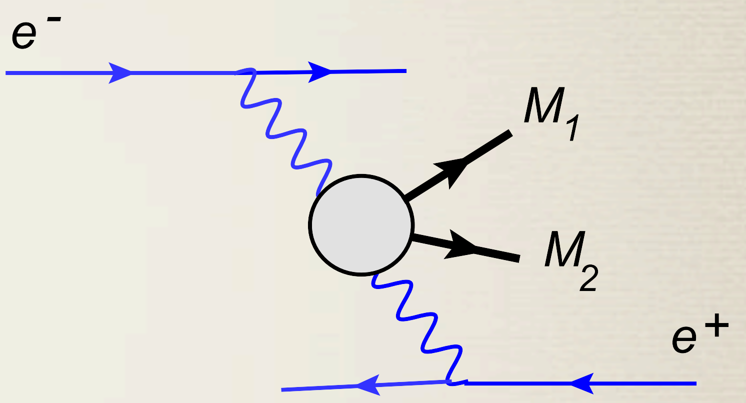
Production of tensor glueball in reaction $\gamma\gamma \to G_2 \pi^0$



Nikolay Kivel

HELMHOLTZ Institut Mainz

based on arXiv:1712.04285

TP II talk, Ruhr-University Bochum, 11th January, 2018

Outline

- Introduction. Glueballs: theory and experiment
- The process $\gamma+\gamma \to G(2^{++})+\pi^0$ as an opportunity to study tensor glueball
- Discussion: questions, suggestions, critics, skepticism, etc.

Interpretation of $q\bar{q}$-states in the quark model

J^{PC}: 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{--}, 2^{-+}, 2^{++}, ...

A modified reproduction of the table from the 2006 Particle Data Book

$n^{2s+1}L_J$	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^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2(1270)$	$f_2'(1525)$	$29.6°$	$28.0°$
1^1D_2	2^{-+}	$\pi_2(1670)$	$K_2(1770)$	$\eta_2(1645)$	$\eta_2(1870)$		
1^3D_1	1^{--}	$\rho(1700)$	$K^*(1680)$	$\omega(1650)$			
1^3D_2	2^{--}		$K_2(1820)$				
2^1S_0	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1295)$	$\eta(1475)$	$-22.4°$	$-22.6°$
2^3S_1	1^{--}	$\rho(1450)$	$K^*(1410)$	$\omega(1420)$	$\phi(1680)$		

$$|\,1\,\rangle = \frac{1}{\sqrt{3}}\,(u\bar{u} + d\bar{d} + s\bar{s})$$

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

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

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

the mixing angle for the nonets:

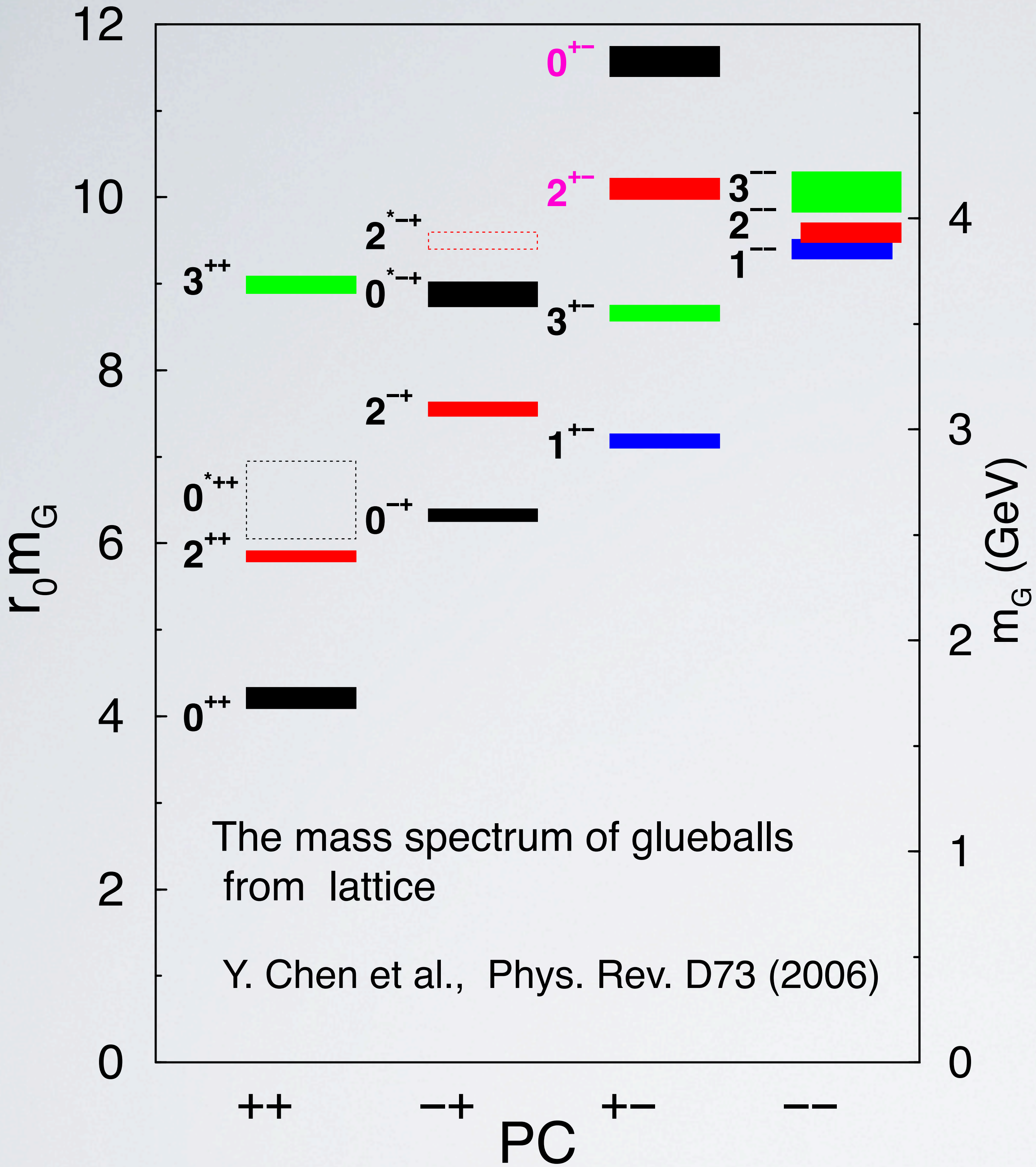
$$\tan\theta_l = \frac{4m_K - m_a - 3m_{f'}}{2\sqrt{2}(m_a - m_K)}$$

$$\tan^2\theta_q = \frac{4m_K - m_a - 3m_{f'}}{-4m_K + m_a + 3m_f}$$

Measuring the masses and decay rates of mesons can be used to identify the quark content of a particular meson

Crede, Mayer, 2009

Glueballs gg-state



J^{PC}	M_G (GeV/c^2)
0^{++}	1.710(.050)(.080)
2^{++}	2.390(.030)(.120)
0^{-+}	2.560(.035)(.120)
1^{+-}	2.980(.030)(.140)
2^{-+}	3.040(.040)(.150)
3^{+-}	3.600(.040)(.170)
3^{++}	3.670(.050)(.180)
1^{--}	3.830(.040)(.190)
2^{--}	4.010(.045)(.200)
3^{--}	4.200(.045)(.200)
2^{+-}	4.230(.050)(.200)
0^{+-}	4.780(.060)(.230)

The lightest glueballs have J^{PC} quantum numbers of normal mesons and would appear as an SU(3) singlet state. If they are near a nonet of the same J^{PC} quantum numbers, they will appear as an extra f-like state. While the fact that there is an extra state is suggestive, the decay rates and production mechanisms are also needed to unravel the quark content of the observed mesons.

Crede, Mayer, 2009

Identifying glueballs gg-state

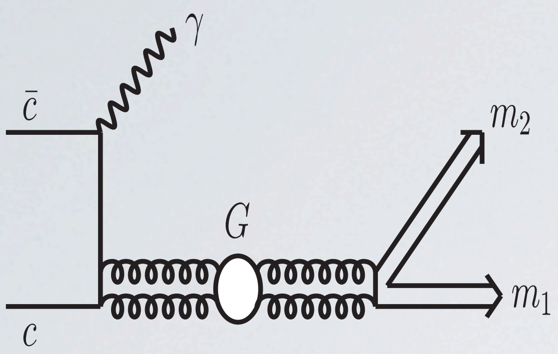
Conclusions from theory

There is a general agreement in that the lightest gluonic state has quantum numbers $J^{PC} = 0^{++}$. One state is located around 1.4-1.7 GeV

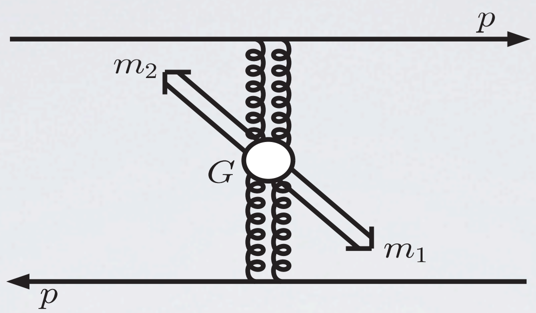
The next heavier states are expected with quantum numbers $J^{PC}=2^{++}$ and with masses $\gtrsim 2$ GeV. Experimental analyses have been difficult so far in this mass region.

Therefore, the search for the scalar gluonic states looks particularly promising despite the experimental and theoretical uncertainties. W. Ochs, J.Phys. G40 (2013)

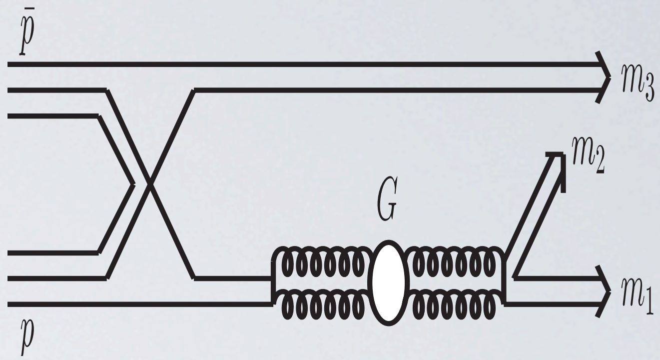
Production of glueballs in gluon-rich processes



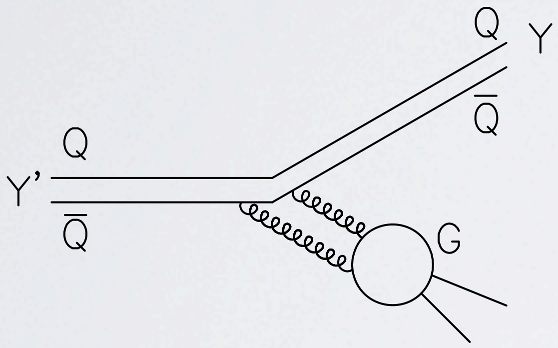
Radiative J/ψ or Υ decays



Central production of mesons:
"double Pomeron exchange"



$p\bar{p}$ annihilation



Decay of excited heavy quarkonium
Υ(n) to ground state Υ

Glueball in $\gamma\gamma$ collisions

a glueball couples to photons only through loop processes and then it is suppressed

in $\gamma\gamma$ reactions

W. Ochs, J.Phys. G40 (2013)

Experimental evidence for tensor 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	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	$11\,\sigma$	✓

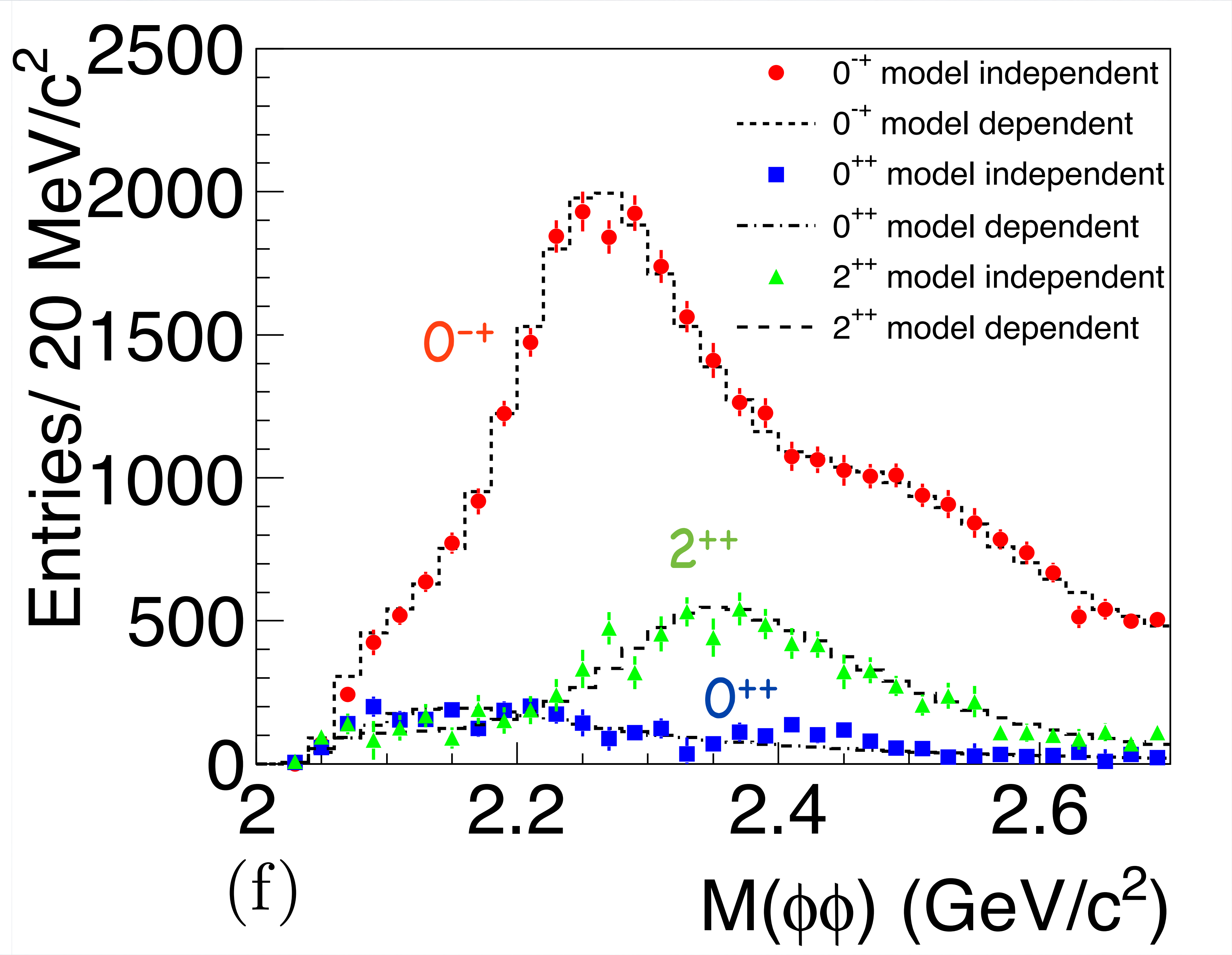
first observed in $\pi^- + p \to \phi\phi n$

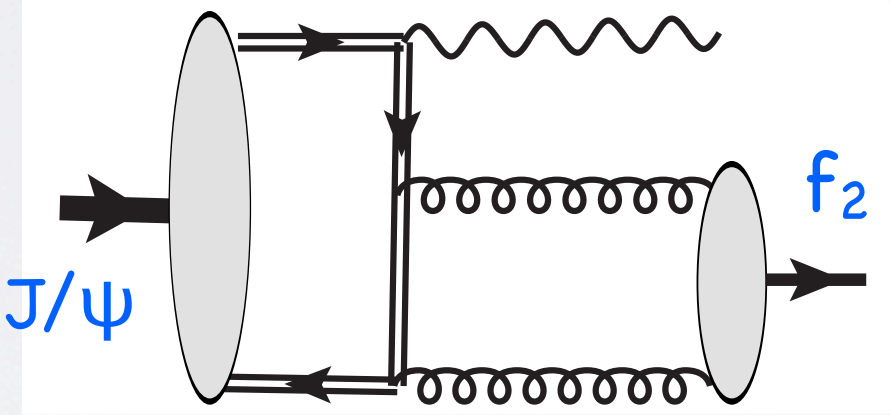
Etkin et al, PRL(1978), PLB(1985), PLB(1988)

Lattice: Chen et al, PRL 111(2013) $f_2(2340)$ might be glueball

Experimental evidence for tensor glueballs

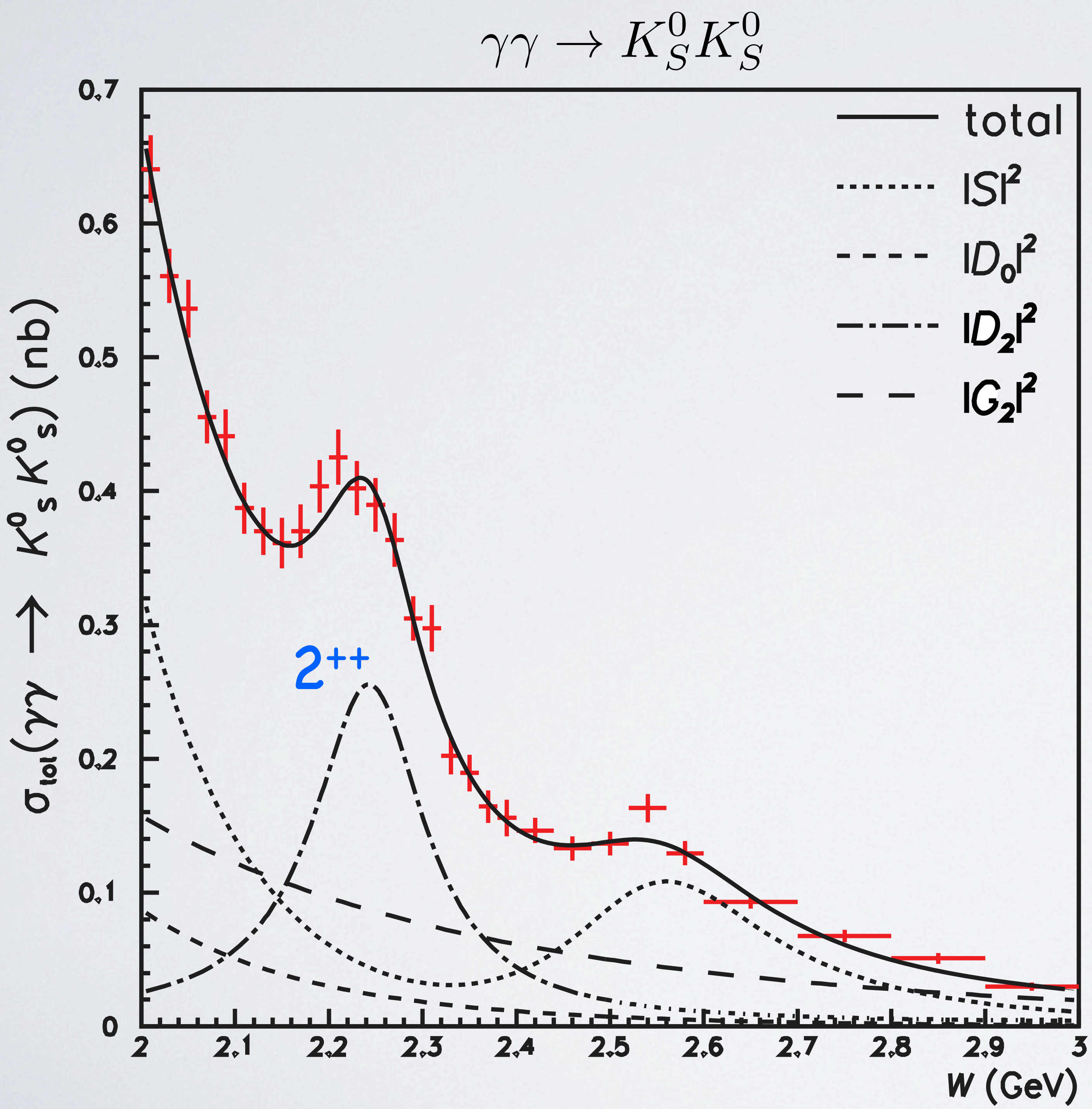
Experiment BES III, Ablikim et al, PRD 93(2016)





Experimental evidence for tensor glueballs

Experiment BELLE, Uehara et al, PTEP (2013)



$f_2(2300)$

$M = 2297 \pm 28$ MeV

$\Gamma = 149 \pm 40$ MeV

Probably this indicates that this meson is $q\bar{q}$-state of have large $q\bar{q}$-component

Can we learn smth about glueballs in hard exclusive reactions?

Advantages

the amplitude sensitive to the wave functions (distribution amplitudes)

strong coupling to gluonic component of WF must be observed

mixing with quarks is well understood (QCD evolution)

special case spin-2: there is gluonic DA which does not mix with quarks (QCD evolution)

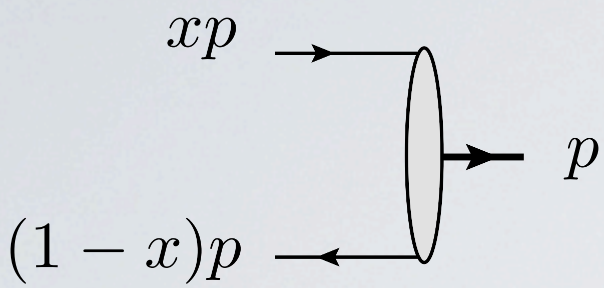
Disadvantages

mixing still can be problematic for interpretation if hadron is $q\bar{q}$ and gg state (depends on the concrete process)

small cross sections at large hard scale Q^2

which reactions can be suggested?

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

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

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

$$\langle p|\bar{\psi}(z)\not{z}\psi(0)|0\rangle\Big|_{z_-=z_\perp=0} \sim f_q \int_0^1 dx\, e^{ixz_+p_-}\phi(x,\mu)$$

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

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

suppressed by powers of 1/Q:

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

$q\bar{q}$ with orbital momentum

coupling to gluons: qq-state

$n^{2s+1}L_J$	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
1^3P_2	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2(1270)$	$f_2'(1525)$	$29.6°$	$28.0°$

Quark DA: $|\bar{q}(+)q(-)(^1S_0)\rangle$

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

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

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

coupling to gluons: qq-state

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

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

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

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

Terazawa, 1990/ Suzuki 1993 (TM dom.)

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

for comparison

$$f_\pi = 130MeV \qquad f_\rho = 221MeV \qquad f_\omega = 198MeV$$

coupling to gluons: qq-state

$n^{2s+1}L_J$	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
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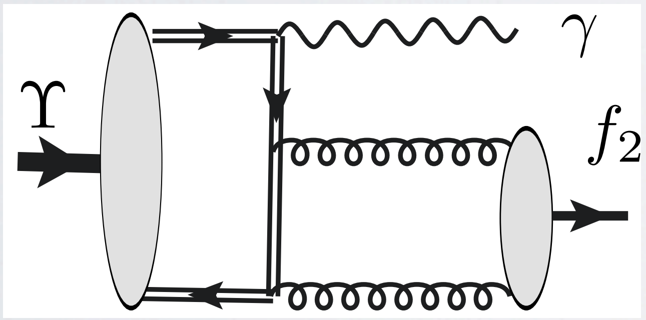
$$\langle f_2(P,\lambda)|z^\alpha z^\beta G^a_{\alpha\mu}(z)G^a_{\beta\mu}(0)|0\rangle\,\Big|_{z_-=z_\perp=0} \sim f_g^S \int_0^1 dx\, e^{ixp_-z_+}\phi_g^S(x)$$

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



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

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

$$f_g^S(\mu^2=4m_b^2) = (14.9\pm0.8)\,\text{MeV}$$

coupling to gluons: qq-state

$n^{2s+1}L_J$	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
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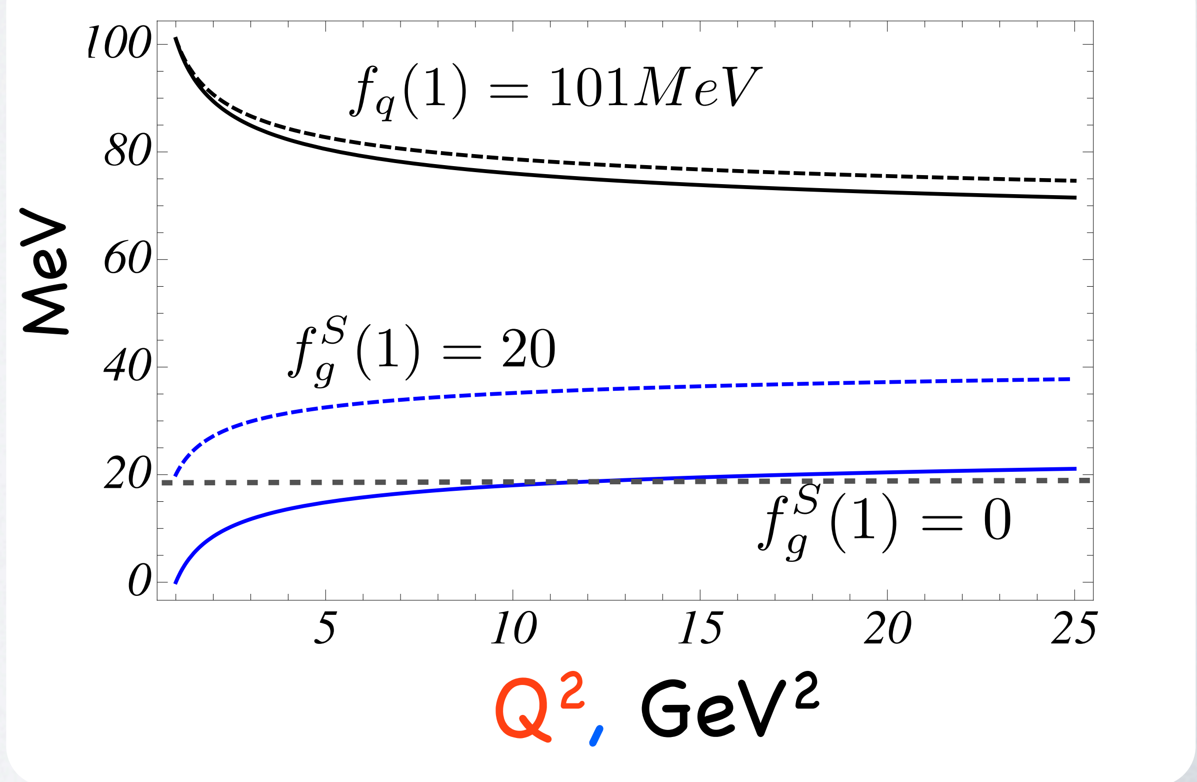
$$f_g^S(\mu^2=4m_b^2) = (14.9\pm 0.8)\,\mathrm{MeV}$$

therefore this result compatible with

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

i.e. the meson consists from $q\bar{q}$
at low normalization point

QCD evolution mixes f_q and f_g^S



Light-cone distribution amplitudes

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

only for tensor state 2^{++} $\quad |g(\pm)g(\pm)(^5S_2)\rangle$

$$\langle M(P,\lambda=2)|z^\alpha z^\beta G_{\alpha\{\mu}(z)G_{\beta\nu\}}(0)|0\rangle|_{z_-=z_\perp=0} = f_g^T e^\perp_{\{\mu\nu\}} \int_0^1 dx\, e^{ixp_-z_+}\phi_g^T(x)$$

such component does not mix with quarks!

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

$$\langle M(P,\lambda=2)|\bar{\psi}(z)\overleftrightarrow{D}_{\{\perp\mu}\overleftrightarrow{D}_{\perp\nu\}}\not{z}\psi(0)|0\rangle \sim \frac{\Lambda^2}{Q^2} \longrightarrow \sim \frac{m^2}{Q^2}\langle f_q\rangle + \ldots$$

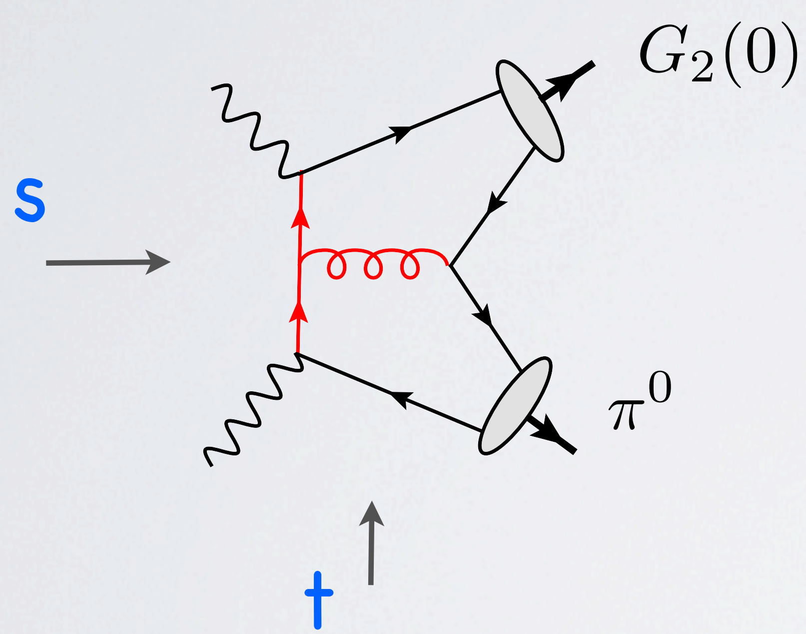
QCD EOM

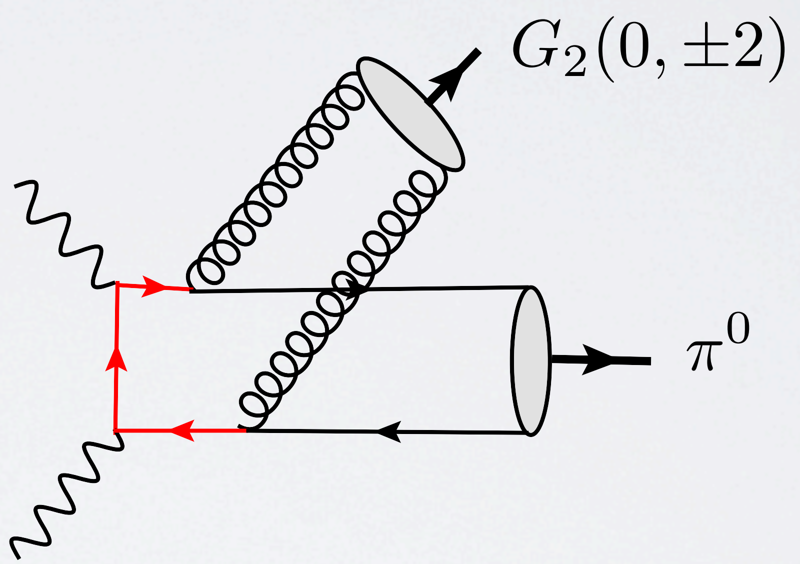
which reactions can be suggested?

One more way to study tensor glueball: $\gamma\gamma \to \pi^0 G(2^{++})$

wide angle scattering $s \sim -t \sim -u \gg \Lambda^2$

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





all terms are of order α_s

BEFORE:

$\gamma\gamma \to G_0 \pi^0$ Atkinson, Sucher and Tsokos, Phys. Lett. 137B (1984)

Wakely and Carlson, Phys. Rev. D 45 (1992)

$\gamma\gamma \to G_{0,2}\, \pi^0$ Ichola and Parisi, Z. Phys. C 66 (1995) 653

One more way to study tensor glueball: $\gamma\gamma \to \pi^0 G(2^{++})$

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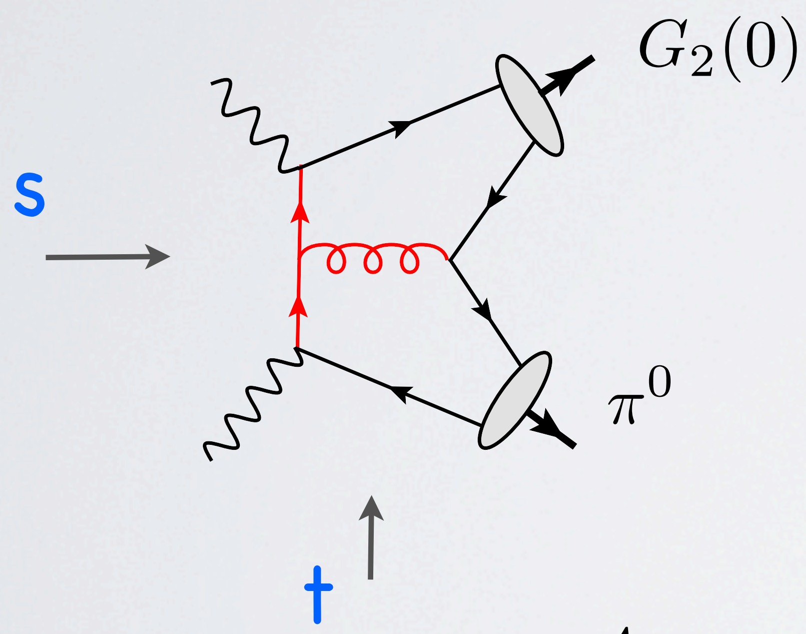
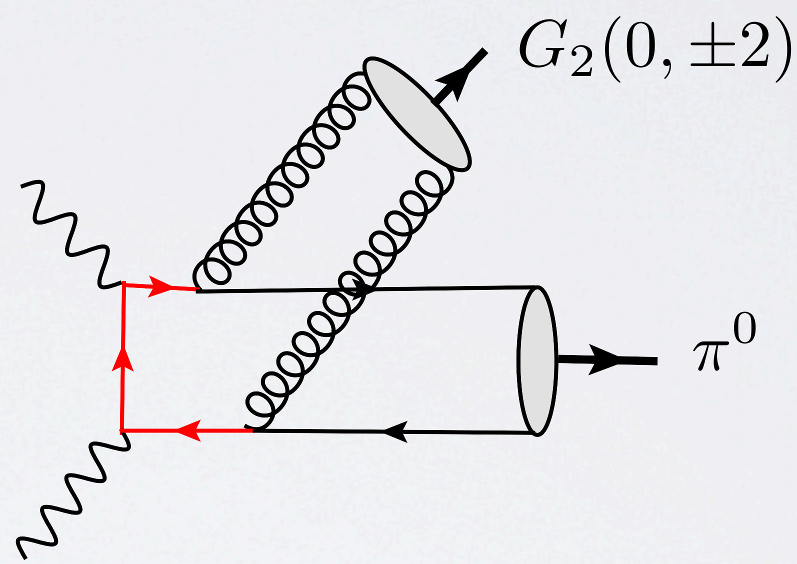




all terms are of order α_s

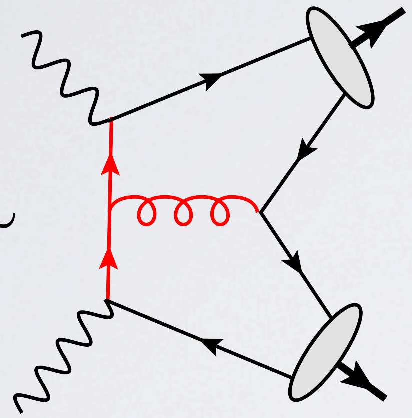
$A_{\pm\pm} : \gamma(\pm)\gamma(\pm) \to G_2(\pm 2)$ tensor gluon DA

$A_{\pm\mp} : \gamma(\pm)\gamma(\mp) \to G(0)$ quark & gluon DAs

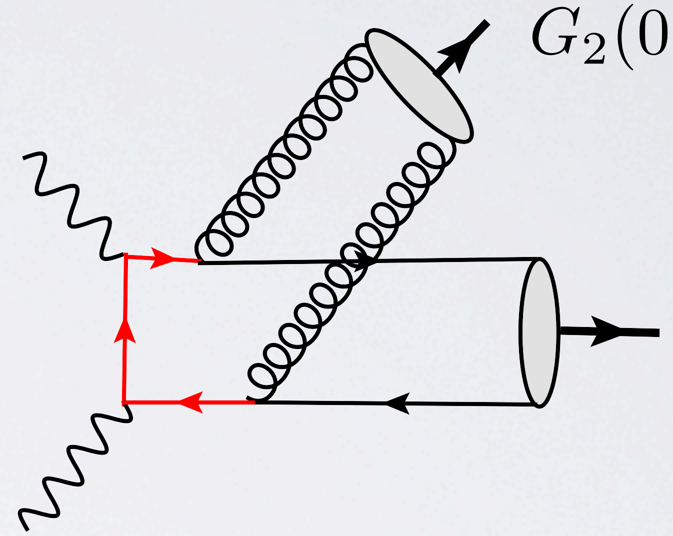
Amplitude and cross section

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

$A_q^{+-} \sim$



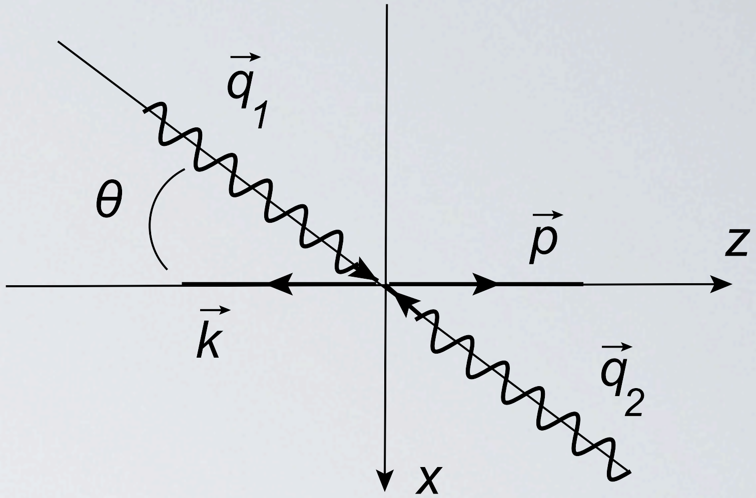
$A_g^{+\pm} \sim$



$$s\to\infty \quad \frac{d\sigma_{\gamma\gamma}[\pi^0 G(2^{++})]}{d\cos\theta} \sim \frac{1}{s}\left(\left|\frac{f_\pi f_g^T}{s} g_{++}(\theta)\right|^2 + \left|\frac{f_\pi f_g^S}{s} g_{+-}(\theta) + \frac{f_\pi f_q}{s} f_{+-}(\theta)\right|^2\right)$$

$f_\pi = 131$ MeV $\qquad f_g^{T,S},\ f_q$ unknown

Angular behaviour

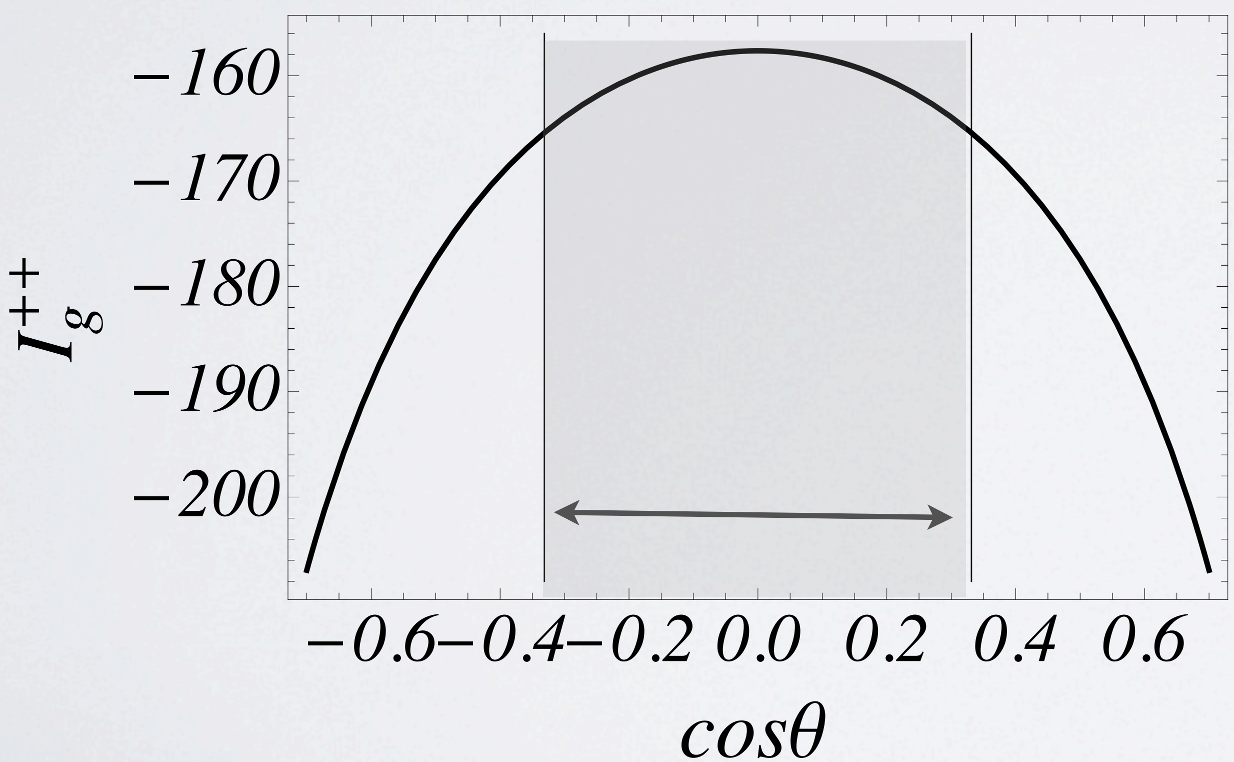


$$A_g^{++} \sim \frac{f_\pi \; f_g^T}{s} \alpha \alpha_s \; I_g^{++}(\cos\theta),$$

$$I_g^{++}(\cos\theta) = \int_0^1 dy \, \frac{\phi_\pi(y)}{y\bar{y}} \int_0^1 dx \frac{\phi_g^T(x)}{x\bar{x}} \, \frac{(-2)}{(1-\cos\theta)x\bar{y} + (1+\cos\theta)y\bar{x}}$$

$$\bar{x} \equiv 1 - x$$

$s = 13 \text{ GeV}^2$



models for the DAs

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

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

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

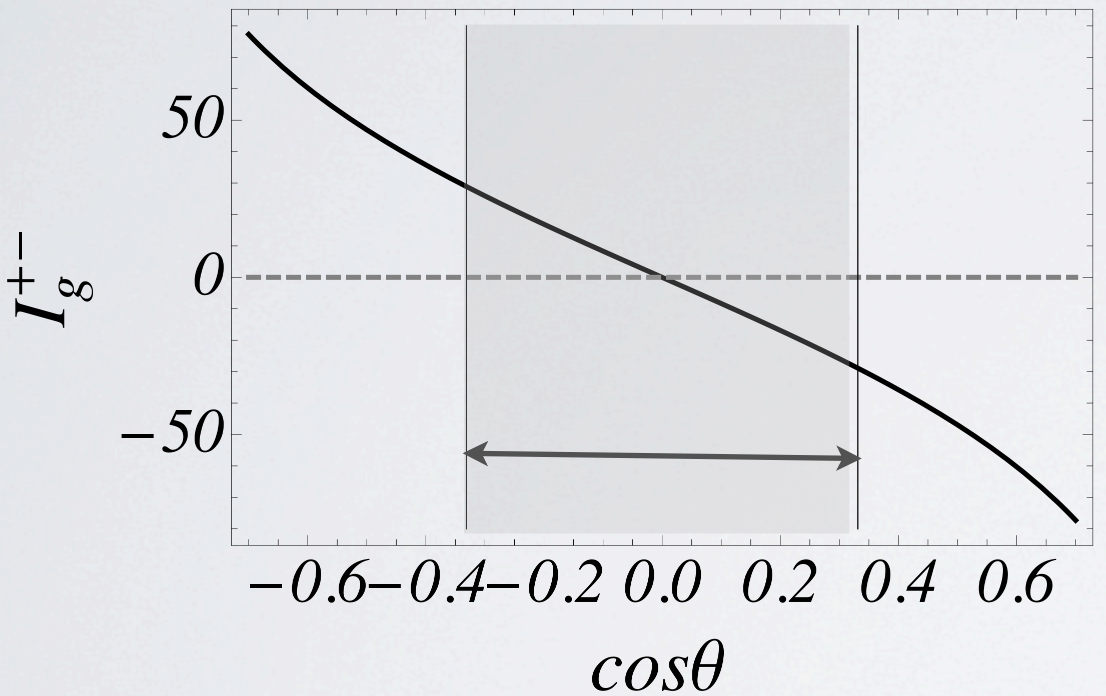
$s \sim -t \sim -u \gg \Lambda^2 \quad \longleftrightarrow \quad |u|, |t| \geq 2.5\text{GeV}^2$

Angular behaviour

$$\bar{x} \equiv 1 - x$$

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

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



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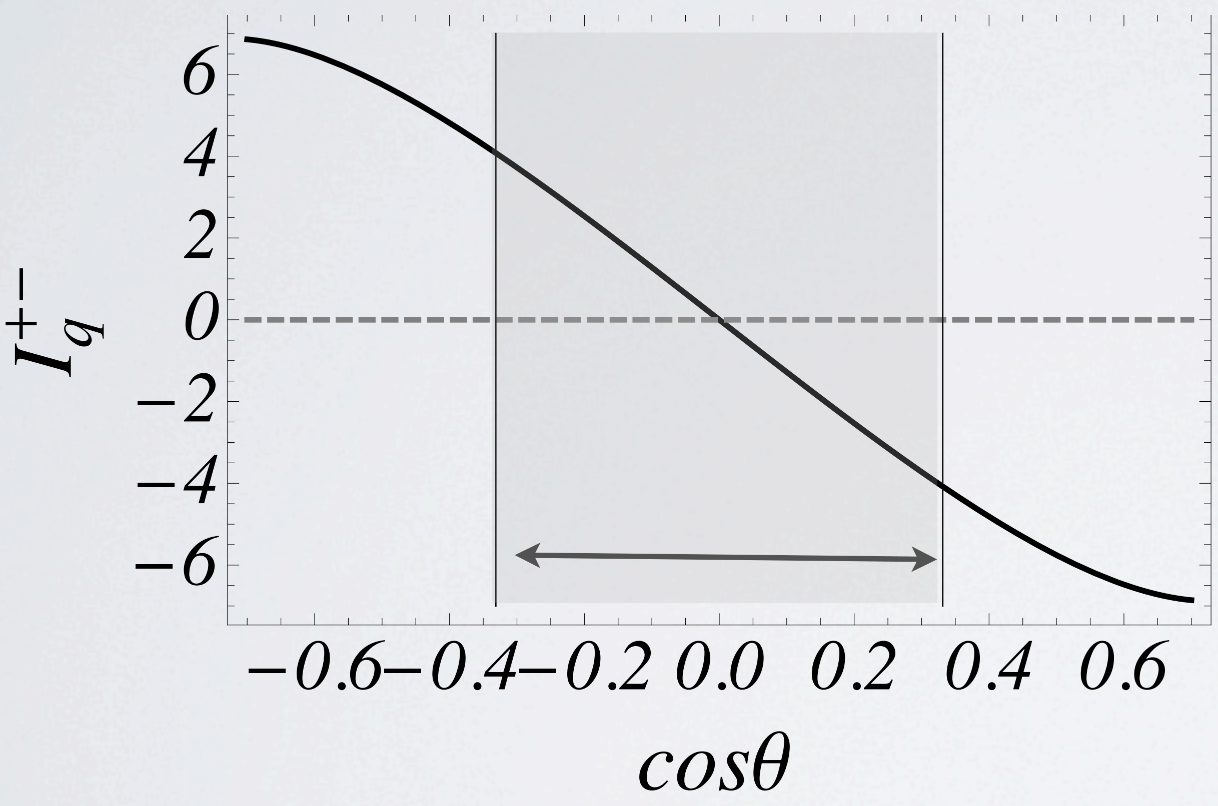
☛ $$|I_g^{++}| \gg |I_g^{+-}|$$

Angular behaviour

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

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



models for the DAs

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

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

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

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

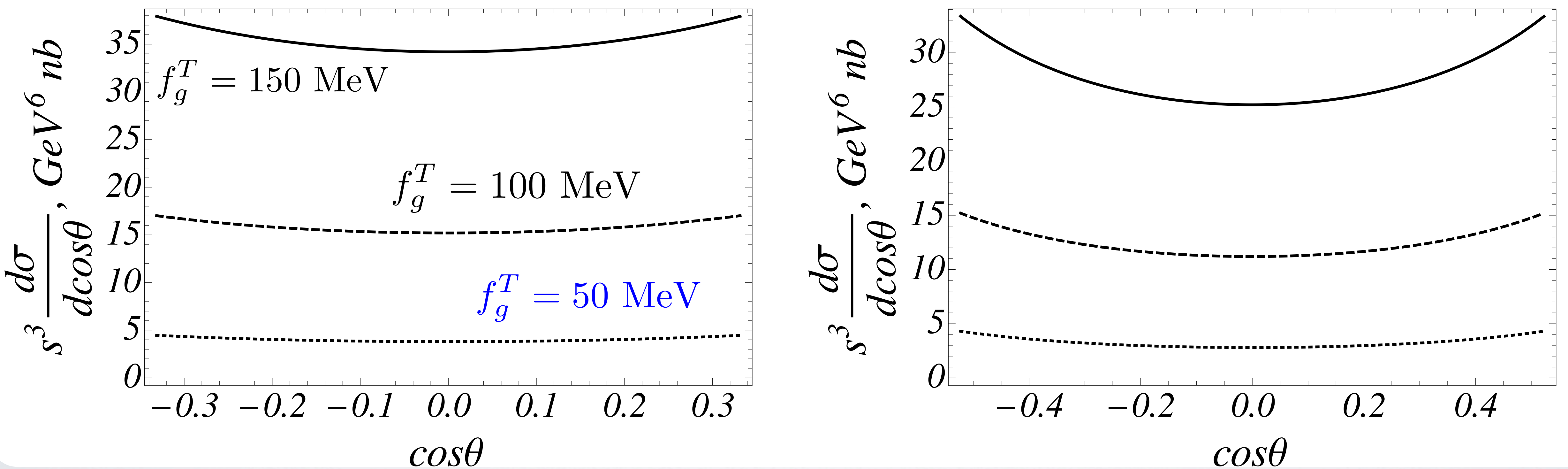
at large angles G_2 is dominantly produced in tensor polarization

Cross section

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

M_G = 2.3 GeV

s = 13GeV^2 s = 16GeV^2



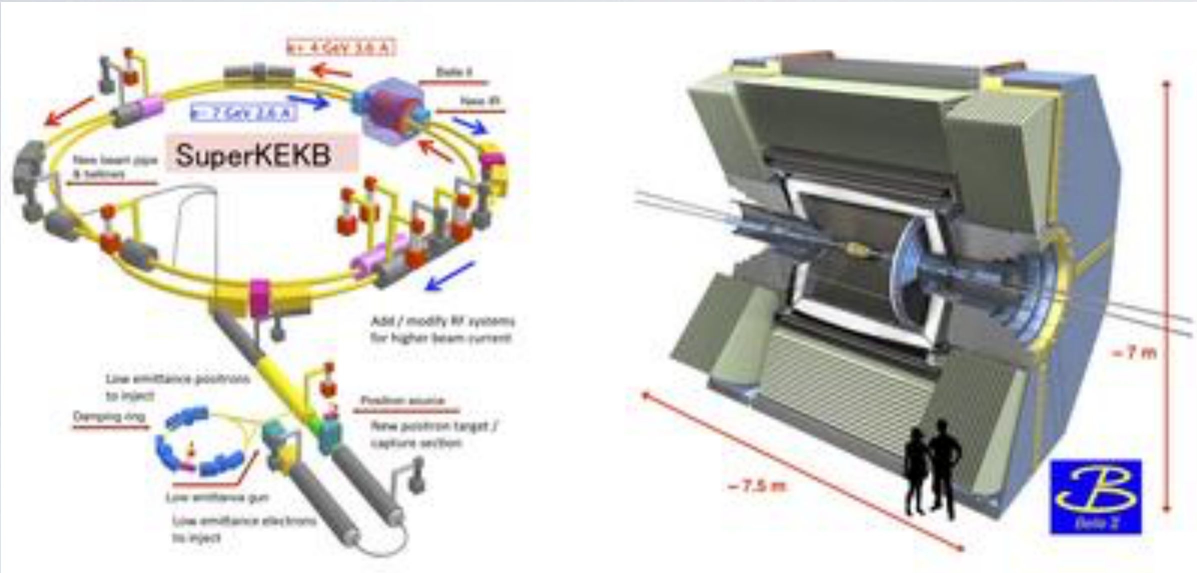
$$|t| \,\&\, |u| > 2.5 \text{ GeV}^2$$

$$f_q(\mu = 1 \text{ GeV}) \simeq 10 - 100 \text{ MeV}$$

$$f_g(\mu = 1 \text{ GeV}) \simeq 100 \text{ MeV}$$

tensor channel is dominant

Can one measure the cross section in BELLE II?



e^+e^- asymmetric collider

KEKB — instantaneous luminosity of 2.11×10^{34} cm^{-2} s^{-1}.

SuperKEKB — instantaneous luminosity of 8×10^{35} cm^{-2} s^{-1}

larger by a factor 40

The ambitious goal is to accumulate an integrated luminosity of 50 attob^{-1} (10^{-18}) by the mid of next decade, which is 50 times more data than the previous Belle detector acquired

A lot of work have been already done

$$W = \sqrt{s}$$

$\gamma\gamma \to \pi^-\pi^+$, $\gamma\gamma \to K^+K^-$	2.4 GeV < W < 4.1GeV	H. Nakazawa et al., **Phys.Lett. B615 (2005)**
$\gamma\gamma \to \pi^0\pi^0$	0.6 GeV < W < 4.1 GeV	S. Uehara et al., Phys. Rev. D 79 (2009)
$\gamma\gamma \to K^0_S \bar{K}^0_S$	1.0 GeV ≤ W ≤ 4.0 GeV	S. Uehara et al., PTEP 2013 (2013)
$\gamma\gamma \to \eta\eta$	1.1 GeV < W < 3.8 GeV	S. Uehara et al., Phys. Rev. D 82 (2010)

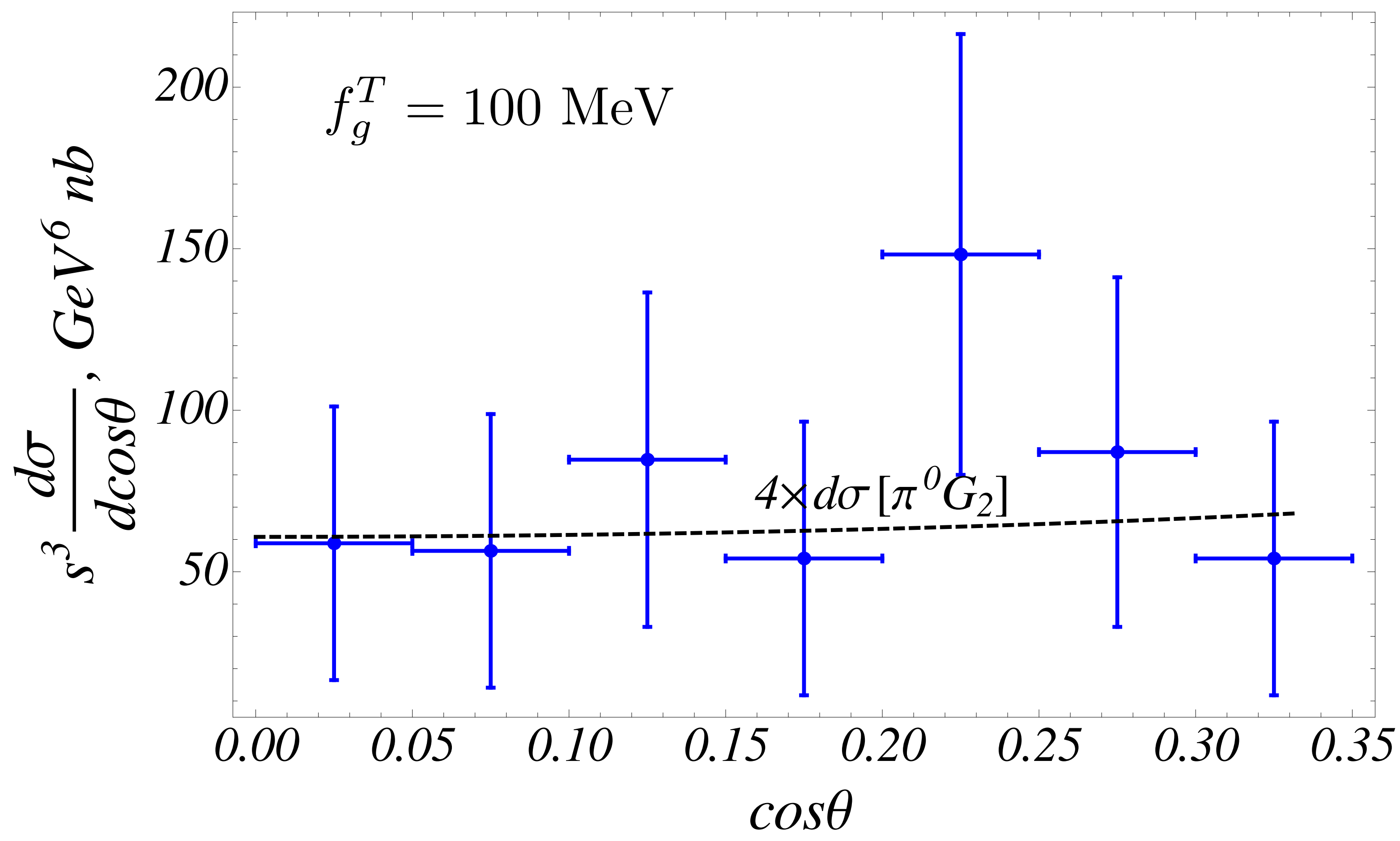
also $\gamma^*\gamma \to \pi^0$

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 $\gamma\gamma \to \pi^0\pi^0$

s = 13GeV² $|t|\,\&\,|u| > 2.5\ \mathrm{GeV}^2$



Conclusion

The glueball production can be measured at BELLE II experiment

Thank you!