Topical Group on Hadronic Physics

EXPLORING THE PROTON STRUCTURE WITH COMPTON SCATTERING

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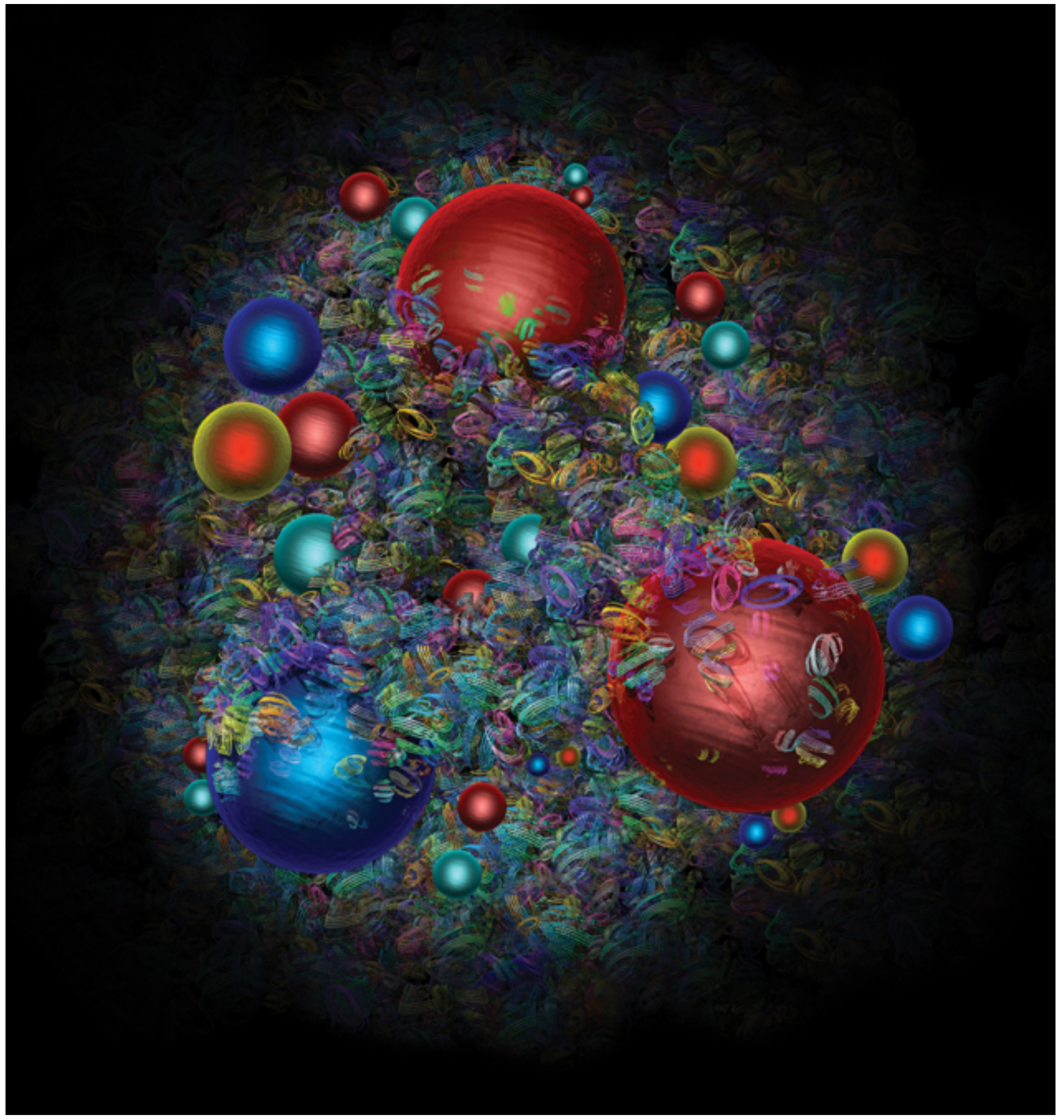
``What proton is depends on how you look at it, or rather on how hard you hit it''

A. Cooper-Sarkar, CERN Courier, June, 2019

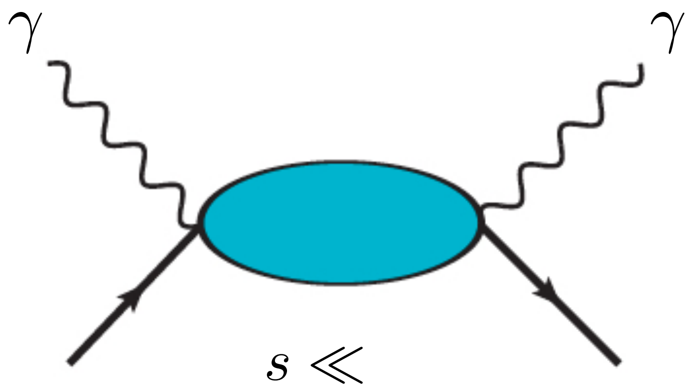


Resolution scale

hadronic d.o.f. — nucleon resonances — partonic d.o.f.

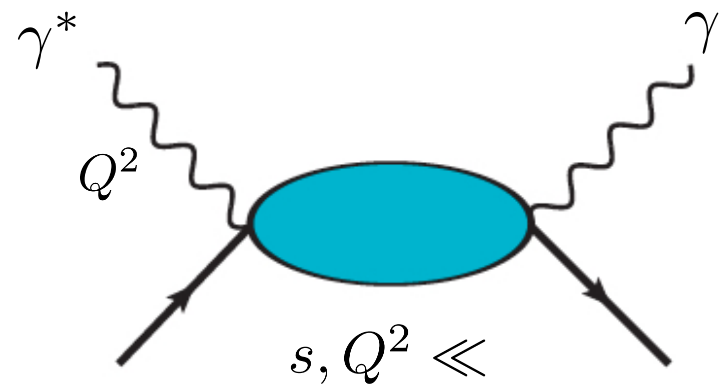
How can we explain the evolving picture of hadrons
from low to high resolution scale?

RCS polarizabilities



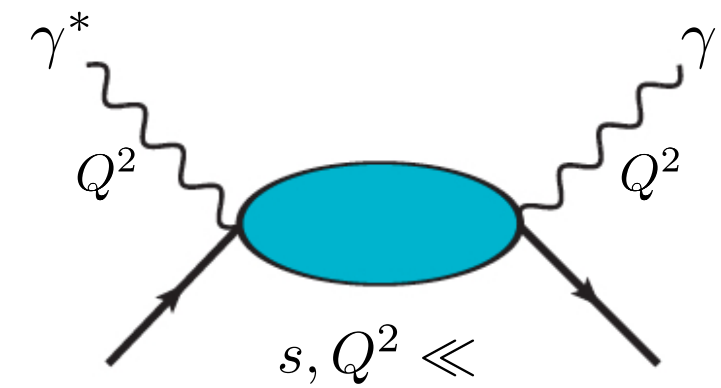
global response

VCS generalized pol.

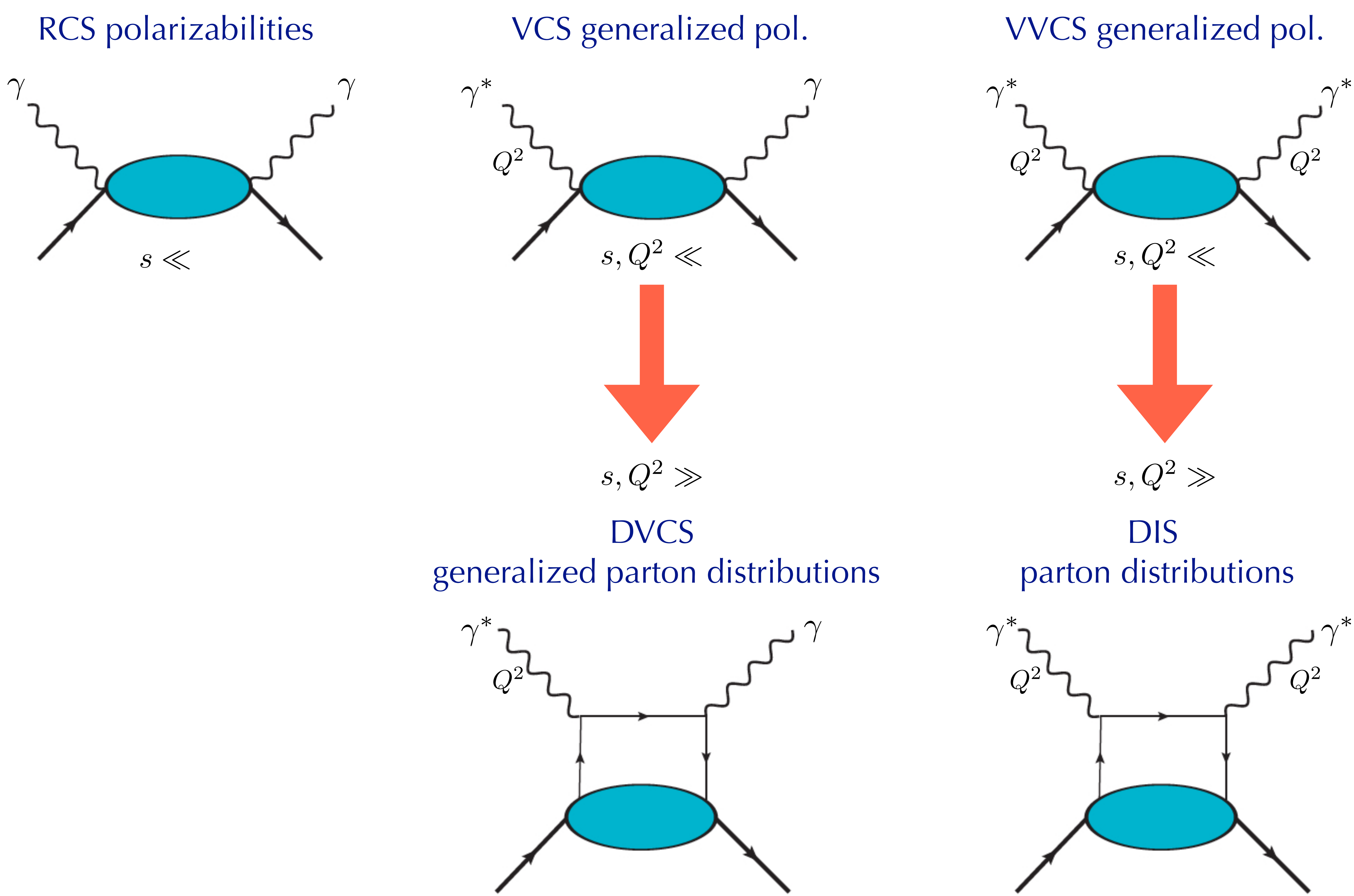


local response
on a distance scale depending on Q^2

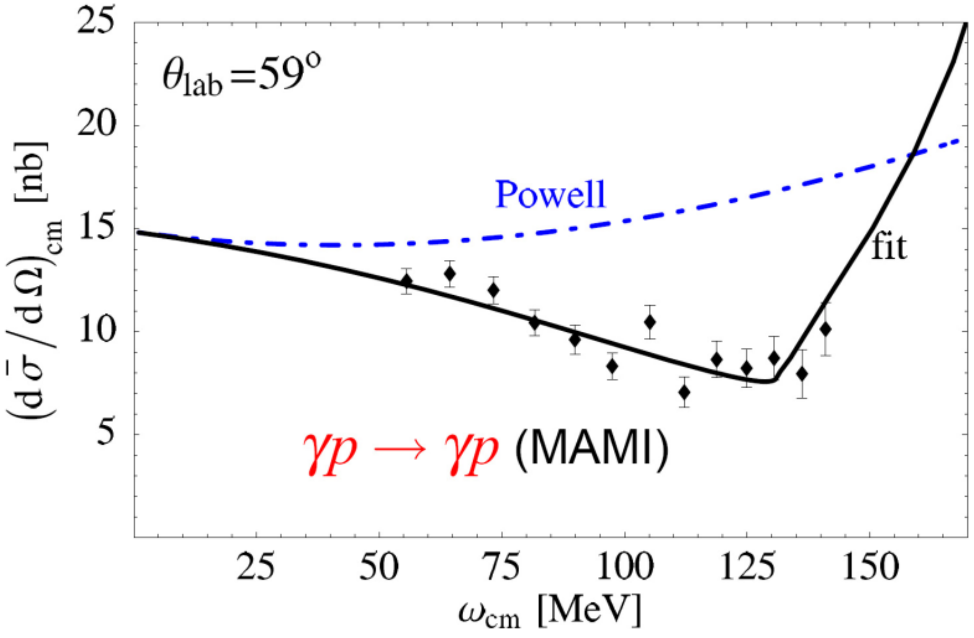
VVCS generalized pol.



inclusive inelastic
structure functions

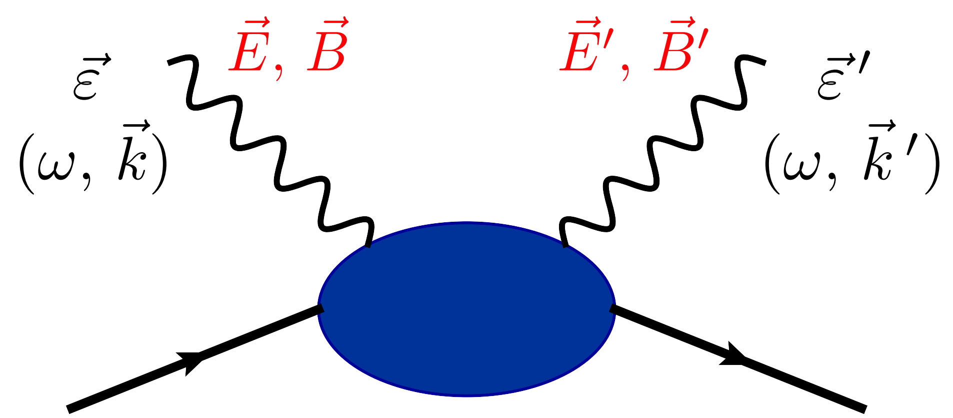

RCS polarizabilities
VCS generalized pol.
VVCS generalized pol.
γ
γ
$s \ll$
γ^*
Q^2
γ
$s, Q^2 \ll$
γ^*
Q^2
γ^*
Q^2
$s, Q^2 \ll$
$s, Q^2 \gg$
$s, Q^2 \gg$
DVCS
generalized parton distributions
DIS
parton distributions
γ^*
Q^2
γ
γ^*
Q^2
γ^*
Q^2

Real Compton Scattering at low energies



Powell cross section: photon scattering off a pointlike nucleon with anomalous magnetic moment

Static polarizabilities: response of the internal nucleon degrees of freedom to a static electric and magnetic field



$$H_{\rm eff}^{\rm pol.} = -2\pi \Big\{ \omega^2 \left[\alpha_{E1} \vec{E}^2 + \beta_{M1} \vec{B}^2 \right]$$ spin-independent dipole

$$+\, \omega^3 \Big[\gamma_{E1E1}\, \vec{\sigma} \cdot (\vec{E} \times \dot{\vec{E}}) + \gamma_{M1M1}\, \vec{\sigma} \cdot (\vec{B} \times \dot{\vec{B}})$$ spin-dependent dipole

$$-2\, \gamma_{M1E2}\, \sigma_i B_j E_{ij} + 2\, \gamma_{E1M2}\, \sigma_i E_j B_{ij} \Big] + \mathcal{O}(\omega^3) \Big\}$$ spin-dependent dipole-quadrupole

RCS Polarizabilities

Measure of the strength of induced polarizations: 2 scalar polarizabilities + 4 spin polarizabilities

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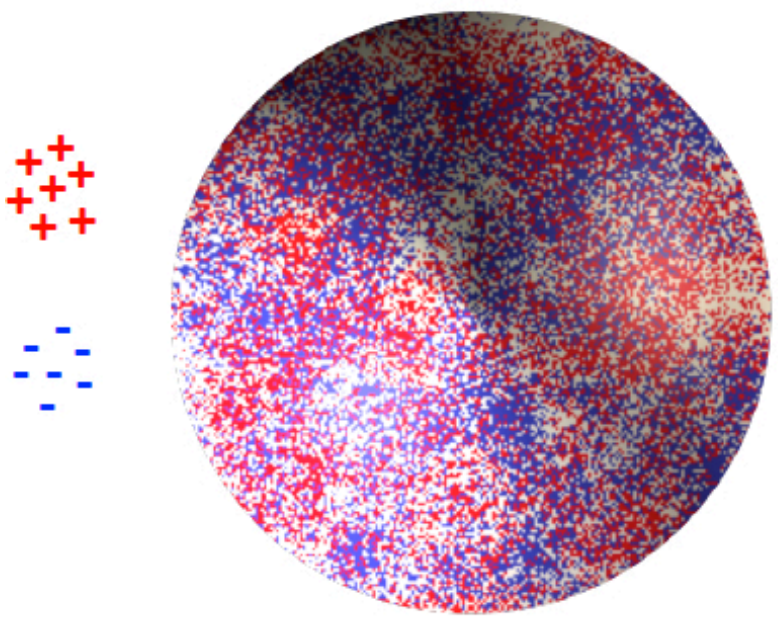

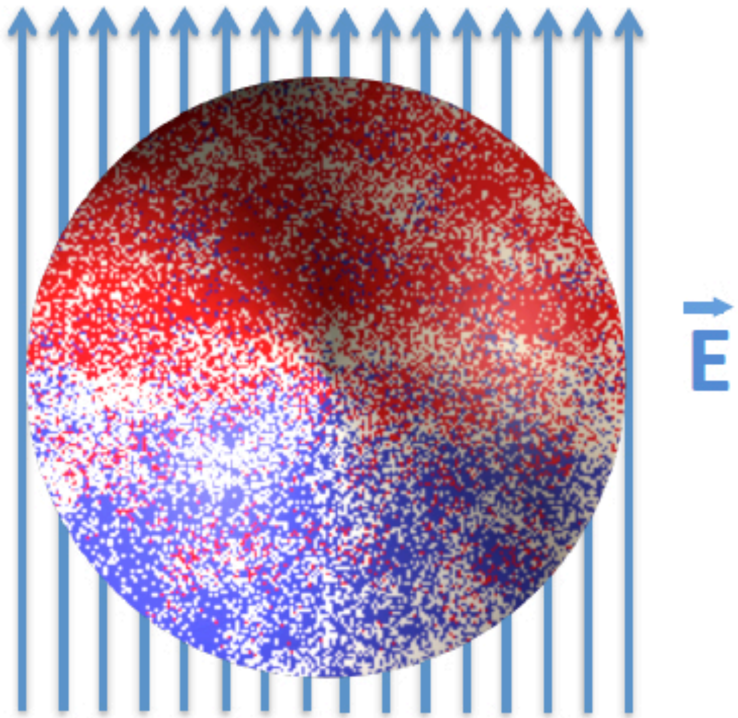

$$\vec{D}_E \sim \alpha_{\mathrm{E1}}\,\vec{E}$$

Unlike atoms,
it is not proportional to volume

$$V \sim \langle r_p \rangle^3 \approx 0.6\,\mathrm{fm}^3$$

$$\alpha_{\mathrm{E1}} \approx 10^{-4}\,V_p$$

much ``stiffer'' than hydrogen!

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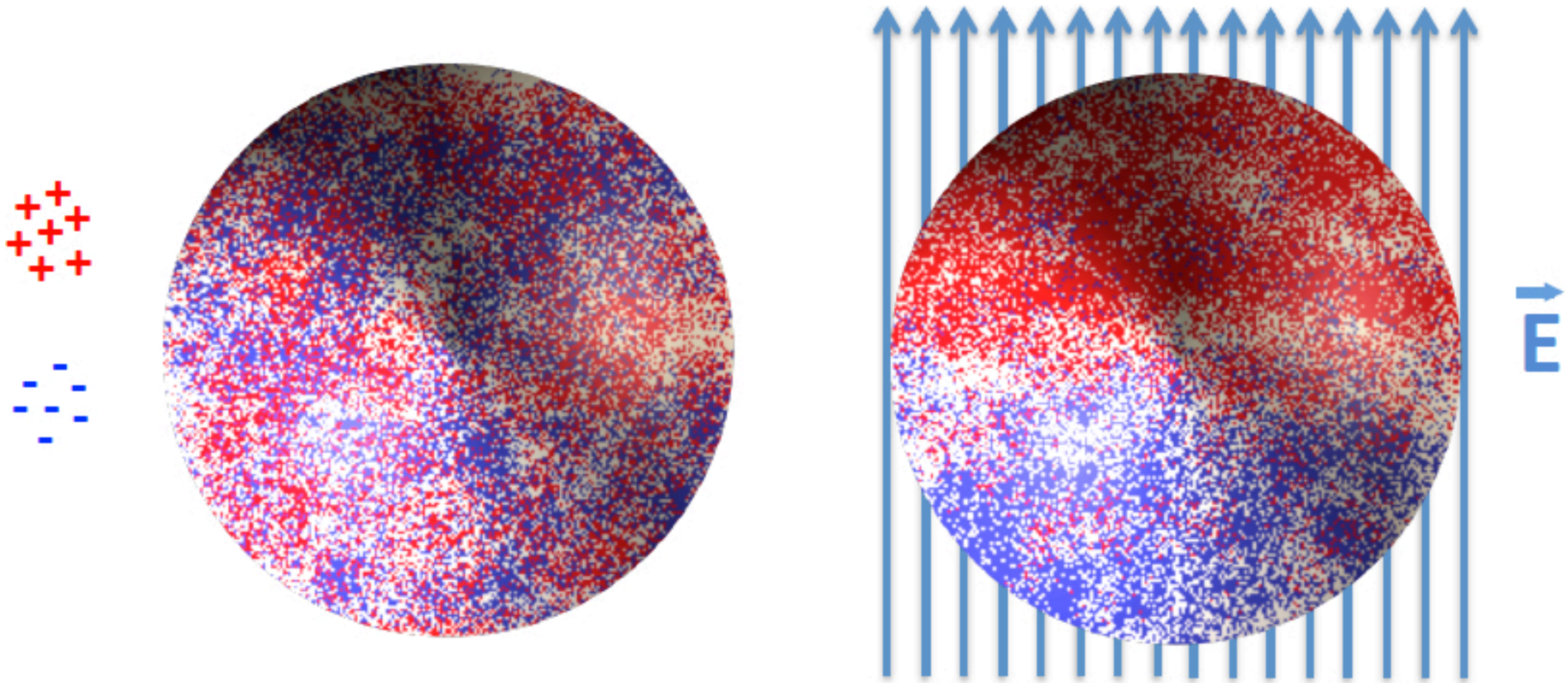

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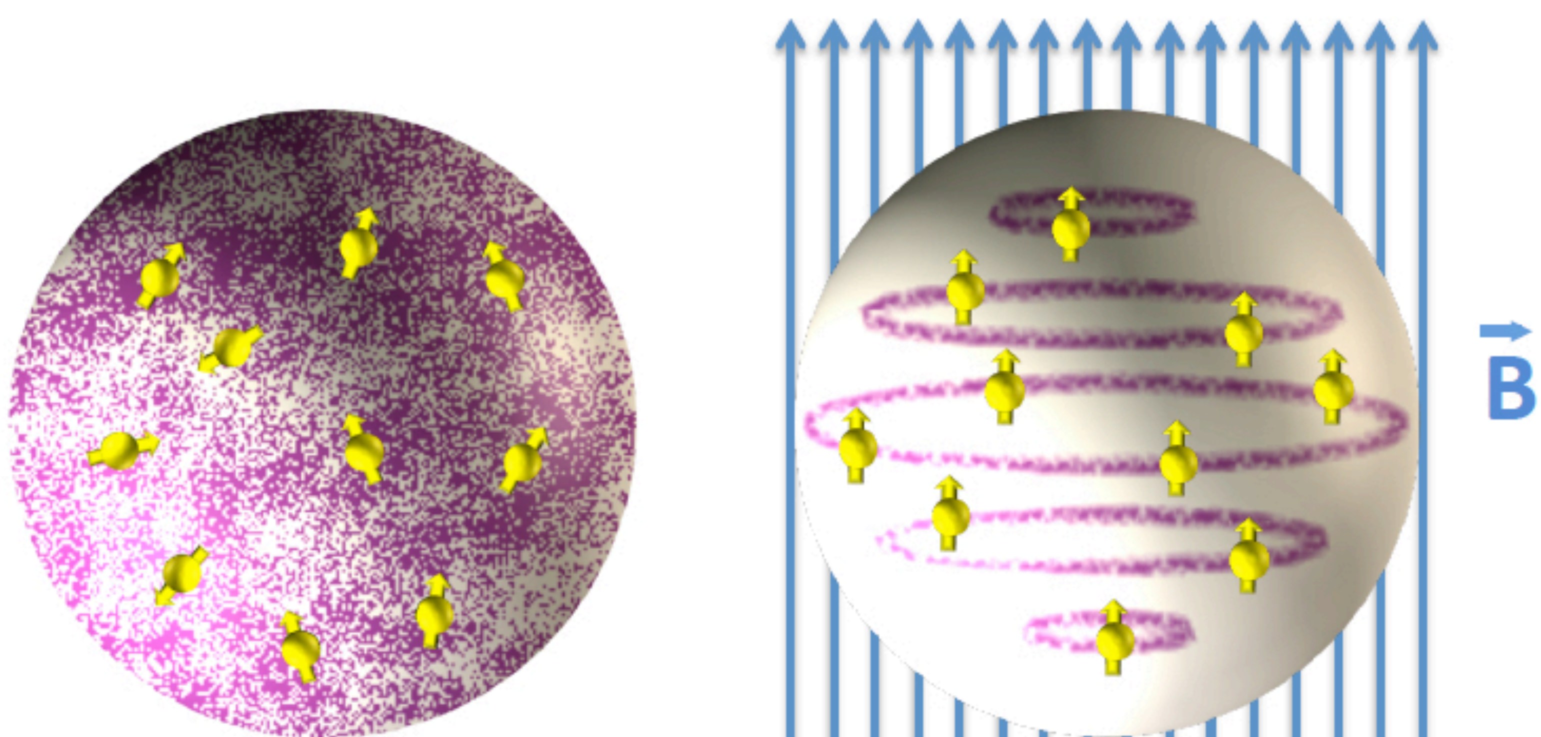


$$\vec{D}_M \sim \beta_{\mathrm{M1}}\, \vec{B}$$

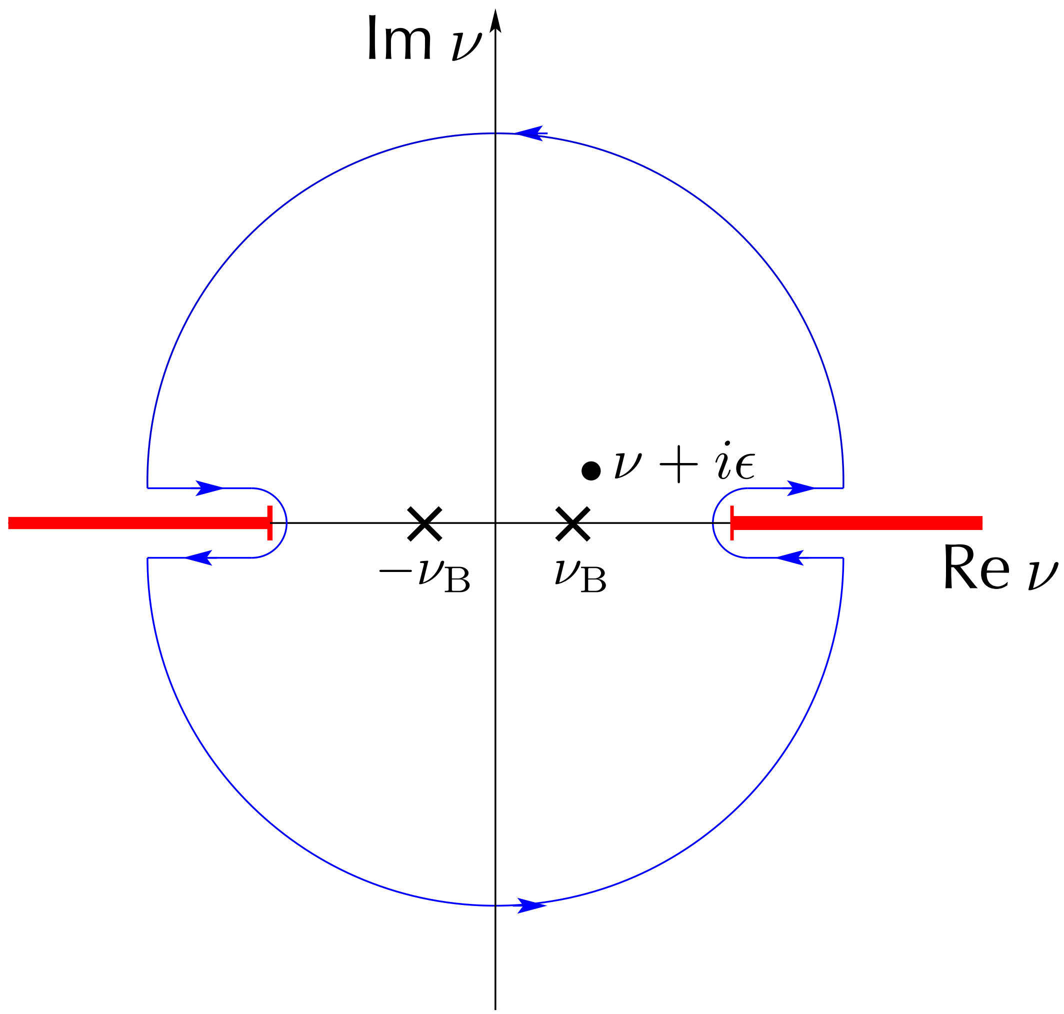
$\beta^{\mathrm{para}}_{\mathrm{M1}} > 0$ proton spin aligns with external field

$\beta^{\mathrm{dia}}_{\mathrm{M1}} < 0$ induced current of pion cloud generates field opposite to the external one

Dispersion Relations at fixed t

$A_i(\nu, t)$:6 analytical functions in the complex ν plane, with cuts and poles on the real axis

$$\nu = E_\gamma + \frac{t}{4M}$$



- Cauchy integral formula

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

- Crossing symmetry and analyticity

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

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

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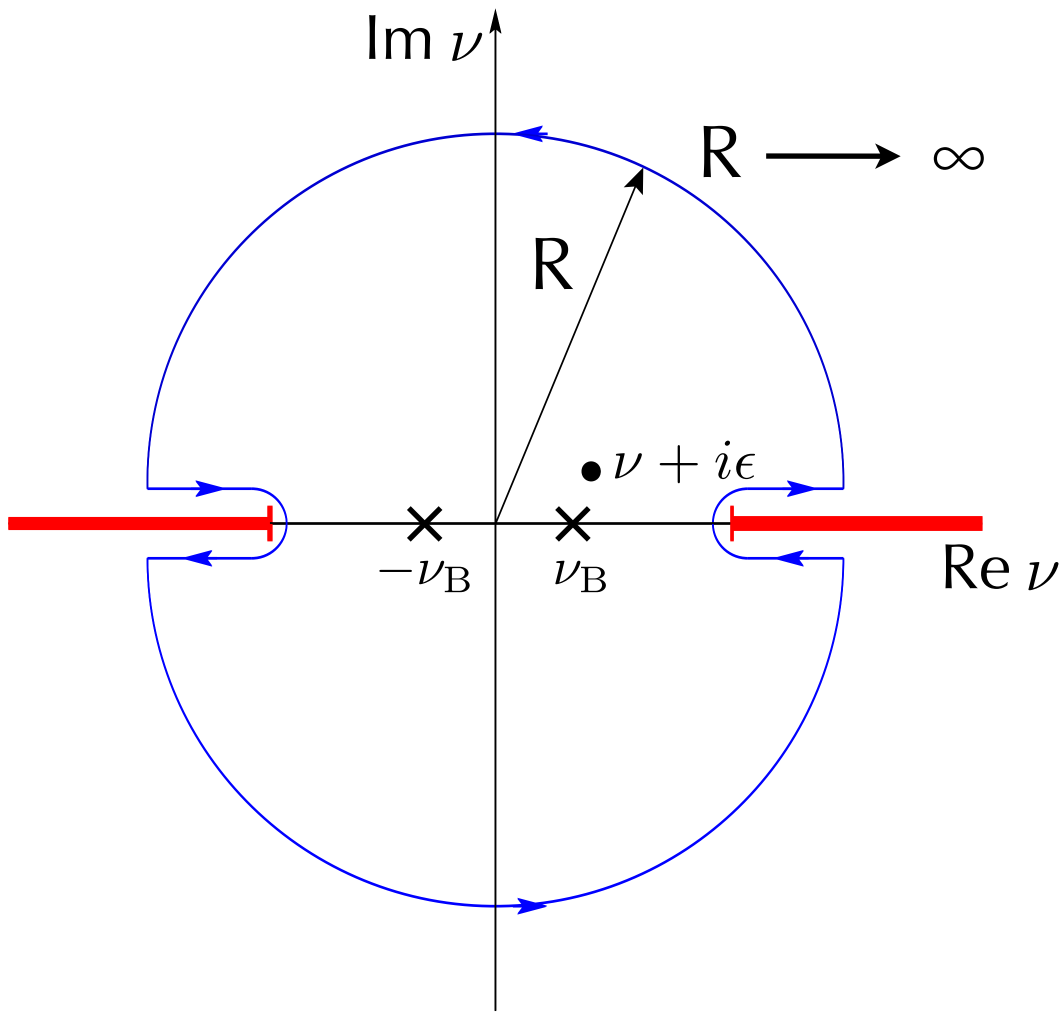

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UNsubtracted Dispersion Relations

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

non-convergent integrals

SUBtracted Dispersion Relations

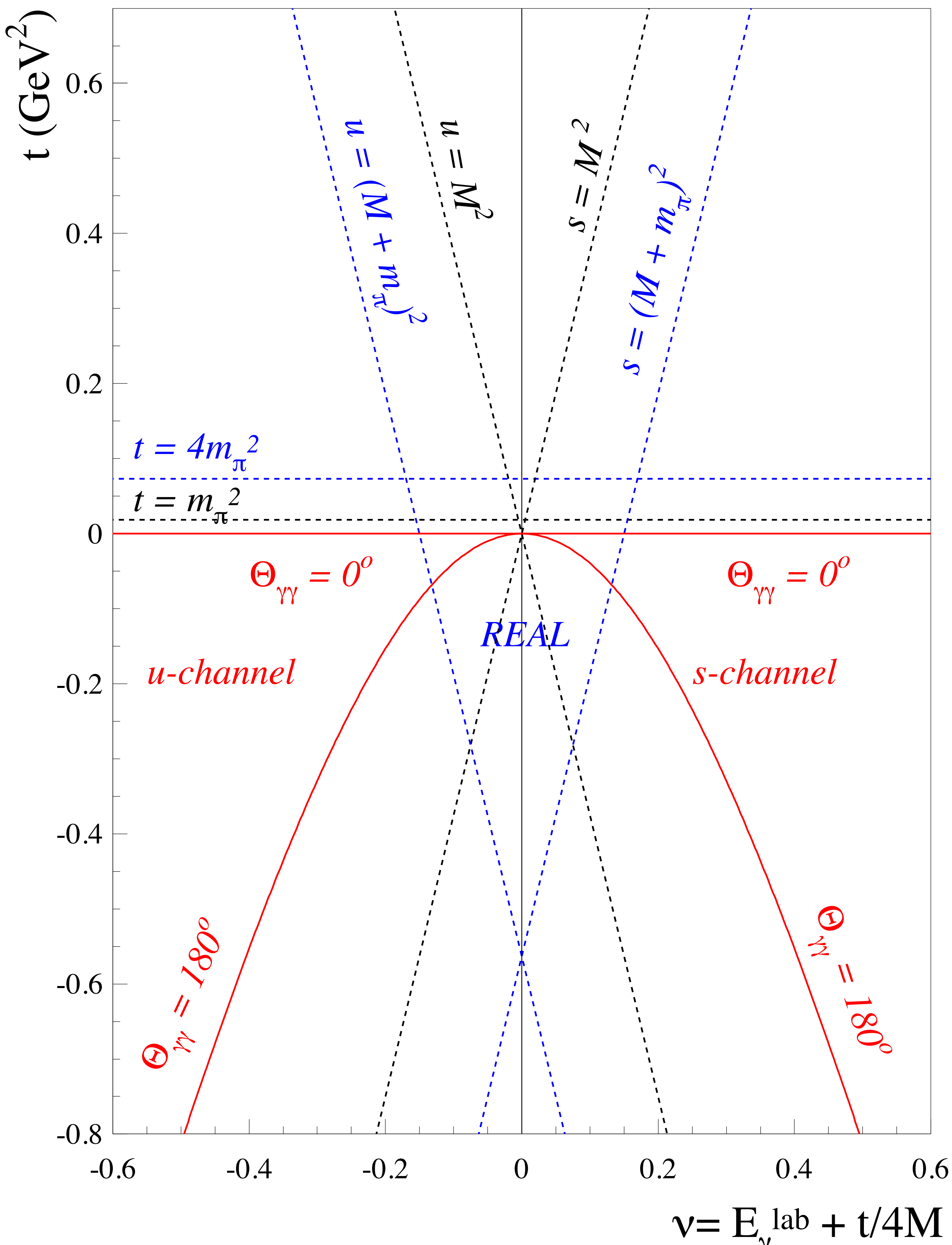
$$\mathrm{Re}\, A_i^{\mathrm{NB}}(\nu, t) = A_i^{\mathrm{NB}}(0, t) + \frac{2}{\pi} \nu^2 \mathrm{P} \int_{\nu_{thr}}^{\infty} \mathrm{Im}_s\, A_i(\nu', t) \frac{d\nu'}{\nu'(\nu'^2 - \nu^2)}$$

subtraction at $\nu = 0$

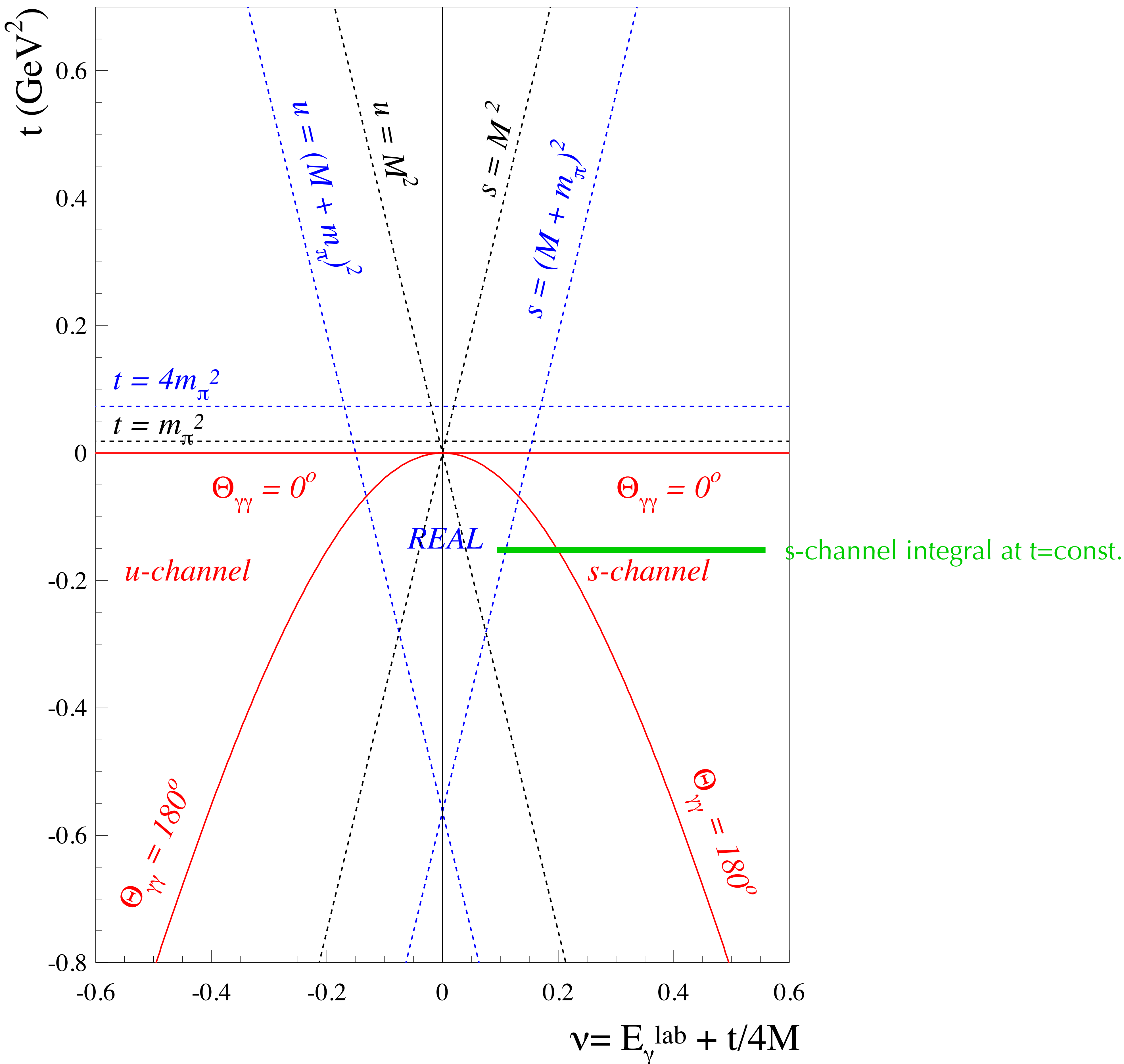
$A_i^{\mathrm{NB}}(0, t) = A_i^{\mathrm{NB}}(0, 0) +$ t-channel SUBtracted dispersion integrals

subtraction at $t = 0$

Mandelstam plane for RCS



Mandelstam plane for RCS



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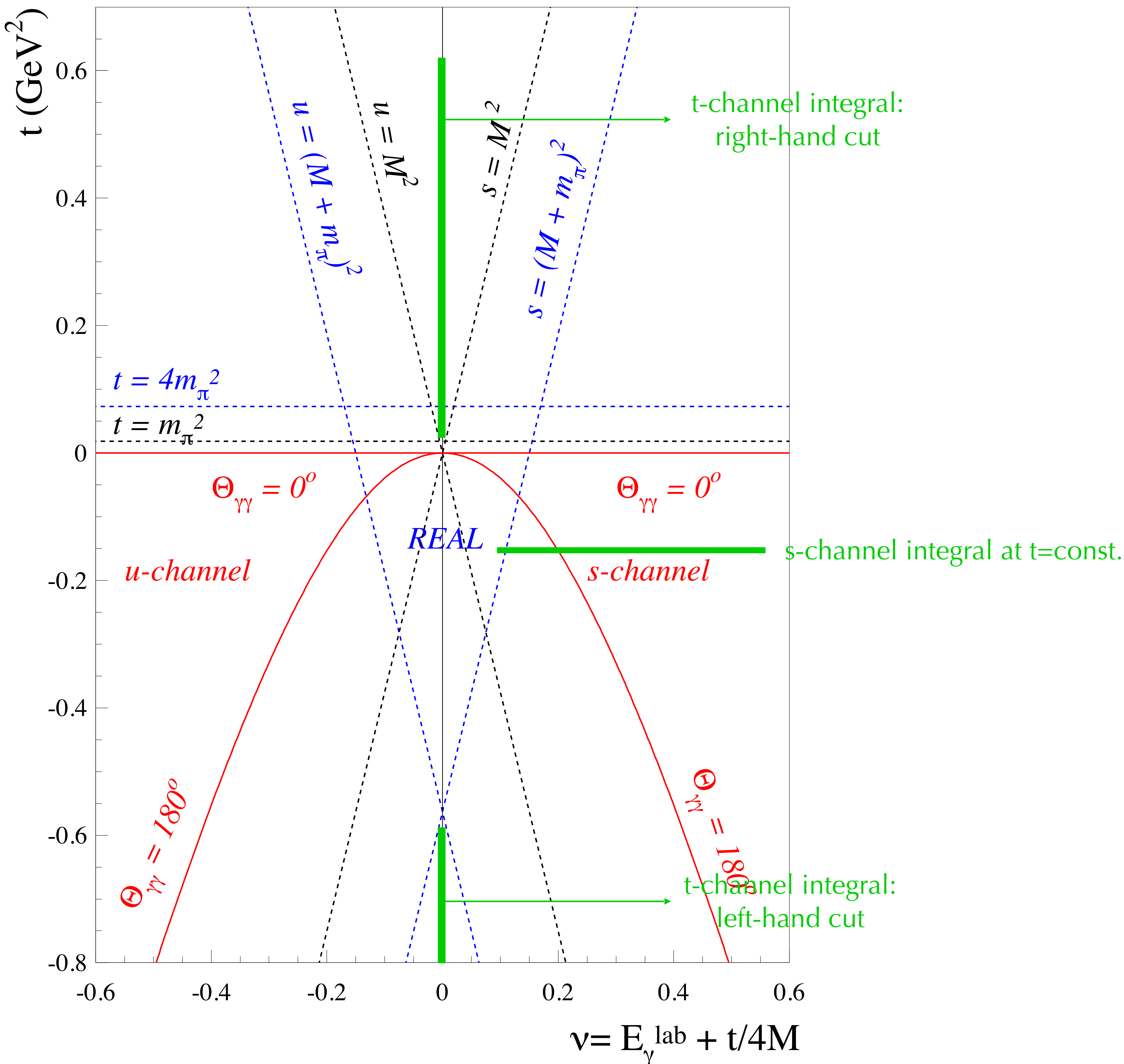

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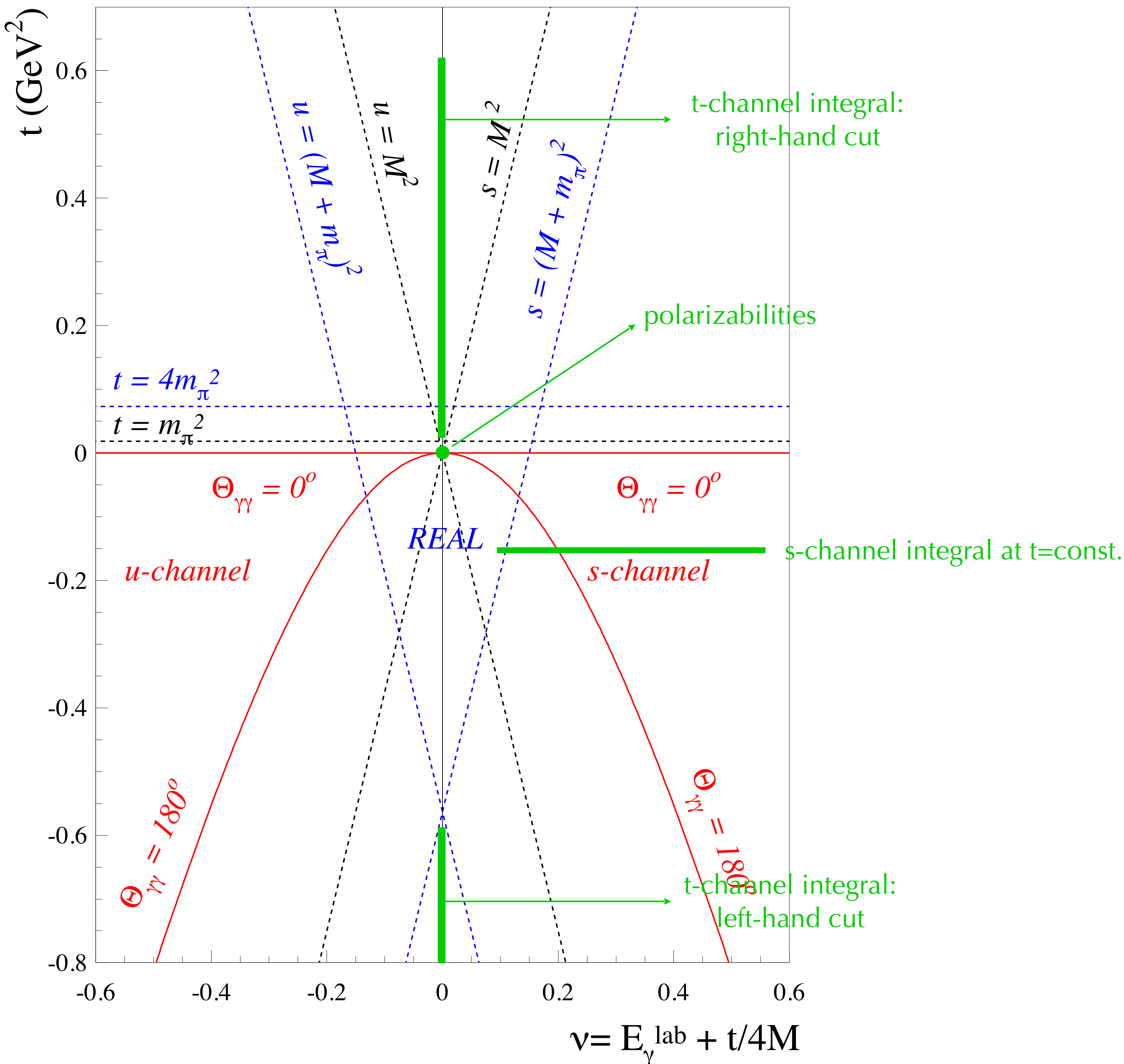
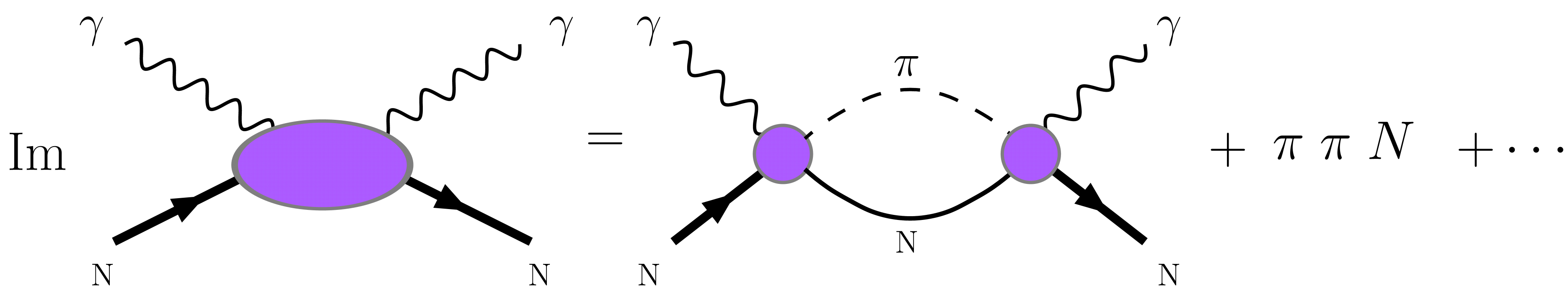


Subtracted Dispersion Relations

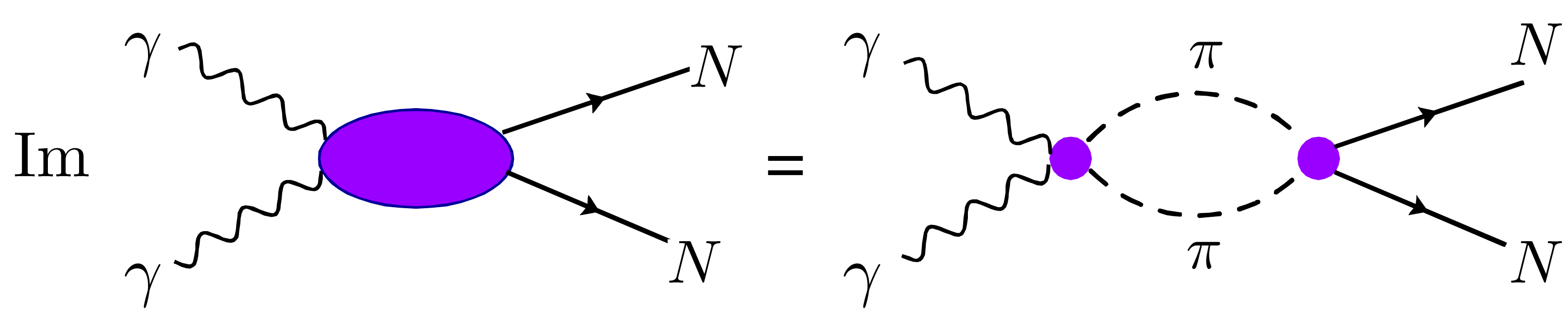
$$A_i(\nu,t) = A_i^s(\nu,0) + A_i^t(0,t) + A_i(0,0)$$

- $A_i^s(\nu,0) \longrightarrow$ subtracted dispersion relations in the s-channel



MAID, Drechsel, Kamalov, Tiator, EPJA34 (2007)

- $A_i^t(0,t) \longrightarrow$ subtracted dispersion relations in the t-channel $\gamma\gamma \to NN$



- $A_i(0,0) \longrightarrow$ polarizabilities: free parameters fitted to data

Gorchtein, Drechsel, B.P., Vanderhaeghen, PRC61 (1999); B.P., Vanderhaeghen, Ann. Rev. Nucl. Part. Sci. 68 (2018)

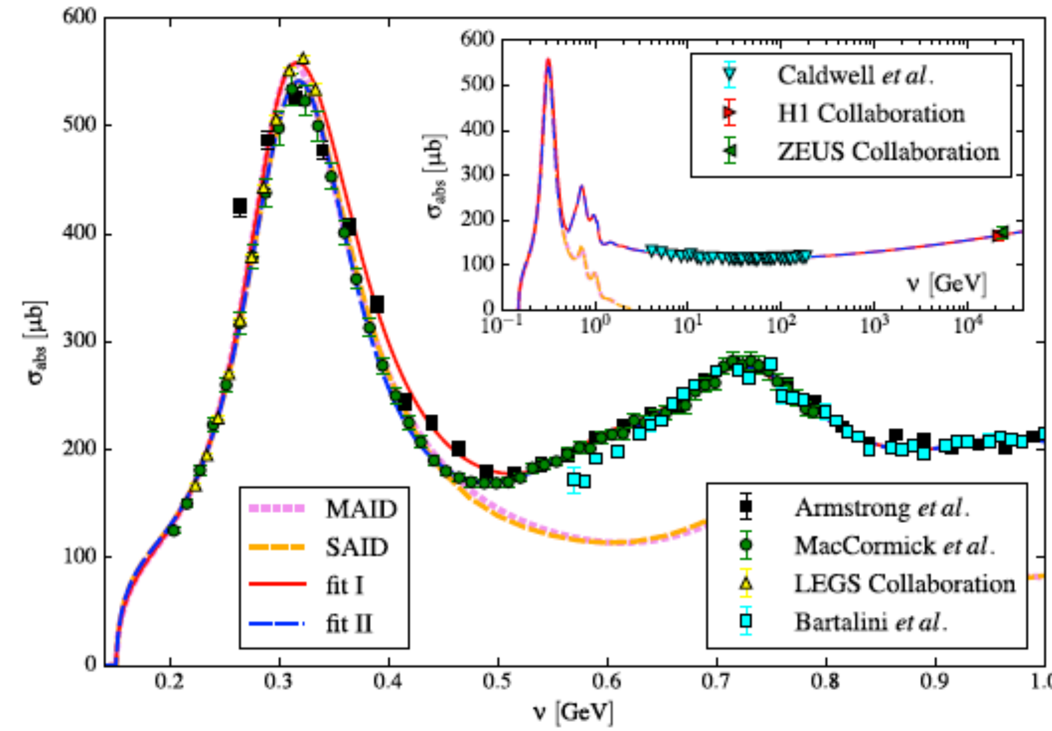
Constraints on the RCS polarizabilities

Baldin sum rule

$$\alpha_{E1} + \beta_{M1} = \frac{1}{2\pi^2} \int_{\nu_{thr}}^{\infty} \frac{\sigma_{1/2} + \sigma_{3/2}}{\nu^2} d\nu$$

$$\alpha_{E1} + \beta_{M1} = (13.8 \pm 0.4) \times 10^{-4}\, \mathrm{fm}^3$$

A1 Coll. (MAMI), EPJA10 (2011)



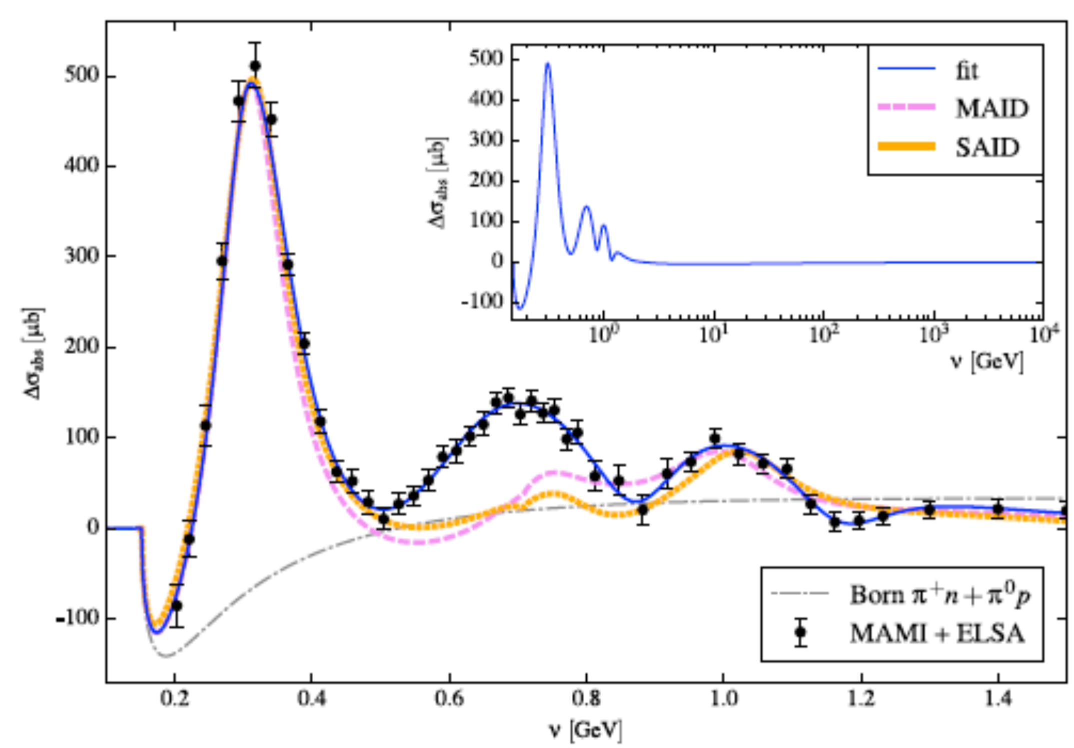
GGT sum rule

$$\gamma_0 = \frac{1}{4\pi^2} \int_{\nu_{thr}}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\nu^3} d\nu$$

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2}$$

$$\gamma_0 = (-1.01 \pm 0.08) \times 10^{-4}\, \mathrm{fm}^4$$

BP, Pedroni, Drechsel, PLB687 (2010)



RCS data above threshold

$$\gamma_\pi = \gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2}$$

$$\gamma_\pi = (-38.7 \pm 1.8) \times 10^{-4}\, \mathrm{fm}^4$$

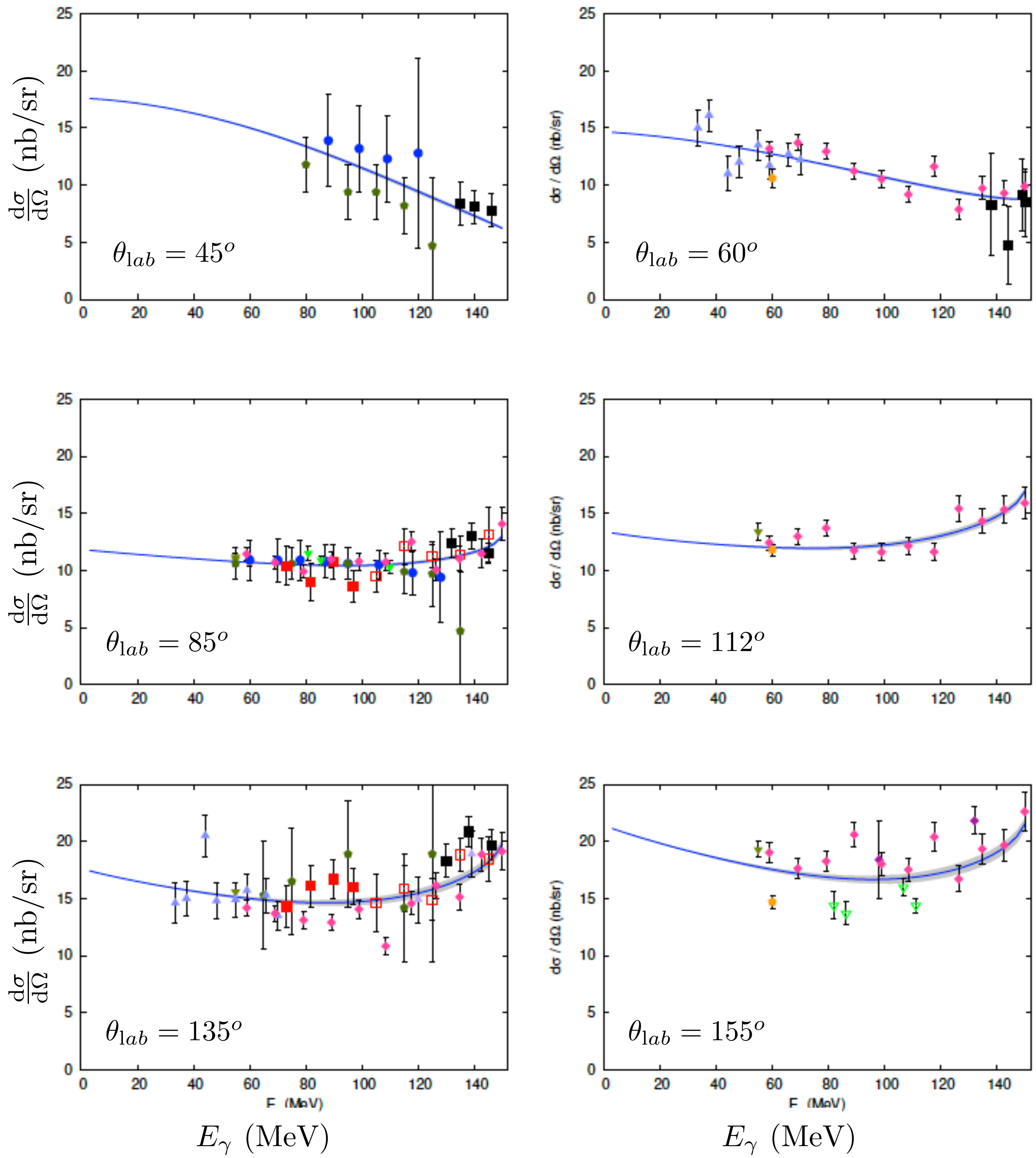
Schumacher, Prog. Part. Nucl. Phys. 55 (2005)

RCS fit below pion-production threshold

α_{E1} and β_{M1}

free parameters

spin polarizabilities
fixed
from sum rules
and DRs



BP, Pedroni, Sconfietti, JPG 42 (2019)

Status of RCS scalar polarizabilities

Extractions from different theoretical models:

BChPT
Lensky et al. [2014]

HBChPT
Mc Govern et al. [2013]

sDRs
Pasquini et al. [2019]

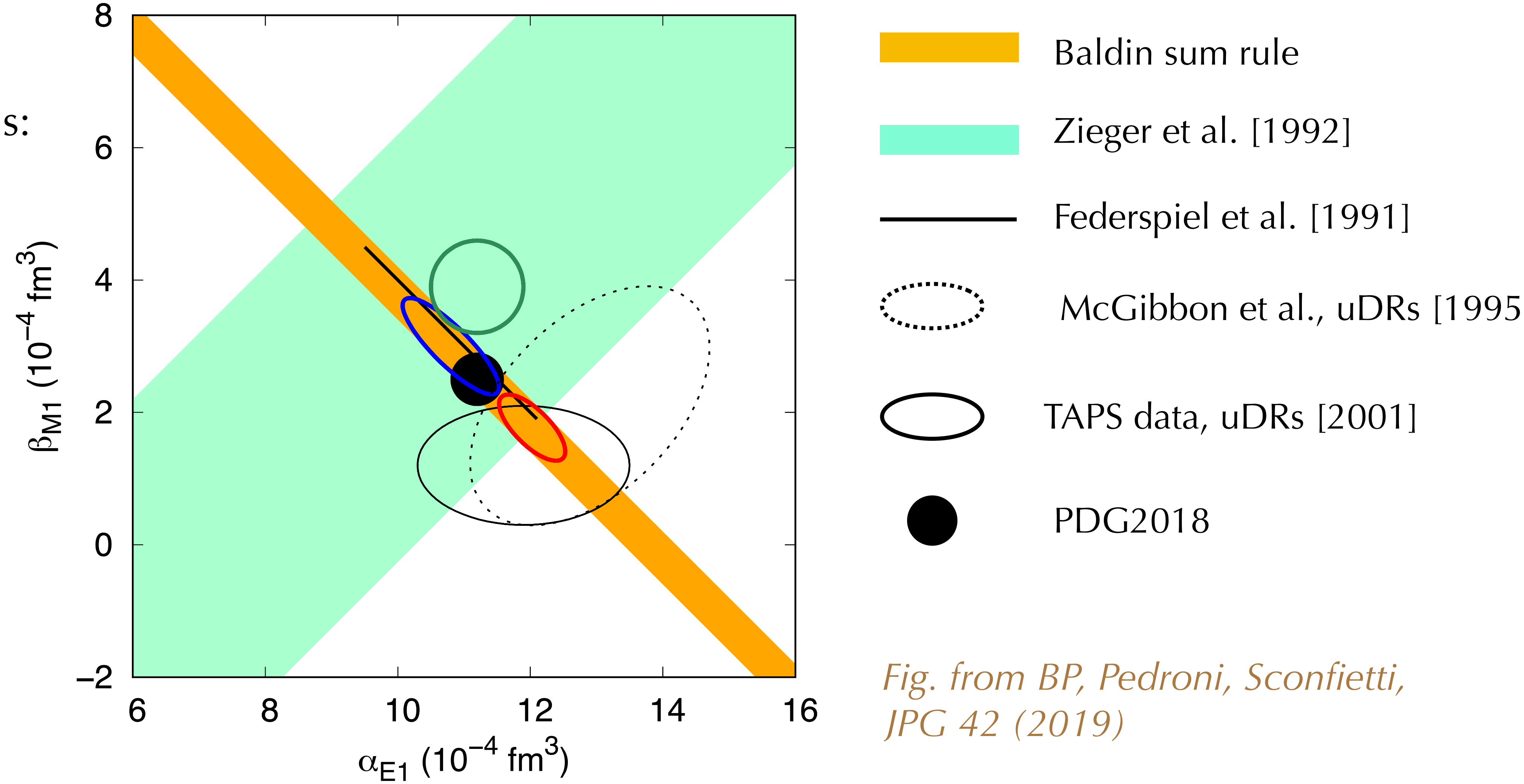


Fig. from BP, Pedroni, Sconfietti, JPG 42 (2019)

PDG2018: $\alpha_{\rm E1} = 11.2 \pm 0.4 \quad \beta_{\rm M1} = 2.5 \pm 0.4$

Baldin sum rule: $\alpha_{\rm E1} + \beta_{\rm M1} = 13.8 \pm 0.4$

New extraction with Subtracted Dispersion Relations:

$$\alpha_{\rm E1} = 12.03^{+0.48}_{-0.54} \qquad \beta_{\rm M1} = 1.77^{+0.52}_{-0.54}$$

BP, Pedroni, Sconfietti, JPG 42 (2019) and to appear in PDG 2021

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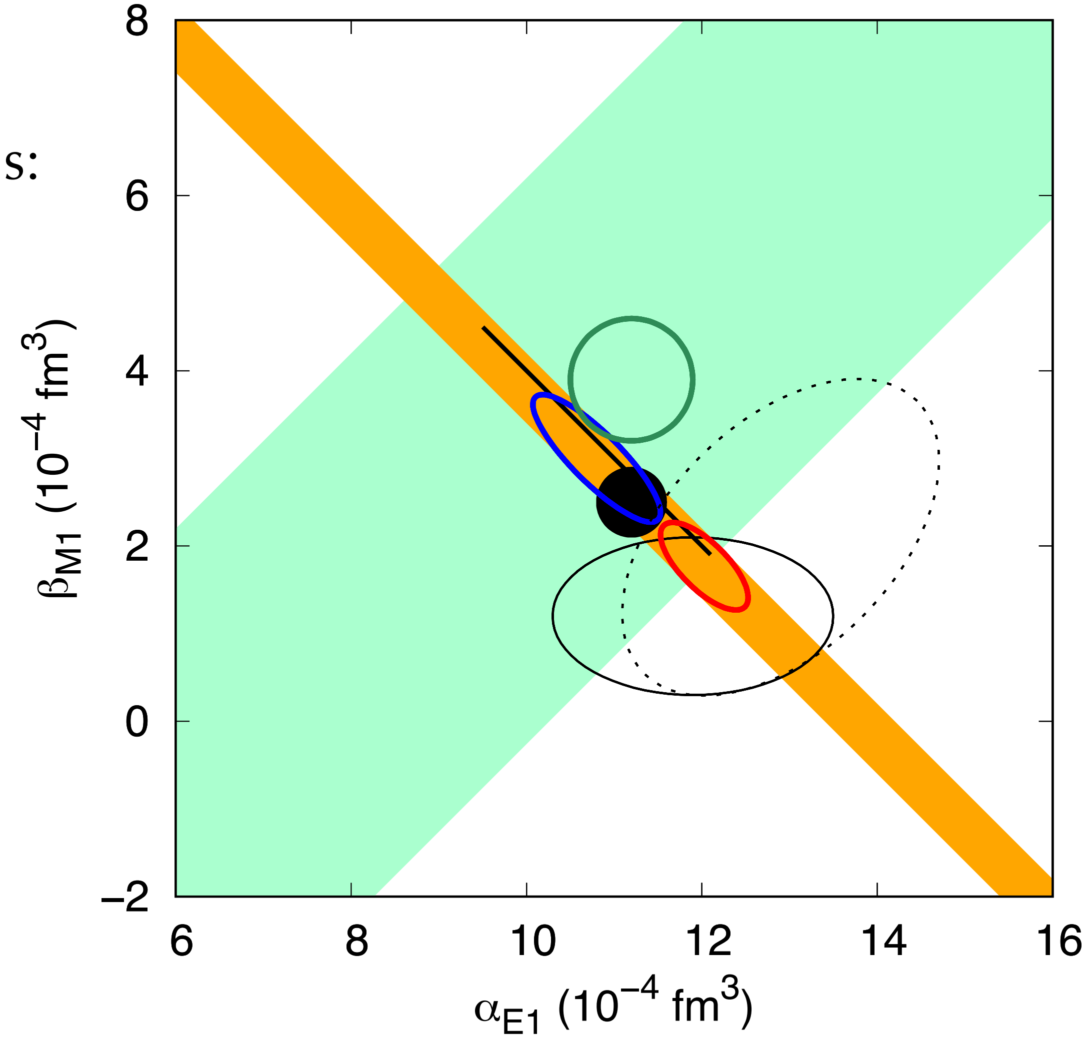

Baldin sum rule

Zieger et al. [1992]

Federspiel et al. [1991]

McGibbon et al., uDRs [1995]

TAPS data, uDRs [2001]

PDG2018

Fig. from BP, Pedroni, Sconfietti, JPG 42 (2019)

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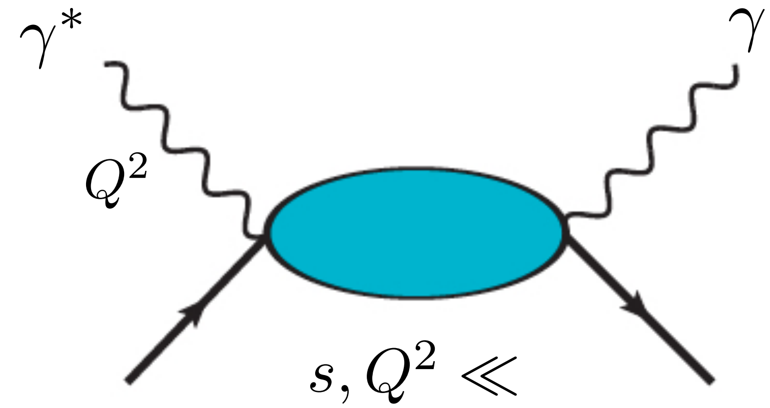
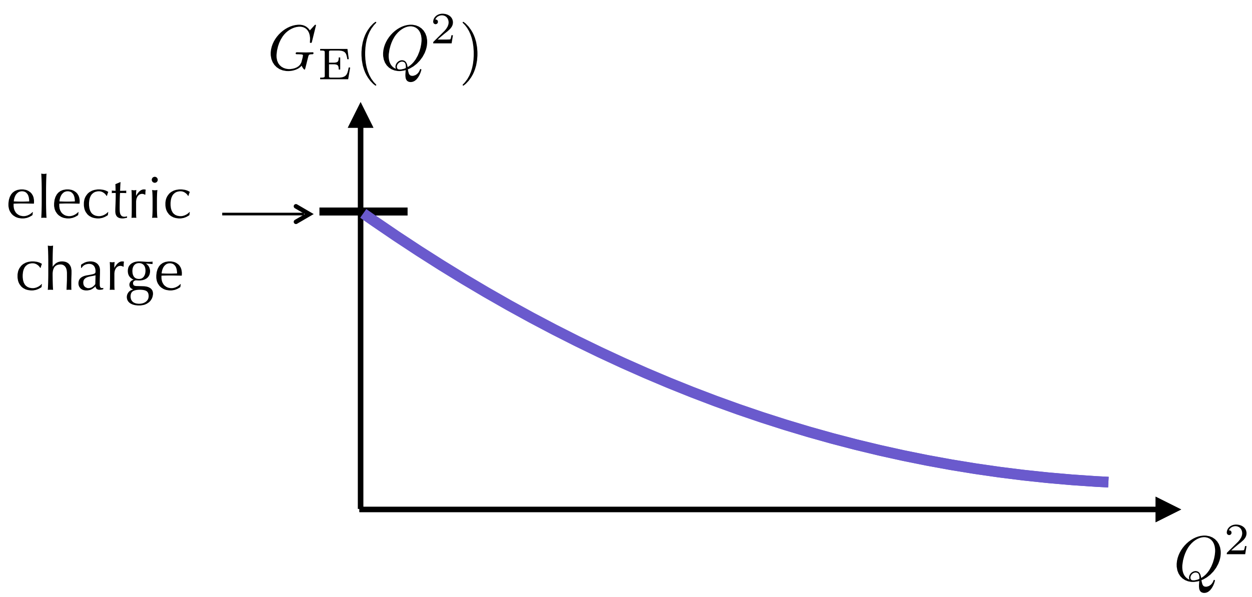
BP, Pedroni, Sconfietti, JPG 42 (2019) and to appear in PDG 2021

DRs used also for the first extraction of spin pol.: A2 Coll. (MAMI), PRC102 (2020); PRL114 (2015)

New data for scalar pol. from MAMI: A2 Coll. (MAMI), to appear in 2021 (PhD Thesis E. Mornacchi)



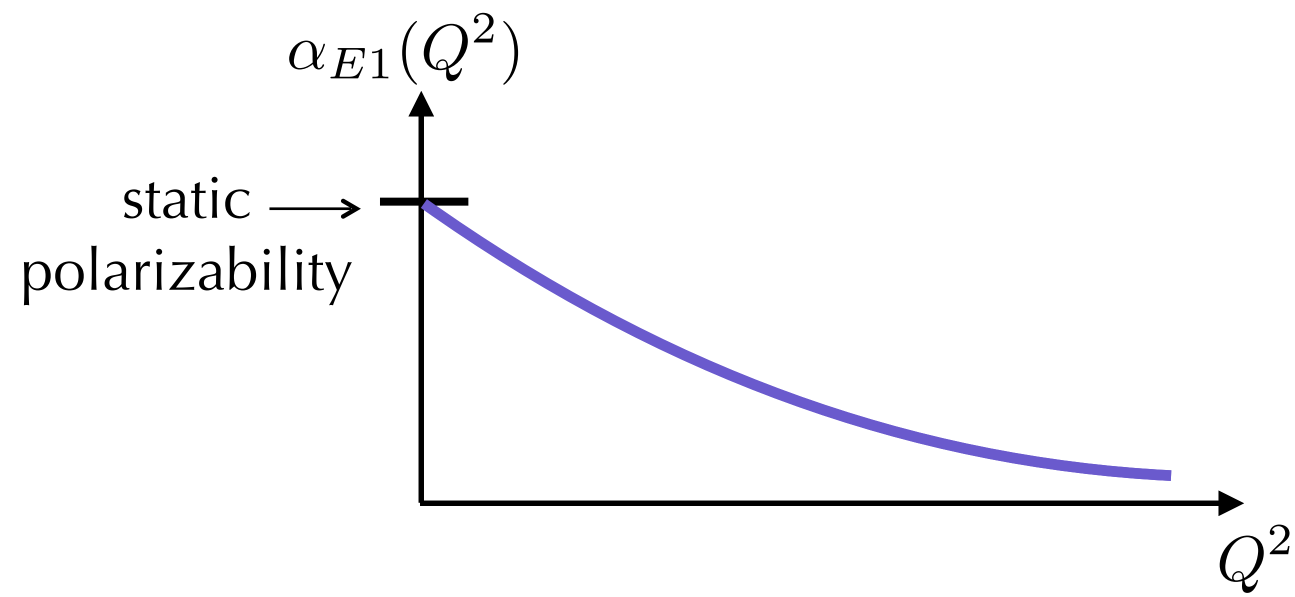
Virtual scattering at threshold can be interpreted
as electron scattering by a target which is in constant electric and magnetic fields



charge

form factor

charge density

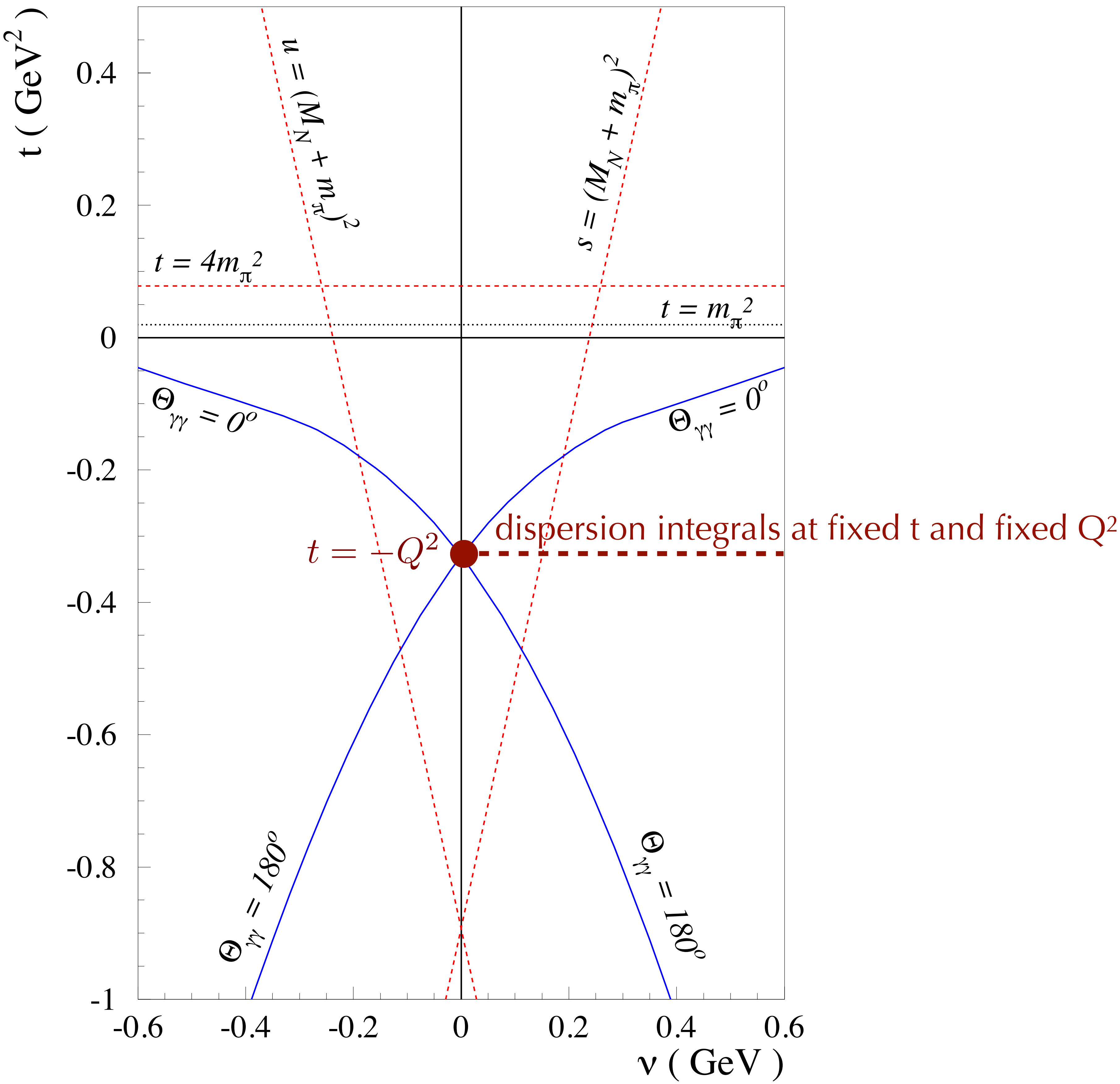


static polarizabilities

generalized polarizabilities

density of induced polarization

Mandelstam Plane for VCS at fixed Q^2



Status of VCS scalar polarizabilities

Unsubtracted DRs fitted to data

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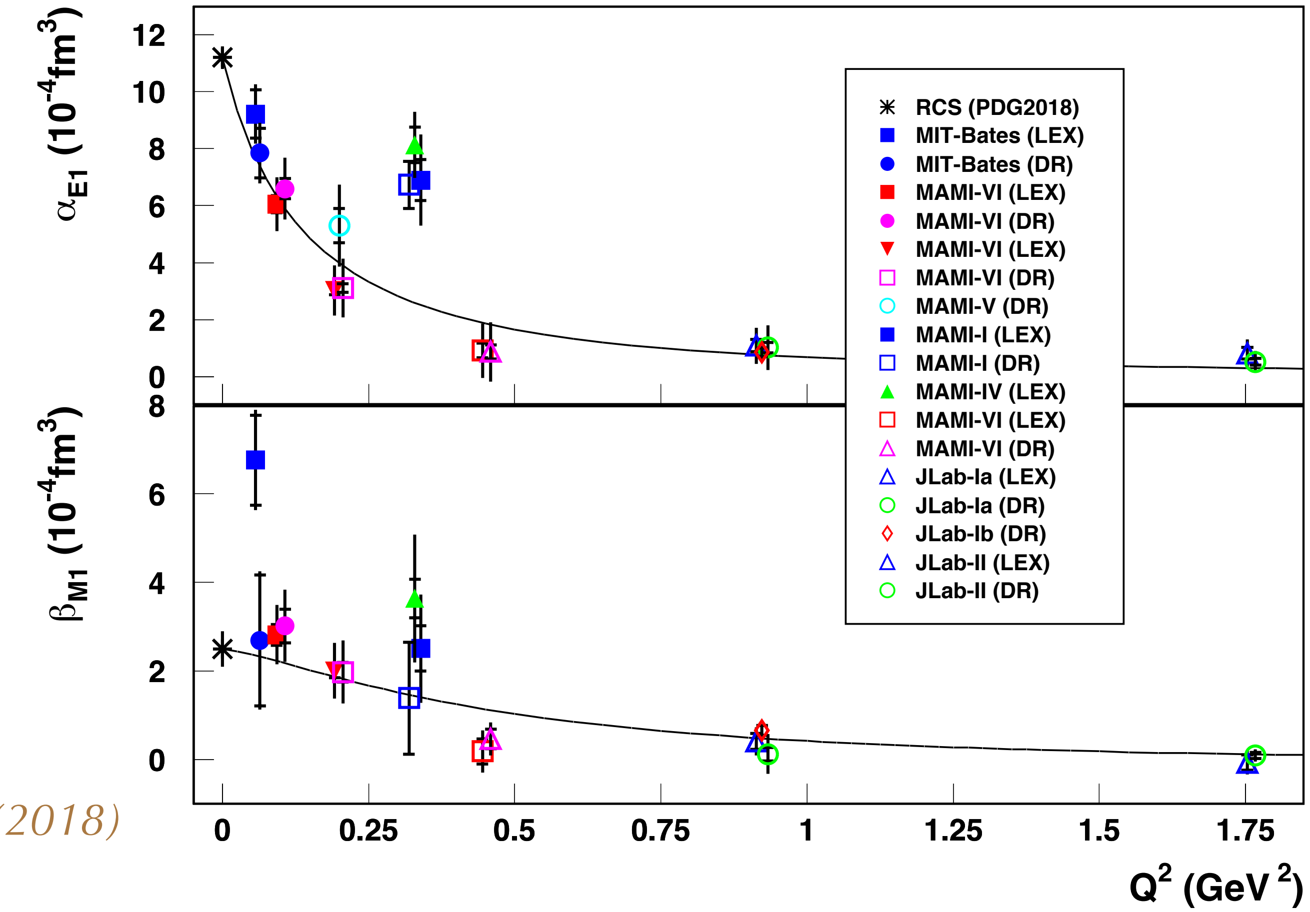
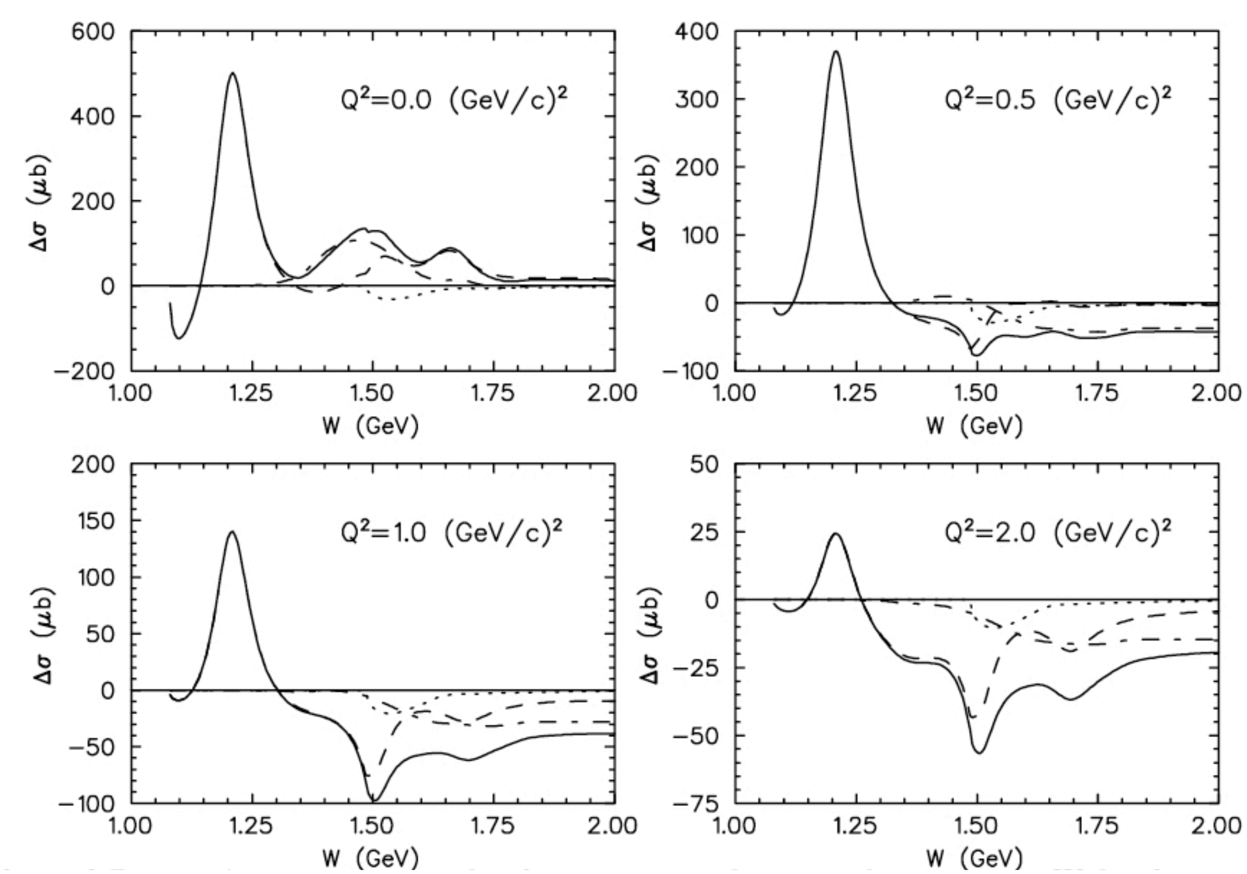
two-parameter fit



BP, Vanderhaeghen, Ann. Rev. Nucl. Part. Sci. 68 (2018)

Fonvieille, BP, Sparveris, Prog. Part. Nucl. Phys.113 (2020)

Input to dispersion integrals:
resonant and non-resonant meson electroproduction amplitudes and multi-meson electroproduction amplitudes
-> probe the whole nucleon spectrum



Status of VCS scalar polarizabilities

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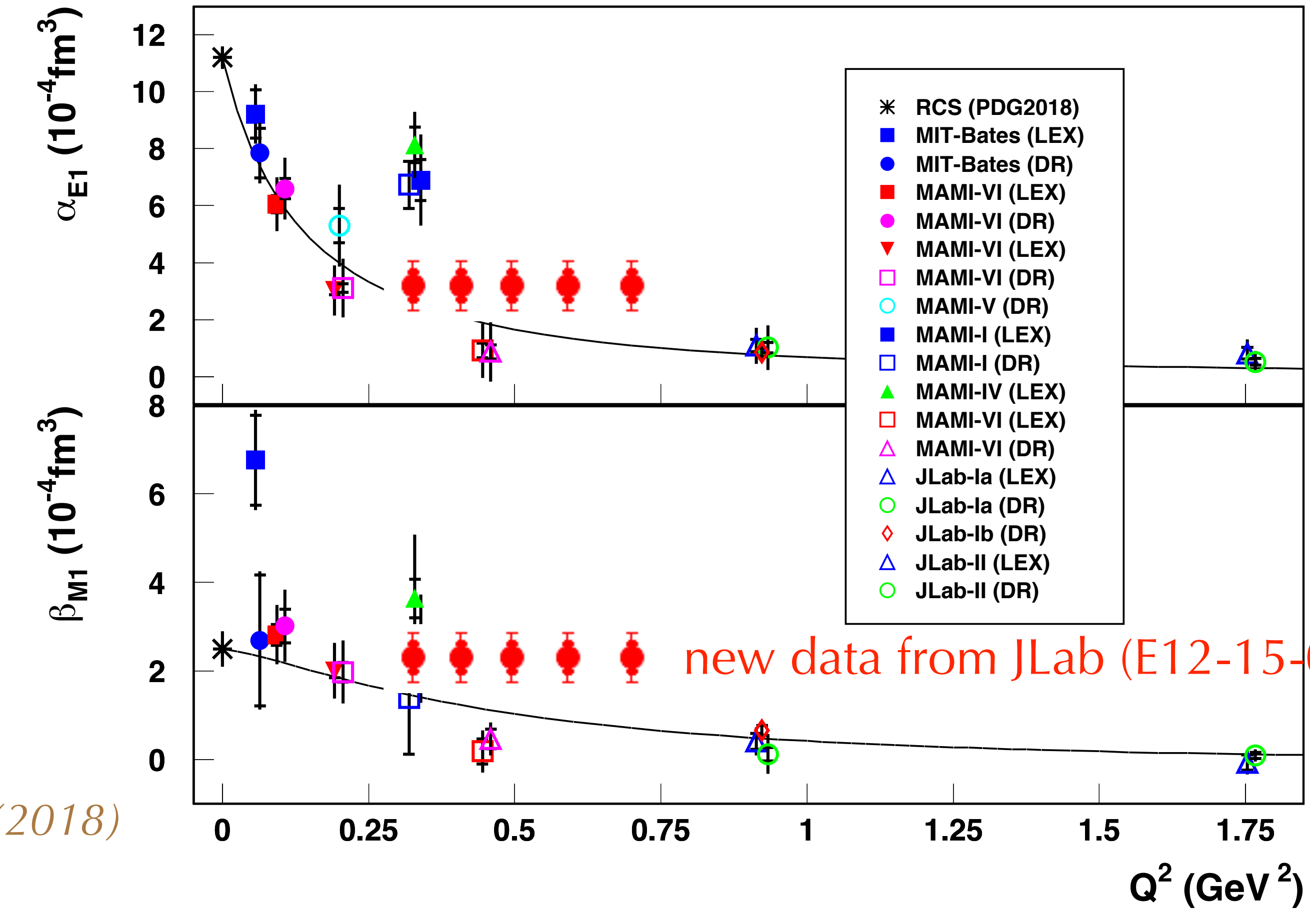

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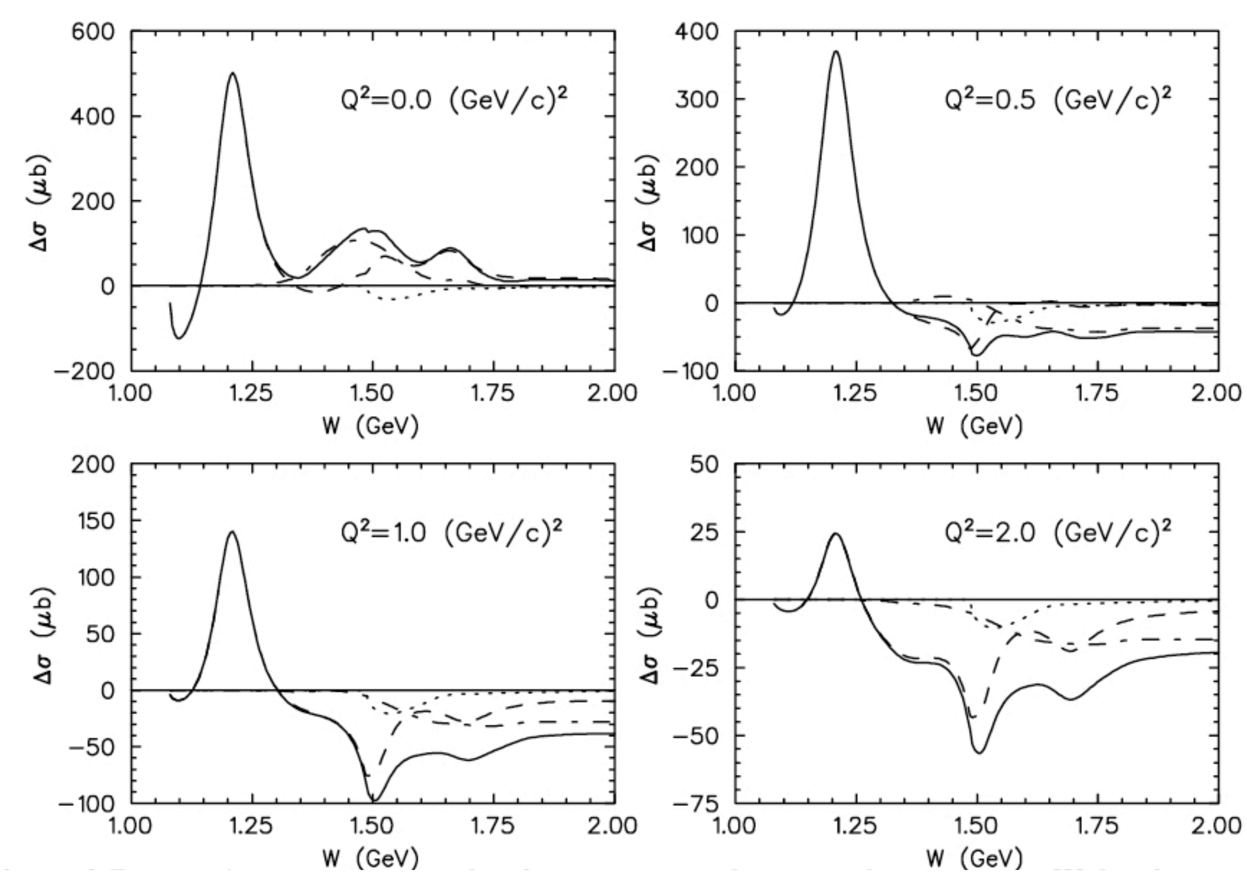
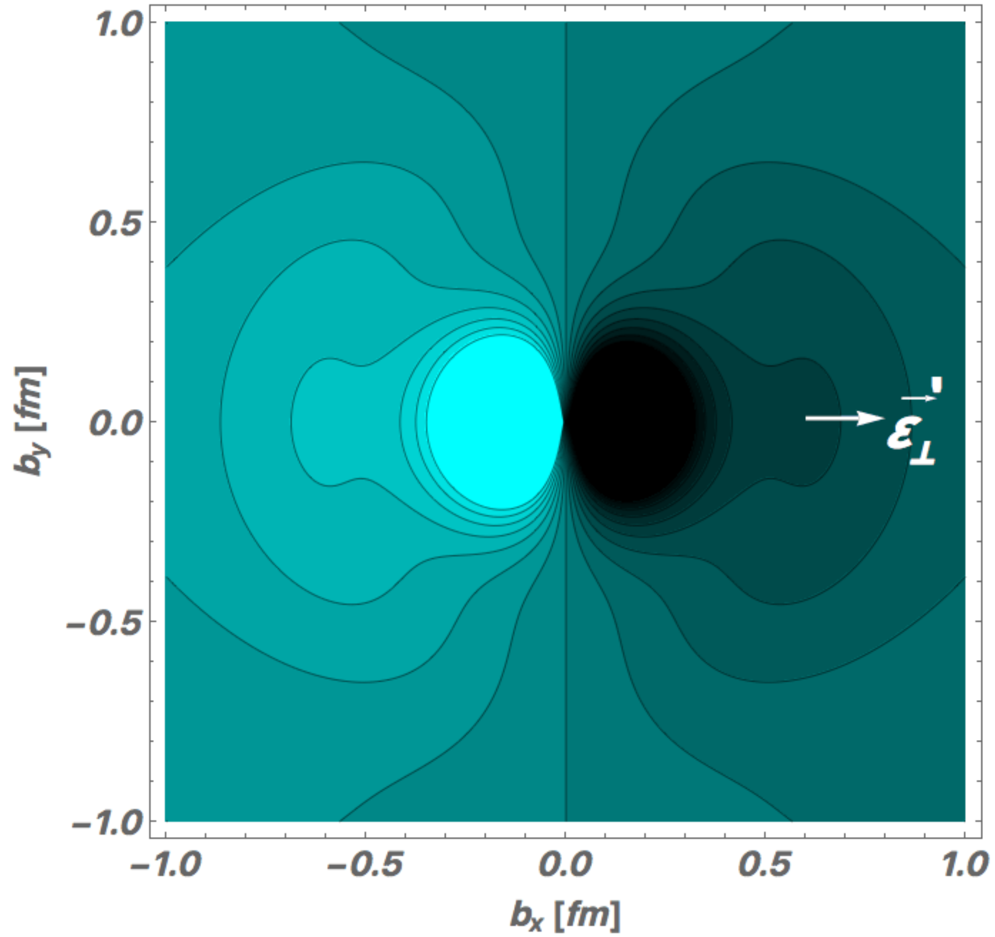
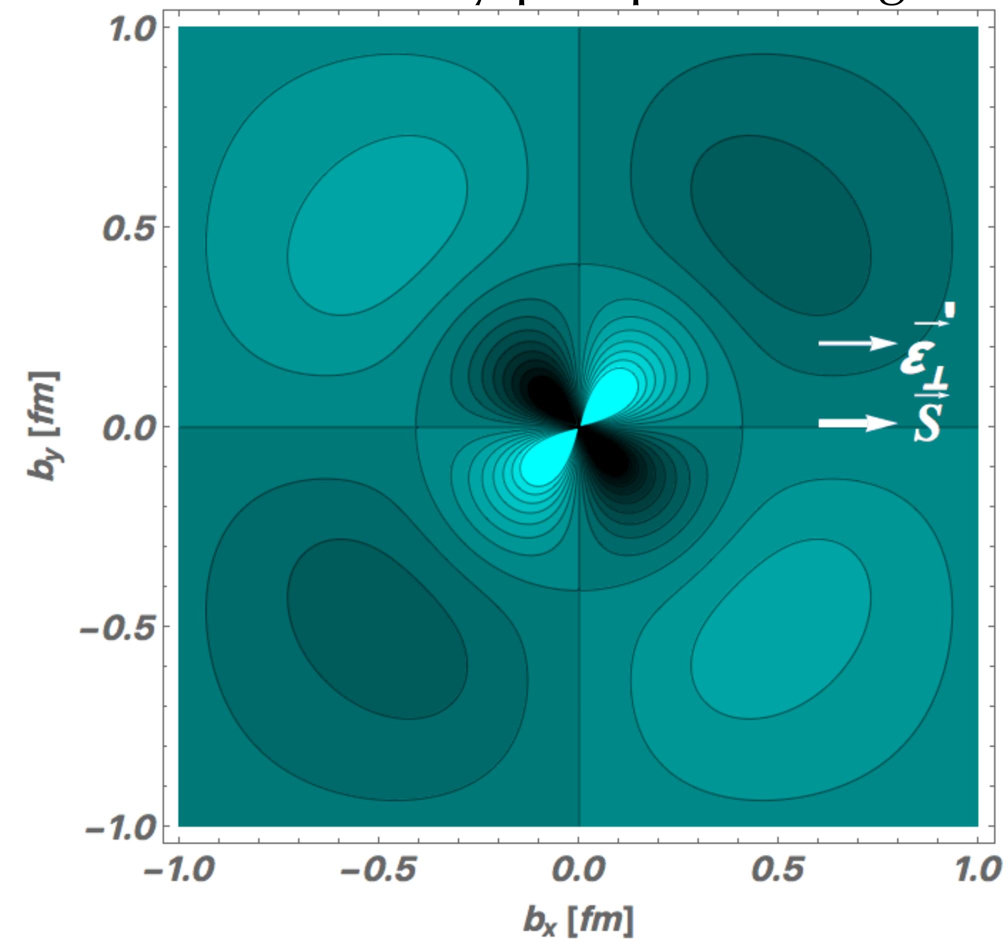


Spatial density of induced polarizations

unpolarized proton target



transversely pol. proton target



light (dark) regions ⟶ larger (smaller) values

Frame with fast moving proton
in the longitudinal direction and $Q^2 = q_\perp^2$

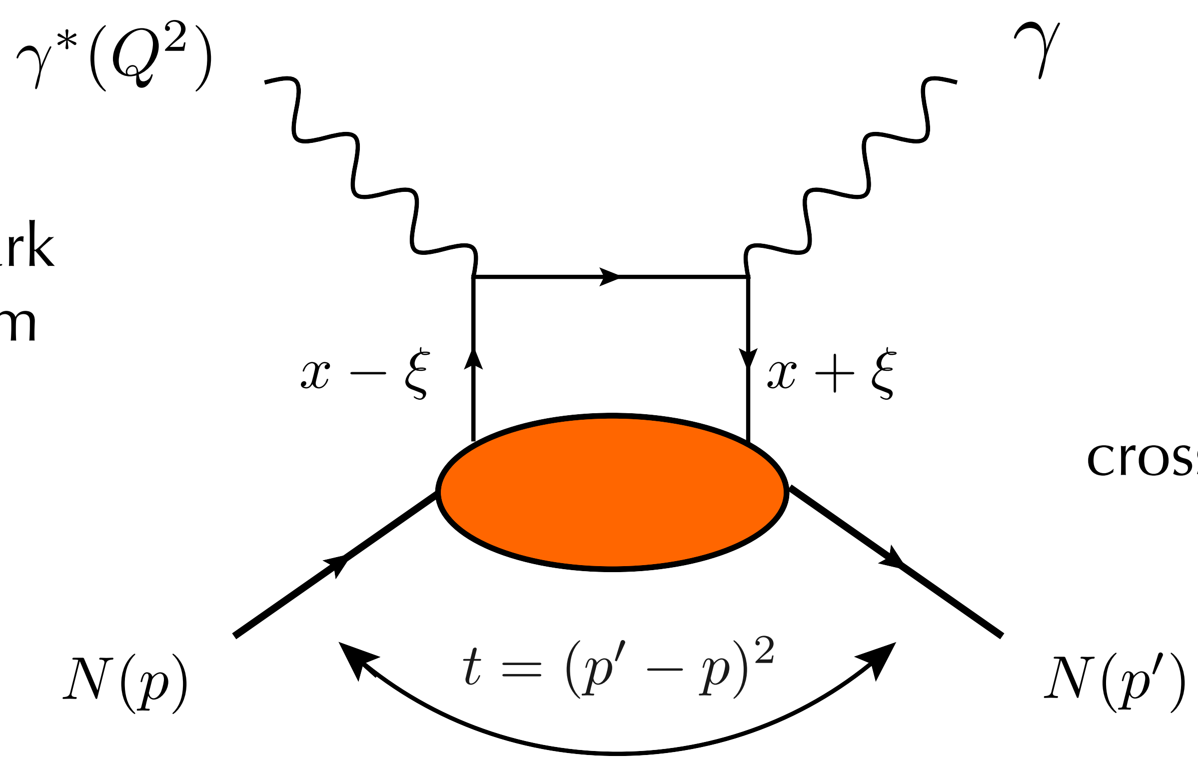
$\vec{q}_\perp \overset{\text{FT}}{\longleftrightarrow} \vec{b}_\perp$

true probabilistic interpretation!

$\vec{E} \sim iq'^0 \vec{\epsilon}'_\perp$ quasi-static electric field ⟶ $\vec{P}$ induced polarization depending on scalar and spin GPs

Gorchtein, Lorcé, BP, Vanderhaeghen, PRL104 (2010) 112001

DVCS at leading twist



x : average fraction of quark longitudinal momentum

ξ : fraction of longitudinal momentum transfer

t : nucleon momentum transfer

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

$\downarrow$

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

$\downarrow$

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

Form Factors of Energy Momentum Tensor

Energy Density Momentum Density

$$T^{\mu\nu} = \begin{array}{cccc} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{array}$$

shear forces

pressure

Energy Flux Momentum Flux

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

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 EMT Form Factors at t=0

$M_2(0)$ nucleon momentum carried by parton

$J(0)$ angular momentum of partons

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

Form Factors of Energy Momentum Tensor

Energy Density | Momentum Density

$$T^{\mu\nu} = \begin{pmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{pmatrix}$$

shear forces

pressure

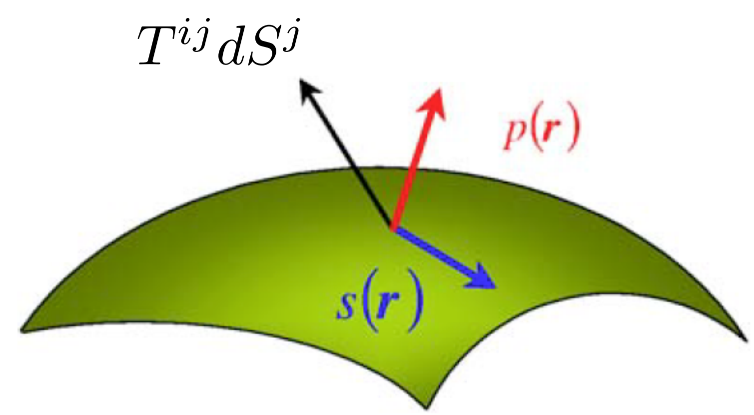
Energy Flux | Momentum Flux

Fourier transform in coordinate space

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

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

“mechanical properties” of nucleon



M. Polyakov, PLB 555 (2003) 57

Dispersion Relations for DVCS amplitudes

- s-channel subtracted 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

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

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

Dispersion Relations for DVCS amplitudes

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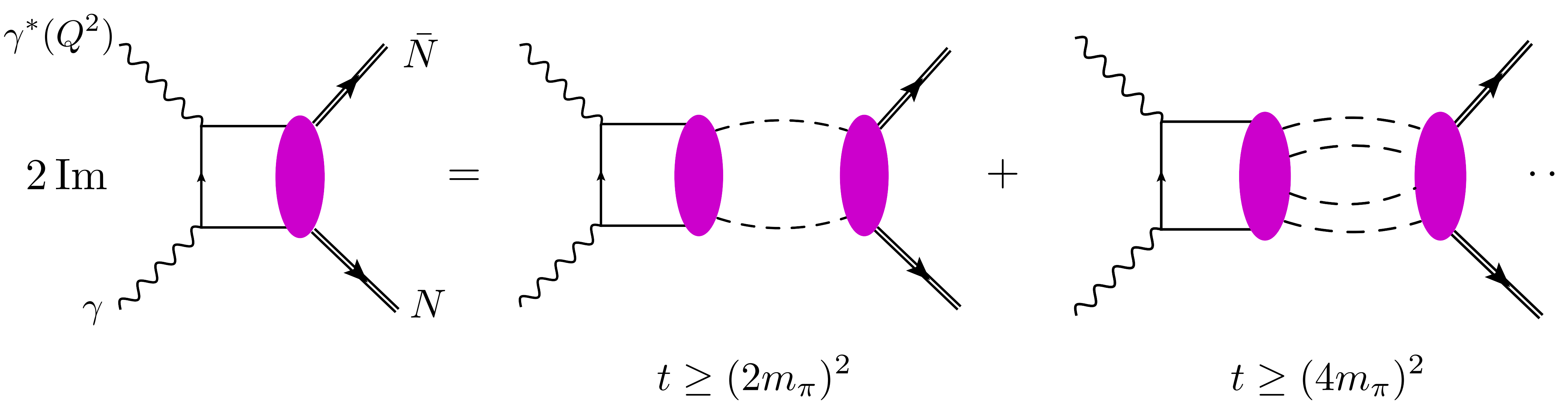
Unitarity relation in t-channel

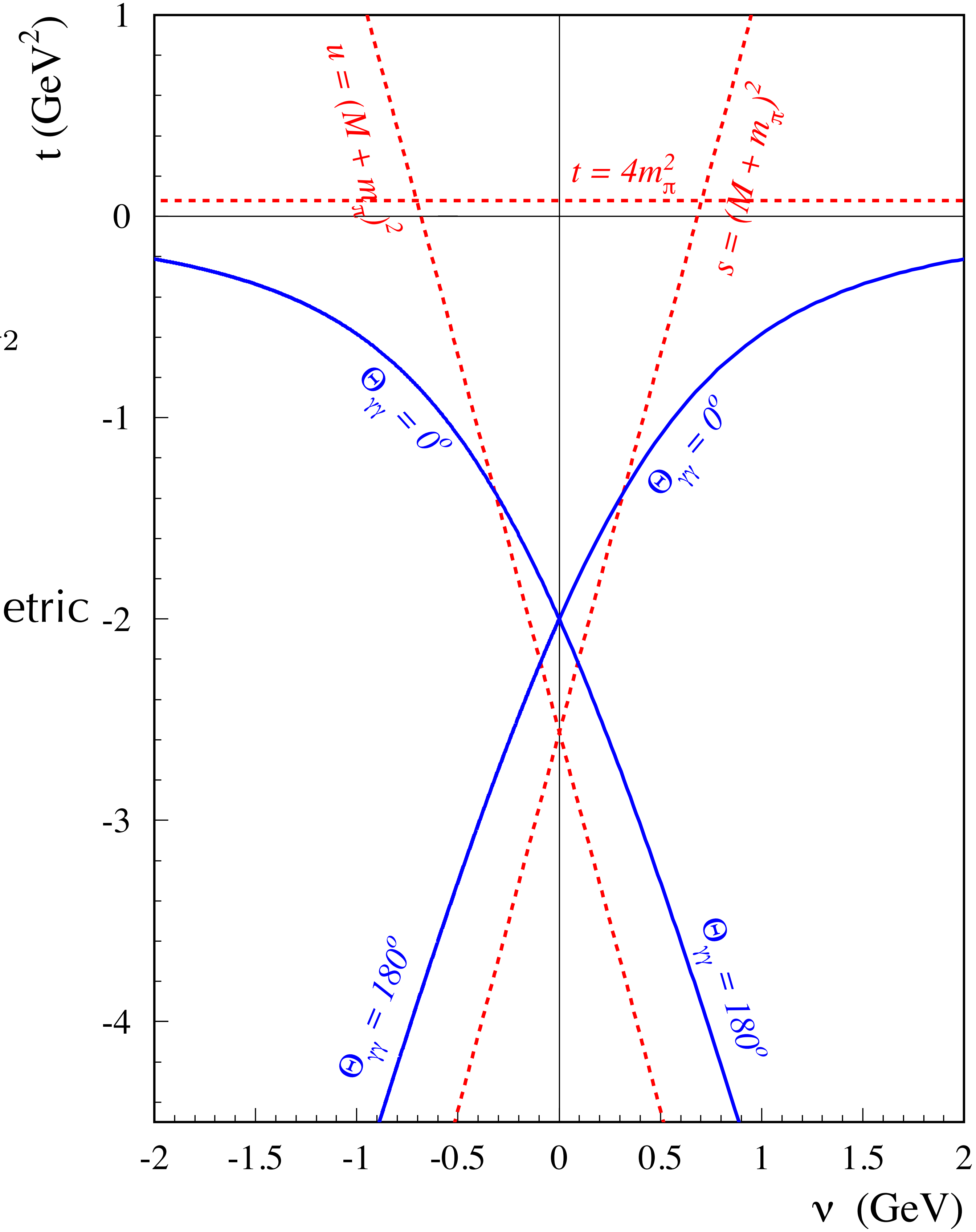


Fixed

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

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

crossing symmetric variable



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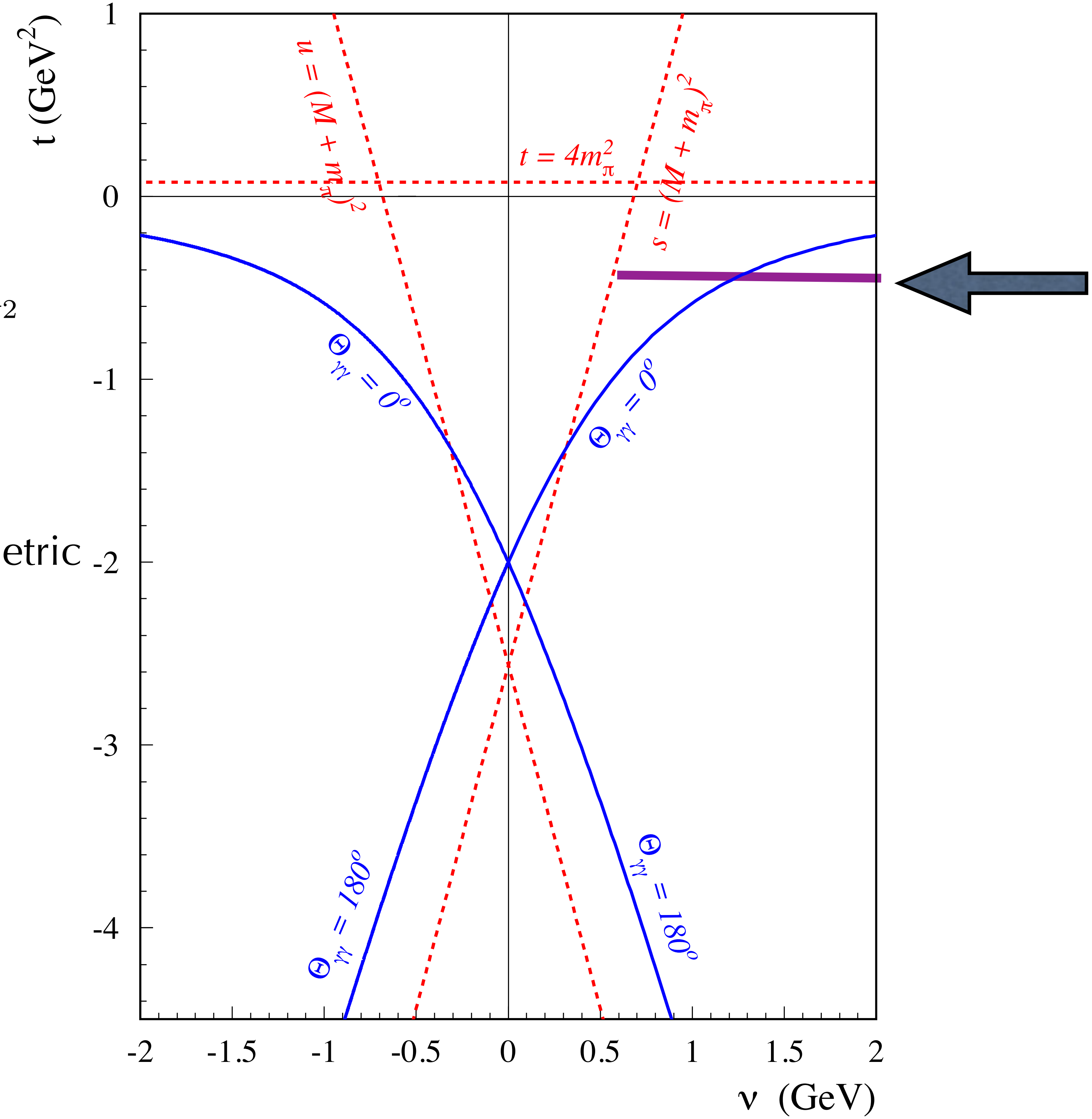


DRs in the s-channel at fixed t

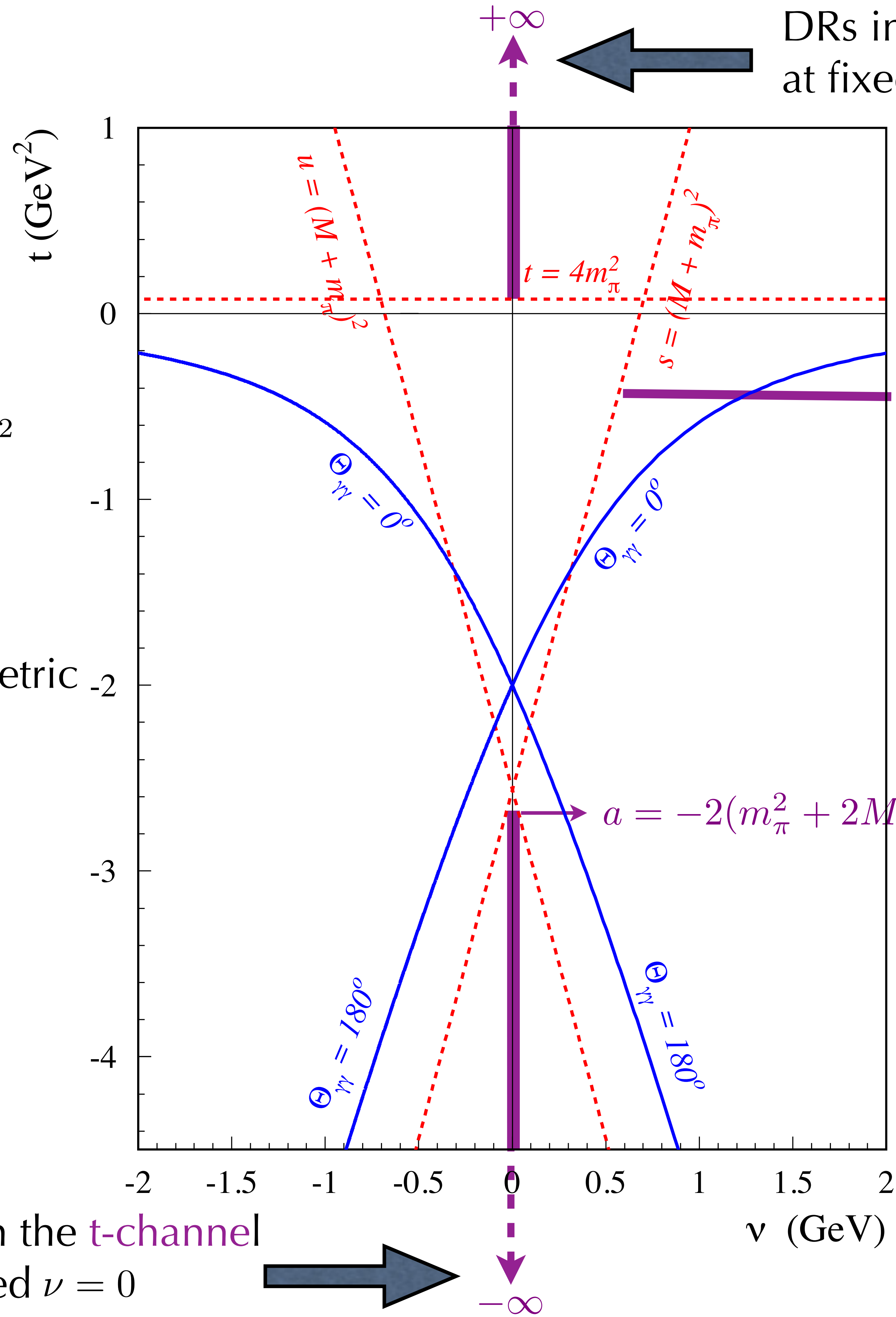
DRs in the t-channel at fixed $\nu = 0$

Fixed

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

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

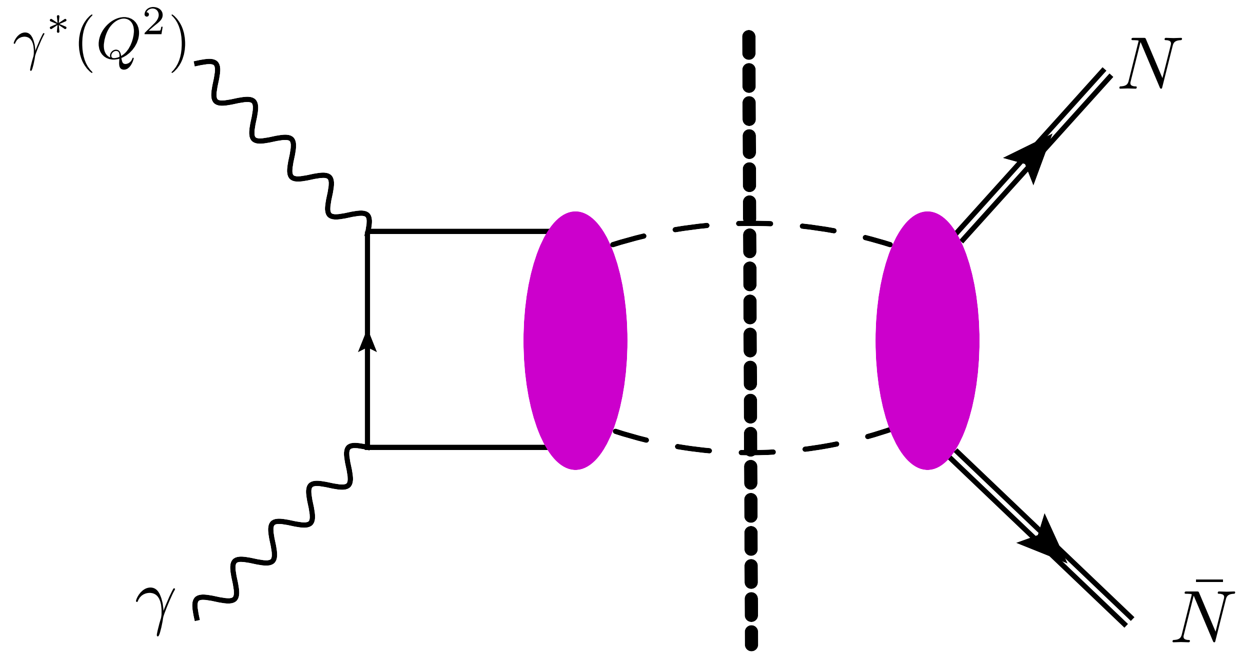
crossing symmetric variable



DRs in the s-channel at fixed t

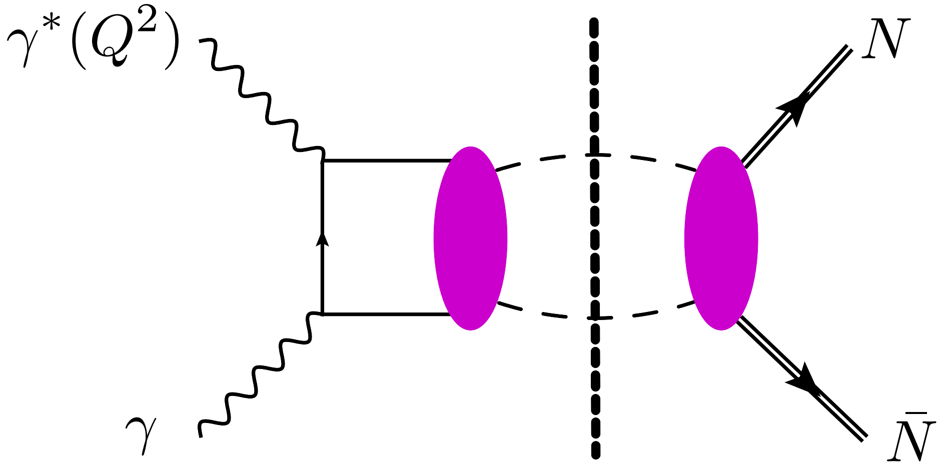
DRs in the t-channel at fixed $\nu = 0$

Unitarity Relations in the t-channel



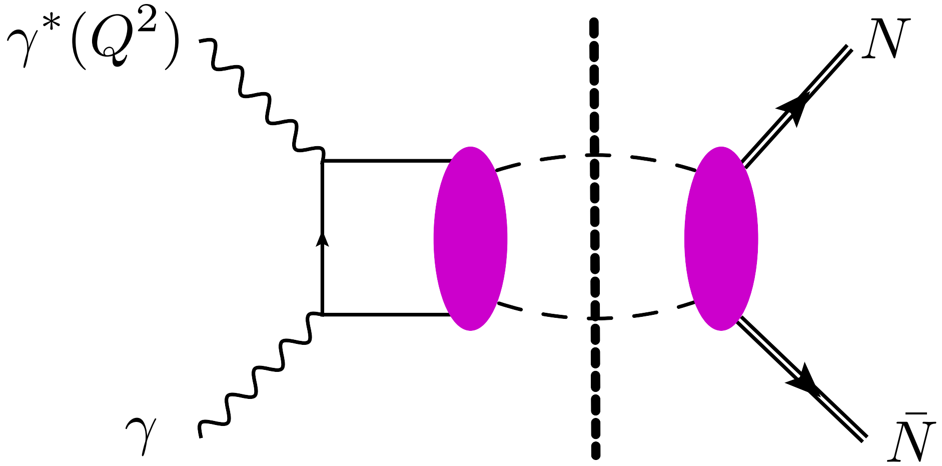
- Charge conjugation
- Partial wave expansion with $\nu = 0 \to \theta_t = 90^o$

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



Two-pion intermediate states with $I = 0$ and $J = 0,\ 2$

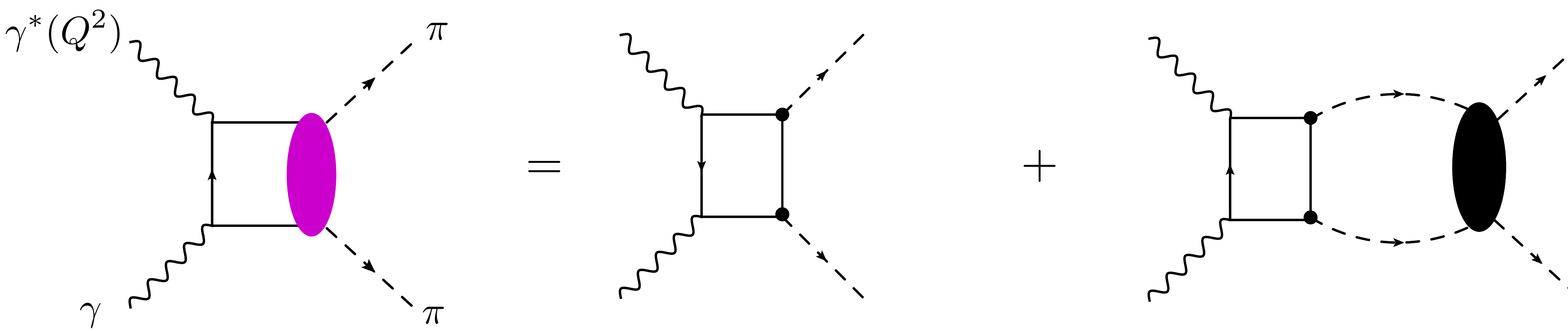
$$D(t) = \sum_{\{n\ odd\}} d_n(t) \longrightarrow \text{DRs for } d_1(t)$$

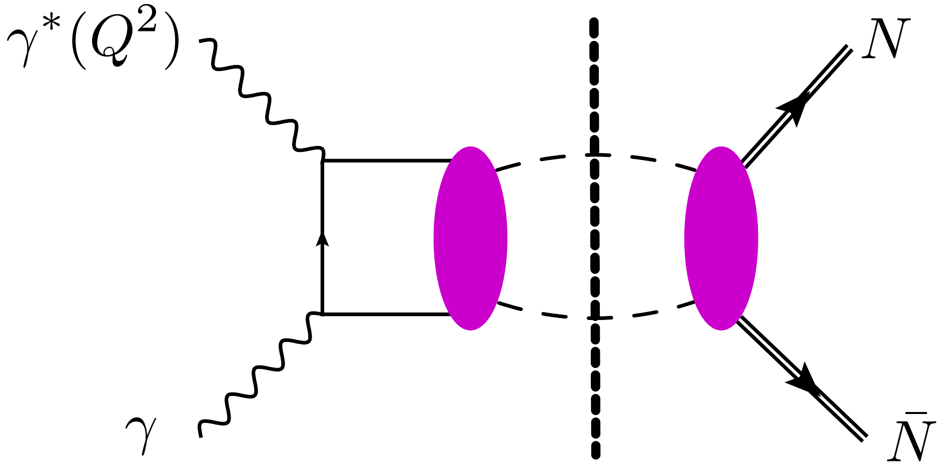


Two-pion intermediate states with $I = 0$ and $J = 0,\, 2$

$$D(t) = \sum_{\{n\, odd\}} d_n(t) \longrightarrow \text{DRs for } d_1(t)$$

- $\gamma^*\gamma \to \pi\pi$: two-pion generalized distribution amplitudes $\longrightarrow$ inputs $\begin{cases} \text{pion singlet PDF} \\ \pi\pi \text{ phase-shifts} \end{cases}$





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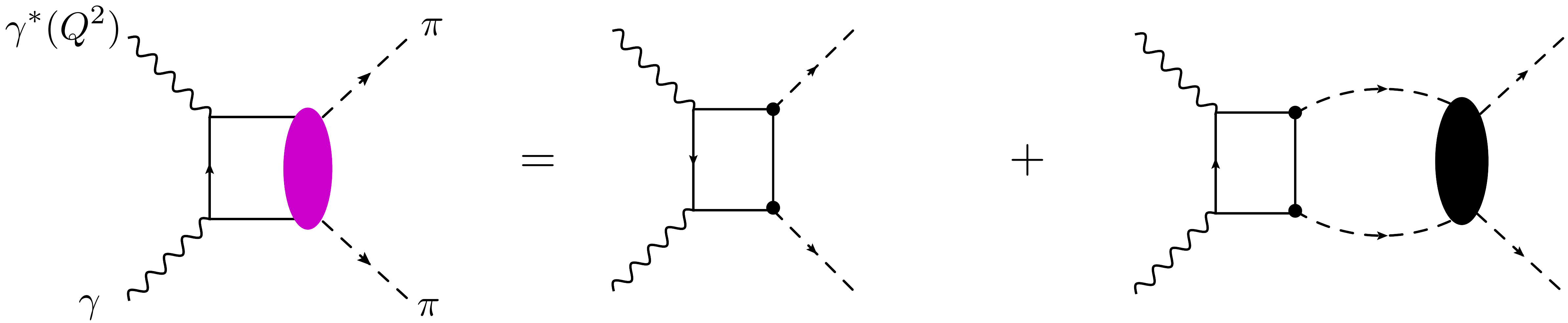
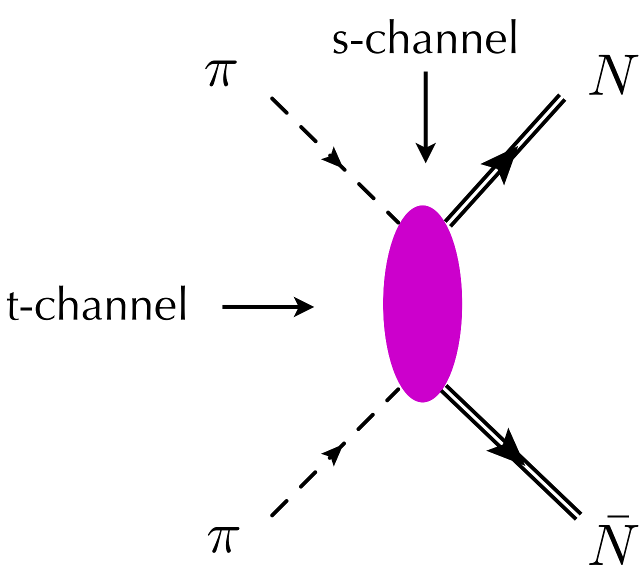


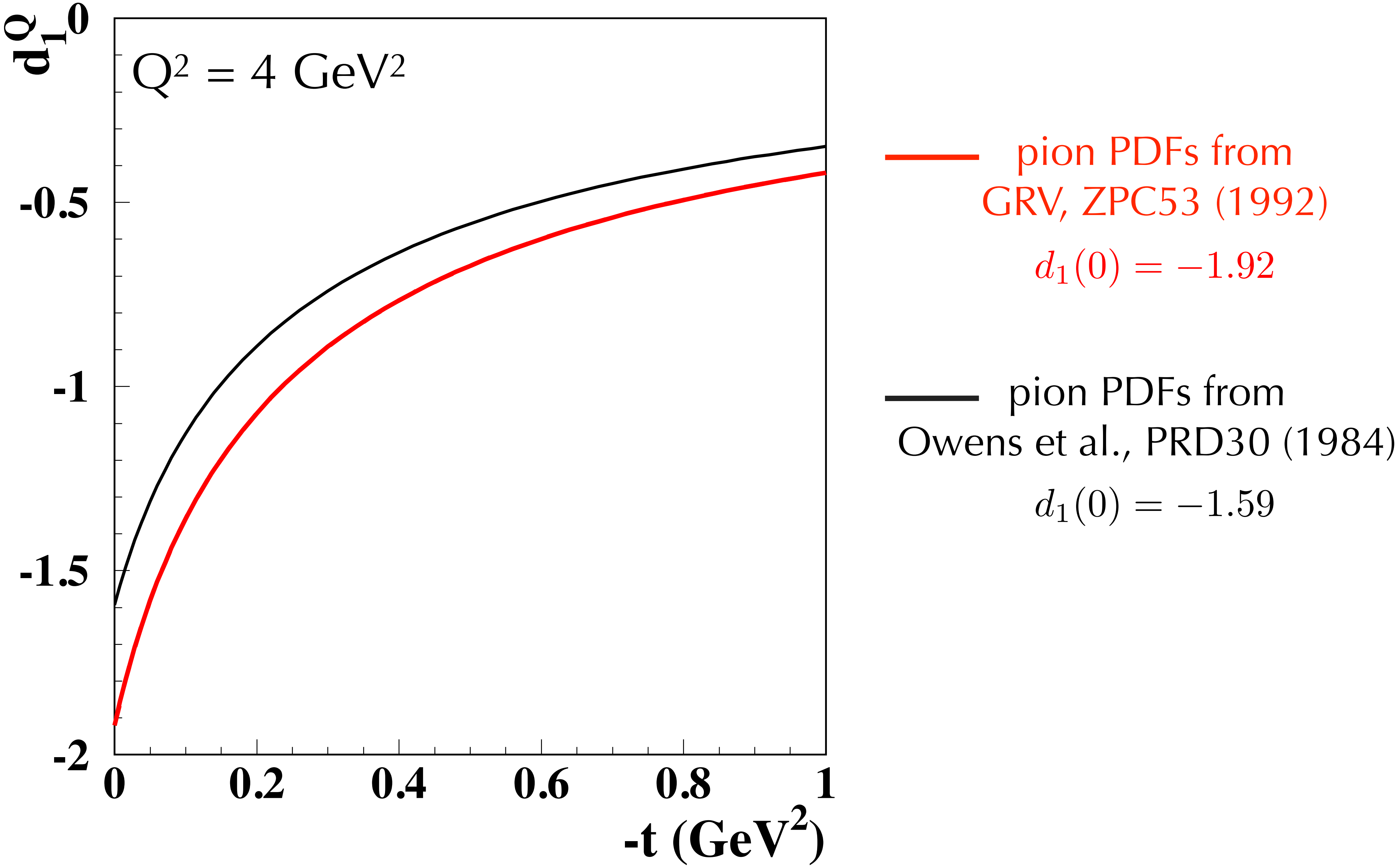
- $\pi\pi \to N\bar{N}$: analytical continuation of s-channel partial-wave helicity amplitudes

$\longrightarrow$ input $\pi\pi$ phase-shifts



DR Results for D-term Form Factor

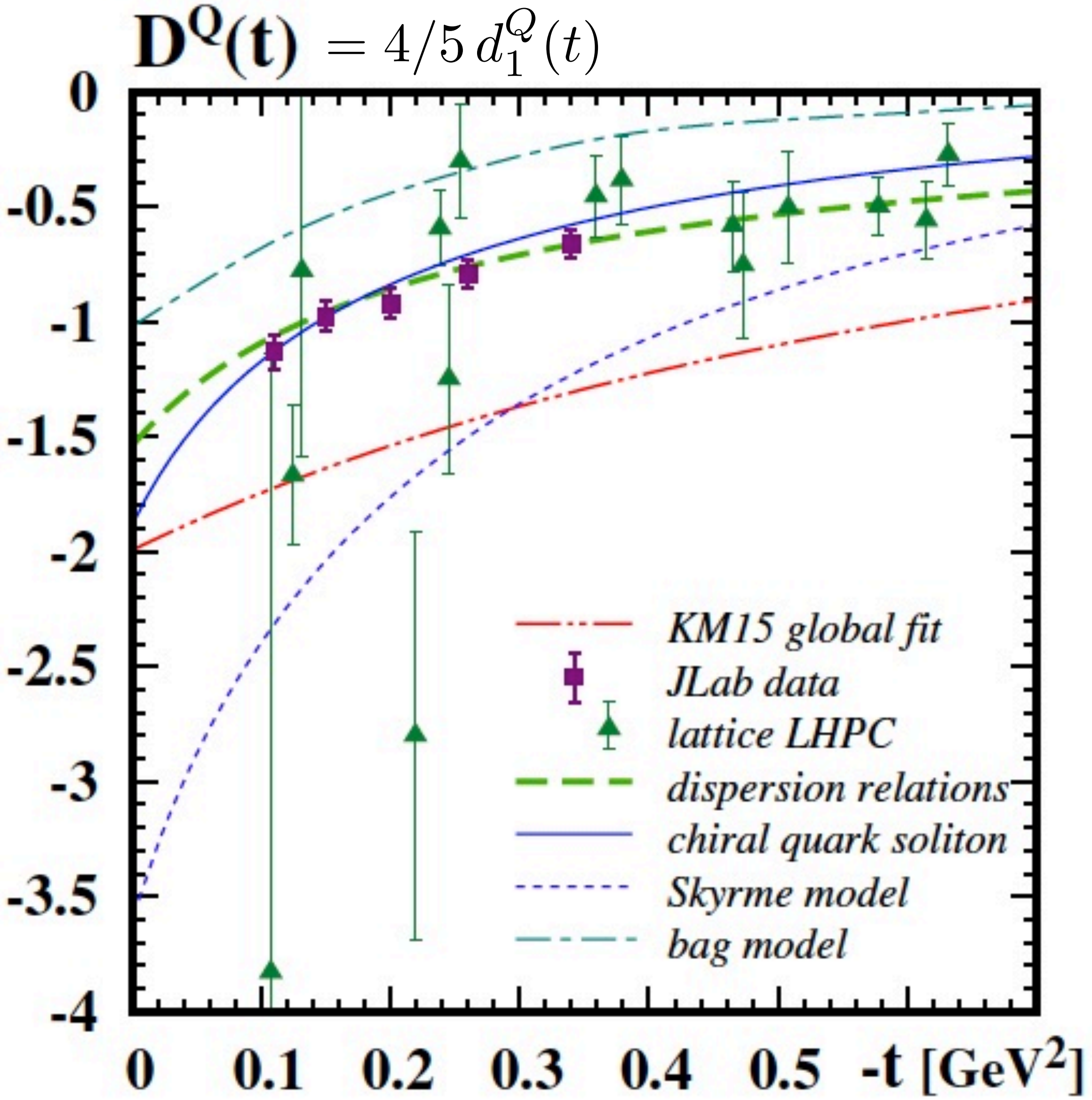
Q= u + d



BP, Polyakov, Vanderhaeghen, PLB 739 (2014) 133

D(t) form factor from data

Girod, Elouadrhiri,Burkert, Nature 557 (2018) 7705
and arXiv: 2104.02031;
CLAS 6GeV data



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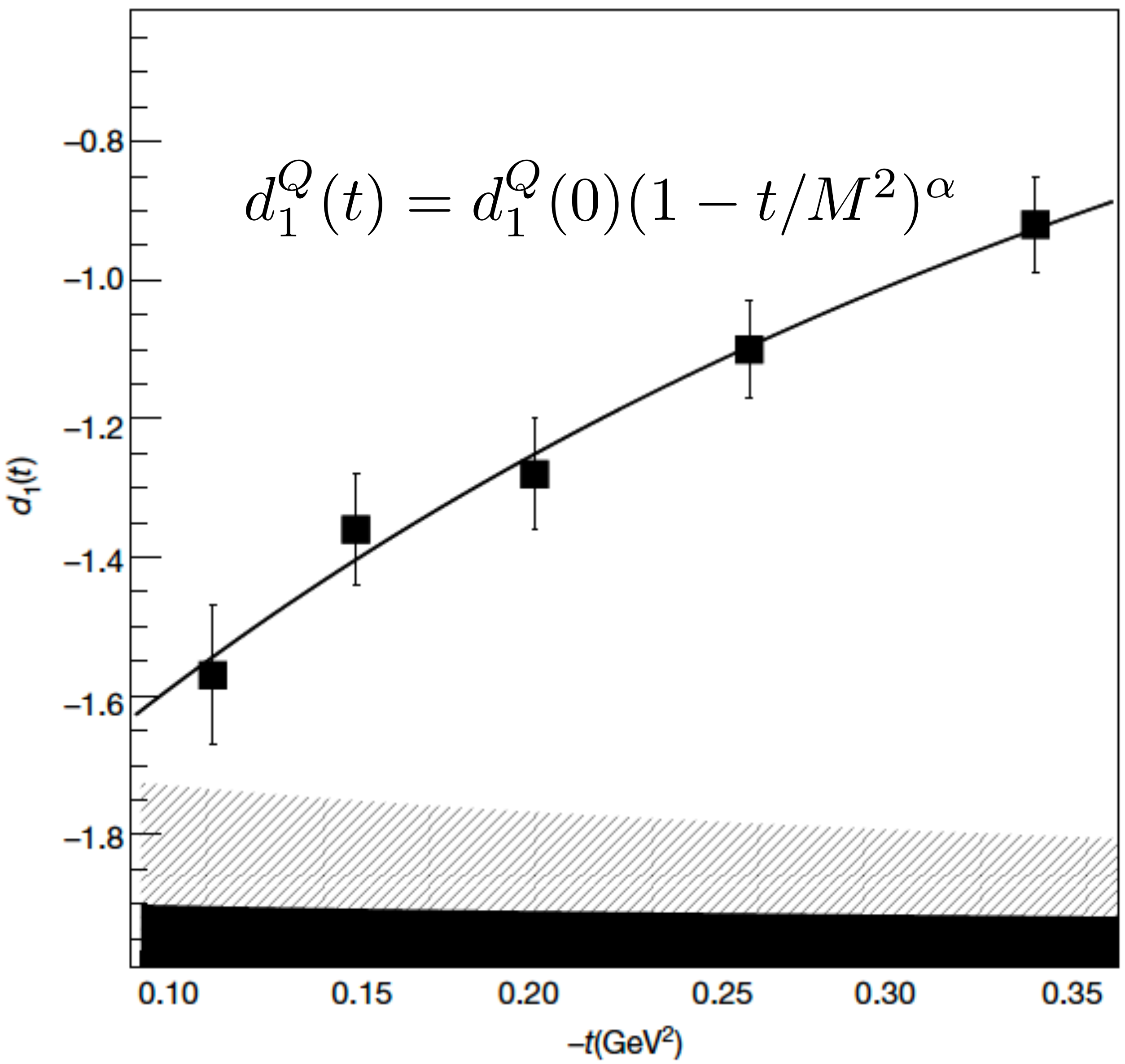

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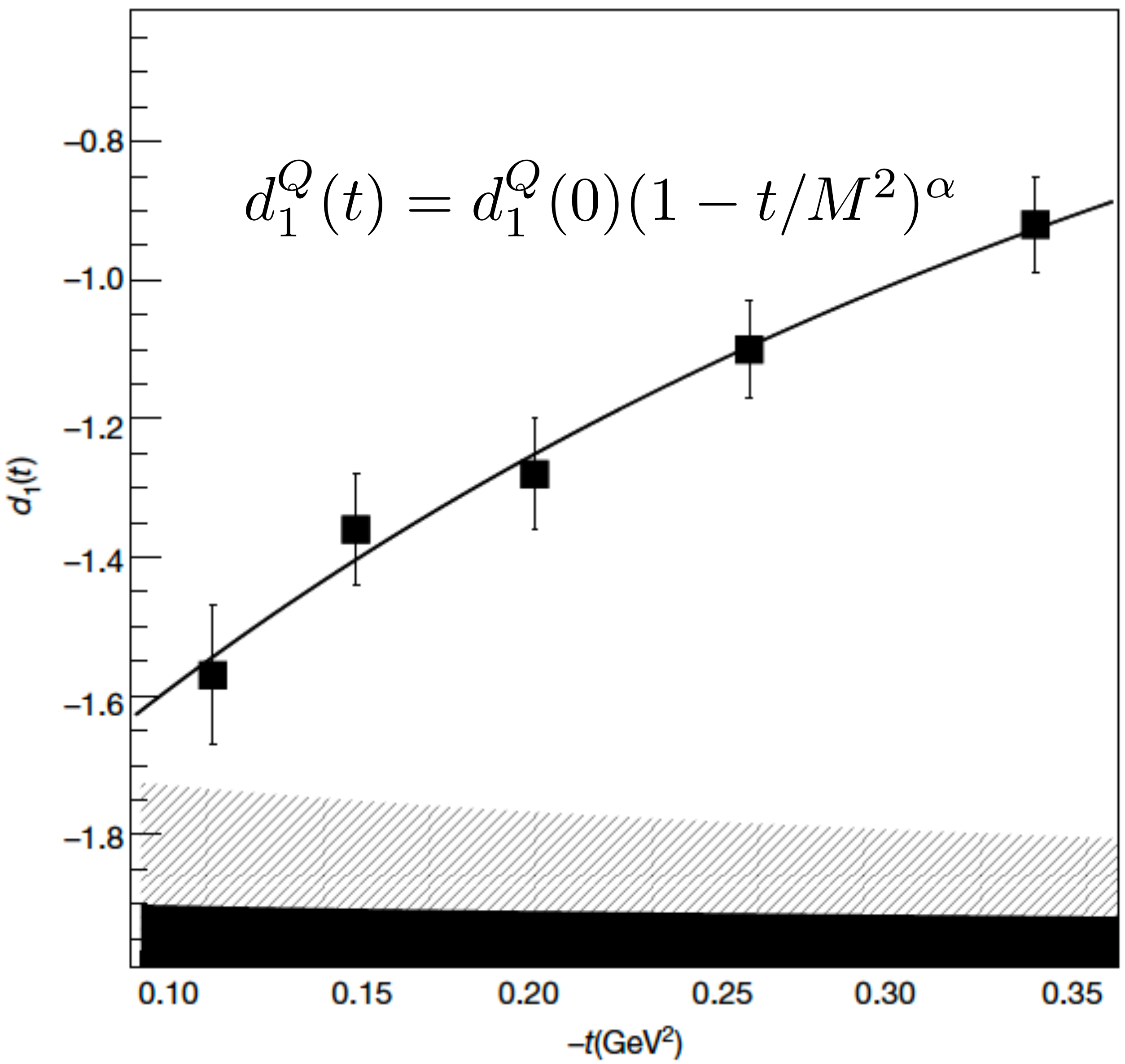
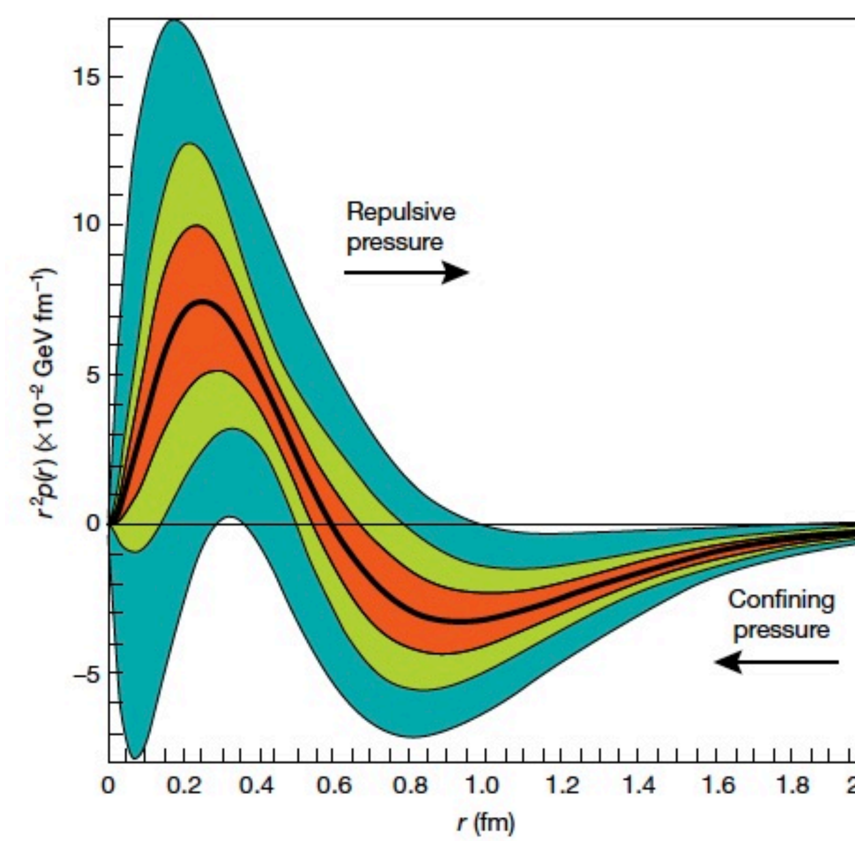
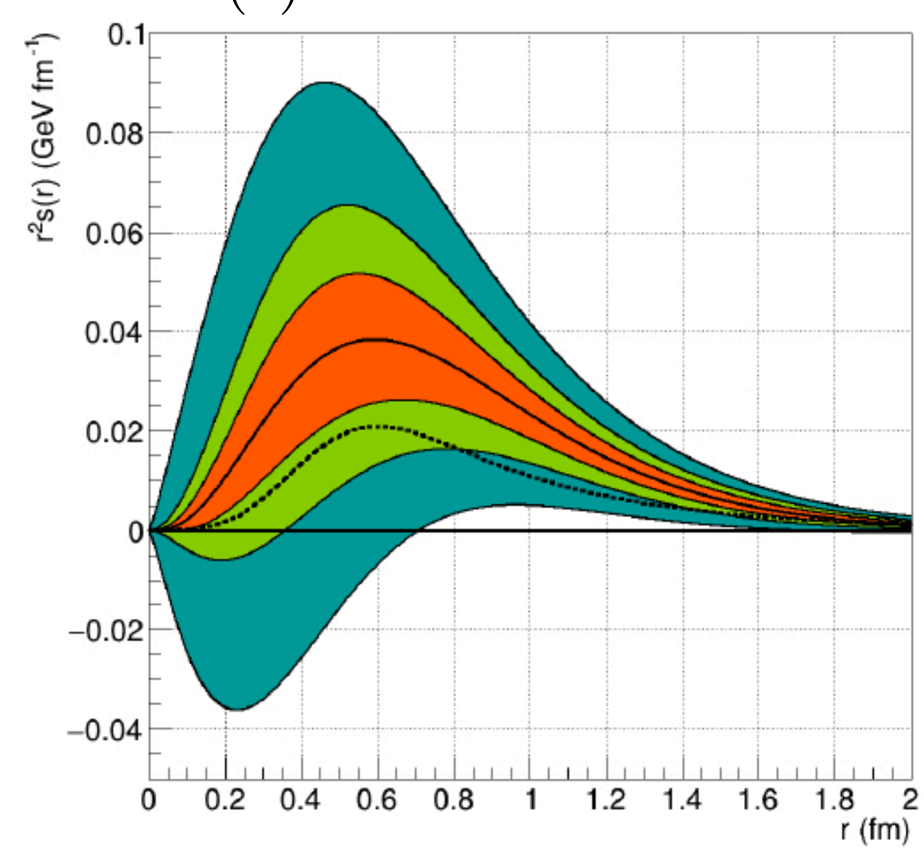


FT

$r^2 p(r)$ radial pressure distribution



$r^2 s(r)$ shear forces distribution

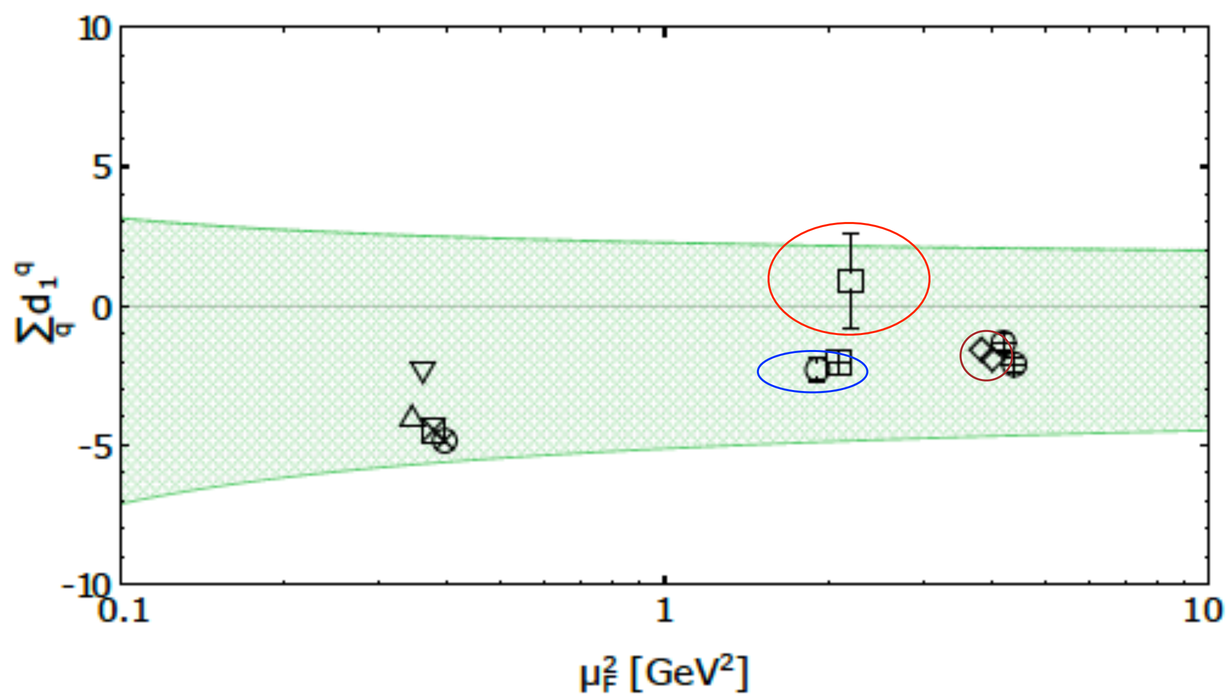


data before 6 GeV JLab
6 GeV JLab data
projected 12 GeV JLab data

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; Dutriex et al, arXiv: 2101.03855

global fit to DVCS data
with artificial neural networks



$\sum_q d_1^q < 0$
in all model calculations
for a stable proton

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

CLAS data, with neural networks Kumericki

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 DRs
	-1.92	4	2	
△	-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 ($\overline{\text{MS}}$)

Dispersion Relations for Compton Scattering

use available information from other channels to constrain nucleon e.m. structure with a minimum of model dependence

Future of Compton Scattering

- Improve accuracy in the extraction of the RCS polarizabilities

  $\longrightarrow$ new upcoming data from MAMI with unprecedented precision

- Constrain the Q^2 dependence of the generalized polarizabilities

  $\longrightarrow$ ongoing analysis of VCS data from JLab

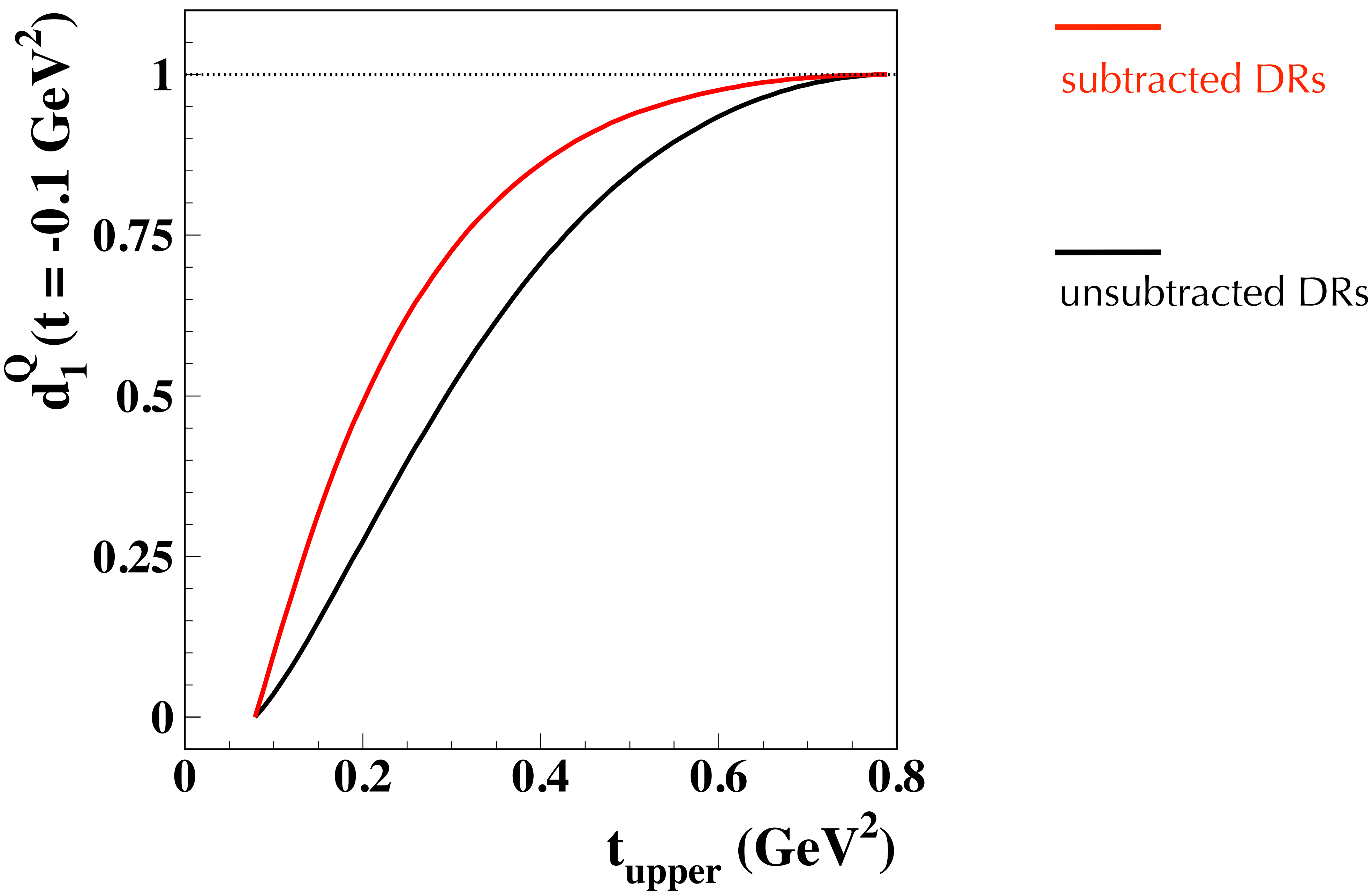
- Big impact on GPD studies from JLab12, COMPASS, and future EIC

- New results for the VVCS polarizabilities from JLab

  $\longrightarrow$ challenge for the theoretical interpretation

Backup Slides

Convergence of DRs

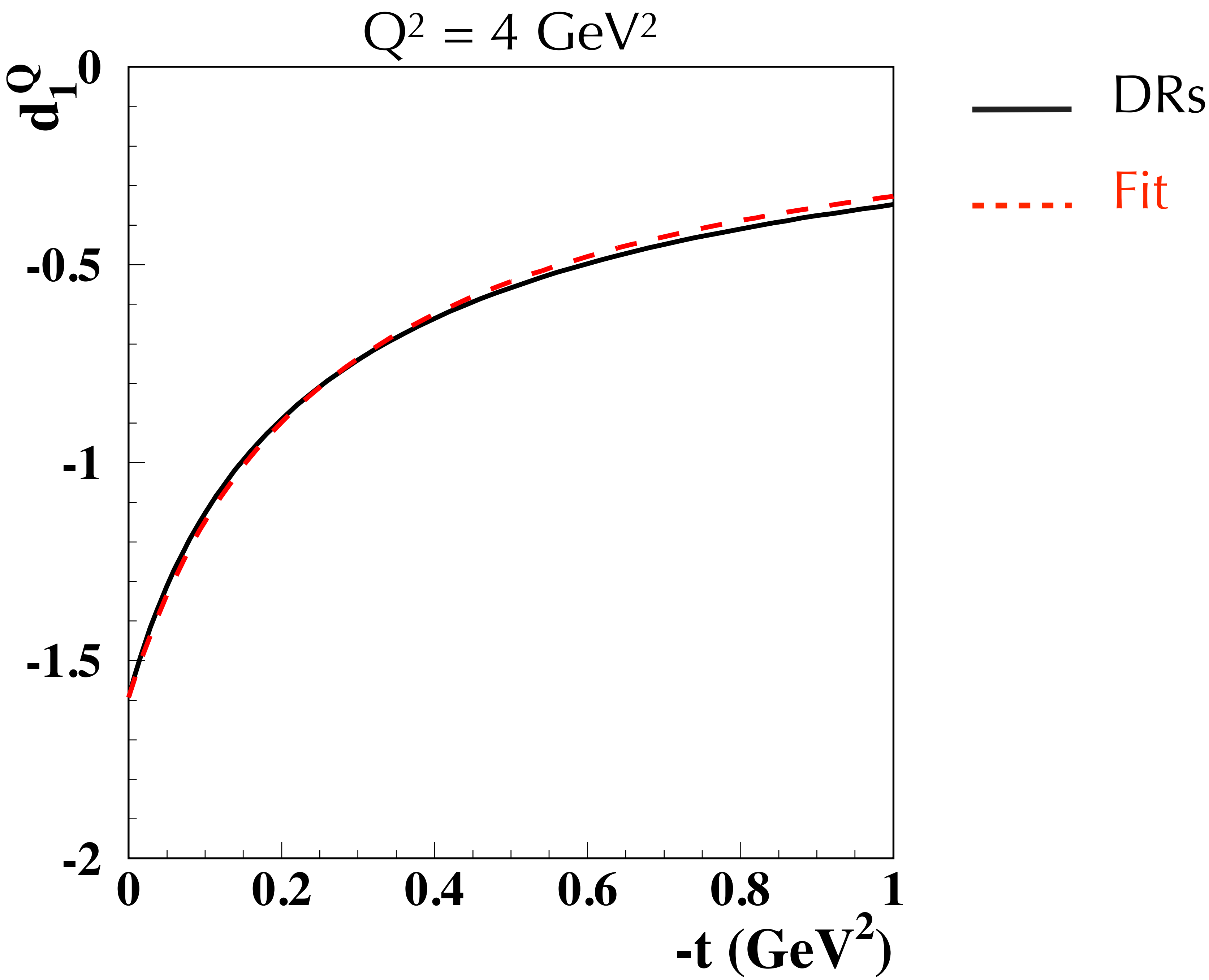


subtracted DRs: $d_1^Q(t) = \quad d_1^Q(0) - \frac{t}{\pi} \int_{4m_\pi^2}^{+\infty} \mathrm{d}t' \, \frac{\mathrm{Im}_t A_2(0,t',Q^2)}{t'(t'-t)}$

subtraction constant to be fitted to data

D-term Form Factor: t-dependence

Q= u + d



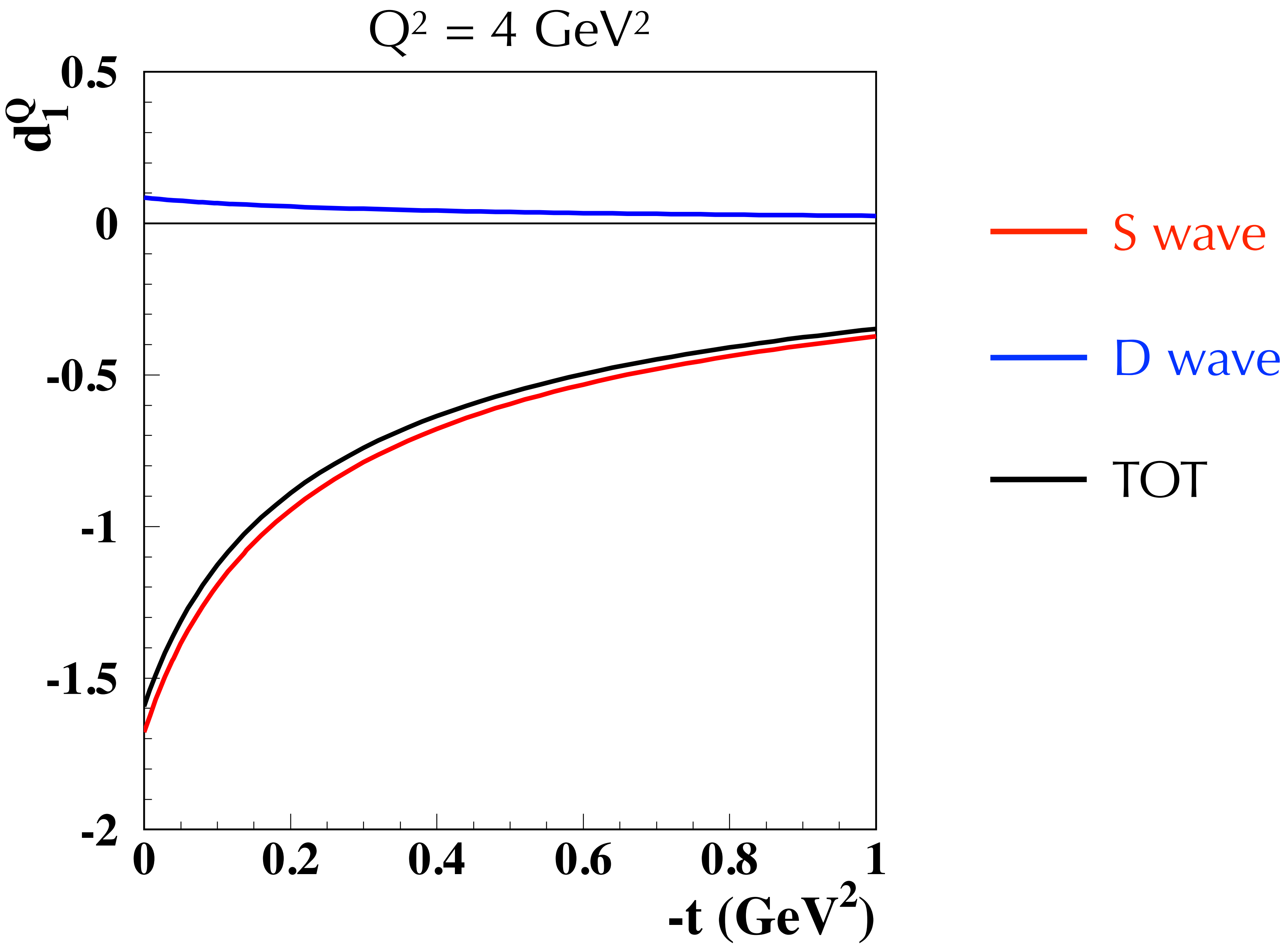
Fit: $F^Q(t) = \dfrac{d_1^Q(0)}{[1 - t/(\alpha M_D^2)]^\alpha}$ with $M_D = 0.487\,\mathrm{GeV}$

$\alpha = 0.841$

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

DR Results for D-term Form Factor

Q= u + d

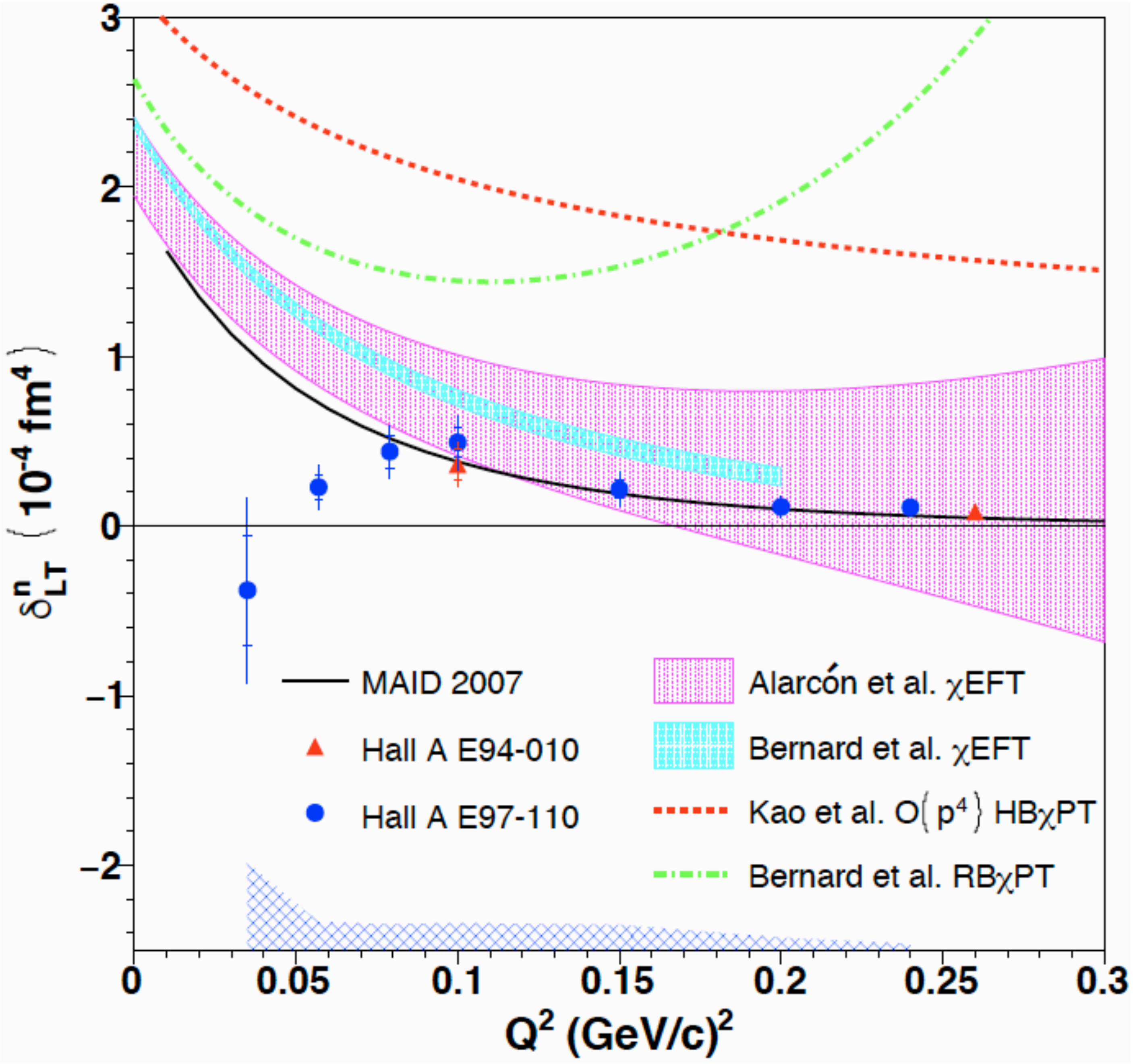


B. Pasquini, M. Polyakov, M. Vanderhaeghen, PLB739 (2014) 133

VVCS Polarizabilities

$$\delta_{LT}(Q^2) = \frac{1}{2\pi^2}\int_{\nu_{thr}}^{\infty} \frac{K(\nu,Q^2)}{\nu}\frac{\sigma_{LT}(\nu,Q^2)}{Q\nu}\mathrm{d}\nu$$

$$= \frac{e^2 4M^2}{\pi Q^6}\int_0^{x_0} x^2[g_1(x,Q^2)+g_2(x,Q^2)]\mathrm{d}x$$



VVCS Polarizabilities

$$\gamma_0(Q^2) = \frac{1}{2\pi^2}\int_{\nu_{thr}}^{\infty} \frac{K(\nu,Q^2)}{\nu}\frac{\sigma_{TT}(\nu,Q^2)}{\nu^3}\mathrm{d}\nu$$

$$= \frac{e^2 4M^2}{\pi Q^6}\int_0^{x_0} x^2[g_1(x,Q^2) - \frac{4M^2}{Q^2}x^2\, g_2(x,Q^2)]\mathrm{d}x$$