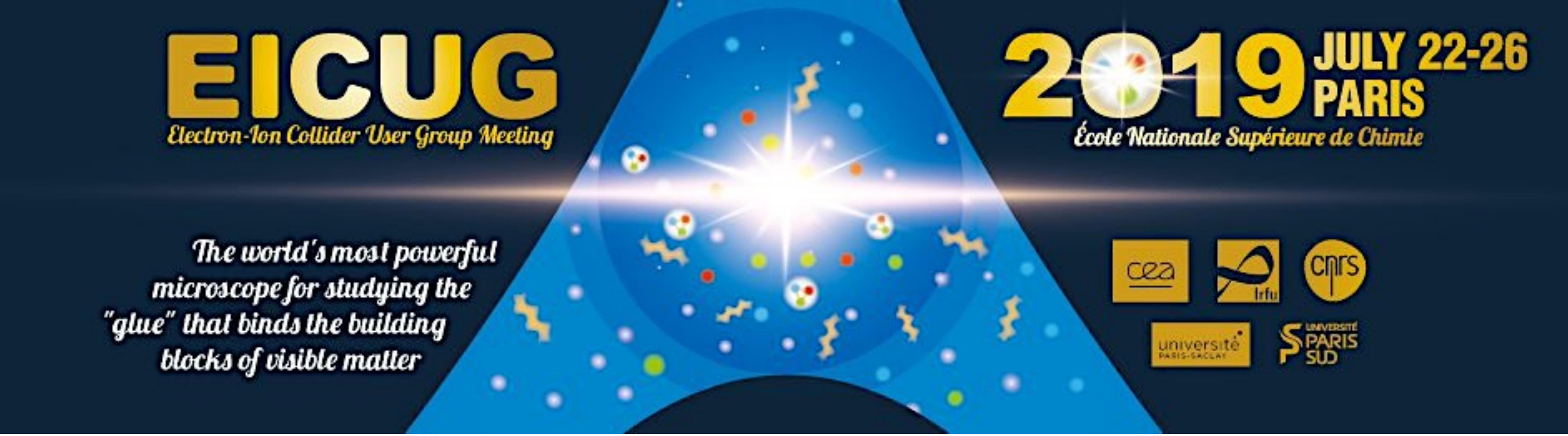

Summary Talk of Parallel Sessions
Theory Talks, Tuesday & Thursday

Bruno El-Bennich
Laboratório de Física Teórica e Computacional
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Universidad Estadual Paulista, São Paulo

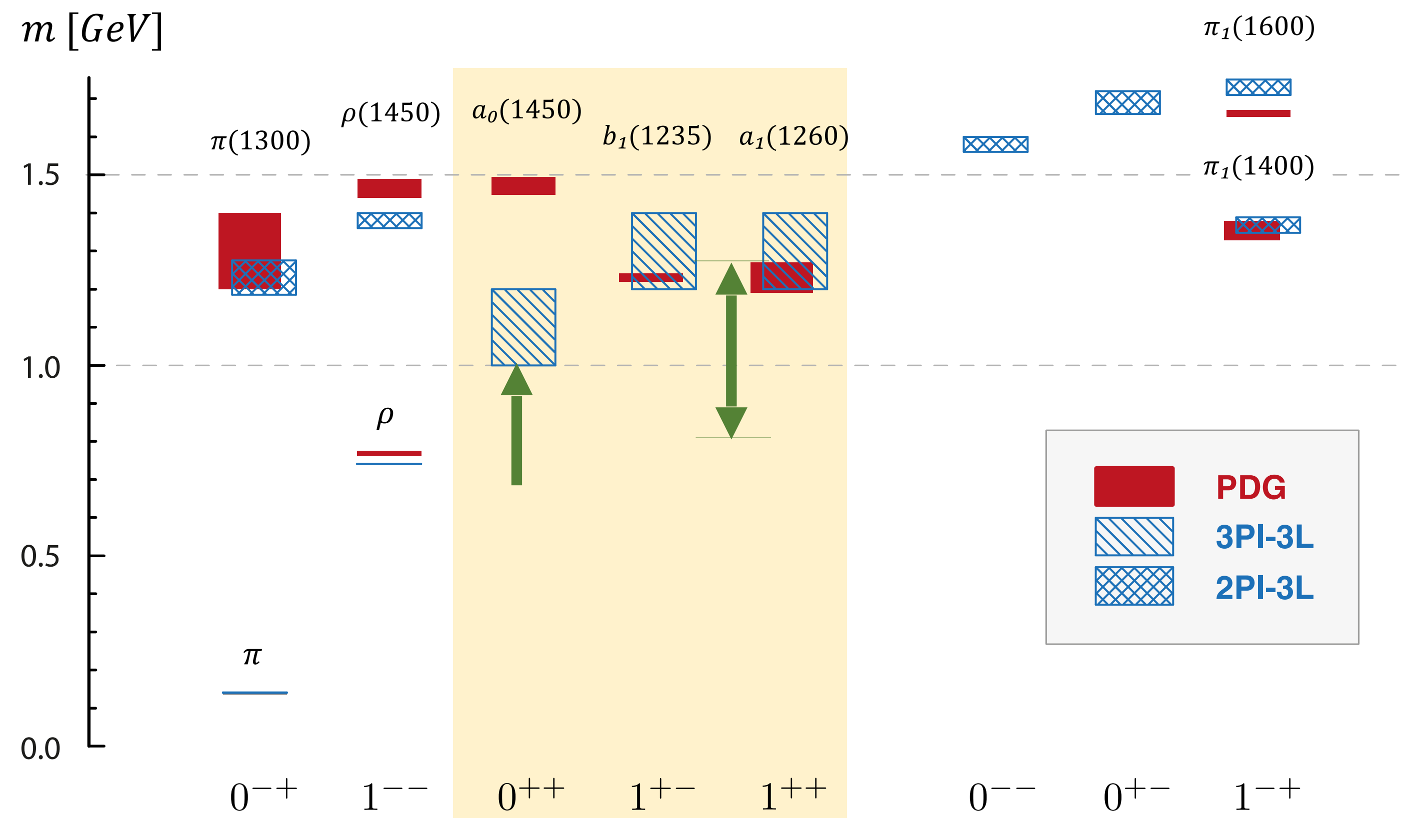
FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

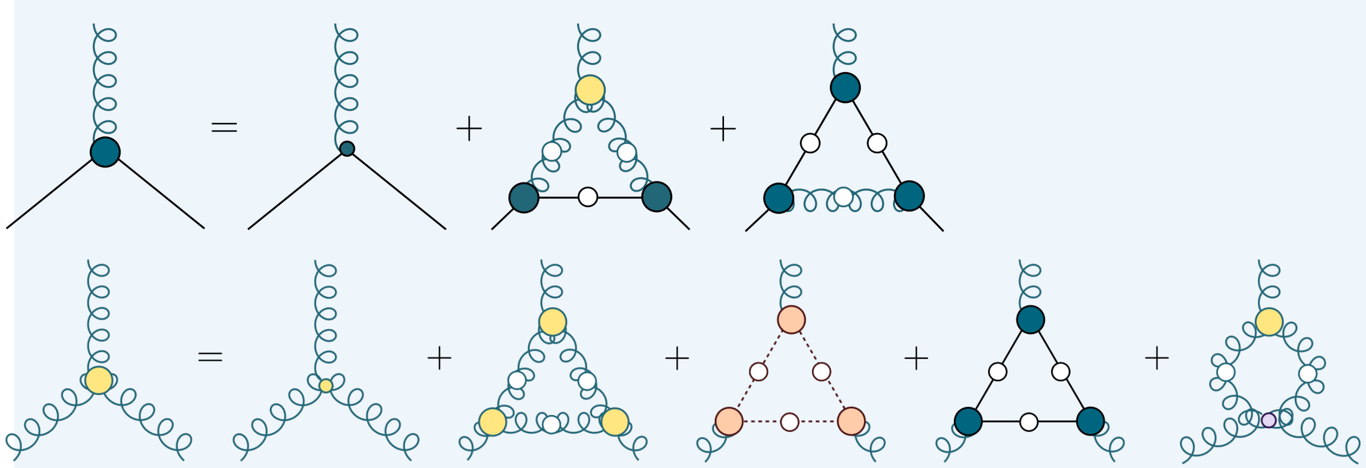
CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

Richard Williams — *"Topics in QCD from Dyson-Schwinger Equations"*

Switching from 2PI-2loop (Rainbow-Ladder) to 3PI-3loop

- Corrects $\rho - a_1$ splitting and degeneracy of axial-vectors.
- Pushes lightest $q\bar{q}$ scalar above 1 GeV.





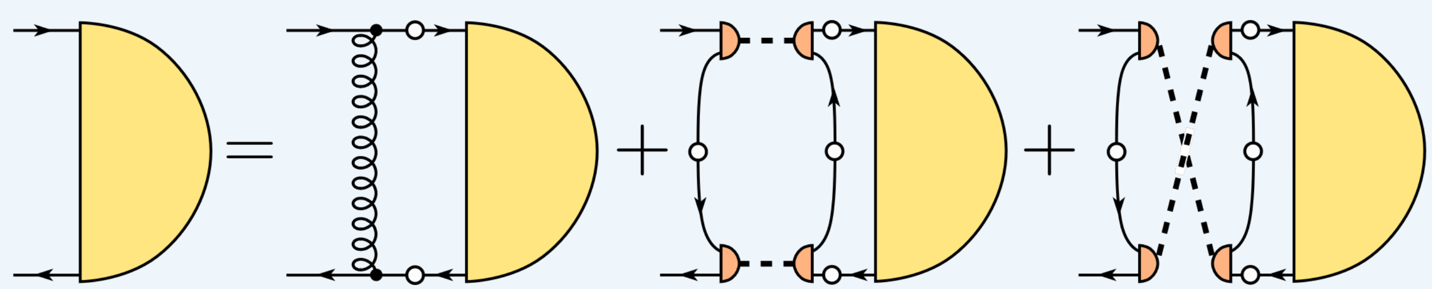
Interaction vertices explicit d.o.f in 3PI approach.

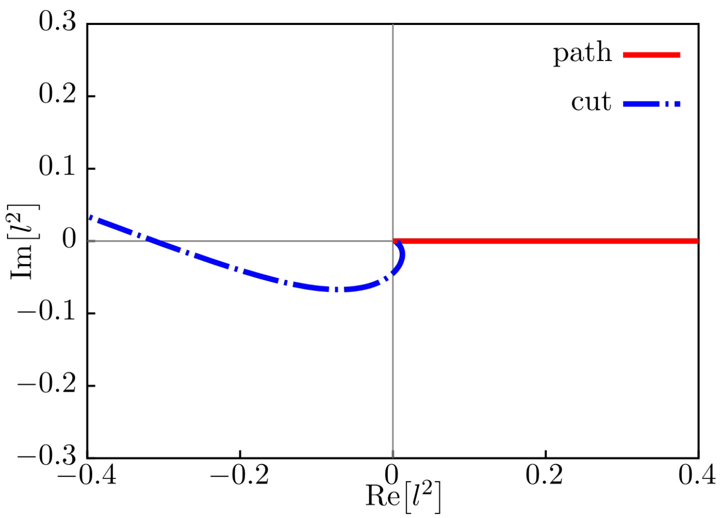
Less modelling.

Parameters are coupling g and the quark masses m_i.

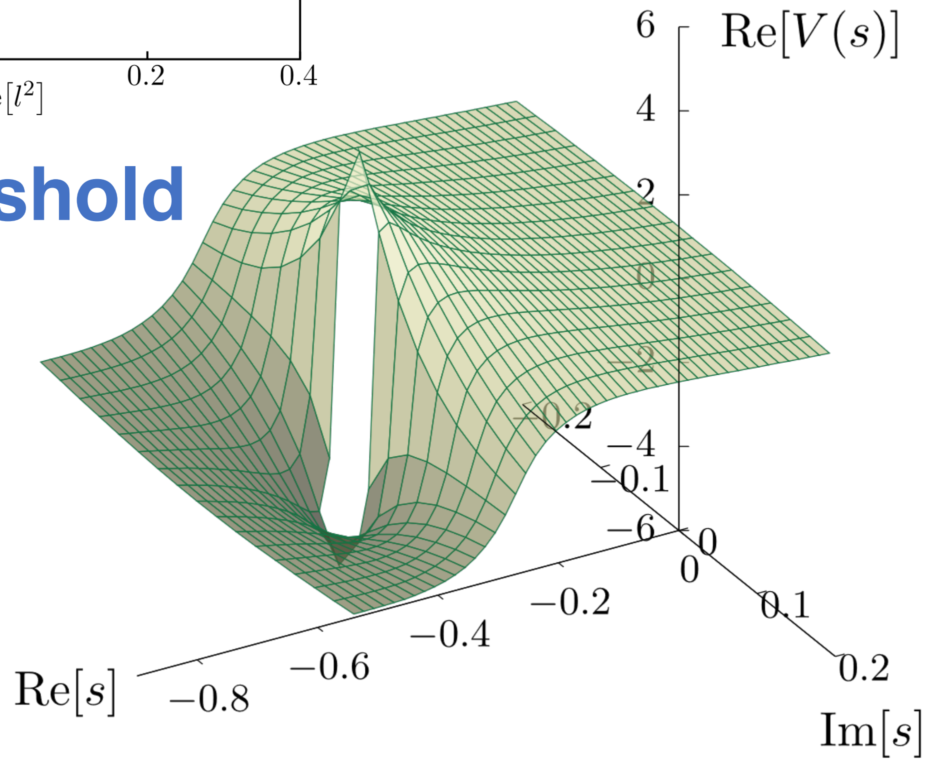
Bound-state resonances:

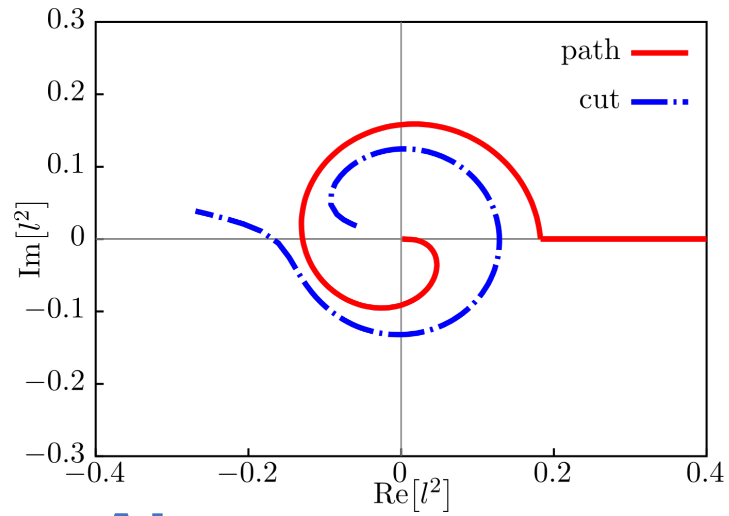
Including decay channels requires integration over intermediate particle poles



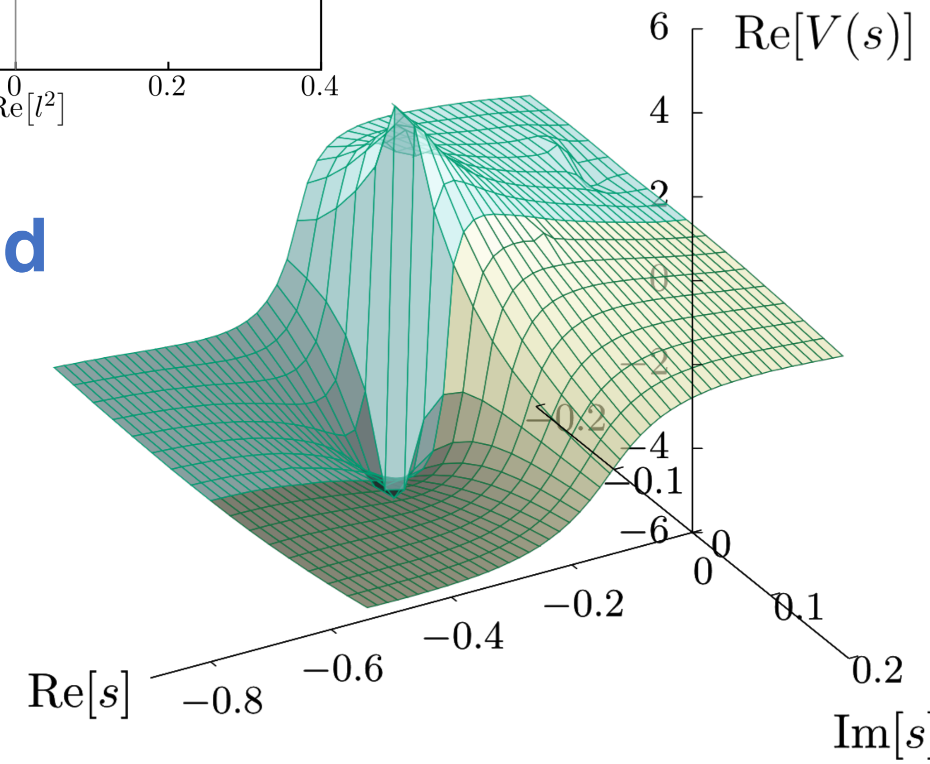


Below threshold





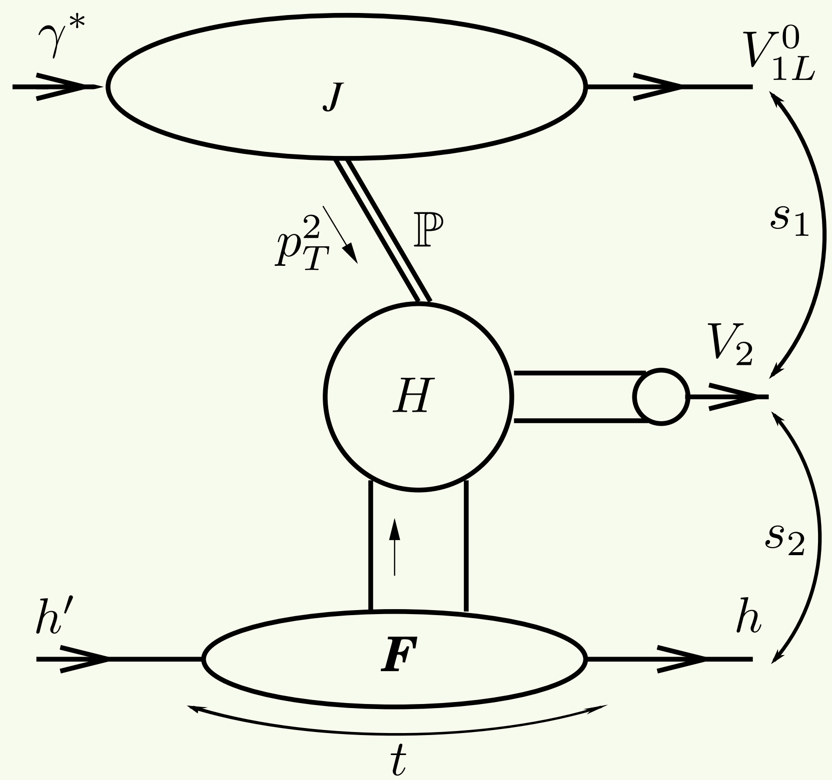
Above threshold



(Euclidean) bound-state pole found in 2nd Riemann sheet, as expected.

Wim Cosyn — *"Probing transversely GPDs in diffractive electroproduction on the proton and deuteron at an EIC"*

Diffractive electroproduction of two vector mesons



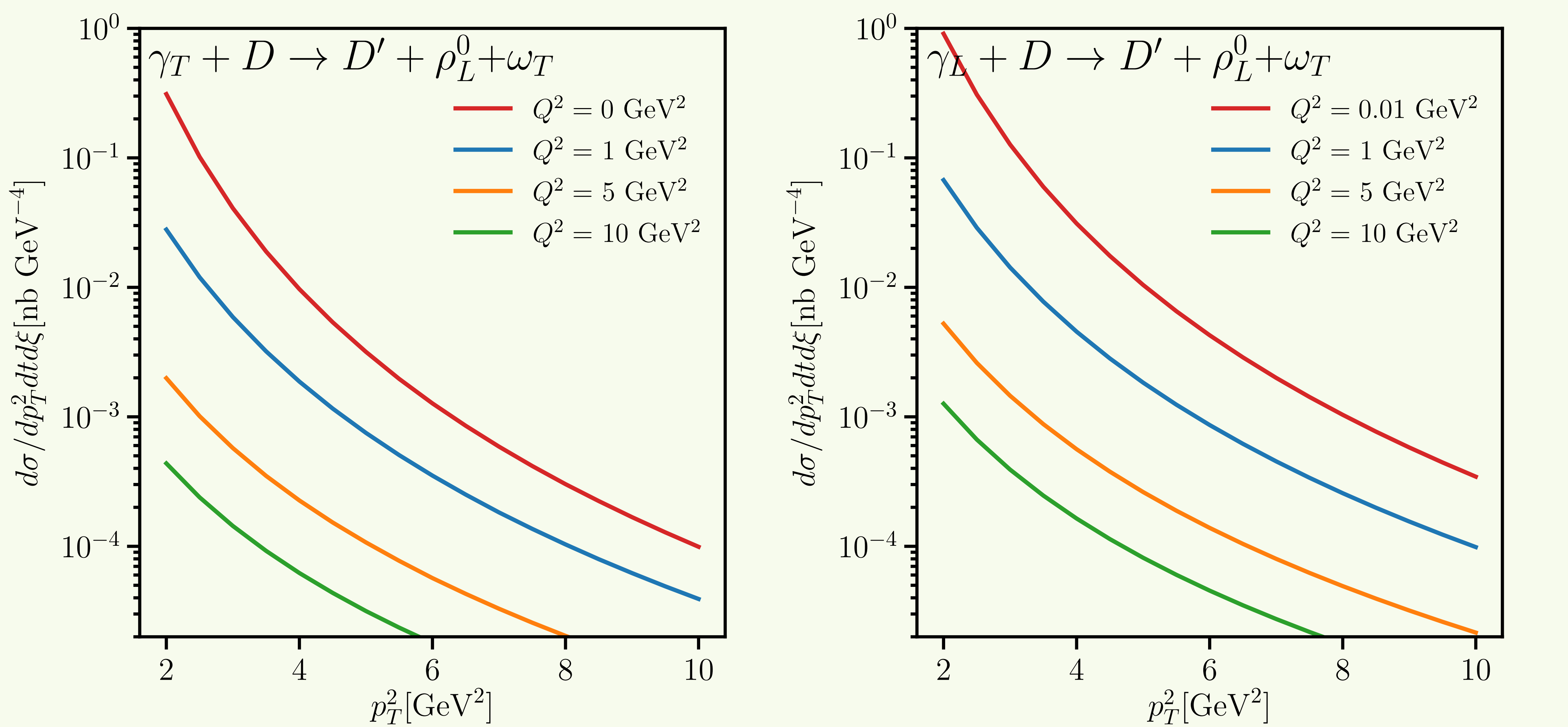
- Two vector mesons are separated by large rapidity gap
- Ordering of scales: invariant mass of two vector mesons $s_1 \ggg$ hadron-(ρ^+/ω) invariant mass $s_2 \sim p^2 \ggg \Lambda_{\text{QCD}}$
- Pomeron $\rightarrow$ two gluon exchange
- No gluon contribution as Pomeron is C-even
- Polarization V_2 determines chiral even or odd GPD entering

- All the hard work already done for the nucleon in
  D.Yu. Ivanov, B. Pire, L. Szymanowski, PLB550 '02
  R. Enberg, B. Pire, L. Szymanowski, EPJC47 '06
- Extension for deuteron straightforward: ω and ϕ ($s - \bar{s}$) production

Wim Cosyn — "*Probing transversely GPDs in diffractive electroproduction on the proton and deuteron at an EIC*"

$\gamma_{L/T} d \rightarrow d \rho^0_L \omega^0_T$ PRELIMINARY

- Chiral odd deuteron GPD
- Calculation at $\xi_D = 0.15$, $t \approx t_{\min} = -0.33$ GeV^2



GPDs theoretical constraints

- Polynomiality:

  Lorentz Covariance

- Positivity:

  Positivity of Hilbert space norms

- Support:

  Relativistic Quantum Mechanic

- Soft Pion theorem

  PCAC and Axial-Vector WTI

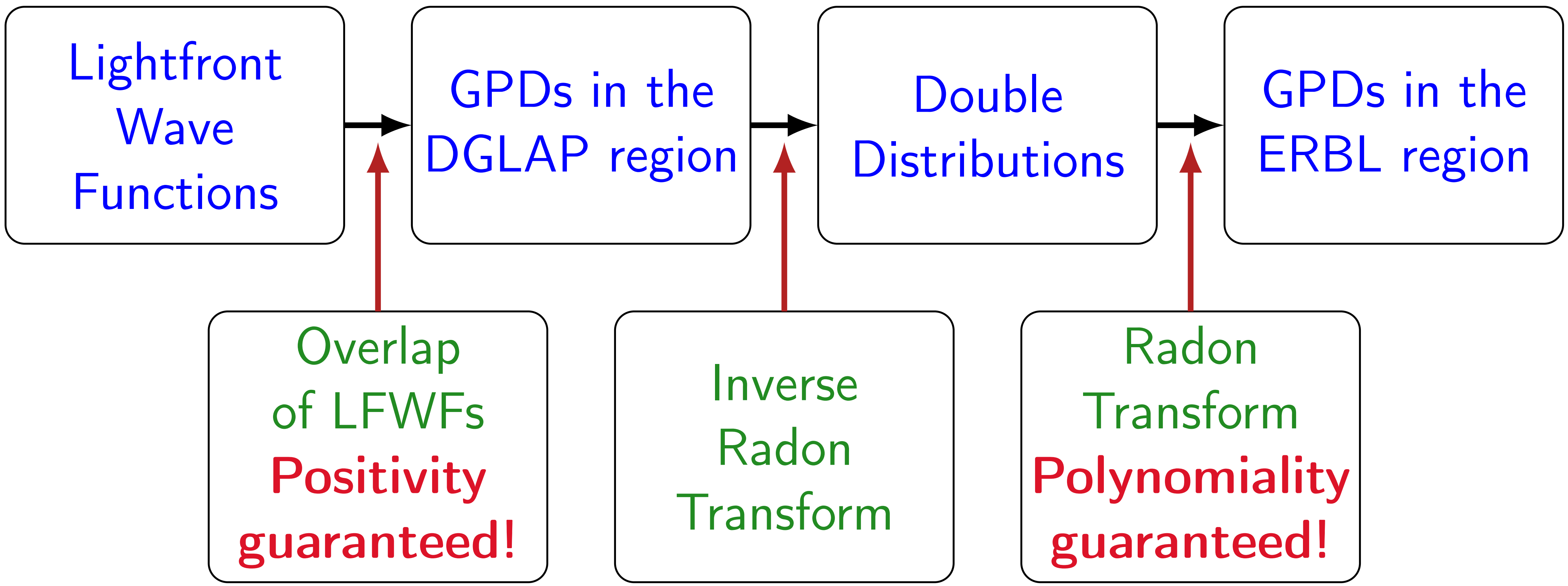
Problems

There is no model (until now) fulfilling a priori all these constraints

People usually choose to fulfil either **polynomiality** or **positivity**

$\rightarrow$ violation of either Lorentz covariance or Hilbert space properties

A new modelling procedure



Both positivity and polynomiality are fulfilled

Eur.Phys.J. C77 (2017) no.12, 906
Phys.Lett. B780 (2018) 287-293

Cédric Lorcé — "Mechanical Properties of Hadrons"

Bare QCD energy-momentum tensor

$$T^{\mu\nu} = \overline{\psi}\gamma^\mu \tfrac{i}{2}\overleftrightarrow{D}^\nu\psi - G^{a\mu\alpha}G^{a\nu}{}_{\alpha} + \tfrac{1}{4}\,\eta^{\mu\nu}G^2$$

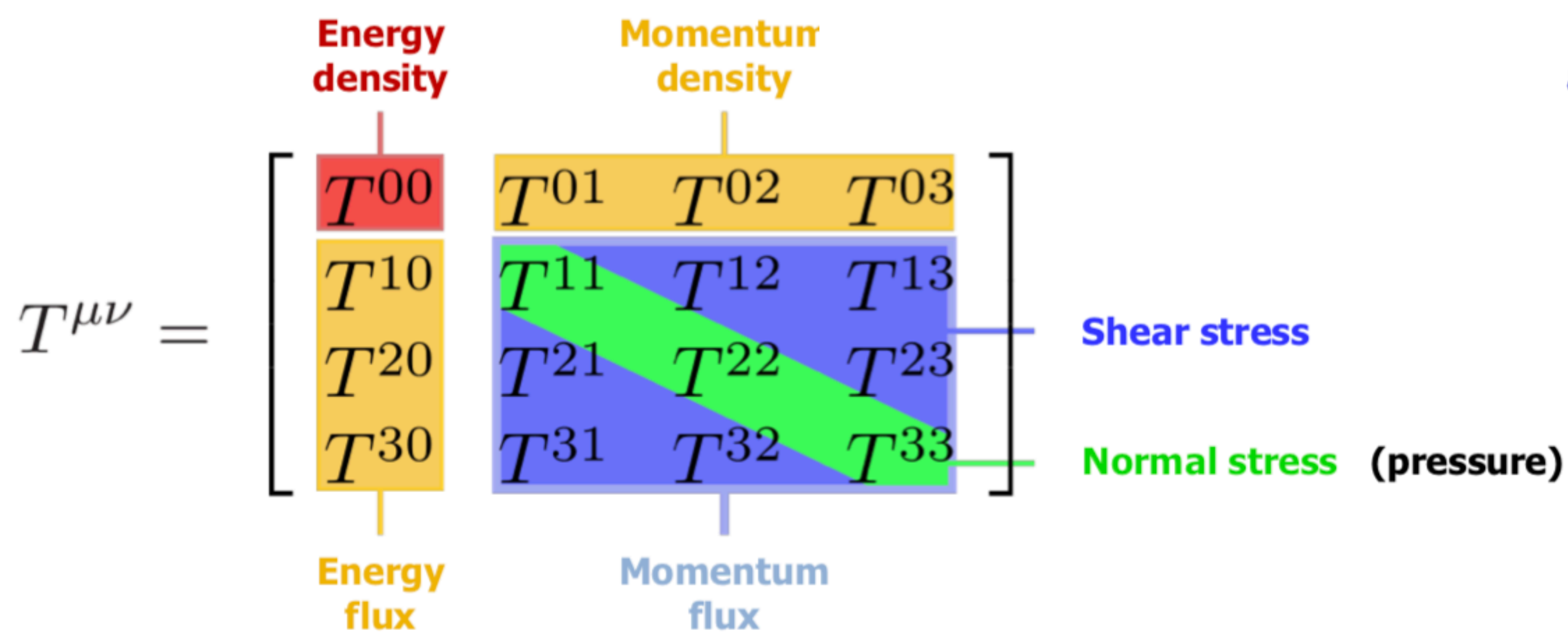
Renormalized trace of the QCD EMT

Mass, spin and pressure all encoded in

$$T^{\mu}{}_{\mu} = \underbrace{\frac{\beta(g)}{2g}\,G^2}_{\text{Trace anomaly}} + (1+\gamma_m)\,\overline{\psi}m\psi$$

Trace anomaly

Quark mass matrix



- **Key information about the structure encoded in EMT**
- **Breit frame defines the spatial distribution at rest**
- **Mechanical properties can be expressed in terms of spatial moments**

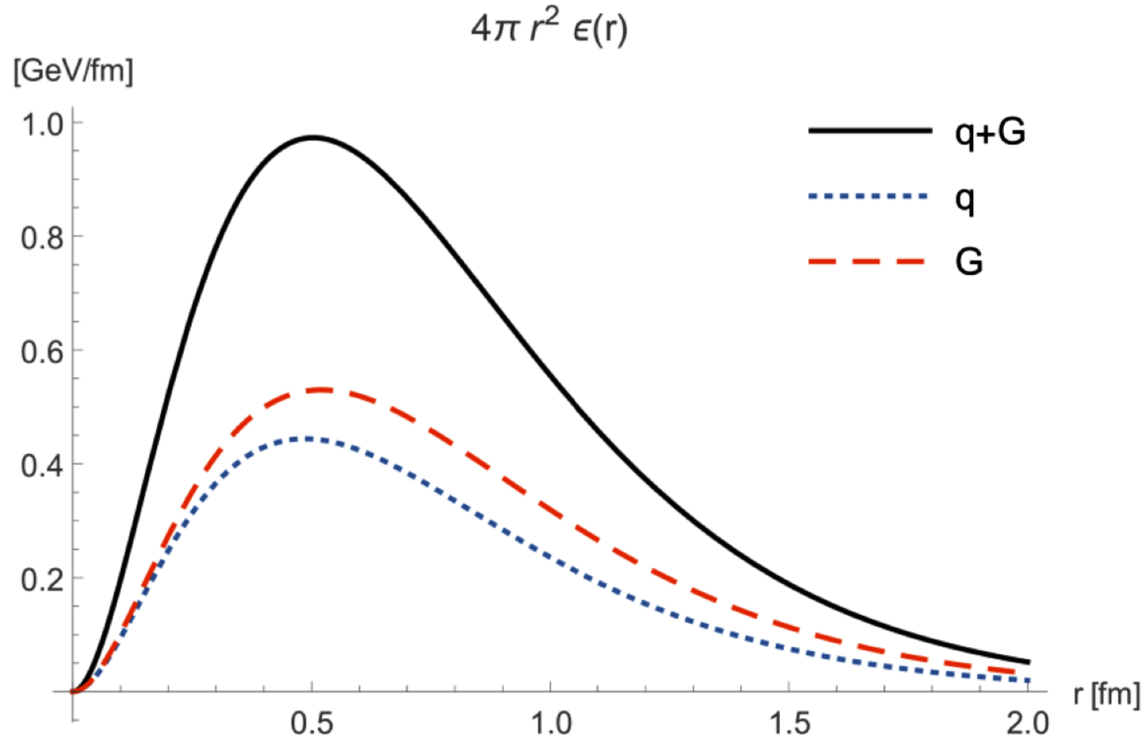
Mass, pressure, moment of inertia, ...

Cédric Lorcé — "Mechanical Properties of Hadrons"

Spin-1/2

$$\langle p', s'|T_a^{\mu\nu}(0)|p, s\rangle = \overline{u}(p', s')\Gamma_a^{\mu\nu}(P, \Delta)u(p, s)$$

$$\Gamma_a^{\mu\nu}(P, \Delta) = \frac{P^\mu P^\nu}{M} A_a(t) + \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu}\Delta^2}{M} C_a(t) + M g^{\mu\nu} \bar{C}_a(t) + \frac{P^{\{\mu} i\sigma^{\nu\}\lambda}\Delta_\lambda}{4M} J_a(t) + \frac{P^{[\mu} i\sigma^{\nu]\lambda}\Delta_\lambda}{4M} D_a(t)$$



$$\sqrt{\langle r^2 \rangle_M} = 0.91\,\text{fm}$$
$$\sqrt{\langle r^2 \rangle_Q} = 0.84 - 0.88\,\text{fm}$$

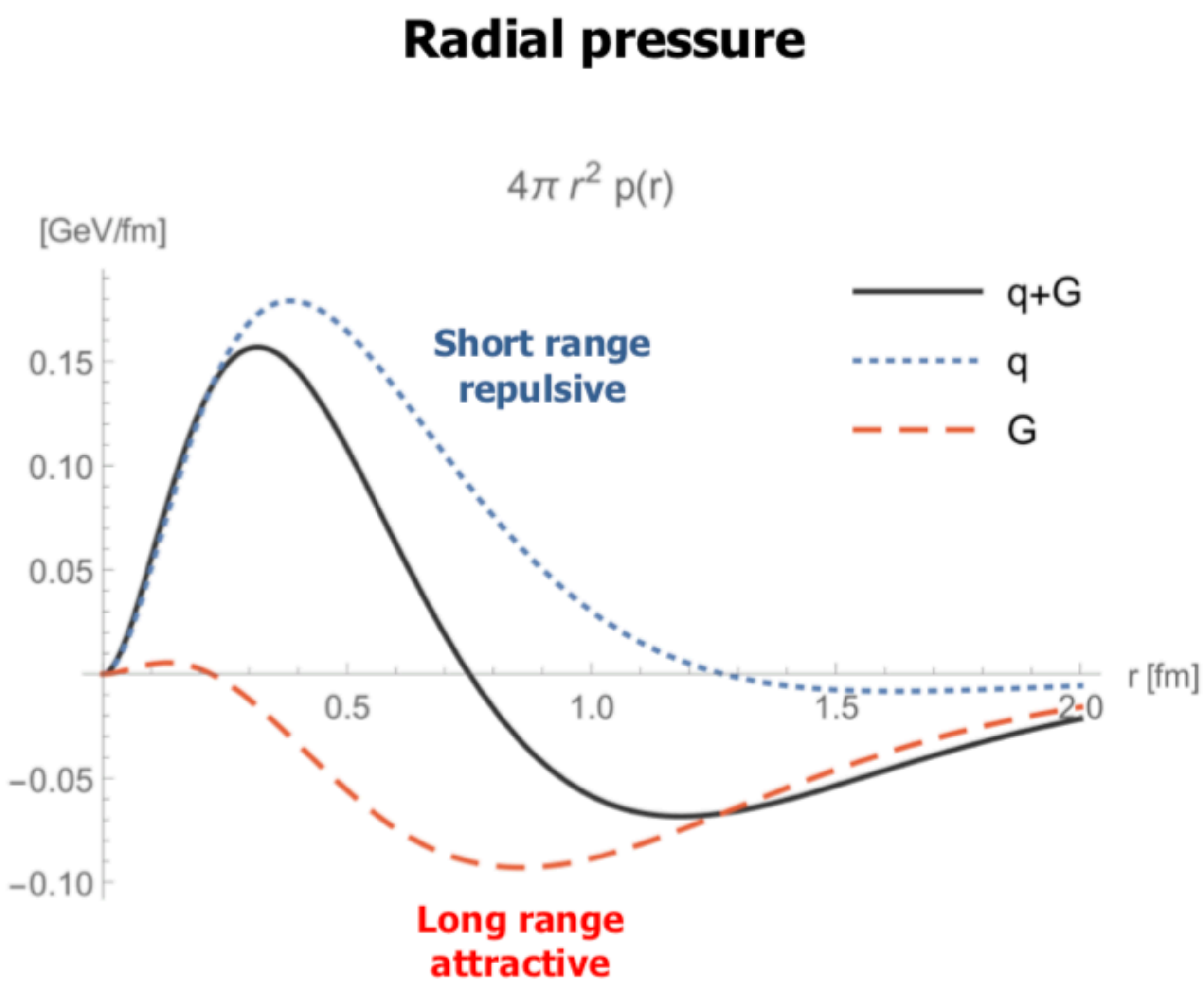
Energy density

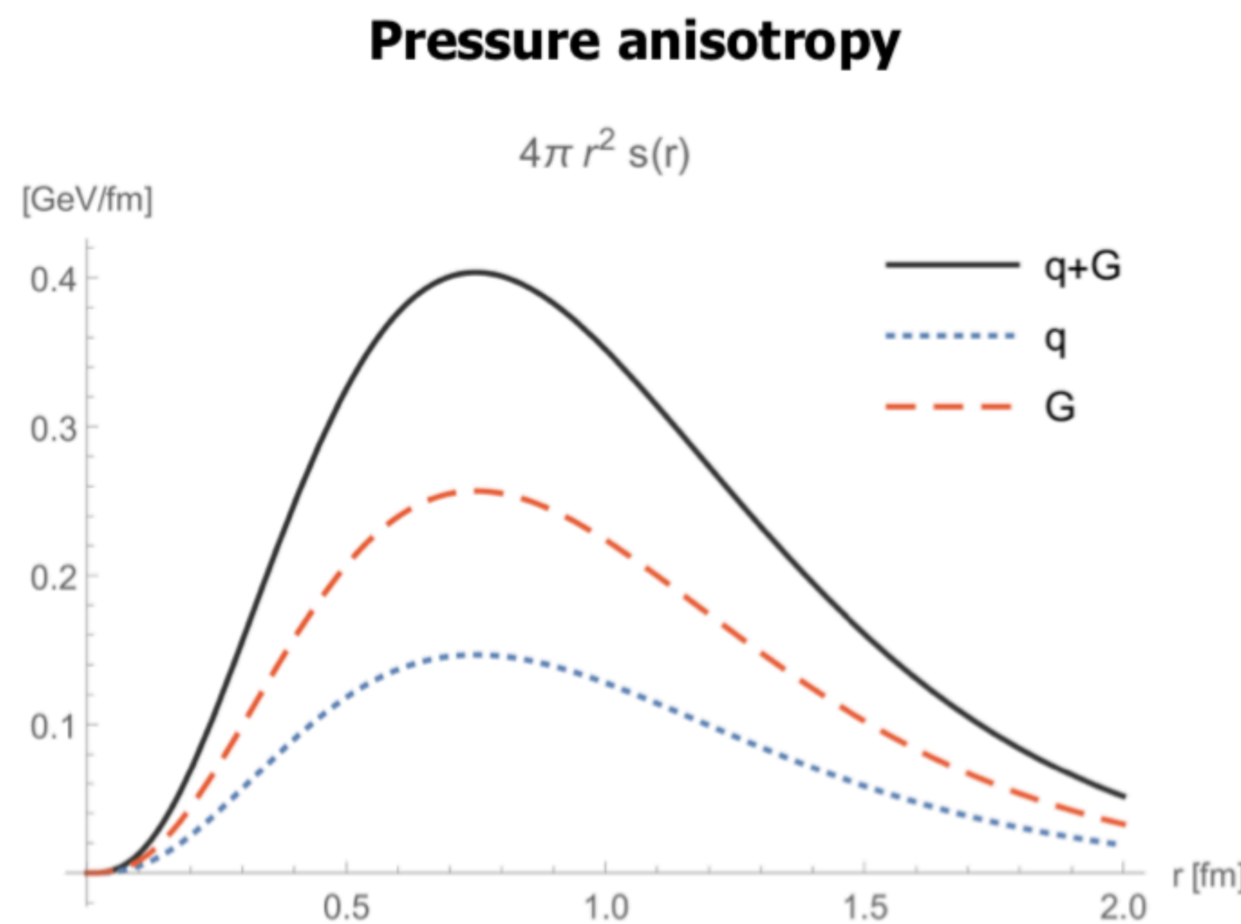
$$\varepsilon_a = \left[A_a(0) + \bar{C}_a(0)\right] \frac{M}{V} \quad \Rightarrow \quad U_i = \varepsilon_i V$$

$$M = \underbrace{U_q}_{\sim 44\%} + \underbrace{U_g}_{\sim 56\%} \qquad \qquad p_q = -p_g \quad (\sim 11\%)$$

$\mu = 2\,\text{GeV}$

Cédric Lorcé — “Mechanical Properties of Hadrons”





Adam Freese — *"Gravitational Form Factors of Mesons and Proton"*

Gravitational form factors and the EMT

- **Gravitational form factors** encode information in the energy-momentum tensor (EMT):

$$\langle p'\lambda' \mid T^q_{\mu\nu}(0) \mid p\lambda\rangle = \bar{u}^{\lambda'}(p')\Big[\gamma_{\{\mu}P_{\nu\}}A^q(t) + \frac{iP_{\{\mu}\sigma_{\nu\}\Delta}}{2m_N}B^q(t) + \frac{\Delta_\mu\Delta_\nu - \Delta^2 g_{\mu\nu}}{4m_N}C^q(t) + m_N g_{\mu\nu}\bar{c}^q(t) + \frac{iP_{[\mu}\sigma_{\nu]\Delta}}{2m_N}D^q(t)\Big]u^\lambda(p)$$

- Three of the GFFs accessible through GPDs:

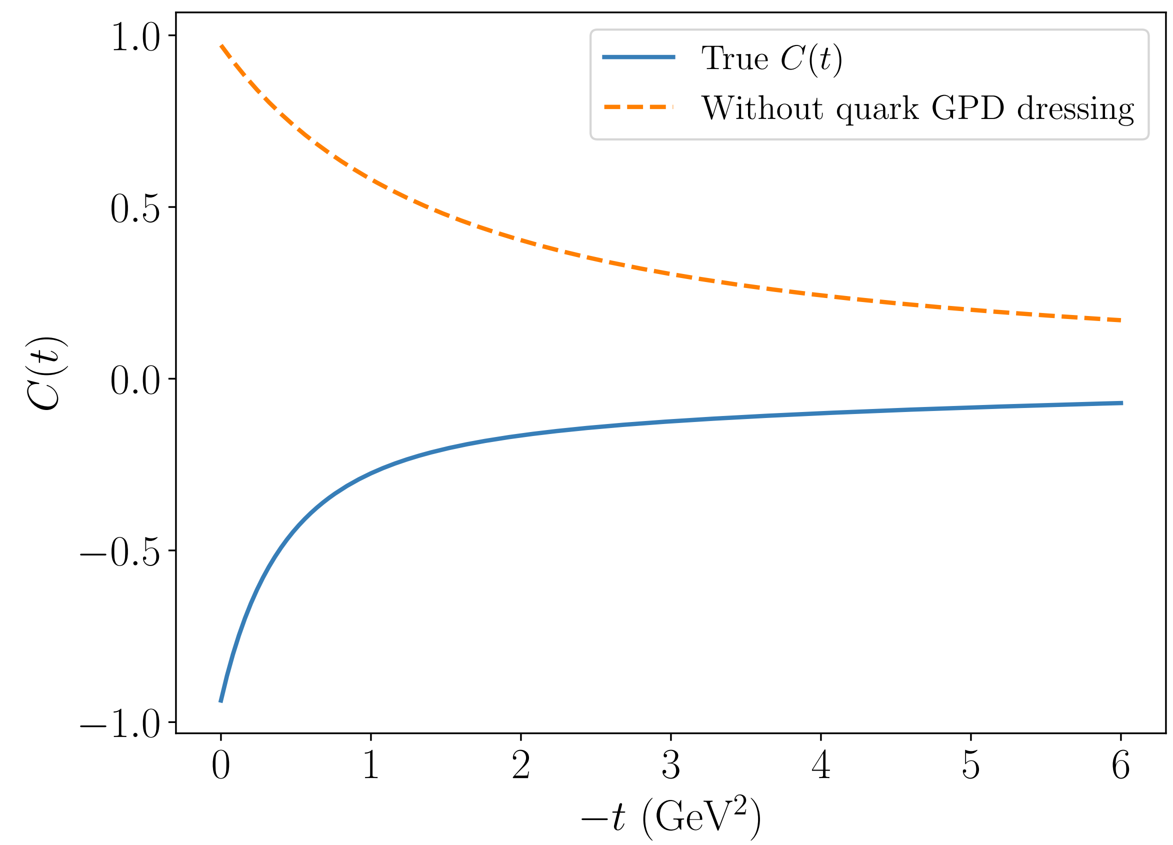
$$\int \mathrm{d}x\, xH^q(x,\xi,t) = A^q(t) + \xi^2 C^q(t)\,, \qquad \int \mathrm{d}x\, xE^q(x,\xi,t) = B^q(t) - \xi^2 C^q(t)$$

- GFFs encode information about distribution of energy, angular momentum, and forces.
- **Cannot do graviton-exchange experiments**—but GPDs allow GFFs to be experimentally accessed! (DVCS, DVMP, . . .)

Adam Freese — “*Gravitational Form Factors of Mesons and Proton*”

$C(t)$ encodes **pressure distribution** (see Peter Schweitzer’s talk)

- $C(0)$ not constrained by conservation laws
- $C(0) < 0$ is a stability condition
- $C(t)$ is affected by quark GPD dressing, but not $A(t)$ or $B(t)$



- $C(0) = -0.94 < 0$ in the NJL model
- Ignoring quark GPD dressing gives $C(0) = 0.97 > 0$
- Proton stability appears to **require** dressing the quark GPD!

Peter Schweitzer — “*D-Term of Nucleon*”

D-term of nucleon

Peter Schweitzer, UConn

- **energy-momentum tensor** $T^{\mu\nu}$ fundamentally important

  nucleon matrix elements of $T^{\mu\nu}$ $\to$ 3 EMT form factors $A(t)$, $J(t)$, $D(t)$

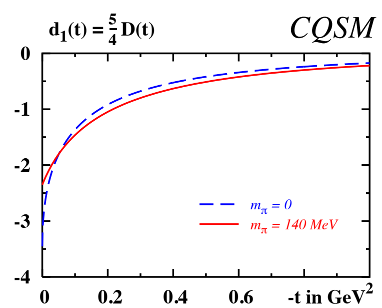
  constraints: **mass** $\Leftrightarrow$ $A(0) = 1$ $\Leftrightarrow$ quarks + gluons carry 100 % of nucleon momentum

  spin $\Leftrightarrow$ $J(0) = \frac{1}{2}$ $\Leftrightarrow$ quarks + gluons carry 100 % of nucleon spin

  D-term $\Leftrightarrow$ $D(0) \equiv D$ $\to$ unconstrained! **Last global unknown!**

- **theory:** free fermion $D = 0$ i.e. D-term 100 % dynamic effect!
  Hudson, PS PRD97 (2018) 056003

- **interaction** $\to$ $D \neq 0$
  chiral quark soliton
  Goeke et al,
  PRD75 (2007) 094021
  agrees with lattice & disp. relation

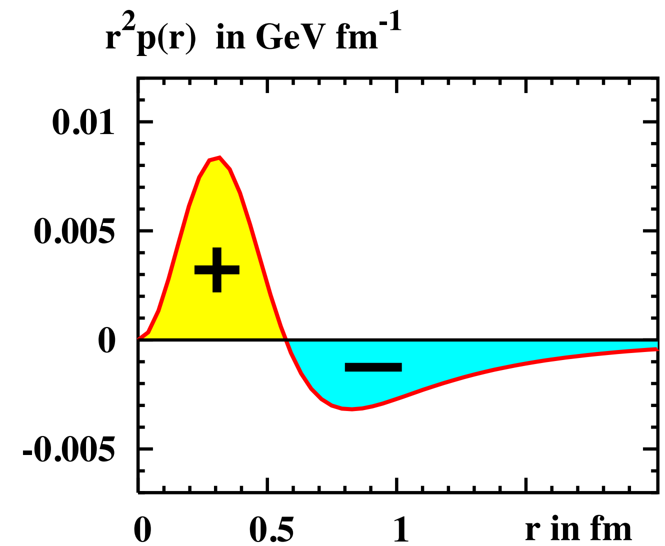


- **experiment**

  π^0 $D^Q \approx -0.7$ from Belle data
  on $\gamma\gamma^* \to \pi^0\pi^0$ in e^+e^-
  Kumano, Song, Teryaev, PRD97 (2018)

  nucleon D from DVCS data from subtraction term in
  fixed-t dispersion relation of Re, Im part of DVCS amplitude
  (accessible *under assumptions* at this point)
  Burkert, Elouadrhiri, Girod, **Nature** 557, 396 (2018)
  K. Kumerički, **Nature** 570, 7759 (2019)

- **explore scale dependence at EIC**
  extract $D(t)$ (!) (vs $A(t)$ and $J(t)$ much harder)
  learn about forces inside hadrons!!



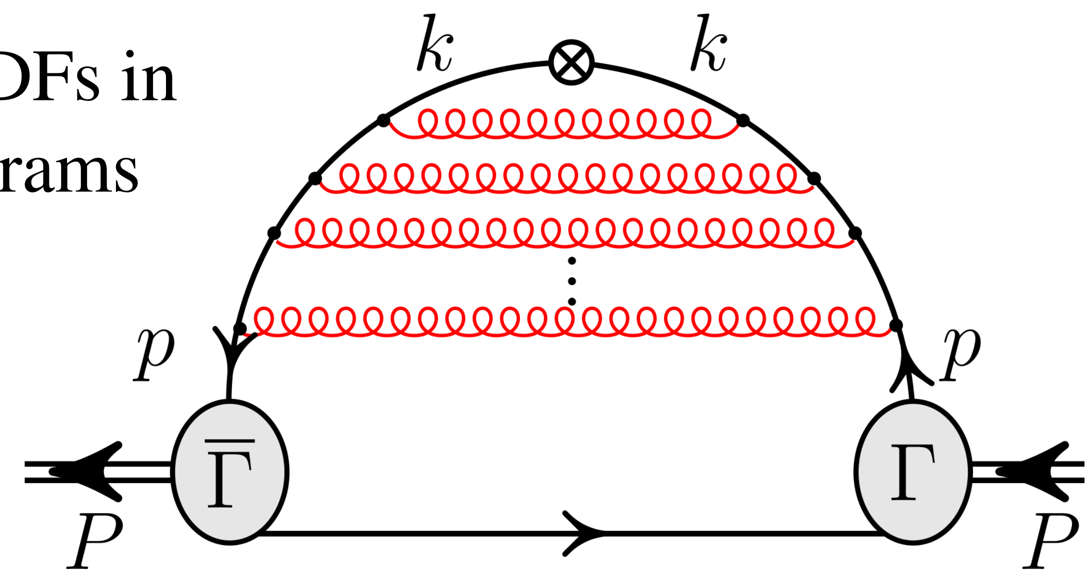
- **interpretation**
  M.V.Polyakov (2003)
  shows how internal forces balance
  related to D-term
  stability $\int_0^\infty \mathrm{d}r\, r^2\, p(r) = 0$
  $D = 4\pi m \int_0^\infty \mathrm{d}r\, r^4\, p(r) < 0$

review:
M.V.Polyakov, PS,
Int.J.Mod.Phys.A **33**, 1830025 (2018)
[arXiv:1805.06596]

Pion PDFs – Self-Consistent DSE Calculations

- To self-consistently determine hadron PDFs in rainbow-ladder must sum all planar diagrams

$$q(x) \propto \text{Tr} \int \frac{d^4p}{(2\pi)^4}\, \overline{\Gamma}_M(p,P)\, S(p) \\ \times \Gamma_q(x,p,n)\, S(p)\, \Gamma_M(p,P)\, S(p-P)$$



- DSEs are formulated in Euclidean space – evaluate $q(x)$ by taking moments
- The *hadron dependent* vertex $\Gamma_q(x,p,n)$ satisfies an inhomogeneous BSE
- However can define a *hadron independent* vertex $\Lambda_q(x,p,n)$

$$\Gamma_q(x,p,n) = \iint dy\, dz\, \delta(x-yz)\, \delta\Big(y - \frac{p\cdot n}{P\cdot n}\Big)\, \Lambda_q(z,p,n)$$

- $\Lambda_q(x,p,n)$ satisfies the inhomogeneous BSE

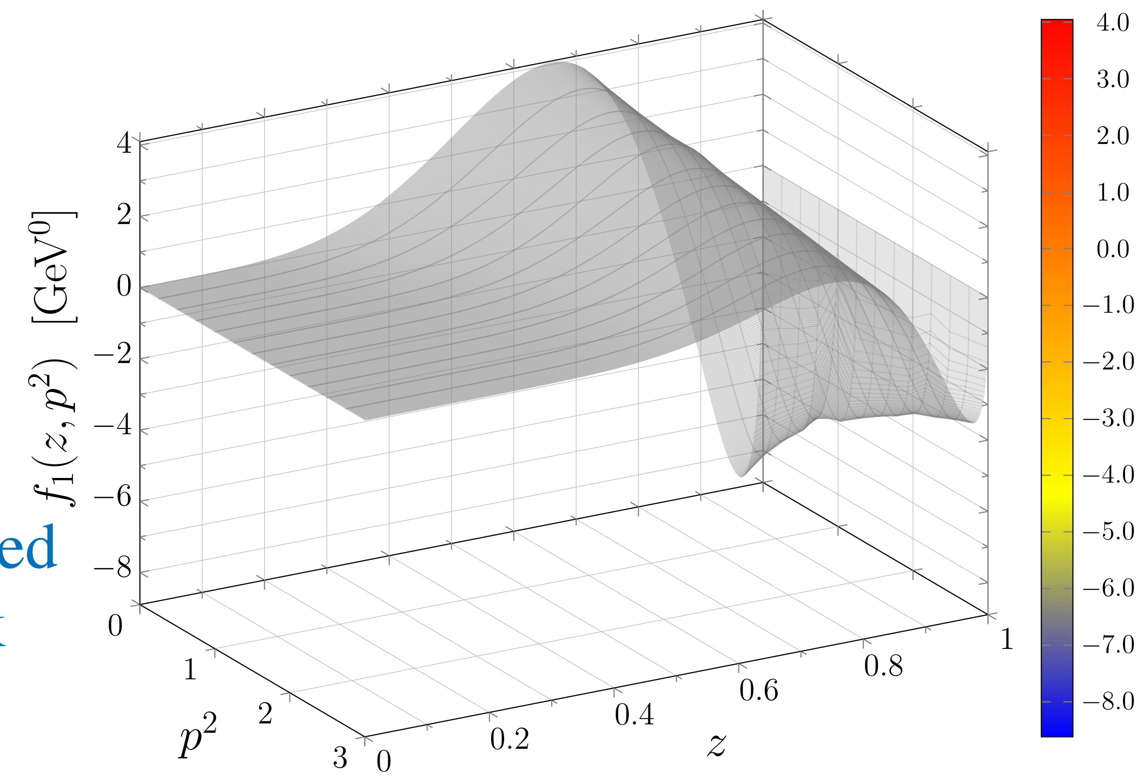
$$\Lambda_q(z,p,n) = iZ_2\, \not{n}\, \delta(1-z) - \iint du\, dw\, \delta(z-uw) \int \frac{d^4\ell}{(2\pi)^4} \delta\Big(w - \frac{\ell\cdot n}{p\cdot n}\Big) \\ \times \gamma_\mu\, \mathcal{K}_{\mu\nu}(p-\ell)\, S(\ell)\, \Lambda_q(u,\ell,n)\, S(\ell)\, \gamma_\nu$$

PDFs of a Dressed Quark

- *Hadron independent* vertex has form

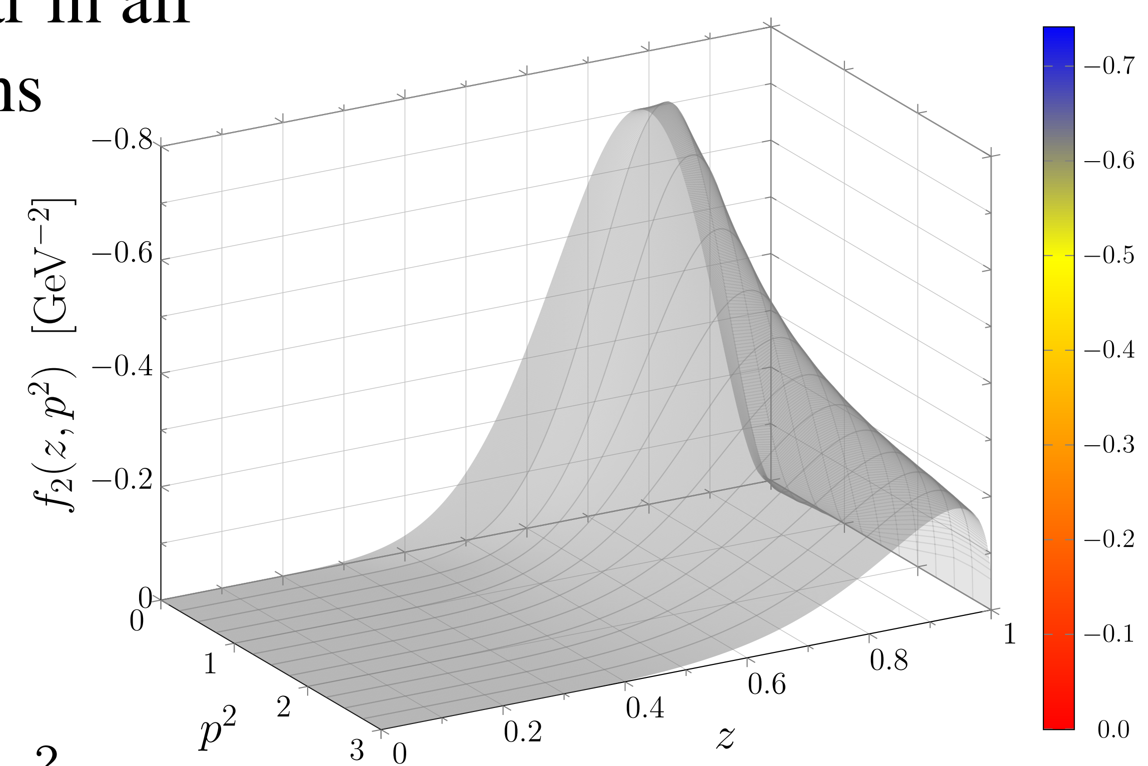
$$\Lambda_q(z,p,n) = i\not{p}\,\delta(1-z) + i\not{p}\,f_1^q(z,p^2) + n\cdot p\left[i\not{p}\,f_2^q(z,p^2) + f_3^q(z,p^2)\right]$$

  - the functions $f_i^q(z,p^2)$ can be interpreted as unpolarized PDFs in a dressed quark of virtuality p^2



- These functions are universal – appear in all RL-DSE unpolarzied PDF calculations

- Distributed support in z is immediate indication gluons carry significant momentum
  - heavier s quark support nearer $z = 1$
  - WIA $\implies$ $\Lambda_q(z,p,n) \propto \delta(1-z)$

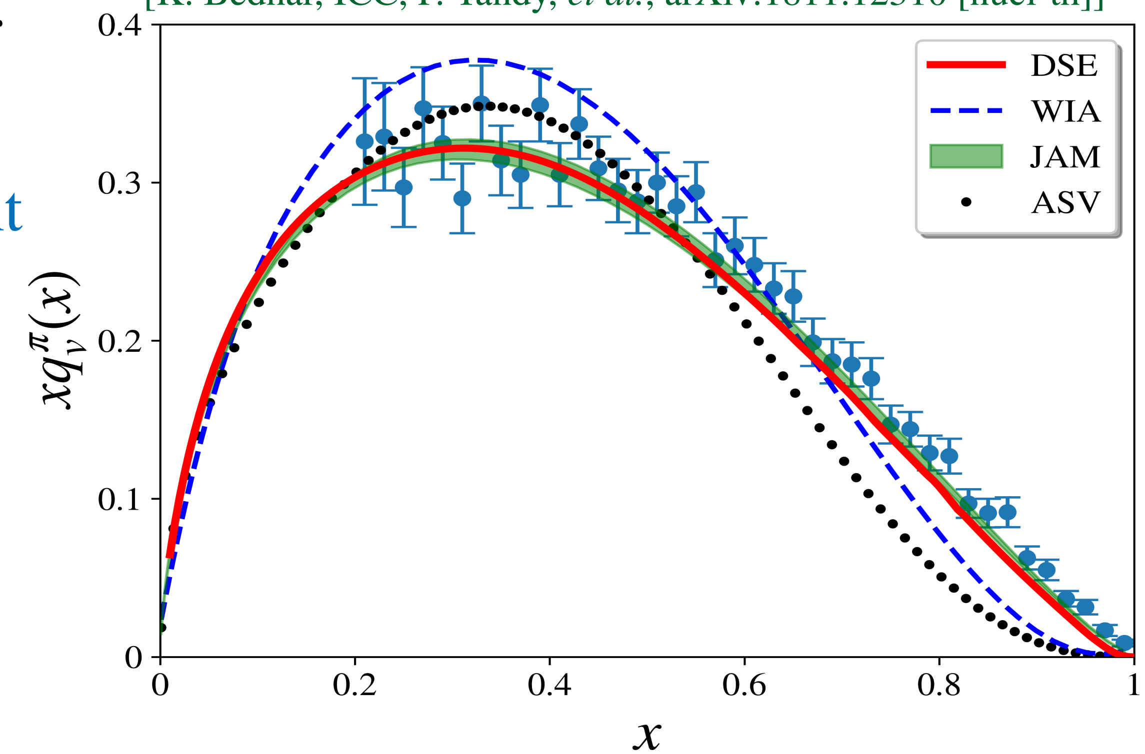


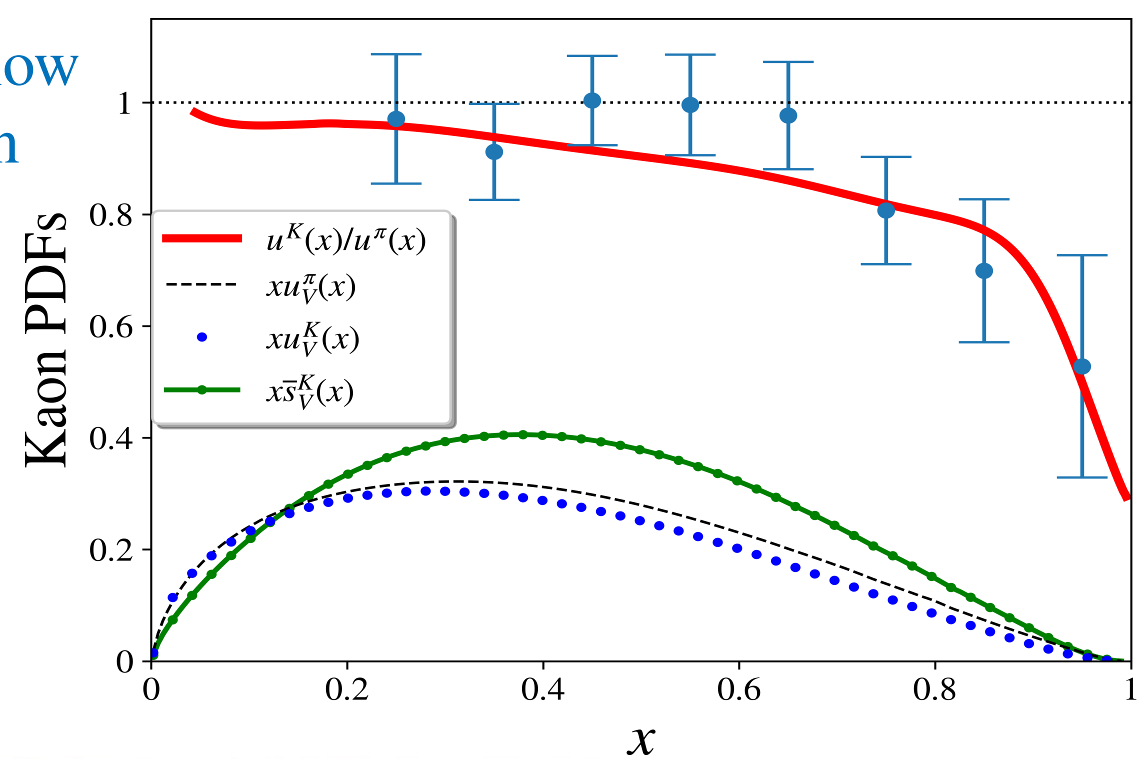
- Renormalization condition means dressing functions vanish when $p^2 = \mu^2$

Self-Consistent DSE Results

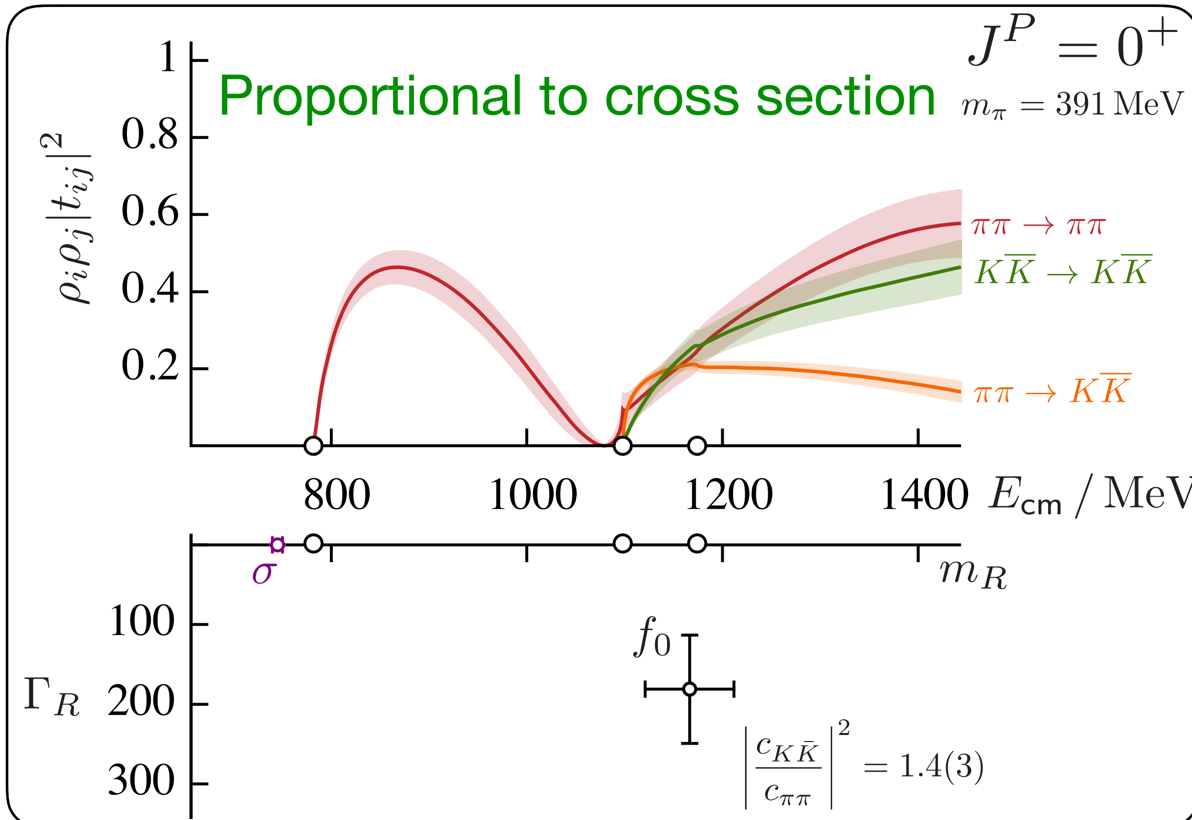
- For pion and kaon PDFs included for first time gluons self-consistently
  - correct RL-DSE pion PDFs in excellent argeement with Conway *et al.* data and recent JAM analysis
  - agrees with $x \to 1$ pQCD prediction
- Treating non-perturbative gluon contributions correctly pushes support of $q_\pi(x)$ to larger x
  - gluons remove strength from $q_\pi(x)$ at low to intermediate x – baryon number then demands increased support at large x
  - cannot be replicated by DGLAP – DSE splitting functions are dressed
- *Immediate consequence of gluon dressing is that gluons carry 35% of pion’s and 30% of kaon’s momentum*

[K. Bednar, ICC, P. Tandy, *et al.*, arXiv:1811.12310 [nucl-th]]

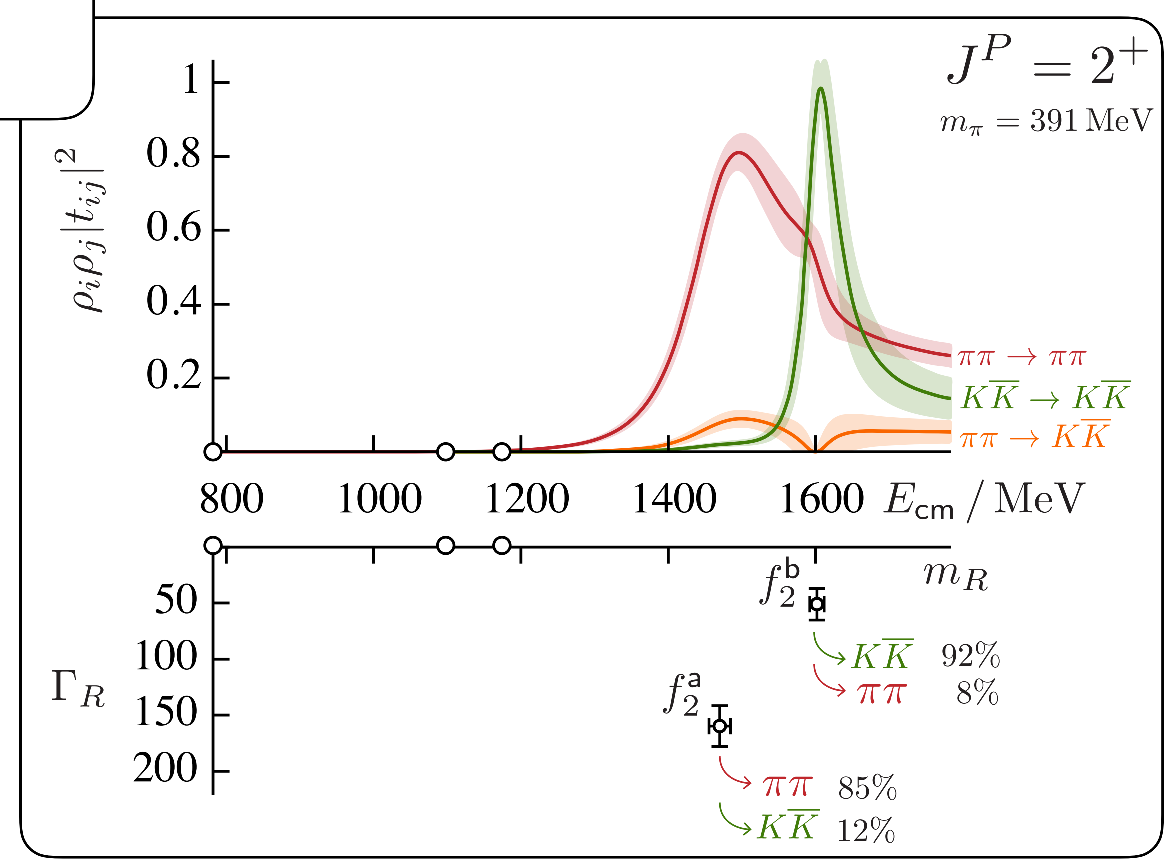




Scalar $\pi\pi$-KK



Isoscalar ππ,KK,ηη scattering in S and D wave and the σ, f₀(980), f₂(1270) mesons from QCD.



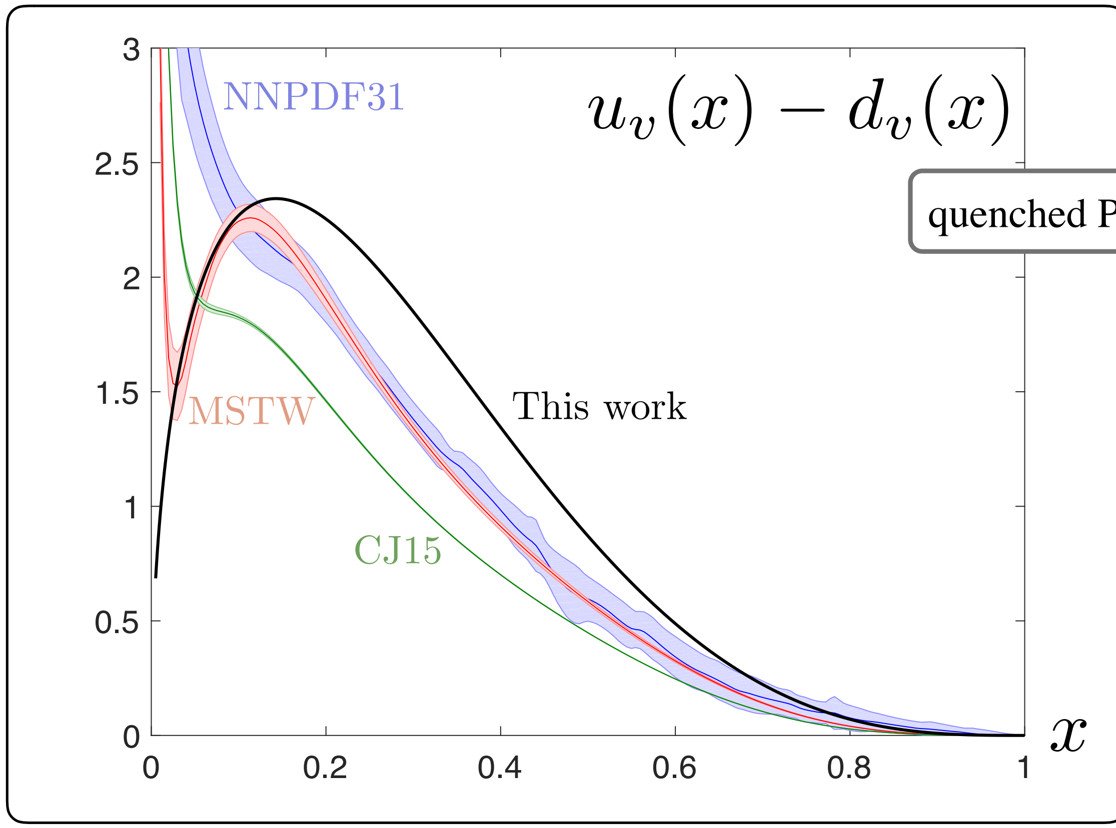
$f_0(980)$ manifests itself as a dip in the $\pi\pi$ cross section

Briceno, Dudek, Edwards, & Wilson (2019)

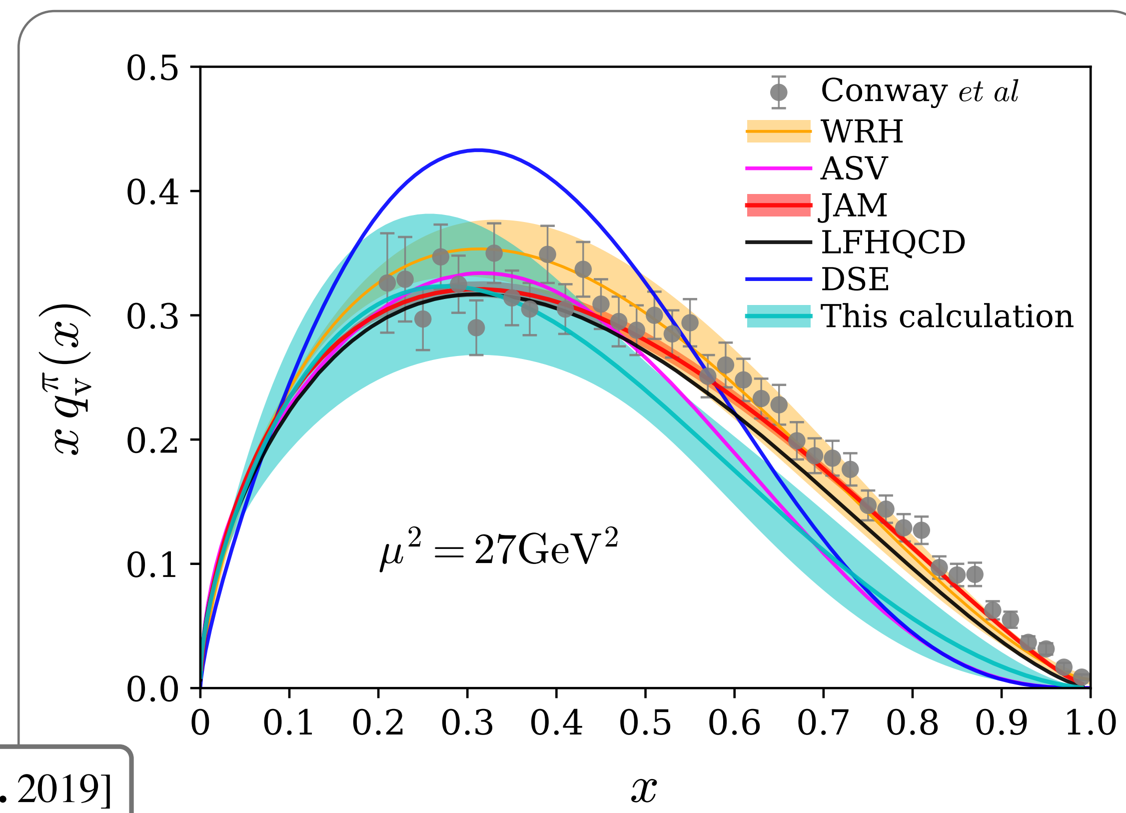
PDFs in the lattice

Pseudo PDFs, not using moments

$\langle N|\mathcal{O}|N\rangle_{\text{latt.}}$ → $\langle N|\mathcal{O}|N\rangle_{\text{Min.}}$ —factorization→ PDFs



quenched PDFs [**Orginos, et al.** 2017]

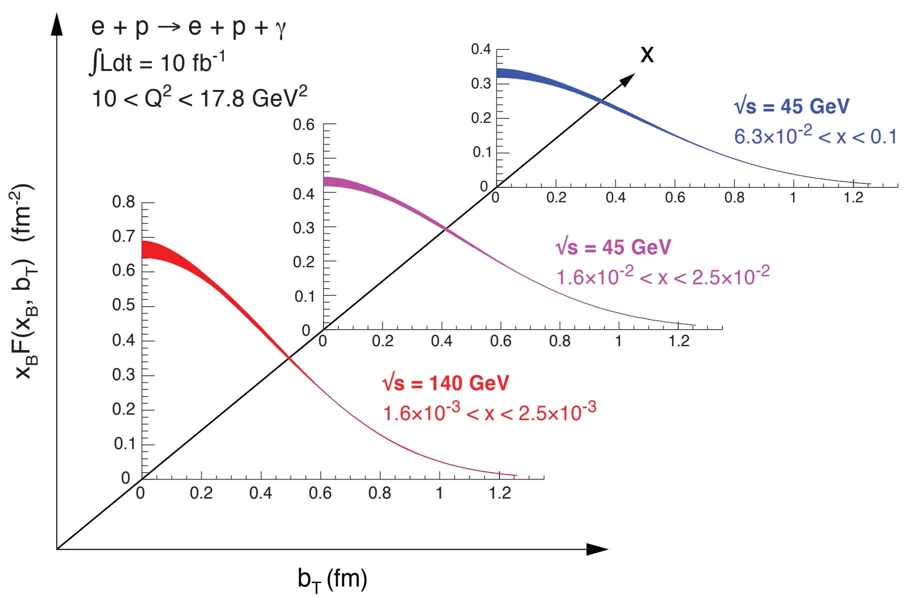


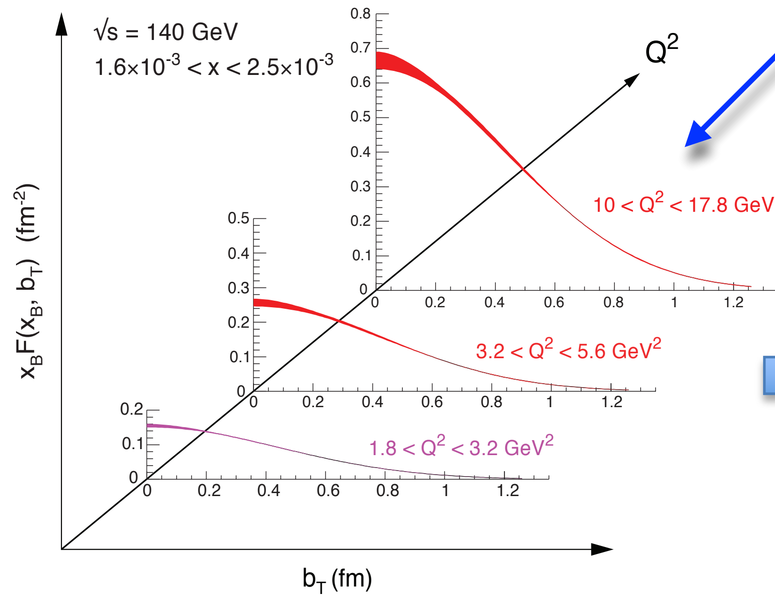
Pion Valence Quark Distribution @ m_π = 400MeV [**Sufian, et al.** 2019]

Salvatore Fazzio — *"Support of Partonic Spatial Imaging at EIC"*

DVCS @ EIC

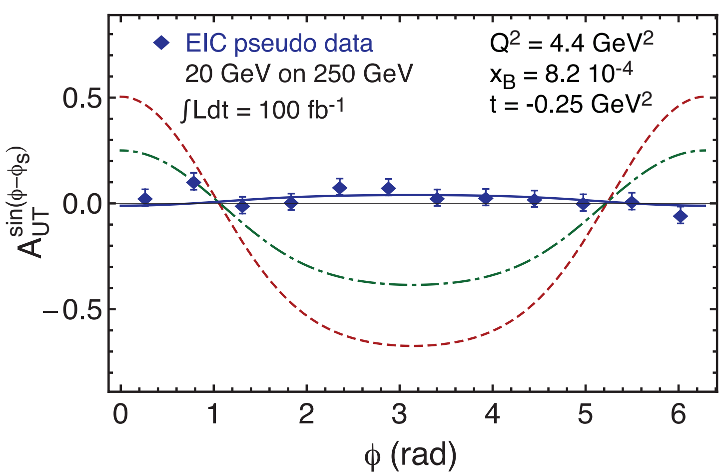
Average partonic densities obtained by Fourier transforming differential cross section measurements





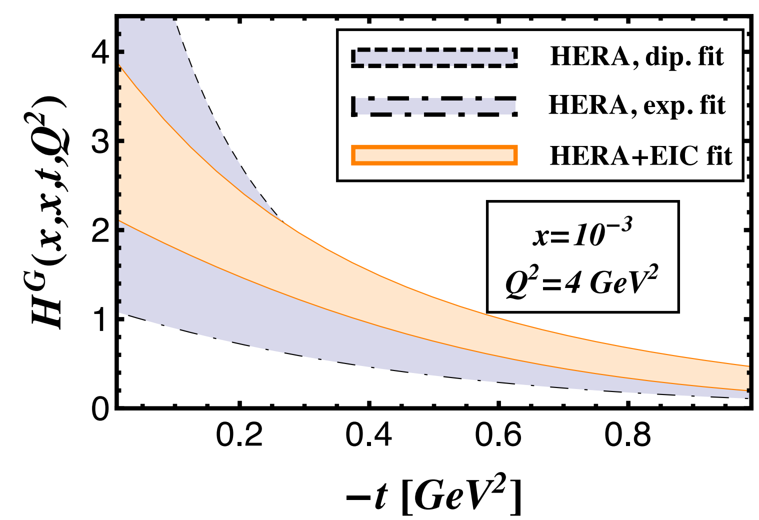
$$\int L = 10fb^{-1}$$

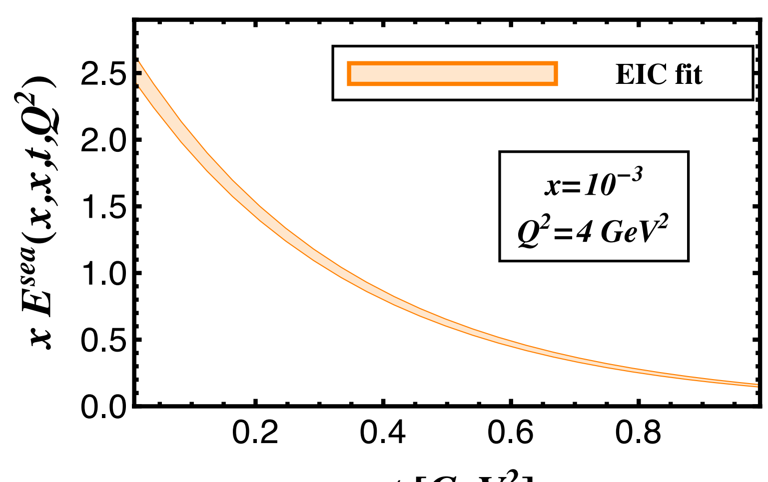
Constrains GPD H



$$\int L = 100fb^{-1}$$

Sensitive to GPD E

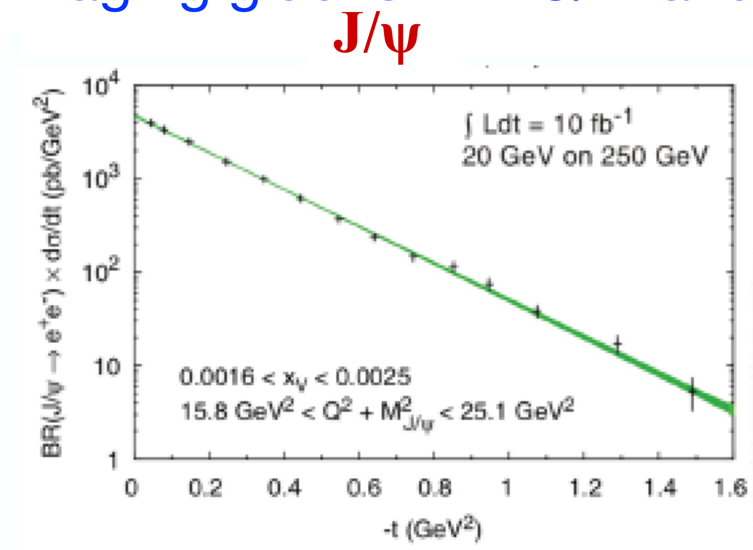


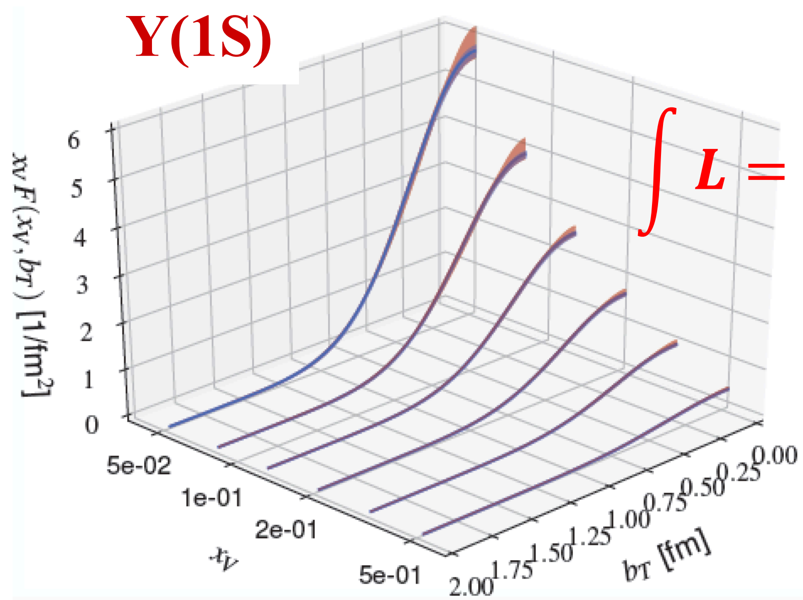


- **Studies performed at the times of the EIC WP era… (DVCS)**
  - E.C.Aschenauer, S.Fazio, K.Kumerički, D. Müller, JHEP09(2013)093
- Global fits of DVCS world data and EIC pseudo-data
- **Good constrain of *H^sea*, and *H^g***
- **Opportunity for first precise extraction of sea-quarks GPD E**

New excitement ahead

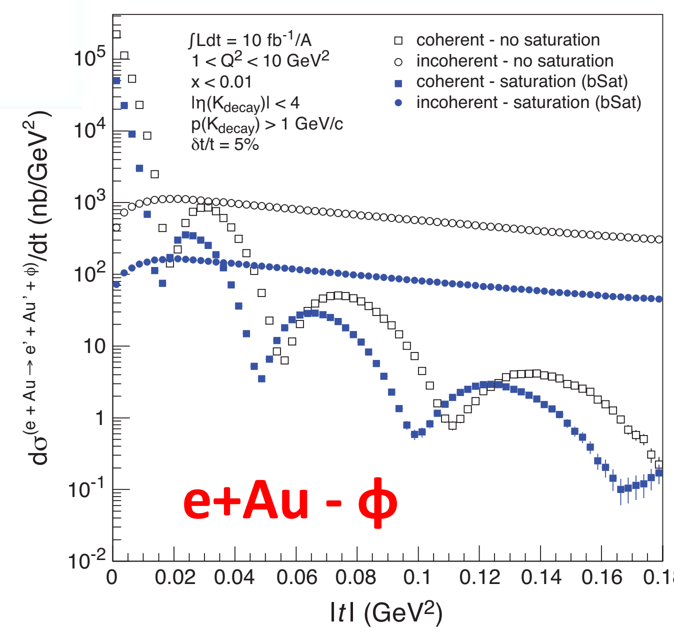
Imaging gluons with J/Ψ and $Y(1S)$





$\int L = 100 fb^{-1}$

$\Longrightarrow$ *average gluon density from t-spectrum*



Goals (needed to fully exploit EIC data):

- Include mesons in global fits (flavor separation, precision in constraining gluons GPDs)
- Assess the sensitivity to extract “D-term”, related to distribution of forces inside the nucleon
- Extract neutron GPDs (via measuring DVCS on D/He3)
- Refine tools to study of GPDs in nuclei (and possible gluon saturation effects)
- Fully develop common software platforms (E.g. PARTONS)
- Go beyond: Can access gluon elliptic Wigner fcn. At EIC?

➤ **Very engaged Community, stay tuned!**