Preserving local gauge invariance for single-meson production currents with t-channel Regge exchanges

PRC**92**, 055503 (2015) & PRC**93**, 045204 (2016)

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THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

Collaborators: Xiao-Yun Wang and Jun He (CAS, Lanzhou & Beijing)

. . . or: *How to marry Regge with Feynman*

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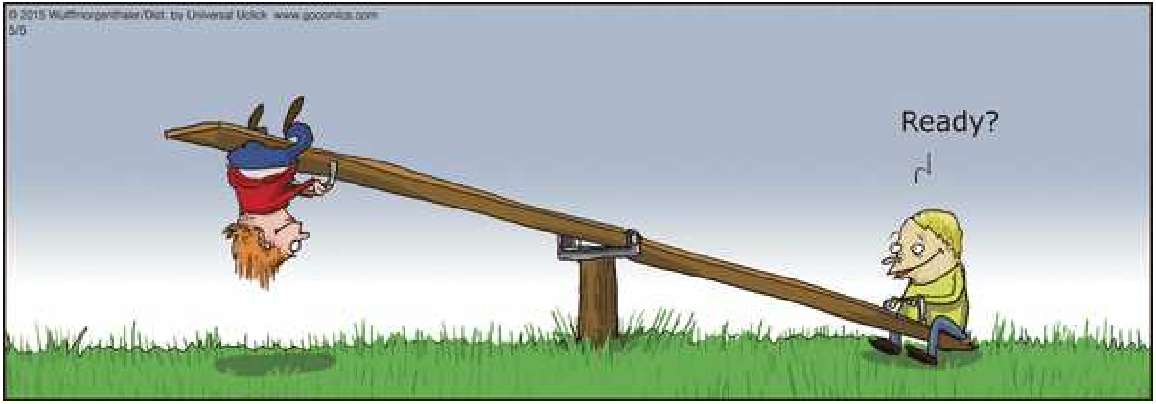
How to marry Regge with Feynman . . .



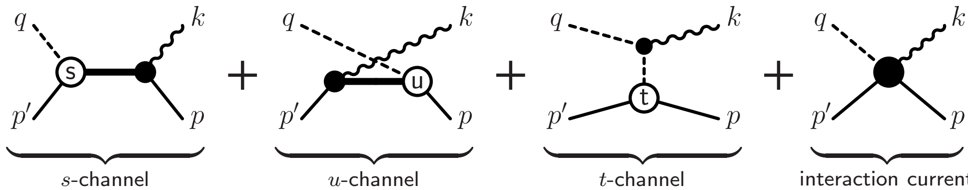
Outline

- Outlining the problem
- Regge-trajectory basics
- How *not* to cure the problem
- The origin of the problem
- Gauge-invariance basics
- Implementation of local gauge invariance
- The cure
- Application: $\gamma + n \to K^+ + \Sigma^*(1385)^-$
- Summary

Outlining the Problem

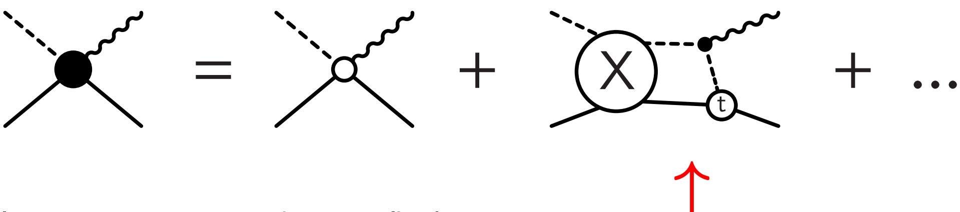
← time —

$M^\mu =$



$$= F_s\, S_i\, J_i^\mu + J_f^\mu\, S_f\, F_u + J_m^\mu\, \Delta_m\, F_t + M_{\text{int}}^\mu$$

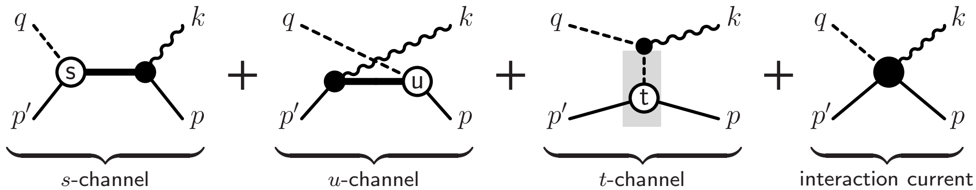
Interaction current:



Interaction current subsumes final-state interaction

Outlining the Problem

$M^\mu =$



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Replace t-channel single-meson exchange by **Regge-trajectory exchange**: $\Delta_m F_t \to \mathcal{P}_m$

Outlining the Problem

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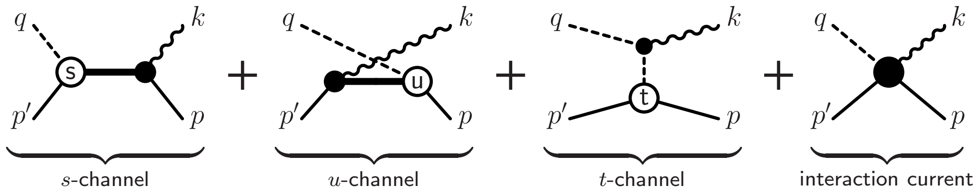

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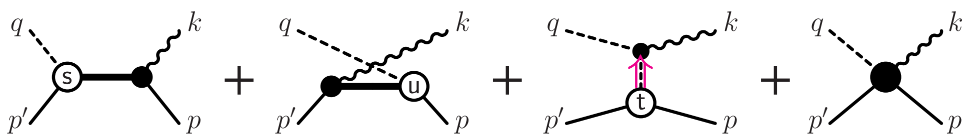
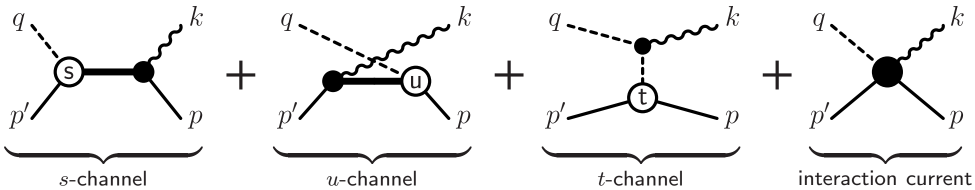


$$= F_s\, S_i\, J_i^\mu + J_f^\mu\, S_f\, F_u + J_m^\mu\, \mathcal{P}_m + M_{\text{int}}^\mu$$

$\mathcal{P}_m$: Regge-trajectory propagator

Outlining the Problem

$M^\mu =$

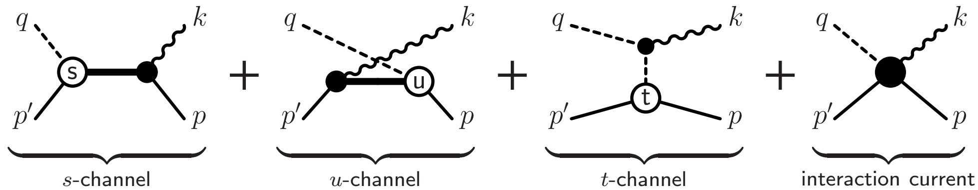


$$k_\mu M^\mu = 0$$

current conserved

$$= F_s \, S_i \, J_i^\mu + J_f^\mu \, S_f \, F_u + J_m^\mu \, \Delta_m \, F_t + M^\mu_{\text{int}}$$

Outlining the Problem

$M^\mu =$  $\qquad k_\mu M^\mu = 0$

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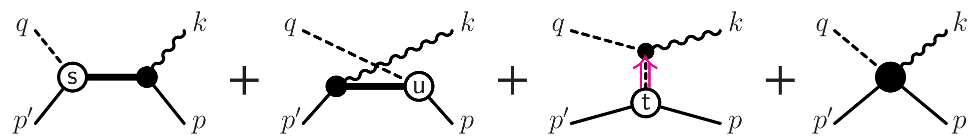
With Reggeized t-channel:

$\mathcal{M}^\mu =$  $\qquad k_\mu \mathcal{M}^\mu \neq 0$

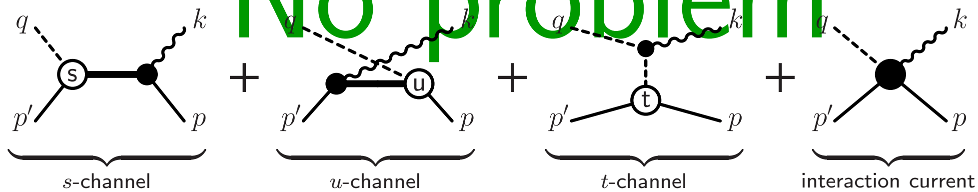
current not conserved

$$= F_s\, S_i\, J_i^\mu + J_f^\mu\, S_f\, F_u + J_m^\mu\, \mathcal{P}_m + M_{\text{int}}^\mu$$

Outlining the Problem

No problem

$M^\mu =$



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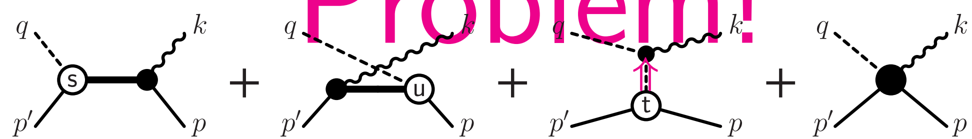
$$= F_s S_i J_i^\mu + J_f^\mu S_f F_u + J_m^\mu \Delta_m F_t + M_{\text{int}}^\mu$$

With Reggeized t-channel:

Problem!

$\mathcal{M}^\mu =$



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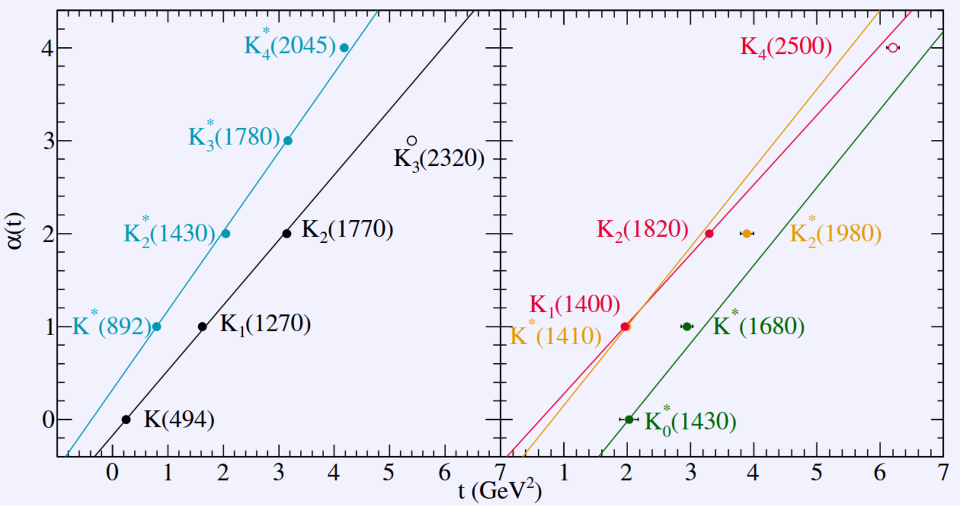
Let's recap Regge . . .

Regge trajectories

Graph stolen from P. Vancraeyveld, PhD Thesis, U. Gent, 2011



Trajectories:

pseudoscalar:

$$\alpha_+(t) = \alpha_0(t) \;, \qquad \alpha_0(t) = \alpha_0' \,(t - M_0^2)$$

vector:

$$\alpha_-(t) = 1 + \alpha_1(t) \;, \qquad \alpha_1(t) = \alpha_1' \,(t - M_1^2)$$

Regge exchange for t-channel:

$m = 0, 1$

$$\Delta_m F_t \to \mathcal{P}_m(t) = \frac{1}{t - M_m^2} \mathcal{F}_m(t) \;,$$

$$\mathcal{F}_m(t) = \left(\frac{s}{s_{\rm sc}}\right)^{\alpha_m(t)} \frac{N[\alpha_m(t);\eta]}{\Gamma\big(1+\alpha_m(t)\big)} \frac{\pi\alpha_m(t)}{\sin\big(\pi\alpha_m(t)\big)}$$

residual Regge function

$s_{\rm sc} = 1\ {\rm GeV}^2$

Regge trajectories

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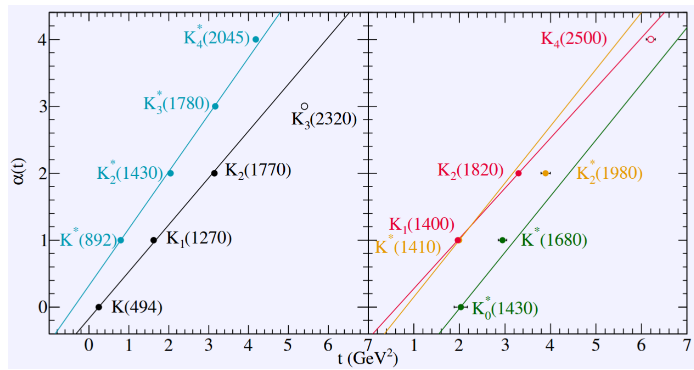
residual Regge function

$s_{\rm sc} = 1\ {\rm GeV}^2$

Signature function:

$$N[\alpha_m(t);\eta] = \eta + (1-\eta)e^{-i\pi\alpha_m(t)}$$

$$\eta = \begin{cases} \frac{1}{2}\ , & \text{pure-signature trajectory} \\ 0\ , & \text{add trajectories: rotating phase} \\ 1\ , & \text{subtract trajectories: constant phase} \end{cases}$$



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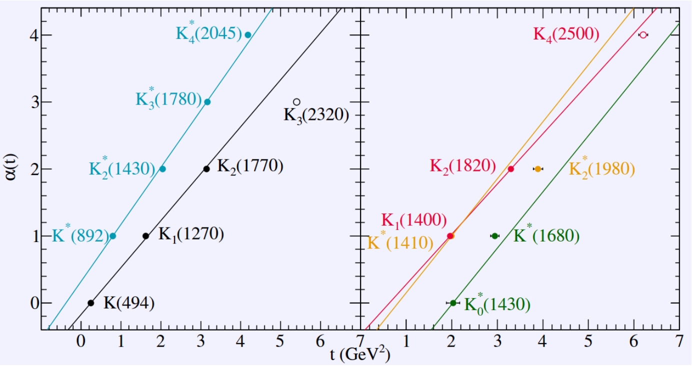


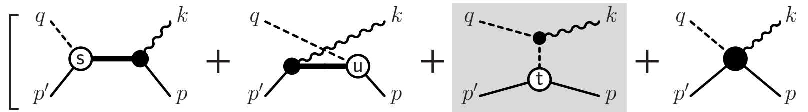
Normalization: $\mathcal{F}_m(M_m^2) = 1$

independent of η

GLV Recipe

Recipe: Take gauge-invariant amplitude M^μ and multiply by *residual function* $\mathcal{F}_m(t)$

$$M^\mu_{\rm GLV} = M^\mu \times \mathcal{F}_m = $$



$$\times \mathcal{F}_m(t)$$

t-channel okay

$$k_\mu M^\mu_{\rm GLV} = \underbrace{[k_\mu M^\mu]}_{=0} \times \mathcal{F}_m = 0$$

GLV Recipe

Guidal, Laget, Vanderhaeghen, NPA 627, 645 (1997)

Recipe: Take gauge-invariant amplitude M^μ and multiply by *residual function* $\mathcal{F}_m(t)$

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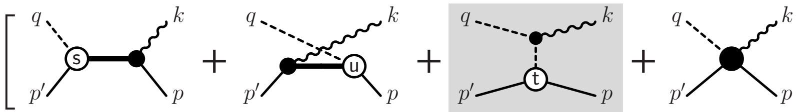

t-channel okay

$$k_\mu M^\mu_{\mathrm{GLV}} = \underbrace{\left[k_\mu M^\mu\right]}_{=0} \times \mathcal{F}_m = 0$$

- Very popular
- Quite successful in providing good descriptions of data for many applications

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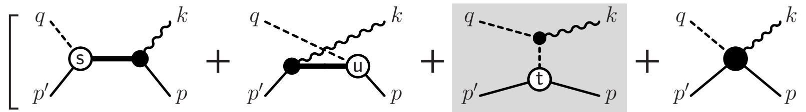

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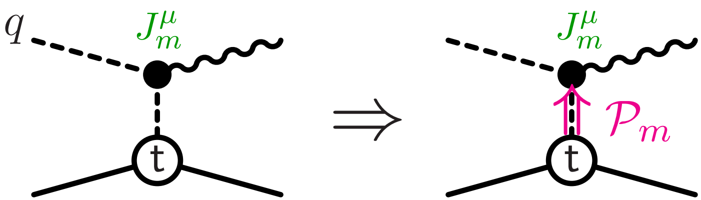
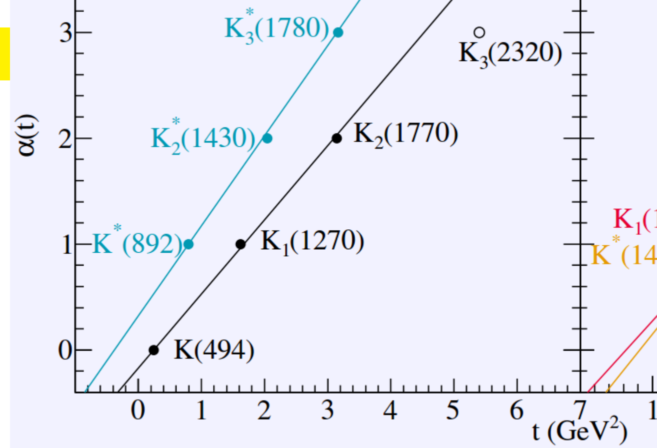
- Very popular
- Quite successful in providing good descriptions of data for many applications
- **Without any dynamical foundation**

Cannot be obtained from field theory in *any* approximation

Origin of Problem

Reason #1:





Every state in the Regge trajectory appears with same current.

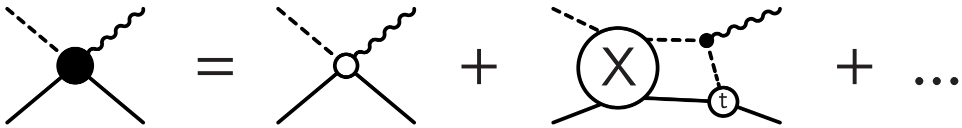
Ward-Takahashi identity:

$$k_\mu J^{\mu}_{m} = (q^2 - M_0^2)Q_m - Q_m(t - M_0^2)$$

$\Rightarrow$ Violates Ward-Takahashi identity for intermediate higher-mass states

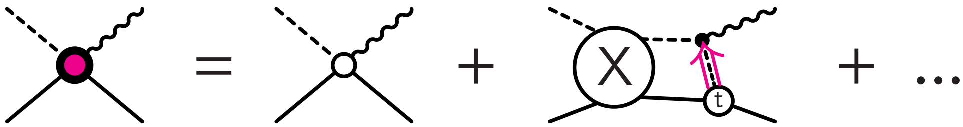
Origin of Problem

Reason #2:



t-Channel exchanges inside interaction current not Reggeized.

Needed: Consistent treatment

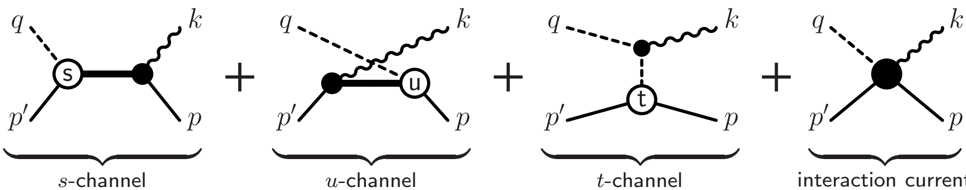


$\Longrightarrow$ Interaction-current contribution must be Reggeized as well

Gauge-invariance recap . . .

Gauge Invariance

$M^\mu =$



$$= F_s\, S_i\, J_i^\mu + J_f^\mu\, S_f\, F_u + J_m^\mu\, \Delta_m\, F_t + M_{\text{int}}^\mu$$

Global gauge invariance

$$k_\mu M^\mu = 0$$

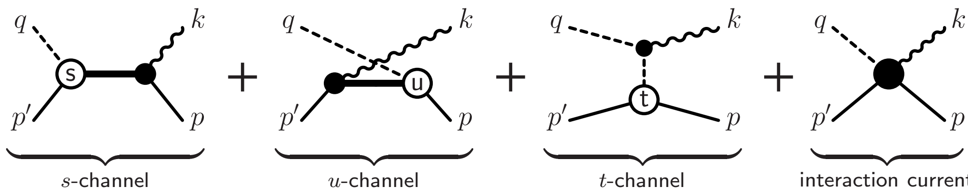
all external hadrons on-shell

$\Phi \to \Phi\, \mathrm{e}^{-i\Lambda}$

conserved current $\Rightarrow$ implies charge conservation

Gauge Invariance

$$M^\mu =$$



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Global gauge invariance $\quad k_\mu M^\mu = 0 \quad$ all external hadrons on-shell

$\Phi \to \Phi\, e^{-i\Lambda}$

conserved current $\Rightarrow$ implies charge conservation

Fixing global gauge invariance does not mean internal damage is fixed as well

Gauge Invariance

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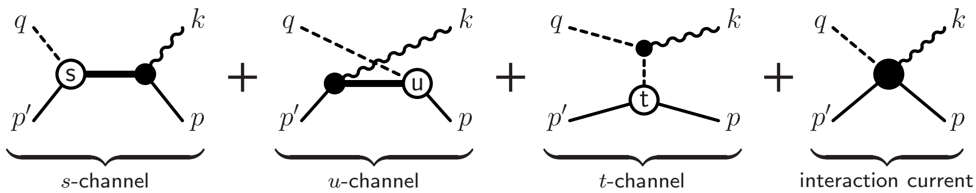

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Local gauge invariance

$$\Phi \to \Phi\, e^{-i\lambda(x)}$$

Generalized Ward-Takahashi identities (gWTI)

$$k_\mu M^\mu = (q^2 - M_m^2) Q_m\, F_t + S_f^{-1}(p') Q_f F_u - F_s Q_i S_i^{-1}(p)$$

$$k_\mu J_m^\mu = (q^2 - M_m^2) Q_m - Q_m (t - M_m^2)$$

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off-shell relations

Gauge Invariance

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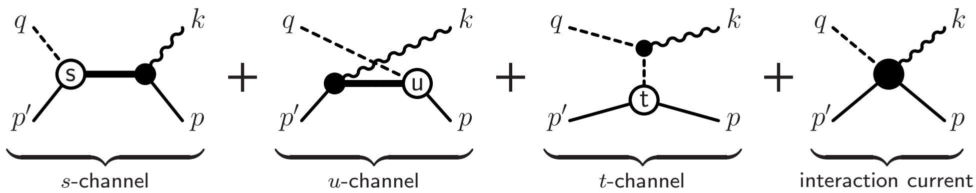

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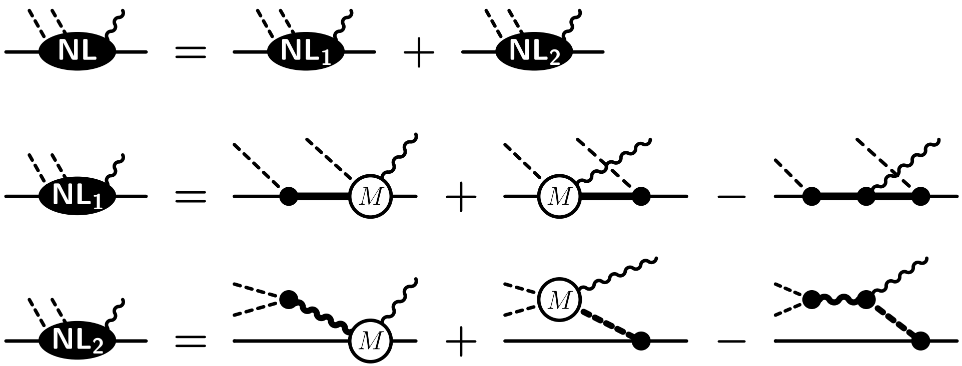
off-shell relations

local gauge invariance $\Rightarrow$ implies existence of e.m. field

Without gWTI underlying e.m. field is damaged

Example: Two-pion production at the no-loop level



Practical Relevance of Local Gauge Invariance

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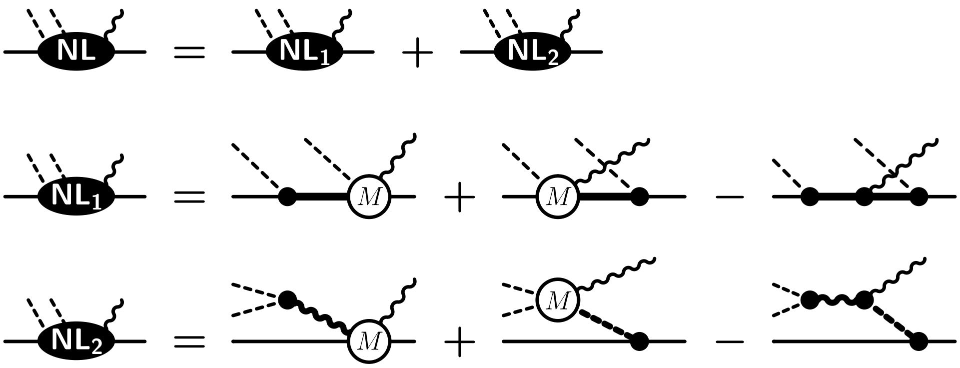

Without gWTI, this amplitude will not be gauge invariant

Generalized Ward-Takahashi Identities

$$(1) \qquad k_\mu M^\mu = (q^2 - M_m^2) Q_m F_t + S_f^{-1}(p') Q_f F_u - F_s Q_i S_i^{-1}(p)$$

$$(2) \qquad k_\mu J_m^\mu = (q^2 - M_m^2) Q_m - Q_m (t - M_m^2) \qquad \text{trivial}$$

$$(3) \qquad k_\mu M_{\text{int}}^\mu = Q_m F_t + Q_f F_u - F_s Q_i$$

Only two relations are independent $\Rightarrow$ Use (2) & (3)

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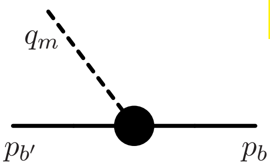

Hadronic vertex

$$F(p_{b'}, p_b) = \boldsymbol{G}(q_m)\, \boldsymbol{\tau}\, f(q_m^2, p_{b'}^2, p_b^2)$$

$$\begin{cases} f_s(s) = f(M_m^2, M_{b'}^2, s) \\ f_u(u) = f(M_m^2, u, M_b^2) \\ f_t(t) = f(t, M_{b'}^2, M_b^2) \end{cases}$$

Interaction-current Ansatz:

$$\boxed{M_{\text{int}}^\mu = m_c^\mu\, f_t(t) + \boldsymbol{G}(q) C^\mu + T_{\text{int}}^\mu} \qquad k_\mu T_{\text{int}}^\mu \equiv 0$$

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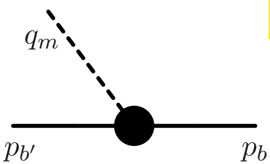

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$\Rightarrow$ Determine C^μ such that (3) is true

Auxiliary Contact Current C^μ

HH, Nakayama, Krewald, PRC74, 045202 (2006)

See also: HH, Wang, He, PRC92, 055503 (2015)

Non-singular

$$C^\mu = -e_m(2q-k)^\mu \frac{f_t - 1}{t - M_m^2}\left(\delta_s f_s + \delta_u f_u - \delta_s\delta_u f_s f_u\right)$$

$$- e_f(2p'-k)^\mu \frac{f_u - 1}{u - M_f^2}\left(\delta_t f_t + \delta_s f_s - \delta_t\delta_s f_t f_s\right)$$

$$- e_i(2p+k)^\mu \frac{f_s - 1}{s - M_i^2}\left(\delta_u f_u + \delta_t f_t - \delta_u\delta_t f_u f_t\right)$$

where

$$\delta_x = \begin{cases} 1 & \text{channel contributes} \\ 0 & \text{channel does not contribute} \end{cases} \qquad x = s, u, t$$

Charge conservation: $Q_m\boldsymbol{\tau} + Q_f\boldsymbol{\tau} - \boldsymbol{\tau}Q_i = e_m + e_f - e_i = 0$

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where

$$\delta_x = \begin{cases} 1 & \text{channel contributes} \\ 0 & \text{channel does not contribute} \end{cases} \qquad x = s, u, t$$

Charge conservation: $$Q_m\boldsymbol{\tau} + Q_f\boldsymbol{\tau} - \boldsymbol{\tau}Q_i = e_m + e_f - e_i = 0$$

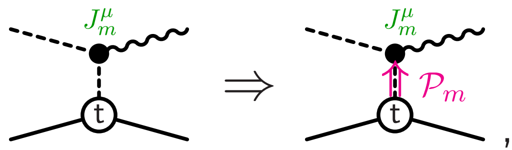
Four-divergence: $$k_\mu C^\mu = e_m f_t + e_f f_u - e_i f_s$$

ensures correct four-divergence for M^μ_{int}

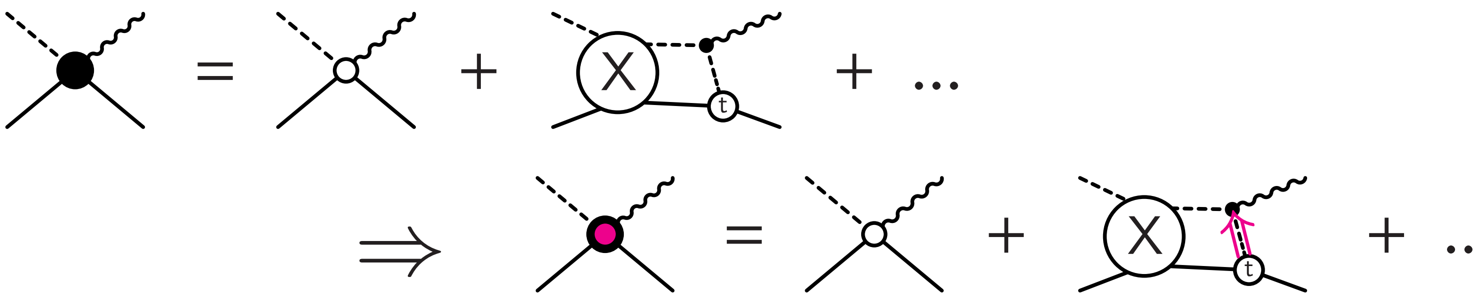
Back to Regge . . .

Reggeizing Final-state Interaction

Reggeize both t-channnel,



and FSI contribution,



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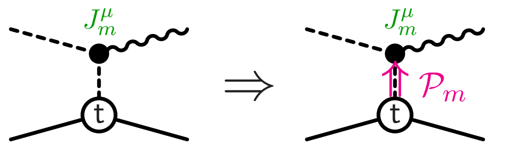

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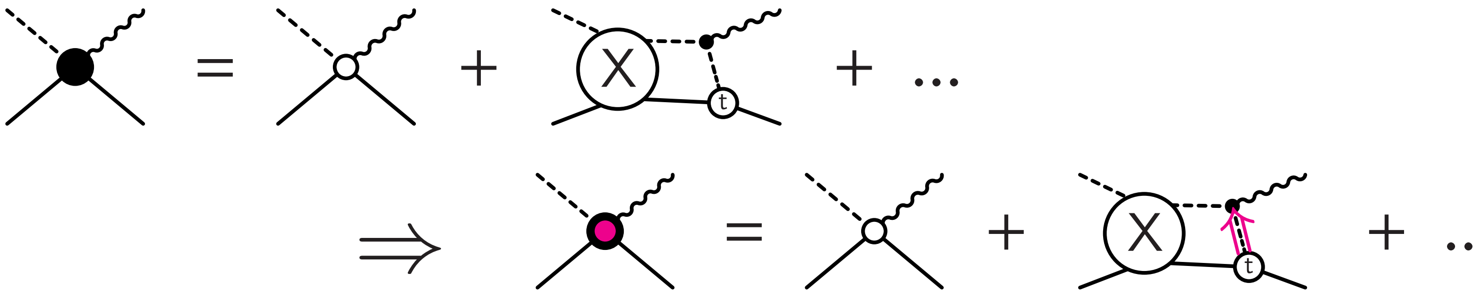
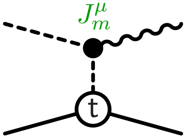


Not necessary to calculate FSI loops $\Rightarrow$ modify C^μ instead

Reggeizing t-Channel

Before Reggeization

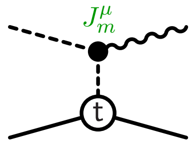
$$J_m^\mu \frac{\boldsymbol{G\tau}}{t - M_m^2} f_t =$$



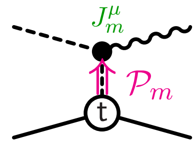
Reggeizing t-Channel

Before Reggeization **After Reggeization**

$$J_m^\mu \frac{\boldsymbol{G\tau}}{t - M_m^2} f_t =$$



$$\Rightarrow$$



$$= J_m^\mu \frac{\boldsymbol{G\tau}}{t - M_m^2} \mathcal{F}_t$$

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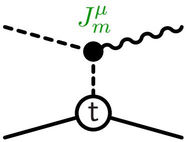

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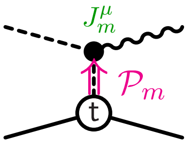

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Reggeization corresponds to an effective prescription for hadronic form factor

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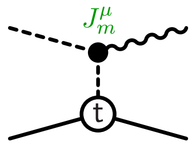
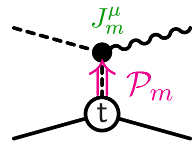


$$\Rightarrow$$



$$= J_m^\mu \frac{\boldsymbol{G\tau}}{t - M_m^2} \mathcal{F}_t$$

Reggeization corresponds to an effective prescription for hadronic form factor

To preserve local gauge invariance,
replace f_t by Regge residual function $\mathcal{F}_t$ everywhere

The Cure: Modified Auxiliary Contact Current $\mathcal{C}^\mu$

$$\boxed{\mathcal{M}^\mu_{\text{int}} = m^\mu_c\,\mathcal{F}_t + \boldsymbol{G}(q)\mathcal{C}^\mu + T^\mu_{\text{int}}}$$

$$k_\mu T^\mu_{\text{int}} \equiv 0$$

Non-singular

$$\begin{aligned}
\mathcal{C}^\mu = &-e_m(2q-k)^\mu \frac{\mathcal{F}_t - 1}{t - M_m^2}\left(\delta_s f_s + \delta_u f_u - \delta_s\delta_u f_s f_u\right) \\
&- e_f(2p'-k)^\mu \frac{f_u - 1}{u - M_f^2}\left(\delta_t \mathcal{F}_t + \delta_s f_s - \delta_t\delta_s \mathcal{F}_t f_s\right) \\
&- e_i(2p+k)^\mu \frac{f_s - 1}{s - M_i^2}\left(\delta_u f_u + \delta_t \mathcal{F}_t - \delta_u\delta_t f_u \mathcal{F}_t\right)
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\end{aligned}$$

Provides correct generalized Ward-Takahashi identity:

$$k_\mu \mathcal{M}^\mu = (q^2 - M_m^2) Q_m \hat{\mathcal{F}}_t + S_f^{-1}(p') Q_f F_u - F_s Q_i S_i^{-1}(p)$$

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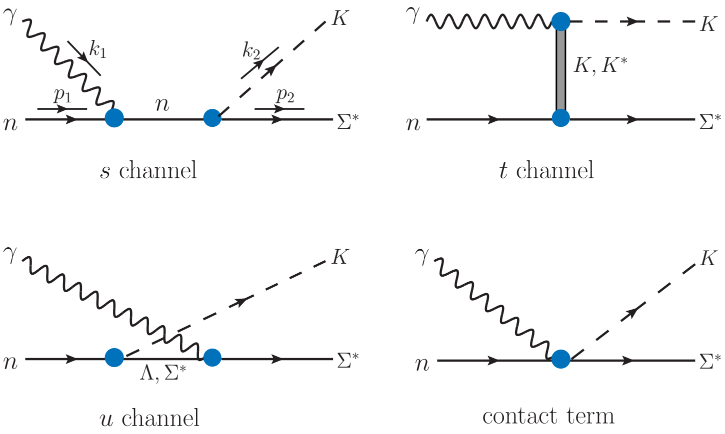
$\Rightarrow$ **Production current locally gauge invariant**

Application: $\gamma + n \to K^+ + \Sigma^*(1385)^-$ Wang, He, HH, PRC93, 045204 (2016)



Compared with data from
CLAS: P. Mattione (CLAS Collaboration),
Int. J. Phys. Conf. Series **26**, 1460101, (2014);
LEPS: K. Hicks et al. (LEPS Collaboration),
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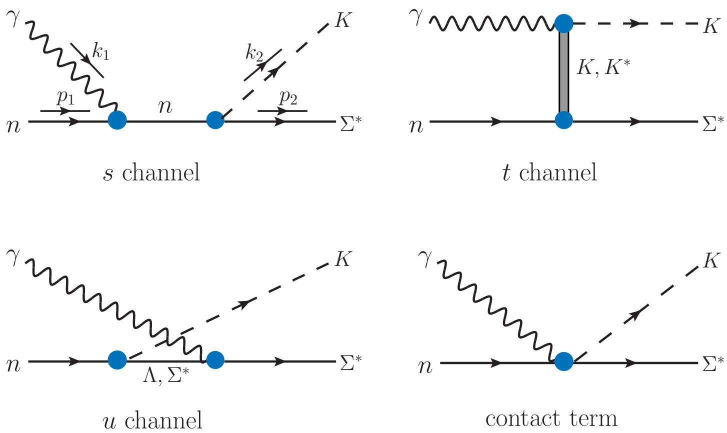

For gauge-invariance considerations, the s-channel is irrelevant.

Interpolation between f_t and $\mathcal{F}_t$:

$$\tilde{f}_t(t) = \mathcal{F}_t(t)\, R_s + f_t(t)\,(1 - R_s)$$

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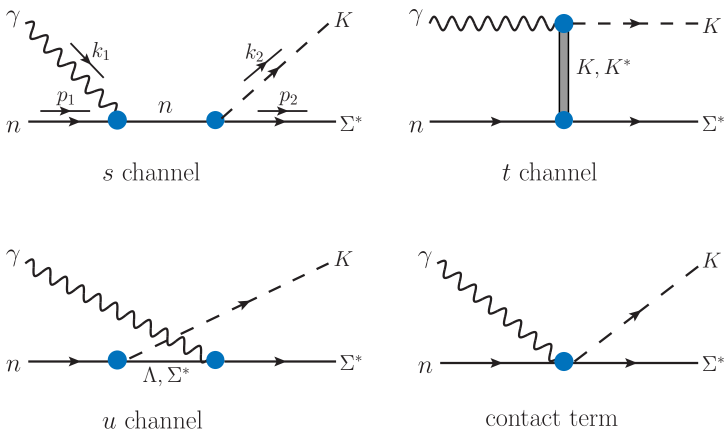

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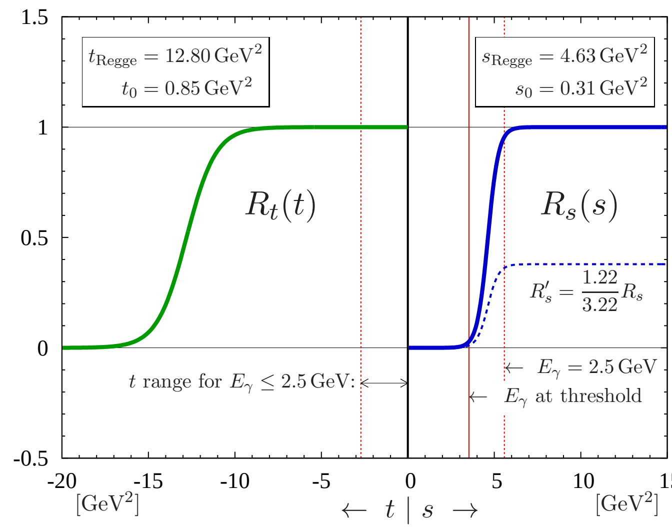

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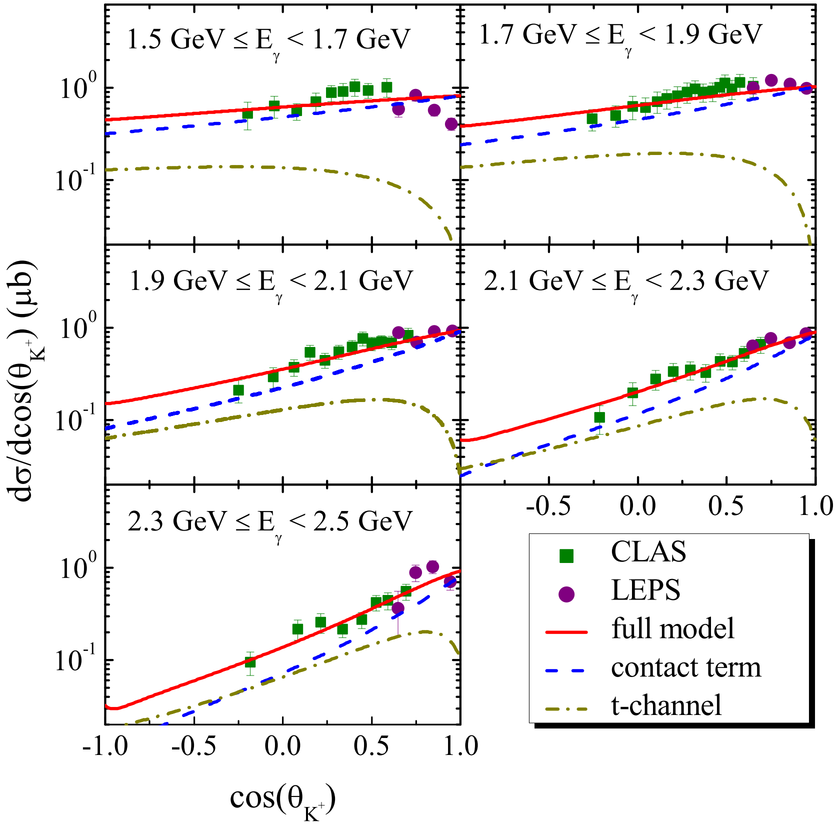

Reggeized contact term provides sizeable contribution

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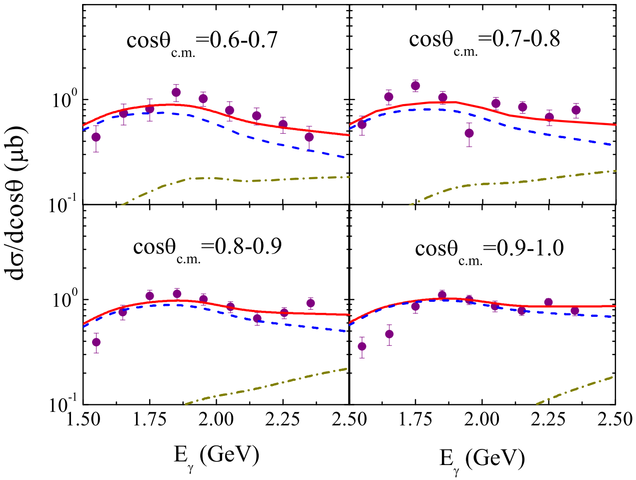
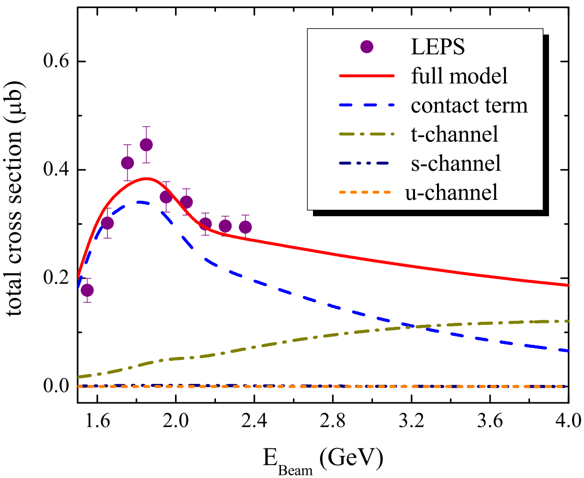
Wang, He, HH, PRC93, 045204 (2016)





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Summary

- Implementation of Regge phenomenology for t-channel exchange corresponds to replacing usual phenomenological form factor f_t by Regge residual function $\mathcal{F}_t$
- Reggeization of t-channel leads to violation of gauge invariance due to *inconsistent* implementation of Reggeization
- Interaction-current M^μ_{int} needs to be Reggeized as well
- Global gauge invariance doesn't constrain dynamics: not a good starting point ~~[GLV]~~
- Correct dynamical basis provided by generalized Ward-Takahashi identities as they follow from local gauge invariance
- The cure: Modify auxiliary contact current C^μ
- Application to $\gamma + n \to K^+ + \Sigma^*(1385)^-$ at energies up to 2.5 GeV requires mixing of conventional and Reggeized t-channel to provide acceptable χ^2
- Method can easily be applied to Reggeizing u-channel as well

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Thank you!