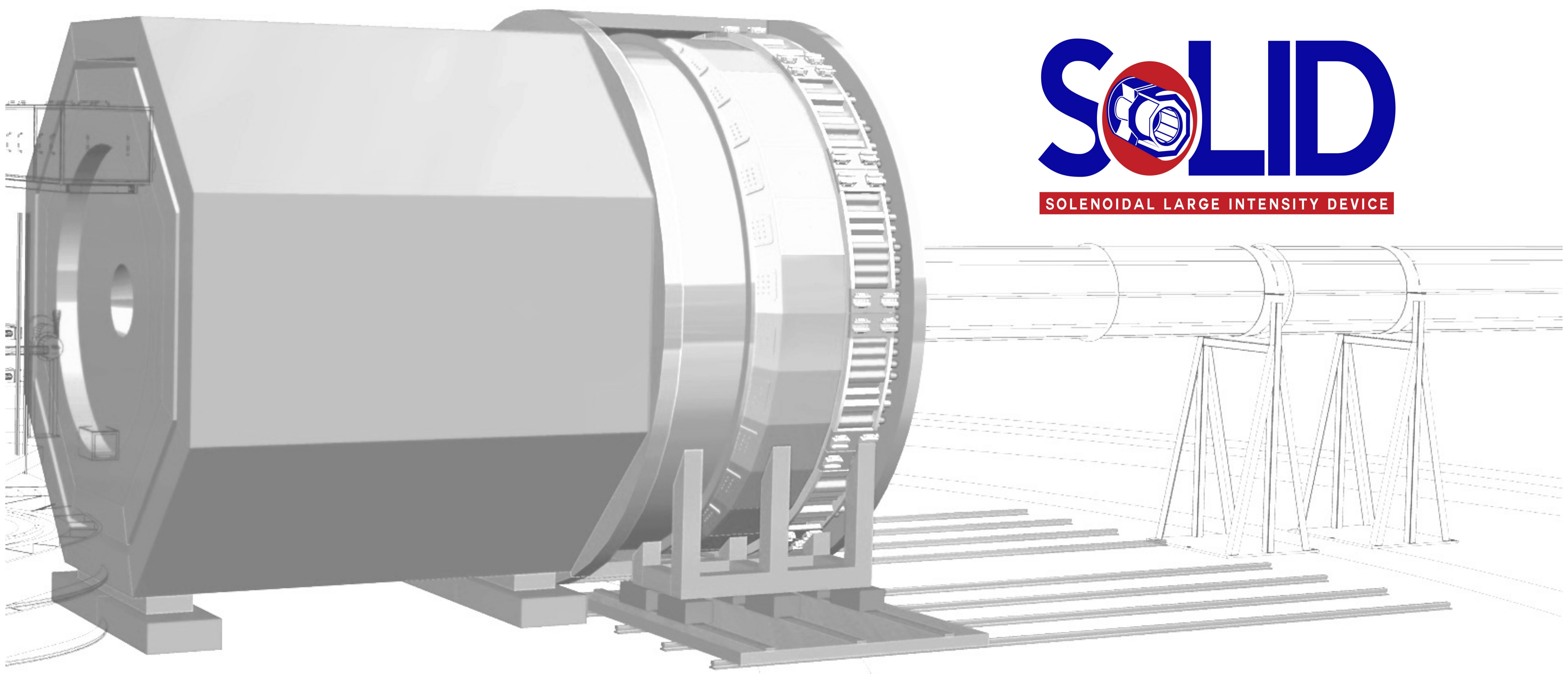
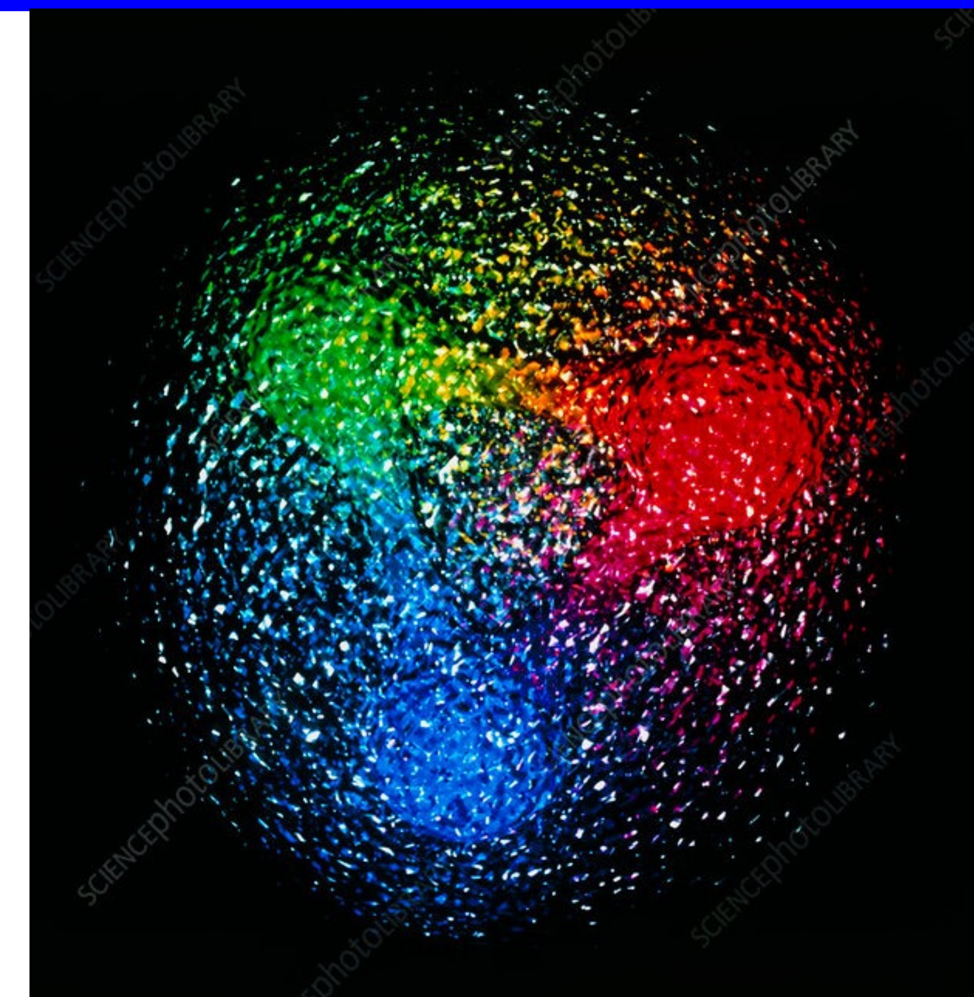
# Measurement of the Unpolarized SIDIS Cross Section from a $^{3}$He Target with SoLID



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# Outline

- SoLID SIDIS setup with transversely and longitudinally polarized $^3$He targets
  - *Setup and experimental details*
- Unpolarized cross-section framework
- Estimated systematic uncertainties
- Results
  - *Unpolarized cross-section SoLID SIDIS projections*
  - *Some physics results from unpolarized cross section*
- Summary and outlook

## ➢ Our run group experiment parasitic to SoLID SIDIS experiments of

**E12-10-006: Single Spin Asymmetries on Transversely Polarized $^3$He (neutron): Rating A**

- ➢ Approved number of days:
  - *48 days* (*11 GeV*) & *21 day* (*8.8 GeV*)

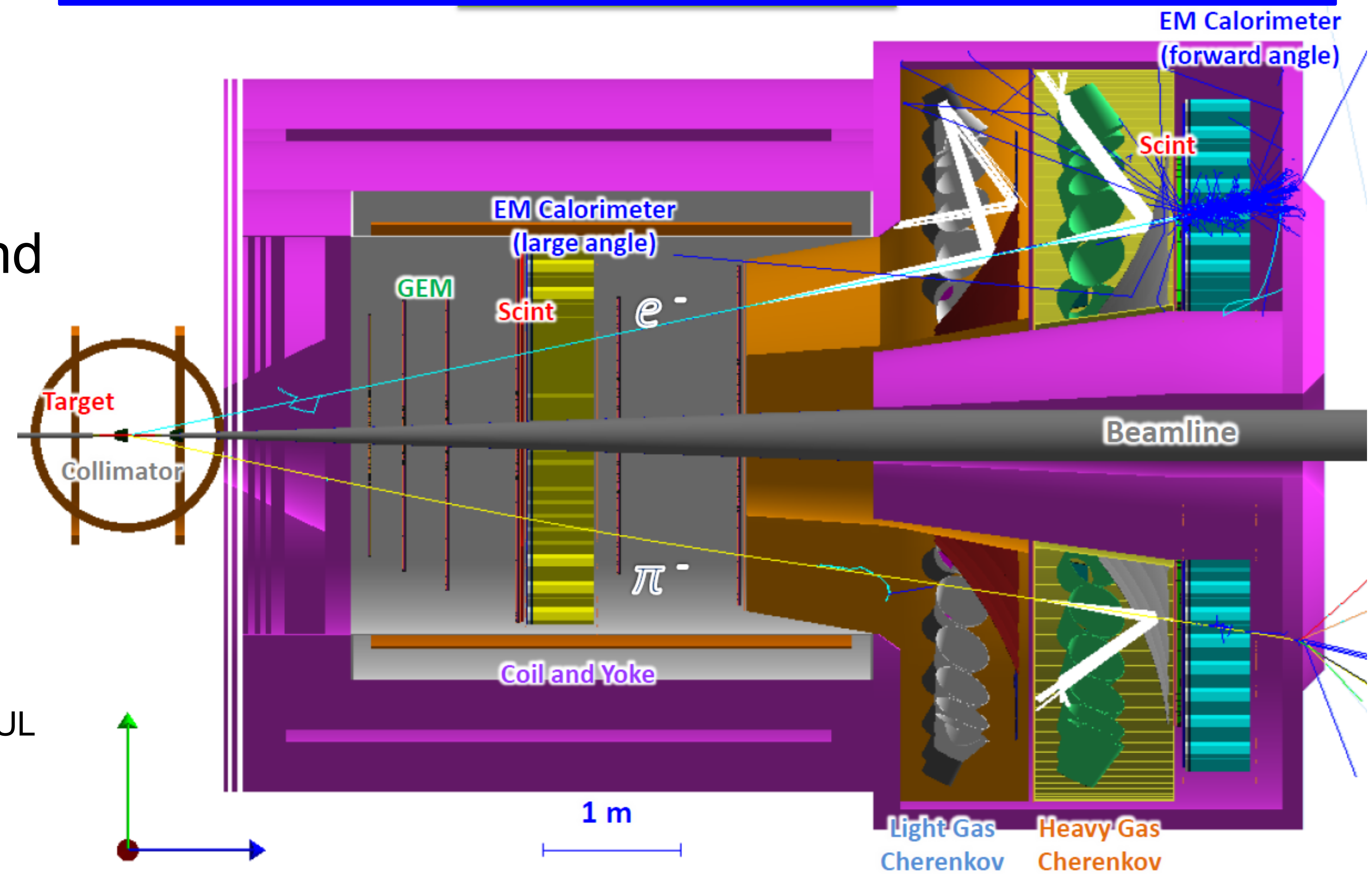
**E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized $^3$He (neutron): Rating A**

- ➢ Approved number of days:
  - *22.5 days* (*11 GeV*) & *9.5 day* (*8.8 GeV*)

- ➢ 10 days requested for study of x-z factorization with Hydrogen/Deuterium gas using reference target cell
- ➢ 3 days of reference cell runs for optics and detector check
- ➢ 5 days of target overhead: spin rotation, polarization measurement
- ➢ 3 days requested with longitudinal target polarization to study systematics of potential $A_{UL}$ contamination

**SIDIS: $e + p \rightarrow e' + \pi^{\pm} + X$**

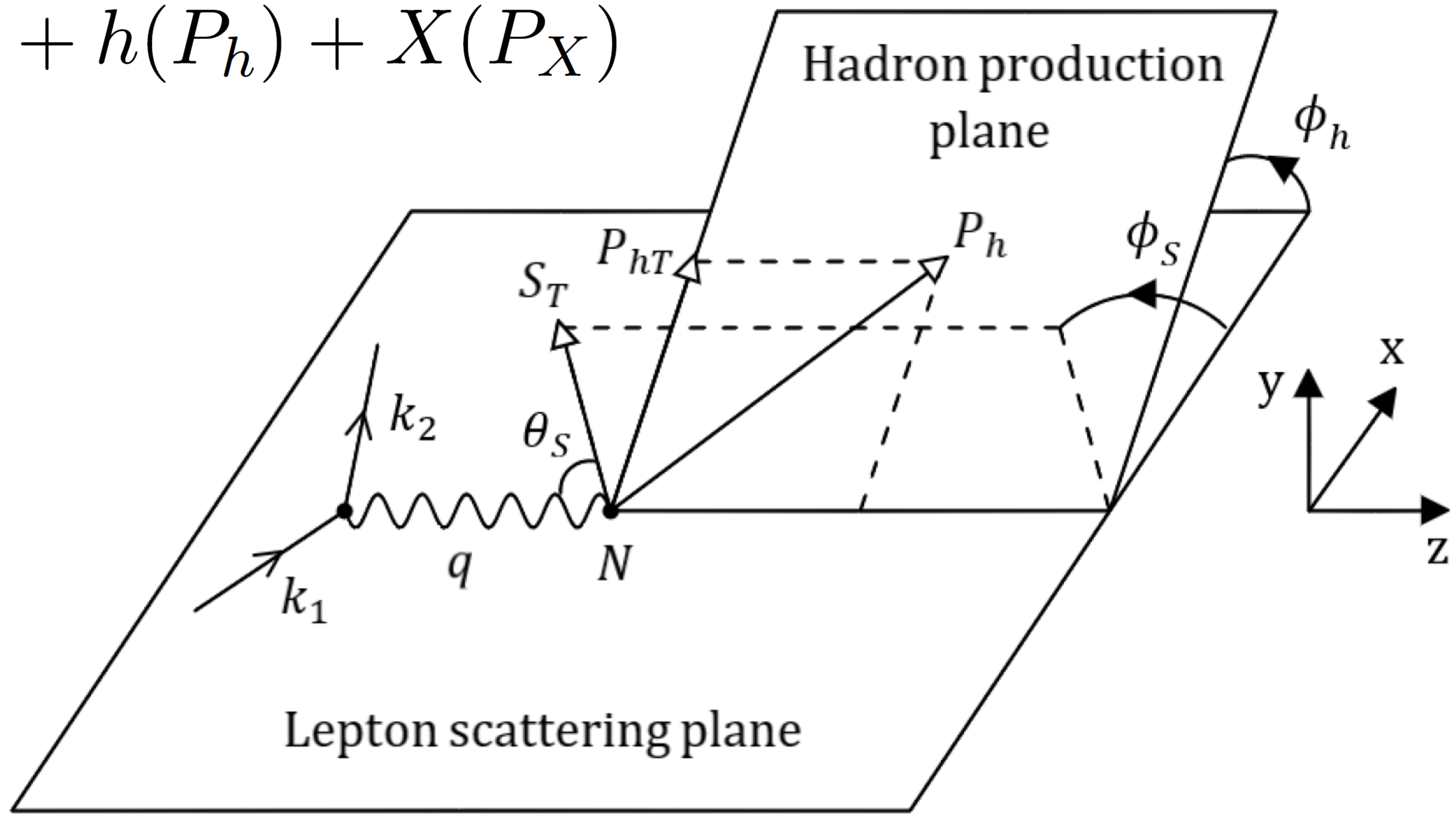
SoLID (SIDIS $^3$He): 11 GeV & 8.8 GeV beam energies



➢ The SIDIS process represented as (four-momenta given in parentheses)

$$l(k_1) + N(P) \to l'(k_2) + h(P_h) + X(P_X)$$

- $l$ - lepton beam
- *N* - nucleon target
- *h* - produced hadron
- *X* - undetected hadron
- q – virtual photon momentum




Azimuthal angle between hadron production and lepton scattering planes designated as $\phi_h$

Kinematics of the SIDIS process:
*assume one-photon exchange approximation*

➢ Express the process cross section in terms of the following kinematic variables

$$x_{bj} = \frac{Q^2}{2P\cdot q}, \qquad y = \frac{P\cdot q}{P\cdot k_1}, \qquad z_h = \frac{P\cdot P_h}{P\cdot q}, \qquad \gamma = \frac{2M_N x_{bj}}{Q}$$

with $q$ and $Q^2$ defined as $q \equiv l - l'$ and $Q^2 \equiv -q^2$

- Unpolarized SIDIS differential cross section given by

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$$\frac{d\sigma}{dx_{bj}dydz_h dP_{hT}^2 d\phi_h} \equiv \mathcal{F}_{\mathcal{UU}} = \mathcal{F}_{\mathcal{UU},\mathcal{A}} \cos 0 + \mathcal{F}_{\mathcal{UU},\mathcal{B}} \cos(\phi_h) + \mathcal{F}_{\mathcal{UU},\mathcal{C}} \cos(2\phi_h)$$

Unpolarized TMD

$\phi_h$ - dependent unpolarized azimuthal modulations

$$\mathcal{F}_{\mathcal{UU},\mathcal{A}} = 2\pi \frac{\alpha^2}{x_{bj} y Q^2} \left(1 + \frac{\gamma^2}{2x_{bj}}\right) c_1 F_{UU},$$

- In this scheme, the unpolarized structure function $F_{UU}$ given by

$$F_{UU} = \sum_q e_q^2 \, x \int d^2\boldsymbol{k}_\perp \, f_q(x, k_\perp) D_q(z, p_\perp)$$

- Use the following Gaussian parameterizations for the TMD PDF and TMD FF

$$f_q(x, k_\perp) = f_q^c(x) \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle}}{\pi \langle k_\perp^2 \rangle} \quad D_q(z, p_\perp) = D_q^c(z) \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\pi \langle p_\perp^2 \rangle}$$

$$F_{UU} = \sum_q e_q^2 \, x_{bj} \, f_q^c(x_{bj}) \, D_q^c(z_h) \frac{e^{-P_{hT}^2/\langle P_T^2 \rangle}}{\pi \langle P_T^2 \rangle}$$

where $\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle$

$$\mathcal{F}_{\mathcal{UU},\mathcal{B}} = 2\pi \frac{\alpha^2}{x_{bj} y Q^2} \left(1 + \frac{\gamma^2}{2x_{bj}}\right) c_2\, F_{UU}^{\cos(\phi_h)},$$

- The second structure function $F_{UU}^{cos(\phi_h)}$, associated to the $cos(\phi_h)$ modulation of the cross section, is a twist-3 quantity of the order of 1/Q

$$F_{UU}^{\cos(\phi_h)} = F_{UU}^{\cos(\phi_h)}\big|_{\mathrm{Cahn}} + F_{UU}^{\cos(\phi_h)}\big|_{\mathrm{BM}}$$

where

$$F_{UU}^{\cos(\phi_h)}\big|_{\mathrm{Cahn}} = -2\sum_q e_q^2\, x \int d^2\boldsymbol{k}_\perp \frac{(\boldsymbol{k}_\perp \cdot \boldsymbol{h})}{Q}\, f_q(x, k_\perp) D_q(z, p_\perp)$$

as the Cahn convolution of unpolarized **TMD PDF** and **TMD FF**

$$F_{UU}^{\cos(\phi_h)}\big|_{\mathrm{BM}} = \sum_q e_q^2\, x \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{Q} \frac{P_{hT} - z\,(\boldsymbol{k}_\perp \cdot \boldsymbol{h})}{k_\perp}\, \Delta f_{q^\uparrow/p}(x, k_\perp)\, \Delta D_{h/q^\uparrow}(z, p_\perp)$$

as the Boer-Mulders convolution of **Boer-Mulders TMD PDF** and **Collins TMD FF**

$$\mathcal{F}_{\mathcal{UU},\mathcal{C}} = 2\pi \frac{\alpha^2}{x_{bj} y Q^2} \left(1 + \frac{\gamma^2}{2x_{bj}}\right) c_3 \, F_{UU}^{\cos(2\phi_h)}$$

- The third structure function $F_{UU}^{\cos(2\phi_h)}$, associated to the $\cos(2\phi_h)$ modulation of the cross section, consists of a twist-4 Cahn and a twist-2 Boer-Mulders contributions

$$F_{UU}^{\cos(2\phi_h)} \approx F_{UU}^{\cos(2\phi_h)}\big|_{\text{Cahn}} + F_{UU}^{\cos(2\phi_h)}\big|_{\text{BM}}$$

where

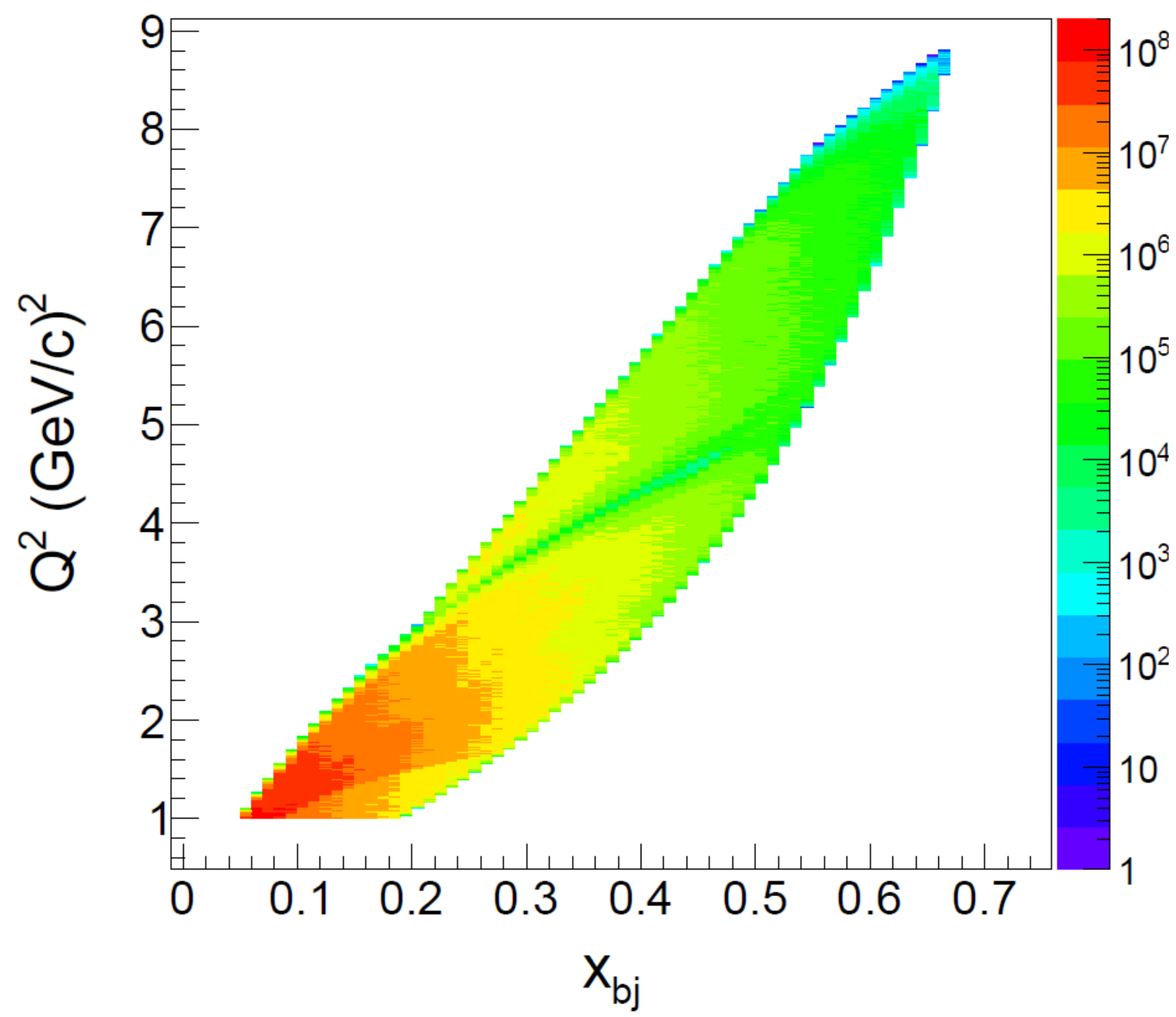
$$F_{UU}^{\cos(2\phi_h)}\big|_{\text{Cahn}} = 2 \sum_q e_q^2 \, x \int d^2\boldsymbol{k}_\perp \, \frac{2(\boldsymbol{k}_\perp \cdot \boldsymbol{h})^2 - k_\perp^2}{Q^2} \, f_q(x, k_\perp) D_q(z, p_\perp)$$

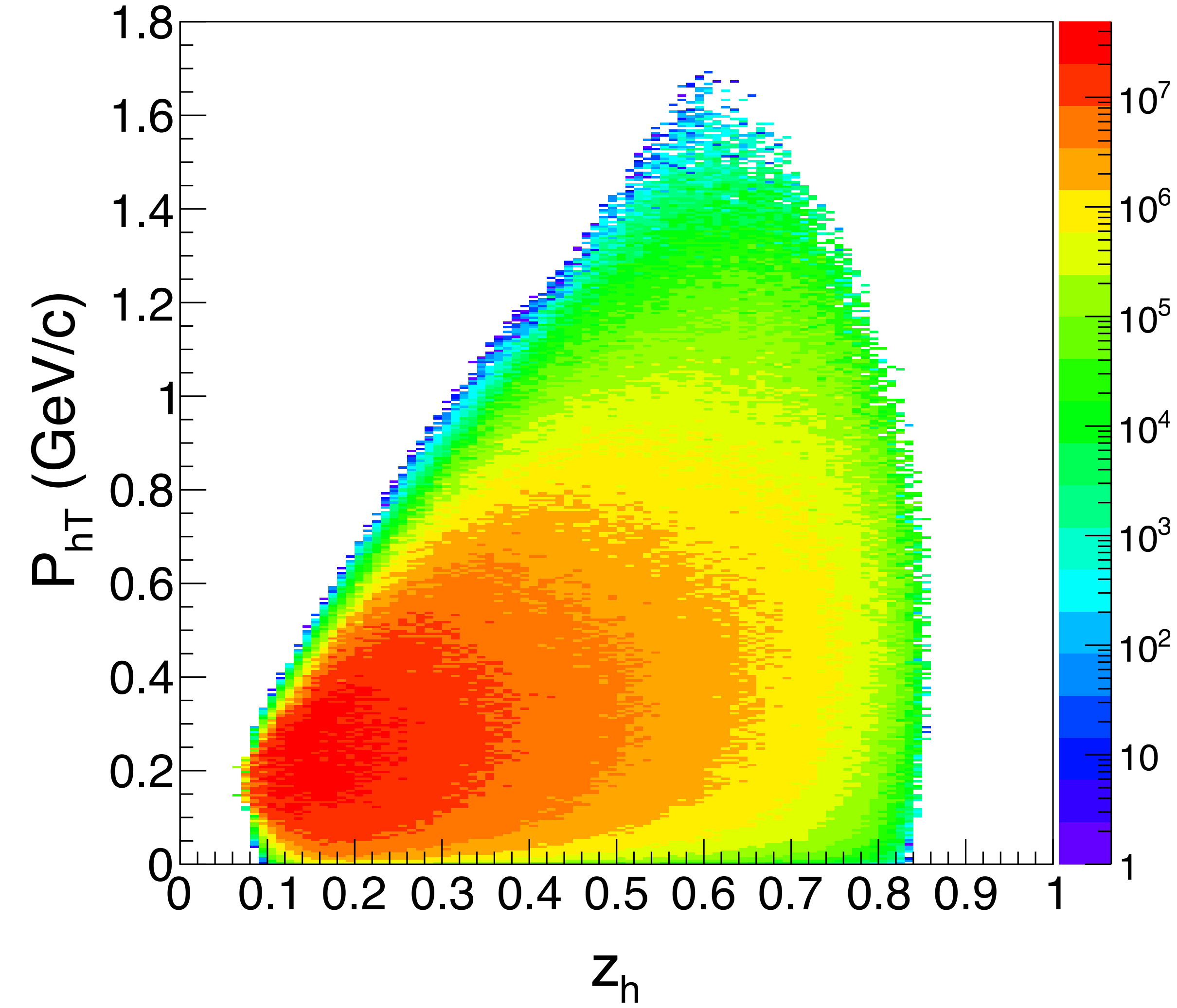
$$F_{UU}^{\cos(2\phi_h)}\big|_{\text{BM}} = -\sum_q e_q^2 \, x \int d^2\boldsymbol{k}_\perp \, \frac{P_{hT}(\boldsymbol{k}_\perp \cdot \boldsymbol{h}) + z\left[k_\perp^2 - 2(\boldsymbol{k}_\perp \cdot \boldsymbol{h})^2\right]}{2 k_\perp p_\perp} \times$$
$$\times \, \Delta f_{q^\uparrow/p}(x, k_\perp) \, \Delta D_{h/q^\uparrow}(z, p_\perp)$$

- Kinematic coverage examples of produced $\pi^+$ particles
  - *11 GeV and 8.8 GeV combined*

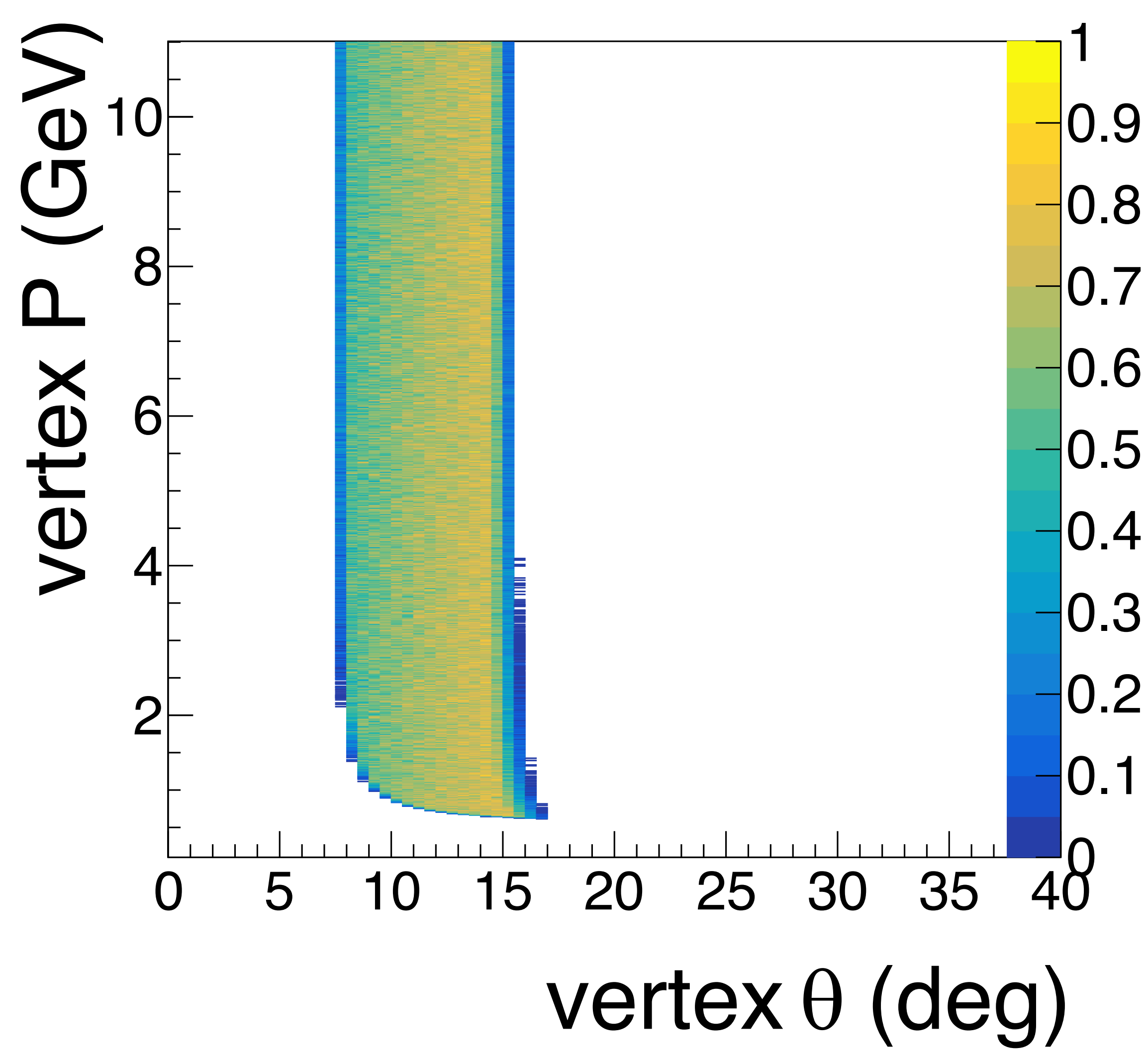
- *Phase-space correlation between* $Q^2$ and $x_{bj}$ *(top-left)*

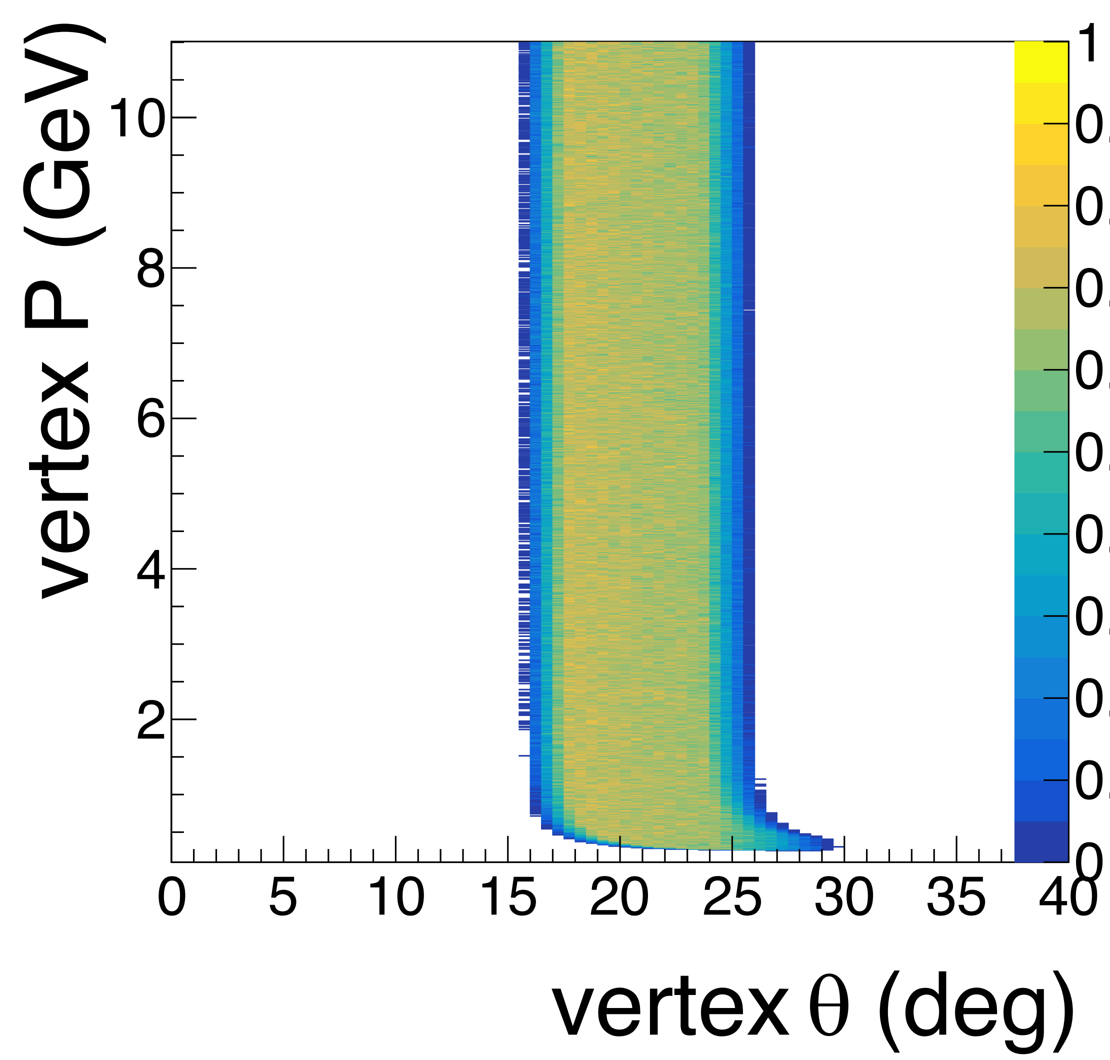
- *Phase-space correlation between* $x_{bj}$ and $z_h$ *(top-right)*




- Electron acceptance as function of angle and momentum forward angle (bottom left) and large angle (bottom right)



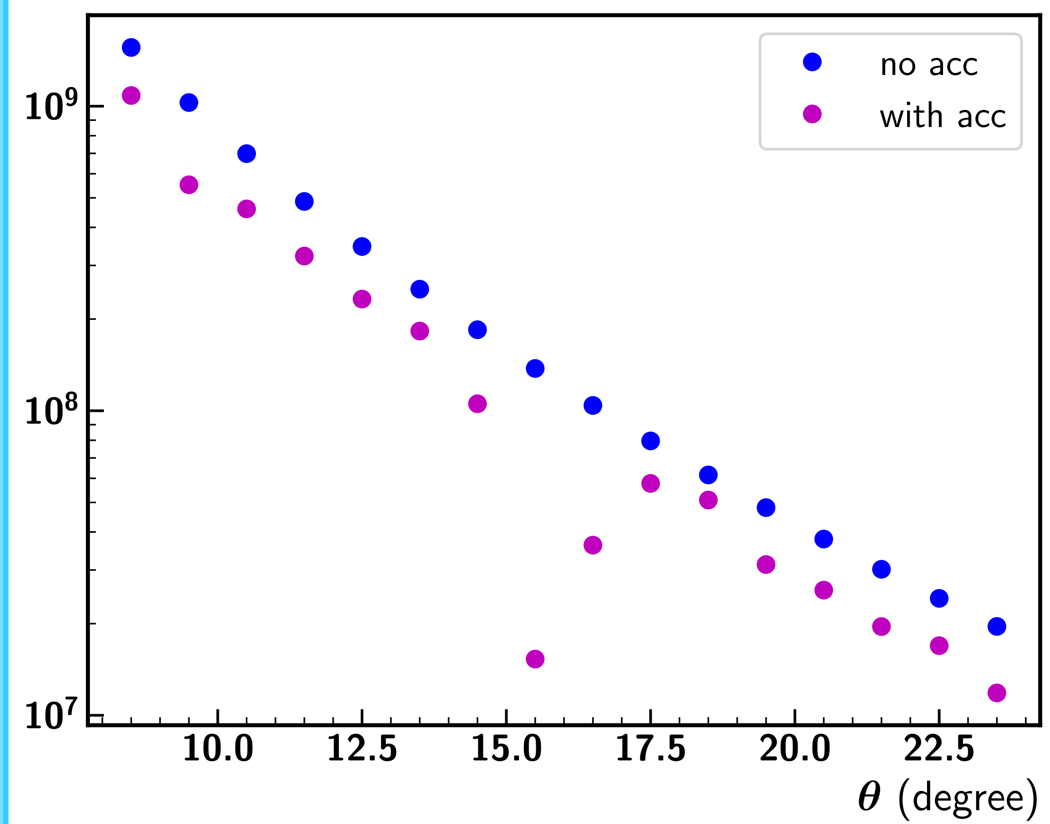



## ➢ Systematic uncertainties of unpolarized cross section: Acceptance uncertainty

Elastic process:

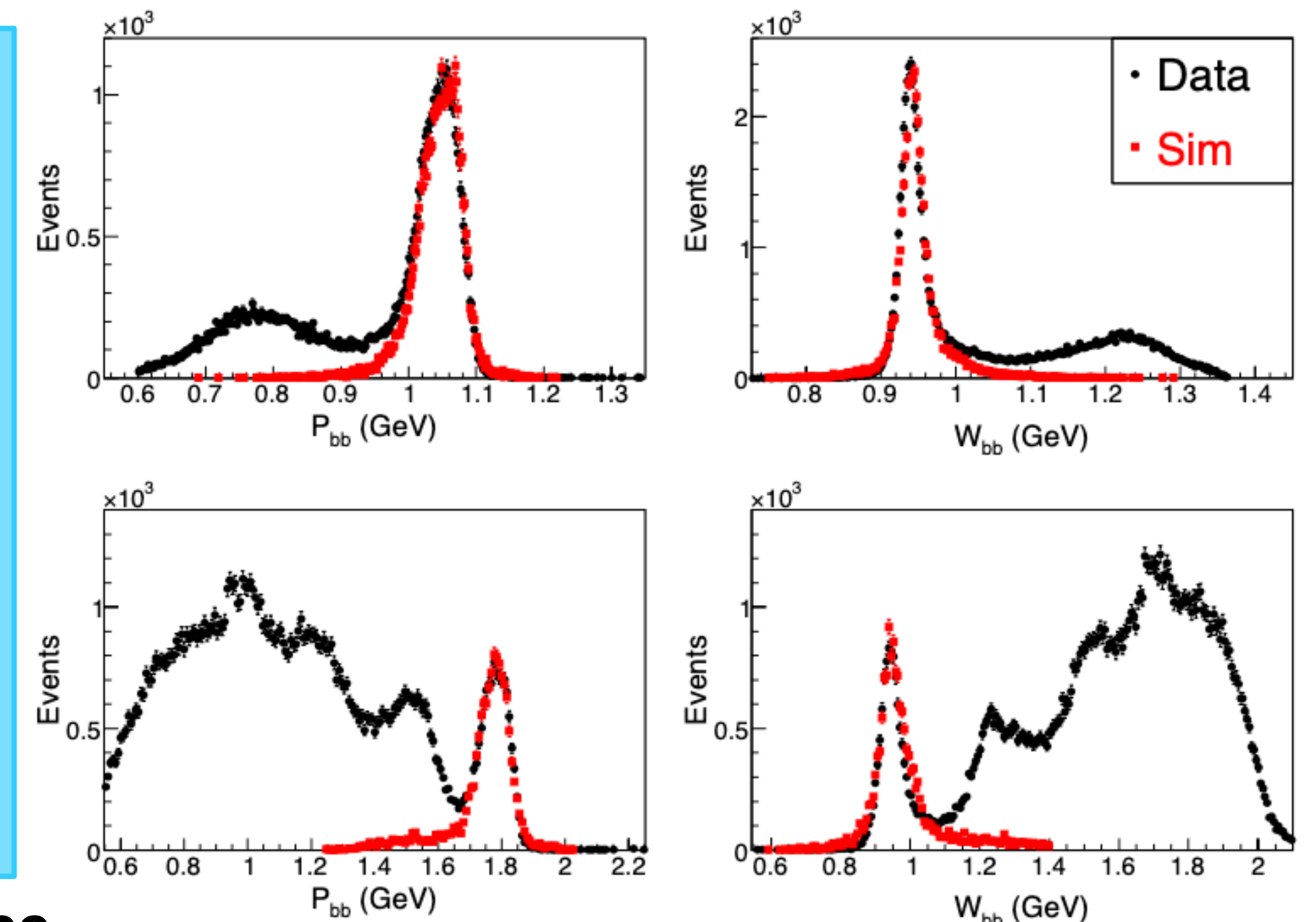
With 2.2 GeV beam energy, 1h could get enough counts (right)

1h run with 4.4 GeV beam energy could also reach enough counts



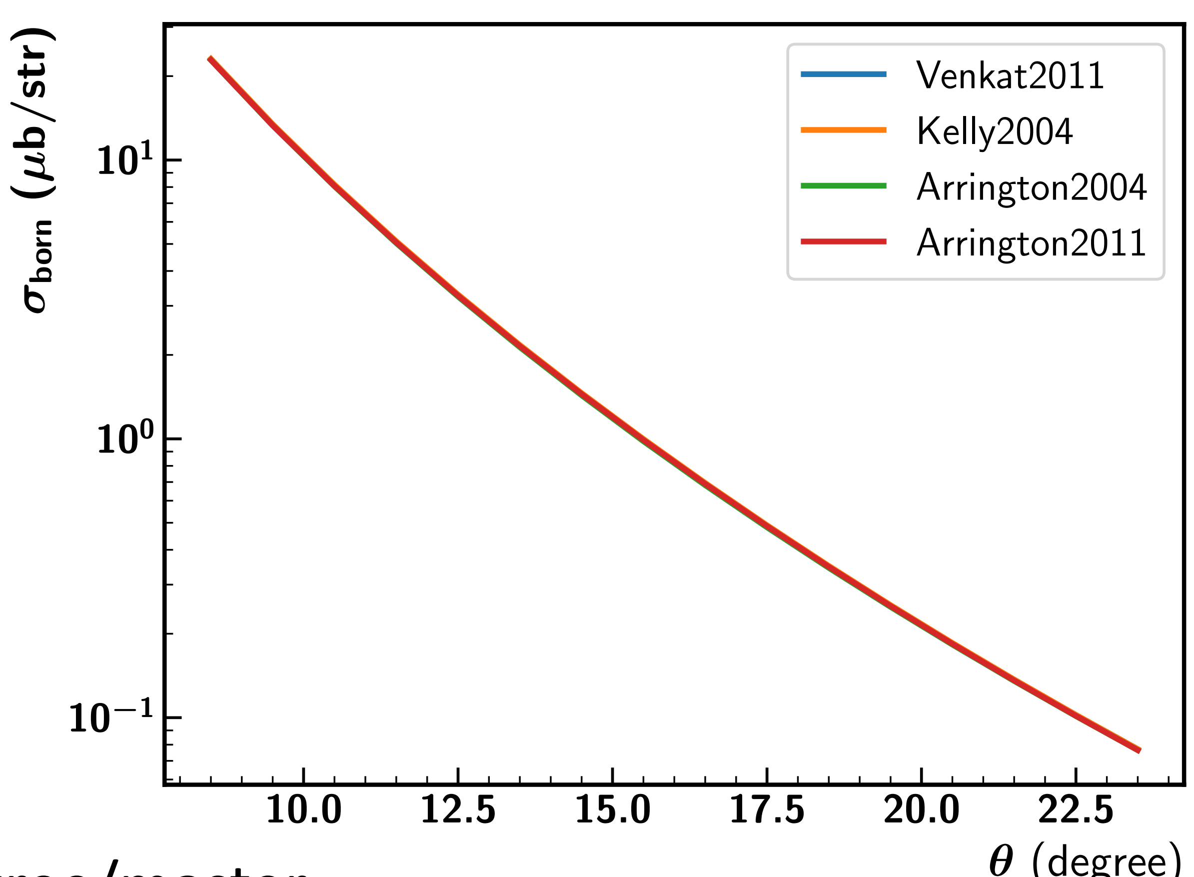

Elastic process for Big Bite using 1.2 (top) and 2.4 (bottom) GeV beam on $H_2$

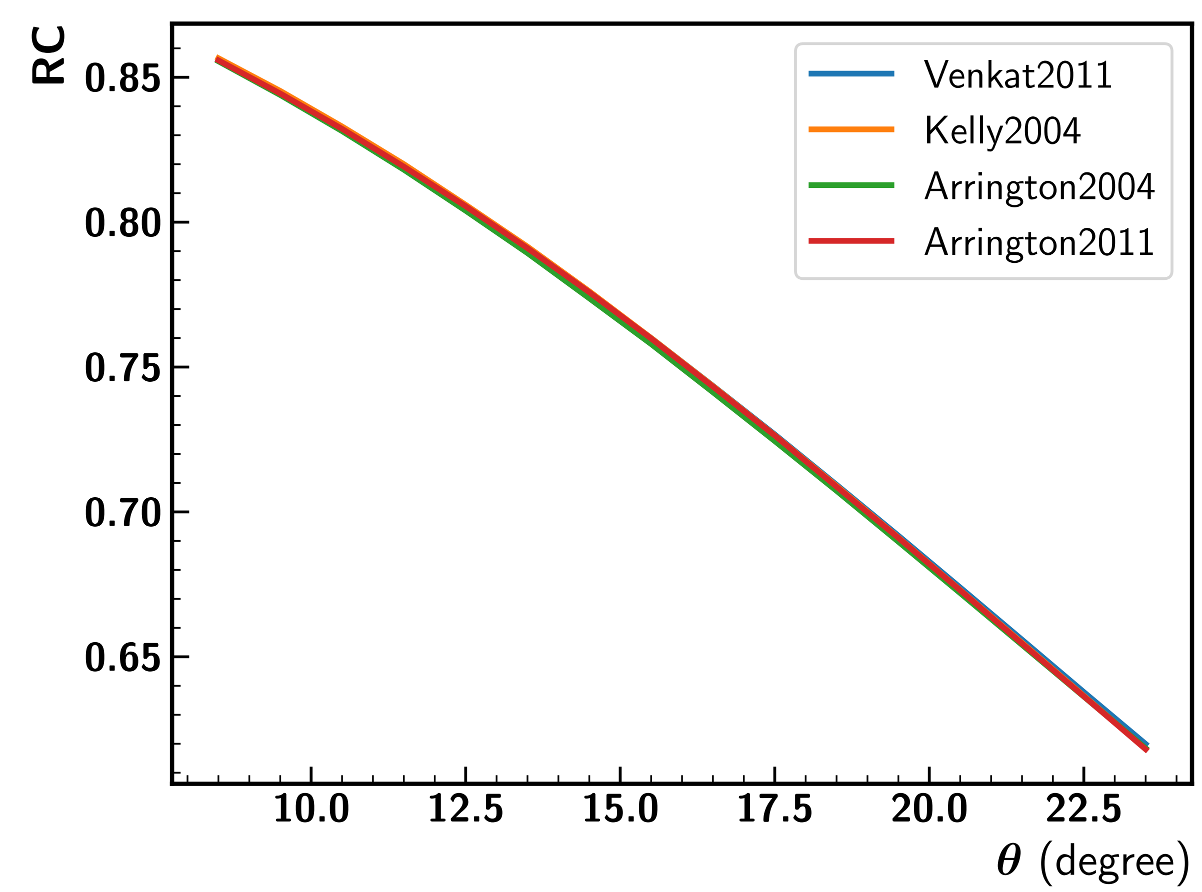
Data/Sim from 6 GeV era experiment




**Phys. Rev. C 95, 035209**

At low beam energy, cross section difference between different calculations being negligible

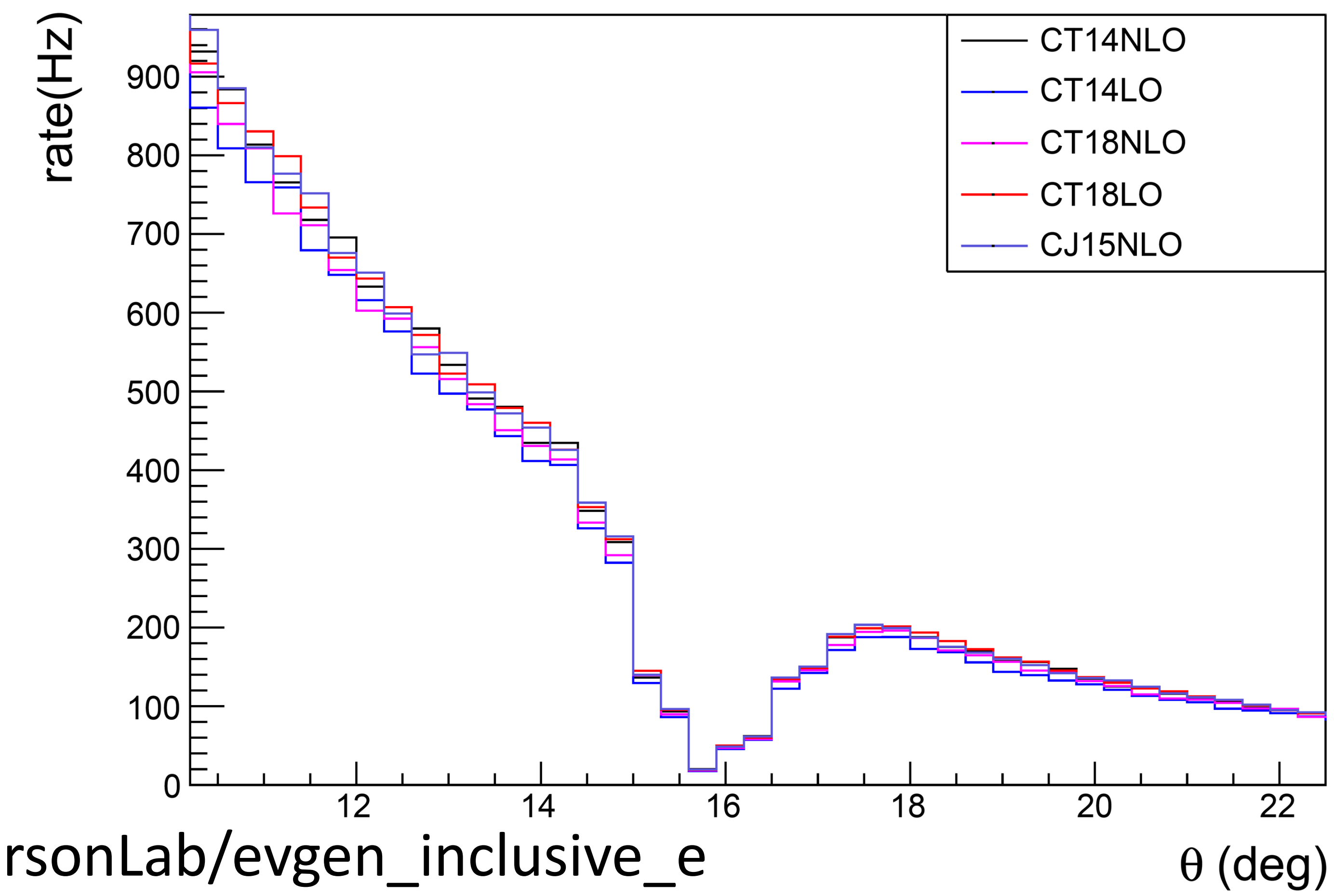


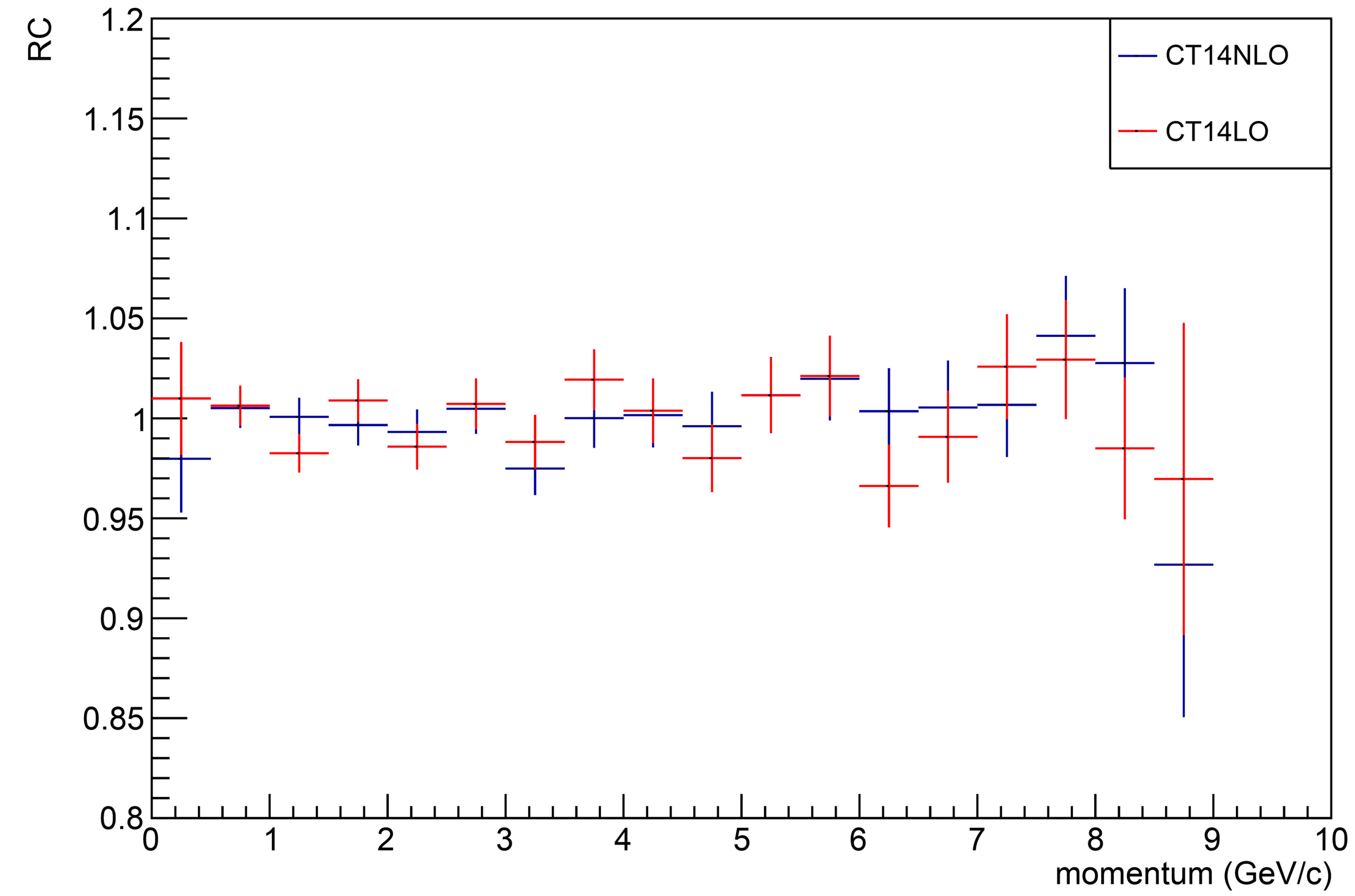

https://github.com/JeffersonLab/PRadSim/tree/master

## ➢ Systematic uncertainties of unpolarized cross section: Acceptance uncertainty

Deep Inelastic Scattering Process




https://github.com/JeffersonLab/evgen_inclusive_e

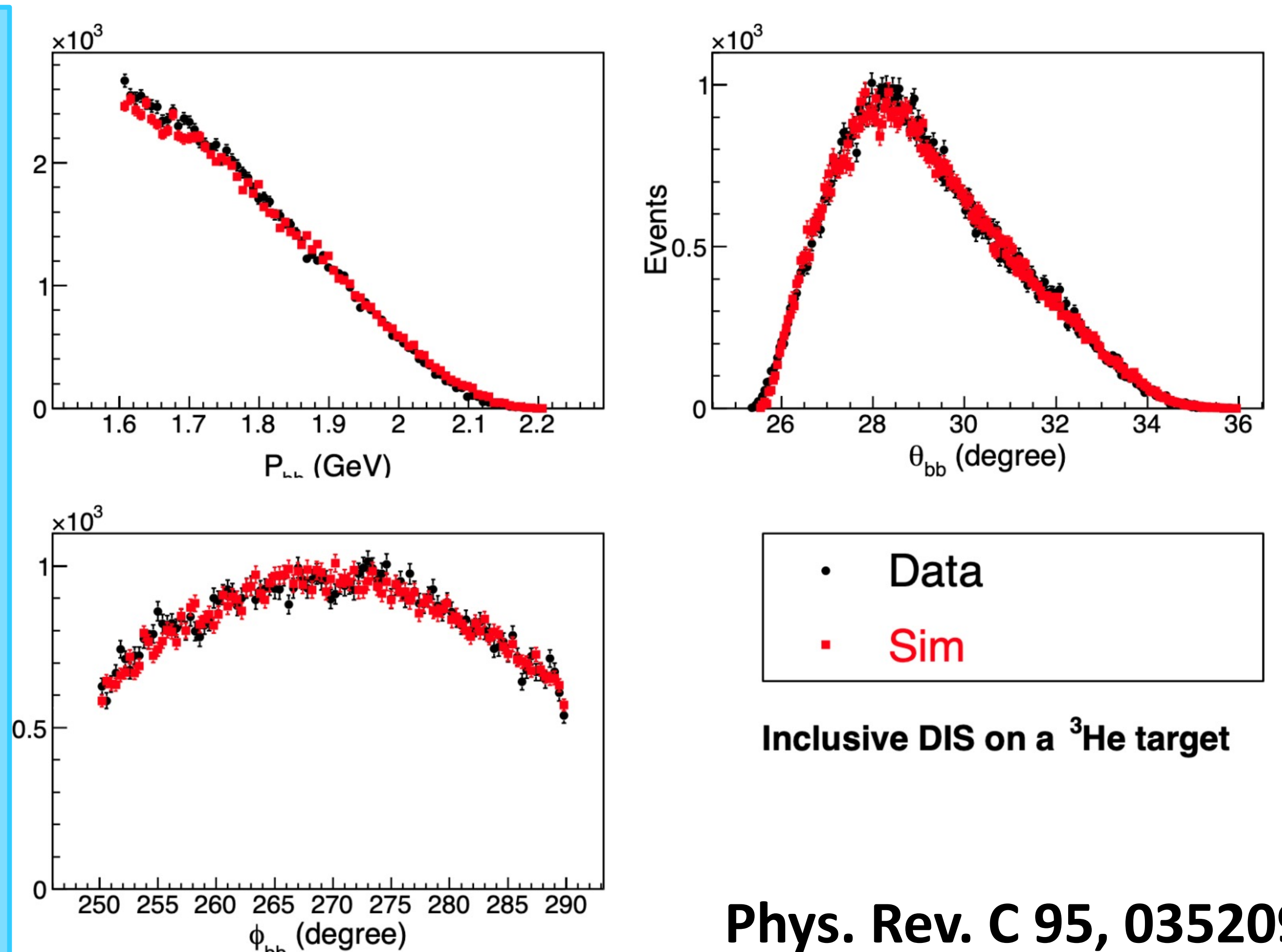



Uncertainty from different DIS models being 3~4%, and from RC being 3%

Data and Simulation comparison for DIS process from 6 GeV era, for Big Bite spectrometer shown on right

Overall normalization can be calibrated by elastic process, then DIS cross section shape to be assigned uncertainty of 3 ~ 4%

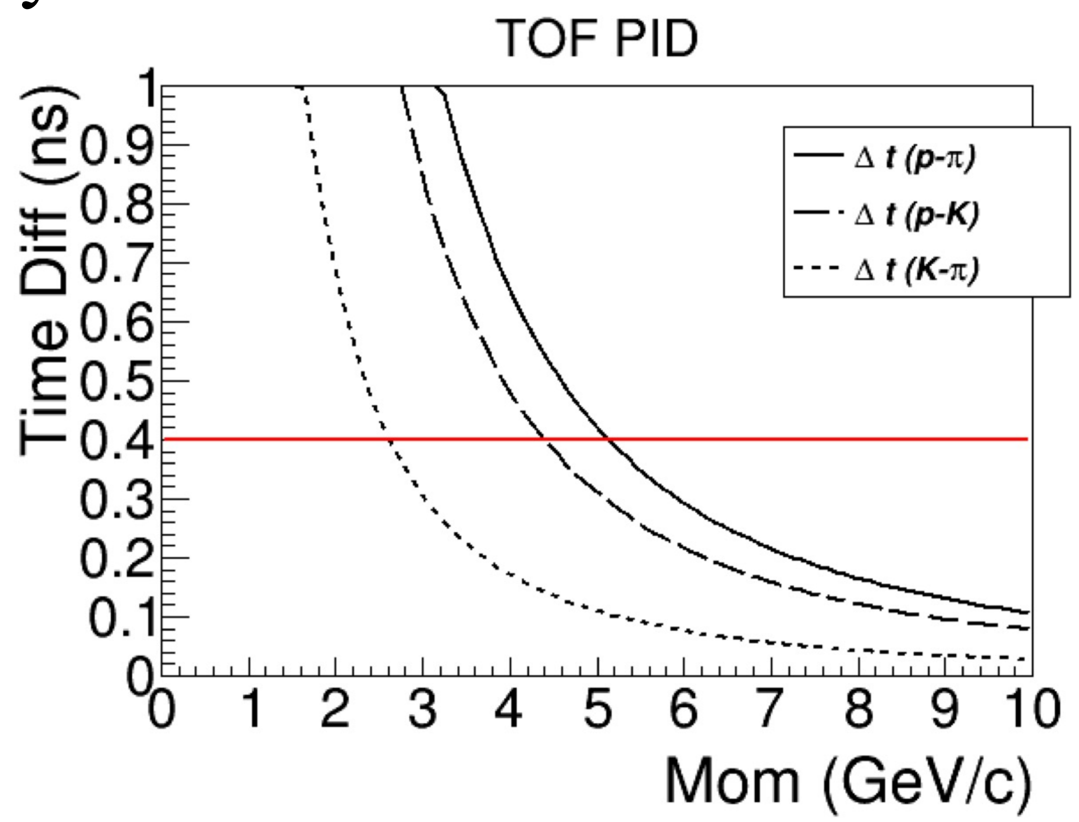
The total uncertainty is around 6%




**Phys. Rev. C 95, 035209**

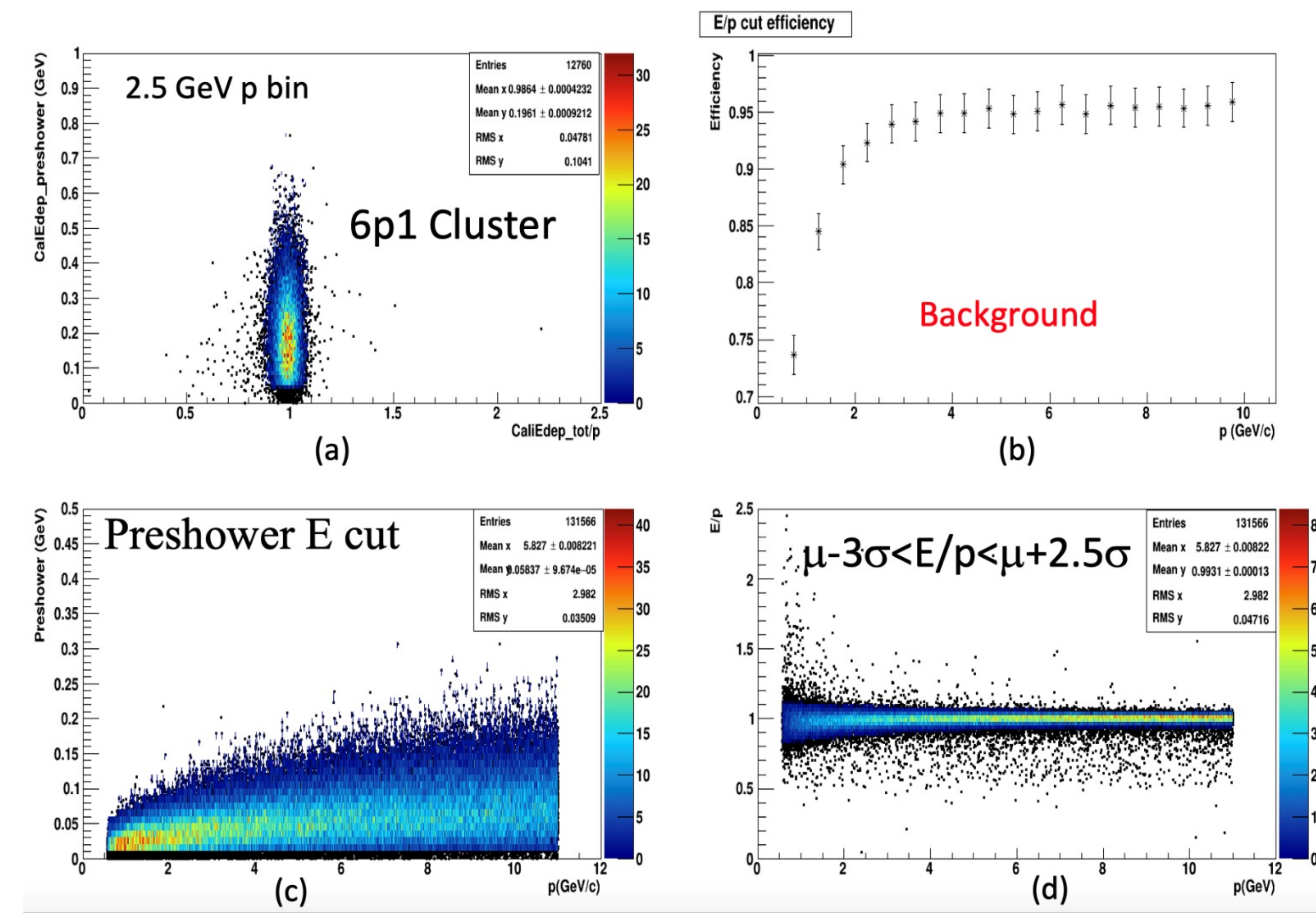
- Pion PID uncertainty

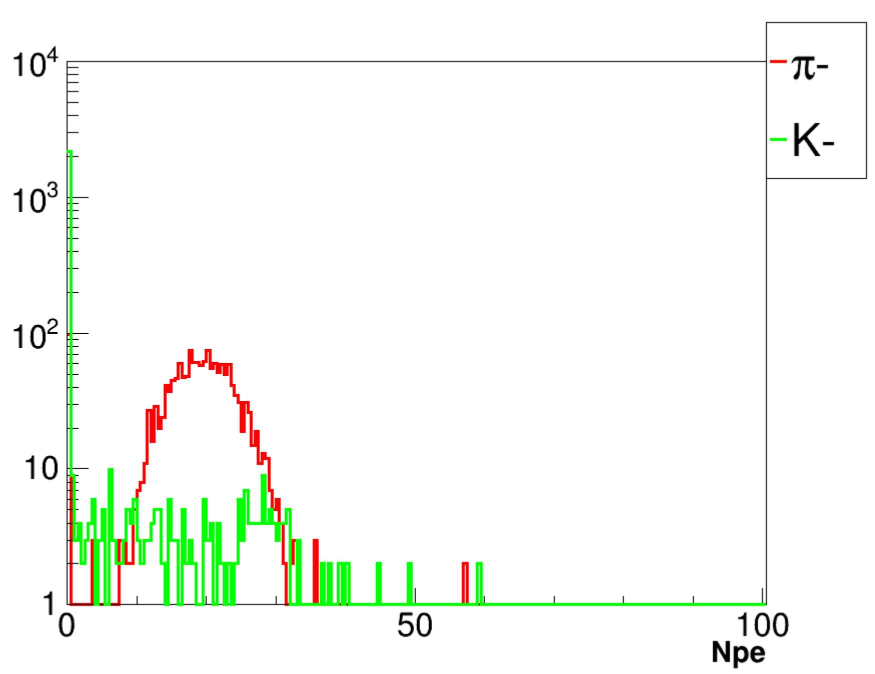
Below Cherenkov threshold, MRPC can separate particles using time of flight

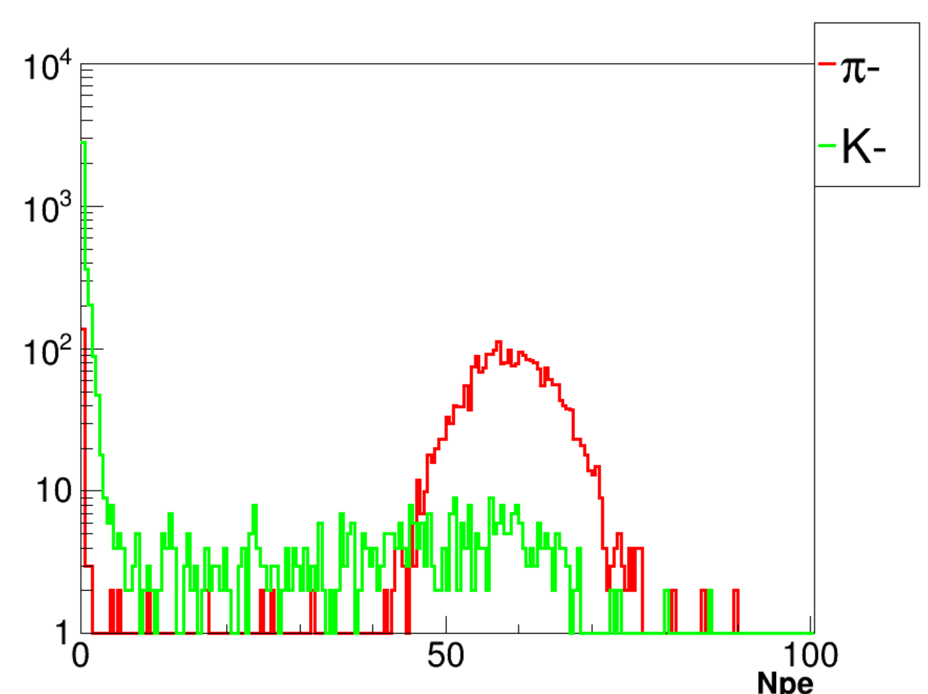



Update on MRPC Plan By Zhihong Ye

- Electron PID uncertainty



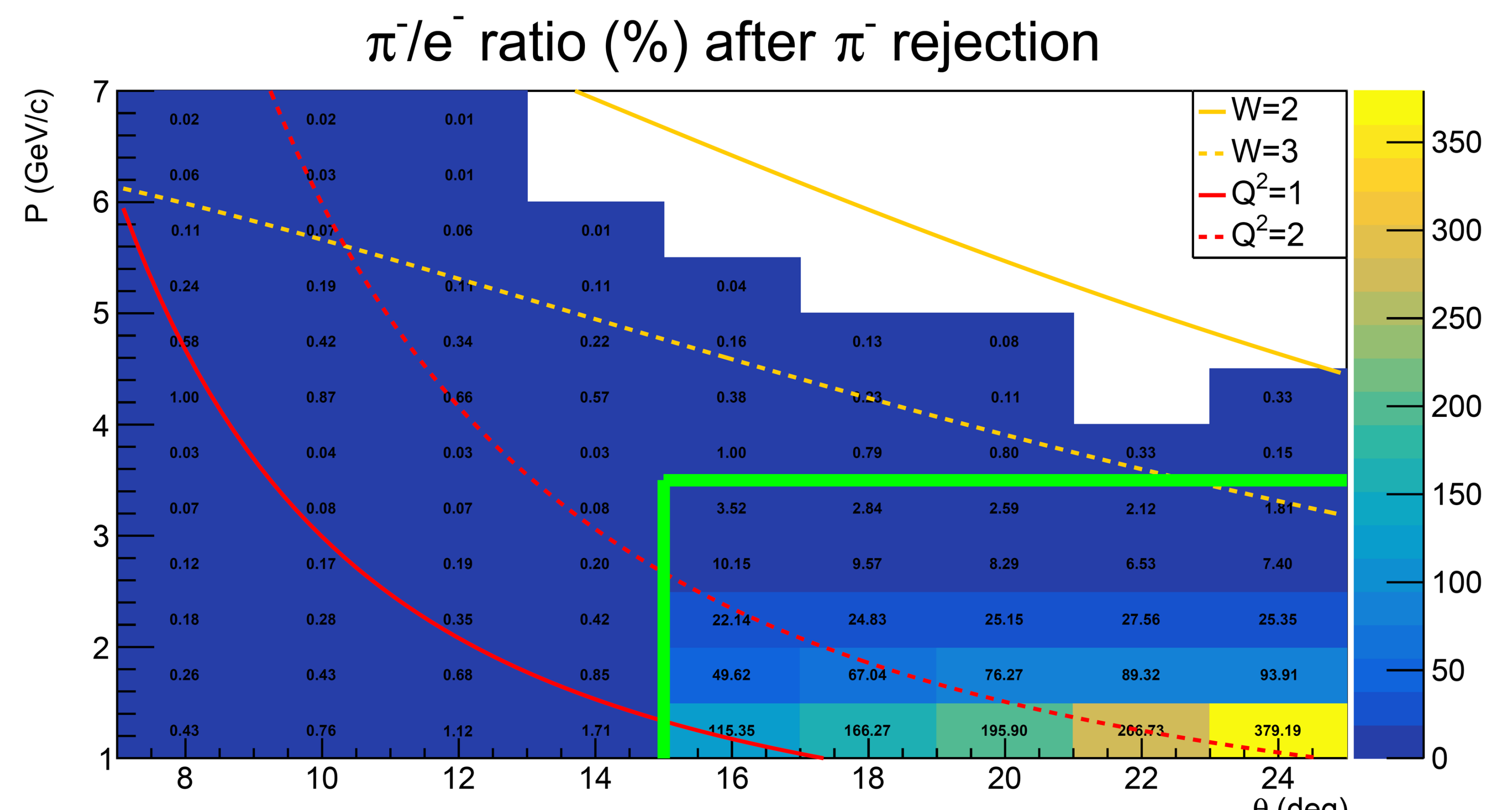




2.5 < P < 3.0 GeV
8° < θ < 9°

7.0 < P < 7.5 GeV
14° < θ < 15°

Pion results in red color, kaon results in green color

Simulation and Update on Heavy Gas Cherenkov Detector By Garth Huber and Zhiwen Zhao




(i) in FA ECal region, $\pi^-/e^-$ ratio is < 1.0% for P > 1.5 GeV/c, while it is < 2% for 1.0 < P < 2.0 GeV/c

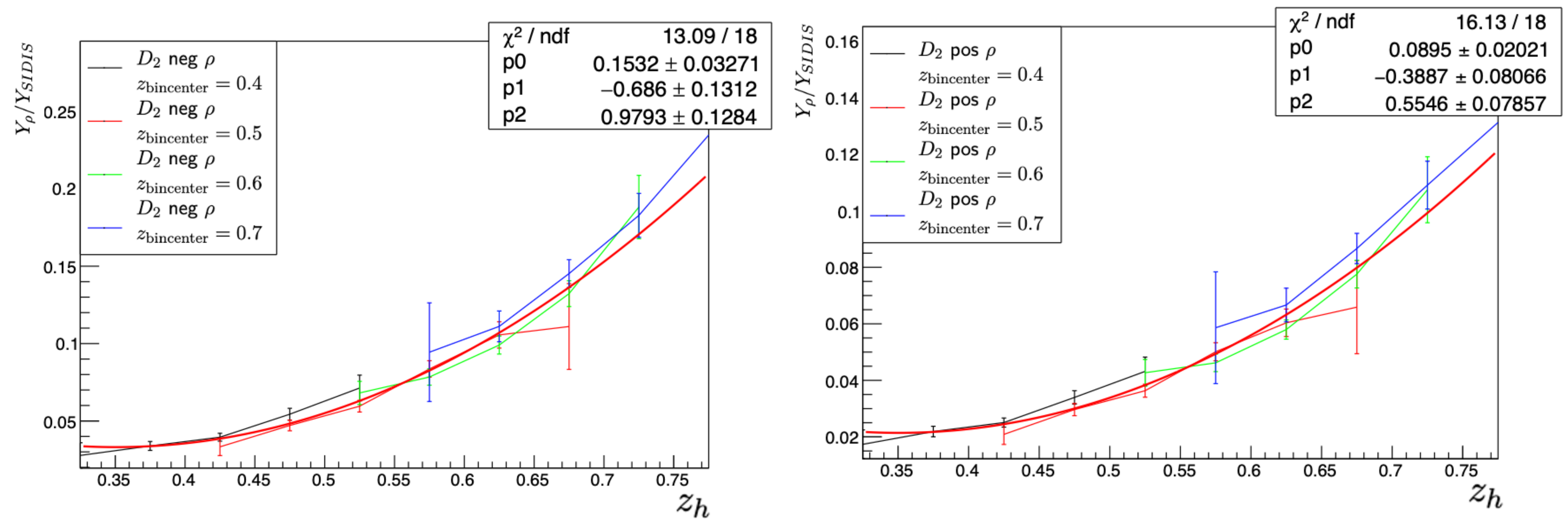
(ii) in LA ECal region, $\pi^-/e^-$ ratio is < 1.0% for P > 3.5 GeV/c (the electron threshold in LA region)

## ➢ Other systematic uncertainty sources

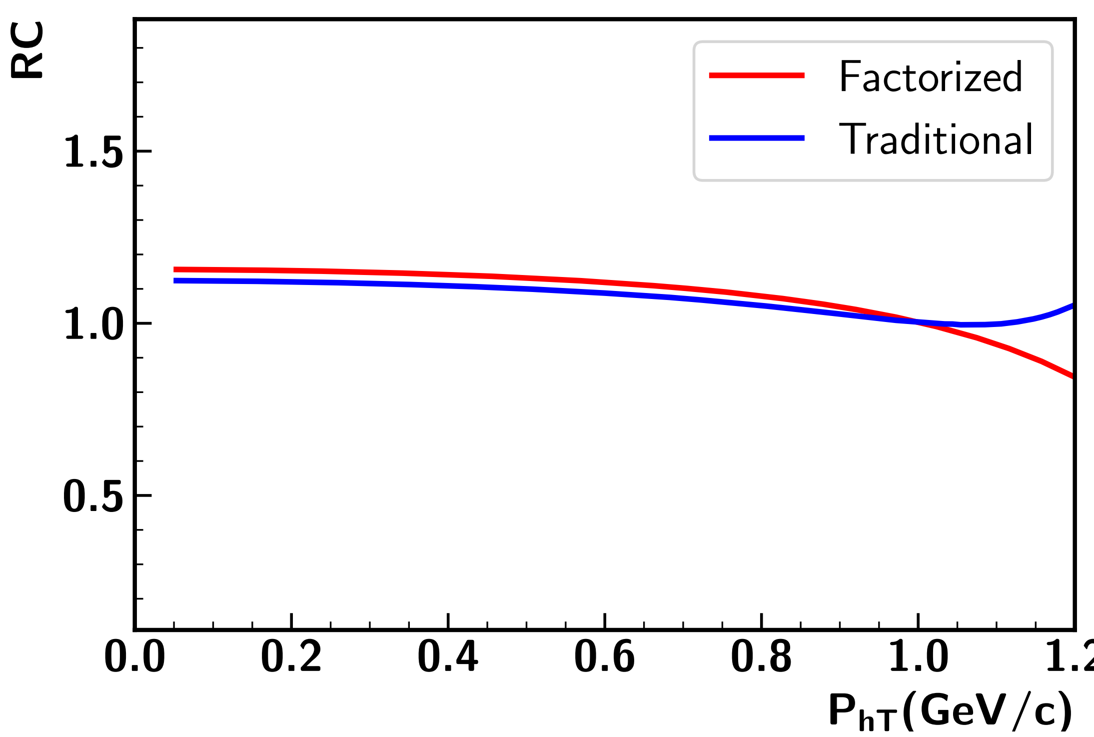
Diffractive ρ fraction to SIDIS for $x_{bj} = 0.35$, $Q^2 = 4\ (GeV/c)^2$ for $D_2$

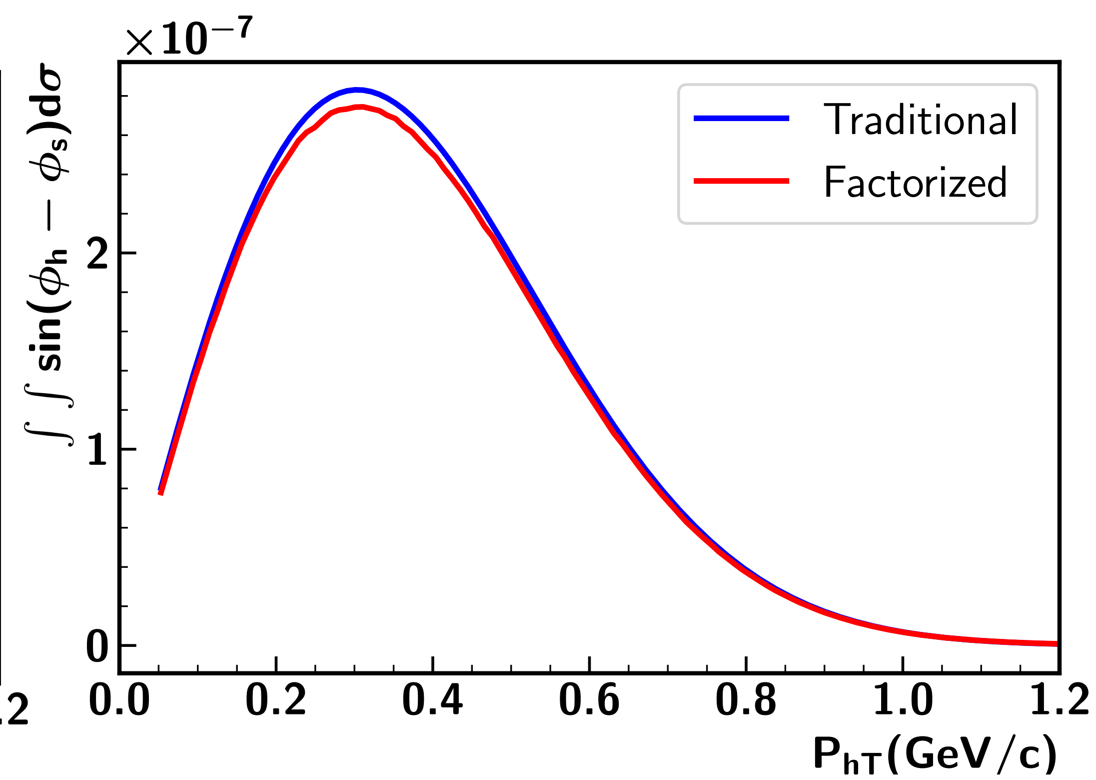
Discrepancy between models agreed to 10% according to 6 GeV era study

Multiplied by ρ yield ratio; uncertainty is < 1%




SIMC HallC Simulation Package




| $x$ | $z$ | $Q^2$ $(GeV/c)^2$ | $\pi^+_H$ (%) | $\pi^-_H$ (%) | $\pi^+_D$ (%) | $\pi^-_D$ (%) |
|---|---|---|---|---|---|---|
| 0.22 | 0.55 | 1.59 | 6.1 ± 0.2 | – | 3.7 ± 0.1 | 5.1 ± 0.2 |
| 0.26 | 0.55 | 1.88 | 5.2 ± 0.1 | – | 3.5 ± 0.1 | 5.1 ± 0.1 |
| 0.30 | 0.55 | 2.17 | 4.6 ± 0.1 | – | 3.4 ± 0.1 | 5.3 ± 0.1 |
| 0.34 | 0.55 | 2.46 | 4.6 ± 0.1 | – | 3.3 ± 0.1 | 5.1 ± 0.1 |
| 0.38 | 0.55 | 2.75 | 4.2 ± 0.1 | – | 2.9 ± 0.1 | 4.8 ± 0.1 |
| 0.42 | 0.55 | 3.04 | 3.8 ± 0.1 | – | 2.7 ± 0.1 | 4.9 ± 0.1 |
| 0.46 | 0.55 | 3.32 | 3.7 ± 0.1 | – | 2.6 ± 0.1 | 4.2 ± 0.1 |
| 0.50 | 0.55 | 3.61 | 3.1 ± 0.1 | – | 2.3 ± 0.1 | 3.6 ± 0.1 |
| 0.54 | 0.55 | 3.90 | 3.2 ± 0.1 | – | 1.9 ± 0.1 | 3.1 ± 0.1 |
| 0.58 | 0.55 | 4.19 | 2.5 ± 0.1 | – | 1.5 ± 0.1 | 2.5 ± 0.1 |

Radiative correction factor for typical JLab kinematic setting at $\sqrt{s} = 4.90$ GeV, $Q^2 = 8\ (GeV/c)^2$, $z_h = 0.375$, $x_{bj} = 0.48$
Discrepancy between two methods is around 2.5%

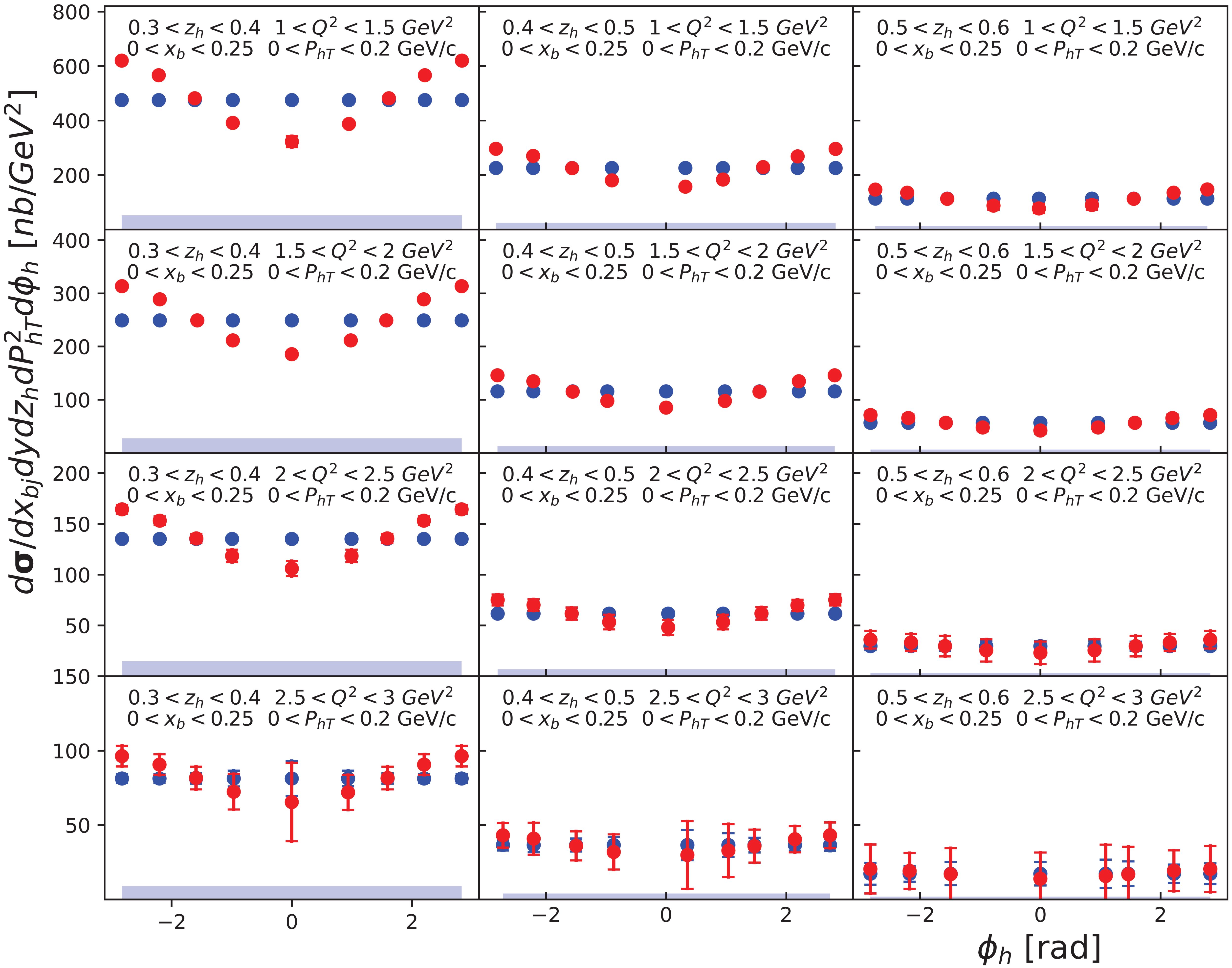
https://indico.bnl.gov/event/18419/contributions/80386/attachments/49832/85265/Jia_Khachatryan_SIDIS-RC.pdf

Exclusive radiative tail yield to SIDIS yield ratio from 6 GeV era; decreasing with increasing $Q^2$
Discrepancy between models agreed to 10-15%;uncertainty to be < 0.6%

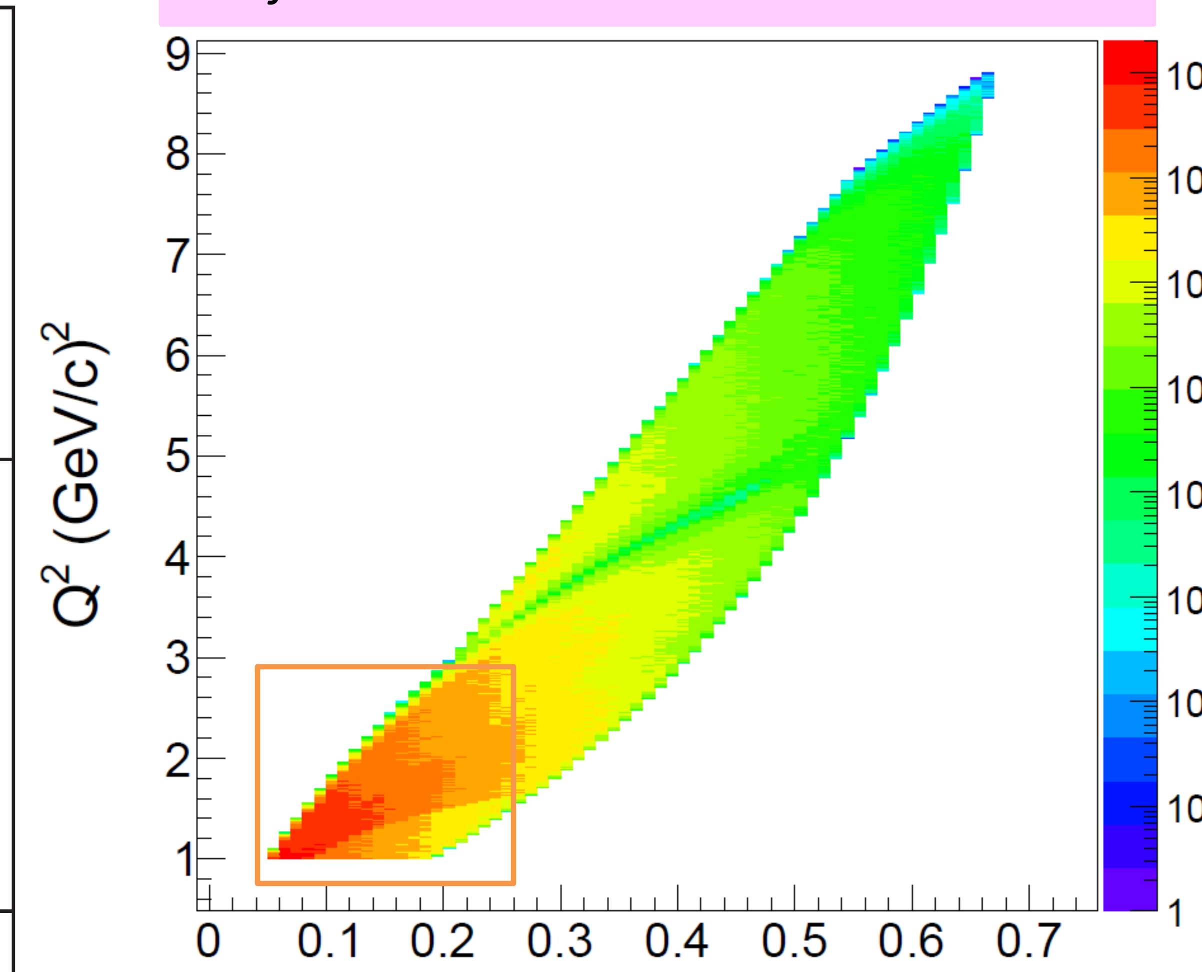
# Systematic uncertainty budget for unpolarized cross section

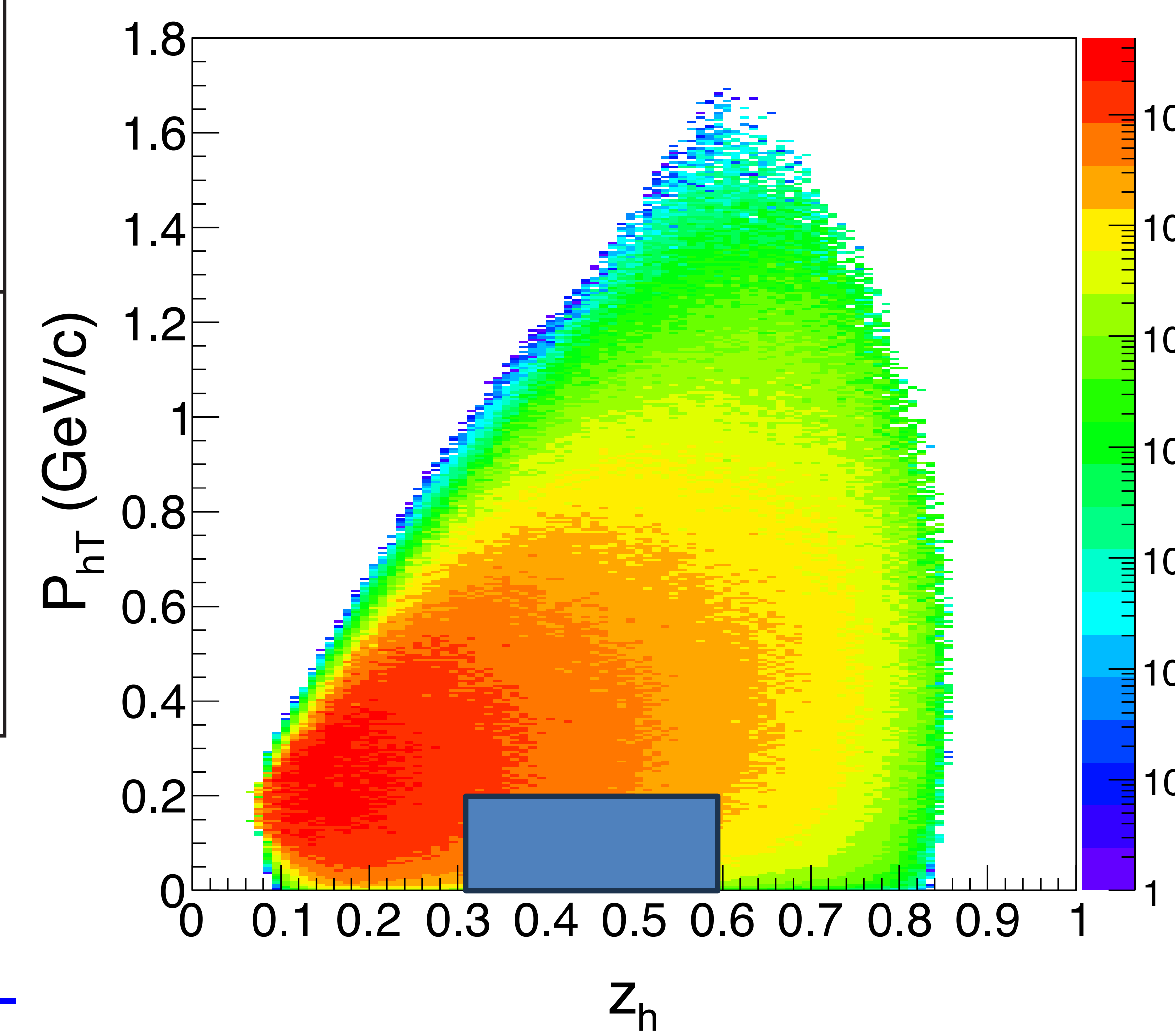
| Sources | Uncertainty |
|---|---|
| Acceptance correction | $8\% \rightarrow 6\%$ |
| Pion detection efficiency | $< 4\%$ |
| Electron detection efficiency | $< 2\%$ |
| Overall detection efficiency | 3% |
| Radiative corrections | $2.5\%$ |
| Radiative backgrounds | $0.6\%$ |
| Vector meson production | $1\%$ |
| Luminosity determination | $2.5\%$ |
| Resolution | $3.5\%$ |
| Total | $< 11\% \rightarrow 10\%$ |

- Produced $\pi^+$ unpolarized cross section at **11 GeV** beam energy

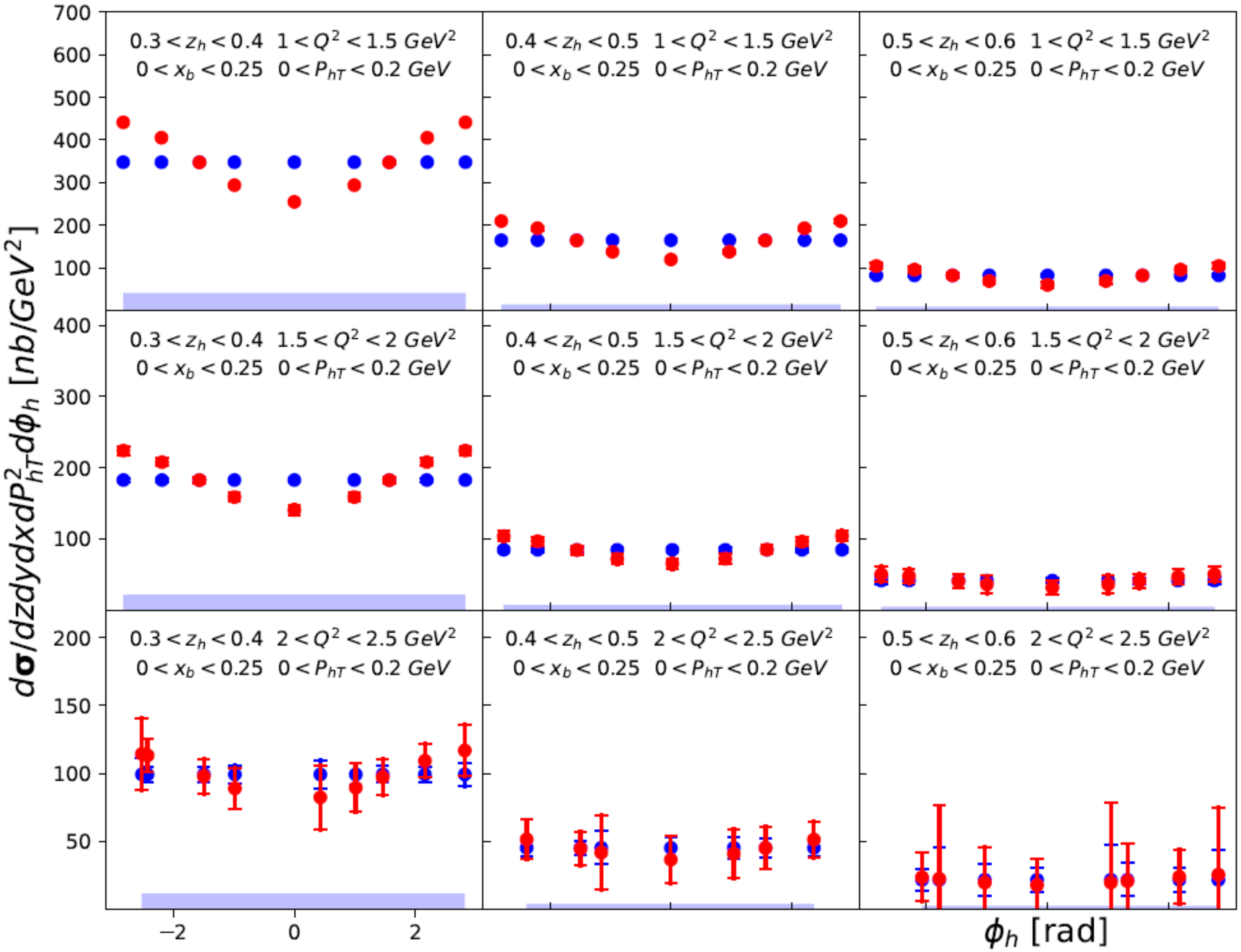



SoLID low-$Q^2$ region, first $x_{bj}$ and first $P_{hT}$ bin ranges

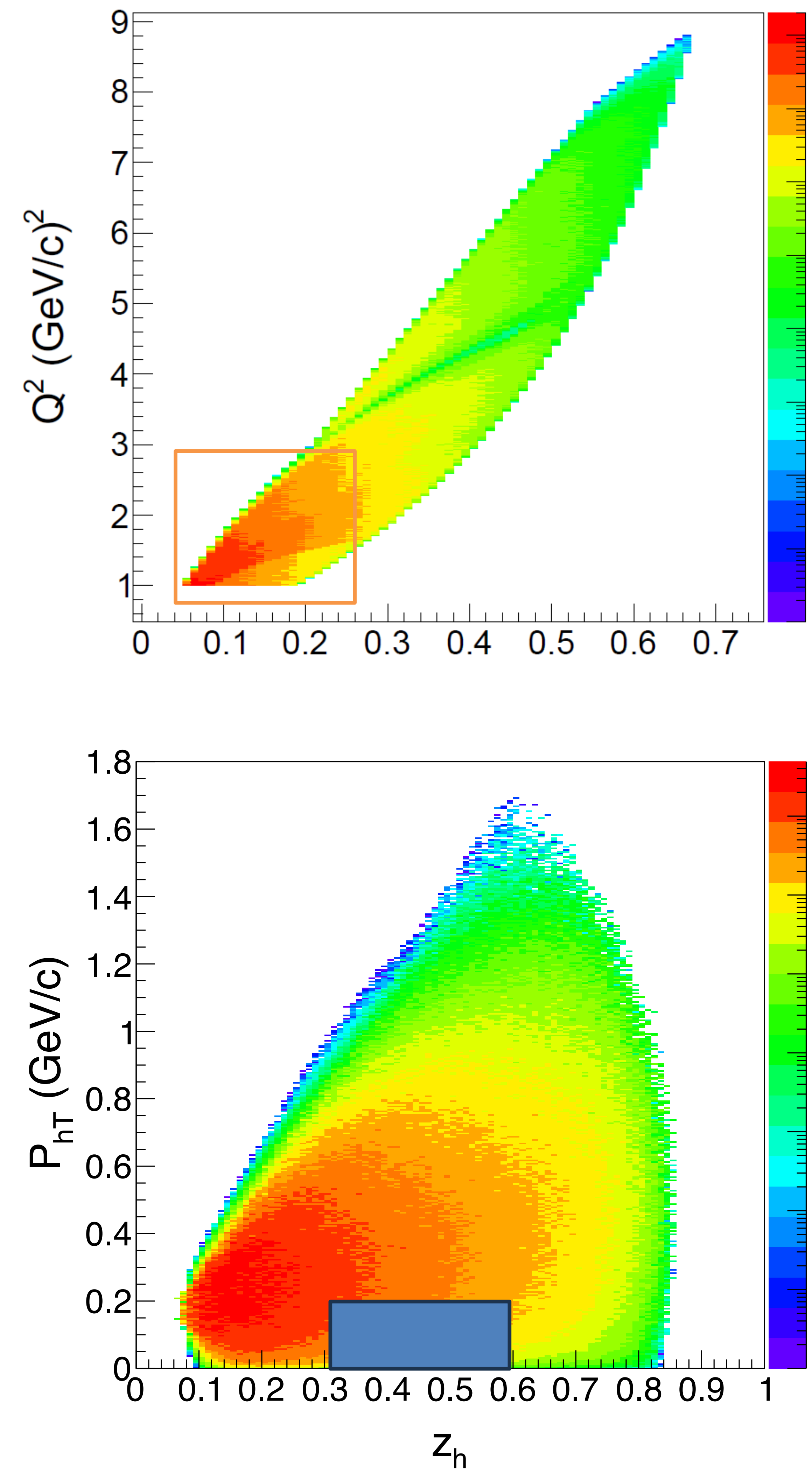


- Produced $\pi^+$ unpolarized cross section at **8.8 GeV** beam energy

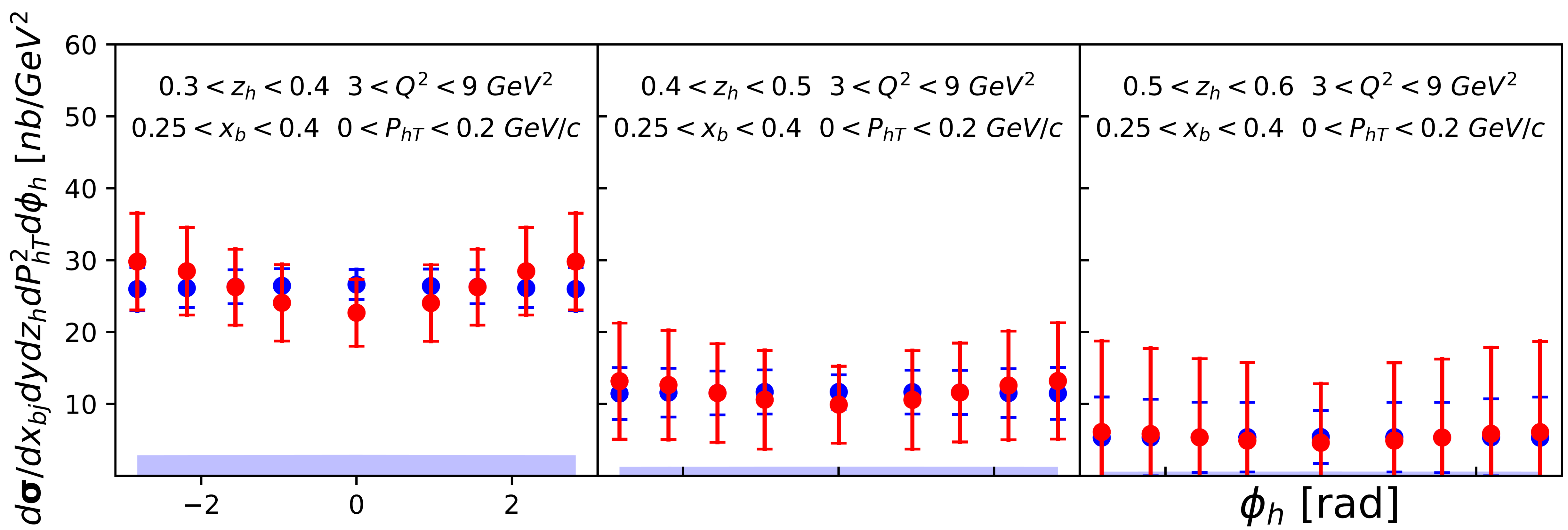


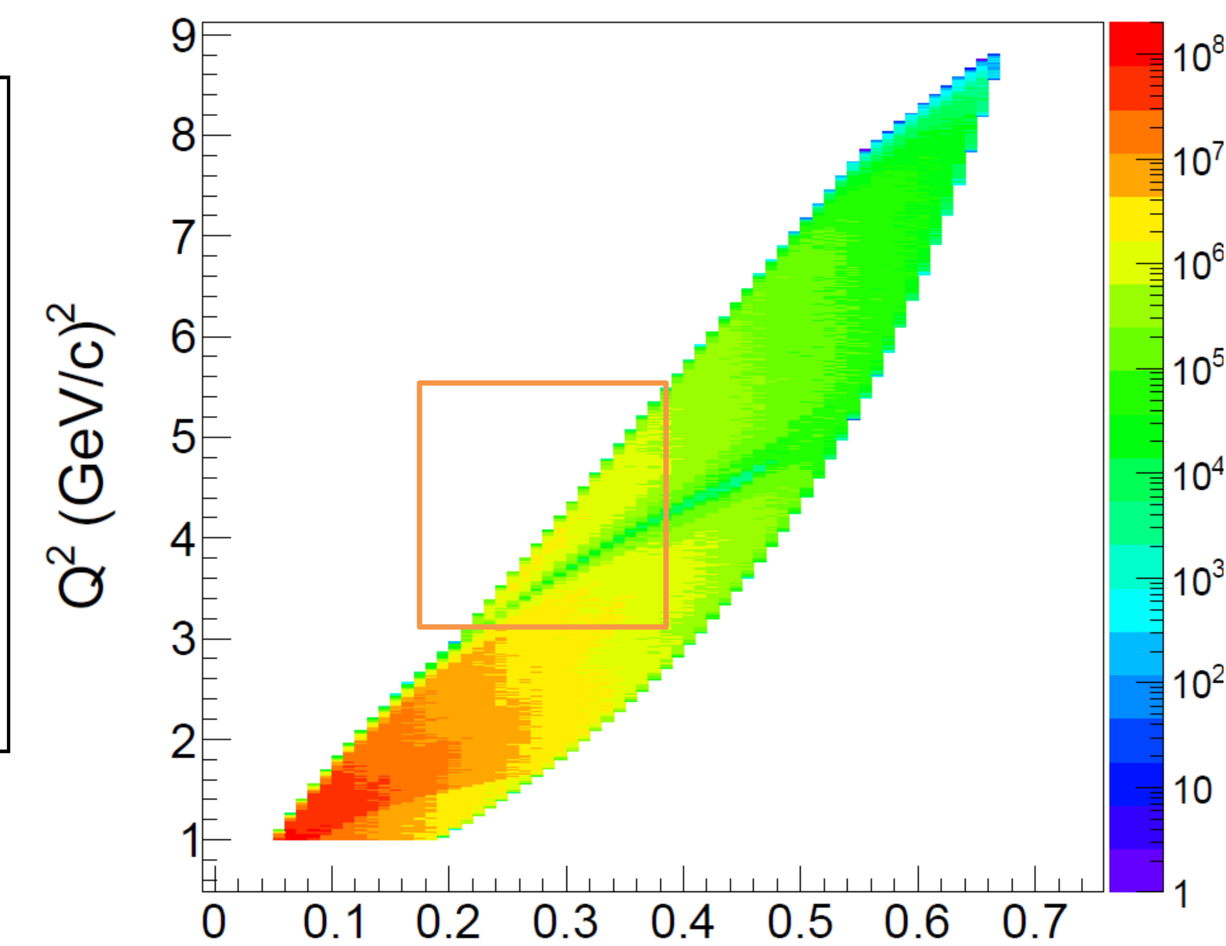

SoLID low-$Q^2$ region, first $x_{bj}$ and first $P_{hT}$ bin ranges

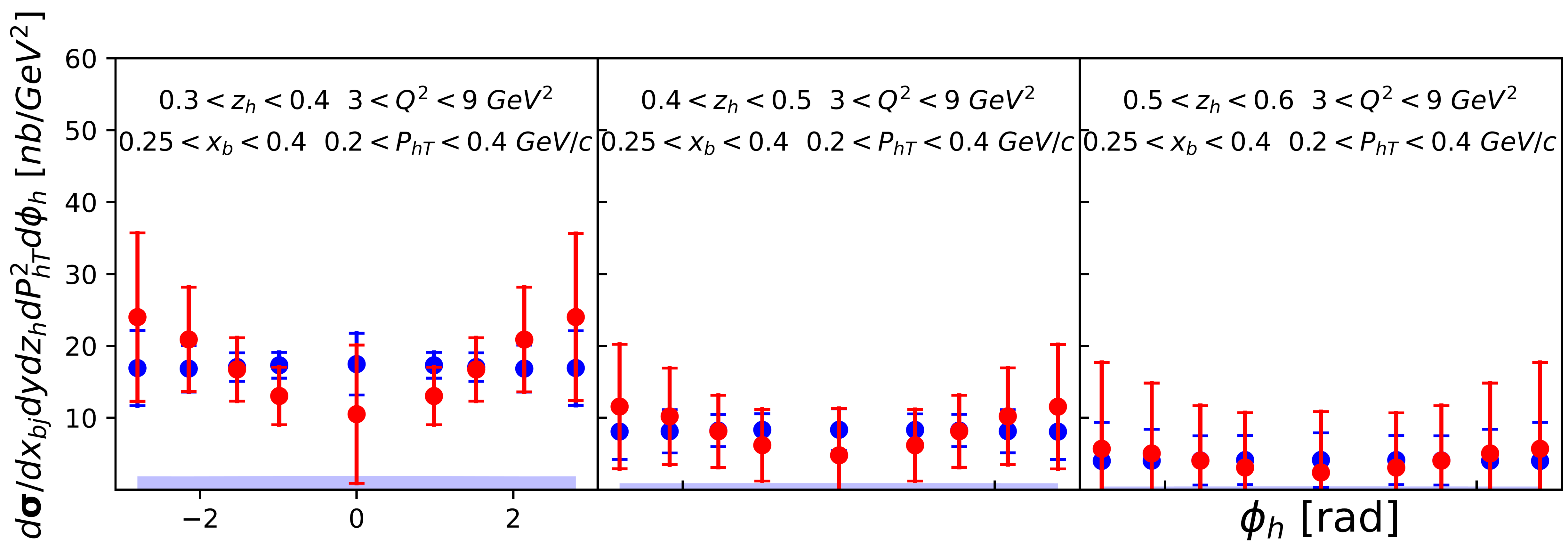


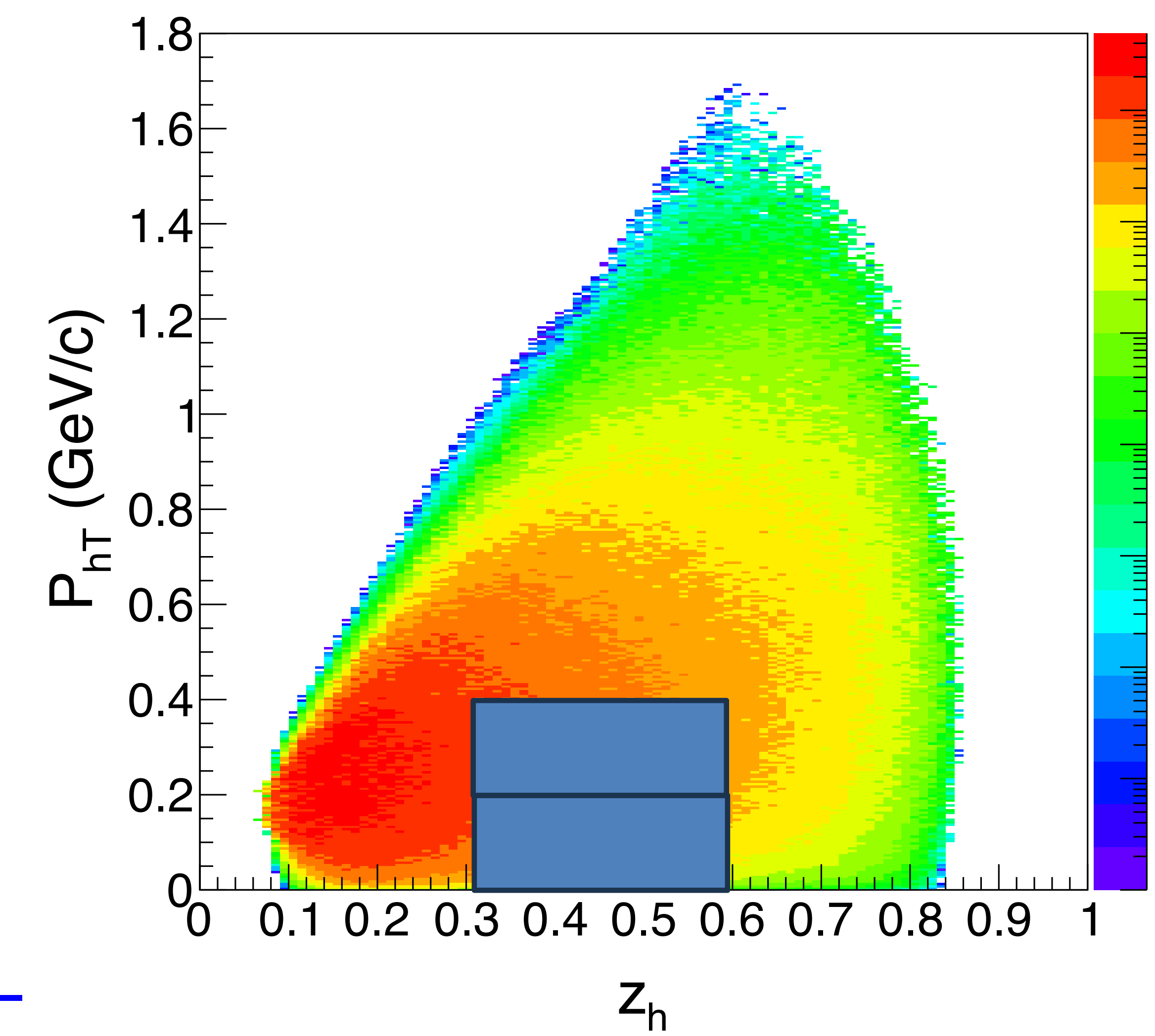
- Produced **$\pi^+$** unpolarized cross section at **11 GeV** beam energy

SoLID high-$Q^2$ region



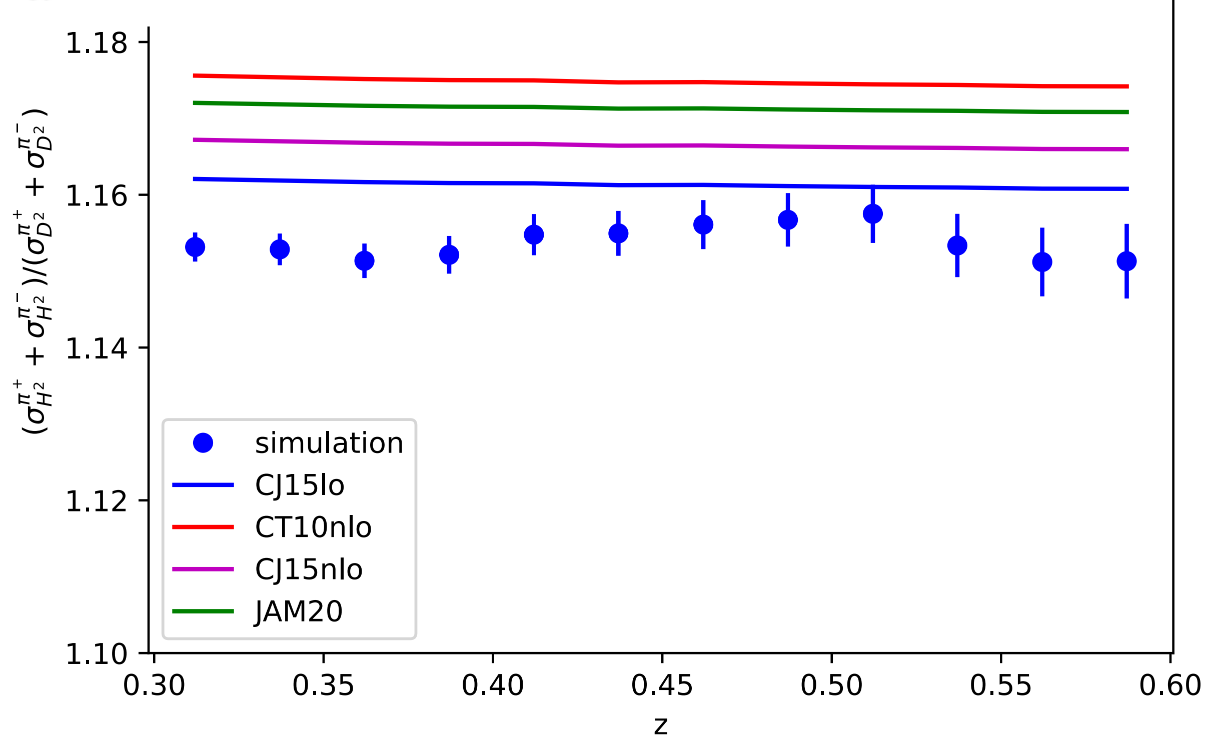



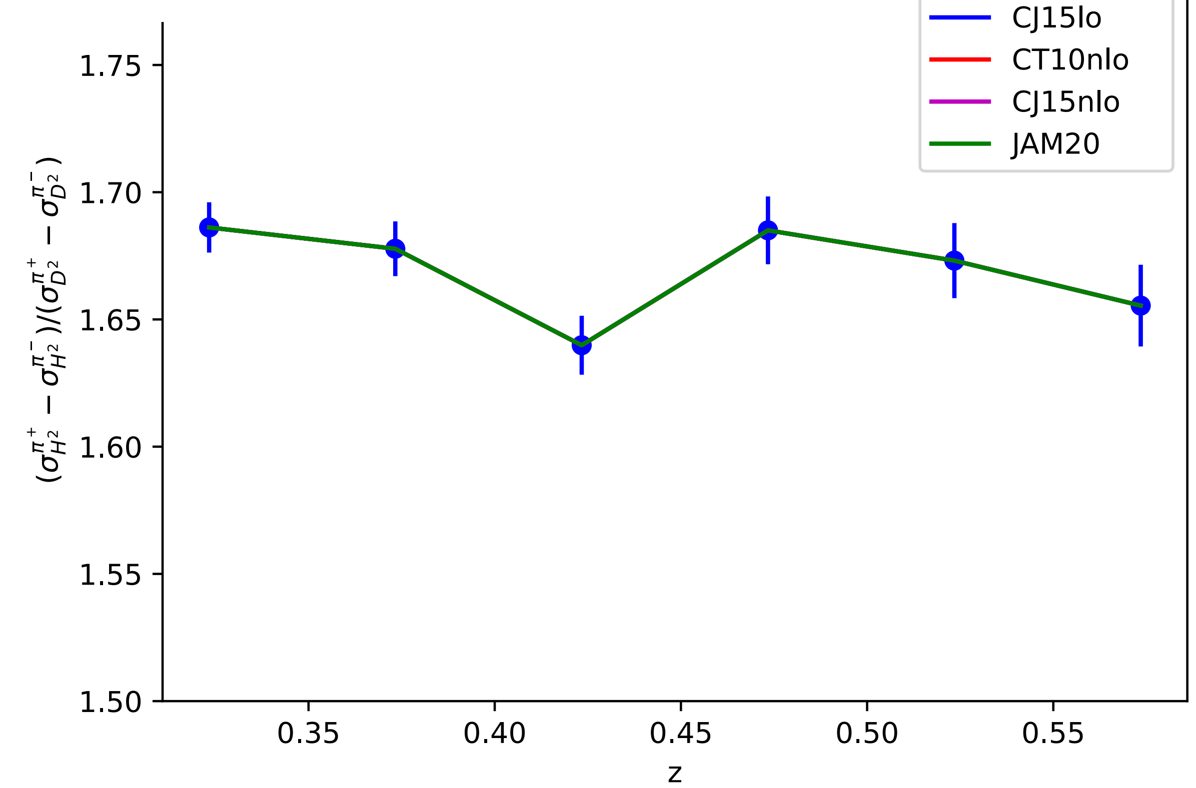
➢ Test of factorization

Assume no $P_{hT}$ dependence and ignore heavy quark contributions

$$\frac{Y_p^{\pi^+}+Y_p^{\pi^-}}{Y_d^{\pi^+}+Y_d^{\pi^-}}=\frac{4u+4\bar{u}+d+\bar{d}}{5(u+\bar{u}+d+\bar{d})}$$

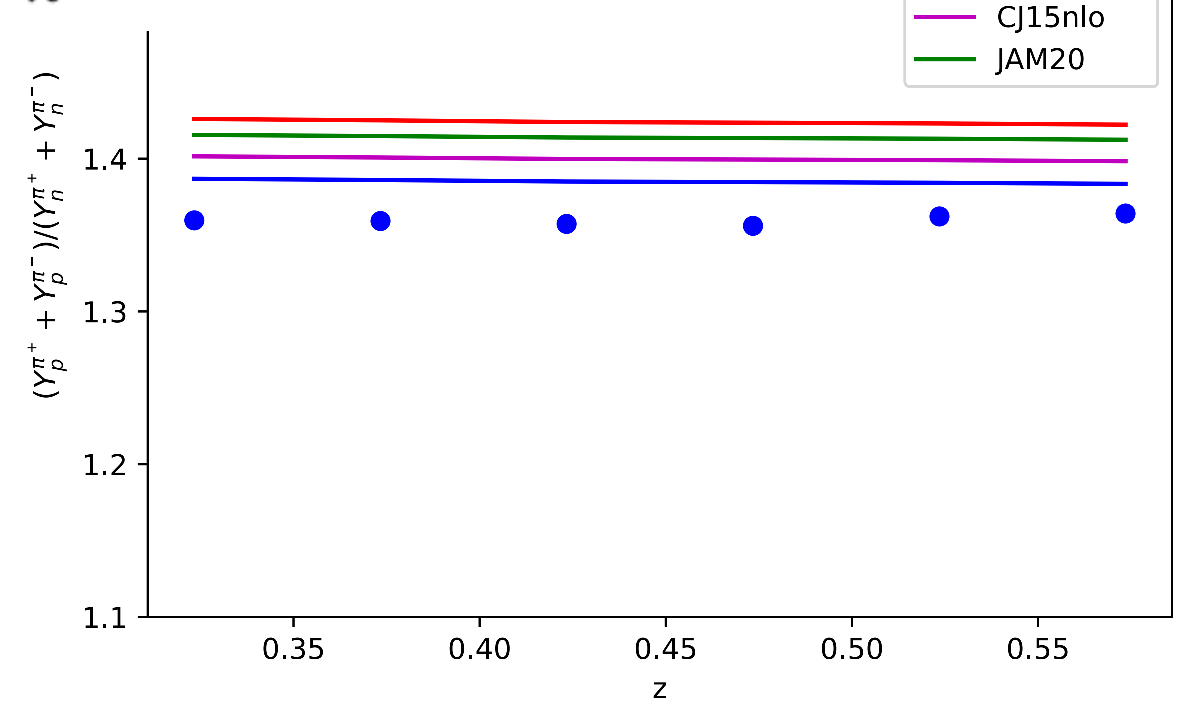



$$\frac{Y_p^{\pi^+}-Y_p^{\pi^-}}{Y_d^{\pi^+}-Y_d^{\pi^-}}=\frac{4u_v-d_v}{3(u_v+d_v)}$$

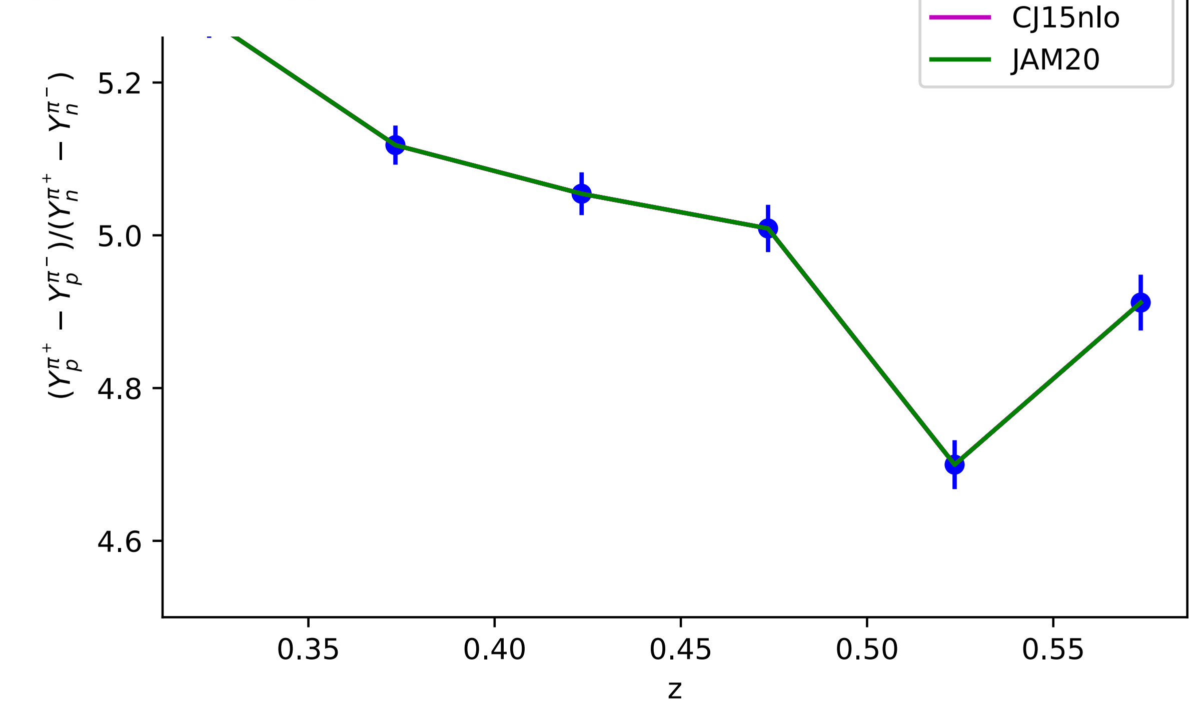



Write two types of simple ratios

$$\frac{Y_p^{\pi^+}+Y_p^{\pi^-}}{Y_n^{\pi^+}+Y_n^{\pi^-}}=\frac{4u+4\bar{u}+d+\bar{d}}{u+\bar{u}+4d+4\bar{d}}$$



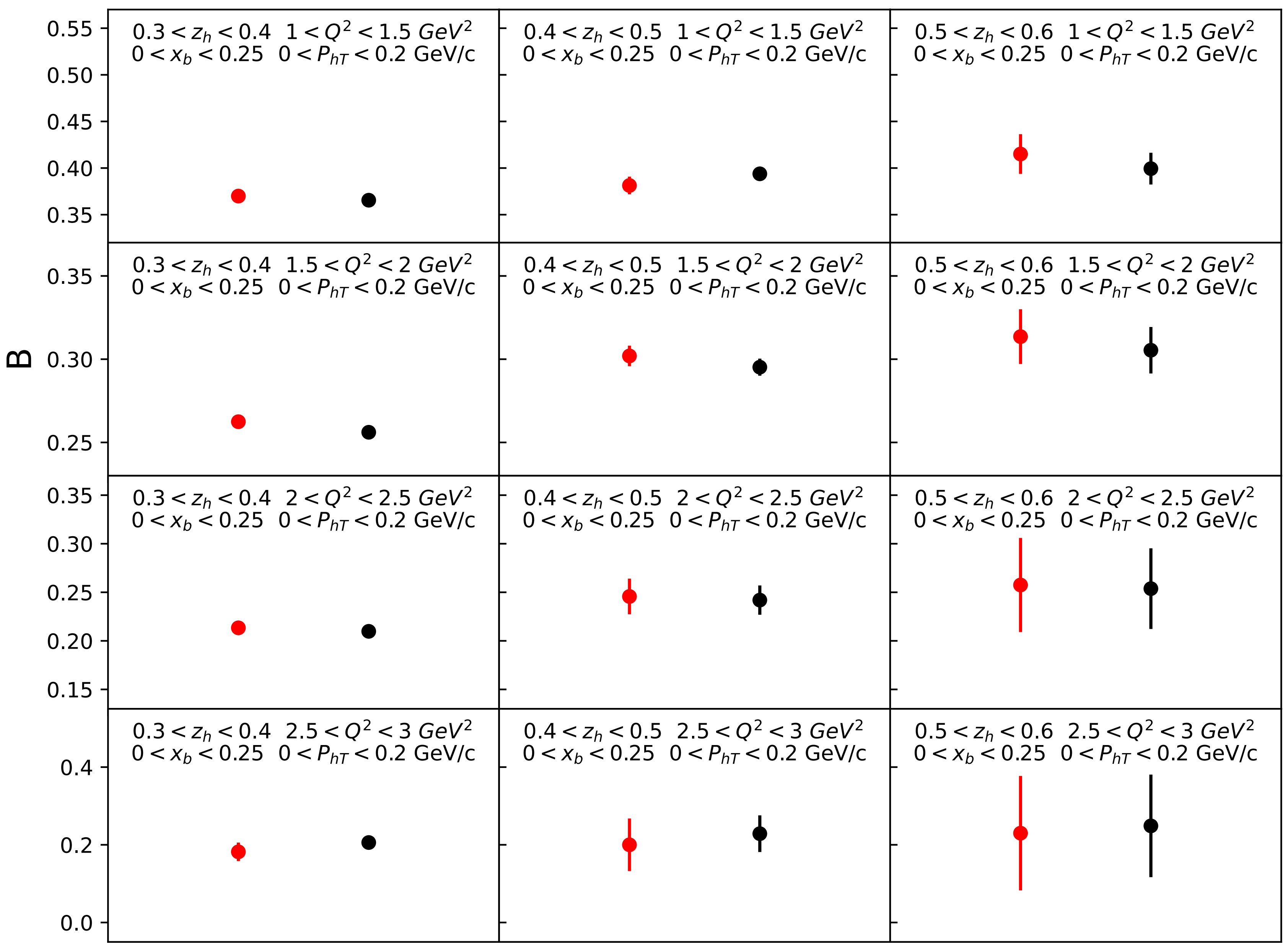

$$\frac{Y_p^{\pi^+}-Y_p^{\pi^-}}{Y_n^{\pi^+}-Y_n^{\pi^-}}=\frac{4u_v-d_v}{4d_v-uv}$$

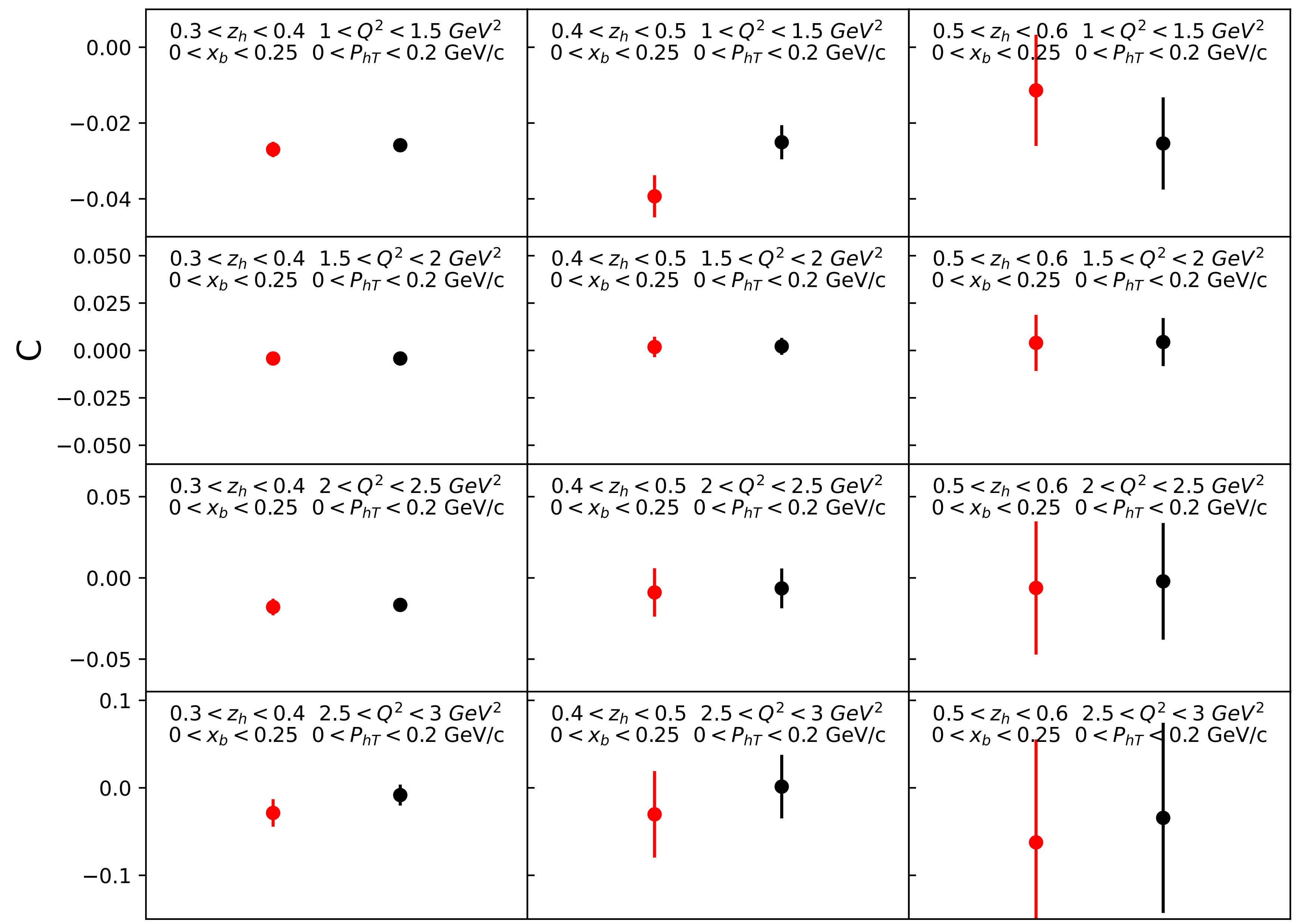


- Azimuthal modulation effect

$$\frac{d\sigma}{dx_{bj}dydz_h dP_{hT}^2 d\phi_h} \equiv \mathcal{F}_{UU} = \mathcal{F}_{UU,\mathcal{A}} \cos 0 + \mathcal{F}_{UU,\mathcal{B}} \cos(\phi_h) + \mathcal{F}_{UU,\mathcal{C}} \cos(2\phi_h)$$

Fitting $\phi_h$ distribution with a simple function: $A(1 - B \cdot \cos(\phi_h) - C \cdot \cos(2\phi_h))$




Red points for $\pi^+$, black points for $\pi^-$

- Transverse momentum widths

$$F_{UU} = \sum_q e_q^2 \, x_{bj} \, f_q^c(x_{bj}) \, D_q^c(z_h) \, \frac{e^{-P_{hT}^2/\langle P_T^2 \rangle}}{\pi \langle P_T^2 \rangle}$$

where $\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle$

$$F_{UU}^{\cos(\phi_h)} = F_{UU}^{\cos(\phi_h)}\big|_{\mathrm{Cahn}} + F_{UU}^{\cos(\phi_h)}\big|_{\mathrm{BM}}$$

$$F_{UU}^{\cos(2\phi_h)} \approx F_{UU}^{\cos(2\phi_h)}\big|_{\mathrm{Cahn}} + F_{UU}^{\cos(2\phi_h)}\big|_{\mathrm{BM}}$$

In model, we have (in GeV²)

$< k_\perp^2 >= 0.604, < p_\perp^2 >= 0.114$

$$\mathrm{Least\_Square} = \sum (pseudodata - Model)^2 / (stat + sys)^2$$

The fitting results shows (in GeV²):

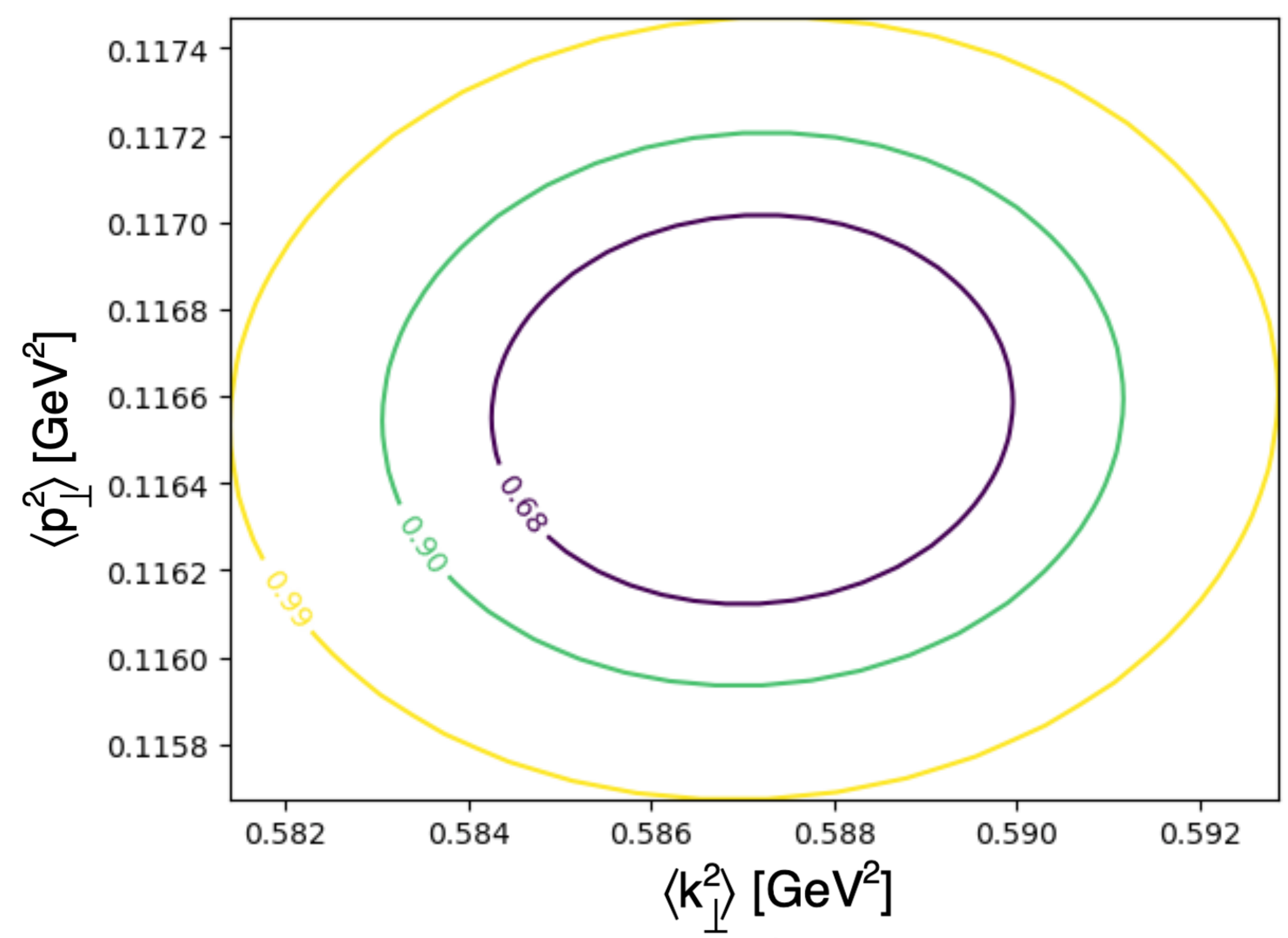
$< k_\perp^2 >= 0.5871 \pm 0.002, < p_\perp^2 >= 0.1165 \pm 0.0003$

Three contours corresponding to confidence levels of 68%, 90% and 99%

Both Cahn and Boer-Mulders contributions included

All data from positive and negative polarities are considered

The fitting results differs from the model by 4%



➢ Calibration beam time request for unpolarized cross-section measurement of this proposal

| Target | Beam energy (GeV) | Field | Time (hour) | Purpose |
|---|---|---|---|---|
| $H_2$ reference cell | 2.2 | Normal | 1 | Acceptance study |
| Empty reference cell | 2.2 | Normal | 1 | Backgrounds subtraction |
| Carbon | 2.2 | Normal | 1 | Acceptance study |
| $H_2$ reference cell | 4.4 | Normal | 1 | Acceptance study |
| Empty reference cell | 4.4 | Normal | 1 | Backgrounds subtraction |
| Carbon | 4.4 | Normal | 1 | Acceptance study |

We are not asking for
new beam time !!!

Reference cell runs, optics
and detector check : 3 Days

Calibration arrangement for related
detector alignment and particle tracking,
for unpolarized cross-section measurement

- With the high luminosity and large acceptance, the SoLID data could provide high precision cross section results with full azimuthal angle coverage

- In our run group proposal, we show unpolarized SoLID SIDIS cross-section results
  - for $\pi^+$ particles at 11/8.8 GeV as well as $\pi^-$ particles at 11 GeV beam energies
  - based on transversely/longitudinally polarized SoLID $^3$He targets

- Systematic uncertainty estimation

- Cross-section pseudo-data obtained in 5-dimensional binning of $(x_{bj}, z_h, Q^2, P_{hT}, \phi_h)$
  - central points from theory calculations, plus SoLID statistical and systematic uncertainties
  - Cross-section with/without azimuthal modulations include uncertainties

- Some possible results extracted from the cross-section data

- Calibration beam time request for unpolarized cross-section measurement of this proposal

Thank You !

Acknowledgements: the entire SoLID collaboration

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# ***Backups***

- Momentum coverage: 1.0 - 7.0 GeV/c; Polar angular coverage: 8.0° - 14.8°
  (*for hadron & electron ID*)
- Momentum coverage: 3.5 - 6.0 GeV/c; Polar angular coverage: 15.7° - 24.0°
  (*for electron ID*)
- Momentum resolution: ~ 2%; Polar angular resolution: 2 mrad
- Azimuthal angular coverage: $2\pi$; Azimuthal angular resolution: 6 mrad
- PID (electron): detection efficiency ≥ 90%; pion contamination < 1%
- PID (pion): detection efficiency ≥ 90%; kaon contamination < 1%
- Total luminosity: $3.74 \cdot 10^{36}$ cm$^{-2}$ sec$^{-1}$
- Beam polarimetry: < 3%; Beam current: 15 $\mu$A
- Many other details in ***SoLID (Solenoidal Large Intensity Device) Updated Preliminary Conceptual Design Report***, ***https://solid.jlab.org/***

- Analytical forms of the Cahn and Boer-Mulders azimuthal modulation given by

$$F_{UU}^{\cos(\phi_h)}|_{\text{Cahn}} = -2\,\frac{P_T}{Q}\sum_q e_q^2\, x_{bj}\, f_q^c(x_{bj})\, D_q^c(z_h)\,\frac{z_h\langle k_\perp^2\rangle}{\langle P_T^2\rangle}\,\frac{e^{-P_{hT}^2/\langle P_T^2\rangle}}{\pi\langle P_T^2\rangle},$$

$$\begin{aligned} F_{UU}^{\cos(\phi_h)}|_{\text{BM}} &= 2e\,\frac{P_T}{Q}\sum_q e_q^2\, x_{bj}\,\frac{\Delta f_{q^\uparrow/p}(x_{bj})}{M_{\text{BM}}}\,\frac{\Delta D_{h/q^\uparrow}(z_h)}{M_{\text{C}}}\,\frac{e^{-P_{hT}^2/\langle P_T^2\rangle_{\text{BM}}}}{\pi\langle P_T^2\rangle_{\text{BM}}^4}\times \\ &\times\frac{\langle k_\perp^2\rangle_{\text{BM}}^2\,\langle p_\perp^2\rangle_{\text{C}}^2}{\langle k_\perp^2\rangle\langle p_\perp^2\rangle}\left[z_h^2\langle k_\perp^2\rangle_{\text{BM}}\left(P_{hT}^2-\langle P_T^2\rangle_{\text{BM}}\right)+\langle p_\perp^2\rangle_{\text{C}}\langle P_T^2\rangle_{\text{BM}}\right], \end{aligned}$$

$$F_{UU}^{\cos(2\phi_h)}|_{\text{Cahn}} = 2\,\frac{P_T^2}{Q^2}\sum_q e_q^2\, x_{bj}\, f_q^c(x_{bj})\, D_q^c(z_h)\,\frac{z_h^2\langle k_\perp^2\rangle^2}{\langle P_T^2\rangle^2}\,\frac{e^{-P_{hT}^2/\langle P_T^2\rangle}}{\pi\langle P_T^2\rangle},$$

$$\begin{aligned} F_{UU}^{\cos(2\phi_h)}|_{\text{BM}} &= -eP_T^2\sum_q e_q^2\, x_{bj}\,\frac{\Delta f_{q^\uparrow/p}(x_{bj})}{M_{\text{BM}}}\,\frac{\Delta D_{h/q^\uparrow}(z_h)}{M_{\text{C}}}\,\frac{e^{-P_{hT}^2/\langle P_T^2\rangle_{\text{BM}}}}{\pi\langle P_T^2\rangle_{\text{BM}}^3}\times \\ &\times\frac{z_h\langle k_\perp^2\rangle_{\text{BM}}^2\,\langle p_\perp^2\rangle_{\text{C}}^2}{\langle k_\perp^2\rangle\langle p_\perp^2\rangle}, \end{aligned}$$

where

$$\langle P_T^2\rangle_{\text{BM}} = \langle p_\perp^2\rangle_{\text{C}} + z_h^2\langle k_\perp^2\rangle_{\text{BM}}$$

$$\langle p_\perp^2\rangle_{\text{C}} = \frac{\langle p_\perp^2\rangle\, M_{\text{C}}^2}{\langle p_\perp^2\rangle + M_{\text{C}}^2}$$

$$\langle k_\perp^2\rangle_{\text{BM}} = \frac{\langle k_\perp^2\rangle\, M_{\text{BM}}^2}{\langle k_\perp^2\rangle + M_{\text{BM}}^2}$$

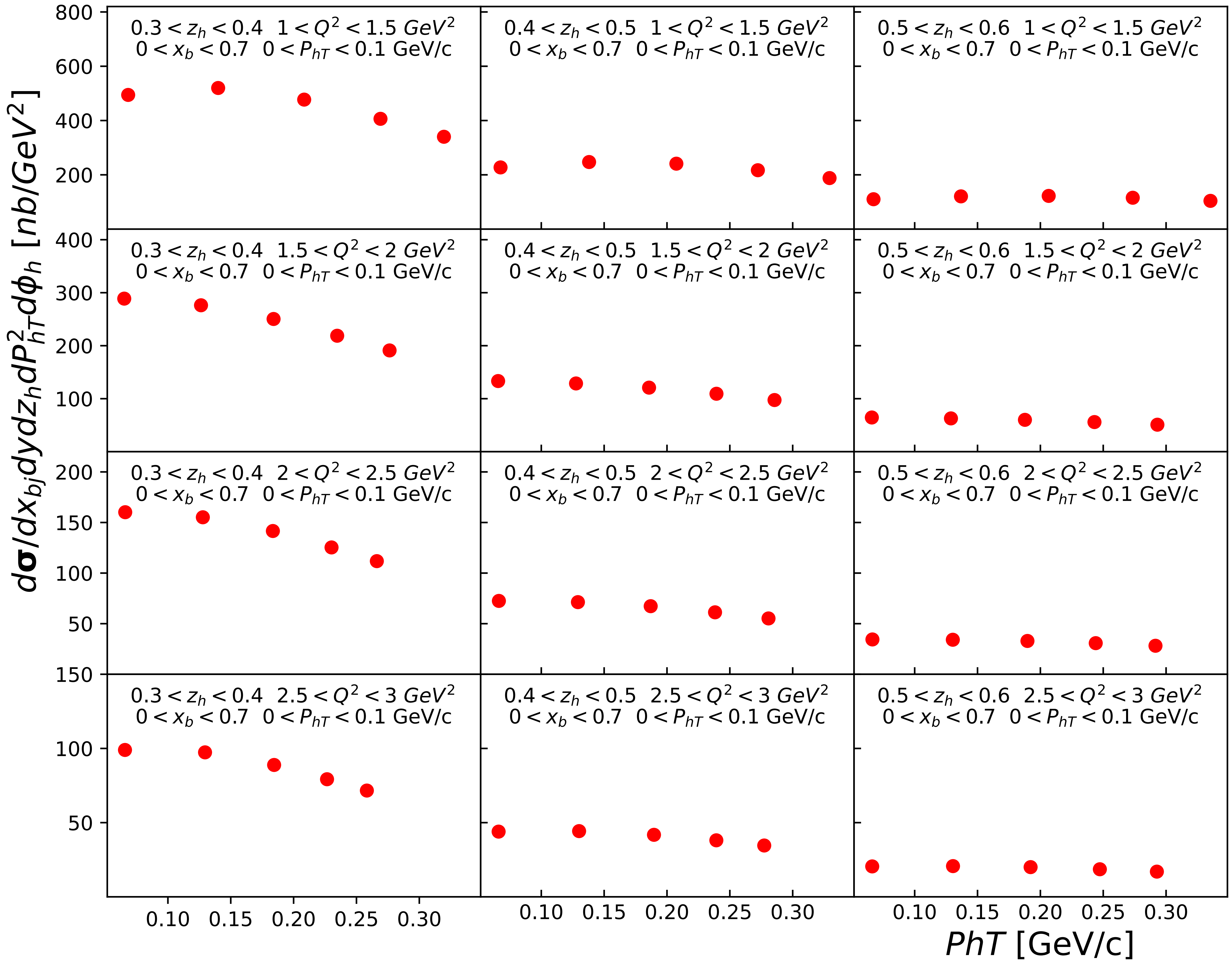
$M_{\text{C}}^2$ and $M_{\text{BM}}^2$ and all the other functional forms to be found in

JHEP 06, 007 (2019)

and

https://github.com/TianboLiu/LiuSIDIS

# Transverse momentum dependence

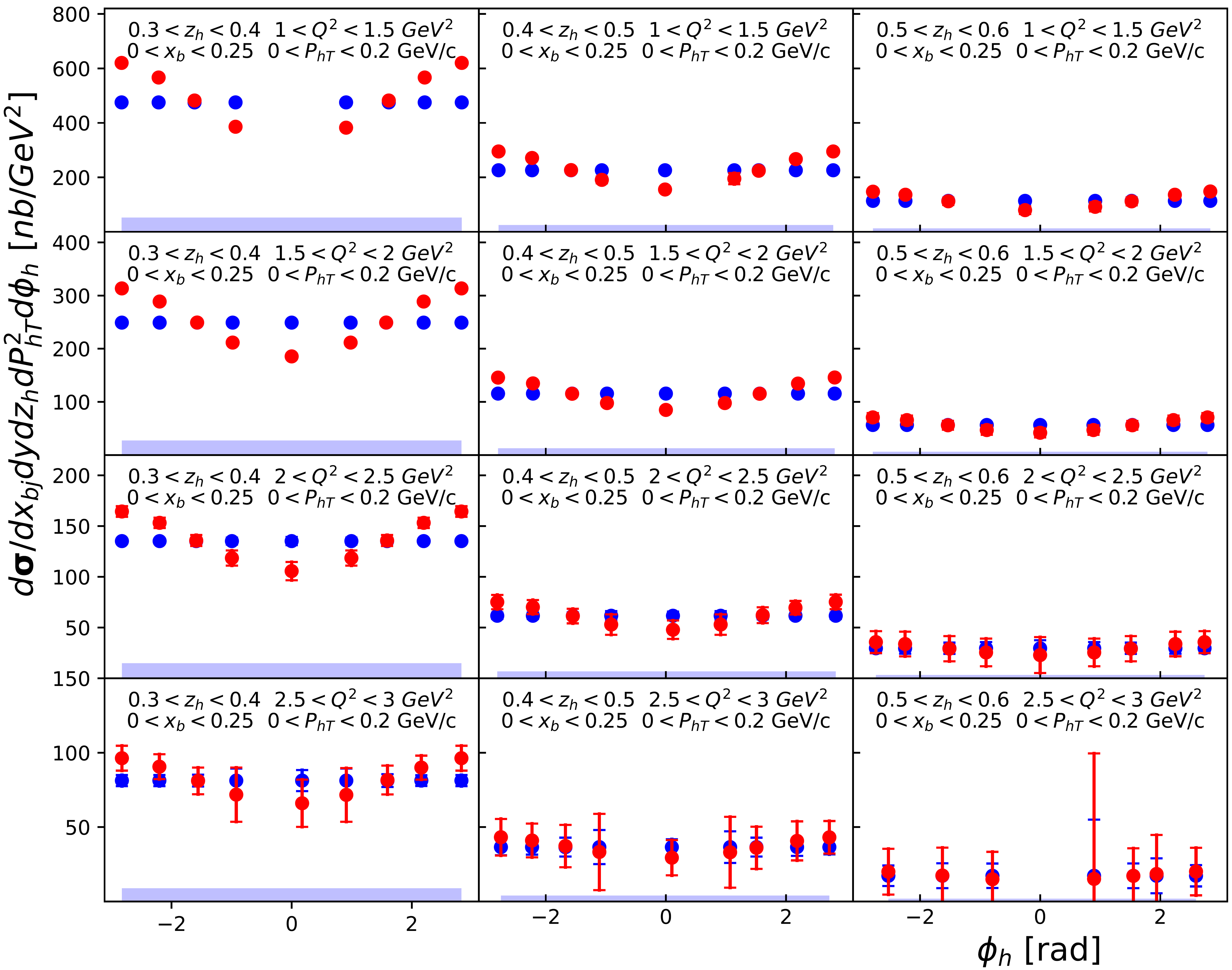



- Produced **$\pi^+$** unpolarized cross section at **11 GeV** beam energy

Red pseudo-data points: *cross section including azimuthal modulations*

*SoLID statistical uncertainties are under points*

- Produced **$\pi^-$** unpolarized cross section at **11 GeV** beam energy




SoLID low-$Q^2$ region, first $x_{bj}$ and first $P_{hT}$ bin ranges

Blue pseudo-data points: *cross section without azimuthal modulations*

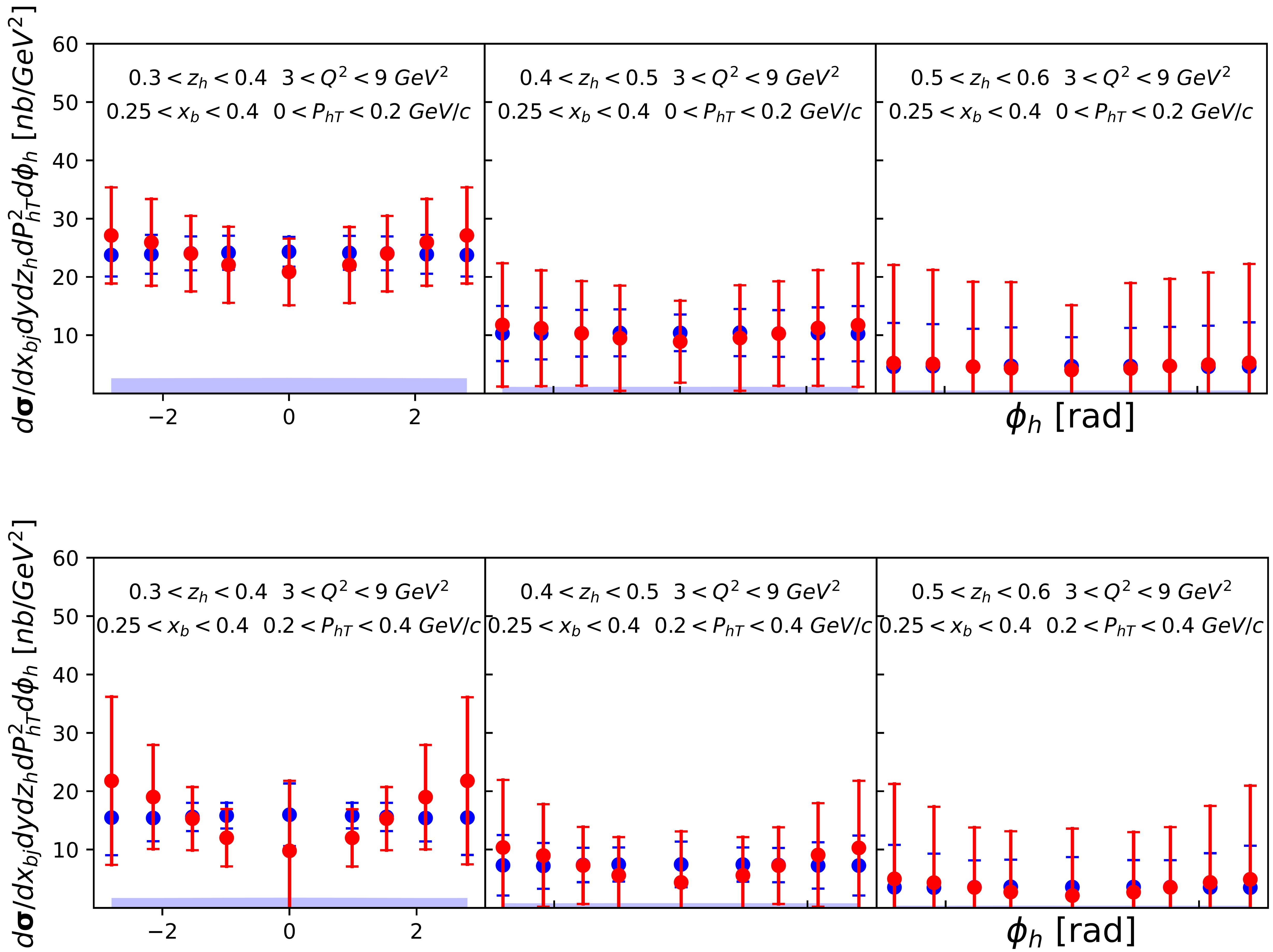
Red pseudo-data points: *cross section including azimuthal modulations*

Vertical error bars: *SoLID statistical uncertainties*

Bottom band in each plot: *SoLID total systematic uncertainties*

- Produced **$\pi^-$** unpolarized cross section at **11 GeV** beam energy

SoLID high-$Q^2$ region




Blue pseudo-data points: *cross section without azimuthal modulations*

Red pseudo-data points: *cross section including azimuthal modulations*

Vertical error bars: *SoLID statistical uncertainties*

Bottom band in each plot: *SoLID total systematic uncertainties*

Calibration arrangement for related detector alignment and particle tracking, for unpolarized cross-section measurement

| Target | Beam energy (GeV) | Field | Time (hour) |
|---|---|---|---|
| $H_2$ reference cell | 2.2 | 50% | 1 |
| Empty reference cell | 2.2 | 50% | 1 |
| Carbon | 2.2 | 50% | 1 |
| $H_2$ reference cell | 2.2 | 0% | 1 |
| Empty reference cell | 2.2 | 0% | 1 |
| Carbon | 2.2 | 0% | 1 |
| $H_2$ reference cell | 4.4 | 50% | 1 |
| Empty reference cell | 4.4 | 50% | 1 |
| Carbon | 4.4 | 50% | 1 |
| $H_2$ reference cell | 4.4 | 0% | 1 |
| Empty reference cell | 4.4 | 0% | 1 |
| Carbon | 4.4 | 0% | 1 |