General-purpose Monte Carlo event generators for an EIC

EIC user group meeting, Paris

Ilkka Helenius

July 25th, 2019

University of Jyväskylä
Department of Physics

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Outline

- An (slightly biased) overview on general-purpose Monte-Carlo event generators for electron-ion colliders, focus on recent developments
- Thanks to Stefan Hoeche, Stefan Prestel, Leif Lönnblad and Simon Plätzer

Outline

1. General-purpose Monte-Carlo event generators
2. Electron-ion collider capabilities in
   - SHERPA
   - HERWIG
   - PYTHIA
3. Summary & Outlook

MCnet

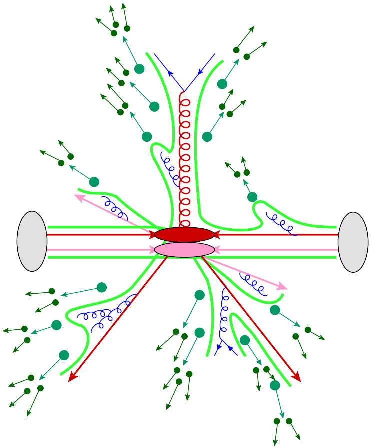
General-purpose Monte Carlo event generators

General philosophy

- Generate exclusive hadronic final states
- Use theory (pQCD) where available, fill in phenomenological models where not
- Tune model parameters globally to data

Event generation in hadronic collision

1. Hard scattering
2. Parton showers (PS)
3. Multiparton interactions (MPIs)
4. Beam remnants
5. Hadronization & Decays



[Figure: S. Prestel]

General-purpose event generators

Pythia (8.243) [Comput. Phys.Commun. 191 (2015) 159]

- Transverse-momentum ordered dipole-based parton shower
- MPIs from regularized $2 \to 2$ scatterings, interleaved with PS
- Hadronization with Lund string model with color reconnection

Herwig (7.1.5) [Eur.Phys.J. C76 (2016) no.4, 196]

- Angular-ordered and Catani-Seymour dipole parton shower
- Automated NLO merging
- Cluster model for hadronization

Sherpa (2.2.7) [arXiv:1905.09127]

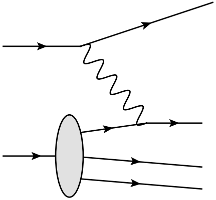
- NLO corrections to (dipole) parton shower
- Electro-weak (EW) corrections
- NNLO for color-singlet processes

Event classification in ep

Virtuality of photon related to scattering angle of the lepton

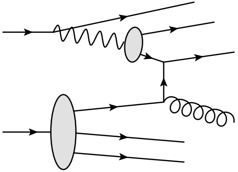
Deep inelastic scattering (DIS)

- High virtuality, $Q^2 >$ a few GeV^2
- Hard scattering between lepton and a parton



Photoproduction

- Low virtuality, $Q^2 \lesssim 1$ GeV^2
  $\Rightarrow$ Direct and resolved contributions
- Factorize γ flux, evolve γp system
- Hard scale provided by the hadronic observable
- Also soft QCD processes, diffraction



Event generation in DIS

Hard scattering

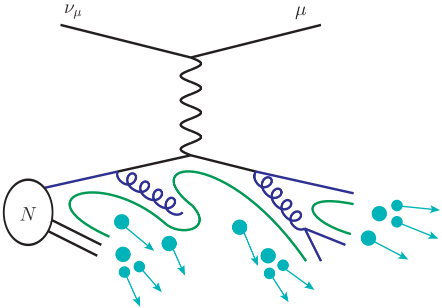
- Convolution between PDFs and matrix element (ME) for partonic scattering

Parton shower

- Final state radiation (FSR)
- Initial state radiation (ISR) for hadron
- QED emissions from leptons
- ME corrections for the hardest splitting
- Matching of high-multiplicity MEs and PS

Hadronization

- Colour reconnection
- Decays to stable hadrons



[Figure: S. Prestel]

Jets in DIS with SHERPA

- ME corrections to splitting kernels in PS
- Merging of MEs with and PS

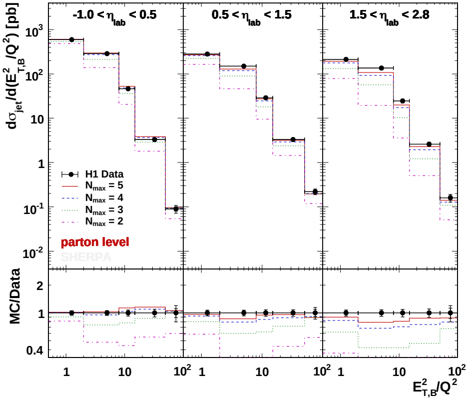
Inclusive jets in DIS at HERA

- $d\sigma$ in terms of $E^2_{T,B}/Q^2$, where $E_{T,B}$ transverse momentum of the jet in Breit frame
- MEs with up to five partons in the final state
- ME and PS domains separated by

$$Q_{cut}(Q^2) = \bar{Q}_{cut}\left(1 + \frac{\bar{Q}^2_{cut}/S^2_{DIS}}{Q^2}\right)^{-\frac{1}{2}},$$

where $\bar{Q}_{cut} = 5$ GeV and $S^2_{DIS} = 0.6$

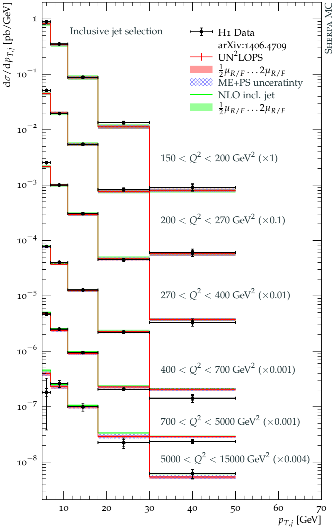
- Increasing N_{max} improves agreement

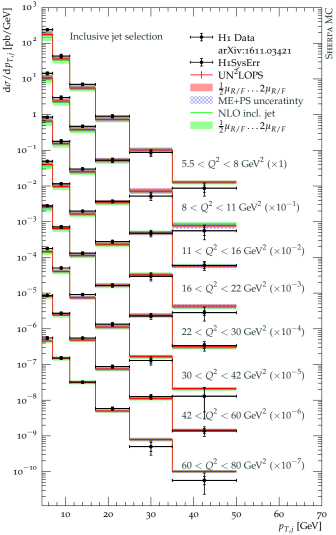


[T. Carli, T. Gehrmann, S. Höche, EPJC 67 (2010) 73]

Matching in DIS at NNLO with SHERPA

- New Sherpa module for DIS at NNLO in QCD
  [Kuttimalai,Li,Höche, arXiv:1809.04192]
- Based on UNLOPS matching
  [Lönnblad, Prestel, arXiv:1211.7278]
  [Li, Prestel, Höche, arXiv:1405.3607]
- Good agreement with HERA high- and low-Q^2 data
- Also di- and tri-jet cross sections well described with
  $$\mu_{F,R}^2 = (Q^2 + (H_T/2)^2)/2$$

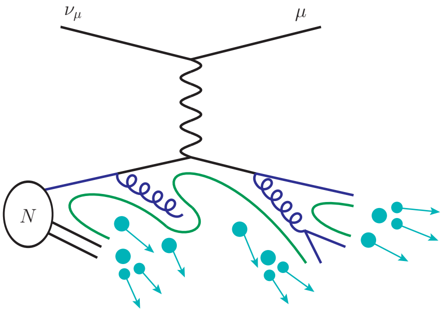




DIS with HERWIG

Overview on DIS capabilities

- Two shower options for DIS:
  - Dipole shower, spin correlations
  - Angular-ordered, spin correlations and QED radiation
- Support for shower variation and on-the-fly weighting to estimate uncertainties
- Development for colour reconnection in the cluster hadronization model
- Fully automated NLO matching



[Figure: S. Prestel]

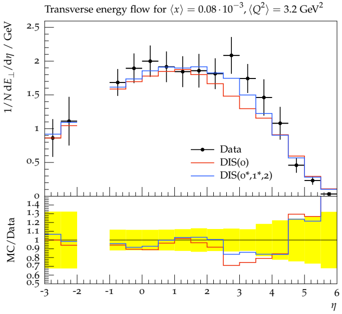
DIS with HERWIG

Transverse energy flow

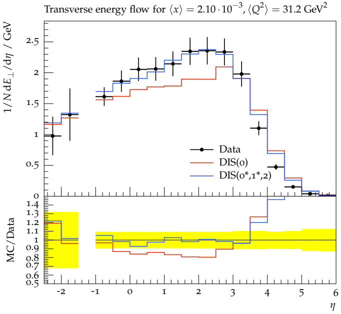
- Process $e^+q \to e^+q$
- Comparison between LO (red) and NLO merged (blue)
- Good description with the NLO corrections

Also photoproduction but still preliminary

Low-Q^2



High-Q^2



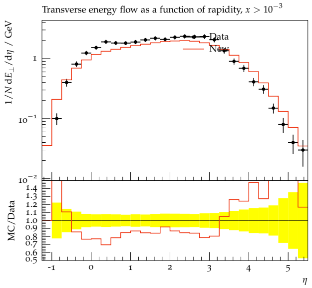
[Data: H1, EPJC 12 (2000) 595]

DIS with Pythia

New shower option: `dipoleRecoil`

[B. Cabouat and T. Sjöstrand, EPJC 78 (2018 no.3, 226)]

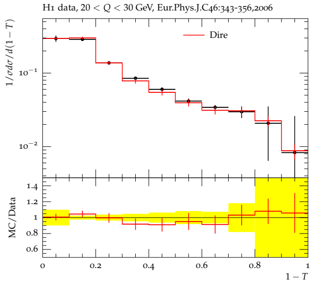
- No PS recoil for the scattered lepton
- Reasonable description of single-particle properties, such as transverse energy flow
- Results based on tune with the default global-recoil shower



DIRE plugin (to be included in PYTHIA 8.3)

[S. Höche, S. Prestel, EPJC 75 (2015) no.9, 461]

- Correct soft-gluon interference at lowest order
- Inclusive NLO corrections to collinear splittings
- Good agreement with HERA data for thurst T



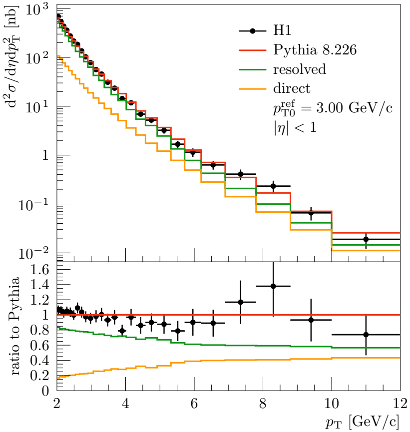
Photoproduction with PYTHIA

Photoproduction in PYTHIA 8

- Hard and soft QCD processes
- Mix of resolved and direct processes
- Photon PDFs from CJKL fit
- MPIs for the resolved processes
  $\Rightarrow$ Regulated with p_{T0} as in pp
- Applicable also for UPCs

Inclusive hadron spectra from H1

- Resolved contribution dominates
- Good agreement with the data using $p_{\mathrm{T0}}^{\mathrm{ref}} = 3.00$ GeV (pp: $p_{\mathrm{T0}}^{\mathrm{ref}} = 2.28$ GeV)
  $\Rightarrow$ MPI probability reduced from pp



[H1: Eur.Phys.J. C10 (1999) 363-372]

Implemented from PYTHIA 8.235

[I.H., C. O. Rasmussen, Eur.Phys.J. C79 (2019) no.5, 413]

- Based on dynamical rapidity gap survival

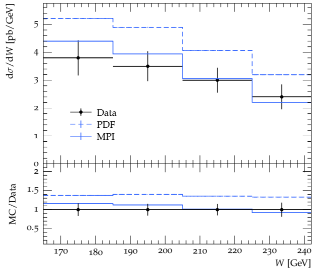
  [C. O. Rasmussen, T. Sjöstrand, JHEP 1602 (2016) 142]

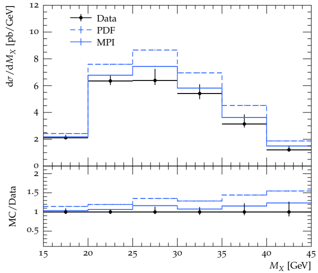
- Begin with factorized approach with diffractive PDFs (Ingelman-Schlein picture)
- Reject events where MPIs between resolved γ and p would destroy the rapidity gap

Comparison to HERA diffractive dijet data

[H1: EPJC 51 (2007) 549, ZEUS: EPJC 55 (2008) 177]

- More MPI suppression towards higher W, M_X
- Natural explanation for observed factorization breaking in pp and γp





Exclusive vector meson production with PYTHIA

Implemented from PYTHIA 8.240

[I.H., C. O. Rasmussen, in progress]

- Based on (pre-HERA) SAS parametrizations

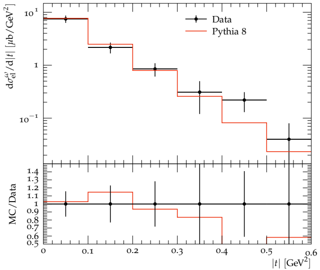
  [G.A. Schuler, T. Sjöstrand, Phys.Rev. D49 (1994) 2257-2267]

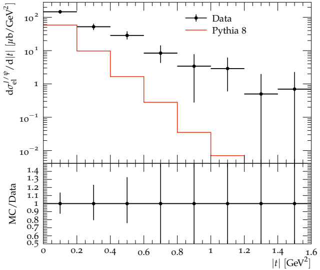
- Includes ρ, ω, ϕ and J/Ψ production via elastic scattering

Comparison to HERA data

- Good agreement with low-mass mesons (ω)
- Underestimate heavy-meson (J/Ψ) production

  $\Rightarrow$ Require improved parametrizations using HERA data





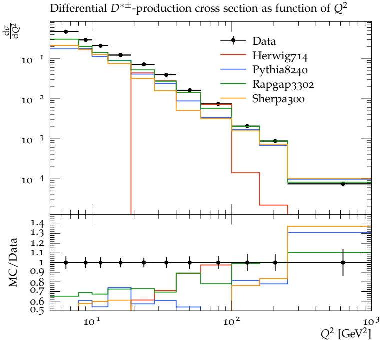
Summary

All event generators can simulate DIS events

- SHERPA: ME corrections and merging with PS, now also at NNLO
- HERWIG: Two shower options and automated NLO matching
- PYTHIA: Recent dipole-recoil shower option, DIRE to be included

Less activities on photoproduction

- HERWIG: Preliminary setup for photoproduction
- PYTHIA: Hard and soft QCD processes, now including also diffractive events and UPCs



[Plot by A. Verbytskyi]

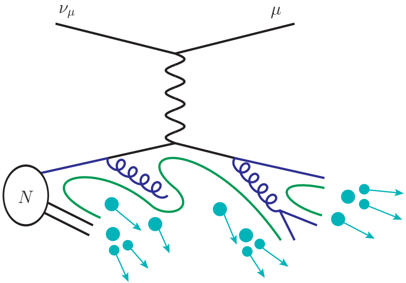
- RIVET analyses for ep data important for generator development

Outlook

eA collisions

- Currently no general purpose MCEG capable to handle nuclear targets with lepton beams (apart from nPDFs)
- In PYTHIA could be addressed by expanding the ANGANTYR model for heavy-ions

  [Bierlich, Gustafson, Lönnblad, Shah, JHEP 1810 (2018) 134]



Open questions

- Smooth merging of DIS (high-Q^2) and photoproduction (low-Q^2) regimes

  $\Rightarrow$ Evidence for ridge in UPCs (low Q^2) but not at HERA in $Q^2 > 5$ GeV^2
- Polarization, TMDs, Wigner functions?

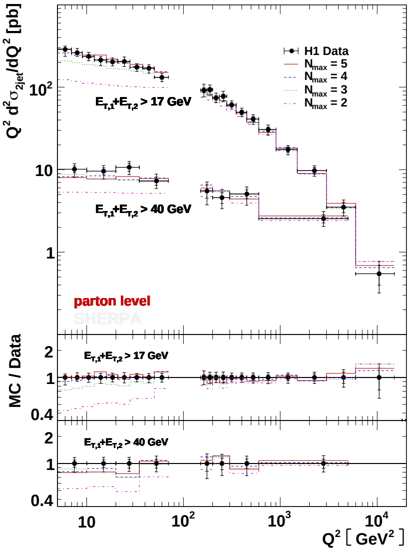
Backup slides

Jets in DIS with SHERPA

- ME corrections to splitting kernels in PS
- Merging of MEs with and PS

Dijets in DIS at HERA

- Kinematics of the H1 data:
  - $-1 < \eta_{\text{lab}} < 2.5$
  - $5 < Q^2 < 15000\ \text{GeV}^2$
  - $E_{\text{T,B}} > 5\ \text{GeV}$
- Below $Q^2 \sim 100\ \text{GeV}^2$ need again several final-state partons to describe the data
- Also three-jet cross section and transverse-energy flows (with cluster hadronization) well described



POWHEG matching in DIS with SHERPA

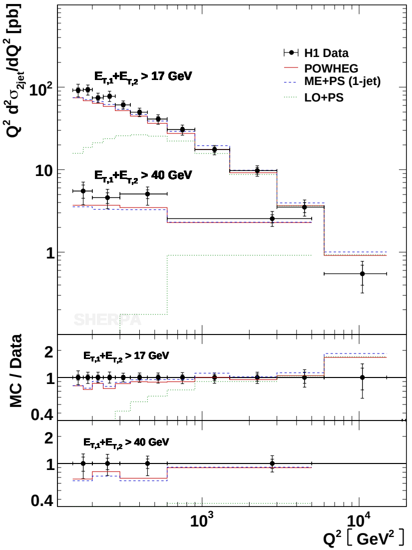
- Provides automated NLO matching with positive event-weights
- Implemented also for DIS in Sherpa

Dijets in DIS at HERA

- Consider NLO correction to the core $e^{\pm}q \to e^{\pm}q$ process
- Compare only to high-Q^2 data
- Large deviations from LO+PS result
- Similar to ME merged with PS

[S. Höche, F. Krauss, M. Schönherr, F. Siegert, JHEP 04 (2011) 024]

[More details in next talk by S. Höche]



Photoproduction in PYTHIA

Direct contribution

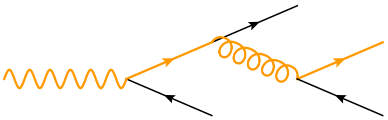
- Photon-parton scattering
- DIS-like: no MPIs but showers

Resolved contribution

- Photon in hadronic state
- PDFs for resolved photons, includes hadron-like and point-like contributions
- Also MPIs and soft QCD processes (elastic, diffraction)

Pythia features

- CJKL PDFs as a default (others via LHAPDF 5)
- Collapse back to unresolved state in ISR (point-like PDFs)
  - $\Rightarrow$ Reject MPIs below the given scale



Dijet photoproduction in ep collisions at HERA

ZEUS dijet measurement

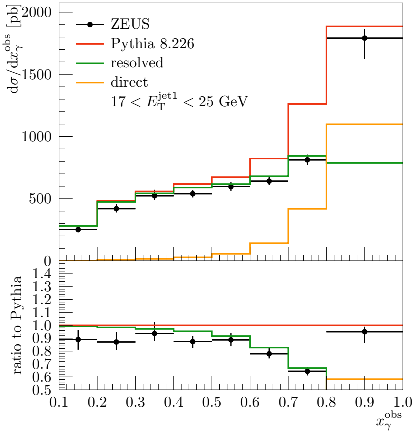
- $Q^2_\gamma < 1.0\ \text{GeV}^2$
- $134 < W_{\gamma p} < 277$ GeV
- $E_T^{\text{jet1}} > 14$ GeV, $E_T^{\text{jet2}} > 11$ GeV
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Direct vs. resolved

- Define

$$x_\gamma^{\text{obs}} = \frac{E_T^{\text{jet1}} e^{\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{\eta^{\text{jet2}}}}{2yE_e}$$

  to discriminate direct and resolved processes (=x in γ at LO parton level)
- At high-x_γ^{obs} direct processes dominate



[ZEUS: Eur.Phys.J. C23 (2002) 615-631]

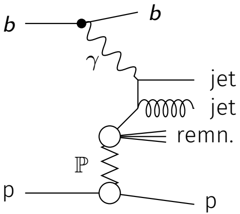
Diffractive dijets in photoproduction

[I.H., C. O. Rasmussen, arXiv:1901.05261 [hep-ph]]

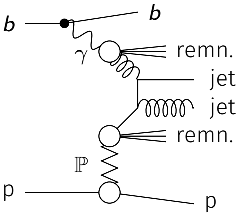
Starting point: Assume factorization of the cross section

- Direct: $\mathrm{d}\sigma^{2\mathrm{jets}} = f_{\gamma}^{b}(x) \otimes \mathrm{d}\sigma^{\gamma j \to 2\mathrm{jets}} \otimes f_{j}^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$
- Resolved: $\mathrm{d}\sigma^{2\mathrm{jets}} = f_{\gamma}^{b}(x) \otimes f_{i}^{\gamma}(x_{\gamma}, \mu^2) \otimes \mathrm{d}\sigma^{ij \to 2\mathrm{jets}} \otimes f_{j}^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$

Direct:



Resolved:



Rapidity gap survival for resolved events

1. Generate diffractive events with dPDFs (PDF selection)

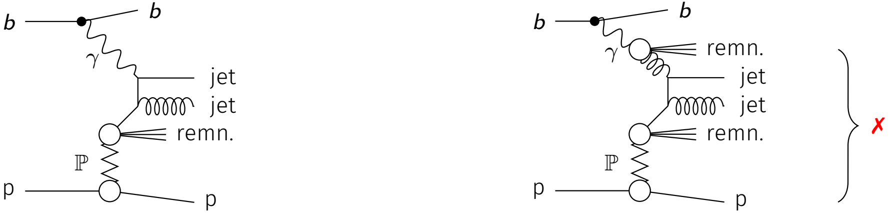
Diffractive dijets in photoproduction

[I.H., C. O. Rasmussen, arXiv:1901.05261 [hep-ph]]

Starting point: Assume factorization of the cross section

- Direct: $\mathrm{d}\sigma^{\mathrm{2jets}} = f_{\gamma}^{b}(x) \otimes \mathrm{d}\sigma^{\gamma j\to \mathrm{2jets}} \otimes f_{j}^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$
- Resolved: $\mathrm{d}\sigma^{\mathrm{2jets}} = f_{\gamma}^{b}(x) \otimes f_{i}^{\gamma}(x_{\gamma}, \mu^2) \otimes \mathrm{d}\sigma^{ij\to \mathrm{2jets}} \otimes f_{j}^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$

Direct: Resolved:



Rapidity gap survival for resolved events

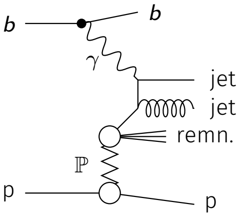
1. Generate diffractive events with dPDFs (PDF selection)
2. Reject events where MPIs in γp system (MPI selection)

Diffractive dijets in photoproduction

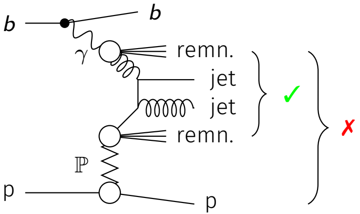
Starting point: Assume factorization of the cross section

- Direct: $\mathrm{d}\sigma^{\mathrm{2jets}} = f_{\gamma}^{b}(x) \otimes \mathrm{d}\sigma^{\gamma j \rightarrow \mathrm{2jets}} \otimes f_{j}^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$
- Resolved: $\mathrm{d}\sigma^{\mathrm{2jets}} = f_{\gamma}^{b}(x) \otimes f_{i}^{\gamma}(x_{\gamma}, \mu^2) \otimes \mathrm{d}\sigma^{ij \rightarrow \mathrm{2jets}} \otimes f_{j}^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{\mathrm{p}}(x_{\mathbb{P}}, t)$

Direct:



Resolved:



Rapidity gap survival for resolved events

1. Generate diffractive events with dPDFs (PDF selection)
2. Reject events where MPIs in γp system (MPI selection)
3. Evolve γIP system, allow MPIs for this subsystem