Progress towards obtaining multidimensional maps of the nucleon inner constituents

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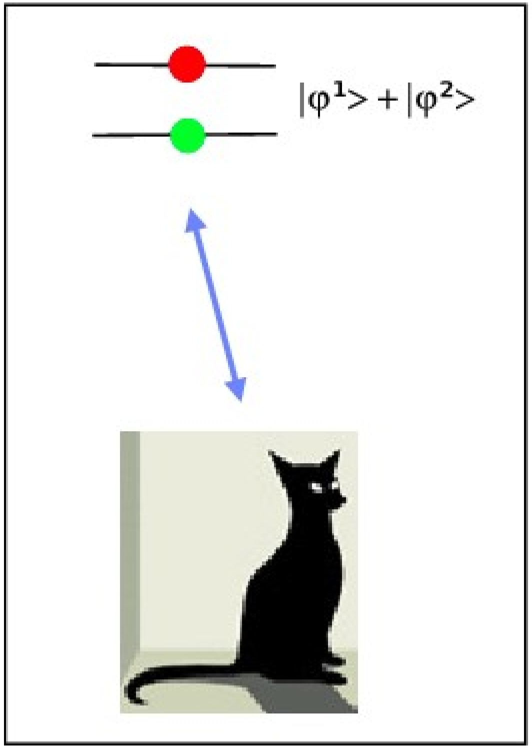
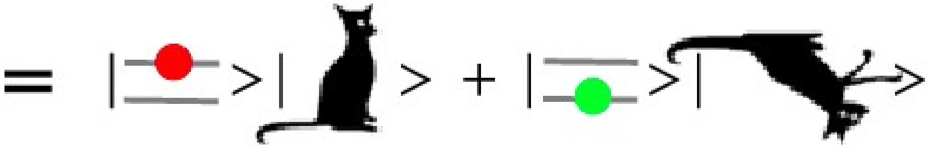
Where do we start?

One day, I asked Mr. S. “What is inside your box?”

Where do we start?

Well, he said something like that:





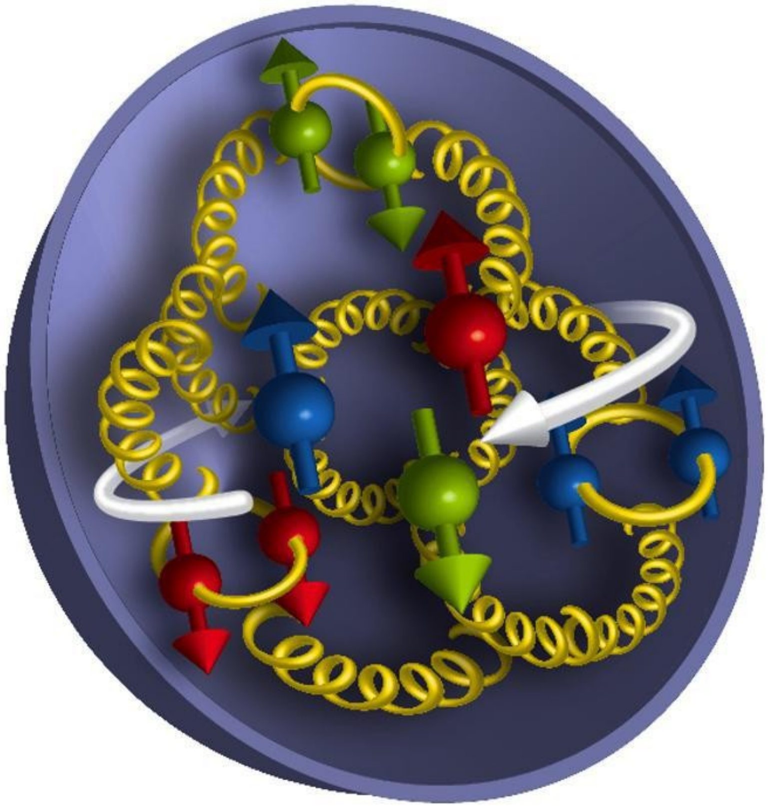
Where do we start?

Me: but inside the cat? And inside the inside of the inside of the…?

Well, someone asked the same question thousands years ago…

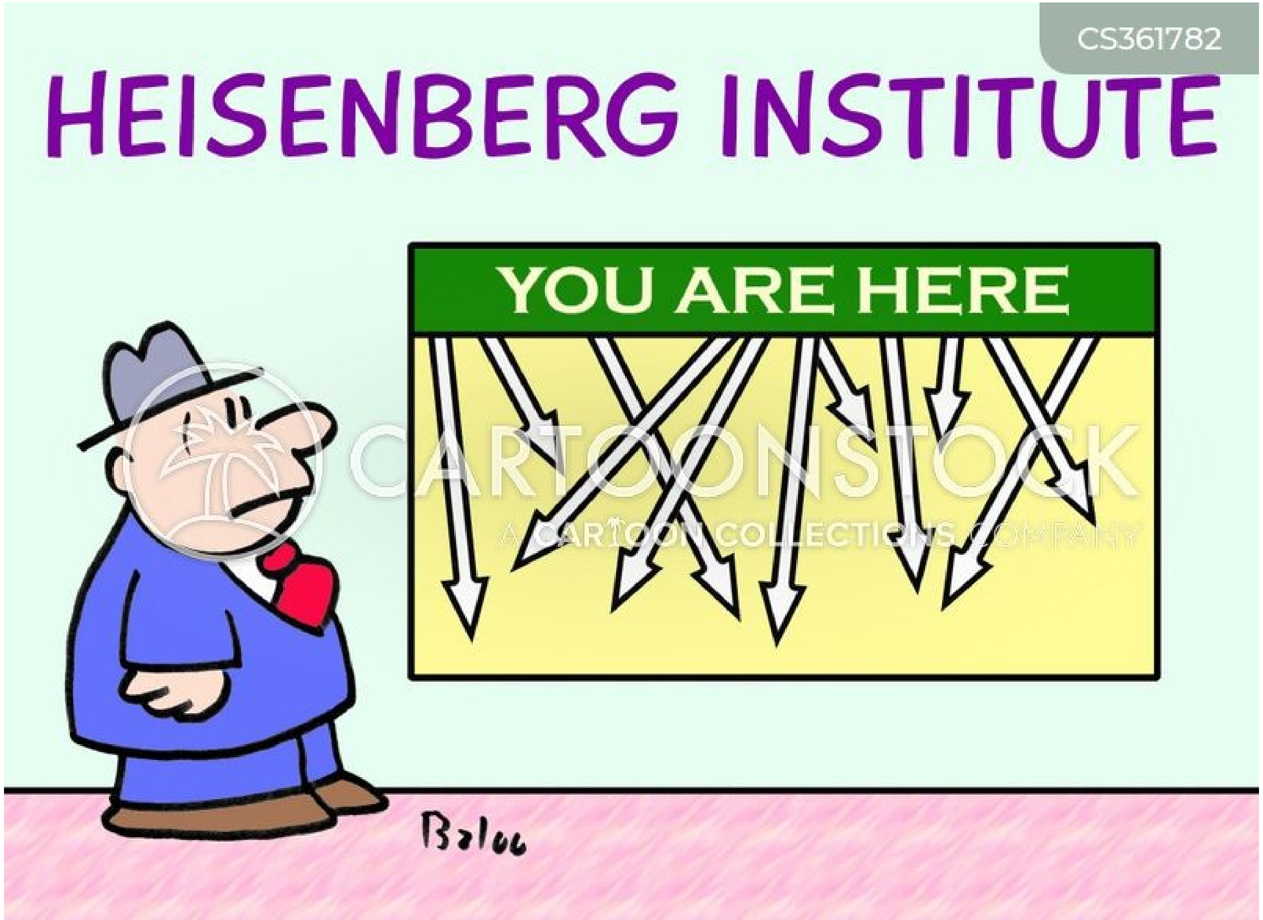
Me: but what is there inside atoms? And inside inside atoms?

What is inside nucleons?



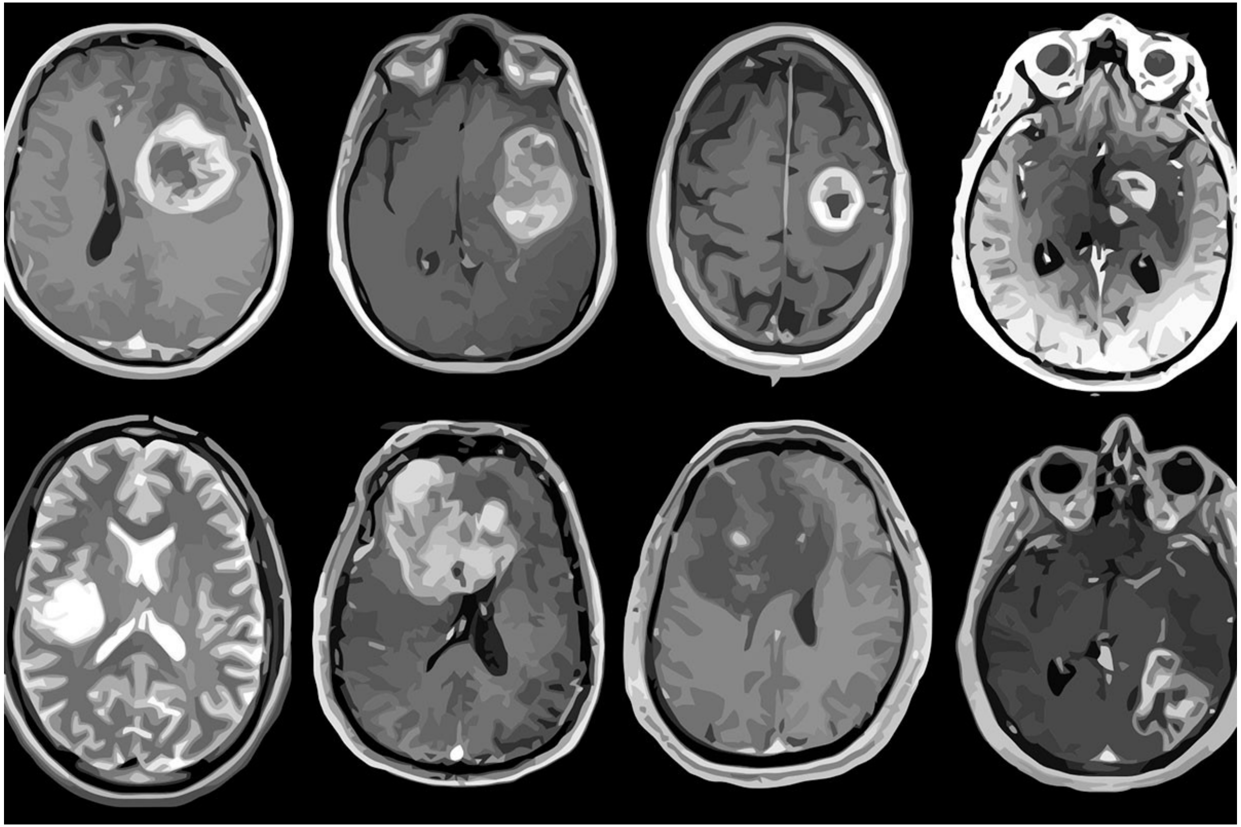
Quarks, antiquarks, gluons
Dynamic effects: spin, angular momentum correlation...

What we want to probe?



Ideally, position <u>and</u> momentum of the partons
with spin...

Nucleon Tomography

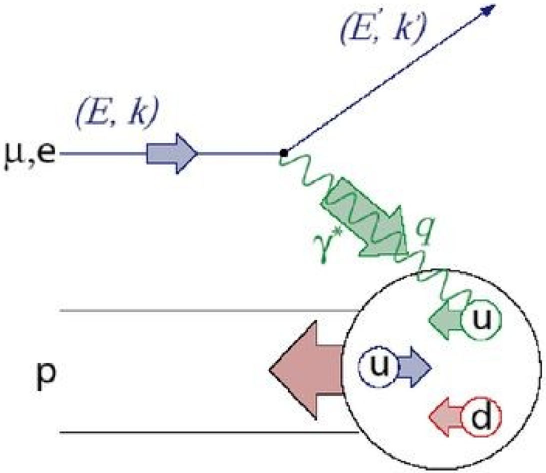


Multidimensional imaging, not like “classical 3D” pictures

quarks = bones, antiquarks = vessels, muscles = gluons…

We can obtain such image!

"1D": longitudinal momentum in Deep Inelastic Scattering



$$Q^2 = -(k-k')^2 \overset{lab}{=} 4EE'\sin^2\frac{\vartheta}{2}$$

$$P\cdot q \overset{lab}{=} M\nu = M(E-E')$$

$$P\cdot k \overset{lab}{=} ME$$

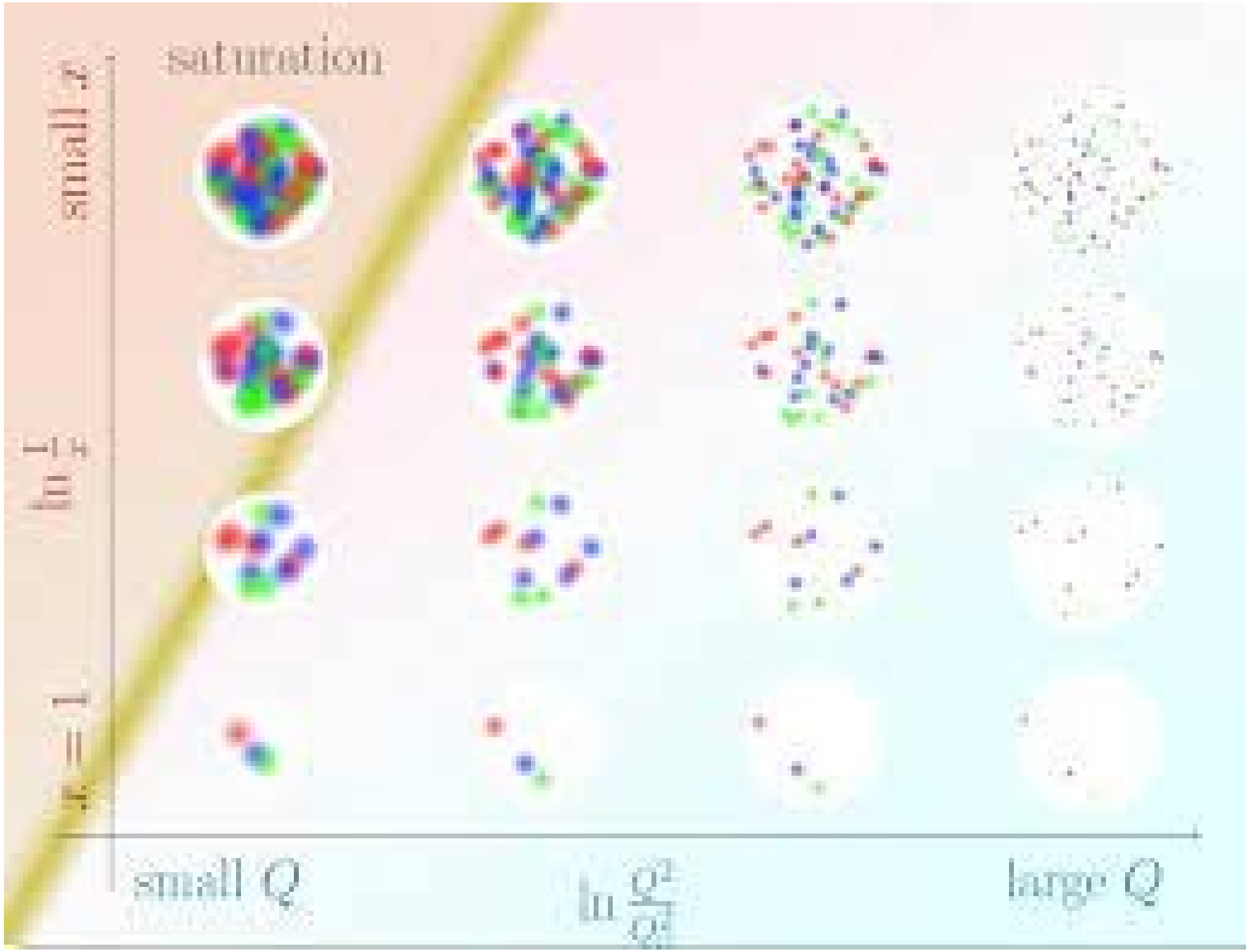
$$x \overset{lab}{=} \frac{Q^2}{2M\nu} = \frac{-q^2}{2P\cdot q}$$

$$y \overset{lab}{=} \frac{\nu}{E} = \frac{P\cdot q}{P\cdot k}$$

$$0 \leq x, y \leq 1$$

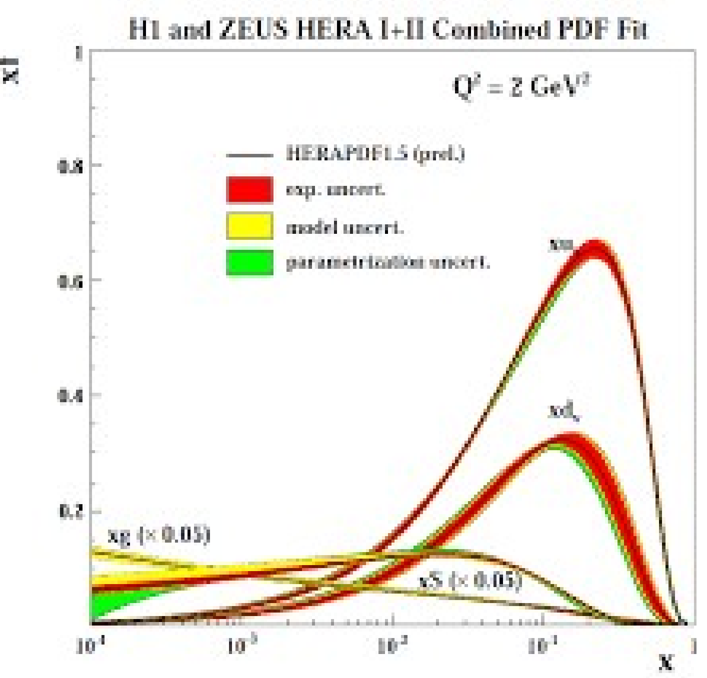
Bjorken-*x*: fraction of longitudinal momentum carried by the struck quark in infinite-momentum frame (Breit)

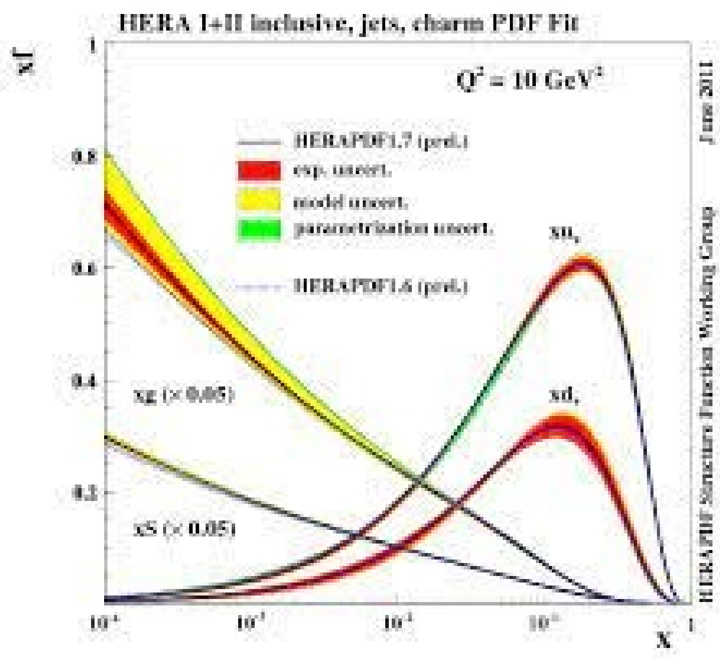
“1D”: longitudinal momentum in Deep Inelastic Scattering
Momentum fraction “x” and resolution/virtuality “Q'^2”

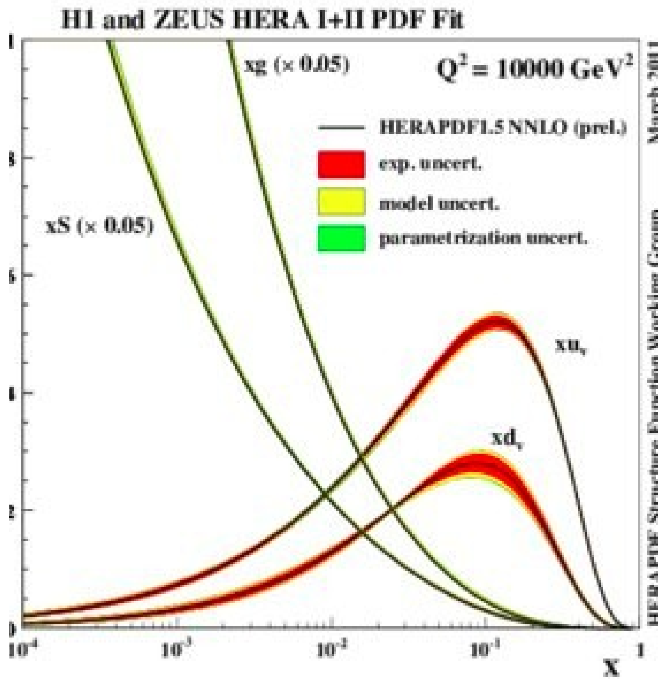


“1D”: longitudinal momentum in Deep Inelastic Scattering

How to interpret the momentum fraction in terms of constituents density





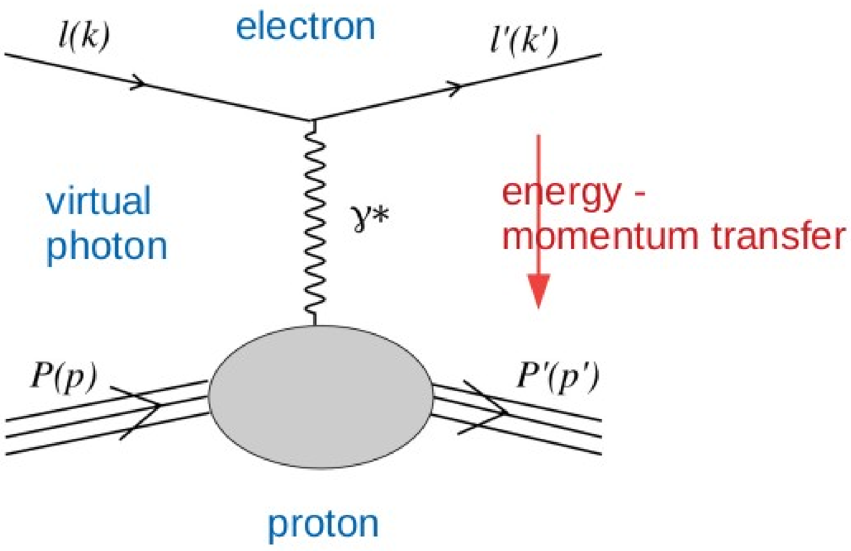


Valence quark dominates
High x, JLab , HERMES
Lower energy experiments

COMPASS

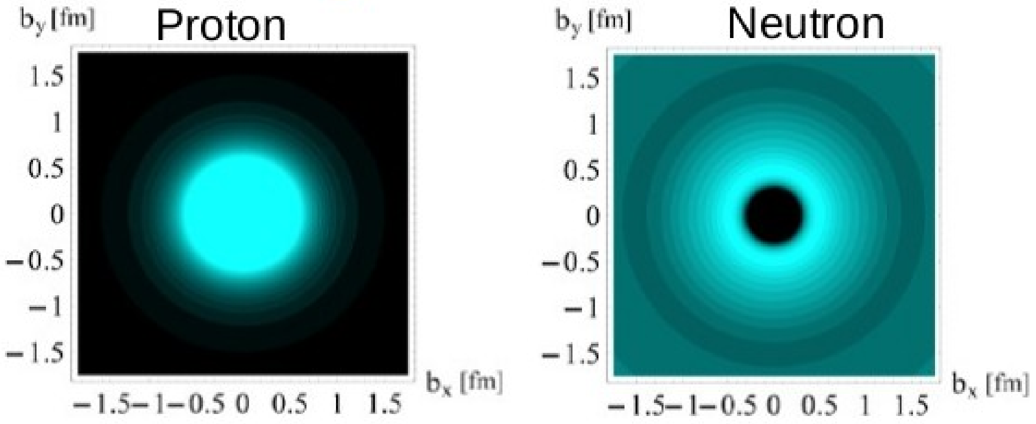
gluon dominates
Low x, colliders HERA, EIC...
High energy, colliders

"2D": Transverse position



Momentum transfer squared t

transverse charge distributions (from M. Vanderhaeghen)



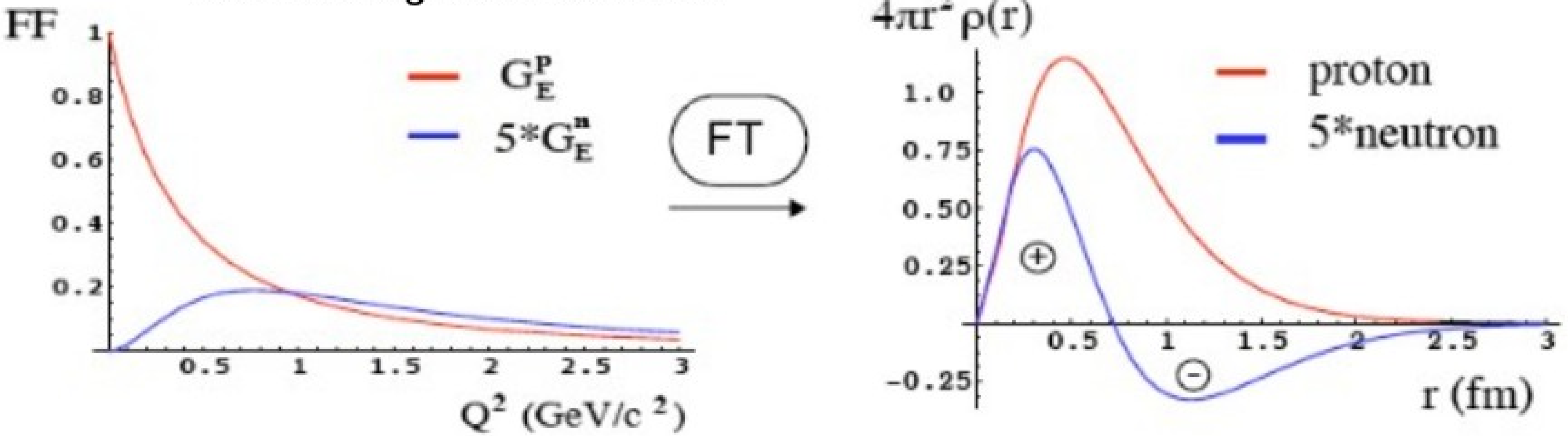
“2D”: Transverse position

Elastic scattering ⇒ lateral deformation of electric and magnetic structure

Screening from other charges (quarks, antiquarks) ⇒ probe only "sees" partial charge

Form Factors:
correction to probability
of scattering off the nucleon

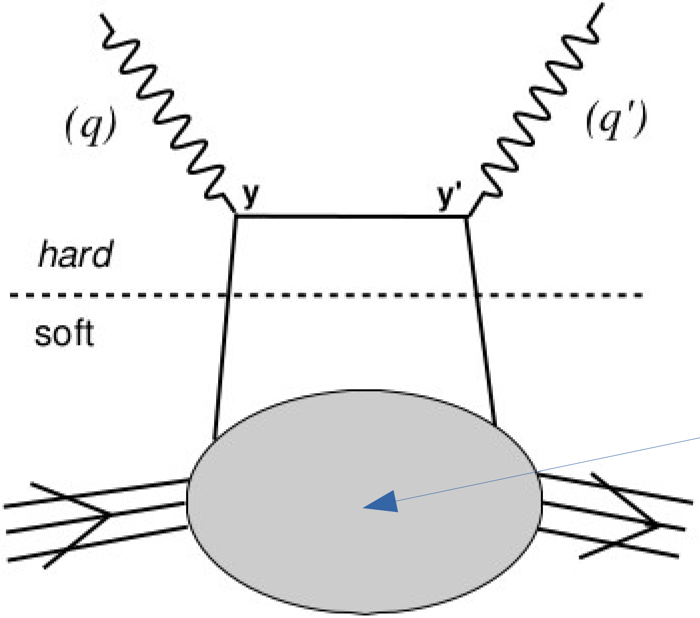
Charge ≡ quarks distributions



Form factors characterize the charge density

3D: “transverse position vs longitudinal momentum”

Reaction:
Deep Inelastic Regime to probe partons (off-diagonal matrix element)
Exclusive to access non-zero transfer momentum (off-forward matrix element)
Matrix elements combination sensitive to Spin-parity and nature of final particle (parity and flavor)
Mass of final particle is a lever arm to access certain kinematics of the functions

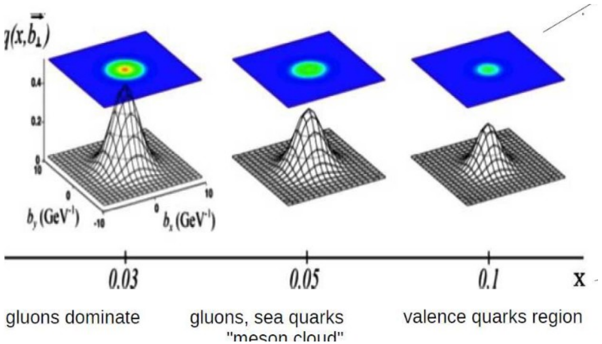


Base handbag diagram “off quark”

Generalized Parton Distribution

Depends on
t Mandelstam, $(p-p')^2$
xi: longitudinal momentum transfer (“hard part”)
x: momentum of the parton
q, q’ virtuality for NLO, higher twist terms

Transverse position in “slices” of momentum

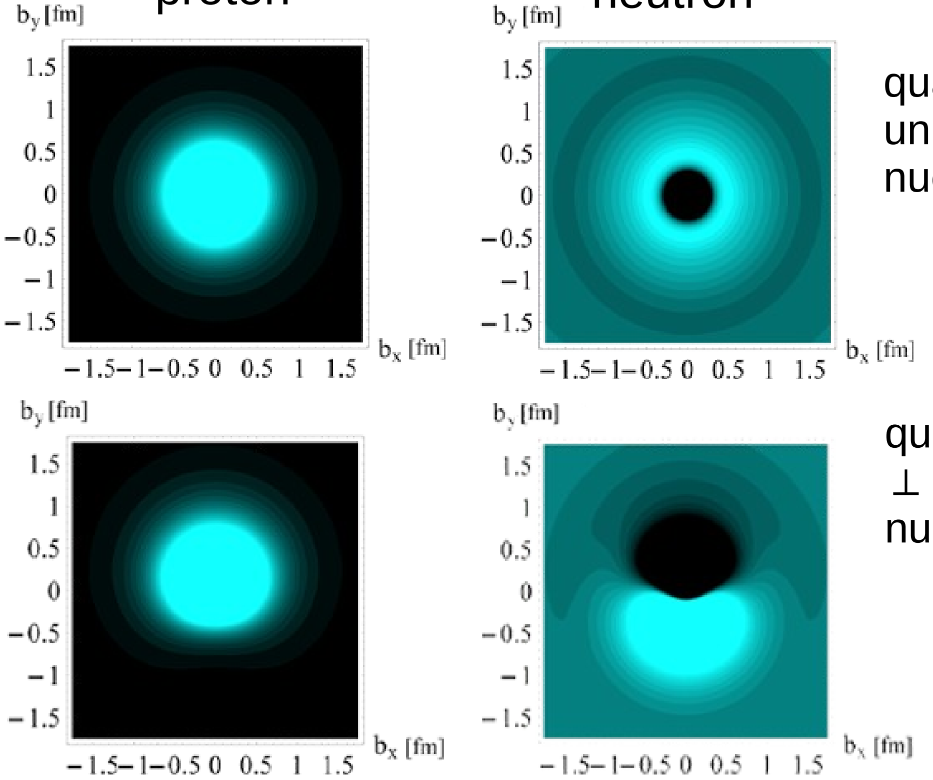


“slices”

quarks x dependent transverse position
distribution in transversely polarized nucleon

proton

neutron



quarks in
unpolarized
nucleon

quarks in
⊥ polarized
nucleon

Each slice have different ratio of gluons and various variety (flavor) of quarks

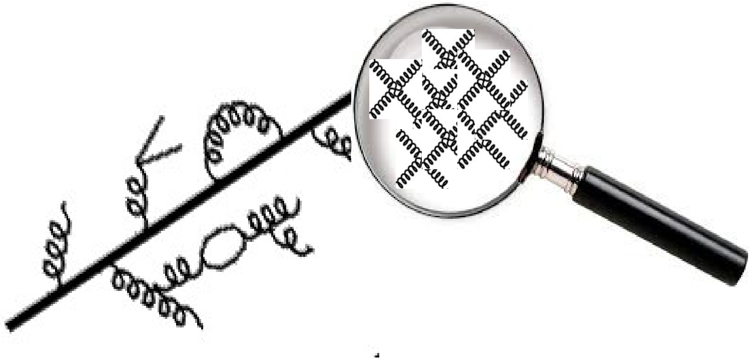
Like slices from MRI

Projections from M. Vanderhaeghen

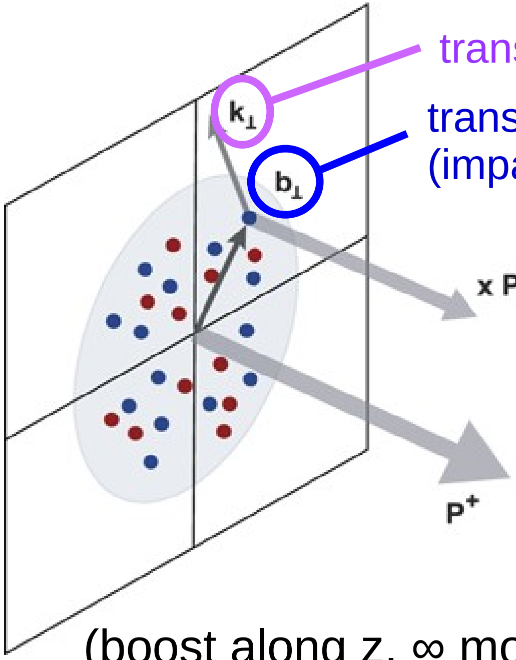
From 1D to “3D” to “5D”

- **Virtuality: q^2**

→ resolution of the probe



- **Transverse distributions: $k_\perp$, $b_\perp$**



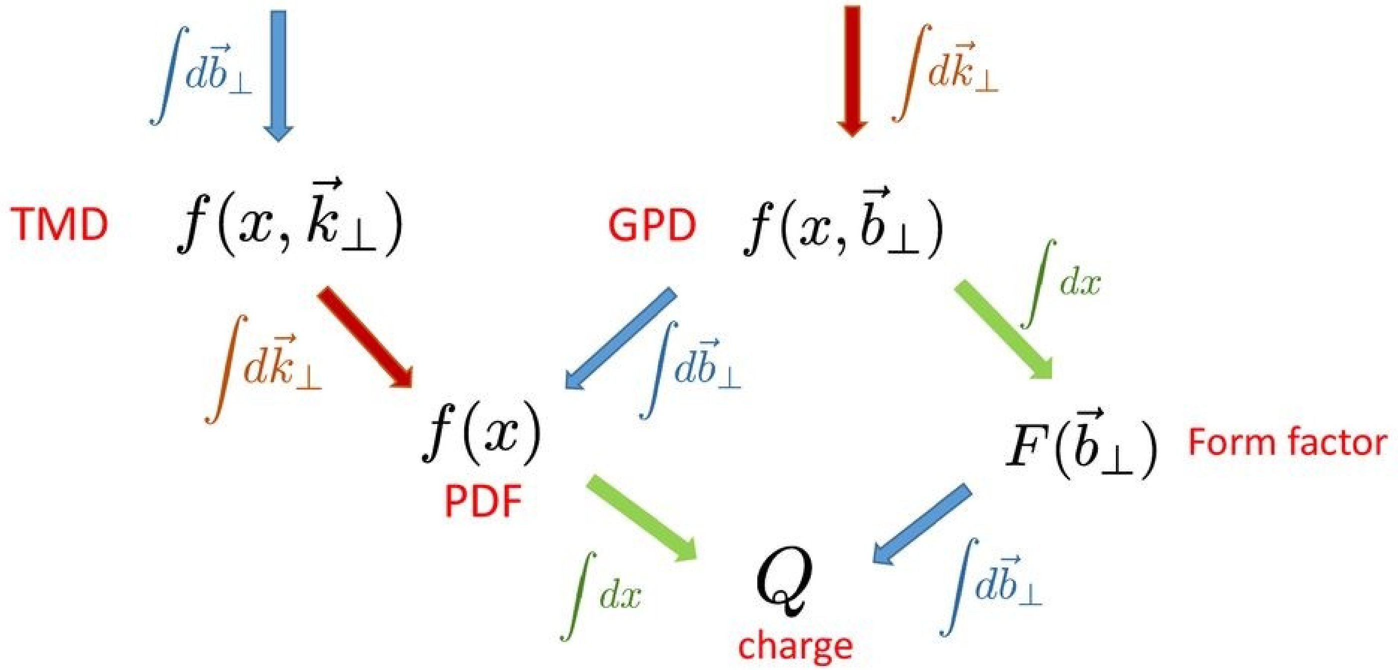
(boost along z, ∞ momentum space)

From 1D to “3D” to “5D”

5D tomography:
Wigner distribution— the “mother distribution”

Belitsky, Ji, Yuan (2003);
Lorce, Pasquini (2011)

$$W(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \int \frac{dz^- d^2 z_\perp}{16\pi^3} e^{ixP^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp} \langle P-\frac{\Delta}{2}|\bar{q}(-z/2)\gamma^+ q(z/2)|P+\frac{\Delta}{2}\rangle$$



Generalized Parton Distributions

Non calculable part of cross section and Generalized Parton Distributions: [Ji's 1997 conventions]

$$H_{\mu\nu}^{TCS} = \frac{1}{2}(-g_{\mu\nu})_\perp \int_{-1}^{1} dx \left(\frac{1}{x-\xi-i\epsilon} + \frac{1}{x+\xi+i\epsilon}\right) \cdot \left(H(x,\xi,t)\,\bar{u}(p')\not{n}\,u(p) + E(x,\xi,t)\,\bar{u}(p')\,i\sigma^{\alpha\beta}n_\alpha \frac{\Delta_\beta}{2m}\,u(p)\right)$$

$$-\frac{i}{2}(\epsilon_{\nu\mu})_\perp \int_{-1}^{1} dx \left(\frac{1}{x-\xi-i\epsilon} - \frac{1}{x+\xi+i\epsilon}\right) \cdot \left(\tilde{H}(x,\xi,t)\,\bar{u}(p')\not{n}\gamma_5\,u(p) + \tilde{E}(x,\xi,t)\,\bar{u}(p')\gamma_5 \frac{\Delta.n}{2m}\,u(p)\right),$$

quark loop part

nucleon structure

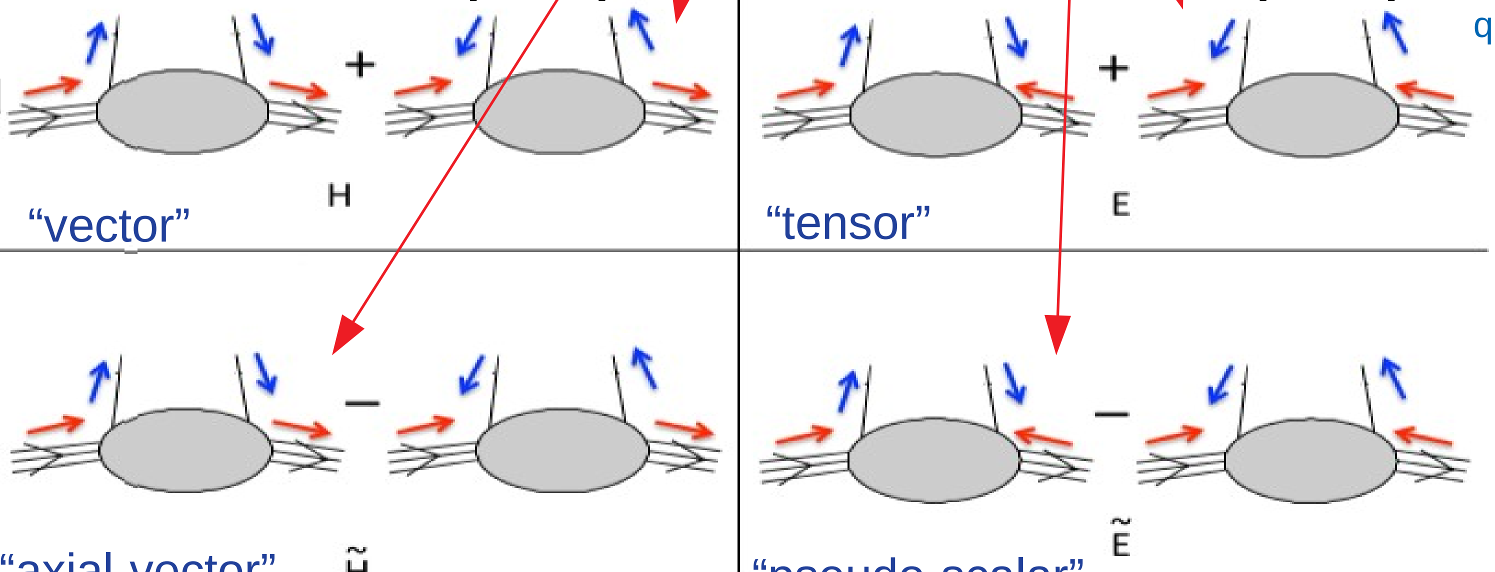
without nucleon spin flip | with nucleon spin flip

quark spin

proton spin

unpolarized GPDs

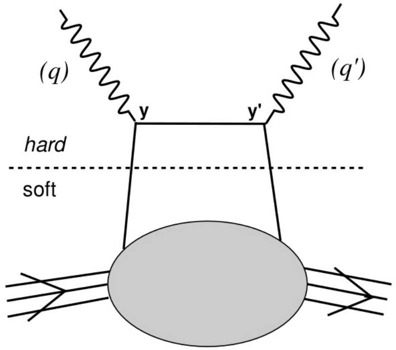
polarized GPDs

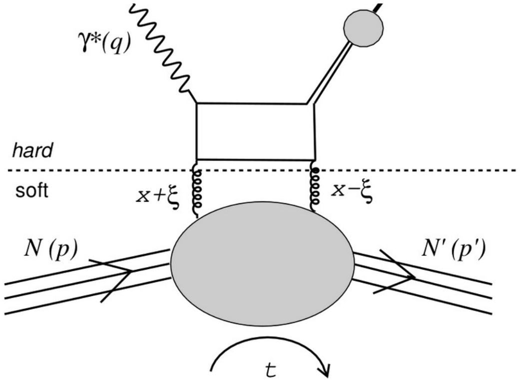


"vector" | "tensor"

"axial-vector" | "pseudo-scalar"

Hard Exclusive Reactions





Generic handbag diagrams

Incoming photon: real or spacelike photon (Q^2)

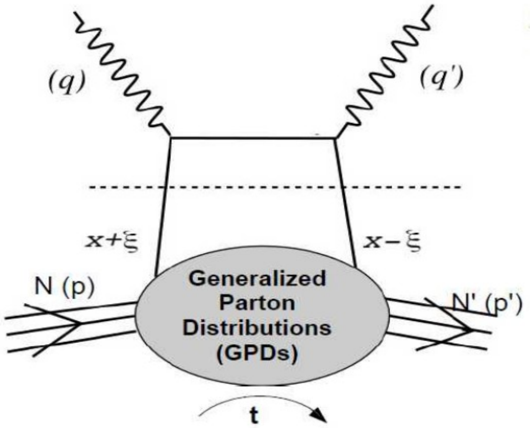
Outgoing particle:

1) Meson: here vector mesons only
HEMP = Hard Exclusive Meson Production
- “light”: rho, omega…
- “heavy”: J/psi, Upsilon...

2) Photon:
Real: DVCS Deeply Virtual Compton Scattering
Timelike Virtual Photon: TCS or DDVCS
Timelike Compton or Double compton Scattering

Note: factorization line

Generalized Parton Distributions



Handbag diagram example

GPD: matrix element that connect N and N' and contain quark/gluons interactions

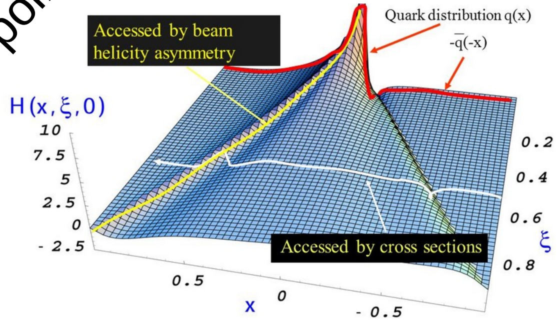
- Contain information about quark and gluon position, spin, ...

1. Extracted at xi (// momentum) and t (momentum transfer ²) from experimental data

"Compton Form Factors": Complex functions of amplitudes

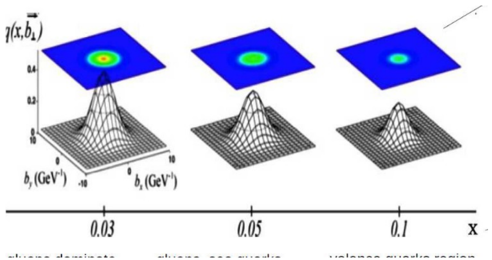
2. Extrapolation to physics points

GPD



3. Fourier transform

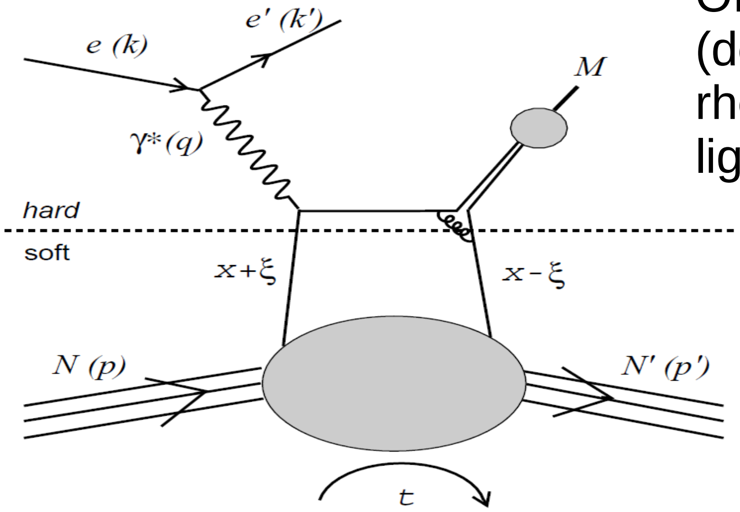
Momentum dependent Impact parameter functions



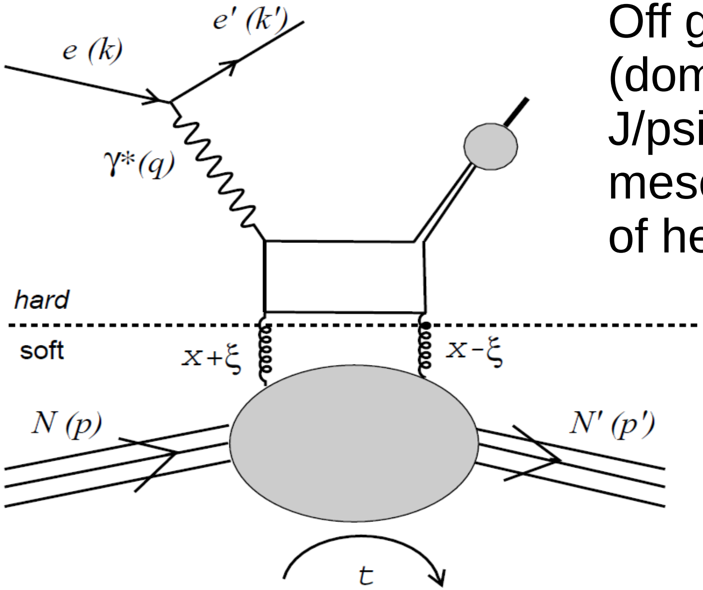
Spin-parity, flavor decomposition, quark/gluons...

- Meson come with various flavor content, and favor a certain spin parity:
Depends on spin, isospin, parity, flavor of valence quarks…

Extracting GPDs from meson for flavor decomposition and studies of certain GPDs



Off quark (dominant for rho & omega, light mesons)

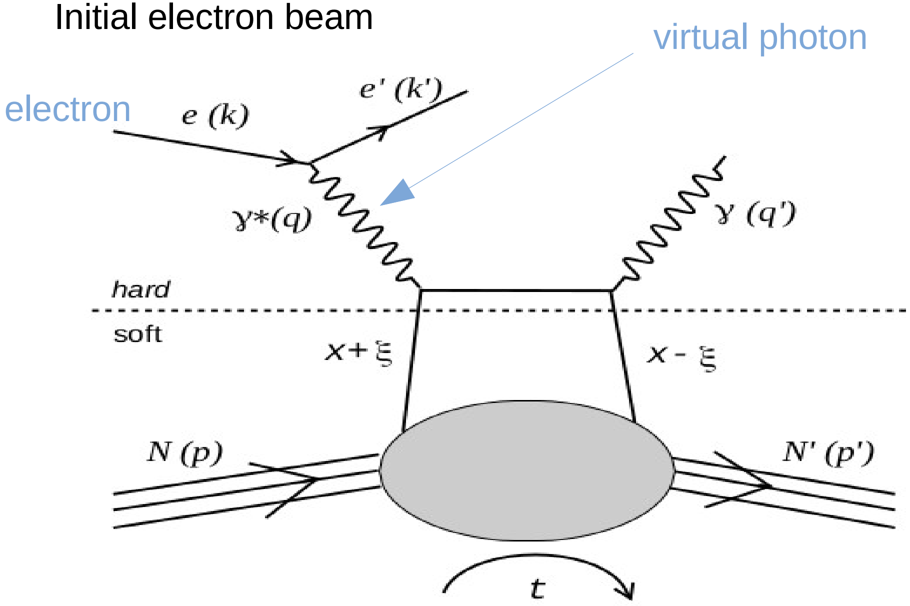


Off gluon (dominant for J/psi, Y, heavy mesons made of heavy quarks

Focus on vector meson: factorization proof + high cross section, neglect higher twist

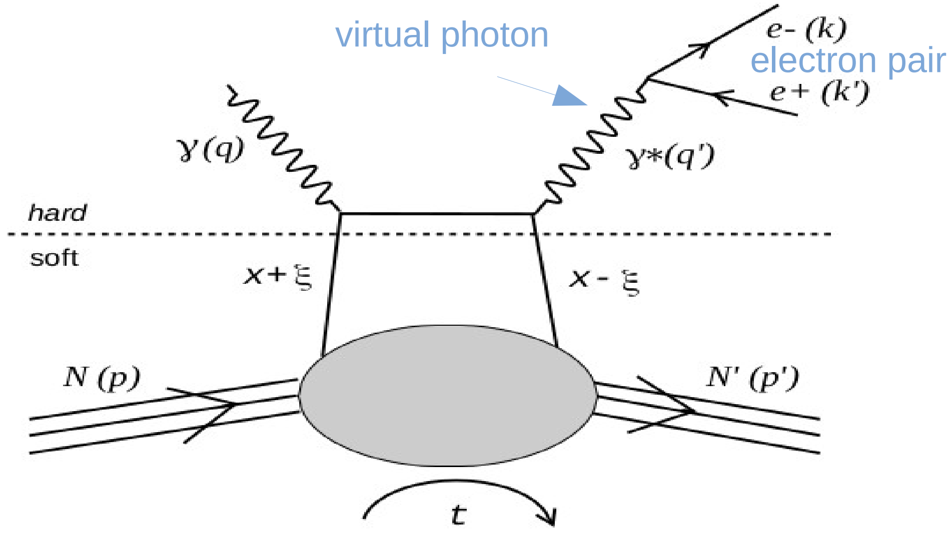
Hard exclusive Virtual Compton Scattering

Initial electron beam



Deeply Virtual Compton Scattering (DVCS)

Final electron pair created



Timelike Compton Scattering (TCS)

Both reactions access same Generalized Parton Distributions, same kinematics Leading order, leading twist

⇒ Many experiments measuring spacelike DVCS, Future experiments will measure Timelike Compton Scattering

Goal: GPDs universality, complementary measurements of polarization observables to constrain all GPDs...

Extraction of GPDs from Compton Form Factors

DVCS amplitude decomposition into Compton Form Factors (TCS similar):

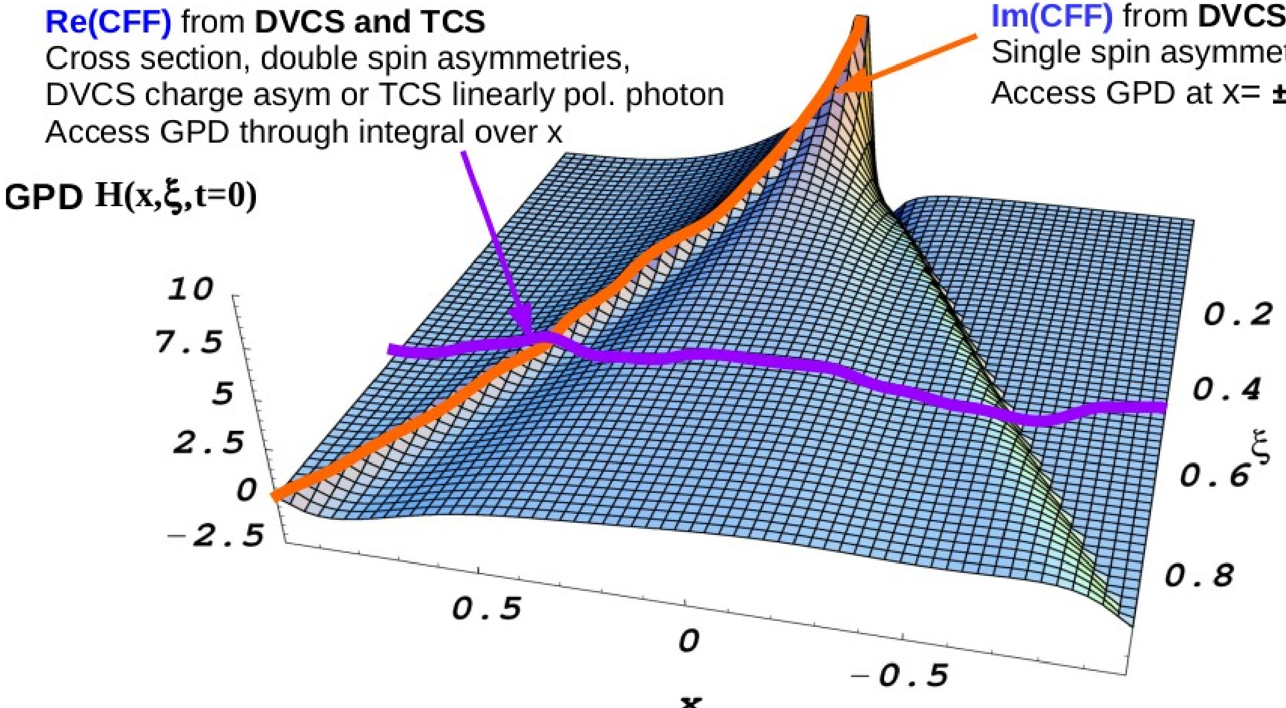
ξ, t = measurable
x = integrals

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

Probing GPD x vs ξ dependence with experimental observables:

Re(CFF) from **DVCS and TCS**
Cross section, double spin asymmetries,
DVCS charge asym or TCS linearly pol. photon
Access GPD through integral over x

Im(CFF) from **DVCS and TCS**
Single spin asymmetries, cross section
Access GPD at x= **±ξ**



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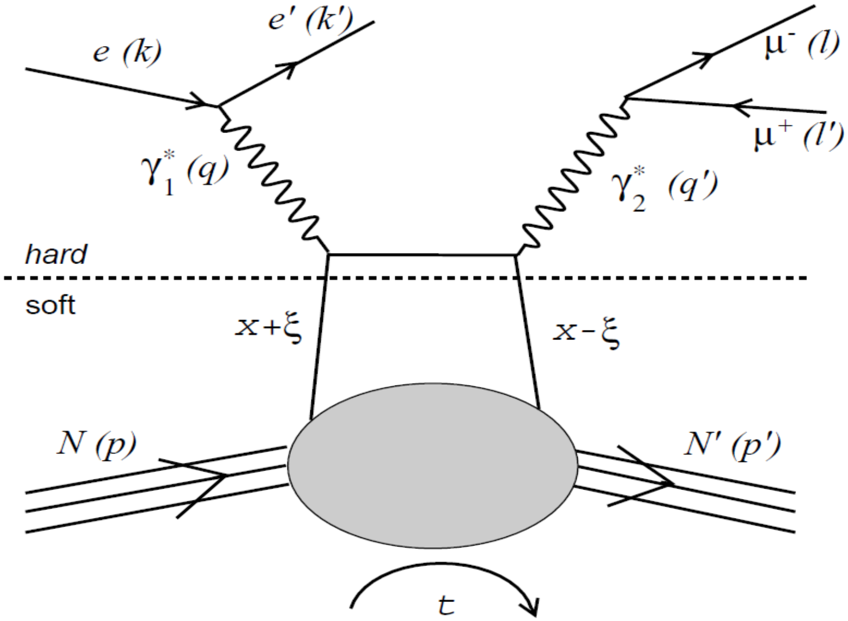
Access non-diagonal part with DDVCS



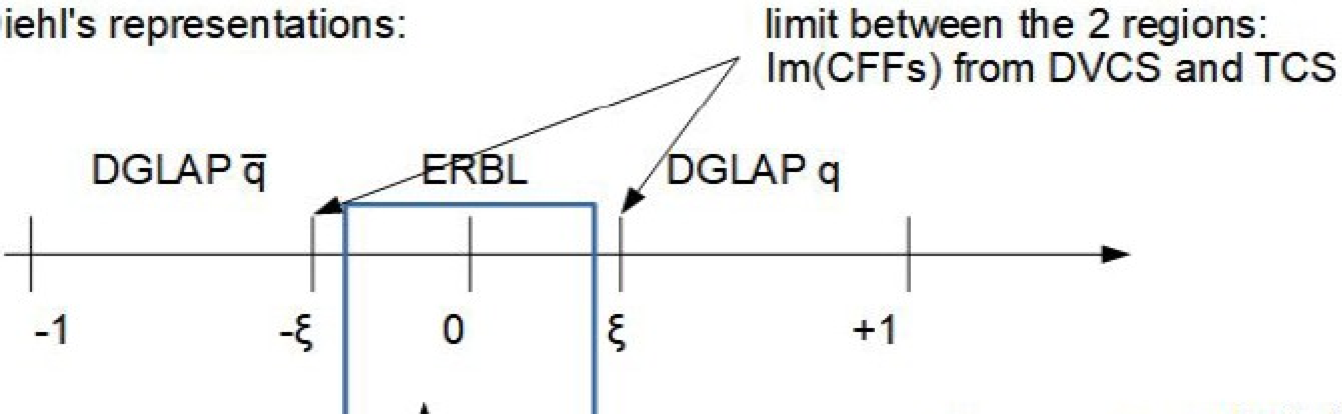
Lever arm in q/q' will access the off-diagonal region

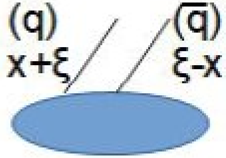
Access non-diagonal part with DDVCS

$\xi>|\xi'|$: ERBL region; $\xi<|\xi'|$ DGLAP region

Quark propagator normalized to ξ at asymtotic limit: $(1-Q'^2/Q^2) / (1+ Q'^2/Q^2)$
→up to t/Q^2 factor, we play with respective value of Q^2 and Q'^2 to go "out of diagonal" for GPD
→neglecting t, we are restricted to $\xi>|\xi'|$

M. Diehl's representations:





partonic interpretation from M. Diehl in ERBL region

need to map this region for GPD models and extrapolations needed for tomographic interpretations at $\xi=0$; GPD extrapolated from $\xi\to0$

Experimental program, JLab Hall C

New GPD measurements
Feasibility studies, observables,
Simulations,
New experiments

Polarized and unpolarized measurements: TCS, vector mesons, quarkonia near threshold

Observables & 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(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

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

*** Recent Hall B measurement**

- Not covering the same kinematic region, and low statistics = hard to use in our fits

*** Need of precision measurement for unpolarized cross section**

*** Need of proton + neutron** for flavor separation and extraction of Hu, Hd, for universality studies and comparison vs DVCS

2 options, both important

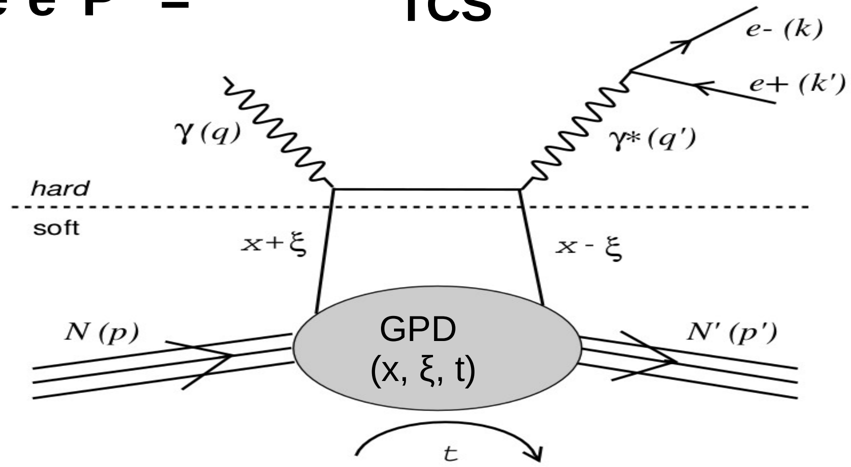
1) Extension of proposed experiment with 10 days unpolarized off NH3
- Needed for interpretation of polarized data and studies of dilution factor
- Can't be interpreted for precision measurement off proton

2) Dedicated precision LH2+LD2 measurement for GPD H
- need for high statistics and precision
- estimation 10 days each target ?

+ complementary polarized measurements

Physics goals

$\gamma P \rightarrow e^+e^- P' =$ **TCS** + **Bethe-Heitler**



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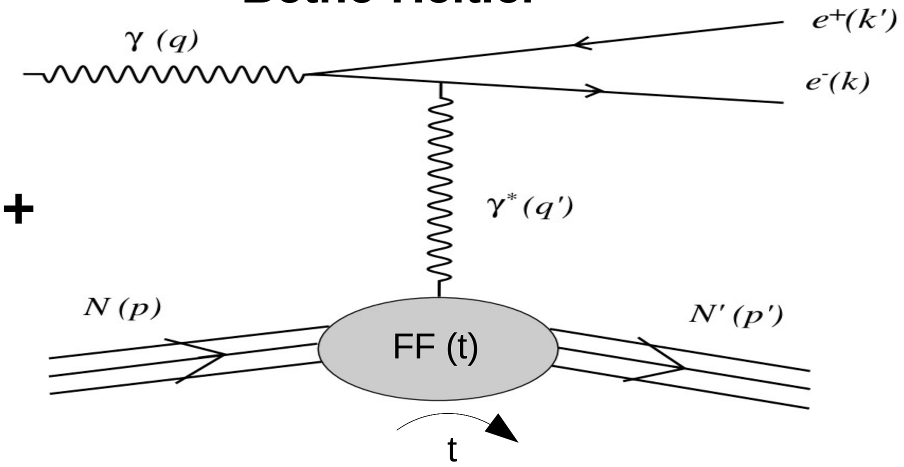
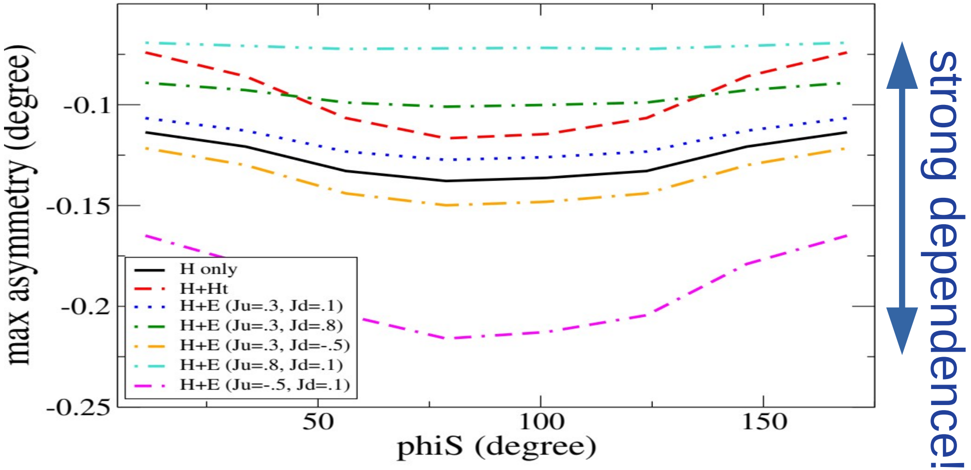
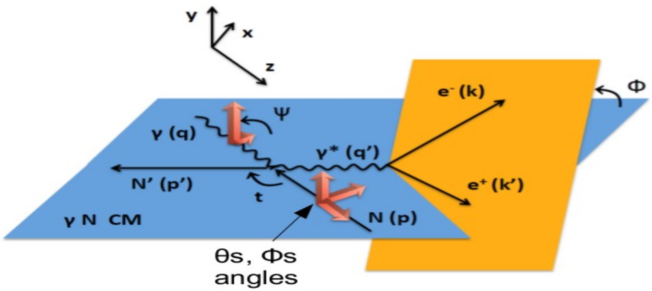


Sin(φ) moment of transverse spin asymmetry vs φ_S,
Dependence in GPD E and $J^{u,d}$ (VGG model)



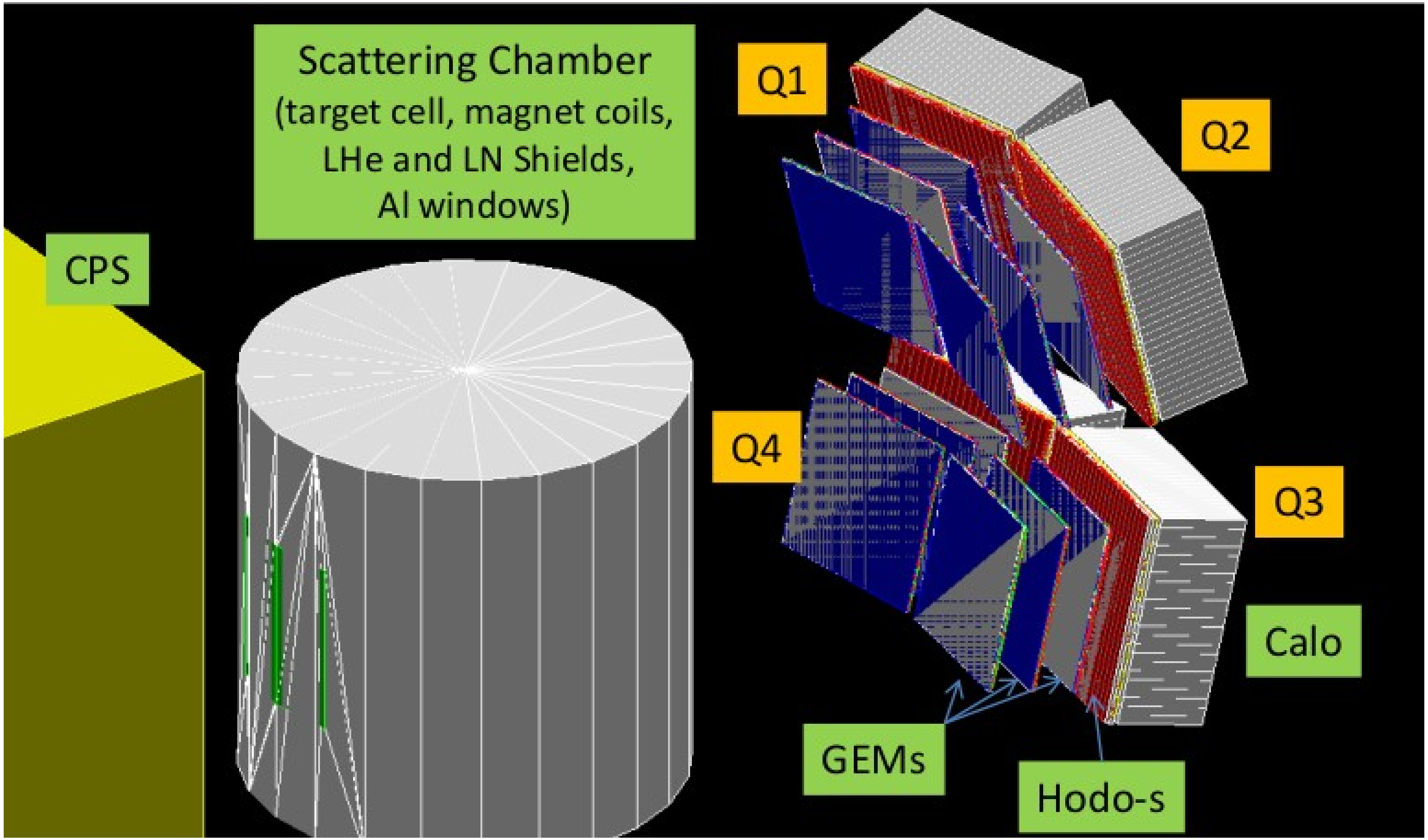


TSA as a function of φ and φ_s

- Sensitive to Im(interference), BH cancels
- Strong dependence in angular momenta,

Sensitivity to GPD E (also to H, Ht)

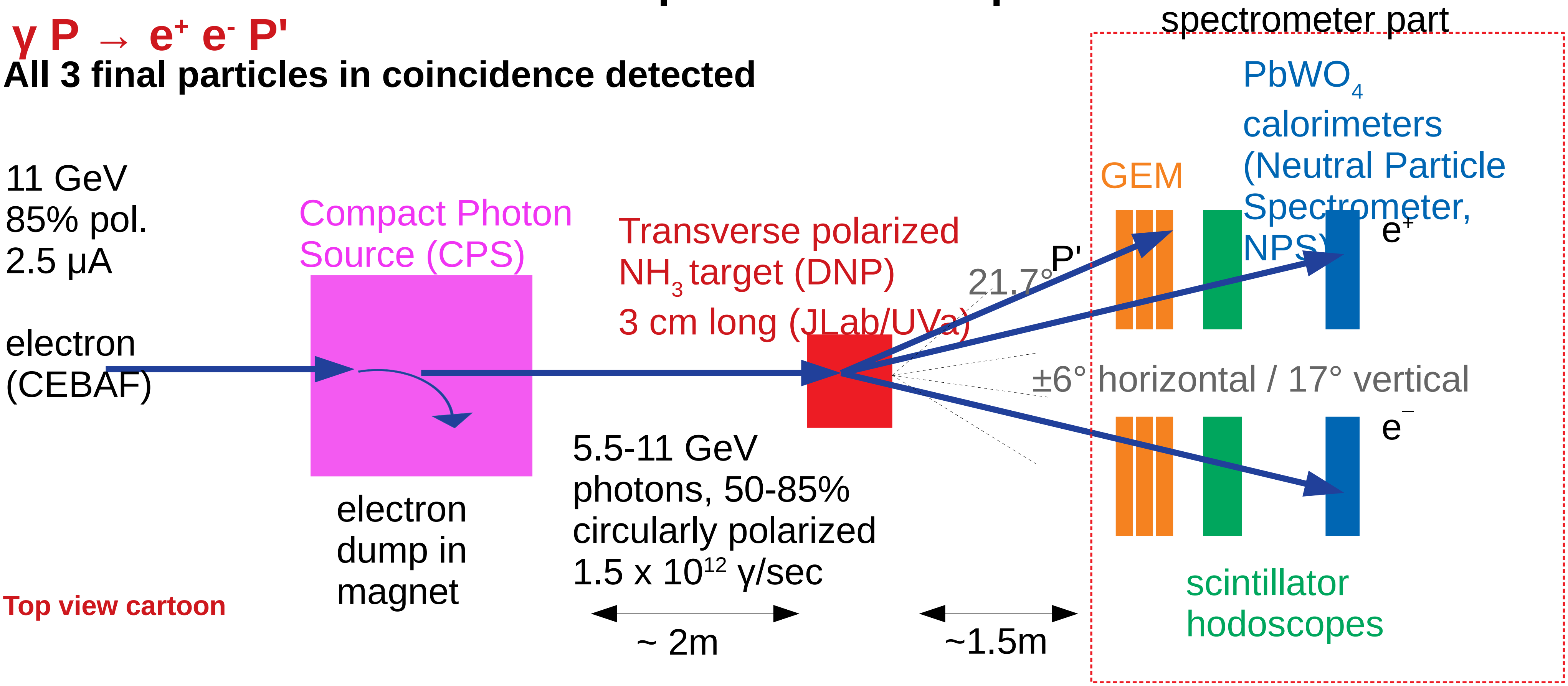
Proposed setup at JLab Hall C



Experimental setup

γ P → e^+ e^- P'

All 3 final particles in coincidence detected



Trigger: GEMs, hodoscopes, calorimeters (all 3 particles)

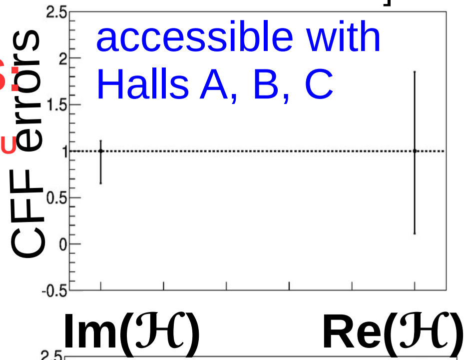
Integrated luminosity: 5.85×10^5 pb^{-1} for 30 PAC days of "physics"

Compton Form Factors from DVCS and TCS

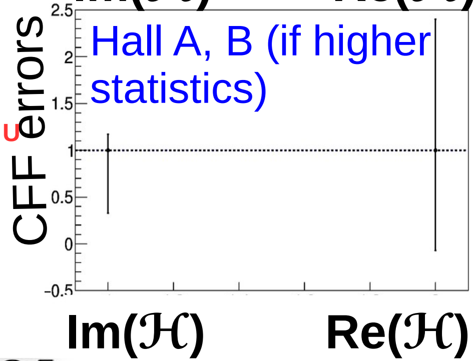
[fit of simulations with same errors]

- **CFFs from TCS can be extracted at same level than DVCS**
- **Im(ℰ) extracted thanks to transverse target**
- **Precision on H greatly improved with new constraints**

DVCS:
σ, $\Delta\sigma_{LU}$



TCS:
σ, $\Delta\sigma_{\odot U}$



<u>Main goal</u>: **GPD E (proton) → unique, not measured in other exp.**

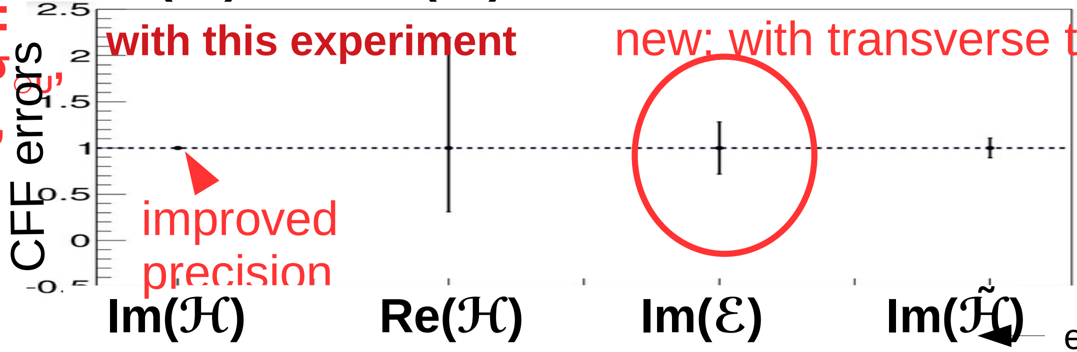
<u>Secondary goal</u>: **complement universality studies**

→universality or breaking? Higher twist/NLO effects?

- Studied with Q² evolution in other experiments
- Comparison of fit results DVCS only, TCS, TCS+DVCS

→**interpretation depends on size of observed effects**

TCS:
σ, $\Delta\sigma_{\odot U}$,
$\Delta\sigma_{UX}$,
$\Delta\sigma_{UY}$

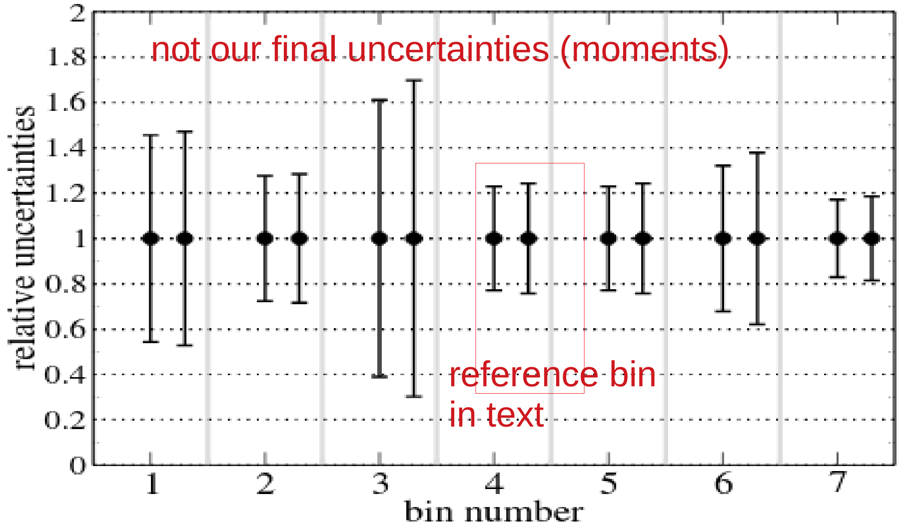


extracted CFFs (generated at value=1)

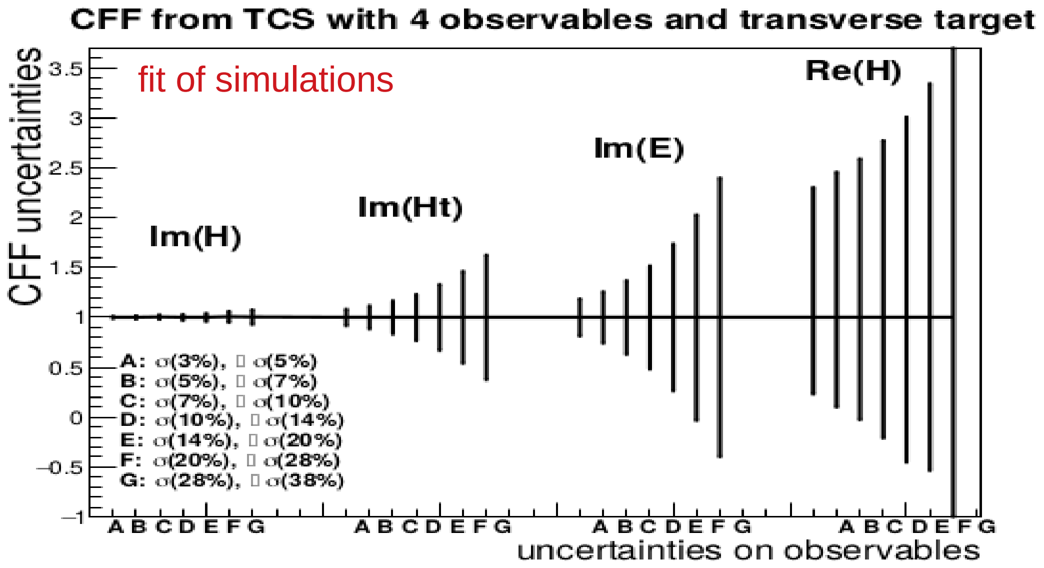
Anticipated results on CFFs

Mostly dominated by complementary unpolarized experiments, due to correlation with GPD H

(illustration) **combined errors** on 2 orthogonal ⊥ asymmetries for first sinus moment, for all bins (to be compared with size of asymmetries vs φ_S)



CFFs uncertainties vs experimental errors
fits on simulations using VGG parametrization



- **Im(H), Re(H), Im(H̃), Im(E) extracted even with very large experimental uncertainties (E, F, G)**
- **Results mostly depend on unpolarized cross section errors (other experiments off LH2)**
- **Our experiment will put constraints on GPD E, J_u & J_d, and reduce errors on Im+Re(H)**

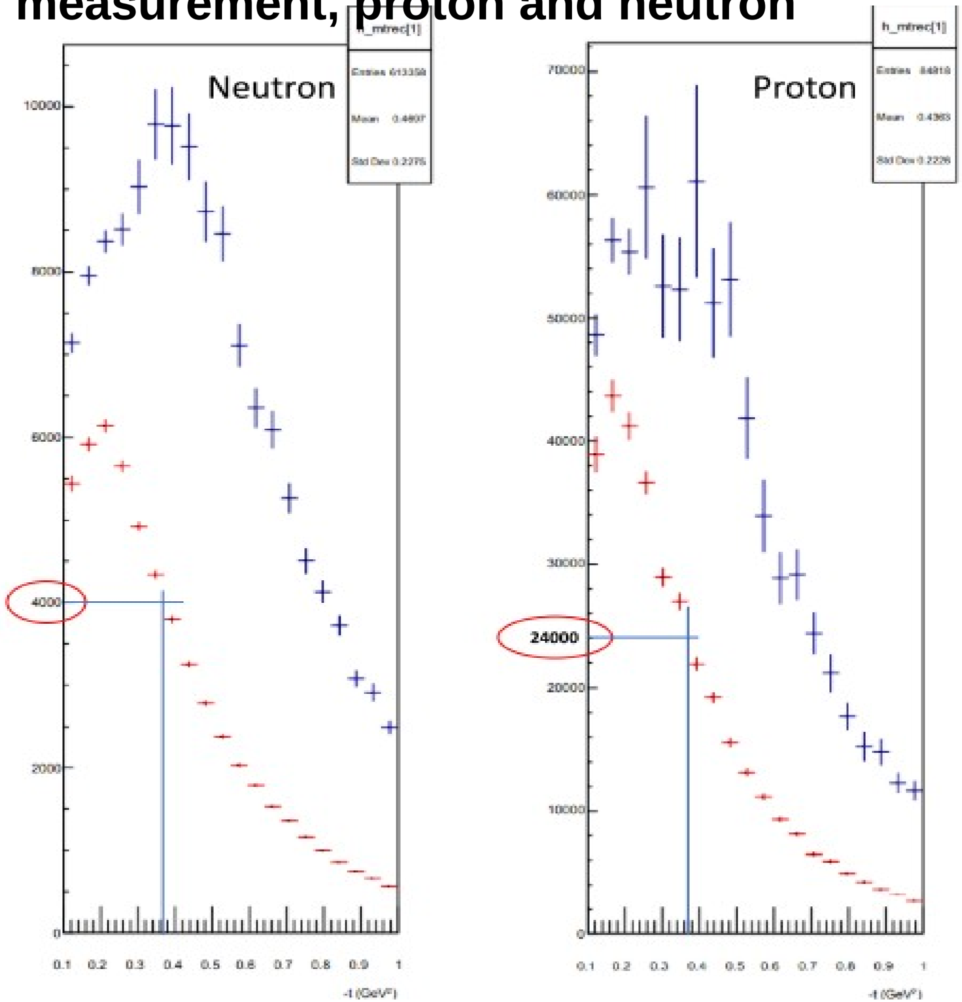
Extension: flavor decomposion & precision measurement, proton and neutron

Number of reconstructed events measured for the TCS reaction depending on $-t$ weighted by the cross section

The data are normalized.

Difference between proton and neutron:

- Measured : x6



Camille's projection demonstrate
1) feasibility of measuring unpolarized proton TCS off LH2 (in terms of counting rates & impact)
2) feasibility of measuring unpolarized neutron TCS off LD2

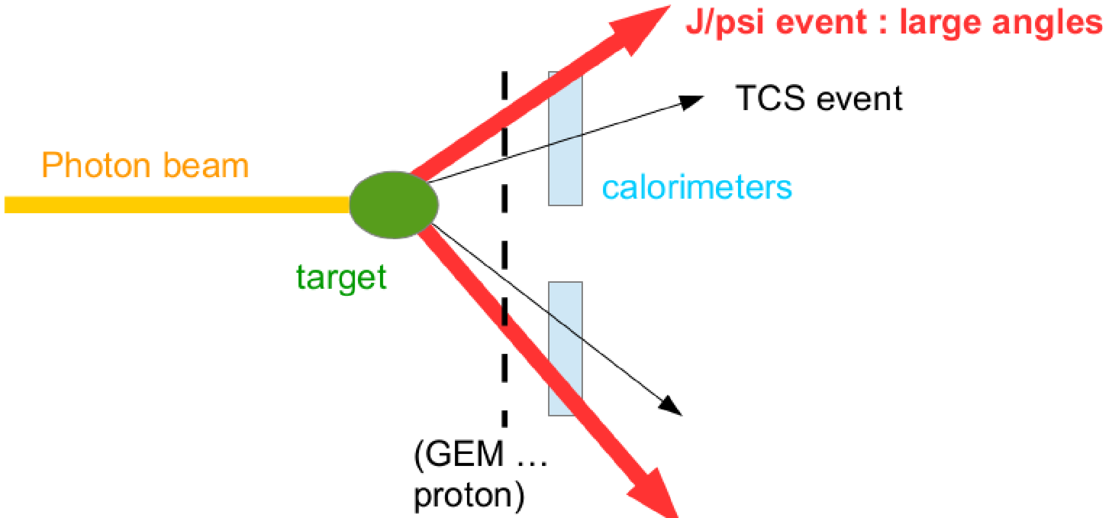
Extension: J/psi (see Erik Talk)

- Energy dependent production mechanisms
- Expected 3 gluon exchange dominance at JLab

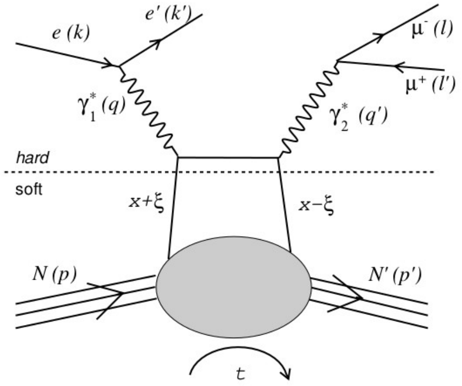
* Using model Brodsky & al. for JLab projections
Generator tuned for JLab & EIC energies with « manual » tuning for dominant cross section, « user choice » parametrizations (pdf...)
(credit : Tyler Schroeder, summer student REU)

Erik's work this year: updating this code and tuning for JLab projections, simulations

Our goals
- similar setup as for TCS
- use of new target magnet : extended acceptance at large angles
- realistic projection to see if an experiment can be done



DDVCS



Our goal / current work

- coming soon with realistic MC for 2 possible setup we are exploring

- prototype muon detector to be placed behind spectrometer

Why using NPS ?

- larger acceptance for electrons
- can't do with HMS/SHMS
- statistic and precision <u>in principle ok</u> (from toy MC) if starting from DVCS or TCS setups

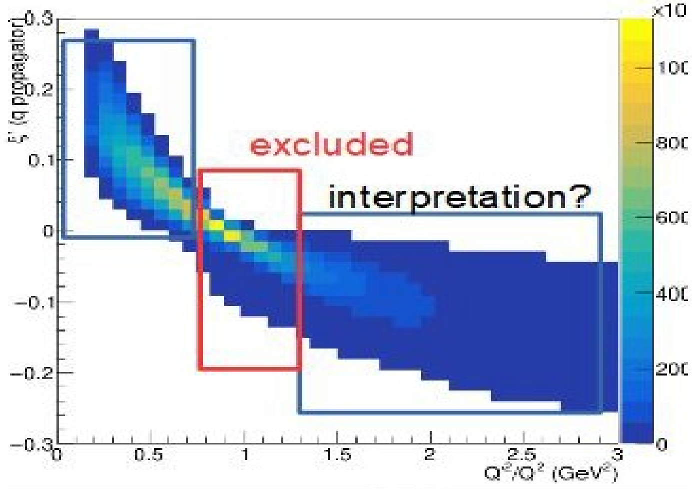
2 options we are exploring

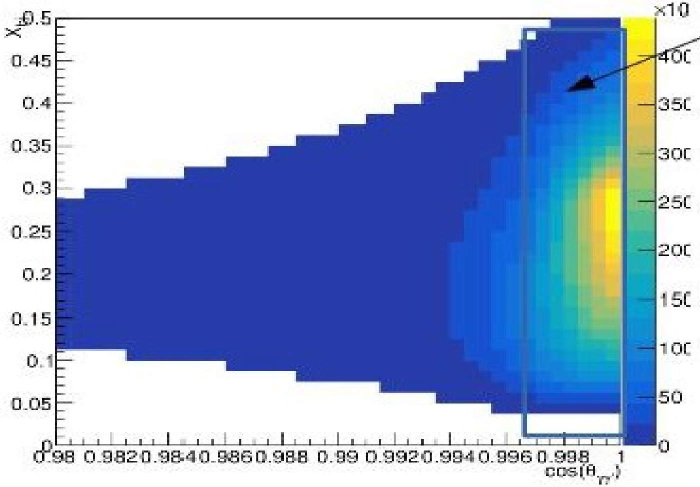
1) similar as DVCS experiment with extra muon detectors (+ shielding, dif trigger...), proton also detected

2) with 2 calo as TCS + muon detectors

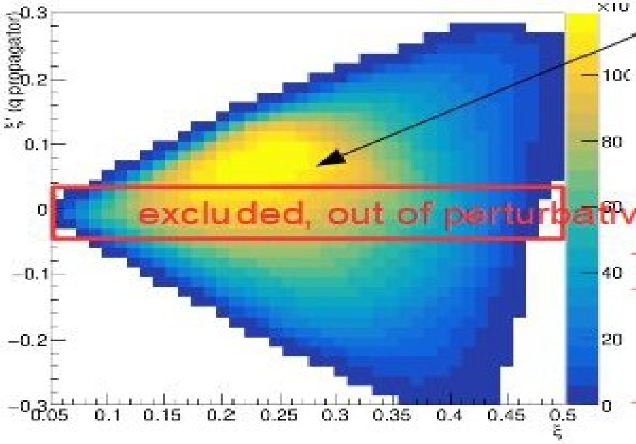
Extension of Hall C DVCS or TCS setup with muon detectors
Plan to develop them at VT
For high intensity DDVCS measurement into muons

Kinematic region we access with Hall C and setups we are looking for





we want to stay here→forward region

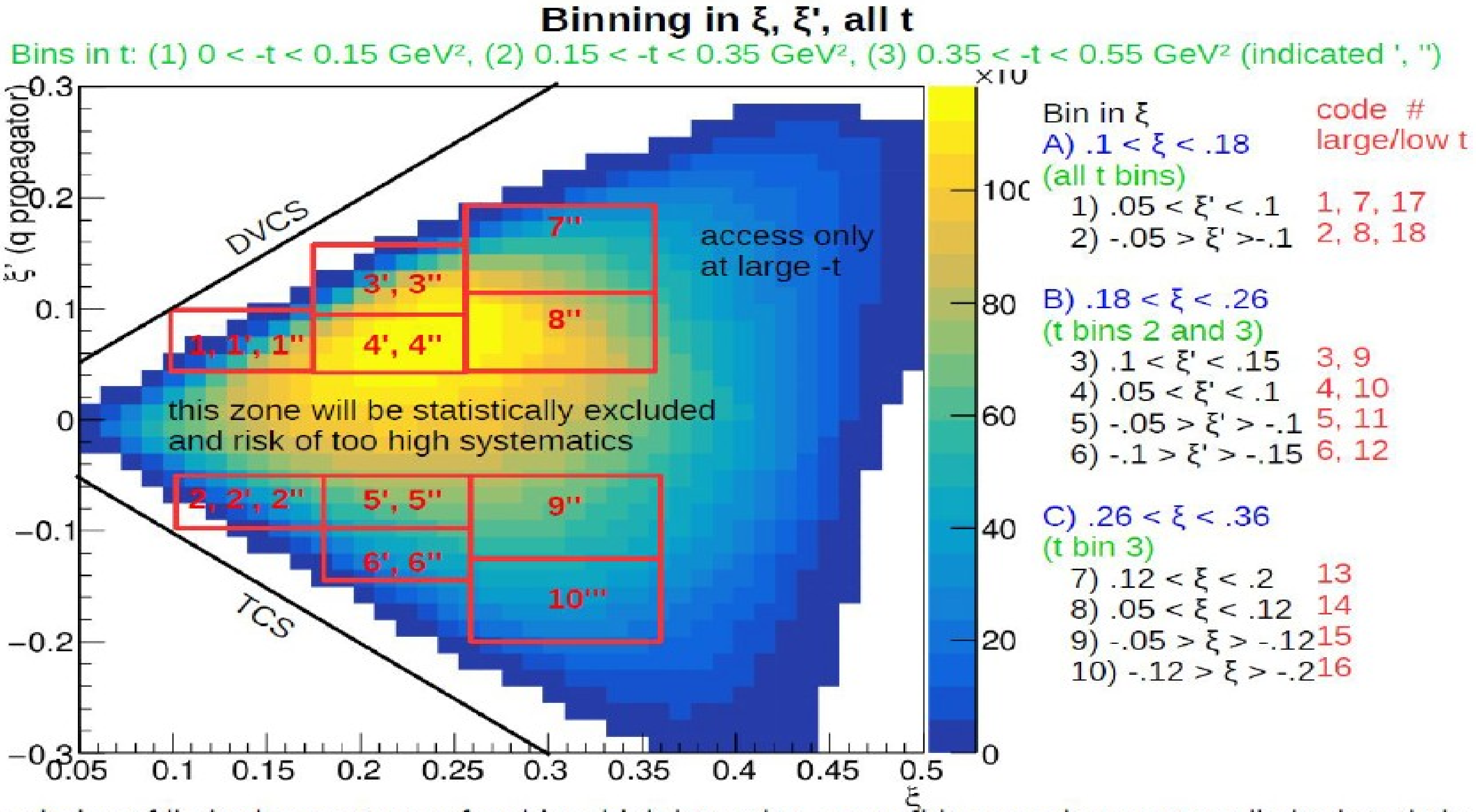


where do we want to have measurement?
this show how much "out of diagonal" we can go

excluded, out of perturbative handbag approach (assuming small t)
→ playing with larger t could get data in this region?
→ but in this case all approximations need to be waved and must be very carefull about interpretations

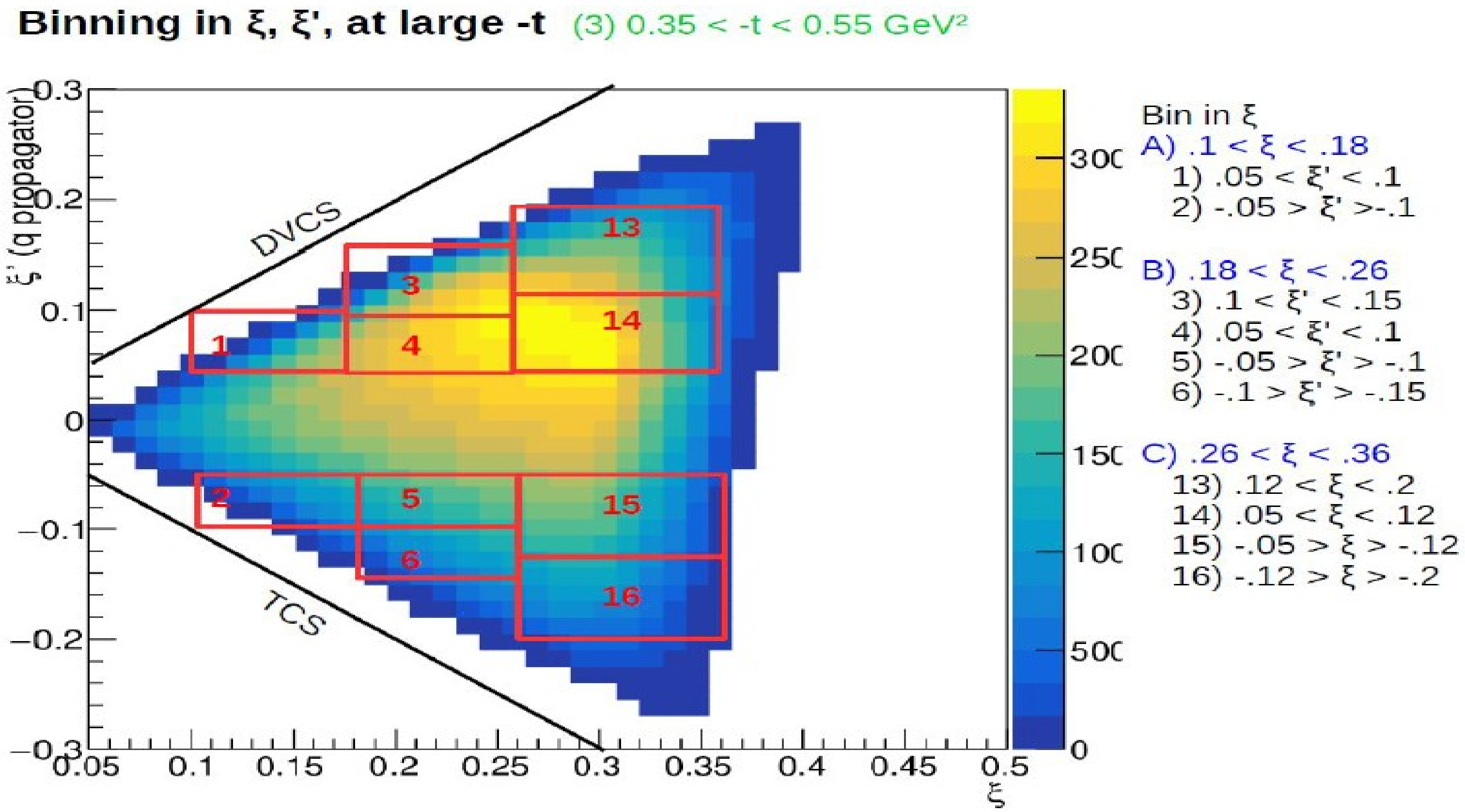
→ also need to be very carefull in this region: resolution in t !!!

Kinematic region we access with Hall C and setups we are looking for

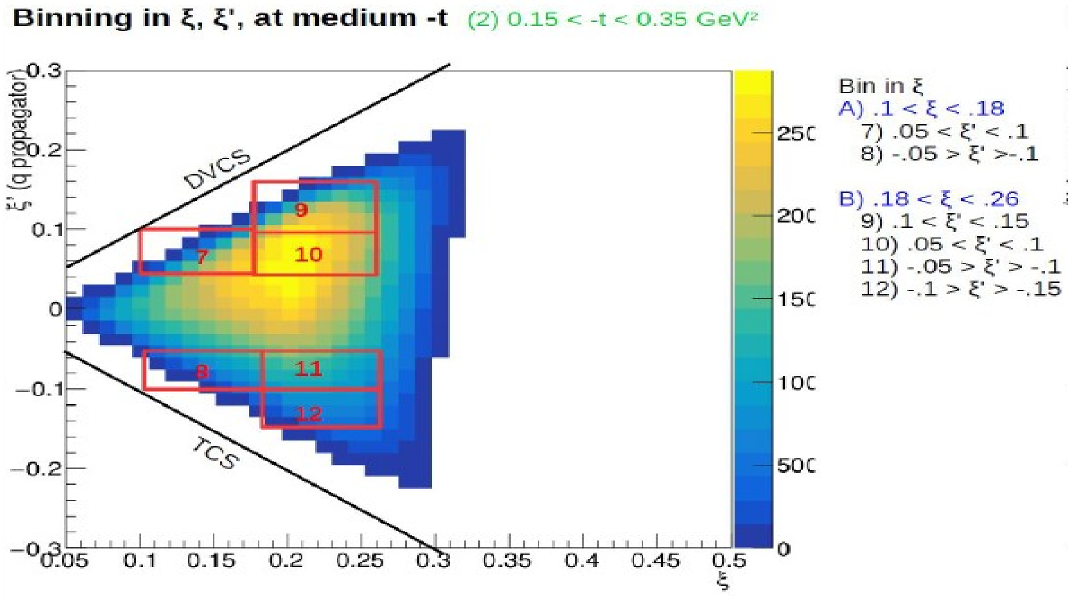


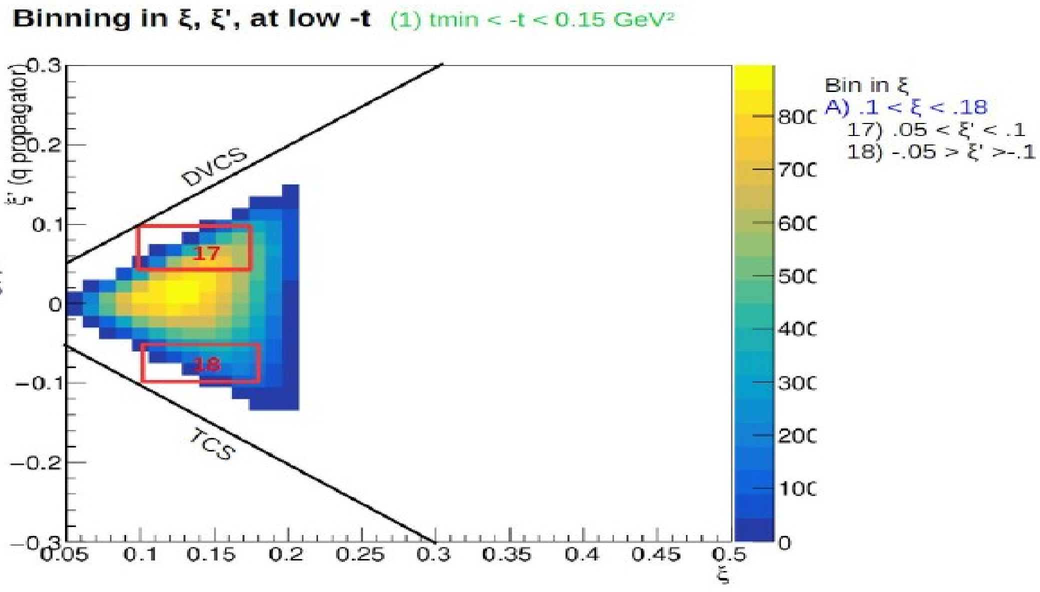
- choice of limited acceptance: few bins, high intensity → some bins may be empty or limited statistic
- no binning in Q^2 and Q'^2: the above selections are cutting bands in the Q^2 vs Q'^2 distribution

Kinematic region we access with Hall C and setups we are looking for



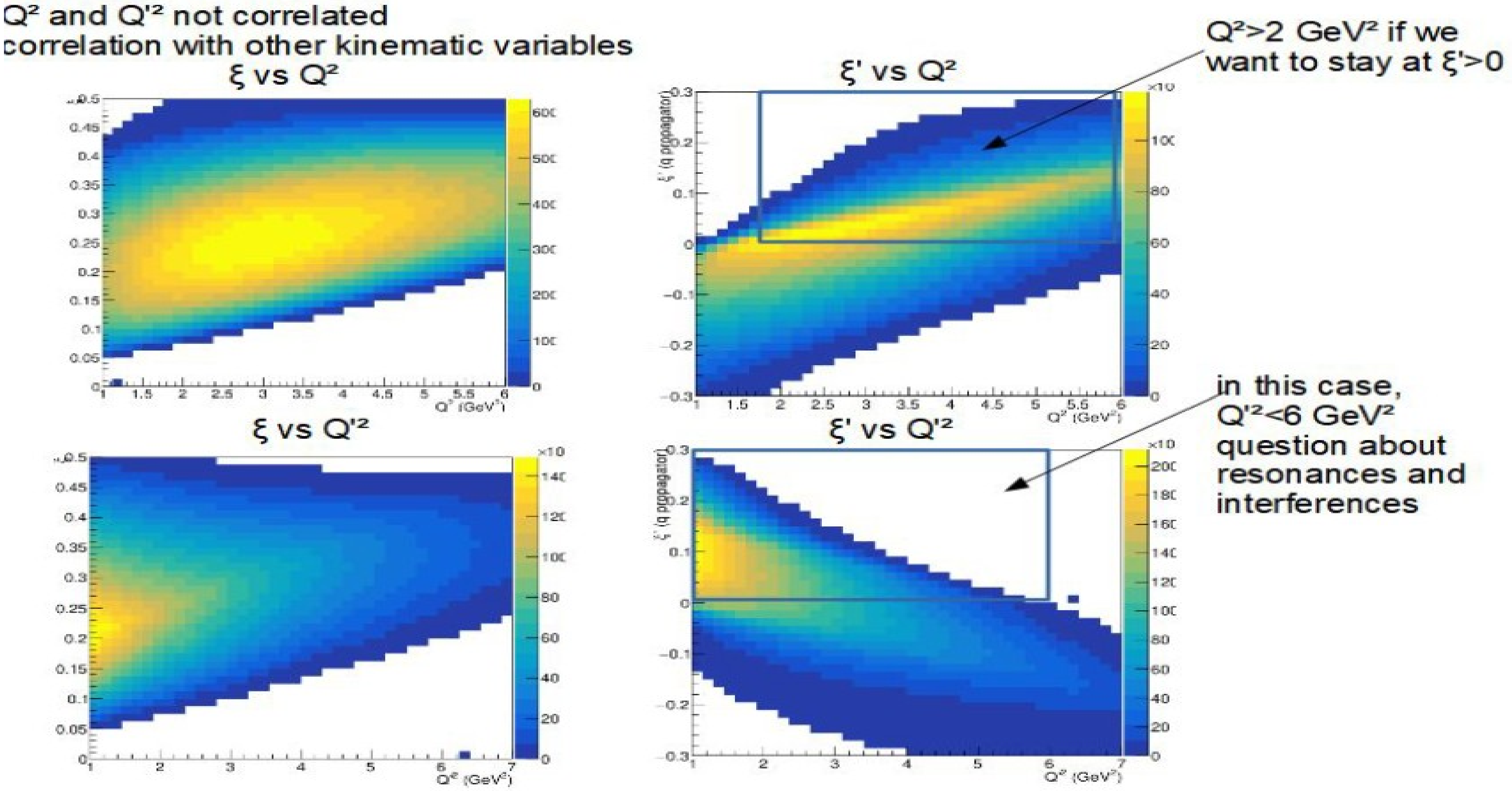
Kinematic region we access with Hall C and setups we are looking for





Kinematic region we access with Hall C and setups we are looking for

Few projections from generated MC : phase space « out of diagonal »

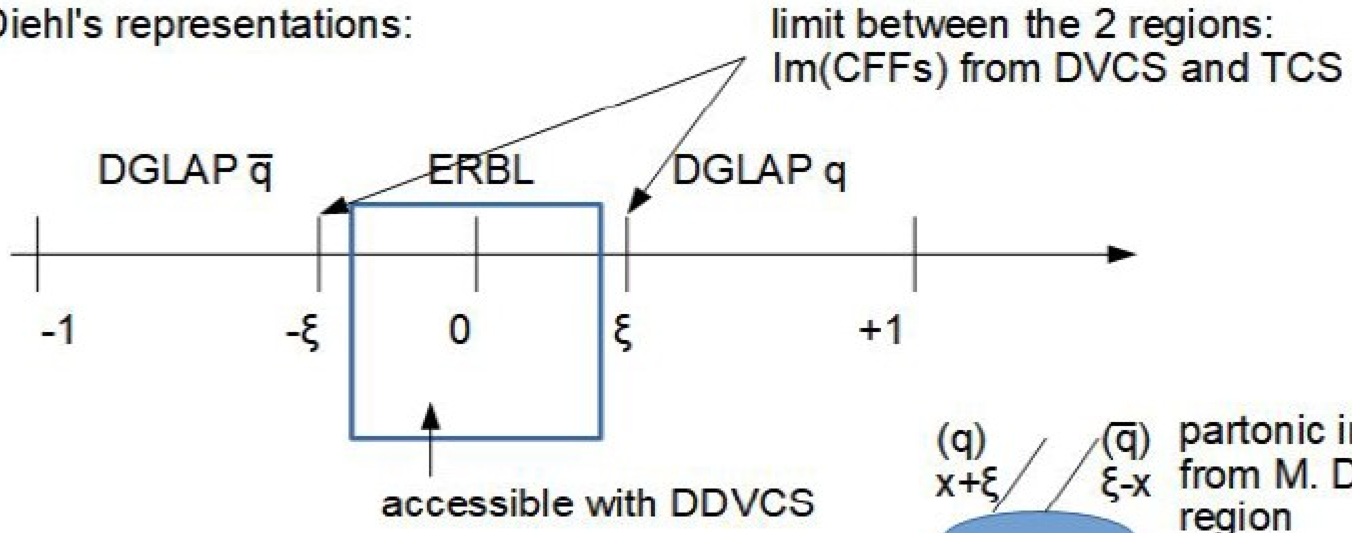


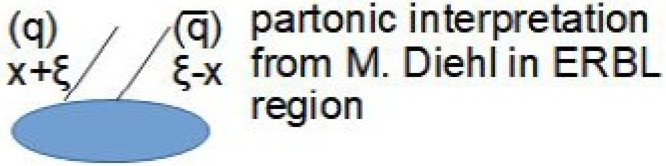
Access non-diagonal part with DDVCS

$\xi>|\xi'|$: ERBL region; $\xi<|\xi'|$ DGLAP region

Quark propagator normalized to ξ at asymtotic limit: $(1-Q'^2/Q^2) / (1+ Q'^2/Q^2)$
$\rightarrow$up to t/Q^2 factor, we play with respective value of Q^2 and Q'^2 to go "out of diagonal" for GPD
$\rightarrow$neglecting t, we are restricted to $\xi>|\xi'|$

M. Diehl's representations:





need to map this region for GPD models and extrapolations needed
for tomographic interpretations at $\xi=0$; GPD extrapolated from $\xi\rightarrow0$

Summary: Why looking at several Compton reactions
And hard exclusive production of mesons together for GPDs ?

Goal : global GPD fits from mesons + Compton-like channels all together

Measurements of vector mesons ($J^p=1^-$ like photon) for complementarity with Compton
& flavor decomposition
- factorization proven (caveat : near threshold not clear)
- high energy enhancement / pomeron exchange

Light vector mesons
- flavor decomposition
- « some » out of diagonal access x vs xi
- complementarity with Compton and already made measurements
- feasible in short term

Heavy mesons, quarkonia
- flavor decomposition + gluons
- not sure of interpretation : non perturbative region near threshold
- possibility to go off diagonal if light meson measuruments prove that we have a way to incorporate meson measurements within Compton-like fits
- photon & electron beam, possibility to demonstrate lepton pair equivalence (or not) + if feasible to reconstruct ee pairs

SUMMARY

- We want to “map” the nucleon inner content (quarks, gluons)
- from 1D to 3D to 5D: functions describing the structure
- Generalized Parton Distributions and tomography

Our JLab current & future plans:

- Timelike Compton Scattering to extract all GPDs & universality

Measurements planned in Hall C, new projections in progress… (see Brannon’s talk)

- Quarkonia (see Erik’s talk near threshold, not shown at higher energy)
- Light vector meson program: flavor decompositon, spin/parity…
- Double Deeply Virtual Compton Scattering: ERBL “meson exchange” region, tomographic interpretations