LUND
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e*A* generators
after the LHC experience

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Outline

- The importance of General purpose event generators
- Collectivity in small systems
- Glauber–Gribov
- DIS
- Ultra-Peripheral Collisions
- Model independent measurements

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My attitude to heavy ions before LHC

- That's just smashing bunches of nucleons together!
- Who is this Glauber guy anyway?
- What do you mean with centrality?
- I'm from Lund, I want to use string fragmentation!
- You measured what?
- Are you really seeing the Quark–Gluon Plasma?

Why General Purpose Event Generators

We need event generators to model our data, but also to model the theory.

It's not enough to tune for one analysis/experiment, we need to tune to everything.

e^+e^-	$\Rightarrow$	Hadronisation and FSR
ep	$\Rightarrow$	ISR and remnant jets.
pp	$\Rightarrow$	UE and MPI
pA	$\Rightarrow$	small dense systems, flow
AA	$\Rightarrow$	large dense systems, jet quenching
eA	$\Rightarrow$	?

- General purpose = HERWIG7, PYTHIA8 and SHERPA
- There are other generators (e.g MadGraph, EPOS4, HIJING, AMPT, UrQMD, . . .), that can be important for EIC
- Personal view on lessons from LHC important for EIC

[herwig.hepforge.org, pythia.org, sherpa-team.gitlab.io]

[arXiv:2301.12517, arXiv:1901.04220, arXiv:nucl-th/0411110, arXiv:nucl-th/9803035]

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Are the *general purpose* event generators ready for nuclei at the EIC?

Can they handle

- e*A*?
- DIS?
- Photo-production?
- Nuclei in general?
- Saturation? Polarisation? Lower energy? Diffraction? ...

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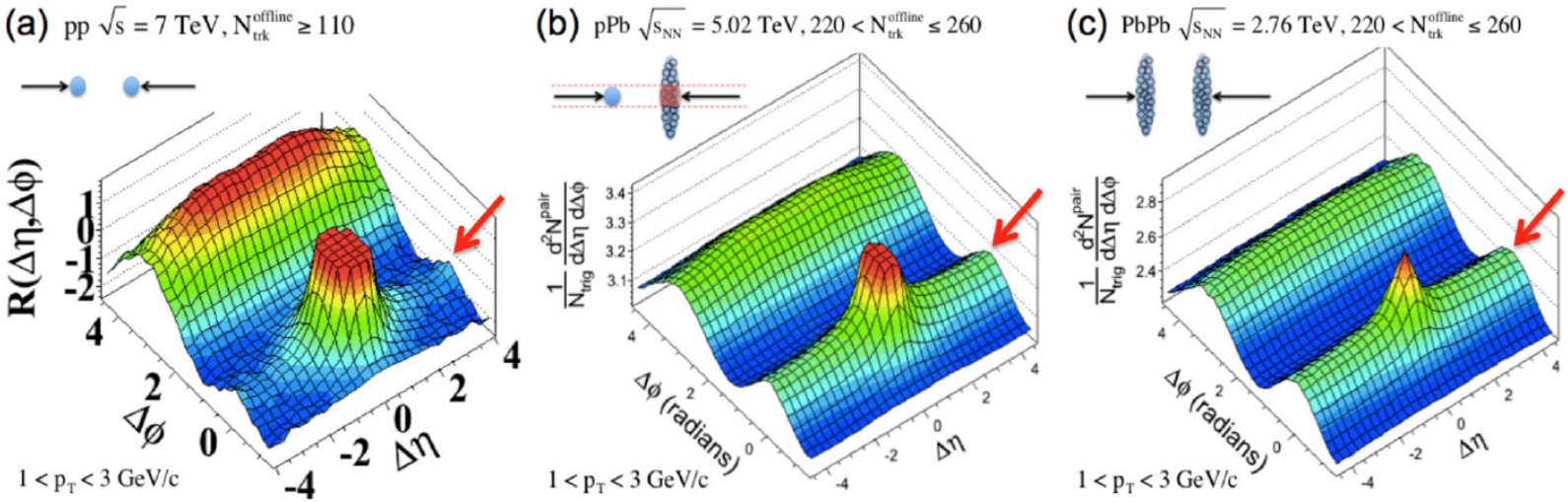
Todo: EVERYTHING

Collectivity



[arXiv:1009.4122]

Collectivity in small systems

We see collective effects in all (?) collision systems

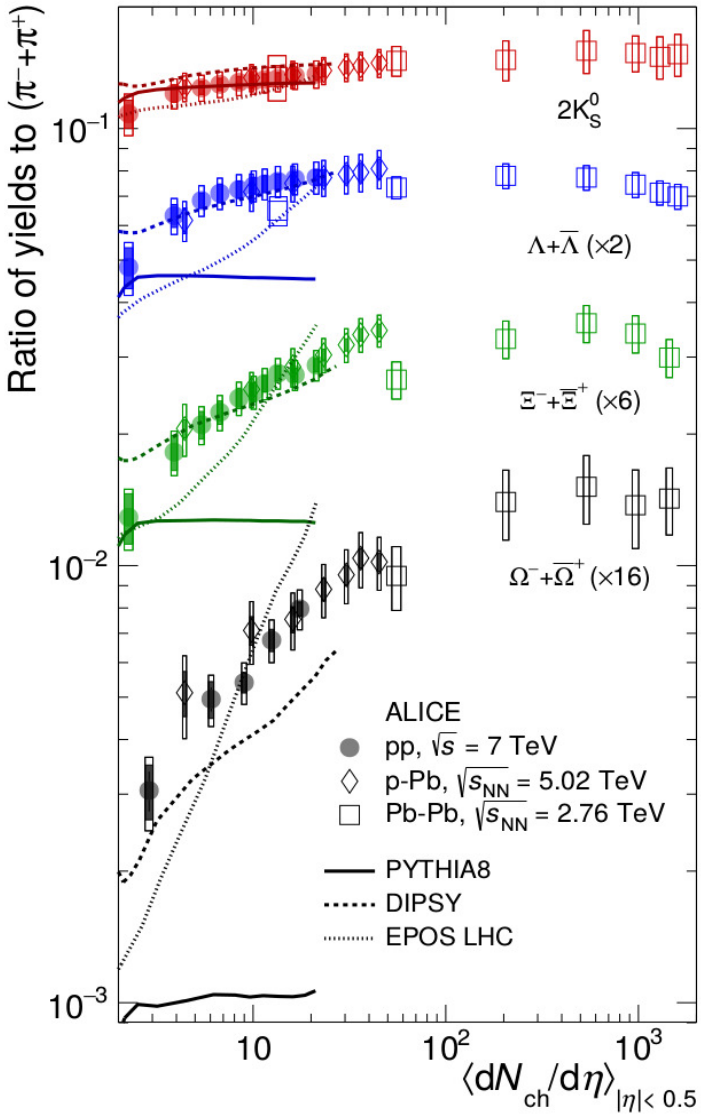
- Flow
- Strangeness enhancement
- Jet quenching (?)

Is there Quark-Gluon Plasma everywhere?

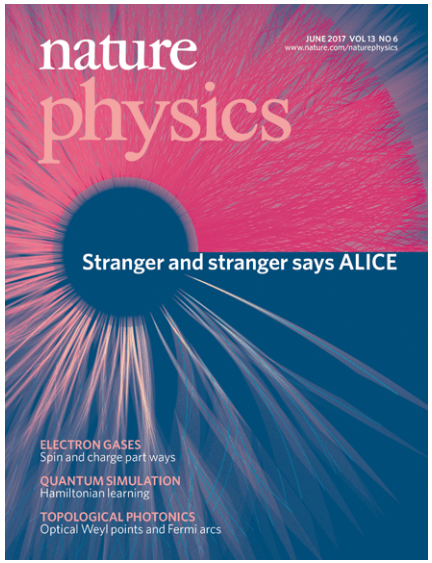
Or are the mechanisms in play in *AA* different from those in pp?

Which ones could become important at the EIC?

Strangeness enhancement



Looks like a common mechanism



Nature Phys. 13 (2017) 535-539

Collective effects in generators

- EPOS4
  - Core (QGP) vs. Corona
- PYTHIA8
  - Colour reconnections (several models)
  - String *shoving*
  - Rope hadronization
  - Hadronic rescattering
  - (also Core-Corona via DCCI2)
- HERWIG7
  - Colour reconnections
- SHERPA
  - Jet quenching (with JEWEL) + . . .

[arXiv:2108.07943, arXiv:1311.0048]

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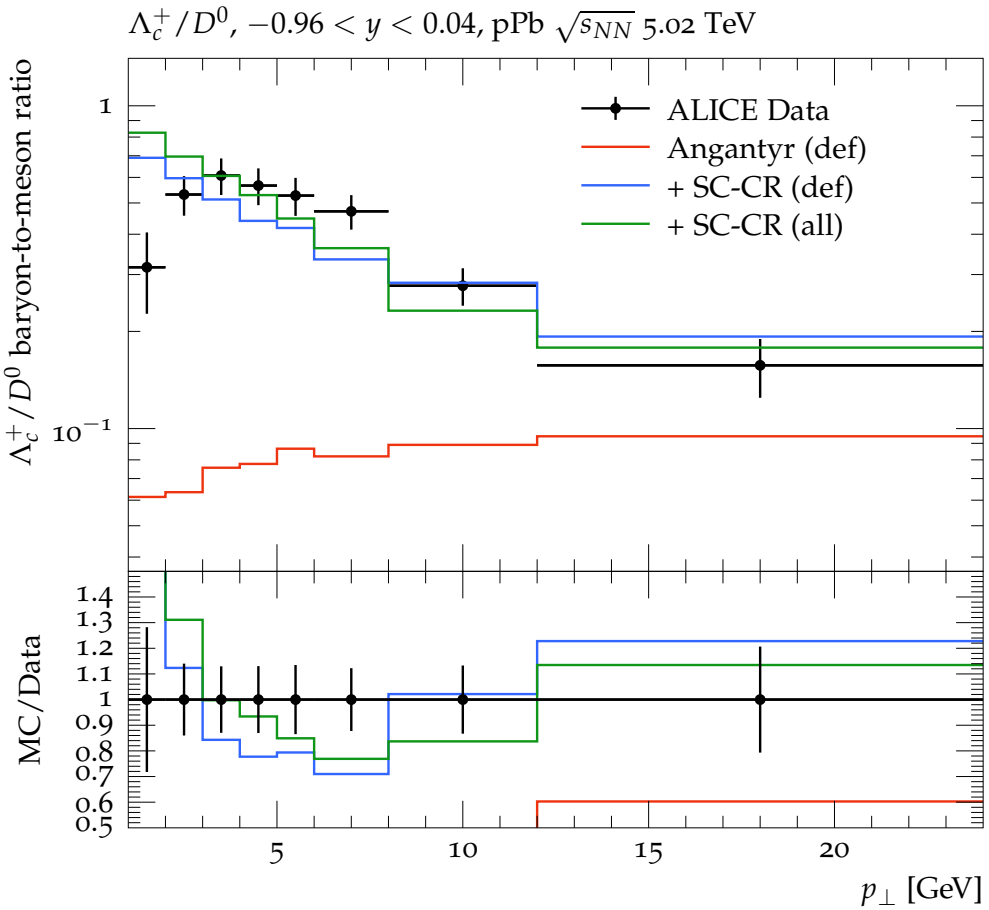
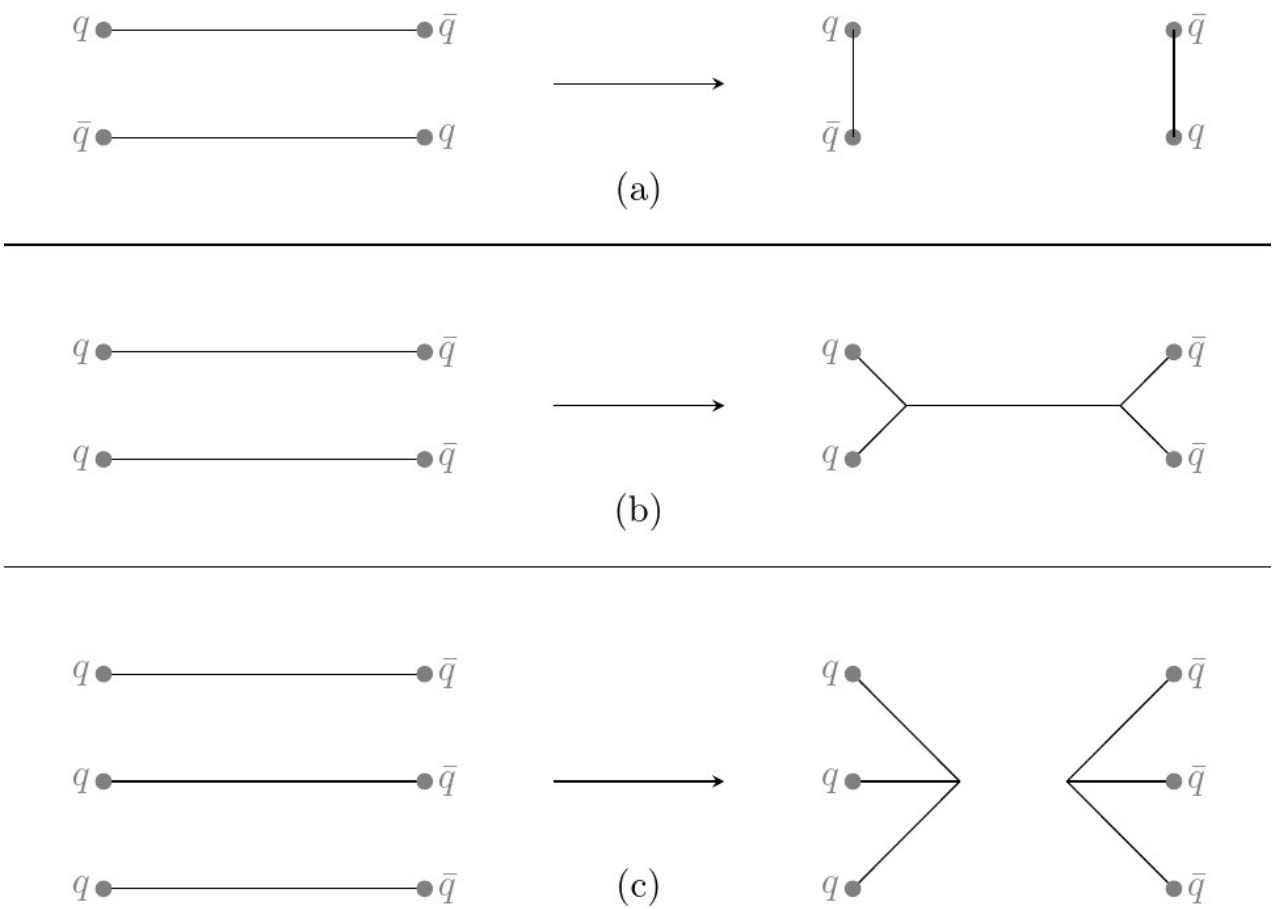
(QCD-based) Colour reconnections



[arXiv:1505.01681, arXiv:2309.12452]

QCD-based Colour reconnections



Glauber Calculations

To get a reasonable handle on hadronic final states in eA we need to add together several eN collisions, and for that we need to do some kind of Glauber calculation to obtain N_{part} (or N_{wounded})

Also, if we want to do R_{AA}-like measurements, we need to understand how many nucleons we hit.

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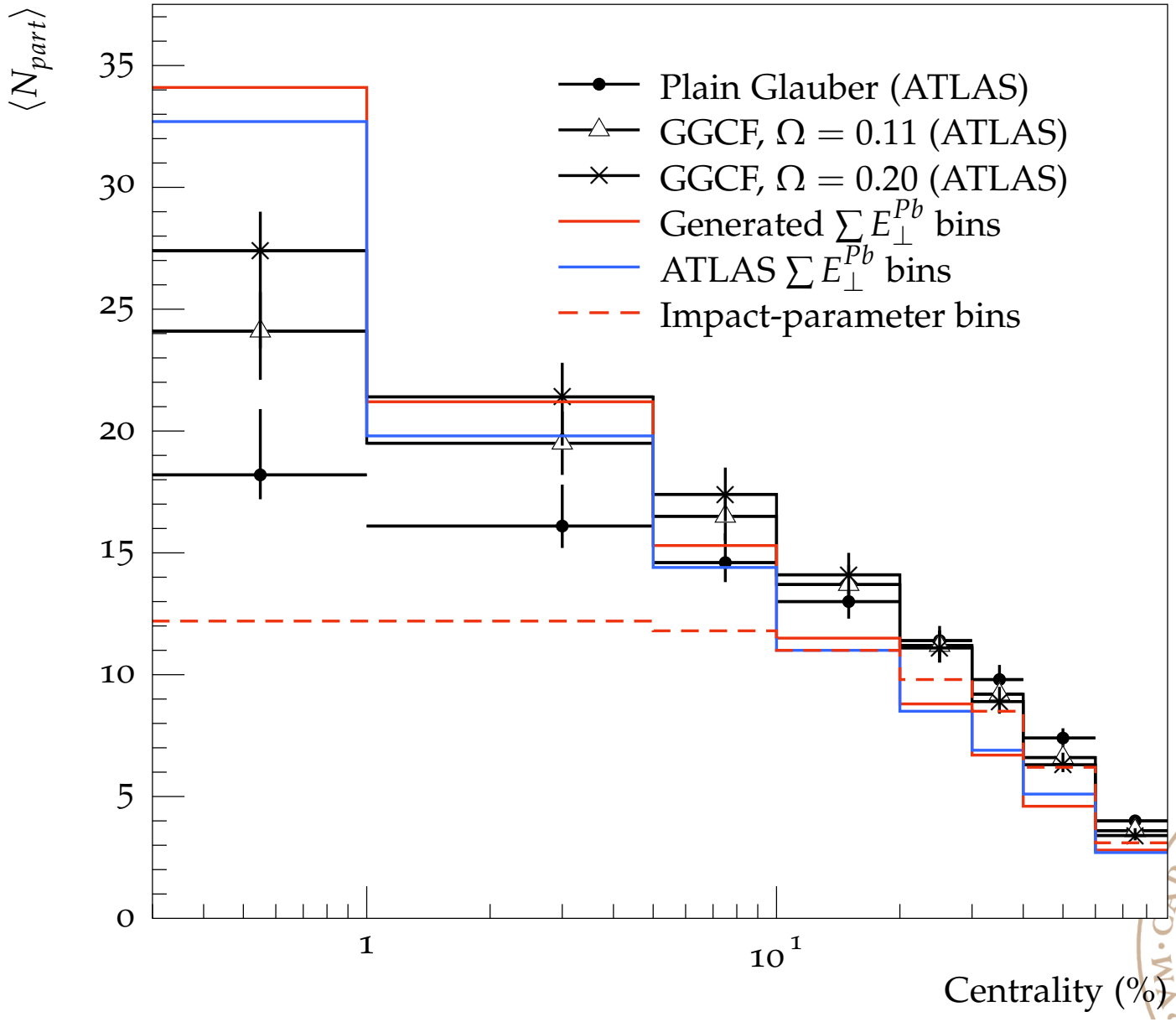
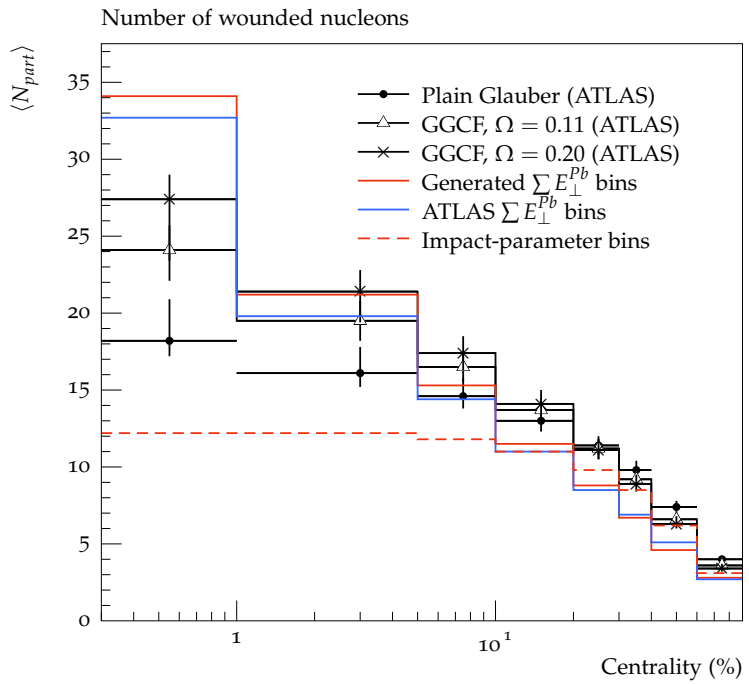
The lesson from pA collisions at the LHC is that we need to worry about fluctuations.

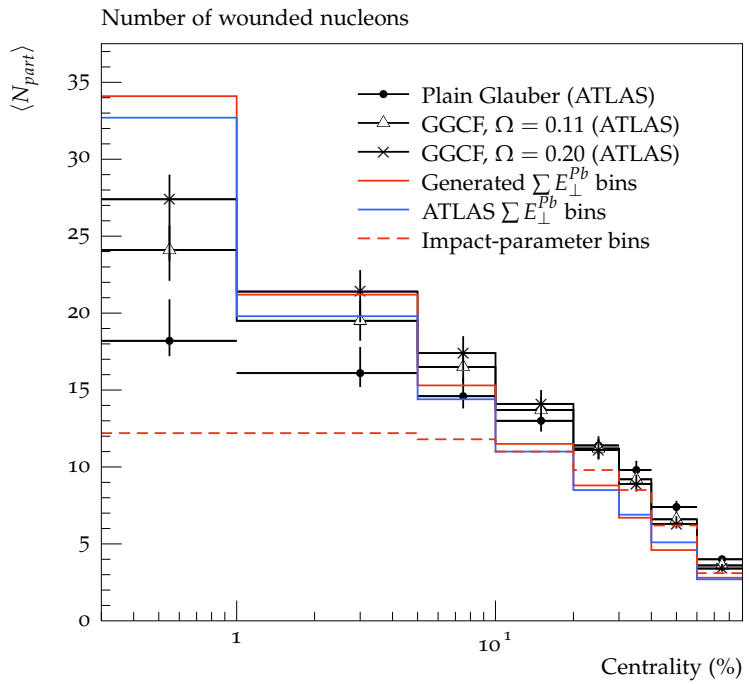
Number of wounded nucleons





For low Q^2 eA we expect Vector Meson Dominance and the situation looks like pA.

[Strikman et al. arXiv:hep-ph/1301.0728, arXiv:1806.10820]



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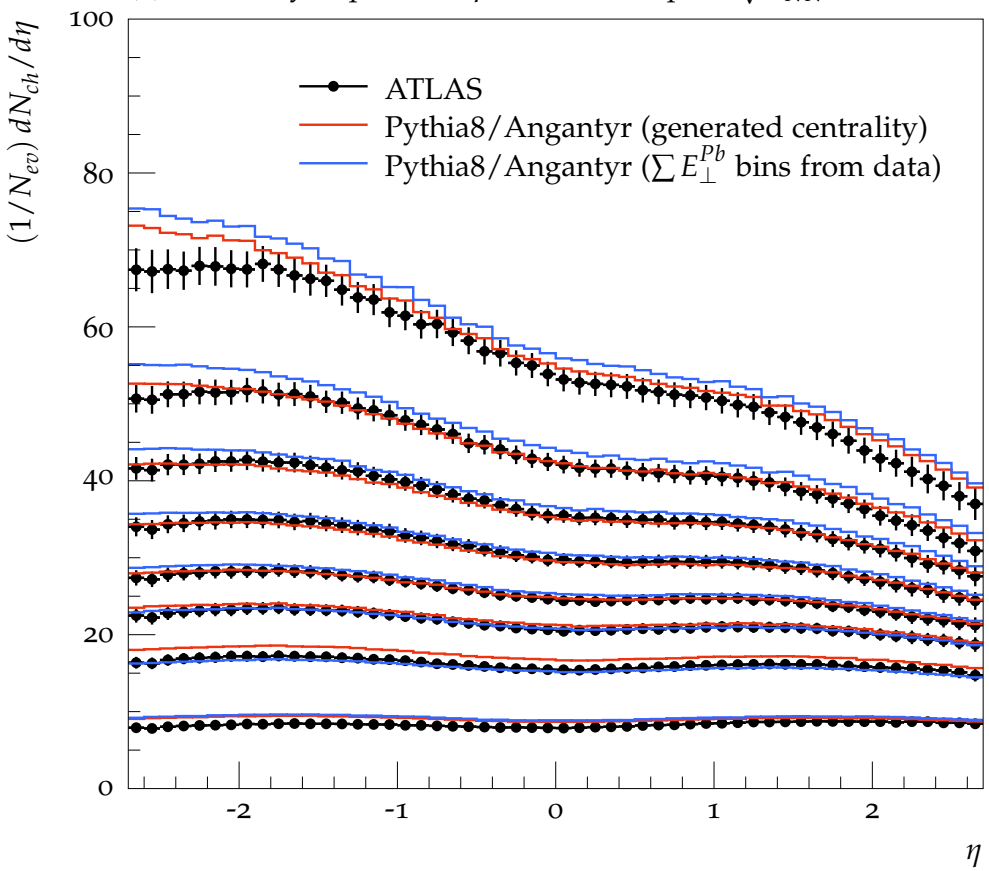
For high Q^2 we need to generate DIS in terms of dipole–nucleon scattering.

[Strikman et al. arXiv:hep-ph/1301.0728, arXiv:1806.10820]

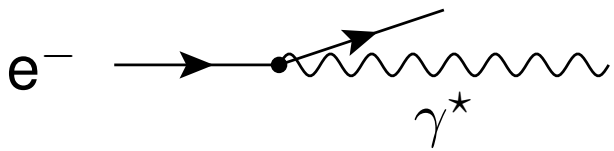
Eta distribution in pPb

(a) Centrality-dependent η distribution, pPb, $\sqrt{S_{NN}} = 5$ TeV.



[arXiv:1508.00848]

The dipole picture in DIS



- In the frame where the target is at rest the photon is emitted long before the ineraction.
- Also the photon splits up long before the interacton
- . . . and radiates
- . . . before hitting the target.
- Hitting another nucleon comes at little extra cost.

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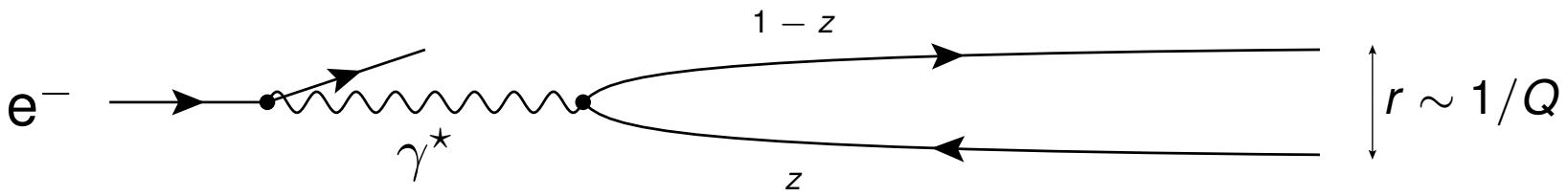

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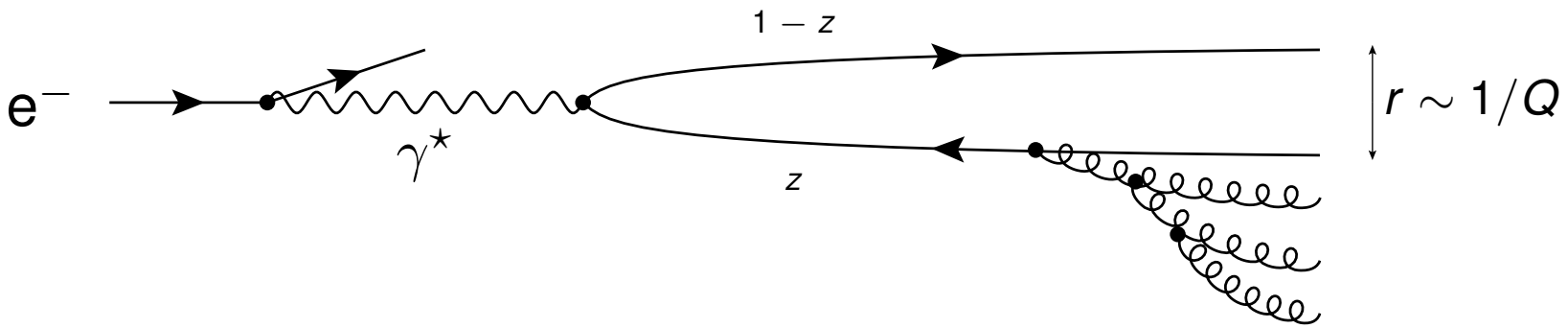

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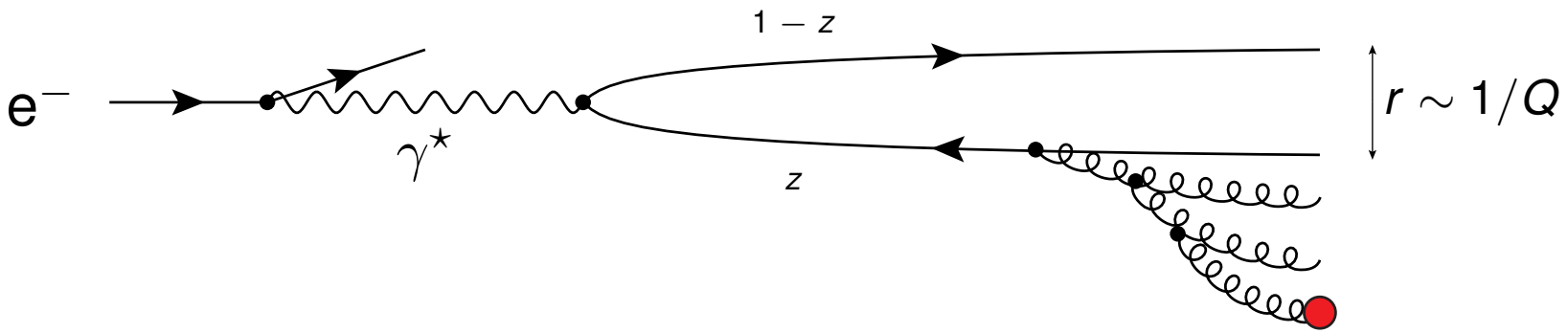

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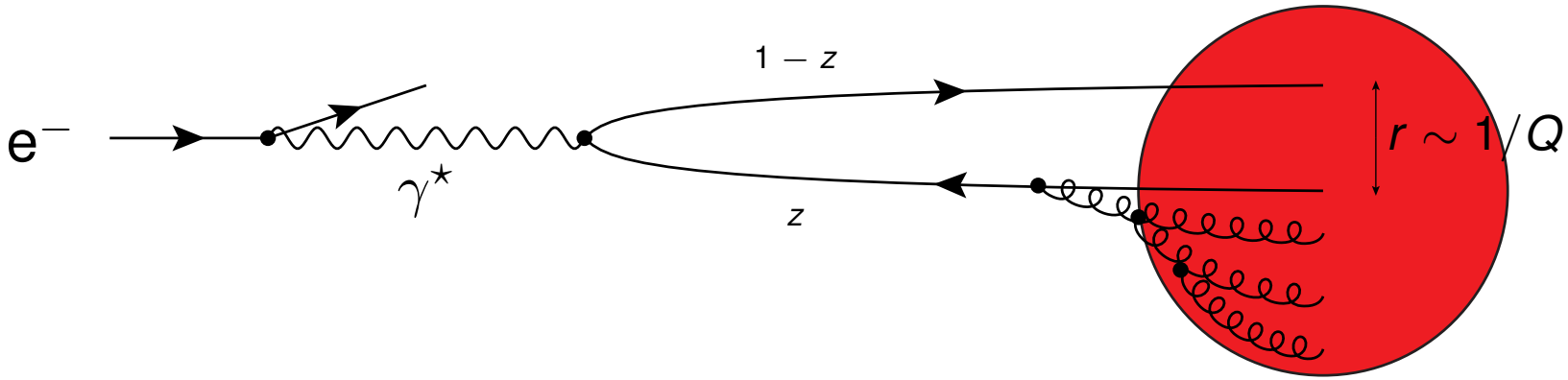

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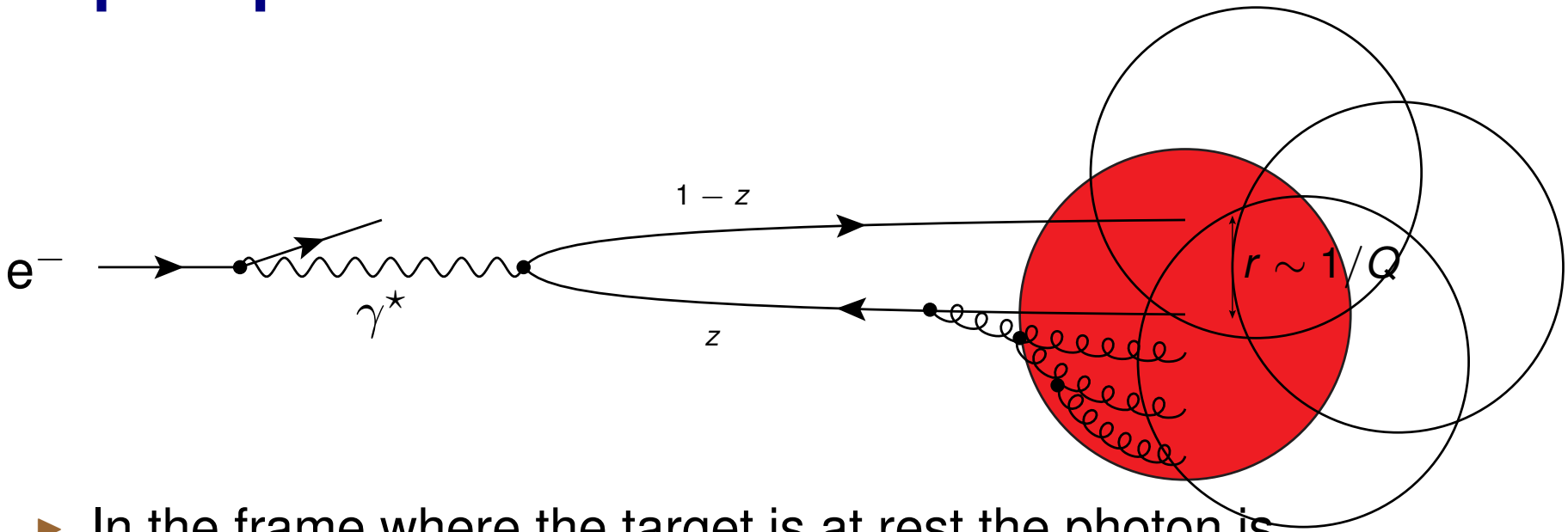

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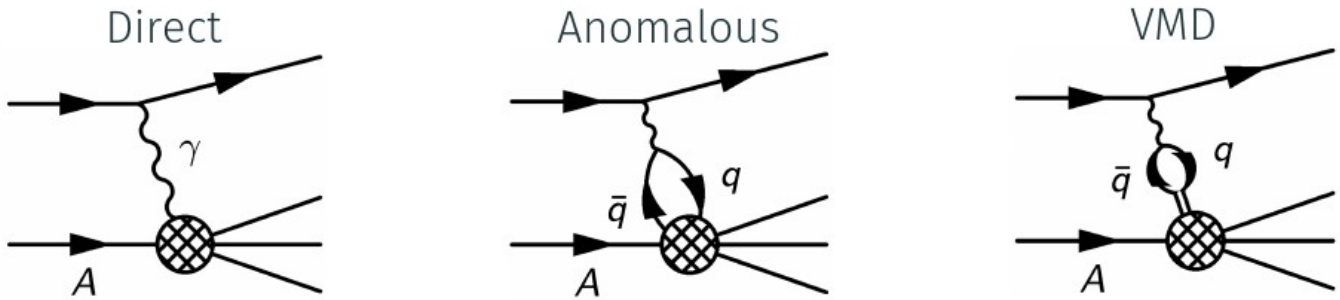
Ultra-peripheral collisions

We can do photo-production at the LHC!

And we can do it in PYTHIA8.

- Treat the $Q^2 \sim 0$ GeV^2 photon as a hadron
- Use a photon flux factor
- and photon PDFs



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

- $f_i^{\gamma,\mathrm{dir}}(x_\gamma, \mu^2) = \delta_{i\gamma}\delta(1 - x_\gamma)$. Like DIS
- $f_i^{\gamma,\mathrm{ano}}(x_\gamma, \mu^2)$: Perturbatively calculable
- $f_i^{\gamma,\mathrm{VMD}}(x_\gamma, \mu^2)$: Non-perturbative, fitted.

$$d\sigma^{BA\to BkI+X} = F_\gamma^B(x) \otimes f_i^{\gamma}(x_\gamma, \mu^2) \otimes f_j^A(x_j, \mu^2) \otimes d\hat{\sigma}^{ij\to kl}(sxx_\gamma x_j)$$

No Angantyr Ions yet, instead use nuclear PDFs

Model-independent measurements

Already at HERA it was realised that comparing measured data with models was difficult.

- HZTool

For the LHC this was generalised and improved in

- Rivet

Analyze Event Generator output and compare with published experimental data, using exactly the same cuts, triggers, etc.

1200+ analyses are already in there.

If you want to make your analyses useful for others — Publish them in Rivet!

[rivet.hepforge.org]

Rivet for Heavy Ions?

The work has started

Centrality calculations has been included

A framework for correlation study is there

Still needed: Jet subtraction

[arXiv:2001.10737]

EIC plans for PYTHIA8

- e*A* (Dipole–nucleon scatterings) in Angantyr
- Swing
- Shoving
- Ropes
- Hadronic rescattering
- Nuclear PDFs
- Photon PDFs
- Polarised string fragmentation (w. Albi Kerbizi)
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To sum up:

- LHC brought HI and HEP communities closer
- If we want to use what we have learned from LHC we need general purpose event generators
- The generator programs are not ready for the EIC (yet)

Thanks!


Vetenskapsrådet
MCnet
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Human resources and mobility
Knut and Alice Wallenberg Foundation
CLASH