Photon-induced processes in PYTHIA 8.3

WORKSHOP ON THE MODELLING OF PHOTON-INDUCED PROCESSES

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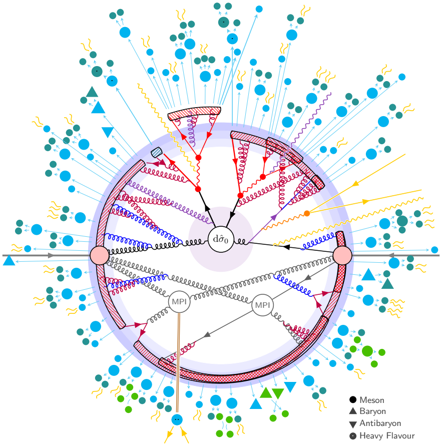
Outline

PYTHIA 8: A general purpose event generator

- Latest release 8.309 (Feb 2023)
- A new physics manual for 8.3
  [SciPost Phys. Codebases 8-r8.3 (2022)]

Outline

1. Pythia basics
2. DIS and photoproduction in e+p
3. Photon-induced processes in LHC
   - Photon fluxes
   - Elastic vs dissociative
   - Photon-ion collisions
4. Summary & Outlook



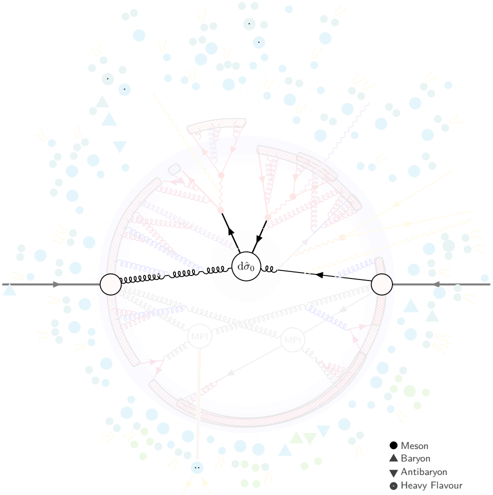
[figure by P. Skands]

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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Classify event generation in terms of "hardness"

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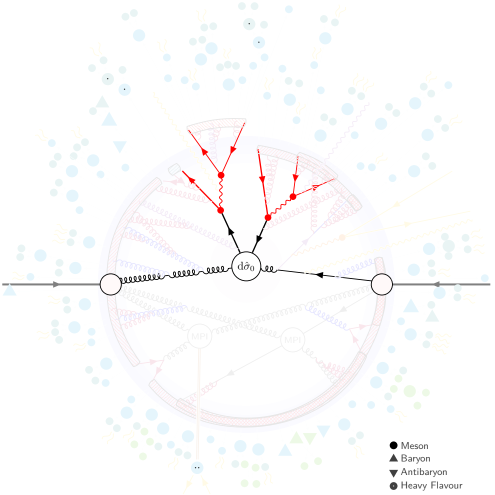
2. Resonance decays $(t, Z, \ldots)$

[figure credit: P. Skands]



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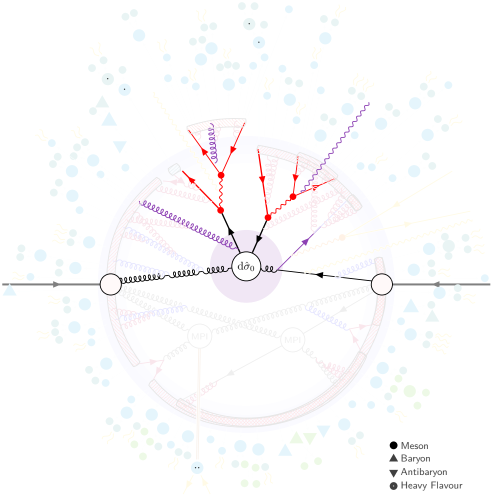
Classify event generation in terms of "hardness"

[figure credit: P. Skands]

1. Hard Process (here $t\bar{t}$)
2. Resonance decays $(t, Z, \ldots)$
3. Matching, Merging and matrix-element corrections



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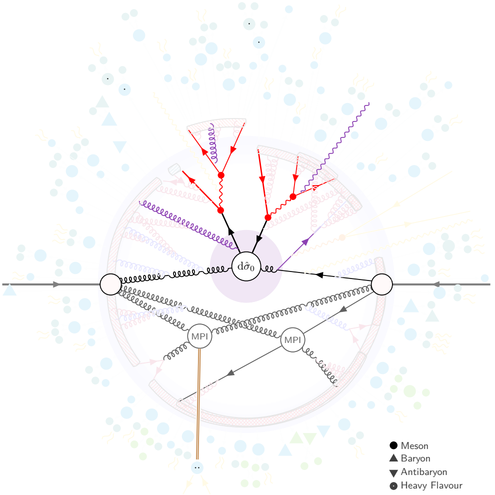

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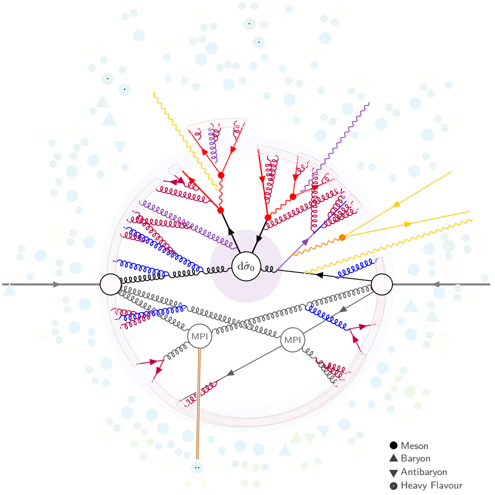

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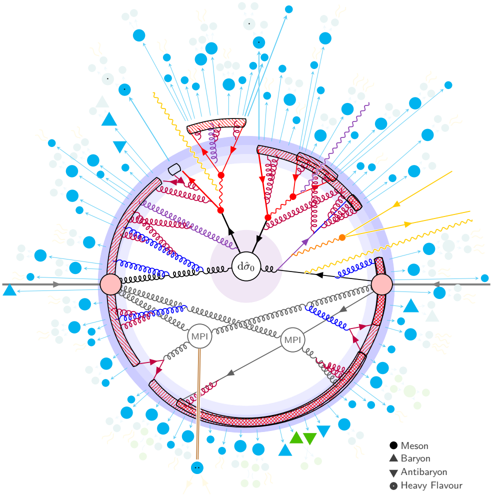

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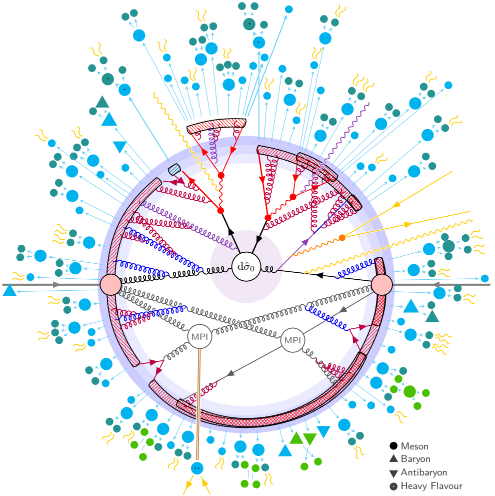
7. Decays, Rescattering



DIS and Photoproduction in e+p

Electron-proton collisions

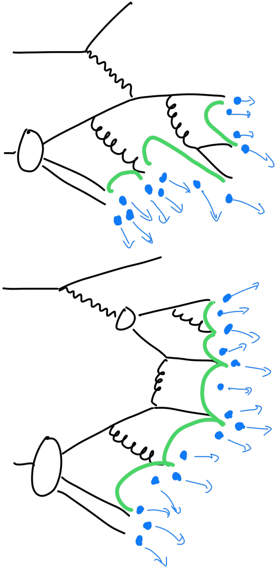
Classified in terms photon virtuality Q^2

Deep inelastic scattering (DIS)

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

Photoproduction (PhP)

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



Event generation in DIS with PYTHIA 8

Hard scattering

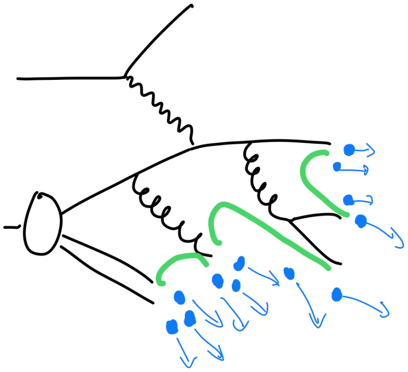
- Convolution between PDFs and matrix element (ME) for partonic scattering

Parton shower

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

Hadronization

- Beam remnants
- String hadronization with colour reconnections
- Decays to stable hadrons



DIS with Pythia

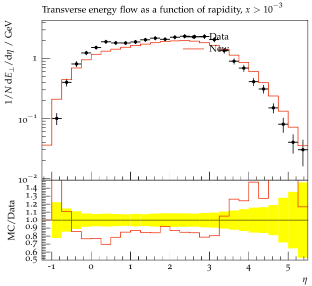
`dipoleRecoil` alternative in Simple Shower

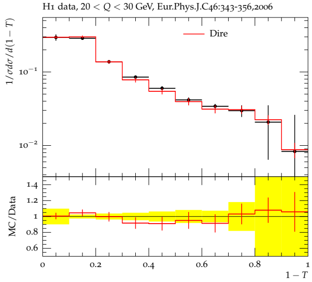
[B. Cabouat and T. Sjöstrand, EPJC 78 (2018 no.3, 226)]

- Replaces two independent DGLAP evolutions of IF/FI dipoles by a coherent dipole evolution
- No PS recoil for the scattered lepton
- Based on tune with the default global-recoil shower without any DIS data

New showers in 8.3

- DIRE [S. Höche, S. Prestel, EPJC 75 (2015) no.9, 461]
- VINCIA [H. Brooks, C. Preuss, P. Skands, JHEP 07 (2020) 032]
- Both applicable to do DIS though tests sparse





Vector boson fusion (VBF)

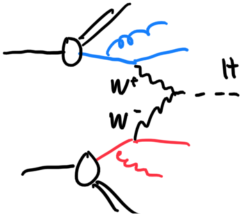
"Double-DIS" process

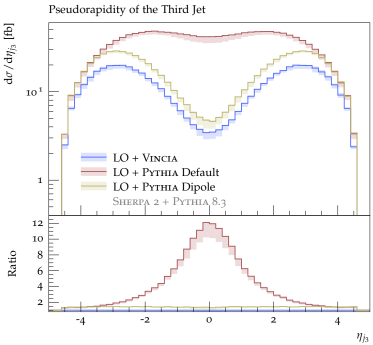
- Two detached colour flows
- No radiation allowed in between

Comparison of different PYTHIA showers

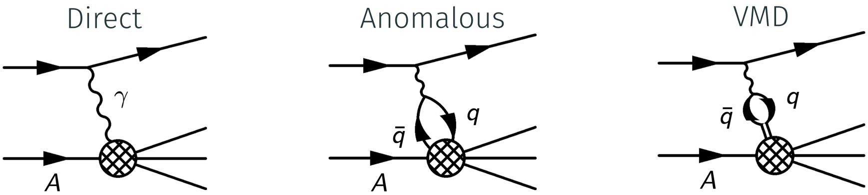
[S. Höche, S. Mrenna. S. Payne, C. T. Preuss, P. Skands, SciPost Phys. 12 (2022) 1, 010]

- At LO third jet from the shower only
- PYTHIA default shower produce radiation also at mid-rapidity
- VINCIA and DIPOLERECOIL show a gap at mid-rapidity, shapes agree well





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

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

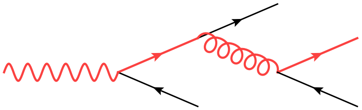
Evolution equation and ISR for resolved photons

ISR probability based on DGLAP evolution

- Add a term corresponding to $\gamma \to q\overline{q}$ 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 only for Simple Shower in PYTHIA



Comparison to HERA dijet photoproduction data

ZEUS dijet measurement

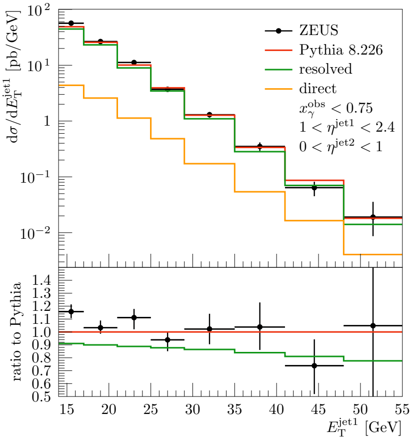
- $Q^2 < 1.0$ GeV^2
- $134 < W_{\gamma p} < 277$ GeV
- $E_T^{\text{jet1}} > 14$ GeV, $E_T^{\text{jet2}} > 11$ GeV
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Two contributions

- Momentum fraction of partons in photon

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

- Sensitivity to process type



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

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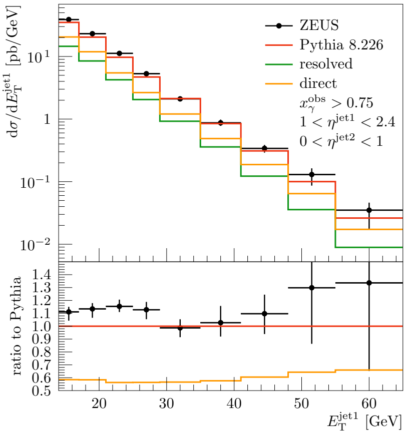
- Sensitivity to process type
- At high-x_γ^{obs} direct processes dominate



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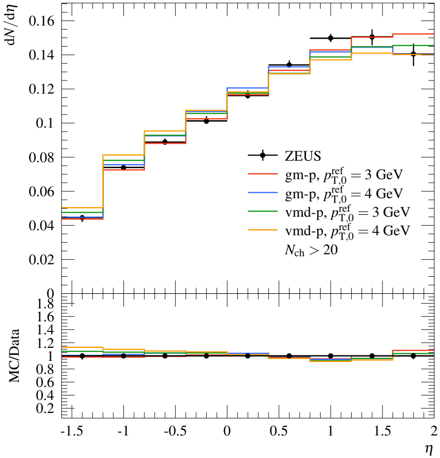
Comparison to ZEUS data for charged hadrons ($N_{ch} > 20$)

Pseudorapidity

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



[ZEUS: JHEP 12 (2021) 102]

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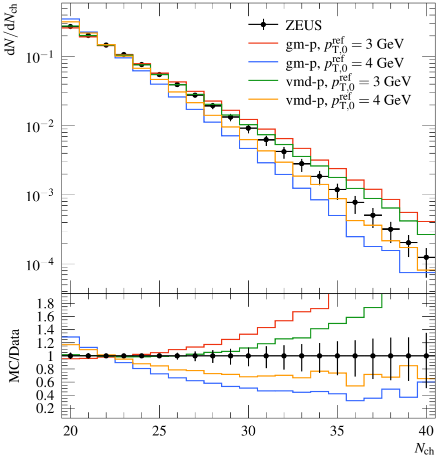
Multiplicity

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



[ZEUS: JHEP 12 (2021) 102]

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

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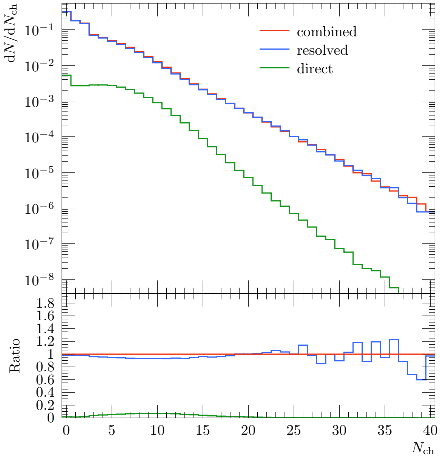
Multiplicity

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



[ZEUS: JHEP 12 (2021) 102]

Photon-induced processes at the LHC

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

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);
  }
};
```

- Create and pass a pointer for this object 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);
```

Kinematics

Kinematically allowed region

- Consider $1 \to 2$ splitting
  - x_{min} from W_{min}, $x_{\text{max}} \approx 1$
  - $Q^2_{\text{min}}(x) \approx \dfrac{x^2 m^2}{(1-x)}$

$\Rightarrow$ Photons from protons larger Q^2

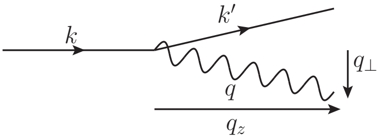
Kinematics derived from x and Q^2

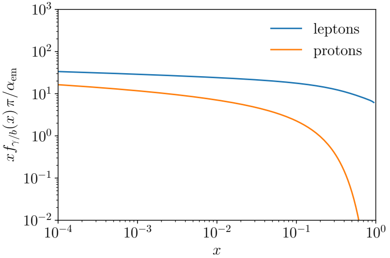
- Finite transverse momentum for photons

$$q_{\mathrm{T}}^2 \propto Q^2$$

$\Rightarrow$ Generate p_{T} also to final state

- How to interface with ME generators?





Possible contributions in p+p

$\gamma\gamma$ with direct (elastic) photons (EE)

- Both photons coherently emitted
- Final state with small (but finite!) p_{T}

Single-dissociative processes (SD)

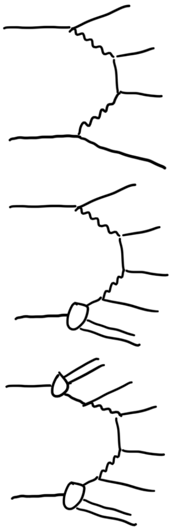
- An elastic photon scatter with a parton
- Parton meaybe a large-Q^2 photon in PDFs
- Other proton breaks up, PS and remnants

Double-dissociative processes (DD)

- Both photons with large Q^2 from PDFs
- As QCD (PS, MPIs) but no colour connection

Resolved photons

- Any QCD process possible

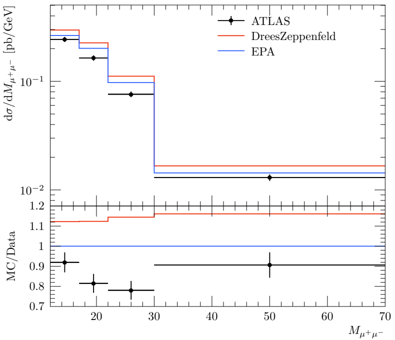


An example process: $\gamma\gamma \to \mu^+\mu^-$

- 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]

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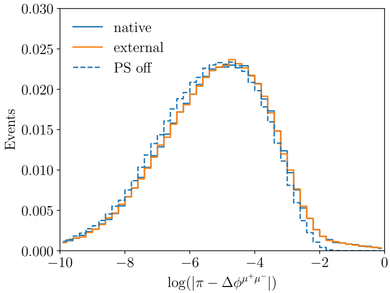
- Implemented natively in Pythia, can also generate with an ME generator (MG5, SC)

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

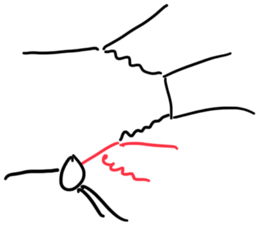


- Needed to tune Pythia primordial k_{T} parameters for external events
- Now (next release) can use Q^2 dependence of the flux

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

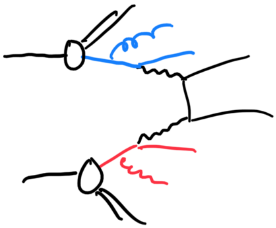
SD contribution

- Now another high-Q^2 photon from PDFs
- Will attach to quark line, possible QCD radiation
- DIS-like IF-dipole, handled properly with `dipoleRecoil` shower option
- No longer back-to-back



DD contribution

- "Double-DIS", no colour connection between the two sides (like in VBF)
- Again, `dipoleRecoil` to make sure no radiation between the systems



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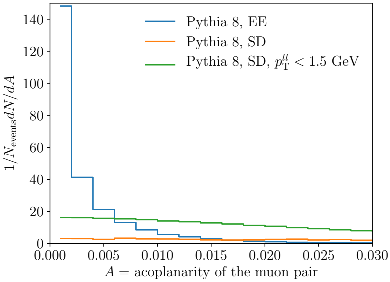


- `main78.cc` provides recommended settings for each of the contributions

Loose ends

Parton shower

- Need **dipoleRecoil** with Simple shower
  - But no specific tuning has been done
  - Tune with **dipoleRecoil** to DIS data?
- How about other PYTHIA showers DIRE and VINCIA?

```
PartonShowers:model = 1,2,3
```

Photon fluxes

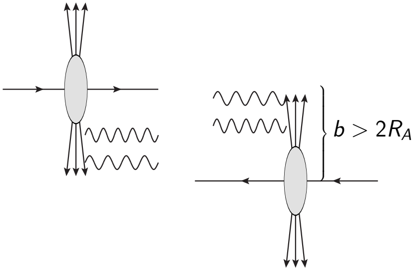
- Ideally use the same photon flux in ME events and PYTHIA for Q^2 sampling
- In addition to flux, one should account for the finite size of protons
  - Hadronic interactions should be removed [Talk by L. Harland-Lang tomorrow]
  - Could also define the flux in the impact-parameter space b

Ultra-peripheral heavy-ion collisions

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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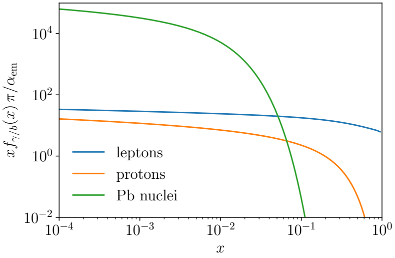


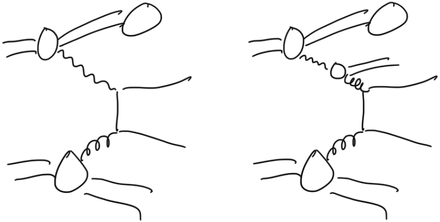
- With heavy nuclei use b-integrated point-like-charge flux

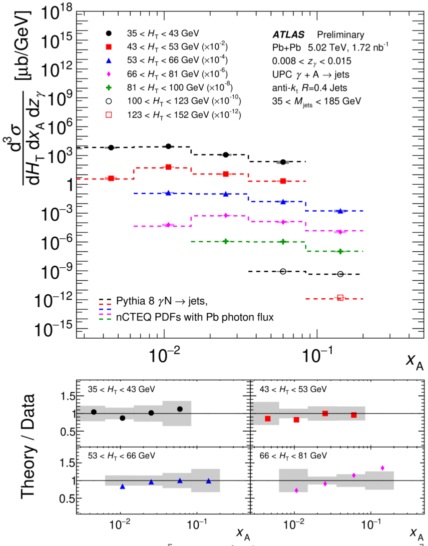
$$f_\gamma^A(x) = \frac{2\alpha_{\rm EM} Z^2}{x\,\pi}\left[\xi\, K_1(\xi)K_0(\xi) - \frac{\xi^2}{2}\left(K_1^2(\xi) - K_0^2(\xi)\right)\right]$$

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

Dijets in ultra-peripheral heavy-ion collisions

- Pythia setup with nucleon target only $\Rightarrow$ 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

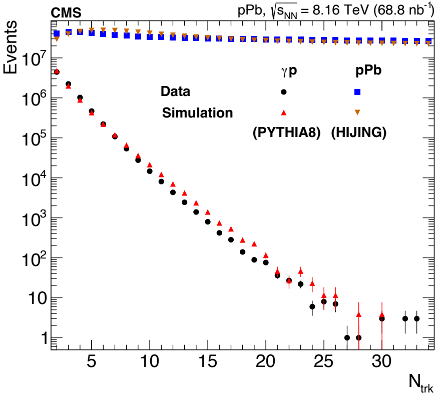




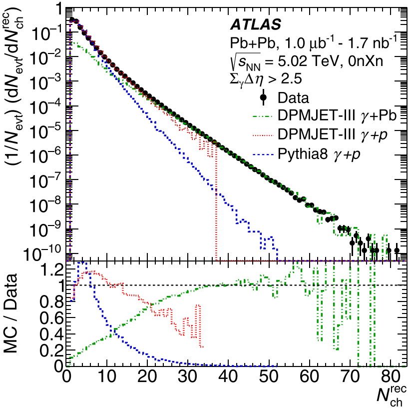
[P. Steinberg @ DIS2023]

Multiplicity distributions in UPCs

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



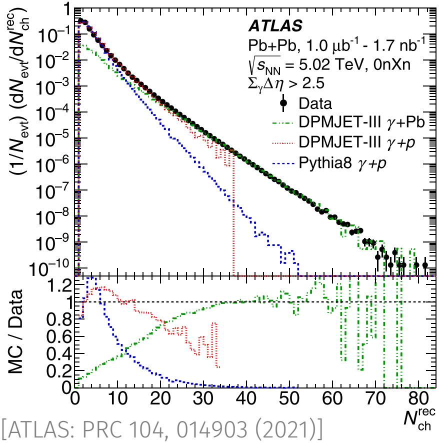
$(\mathrm{Pb} \to \gamma)$+Pb:[ATLAS: PRC 104, 014903 (2021)]



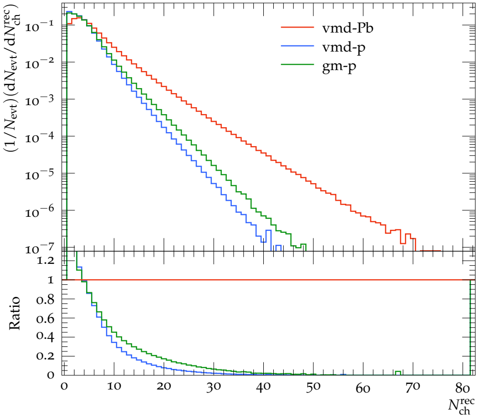
- Multiplicity distribution well reproduced in γp interactions

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

Comparison with data for γ+A (preliminary)



[ATLAS: PRC 104, 014903 (2021)]



- ATLAS data not corrected for efficiency
- Relative increase in multiplicity well in line with the VMD setup

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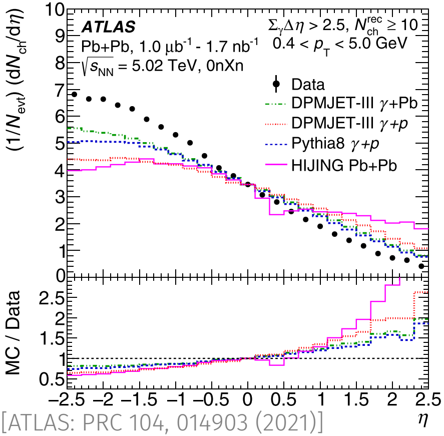

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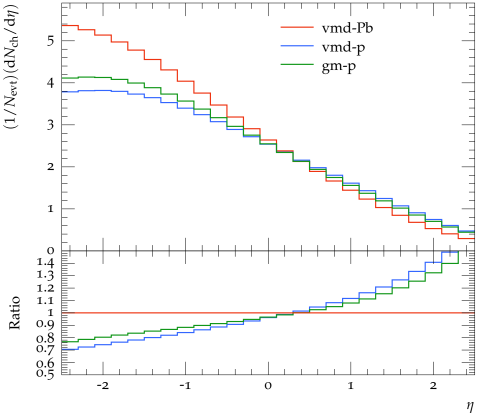


- ATLAS data not corrected for efficiency
- Relative shift in rapidity distribution in line with the VMD setup using Angantyr

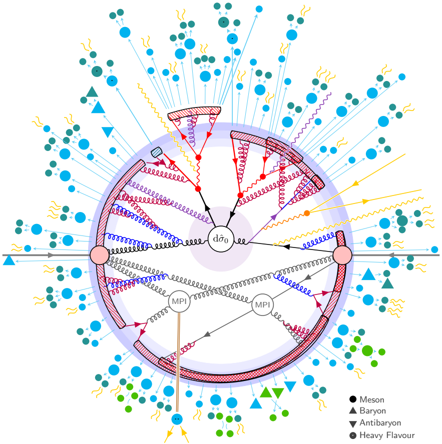
Summary & Outlook

Photon-induced processes in PYTHIA

- In e+p validated setup for photoproduction at HERA
- In p+p can simulate elastic and dissociative contributions
- First steps for full γ+A

Work still needed

- Test and validate different parton showers for DIS
- Finite-size effects for EE
- Different shower implementations for dissociative processes



[figure by P. Skands]

Summary & Outlook

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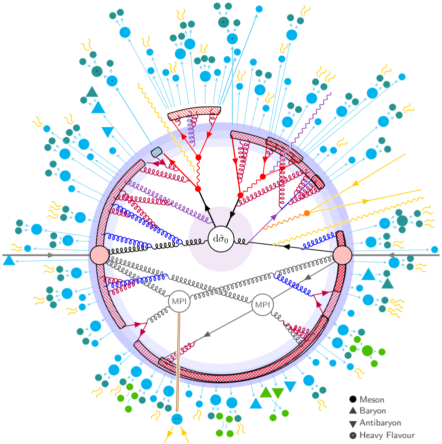


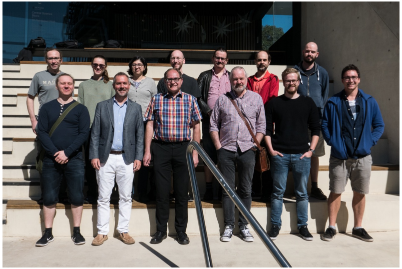
[figure by P. Skands]

What else?

Backup slides

PYTHIA Collaboration

- Christian Bierlich (Lund University)
- 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)
- Stefan Prestel (Lund University)
- 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]

Pythia Collaboration

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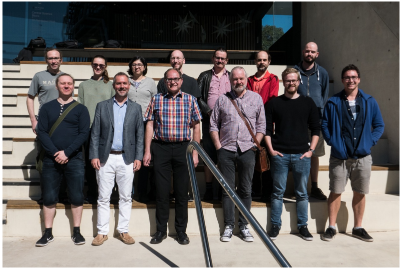


[Pythia meeting in Monash 2019]

- 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

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

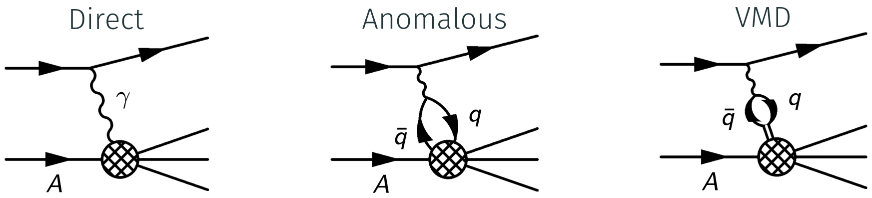
where $P_{i\gamma}(x) = 3\,(x^2 + (1-x)^2)$ for quarks, 0 for gluons (LO)

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

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

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

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



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

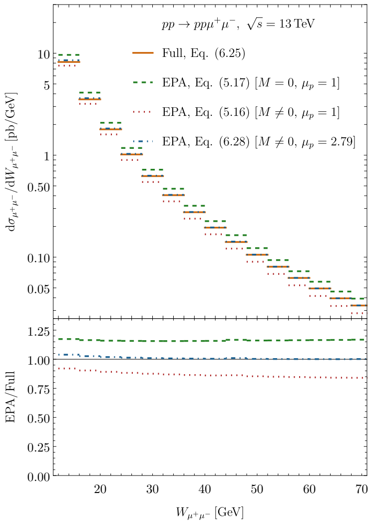
$$c_V = \frac{4\pi\alpha_{\mathrm{EM}}}{f_V^2}$$

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 $pp \to \gamma\gamma \to \mu^+\mu^-$
- 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

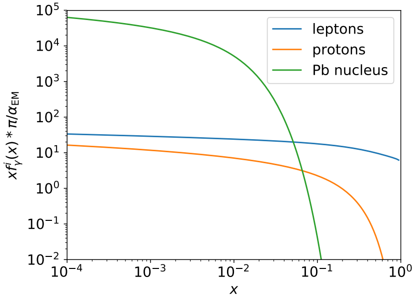


[S. Yrjänheikki, MSc thesis]

Photon fluxes in PYTHIA 8

- Enable γ+p in e+p

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



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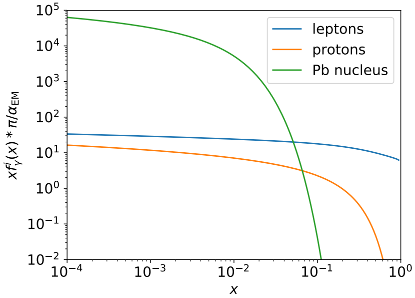

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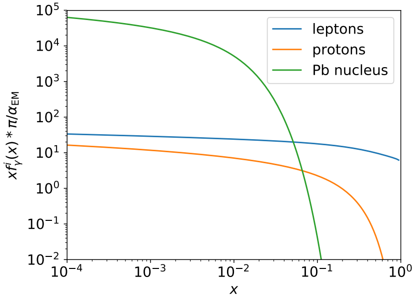
```
pythia.readString("Beams:idA = 2212");
pythia.readString("Beams:idB = 2212");
pythia.readString("PDF:beamA2gamma = on");
```

- 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);
```



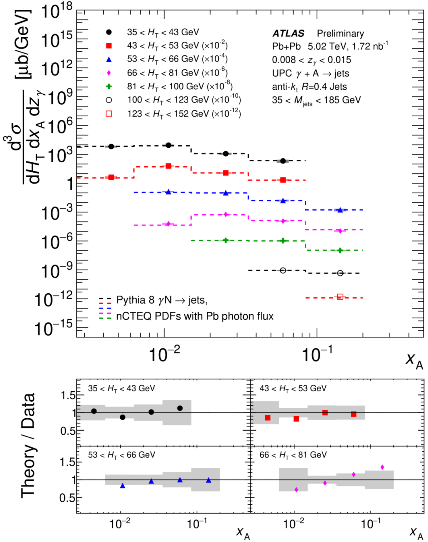
For more examples see `main68.cc`, `main69.cc`, `main70.cc`, `main78.cc` in examples directory

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]

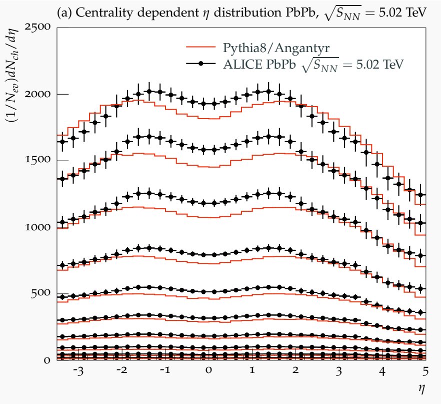
Heavy-ion collisions

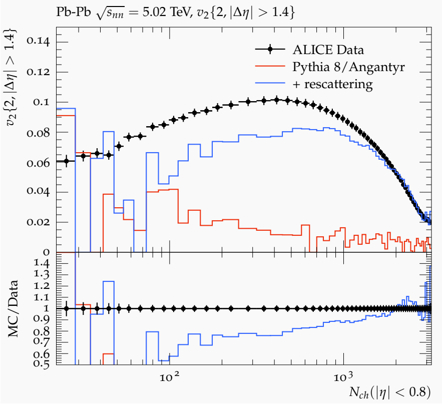
- Angantyr in Pythia provides a full heavy-ion collisions framework

  [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]

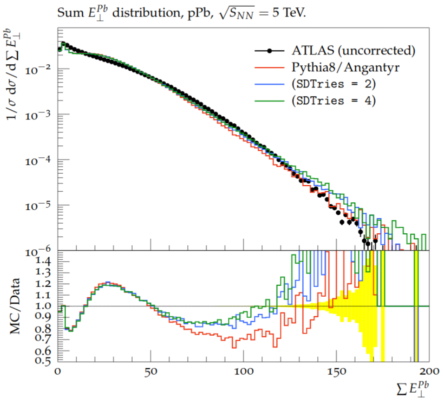


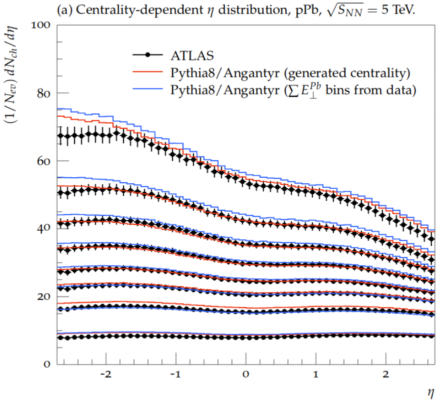


p+A collisions

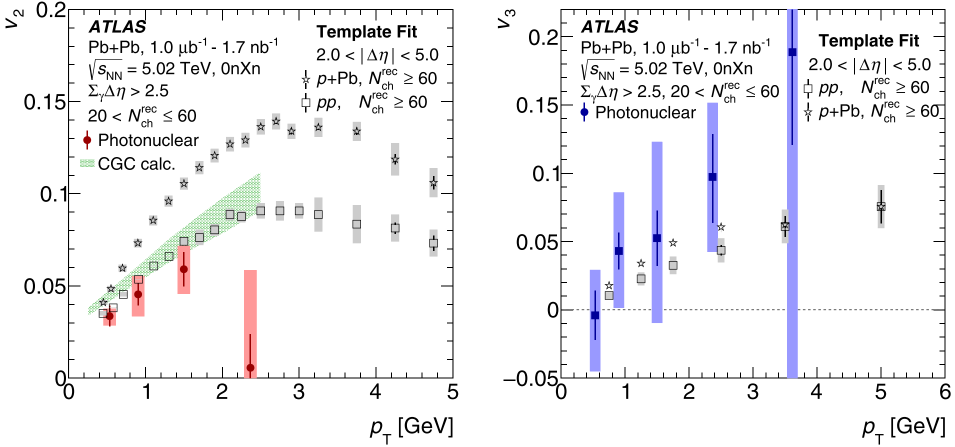
[Bierlich, Gustafson, Lönnblad & Shah: 1806.10820]

- 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

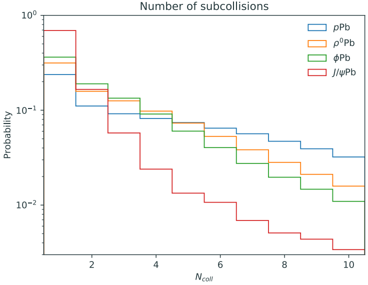


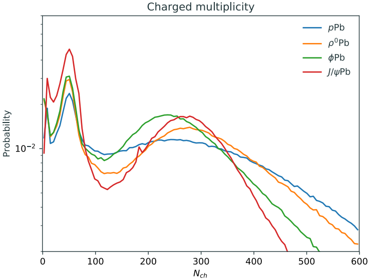
- Non-zero flow coefficients also for γ+Pb
- Expected baseline from MC simulations?

γ+A in PYTHIA 8, work in progress [Marius Utheim]

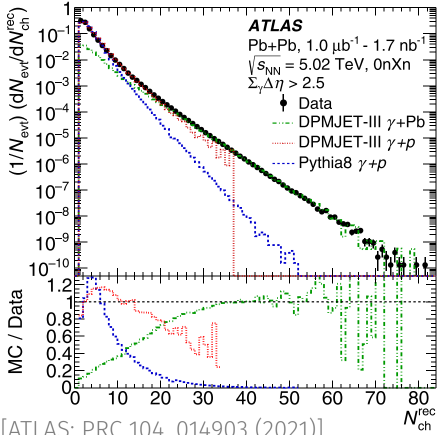
Use Angantyr for interactions with heavy nuclei

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

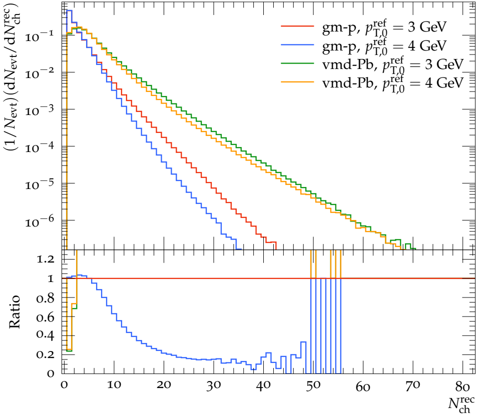




Comparison with data for γ+A (preliminary)



[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

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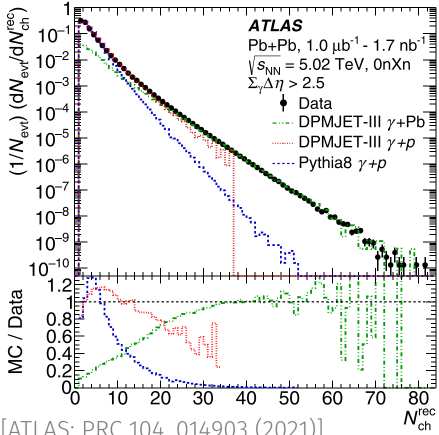

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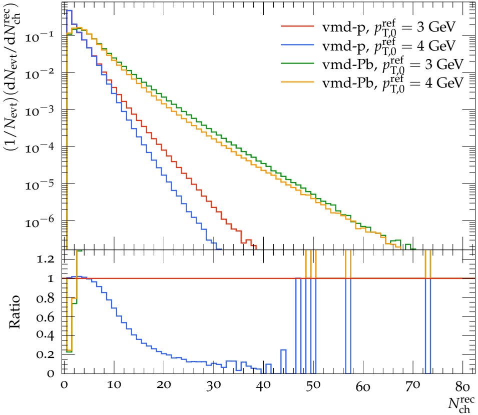

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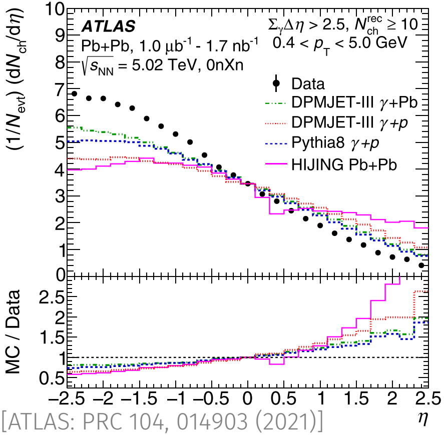

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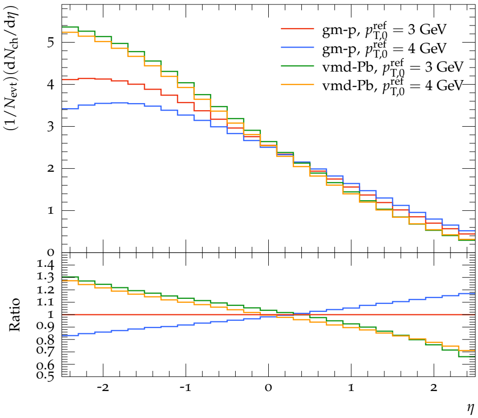

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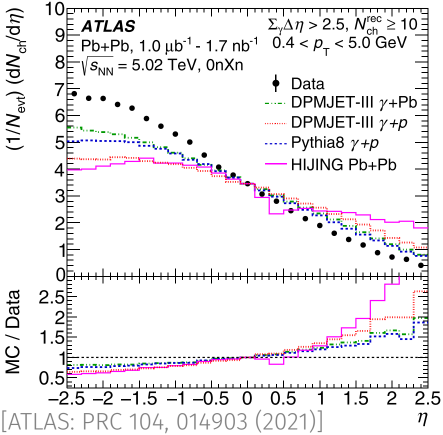

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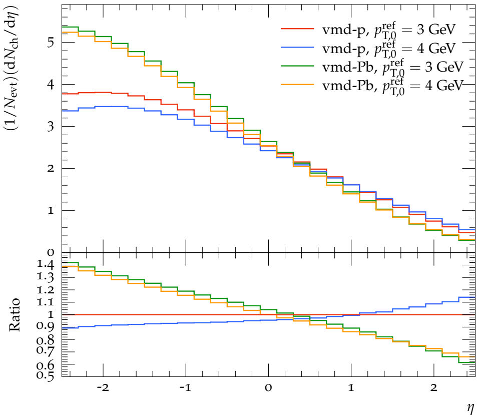

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