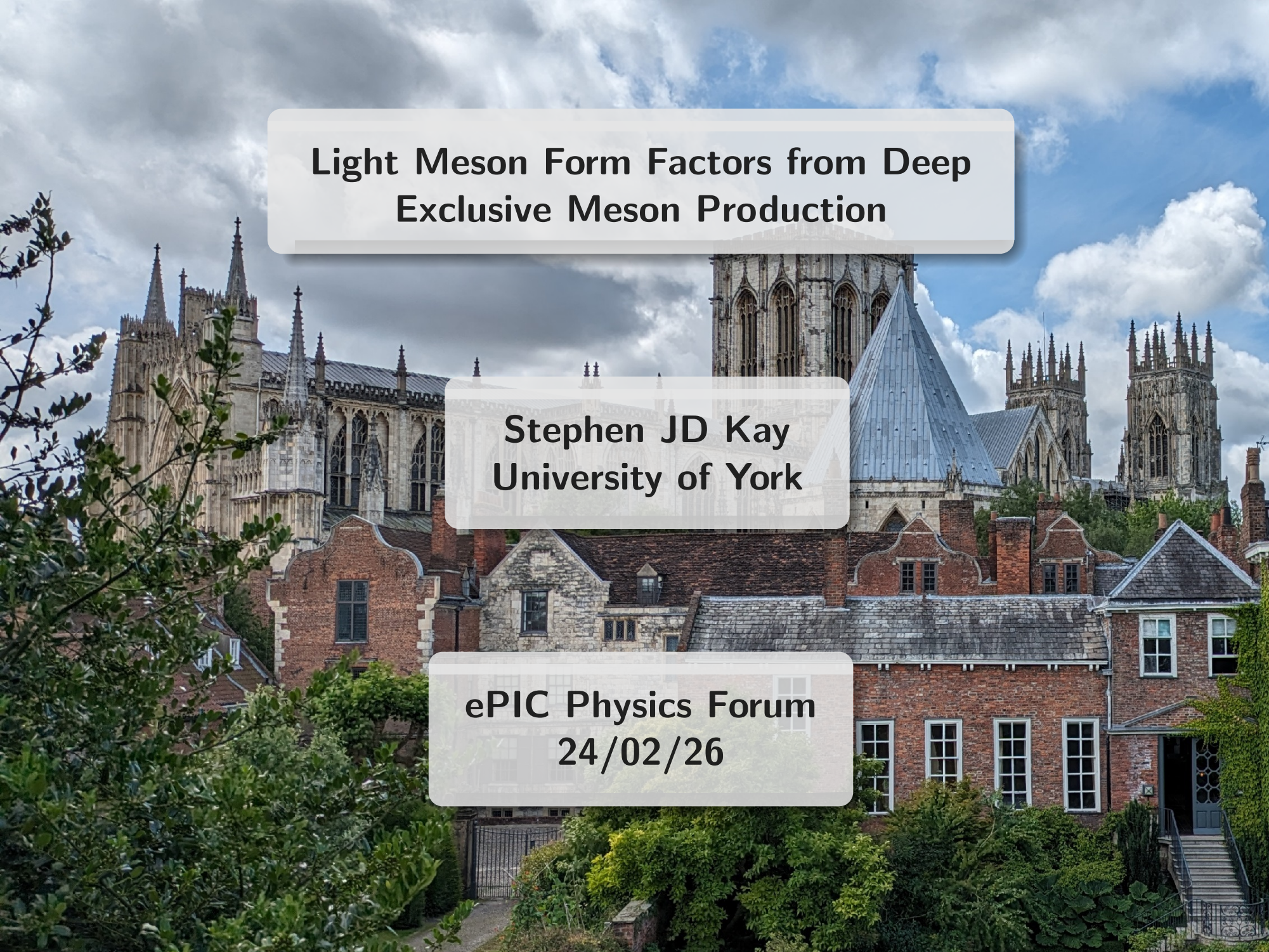


# Light Meson Form Factors from Deep Exclusive Meson Production

Stephen JD Kay
University of York

ePIC Physics Forum
24/02/26

# Why Meson Structure - Hadron Mass Budgets

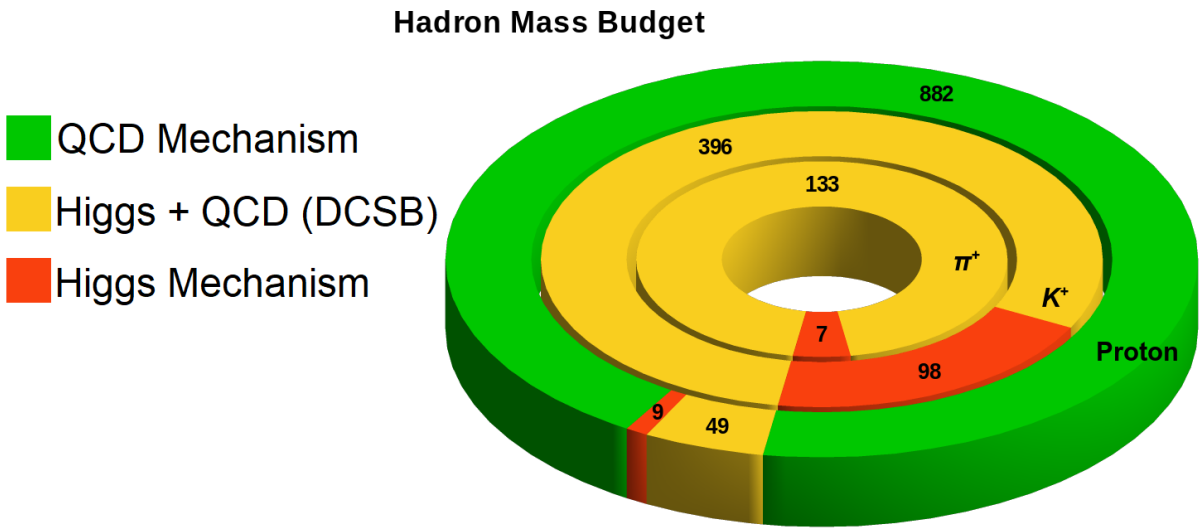
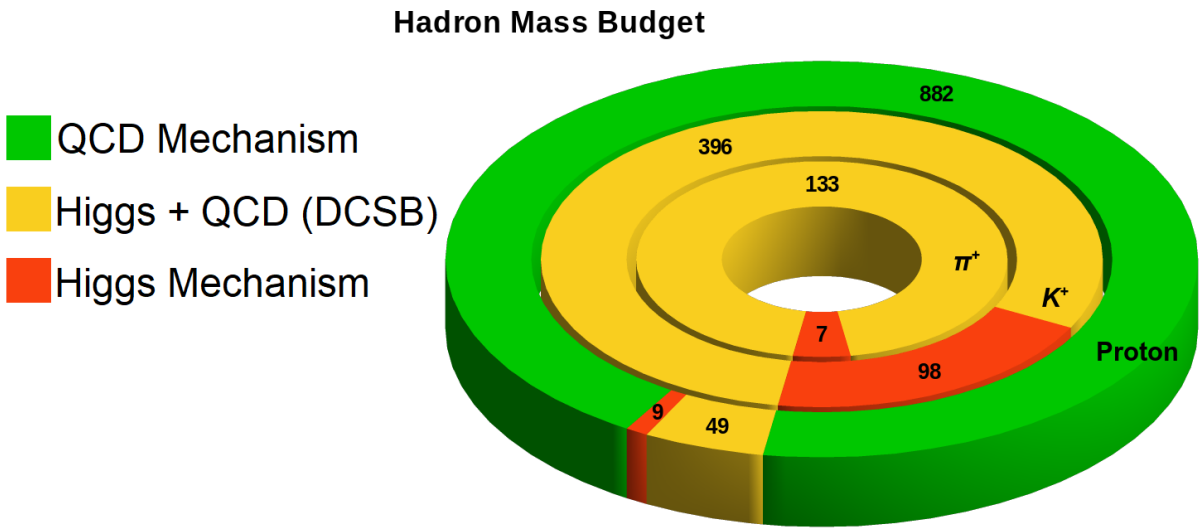



Image - G. Huber, modified figure from https://doi.org/10.1088/1361-6471/abf5c3

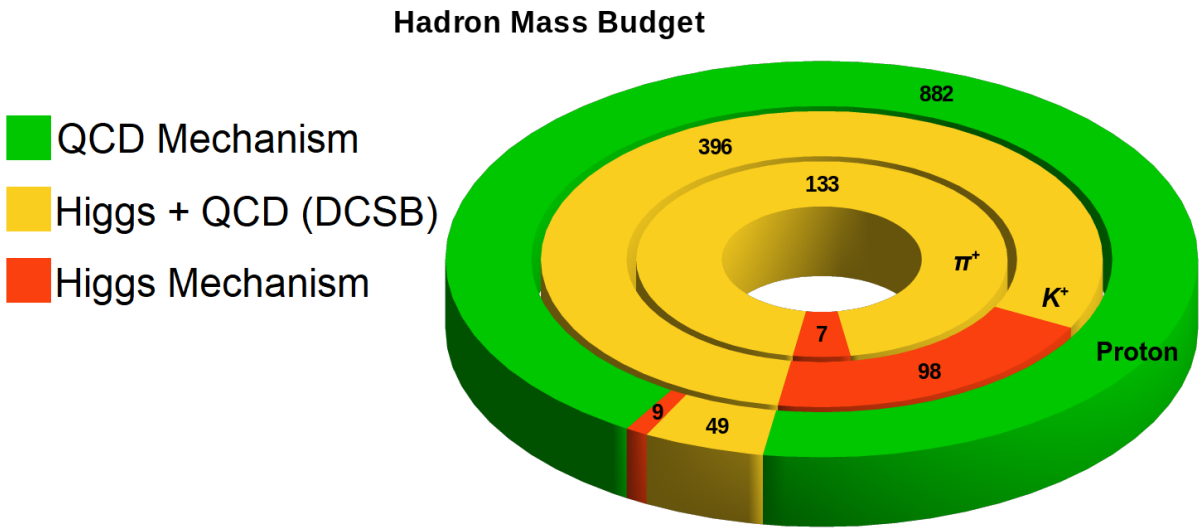
# Why Meson Structure - Hadron Mass Budgets




- Only the portion in red is directly from the Higgs current
- Multiple mechanisms at play to give hadrons their mass

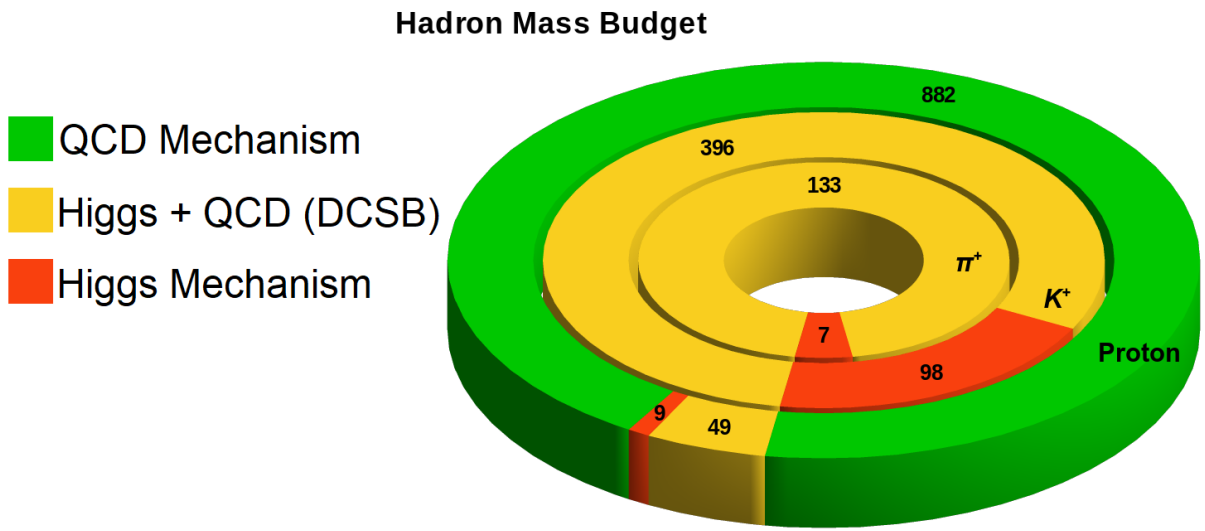
Image - G. Huber, modified figure from https://doi.org/10.1088/1361-6471/abf5c3

# Why Meson Structure - Hadron Mass Budgets



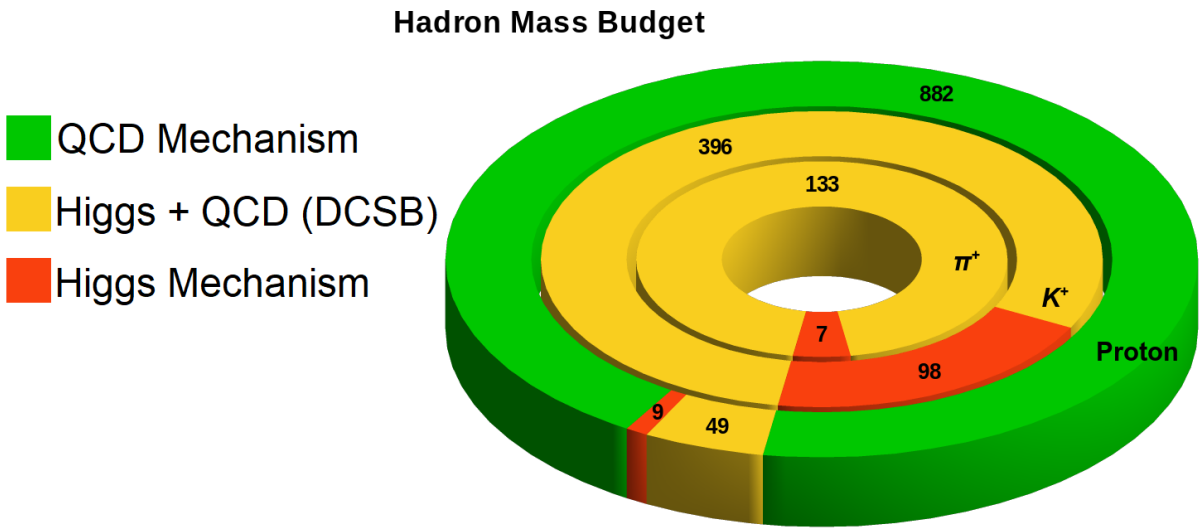

- Only the portion in red is directly from the Higgs current
- Multiple mechanisms at play to give hadrons their mass
  - Mass generation mechanisms intricately connected to structure

# Why Meson Structure - Hadron Mass Budgets




- Only the portion in red is directly from the Higgs current
- Multiple mechanisms at play to give hadrons their mass
  - Mass generation mechanisms intricately connected to structure
- **The simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground**

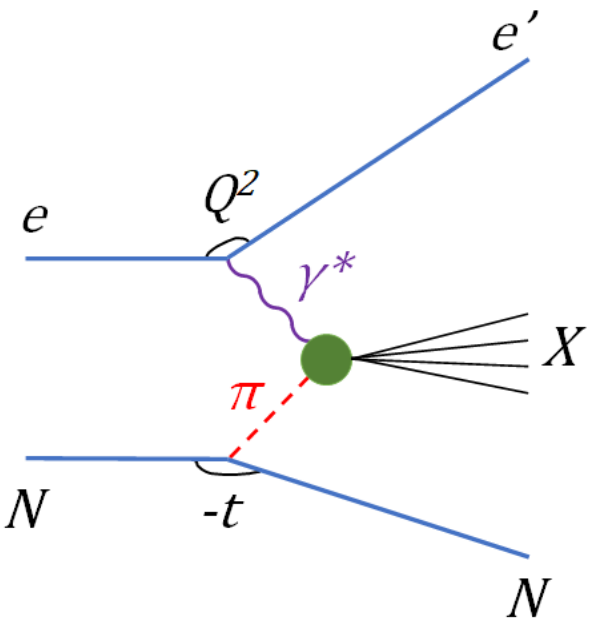
# Why Meson Structure - Hadron Mass Budgets




- Only the portion in red is directly from the Higgs current
- Multiple mechanisms at play to give hadrons their mass
  - Mass generation mechanisms intricately connected to structure
- **The simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground**
- How can we examine their structure?

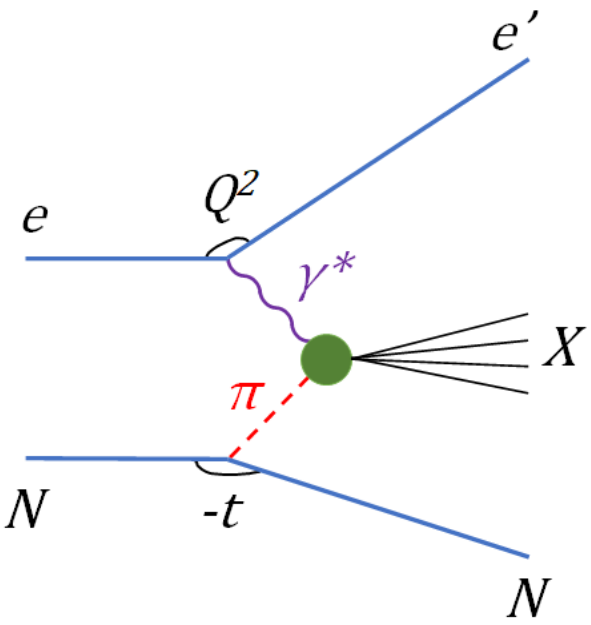
# The Sullivan Process

- Can use the Sullivan process to study meson structure



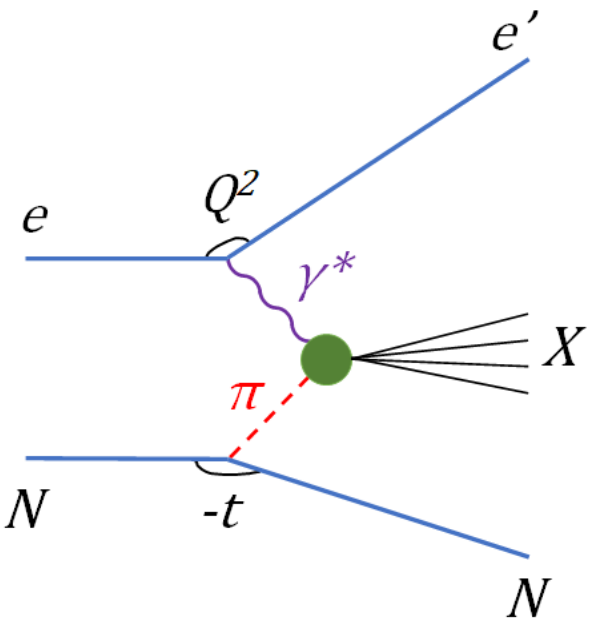
# The Sullivan Process

- Can use the Sullivan process to study meson structure
  - Scattering from nucleon-meson fluctuations
  - $\pi/K$ SF: quark-gluon momentum fractions
  - $\pi/K$ FF: how EHM manifests in the wave function



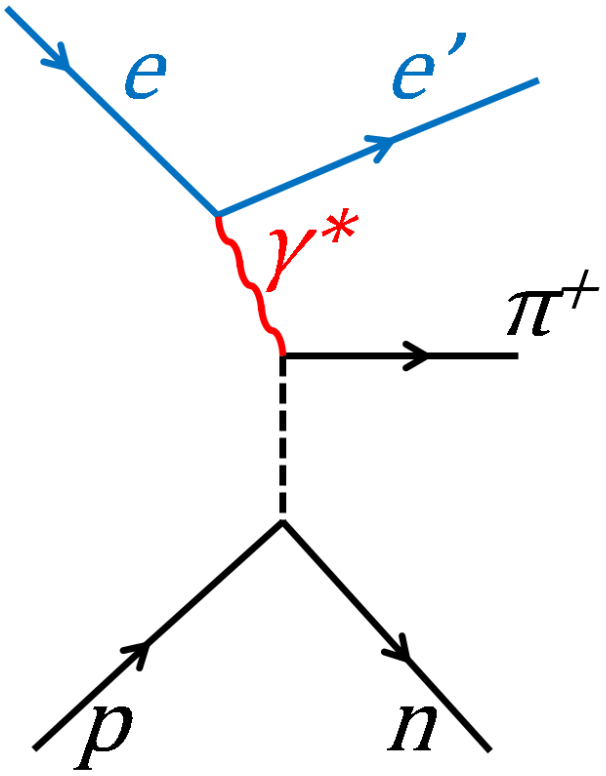
# The Sullivan Process

- Can use the Sullivan process to study meson structure
  - Scattering from nucleon-meson fluctuations
  - $\pi/K$ SF: quark-gluon momentum fractions
  - $\pi/K$ FF: how EHM manifests in the wave function
- Can measure this as Tagged DIS
  - Measure $\pi/K$ structure functions



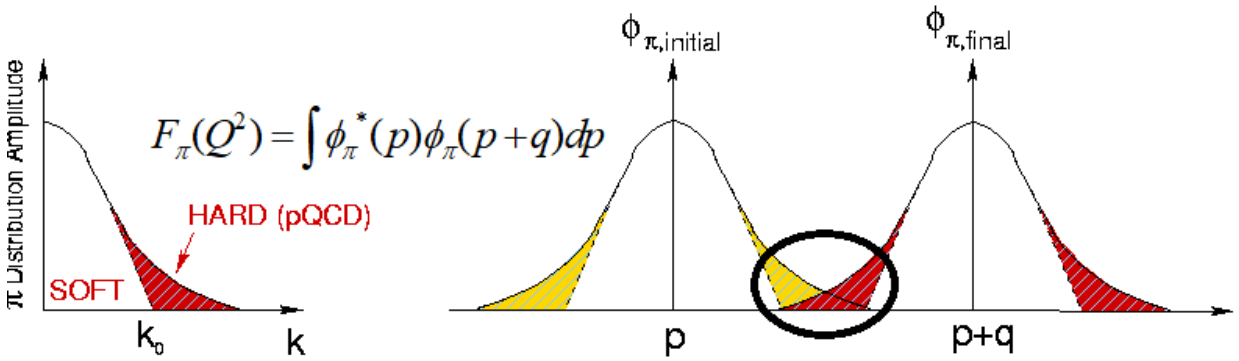
# The Sullivan Process

- Can use the Sullivan process to study meson structure
  - Scattering from nucleon-meson fluctuations
  - $\pi/K$ SF: quark-gluon momentum fractions
  - $\pi/K$ FF: how EHM manifests in the wave function
- Can measure this as Tagged DIS
  - Measure $\pi/K$ structure functions
- OR, if X is restricted to a single $\pi$ or $K$, have **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**)
  - **Access to meson form factors**
  - $F_\pi$ and $F_K$



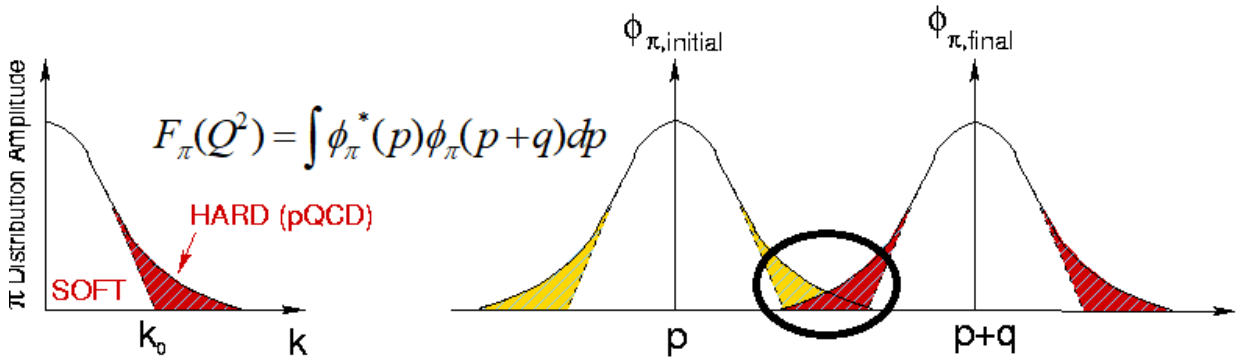
# Quantifying Meson Structure - Meson Form Factors

- Charged pion ($\pi^{\pm}$) and kaon ($K^{\pm}$) form factors ($F_{\pi}$, $F_K$) are key QCD observables
  - Momentum space distributions of partons within hadrons



# Quantifying Meson Structure - Meson Form Factors

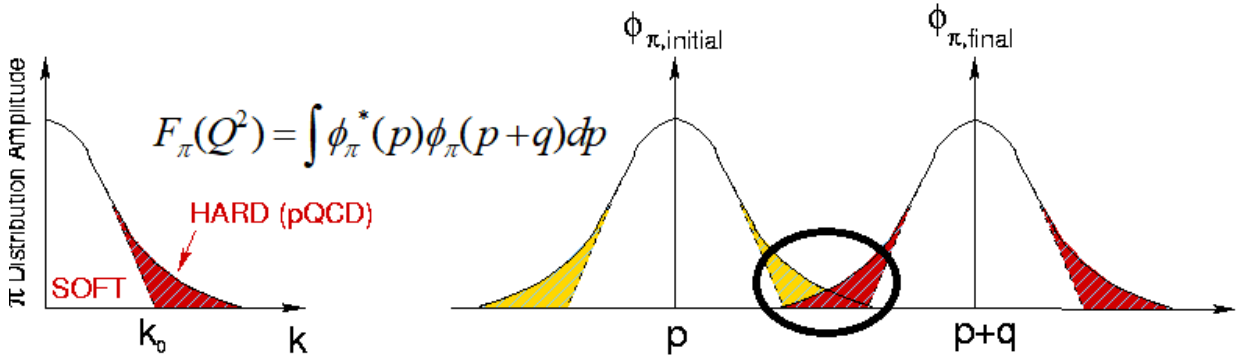
- Charged pion ($\pi^{\pm}$) and kaon ($K^{\pm}$) form factors ($F_\pi$, $F_K$) are key QCD observables
  - Momentum space distributions of partons within hadrons




- Meson wave function can be split into $\phi_\pi^{\text{soft}}$ $(k < k_0)$ and $\phi_\pi^{\text{hard}}$, the hard tail
  - Can treat $\phi_\pi^{\text{hard}}$ in pQCD, cannot with $\phi_\pi^{\text{soft}}$
  - Form factor is the overlap between the two tails (right figure)

# Quantifying Meson Structure - Meson Form Factors

- Charged pion ($\pi^{\pm}$) and kaon ($K^{\pm}$) form factors ($F_\pi$, $F_K$) are key QCD observables
  - Momentum space distributions of partons within hadrons



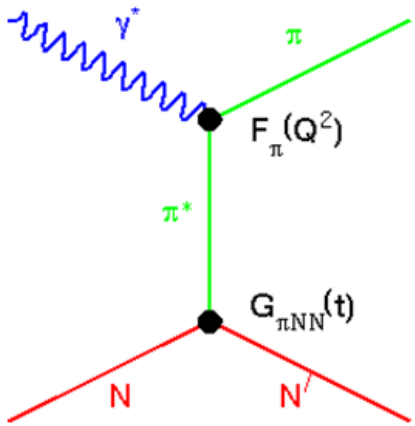

- Meson wave function can be split into $\phi_\pi^{\text{soft}}$ $(k < k_0)$ and $\phi_\pi^{\text{hard}}$, the hard tail
  - Can treat $\phi_\pi^{\text{hard}}$ in pQCD, cannot with $\phi_\pi^{\text{soft}}$
  - Form factor is the overlap between the two tails (right figure)
- **$F_\pi$ and $F_K$ of special interest in hadron structure studies**
  - $\pi$ - Lightest QCD quark system, simple
  - $K$ - Another simple system, contains strange quark

# Measurement of $F_\pi$ at High $Q^2$

- To access $F_\pi$ at high $Q^2$, must measure $F_\pi$ indirectly
  - Use the "pion cloud" of the proton via $p(e, e'\pi^+ n)$

# Measurement of $F_\pi$ at High $Q^2$

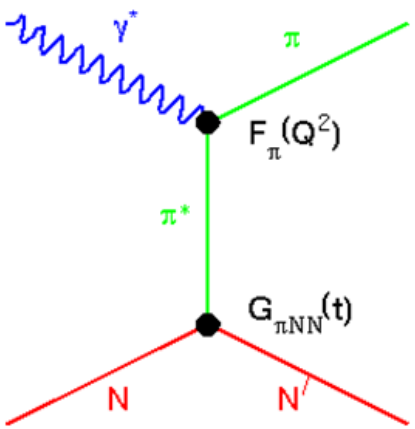
- To access $F_\pi$ at high $Q^2$, must measure $F_\pi$ indirectly
  - Use the "pion cloud" of the proton via $p(e, e'\pi^+ n)$
- At small $-t$, the pion pole process dominates $\sigma_L$



# Measurement of $F_\pi$ at High $Q^2$

- To access $F_\pi$ at high $Q^2$, must measure $F_\pi$ indirectly
  - Use the "pion cloud" of the proton via $p(e, e'\pi^+ n)$
  - At small $-t$, the pion pole process dominates $\sigma_L$
- In the Born term model, $F_\pi^2$ appears as -

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)$$

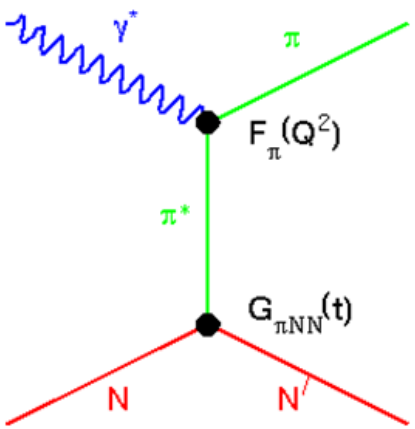


# Measurement of $F_\pi$ at High $Q^2$

- To access $F_\pi$ at high $Q^2$, must measure $F_\pi$ indirectly
  - Use the "pion cloud" of the proton via $p(e, e'\pi^+ n)$
- At small $-t$, the pion pole process dominates $\sigma_L$
- In the Born term model, $F_\pi^2$ appears as -

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)$$

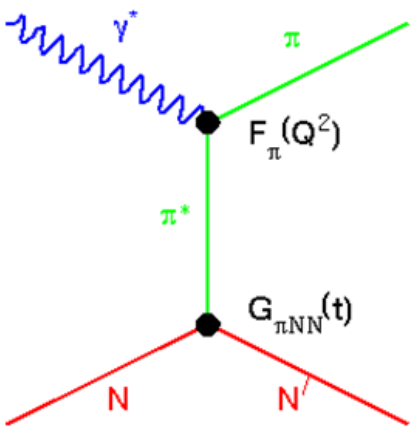
- We do not use the Born term model



# Measurement of $F_\pi$ at High $Q^2$

- To access $F_\pi$ at high $Q^2$, must measure $F_\pi$ indirectly
  - Use the "pion cloud" of the proton via $p(e, e'\pi^+ n)$
- At small $-t$, the pion pole process dominates $\sigma_L$
- In the Born term model, $F_\pi^2$ appears as -

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)$$

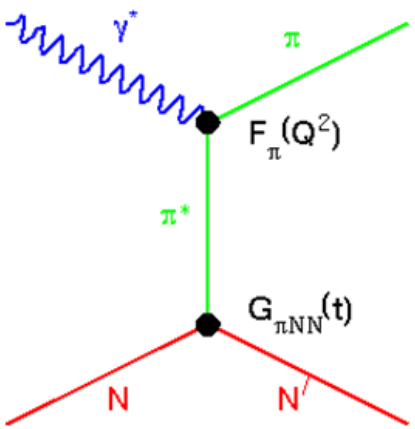



- We do not use the Born term model
- Drawbacks of this technique -
  - Isolating $\sigma_L$ experimentally challenging
  - Theoretical uncertainty in $F_\pi$ extraction
    - Model dependent
      (smaller dependency at low -t)

# Measurement of $F_\pi$ at High $Q^2$

- To access $F_\pi$ at high $Q^2$, must measure $F_\pi$ indirectly
  - Use the "pion cloud" of the proton via $p(e, e'\pi^+ n)$
- At small $-t$, the pion pole process dominates $\sigma_L$
- In the Born term model, $F_\pi^2$ appears as -

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)$$




- We do not use the Born term model
- Drawbacks of this technique -
  - Isolating $\sigma_L$ experimentally challenging
  - Theoretical uncertainty in $F_\pi$ extraction
    - Model dependent
      (smaller dependency at low -t)
  - At a collider, isolate $d\sigma_L/dt$ from $d\sigma_{uns}/dt$, using a model
  - Measure Sullivan **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**)

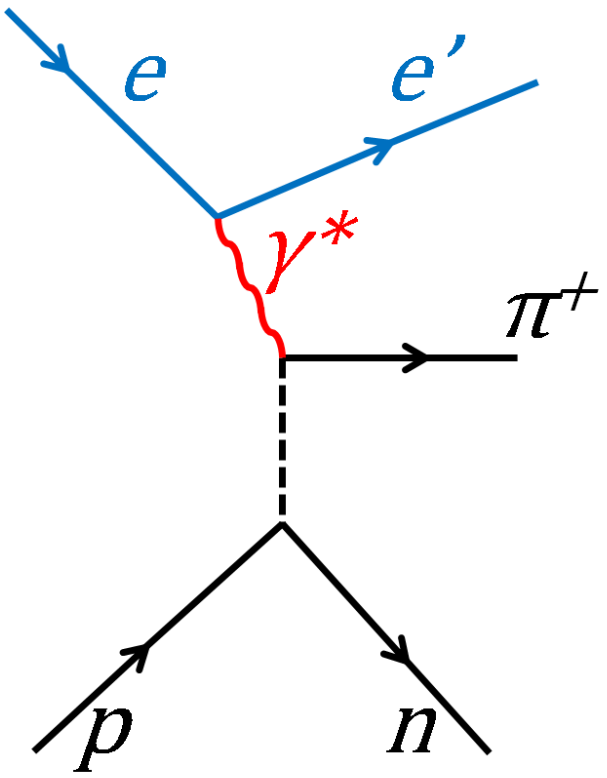
# Ingredients for Sullivan DEMP

- Sullivan DEMP as a process is fairly self descriptive!
- Consider the $p(e, e'\pi^+ n)$ reaction

# Ingredients for Sullivan DEMP

- Sullivan DEMP as a process is fairly self descriptive!
- Consider the $p(e, e'\pi^+ n)$ reaction

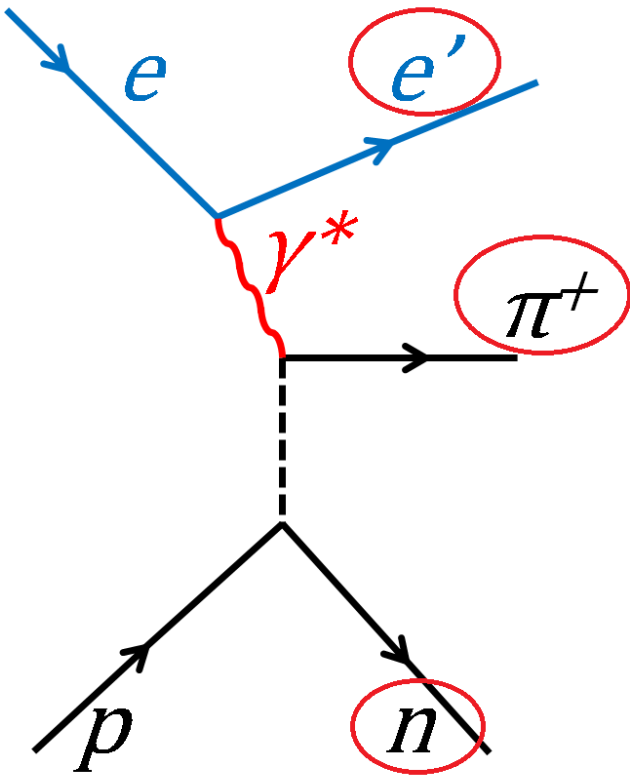
- $e$ scatters from $p$ ($\pi^+$ cloud), exchanging $\gamma^*$



# Ingredients for Sullivan DEMP

- Sullivan DEMP as a process is fairly self descriptive!
- Consider the $p(e, e'\pi^+ n)$ reaction

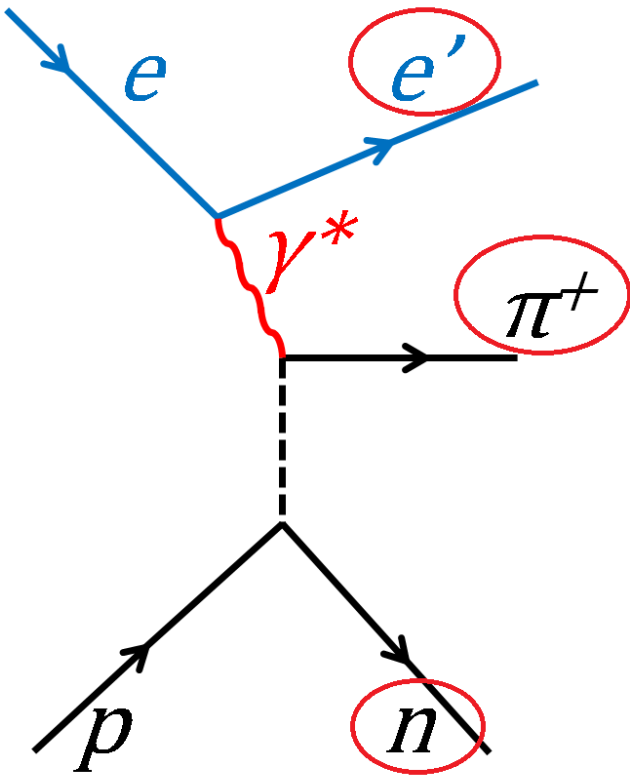
- $e$ scatters from $p$ ($\pi^+$ cloud), exchanging $\gamma^*$
- $e'$, $\pi^+$ and $n$ final state



# Ingredients for Sullivan DEMP

- Sullivan DEMP as a process is fairly self descriptive!
- Consider the $p(e, e'\pi^+ n)$ reaction

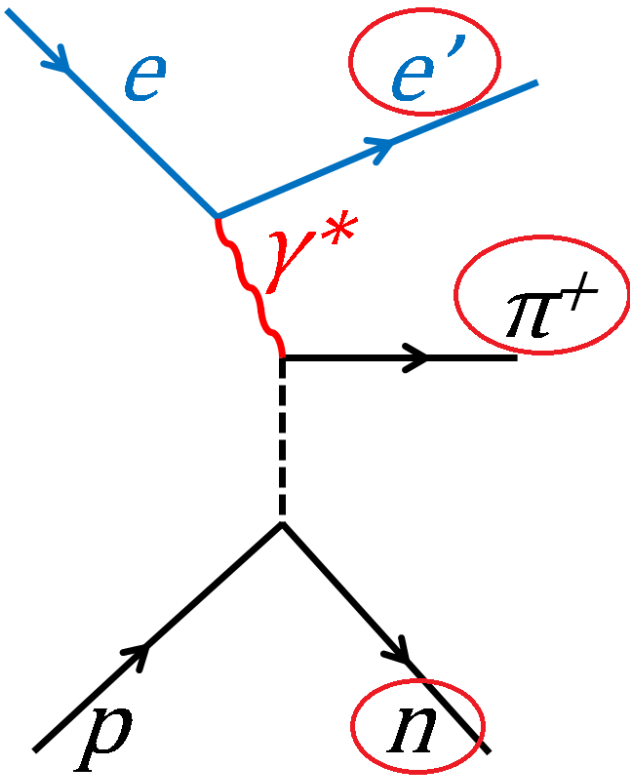
- $e$ scatters from $p$ ($\pi^+$ cloud), exchanging $\gamma^*$
- $e'$, $\pi^+$ and $n$ final state



# Ingredients for Sullivan DEMP

- Sullivan DEMP as a process is fairly self descriptive!
- Consider the $p(e, e'\pi^+ n)$ reaction

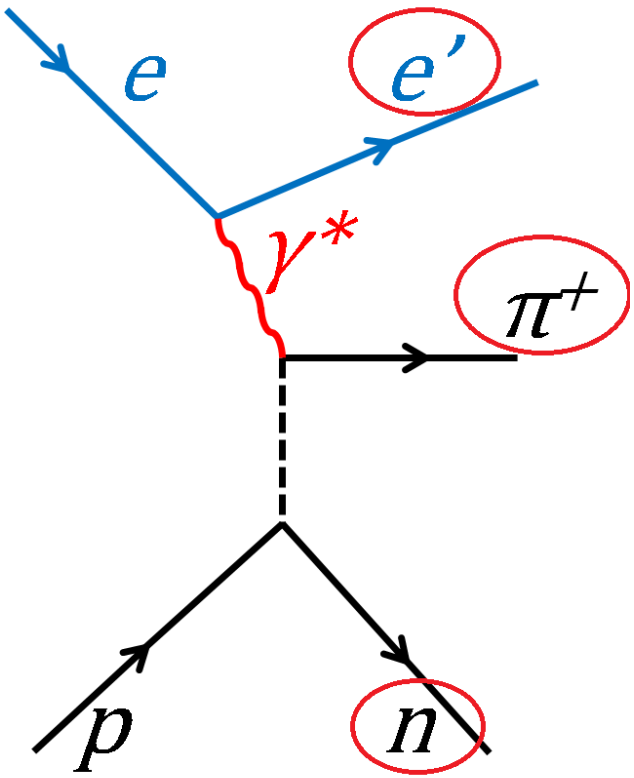
- $e$ scatters from $p$ ($\pi^+$ cloud), exchanging $\gamma^*$
- $e'$, $\pi^+$ and $n$ final state
- Can also measure $n(e, e'\pi^- p)$ in $e + D$
- Kaon DEMP, $\pi^+ \rightarrow K^+$ and $n \rightarrow \Lambda^0$
  - $p(e, e'^+\Lambda^0)$
  - $p(e, e'^+\Sigma^0)$
    - **Hyperons decay!**



# Ingredients for Sullivan DEMP

- Sullivan DEMP as a process is fairly self descriptive!
- Consider the $p(e, e'\pi^+ n)$ reaction

- $e$ scatters from $p$ ($\pi^+$ cloud), exchanging $\gamma^*$
- $e'$, $\pi^+$ and $n$ final state
- Can also measure $n(e, e'\pi^- p)$ in $e + D$
- Kaon DEMP, $\pi^+ \rightarrow K^+$ and $n \rightarrow \Lambda^0$
  - $p(e, e'^+\Lambda^0)$
  - $p(e, e'^+\Sigma^0)$
    - **Hyperons decay!**
- **So just need $e + p$ or $e + D$ collisions**



# Simulating Events - DEMPgen

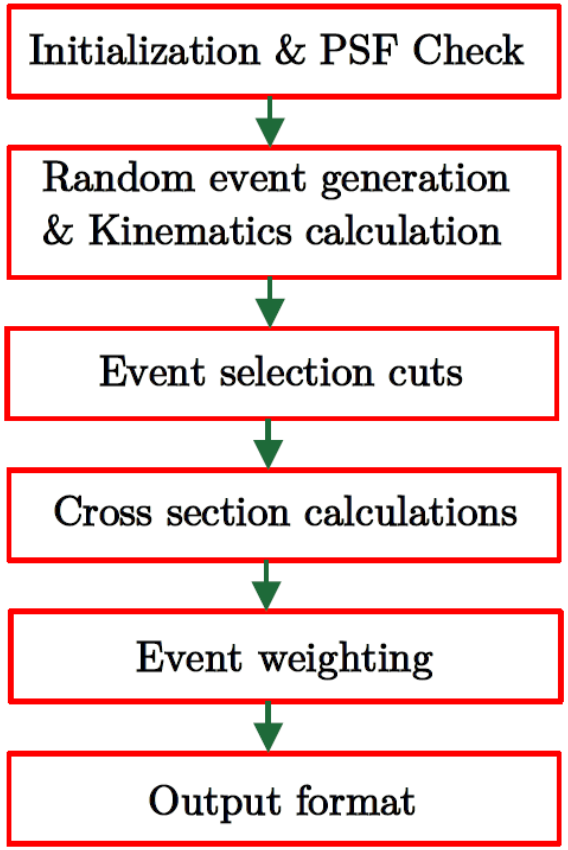
- DEMPgen - **D**eep **E**xclusive **M**eson **P**roduction event generator
- DEMPgen uses parameterised Regge-based models

# Simulating Events - DEMPgen

- DEMPgen - **D**eep **E**xclusive **M**eson **P**roduction event generator
- DEMPgen uses parameterised Regge-based models
- Fixed target (JLab) and colliding beams (EIC) modes

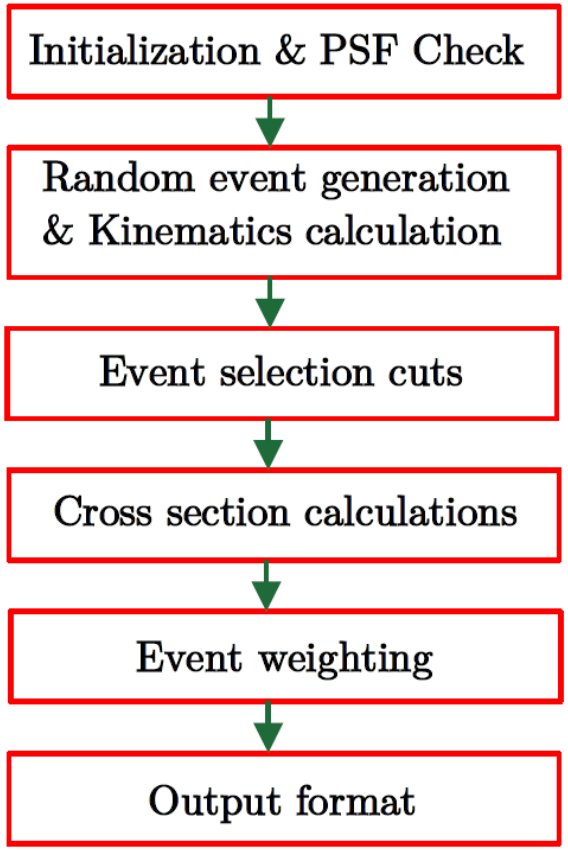
# Simulating Events - DEMPgen

- DEMPgen - **D**eep **E**xclusive **M**eson **P**roduction event generator
- DEMPgen uses parameterised Regge-based models
- Fixed target (JLab) and colliding beams (EIC) modes
- Feed in an input .json file
  - Specify conditions
  - Beam energies, number of events etc



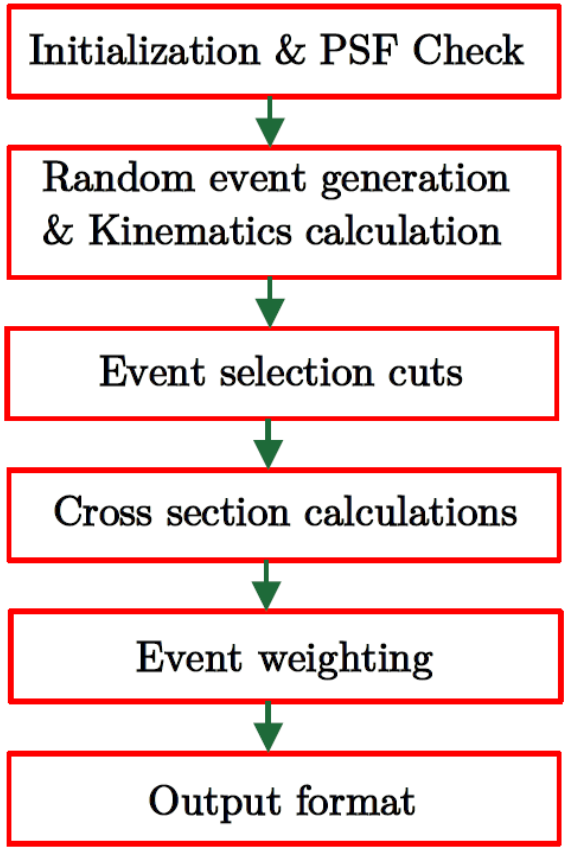
# Simulating Events - DEMPgen

- DEMPgen - **D**eep **E**xclusive **M**eson **P**roduction event generator
- DEMPgen uses parameterised Regge-based models
- Fixed target (JLab) and colliding beams (EIC) modes
- Feed in an input .json file
  - Specify conditions
  - Beam energies, number of events etc
- Several reactions available
  - $p(e, e'\pi^+ n)$
  - $p(e, e'K^+\Lambda)$
  - ...



# Simulating Events - DEMPgen

- DEMPgen - **D**eep **E**xclusive **M**eson **P**roduction event generator
- DEMPgen uses parameterised Regge-based models
- Fixed target (JLab) and colliding beams (EIC) modes
- Feed in an input .json file
  - Specify conditions
  - Beam energies, number of events etc
- Several reactions available
  - $p(e, e'\pi^+ n)$
  - $p(e, e'K^+\Lambda)$
  - ...
- Further details in recent paper
  https://doi.org/10.1016/j.cpc.2024.109444



# Early Science - Opportunities for Sullivan DEMP

- Given our requirements, $e + p$ or $e + D$ collisions, what do the early science prospects look like?

# Early Science - Opportunities for Sullivan DEMP

- Given our requirements, $e + p$ or $e + D$ collisions, what do the early science prospects look like?

| | Species | Energy (GeV) | Luminosity/year (fb-1) | Electron polarization | p/A polarization |
|---|---|---|---|---|---|
| **YEAR 1** | e+Ru or e+Cu | 10 x 115 | 0.9 | NO (Commissioning) | N/A |
| **YEAR 2** | e+D<br>e+p | 10 x 130 | 11.4<br>4.95 - 5.33 | LONG | NO<br>TRANS |
| **YEAR 3** | e+p | 10 x 130 | 4.95 - 5.33 | LONG | TRANS and/or LONG |
| **YEAR 4** | e+Au<br>e+p | 10 x 100<br>10 x 250 | 0.84<br>6.19 - 9.18 | LONG | N/A<br>TRANS and/or LONG |
| **YEAR 5** | e+Au<br>e+3He | 10 x 100<br>10 x 166 | 0.84<br>8.65 | LONG | N/A<br>TRANS and/or LONG |

**Note: the eA luminosity is per nucleon**

# Early Science - Opportunities for Sullivan DEMP

- Given our requirements, $e + p$ or $e + D$ collisions, what do the early science prospects look like?

| | Species | Energy (GeV) | Luminosity/year (fb-1) | Electron polarization | p/A polarization |
|---|---|---|---|---|---|
| YEAR 1 | e+Ru or e+Cu | 10 x 115 | 0.9 | NO (Commissioning) | N/A |
| YEAR 2 | e+D<br>e+p | 10 x 130 | 11.4<br>4.95 - 5.33 | LONG | NO<br>TRANS |
| YEAR 3 | e+p | 10 x 130 | 4.95 - 5.33 | LONG | TRANS and/or LONG |
| YEAR 4 | e+Au<br>e+p | 10 x 100<br>10 x 250 | 0.84<br>6.19 - 9.18 | LONG | N/A<br>TRANS and/or LONG |
| YEAR 5 | e+Au<br>e+3He | 10 x 100<br>10 x 166 | 0.84<br>8.65 | LONG | N/A<br>TRANS and/or LONG |

Note: the eA luminosity is per nucleon

- Opportunities with 10x130 and 10x250 e+p as early as year 2

# Early Science - Opportunities for Sullivan DEMP

- Given our requirements, $e + p$ or $e + D$ collisions, what do the early science prospects look like?

| | Species | Energy (GeV) | Luminosity/year (fb-1) | Electron polarization | p/A polarization |
|---|---|---|---|---|---|
| YEAR 1 | e+Ru or e+Cu | 10 x 115 | 0.9 | NO (Commissioning) | N/A |
| YEAR 2 | e+D<br>e+p | 10 x 130 | 11.4<br>4.95 - 5.33 | LONG | NO<br>TRANS |
| YEAR 3 | e+p | 10 x 130 | 4.95 - 5.33 | LONG | TRANS and/or LONG |
| YEAR 4 | e+Au<br>e+p | 10 x 100<br>10 x 250 | 0.84<br>6.19 - 9.18 | LONG | N/A<br>TRANS and/or LONG |
| YEAR 5 | e+Au<br>e+3He | 10 x 100<br>10 x 166 | 0.84<br>8.65 | LONG | N/A<br>TRANS and/or LONG |

Note: the eA luminosity is per nucleon

- Opportunities with 10x130 and 10x250 e+p as early as year 2
- Assume $\int \mathcal{L} = 5\ fb^{-1}$ in projections

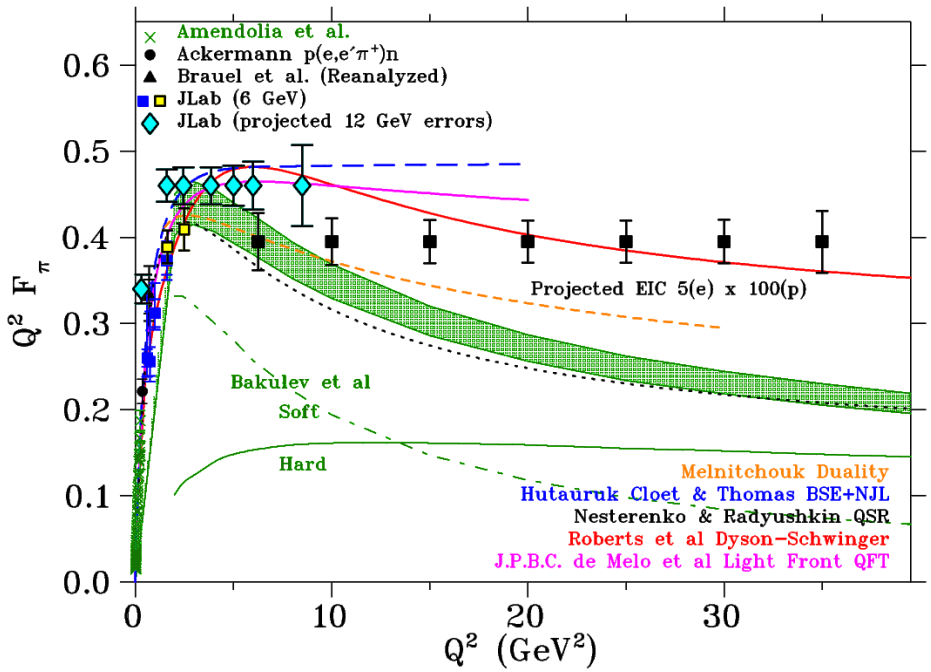
# Where we were...

- Early simulations and projections for $F_\pi$ looked promising

# Where we were...

- Early simulations and projections for $F_\pi$ looked promising

- Initially focused on 5$x$100

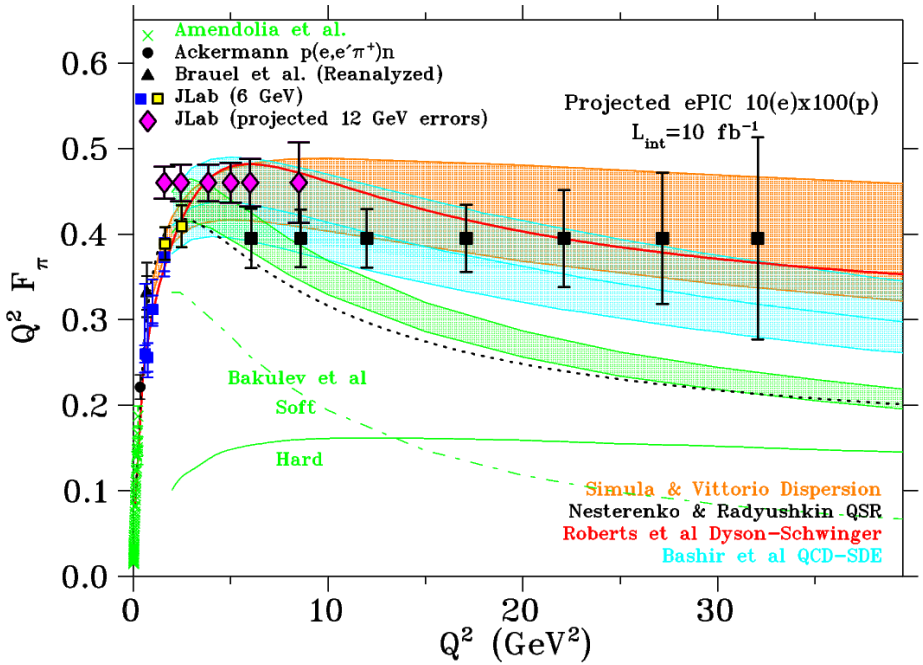



Projection plots by G.M. Huber, University of Regina

# Where we were...

- Early simulations and projections for $F_\pi$ looked promising

- Initially focused on 5$x$100
- 10$x$100 also looked good

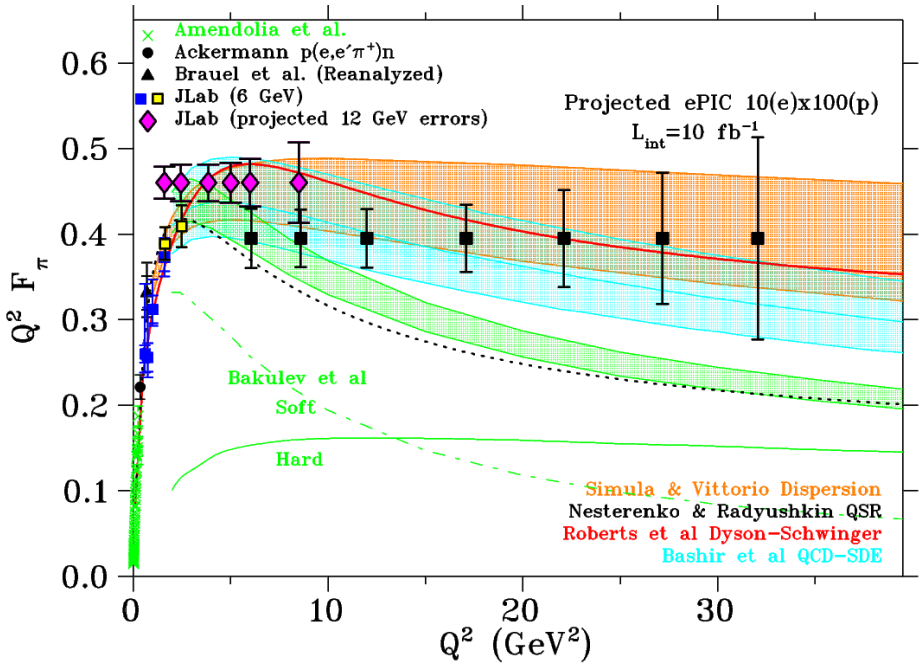



Projection plots by G.M. Huber, University of Regina

# Where we were...

- Early simulations and projections for $F_\pi$ looked promising

- Initially focused on 5$x$100
- 10$x$100 also looked good
- Higher $Q^2$ seemed to be statistics constrained

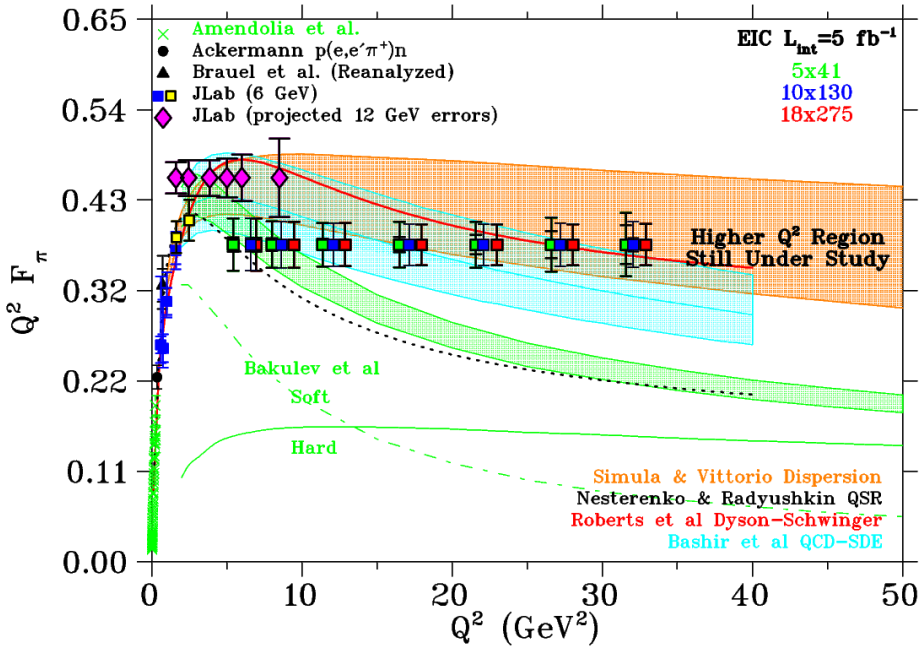



Projection plots by G.M. Huber, University of Regina

# Where we were...

- Early simulations and projections for $F_\pi$ looked promising

- Initially focused on 5x100
- 10x100 also looked good
- Higher $Q^2$ seemed to be statistics constrained
- Improvements to generator efficiency



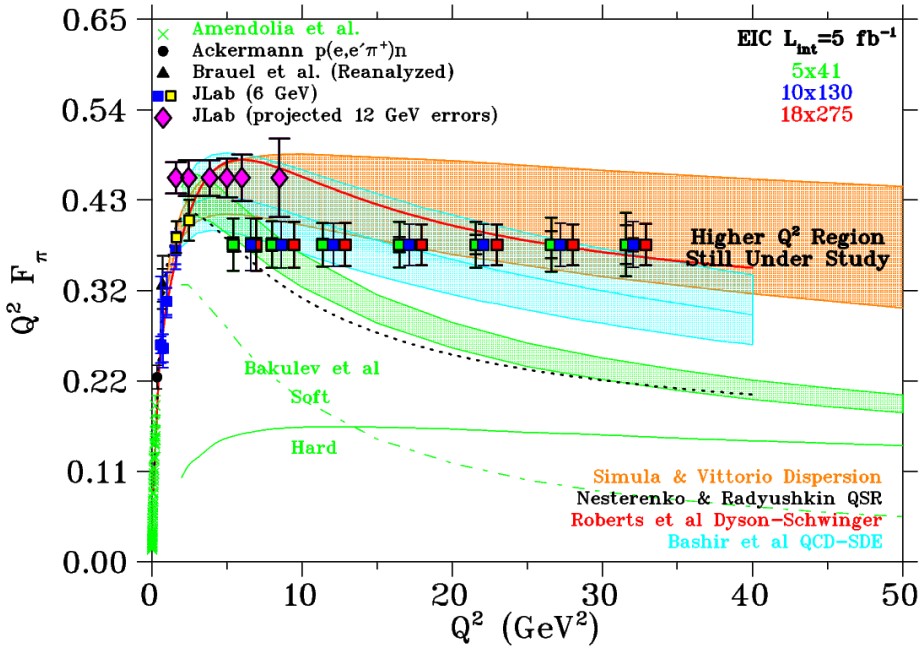

- Signs that $Q^2 > 35 GeV^2$ looked possible
  - Across multiple beam energy combinations
  - May need higher $\int \mathcal{L}$ than early science

Projection plots by G.M. Huber, University of Regina

# Where we were...

- Early simulations and projections for $F_\pi$ looked promising

- Initially focused on 5x100
- 10x100 also looked good
- Higher $Q^2$ seemed to be statistics constrained
- Improvements to generator efficiency
- Only one "early science" config here though!




- Signs that $Q^2 > 35 GeV^2$ looked possible
  - Across multiple beam energy combinations
  - May need higher $\int \mathcal{L}$ than early science

Projection plots by G.M. Huber, University of Regina

# Latest Simulation Campaign Input

- Generated new 10x130 and 10x250 files from DEMPgen
- Used DEMPgen v1.2.4 to generate new files
  - Assume $\int \mathcal{L} = 5\ fb^{-1}$ in projections

Used $\mathcal{L} \approx 0.2629 \times 10^{33} cm^{-2} s^{-1}$, based upon assumptions on per fill $\int \mathcal{L}$ in Elke's slides.

# Latest Simulation Campaign Input

- Generated new 10x130 and 10x250 files from DEMPgen
- Used DEMPgen v1.2.4 to generate new files
  - Assume $\int \mathcal{L} = 5\ fb^{-1}$ in projections
- Ran $p(e, e'\pi^+ n)$ split into three $Q^2$ ranges
  - $3 < Q^2 < 10$, $10 < Q^2 < 20$ and $20 < Q^2 < 35$
  - Roughly ~400k generated per $Q^2$ range

Technically, actually a cut on the range of $\theta_{e'}$ values, directly feeds into $Q^2$

# Latest Simulation Campaign Input

- Generated new 10x130 and 10x250 files from DEMPgen
- Used DEMPgen v1.2.4 to generate new files
  - Assume $\int \mathcal{L} = 5\ fb^{-1}$ in projections
- Ran $p(e, e'\pi^+ n)$ split into three $Q^2$ ranges
  - $3 < Q^2 < 10$, $10 < Q^2 < 20$ and $20 < Q^2 < 35$
  - Roughly ~400k generated per $Q^2$ range
- Constrained $-t$ to $< 0.4\ GeV^2$
- Submitted for October campaign
  - Used 10x130 and 10x250 epic-craterlake detector config
  - ip6_ep_130x10 and ip6_ep_250x10 afterburner configs applied

# Latest Simulation Campaign Input

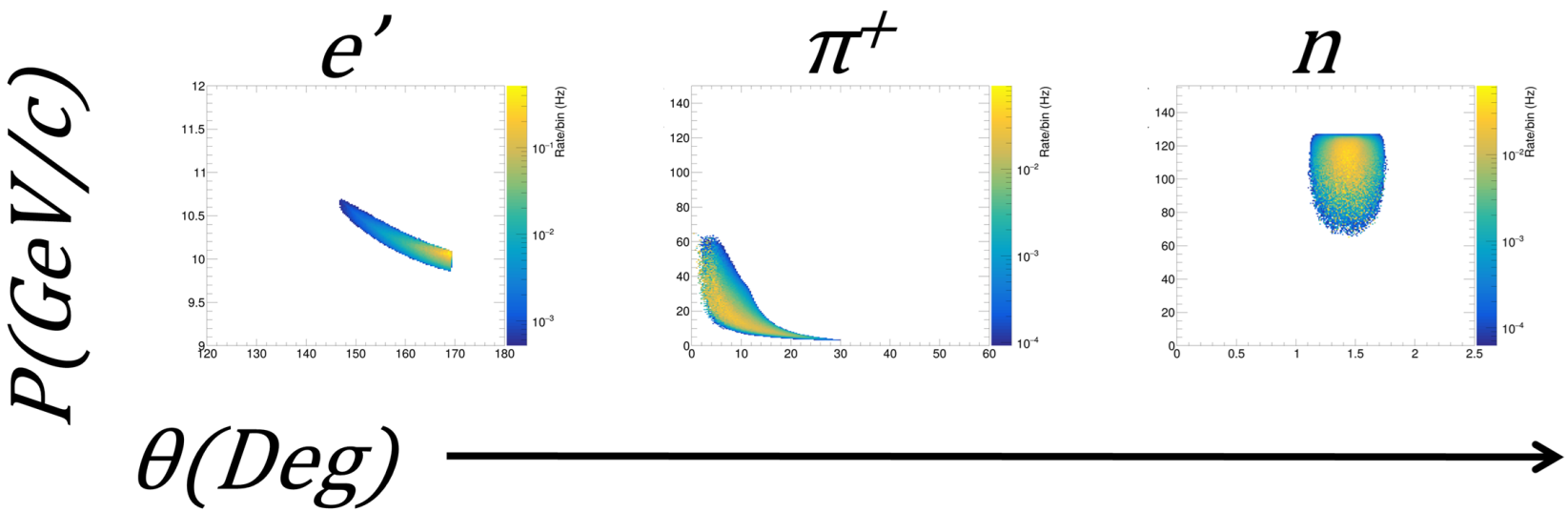
- Generated new 10x130 and 10x250 files from DEMPgen
- Used DEMPgen v1.2.4 to generate new files
  - Assume $\int \mathcal{L} = 5\ fb^{-1}$ in projections
- Ran $p(e, e'\pi^+ n)$ split into three $Q^2$ ranges
  - $3 < Q^2 < 10$, $10 < Q^2 < 20$ and $20 < Q^2 < 35$
  - Roughly ~400k generated per $Q^2$ range
- Constrained $-t$ to $< 0.4\ GeV^2$
- Submitted for October campaign
  - Used 10x130 and 10x250 epic-craterlake detector config
  - ip6_ep_130x10 and ip6_ep_250x10 afterburner configs applied
- **Results shown (and in Analysis Note) are all from 25.10.2 simulation campaign output unless otherwise stated**

# DEMP Kinematics - Truth Distributions

- For 10 GeV electrons on 130 GeV protons (10x130), where do products go?

# DEMP Kinematics - Truth Distributions

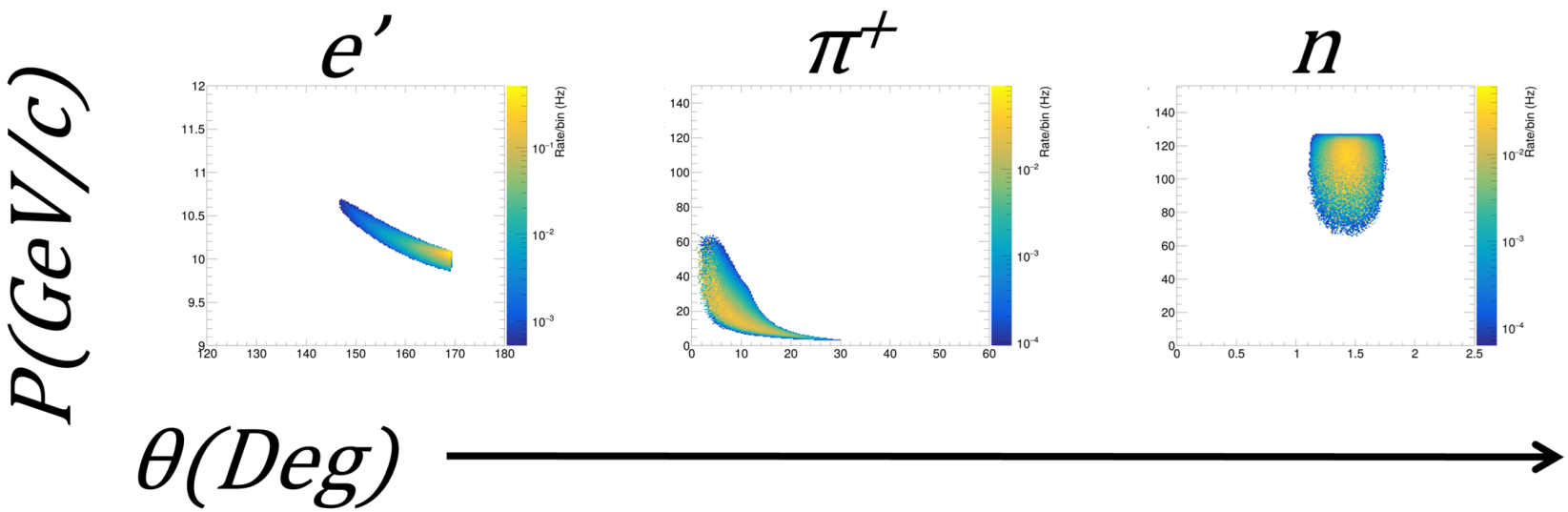
- For 10 GeV electrons on 130 GeV protons (10x130), where do products go?
- $e'$ and $\pi^+$ hit the central detector, neutron in FF detectors
  - ZDC in particular critical for low $-t$ neutrons




Beam effects *not* removed here. Note, in $\eta$ the ranges are $-1.15 < \eta_{e'} < -2.45$ , $0 < \eta_{\pi^+} < 0.9$ and $4 < \eta_n < 5.1$.

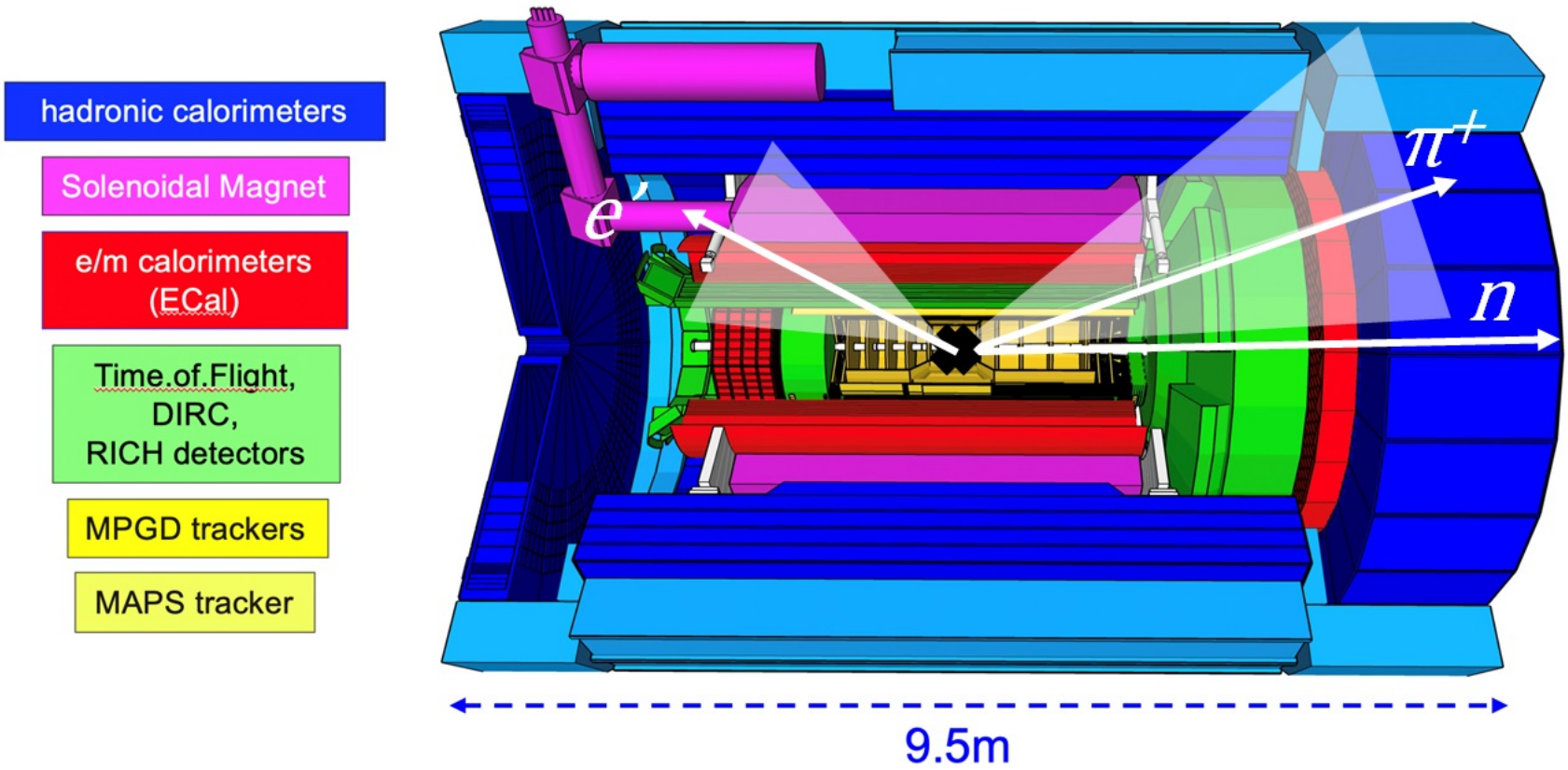
# DEMP Kinematics - Truth Distributions

- For 10 GeV electrons on 130 GeV protons (10x130), where do products go?
- $e'$ and $\pi^+$ hit the central detector, neutron in FF detectors
  - ZDC in particular critical for low $-t$ neutrons
- Note that the $Z$ scale is a rate in $Hz$



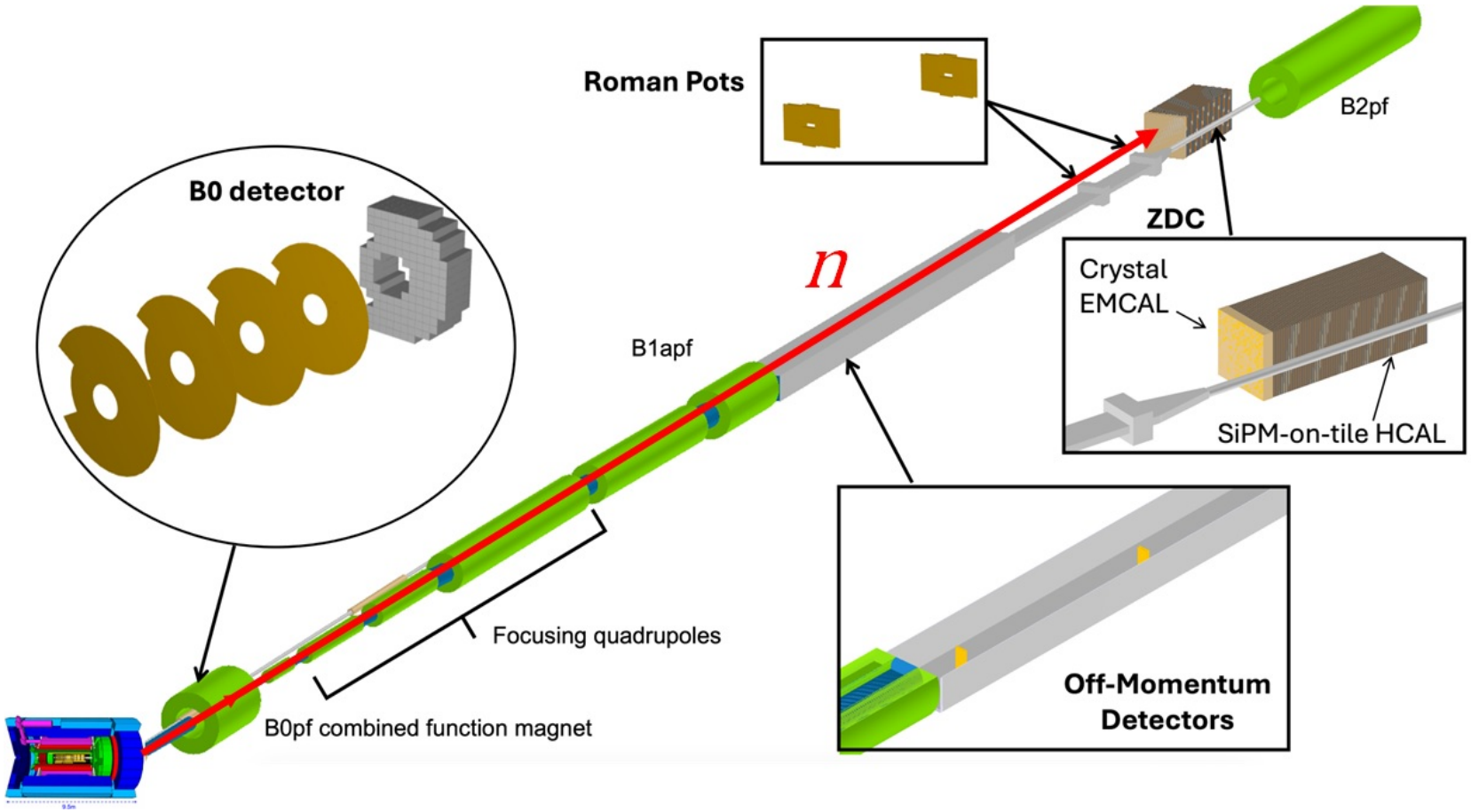
# DEMP Kinematics - Visualising with ePIC

- $e'$ and $\pi^+$ hit the central detector



# DEMP Kinematics - Visualising with ePIC

- $e'$ and $\pi^+$ hit the central detector
- n very forward focused, ZDC or B0



# DEMP Analysis Overview - Event Selection Cuts

- Need to select out $e'$, $\pi^+$, $n$ triple coincidence events
- To begin, require that simultaneously we have -

# DEMP Analysis Overview - Event Selection Cuts

- Need to select out $e'$, $\pi^+$, $n$ triple coincidence events
- To begin, require that simultaneously we have -
  - One negatively charged track in the $-z$ direction (the $e'$)
    - "ElectronFinder" equivalent cuts applied, see next slide
  - One positively charged track in the $+z$ direction ($\pi^+$)
  - A high energy reconstructed neutron in the ZDC
    - $E_n > 40$ *GeV*
    - $\theta_n^* < 4$ *mrad*

$E_n > 120$ *GeV* for 10x250, $\theta^*$ is after a rotation of 25 mRad around the proton axis to remove the crossing angle

# DEMP Analysis Overview - Event Selection Cuts

- Need to select out $e'$, $\pi^+$, $n$ triple coincidence events
- To begin, require that simultaneously we have -
  - One negatively charged track in the $-z$ direction (the $e'$)
    - "ElectronFinder" equivalent cuts applied, see next slide
  - One positively charged track in the $+z$ direction ($\pi^+$)
  - A high energy reconstructed neutron in the ZDC
    - $E_n > 40$ *GeV*
    - $\theta_n^* < 4$ *mrad*
- Calculate $Q^2$, cut on $5 < Q^2_{DA} < 35$ GeV$^2$

# DEMP Analysis Overview - Event Selection Cuts

- Need to select out $e'$, $\pi^+$, $n$ triple coincidence events
- To begin, require that simultaneously we have -
  - One negatively charged track in the $-z$ direction (the $e'$)
    - "ElectronFinder" equivalent cuts applied, see next slide
  - One positively charged track in the $+z$ direction ($\pi^+$)
  - A high energy reconstructed neutron in the ZDC
    - $E_n > 40$ *GeV*
    - $\theta_n^* < 4$ *mrad*
- Calculate $Q^2$, cut on $5 < Q^2_{DA} < 35$ GeV$^2$
- Calculate remaining kinematic quantities and apply cuts:
  - $0 < -t_{eXBABE} < 1.4$ GeV$^2$, $W > 0$ GeV and $y_{DA} > 0.01$
  - Using the tRECO convention for -t reconstruction methods

# DEMP Analysis Overview - Event Selection Cuts

- Need to select out $e'$, $\pi^+$, $n$ triple coincidence events
- To begin, require that simultaneously we have -
  - One negatively charged track in the $-z$ direction (the $e'$)
    - "ElectronFinder" equivalent cuts applied, see next slide
  - One positively charged track in the $+z$ direction ($\pi^+$)
  - A high energy reconstructed neutron in the ZDC
    - $E_n > 40$ *GeV*
    - $\theta_n^* < 4$ *mrad*
- Calculate $Q^2$, cut on $5 < Q^2_{DA} < 35$ GeV$^2$
- Calculate remaining kinematic quantities and apply cuts:
  - $0 < -t_{eXBABE} < 1.4$ GeV$^2$, $W > 0$ GeV and $y_{DA} > 0.01$
  - Using the tRECO convention for -t reconstruction methods
- Apply final exclusivity cuts
  - Missing mass, $\Delta\theta^*$ and $\Delta\phi^*$ cuts
- Cut on $18 < \sum (E - P_z) < 22$ GeV

# DEMP Analysis Overview - Event Selection Cuts

- Need to select out $e'$, $\pi^+$, $n$ triple coincidence events
- To begin, require that simultaneously we have -
  - One negatively charged track in the $-z$ direction (the $e'$)
    - "ElectronFinder" equivalent cuts applied, see next slide
  - One positively charged track in the $+z$ direction ($\pi^+$)
  - A high energy reconstructed neutron in the ZDC
    - $E_n > 40$ *GeV*
    - $\theta_n^* < 4$ *mrad*
- Calculate $Q^2$, cut on $5 < Q^2_{DA} < 35$ GeV$^2$
- Calculate remaining kinematic quantities and apply cuts:
  - $0 < -t_{eXBABE} < 1.4$ GeV$^2$, $W > 0$ GeV and $y_{DA} > 0.01$
  - Using the tRECO convention for -t reconstruction methods
- Apply final exclusivity cuts
  - Missing mass, $\Delta\theta^*$ and $\Delta\phi^*$ cuts
- Cut on $18 < \sum(E - P_z) < 22$ GeV
- Full analysis code on on GitHub, details in Analysis Note

https://github.com/sjdkay/ePIC_DEMP_Analysis and https://doi.org/10.5281/zenodo.18681414

# Electron ID Details

- Adopted series of cuts comparable to ElectronFinder

# Electron ID Details

- Adopted series of cuts comparable to ElectronFinder
- Find highest energy cluster in Endcap ECal and Barrel ECal, check $E_{Clus} > 0.8 \times E_{eBeam}$
  - If in barrel, require cluster is in -ve $z$

# Electron ID Details

- Adopted series of cuts comparable to ElectronFinder
- Find highest energy cluster in Endcap ECal and Barrel ECal, check $E_{Clus} > 0.8 \times E_{eBeam}$
  - If in barrel, require cluster is in -ve $z$
- Check for good, $-ve$ charge track in the $-ve$ $z$ direction
  - Require $|\underline{P}_{Track}| > 0.8 \times E_{eBeam}$

# Electron ID Details

- Adopted series of cuts comparable to ElectronFinder
- Find highest energy cluster in Endcap ECal and Barrel ECal, check $E_{Clus} > 0.8 \times E_{eBeam}$
  - If in barrel, require cluster is in -ve $z$
- Check for good, $-ve$ charge track in the $-ve$ $z$ direction
  - Require $|\underline{P}_{Track}| > 0.8 \times E_{eBeam}$
- Combine track and cluster information, cut on $0.9 < E/P < 1.2$
- **If event retained after this cut, use track info as e'**

See WG presentation for details

# Electron ID Details

- Adopted series of cuts comparable to ElectronFinder
- Find highest energy cluster in Endcap ECal and Barrel ECal, check $E_{Clus} > 0.8 \times E_{eBeam}$
  - If in barrel, require cluster is in -ve $z$
- Check for good, $-ve$ charge track in the $-ve$ $z$ direction
  - Require $|\underline{P}_{Track}| > 0.8 \times E_{eBeam}$
- Combine track and cluster information, cut on $0.9 < E/P < 1.2$
- **If event retained after this cut, use track info as e'**
- For tracks with $160^\circ < \theta < 163^\circ$, use **track info only** if it is good. Do not require a good cluster too
  - Poor cluster reconstruction in endcap/barrel overlap region

# Kinematic Reconstruction - $Q^2$

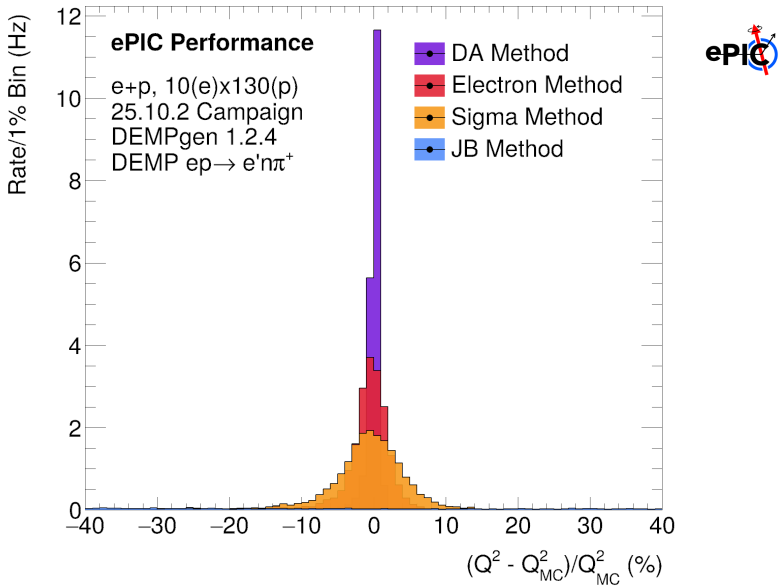
- Various ways to calculate $Q^2$ (and $\therefore x, y$)

See details of each calculation in this tutorial

# Kinematic Reconstruction - $Q^2$

- Various ways to calculate $Q^2$ (and $\therefore x, y$)
- Evaluated the electron, JB, DA and sigma methods
- DA method appears to perform best for DEMP across broad kinematic range

- DA method correlates well with truth
- Electron and sigma methods perform OK, but not as well.
- JB method clearly not valid for these kinematics

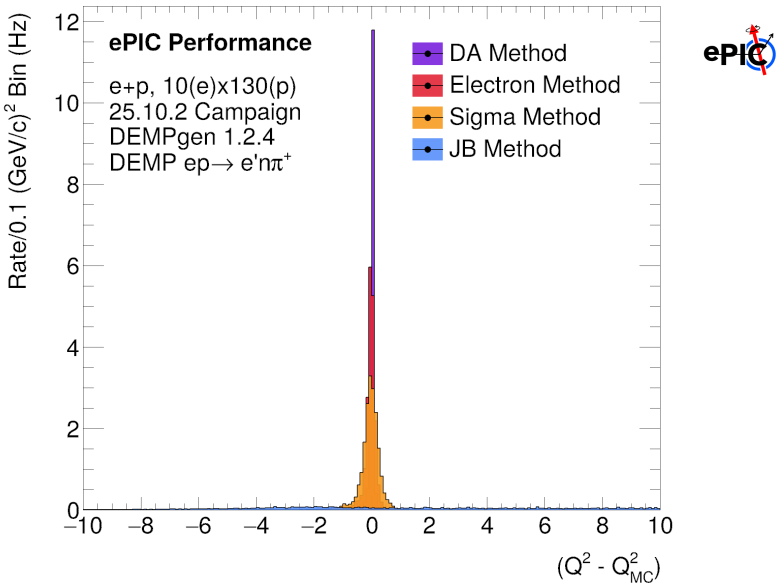



$\sigma(DA) = 1.205$, $\sigma(Electron) = 3.144$, $\sigma(Sigma) = 6.054$, $\sigma(JB) = N/a$.

# Kinematic Reconstruction - $Q^2$

- Various ways to calculate $Q^2$ (and $\therefore x, y$)
- Evaluated the electron, JB, DA and sigma methods
- DA method appears to perform best for DEMP across broad kinematic range

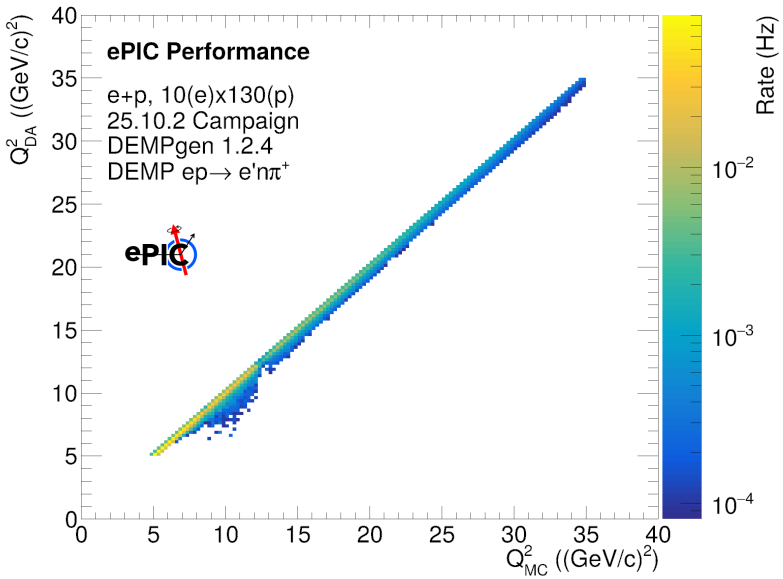
- DA method correlates well with truth
- Electron and sigma methods perform OK, but not as well.
- JB method clearly not valid for these kinematics
- Evident when looking at <u>absolute</u> difference too



# Kinematic Reconstruction - $Q^2$

- Various ways to calculate $Q^2$ (and $\therefore x, y$)
- Evaluated the electron, JB, DA and sigma methods
- DA method appears to perform best for DEMP across broad kinematic range

- $Q^2_{DA}$ correlates well with truth
- Cut on $5 < Q^2_{DA} < 35$ GeV$^2$ before further event processing



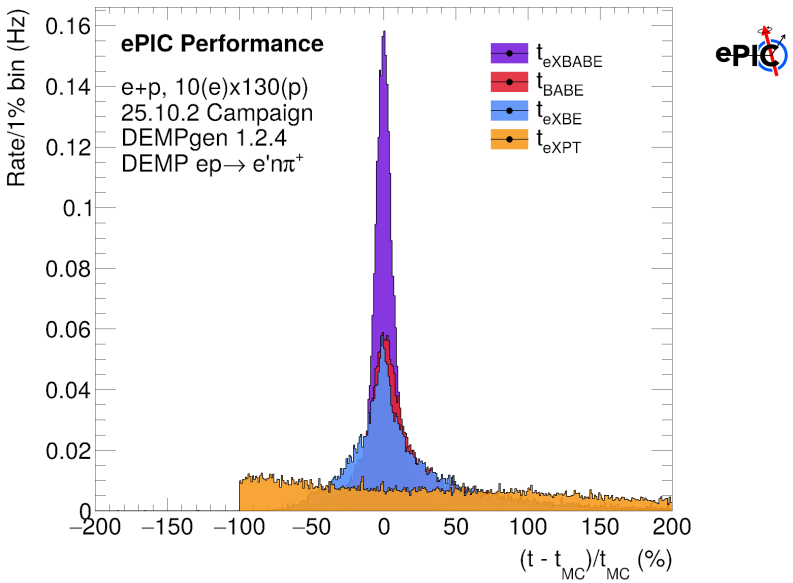
# Kinematic Reconstruction - $-t$

- Can reconstruct $-t$ in multiple ways (see $t_{RECO}$ document)

# Kinematic Reconstruction - $-t$

- Can reconstruct $-t$ in multiple ways (see $t_{RECO}$ document)
- "Best" way for DEMP is $\rightarrow -t_{eXBABE} = (\vec{p} - \vec{n}_{Corr})^2$
- Exploit exclusive nature of the reaction, generic implementation available in code here

- $-t_{eXBABE}$ correlates well with truth
- Far better than methods using uncorrected neutron track ($t_{BABE}$) and methods utilising electron information ($t_{eX}$) and electron $P_T$ ($t_{eXPT}$) info

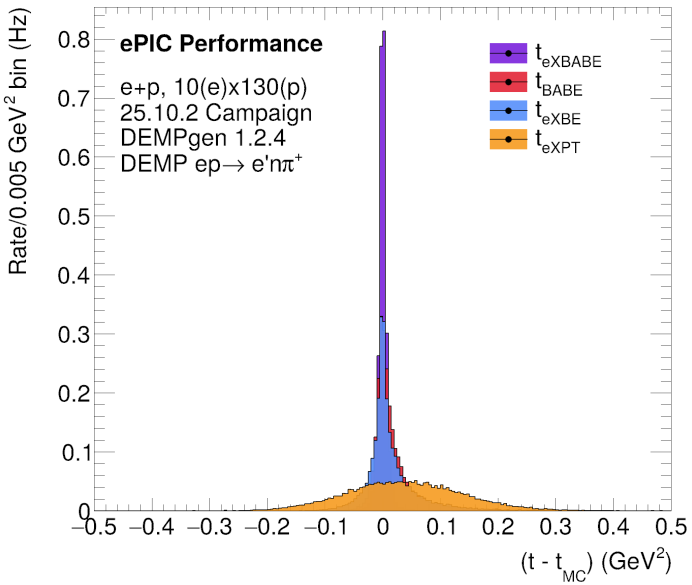



$\sigma(eXBABE) = 11.03$, $\sigma(BABE) = 42.67$, $\sigma(eXBE) = 43.26$, $\sigma(eXPT) = 83.92$. **All $e'\pi^+n$ triple coincidence**

# Kinematic Reconstruction - $-t$

- Can reconstruct $-t$ in multiple ways (see $t_{RECO}$ document)
- "Best" way for DEMP is $\rightarrow -t_{eXBABE} = (\vec{p} - \vec{n}_{Corr})^2$
- Exploit exclusive nature of the reaction, generic implementation available in code here

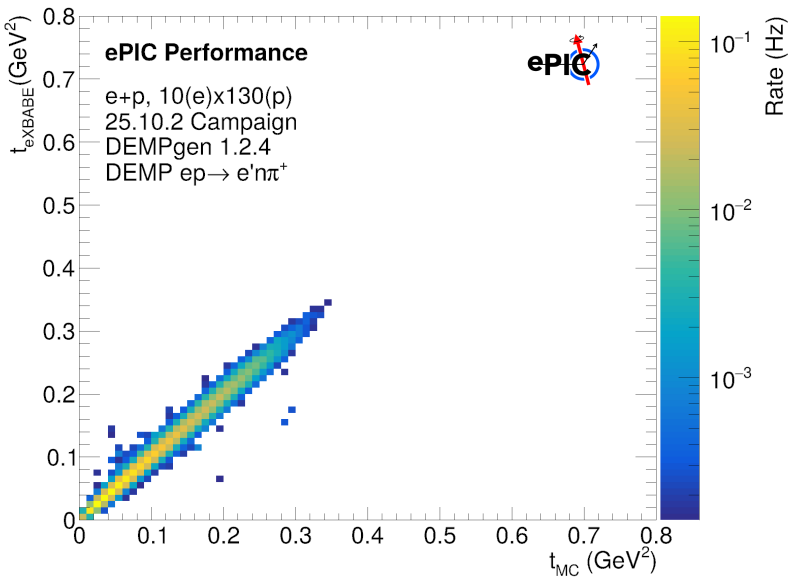
- $-t_{eXBABE}$ correlates well with truth
- Far better than methods using uncorrected neutron track ($t_{BABE}$) and methods utilising electron information ($t_{eX}$) and electron $P_T$ ($t_{eXPT}$) info
- Again, true for absolute difference too



# Kinematic Reconstruction - $-t$

- Can reconstruct $-t$ in multiple ways (see $t_{RECO}$ document)
- "Best" way for DEMP is $\rightarrow -t_{eXBABE} = (\vec{p} - \vec{n}_{Corr})^2$
- Exploit exclusive nature of the reaction, generic implementation available in code here

- $-t_{eXBABE}$ correlates well with truth
- Cut on $-t_{eXBABE} < 0.45$ GeV$^2$
- For form factor extraction, want lowest $-t$ bins




Note, events only generated to $-t$ 0.4 GeV$^2$

# Exclusivity Cuts - $\Delta\theta^*$ and $\Delta\phi^*$ Cuts

- Under the assumption that an exclusive $p(e, e'\pi^+ n)$ event is detected, the vector $\underline{P}_{Miss} = (\underline{e} + \underline{p}) - (\underline{e'}_{Rec} + \underline{\pi}_{Rec})$ **should** roughly correspond to $n_{rec}$
- $\underline{P}_{Miss}$ hit location on ZDC should match $\underline{n}_{rec}$

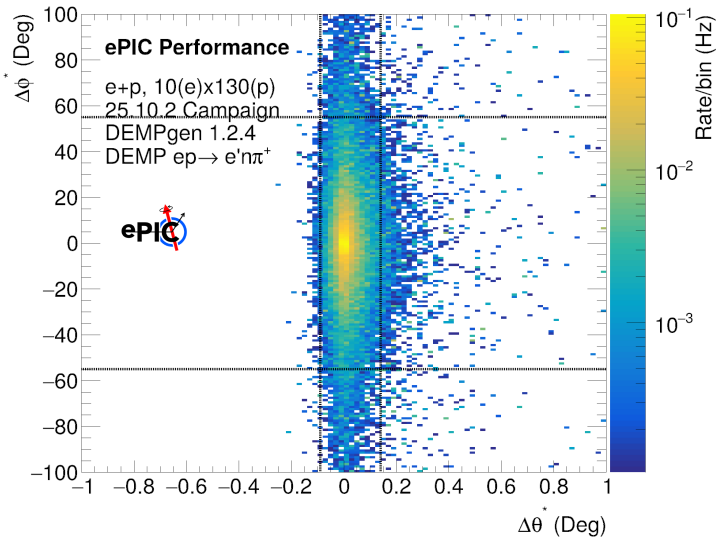
# Exclusivity Cuts - $\Delta\theta^*$ and $\Delta\phi^*$ Cuts

- Under the assumption that an exclusive $p(e, e'\pi^+ n)$ event is detected, the vector $\underline{P}_{Miss} = (\underline{e} + \underline{p}) - (\underline{e'}_{Rec} + \underline{\pi}_{Rec})$ **should** roughly correspond to $n_{rec}$
- $\underline{P}_{Miss}$ hit location on ZDC should match $\underline{n}_{rec}$
- For a non-exclusive event, this would not be true
  - Effectively an additional "exclusivity" constraint

# Exclusivity Cuts - $\Delta\theta^*$ and $\Delta\phi^*$ Cuts

- Under the assumption that an exclusive $p(e, e'\pi^+ n)$ event is detected, the vector $\underline{P}_{Miss} = (\underline{e} + \underline{p}) - (\underline{e'}_{Rec} + \underline{\pi}_{Rec})$ **should** roughly correspond to $n_{rec}$
- $\underline{P}_{Miss}$ hit location on ZDC should match $\underline{n}_{rec}$
- For a non-exclusive event, this would not be true
  - Effectively an additional "exclusivity" constraint

- Use difference in angles between $\underline{P}_{Miss}$ and $\underline{n}_{rec}$ - $\Delta\theta^*$ and $\Delta\phi^*$

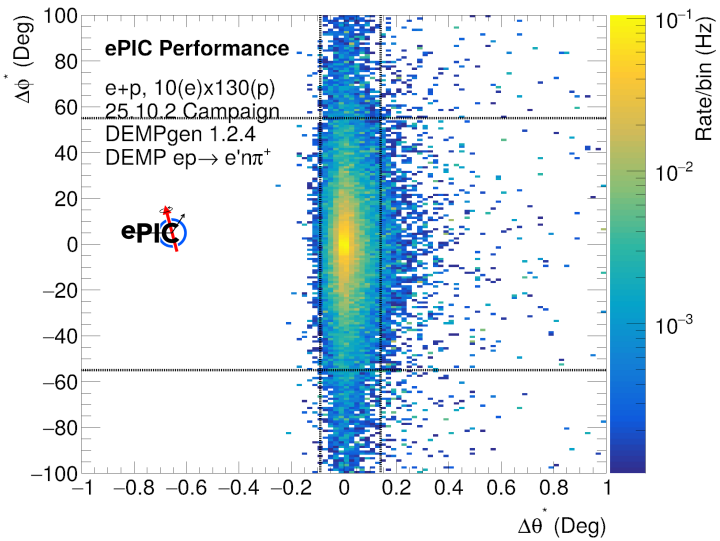



$\Delta\theta^* = \theta^*_{PMiss} - \theta_{*\,ZDC}$ and $\Delta\phi^* = \phi^*_{PMiss} - \phi^*_{ZDC}$, $^*$ denotes this is after 25 mRad rotation about proton axis.

# Exclusivity Cuts - $\Delta\theta^*$ and $\Delta\phi^*$ Cuts

- Under the assumption that an exclusive $p(e, e'\pi^+ n)$ event is detected, the vector $\underline{P}_{Miss} = (\underline{e} + \underline{p}) - (\underline{e'}_{Rec} + \underline{\pi}_{Rec})$ **should** roughly correspond to $n_{rec}$
- $\underline{P}_{Miss}$ hit location on ZDC should match $\underline{n}_{rec}$
- For a non-exclusive event, this would not be true
  - Effectively an additional "exclusivity" constraint

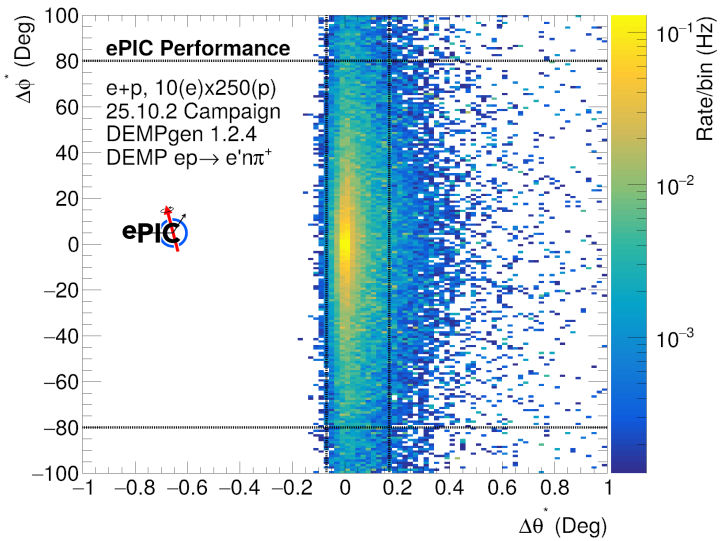
- Use difference in angles between $\underline{P}_{Miss}$ and $\underline{n}_{rec}$ - $\Delta\theta^*$ and $\Delta\phi^*$
- For 10x130, retain only $-0.09° < \Delta\theta^* < 0.14°$ and $-55° < \Delta\phi^* < 55°$



# Exclusivity Cuts - $\Delta\theta^*$ and $\Delta\phi^*$ Cuts

- Under the assumption that an exclusive $p(e, e'\pi^+ n)$ event is detected, the vector $\underline{P}_{Miss} = (\underline{e} + \underline{p}) - (\underline{e'}_{Rec} + \underline{\pi}_{Rec})$ **should** roughly correspond to $n_{rec}$
- $\underline{P}_{Miss}$ hit location on ZDC should match $\underline{n}_{rec}$
- For a non-exclusive event, this would not be true
  - Effectively an additional "exclusivity" constraint

- Use difference in angles between $\underline{P}_{Miss}$ and $\underline{n}_{rec}$ - $\Delta\theta^*$ and $\Delta\phi^*$
- For 10x130, retain only $-0.09° < \Delta\theta^* < 0.14°$ and $-55° < \Delta\phi^* < 55°$
- Cut values differ for 10x250




$-0.07° < \Delta\theta^* < 0.17°$ and $-80° < \Delta\phi^* < 80°$

# Exclusivity Cuts - Missing Mass

- Additional exclusivity cuts on the missing mass
- In a $p(e, e'\pi^+ n)$ event, no missing particles, define:

# Exclusivity Cuts - Missing Mass

- Additional exclusivity cuts on the missing mass
- In a $p(e, e'\pi^+ n)$ event, no missing particles, define:
- $\underline{P}_{M\_DEMP} = (\underline{e} + \underline{p}) - (\underline{e'} + \underline{\pi}^+ + \underline{n})$
  - Missing momentum of the whole reaction
  - Exclusive, so should be $\sim 0$!

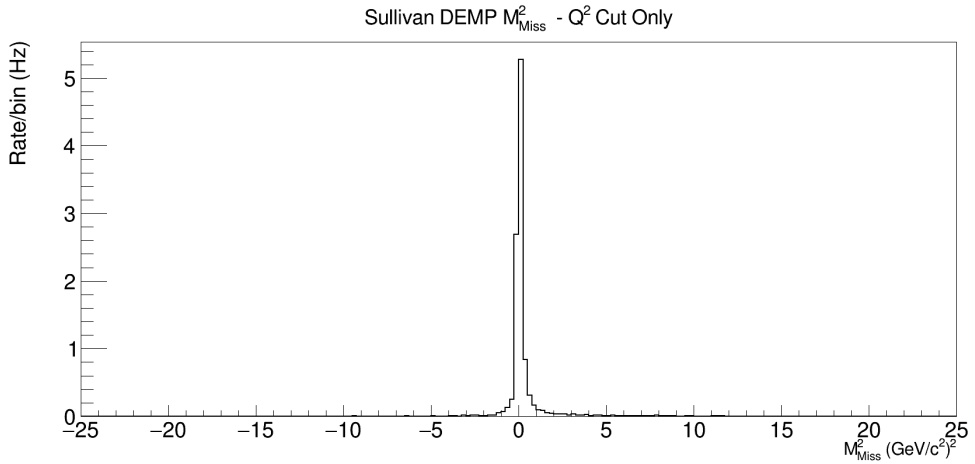
# Exclusivity Cuts - Missing Mass

- Additional exclusivity cuts on the missing mass
- In a $p(e, e'\pi^+ n)$ event, no missing particles, define:
- $\underline{P}_{M\_DEMP} = (\underline{e} + \underline{p}) - (\underline{e'} + \underline{\pi}^+ + \underline{n})$
  - Missing momentum of the whole reaction
  - Exclusive, so should be $\sim 0$!
- Take $.M2()$ and $.M()$ of this 4-vector, apply cuts
- Should remove any non-exlcusive events, e.g. DIS

Cut on $\underline{P}_{M\_DEMP}.M2() > -1$ $(\text{GeV/c}^2)^2$ and $|\underline{P}_{M\_DEMP}.M()| < 0.75$ $\text{GeV/c}^2$

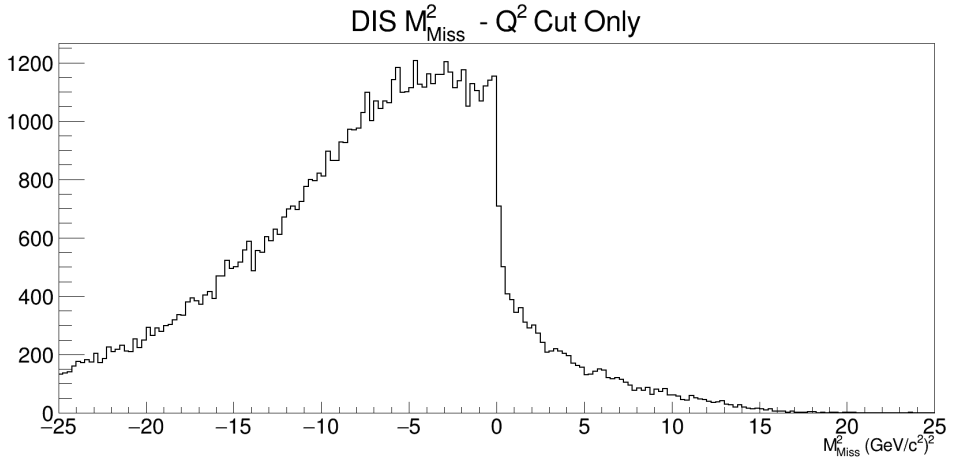
# Exclusivity Cuts - Missing Mass

- Additional exclusivity cuts on the missing mass
- In a $p(e, e'\pi^+ n)$ event, no missing particles, define:
- $\underline{P}_{M\_DEMP} = (\underline{e} + \underline{p}) - (\underline{e'} + \underline{\pi^+} + \underline{n})$
  - Missing momentum of the whole reaction
  - Exclusive, so should be $\sim 0$!
- Take $.M2()$ and $.M()$ of this 4-vector, apply cuts
- Should remove any non-exlcusive events, e.g. DIS
- Distributions for Sullivan DEMP and DIS are very different



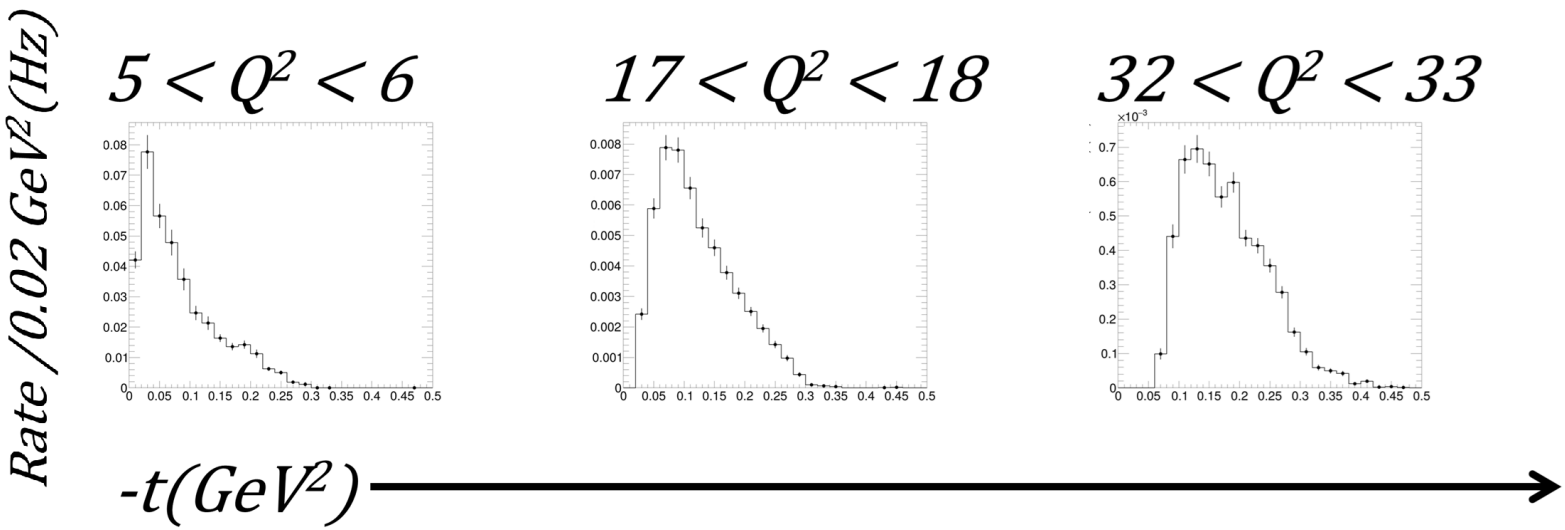
# Exclusivity Cuts - Missing Mass

- Additional exclusivity cuts on the missing mass
- In a $p(e, e'\pi^+ n)$ event, no missing particles, define:
- $\underline{P}_{M\_DEMP} = (\underline{e} + \underline{p}) - (\underline{e'} + \underline{\pi^+} + \underline{n})$
  - Missing momentum of the whole reaction
  - Exclusive, so should be $\sim 0$!
- Take $.M2()$ and $.M()$ of this 4-vector, apply cuts
- Should remove any non-exlcusive events, e.g. DIS
- Distributions for Sullivan DEMP and DIS are very different



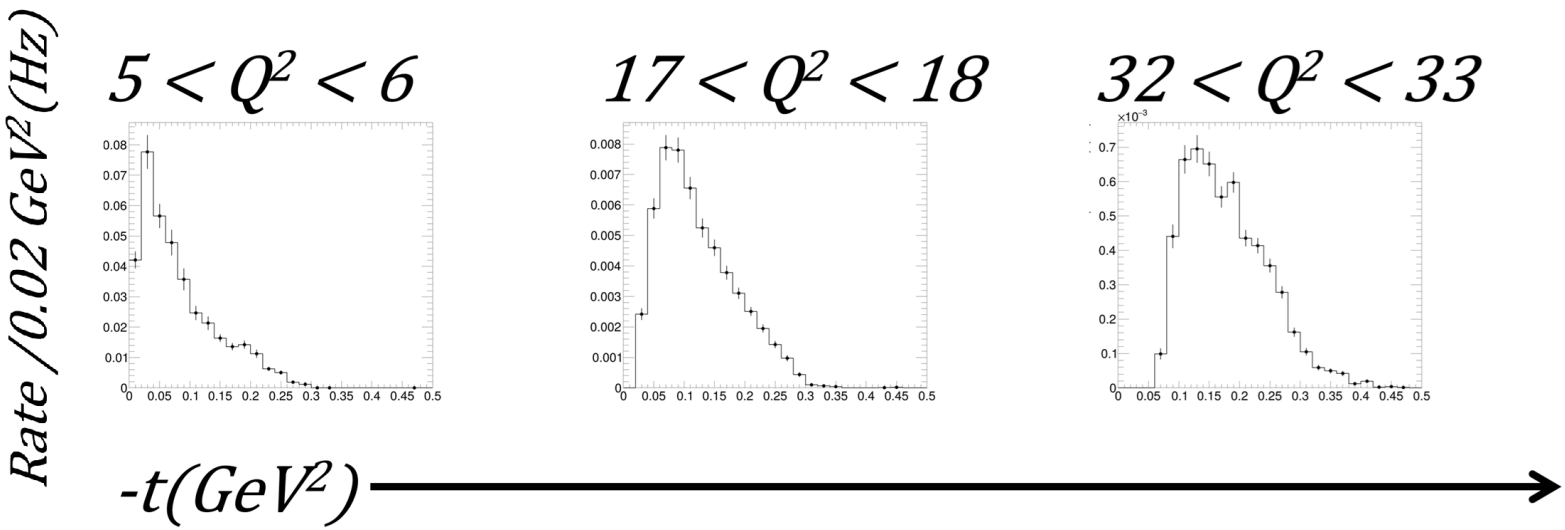
# DEMP Analysis Results - $Q^2, -t$ Binning

- After applying cuts, bin in $Q^2$ and $-t$
  - $-t$ bins 0.02 $GeV^2$ wide
  - $Q^2$ bins 1 $GeV^2$ wide



# DEMP Analysis Results - $Q^2, -t$ Binning

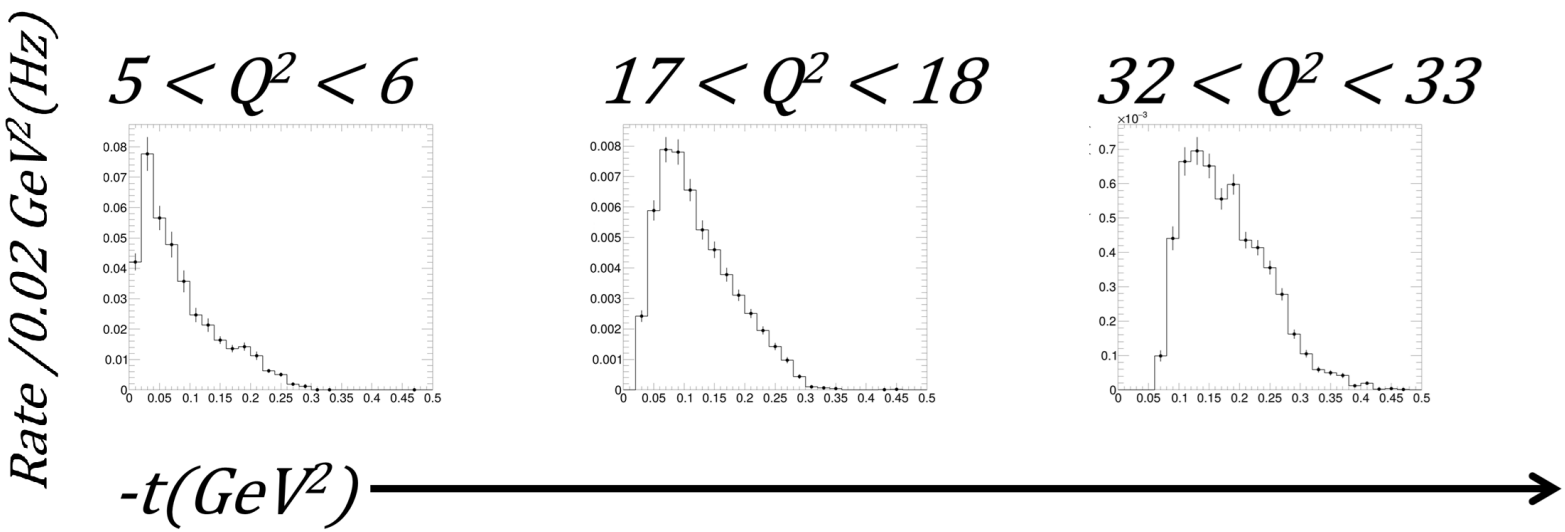
- After applying cuts, bin in $Q^2$ and $-t$
  - $-t$ bins 0.02 $GeV^2$ wide
  - $Q^2$ bins 1 $GeV^2$ wide
  - Rebin if stats low or bin migration an issue




Want bin width to be larger than resolution per bin, see next slide

# DEMP Analysis Results - $Q^2, -t$ Binning

- After applying cuts, bin in $Q^2$ and $-t$
  - $-t$ bins 0.02 $GeV^2$ wide
  - $Q^2$ bins 1 $GeV^2$ wide
  - Rebin if stats low or bin migration an issue
- From rate per bin, extrapolate to number of events with $\int \mathcal{L} = 5\ fb^{-1}$, project to $F_\pi$



# DEMP Analysis Results - $-t$ Bin Widths

- Want $-t$ bins to be at least as wide as the $-t$ resolution
- Bin migration will be a big issue otherwise

# DEMP Analysis Results - $-t$ Bin Widths

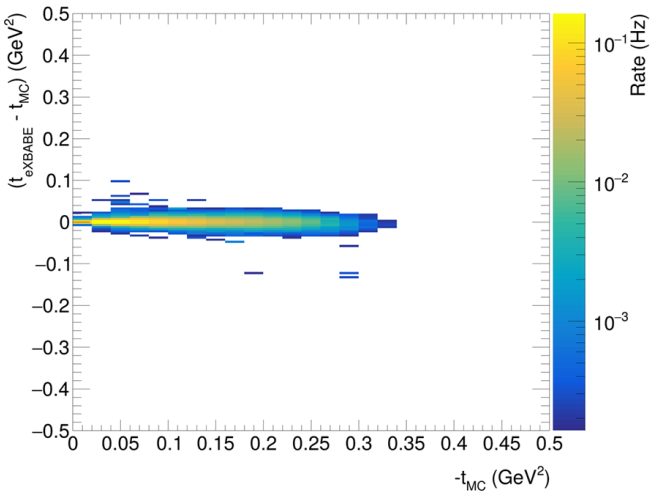
- Want $-t$ bins to be at least as wide as the $-t$ resolution
- Bin migration will be a big issue otherwise
- Check $-t$ resolution
  - Across full $Q^2$ range and in distinct $Q^2$ regions

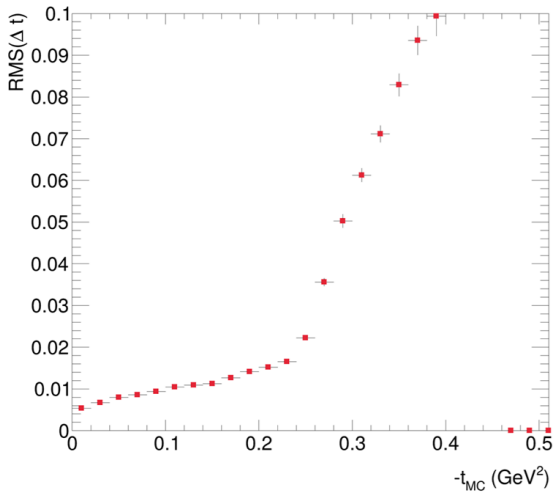
# DEMP Analysis Results - $-t$ Bin Widths

- Want $-t$ bins to be at least as wide as the $-t$ resolution
- Bin migration will be a big issue otherwise
- Check $-t$ resolution
  - Across full $Q^2$ range and in distinct $Q^2$ regions
- Take RMS value of slices of $\Delta t = t_{eXBABE} - t_{MC}$ as a function of $-t_{MC}$
- **For $F_\pi$ extraction, only lowest $\sim$5 viable $-t$ bins are needed**

# DEMP Analysis Results - $-t$ Bin Widths

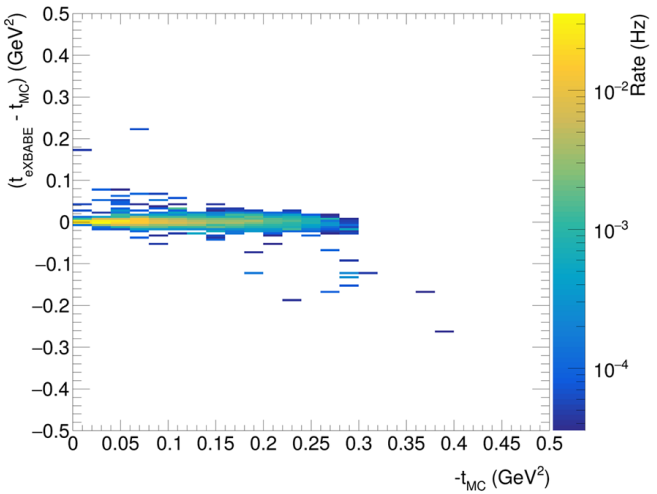
- Want $-t$ bins to be at least as wide as the $-t$ resolution
- Bin migration will be a big issue otherwise
- Check $-t$ resolution
  - Across full $Q^2$ range and in distinct $Q^2$ regions
- Take RMS value of slices of $\Delta t = t_{eXBABE} - t_{MC}$ as a function of $-t_{MC}$
- 10x130 across $5 < Q^2_{DA} < 35$ GeV$^2$, comfortably below 0.02 in lowest $-t$ bins

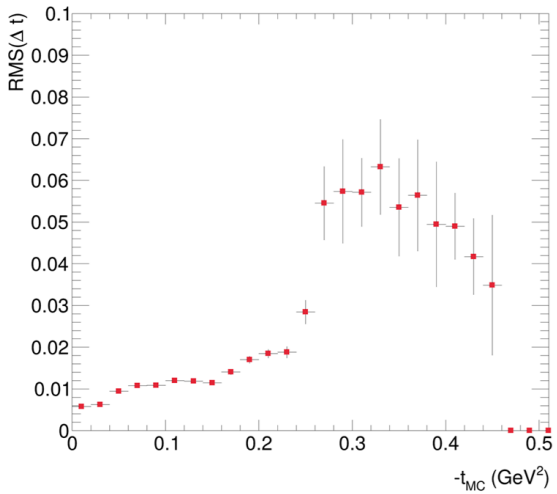


# DEMP Analysis Results - $-t$ Bin Widths

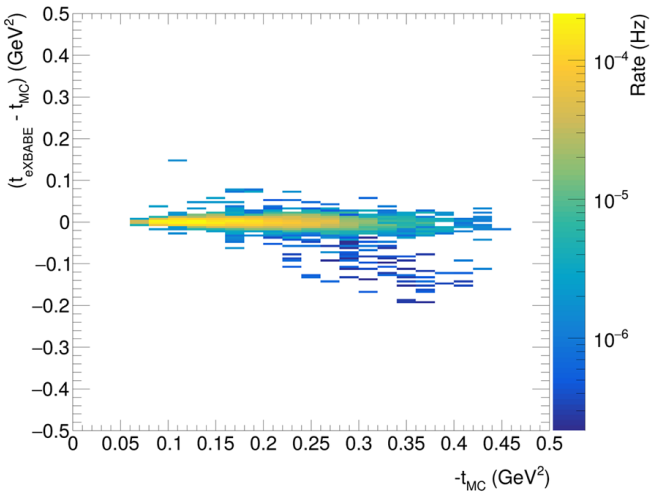
- Want $-t$ bins to be at least as wide as the $-t$ resolution
- Bin migration will be a big issue otherwise
- Check $-t$ resolution
  - Across full $Q^2$ range and in distinct $Q^2$ regions
- Take RMS value of slices of $\Delta t = t_{eXBABE} - t_{MC}$ as a function of $-t_{MC}$
- 10x130 for $5 < Q^2_{DA} < 6$ GeV$^2$

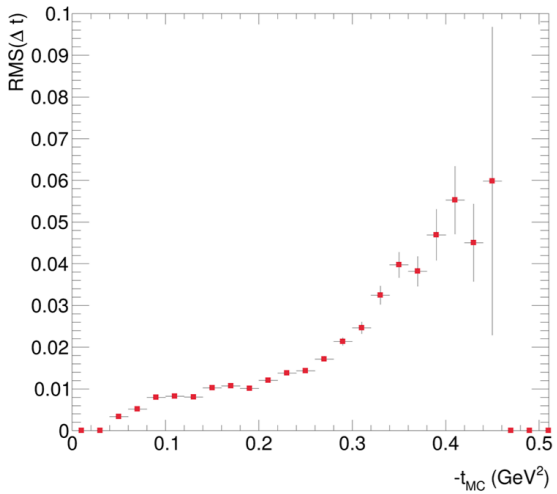


# DEMP Analysis Results - $-t$ Bin Widths

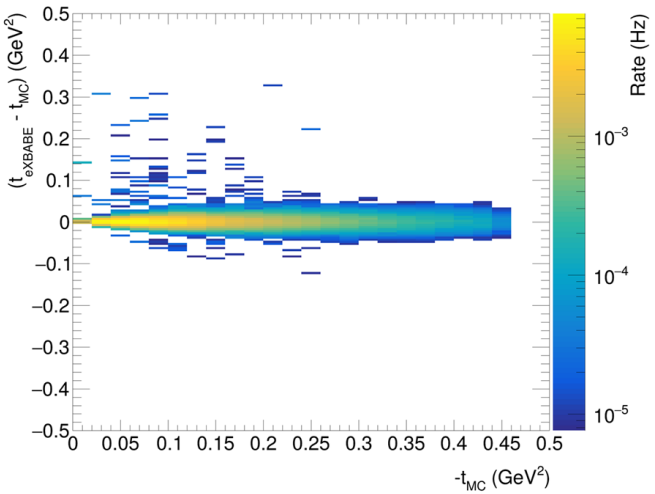
- Want $-t$ bins to be at least as wide as the $-t$ resolution
- Bin migration will be a big issue otherwise
- Check $-t$ resolution
  - Across full $Q^2$ range and in distinct $Q^2$ regions
- Take RMS value of slices of $\Delta t = t_{eXBABE} - t_{MC}$ as a function of $-t_{MC}$
- 10x130 across $32 < Q^2_{DA} < 33$ GeV$^2$, $-t_{min}$ migration clear, $-t$ resolution very good

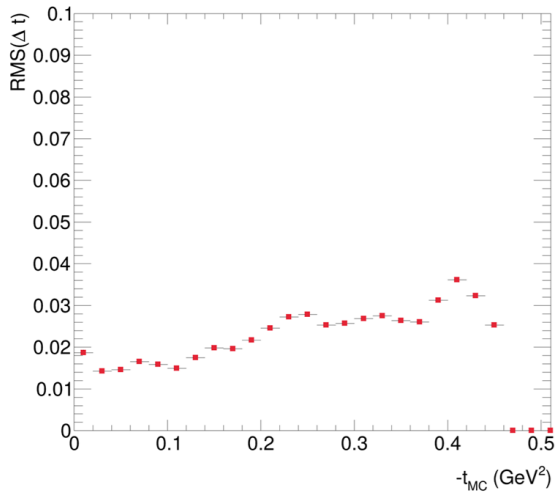


# DEMP Analysis Results - $-t$ Bin Widths

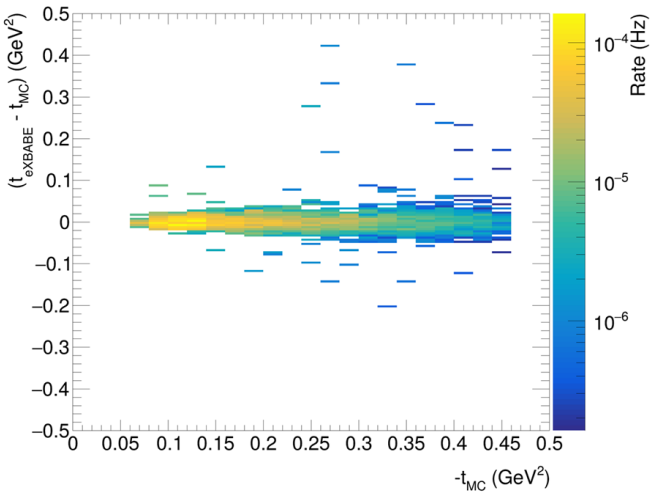
- Want $-t$ bins to be at least as wide as the $-t$ resolution
- Bin migration will be a big issue otherwise
- Check $-t$ resolution
  - Across full $Q^2$ range and in distinct $Q^2$ regions
- Take RMS value of slices of $\Delta t = t_{eXBABE} - t_{MC}$ as a function of $-t_{MC}$
- 10x250 across $5 < Q^2_{DA} < 35$ GeV$^2$, resolution is worse, but still acceptable in lowest $-t$ bins

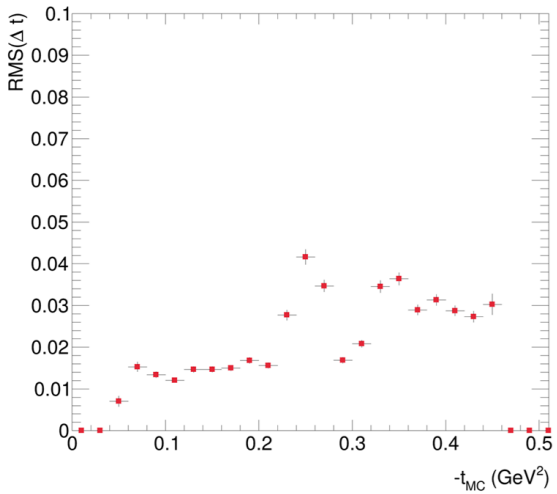


# DEMP Analysis Results - $-t$ Bin Widths

- Want $-t$ bins to be at least as wide as the $-t$ resolution
- Bin migration will be a big issue otherwise
- Check $-t$ resolution
  - Across full $Q^2$ range and in distinct $Q^2$ regions
- Take RMS value of slices of $\Delta t = t_{eXBABE} - t_{MC}$ as a function of $-t_{MC}$
- 10x250 across $32 < Q^2_{DA} < 33$ GeV$^2$, worse than 10x130 but still acceptable



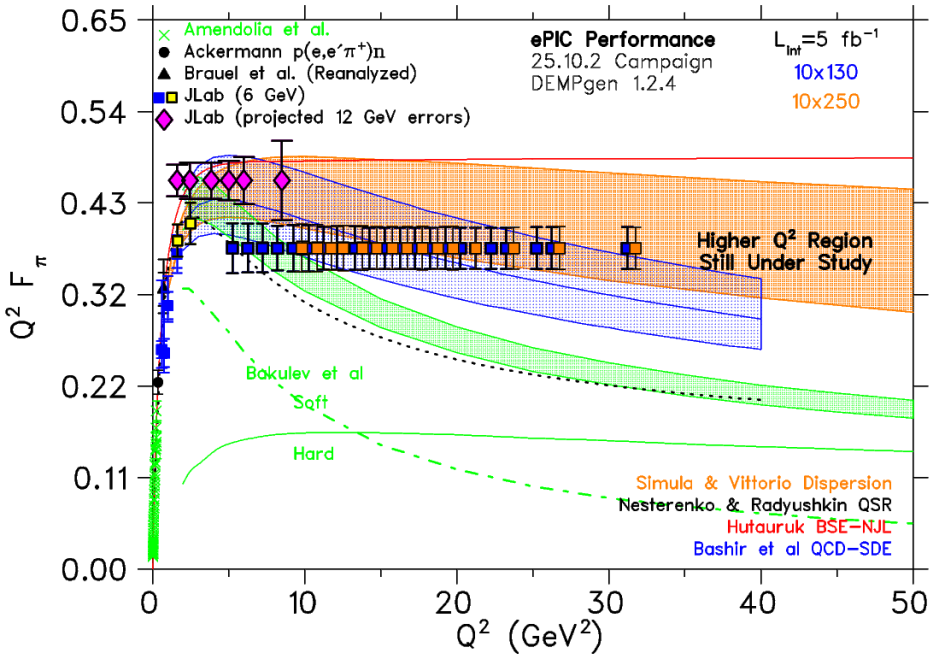
# $F_\pi$ Early Science Outlook

- With changes, how do things look for early science?

# $F_\pi$ Early Science Outlook

- With changes, how do things look for early science?

- ePIC $\rightarrow$ $F_\pi$ to high $Q^2$
- **Error bars represent real projected error bars**
  - Inner bar - statistical
  - Outer bar - systematic
  - $\delta R = R$, $R = \sigma_L/\sigma_T$
  - $R = 0.013 - 014$ at lowest $-t$ from VR model

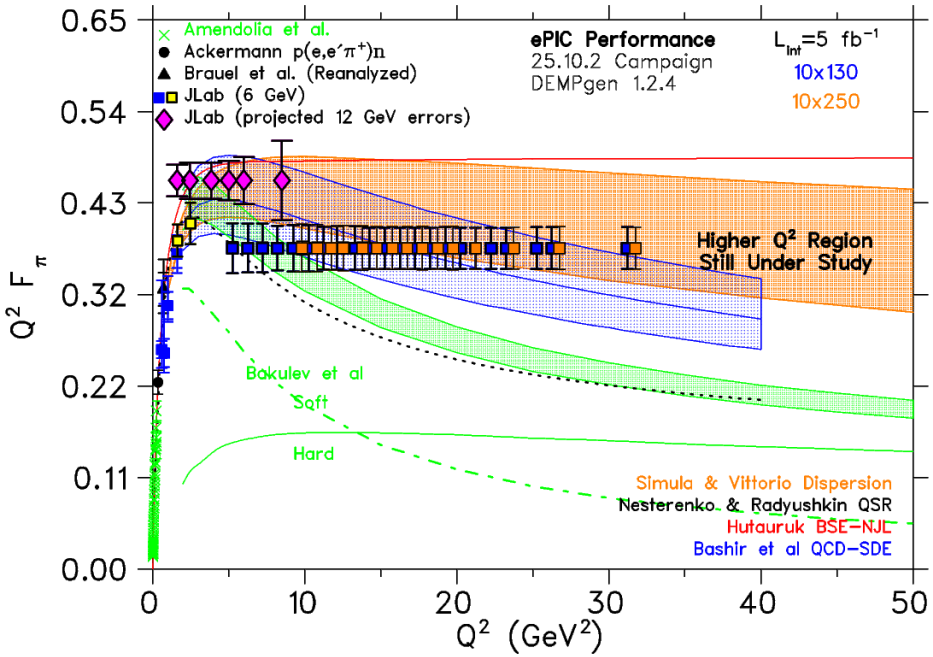



Projection plots by G.M. Huber, University of Regina

# $F_\pi$ Early Science Outlook

- With changes, how do things look for early science?

- ePIC $\rightarrow F_\pi$ to high $Q^2$
- **Error bars represent real projected error bars**
  - Inner bar - statistical
  - Outer bar - systematic
  - $\delta R = R$, $R = \sigma_L/\sigma_T$
  - $R = 0.013 - 014$ at lowest $-t$ from VR model
- Much finer $Q^2$ binning now!

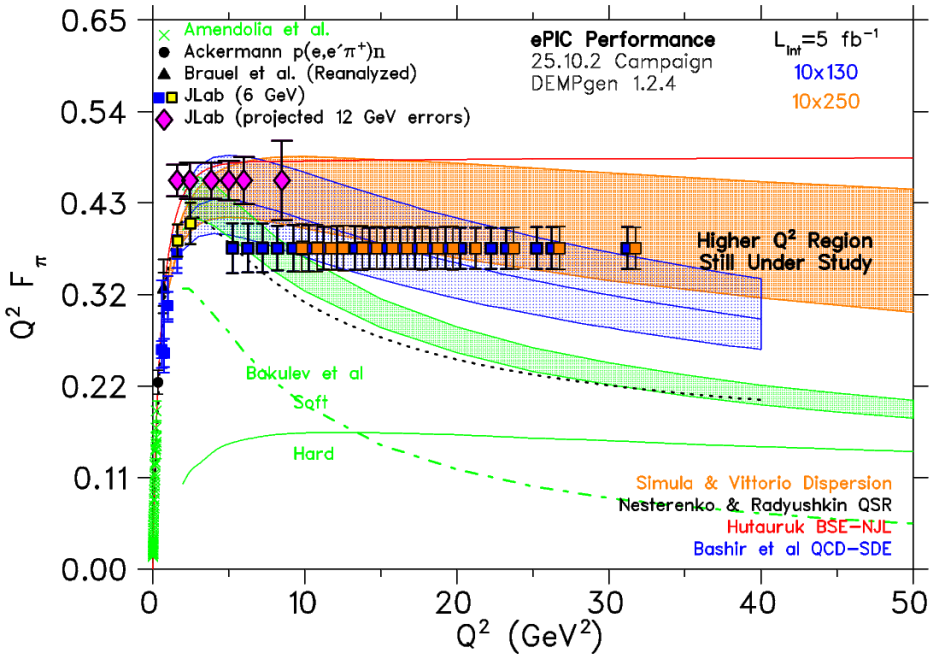



Projection plots by G.M. Huber, University of Regina

# $F_\pi$ Early Science Outlook

- With changes, how do things look for early science?

- ePIC $\rightarrow F_\pi$ to high $Q^2$
- **Error bars represent real projected error bars**
  - Inner bar - statistical
  - Outer bar - systematic
  - $\delta R = R$, $R = \sigma_L/\sigma_T$
  - $R = 0.013 - 014$ at lowest $-t$ from VR model
- Much finer $Q^2$ binning now!
  - Early science $\int \mathcal{L}$, looks promising!
  - How high in $Q^2$ will be possible?
  - When do statistical limitations bite?



# DIS Background Studies

- Wanted to test efficacy of cuts on non-DEMP events

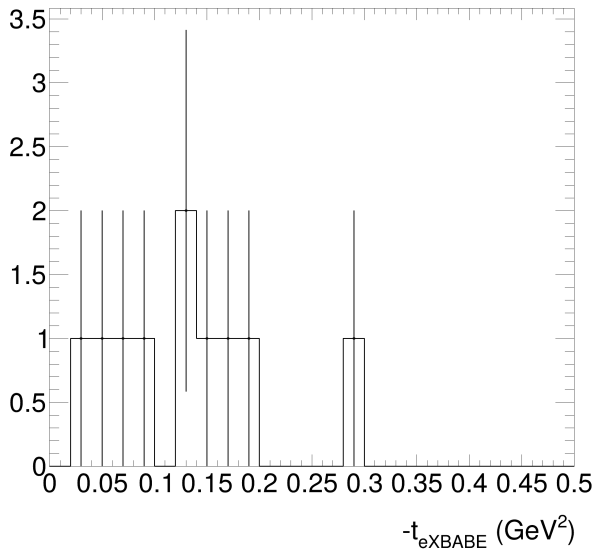
# DIS Background Studies

- Wanted to test efficacy of cuts on non-DEMP events
- Processed DIS sample through previous analysis
  - Not much survived
- With all selection cuts, no major concerns
  - Even after significant scaling for DIS events

# DIS Background Studies

- Wanted to test efficacy of cuts on non-DEMP events
- Processed DIS sample through previous analysis
  - Not much survived
- With all selection cuts, no major concerns
  - Even after significant scaling for DIS events

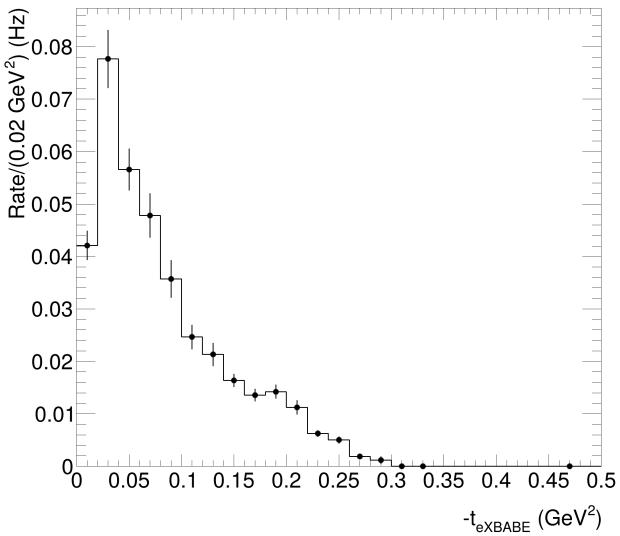
- Bins of $-Q^2$ and $-t$
- DIS $5 < Q^2 < 6$
- Very little leakthrough
- Even with scale factor of $\sim 6400$, not bad
- Probably an overestimate, majority in lower $Q^2$ bins



# DIS Background Studies

- Wanted to test efficacy of cuts on non-DEMP events
- Processed DIS sample through previous analysis
  - Not much survived
- With all selection cuts, no major concerns
  - Even after significant scaling for DIS events

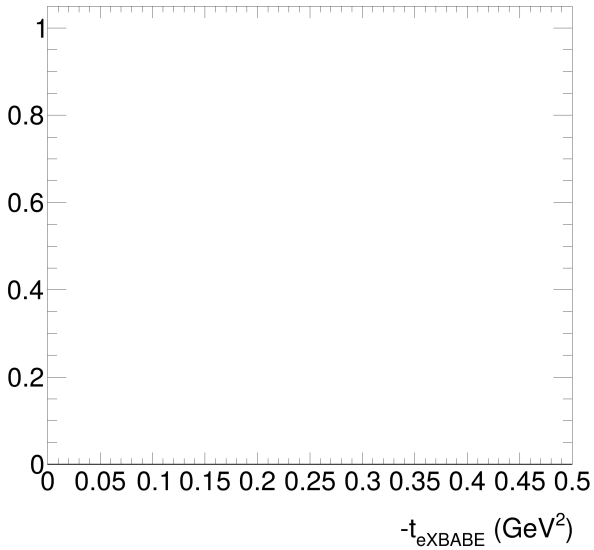
- Bins of $-Q^2$ and $-t$
- For comparison, Sullivan DEMP $5 < Q^2 < 6$
- Tail off as $-t$ increases
- Note this is a rate in Hz... so also need to scale



# DIS Background Studies

- Wanted to test efficacy of cuts on non-DEMP events
- Processed DIS sample through previous analysis
  - Not much survived
- With all selection cuts, no major concerns
  - Even after significant scaling for DIS events

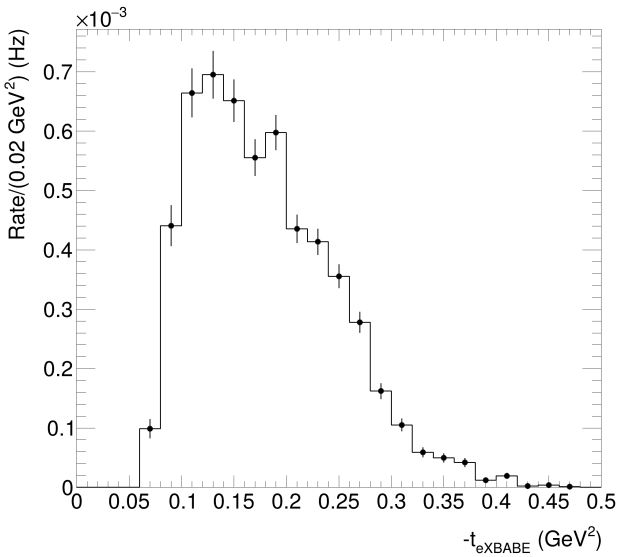
- Bins of $-Q^2$ and $-t$
- DIS $32 < Q^2 < 33$
- Nothing here
- Scaling smaller ($\sim 400$) in this region too



# DIS Background Studies

- Wanted to test efficacy of cuts on non-DEMP events
- Processed DIS sample through previous analysis
  - Not much survived
- With all selection cuts, no major concerns
  - Even after significant scaling for DIS events

- Bins of $-Q^2$ and $-t$
- Sullivan DEMP
  $32 < Q^2 < 33$
- Rate falls strongly with $Q^2$



# Next Steps - Future Work

- A range of future topics to pursue
  - Some of DEMP specific interest, **some of broad interest**

# Next Steps - Future Work

- A range of future topics to pursue
  - Some of DEMP specific interest, **some of broad interest**
- Kaon DEMP channels need further study
  - **Hyperon reconstruction and kaon PID**

# Next Steps - Future Work

- A range of future topics to pursue
  - Some of DEMP specific interest, **some of broad interest**
- Kaon DEMP channels need further study
  - **Hyperon reconstruction and kaon PID**
- Deuteron studies and DEMPgen upgrades are also needed
  - **Electron vs pion PID, purity studies**, spectator tagging

# Next Steps - Future Work

- A range of future topics to pursue
  - Some of DEMP specific interest, **some of broad interest**
- Kaon DEMP channels need further study
  - **Hyperon reconstruction and kaon PID**
- Deuteron studies and DEMPgen upgrades are also needed
  - **Electron vs pion PID, purity studies**, spectator tagging
- Fold in impact of systematics studies
  - PID/Tracking across particle species. Need to understand backgrounds

# Next Steps - Future Work

- A range of future topics to pursue
  - Some of DEMP specific interest, **some of broad interest**
- Kaon DEMP channels need further study
  - **Hyperon reconstruction and kaon PID**
- Deuteron studies and DEMPgen upgrades are also needed
  - **Electron vs pion PID, purity studies**, spectator tagging
- Fold in impact of systematics studies
  - PID/Tracking across particle species. Need to understand backgrounds
- ... including machine backgrounds, mixed event samples
  - May need some modifications to DEMPgen to retain weights

# Summary and Outlook

- Many topics to investigate next for the Sullivan process

# Summary and Outlook

- Many topics to investigate next for the Sullivan process
- Some topics of broader interest
  - Hyperon reconstruction
  - Kaon PID performance
  - Pion vs electron PID
  - Systematics studies

# Summary and Outlook

- Many topics to investigate next for the Sullivan process
- Some topics of broader interest
  - Hyperon reconstruction
  - Kaon PID performance
  - Pion vs electron PID
  - Systematics studies
- Pion Sullivan DEMP, $p(e, e'\pi^+ n)$, provide access to $F_\pi$
  - Results for early science $ep$ configs look very promising
  - **Analysis note now available**

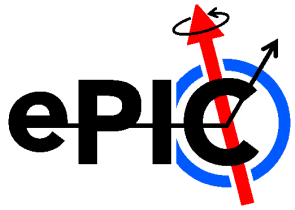
# Summary and Outlook

- Many topics to investigate next for the Sullivan process
- Some topics of broader interest
  - Hyperon reconstruction
  - Kaon PID performance
  - Pion vs electron PID
  - Systematics studies
- Pion Sullivan DEMP, $p(e, e'\pi^+ n)$, provide access to $F_\pi$
  - Results for early science $ep$ configs look very promising
  - **Analysis note now available**
- Sullivan process is a very good test of FF detector performance
  - Particularly the ZDC

# Thanks for listening, any questions?

UNIVERSITY of York

University of Regina





Science and Technology Facilities Council

With thanks to the Meson Structure Working Group

stephen.kay@york.ac.uk

This research was supported by UK Research and Innovation: Science and Technology Facilities Council (UKRI:STFC) grant ST/W004852/1 and the Natural Sciences and Engineering Research Council of Canada (NSERC) grant SAPPJ-2025-00040