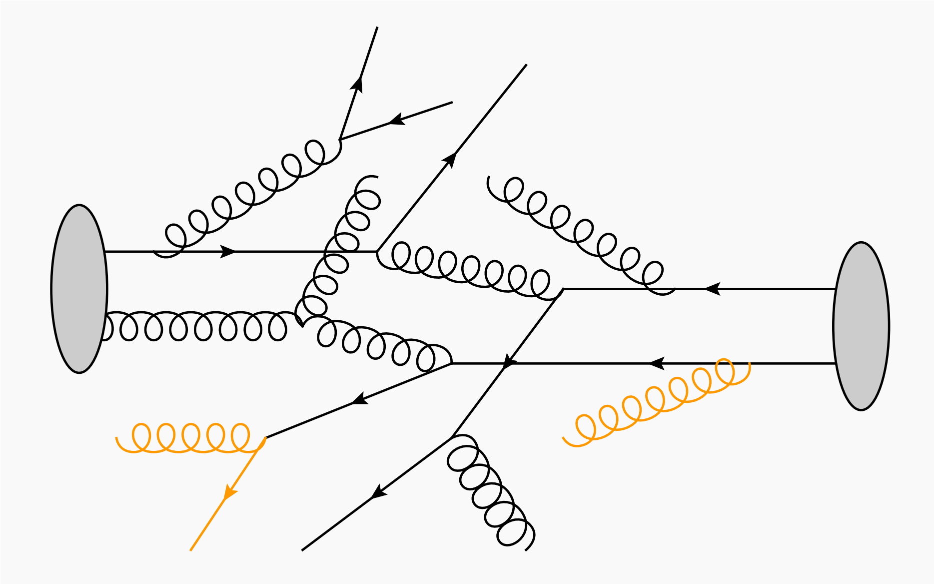
Investigation of the underlying event in photon-initiated processes

J.M. Butterworth (UCL), I. Helenius (University of Jyväskylä),
J.J. Juan Castella (University of Cambridge),
S. Sanjrani (University of Bristol) and **M. Wing (UCL)**

- Motivation
- Approach: use of Pythia, Rivet, MPI models and data
- Comparison to data from e^+e^- and *ep* collisions
- "Tunes" to data from e^+e^- and *ep* collisions
- Summary and outlook

Motivation — high-energy hadronic interactions

- The underlying event or multi-parton interactions (MPIs) play a significant role in high-energy hadronic scattering.
- Much has been understood in proton−(anti)proton collisions through
  - Lots of data at different centre-of-mass energies, different kinematic regions, etc.
  - Dedicated measurements
  - Model development
  - Documentation and preservation of measurements
  - Tuning of models to data
  - Encapsulating our understanding in Monte Carlo simulations.

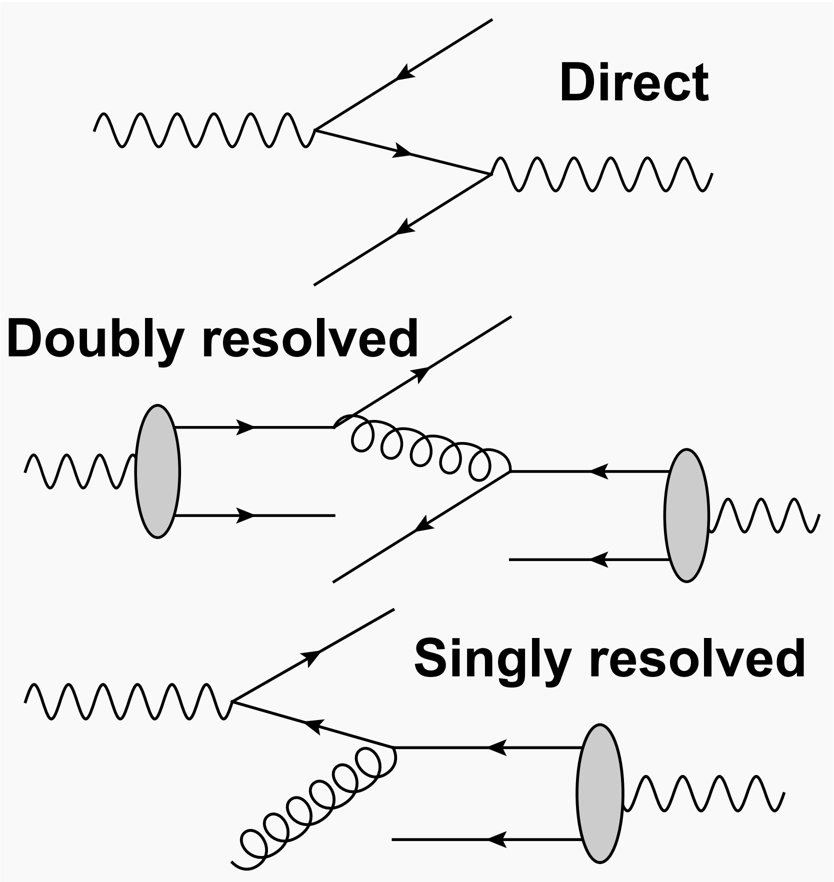


- What about photon-initiated processes ?

Motivation — high-energy photon interactions

- Collisions with photons do not just involve point-like photons
  - Direct processes
  - No MPIs.
- We can have photons which develop a structure
  - Resolved photons
  - Photons fluctuate to a hadronic state
  - Partonic content from photon PDFs
  - Can have MPIs in doubly-resolved processes.

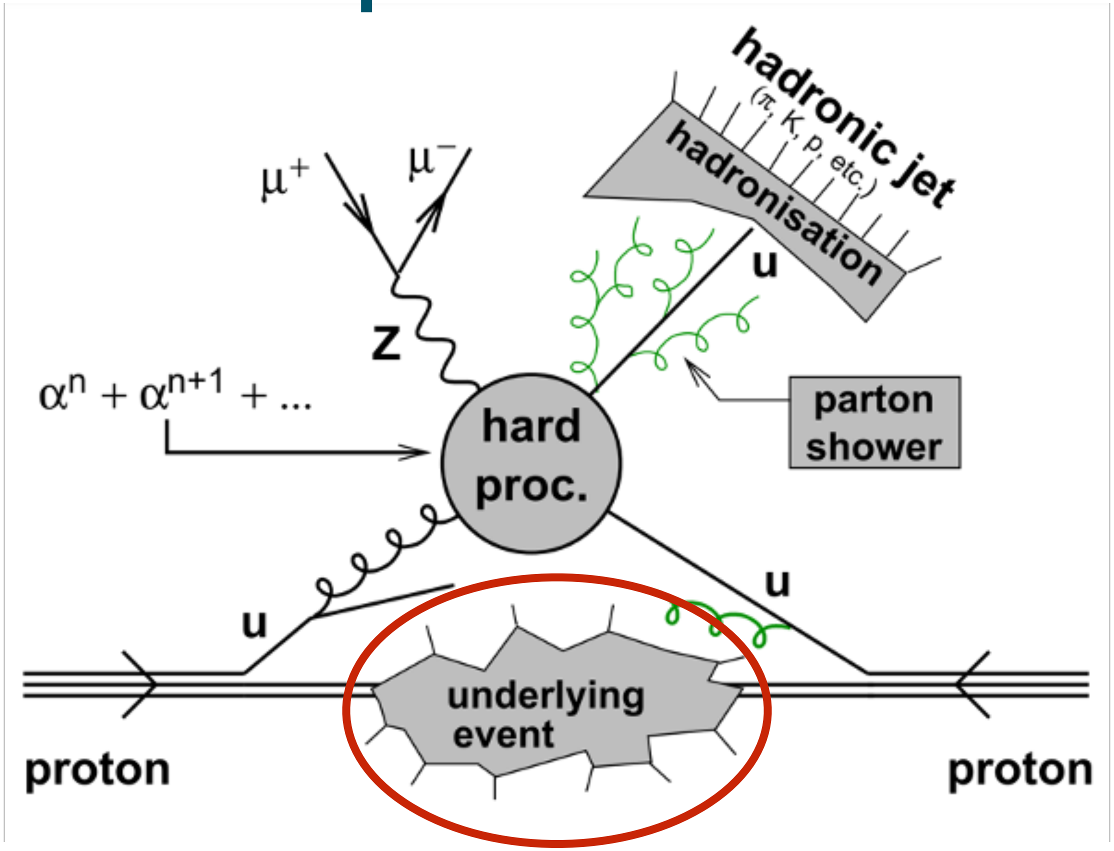
Photon−photon collisions



Motivation — high-energy photon interactions

- Understanding photon-initiated processes is important
  - *γγ* collisions in e^+e^- colliders
  - Photoproduction, *γp*, in *ep/A* collisions.
- We can learn a lot from LEP and HERA data
  - Various measurements sensitive to the underlying event
  - Models can be used to compare to the data.
- This can impact on our understanding for future e^+e^- colliders and future *ep/A* colliders like the EIC.
- Also relevant for *γγ* at the LHC*.*
- And for *γp/A* interactions at the LHC.

Motivation — multi-parton interactions

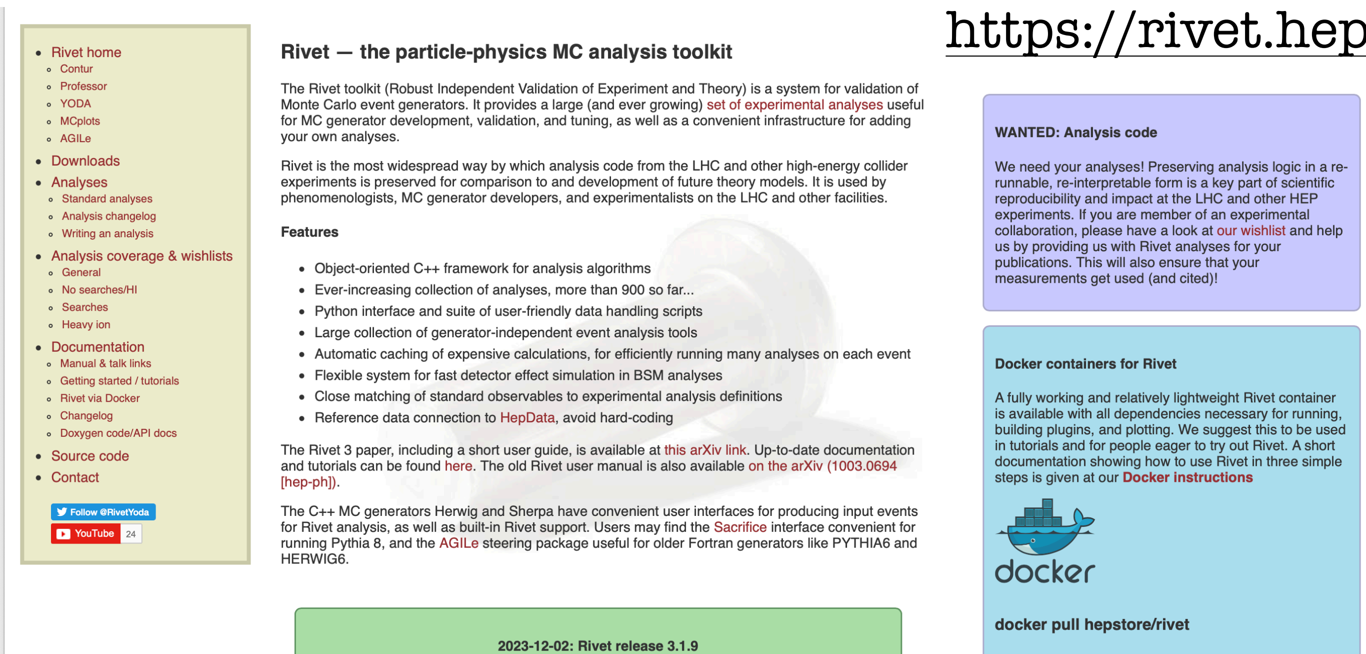


- MPIs contribute to the underlying event activity.
- Dominated by low transverse momentum, “soft”, process.
- Modelled with Monte Carlo generators, here using Pythia.
- What is the nature of multi-parton interactions in photon-initiated processes ?

Approach

- Many comparisons of MC models to *pp/p$\bar{p}$* data and tunes of parameters in the MPI model
  - Generally describe data well, including energy dependence.
  - How does the same model describe *γγ* and *γp* data?
- Use Pythia8 MC with MPI model.
- Use Rivet framework to access numerous results from data and compare with Pythia

https://rivet.hepforge.org/



Approach

- Including more routines in Rivet covering more *γγ* and *γp* analyses and wider phase space.
- Considered data:
  - Particle production at LEP
  - Dijet production at LEP
  - Particle production at HERA
  - Jet production at HERA, both low E_T and high E_T
- Considered several options for MPIs in Pythia.
- Detailed comparisons and some best descriptions, but not really “tuned”.

MPI models

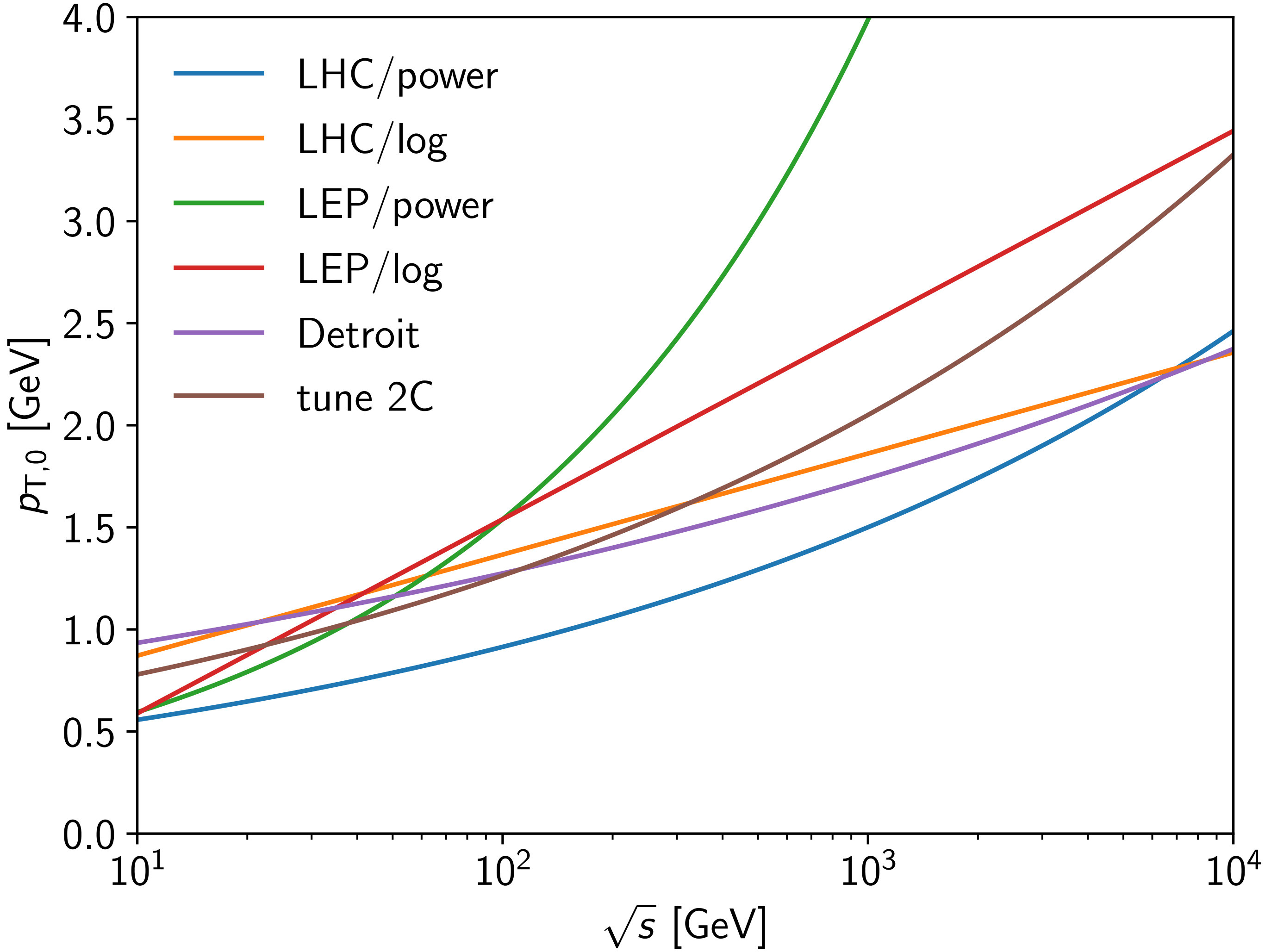
- LHC/POWER or Monash tune: default in Pythia for *pp* (and *ep*).
- LEP/LOG: default $\gamma\gamma$ tune.
- LHC/LOG: LHC/POWER but p_{T0} scaling law is logarithmic
- LEP/POWER: LEP/LOG but p_{T0} scaling law is power
- Detroit: tune to describe RHIC data, *pp* collisions at *200 GeV*
- 2C: tune to describe CDF data

$$p_{T0} = p_{T0}^{ref} + \alpha \ln \frac{\sqrt{s}}{\sqrt{s^{ref}}}$$

$$p_{T0} = p_{T0}^{ref} \left(\frac{\sqrt{s}}{\sqrt{s^{ref}}} \right)^{\alpha}$$

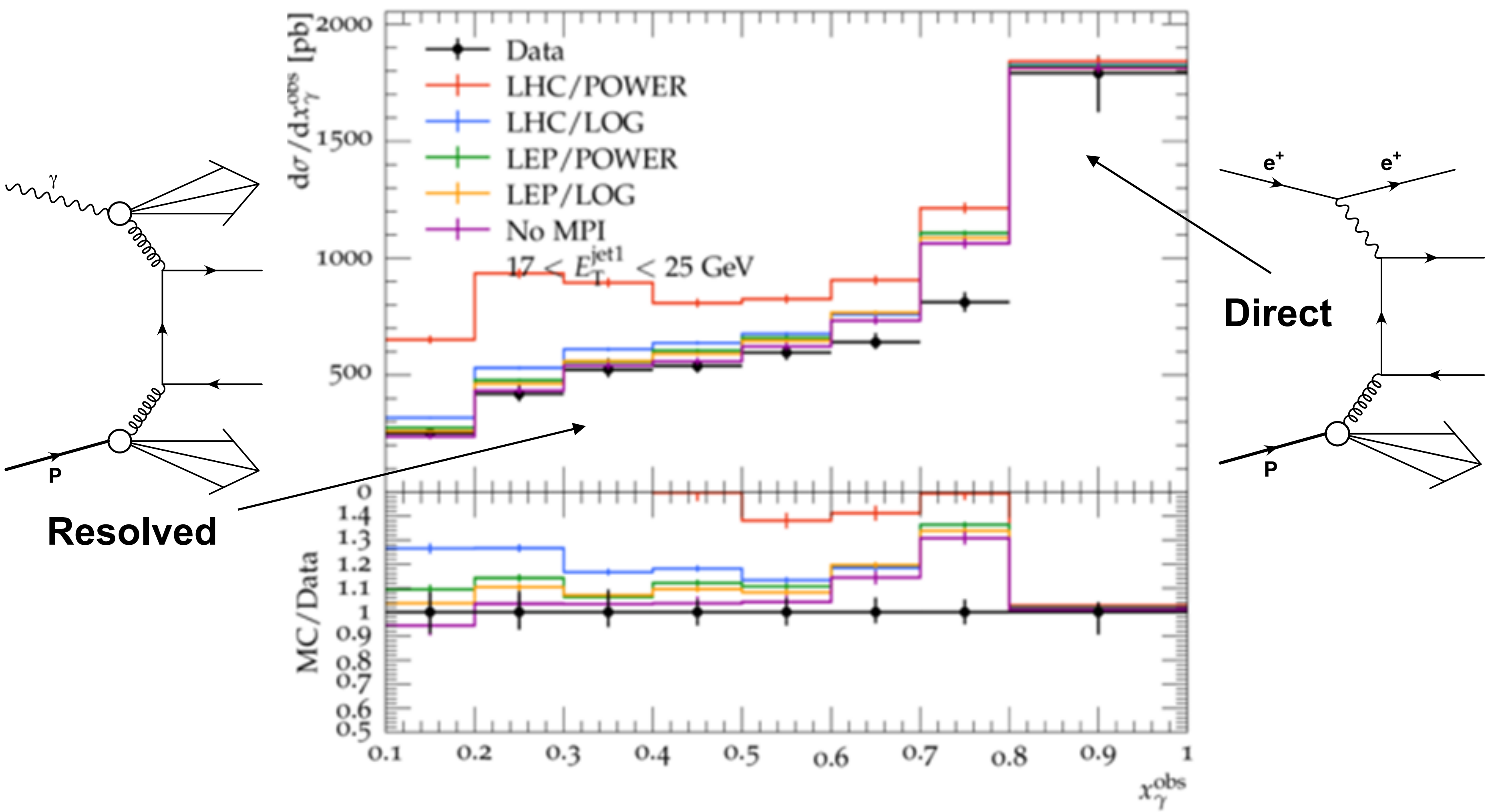
Parameter	LHC	LEP
p_{T0}^{ref}	2.28 GeV	1.54 GeV
$\sqrt{s^{ref}}$	7000 GeV	100 GeV
α	0.215	0.413
Scaling	Power	Logarithmic

MPI models



4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$p_{T,0}$ [GeV]
LHC/power
LHC/log
LEP/power
LEP/log
Detroit
tune 2C
10^1
10^2
10^3
10^4
$\sqrt{s}$ [GeV]

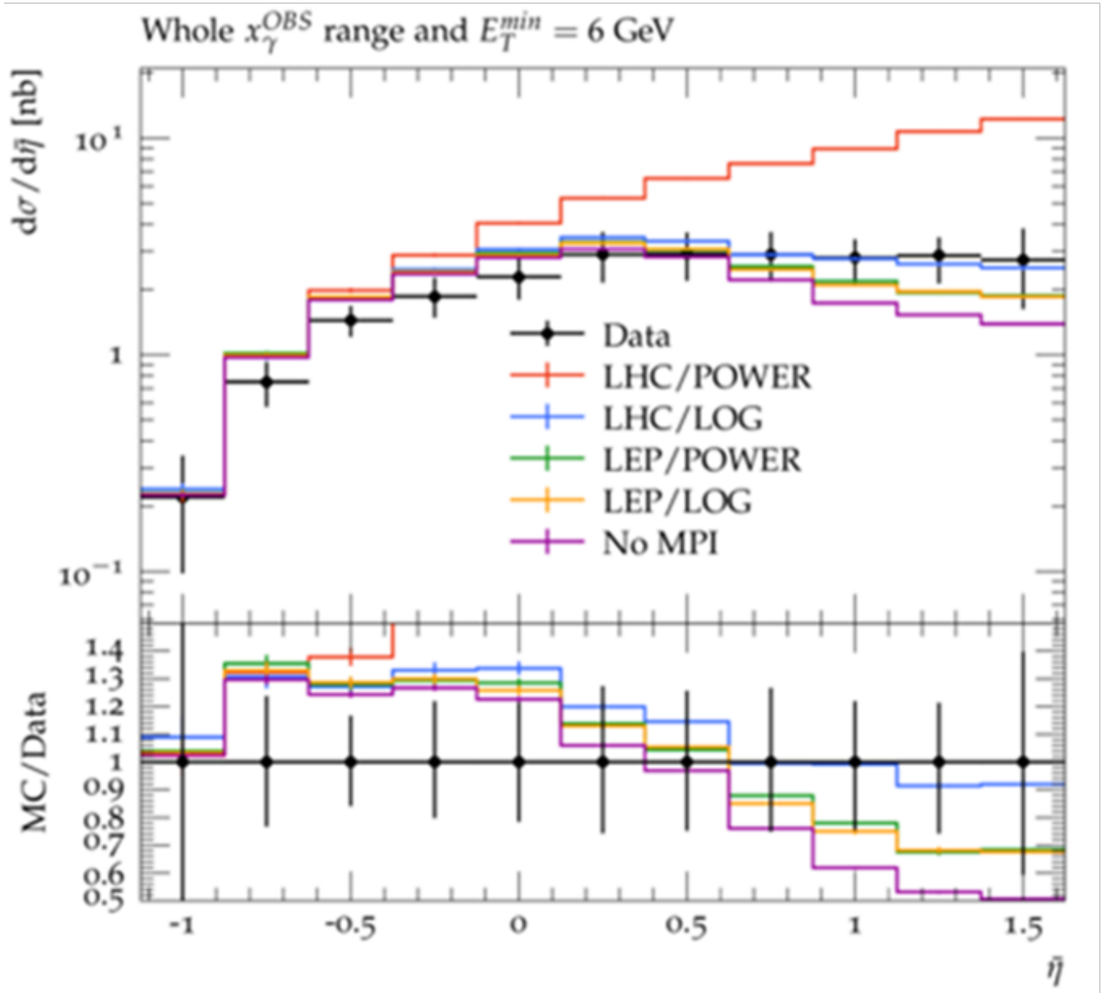
Default models compared to *ep* dijet data



Do not use the default Pythia LHC/POWER MPI model !

ZEUS Coll., EPJ **C23** (2002) 614

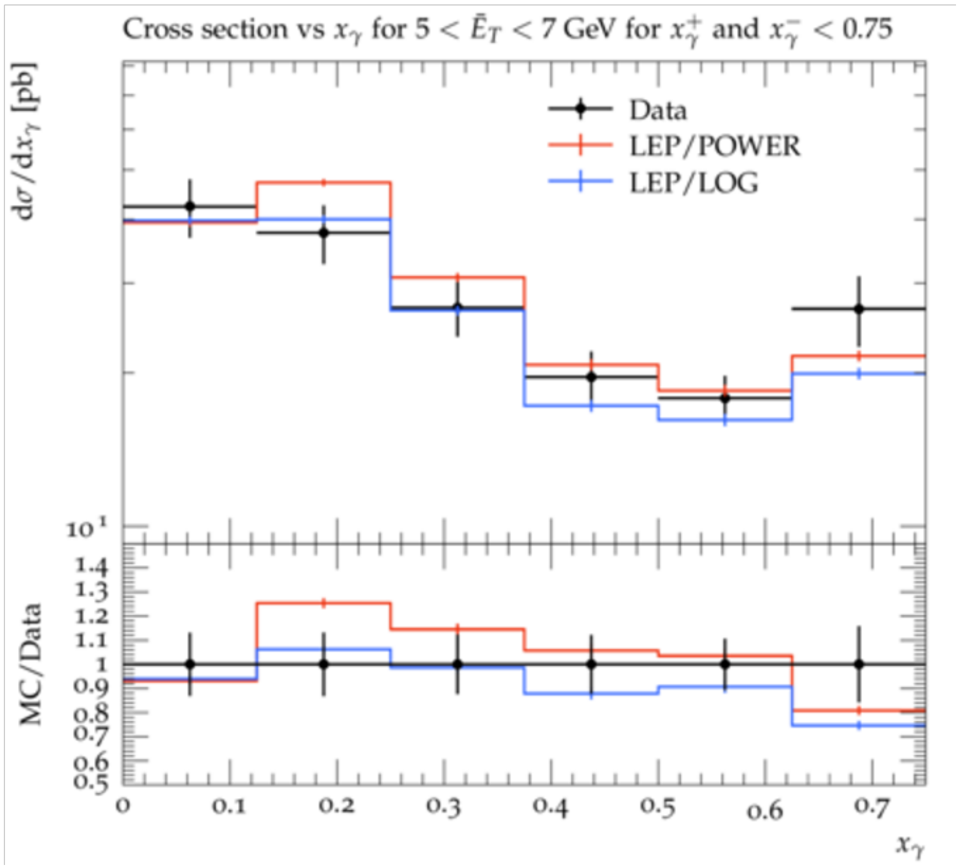
Default models compared to *ep* dijet data—lower E_T

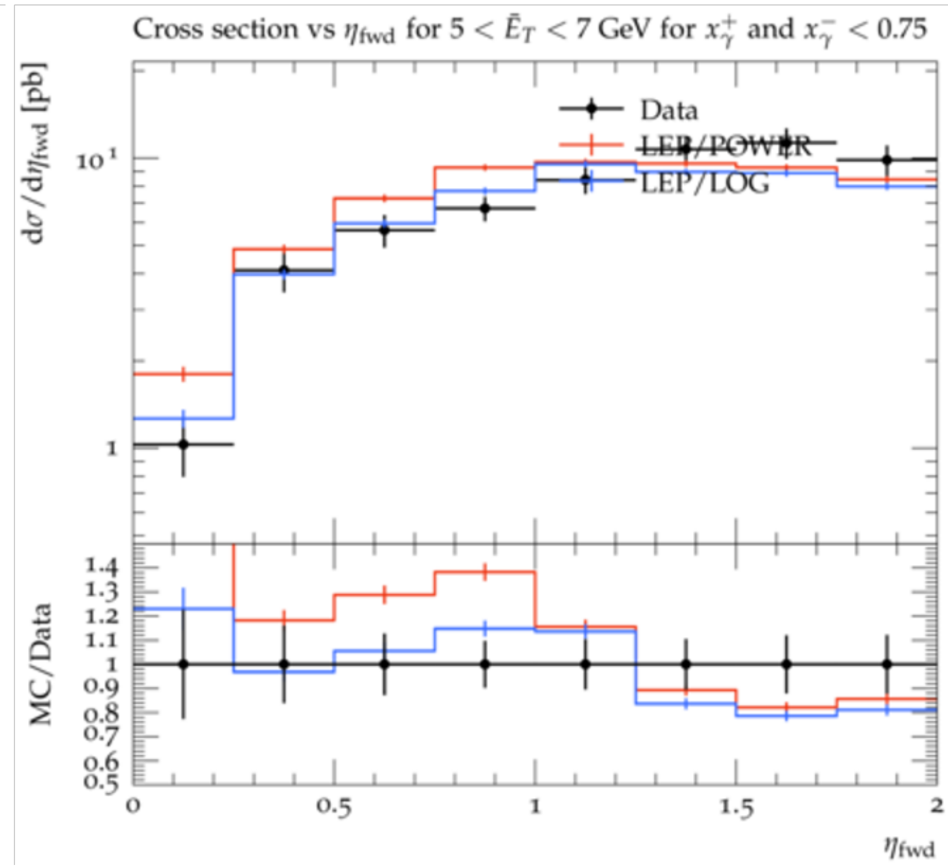


LHC/POWER too high and No MPI too low.

ZEUS Coll., EPJ **C1** (1998) 109

Default models compared to $\gamma\gamma$ dijet data



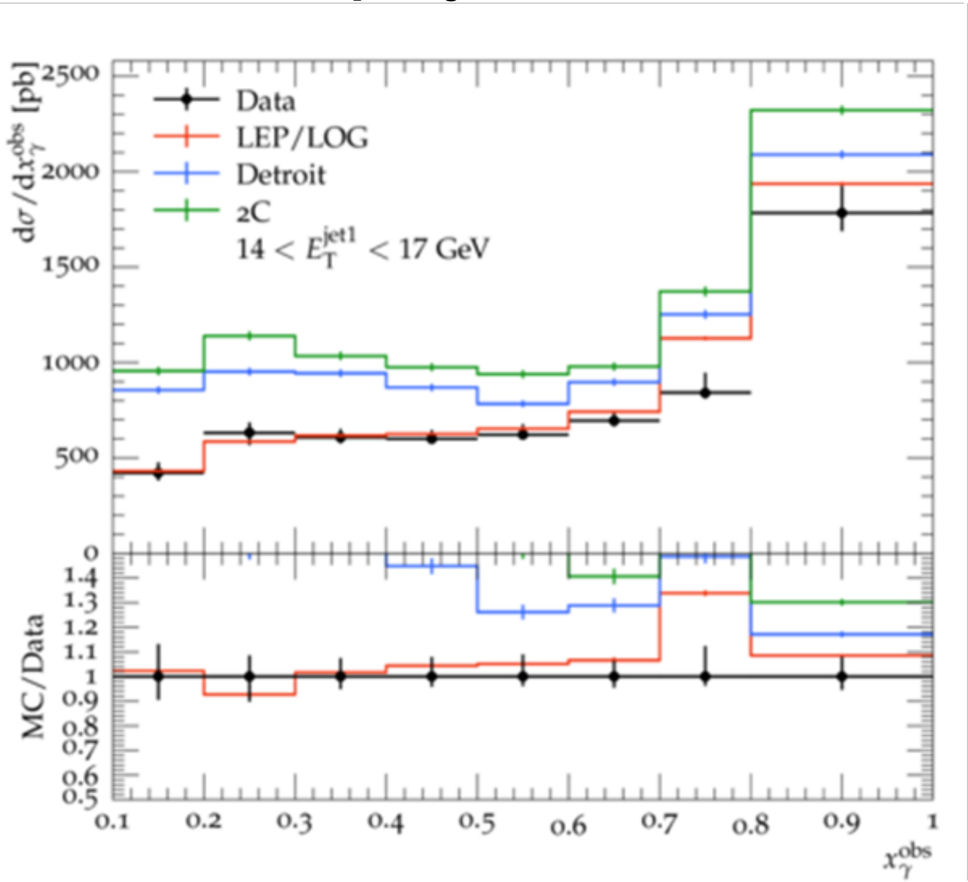


Doubly-resolved $\gamma\gamma$ data well described by LEP models and better by LEP/LOG

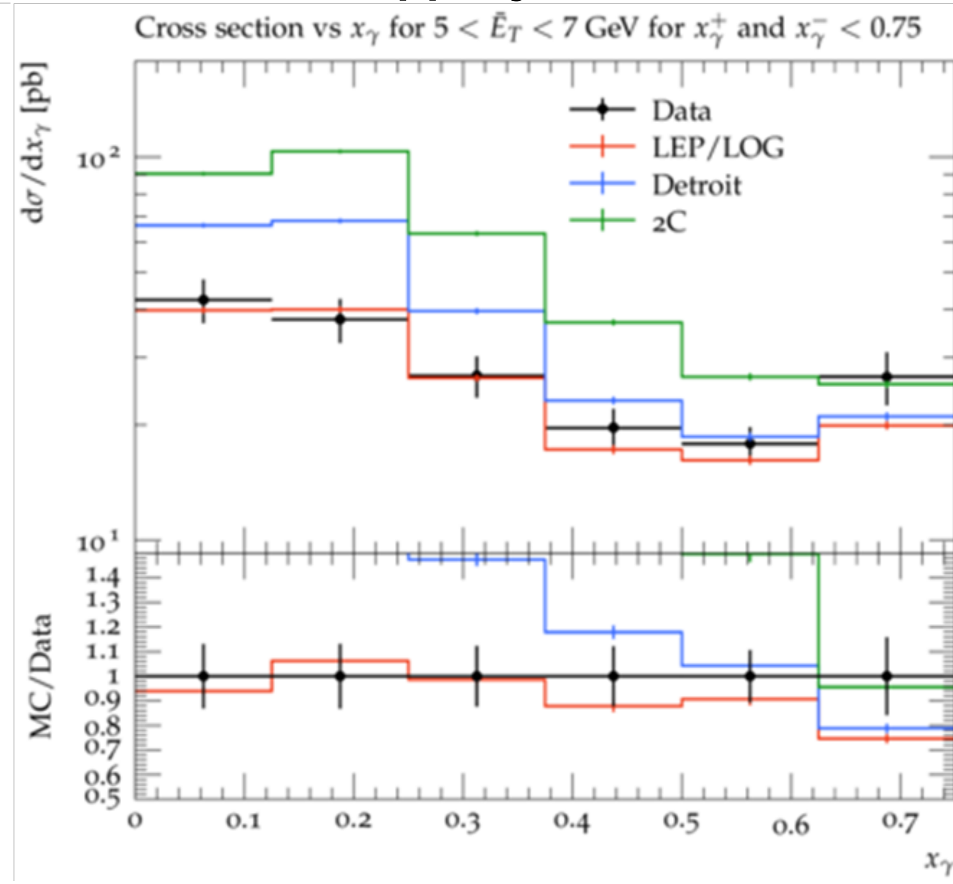
OPAL Coll., EPJ
C31 (2003) 307

Other models for low energy

_ep_ dijet data



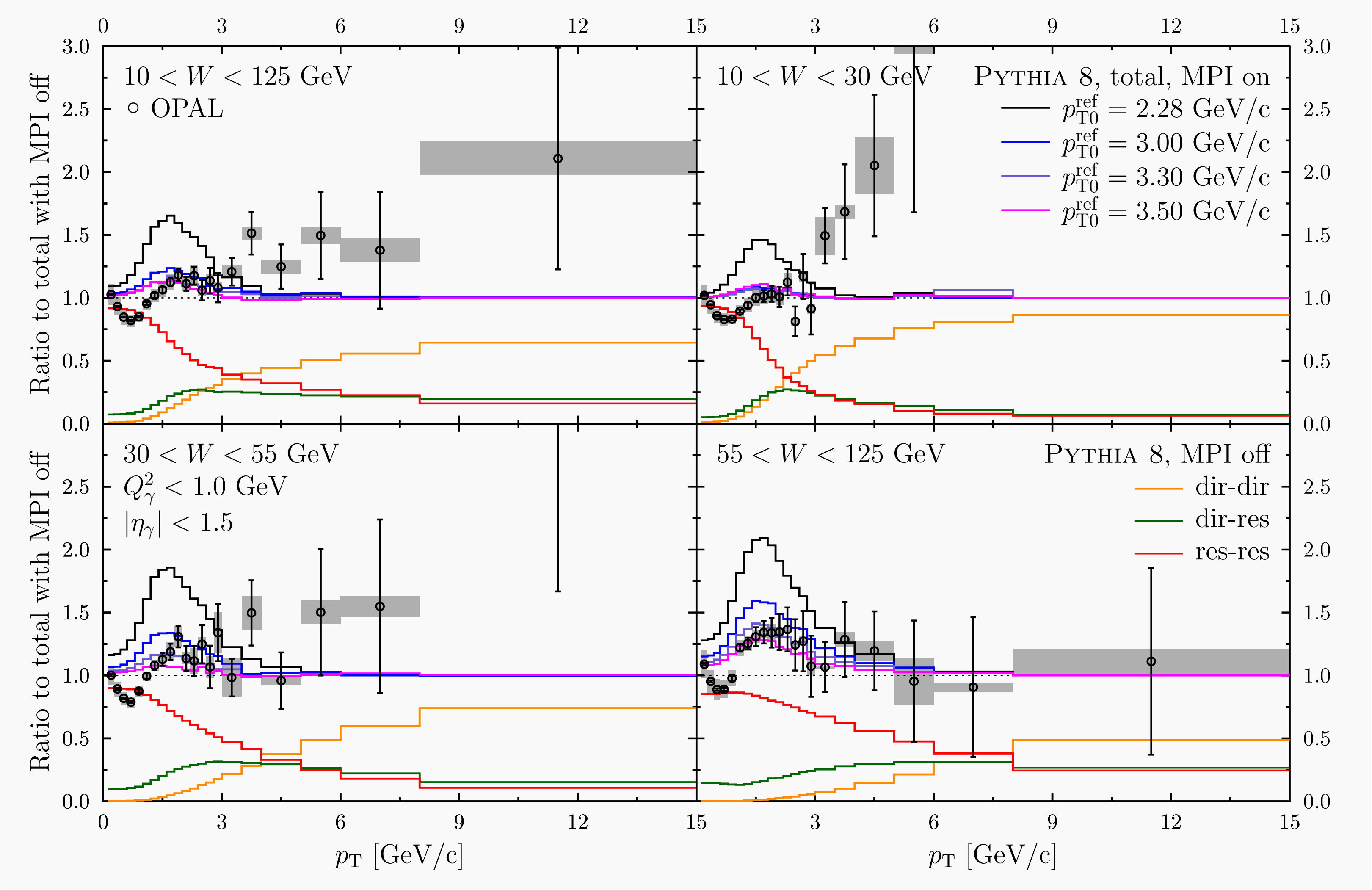
_γγ_ dijet data



Tunes specifically designed for *pp* data with √*s ~ 200 − 300 GeV*. Do not describe HERA and LEP data of similar centre-of-mass energy.

“Tuning” to γγ data

I. Helenius, arXiv:1708.09759



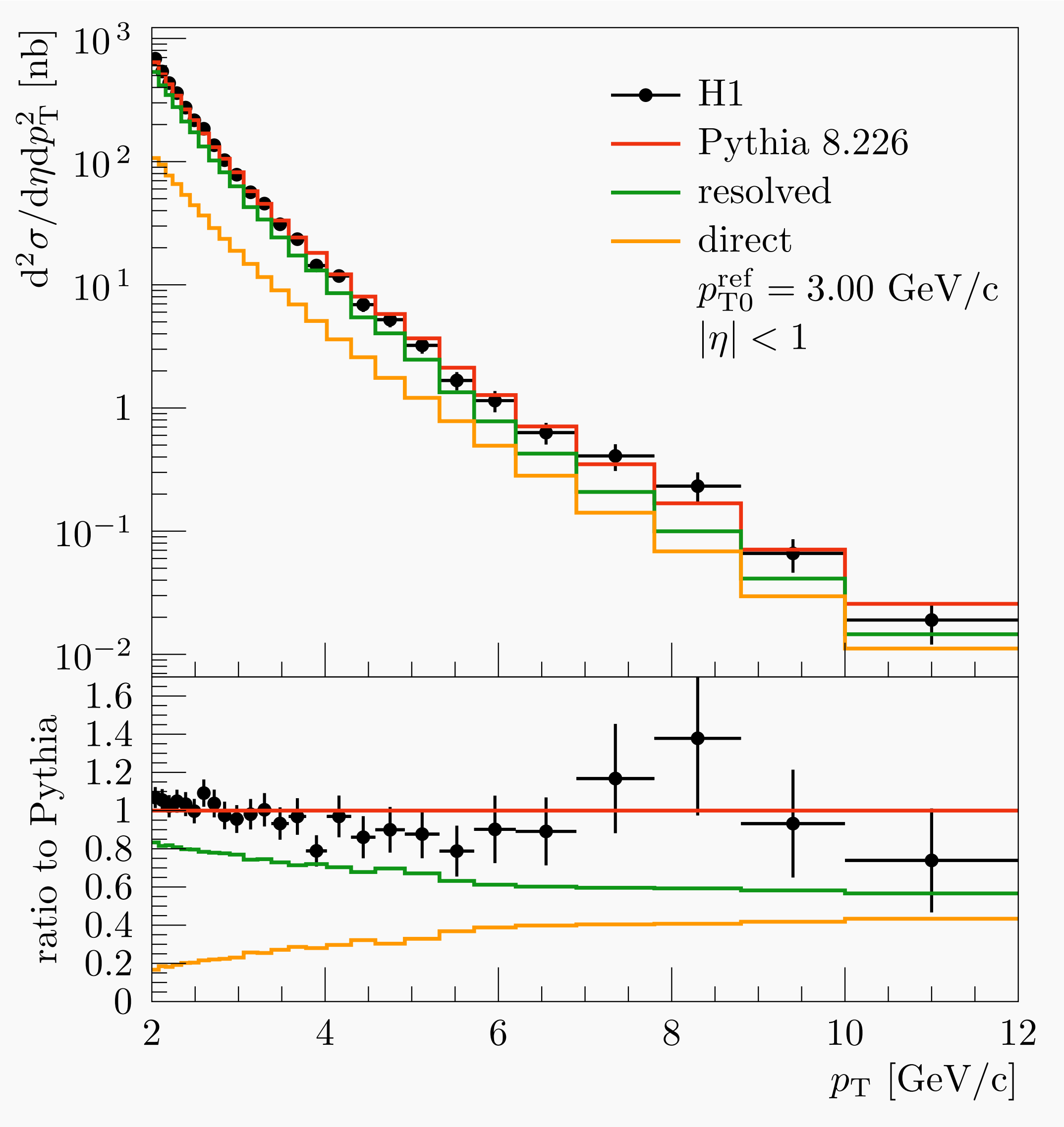
OPAL Coll., EPJ **C6** (1999) 253

- “Out of the box”, default p_{T0}^{ref} = *2.28 GeV* too many hadrons
- Can “tune” and get a best description with p_{T0}^{ref} = *3.3 GeV*

“Tuning” to *ep* data

I. Helenius, arXiv:1708.09759

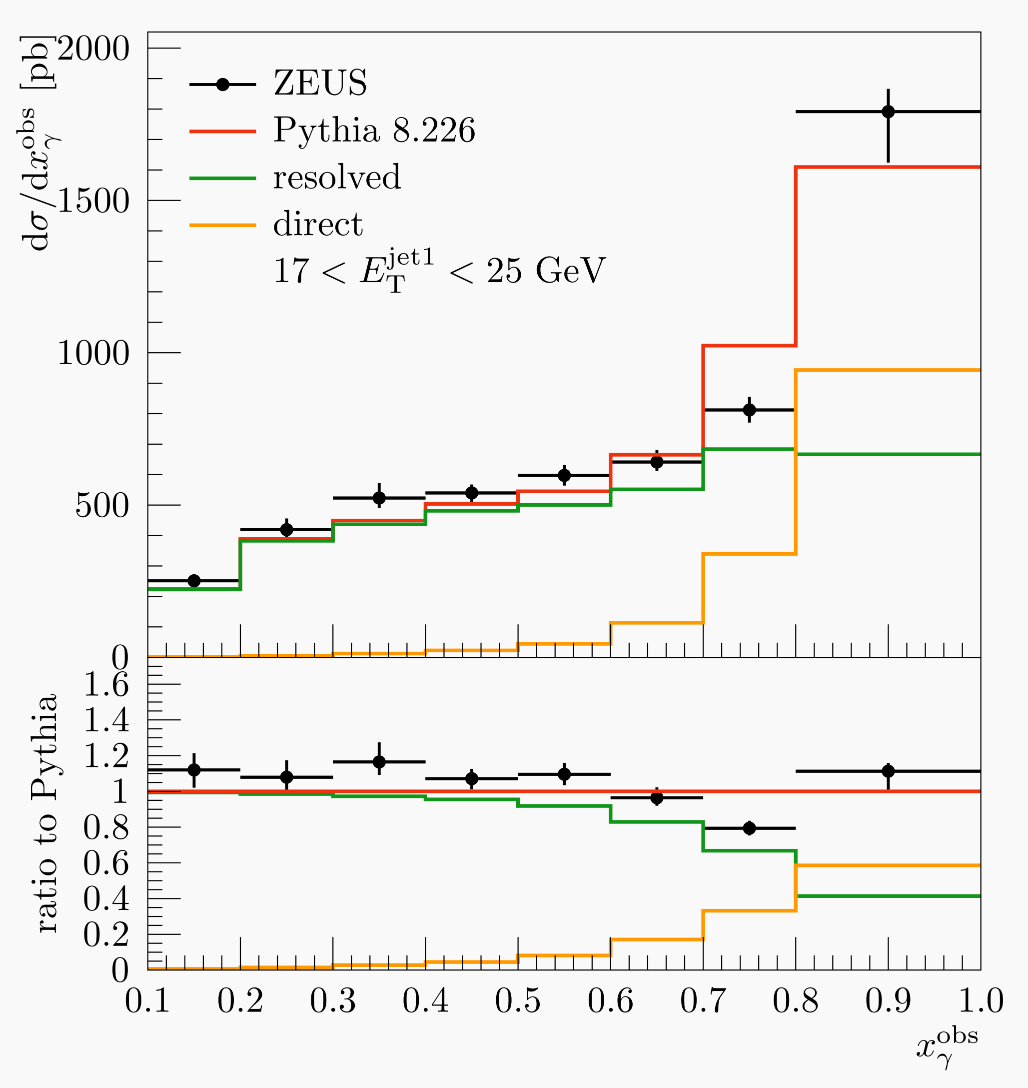
- Charged particle p_T spectra.
- Resolved contribution dominates.
- Data best described by p_{T0}^{ref} = *3 GeV**.
- Similar to *γγ* result.
- Got similar results tuning *α* instead, with *α* = 0.05 − 0.10 (cf. LHC, *α* = 0.215)



H1 Coll., EPJ **C10** (1999) 363

* See also: ZEUS Coll., JHEP **12** (2021) 102

“Tune” compared to *ep* dijet data



Good description of high-E_T jet data, similar to other models that do well.

Summary and conclusions

- Default *pp* tunes do not describe HERA data.
- Can describe all available HERA data with default LEP models and "tuned" models.
- Can get simultaneous tune/description of HERA and LEP data.
- Cannot get a simultaneous description of HERA/LEP and *pp* data, even using different settings tuned to *pp* data at the same centre-of-mass energy.
- Data favours fewer MPIs with photon-initiated processes than with protons.

Outlook

- Adding analysis routines (and knowledge) to Rivet.
- Do more detailed comparison/tune to all data—merging studies.
- Write a paper on findings and better understanding of photon-initiated processes.
- Provide better simulations of processes at future colliders with photons, e.g. the EIC and $\gamma\gamma$ or $\gamma p/A$ collisions at the LHC.