DEMPgen: Physics event generator for Deep Exclusive Meson Production at Jefferson Lab and the EIC

https://arxiv.org/abs/2403.06000

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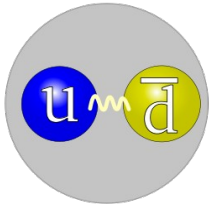
July 19, 2024

JLab EIC Weekly Meeting

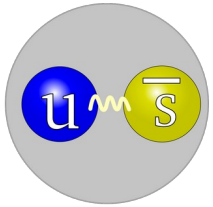
University of Regina

Motivation

- Emergence of hadronic mass generation is directly linked to the internal structure of the constituents ($\pi^{\pm}$, $K^{\pm}$).



Pion (π^{+})



Kaon (K^{+})

  - Can examine this internal structure by looking at quantities like the form factor.
  - Form factor describes the spatial distribution of partons within a hadron.
- Comparing pion ($\pi^{\pm}$) and kaon ($K^{\pm}$) form factors (F_{π}, F_{K}) provides unique information on mass generation mechanisms.
- One of the ways to measure the form factor is through Deep Exclusive Meson Production (DEMP) reactions.

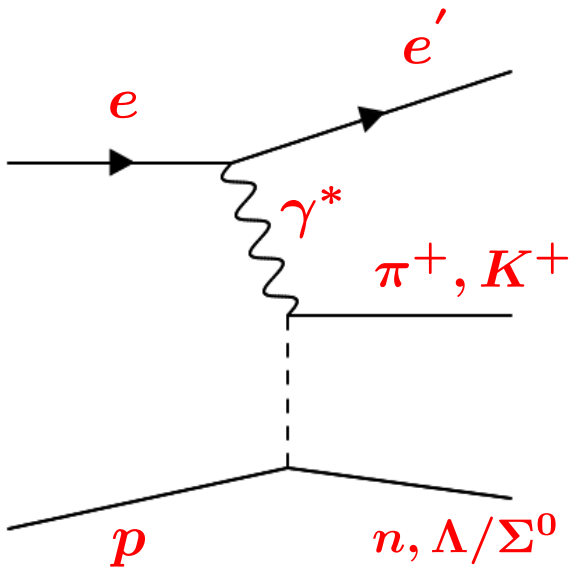
http://lichen.phys.uregina.ca/

DEMP reactions

- For π^+, K^+ electroproduction reactions:

$$e + p \rightarrow e' + \pi^+ + n$$
$$\rightarrow e' + K^+ + \Lambda/\Sigma^0$$

- At Jlab, we detect e', π^+ or K^+, and reconstruct n or Λ/Σ^0.
- At EIC (triple coincidence experiment), we need to track all the three final state particles.
  - Missing momentum resolution is insufficient to uniquely reconstruct recoil.
- Need an event generator!



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Kinematic variables

- Basic kinematic invariants can be written as

$$e + p \rightarrow e^{'} + \pi^{+} + n$$
$$\rightarrow e^{'} + K^{+} + \Lambda/\Sigma^{0}$$

  - ep squared CM energy

$$s = (e + p)^2$$

  - γ^{*}p squared CM energy

$$W^2 = (\gamma^{*} + p)^2$$

  - Photon virtuality

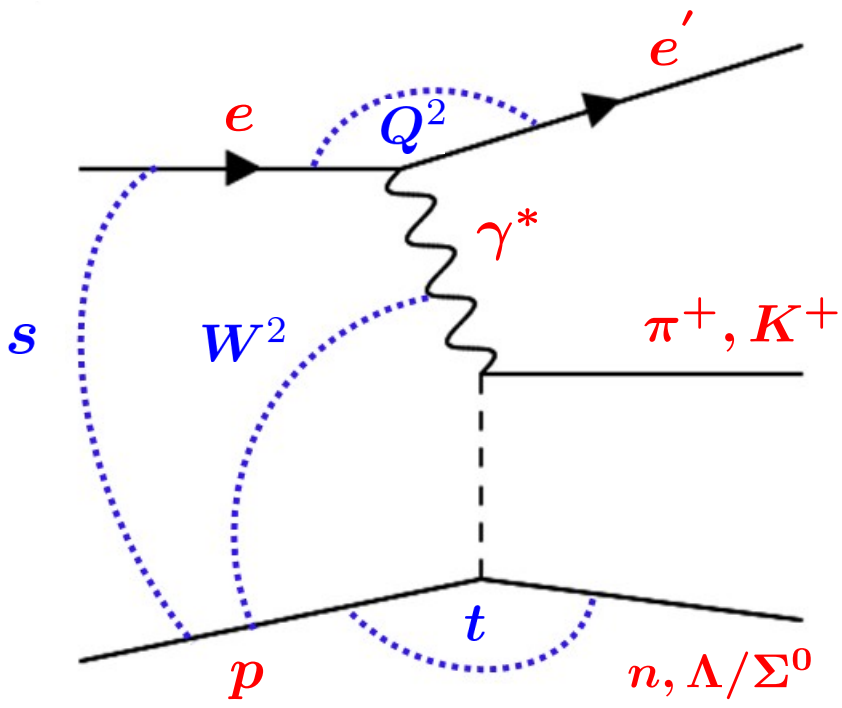
$$Q^2 = -q^2 = (e - e^{'})^2$$

  - Squared 4-momentum transfer to the nucleon

$$t = (p - Recoil)^2 = (\gamma^{*} - Ejectile)^2$$

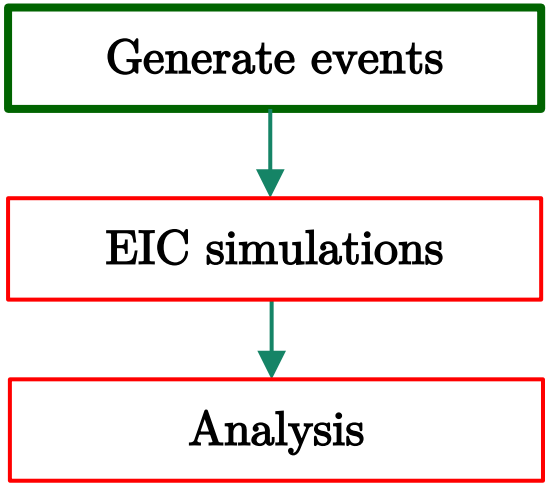
Ejectile : π^{+}, K^{+}

Recoil : n, Λ, Σ^{0}



Feasibility studies at EIC

- Focus on feasibility studies of DEMP reactions through ePIC simulations at EIC.
- The first step will be to generate an event sample.



Monte Carlo event generator - DEMPgen

- Focuses on two key modules:
  - Colliding beam kinematics mode for the Electron-Ion Collider.
  - Fixed target kinematics mode for the SoLID experiment.
- For the EIC, it currently incorporates three reactions:
  - $p(e,e'\pi^+n)$ → π^+ electroproduction
  - $p(e,e'K^+\Lambda)$
  - $p(e,e'K^+\Sigma^0)$

  } K^+ electroproduction

Ejectile : π^+, K^+

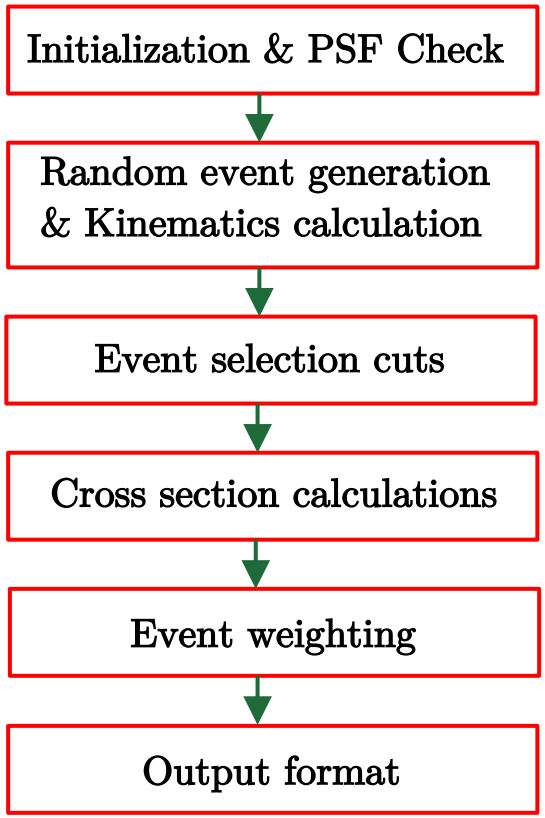
Recoil : n, Λ, Σ^0

- Consider the head-on collision between the electrons & protons at different beam energies, including, 5(e) × 41(p), 5(e) × 100(p), 10(e) × 100(p), and 18(e) × 275(p).
- It is a weighted event generator.

https://github.com/JeffersonLab/DEMPgen

Monte Carlo event generator - DEMPgen

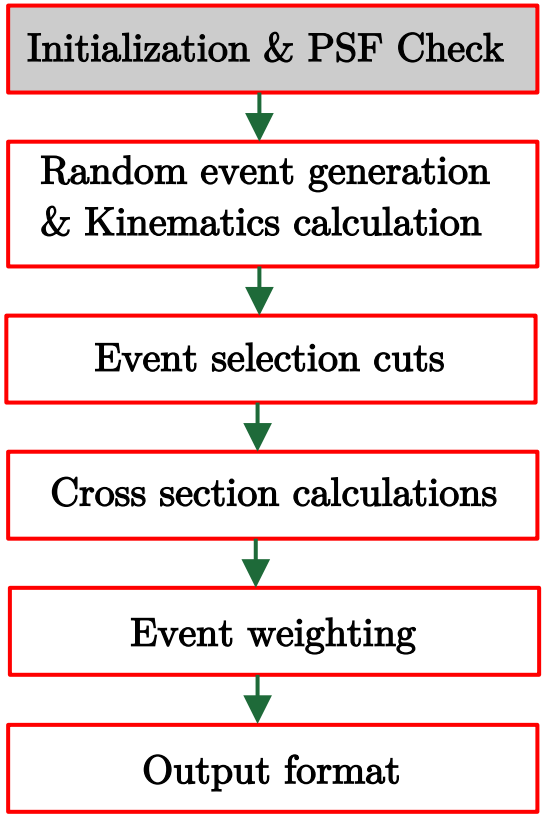
- How does the generator work?



Described based on the upcoming release, DEMPgen – v1.2.0

Monte Carlo event generator - DEMPgen

- How does the generator work?



Initialization & PSF check

- Start initialization by reading an input .json file containing several input parameters, such as beam energies, requested events, output file type, electron energies, electron and ejectile angles, etc.

  Consider 5(e) × 100(p) beam energy combination for π^+ reaction:

  User-defined limits:

e_En_Low	e_En_High	e_Theta_Low	e_Theta_High	Ejectile_Theta_Low	Ejectile_Theta_High
2.5	12.5	60.0	175.0	0.0	50.0

- Phase Space Factor (PSF) module constrain the user-defined electron and ejectile energy/angle ranges based on the kinematic variable cuts (Q^2 ,W, and -t).

Initialization & PSF check

Allowed phase space limits:

e_En_Low	e_En_High	e_Theta_Low	e_Theta_High	Ejectile_Theta_Low	Ejectile_Theta_High
2.5	12.5	60.0	175.0	0.0	50.0
4.9	6.62	116.925	158.785	1.5	50.0

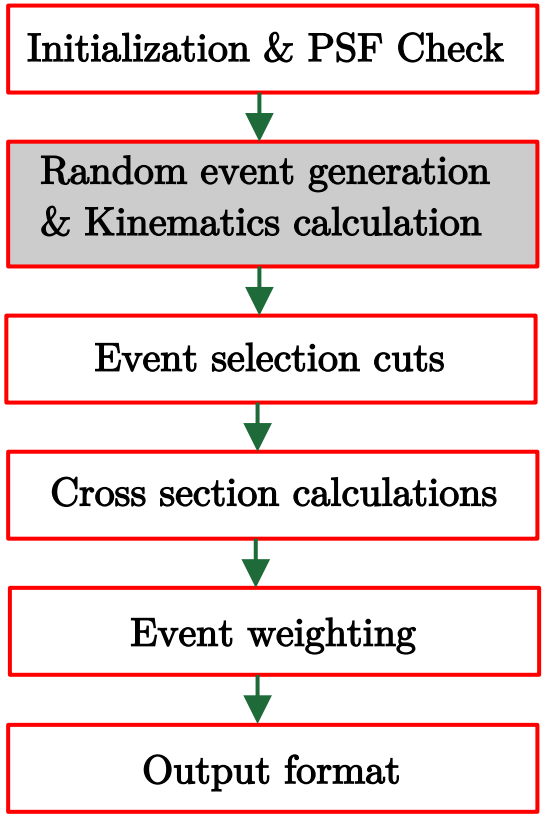
- Calculate the PSF, which is the fraction of the total kinematically accessible phase space that is covered by the event generator, using constrained ranges.
  - Critical for calculating event weights.

$$PSF = (E_{e'Max} - E_{e'Min}) d\Omega_{e'}(\theta, \phi)\, d\Omega_{Ejectile}(\theta, \phi)$$

- Time-efficient, with more recorded events per file, and without wasting CPU resources.

Monte Carlo event generator - DEMPgen

- How does the generator work?



Random event generation & Kinematics calculation

- Relevant differential cross section is 5-fold ($\theta_{e'}$, $\phi_{e'}$, $E_{e'}$, θ_{Ej} , ϕ_{Ej}).
- Randomly generate scattered electron & ejectile energy/angles with in the phase space limits.
- Calculate the scattered electron's four momentum (P).
- Calculate the virtual photon.
- Solve for the ejectile's energy (E) using four-momentum conservation at the photon-ejectile vertex.
- Calculate the recoil's direction and four momentum (P) using energy and momentum conservation at the physics reaction vertex.

$$e + p \rightarrow e' + Ejectile + Recoil$$

- Determine the kinematic variables Q^2 ,W, and -t as soon as relevant information is obtained.

Monte Carlo event generator - DEMPgen

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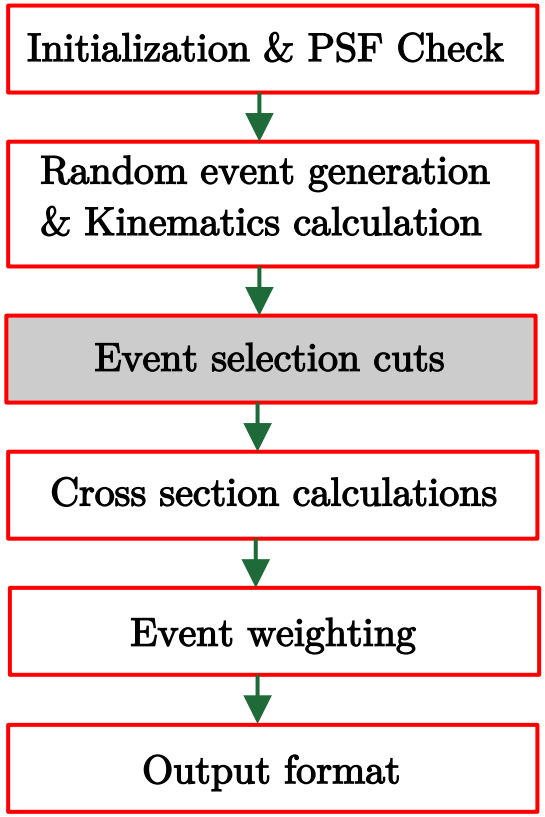

Event selection cuts

- Cut on ejectile's energy being a NaN value.
- Energy and momentum conservation cut at the physics reaction vertex.
- $W^2 > 0$ cut.

} Unphysical events

- Q^2 cut
- W cut
- -t cut

} Depends on the requested reaction & limits come from the theoretical model's parametrization.

Monte Carlo event generator - DEMPgen

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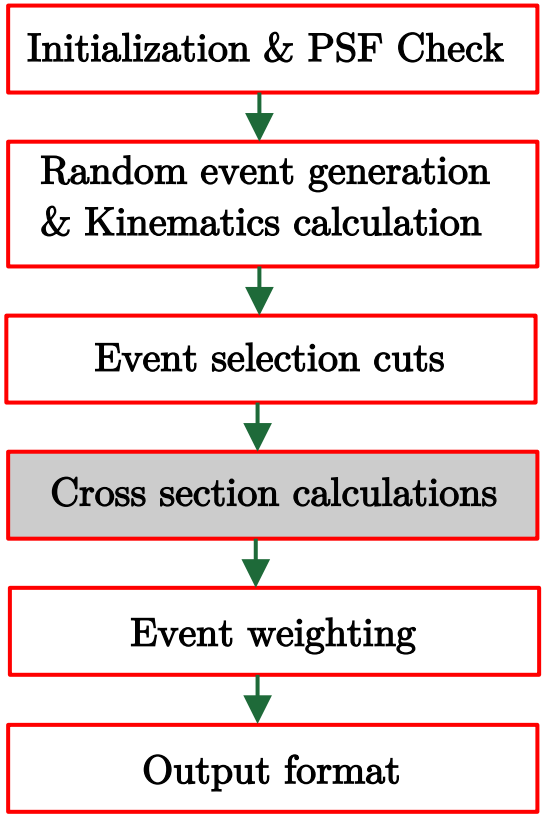


Cross section calculations

- Exclusive reaction cross-section in the collider frame is:

$$\frac{d^5\sigma}{dE^{Col}_{e'}\,d\Omega^{Col}_{e'}\,d\Omega^{Col}_{Ej}} = (\Gamma^{Col}_{\nu}) \left(\frac{d\Omega^{CM}_{Ej}}{d\Omega^{Col}_{Ej}}\right) \left(\frac{d^2\sigma}{d\Omega^{CM}_{Ej}}\right)$$

Virtual photon flux factor

Jacobian for the conversion from CM to Col frame

$$\frac{d^2\sigma}{d\Omega^{CM}_{Ej}} = \mathrm{J} \left(\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}\right)$$

Jacobian

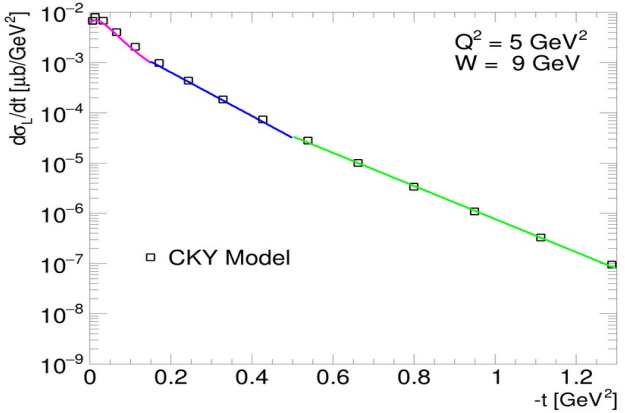
Parametrized theoretical models

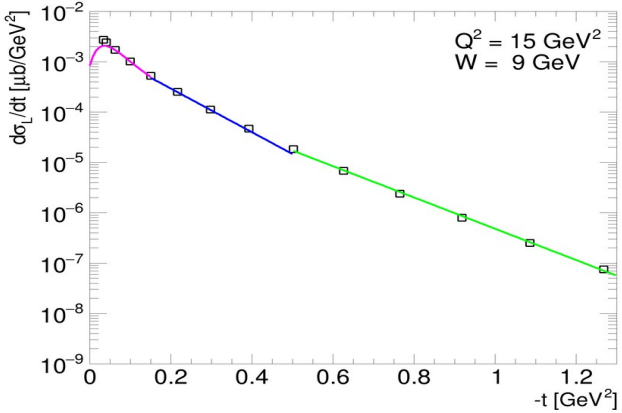
https://arxiv.org/abs/2403.06000

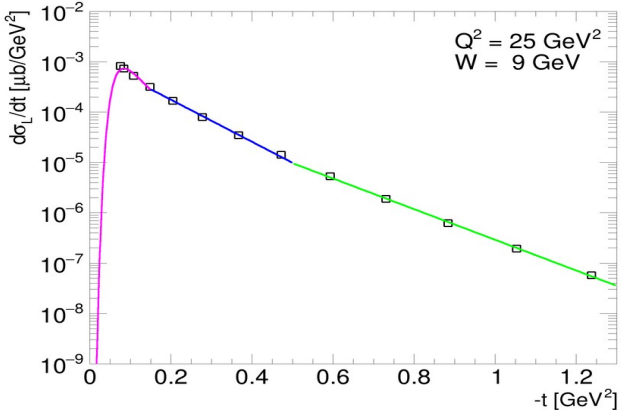
Parametrization of theoretical model for π^+ module

- Begin with p(e,e' π^+n) reaction.
- Use the Regge-based p(e,e' π^+n) model from T.K. Choi, K.J. Kong and B.G. Yu (CKY) - arXiv 1508.00969
  - MC event generator created by parametrizing CKY σ_L, σ_T for $3<Q^2<35$, $2<W<10.2$, $0<-t<1.3$.
    - Parametrize in step sizes of 0.2 GeV in W and 1 GeV^2 in Q^2.
  - Parametrize σ_L with a landau, exponential, and exponential.

σ_L







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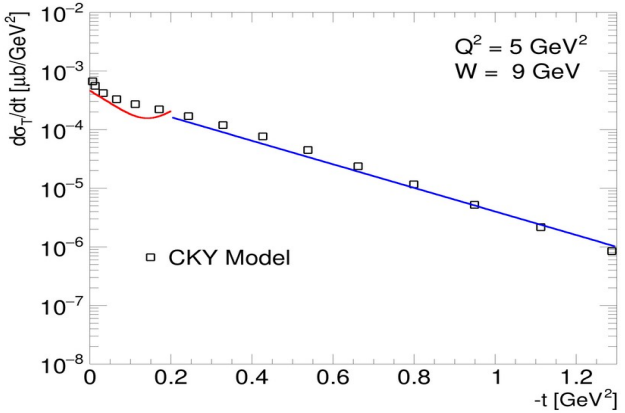
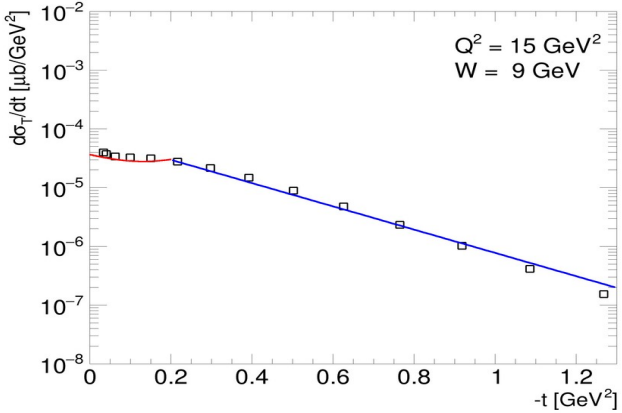
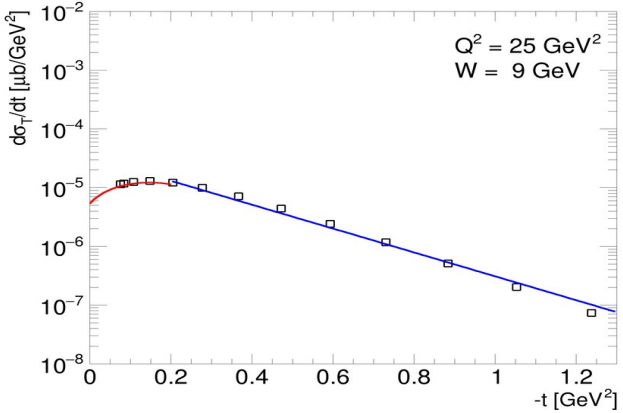
σ_T







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Parametrization of theoretical model for Λ Channel

- Two channels for the kaon module.
- Begin with p(e,e' $K^+\Lambda$) reaction.
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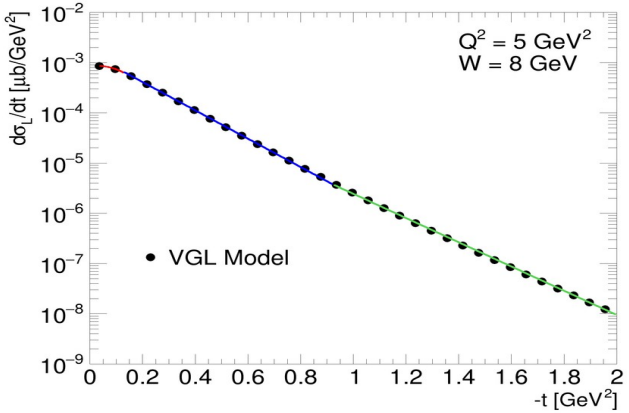
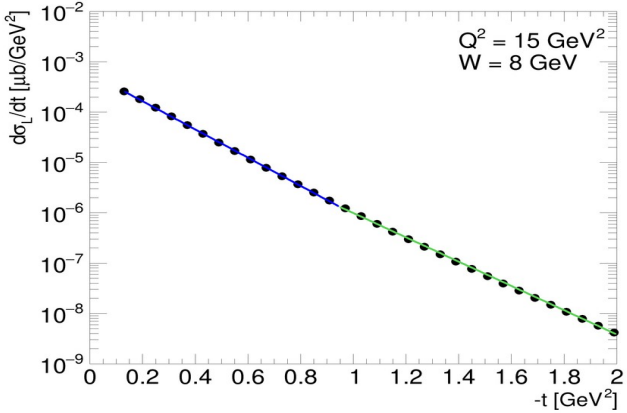
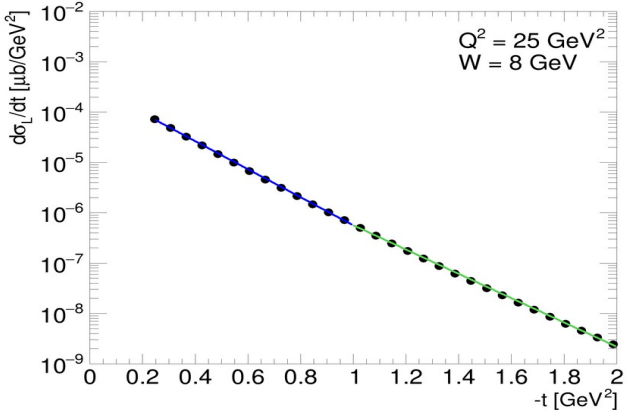
σ_L







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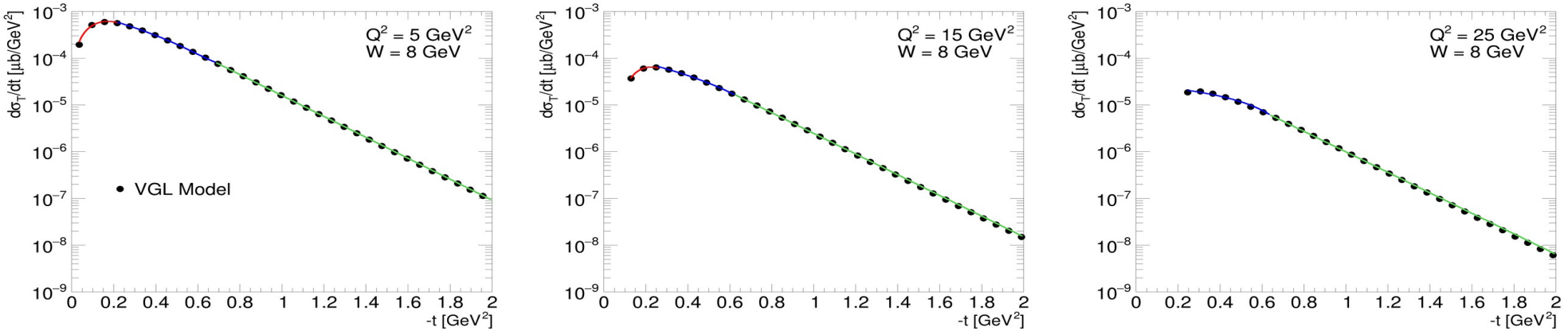
σ_T



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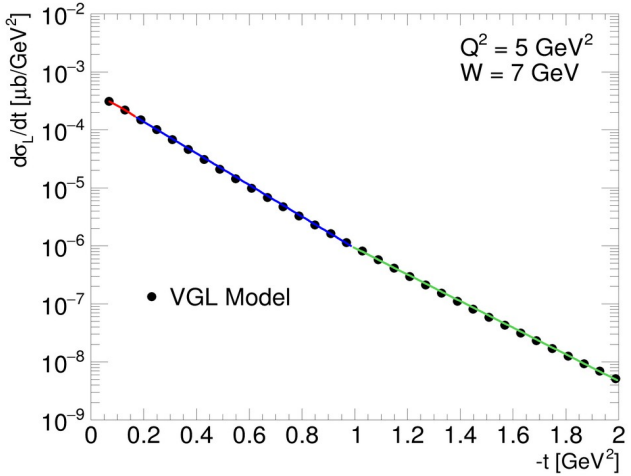
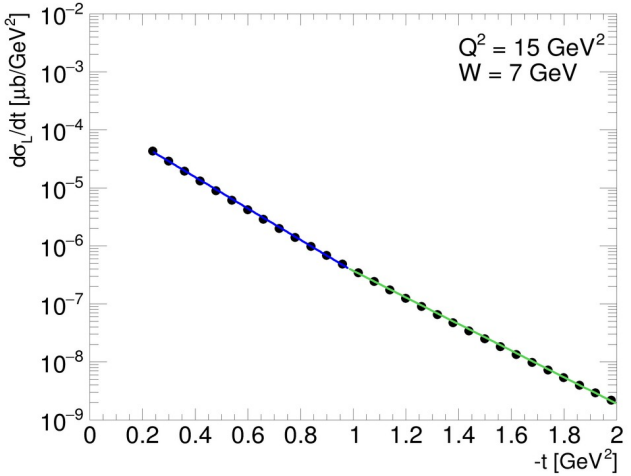
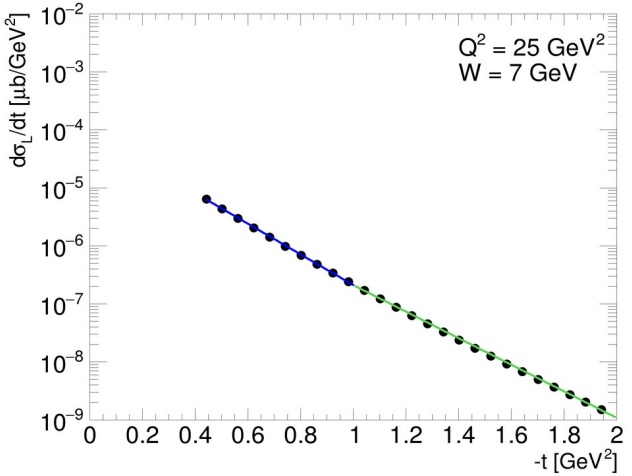
    - Parametrize in step sizes of 1 GeV in W and 1 GeV^2 in Q^2.
  - Parametrize σ_L with a polynomial, exponential, and exponential.

σ_L







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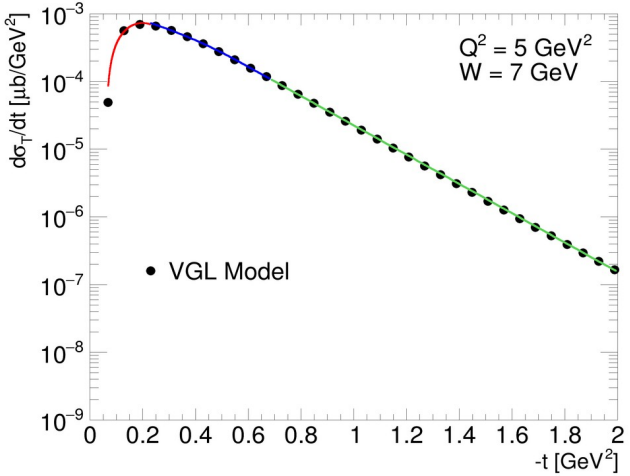
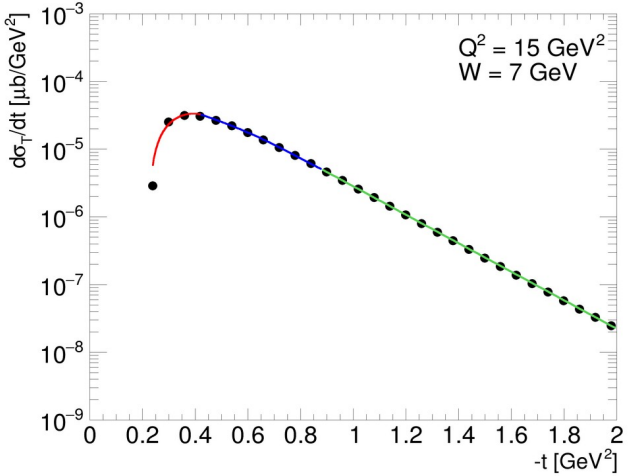
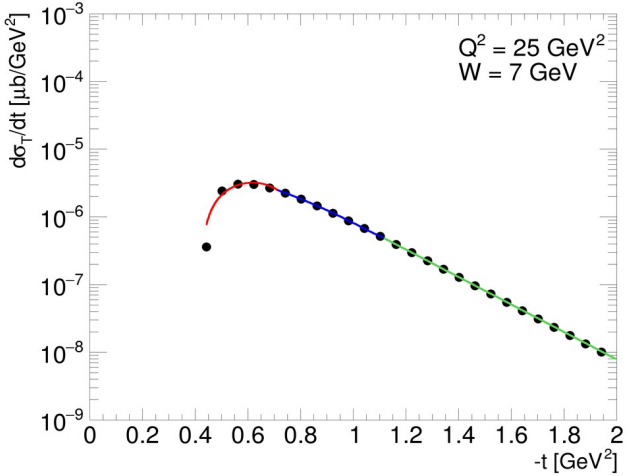
σ_T







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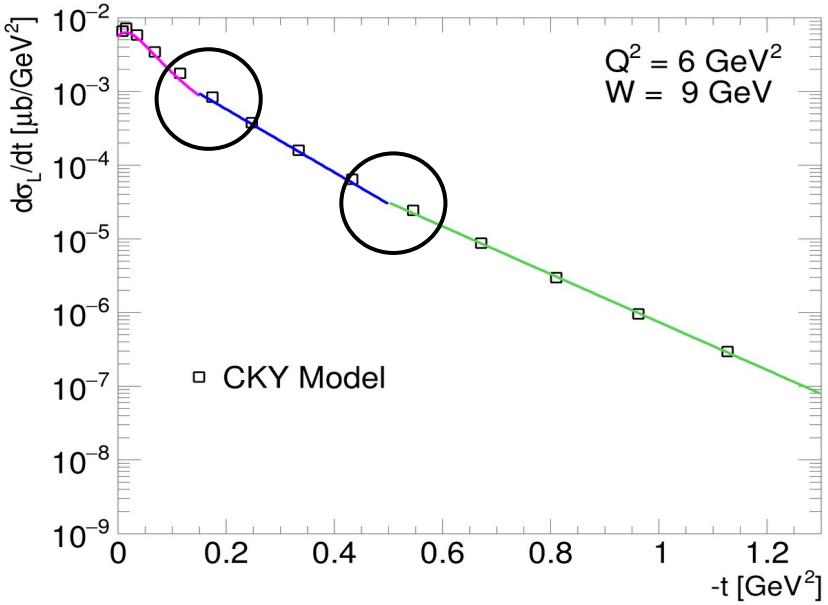
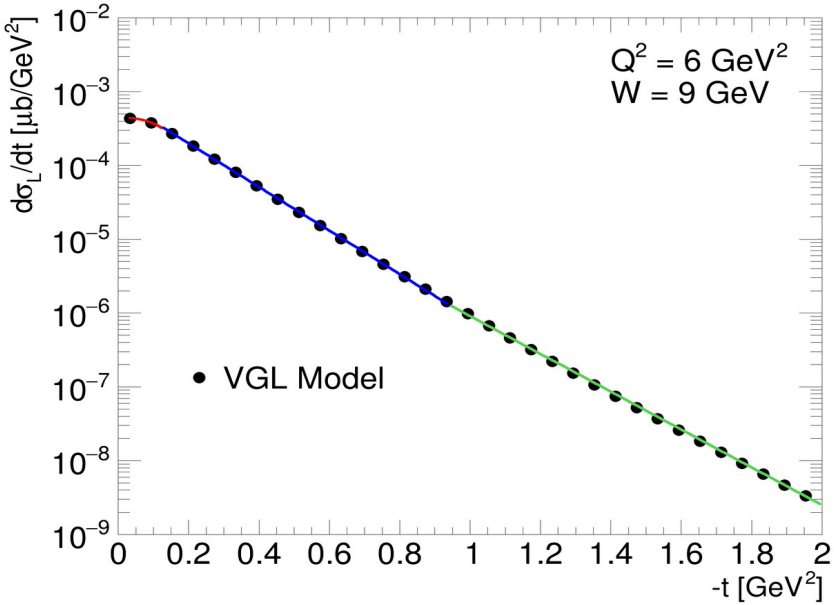
DEMPgen improvements for the K^+ module

- π^+ module was written first.
- K^+ module includes some additional improvements in the algorithm.
  - Removed discontinuities between the parametrizing functions by finding the intersection points between them.

$\sigma_L\,(\pi^+)$



$\sigma_L\,(K^+\,\Lambda)$

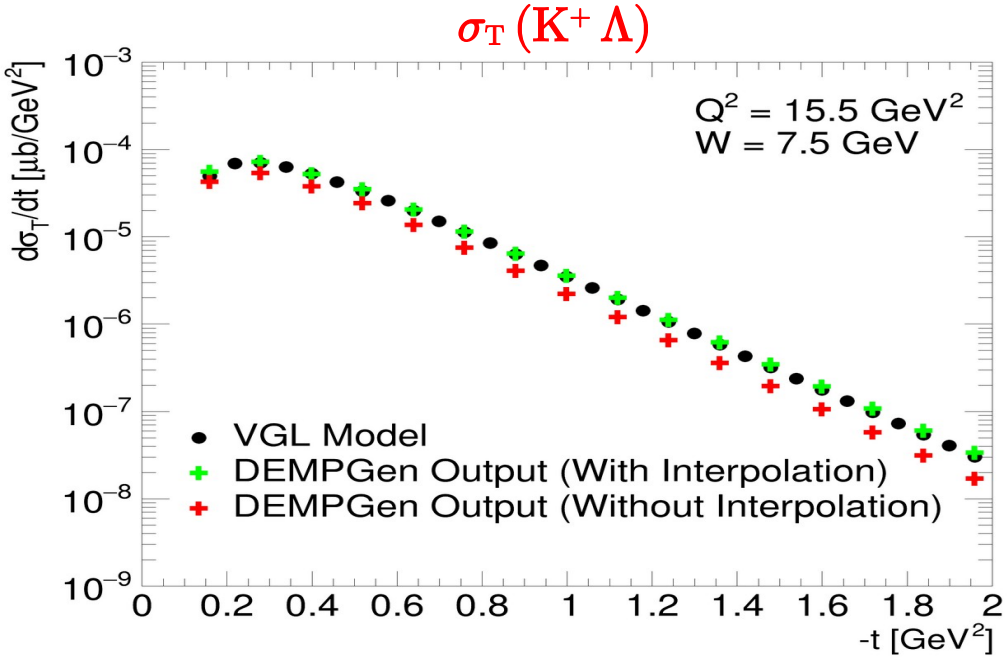


DEMPgen improvements for the K^+ module

- Because of the finite step size in W and Q^2, implemented a new method to interpolate the parametrization.

$$f(x,y) = f(a,b) + f_x(a,b)(x-a) + f_y(a,b)(y-b)$$

- For now, interpolation is only in the kaon module.
- Plan to incorporate it in the pion module soon.



W	Q^2
7	15
8	16

→ Stepsize of 1

Monte Carlo event generator - DEMPgen

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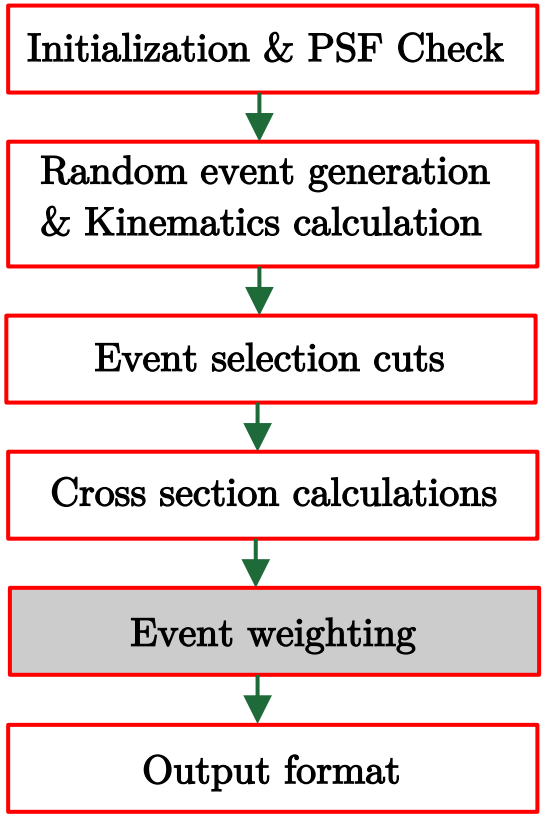

Event weighting

- Event weight is calculated for the generated events using the following equation:

$$\text{Weight} = \frac{\sigma \times PSF \times CF \times \mathcal{L}}{N_{Requested}}$$

Where,

σ is the 5-fold cross section in the collider frame.

$$\frac{d^5\sigma}{dE_{e'}^{Col} d\Omega_{e'}^{Col} d\Omega_{Ej}^{Col}}$$

PSF is the phase space factor.

CF is a unit conversion factor.

$\mathcal{L}$ is the luminosity, and

$N_{Requested}$ is the number of events that the DEMPgen tried to produce.

- Resulting weight value is the expected reaction rate at the given luminosity, expressed in units of Hz.
- Event weights must be retained throughout the analysis framework.

Monte Carlo event generator - DEMPgen

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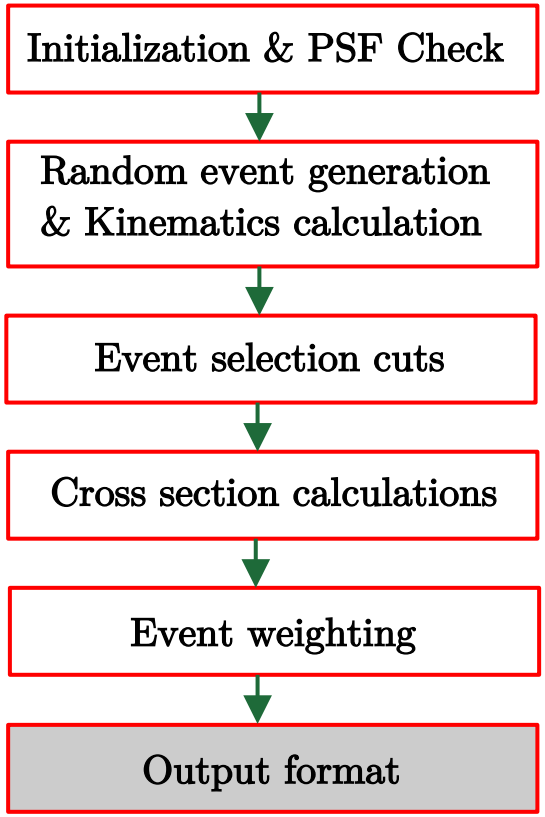
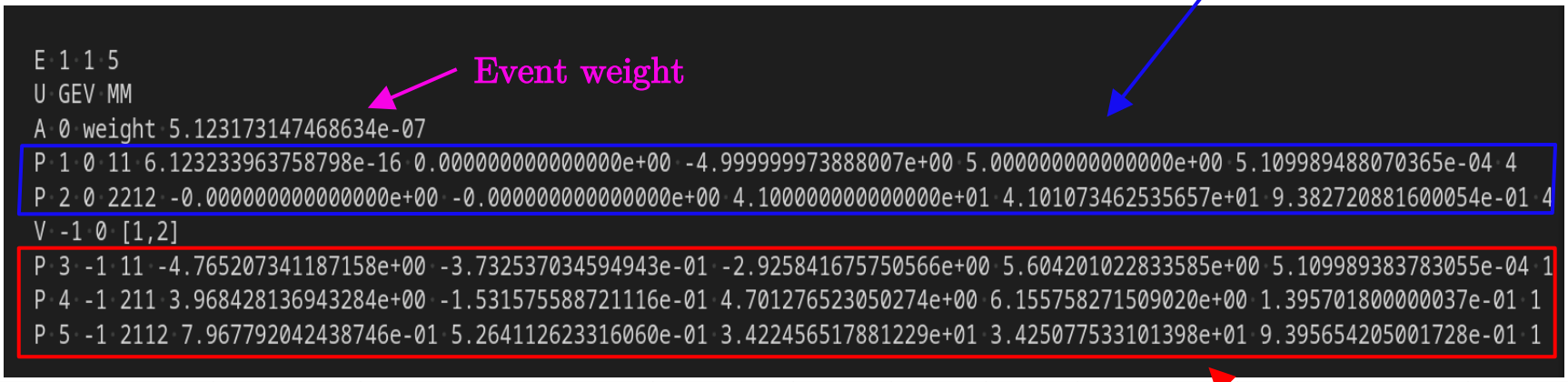


Output format

- Produce output in one of these three options: LUND, Pythia6, or HEPMC3, with an optional ROOT output format.
- Generate a txt file, regardless of the choice, that contains additional information about events, including requested, generated, and those failed due to various cuts, etc.



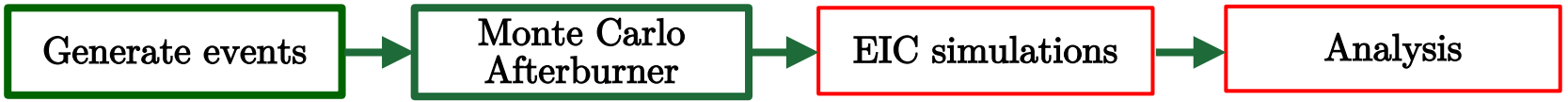
particle_line	part_id	parent_vertex_id	pdg_id	px	py	pz	energy	particle_mass	status

Example of HEPMC3 format

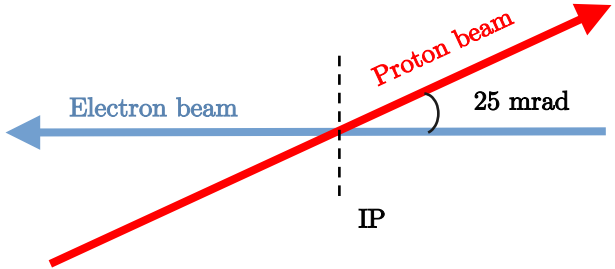
Scattered particles

Simulation studies at EIC

- Incoming beams collide at a crossing angle of 25 mrad.



  - Monte Carlo afterburner includes crossing angle, beam energy spread, angular beam divergence, bunch length, etc.

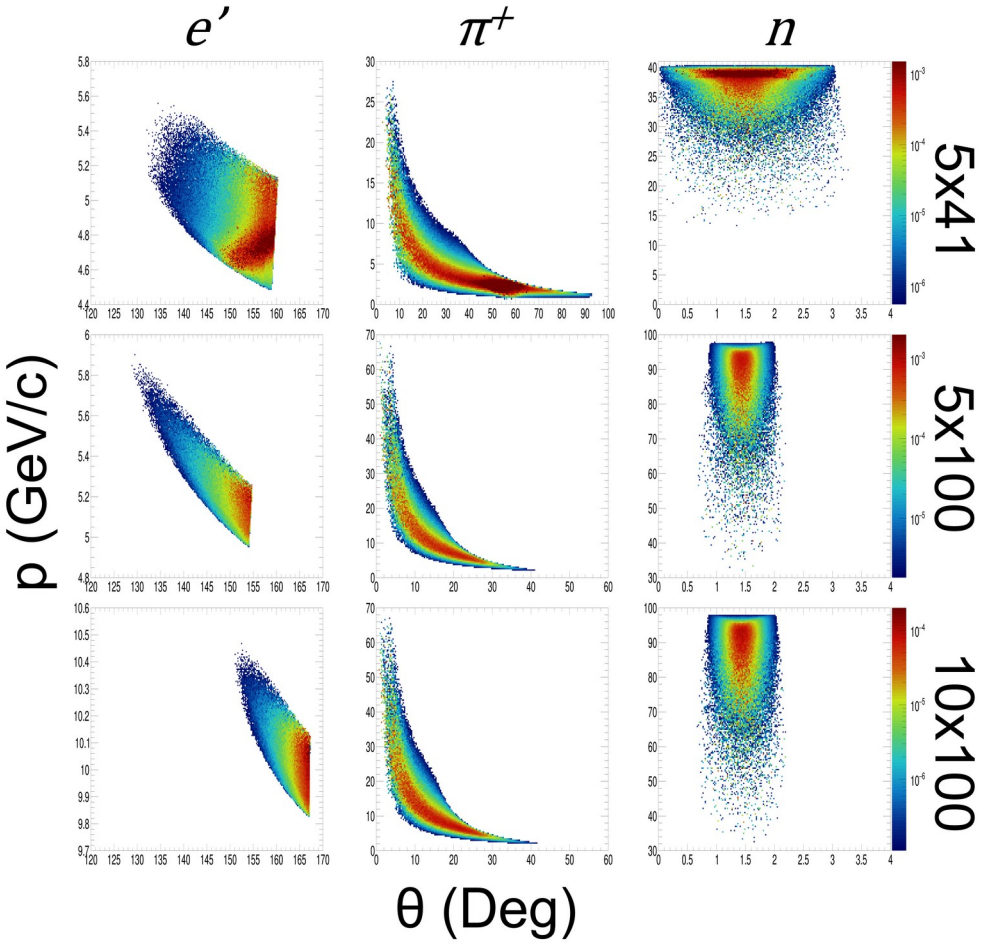


- DEMPgen has the capability to generate events directly with the correct crossing angles.
  - Turned it off to maintain compatibility with EIC simulations framework.

https://github.com/eic/afterburner

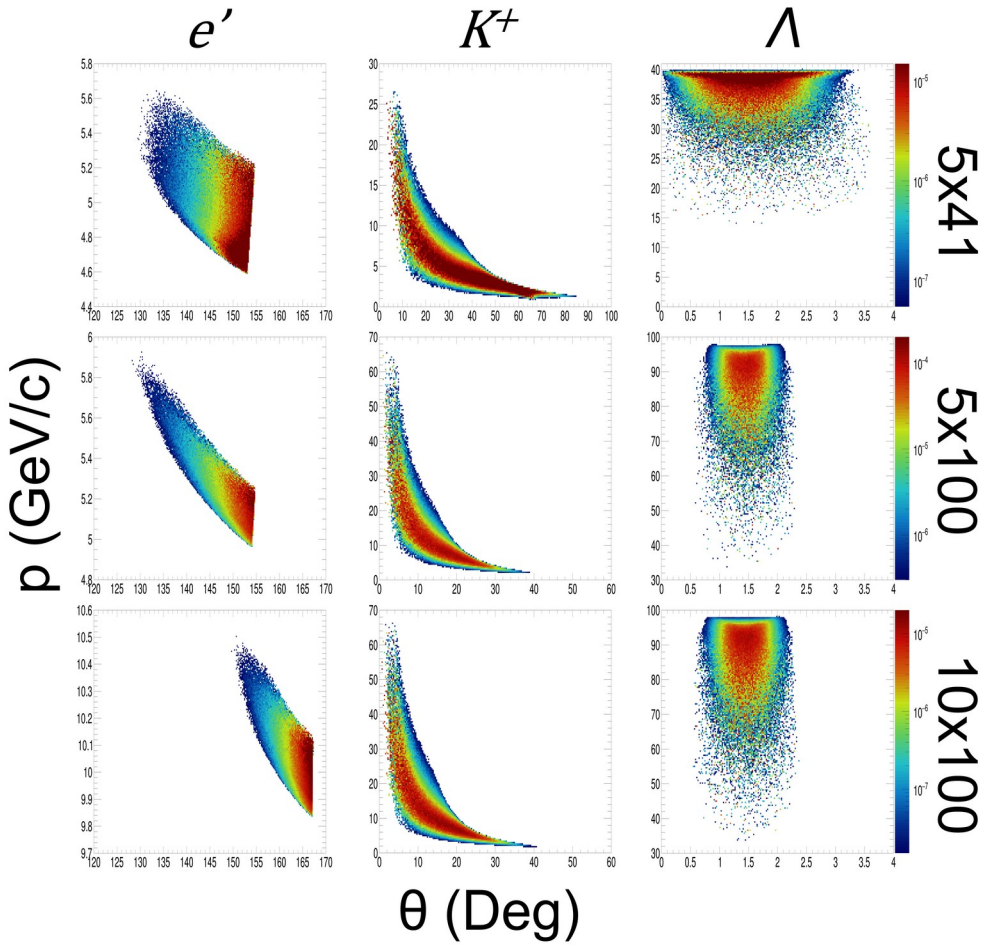
Spatial topology of π^+ module at ePIC detector

- 5(e^-) on 41(p) GeV, 5(e^-) on 100(p) GeV, 10(e^-) on 100(p) GeV Collisions.
- For $5<Q^2<35$, $2<W<10.2$, and $0<-t<1.3$.
- Events weighted by cross-section.
- 25 mrad crossing angle.



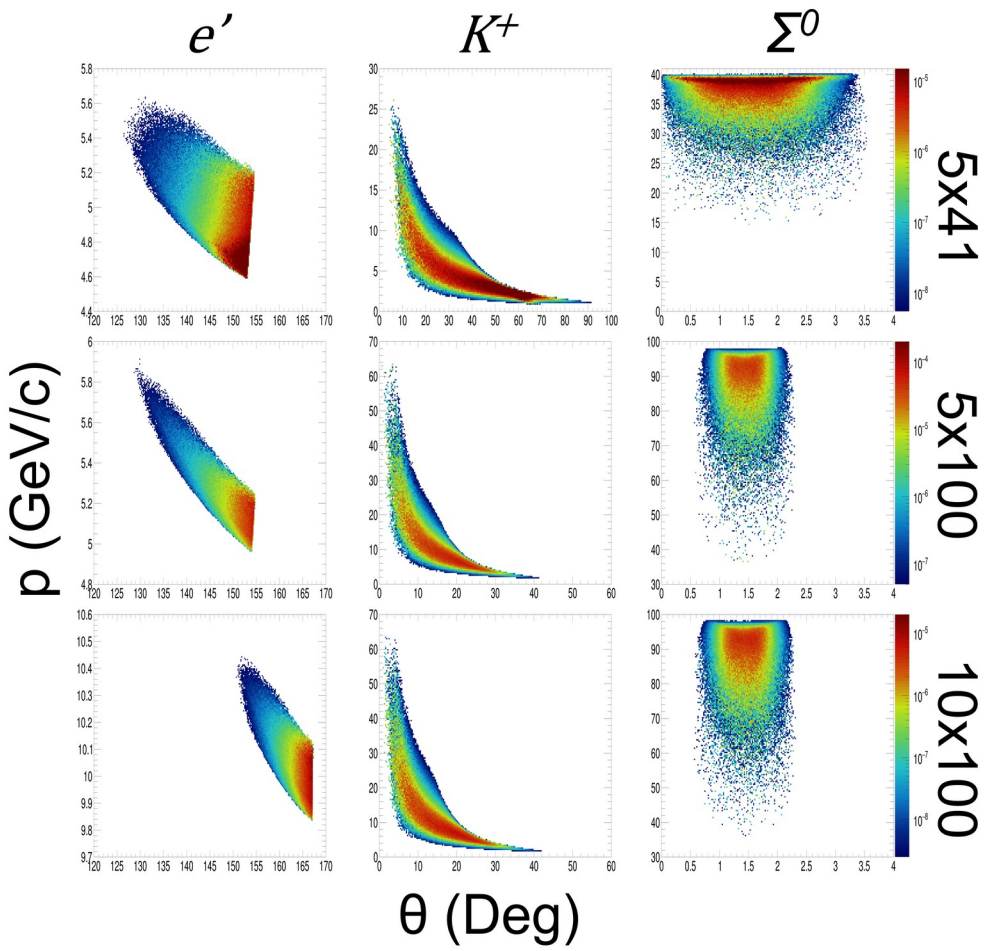
Spatial topology of Λ Channel at ePIC detector

- 5(e^-) on 41(p) GeV, 5(e^-) on 100(p) GeV, 10(e^-) on 100(p) GeV Collisions.
- For $5<Q^2<35$, $2<W<10$, and $0<-t<2$.
- Events weighted by cross-section.
- 25 mrad crossing angle.



Spatial topology of Σ^0 Channel at ePIC detector

- 5(e^-) on 41(p) GeV, 5(e^-) on 100(p) GeV, 10(e^-) on 100(p) GeV Collisions.
- For $5<Q^2<35$, $2<W<10$, and $0<-t<2$.
- Events weighted by cross-section.
- 25 mrad crossing angle.

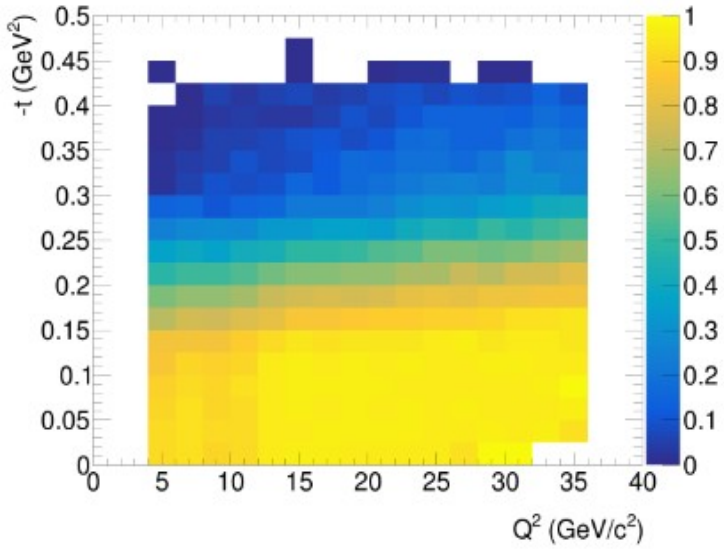


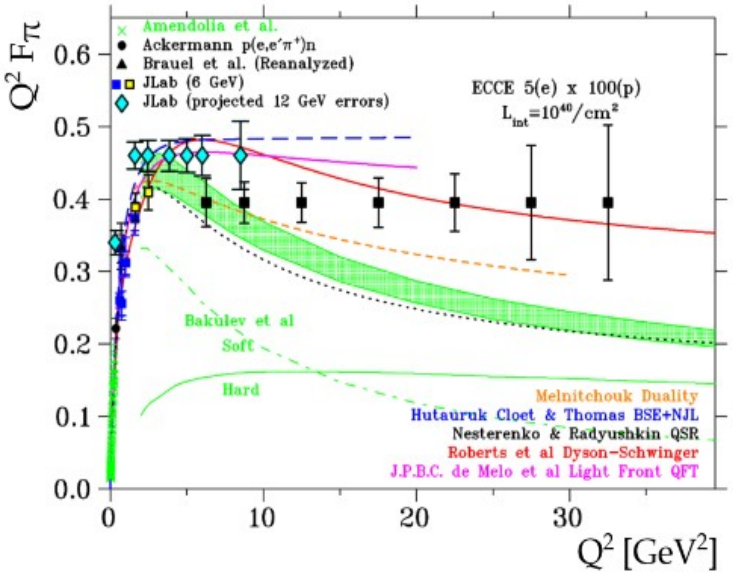
DEMPgen modularity

- Structured modularly, enabling the addition of new exclusive reactions over time.
- To add a new reaction:
  - Find the appropriate theoretical model for the given reaction.
  - Parametrize the cross-section components over wide kinematic ranges.
  - Input the parametrized values into the txt file, similar to the K^+ module.
  - Set up the masses for the ejectile, & recoil in the main DEMPgen routine.
- Contact us at *Garth.Huber@uregina.ca*, *stephen.kay@york.ac.uk*, & *Love.Preet@uregina.ca* if you encounter any issues.

ECCE simulation studies using DEMPgen

- Used DEMPgen v1.0.0 π^+ module to generate events & passed through ECCE simulations.
  - Measured $e^{'}\pi^+ n$ triple coincidence to generate kinematic distribution plots.
- Utilizing the upcoming version of DEMPgen to generate plots for the EIC TDR.

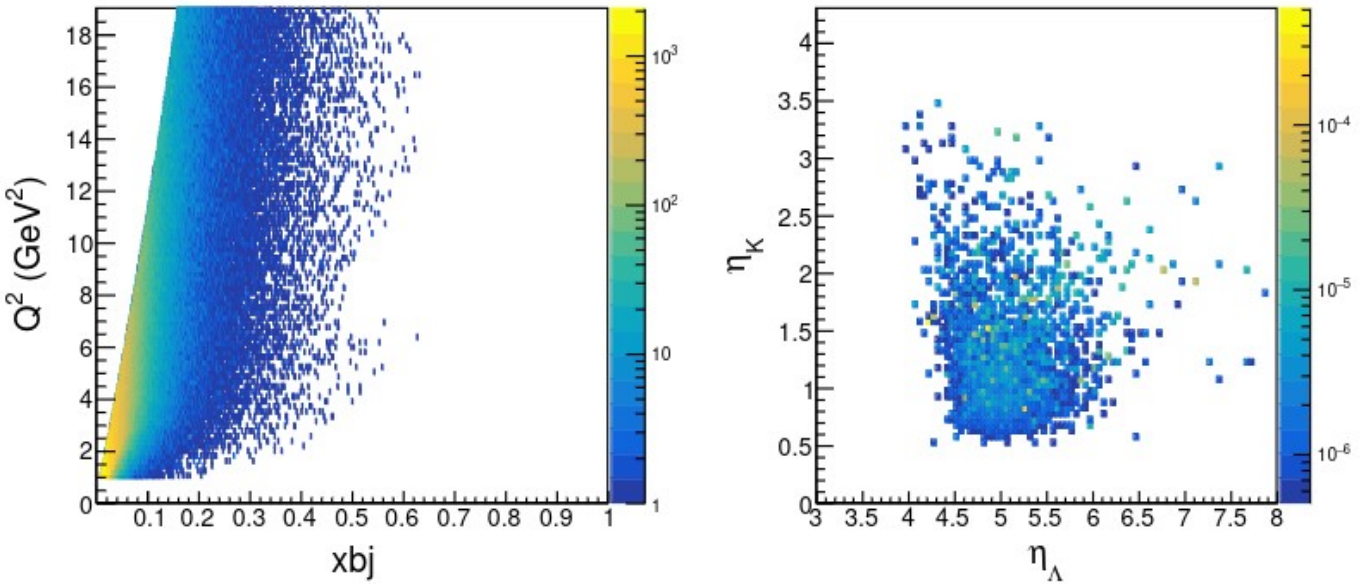




https://www.sciencedirect.com/science/article/pii/S0168900223002280

DEMPgen used in the community

- Zhoudunming Tu utilized DEMPgen v1.0.0 to generate kinematic distribution plots for exclusive Λ hyperon polarization studies.
  - Calculate the runtime of the experiment to achieve desired event yield.



https://journals.aps.org/prc/abstract/10.1103/PhysRevC.109.055205

Summary

- Works fine for both pion and kaon electroproduction reactions.
- Will extend parametrization ranges & employ interpolation techniques in the pion module too.
- Will include electron radiation effects & the measurements with deuteron or other beams.
- Modular in form, allowing additional reactions to be addded over time.
- Next step is to process the generated events through the EIC ePIC simulations.
  - Will give us an indication of the feasibility of DEMP measurements at EIC.
- If the measurement is possible, we can measure the form factor of mesons over the wide kinematic range at EIC.
  - Will give us an insight into the mass generation mechanism of hadrons.

Thank you !

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University of Regina

NSERC CRSNG

UNIVERSITY of York

Science and Technology Facilities Council

EIC-Canada

This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), FRN: SAPPJ-2023-00041

& UK Research and Innovation: Science and Technology Facilities council (UKRI:STFC) grant ST/W004852/1

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