Generalized Parton Distributions, from JLab to EIC

What new can we learn at JLab in-between with new measurements, new reactions, with and without a luminosity and/or energy upgrade?

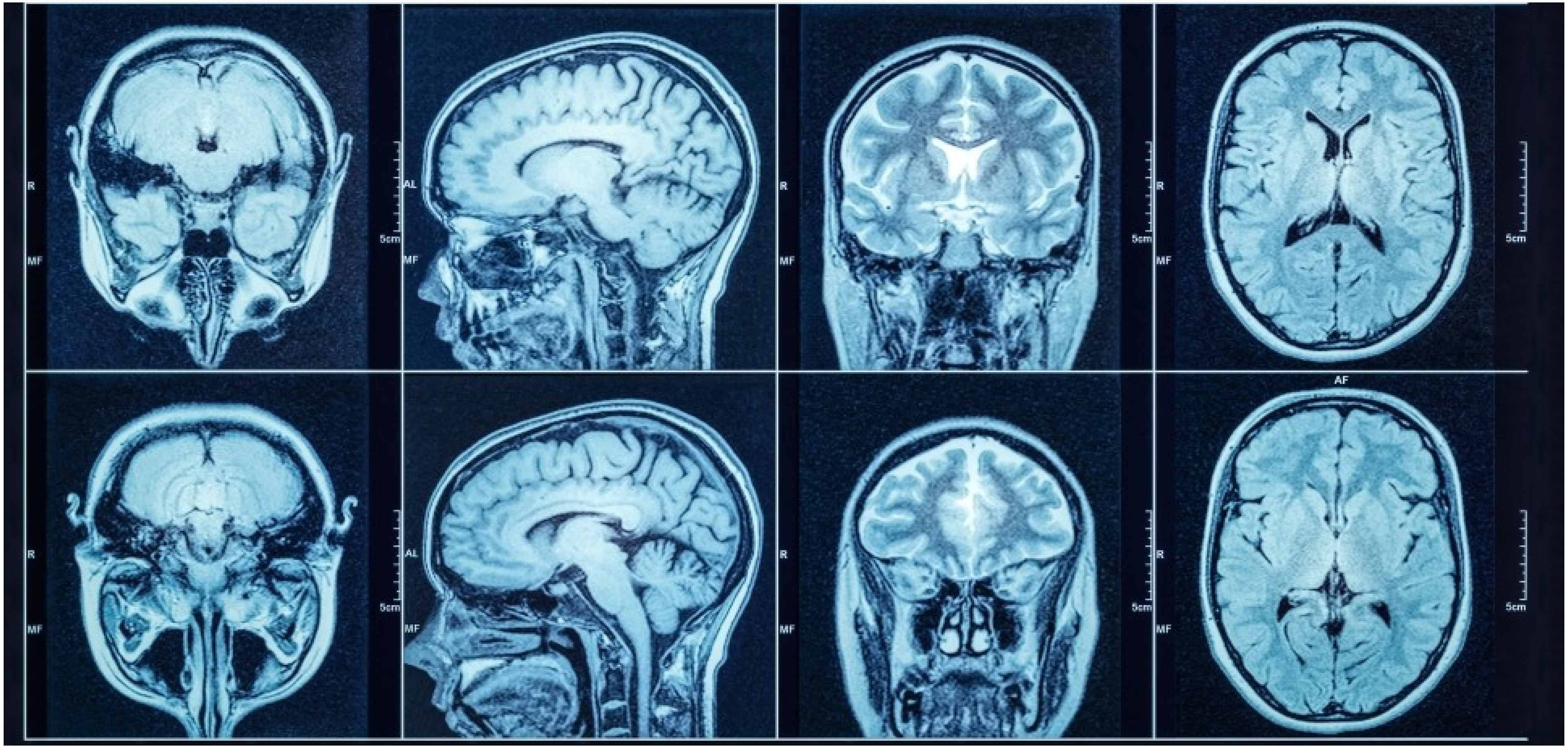
PARTONIC STRUCTURE OF THE HADRONS

Marie Boër, Virginia Tech

ECT* Trento, Italy; Sept. 28th, 2022

Goals

Tomography: a nice sounding world we are using a lot to sell our measurements



Can we really do it at the partonic level?

What is the status, what can we achieve?

What are our limitations?

How to go beyond?

Goals

Status: most of the models are constrained by DVCS measurements

(see talks on Thursday: Carlos, Silvia...)

(see Marija's talk Friday and others to go beyond)

Large x region: JLab Hall A & B, HERMES
Intermediate x: HERMES, COMPASS
Low x: H1/ZEUS, future EIC

DVCS measurements in the valence quark region

HERMES: largest data set, all polarizations for beam and target. BUT: large uncertainties

JLab Hall A: precision measurements, unpolarized and beam polarized
JLab Hall B: unpolarized and beam polarized, target // polarized

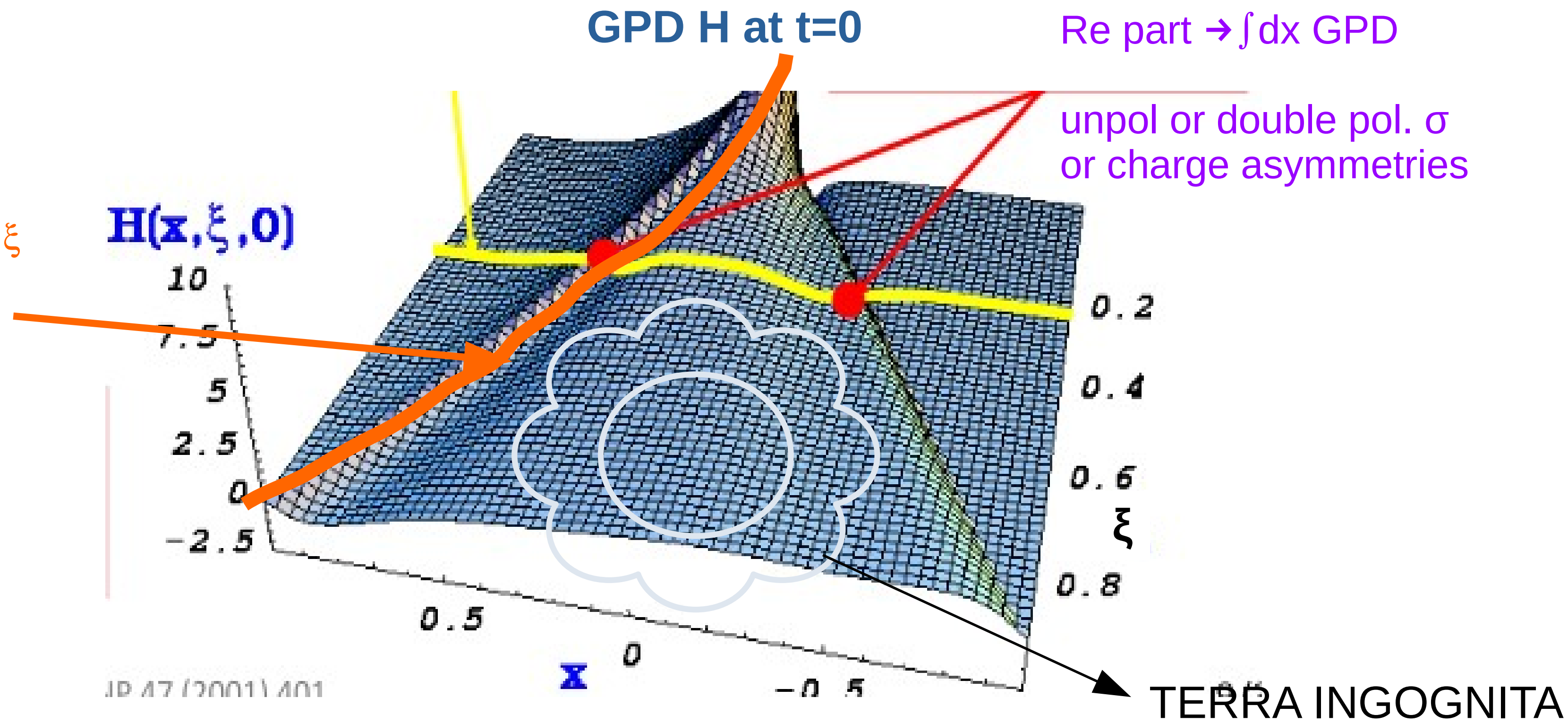
=== Constrain CFF Im(H), Re(H) with lower precision, H~ thanks to polarized measurements
Large errors propagate to CFF with HERMES data

New DVCS measurements at JLab 12 GeV and possible at higher energy:
Will improve the precision, allow for NLO studies and add more bins (see other talks).

What are the limitations of focusing on DVCS?

Extracting CFFs with DVCS

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



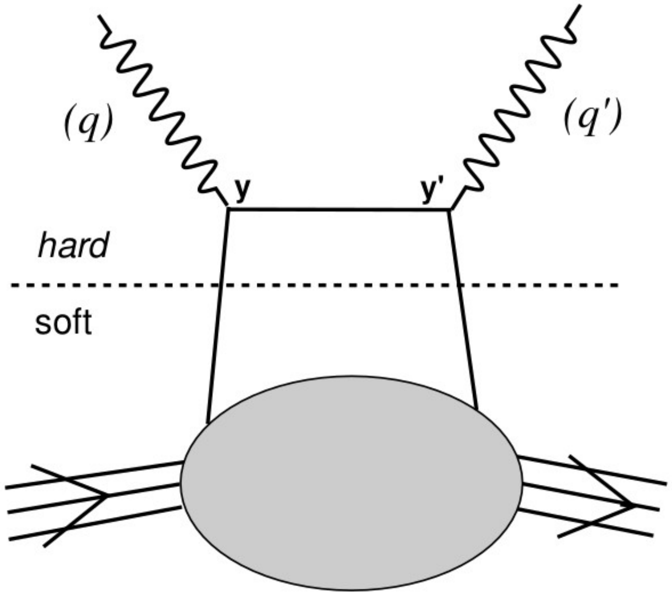
Restricted to the "diagonal" x=xi

Tomographic interpretations rely on extrapolating to zero skewness!
We have one point

Pushing the limits

Now I will not talk about DVCS anymore, but its complementarity with other reactions

Compton-like reactions



DVCS: special case when final photon is real, incoming is spacelike

TCS: special case when incoming photon is real, outgoing is timelike

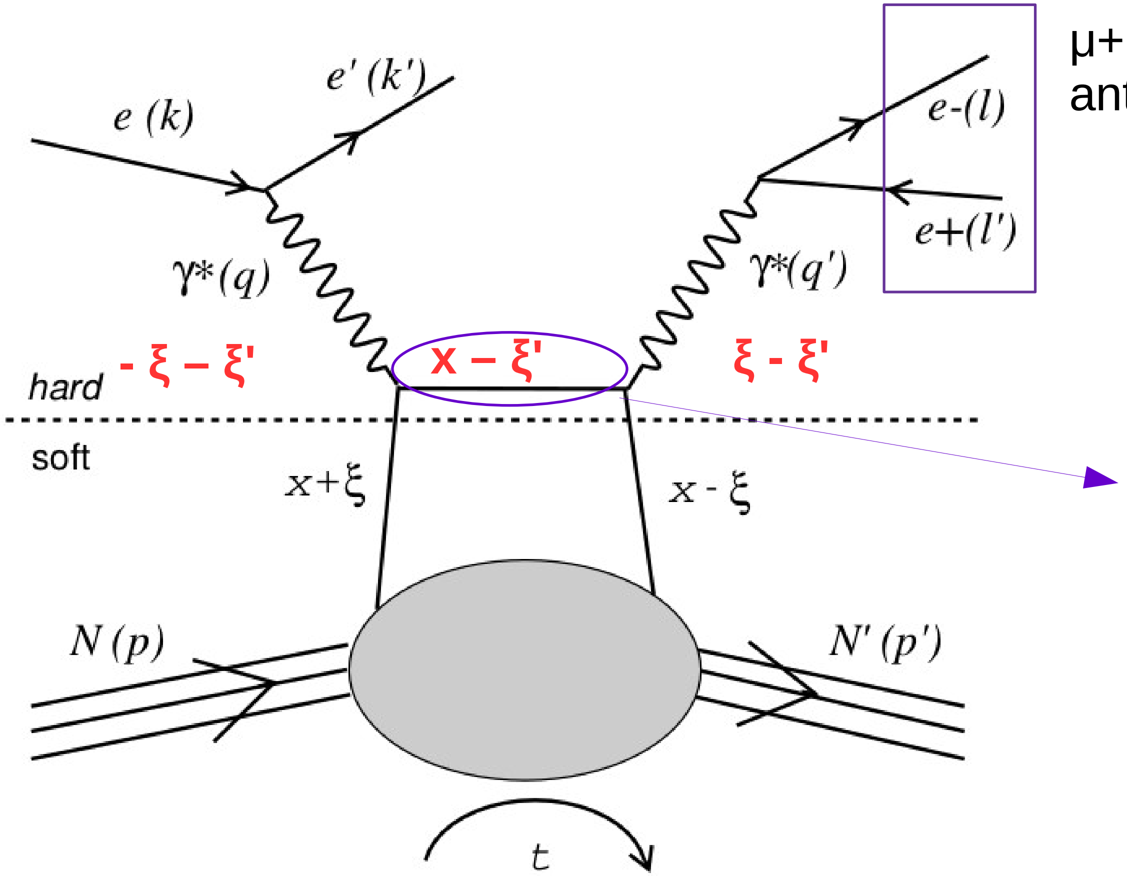
DDVCS: both photon are virtual. More general

Other: multi-photons… (not in this talk)

2 photons involved: exchange from vector to vector particles

In this talk I will focus on Compton-like and Vector mesons. Reasons:
- complementary approaches for extracting CFFs, for chiral even GPDs
- factorization is proven
- we want to find a way to go “off diagonal” and complement what we already know from DVCS
- “old style” approach with mass evolution

Compton-like: DVCS, TCS, DDVCS



μ+μ- → avoid antisymmetrisation

- ξ = + component of P=(p+p') in light cone frame. GPDs depend on it. "skewness"
- ξ' = + component of $\bar{q}$=(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

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

(similar for TCS)

Re (CFF, noté $\mathcal{H}$) Im ($\mathcal{H}$)

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

With $\xi' = \frac{x_B}{2 - x_B}$ and $\xi = \xi' . \frac{Q^2 + Q'^2}{Q^2}$ (our notations, VGG models for JLab projections)

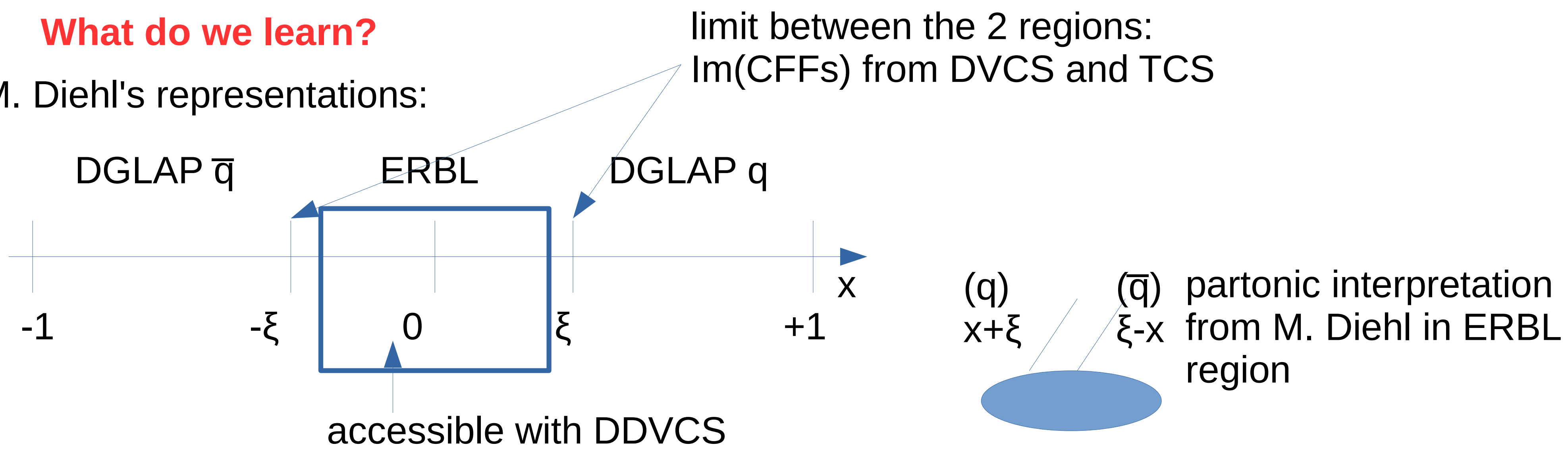
Compton-like: DVCS, TCS, DDVCS

TCS and DVCS access Im(CFFs) at x = 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 gives 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

What do we learn?

M. Diehl's representations:



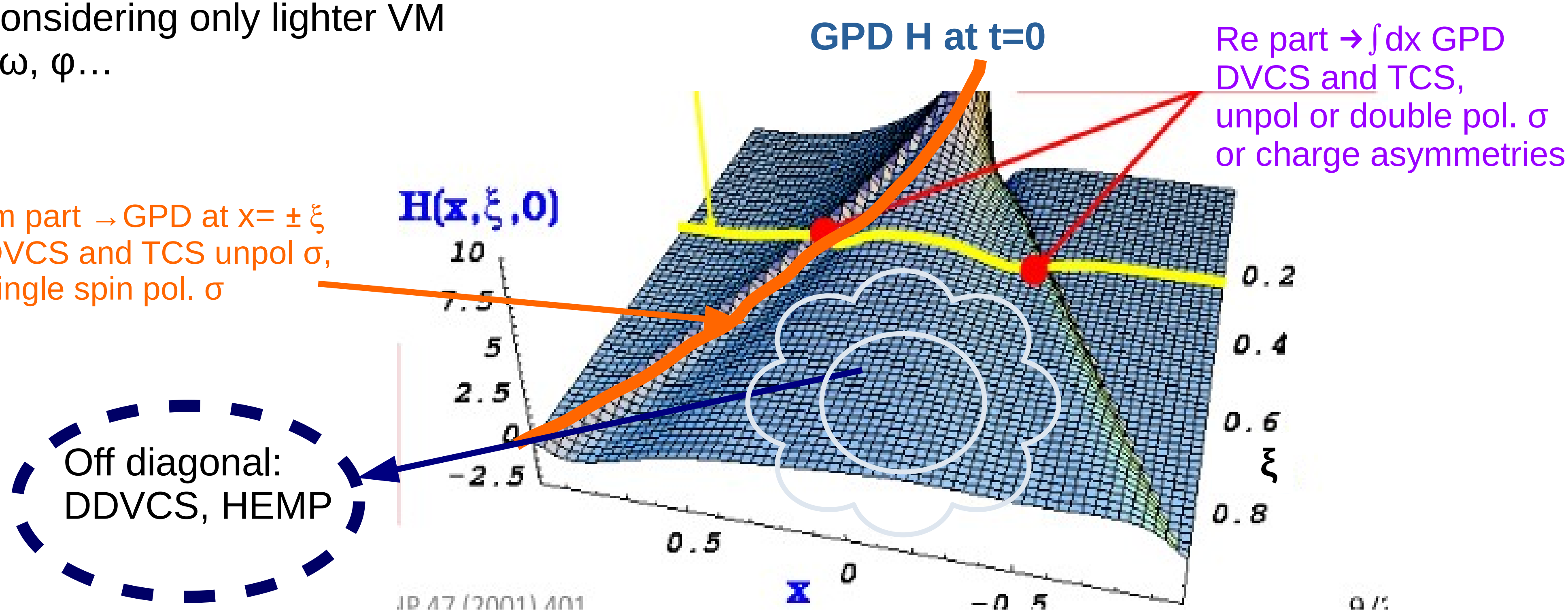
Advantages of a multichannel fit approach

“diagonals” with DVCS and TCS, “off diagonal” ERBL region with DDVCS

Slightly off diagonal with light mesons (meson mass gives lever arm)

* this picture for quark GPDs, unclear for gluon exchange diagram

* considering only lighter VM
ρ, ω, φ…



GPD in VGG model,
from Guichon, Vanderhaeghen, Guidal
Image: M. Guidal

TCS from 11 to 22 GeV at JLab

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 proposed
Circularly polarized beam	Easiest observable to measure at JLab	Im(H), Im(H) Sensitivity to quark angular momenta, in particular for neutron	CLAS 12, SoLID approved NPS proposed
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(H)	no / "for free"?
Transversely polarized target	Polarized target, and high luminosity: binning in θs, φs	Im(H), Im(E)	NPS proposed
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

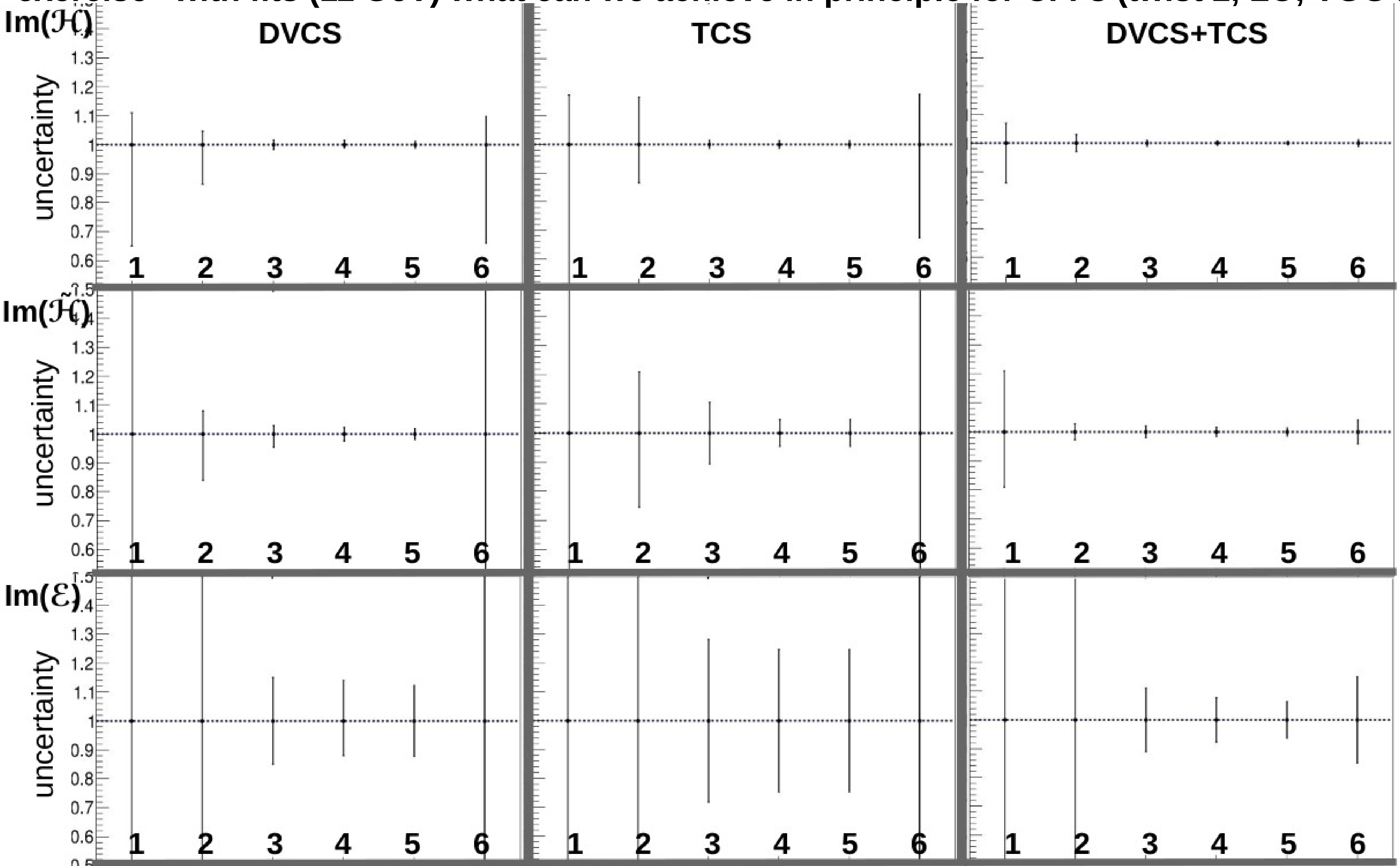
TCS off the neutron

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

* based on CFF fit studies. Table prepared in 2017, updated, still accurate

TCS from 11 to 22 GeV at JLab

“exercise” with fits (11 GeV) what can we achieve in principle for CFFs (twist 2, LO, VGG model)



Observable sets (all):

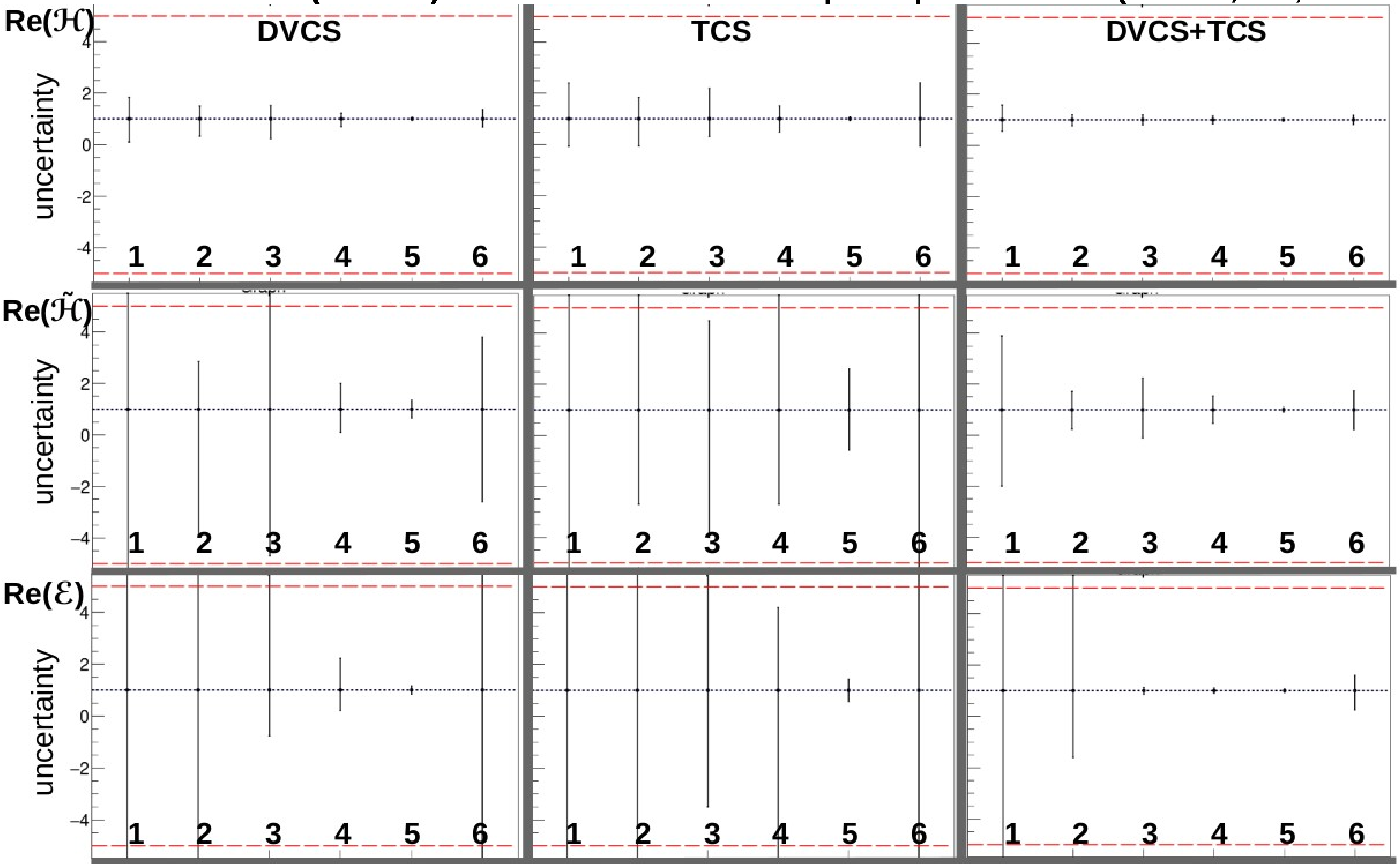
1) σ, $\Delta\sigma_{LU}$
2) σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$
3) σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UT}$ (x2)
4) σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UT}$ (x2) $\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$
5) σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UT}$ (x2) $\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$, $\Delta\sigma_{LT}$ (x2)

For set #6:

DVCS:	σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{C}$
TCS:	σ, $\Delta\sigma_{\odot U}$, $\Delta\sigma_{LU}$
DVCS+TCS:	2) of DVCS + 3) of TCS

TCS from 11 to 22 GeV at JLab

“exercise” with fits (11 GeV) what can we achieve in principle for CFFs (twist 2, LO, VGG model)



Observable sets (all):

1) σ, $\Delta\sigma_{LU}$
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5) σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UT}$ (x2) $\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$, $\Delta\sigma_{LT}$ (x2)

For set #6:

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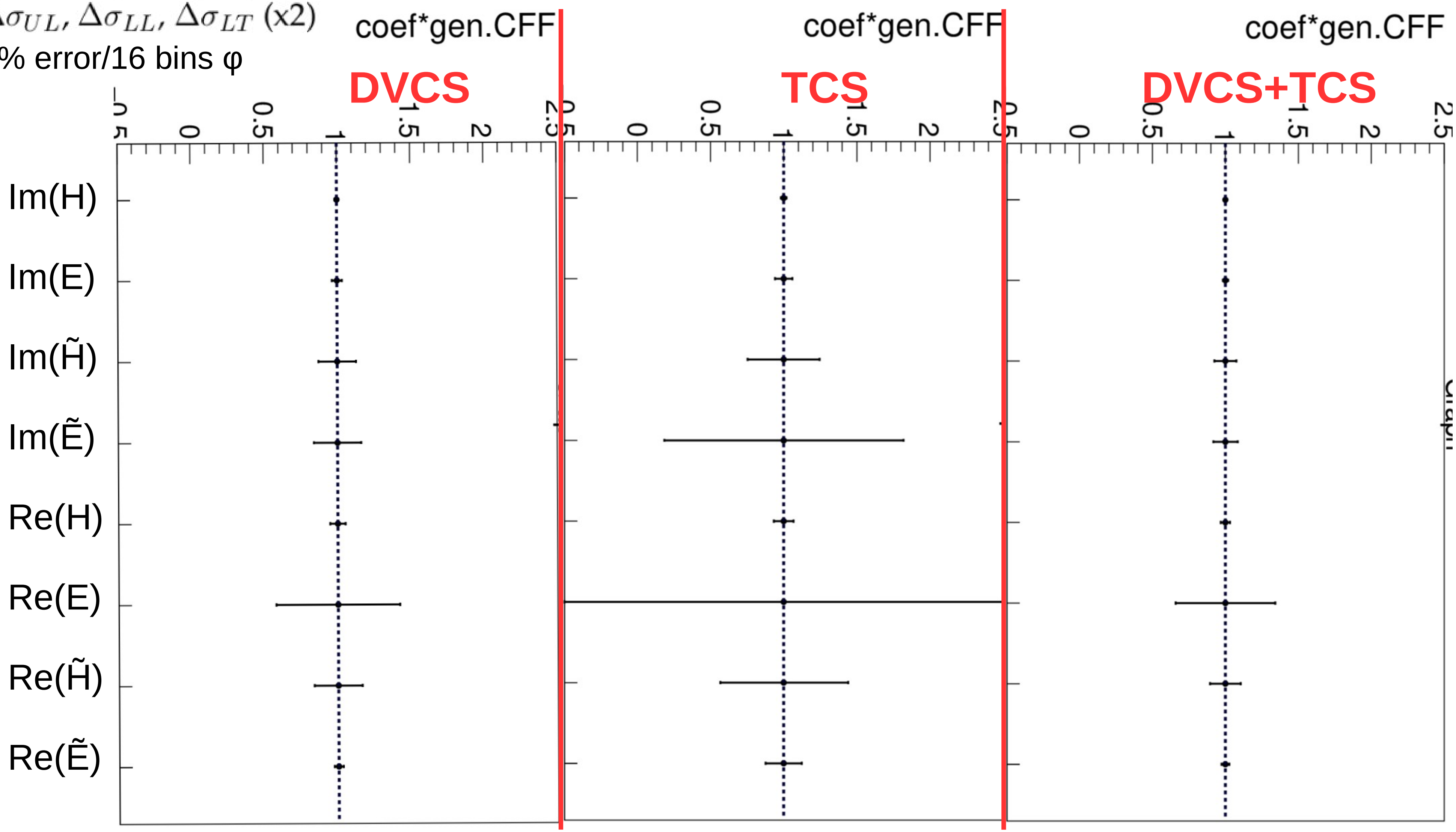
TCS:	σ, $\Delta\sigma_{\odot U}$, $\Delta\sigma_{LU}$
DVCS+TCS:	2) of DVCS + 3) of TCS

Global fits of Compton Form Factors with TCS

5) σ, $\Delta\sigma_{LU}$, $\Delta\sigma_{UT}$ (x2)
$\Delta\sigma_{UL}$, $\Delta\sigma_{LL}$, $\Delta\sigma_{LT}$ (x2)
7% error/16 bins φ



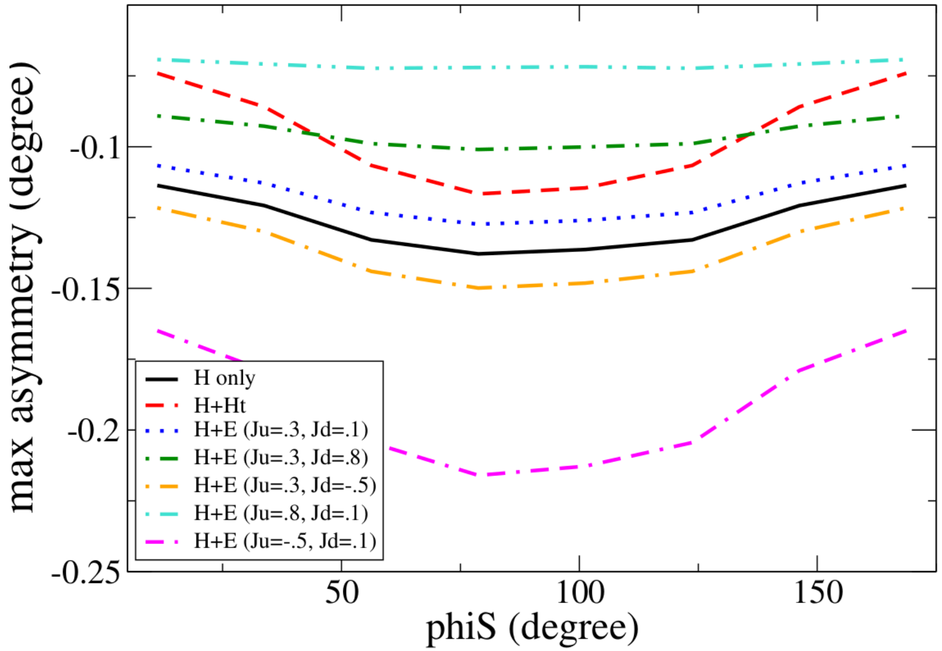
8 independent variables for each process: all unpolarized and polarized cross section differences
-t=.2 GeV², ξ=.15, Q²=2 GeV² or Q'²=4.5 GeV², E=11 GeV for DVCS, θ=90° for TCS
at asymptotic limit

This figure: assumes Hall A + Hall C + complementary measurements.
SoLID only: universality studies for GPD H, with Hall C: GPD E

TCS from 11 to 22 GeV at JLab

Enhanced sensitivity to quark angular momenta with some TCS observables

With transverse target spin asymmetries,
Max asym projection with various Ju Jd scenarii



Neutron TCS beam spin asymmetry
Change of sign (small A for DVCS & TCS)

Main goals (multi-observables approach)

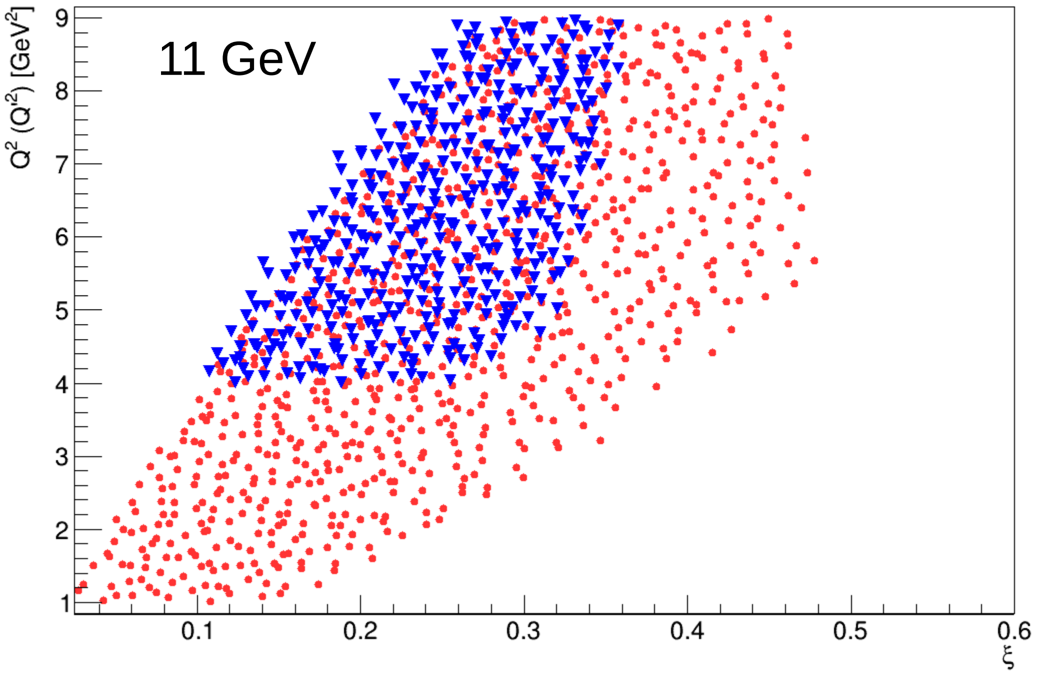
- independent data set with TCS to access all CFFs, comparison with DVCS for universality
- complementary multi-observable fits
- understanding of higher twists and NLO effects; need 2 reactions
- depending on technical difficulties to access certain observables with DVCS or TCS, some physics aspects can be enhanced with easier to access observables in one of the reaction (here displayed Ju and Jd, and GPD E)

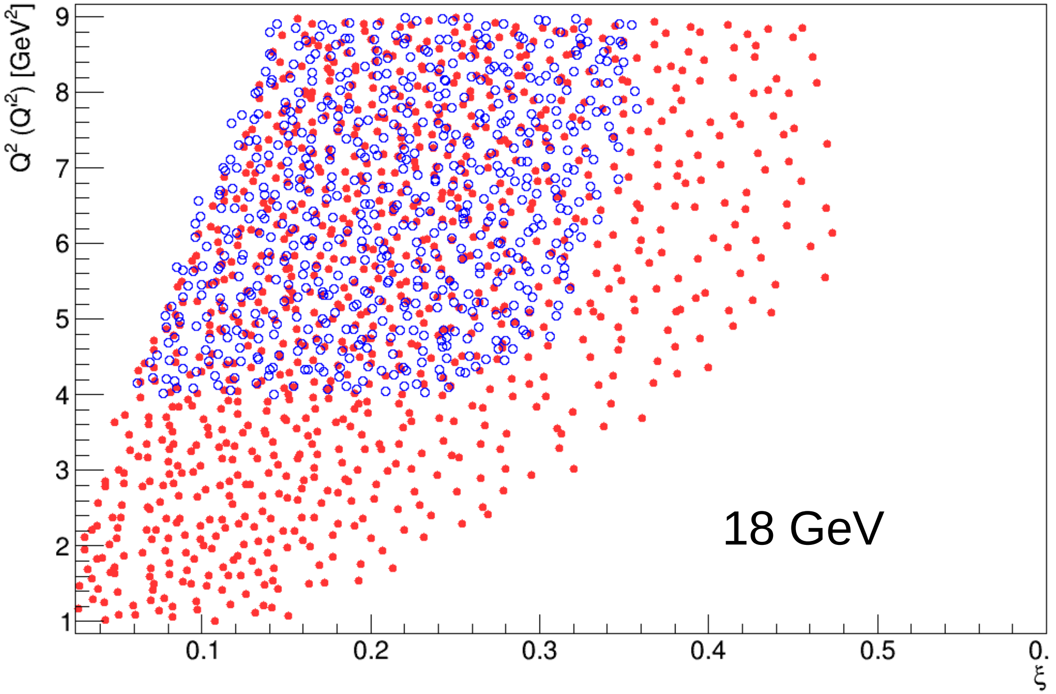
TCS from 11 to 22 GeV at JLab

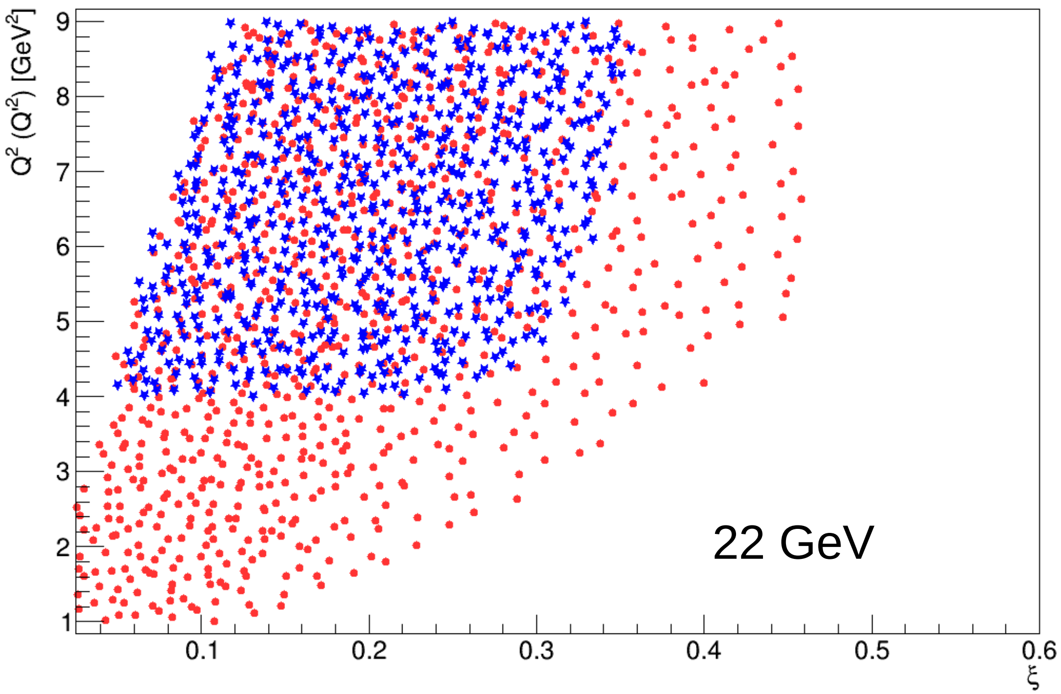
Blue = TCS
Red = DVCS
Matching region for universality studies
Bins in t & xi: large coverage

Cuts: beam energy (real photon from 5 to Emax)
W^2=2 GeV (DVCS)
-t from 0 to 1 (t-channel region)

Phase space theoretically accessible at JLab

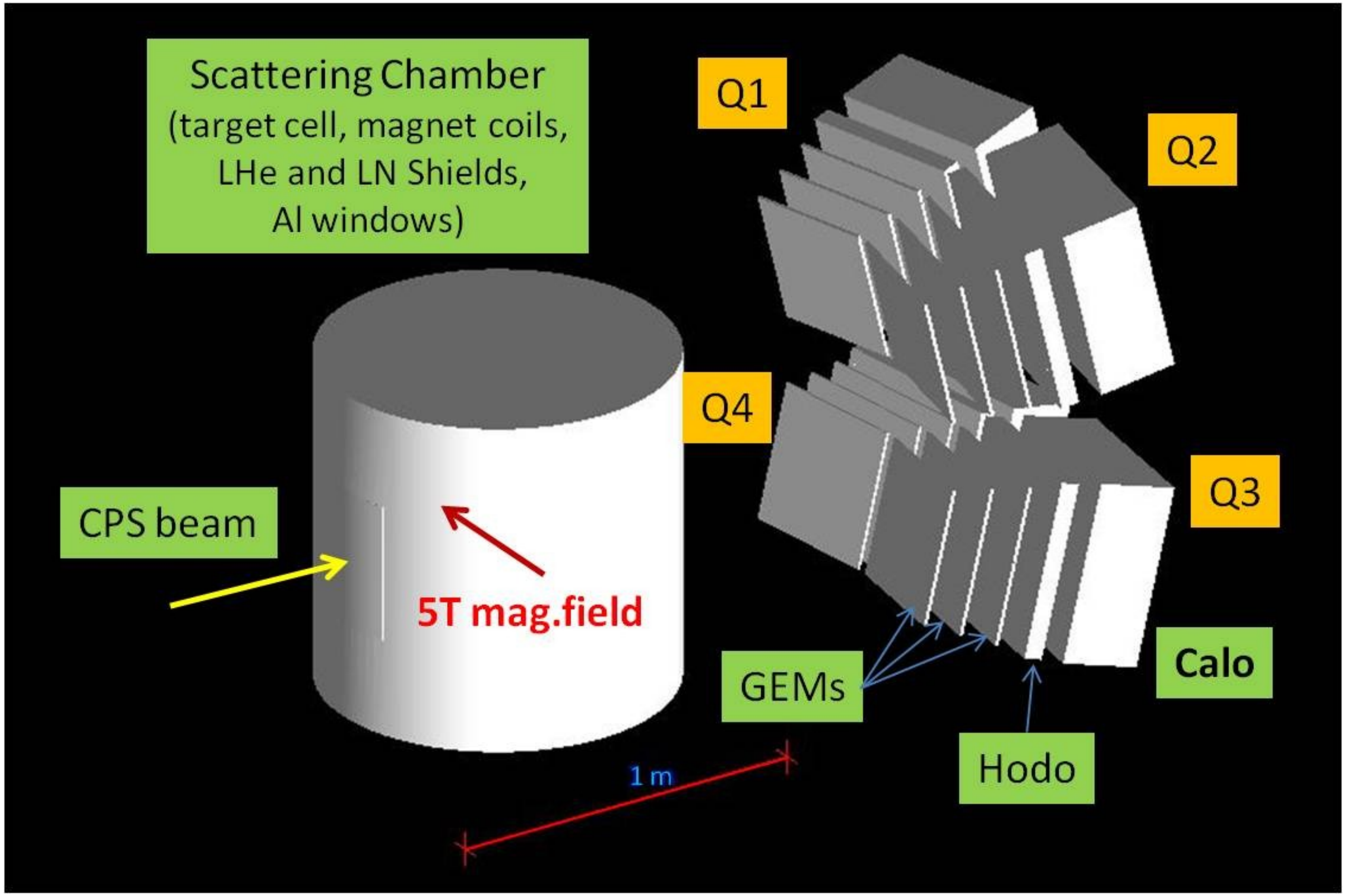






Measuring TCS and beyond at JLab, Hall A & C

Hall C proposed experiment for TCS transverse target asymmetries



CPS: Compact Photon Source
High intensity untagged photon
50-85% polarized, 10^{12} g/sec

NH3 target (DNP)

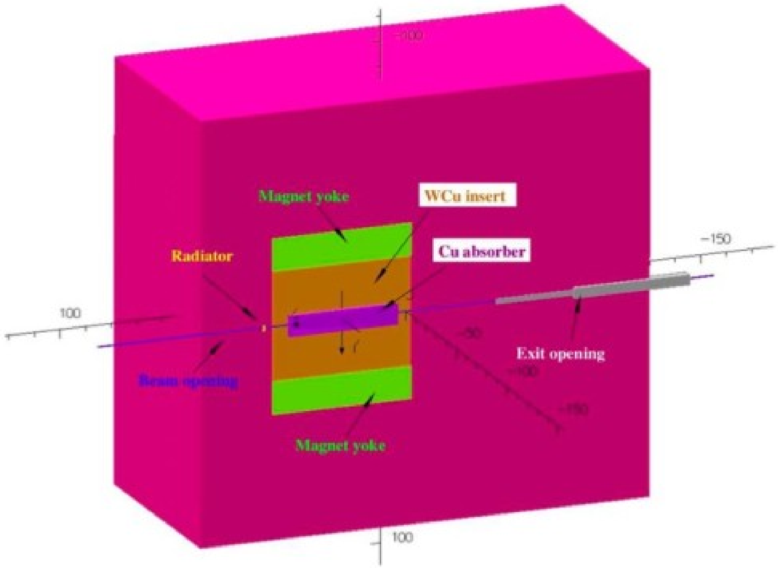
4 quadrants
GEM+hodoscopes+PbW04 calo
(2xNPS)

- Deferred in 2022: PAC50 asked for collaborators to achieve all the technical developments (background, PID...), Very positive on the physics. Discussions at JLab about other things that can be done with this setup using the same or additional beam time (other polarizations, other channels).

- Proponents also studied unpolarized TCS off P & N with similar setup,
// polarized off ND3 (neutron CFF Im(E)) === not proposed yet, focusing on priority measurement first.

Measuring TCS and beyond at JLab, Hall A & C

Additional measurements recently enabled thanks to new technical developments

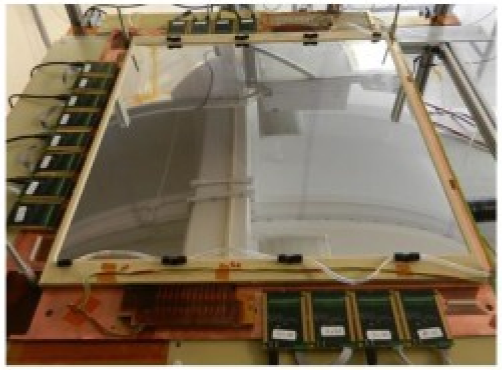


Compact photon Source

Will be used in Hall C (WACS, *TCS…)
Can be used in Hall A, together with SBS or SoLID
(no proposed experiments yet, but some ideas)

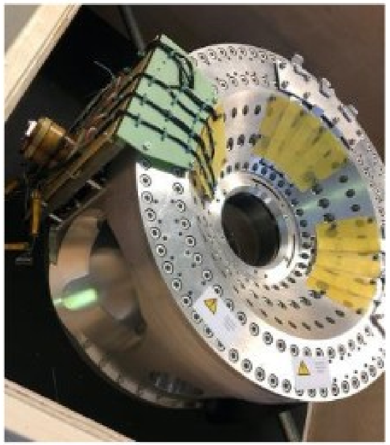
NPS calorimeter: will be first used for DVCS (see Carlos' talk), almost operational. Assembled this summer by Orsay, ASNL & al teams

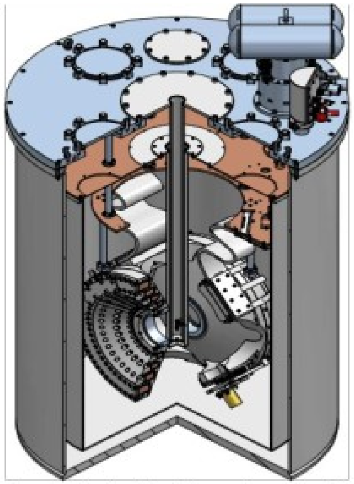
SBS GEM
Used in experiments now, we will learn from Hall A about high rate Tolerance (main concern for Hall C TCS)



SBS BT GEM prototype
(*K.Gnanvo et al., NIMA 782 (2015) 77-86*)

From TCS to transversely polarized J/psi in Hall C





Horizontal field orientation

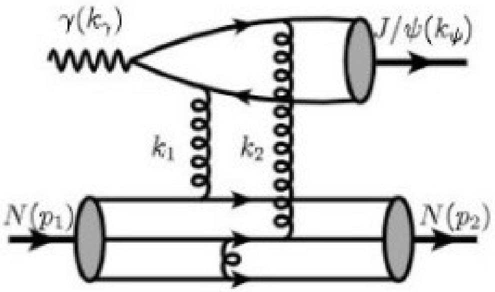
Polarized NH3 target and new polarizing magnet
Arrived at JLab in 2021

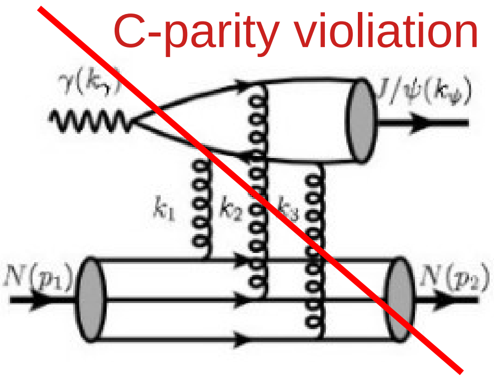
5T
Increase acceptance from 18° to 25°

=== access more channels at large angle!

Transverse polarized J/psi: learning about structure and mechanisms
=== approach: extrapolation of high energy measurements (PHENIX, COMPASS) to “near threshold”
- is this approach valid? 3 gluon mechanism is prohibited: are we getting large asymmetries?
- can we have a GPD interpretation near threshold?

- New magnet allow extension to parallel measurements of J/psi near threshold transverse target (never proposed, MC studies done – our setup can do it at larger angles)





Left-right asymmetries:
Diluted, or large?
Depends on production mechanism

GPD interpretation near threshold?
How to parametrize N structure?

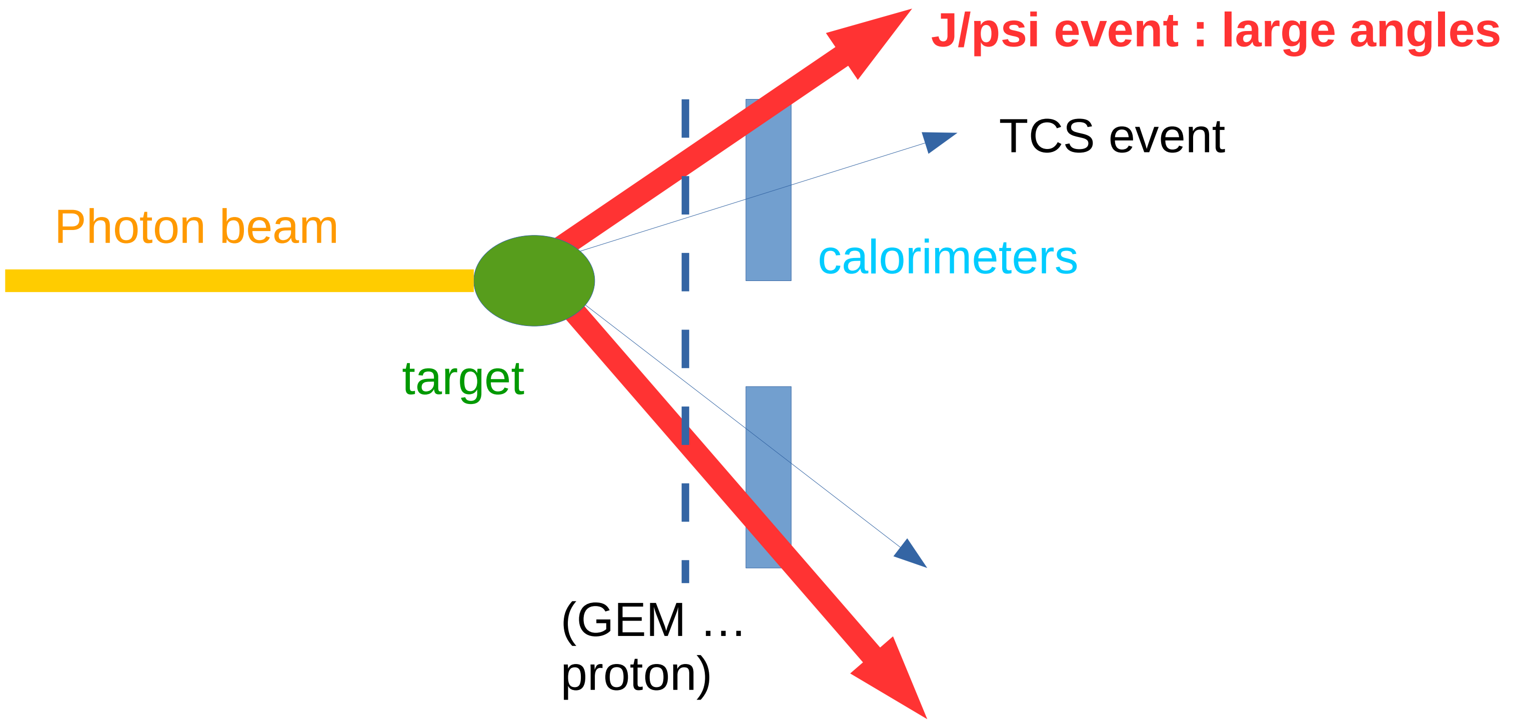
Looking for theoretical input and collaborators!

From TCS to transversely polarized J/psi in Hall C

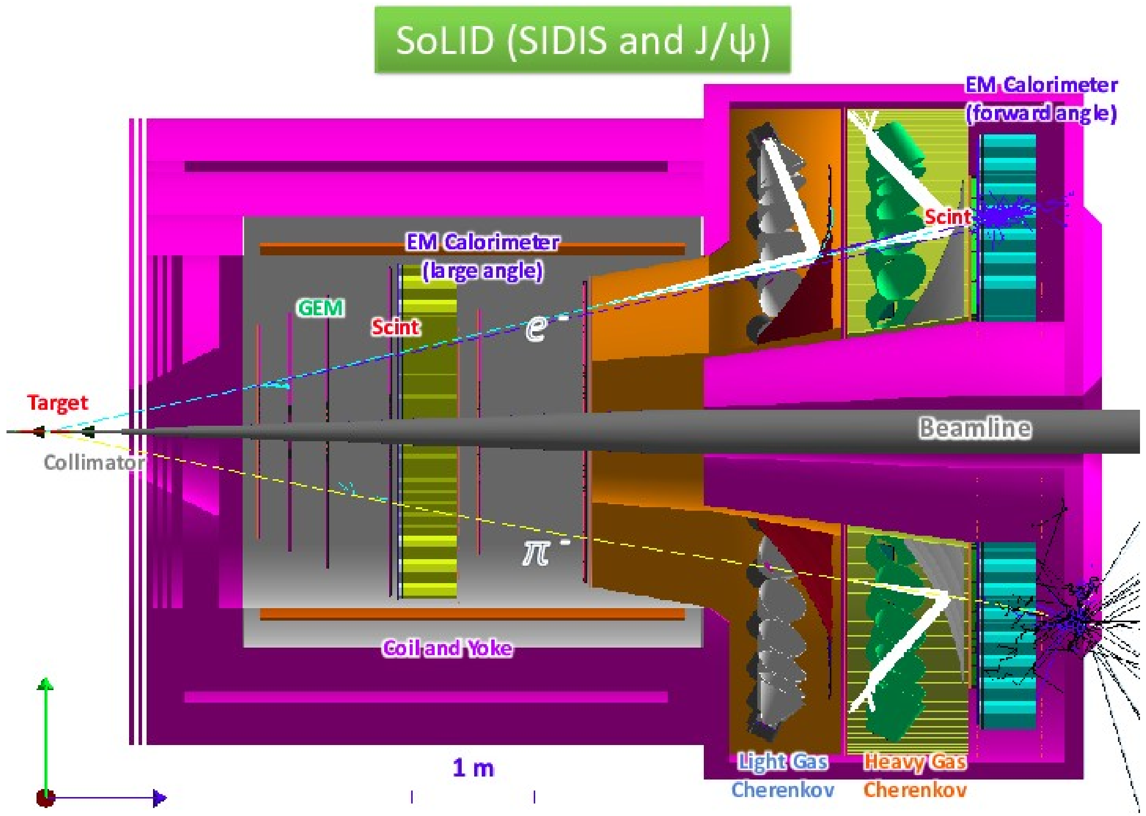
- Should be feasible, here energy dependence will be critical (11 GeV to 22 GeV)
3 gluon vanishing can be tested with polarized target, exclusive or semi-inclusive with E dependence

NEED INPUT

HIGHER ENERGY AND INTENSITY WILL BE CRITICAL FOR SUCH A MEASUREMENT



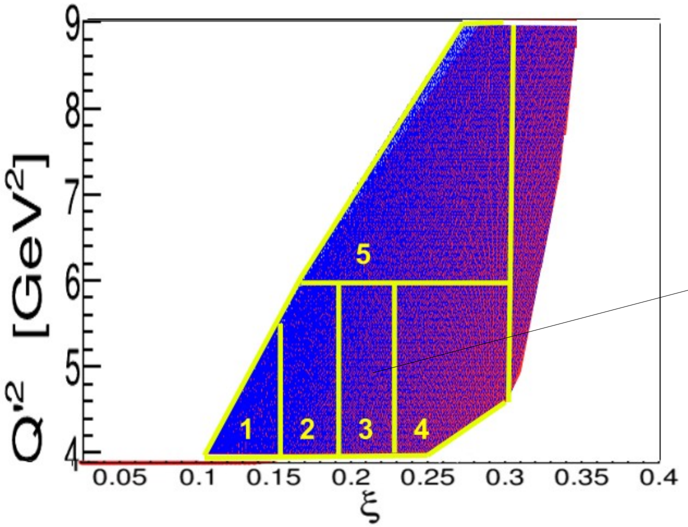
Measuring TCS and beyond at JLab, Hall A & C



SoLID setup for J/ψ approved exp.
50 days at flux 10^37 $cm^{-2}s^{-1}$
LH2 unpolarized target

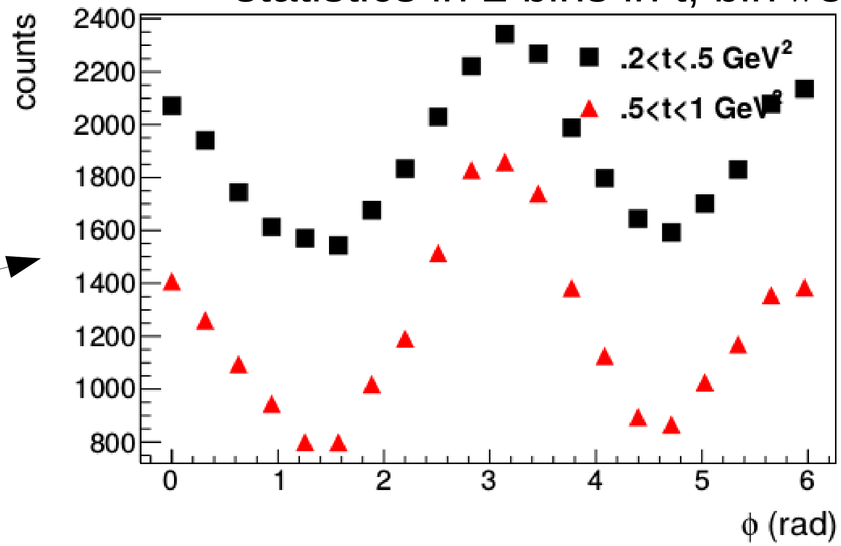
x-sec and BSA with high statistic
→ binning in Q'²: evolution...
→ studies of GPD universality by comparing H extracted from TCS and DVCS

- from electron beam



bin 3

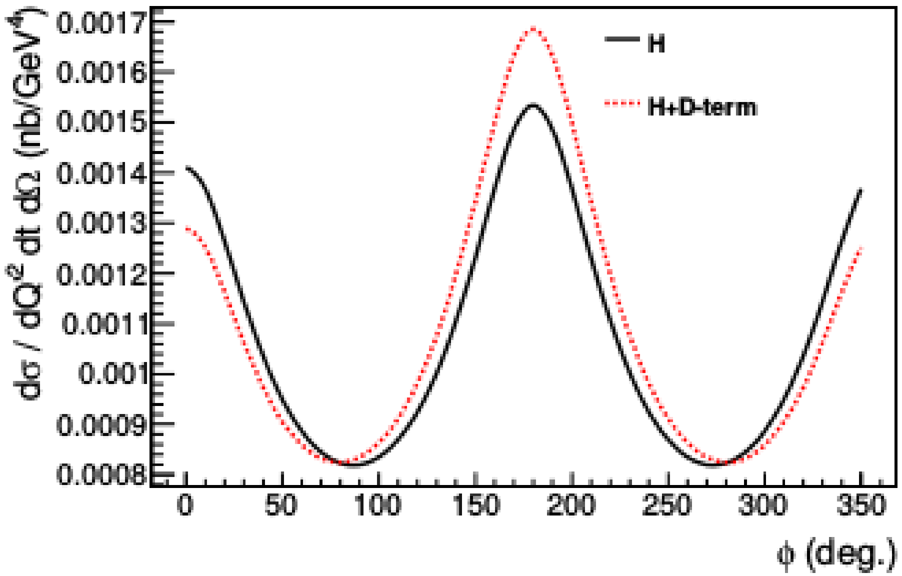
statistics in 2 bins in t, bin #3 (Q'², ξ)



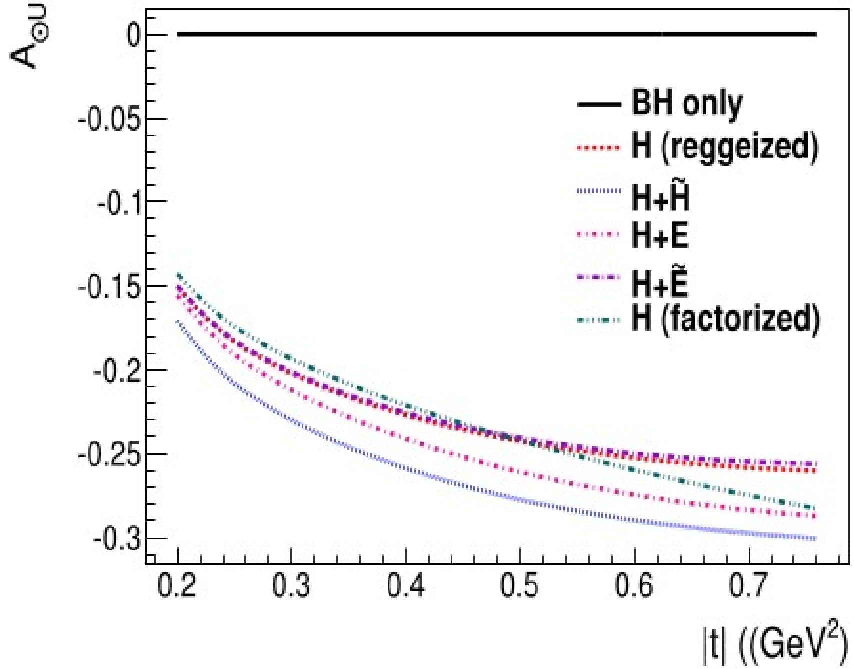
* see Sylvester talk for J/psi and SoLID setup

TCS with SoLID high precision measurement for GPDs universality

unpolarized x-sec vs φ, sensitivity to D-term (GPD H = VGG)



parametrization and t- dependence of beam spin asymmetry



- Unpolarized cross section
- Beam polarized cross section differences

Large acceptance and high intensity measurement will enable access to cross sections

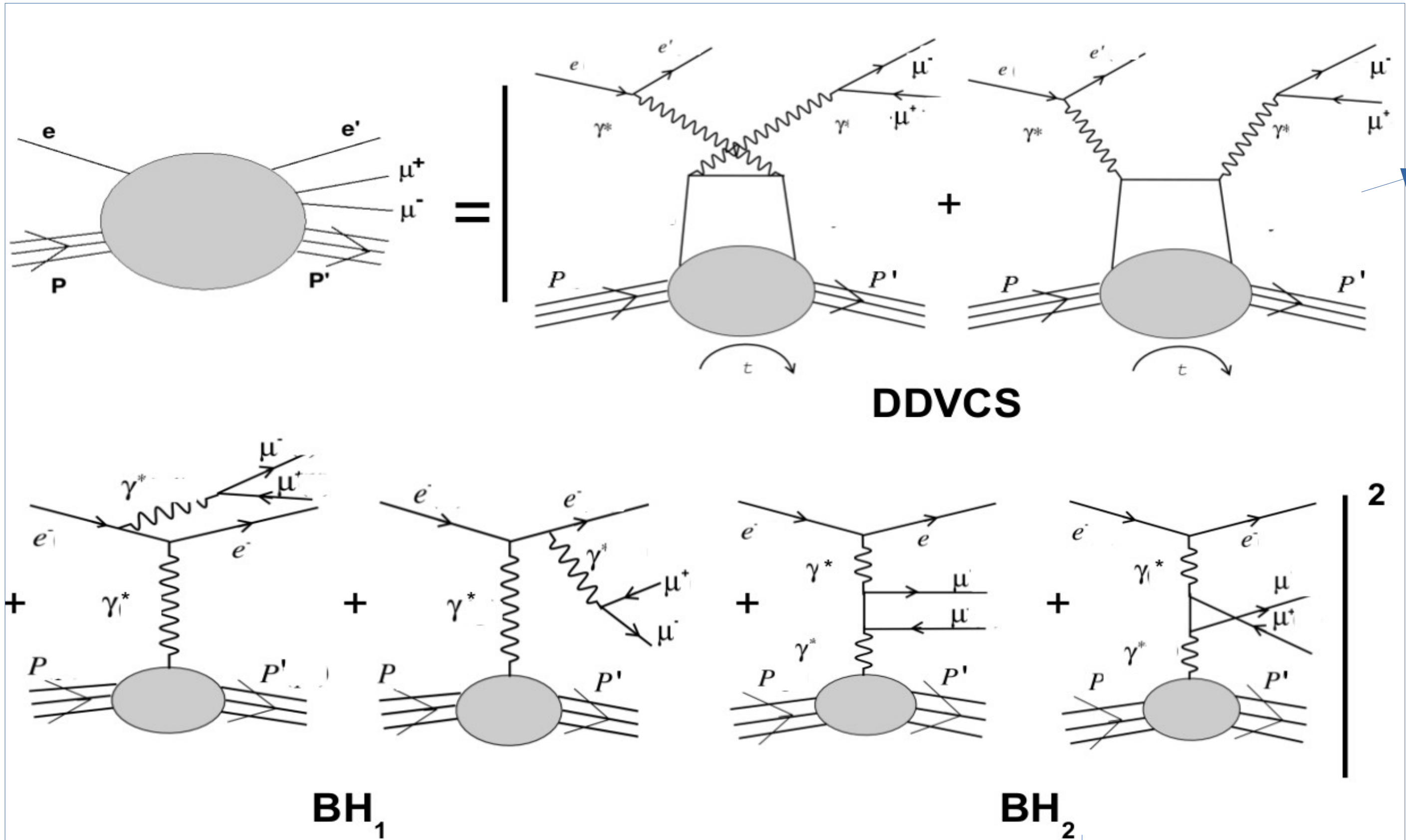
- extracting GPD H with enough precision level for GPD universality studies
- complement other TCS programs (need unpolarized cross section as “basis”)
- complement DVCS measurement in multi-channel fit approach

Measuring DDVCS at JLab, Hall A & C

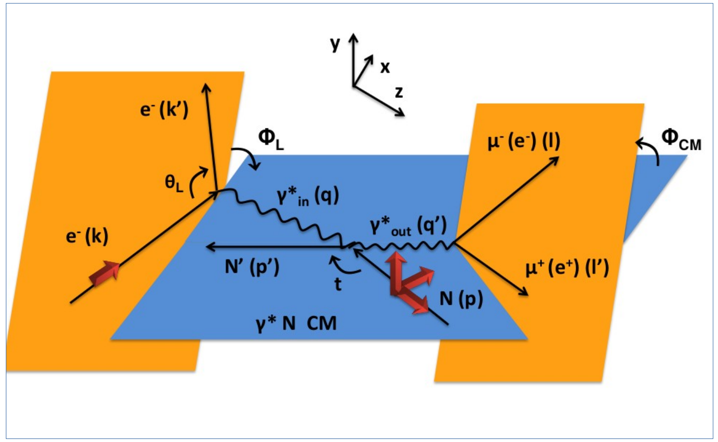
* DDVCS with SoLID: see Alexandre's talk (efforts in Hall B, not in this talk)

Motivations: extrapolation to zero skewness, access to ERBL region of GPDs

- understanding of DDVCS+BH angular behavior is critical (as for TCS)
- technically difficult: **muon detector** for low energy, statistics



no favored direction for γ* emission or decay leptons



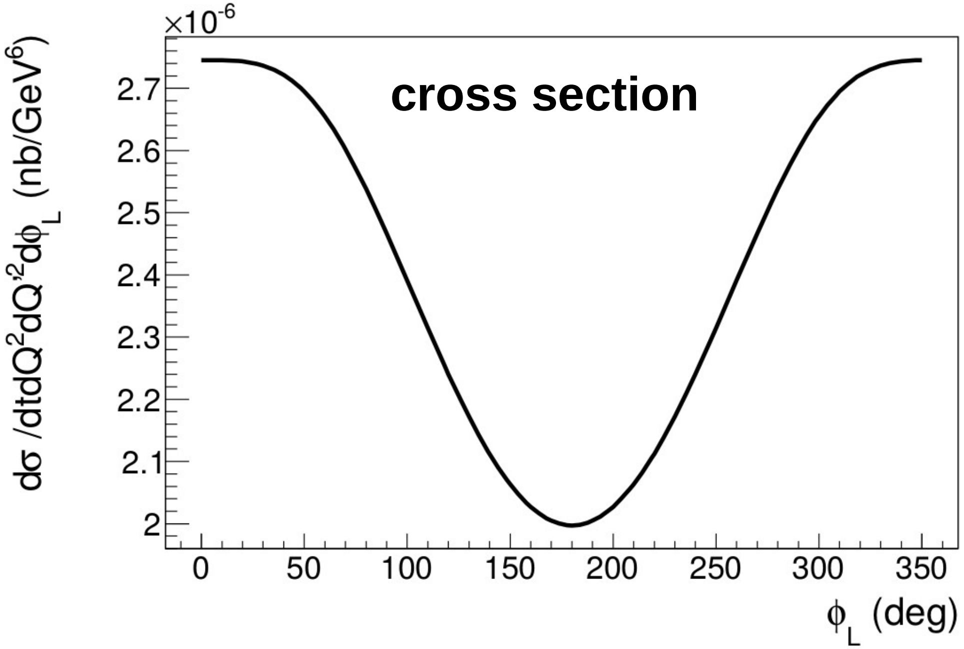
peak when γ' becomes collinear to e related to φ_{LH}=0, and depends $\cos\theta_{\gamma\gamma}$ (kinematics) and "γ"→e' angle

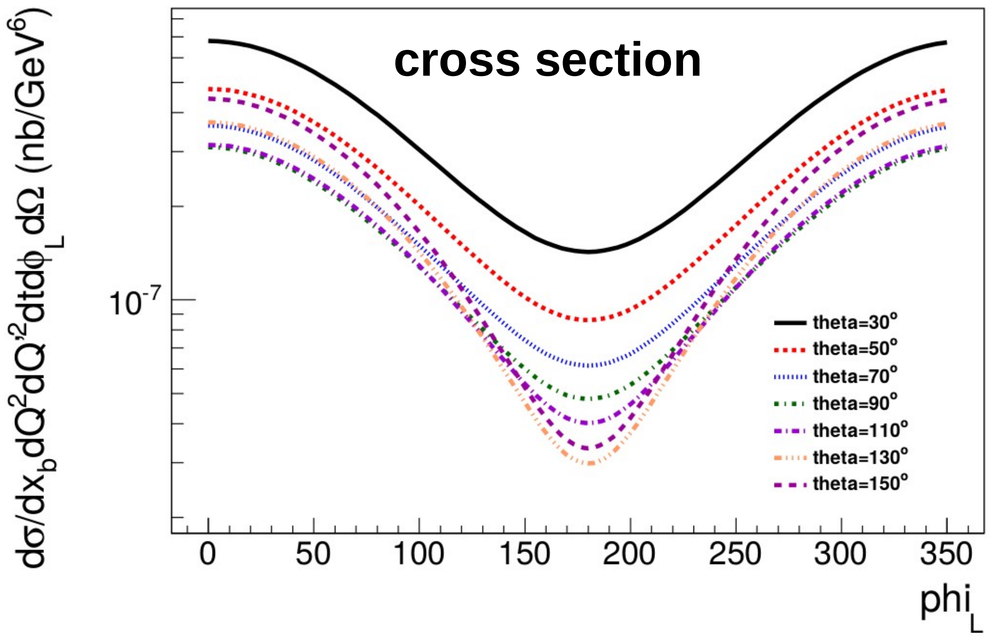
2 peaks when μ+ or μ- become collinear to γ related to φ_{LH}=0 and 180°, and depends $\cos\theta_{\gamma\gamma}$ (kinematics) which position the value of θ_{CM} for the peaks

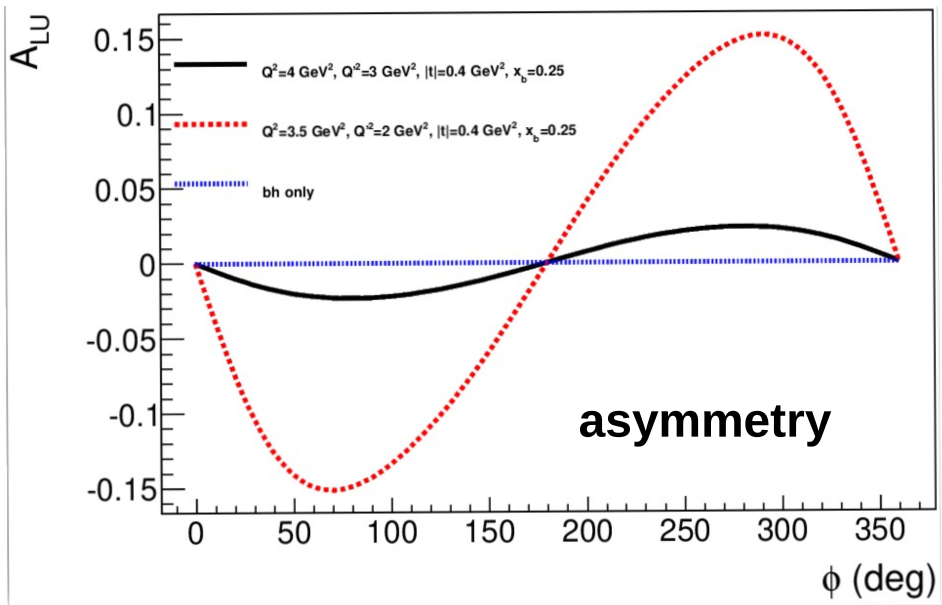
DDVCS angular behavior and observables

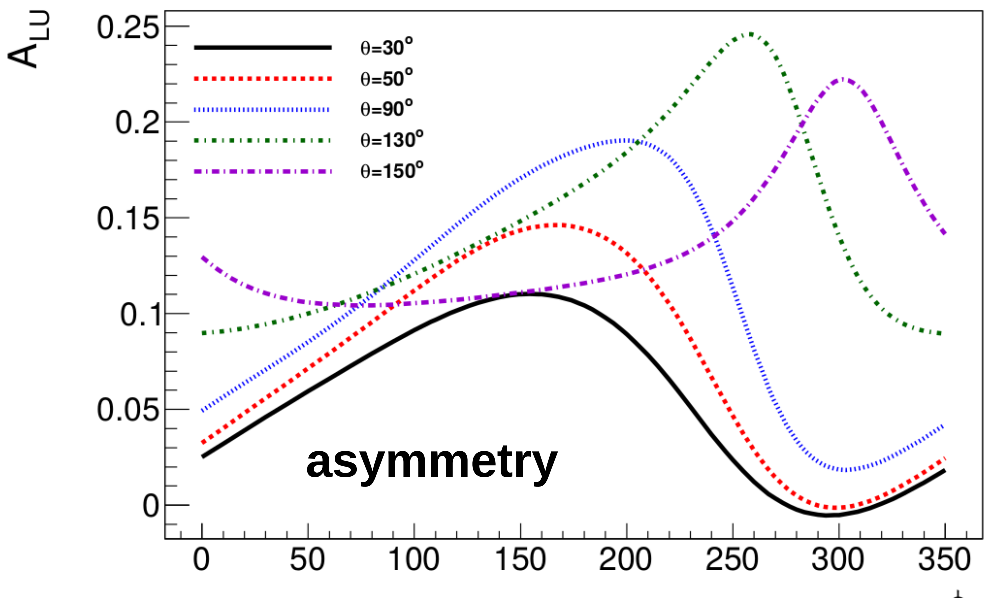
φ_L behavior. similar than DVCS; **but correlations with final angles and "BH2"**

Φ_{CM}, θ_{CM}: !!! difficult need good interpretation, redefinition of observables...







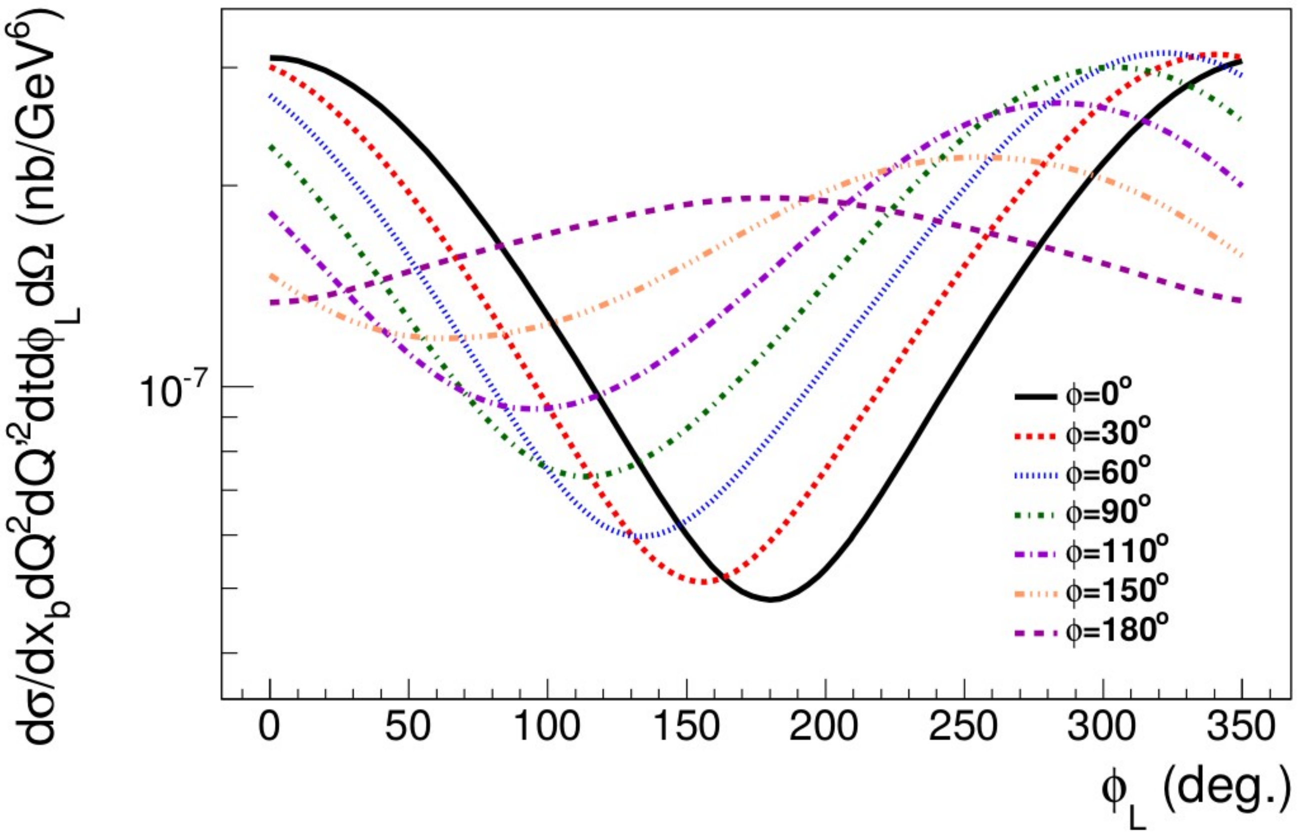


left= integrated over θ, right=not integrated

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

DDVCS angular behavior and observables

correlation between the azimuthal angles in DDVCS



- To extract CFFs: 2D fits in φ_{CM}, φ_{LH}, as a function of ξ, ξ', t or ξ' replaced by <Q^2/Q'^2> (bin)

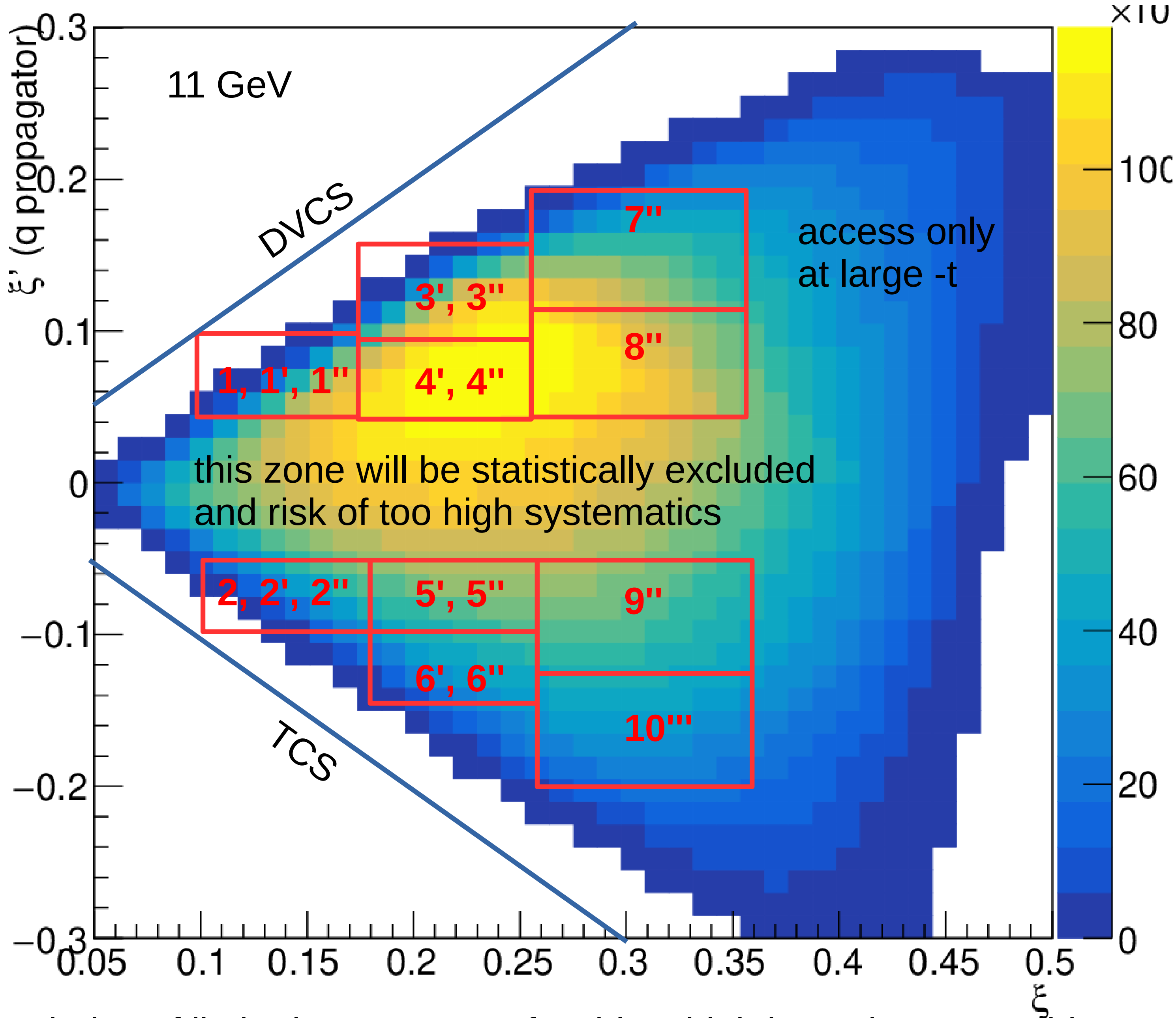
- extract Im($\mathcal{H}$) (ξ', ξ, t) with unpolarized cross section and beam asym. (to measure first)

GPDs from DDVCS can be extracted, but one need to
1) take angular correlation into account (similar than TCS)
2) 2 or 3D fits of angles

Phenomenology efforts needed

+ Muon detector, high intensity, detectors able to handle high rates and background

Measuring DDVCS at JLab, Hall A & C



Bin in ξ — code # large/low t

A) .1 < ξ < .18
(all t bins)
1) .05 < ξ' < .1 — 1, 7, 17
2) -.05 > ξ' >-.1 — 2, 8, 18

B) .18 < ξ < .26
(t bins 2 and 3)
3) .1 < ξ' < .15 — 3, 9
4) .05 < ξ' < .1 — 4, 10
5) -.05 > ξ' > -.1 — 5, 11
6) -.1 > ξ' > -.15 — 6, 12

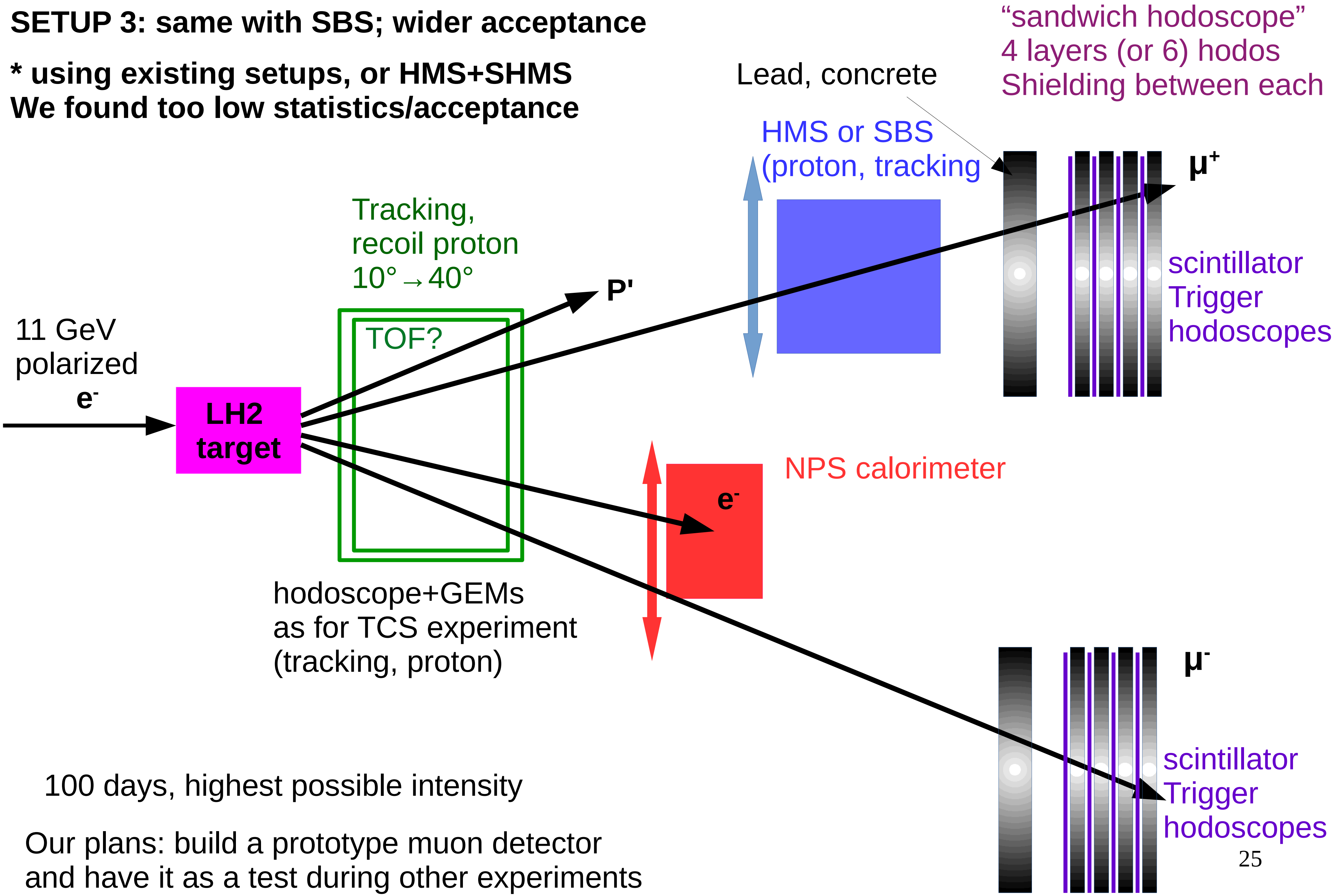
C) .26 < ξ < .36
(t bin 3)
7) .12 < ξ < .2 — 13
8) .05 < ξ < .12 — 14
9) -.05 > ξ > -.12 — 15
10) -.12 > ξ > -.2 — 16

- choice of limited acceptance: few bins, high intensity → some bins may be empty or limited statistic
- no binning in Q^2 and Q'^2: the above selections are cutting bands in the Q^2 vs Q'^2 distribution
- next 3 slides: same figure ξ' vs ξ, separated for the 3 bins in t

SETUP 1: starting from DVCS with NPS

SETUP 3: same with SBS; wider acceptance

*** using existing setups, or HMS+SHMS**
We found too low statistics/acceptance



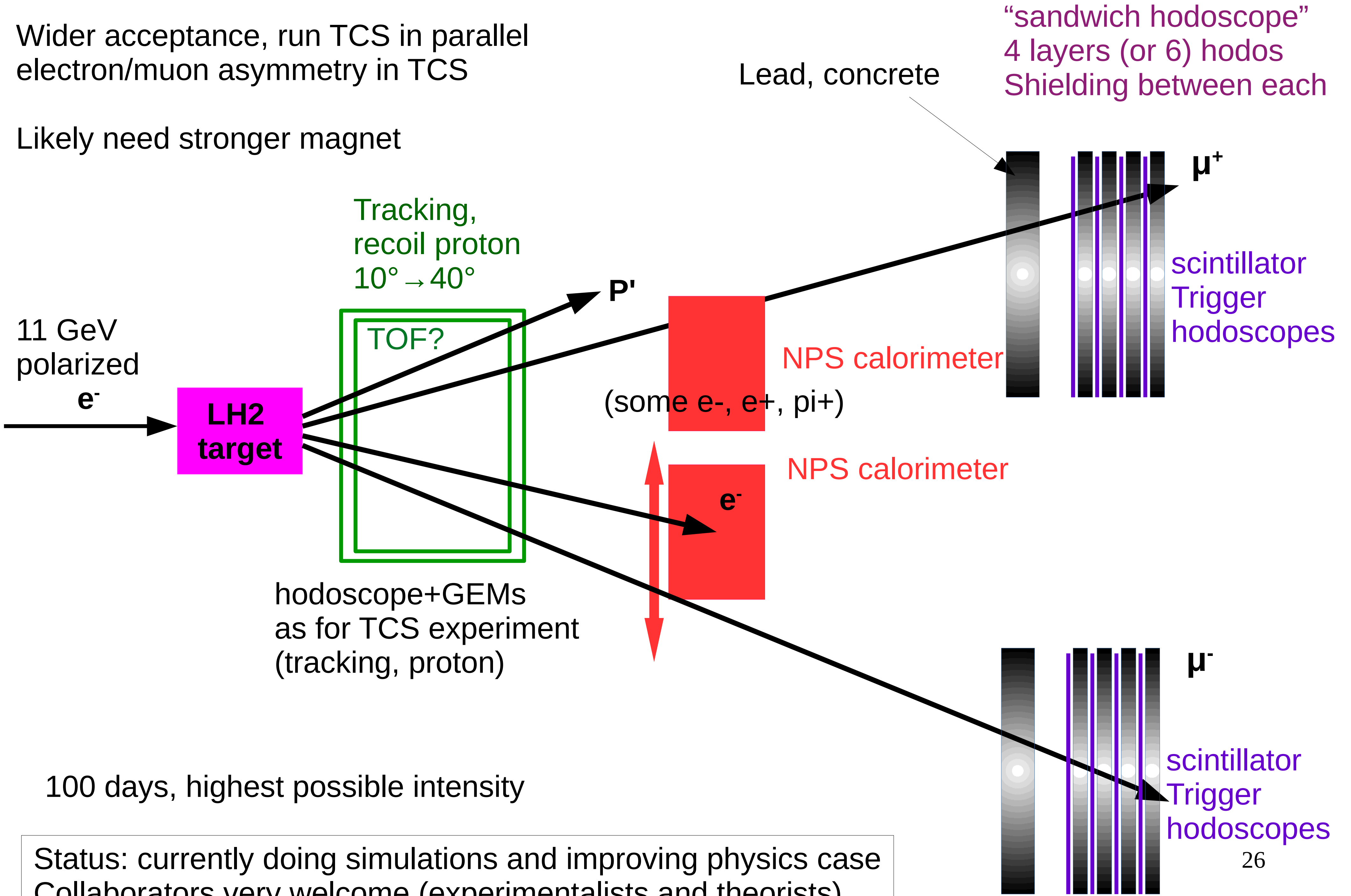
100 days, highest possible intensity

Our plans: build a prototype muon detector
and have it as a test during other experiments

SETUP 2: starting from TCS with NPS

Wider acceptance, run TCS in parallel
electron/muon asymmetry in TCS

Likely need stronger magnet



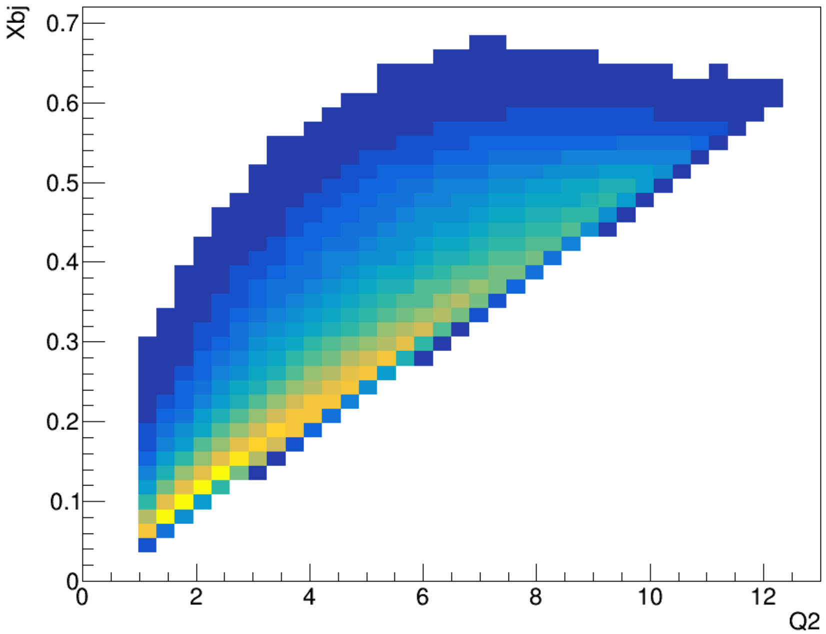
100 days, highest possible intensity

Status: currently doing simulations and improving physics case
Collaborators very welcome (experimentalists and theorists)

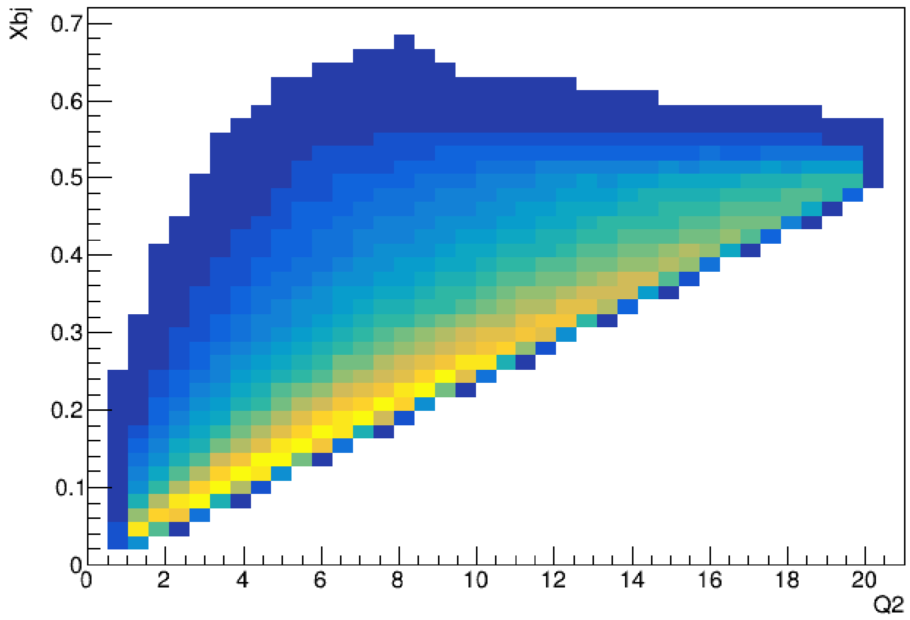
DDVCS accessible phase space from 11 to 22 GeV

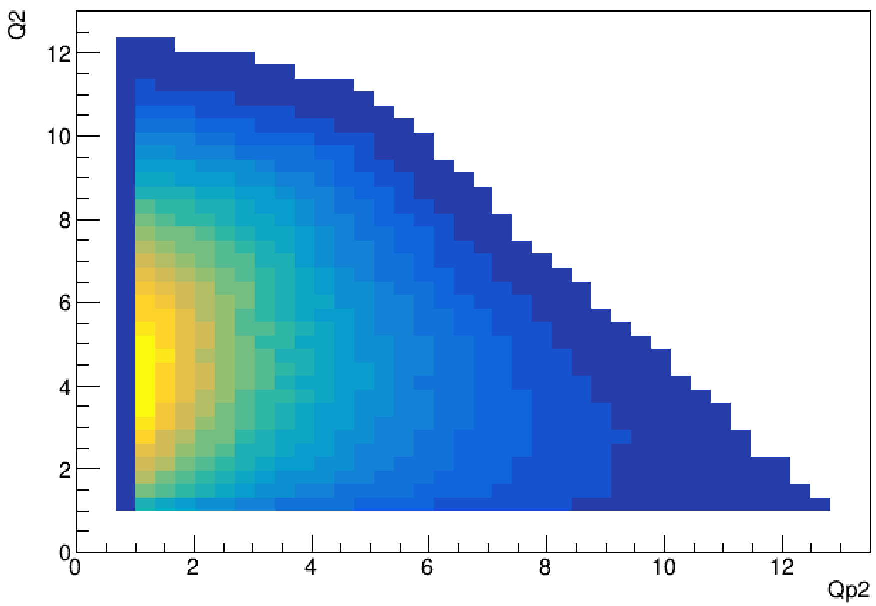
(no cuts)

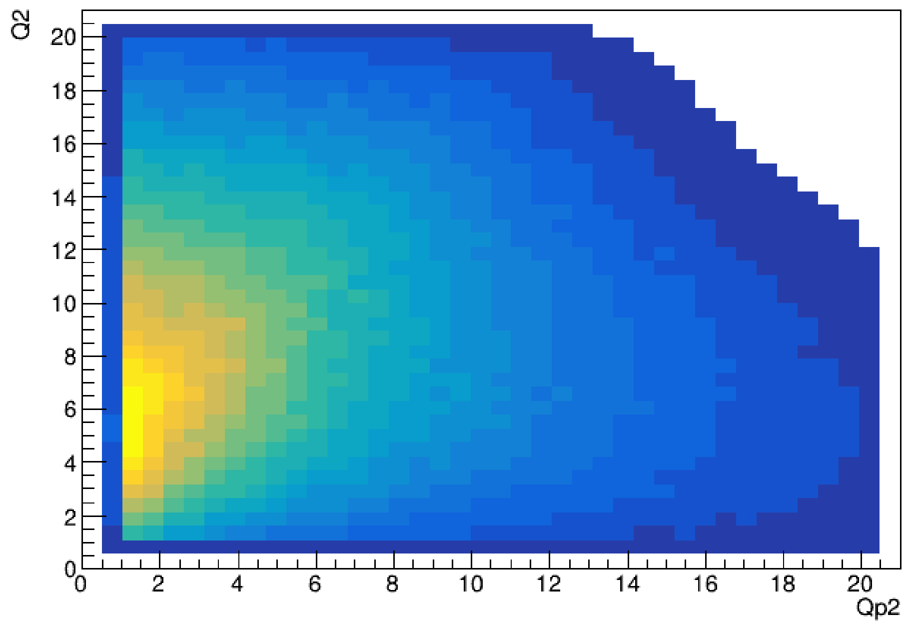
11 GeV



22 GeV







Main question: cross section drop, has to come with increased intensity

Going further with mesons

J/Psi

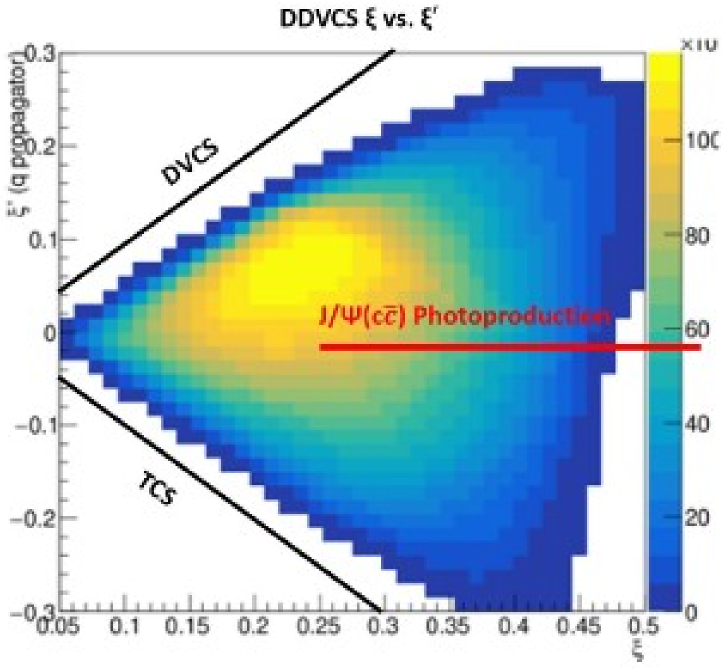


Figure: DDVCS ξ vs. ξ' with J/Ψ Photoproduction, DVCS, and TCS cartoon overlay shown.

Accessing off diagonal with VM?

(figure from E. Wrightson for J/psi Photoproduction)

Electroproduction: access in the timelike region

* NB; unclear since gluon loop

Light VM: not so much “off diagonal”, but still better than no point and can reach high statistics “mass dependence” approach

J/psi accessible phase space

J/Psi

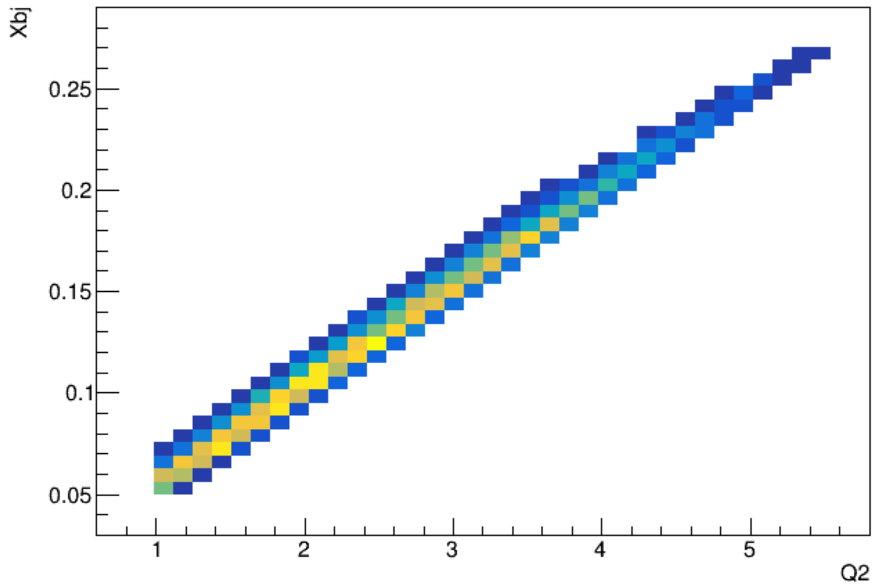
Mass range with 11 GeV: 1 to ~3.4 GeV
=> near threshold J/psi
=> unclear GPD interpretation
- good for studies of J/psi structure and production mechanisms

(assuming GPD interpretation, see Sylvester's talk for broader physics purposes)

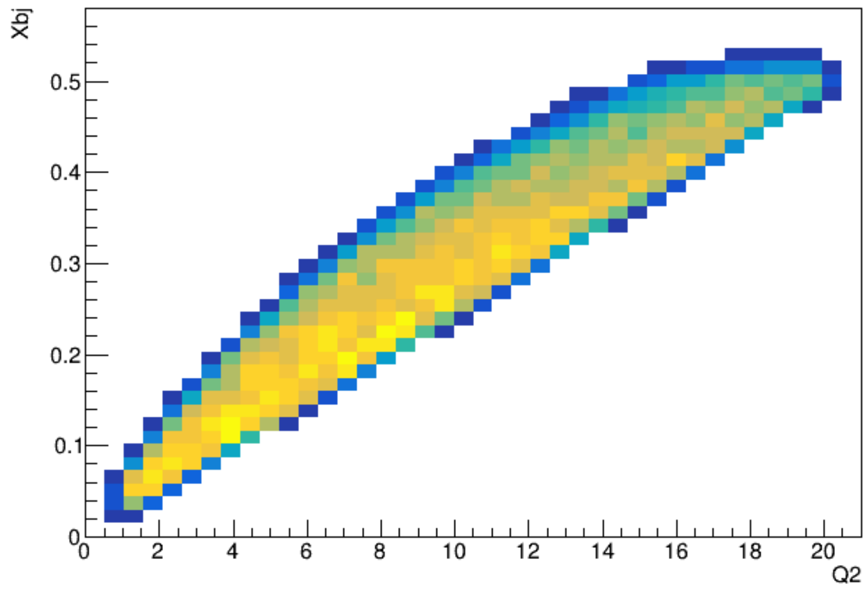
Mass range with 22 GeV: 1 to ~4.5 GeV
=> above threshold (provided luminosity)
=> can interpret into GPDs?
- need theoretical studies at high x (projections for high energy mostly / low x)
- should be feasible, worth to study

(no cuts)

11 GeV



22 GeV



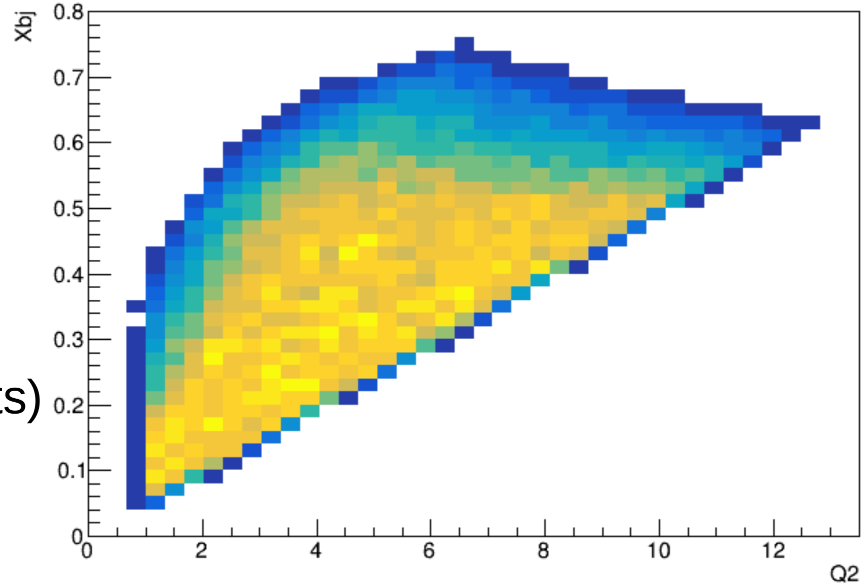
Going further with mesons

Other VM HEMP (Q^2>1 GeV^2)

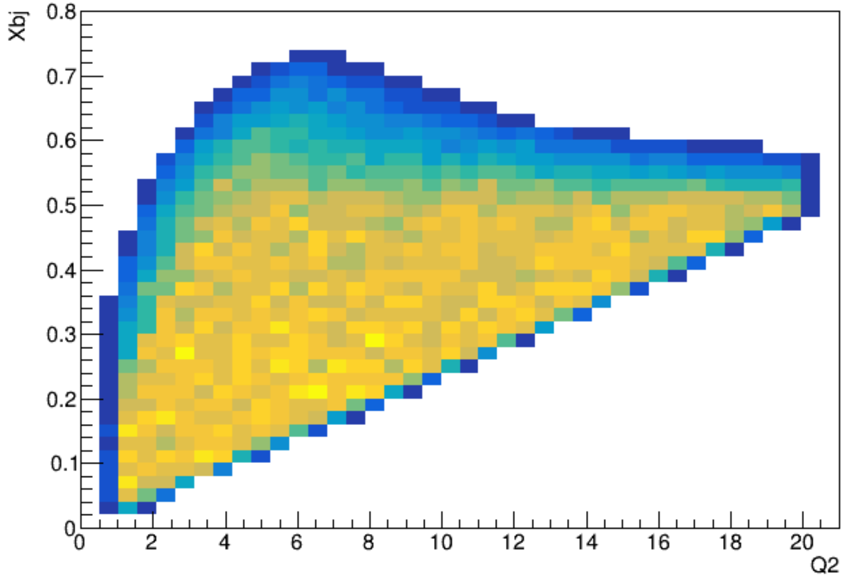
Rho meson

11 GeV

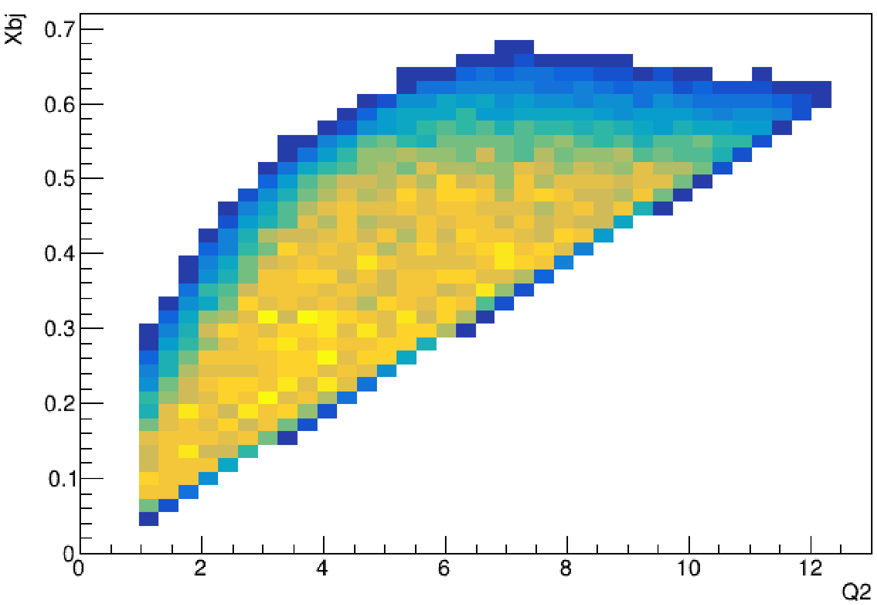
(no cuts)

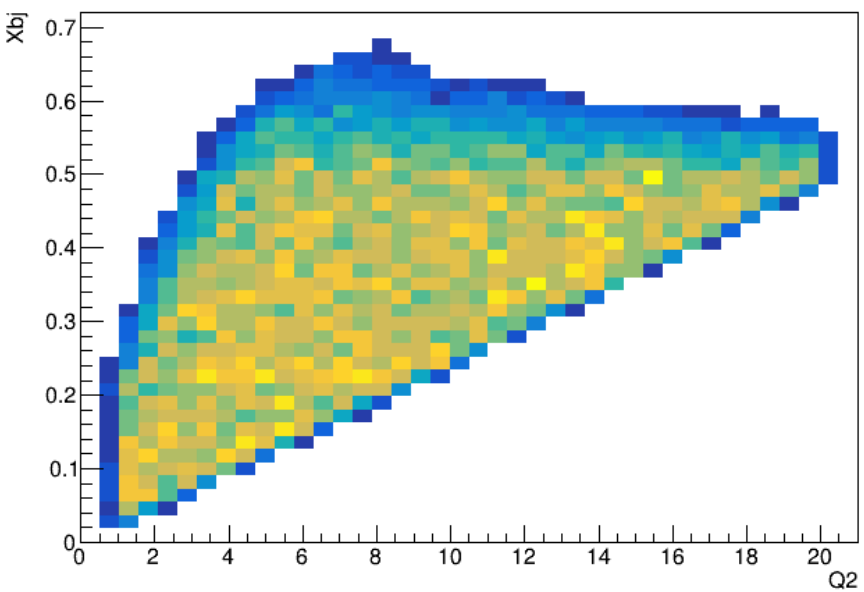


22 GeV



Phi meson





Going further with mesons

ρ, ω, φ…

- Large cross sections. Will increase with energy
  ^^ good point for an energy upgrade! Need to start building knowledge at 11 GeV.

- Measured in large acceptance experiments (JLab Hall B, can be done with SoLID, HERA, HERMES…)

- What about Hall A (SBS) and Hall C (HMS, SHMS, NPS..) high precision, low acceptance measurements?
(provocative question: do we need it? =decrease uncertainties to build a precision data set for CFF extraction) === see Marija's talk Friday for theoretical interpretation and fits

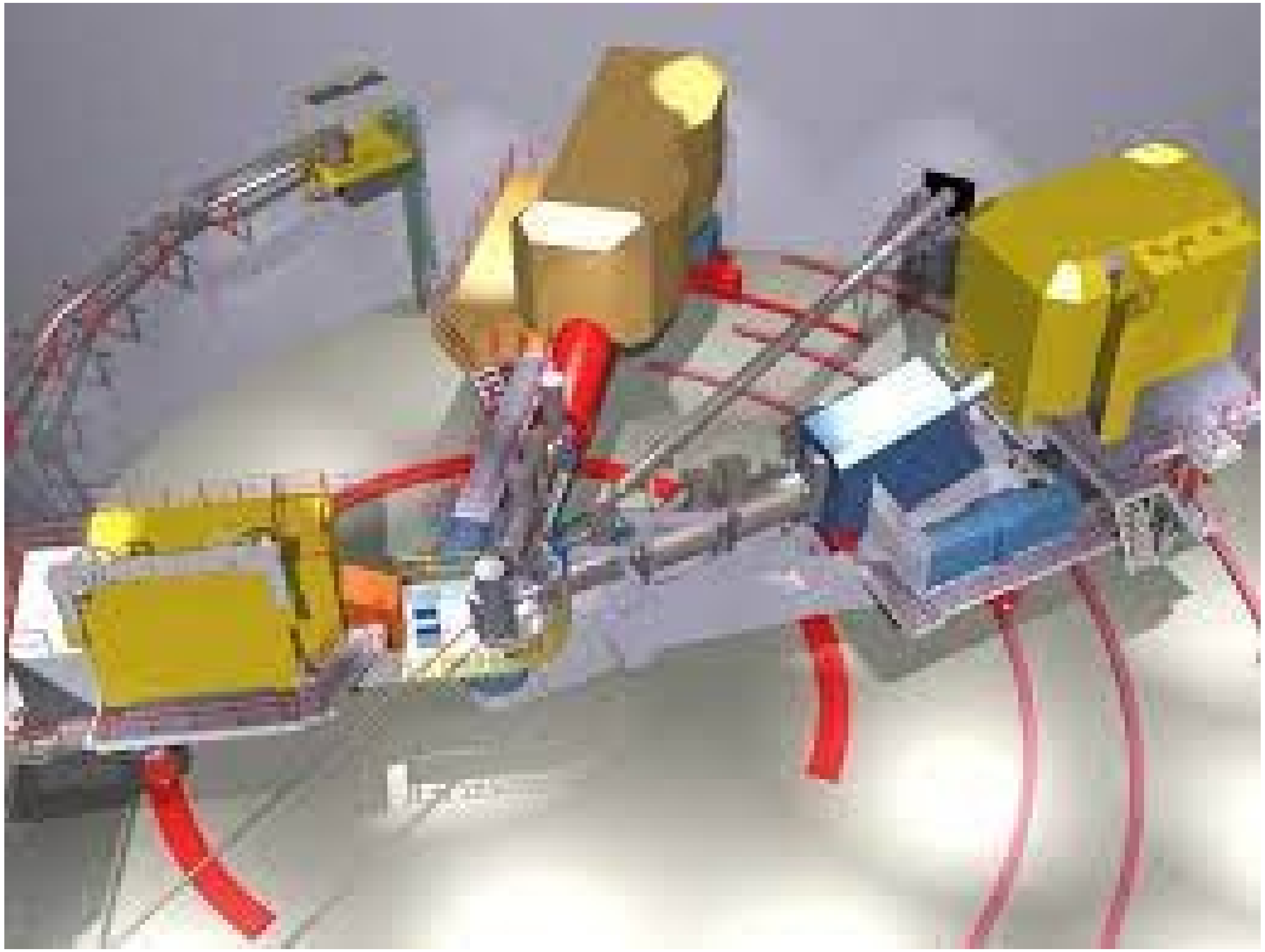
Can we develop precision measurements at JLab Hall C?
(advantages: high statistics, polarized target, possibility to have different detectors, dedicated measur...)
How polarized light VM measurements in Hall C can improve our knowledge of GPDs?

=== other motivations (complementary to Compton-like reactions
- flavor separation (u, d, s)
- enhancement of some CFFs due to parity
- can obtain a large statistic data set
- can do polarized measurements (SDME…)

Also improve background suppression in Compton-like channels

Going further with mesons

* currently exploring what can be done in Hall C and how, with minimal technical developments.
(plan to release studies by January and presentation by D. Biswas at DNP in October)



ρ, φ:
Minimal modifications, SHMS+HMS. Need cherenkov for PID

ω: added NPS

Without intensity and energy upgrade: polarized measurements, already learn a lot

With energy upgrade: ‘mass” and energy evolution for VM. Improve both GPD knowledge and meson wave-function parametrization, also critical for GPD interpretations

SUMMARY

- A lot of opportunities with last 11 GeV upgrade at JLab

- Physics program for GPDs can be improved a lot by developing studies of other reactions beyond DVCS, not only in “large acceptance” spectrometers, but also in “high precision” dedicated experiments in Hall A and C

- Intensity is critical for TCS and DDVCS. Energy upgrade will increase the phase space, but shouldn’t be at the cost of decreasing the statistics (has to be balanced with higher intensity)

- Energy upgrade can provide a lot of new data points to enable CFF extraction and extrapolation to zero skewness with new high precision VM measurements

- Polarized measurements, multi-reaction multi-observable approach will improve our knowledge of GPDs. The community will benefit a lot from building new programs and exploring new opportunities with reactions for which we lack of measurements

PARTONIC STRUCTURE OF THE HADRONS