Connecting theory to experiment and Event Generator development for hard exclusive reactions

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QCD evolution, May 2025, Jefferson Lab

Outline

- Goals

- Software framework

- GPD models, Compton Form Factors and cross sections formalism

- Event generator

- Projections

- Fits

Credit in parts of this work and presentation: Kemal Tezgin (current postdoc),
Tyler Schroeder, Renaud Lustrat (former undergrads) + few other undergraduates

This work is supported by DOE grants DE-SC0025657 (multichannel, experimental aspects)
and DE-SC0024618 (software, models)

Our goals and about this project

- Theoretical projections and feeding event generators for experimental projections for various hard exclusive reactions

- Ability to use different models of GPDs and different formalism for the cross sections

- Compute various observables

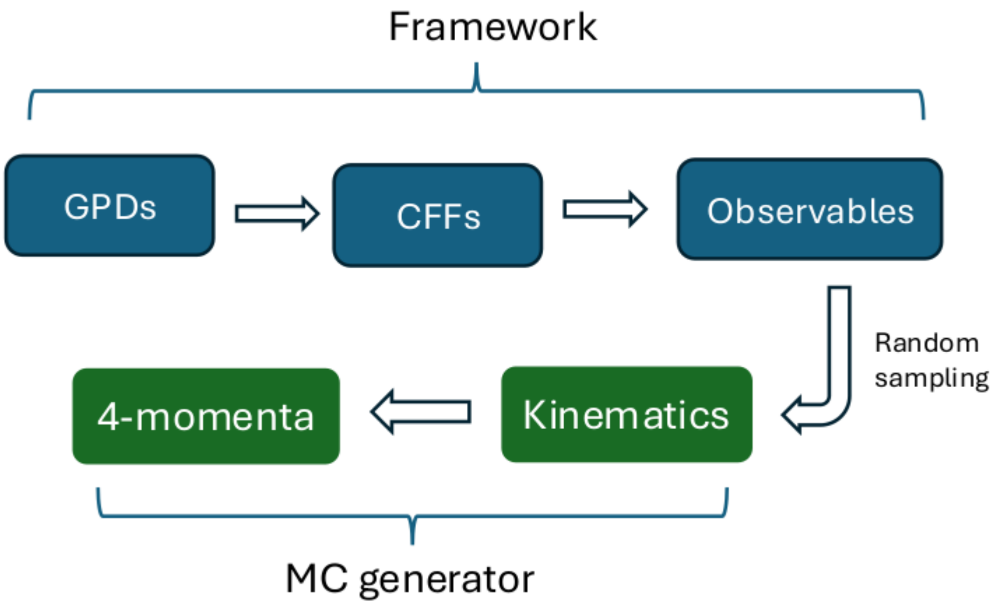
- Impact studies and fits of CFFs

- Multi-channel analysis

- C++ software containing our various models which can be interfaced to fitter codes, event generators and experimental Monte-Carlo

- First version of this work in 2015, with significant updates in 2018/2019/2021, and major developments since Kemal Tezgin joined the group in 2024 with EXCLAIM collaboration

Architecture of the C++ software



What has been done so far (credit: Kemal Tezgin):

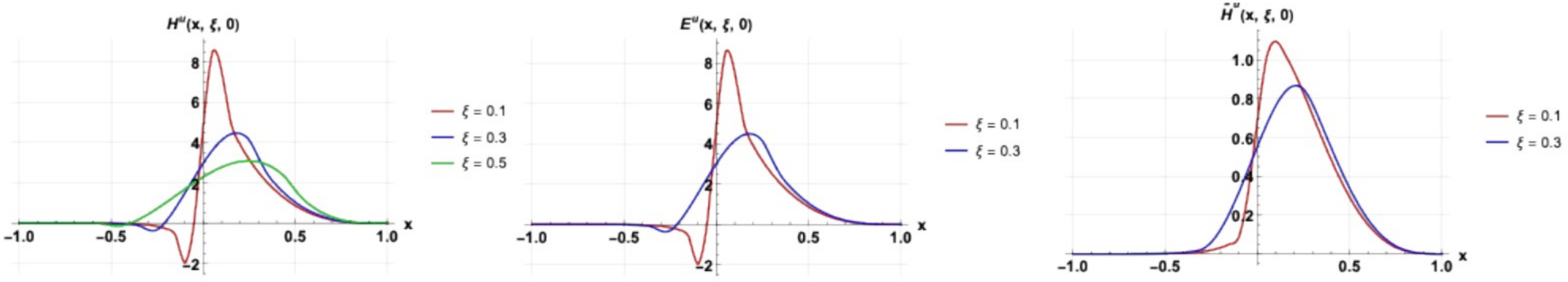
Modular structure: each component has a well-defined role

Processes: DVCS, π^+ and π^- (handbag-based), ϕ and J/ψ (HQCD)

Concept: use building blocks of the hadrons, such as GPDs and/or CFFs, to describe observables

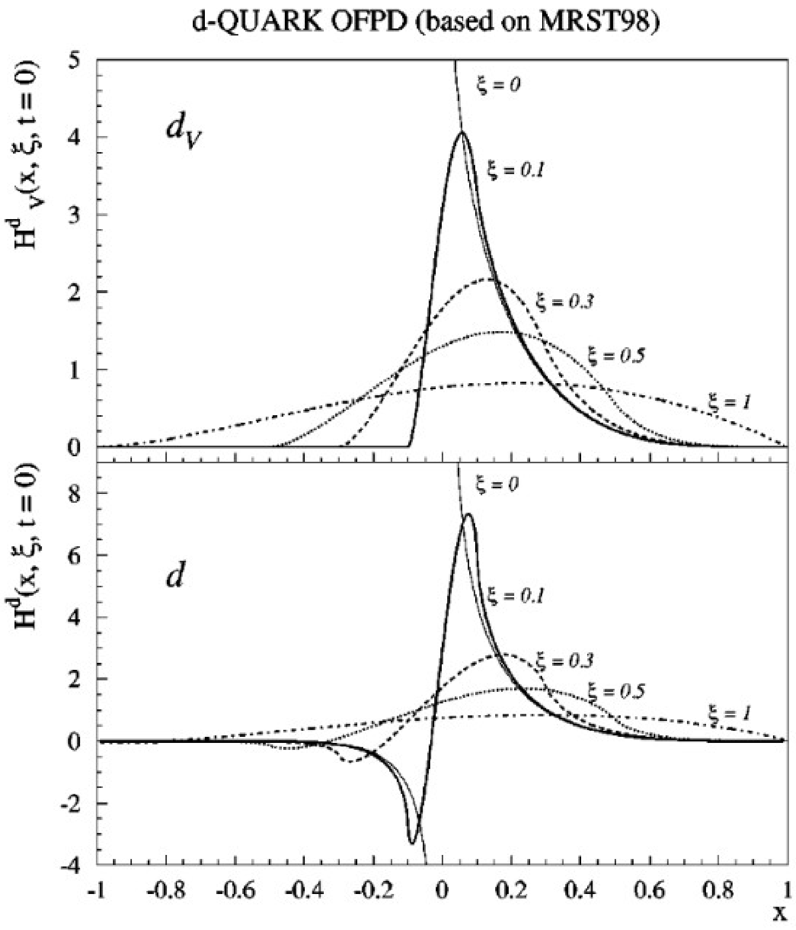
GPD models implemented

Available GPD models: VGG, GK
PDFs used: MRST1998, LSS1998
EM Form Factors used: Kelly's parametrization



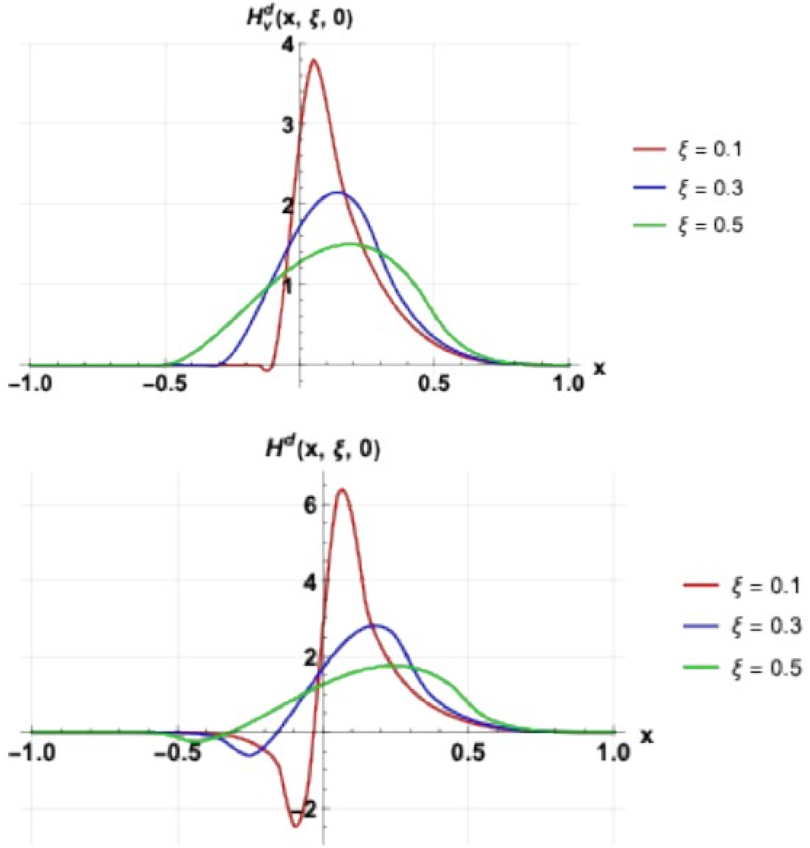
VGG GPDs for different ξ-values

VGG model comparison



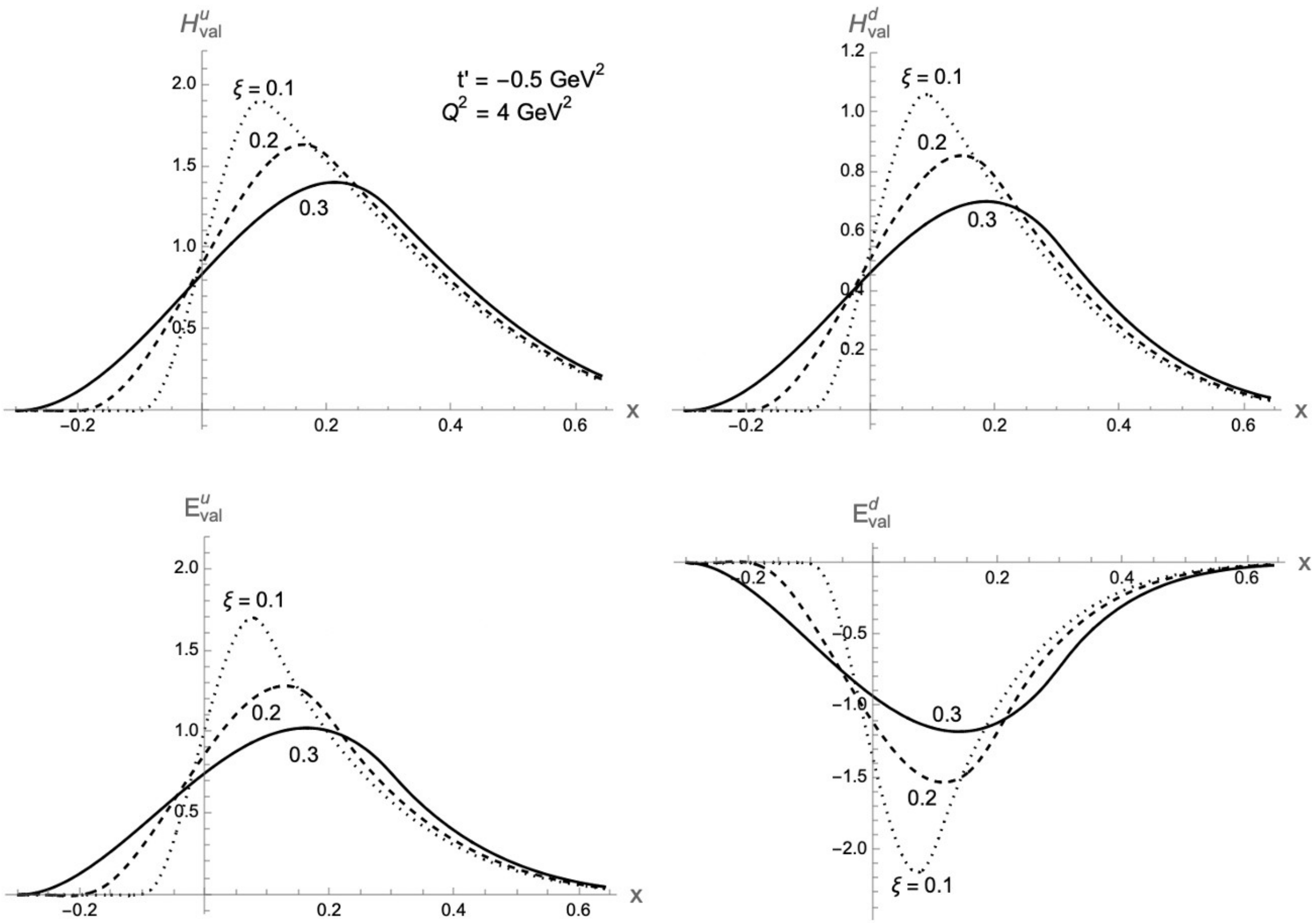
Vanderhaeghen, Guichon, Guidal (1999)

from this code:



* at t=0 to compare with 1999 article

GK model GPDs



Cross section of the electroproduction process

DVCS+BH

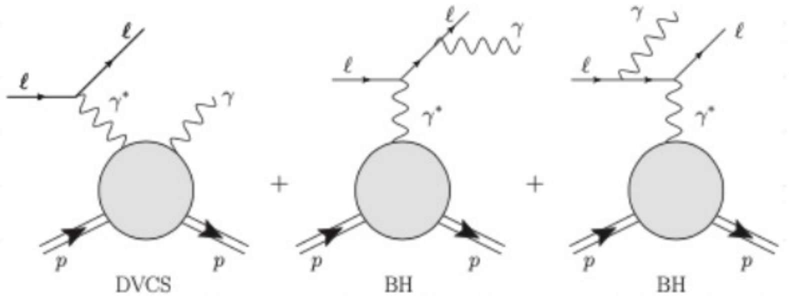
$$\frac{d\sigma}{dx_{\mathrm{B}}dyd|\Delta^2|d\phi d\varphi} = \frac{\alpha^3 x_{\mathrm{B}} y}{16\,\pi^2\,\mathcal{Q}^2\sqrt{1+\epsilon^2}}\left|\frac{\mathcal{T}}{e^3}\right|^2 .$$

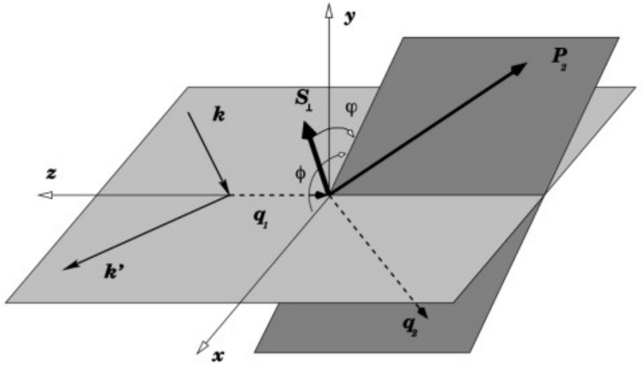
Belitsky, Müller, Kirchner, Nucl. Phys. B 629 (2002)
Kriesten et al., Phys. Rev. D 101 (2020)

$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{e^6}{x_{\mathrm{B}}^2 y^2 (1+\epsilon^2)^2 \Delta^2\,\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{\mathrm{BH}} + \sum_{n=1}^{2} c_n^{\mathrm{BH}}\cos(n\phi) + s_1^{\mathrm{BH}}\sin(\phi)\right\},$$

$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = \frac{e^6}{y^2\mathcal{Q}^2}\left\{c_0^{\mathrm{DVCS}} + \sum_{n=1}^{2}\left[c_n^{\mathrm{DVCS}}\cos(n\phi) + s_n^{\mathrm{DVCS}}\sin(n\phi)\right]\right\},$$

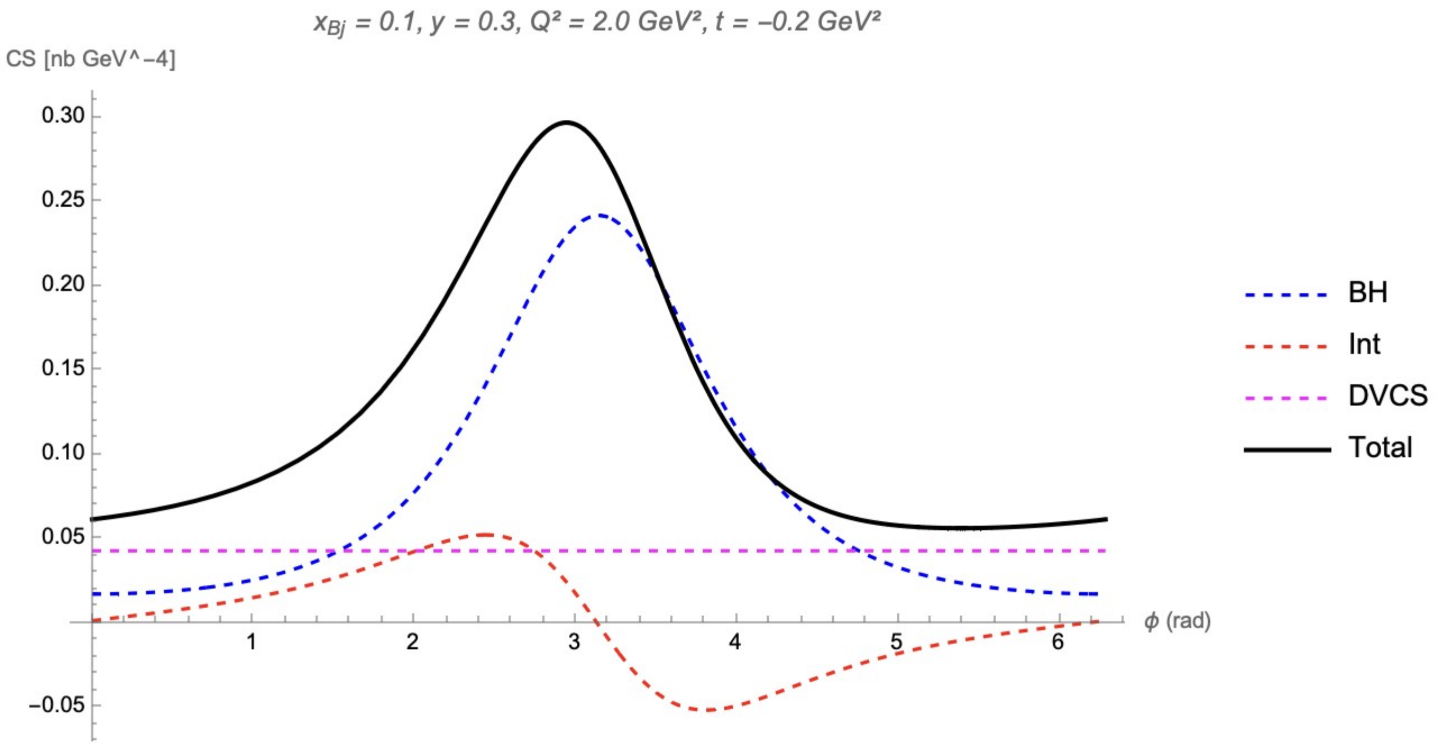
$$\mathcal{I} = \frac{\pm e^6}{x_{\mathrm{B}} y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\},$$





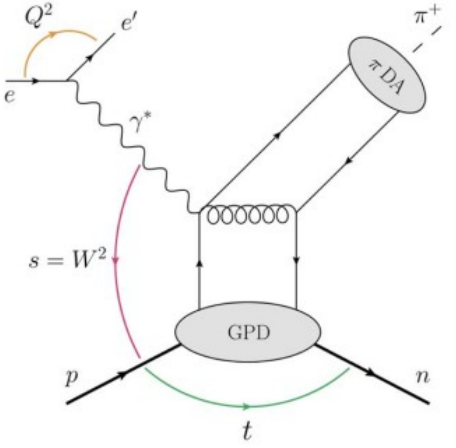
BMK cross section

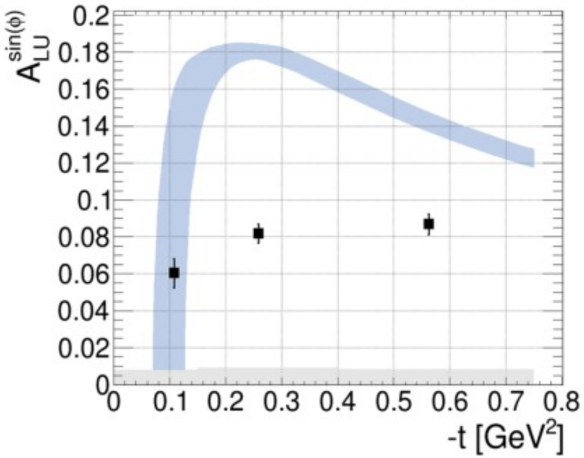
- Unpolarized cross section of the electroproduction process with the VGG GPDs
- Leading twist and leading order



DVMP

In our software, based on GK model: pions





S. Diehl et al., PRL 125 (2020)

- Based on effective handbag approach: factorizes the process into GPDs and subprocesses
- Allow access to chiral-odd GPDs $\widetilde{H}_T$ and $\tilde{E}_T$
- Beam spin asymmetry calculation based on the GK model

$$BSA(t, \phi, x_B, Q^2) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

$$= \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos 2\phi} \cos 2\phi},$$

Software: our next steps

- Adding GPDs from GLL model and other versions of VGG (maybe other models too)

- Adding more options for FFs and pdfs parametrizations to fit a broader kinematic range

parametrization

- Completing implementation of cross sections we have in other codes based on VGG, GK, BKM, GLL models, for comparisons in projections and systematic studies in so-called “model-independent” fits => are we really model independent?

- Adding other reactions we have in various independent codes / from various groups (so far DVCS, π^+, π°; next step TCS, DDVCS, vector mesons/quarkonias)

- Current work from UVA group and Kemal on new DVCS formulation

observables

=> Status is we can make projections and the structure is in place, we need to implement various modules and expend models

AI for Nuclear Physics: the EXCLAIM project

arXiv:2408.00163v1 [hep-ph]

S. Liuti, [a] D. Adams[a] M. Boër[b] G.W. Chern[a] M. Cuic[a] M. Engelhardt[c] G.R. Goldstein[d] B. Kriesten[e,*] Y. Li[f] H.W. Lin[g] M. Sievert[c] D. Sivers[h,*]

This work in preparation with the EXCLAIM collaboration

(some of us below)

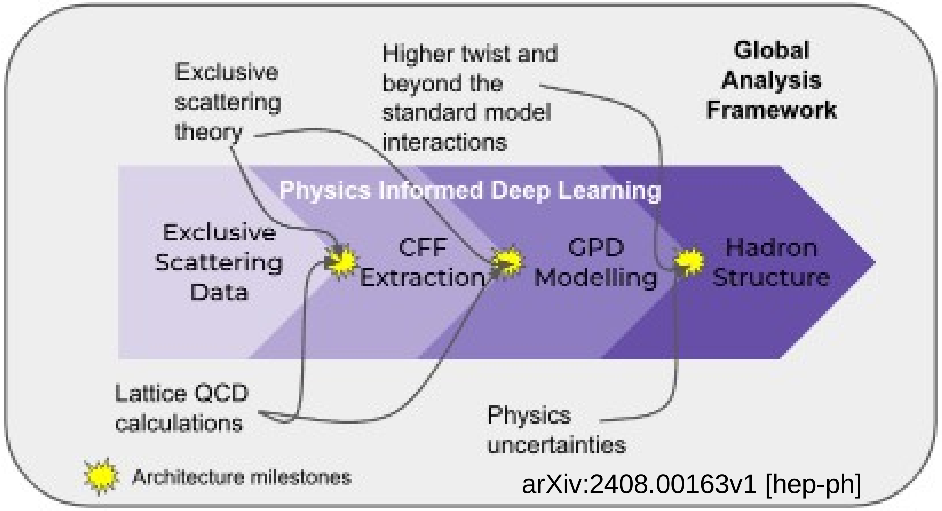
The EXCLAIM collaboration

https://exclaimcollab.github.io/web.github.io/#/

CoPIs: Marie Boer, Gia-Wei Chern , Michael Engelhardt, Gary Goldstein, Yaohang Li, Huey-Wen Lin, SL, Matt Sievert, Dennis Sivers

Postdocs: Douglas Adams, Marija Cuic, Saraswati Pandey, Emanuel Ortiz, Kemal Tegzin

EXCLAIM collaboration goals and connection to this work



Pipeline of physics informed deep learning framework that goes from exclusive scattering data to information on hadron structure

- Using AI/ML tools at various levels, in simulations, fitting data, analysis, connecting lattice data and phenomenological models… [we have collaborators from theory, lattice, CS]

- This software enables to connect and/or compare various models and expend the fitting framework, as well as input for event generator to make experimental projections, “fed-back” into analysis tools (all this work in progress)

Event Generators

DEEPGen (Deep Exclusive Electro- and Photo-production Generator)
Developed for projections of future experiments at JLab since 2015 (last public version released 2019). Has been successfully tested against JLab data and other codes

and it's EIC-kinematic extension DEEPSim (developed since 2021 – not public yet, we still want to improve it and add more models and reactions)

<u>DEEPGen</u>

DVCS
TCS
DDVCS
VCS
Elastic, DIS
pion (low Q^2)
kaon (low Q^2)

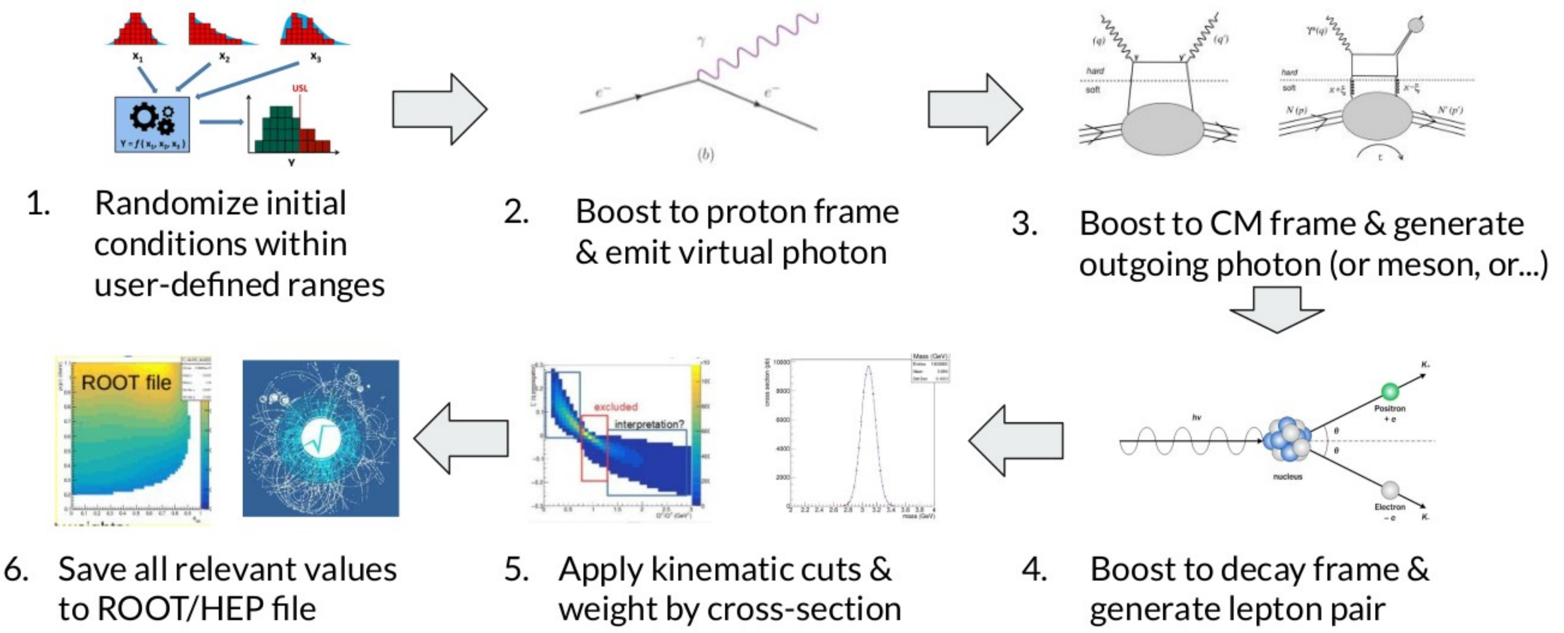
test versions for:
phi, rho, J/psi

<u>DEEPSim</u>

rho
J/psi
Upsilon
not completely tested: DVCS, TCS

https://solid.jlab.org/wiki/index.php/DEEPGen_event_generator

Principle



Specific: - weighted events, multiple weights possible (various models, subprocesses…)
- input grids, can use various models
- output to any format (root, HEP, can feed into GEANT)
- possible kinematic cuts or spatial cut, for instance for Hall A/C experiments

Specific to DEEPGen

tuned to JLab kinematics (11 GeV, special version for 22 GeV)
optional tuning for Hall C experiments (narrow angles)

- user defined kinematic range
- target material (proton, neutron, nucleus*) and polarization (perp or //)
- beam energy and polarization. Electron and (polarized) photon supported)

- output format
- spatial / kinematic cuts
- radiative corrections*

model (any process)

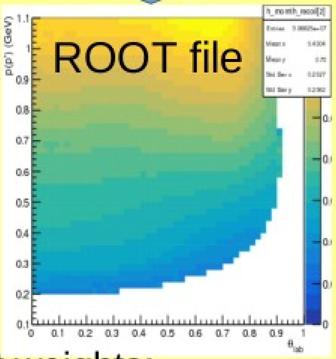
$$\frac{d^4\sigma}{dQ'^2 dt d\Omega}(\gamma p \to p' e^+ e^-) = \frac{1}{(2\pi)^4}\frac{1}{64}\frac{1}{(2ME_\gamma)^2} \mid T^{BH} + T^{TCS} \mid^2$$

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
```

Will feed from our new software

MAIN EXE



event weights:
polarized, unpolarized,
asymmetries, only BH...
here: TCS/BH p(P) vs θ(lab)

user input file (here: TCS)

Variable name	usage	limits (grid)	default value
Experimental configuration	Beam and target parameters		
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} cm^{-2}
out leptons	electron (1) or muon (2)	1 or 2	2
Target lenght	luminosity	-	15 cm
Target composition (A,Z)	luminosity	single atoms	(1,1) or 1001
Target = p (1) or n (2)	weight	1, 2	1
	Polarization options		
Beam polarization dilution 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
Kinematics	Kinematic range		
Photon energy	photon	[4.5, 11.5]	[5, 10.5]
-t	Mandelstam variable	xx	[.05, .7]
Q'^2	final photon virtuality	xx	[.09, .3]
θ_{CM}	azimuthal angle of decay leptons	[40°, 140°]	[40°, 140°]
Q^2_{max}	quasi-real photons maximal virtuality	0 to ~ 0.5	0.3

*nucleus: only target density, no nuclear effect *rc next slide

Specific to DEEPGen

DVCS, TCS, DDVCS: based on VGG model GPDs

VCS, pions: based on MAID 2007 (Pasquini et al.)

quarkonia (J/psi, Upsilon – in “high energy” version) “homemade” parametrization based on Brodsky et al.

Radiative corrections: based on Mo&Tsai, user-defined cut-off, only external correction implemented
Calculating bremsstrahlung in the target and internal real corrections as "equivalent radiator"
Use virtual photon flux correction factor to rescale the energy to the electron beam after corrections.
For heavy target and high energy beam, possibility to radiate a cascade of photons in the target.
[internal corrections will be added for Compton-like reactions, already implemented to VCS]

Photoproduction: photon beam is coming from bremsstrahlung and/or quasi-real photons.
outgoing electron can radiate photons, as ig the interaction happen at half of the target lenght.
Beam energy profile is corrected at analysis level (for experimental projections)

Polarization vectors: each target nucleon and electron is assigned a random spin, photons can also be linearly polarized. Output file provides all options: unpolarized, single and double polarized cross-sec.

Event weighting

DVCS+BH and VCS+BH weights are expressed in nb.GeV-4rad-1

W (unpolarized) = dσ/(dt dQ² dxbj d_φ)

TCS+BH weights are expressed in pb.GeV-4.rad-2

DDVCS+BH weights are expressed in pb.GeV-6.rad-3

VCS+BH weights are expressed in pb.GeV-4

exclusive π° or π+N weights are expressed in nb.GeV-4

```
target_spindir  = spin orientation of target (+1 or -1)
beam_spindir    = spin orientation of beam (+1 or -1)
polbeamdeg      = beam polarization transfer times initial electron polarization rate (dilution factor)
poltargetdeg    = dilution factor of target polarization
```

user defined polarization options

```
W_tot_unpol     = actual total unpolarized cross section with flux factor for quasi real beam
W_BH            = B-H "only" unpolarized cross section with flux factor for quasi real beam
W_TCS           = TCS "only" unpolarized cross section with flux factor for quasi real beam
W_tot_pol       = beam + target actual polarized cross section (quasi real beam + flux / dilution factors)
W_tot_pol_beam  = beam only polarized cross section (quasi real photon + flux / dilution factor)
W_tot_pol_target = target polarized cross section (quasi real photon + flux  / dilution factor)
BSA             = approximate single beam spin asymmetry at this kinematic (no dilution)
TSA             = approximate single target spin asymmetry (no dilution)
BTSA            = approximate double beam and target spin asymmetry (no dilution)

cross_tot_unpol = unpolarized cross section for real photon beam
cross_BH        = Bethe-Heitler "only" unpolarized cross section for real photon beam
cross_TCS       = TCS "only" unpolarized cross section for real photon beam
cross_tot_pol   = beam + target polarized cross section (real photon / dilution factors)
cross_tot_pol_beam = beam only polarized cross section (real photon / dilution factor)
cross_tot_pol_target = target polarized cross section (real photon / dilution factor)
```

very good to have for systematic studies, impact studies, experimental projections to assess feasibility

especially when BH largely dominant

Event weighting

DVCS+BH and VCS+BH weights are expressed in nb.GeV-4rad-1 W (unpolarized) = dσ/(dt dQ² dxbj d_φ)

TCS+BH weights are expressed in pb.GeV-4.rad-2

DDVCS+BH weights are expressed in pb.GeV-6.rad-3

VCS+BH weights are expressed in pb.GeV-4

exclusive π° or π+N weights are expressed in nb.GeV-4

VCS case includes virtual corrections

```
W_VCS_born      = VCS "only" unpolarized cross section, contains only the 2 born diagrams for photon emitted by the proton
W_VCS_nb        = VCS "only" unpolarized cross section, contains only the higher order terms/diagrams (non Born)
```

TCS case with linear photon polarization (diamond)

```
phi_s           = target spin orientation relative to the reaction plane (photons)
Psi_s           = angle between reaction plane and spin direction of linearly polarized incoming photon (option linear polarization
only)
cross_BH_x      = polarized differential cross section for BH if the beam spin is oriented "in plane" for the given kinematic
cross_BH_y      = polarized differential cross section for BH if the beam spin is oriented "tangent to plane" for the given
kinematic
```

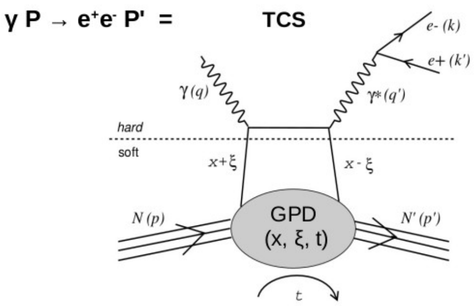
TCS specific: generator level rejection of events near BH peaks

```
FlagSing        = if =1, this event is in the near-singularity region and has to be rejected for proper reconstruction (cut in θ, φ
thetamin_nocut  = minimal θ above the near-singularity region for this given E, t, Q'²
```

Kinematic cuts / effective observables

TCS specific: generator level rejection of events near BH peaks

```
FlagSing         = if =1, this event is in the near-singularity region and has to be rejected for proper reconstruction (cut in θ,
thetamin_nocut   = minimal θ above the near-singularity region for this given E, t, Q'²
```



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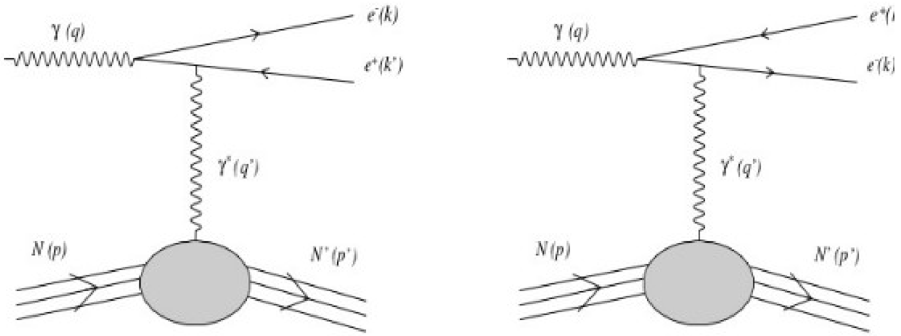
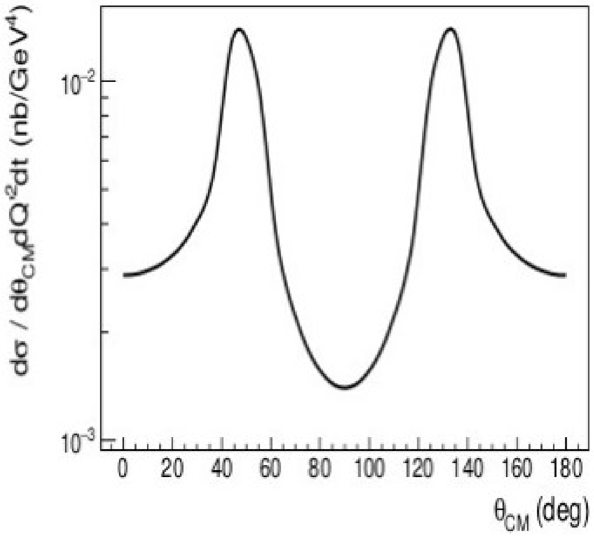
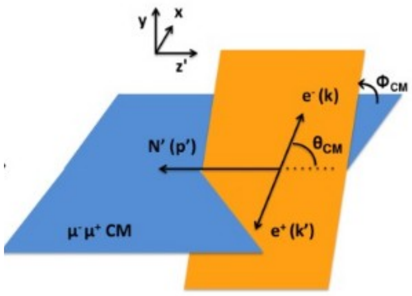


Figure 1: Bethe-Heitler leading order and leading twist diagrams.





effect in pair production (TCS here, DDVCS)

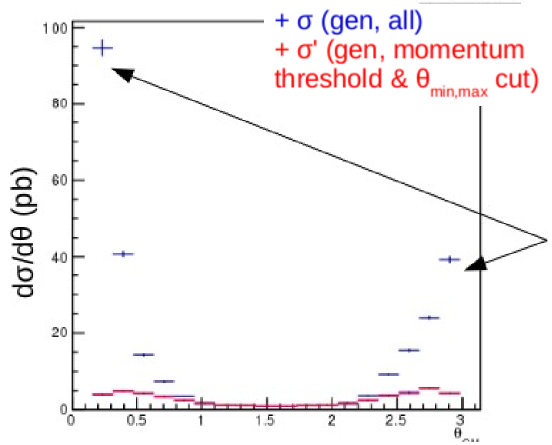
each diagram responsible for a “sharp peak”
when e+ or e- becomes collinear to photon
Depends on t, Q'^2, E

Kinematic cuts / effective observables

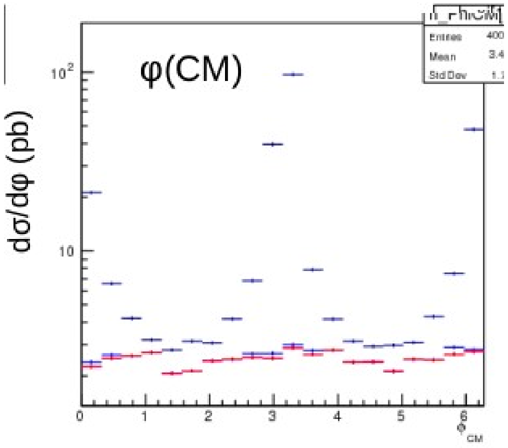
TCS specific: generator level rejection of events near BH peaks

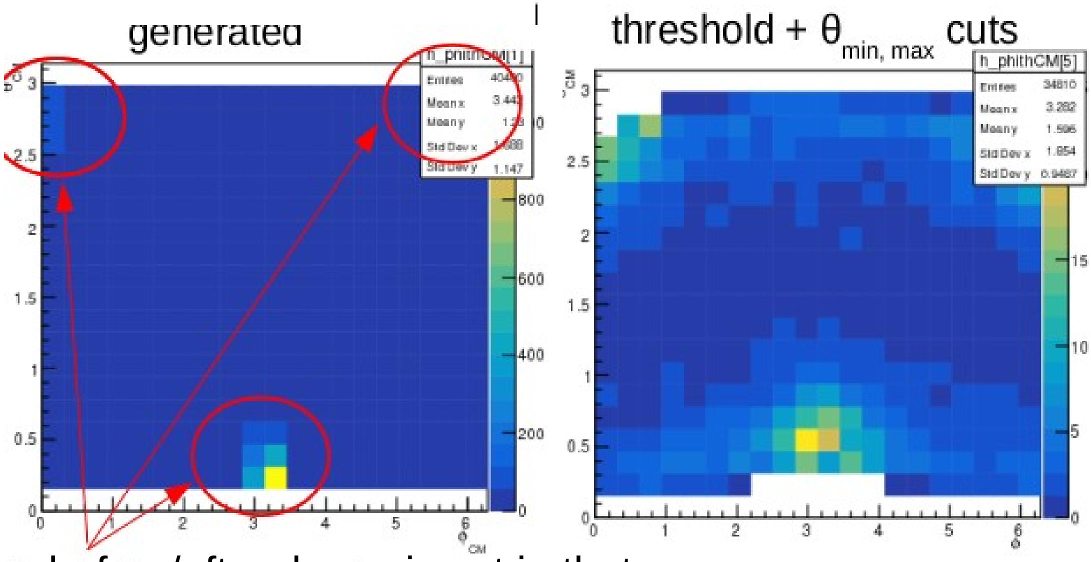
```
FlagSing          = if =1, this event is in the near-singularity region and has to be rejected for proper reconstruction (cut in θ,
thetamin nocut    = minimal θ above the near-singularity region for this given E, t, Q'²
```

(1) θ_{CM} integrated distribution



peaks, “removed” by flag in generated data





before/after dynamic cut in theta

Why multiple weights?
Example of quick impact studies

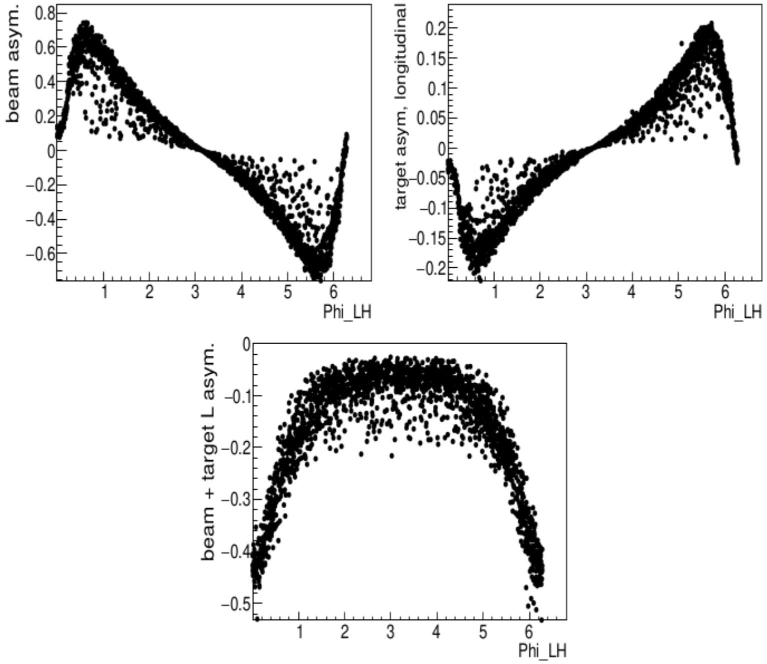


Figure 14: DVCS+BH generated spin asymmetries from a polarized electron beam (top left panel), longitudinally polarized target (top right panel), polarized beam+longitudinally polarized target (bottom panel). The beam energy is set at 11 GeV and $0.2 < x_{bj} < 0.25$, $4 < Q^2 < 5$ GeV^2, $-0.6 < t < -0.5$ GeV^2. Asymmetries are displayed as a function of ϕ_{LH} (rad.).

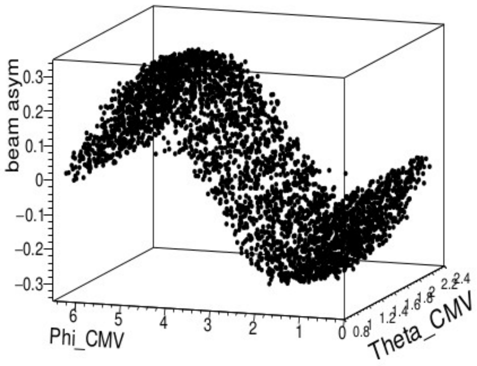


Figure 16: TCS+BH beam spin asymmetry as a function of ϕ, for 5<E$_\gamma$<11.4 GeV, $6.5 < Q'^2 < 7$ GeV^2 and 0.6<-t<0.7 GeV^2.

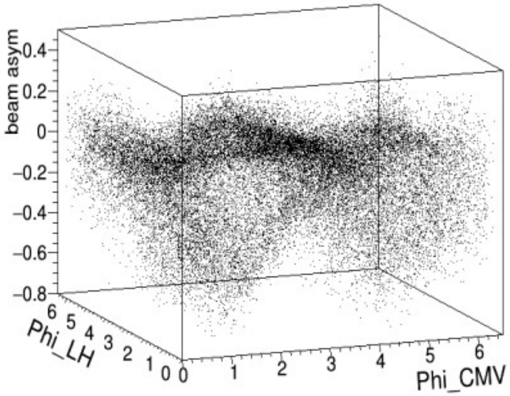
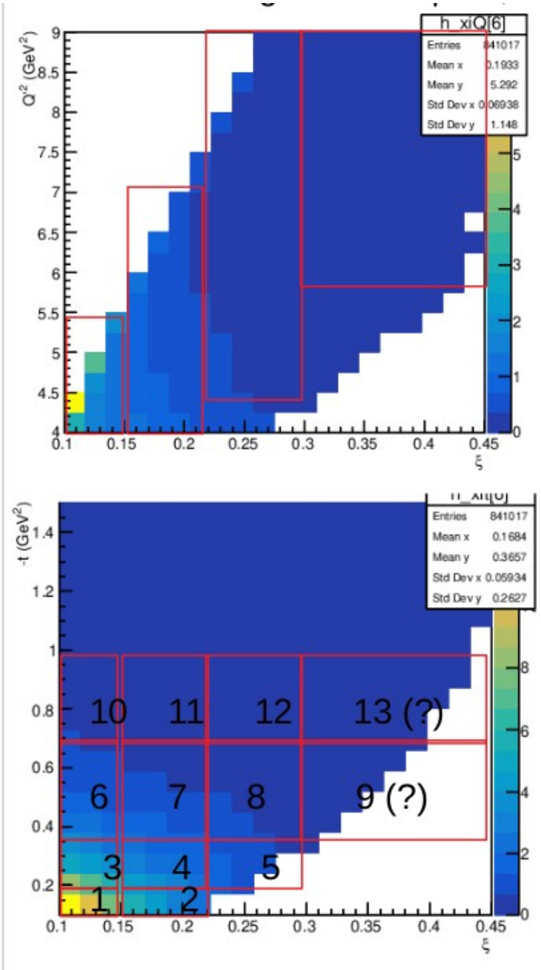


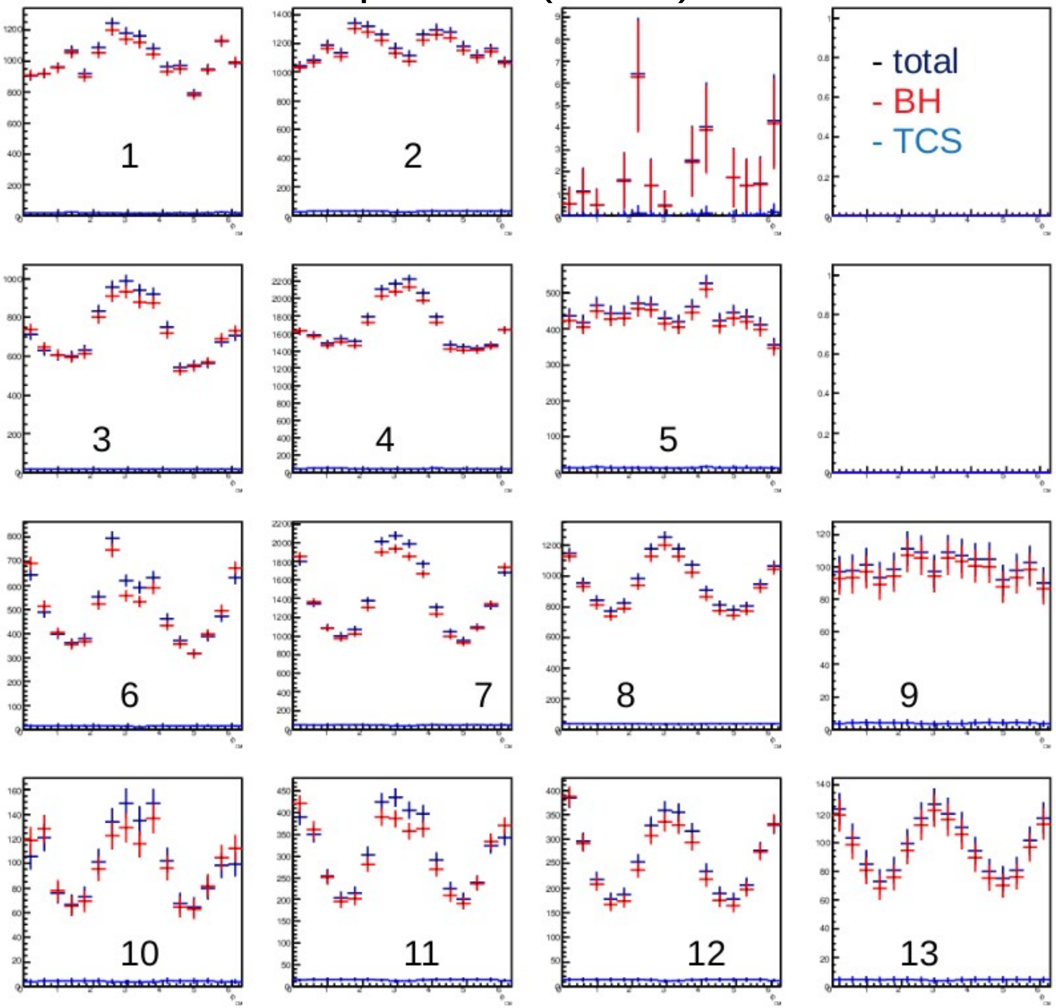
Figure 18: DDVCS+BH beam spin asymmetry as a function of ϕ_{CM} and ϕ_{LH} (units are radians).

- checking spread and size of asymmetries in specific bins
- comparison with “calculated”/ “measured” from polarized cross sections or generator calculated asymmetries
- numerical way to calculate “effective” observables (in particular with kinematic dependent angular cuts in TCS and DDVCS)

Example of impact study for TCS with a transverse polarized target

counts for each phi bins (x-axis) and kinematic xi, t bins

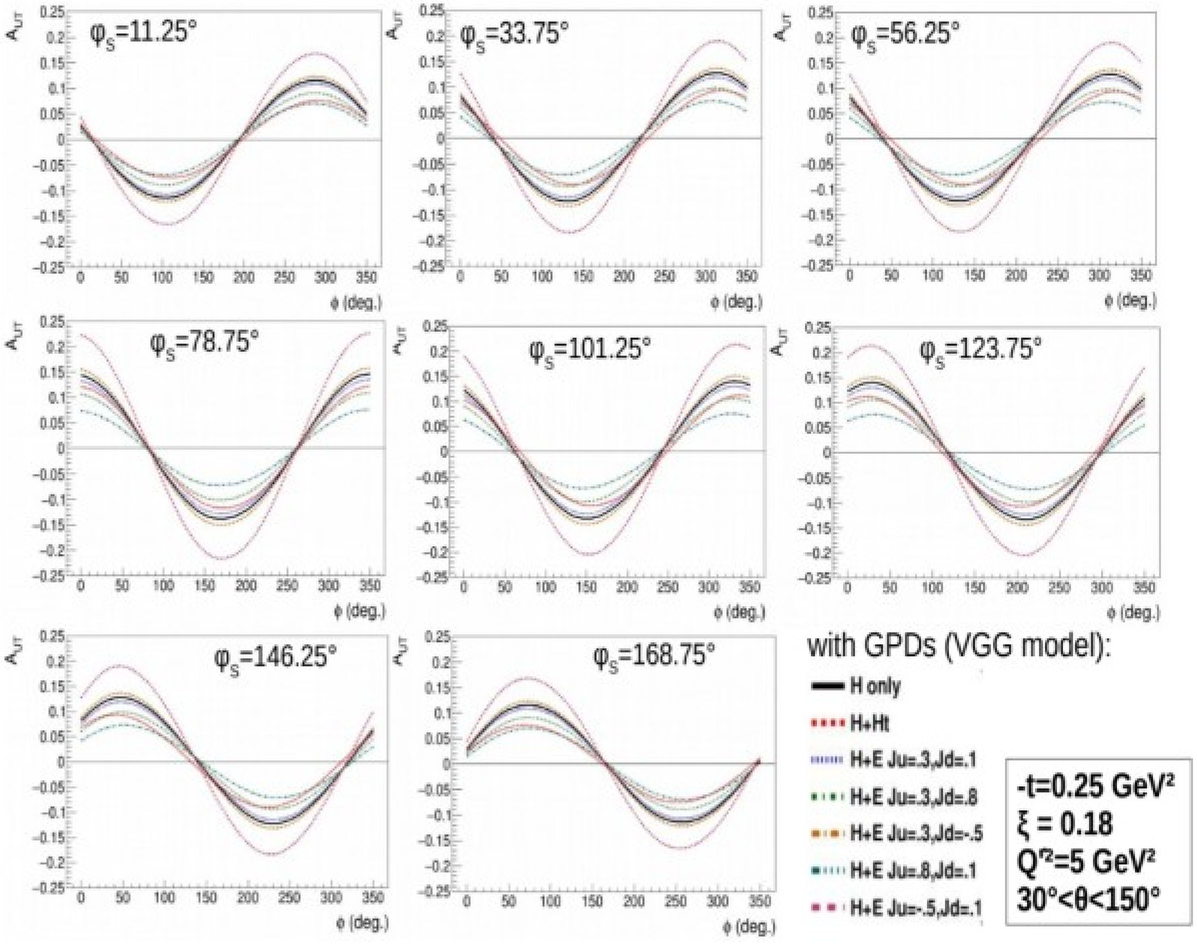




Example of impact study for TCS with a transverse polarized target

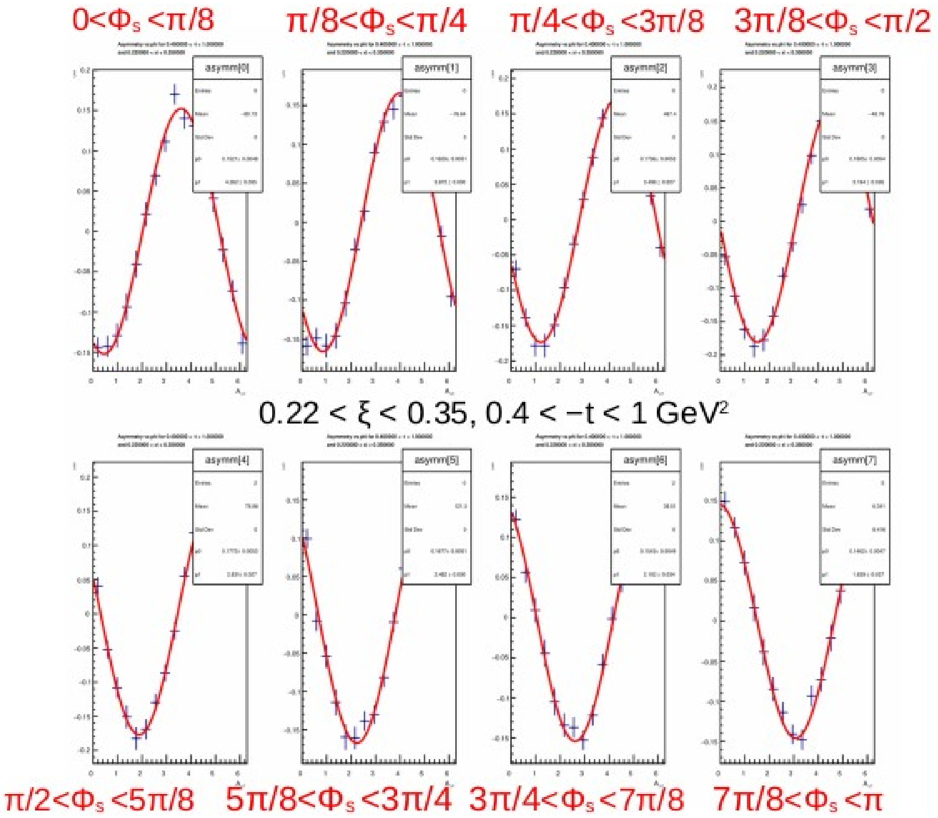
Calculated single asymmetries from various model versions

TSA has strong dependence on GPD E parameterization and quark angular momenta.
[from C12-15-005]

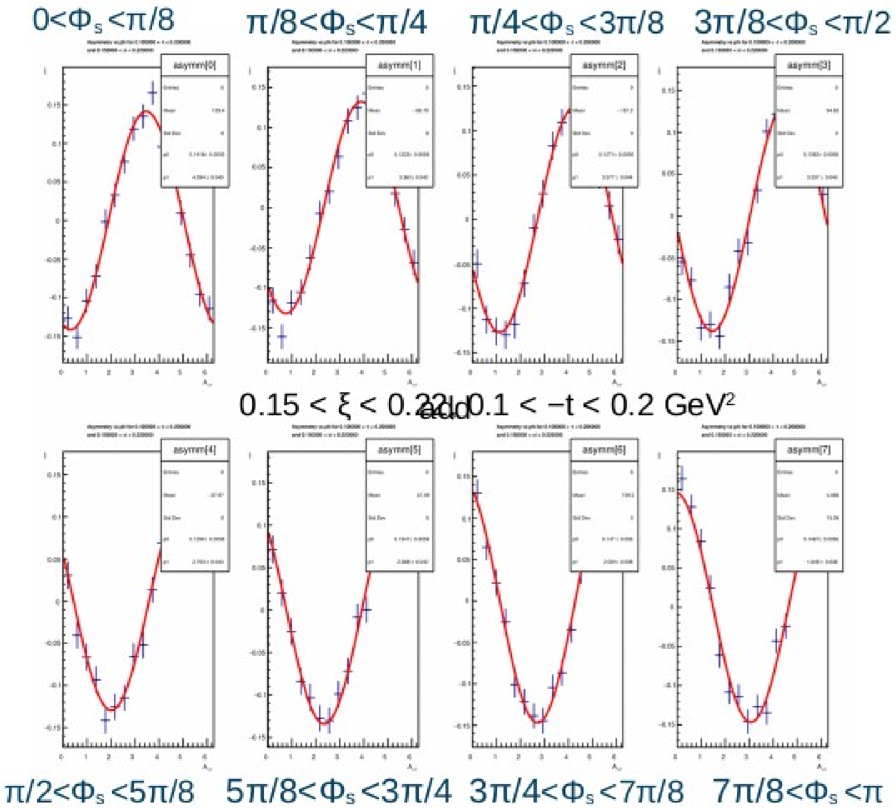


* part has been presented to Jlab PAC in 2022, part never proposed
* figures: MB or Brannon Semp

Projected single spin asymmetries in various bins



$0.22 < \xi < 0.35$, $0.4 < -t < 1$ GeV^2



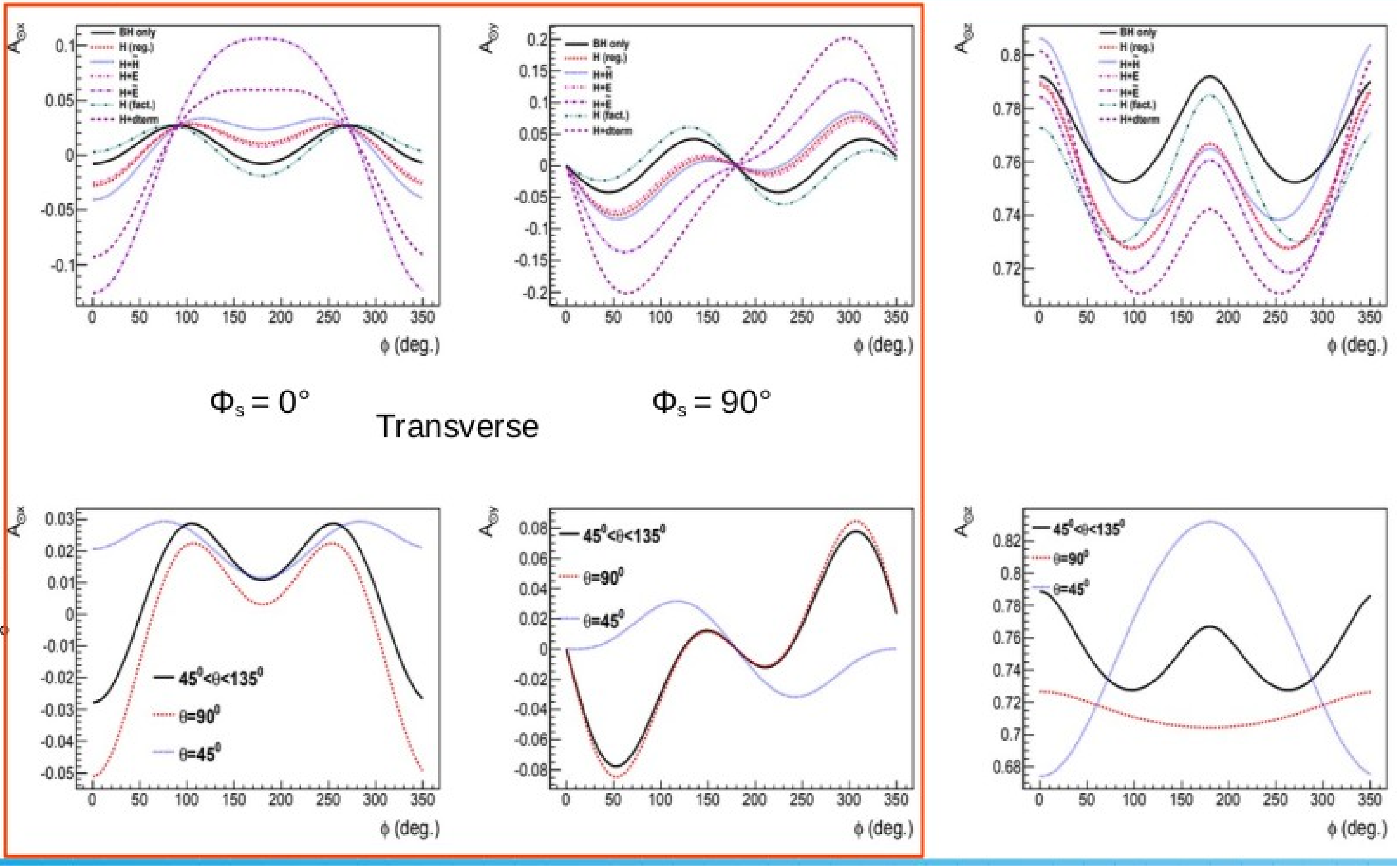
$0.15 < \xi < 0.22$ add $0.1 < -t < 0.2$ GeV^2

Calculated double asymmetries from various model versions

BTSA has a dependence on the real parts of all CFF

$\xi = 0.2$, $-t = 0.4$ GeV^2 and $Q'^2 = 7$ GeV^2

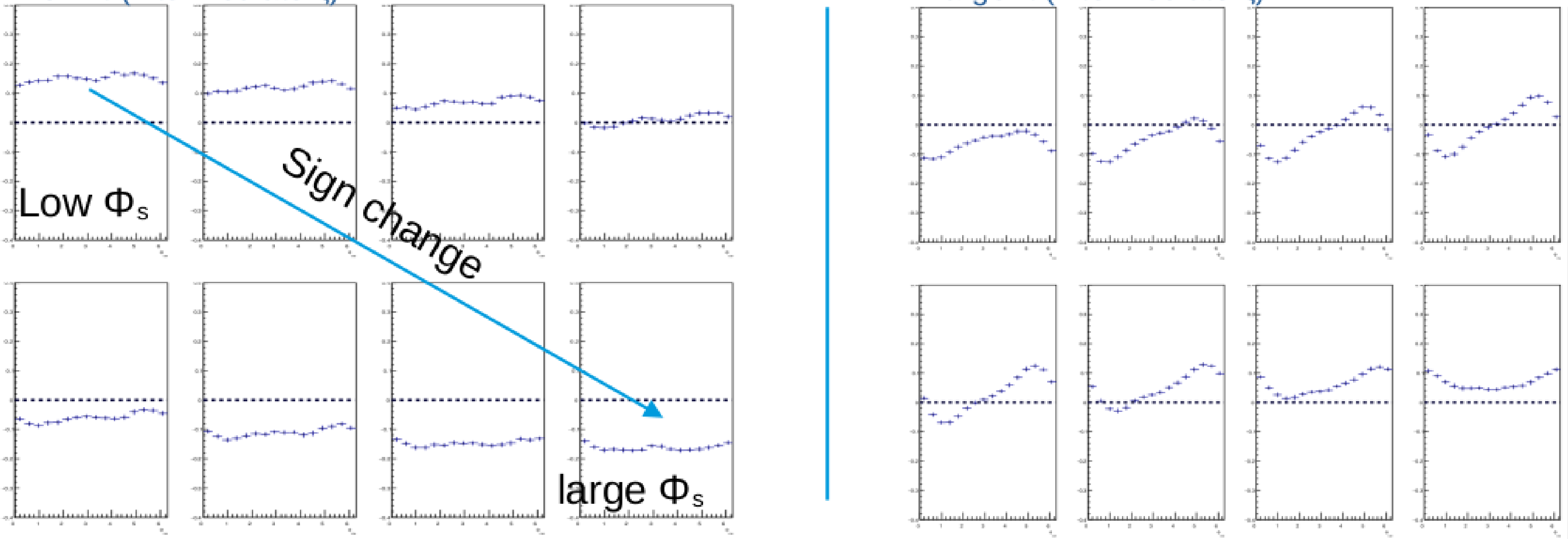
Asymmetry for transverse target isn't as different for 90° (Highest TCS vs BH) vs integrated as compared to 45° (Highest BH)
Because of this, we can use the integral to measure TCS



Projected (ideal) double spin asymmetries in various bins

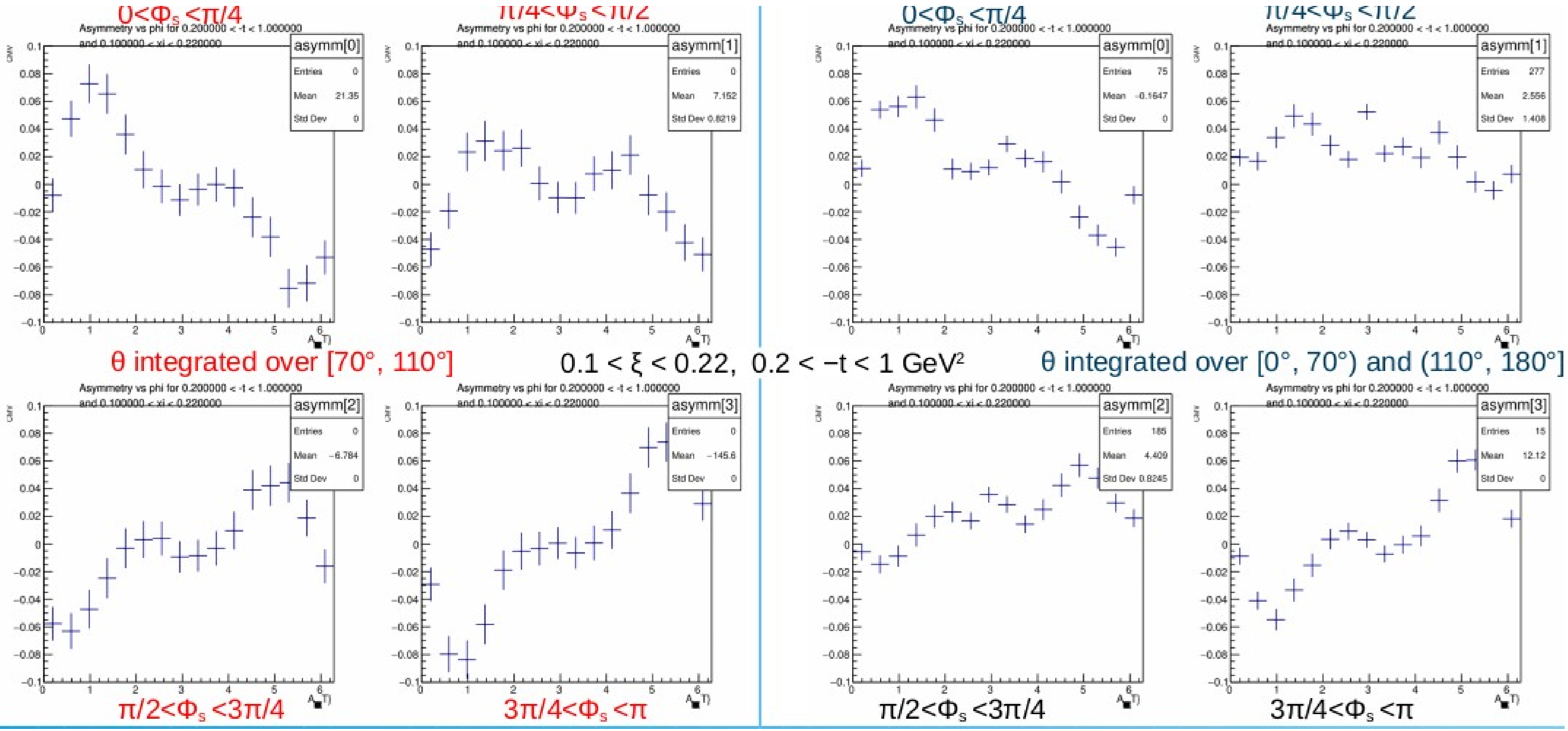
Evolutions of the shapes vs Φ, bins in Φ_s from 0 to π at intermediate ξ and for 2 bins in t

Low -t (intermediate ξ) Large -t (intermediate ξ)



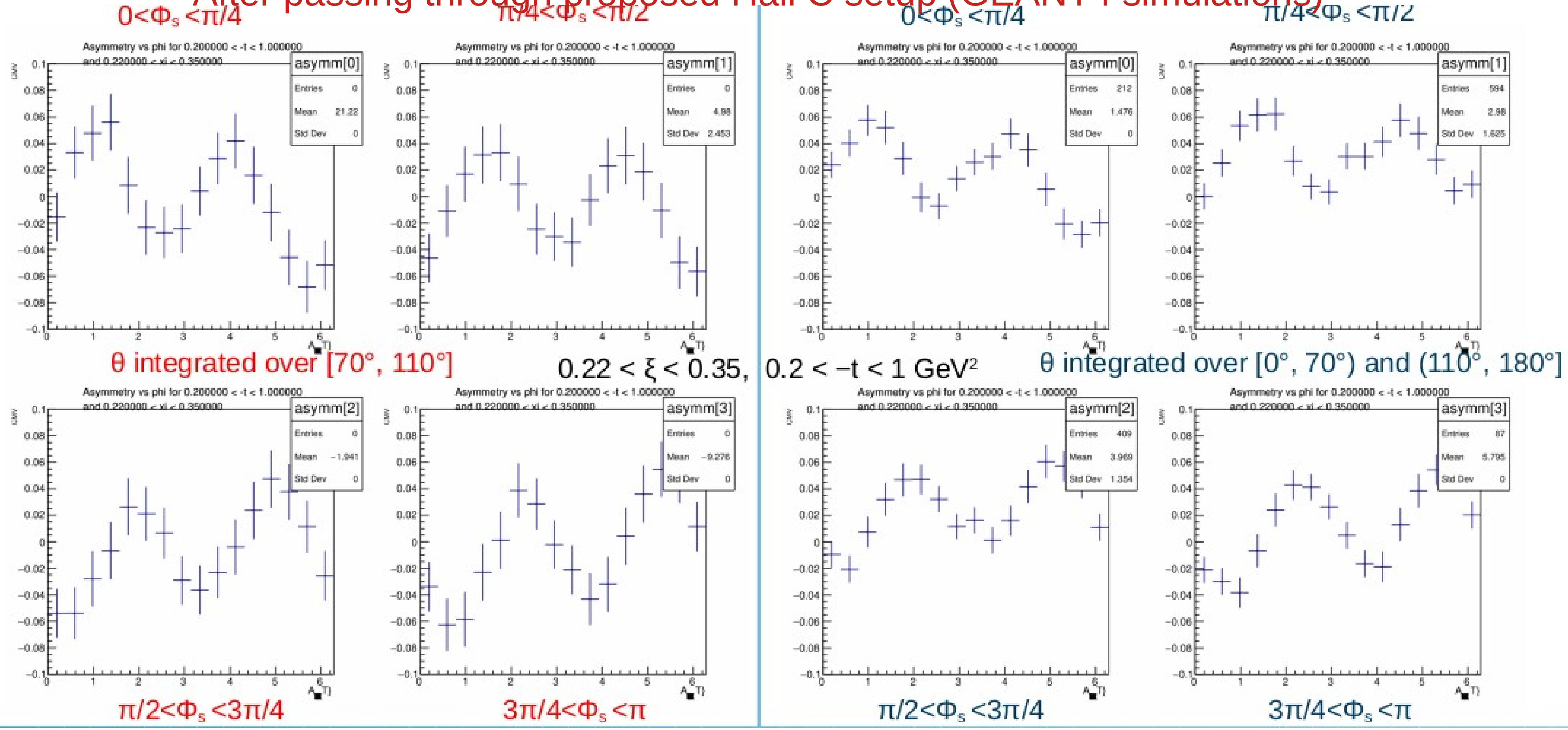
- **Harmonic structure of BTSA mostly depends on t & ξ bins**
- BH doesn’t cancel, nor is it TCS “only”. Harder to interpret **but**: best to access Re(CFF) and any information is a major input to models and especially for discriminating Double Distribution “types” vs other kinds (strongly differ on Re CFF)
- Total BTSA different enough to pure BH BTSA to extract CFFs [see next slide]

Projected (realistic) double spin asymmetries in various bins
After passing through proposed Hall C setup (GEANT4 simulations)



large t, low xi

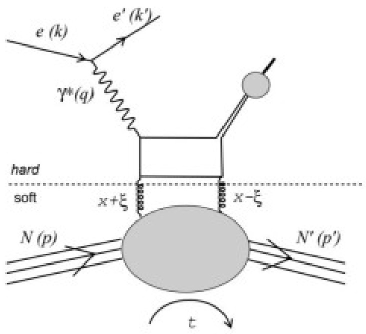
Projected (realistic) double spin asymmetries in various bins
After passing through proposed Hall C setup (GEANT4 simulations)



large t, large xi

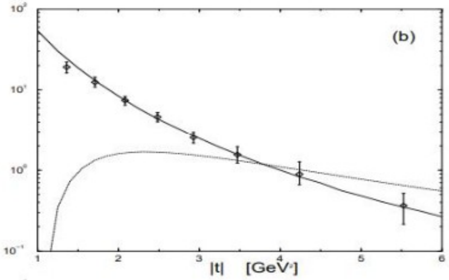
Expansion to EIC with quarkonia

From work done with some undergrad students
(here JLab = Erik Wrightson mainly, EIC = Tyler Schroeder mainly)
slides credit: Tyler



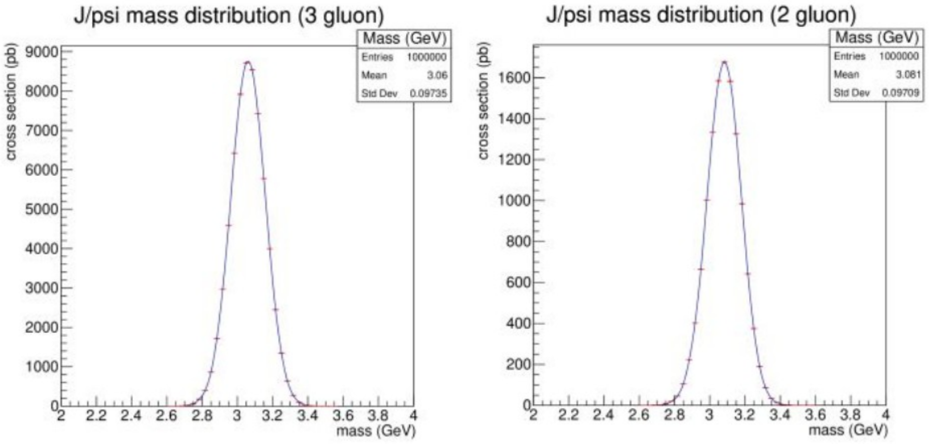
- Two domains:
  - **Low energy (JLab):** polarized J/Ψ
    - Near threshold, dominated by 3-gluon interaction?
    - Factorization is unclear
  - **High energy (EIC, EICC):** access gluon GPDs at high energy
    - J/Ψ and Υ
    - Factorization has been demonstrated (Collins, 2004)
    - Focus on photoproduction & electroproduction into e^+e^-, $\mu^+\mu^-$ pairs

Quarkonia Production



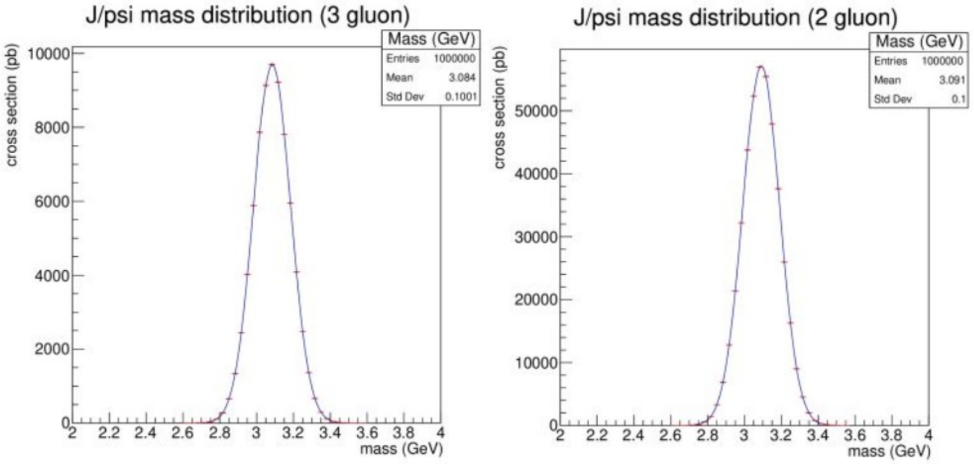
- **Flexible framework** for meson production
- Hard exclusive **J/Ψ** production
  - User provides ratio between **two-gluon** and **three-gluon** cross-sections
  - Two-gluon dominates at EIC et al, three-gluon near threshold
    - Three-gluon gives more flexible momentum transfer
- Hard exclusive **ϒ** production
  - Currently using similar model to J/Ψ
  - Plan to compare w/ numerical BKFL xsec: $\mathcal{F}_{BFKL}(s',t) = \frac{t^2}{(2\pi)^3} \int d\nu \frac{\nu^2}{(\nu^2+1/4)^2} e^{\chi(\nu)z} I_\nu^{q^*}(Q_\perp) I_\nu^{\gamma V}(Q_\perp),$
  - Handles 1S, 2S, 3S resonances
- Currently extending to **other vector mesons**
- **Easy to swap GPDs in and out** by design
  - Using generic model for EIC projections (GPD = PDF * *t*-dependent dipole)
  - Includes both quark & gluon GPDs
  - VGG model for JLab projections
- Current reference: CTEQ 2018 data for PDFs
  - *t* dependence experimentally set to $e^{1.13t}$ (Brodsky et. al, 2000)
  - May require tuning for high energies at EIC (fits from HERA, etc.)
- Use meson mass as factorization scale

Projections (J/Ψ, near threshold)



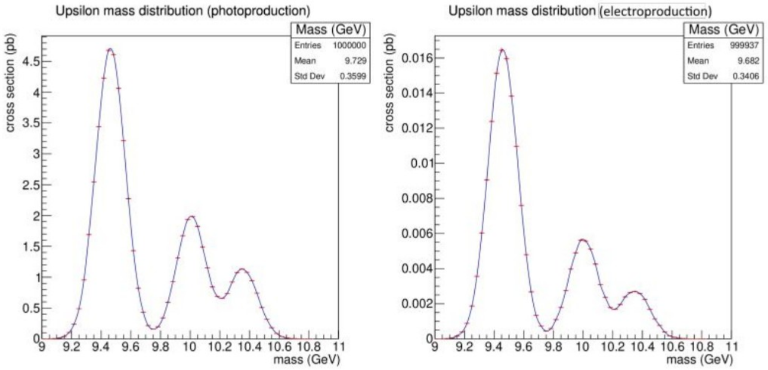
(photoproduction, 10% smearing) At low energy, 3-gluon dominates in our model

Projections (J/Ψ, high energy)



(photoproduction, 10% smearing) At higher energies, 2-gluon dominates in our model

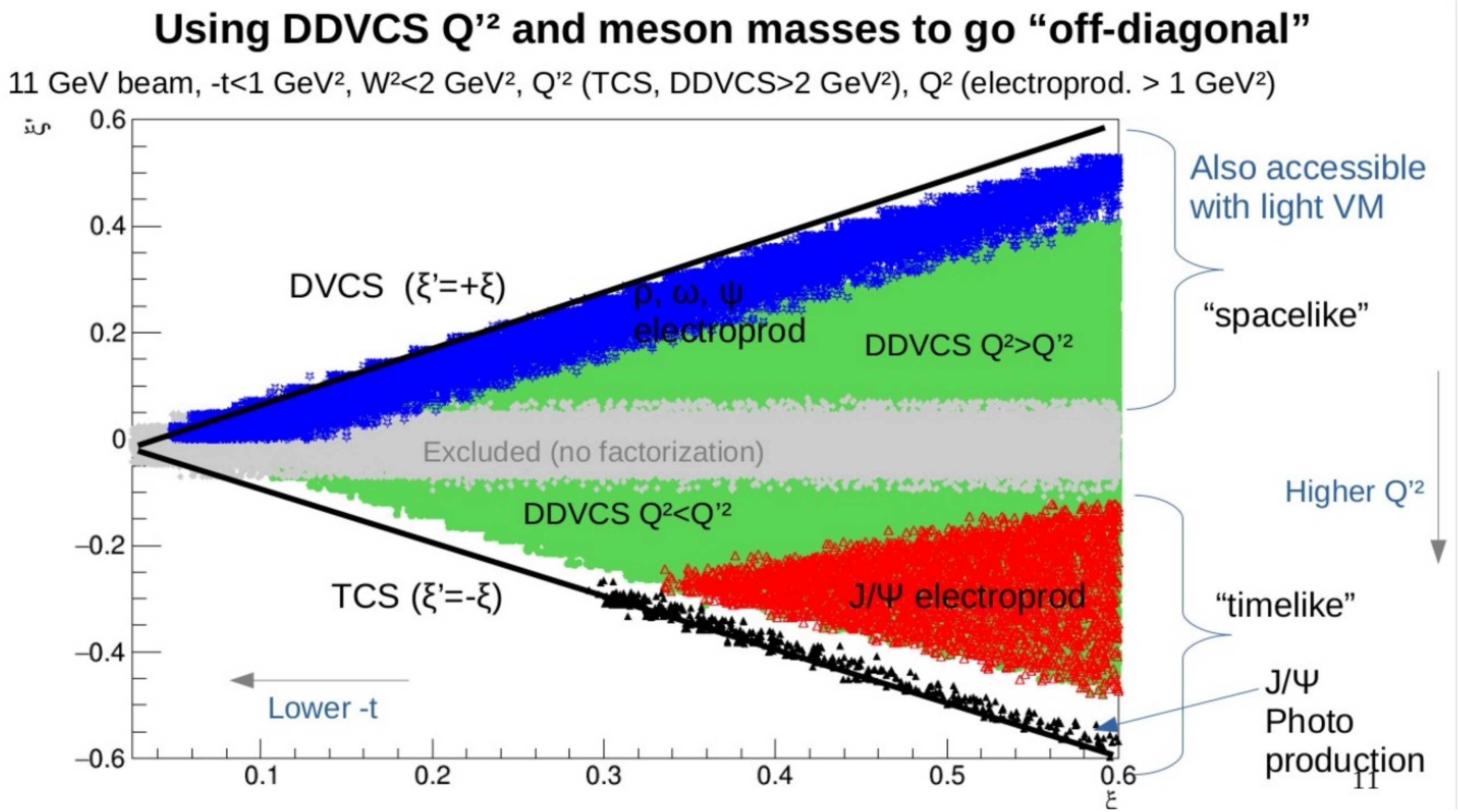
Projections (ϒ)



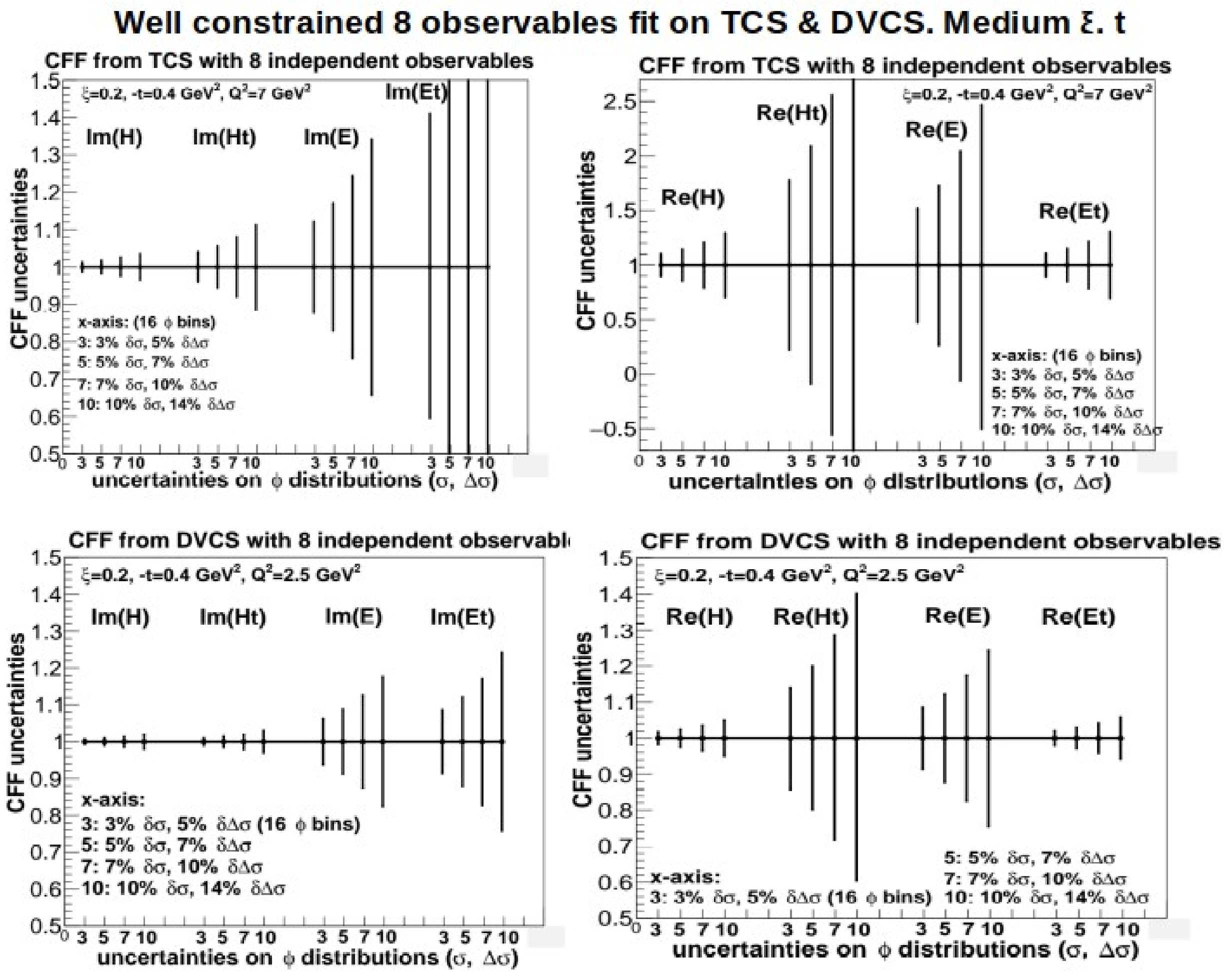
(1S, 2S, 3S normalization extrapolated from LHC)

Some projections made by Tyler from the generator, data used for projections
(not discussing here experimental considerations)

Why multichannel approach and universality studies?

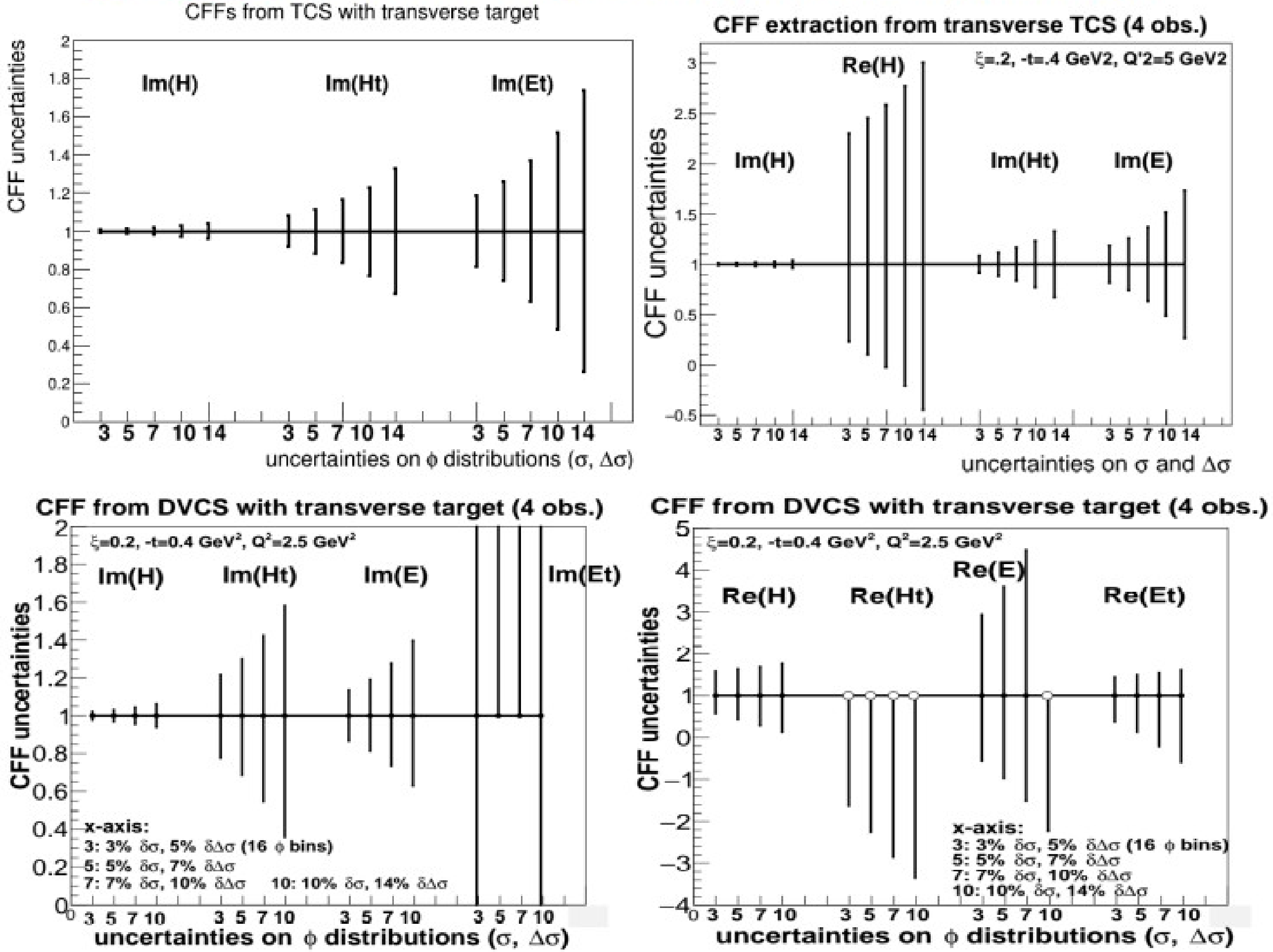


Last step: "backtracking" from real or MC data to original CFFs and GPDs in a single or multichannel approach



Last step: "backtracking" from real or MC data to original CFFs and GPDs in a single or multichannel approach

TCS or DVCS with transverse target & beam polarized (4 obs.) Medium ξ, t



SUMMARY

We are developing a full software framework to go from GPDs to CFFs and observable projections up to experimental projections, using an event generator

- multiple GPD and phenomenological model used

- collaboration with theorists / CS

- event generator already used for experiments at Jlab, extensions for EIC

- fits, currently done independently, will be added to this software

- software to be published (hopefully) end of the year