Photo-nuclear collisions in Pythia 8

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

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Ilkka Helenius

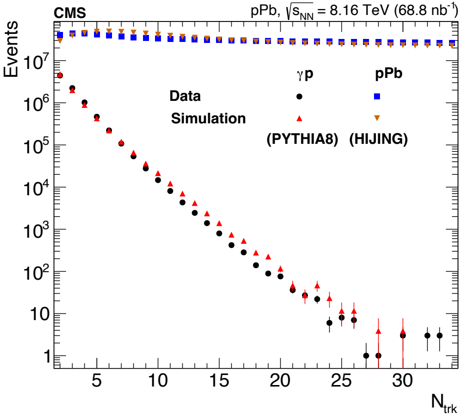
December 15th, 2023

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

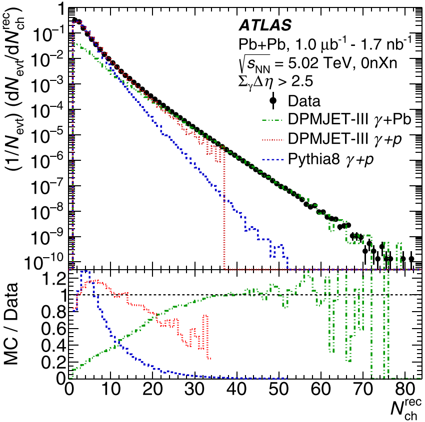
ACADEMY OF FINLAND
CoE in Quark Matter

Motivation: data for inclusive γ-p and γ-Pb from UPCs at the LHC

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



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



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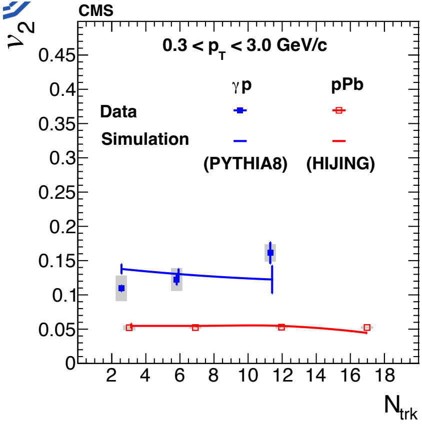

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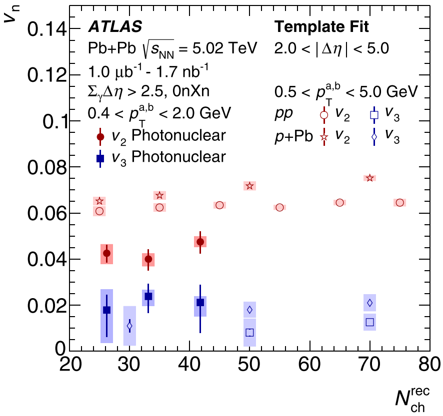


- Multiplicity distribution well in line for γ-p but γ-p not enough for γ-Pb
- CMS γ-p v_2 reproduced with Pythia, ATLAS data show finite v_2 and v_3 in γ-Pb

Outline

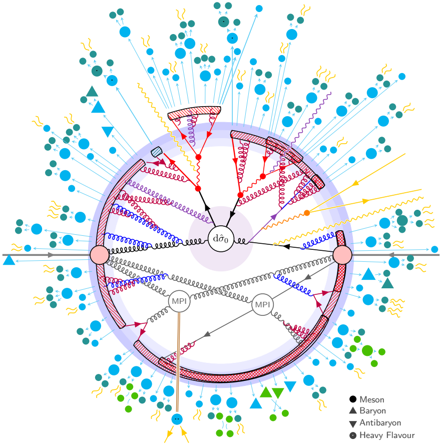
PYTHIA 8: A general purpose event generator

- Latest release 8.310 (July 2023)
- A new physics manual for 8.3

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

Outline

1. Pythia 8 basics
2. Photoproduction in e+p at HERA
3. UPCs at the LHC
   - Photon fluxes in Pythia
   - Photon-ion collisions
   - v_2 extraction
4. Summary & Outlook



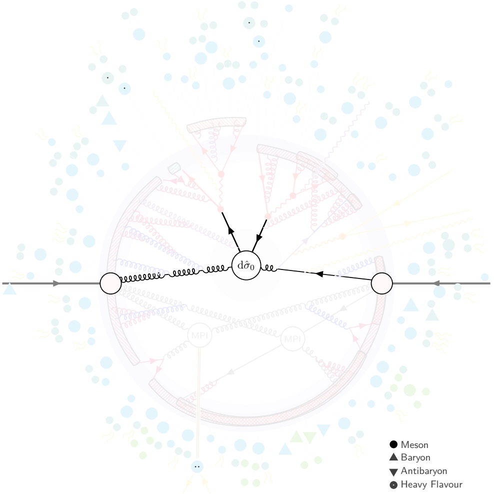
[figure by P. Skands]

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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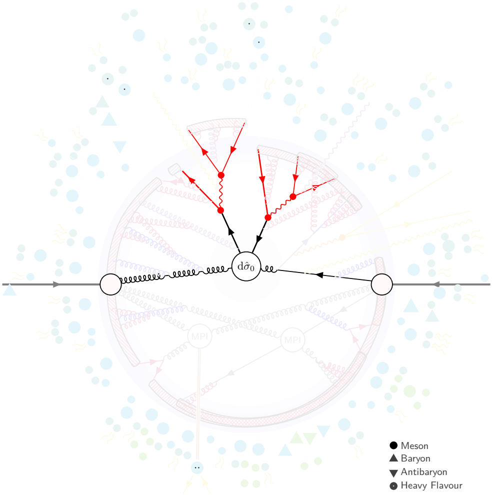

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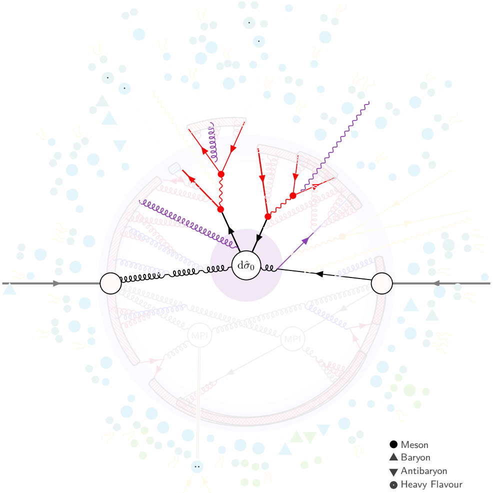
[figure credit: P. Skands]



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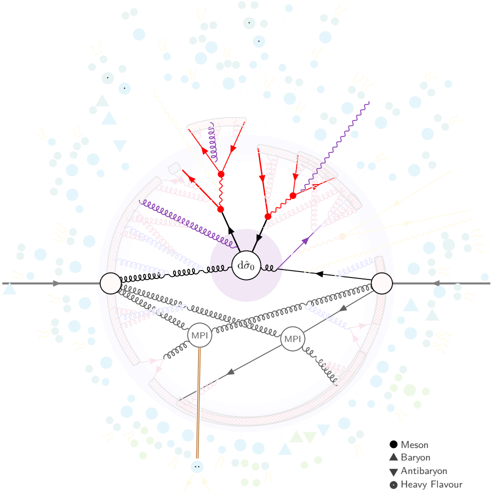

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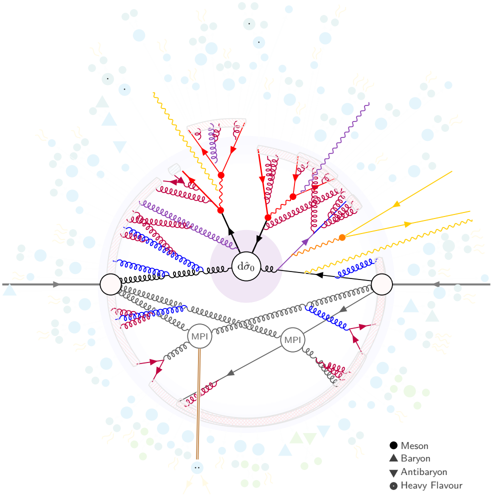

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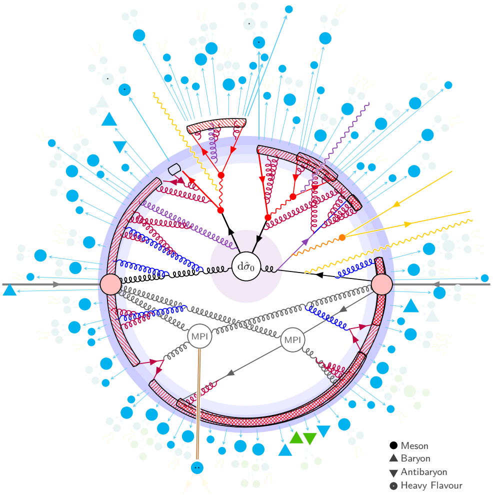

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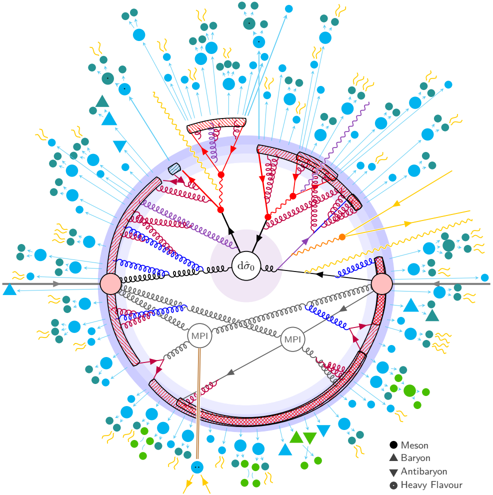
6. Hadronization, Beam remnants
7. Decays, Rescattering

[figure credit: P. Skands]



Photoproduction in HERA

Electron-proton collisions and connection to UPCs

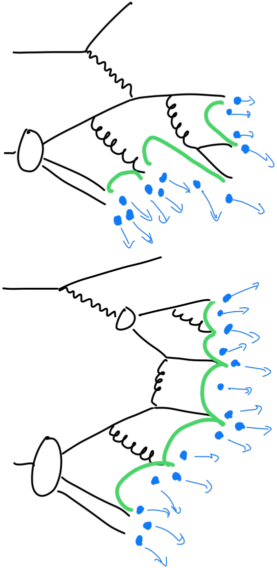
Classified in terms photon virtuality Q^2

Deep inelastic scattering (DIS)

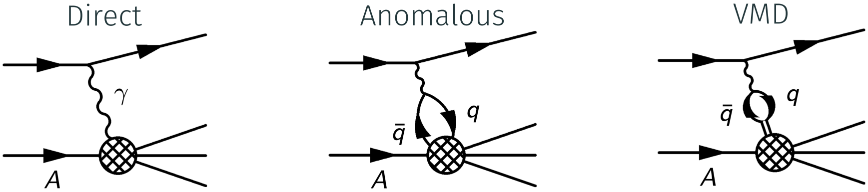
- High virtuality, $Q^2 >$ a few GeV^2
- Lepton scatters off a parton by exchanging a highly virtual photon

Photoproduction (PhP)

- Low virtuality, $Q^2 \to 0$ GeV^2
  $\Rightarrow$ Similar to UPCs
- Photon may fluctuate into a hadronic state, resolved in the interaction
- Hard scale μ provided by the final state



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

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

Evolution equation and ISR for resolved photons

ISR probability based on DGLAP evolution

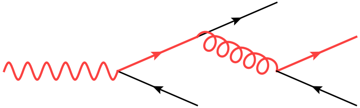
- Add a term corresponding to $\gamma \rightarrow \mathrm{q}\overline{\mathrm{q}}$ to (conditional) ISR probability

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

- 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 only for Simple Shower in PYTHIA



Comparison to HERA dijet photoproduction data

ZEUS dijet measurement

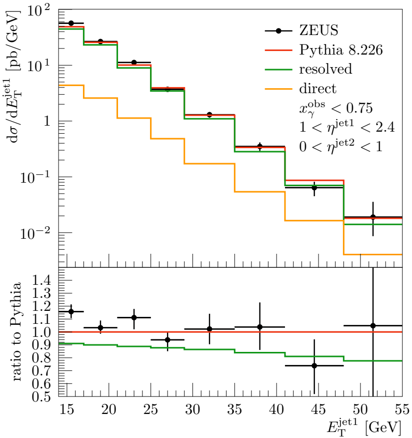
- $Q^2 < 1.0\ \mathrm{GeV}^2$
- $134 < W_{\gamma\mathrm{p}} < 277\ \mathrm{GeV}$
- $E_\mathrm{T}^\mathrm{jet1} > 14\ \mathrm{GeV}$, $E_\mathrm{T}^\mathrm{jet2} > 11\ \mathrm{GeV}$
- $-1 < \eta^{\mathrm{jet1,2}} < 2.4$

Two contributions

- Momentum fraction of partons in photon

$$x_\gamma^\mathrm{obs} = \frac{E_\mathrm{T}^\mathrm{jet1} e^{\eta^\mathrm{jet1}} + E_\mathrm{T}^\mathrm{jet2} e^{\eta^\mathrm{jet2}}}{2yE_\mathrm{e}} \approx x_\gamma$$

- Sensitivity to process type



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

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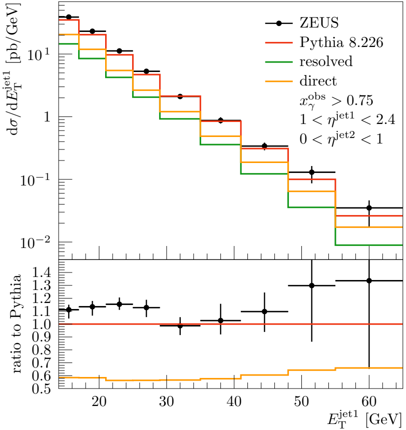
- Sensitivity to process type
- At high-x_γ^{obs} direct processes dominate



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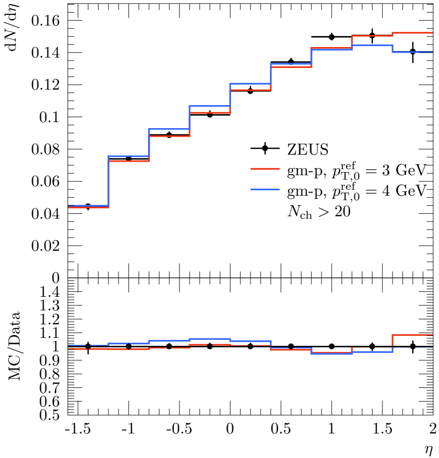
Comparison to ZEUS data for charged hadrons ($N_{\mathrm{ch}} > 20$)

Pseudorapidity

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



[ZEUS: JHEP 12 (2021) 102]

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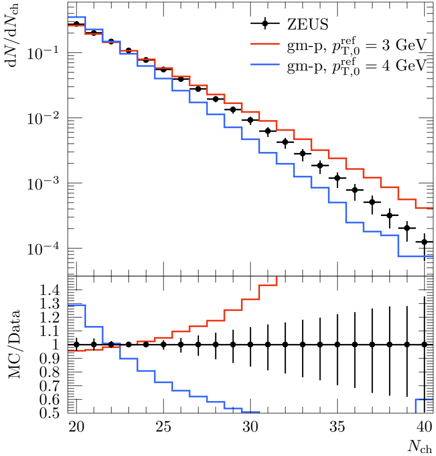
Multiplicity

- Sensitivity to MPI parameters, clear support for MPIs
- Data within $p_{\mathrm{T},0}$ variations
- Good baseline to study γ+A in UPCs



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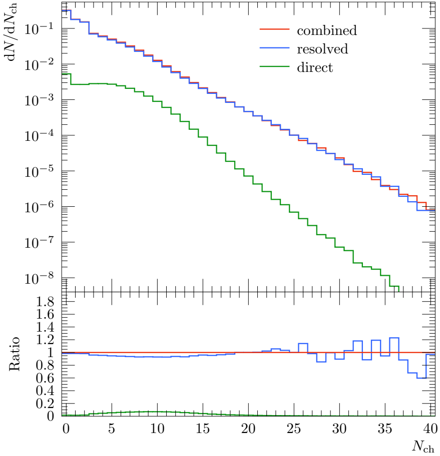
Multiplicity

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

  $\Rightarrow$ Focus on resolved processes



[ZEUS: JHEP 12 (2021) 102]

Photon fluxes in Pythia 8

Photon fluxes from Equivalent Photon Approximation (EPA)

- In case of a point-like lepton we have (neglecting electron mass)

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

- For protons need to include form factors, using dipole form factor

$$f_\gamma^{\mathrm{p}}(x, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{x}{Q^2} \frac{1}{(1 + Q^2/Q_0^2)^4} \left[\frac{2(1+\mu_{\mathrm{p}}\tau)}{1+\tau} \left(\frac{1-x}{x^2} - \frac{M_{\mathrm{p}}^2}{Q^2} \right) + \mu_{\mathrm{p}}^2 \right]$$

where $\tau = Q^2/4M_{\mathrm{p}}^2$, $\mu_{\mathrm{p}} = 2.79$, $Q_0^2 = 0.71\ \mathrm{GeV}^2$

- Drees-Zeppenfeld approximation ($M_{\mathrm{p}} = 0, \mu_{\mathrm{p}} = 1$)

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

$\Rightarrow$ Large Q^2 suppressed wrt. leptons $\Rightarrow$ photoproduction

- In ME generators (such as MG5) integrated over Q^2 and assumed collinear

Define your own photon flux for PYTHIA 8

- Derive a new object from PDF class

```
class Proton2gammaEPA : public PDF {

public:

  // Constructor.
  Proton2gammaEPA(int idBeamIn) : PDF(idBeamIn) {}

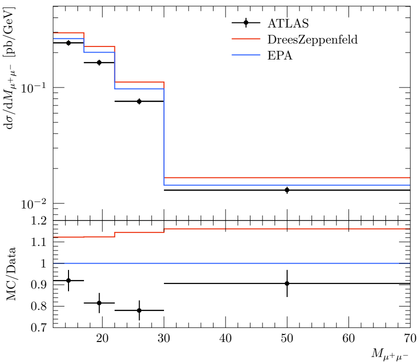
  // Update the photon flux.
  void xfUpdate(int , double x, double Q2) {

    double m2proton = pow2(0.938);
    double mup2 = pow2(2.79);
    double Q20 = 0.71;
    double FQ4 = 1. / pow4( 1 + Q2 / Q20 );
    double coupling = 0.5 * 0.007297353080 / M_PI * FQ4;
    double tau = Q2 / (4. * m2proton);
    xgamma = coupling * ( pow2(x) / Q2 ) * ( 2. * (1. + mup2*tau ) / (1. + tau)
           * ( (1 - x)/pow2(x) - m2proton / Q2 ) + mup2);
  }
};
```

- Pass as a pointer to PYTHIA

```
  pythia.readString("PDF:beamA2gamma = on");
  pythia.readString("PDF:beamB2gamma = on");
  pythia.readString("PDF:proton2gammaSet = 0");
  PDFPtr photonFluxA = make_shared<Proton2gammaEPA>(2212);
  PDFPtr photonFluxB = make_shared<Proton2gammaEPA>(2212);
  pythia.setPhotonFluxPtr(photonFluxA, photonFluxB);
```

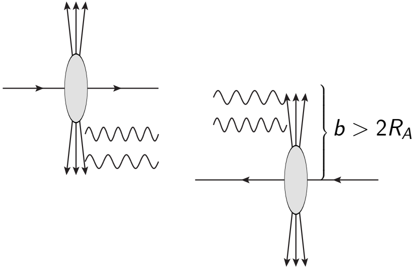
Example in p-p: $\gamma\gamma \rightarrow \mu^+\mu^-$



[ATLAS: PLB 777 (2018) 303-323]

- No finite-size effects accounted

Ultraperipheral heavy-ion collisions



- Large impact parameter ($b \gtrsim 2R_A$)
  $\Rightarrow$ No strong interactions
- Large flux due to large EM charge of nuclei

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

- 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, $Q^2 \ll 1\ \mathrm{GeV}^2$

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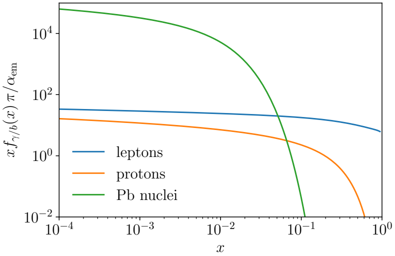

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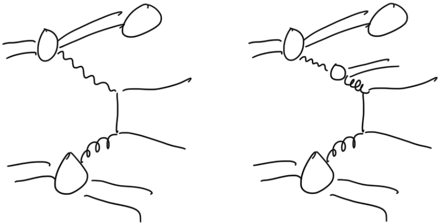
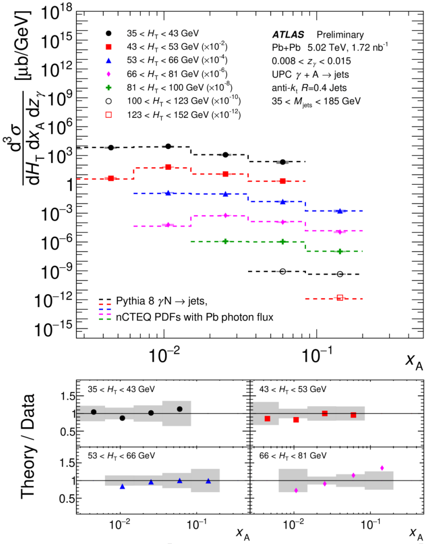
Dijets in ultra-peripheral heavy-ion collisions

- Pythia setup with nucleon target only ⇒ Not a realistic background for jet reconstruction
- Good agreement out of the box when accounting both direct and resolved
- Also EM nuclear break-up significant





[P. Steinberg @ DIS2023]

Photon-ion collisions

Modelling γ-A with Pythia

[by Marius Utheim]

Aim to simulate high-multiplicity events

- Dominated by resolved photons

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

  - Use VM PDFs from SU21

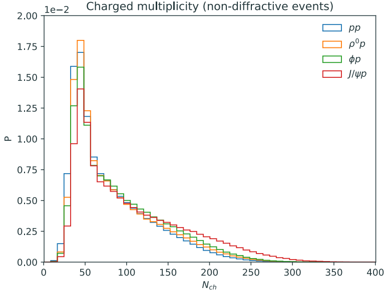
    [Sjöstrand, Utheim; Eur.Phys.J.C 82 (2022) 1, 21]

  - Cross sections from SaS

    [Schuler, Sjöstrand; Phys.Rev.D 49 (1994) 2257-2267]

  - Sample collision energy from flux

⇒ VMD-nucleon scatterings



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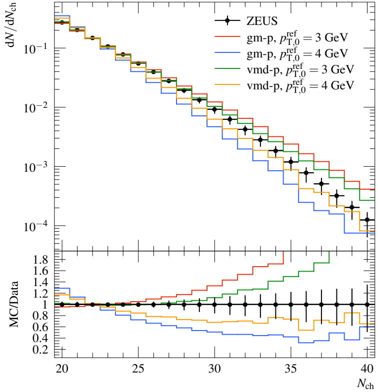
⇒ VMD-nucleon scatterings

  - In line with the full photoproduction



[ZEUS: JHEP 12 (2021) 102]

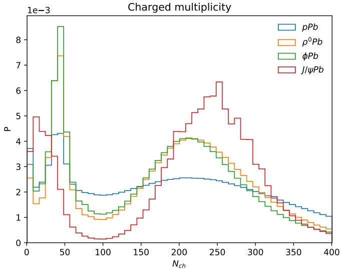
Modelling γ-A with Pythia [by Marius Utheim]

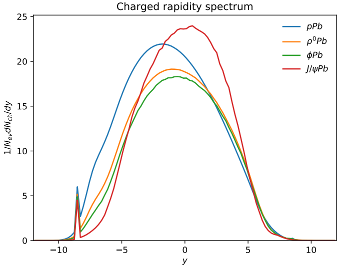
Angantyr model for heavy ions in Pythia

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

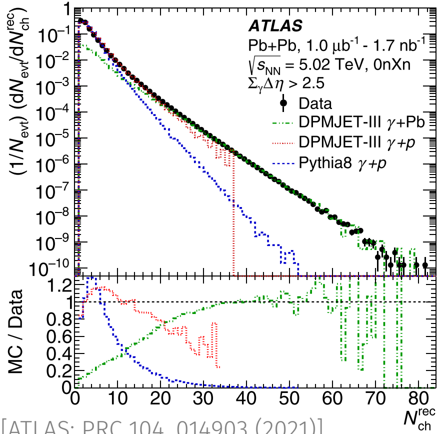
- Monte Carlo Glauber to sample nucleon configurations
- Cross section fluctuations, fitted to partial nucleon-nucleon cross sections
- Secondary (wounded) collisions as diffractive excitations
- Can now handle generic hadron-ion and varying energy [I.H., Utheim; in progress]

⇒ VMD-nucleus scatterings

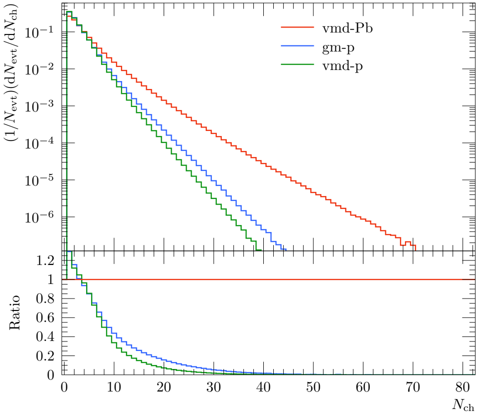

Charged multiplicity


Charged rapidity spectrum

Comparison with data for γ+A (preliminary)



[ATLAS: PRC 104, 014903 (2021)]



- 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

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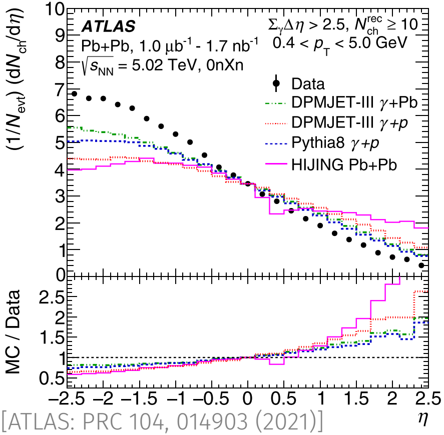

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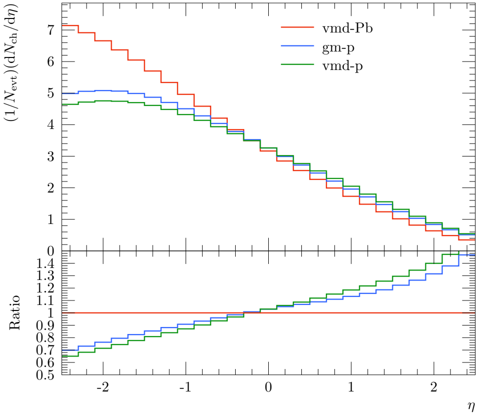


- Multiplicity cut adjusted according to the limited efficiency
- Good description of the measured rapidity distribution with the VMD-Pb setup

Two-particle correlations in ATLAS analysis

- ATLAS apply template-fitting method to extract v_n from two-particle correlations
  - Perform a Fourier fit to obtain c_n's for low-multiplicity events (nonflow?)

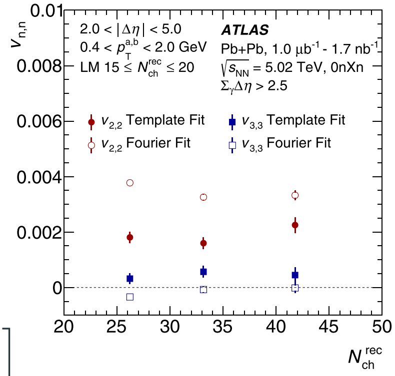
$$Y^{\mathrm{LM}}(\Delta\phi) = c_0 + 2 \cdot \sum_{n=1}^{4} c_n \cos(n\Delta\phi)$$

  - Fit high multiplicity $v_{n,n}$'s on top

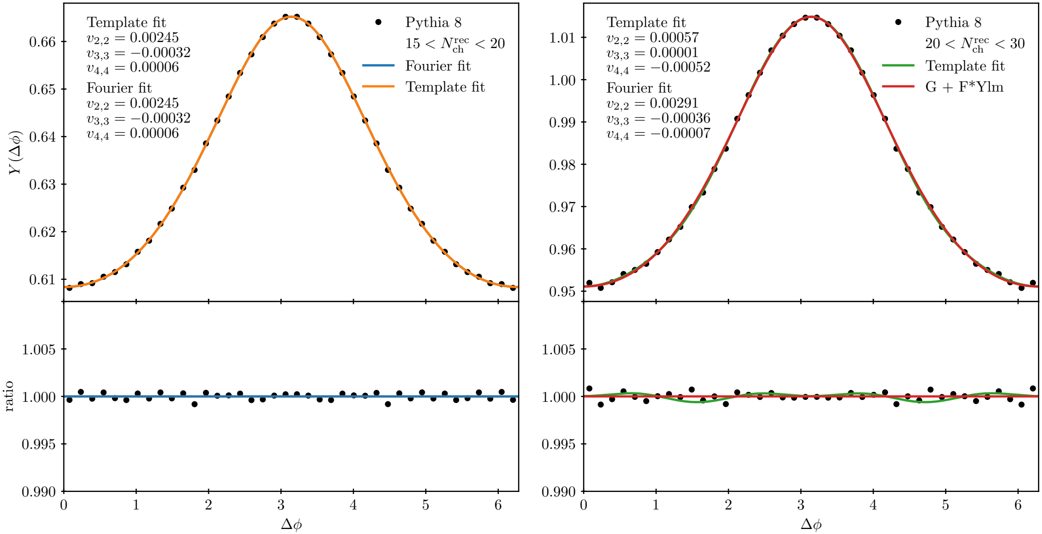
$$Y^{\mathrm{HM}}(\Delta\phi) = F \cdot Y^{\mathrm{LM}}(\Delta\phi) + G \left[1 + 2 \cdot \sum_{n=2}^{4} v_{n,n} \cos(n\Delta\phi)\right]$$

Free parameters c_n, $v_{n,n}$, F, G

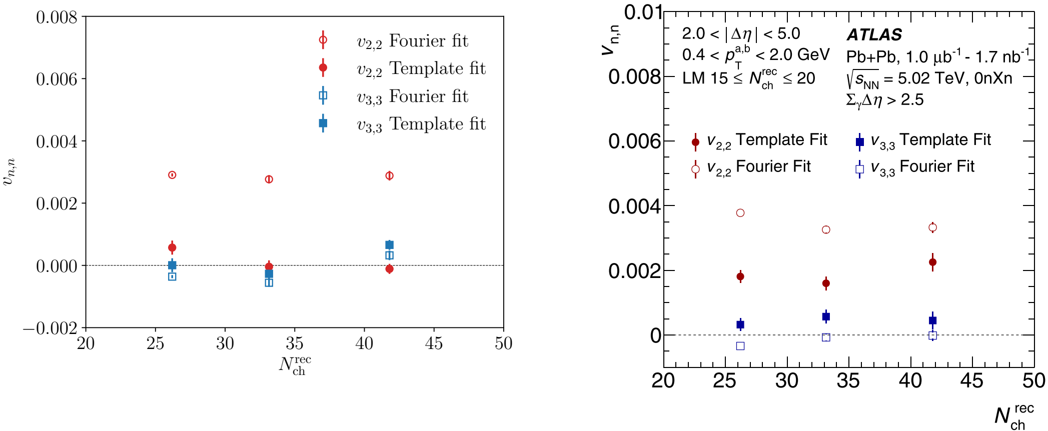
- Can now repeat the fit with Pythia results



Template fit to Pythia simulations



Comparison to ATLAS v_n data



- Simulated results in line with the direct Fourier fit for $v_{2,2}$
- Consistent with zero after template fitting (non-flow subraction)
- String interactions in high-multiplicity hadronization, hadronic rescattering?

Summary & Outlook

Summary

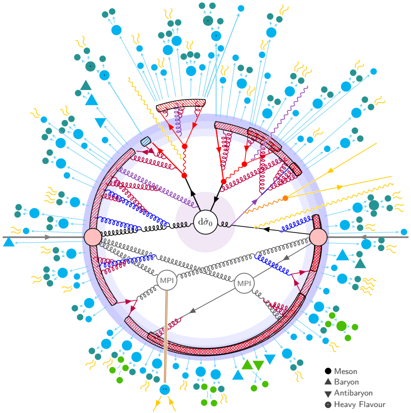
- In e+p validated setup for photoproduction at HERA
- Includes fluxes relevant for proton and heavy-ion UPCs
- First steps for full γ+A (8.311)

⇒ In line with multiplicity distributions

⇒ As such not consistent with finite v_2

Outlook

- Include full photon structure
- Study different string-interaction effects for high-multiplicity events

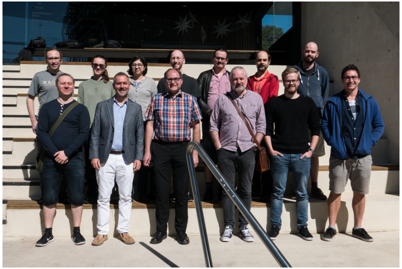


[figure by P. Skands]

Backup slides

PYTHIA Collaboration

- 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 (ETH Zurich)
- Torbjörn Sjöstrand (Lund University)
- Peter Skands (Monash University)
- Marius Utheim (University of Jyväskylä)
- Rob Verheyen (University College London)



[Pythia meeting in Monash 2019]

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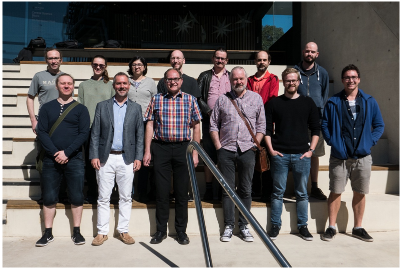


[Pythia meeting in Monash 2019]

- Spokesperson
- Codemaster
- Webmaster

`https://pythia.org`

`authors@pythia.org`

Evolution equation and PDFs for resolved photons

DGLAP equation for photons

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

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

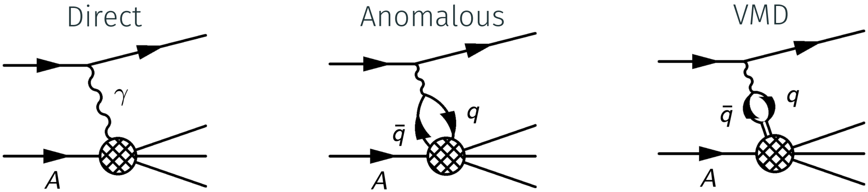
where $P_{i\gamma}(x) = 3\,(x^2 + (1-x)^2)$ for quarks, 0 for gluons (LO)

- 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

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



Direct

Anomalous

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

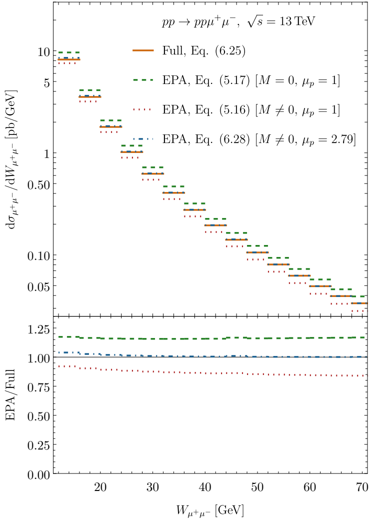
$$c_V = \frac{4\pi\alpha_{\mathrm{EM}}}{f_V^2}$$

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

Equivalent photon approximation

Compare to full calculation

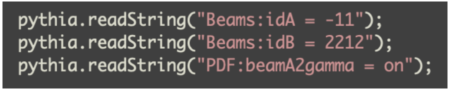
- Example process $pp \rightarrow \gamma\gamma \rightarrow \mu^+\mu^-$
- Different approximations (e.g.) by Drees and Zeppenfeld $\sim$ 20% difference to full calculation
- Keeping finite mass and correct magnetic moment provides $\sim$ few percent accuracy
- Not checked for other observables, such as acoplanarity



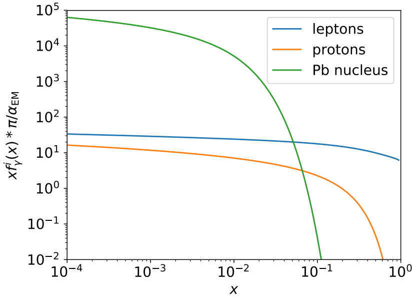
[S. Yrjänheikki, MSc thesis]

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");
```



Photon fluxes in PYTHIA 8

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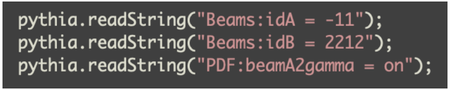

```
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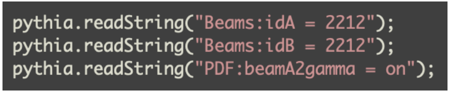
```

- Enable γ+p in p+p



```
pythia.readString("Beams:idA = 2212");
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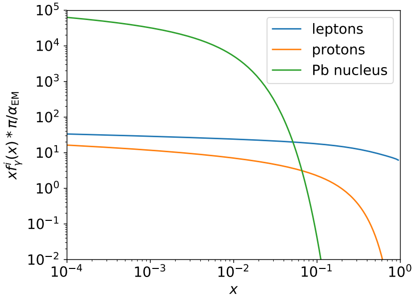
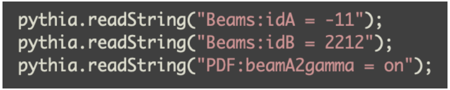


Photon fluxes in PYTHIA 8

- Enable γ+p in e+p



```
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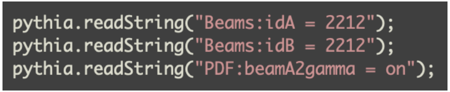
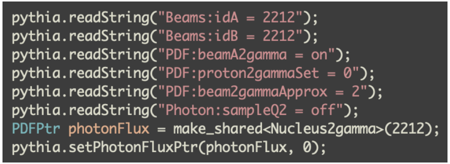
pythia.readString("PDF:beamA2gamma = on");
```

- Enable γ+p in p+p

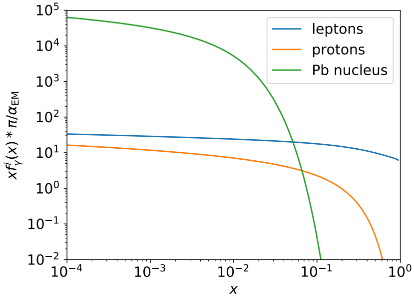


```
pythia.readString("Beams:idA = 2212");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
```

- Enable γ+p in Pb+p



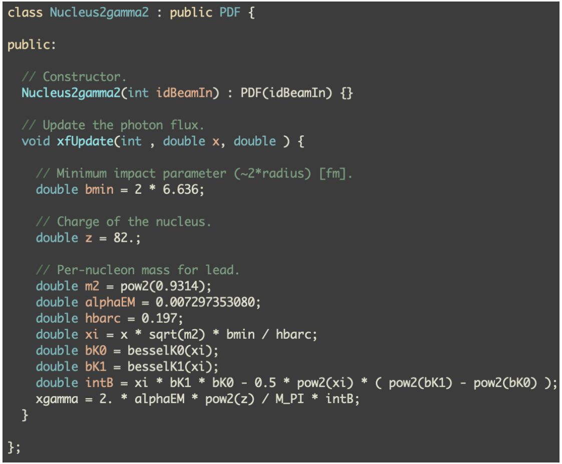
```
pythia.readString("Beams:idA = 2212");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
pythia.readString("PDF:proton2gammaSet = 0");
pythia.readString("PDF:beam2gammaApprox = 2");
pythia.readString("Photon:sampleQ2 = off");
PDFPtr photonFlux = make_shared<Nucleus2gamma>(2212);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

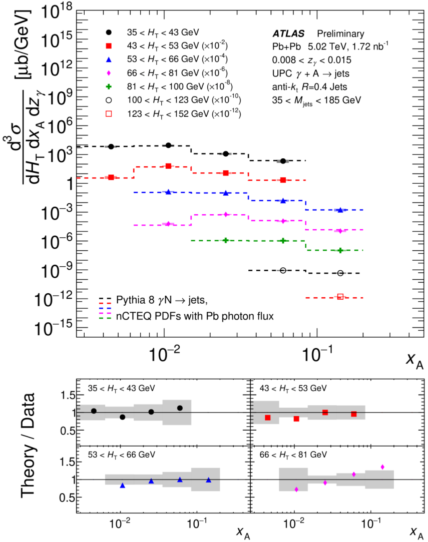
    // Minimum impact parameter (~2*radius) [fm].
    double bmin = 2 * 6.636;

    // 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`]



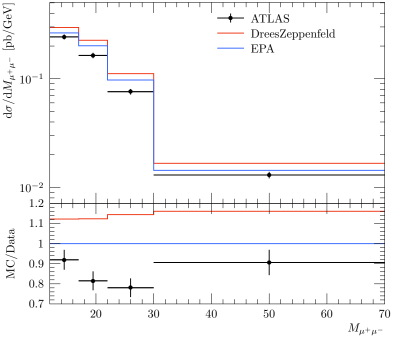
[P. Steinberg @ DIS2023]

An example process: $\gamma\gamma \rightarrow \mu^+\mu^-$

- Can take place in EE, SD and DD (also DY processes with resolved photons?)
- Implemented natively in Pythia, can also generate with an ME generator (MG5, SC)

EE contribution

- Clean process to study fluxes
- However, fluxes only does not account for finite-size effects



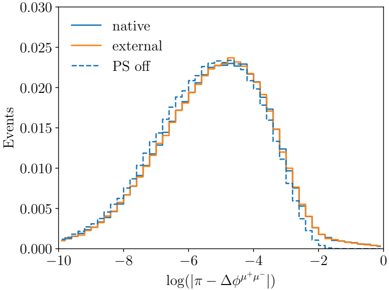
[ATLAS: PLB 777 (2018) 303-323]

An example process: $\gamma\gamma \to \mu^+\mu^-$

- Can take place in EE, SD and DD (also DY processes with resolved photons?)
- Implemented natively in Pythia, can also generate with an ME generator (MG5, SC)

EE contribution

- Clean process to study fluxes
- However, fluxes only does not account for finite-size effects
- Not quite back-to-back due to
  - p_T generated by non-collinear photons
  - QED radiation in the final state
- Acoplanarity $|\pi - \Delta\phi|$ quantify the effect



- Needed to tune Pythia primordial k_T parameters for external events
- Can use (user-defined) flux for Q^2 sampling

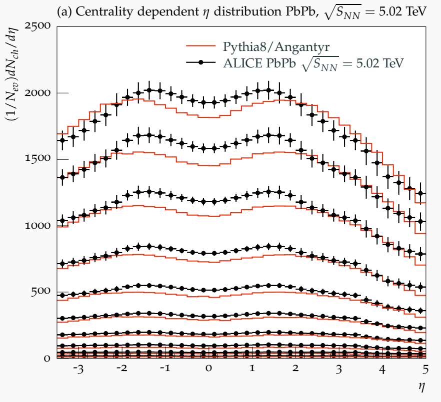
Heavy-ion collisions

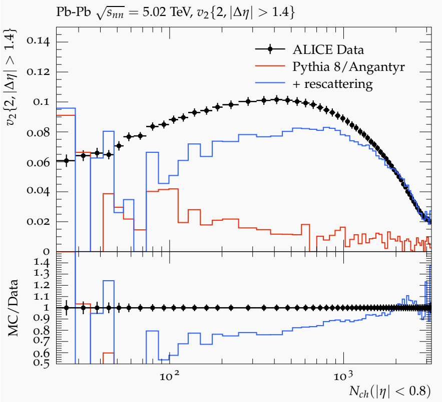
- Angantyr in Pythia provides a full heavy-ion collisions framework

[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]

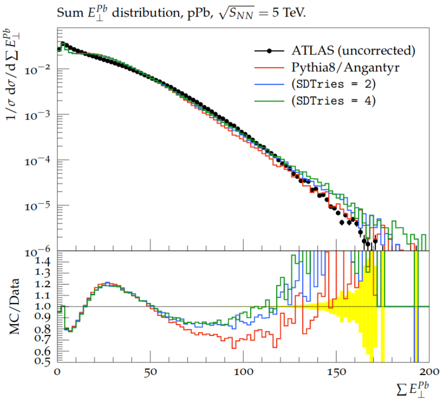


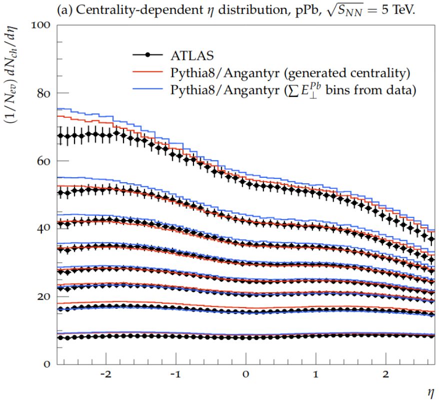


p+*A* collisions

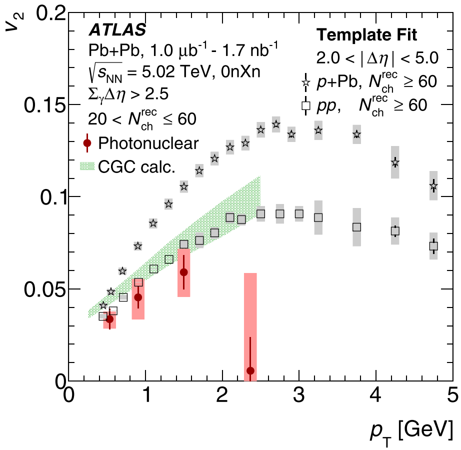
[Bierlich, Gustafson, Lönnblad & Shah: 1806.10820]

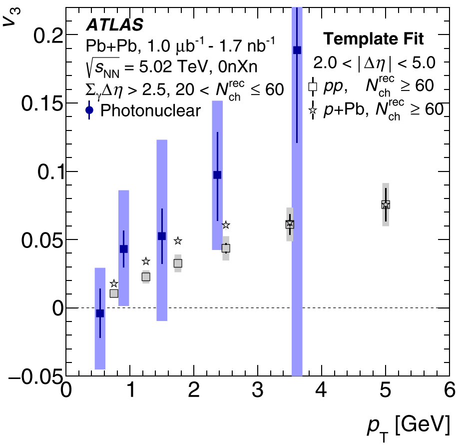
- Angantyr can be applied also to asymmetric p+*A* collisions
- The centrality measure well reproduced
- Similarly centraility-dependent multiplicities


Sum $E_\perp^{Pb}$ distribution, pPb, $\sqrt{S_{NN}} = 5$ TeV.


(a) Centrality-dependent η distribution, pPb, $\sqrt{S_{NN}} = 5$ TeV.

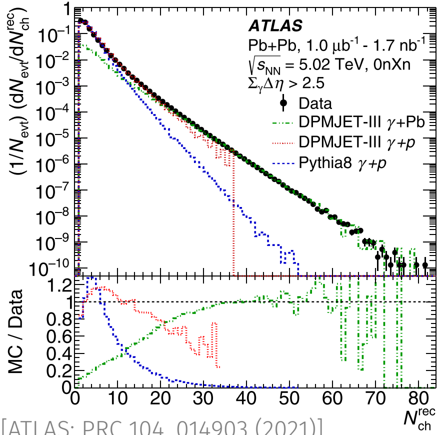
ATLAS data for v_n in γ+Pb



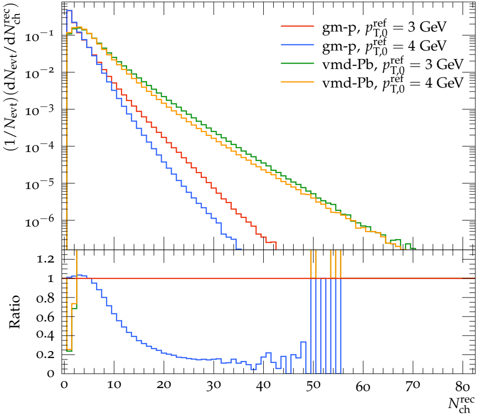


- Non-zero flow coefficients also for γ+Pb
- Expected baseline from MC simulations?

Comparison with data for γ+A (preliminary)

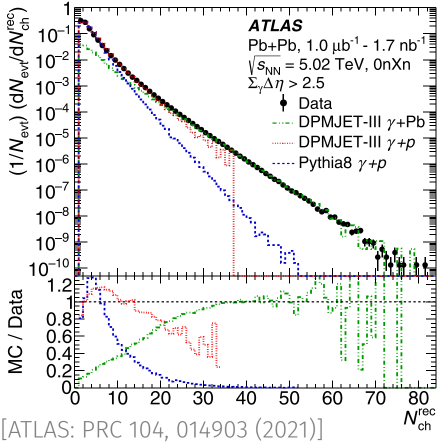


[ATLAS: PRC 104, 014903 (2021)]



- 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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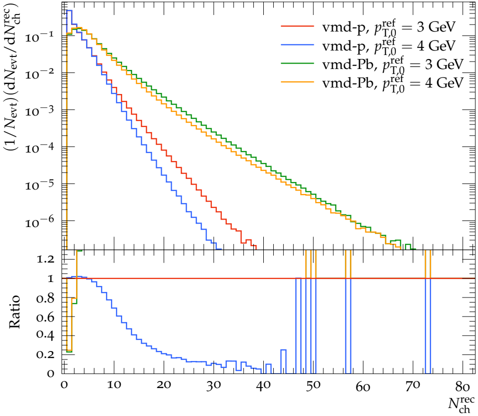

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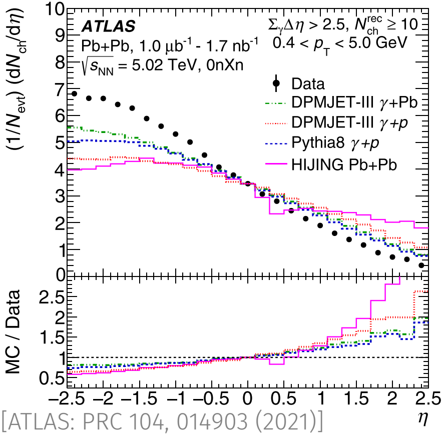
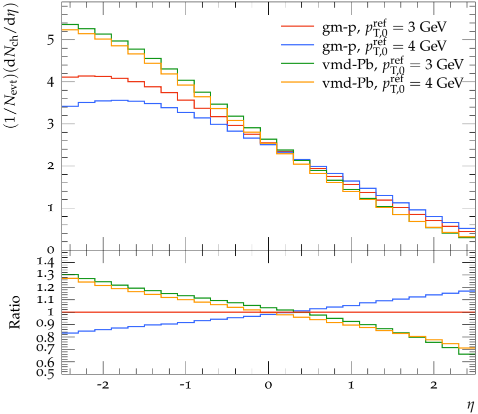
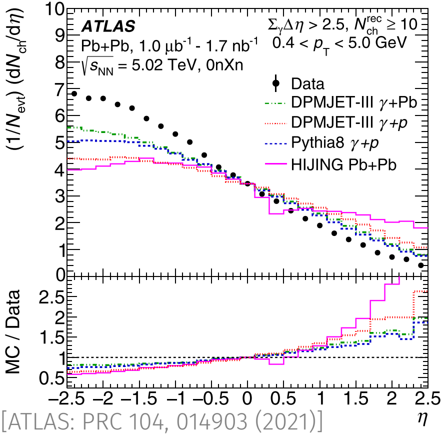


[ATLAS: PRC 104, 014903 (2021)]



- 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

Comparison with data for γ+A (preliminary)



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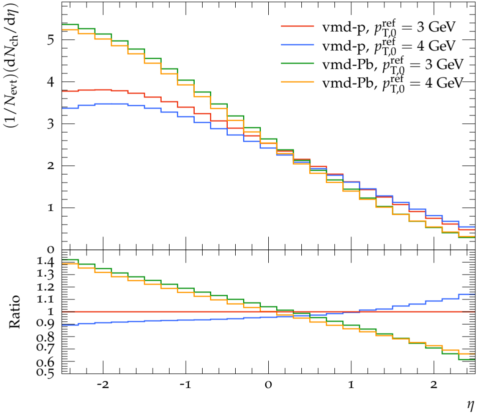

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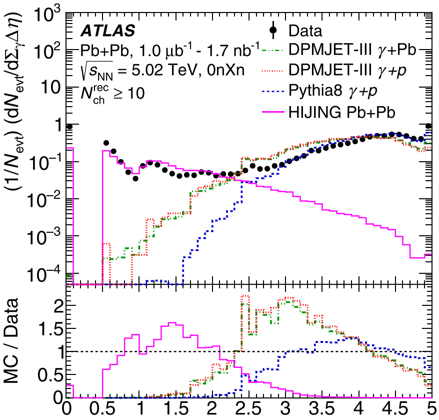

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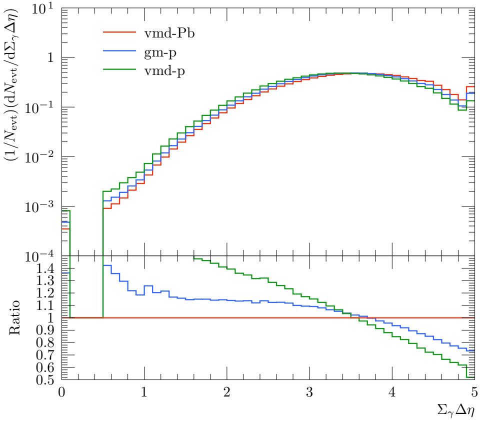
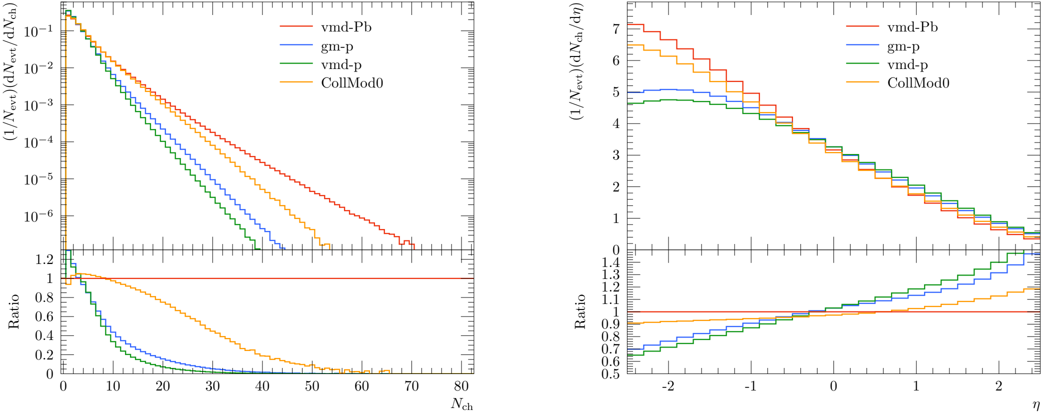


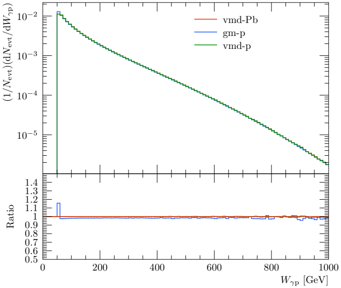
- $\Sigma_\gamma \Delta\eta$: Sum of rapidity gaps for which $\Delta\eta > 0.5$
- Similar for γ-p and γ-Pb

Role of cross section fluctuations

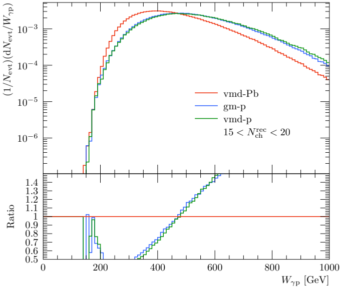


- High-multiplicity tail less pronounced with `Angantyr:CollisionModel = 0` with fixed nucleon radius, ATLAS data seem to favour fluctuations

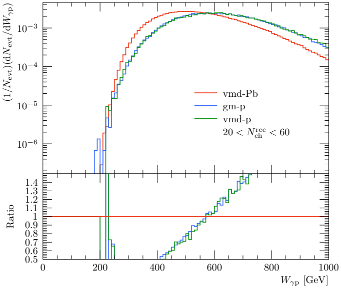
Energy distributions vs. multiplicity



$\langle W_{\gamma\mathrm{Pb}} \rangle \approx 150$



$\langle W_{\gamma\mathrm{Pb}} \rangle \approx 470$



$\langle W_{\gamma\mathrm{Pb}} \rangle \approx 570$