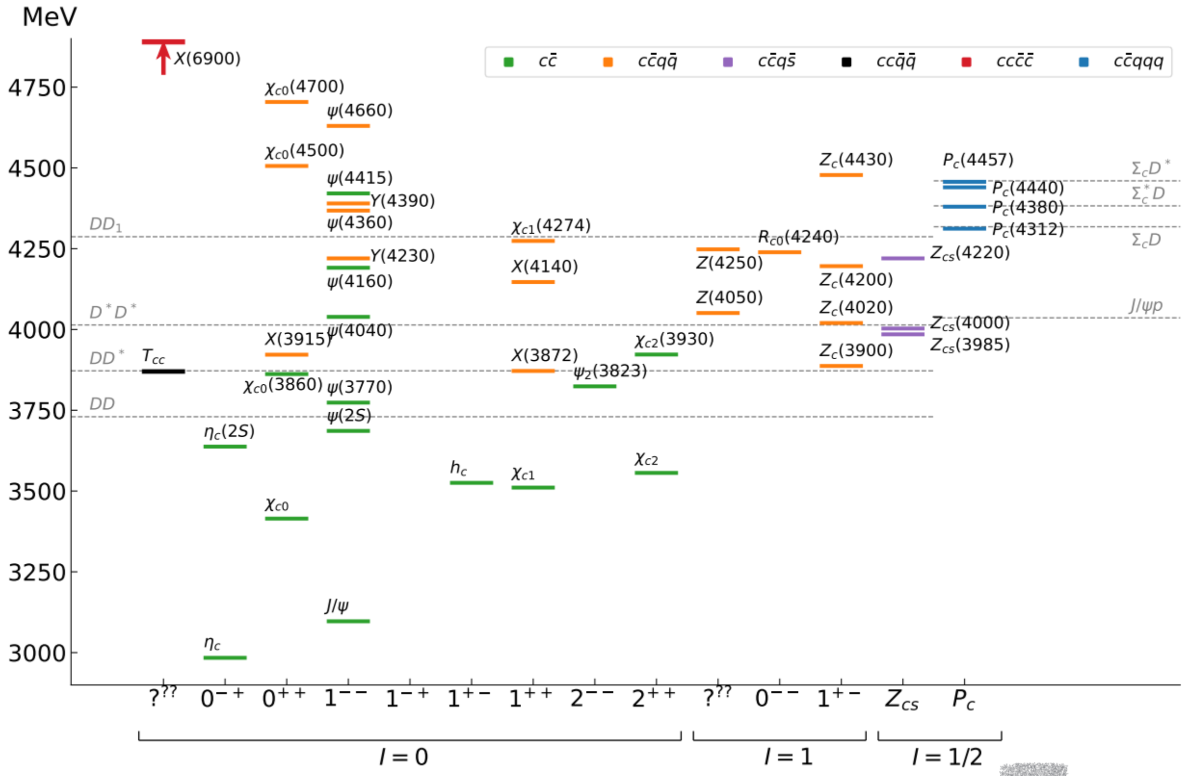
Prospects for Exotic Mesons at the EIC

Hadron 2023, Genoa

Derek Glazier
University of Glasgow
06/06/2023

Charmonium Exotics



Experimental candidates still increasing

Most outwith $c\bar{c}$

Some J^{PC} with no exotics

Experimentally measured charmonia, XYZ and pentaquark spectra from

ELSEVIER Progress in Particle and Nuclear Physics
Volume 127, November 2022, 103981

Review

Novel approaches in hadron spectroscopy JPAC

The Electron Ion Collider and ePIC

EIC - Electron Ion Collider

Polarized electron and polarized ion collider

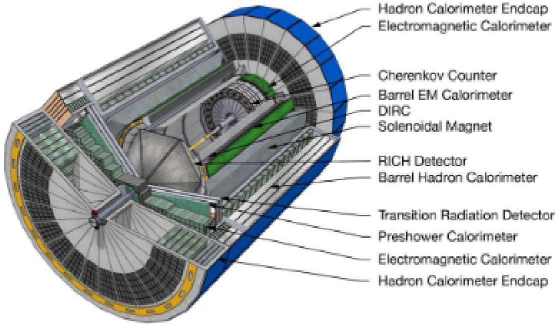
5-18 GeV Electrons

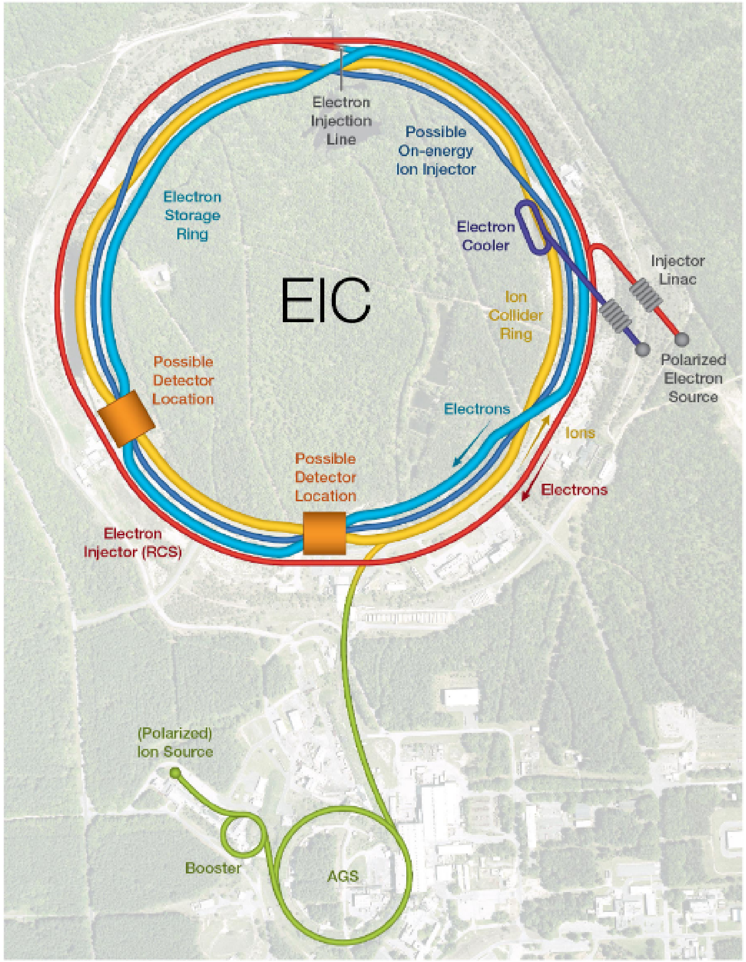
41-275 GeV Proton (+other ions)

Substituting ring of RHIC (BNL) with an electron beamline.

ePIC - electron-Proton/Ion Collider Experiment

Primary detector design for IP6 (currently STAR)





Construction timeline 2025-2031/32

Spectroscopy at the EIC

Can use quasi-real photon production (e- scattering with $Q^2 \sim 0$)

- required electron detection very close to beam (< 10mrad)
- (relatively) high virtual photon flux
- transverse/longitudinal photon polarisation
- polarised target proton
- large acceptance detector

Physics benefits

- existence in photoproduction provides strong validation
  most states only seen in single production mechanisms
- minimises rescattering mechanisms due to broad W range
- in principle can produce any state/decay mode
- polarisation observables may provide additional insight

Challenges

- (Very) low cross section/branching ratios
- detection of electron along e- beam direction
- detection of nucleon along proton beam direction

Quasi-Real Photon Tagger

Quasi-real tagging (low Q^2) (θ_e<10 mrad)

Status

Geometry integrated into EPIC simulation
Clustering, tracking and particle reconstruction
Early stages of integrating into EICrecon with ACTS

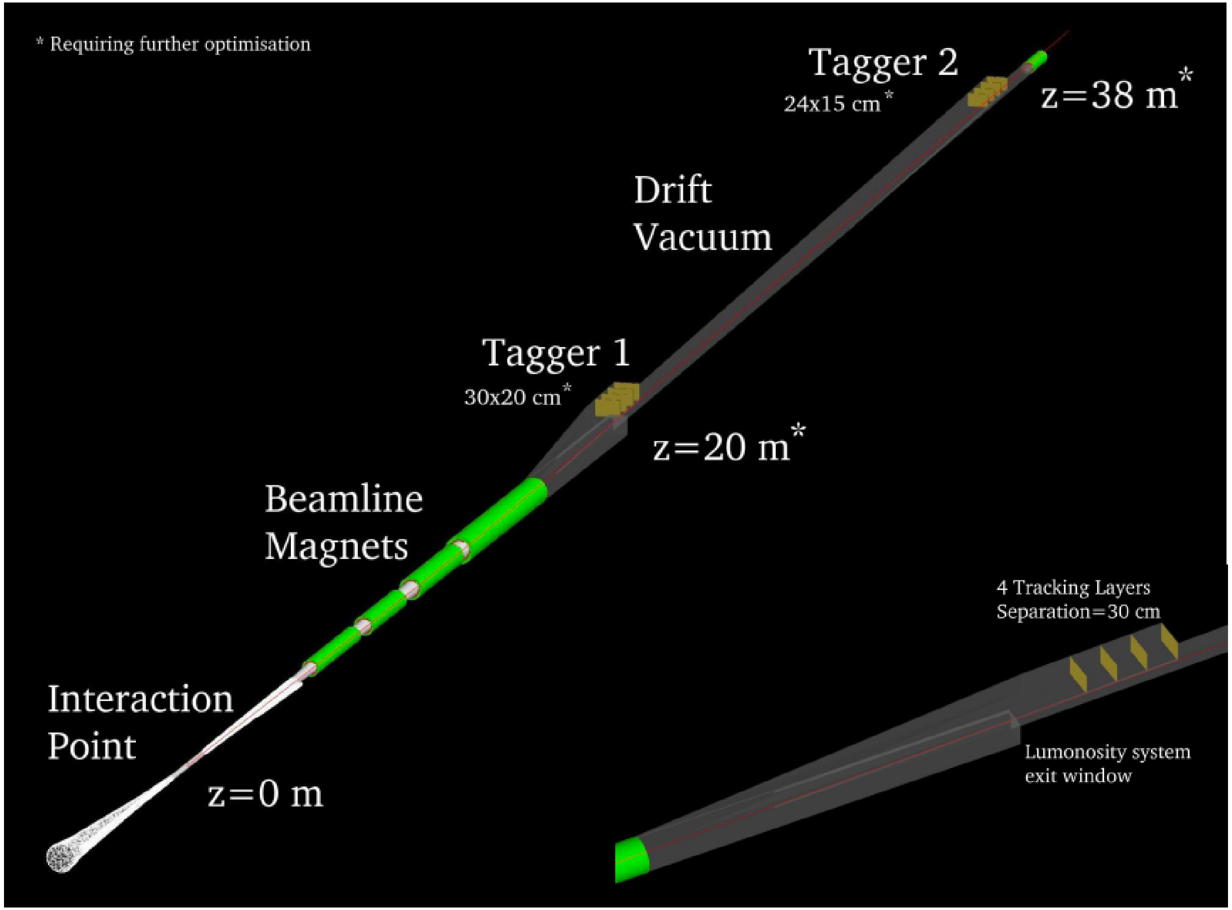
Detector Goals

Large acceptance (>10%)
Good energy resolution $\lesssim$1%
Reconstruction of scattering plane (polarization)
Very high rate capability

Optimum solution

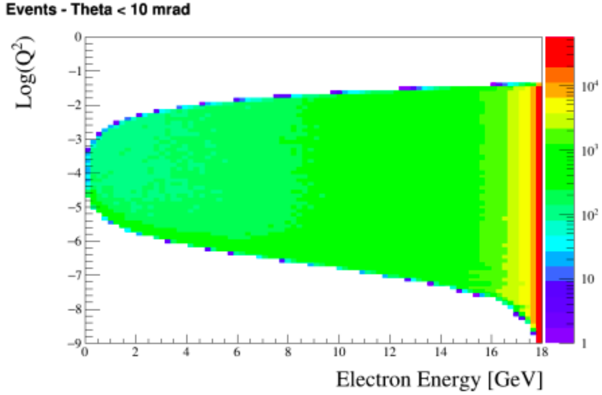
Two in-vacuum tagger modules
3 or 4 layers of pixel detectors
Calorimeter not required (cf. current design)

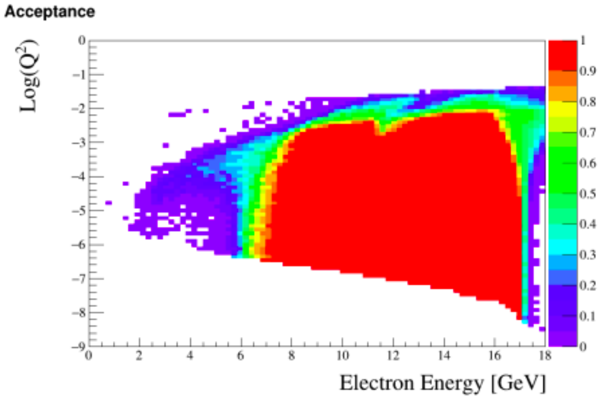
Best technology Timepix4



Ideal photon tagger

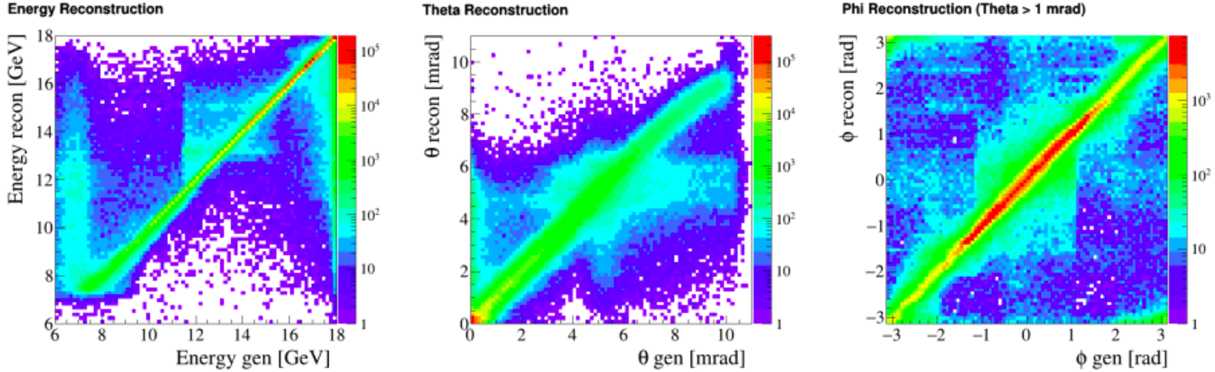
Detector acceptance

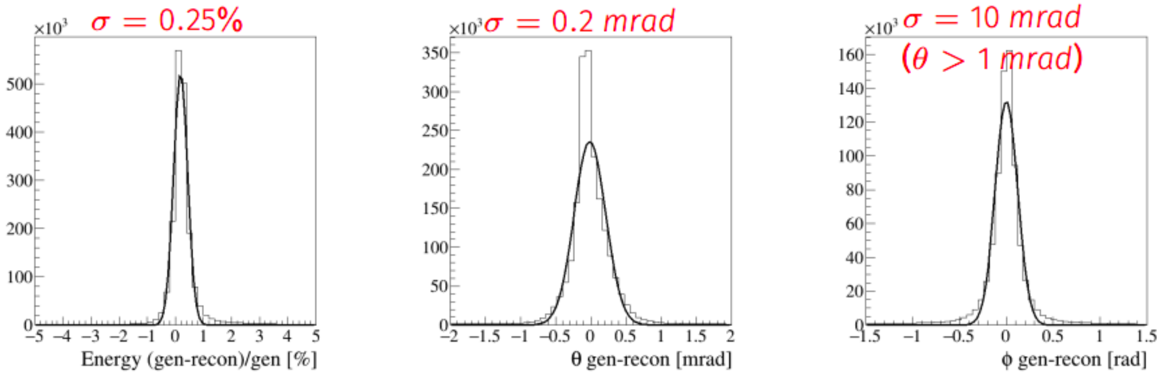




Integrated efficiency = 29%

Kinematic reconstruction (using neural network)





Resolutions

In vacuum tracker and reconstruction technique provides better energy resolution than baseline calorimeter with improved θ and ϕ.

Real photon tagger

Detector acceptance

Kinematic reconstruction (using neural network)

That was for ideal situation of detector in beamline vacuum.

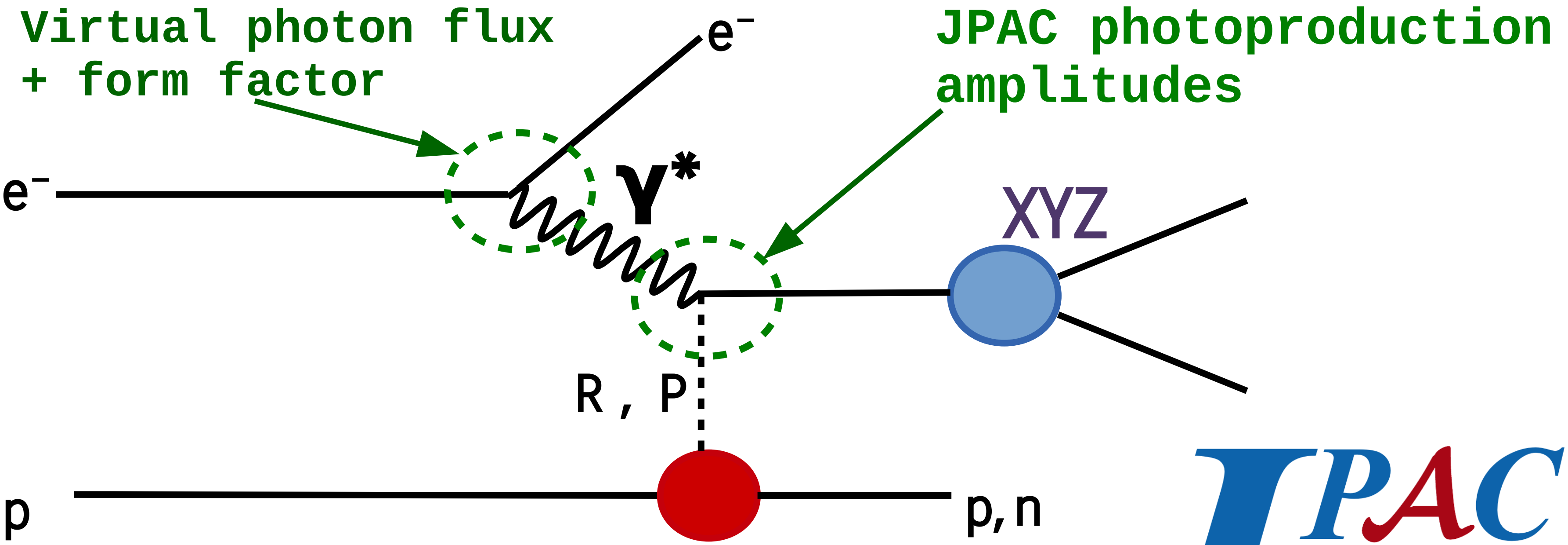
Reality will be outside with poorer acceptance and resolution

Currently under study

resolution than baseline calorimeter with improved θ and ϕ.

Quasi-real Photoproduction of XYZ

Factorise 2 photon vertices



XYZ spectroscopy at electron-hadron facilities: Exclusive processes

M. Albaladejo, A. N. Hiller Blin, A. Pilloni, D. Winney, C. Fernández-Ramírez, V. Mathieu, and A. Szczepaniak
(Joint Physics Analysis Center)

Phys. Rev. D **102**, 114010 – Published 7 December 2020

https://github.com/dwinney/jpacPhoto

Event Generator (Formal)

$$\frac{d^4\sigma}{ds\,dQ^2\,d\phi\,dt} = \frac{d^2\sigma_{e,\gamma*e'}}{dsdQ^2}\frac{d^2\sigma_{\gamma*+p\to V+p}(s,Q^2)}{d\phi\,dt}$$

→ Integrate for event rate

$$\frac{d^2\sigma_{e,\gamma*e'}}{dsdQ^2} = \frac{\alpha}{2\pi}\cdot\frac{K.L}{E}\cdot\frac{1}{Q^2}\cdot\frac{1}{(s-M^2+Q^2)}$$

$$Q^2 = 2\,E\,M\,x\,y$$

$$W^2 = M^2 + 2\,E\,M\,y - Q^2$$

$$L = \frac{1+(1-y)^2}{y} - \frac{2m_e^2\,y}{Q^2}$$

$$\frac{d^2\sigma_{\gamma*+p}}{d\phi\,dt} = \frac{d\sigma^T(Q^2,s)}{d\phi\,dt} + (\epsilon+\delta)\frac{d\sigma^L(Q^2,s)}{d\phi\,dt}$$

$$K = \frac{W^2-M^2}{2M} = \nu(1-x) = Ey(1-x) = \nu - \frac{Q^2}{2M}$$

$$\frac{d^2\sigma^T(Q^2,s)}{d\phi\,dt} = \frac{d^2\sigma_{\gamma+p\to V+p}}{d\phi\,dt}F(Q^2)$$

$$\frac{d^2\sigma^L(Q^2,s)}{d\phi\,dt} = 0$$

$$\frac{d^2\sigma_{\gamma+p\to V+p}}{d\phi\,dt} = \frac{1}{128\pi^2 s}\frac{1}{|\mathbf{p}_{\gamma*cm}|^2}|M(s,t)|^2$$

→ $|M(s,t)|^2$ JPAC Photoproduction Amplitudes

Example, X and Y production

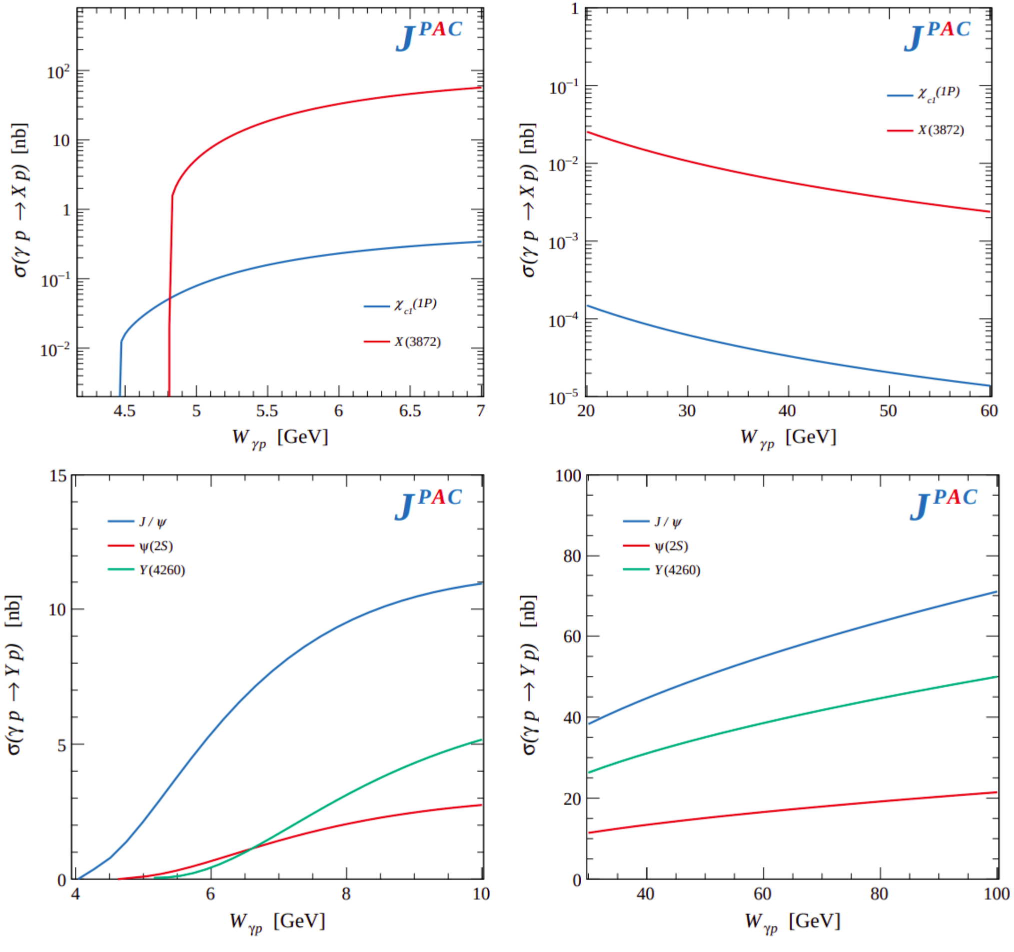
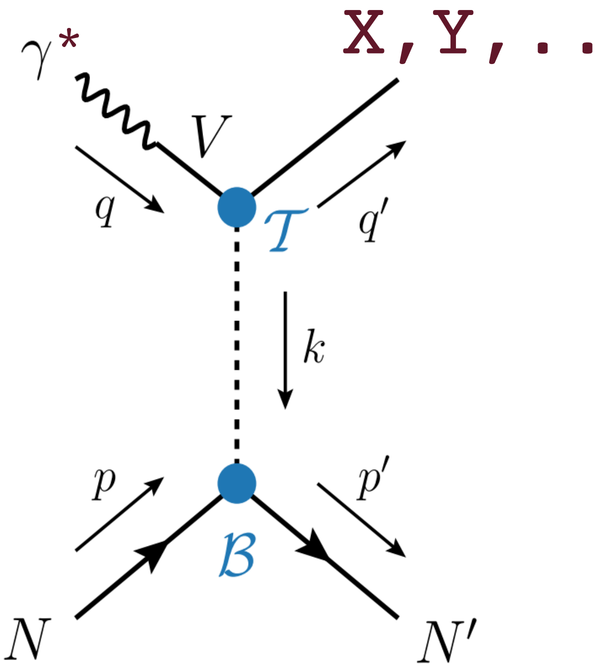


FIG. 7. Cross sections for $Y(4260)$ photoproduction compared to the J/ψ and $\psi(2S)$ at low (left) and high (right) energies.

X – pion exchange
High at threshold
With high virtual
Photon flux

Y – pomeron exchange
Increases with energy
With low virtual
Photon flux

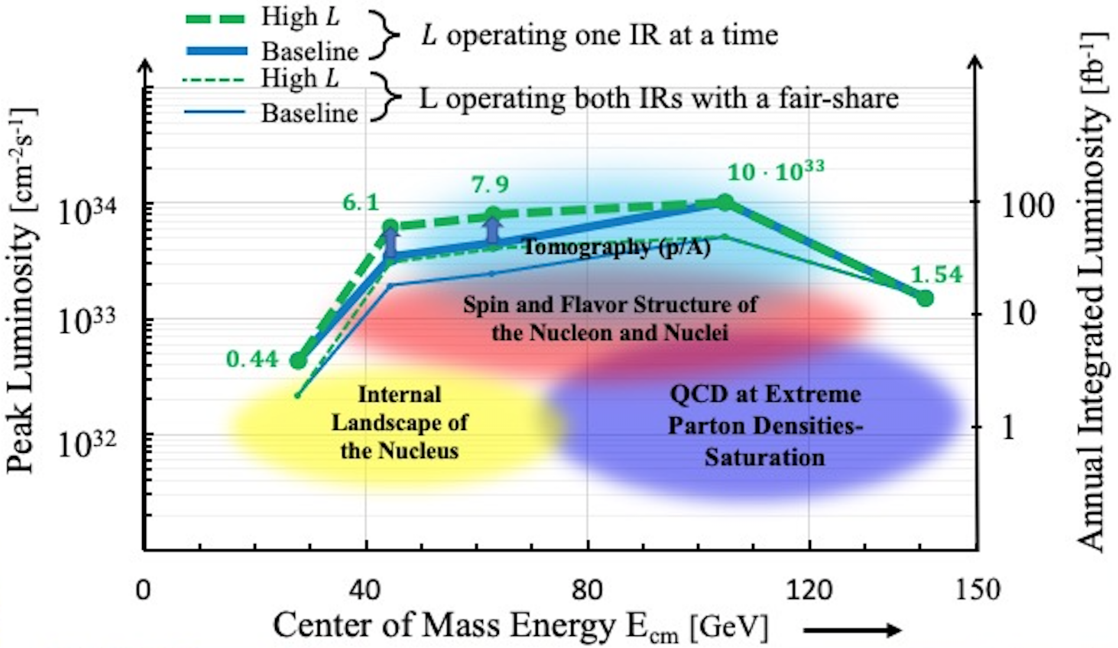


XYZ spectroscopy at electron-hadron facilities: Exclusive processes

M. Albaladejo, A. N. Hiller Blin, A. Pilloni, D. Winney, C. Fernández-Ramírez, V. Mathieu, and A. Szczepaniak (Joint Physics Analysis Center)
Phys. Rev. D **102**, 114010 – Published 7 December 2020

Production estimates for various Exotic candidates

https://www.sciencedirect.com/science/article/pii/S0146641023000133?via%3Dihub



X,Z production benefit from low CM energies
Luminosity too low at 28 GeV
Here focus on 41 GeV configuration
Luminosity assumed 6.1 x 10^{33} cm^{-2}s^{-1}

** Taken from

Progress in Particle and Nuclear Physics
Available online 4 March 2023, 104032
In Press, Corrected Proof What's this?

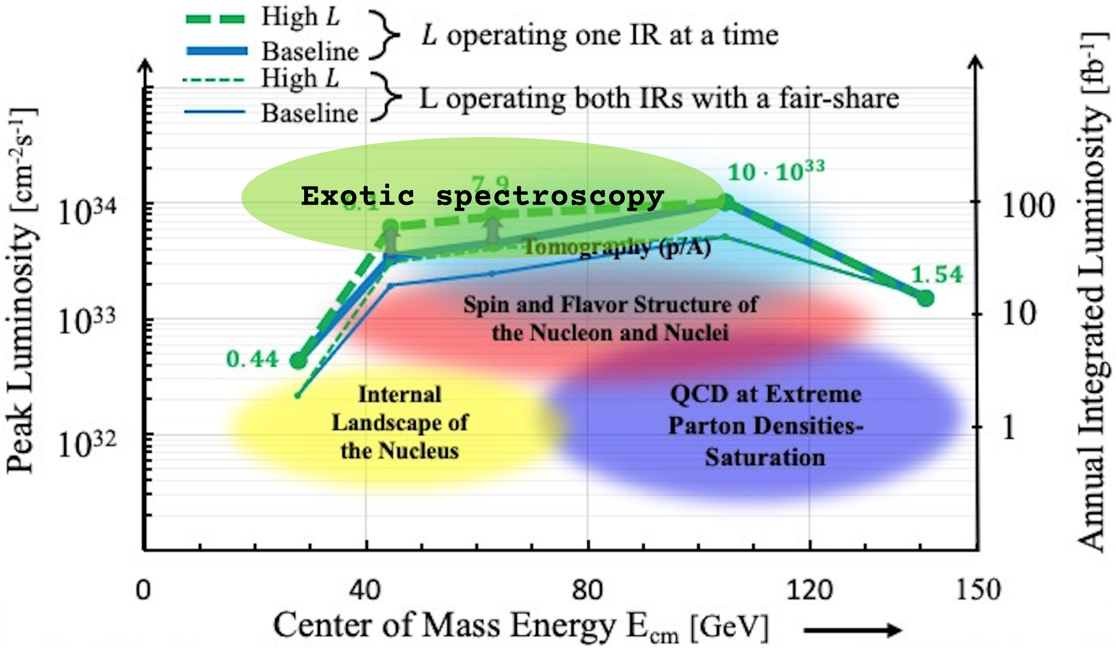
Review

Precision studies of QCD in the low energy domain of the EIC

TABLE II. Summary of results for production of some states of interest at the EIC electron and proton beam momentum $5 \times 100(GeV/c)$ (for electron x proton). Columns show : the meson name; our estimate of the total cross section; production rate per day, assuming a luminosity of 6.1×10^{33} cm^{-2}s^{-1}; the decay branch to a particular measurable final state; its ratio; the rate per day of the meson decaying to the given final state.

Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\ \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\ J/\Psi$	100	46
$Z_{cs}(4000)$	0.23	0.20 M	$J/\Psi\ K^+$	10	1.2 k
$Z_b(10610)$	0.04	0.034 M	$\Upsilon(2S)\ \pi^+$	3.6	24

Production estimates for various Exotic candidates



X,Z production benefit from low CM energies
Luminosity too low at 28 GeV
Here focus on 41 GeV configuration
Luminosity assumed 6.1 x 10^{33} cm^{-2}s^{-1}

** Taken from

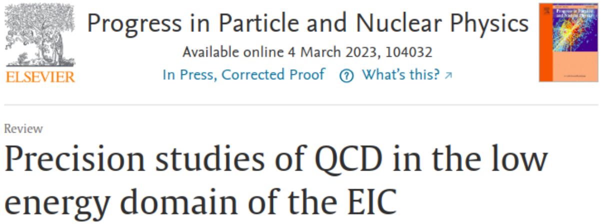


TABLE II. Summary of results for production of some states of interest at the EIC electron and proton beam momentum $5 \times 100(GeV/c)$ (for electron x proton). Columns show : the meson name; our estimate of the total cross section; production rate per day, assuming a luminosity of 6.1×10^{33} cm^{-2}s^{-1}; the decay branch to a particular measurable final state; its ratio; the rate per day of the meson decaying to the given final state.

Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\ \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\ J/\Psi$	100	46
$Z_{cs}(4000)$	0.23	0.20 M	$J/\Psi\ K^+$	10	1.2 k
$Z_b(10610)$	0.04	0.034 M	$\Upsilon(2S)\ \pi^+$	3.6	24

Production rate estimates only

Detection not included

Simulations for ECCE Proposal

Produce X,Y,ψ(2S) based on jpacPhoto & elSpectro

Produce events for 10 fb^{-1} (2-3 weeks)

Here focus on 5 Gev e- and 100 GeV proton beams

Approximately 300k events

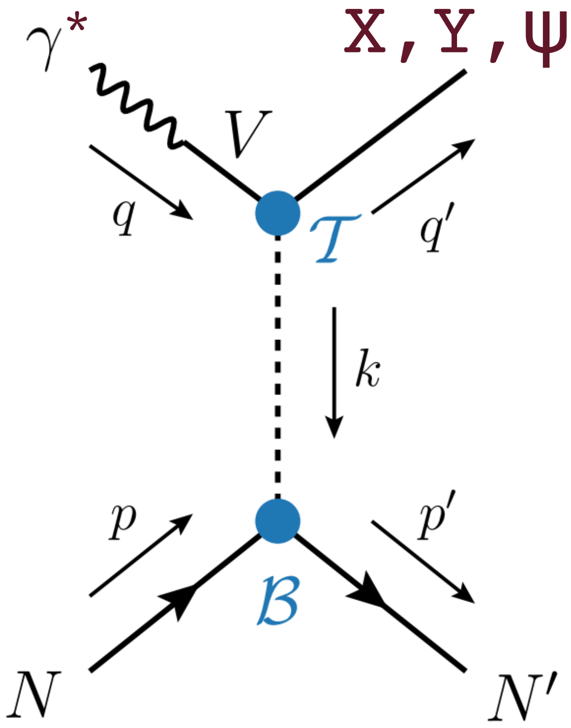
Exclusive acceptance estimate around 10%

Simple Analysis results :

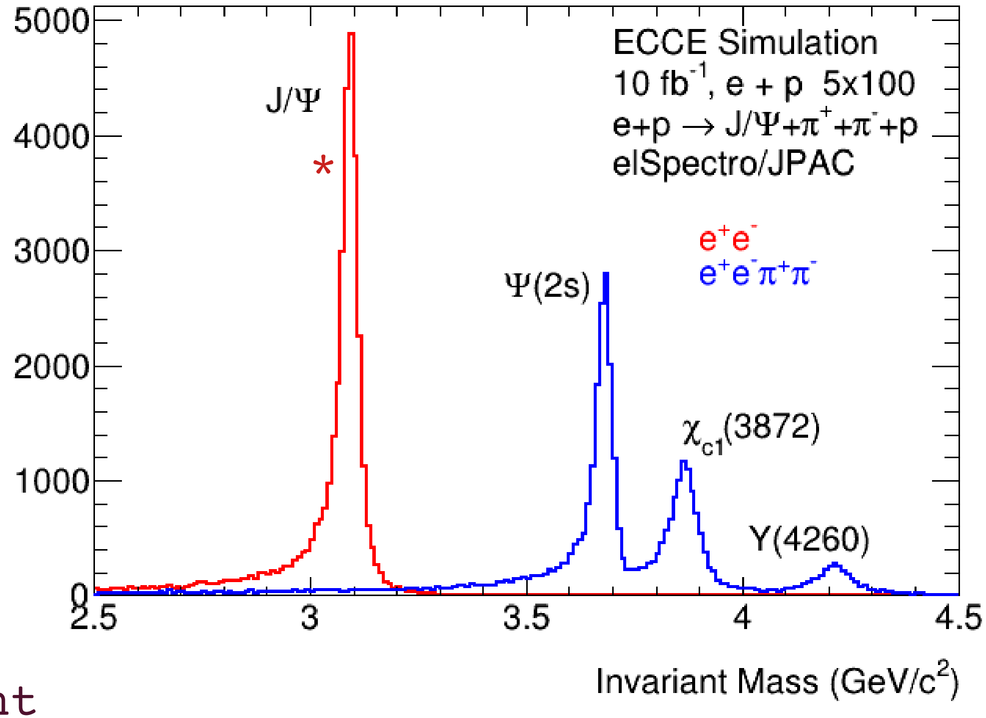
- Just using track momentum
- Take PID from truth (100% efficient)
- Calculate Energy from momentum

ECCE Spectroscopy Simulations

Meson → $J/\psi\ (e^+e^-)\ \pi^+\pi^-$



ecce-note-phys-2021-12



Low Q^2 => small angles very important

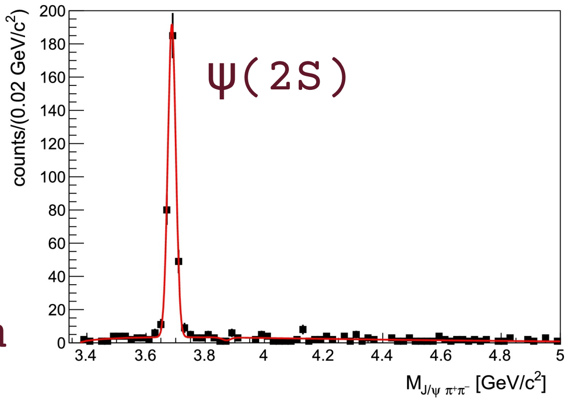
Low t e-′ and nucleon detection

* only J/ψ from Meson decays

X(3872) at COMPASS

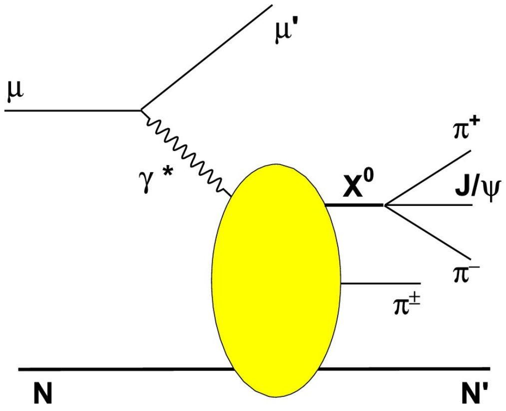
Physics Letters B
Volume 783, 10 August 2018, Pages 334-340

Search for muoproduction of $X(3872)$ at COMPASS and indication of a new state $\widetilde{X}(3872)$

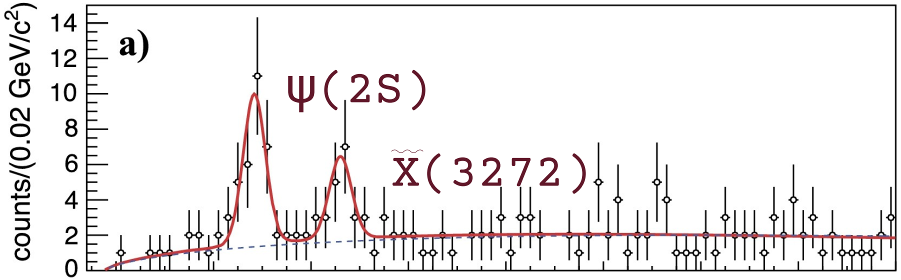


Little signal in direct J/ψππ

Similar production mechanism

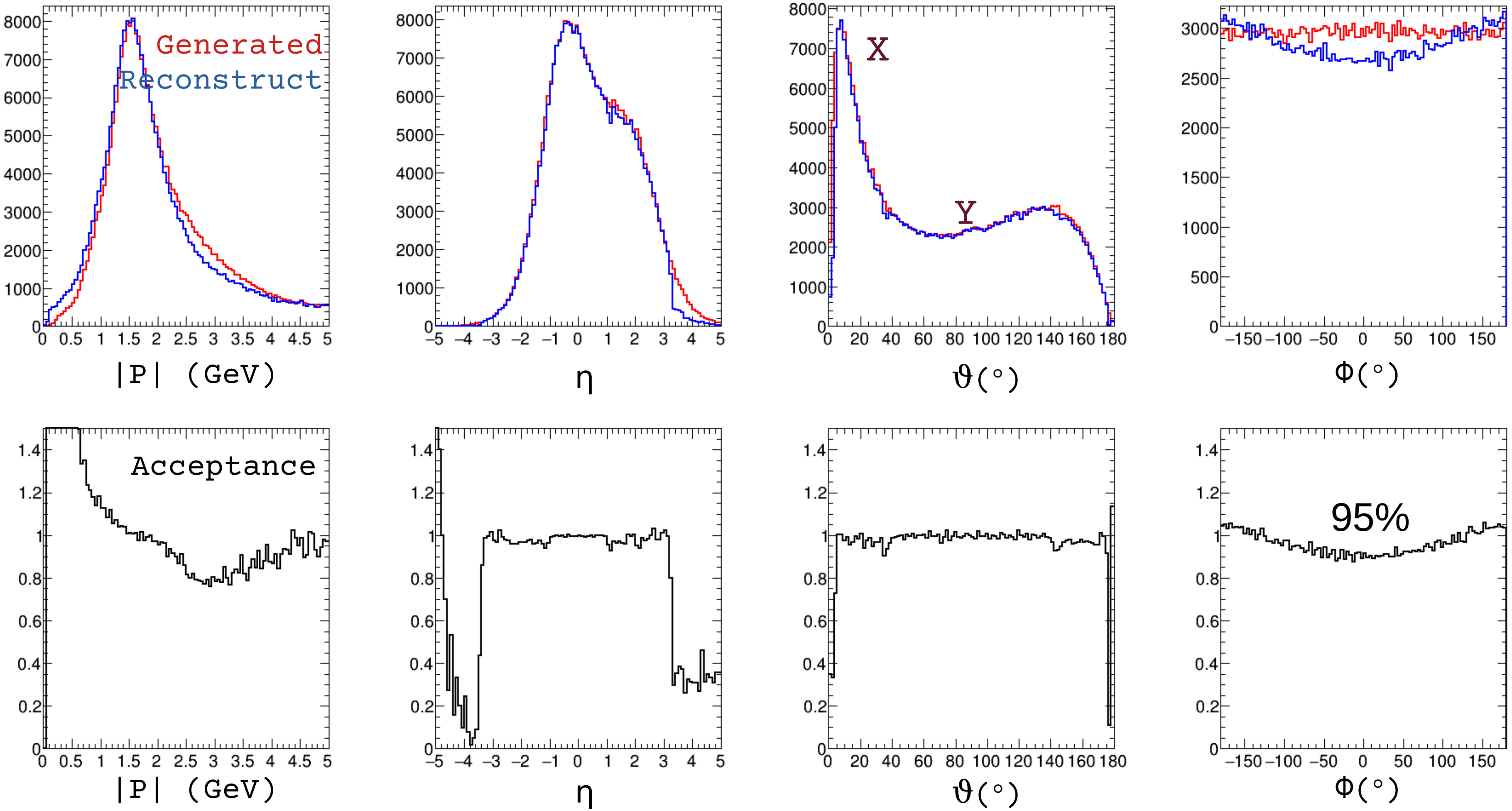


But X like peak
Seen when produced
With extra pion



Suggest a 1+- state instead of 1++ …

J/ψ decay e+ acceptances at 1.5T



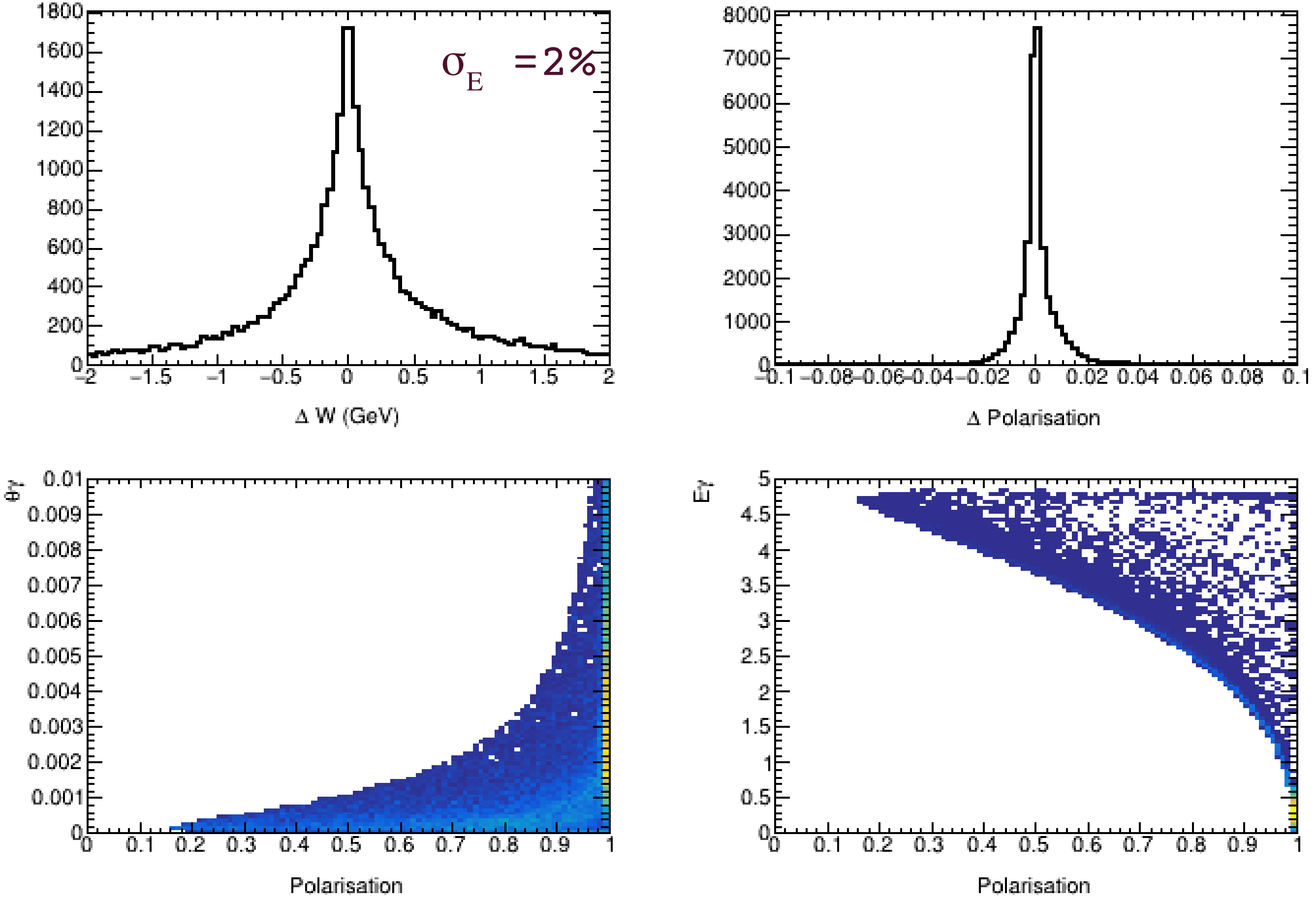
Other Useful Kinematics

Low Quasi-real Tagger can also provide :

Reaction W

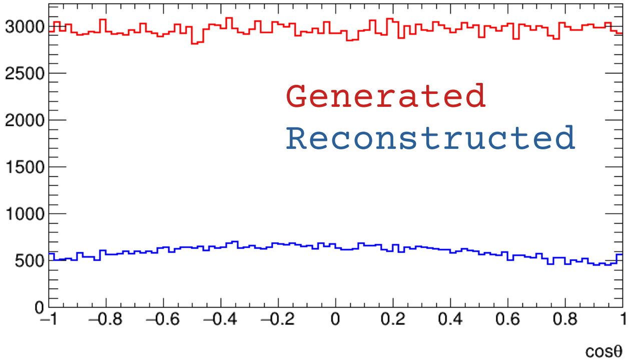
Electron scatter plane

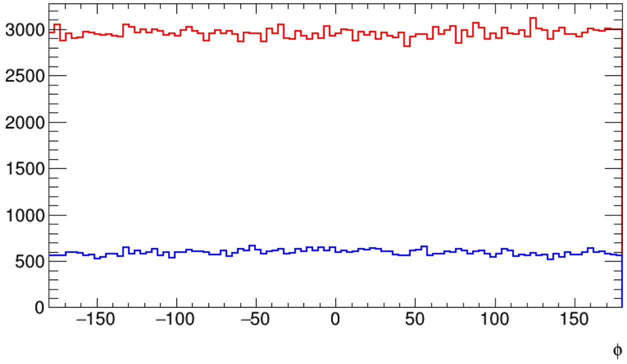
Transverse Polarisation
=> extra observables
(photon asymmetries,
polarised SDMEs)

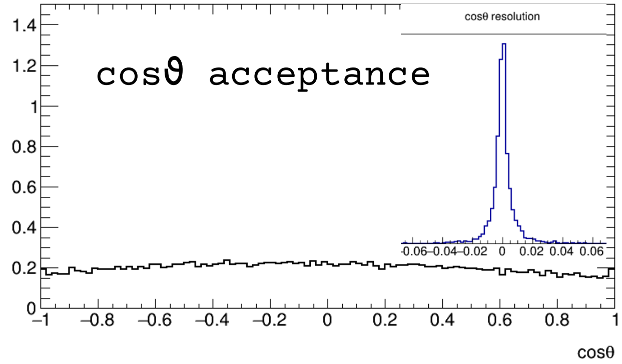


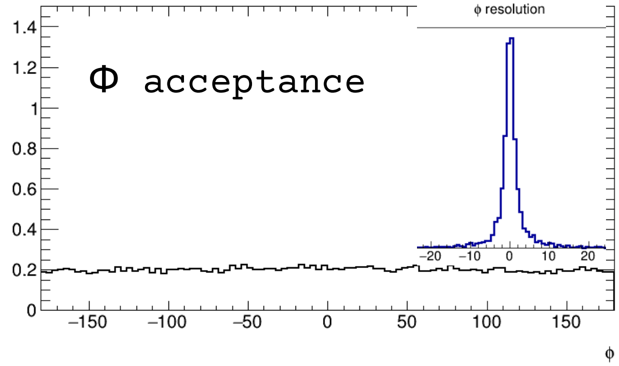
** Dependent on final
Quasi-real photon tagger design

Meson Decay angles









Decay angles of J/ψ in X rest frame

* Flat acceptances
* “Good” resolutions

  0.01 cosϑ

  5° Φ

*Looks good for SDME and quantum numbers

See later

Z_c(3900) quasi-real photoproduction

$Z_c \to J/\psi\ \pi+$

Branch R. 10%

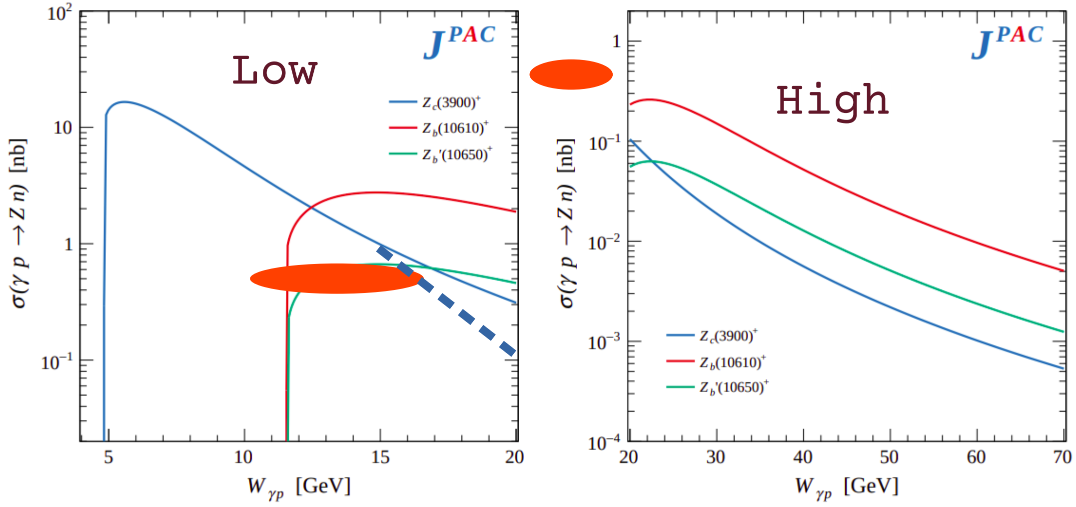
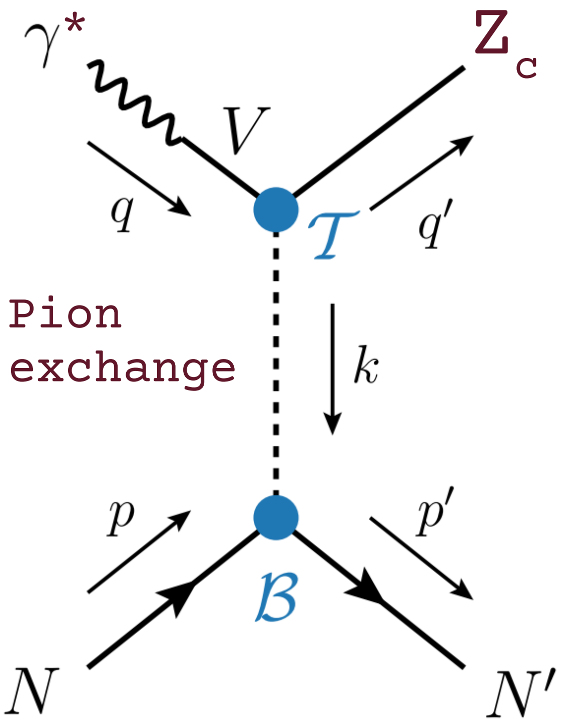


FIG. 2. Integrated cross sections for the three Z states considered. Left panel: predictions for fixed-spin exchange, which we expect to be valid up to approximately 10 GeV above each threshold. Right panel: predictions for Regge exchange, valid at high energies.



JPAC model for Z_c

Interpolation from low to high

COMPASS upper limit PLB 742,300 2015

Suggest estimates could be high by order of magnitude at W ~ 10 GeV

Semi Inclusive Meson Production

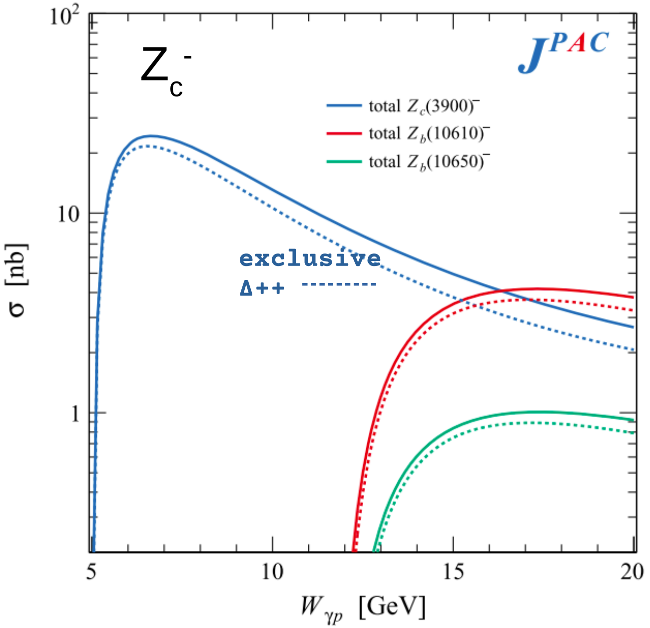
XYZ spectroscopy at electron-hadron facilities. II. Semi-inclusive processes with pion exchange

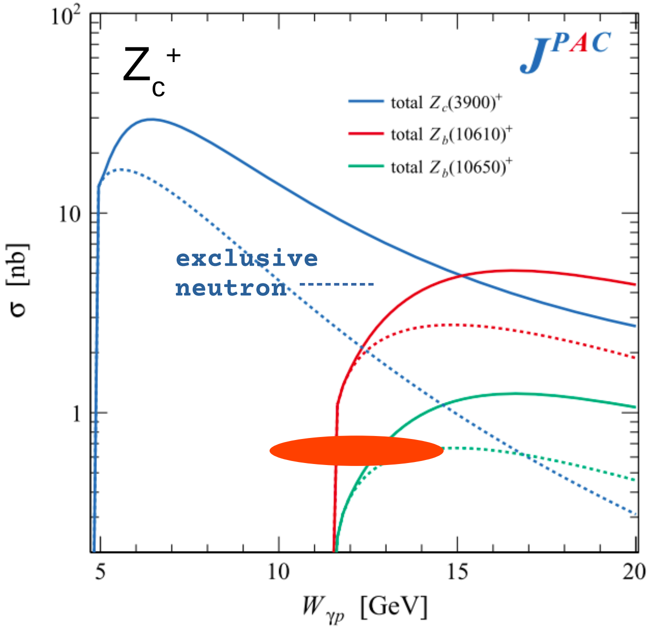
D. Winney, A. Pilloni, V. Mathieu, A. N. Hiller Blin, M. Albaladejo, W. A. Smith, and A. Szczepaniak (Joint Physics Analysis Center)

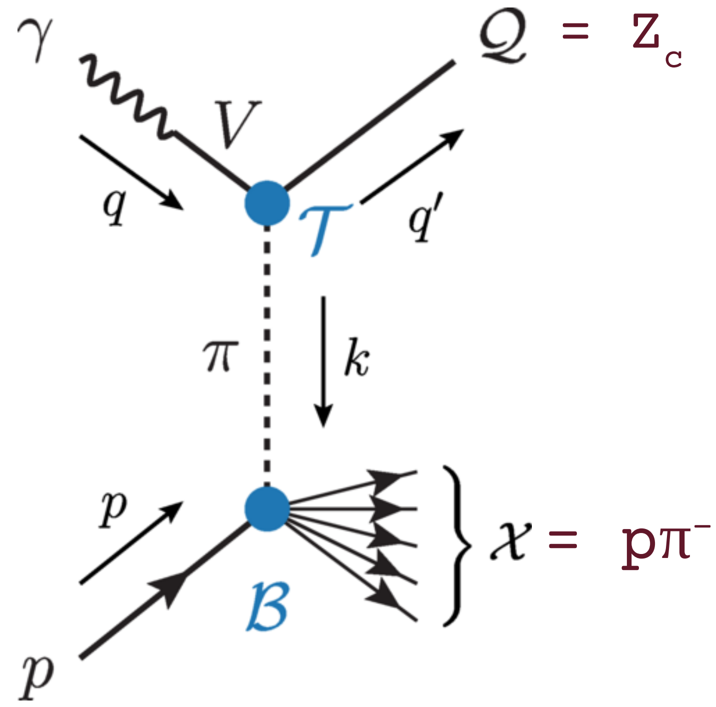
Phys. Rev. D **106**, 094009 – Published 7 November 2022

$$E_{\mathcal{Q}} \frac{d^3\sigma}{d^3 q_f} = \frac{K}{16\pi^3} |T_\pi(t) \mathcal{P}_\pi|^2 \sigma_{\text{tot}}^{\pi^* N},$$

Bottom vertex => SAID pion scattering

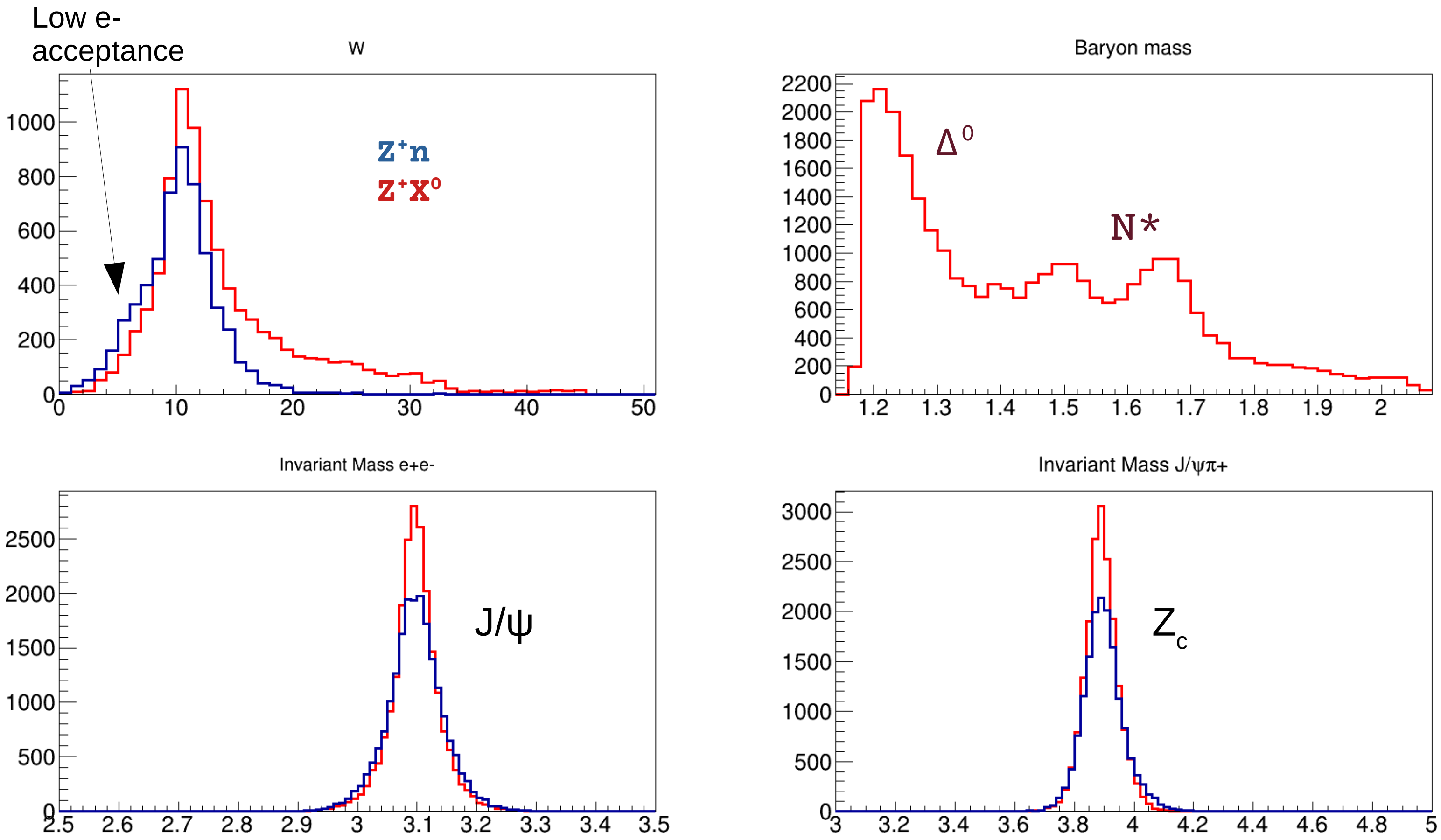






Inclusive higher at high W =>
Better meson detection
- more transverse momentum
Better e−′ detection
- higher acceptance at lower $P_{e'}$

Detected events for Z^+X^0 @ 5x100



Require e-' detection
Quasi-real tagger
$0.45E_0 < E < 0.95E_0$
$\theta < 6$ mrad, $\sigma_E = 1\%$

"Simulations" with
Eic-smear fastmc
10fb-1 (~2 weeks)

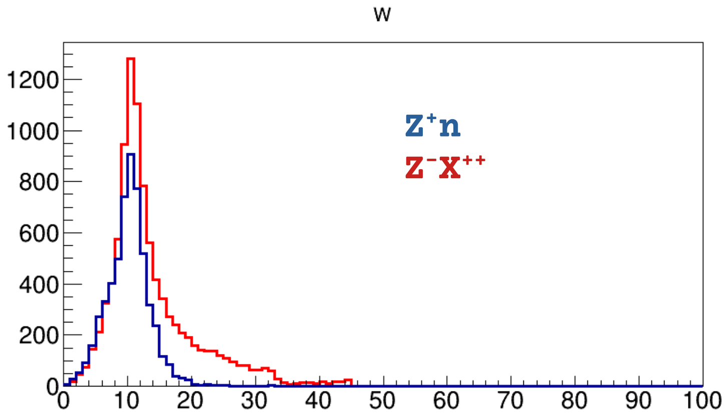
Semi-inc σ 30% lower

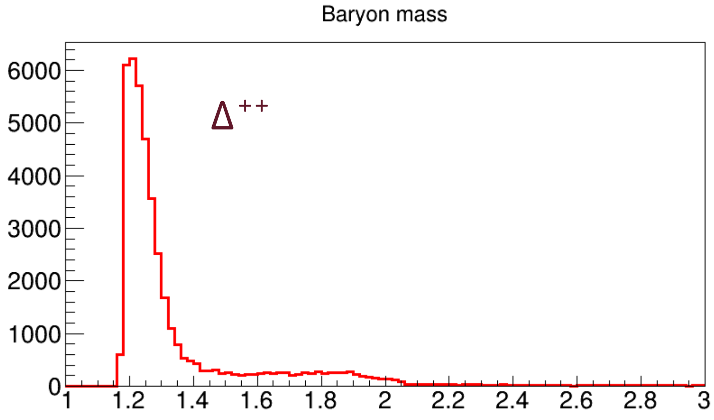
But weighted to high W

=> better e- acceptance
better Z+ acceptance

Ignore X^0 detection

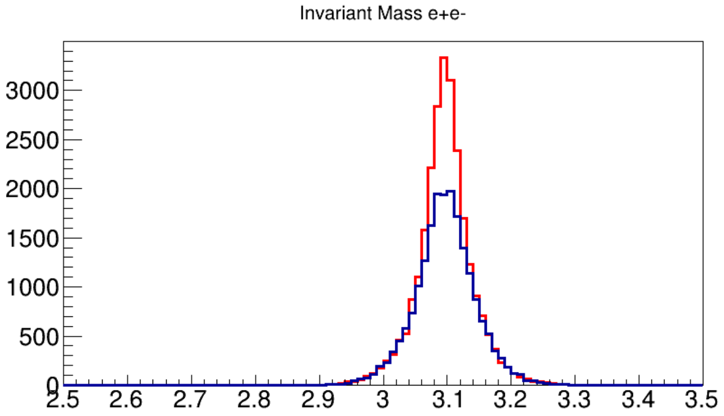
Detected events for Z^-X^{++} @ 5x100

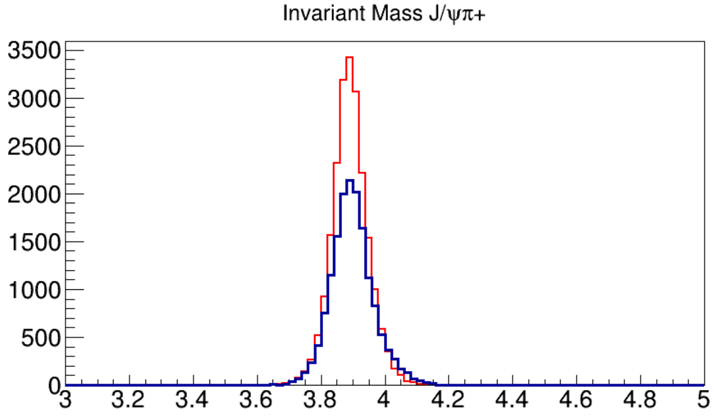




Require e-' detection
Quasi-real tagger
$0.45E_0 < E < 0.95E_0$
$\theta<6$ mrad, $\sigma_E = 1\%$

"Simulations" with
Eic-smear fastmc





Semi-inc σ similar

Weighted to high W

=> better e- acceptance
better Z+ acceptance

Ignore X^{++} detection

Overall > factor 3 more events with inclusive channels

Charmonium(like) spectroscopy with Energy upgraded CLAS12
Opportunities with Jlab Energy and Luminosity Upgrade
26th September 2022

https://indico.ectstar.eu/event/152/contributions/3134/attachments/2004/2614/ECTstarCLAS24.pdf

See also

Prospects for XYZ Spectroscopy at GlueX, Sean Dobbs

https://indico.ectstar.eu/event/152/contributions/3136/attachments/2006/2617/Trento_JLabUpgrade22.pdf

Science at the luminosity frontier : Jefferson Lab at 22 GeV

https://www.jlab.org/conference/luminosity22gev

https://indico.jlab.org/event/677/contributions/11996/attachments/8793/12692/XYZMitchell.pdf , R. Mitchell

https://indico.jlab.org/event/677/contributions/11997/attachments/8794/12693/XYZ_jlab.pptx , A. Pilloni

White paper (to be published)

“Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab”

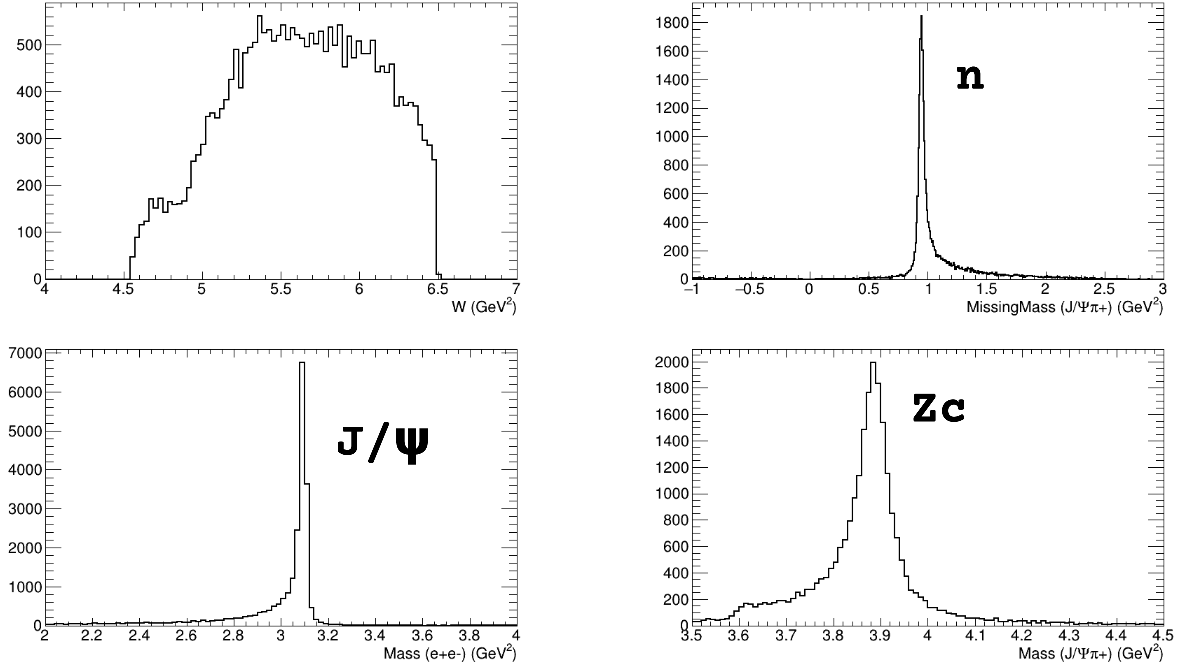
P. Rossi “New Opportunites with Jefferson Lab at 22 Gev” Thursday 10am

Full CLAS12 simulation at 22GeV

Use full CLAS12 gemc simulation and reconstruction

Assume scattered e- detected in “Zero degree spectrometer”

Do not detect the recoil neutron -reconstruct from other particles masses



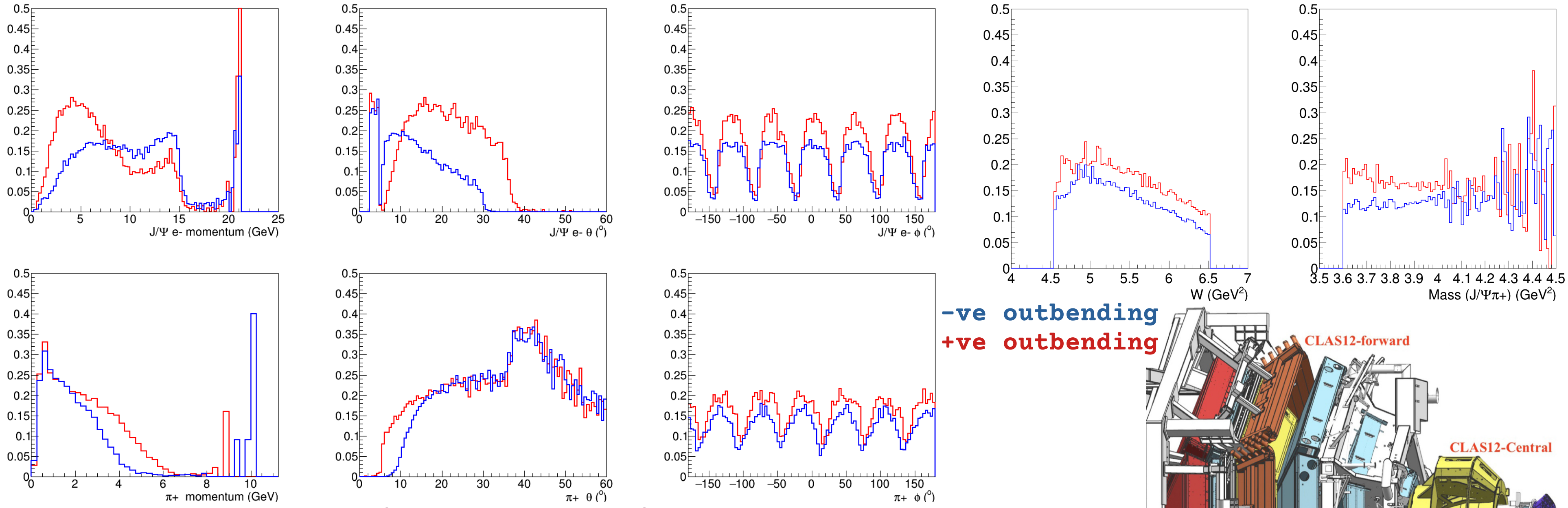
J/ψ Near-Threshold Photoproduction off the Proton and Neutron with CLAS12

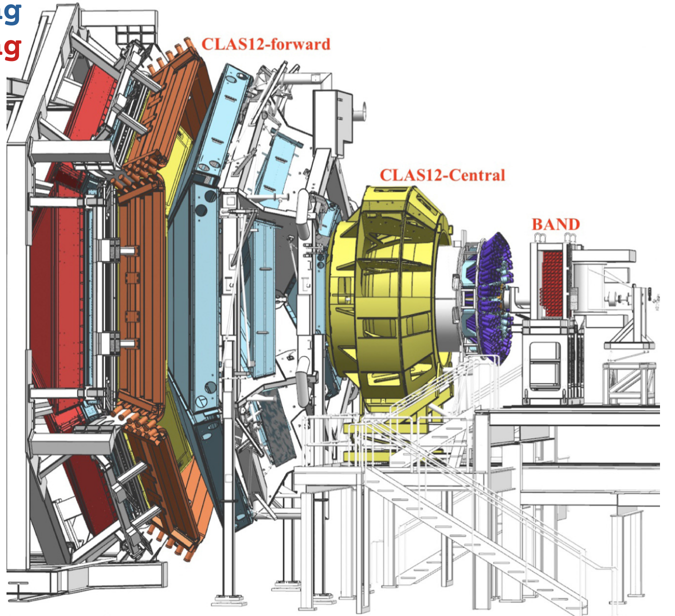
R. Tyson, 1630 Thursday

Exploring the gravitational structure of the proton with the dilepton final state…

P. Chatagnon, 0930 Friday

Acceptances @ 22GeV





Results for combined detection of 2e−,e+,π+
Assuming luminosity $10^{35}cm^{-2}s^{-1}$
and 50 days gives 210k (109k) events.
With 22 (17) GeV beam momentum
Acceptance ~ 10% for ~20k events
CLAS12 could be supplemented with
new quasi-real tagger for this

Z_c decay and amplitudes

$$\mathcal{I}(\Omega,\Phi) = \mathcal{I}^0(\Omega) - \mathcal{P}.\mathcal{I}^1(\Omega)\cos 2\Phi - \mathcal{P}.\mathcal{I}^2(\Omega)\sin 2\Phi.$$

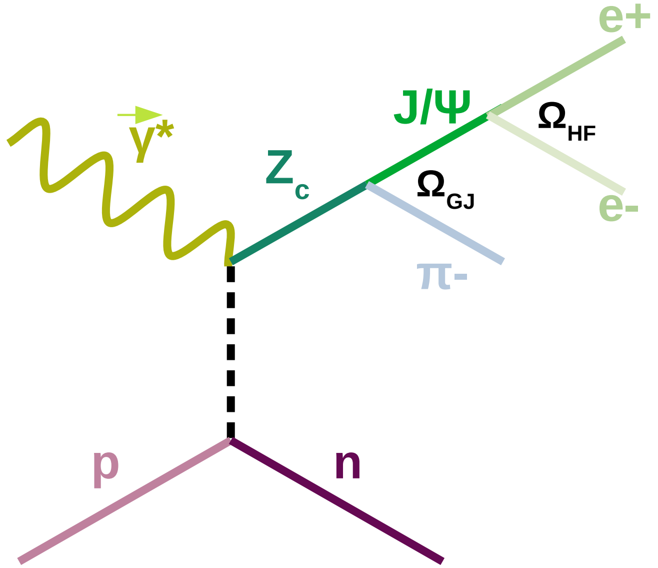
$$\mathcal{I}^\alpha(\Omega,\Phi) = \sum_{r,r'}\sum_{m,m'}\sum_{\lambda,\lambda'}\sqrt{\frac{2l+1}{4\pi}}\sqrt{\frac{2s+1}{4\pi}}\sqrt{\frac{2l'+1}{4\pi}}\sqrt{\frac{2s'+1}{4\pi}}$$
$$\times (l,0;s,\lambda|j,\lambda)(l',0;s',\lambda'|j',\lambda')$$
$$\times D^j_{m,\lambda}(\phi_{GJ},\theta_{GJ},0)D^s_{\lambda,0}(\phi_{HF},\theta_{HF},0)R_{Yi}(m_Y)$$
$$\times D^{j'*}_{m',\lambda'}(\phi_{GJ},\theta_{GJ},0)D^{s'*}_{\lambda',0}(\phi_{HF},\theta_{HF},0)R^*_{Yi'}(m_Y)\times\rho^\alpha_{rr',mm'}.$$

$$\rho^0_{rr',mm'} = \sum_k T^{k,\eta}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta'}_{r,m}T^{k,\eta'}_{r',m'},$$

$$\rho^1_{rr',mm'} = \sum_k T^{k,\eta'}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta}_{r,m}T^{k,\eta'}_{r',m'},$$

$$\rho^2_{rr',mm'} = i\sum_k -T^{k,\eta'}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta}_{r,m}T^{k,\eta'}_{r',m'},$$

r = {j,l,s} = {j=1,l=(0,2),s=1}
And m = -1,0,1 for Z→ J/Ψ+π
k = spin of proton
η = photon helicity

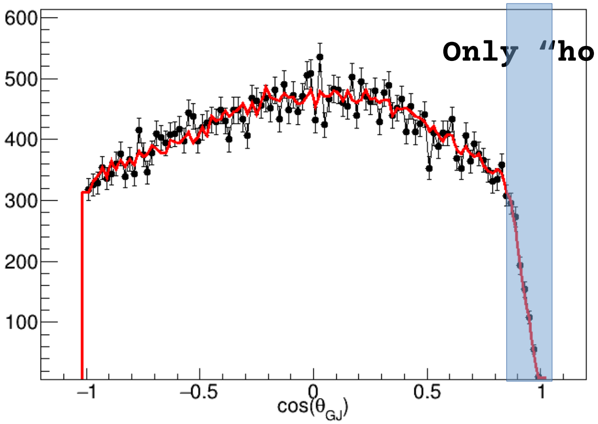


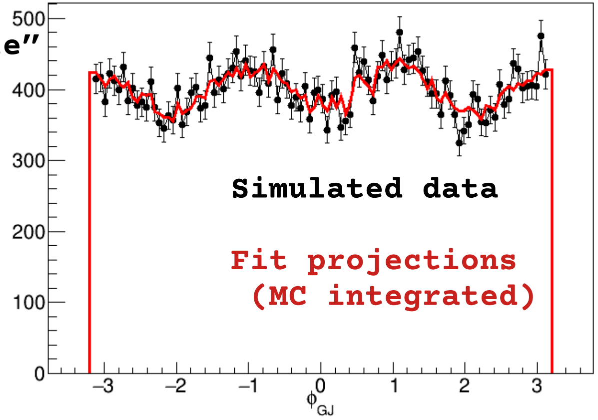
Could determine production amplitudes for partial waves in terms of J,L,S,M,P of resonance, photon helicity

Can this give any information on structure/nature ?

e.g $T_S/T_D \rightarrow 0$ "if molecular", large "if tetraquark"
$|T^{\eta=+1}_{m=1} - T^{\eta=-1}_{m=-1}| \rightarrow 0$ "if tetraquark"

Extracting spin information simulation @EIC





Generate data with given Transition amplitudes.

Fit model on simulated data

$j<3$, $|m|<j$, $l<4$, $s=1$, $\eta=\pm1$

$|T^{\eta}_{jlsm}|$ T^{+}_{1011} = 0.34±0.01 (0.35)

T^{+}_{101-1} = 0.43±0.01 (0.45)

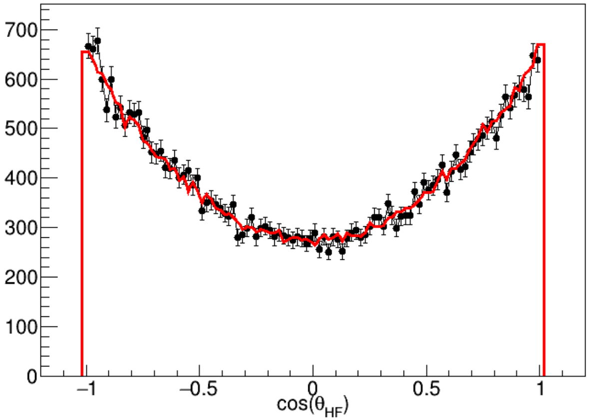
T^{+}_{1210} = 0.55±0.01 (0.55)

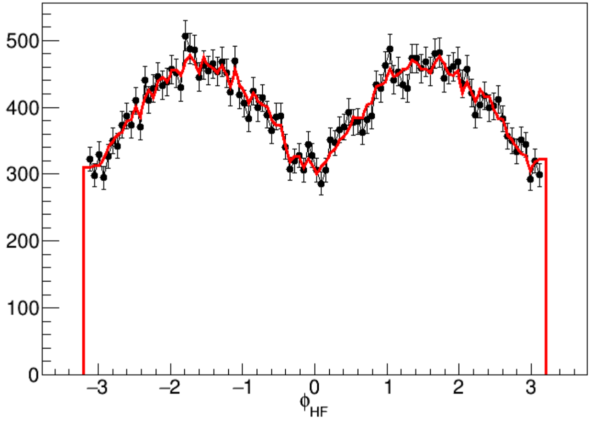
ϕ^{η}_{jlsm} ϕ^{+}_{1011} = 0.04±0.04 (0.04)

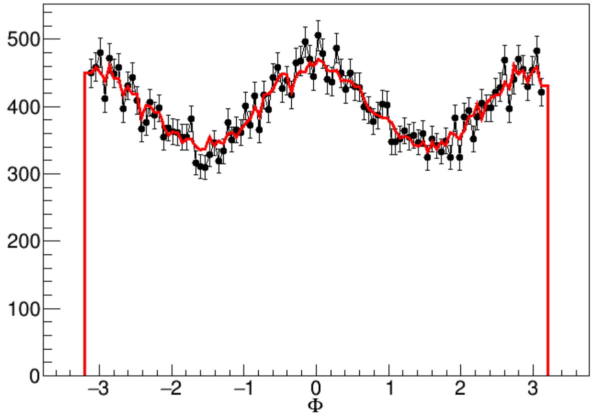
ϕ^{+}_{101-1} = 1.24±0.04 (1.20)

ϕ^{+}_{1210} = 2.20±0.04 (2.20)

All other amplitudes consistent with 0







Toy dataset consists 40k events, estimated 20 weeks running, eic-smear.

Conclusions

The EIC could provide a new tool for investigating exotic states

Low (and uncertain) cross sections and small branching ratios are main issue. Detector designs ongoing

Production rates at nominal luminosities could be up to O(1000)/day

We could expect to reconstruct around 10% fully exclusive events (most events lost in far forward/backward regions)

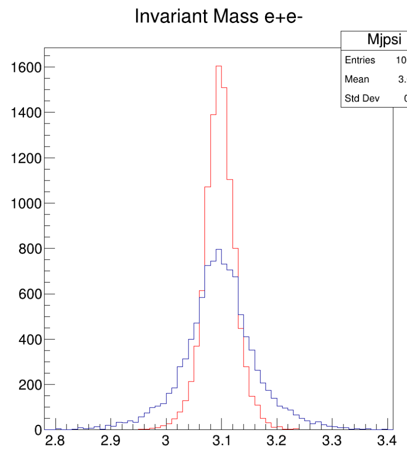
Inclusive channels can significantly enhance the yields

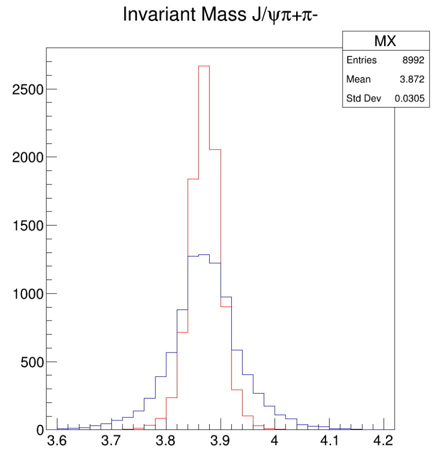
Given sufficient statistics polarised SDMEs should be measurable

Many possible mesons and final states to simulate…

Further work on best Physics observables needed.

Detector effects on Invariant Masses





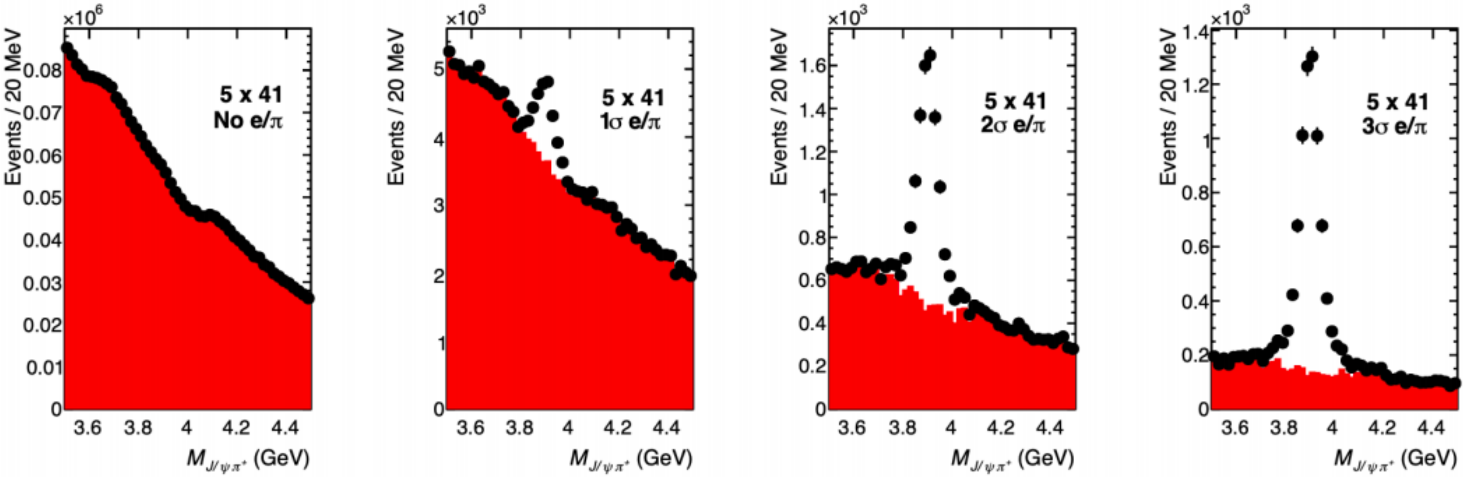
EIC smear for different field strengths

1.5T (65MeV)

3.0T (30MeV)

Will actually have ~1.7T

e/π seperation also significantly improves signal/background



Pythia

$Z_c \rightarrow J/\psi\pi^+$

J.Stevens
from yellow report

Photoproduction of exotic mesons

1) Identify photoproduction of the narrow XYZ states. Typically these have only been seen in 1 production mechanism and photoproduction offers a clean mechanism whereby any resonance should be able to be photoproduced and therefore we would validate if these are real poles.

2) As photoproduction can produce any state we may see states that haven't been produced in other mechanisms. For example no "exotic" tensor mesons have been identified yet.

3) Photoproduction offers a means to determine quantum numbers of produces states, in particular we may search for broader overlapping states. Polarised beams give us a greater handle on this.

4) The nature of the observed states is a matter of great discussion. How these states behave in different production mechanism can help us understand the underlying dynamics (tetraquark, molecules, hybrids). Things like photocouplings or even Q2 dependences can be helpful here.

5) We can look for many varieties of decay products $J/\psi + \pi$ or K or vector or ... which are not well established at other experiments.

Useful Exclusivity variables

i.e. If measure everything

ΔP_t difference : Here we take proton in Far Forward

= P_t {calculated proton – measured proton}

$\Delta\Phi$, Production Plane difference : Φ_{meson} – Φ_{proton}

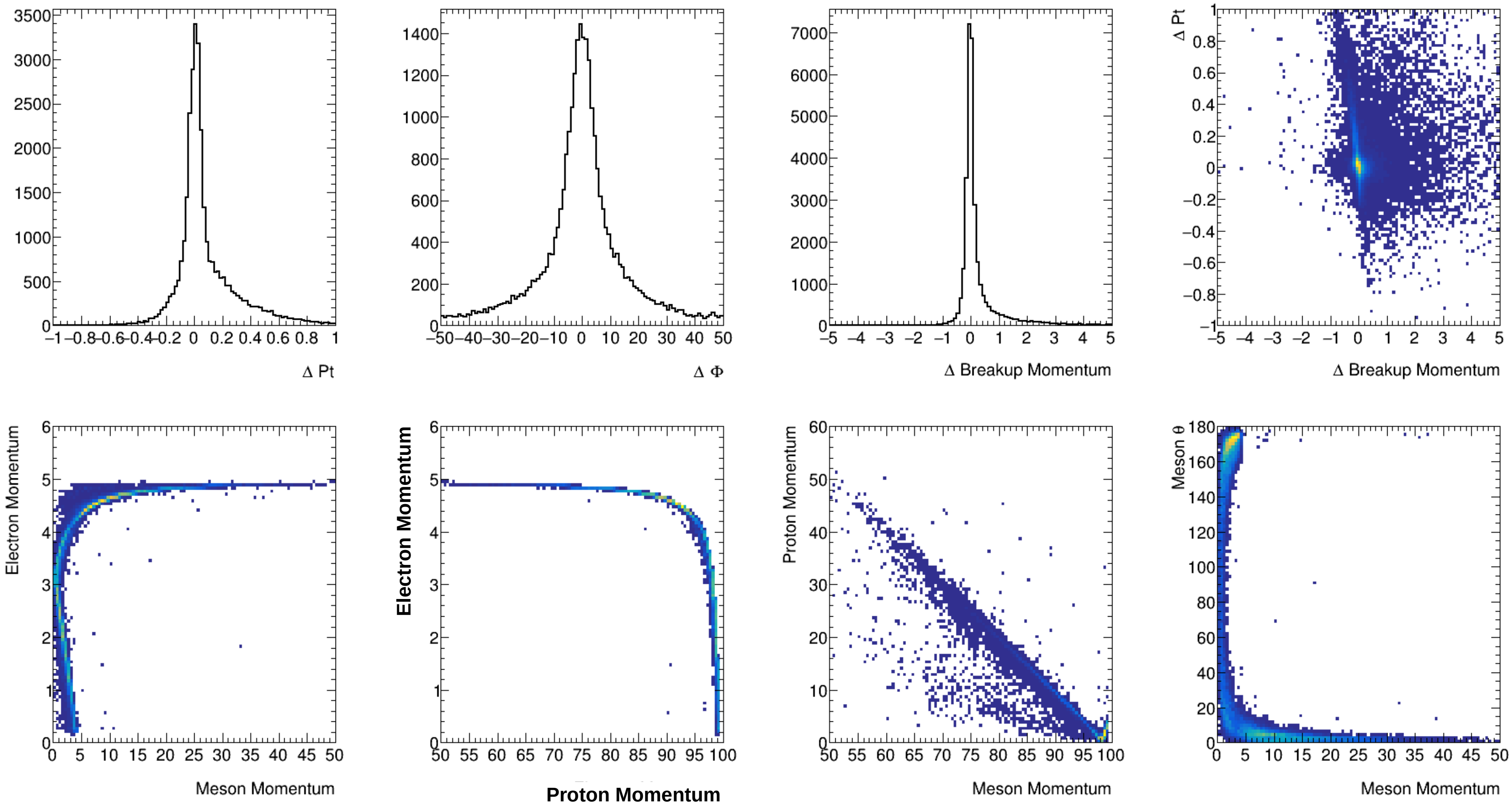
Centre of Momentum frame Δ Breakup Momentum, P_{break} :

$P_{break}(E_\gamma, M_p, M_{meson})$ – $P_{break}(E_\gamma, meson)$ second term boosts meson into CM

γ= (e^- beam) – (e'^- scattered) Here we take e-' in QuasiReal Tagger

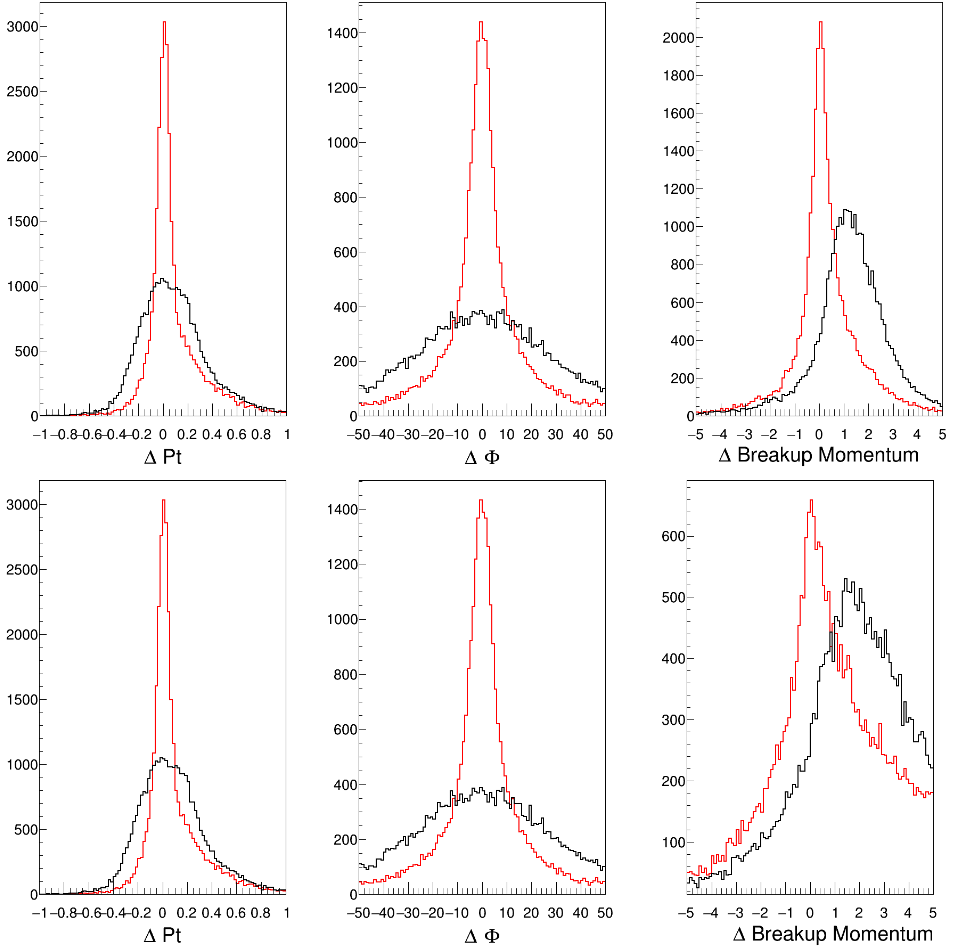
* Can also P_z of nucleon, giving 1 further condition

True Electron, True Proton, Realistic Meson



Missing Pion Background

Proton-Meson observables Electron-Meson



Top 2% electron resolution
Bottom 10% electron resolution

Fully Exclusive
Missing Pion

Some discrimination between Exclusive Signal and background

Exclusive Photoproduction (Quasi-real)

Observation of XYZ states in photoproduction
- independent confirmation

Different production mechanism, different kinematics

Measurement of polarisation observables and photocouplings
- insights into production mechanisms and internal structure

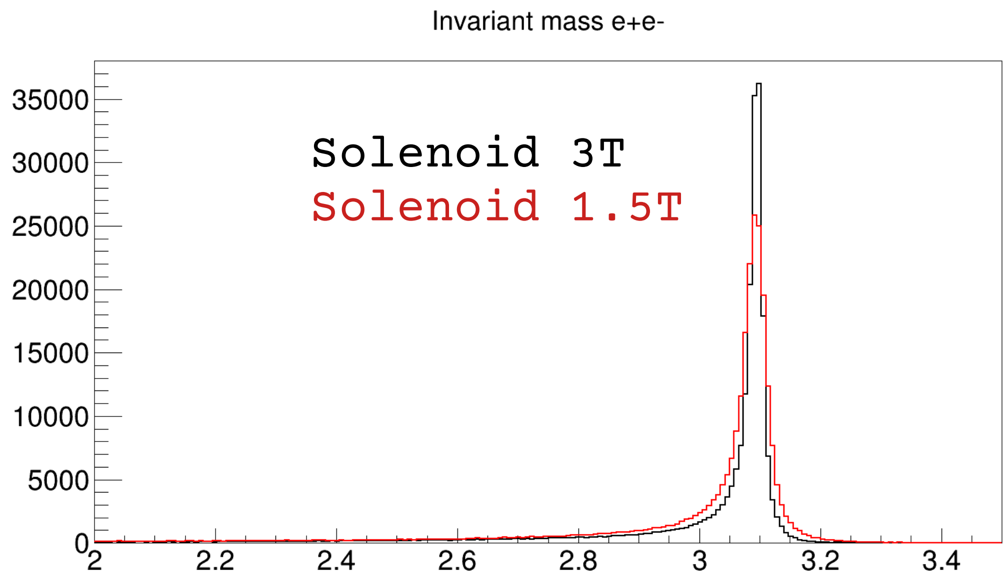
XYZ spectroscopy at electron-hadron facilities: Exclusive processes

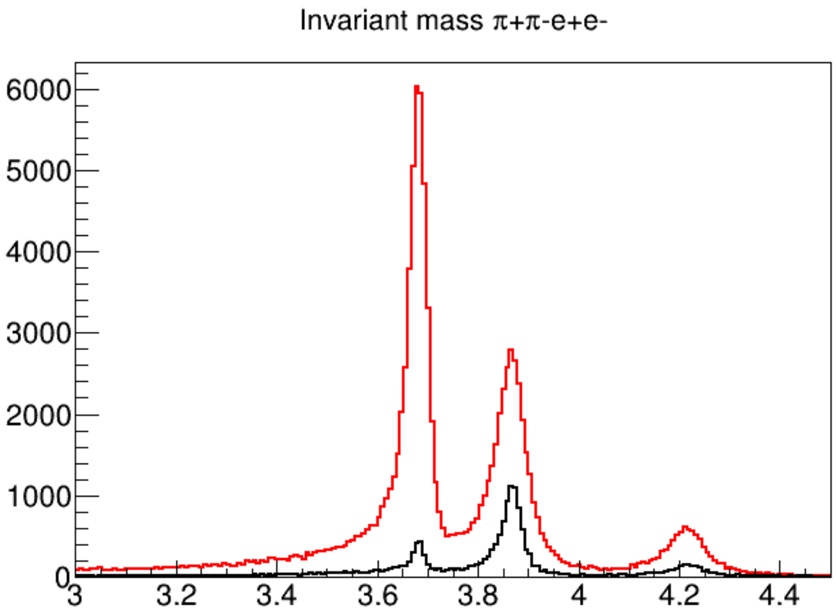
M. Albaladejo, A. N. Hiller Blin, A. Pilloni, D. Winney, C. Fernández-Ramírez, V. Mathieu, and A. Szczepaniak
(Joint Physics Analysis Center)
Phys. Rev. D **102**, 114010 – Published 7 December 2020

See D.Winney
Exotic Spectroscopy
at the EIC

- qualitative behaviour and order of magnitude estimates

Invariant masses with ECCE

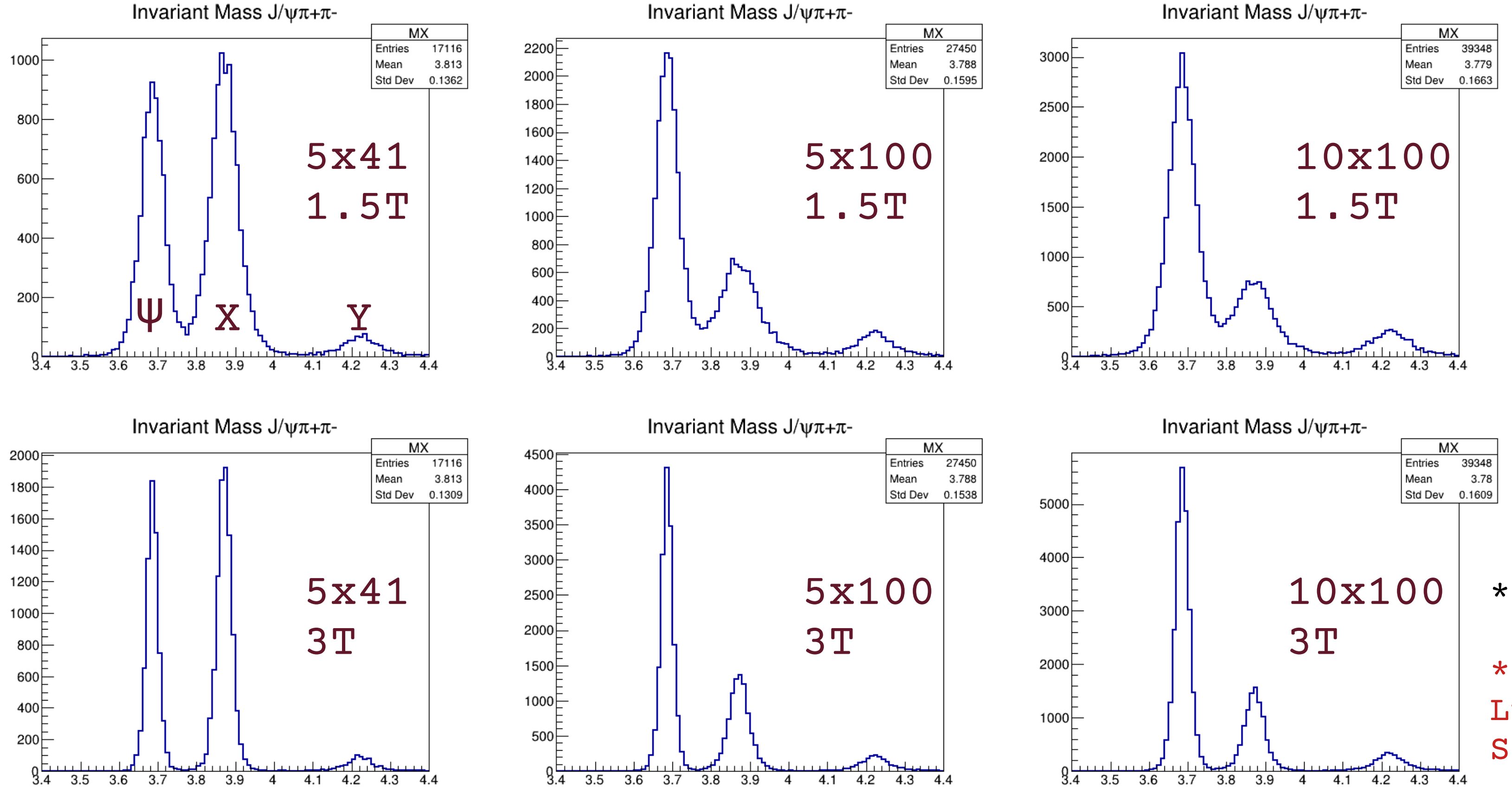


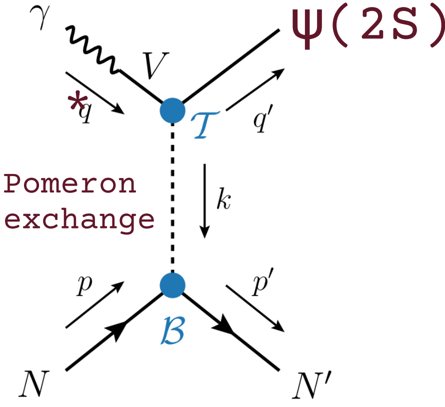


Acceptances for full final state much lower at 3T Solenoid
- low energy pions

X & Y & ψ(2S)

Invariant mass distributions for different beam/ magnetic fields

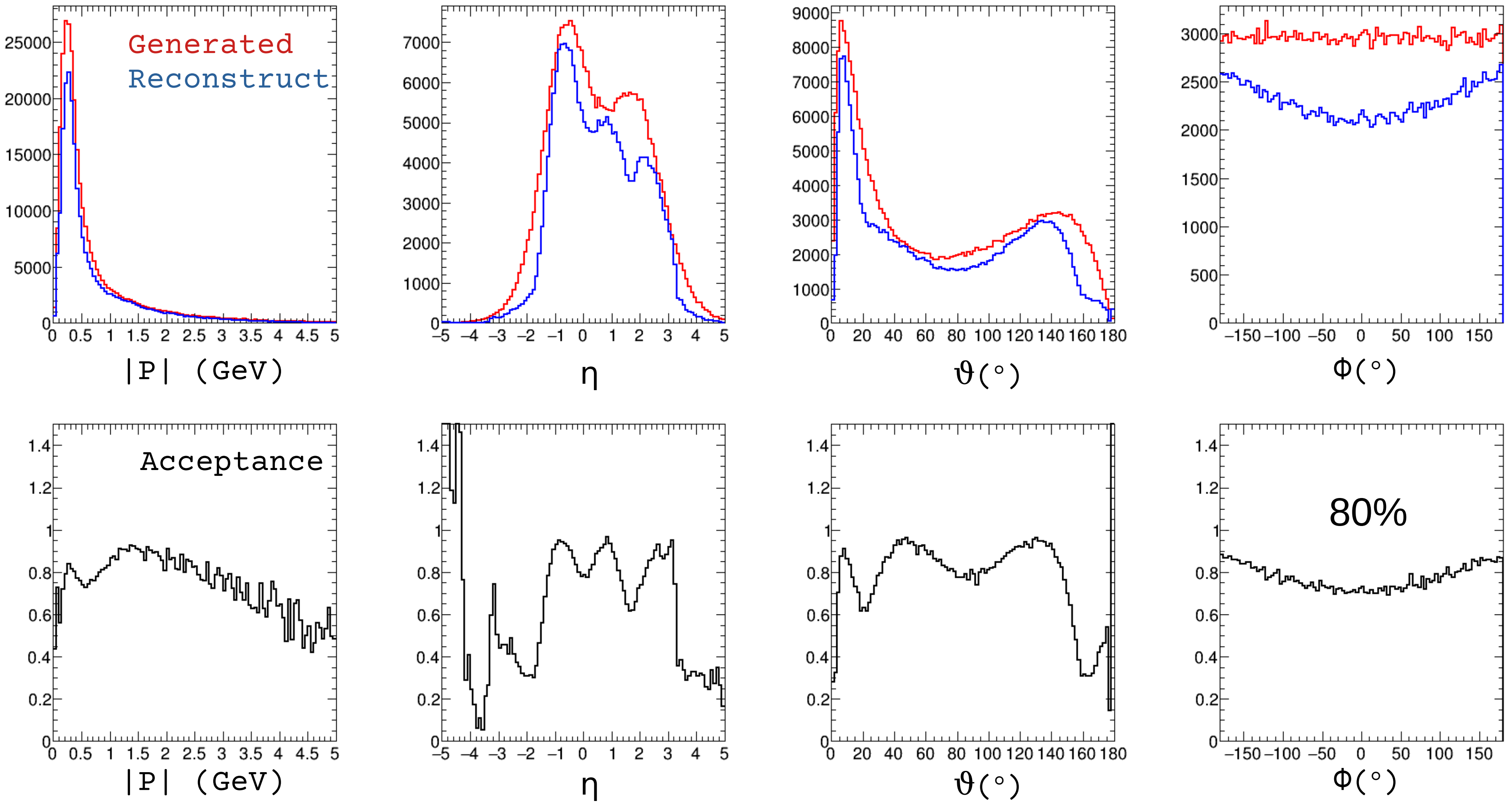




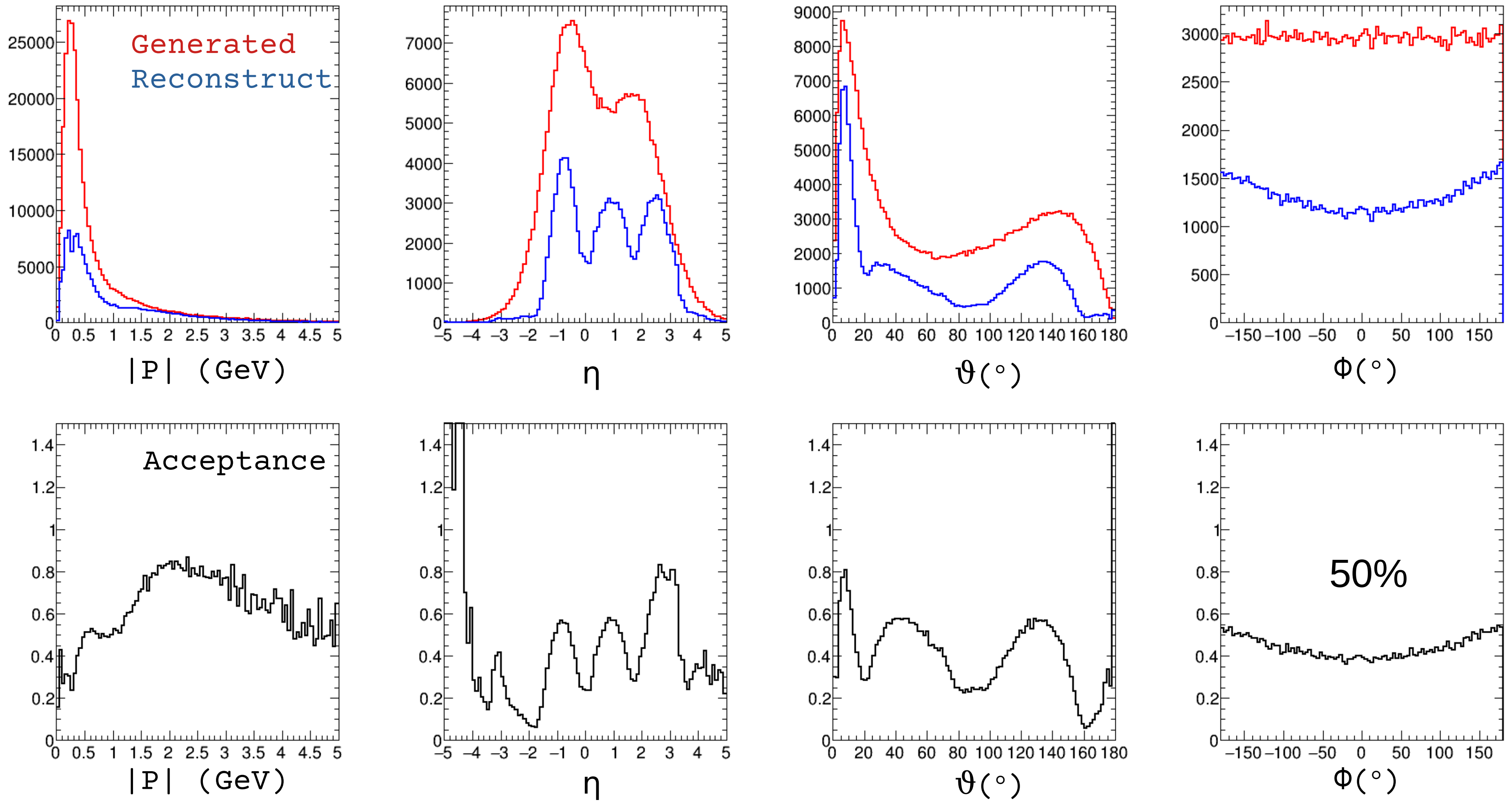
* With EIC-smear
Not ECCE
** Assumes same
Luminosity
See slide 4

X better at low proton Energy, Y,ψ better at high proton Energy

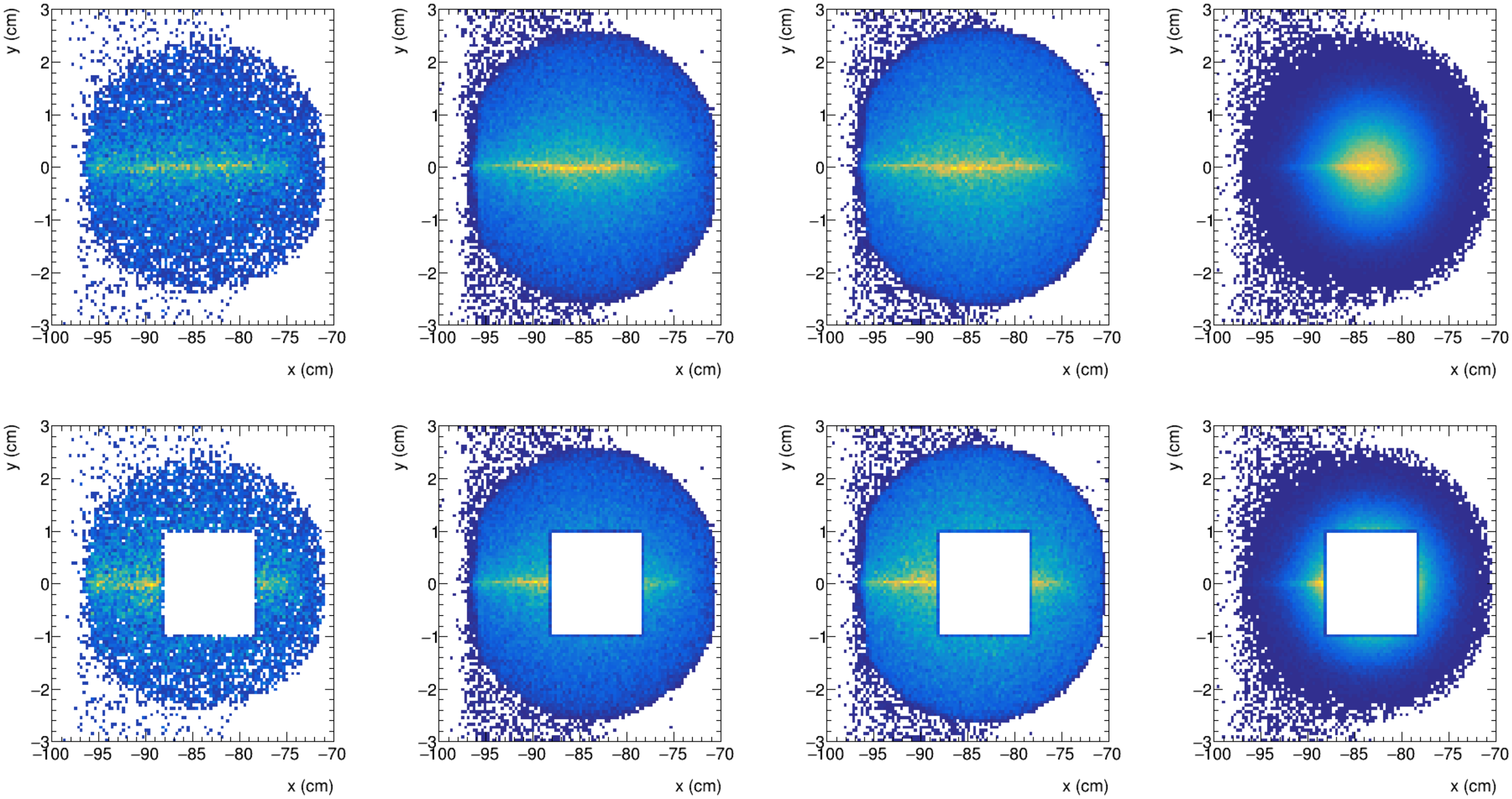
π+ acceptances at 1.5T



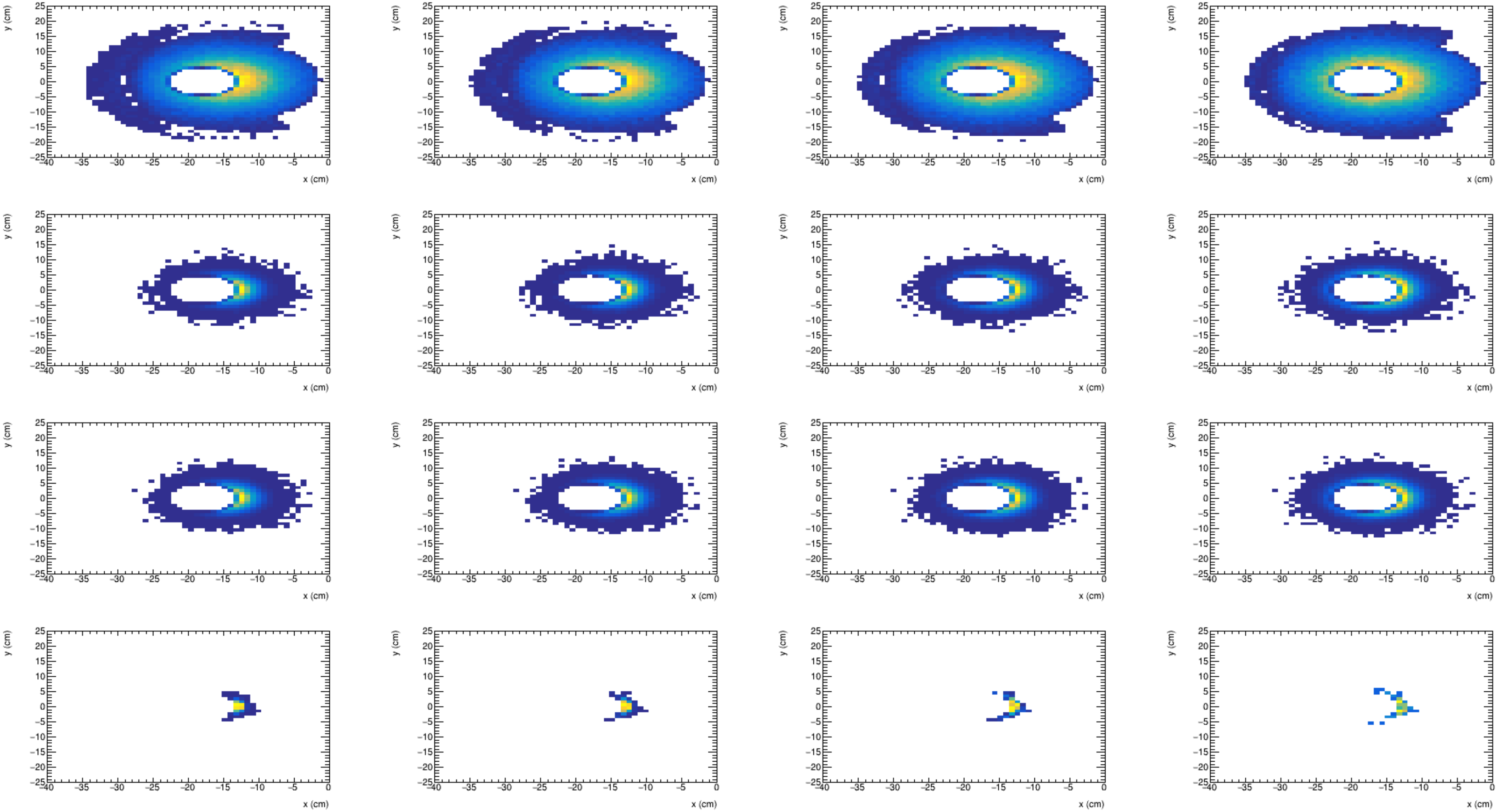
π+ acceptances at 3T



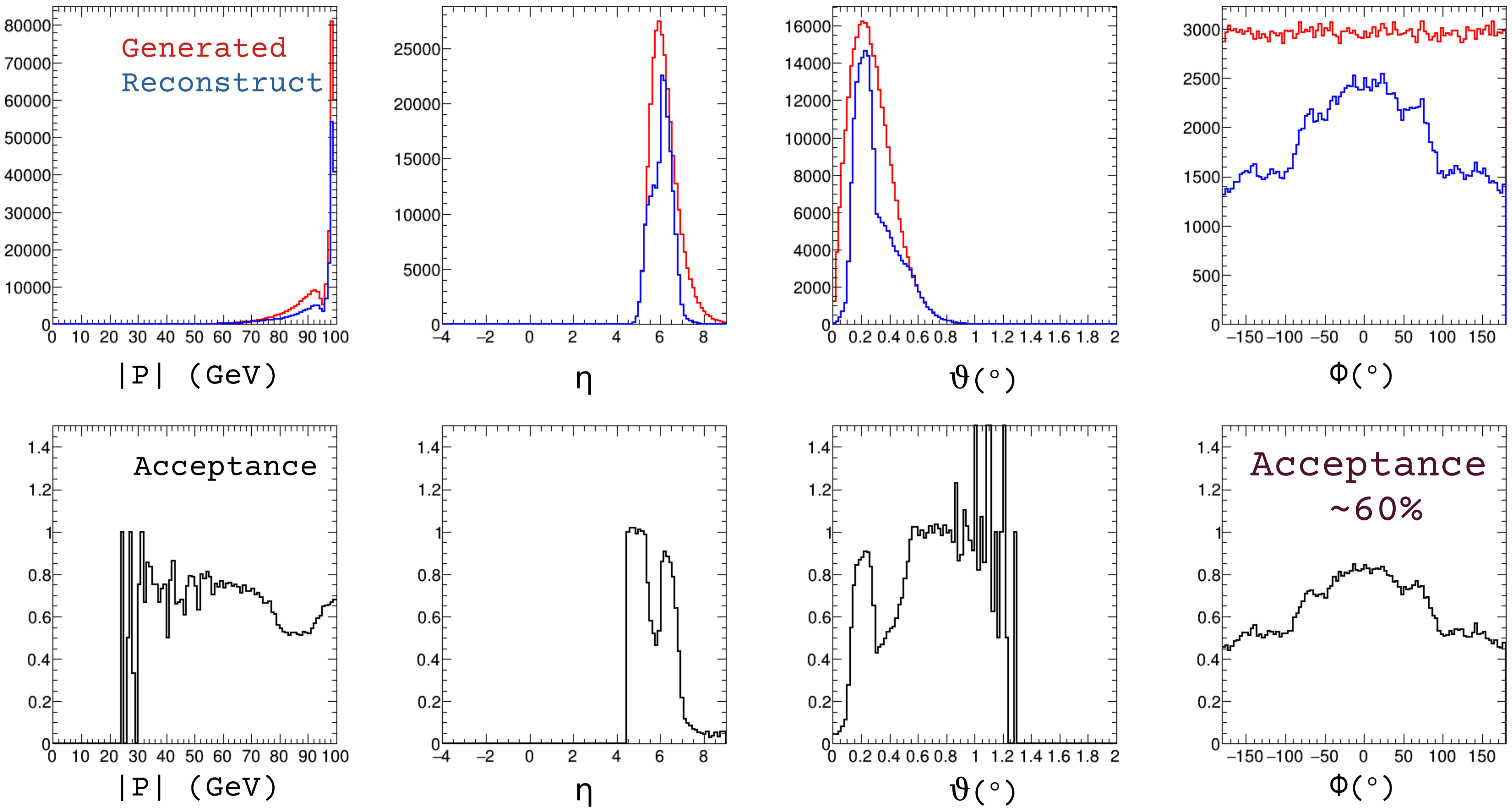
Far Forward Roman Pot Acceptance



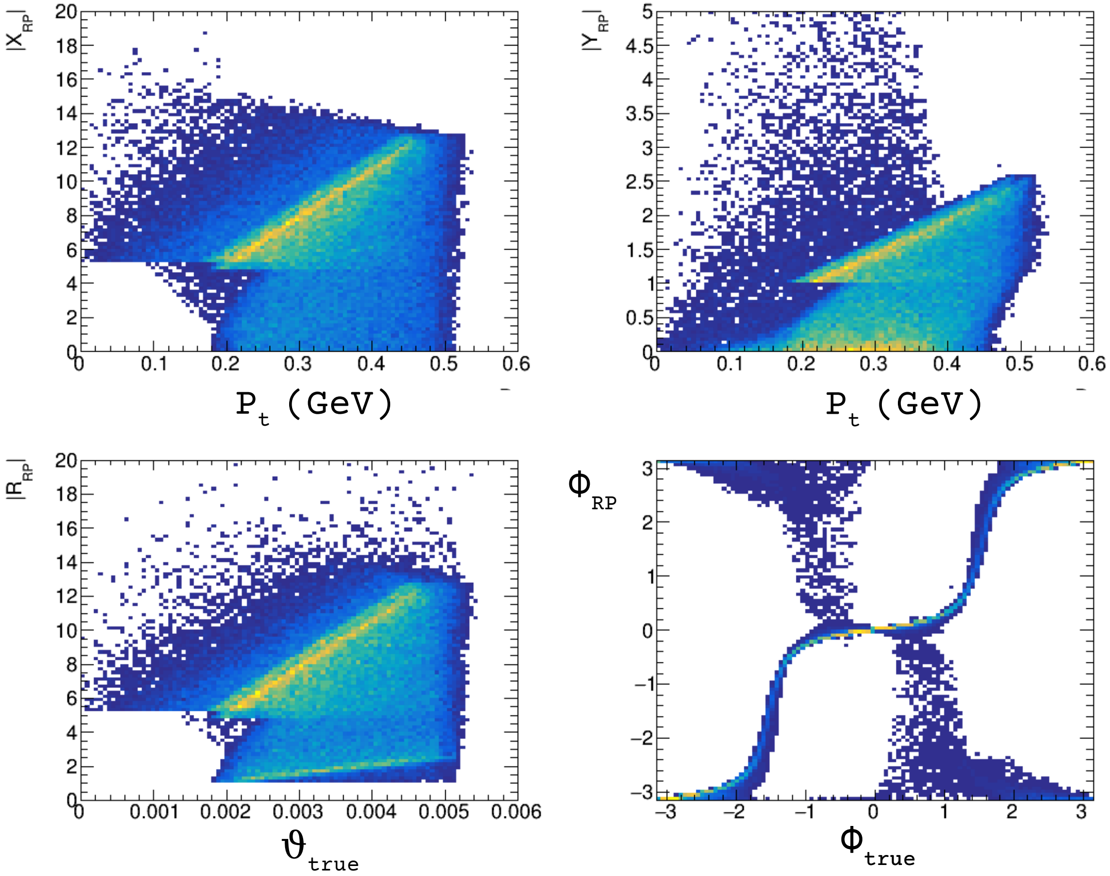
Far Forward B0 Acceptance



Proton Detection B0 and RP



Roman Pot position and momentum



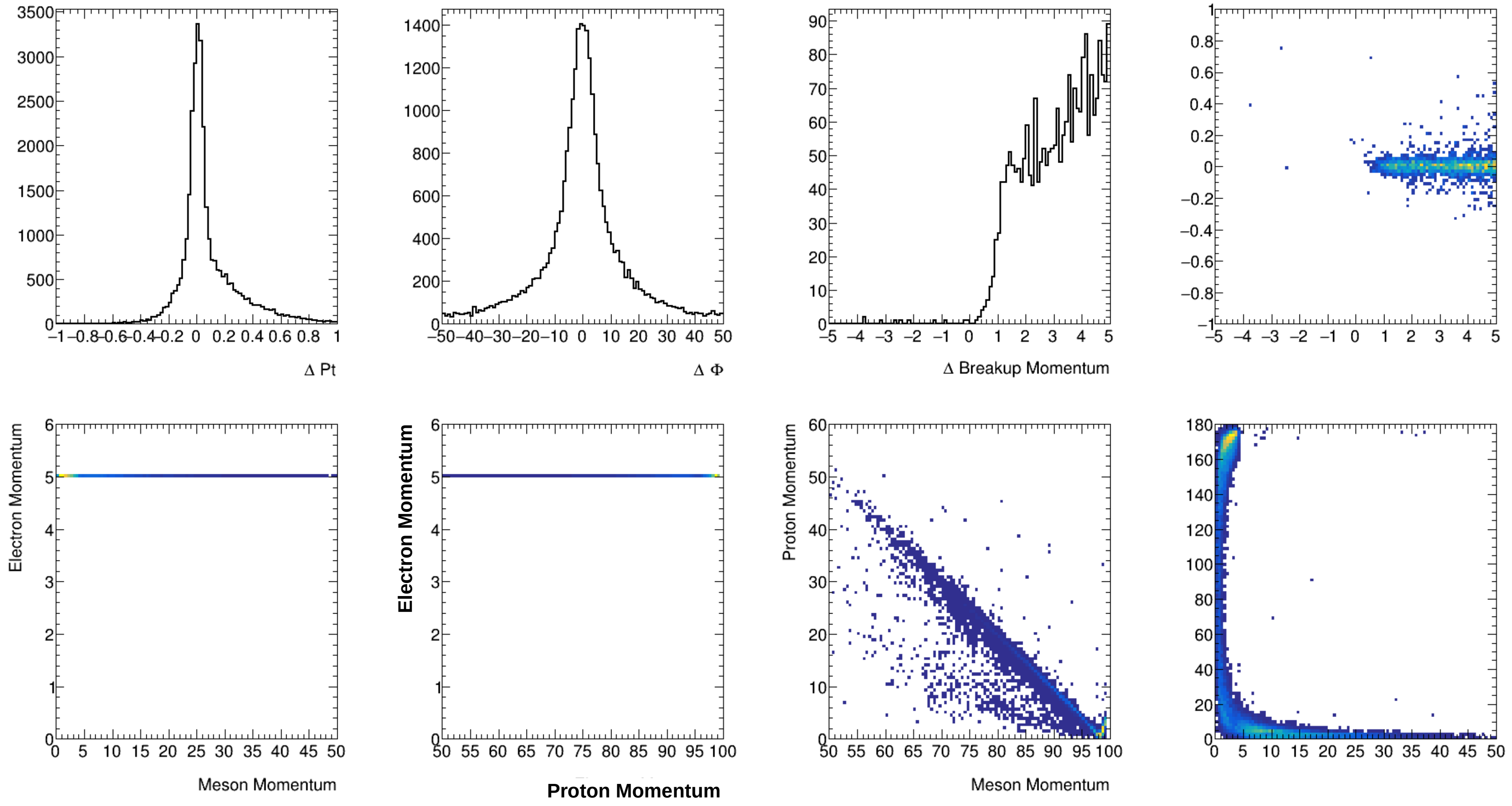
Correlation between position and P_t, but dependent on Φ_{RP}

Proton Φ_{true} correlated with Φ_{RP}
=>Assume it can be reconstructed

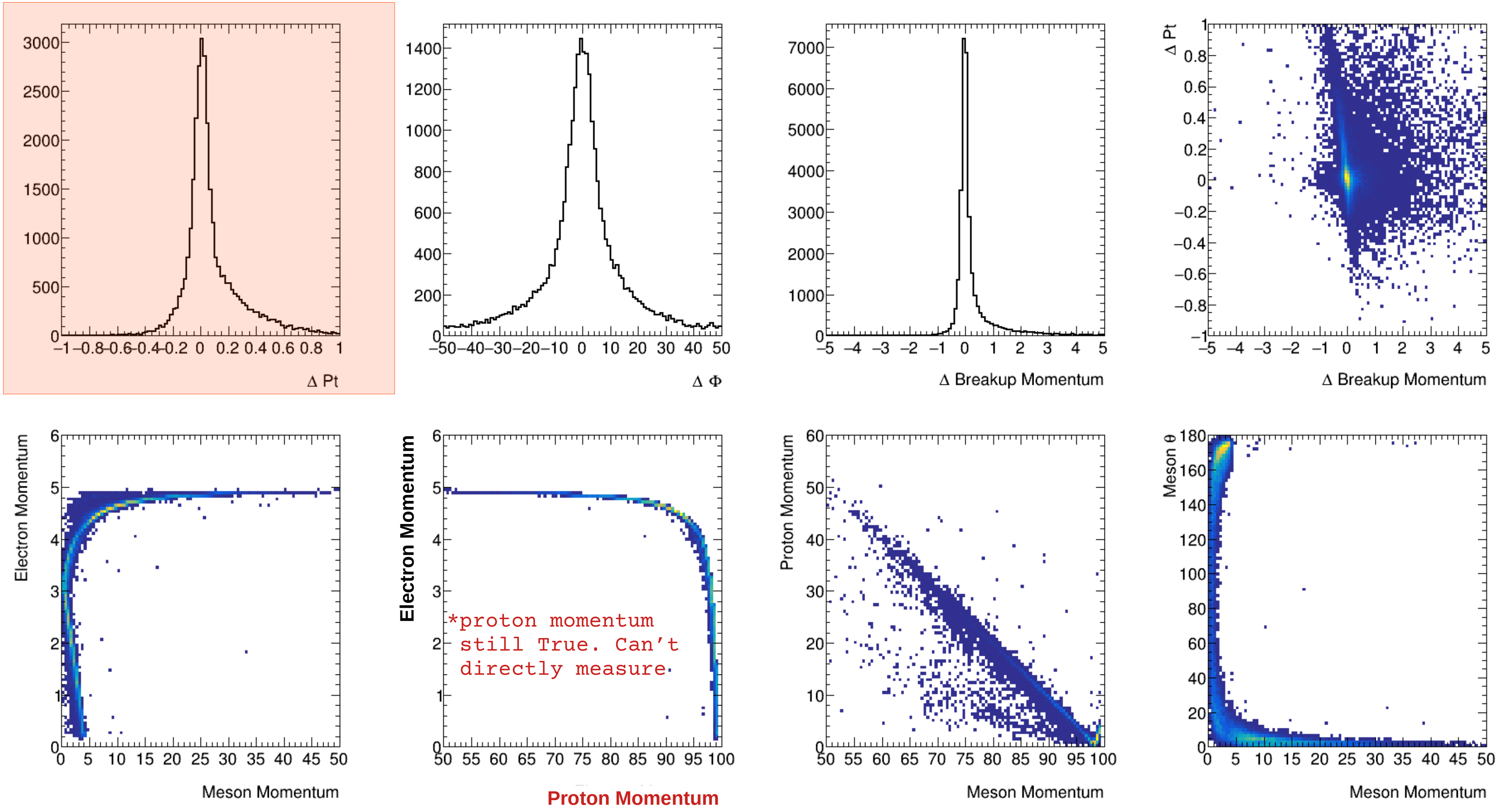
For these studies, if proton detected in RP 6% P_t resolution,
B0 3% P_t resolution

Assume (unrealistic) perfect Φ reconstruction

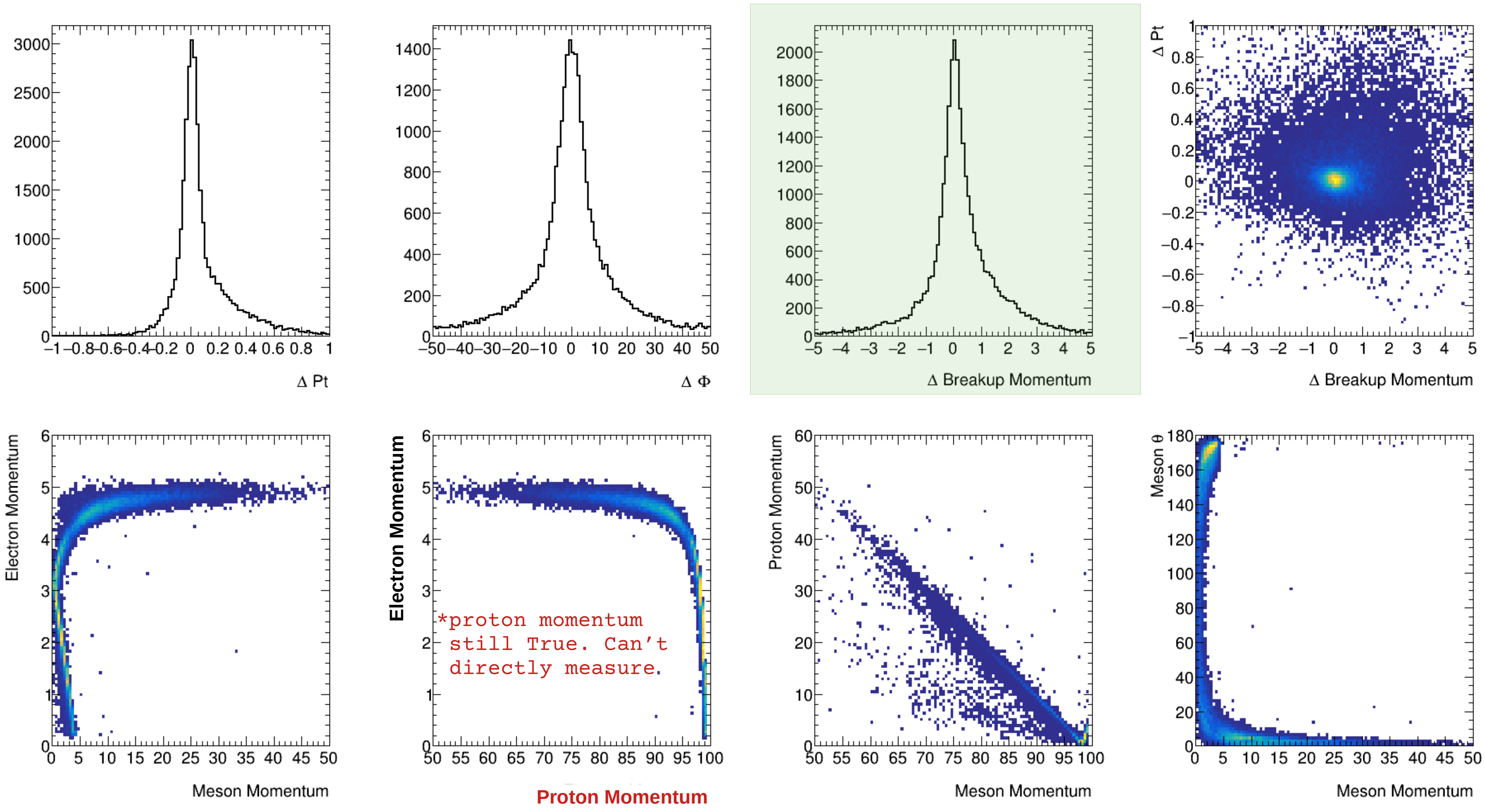
No Electron, True Proton, Realistic Meson



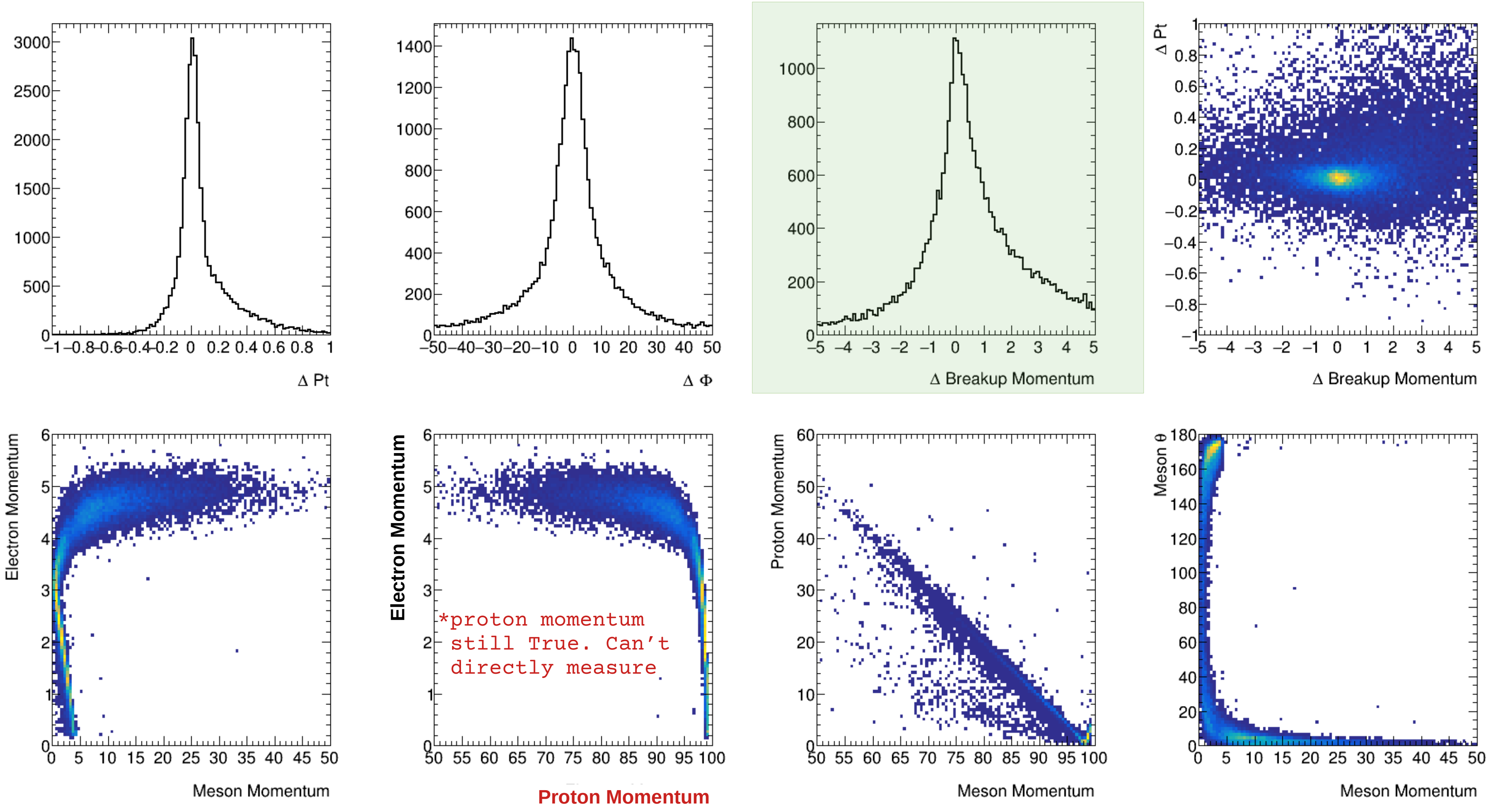
True Electron, “Realistic” Proton



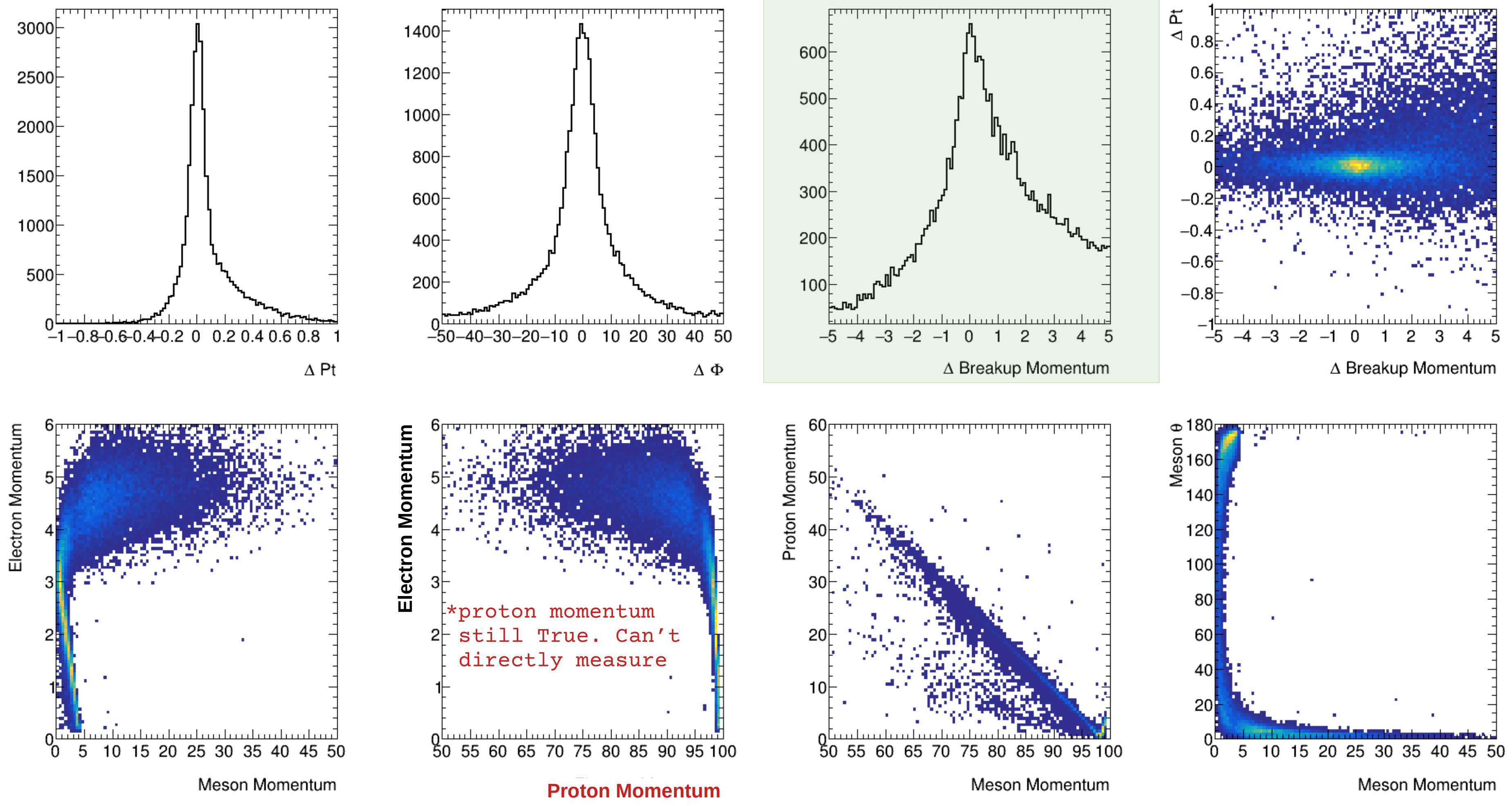
+ Electron 2% energy resolution



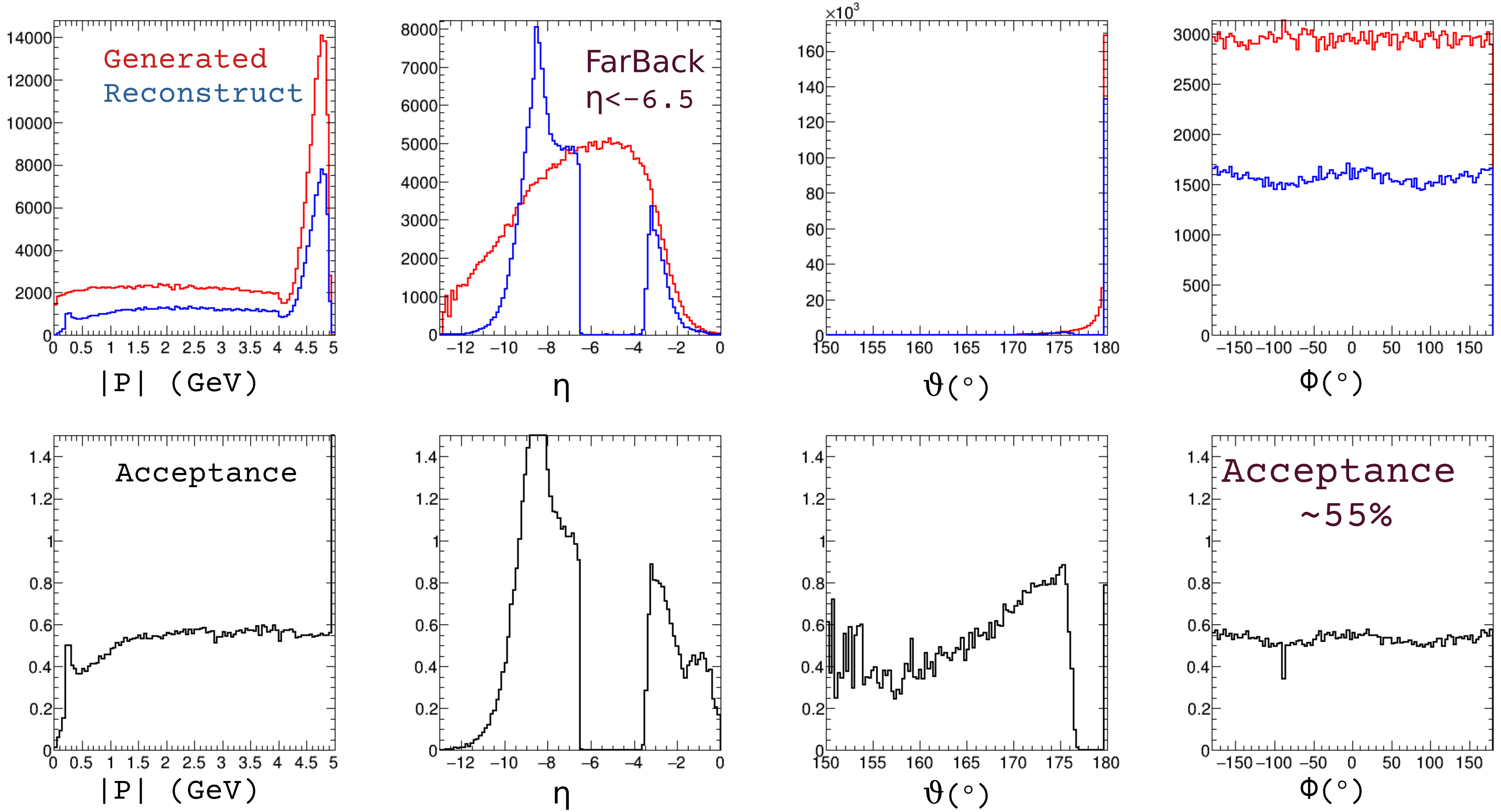
+ Electron 5% energy resolution



+ Electron 10% energy resolution



Electron Detection



Pixel tracker

Pixel dimension	=	$55 \times 55\ \mu m$
Detector area (512×448 pixels)	=	7 cm^2
Detectors in layer (4 x 3)	=	12
Layer area ($12 \times 7\ cm^2$)	=	84 cm^2
Pixels in layer (12 * 512 $\times$ 448 pixels)	=	2.75M
Average rate per pixel (4 GHz / 2.75 M pixels)	=	**1.5 kHz**
Total bit rate per detector (256 Gb/s / 12)	=	**22 Gb/s**

	Hit Rate (Mean)	Hit Rate (Max)	Bit Rate (Mean)	Bit Rate (Max)
Pixel	1.5 kHz	**6.0 kHz**	96 kb/s	**384 kb/s**
Detector	344 MHz	**1.4 GHz**	22 Gb/s	**88 Gb/s**
Layer	4.0 GHz	—	**256 Gb/s**	—

	Requirement	Timepix4	AC-LGAD	MAPS
Readout	—	SPIDR4	EICROC	Direct ?
Pixel Size (μm)	50×50	55×55	500×500	20×20
Sensor thickness (μm)	—	100	50	20
Detector size (pixels)	—	512×448	64×64	Various
Detector area (cm^2)	—	6.94	10.24	Various
Layer Area (cm^2)	100	83 (3x4 Timepix4)	92 (3x3)	Various
Power consumption (W/cm^2)	As low as possible	1.0	0.4	0.15
Timing resolution (ns)	< 12	0.2	0.03	9
Minimum threshold (fC)	—	1.2	2.0	0.48
Individual pixel thresholds	—	Yes	Yes	No
Pixel hits in MIPS cluster	—	3	30	5 ?
Rate (various units)				
Hits/pixel/s (max)	6×10^3	10.7×10^3	N/A	
Hits/detector/s (max)	1.4×10^9	2.5×10^9		
Bits/detector/s (max)	88×10^9	160×10^9		
Bits/layer/s (integrated)	256×10^9	$> 240 \times 10^9$		