New software for multi-model and multi-channel GPD studies

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Our Goals

- Have a tool to make projections (theoretical) and “feed” event generators for experimental projections, impact studies and analysis

- Comparison of several models: using flexible modules to enable projections from various GPD models as an input / choice of calculations or formalism (DD, HQCD...)

- Evolution / radiative corrections: partially worked on it, also as optional module

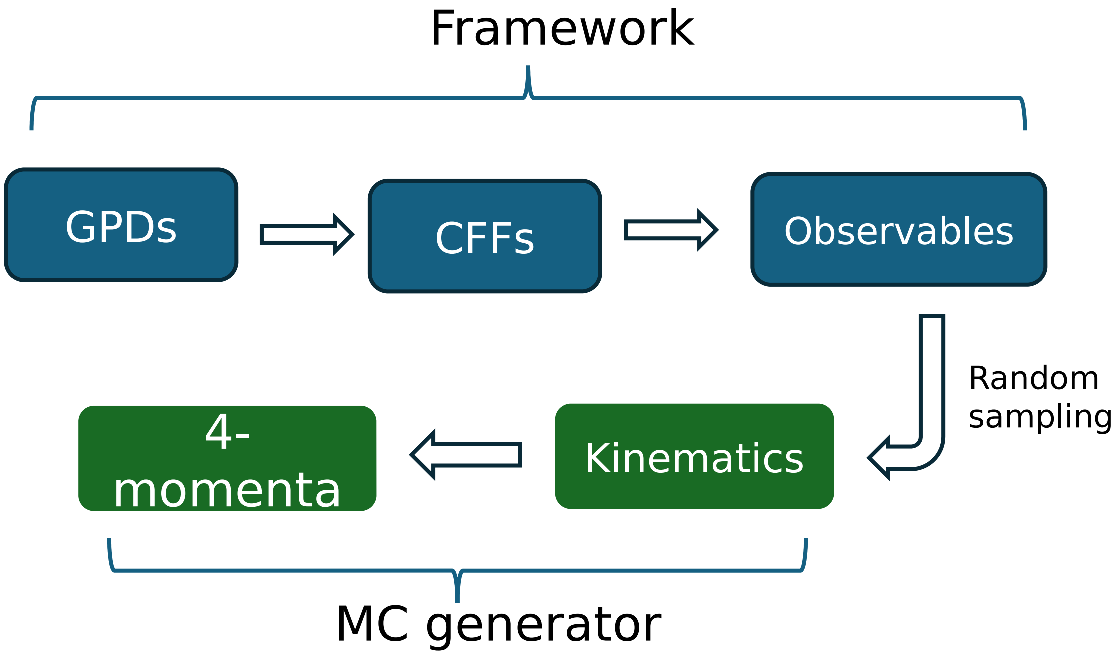
- Multiple reactions: implementing (Hard exclusive) Compton-like and Meson reactions

- Fitting tool: not in this software yet (separate) to enable comparison of results between models, multichannel fits and interpretation of experimental results / “feed” models

=> work is collaboration between theorists (EXCLAIM project and others) and experimentalists to improve available tools and projections. Project led by Kemal Tezgin.

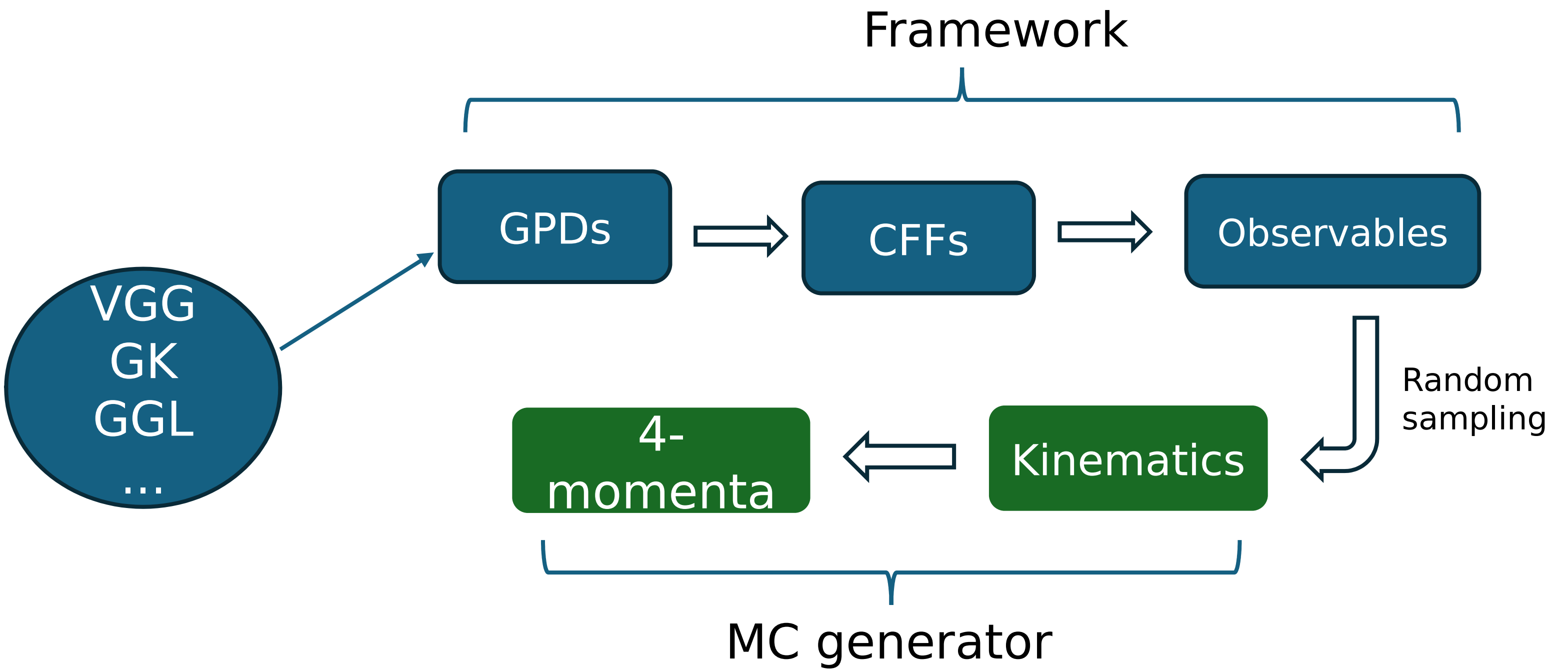
Credit to Kemal Tezgin for a lot of what is presented today and slides

Architecture



- Modular structure: each component has an isolated role and can easily be extended
- Processes: DVCS, TCS, pi0/pi+ already implemented. phi, J/psi in HQCD. Other soon to come.
- Model type: handbag based (VGG, Goloskokov-Kroll, Liuti-Goldstein…) and holographic QCD (Zahed, Mamo)
- Concept: use building blocks of the hadrons such as GPDs/ CFFs to describe observables
- Written in C++ with interface for experimental users, can be interfaced to fits, event generators, MC

GPD models



- Available GPD models: VGG, GK; In progress: GGL
- PDFs used: MRST1998, LSS1998 (for the VGG model)
- EM Form Factors used: Kelly's parametrization (for the VGG model)

GPD Models

The VGG model is based on double distributions

Vanderhaeghen, Guichon, Guidal (1999)

polynomiality
forward limit

$$H^q(x,\xi,t) = \frac{1}{1+\xi}\{f^q(X,\zeta,t)\} \quad \text{for} \quad \xi \leqslant x \leqslant 1,$$

$$H^q(x,\xi,t) = \frac{1}{1+\xi}\{f^q(X,\zeta,t) - f^{\bar{q}}(\zeta - X,\zeta,t)\}$$

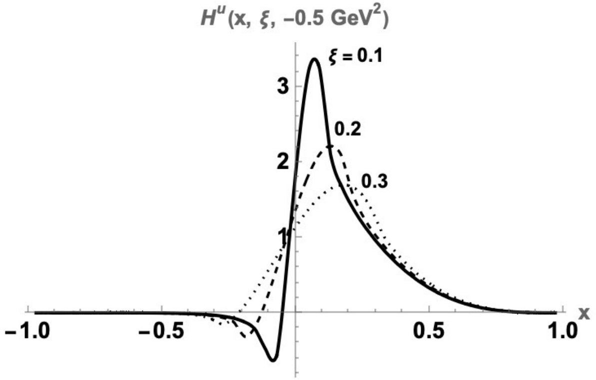
$$\text{for} \quad -\xi \leqslant x \leqslant \xi,$$

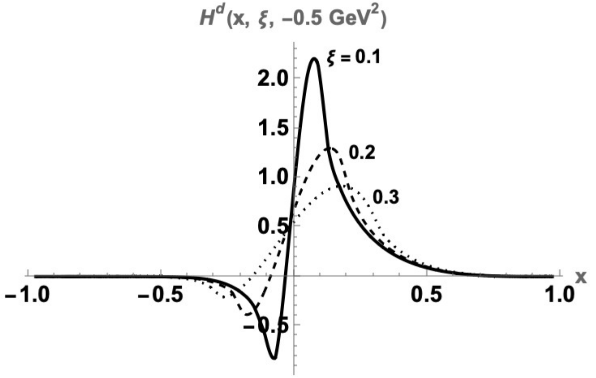
$$H^q(x,\xi,t) = \frac{1}{1+\xi}\{-f^{\bar{q}}(\zeta - X,\zeta,t)\}, \quad \text{for} \quad -1 \leqslant x \leqslant -\xi$$

$$f^q(X,\zeta,t) = \int_0^{\bar{X}/\bar{\zeta}} dy \; F^q(X - \zeta y, y, t), \quad \text{for} \quad X \geqslant \zeta,$$

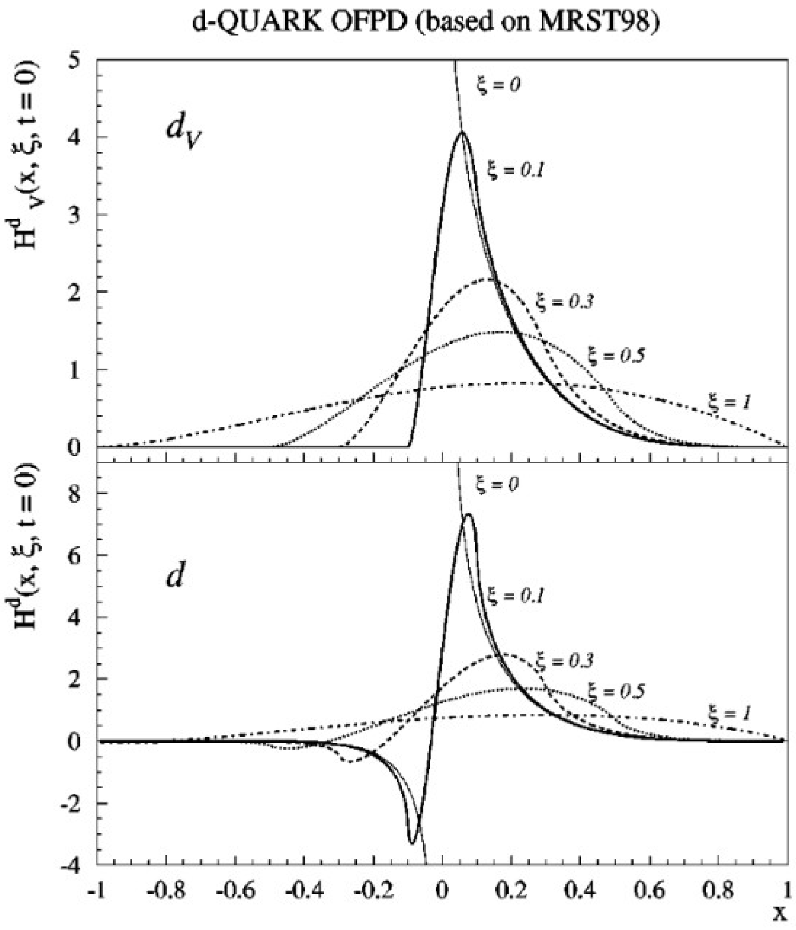
$$f^q(X,\zeta,t) = \int_0^{X/\zeta} dy \, F^q(X - \zeta y, y, t), \quad \text{for} \quad X \leqslant \zeta$$

$$F^q(\tilde{x},y,t) = F_1^q(t)/F_1^q(0)\, q(\tilde{x})\, 6\, \frac{y(1-\tilde{x}-y)}{(1-\tilde{x})^3}$$



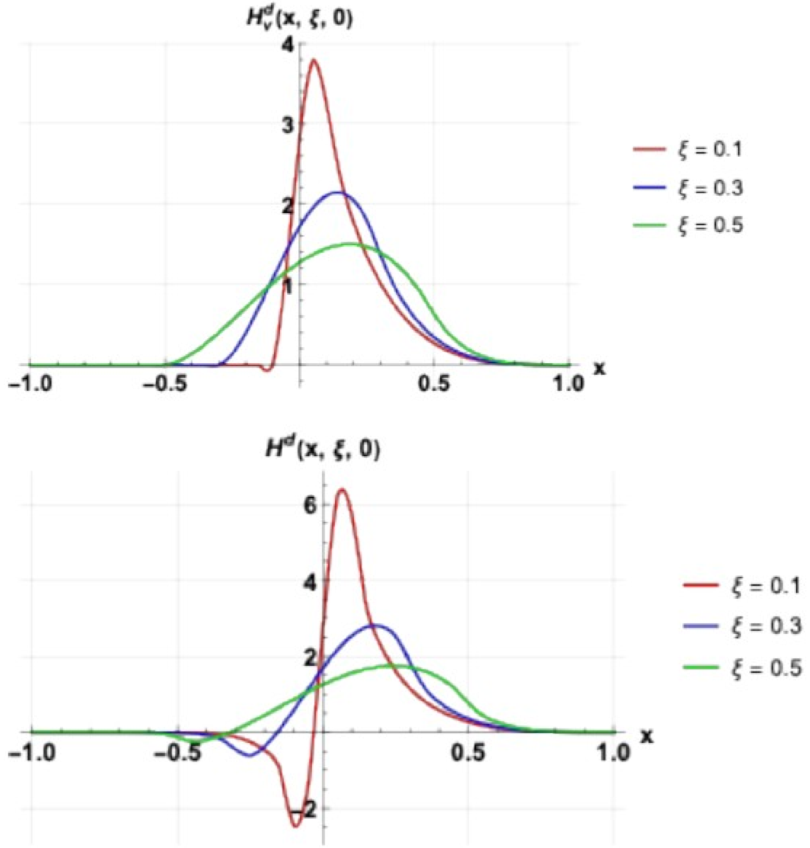


VGG model comparison



Vanderhaeghen, Guichon, Guidal (1999)

from this code:



* at t=0 to compare with 1999 article

GPD Models

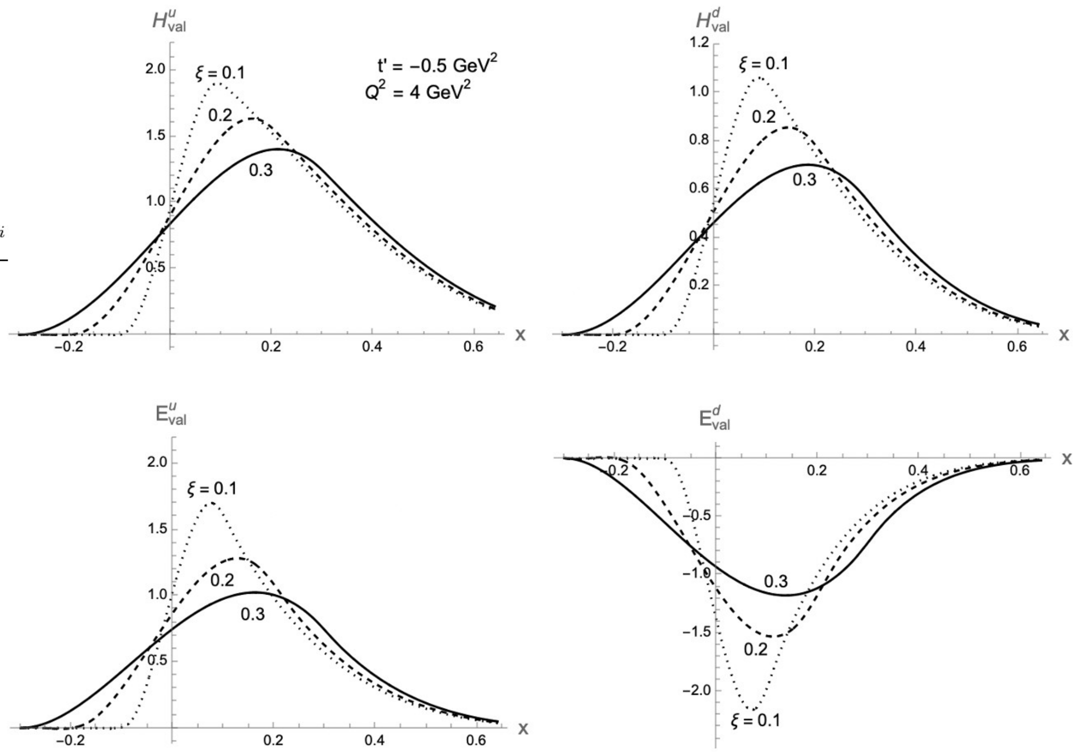
The GK model is also based on double distributions

Goloskokov, Kroll (2008)

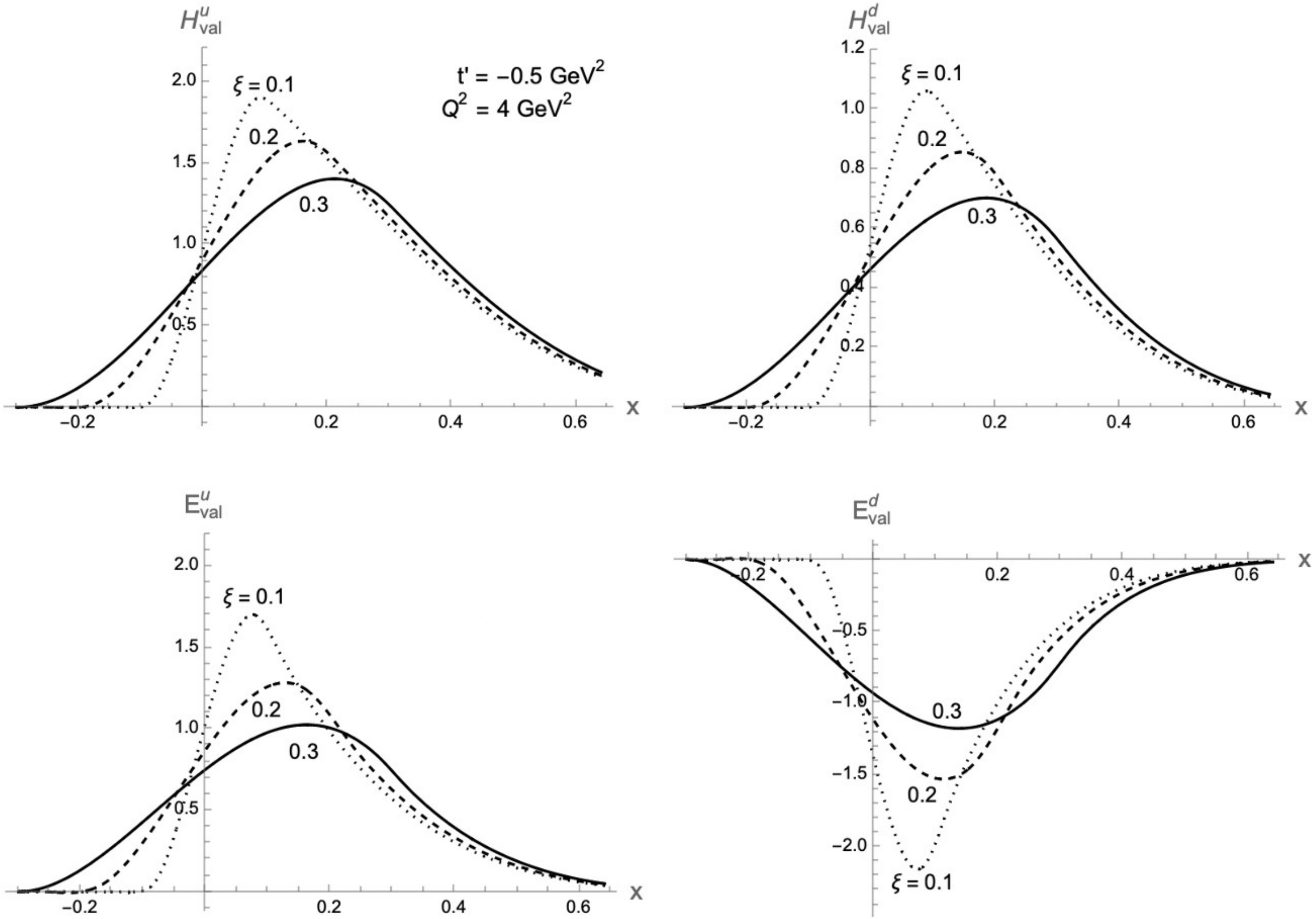
$$H_i(\bar{x},\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-\bar{x})\, f_i(\beta,\alpha,t)$$

$$f_i(\beta,\alpha,t) = e^{b_i t} \mid \beta \mid^{-\alpha_i' t}\, h_i(\beta)\, \frac{\Gamma(2n_i+2)}{2^{2n_i+1}\,\Gamma^2(n_i+1)}\, \frac{[(1-|\beta|)^2-\alpha^2]^{n_i}}{(1-|\beta|)^{2n_i+1}}$$

$$\begin{aligned} h_g(\beta) &= |\beta| g(|\beta|) & n_g &= 2\,, \\ h^q_{\rm sea}(\beta) &= q_{\rm sea}(|\beta|)\,{\rm sign}(\beta) & n_{\rm sea} &= 2\,, \\ h^q_{\rm val}(\beta) &= q_{\rm val}(\beta)\,\Theta(\beta) & n_{\rm val} &= 1\,. \end{aligned}$$



GK model GPDs



CFFs at LO

CFFs at LO can be computed as:

$$\mathcal{H}^q = \int_{-1}^{1} dx\ C_0 H^q(x,\xi,t)$$
$$= \left[-P.V \int_{-1}^{1} dx \left(\frac{1}{x+\xi} + \frac{1}{x-\xi}\right) H^q(x,\xi,t)\right] + i\pi(H^q(\xi,\xi,t) - H^q(-\xi,\xi,t))$$

Imaginary part can easily be computed analytically:

$$Im\mathcal{H} = \pi(H(\xi,\xi,t) - H(-\xi,\xi,t))$$
$$= \pi\left(\frac{H^+(\xi,\xi,t) + H^-(\xi,\xi,t)}{2} - \frac{H^+(-\xi,\xi,t) + H^-(-\xi,\xi,t)}{2}\right)$$
$$= \pi H^+(\xi,\xi,t)$$

$$Re\mathcal{H} = -\left(\int_0^1 dx \frac{H^+(x,\xi,t)}{x+\xi} + \int_0^1 dx \frac{H^+(x,\xi,t) - H^+(\xi,\xi,t)}{x-\xi} + H^+(\xi,\xi,t)\log\left(\frac{1-\xi}{\xi}\right)\right)$$

Cross section of the electroproduction process

DVCS+BH

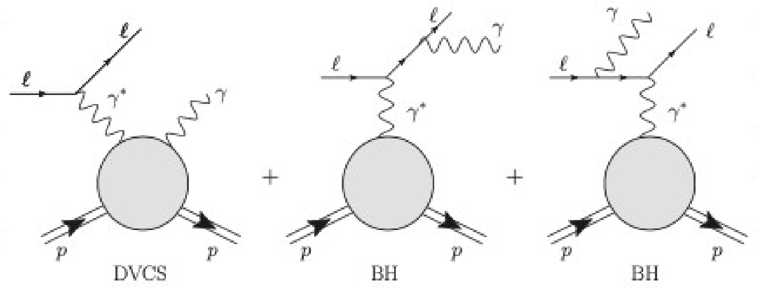
$$\frac{d\sigma}{dx_{\mathrm{B}}dyd|\Delta^2|d\phi d\varphi} = \frac{\alpha^3 x_{\mathrm{B}} y}{16\,\pi^2\,\mathcal{Q}^2\sqrt{1+\epsilon^2}} \left|\frac{\mathcal{T}}{e^3}\right|^2 .$$

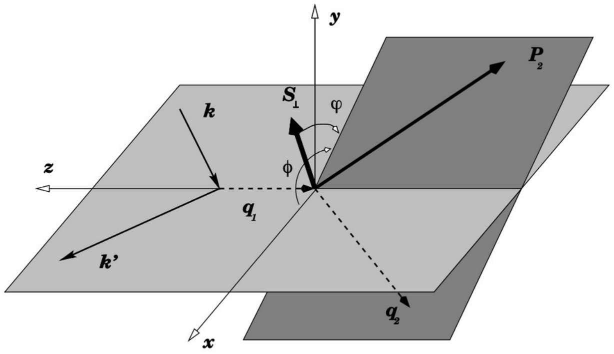
Belitsky, Müller, Kirchner (2002)
Kriesten, Liuti, Calero-Diaz, Keller, Meyer, Goldstein, Gonzalez-Hernandez (2020)

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

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

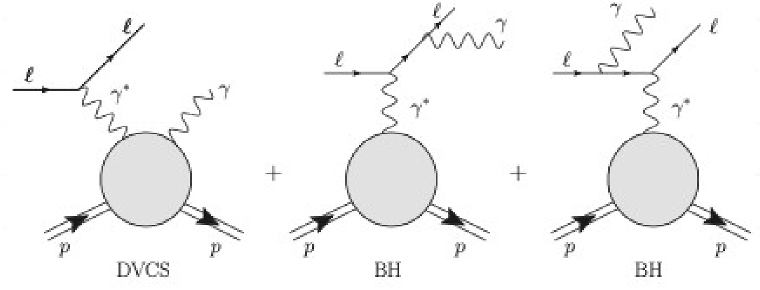
$$\mathcal{I} = \frac{\pm e^6}{x_{\mathrm{B}} y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\} ,$$

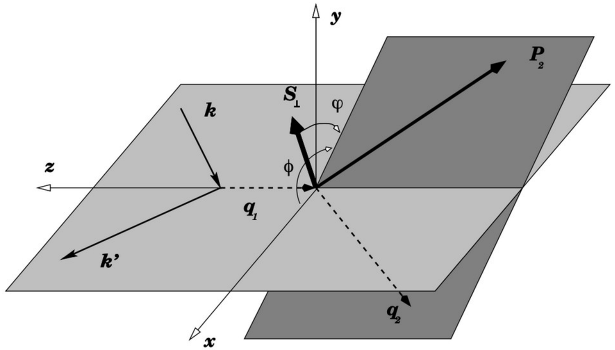




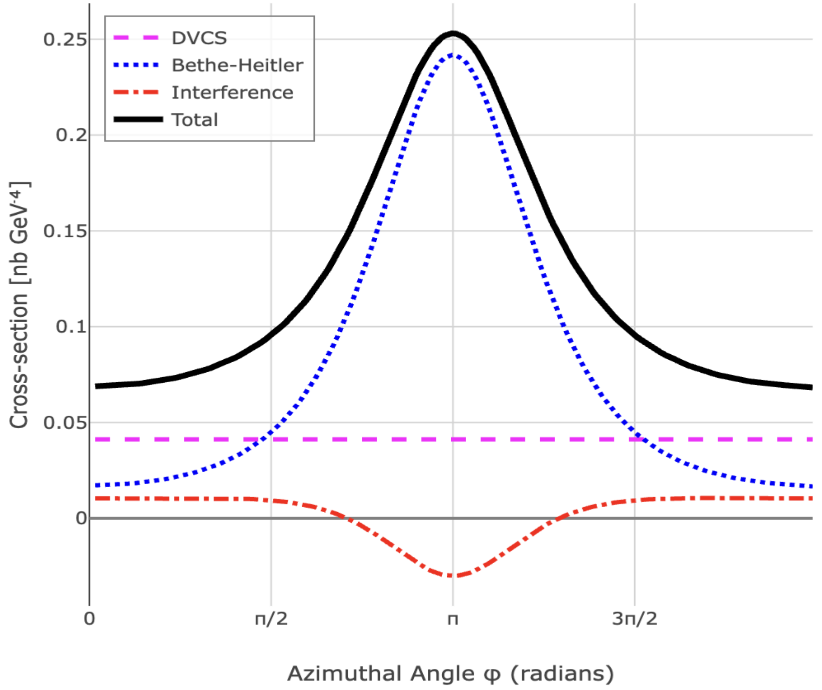
DVCS cross section

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



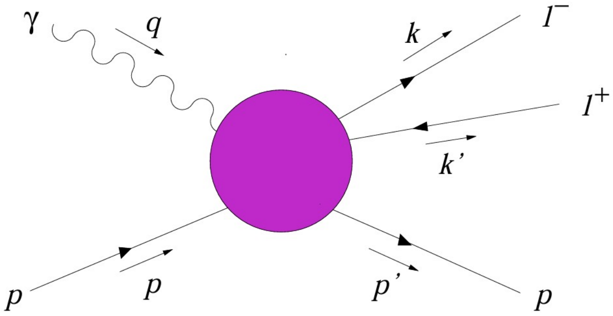


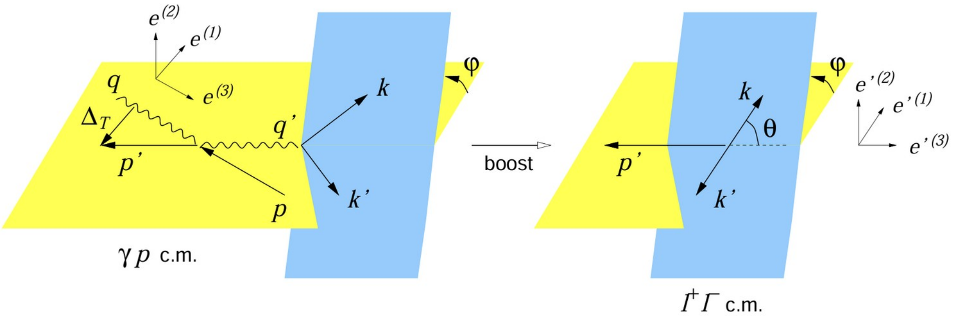
x_B=0.1, y=0.3, Q^2=2 GeV^2, t=-0.2 GeV^2



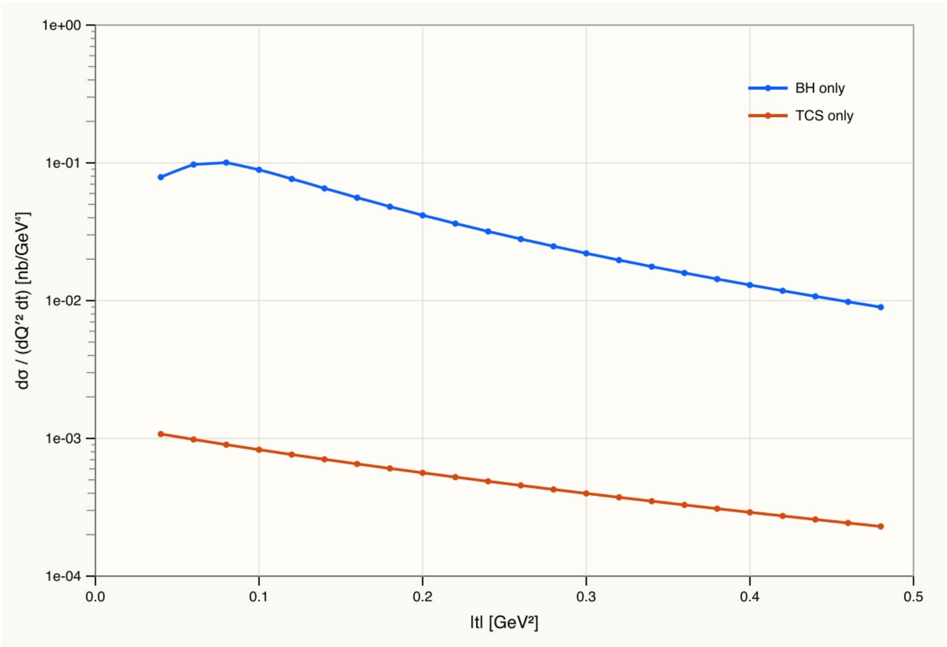
TCS cross section

- Unpolarized cross section of the time-like Compton scattering with the VGG GPDs
- Leading twist and leading order





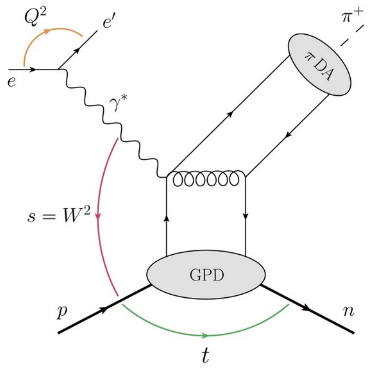
s = 25 GeV², Q'²

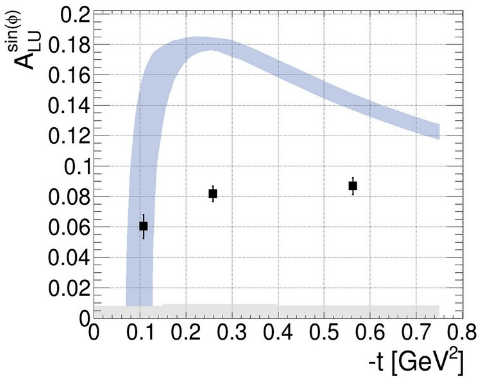


DVMP (pion here)

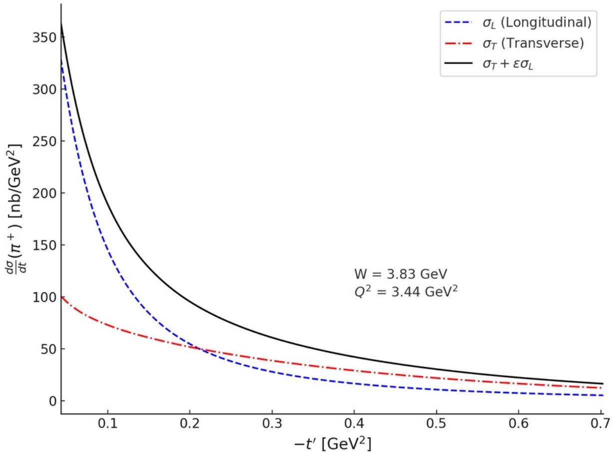
$$BSA(t,\phi,x_B,Q^2) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos 2\phi}\cos 2\phi},$$

- Based on effective handbag approach in the GK model: factorizes the process into GPDs and subprocesses Goloskokov, Kroll (2010)
- Allow extraction and constrain of the chiral-even GPDs () & the chiral-odd GPD
- Higher twist effects: Helicity-flip GPD coupled with twist-3 pion wave function
- Dominance of the pion-pole contribution at low momentum transfer
- at low |t|, at high |t|



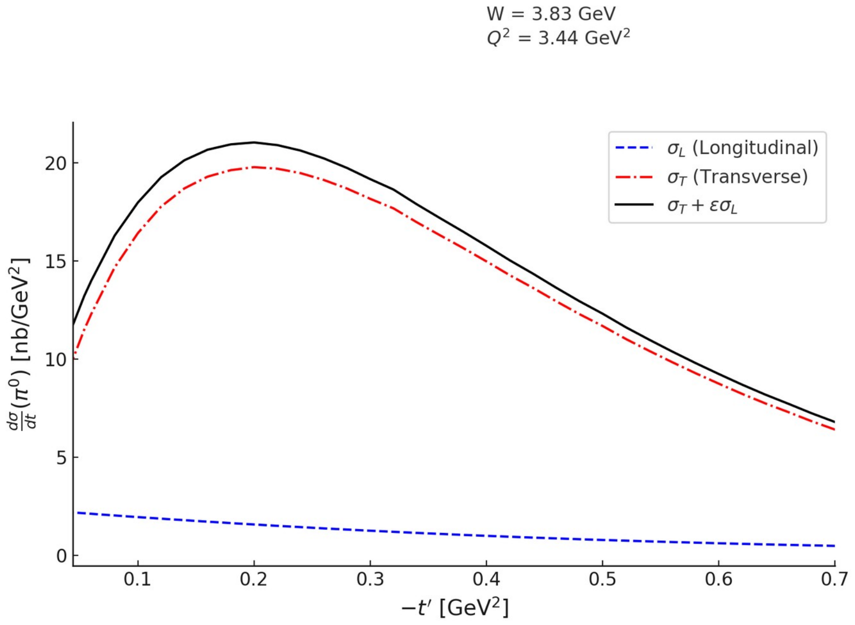


S. Diehl et al., PRL 125 (2020)



DVMP (pion here)

- Based on effective handbag approach in the GK model: factorizes the process into GPDs and subprocesses
  Goloskokov, Kroll (2011)
- Particularly sensitive to the transversity GPDs   and
- No pion-pole contribution
- Dominance of transversity GPDs
- Highlights the higher-twist effects



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, TCS, π^+, π°; vector mesons/quarkonias)

- Plug into event generator and fitter code which so far are separated

observables

Plan is to publish and release this first version very soon after a few necessary x-checks

Then work on fits and implementing more options.

Want to present some finalized public version over the summer

Software: our next steps

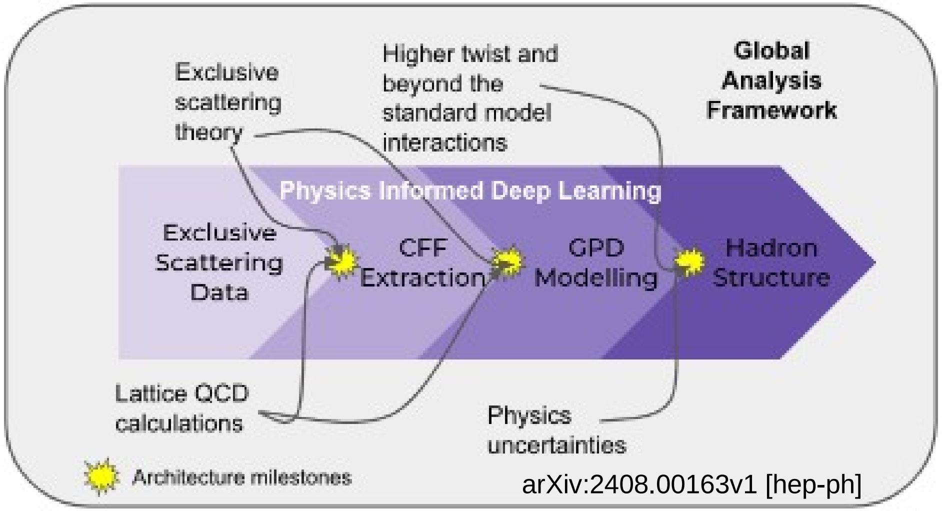
Radiative corrections: so far we have them at generator level but not in the code. Need to calculate/implement from articles “internal” corrections. External corrections dealt with generator.

- based on Mo&Tsai, user-defined cut-off
- 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.

QCD NLO corrections and higher twists

- UVA group working on it for DVCS, will be implemented as an independent module for flexibility
- some higher twists in our separate code, yet to be added into the software (minor effect)

Experimental-theory connection and EXCLAIM project



arXiv:2408.00163v1 [hep-ph]

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, computing]

- 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

Connection with experiment, what interest for SBS?

- So far we used separate code to feed homemade event generator and make projections for Hall A (SoLID), Hall C (NPS and HMS/SHMS), Hall D (GlueX) and EIC.
- Are planning to take SBS into the configuration for potential experiments in Hall C

- Event generator:
https://solid.jlab.org/wiki/index.php/DEEPGen_event_generator

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

Available processes (previous versions until now):
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.
=> now extending to this multi-model software. We still need to generate grids.

Generator “philosophy” with multiple weighting options
Example of quick impact studies

Now will also have various models

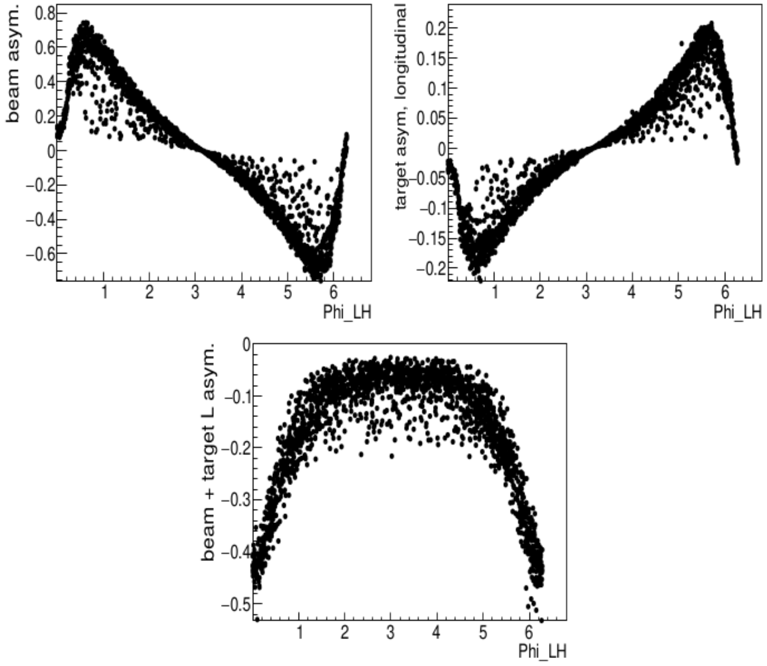


Figure 14: DVCS+BH generated spin asymmetries from a polarized electron beam (top left panel), longitudinally polarized target (top right panel), polarized beam+longitudinally polarized target (bottom panel). The beam energy is set at 11 GeV and $0.2 < x_{bj} < 0.25$, $4 < Q^2 < 5$ GeV^2, $-0.6 < t 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

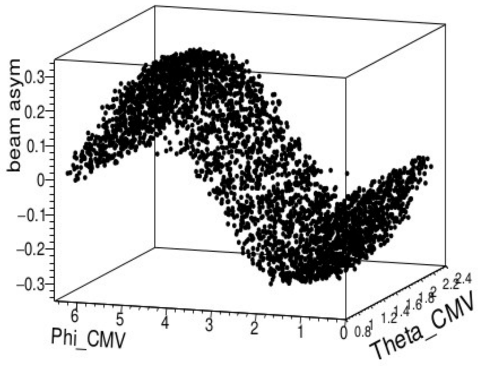


Figure 16: TCS+BH beam spin asymmetry as a function of ϕ, for 5<E_γ<11.4 GeV, $6.5 < Q'^2 < 7$ GeV^2 and 0.6<-t<0.7 GeV^2.

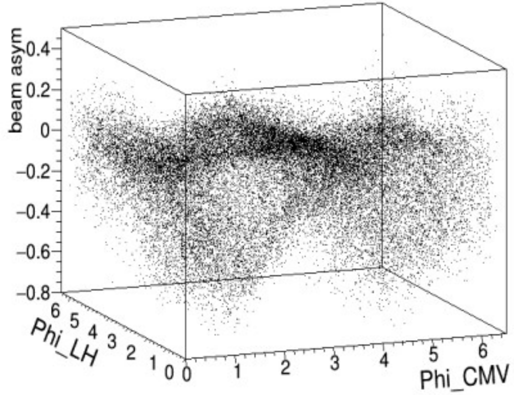
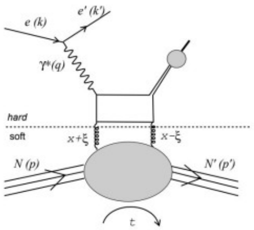


Figure 18: DDVCS+BH beam spin asymmetry as a function of ϕ_{CM} and ϕ_{LH} (units are radians).

- 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)

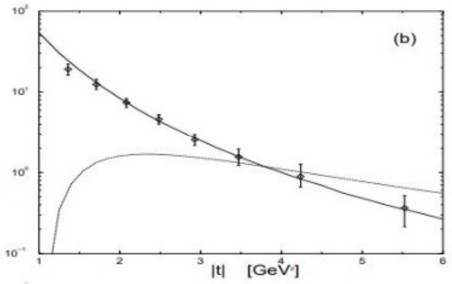
Expansion "from JLab to EIC" with quarkonia



- 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

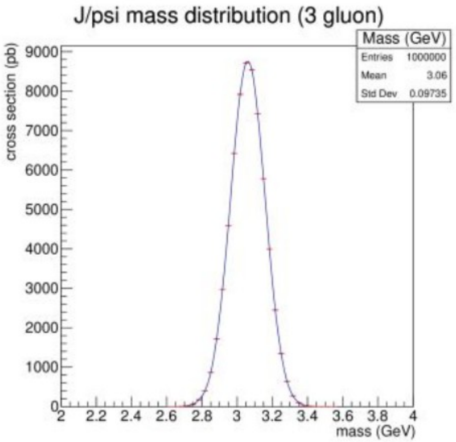
Work done with our generator, now we also have this software with HQCD for phi and J/psi that we can use to extrapolate between all kinematic range.
Issue we need to figure out: no GPD description anymore with HQCD. Can make comparisons / extrapolate

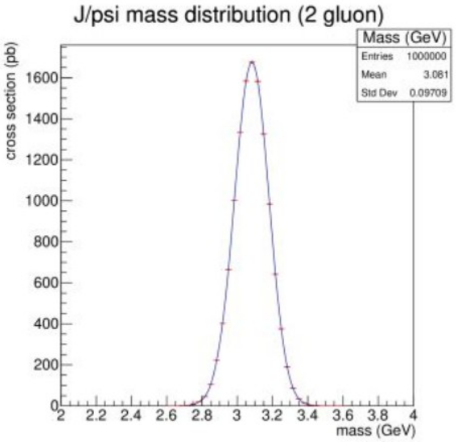
Quarkonia Production



- **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

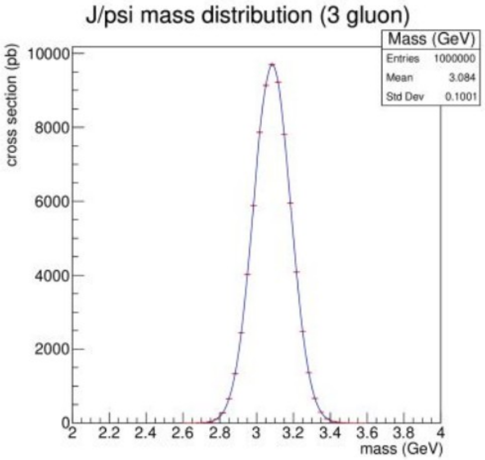
Projections (J/Ψ, near threshold)

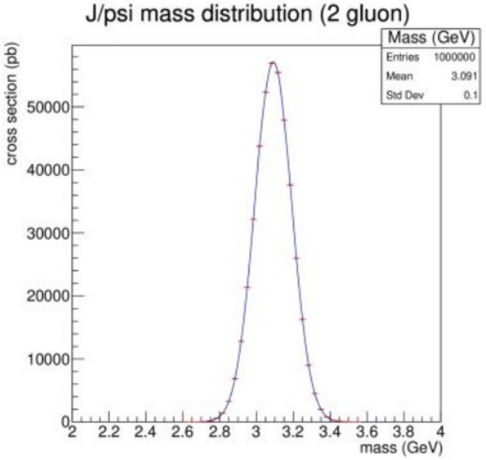




(photoproduction, 10% smearing) At low energy, 3-gluon dominates in our model

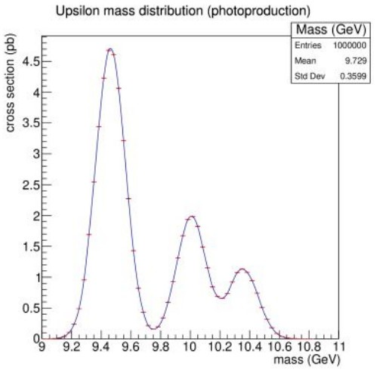
Projections (J/Ψ, high energy)

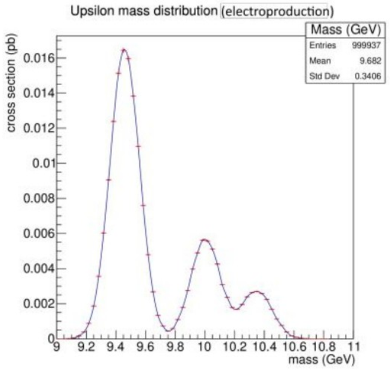




(photoproduction, 10% smearing) At higher energies, 2-gluon dominates in our model

Projections (Υ)

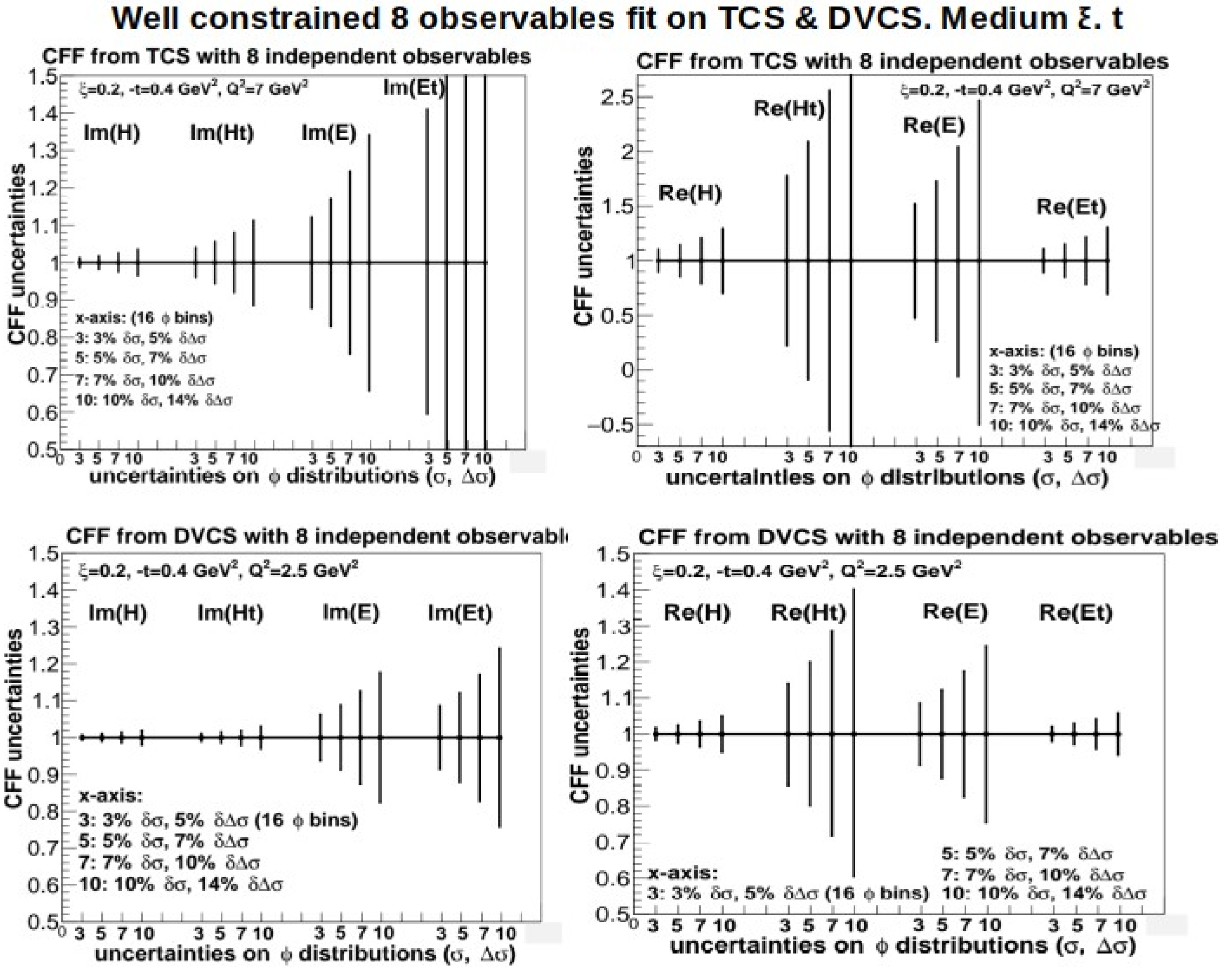




(1S, 2S, 3S normalization extrapolated from LHC)

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

Fits (future version / collaboration with EXCLAIM): “backtracking” from real or MC data to original CFFs and GPDs in a single or multichannel approach



done using
VGG model for GPDs
(external code from MB)

SUMMARY

We are developing a full software framework to go from GPDs to CFFs and observable projections up to experimental projections

- multiple GPD and phenomenological models implemented. Will extend to more

- collaboration between experimentalists, theorists and computer scientists for some extensions

- will feed our event generator that’s already used for experiments at Jlab, extensions for EIC

- fits, currently done independently, will be added to this software as a separate module as well

- Software version 1 with LO DVCS, TCS, pi will be released later this spring with user interface for experimentalists

- Planning to work over summer on new modules such as fitter module, more models, plug-in event generator and connections to MC for experiments. Should be presented in July