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On the analytic properties of the Landau gauge gluon and quark propagators

and related aspects of confinement in the covariant gauge

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415th WE Heraeus Seminar
Quarks and Hadrons in Strong QCD

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Outline

1. Basic Concepts
   - Covariant Gauge Theory
   - Kugo–Ojima confinement criterion
   - QCD Green functions & Positivity
2. Analytic properties of propagators
   - Positivity violation for the gluon propagator
   - Analytic structure of quark propagator
3. Summary and Outlook

Covariant Gauge Theory

Gauge theory: Unphysical degrees of freedom!

QED: Physical states obey Lorentz condition.

$$\partial_\mu A^\mu |\Psi\rangle = 0 \quad (\mathrm{Gupta-Bleuler}).$$

$\Rightarrow$ Two physical massless photons.

Time-like photon (i.e. negative norm state!) cancels

longitudinal photon in S–matrix elements!

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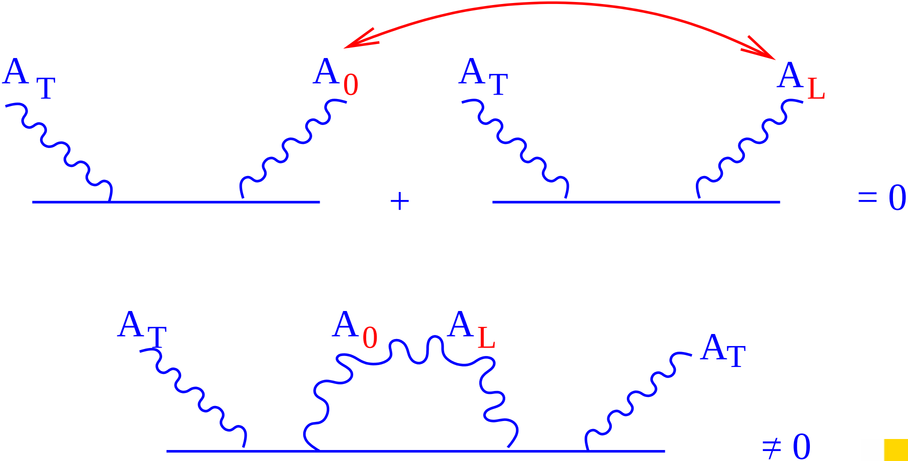
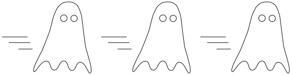
In S-Matrix

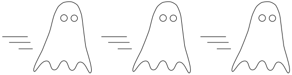


Covariant Gauge Theory

QCD in a covariant gauge:



Faddeev–Popov ghosts = anticomm. scalar fields.



Global ghost field as ‘gauge parameter‘:

BRST symmetry of the gauge-fixed action!

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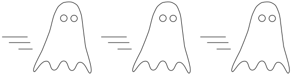

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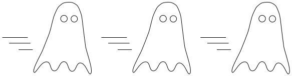

Global ghost field as ‘gauge parameter‘:

BRST symmetry of the gauge-fixed action!

Covariant Gauge Theory

Symmetry of the gauge-fixed generating functional:

$$\delta_B A^a_\mu = D^{ab}_\mu c^b \lambda , \qquad \delta_B q = -igt^a c^a q \lambda ,$$
$$\delta_B c^a = -\frac{g}{2} f^{abc} c^b c^c \lambda , \qquad \delta_B \bar{c}^a = \frac{1}{\xi} \partial_\mu A^a_\mu \lambda ,$$

Becchi–Rouet–Stora & Tyutin (BRST), 1975

- Parameter $\lambda \in$ Grassmann algebra of the ghost fields
- λ carries ghost number $N_{FP} = -1$
- Via Noether theorem: BRST charge operator Q_B
- generates ghost # graded algebra $\delta_B \Phi = \{iQ_B, \Phi\}$

Covariant Gauge Theory

BRST algebra: $Q_B^2 = 0$, $[iQ_c, Q_B] = Q_B$,

- complete in indefinite metric state space $\mathcal{V}$.
- generates ghost # graded $\delta_B \Phi = \{iQ_B, \Phi\}$.
- $\mathcal{L}_{GF} = \delta_B \left(\bar{c} \left(\partial_\mu A^\mu + \frac{\alpha}{2} B \right) \right)$ BRST exact.

Positive definite subspace $\mathcal{V}_{\rm pos} = {\rm Ker}(Q_B)$
(*i.e.* all states $|\psi\rangle \in \mathcal{V}$ with $Q_B|\psi\rangle = 0$)
contains ${\rm Im} Q_B$ (*i.e.* all states $Q_B|\phi\rangle$),
c.f. exterior derivative in differential geometry.

Hilbert space: cohomology $\mathcal{H} = \frac{{\rm Ker} Q_B}{{\rm Im} Q_B} \simeq \mathcal{V}_s$ BRST singlet
longitudinal & timelike gluons, ghosts : elementary BRST quartet

(c.f. Gupta–Bleuler mechanism in QED)

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NB: BRST symmetry of Green functions

most convenient device to derive STIs:

BRST symmetry of Green functions

(C. H. Llewellyn-Smith, 1980)

Start from the BRST invariance of

$$\delta_B \langle c^a(x)\, \bar{c}^b(y)\, \bar{c}^c(z) \rangle = 0$$

yields, when neglecting irreducible ghost-ghost scattering contr.,

$$\widetilde{Z}_1 \tfrac{1}{2} g f^{ade} (2\pi)^4\, \delta^4(p+q+k) \left\{ D_G^{eb}(-q)\, D_G^{dc}(-k) - D_G^{db}(-q)\, D_G^{ec}(-k) \right\} =$$

$$= \tfrac{1}{\xi} i k_\mu\, D_{\mu\nu}^{cd}(k)\, D_G^{ae}(p)\, G_\nu^{def}(k,p,-q)\, D_G^{fb}(-q)$$

$$- \tfrac{1}{\xi} i q_\mu\, D_{\mu\nu}^{bd}(q)\, D_G^{ae}(p)\, G_\nu^{def}(q,p,-k)\, D_G^{fc}(-k)$$

(see e.g. L. von Smekal et al, 1997)

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Kugo–Ojima confinement criterion

$\Rightarrow$ Physical states are BRST singlets!
(BRST cohomology: Hilbert space $\mathcal{H} = \frac{\mathrm{Ker}\, Q_{BRST}}{\mathrm{Im}\, Q_{BRST}}$.)

Time–like and longitudinal gluons (BRST quartet) removed from asymptotic states as in QED, but:

Transverse gluons also BRST quartets?
(*cf*. **Kugo–Ojima confinement criterion**)

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Kugo–Ojima confinement criterion

Realization of Confinement depends on global gauge structure:
Globally conserved current ($\partial^\mu J^a_\mu = 0$)

$$J^a_\mu = \partial^\nu F^a_{\mu\nu} + \{Q_B, D^{ab}_\mu \bar{c}^b\}$$

with charge $$Q^a = G^a \quad + \quad N^a.$$

QED: MASSLESS PHOTON states in both terms.
Two different combinations yield:
unbroken global charge $\tilde{Q}^a = G^a + \xi N^a$.
spont. broken displacements (photons as Goldstone bosons).

No massless gauge bosons in $\partial^\nu F^a_{\mu\nu}$: $G^a \equiv 0$.
(QCD, e.w. Higgs phase, ...)

Kugo–Ojima confinement criterion

QCD: Unbroken global charge

$$Q^a = N^a = \{Q_B, \int d^3x D_0^{ab}\bar{c}^b\}$$

well–defined in $\mathcal{V}$.
With $D_\mu^{ab}\bar{c}^b(x) \stackrel{x^0 \to \pm\infty}{\longrightarrow} (\delta^{ab} + u^{ab})\partial_\mu \bar{\gamma}^b + \ldots$

$\Rightarrow$ 2nd Kugo-Ojima Confinement Criterion:

$$u^{ab}(0) = -\delta^{ab}$$

where

$$\int dx e^{ip(x-y)} \langle 0| T\ D_\mu c^a(x) g(A_\nu \times \bar{c})^b(y)|0\rangle$$
$$=: \ (g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) u^{ab}(p^2),$$

If fulfilled: **Physical States $\equiv$ BRST singlets $\equiv$ color singlets!**

Kugo–Ojima confinement criterion

In Landau gauge:

Ghost propagator more sing. than simple pole

$\Downarrow$

Kugo-Ojima criterion

T. Kugo, hep-th/9511033, Int. Symp. “BRS Symmetry”, Kyoto.

QCD Green functions & Positivity

Assume: States with transverse gluons violate positivity!

These states do not belong to $\mathrm{Ker} Q_B$!

BRST quartet:
transverse gluon, gluon-ghost; gluon-antighost, 2-gluon

$\Longrightarrow$ **Kinematical Gluon Confinement:** Cancelations of quartets of Feynman diagrams s.t. there are **no asymptotic transverse gluons!**

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NB: Picturing Gluon Confinement

Assume DSE scaling solution to be valid:

- Gluon propagator vanishes on the light cone, and
- *n*-point gluon vertex functions diverge on the light cone!

$\Rightarrow$ Attempts to kick a gluon free (*i.e.* to produce a real gluon) immediately results in production of infinitely many virtual soft gluons!

$\Rightarrow$ perfect color charge screening
+ quartet cancelation:
Gluon (color charge) confinement!

PS: If you can agree on the mechanism but not on the semantics,
let's call this differently!?!

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Positivity: $\langle\Omega|A^\dagger A|\Omega\rangle \geq 0$ for local operator A.

But spectral sum rule for gluon correlation function:

$$Z_3^{-1} = Z + \int_{m^2}^{\infty} d\kappa^2 \rho(\kappa^2) \quad \text{with} \quad Z_3 = \left(\frac{g^2}{g_0^2}\right)^\gamma$$

in linear covariant gauges.

Antiscreening: $Z_3^{-1} \to 0$, *i.e.* $Z_3^{-1} \leq Z$, $\Rightarrow \rho(\kappa^2) \leq 0$.

Oehme–Zimmermann superconvergence relation:
Antiscr. contradicts positivity of gluon spectral density!
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Non–perturbatively true?

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Non–perturbatively true?

Positivity violation for the gluon propagator

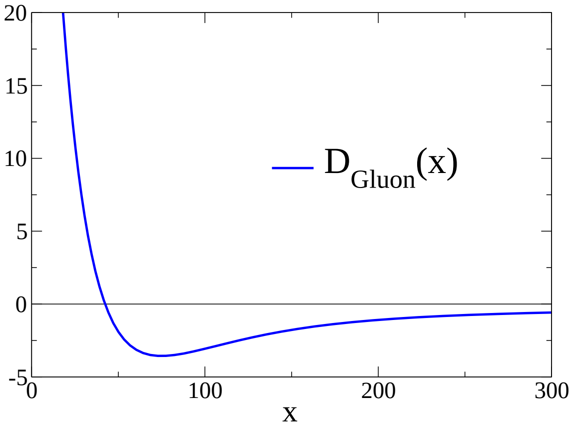
Simple argument [Zwanziger]:
IR vanishing gluon propagator implies

$$0 = D_{gluon}(k^2 = 0) = \int d^4x D_{gluon}(x)$$

$\Longrightarrow$ $D_{gluon}(x)$ has to be negative for some values of x.

Positivity violation for the gluon propagator

Fourier transform of DSE result:



Gluon Confinement!

Positivity violation for the gluon propagator

No Lehmann representation

$$D_{gluon}(k^2) = \int_0^\infty dm^2 \frac{\rho(m^2)}{k^2+m^2} \text{ with } \rho(m^2) \geq 0!$$

$\Rightarrow$ Signal for **confined gluons**.

- Non-perturbative realization of Oehme–Zimmermann superconvergence relation

Positivity violation for the gluon propagator

Analytic structure of the gluon propagator:
(R.A., W. Detmold, C.S. Fischer and P. Maris, PR**D70** (2004) 014014)
Running coupling in minMOM scheme precisely represented by:

$$\alpha_{\text{fit}}(p^2) = \frac{\alpha_S(0)}{1 + p^2/\Lambda^2_{\text{QCD}}} + \frac{4\pi}{\beta_0} \frac{p^2}{\Lambda^2_{\text{QCD}} + p^2} \left(\frac{1}{\ln(p^2/\Lambda^2_{\text{QCD}})} - \frac{1}{p^2/\Lambda^2_{\text{QCD}} - 1} \right)$$

with $\beta_0 = (11N_c - 2N_f)/3$

- Landau pole subtracted
- analytic in complex p^2 plane except real timelike axis
- logarithm produces cut for real $p^2 < 0$
- Cutkosky's rule obeyed

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- IR part: cut for $-\Lambda^2_{\text{QCD}} < p^2 < 0$
- D^{fit}_{gluon}: cut along negative, i.e. timelike, half-axis!

Wick rotation possible!

- w arbitrary normalization parameter
- $\kappa = \frac{93-\sqrt{1201}}{98}$ fixed from IR analysis
- $\gamma = \frac{-13N_c+4N_f}{22N_c-4N_f}$ from perturbation theory
- **Effectively one parameter**[†]**:** $\Lambda_{\text{QCD}} \approx$ **500 MeV!**

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from fits to lattice data: $\Lambda_{\text{QCD}} \approx 400$ MeV

UNI GRAZ

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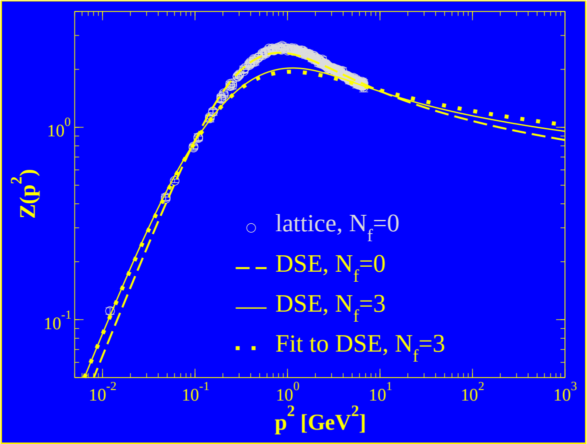

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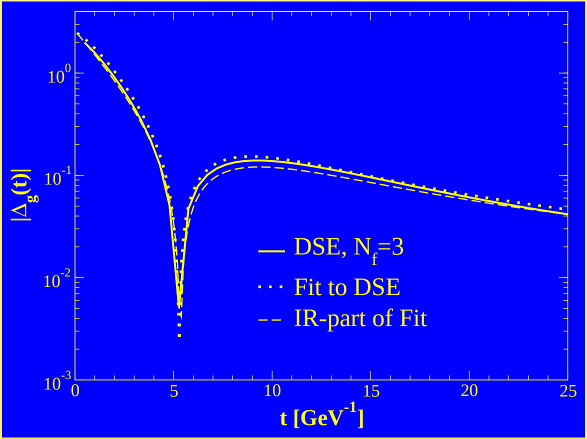

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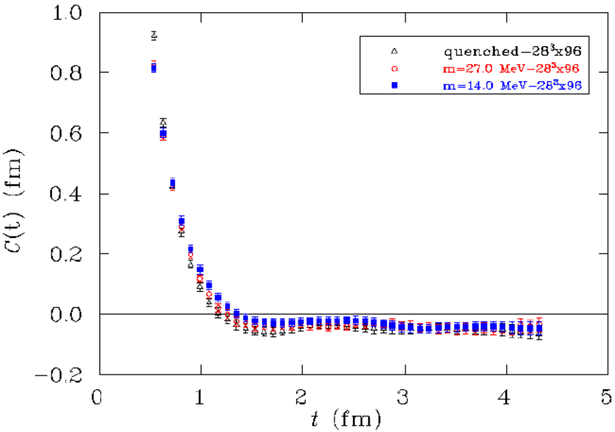
Positivity violation for the gluon propagator

Recent corresponding lattice results e.g.

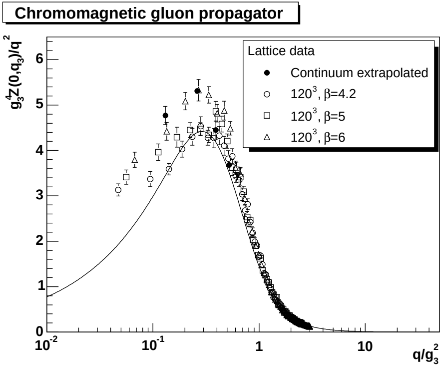
P. Bowman et al., Phys.Rev.D76 (2007) 094505



Gluon propagator at high T:

A. Maas, J. Wambach, RA, EPJ **C37** (2004) 335; **C42** (2005) 93.

A. Cucchieri, T. Mendes and A.R. Taurines, PR **D67** (2003) 091502.

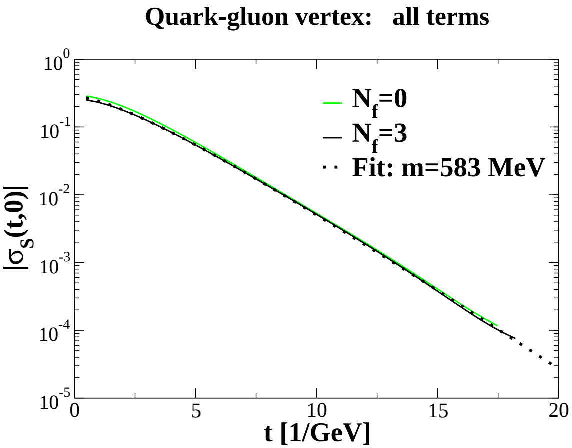


Gribov-Zwanziger / Kugo-Ojima scenario
applies in confined and deconfined phase!

Analytic structure of quark propagator

(R.A., W. Detmold, C.S. Fischer and P. Maris, PR**D70** (2004) 014014)

Positivity of the Landau gauge quark propagator from DSE solution with ansatz for quark-gluon vertex:



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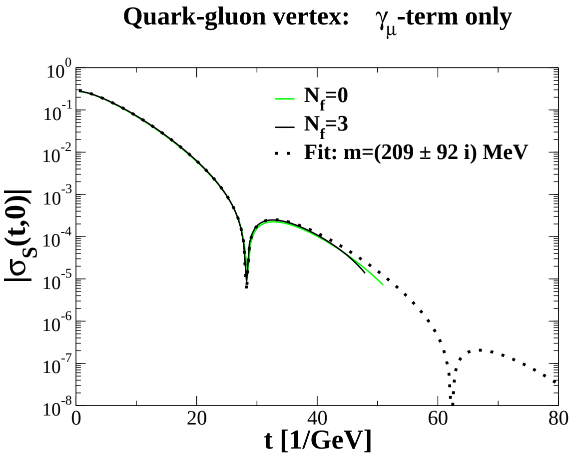

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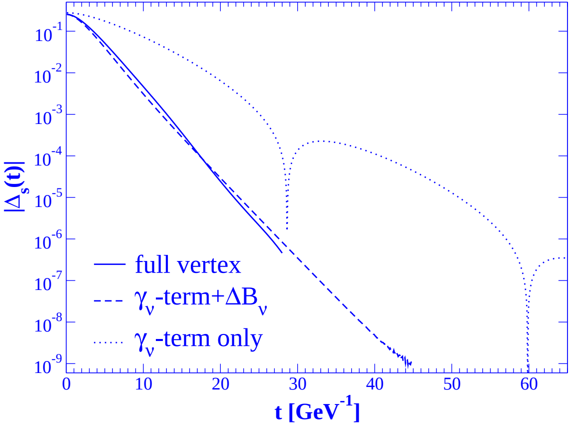

Importance of self-cons. **scalar** quark-gluon coupling!

Analytic structure of quark propagator

- Result welcome in strong-coupling QED ...
- Puzzling in QCD ...

R.A., C.S. Fischer, F. Llanes-Estrada, K. Schwenzer, in preparation;
talks by Christian Fischer and Richard Williams

IR singular Quark-Gluon-Vertex related to

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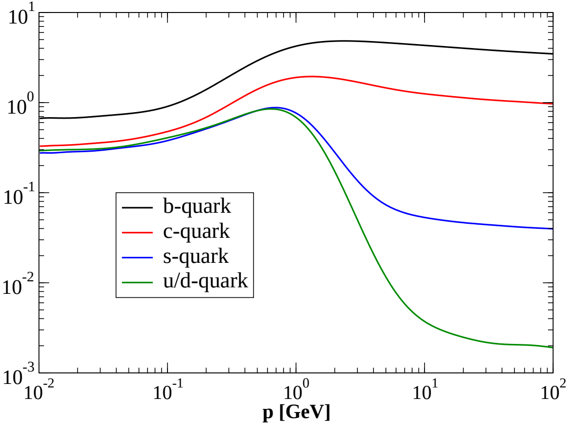
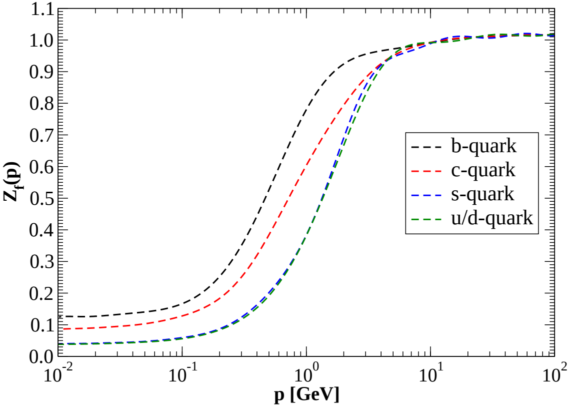
Quark mass functions:



Solution of coupled DSEs of Quark Propagator and Quark-Gluon-Vertex:

Quark renormalization functions:



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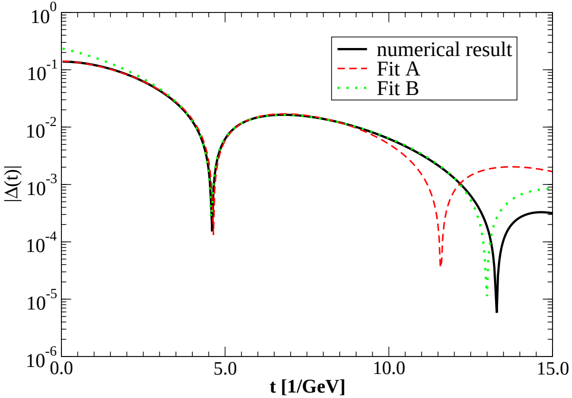
Quark Schwinger function (here chiral limit):



Summary and Outlook

Analytic properties of Landau gauge QCD propagators:

- Gluons (“confined by ghosts´´): Positivity violated!
  Gluons removed from *S*–matrix!
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  • Cut
  • Wick rotation possible
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