Photoproduction and Ultraperipheral collisions in Pythia 8

Oxford theory seminar

Ilkka Helenius

May 2nd, 2024

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Research Council of Finland

Centre of Excellence in Quark Matter

Outline

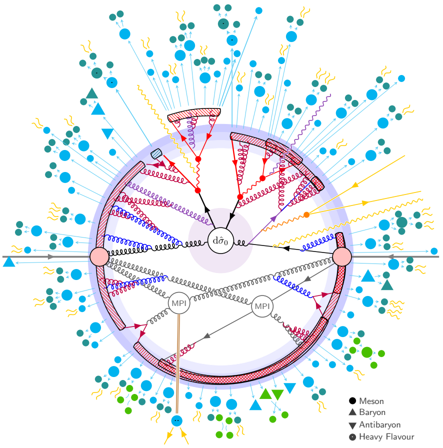
Pythia 8: A general purpose event generator

- Latest release 8.311 (March 2024)
- A new physics manual for 8.3

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

Outline

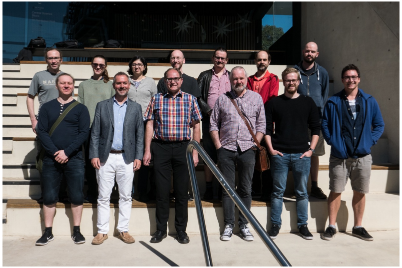
1. Pythia 8 basics
2. Structure of real photons
3. Photoproduction in e+p
4. Ultraperipheral collisions (UPCs)
5. Summary & Outlook



[figure by 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/Oxford)
- Marius Utheim (University of Jyväskylä)
- Rob Verheyen (University College London)



[Pythia meeting in Monash 2019]

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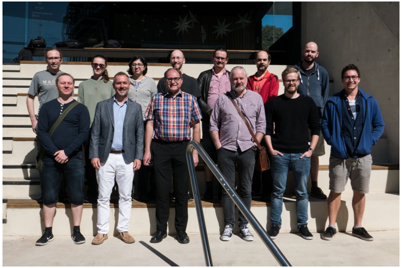


[Pythia meeting in Monash 2019]

- Spokesperson
- Codemaster
- Webmaster

`https://pythia.org`

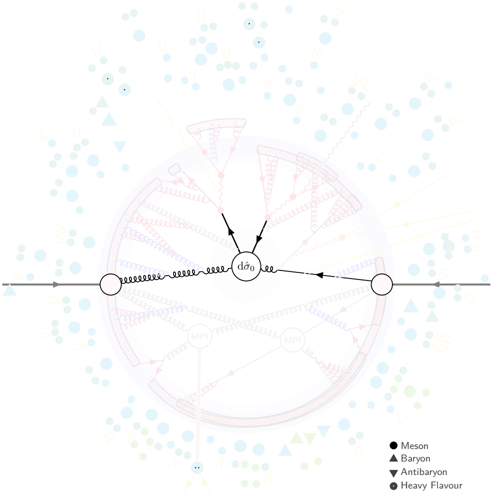
`authors@pythia.org`

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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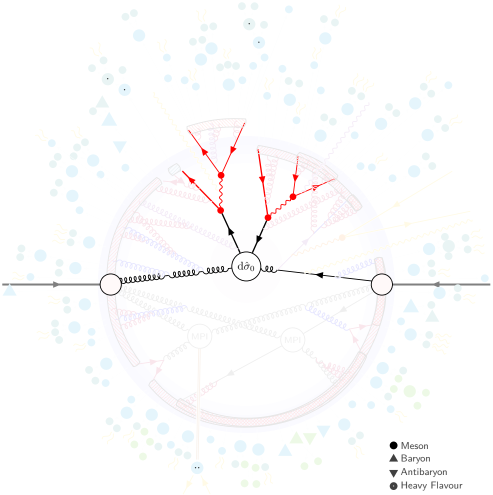

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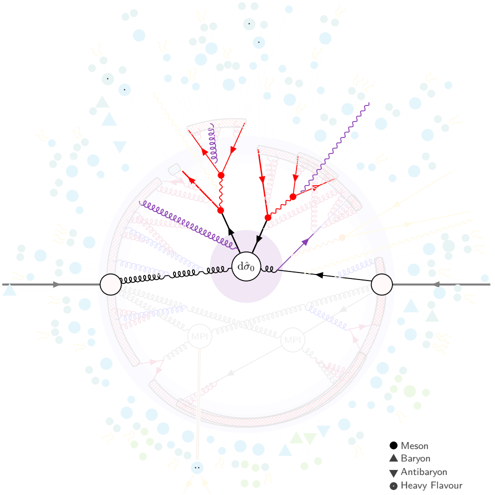
3. Matching, Merging and matrix-element corrections



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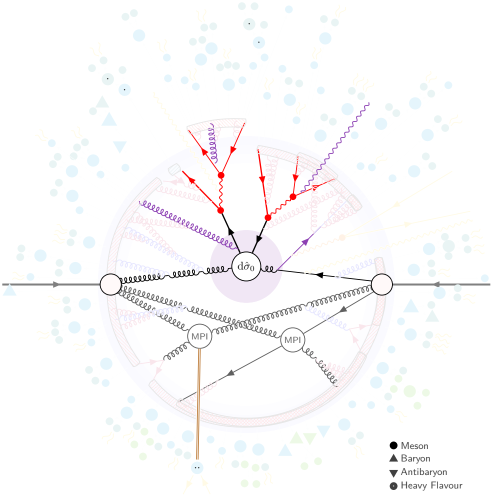

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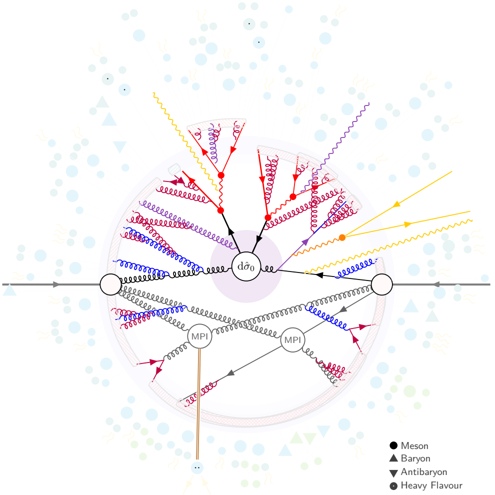

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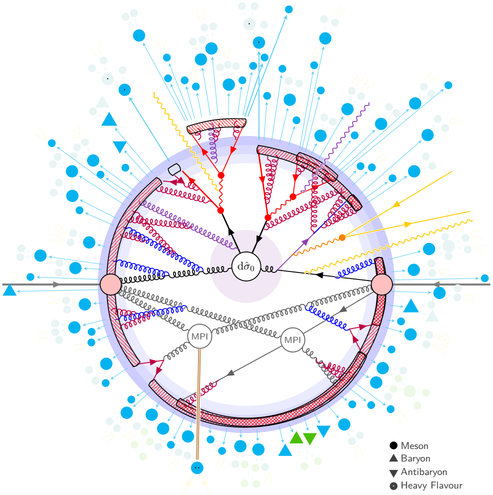

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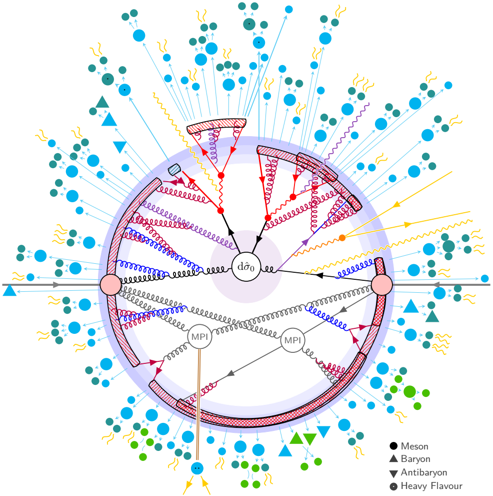
6. Hadronization, Beam remnants
7. Decays, Rescattering



Structure of real photons

Electron-proton collisions

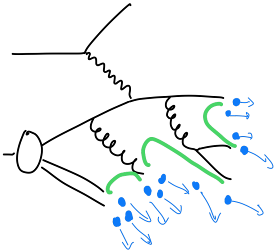
Classified in terms photon virtuality Q^2

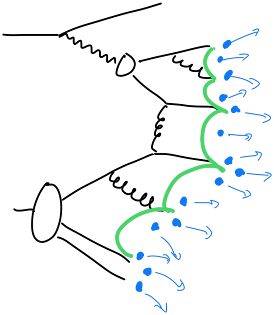
Deep inelastic scattering (DIS)

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

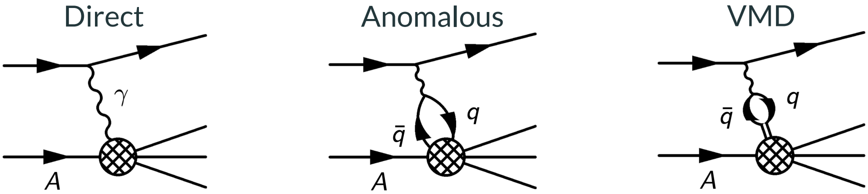
Photoproduction (PhP)

- Low virtuality, $Q^2 \rightarrow 0$ GeV^2
- Factorize photon flux, evolve γp system
- 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

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

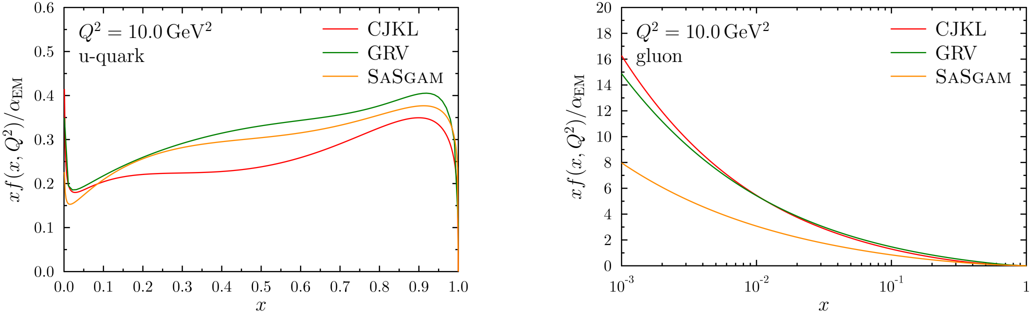
PDFs for resolved photons

DGLAP equation for photons

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

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

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



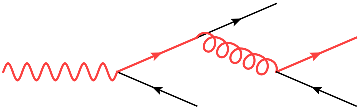
Evolution equation and ISR for resolved photons

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 (anomalous) part of the PDFs
  - No further ISR or MPIs below the scale of the splitting
  - Implemented for the default Simple Shower in Pythia 8



Multiparton interactions (MPIs) with resolved photons

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

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

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

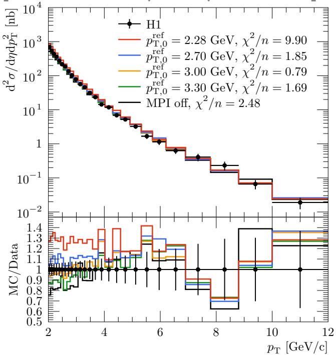
- Partonic cross section diverges at $p_{\mathrm{T}} \rightarrow 0$

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

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

- Energy-dependent parametrization:
  $p_{\mathrm{T0}}(\sqrt{s}) = p_{\mathrm{T0}}^{\mathrm{ref}}(\sqrt{s}/\sqrt{s_{\mathrm{ref}}})^{\alpha}$
- Number of interactions: $\langle n \rangle = \sigma_{\mathrm{int}}(p_{\mathrm{T0}})/\sigma_{\mathrm{nd}}$

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



- Use H1 data to (re-)tune parameter(s)
- $\langle W_{\gamma\mathrm{p}} \rangle \approx 200$ GeV

Photoproduction in e+p

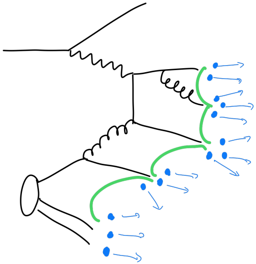
Photoproduction in electron-proton collisions

Direct processes

- Convolute photon flux f_γ with proton PDFs f_i^{p} and $\mathrm{d}\hat{\sigma}$

$$\mathrm{d}\sigma^{\mathrm{ep}\to kl+X} = f_\gamma^{\mathrm{e}}(x, Q^2) \otimes f_j^{\mathrm{p}}(x_{\mathrm{p}}, \mu^2) \otimes \mathrm{d}\hat{\sigma}^{\gamma j\to kl}$$

- Generate FSR and ISR for proton side

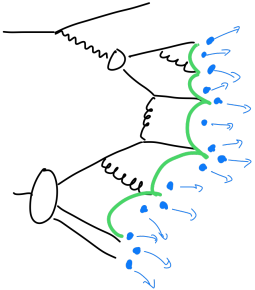


Resolved processes

- Convolute also with photon PDFs

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

- Sample x and Q^2, setup γp sub-system with $W_{\gamma\mathrm{p}}$
- Evolve γp as any hadronic collision (including MPIs)



Photon flux from EPA

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

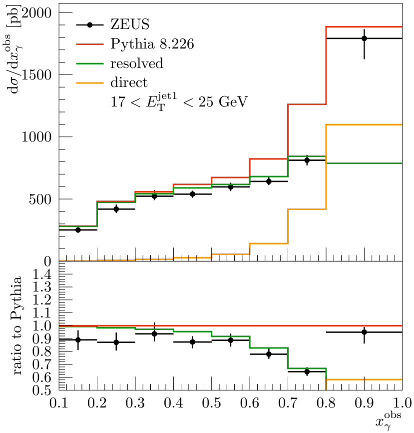
Comparison to HERA dijet photoproduction data

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



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

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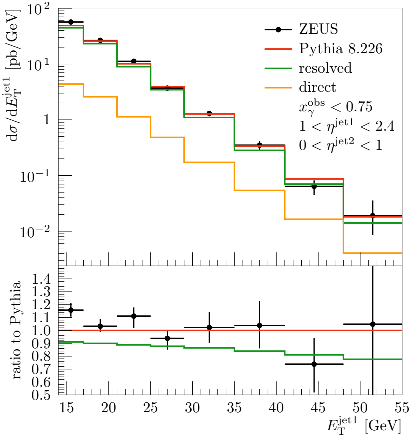

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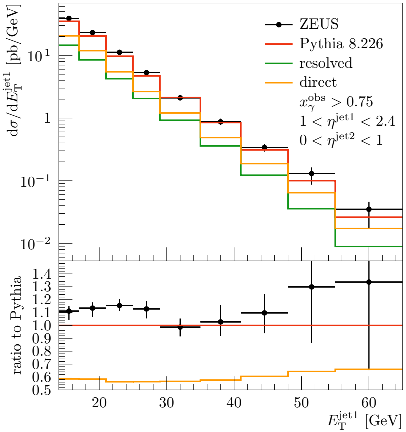

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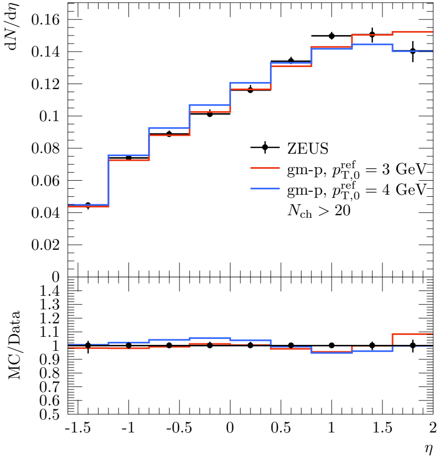
Comparison to ZEUS data for charged hadrons ($N_{ch} > 20$)

Pseudorapidity

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



[ZEUS: JHEP 12 (2021) 102]

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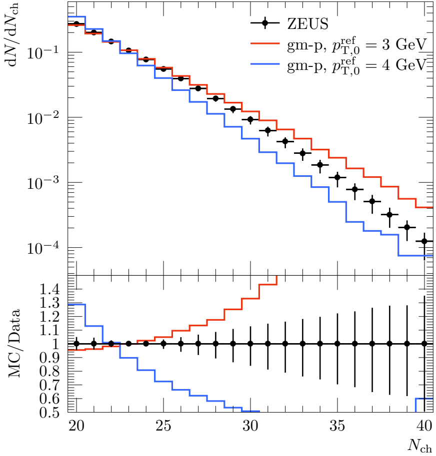
Multiplicity

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



[ZEUS: JHEP 12 (2021) 102]

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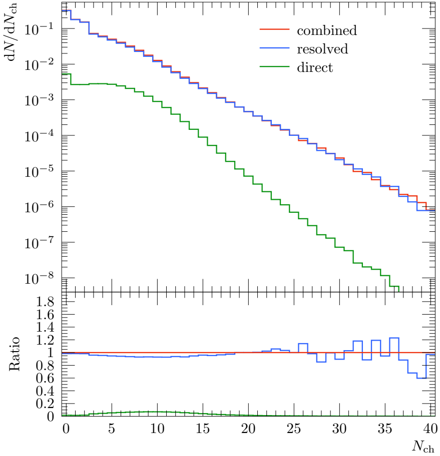
Multiplicity

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



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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

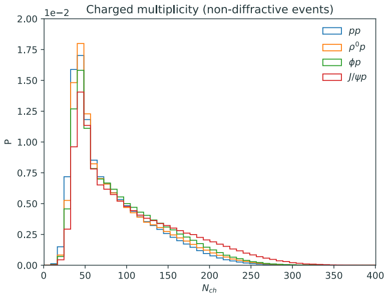
    [Sjöstrand, Utheim; EPJC 82 (2022) 1, 21]

  - Cross sections from SaS

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

  - Sample collision energy from flux

⇒ Vector meson-proton scatterings



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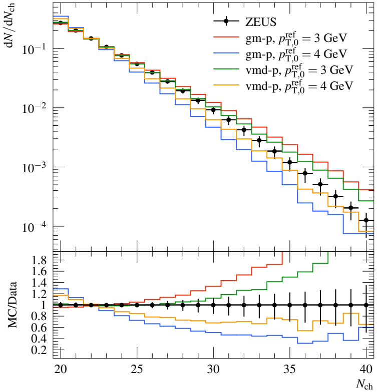
⇒ Vector meson-proton scatterings

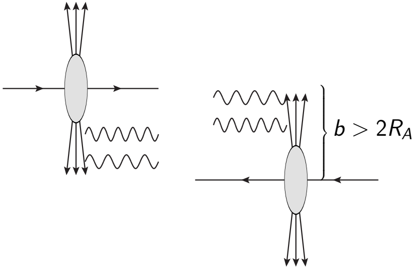
  - In line with the full photoproduction



[ZEUS: JHEP 12 (2021) 102]

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

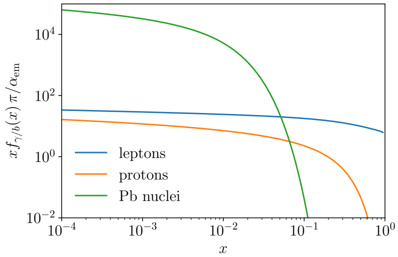
- Define flux in impact-parameter space $\Rightarrow$ Reject hadronic interactions with $b_{\min}$
- Integrating the point-like approximation we get

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

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

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

Ultraperipheral heavy-ion collisions



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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

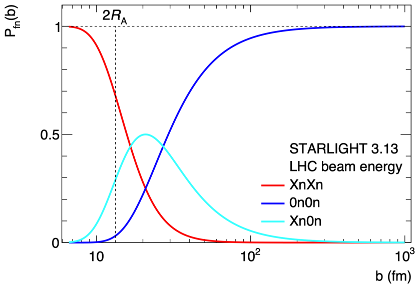
$\Rightarrow$ *A*+*A* (hadronic interaction)

Xn0n: At least one neutron only on one side

$\Rightarrow \gamma$+*A*

0n0n: No neutrons on either side

$\Rightarrow \gamma+\gamma$



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

Possible caveats

- Additional EM interactions may break up the nuclei in "near-encounter" events
- 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]

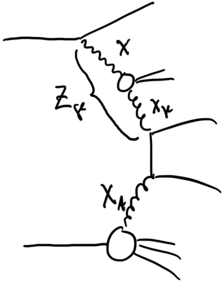
Dijets in ultra-peripheral heavy-ion collisions in Xn0n

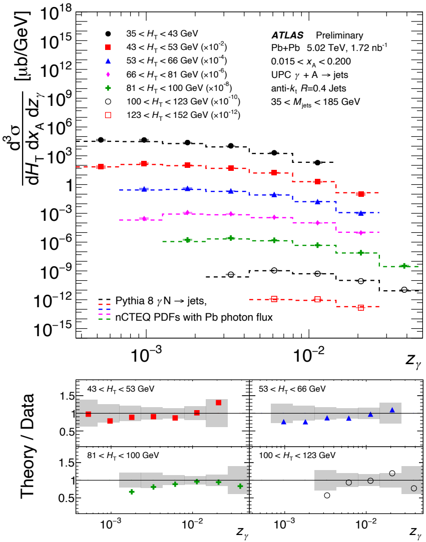
- Good agreement out of the box when accounting both direct and resolved
- EM nuclear break-up significant
- Pythia setup with nucleon target only
  $\Rightarrow$ Is such a setup enough for γ+A?

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

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

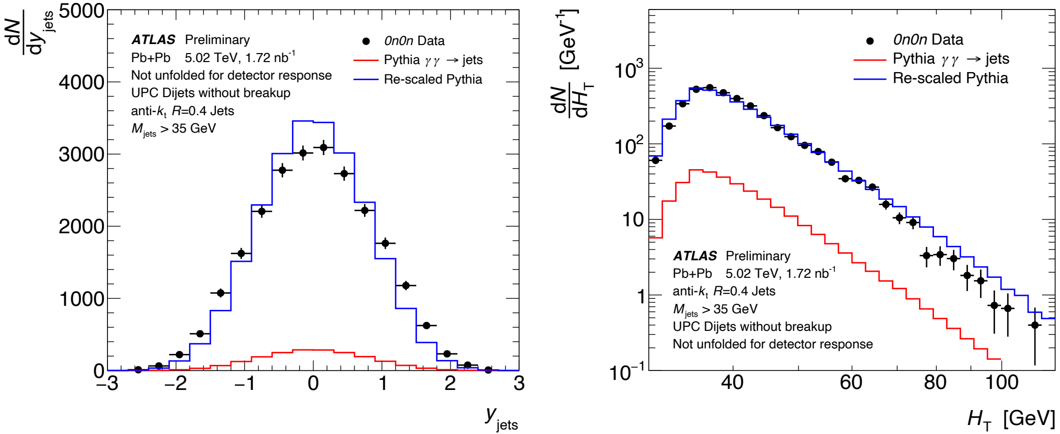
$$x_A = \frac{M_{\mathrm{jets}}}{\sqrt{s_{\mathrm{NN}}}} e^{-y_{\mathrm{jets}}}$$





See also [Eskola, Guzey, IH, Paakkinen, Paukkunen; arXiv:2404.09731] [ATLAS-CONF-2022-021]

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

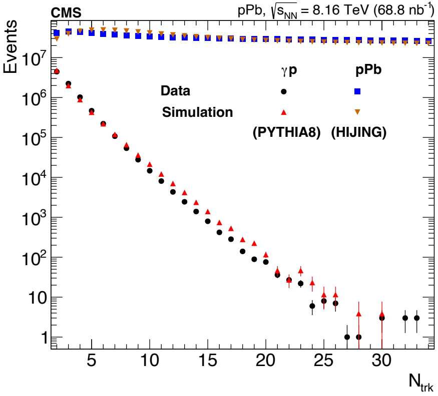


[ATLAS-CONF-2022-021]

- 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?

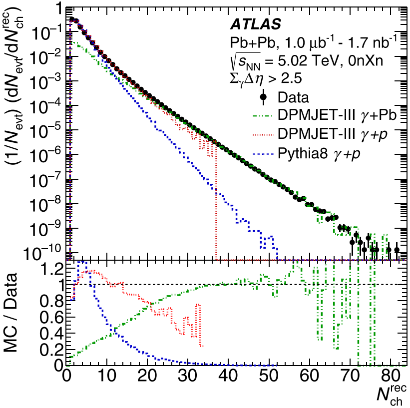
Multiplicity distributions in UPCs

γ+p: [CMS: Murillo Quijada, QM2022]



- Multiplicity distribution well reproduced in γ+p interactions

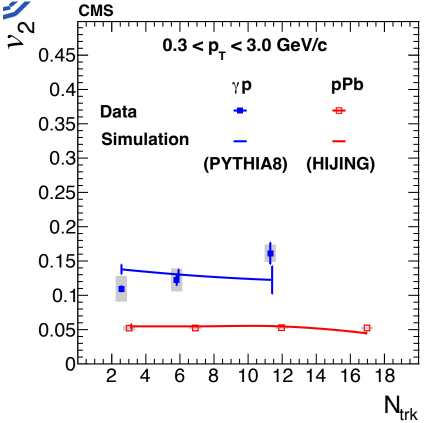
γ+Pb: [ATLAS: PRC 104, 014903 (2021)]



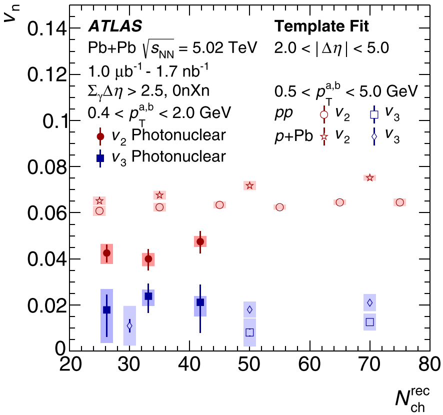
- High multiplicities missed with γ+p
  $\Rightarrow$ Multi-nucleon interactions

Collectivity in UPCs at the LHC

γ+p [CMS: Murillo Quijada, QM2022]



γ+Pb [ATLAS: PRC 104, 014903 (2021)]



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

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

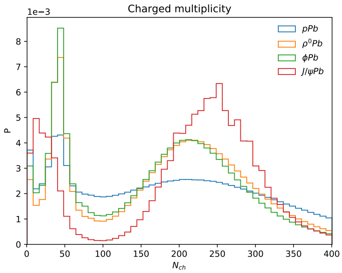
Modelling γ+A with Pythia [with Marius Utheim]

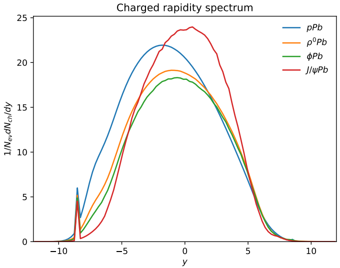
Angantyr model for heavy ions in Pythia

[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]

$\Rightarrow$ VMD-nucleus scatterings





Modelling γ+A with Pythia [with Marius Utheim]

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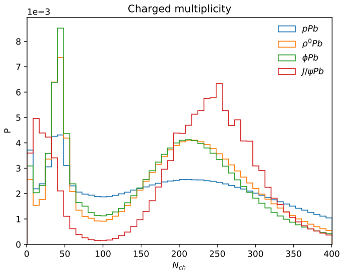
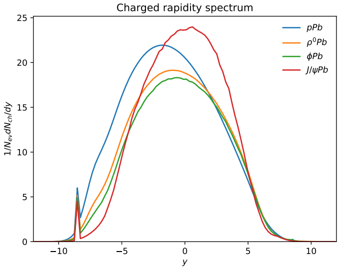
- Cross section fluctuations, fitted to partial nucleon-nucleon cross sections
- Secondary (wounded) collisions as diffractive excitations
- Can now handle generic hadron-ion and varying energy [I.H., Utheim; in progress]

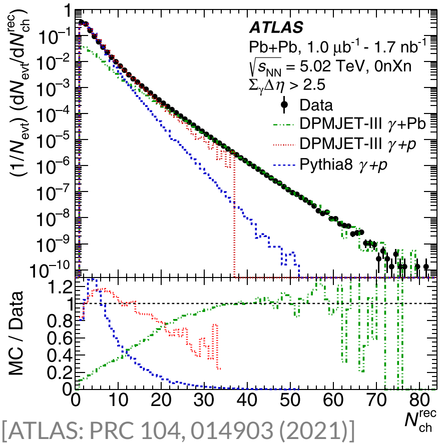
⇒ VMD-nucleus scatterings

⇒ Hadronic cascades from cosmic rays

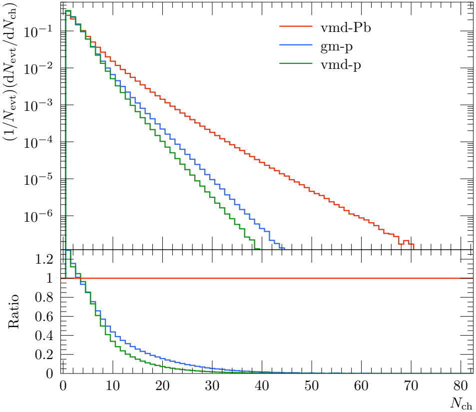




Comparison with data for γ+A

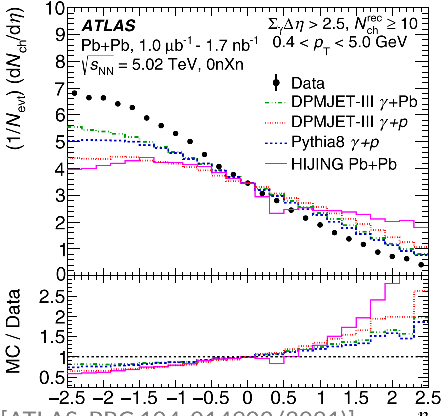


[ATLAS: PRC 104, 014903 (2021)]

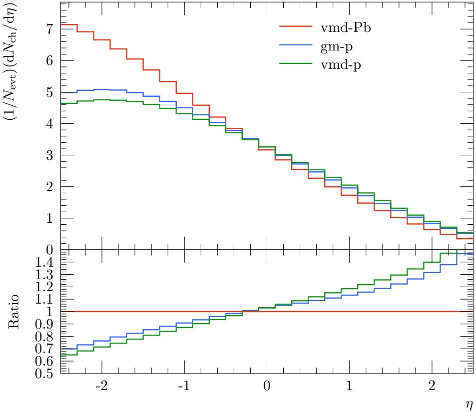


- ATLAS data not corrected for efficiency, estimated with $N_{ch}^{rec} \approx 0.8 \cdot N_{ch}$
- Relative increase in multiplicity well in line with the VMD-Pb setup

Comparison with data for γ+A



[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

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 (non-flow?)

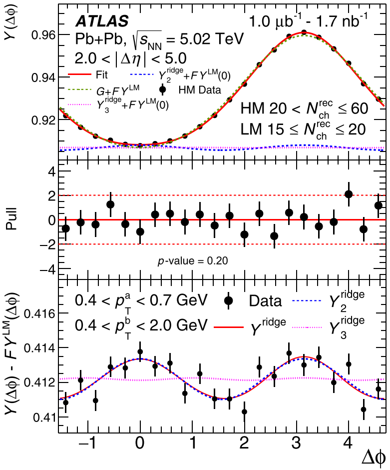
$$Y^{\mathrm{LM}}(\Delta\phi) = c_0 + 2\cdot\sum_{n=1}^{4} c_n \cos(n\Delta\phi)$$

  - 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

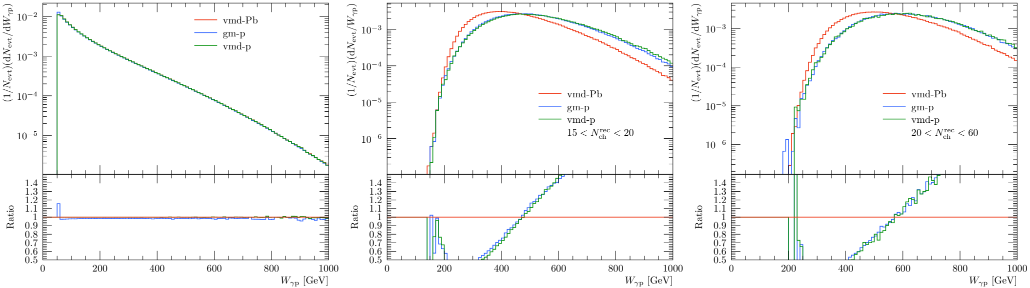


[ATLAS: PRC 104, 014903 (2021)]

Invariant mass distribution vs. multiplicity

Event multiplicity increases with the collision energy

⇒ Multiplicity binning will bias W distribution

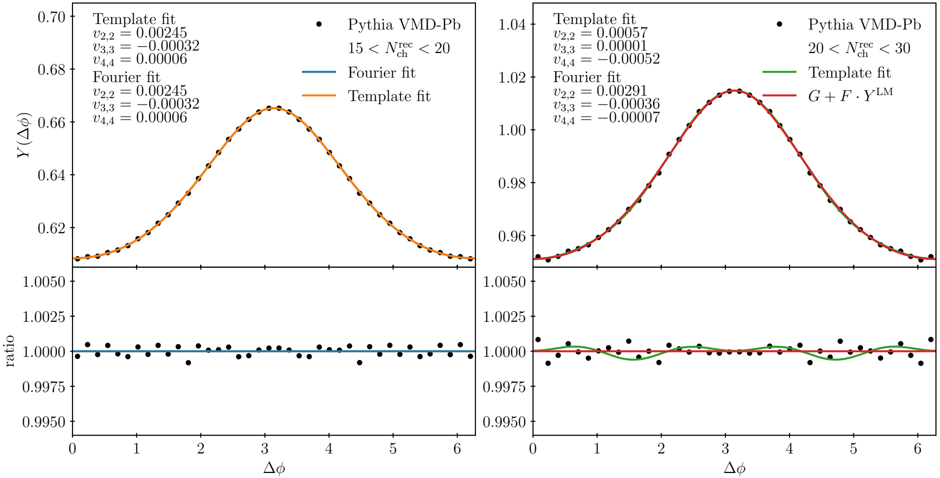


$\langle W_{\gamma Pb} \rangle \approx 150$ GeV $\langle W_{\gamma Pb} \rangle \approx 470$ GeV $\langle W_{\gamma Pb} \rangle \approx 570$ GeV

⇒ Low- and high-multiplicity event samples have different $\langle W \rangle$

⇒ Is the non-flow subtraction still meaningful?

Template fit to Pythia simulations

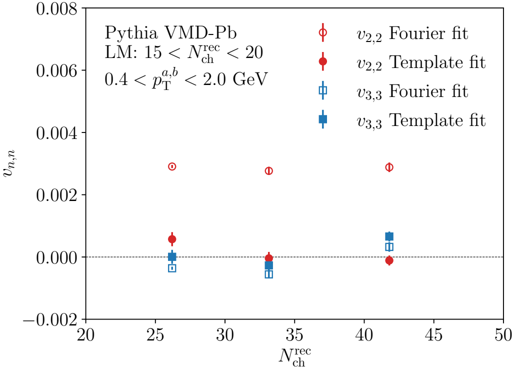


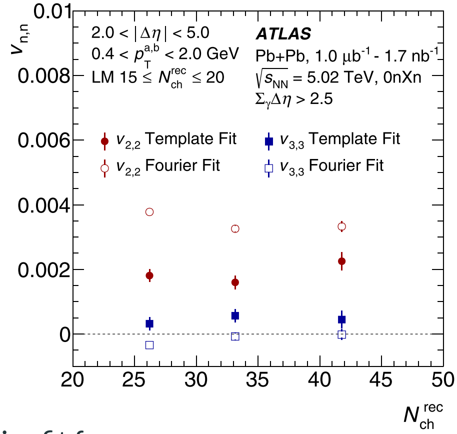
- No significant additional modulation in high-multiplicity events

Template fit = comined LM & HM fit

Fourier fit = direct F-fit separately to LM & HM samples

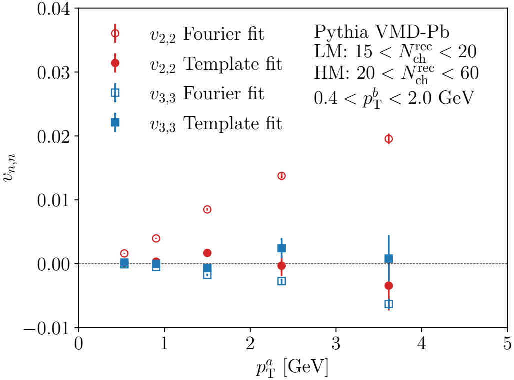
Comparison to ATLAS $v_{n,n}$ data

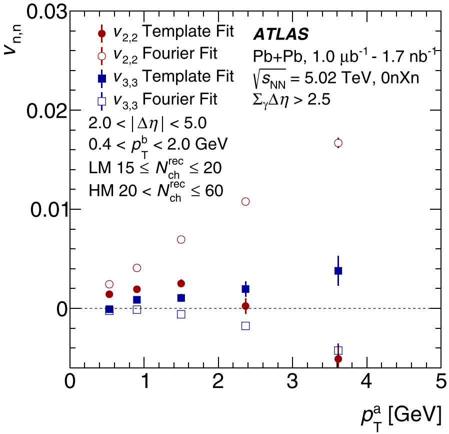




- Simulated results in line with the direct Fourier fit for $v_{2,2}$
- Consistent with zero after template fitting (non-flow subraction)

Comparison to ATLAS $v_{n,n}$ 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?

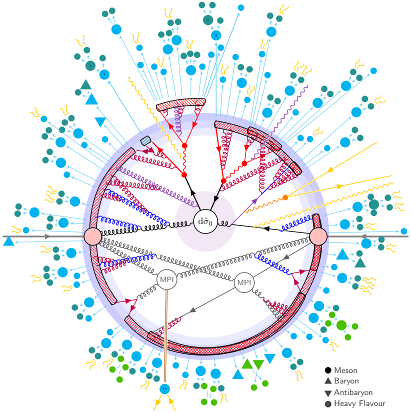
Summary & Outlook

Summary

- Ultraperipheral collisions connect LHC physics to e+p/A in HERA and EIC
- Recent HERA data will provide further constraints on Pythia implementation
- First steps towards γ+A in 8.311
  - ⇒ In line with multiplicity distributions
  - ⇒ As such not consistent with finite v_2

Outlook

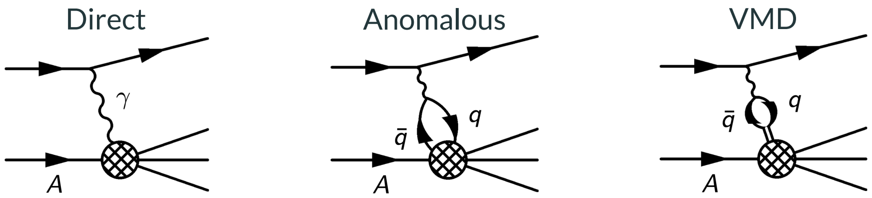
- Study different string-interaction effects for high-multiplicity events
- Study role of diffraction in UPCs



[figure by P. Skands]

Backup slides

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

Photon fluxes from Equivalent Photon Approximation (EPA)

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

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

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

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

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

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

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

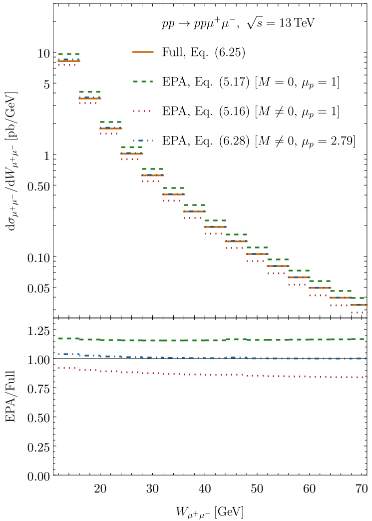
$\Rightarrow$ Large Q^2 suppressed wrt. leptons $\Rightarrow$ photoproduction

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

Equivalent photon approximation

Compare to full calculation

- Example process $pp \to \gamma\gamma \to \mu^+\mu^-$
- 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]

Define your own photon flux for Pythia 8

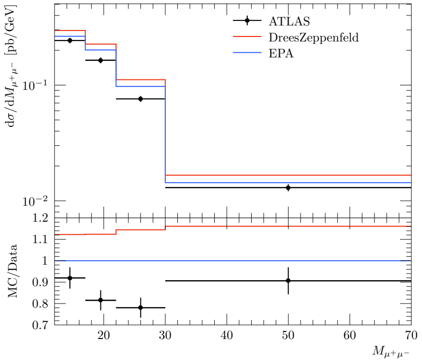
- Derive a new object from PDF class

```
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: $\gamma\gamma \to \mu^+\mu^-$



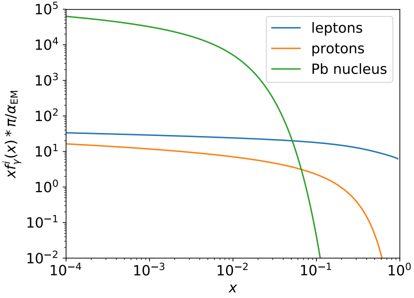
[ATLAS: PLB 777 (2018) 303-323]

- No finite-size effects accounted

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");
```



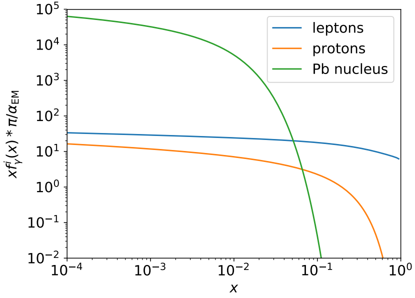
Photon fluxes in Pythia 8

- Enable γ+p in e+p

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



Photon fluxes in Pythia 8

- Enable γ+p in e+p

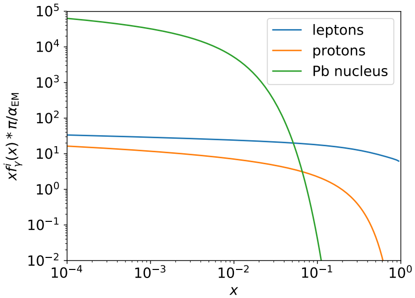
```
pythia.readString("Beams:idA = -11");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
```

- 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);
```

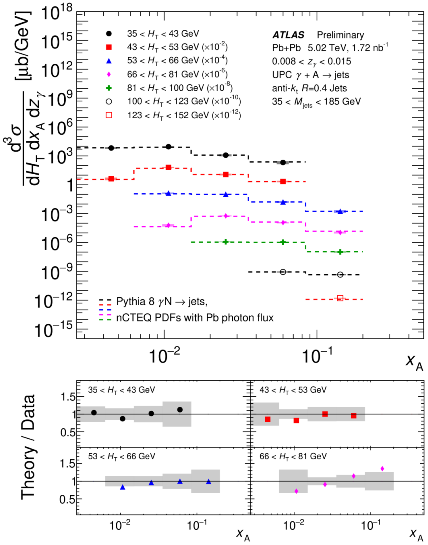


For more examples see `main68.cc`, `main69.cc`, `main70.cc`, `main78.cc` in examples directory

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`]

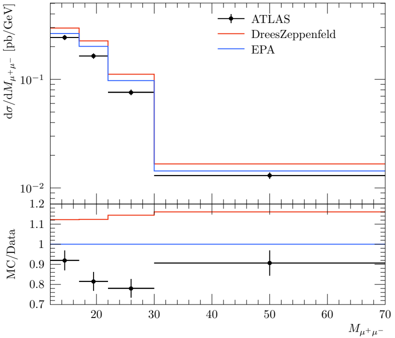
[P. Steinberg @ DIS2023]

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

- 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



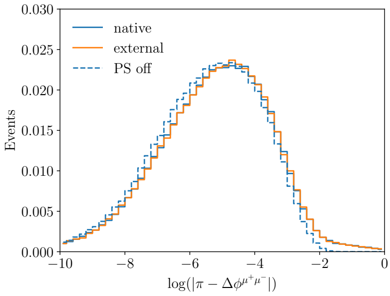
[ATLAS: PLB 777 (2018) 303-323]

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

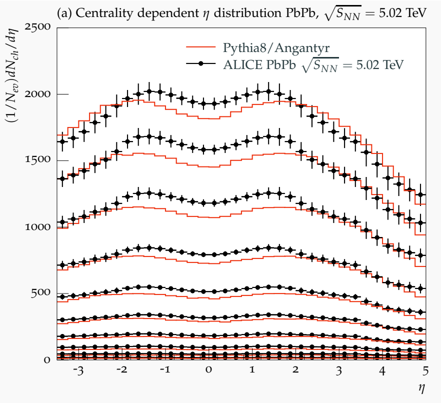
Heavy-ion collisions

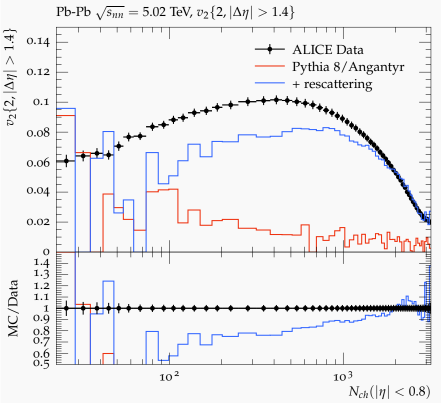
- Angantyr in Pythia provides a full heavy-ion collisions framework

[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]

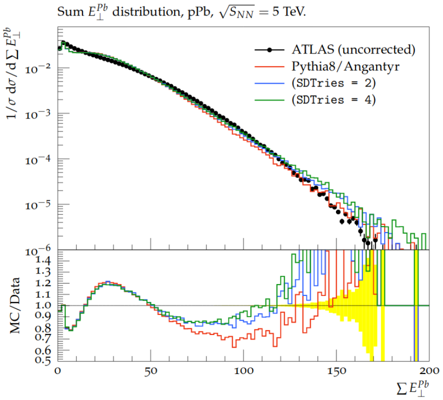


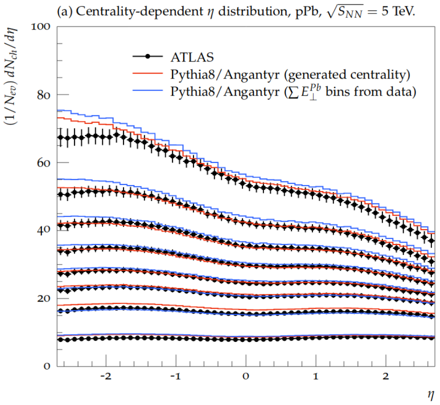


p+*A* collisions

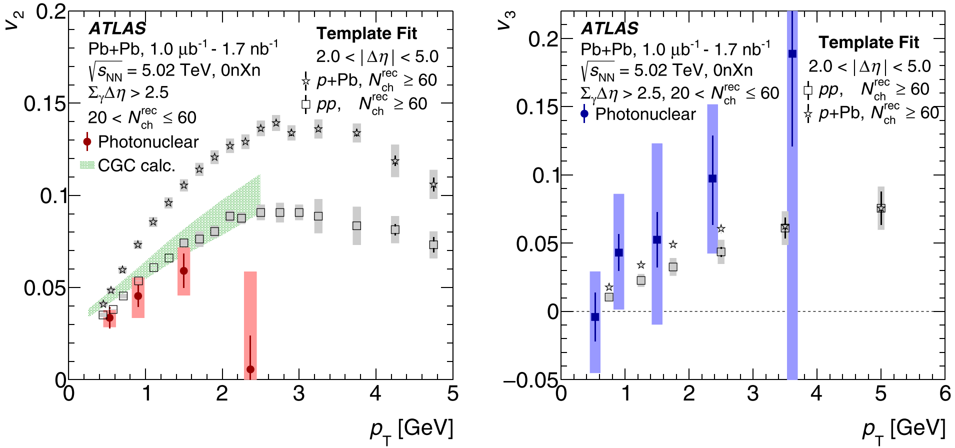
[Bierlich, Gustafson, Lönnblad & Shah: 1806.10820]

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



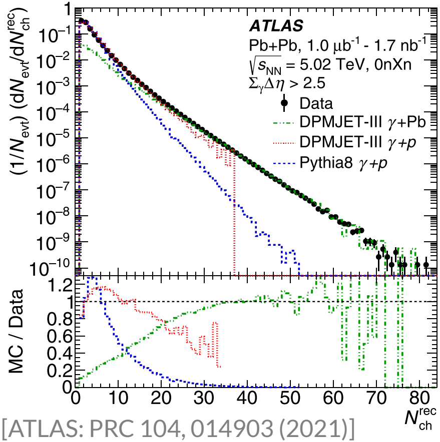


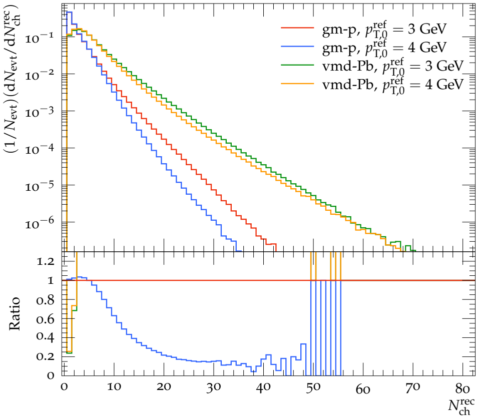
ATLAS data for v_n in γ+Pb



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

Comparison with data for γ+A (preliminary)

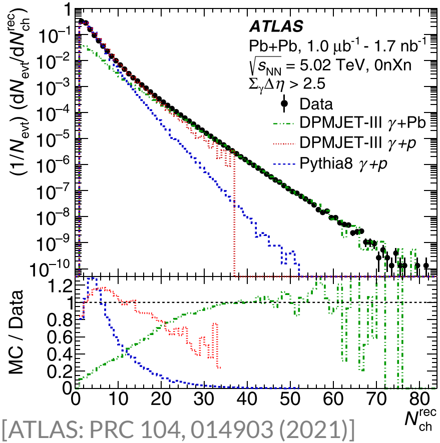




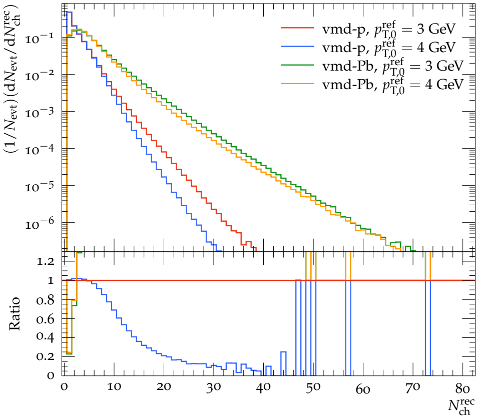
[ATLAS: PRC 104, 014903 (2021)]

- 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)

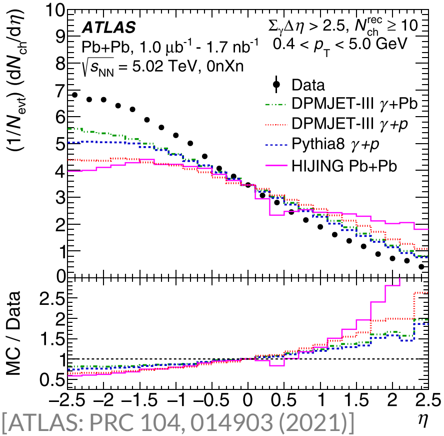


[ATLAS: PRC 104, 014903 (2021)]

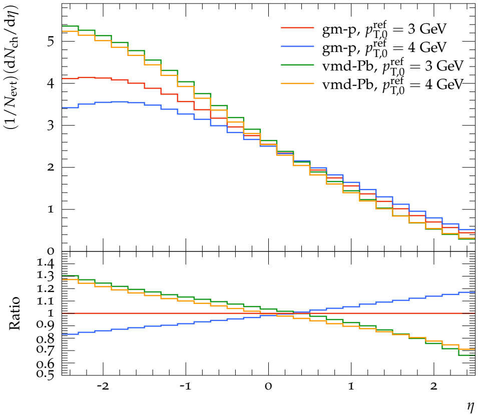


- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative increase in multiplicity well in line with the VMD setup

Comparison with data for γ+A (preliminary)

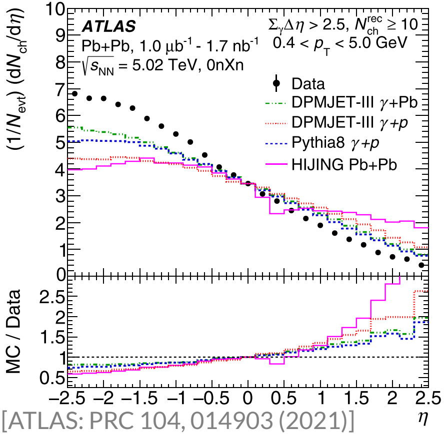


[ATLAS: PRC 104, 014903 (2021)]

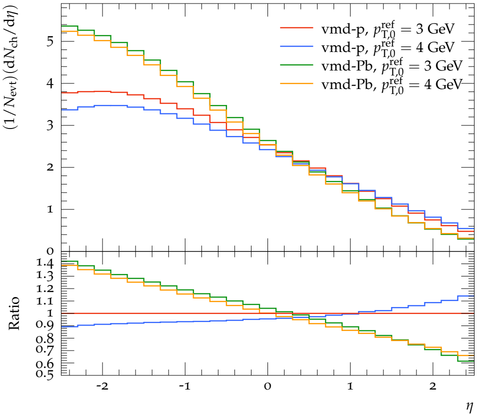


- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative shift in rapidity distribution in line with the VMD setup using Angantyr

Comparison with data for γ+A (preliminary)

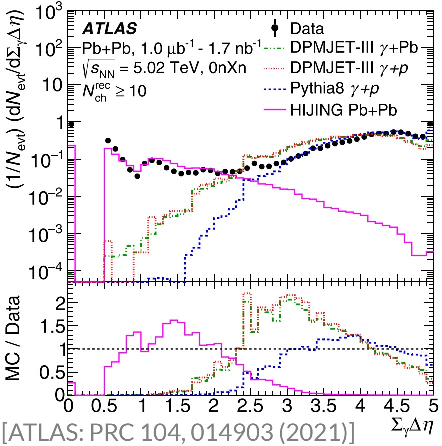


[ATLAS: PRC 104, 014903 (2021)]

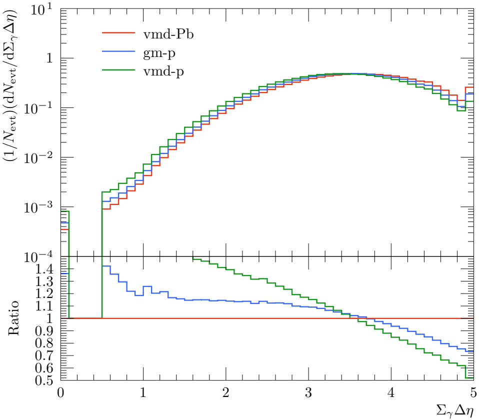


- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative shift in rapidity distribution in line with the VMD setup using Angantyr

Comparison with data for γ+A (preliminary)

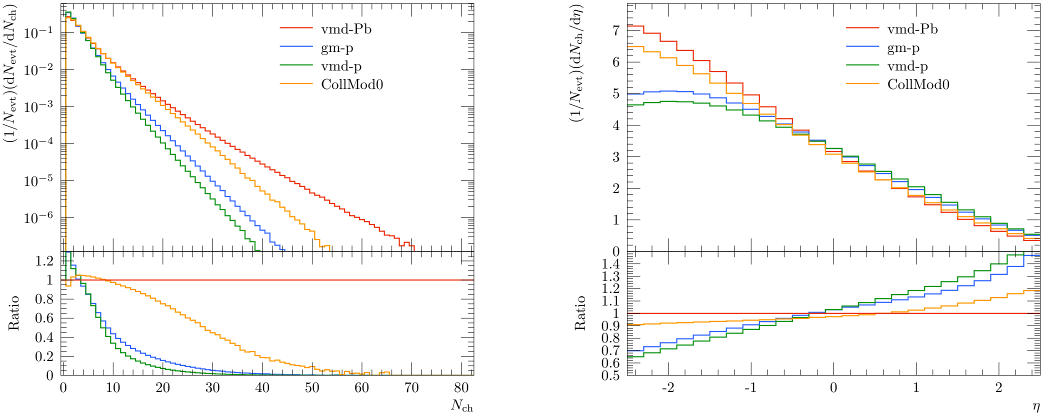


[ATLAS: PRC 104, 014903 (2021)]



- $\Sigma_\gamma \Delta\eta$: 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