

# Update on GPD studies from quarkonia (J/psi, Upsilon), rho & Compton-like for EIC/ECCE with eP

Virginia Tech group

Marie Boër

Students: Kevin Sanford<sup>1</sup>, Tyler Schroeder<sup>2</sup>, Erik Wrightson

Sept. 17th, 2021 - Exclusive PWG / ECCE

1

now back to: 1. UCSC, 2. W&M

# Goals, methods, results

- 1) Providing a generic event generator to study several  $eP \rightarrow e'P' A$  reactions ( $A=\text{vector}$ )
- 2) Focus on Compton-like + vector mesons: similar goals and physics  
+ expected larger cross-sections at high energy. Mostly access GPDs H & E ( $q, g$ )
- 3) Using same model for various process and hands on generator + reconstruction in order to demonstrate feasibility for GPD extractions and observables to be measured, accuracy, without any unknown. Flexible framework can be used by ECCE collaboration
- 4) What can be done realistically / what cannot with ECCE

## In this talk:

- 1) GPD parameterization choices
- 2) Other model considerations
- 3) Generator input & output
- 4) Projections for quarkonia:  $J/\psi$ ; Upsilon
- 5) What can be done and what cannot with quarkonia
- 6) Projections for TCS
- 7) Projections for DDVCS
- 8) What can be done and what cannot with TCS & DDVCS
- 9) Items to discuss
- 10) Summary
- 11) Ressources

# 1) GPD parametrization choices

- Lowest energy, and for TCS and DDVCS: GPD H from VGG model

Remark: mostly parametrized from lower energy fits, acceptable for lower energy and first order projections. No huge model dependence expected on unpolarized observables nor Im part (dominant)  
→ can rely on counting rates. Twist 2, LO projections (NLO up to 10%)

- Quarkonia: our „tuned“ parametric model, consider low x limit and acceptable factorized parametrization with  $\exp(-t)$  dependence, with PDF from CTEQ.

Quarks and gluons included + higher twist (2 or 3 gluons exchange)

- What can still be improved:

- other parametrization for pdf and FF based on high energy fits
- improved gluon GPD parameterization

- For the purpose of the work (unpolarized observables, distributions, counting rates, resolutions / feasibility ), approximations done here are all acceptable. Further theoretical studies may be needed to compare various models and projection of more accurate polarized observables and/or GPD fitting

References: see presentations from Tyler Schroeder on quarkonia, from Kevin Sanford on rho, articles they are citing.

Jlab Hall C note #999 for TCS and DDVCS and event generator principle (M.B.)

## 2) Other model considerations

**For quarkonia** we provide several options.

- 1) assuming 2 gluon exchange dominance (lower twist)
- 2) extrem of 3 gluon exchange
- 3) fair share of 2 or 3 gluon exchange based on extrapolation from other experiments (also see Tyler's talks)  
→ We are providing 3 weights for each events
- 4) Upsilon: 1S, 2S, 3S
- 5) Various resolution on mass peaks

### **For TCS:**

Very important: model kin cuts, variable integration range over theta

- 1) Extreme case: only BH
- 2) Realistic: BH+TCS
- 3) Polarized: beam and/or target polarized (circ. Quasi-real photon), all combinations

### **For DDVCS:**

Similar as TCS, only beam polarized

**Note:** most is already coded and checked, cross section grids for „compton“ need rebuild + kin cuts tuning (takes some calculation time on farm)

# 3) Generator input & output

## DEEPSim generator

### Example for Compton-like reactions:

model (any process)

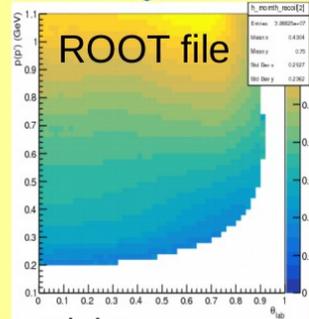
$$\frac{d^4\sigma}{dQ^2 dt d\Omega}(\gamma p \rightarrow p' e^+ e^-) = \frac{1}{(2\pi)^4} \frac{1}{64} \frac{1}{(2ME_\gamma)^2} |T^{BH} + T^{TCS}|^2$$

grids of polarized  
BH / TCS / BH+TCS

1.816930e-02 1.090707e-02 1.105740e-02 1.852696e-02  
 4 1.859244e-02 1.048393e-02 1.181284e-02 1.777151e-02  
 4 1.861872e-02 1.045765e-02 1.285992e-02 1.672443e-02  
 4 1.824557e-02 1.083079e-02 1.409615e-02 1.548821e-02  
 4 1.750952e-02 1.156685e-02 1.540050e-02 1.418385e-02

**New models input  
are very welcome**

MAIN EXE



event weights:  
polarized, unpolarized,  
asymmetries, only BH...  
here: TCS/BH p(P) vs  $\theta(\text{lab})$

user input file

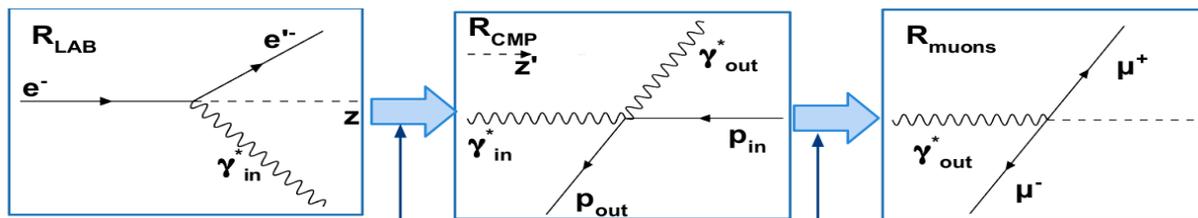
Variable name	usage	limits (grid)	default value
TCS			
Experimental configuration	<b>Beam and target parameters</b>		
Beam type	real photon (0) initial electron (1)	0 or 1	0 or 1
Beam energy (if electron beam)	used to calculate the photon flux	[~ 6, 12] GeV	11
Luminosity	used for normalization	-	$10^{35} \text{ cm}^{-2}$
out leptons	electron (1) or muon (2)	1 or 2	2
Target length	luminosity	-	15 cm
Target composition (A,Z)	luminosity	single atoms	(1,1) or 1001
Target = p (1) or n (2)	weight	1, 2	1
<b>Polarization options</b>			
Beam polarization factor	polarized cross sections	[0, 1]	0.8
Beam pol. vector direction	case linearly polarized	1 (x-axis), 2 (y-axis) or 3 (45°)	1
Target polarization direction	polarized targets	0 (unpolarized), 1 (x-axis), 2 (y-axis), 3 (z-axis)	3
Target dilution factor	polarized targets	0 to 1	0.7
<b>Kinematic range</b>			
Photon energy	photon	[4.5, 11.5]	[5, 10.5]
-t	Mandelstam variable	xx	[.05, .7]
Q <sup>2</sup>	final photon virtuality	xx	[.09, .3]
$\theta_{CM}$	azimuthal angle of decay leptons	[40°, 140°]	[40°, 140°]
Q <sup>2</sup> <sub>max</sub>	quasi-real photons maximal virtuality	0 to ~ 0.5	0.3

Output: ROOT (quick studies) + HEP/kin file

Can easily be converted into EICsmear if needed

Advantage: multiple event weighting for same reaction (modeling...)

### 3) Generator input & output



Steps:

1. Generate “flat” in 4 to 7 kinematic variables (invariants + angles).  
\* likely update to log bins

2. Calculate CM energy, boost to proton’s rest frame (for compatibility & checks with JLab’s code) “equivalent fix target”

3. e- beam emits a photon (polar vectors...)

4. Boost to gamma-P CM  
5. Generate gamma\_out  
Or rho, J/psi, Upsilon (focus on VM & Compton)

6. Boost to rho rest frame  
7. Generate pair of leptons or mesons  
8. Boost back (1) CM, (2) fix target, (3) collider

9. subdivide in kinematic bins (4 to 7, depends reaction)  
10. Reading pre-calculated+interpolations (case for Compton-like)

OR use analytic x-sec (case for rho, J/psi, Upsilon here)  
- More flexible, more model uncertainty  
- Here: factorize e part\*photoproduction

11. Weight events (various weights)

12. Fill into ROOT & HEP files + extra file for saving kinematics and various weights [different models, different sub-processes for studies]

### 3) Generator input & output

#### HEP file (Jpsi, first 2 events)

```
3
1 11 0 0 -2.65143 0.259924 9.48429 0.105658
1 -11 0 0 -0.0794149 -1.86079 7.30896 0.105658
1 2212 0 0 0.669656 0.712873 0.618052 0.938272
3
1 11 0 0 0.615206 -0.722728 4.93517 0.105658
1 -11 0 0 -2.50287 -0.420359 33.8468 0.105658
1 2212 0 0 1.31018 0.955075 1.4644 0.938272
```

#### Associated kin file (Jpsi, 2 events)

```
Q2,      t      tmin  Xbj      phi_in  phi_out  theta_out  cross sections
8.60189 -1.03465 -0.00567202 0.406789 4.65583 1.44032 0.269702 8.04633e-06 0 0
6.46628 -2.70119 -0.00895485 0.314746 1.90611 2.41397 0.0891199 4.36322e-07 0 0
```

#### ROOT file 1 event (J/psi)

```
LV_gamma_in  = 5.98165,
              1.93423, -2.13369, 6.09899
ALV_gamma_out_lab = 6.40913,
                  1.49806, 0, 5.37971
ALV_Recoil_lab = 2.4252,
                 -0.0969557, -1.54558, 1.61339
ALV_minus_lab = 1.61763,
                1.38474, -0.708853, 0.443552
ALV_plus_lab  = 4.88522,
                0.646455, 0.120737, 4.84074
ALV_el_in     A= 41.3674,
              0, 0, 41.3674
ALV_el_out    = 35.3858,
              -1.93418, 2.13362, 35.2683
yy            = 0.146004
WW            = 110.892
Q2            = 9.71142
Xbj           = 0.864522
phi_beam      = 2.3072
theta_gamma   = 6.23808
theta_beam    = 1.49167e-154
Qp2           = 9.89149
tt            = -2.79029
ttmin         = -0.00979444
epsilon       = 0.987644
eta_g         = 1.21908
```

```
pT_g         = 1.49806
eta_recoil   = 0.802195
eta_el       = 3.19965
eta_minus    = 0.281399
eta_plus     = 2.69382
Phi_CMV      = 4.35762
Theta_CMV    = 2.31521
W_tot_unpol  = 1
W_tot_pol    = 1
W_par1       = 1
W_par2       = 1
EventNumber  = 3
TrueEventNumber = 3
```

2 options

ROOT is more versatile

# Input file for what I show

\* input file for jpsi into leptons production  
\* don't change options order and only fill numbers  
\* comment lines with \*

\* Beam Type: 0= photoproduction, 1= quasi-photoproduction (electron beam), 2= electro-production

2

\* Photon energy (GeV) (set only for beam options 1 and 2, otherwise put something wide or set instead of xbj)

\* min

2

\* max

100

\* Electron energy (GeV)

41

\* Photon max angle for quasi-real (set 0 if pure photon or electron beam) (radian)

0

\* Total number of events to generate

5000000

\* outgoing lepton: 1=electrons, 2=muons

2

\* Proton energy (GeV)

5

\* A if nuclear beam

1

\* Z if nuclear beam

1

\* interaction off proton (1) or neutron (2)

1

\* Q2 min (GeV2) - electron beam, otherwise set 0

2

\* Q2 max (GeV2) - electron beam. set 0.3 for quasi-real or customized value

20

\* electron beam polarization rate

1

\* proton beam polarization orientation (0=none, 3=parallel, 2, 3 = transverse, default=3)

3

\* proton beam polarization rate

1

\* -t min (GeV2)

0.5

\* -t max (GeV2)

4

\* jpsi mass range min (GeV)

2.9

\* jpsi mass range max (GeV)

3.5

\* theta min (final pair) degree

10

\* theta max (final pair) degree

170

\* xbj min (only electroproduction, otherwise set to 0)

0

\* xbj max (only electroproduction, otherwise set to 1)

1

\* output type (1=root only, 2=HEP only, 3=ROOT+HEP)

3

\* cross section ratio (dont set)

1

## 4) Projections for quarkonia: J/psi

### Input kinematics (our choice):

Electroproduction:  $E(\text{beams})$ ,  $Q^2$ ,  $x_{bj}$ ,  $t$ ,  $\phi(\text{pair})$ ,  $\theta(\text{pair})$ ,  $\phi(\text{electron})$  + J/psi mass range

Photoproduction/quasi-real:  $E(\text{photon})$ ,  $t$ ,  $\phi(\text{pair})$ ,  $\theta(\text{pair})$  + J/psi mass range

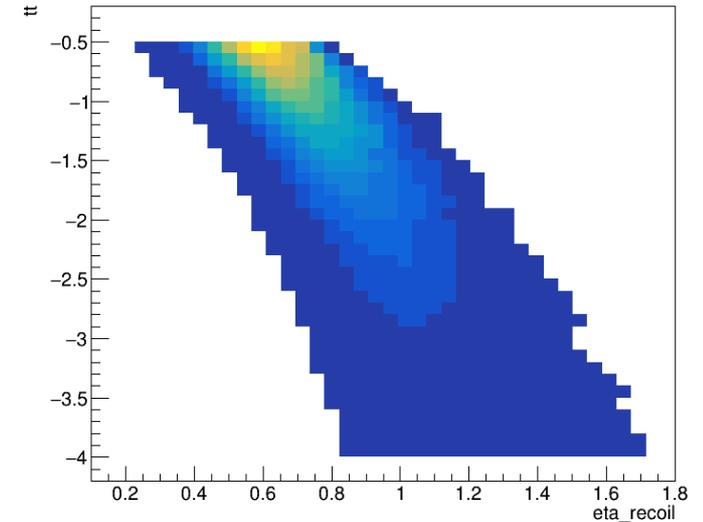
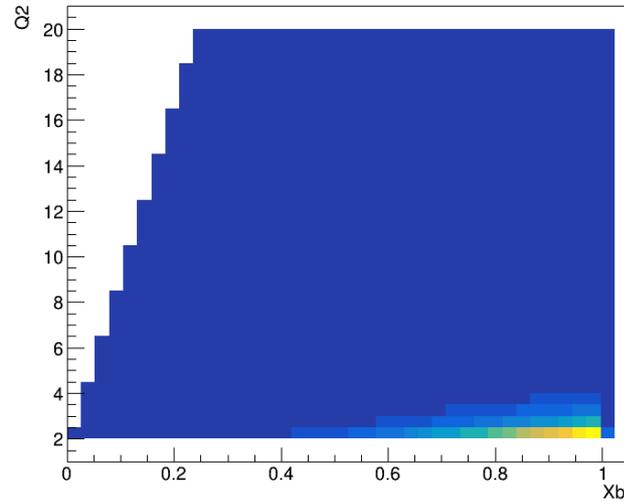
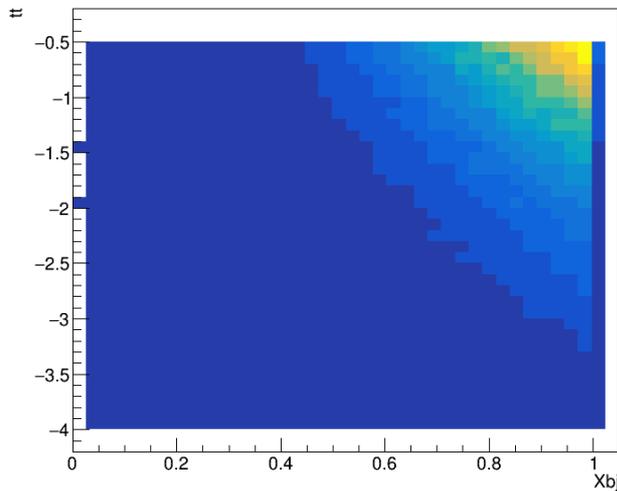
Files are in: `/work/eic/users/mboer/ROOTfiles/JPsi/`

2D:

$t$  vs  $x_{bj}$ , normalized, all

$Q^2$  vs  $x_{bj}$ , normalized, all

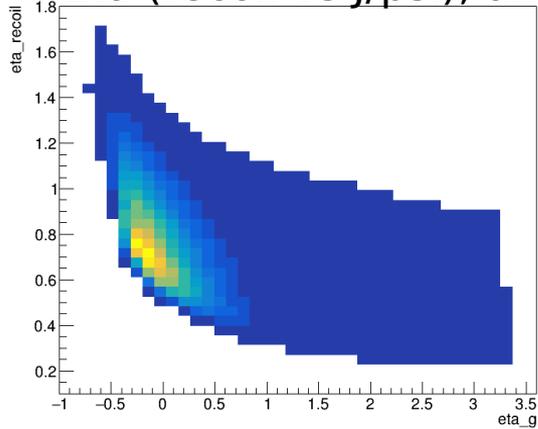
$t$  vs  $\eta(\text{proton})$ ,  
normalized, all



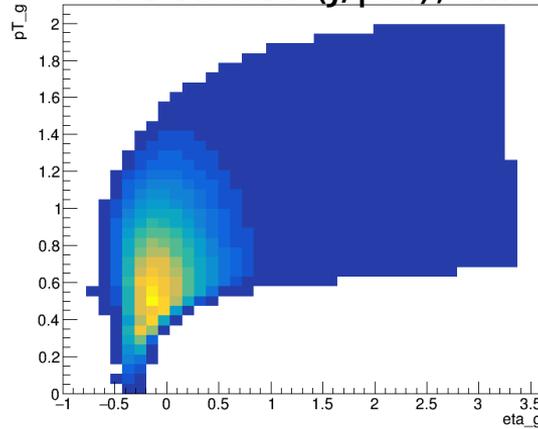
5M events, 41 / 5 GeV beams

## 4) Projections for quarkonia: J/psi

Eta (recoil vs J/psi), all



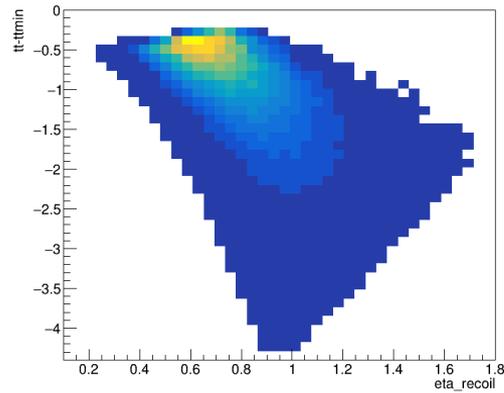
Pt vs eta (J/psi), all



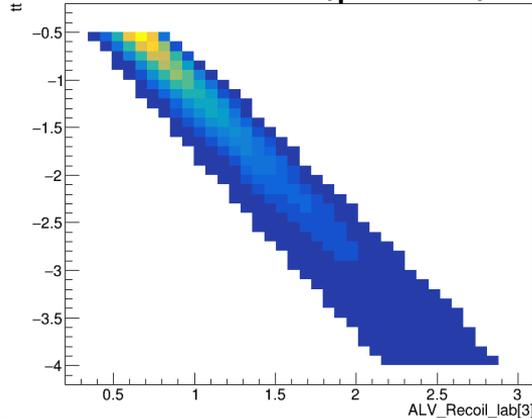
2D weighted distributions seem accurate  
Allow for preliminary binning and locating good events

All particles should be within acceptance  
NB: we want muons

t-tmin vs eta (proton), all



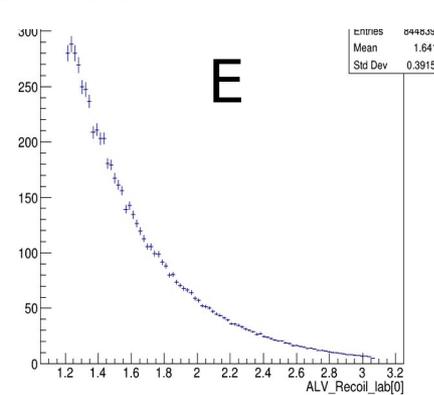
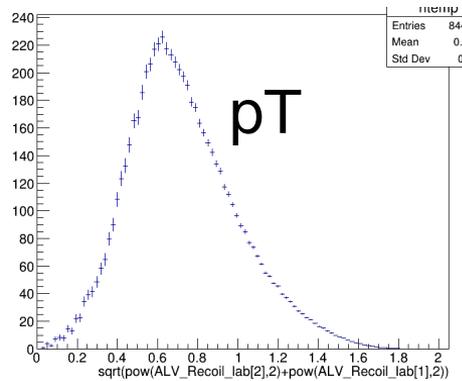
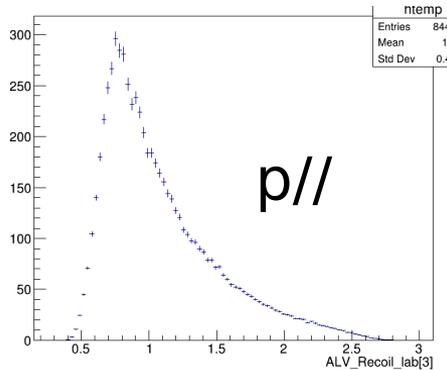
t vs // mom. (proton) lowest rapidity ( $<|1|$ )



(note tmin was neglected in weighting in this version)

# 4) Projections for quarkonia: J/psi

Proton distributions (normalized) lowest rapidity of J/psi only

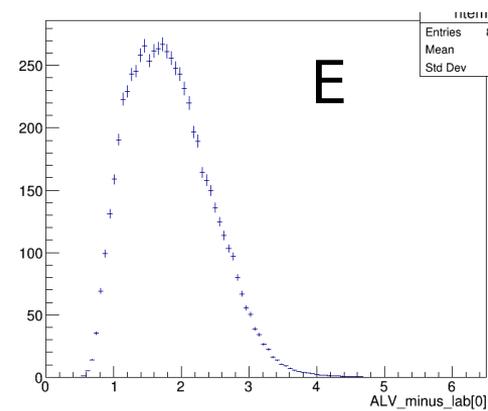
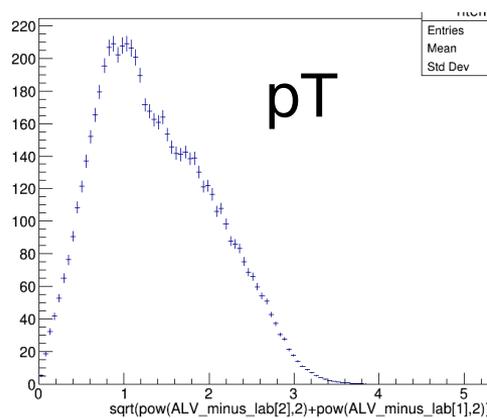
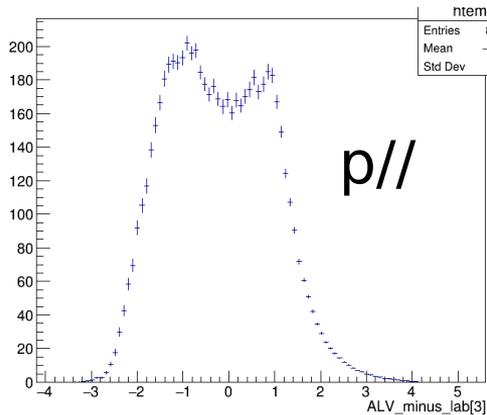


We expect protons up to 3 GeV energy

$pT$  up to 1.8, mostly near .7 GeV  
P threshold:  $\sim .5$  GeV

Main question:  
Resolution in  $t$ ???

Muon distributions (normalized) lowest rapidity of J/psi only



Muon  $E$  threshold  $\sim .5$  GeV,  $P$  and  $pT$  up to 3 GeV  $\rightarrow$  narrowing to bin  $\sim 1$  GeV?

# 4) Projections for quarkonia: Upsilon

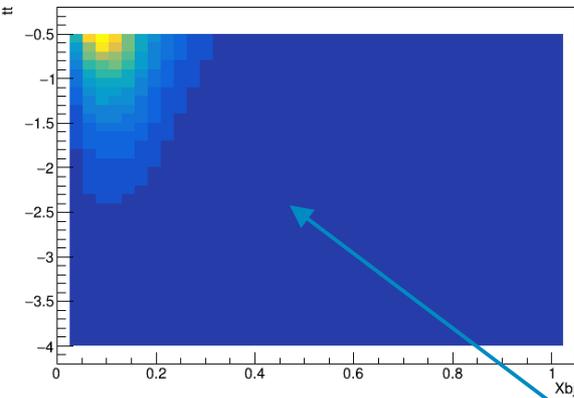
## Input kinematics (our choice):

Electroproduction:  $E(\text{beams}), Q^2, x_{bj}, t, \phi(\text{pair}), \theta(\text{pair}), \phi(\text{electron}) + J/\psi$  mass range

Photoproduction/quasi-real:  $E(\text{photon}), t, \phi(\text{pair}), \theta(\text{pair}) + J/\psi$  mass range

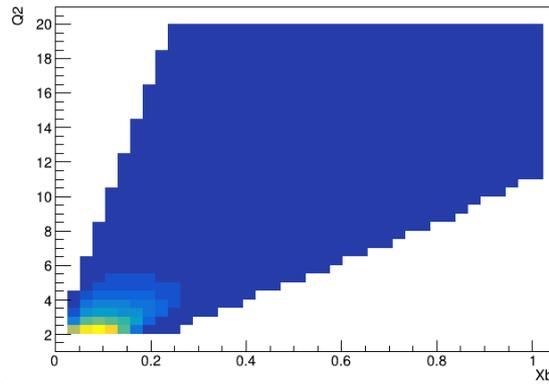
File in: /work/eic/users/mboer/ROOTfiles/Upsilon/  
2D

$t$  vs  $x_{bj}$ , all, weighted

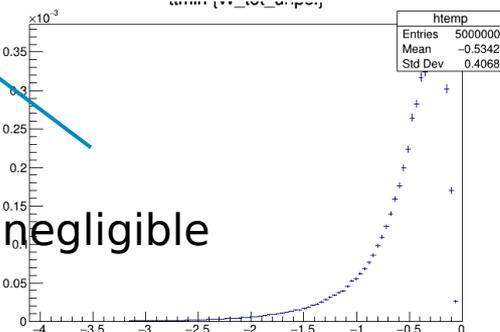
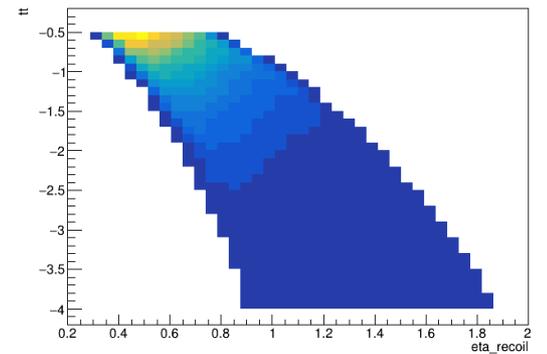


Note:  
 $t_{min}$  is not negligible

$Q^2$  vs  $x_{bj}$ , all, weighted



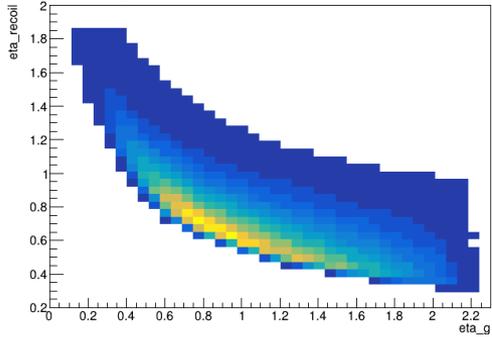
$T$  vs  $\eta(P)$ , all, weighted



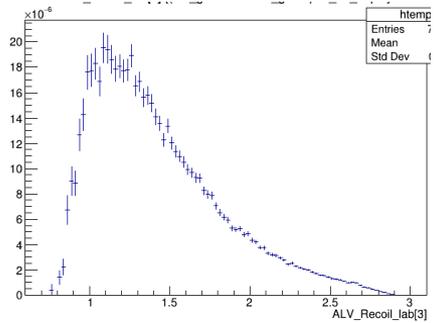
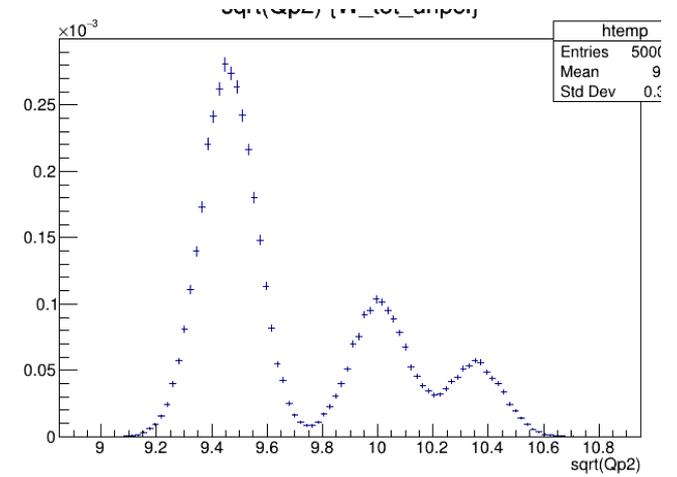
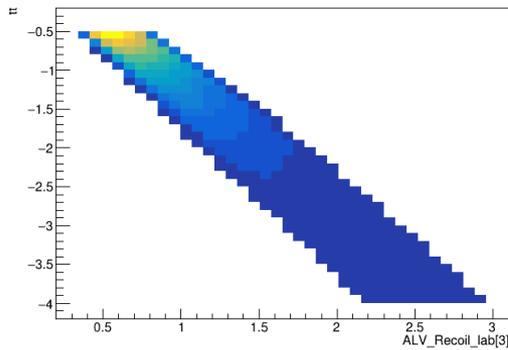
As expected; quite different from  $J/\psi$ . Rates much lower  $\rightarrow$  feasible?  
 $t_{min}$  quite high

# 4) Projections for quarkonia: Upsilon

Rapidity recoil vs Y

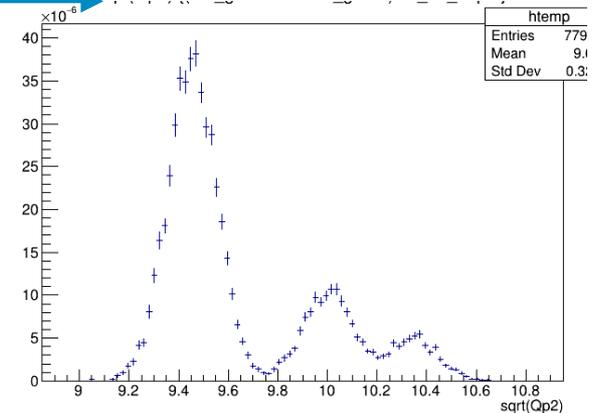


t vs recoil momentum //



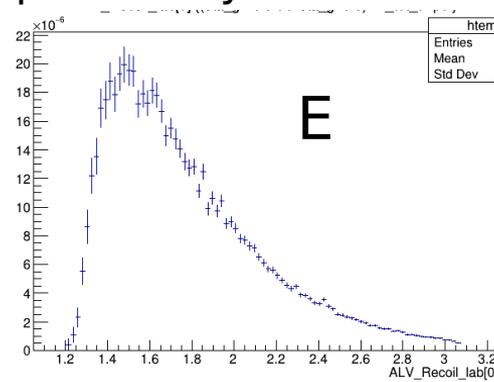
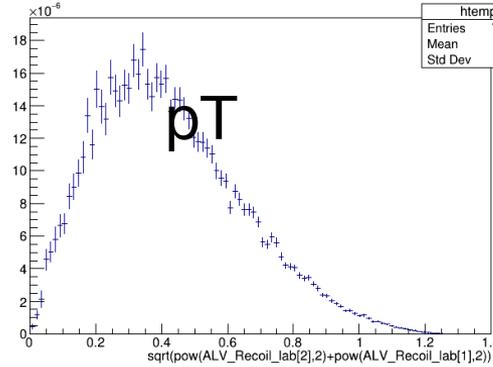
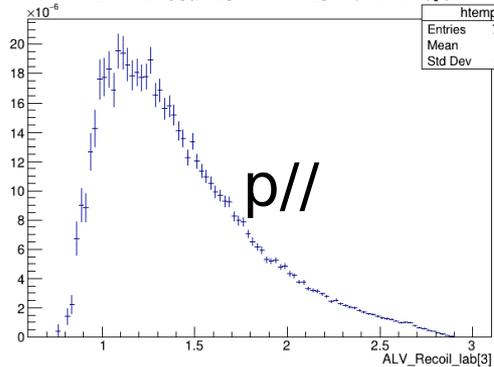
Select rapidity  $< |.6|$   
Same distrib in mass

(reminder we mix  
1S, 2S, 3S)



# 4) Projections for quarkonia: Upsilon

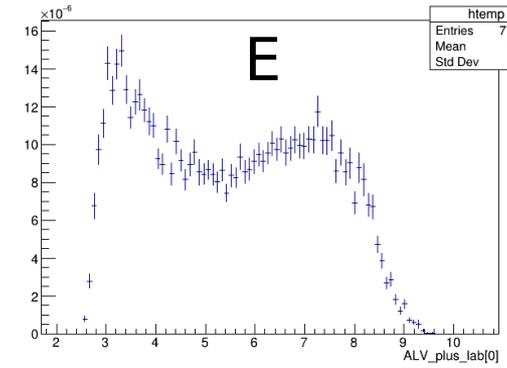
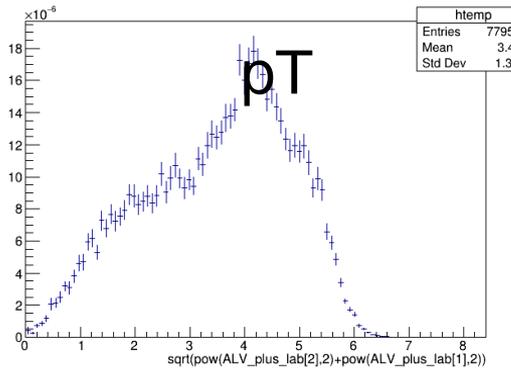
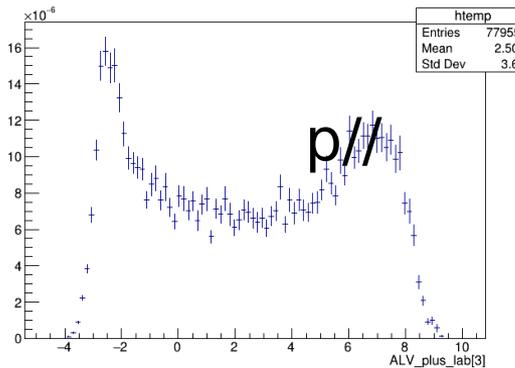
Proton distributions (normalized) lowest rapidity of upsilon only



Question is more if we have enough counting rates than detection of particles, quite difficult vs. J.psi.

Better at higher E?  
→ likely  
Will do same study

Muon distributions (normalized) lowest rapidity of upsilon only



Of course resol  
In t is crucial point

Recoil threshold momentum  $\sim 0.5$  GeV. Max  $\sim 3$ . max  $p_T \sim 1.2$  (lower than J/psi)

Muon from 2.5 to 9.5 GeV energy (asymmetric „favored“?) mom up to 9 GeV,  $p_T < 6.5$  GeV

## 5) Discussion: projections for quarkonia What can be done and what cannot

**Most important: focus on this presentation on decays into muon pairs**

Why? → antisymmetrisation terms make it (very hard) impossible to extract GPDs from  $e+e^-$  due to no distinction between same-fermion final state

→ **only GPD interpretation from quarkonia into muon pair**

→ **J/psi and Upsilon in  $\mu^+\mu^-$  are great tools for studying gluon GPDs of proton/neutron**

→ Unpolarized J/psi and Upsilon in any lepton for spectroscopy (pentaquark,  $\psi'$ ,  $\chi_{c\dots}$ )

→ Polarized J/psi and Upsilon in any lepton to understand production mechanisms and higher twist effects (see also SIDIS)

→ **Quarkonia into muons with polarized e and/or P for other GPDs (E<sup>g</sup>...) studies of angular momenta**

**Need to double check weights & counting rates to see how much binning can be done in rapidity, t, xi...**

## 5) Discussion: projections for quarkonia

### What can be done and what cannot

#### What can be done:

- unpolarized and P polarized cross sections / asymmetries of quarkonia into muons
- extracting GPD H (& E?) from simple model cross section
- Counting rates:  $J/\psi$  = yes, very likely; Upsilon: more difficult, need more precise rates study

#### What cannot be done:

- quarkonia into electrons for GPDs

#### What still to study / do:

- full reconstruction / acceptance
- checking resolution in  $t$  (most important) (feasibility / interpretations)
- polarized cross-sections (?)
- most informative plots to select
- more accurate binning for  $J/\psi$ , likely cannot bin  $Y$

## Projections for rho

\* I have not checked yet all cross sections and want to update model in code. Showing from unweighted only

File in `/work/eic/users/mboer/ROOTfiles/Rho/`

## 6) Projections for TCS+BH

### **Input kinematics (our choice):**

Photoproduction/quasi-real:  $E(\text{photon})$ ,  $t$ ,  $\phi(\text{pair})$ ,  $\theta(\text{pair})$ ,  $Q'^2$ , ( $\phi_S$  if P polarized)

Files are in `/work/eic/users/mboer/ROOTfiles/TCS/`

Note: not yet properly normalized and need implementation of dynamic cuts for integral in  $\theta$  over the BH related to final lepton pair

# 6) TCS+BH, what to be cautious at

**Main: BH peaks + wise choice of kinematic regions, dynamic cuts**

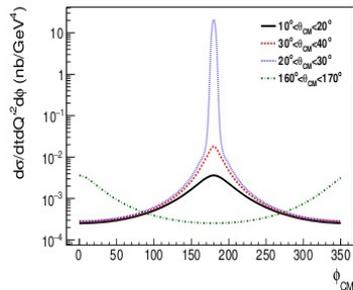


Figure 9: BH cross section as a function of  $\phi_{CM}$  at  $Q^2 = 5 \text{ GeV}^2$ ,  $-t=0.3 \text{ GeV}^2$ ,  $E_\gamma=9.5 \text{ GeV}$  and integrated over  $\theta_{CM}$  on various ranges (colored curves).

From Hall D note (2018)

- 1) BH integrated over various ranges in theta, dominated by e+ or e- near collinear to gamma
- 2) artifacts/spikes when running near the peaks  $\rightarrow$  integration possible only in selected range
- 3) Dynamic cut proposed

\* for Jlab energy; generalize to EIC, Running similar table of cuts once preliminary studies done

integration possible only in selected range

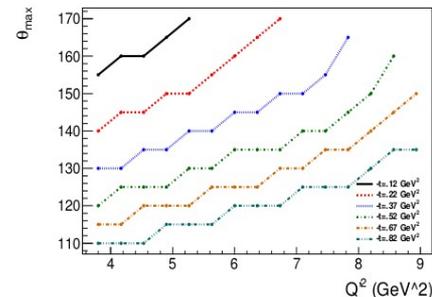
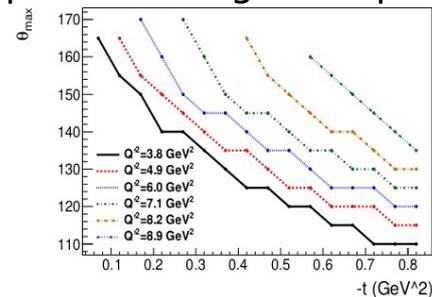


Figure 11: Values of  $\theta_{max}$  for a fix beam energy  $E_\gamma = 9.5 \text{ GeV}$ , as a function of  $t$  for different values of  $Q^2$  (top panel) and as a function of  $Q^2$  for different values of  $-t$  (bottom panel).

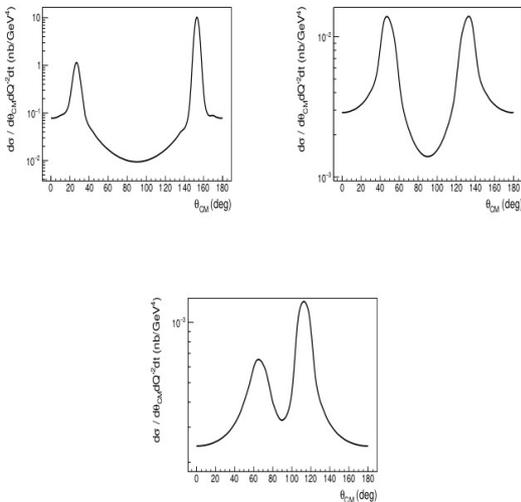


Figure 10: BH cross section as a function of  $\theta_{CM}$  for  $E_\gamma=9.5 \text{ GeV}$ ,  $Q^2 = 5 \text{ GeV}^2$ ,  $0 < \phi_{CM} < 360^\circ$  and  $-t=0.3 \text{ GeV}^2$  (top left panel),  $-t=0.8 \text{ GeV}^2$  (top right panel),  $-t=1.5 \text{ GeV}^2$  (bottom panel).

# 7) Projections for DDVCS+BH

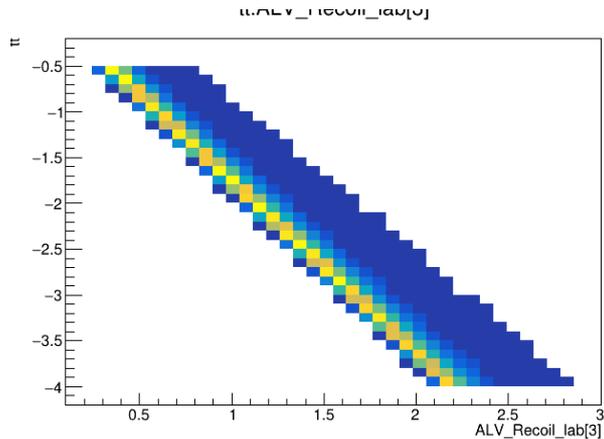
## Input kinematics (our choice):

$E(\text{beams})$ ,  $Q^2$ ,  $x_{bj}$ ,  $t$ ,  $\phi(\text{pair})$ ,  $\theta(\text{pair})$ ,  $\phi(\text{electron})$ ,  $Q'^2$

Important is deconvolution of  $x_i$  and  $x_i'$ : access off diagonal  $x=x_i$  of GPDs

Files are in `/work/eic/users/mboer/ROOTfiles/DDVCS/`

$t$  vs recoil momentum



→ most important is understanding  
Angular correlations Bethe-Heitler

Limitation: resolution in  $t$

Note: not yet properly normalized and need implementation of dynamic cuts for integral  
In  $\theta$  over the BH related to final muon pair

Similar issues as TCS but more difficult & more kinematic dependences  
(4D dynamic cuts to calculate to produce the table)

## 8) TCS, DDVCS: what do we learn, what can we do

- TCS into muons or electrons; DDVCS into muons (same as quarkonia)

- **Most important with Bethe-Heitler:**

**Interpreting final pair peaks / localising the regions and cutting them out**

**TCS: GPD universality / higher twists + DVCS comparisons**

**DDVCS: tomography + ERBL region**

We have to be very careful with Bethe-Heitler!

Regions with most counting rates are not good for physics

DDVCS needs to be interpreted from TCS+BH behavior, not DVCS

## 9) Further items to discuss

### Crossing Angle

Crossing angle energy correction: where is that applied?

Should I correct the beam energy or can I include the crossing angle at generation level?

Crossing angle ignored in rotations: should I?

→ all rotations will be checked again and crossing angle included to see if any difference

Other approximations ( $m_e$ ,  $M2 < Q2$ ...): check impact and/or include corrections

May have small impact on resolution studies

### Observables vs kinematics and vs $\phi(\text{in})$ , $\phi(\text{out})$

- cross-sections
- asymmetries?

### Kinematic dependence

$t$ ,  $Q^2$ ,  $Q'^2$  or mass,  $\phi(\text{in})$ ,  $\phi(\text{out})$ ,  $\theta(\text{out})$ ,  $x_{\text{bj}}...$

$x_i$ ,  $(x_i')$ ,  $\eta$ ,  $p_T...$

## 10) Summary

- Framework ready, still few optimizations and checks for generating deep Compton-like reactions and vector mesons (quarkonia + light)
- DEEPSim is a dedicated generator, inspired and based on tools developed for Jlab and tools and modeling developed specifically for EIC
- Jlab version (DEEPSim) has been cross-checked several times and includes more options than DeepSim, also has been working well with real data. However DEEPSim may benefit from more cross checks
- Currently supported or near final version:  
J/psi, Upsilon, TCS, DDVCS, rho

### Next step:

- 5M of each reaction has been produced → run them through reconstruction, check if everything is fine and can be run into full production
- cross-check of event weighting
- binning and kinematic projections

# 11) Resources

ROOTfiles and HEP files  
/work/eic/users/mboer/ROOTfiles/(reaction)

Generator code (on jlab)  
/home/mboer/Public/DEEPSim\_public

How it works: Hall C public note #999

TCS/BH peaks and kinematic cuts (study for Hall D) Hall D public note

Presentations from Tyler Schroeder July 2021 ECCE exclusive PWG

Tyler's report:

Tyler's poster: