Workshop: EICUG detector 2 meeting

Hard Exclusive Reactions: dilepton channels

CFNS center workshop, Dec. 6-8th, 2022, Stony Brook, USA

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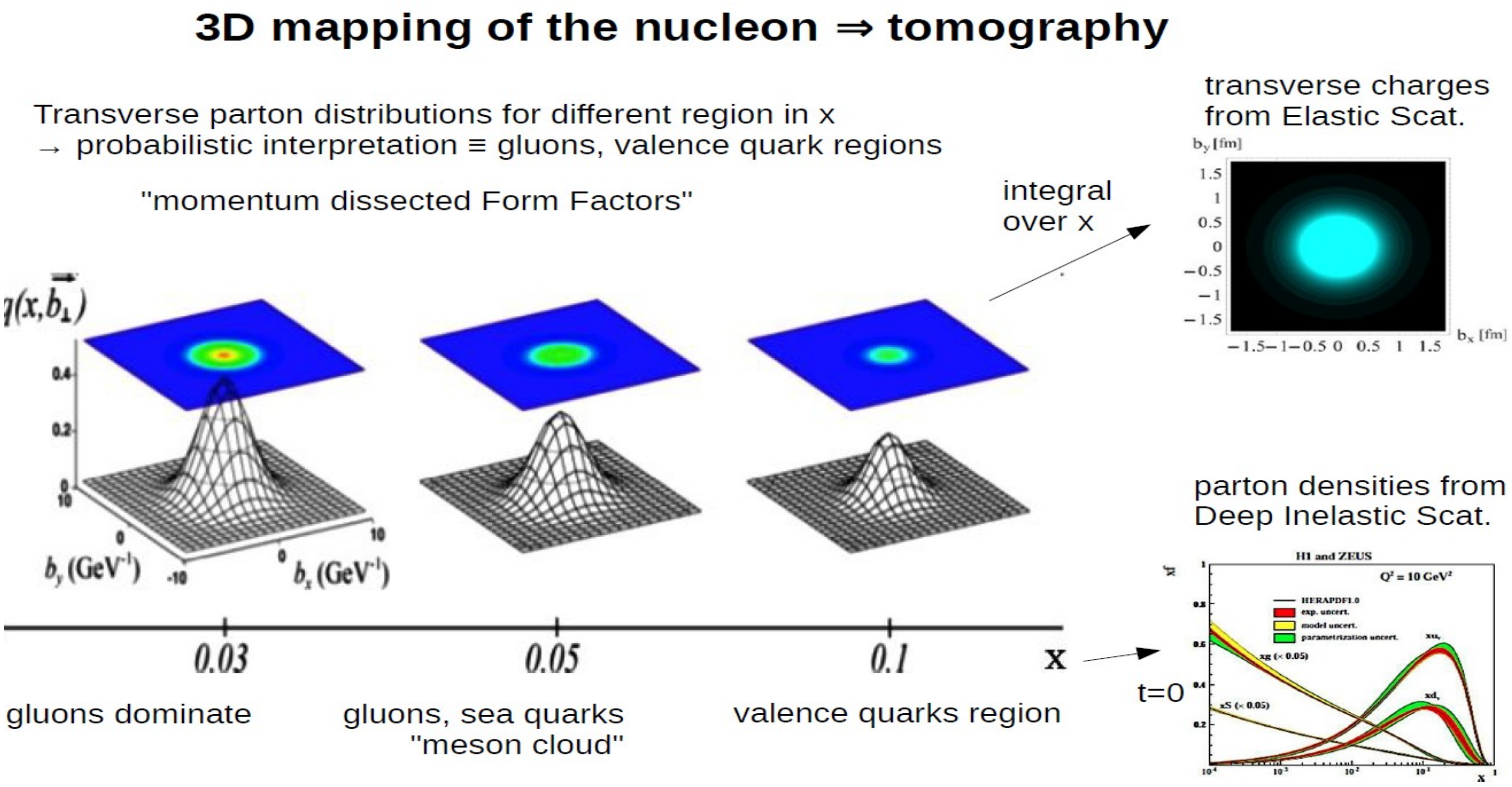
PARTONIC STRUCTURE OF THE HADRONS

Motivations

* Hard Exclusive Compton-like reactions
* Hard Exclusive Vector Meson Production

Dilepton channels only in this presentation



Outline

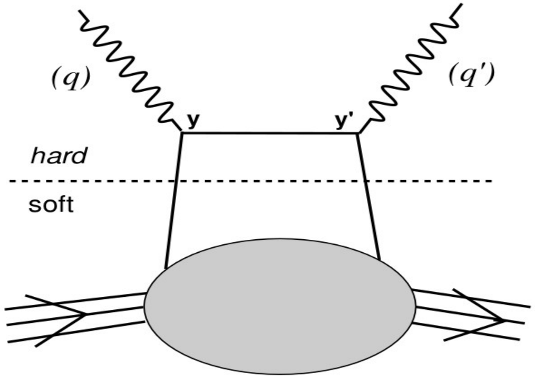
1) Motivations
2) Our tools, context
3) TCS (JLab future)
4) DDVCS (JLab future)
5) J/psi and Upsilon EIC
6) Discussion: detecting muons

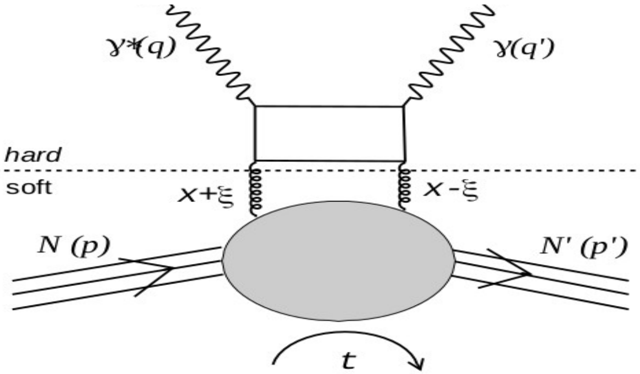
Motivations

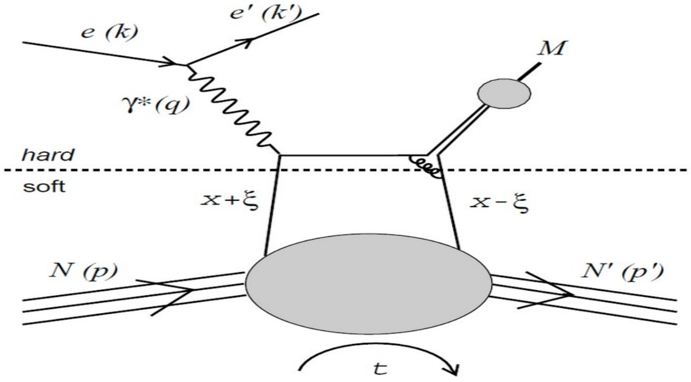
In this presentation: TCS, DDVCS, J/psi, Upsilon
Into muons

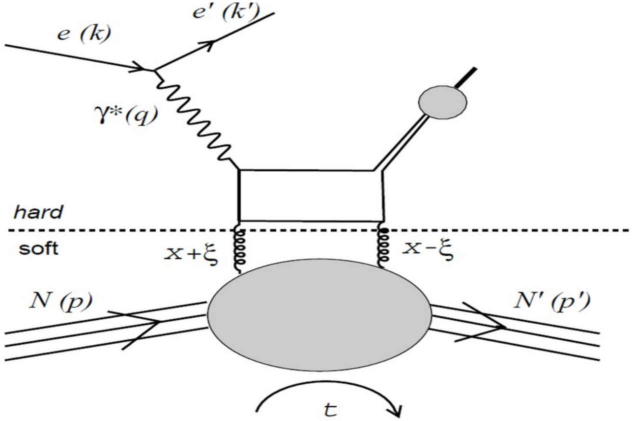
- Multichannel approach for GPD fits
- Compton-like+vector mesons == complementary approach

* showing some projections for JLab,
Some at EIC energy

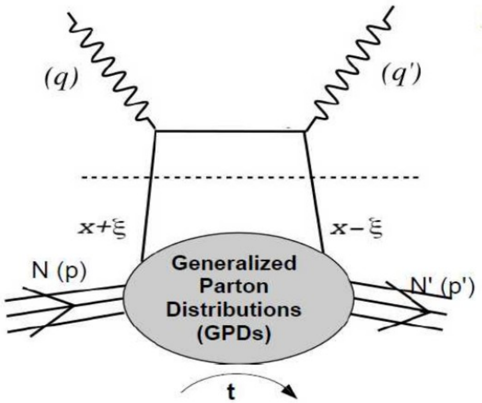


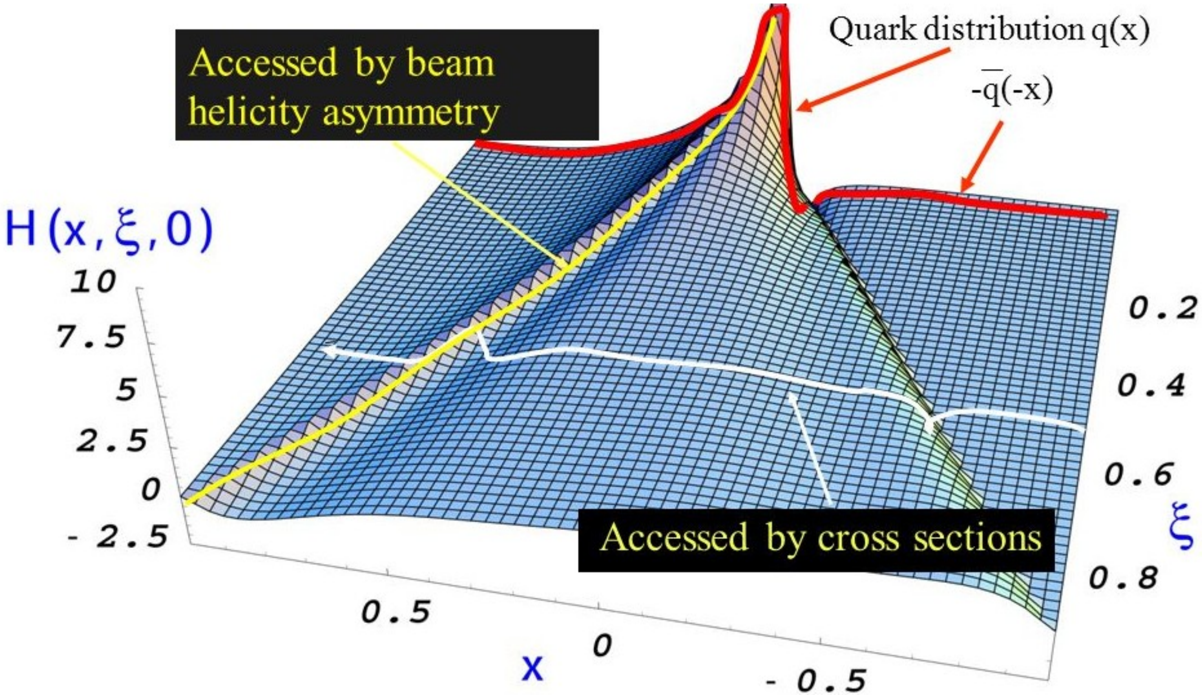






Generalized Parton Distributions (DVCS or TCS, “diagonal”)



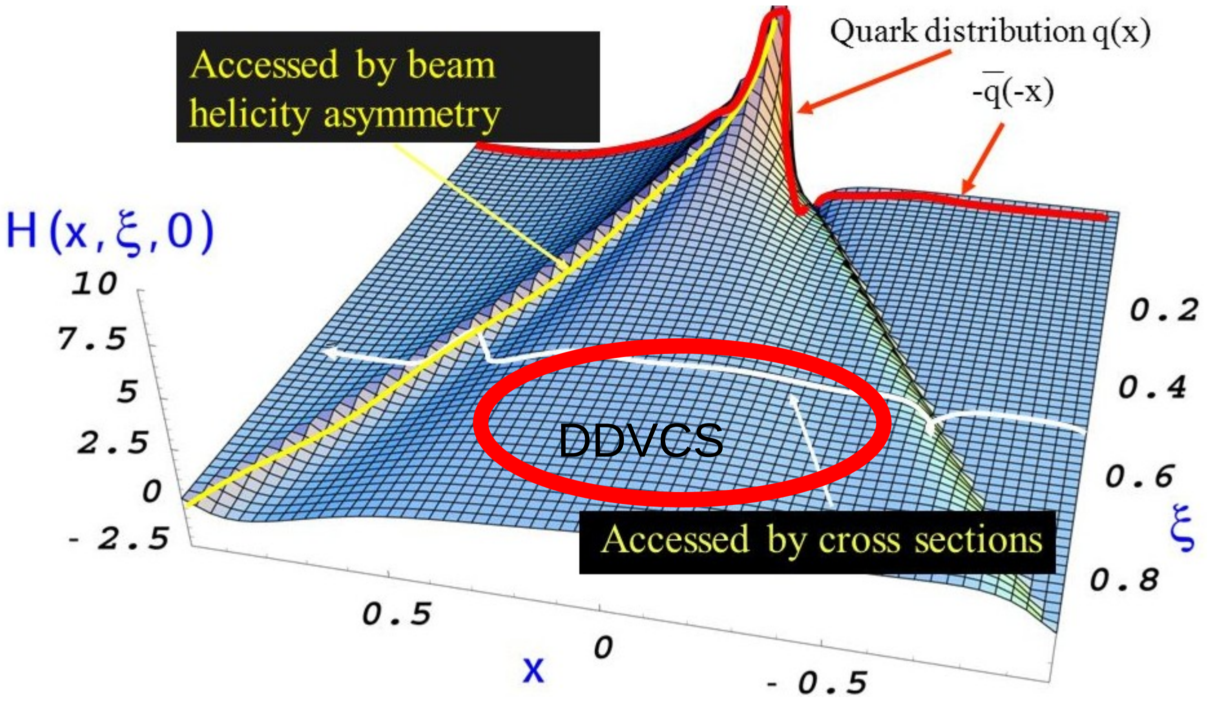


Extracted at ξ (skewness // momentum)
and t (momentum transfer ²)
from experimental data [can’t access x]

Various “parts” of the GPD accessible via different reactions or observables

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \underbrace{P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx}_{\mathrm{Re}\,(\mathcal{H})} - \underbrace{i\pi H(\pm\xi,\xi,t)}_{\mathrm{Im}\,(\mathcal{H})} + \ldots$$

Generalized Parton Distributions: “off diagonal”

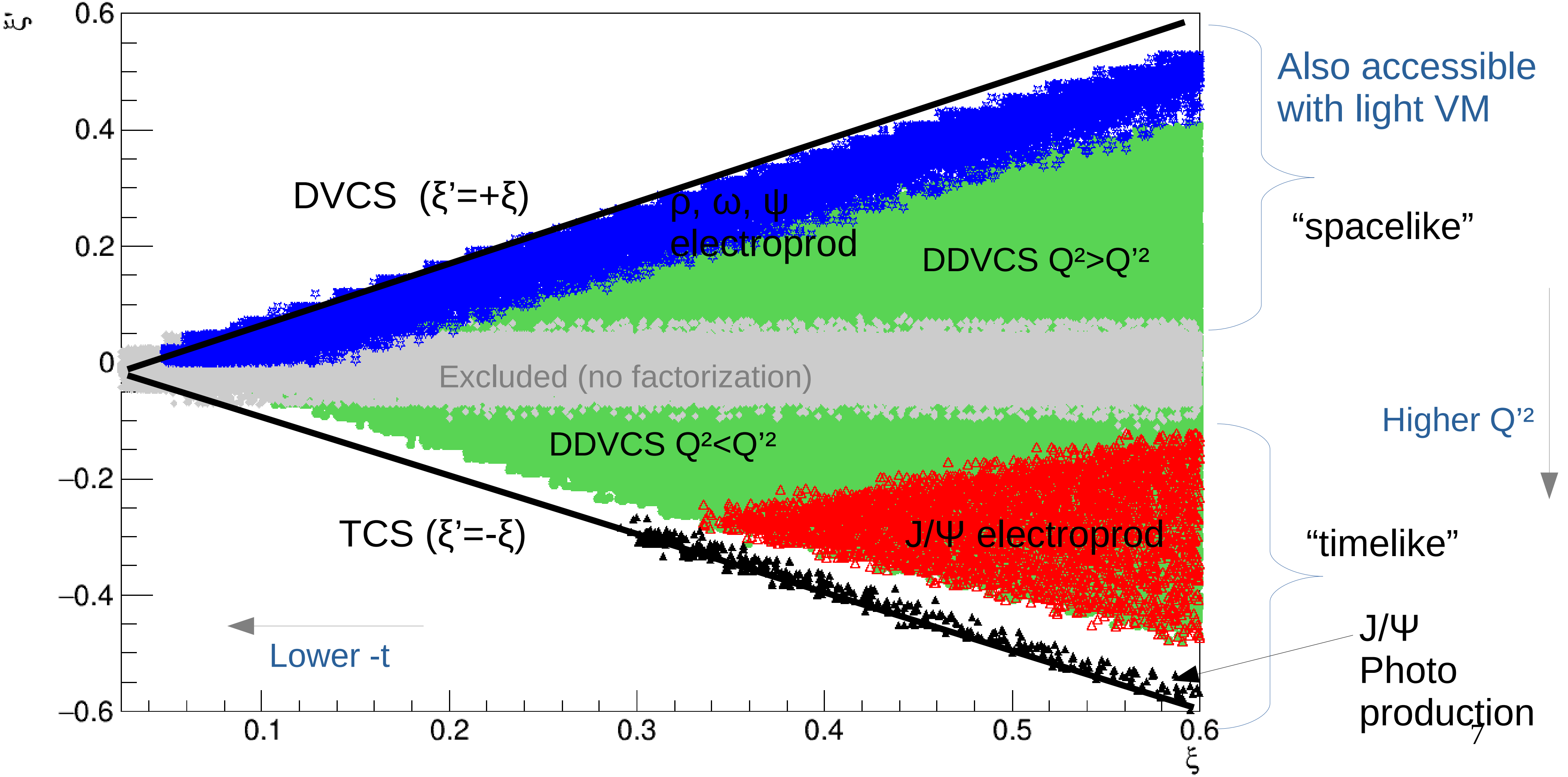


“diagonal”: $$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon}\,dx + \ldots \sim \underbrace{P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi}\,dx}_{\mathrm{Re}\,(\mathcal{H})} \underbrace{- i\pi H(\pm\xi,\xi,t)}_{\mathrm{Im}\,(\mathcal{H})} + \ldots$$

“off diagonal”: $$T^{DDVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x - (2\xi' - \xi) + i\varepsilon}\,dx + \ldots \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x - (2\xi' - \xi)}\,dx - i\pi H(2\xi' - \xi,\xi,t) + \ldots$$

Using DDVCS Q'² and meson masses to go "off-diagonal"

11 GeV beam, -t<1 GeV², W²<2 GeV², Q'² (TCS, DDVCS>2 GeV²), Q² (electroprod. > 1 GeV²)



Why multi-reaction approach with TCS, DDVCS, VM?

* TCS and DVCS access Im(CFFs) at $x = \pm\xi$
=> complementary measurements, access same CFFs,
- GPD universality studies with independent TCS data set
- higher twist/order studies in comparison, can help understanding “effects” seen in DVCS
- combined data set for additional constraints to GPDs

* DDVCS (and meson masses*) give a lever arm for going “off diagonal”, needed to extrapolate to zero skewness
- tomographic interpretations
- can move from “timelike” to “spacelike” region
- complementary observables for GPD data sets in multichannel approach

* J/psi, Upsilon (and other VM): Use mass as lever arm in propagator CFF
Extrapolate to zero-skewness case using “mass evolution” at fixed Q^2 (together with other VM)
(some caveat in this approach)

* factorization limits, higher twist…

EIC is ideal place to study NLO effects and diminish higher twist effects observed (?) at JLab or other lower energy experiments

Not in this work, but other approaches include studies of resonances, pentaquark...

Our tools and models

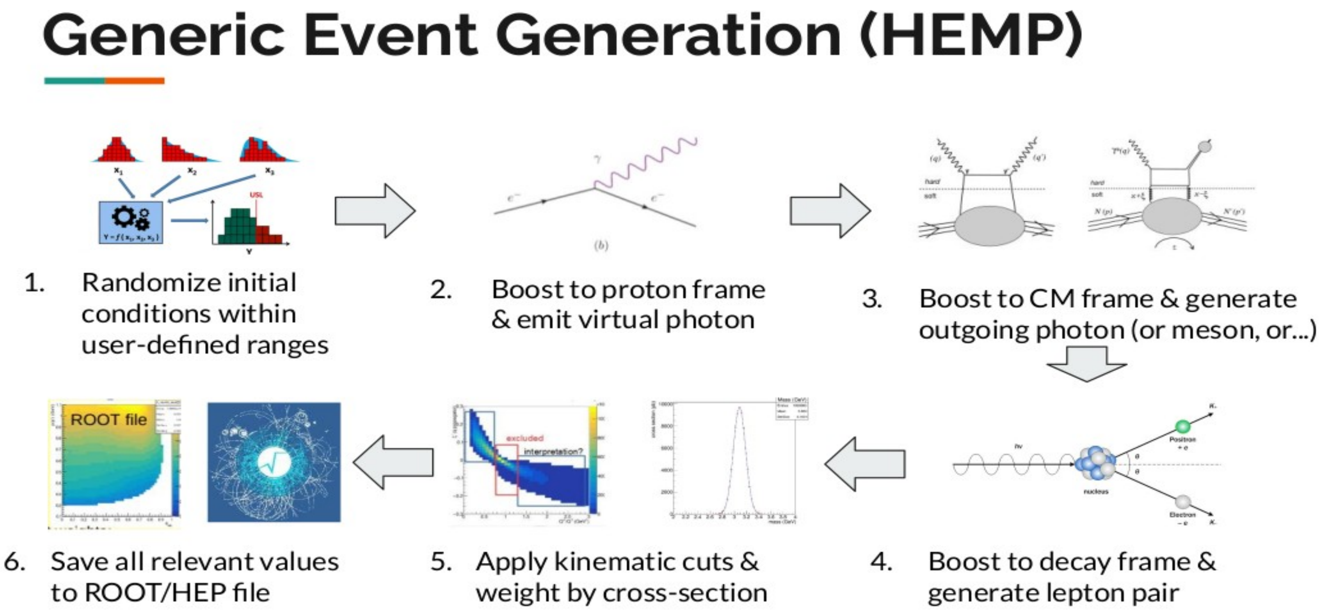
DEEPSim event generator developed for EIC projections, based on DEEPGen generator, developed for JLab

DEEPGen:
Hard exclusive processes:
- DVCS
- TCS
- DDVCS
- some VM and PS mesons

* some public versions for DEEPGen, not yet for DEEPSim

Other processes:
- VCS
- Elastic scattering
- DIS
- Low energy pion
- Low energy kaon

DEEPSim (in progress, for EIC):
Hard exclusive processes:
- DVCS
- TCS
- DDVCS
- HEMP
- ρ
- J/Ψ
- ϒ



DEEPSim Event Generator

Some technical features

DEEPGen and DEEPSim are weighted generators

- Avoid peaks & spikes in regions that are less physically interesting

Multi-weighting system

- 2 gluon only, BH only, meson+BH interference only,..
- Allow tuning at analysis level
- Saves significant CPU time

Model: VGG for JLab,
“homemade” for EIC

DEEPSim only: Crossing angle corrections (optional)

DEEPGen (DEEPSim in progress):

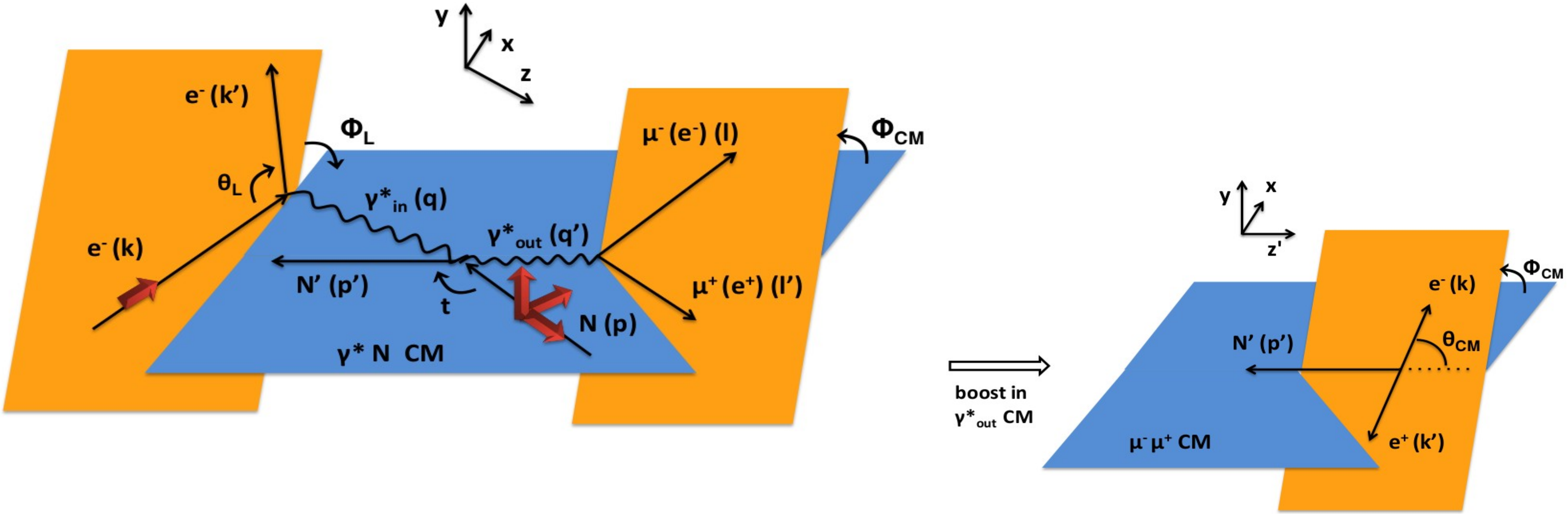
- Radiative corrections and polarization vectors
- Polarized cross sections

In particular **tools at generator level** to perform kinematic and physics studies: cut out Bethe-Heitler peaks...

TCS and DDVCS (electron beam)

EIC: quasi-real photoproduction for TCS ; JLab: real or quasi-real
Initial electron beam in both case

Unpolarized TCS: 5-differential; unpolarized DDVCS: 7-differential
(below: angles / kinematics for DDVCS or quasi-real TCS)



* I only have projections for JLab

TCS at JLab: what can we get, motivations, JLab (potential) experiments

Observable (proton target)	Experimental challenge	Main interest for GPDs	JLab experiments
Unpolarized cross section	1 or 2 order of magnitude lower than DVCS, require high luminosity	Im + Re part of amplitude. Re(H), Im(H)	CLAS 12, SoLID approved NPS conditionnal
Circularly polarized beam	Easiest observable to measure at JLab	Im(H), Im($\tilde{H}$) Sensitivity to quark angular momenta, in particular for neutron	CLAS 12, SoLID approved NPS conditionnal
Linearly polarized beam	Need high luminosity, at least 10x more than for circular beam, and electron tagging	Re(H), D-term. Good to discriminate models and very important to bring constrains to real part of CFF	GlueX (?)
Longitudinaly polarized target	Polarized target	Im($\tilde{H}$)	no / "for free"?
Transversely polarized target	Polarized target, and high luminosity: binning in θs, φs	Im($\tilde{H}$), Im(E)	NPS conditionnal
Double spin asymmetry with circularly polarized beam	Polarized target, very high luminosity, precision measurement	Real part of all CFF	no / "for free"?
Double spin asymmetry with longitudinally polarized beam	Polarized target, electron tagging, very high luminosity and precision	Not the most interesting, Im(CFFs) but difficult to measure	no

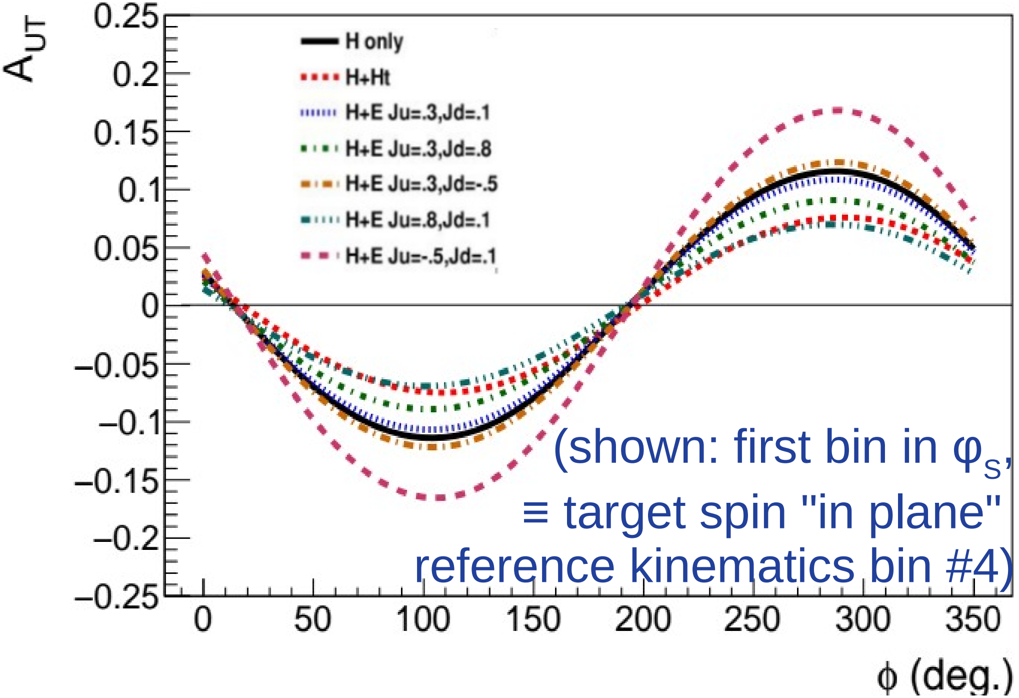
Pierre's talk

TCS off the neutron
- similar, need higher luminosity and proton or neutron tagging
- target spin asymmetries are expected to be larger, and beam spin asymmetries are smaller

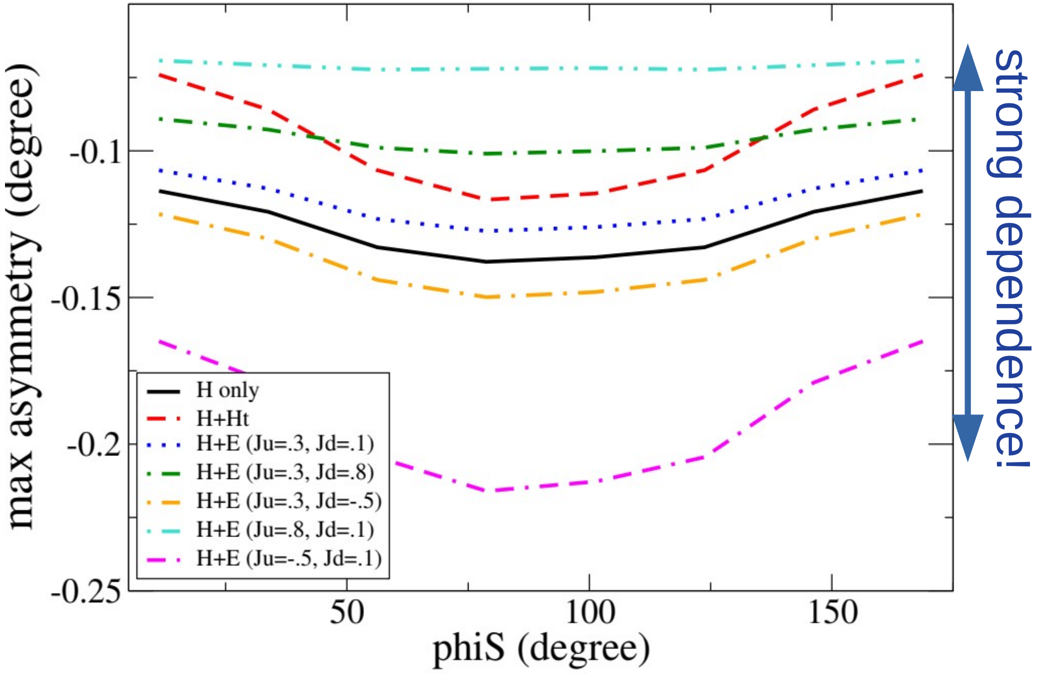
TCS in Hall C with transverse target

Transverse target spin asymmetry “as will be measured in Hall C”

Dependence in GPD parametrization and J_u, J_d (VGG model) vs φ and φ_S



Sin(φ) moment of transverse spin asymmetry vs φ_S, Dependence in GPD E and $J^{u,d}$ (VGG model)

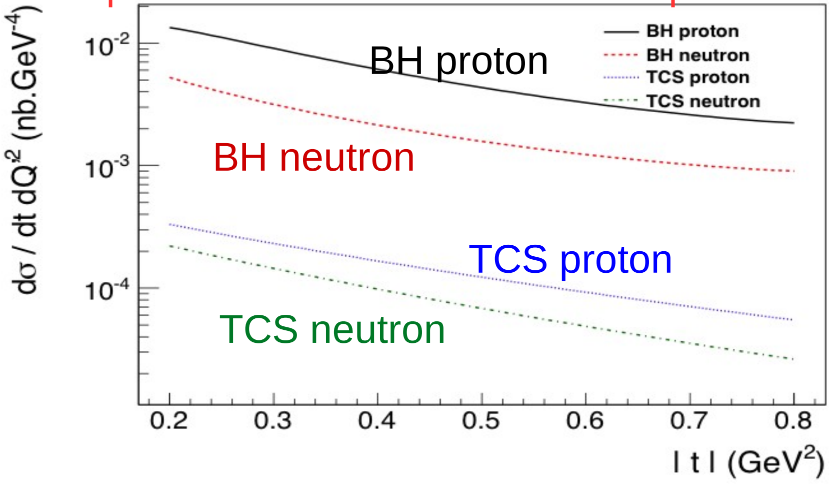


- **Unique access to GPD E of the proton and quark angular momenta**
- **GPD universality studies (TCS vs DVCS)**
- **Independent observables for GPD data sets and global fits in valence region**
- **Most knowledge on GPDs from DVCS: complex conjugate, TCS access same information**

Other observables for TCS

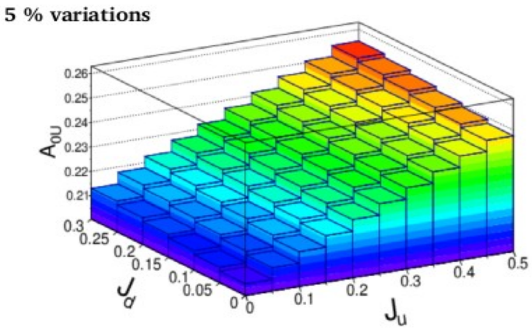
- **Neutron: flavor separation and spin**

Unpolarized cross section vs -t off p or n

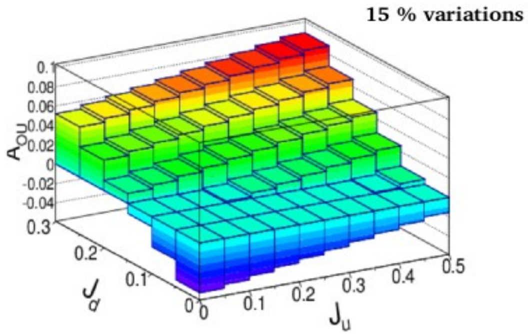


- σ off neutron not suppressed, sizeable asymmetries
- similar sensitivities to GPDs expected
- strong sensitivity to J_u, J_d

BSA proton



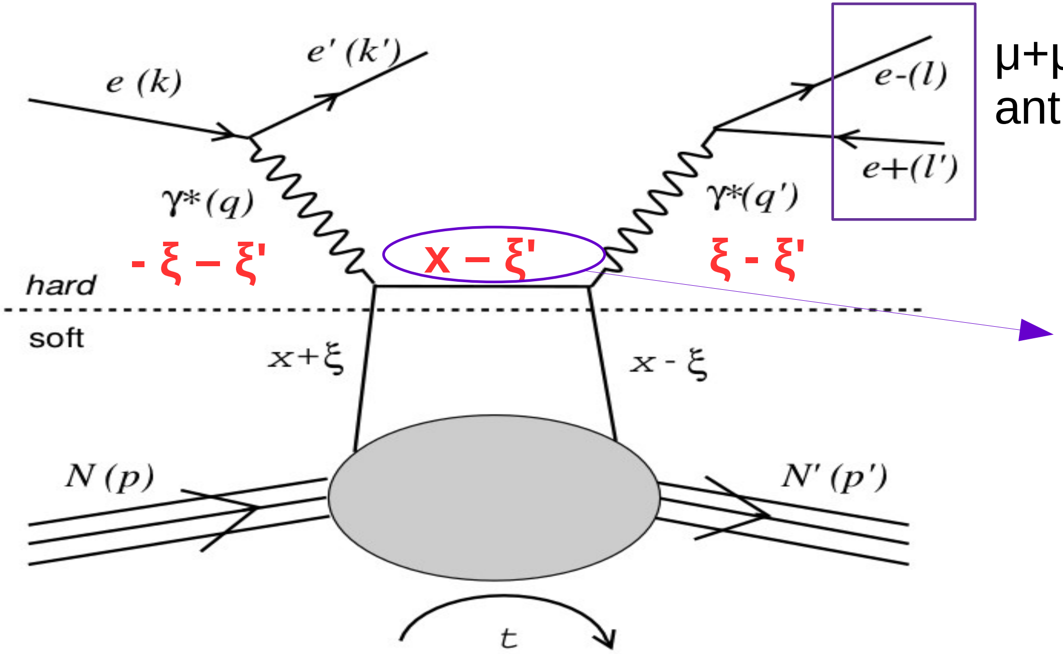
BSA neutron



- **Unpolarized and polarized neutron**: off LD_2, ND_3...
- **Nuclear targets (Hall C, A?)**: possible extension of PR12-18-005 off unpolarized N_2
- **Precision unpolarized measurement (Hall C, A?):** off LH2, similar setup
- **Longitudinally polarized target (Hall C, A?):** single and double spin asymmetries (Im+Re $\tilde{H}$, E...)
- **Linearly polarized beam (GlueX ? Hall A/C ?)**: Re(H)

Projections made for several observables, working on realistic MC and new proposals

Double Deeply Virtual Compton Scattering (notations)



μ+μ- → avoid antisymmetrisation

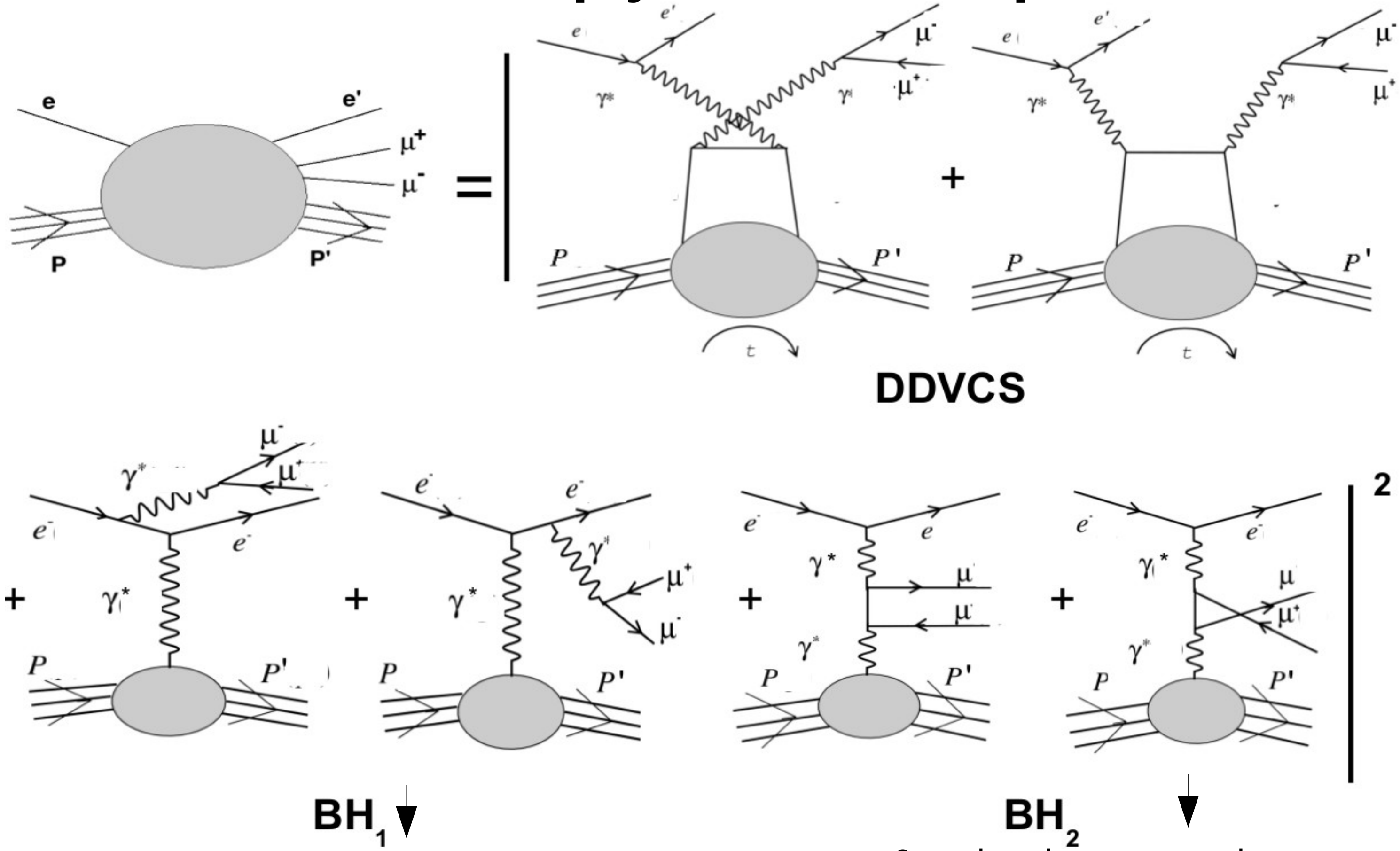
- ξ = + component of P=(p+p') in light cone frame. GPDs depend on it. "skewness"
- ξ' = + component of $\overline{q}$=(q+q')/2 in light cone frame. quark propagator can be related to x_{bj}

Special cases (at asymp. limit):
DVCS: ξ'=ξ; TCS: ξ'=-ξ

Mesons: fixing Q'² at meson mass squared

Lever arm to go “off diagonal”
Provided by relative virtuality of the photons

Double Deeply Virtual Compton Scattering

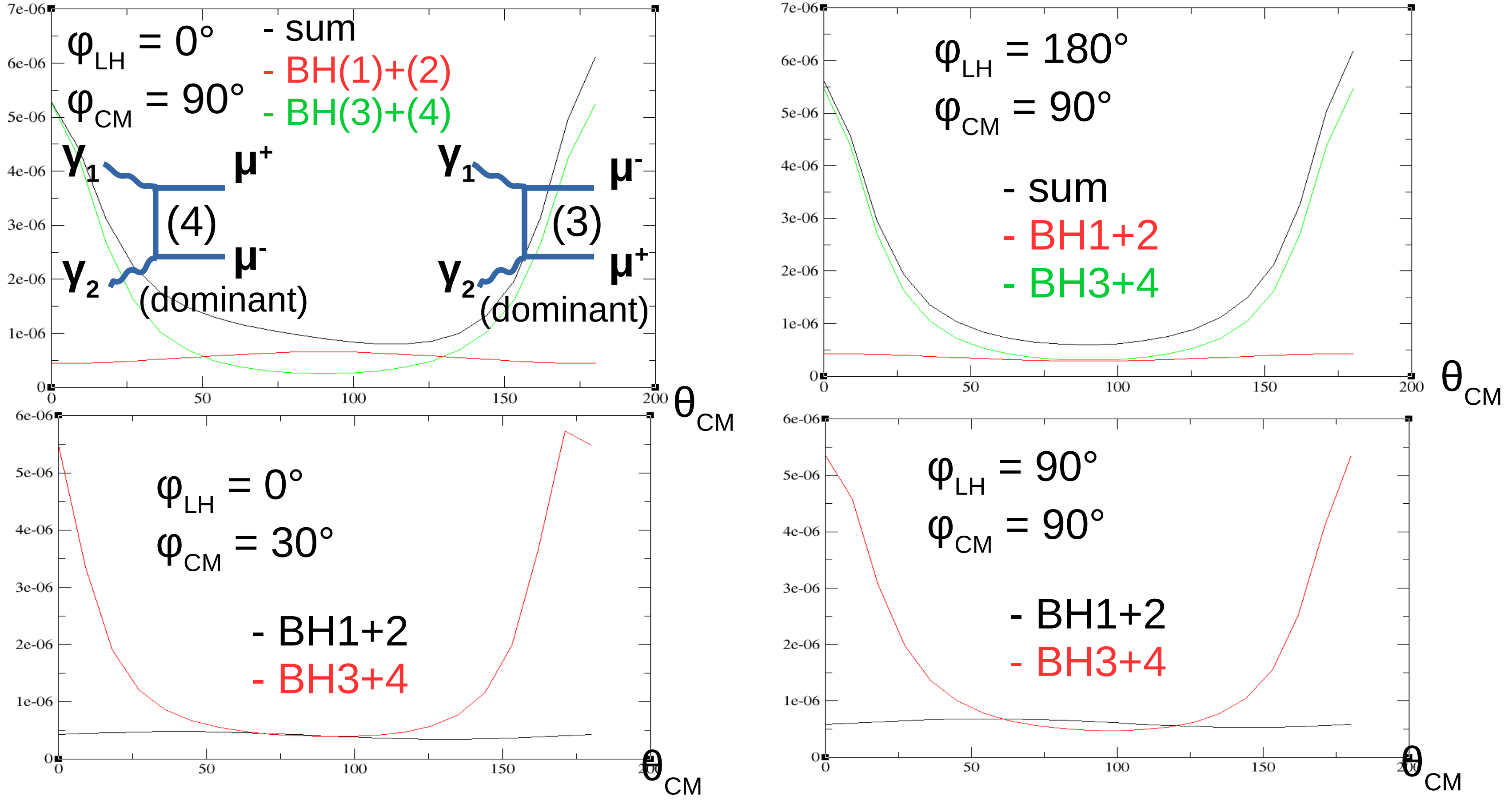


no favored direction for γ* emission or decay leptons

peak when γ' becomes collinear to e
related to $\varphi_{LH}=0$,
and depends $\cos\theta_{\gamma\gamma}$ (kinematics)
and "γ"→e' angle

2 peaks when μ+ or μ- become collinear to γ
related to $\varphi_{LH}=0$ and 180°,
and depends $\cos\theta_{\gamma\gamma}$ (kinematics) which position the value of θ_{CM} for the peaks

Angular correlations: complex shapes in angular distributions. Coming from interferences between the different diagrams and correlations between the angles

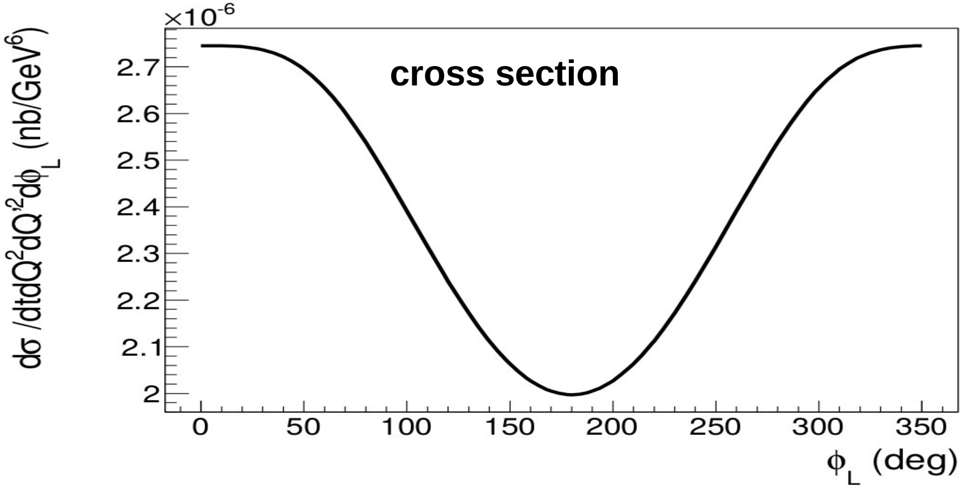


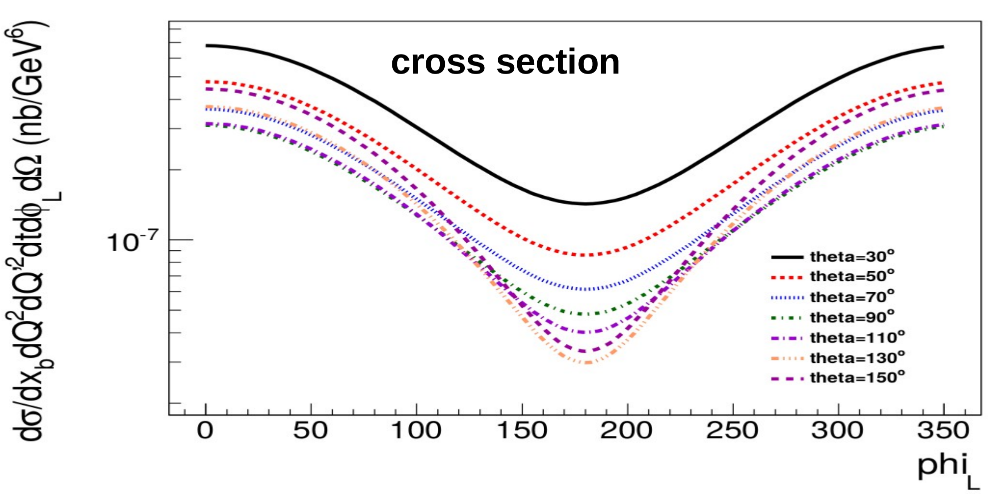
Can be understood from TCS phenomenology == importance to interpret DDVCS from TCS, not DVCS

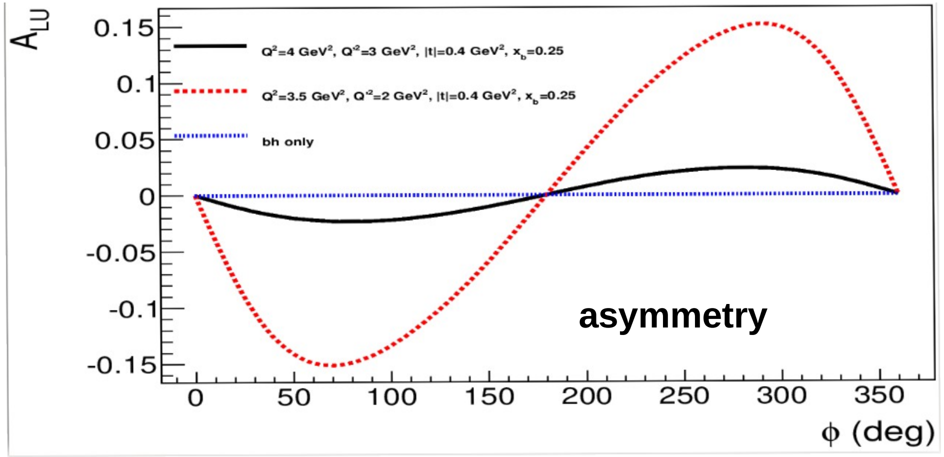
peaks at 0° and 180° : associated to bh(3) and (4) peaks. bh(1) and (2) almost flat in θ

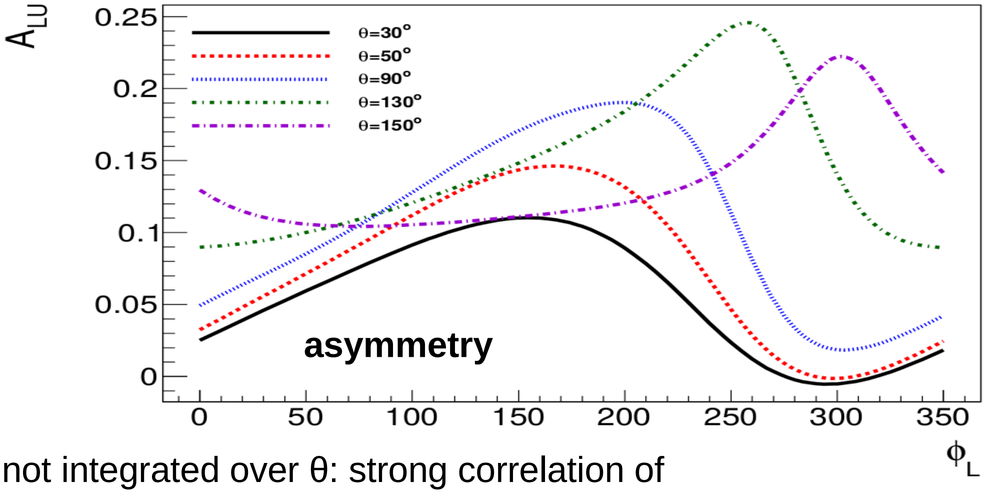
All Figs.: xbj=.24, Q^2=3.6 GeV^2, Q'^2=1.7 GeV^2, -t=.19 GeV^2. Axis: $d\sigma/dx dt dQ^2 dQ'^2 d\varphi d\varphi d\theta$ nb/GeV^6

Observables for DDVCS measurements at JLab





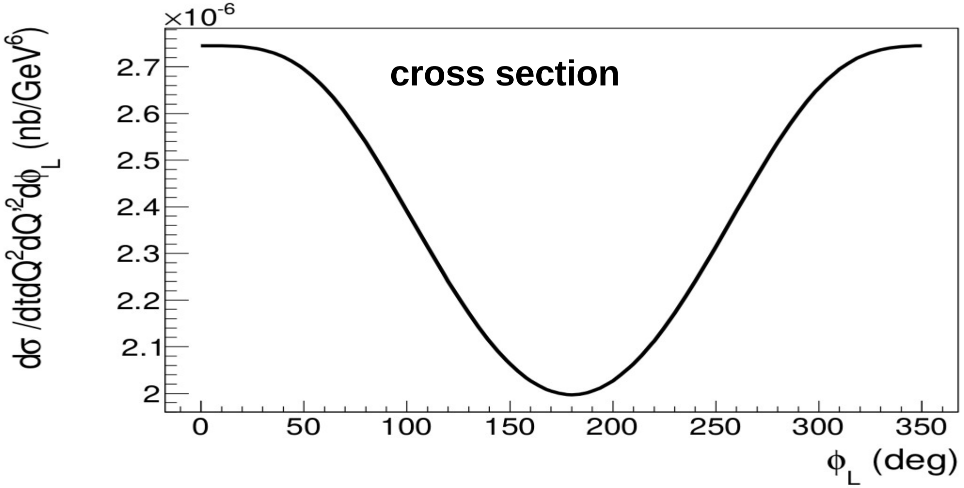


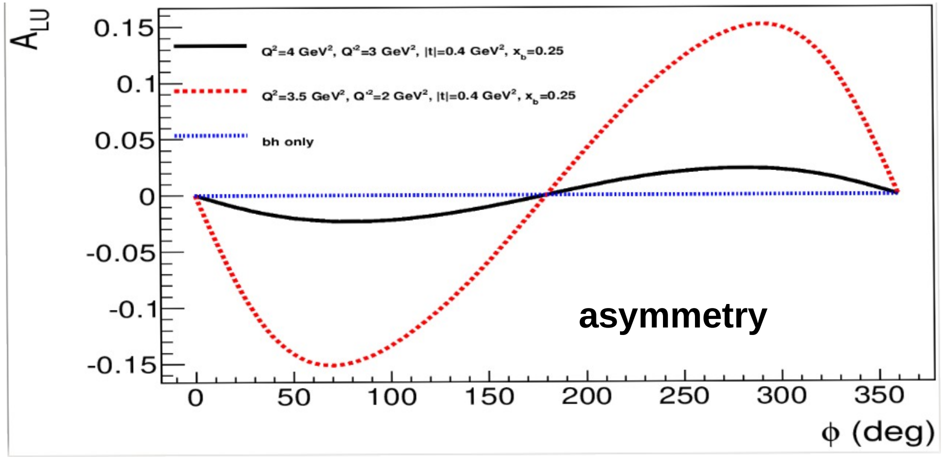


left= integrated over θ, right=not integrated

if not integrated over θ: strong correlation of A_{LU} with θ (rate of “BH2”)

Observables for DDVCS measurements at JLab





left= integrated over θ, right=not integrated

unpolarized cross section
access |DDVCS|*|BH| term
it represent up to 10% of total x-section

can access Im(H), maybe Re(H)
if good enough precision on the measurement
also need φ_{CM} vs φ_{LH} mapping

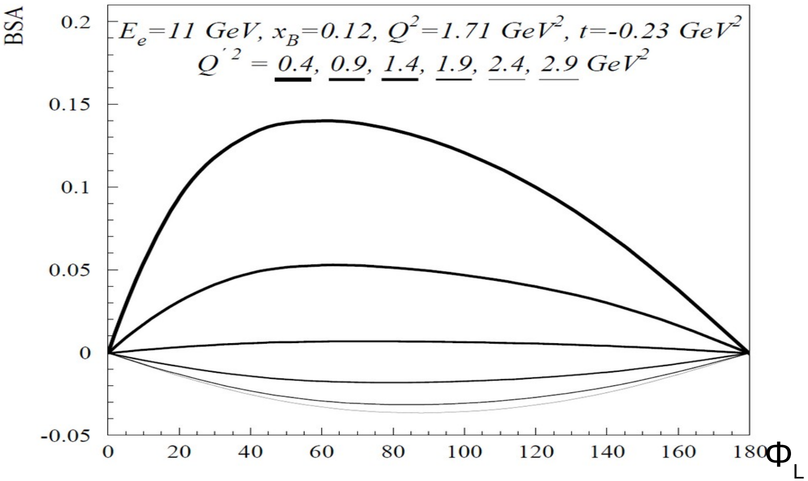
beam spin asymmetry.
purely coming from interference between BH(1+2)*DDVCS
asymmetries are sizeable.
however, shapes are complex
need of 2D φ_{CM} vs φ_{LH} mapping to access Im(H)
Change of sign to be observed in different kinematic regions

Observables for DDVCS measurements at JLab

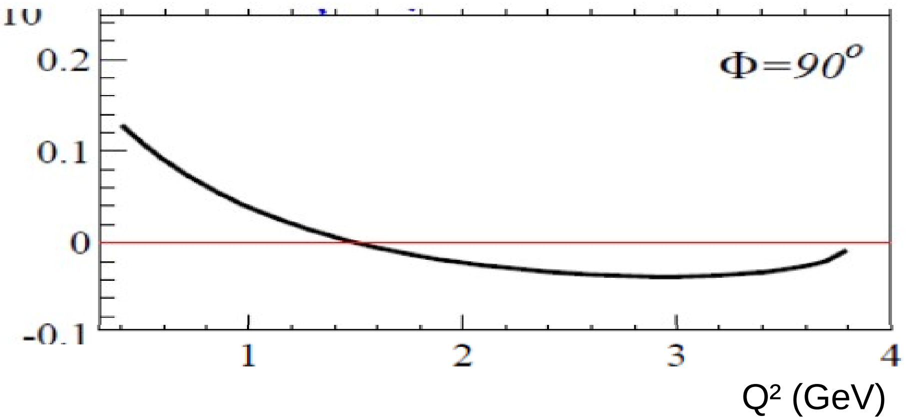
Sign change in BSA and interplay “spacelike” “timelike” regions

Calculations from M. Guidal

→ scan of BSA in Q'² at fixed Q²



→ sign change in BSA vs Φ_L and vs φ_{CM} when Q'² ≈ Q²
asymmetry Q² scan



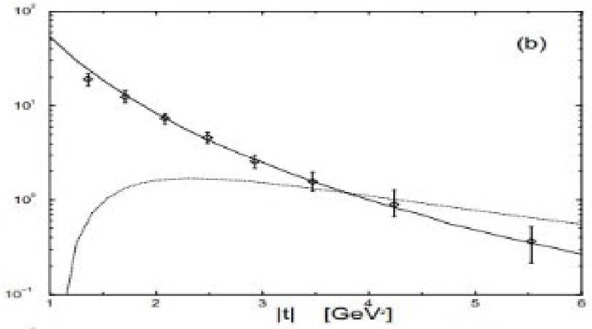
- Probing GPDs at x ≠ ξ → tomographic interpretations....
- Expectation of sign change for observables sensitive to Im (DDVCS) when moving from « spacelike » to « timelike » region

→ this reaction is unique for probing effects between these 2 regions.

Projections for quarkonia at EIC

(slides from Tyler Schroeder, W&M graduate, VT summer student in 2021)

Quarkonia Production

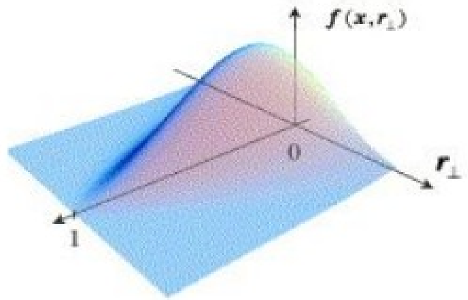


- **Flexible framework** for meson production
- Hard exclusive **J/Ψ** production
  - User provides ratio between **two-gluon** and **three-gluon** cross-sections
  - Two-gluon dominates at EIC et al, three-gluon near threshold
    - Three-gluon gives more flexible momentum transfer
- Hard exclusive **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**

Note: 3 gluon mode turned off after discussion with theorists (forbidden transition), no impact on results

GPD parameterizations

- **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
- 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.)



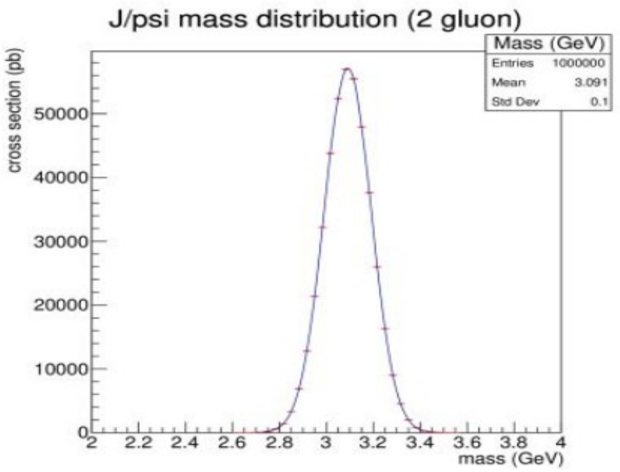
(slides from Tyler Schroeder, W&M graduate, VT summer student in 2021)

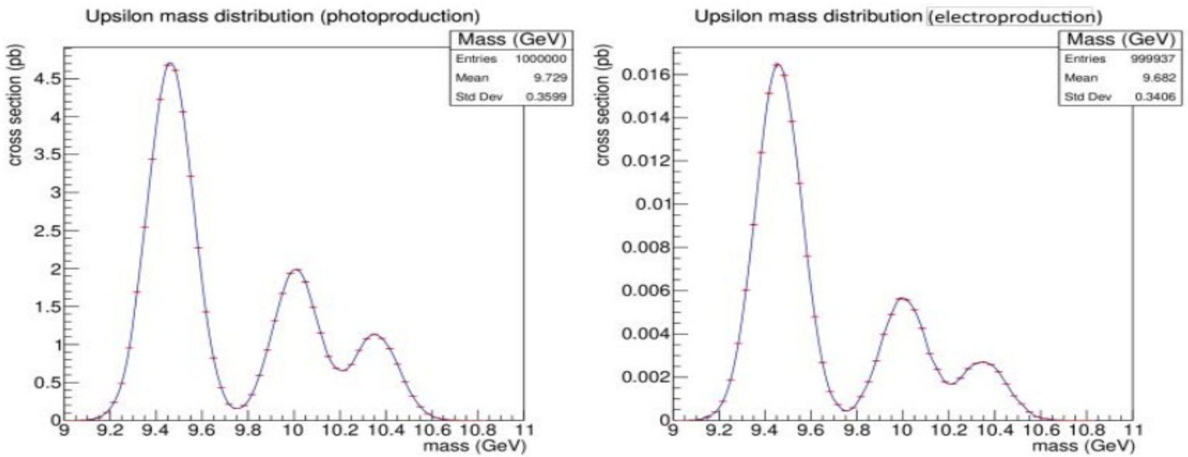
Production modes

- J/Ψ: Both **photoproduction** (JLab) & **electroproduction** (EIC et. al) handled by **same cross-sections** (varying 2-3 gluon ratio)
- Beam:
  - Quasi-photoproduction & electroproduction for EIC: scale by **flux factor** (HERA collab. Z)
  - JLab: not factorized for electroproduction, using quasi-real photon flux + Bremsstrahlung (dep. on target) for quasi-photoproduction
  - Real photoproduction possible at JLab
- Spin:
  - Polarization handled at JLab (weighting still a work in progress)
  - Would like to expand to EIC energies
- Measuring both J/Ψ and ϒ through lepton decay modes (e^+e^-, $\mu^+\mu^-$)

(slides from Tyler Schroeder, W&M graduate, VT summer student in 2021)

Some cross sections for quarkonia (not realistic normalization, acceptance)
Out of Tyler's work in 2021





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

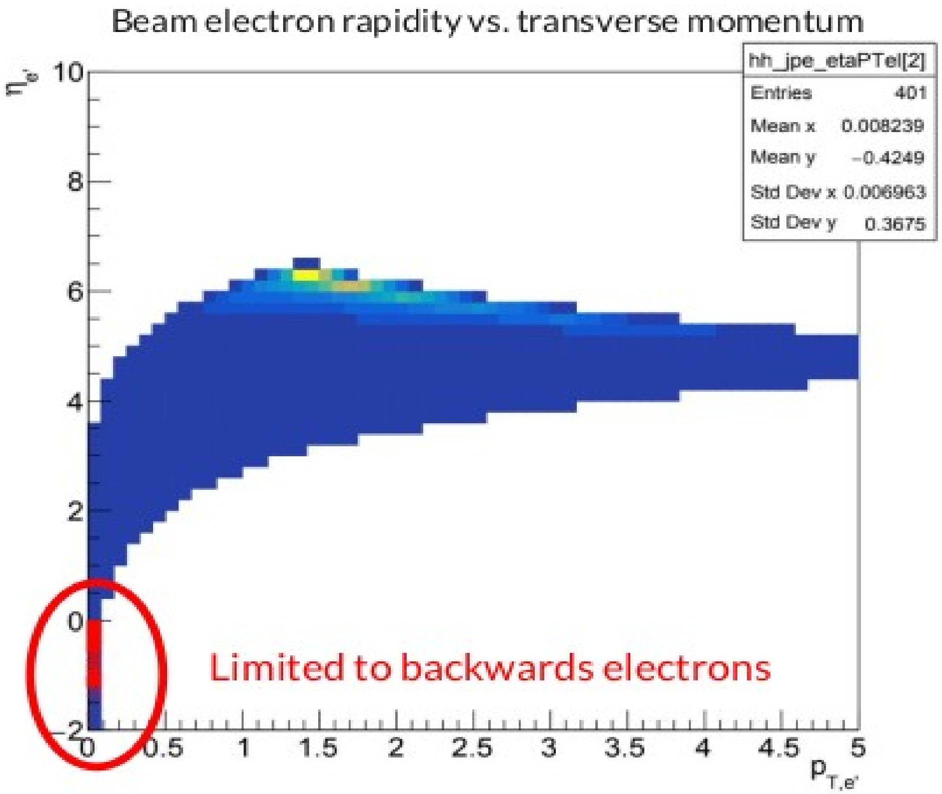
Assuming 10% resolution with muons, we can distinguish Y resonances

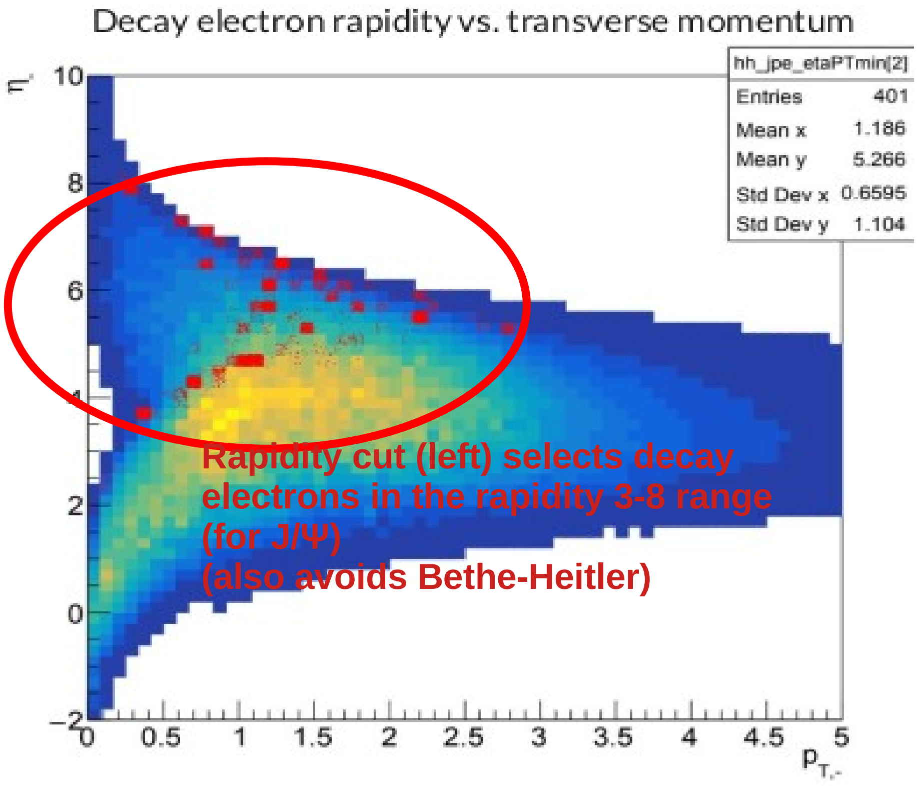
Mass resolution for Y peaks likely to not be sufficient for distinction into electrons

This is one argument for muons, but can we really study exclusive quarkonia into electrons for GPDs? (low -t, exclusivity, low statistics/high background/BH interference, semi-inclusive background and associated production...)

Projection for 5x41 GeV beams, done by Tyler Schroeder

J/Psi rapidity vs pT for decay vs pair electron (no acceptance cut)

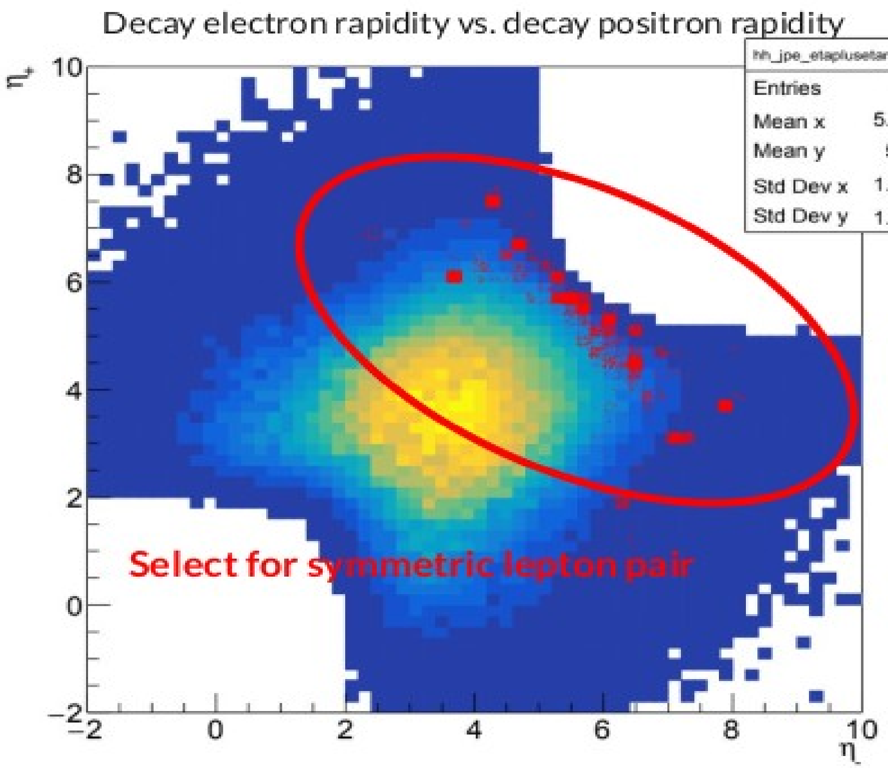


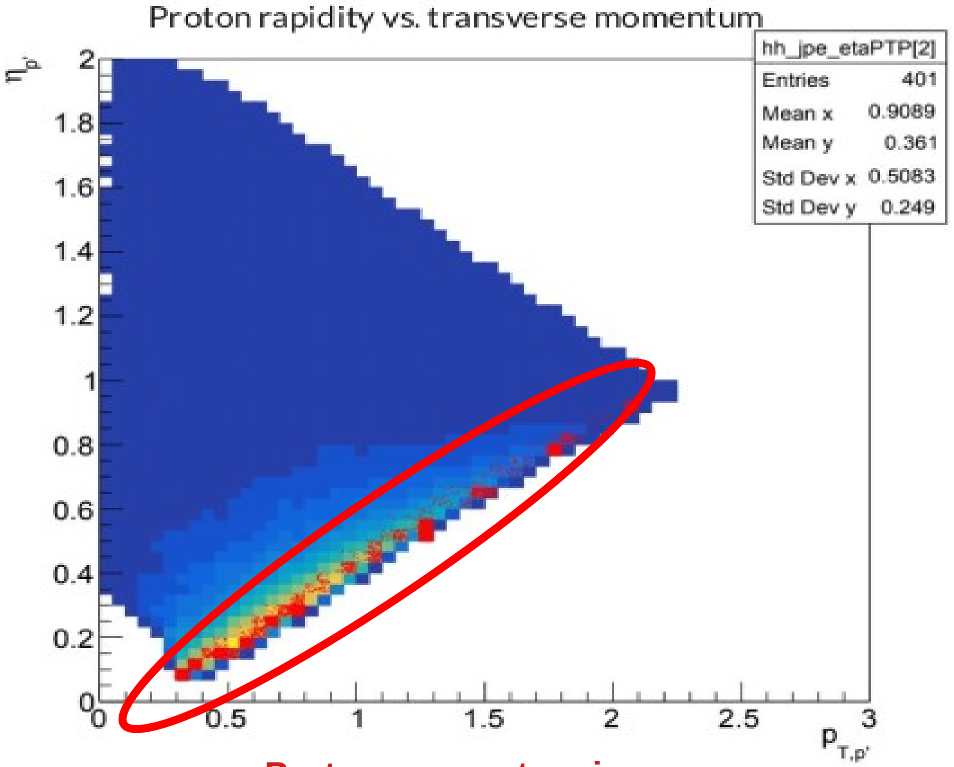


Being “safe” limits us to electrons close to the rapidity acceptance limits for EIC
- limit eta 3.5 can’t be extended (tracking, beamline…) should be same or lower with a det 2.

Access all the range with muons (besides acceptance limits)

J/Psi proton rapidity vs pT for “symmetric pairs” (no acceptance cut)





- cut applied to stay out of BH peaks region,
Selects accessible region in t
Want to stay at lower t.

Proton momentum is unconstrained, but only lowest rapidity is measured
-> selects the range in t for GPDs

When and why we prefer to avoid di-electrons for quarkonia and DDVCS:

- Low virtuality photon, “quasi real” production: OK, electron is going backward, we should be able to neglect anti-symmetrization effects since large rapidity gap and are in “different” phase space. **Resolution may be the limitation**

All other kinematics:

* If final leptons are electrons, we have 2 identical leptons!
- Need antisymmetrization of wavefunction (hard to extract GPDs)
- experimentally define the kinematics ???

High risk to “create” a what we are looking for, can’t reduce background.

At EIC, scattered electron can go backwards
- For very specific kinematics, we assume small interference
- Ideally, assumption can be checked with e+e- vs. mu+mu-

Solutions: large rapidity gap (EIC), photoproduction (JLab+EIC w/ hard scale provided by meson mass or large Q'^2), **and/or muon detectors**

Why (not) adding muon detectors?

Lots of questions if EIC is without muon detectors

- Can the same physics be done with electrons? Would the interesting kinematics still be accessible?

- PID good enough for muons without dedicated detectors?

Our plans:

- Full simulations with electrons and muons, including resolution effect and acceptance
What can be achieve without muon detectors/trigger?

- Adding simple detector (hodoscope) near beamline: how does it improve PID?

Constraints for our physics: need statistics (OK for J/psi), need lower -t, need all decay particle, need precision (10%)?

- work presented here is very preliminary, we want to see experimental pros and cons of adding muon detectors/trigger

- we lack of manpower in our group for now

=== We want to see what can and can’t be done to improve physics outcome in channels producing muons.

SUMMARY: for discussion

Physics conclusion: we need to study these channels with muons

- for exclusive physics (GPDs…)
- likely for semi-inclusive physics (TMDs…) but we haven't explore it yet

Experimental side:

- is it possible to add muon detectors?
- what kind of detector or trigger?
- cost?
- significant improvement in PID?
- what can be achieved without dedicated muon detectors?

Open questions:
- How not having muon or fine resolution affects GPD extraction?
- Other physics, with/without muons?
- Quarkonia + charmed/beauty meson?
- TMDs and other nucleon's imaging approach in the low -t region?
- certainly many more questions!