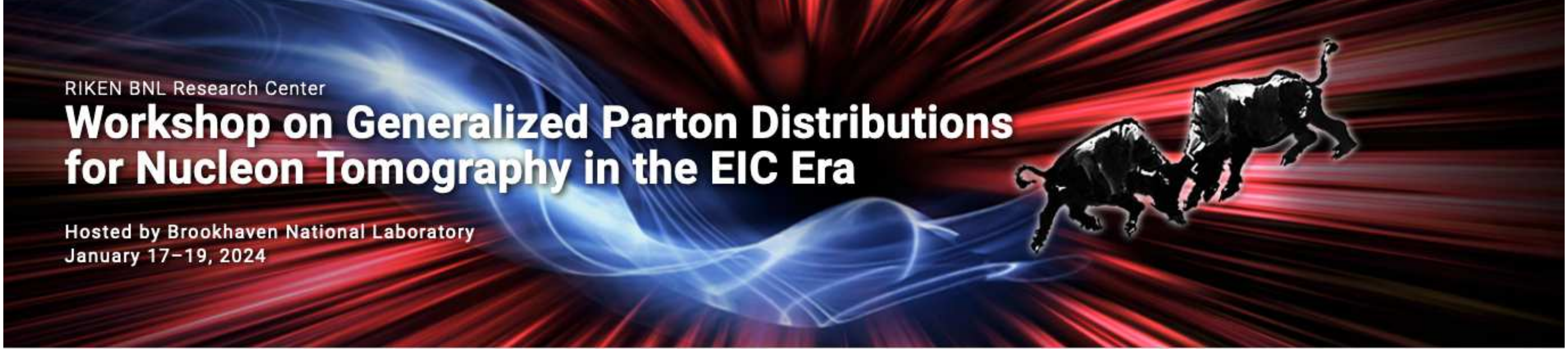


THE D-TERM FORM FACTOR FROM DISPERSION RELATIONS IN DEEPLY VIRTUAL COMPTON SCATTERING

BARBARA PASQUINI

University of Pavia and INFN Pavia

UNIVERSITÀ DI PAVIA

INFN Istituto Nazionale di Fisica Nucleare

Outline

- s-channel Dispersion Relations (DRs) for twist-2 amplitudes in terms of GPDs
  ⟶ link between subtraction function in s-channel DRs and D-term form factor

- D-term form factor t-channel dispersion relations

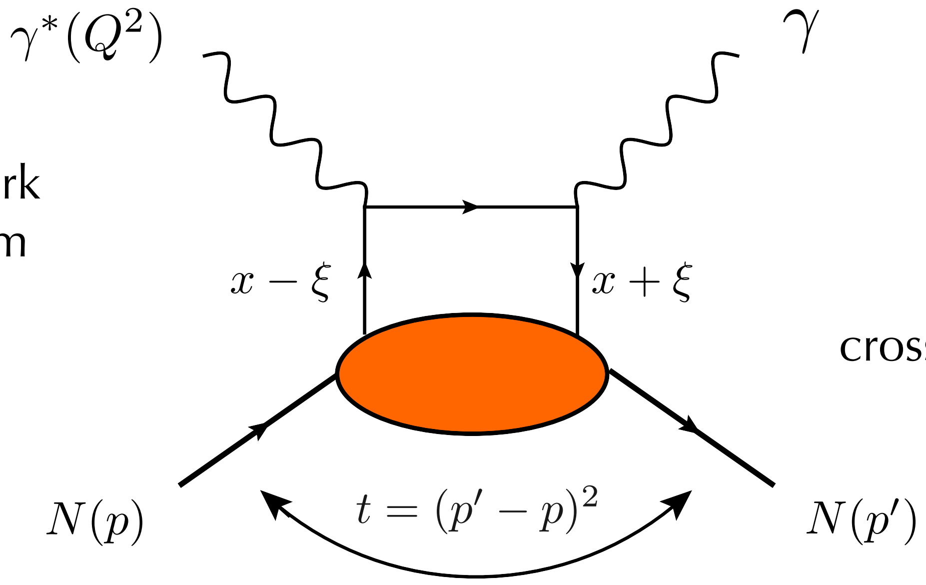
- Results and comparison with phenomenological extractions

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	long. polarized quark
$A_1 = \mathcal{H} + \mathcal{E}$	$A_3 = \tilde{\mathcal{H}}$
$A_2 = -\mathcal{E}$	$A_4 = \tilde{\mathcal{E}}$

Twist-2 DVCS amplitudes

$$A_i(\xi,t) = \int_0^1 \mathrm{d}x\, F_i^+(x,\xi,t) \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right] \qquad (i=1,\ldots,4)$$

- Involve singlet GPDs: $F_i^+ = \{H^+ + E^+, -E^+, \tilde{H}^+, \tilde{E}^+\}$

$$F_i^+(x,\xi,t) = F_i(x,\xi,t) - F_i(-x,\xi,t)$$

- Imaginary part: GPD at $x=\xi$

$$\mathrm{Im}\, A_i(\xi,t) = -\pi F_i^+(\xi,\xi,t)$$

- Real part involves convolution integral:

$$\mathrm{Re}\, A_i(\xi,t) = \mathcal{P}\int_0^1 \mathrm{d}x\, F_i^+(x,\xi,t) \left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right]$$

*the dependence on Q^2 is implicit

Dispersion relations at fixed t and Q^2

energy variables: $\nu = \frac{s-u}{4M_N} = \frac{Q^2}{4M_N\xi}$ and $\nu' = \frac{Q^2}{4M_N x}$

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

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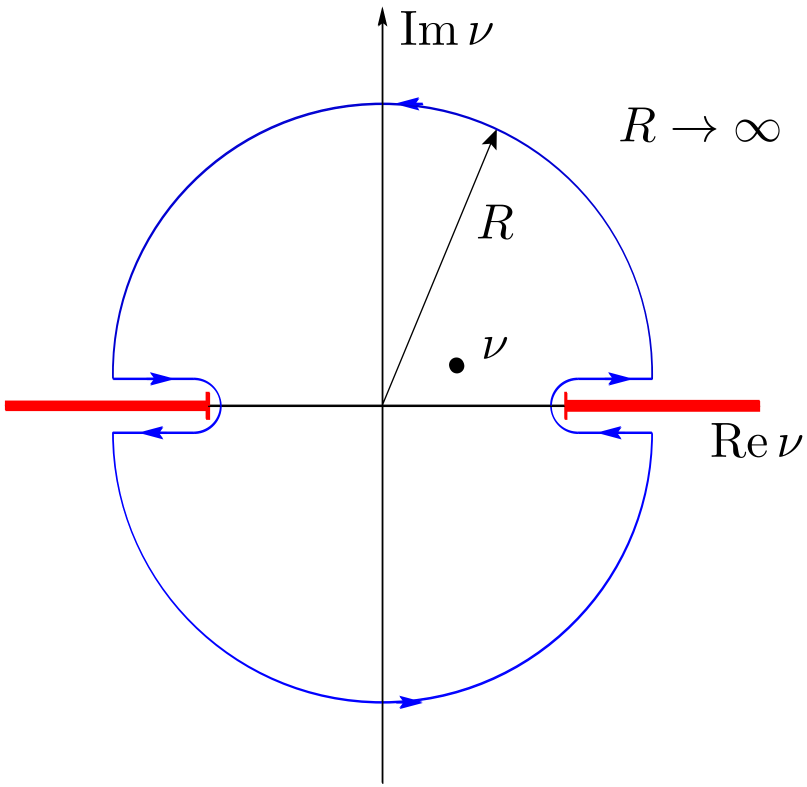
$A_i(\nu, t)$: analytical functions in the complex ν plane, with cuts on the real axis



- Cauchy integral formula

$$A_i(\nu, t) = \frac{1}{2\pi i}\oint_C d\nu' \frac{A_i(\nu', t)}{\nu' - \nu}$$

Dispersion relations at fixed t and Q^2

energy variables: $\nu = \frac{s-u}{4M_N} = \frac{Q^2}{4M_N \xi}$ and $\nu' = \frac{Q^2}{4M_N x}$

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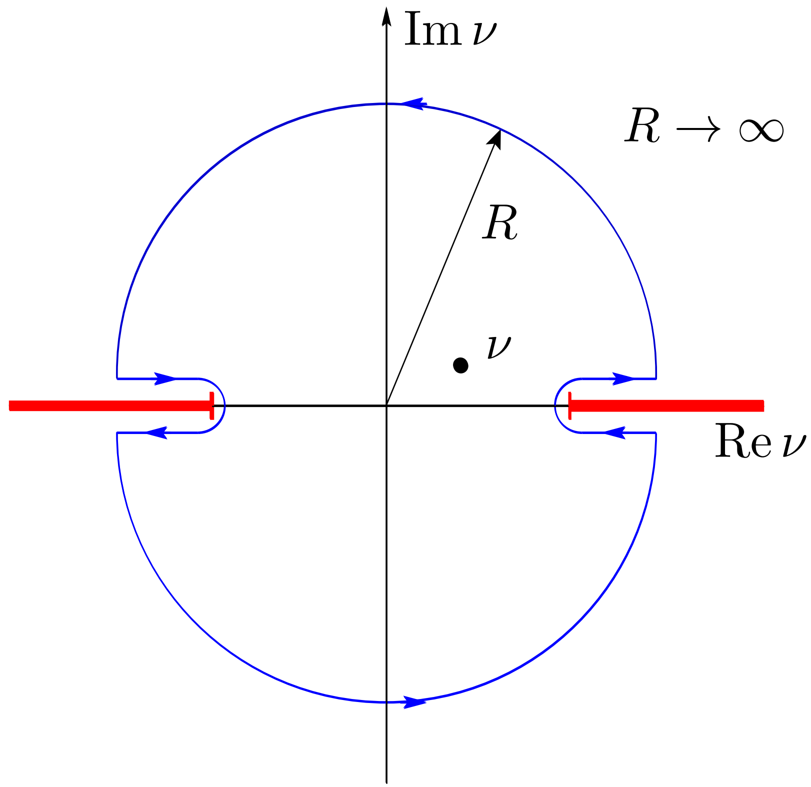

- Cauchy integral formula

$$A_i(\nu, t) = \frac{1}{2\pi i} \oint_C d\nu' \frac{A_i(\nu', t)}{\nu' - \nu}$$

- Crossing symmetry and analyticity

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

Unsubtracted Dispersion Relations

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

non-convergent integrals for A_2

Unsubtracted Dispersion Relations

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non-convergent integrals for A_2

Subtracted Dispersion Relations

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

subtraction at $\nu = 0$

Dispersion relations in terms of GPDs

once subtracted fixed-t DR in the variable x

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

- imaginary part in terms of GPDs: $\mathrm{Im}\, A_2(\xi, t) = \pi E^+(x, \xi = x, t)$

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

- real part from convolution integral:

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

- difference between convolution and dispersion integrals:

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

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

Subtraction Function

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

⇨ Subtraction function is independent of ξ ⟶ formally put $\xi = 0$

$$\Delta(t) = 2\,\mathcal{P}\int_0^1 \mathrm{d}x \frac{1}{x}\left[E^+(x,x,t) - E^+(x,0,t)\right]$$

⇨ Time-Reversal invariance: GPD even in ξ: $E(x,x,t) = E(x,-x,t)$

$$\Delta(t) = 2\,\mathcal{P}\int_{-1}^1 \mathrm{d}x \frac{1}{x}\left[E(x,x,t) - E(x,0,t)\right]$$

Anikin, Teryaev (2007); Radyushkin (2012)

Subtraction Function: relation with D-term

$$\int_{-1}^{1}\frac{\mathrm{d}x}{x}[E(x,x+\xi,t)-E(x,\xi,t)] = \int_{-1}^{1}\frac{\mathrm{d}x}{x}\sum_{n=1}^{\infty}\frac{x^n}{n!}\frac{\partial^n}{\partial\xi^n}E(x,\xi,t)$$

$$= \sum_{n=0}^{\infty}\frac{1}{(n+1)!}\frac{\partial^{n+1}}{\partial\xi^{n+1}}\left[\int_{-1}^{1}\mathrm{d}x\,x^n E(x,\xi,t)\right]$$

⇨ Polinomiality of Mellin moments of GPDs

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

$$\int_{-1}^{1}\frac{\mathrm{d}x}{x}[E(x,x+\xi,t)-E(x,\xi,t)] = \sum_{n=0}^{\infty}e_{n+1}^{(n)}(t)$$

⇨ Highest moment generated by Polyakov-Weiss D-Term $e_{n+1}^{(n)} = -\int_{-1}^{1}\mathrm{d}z\,z^n D(z,t)$

$$\Delta(t) = 2\mathcal{P}\int_{-1}^{1}\mathrm{d}x\frac{1}{x}\left[E(x,x,t)-E(x,0,t)\right] = -2\int_{-1}^{1}\mathrm{d}z\frac{D(z,t)}{1-z}$$

Subtraction Function: relation with D-term

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

⇨ Gegenbauer expansion of D-term $D(z,t) = (1-z^2) \sum_{\substack{n=1 \\ n\, odd}}^{\infty} d_n(t) C_n^{(3/2)}(z)$

$$\Delta(t) = -4 \sum_{\{n\, odd\}}^{\infty} d_n(t)$$

⇨ Relation to EMT for factors $d_1(t) = \frac{5}{4} D(t) = 5\, C(t)$

Dispersion Relations for DVCS amplitudes

- s-channel subtracted DRs:

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

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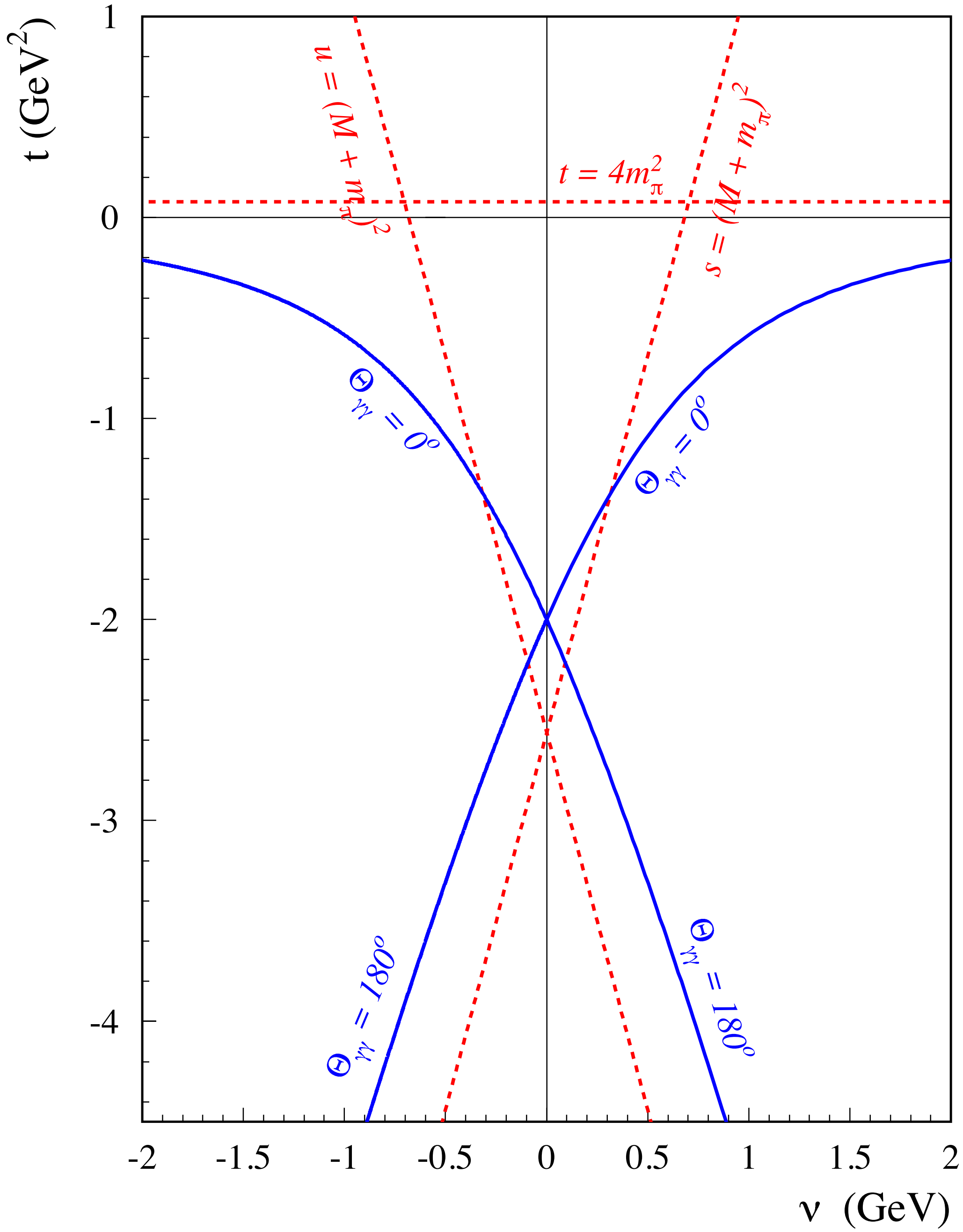
- t-channel DRs for subtraction function

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

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

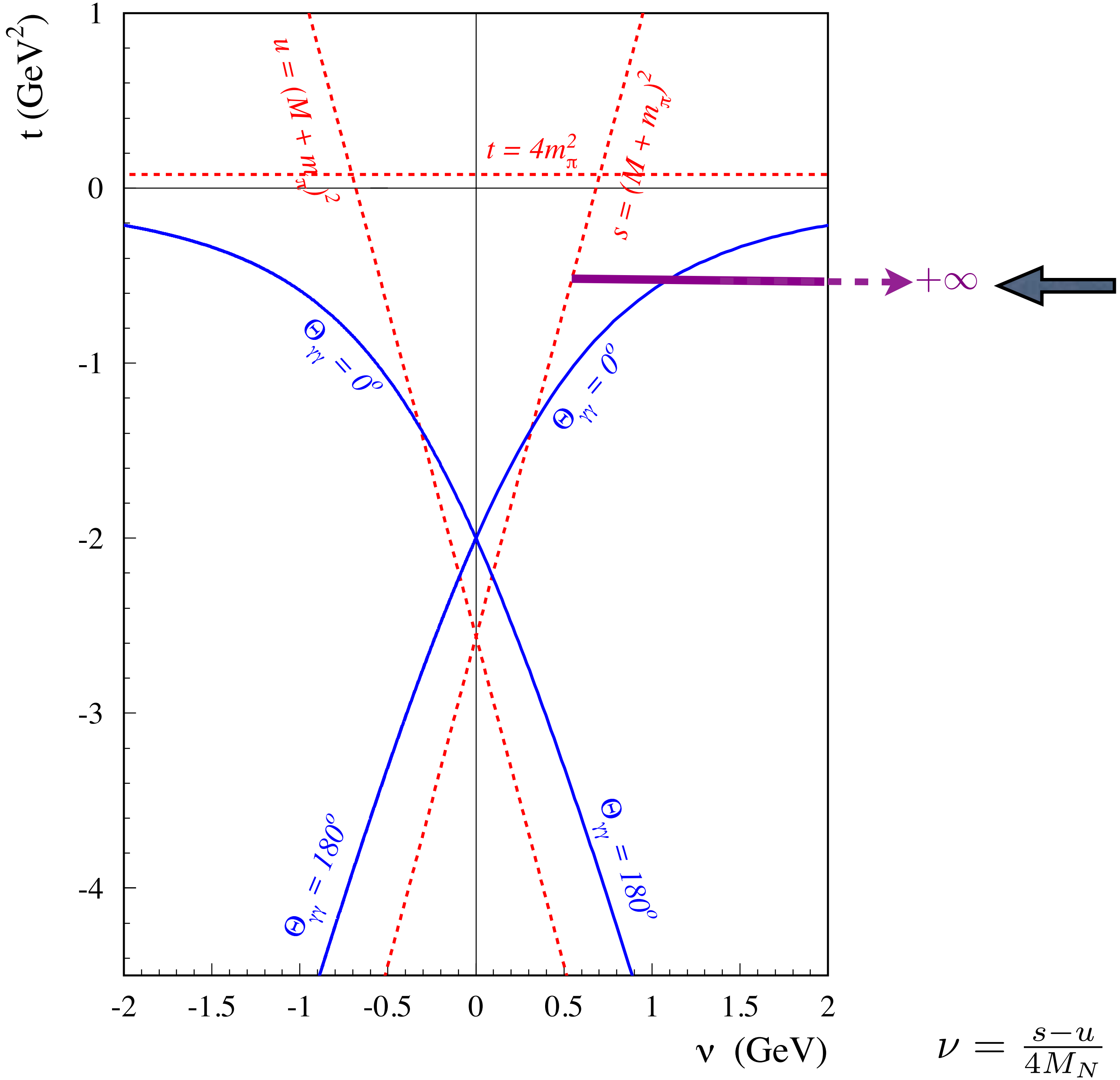
Fixed $Q^2 = 2\,\mathrm{GeV}^2$



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

crossing symmetric variable

Fixed $Q^2 = 2\,\mathrm{GeV}^2$



DRs
in the s-channel
at fixed t

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

crossing symmetric variable

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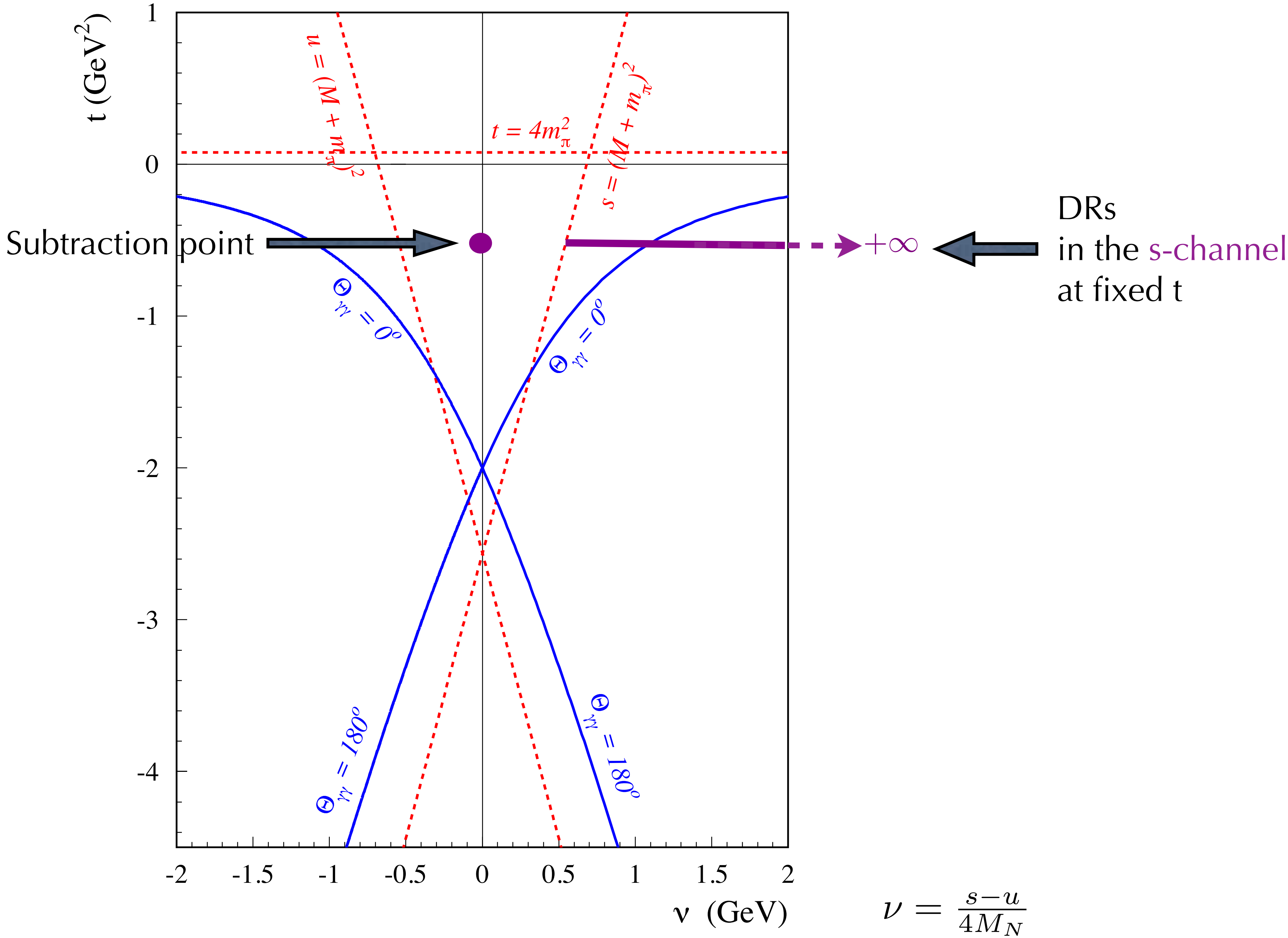

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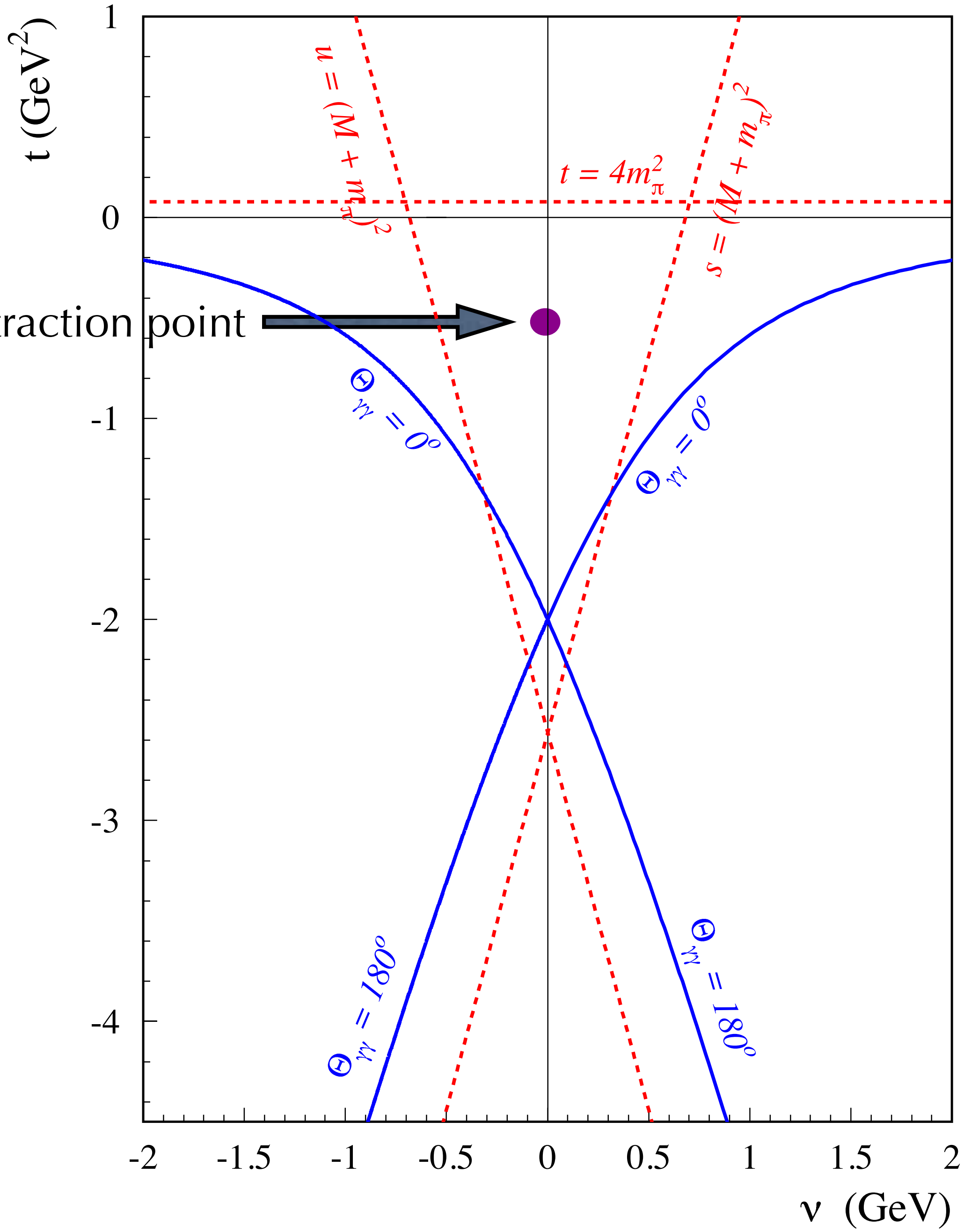

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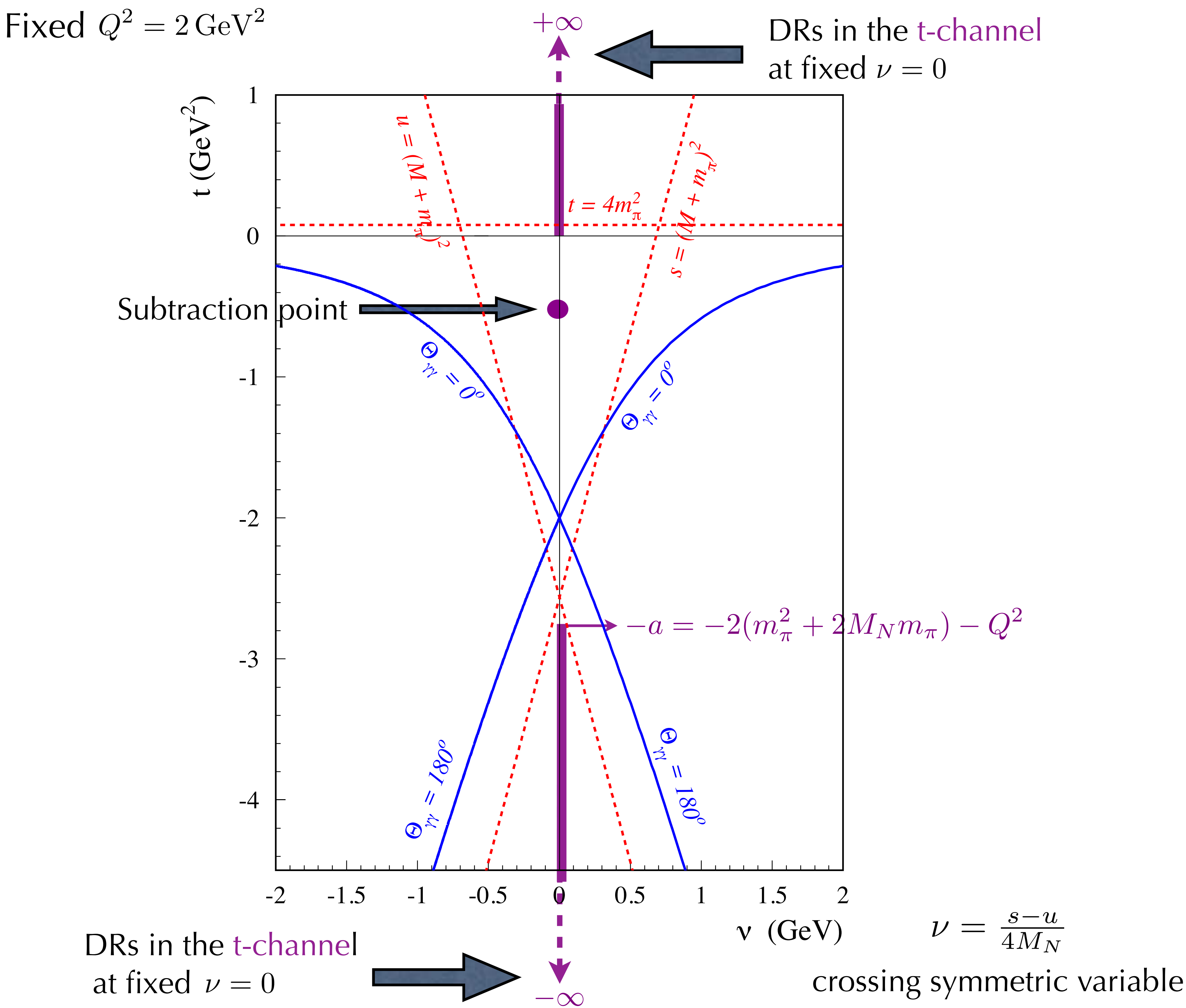

Fixed $Q^2 = 2\,\mathrm{GeV}^2$
$+\infty$
DRs in the t-channel
at fixed $\nu = 0$
t (GeV^2)
1
0
-1
-2
-3
-4
$u = (M + m_\pi)^2$
$t = 4m_\pi^2$
$s = (M + m_\pi)^2$
Subtraction point
$\Theta_{\gamma\gamma} = 0^o$
$\Theta_{\gamma\gamma} = 0^o$
$-a = -2(m_\pi^2 + 2M_N m_\pi) - Q^2$
$\Theta_{\gamma\gamma} = 180^o$
$\Theta_{\gamma\gamma} = 180^o$
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ν (GeV)
$\nu = \frac{s-u}{4M_N}$
crossing symmetric variable
DRs in the t-channel
at fixed $\nu = 0$
$-\infty$

Dispersion Relations for DVCS amplitudes

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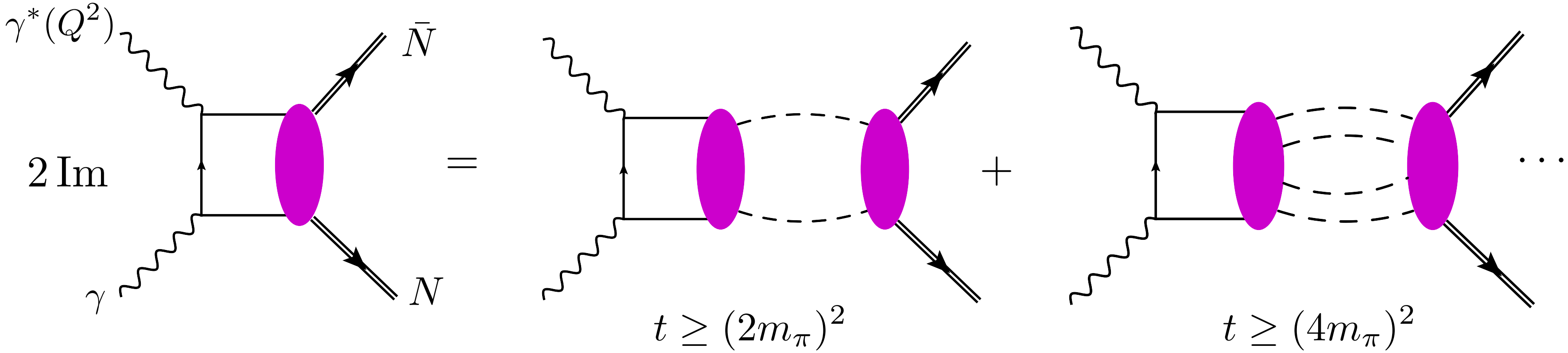
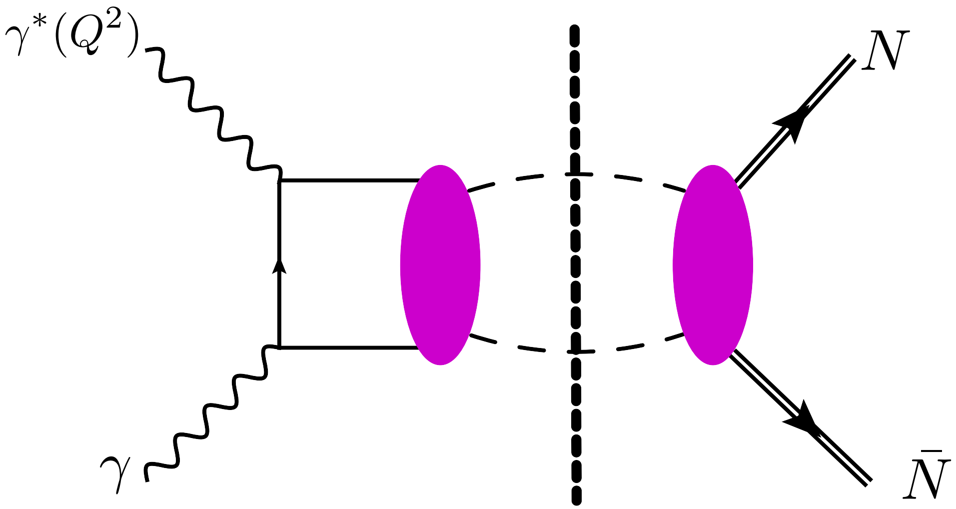
Unitarity relation in t-channel



Unitarity relation in the t-channel: two-pion intermediate state

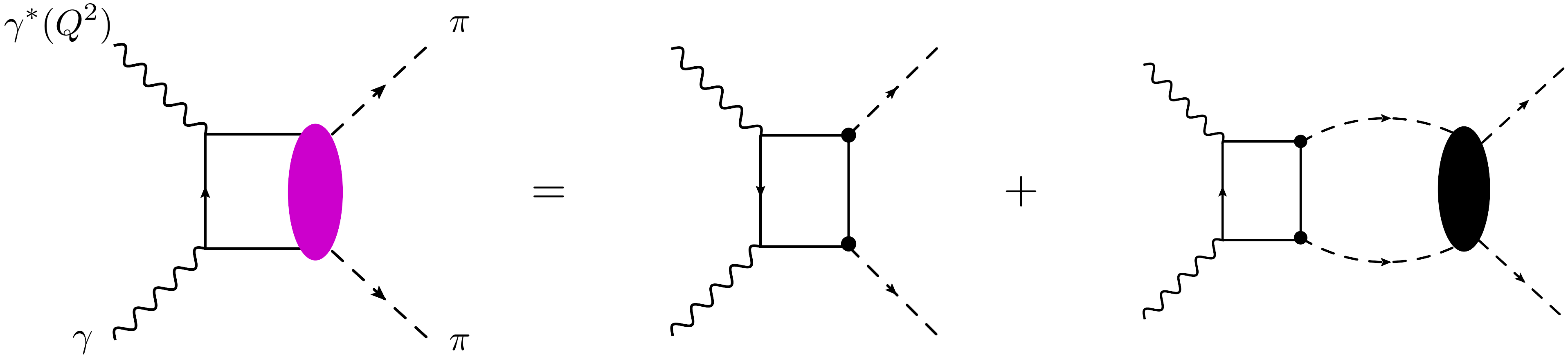


- Charge conjugation and Parity
- Partial wave expansion with $\nu = 0 \rightarrow \theta_t = 90^o$

two-pion intermediate state with
$I = 0 \qquad J = 0, 2, \cdots$

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

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



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

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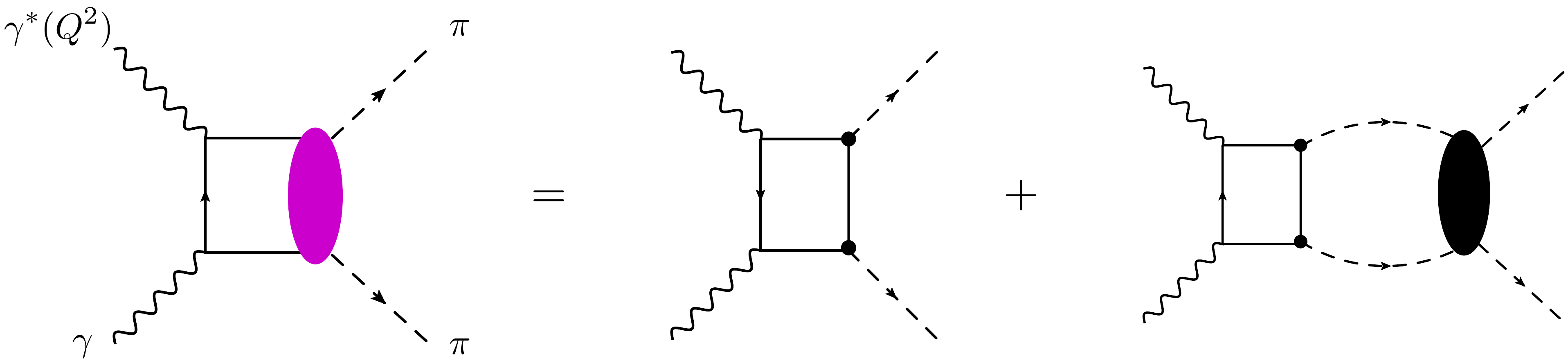

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take contribution only from S and D waves ⟶ DRs for $d_1(t)$

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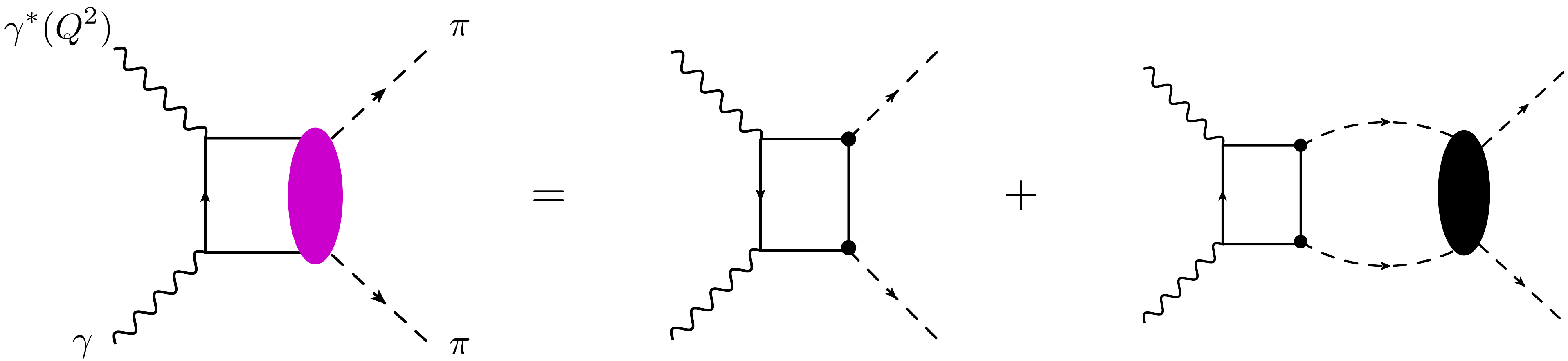

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take contribution only from S and D waves ⟶ DRs for $d_1(t)$

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

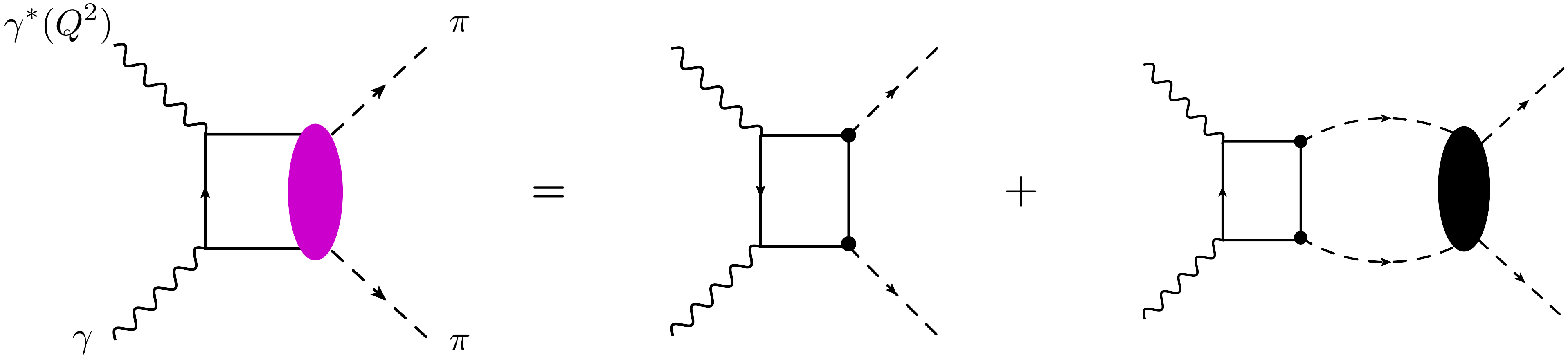
$$\tilde{B}_{12}(t) = \beta^2 B_{12}(0) f_2(t)$$

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

↓ $\pi\pi$ phase shifts

M. Polyakov, 1999

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



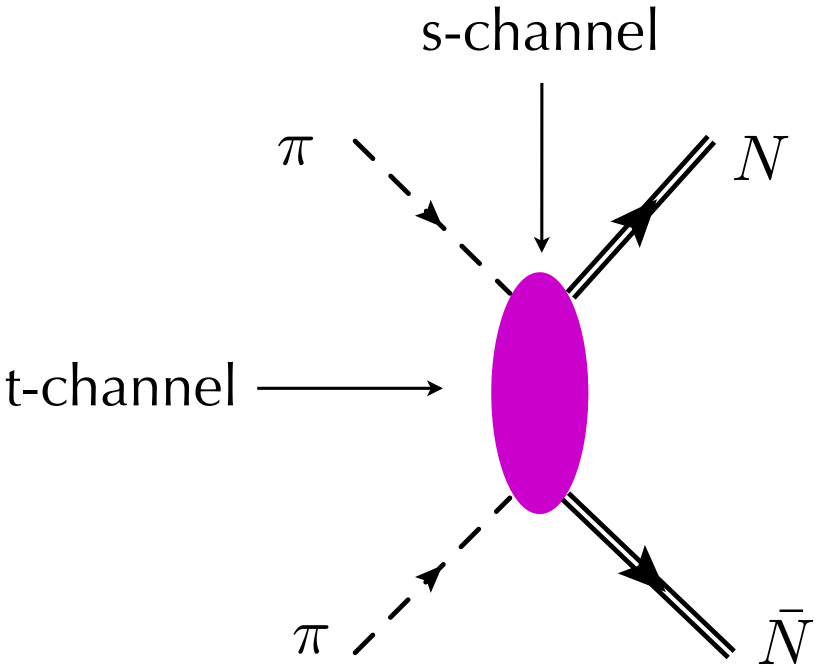
$$\Phi_q^{\pi\pi} = 6\, z(1-z) \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} \sum_{\substack{l=0 \\ \text{even}}}^{n+1} \tilde{B}_{nl}^{q}(t)\, C_n^{(3/2)}(2z-1)\, P_l(\cos\theta_{\pi\pi})$$

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

input ⇒ $\pi\pi$ phase shifts

pion PDFs

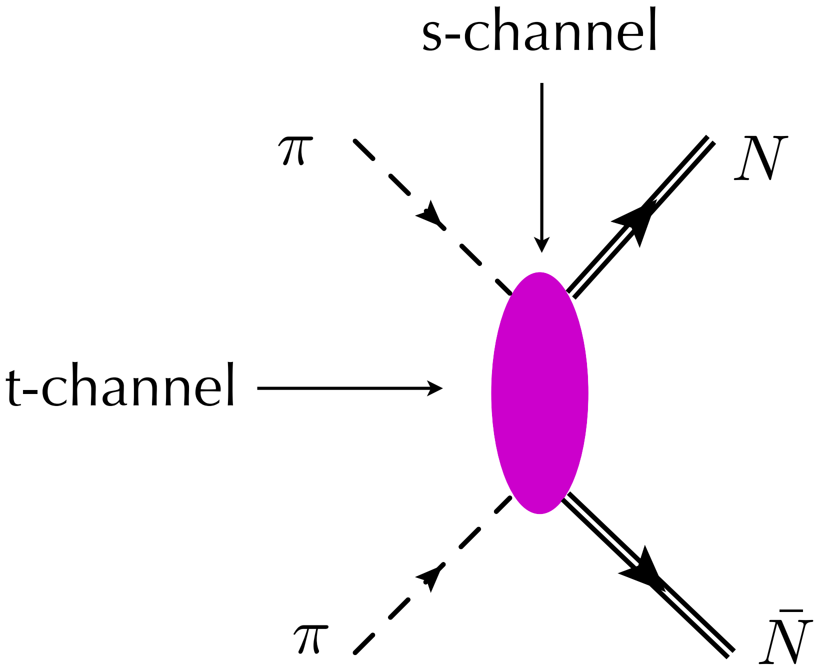
$\pi\pi \to N\bar{N}$ scattering amplitudes



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
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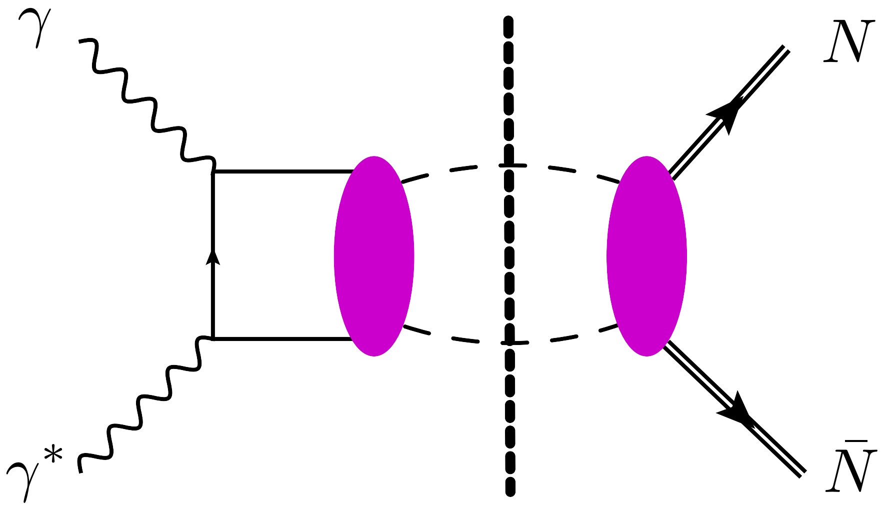
input ⇨ $\pi\pi$ phase shifts

G. Hoehler, 1983

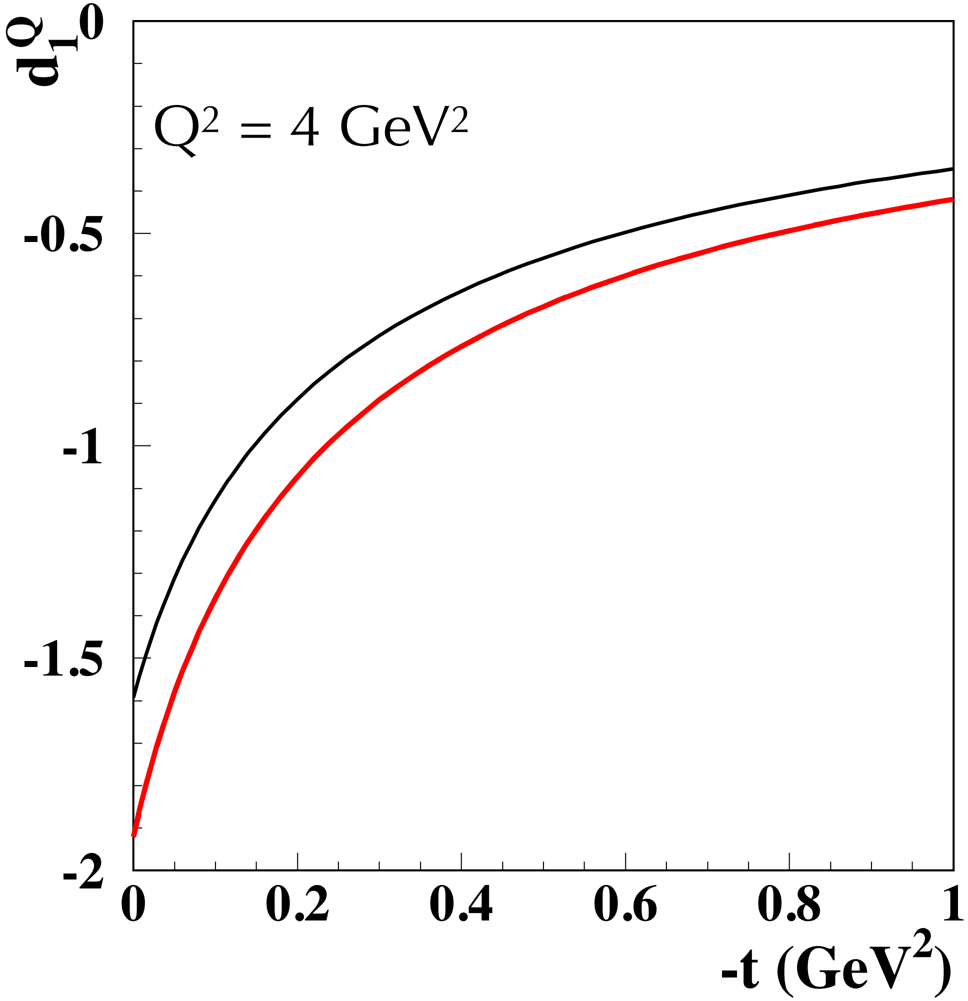
Intermediate summary: input for t-channel DRs



- two pion intermediate states ⟶ upper limit of integration is $t = 0.78\,\mathrm{GeV}^2$
- partial wave expansion and take $I = 0,\ J = 0, 2$ ⟶ DRs for $d_1(t)$
- $\gamma^*\gamma \to \pi\pi$: GDAs with input from first moment of flavor singlet 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

D-term form factor: dependence on pion PDFs

Q= u + d



pion PDFs from GRV, ZPC53 (1992)

$d_1(0) = -1.92$

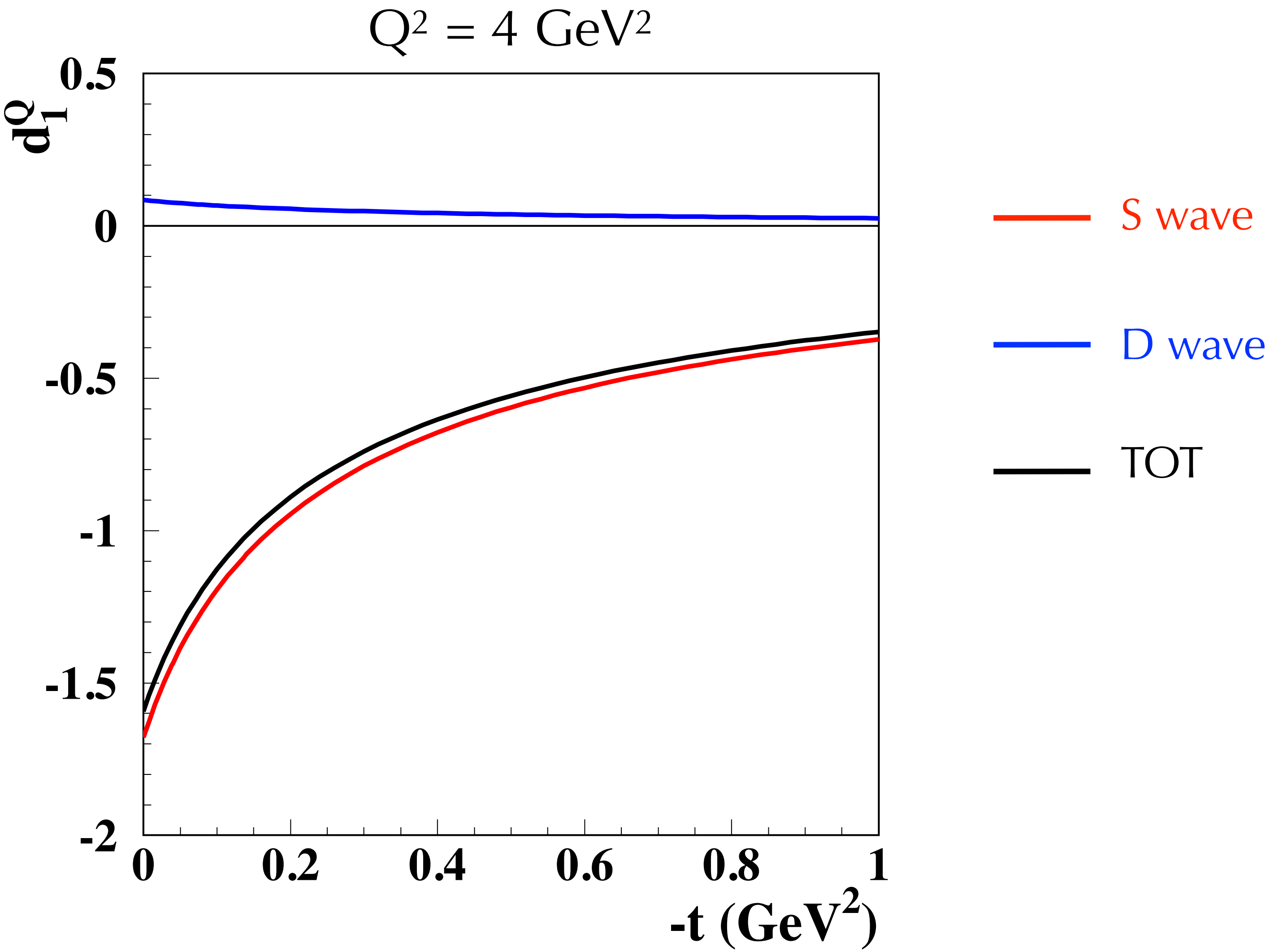
pion PDFs from Owens et al., PRD30 (1984)

$d_1(0) = -1.59$

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)*

D-term form factor: partial-wave decomposition

Q= u + d



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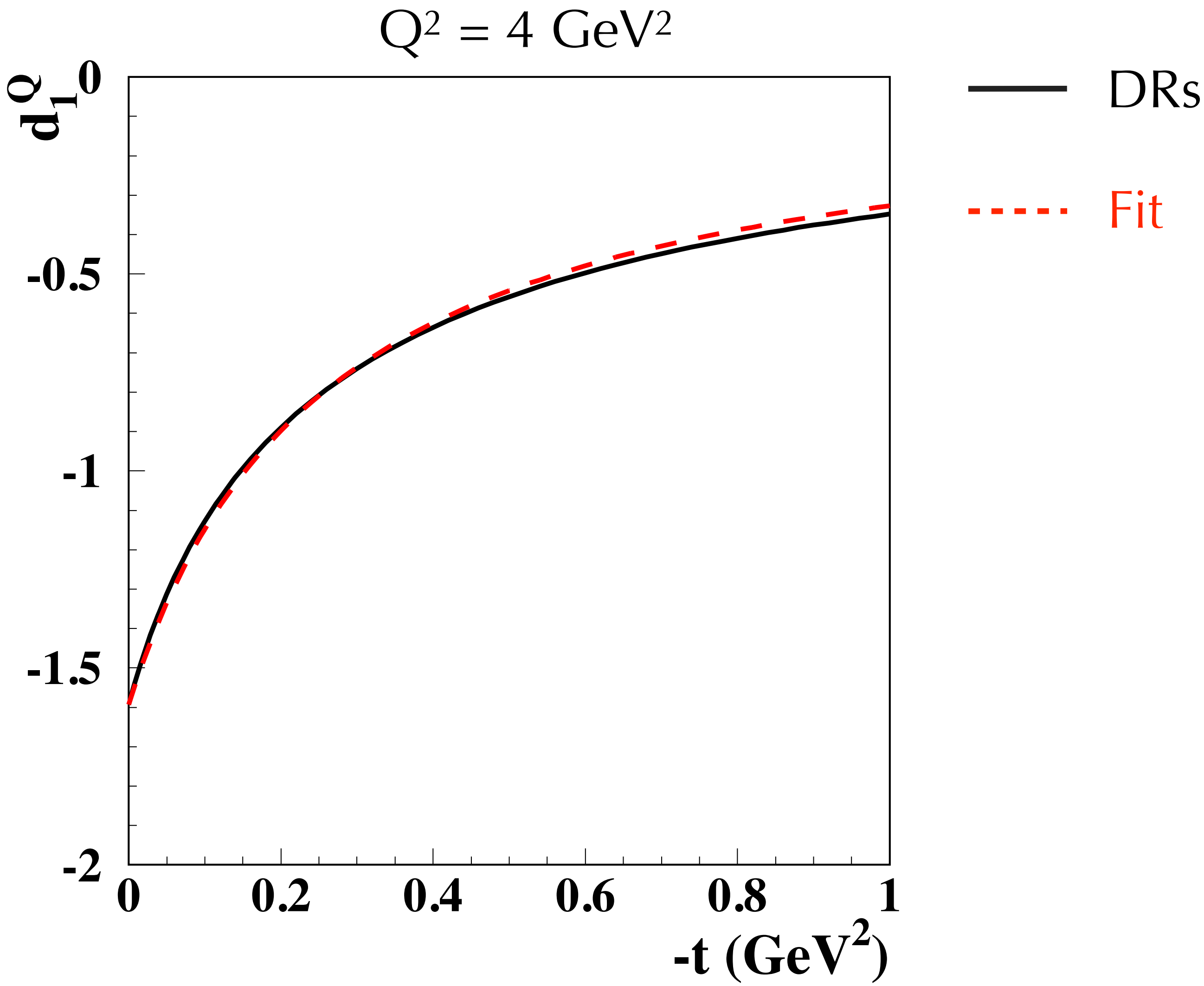
D-term form factor: t-dependence

Q= u + d

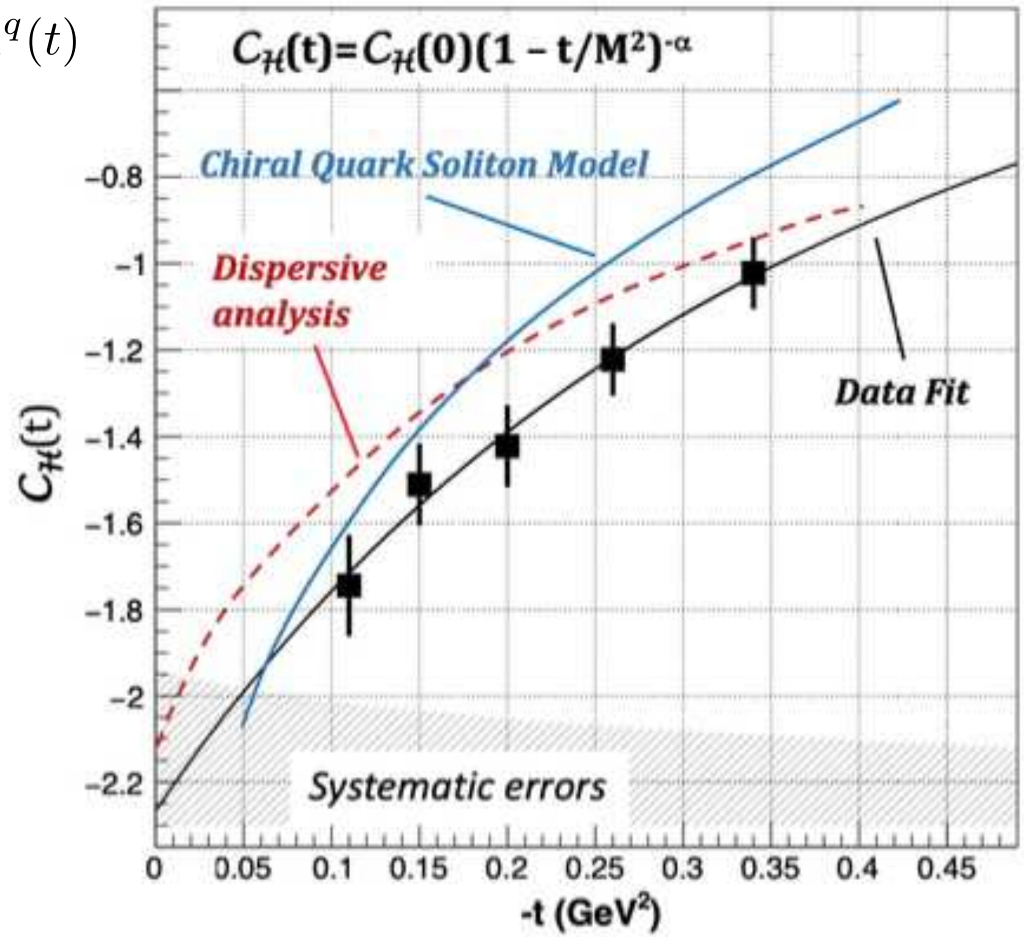


Fit: $d_1(t) = \dfrac{d_1(0)}{[1 - t/(\alpha M_D^2)]^\alpha}$ with $M_D = 0.487\,\text{GeV}$

$\alpha = 0.841$

Extraction of D-term form factor

$$\mathcal{C}_H(t) = -2\sum_q e_q^2 \Delta^q(t)$$



Extraction from data:

- neglecting gluon contribution
- assuming:

$$\mathcal{C}_H(t) = 8\sum_q e_q^2 \sum_{\substack{n=1 \\ n\ odd}}^{\infty} d_n(t) \approx \frac{10}{9} d_1^Q(t)$$

Fit to data: $\mathcal{C}_H(t) = \dfrac{\mathcal{C}_H(0)}{(1 - t/M^2)^\alpha}$

$\mathcal{C}_H(0) = -2.27 \pm 0.16 \pm 0.36$ $\lambda = 2.76 \pm 0.23 \pm 0.48$

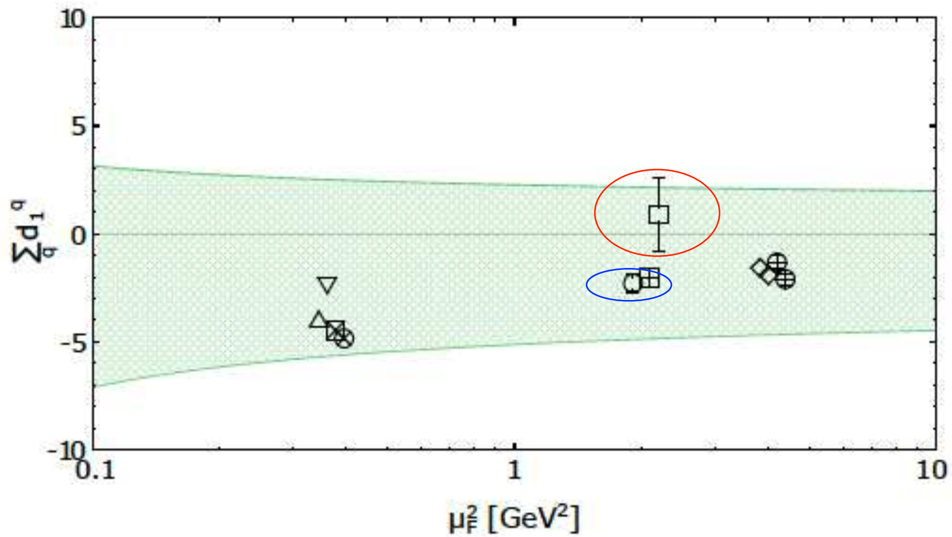
$M^2 = 1.02 \pm 0.13 \pm 0.21\,\mathrm{GeV}^2$

Girod, Elouadrhiri, Burkert,Nature 557 (2018) 7705; Burkert, et al., Rev. Mod. Phys. 95 (2023) 014002

Necessary to verify model assumptions in the exp extraction
with more data coming from JLab, COMPASS and the future EIC, EIcC

Kumericki, Nature 570 (2019) 7759; Dutrieux et al, Eur. Phys. J. C81 (2021) 4

global fit to DVCS data
with artificial neural networks



CLAS data, with fixed param.,
Girod et al.

CLAS data, with neural networks
Kumericki

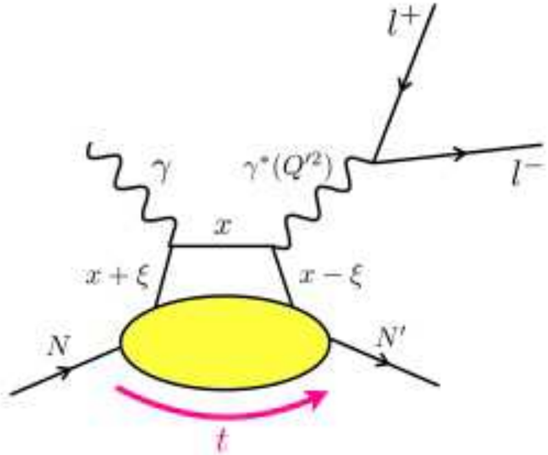
$$\sum_q d_1^q < 0$$

in all model calculations
for a stable proton

Marker in Fig. 3	$\sum_q d_1^q(\mu_F^2)$	μ_F^2 in GeV^2	# of flavours	Type
○	$-2.30 \pm 0.16 \pm 0.37$	2.0	3	from experimental data
□	0.88 ± 1.69	2.2	2	from experimental data
◇	-1.59	4	2	t-channel saturated model
	-1.92	4	2	t-channel saturated model
△	-4	0.36	3	χQSM
▽	-2.35	0.36	2	χQSM
⊠	-4.48	0.36	2	Skyrme model
⊞	-2.02	2	3	LFWF model
⊗	-4.85	0.36	2	χQSM
⊕	-1.34 ± 0.31	4	2	lattice QCD ($\overline{\text{MS}}$)
	-2.11 ± 0.27	4	2	lattice QCD ($\overline{\text{MS}}$)

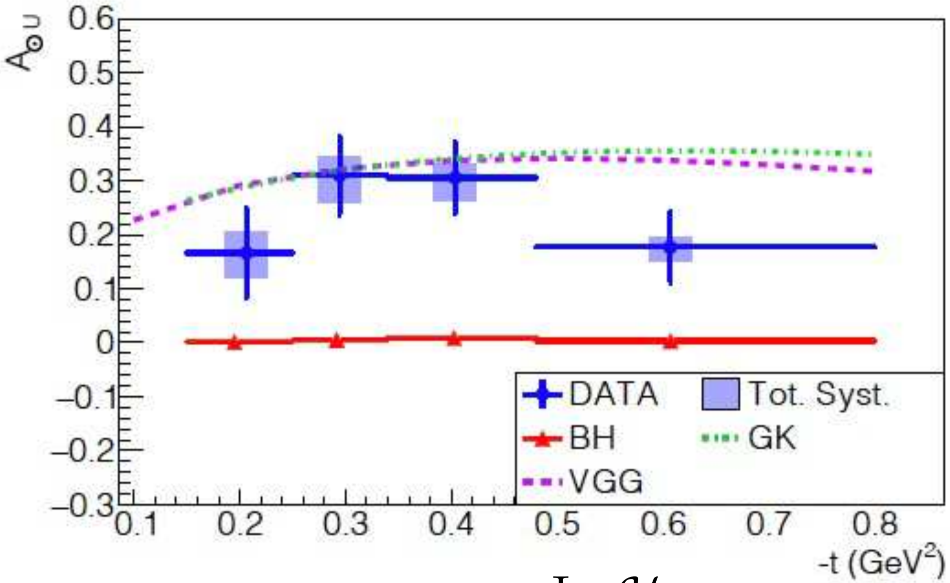
D-term from observables: Timeline Compton Scattering

Chatagnon et al. (CLAS12 Coll.), PRL127, 262501(2021)



photon polarization asymmetry

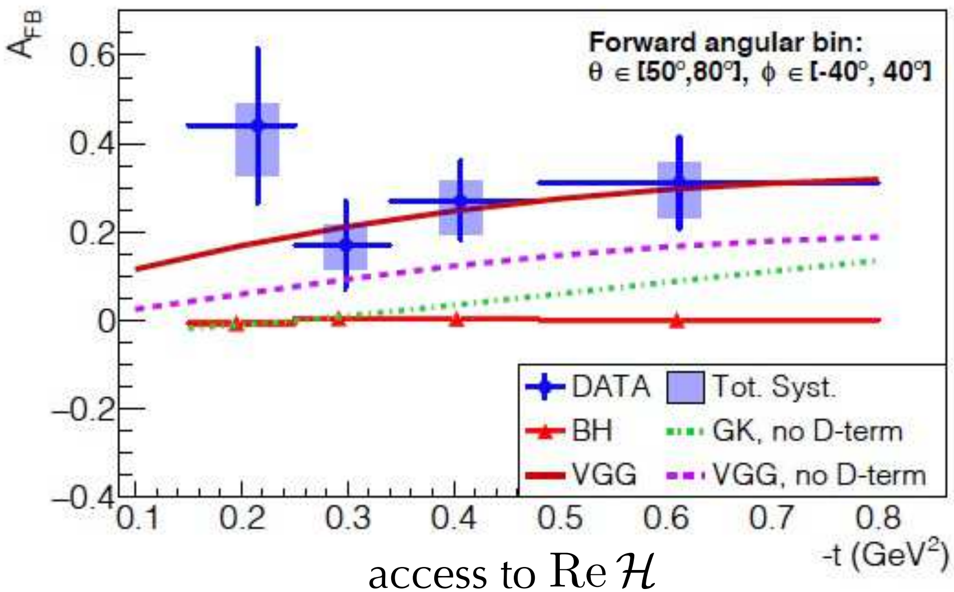
$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$



access to $\mathrm{Im}\,\mathcal{H}$

forward-backward asymmetry

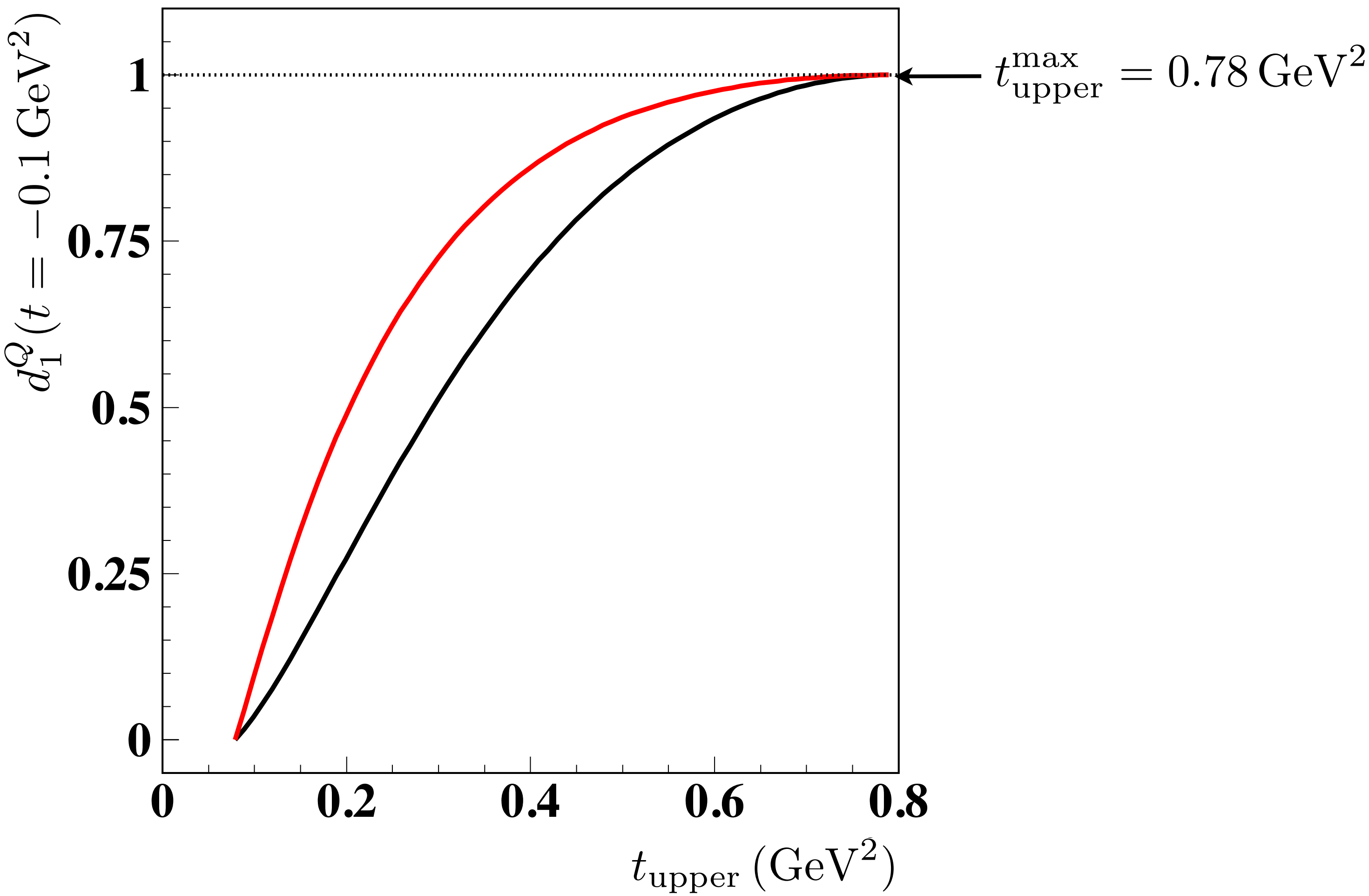
$$A_{FB} = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ - \theta, 180^\circ + \phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ - \theta, 180^\circ + \phi)}$$



access to $\mathrm{Re}\,\mathcal{H}$

- ✓ Input fro D-term from dispersion relations
- ✓ New promising path towards the extraction of $\mathrm{Re}\,\mathcal{H}$ and then the D-term
- ✓ Further data from JLab12 and future EIC

Convergence of Dispersion Integrals



unsubtracted DRs

$$d_1(t) = -\frac{1}{\pi}\int_{4m_\pi^2}^{t_{\mathrm{upper}}} \mathrm{d}t' \, \frac{\mathrm{Im}_t\, A_2(0,t')}{t'-t}$$

subtracted DRs

$$d_1(t) = d_1(0) - \frac{t}{\pi}\int_{4m_\pi^2}^{t_{\mathrm{upper}}} \mathrm{d}t' \, \frac{\mathrm{Im}\, A_2(0,t')}{t'(t'-t)}$$

subtraction constant as input parameter

Summary

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

- Subtraction functions for twist-2 DVCS amplitudes
  relation to D-term form factor

- D-term from t-channel Dispersion Relations

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

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

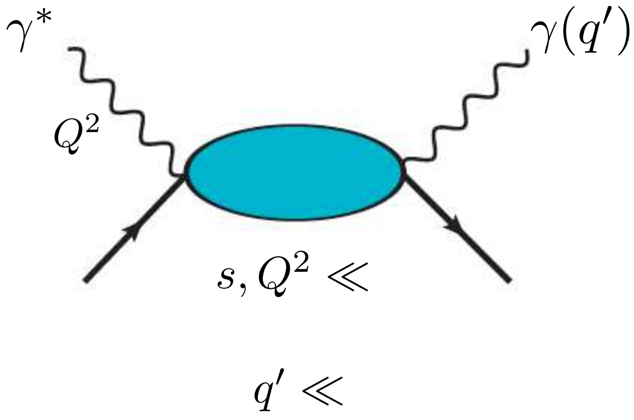
- DR predictions for $d_1(t) = \frac{5}{4} D(t) = 5\, C(t)$

  slow convergence of unsubtracted dispersion integral

  DR results in good agreement with phenomenological evidence of D-term

BACKUP SLIDES

VCS generalized pol.

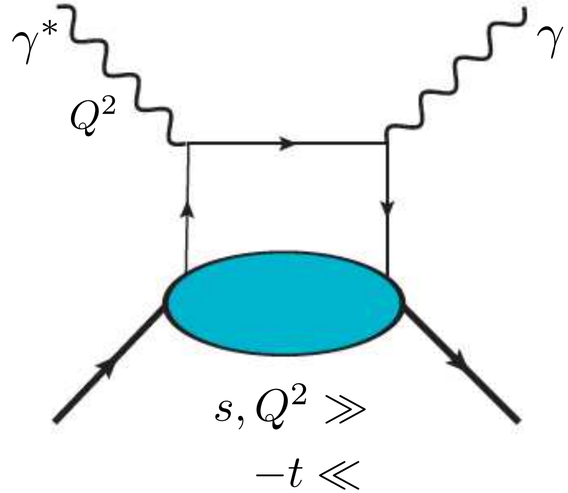


electron scattering by a target which is in constant electric and magnetic fields

$\downarrow$ $q_\perp \to b_\perp$

Spatial distribution of electric and magnetic polarization density

DVCS
generalized parton distributions



EMT form factors

$\downarrow$ $-t \to b_\perp$

Spatial distribution of mechanical properties and gluons fields

VCS in low energy region

$$\mathrm{T}^{\mathrm{VCS}} = \varepsilon_\mu \varepsilon'^{\,*}_\nu \sum_{i=1}^{12} F_i(Q^2,\nu,t)\rho_i^{\mu\nu} \qquad (i=1,\ldots,12)$$

$F_i(Q^2,\nu,t) = F_i^{\mathrm{pole}} + F_i^{\mathrm{inel}}$ analytical functions with cuts and poles on the real axis

⟶ for 10 functions UNsubtracted DRs

$$\mathrm{Re}F_i^{\mathrm{NB}}(Q^2,\nu,t) = \frac{2}{\pi}\mathcal{P}\int_{\nu_{thr}}^{\infty} \mathrm{Im}_s\, F_i(Q^2,\nu',t)\frac{\nu' \mathrm{d}\nu'}{\nu'^{\,2}-\nu^2}$$

↑

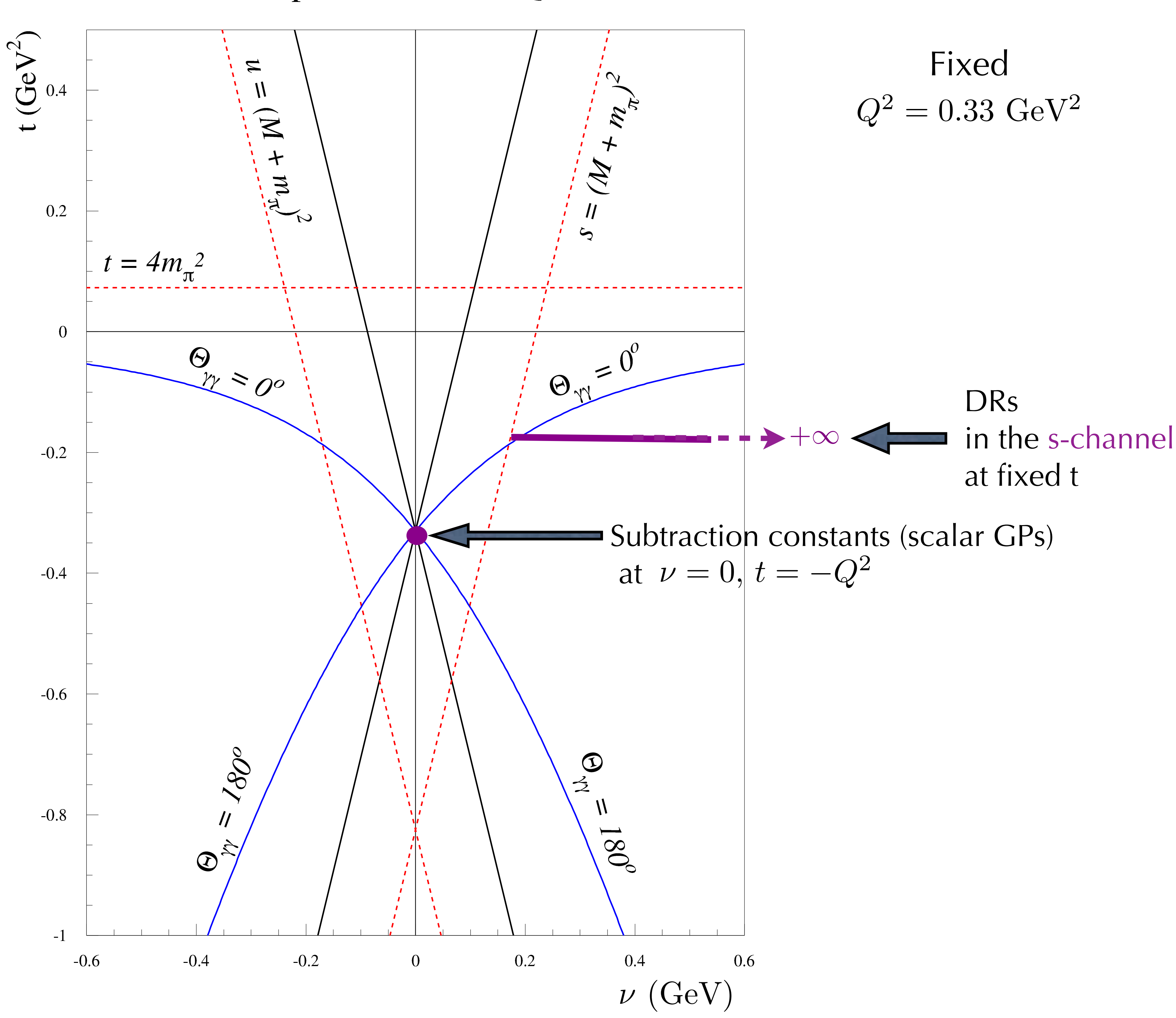
unitarity input: $\gamma^* N \to X$

⟶ 2 functions subtracted DRs

$$\mathrm{Re}F_i^{\mathrm{inel}}(Q^2,\nu,t) = F_i^{\mathrm{inel}}(Q^2,0,t) + \frac{2}{\pi}\nu^2\,\mathcal{P}\int_{\nu_{thr}}^{\infty} \mathrm{Im}_s\, F_i(Q^2,\nu',t)\frac{\nu' \mathrm{d}\nu'}{\nu'(\nu'^{\,2}-\nu^2)}$$

↑

subtraction functions (scalar GPs)



Fixed
$Q^2 = 0.33$ GeV^2
t (GeV^2)
ν (GeV)
$t = 4m_\pi^2$
$u = (M + m_\pi)^2$
$s = (M + m_\pi)^2$
$\Theta_{\gamma\gamma} = 0^o$
$\Theta_{\gamma\gamma} = 0^o$
$\Theta_{\gamma\gamma} = 180^o$
$\Theta_{\gamma\gamma} = 180^o$
$+\infty$
DRs
in the s-channel
at fixed t
Subtraction constants (scalar GPs)
at $\nu = 0,\ t = -Q^2$
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.6
-0.4
-0.2
0
0.2
0.4
0.6