Electron-ion collisions in Pythia 8

MC4EIC 2024

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Research Council of Finland

Centre of Excellence in Quark Matter

Outline

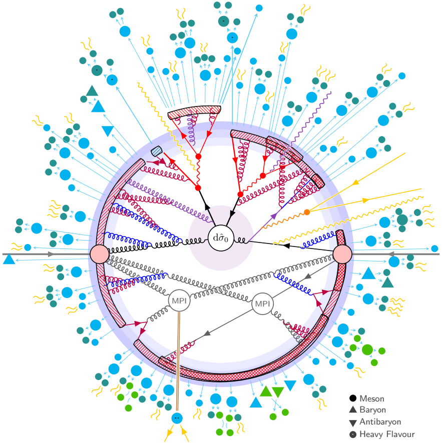
Pythia 8: A general purpose event generator

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

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

Outline

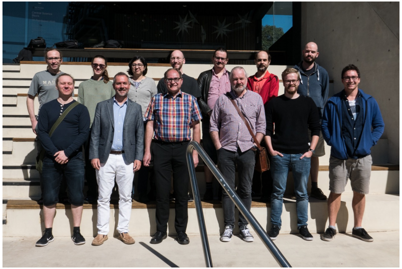
1. Pythia 8 basics
2. Deep inelastic scattering (DIS)
3. Photoproduction in e+p
4. Ultraperipheral heavy-ion collision collisions (UPCs)
5. Summary & Outlook



[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]

`https://pythia.org`

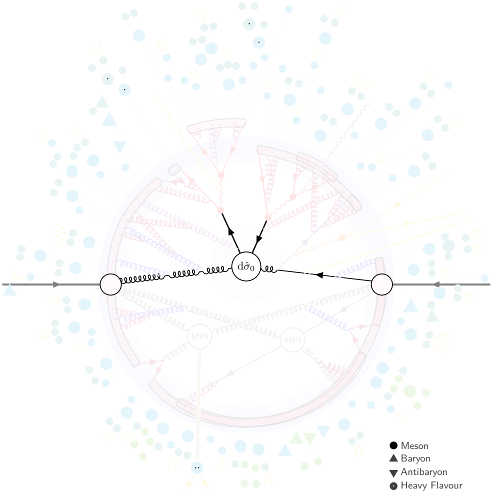
`authors@pythia.org`

Physics modelled within Pythia 8

Classify event generation in terms of "hardness"

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

[figure credit: P. Skands]



Physics modelled within Pythia 8

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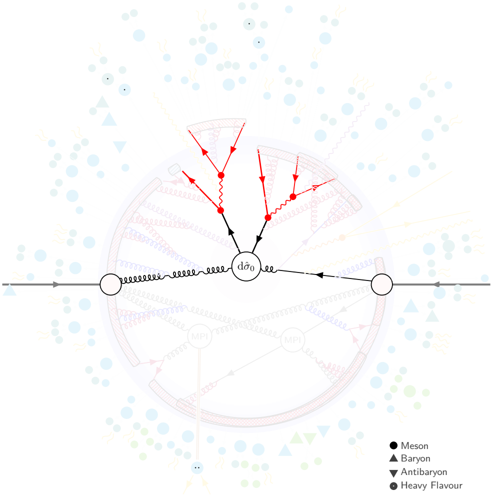
2. Resonance decays ($t, Z, \ldots$)

[figure credit: P. Skands]



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[figure credit: P. Skands]

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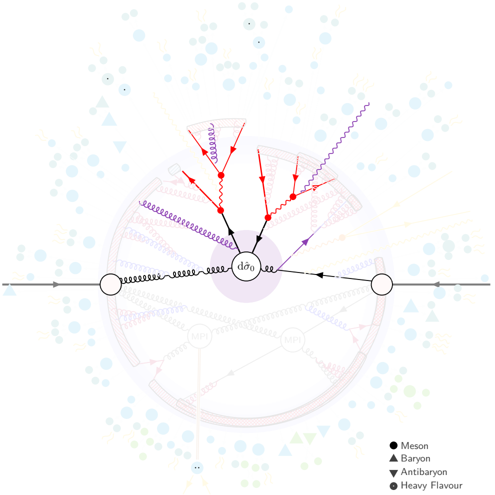

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Classify event generation in terms of "hardness"

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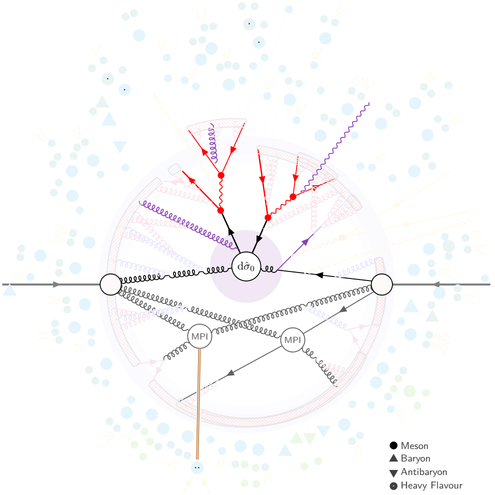
4. Multiparton interactions

[figure credit: P. Skands]



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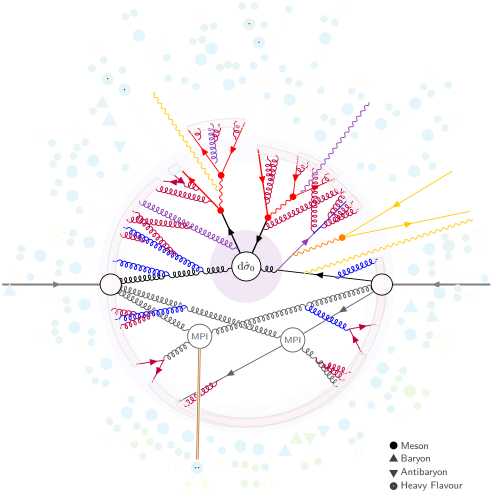
5. Parton showers: ISR, FSR, QED, Weak

[figure credit: P. Skands]



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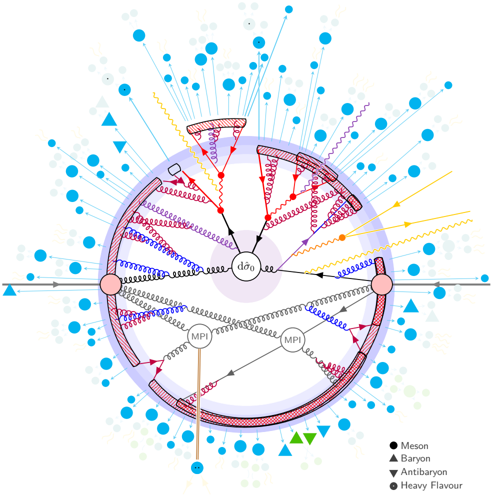
[figure credit: P. Skands]



Physics modelled within Pythia 8

Classify event generation in terms of “hardness”

[figure credit: P. Skands]

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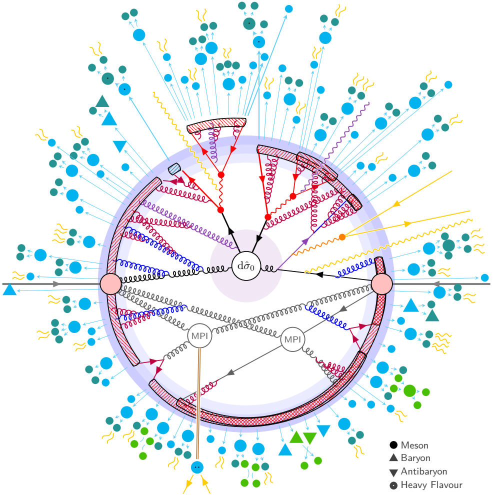
7. Decays, Rescattering



Multiparton interactions (MPIs)

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

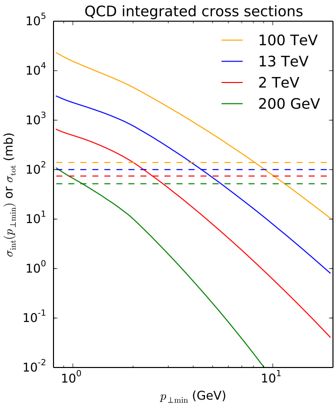
$$\frac{d\mathcal{P}_{\text{MPI}}}{dp_{\text{T}}^2} = \frac{1}{\sigma_{\text{nd}}(\sqrt{s})} \frac{d\sigma^{2\to 2}}{dp_{\text{T}}^2}$$

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

- Partonic cross section diverges at $p_{\text{T}} \to 0$
  $\Rightarrow$ Introduce a screening parameter p_{T0}

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

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



- $\sigma_{\text{int}}(p_{\text{T,min}})$ exceeds σ_{tot}
  $\Rightarrow$ Several interactions

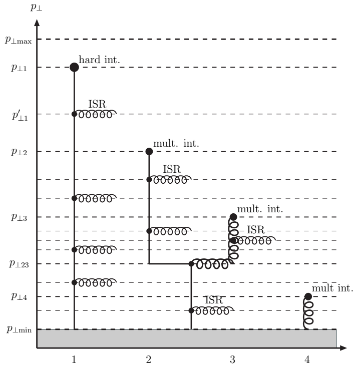
Parton-level evolution

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

- Probability for something to happen at given p_T

$$\frac{d\mathcal{P}}{dp_T} = \left(\frac{d\mathcal{P}_{MPI}}{dp_T} + \sum \frac{d\mathcal{P}_{ISR}}{dp_T} + \sum \frac{d\mathcal{P}_{FSR}}{dp_T}\right) \times \exp\left[-\int_{p_T}^{p_T^{max}} dp'_T \left(\frac{d\mathcal{P}_{MPI}}{dp'_T} + \sum \frac{d\mathcal{P}_{ISR}}{dp'_T} + \sum \frac{d\mathcal{P}_{FSR}}{dp'_T}\right)\right]$$

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



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

Simultaneous partonic evolution

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

Available beam configurations in Pythia 8

Hadronic collisions

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

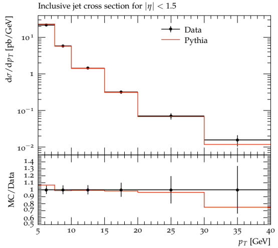
Collisions with leptons

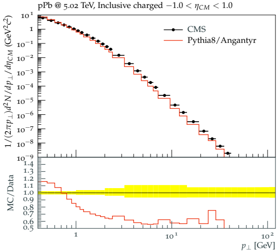
- $\mathrm{e}^+\mathrm{e}^-$, including $\gamma\gamma$ (also in p-p)
- e-p: (neutrino) DIS, photoproduction with soft and hard QCD processes

Heavy-ion collisions with Angantyr

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

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





[C. Bierlich, G. Gustafson, L. Lönnblad, H. Shah: JHEP10(2018)134]

Electron-proton collisions

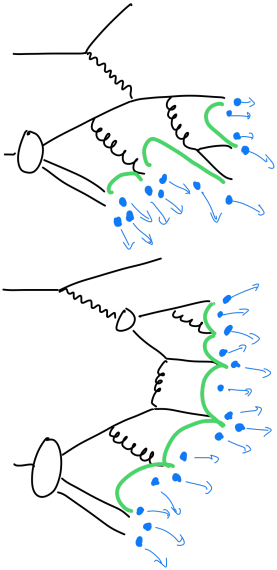
Classified in terms photon virtuality Q^2

Deep inelastic scattering (DIS)

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

Photoproduction

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



Deep inelastic scattering

Event generation in DIS with Pythia 8

Hard scattering

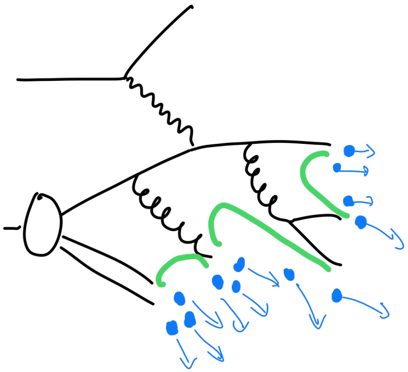
- Convolution between PDFs and matrix element (ME) for partonic scattering

Parton shower

- Final state radiation (FSR)
- Initial state radiation (ISR) for hadron
- QED emissions from leptons (omitted)

Hadronization

- String hadronization with colour reconnections
- Decays to stable hadrons

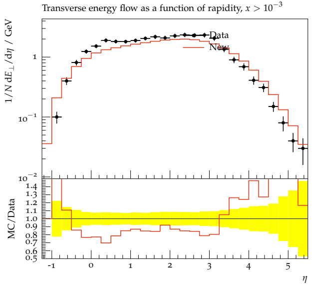


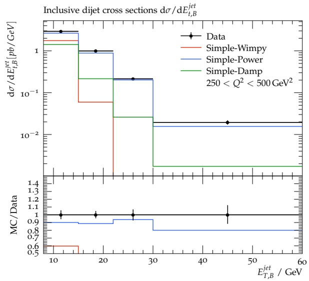
Parton shower options for DIS in Pythia I

The default shower with `dipoleRecoil` option

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

- No PS recoil for the scattered lepton
- Emissions from initial-final dipole
- No shower-specific tuning done
- Event shapes
  - Reasonable description of single-particle properties, such as transverse energy flow
  - Differences for energy-energy correlators
- Jet production
  - First emission match with matrix element
  - Can use "power shower" to fill the phase space
  - Good description of high-Q^2 dijets [See Joni's talk]





Parton shower options for DIS in Pythia II

Vincia antenna shower `PartonShowers:model = 2`

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

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

Dire in Pythia `PartonShowers:model = 3`

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

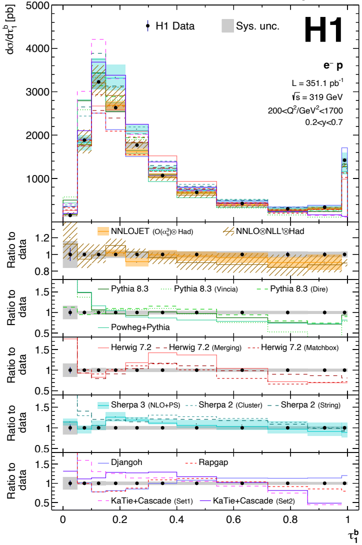
- Correct soft-gluon interference at lowest order
- Inclusive NLO corrections to collinear splittings

H1 measurement 1-jettiness

$$\tau_1^b = \frac{2}{Q^2} \sum_{i \in HFS} \min[xP \cdot p_i, (q + xP) \cdot p_i]$$

- Sensitive to parton shower details

[H1: arXiv:2403.10109 [hep-ex]]



Photoproduction in e+p

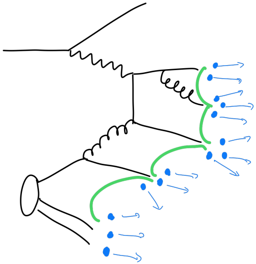
Photoproduction in electron-proton collisions

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

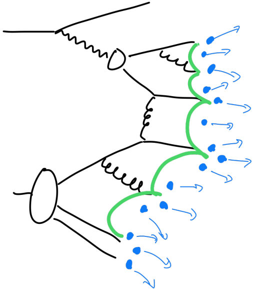


Resolved processes

- 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 $\gamma\mathrm{p}$ sub-system with $W_{\gamma\mathrm{p}}$
- Evolve $\gamma\mathrm{p}$ 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

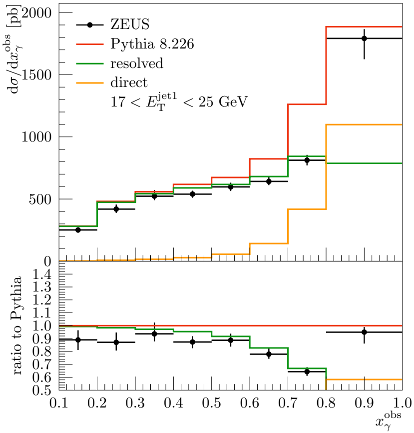
- $Q^2 < 1.0\,\text{GeV}^2$
- $134 < W_{\gamma p} < 277\,\text{GeV}$
- $E_T^{\text{jet1}} > 14\,\text{GeV}, E_T^{\text{jet2}} > 11\,\text{GeV}$
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Two contributions

- Momentum fraction of partons in photon

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

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



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

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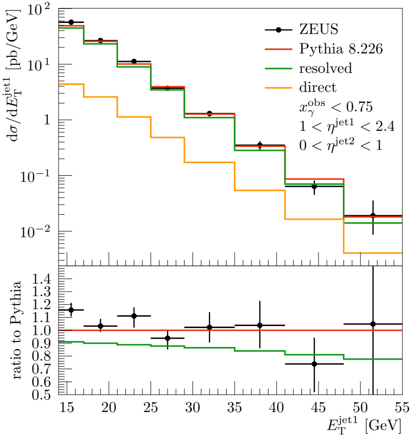

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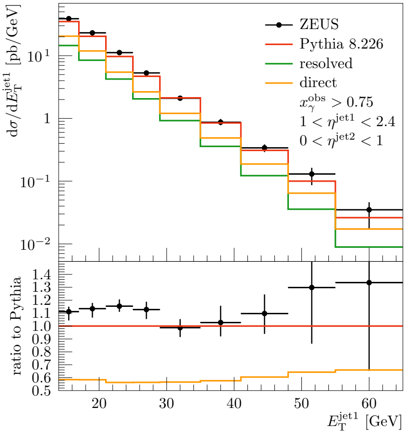

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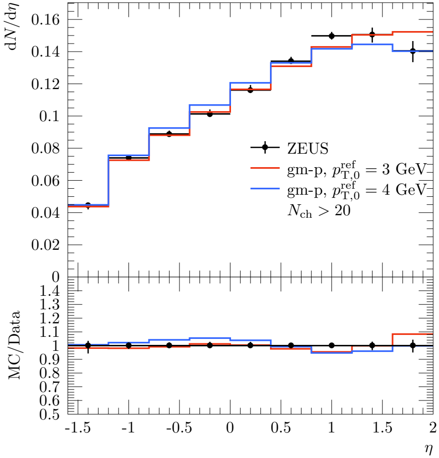
Comparison to ZEUS data for charged hadrons ($N_{ch} > 20$)

Pseudorapidity

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



[ZEUS: JHEP 12 (2021) 102]

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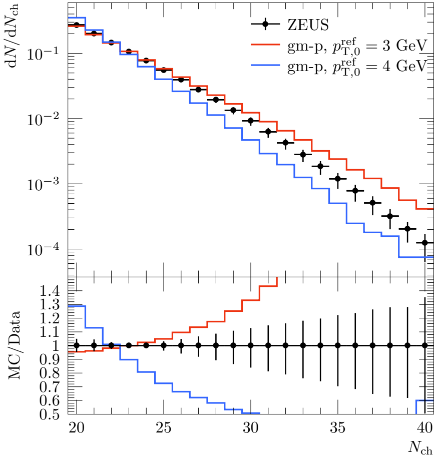
Multiplicity

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



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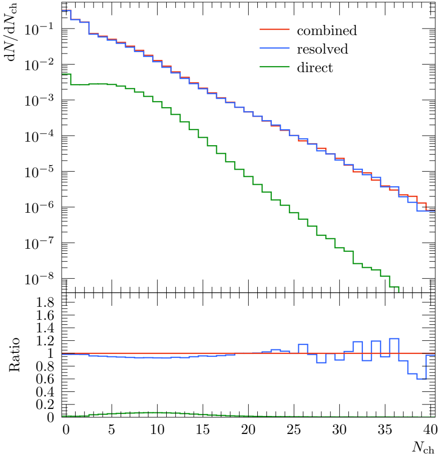
Multiplicity

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



[ZEUS: JHEP 12 (2021) 102]

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

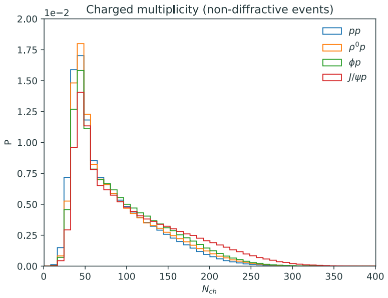
  [Sjöstrand, Utheim; EPJC 82 (2022) 1, 21]

- Cross sections from SaS

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

- Sample collision energy from flux

⇒ Vector meson-proton scatterings



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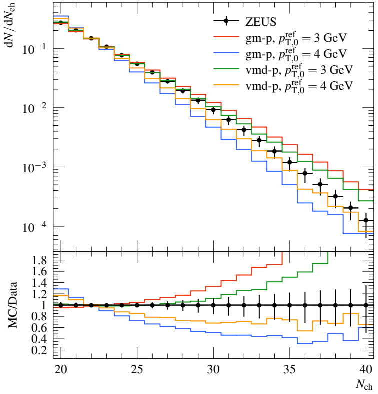
⇒ Vector meson-proton scatterings
  - In line with the full photoproduction



[ZEUS: JHEP 12 (2021) 102]

Intermediate Q^2 region

Solid theory for $Q^2 = 0$ and at high Q^2

$\Rightarrow$ What happens in between?

Pythia 6 (inspired) model ($\neq$ Pythia 8)

- Select suitable scales and suppress contributions by hand

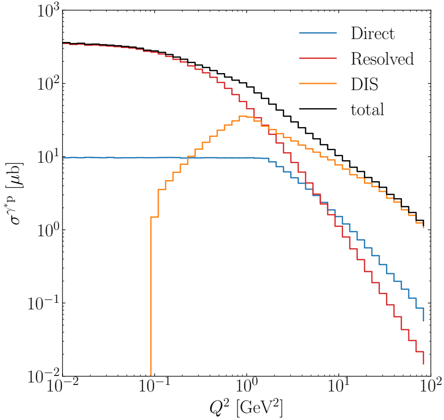
$$\sigma_{\mathrm{tot}}^{\gamma^* \mathrm{p}} = \tilde{\sigma}_{\mathrm{DIS}}^{\gamma^* \mathrm{p}} \exp\left[-\frac{\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}}}{\tilde{\sigma}_{\mathrm{DIS}}^{\gamma^* \mathrm{p}}}\right] + \tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}} + \tilde{\sigma}_{\mathrm{Res}}^{\gamma^* \mathrm{p}}$$

where

- $\tilde{\sigma}_{\mathrm{DIS}}^{\gamma^* \mathrm{p}} = \left[\frac{Q^2}{Q^2+m_\rho^2}\right]^2 \sigma_{\mathrm{DIS}}^{\gamma^* \mathrm{p}}$
- $\tilde{\sigma}_{\mathrm{Res}}^{\gamma^* \mathrm{p}} = \sigma_{\mathrm{Res}}^{\gamma^* \mathrm{p}} \left[\frac{m_\rho^2}{m_\rho^2+Q^2}\right]^2 \left[\frac{W^2}{W^2+Q^2}\right]^n$
- $\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^* \mathrm{p}} = \sigma_{\mathrm{Dir}}^{\gamma^* \mathrm{p}}(\hat{p}_{\mathrm{T,min}} = max(Q, p_{\mathrm{T,min}}))$

$p_{\mathrm{T,min}} = 1.3\,\mathrm{GeV},\ n = 3,\ m_\rho = 0.7755\,\mathrm{GeV}$

$\sqrt{s} = 318$ GeV, $W_{\mathrm{min}} = 100$ GeV:



Intermediate:

$0.5 \lesssim Q^2 \lesssim 5.0\,\mathrm{GeV}^2$

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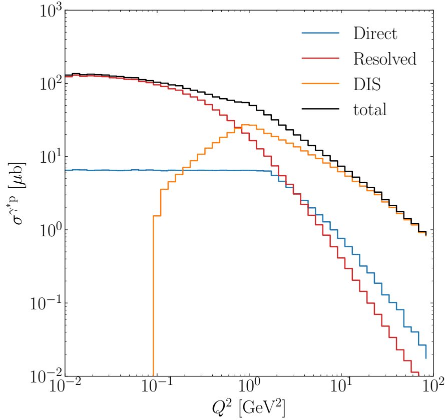
where

- $\tilde{\sigma}_{\text{DIS}}^{\gamma^* p} = \left[\frac{Q^2}{Q^2+m_\rho^2}\right]^2 \sigma_{\text{DIS}}^{\gamma^* p}$
- $\tilde{\sigma}_{\text{Res}}^{\gamma^* p} = \sigma_{\text{Res}}^{\gamma^* p} \left[\frac{m_\rho^2}{m_\rho^2+Q^2}\right]^2 \left[\frac{W^2}{W^2+Q^2}\right]^n$
- $\tilde{\sigma}_{\text{Dir}}^{\gamma^* p} = \sigma_{\text{Dir}}^{\gamma^* p}(\hat{p}_{\text{T,min}} = max(Q, p_{\text{T,min}}))$

$p_{\text{T,min}} = 1.3\,\text{GeV},\ n = 3,\ m_\rho = 0.7755\,\text{GeV}$

$\sqrt{s} = 140$ GeV, $W_{\text{min}} = 10$ GeV:



Intermediate:
$0.3 \lesssim Q^2 \lesssim 3.0\,\text{GeV}^2$

Intermediate Q^2 region

Solid theory for $Q^2 = 0$ and at high Q^2

$\Rightarrow$ What happens in between?

Pythia 6 (inspired) model ($\neq$ Pythia 8)

- Select suitable scales and suppress contributions by hand

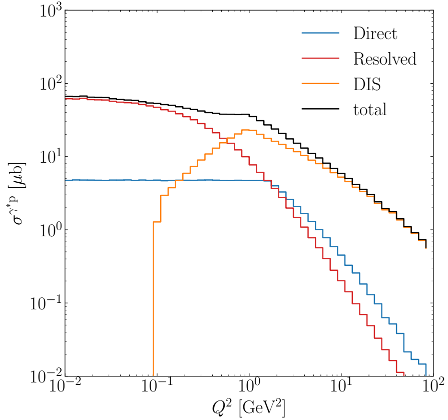
$$\sigma_{\mathrm{tot}}^{\gamma^*\mathrm{p}} = \tilde{\sigma}_{\mathrm{DIS}}^{\gamma^*\mathrm{p}} \exp\left[-\frac{\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^*\mathrm{p}}}{\tilde{\sigma}_{\mathrm{DIS}}^{\gamma^*\mathrm{p}}}\right] + \tilde{\sigma}_{\mathrm{Dir}}^{\gamma^*\mathrm{p}} + \tilde{\sigma}_{\mathrm{Res}}^{\gamma^*\mathrm{p}}$$

where

- $\tilde{\sigma}_{\mathrm{DIS}}^{\gamma^*\mathrm{p}} = \left[\frac{Q^2}{Q^2+m_\rho^2}\right]^2 \sigma_{\mathrm{DIS}}^{\gamma^*\mathrm{p}}$
- $\tilde{\sigma}_{\mathrm{Res}}^{\gamma^*\mathrm{p}} = \sigma_{\mathrm{Res}}^{\gamma^*\mathrm{p}} \left[\frac{m_\rho^2}{m_\rho^2+Q^2}\right]^2 \left[\frac{W^2}{W^2+Q^2}\right]^n$
- $\tilde{\sigma}_{\mathrm{Dir}}^{\gamma^*\mathrm{p}} = \sigma_{\mathrm{Dir}}^{\gamma^*\mathrm{p}}(\hat{p}_{\mathrm{T,min}} = max(Q, p_{\mathrm{T,min}}))$

$p_{\mathrm{T,min}} = 1.3\,\mathrm{GeV},\ n = 3,\ m_\rho = 0.7755\,\mathrm{GeV}$

$\sqrt{s} = 85$ GeV, $W_{\mathrm{min}} = 10$ GeV:



Intermediate:

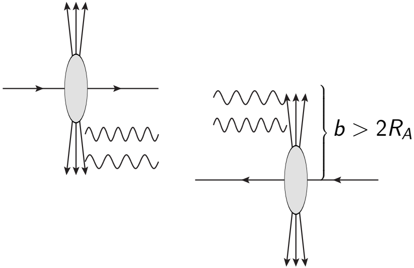
$0.2 \lesssim Q^2 \lesssim 2.0\,\mathrm{GeV}^2$

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

- Large impact parameter ($b \gtrsim 2R_A$)
  $\Rightarrow$ No strong interactions
- At LHC relevant for p+p, p+Pb, Pb+Pb
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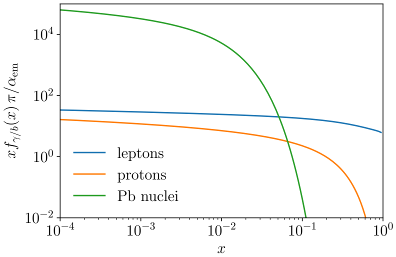

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$$f_\gamma^A(x) = \frac{2\alpha_{\mathrm{EM}} Z^2}{x\,\pi}\left[\xi\, K_1(\xi) K_0(\xi) - \frac{\xi^2}{2}\left(K_1^2(\xi) - K_0^2(\xi)\right)\right]$$

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

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

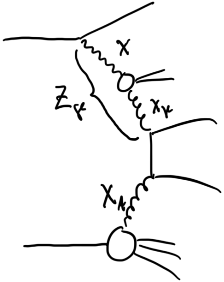
Dijets in ultra-peripheral heavy-ion collisions in Xn0n

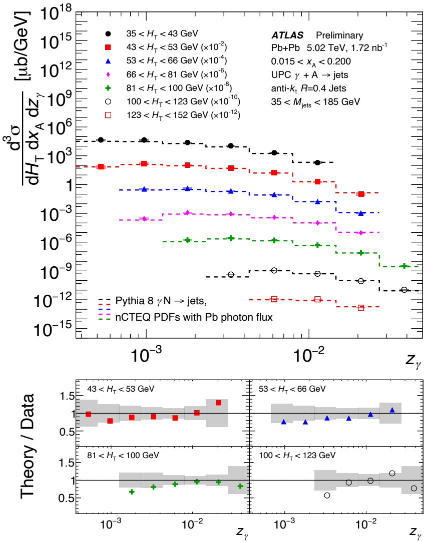
- Good agreement out of the box when accounting both direct and resolved
- EM nuclear break-up significant
- Pythia setup with nucleon target only
  $\Rightarrow$ Is such a setup enough for γ+A?

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

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

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

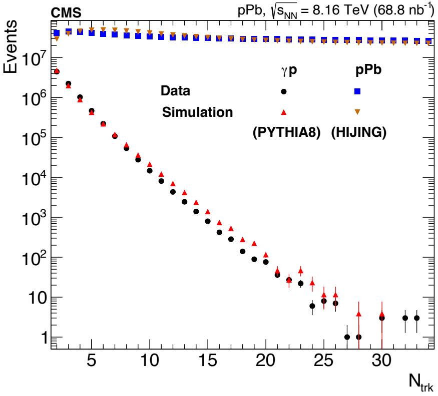




See also [Eskola, Guzey, IH, Paakkinen, Paukkunen; arXiv:2404.09731] [ATLAS-CONF-2022-021]

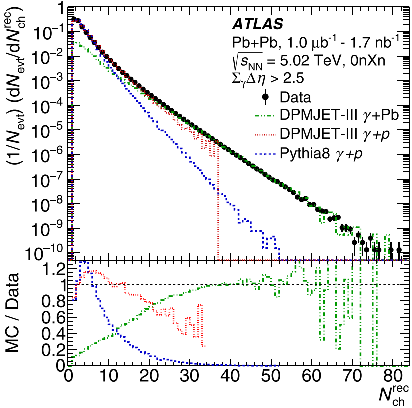
Multiplicity distributions in UPCs

γ+p: [CMS: Murillo Quijada, QM2022]



- Multiplicity distribution well reproduced in γ+p interactions

γ+Pb: [ATLAS: PRC 104, 014903 (2021)]



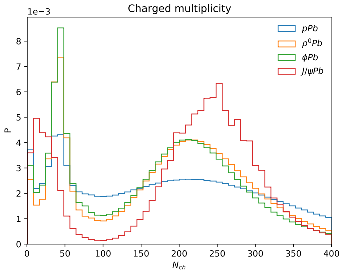
- High multiplicities missed with γ+p
  $\Rightarrow$ Multi-nucleon interactions

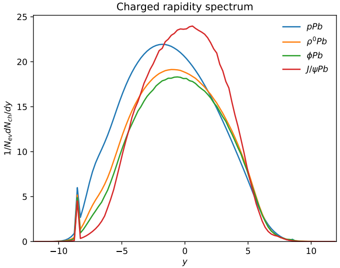
Angantyr model for heavy ions in Pythia

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

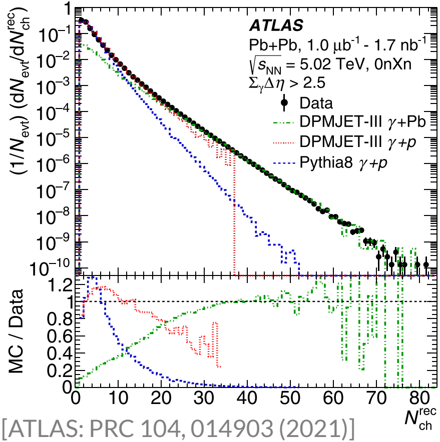
- Monte Carlo Glauber to sample nucleon configurations
- Cross section fluctuations, fitted to partial nucleon-nucleon cross sections
- Secondary (wounded) collisions as diffractive excitations
- Can now handle generic hadron-ion and varying energy [I.H., Utheim; in progress]

⇒ VMD-nucleus scatterings

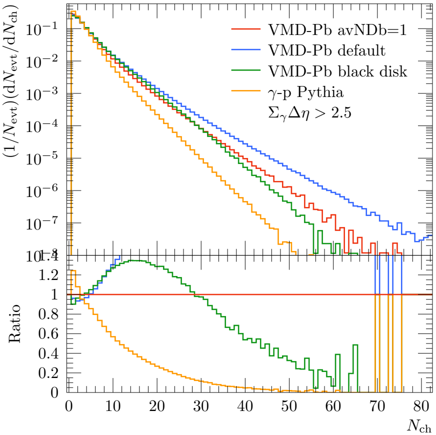




Comparison with data for γ+A

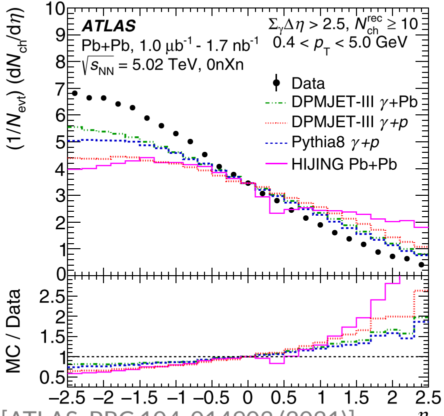


[ATLAS: PRC 104, 014903 (2021)]

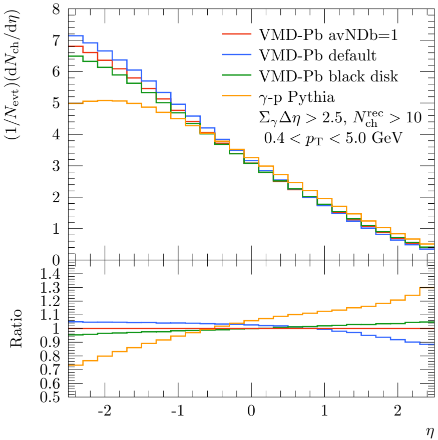


- ATLAS data not corrected for efficiency, estimated with $N_{ch}^{rec} \approx 0.8 \cdot N_{ch}$
- Relative increase in multiplicity well in line with the VMD-Pb setup

Comparison with data for γ+A

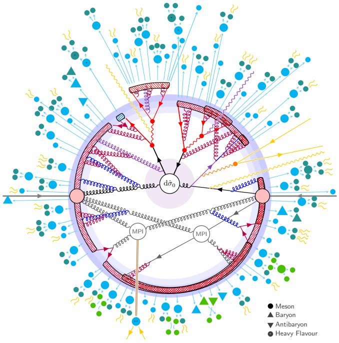


[ATLAS: PRC 104, 014903 (2021)]



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

Summary & Outlook



[figure by P. Skands]

Deep inelastic scattering

- Several parton showers available

⇒ No specific tuning, sparse validation

Photoproduction

- Soft and hard QCD processes included
- Validated against some HERA data

⇒ More global MPI tuning

⇒ Model transition from photoproduction to DIS

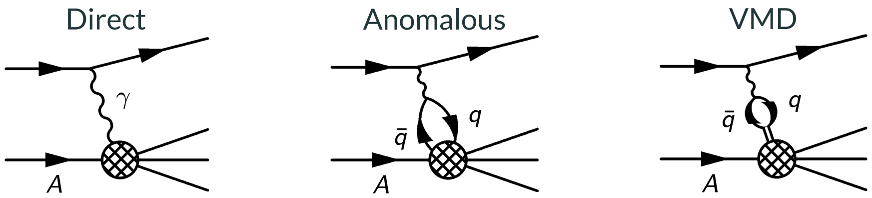
Nuclear target

- First steps with VMD+*A* in 8.311, applied to UPCs at the LHC
- In line with single-particle observables analyzed by ATLAS

⇒ Further modelling to include complete structure of real photons

Backup slides

Vector meson dominance (VMD)



Linear combination of three components

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

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

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

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

Photon fluxes from Equivalent Photon Approximation (EPA)

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

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

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

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

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

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

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

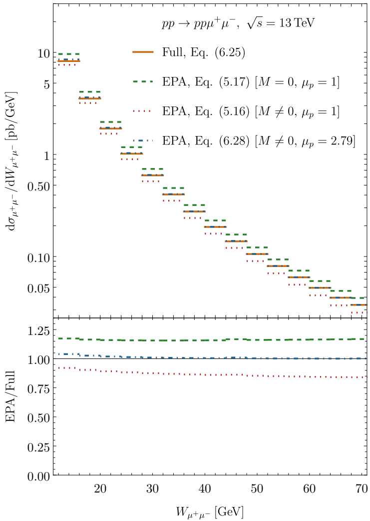
$\Rightarrow$ Large Q^2 suppressed wrt. leptons $\Rightarrow$ photoproduction

- 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

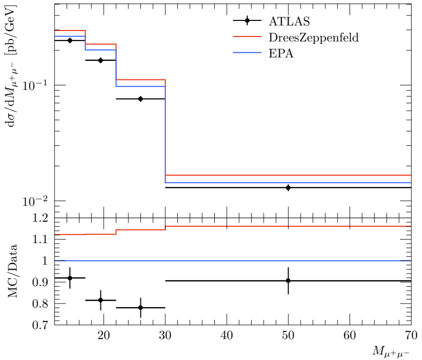
- Derive a new object from PDF class

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



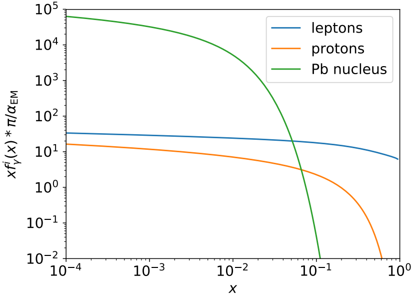
[ATLAS: PLB 777 (2018) 303-323]

- 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");
```



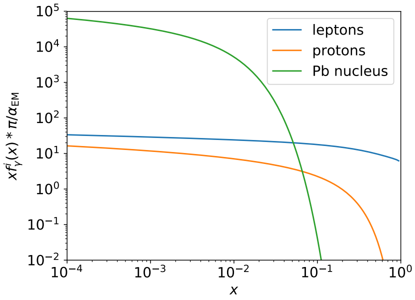
Photon fluxes in Pythia 8

- 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

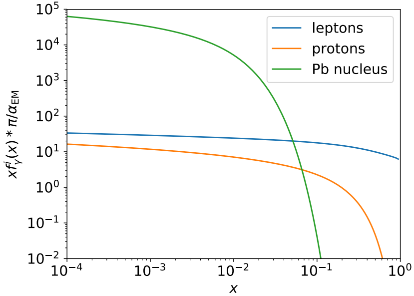
```
pythia.readString("Beams:idA = -11");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
```

- 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);
```



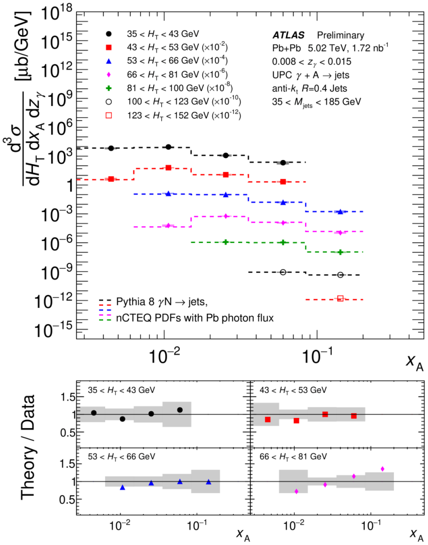
For more examples see `main68.cc`, `main69.cc`, `main70.cc`, `main78.cc` in examples directory

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`]



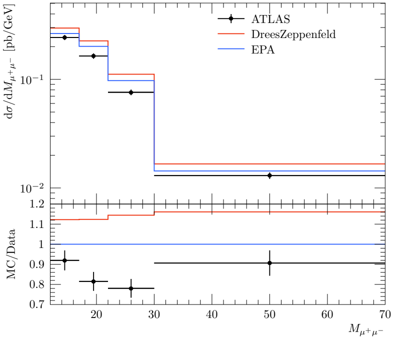
[P. Steinberg @ DIS2023]

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



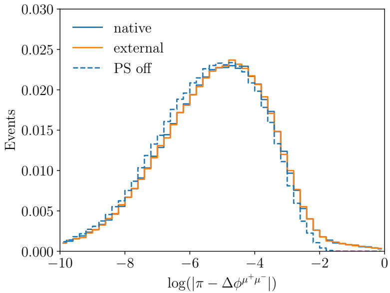
[ATLAS: PLB 777 (2018) 303-323]

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

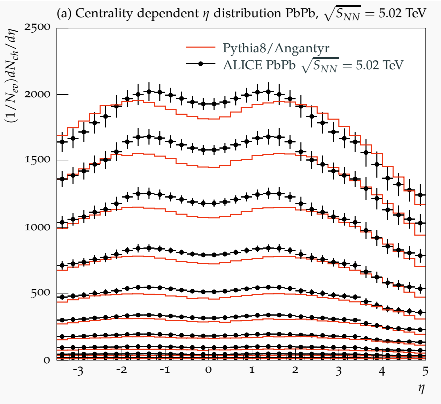
Heavy-ion collisions

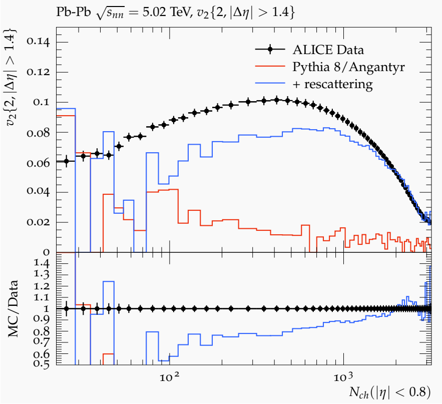
- Angantyr in Pythia provides a full heavy-ion collisions framework

[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]

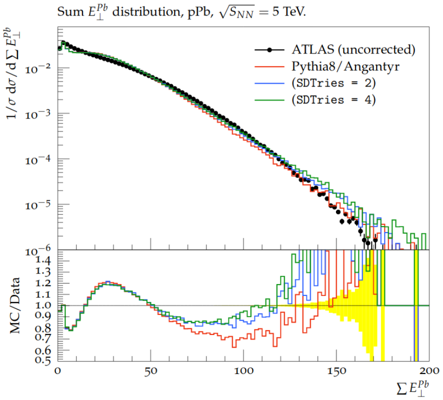


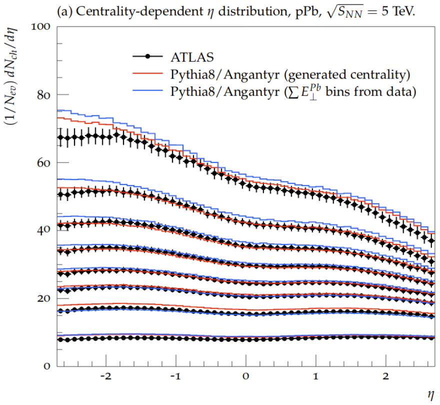


p+A collisions

[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





Experimental heavy-ion UPC classification

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

XnXn: At least one neutron on both sides

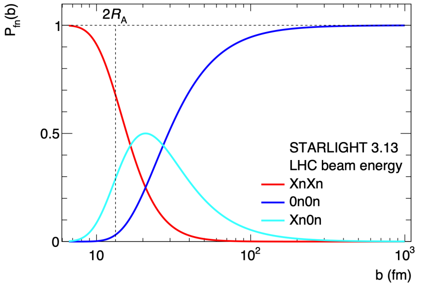
$\Rightarrow$ *A*+*A* (hadronic interaction)

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

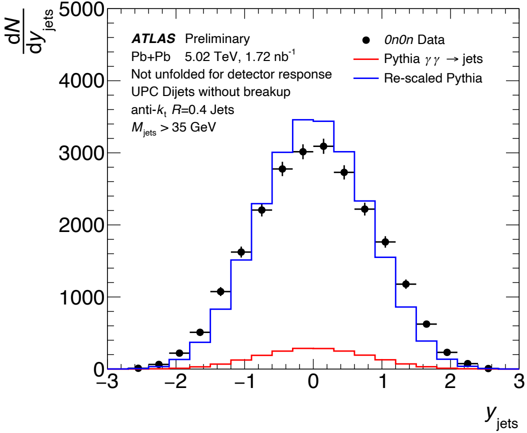
Possible caveats

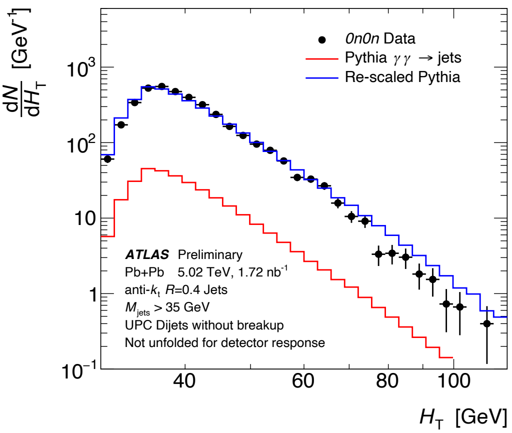
- Additional EM interactions may break up the nuclei in "near-encounter" events
- Also diffractive processes will keep nuclei intact

$\Rightarrow$ Xn0n condition will remove diffractive contribution to $\gamma+A$

See e.g. [Guzey, Klasen; PRD 104 (2021) 11 114013]

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



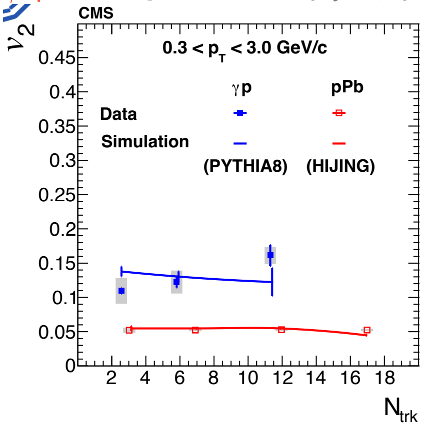


[ATLAS-CONF-2022-021]

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

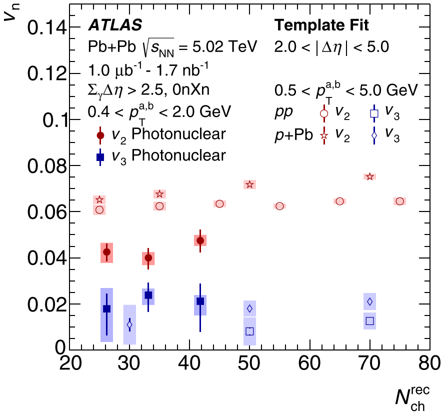
Collectivity in UPCs at the LHC

γ+p [CMS: Murillo Quijada, QM2022]



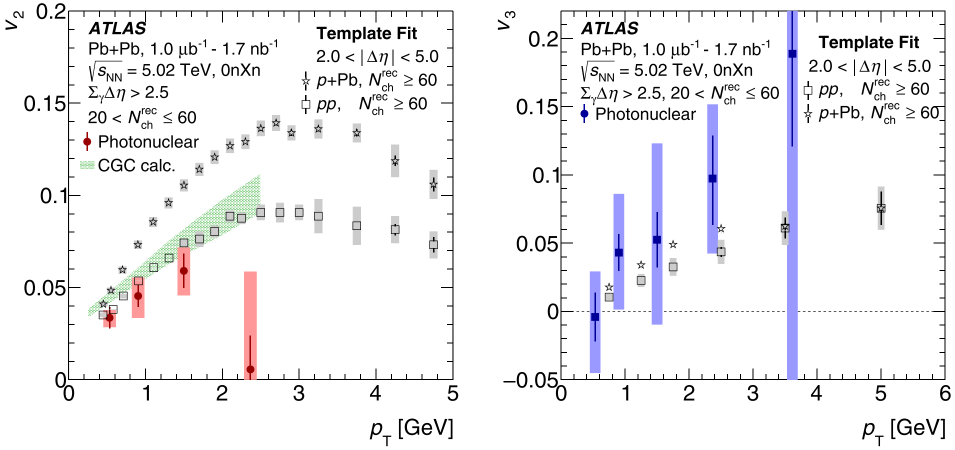
- Finite v_2 for γ+p, in line with Pythia
  $\Rightarrow$ Jet-like correlations?

γ+Pb [ATLAS: PRC 104, 014903 (2021)]



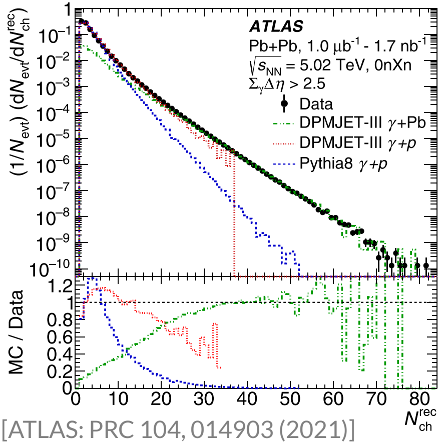
- Finite v_n also after Template fit subtracting “non-flow”

ATLAS data for v_n in γ+Pb

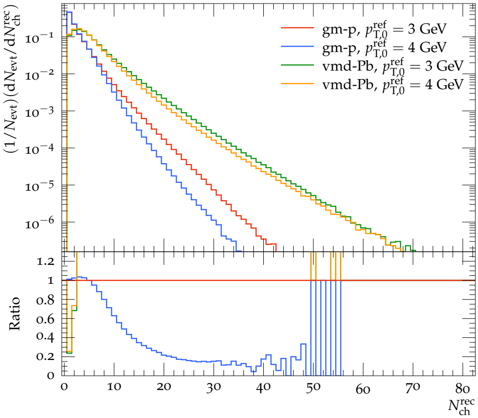


- Non-zero flow coefficients also for γ+Pb
- Expected baseline from MC simulations?

Comparison with data for γ+A (preliminary)

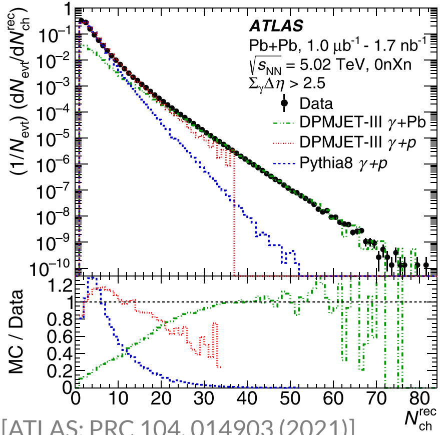


[ATLAS: PRC 104, 014903 (2021)]

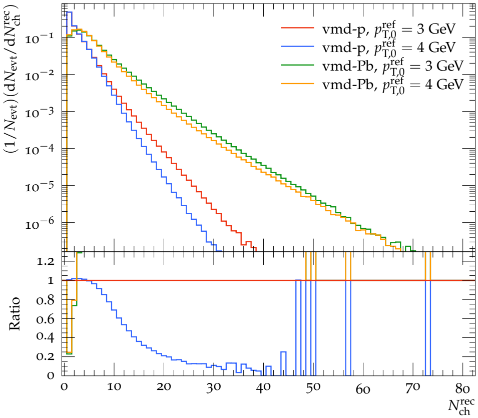


- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative increase in multiplicity well in line with the VMD setup

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
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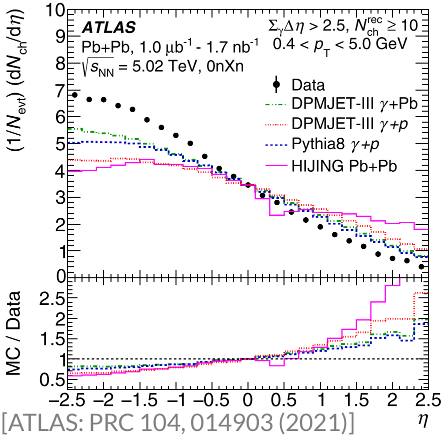
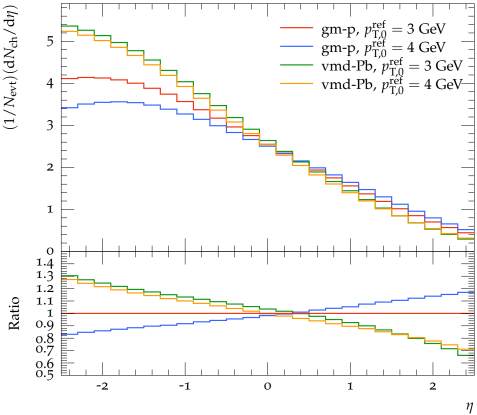
Comparison with data for γ+A (preliminary)

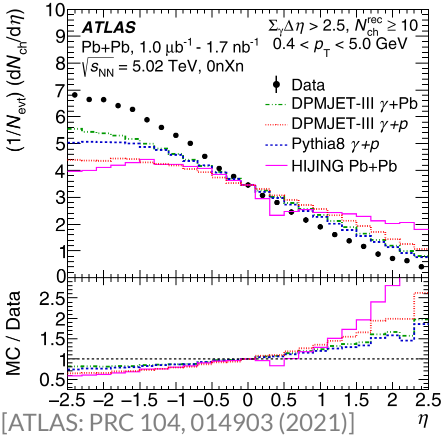


[ATLAS: PRC 104, 014903 (2021)]

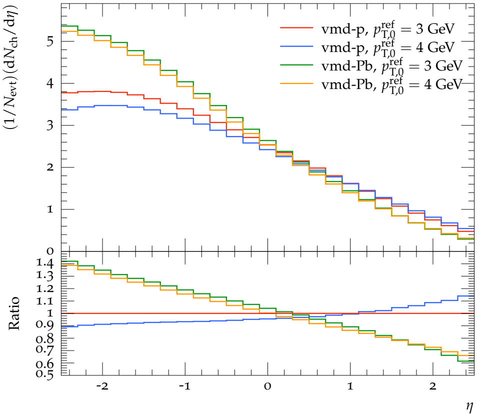


- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative shift in rapidity distribution in line with the VMD setup using Angantyr

Comparison with data for γ+A (preliminary)

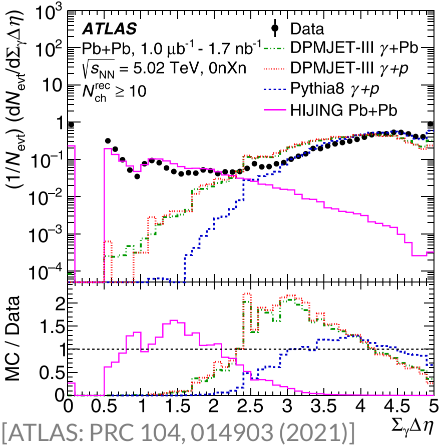


[ATLAS: PRC 104, 014903 (2021)]

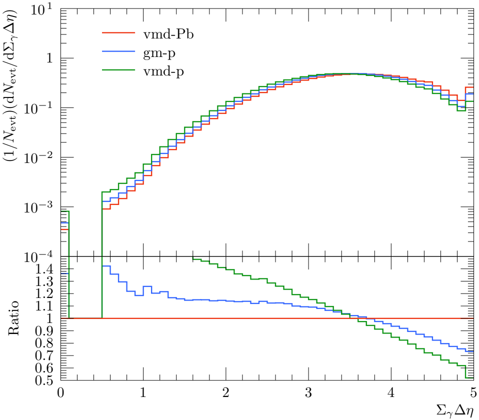


- Pythia8 γ+p in ATLAS result should correspond to gm-p on right
- Relative shift in rapidity distribution in line with the VMD setup using Angantyr

Comparison with data for γ+A (preliminary)

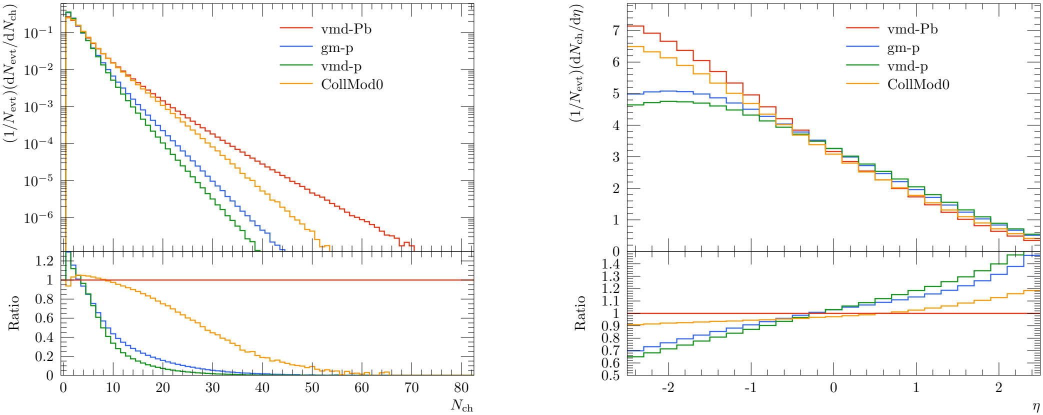


[ATLAS: PRC 104, 014903 (2021)]



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