Ultra-peripheral collisions in Pythia

PHENOMENAL MEETING

Ilkka Helenius

April 18th, 2023

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UNIVERSITY OF JYVÄSKYLÄ

ACADEMY OF FINLAND
CoE in Quark Matter

Outline

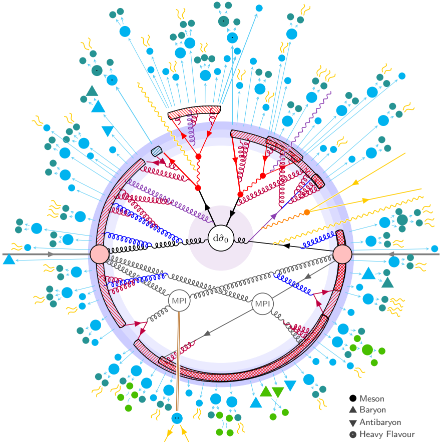
PYTHIA 8: general purpose event generator

- Latest release 8.309 (Feb 2023)
- A new physics manual for 8.3

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

Outline

1. Pythia basics
2. Photoproduction in ep
3. Ultraperipheral collisions (UPCs)
   - Photon fluxes
   - γ+A interactions
4. Summary & Outlook



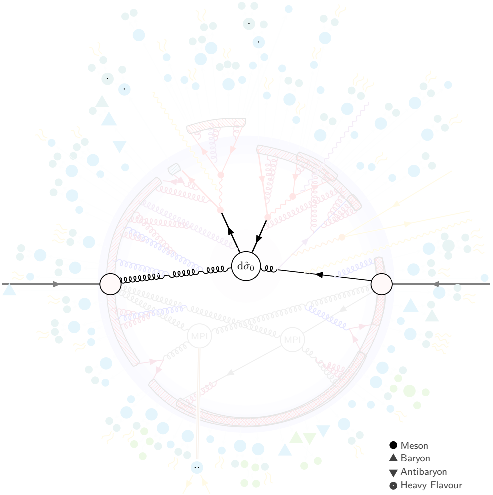
[figure by P. Skands]

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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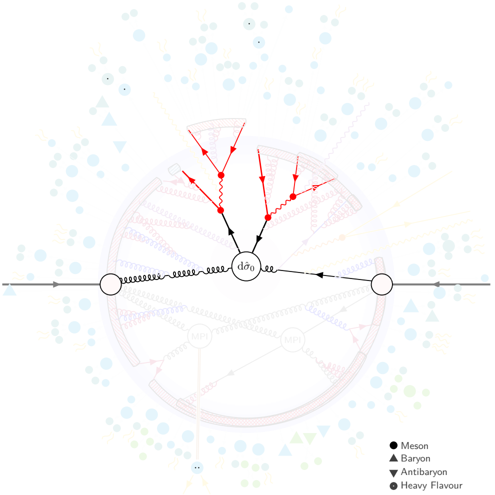

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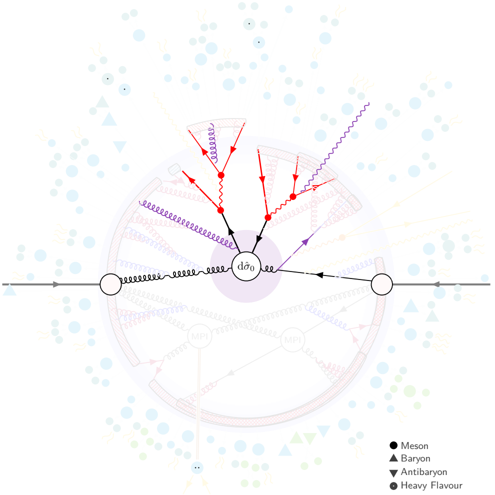
[figure credit: P. Skands]



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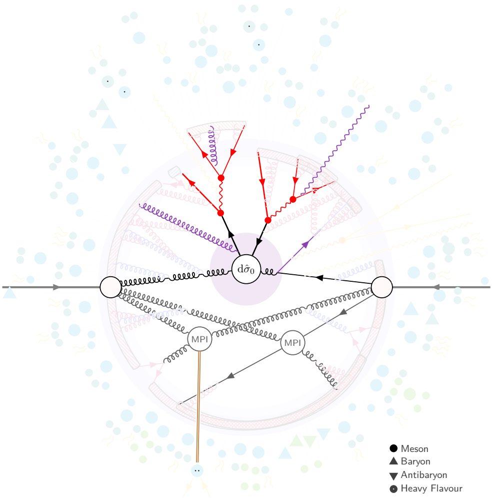
[figure credit: P. Skands]



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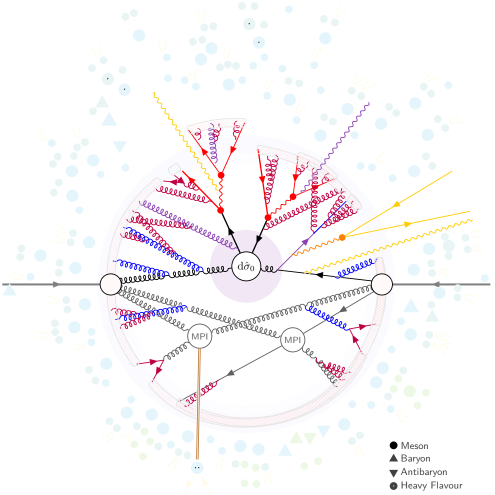
[figure credit: P. Skands]



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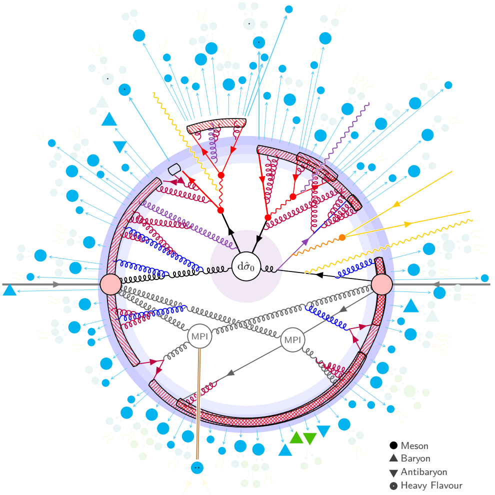
[figure credit: P. Skands]



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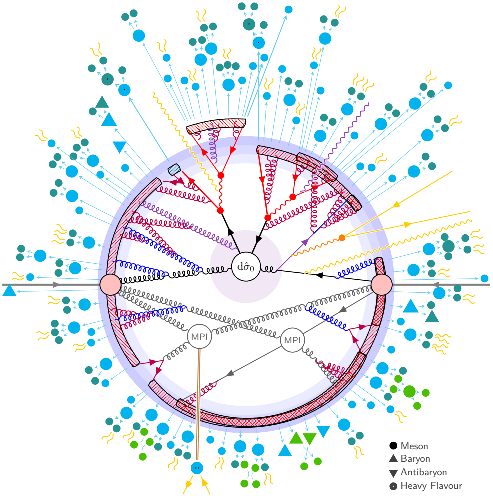
7. Decays, Rescattering



Multiparton interactions (MPIs) in PYTHIA 8

Several partonic scatterings in one collision event

- Probability from 2 → 2 QCD scattering

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

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

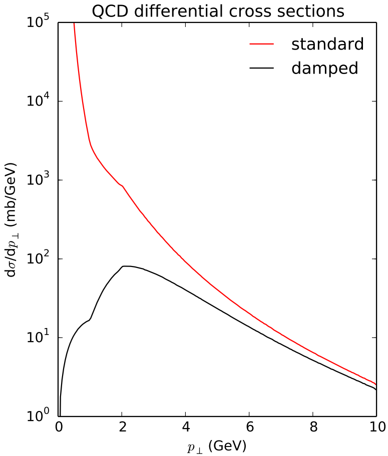
  ⇒ Regulate with a screening parameter p_{T0}

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

- Average number of interactions:

  $\langle n \rangle = \sigma_{\mathrm{int}}(p_{\mathrm{T0}})/\sigma_{\mathrm{nd}}$

- Also impact-parameter dependence



[figure by T. Sjöstrand]

Electron-proton collisions

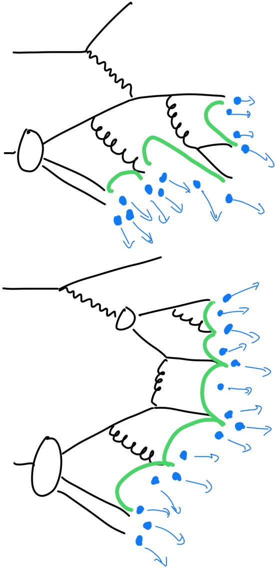
Classified in terms photon virtuality Q^2

Deep inelastic scattering (DIS)

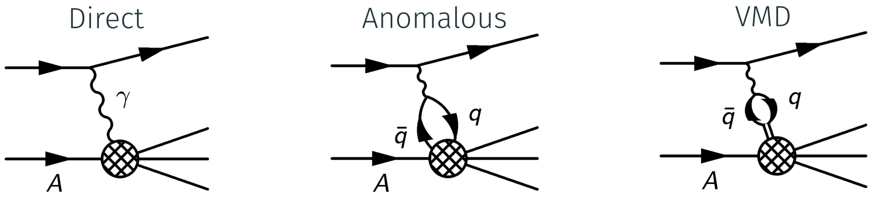
- High virtuality, $Q^2 > \text{a few GeV}^2$
- Lepton scatters off from a parton by exchanging a highly virtual photon

Photoproduction (PhP)

- Low virtuality, $Q^2 \to 0\ \text{GeV}^2$
- Hard scale μ provided by the final state
- Resolved contribution gives rise to MPIs
- Also soft QCD process are possible



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



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

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

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

Factorized cross section

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

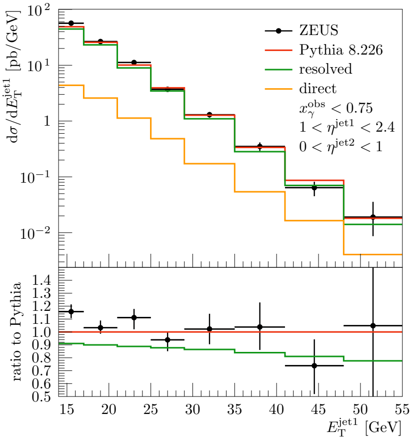
Comparison to HERA dijet photoproduction data

ZEUS dijet measurement

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

Two contributions

- Momentum fraction of partons in photon
$$x_\gamma^{\text{obs}} = \frac{E_T^{\text{jet1}} e^{\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{\eta^{\text{jet2}}}}{2yE_e} \approx x_\gamma$$
- Sensitivity to process type



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

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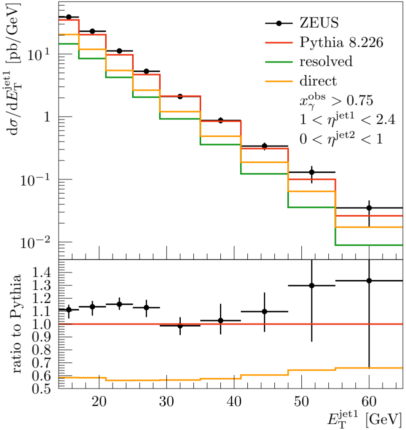
- Sensitivity to process type
- At high-x_γ^{obs} direct processes dominate



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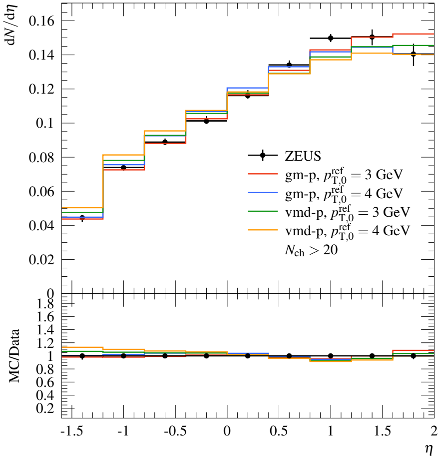
Comparison to ZEUS data for charged hadrons ($N_{ch} > 20$)

Pseudorapidity

- Data well reproduced with full photoproduction and VMD only
- Not sensitive to MPI modelling



[ZEUS: JHEP 12 (2021) 102]

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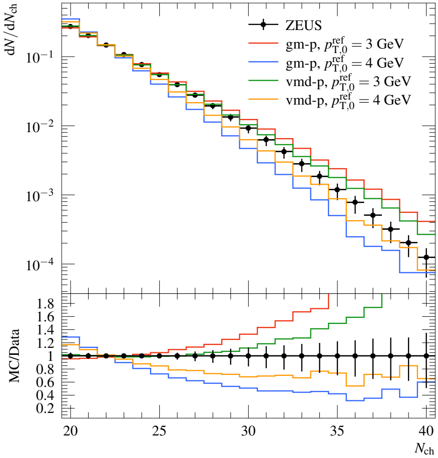
Multiplicity

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



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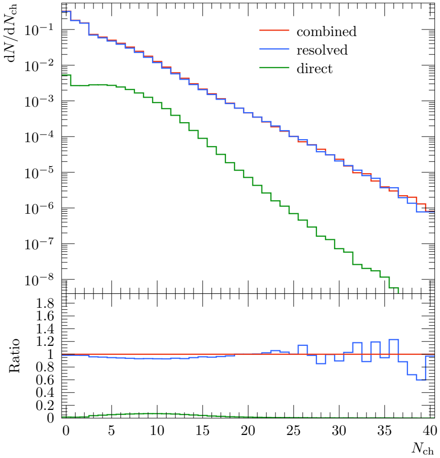
Multiplicity

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



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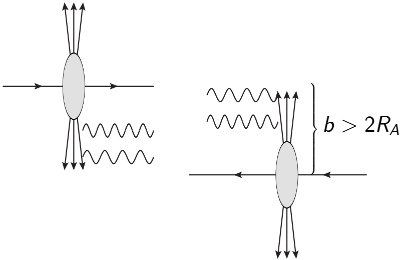
Ultraperipheral collisions

- Large impact parameter
  $\Rightarrow$ No strong interactions
- But charged particles emit photons
- At LHC relevant for p+p, p+Pb, Pb+Pb



Allows to study

- γ γ collisions, useful to study flux
- Exclusive particle production in γ+p and γ+Pb
- Inclusive photo-nuclear processes

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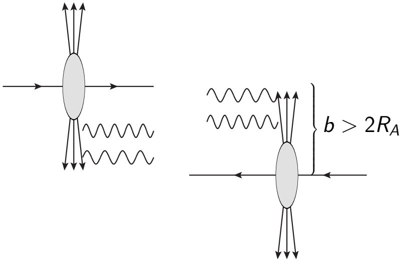
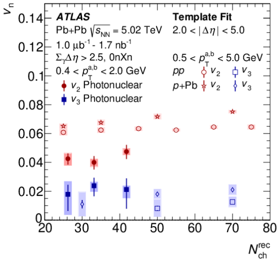


Allows to study

- $\gamma\,\gamma$ collisions, useful to study flux
- Exclusive particle production in γ+p and γ+Pb
- Inclusive photo-nuclear processes
  - Hint of collectivity in γ+Pb



[ATLAS: PRC 104, 014903 (2021)]

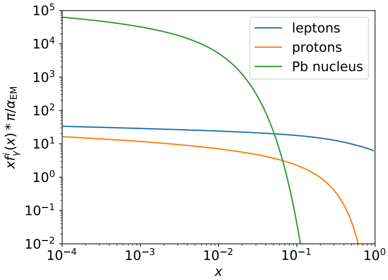
Equivalent photon approximation

- In case of a point-like lepton we have

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

- For protons need to account the form factor

$$f_\gamma^p(x,Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{(1+(1-x)^2)}{x}\frac{1}{Q^2}\frac{1}{(1+Q^2/Q_0^2)^4}$$



where $Q_0^2 = 0.71\ \mathrm{GeV}^2$ (Drees-Zeppenfeld) $\Rightarrow$ Large Q^2 heavily suppressed

- With heavy nuclei use b-integrated point-like-charge flux

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

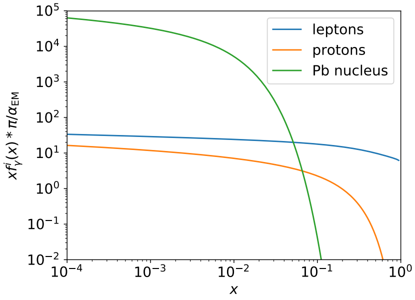
where $\xi = b_{\mathrm{min}}\,x\,m$ where b_{min} reject nuclear overlap, $Q^2 \ll 1\ \mathrm{GeV}^2$

$\Rightarrow$ Can apply photoproduction framework with all these beams!

Photon fluxes in PYTHIA 8

- Enable γ+p in e+p

```
pythia.readString("Beams:idA = -11");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
```



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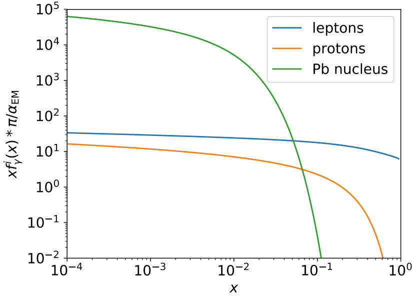

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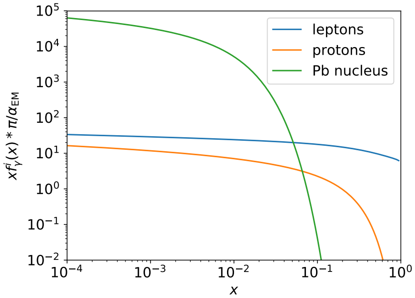
```

- Enable γ+p in Pb+p

```
pythia.readString("Beams:idA = 2212");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
pythia.readString("PDF:proton2gammaSet = 0");
pythia.readString("PDF:beam2gammaApprox = 2");
pythia.readString("Photon:sampleQ2 = off");
PDFPtr photonFlux = make_shared<Nucleus2gamma>(2212);
pythia.setPhotonFluxPtr(photonFlux, 0);
```



For more examples see `main68.cc`, `main69.cc`, `main70.cc`, `main78.cc` in examples directory

Photon fluxes in PYTHIA 8

- Not enough? Define your own flux

```
class Nucleus2gamma2 : public PDF {

public:

  // Constructor.
  Nucleus2gamma2(int idBeamIn) : PDF(idBeamIn) {}

  // Update the photon flux.
  void xfUpdate(int , double x, double ) {

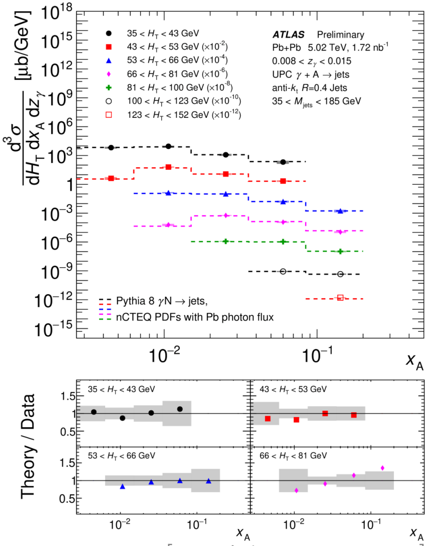
    // Minimum impact parameter (~2*radius) [fm].
    double bmin = 2 * 6.636;

    // Charge of the nucleus.
    double z = 82.;

    // Per-nucleon mass for lead.
    double m2 = pow2(0.9314);
    double alphaEM = 0.007297353080;
    double hbarc = 0.197;
    double xi = x * sqrt(m2) * bmin / hbarc;
    double bK0 = besselK0(xi);
    double bK1 = besselK1(xi);
    double intB = xi * bK1 * bK0 - 0.5 * pow2(xi) * ( pow2(bK1) - pow2(bK0) );
    xgamma = 2. * alphaEM * pow2(z) / M_PI * intB;
  }

};
```

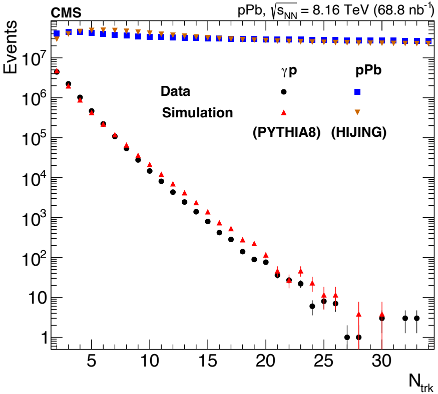
[from `main70.cc`]



[P. Steinberg @ DIS2023]

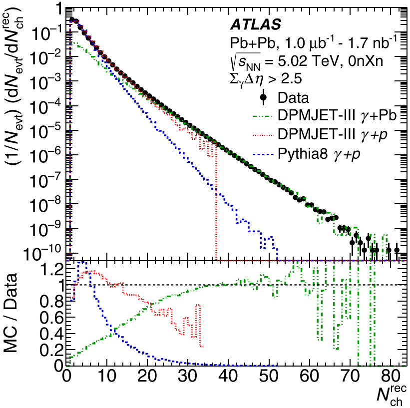
Multiplicity distributions in UPCs

(Pb $\rightarrow \gamma$)+p: [CMS: Murillo Quijada, QM2022]



- Multiplicity distribution well reproduced in γp interactions

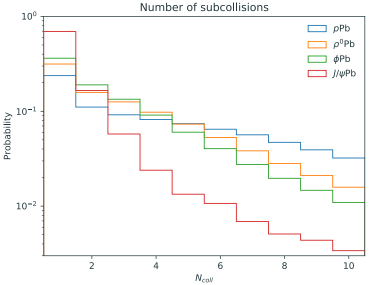
(Pb $\rightarrow \gamma$)+Pb:[ATLAS: PRC 104, 014903 (2021)]

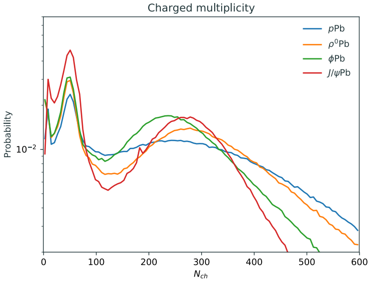


- High multiplicities missed with γp
  $\Rightarrow$ Multi-nucleon interactions

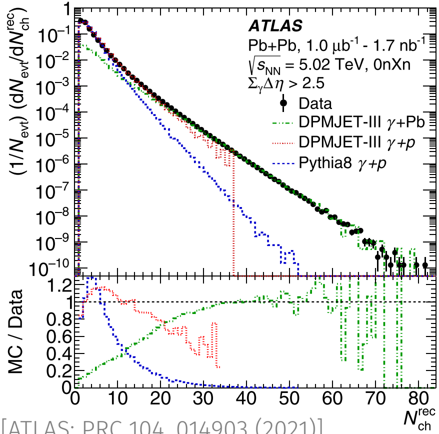
Use Angantyr for interactions with heavy nuclei

- Full γ+A not in place
- But we have setup an explicit VMD model
  - Photon a linear combination of vector-mesons states up to J/Ψ
  - Rely on upcoming implementation of generic hadron - ion collisions
    $\Rightarrow$ To be included in PYTHIA 8.310
  - Cover bulk of the cross section
  - Dominant contribution at high multiplicity





Comparison with data for γ+A (preliminary)



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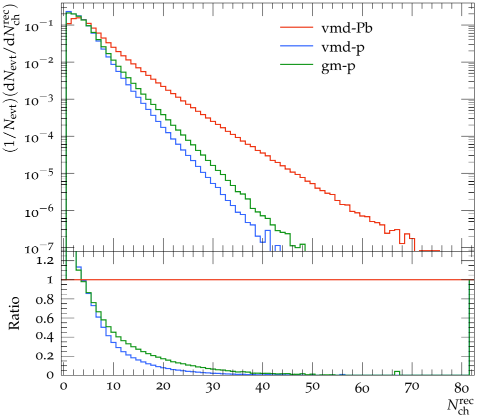
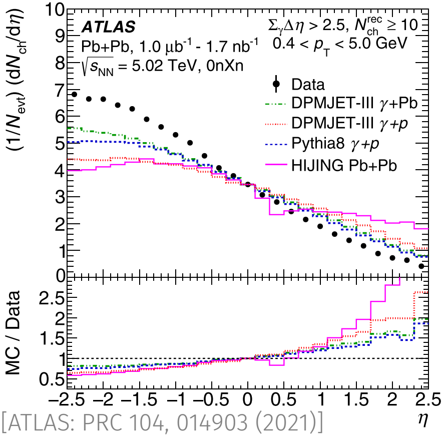


- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative increase in multiplicity well in line with the VMD setup

Comparison with data for γ+A (preliminary)



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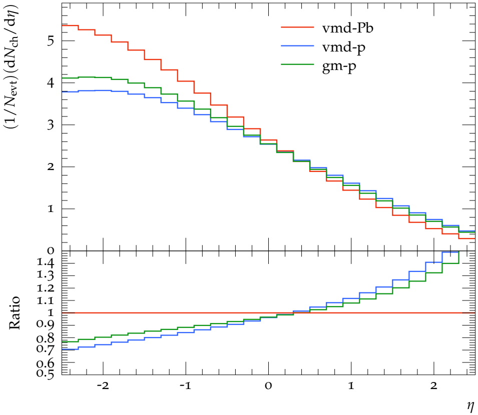


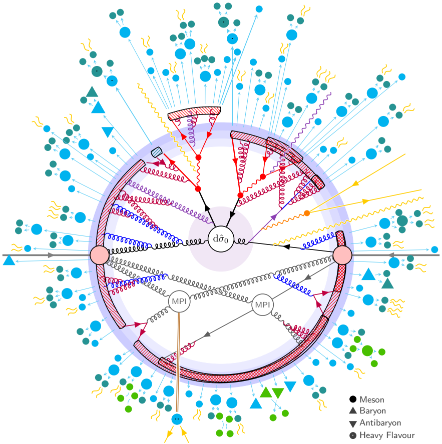
- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative shift in rapidity distribution in line with the VMD setup using Angantyr

Photoproduction and UPCs in Pythia 8.3

- Can simulate γ+p and γ+γ in different beam configurations
- Direct and resolved contributions
- Non-diffractive, diffractive and elastic available
- Flexible flux sampling

Outlook

- First steps to simulate γ+A with the VMD implementation
  - In line with ATLAS results
- Collective effects (finite v_n) in γ+A?



[figure by P. Skands]

UPC 2023: International workshop on the physics of Ultra Peripheral Collisions

11–15 Dec 2023
Playa del Carmen
America/Cancun timezone

Enter your search term

The first international workshop on the physics of Ultra Peripheral Collisions will be organized at Hotel Iberostart Tucan/Quetzal in Playa del Carmen, Mexico from December 11-15, 2023.

There will be a student day on Sunday, December 10.

Backup slides

Evolution equation and 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)

- Resulting PDFs has point-like (or anomalous) and hadron-like components

$$f_i^{\gamma}(x, Q^2) = f_i^{\gamma,\mathrm{pl}}(x, Q^2) + f_i^{\gamma,\mathrm{had}}(x, Q^2)$$

  - $f_i^{\gamma,\mathrm{pl}}$: Calculable from perturbative QCD
  - $f_i^{\gamma,\mathrm{had}}$: Requires non-perturbative input fixed in a global analysis

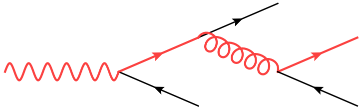
Evolution equation and ISR for resolved photons

ISR probability based on DGLAP evolution

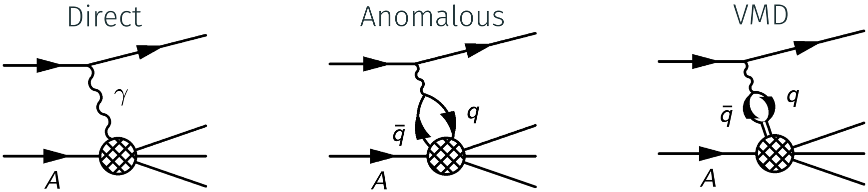
- Add a term corresponding to $\gamma \to q\bar{q}$ to (conditional) ISR probability

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

- Corresponds to ending up to the beam photon during evolution
  $\Rightarrow$ Parton originated from the point-like part of the PDFs
  - No further ISR or MPIs below the scale of the splitting
  - No need for beam remnants



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



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

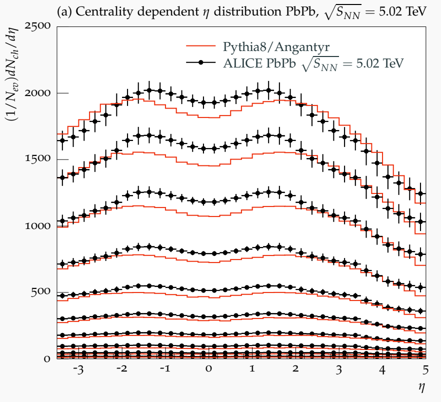
Heavy-ion collisions

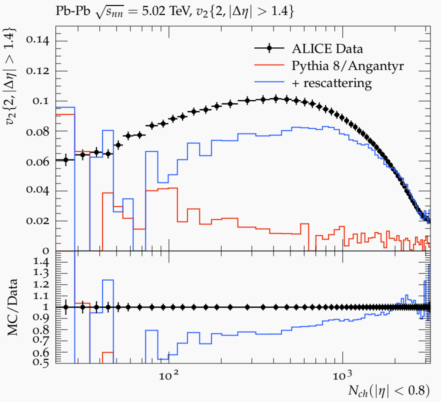
- Angantyr in Pythia provides a full heavy-ion collisions framework

[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]

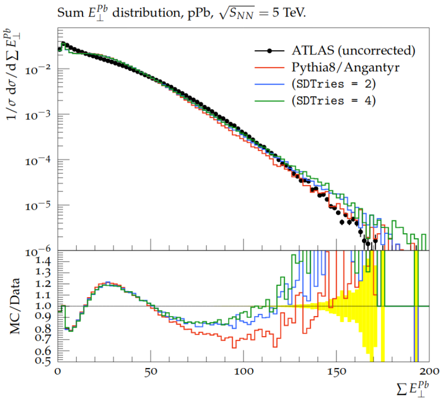


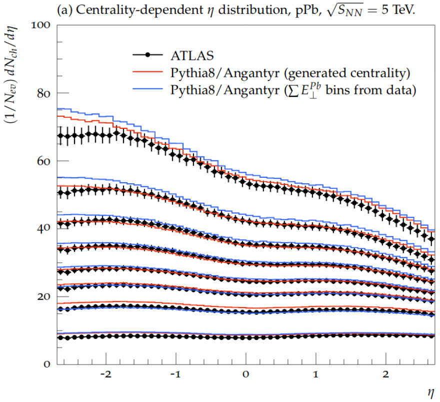


p+A collisions

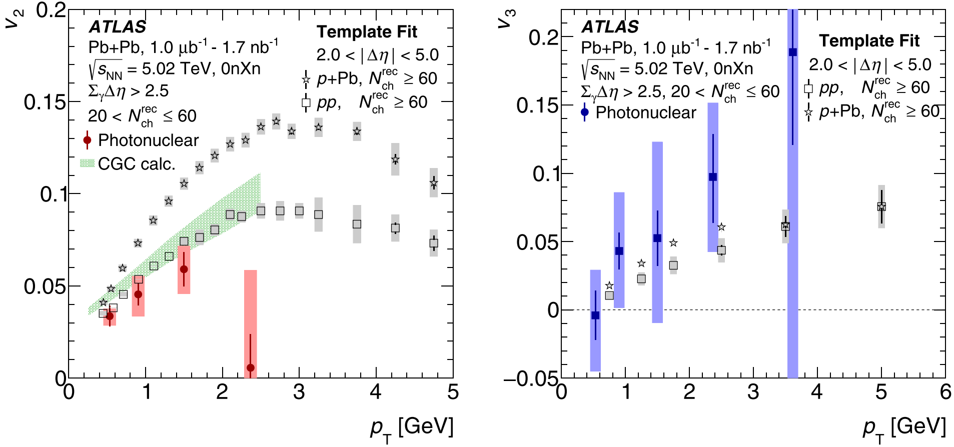
[Bierlich, Gustafson, Lönnblad & Shah: 1806.10820]

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



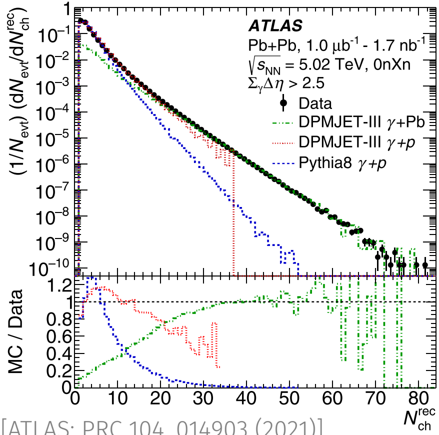


ATLAS data for v_n in γ+Pb

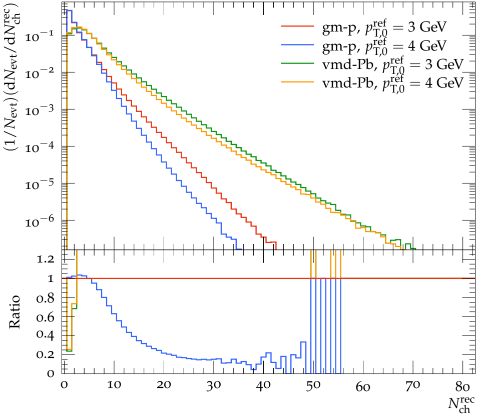


- Non-zero flow coefficients also for γ+Pb
- Expected baseline from MC simulations?

Comparison with data for γ+A (preliminary)

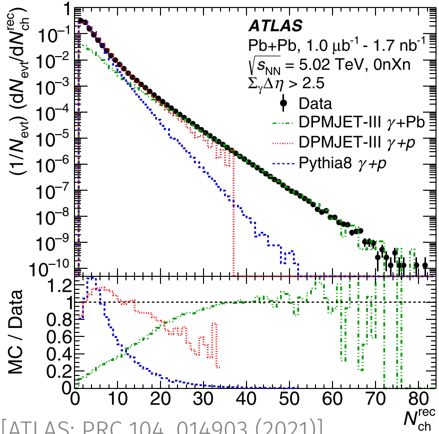


[ATLAS: PRC 104, 014903 (2021)]



- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative increase in multiplicity well in line with the VMD setup

Comparison with data for γ+A (preliminary)



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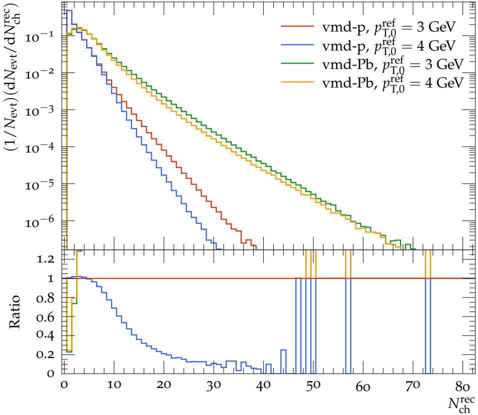

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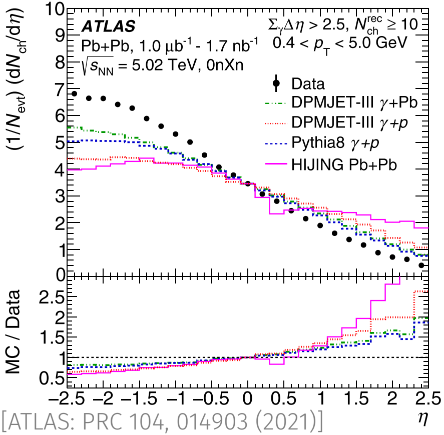

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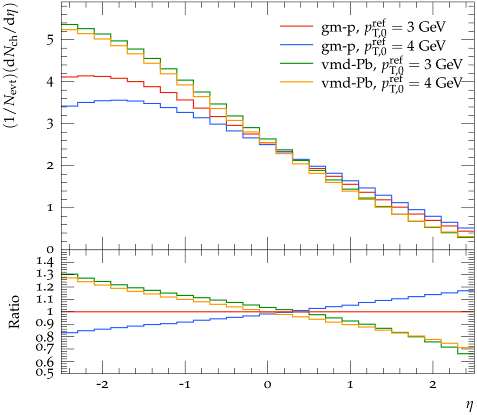

- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative shift in rapidity distribution in line with the VMD setup using Angantyr

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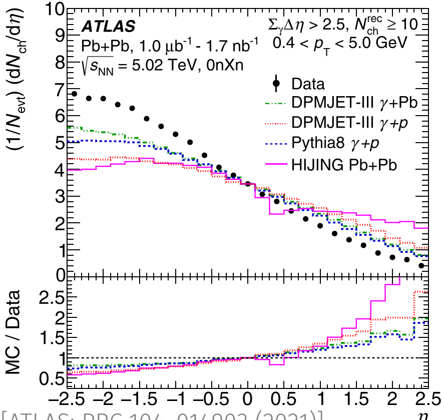

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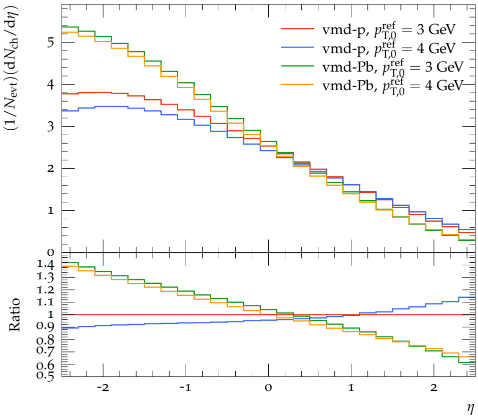

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