MC Generators today and tomorrow

DIS 2022

Ilkka Helenius

May 2nd, 2022

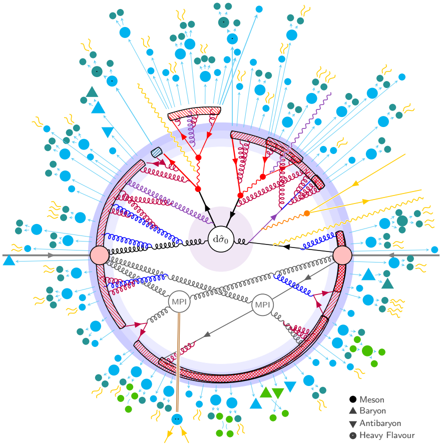
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

ACADEMY OF FINLAND
CoE in Quark Matter

Outline

- An overview of recent and going developments in general-purpose Monte-Carlo event generators

[figure credit: P. Skands]



Outline

1. General-purpose event generators
2. Parton showers and precision
3. Hadronization
4. Different beam configurations
   e^+e^-, ep, γp, pA, AA, ...
5. Summary & Outlook

Thanks to: P. Skands, C. Bierlich, S. Prestel and S. Plätzer

General-purpose event generators

Philosophy

- Generate exclusive hadronic final states using Monte-Carlo methods
- Use perturbative QCD where applicable, fill in with phenomenological models
- Tune model parameters globally to data

Main players

- Pythia (8.307) `https://pythia.org` [arXiv:2203.11601 [hep-ph]]
- Herwig (7.2.2) `https://herwig.hepforge.org` [Eur.Phys.J. C80 (2020) 452]
- Sherpa (2.2.11) `https://sherpa-team.gitlab.io` [SciPost Phys. **7** (2019) no.3, 034]

Not covered

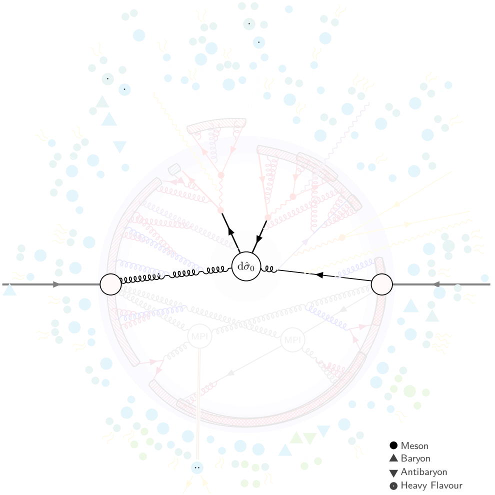
- Matrix-element generators (MadGraph5aMC, Powheg, ...)
- Specialized event generators (MCFM, NNLOJET, Starlight, ...)
- Related tools (Rivet, HepMC3, FastJet, LHAPDF, Contur, ...)

Overview of included physics

Classify event generation in terms of "hardness"

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

[figure credit: P. Skands]



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Classify event generation in terms of "hardness"

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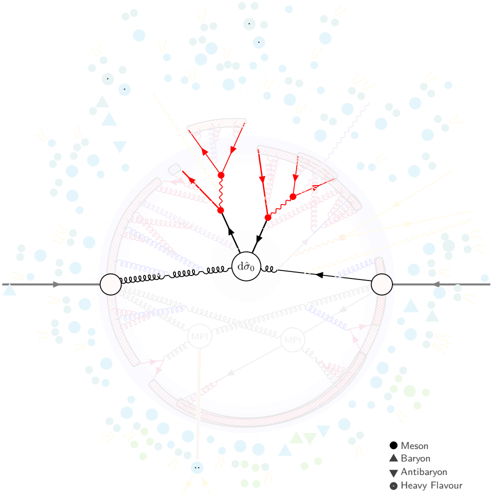
2. Resonance decays $(t, Z, \ldots)$

[figure credit: P. Skands]



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Classify event generation in terms of "hardness"

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

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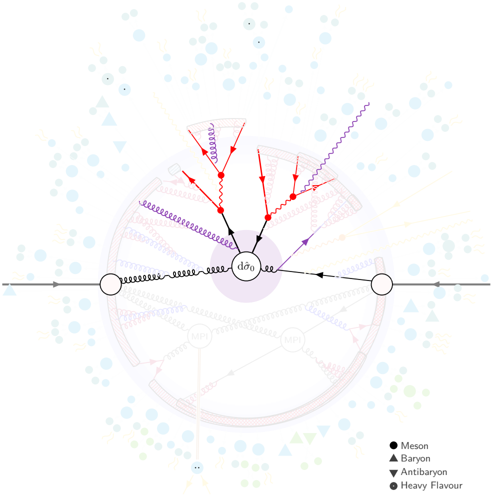

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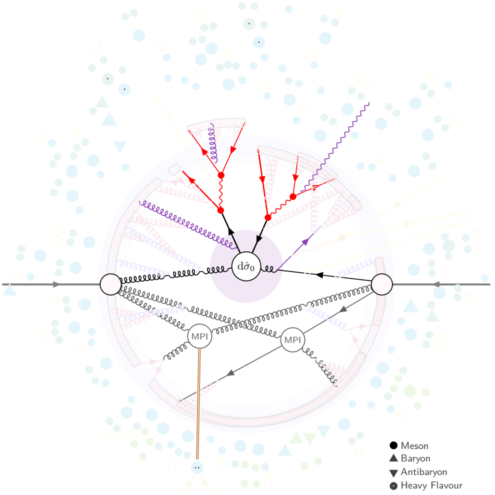
4. Multiparton interactions

[figure credit: P. Skands]



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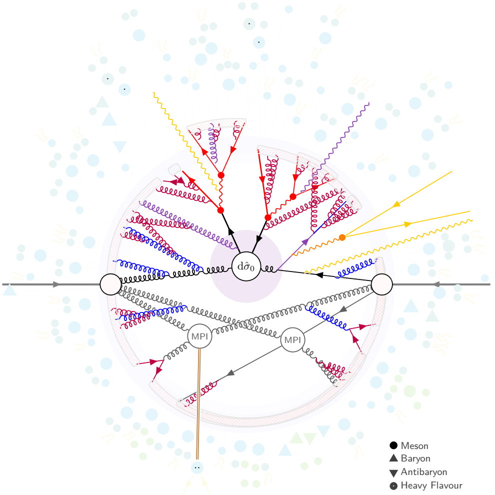
5. Parton showers: ISR, FSR, QED, Weak

[figure credit: P. Skands]



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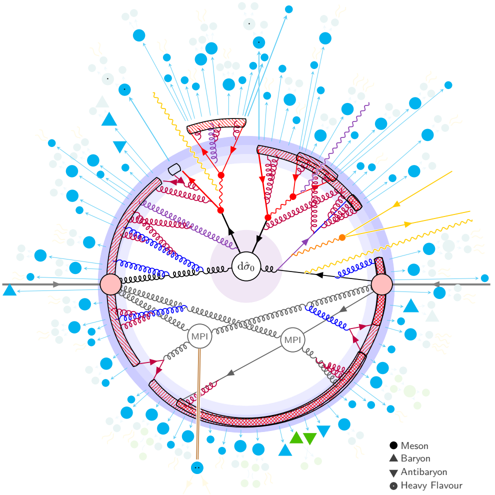

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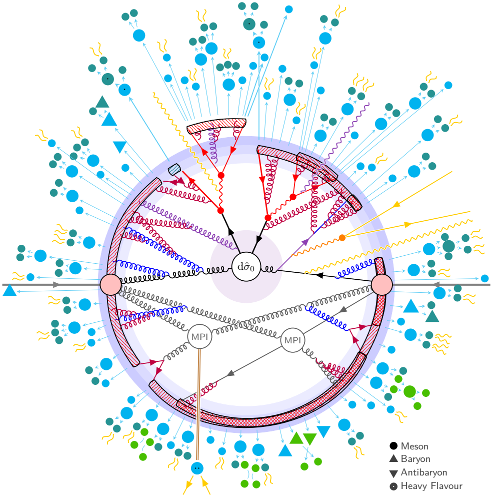
6. Hadronization, Beam remnants
7. Decays, Rescattering

[figure credit: P. Skands]



Parton showers and precision

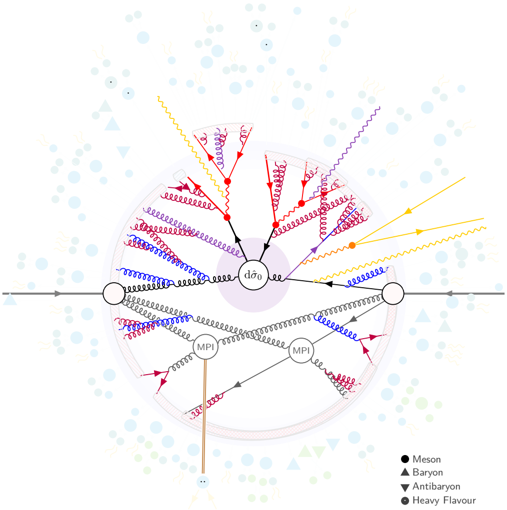
Parton Showers provide leading-log resummation

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
- 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

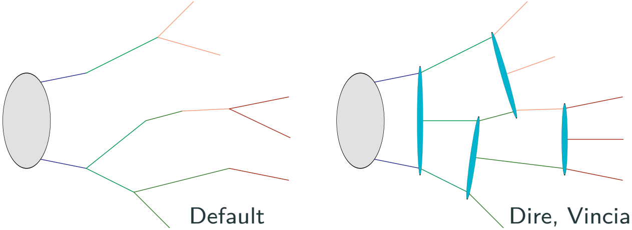
NLO merging:

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

Pythia parton-shower implementations

Default [Sjöstrand & Skands: EPJC 39 (2005) 129-154]

- Evolution in p_T for interleaved MPIs
- ME corrections for the first splitting



Vincia [Brooks, Preuss, Skands & Verheyen: 1907.08980, 2002.04393, 2003.00702, 2008.09468]

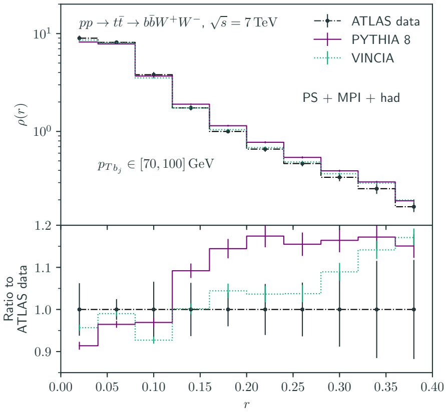
- Coherent evolution (antenna pattern)
- Iterated LO ME corrections
- QCD, QED, and EW (all splittings), interleaved resonance decays

Dire [Gellersen, Höche & Prestel: 1506.05057, 2109.09706]

- Coherent evolution, split into collinear regions
- NLO corrections for the evolution, ME corrections
- QCD, QED, $\sim$ EW, dark photons

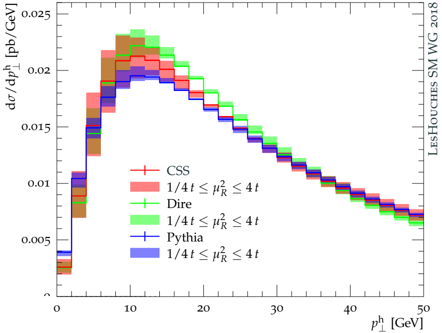
Pythia parton-shower implementations

Vincia example: b-jet profile in $t\bar{t}$



- Narrower jet profile in Vincia favoured by the data

Dire example: Higgs p_T spectrum



- Dire predicts softer p_T spectrum than default Pythia shower

Herwig parton-shower implementations

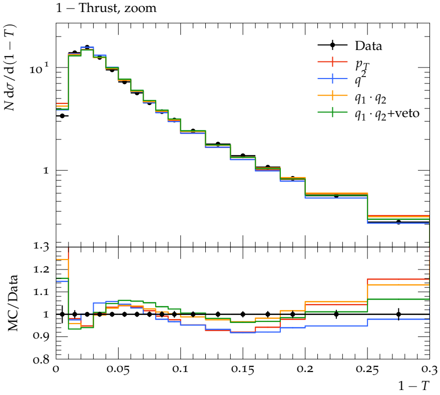
Shower options

- Angular-ordered shower
- Catani-Seymour dipole shower

Recent developments

- Angular-ordered EW shower
  [Masouminia & Richardson 2108.10817]
- Study on evolution variable and logarithmic accuracy
  [Bewick, Ferrario Ravasio, Richardson, Seymour, JHEP 04 (2020) 019 & 2107.04051]
- Spin correlations in both showers
  [Webster & Richardson EPJC 80 (2020)]

Example: Thrust in e^+e^- from LEP



- The new default, dot-product scheme, improve description at intermediate T $\left(= \frac{\sum_i |n \cdot p_i|}{\sum_i |p_i|} \right)$

Sherpa parton-shower implementations

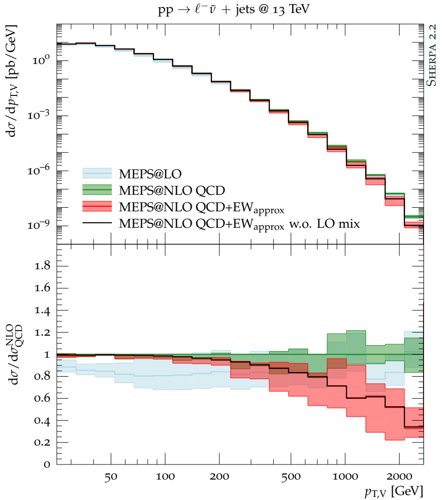
Shower options

- Built-in Catani-Seymour dipole parton shower
- Dire as a plugin

Recent developments

- Higher-order corrections for QCD shower
- Sub-leading color effects
- NLO corrections for EW splittings
  - EW corrections become important at high p_T

Example: p_T of W in pp collisions



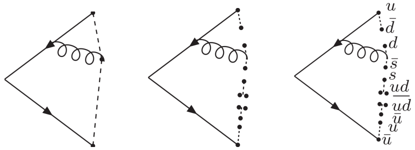
[SciPost Phys. **7** (2019) no.3, 034]

Hadronization

Hadronization models

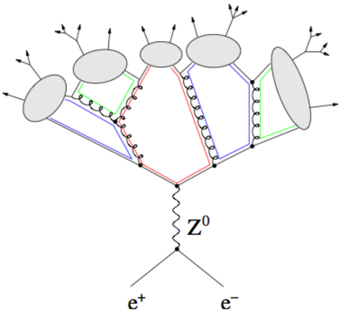
String hadronization

- 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

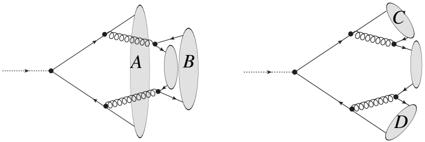


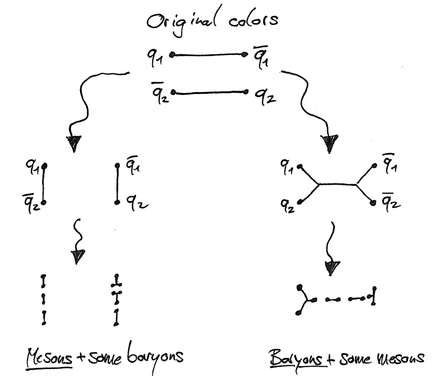
Colour reconnection (CR)

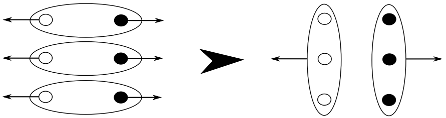
- Parton-shower splittings provide an initial colour configuration
- Reconnecting the coloured partons might reduce the string length / Cluster masses

⇒ Typically leads to baryon enhancement

⇒ Larger effects at high multiplicities

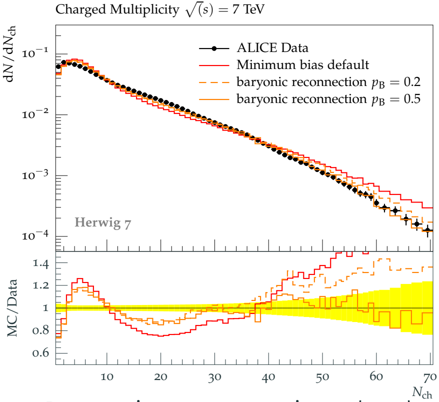






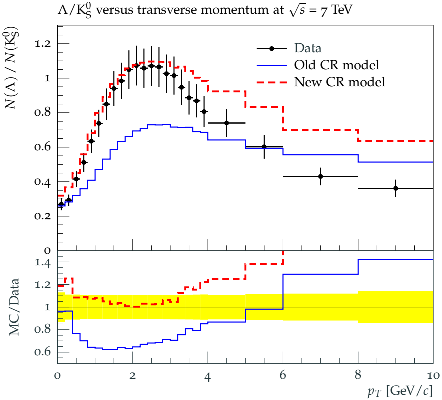
Colour reconnection effects

Herwig CR model [Gieseke, Kirchgaesser, Plätzer: EPJC 78 (2018) 2, 99]



- Baryonic reconnections lead to lower multiplicities

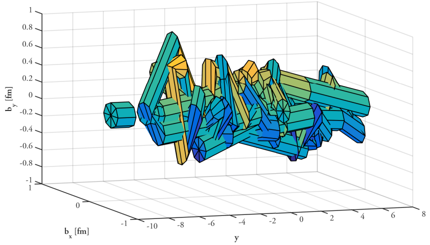
Pythia QCD-inspired CR model [Christiansen, Skands: JHEP 1508 (2015) 003]



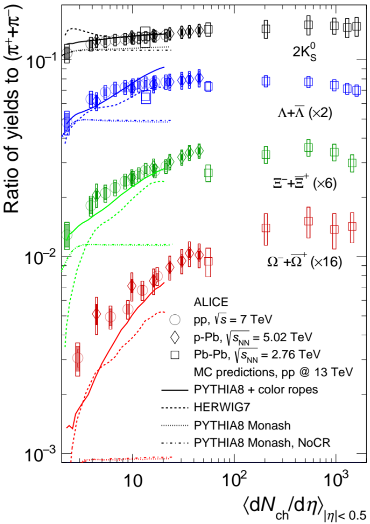
- New QCD-based CR model increase baryon density further

Rope hadronization [Bierlich, Gustafson, Lönnblad, Tarasov: JHEP 03 (2015) 148]

- Introduce a finite width for the colour field



- Overlapping strings enhance string tension
  - Strangeness and baryon enhancement
- Similar effects from non-perturbative $g \to s\bar{s}$ splittings in Herwig

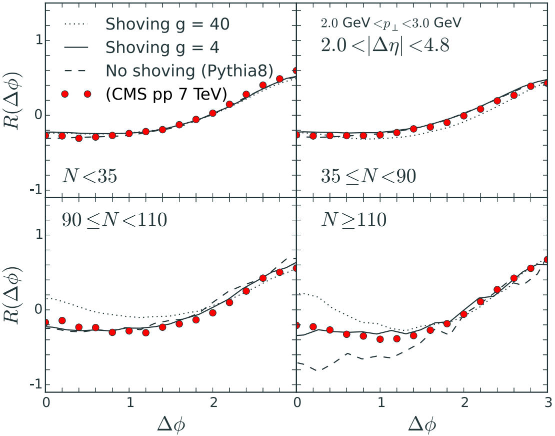


[Vislavicius: MPI@LHC 2019]

Interacting strings

String shoving [Bierlich, Gustafson, Lönnblad: PLB 779 (2018) 58-63]

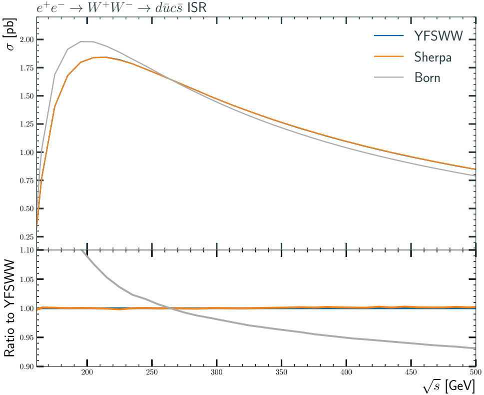
- Repulsion between overlapping strings produce long-range correlations (the ridge effect)
- Flow-like effects in two-particle correlations in high-multiplicity pp collisions



Different beam configurations

e^+e^- collisions

Sherpa implementation of YFS resummation for QED effects

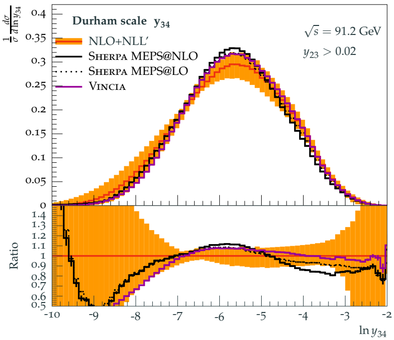


[Price et al., to appear]

- Good agreement with previous calculations for W^+W^-

Compare NLO+NLL' resummed result to merged MC with hadronization

four-jet resolution y_{34}

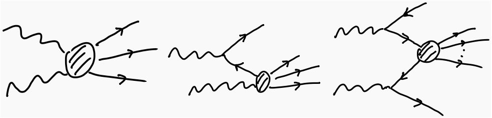


[Baberuxki et al. JHEP 04 (2020), 112]

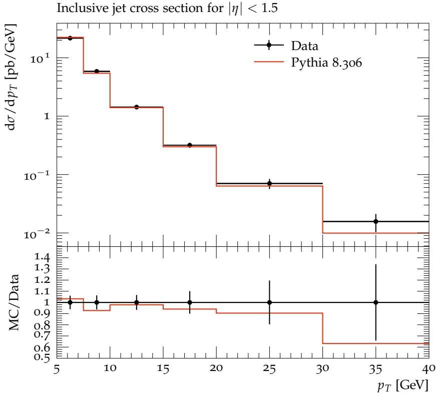
- Some differences wrt. Vincia shower in Pythia

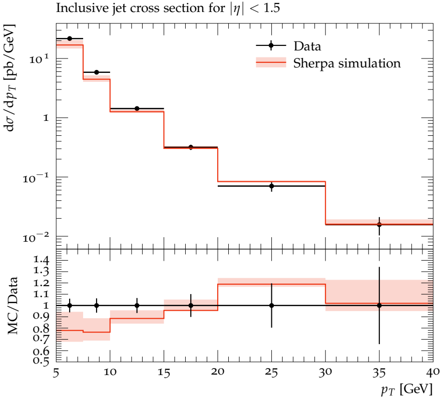
$\gamma\gamma$ in e^+e^- collisions

- Sherpa implementation based on LO processes and EPA
- Similar setup included in Pythia



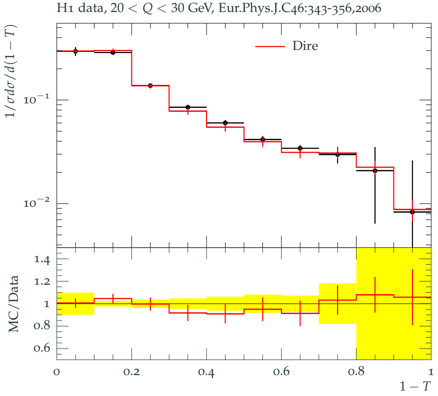
[Meinzinger, et. al., in progress]

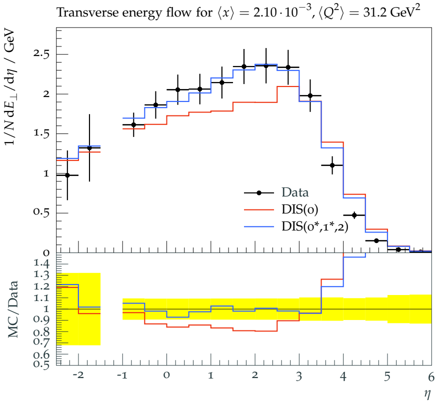




ep collisions

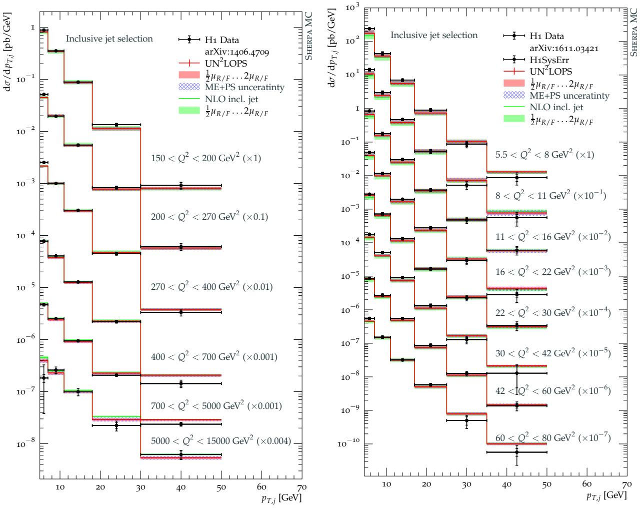
- DIS-like events can be generated by all the generators, photoproduction varies
- In fact, several shower models available to chart uncertainty
- Herwig includes NLO merging for DIS (blue)





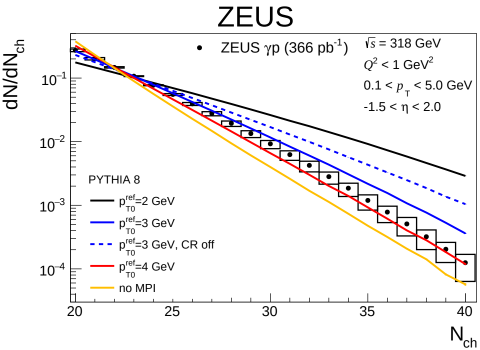
Matching in DIS at NNLO with SHERPA

- 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
  $$\mu^2_{\mathrm{F,R}} = (Q^2 + (H_\mathrm{T}/2)^2)/2$$

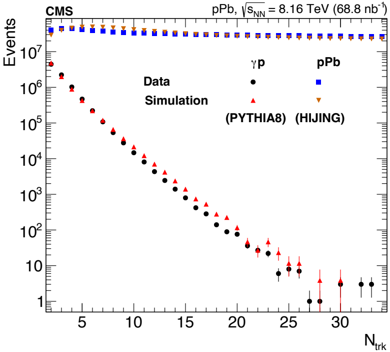


Photoproduction and UPCs

- Pythia has a complete setup for photoproduction, can be applied also to UPCs as well (Pb $\rightarrow \gamma + \mathrm{p}$)



[ZEUS: JHEP 12 (2021) 102]



[Murillo Quijada (CMS), QM 2022]

- Multiplicity well described when including MPIs in γp
- Fair agreement also in UPCs

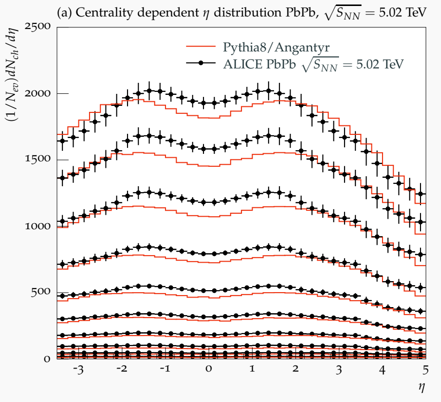
Heavy-ion collisions

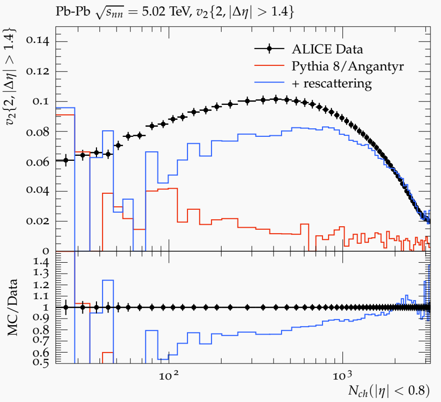
- Angantyr in Pythia provides a full heavy-ion collisions framework

[Bierlich, Gustafson, Lönnblad & Shah: 1806.10820]

- Hadronic rescattering can be included as well, enhances collective effects

[CB, Ferreres-Solé, Sjöstrand & Utheim: 1808.04619, 2005.05658, 2103.09665]

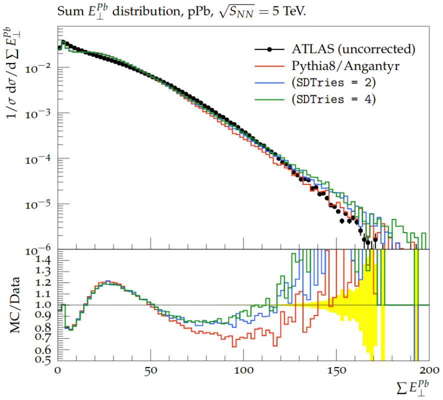


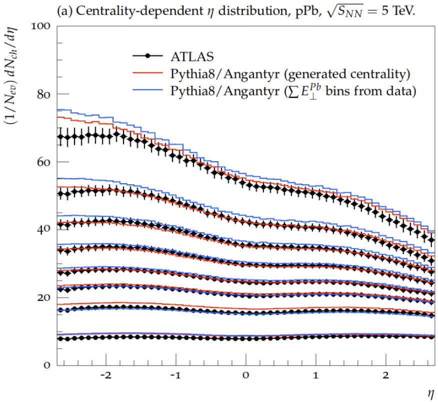


p+A collisions

[Bierlich, Gustafson, Lönnblad & Shah: 1806.10820]

- Angantyr can be applied also to asymmetric p+A collisions
- The centrality measure well reproduced
- Similarly centraility-dependent multiplicities





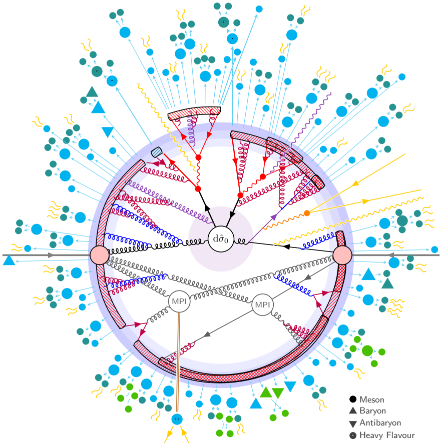
MC generators

Today

- LHC-hardened showers and hadronization models
- Precision up-to-date with fixed-order calculations
- Broad range of beam combinations

Tomorrow

- Increased precision for wider selection of processes
- Getting ready for next generation of colliders (EIC, e^+e^- colliders)



[figure by P. Skands]

...And plenty of other interesting developments!