Pythia 8 for EIC

MC4EIC

Ilkka Helenius

July 9, 2025

Outline

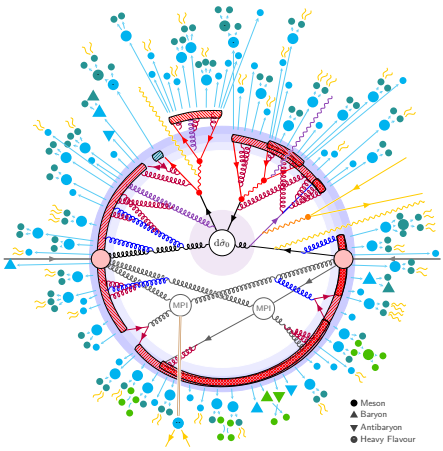
Pythia 8: A general purpose event generator

- Latest release 8.315 (May 27, 2025)
- A complete physics manual for 8.3

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

Outline

- Introduction to Pythia 8
- Deep inelastic scattering (DIS)
- Photoproduction Pythia 8
  - Proton target
  - Nuclear target
- Summary & Outlook

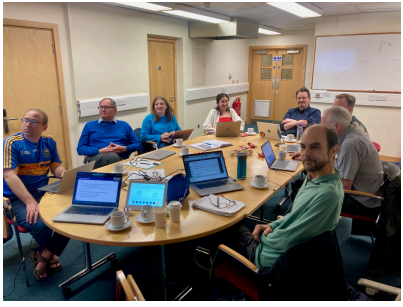


[figure by P. Skands]

Pythia 8 Collaboration

Current members (in 8.315 release)

- Javira Altmann (Monash University)
- Christian Bierlich (Lund University)
- Naomi Cooke (University of Glasgow)
- 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)



[Pythia Week in Oxford 2024]

- Spokesperson
- Codemaster
- Webmaster

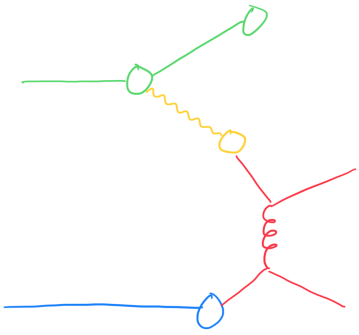
`https://pythia.org`

`authors@pythia.org`

Simulations with Pythia 8

1. Hard Process
   - Scattering process from perturbative QCD

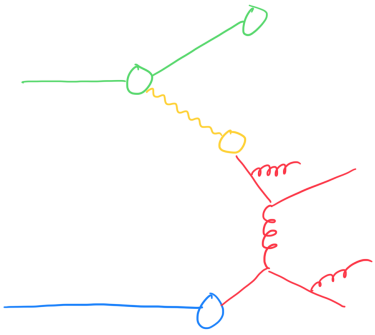
$$\mathrm{d}\sigma^{AB\to kl+X} = f_\gamma^A(y) \otimes f_i^\gamma(x_\gamma, \mu^2) \otimes f_j^B(x_p, \mu^2) \otimes \mathrm{d}\sigma^{ij\to kl}$$



Simulations with Pythia 8

1. Hard Process
2. Parton showers
   - Apply DGLAP evolution equations

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

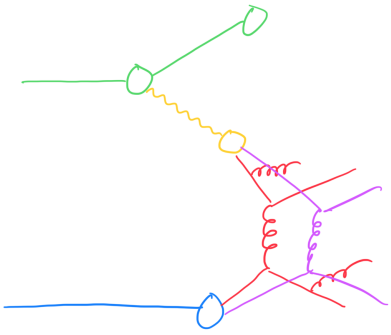


Simulations with Pythia 8

1. Hard Process
2. Parton showers
3. Multiparton interactions (MPIs)
   - Regulate cross section with p_{T0}

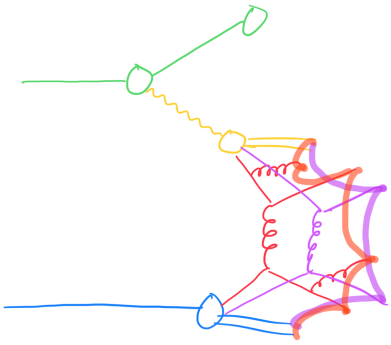
$$\frac{\mathrm{d}\sigma^{2\to 2}}{\mathrm{d}p_{\mathrm{T}}^2} \propto \frac{\alpha_{\mathrm{s}}(p_{\mathrm{T}}^2)}{p_{\mathrm{T}}^4} \to \frac{\alpha_{\mathrm{s}}(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)}{(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)^2}$$

   - Can interpret as colour screening



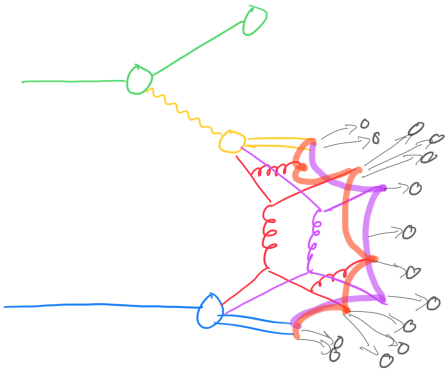
Simulations with Pythia 8

1. Hard Process
2. Parton showers
3. Multiparton interactions (MPIs)
4. Hadronization
   - Add beam remnants
   - Connect partons with colour strings



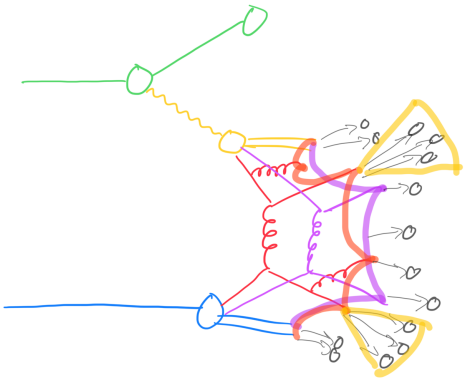
Simulations with Pythia 8

1. Hard Process
2. Parton showers
3. Multiparton interactions (MPIs)
4. Hadronization
   - Add beam remnants
   - Connect partons with colour strings
   - Let strings decay into stable hadrons with Lund string model



Simulations with Pythia 8

1. Hard Process
2. Parton showers
3. Multiparton interactions (MPIs)
4. Hadronization
5. Analyze the event by deriving an observable of interest, e.g. by running jet algorithm



Available beam configurations in Pythia 8

Hadronic collisions

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

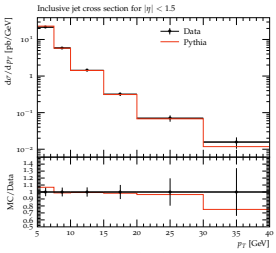
Collisions with leptons

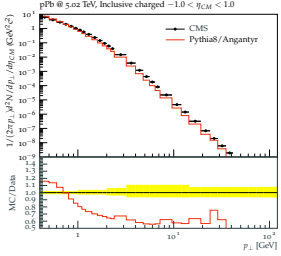
- $\mathrm{e}^+\mathrm{e}^-$, including $\gamma\gamma$ (also in p-p)
- e-p: (neutrino) DIS, photoproduction with soft and hard QCD processes

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]

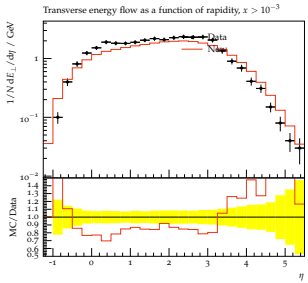




Alternative shower model `dipoleRecoil`

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

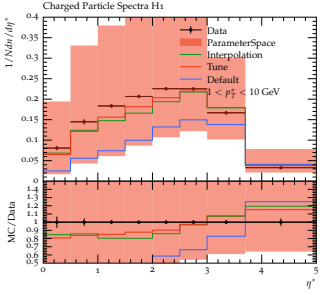
- Alternative to the default global recoil approach, keeps the scattered lepton momentum intact
- Reasonable description of single-particle properties, such as transverse energy flow



Ongoing improvements

- Fix for kinematics construction in DIS (8.316)
- A Preliminary tune to HERA DIS data with

Parameter	Value	Default	Min	Max
StringZ:aLund	1.24	0.68	0.40	1.60
StringZ:bLund	0.73	0.98	0.40	1.60
StringPT:sigma	0.474	0.335	0.250	0.800



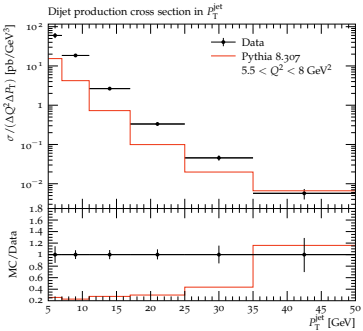
Jet production in DIS

[I. Helenius, J. Laulainen, C.T. Preuss: JHEP 05 (2025) 153]

- 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]

Multi-jet merging in DIS

`main164.cc`

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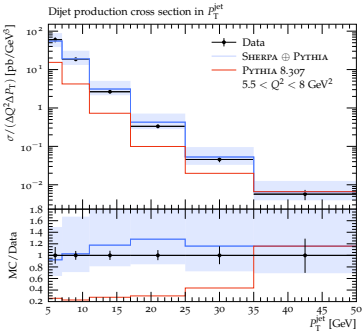
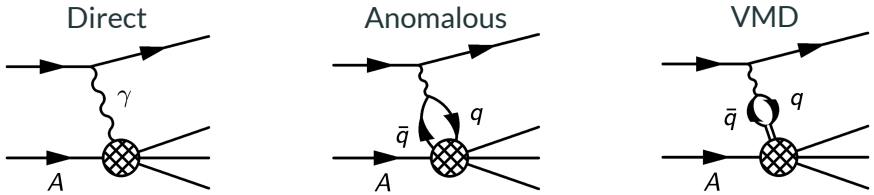


[H1: EPJC 77 (2017) 215]

Photon structure at $Q^2 \approx 0$ GeV^2



Partonic structure of resolved (anom. + VMD) photon encoded in photon PDFs

$$f_i^{\gamma}(x_\gamma, \mu^2) = f_i^{\gamma,\text{dir}}(x_\gamma, \mu^2) + f_i^{\gamma,\text{anom}}(x_\gamma, \mu^2) + f_i^{\gamma,\text{VMD}}(x_\gamma, \mu^2)$$

- $f_i^{\gamma,\text{dir}}(x_\gamma, \mu^2) = \delta_{i\gamma}\delta(1 - x_\gamma)$
- $f_i^{\gamma,\text{anom}}(x_\gamma, \mu^2)$: Perturbatively calculable
- $f_i^{\gamma,\text{VMD}}(x_\gamma, \mu^2)$: Non-perturbative, fitted or vector-meson dominance (VMD)

Validation against HERA dijet data

main343.cc

ZEUS dijet measurement

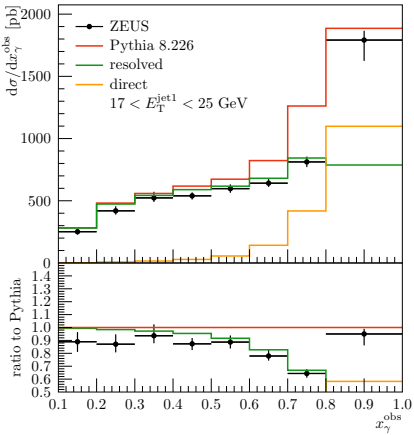
- $Q^2 < 1.0\,\text{GeV}^2$
- $134 < W_{\gamma p} < 277\,\text{GeV}$
- $E_T^{\text{jet1}} > 14\,\text{GeV}, E_T^{\text{jet2}} > 11\,\text{GeV}$
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Two contributions

- Momentum fraction of partons in photon

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

- At high-x_γ^{obs} direct processes dominate



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

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

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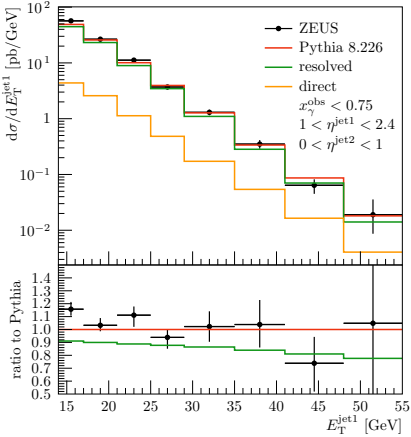

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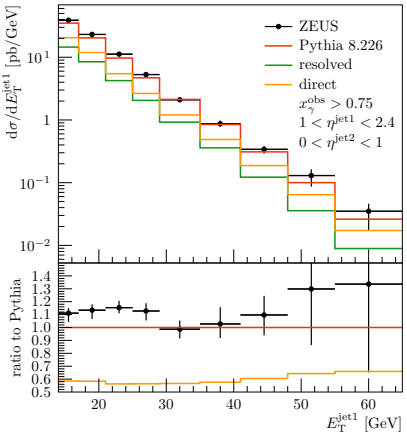

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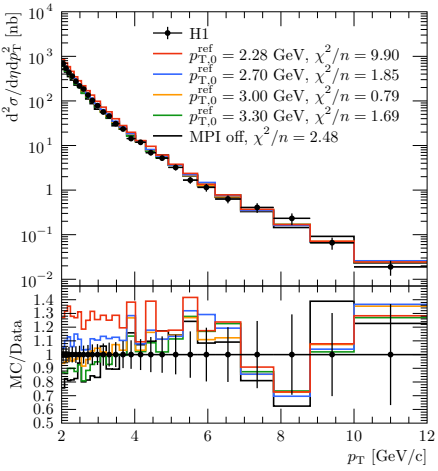
See also: [I.H., P. Meinzinger, S. Plätzer, P. Richardson: arXiv:2406.08026 [hep-ph]]

Charged particle photoproduction in HERA

H1 p_T spectrum

- Data for $W_{\gamma p} \approx 200$ GeV
- Some sensitivity to MPI parameters at low p_T
- Rivet analysis available



[H1: EPJC 10 (1999) 363-372]

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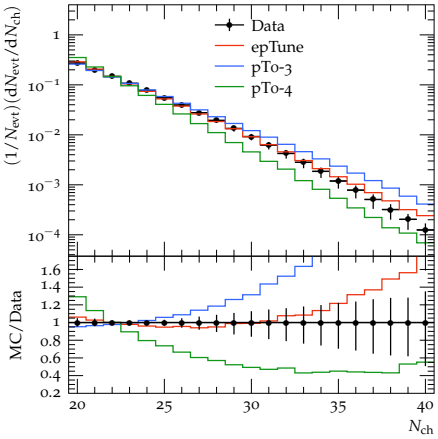
ZEUS multiplicity distribution

- High multiplicities very sensitive to MPIs
- Improved description using preliminary ep tune
- Rivet analysis in the works



[ZEUS: JHEP 12 (2021) 102]

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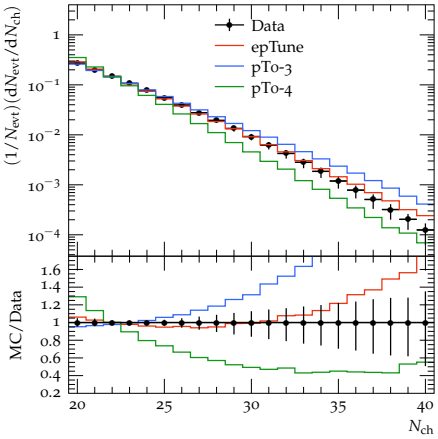
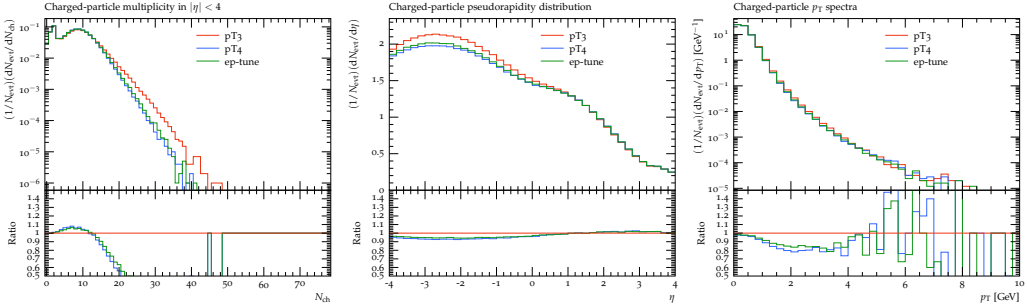
⇒ Input for validation and tuning



[ZEUS: JHEP 12 (2021) 102]

Photoproduction on proton target at the EIC

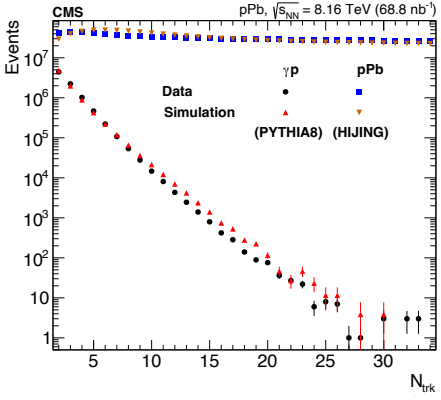
- Min. bias events with $E_e = 18$ GeV and $E_p = 275$ GeV with $W_{min} = 50$ GeV
- Compare results with different MPI parameterizations



- Uncertainties will be reduced after tuning to HERA photoproduction data

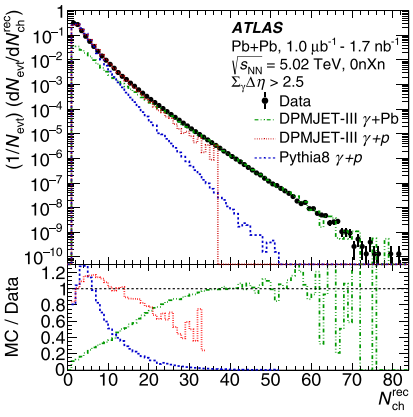
Multiplicity distributions in UPCs at the LHC

γ+p: [CMS: Murillo Quijada, QM2022]



- Multiplicity distribution well reproduced in γ+p interactions

γ+Pb: [ATLAS: PRC 104, 014903 (2021)]



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

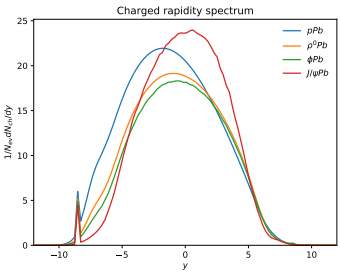
Nuclear targets with Pythia

Angantyr model for heavy ions in Pythia

[Bierlich, Gustafson, Lönnblad, Shah; JHEP 10 (2018) 134]

- 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

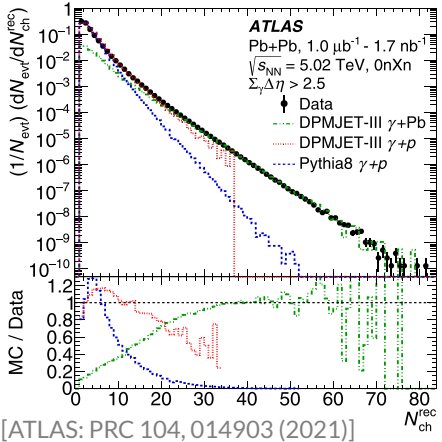
⇒ VMD-nucleus scatterings



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

Multiplicity distributions in UPCs at the LHC with Pythia

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



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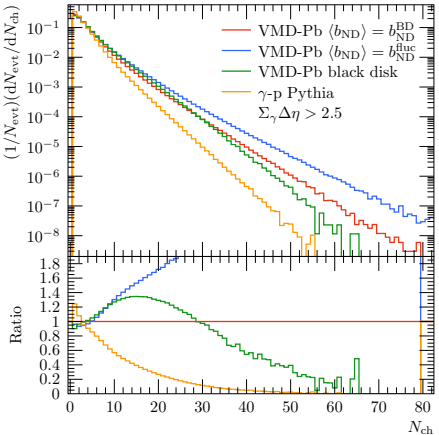
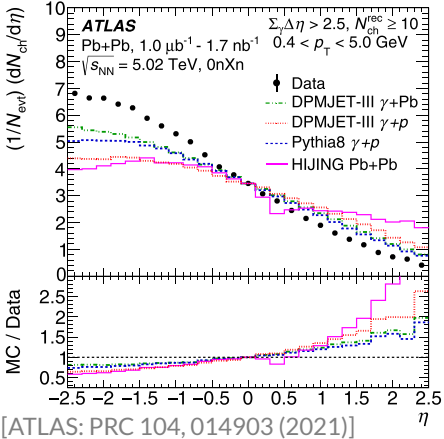


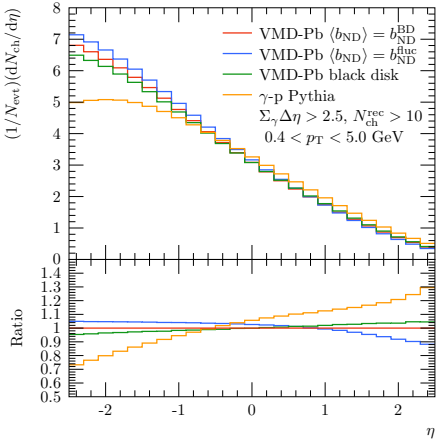
- ATLAS data not corrected for efficiency, estimated with $N_{\mathrm{ch}}^{\mathrm{rec}} \approx 0.8 \cdot N_{\mathrm{ch}}$
- Relative increase in multiplicity well in line with the VMD-Pb setup

Rapidity distributions in UPCs at the LHC

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



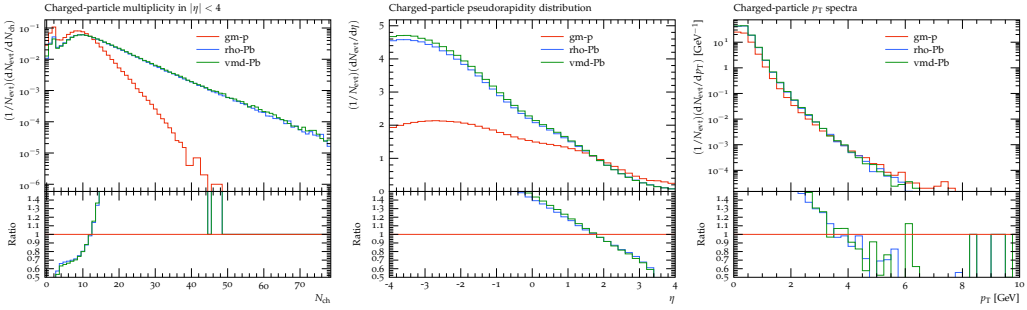
[ATLAS: PRC 104, 014903 (2021)]



- Multiplicity cut adjusted according to the limited efficiency
- Good description of the measured rapidity distribution with the VMD-Pb setup

Photoproduction on nuclear target at the EIC

- Min. bias events with $E_e = 18$ GeV and $E_n = 275$ GeV with $W_{\text{min}} = 50$ GeV
- Compare results with proton and nuclear targets, latter modelled with VMD



- A similar increase of high-multiplicity events as in UPCs at the LHC
- More particles produced in the lead-going direction
- VMD: in 80 % of events the photon fluctuates into a ρ meson

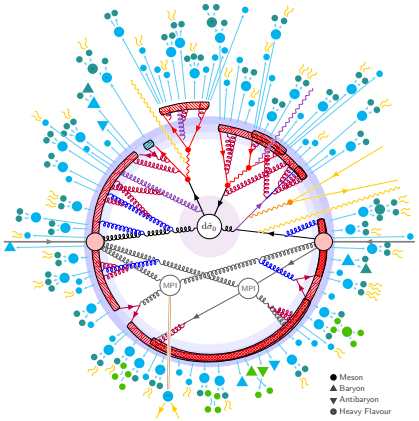
Summary & Outlook

Summary

- Pythia implementation of γp tested extensively against HERA data
- Still room for further validation and tuning (HERA, UPC@LHC, …)
- VMD to model collisions with nuclear targets, in line with ATLAS UPC data

Ongoing efforts

- Automated MPI tuning for DIS and γp
- Improvemnts for DIS handling
- Further model improvements and validation with nuclear targets



[figure by P. Skands]

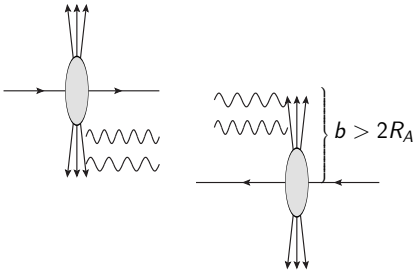
Backup slides

Ultraperipheral heavy-ion collisions

- Large impact parameter ($b \gtrsim 2R_A$)
  $\Rightarrow$ No strong interactions
- EM field of fast-moving charges described as a flux of low-virtuality photons
- At LHC relevant for p+p, p+Pb, Pb+Pb
- Similar to γp in e+p colliders (HERA)

Can study

- $\gamma\gamma$ to l^+l^-, $\gamma\gamma$, Higgs, ...
- Exclusive particle production in γp/Pb where also target hadron survives
- Inclusive processes, target hadron breaks up, jets, hadrons, multiplicities



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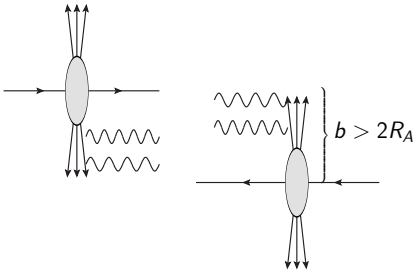


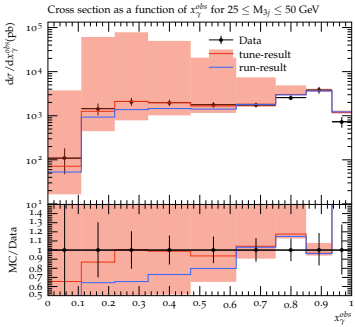
MPI tuning for γp [in progress]

Automized tuning with `Professor 2`[†]

- Use the 3-/4-jet data from ZEUS
- Vary p_{T0}^{ref} and α, 100 points in parameter space
- Build interpolating function, minimize χ^2

Preliminary findings

- Large sensivity to MPI parameters at small x_γ^{obs}
- A good fit simultaneously to several observables



[ZEUS: NPB 792 1 (2008)]

See also:

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

[†] [A. Buckley, H. Hoeth, H. Lacker, H. Schulz, J.E. von Seggern: EPJC 65 (2010) 331-357]

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Preliminary findings

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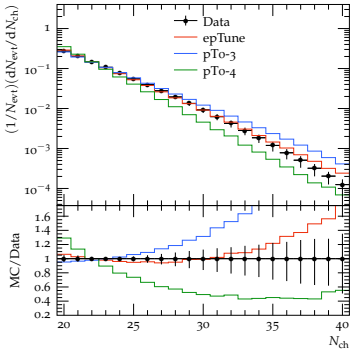
- A good fit simultaneously to several observables
- Tune improve agreement with ZEUS multiplicity distribution



[ZEUS: JHEP 12 (2021) 102]

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[†] [A. Buckley, H. Hoeth, H. Lacker, H. Schulz, J.E. von Seggern: EPJC 65 (2010) 331-357]

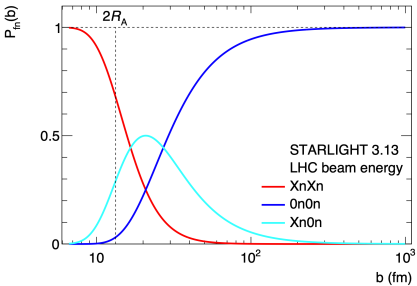
Experimental heavy-ion UPC classification

- 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

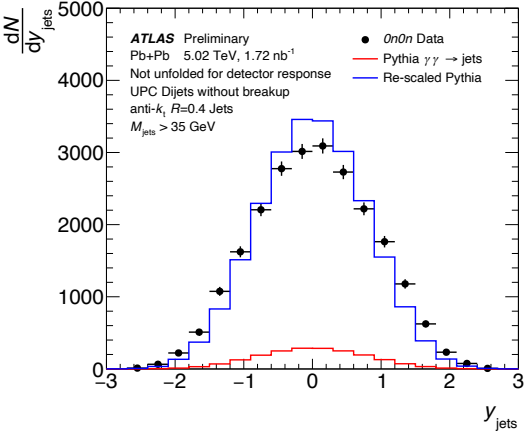


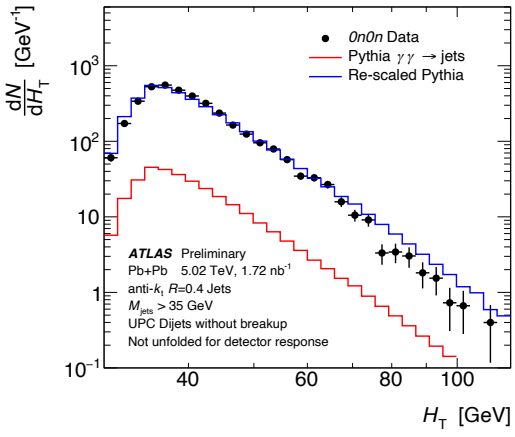
Ann.Rev.Nucl.Part.Sci. 70 (2020) 323-354

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 0n0n



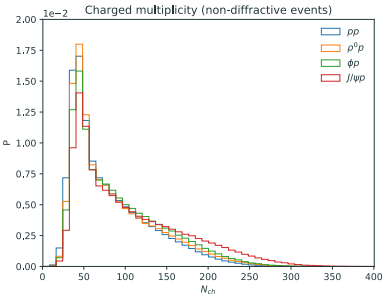


[ATLAS-CONF-2022-021]

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

Alternative VMD-based approach [with Marius Utheim]

- Resolved contribution dominates total cross section
  - ⇒ 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
- ⇒ Vector meson-proton scatterings



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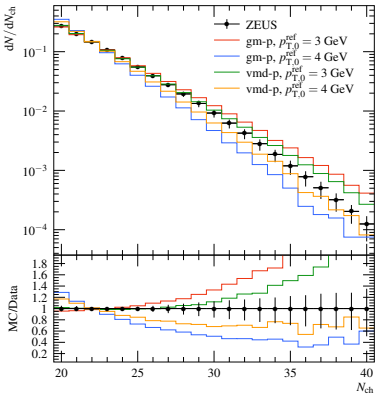
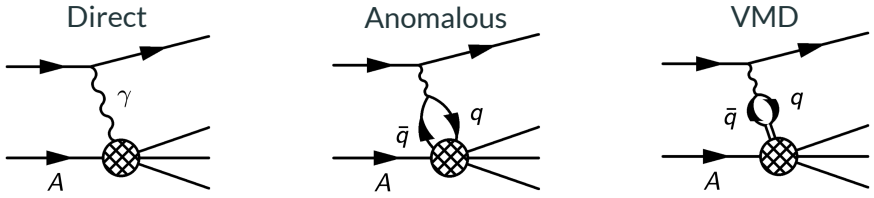
⇒ Vector meson-proton scatterings

  - In line with the full photoproduction



[ZEUS: JHEP 12 (2021) 102]

Vector meson dominance (VMD)



Linear combination of three components

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

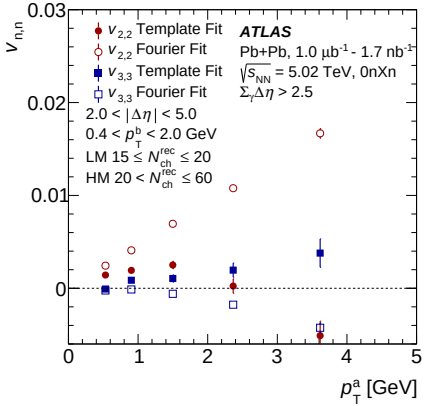
where the last term includes a linear combination of vector meson states up to J/Ψ

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

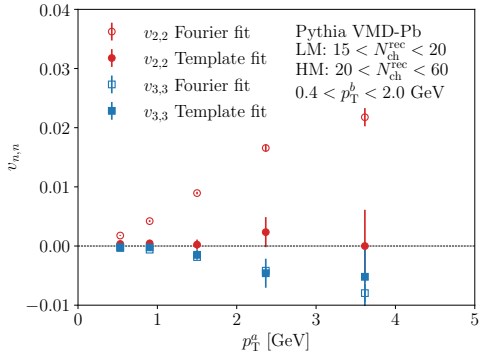
V	$f_V^2/(4\pi)$
ρ^0	2.20
ω	23.6
ϕ	18.4
J/Ψ	11.5

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

  $\Rightarrow$ Revisit with final state effects such as rope hadronization and string showing

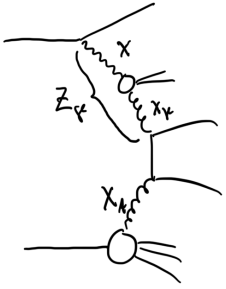
Dijets in ultra-peripheral heavy-ion collisions in Xn0n

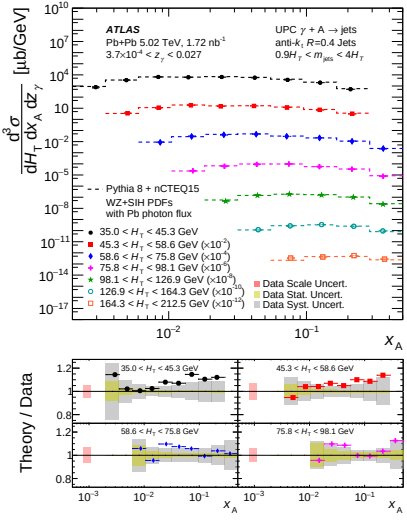
- Good agreement out of the box when accounting both direct and resolved
- EM nuclear break-up significant
- Pythia setup with nucleon target only
  $\Rightarrow$ Is such a setup enough for γ+A?

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

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

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

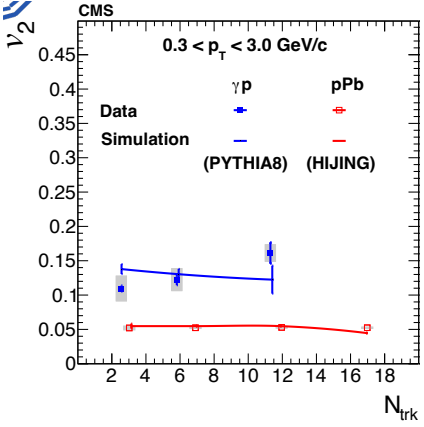




[ATLAS: PRD 111 (2025) 5, 052006]

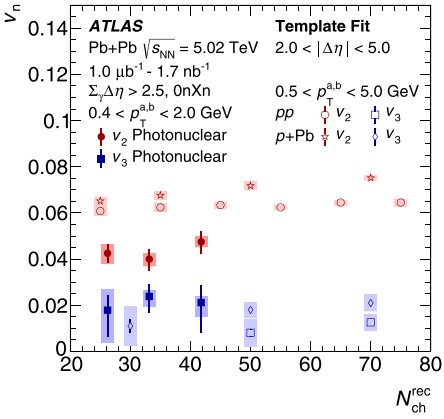
Collectivity in UPCs at the LHC

γ+p [CMS: Murillo Quijada, QM2022]



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

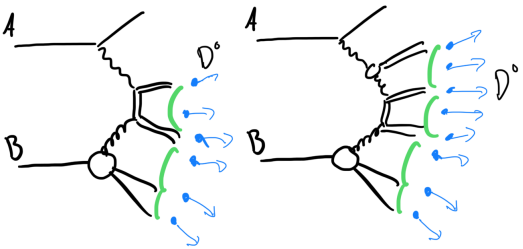
γ+Pb [ATLAS: PRC 104, 014903 (2021)]

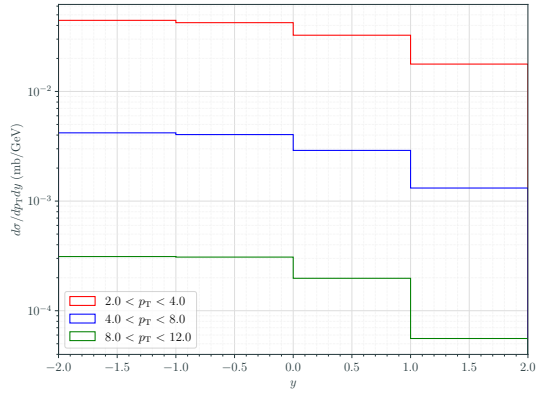


- Finite v_n also after Template fit subtracting "non-flow"

Inclusive D-meson production in UPCs

- New experimental analyses 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]