Emergent phenomena
in strong dynamics

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Emergent mass and its consequences in the Standard Model
Trento, Italy
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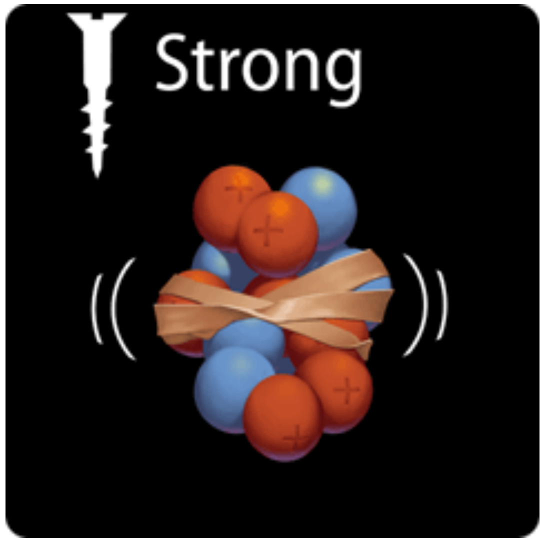
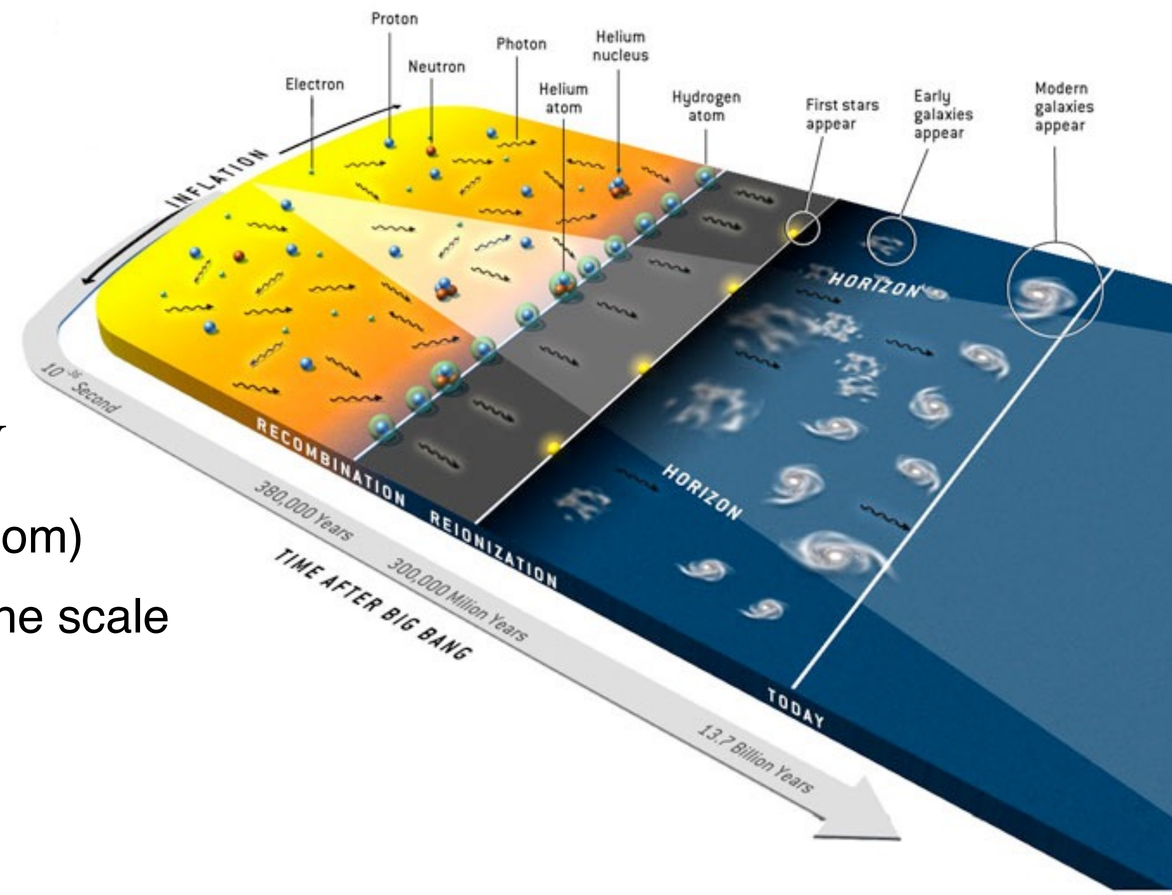
Standard Model: QCD

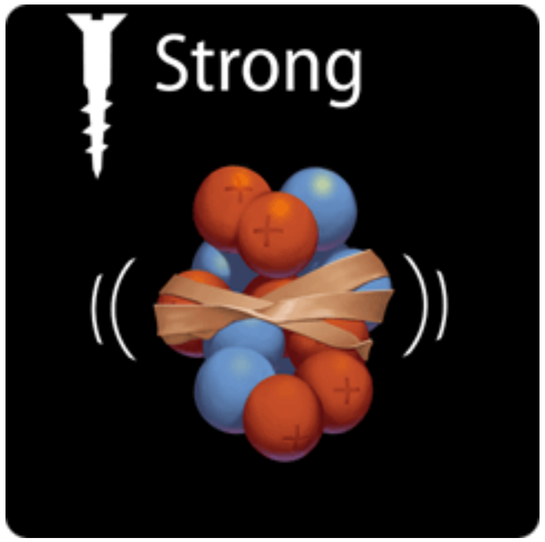


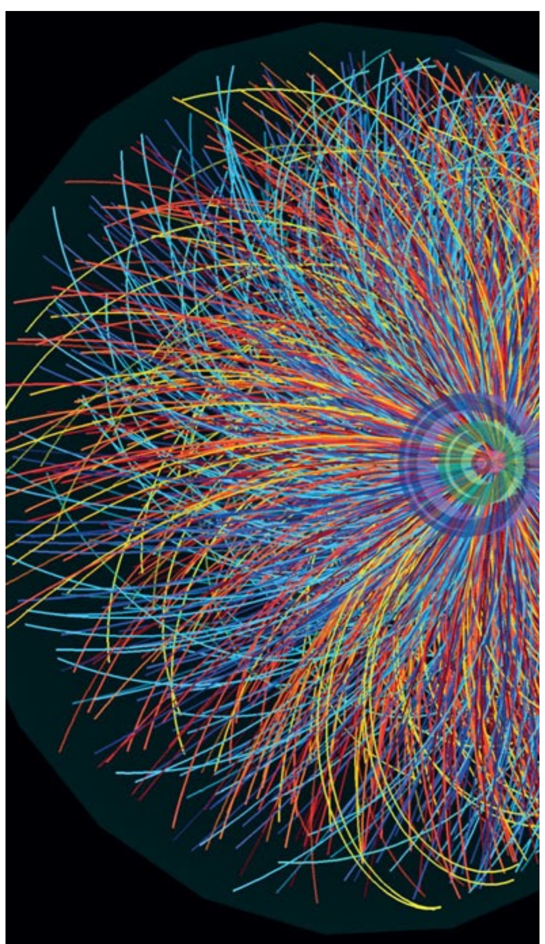
- **QCD started 10^{-6} secs. after the Big-Bang:**
  it is the glue that binds us all, and understanding its dynamics has profound implications
  - **Explain how massless gluons and light quarks are confined** and bind together to form hadrons…
  - **…thereby explain the origin of ~98% of the mass** in the visible Universe



- **QCD is *likely* a perfect theory**
  nothing needs to be added or changed
  - **Validated** over an incredible energy range: $0 \lesssim E \leq 8000\,\mathrm{GeV}$
  - **Unlikely to break down** at any energy scale (asymptotic freedom)
  - **No intrinsic parameters,** just need one observable to define the scale $\Lambda_{\mathrm{QCD}} \simeq 200 - 300\ \mathrm{MeV}$ QCD's "standard kilogram"
- **QCD is *a theory* not an effective theory**
- **However, it is innately nonperturbative**
  a priori no idea what such theory can produce

QCD: degrees of freedom





- **QCD basic degrees of freedom:**
  matter (quarks); gauge (gluons)

$$q_{\mathrm{f}}^{i}\begin{cases}\text{color} & i=1,2,3\\ \text{flavor} & \mathrm{f}=u,d,s,c,b,t\end{cases}\qquad A_{\mu}^{a}\begin{cases}\text{color} & a=1,\dots,8\\ \text{spin} & \varepsilon_{\mu}^{\pm,0}\end{cases}$$

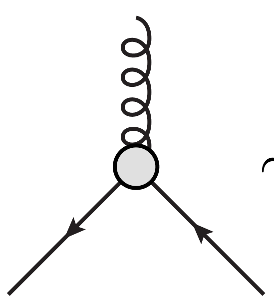
- **QCD action:**
  encodes all the dynamics

$$S_{\mathrm{QCD}}=\int \mathrm{d}^4x\,(\mathcal{L}_{\mathrm{I}}+\mathcal{L}_{\mathrm{GF+FPG}})$$

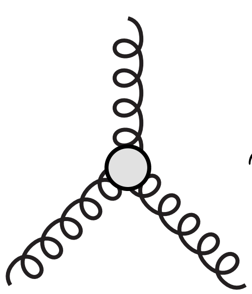
$$\mathcal{L}_{\mathrm{I}}=\bar{q}_{\mathrm{f}}^{i}(i\gamma^{\mu}D_{\mu}-m)_{ij}q_{\mathrm{f}}^{j}-\frac{1}{4}F_{\mu\nu}^{a}F_{a}^{\mu\nu}$$

$$D_{\mu}=\partial_{\mu}-igA_{\mu}^{a}T^{a}\qquad F_{\mu\nu}^{a}=\partial_{\mu}A_{\nu}^{a}-\partial_{\nu}A_{\mu}^{a}+gf^{abc}A_{\mu}^{b}A_{\nu}^{c}$$

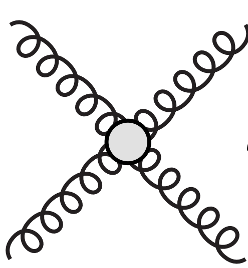
- **QCD (self-)interactions**
  dictate the theory’s behavior



$\sim gA\bar{q}q$

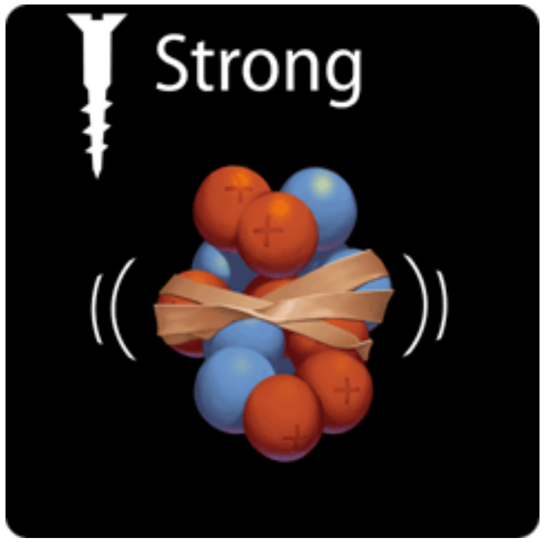


$\sim gA^3$

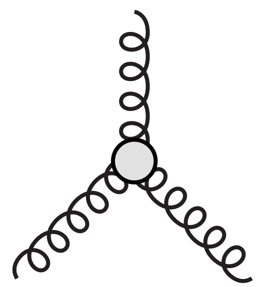


$\sim g^2A^4$

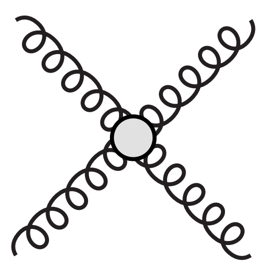
QCD: asymptotic freedom



- **Gluon self-interaction runs**
  implies QCD is non perturbative and quark/gluons are confined



$\sim gA^3$



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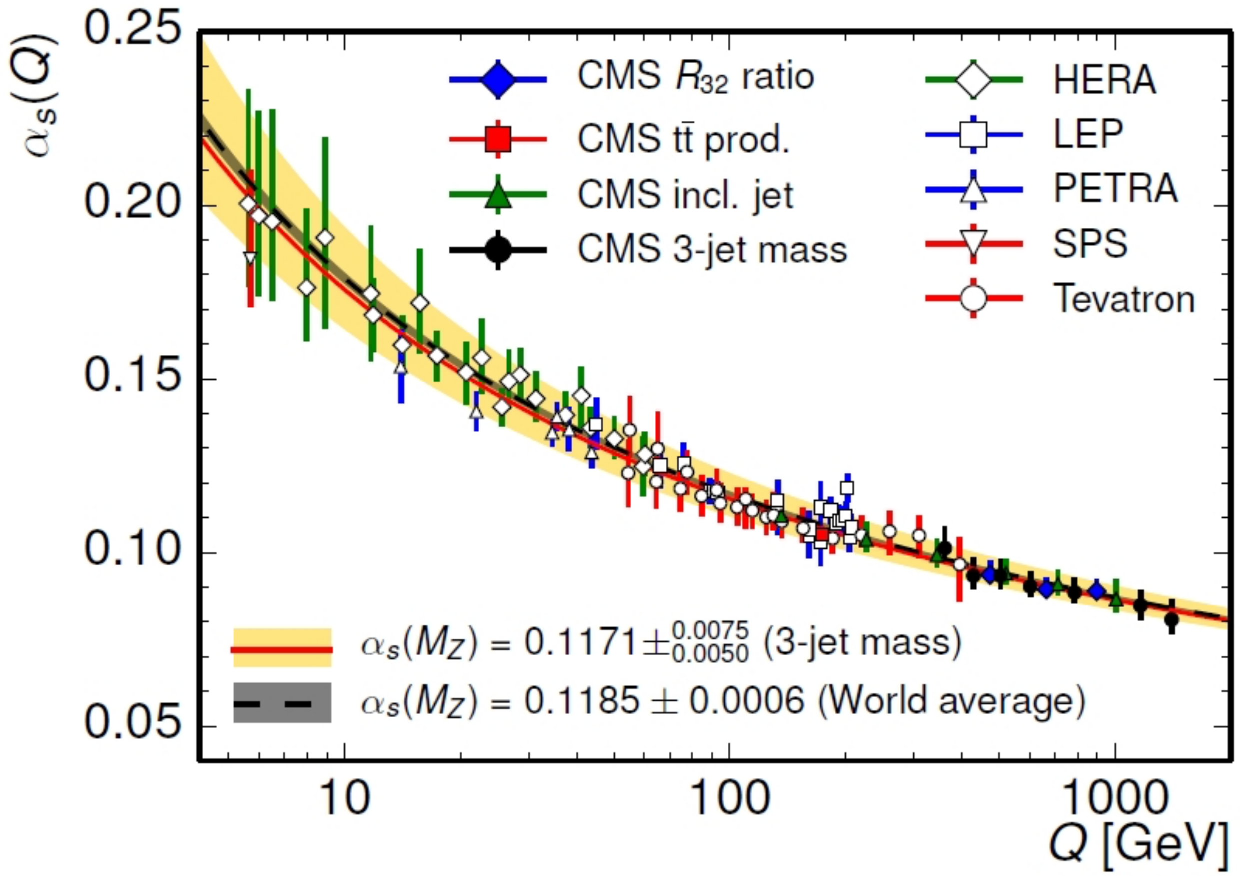
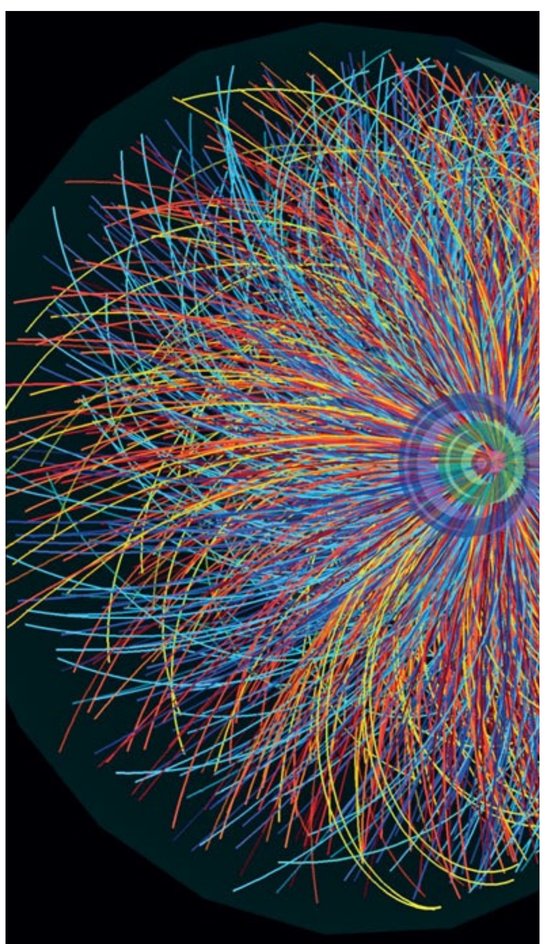
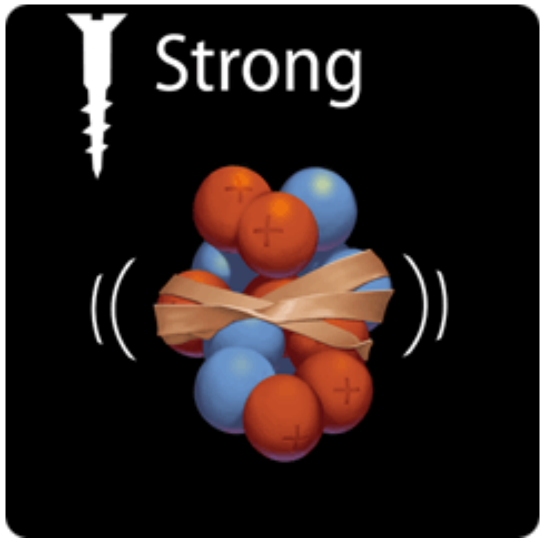




- **QCD interaction strength:**
  grows with separation between gluons and quarks

- **Typical scale of hadron physics**
  $r \sim 2\ \mathrm{fm} \qquad \alpha \sim 0.5$
  - **Perturbation theory breaks down at this distance**
    QCD is entirely nonperturbative across almost the entire proton's volume

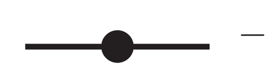
QCD: Schwinger-Dyson equations



- **Understanding the origin of mass in QCD**
  is quite likely inseparable from understanding confinement

- **One possible way of addressing this are Schwinger-Dyson eqs**
  which are quantum eom of Green's functions

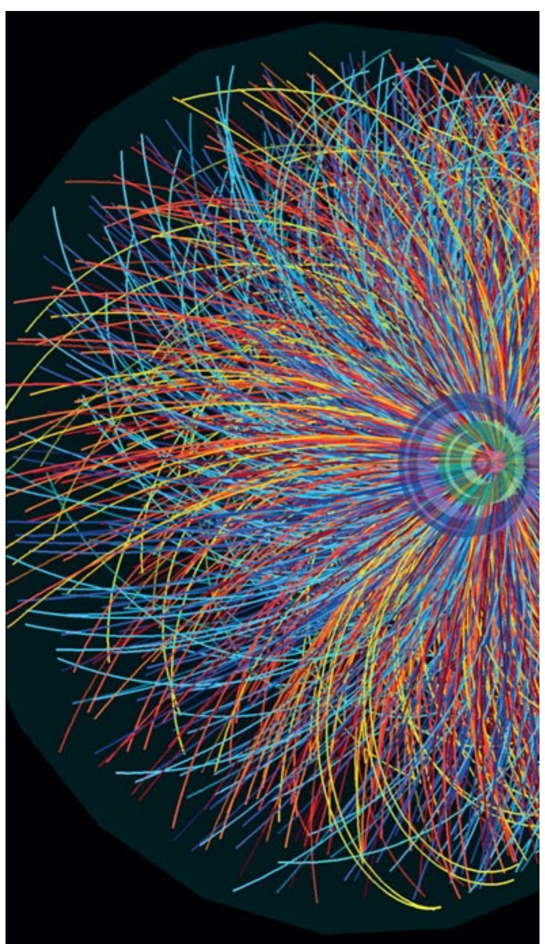
- **SDEs: nonperturbative, covariant, IR/UV, light/heavy quarks; but:**
  infinite system of coupled integral equations
  - **Needs reliable truncation schemes**
    plus requires a gauge to be chosen (Landau)

- **Concentrate on SDE for 2-point functions** 
  - **Three equations to be considered**
    quarks, gluons and ghosts

$$\mathcal{L}_{\rm GF+FPG} = s(\bar{c}^a\mathcal{F}^a - \xi/2\bar{c}^a b^a)$$

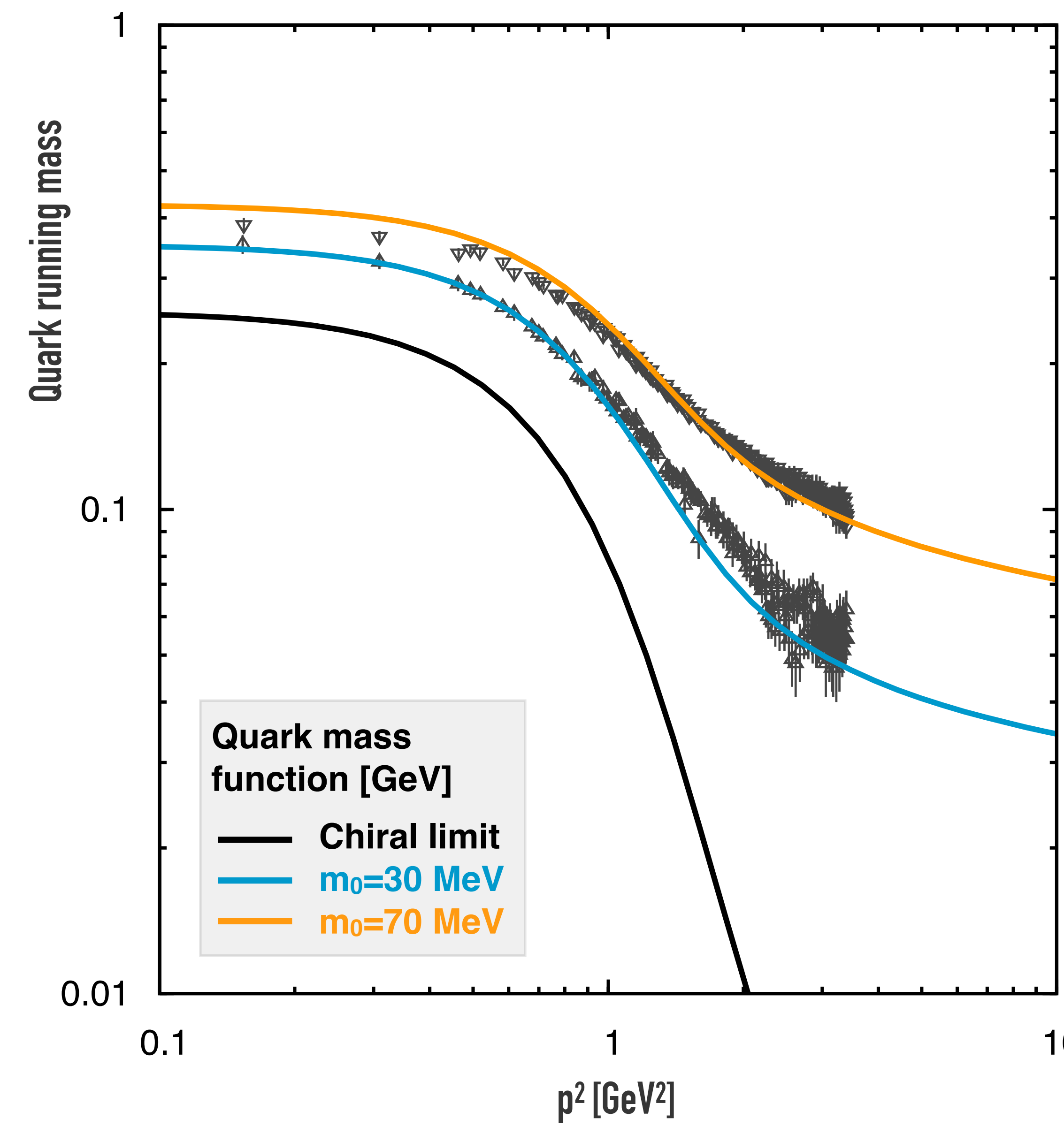
  - **Gauge fixing + FP ghost:**
    BRST exact, does not appear in the spectrum

- **Capture two emergent phenomena**
  - Dynamical mass generation
  - Confinement (?)

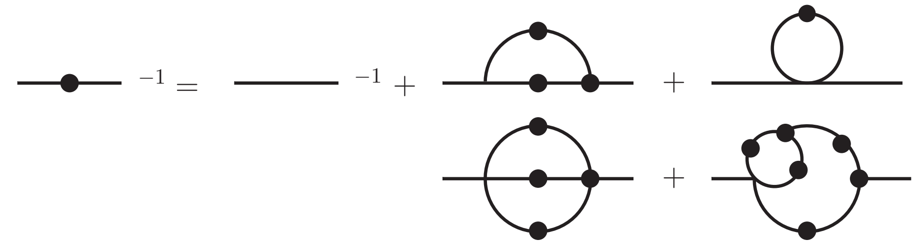


Dynamical quark mass

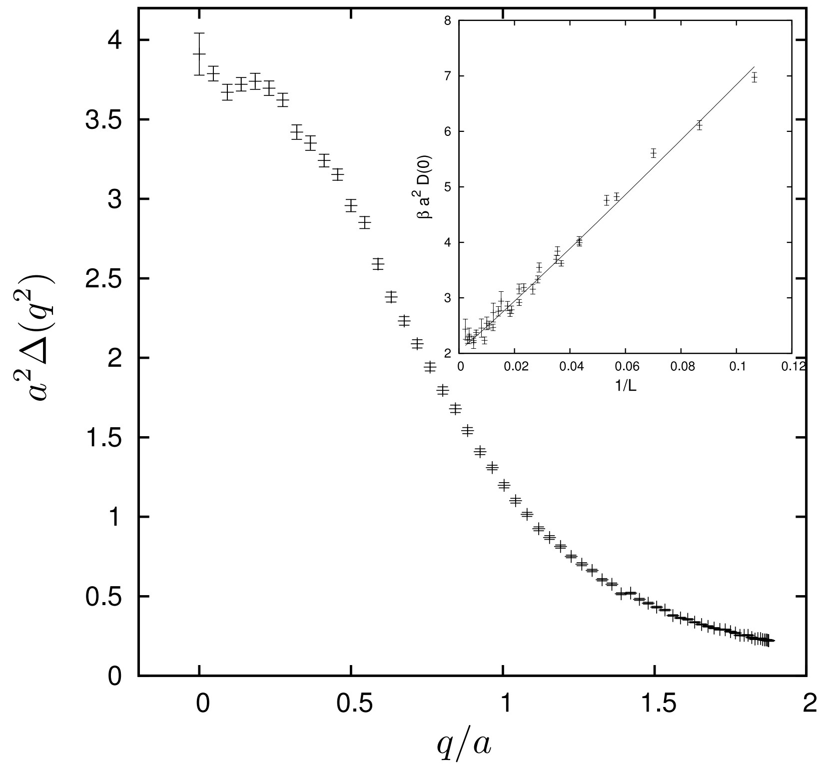
- **Dynamical chiral symmetry breaking:** generates “constituent-quark” masses
- **Add nothing to QCD:** effect achieved purely through the theory’s dynamics
- **Most important mass generating mechanism:** responsible for ~98% of the proton’s mass (Higgs mechanism almost irrelevant for light quarks)



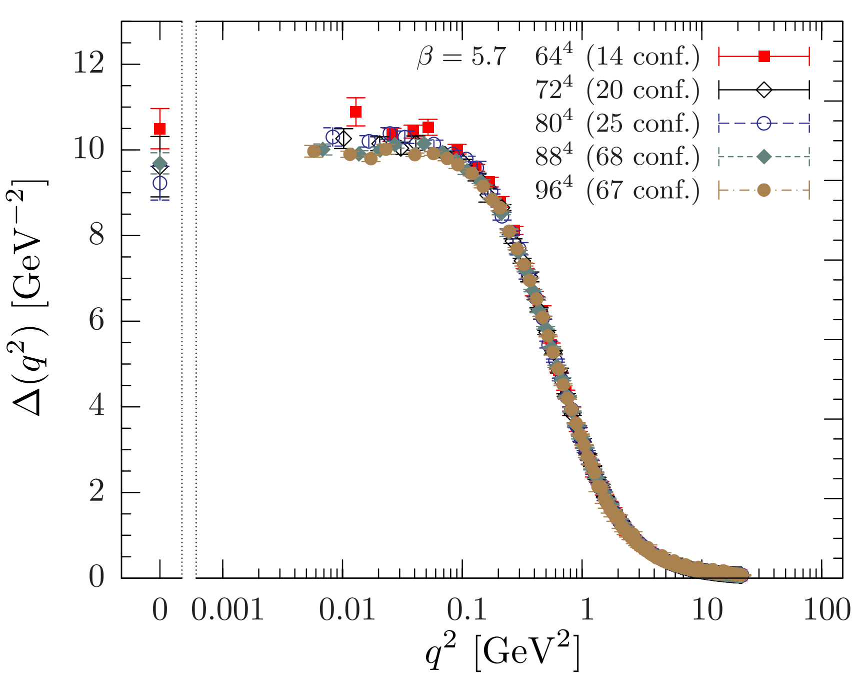
What about gluons?



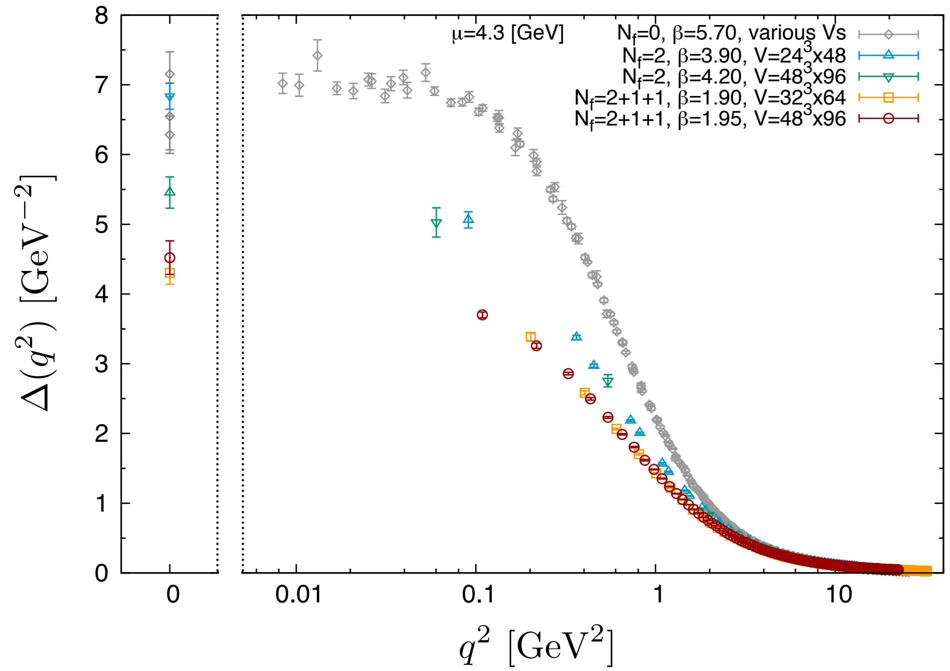
- **Landau gauge** (quenched)
  Cucchieri, Mendes POS LATTICE (2007)



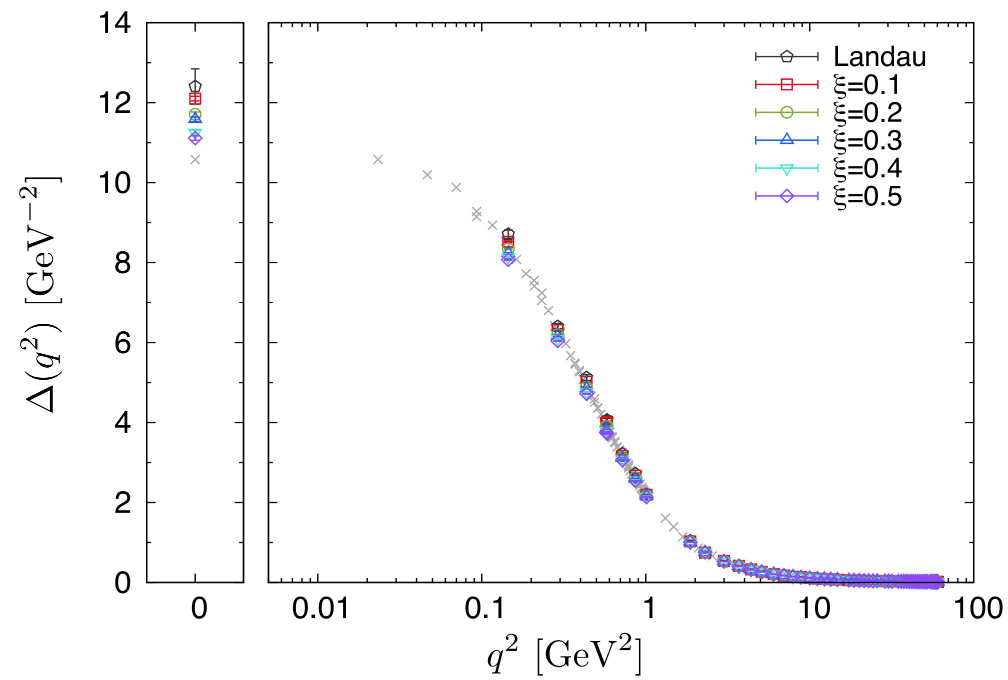
Bogolubsky, Ilgenfritz, Muller-Preussker, Sternbeck, PLB 676 (2009)



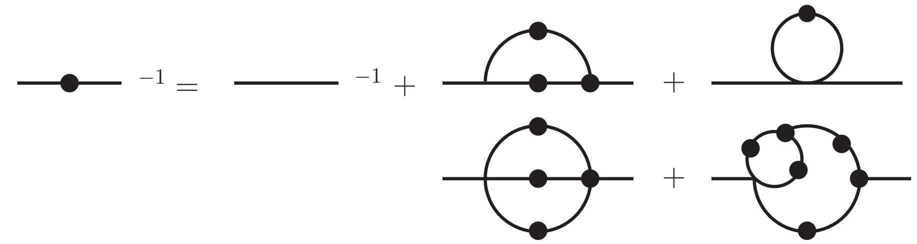
- **Landau gauge** (unquenched)
  Ayala, Bashir, DB, Cristoforetti, Rodriguez-Quintero, PRD 86 (2012)



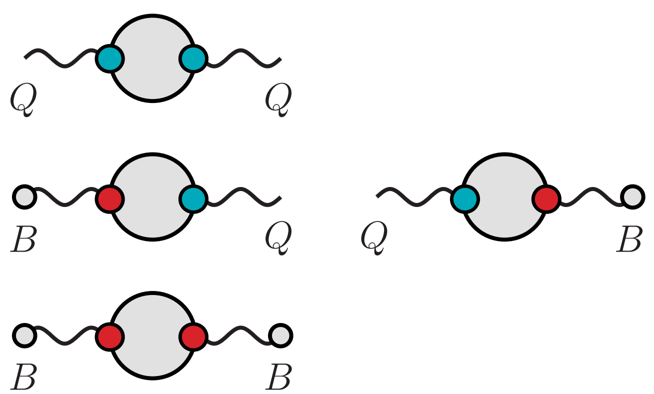
- **Linear gauges** (quenched)
  Bicudo, DB, Cardoso, Oliveira, Silva, PRD 92 (2015)

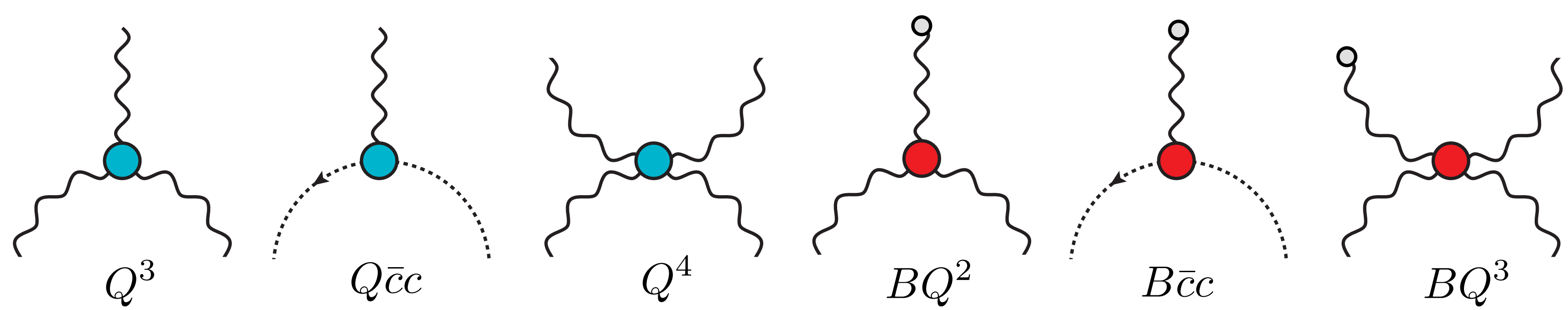


What about gluons?

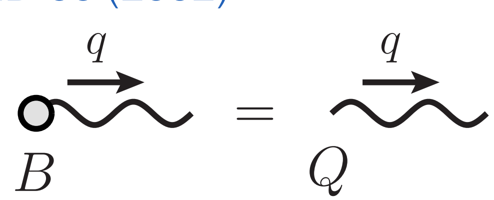


- **IR Saturating/massive gluon propagator**
  challenging from a continuous perspective
- **Best understood within PT-BFM framework**
  DB, Papavassiliou, PRD 77 (2008); JHEP 0811 (2008); PR 479 (2009)
- **Split gauge field**
  into background (B) and quantum fluctuating (Q) parts
  Abbott, NPB 185 (1981)
- **Resummed Green's functions**
  with better truncations properties
- **Algebraic relations**
  with original functions in all cases of interest
- **Proliferation of Green's functions**
  three possibilities in two-point gluon sector





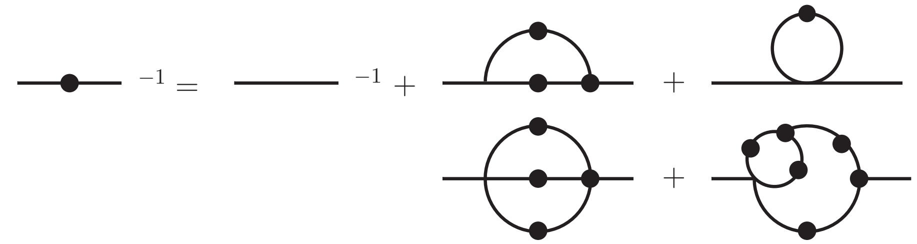
- **Symmetry induced identities**
  relate B and Q functions; in 2-point sector:
  DB, Papavassiliou, PRD 66 (2002)

$[1 + G(q^2)]^{-1} \times$ 

- **G function known**
  constrained by antiBRST symmetry
  DB, Quadri, PRD 88 (2013)

$$1 + G(0) = F^{-1}(0)$$

What about gluons?



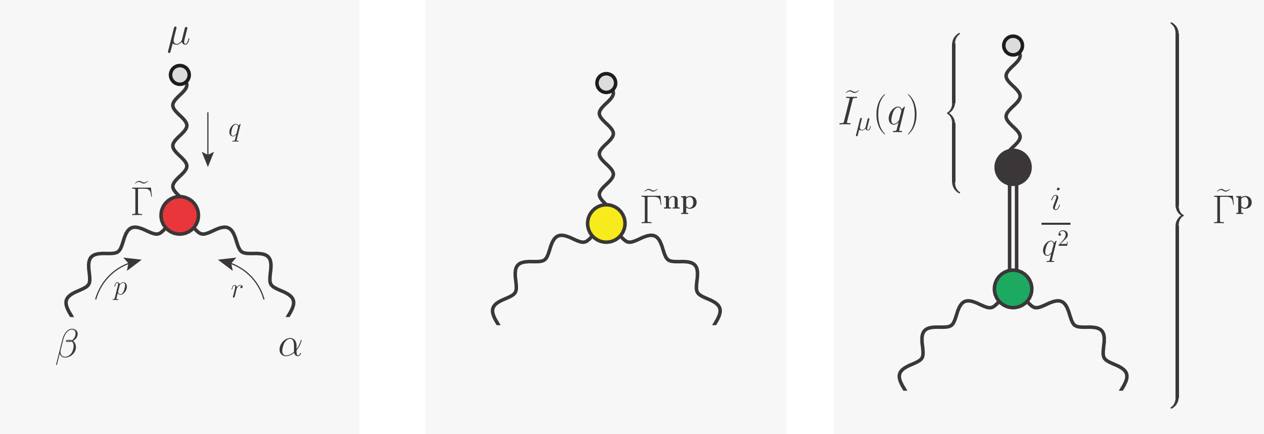
- **Schwinger mechanism**
  propagator Dyson resums to
  Schwinger, PR 125 (1962)
  Schwinger, PR 128 (1962)

$$\Delta(q^2) = \frac{1}{q^2\left[1+\Pi(q^2)\right]}$$

- **If** $\Pi(q^2)$ **has a pole at** $q^2=0$ the gauge boson becomes massive even if it was massless in the absence of interactions

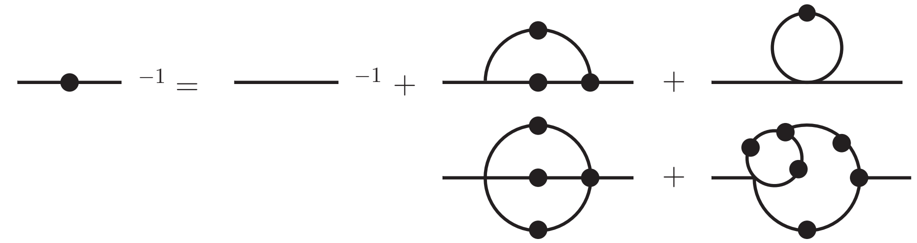
- **Yes, but in QCD?**
  - **PT-BFM theorem**: *in any covariant gauge* $\Delta(0)=0$ *in the absence of vertex non-analyticities*
    Aguilar, DB, Figueiredo, Papavassiliou, PRD 94 (2016)
  - **Way out:** require **massless, longitudinally coupled** Goldstone like **poles** $1/q^2$
  - **Occur dynamically** (even in the **absence** of canonical **scalar fields**) as **composite (colored) excitations** in a **strongly coupled** gauge theory
    Jackiw, Johnson, PRD 8 (1973)
    Cornwall, Norton, PRD 8 (1973)
    Eichten, Feinberg, PRD10 (1974)

$$\widetilde{\Gamma}_{\mu\alpha\beta}(q,r,p) = \widetilde{\Gamma}^{\mathbf{np}}_{\mu\alpha\beta}(q,r,p) + \widetilde{\Gamma}^{\mathbf{p}}_{\mu\alpha\beta}(q,r,p)$$

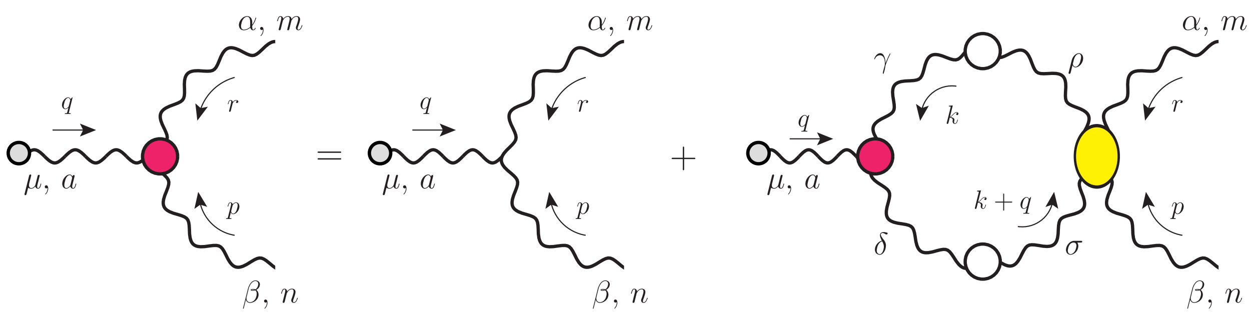


- **3-gluon vertex**
  contains non-analyticities
- **Not kinematic singularities**
  composite excitations produced by strong dynamics
- **Do not appear in the S-matrix**
  (longitudinally coupled)

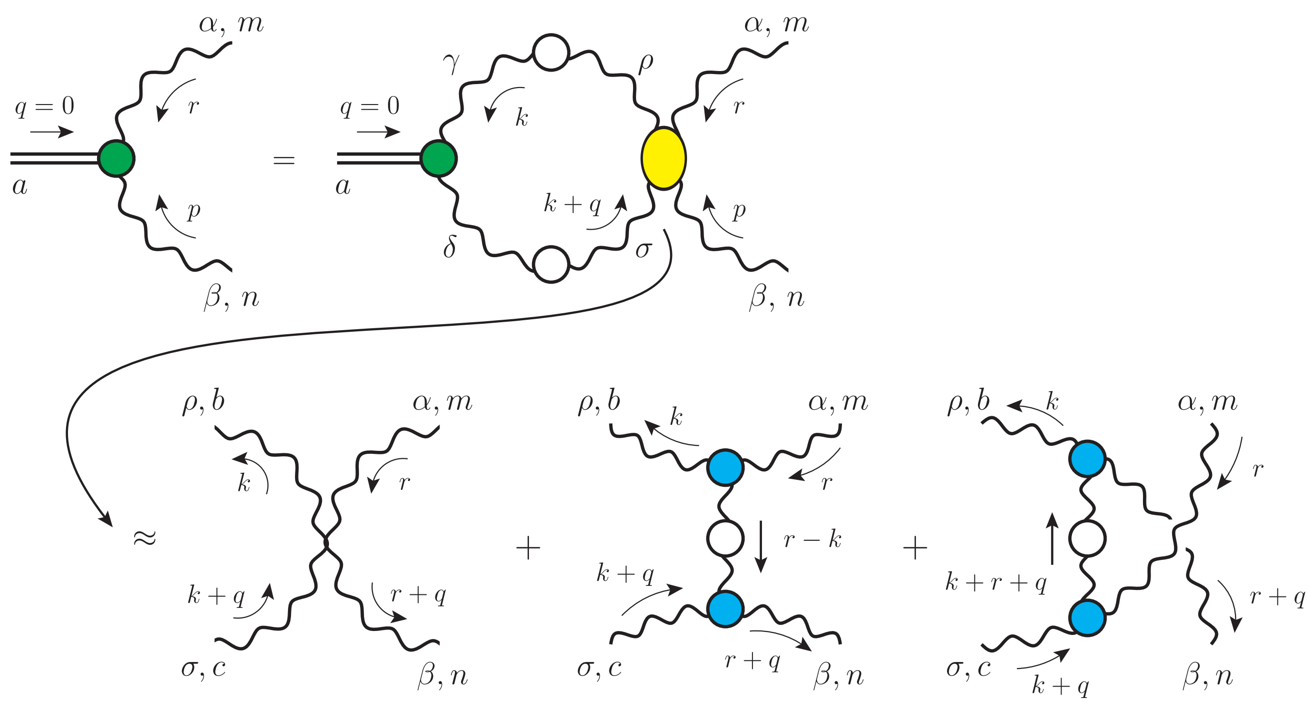
What about gluons?

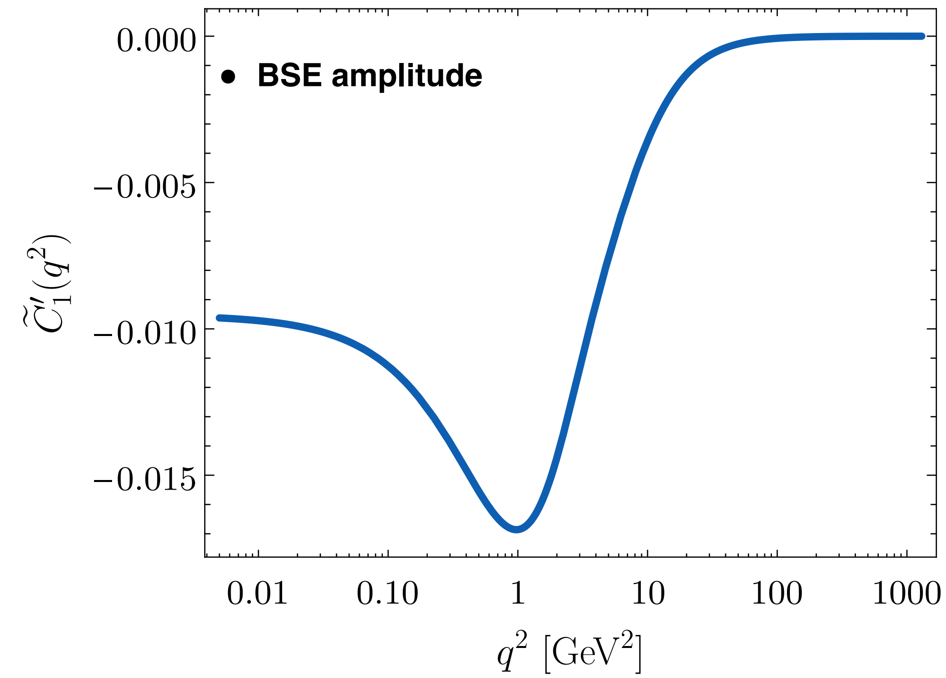


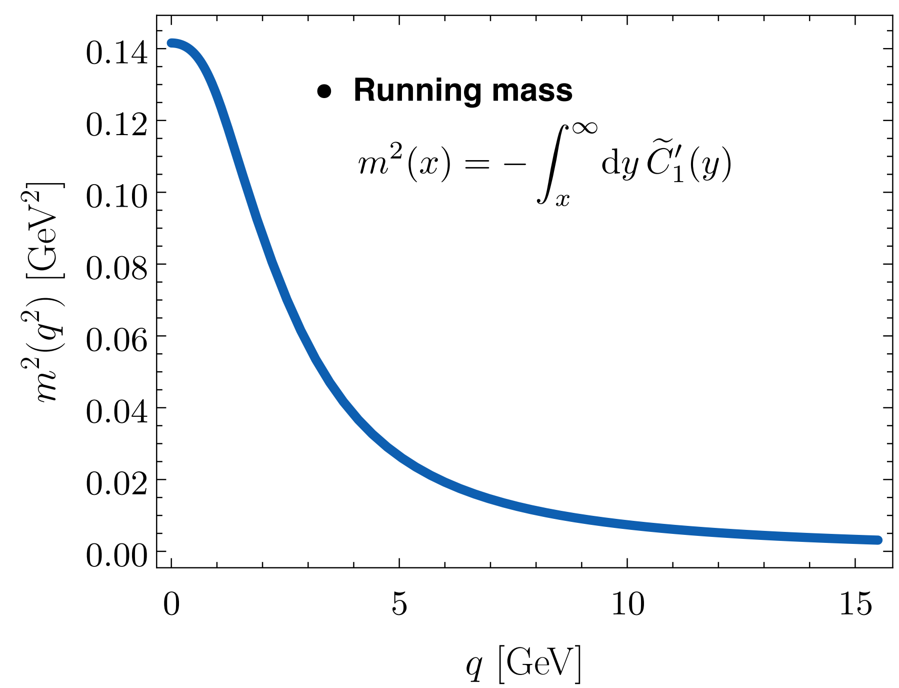
- **Consider BSE for the full vertex**



- **Replace vertex:** $\Gamma \to \Gamma^{\mathbf{np}} + \Gamma^{\mathbf{p}}$
  expand and equate terms linear in q
  DB, Papavassiliou, PRD 97 (2018)



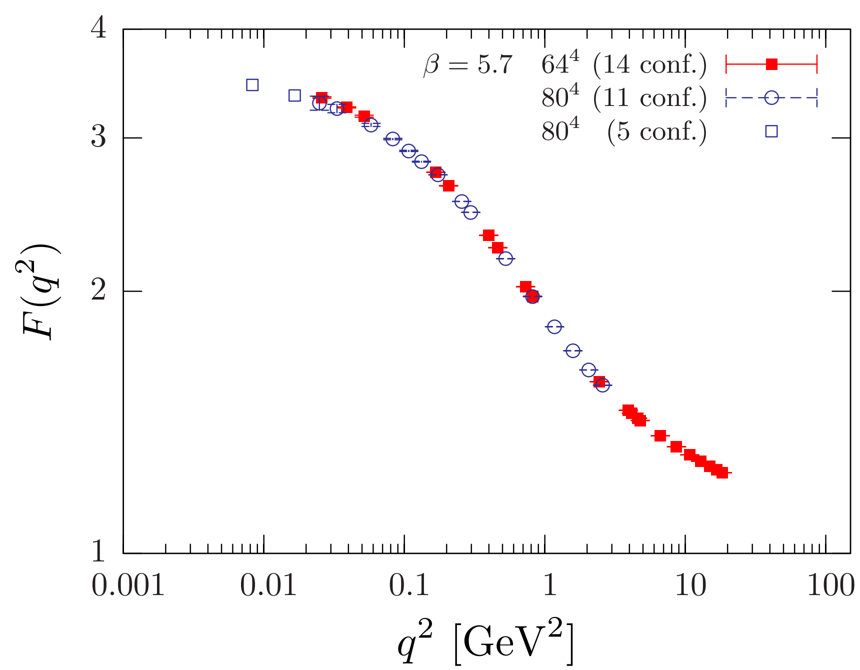




And ghosts?

- **Ghost remains massless**
  even at non-perturbative level
- **Lattice results**
  confirmed by continuous studies
- **Ghost dressing function saturates**
  $F(q^2) = q^2 D(q^2)$
- **IR propagator diverges**
  $D(q^2) \sim c/q^2$

- **Landau gauge** (quenched)
  Bogolubsky, Ilgenfritz, Muller-Preussker, Sternbeck, PLB 676 (2009)



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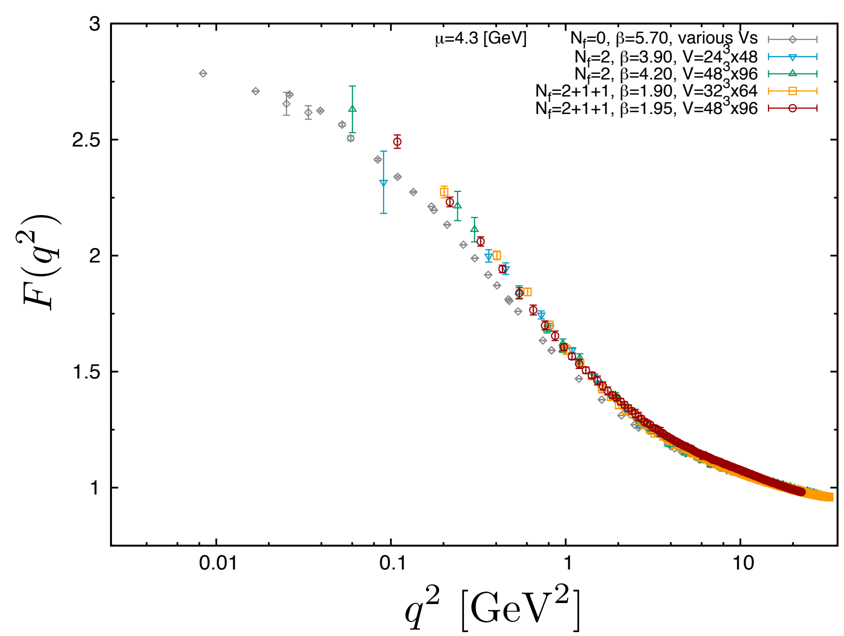


And ghosts?

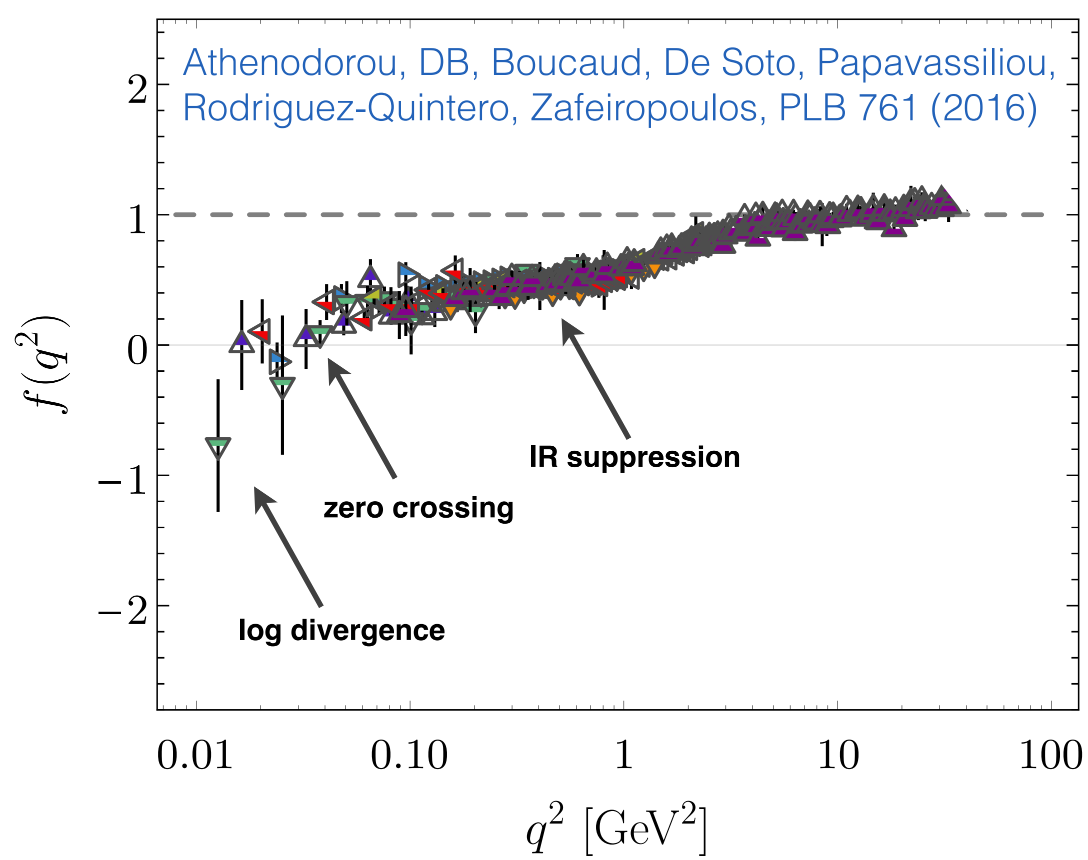
- **Ghost masslessness**
  phenomenologically very important
  Aguilar, DB, Ibañez, Papavassiliou, PRD 89 (2014)

$$\Delta^{-1}(q^2) \sim q^2 \left[1 + \underbrace{\log \frac{q^2 + m^2(q^2)}{\mu^2}}_{\text{gluon loops}} + \underbrace{\log \frac{q^2}{\mu^2}}_{\text{ghost loops}}\right] + m^2(q^2)$$

- **IR behavior of derivative of the gluon propagator**
  entirely determined by ghost loops

$$\partial_{q^2}\Delta^{-1}(q^2) \sim \log \frac{q^2}{\mu^2} \underset{q^2 \to 0}{\to} -\infty$$

- **Related to 3-gluon vertex form factor**
  proportional to tree-level tensor structure
  Aguilar, DB, Ibañez, Papavassiliou, PRD 89 (2014)
  - **Suppression wrt tree-level value**
    vertex must drop below 1
  - **Zero crossing**
    in the (deep?) IR followed by
  - **Log divergence**
    as $q^2 \to 0$



PDAs within a DS framework

- **Meson leading twist PDA**
  projection of BS wave-function onto the light-front
  Chang, Cloet, Cobos-Martinez, Roberts, Schmidt, PRL 110 (2013)

$$f_{\mathrm{PS}}\varphi(x,\zeta) = Z_2(\zeta,\Lambda)\mathrm{Tr}_{\mathrm{CD}}\int_{\mathrm{d}q}^{\Lambda}\delta(n\cdot q_+ - x n\cdot P)\gamma_5(\gamma\cdot n)\chi_{\mathrm{PS}}(q,P)$$

f_{PS}
- **Meson's decay constant**
  (normalization of PDAs) $\int_0^1 \mathrm{d}x\,\phi(x,\zeta) = 1$

$Z_2(\zeta,\Lambda)$
- **Quark wave-function renormalization**
  evaluated at ζ (2 GeV)

$\int_{\mathrm{d}q}^{\Lambda}$
- **Poincaré invariant regularization**
  of 4-dimensional integral

$\delta(n\cdot q_+ - x n\cdot P)$
- n **light-cone vector;** P **meson momentum**
  $n\cdot P = -m_{\mathrm{PS}}$ $\quad P^2 = -m_{\mathrm{PS}}^2$

$\chi_{\mathrm{PS}}(q,P)$
- **BS wave-function:** $\chi_{\mathrm{PS}}(q,P) = S_{f_1}(q_+)\Gamma_{\mathrm{PS}}(q,P)S_{f_2}(q_-)$

$q_+ = q + \eta P$
$q_- = q - (1-\eta)P$

$\Gamma_{\mathrm{PS}}(q,P)$
- **BS amplitude**
  solution of the homogeneous BS equation

$$\Gamma_{\mathrm{PS}}^{\alpha\beta}(k,P) = \int_q \mathcal{K}^{\alpha\alpha';\beta\beta'}(q_\pm,k_\pm)[S_{f_1}(q_+)\Gamma_{\mathrm{PS}}^{\alpha\beta}(q,P)S_{f_2}(q_-)]_{\alpha'\beta'}$$

$S_{f_1}(q_+)$
- **Quark propagator**
  solution of the gap equation

$$S_f^{-1}(k) = Z_2(-i\gamma\cdot k + m_f) + Z_1\int_{\mathrm{d}\,q}^{\Lambda} g^2 D^{\mu\nu}(k-q)\frac{\lambda^a}{2}\gamma_\mu S(q)\frac{\lambda^a}{2}\Gamma_\nu(q,k)$$

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$$f_{\rm PS}\varphi(x,\zeta) = Z_2(\zeta,\Lambda)\mathrm{Tr}_{\rm CD}\int_{\mathrm{d}q}^{\Lambda}\delta(n\cdot q_+ - x n\cdot P)\gamma_5(\gamma\cdot n)\chi_{\rm PS}(q,P)$$

- **Not accessible** in Euclidean space

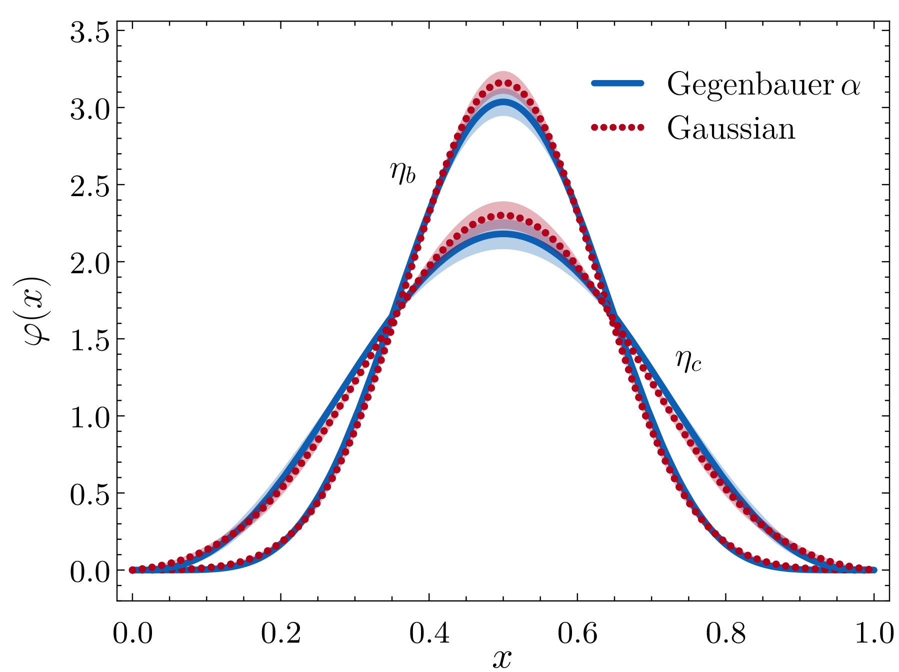
- **Mellin moments**
  used for reconstructing the PDA

$$\langle x^m\rangle = \frac{1}{f_{\rm PS}} Z_2(\zeta;\Lambda)\mathrm{Tr}_{\rm CD}\int_{\mathrm{d}q}^{\Lambda}\frac{(n\cdot q_+)^m}{(n\cdot P)^{m+1}}\gamma_5(\gamma\cdot n)\,\chi_{\rm PS}(q;P)$$

- **Highly oscillatory integral** in Euclidean space
- **Requires damping factor** and extrapolation
  $1/(1+r^2k^2)^m; \qquad r^2\to 0$

- **Two possible representations**
  for determining the full amplitude
  - **Gegenbauer**
    $\varphi(x) = \mathcal{N}x^\alpha(1-x)^\beta$
  - **Gaussian**
    $\varphi(x) = \mathcal{N}[1-(2x-1)^2]\,\mathrm{e}^{\mathfrak{a}^2(1-(2x-1)^2)+\mathfrak{b}^2(2x-1)}$

- **Main difference**
  behavior as $x\to 1$
  - **Affects the inverse moment** $\int_0^1 \mathrm{d}x\,\phi(x)/(1-x)$
    large Q^2 behavior of form factors
  - **Heavy-heavy limit:** $\varphi(x)\to\delta(1-x/2)$
  - **Heavy-light limit:** $\varphi(x)\to\delta(1-x)$

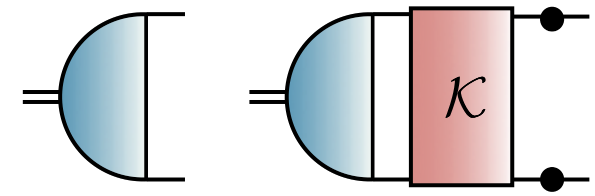


Propagators and BS amplitudes

- **Use RL truncation**
  for gap and BS equation

  $\Gamma_\nu = \gamma_\nu$

  $\mathcal{K}[S\Gamma_{\rm PS}S] = -P^{\mu\nu}\mathcal{G}\gamma_\mu[S\Gamma_{\rm PS}S]\gamma_\nu$



- **For the interaction**
  we set

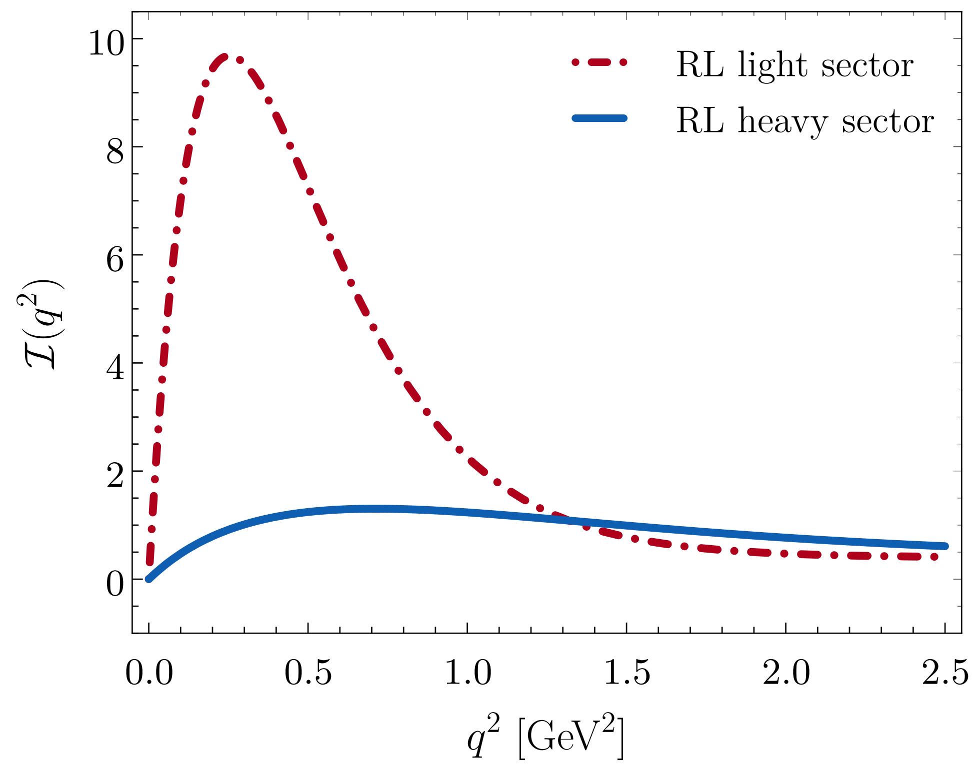
  Qin, Chang, Liu, Roberts and Wilson, PRC 84 (2011)

$$\mathcal{I}(k^2) = k^2\,\frac{\mathcal{G}_{\rm IR}(k^2)+\mathcal{G}_{\rm UV}(k^2)}{4\pi}$$

$$\mathcal{G}_{\rm IR}(k^2) = \frac{8\pi^2}{\omega^5}\varsigma^3 {\rm e}^{-k^2/\omega^2}$$

$$\mathcal{G}_{\rm UV}(k^2) = \frac{96\pi^2}{25}\,\frac{1-e^{-k^2/1[{\rm GeV}^2]}}{k^2\log[{\rm e}^2-1+(1+k^2/\Lambda^2)^2]}$$

  - **Light quark sector** (GeV)
    $\varsigma = 0.8; \qquad \omega = 0.5$
  - **Heavy quark sector** (GeV)
    $\varsigma = 0.6; \qquad \omega = 0.8$



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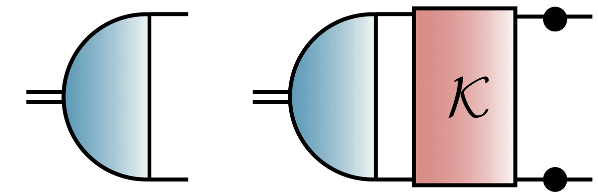


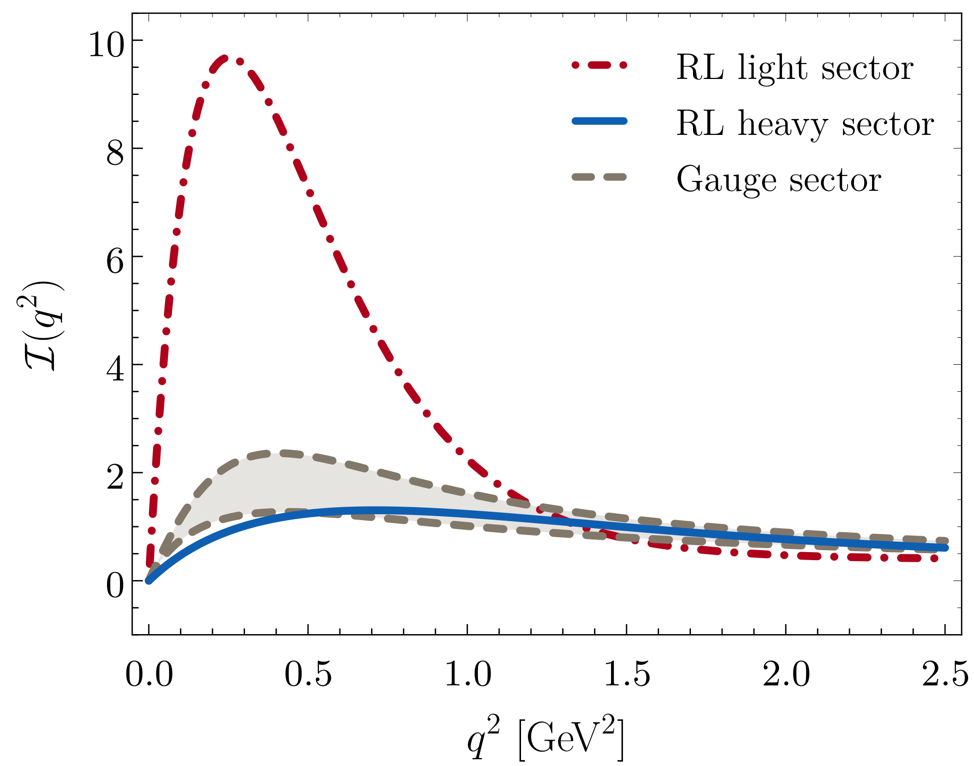
- **For the interaction**
  we set
  Qin, Chang, Liu, Roberts and Wilson, PRC 84 (2011)

$$\mathcal{I}(k^2) = k^2\,\frac{\mathcal{G}_{\rm IR}(k^2) + \mathcal{G}_{\rm UV}(k^2)}{4\pi}$$

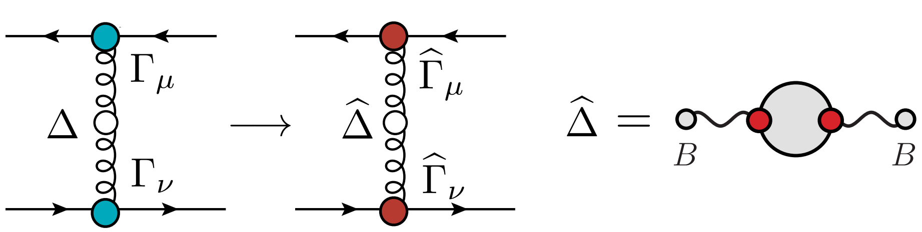
$$\mathcal{G}_{\rm IR}(k^2) = \frac{8\pi^2}{\omega^5}\varsigma^3 {\rm e}^{-k^2/\omega^2}$$

$$\mathcal{G}_{\rm UV}(k^2) = \frac{96\pi^2}{25}\,\frac{1-e^{-k^2/1[{\rm GeV}^2]}}{k^2\log[{\rm e}^2-1+(1+k^2/\Lambda^2)^2]}$$

  - **Light quark sector** (GeV)
    $\varsigma = 0.8; \qquad \omega = 0.5$
  - **Heavy quark sector** (GeV)
    $\varsigma = 0.6; \qquad \omega = 0.8$

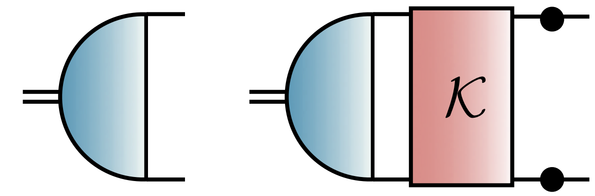


- **Heavy sector interaction**
  overlaps with gauge sector kernel determination
  DB, Chang, Papavassiliou, Roberts, PLB 742 (2015)



Propagators and BS amplitudes

- **Use RL truncation**
  for gap and BS equation



$$\Gamma_\nu = \gamma_\nu$$

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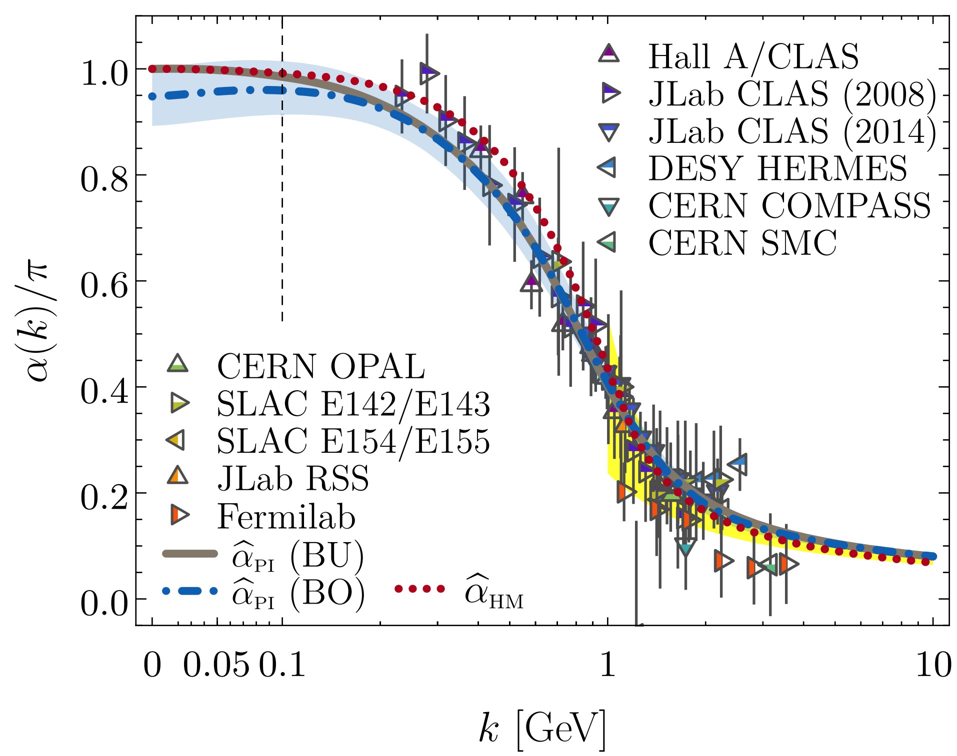

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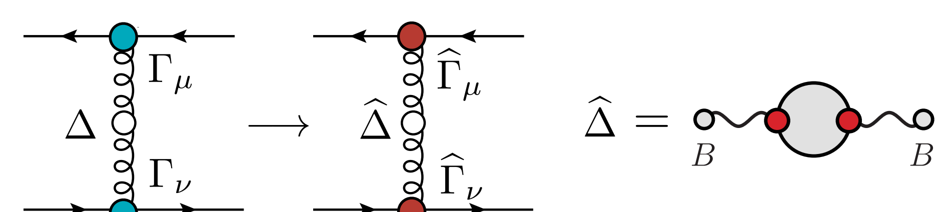
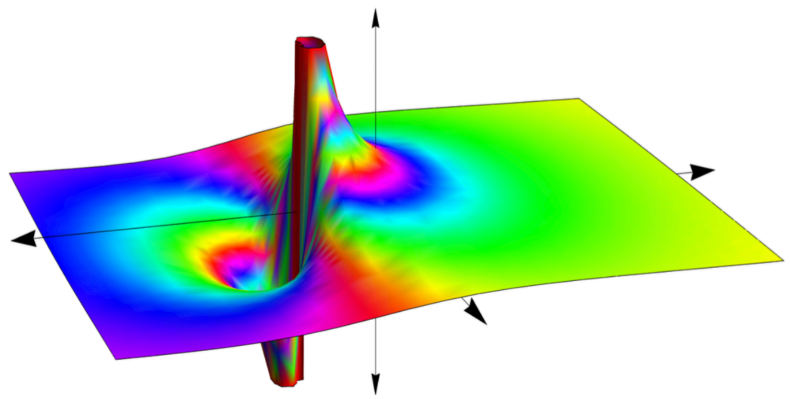
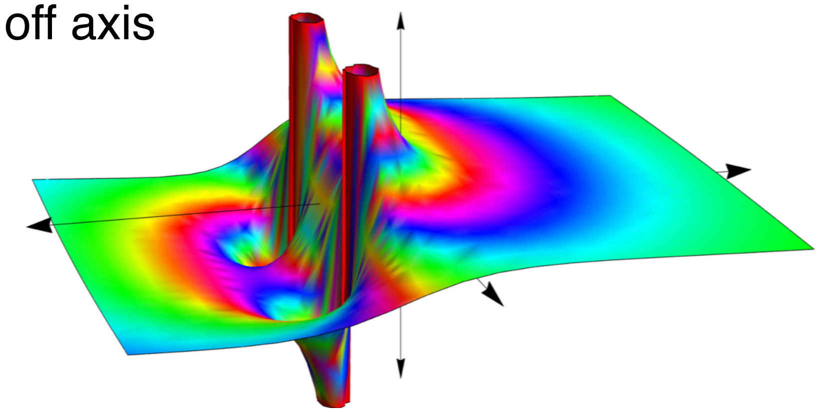


Propagators and BS amplitudes

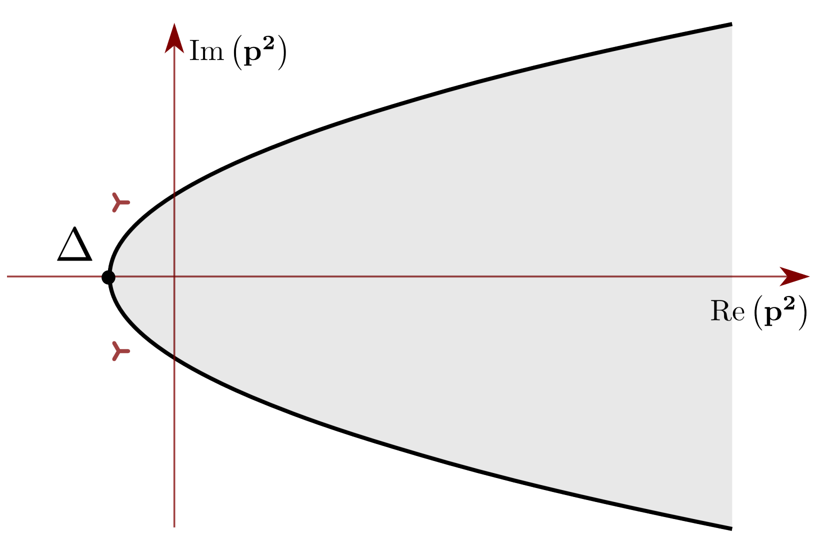
- **SDE solutions**
  dramatic change in the analytic structure
  - **Normal particle**
    mass pole on the real axis
  - **SDE solutions**
    interactions move the mass pole off axis





  - **Complex conj. singularities**
    characterized by a dynamically generated mass scale

- **SDE singularities**
  impacts our ability to find BS solutions
  - **Quark propagators**
    need to be known on a parabolic region



  - **Cauchy th. not valid**
    if singularities are inside the contour
  - **Maximize parabola apices**
    probe bound states up to $M = \Delta_h + \Delta_l \;\; (\Delta_h \gg \Delta_l)$
  - **Use freedom to unbalance legs**
    in BS equation

$$q_+ = q + \eta P \qquad\qquad \eta \in [\Delta_h/M, 1 - \Delta_l/M]$$
$$q_- = q - (1-\eta)P$$

  - **Still, if gap is too big**
    no BS solution exists anyway

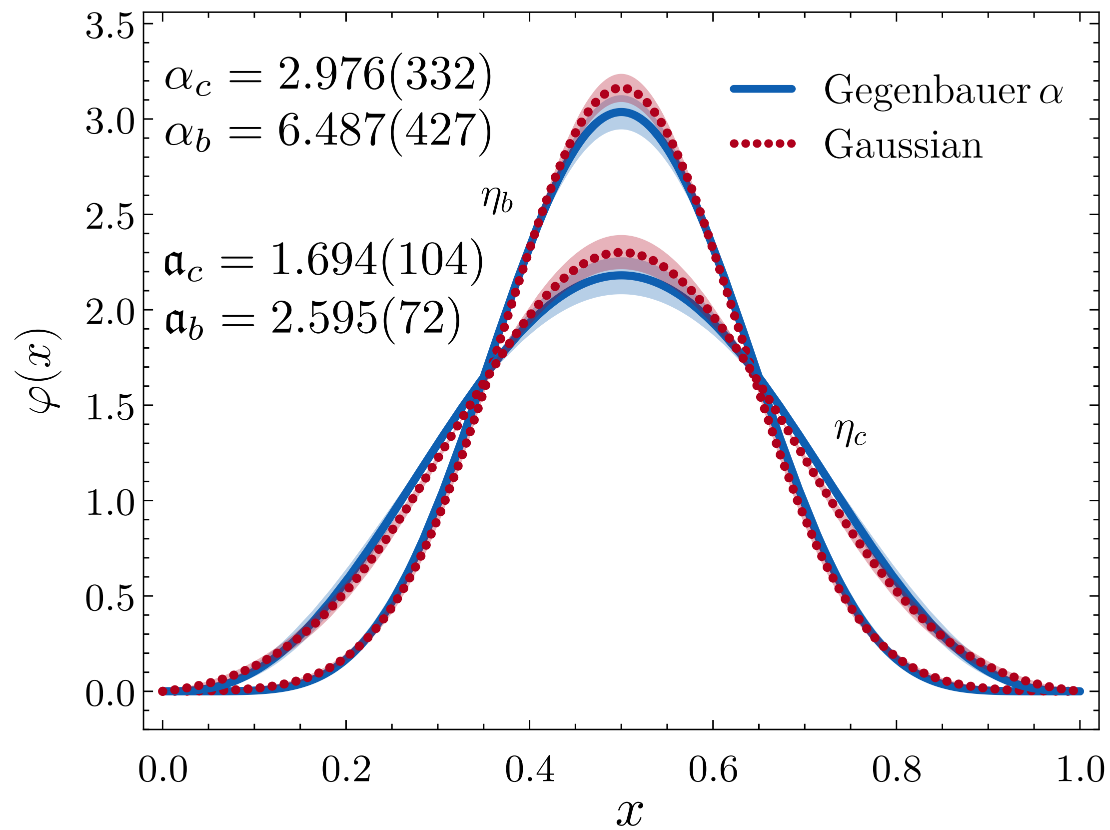
Heavy-light systems in RL

- **Choose current masses**
  for heavy quarks (in GeV): $m_c = 1.25,\ m_b = 4.35$

- **Fix interaction parameters**
  to heavy sector values: $\varsigma = 0.6;\ \omega = 0.8$

- **Evaluate properties of η mesons**

			Exp.		lQCD	
	m_i	f_i	m_i	f_i	m_i	f_i
η_c	2.98	0.272	2.98	0.238	2.98	0.279
η_b	9.38	0.501	9.39	/	9.39	0.472



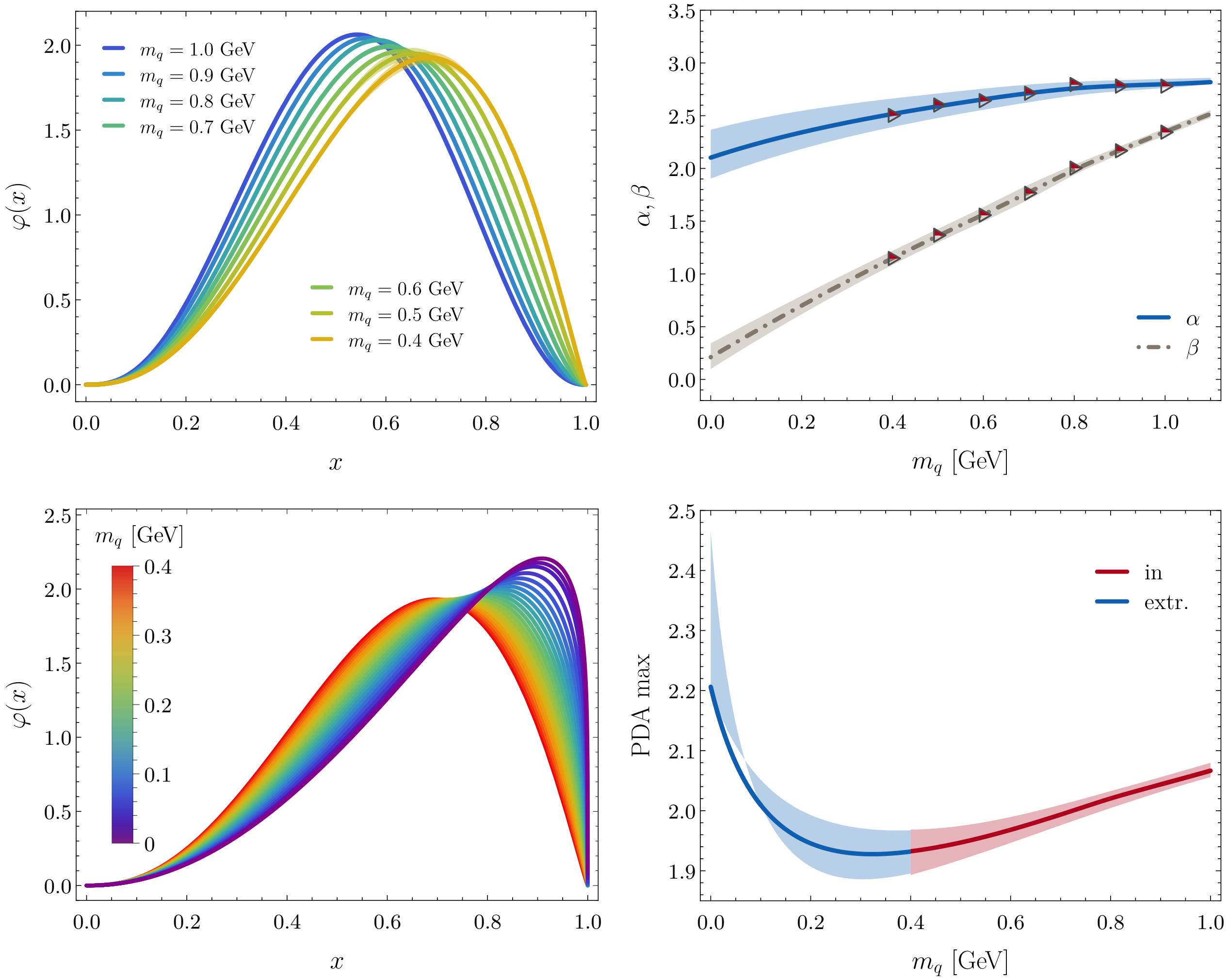
- **Construct an array of fictitious $h\bar{q}$ pseudoscalar mesons**
  down to the lowest m_q RL can accommodate
  - **Charm sector:** $m_q \sim 0.4$
  - **Bottom sector:** $m_q \sim 1.3$

- **Estimate PDAs parameters**
  use them to (SPM) extrapolate to lower m_q masses

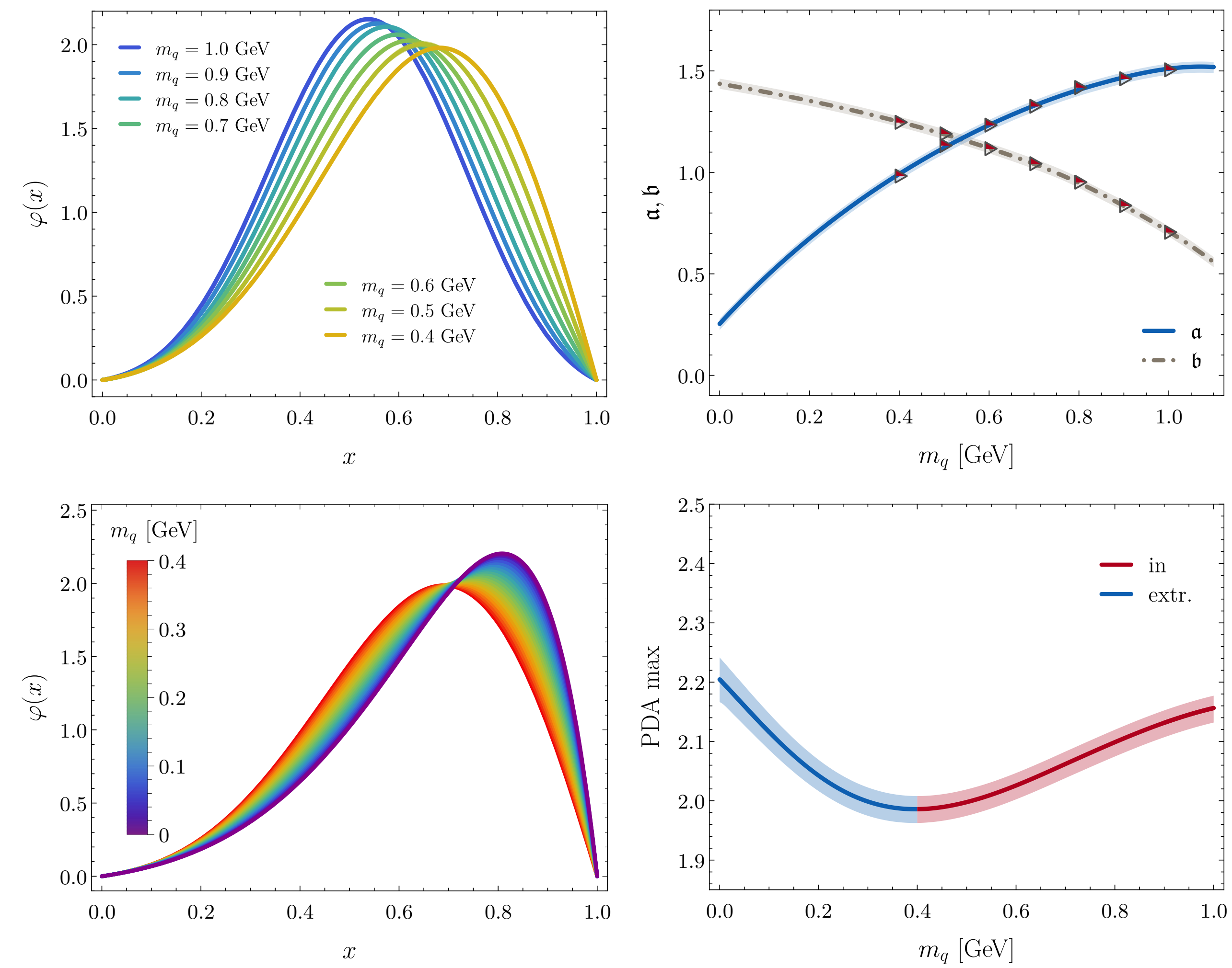
Charm sector

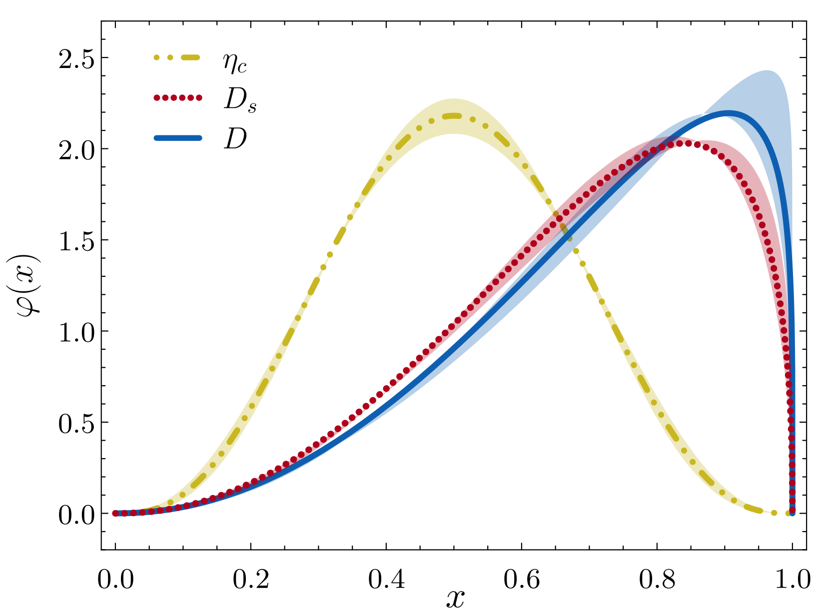
m_q	α	β	$\mathfrak{a}$	$\mathfrak{b}$
m_s	$2.212^{0.228}_{0.184}$	$0.418^{0.102}_{0.123}$	$0.442^{0.025}_{0.030}$	$1.404^{0.025}_{0.025}$
m_u	$2.107^{0.254}_{0.168}$	$0.220^{0.107}_{0.143}$	$0.262^{0.025}_{0.030}$	$1.436^{0.025}_{0.025}$

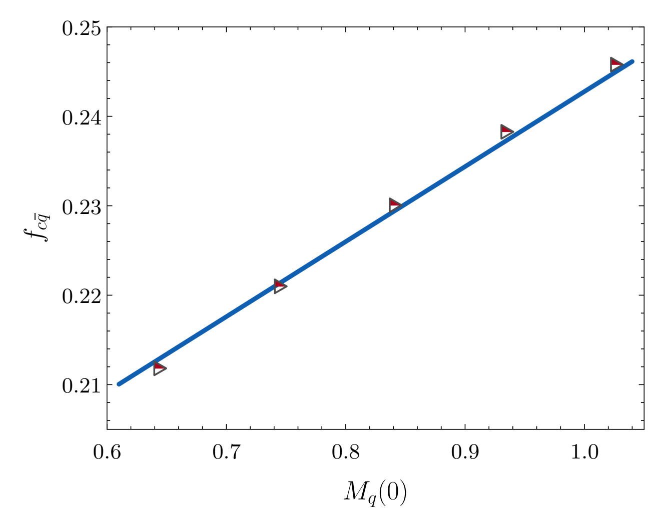
- **Gegenbauer**

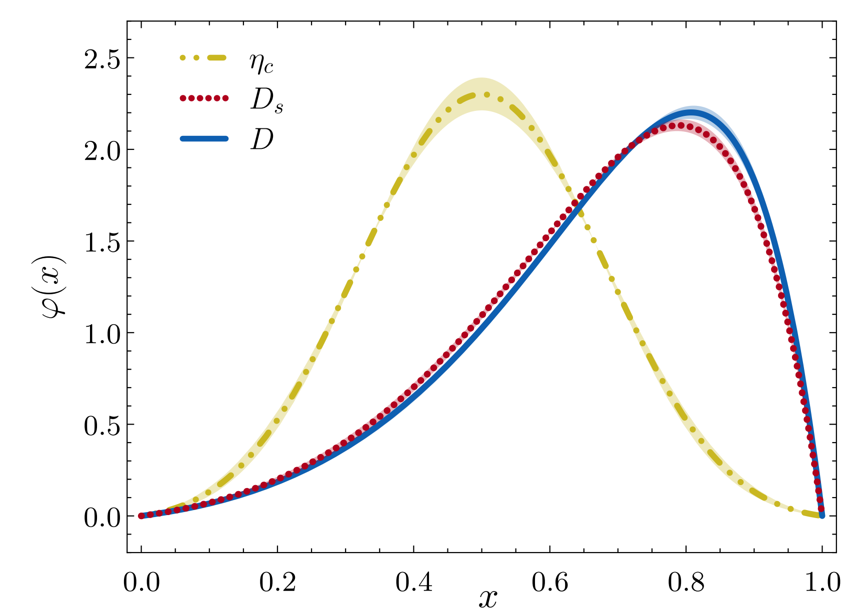


- **Gaussian**









Charm sector

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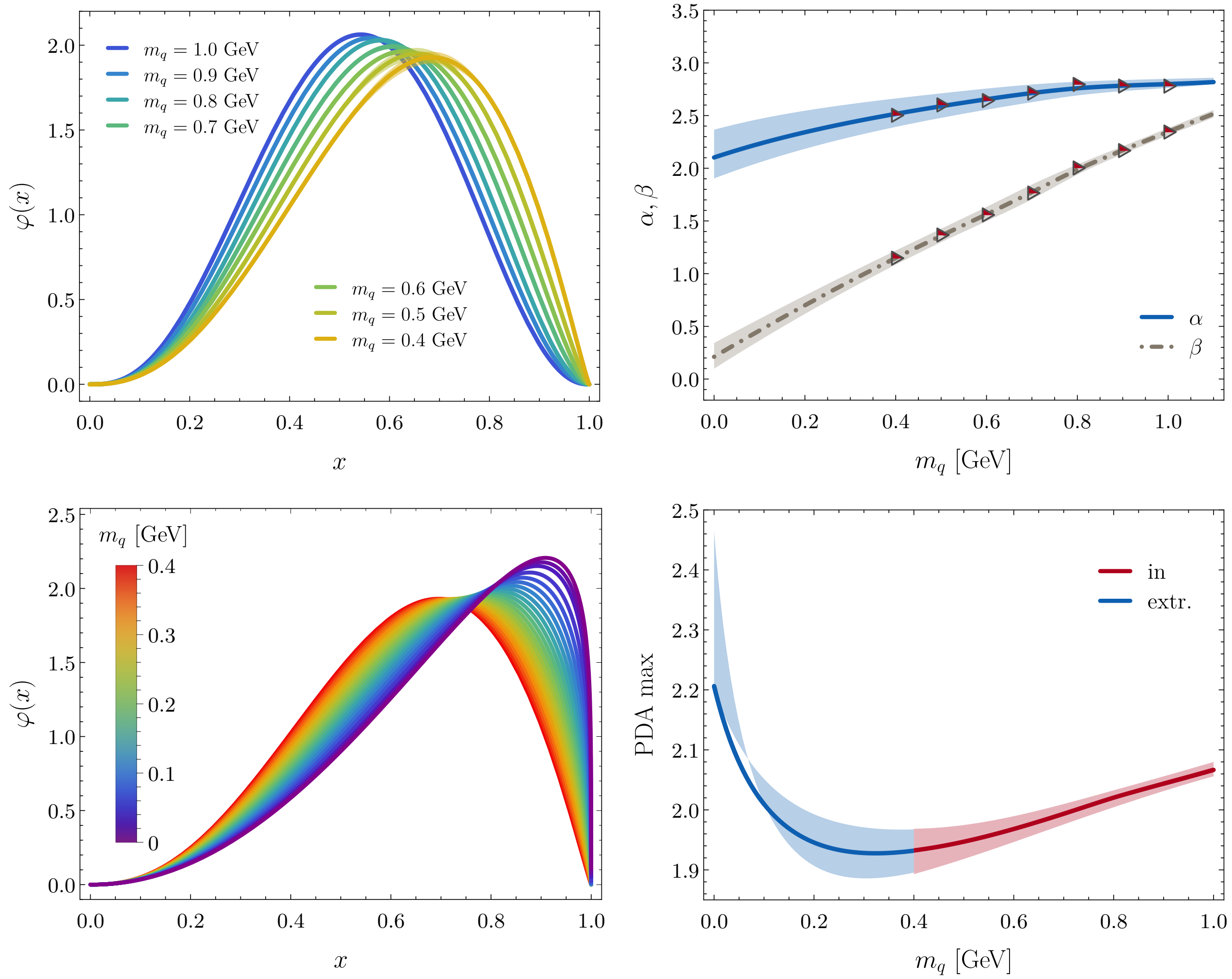

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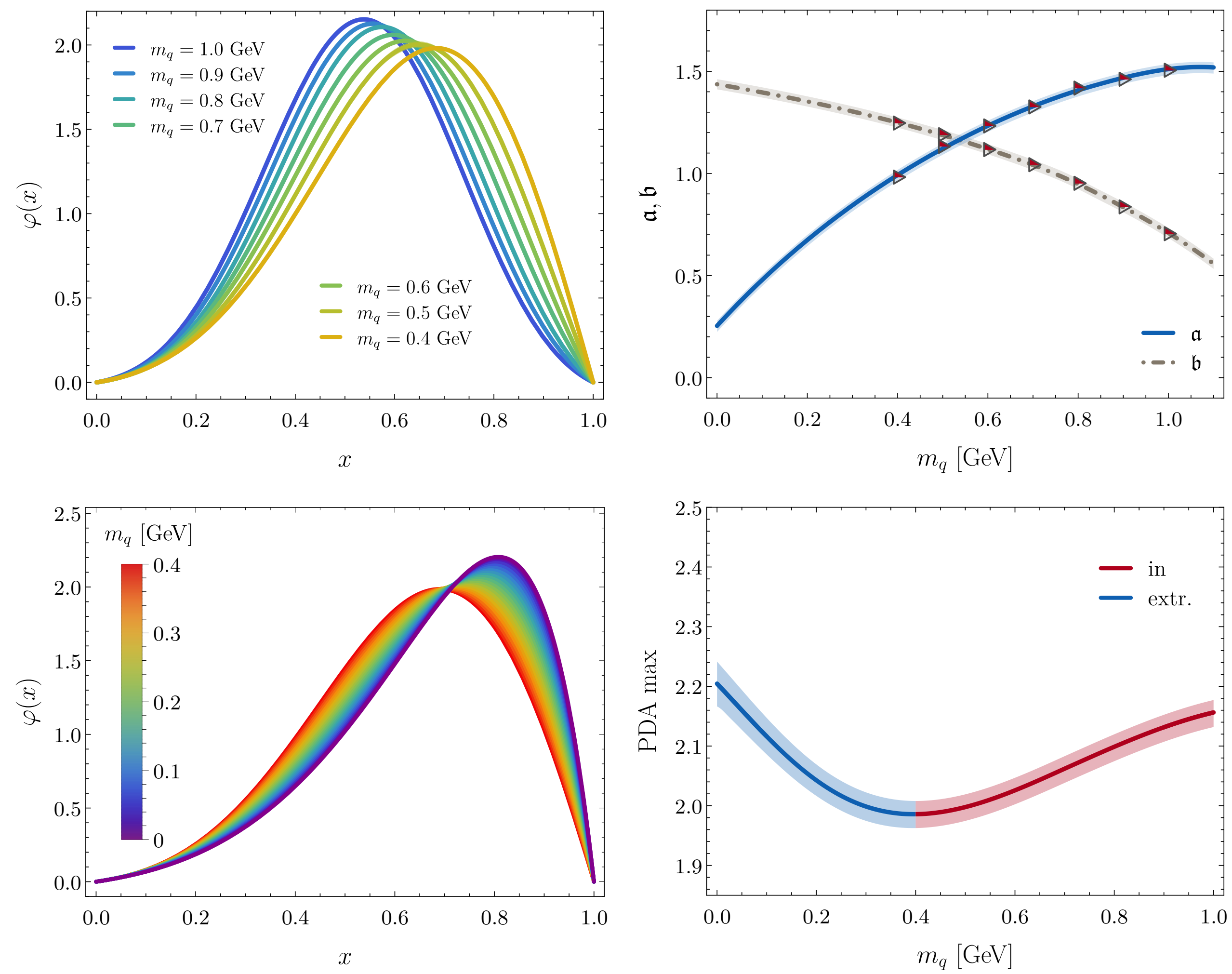
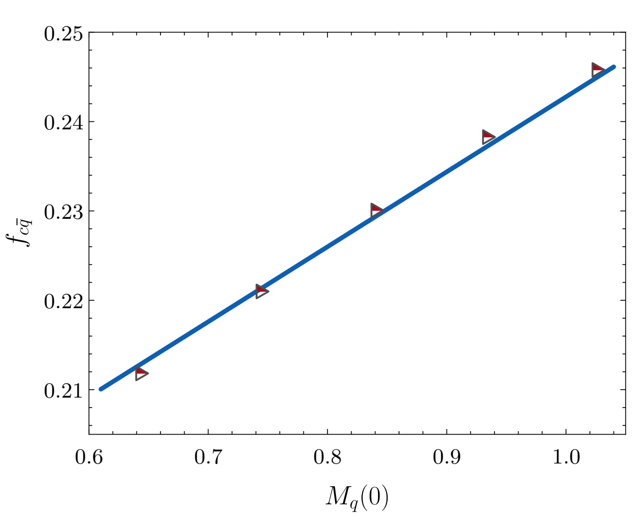
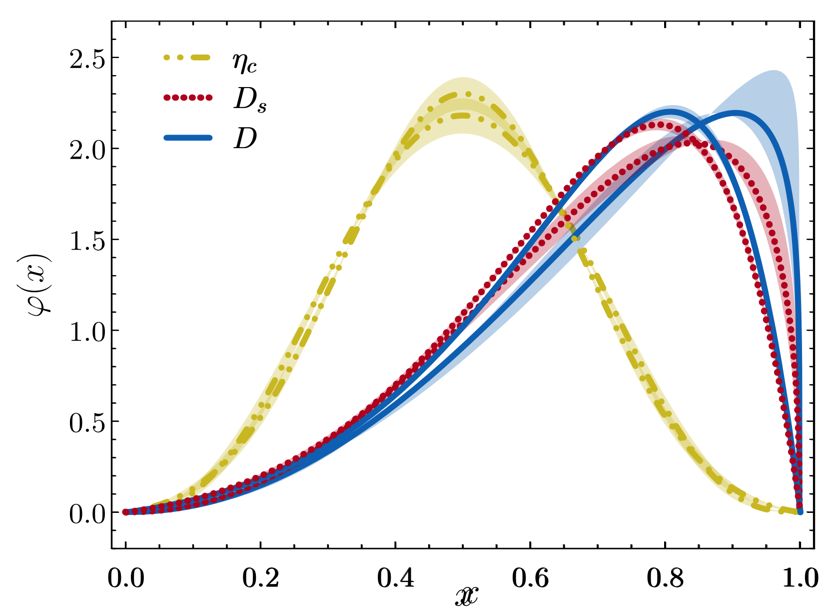


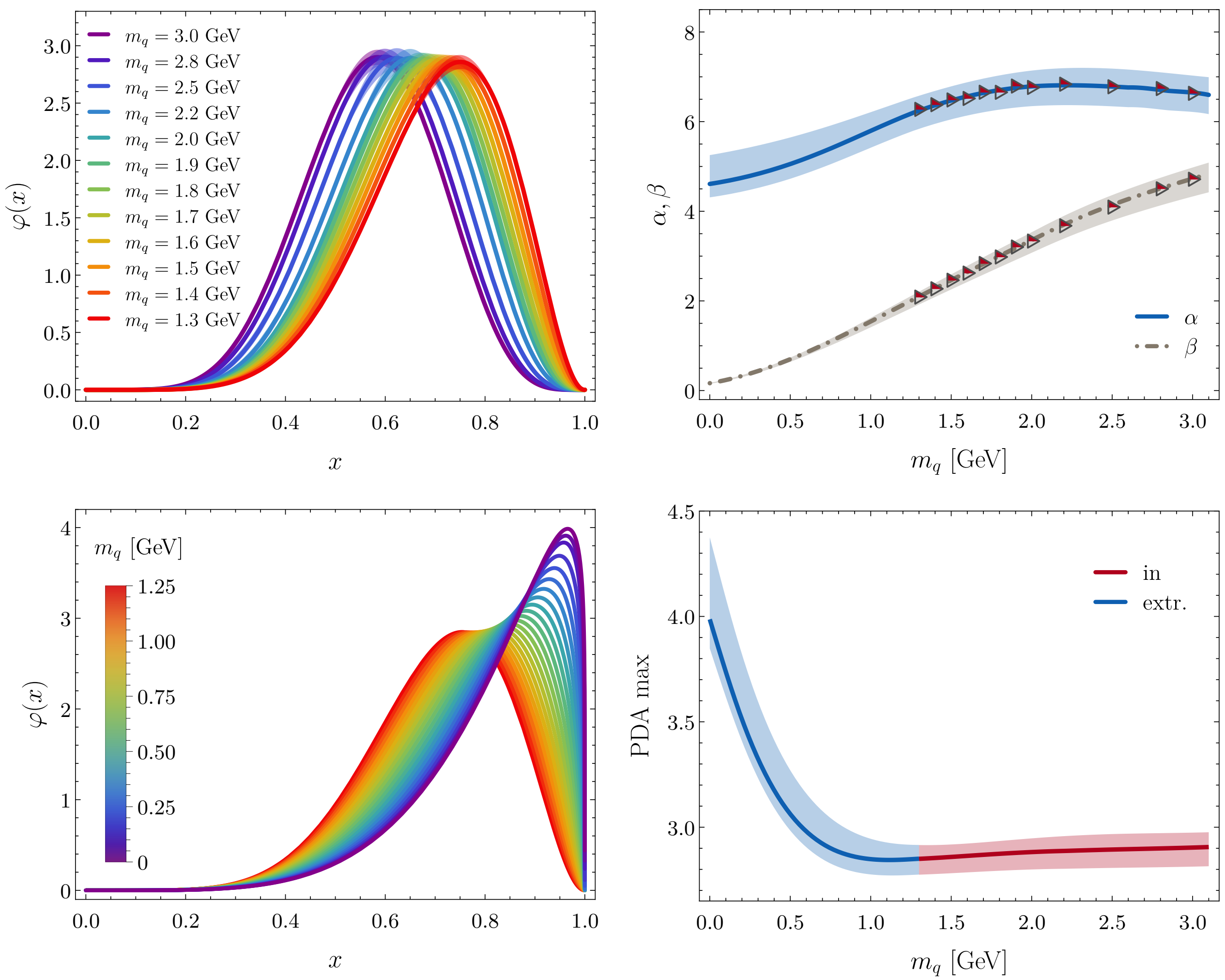




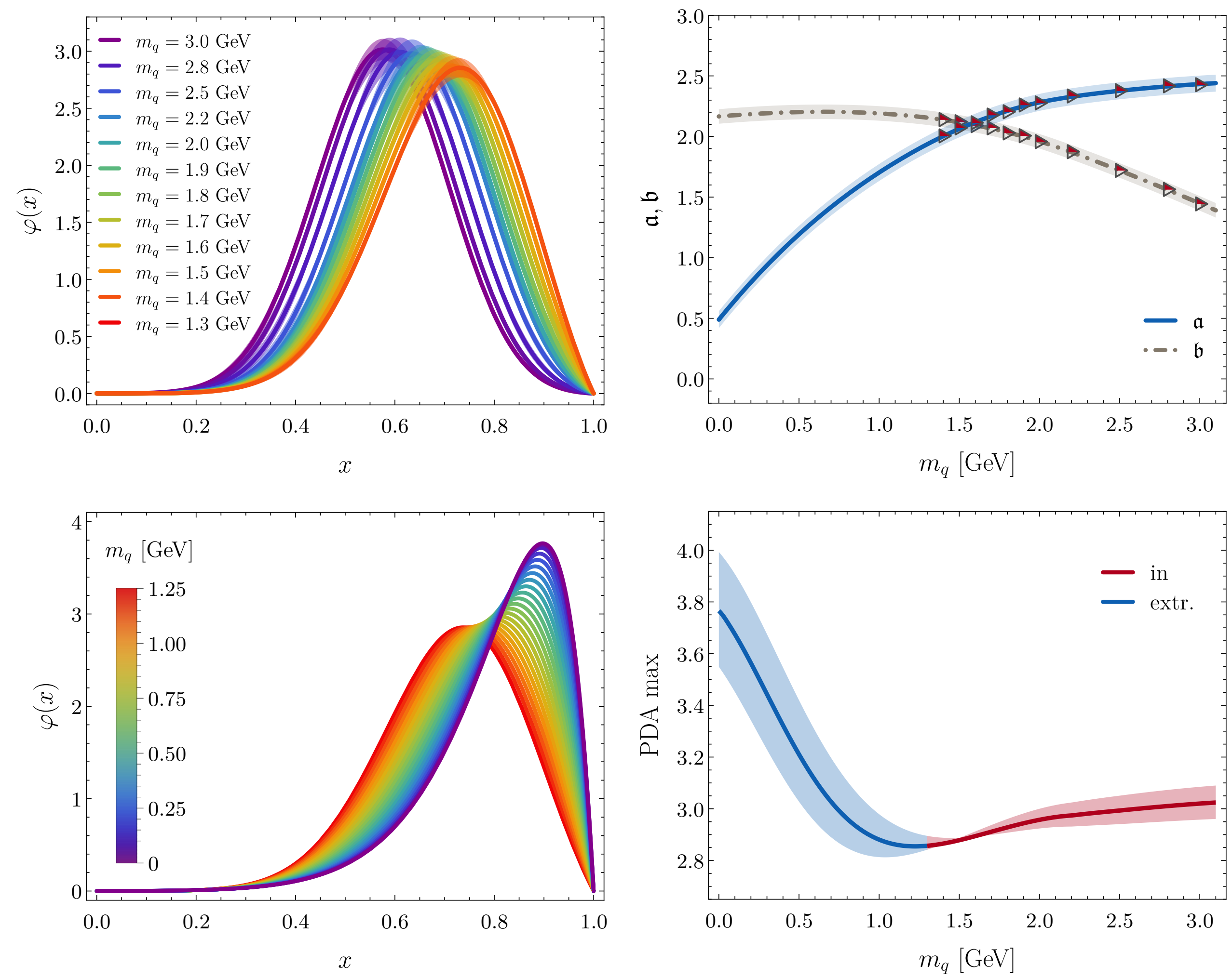
Bottom sector

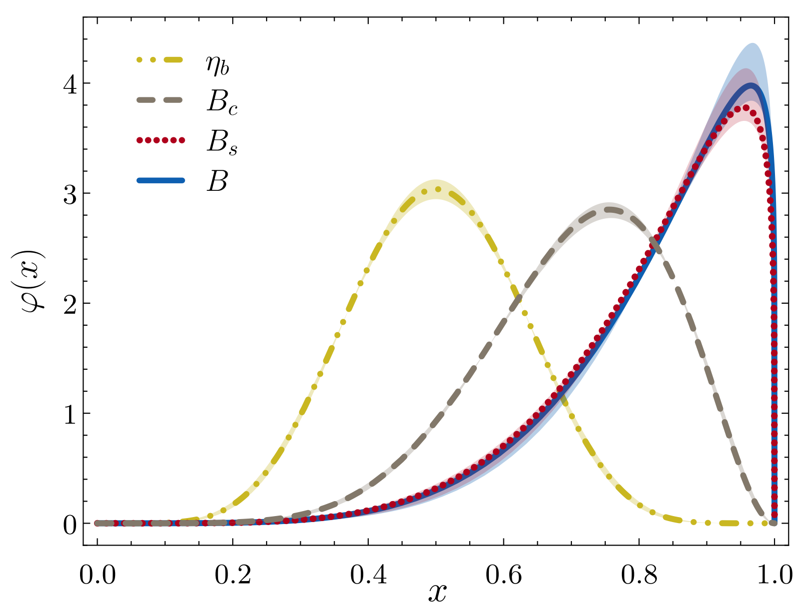
m_q	α	β	$\mathfrak{a}$	$\mathfrak{b}$
m_c	$6.179^{0.398}_{0.379}$	$1.994^{0.342}_{0.141}$	$1.901^{0.070}_{0.070}$	$2.163^{0.060}_{0.060}$
m_s	$4.660^{0.760}_{1.240}$	$0.230^{0.125}_{0.108}$	$0.621^{0.070}_{0.070}$	$2.174^{0.060}_{0.060}$
m_u	$4.612^{0.714}_{1.287}$	$0.144^{0.054}_{0.118}$	$0.495^{0.070}_{0.070}$	$2.166^{0.060}_{0.060}$

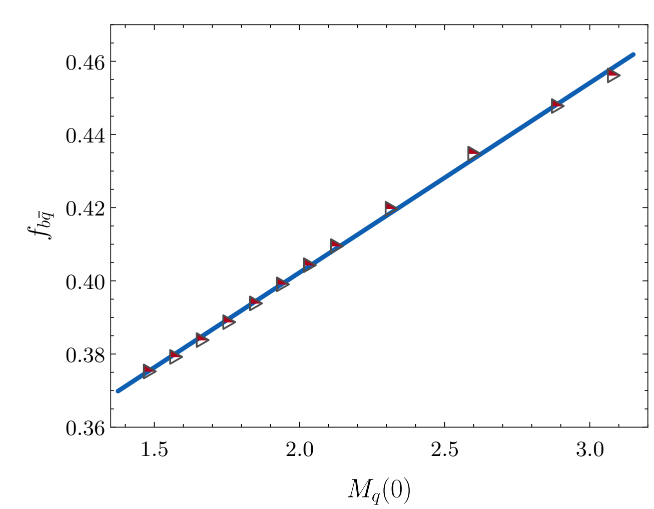
- **Gegenbauer**

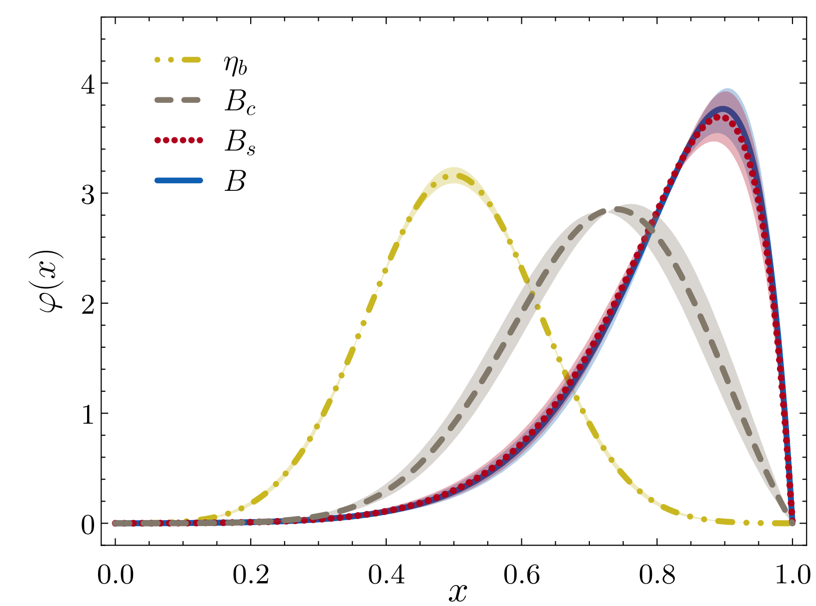


- **Gaussian**









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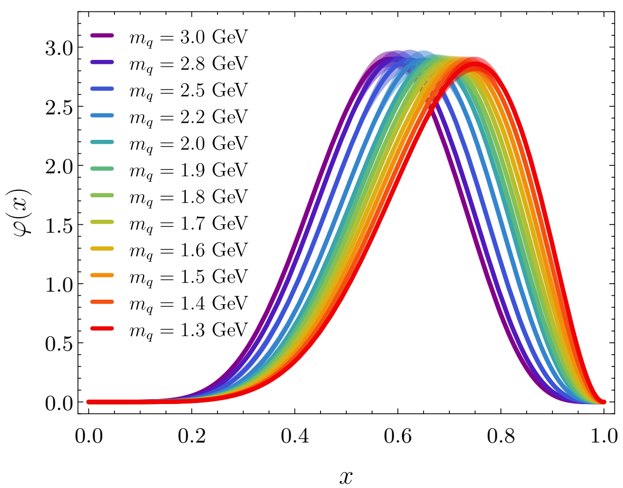
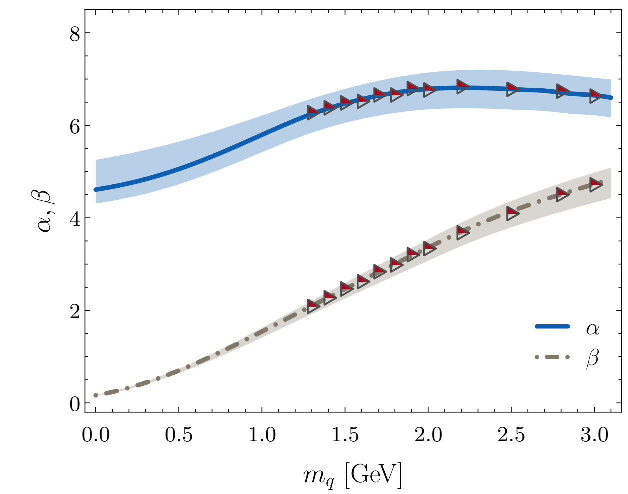
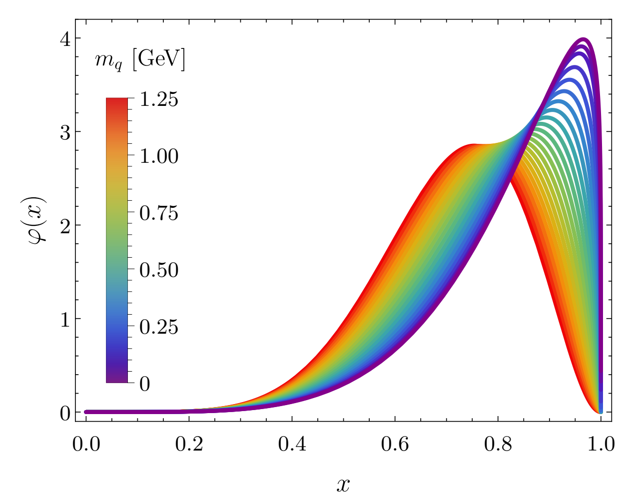
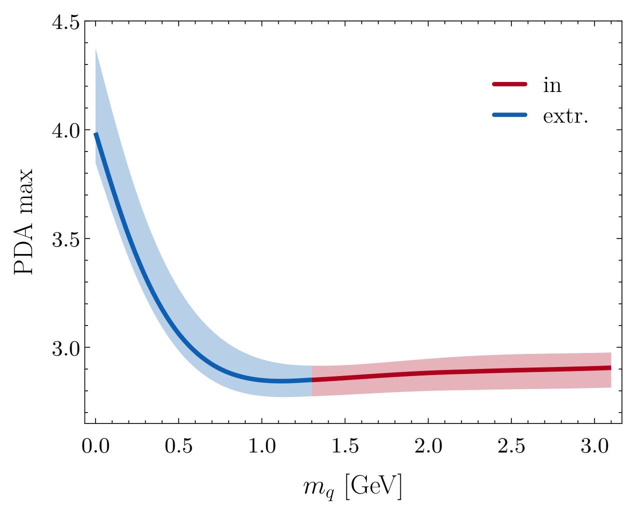
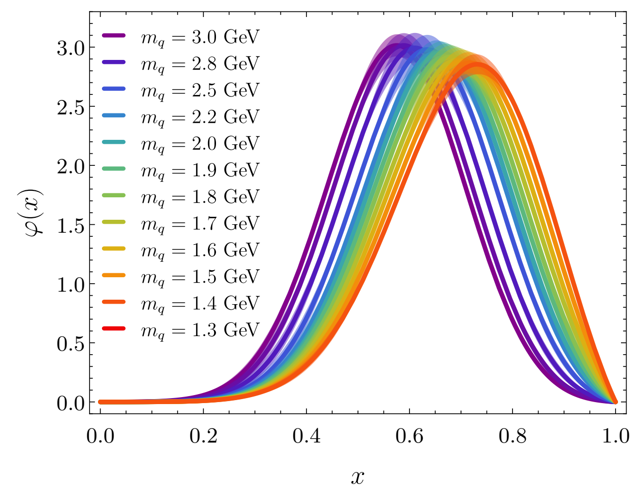


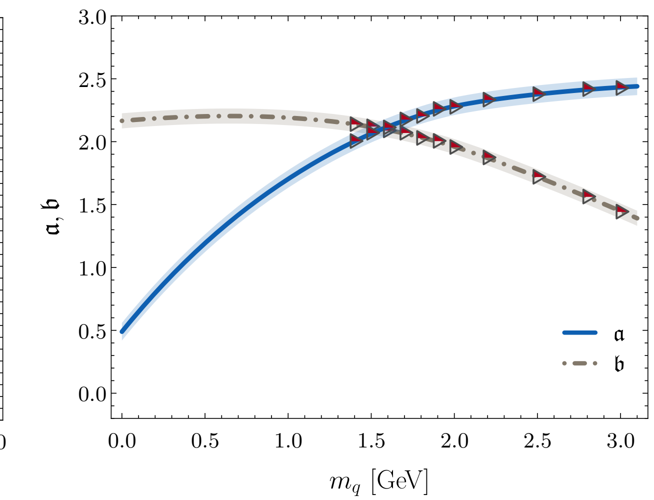


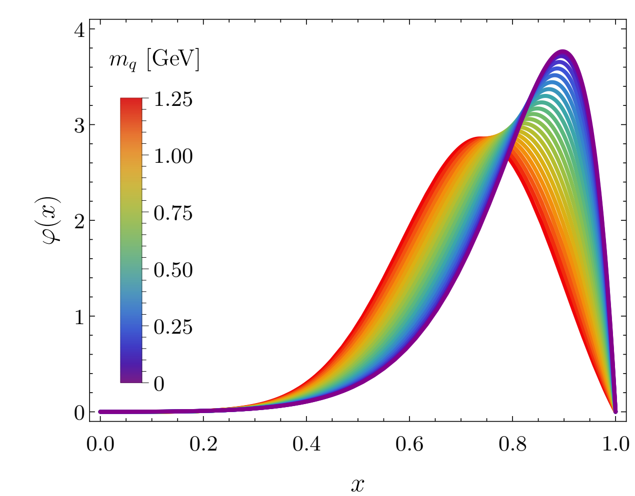


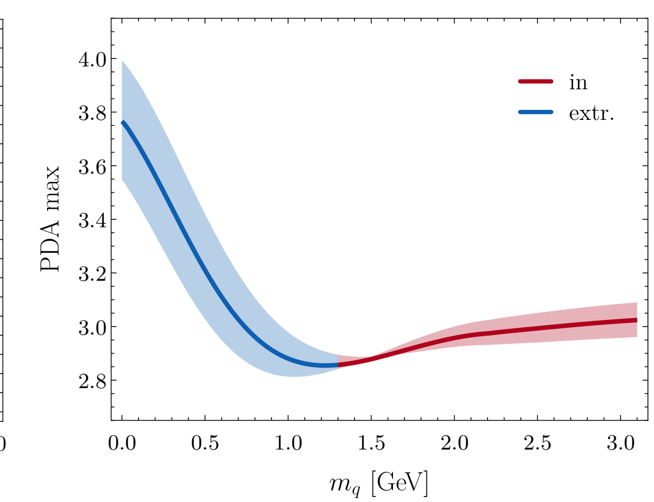


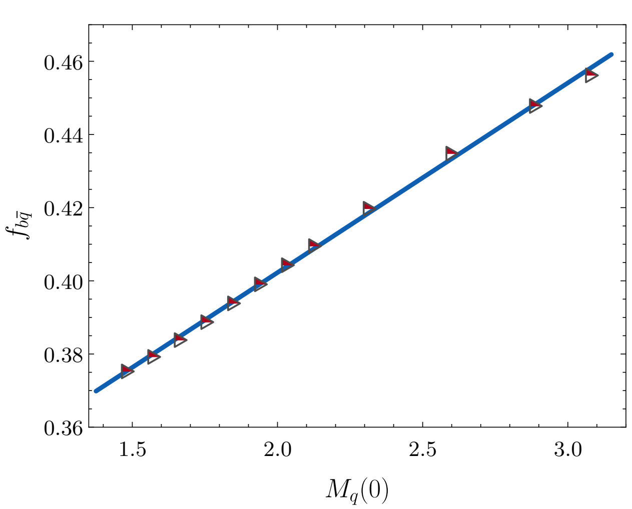
- **Gaussian**

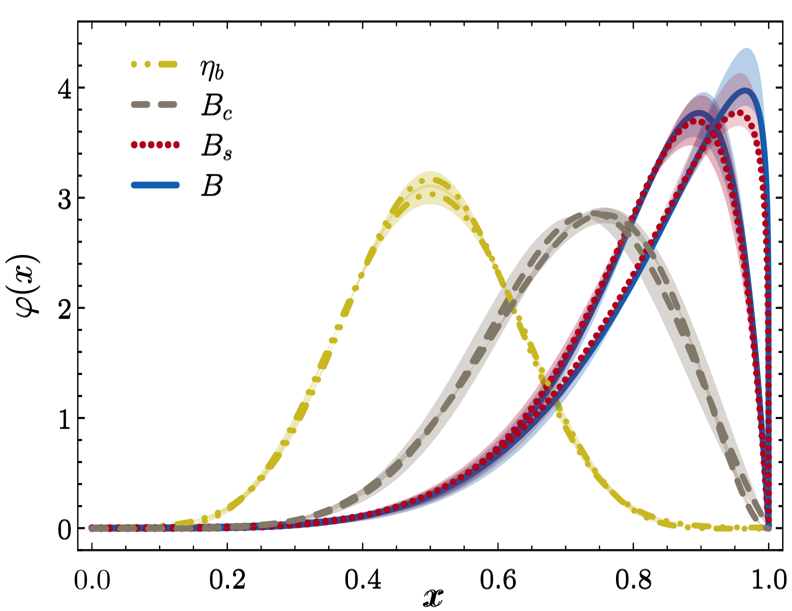


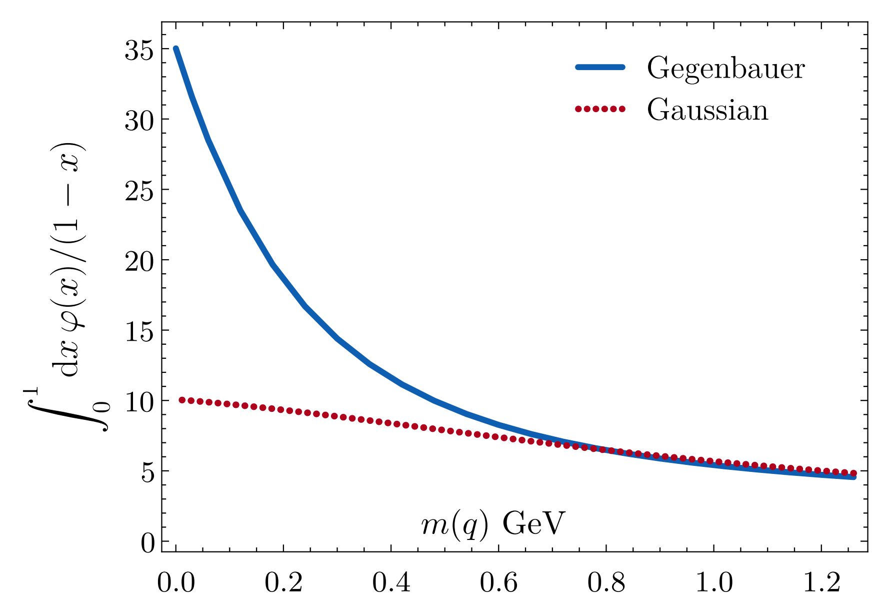


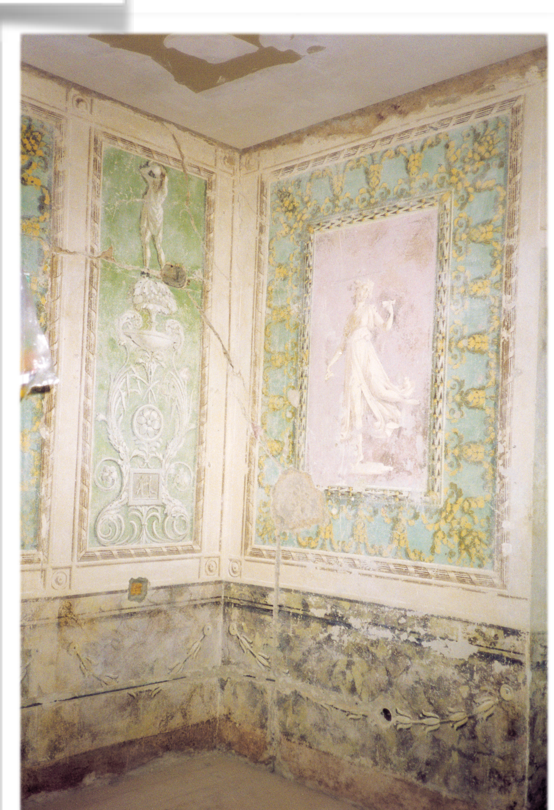












thank**you**