Event generator overview

MC4EIC

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Outline

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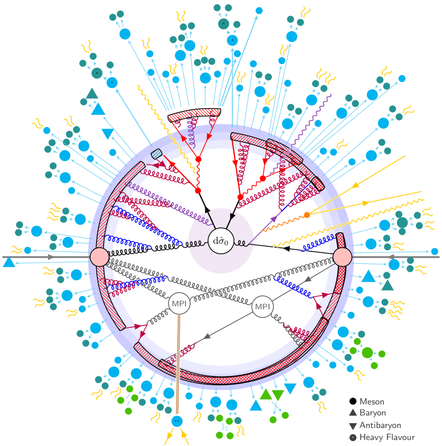
1. Event generators for high energy colliders
2. Electroproduction
3. Photoproduction
4. Diffractive processes
5. Tuning
6. MC4EIC recap



[figure by P. Skands]

Event generators

General purpose event generators

- Aim to provide a full description of a collision event, ie. exclusive hadronic final states, using Monte Carlo methods
- Use perturbative QCD where applicaple, fill in with phenomenologica models
- Main players:
  - Herwig (7.3.0) `https://herwig.hepforge.org` [Eur.Phys.J. C80 (2020) 452]
  - Pythia (8.315) `https://pythia.org` [SciPost Phys. Codebases 8-r8.3 (2022)]
  - Sherpa (3.0.1) `https://sherpa-team.gitlab.io` [JHEP 12 (2024) 156]

Specialized event generators

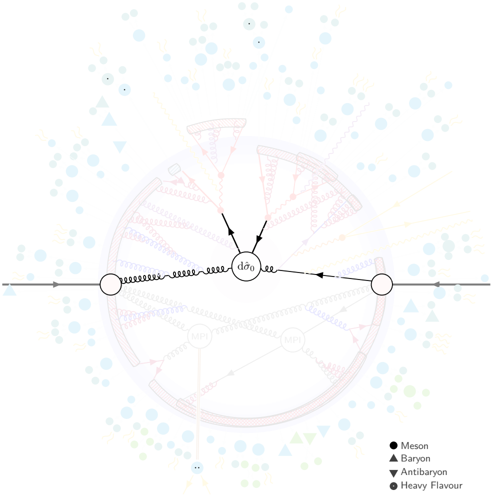
- Matrix-element (Hard-process) generators for higher perturbative accuracy and multiplicities: Madgraph5(_aMC@NLO), POWHEG(-BOX)
- Fixed-order codes: MCFM, NNLOJET, ...

Physics modelled within generators

Classify event generation in terms of "hardness"

1. Hard Process (here $t\bar{t}$)

[figure credit: P. Skands]



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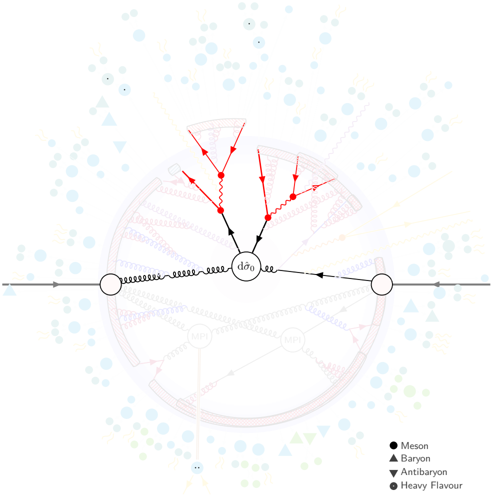
1. Hard Process (here $t\bar{t}$)
2. Resonance decays ($t, Z, \ldots$)



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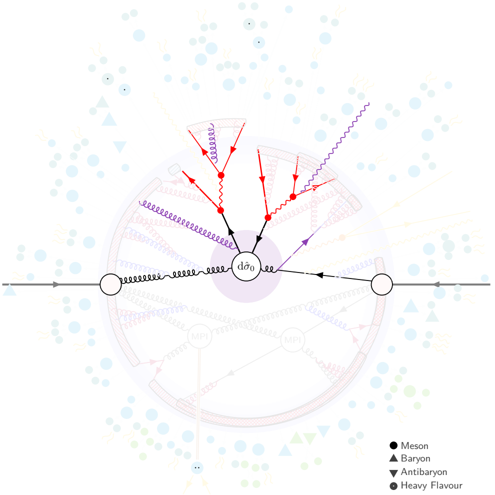
1. Hard Process (here $t\bar{t}$)
2. Resonance decays $(t, Z, \ldots)$
3. Matching, Merging and matrix-element corrections



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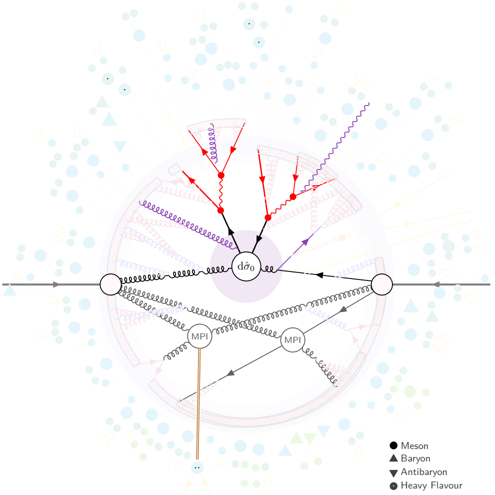
4. Multiparton interactions

[figure credit: P. Skands]



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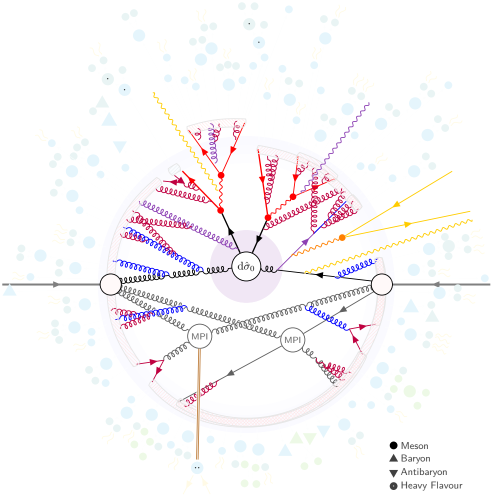
5. Parton showers: ISR, FSR, QED, Weak

[figure credit: P. Skands]



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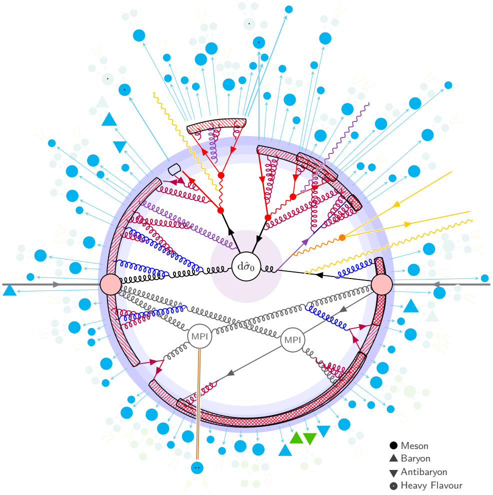
6. Hadronization, Beam remnants



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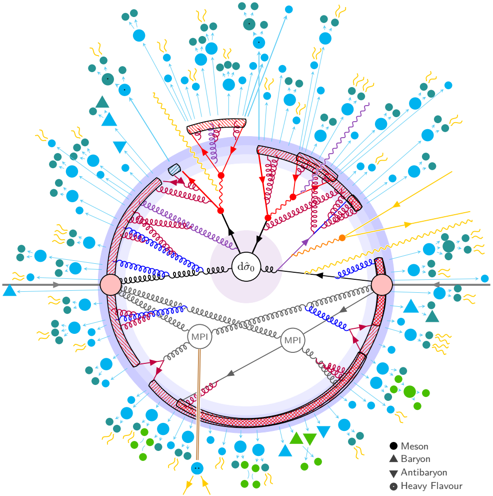
6. Hadronization, Beam remnants
7. Decays, Rescattering

[figure credit: P. Skands]



Parton Showers provide leading-log resummation

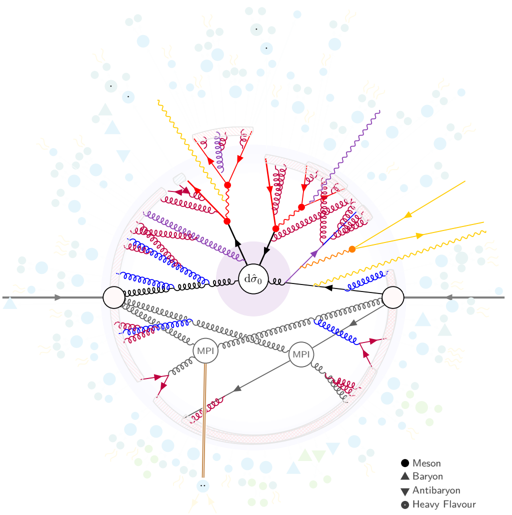
Dress the partons by generating explicit branchings iteratively

- Start from highly-virtual partons, evolve down to low scales with DGLAP
- Splitting probabilities from

$$d\mathcal{P}_a(z, Q^2) = \frac{dQ^2}{Q^2}\frac{\alpha_s(Q^2)}{2\pi}\sum_{b,c} P_{a\to bc}(z)dz$$

where $P_{a\to bc}(z)$ splitting kernels

- Different choices in ordering variable and phase-space mapping lead to some differences between different implementations



Improve precision: Matching and merging

Combine multi-jet (fixed-order) calculations with each other and with PS

Matrix element corrections (MECs):

- Correct first PS splitting ($2 \to 2 + 1$) with the full matrix element ($2 \to 3$)

Matching:

- Combine $\{n, n + 1\}$-parton states from NLO ME generator with parton shower
- Exclude overlap by subtraction or by correction factors
- NLO precision for n-parton observables

Merging:

- Combine $\{n, n + 1, \ldots, n + m\}$ events from ME generators with each other and parton shower
- Overlap removed by applying cuts and vetoes

NLO merging:

- As above but with NLO MEs, overlap removed by subtraction
- NLO precision for inclusive $(n + i)$-parton observables

Multiparton interactions (MPIs)

- MPIs from $2 \to 2$ QCD cross sections

$$\frac{d\mathcal{P}_{\mathrm{MPI}}}{dp_T^2} = \frac{1}{\sigma_{\mathrm{nd}}(\sqrt{s})} \frac{d\sigma^{2\to 2}}{dp_T^2}$$

$\sigma_{\mathrm{nd}}(\sqrt{s})$ is the non-diffractive cross section

- Partonic cross section diverges at $p_T \to 0$

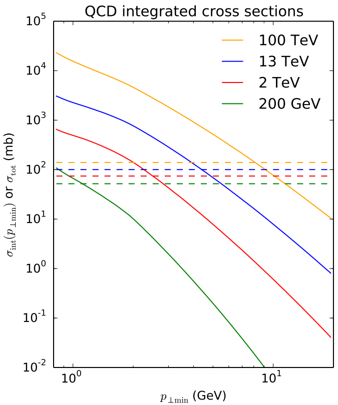
$\Rightarrow$ Introduce a screening parameter p_{T0}

$$\frac{d\sigma^{2\to 2}}{dp_T^2} \propto \frac{\alpha_s(p_T^2)}{p_T^4} \to \frac{\alpha_s(p_{T0}^2 + p_T^2)}{(p_{T0}^2 + p_T^2)^2}$$

- Energy-dependent parametrization:

$p_{T0}(\sqrt{s}) = p_{T0}^{\mathrm{ref}}(\sqrt{s}/\sqrt{s_{\mathrm{ref}}})^{\alpha}$

- Number of interactions: $\langle n \rangle = \sigma_{\mathrm{int}}(p_{T0})/\sigma_{\mathrm{nd}}$



- $\sigma_{\mathrm{int}}(p_{T,\mathrm{min}})$ exceeds σ_{tot}

$\Rightarrow$ Several interactions

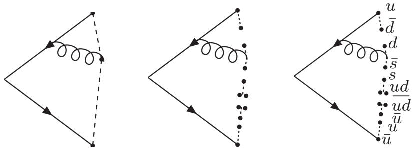
Hadronization models

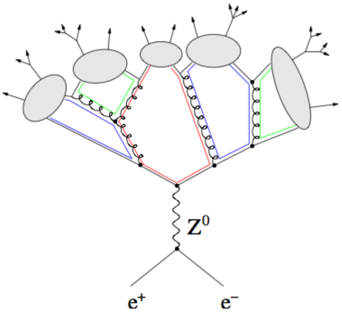
String hadronization

- Implemented in Pythia, can be interfaced from Sherpa
- Colour string between colour charges, hadrons formed from string breaking

Cluster model

- Implemented in Herwig and Sherpa
- Gluons are forced to make $q\bar{q}$ pairs
- Form colour-singlet clusters, these decay isotropically into hadrons





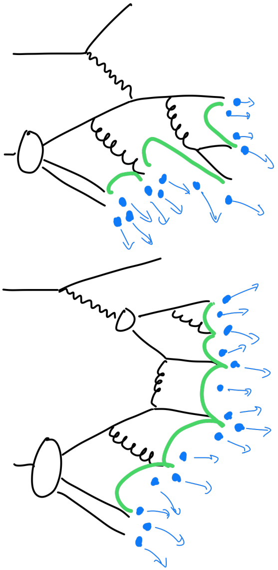
Electron-hadron collisions

Electroproduction (deep inelastic scattering, DIS)

- Lepton scatters off a parton by exchanging a highly virtual photon
- High virtuality, $Q^2 > $ a few GeV^2
- Hard process + Parton showers

Photoproduction (PhP)

- Low virtuality, $Q^2 \rightarrow 0\ \text{GeV}^2$
- Photon may fluctuate into a hadronic state, resolved in the interaction $\Rightarrow$ MPIs
- Factorize photon flux, evolve γp system
- Also soft QCD processes, diffraction



Electroproduction

Event generation in DIS

Hard scattering

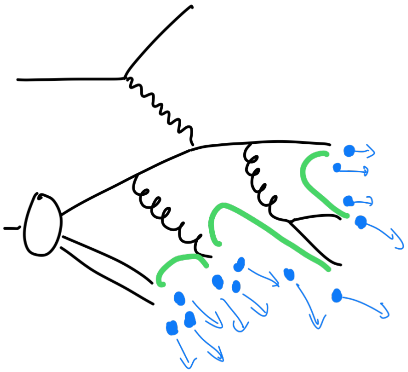
- Convolution between PDFs and matrix element (ME) for partonic scattering

Parton shower

- Final state radiation (FSR)
- Initial state radiation (ISR) for hadron
- QED emissions from leptons

Hadronization

- String/cluster hadronization with colour reconnections
- Decays to stable hadrons



H1 data for 1-jettiness

Pythia

- Default shower with the dipole-recoil option
- Vincia sectorized parton shower
- Dire parton shower

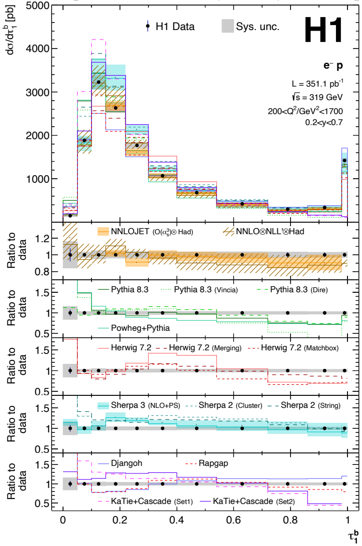
Herwig

- Default angular-ordered shower
- Matching (Matchbox) and merging

Sherpa

- With cluster and string hadronization
- NLO matching

[H1: EPJC 84 (2024) 8, 785]



Photoproduction

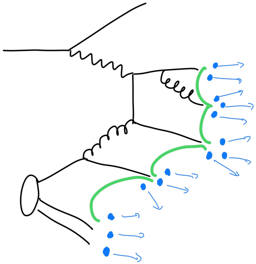
Photoproduction in electron-proton collisions

Direct processes

- Convolute photon flux f_γ with proton PDFs f_i^{p} and $\mathrm{d}\hat{\sigma}$

$$\mathrm{d}\sigma^{\mathrm{ep}\to kl+X} = f_\gamma^{\mathrm{e}}(x, Q^2) \otimes f_j^{\mathrm{p}}(x_{\mathrm{p}}, \mu^2) \otimes \mathrm{d}\hat{\sigma}^{\gamma j\to kl}$$

- Generate FSR and ISR for proton side

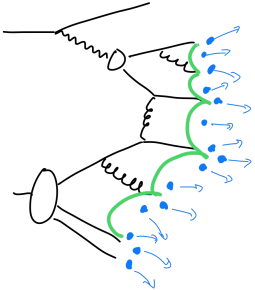


Resolved processes

- Convolute also with photon PDFs

$$\mathrm{d}\sigma^{\mathrm{ep}\to kl+X} = f_\gamma^{\mathrm{e}}(x, Q^2) \otimes f_i^{\gamma}(x_\gamma, \mu^2) \otimes f_j^{\mathrm{p}}(x_{\mathrm{p}}, \mu^2) \otimes \mathrm{d}\sigma^{ij\to kl}$$

- Sample x and Q^2, setup $\gamma\mathrm{p}$ sub-system with $W_{\gamma\mathrm{p}}$
- Evolve $\gamma\mathrm{p}$ as any hadronic collision (including MPIs)



Photon flux from EPA

$$f_\gamma^{\mathrm{e}}(x, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{1}{Q^2}\frac{(1+(1-x)^2)}{x}$$

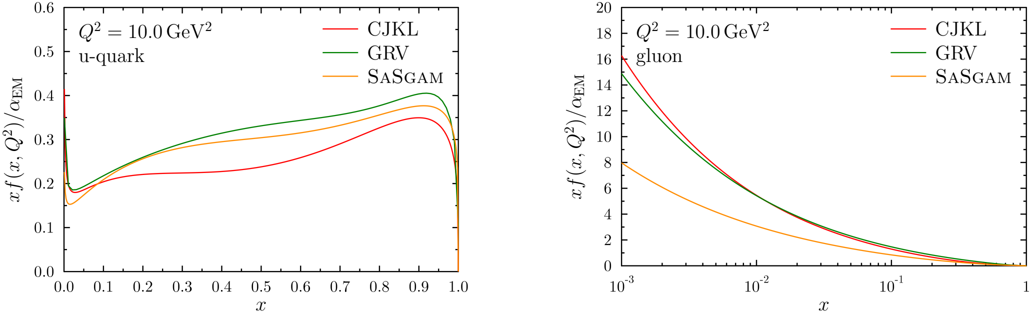
PDFs for resolved photons

DGLAP equation for photons

- Additional term due to $\gamma \to q\bar{q}$ splittings

$$\frac{\partial f_i^{\gamma}(x,Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{\mathrm{em}}}{2\pi} e_i^2 P_{i\gamma}(x) + \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z)\, f_j(x/z, Q^2)$$

where $P_{i\gamma}(x) = 3\,(x^2 + (1-x)^2)$ for quarks, 0 for gluons (LO)



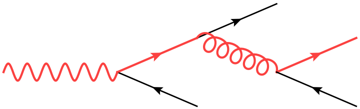
Evolution equation and ISR for resolved photons

ISR probability based on DGLAP evolution

- Add a term corresponding to $\gamma \to q\bar{q}$ to (conditional) ISR probability

$$\mathrm{d}\mathcal{P}_{a\leftarrow b} = \frac{\mathrm{d}Q^2}{Q^2}\frac{\alpha_\mathrm{s}}{2\pi}\frac{x' f_a^{\gamma}(x', Q^2)}{x f_b^{\gamma}(x, Q^2)} P_{a\to bc}(z)\,\mathrm{d}z + \frac{\mathrm{d}Q^2}{Q^2}\frac{\alpha_\mathrm{em}}{2\pi}\frac{e_b^2\, P_{\gamma\to bc}(x)}{f_b^{\gamma}(x, Q^2)}$$

- Corresponds to ending up to the beam photon during evolution
  $\Rightarrow$ Parton originated from the point-like (anomalous) part of the PDFs
  - No further ISR or MPIs below the scale of the splitting
  - Implemented for the default Simple Shower in Pythia 8

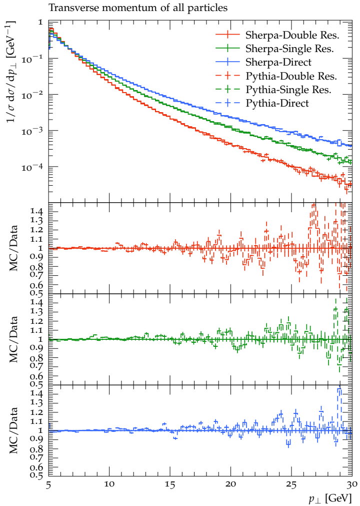


Comparisons between Pythia, Sherpa and Herwig

[I. Helenius, P. Meinzinger, S. Plätzer, P. Richardson: arXiv:2406.08026 [hep-ph]]

Compare different generators for photoproduction

- Good agreement at ME-level
- Differences build up from inputs and modelling
- Scale variations large at LO



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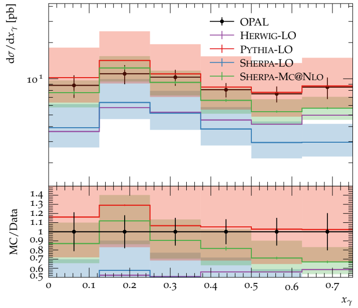
Dijets in $\gamma\gamma$ (LEP)



[OPAL: PLB 651 (2007) 92-101]

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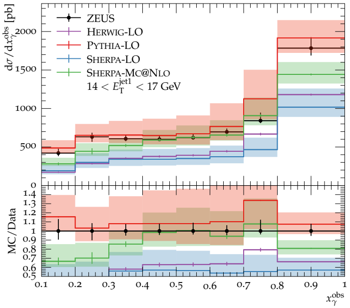
Dijets in γp (HERA)



[ZEUS: EPJC 23 (2002) 615-631]

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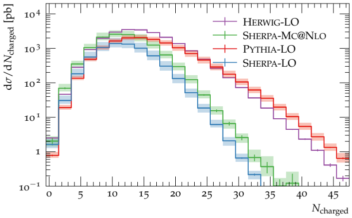
Solid predictions for EIC require

- Validated inputs: (γ)PDFs, accurate flux
- Improved modelling for PS and remnant handling
- Tuning of models to HERA and LEP data

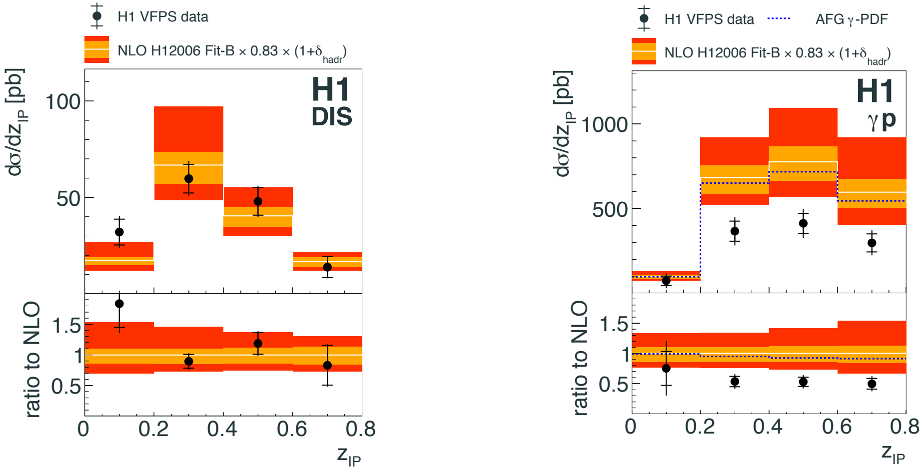
Predictions for multiplicity distributions in EIC



Diffractive processes

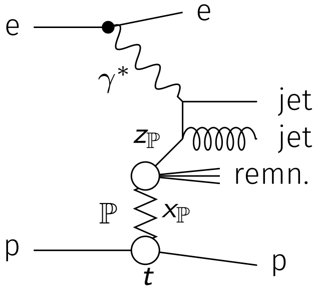
Diffractive dijets at HERA

[H1: JHEP 1505 (2015) 056]



- Good agreement between H1 data and NLO calculation in DIS regime (high-Q^2)
- NLO overshoot the data in photoproduction (low-Q^2)

Hard diffraction in DIS



Diffractive dijets

- Virtual photon interacts with Pomeron from proton producing jets
- Signature: scattered proton or a rapidity gap between proton and Pomeron remnant

Factorized cross section for diffractive dijets

- DIS: $d\sigma^{2\text{jets}+X} = f_i^{IP}(z_{IP}, \mu^2) \otimes f_{IP}^{p}(x_{IP}, t) \otimes d\sigma^{ie\rightarrow 2\text{jets}}$

  where f_{IP}^{p} is Pomeron flux and f_i^{IP} diffractive PDF (dPDF)
- Factorization verifed by H1 and ZEUS at HERA

Hard diffraction in photoproduction

Factorization-based approach

- Direct:

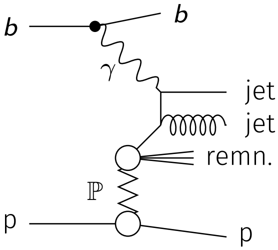
$$d\sigma^{2\text{jets}} = f_\gamma^b(x) \otimes d\sigma^{\gamma j\to 2\text{jets}} \otimes f_j^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{p}(x_{\mathbb{P}}, t)$$

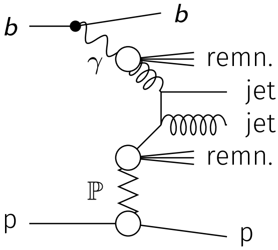
- Resolved:

$$d\sigma^{2\text{jets}} = f_\gamma^b(x) \otimes f_i^{\gamma}(x_\gamma, \mu^2) \otimes d\sigma^{ij\to 2\text{jets}} \otimes f_j^{\mathbb{P}}(z_{\mathbb{P}}, \mu^2) \otimes f_{\mathbb{P}}^{p}(x_{\mathbb{P}}, t)$$

Factorization breaking

- Suppression wrt. factorized approach around 10%–50% at HERA
- Even larger effects seen in pp (and p$\bar{\text{p}}$)
- Potential explanation additional interactions between photon remnants and the proton covering the rapidity gap





Hard diffraction in photoproduction

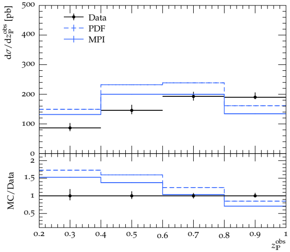
Pythia [I.H., C. O. Rasmussen, EPJC (2019) 79:413]

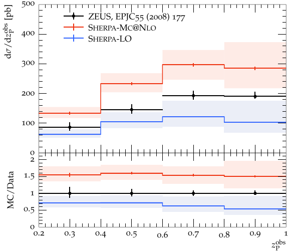
- Based on diffractive PDFs at LO
- Factorization breaking effects with dynamical rapidity gap survival with MPI rejection
  $\Rightarrow$ Suppression in line with the HERA data

Sherpa [F. Krauss, P. Meinzinger, EPJC 84 (2024) 9, 894]

- Both LO and NLO available
- NLO tend to overshoot the data
- Factorization breaking effects studies by scaling resolved and direct components

Three Rivet routines available (2 for H1, 1 ZEUS)





Tuning

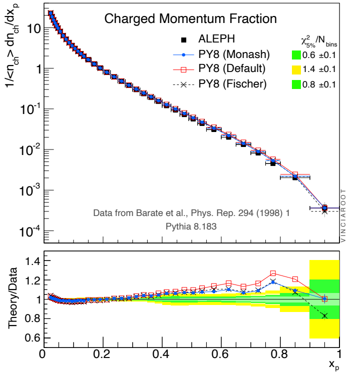
MC tuning

Need for tuning

- Modelling complete collision events require phenomenological models
- These involve parameters that have to fixed using experimental data
- Should be “global” to retain predictability of a given model (eg. energy dependence)

Tools for automated tuning

- Rivet provides easy comparison between data and simulations
- Professor 2 provides Rivet-based framework to optimize parameters by minimizing χ^2



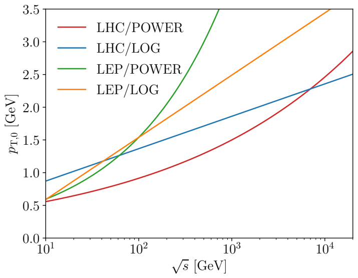
[P. Skands, S. Carrazza, J. Rojo, EPJC 74(8), 3024 (2014)]

An example: Tuning MPIs in photoproduction

[J.M. Butterworth, I. H., J.J. Juan Castella, B. Pattengale, S. Sanjrani, M. Wing: SciPost Phys. 17 (2024) 6, 158]

Systematic comparisons of existing MPI tunes

- Vary $p_{T,0}$ parametrization
- pp at LHC and Tevatron and for $\gamma\gamma$ from LEP
- Data for jet and charged-particle production for pp, γp and $\gamma\gamma$ (10 data sets in total)



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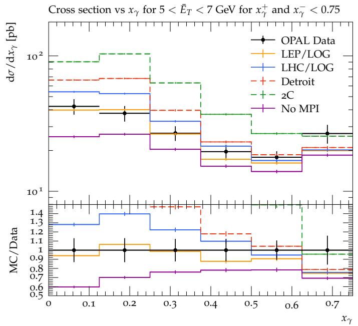
Conclusions

- Can find good agreement for $\gamma\gamma$



[OPAL: EPJC 31, 307 (2003)]

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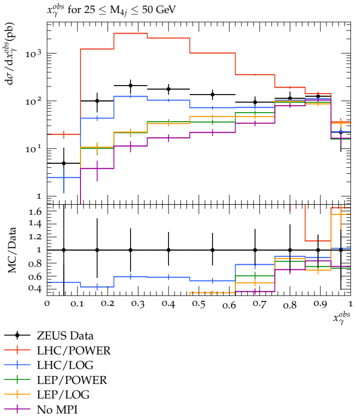

[ZEUS: NPB 792 1 (2008)]

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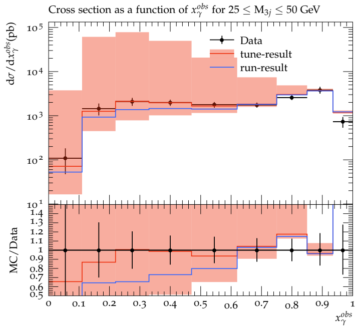

[In progress]

Conclusions

- Can find good agreement for $\gamma\gamma$ and γp
- Published new Rivet analyses enabling dedicated tunes for each beam configuration
- Automatized parameter optimization with Professor 2

MC4EIC recap

MC4EIC

- Monte Carlo event generators required for detector planning and analysis
- Follow up MC development relevant to EIC with MC working group in the EICUG

Previous workshops, following MCEGs in 2018 and 2019

- MC4EIC 2021, Remote, hosted by CFNS
  - Kick of to review experimental needs for theory and event generators
- MC4EIC 2022, Remote, hosted by BNL
  - Reports from MC developers and experimentalists, live notes
- MC4EIC 2024, In-person meeting in Durham
  - Reports from general purpose and specialized event generators
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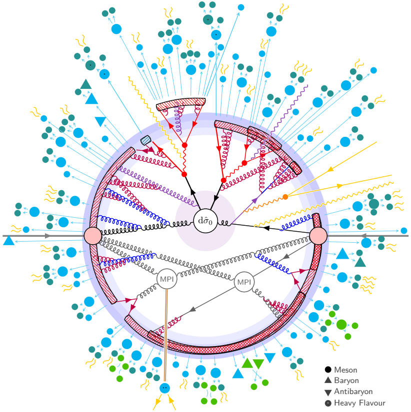
Summary & Outlook

Many recent developments in different areas relevant for EIC

- Extend capabilities for different processes in event generators
- Precision improvements with matching and merging
- First validation and tuning efforts completed/ongoing

Things to work on

- Radiative effects, nuclear targets, diffraction
- What else? How to communicate experimental needs? Rivet analyses?



[figure by P. Skands]