DVCS on a virtual pion at EIC and EICC

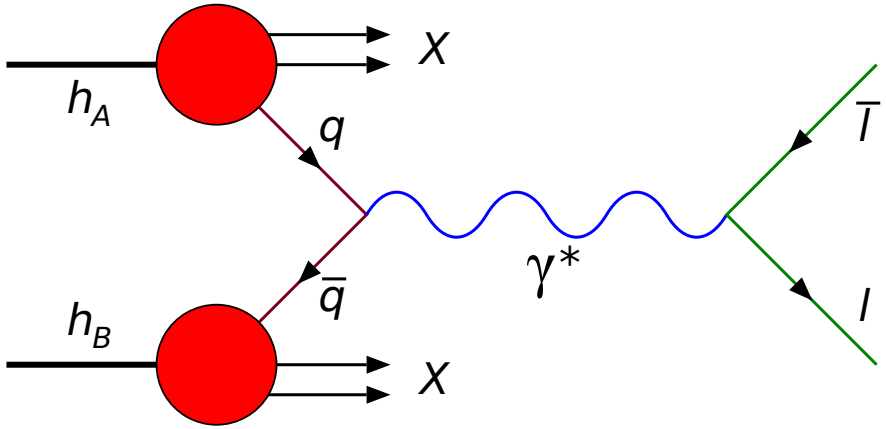
The pion structure

- The pion is a much simpler object than the proton (2 GPDs vs 8 GPDs):
  => Non-perturbative techniques improved and models of Form Factors/PDFs and now GPDs can be computed.

- Although theoretically easier, experimentally it is challenging to probe its inner structure.

PDF accessed with Drell-Yan

- Impinging a pion beam onto a proton target like in COMPASS experiment, one can access the PDF of the pion via Drell-Yan.



- But accessing the pion structure with an electron beam would require a luminosity unreachable with pion beams.

The Sullivan process

- It was noticed that in the final state of electron scattering events, a nucleon was « surviving » with a low momentum transfer :
  The virtual photon is interacting with the meson cloud.

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One-Pion Exchange and Deep-Inelastic Electron-Nucleon Scattering

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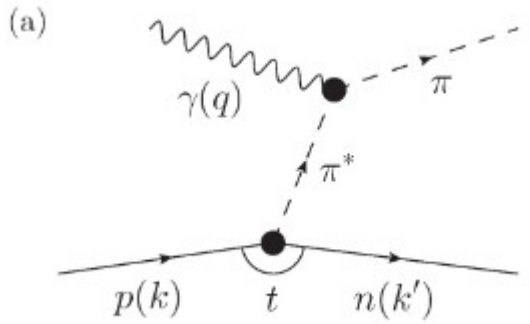
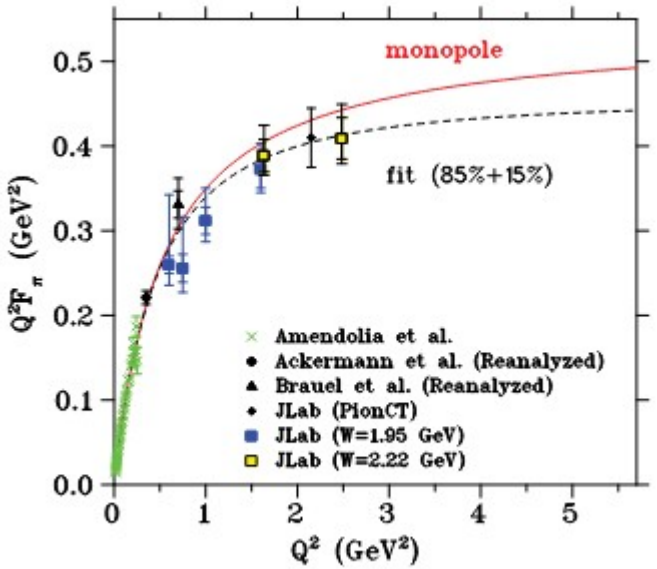
(Received 29 November 1971)

The role of one-pion exchange is examined in the deep-inelastic region for electron-nucleon scattering. Exclusive channels like πN, $\pi\Delta$ will contribute negligible, nonscaling contributions to σ_S. On the other hand, inclusive final states like N + "anything," where the detected final nucleon is slow in the lab system, afford the opportunity to experimentally determine the structure functions for electron-pion scattering provided the characteristic one-pion-exchange structure (dip or peak) is observed at small momentum transfer.

Form Factors at large momentum transfer

- By measuring ep → e n pi$^+$, one can access the pion form factor.
- With t-low enough, the process can be seen as a Sullivan process.
- Now, experimentally, the measurement is quite complicated because it requires a Rosenbluth separation (Only through the longitudinal cross section).

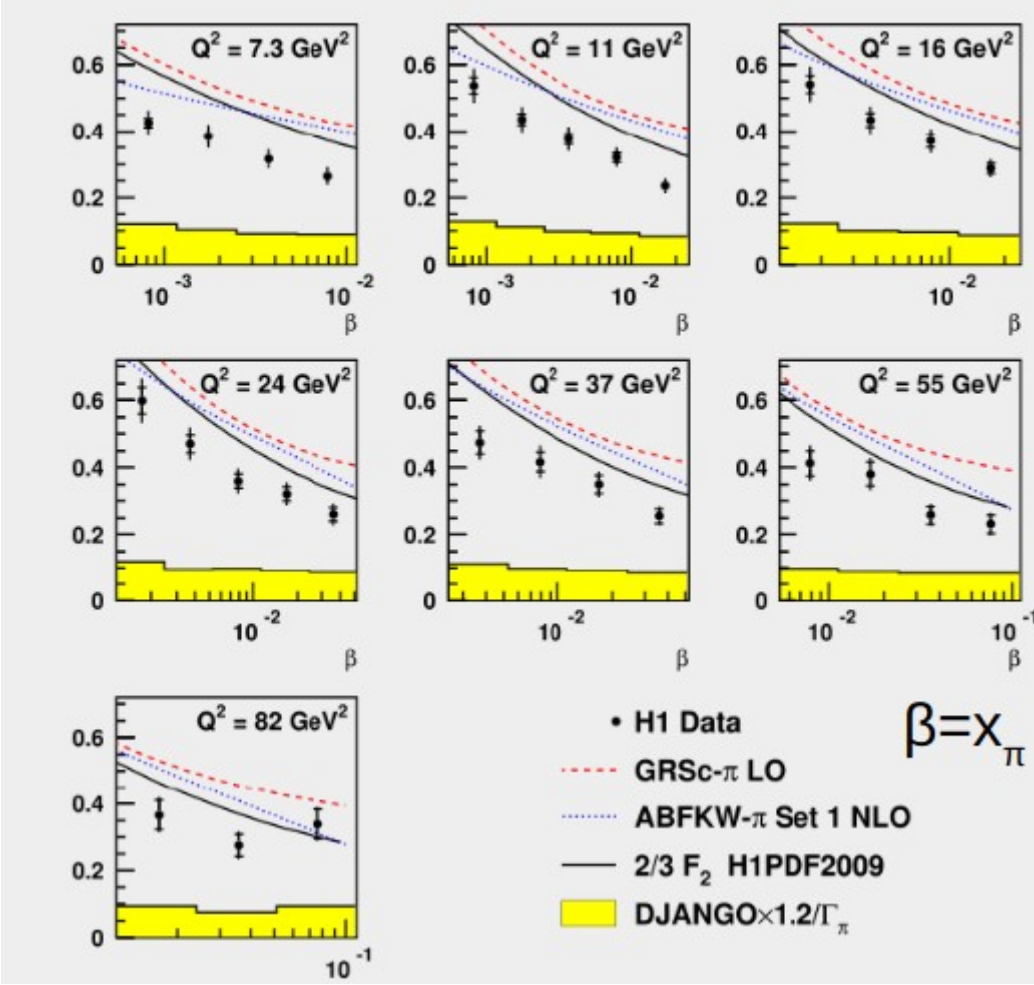




Huber et al. PhysRevC. 78.045203

PDFs through Sullivan process

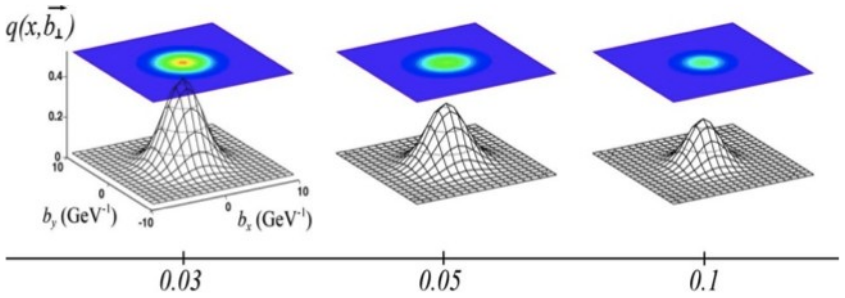
- Same idea as the form factors however the final state is « unconstrained » apart from detecting a recoil nucleon with low-momentum transfer t.
- First measurement at HERA.
- Conditionnally approved experiment in Hall A, and as well feasible to EIC.



The H1 Collaboration, Aaron, F.D., Alexa, C. et al. Eur. Phys. J. C (2010) 68: 381.

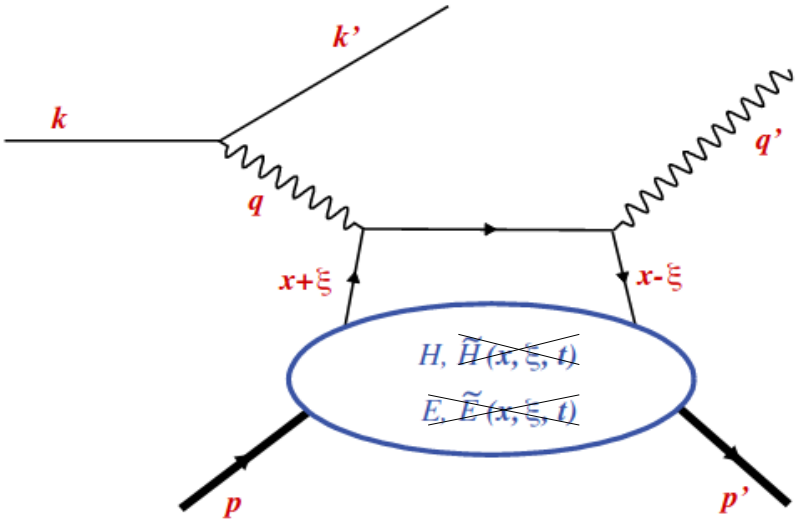
But are GPDs accessible via Sullivan process ?

- GPD : Generalized parton distributions.
  It provides correlation between longitudinal momentum and transverse position of partons in a hadron.



- It is accessible via exclusive processes, with a final state completely determined.

Deeply virtual compton scattering



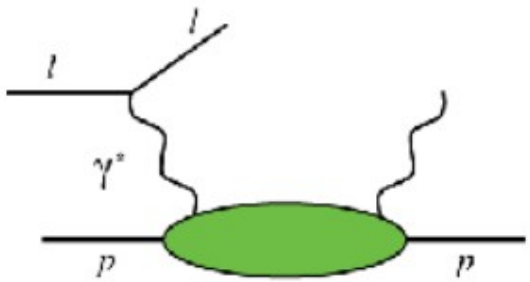
- $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi \sim \frac{x_B}{2 - x_B}$ the longitudinal momentum transfer.
- $t = (p - p')^2$ squared momentum transfer to the nucleon.

The GPDs enter the DVCS amplitude through a complex integral. This integral is called a *Compton form factor* (CFF).

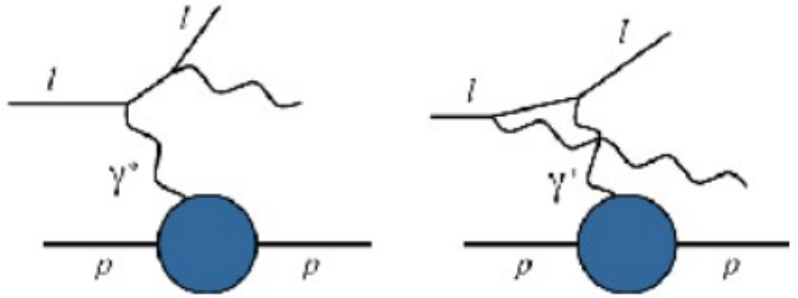
$$\mathcal{H}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \ .$$

Photon Electroproduction

Experimentally we measure the cross section of the process $ep \to ep\gamma$.



DVCS



Bethe-Heitler

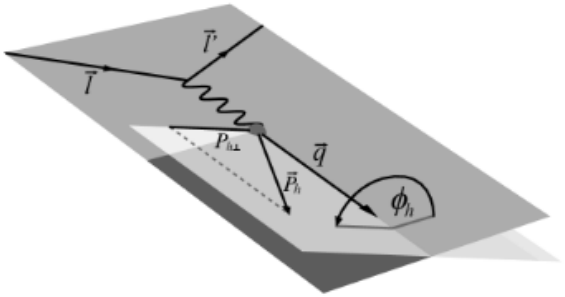
The measured cross section is the coherent sum of both amplitudes :
- Here an interference term appears and offers unique opportunity to access both real and imaginary parts of CFF.

$$\frac{d^5\sigma^{e\pi\to e\gamma\pi}(\lambda,\pm e)}{dy_\pi dx_B^\pi dt_\pi d\phi d\phi_e} = \frac{d^2\sigma_0}{dQ^2dx_B^\pi}\frac{1}{e^6} \times \left[|\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{I}\right],$$

$$\frac{d^2\sigma_0}{dQ^2dx_B^\pi} = \frac{\alpha_{\rm QED}^3 x_B^\pi y_\pi}{16\pi^2 Q^2\sqrt{1+\epsilon^2}},$$

$$\epsilon^2 = 4m_\pi^2 (x_B^\pi)^2/Q^2,$$

Harmonic structure of the cross section



We can partially unfold the contributions, studying the ϕ-dependence.

$$|\mathcal{T}^{BH}|^2 = \frac{e^6 \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)}{x_B^2 t y^2 (1+\epsilon^2)^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \quad \leftarrow \text{KNOWN!}$$

$$\left|\mathcal{T}^{DVCS}\right|^2 = \frac{e^6}{y^2 Q^2}\left\{c_0^{DVCS} + \sum_{n=1}^{2}\left[c_n^{DVCS}\cos(n\phi) + \lambda s_1^{DVCS}\sin(n\phi)\right]\right\}$$

$$\mathcal{I} = \frac{e^6}{x_B y^3 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi) t}\left\{c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + \lambda s_n^{\mathcal{I}}\sin(n\phi)\right]\right\}$$

Accessing the CFF

The CFFs are encapsulated in c_n and s_n, offering a parameterization of the cross section. In the leading twist approximation for unpolarized target:

$$c_0^{DVCS} \propto \mathcal{C}^{DVCS}(\mathcal{F},\mathcal{F}^*) = 4(1-x_B)\mathcal{H}\mathcal{H}^* + \cdots \quad (1)$$

$$c_1^{\mathcal{I}} \propto Re\ \mathcal{C}^{\mathcal{I}}(\mathcal{F}) = F_1\ Re\mathcal{H} + \cancel{\xi(F_1+F_2)\ Re\widetilde{\mathcal{H}}} - \cancel{\frac{t}{4M^2}F_2\ Re\mathcal{E}},$$

$$s_1^{\mathcal{I}} \propto Im\ \mathcal{C}^{\mathcal{I}}(\mathcal{F}) = F_1\ Im\mathcal{H} + \cancel{\xi(F_1+F_2)\ Im\widetilde{\mathcal{H}}} - \cancel{\frac{t}{4M^2}F_2\ Im\mathcal{E}},$$

- As already mentionned earlier, the pion has only the GPD H => the unique CFF is constrained by only playing with the beam polarization.

Related Articles

- Articles used for experimental study :
  -EICC white paper Frontiers of Physics, Volume 16 Issue (6):64701, 2021
  -EIC Yellow report https://arxiv.org/abs/2103.05419

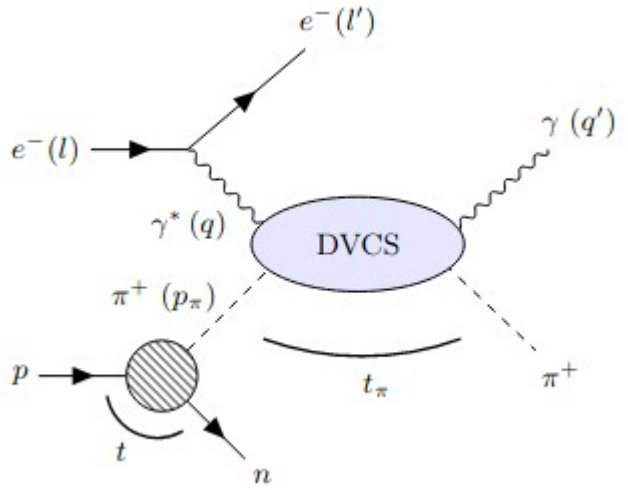
- Articles used for theory :
  -Morgado Chavez et al.,
  Pion GPDs: A path toward phenomenology, arXiv 2110.06052
  -Belitsky, Muller Phys.Rev.D 79:014017, 2009
  -Amrath et al. Eur.Phys.J.C 58:179-192, 2008

Sullivan DVCS

- DVCS depends on 4 kinematical variables :
  Q^2, xB/y, t_pi, phi.

- For Sullivan DVCS, we need two additional variables to characterize the virtual pion :
  - t : momentum transfer to nucleon
  - x_pi : the energy fraction carried by the pion in the ep com-frame.

- The total cross section will be the product of the DVCS cross section and a virtual pion flux depending on t and x_pi.



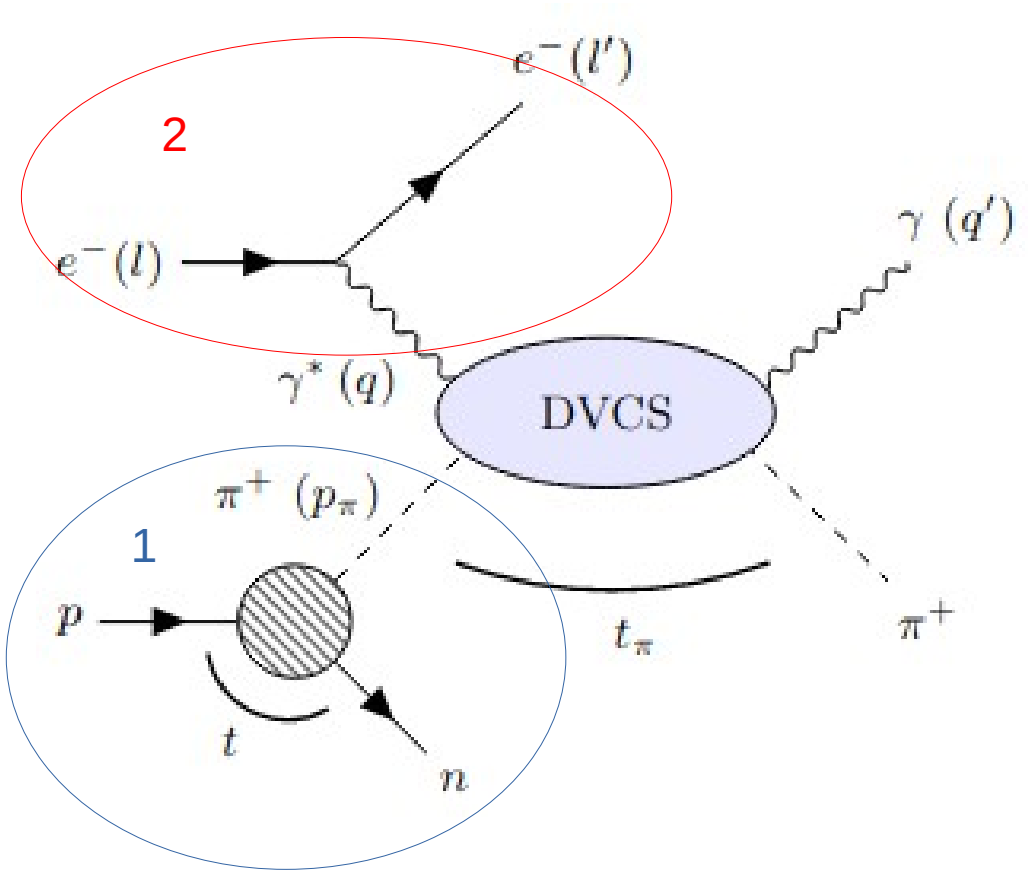
$$\frac{d^8\sigma^{\mathrm{Sul}}(\lambda,\pm e)}{dydQ^2dt_\pi d\phi d\phi_e dt dx_\pi d\phi_n} = x_\pi \frac{g^2_{\pi NN}}{16\pi^3} F(t)^2 \frac{-t}{(m_\pi^2 - t)^2} |J^{Q^2}_{x_B^\pi}| \frac{d^5\sigma^{e\pi\to e\gamma\pi}(\lambda,\pm e)}{dy_\pi dx_B^\pi dt_\pi d\phi d\phi_e}$$

Regarding the event generation

1) First we generate the virtual pion :
- t uniformely in [-0,6 ; 0],
- x_pi in a depending on t,
- and phi_N, rotation around proton axis.

2) Then the virtual photon is generated with :
- Q^2 in [1 ; 100] GeV^2
- y depending on Q^2
- phi_e, rotation around virtual photon axis

3) Once both virtual pion and photons are characterized, then t_pi in [-0,6 ; 0] and phi are generated.



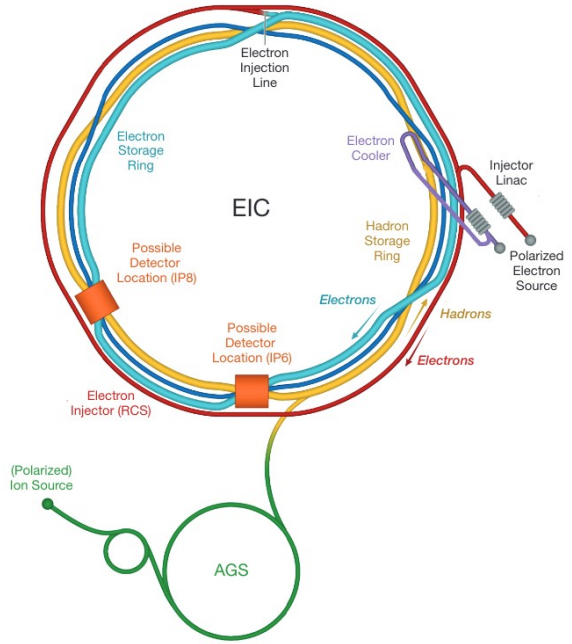
Events are then weighted by the cross section and a phase space factor.

The electron ion collider

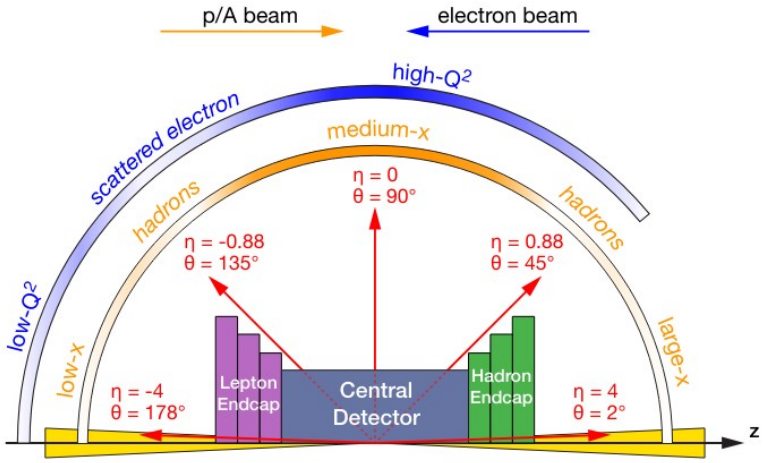
The electron-ion collider will be located in Brookheaven National Laboratory.

It will offer logitudinally polarized electron beam and transversely polarized protons.

Beams	Collision energy modes (GeV)							
	E_e	E_h	E_e	E_h	E_e	E_h	E_e	E_h
$e+p$	18	275	10	100	5	100	5	41



For our studies, we used a Toy geometry of the detector :
- Photon detected for |eta|<4.
- Electron detected and identified for |eta|<3,5.
- Neutron detected in the ZDC if theta<5,5 mrad.
- Pion detected either if |eta|<4 or theta between 6 and 20 mrad.



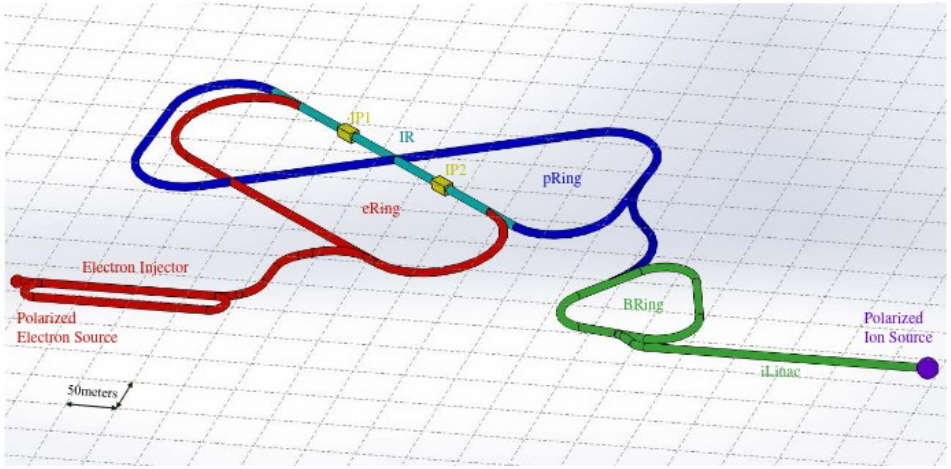
The electron ion collider in China

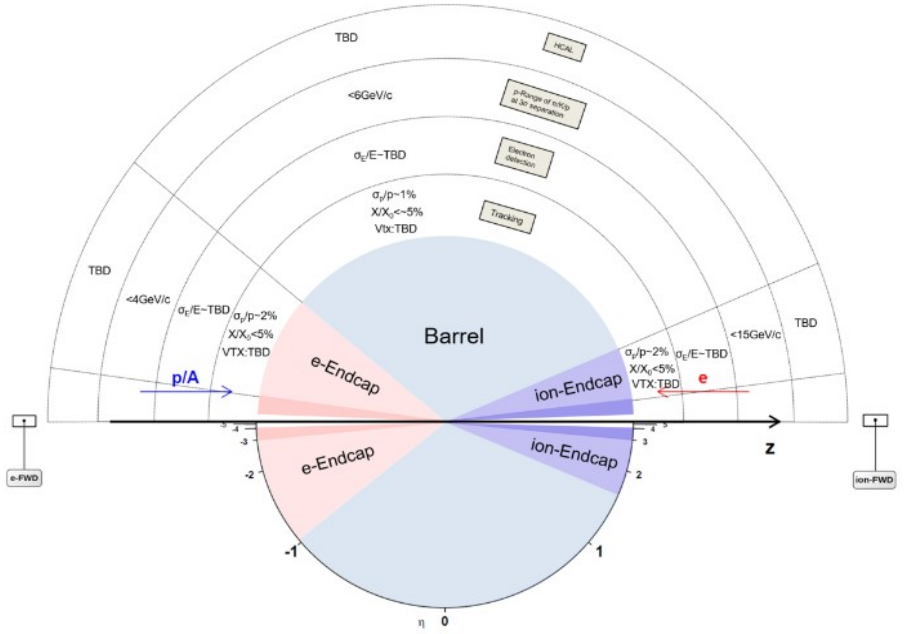
-There is a project to build an electron-ion collider facility in China, un an upgrade of the HIAF facility.

-Electron energy will be 3,5 GeV while proton energy will reach up to 20 GeV : More ideal to access valence region.

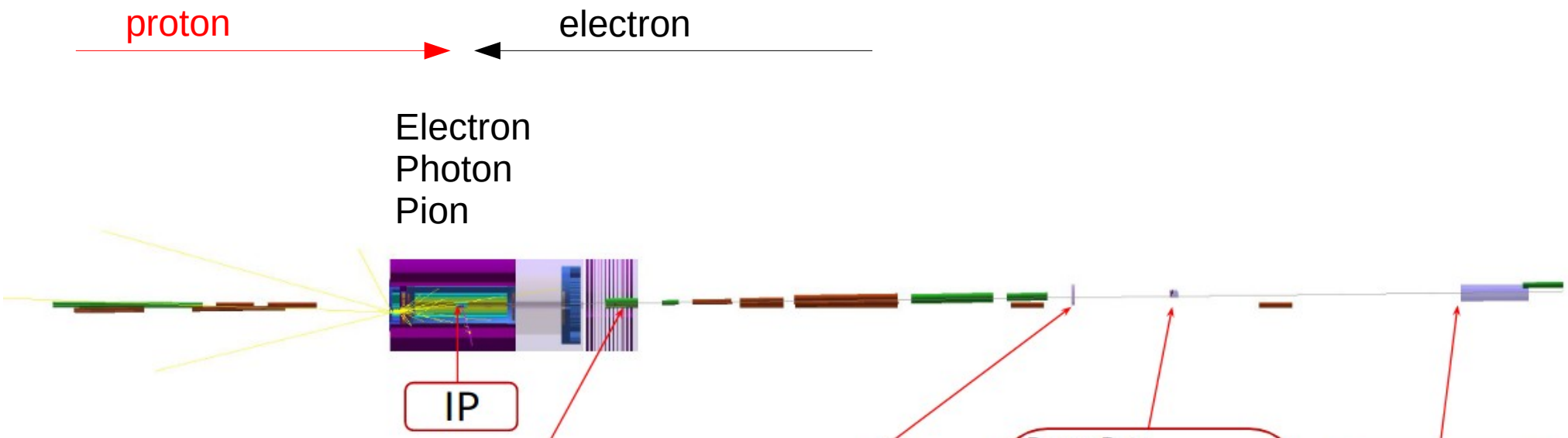
-The electron longitudinal polarization will reach 80 % and an expected luminosity of 50 fb-1 / year.

-For our study, we considered almost same geometry as for EIC except for the neutron calorimeter : No information is provided in the white paper.
=> Ideal detection of the neutron.

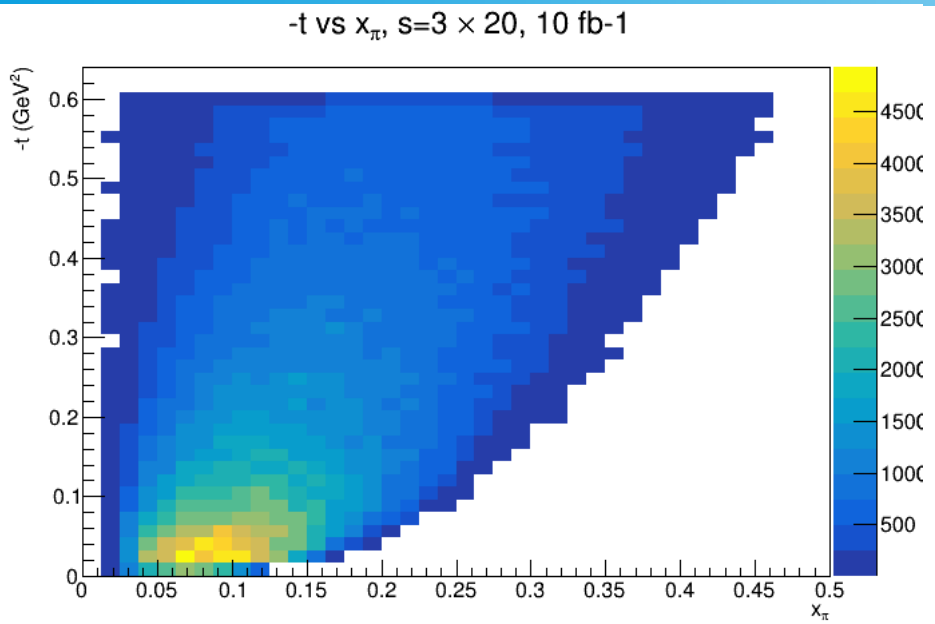


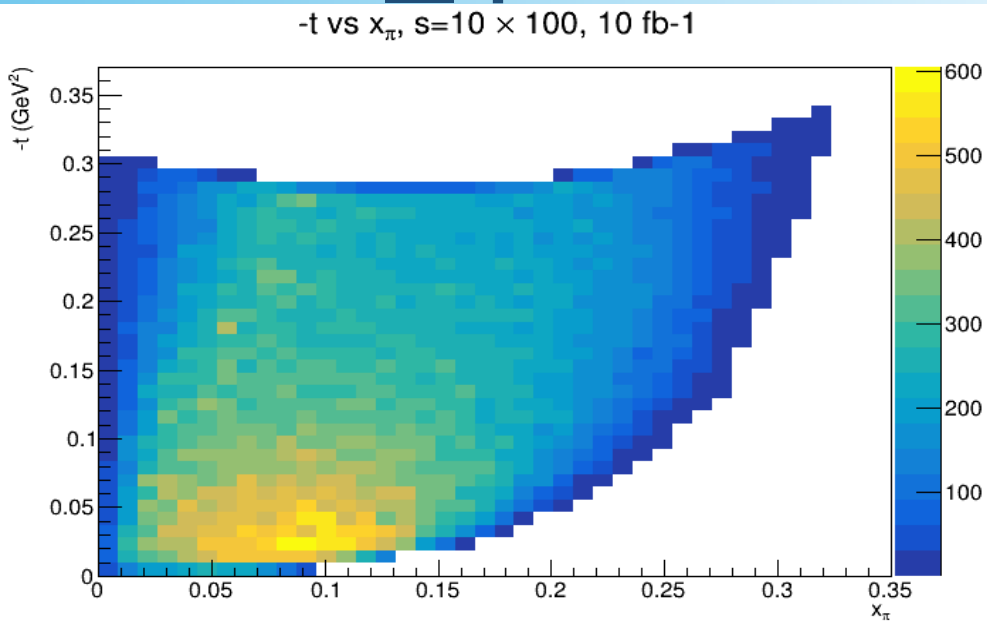


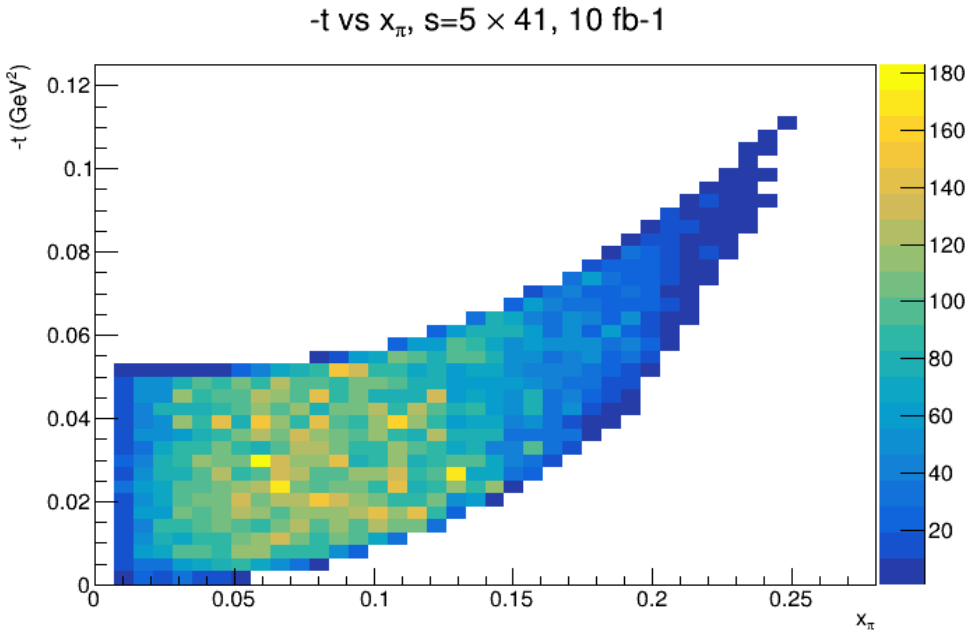
Detector Layout

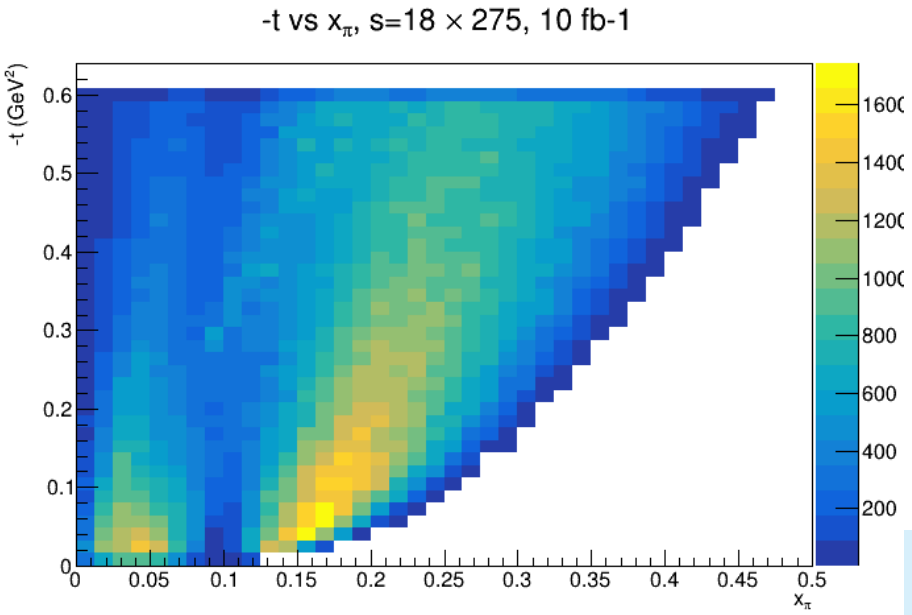


Kinematics : t and x_\pi

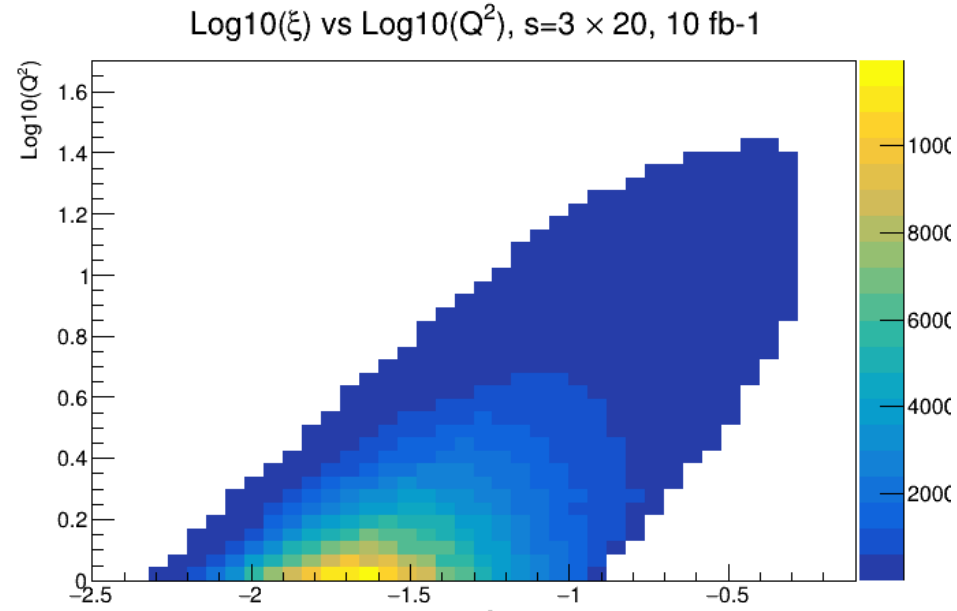


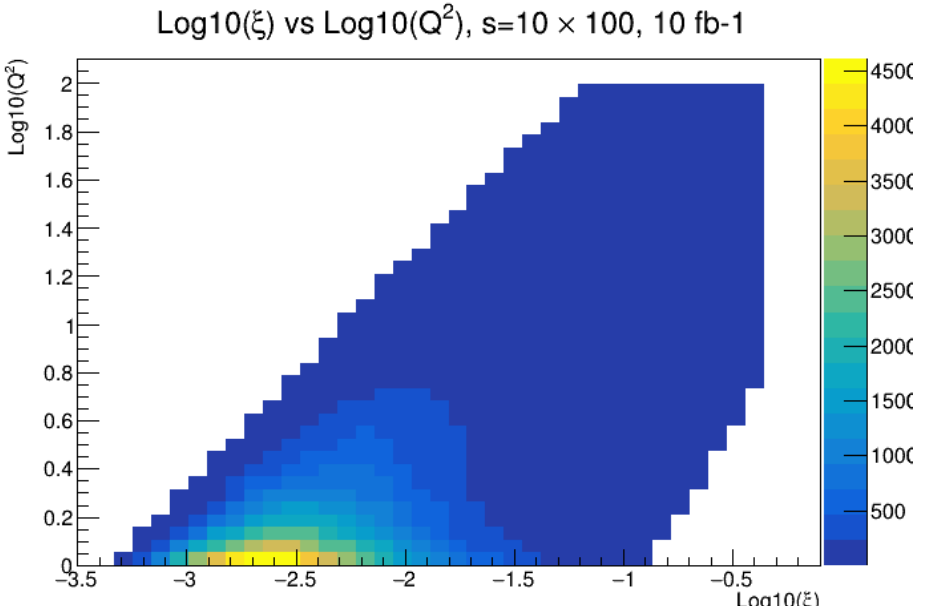


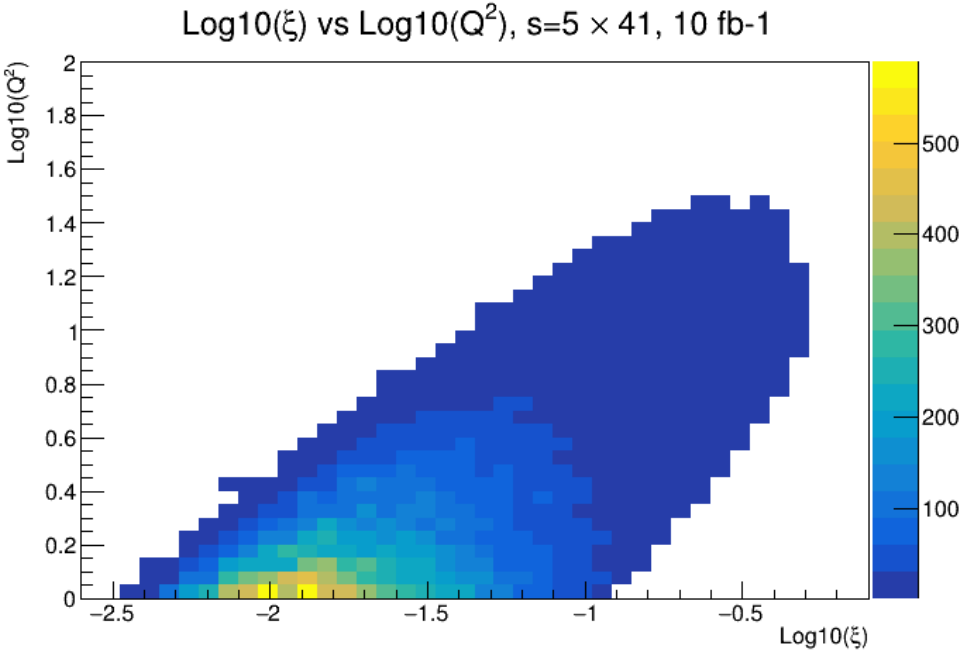


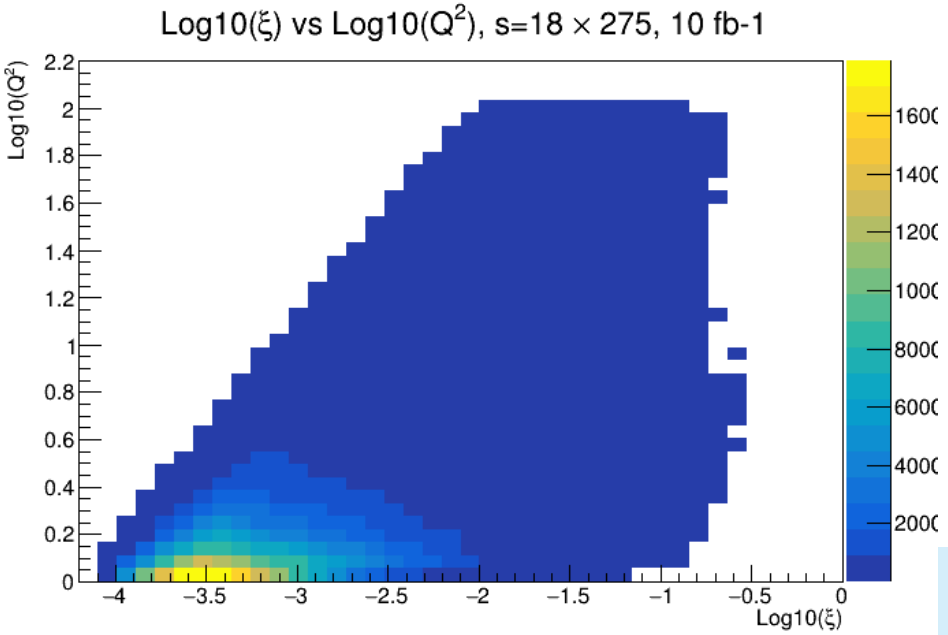


Kinematics : Q^2 and \xi

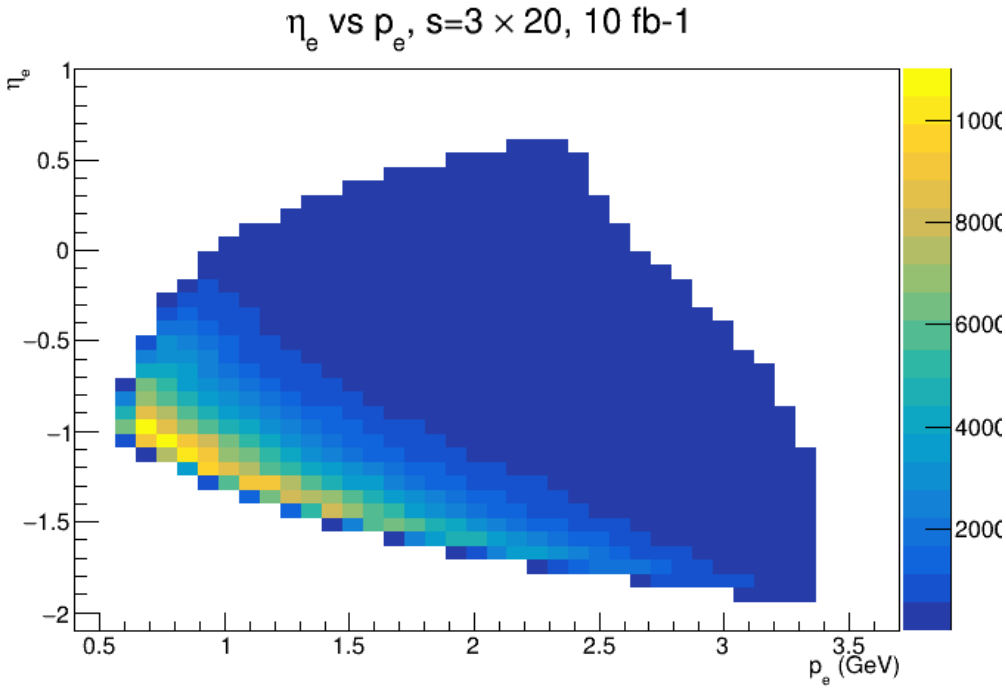


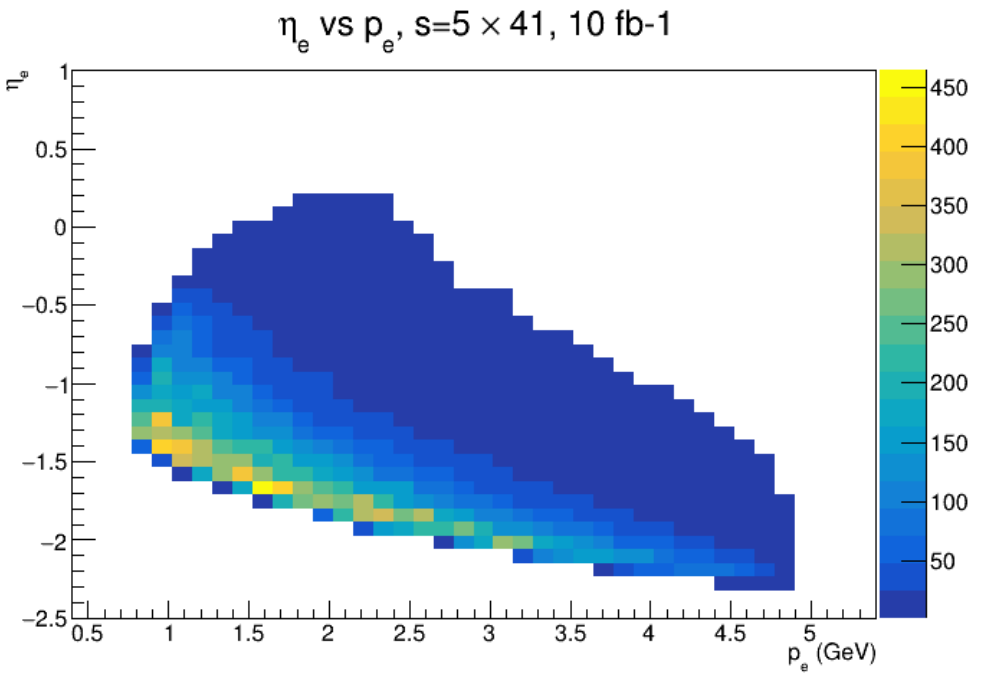


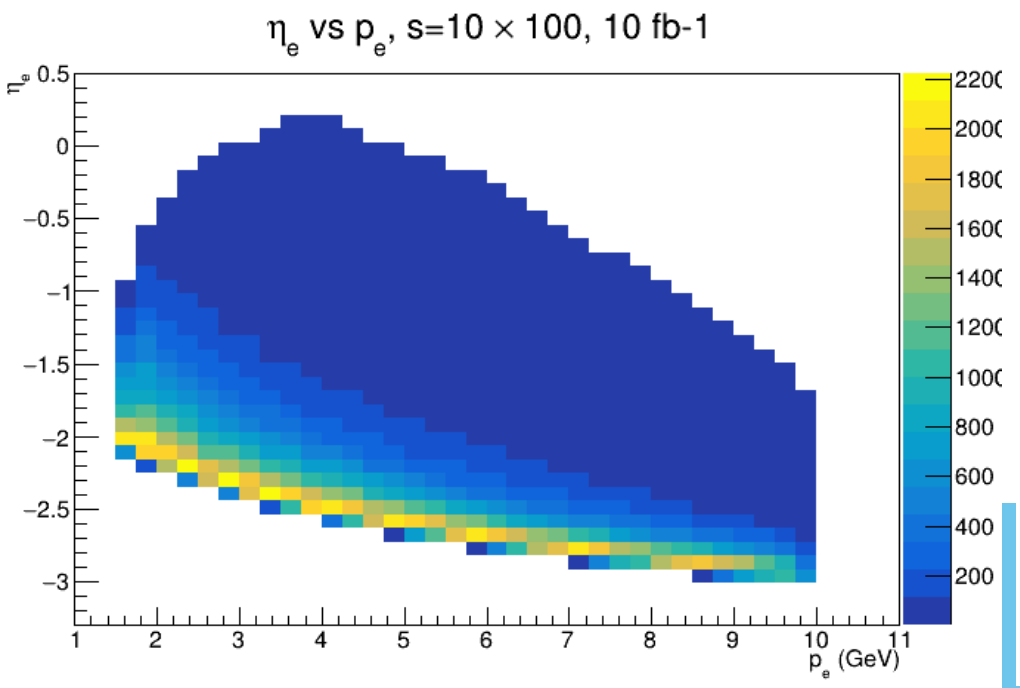


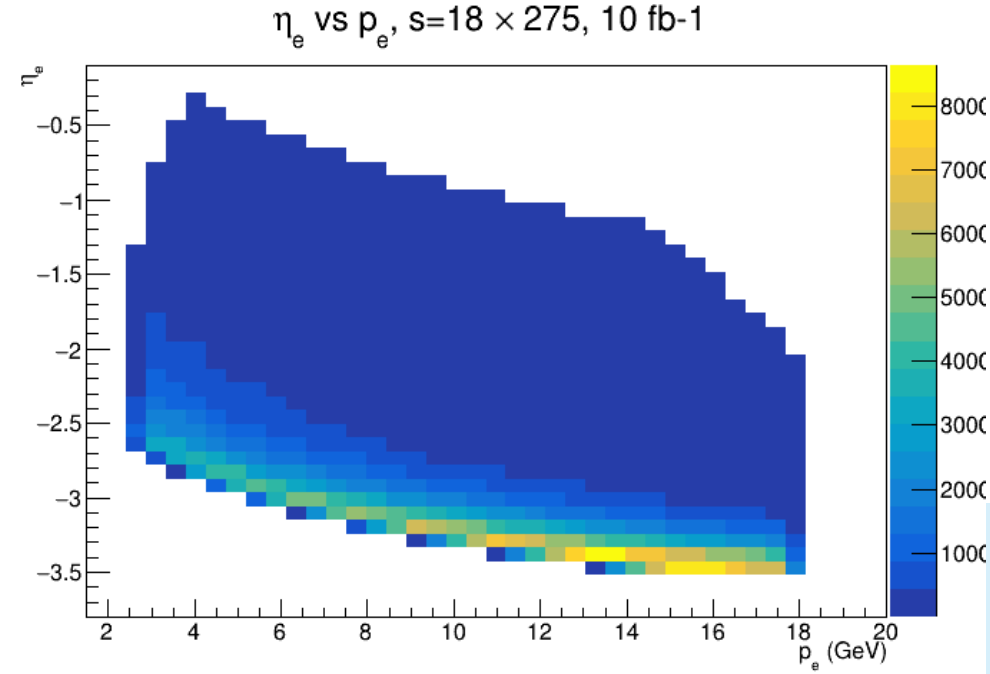


Electron distributions

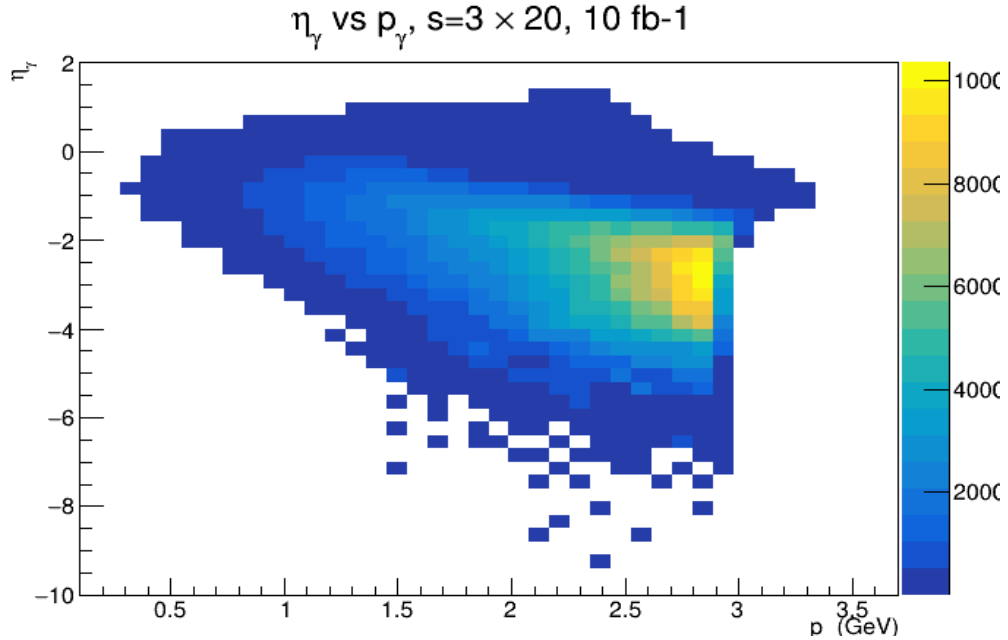


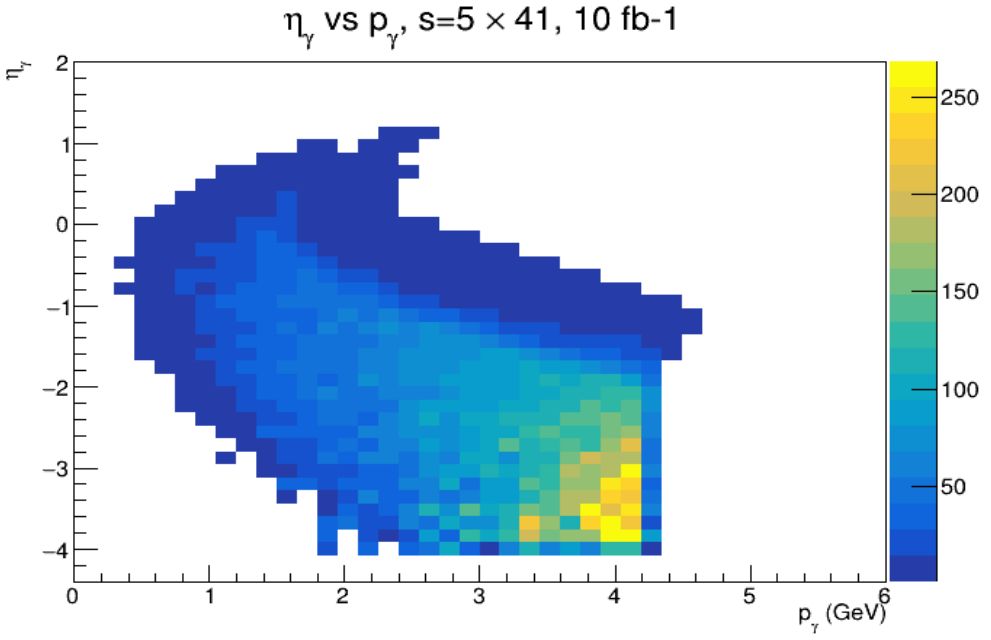


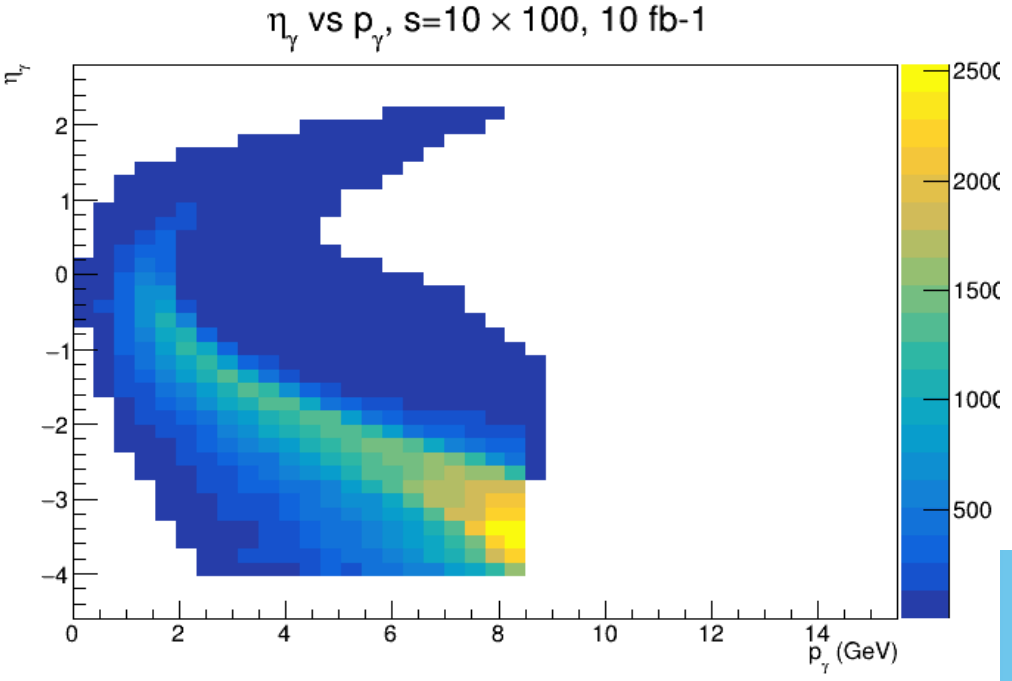


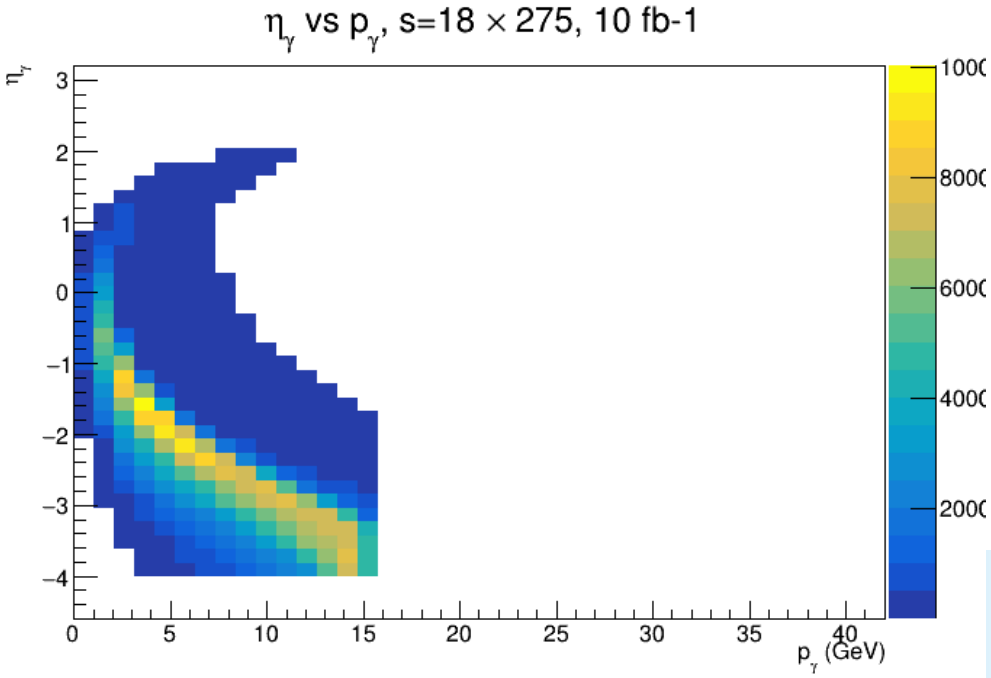


Photon distributions

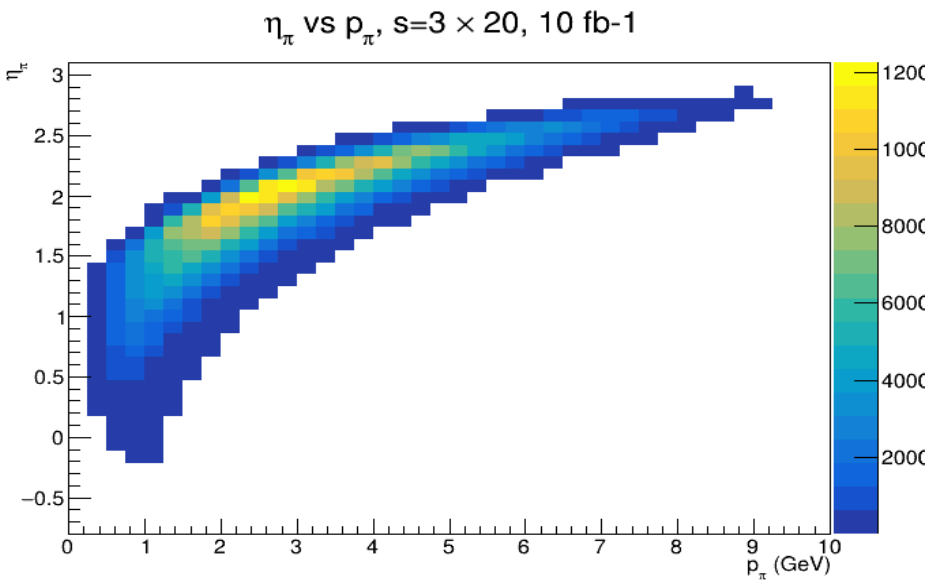


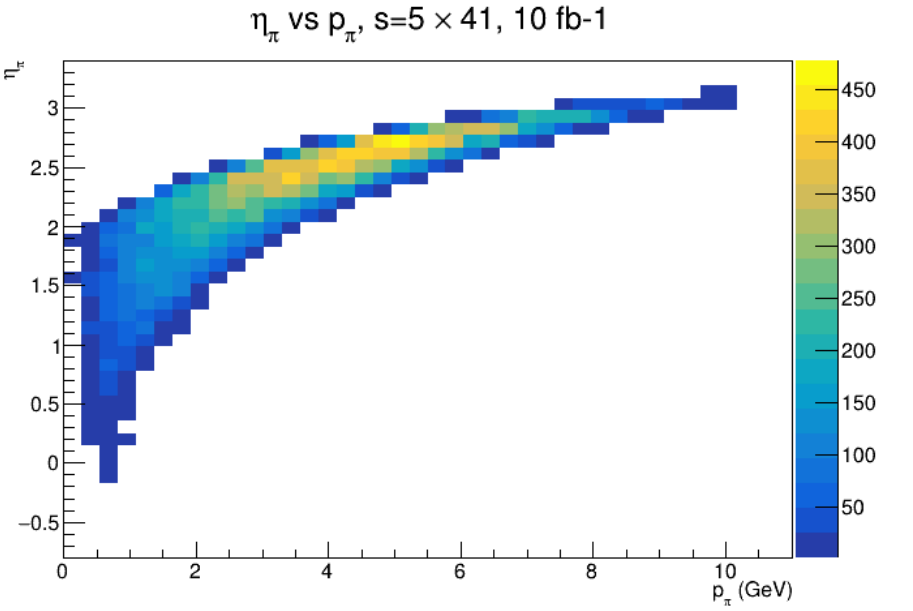


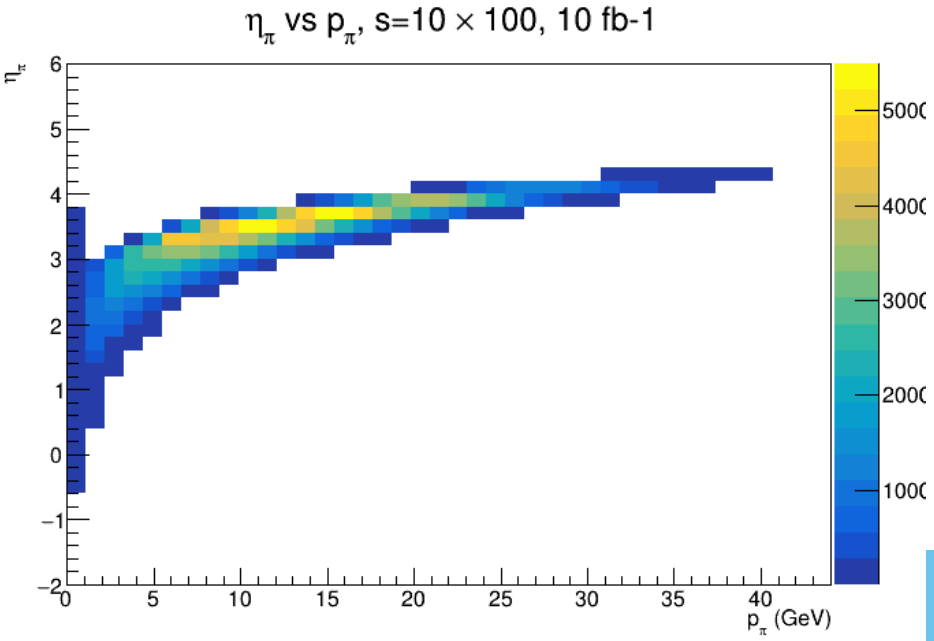


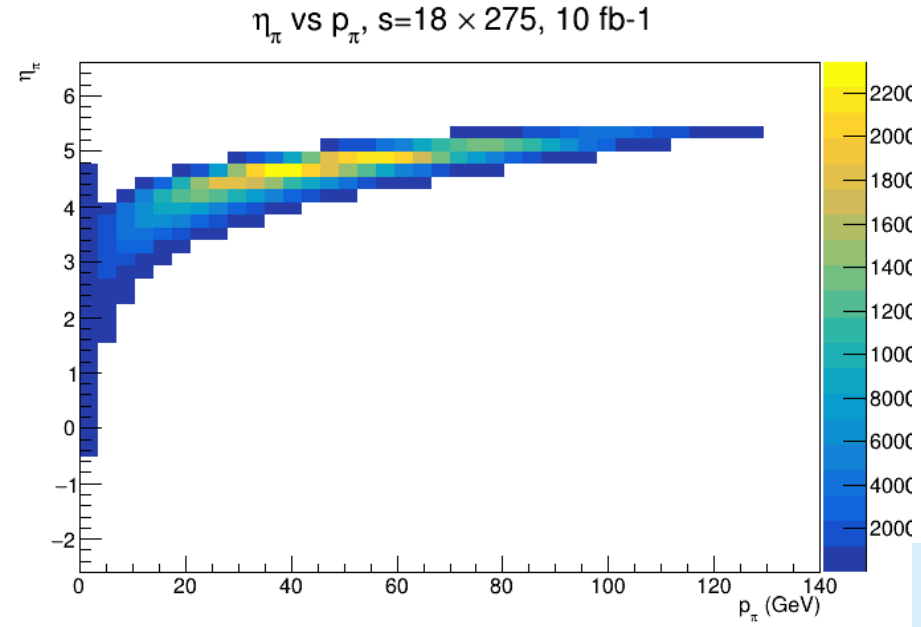


Recoil Pion distributions

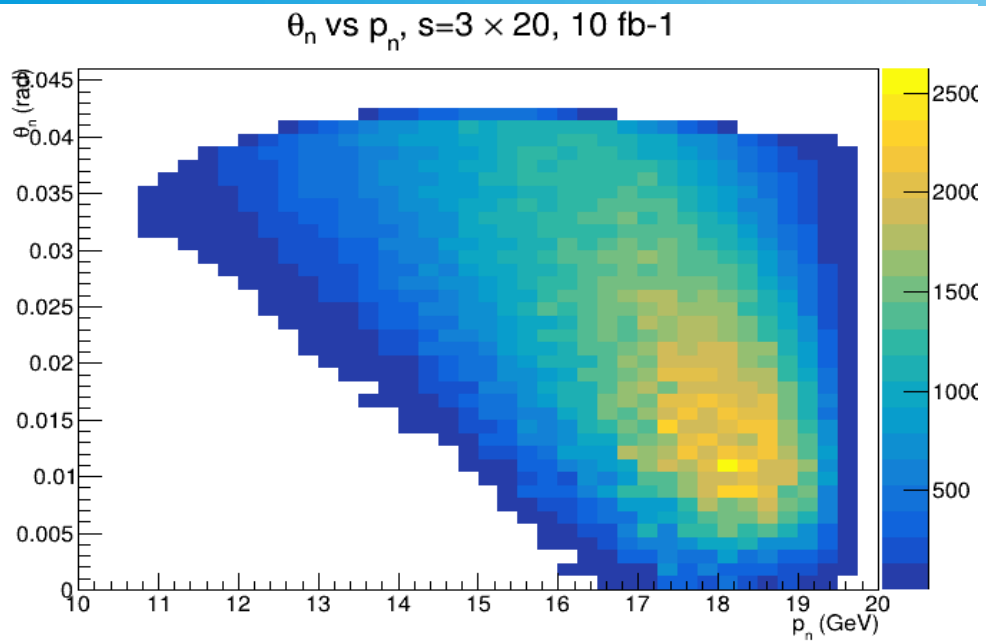


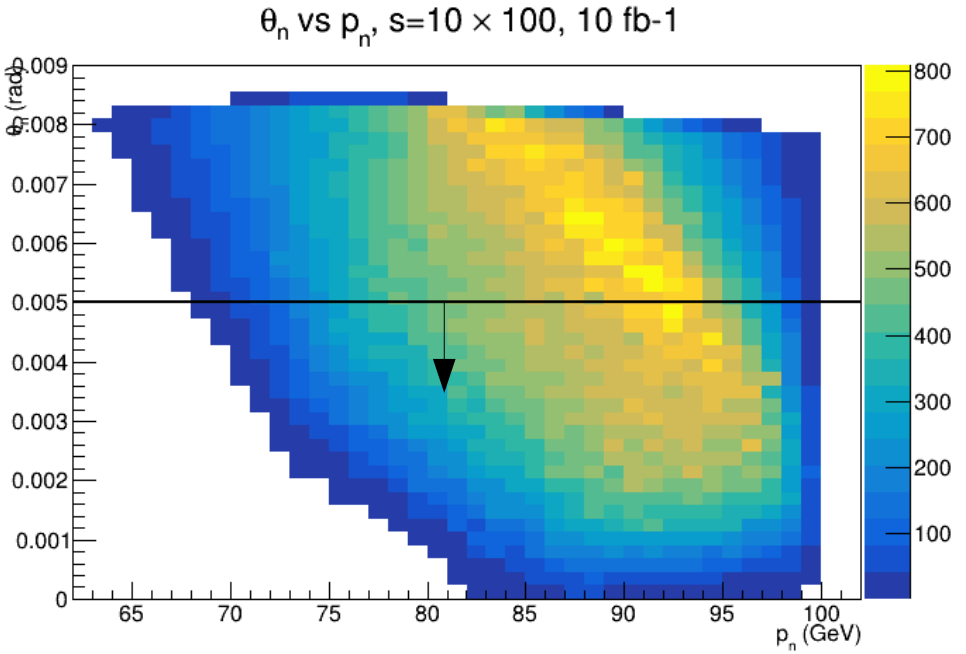


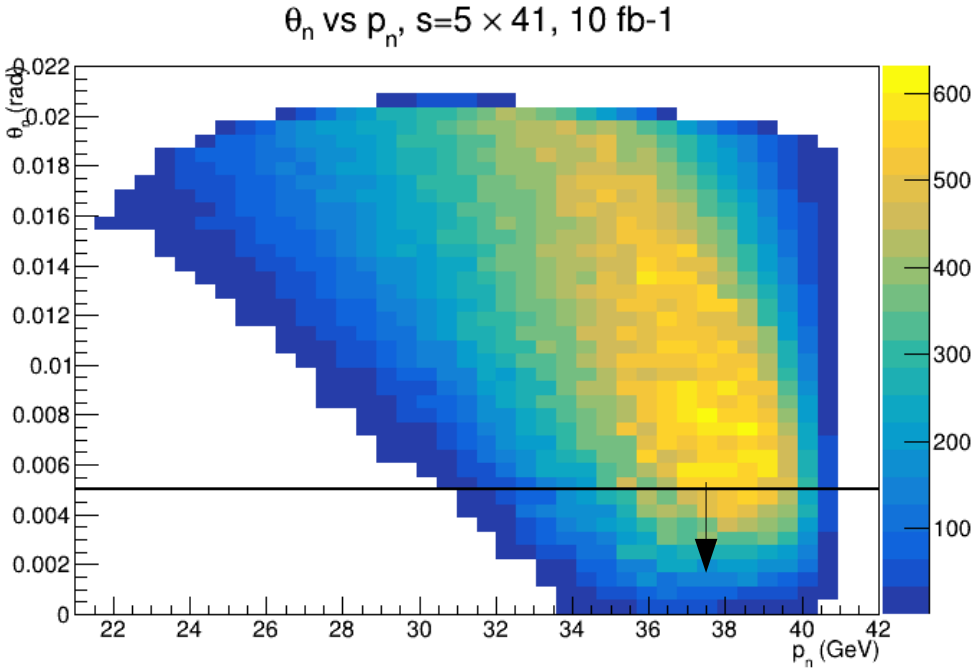


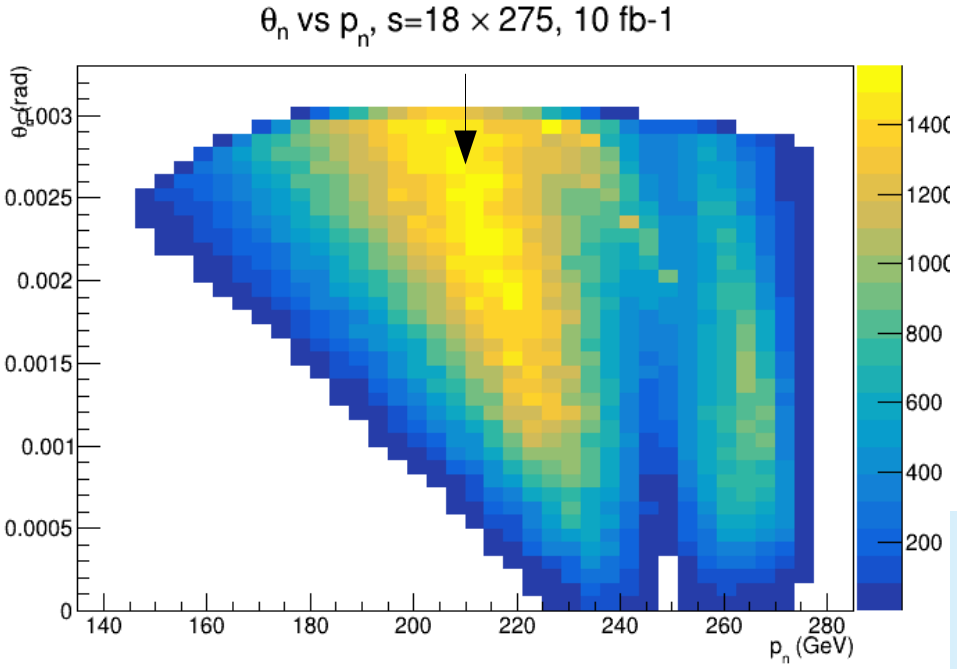


Neutron distributions



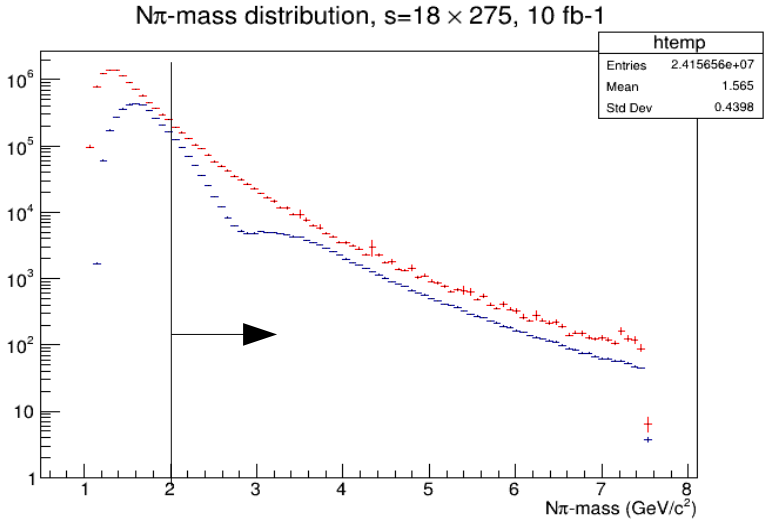


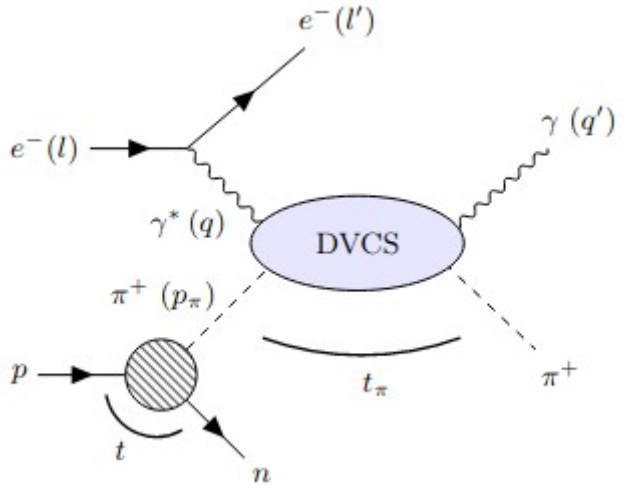




Sullivan process validity

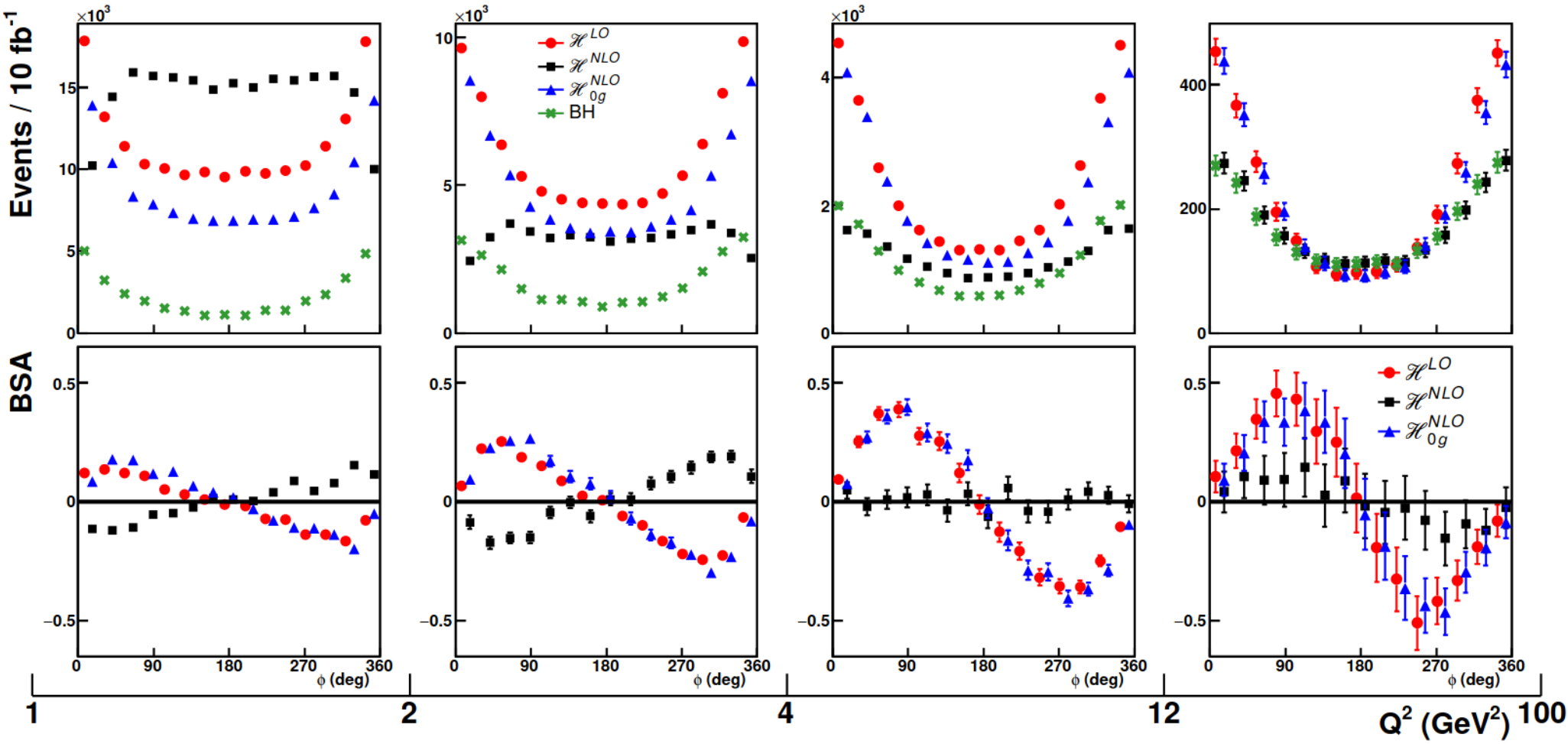
- The invariant mass of the N-pion system must be greater than 2 GeV to avoid resonances contribution (e p → e Delta gamma).





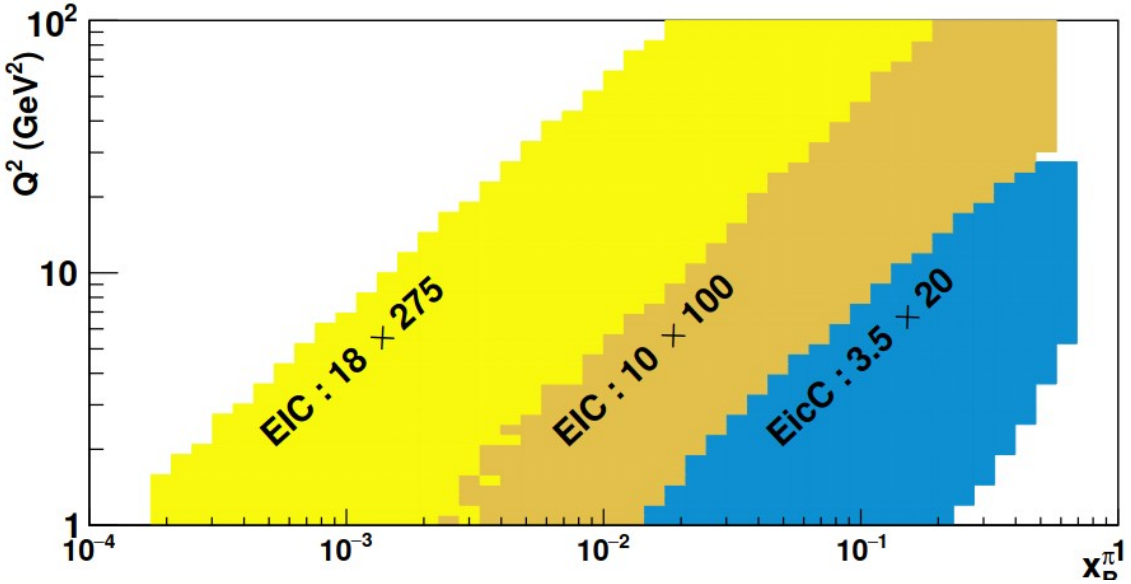
- Possible contribution from rho-to-pi but needs a model to evaluate them. The smaller the pion virtuality, the better.

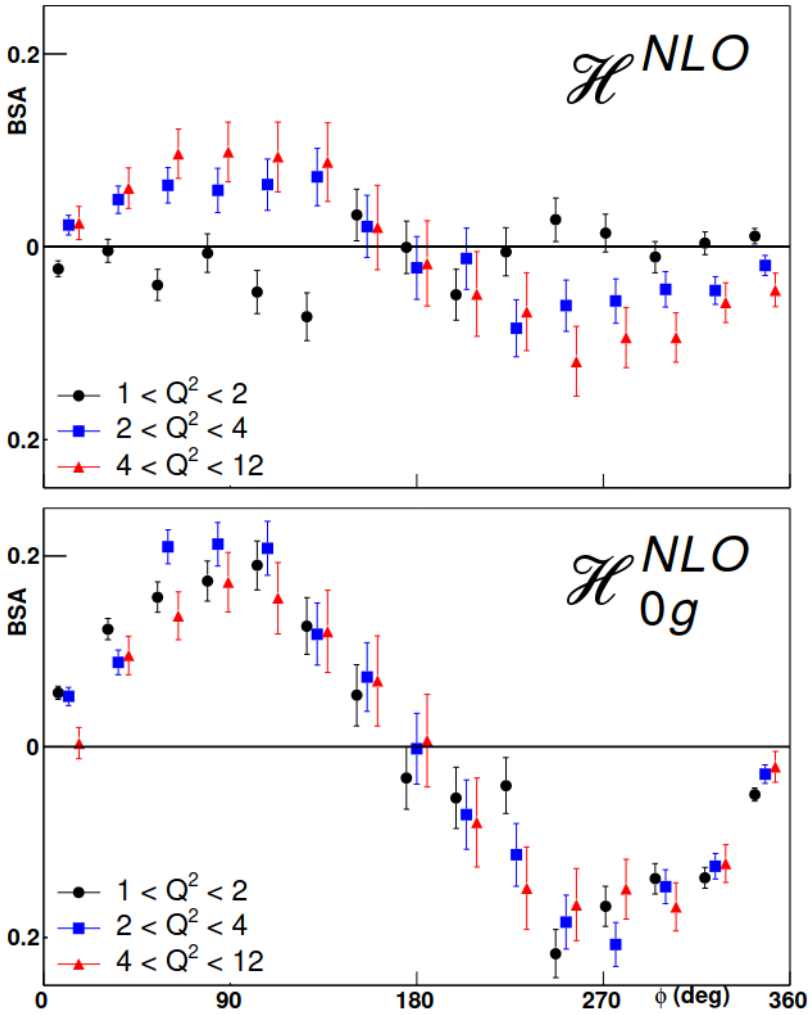
Comparison for scenarii



Gluons contributing negatively to the DVCS amplitude except at small Q^2 because of their number.

Gluons even in the valence





Even in the valence region at EICC, gluons can be spotted by a steep Q^2 – dependence of the asymmetry at low Q^2

What remains to be done...

- The process is definitely measurable. If the model is accurate, features in BSA could help us to pin down gluon dominance.
- Now, need to plug events in real EIC simulation to determine the resolution on the kinematical variables and use a more realistic acceptance.
- Refine the binning and perform t_pi-scan studies.

More exclusive processes on pion

- Jose et al. provide us GPD models for both quarks and gluons in pion. From EIC measurements/simulation, would it be possible to retrieve the quark/gluon information from DVCS measurements ?

- What about DVMP (Phi-electroproduction) on the virtual pion ? Definitely helping to constrain gluonic content.

- Need to look into pi0… (Thank you Bernard)