g \rightarrow q\bar{q}}^{\lambda_{g_1}\lambda_q\lambda_{\bar{q}}} \left(\mathcal{M}_{g \rightarrow q\bar{q}}^{\lambda'_{g_1}\lambda_q\lambda_{\bar{q}}} \right)^*$$

N : norm factor such that $\text{Tr } D_{g_1} = 1$,

[Einstein summation over $\lambda_q, \lambda_{\bar{q}}$]



[Richardson, Webster, arXiv:1807.01955]

HERWIG 7: Spin Correlations via Collins & Knowles

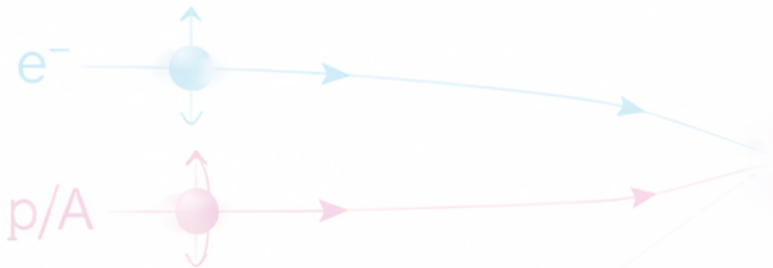
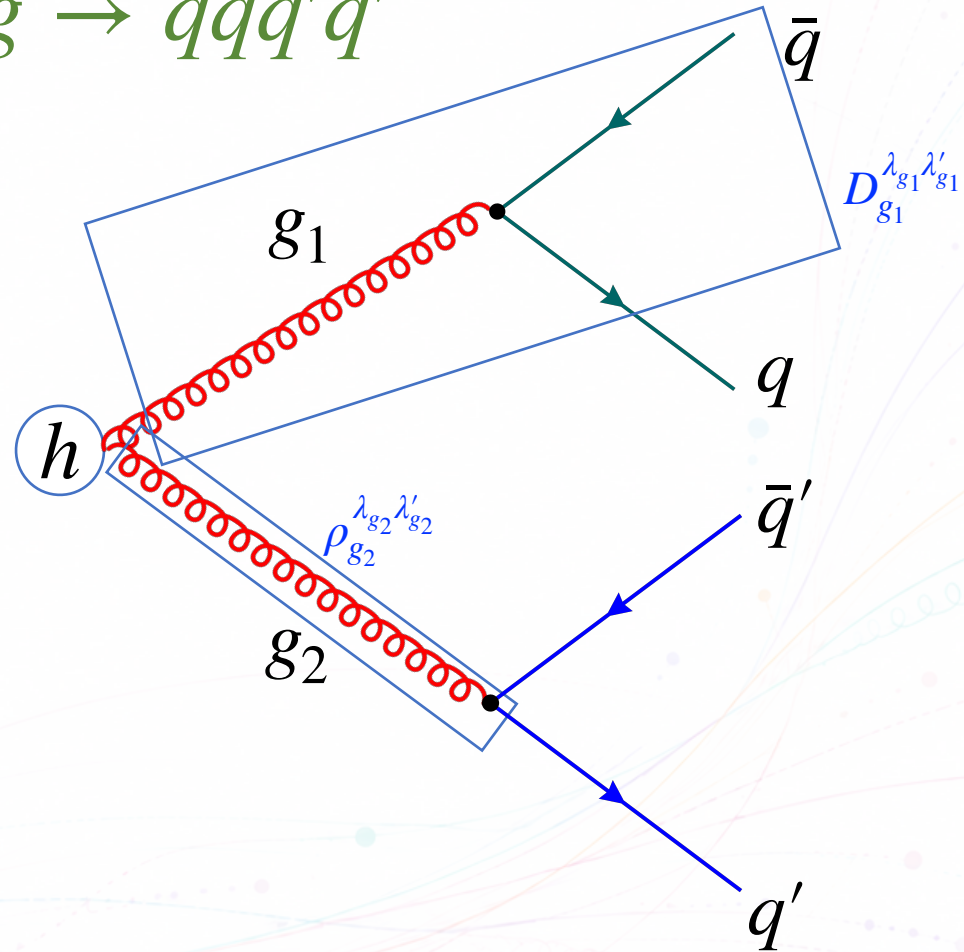
Example: $h \rightarrow gg \rightarrow q\bar{q}q'\bar{q}'$

Step 5: Generate the second gluon's shower branching using its spin-density matrix:

$$\rho_{g_2}^{\lambda_{g_2}\lambda'_{g_2}} = \frac{1}{N} \mathcal{M}_{h \rightarrow gg}^{\lambda_{g_1}\lambda_{g_2}} \left(\mathcal{M}_{h \rightarrow gg}^{\lambda'_{g_1}\lambda'_{g_2}} \right)^* \times D_{g_1}^{\lambda_{g_1}\lambda'_{g_1}}$$

i.e. according to the distribution:

$$\rho_{g_2}^{\lambda_{g_2}\lambda'_{g_2}} \mathcal{M}_{g \rightarrow q\bar{q}}^{\lambda_{g_2}\lambda_{q'}\lambda_{\bar{q}'}} \left(\mathcal{M}_{g \rightarrow q\bar{q}}^{\lambda'_{g_2}\lambda'_{q'}\lambda'_{\bar{q}'}} \right)^*$$



[Richardson, Webster, arXiv:1807.01955]

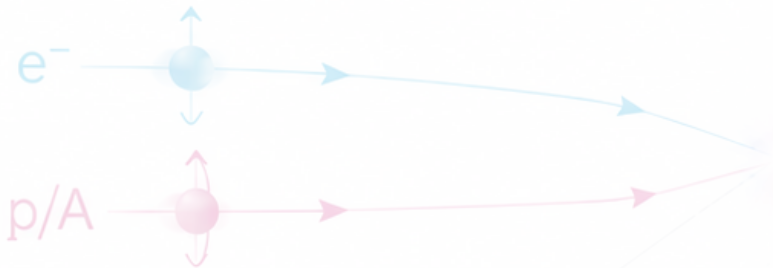
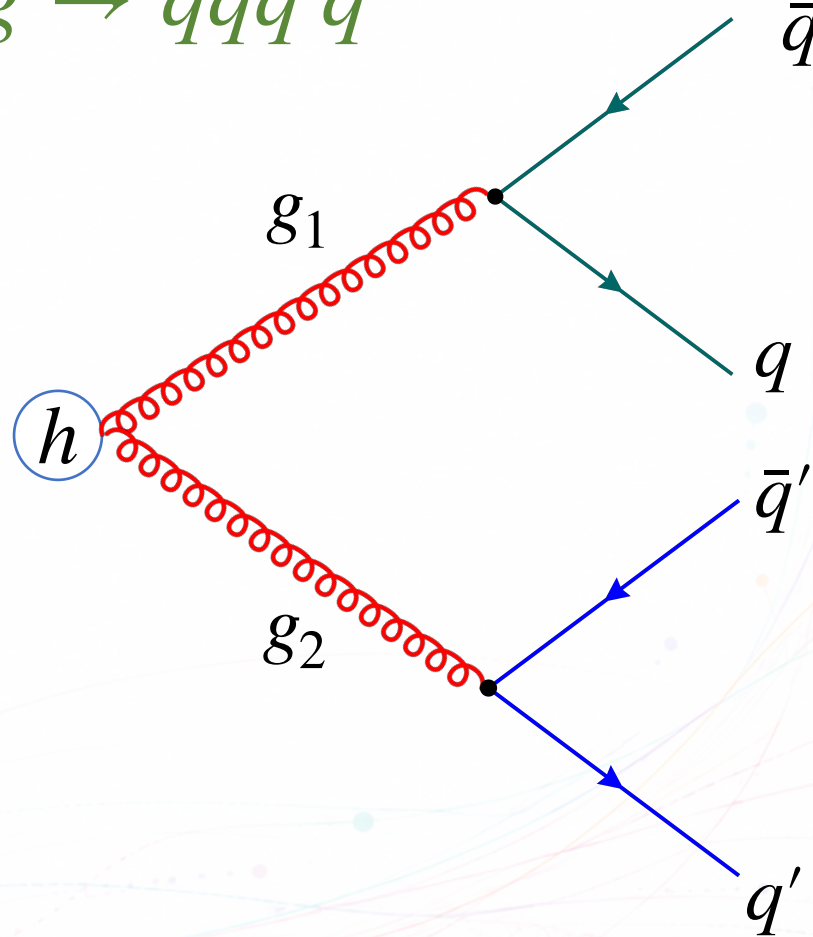
HERWIG 7: Spin Correlations via Collins & Knowles

Example: $h \rightarrow gg \rightarrow q\bar{q}q'\bar{q}'$

Putting all the terms together, momenta of particles generated according to:

$$\mathcal{M}_{h \rightarrow gg}^{\lambda_{g1} \lambda_{g2}} \left(\mathcal{M}_{h \rightarrow gg}^{\lambda'_{g1} \lambda'_{g2}} \right)^* \mathcal{M}_{g \rightarrow q\bar{q}}^{\lambda_{g1} \lambda_q \lambda_{\bar{q}}} \left(\mathcal{M}_{g \rightarrow q\bar{q}}^{\lambda'_{g1} \lambda_q \lambda_{\bar{q}}} \right)^* \mathcal{M}_{g \rightarrow q'\bar{q}'}^{\lambda_{g2} \lambda_{q'} \lambda_{\bar{q}'}} \left(\mathcal{M}_{g \rightarrow q'\bar{q}'}^{\lambda'_{g2} \lambda_{q'} \lambda_{\bar{q}'}} \right)^*$$

i.e. the full spin-correlated shower approximation.



[Richardson, Webster, arXiv:1807.01955]

HERWIG 7: Spin Correlations with the Hard Process

[Masouminia, **AP**, Richardson, arXiv:2606.23845]

🌀 Longitudinally-polarized hadrons:

$$f_i(x, Q^2) = f_{i+}(x, Q^2) + f_{i-}(x, Q^2) \rightarrow \text{PDF}$$

$$\Delta f_i(x, Q^2) = f_{i+}(x, Q^2) - f_{i-}(x, Q^2) \rightarrow \text{helicity PDF}$$

🌀 Define a **spin-density matrix** for parton i entering hard process:

$$H_i^{\tau\tau'}(x, Q^2) = \frac{1}{2} \begin{pmatrix} 1 - \lambda_i(x, Q^2) & 0 \\ 0 & 1 + \lambda_i(x, Q^2) \end{pmatrix}, \quad [\text{negative helicity first}]$$

where: $\lambda_i = P_z \frac{\Delta f_i(x, Q^2)}{f_i(x, Q^2)}$, P_z is the polarization of the *hadron* [$\rightarrow$ potential issues with positivity].

$\Rightarrow H_i^{\tau\tau'}(x, Q^2)$ is the object passed to the polarized parton shower evolution in **HERWIG 7**.

HERWIG 7 NLO Polarized DIS with Spin Correlations

[Masouminia, **AP**, Richardson, arXiv:2606.23845]

Extension of original **POWHEG** implementation of **NLO DIS** to **polarized MEs**.

[d'Errico, Richardson, arXiv:1106.2983]

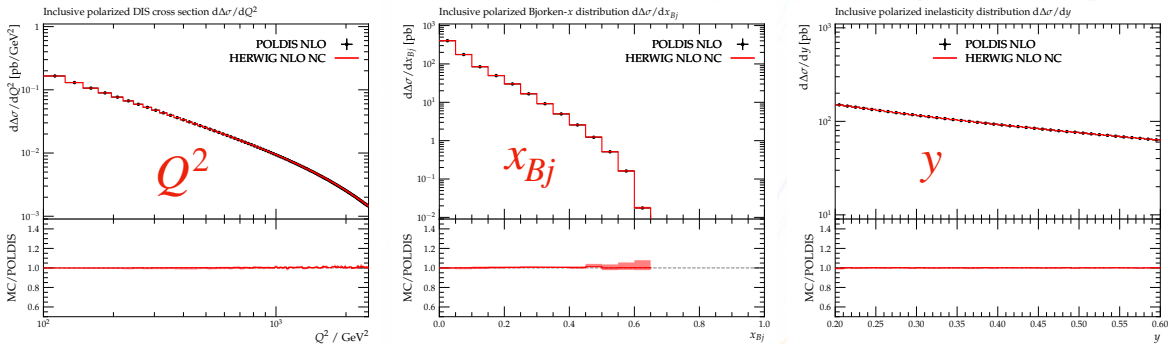
[see also: Borsa, Jäger, arXiv:2404.07702]

Validated vs. **POLDIS** @ NLO in EIC phase space [Borsa, de Florian, Pedron, arXiv:2010.07354, arXiv:2005.10705].

NNPDFpol 2.0

Setup	Observable	HERWIG [pb]	POLDIS [pb]	HW/POLDIS
γ	$\sigma_{0,\gamma}$	1104.80 ± 0.01	1104.80 ± 0.06	0.99999 ± 0.00005
γ	$\Delta\sigma_\gamma$	34.454 ± 0.005	34.4513 ± 0.0016	1.00008 ± 0.00015
Z	$\sigma_{0,Z}$	1.098113 ± 0.000005	1.098050 ± 0.000072	1.00006 ± 0.00007
Z	$\Delta\sigma_{LL,Z}$	0.044271 ± 0.000005	0.044267 ± 0.000005	1.00009 ± 0.00017
γZ	$\sigma_{0,\gamma Z}$	1114.949 ± 0.004	1114.972 ± 0.056	0.99998 ± 0.00005
γZ	$\Delta\sigma_{LL,\gamma Z}$	38.999 ± 0.004	38.9955 ± 0.0017	1.00010 ± 0.00010
int.	$\sigma_{0,int}$	9.055 ± 0.008	9.071 ± 0.079	0.9982 ± 0.0087
int.	$\Delta\sigma_{LL,int}$	4.501 ± 0.006	4.5000 ± 0.0023	1.0002 ± 0.0015

→ per-mille agreement or better for dominant channels



Effect of the spin correlations investigated:

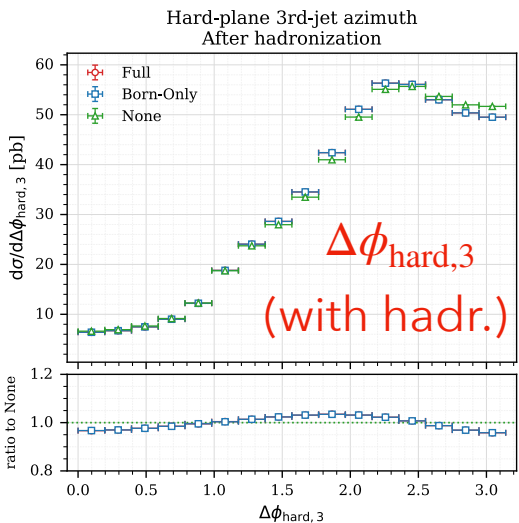
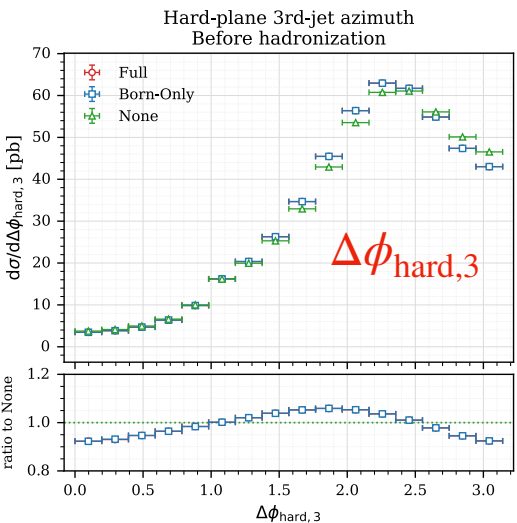
Full = Full spin-density matrices for real emission,

Born = Born-level spin initialization,

None = No hard process spin density matrices.

→ **~ 5 – 10 %** effects in third-jet angle relative to hard-emission plane ($\Delta\phi_{\text{hard},3}$).

→ **TO-DO**: investigate these in concrete pheno studies!



HERWIG 7 Phenomenological Studies of Polarized DIS

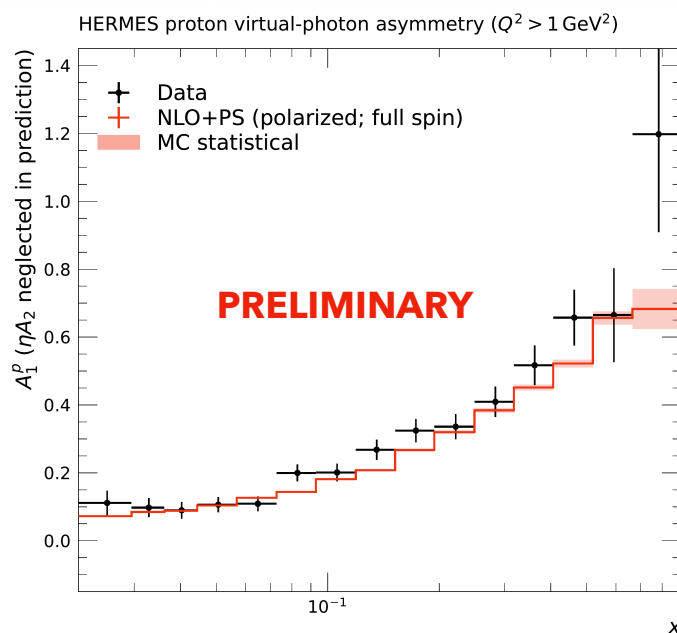


[Baldonado, Masouminia, **AP**, Richardson, to appear]

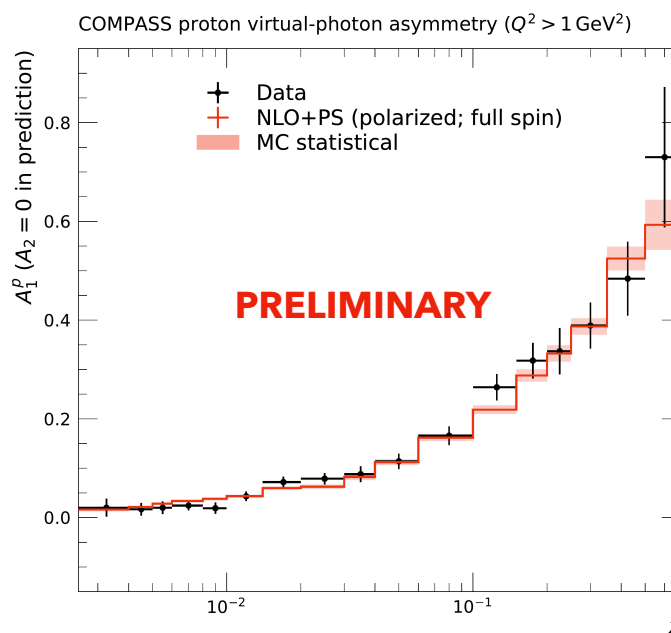
Asymmetries in polarized DIS: **HERMES & COMPASS results vs. HERWIG 7:**

Observable: $A_1 \simeq \frac{1}{D} \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$ vs. **Bjorken** x [D = lepton-to-virtual-photon **depolarization** factor].

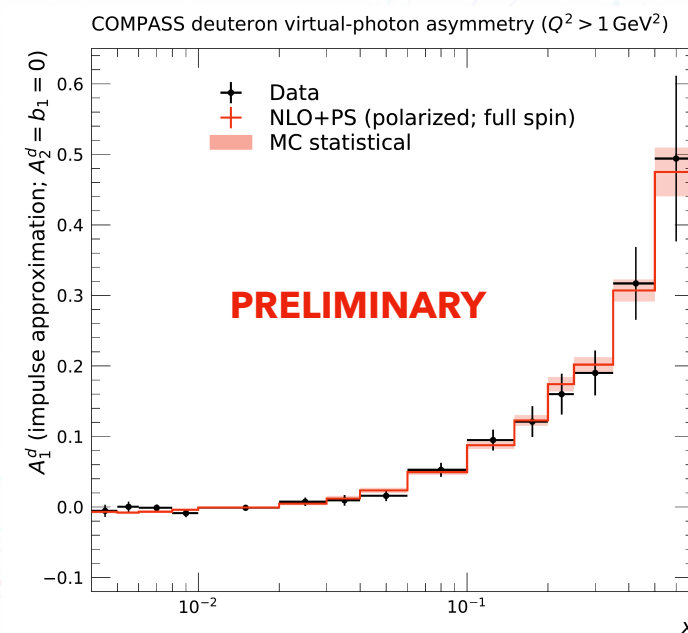
Note: NNPDFpol 2.0 used → experimental results already in the PDF fit.



HERMES 2007: 27.6 GeV longitudinally-polarized **positrons** scattered from a longitudinally polarized internal **atomic-hydrogen** target [hep-ex/0609039].



COMPASS 2016: 200 GeV longitudinally-polarized positive **muons** scattered from a longitudinally polarized NH_3 **proton** target [arXiv:1503.08935].



COMPASS 2017: 160 GeV longitudinally polarized positive **muons** scattered from a longitudinally polarized ^6LiD **deuteron** target [with per-nucleon **impulse approximation**] [arXiv:1612.00620].

Conclusions & Outlook

EIC takeaways:

Polarized DIS: NLO POWHEG validated against POLDIS at per-mille level,

Spin correlations: visibly affect third-jet-sensitive observables;

Photoproduction: precision requires NLO+PS, modern photon PDFs and resolved-photon MPI/remnant modelling.

HERWIG is becoming ready for precision polarized-DIS studies at the EIC; photoproduction and SIDIS remain major development priorities.



HERWIG 7 Roadmap:

Current version (HERWIG 7.3.0)

- EW shower
- HQET in hadronisation and decay
- Dynamic approach to cluster splitting, ...

Upcoming release (HERWIG 7.4)

- Generalized angular-ordered PS
- Quarkonium production in AO shower
- String-model interface and tuning
- KrkNLO matching for colour singlets
- Strongly interacting dark matter
- Dynamic cluster model
- Di-quark and baryonic colour reconnection
- Longitudinally polarized DIS at NLO+PS (POWHEG)**
- Exotic processes: instantons and sphalerons, ...

Longer-term priorities

- NLL dipole shower
- Complete photoproduction support: NLO+PS, resolved-photon MPI and remnants**
- SIDIS**
- eA scattering**
- Matchbox improvements and UFO interface
- In-medium parton shower, ...**



For easy installation of HERWIG 7.3.0 on Ubuntu 26.04 (amd64):

```
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```

```
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```

```
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```

macOS Homebrew packages coming soon!

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Thanks!

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Electroweak Parton Shower in HERWIG 7

At TeV scales, **EW corrections** can become large $\sim \alpha_w \log^2(Q^2/M_W^2)$

→ **QCD⊕QED⊕EW** parton shower [available in HERWIG 7.3.0].

→ EW splitting functions → **helicity dependent**.

But: Longitudinal polarization vector is gauge-dependent:

$$\epsilon_L^\mu(p) \rightarrow \epsilon_L^\mu(p) + \alpha \frac{p^\mu}{M_V}$$

Subtraction-Longitudinal (SL) picture: Removing the p^μ/M_V term from the branching operator can miss ultra-collinear longitudinal dynamics. [Dawson, Nucl.Phys.B249(1985) 42, Masouminia, Richardson, arXiv:2108.10817, Dittmaier, Reyer,

arXiv:2507.06568].

Gauge-Invariant (GI) completion: keep the piece, add the uniquely-fixed Goldstone-matching term [Masouminia, Richardson, arXiv:2602.19927]. **SL** $\approx$ **GI** @ high energies (high $\tilde{q}$), differences at low energies.

