Photoproduction

MC4EIC 2024

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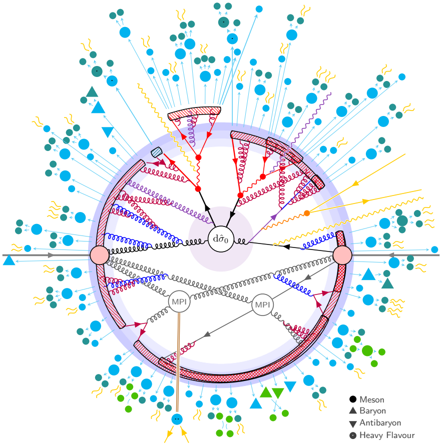
Centre of Excellence in Quark Matter

Outline

- MC modelling of photoproduction and some selected data comparisons

Outline

1. Introduction
2. Structure of (quasi-)real photons
3. Jet production
4. Single-particle observables
5. Multiparticle correlations
6. Summary & Outlook



[figure by P. Skands]

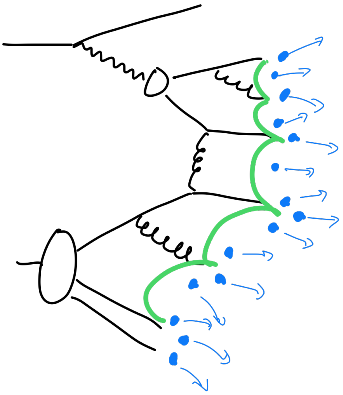
Introduction

Photoproduction

- High-energy collisions with real photons as beam particles
- In the $Q^2 \to 0$ limit can factorize photon flux, f_γ, from the hard interaction

$$\mathrm{d}\sigma^{AB} = f_\gamma^A(x, Q^2) \otimes \mathrm{d}\sigma^{\gamma B}$$

- Can be studied in colliders with charged beams
  - e^+e^-: LEP, γ-γ, also γ^*-γ
  - e-p: HERA, γ-p, EIC: γ-p and γ-A
  - p-p: LHC, γ-p, γ-γ
  - p-A: LHC, γ-p, γ-γ
  - A-A: LHC, γ-A, γ-γ



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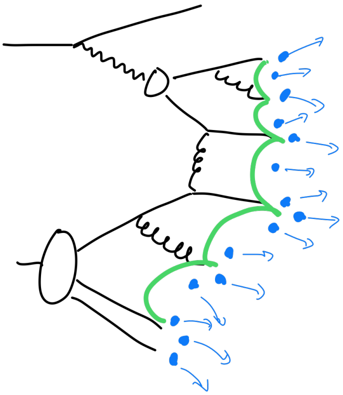


Equivalent photon approximation

Photon fluxes for different beams

- In case of a point-like lepton we have

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

- For protons need to account the form factor

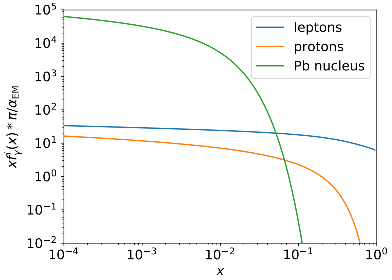
$$f_\gamma^p(x, Q^2) = \frac{\alpha_{\rm em}}{2\pi} \frac{(1+(1-x)^2)}{x} \frac{1}{Q^2} \frac{1}{(1+Q^2/Q_0^2)^4}$$

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

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

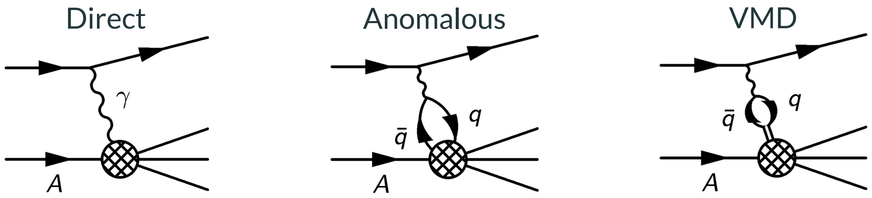
$$f_\gamma^A(x) = \frac{2\alpha_{\rm EM} Z^2}{x\,\pi} \left[\xi\, K_1(\xi) K_0(\xi) - \frac{\xi^2}{2}\left(K_1^2(\xi) - K_0^2(\xi)\right)\right]$$

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



Structure of real photons

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



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

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

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

Factorized cross section

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

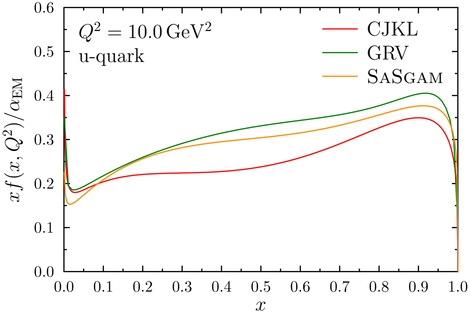
PDFs for resolved photons

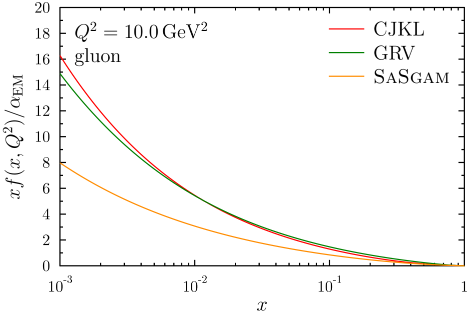
DGLAP equation for photons

- 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)





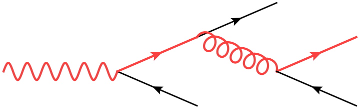
Evolution equation and ISR for resolved photons

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



Jet photoproduction

Jet photoproduction

Factorize the cross section

- Direct processes: Convolute photon flux f_γ with proton PDFs f_i^p and partonic coefficient functions $d\hat{\sigma}$

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

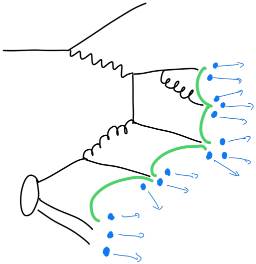
- Resolved processes: Convolute also with photon PDFs

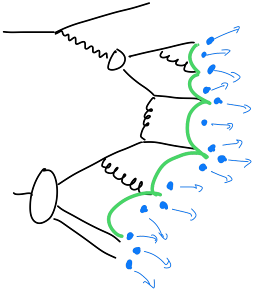
$$d\sigma^{ep\to kl+X} = f_\gamma^e(x,Q^2) \otimes f_i^\gamma(x_\gamma,\mu^2) \otimes f_j^p(x_p,\mu^2) \otimes d\sigma^{ij\to kl}$$

- In case of γ-γ convolute with two photon fluxes

Generate parton showers and MPIs for resolved events

- Sample x and Q^2, setup γ-p sub-system with $W_{\gamma p}$
- Evolve γ-p (γ-γ) as any hadronic collision (with MPIs)
- Add beam remants for resolved photons

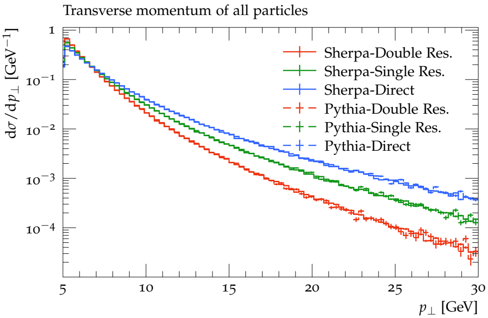


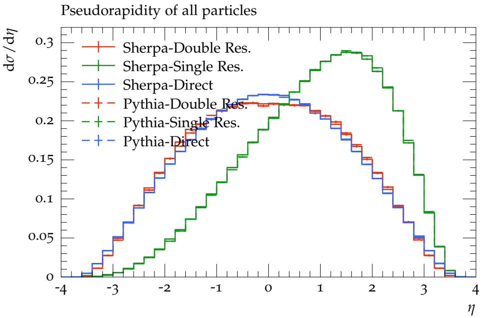


Jet photoproduction

A comparison study between Herwig, Sherpa and Pythia for jet photoproduction

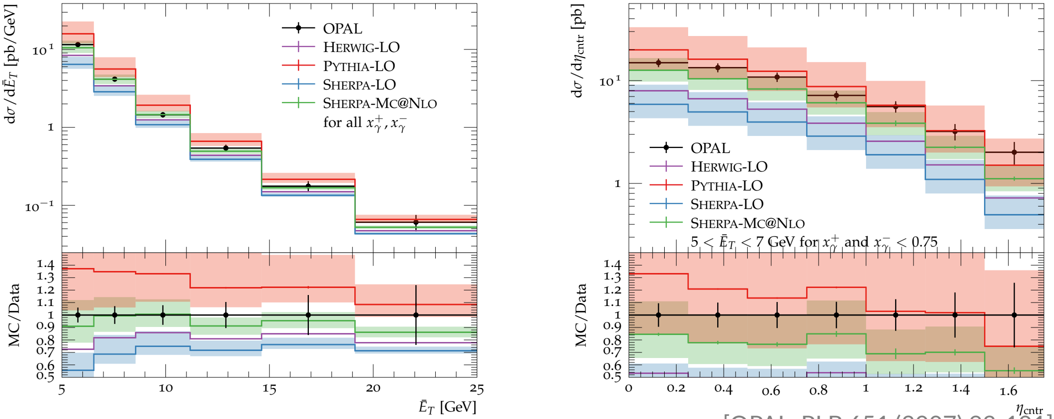
[I. Helenius, P. Meinzinger, S. Plätzer, P. Richardson: in progress]





- Start with hard-process partons in LEP-like setup
- Pythia and Sherpa in agreement when identical
  α_s, PDFs, photon flux, sub-processes with massive partons...

Jet photoproduction in LEP [I. Helenius, P. Meinzinger, S. Plätzer, P. Richardson: in progress]



[OPAL: PLB 651 (2007) 92-101]

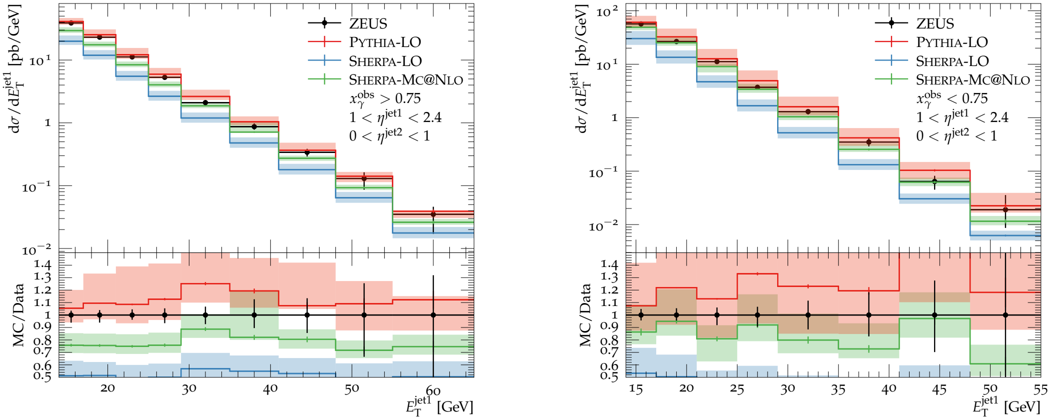
- Large LO $\rightarrow$ NLO correction in Sherpa, uncertainty from scale variations
- Herwig LO close to Sherpa LO, NLO with matchbox underway
- Pythia result with highest cross section, still within the uncertainties

Jet photoproduction in LEP [I. Helenius, P. Meinzinger, S. Plätzer, P. Richardson: in progress]

- Summary of the modelling differences between the generators

Property	Pythia	Sherpa	Herwig
Flux	LL	NLL	LL
$\alpha_s(M_Z^2)$	0.130, 1-loop running	0.118, 3-loop running	
PDFs	CJKL	SAS2M	SAS2M
Remnants	forced splittings/PS rejection	PS rejection	forced splitting
$\gamma \to q\bar{q}$ Splitting	yes	no	no
MPI tuning	preliminary γ-p/γ-γ tune	untuned	untuned

Jet photoproduction in HERA [I. Helenius, P. Meinzinger, S. Plätzer, P. Richardson: in progress]

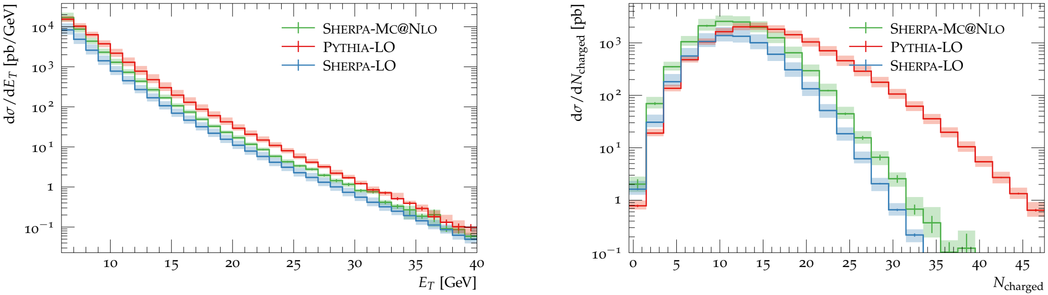


[ZEUS: EPJC 23 (2002) 615-631]

- Similar hierarchy as for LEP comparisons
- Herwig results on their way

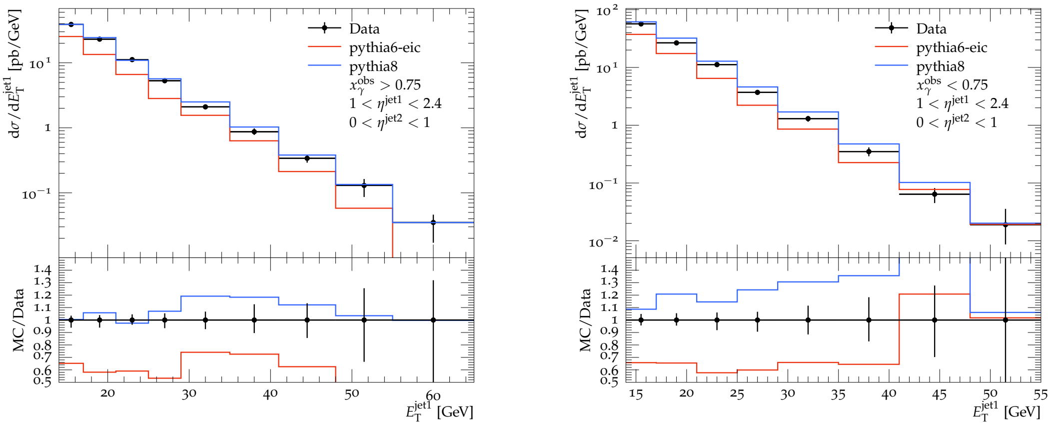
Jet photoproduction in EIC

[I. Helenius, P. Meinzinger, S. Plätzer, P. Richardson: in progress]



- We set up a Rivet analysis with highest-energy EIC-kinematics with similar jet reconstruction as in HERA
- Similar observations in jet E_T spectra as with HERA kinematics
- Large differences in multiplicity distribution (lack of tuning)

Jet photoproduction in HERA



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

- Possible to run Rivet analyses for Pythia 6 provided in the EIC MCEG GitLab
- Enable systematic comparisons with the modern generators

Single-particle observables

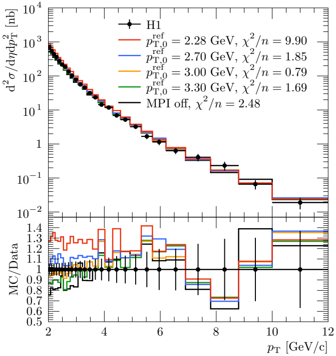
Charged-particle production in HERA

Single-inclusive hadrons

- Allows to study events at lower p_T
- More sensitive to hadronization and MPI effects than inclusive-/di-jet data
- May require soft QCD modelling

H1 analysis

- Photon flux integrated out, data for γ-p at $\langle W_{\gamma p} \rangle \approx 200$ GeV
- Rivet routine added in 3.1.10 release



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

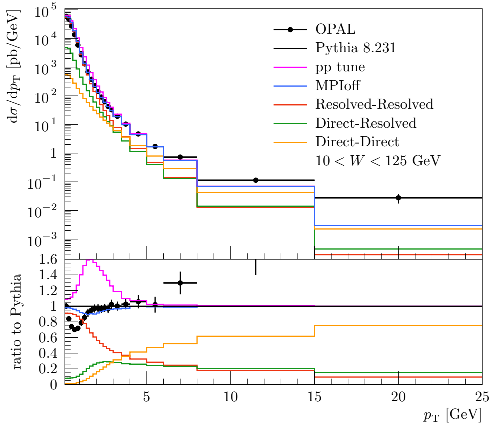
Charged-particle production in LEP

Single-inclusive hadrons

- Double-resolved photons dominate at low p_T, only these have MPIs
- Single-resolved contribute $\sim$ 20%
- Direct processes take over above $p_T \sim 5$ GeV/c

OPAL data

- Again potential to constrain MPI parameters
- Rivet routine added in 3.1.10 release



[OPAL: PLB 651 (2007) 92-101]

Charged-particle production in LEP

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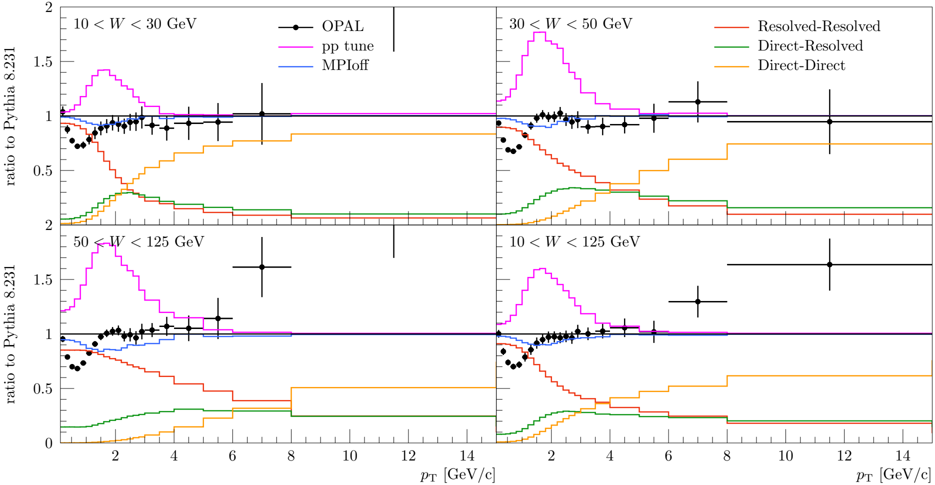


- A handle for energy dependence (LEP/LOG-tune in Pythia)

Multi-particle correlations

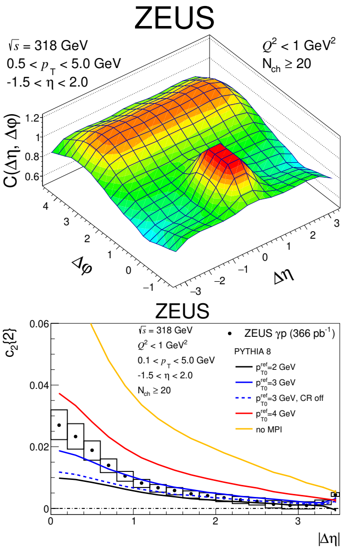
Multi-particle correlations

Correlations can arise from

- Jets, particle decays, rescattering
- Initial state effects, eg. CGC
- Final-state effects
  - hydrodynamic evolution of quark-gluon plasma,
  - Collectivity in hadronization, eg. string interactions

ZEUS analysis

- High-multiplicity events ($N_{ch} > 20$)
- Reasonable agreement with MPIs in Pythia
- Rivet routine in progress



[ZEUS: JHEP 12 (2021) 102]

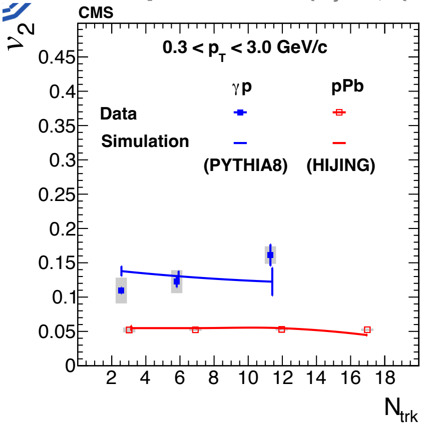
Collectivity in γ-p at the LHC

CMS analysis for p+Pb

[CMS: Murillo Quijada, QM2022]

- Pb provides photon flux, γ-p at energies similar to HERA and beyond
- Fourier fit to $dN/d\Delta\phi$ to obtain v_2
- Finite v_2 for γ-p, in line with Pythia
- No explicit collectivity included in the model

$\Rightarrow$ No collective behaviour observed



Two-particle correlations in γ-A by ATLAS

- 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

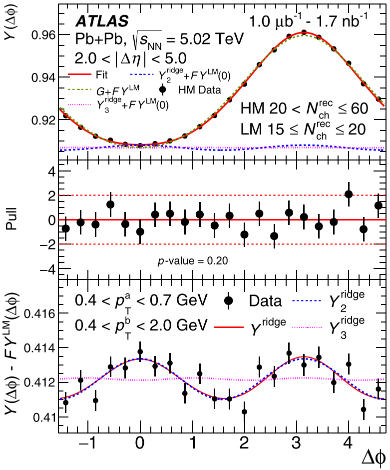
$$Y^{\mathrm{LM}}(\Delta\phi) = c_0 + 2 \cdot \sum_{n=1}^{4} c_n \cos(n\Delta\phi)$$

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

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

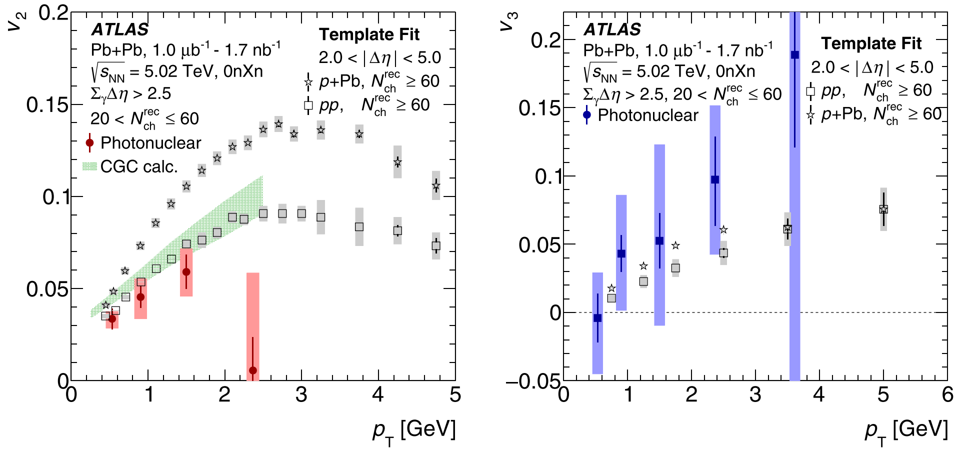
Free parameters c_n, $v_{n,n}$, F, G

- Should subtract the "non-flow" contributions



[ATLAS: PRC 104, 014903 (2021)]

ATLAS data for v_n in γ+Pb



- Non-zero flow coefficients for γ+Pb, even after the template fit
- Expected baseline from MC simulations? Hydro or hadronization effect?

Summary & Outlook

Summary

- Photoproduction provides access to rich structure of real photons
- Modern event generators can handle different contributions
- Not only HERA data available, also LEP and LHC should be included
- Number of Rivet available analyses has increased in recent years

  $\Rightarrow$ Enables systematic and global tuning of MC generator parameters

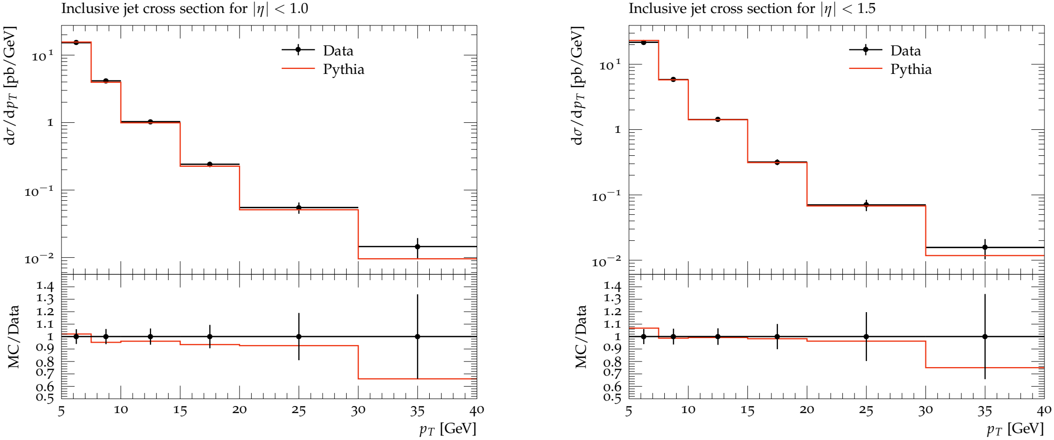
Open questions

- Obviously still important Rivet analysis missing, which ones?
- Interplay with photon PDF fitting and MPIs?
- UPCs at the LHC provides first collider-energy γ-A

  $\Rightarrow$ Origin of the collective behaviour? Relevant for EIC?

Backup slides

Jet photoproduction in LEP



[OPAL: PLB658 (2008) 185-192, 2008]

- Also a more recent jet analysis in γ-γ from LEP available
- Only p_T with varying η range