Pythia 8 development in Jyväskylä

Particle physics days 2024

Ilkka Helenius

November 28, 2024

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Research Council of Finland

Centre of Excellence in Quark Matter

Pythia 8 event generator

Pythia 8: A general purpose event generator

- Latest release 8.312 (May 2024)
- A complete physics manual for 8.3

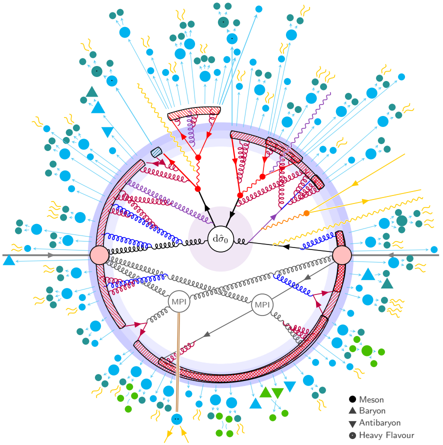
  [SciPost Phys. Codebases 8-r8.3 (2022)]

Pythia in Jyväskylä

- MC4EIC – Monte Carlo event generation for electron-ion colliders

  Academy research fellow (2020–2025)
- HD-Pythia – Hard and diffractive scattering processes in high-energy nuclear collisions with Pythia

  Academy research project (2024–2028)



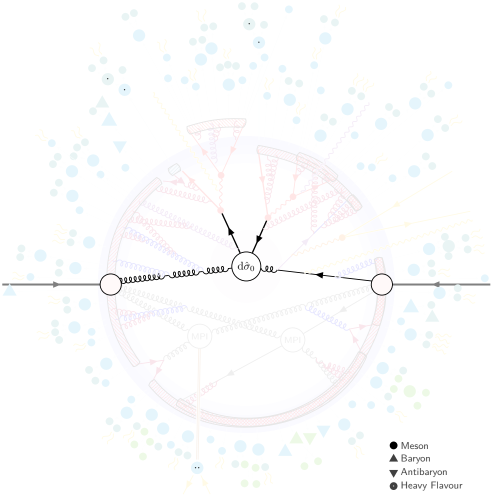
[figure by P. Skands]

Physics modelled within Pythia 8

Classify event generation in terms of "hardness"

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

[figure credit: P. Skands]



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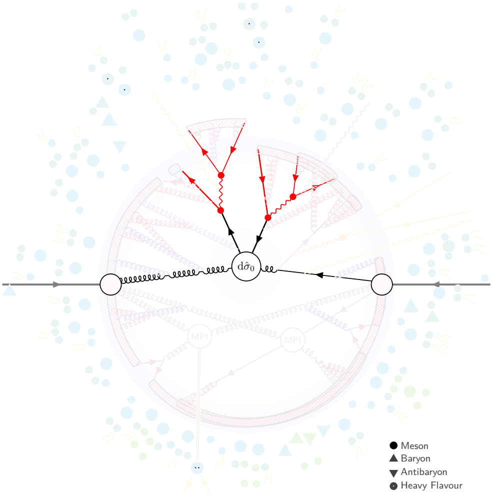

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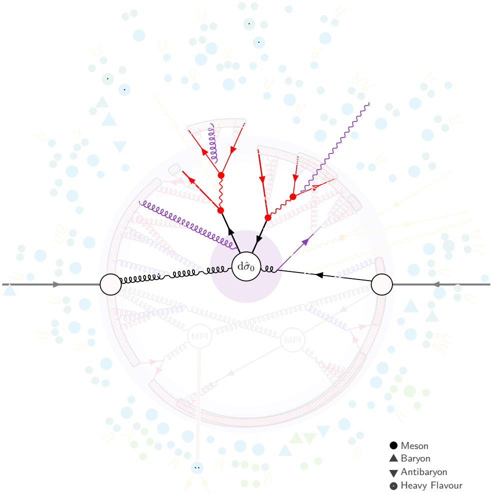

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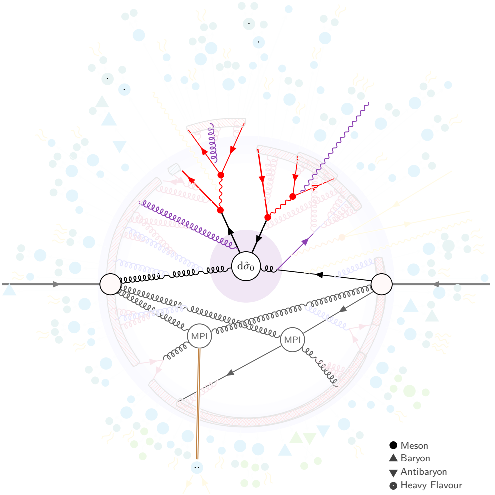

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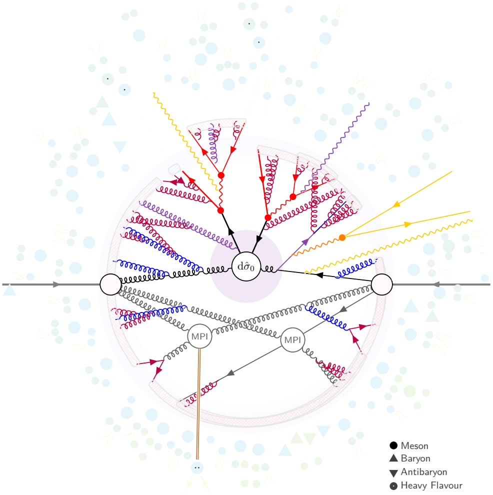

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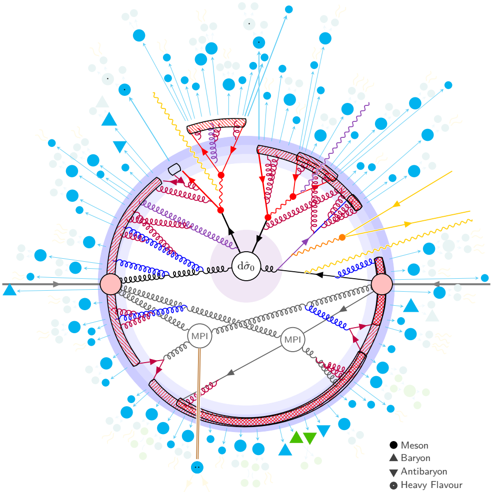

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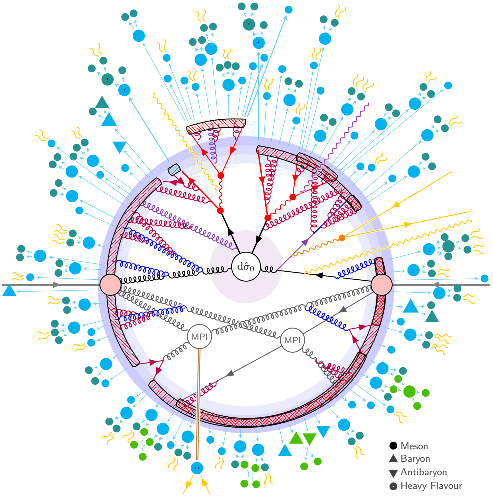
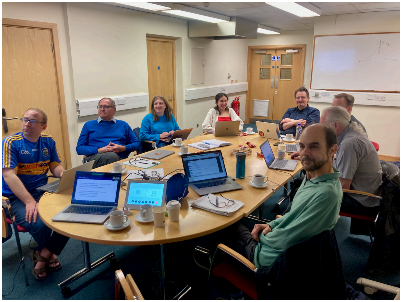
7. Decays, Rescattering

[figure credit: P. Skands]



Pythia Collaboration

- Javira Altmann (Monash University)
- Christian Bierlich (Lund University)
- Naomi Cooke (University of Glasgow)
- Nishita Desai (TIFR, Mumbai)
- Leif Gellersen (Lund University)
- Ilkka Helenius (University of Jyväskylä)
- Philip Ilten (University of Cincinnati)
- Leif Lönnblad (Lund University)
- Stephen Mrenna (Fermilab)
- Christian Preuss (University of Wuppertal)
- Torbjörn Sjöstrand (Lund University)
- Peter Skands (Monash University)
- Marius Utheim (University of Jyväskylä)
- Rob Verheyen (University College London)



[Pythia Week in Oxford 2024]

`https://pythia.org`

`authors@pythia.org`

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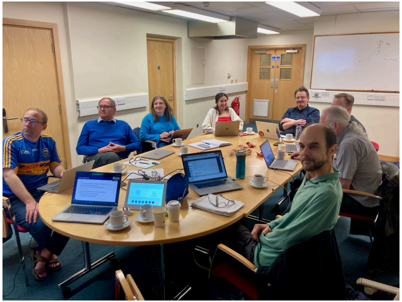

[Pythia Week in Oxford 2024]

- Spokesperson
- Codemaster
- Webmaster

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Available beam configurations in Pythia 8

Hadronic collisions

- p-p: hard, soft and low-energy processes
- *h*-p, where $h = \pi^{\pm,0}, \mathrm{K}^{\pm,0}, \phi^0, \ldots$

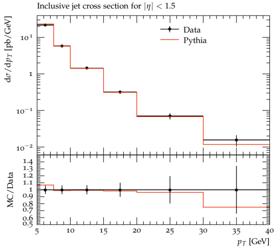
Collisions with leptons

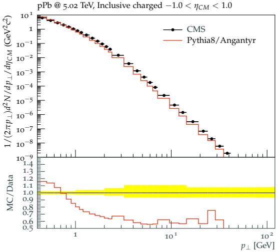
- $\mathrm{e}^+\mathrm{e}^-$, including $\gamma\gamma$ (also in p-p)
- e-p: (neutrino) DIS, photoproduction with soft and hard QCD processes

Heavy-ion collisions with Angantyr

- *A*-*A*, p-*A* and *h*-*A*
- UPCs with proton target, also VMD-*A*
- Some cosmic-ray related processes

[OPAL: PLB 658 (2008) 185-192]





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[Being worked in Jyväskylä]

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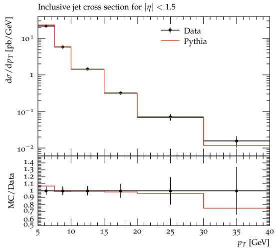
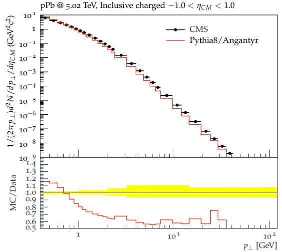




ep and ee collisions

Electron-proton collisions

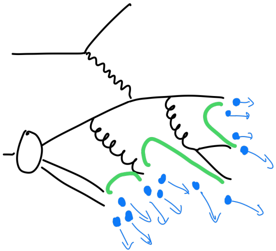
Classified in terms photon virtuality Q^2

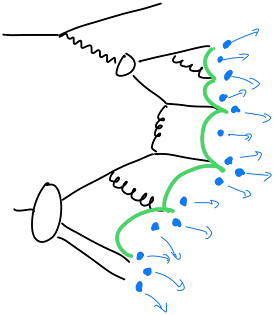
Deep inelastic scattering (DIS)

- High virtuality, $Q^2 >$ a few GeV^2
- Lepton scatters off from a parton by exchanging a highly virtual photon

Photoproduction

- Low virtuality, $Q^2 \rightarrow 0$ GeV^2
  $\Rightarrow$ Direct and resolved contributions
- Factorize γ flux, evolve γp system
- Hard scale provided by the final state
- Also soft QCD processes, diffraction





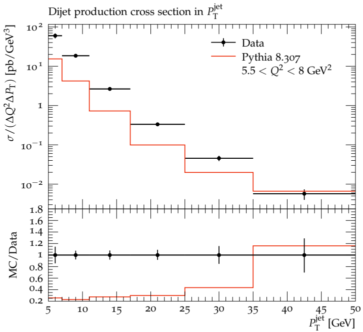
Multi-jet merging in DIS [I. Helenius, J. Laulainen, C.T. Preuss: arXiv:2410.20950 [hep-ph]]

Jet production in DIS

- Parton shower generate emissions from a Born-level hard-process
- Accurate only for soft and collinear emissions
- Matrix element corrections helps at high-Q^2 but still misses low-Q^2 high-E_T part

Merging in DIS

- Start from hard events with several partons in the final state
- Combine with parton shower emissions using merging algorithms to avoid double counting



[H1: EPJC 77 (2017) 215]

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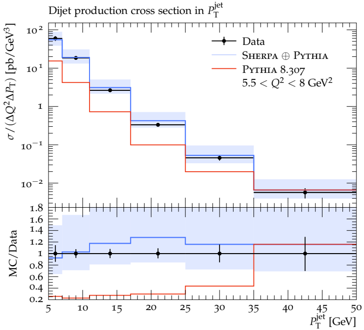

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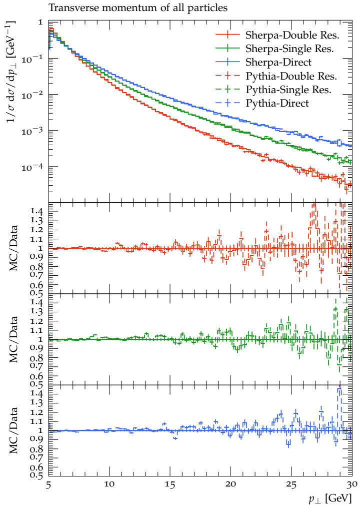
Comparisons between Pythia, Sherpa and Herwig

[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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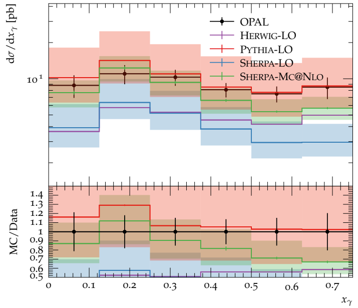

[OPAL: PLB 651 (2007) 92-101]

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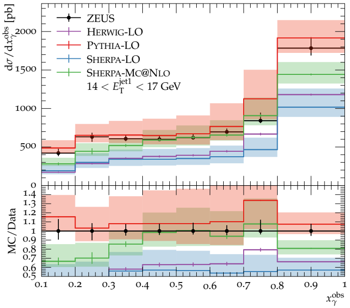

[ZEUS: EPJC 23 (2002) 615-631]

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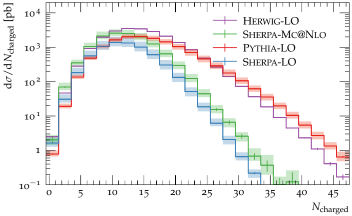
Solid predictions for EIC require

- 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



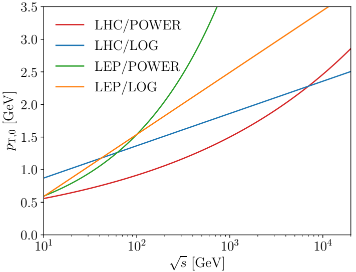
MPIs in photoproduction

[J.M. Butterworth, I. Helenius, J.J. Juan Castella, B. Pattengale, S. Sanjrani, M. Wing:

arXiv:2408.15842 [hep-ph], accepted for SciPost Physics]

Systematic comparisons of MPI tunes

- 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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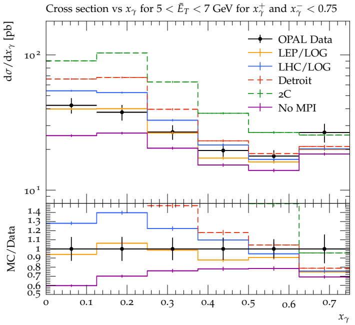
- Further constraints from 3- and 4-jet production
- Published new Rivet analyses enabling dedicated tunes for each beam configuration



[OPAL: EPJC 31, 307 (2003)]

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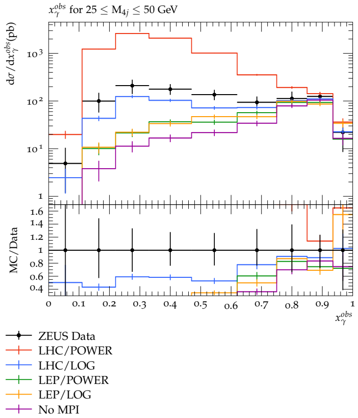


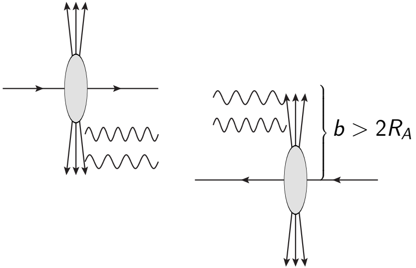
[ZEUS: NPB 792 1 (2008)]

Ultraperipheral collisions (UPCs)

Ultraperipheral heavy-ion collisions

- Large impact parameter ($b \gtrsim 2R_A$)
  $\Rightarrow$ No strong interactions
- At LHC relevant for p+p, p+Pb, Pb+Pb
- Large flux due to large EM charge of nuclei

$\Rightarrow$ $\gamma\gamma$ and γA collisions



Photon flux from equivalent photon approximation

- Define flux in impact-parameter space $\Rightarrow$ Reject hadronic interactions with b_{min}
- Integrating the point-like approximation we get

$$f_\gamma^A(x) = \frac{2\alpha_{\text{EM}} Z^2}{x\,\pi}\left[\xi\, K_1(\xi) K_0(\xi) - \frac{\xi^2}{2}\left(K_1^2(\xi) - K_0^2(\xi)\right)\right]$$

where $\xi = b_{\text{min}}\, x\, m$ where $b_{\text{min}} \approx 2R_A$ and m per nucleon mass

- Nuclear form factor heavily suppresses Q^2 of the photon $\Rightarrow$ Photoproduction!

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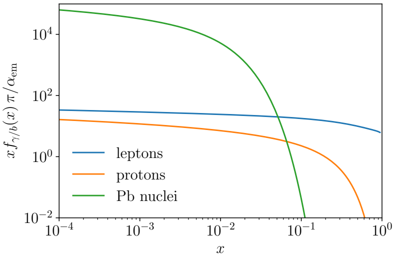

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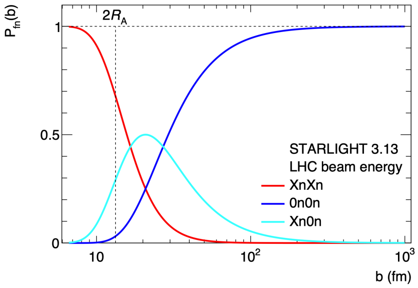
Experimental heavy-ion UPC classification

- Event selection typically relies on Zero-degree calorimeters ($X > 0$)

XnXn: At least one neutron on both sides
$\Rightarrow$ A+A (hadronic interaction)

Xn0n: At least one neutron only on one side
$\Rightarrow$ γ+A

0n0n: No neutrons on either side
$\Rightarrow$ γ+γ



Ann.Rev.Nucl.Part.Sci. 70 (2020) 323-354

Possible caveats

- Additional EM interactions may break up the nuclei in "near-encounter" events
  [Eskola, Guzey, Helenius, Paakkinen, Paukkunen; PRC 110 (2024) 054906]
- Also diffractive processes will keep nuclei intact
  $\Rightarrow$ Xn0n condition will remove diffractive contribution to γ+A
  See e.g. [Guzey, Klasen; PRD 104 (2021) 11 114013]

Dijets in ultra-peripheral heavy-ion collisions in Xn0n

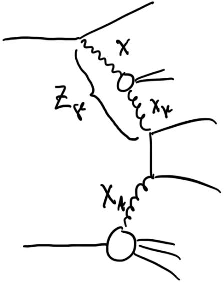
- Good agreement out of the box when accounting both direct and resolved
- EM nuclear break-up significant
- Pythia setup with nucleon target only

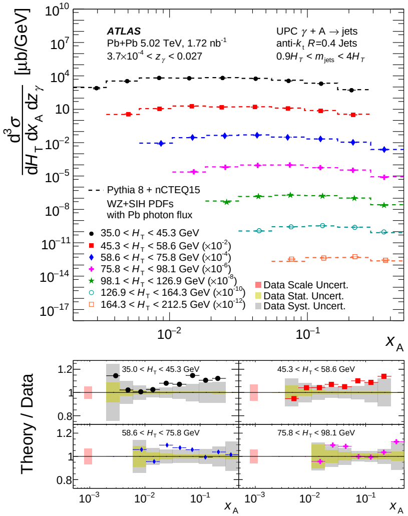
  $\Rightarrow$ Is such a setup enough for γ+A?

$$H_T = \sum_i p_{T,i}$$

$$z_\gamma = \frac{M_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{+y_{\text{jets}}}$$

$$x_A = \frac{M_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{-y_{\text{jets}}}$$

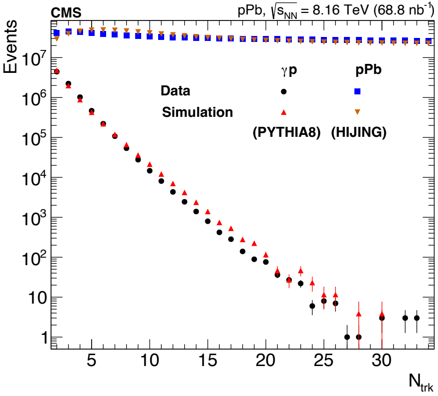




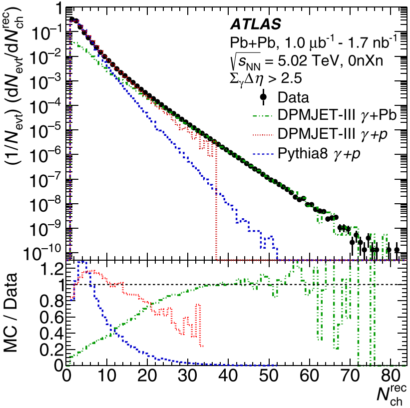
[ATLAS: arXiv:2409.11060]

Multiplicity distributions in UPCs

γ+p: [CMS: Murillo Quijada, QM2022]



γ+Pb: [ATLAS: PRC 104, 014903 (2021)]

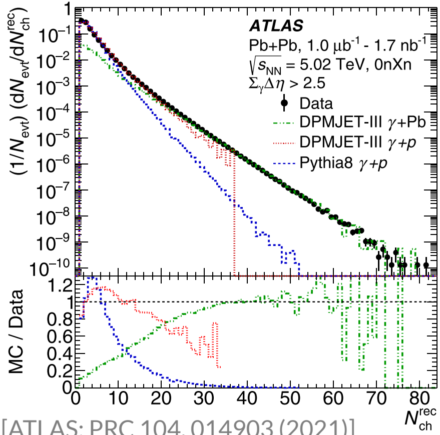


- Multiplicity distribution well reproduced in γ+p interactions

- High multiplicities missed with γ+p $\Rightarrow$ Multi-nucleon interactions

Modelling γ+A with Pythia

[I. Helenius, M. Utheim: EPJC 84 (2024) 11, 1155]



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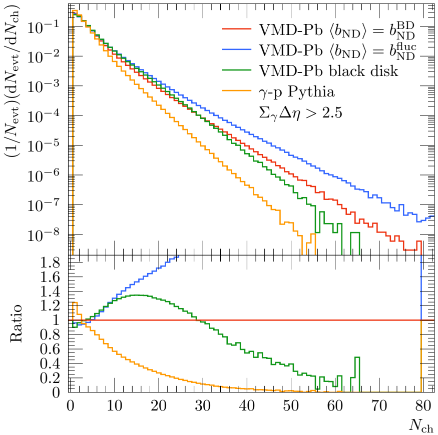
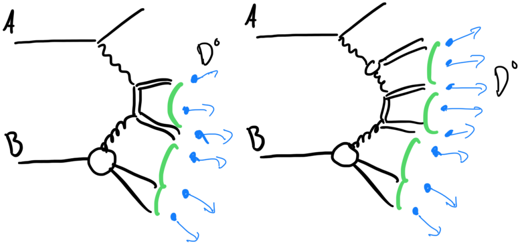
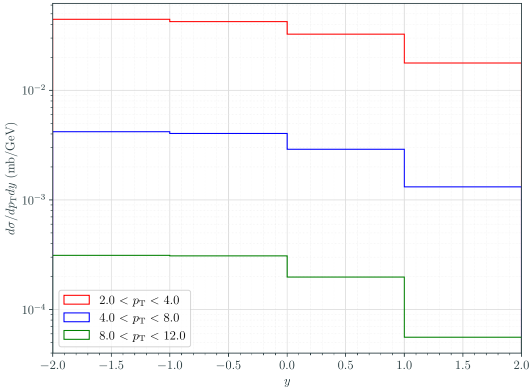


- ATLAS data not corrected for efficiency, estimated with $N_{ch}^{rec} \approx 0.8 \cdot N_{ch}$
- Relative increase in multiplicity well in line with the VMD-Pb setup

Inclusive D-meson production in UPCs

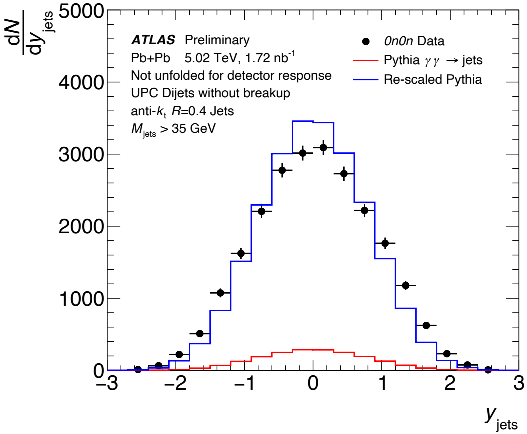
- New experimental analysis for open charm production in UPCs ongoing in CMS and ALICE
- Can use Pythia UPC implementation to calculate cross-section predictions

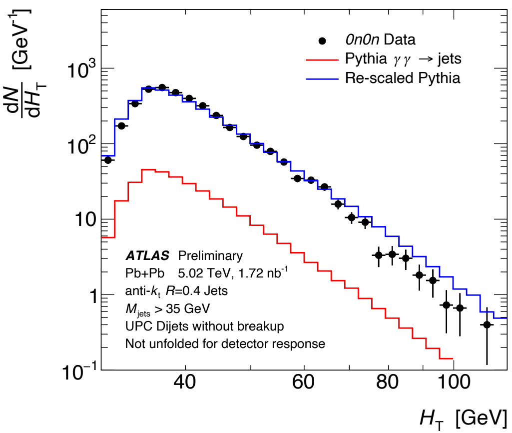




[A.-M. Levälampi: Research training thesis, 2024]

Dijets in ultra-peripheral heavy-ion collisions in 0n0n





[ATLAS-CONF-2022-021]

- Per-event yield underestimated by a factor of ten!
- Shape in a reasonable agreement
- $\gamma\gamma \to \mu^+\mu^-$ ok so likely a QCD effect $\Rightarrow$ Contribution from diffractive events?

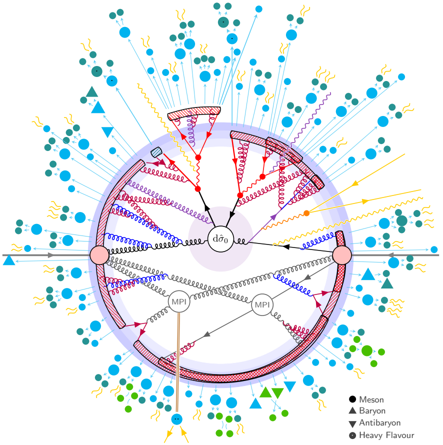
Summary & Outlook

MC4EIC

- Multi-jet merging in DIS
- MPI tuning for $\gamma\gamma$ and γp
- Comparisons between other event generators for photoproduction
- A model for photon-ion interactions, applied to UPCs, relevant also for EIC

HD-Pythia

- Improve modelling of hard processes in nuclear collisions
- Implement photon-initiated diffraction with nuclear beams



[figure by P. Skands]

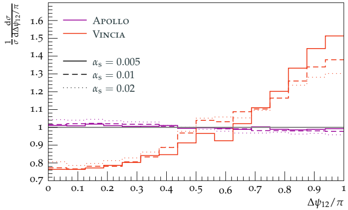
Backup slides

Recent highlights

New parton shower Apollo

C.T. Preuss: JHEP 07 (2024) 161

- Improved antenna shower heriting from Vincia
  $\Rightarrow$ Easy to combine with fixed-order
- Improved recoil handling similar to Alaric
  $\Rightarrow$ First NLL accurate parton shower in Pythia
- Currently only for e^+e^-

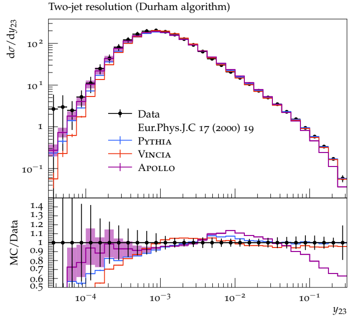


Machine-learning based hadronization

C. Bierlich, P. Ilten, S. Mrenna et al. (ML-HAD):

SciPost Phys. 17 (2024) 2, 045, arXiv:2410.06342

- Learn fragmentation functions from data
- Currently tested in a simplified $q\bar{q}$ case



Multiparton interactions (MPIs)

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

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

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

- Partonic cross section diverges at $p_{\mathrm{T}} \to 0$

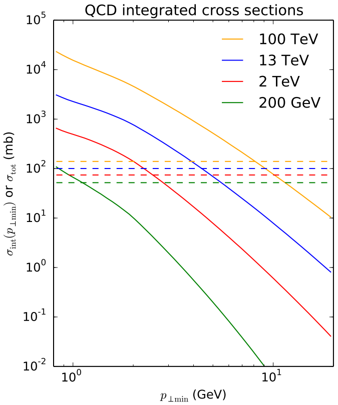
$\Rightarrow$ Introduce a screening parameter p_{T0}

$$\frac{d\sigma^{2\to 2}}{dp_{\mathrm{T}}^2} \propto \frac{\alpha_{\mathrm{s}}(p_{\mathrm{T}}^2)}{p_{\mathrm{T}}^4} \to \frac{\alpha_{\mathrm{s}}(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)}{(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)^2}$$

- Energy-dependent parametrization:

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

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



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

$\Rightarrow$ Several interactions

Parton-level evolution

Common evolution scale (p_T) for FSR, ISR and MPIs

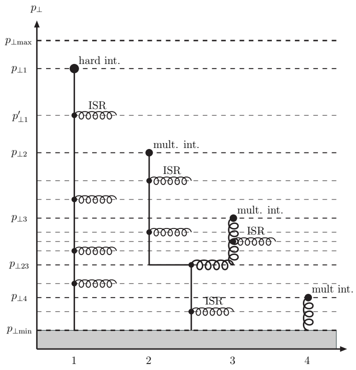
- Probability for something to happen at given p_T

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\mathrm{T}} = \left(\frac{\mathrm{d}\mathcal{P}_\mathrm{MPI}}{\mathrm{d}p_\mathrm{T}} + \sum \frac{\mathrm{d}\mathcal{P}_\mathrm{ISR}}{\mathrm{d}p_\mathrm{T}} + \sum \frac{\mathrm{d}\mathcal{P}_\mathrm{FSR}}{\mathrm{d}p_\mathrm{T}}\right)$$
$$\times \exp\left[-\int_{p_\mathrm{T}}^{p_\mathrm{T}^\mathrm{max}} \mathrm{d}p'_\mathrm{T} \left(\frac{\mathrm{d}\mathcal{P}_\mathrm{MPI}}{\mathrm{d}p'_\mathrm{T}} + \sum \frac{\mathrm{d}\mathcal{P}_\mathrm{ISR}}{\mathrm{d}p'_\mathrm{T}} + \sum \frac{\mathrm{d}\mathcal{P}_\mathrm{FSR}}{\mathrm{d}p'_\mathrm{T}}\right)\right]$$

where $\exp[\ldots]$ is a Sudakov factor (probability that nothing else has happened before p_T)

Simultaneous partonic evolution

1. Start the evolution from the hard-process scale
2. Sample p_T for each $\mathcal{P}_i$, pick one with highest p_T
3. Continue until $p_{\mathrm{T}\min} \sim \Lambda_\mathrm{QCD}$ reached



[T. Sjöstrand, P. Skands: EPJC 39 (2005) 129-154]

Parton shower options for DIS in Pythia

The default shower with `dipoleRecoil`

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

- First emission match with matrix element
- No PS recoil for the scattered lepton
- No shower-specific tuning done

Vincia antenna shower

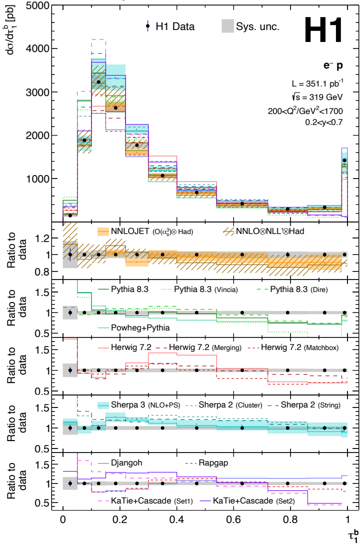
[H. Brooks, C. T. Preuss, P. Skands, JHEP 07 (2020) 032]

- QCD, QED, EW, interleaved with MPIs
- Efficient multi-jet merging with sectors

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

- Correct soft-gluon interference at lowest order
- Inclusive NLO corrections to collinear splittings

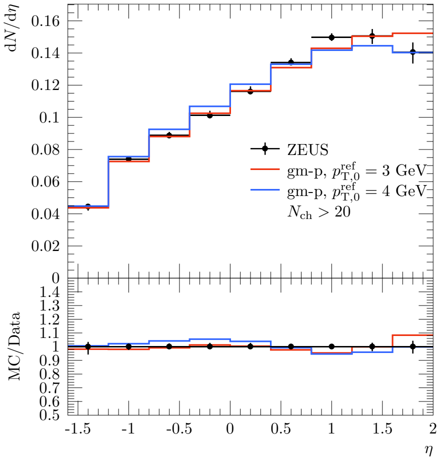
[H1: Eur.Phys.J.C 84 (2024) 8, 785]



Comparison to ZEUS data for charged hadrons ($N_{\text{ch}} > 20$)

Pseudorapidity

- Data well reproduced
- Not sensitive to MPI modelling ($p_{\text{T},0}$)



[ZEUS: JHEP 12 (2021) 102]

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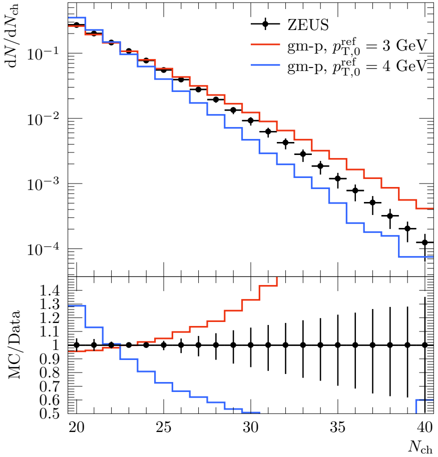
Multiplicity

- Sensitivity to MPI parameters, clear support for MPIs
- Data within $p_{T,0}$ variations



[ZEUS: JHEP 12 (2021) 102]

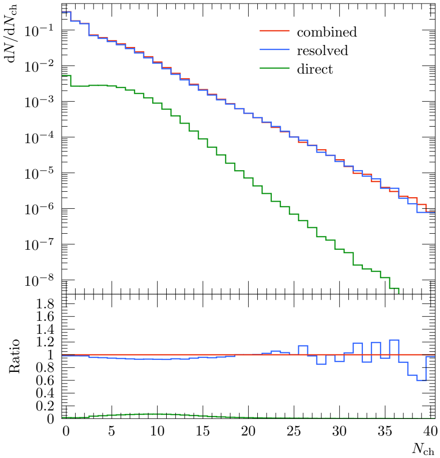
Comparison to ZEUS data for charged hadrons ($N_{ch} > 20$)

Pseudorapidity

- Data well reproduced
- Not sensitive to MPI modelling ($p_{T,0}$)

Multiplicity

- Sensitivity to MPI parameters, clear support for MPIs
- Data within $p_{T,0}$ variations
- Direct contribution negligible in high-multiplicity events ($N_{ch} > 20$)



[ZEUS: JHEP 12 (2021) 102]

Comparisons between Pythia, Sherpa and Herwig

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

- Summary of the modelling differences between the generators

Property	Pythia	Sherpa	Herwig
Flux	LL	NLL	LL
$\alpha_s(M_Z^2)$	0.130, 1-loop running	0.118, 3-loop running	
PDFs	CJKL	SAS2M	SAS2M
Remnants	forced splittings/PS rejection	PS rejection	forced splitting
$\gamma \to q\bar{q}$ Splitting	yes	no	no
MPI tuning	preliminary γ-p/γ-γ tune	untuned	untuned

Alternative VMD-based approach [with Marius Utheim]

- Resolved contribution dominates total cross section

$\Rightarrow$ Set up an explicit VMD model with linear combination of vector-meson states (ρ, ω, ϕ and J/ψ)

- Use VM PDFs from SU21

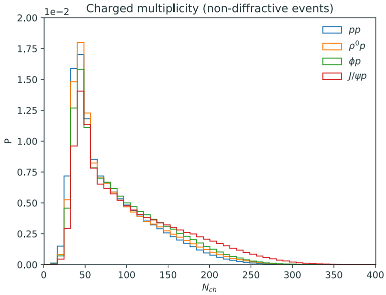
  [Sjöstrand, Utheim; EPJC 82 (2022) 1, 21]

- Cross sections from SaS

  [Schuler, Sjöstrand; PRD 49 (1994) 2257-2267]

- Sample collision energy from flux

$\Rightarrow$ Vector meson-proton scatterings



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  - Cross sections from SaS

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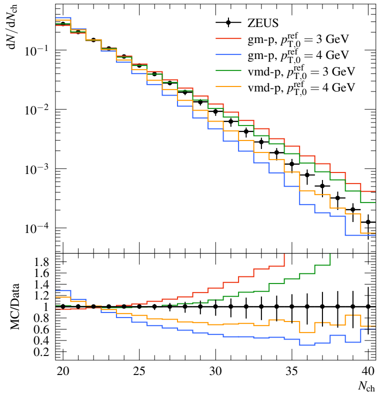
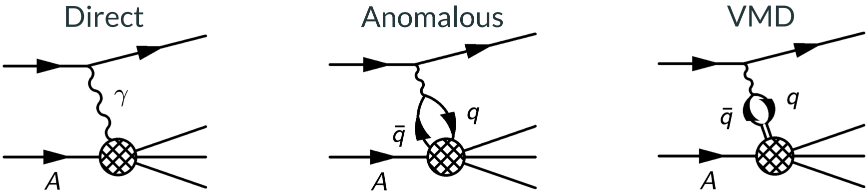
⇒ Vector meson-proton scatterings

  - In line with the full photoproduction



[ZEUS: JHEP 12 (2021) 102]

Vector meson dominance (VMD)



Linear combination of three components

$$|\gamma\rangle = c_{\mathrm{dir}}|\gamma_{\mathrm{dir}}\rangle + \sum_q c_q|q\bar{q}\rangle + \sum_V c_V|V\rangle$$

where the last term includes a linear combination of vector meson states up to J/Ψ

$$c_V = \frac{4\pi\alpha_{\mathrm{EM}}}{f_V^2}$$

V	$f_V^2/(4\pi)$
ρ^0	2.20
ω	23.6
ϕ	18.4
J/Ψ	11.5

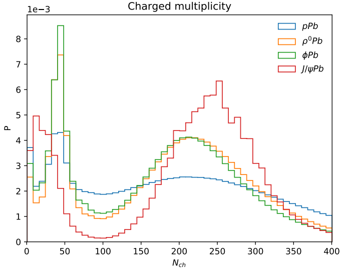
Modelling γ+A with Pythia

[I. Helenius, M. Utheim: arXiv:2406.10403 [hep-ph]; Accepted for publication in EPJC]

Angantyr model for heavy ions in Pythia

- Monte Carlo Glauber to sample nucleon configurations
- Cross section fluctuations, fitted to partial nucleon-nucleon cross sections
- Secondary (wounded) collisions as diffractive excitations
- Can now handle generic hadron-ion and varying energy

$\Rightarrow$ VMD-nucleus scatterings



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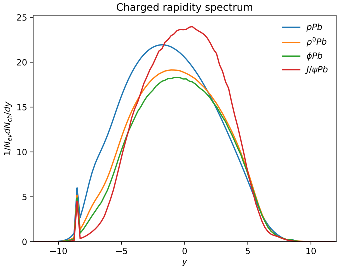
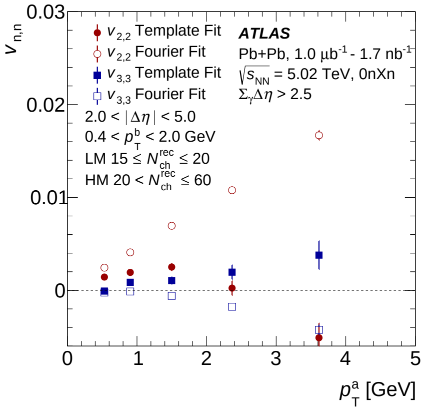
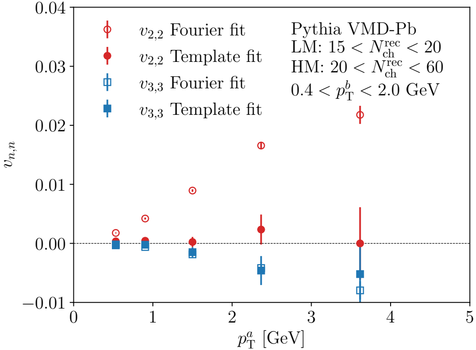


Two-particle correlations in γ+A with Pythia

[ATLAS: PRC 104, 014903 (2021)]



[I. Helenius, M. Utheim: EPJC 84 (2024) 11, 1155]

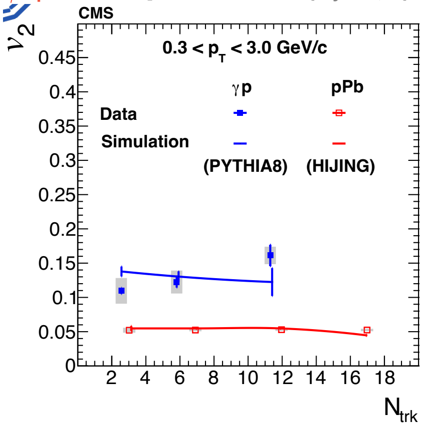


- No finite v_2 left after template fit in the Pythia simulation

  ⇒ Revisit with final state effects such as rope hadronization and string showing

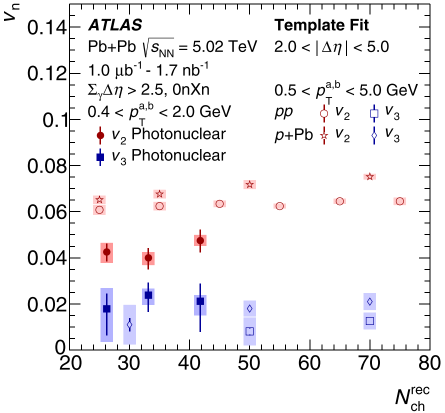
Collectivity in UPCs at the LHC

γ+p [CMS: Murillo Quijada, QM2022]



- Finite v_2 for γ+p, in line with Pythia
  $\Rightarrow$ Jet-like correlations?

γ+Pb [ATLAS: PRC 104, 014903 (2021)]



- Finite v_n also after Template fit subtracting "non-flow"