Delia Hasch

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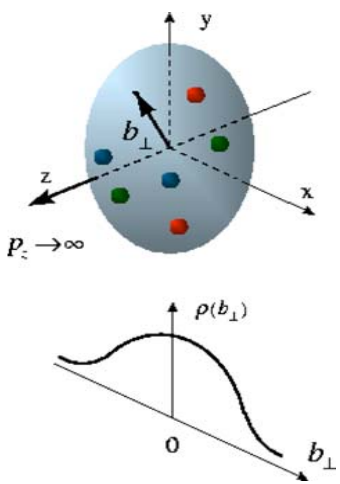
towards a 3D imaging of hadrons: GPDs

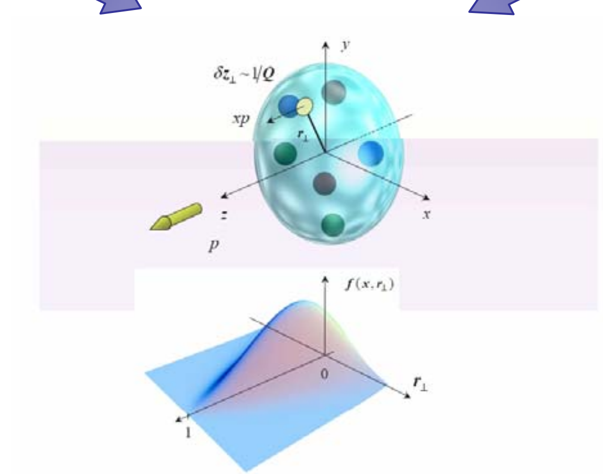
- **a brief introduction (an experimentalists point of view)**
- **a personal selection of recent results**
- **models & data**
- **conclusion & perspectives**

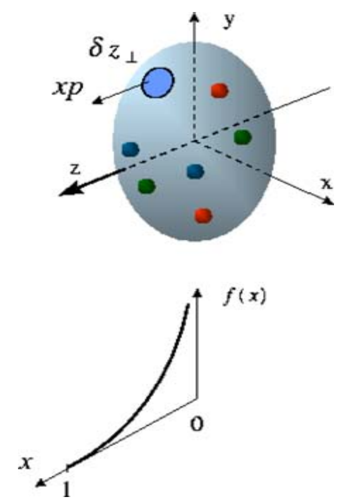
nucleon studied for decades:

form factors
location of partons in nucleon

parton distributions
longitudinal momentum fraction x







generalised parton distributions (GPDs)
longitudinal momentum fraction x at transverse location $b_\perp$

only known framework to gain information on 3D picture of hadrons

why GPDs ?

→ **3D structure of hadrons** : nucleon tomography

nucleon tomography

[M. Burkardt, M. Diehl 2002]

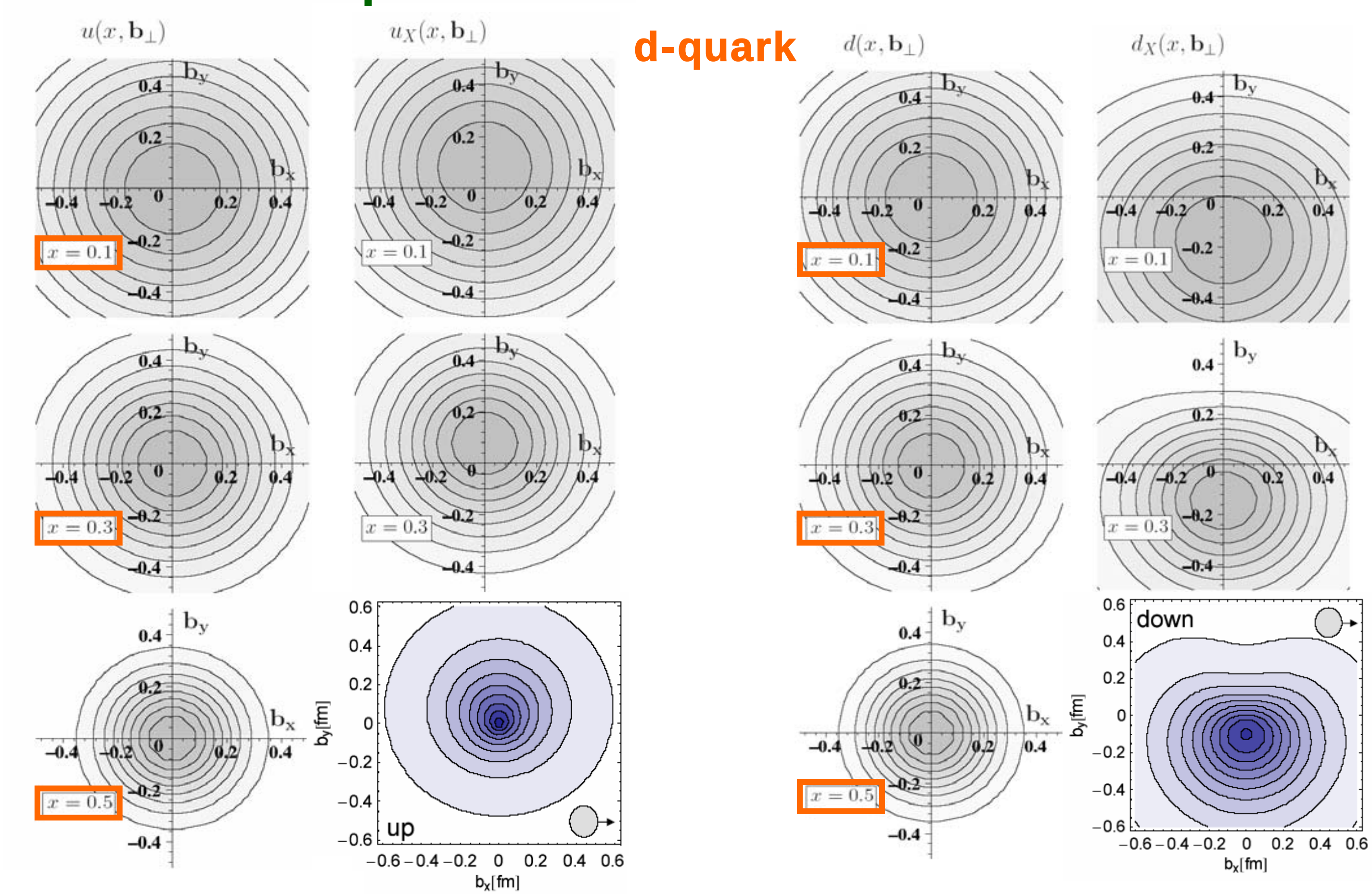
FT (GPD) : momentum space → impact parameter space:

probing partons with specified long. momentum @transverse position $\mathbf{b}_\perp$

polarised nucleon:

u-quark

d-quark



from lattice

why GPDs ?

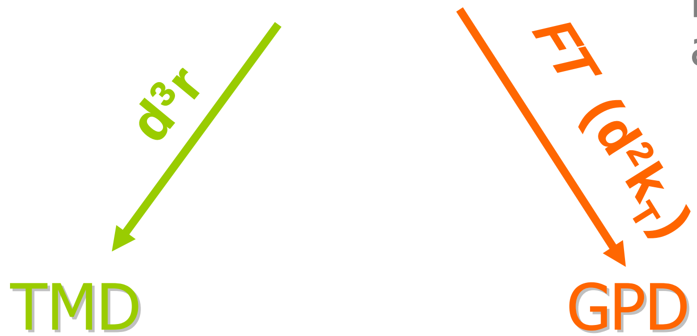
→ **3D structure of hadrons :** nucleon tomography

→ **complementary to TMDs :**

Wigner distribution: ("mother" function)

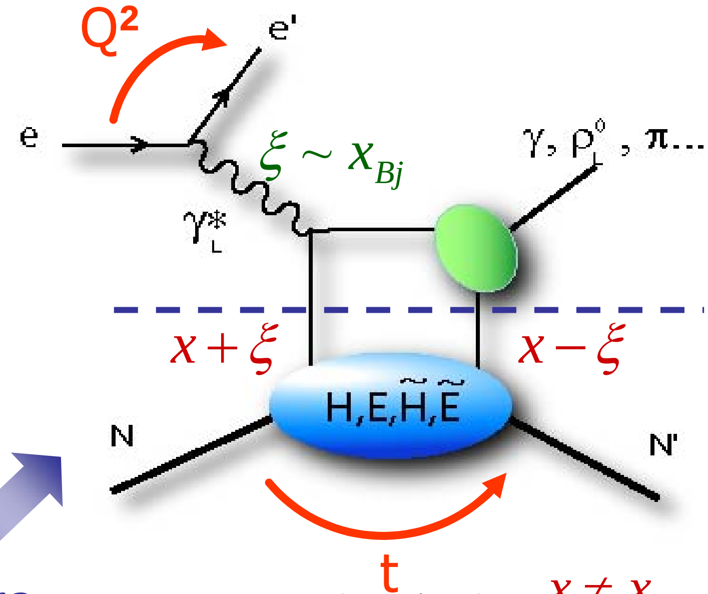
$$W_{\mathrm{p}}^{u}(\vec{r}, k)$$

probability to find a quark **u** in a nucleon **P** with a certain polarisation in a position **r** and momentum **k**



→ **phenomena of single-spin asymmetries**

what do we know about GPDs ?



$\boxed{Q^2 >>, t <<}$

appear in factorisation theorem for *hard exclusive processes*

$H(x,\xi,t)$ $\quad x \neq x_{Bj}$ $\quad \xi \sim x_{Bj}$

form factors

$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1(t)$$

$\vdots$

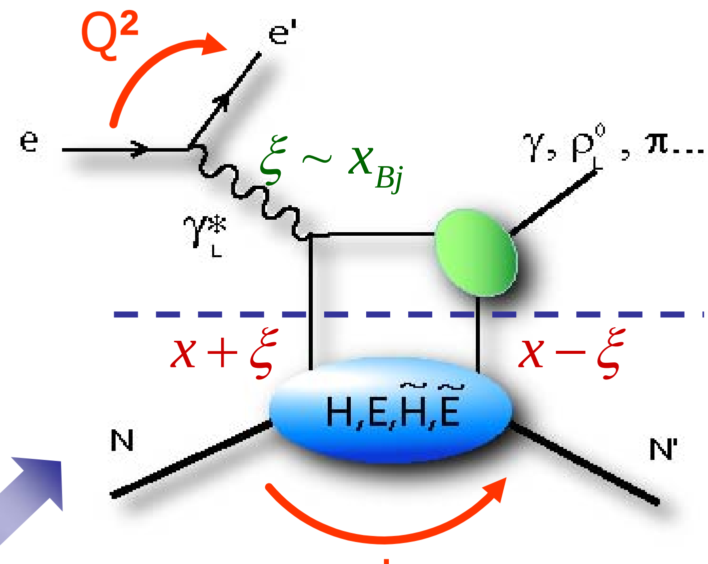
PDFs

$$H^{q,g}(x,0,0) = q(x)$$
$$\widetilde{H}^{q,g}(x,0,0) = \Delta q(x)$$

$E, \widetilde{E}$: *nucleon helicity flip* → don't appear in DIS

→ new information !

what do we know about GPDs ?



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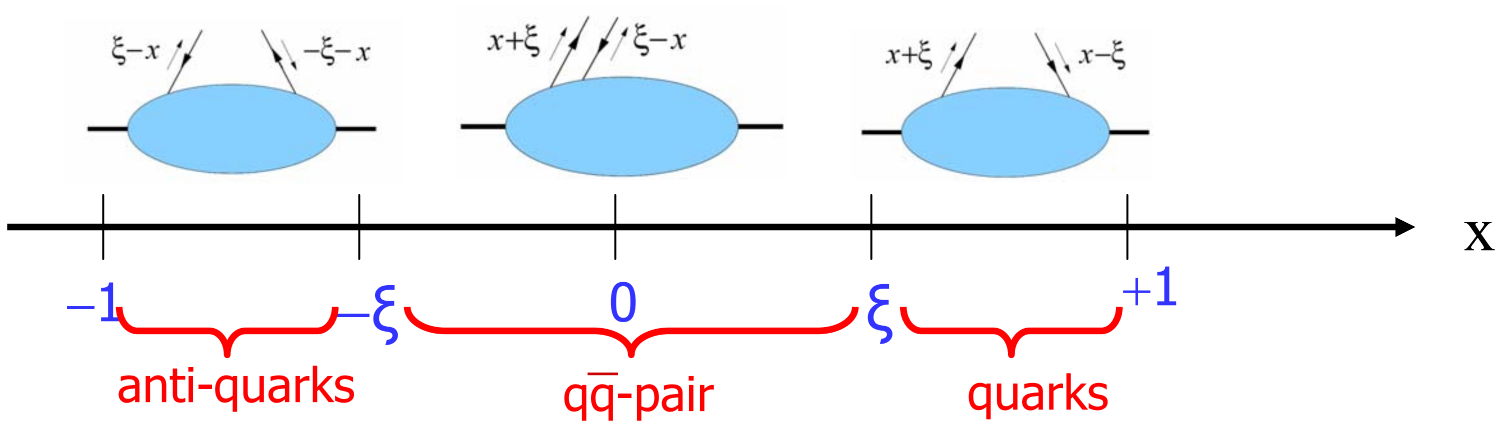
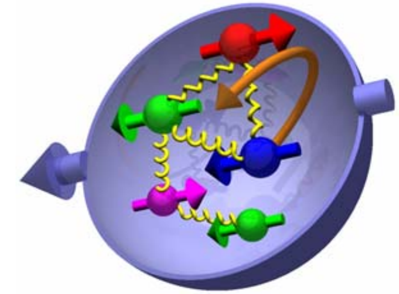


GPDs and the spin puzzle



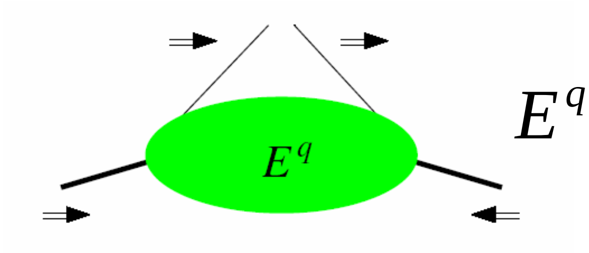
nucleon spin:

$$s_z^n = \frac{1}{2} = \frac{1}{2}\sum_q \Delta q + L_z^q + \Delta G + L_z^g = J_q + J_g$$

≈30% ≈zero

[X. Ji, 1997]

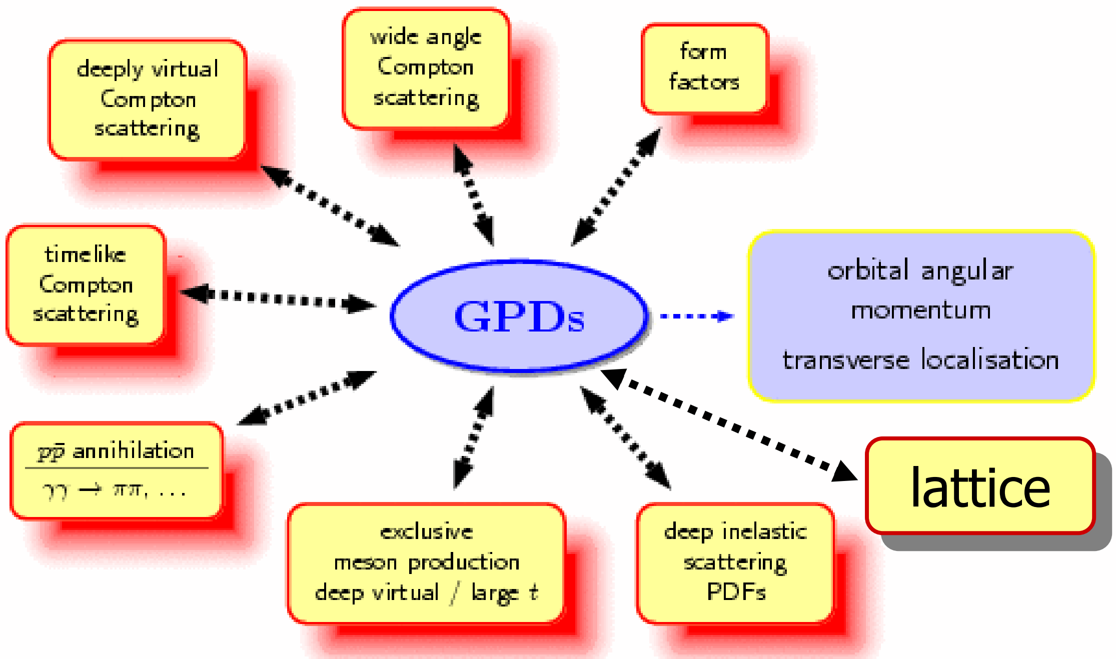
$$J_{q,g} = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} x dx \left[H^{q,g}(x,\xi,t) + E^{q,g}(x,\xi,t) \right]$$



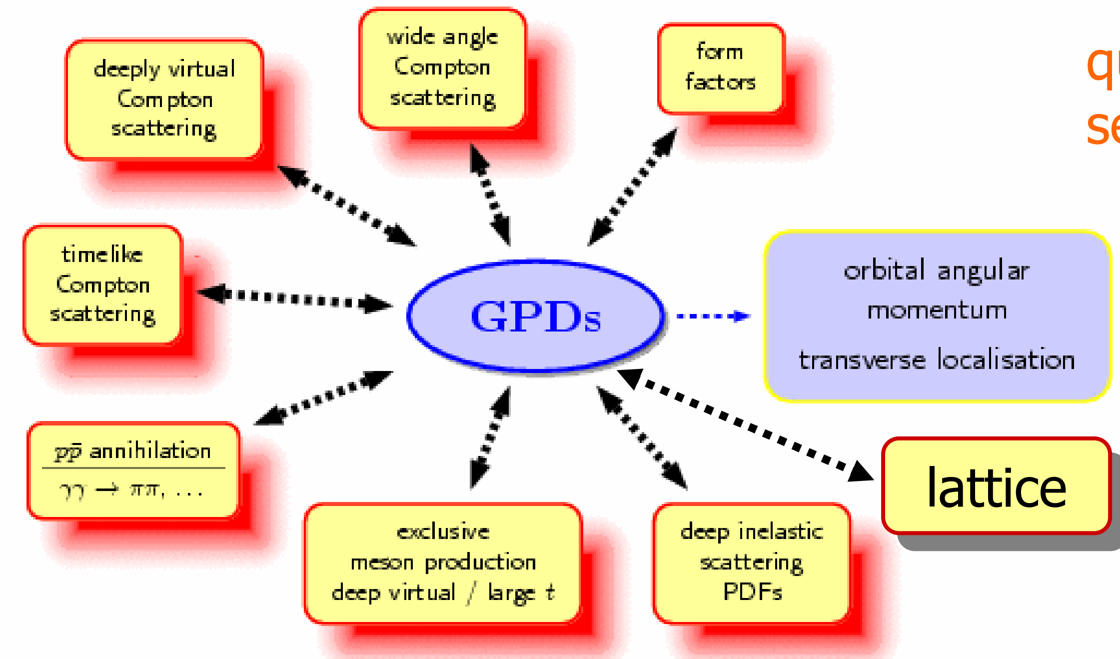
$E^q \neq 0$ *requires* orbital angular momentum

proton helicity flipped but quark helicity conserved

how to access GPDs ?



how to access GPDs ?



quantum number of final state selects different GPDs:

- VM (ρ, ω, ϕ): H E
- PS mesons (π, η): $\tilde{H}$ $\tilde{E}$
- DVCS (γ): H, E, $\tilde{H}$, $\tilde{E}$

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$
ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

→ DVCS most clean process for gaining information on GPDs

→ meson provide info on quark flavours

VM: quark and gluon GPDs appear at same order α_s

accessing GPDs: caveats

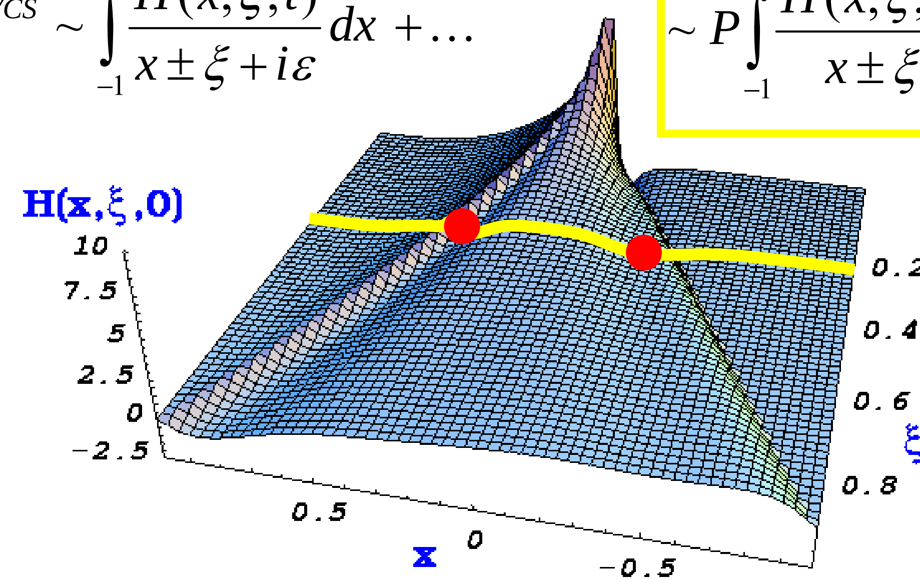
- $H(x,\xi,t)$ but only ξ and t accessible experimentally
- x is mute variable (integrated over):

→ apart from cross-over trajectory (ξ=x) GPDs not directly accessible: deconvolution needed ! (model dependent)

→ GPD moments cannot be directly revealed, extrapolations t → 0 are model dependent

e.g.

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



cross sections & beam-charge asymmetry ~ Re(T^{DVCS})

beam or target-spin asymmetries ~ Im(T^{DVCS})

the ideal experiment for measuring hard exclusive processes

the ideal experiment for measuring hard exclusive processes

- high+variable beam energy
  - → hard regime
  - → wide kinematic range
- high luminosity
  - → small cross sections
  - → measure in 3 kinematic variables simultanously
- complete event reconstruction
  - → ensure exclusivity

... doesn't exist (yet)...

the menu

- data from exclusive VM over wide kinematic range

  JLab → HERMES → COMPASS → HERA-collider

  → role of quarks and gluons

  → NLO corrections

- exclusive PS mesons production

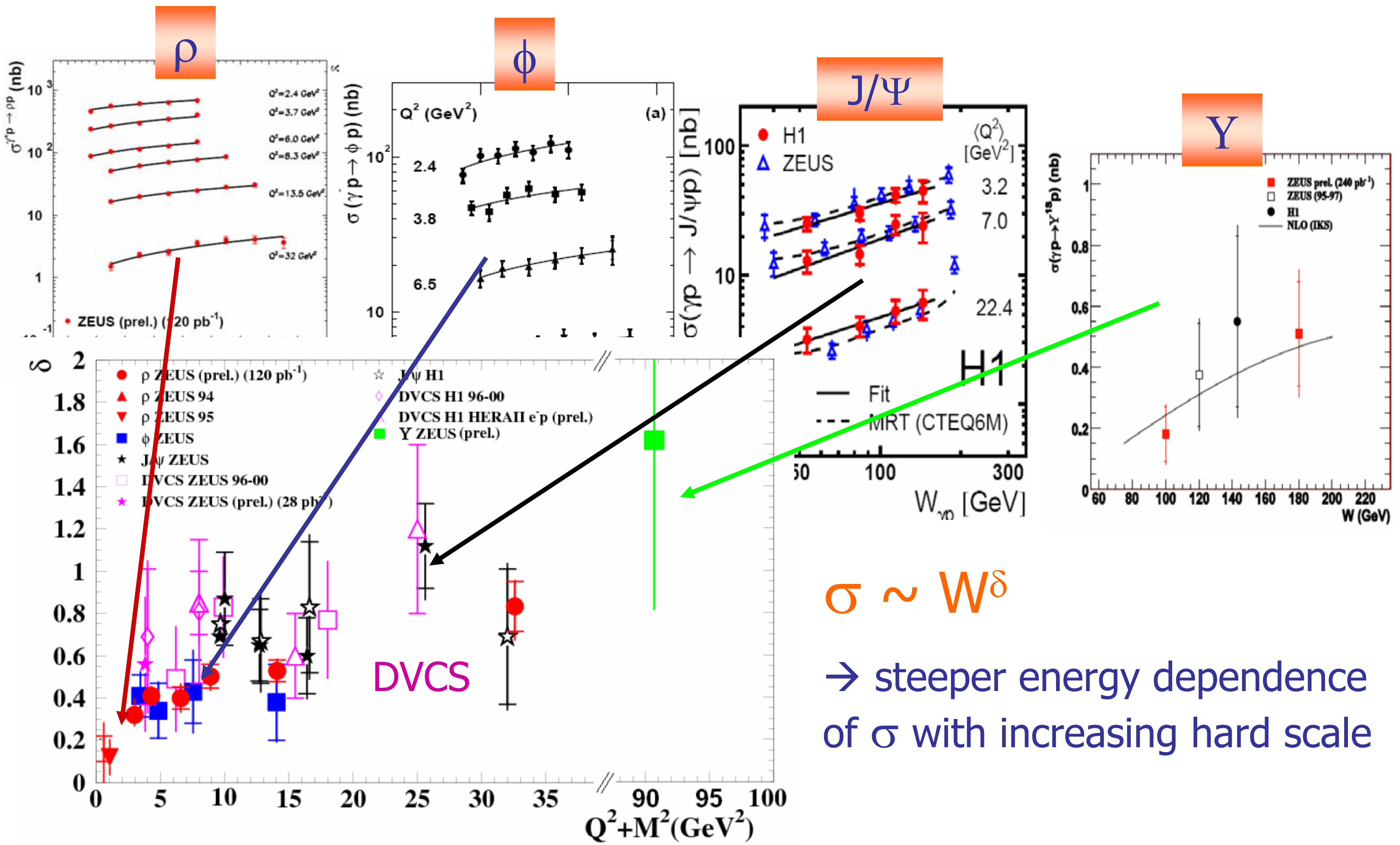
  → role of power corrections

- DVCS: from first signals → detailed measurements

reminder: for meson production factorisation only for σ_L (σ_T suppressed by $1/Q^2$)

VM production @small x

W & *t* **dependences**: probe transition from soft → hard regime

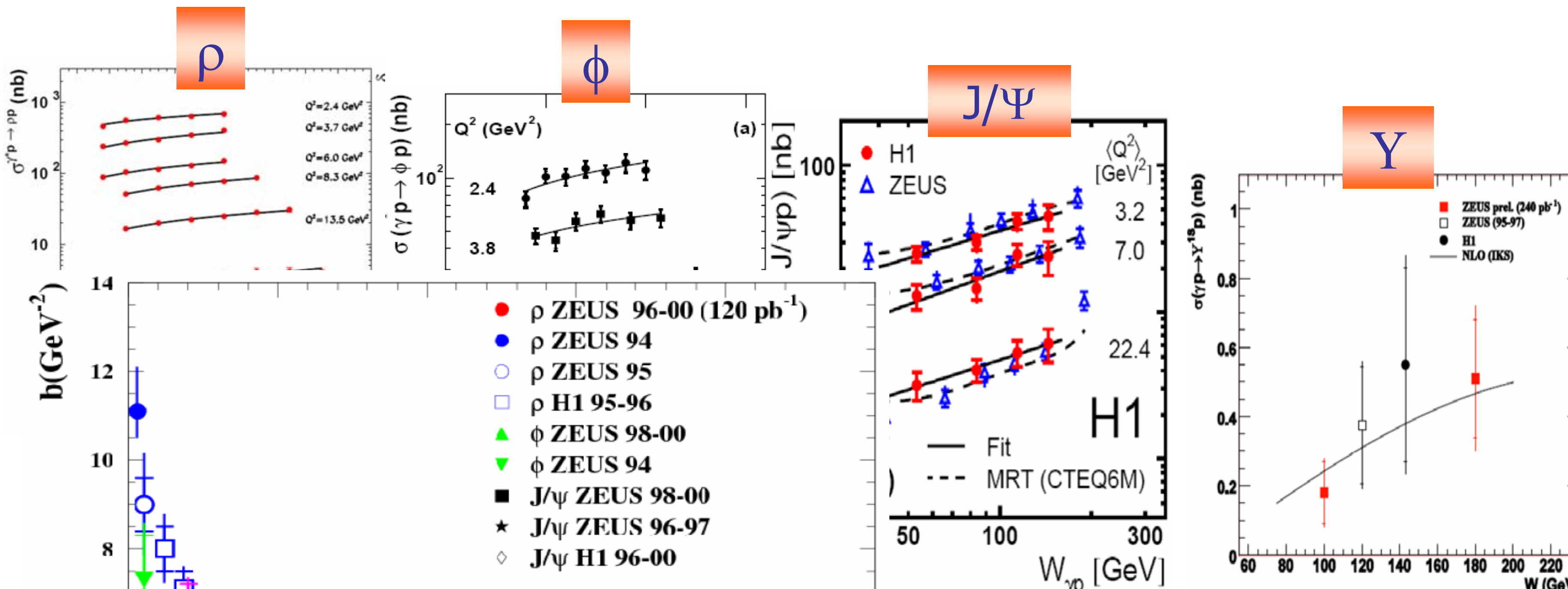


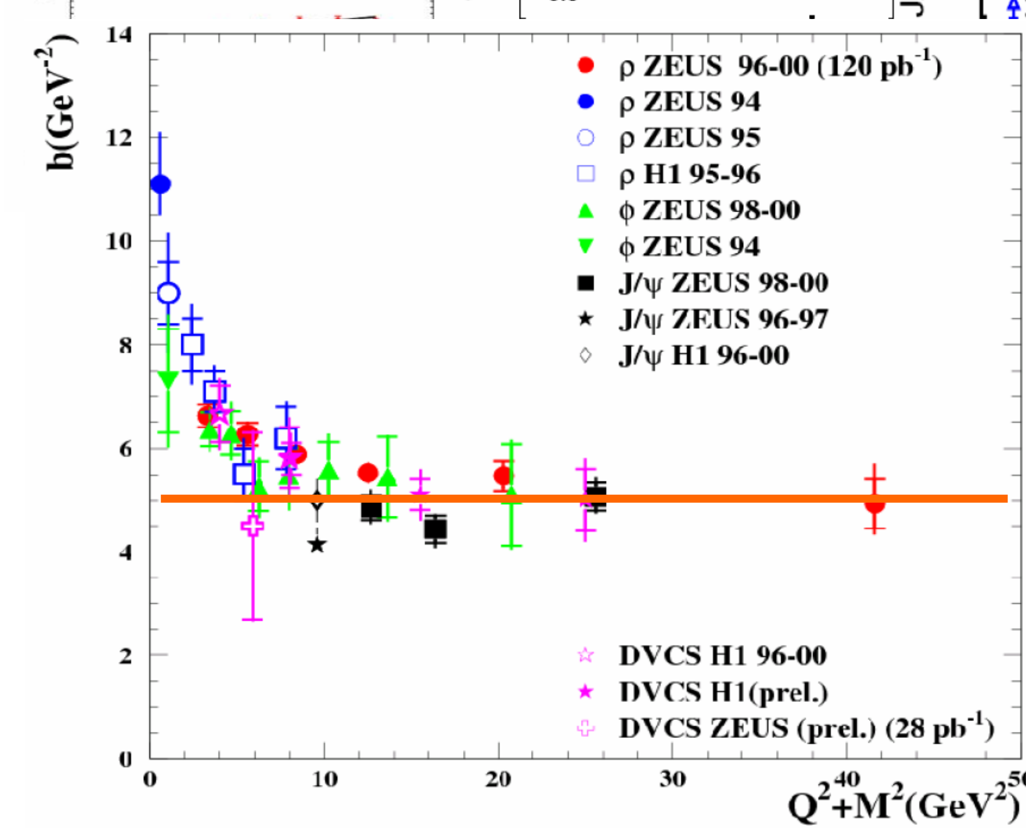
$\sigma \sim W^{\delta}$

→ steeper energy dependence of σ with increasing hard scale

VM production @small x

W & *t* **dependences**: probe transition from soft → hard regime

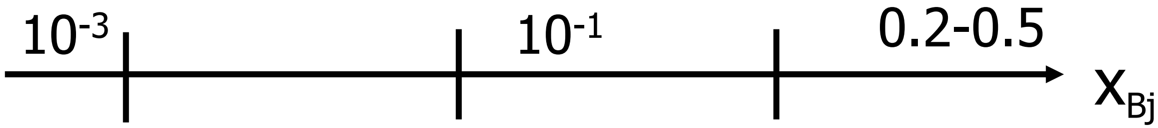




$\sigma \sim e^{-b|t|}$

→ universality of b-slope parameter: point-like configurations dominate

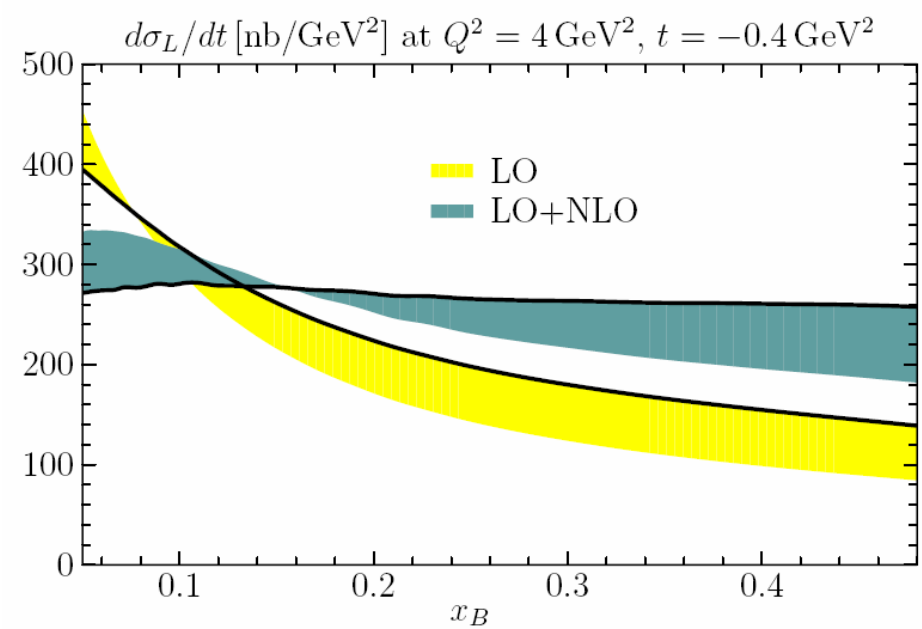
VM production: small → high x



HERA-collider COMPASS/HERMES JLab

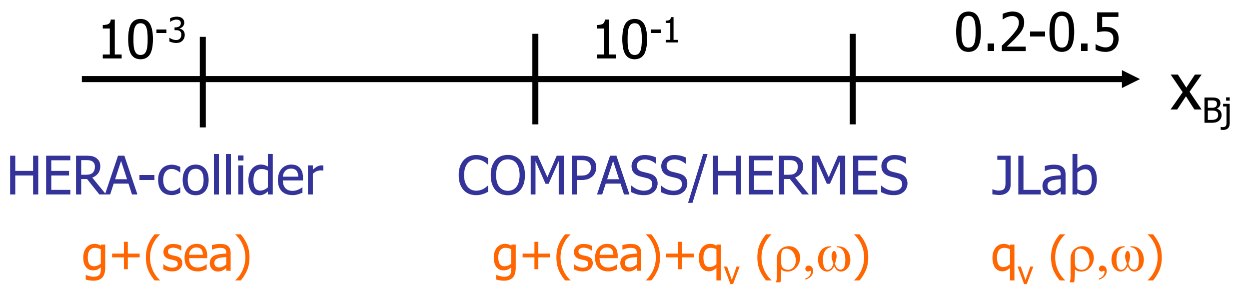
g+(sea) g+(sea)+q_v (ρ,ω) q_v (ρ,ω)

- NLO corrections to VM production are large: [M.Diehl, W.Kugler arXiv0708.1121]

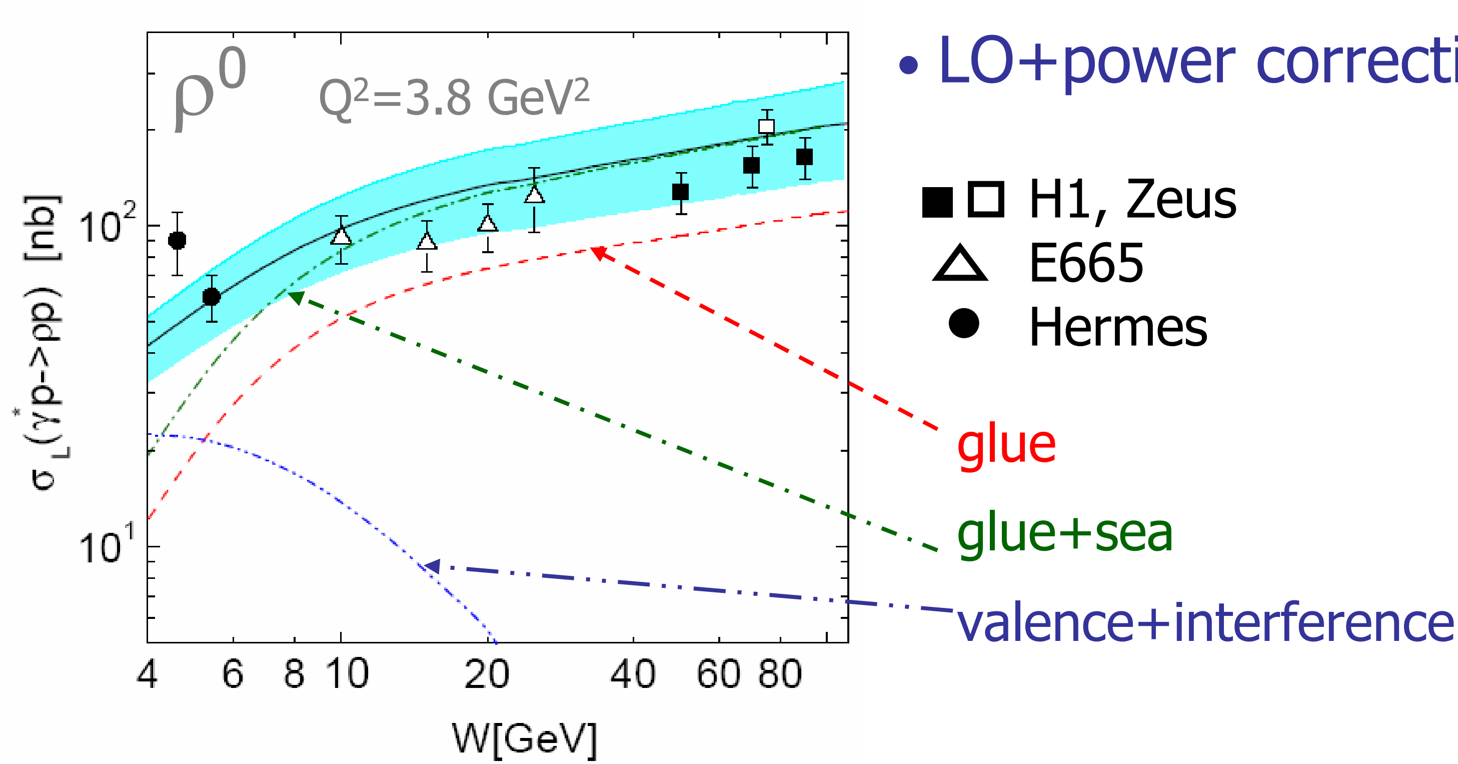


- ρ^0 cross section @typical kinematics of compass / hermes / jlab12

VM production: small → high x



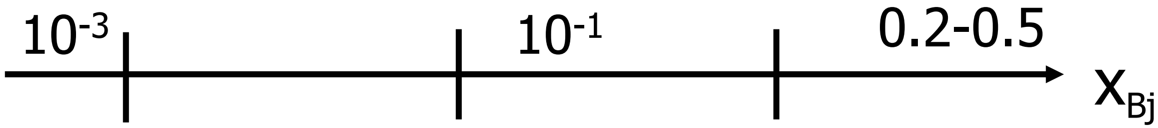
- ...despite: LO GPD model (handbag fact.) [S.Goloskokov, P.Kroll arXiv0711.4736]



- LO+power corrections

■ □ H1, Zeus
△ E665
● Hermes

VM production: small → high x

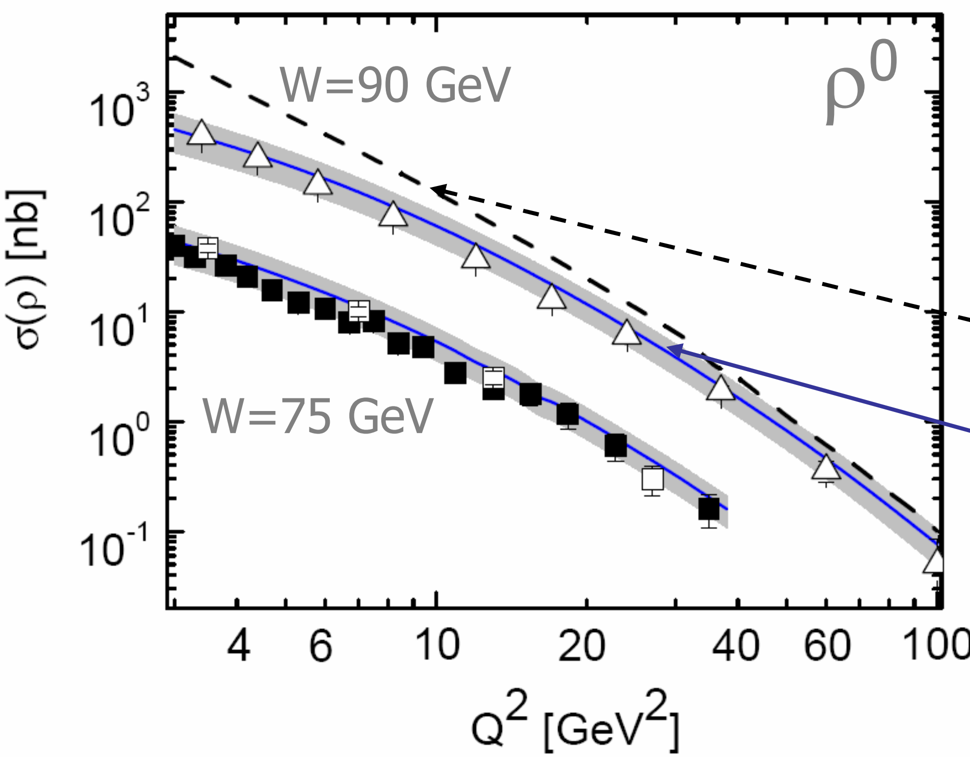


HERA-collider — g+(sea)

COMPASS/HERMES — g+(sea)+q_v (ρ,ω)

JLab — q_v (ρ,ω)

- …despite: LO GPD model (handbag fact.) [S.Goloskokov, P.Kroll arXiv0711.4736]



- LO+power corrections

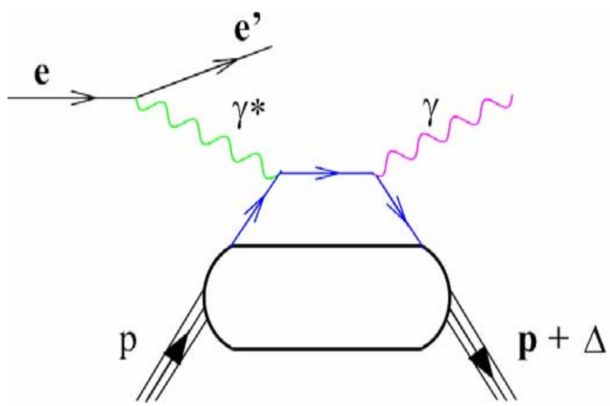
deeply virtual compton scattering

DVCS

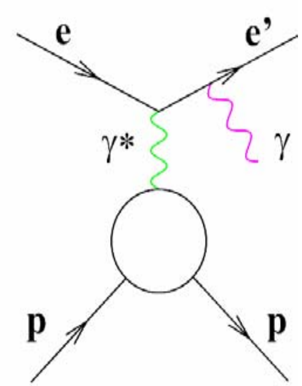
→ $H, \widetilde{H}, E, \widetilde{E}$

most clean channel for interpretation in terms of GPDs (full factorisation proof)

DVCS



Bethe-Heitler



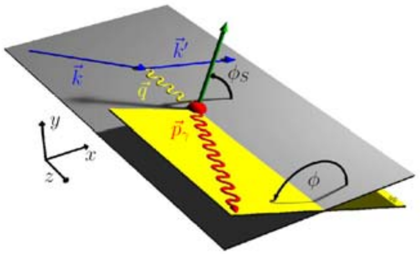
@HERMES/JLab:

DVCS << Bethe-Heitler

$$\frac{d^4\sigma}{dx_B\, dQ^2\, d|t|\, d\phi} \propto |T_{DVCS}+T_{BH}|^2 = |T_{DVCS}|^2 + |T_{BH}|^2 + \underbrace{T_{DVCS}T^*_{BH} + T^*_{DVCS}T_{BH}}_{I}$$

→ leads to non-zero azimuthal asymmetries:

DVCS @amplitude level



$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

$I \sim \Delta\sigma$

→ different charges: e^+ e^- *(only @HERA!):*

$$\Delta\sigma_C \sim \cos\phi \cdot \mathrm{Re}\{\, H + \cancel{\xi \tilde{H}} + \ldots \}$$ ➡ H

→polarisation observables:

$$\Delta\sigma_{LU} \sim \sin\phi \cdot \mathrm{Im}\{H + \cancel{\xi \tilde{H}} + \cancel{kE}\}$$ ➡ H

$\Delta\sigma_{UT}$

beam target

$$\Delta\sigma_{UL} \sim \sin\phi \cdot \mathrm{Im}\{\tilde{H} + \cancel{\xi H} + \ldots\}$$ ➡ $\tilde{H}$

$$\Delta\sigma_{UT} \sim \sin(\phi-\phi_S)\cos\phi \cdot \mathrm{Im}\{k(\cancel{H} - E) + \ldots \}$$ ➡ H, E

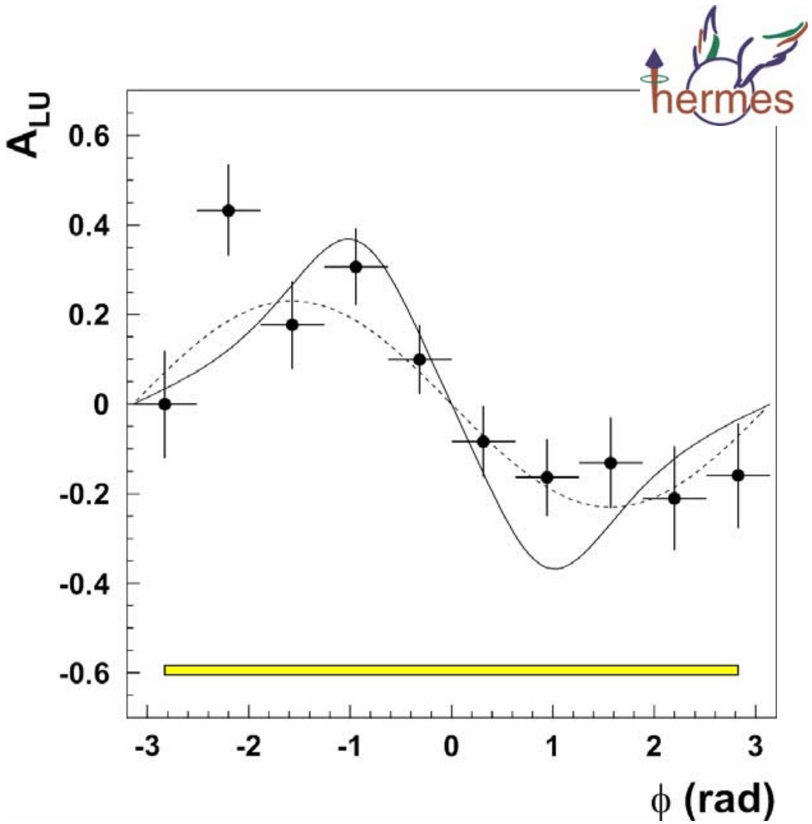
$\xi = x_B/(2-x_B)$, $k = t/4M^2$

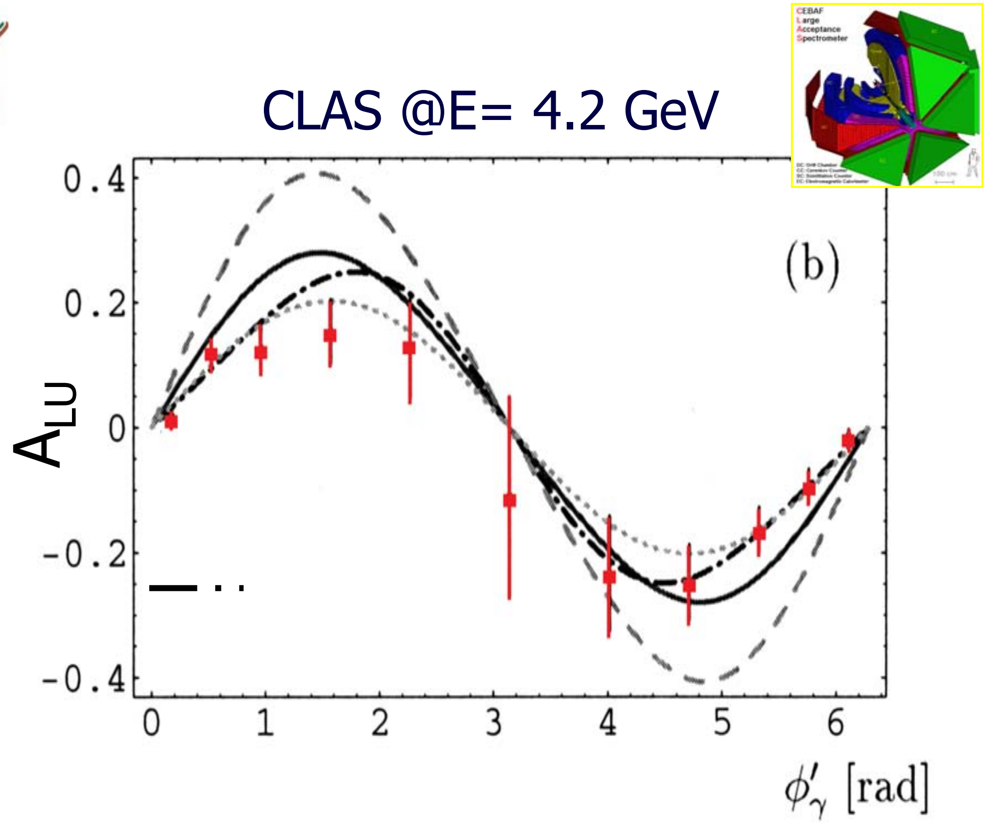
kinematically suppressed @HERMES and JLab energies

first DVCS signals: A_{LU}

-- from interference term --

[PRL87(2001)]

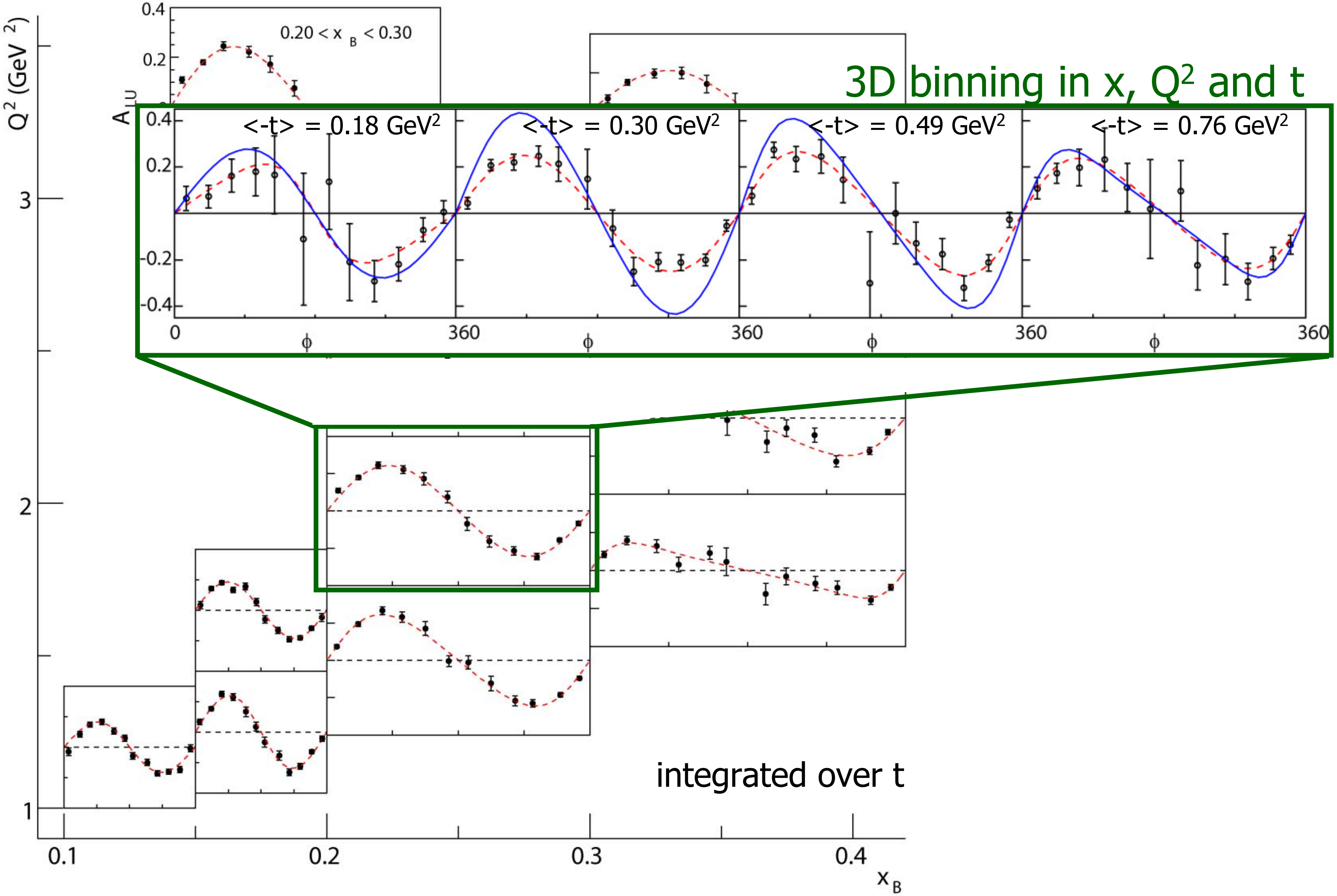




→ sinϕ dependence indicates dominance of handbag contribution

call for high statistics

JLab: E1-DVCS beam-spin asymmetry



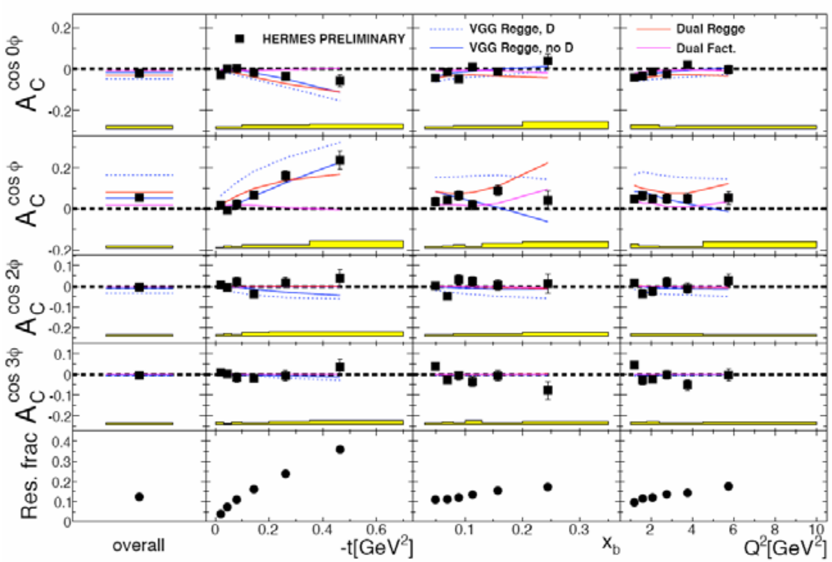
call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ **separation of interference term + DVCS²**

$$\sigma_{\mathrm{LU}}(\phi; P_{\mathrm{l}}, e_{\mathrm{l}}) = \sigma_{\mathrm{UU}}(\phi) \cdot \{1 + P_{\mathrm{l}} A_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + e_{\mathrm{l}} P_{\mathrm{l}} A_{\mathrm{LU}}^{\mathcal{I}}(\phi) + e_{\mathrm{l}} A_{\mathrm{C}}(\phi)\}$$

$$\sum_{n=1}^{2} s_n^{\mathrm{I}} sin(n\phi) \qquad \sum_{n=0}^{3} c_n^{I} cos(n\phi)$$



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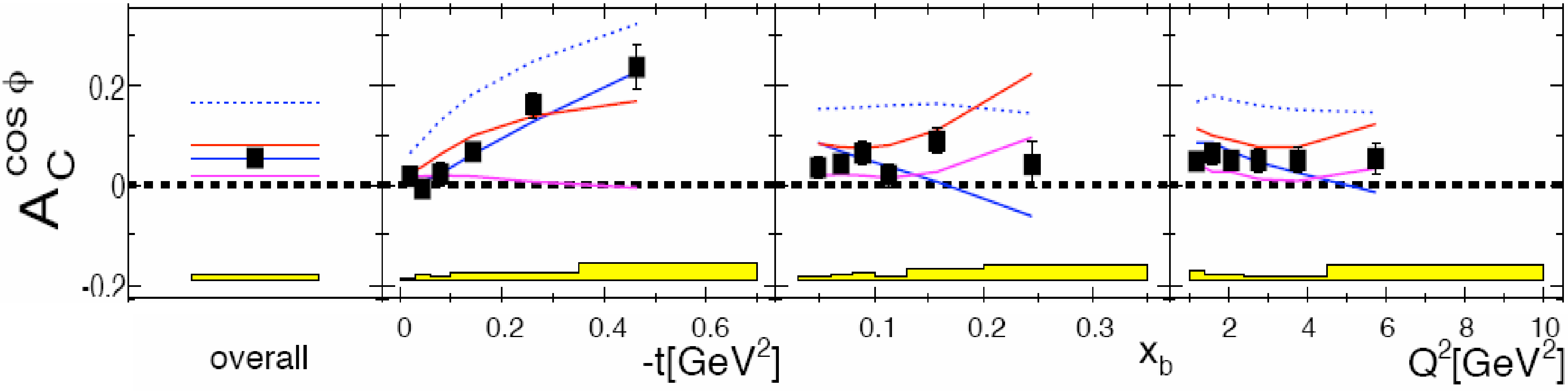
HERMES: combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS²

beam *charge* asymmetry: HERMES preliminary $\propto \mathrm{Re}[F_1\mathcal{H}]$



GPD models: VGG — w/o D-term / with D-term — regge-ansatz for t-depend.

dual — regge-ansatz for t-dependence / factorised t-dependence

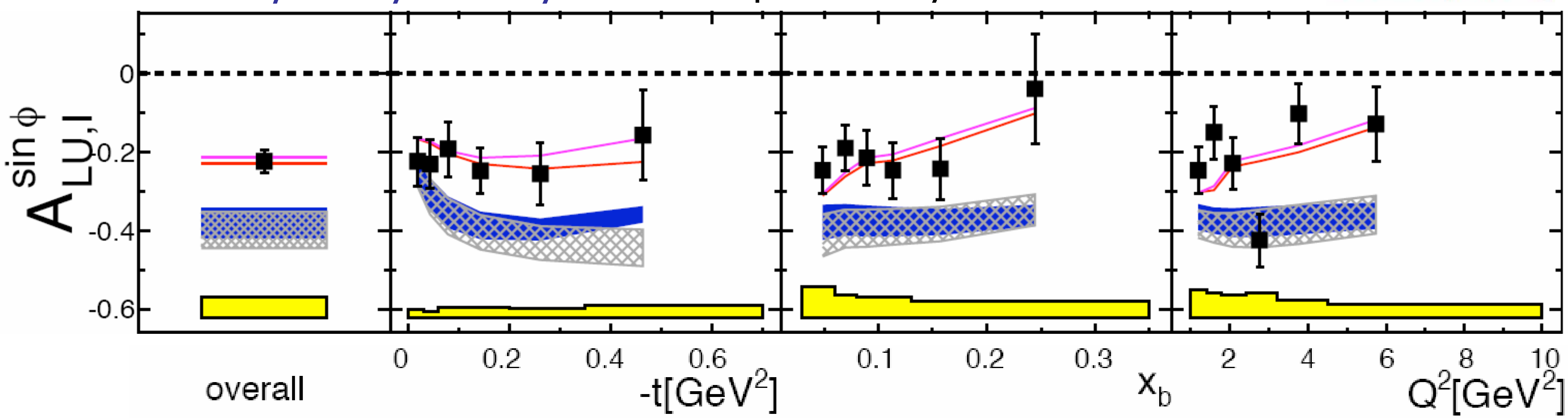
[Guzey, Teckentrup 2006]

call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ separation of interference term + $DVCS^2$

beam *spin* asymmetry: HERMES preliminary $\propto Im[F_1\mathcal{H}]$



GPD models: VGG — regge-ansatz for t-dependence; factorised t-dependence

dual — regge-ansatz for t-dependence; factorised t-dependence

a word about GPD models

VGG: [Vanderhaegen, Guichon, Guidal 1999]

- double distributions ; factorised or regge-inspired t-dependence
- D-term to restore full polynomiality
- skweness depending on free parameters b_{val} & b_{sea}
- includes tw-3 (WW approx)

dual: [Guzey, Teckentrup 2006]

- GPDs based on infinite sum of t channel resonances
- factorised or regge-inspired t-dependence
- tw-2 only

a word about GPD models

VGG: [Vanderhaegen, Guichon, Guidal 1999]

- double distributions ; fa
- D-term to restore full po
- skweness depending on
- includes tw-3 (WW appro

→ describes well A_C and A_{UT} data
→ fails for A_{LU}
→ A_c favour 'no D-term' ← contradicts χQSM & lattice results

dual: [Guzey, Teckentrup 2006]

- GPDs based on infinite s
- factorised or regge-inspi
- tw-2 only

→ describes well spin-asymmetries
→ fails for unpol. cross sections (HallA)

→ call for new, more sophisticated parametrisations of GPDs

… more models on the way: e.g. generalisation of Mellin transform technique

…nevertheless: first attempts to constrain J_q

observables sensitive to E:

(J_q input parameter in ansatz for E)

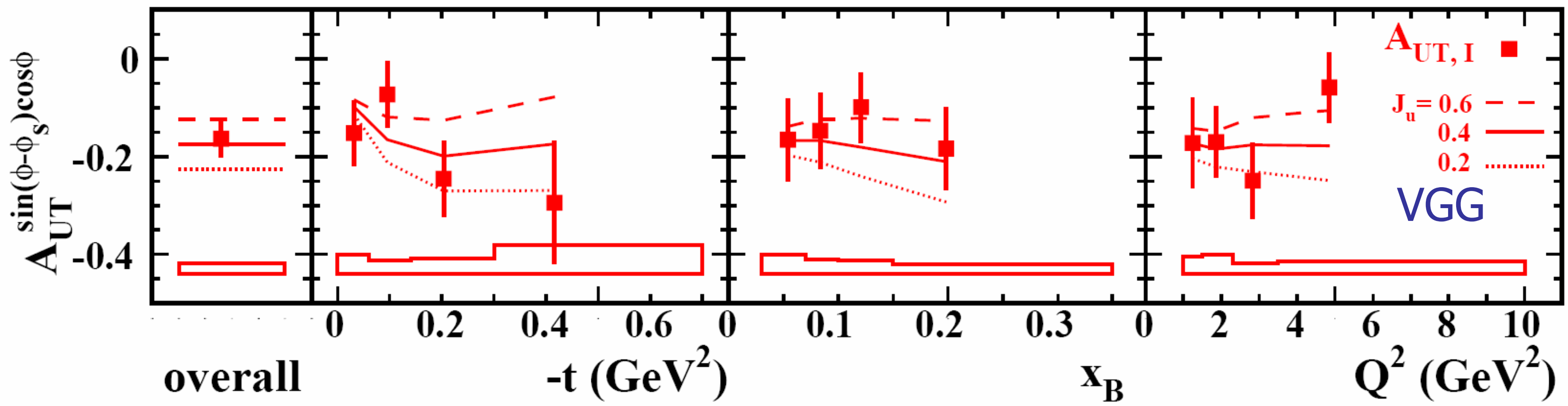
$$J_q = \frac{1}{2}\int_{-1}^{1} x\,dx\,\left(H^q + E^q\right)$$

- DVCS A_{UT} : HERMES
- nDVCS A_{LU} : Hall A
- ρ^0 A_{UT} : HERMES

…nevertheless: first attempts to constrain J_q

J_q input parameter in ansatz for E:

[JHEP06(2008)]



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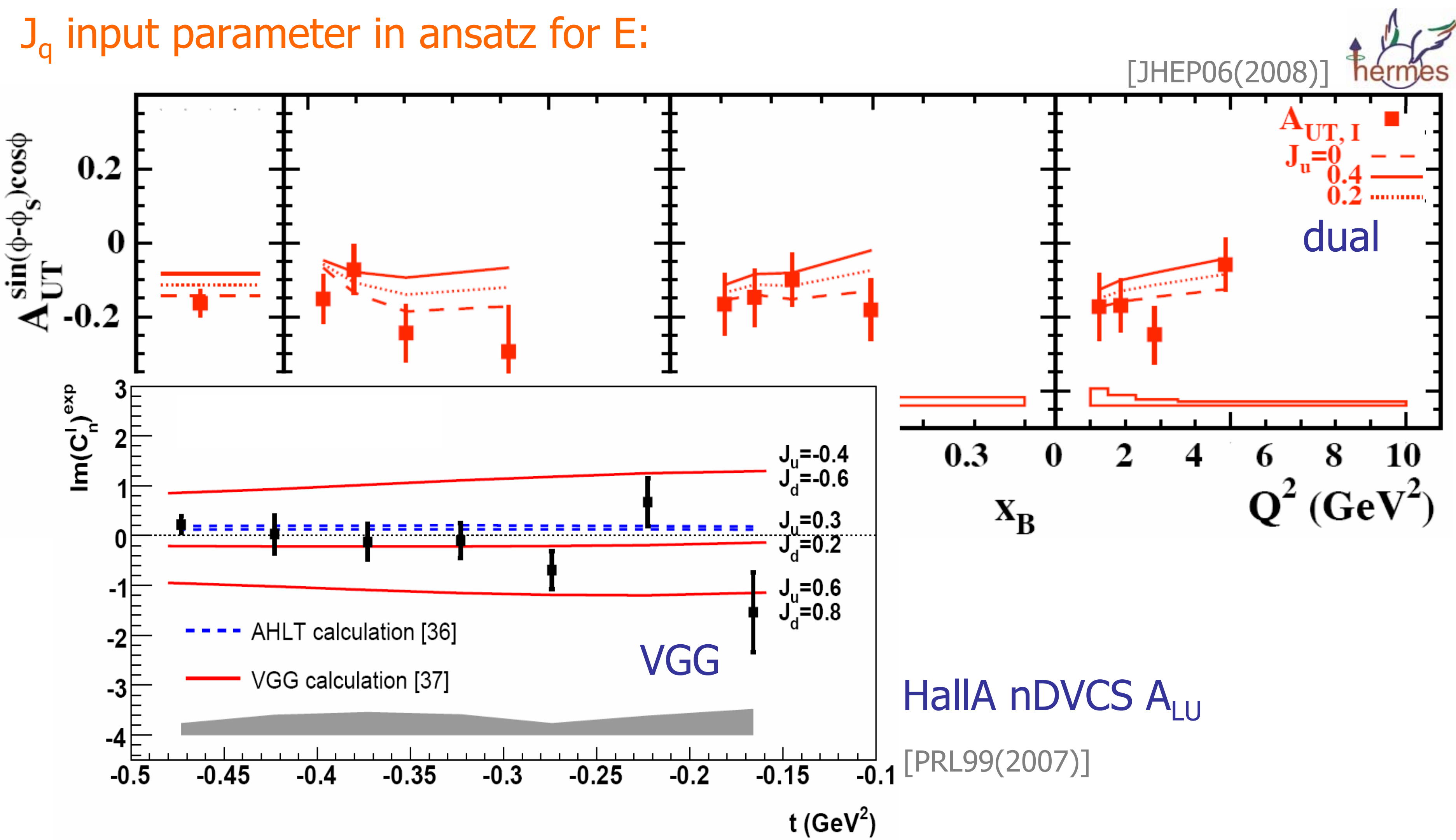
[JHEP06(2008)]

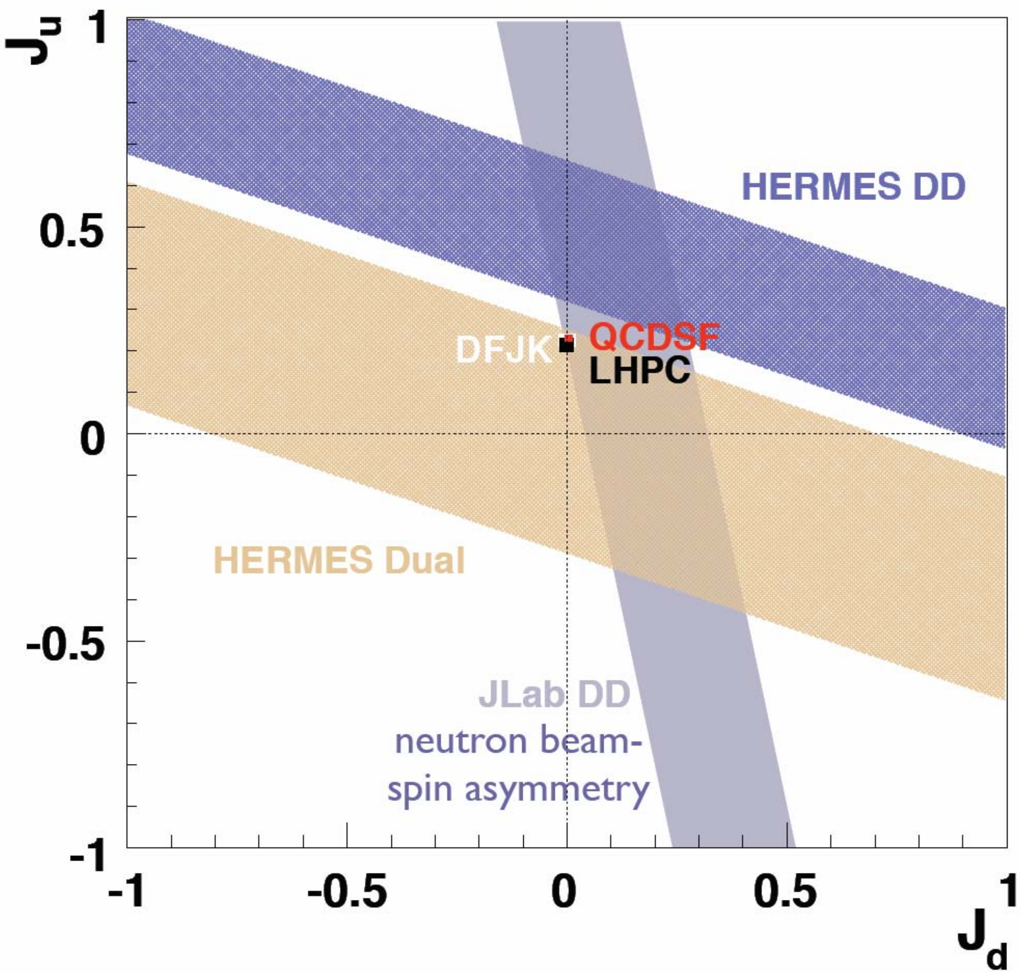


HallA nDVCS A_{LU}

[PRL99(2007)]

…nevertheless: first attempts to constrain J_q

J_q input parameter in ansatz for E:



→ demonstrates model dependence of these analyses

→ data are free to be re-used at any time with new models ☺

conclusions

GPDs

contain a wealth of new information on hadron structure at parton level

→ only known framework allowing a 3D imaging of hadrons ←

... BUT they are intricate functions...

complementary to TMDs : relations GPDs ←→ TMDs [M. Burkardt, M. Schlegel]

GPDs offer a way to measure transversity!

→see talk by G. Goldstein

- increasing amount and precision of experimental data
- large “flow” of new data expected soon (JLab, HERMES, COMPASS)
- ‘standard’ models/parametrisations of GPDs too simple

  → models should describe large variety of different observables over wide kinematic range

prior to any conclusion about GPDs from data: call for new, more sophisticated parametrisations

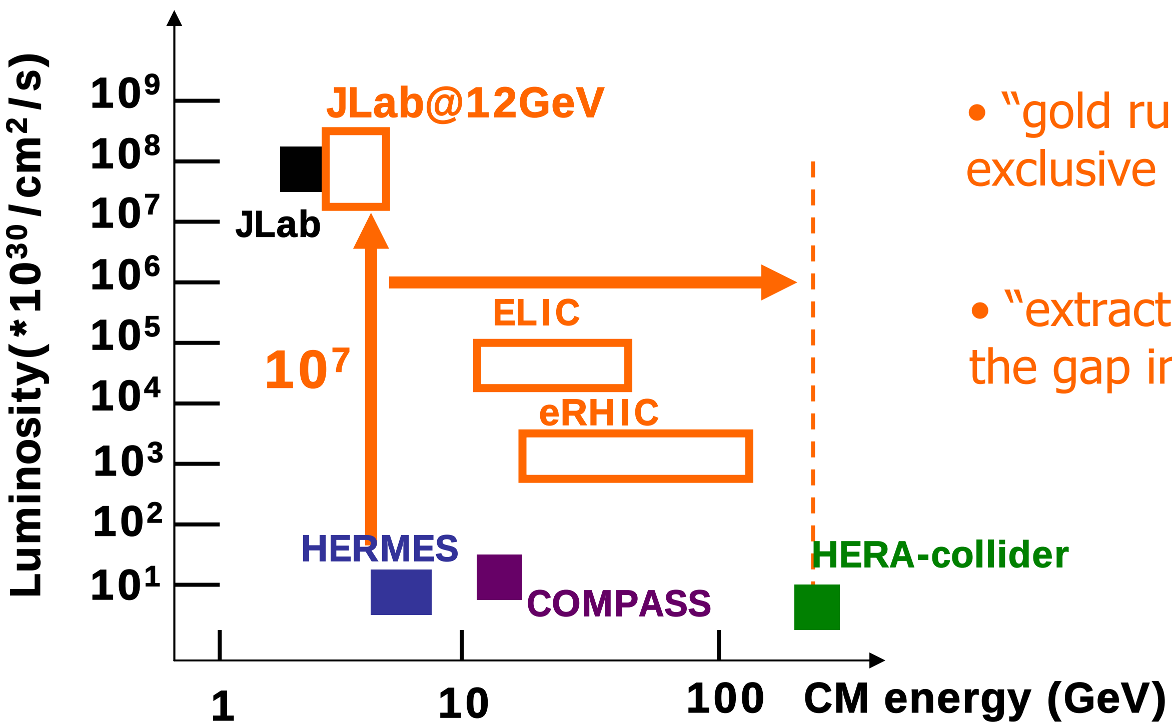
perspectives for GPDs

@ new facilities:

- high beam energy (hard regime, wide kinematic range)
- very high luminosity (small xsections, multi-D analyses)
- complete event reconstruction (ensure exclusivity)

→ exploration of new channels: WACS, time like DVCS, ...

→ ideas for accessing GPDs @LHC, @GSI, ...



- "gold rush" for studying hard exclusive processes & GPDs
- "extraction" of GPDs requires filling the gap in kinematic coverage

perspectives for GPDs & TMDs

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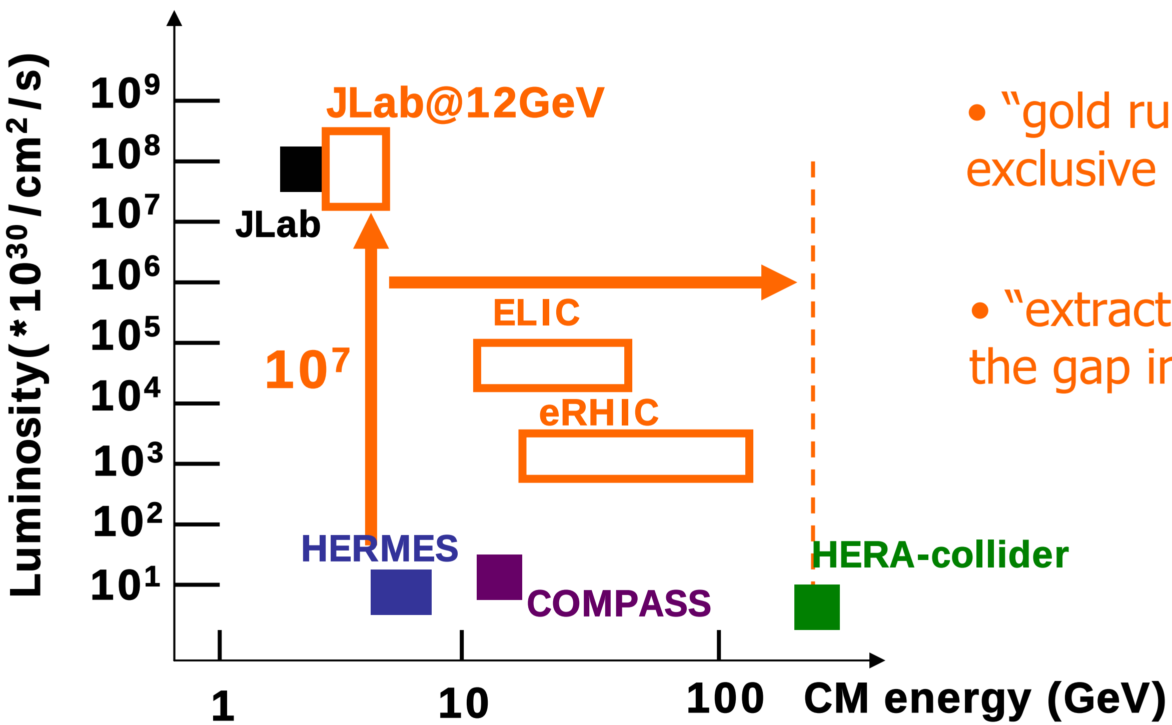

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