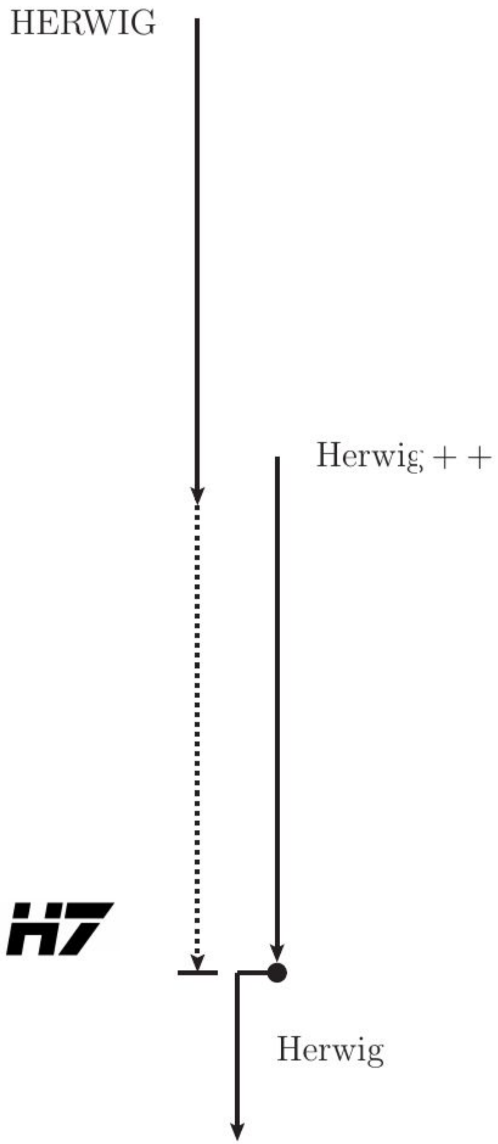
Progresses on Herwig and KrKNLO

Andrzej Siódmok
Jagiellonian University

NCN: 2019/34/E/ST2/00457

Herwig Evolution



HERWIG (Hadron Emission Reactions With Interfering Gluons):
Fortran code, last version 6.521
(1992-2002)

[Marchesini, Webber, Abbiendi, Corcella, Knowles, Moretti, Odagiri, Richardson, Seymour, Stanco]

Herwig++ (C++, improved physics, 2004):

[Bähr, Gieseke, Gigg, Grellscheid, Hamilton, Latunde-Dada, Plätzer, Richardson, Seymour, Sherstnev, Tully, Webber]

last version 2.7.1 (2014)

[Bellm, Gieseke, Grellscheid, Papaefstathiou, Plätzer, Richardson, Rohr, Schuh, Seymour, AS, Wilcock, Zimmermann]

intended to fully replace Fortran version

experimental and phenomenological evolution over time
$\Rightarrow$ precision as key goal

Herwig 7.0 (2016)

Evolution of fHERWIG/Herwig++ subsumed as “7 $>$ 6.5”.
“Better than fHERWIG in any aspect plus more”.

[Bellm, Gieseke, Grellscheid, Plätzer, Rauch, Reuschle, Richardson, Schichtel, Seymour, AS, Wilcock, Fischer, Harrendorf, Nail, Papaefstathiou, D. Rauch]

Herwig 7.3 coming soon

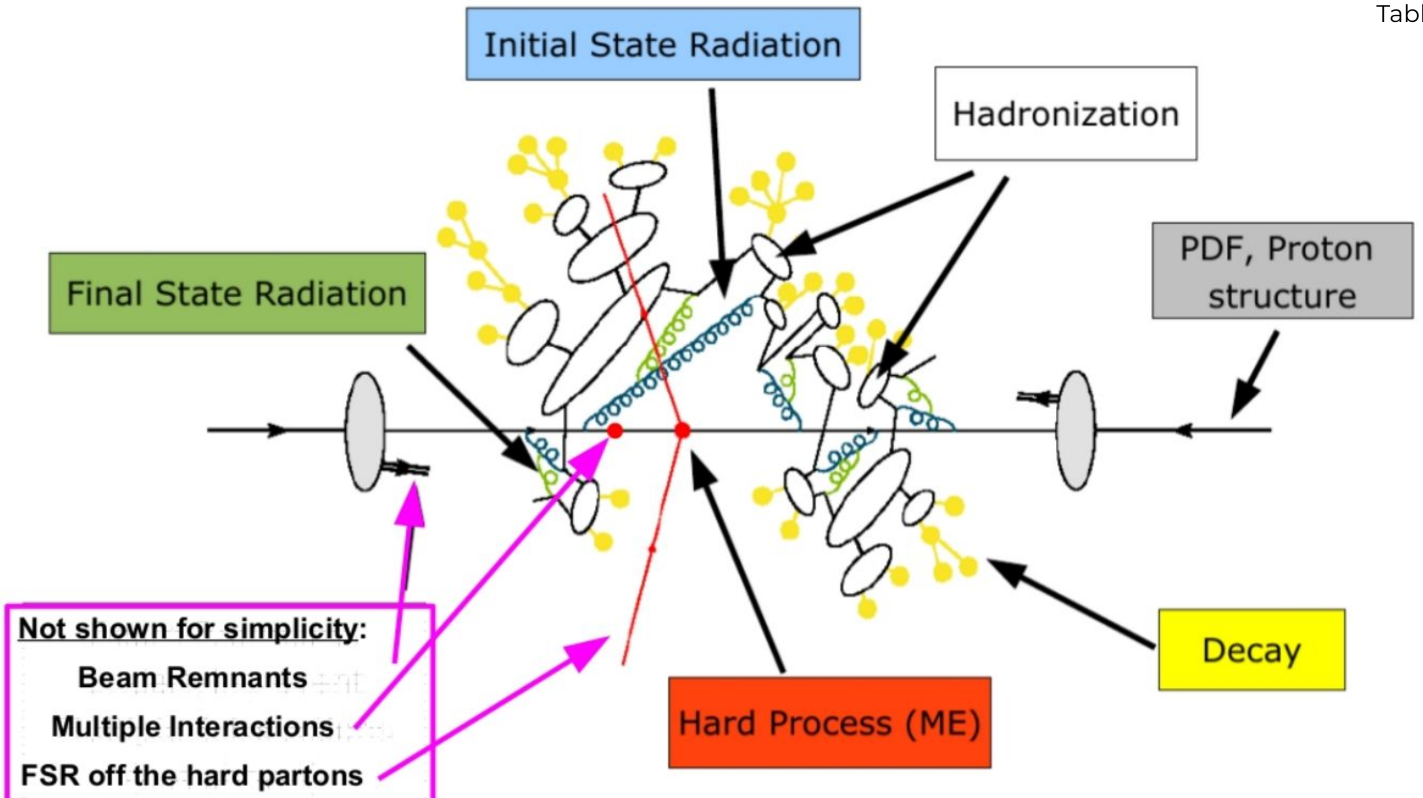
τ(HERWIG) $\sim$ τ(Herwig++) $\gtrsim$ 15 years.

Herwig 7- on behalf of the Herwig team

Hadron Emission Reactions With Interfering Gluons

	Current release series	Hard matrix elements	Shower algorithms	NLO Matching	Multijet merging	MPI	Hadronization	Shower variations
H7	Herwig 7	Internal, libraries, event files	QTilde, Dipoles	Internally automated	Internally automated	Eikonal	Clusters, (Strings)	Yes

Table from S. Plätzer



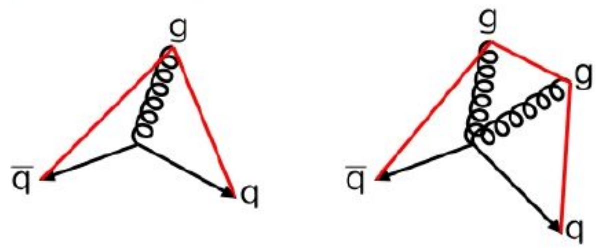
Plot from S. Gieseke

Parton-showers in Herwig 7: Status

Angular-ordered Parton Shower

- Angular-ordered
- Colour coherence by construction
- No full coverage of phase-space (fixed by Hard Matrix corrections)

Catani-Seymour Dipole Shower



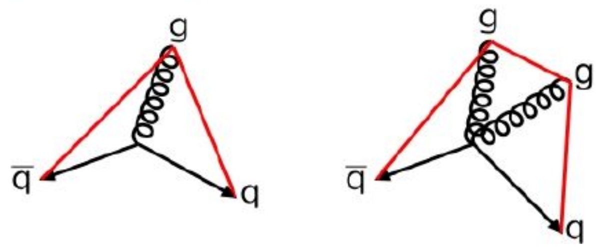
- p_T-ordered
- Colour coherence
- Full phase space
- Catani-Seymour dipoles

Recent developments triggered by understanding the accuracy of parton shower

[PanScales: Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, …]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

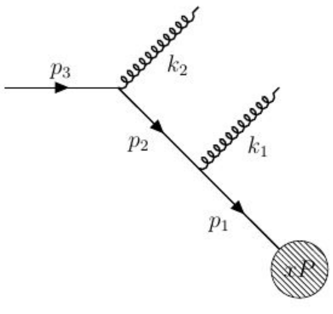
Angular-ordered Parton Shower

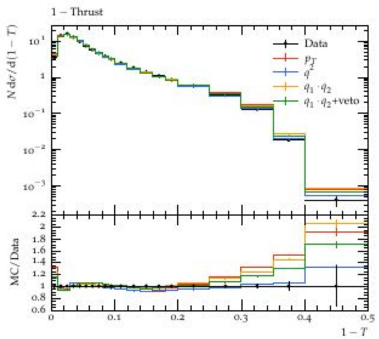
Catani-Seymour Dipole Shower

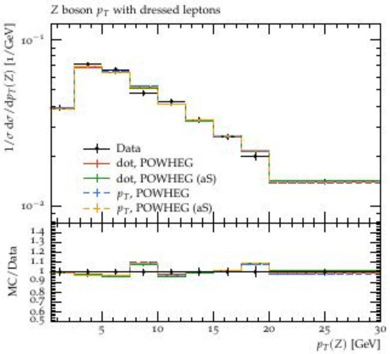


Not only present in dipole showers, can even screw up angular ordered ones:

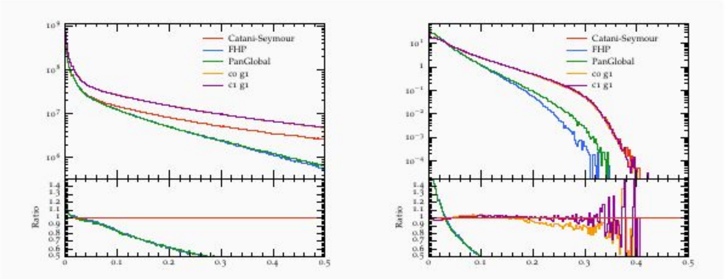
[Bewick, Ferrario, Richardson, Seymour —JHEP 04 (2020) 019 & 01 (2022) 026]







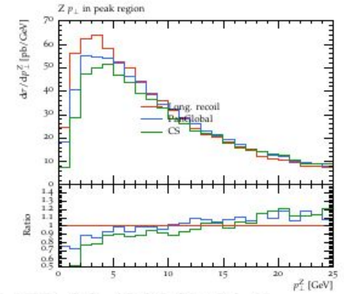
Herwig dipole shower is on track:



(e) C Parameter

(f) Heavy Jet Mass

Investigating a large class of accurate kinematic mappings and issues in the initial state.



[Forshaw, Holguin, Plätzer – JHEP 09 (2020) 014]

[Duncan, Holguin, Plätzer — ongoing]

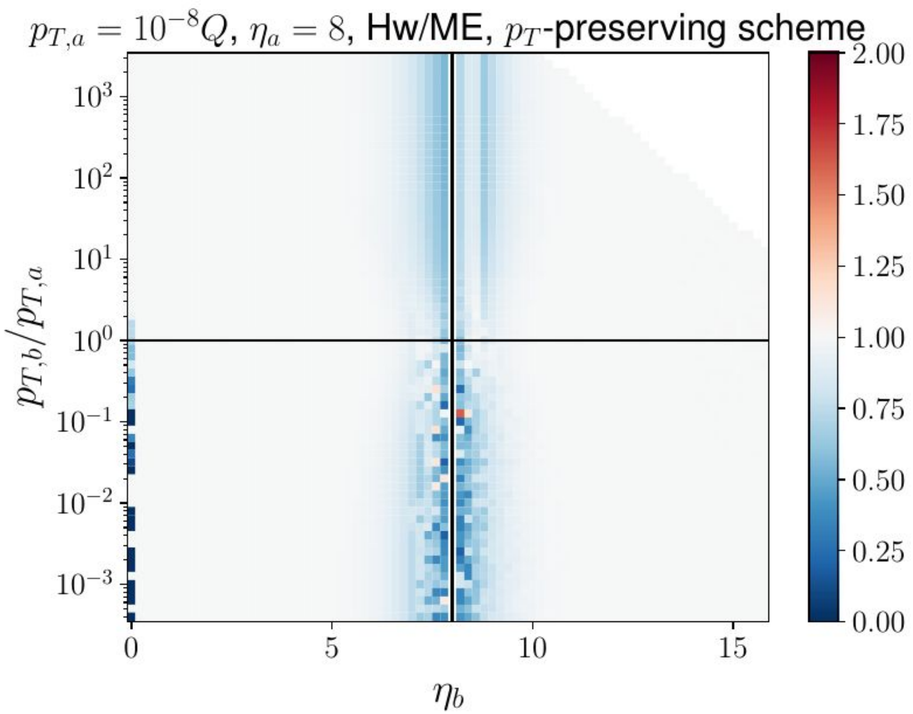
Parton-showers in Herwig 7: Accuracy of Parton Showers

Herwig designed to be **NLL** [G. Marchesini and B. R. Webber, Nucl. Phys. B **310** (1988), 461-526]

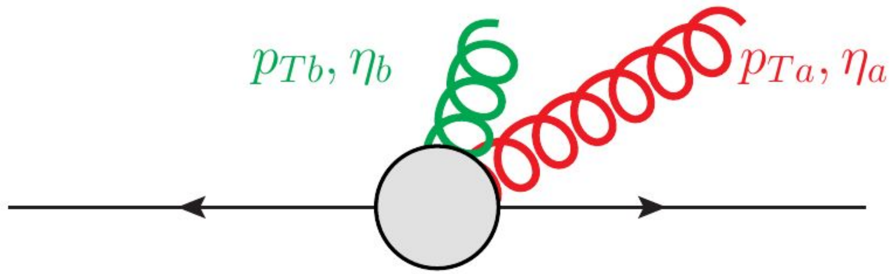
$$\tilde{q}^2_{\tilde{ij}\to i,j} = \boxed{\frac{p_T^2}{z^2(1-z)^2}} \approx E^2_{\tilde{ij}}\theta^2_{i,j}$$

[Gieseke, Stephens, Webber, JHEP **12** (2003), 045]

NLL matrix-element test (✓)



Reproduce the matrix element for



when $\boxed{|\eta_a - \eta_b| \gtrsim \mathcal{O}(1)}$, with $\eta = -\log\tan\theta/2$

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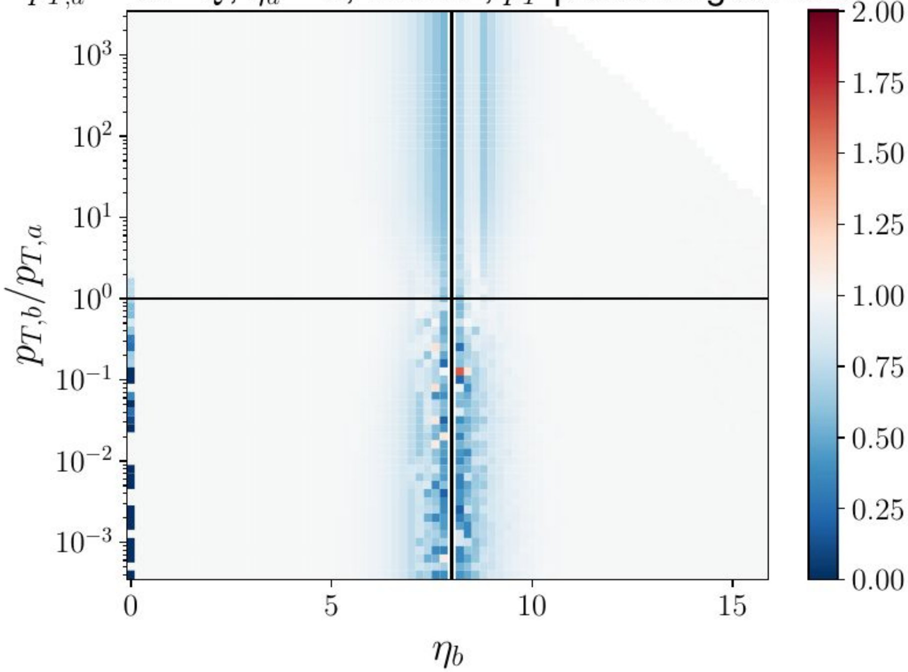
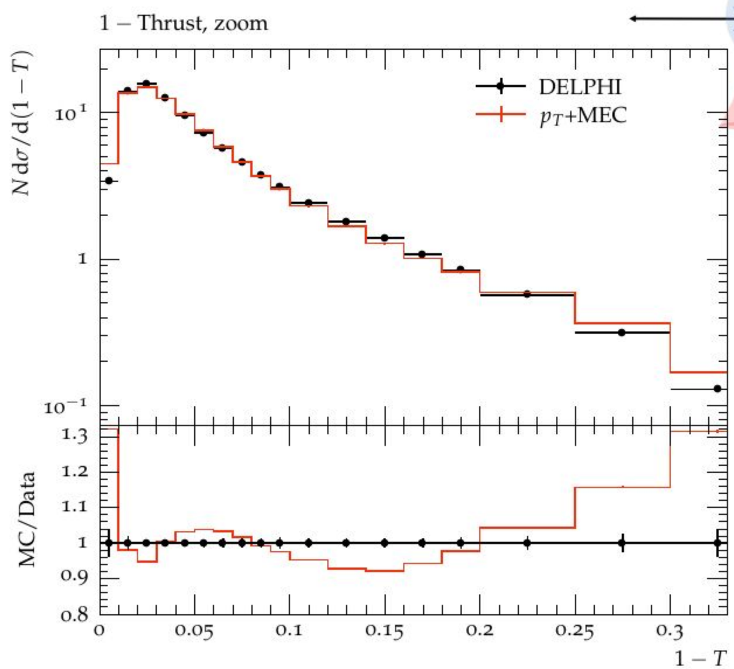
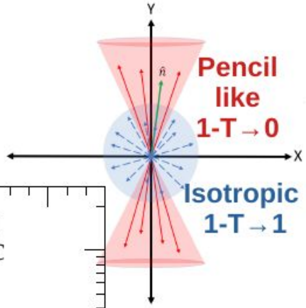
$p_{T,a} = 10^{-8}Q$, $\eta_a = 8$, Hw/ME, p_T-preserving scheme



LEP data (✗)





with Matrix Element Corrections

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[Reichelt, Richardson, AS, Eur. Phys. J. C **77** (2017) no.12, 876]

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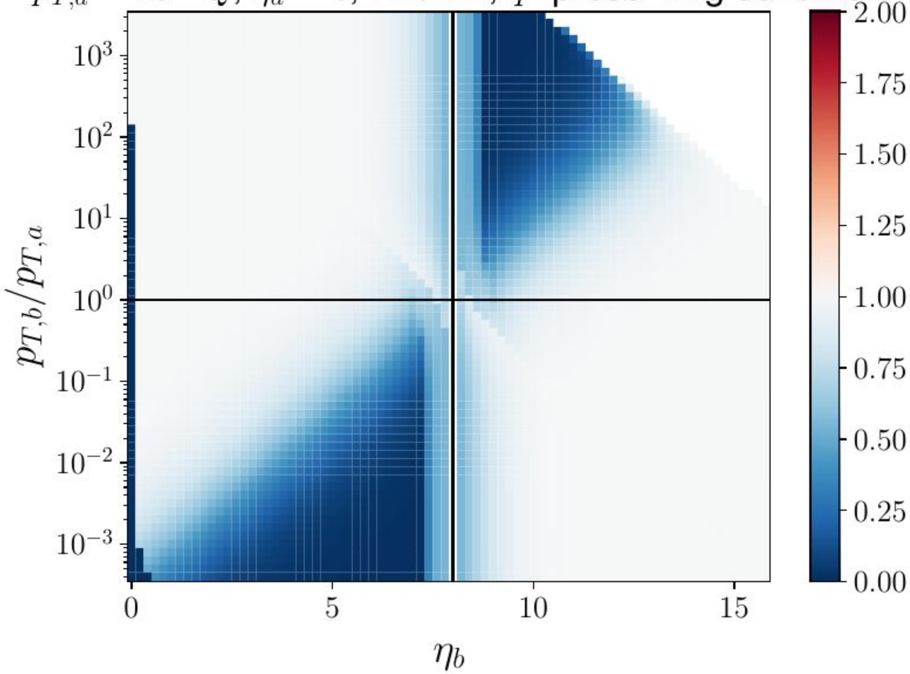

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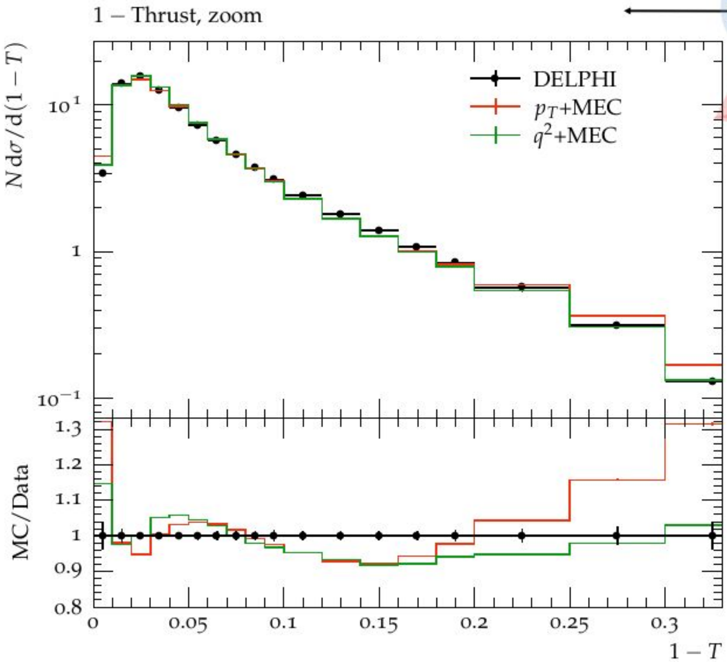

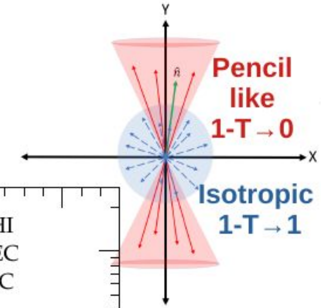

with Matrix Element Corrections

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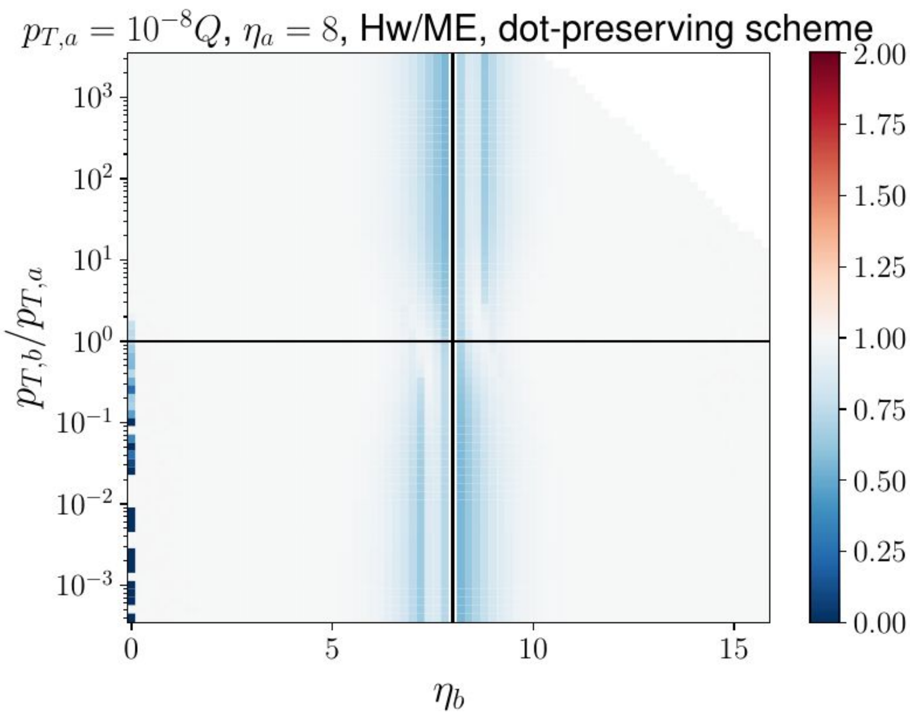
[Bewick, Ravasio, Richardson, Seymour, JHEP **04** (2020), 019]

NLL matrix-element test



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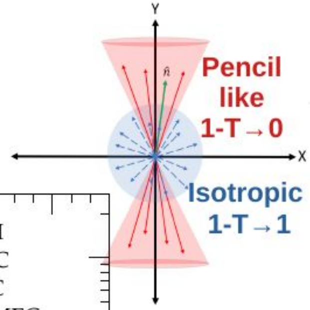
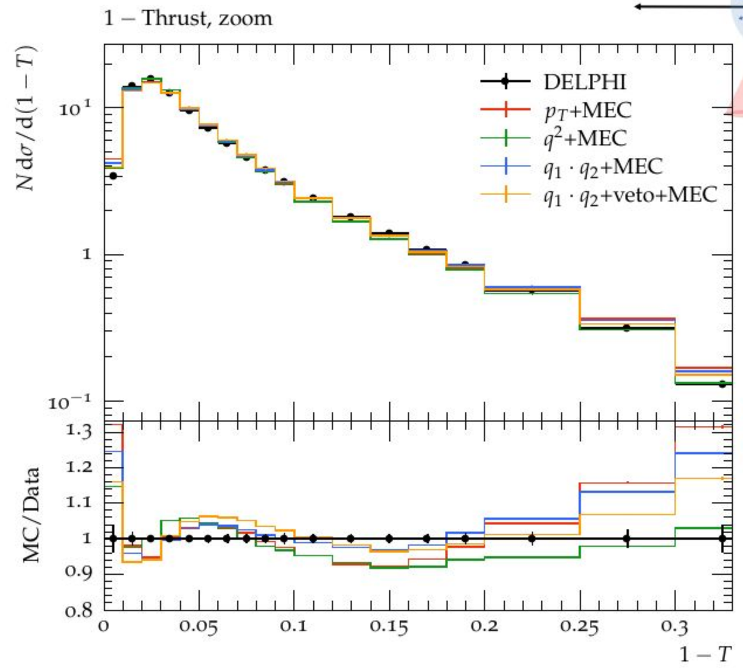




with Matrix Element Corrections and exact phase space factorization

Parton-showers in Herwig 7: EW Angular-Ordered Shower

[A. Masouminia, P. Richardson JHEP 04 (2022) 112]

Derive quasi-collinear EW splittings of the SM in their spin-unaveraged forms:

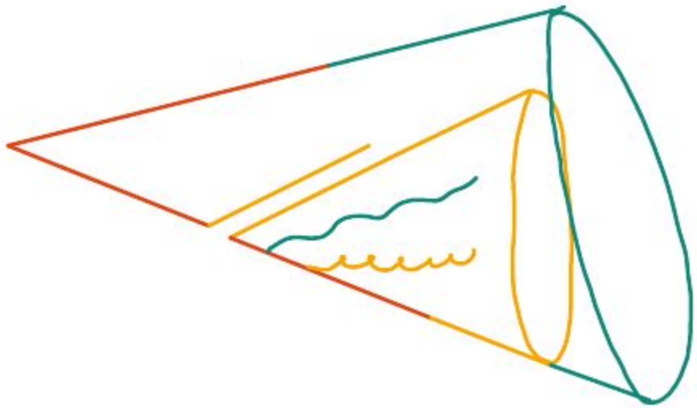
$$q \to q' W^{\pm}, \quad q \to q Z^0, \quad q \to qH$$

Gauge boson splittings

$$W^{\pm} \to W^{\pm} Z^0, \qquad W^{\pm} \to W^{\pm} \gamma, \qquad Z^0 \to W^+ W^-, \qquad \gamma \to W^+ W^-,$$

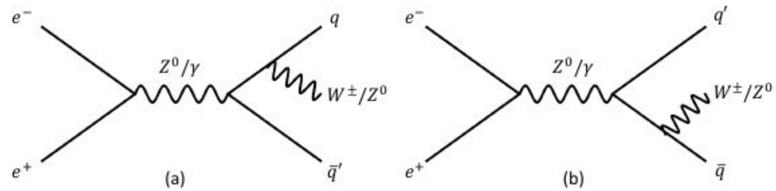
$$W^{\pm} \to W^{\pm} H, \qquad Z^0 \to Z^0 H.$$

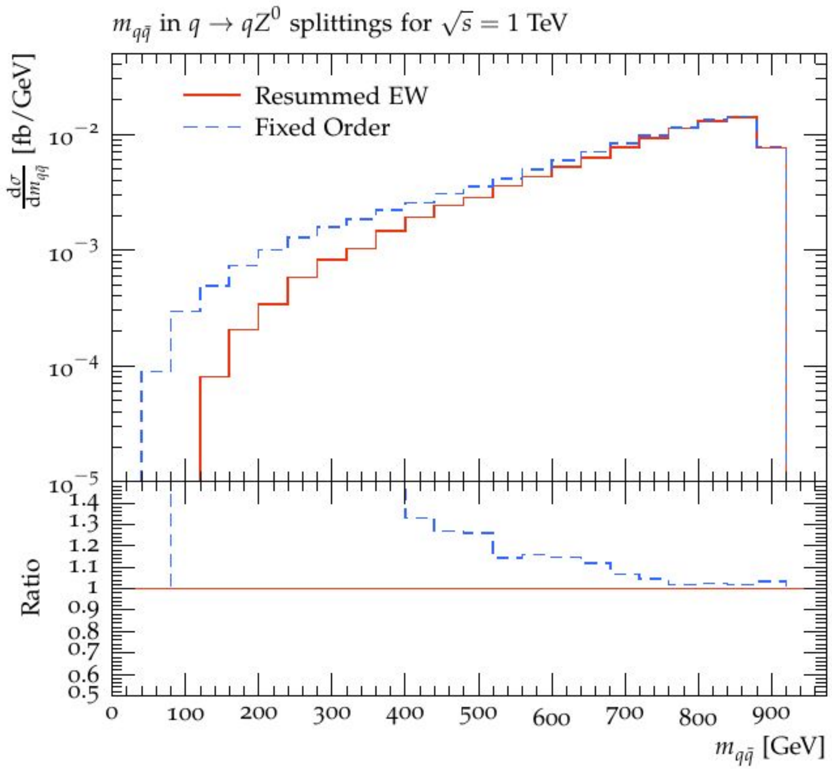
EW and QCD showers are interleaved.
However, different charges require different angular ordering cones:
one evolution variable per interaction.

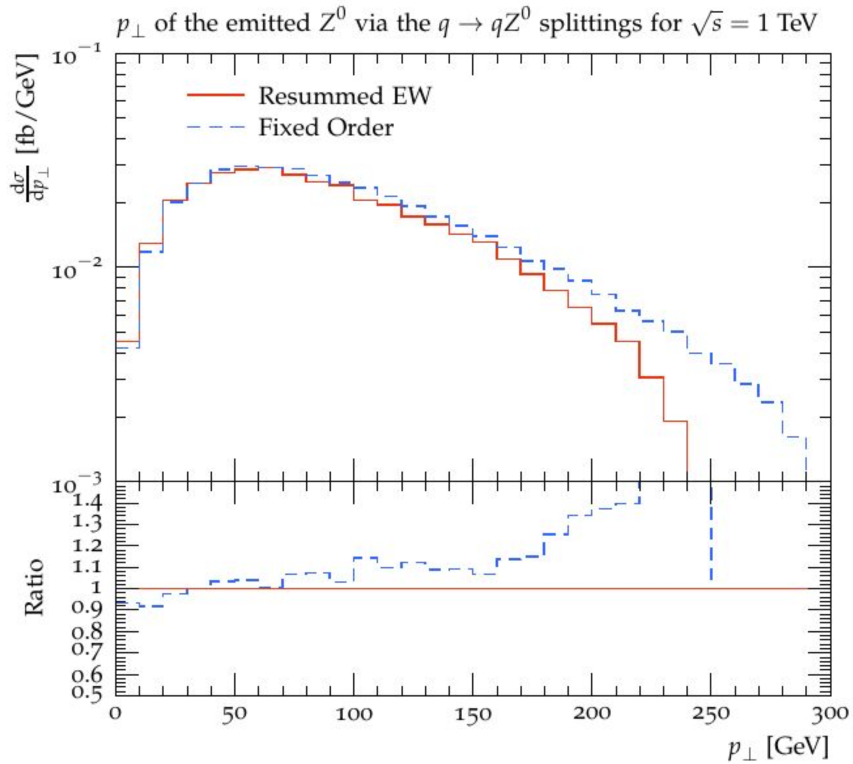


[A. Masouminia, P. Richardson JHEP 04 (2022) 112]

Validation and examples:







$q \to qZ^0$ EW branching in Herwig 7 for $\sqrt{s} = 1$ TeV.

Parton-showers in Herwig 7: EW Angular-Ordered Shower

[A. Masouminia, P. Richardson JHEP 04 (2022) 112]

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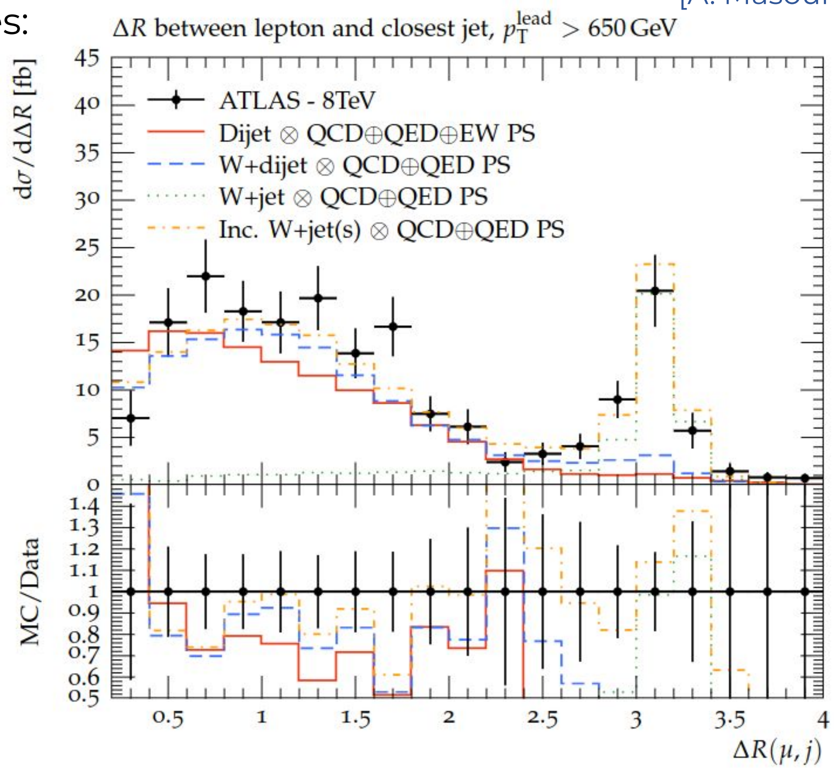


Used already for Phenomenology of Electroweak Corrections

[A. Masouminia,, N. Darvishi, Nucl.Phys.B 985 (2022) 116025]

Next steps:

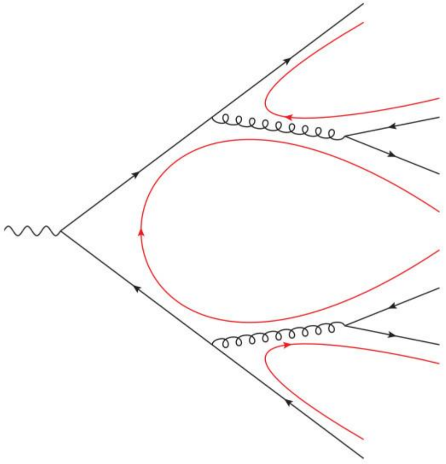
- EW matching and updating to a NLO EW PS.
- EW radiations in Dipole shower.
- BSM radiations is now possible.
- Effect of EW PS is precision calculation.
- Coming soon in Herwig 7.3.
- Related work ongoing, e.g. [Plätzer, Sjödahl — arXiv:2204.03258]

Cluster model in nutshell

[Webber NPB238(1984)492]

What if we have PS (more perturbative input before hadronization).

The philosophy of the model: use information from perturbative QCD as an input for hadronization.
QCD **pre-confinement** discovered by Amati & Veneziano [*Phys.Lett.B* 83 (1979) 87-92]:



- QCD provide pre-confinement of colour

. . .

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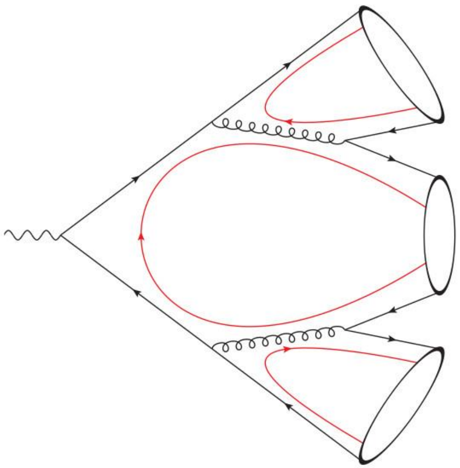

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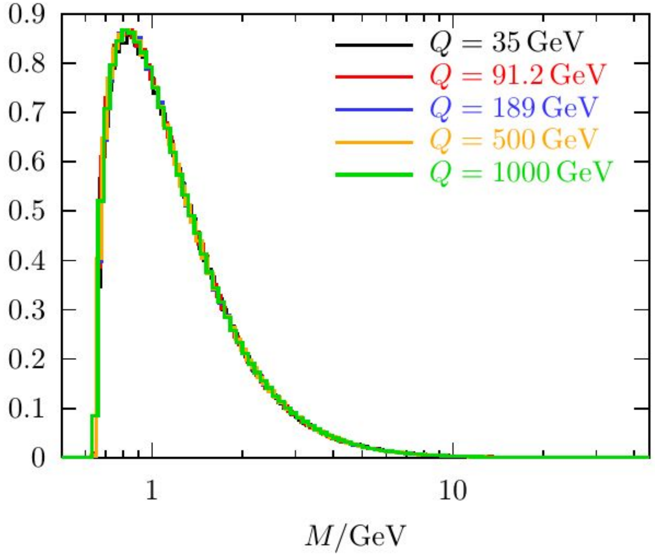
[S. Gieseke, A. Ribon, MH Seymour, P Stephens, B Webber JHEP 0402 (2004) 005]



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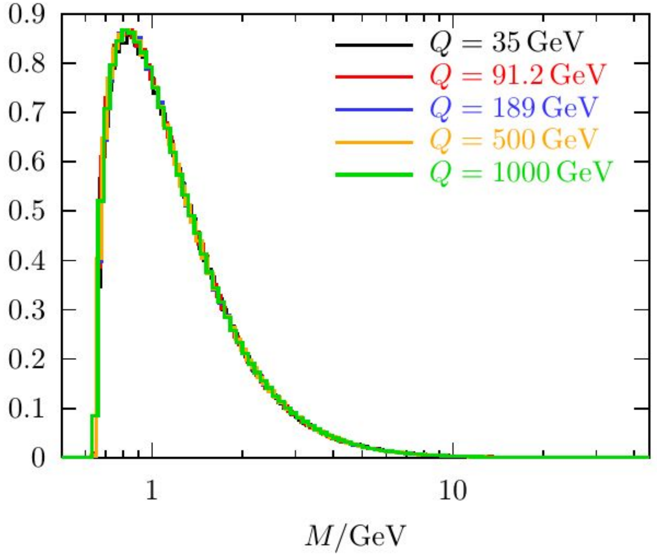
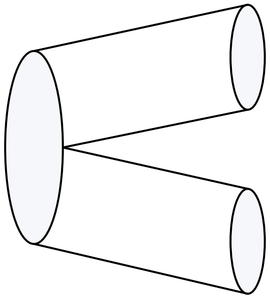
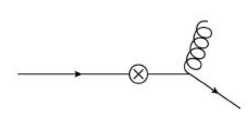
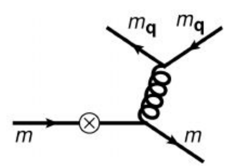
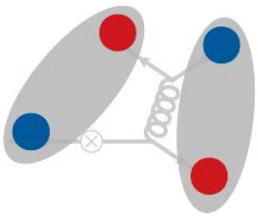
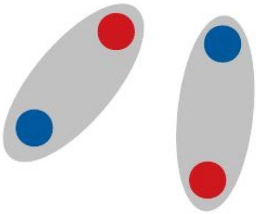


- QCD provide pre-confinement of colour
- Colour-singlet pair end up close in phase space and form highly excited hadronic states, the clusters
- Pre-confinement states that the spectra of clusters are independent of the hard process and energy of the collision
- Peaked at low mass (1-10 GeV) typically decay into 2 hadrons

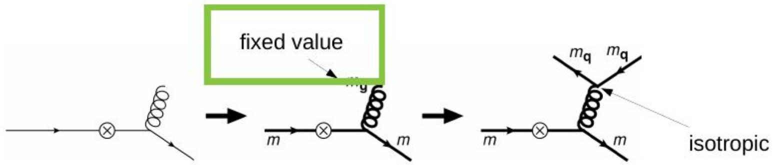
- Small fraction of clusters too heavy for isotropic two-body decay, heavy cluster decay first into lighter cluster C → CC, or radiate a hadron C → HC, it is rather string-like.
- ~ 15% of primary clusters get split but ~ 50% of hadrons come from them!

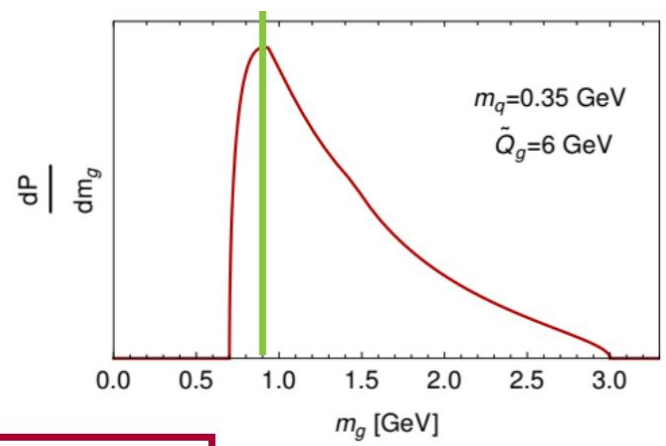


Dynamic model: cluster fission

parton shower	forced splitting and constituent masses	cluster formation	cluster fission
			

Gluon splitting:

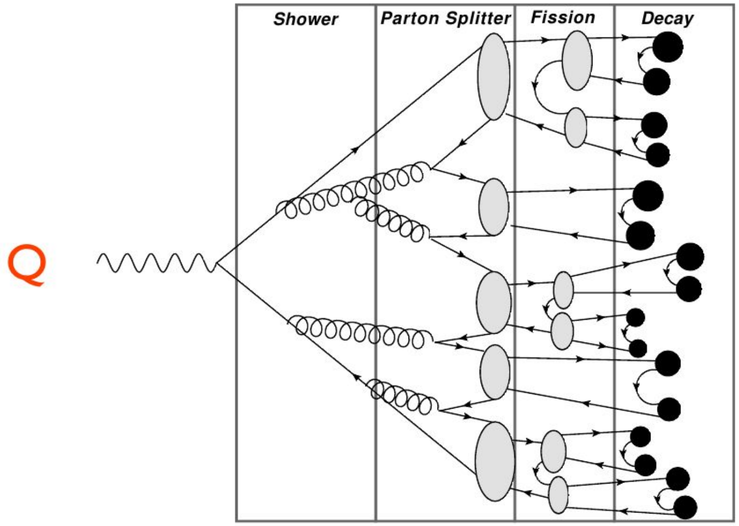




$$\mathrm{d}P(g \to q\bar{q}) \sim \frac{\mathrm{d}q^2}{q^2}\alpha_s(q^2)\left(1 - 2z(1-z) + \frac{2m_q^2}{q^2}\right)\Theta\left(q^2 z(1-z) - m_q^2\right)$$

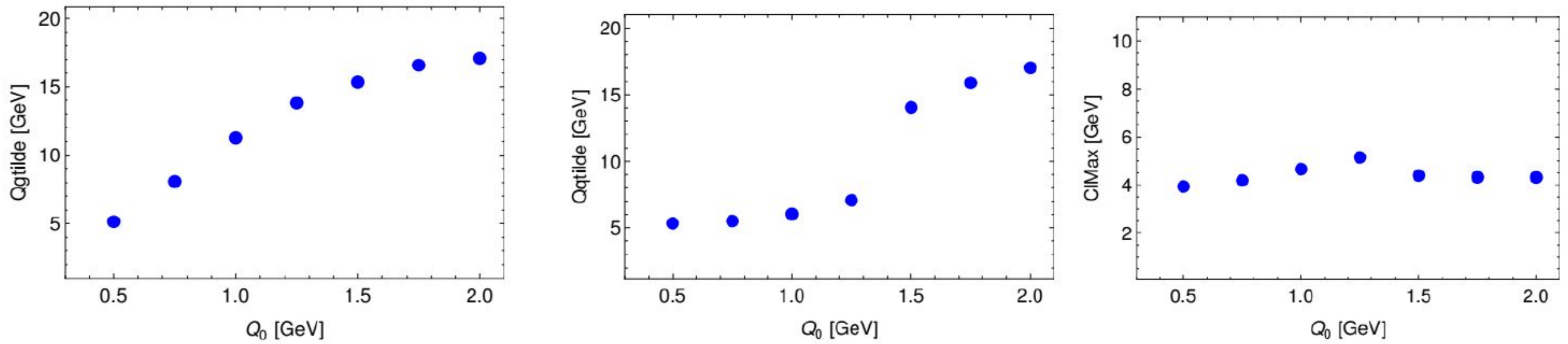
[Hoang, Plätzer, Samitz — in progress]

Matching the cluster model to the shower



constrain by cutoff response

constrain by tuning



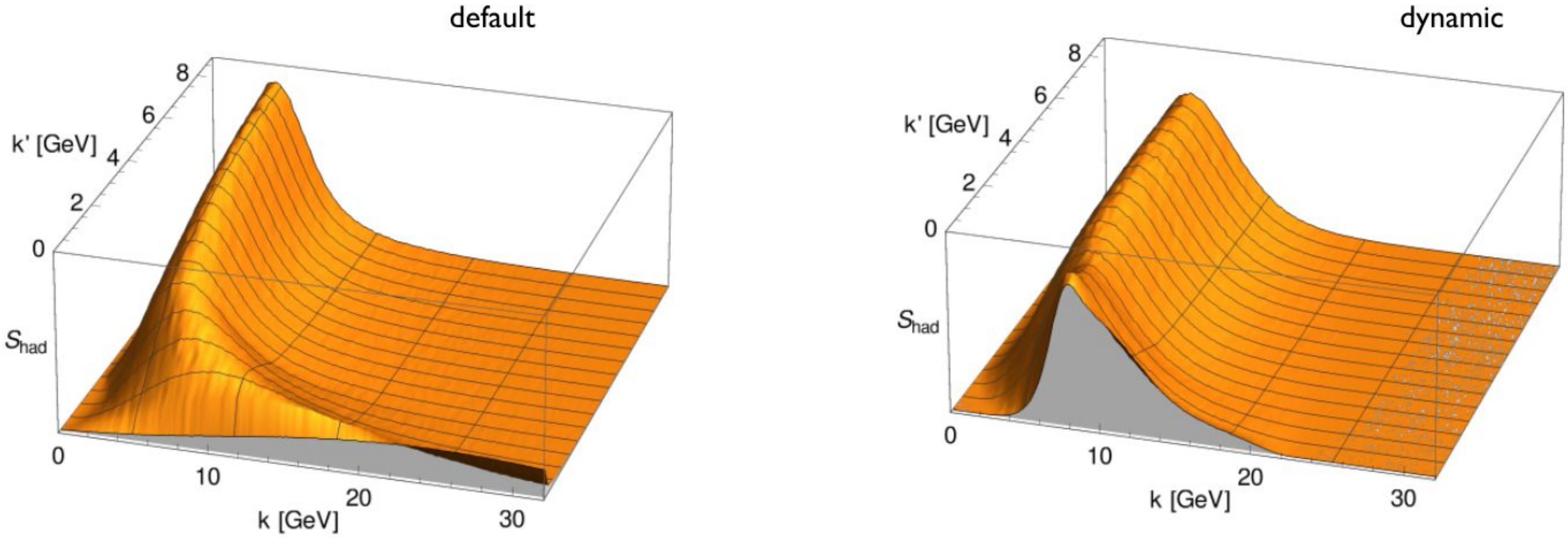
Gluon splitting and cluster fission drivers pick up cutoff dependence.

Significantly reduced sensitivity to other cluster parameters.

[Hoang, Plätzer, Samitz — in progress]

Matching the cluster model to the shower

Significantly different shapes of hadronization corrections



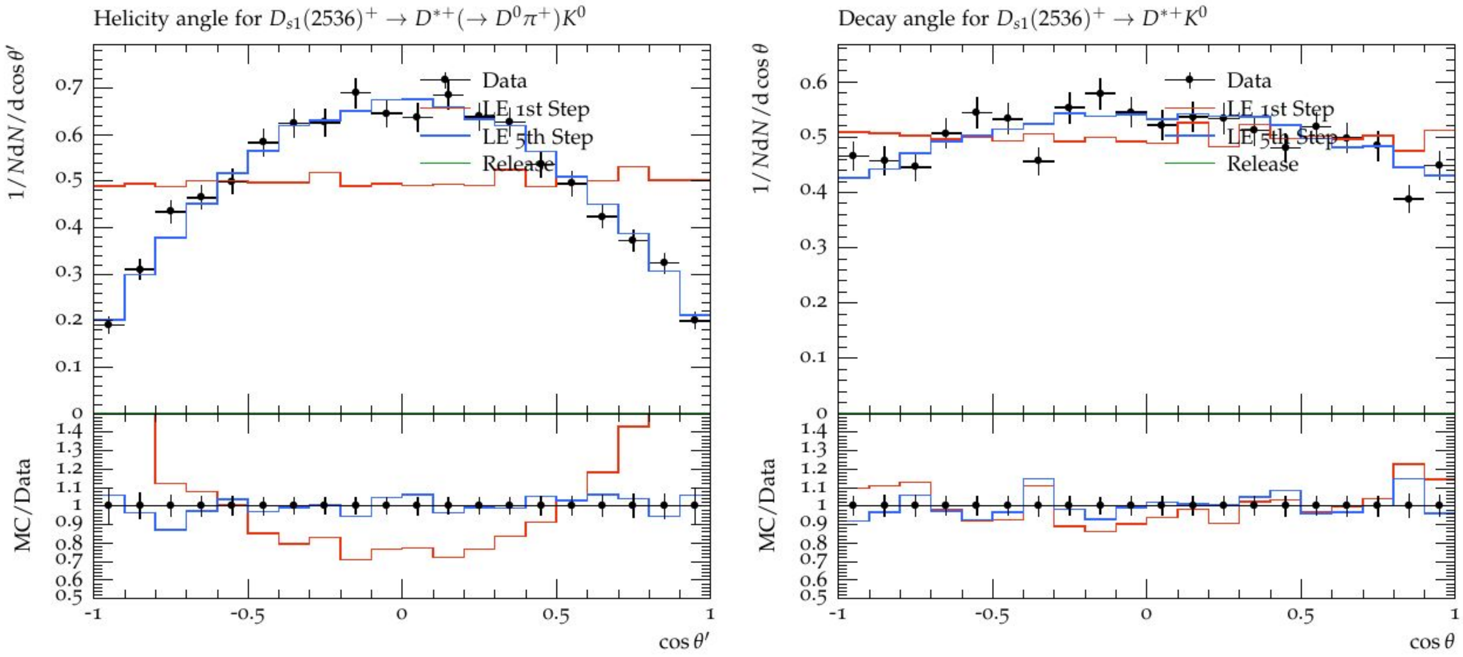
C parameter parton versus hadron level

Analytically, for event shapes, dynamic model gives you a universal shift in the distribution.

[Hoang, Plätzer, Samitz — in progress]

H7

"Polarization of Heavy Hadrons" Aidin Masouminia & Peter Richardson [to be published]



LEP measurement of decay angles in the decay $D_{s1}(2536)^+ \to D^{\star+}K^0$ at $\sqrt{s} = 10.6$ GeV.

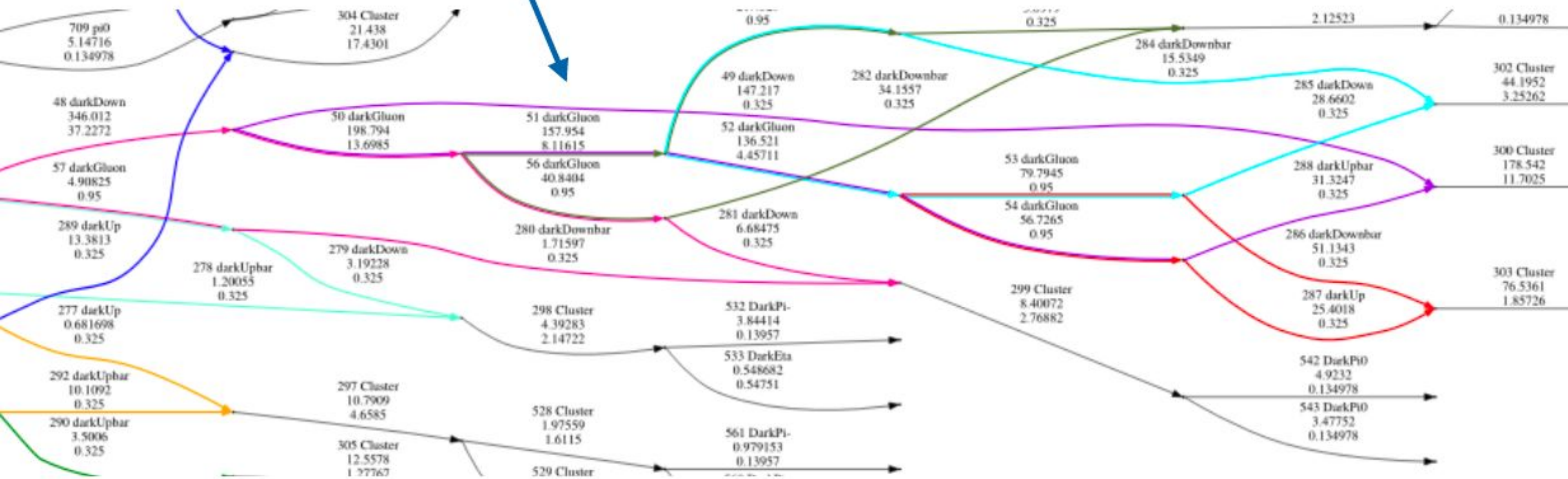
Dark Cluster Hadronization

More flexible cluster hadronization

[Plätzer, Stafford]

Hidden valley angular ordered shower, based on new shower interactions framework

[Masouminia, Richardson]

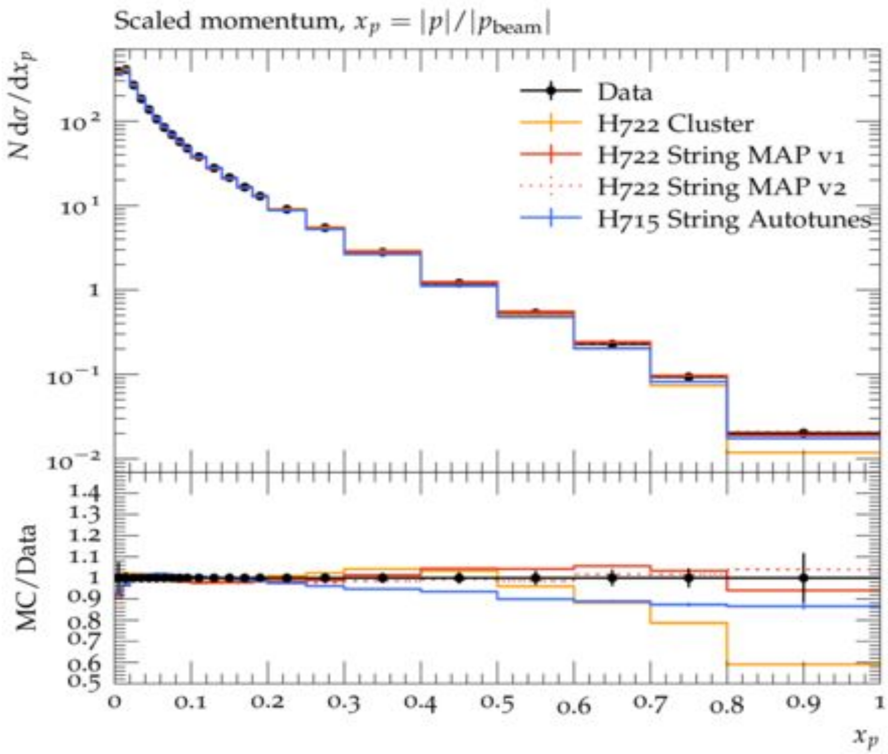


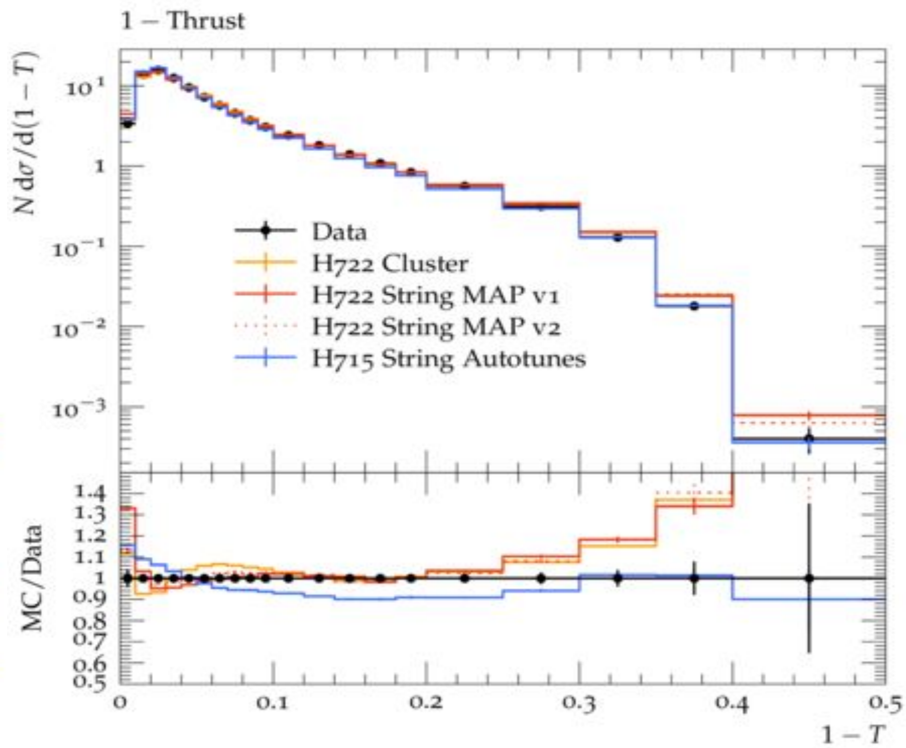
[Kulkarni, Masouminia, Papaefstathiou, Plätzer, Siodmok, Stafford — in progress]

Tuning Angular Ordered PS + String [M.Myska, P. Sarmah, AS to be published]

To **evaluate uncertainties** stemming from the hadronization, Sherpa provides an interface to the Lund string fragmentation in Pythia 6, Herwig has an interface using P8I [Lönnblad] to the Lund string fragmentation in Pythia 8

- Plots from the analysis DELPHI_1996_S3430090



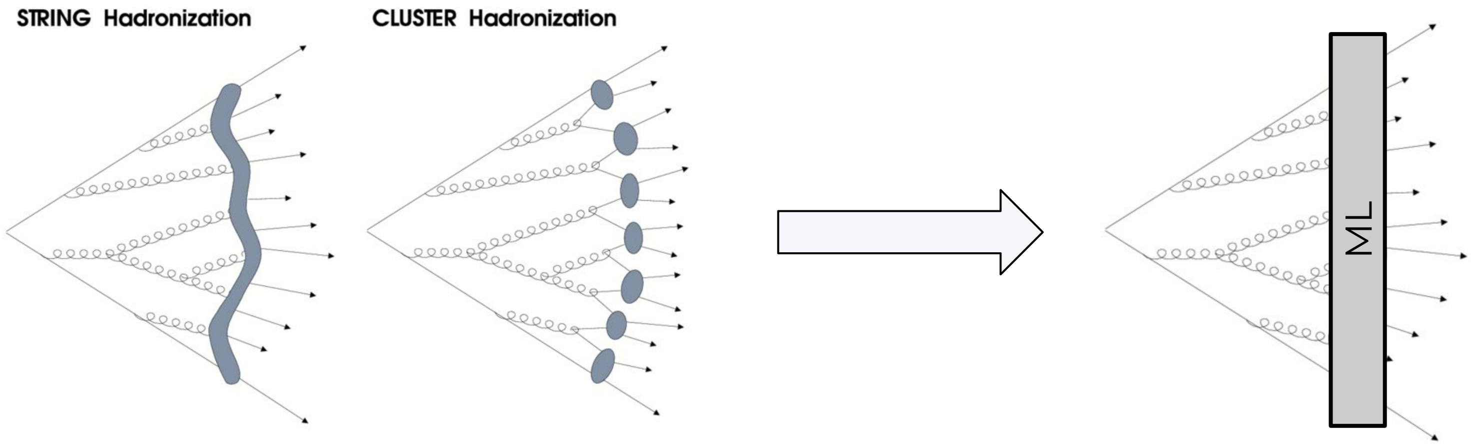


ML Hadronization

Hadronization:

Early 1980's

Early 2020's
(lot of progress in ML)



- ➔ Increased control of perturbative corrections ⇒ more often the precision of LHC measurements is limited by MCEG's non-perturbative components, such as hadronization.
- ➔ Hadronization (phenomenological models with many free parameters ~ 30 parameters)
- ➔ Hadronization is a fitting problem ML is proved to be well suited for such a problems.

NNPDF

NNPDF used successfully ML to nonperturbative Parton Density Functions (PDF)
Fragmentation functions (closely related to hadronization) were considered the counterpart of PDFs.

First steps for ML hadronization:

- HADML - Generative Adversarial Networks [A. Ghosh, Xi. Ju, B. Nachman **AS**, *Phys.Rev.D* 106 (2022) 9]
- MLhad - Variational Autoencoder [P. Ilten, T. Menzo, A. Youssef and J. Zupan, arXiv:2203.04983]

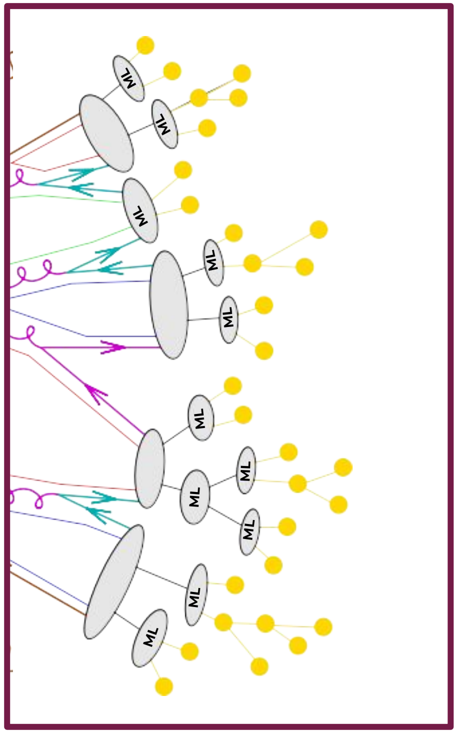
HADML Results

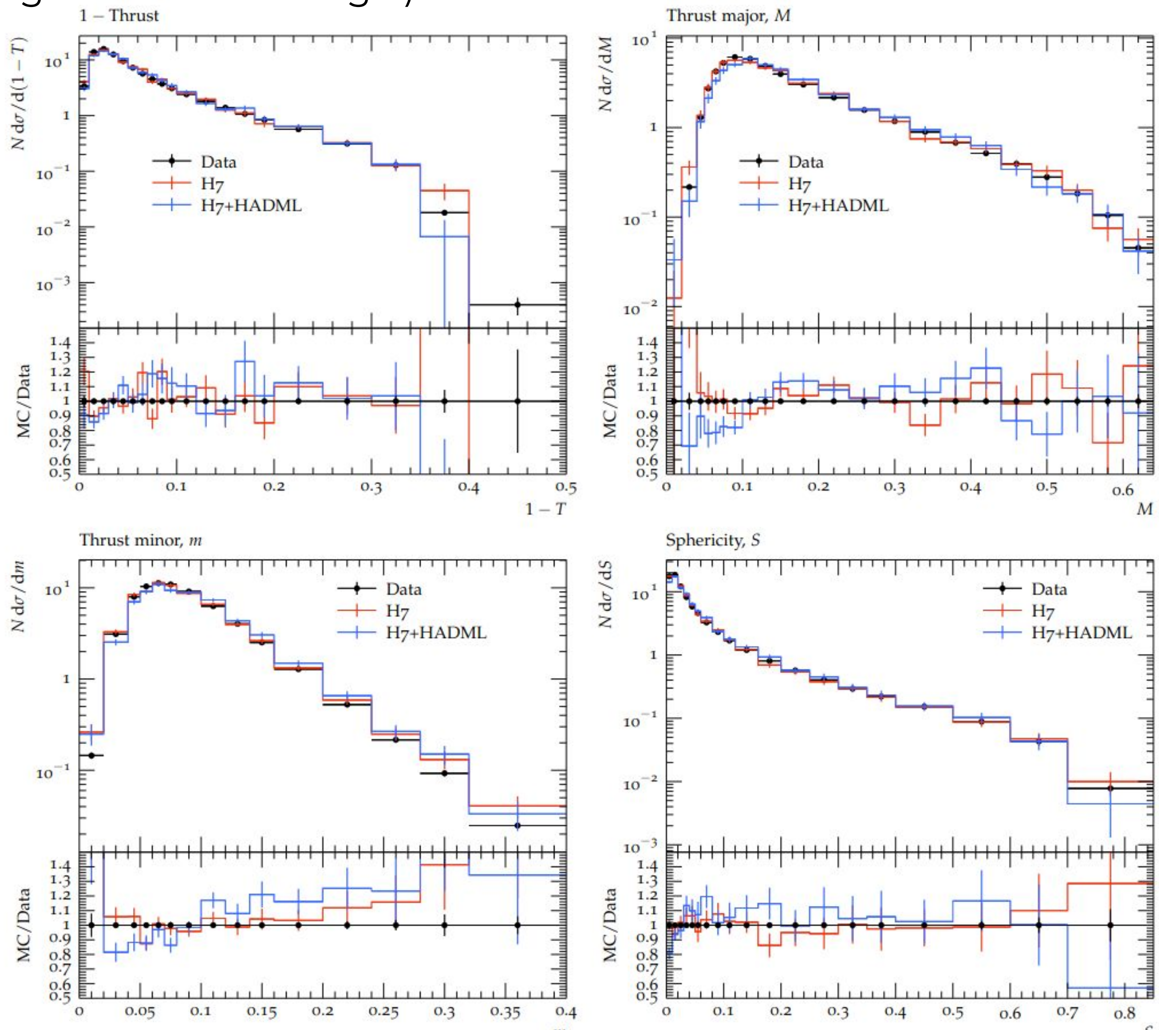
[A. Ghosh, Xi. Ju, B. Nachman AS, Phys.Rev.D 106 (2022) 9]

Full-event Validation

(Full events using HADML integrated into Herwig 7)

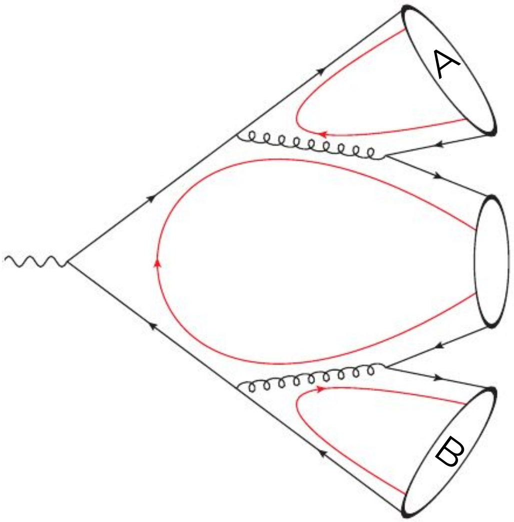
LEP DELPHI **Data**





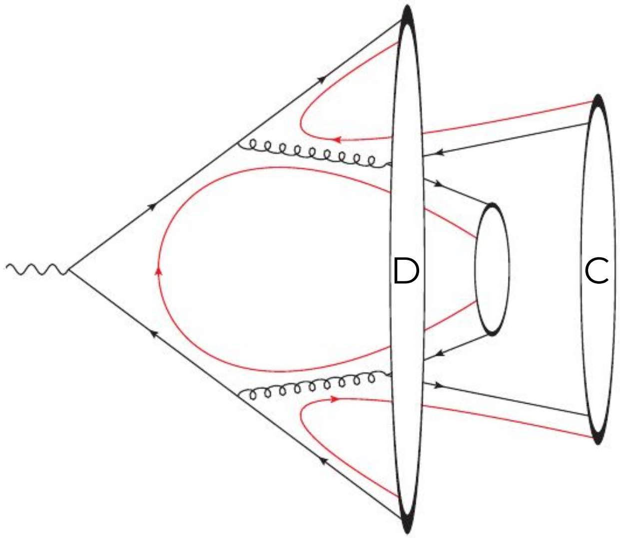
The ultimate goal of is to train the ML model directly on data to improve hadronization models.

First step: [J. Chan, A. Ghosh, Xi. Ju, A.Kania, B. Nachman, V. Sangli, **AS,** 2305.17169]



Extending Herwig's hadronization model:

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*

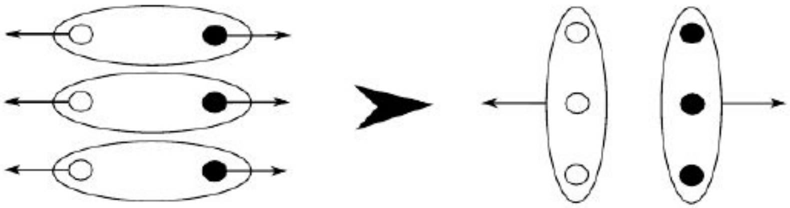


Extending Herwig's hadronization model:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, if $M_C + M_D < M_A + M_B$ accept alternative clustering with probability p_{reco}

Different approaches in Herwig

- "Space-time CR" [J. Bellm, C. Duncan, S. Gieseke, M. Myska, **AS** EPJC 79 (2019) no.12, 1003]
- "Baryonic colour reconnection" [S. Gieseke, P. Kirchgaeßer, S. Plätzer Eur.Phys.J. C78 (2018)]



- Colour Reconnection from Soft Gluon Evolution [Gieseke, Kirchgaesser, Plätzer, **AS** JHEP 11 (2018) 149]

(see Simon's Plätzer talk)

Progresses on KrKNLO

What is KrKNLO? :)

It is the youngest NLO+PS matching method.

[Silvia’s talk]

Going beyond NLL

spin-off of

Other groups’ work (prior to our NLL understanding): Jadach et al 1103.5015 & 1503.06849, Li & Skands 1611.00013, Höche & Prestel 1705.00742,+Krauss 1705.00982, +Dulat 1805.03757,

Why would you like another method of NLO+PS matching?

- The method is extremely simple.
- No negative weight events.
- In angular ordered PS - no need for a truncated shower.
- Simple at NLO ⇒ you may hope that pushing the method to
- NNLO+NLO PS should be possible

Idea behind the KrKNLO method

Basic idea of the MC scheme

DY cross section at NLO in collinear $\overline{\text{MS}}$ factorization for the $q\bar{q}$ channel:

$$\sigma^1_{\text{DY}} - \sigma^B_{\text{DY}} = \sigma^B_{\text{DY}}\, D_1^{\overline{\text{MS}}}(x_1, \mu^2) \otimes \frac{\alpha_s}{2\pi} C_q^{\overline{\text{MS}}}(z) \otimes D_2^{\overline{\text{MS}}}(x_2, \mu^2)\,,$$

where

$$C_q^{\overline{\text{MS}}}(z) = C_F \left[4\,(1+z^2) \left(\frac{\ln(1-z)}{1-z} \right)_+ - 2\frac{1+z^2}{1-z} \ln z + \delta(1-z) \left(\frac{2}{3}\pi^2 - 8 \right) \right].$$

All solutions for NLO + PS matching which use $\overline{\text{MS}}$ PDFs, need to implement collinear remnant term of the type $4\,(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+$ that are technical artefacts of $\overline{\text{MS}}$ scheme.

The implementation is not easy since those terms correspond to the collinear limit but Monte Carlo lives in 4 dimensions and not in the phase space restricted by $\delta(k_T^2)$.
The idea behind the MC scheme is to absorb those terms to PDF.

Procedure:

1. Take a parton shower that covers the (α, β) phase space completely (no gaps, no overlaps) and produces emissions according to approx. real matrix element K.
2. Upgrade the real emissions to exact ME R by reweighting the PS events by $W_R = R/K$.
3. We define the coefficion function $C^R(z) = \int (R - K)$. To avoid unphysical artifacts of $\overline{\mathrm{MS}}$.
4. Transform PDF for $\overline{\mathrm{MS}}$ scheme to this new physical MC factorization scheme.
5. As a result the virtual+soft correction, Δ_{S+V}, is just a constant, without x-depended collinear remnant terms now. Multiply the whole result by $1 + \Delta_{S+V}$ to achieve complete NLO accuracy.

KrKNLO

1. Run LO PS[1] (Herwig/Sherpa) using MC PDF (via LHAPDF interface)
2. Get and an event record (for example in the HepMC format).

```
GenEvent: #8 ID=0 SignalProcessGenVertex Barcode: 0
 Momenutm units:     GEV     Position units:      MM
 Cross Section: 697.653 +/- 206.627
 Entries this event: 1 vertices, 5 particles.
 Beam Particles are not defined.
 RndmState(0)=
 Wgts(9)=(0,3023.17) (1,0.17886) (2,3023.17) (3,9) (4,0) (5,1.14371) (6,0) (7,1) (8,1)
 EventScale -1 [energy]          alphaQCD=0.139387       alphaQED=-1
                                    GenParticle Legend
        Barcode   PDG ID      ( Px,       Py,       Pz,      E ) Stat  DecayVtx
________________________________________________________________________________
GenVertex:       -1 ID:    0 (X,cT):0
 I: 2     10001        1 +0.00e+00,+0.00e+00,+6.26e+02,+6.26e+02   2        -1
          10002       21 +0.00e+00,+0.00e+00,-1.84e+01,+1.84e+01   2        -1
 O: 3     10003        1 -1.82e+00,+5.68e-01,-1.50e+01,+1.51e+01   1
          10004       11 +2.58e+01,+9.16e+00,+5.71e+02,+5.71e+02   1
          10005      -11 -2.40e+01,-9.73e+00,+5.17e+01,+5.78e+01   1
```

3. Book histograms (for example using Rivet) with MC weight calculated from the event record (and information on α_s).

It is almost as fast as LO+PS calculation!

KrKNLO - history

[S. Jadach, W. Placzek, S. Sapeta, AS, M. Skrzypek, JHEP 1510 (2015) 052]

- Our approach to NLO+PS matching (example: Drell-Yan)

Real part:

$$W_R^{q\bar{q}}(\alpha,\beta) = 1 - \frac{2\alpha\beta}{1+(1-\alpha-\beta)^2}$$
$$W_R^{qg}(\alpha,\beta) = 1 + \frac{\alpha(2-\alpha-2\beta)}{1+2(1-\alpha-\beta)(\alpha+\beta)}$$

Virtual + soft:

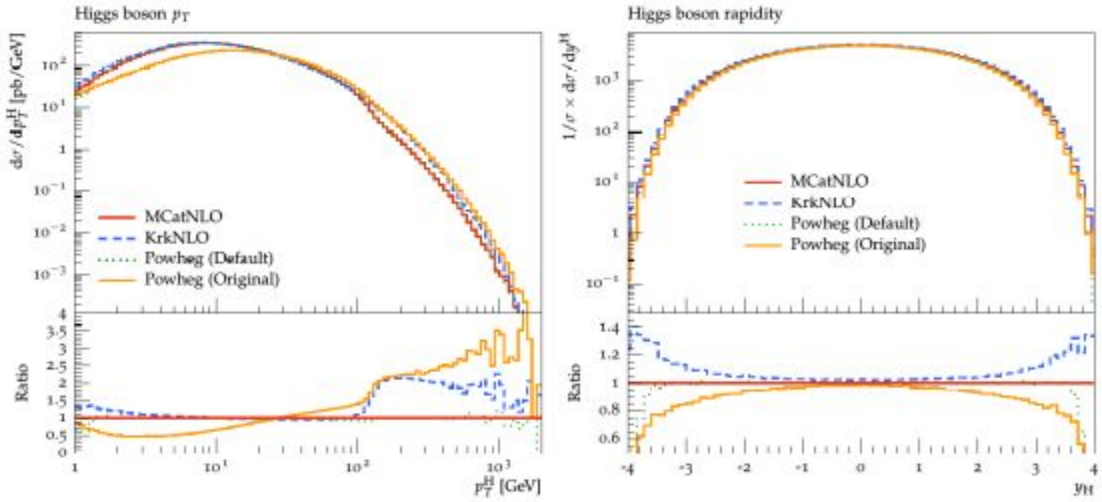
$$W_{V+S}^{q\bar{q}} = \frac{\alpha_s}{2\pi} C_F \left[\frac{4}{3}\pi^2 - \frac{5}{2}\right]$$
$$W_{V+S}^{qg} = 0$$

- PDF in MC factorization scheme - full definition

[S. Jadach, W. Placzek, S. Sapeta, AS, M. Skrzypek, Eur.Phys.J.C 76 (2016) 12]

- KrkNLO for the Higgs boson production

[S. Jadach, G. Nail, W. Placzek, S. Sapeta, AS, M. Skrzypek, Eur.Phys.J. C77 (2017)]



Progresses on KrKNLO

KrkNLO

Recent work: S. Jadach, W. Płaczek, S. Plätzer, P. Sarmah, AS, J. Whitehead

Automation

Hybrid matching (Krk+MC@)NLO

[P. Nason, G. Salam JHEP 01 (2022) 067]

More processes:
W, diphoton, W+W-,...

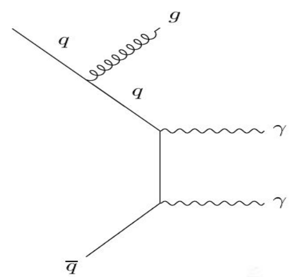
Spin correlations for Z decay products → comparison with the data
[Seymour Nucl.Phys. B436 (1995) 443-460]

Matching to higher orders NNLO
[Z+jet as an intermediate step]

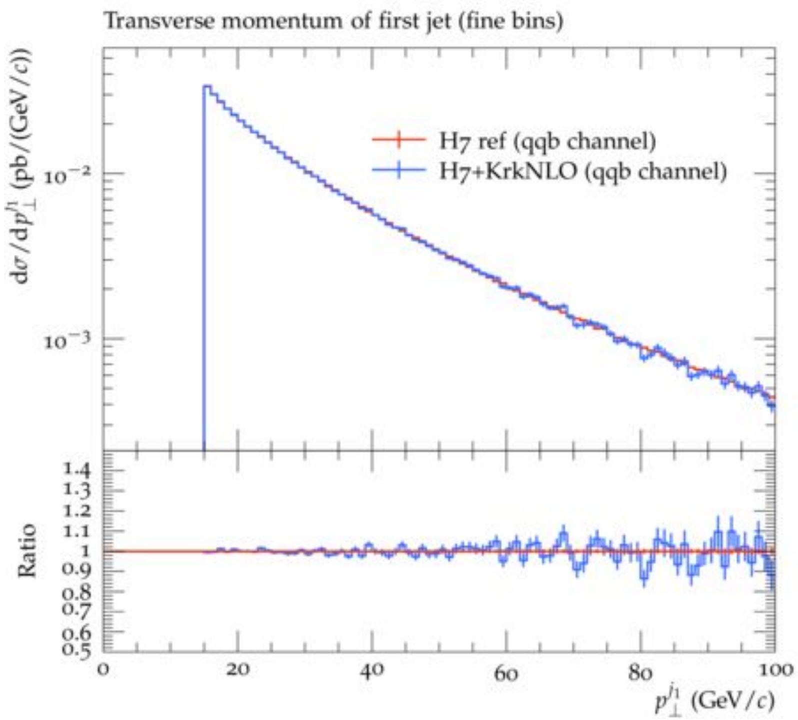
Universality

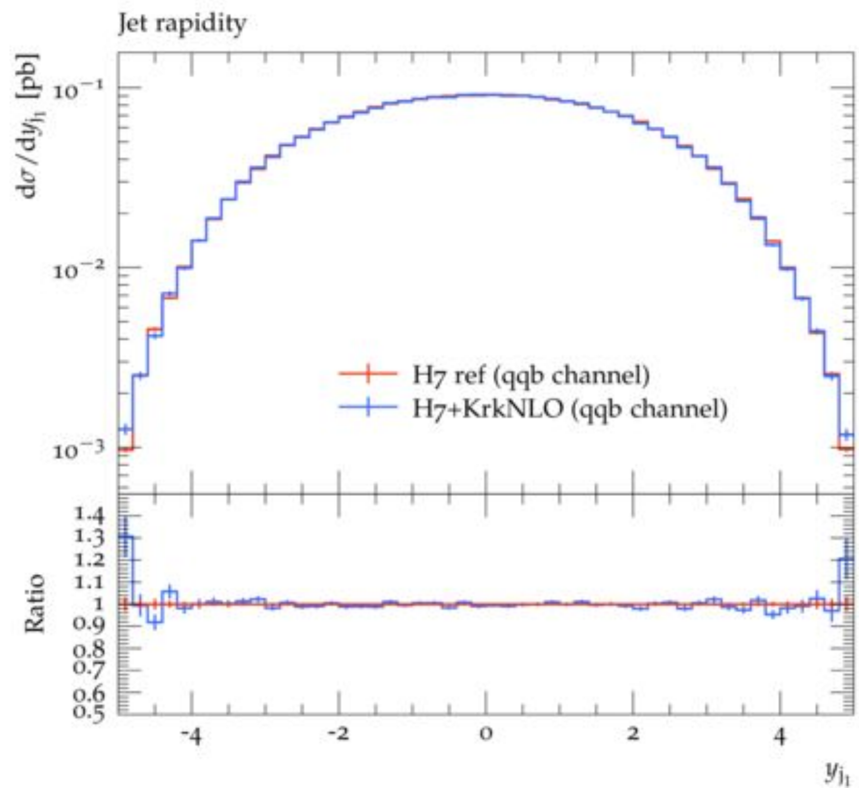
KrKNLO - di-photon (1st process not used to define MC PDF)

W_R weight validation against fixed order:



$q\bar{q}$ **Channel**



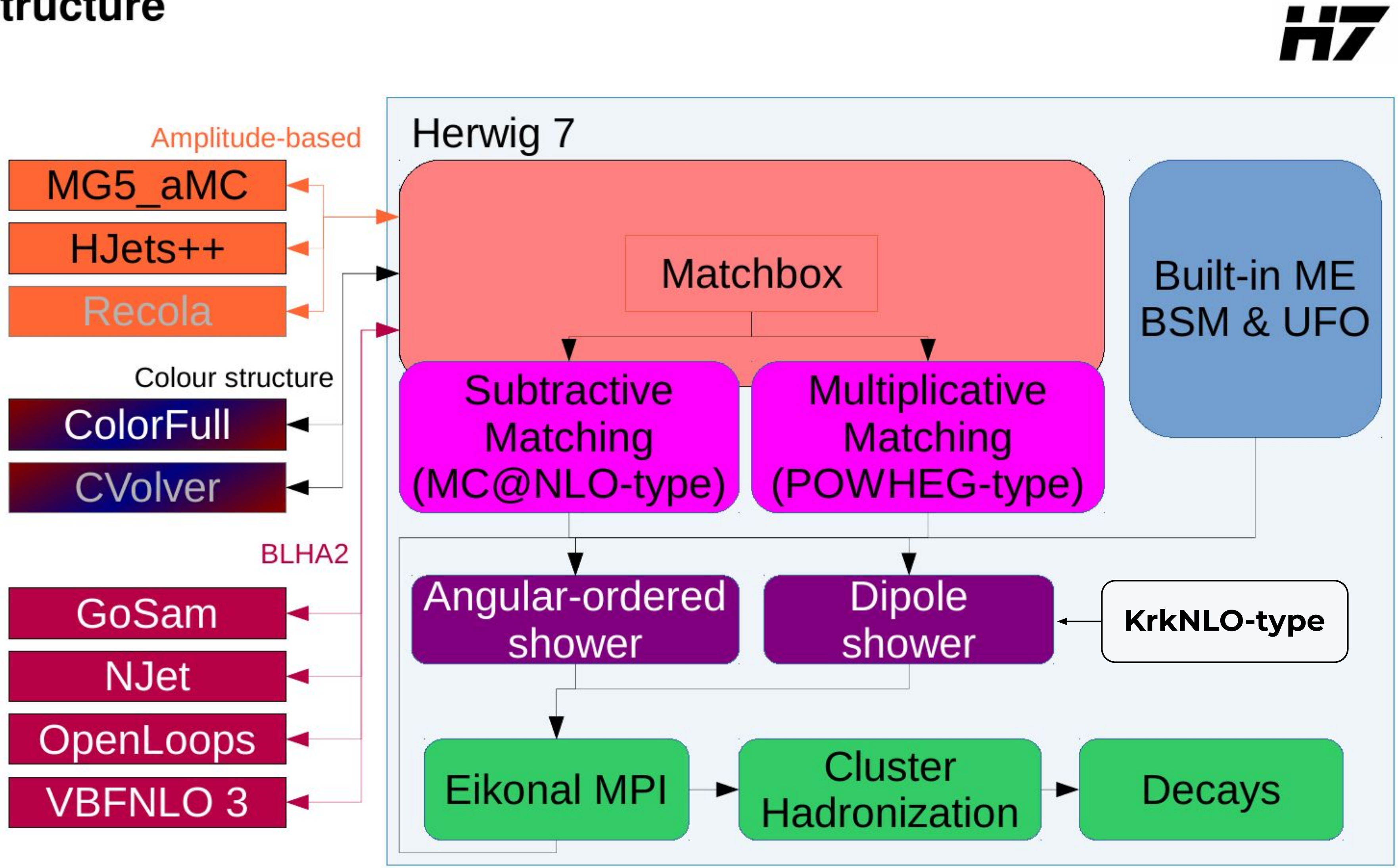


KrkNLO - 1 emission only, Sudakov unweighted

W_{VS} weight is also validated

KrKNLO - automation, (Krk+MC@)NLO - MatchBox change

Structure



Plot from S. Plätzer

KrKNLO - automation, (Krk+MC@)NLO - MatchBox change

Matchbox's automated NLO matching divides contributions into three subtypes, generated independently:

- born-type:

$$\mathrm{d}\phi_m \; u(\phi_m) \; \Theta_{\mathrm{cut}} \left[\phi_m\right] \left\{ \mathrm{B}(\phi_m) + \mathrm{V}(\phi_m) + \sum_{\alpha} \left[\mathrm{I}^{(\alpha)}(\phi_m) + \mathrm{d}x \; (\mathrm{P}+\mathrm{K})^{(\alpha)}(x;\phi_m) \right] \right\}$$

- '*virtual*' shower subtraction:

$$\mathrm{d}\phi_{m+1} \left\{ -\sum_{\alpha} u(\Phi_m^{(\alpha)}) \; \Theta_{\mathrm{cut}} \left[\Phi_m^{(\alpha)}\right] \mathrm{D}^{(\alpha)} \left(\phi_{m+1}\right) \; \Theta_{\mu_s}^{(\alpha)} \right.$$

$$\left. + \sum_{\alpha} u(\Phi_m^{(\alpha)}) \; \Theta_{\mathrm{cut}} \left[\Phi_m^{(\alpha)}\right] \; \Theta_{\mathrm{PS}}^{(\alpha)} \left[\phi_{m+1}\right] \; \mathrm{PS}^{(\alpha)} \left[\phi_{m+1}\right] \; \Theta_{\mu_s}^{(\alpha)} \right\}$$

- '*real*' shower subtraction:

$$\mathrm{d}\phi_{m+1} \; u(\phi_{m+1}) \left\{ \mathrm{R}(\phi_{m+1}) \; \Theta_{\mathrm{cut}} \left[\phi_{m+1}\right] + \sum_{\alpha} (\Theta_{\mu_s}^{(\alpha)} - 1) \; \mathrm{D}^{(\alpha)}(\phi_{m+1}) \; \Theta_{\mathrm{cut}} \left[\Phi_m^{(\alpha)}\right] \right.$$

$$\left. - \sum_{\alpha} \Theta_{\mathrm{PS}}^{(\alpha)} \left[\phi_{m+1}\right] \; \mathrm{PS}^{(\alpha)}\left[\phi_{m+1}\right] \; \Theta_{\mu_s}^{(\alpha)} \; \Theta_{\mathrm{cut}} \left[\Phi_m^{(\alpha)}\right] \right\}$$

KrKNLO - automation, (Krk+MC@)NLO - MatchBox change

In practice, the 'virtual shower subtraction' can generate negative weights, whenever the dipoles oversubtract the shower.

Alternative structure:

- rather than a subtraction mapping for these terms, use a splitting
- combine born-type and virtual shower subtraction into a single 'InclusiveME':

$$
\begin{aligned}
\mathrm{d}\phi_m \; u(\phi_m)\, \Theta_{\text{cut}}\,[\phi_m] \quad & \Bigg[\Bigg\{ \mathsf{B}(\phi_m) + \mathsf{V}(\phi_m) + \sum_\alpha \Big[\mathsf{I}^{(\alpha)}(\phi_m) + \mathrm{d}x \, (\mathsf{P}+\mathsf{K})^{(\alpha)}(x;\phi_m) \Big] \Bigg\} \\
& - \sum_\alpha \mathrm{d}q^{(\alpha)} \left\{ \mathsf{D}^{(\alpha)} \left(\Phi^{(\alpha)}_{m+1} \right) \Theta^{(\alpha)}_{\mu_s} \right\} \\
& + \sum_\alpha \mathrm{d}q^{(\alpha)} \left\{ \Theta^{(\alpha)}_{\mathsf{PS}} \left[\Phi^{(\alpha)}_{m+1} \right] \, \mathsf{PS}^{(\alpha)} \left[\Phi^{(\alpha)}_{m+1} \right] \, \Theta^{(\alpha)}_{\mu_s} \right\} \Bigg]
\end{aligned}
$$

This will reduce the fraction of negative weights.

KrKNLO - automation, (Krk+MC@)NLO - MatchBox change

New very flexible structure of Matchbox:

$$\hat{\sigma}^{\mathrm{NLO+PS}}[u] = \hat{\sigma}^{\mathrm{NLO}}[u] + \mathcal{O}\left(\alpha_s^2\right) + \mathcal{O}\left(\frac{\mu_s}{Q}\right)$$

leads to:[1]

$$\begin{aligned}
&\mathrm{d}\phi_m\, u(\phi_m)\, \Theta_{\mathrm{cut}}[\phi_m] && \Bigg[\Bigg\{ \mathrm{B}(\phi_m) + \mathrm{V}(\phi_m) + \sum_\alpha \Big[\mathrm{I}^{(\alpha)}(\phi_m) + \mathrm{d}x\, (\mathrm{P}+\mathrm{K})^{(\alpha)}(x;\phi_m) \Big] \Bigg\} \\
& && - \sum_\alpha \mathrm{d}q^{(\alpha)} \Big\{ \mathrm{D}^{(\alpha)}\left(\Phi_{m+1}^{(\alpha)}\right) \Big\} + \sum_\alpha \mathrm{d}q^{(\alpha)} \Big\{ f^{(\alpha)}(\Phi_{m+1}^{(\alpha)}) \Big\} \\
& && + \sum_\alpha \mathrm{d}q^{(\alpha)} \Big\{ \Theta_{\mathrm{PS}}^{(\alpha)} \left[\Phi_{m+1}^{(\alpha)}\right]\ \mathrm{PS}^{(\alpha)} \left[\Phi_{m+1}^{(\alpha)}\right]\ \Theta_{\mu_s}^{(\alpha)} \Big\} \Bigg] \\
&+\mathrm{d}\phi_{m+1}\, u(\phi_{m+1}) && \Bigg[\mathrm{R}(\phi_{m+1})\, \Theta_{\mathrm{cut}}[\phi_{m+1}] - \sum_\alpha \Big\{ f^{(\alpha)}(\phi_{m+1}) \Big\}\, \Theta_{\mathrm{cut}} \left[\Phi_m^{(\alpha)}(\phi_{m+1})\right] \\
& && - \sum_\alpha \Big\{ \Theta_{\mathrm{PS}}^{(\alpha)}[\phi_{m+1}]\ \mathrm{PS}^{(\alpha)}[\phi_{m+1}]\, \Theta_{\mu_s}^{(\alpha)} \Big\}\, \Theta_{\mathrm{cut}} \left[\Phi_m^{(\alpha)}(\phi_{m+1})\right] \Bigg]
\end{aligned}$$

Currently we are validation the implementation against old version

Enables:

- **Automation of KrkNLO (validation by results “by hand”, Z, H, di-photons)**
- **Hybrid methods like (Krk+MC@)NLO**
- **Less negative weights in other matching methods**

Summary

Herwig 7:

Parton Shower:

- Recent developments triggered by understanding the accuracy of Parton Shower
- EW Shower will be available in next release Herwig 7.3 (coming soon)
- BSM Showers possible

Hadronization:

- Dynamic model
- Polarization of Heavy Hadrons
- Dark Hadronization

Matching:

- Matchbox new structure - less negative weights, many new possibilities (see KrkNLO)

Herwig 7.3 (coming soon)

KrkNLO:

New processes:

- di-photon - coming soon
- W - coming soon

Spin-correlation:

- W/Z

Automation:

- Possible after Matchbox is ready

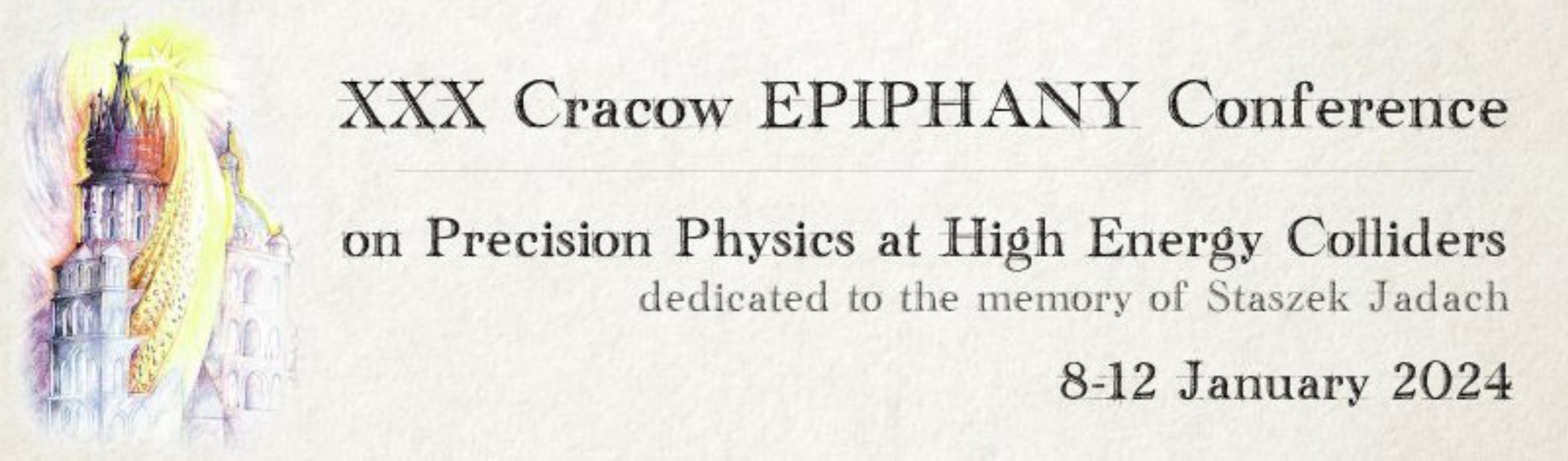
(Krk+MC@)NLO

- Possible after Matchbox is ready

Longer term:

- NNLO + PS (step Z+jet NLO)
- Universality

Advertisement



Polarization of Heavy Hadrons

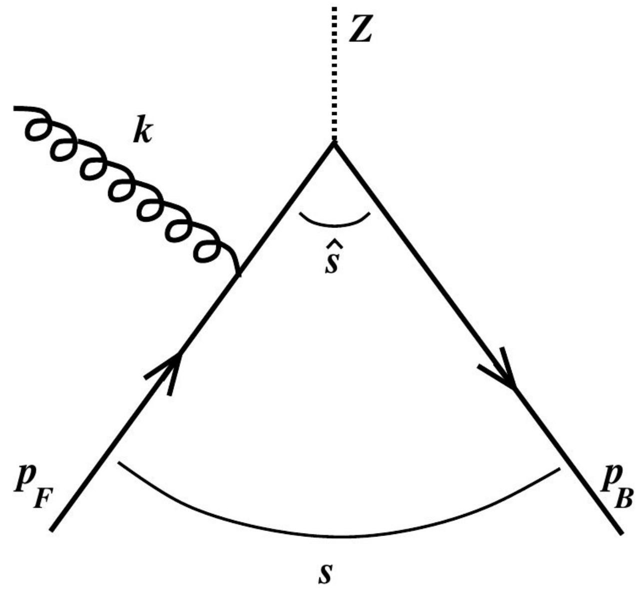
1st Step: Passing through the polarization of heavy hadrons at the end of parton shower. [arXiv:hep-ph/9308241]

- For $m_Q \gg \Lambda_{\text{QCD}}$, the light degrees of freedom become insensitive to m_Q.
- Heavy quarks act as non-recoiling sources of color at the end of PS.
- A spin-flavor symmetry appears for heavy quarks.
- A net polarization of the initial heavy quark may be detected, either in a polarization of the final ground state or in the decay products of the **excited heavy mesons** and **heavy baryons**.
- **Falk-Peskin "no-win" theorem**: no polarization information would be found in non-excited mesons.

2nd Step: Improving the Strong decay modes the excited heavy mesons, i.e charm, and bottom mesons.

- Heavy Quark Effective Field Theory (HQEFT) usually determines which decay modes are possible and also gives the relations between the involving couplings.
- In the absence of experimental data on many of the decays, we need to rely on HQ symmetries to determine the decay modes, widths and branching ratios.
- We consider charm and bottom meson decays with: [arXiv:hep-ph/9209239]
  - $J^P = 0^-, 1^-$ doublets with $l = 0$ (D and D^*).
  - $J^P = 1^+, 2^+$ doublets with $l = 1$ and $j = 3/2$ (D_1 and D_2^*).
  - $J^P = 0^+, 1^+$ doublets with $l = 1$ and $j = 1/2$ (D_0^* and D_1').

Drell-Yan process



$s = (p_F + p_B)^2$

$z = \frac{\hat{s}}{s}$

Sudakov variables:

$$\alpha = \frac{2k \cdot p_B}{\sqrt{s}} = \frac{2k^+}{\sqrt{s}}$$

$$\beta = \frac{2k \cdot p_F}{\sqrt{s}} = \frac{2k^-}{\sqrt{s}}$$

$$z = 1 - \alpha - \beta$$

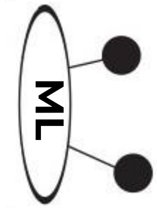
$$k_T^2 = s\alpha\beta$$

$$y = \frac{1}{2} \ln \frac{\alpha}{\beta}$$

Towards a Deep Learning Model for Hadronization

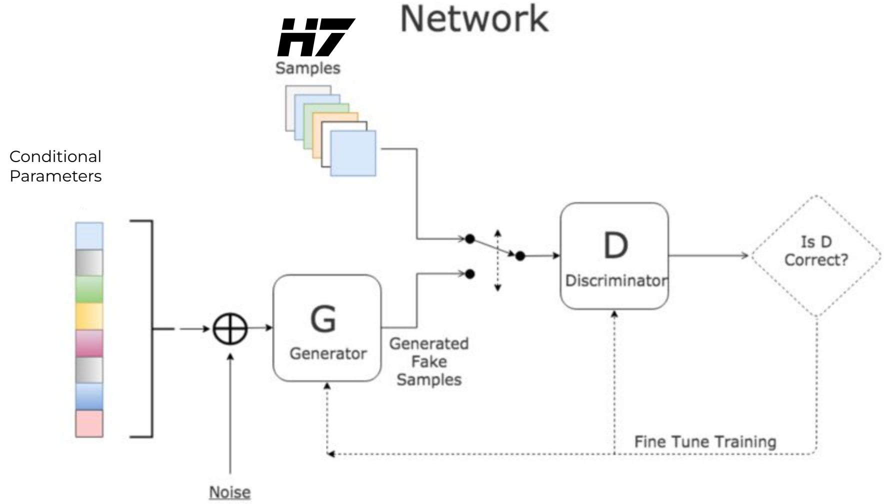
ML hadronization

1st step: generate kinematics of a cluster decay to 2 hadrons



How?

Generative Adversarial Network

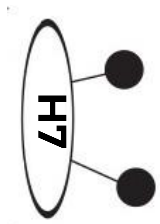


Training data:

H7

e^+e^- collisions at $\sqrt{s} = 91.2$ GeV

Cluster $(E,\ p_x,\ p_y,\ p_z)$



$\pi^0(E,\ p_x,\ p_y,\ p_z)$

$\pi^0(E,\ p_x,\ p_y,\ p_z)$

Pert = 0/1 memory of quarks direction