The D-Term Form Factor from Dispersion Relations in Deeply Virtual Compton Scattering

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3DSPIN MAPPING THE PROTON IN 3D
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Outline

- GPDs and form factors of energy-momentum tensor

- Dispersion Relations (DRs)
  for Deeply Virtual Compton Scattering (DVCS)

- D-Term Form Factor
  - ✓ subtraction function in s-channel DRs
  - ✓ predictions from DRs in the t-channel
  - ✓ physical content

Nucleon Structure Properties

em	$\partial_\mu J^\mu_{\text{em}} = 0$	$\langle N' \| J^\mu_{\text{em}} \| N \rangle \longrightarrow$	$Q,\ \mu$
weak	$\partial_\mu J^\mu_{\text{weak}} = 0$	$\langle N' \| J^\mu_{\text{weak}} \| N \rangle \longrightarrow$	$g_A,\ g_p$
gravity	$\partial_\mu T^{\mu\nu}_{\text{grav}} = 0$	$\langle N' \| T^{\mu\nu}_{\text{grav}} \| N \rangle \longrightarrow$	$M_N,\ J,\ d_1$

$Q_{\text{prot}} = 1.602176487(40) \times 10^{-19}\,\text{C}$

$\mu_{\text{prot}} = 2.792847356(23)\mu_N$

$M_{\text{prot}} = 938.272013(23)\,\text{MeV}$

$g_p = 8 - 12$

$g_A = 1.2694(28)$

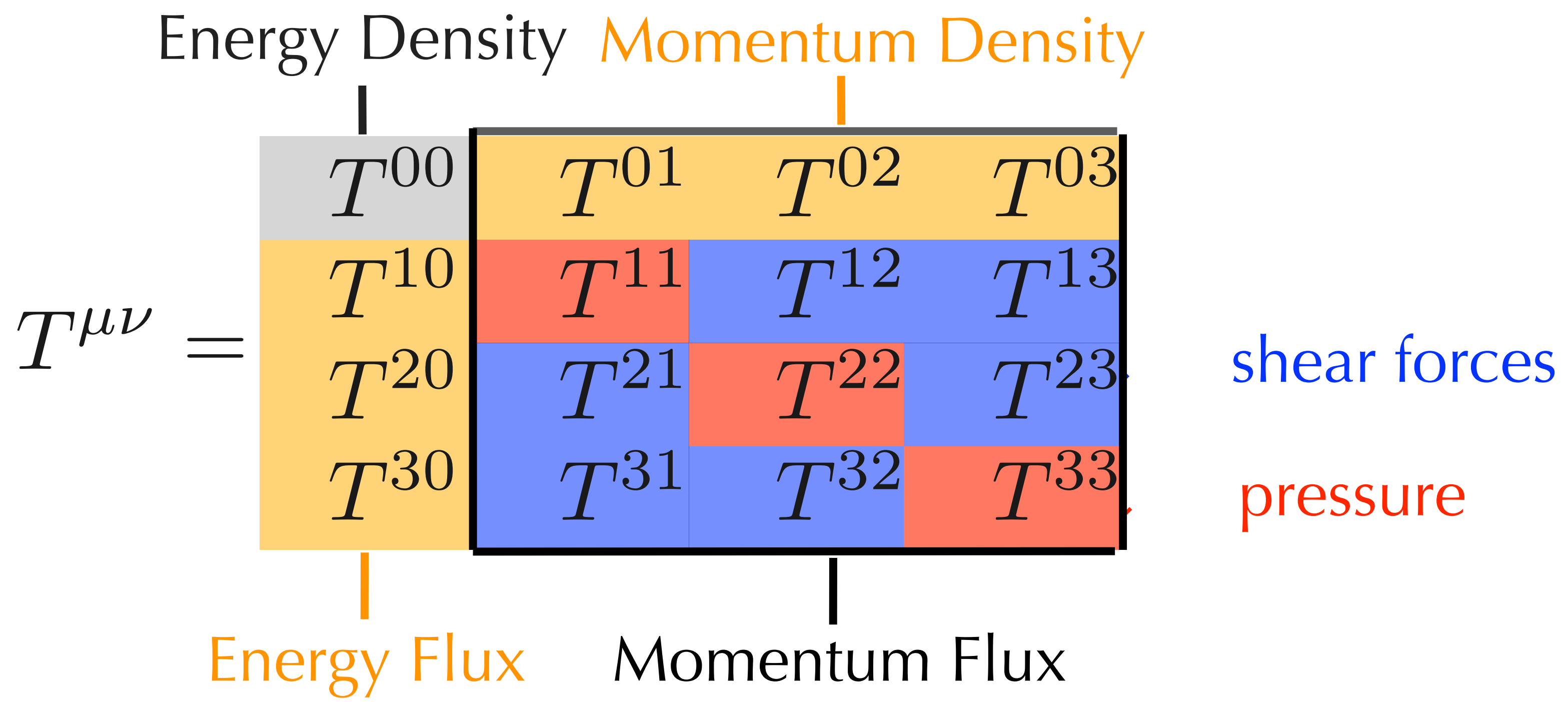
$J = \frac{1}{2}$

$d_1 = ??$

can be accessed from GPDs in hard exclusive reactions

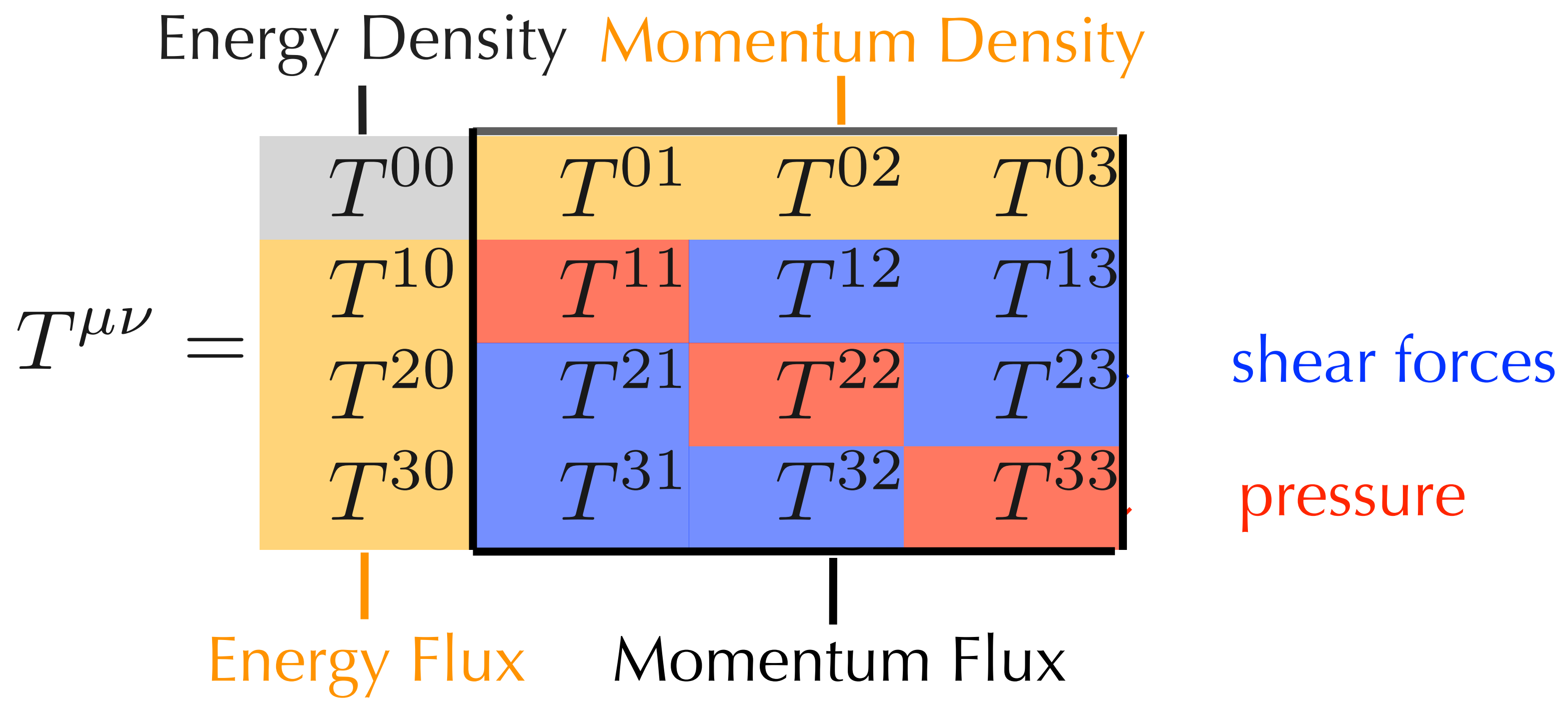
Talk by M. Polyakov and O. Teryaev

Form Factors of Energy Momentum Tensor



$$\langle P'|T^{Q,G}_{\mu\nu}|P\rangle = \bar{u}(P')[M_2^{Q,G}(t)\,\frac{P_\mu P_\nu}{M_N} + J^{Q,G}(t)\,\frac{i(P_\mu\sigma_{\nu\rho} + P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M_N} + d_1^{Q,G}(t)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N} \pm \bar{c}(t)g_{\mu\nu}]u(P)$$

Form Factors of Energy Momentum Tensor



$$\langle P'|T_{\mu\nu}^{Q,G}|P\rangle = \bar{u}(P')[M_2^{Q,G}(t)\,\frac{P_\mu P_\nu}{M_N} + J^{Q,G}(t)\,\frac{i(P_\mu\sigma_{\nu\rho} + P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M_N} + d_1^{Q,G}(t)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N} \pm \bar{c}(t)g_{\mu\nu}]u(P)$$

Relation with second-moments of GPDs:

$$\sum_q \int \mathrm{d}x\, x\, H^q(x,\xi,t) = M_2^Q(t) + \frac{4}{5}\, d_1^Q(t)\xi^2$$

$$\sum_q \int \mathrm{d}x\, x\, E^q(x,\xi,t) = 2J^Q(t) - M_2^Q(t) - \frac{4}{5}\, d_1^Q(t)\xi^2$$

"Charges" of the EM Tensor Form Factors at t=0

$M_2(0)$ nucleon momentum carried by partons

$J(0)$ angular momentum of partons

$d_1(0)$ D-term related to "stability" of the nucleon

Fourier transform in coordinate space

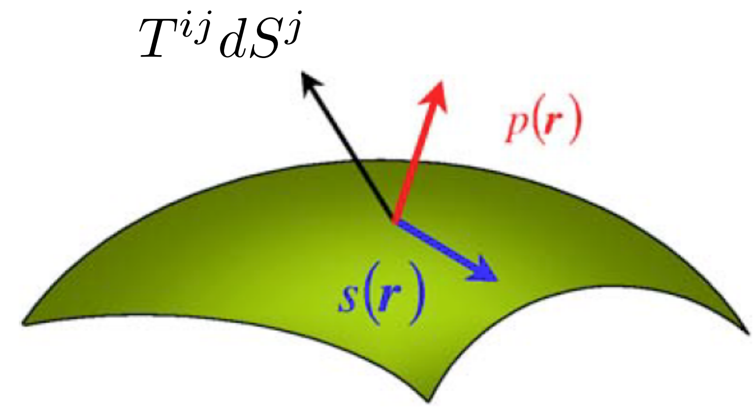
$$T_{ij}^{Q}(\vec{r}) = s(\vec{r})\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\delta_{ij}\right) + p(\vec{r})\,\delta_{ij}$$

shear forces

pressure

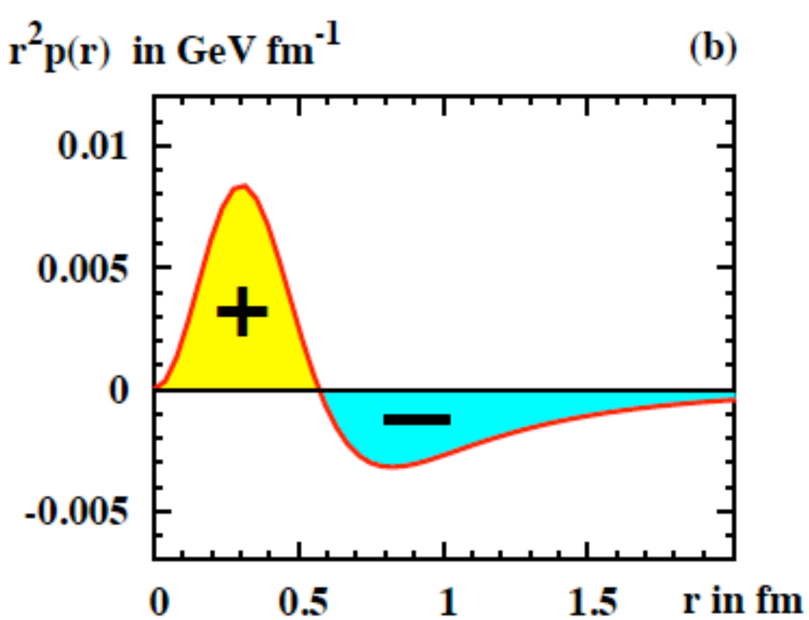
$$d_1^Q(0) = 5\pi M_N \int_0^\infty \mathrm{d}r\, r^4\, p(r)$$

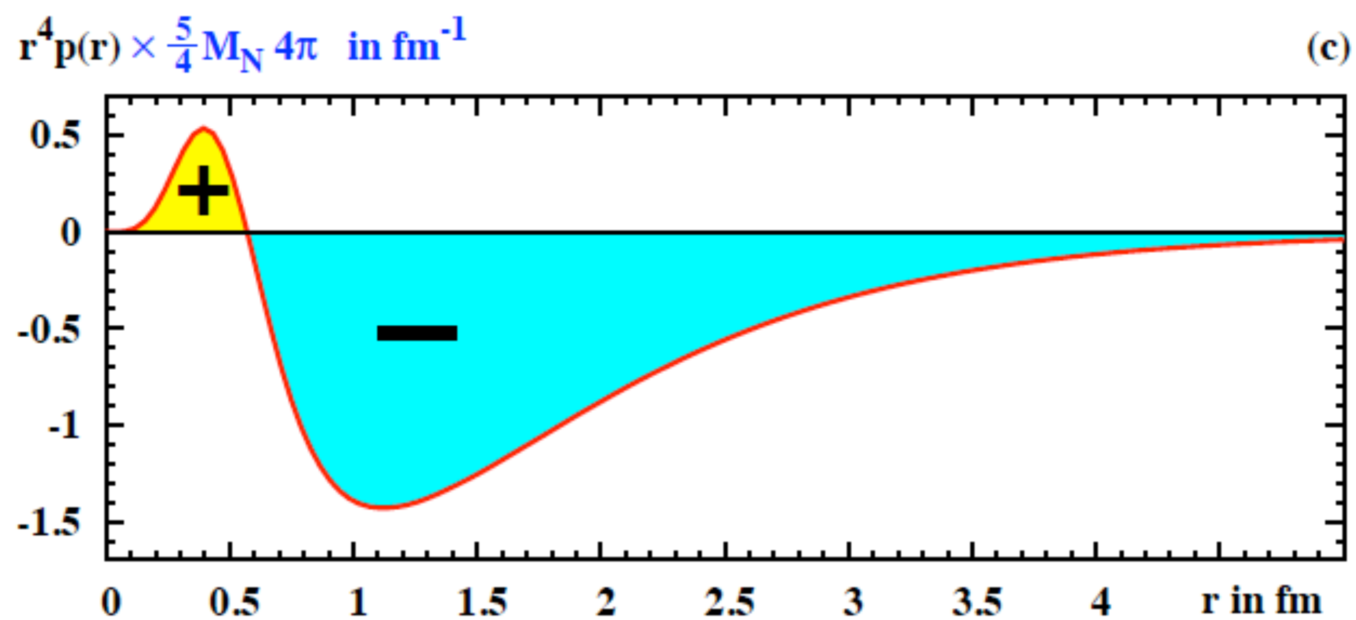
"mechanical properties" of nucleon



M. Polyakov, PLB 555 (2003) 57

Chiral quark soliton model





$$\int_0^\infty \mathrm{d}r\, r^2\, p(r) = 0$$

stability condition

$$\int_0^\infty \mathrm{d}r\, r^4\, p(r) < 0$$

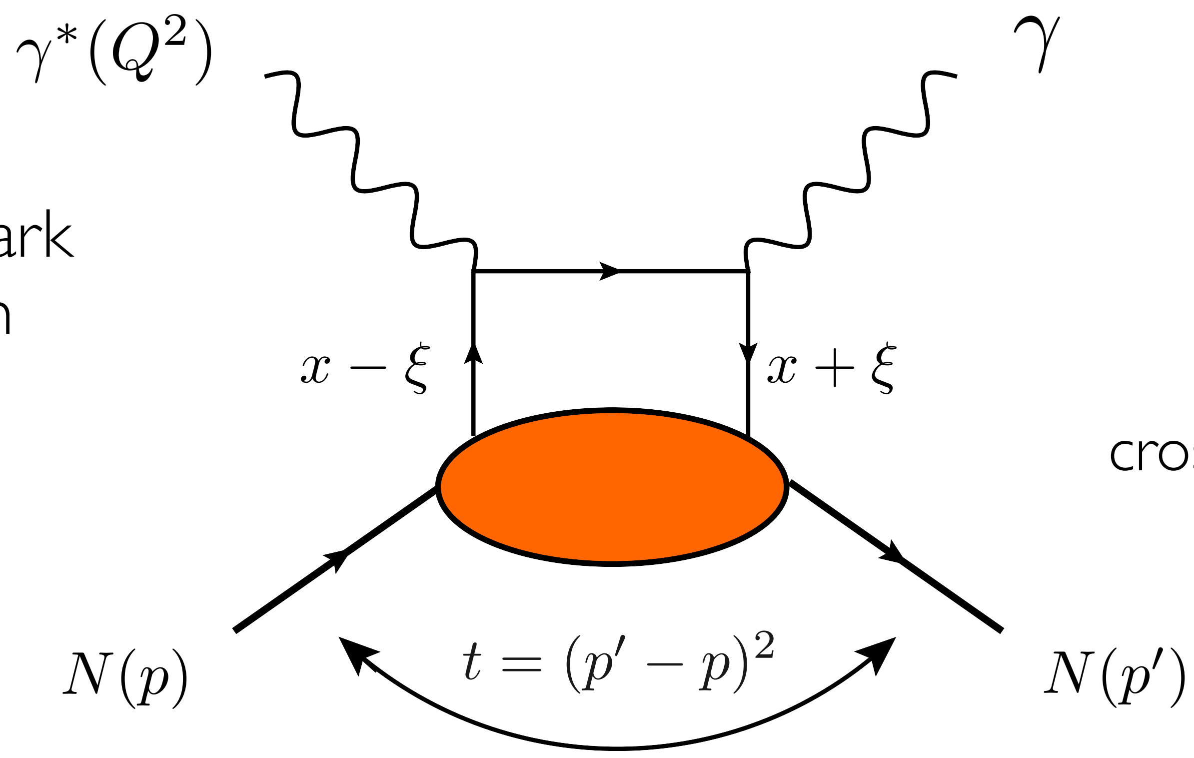
Schweitzer et al., PRD 75 (2007) 094021

DVCS at leading twist

x : average fraction of quark longitudinal momentum

ξ : fraction of longitudinal momentum transfer

t : nucleon momentum transfer



$t \ll \nu,\ Q^2$

↓

crossing symmetric variable

$$\nu = \frac{s-u}{4M_N}$$

DVCS tensor at twist 2: $T^{\mu\nu} = \sum_{i=1}^{4} A_i(\nu, t, Q^2)\, O_i^{\mu\nu}$

unpolarized quark

$$A_1 = \mathcal{H} + \mathcal{E}$$

$$A_2 = \mathcal{E}$$

long. polarized quark

$$A_3 = \tilde{\mathcal{H}}$$

$$A_4 = \tilde{\mathcal{E}}$$

Compton form factors: $\mathcal{F} = \int_0^1 \mathrm{d}x\, F^+(x,\xi,t,Q^2) \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon} \right]$ $\quad F = \left\{ H,\, E,\, \tilde{H},\, \tilde{E} \right\}$

↓

singlet GPDs: $F^+(x,\xi,t) = F(x,\xi,t) - F(-x,\xi,t)$

DVCS at leading twist

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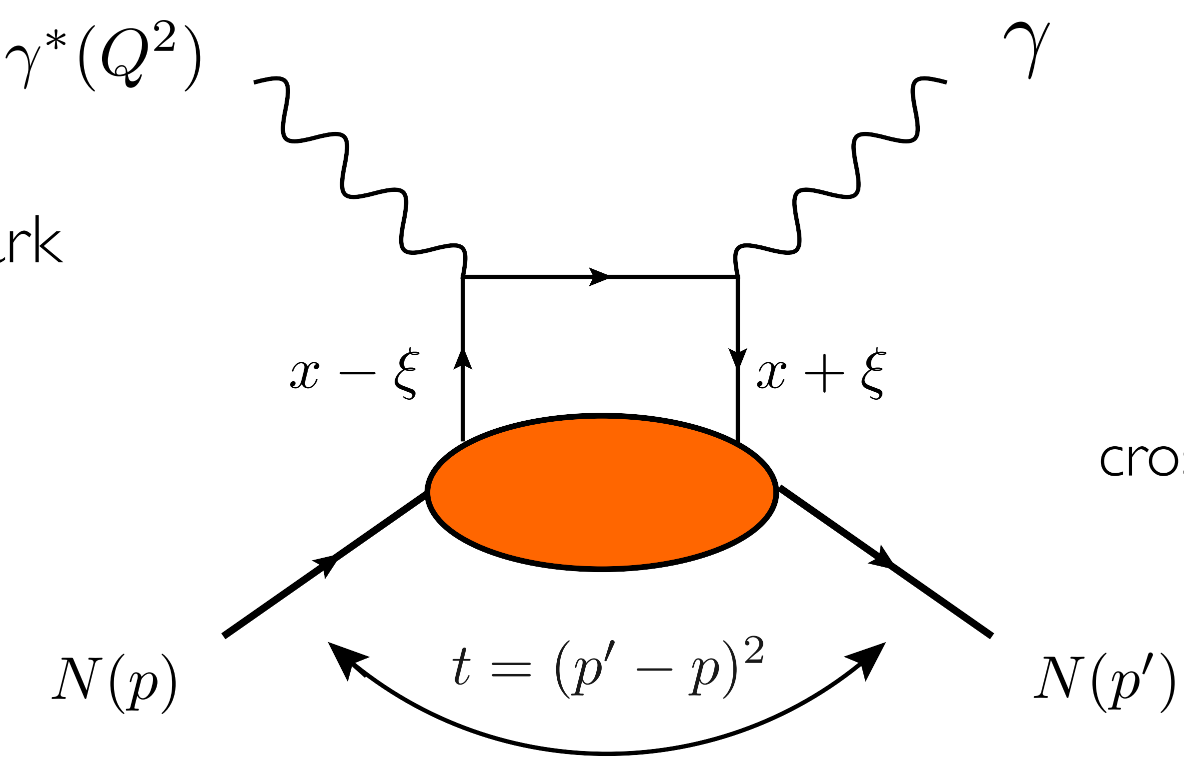

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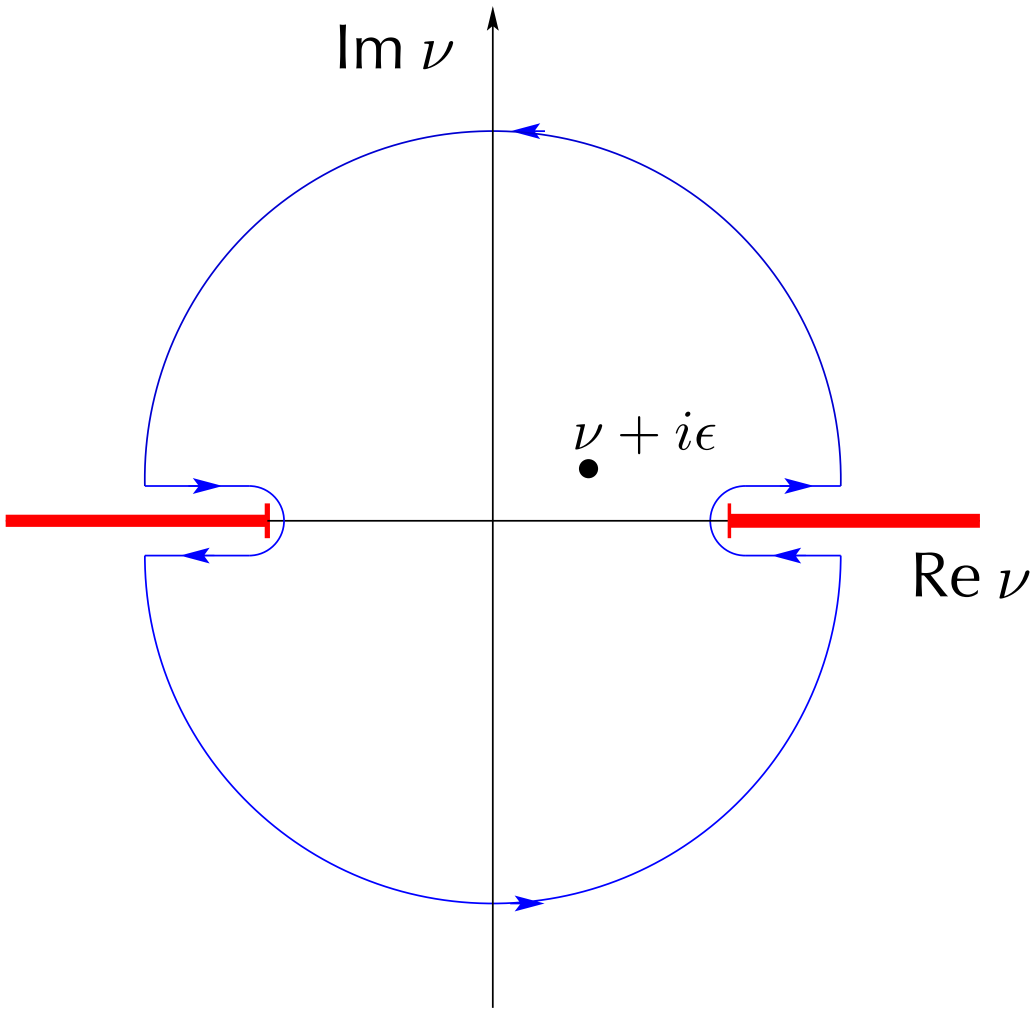
Dispersion Relations at fixed t and Q^2

$A_i(\nu, t, Q^2)$: analytical functions in the complex ν plane, with cuts on the real axis

Drechsel, B.P., Vanderhaeghen, Phys. Rept. 378 (2003); B.P., Vanderhaeghen, Ann. Rev. Nucl. Part. Sci. 68 (2018)

Dispersion Relations at fixed t and Q²

$A_i(\nu, t, Q^2)$: analytical functions in the complex ν plane, with cuts on the real axis



- Cauchy integral formula

$$A_i(\nu, t, Q^2) = \oint_C \mathrm{d}\nu' \frac{A_i(\nu', t, Q^2)}{\nu' - \nu}$$

Drechsel, B.P., Vanderhaeghen, Phys. Rept. 378 (2003); B.P., Vanderhaeghen, Ann. Rev. Nucl. Part. Sci. 68 (2018)

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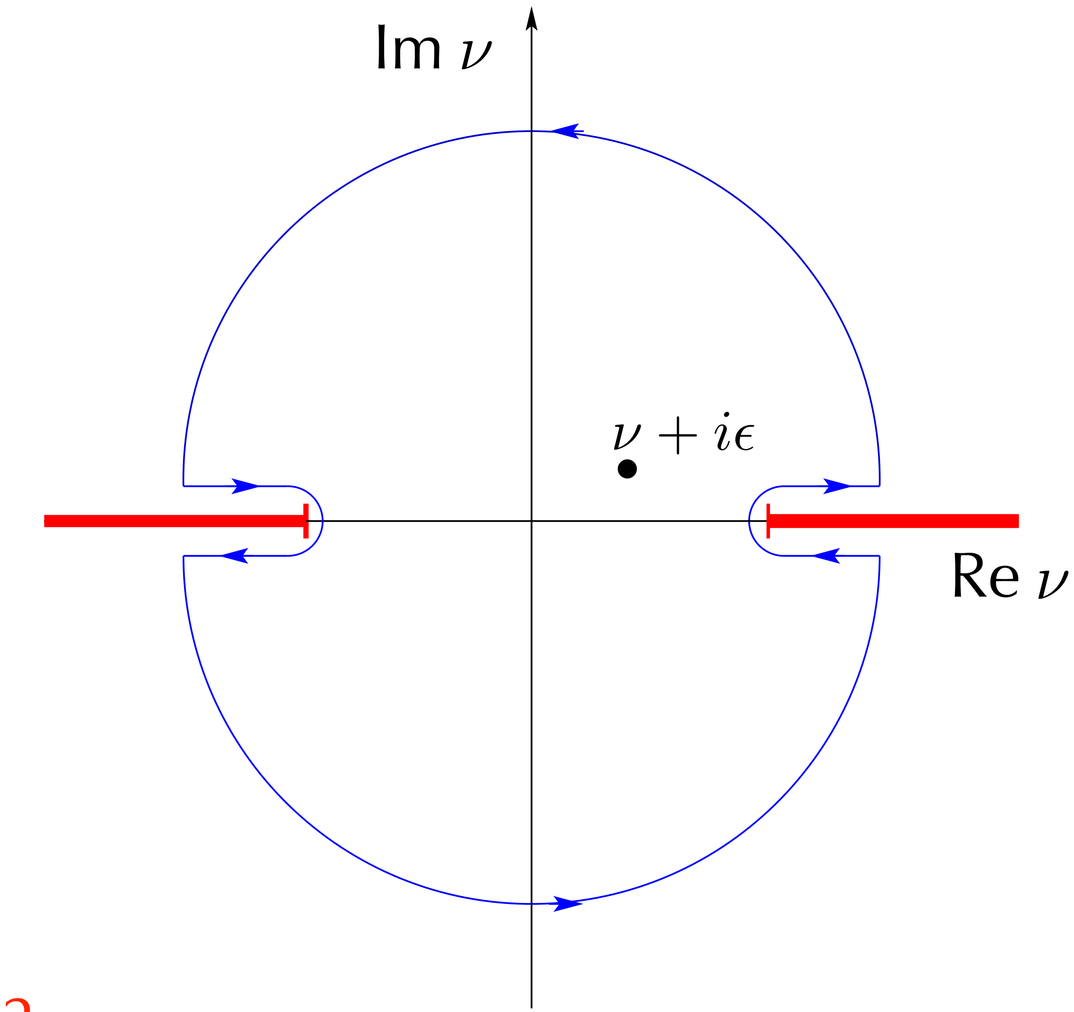

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$$A_i(\nu, t, Q^2) = \oint_C \mathrm{d}\nu' \frac{A_i(\nu', t, Q^2)}{\nu' - \nu}$$

- Crossing symmetry and analyticity

$$A_i(\nu, t, Q^2) = A_i(-\nu, t, Q^2) \qquad A_i(\nu^*, t, Q^2) = A_i^*(\nu, t, Q^2)$$

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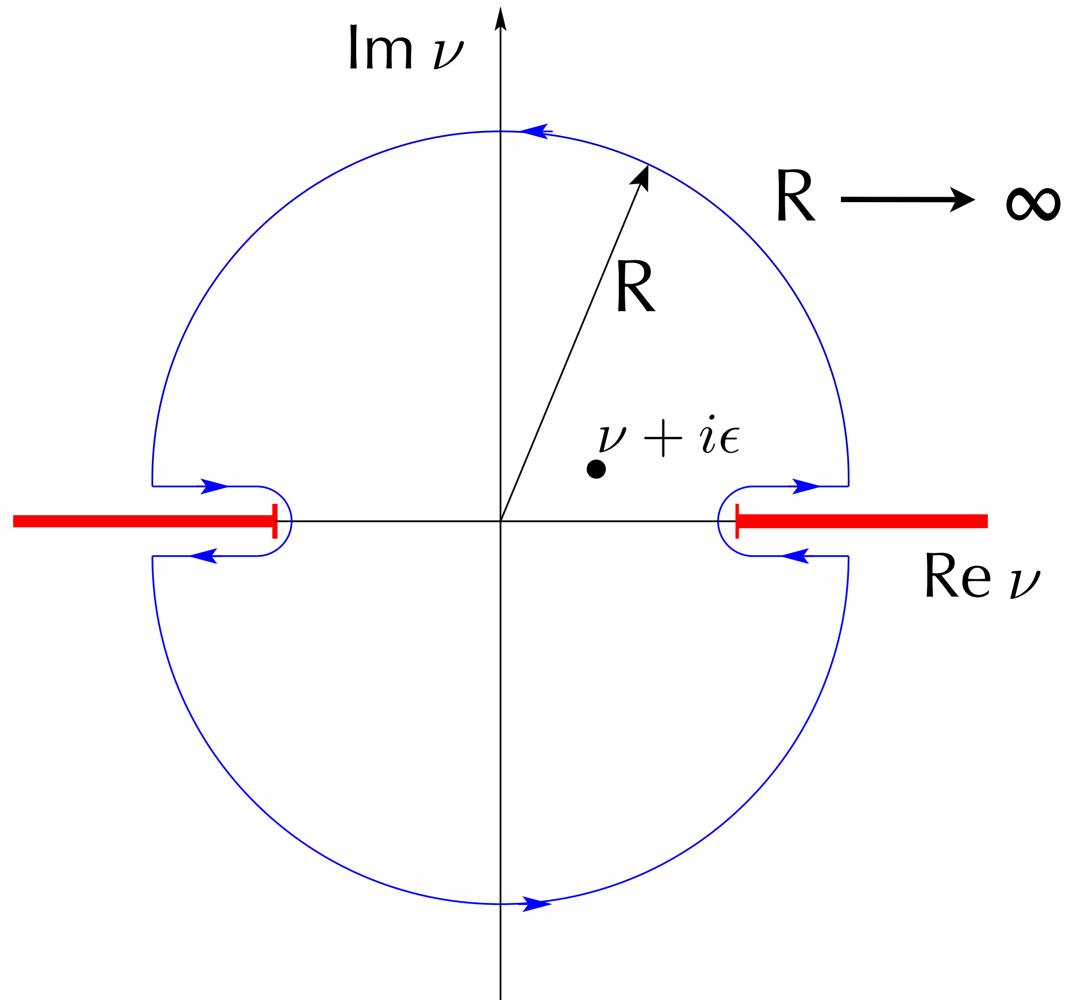

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Unsubtracted Dispersion Relations

$$\mathrm{Re}\, A_i(\nu, t, Q^2) = \frac{2}{\pi} \int_{\nu_0}^{\infty} \mathrm{Im}\, A_i(\nu', t, Q^2) \frac{\nu' \mathrm{d}\nu'}{\nu'^2 - \nu^2} \qquad (i = 1, \cdots, 4)$$

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non-convergent integrals

↓

Subtracted Dispersion Relations

$$\mathrm{Re}\, A_2(\nu, t, Q^2) = A_2(0, t, Q^2) + \frac{2}{\pi}\nu^2 \mathcal{P}\int_{\nu_0}^{\infty} \mathrm{Im}\, A_2(\nu', t, Q^2)\frac{\mathrm{d}\nu'}{\nu'(\nu'^2 - \nu^2)}$$

↓

subtraction at $\nu = 0$

Dispersion Relations in terms of GPDs

energy variables ⟶ $\nu = \frac{Q^2}{4M_N\xi}$ $\nu' = \frac{Q^2}{4M_N x}$

once subtracted fixed-t DRs in the variable x

$$\mathrm{Re}\, A_2(\nu, t, Q^2) = \Delta(t, Q^2) + \frac{2}{\pi}\mathcal{P}\int_0^1 \frac{\mathrm{d}x}{x}\, \frac{\mathrm{Im}\, A_2(x, t, Q^2)}{(\xi^2/x^2 - 1)}$$

link with twist-2 GPDs: $\mathrm{Im}\, A_2(x, t, Q^2) = \pi E^+(x, \xi = x, t, Q^2)$

$$\mathrm{Re}\, A_2(\nu, t, Q^2) = \Delta(t, Q^2) + \mathcal{P}\int_0^1 \mathrm{d}x\, E^+(x, x, t, Q^2)\left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right]$$

$\Delta(t, Q^2)$ ↓ subtraction function

$E^+(x, x, t, Q^2)$ ↓ accessible through spin asymmetries

Anikin, Teryaev (2007); Kumericki-Passek, Mueller, Passek (2008); Diehl, Ivanov (2007);

Polyakov, Vanderhaeghen (2008); Goldstein, Liuti (2009); Mueller, Semenov (2015)

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↓

$$\mathrm{Re}\, A_2(\nu,t,Q^2) = -\mathcal{P}\int_0^1 \mathrm{d}x\, E^+(x,\xi,t,Q^2)\left[\frac{1}{x-\xi}+\frac{1}{x+\xi}\right]$$

Anikin, Teryaev (2007); Kumericki-Passek, Mueller, Passek (2008); Diehl, Ivanov (2007);

Polyakov, Vanderhaeghen (2008); Goldstein, Liuti (2009); Mueller, Semenov (2015)

Subtraction Function

$$\Delta(t,Q^2)=\mathcal{P}\int_0^1 \mathrm{d}x\,[E^+(x,\xi,t,Q^2)-E^+(x,x,t,Q^2)]\left[\frac{1}{\xi-x}-\frac{1}{x-\xi}\right]$$

Make use of:

ξ-independence ⟶ take $\xi=0$

Time-Reversal invariance ⟶ $E(x,x,t)=E(x,-x,t)$

Lorentz invariance ⟶ polinomiality of Mellin moments of GPDs

$$\int_{-1}^1 \mathrm{d}x\, x^n\, E(x,\xi,t)=e_0^{(n)}(t)+e_2^{(n)}(t)\xi^2+\cdots+e_{n+1}^{(n)}(t)\xi^{n+1}$$

highest power generated by
Polyakov-Weiss D-term form factor $D(z,t)$

Anikin, Teryaev (2007); Radyushkin (2012)

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highest power generated by Polyakov-Weiss D-term form factor $D(z,t)$

$$\Delta(t,Q^2)=-\frac{4}{N_f}D(t,Q^2)$$

with $D(t,Q^2)=\frac{1}{2}\int_{-1}^1 \mathrm{d}z\,\frac{D(z,t,Q^2)}{1-z}$

Anikin, Teryaev (2007); Radyushkin (2012)

Dispersion Relations for DVCS amplitudes

- s-channel DRs:

$$\mathrm{Re}\, A_2(\nu, t, Q^2) = \Delta(t, Q^2) + \frac{2}{\pi}\nu^2 \mathcal{P} \int_{\nu_0}^{\infty} \mathrm{Im}\, A_2(\nu', t, Q^2) \frac{\mathrm{d}\nu'}{\nu'(\nu'^2 - \nu^2)}$$

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- t-channel DRs for subtraction function

$$\Delta(t, Q^2) = -\frac{4}{N_f}\, D(t, Q^2) = \frac{1}{\pi} \int_{4m_\pi^2}^{\infty} \mathrm{d}t' \, \frac{\mathrm{Im}_t\, A_2(0, t', Q^2)}{t' - t} + \frac{1}{\pi} \int_{-\infty}^{-a} \mathrm{d}t' \, \frac{\mathrm{Im}_t\, A_2(0, t', Q^2)}{t' - t}$$

↓

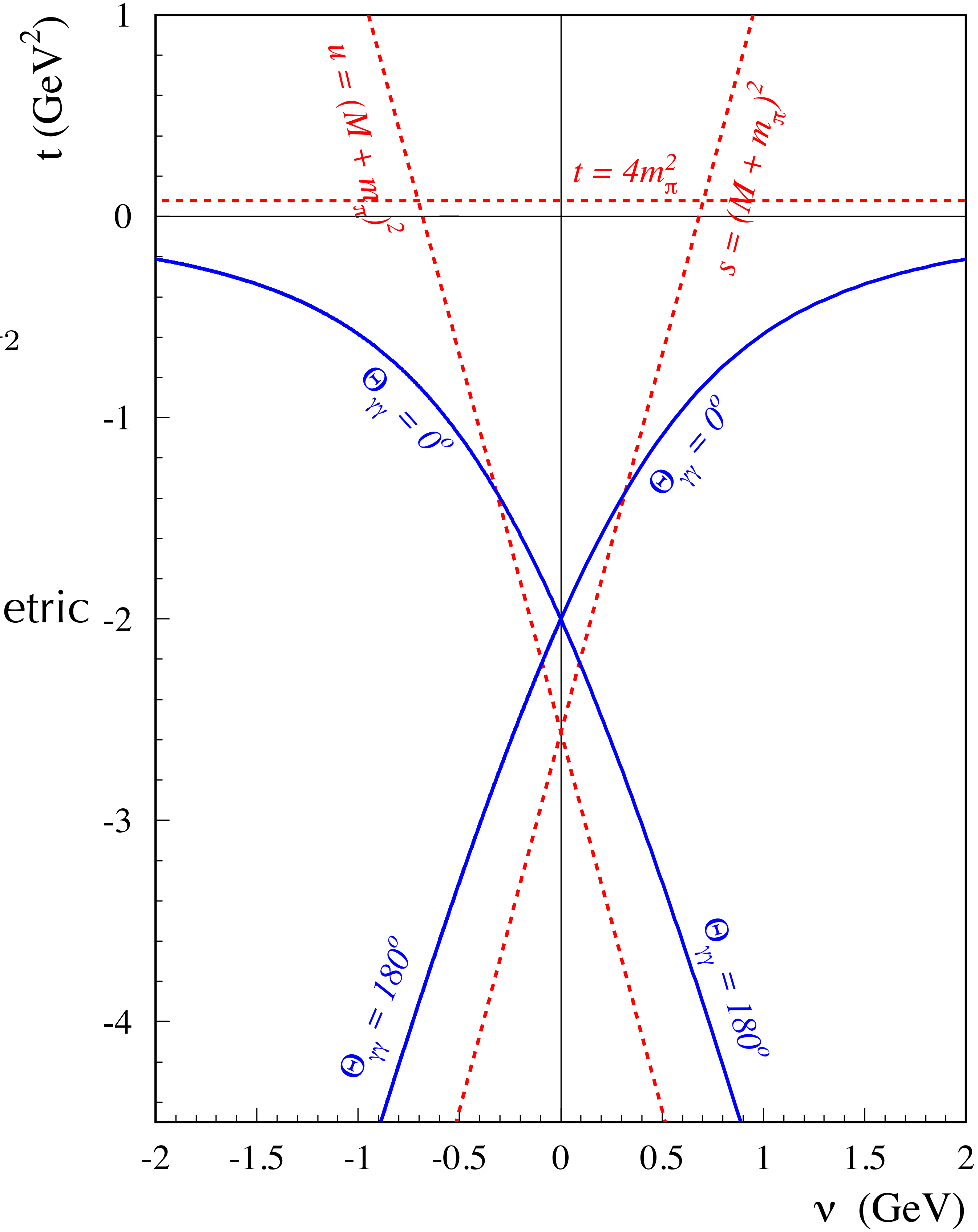
$$-a = -2(m_\pi^2 + 2M_N m_\pi) - Q^2$$

Fixed

$Q^2 = -2\ \mathrm{GeV}^2$

$\nu = \frac{s-u}{4M_N}$

crossing symmetric variable



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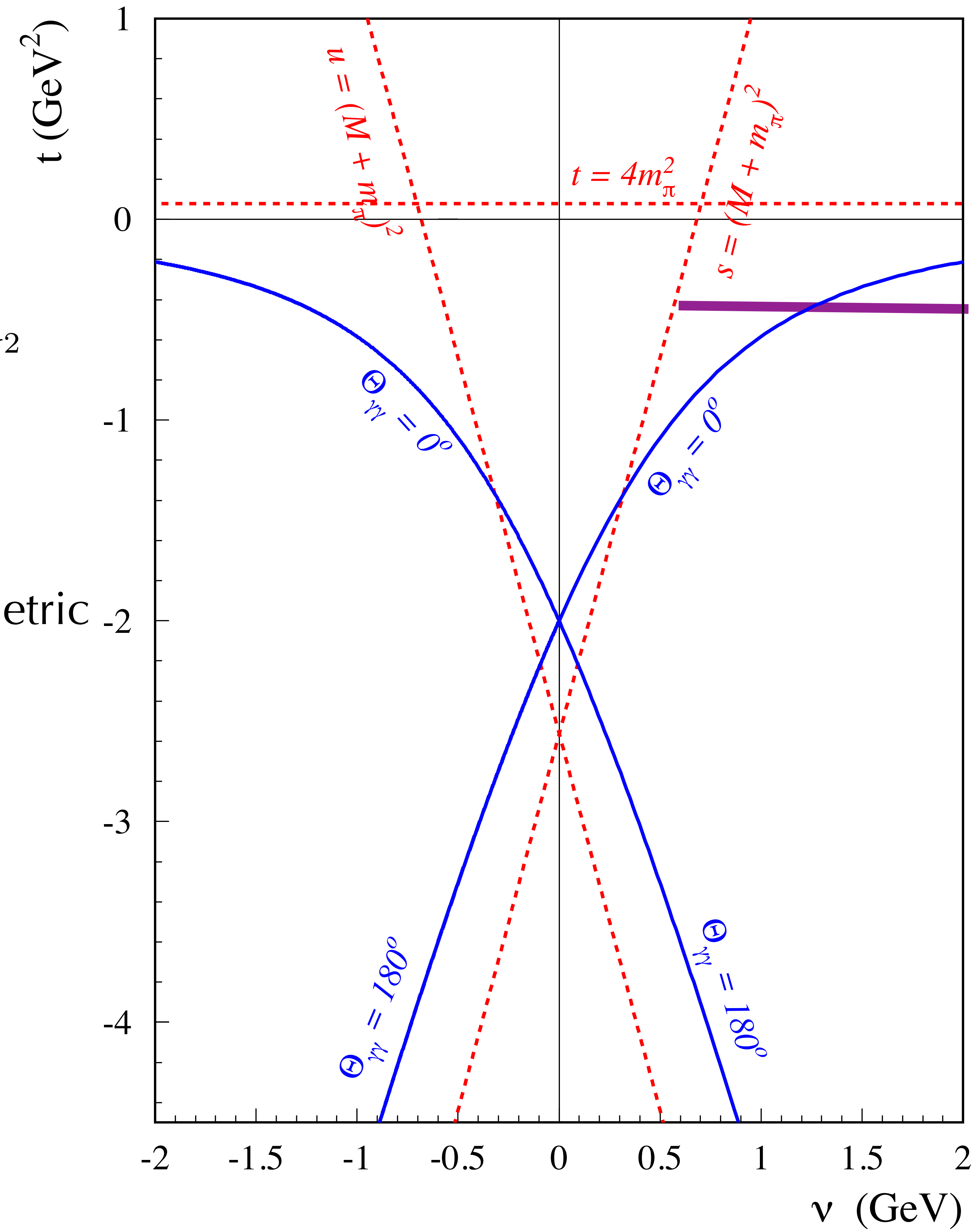
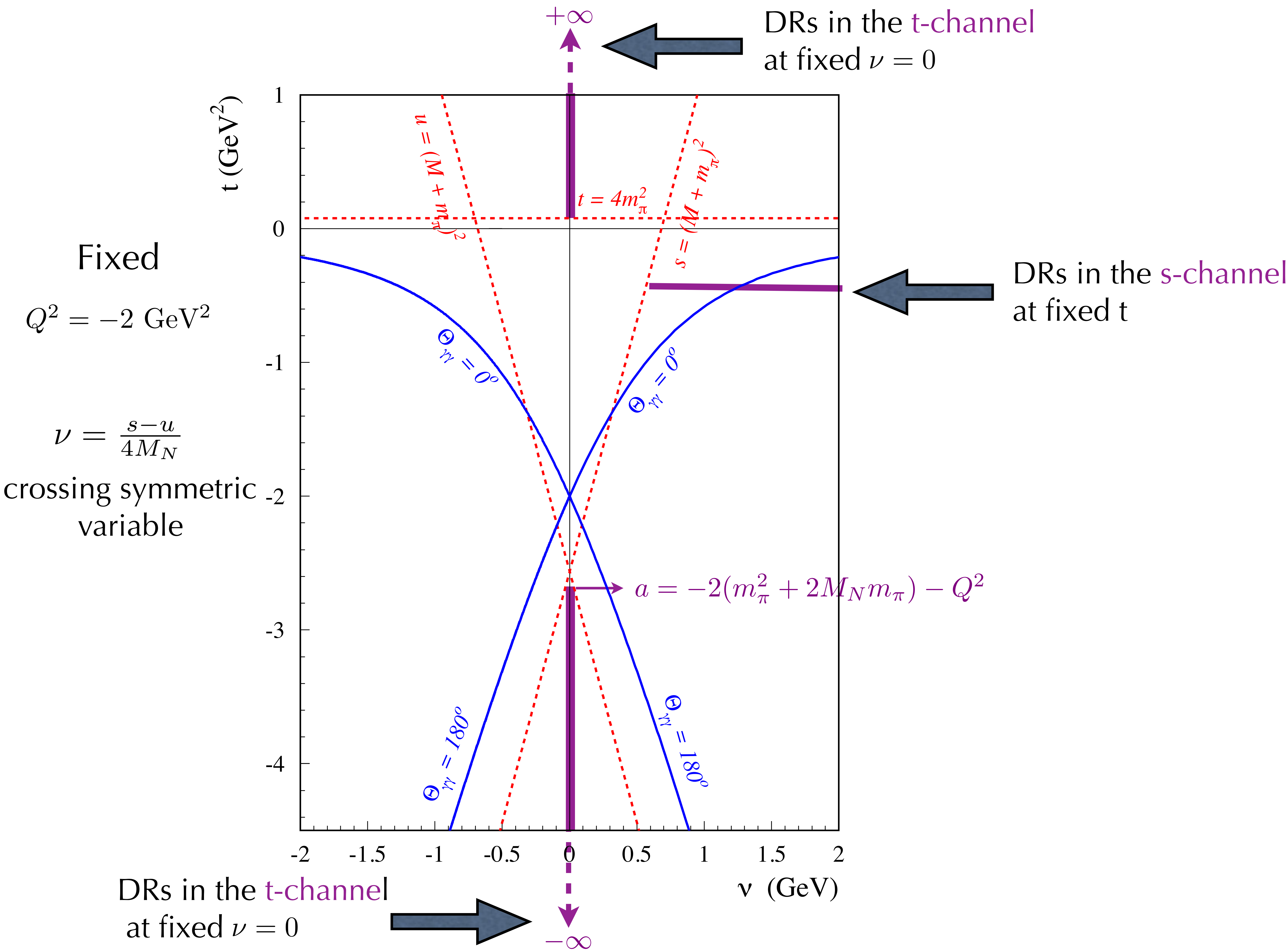


DRs in the s-channel at fixed t



DRs in the t-channel
at fixed ν = 0
+∞
DRs in the s-channel
at fixed t
Fixed
Q² = −2 GeV²
ν = (s−u)/(4M_N)
crossing symmetric
variable
t (GeV²)
ν (GeV)
t = 4m_π²
u = (M + m_π)²
s = (M + m_π)²
Θ_γγ = 0°
Θ_γγ = 0°
Θ_γγ = 180°
Θ_γγ = 180°
a = −2(m_π² + 2M_N m_π) − Q²
DRs in the t-channel
at fixed ν = 0
−∞

Dispersion Relations in the t-channel

$$\Delta(t,Q^2) = \mathrm{Re}\,A_2(0,t,Q^2) = \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} \mathrm{d}t' \, \frac{\mathrm{Im}_t\, A_2(0,t',Q^2)}{t'-t} + \frac{1}{\pi}\int_{-\infty}^{-a} \mathrm{d}t' \, \frac{\mathrm{Im}_t\, A_2(0,t',Q^2)}{t'-t}$$

$$-a = -2(m_\pi^2 + 2M_N m_\pi) - Q^2 \to -\infty$$

Dispersion Relations in the t-channel

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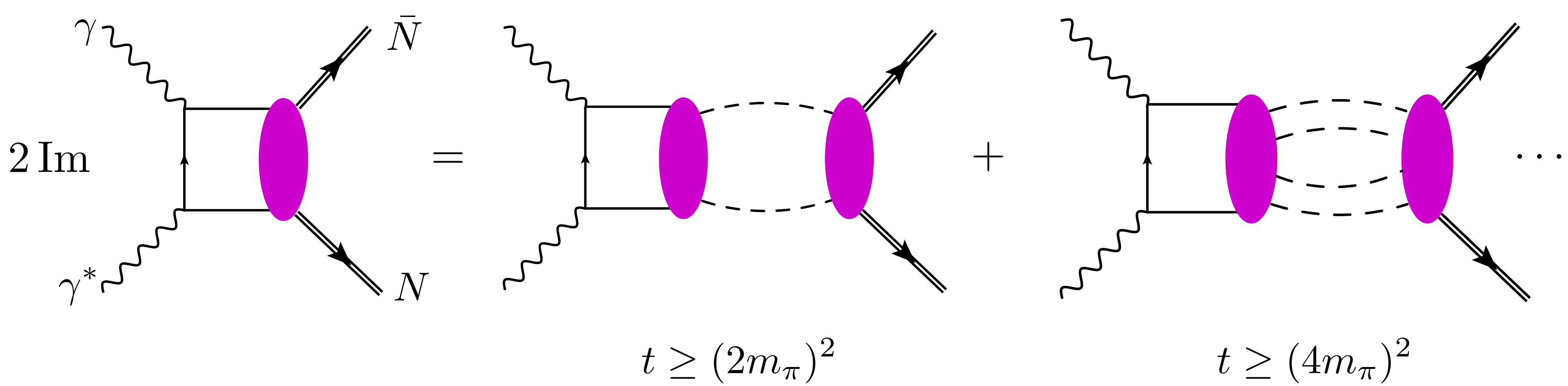
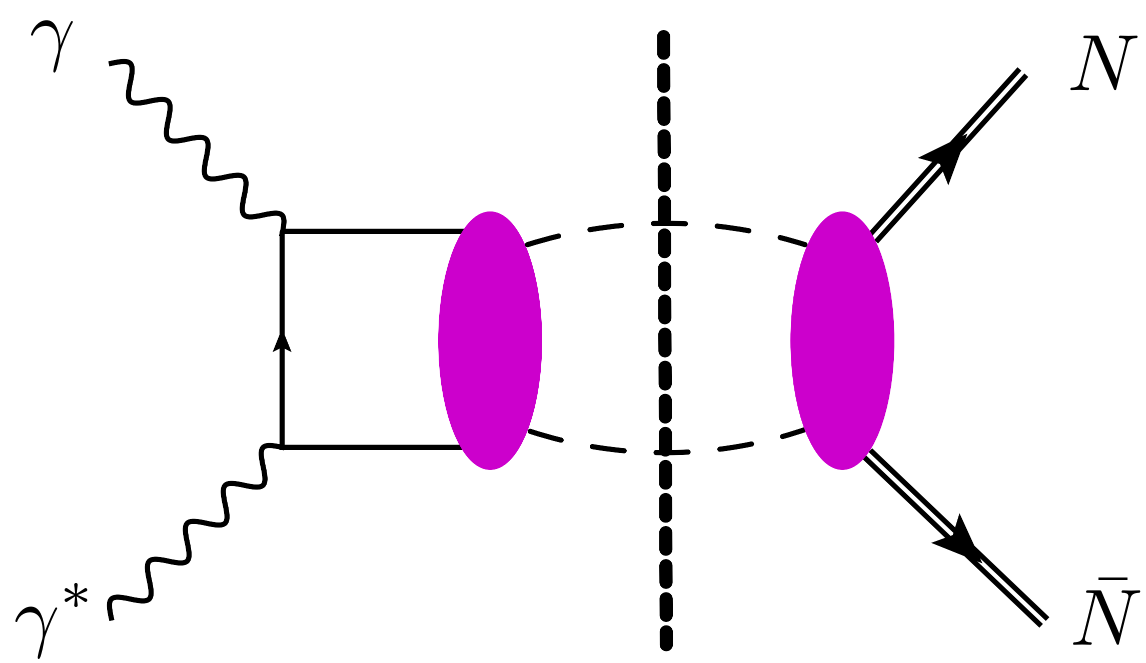
$$-a = -2(m_\pi^2 + 2M_N m_\pi) - Q^2 \to -\infty$$

Unitarity relation in t-channel



Unitarity Relations in the t-channel

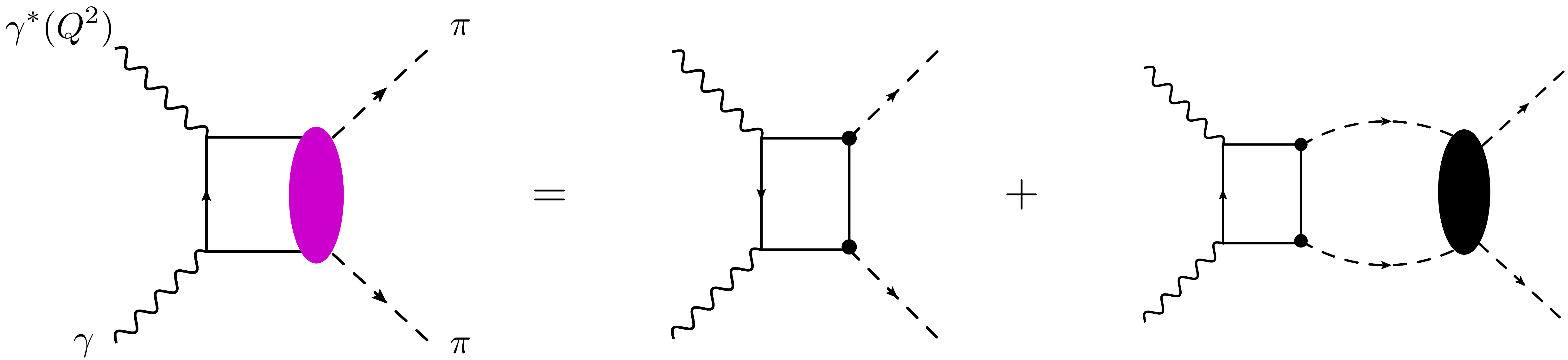


- Charge conjugation
- Partial wave expansion with $\nu = 0 \rightarrow \theta_t = 90^o$

two-pion intermediate state with

$I = 0 \qquad J = 0, 2, \cdots$

$\gamma^*\gamma \to \pi\pi$: two-pion GDAs



$$\Phi_q^{\pi\pi} = 6\,z(1-z) \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} \sum_{\substack{l=0 \\ \text{even}}}^{n+1} \tilde{B}^q_{nl}(t)\, C_n^{(3/2)}(2z-1)\, P_l(\cos\theta_{\pi\pi})$$

unitarized S- and D- waves: dispersive (Omnès) representation

S wave

$$\tilde{B}_{10}(t) = -B_{12}(0)\frac{3C-\beta^2}{2} f_0(t)$$

$$B_{12}(0) = \frac{10}{9}\int \mathrm{d}x\, x \frac{1}{N_f}\sum_f [q_\pi^f(x) + \bar{q}_\pi^f(x)]$$

→ pion PDFs

D wave

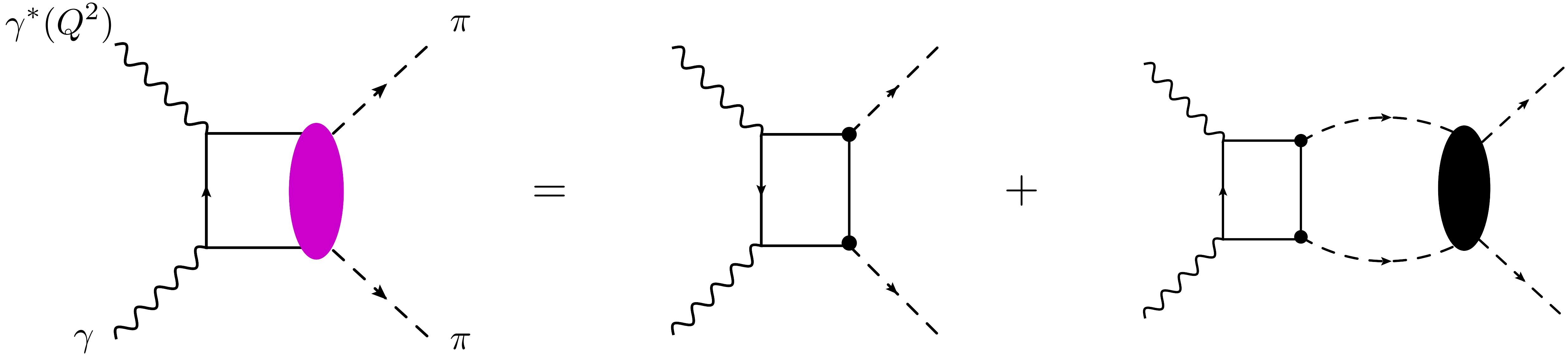
$$\tilde{B}_{12}(t) = \beta^2 B_{12}(0) f_2(t)$$

$$f_l(t) = \exp\left[\frac{t}{\pi}\int_{4m_\pi^2}^{\infty} \mathrm{d}t' \frac{\delta_l^0(t')}{t'(t'-t-i\epsilon)}\right]$$

→ $\pi\pi$ phase shifts

M. Polyakov, 1999

$\gamma^*\gamma \to \pi\pi$: two-pion GDAs

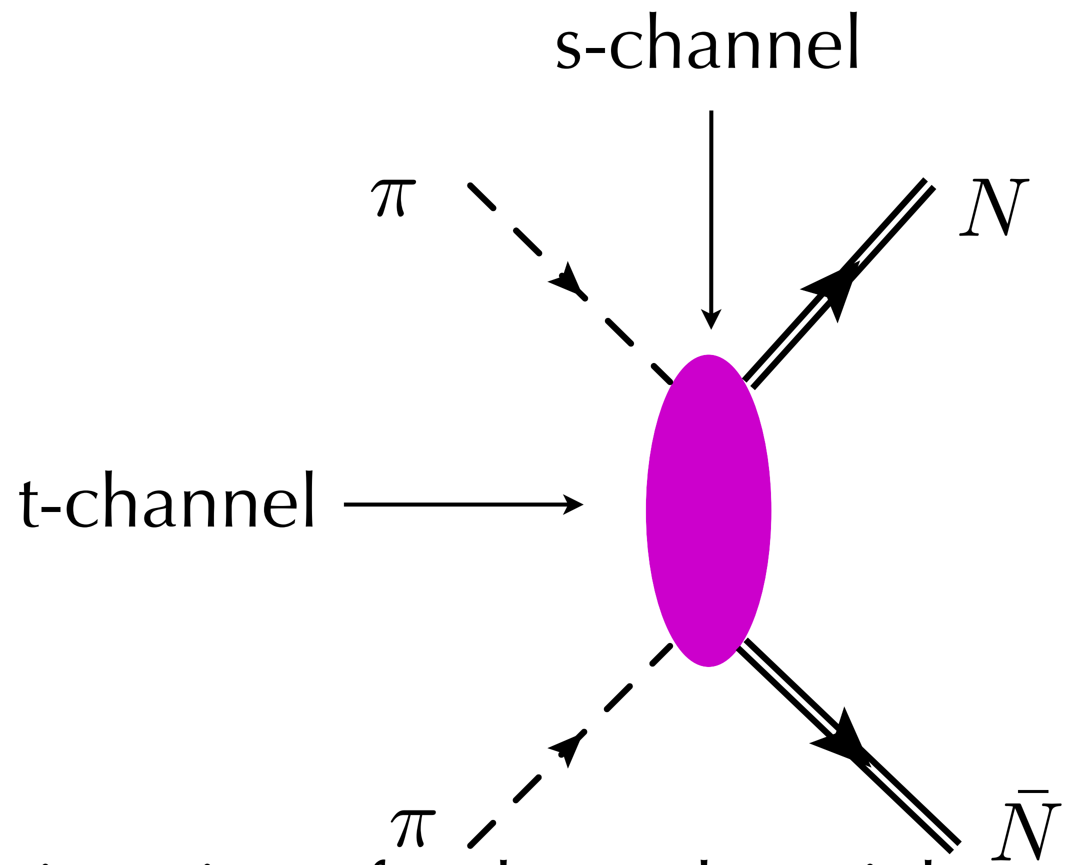


unitarized S- and D- waves: dispersive (Omnès) representation

input ⇨ $\pi\pi$ phase shifts
pion PDFs

M. Polyakov, 1999

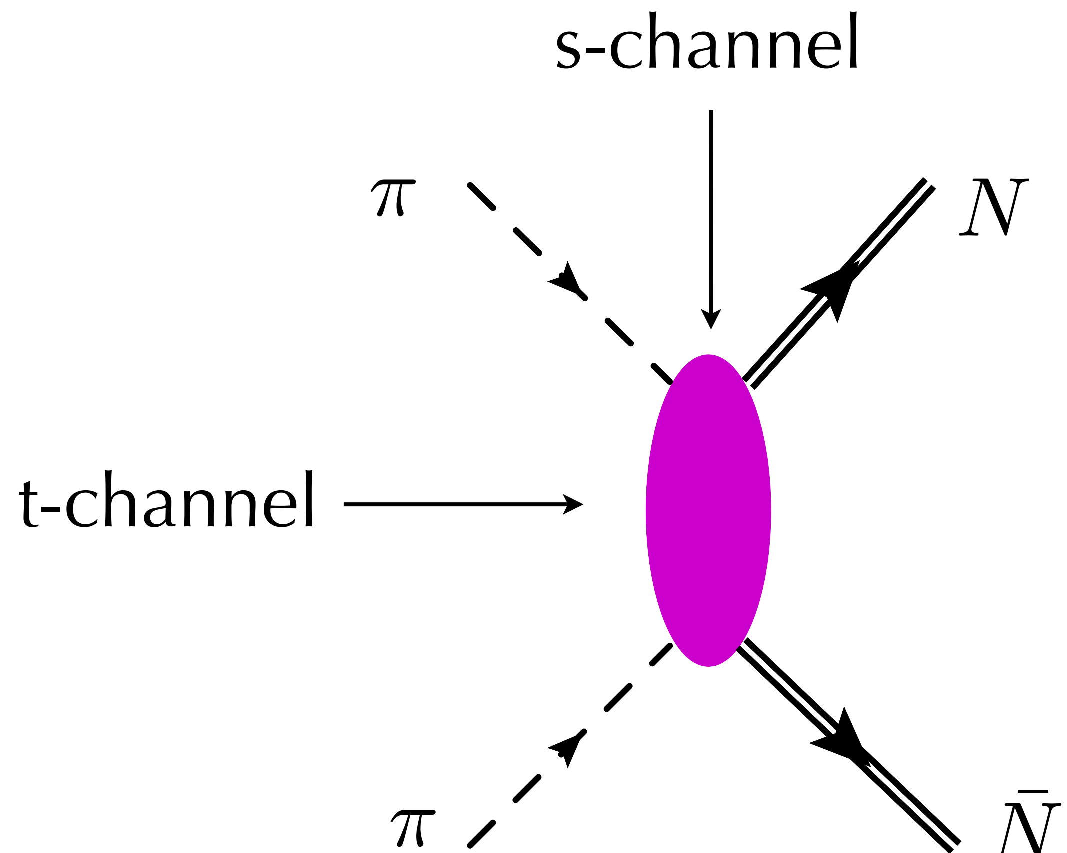
$\pi\pi \to N\bar{N}$ scattering amplitudes



analytical continuation of s-channel partial-wave helicity amplitudes
calculated from DRs

G. Hoehler, 1983

$\pi\pi \to N\bar{N}$ scattering amplitudes

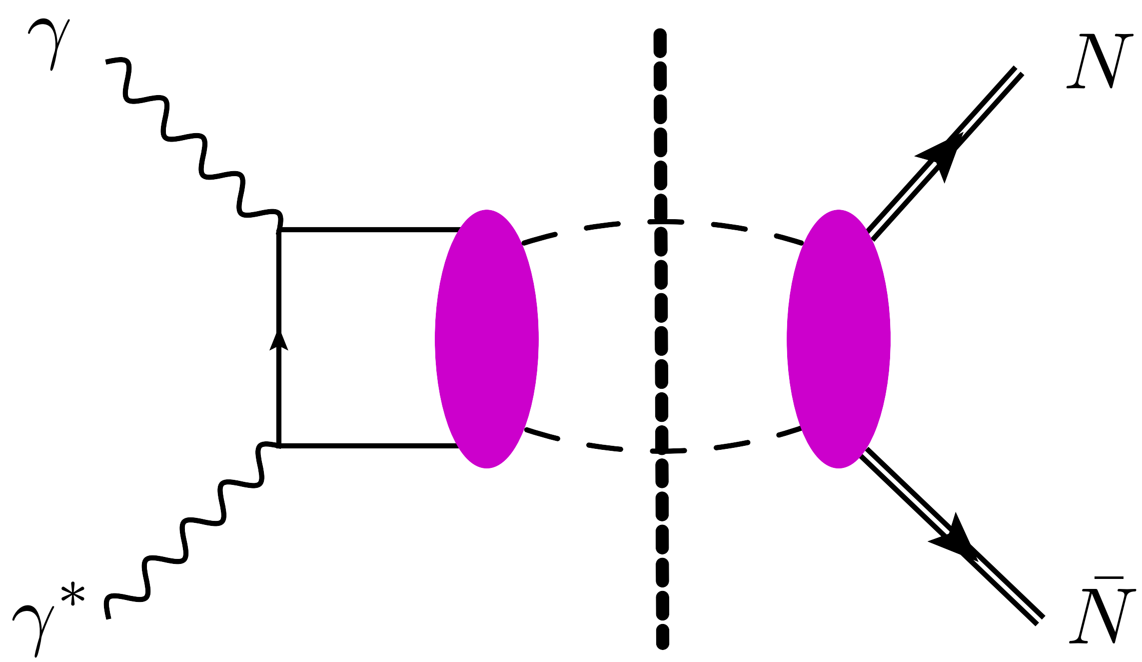


analytical continuation of s-channel partial-wave helicity amplitudes
calculated from DRs

input $\Rightarrow$ $\pi\pi$ phase shifts

G. Hoehler, 1983

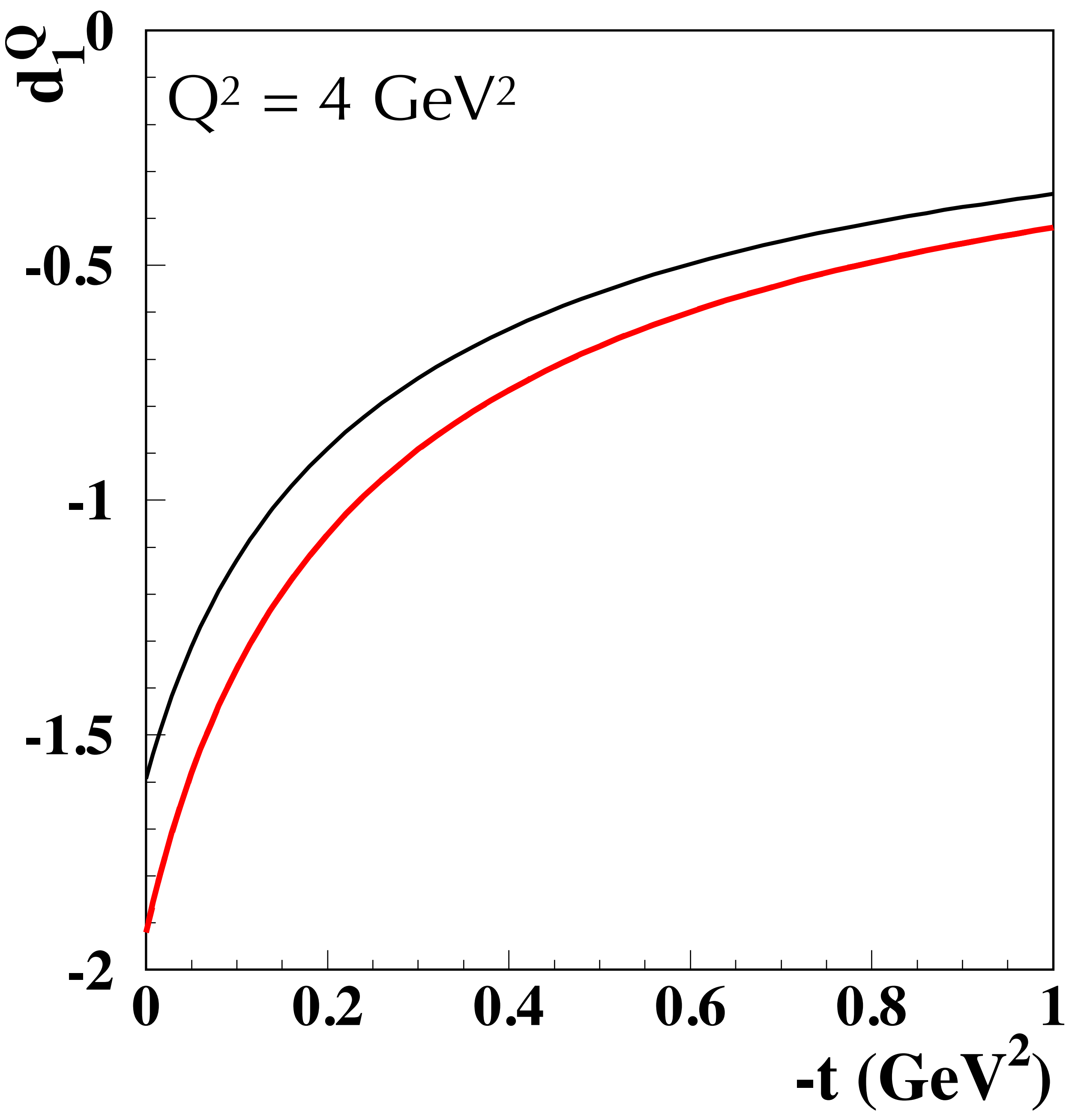
Intermediate summary: input for t-channel DRs



- two pion intermediate states ⟶ partial wave expansion and take $I = 0,\ J = 0, 2$
- expansion in Gegenbauer polynomials: $D(t) = \sum_{\{n\ odd\}} d_n(t)$ ⟶ DRs for $d_1(t)$
- $\gamma^*\gamma \to \pi\pi$: GDAs with input from pion PDFs and $\pi\pi$ phase shifts
- $\pi\pi \to N\bar{N}$: analytical continuations of pion-nucleon scattering amplitudes with input from $\pi\pi$ phase shifts

DR Results for D-term Form Factor

Q= u + d



pion PDFs from GRV, ZPC53 (1992)

$d_1(0) = -1.92$

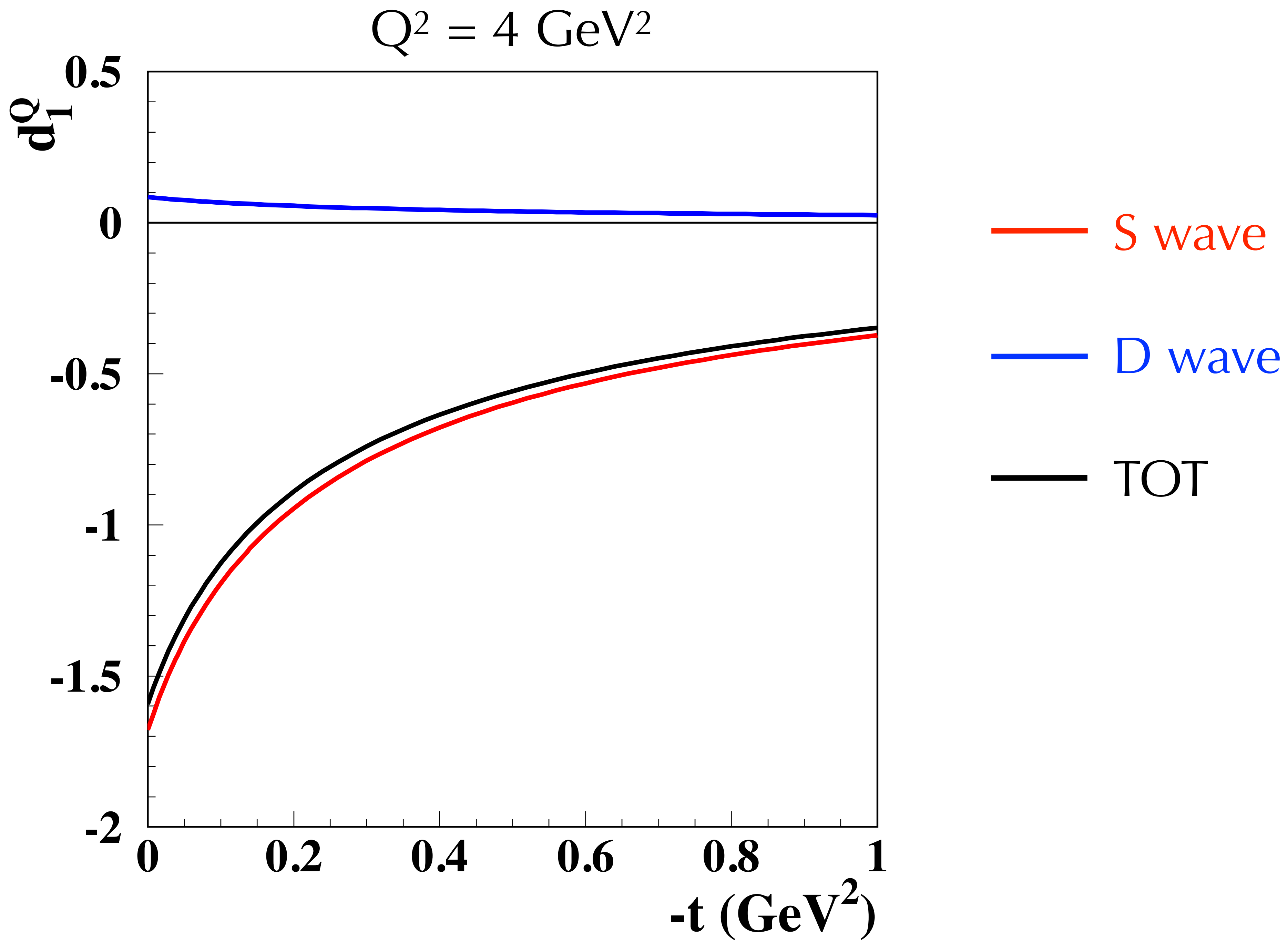
pion PDFs from Owens et al., PRD30 (1984)

$d_1(0) = -1.59$

χQSM	Skyrme model	Effective LFWFs
$d_1^Q(0) = -2.35$	$d_1^Q(0) = -4.48$	$d_1^Q(0) = -2.01$
Schweitzer et al., (2007)	*Schweitzer et al., (2007)*	*Mueller and Hwang, (2014)*

DR Results for D-term Form Factor

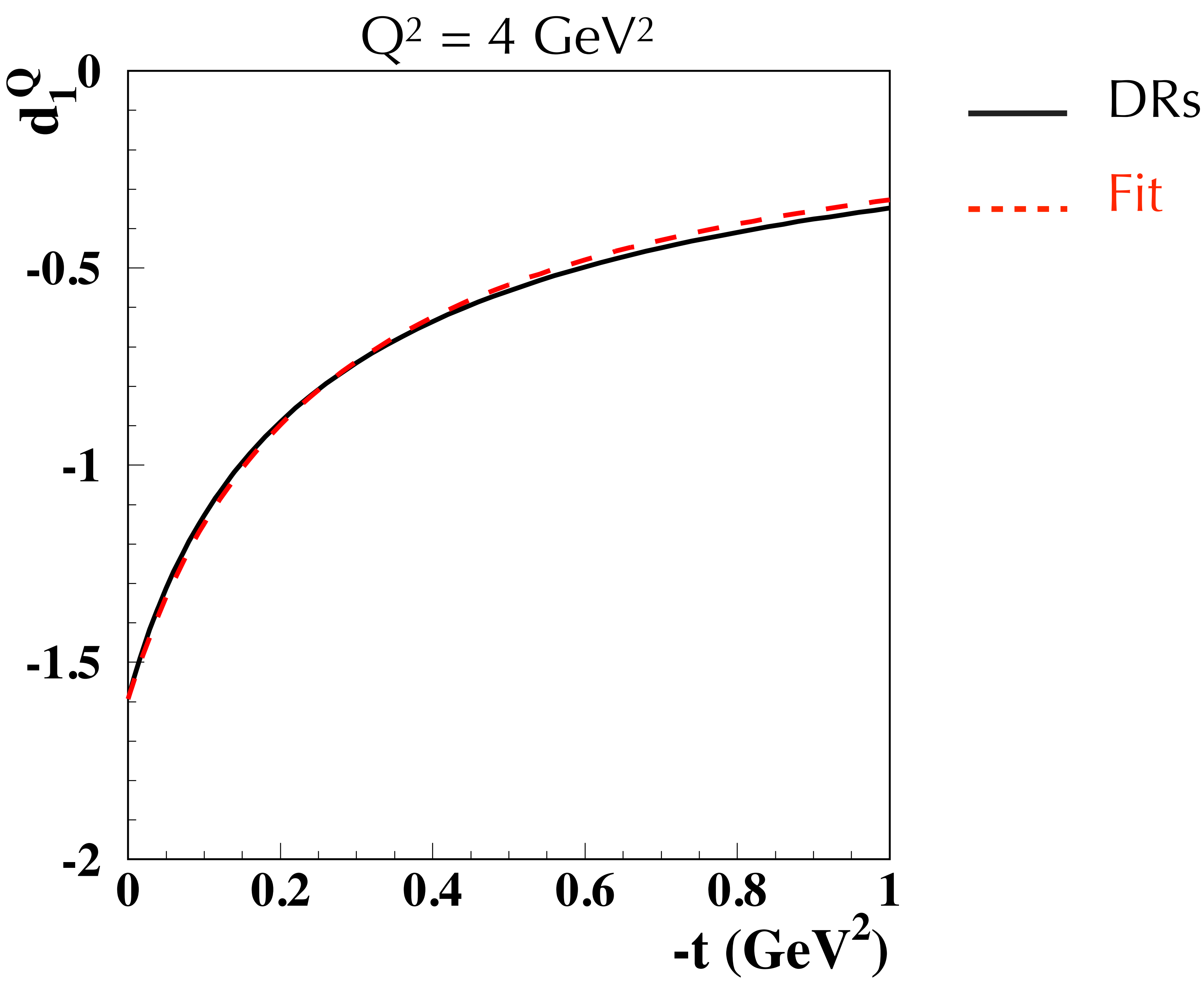
Q= u + d



B. Pasquini, M. Polyakov, M. Vanderhaeghen, PLB739 (2014) 133

D-term Form Factor: t-dependence

Q= u + d

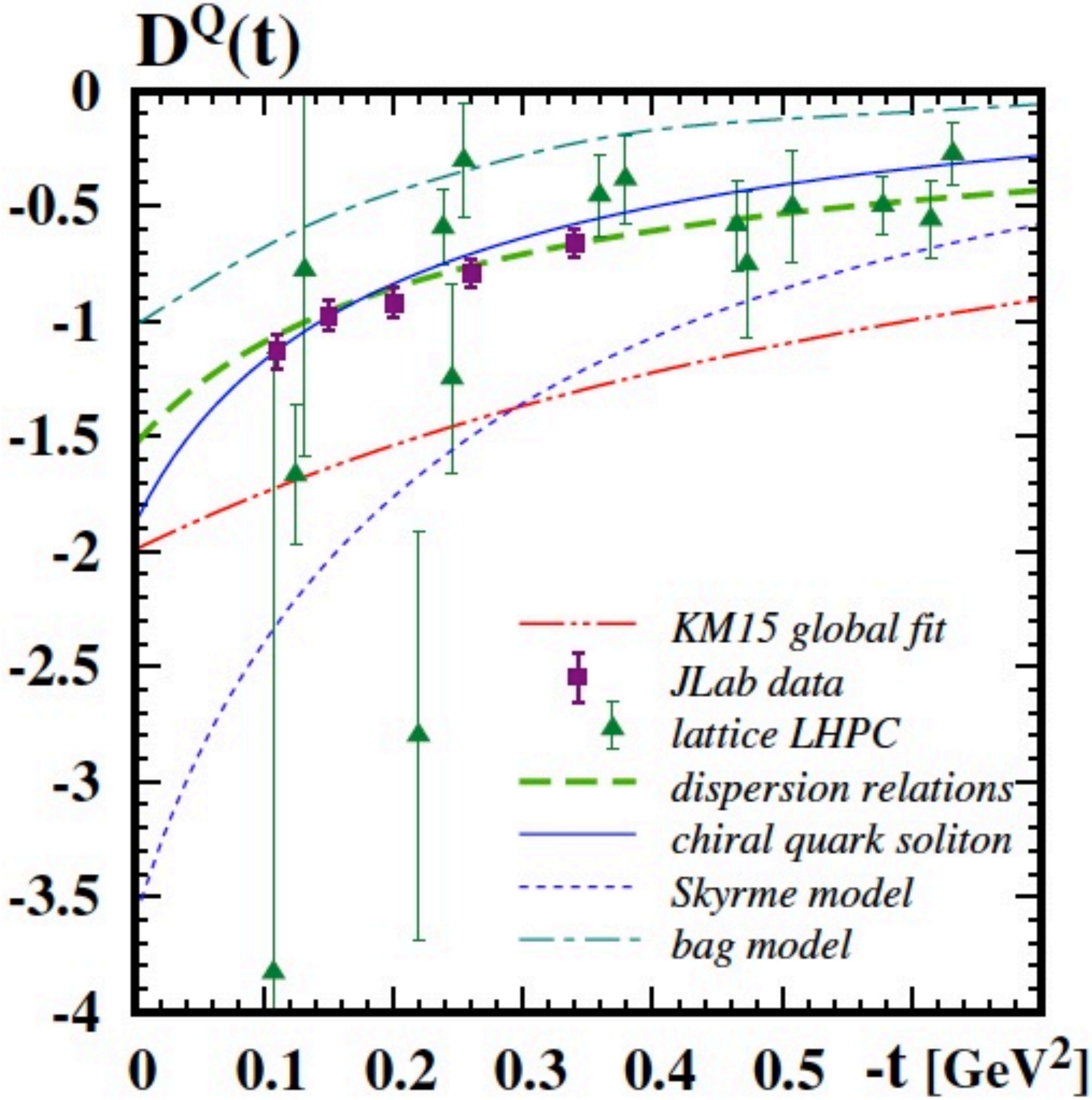


Fit: $F^Q(t) = \frac{d_1^Q(0)}{[1 - t/(\alpha M_D^2)]^\alpha}$ with $M_D = 0.487\,\mathrm{GeV}$

$\alpha = 0.841$

B. Pasquini, M. Polyakov, M. Vanderhaeghen, PLB739 (2014) 133

D(t) form factor from data



Polyakov and Schweitzer, arXiv:1805:06596

Girod, Elouadrhiri,Burkert, Nature 557 (2018) 7705

Summary

- Dispersion Relations for DVCS amplitudes
  constraints from analyticity, crossing, built in

- Subtraction functions for twist-2 DVCS amplitudes

  for $H + E$ and $\tilde{H}$: no subtractions

  for $\tilde{E}$: pseudoscalar meson poles

  for E : D-term

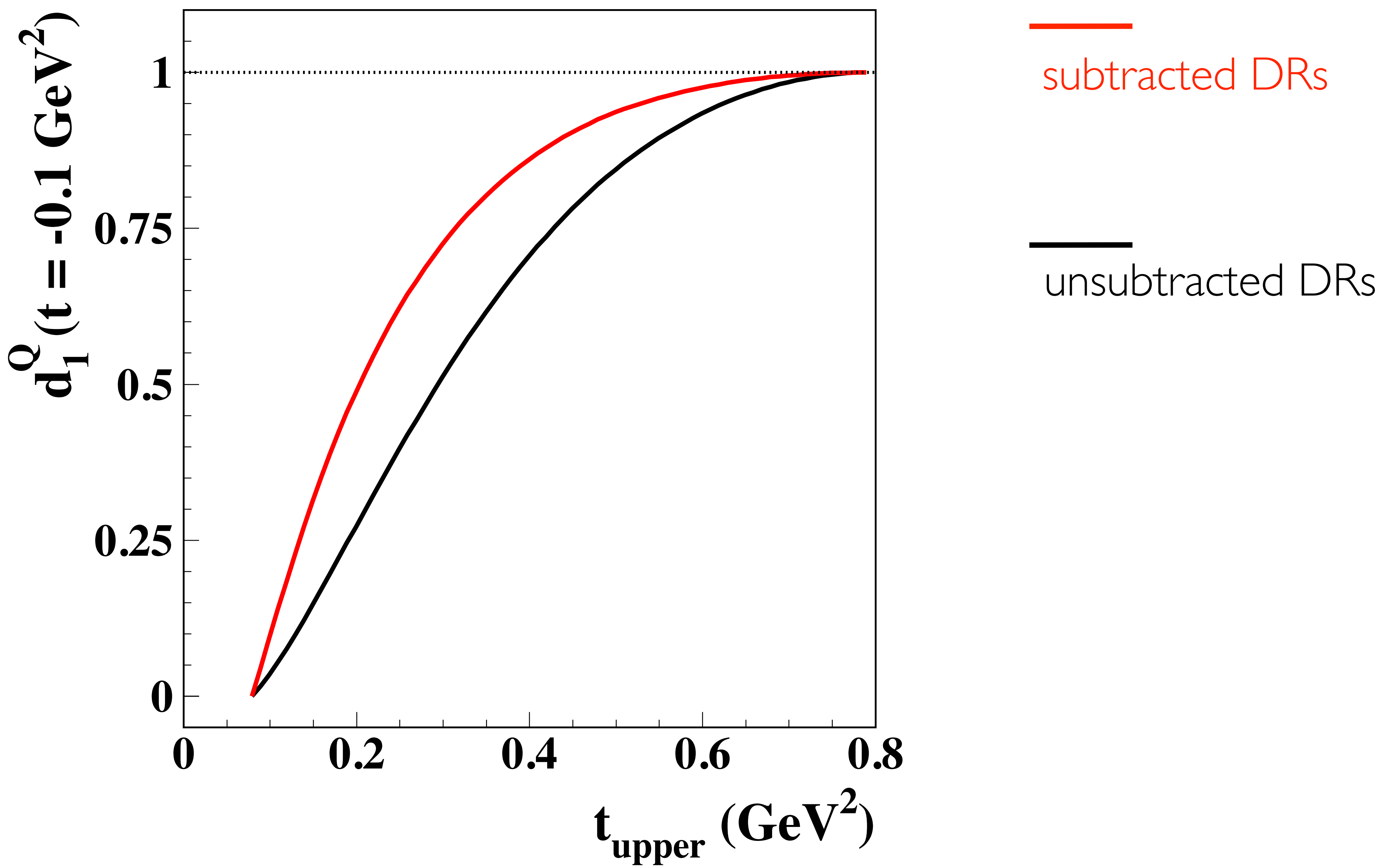
- D-term from t-channel Dispersion Relations

  D-term $\longrightarrow$ two-pion correlated state with I=0, J=0, 2

  model independent representation
  with input from two-pion GDAs and pion-nucleon scattering

Backup Slides

Convergence of DRs



subtracted DRs: $d_1^Q(t) = \quad d_1^Q(0) - \frac{t}{\pi}\int_{4m_\pi^2}^{+\infty} \mathrm{d}t' \, \frac{\mathrm{Im}_t A_2(0,t',Q^2)}{t'(t'-t)}$

subtraction constant to be fitted to data