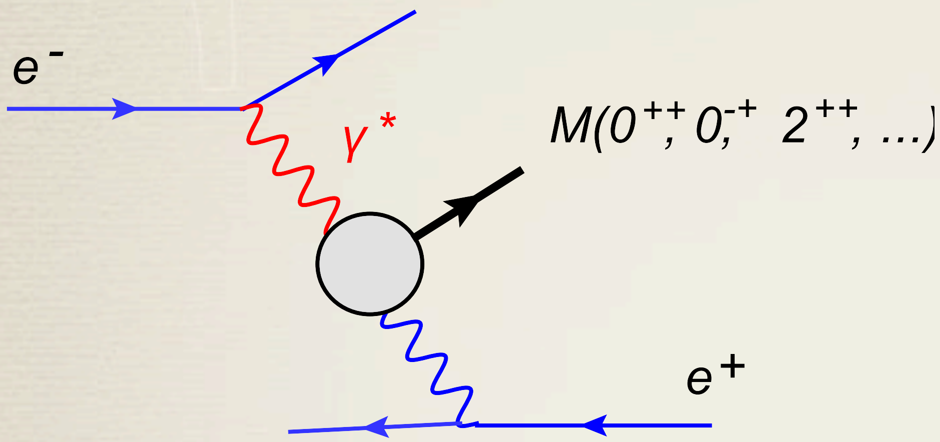
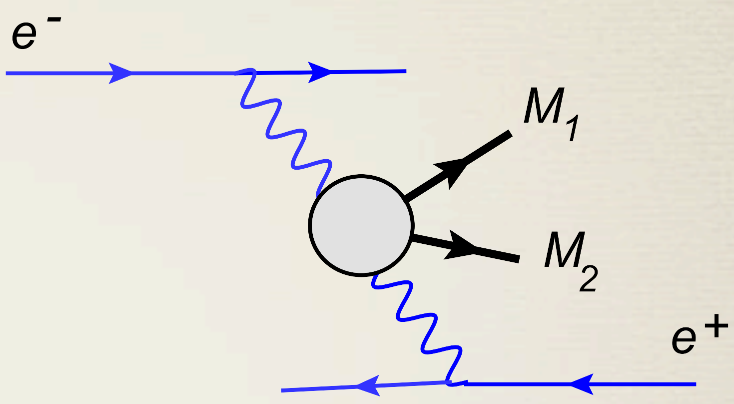
$\gamma^*\gamma \to f_2(1230)$ and $\gamma\gamma \to G_2\pi^0$ within QCD framework





Nikolay Kivel

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KEK seminar, 14th November, 2017, Japan

Outline

- Introduction: pQCD description of hard exclusive processes

- $\gamma^* + \gamma \to f_2(1270)$ as example of $q\bar{q}$-meson

  Braun, Kivel, Strohmaier, Vladimirov JHEP 1606 (2016)

- An opportunity to study glueball in $\gamma + \gamma \to G(2^{++}) + \pi^0$

  Kivel, Vanderhaeghen, to be published

- Discussion: suggestions, critics, skepticism, etc.

Introduction: QCD factorisation

QCD factorization <=> effective field theory approach

Two scales: hard and soft $Q^2 \gg \Lambda^2$ hadronic scale

Λ/Q small $\qquad \mathcal{A}(Q^2) \simeq H(Q^2) * S(\Lambda)$

Hard part is defined by a hard subprocess $p_h^2 \sim Q^2$

$$H(Q^2) = Q^{-2n} \left\{ h_{\rm LO} \left(\ln \frac{Q^2}{\Lambda^2} \right)^{\gamma_{LO}} + h_{\rm NLO}\, \alpha_s(Q^2) \left(\ln \frac{Q^2}{\Lambda^2} \right)^{\gamma_{NLO}} + \mathcal{O}(\alpha_s^2) \right\}$$

scaling behavior Q^{-2n} is the model independent QCD prediction (!) which can be checked by experiment

Log corrections can be systematically computed in pQCD $\alpha_s(Q^2) \sim \ln^{-1} Q^2/\Lambda^2 \ll 1$

Introduction: QCD factorisation

QCD factorization <=> effective field theory approach

Two scales: hard and soft $Q^2 \gg \Lambda^2_{QCD}$

$$Q \to \infty \qquad \mathcal{A}(Q^2) \simeq H(Q^2) * S(\Lambda)$$

Soft part is associated with a soft subprocess $p_s^2 \sim \Lambda^2$

defined as a matrix element in QCD

process independent (universality)

can be estimated only in the framework of
some nonperturbative approach
or
can be constrained from the experimental data

Gamma-f_2 transition FF's

$\gamma^*(q)\gamma(q') \to f_2(p)$ $\Gamma[f_2] = 185\text{MeV}$ $Br[f_2 \to \pi\pi] \sim 85\%$

assignment of known mesons to quark-model states

$n^{2s+1}L_J$	J^{PC}	$I=1$ $u\bar{d}\cdots$	$I=\frac{1}{2}$ $u\bar{s}\cdots$	$I=0$ f	$I=0$ f'	θ_q	θ_l
1^1S_0	0^{-+}	π	K	η	η'	$-11.5°$	$-24.6°$
1^3S_1	1^{--}	ρ	K^*	ω	ϕ	$38.7°$	$36.0°$
1^1P_1	1^{+-}	$b_1(1235)$	K_{1B}	$h_1(1170)$	$h_1(1380)$		
1^3P_0	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1370)$	$f_0(1710)$		
1^3P_1	1^{++}	$a_1(1260)$	K_{1A}	$f_1(1285)$	$f_1(1420)$		
1^3P_2	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2(1270)$	$f_2'(1525)$	$29.6°$	$28.0°$

flavor mixing in SU(3) $|\,8\,\rangle = \frac{1}{\sqrt{6}}(u\bar{u}+d\bar{d}-2s\bar{s})$ $|\,1\,\rangle = \frac{1}{\sqrt{3}}(u\bar{u}+d\bar{d}+s\bar{s})$

$$f = \cos\theta\ |\,1\,\rangle + \sin\theta\ |\,8\,\rangle$$
$$f' = \cos\theta\ |\,8\,\rangle - \sin\theta\ |\,1\,\rangle$$

$$|f_2\rangle = 0.70|u\bar{u}+d\bar{d}\rangle + 0.11|s\bar{s}\rangle$$

γ f₂ transition Form Factors $\gamma^*(q)\gamma(q') \to f_2(1270)$

There are 3 amplitudes = transitions FFs

$$T^{\mu\nu} = i\int d^4x\, e^{-i(qx)}\langle f_2(P,\lambda)|T\{j^\mu_{\rm em}(x) j^\nu_{\rm em}(0)\}|0\rangle = T_0^{\mu\nu} + T_1^{\mu\nu} + T_2^{\mu\nu}$$

$$T_0^{\mu\nu} = (-g_\perp^{\mu\nu})\, e^{(\lambda)*}_{\alpha\beta} (q-q')^\alpha (q-q')^\beta \frac{m^2}{(2qq')^2} T_0(Q^2)\,,$$

$$T_1^{\mu\nu} = e^{(\lambda)*}_{\alpha\beta}\ (-g_\perp^{\alpha\nu})\,(q-q')^\beta \left[q^\mu - q'^\mu \frac{q^2}{(qq')}\right] \frac{m^2}{(2qq')^2} T_1(Q^2)\,,$$

$$T_2^{\mu\nu} = e^{(\lambda)*}_{\alpha\beta}\left[g_\perp^{\alpha\mu} g_\perp^{\beta\nu} - \frac{1}{2} g_\perp^{\mu\nu} \frac{m^2}{(2qq')^2}(q-q')^\alpha (q-q')^\beta\right] T_2(Q^2)$$

$q_\mu g_\perp^{\beta\nu} = q'_\nu g_\perp^{\mu\nu} = 0$ transverse q & q'

$$-q^2 \equiv Q^2 > 0$$

γ f₂ transition Form Factors $\gamma^*(q)\gamma(q') \to f_2(1270)$

There are 3 amplitudes = transitions FFs

$\gamma^*(\pm)\gamma(\pm) \to f_2(0)$ $\qquad$ $\gamma^*(0)\gamma(\pm) \to f_2(\mp)$ $\qquad$ $\gamma^*(\mp)\gamma(\pm) \to f_2(\mp 2)$

$T_0(Q^2)$ $\qquad$ $T_1(Q^2)$ $\qquad$ $T_2(Q^2)$

$Q^2=0$

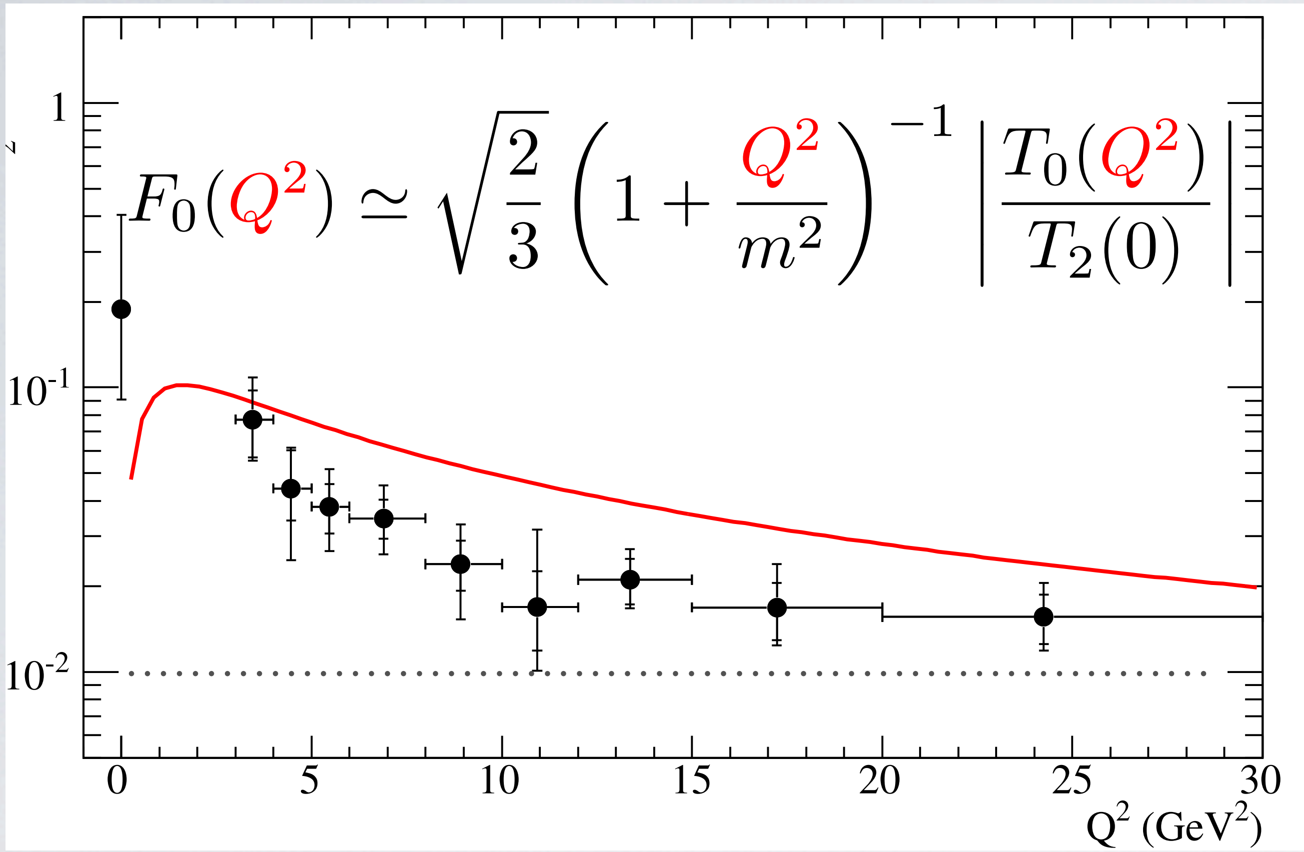
$$\Gamma[f_2 \to \gamma\gamma] = \frac{\pi\alpha^2}{5m}\left(\frac{2}{3}|T_0(0)|^2 + |T_2(0)|^2\right) = 3.03(40)\,\mathrm{keV}$$

$$\frac{\Gamma_{\gamma\gamma}^{\Lambda=0}}{\Gamma_{\gamma\gamma}^{\Lambda=2}} \simeq (3.7 \pm 0.3) \times 10^{-2} \qquad |T_0(0)| \ll |T_2(0)|$$

Belle 2008, Uehara et al

$$|T_2(0)| \simeq \sqrt{\frac{5m}{\pi\alpha^2}\Gamma[f_2 \to \gamma\gamma]} = 339(22)\,\mathrm{MeV}$$

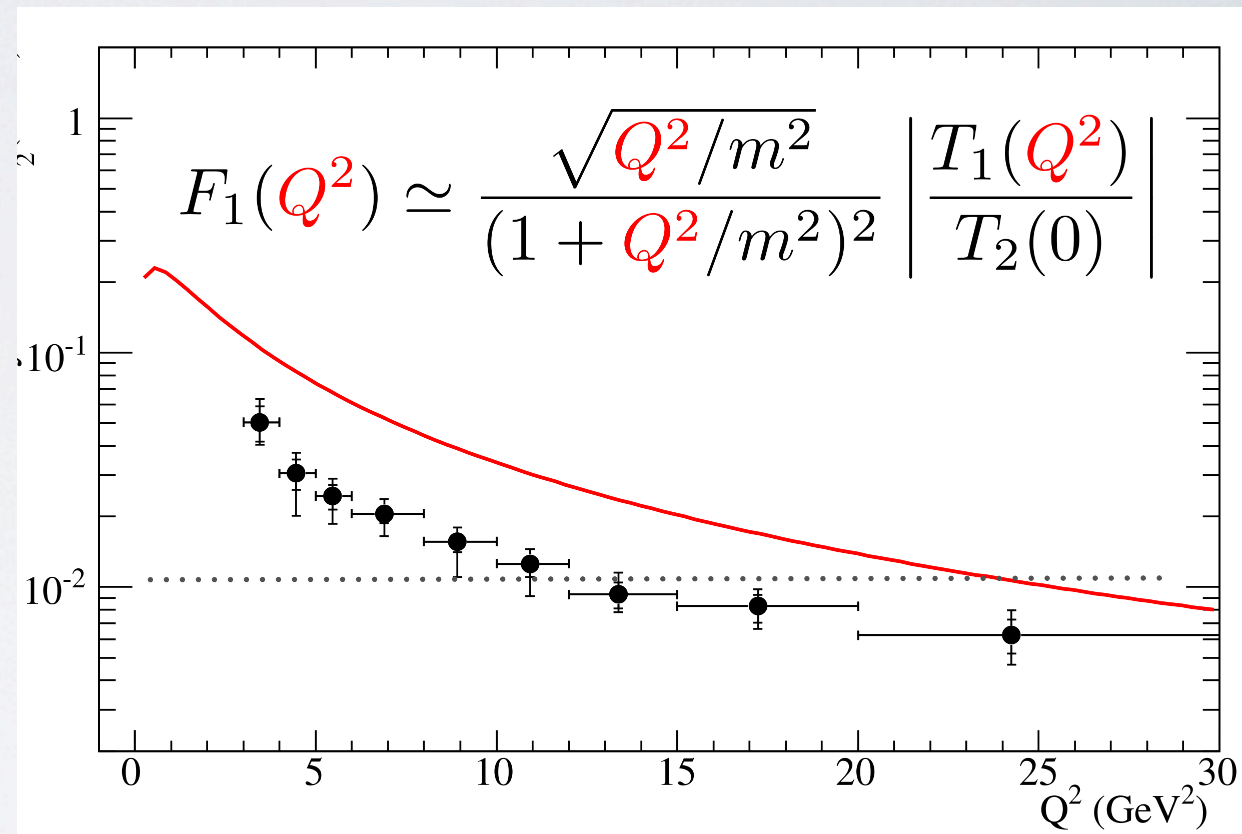
$\gamma\, f_2$ transition Form Factors

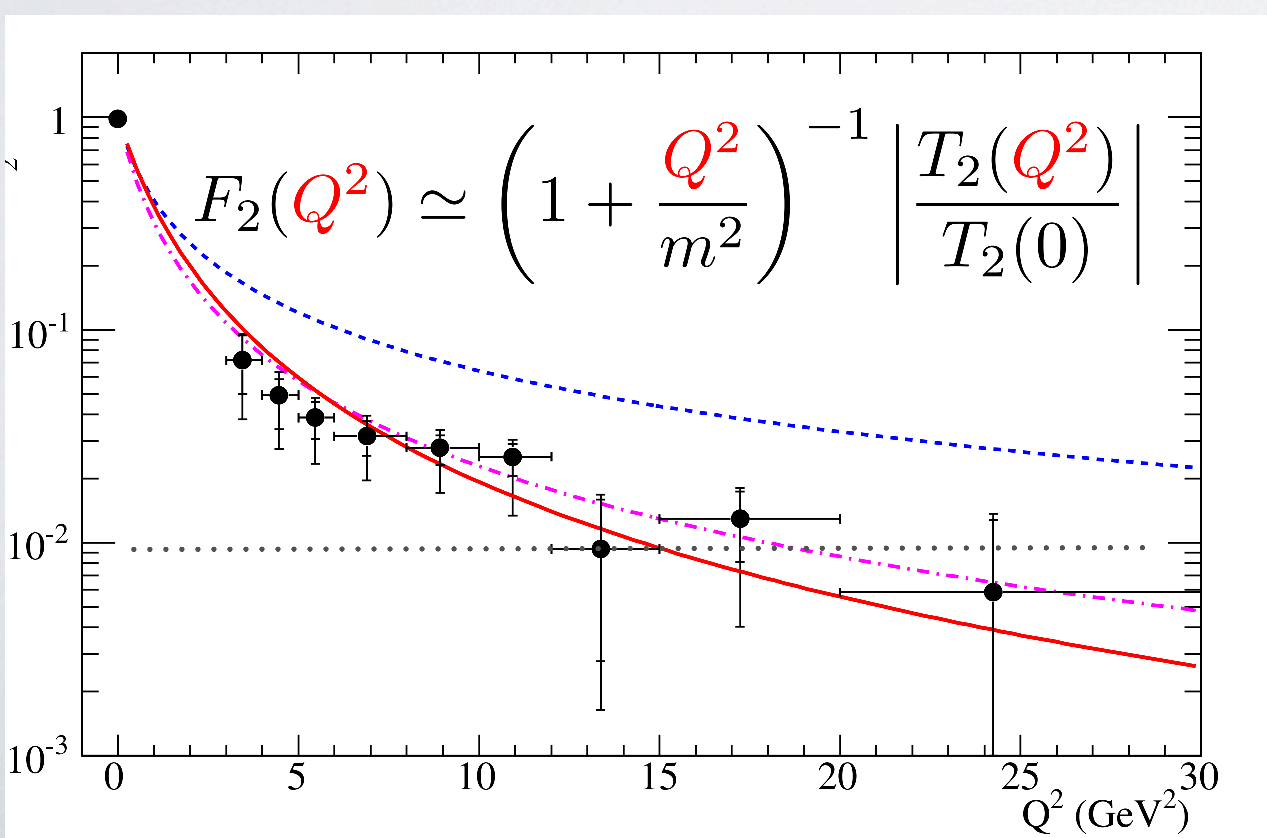


BELLE, Masuda et al.

Phys.Rev. D93 (2016) no.3, 032003

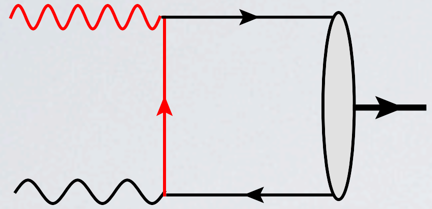
$$3\mathrm{GeV}^2 < Q^2 < 30\mathrm{GeV}^2$$



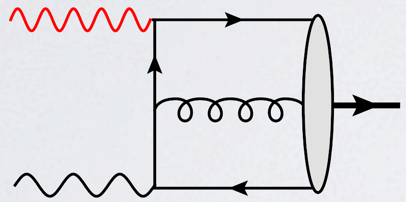
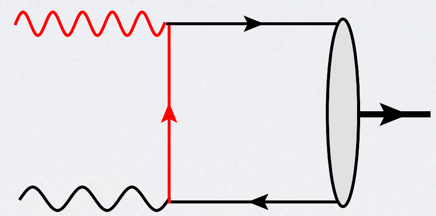


f_2 transition FF's in pQCD

$|\bar{q}q(^1S_0)\rangle$

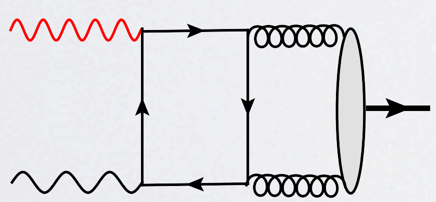
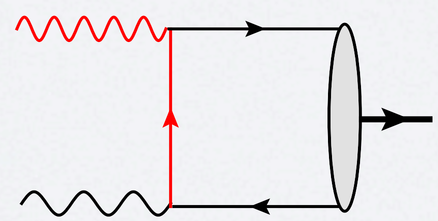
$T_0(Q^2)$  $f_2(0)$ twist-2 distribution amplitude

$|\bar{q}q(^1S_0)g(\pm)\rangle$ $|\bar{q}q(^1P_1)\rangle$

$T_1(Q^2)$  $f_2(\pm)$ +  $f_2(\pm)$ twist-3 DAs

twist-3 twist-3 kinematical

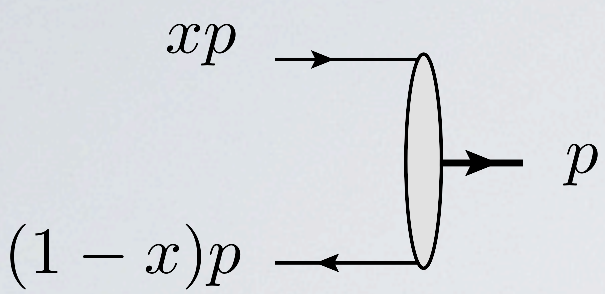
$|g(\pm)g(\pm)(^5S_2)\rangle$ $|\bar{q}q(^1D_2)\rangle$

$T_2(Q^2)$  $f_2(\pm 2)$ +  $f_2(\pm 2)$ + ... $\cancel{|\bar{q}q(^3P_1)g(\pm)\rangle}$

$\cancel{|\bar{q}q(^1S_0)g(\pm)g(\pm)\rangle}$

twist-2 twist-4 kinematical

Light-cone distribution amplitudes



$$\sim \int_{|k_\perp|<\mu} d^2k_\perp \Psi_{BS}(x,k_\perp) = \phi(x,\mu)$$

describes the momentum-fraction distribution of partons at zero transverse separation in a 2-particle Fock state

$$|\bar{q}q(^1S_0)\rangle \qquad \langle f_2(p)|\bar{\psi}(z)\not{z}\psi(0)|0\rangle\,\big|_{z_-=z_\perp=0} \sim \int_0^1 dx\, e^{ixz_+p_-}\phi_2(x,\mu)$$

$$V_\pm = V_0 \pm V_3$$

μ is the factorization scale (renormalization of the operator in QCD)

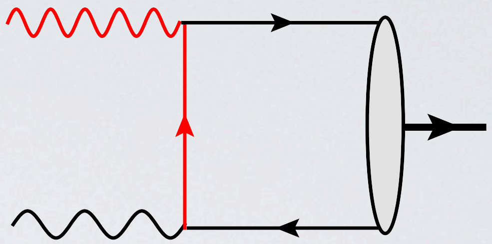
suppressed by powers of 1/Q:

multiparticle states: $q\bar{q}g$

$q\bar{q}$ with orbital momentum

gamma-f₂: T₀

$T_0(Q^2)$ $\gamma^*(\pm)\gamma(\pm) \to f_2(0)$



$|\bar{q}q(^1S_0)\rangle$

$$T_0(Q^2) \simeq \langle f_q \rangle \int dx \frac{\phi_2(x)}{x}$$

$$\langle f_q \rangle = \frac{4}{9} f_u(\mu) + \frac{1}{9} f_d(\mu) + \frac{1}{9} f_s(\mu)$$

simplest model $\phi_2(x) = 30x(1-x)(2x-1)$

normalization constant $\frac{1}{2}\langle f_2(P,\lambda)|\bar{q}\left[\gamma_\mu i \overleftrightarrow{D}_\nu + \gamma_\nu i \overleftrightarrow{D}_\mu\right] q|0\rangle = f_q m^2 e^{(\lambda)*}_{\mu\nu}$

$f_u(1\mathrm{GeV}) = f_d(1\mathrm{GeV}) = 101(10)\mathrm{MeV}$

$f_s(1\mathrm{GeV}) \approx 0$

Aliev, Shifman 1982 (QCD SR, TM dom.)

Terazawa, 1990, Suzuki 1993 (TM dom.)

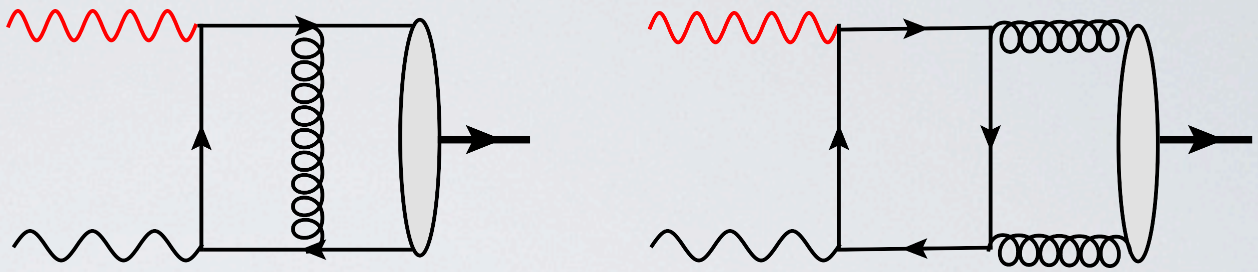
Cheng, Koike, Yang 2010 (QCD SR, TM dom.)

for comparison

$f_\pi = 130MeV$ $f_\rho = 221MeV$ $f_\omega = 198MeV$ $f_\phi = 161MeV$

$T_0(Q^2)$

NLO & LLog resummation
involves gluons



Gluon DA: $|g(\pm)g(\mp)(^1S_0)\rangle$

$$\langle f_2(P,\lambda)|z^\alpha z^\beta G^a_{\alpha\mu}(z)G^a_{\beta\mu}(0)|0\rangle\,\Big|_{z_-=z_\perp=0} \sim \int_0^1 dx\, e^{ixp_-z_+}\phi_g^S(x)$$

simplest model $\quad \phi_g^S(x) = f_g^S m^2\, 30x^2(1-x)^2$

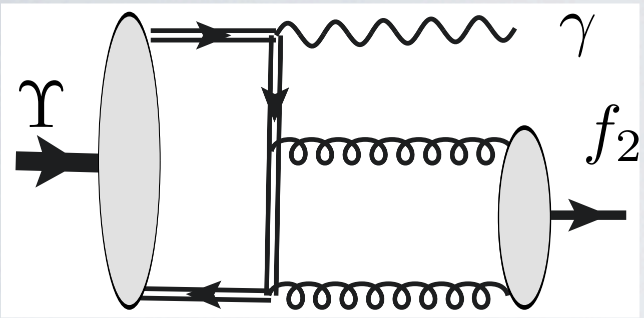
normalization constant

$$\langle f_2(P,\lambda)|z^\alpha z^\beta G^a_{\alpha\mu}(0)G^a_{\beta\mu}(0)|0\rangle\,\Big|_{z_-=z_\perp=0} = -f_g^S m^2\, z^\alpha z^\beta e^{(\lambda)*}_{\alpha\beta}\,\Big|_{z_-=z_\perp=0}$$

expected to be small for $q\bar{q}$ mesons at low normalization

gamma-f_2 To FF: coupling to gluons

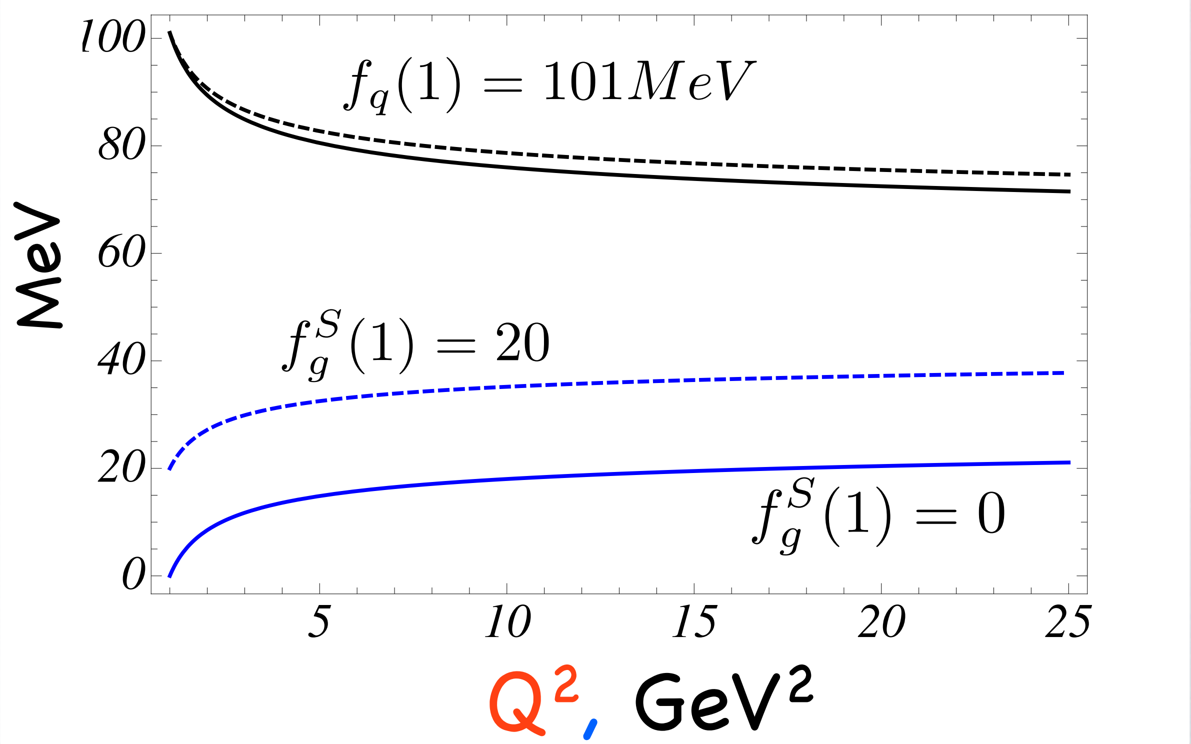
rich gluon process $\Upsilon(1S) \to \gamma f_2 \qquad M_\Upsilon = 9.5\text{GeV} \qquad m_b \simeq 4.5\text{GeV}$



$$\frac{Br[\Upsilon(1S) \to \gamma\ f_2]}{Br[\Upsilon(1S) \to e^+e^-]} = \frac{64\pi}{3} \frac{\alpha_s^2(4m_b^2)}{\alpha} \left(1 - \frac{m_{f_2}^2}{M_\Upsilon^2}\right) \frac{[5f_g^S/4]^2}{m_b^2}$$

$$f_g^S(\mu^2 = 4m_b^2) = (14.9 \pm 0.8)\,\text{MeV}$$

QCD evolution mixes f_q and f_g^S



therefore this result compatible with

$$f_g^S(1\,\text{GeV}) \approx 0$$

i.e. the meson only consists from quarks at low normalization point

gamma-f_2 T_0 FF

target mass effect

soft overlap LCSR approach

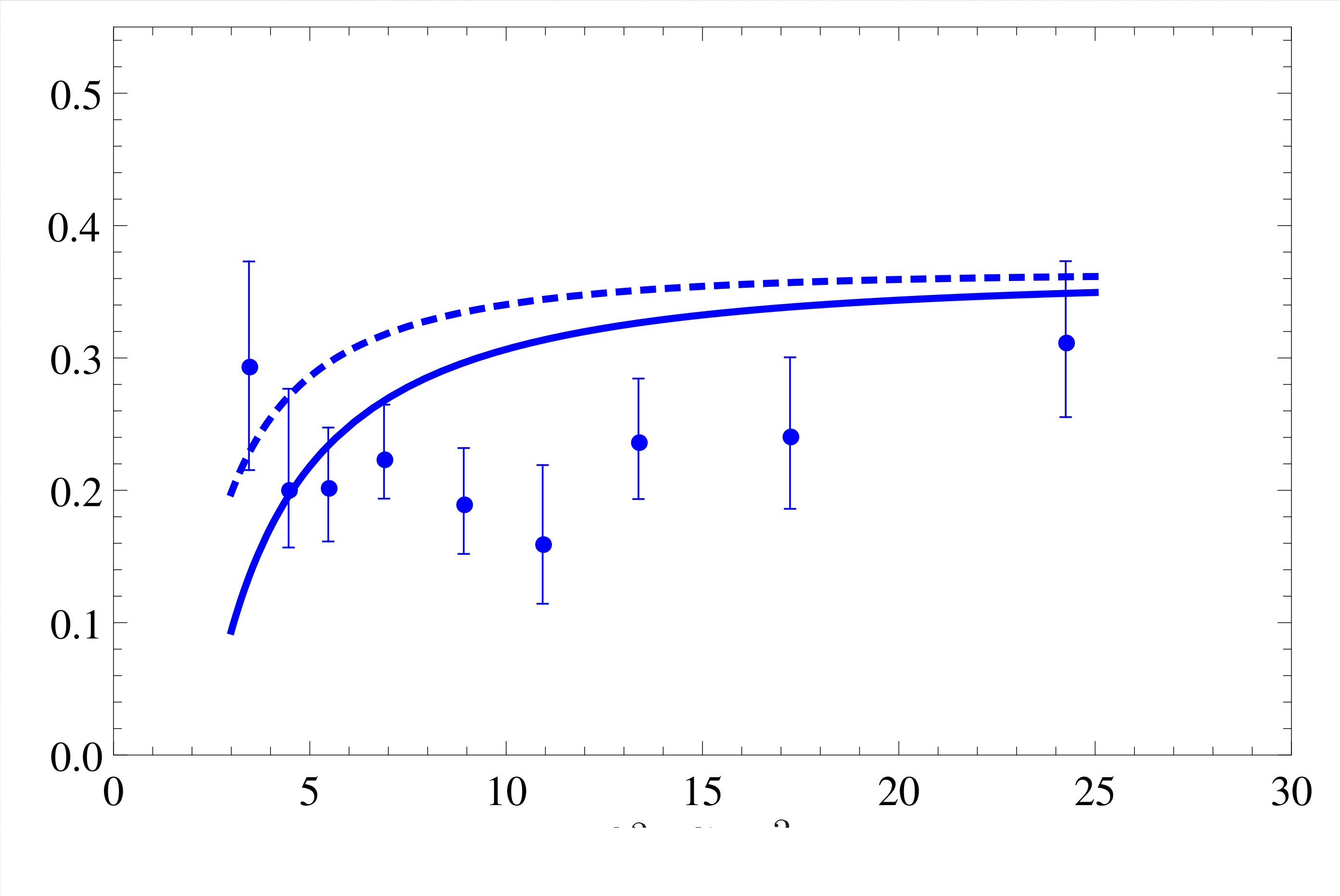
$$T_0 = 5\langle f_q\rangle - \frac{\alpha_s(Q^2)}{\pi}\left(\frac{5}{27}\langle f_q\rangle + \frac{215}{27}f_g^S\right) - 5\frac{m^2}{Q^2}\langle f_q\rangle + T_0^{\rm PC}(Q^2)$$

LO

NLO: q+g

power suppressed

$$\frac{T_0(Q^2)}{T_2(0)}$$



Q^2, GeV^2

$T_0(0)/T_2(0) \simeq 4\%$

data BELLE 2015

$3\mathrm{GeV}^2 \le Q^2 \le 30\mathrm{GeV}^2$

it seems that the value of f_q is overrated ...

idea: to extract normalization from

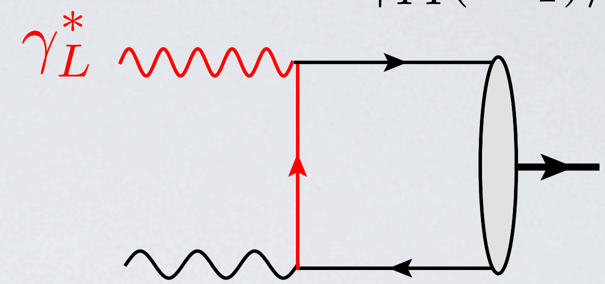
$$e^+e^- \to \gamma^* \to f_2 + \gamma$$

$$q^2 \simeq 100\mathrm{GeV}^2$$

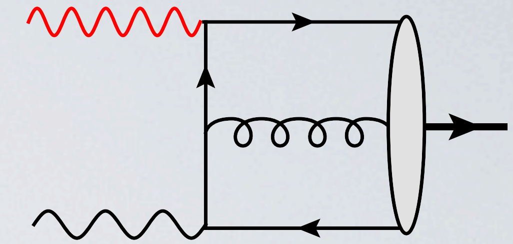
$T_1(Q^2)$

$T_1(Q^2) \qquad \gamma^*(0)\gamma(\pm) \to f_2(\mp)$

$|\bar{q}q(^1P_1)\rangle$

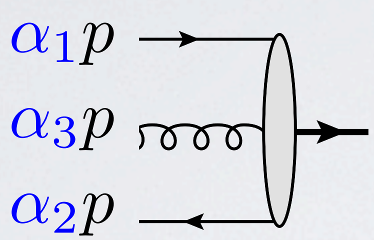


$|\bar{q}q(^1S_0)g\rangle$



DAs of twist-3:

$|\bar{q}q(^1S_0)g\rangle$



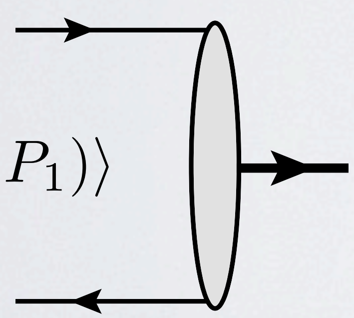
$$f_q m^2 360\alpha_1\alpha_2^2\alpha_3\Big[\zeta_3 + \frac{1}{2}\omega_3(7\alpha_2 - 3) + \dots\Big]$$

$$f_q m^2\, 360\alpha_1\alpha_2^2\alpha_3\Big[\frac{1}{2}\widetilde{\omega}_3(\alpha_1 - \alpha_3) + \dots\Big]$$

$$\alpha_1 + \alpha_2 + \alpha_3 = 1$$

QCD sum rule: $\zeta_3 = 0.15(8) \qquad \omega_3 = -0.2(3) \qquad \widetilde{\omega}_3 = 0.06(1) \qquad \mu = 1\mathrm{GeV}$

$|\bar{q}q(^1P_1)\rangle$



$$\langle f_2(P,\lambda)|z^\alpha \bar{q}(z)\gamma_\alpha\{\overrightarrow{D}^\perp_\mu - \overleftarrow{D}^\perp_\mu\}q(0)|0\rangle|_{z_-=z_\perp=0} \to e^{(\lambda)*}_{-\mu_\perp}\int_0^u dv\,\frac{\phi_2(v)}{\bar{v}} + \int_u^1 dv\,\frac{\phi_2(v)}{v}$$

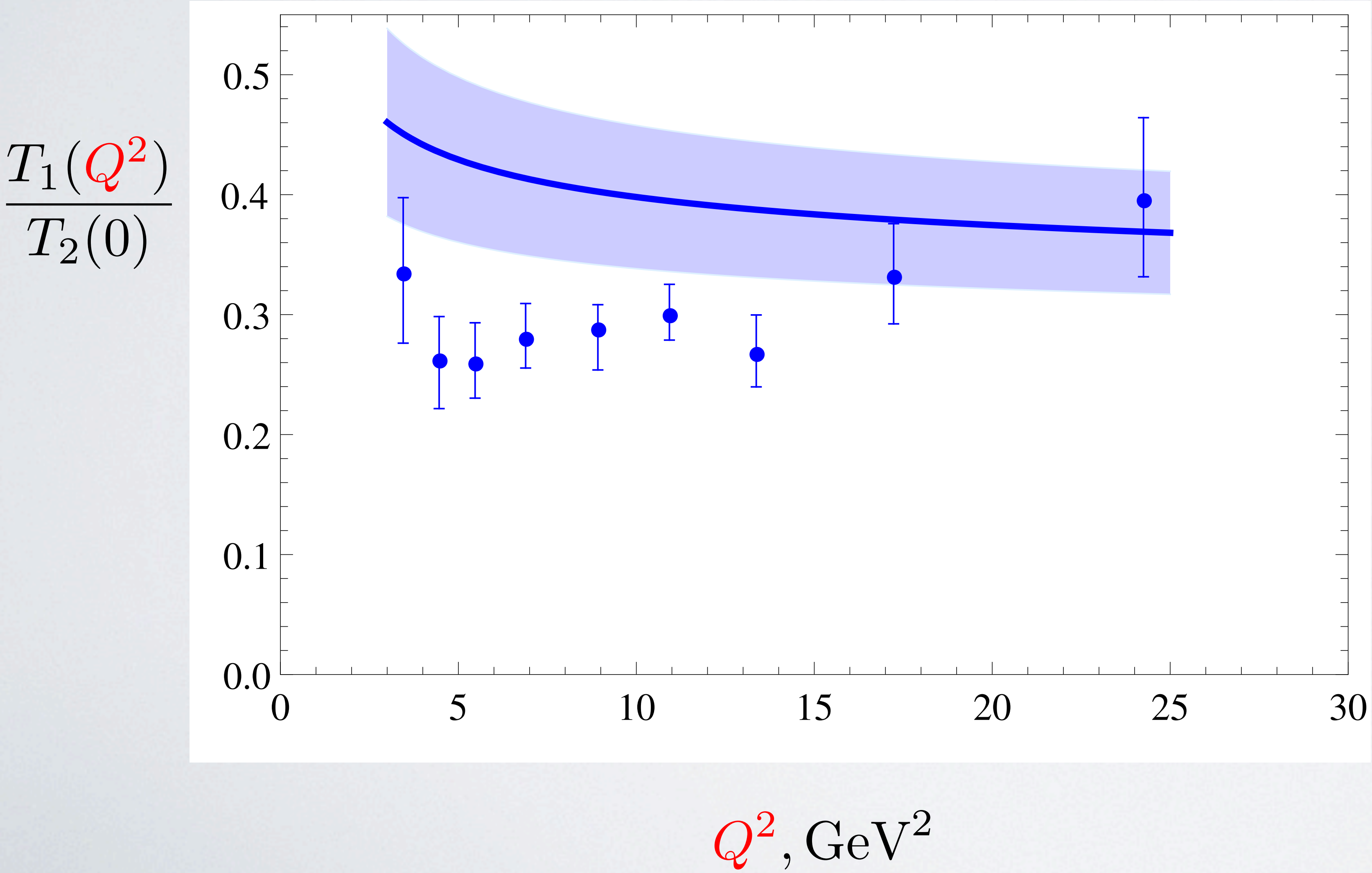
$$\langle f_2(P,\lambda)|z^\alpha \bar{q}(z)\gamma_\alpha\gamma_5\{\overrightarrow{D}^\perp_\mu - \overleftarrow{D}^\perp_\mu\}q(0)|0\rangle|_{z_-=z_\perp=0} \to e^{(\lambda)*}_{-\mu_\perp}\int_0^u dv\,\frac{\phi_2(v)}{\bar{v}} - \int_u^1 dv\,\frac{\phi_2(v)}{v}$$

Wandzura-Wilczek part

gamma-f_2 T_0 FF

$$T_1(Q^2) = \frac{10}{3}\langle f_q \rangle \left[1 + 4\zeta_3 + \frac{9}{16}(\omega_3 - \widetilde{\omega}_3)\right]$$

$\mu = 1\text{GeV}$ $\zeta_3 = 0.15(8)$ $\omega_3 = -0.2(3)$ $\widetilde{\omega}_3 = 0.06(1)$ QCD SR



data BELLE 2015

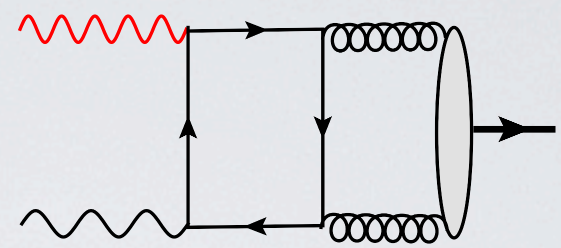
$3.5\text{GeV}^2 \leq Q^2 \leq 24\text{GeV}^2$

power corrections are expected to be negative

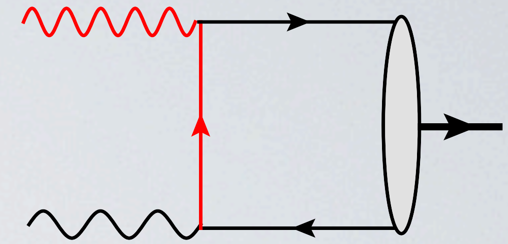
it seems that the value of f_q is overrated ...

gamma-f$_2$ T$_2$ FF

$T_2(Q^2)$ $\quad$ $\gamma^*(\mp)\gamma(\pm) \to f_2(\mp 2)$



$|gg(^5S_2)\rangle$



$|\bar{q}q(^1D_2)\rangle$

one more gluon DA of twist-2: do not mix with quarks!

$|gg(^5S_2)\rangle$

$$\langle f_2(P)|z^\alpha z^\beta G_{\alpha\{\mu}(z)G_{\beta\nu\}}(0)|0\rangle|_{z_-=z_\perp=0} = f_g^T e^\perp_{\{\mu\nu\}} \int_0^1 dx\, e^{ixp_- z_+} \phi_g^T(x)$$

simplest model $\quad \phi_g^T(x) = 30x^2(1-x)^2$ $\quad$ unknown parameter f_g^T

$|\bar{q}q(^1D_2)\rangle$

$$\langle f_2(P)|\bar\psi(z) \overleftrightarrow{D}_{\{\perp\mu} \overleftrightarrow{D}_{\perp\nu\}} \not{z} \psi(0)|0\rangle \sim \frac{\Lambda^2}{Q^2} \quad \Longrightarrow \quad \sim \frac{m^2}{Q^2}\langle f_q\rangle + \dots$$

QCD EOM

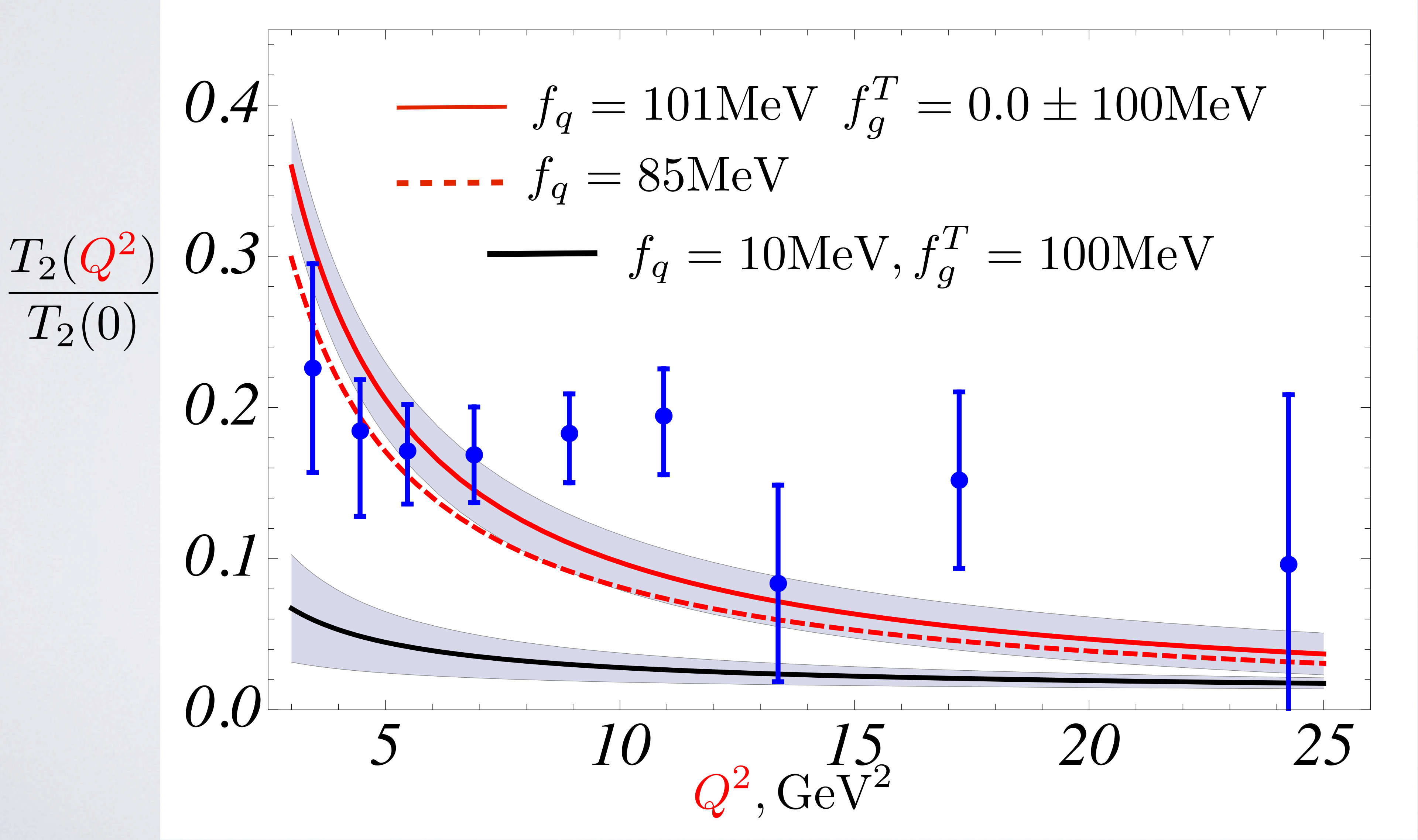
gamma-f_2 T_2 FF

LO $^1D_2$ quarks

virtual c-quarks, small

$$T_2(Q^2) = \frac{20}{3}\frac{m^2}{Q^2}\langle f_q\rangle + \frac{5}{3}\frac{\alpha_s(Q^2)}{\pi} f_g^T\left[1+\frac{8}{3}\lambda(m_c^2/Q^2)\right]$$

data BELLE 2015 $3.5\mathrm{GeV}^2 \le Q^2 \le 24\mathrm{GeV}^2$



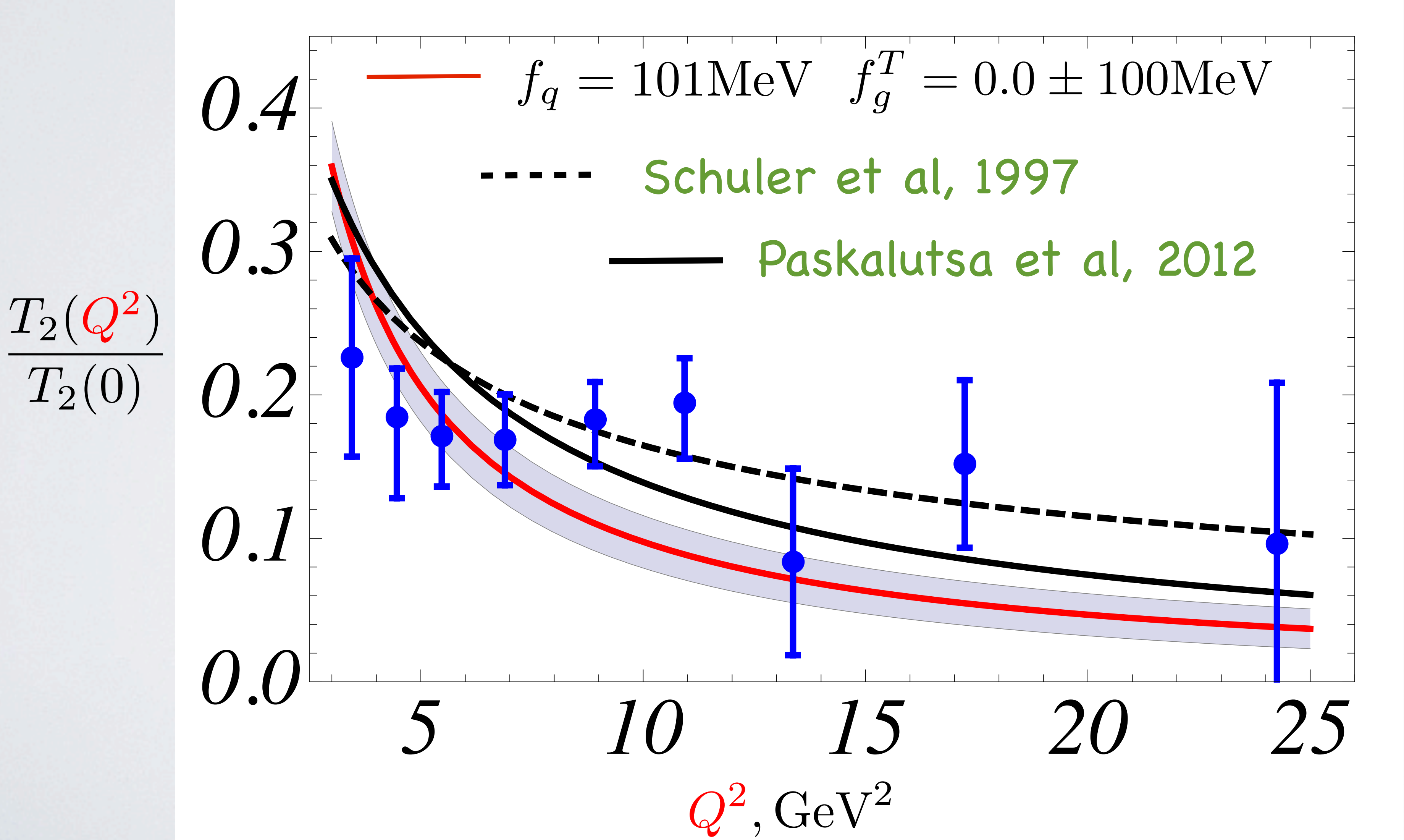
$$\frac{\alpha_s(Q^2)}{\pi} = 0.1\text{–}0.06$$

gamma-f_2 T_2 FF

virtual c-quarks, small

$$T_2(Q^2) = \frac{20}{3}\frac{m^2}{Q^2}\langle f_q\rangle + \frac{5}{3}\frac{\alpha_s(Q^2)}{\pi} f_g^T \left[1 + \frac{8}{3}\lambda(m_c^2/Q^2)\right]$$

data BELLE 2015 $3.5\mathrm{GeV}^2 \le Q^2 \le 24\mathrm{GeV}^2$

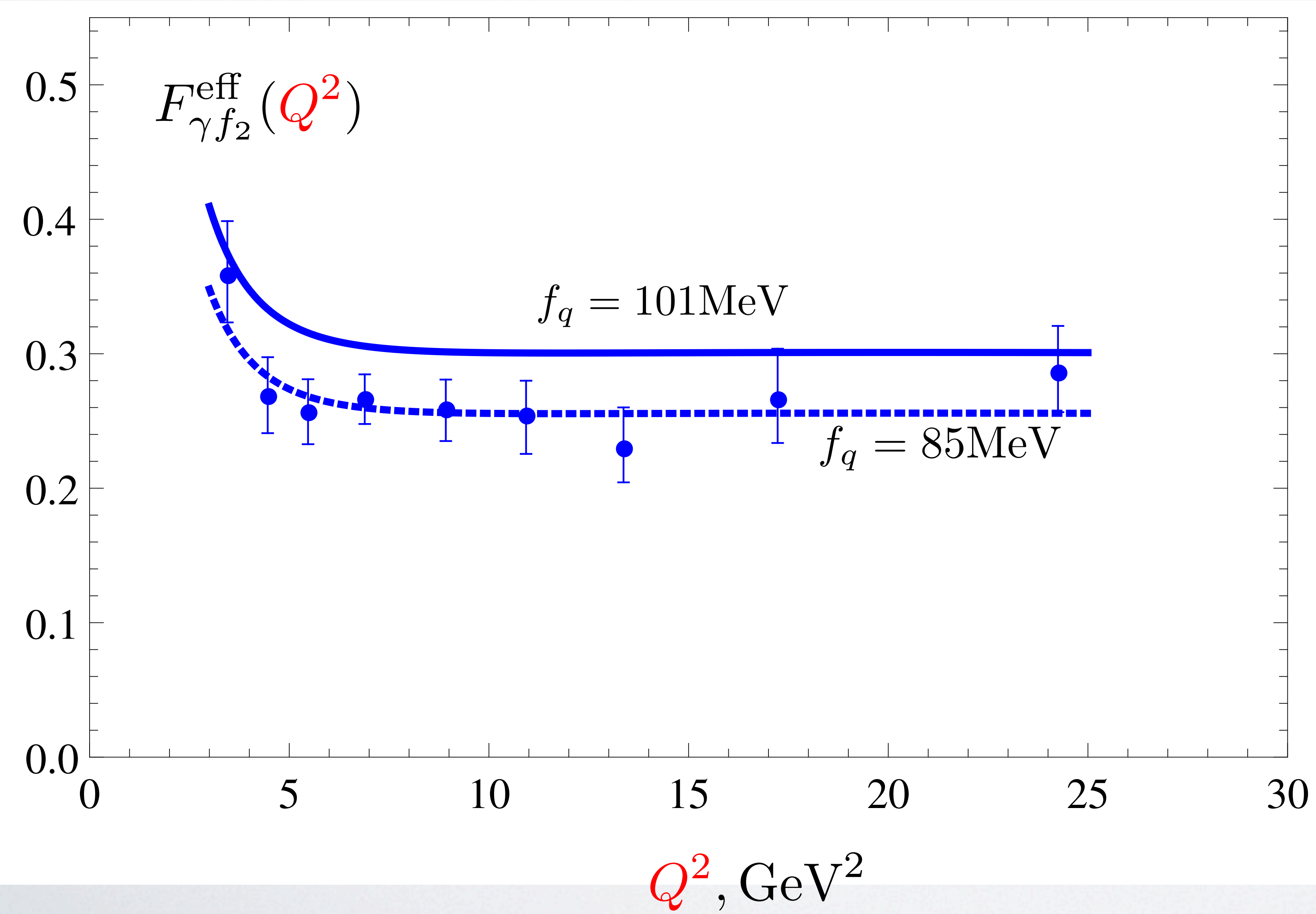


$$\frac{\alpha_s(Q^2)}{\pi} = 0.1\text{–}0.06$$

Scaling behavior

$$F^{\rm eff}_{\gamma f_2}(Q^2) = \sqrt{\frac{2}{3}\left|\frac{T_0(Q^2)}{T_2(0)}\right|^2 + \frac{Q^2 m^2}{(m^2+Q^2)^2}\left|\frac{T_1(Q^2)}{T_2(0)}\right|^2 + \left|\frac{T_2(Q^2)}{T_2(0)}\right|^2}$$

good scaling behavior for Q^2>4-5 GeV^2



data BELLE 2015

$$3.5\mathrm{GeV}^2 \leq Q^2 \leq 24\mathrm{GeV}^2$$

$$T_0 \simeq 5\langle f_q\rangle - \frac{\alpha_s(Q^2)}{\pi}\left(\frac{5}{27}\langle f_q\rangle + \frac{215}{27} f_g^S\right)$$

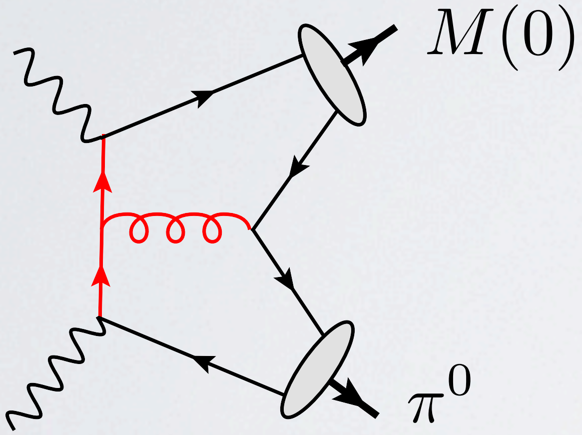
$$T_1 \simeq \frac{10}{3}\langle f_q\rangle\left[1 + 4\zeta_3 + \frac{9}{16}(\omega_3 - \tilde{\omega}_3)\right]$$

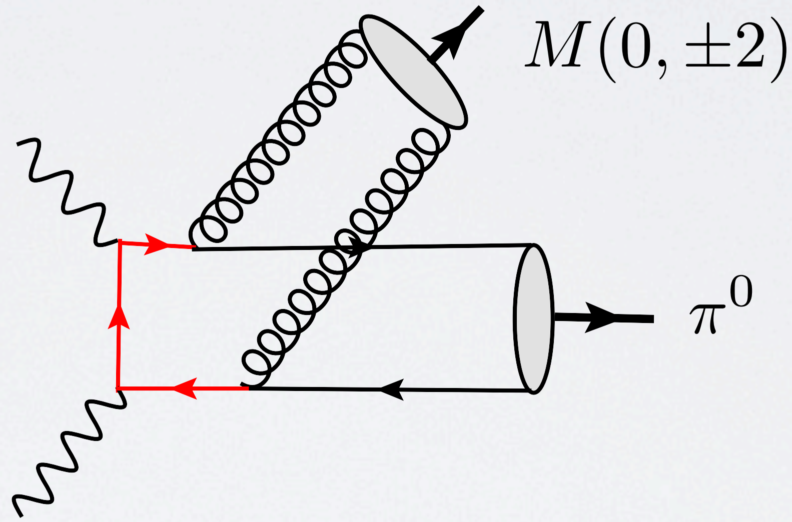
$$T_2 \simeq \frac{5}{3}\frac{\alpha_s(Q^2)}{\pi} f_g^T + \frac{20}{3}\frac{m^2}{Q^2} f_q$$

One more way to use tensor coupling: glueball production

$$\gamma\gamma \to \pi^0 G(2^{++})$$

$$\frac{d\sigma_{\gamma\gamma}[\pi^0 G(2^{++})]}{d\cos\theta} = \frac{1}{64\pi}\,\frac{s+m^2}{s^2}\left(|\overline{A_{++}}|^2 + |\overline{A_{+-}}|^2\right)$$





all terms are of order α_s

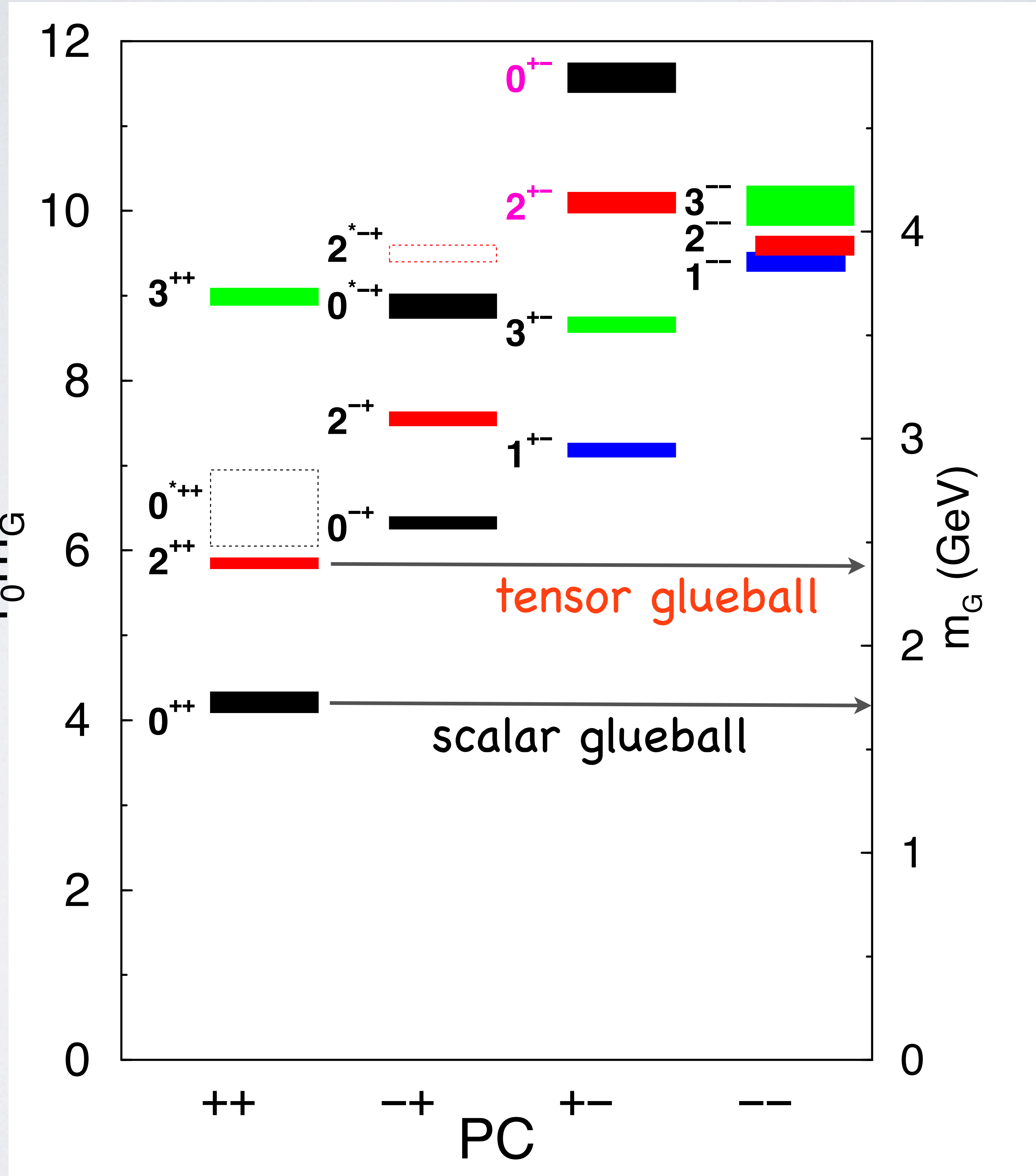
$A_{\pm\pm} : \gamma(\pm)\gamma(\pm) \to M(\pm 2)$ only tensor gluons

$A_{\pm\mp} : \gamma(\pm)\gamma(\mp) \to M(0)$ quarks & scalar gluons

Predictions & evidence for glueballs

Lattice

(Morningstar, Peardon, 1999)



Predictions & evidence for glueballs

Experiment BES III, Ablikim et al, PRD 93(2016)

TABLE I. Mass, width, $\mathcal{B}(J/\psi \to \gamma X \to \gamma\phi\phi)$ (B.F.) and significance (Sig.) of each component in the baseline solution. The first errors are statistical and the second ones are systematic.

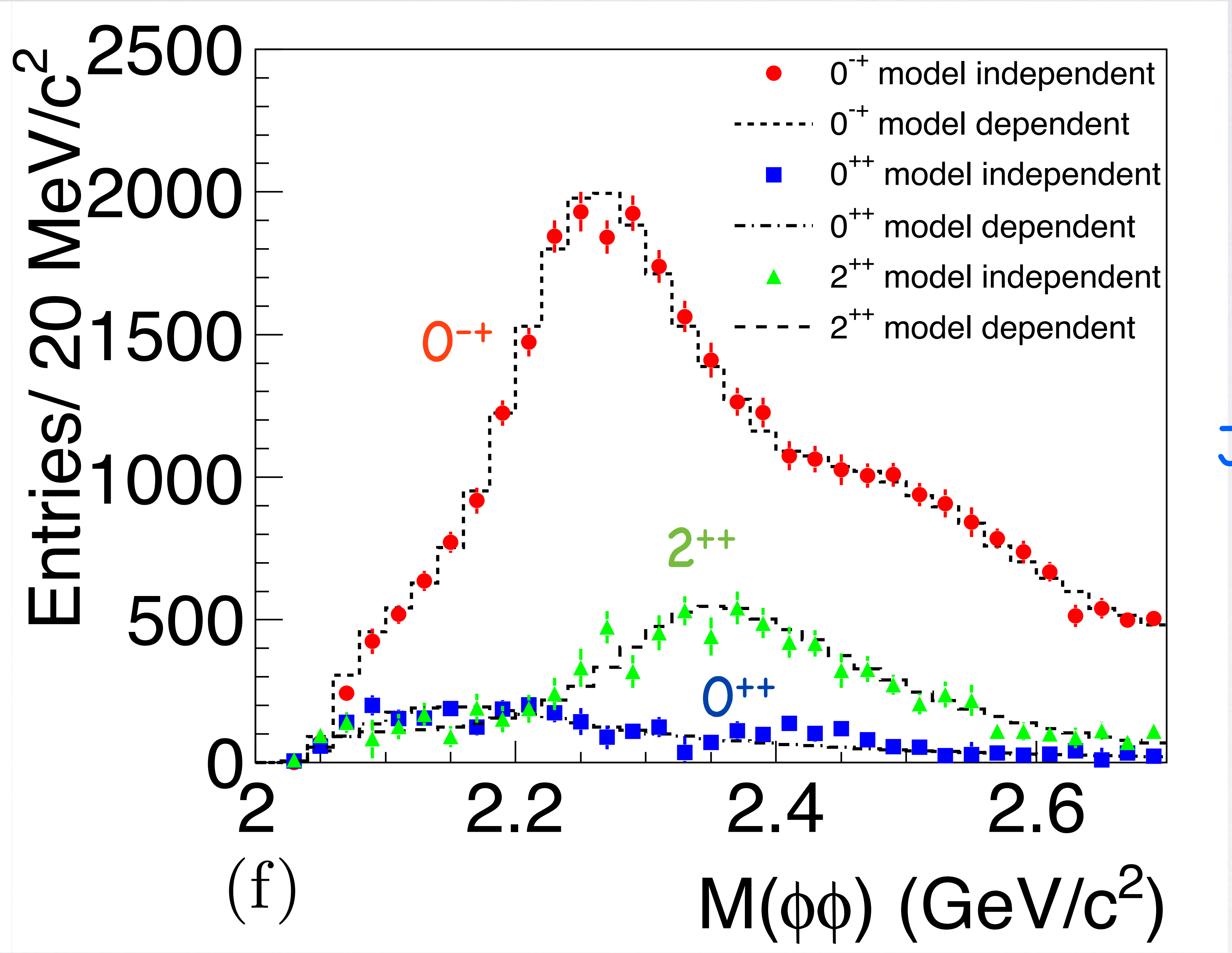
Resonance	M(MeV/c^2)	Γ(MeV/c^2)	B.F.($\times 10^{-4}$)	Sig.	PDG
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	$9.5\ \sigma$	✓
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	$6.4\ \sigma$	✓
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	$11\ \sigma$	✓

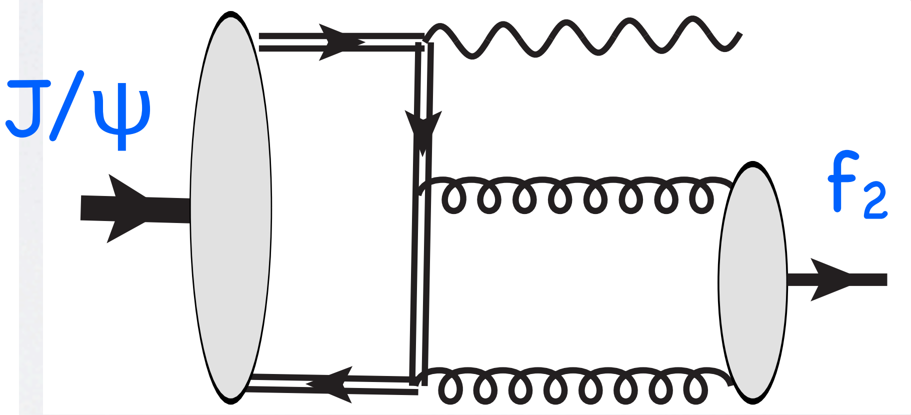
first observed in $\pi^- + p \to \phi\phi n$

Etkin et al, PRL(1978), PLB(1985), PLB(1988)

Predictions & evidence for glueballs

Experiment BES III, Ablikim et al, PRD 93(2016)

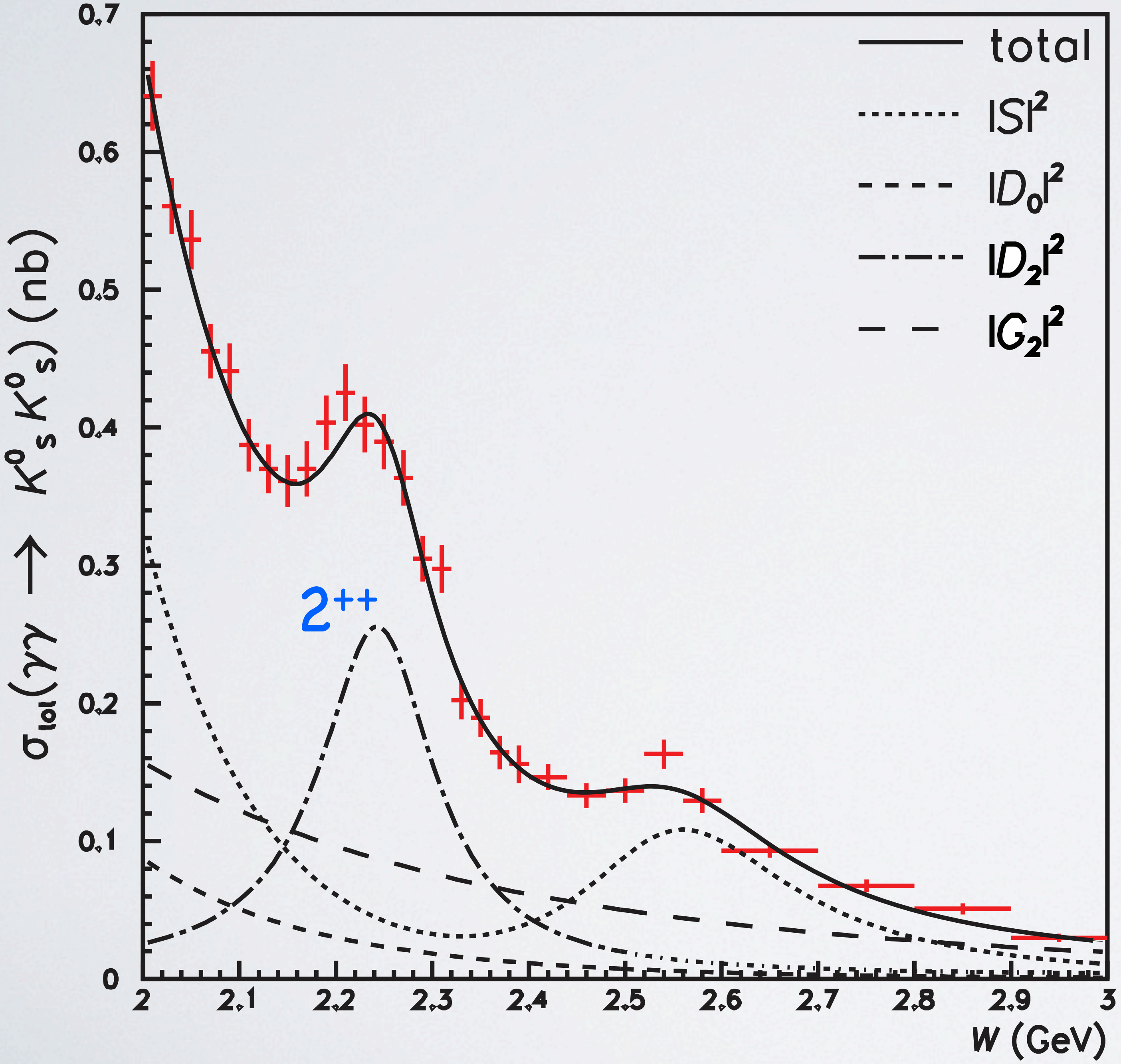




Predictions & evidence for glueballs

Experiment BELLE, Uehara et al, PTEP (2013)

$\gamma\gamma \to K_S^0 K_S^0$



$f_2(2300)$

$M = 2297 \pm 28$ MeV

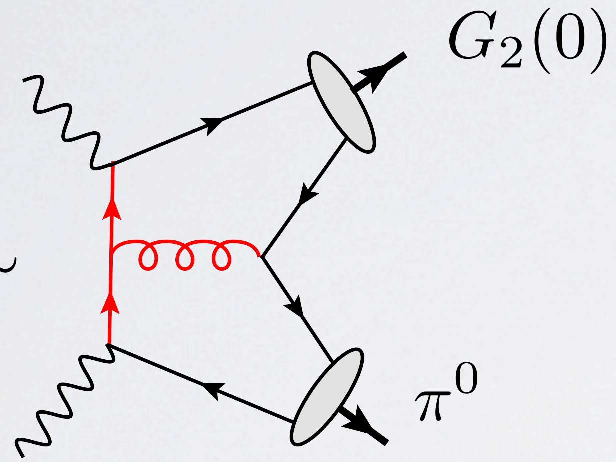
$\Gamma = 149 \pm 40$ MeV

Glueball or $q\bar{q}$-state ?

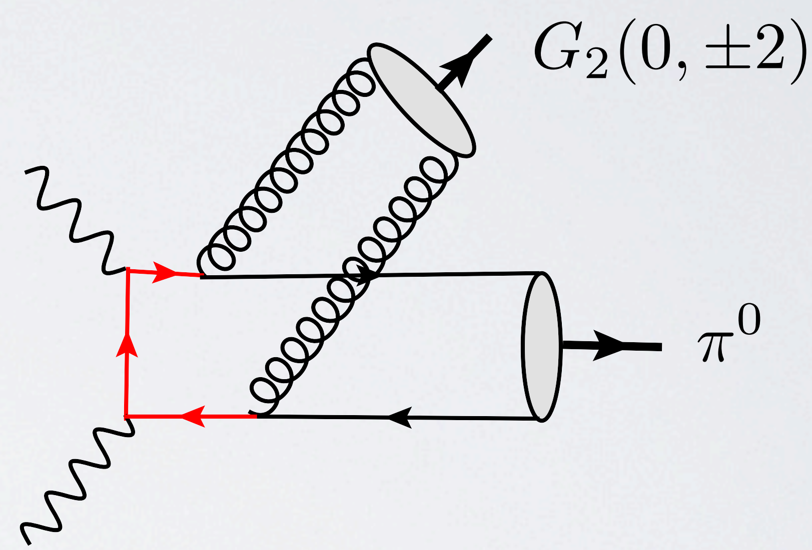
Glueball cross section at large energy

$$\frac{d\sigma_{\gamma\gamma}[\pi^0 G_2]}{d\cos\theta} = \frac{1}{64\pi}\frac{s+m^2}{s^2}\left(|A_g^{++}|^2 + \frac{8}{3}|A_q^{+-} + A_g^{+-}|^2\right)$$

$A_q^{+-} \sim$



$A_g^{+\pm} \sim$



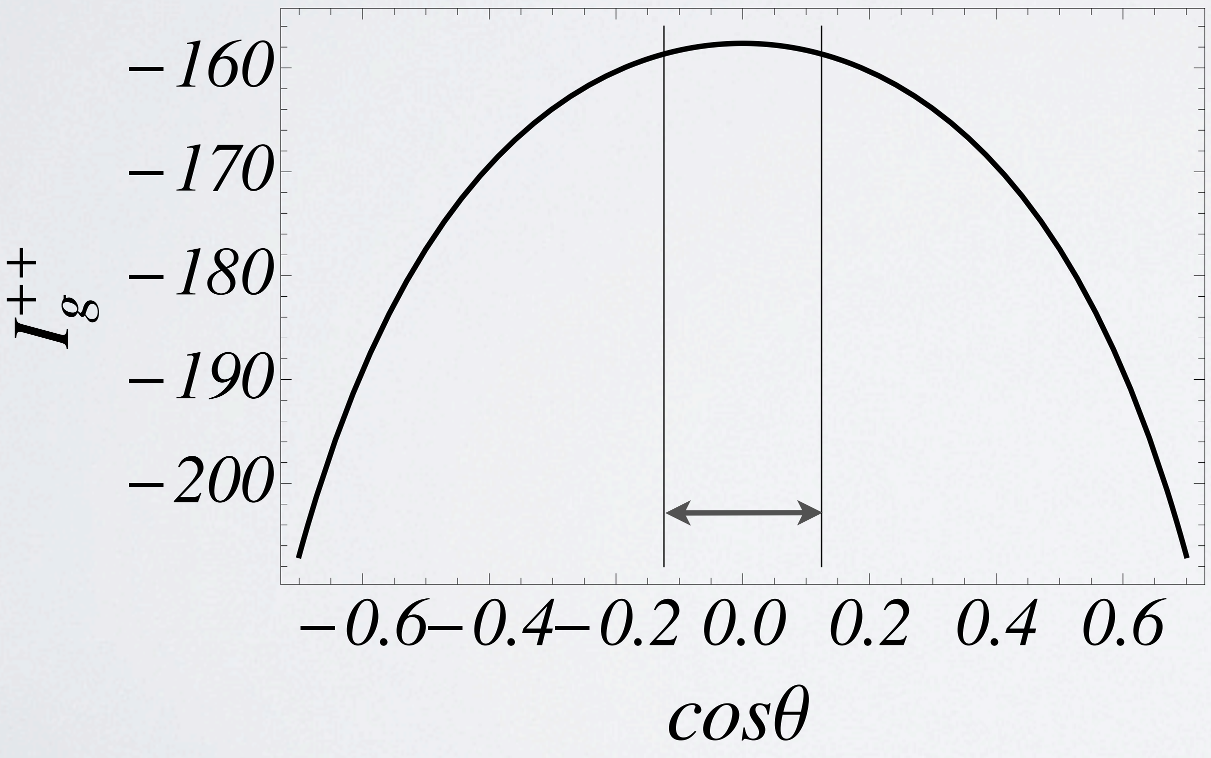
$s \to \infty \qquad \frac{d\sigma_{\gamma\gamma}[\pi^0 G(2^{++})]}{d\cos\theta} \sim \frac{1}{s}\frac{f_\pi^2 f_G^2}{s^2} f(\theta) \qquad f_\pi = 130 MeV$

Angular dependence

$$A_g^{++} \sim \frac{f_\pi \; f_g^T}{s} \alpha\alpha_s \; I_g^{++}[\cos\theta],$$

$$I_g^{++}(\eta) = \int_0^1 dy \; \phi_\pi(y) \int_0^1 dx \frac{\phi_g^T(x)}{x\bar{x}} \; \frac{2}{y\bar{y}} \frac{1}{2xy - x - y + \eta(x-y)}.$$

$s = 11\text{GeV}^2$



$\longleftrightarrow \quad |u|, |t| \geq 2.5\text{GeV}^2$

models for the DAs

$$\phi_g^T(x) = \phi_g^S(x) = 30x^2\bar{x}^2$$

$$\phi_\pi(y) \simeq 6y\bar{y} + 6a_2(\mu)y\bar{y}C_2^{3/2}(2y-1)$$

$$a_2(\mu = 1\text{GeV}) = 0.20$$

Angular dependence

$$A_g^{+-} \sim \frac{f_\pi f_g^S}{s} \alpha\alpha_s \; I_g^{+-}(\cos\theta)$$

$$I_g^{+-}(\eta) = \int_0^1 dy \frac{\phi_\pi(y)}{y\bar{y}} \int_0^1 dx \frac{\phi_g^S(x)}{x\bar{x}} \; \frac{1-2x-\eta}{x\bar{\eta} + y(1-2x+\eta)}$$

$$A_q^{+-} \sim \frac{f_\pi f_q}{s} \; \alpha\alpha_s I_q^{+-}(\cos\theta)$$

$$I_q^{+-}(\eta) = \int_0^1 dy \; \frac{\phi_\pi(y)}{y\bar{y}} \int_0^1 dx \; \frac{\phi_2(x)}{x\bar{x}} \, \frac{\eta(1-\eta^2)(y-x)(1-x-y)^2}{[(1-x-y)^2(1-\eta^2)+4x\bar{x}y\bar{y}]}$$

models for the DAs

$$\phi_g^S(x) = 30x^2\bar{x}^2$$

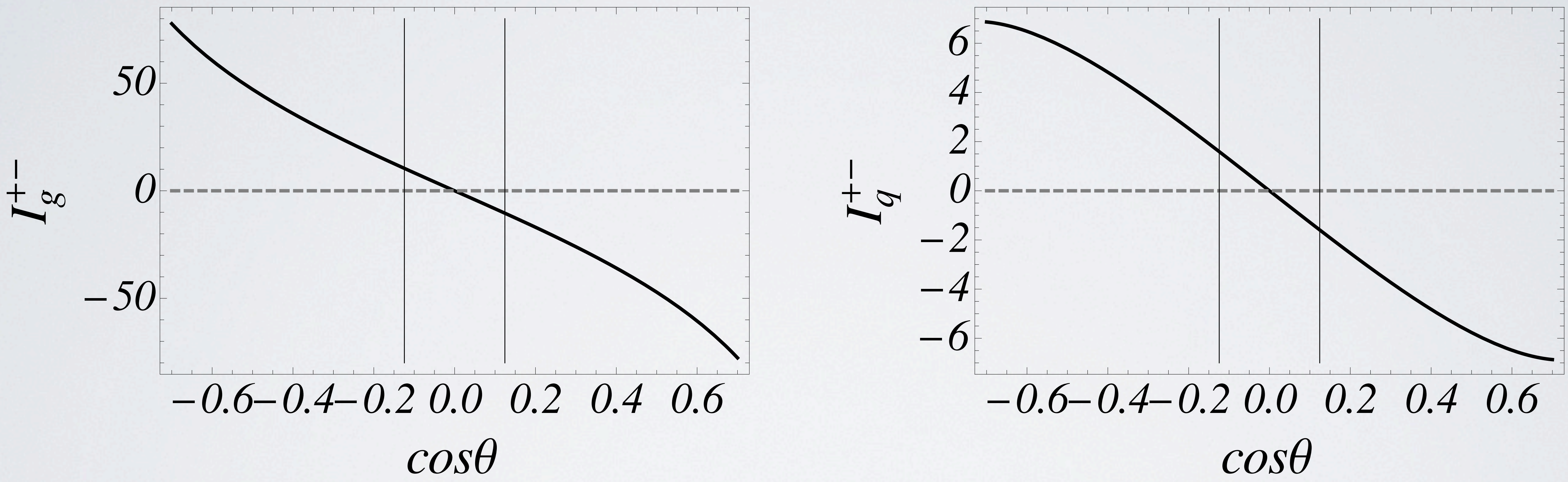
$$\phi_2(x) = 30x\bar{x}(2x-1)$$

$$\phi_\pi(y) \simeq 6y\bar{y} + 6a_2(\mu)y\bar{y}C_2^{3/2}(2y-1) \qquad a_2(\mu = 1\text{GeV}) = 0.20$$

Angular dependence

$$A_g^{+-} \sim \frac{f_\pi f_g^S}{s} \alpha \alpha_s \; I_g^{+-}(\cos\theta) \qquad A_q^{+-} \sim \frac{f_\pi f_q}{s} \; \alpha \alpha_s I_q^{+-}(\cos\theta)$$

$$s = 11 \text{GeV}^2$$



$$\longleftrightarrow \quad |u|, |t| \geq 2.5 \text{GeV}^2$$

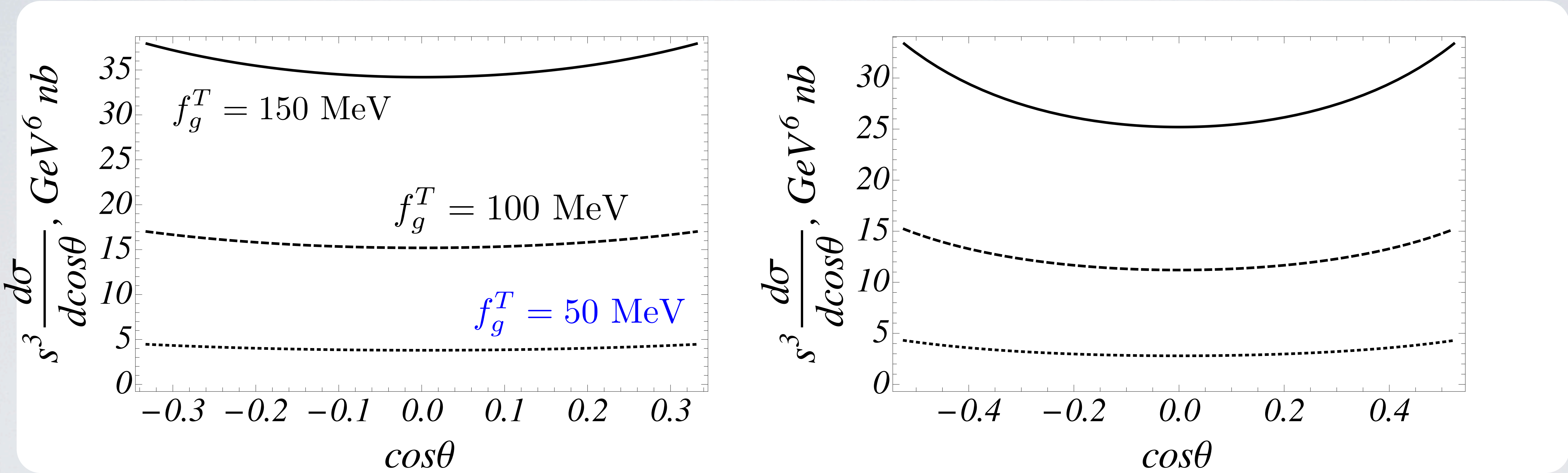
$$|I_g^{++}| \gg |I_g^{+-}| \gg |I_q^{+-}|$$

at large angles G_2 is produced in tensor polarization

Glueball cross section

M_G = 2.3 GeV

s = 13GeV² s = 16GeV²



$$|t|\ \&\ |u| > 2.5\ \mathrm{GeV}^2$$

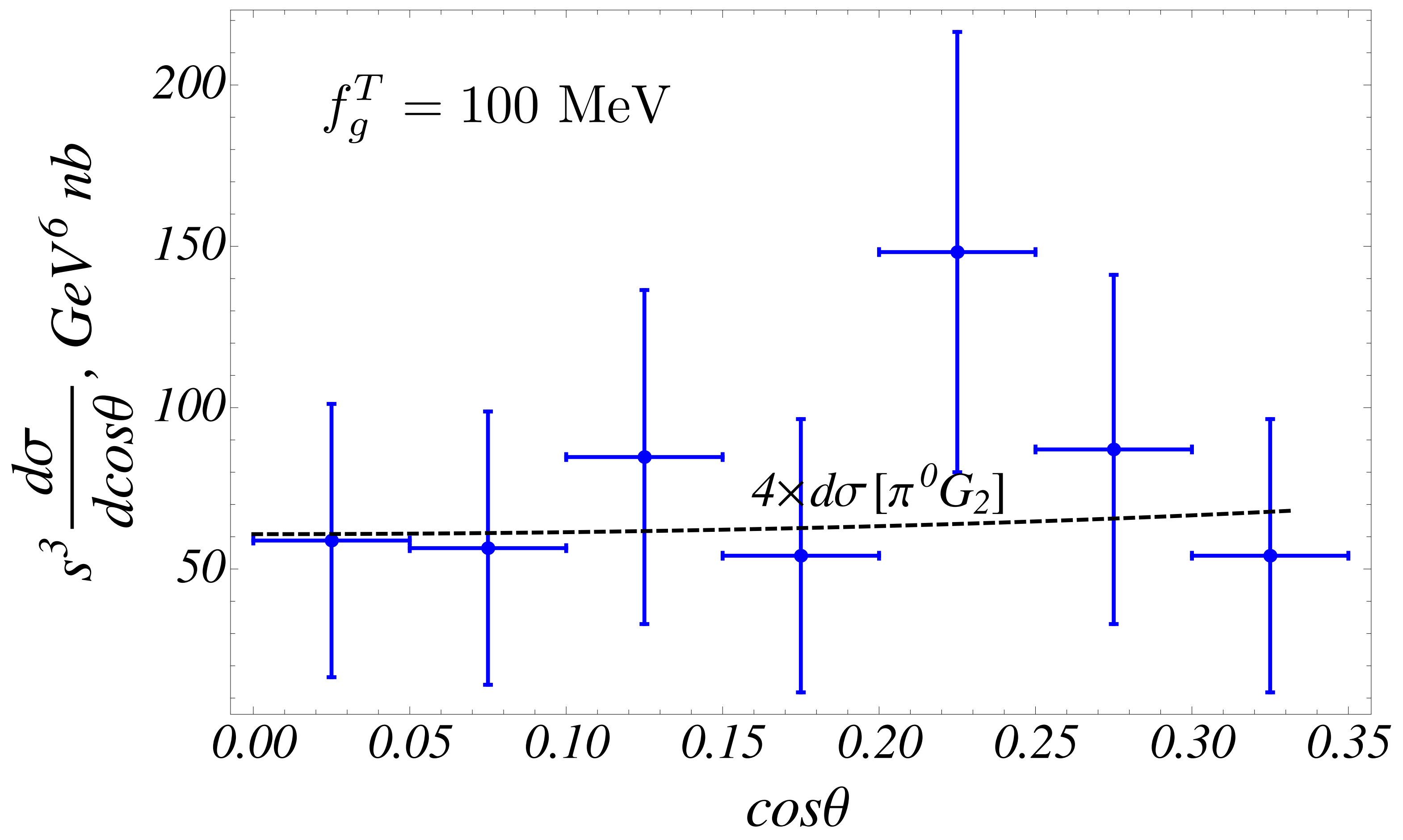
tensor channel is dominant

Can one measure the glueball cross section in BELLE II?

$$\frac{d\sigma[\gamma\gamma \to \pi^0 G_2(2340) \to \pi^0 \phi\phi]}{d\cos\theta}$$

Comparison with BELLE data $\gamma\gamma \to \pi^0\pi^0$ Uehara et al. PRD 79 (2009)

s = 13GeV^2 $|t|\ \&\ |u| > 2.5\ \mathrm{GeV}^2$



Conclusions

- QCD predicts the scaling behavior of the $\gamma^*\gamma \to f_2$ form factors

- The QCD predictions are in agreement with BELLE data. More precise data is required in order to better constrain meson DAs

- Production of tensor glueball at large energies and momentum transfers in QCD $\gamma\gamma \to \pi^0 G(2^{++})$

  Dominance of the tensor polarization

  Direct coupling to gluon wave function (no quark mixing, model independent)

  Probably, can be observed in BELLE II

Thank you!