Electromagnetic form factors of light & heavy baryons

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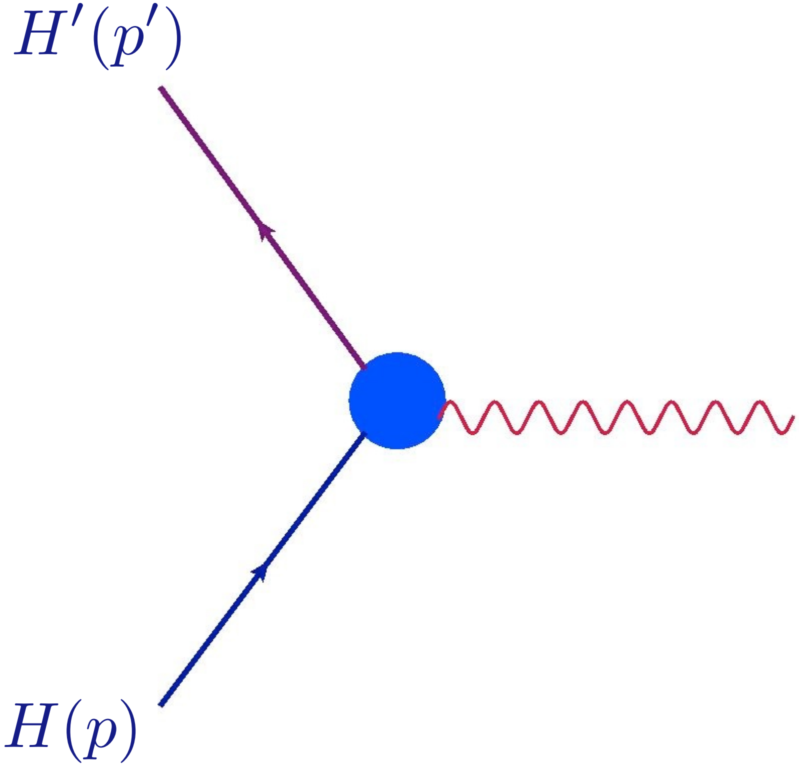
Traditional way of a hadron structure

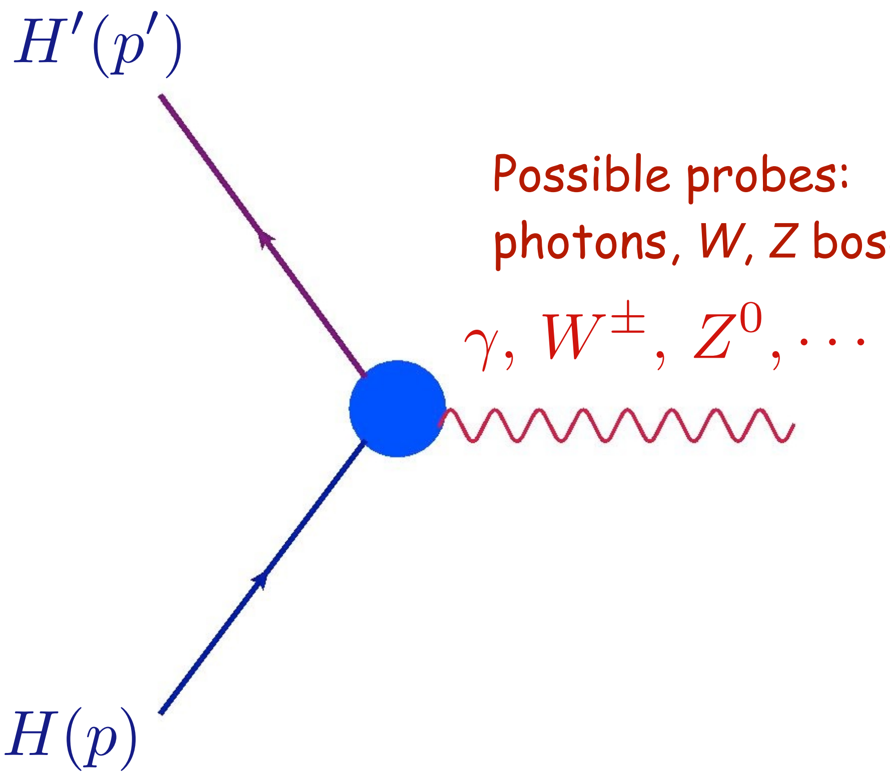
Traditional way of studying structures of hadrons



Traditional way of a hadron structure

Traditional way of studying structures of hadrons

Possible probes:
photons, *W*, *Z* bosons, mesons, nucleons......



Traditional way of a hadron structure

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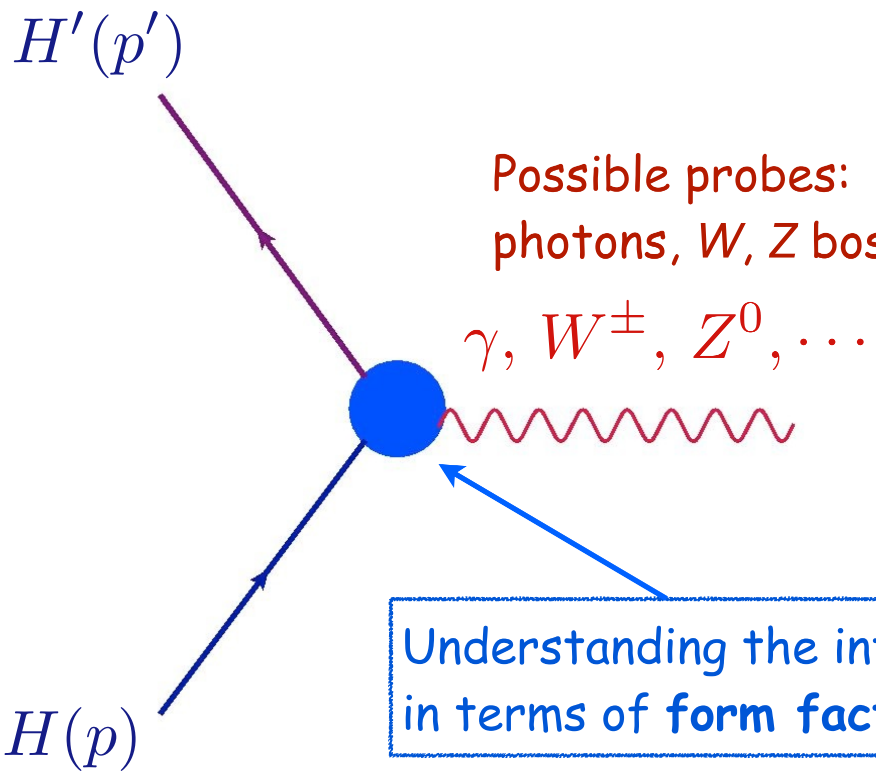
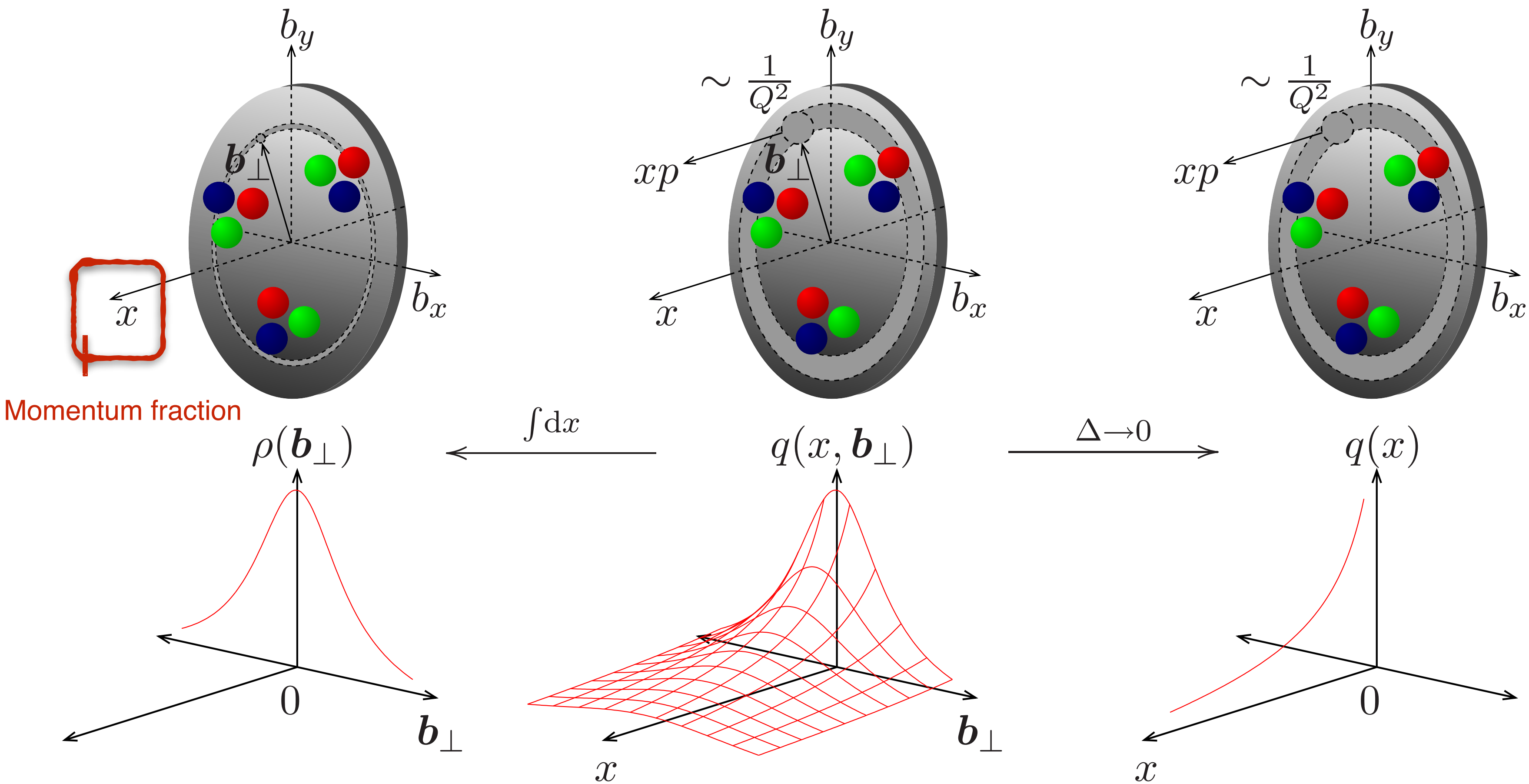


Possible probes:
photons, *W*, *Z* bosons, mesons, nucleons......

Understanding the internal structures of hadrons *H* in terms of **form factors**

Modern understanding of a baryon structure



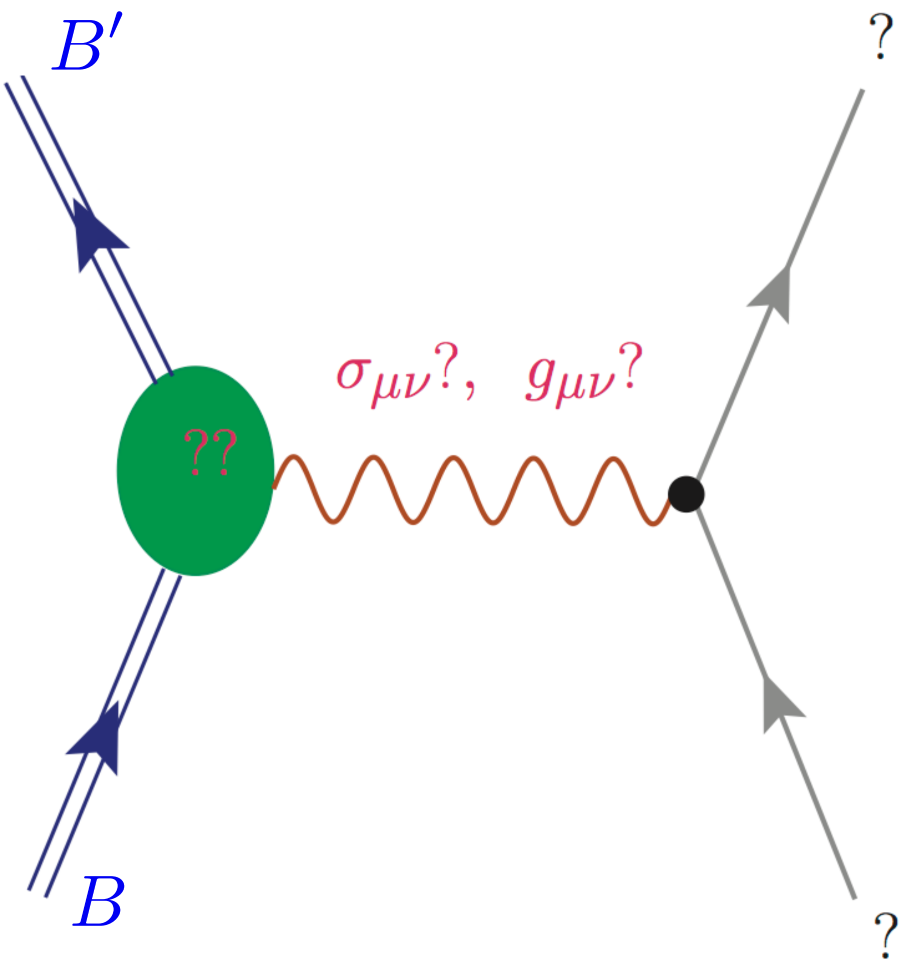
Transverse densities
of Form factors

GPDs
Nucleon Tomography

Structure functions
Parton distributions

Modern understanding of a baryon structure

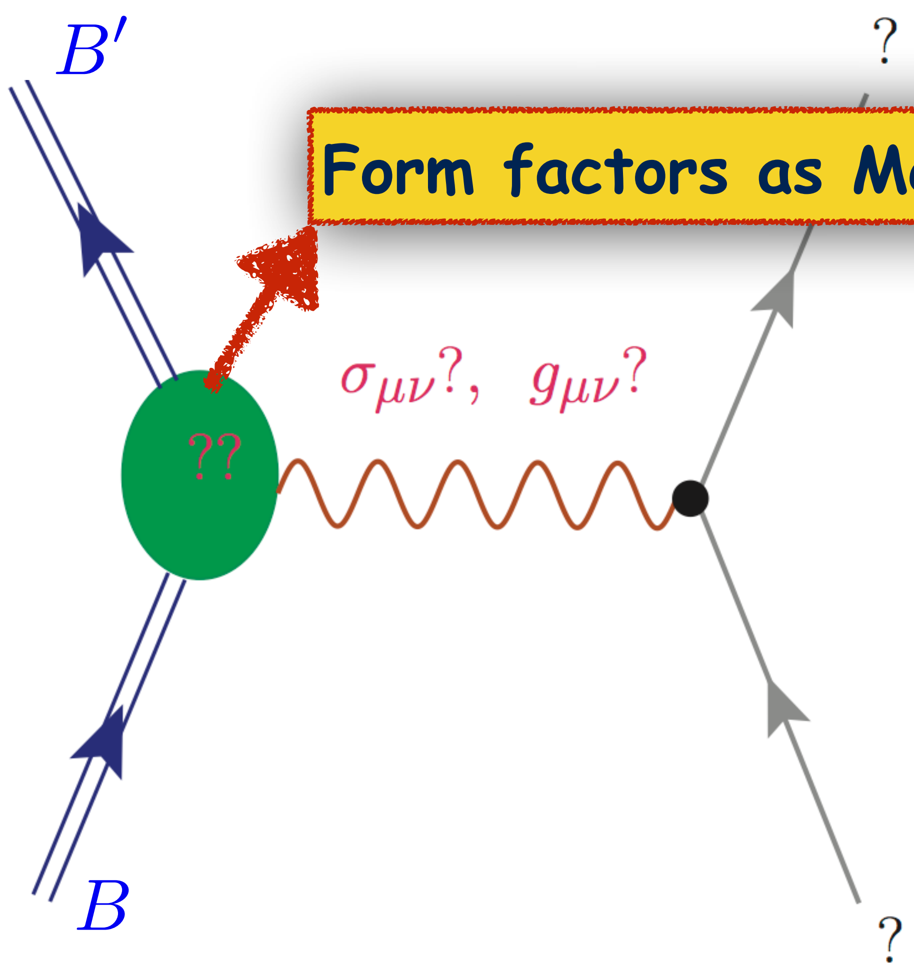
Probes are unknown for **Tensor form factors**
and the **Energy-Momentum Tensor form factors!**



Modern understanding of a baryon structure

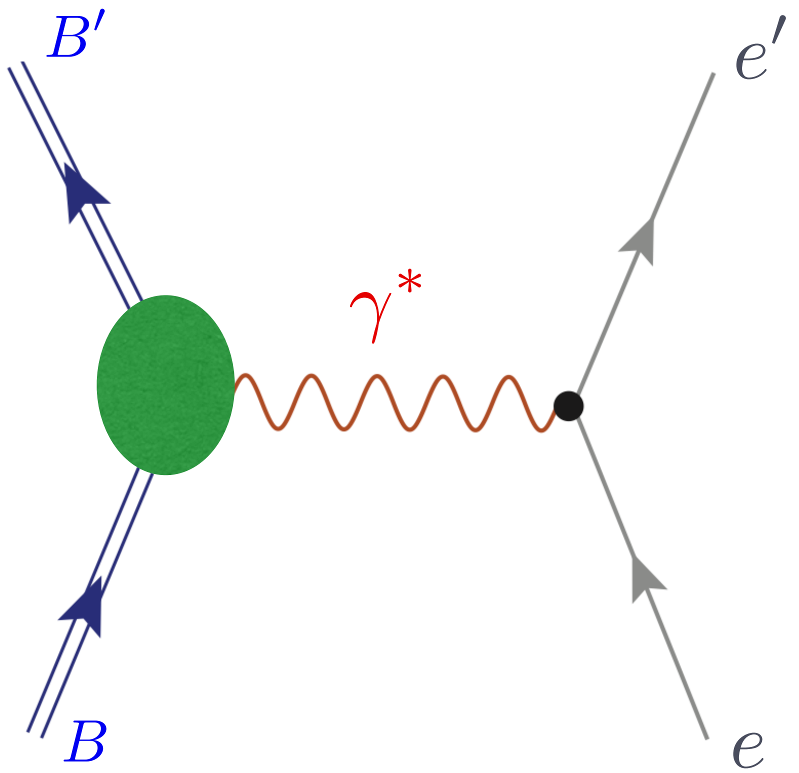
Probes are unknown for **Tensor form factors**
and the **Energy-Momentum Tensor form factors!**

Form factors as Mellin moments of the GPDs



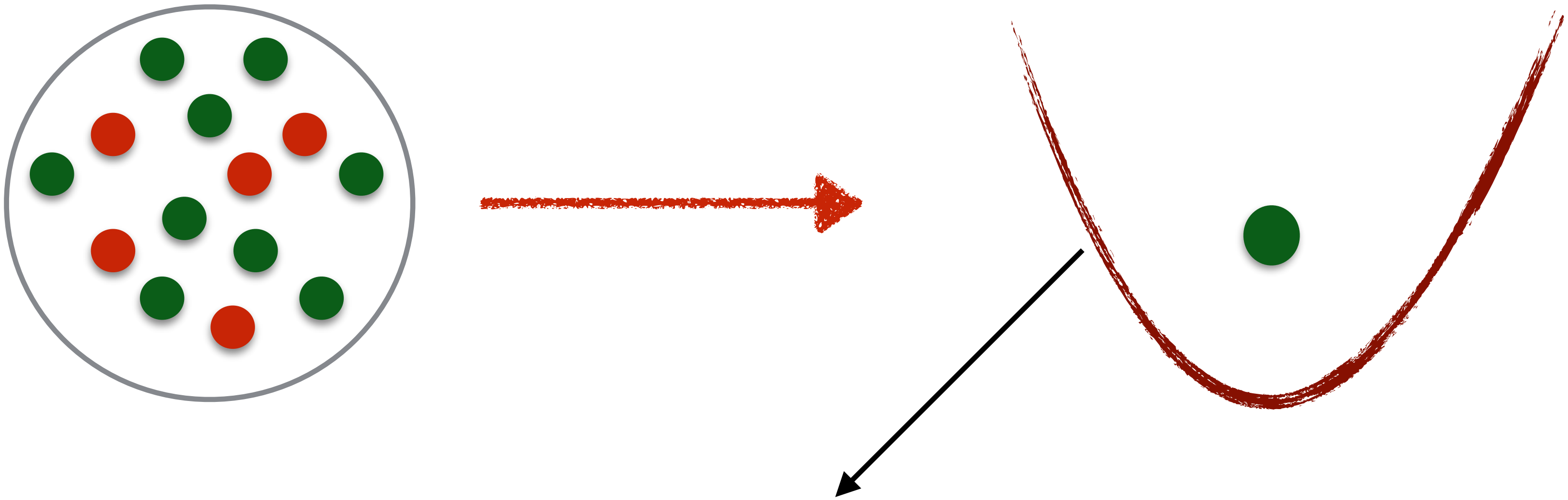
Modern understanding of a baryon structure

Even in this modern view point, knowing the EMFFs of baryons is the first step toward the full understanding of their structures.



Mean-Field Approximation

Simple picture of a mean-field approximation



Mean-field potential that is produced by all other particles.

- Nuclear shell models
- Ginzburg-Landau theory for superconductivity
- Quark potential models for baryons

Mean-Field Approximation

More theoretically defined mean fields

Given action, $S[\phi]$

$$\left.\frac{\delta S}{\delta \phi}\right|_{\phi=\phi_0} = 0$$: Solution of this saddle-point equation ϕ_0

Key point: Ignore the quantum fluctuation.

→ How we can understand the structure of baryons, based on this mean field approach, this is the subject of the present talk.

Baryon in pion mean fields

* A baryon can be viewed as a state of Nc quarks bound by mesonic **mean fields** (E. Witten, NPB, 1979 & 1983).

→ Its mass is proportional to *Nc*, while its width is of order *O(1)*.
Mesons are weakly interacting (Quantum fluctuations are suppressed by 1/Nc: *O(1/Nc)*.

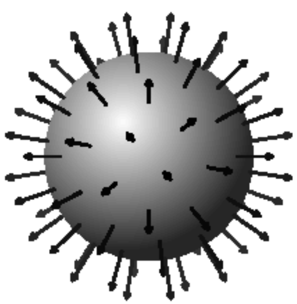
Meson mean-field approach (Chiral Quark-Soliton Model)

* Baryons as a state of Nc quarks bound by mesonic mean fields.

$$S_{\rm eff} = -N_c \mathrm{Tr}\ln\left(i\partial\!\!\!/ + iMU^{\gamma_5} + i\hat{m}\right)$$

* Key point: Hedgehog Ansatz

$$\pi^a(\boldsymbol{r}) = \begin{cases} n^a F(r),\ n^a = x^a/r, & a = 1,\,2,\,3 \\ 0, & a = 4,\,5,\,6,\,7,\,8. \end{cases}$$


hedgehog

→ It breaks spontaneously $\mathrm{SU(3)}_{\rm flavor} \otimes \mathrm{O(3)}_{\rm space} \to \mathrm{SU(2)}_{\rm isospin+space}$

Baryon in pion mean fields

✱ Merits of the Chiral Quark-Soliton Model

- It is directly related to nonperturbative QCD via the Instanton vacuum.

  → Natural scale of the model given by the instanton size:

  $$\rho \approx (600\,\mathrm{MeV})^{-1}$$

- Fully relativistic quantum-field theoretic model:

  It explains almost all properties of the lowest-lying baryons.

- It describes the light & heavy baryons on an equal footing

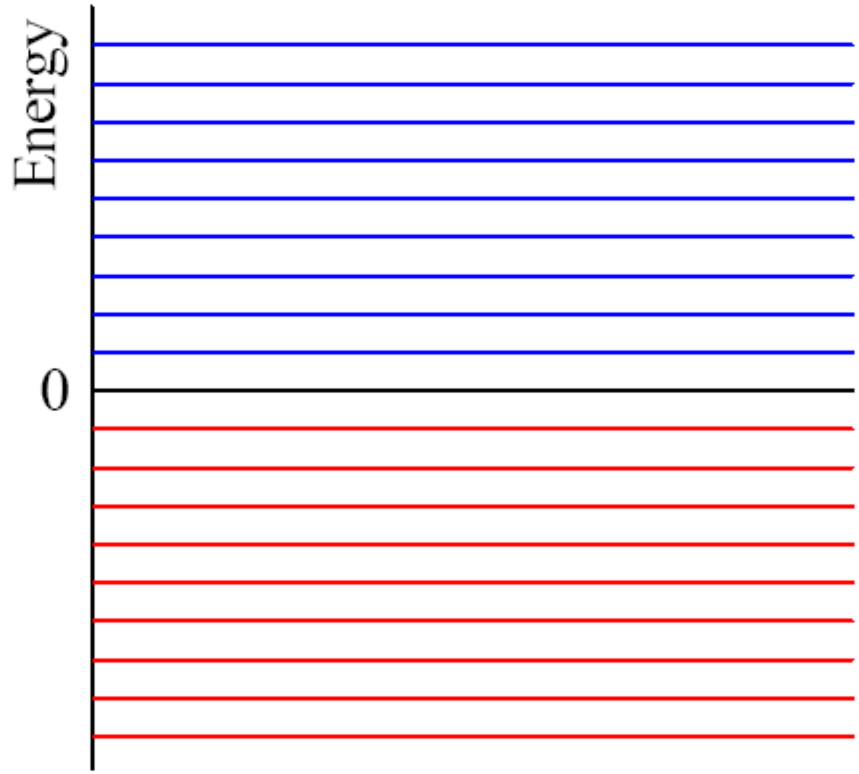
  (Advantage of the mean-field approach) .

- Basically, no free parameter to fit the experimental data.
  Cutoff parameter is fixed by the pion decay constant, and
  Dynamical quark mass (M=420 MeV) is fixed by the proton
  radius.

Baryon in pion mean fields

HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Baryon in pion mean fields



HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

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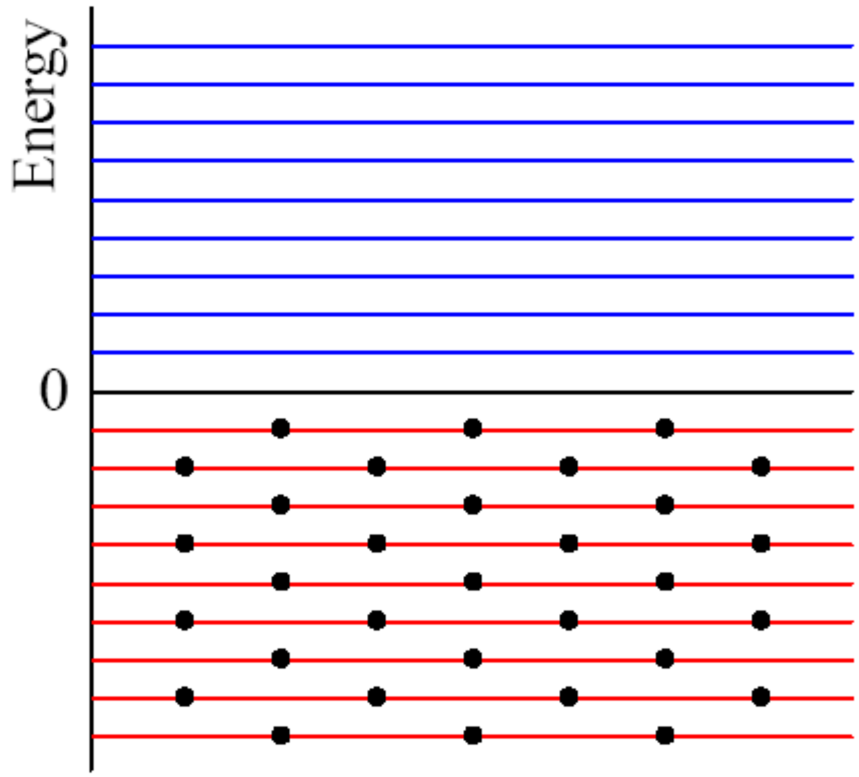

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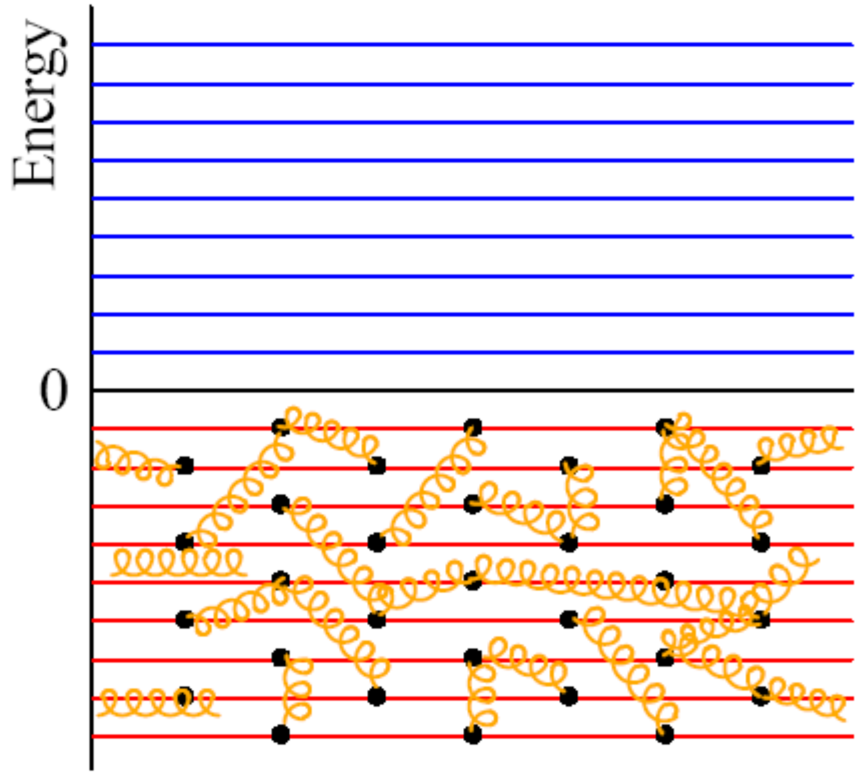

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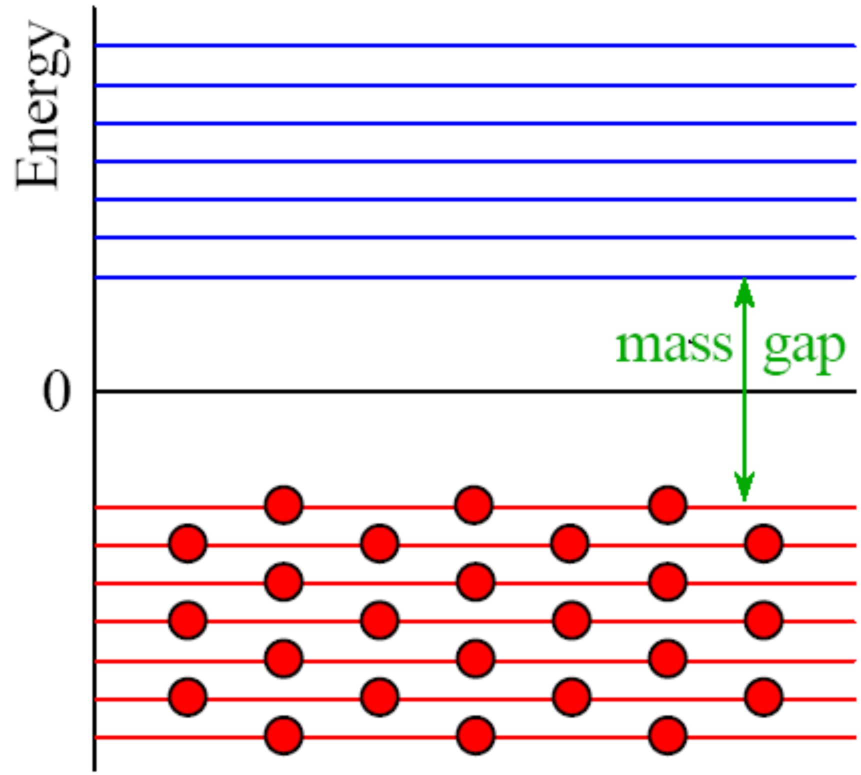

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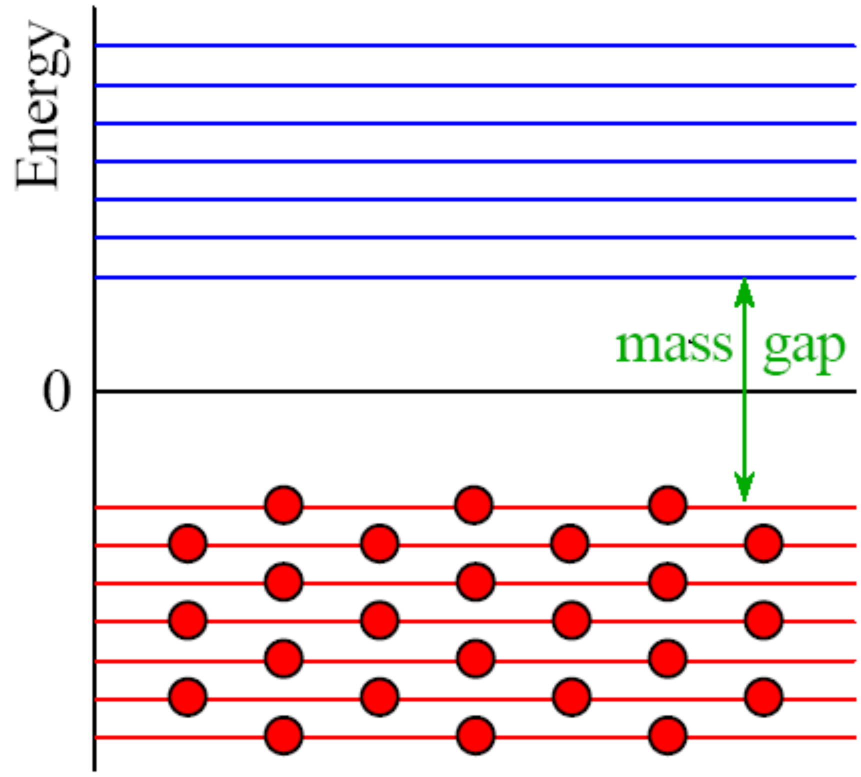

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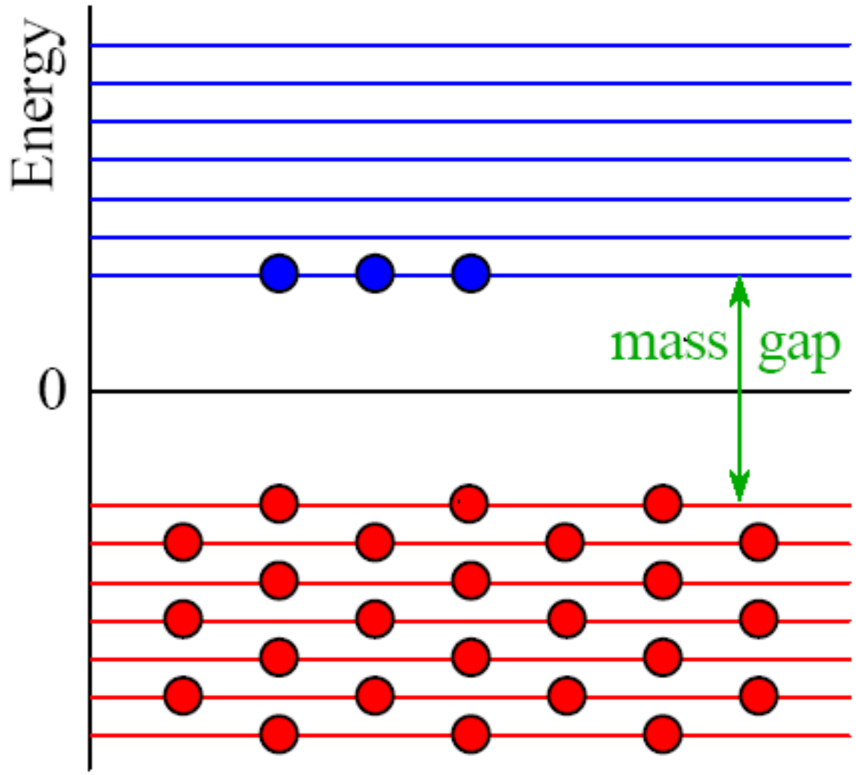

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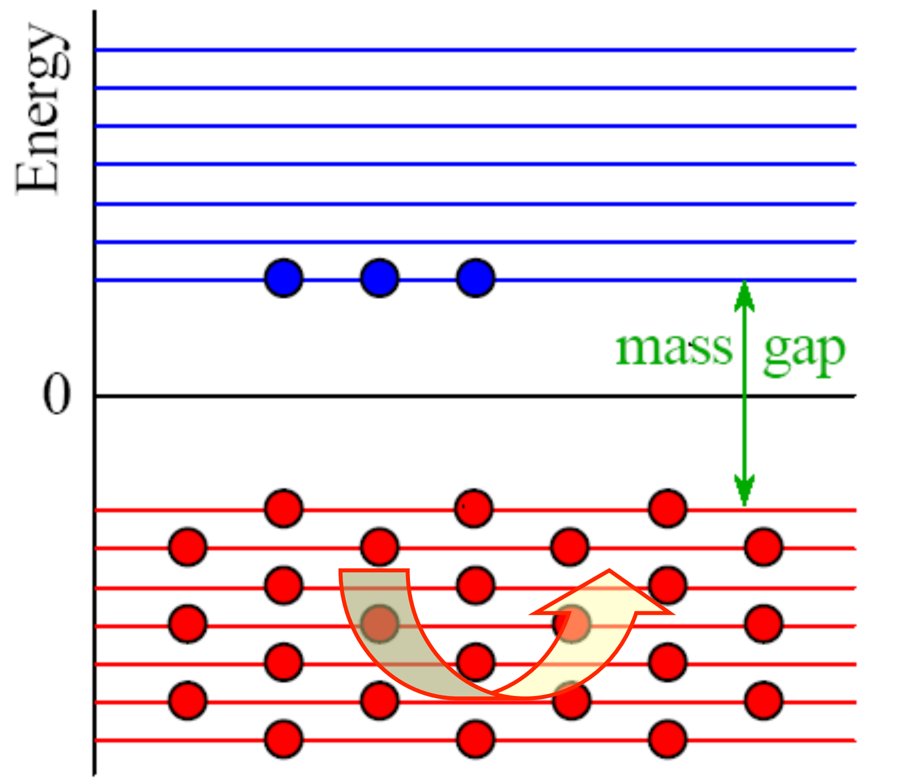

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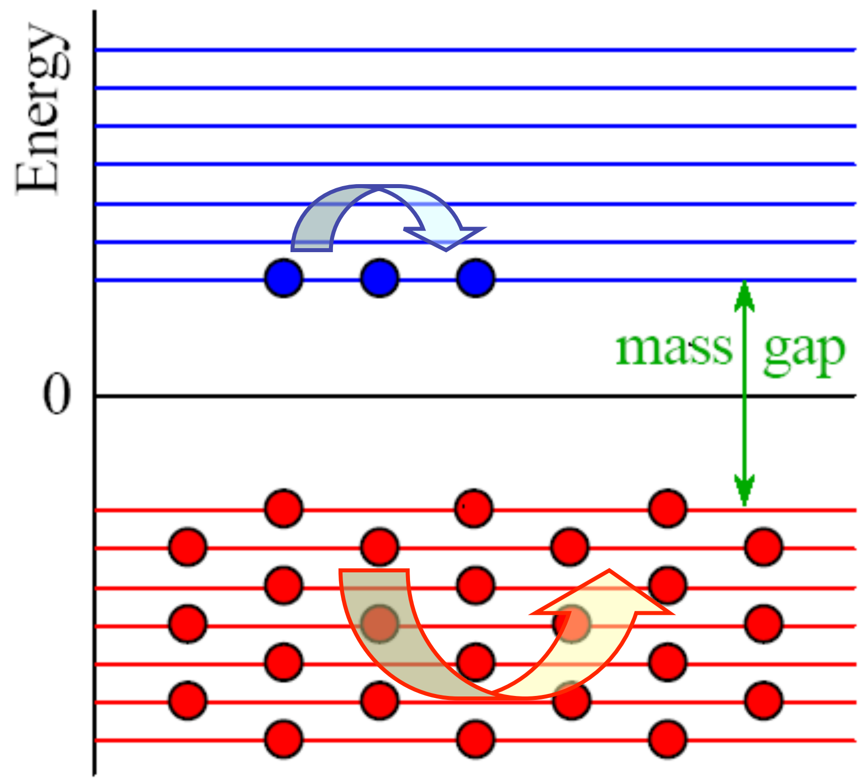

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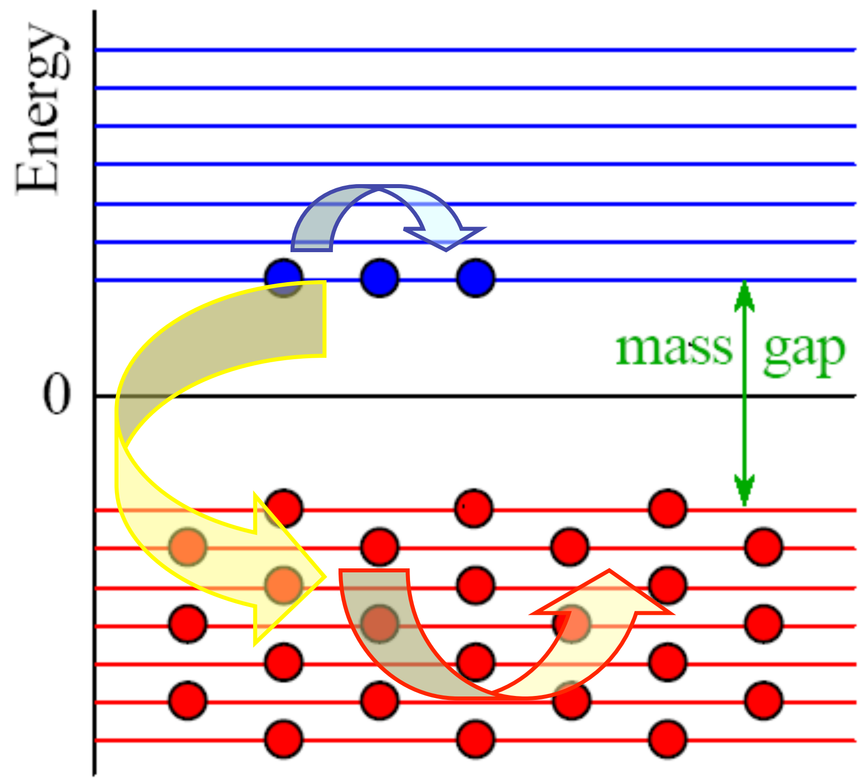

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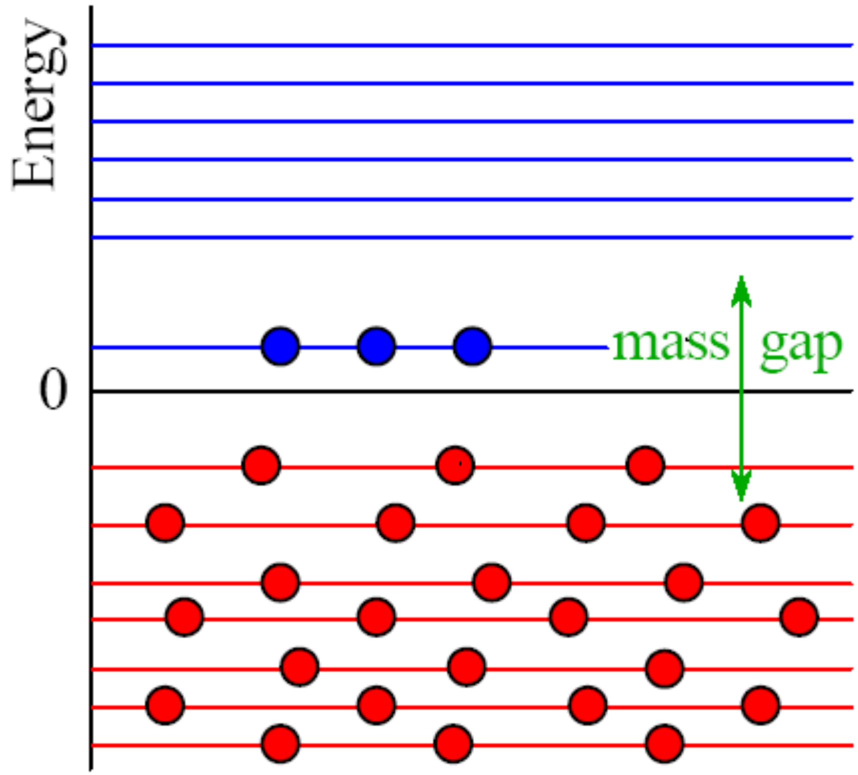

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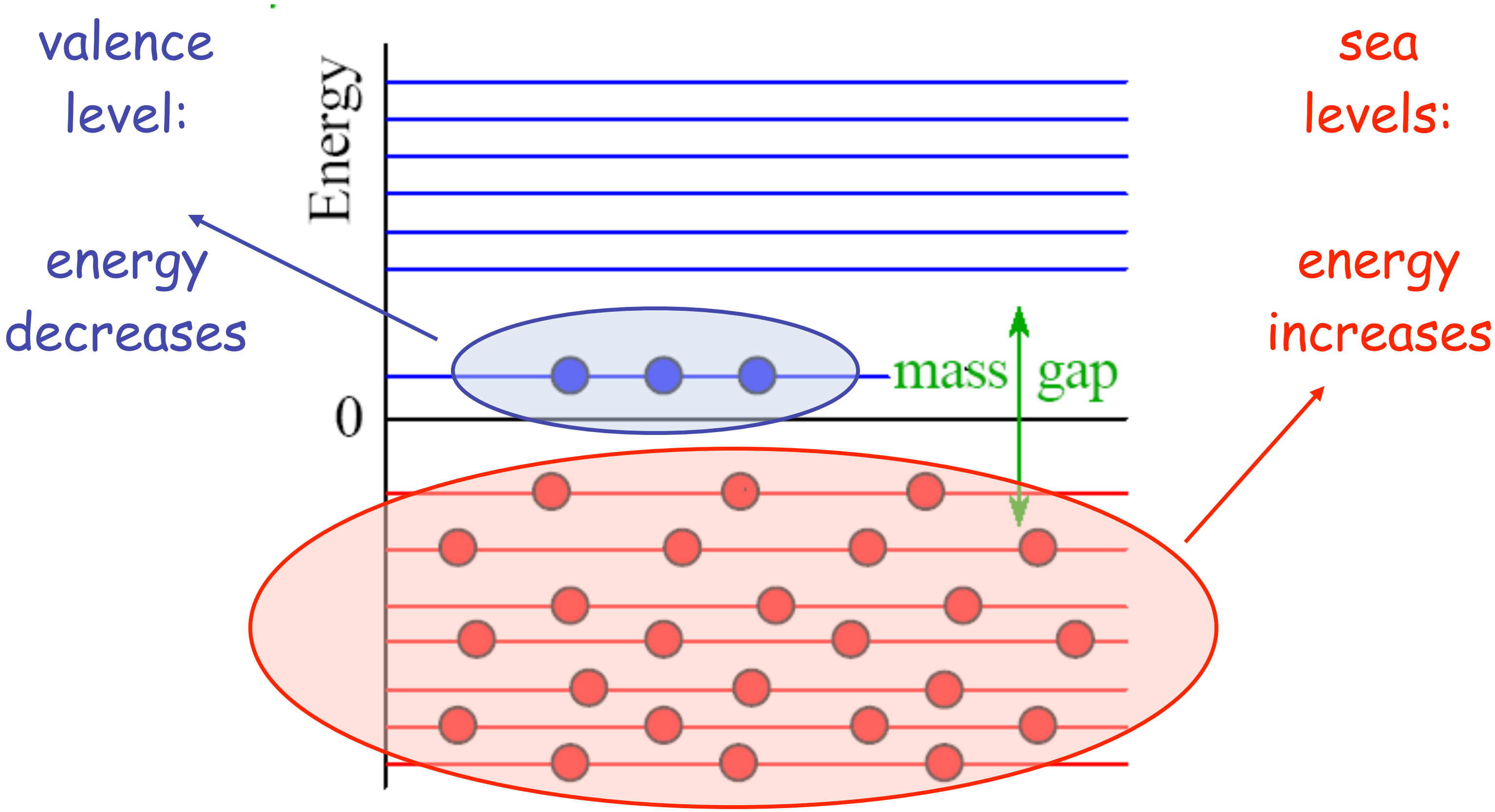
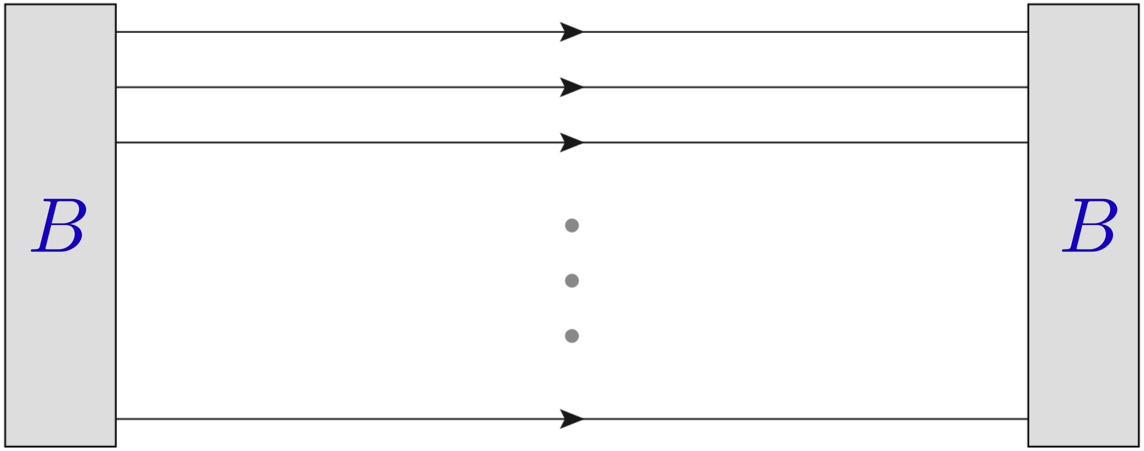
Baryon in pion mean fields



system is stabilized

HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

A light baryon in pion mean fields

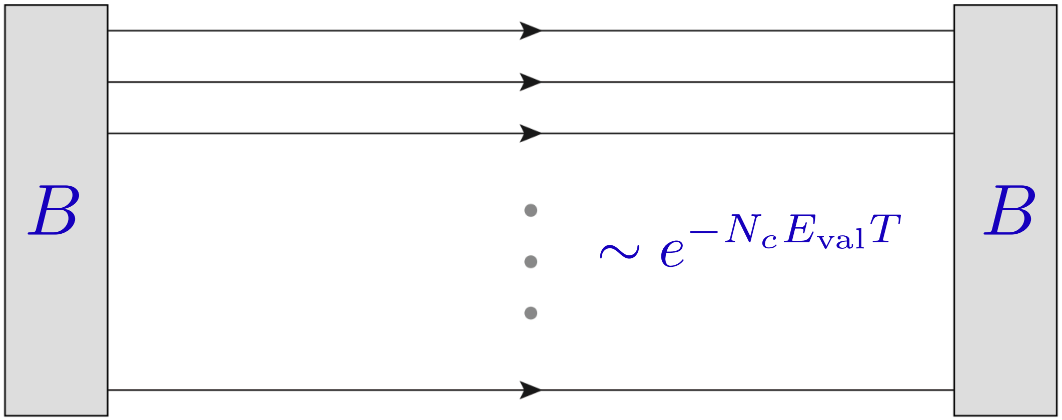


$$\langle J_B J_B^\dagger \rangle_0 \sim e^{-N_c E_{\rm val} T}$$

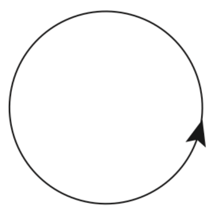
Presence of Nc quarks will polarize the vacuum or create mean fields.

Nc valence quarks → Vacuum polarization or meson mean fields

A light baryon in pion mean fields



$$E_{\rm cl} = N_c E_{\rm val} + E_{\rm sea}$$



$$\sim e^{-E_{\rm sea} T}$$

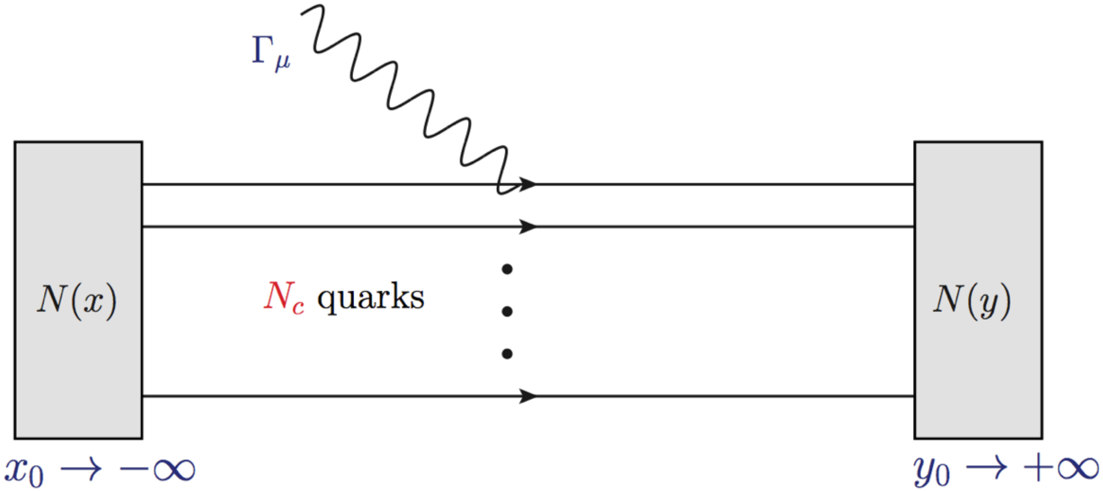
Classical Nucleon mass is described by the Nc valence quark energy and sea-quark energy.

$$\frac{\delta E_{cl}}{\delta U} = 0 \longrightarrow M_{\rm cl} \longrightarrow P(r)$$

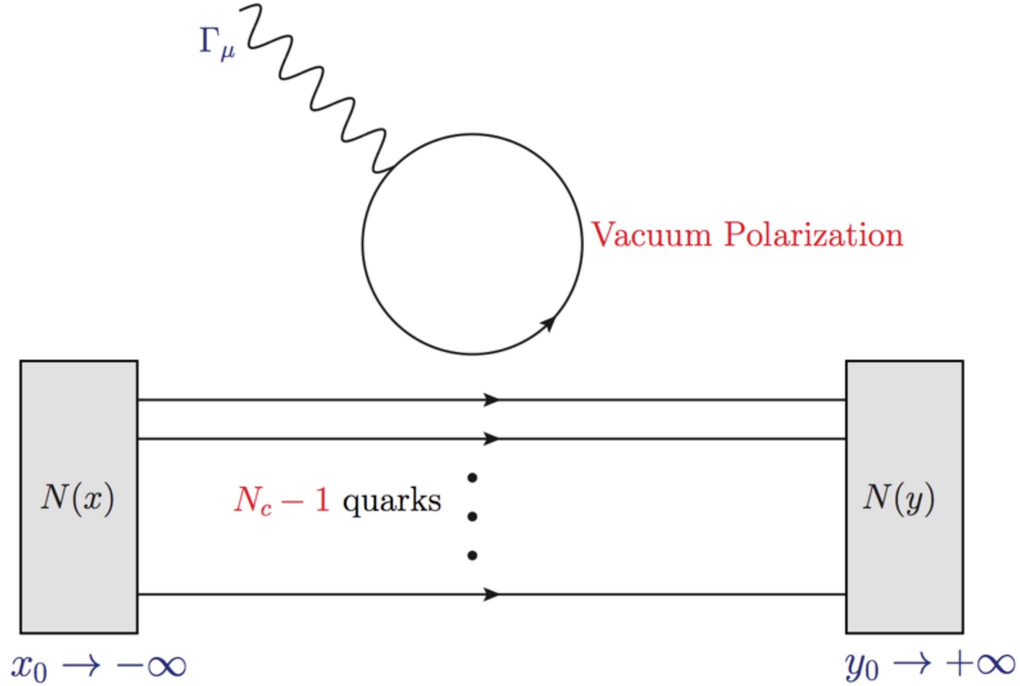
P(r): Soliton profile function
or Soliton field

An observable for the light baryon

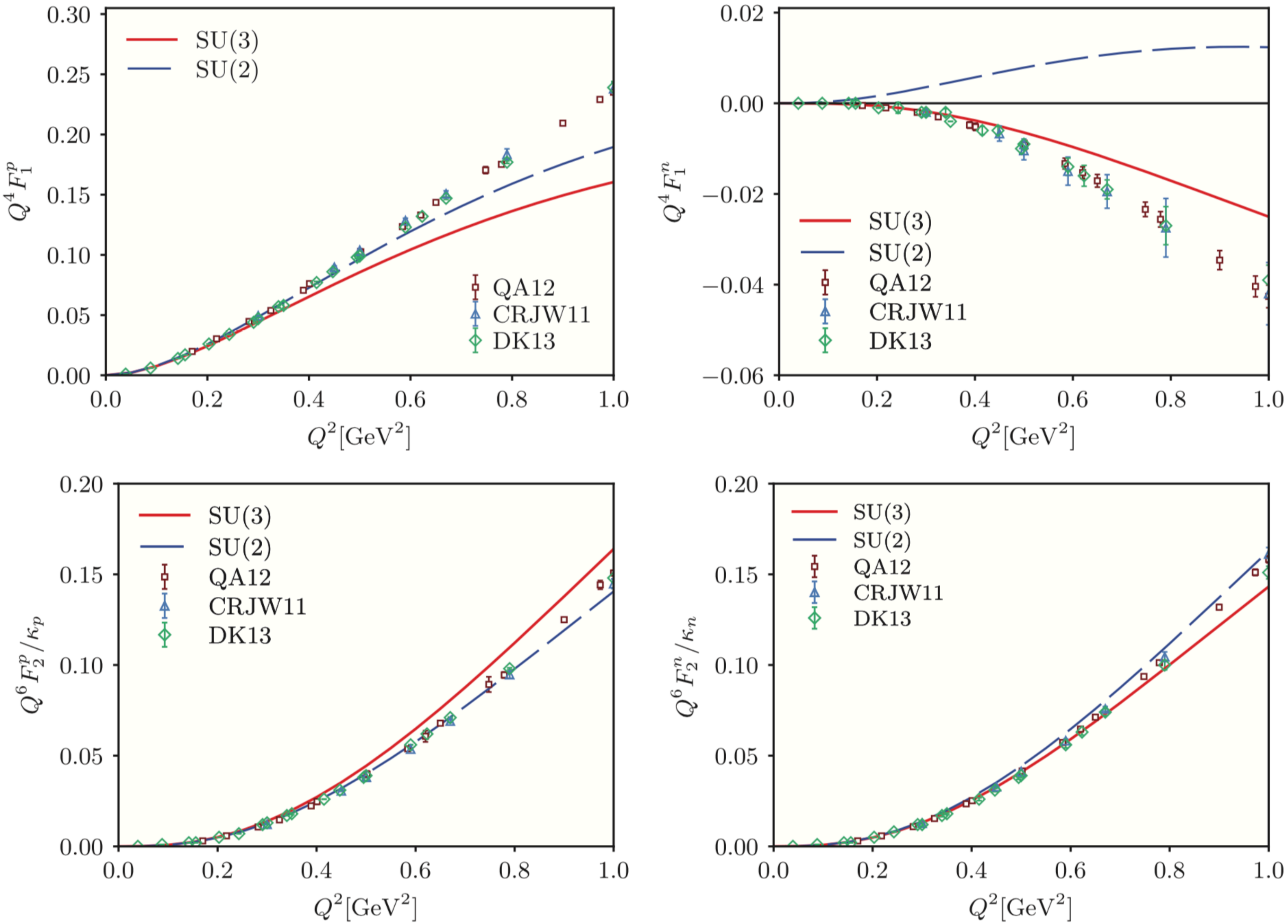
Valence part



Sea part



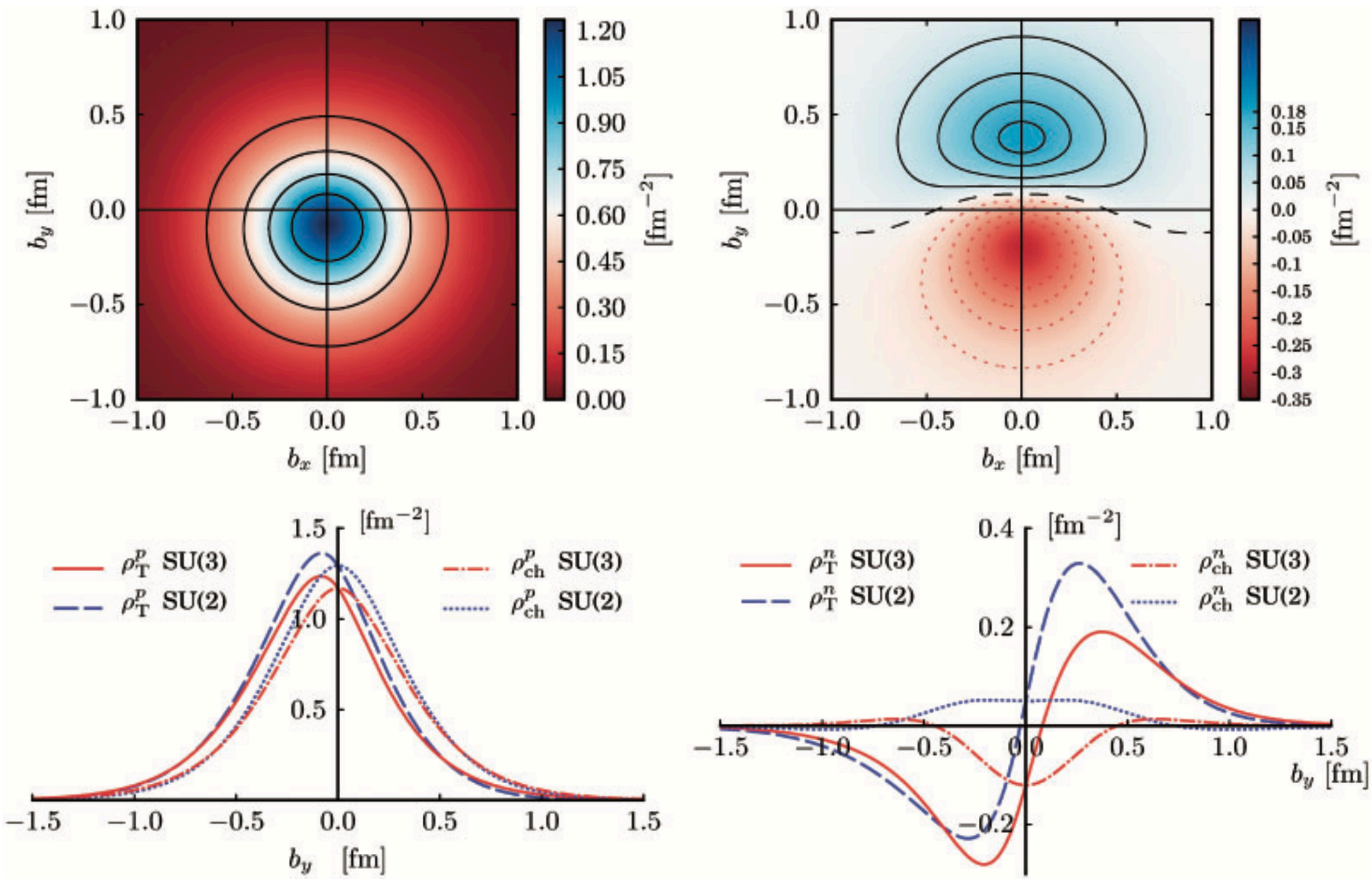
Proton & neutron EM fom factors



Silva, Urbano, HChK, PTEP, 2018

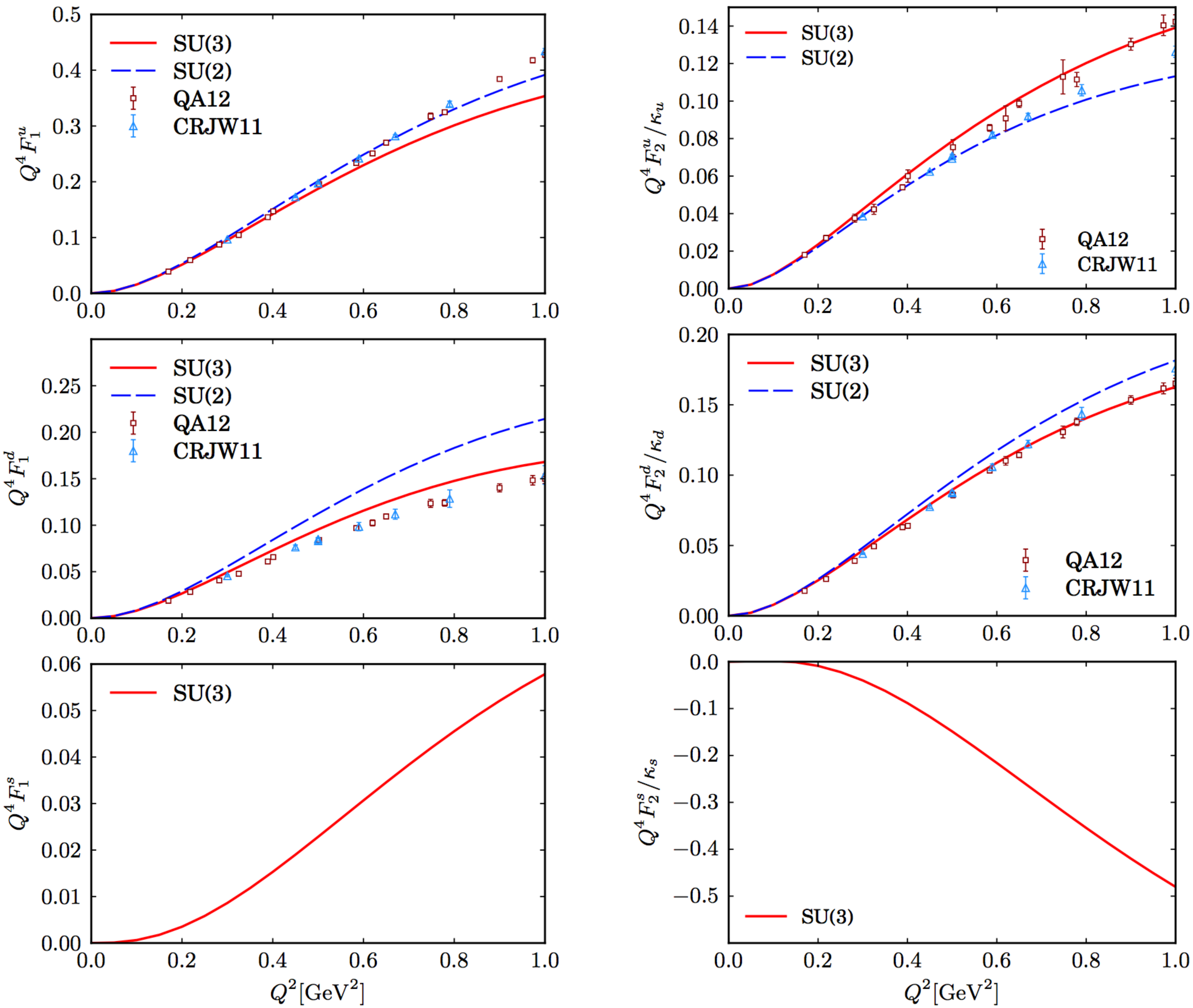
Proton & neutron transverse charge densities

Nucleon polarized along the x direction



Silva, Urbano, HChK, PTEP, (2018)

Flavor structure



Up quark FFs

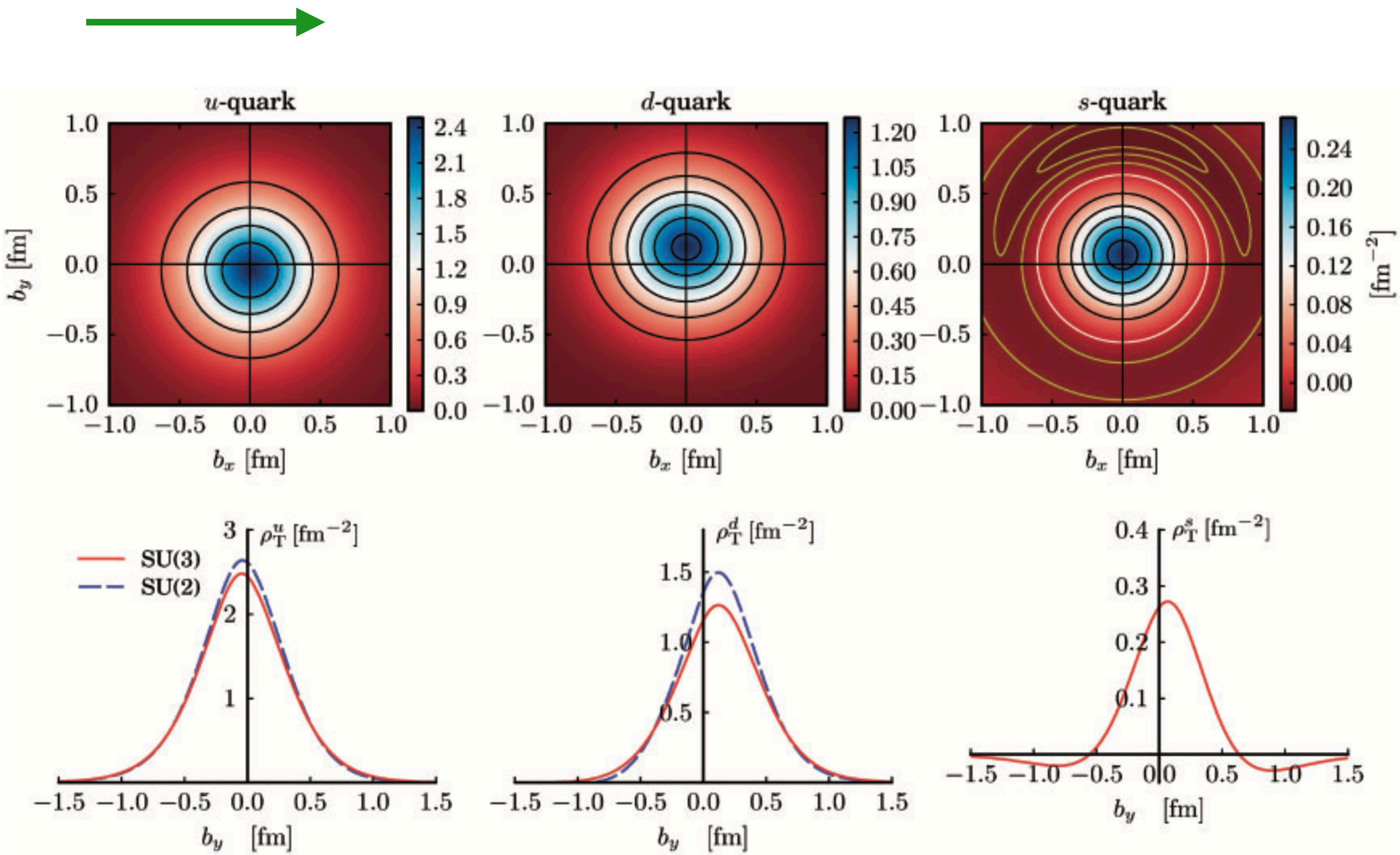
Down quark FFs

Strange quark FFs

Silva, Urbano, HChK, PTEP, (2018)

Flavor structure

Nucleon polarized along the x direction



Silva, Urbano, HChK, PTEP, (2018)

EM Form factors of the baryon decuplet

EM form factors of the baryon decuplet

- Spin 3/2 baryons have more complicated structures: Four-independent EM form factors.

$$\langle B(p', s)|V^{\mu}(0)|B(p, s)\rangle$$
$$= -\overline{u}^{\alpha}(p', s)\left[\gamma^{\mu}\left\{F_1^* g_{\alpha\beta} + F_3^* \frac{q_\alpha q_\beta}{4M_B^2}\right\} + i\frac{\sigma^{\mu\nu}q_\nu}{2M_B}\left\{F_2^* g_{\alpha\beta} + F_4^* \frac{q_\alpha q_\beta}{4M_B}\right\}\right] u^{\beta}(p, s)$$

- Multipole EM form factors

$$G_{E0}(Q^2) = (1 + \frac{2}{3}\tau)[F_1^* - \tau F_2^*] - \frac{1}{3}\tau(1+\tau)[F_3^* - \tau F_4^*],$$
$$G_{E2}(Q^2) = [F_1^* - \tau F_2^*] - \frac{1}{2}(1+\tau)[F_3^* - \tau F_4^*],$$
$$G_{M1}(Q^2) = (1 + \frac{4}{5}\tau)[F_1^* + F_2^*] - \frac{2}{5}\tau(1+\tau)[F_3^* + F_4^*],$$
$$G_{M3}(Q^2) = [F_1^* + F_2^*] - \frac{1}{2}(1+\tau)[F_3^* + F_4^*].$$

EM form factors of the baryon decuplet

- Multipole EM form factors

$$G_{E0}(Q^2) = \int \frac{d\Omega_q}{4\pi} \langle B(p',3/2)|J^0(0)|B(p,3/2)\rangle,$$

$$G_{E2}(Q^2) = -\int d\Omega_q \sqrt{\frac{5}{4\pi}}\frac{3}{2}\frac{1}{\tau} \langle B(p',3/2)|Y^*_{20}(\Omega_q)J^0(0)|B(p,3/2)\rangle,$$

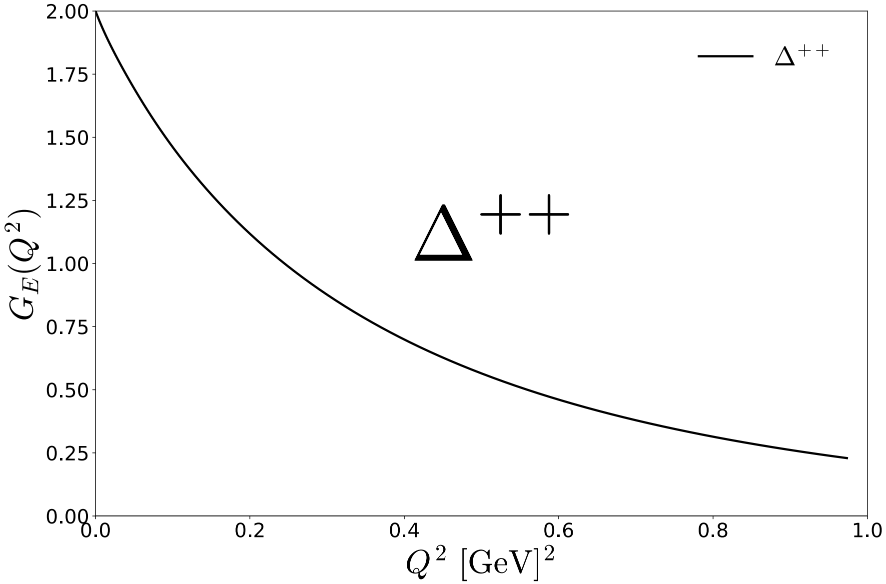
$$G_{M1}(Q^2) = 2M_B\frac{3}{4\sqrt{\pi}} \int \frac{d\Omega_q}{i|\boldsymbol{q}|^2} q^i \epsilon^{ik3} \langle B(p',3/2)|Y^*_{00}(\Omega_q)J^k(0)|B(p,3/2)\rangle.$$

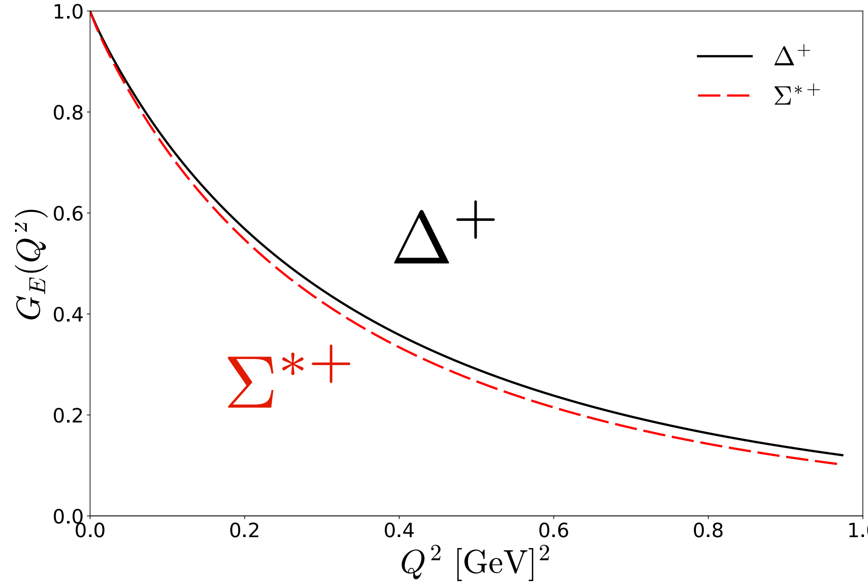
$$G_{M3} = (-i)\frac{35\pi}{2}\sqrt{\frac{12}{7\pi}}M_B\frac{1}{|\boldsymbol{q}|}\int d^3z j_3(|\boldsymbol{q}||\boldsymbol{z}|)\langle B(p',3/2)|\left\{Y_3 \otimes J_1\right\}_{30}|B(p,3/2)\rangle$$

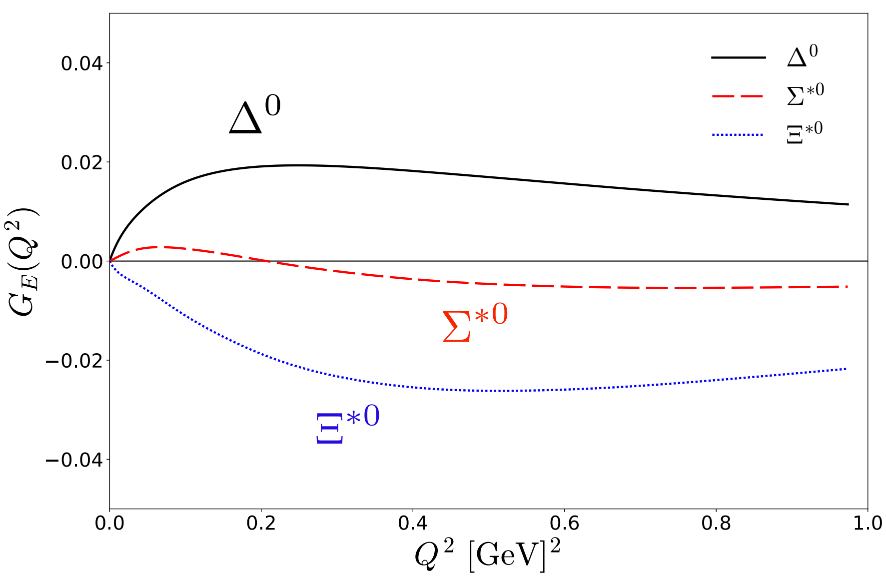
- M3 form factors vanish within any chiral solitonic approach (Leinweber et al., PRD 46, 3067 (1992)).
- We need to go beyond the mean-field approachto compute the M3 form factor.

M3 form factors should be very small.

E0 form factors of the baryon decuplet

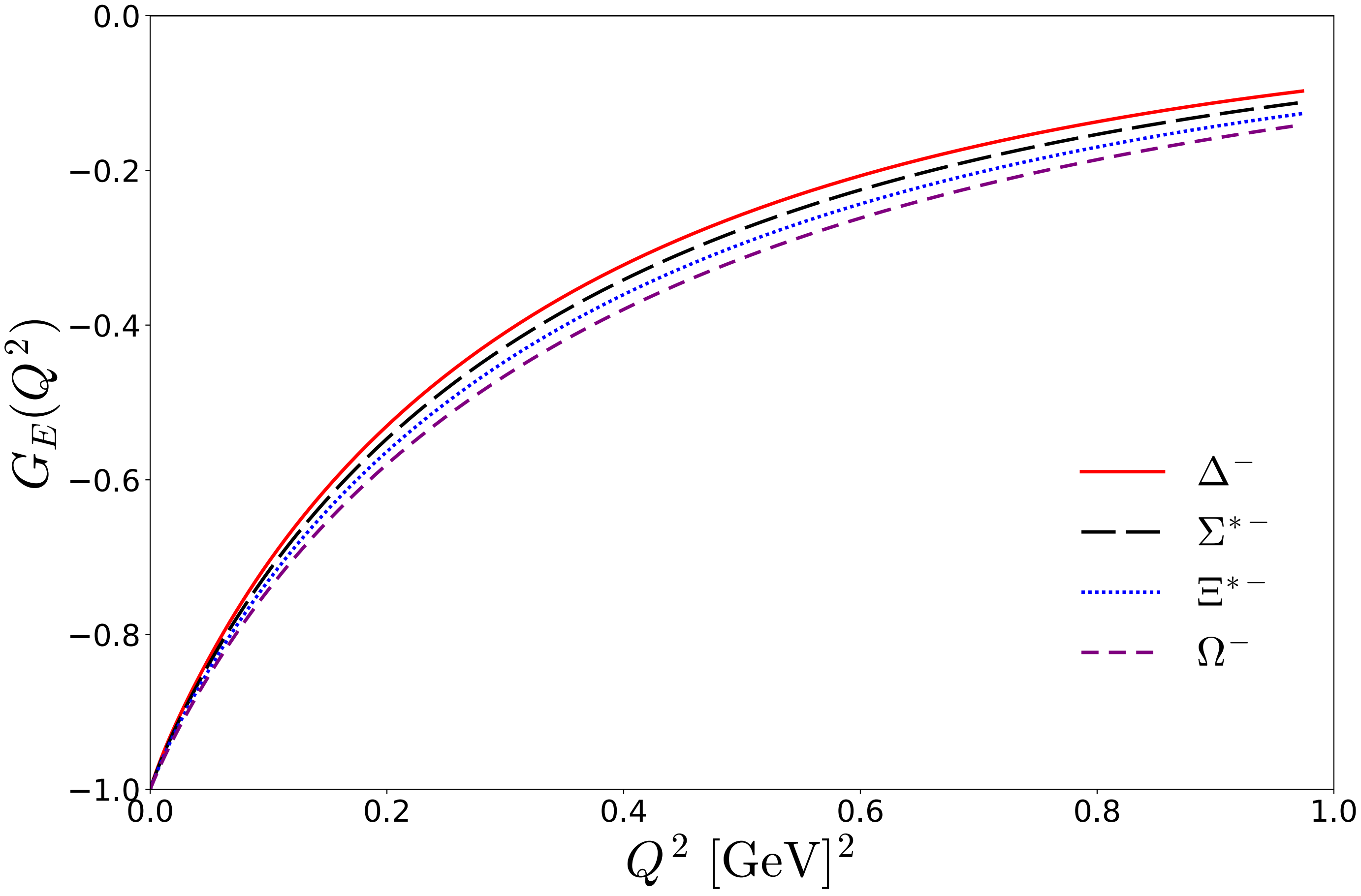






J.-Y. Kim & HChK, in preparation

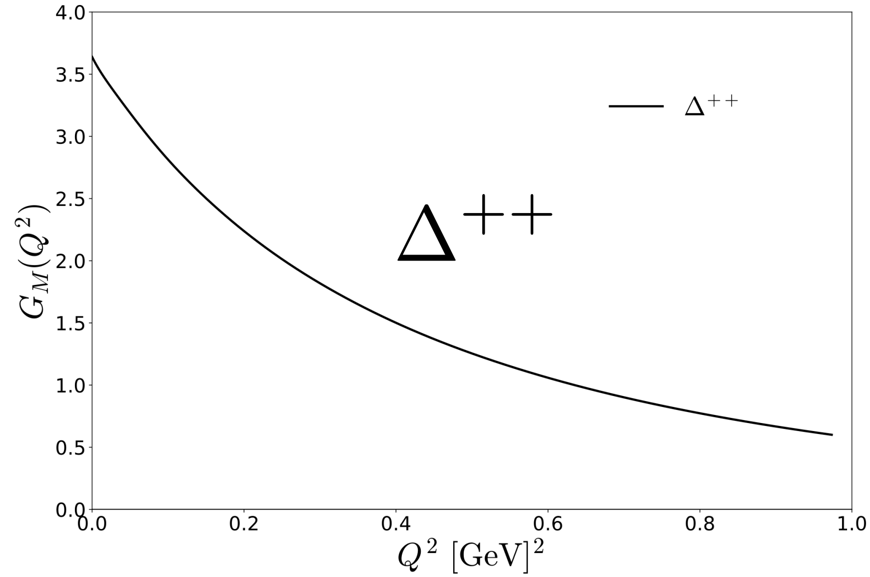
E0 form factors of the baryon decuplet

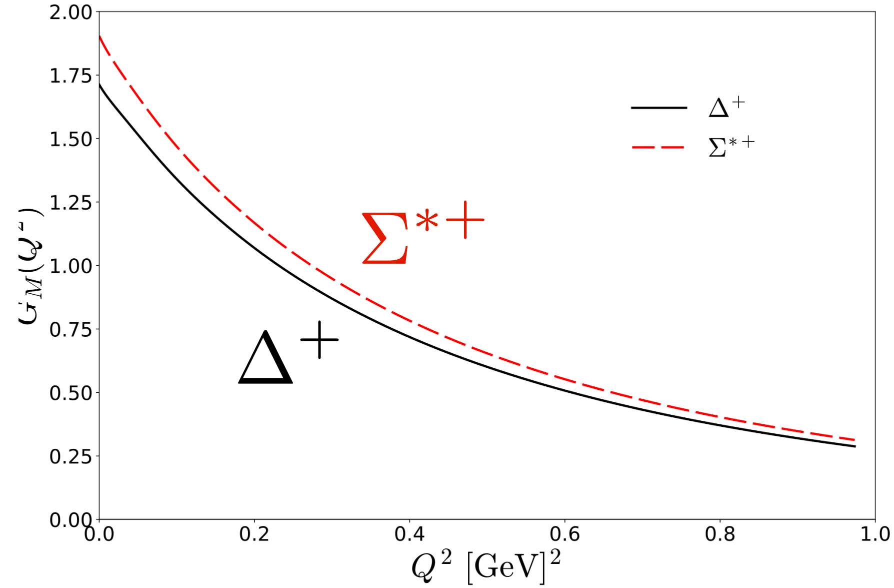


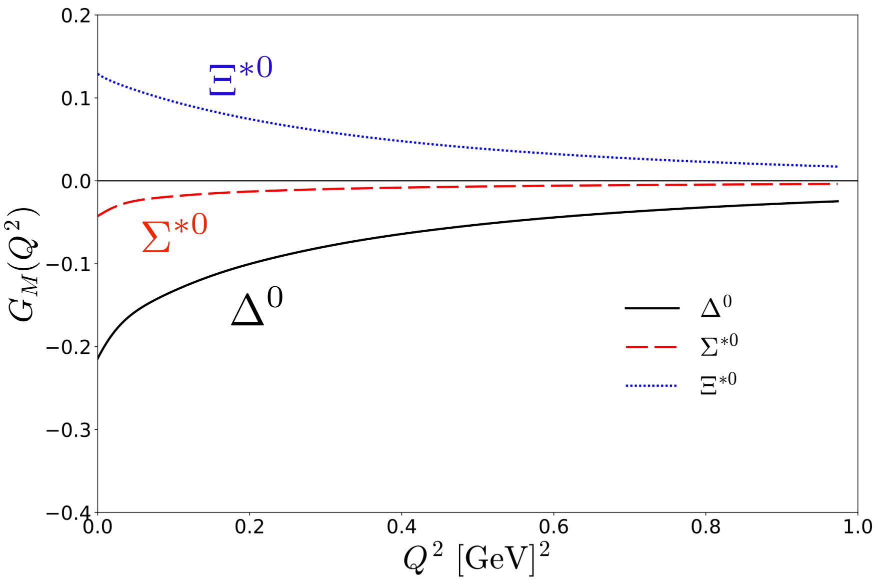
With more strangeness, the E0 form factors fall off more slowly.

J.-Y. Kim & HChK, in preparation

M1 form factors of the baryon decuplet

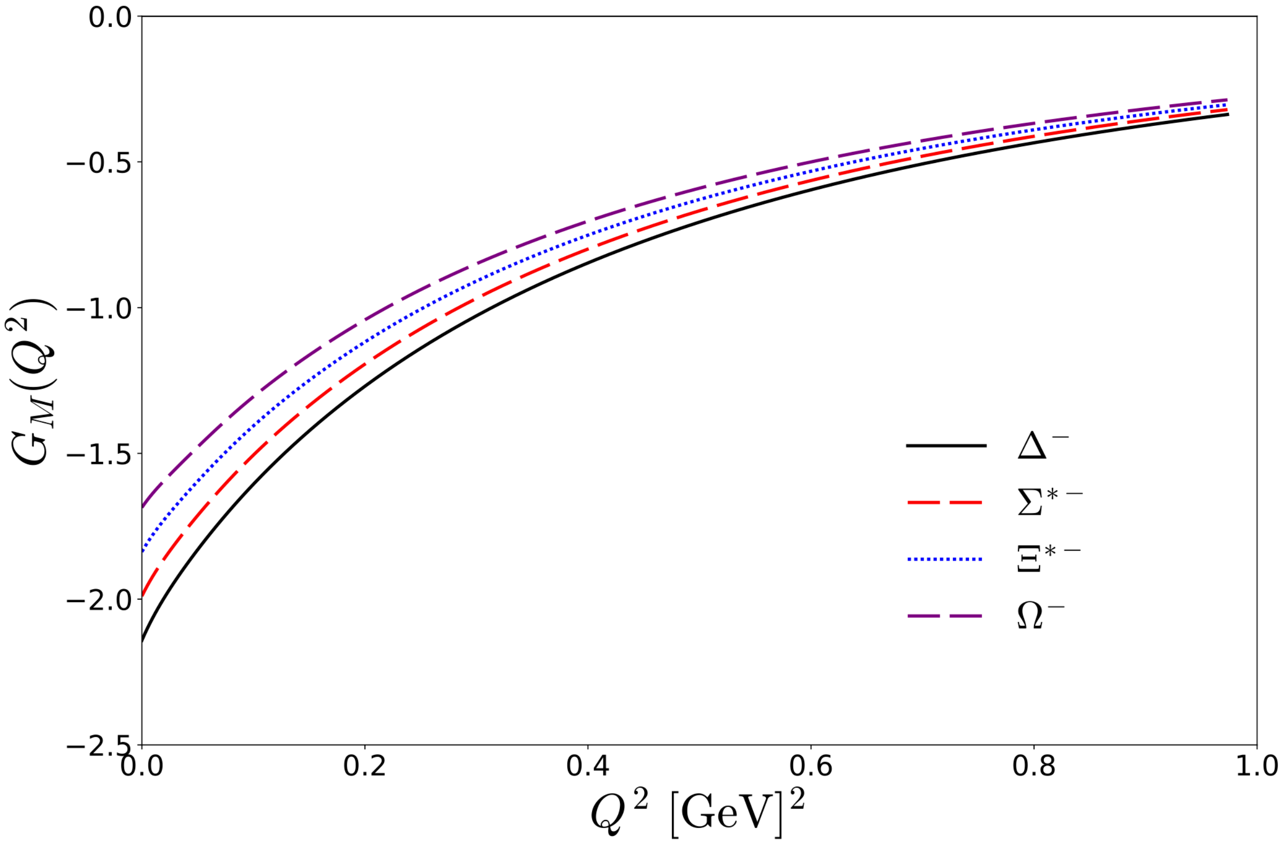






J.-Y. Kim & HChK, in preparation

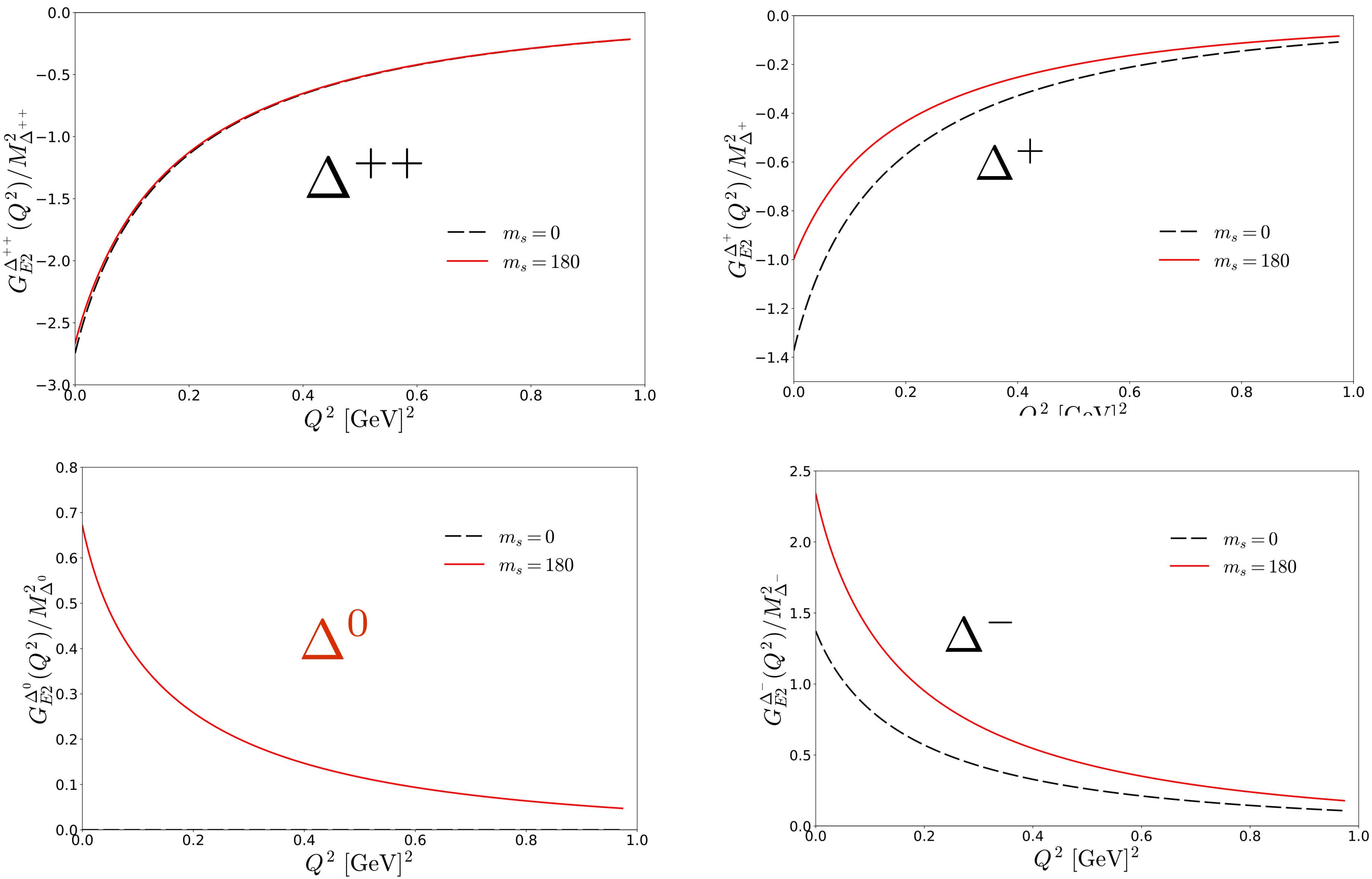
M1 form factors of the baryon decuplet



Magnetic moments get smaller as the strangeness increases.

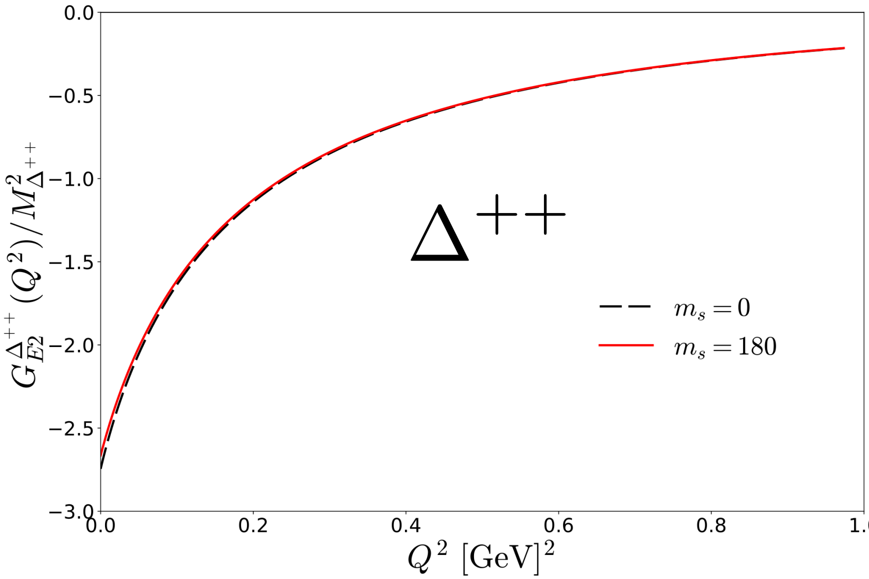
J.-Y. Kim & HChK, in preparation

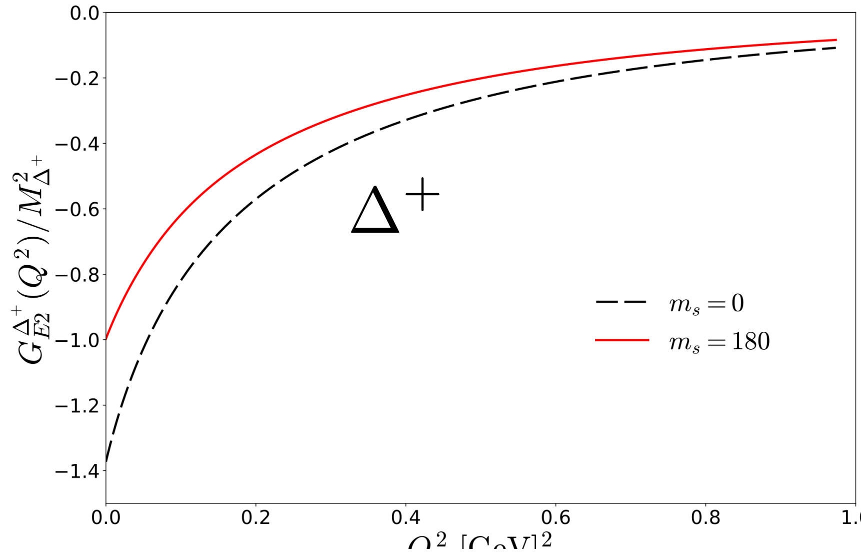
E2 form factors of the baryon decuplet

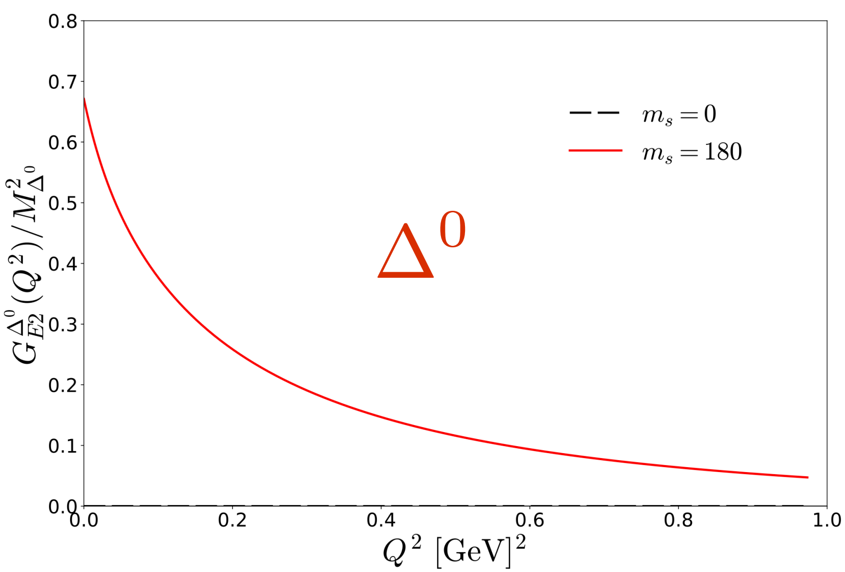


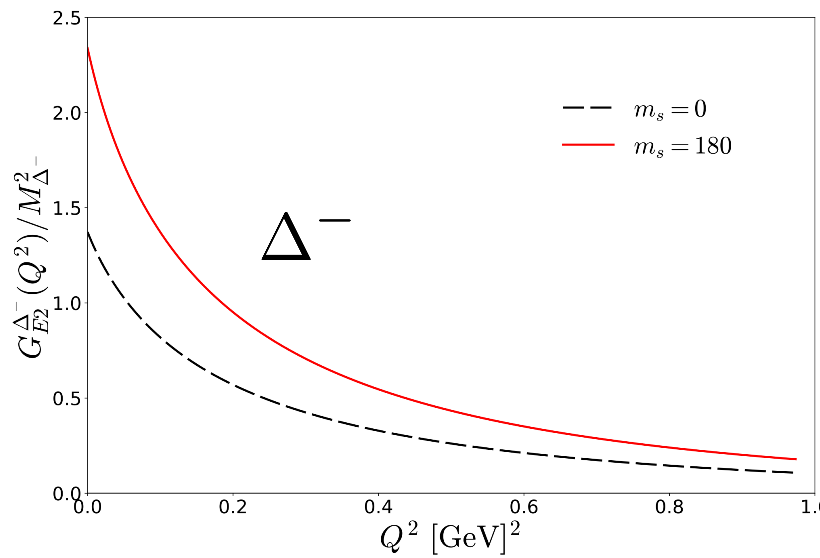
J.-Y. Kim & HChK, in preparation

E2 form factors of the baryon decuplet



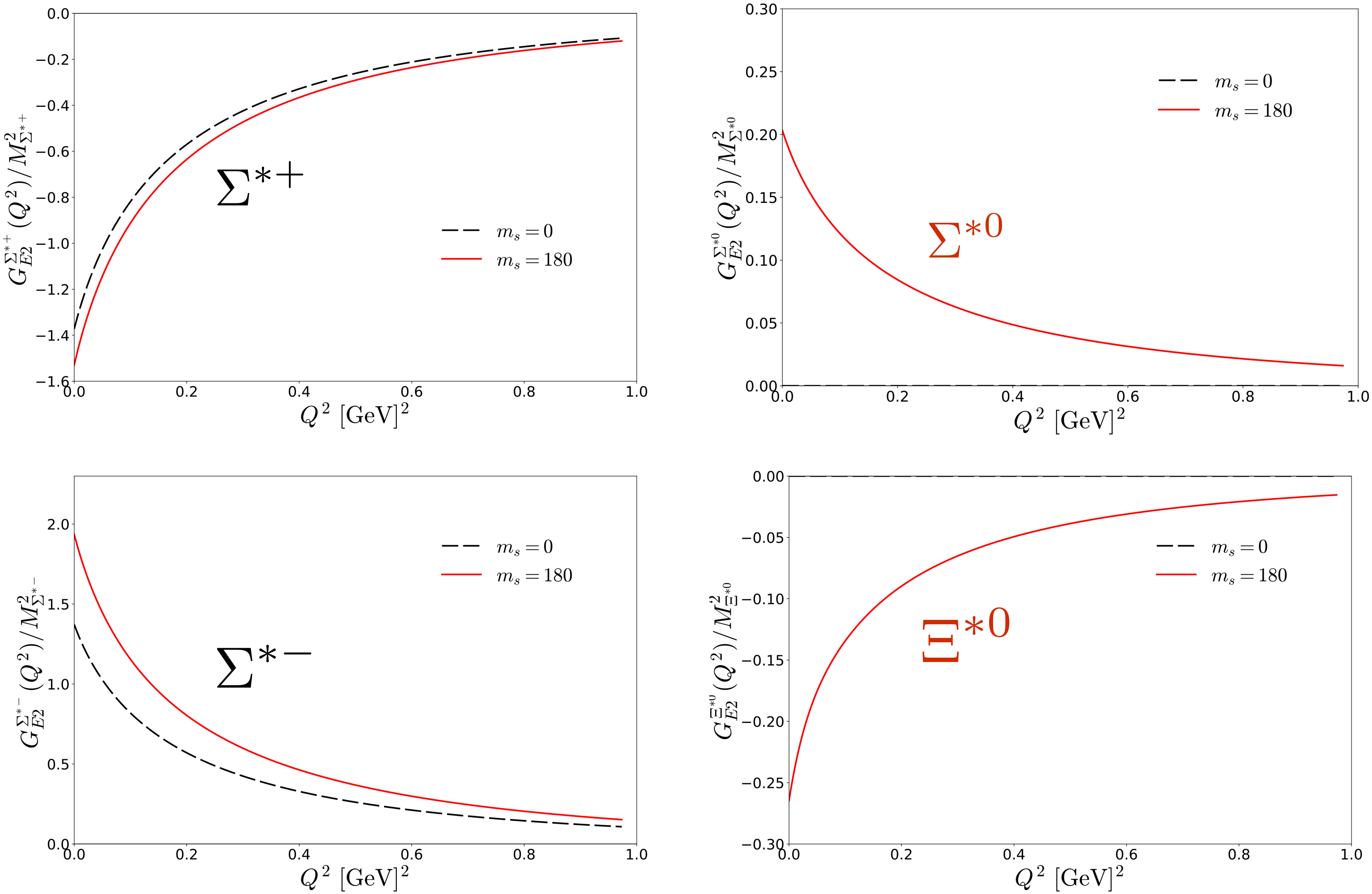






J.-Y. Kim & HChK, in preparation

E2 form factors of the baryon decuplet



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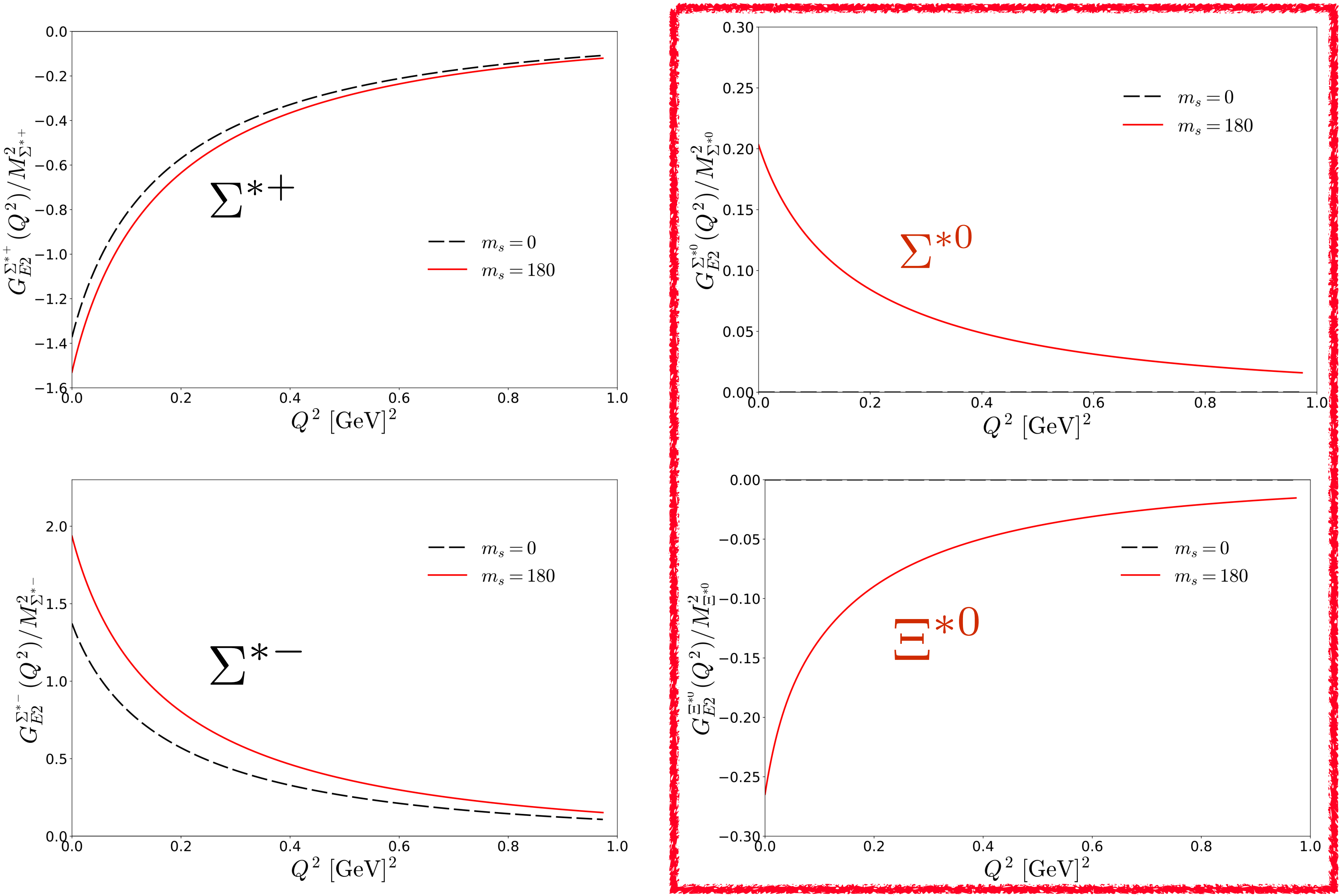

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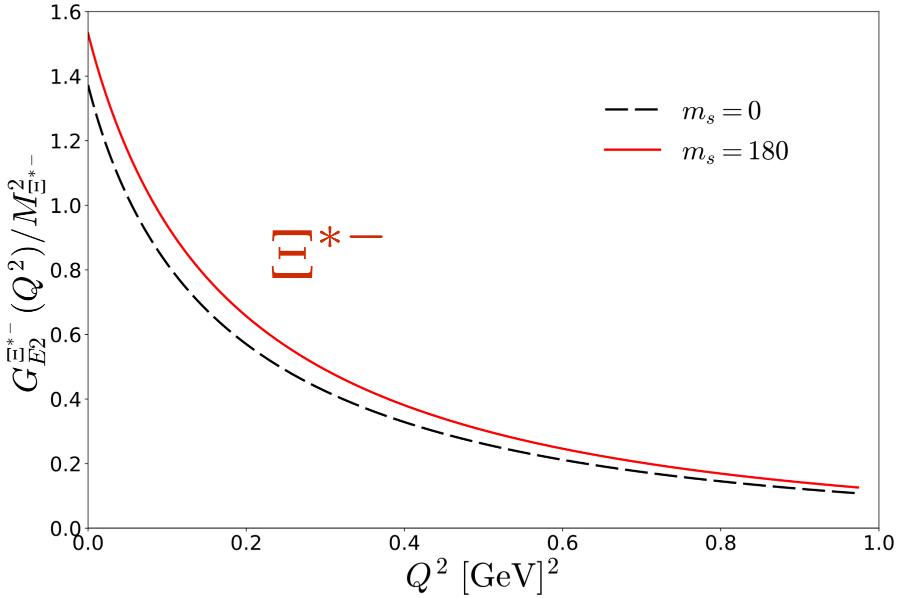
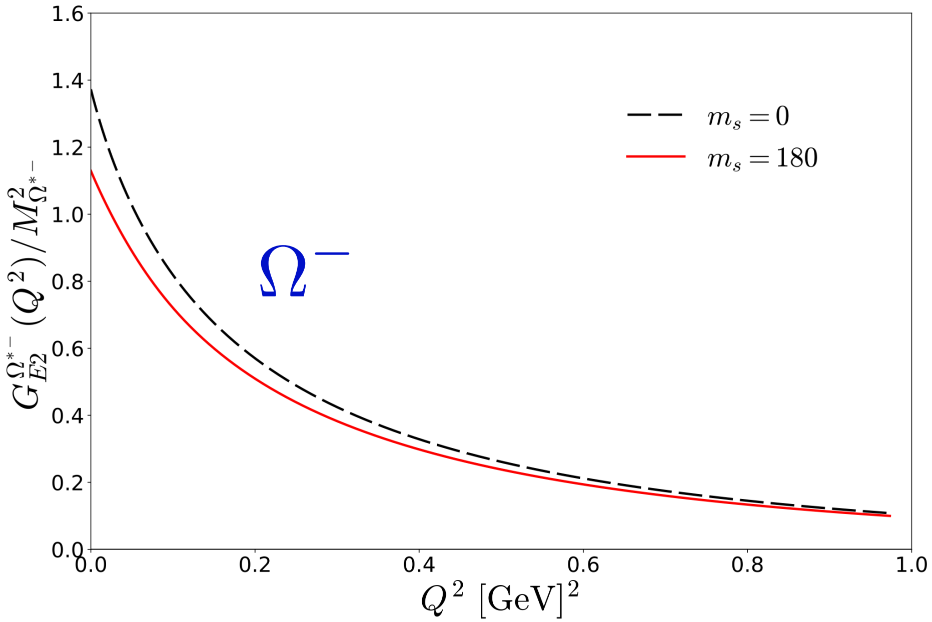
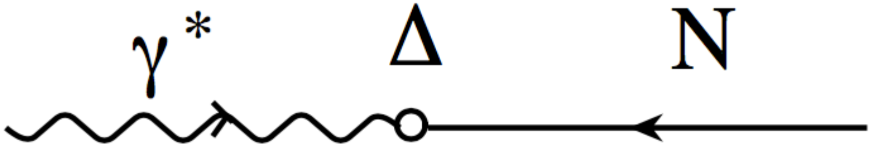




Effects of SU(3) symmetry breaking reduce the magnitude of the Omega E2 form factor.

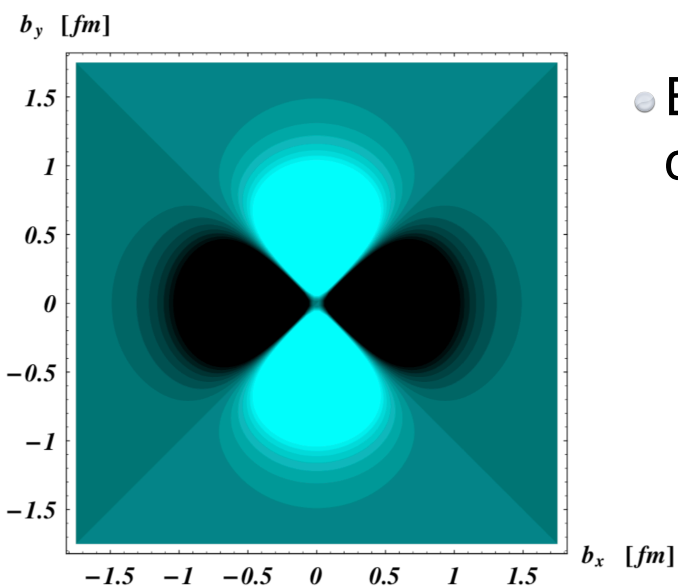
J.-Y. Kim & HChK, in preparation

EM transition form factors of the decuplet



$$(\omega, \boldsymbol{q}) \qquad (E_\Delta, \boldsymbol{0}) \qquad (E_N, -\boldsymbol{q})$$

- EM transition FFs provide information on how the Delta looks like.

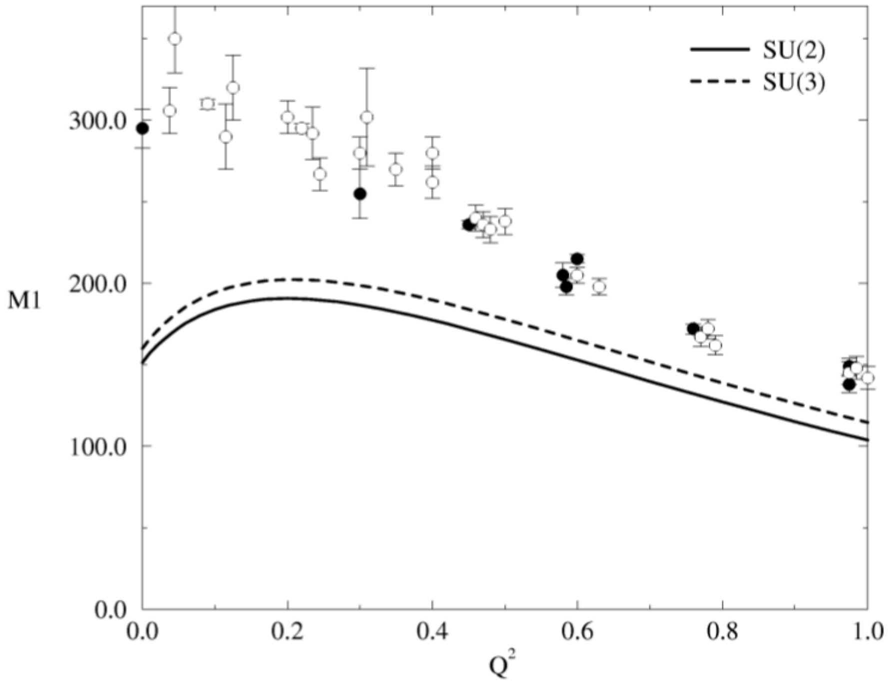


- EM transition FFs are related to the VBB coupling constants through VDM & CFI.

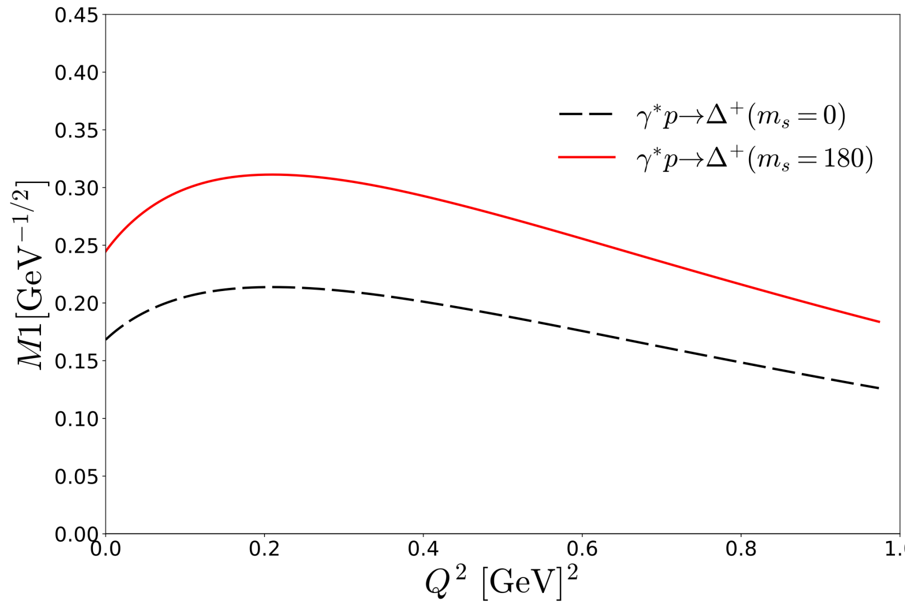
→ Essential to understand a production mechanism of hadrons.

Carlson & Vanderhaeghen, PRD 100 (2008) 032004

EM transition form factors of the decuplet



Former work



Present work

Silva et al. NPA 675, 637 (2000)

Effects of SU(3) symmetry breaking are sizable.

Black circle

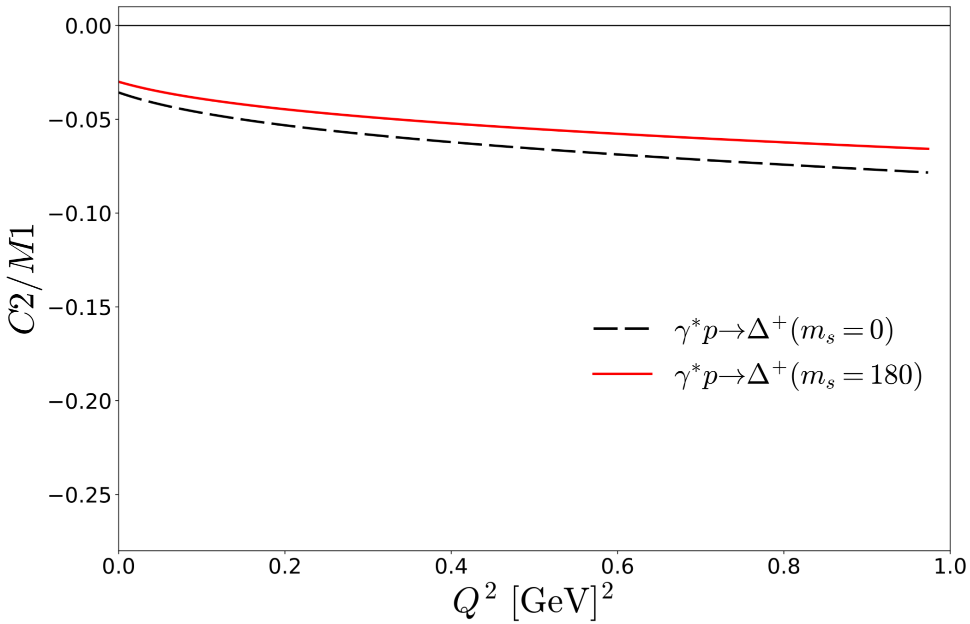
[46] W.W. Ash et al., Phys. Lett. B 24 (1967) 154.
[47] W. Bartel et al., Phys. Lett. B 28 (1968) 148.
[48] S. Stein et al., Phys. Rev. D 12 (1975) 1884.

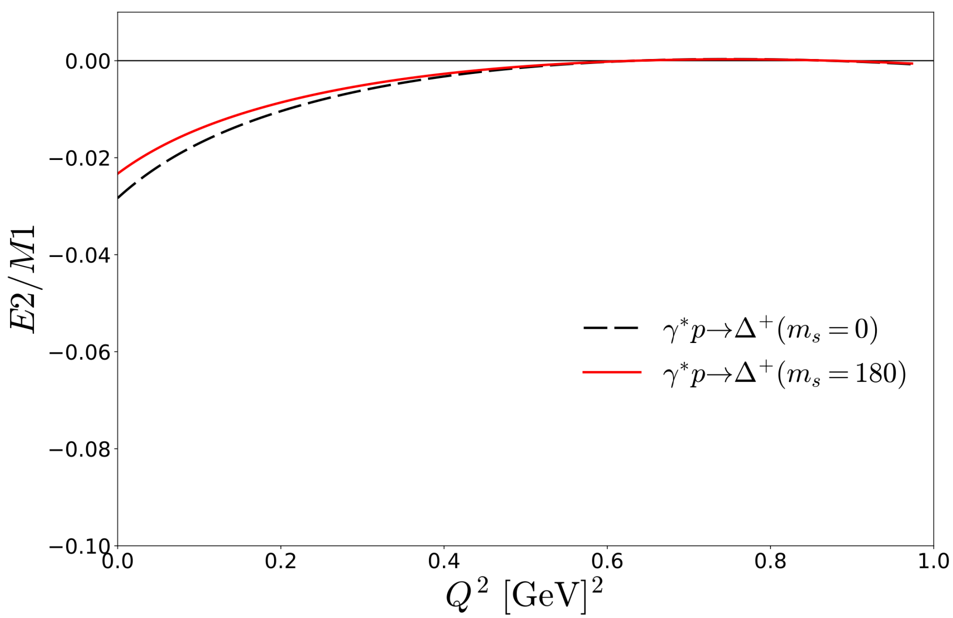
Open circle

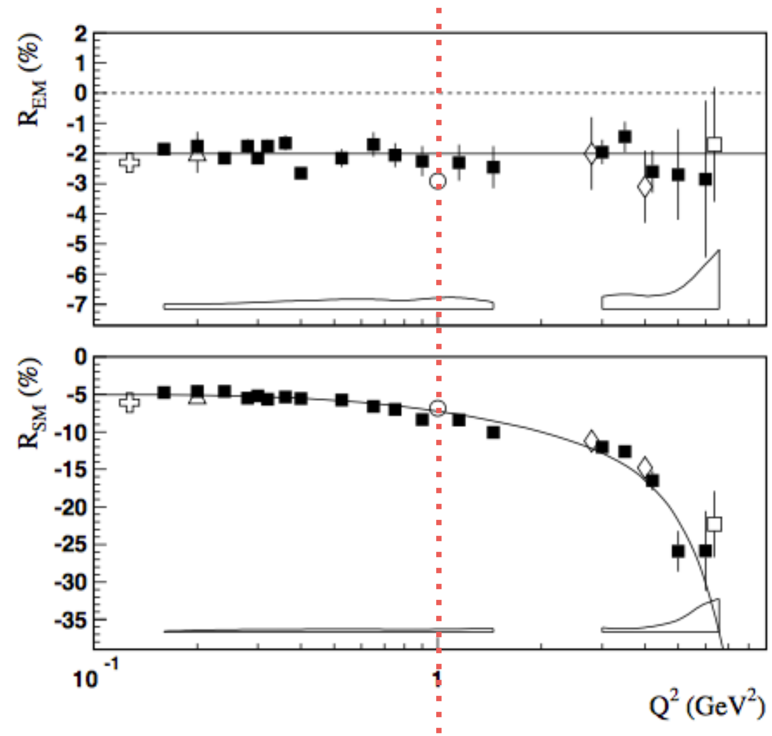
[5] S. Galster et al., Phys. Rev. D 5 (1972) 519.
[6] C. Mistretta et al., Phys. Rev. 184 (1968) 1487.

J.-Y. Kim & HChK, in preparation

E2/M1 & C2/M1 Ratios







JLab(squares, diamonds, circle),
MAMI(triangle,cross)

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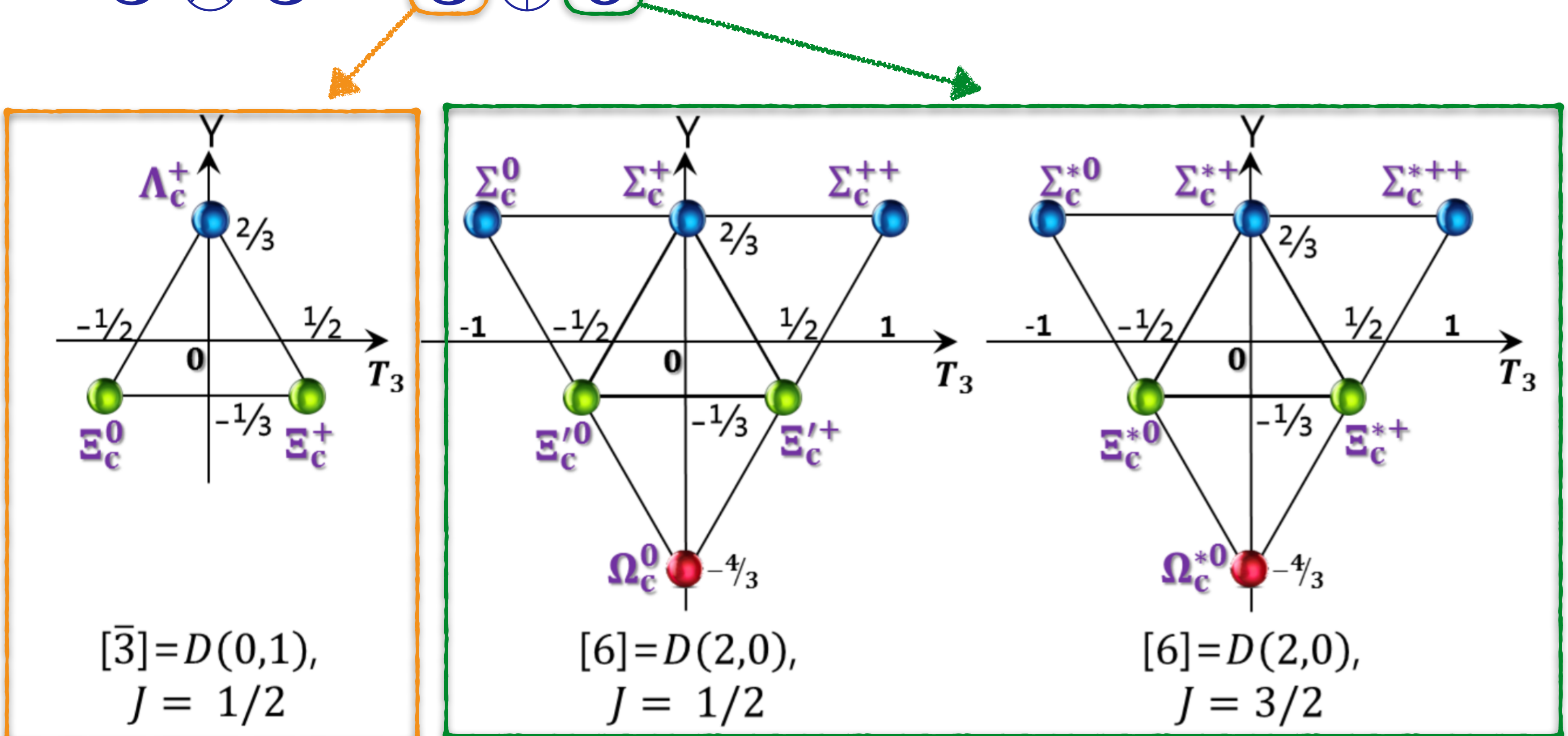
EM Form factors of the singly heavy baryons: the antri-triplet & the sextet

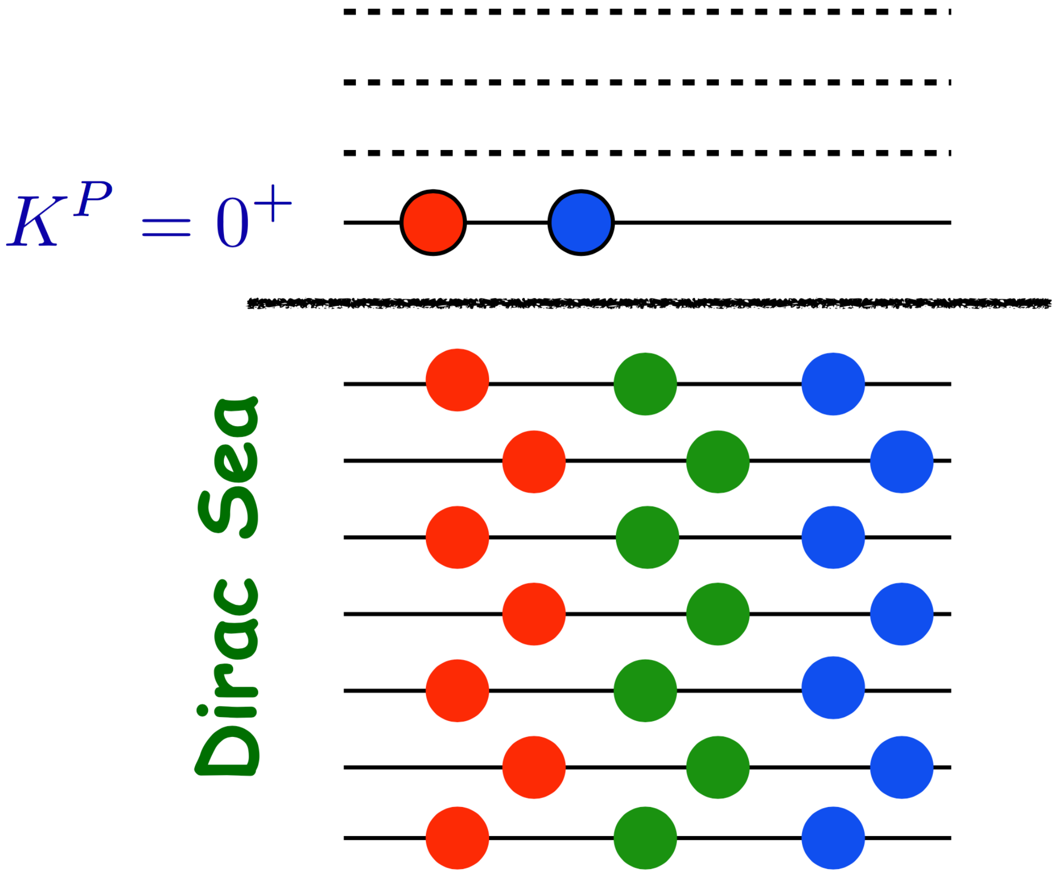
Singly heavy baryons in SU(3)

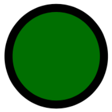
- In the heavy quark mass limit, a heavy quark spin is conserved, so light-quark spin is also conserved.
- In this limit, a heavy quark can be considered as **a color static source**.
- Dynamics is governed by light quarks.

$$\mathbf{3} \otimes \mathbf{3} = \boxed{\bar{\mathbf{3}}} \oplus \boxed{\mathbf{6}}$$



Heavy baryons

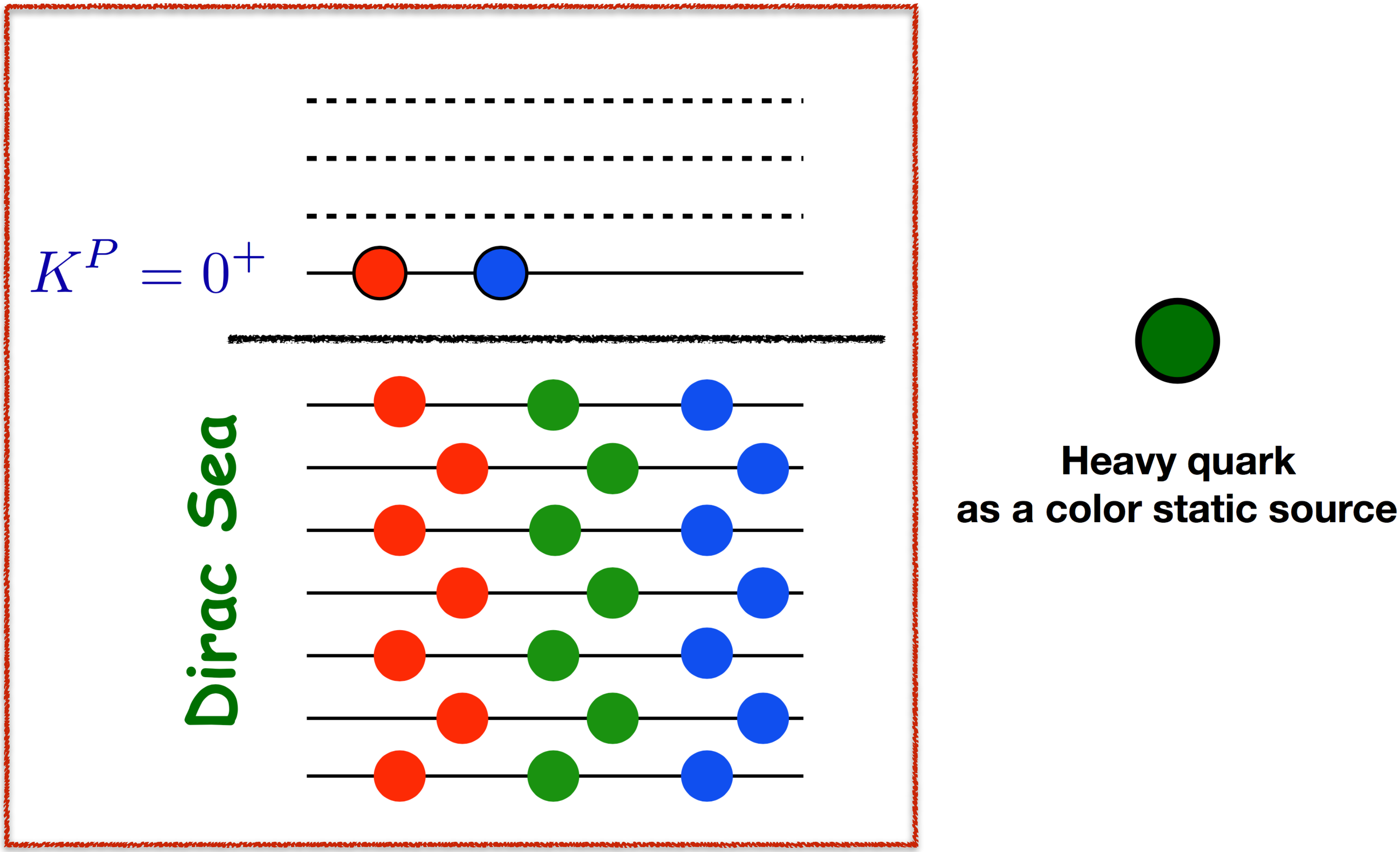




Heavy quark as a color static source

Yang et al. PRD 94, 071502(R) (2016)

Heavy baryons



Nc-1 light quarks govern a singly heavy baryon.

Yang et al. PRD 94, 071502(R) (2016)

Heavy baryons

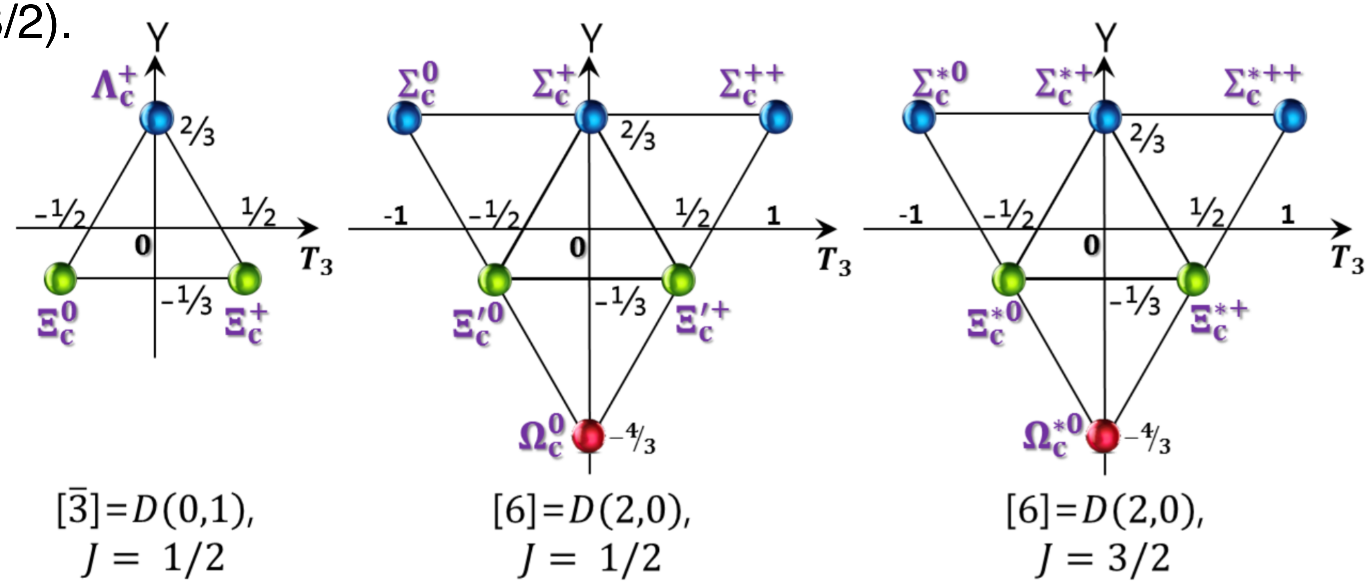
Nc-1 quarks represent heavy-baryon spectra.

$$Y' = \frac{N_c - 1}{3}$$

Grand spin: $K = 0 \to T = J$

- The lowest rotationally excited states $\mathbf{3} \times \mathbf{3} = \overline{\mathbf{3}} + \mathbf{6}$

* T=0 for a anti-triplet: J=0 for it. Combining a charm quark with spin 1/2, we have one anti-triplet.
* T=1 for a sextet: J=1. We have two sextets with a charm quark. (1/2, 3/2).



$Y' = 2/3$

Electromagnetic form factors of heavy baryons

- Electric form factors of singly heavy baryons are governed by the light quarks.
- Heavy quark does not contribute to the magnetic form factors in the infinitely heavy-quark mass limit.

J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

Electromagnetic form factors of heavy baryons

$$J_\mu(x) = \bar{\psi}(x)\gamma_\mu \hat{\mathcal{Q}}\psi(x) + e_Q \bar{\Psi}\gamma_\mu \Psi$$

- Electric form factors of singly heavy baryons are governed by the light quarks.
- Heavy quark does not contribute to the magnetic form factors in the infinitely heavy-quark mass limit.

J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

Electromagnetic form factors of heavy baryons

$$J_\mu(x) = \bar{\psi}(x)\gamma_\mu \hat{\mathcal{Q}}\psi(x) + e_Q \bar{\Psi}\gamma_\mu \Psi$$

A heavy quark is a point-like particle.

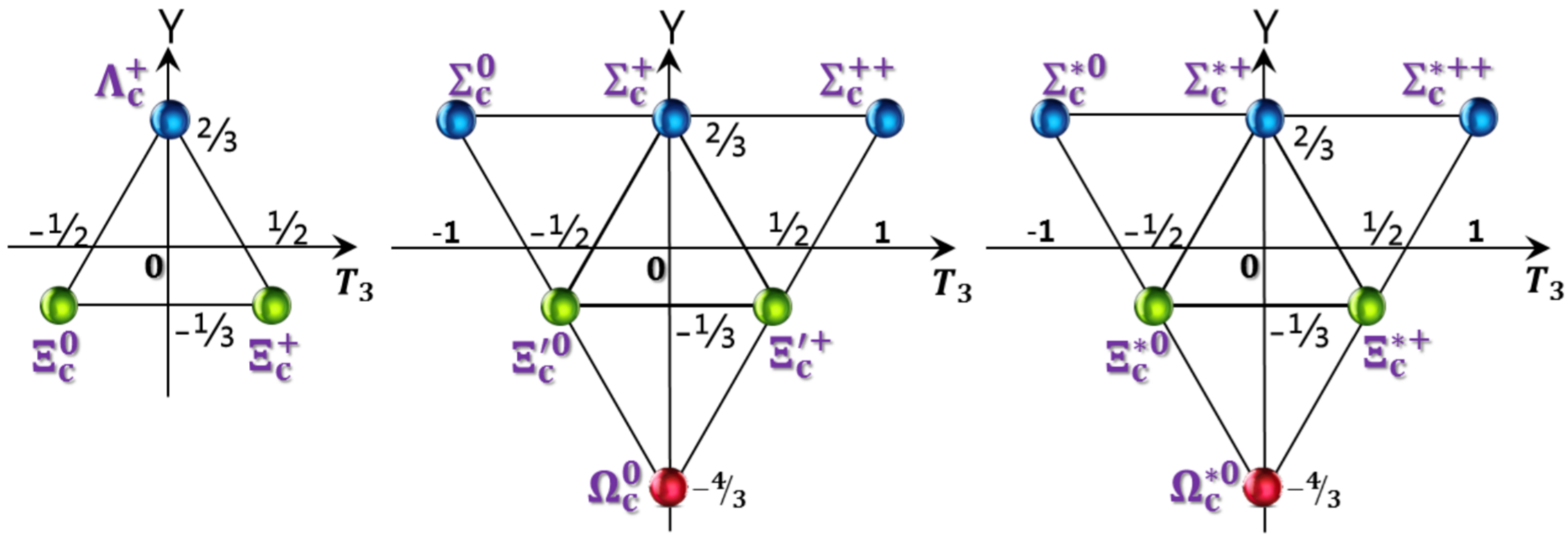
↓

It contributes only to the charge.

- Electric form factors of singly heavy baryons are governed by the light quarks.
- Heavy quark does not contribute to the magnetic form factors in the infinitely heavy-quark mass limit.

J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

Electromagnetic form factors of heavy baryons



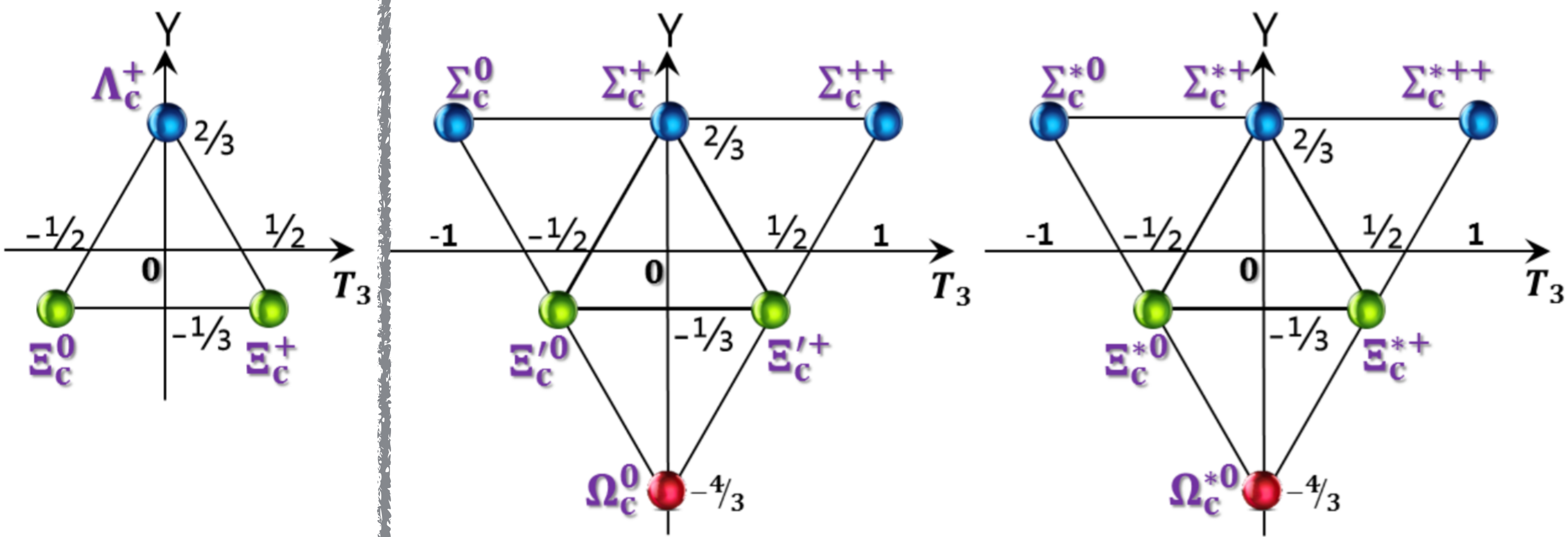
$[\bar{3}]=D(0,1)$, $J = 1/2$

$[6]=D(2,0)$, $J = 1/2$

$[6]=D(2,0)$, $J = 3/2$

J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

Electromagnetic form factors of heavy baryons



$[\bar{3}]=D(0,1)$, $J = 1/2$

$[6]=D(2,0)$, $J = 1/2$

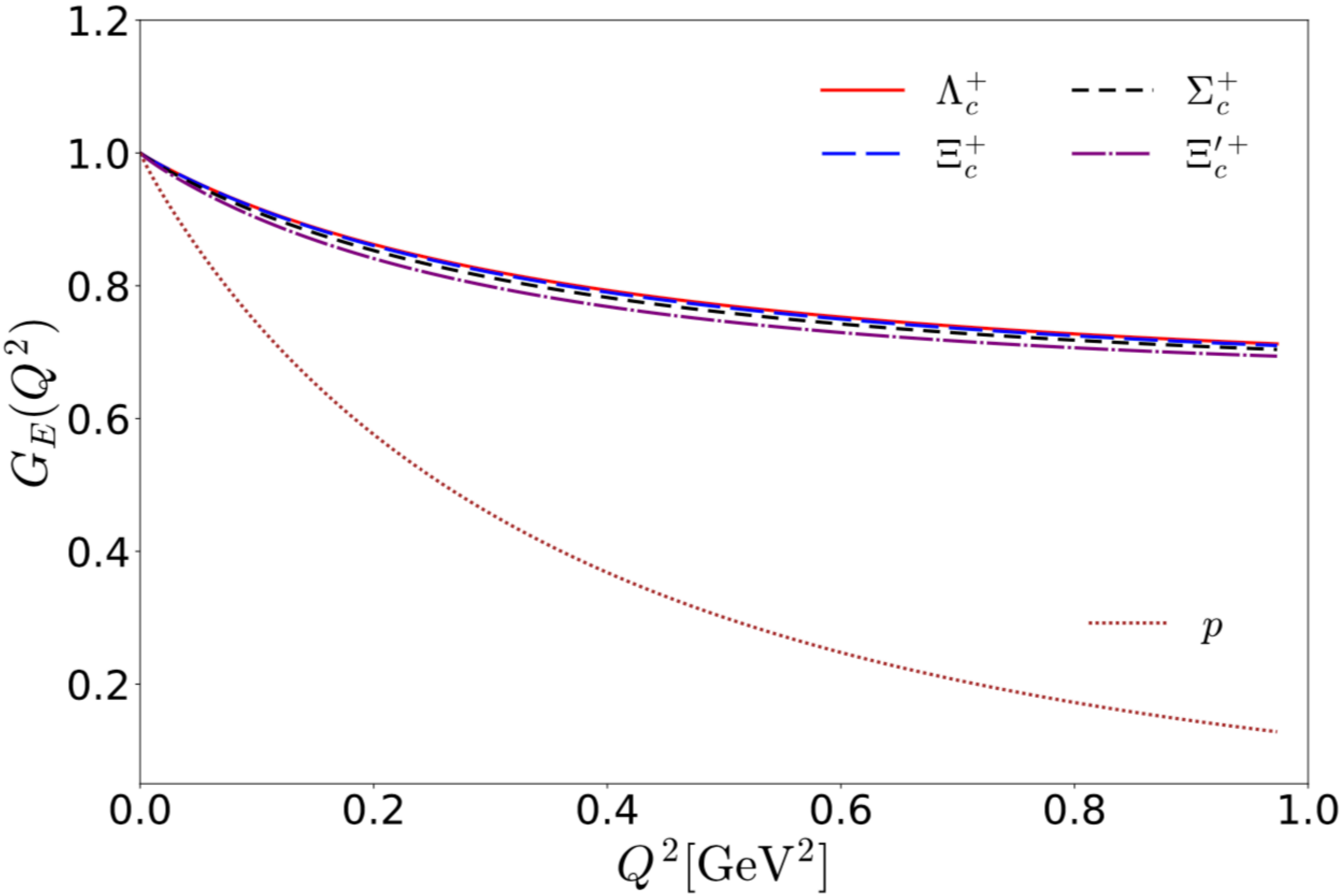
$[6]=D(2,0)$, $J = 3/2$

No magnetic form factor for the baryon antitriplet in a mean-field approach!

J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

Electromagnetic form factors of heavy baryons

Electric form factors

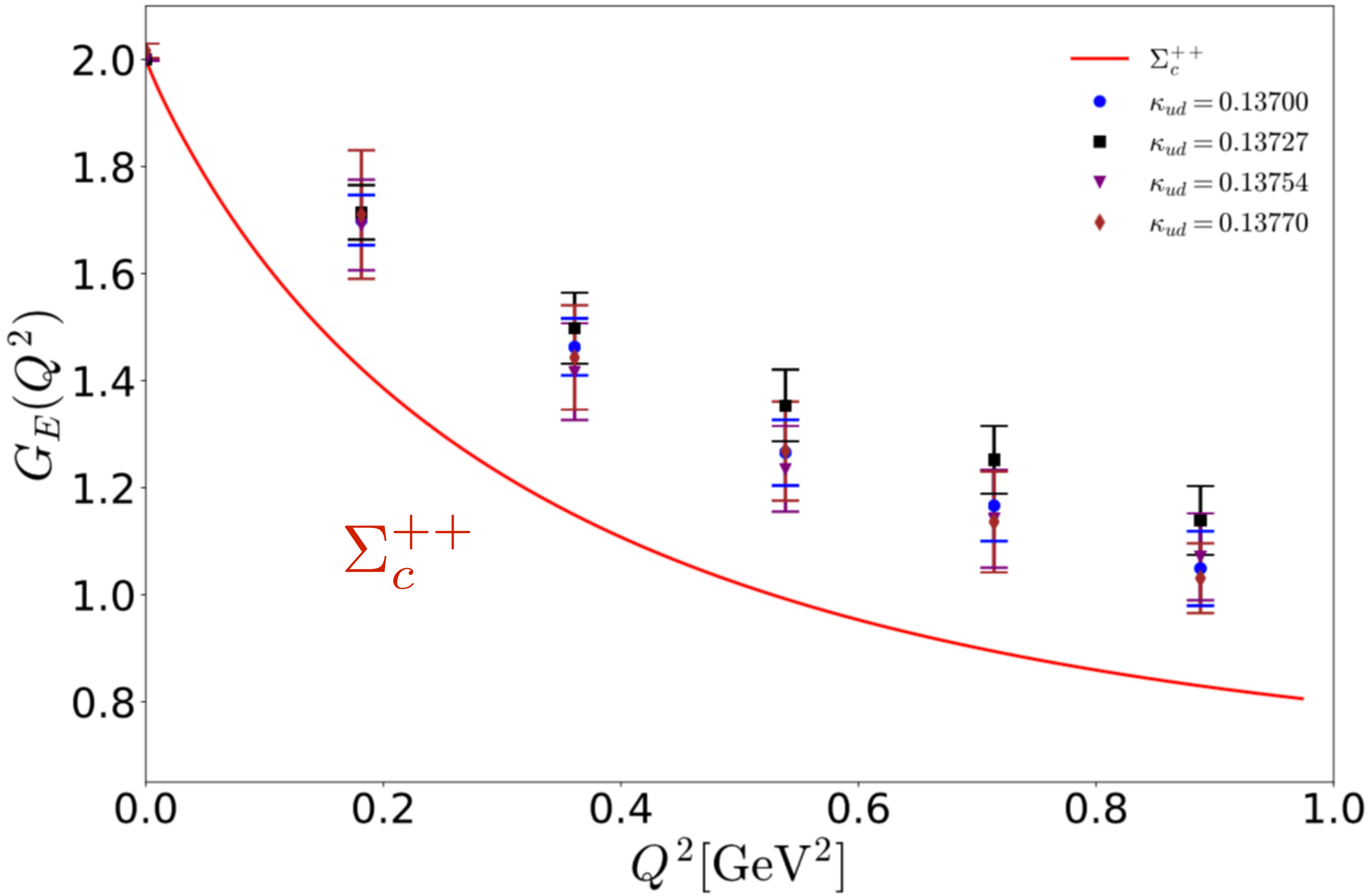


J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

Electromagnetic form factors of heavy baryons

Electric form factors

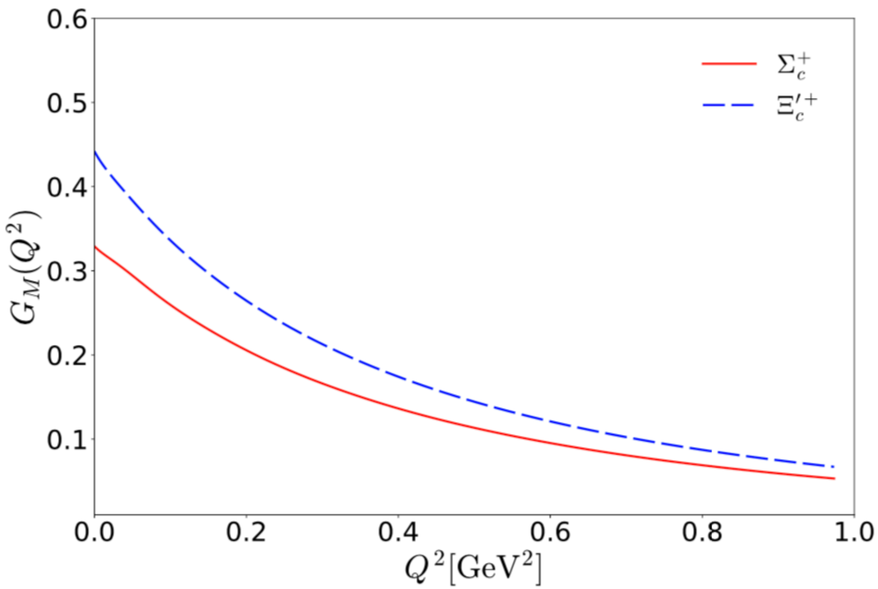
K. U. Can et al., JHEP. 05, (2014) 125

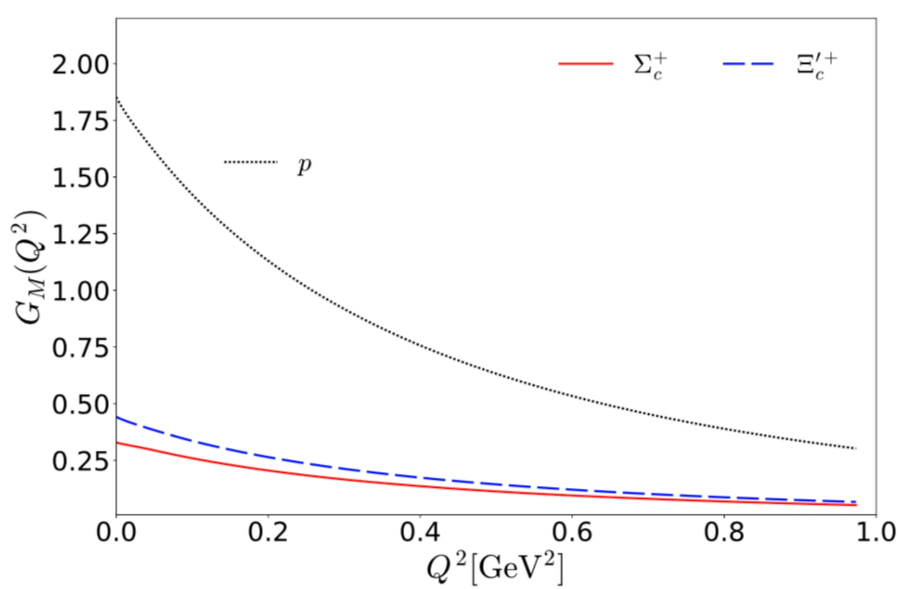


J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

Electromagnetic form factors of heavy baryons

Magnetic form factors



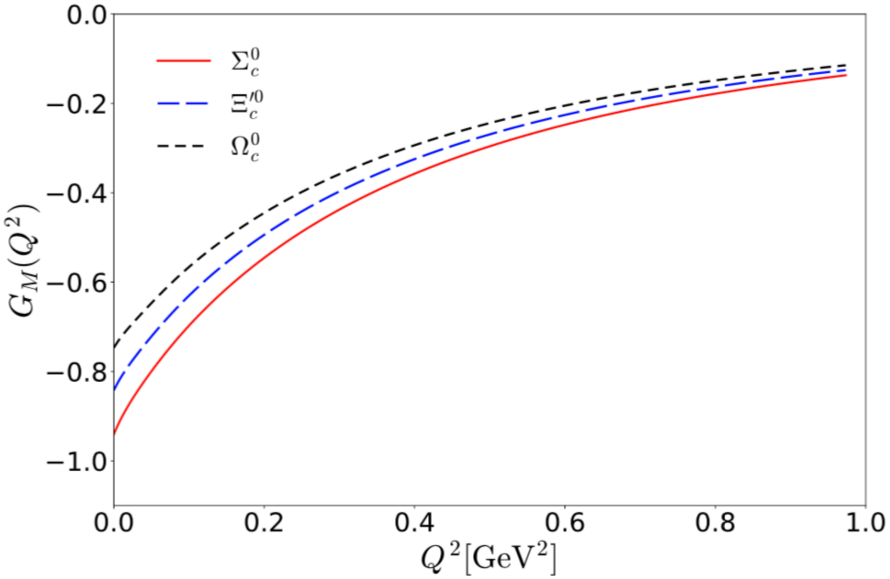


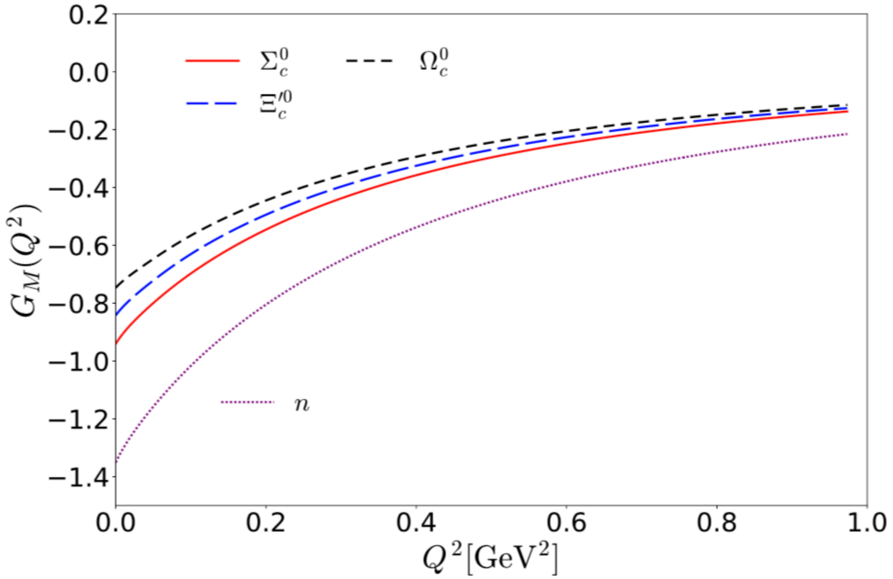
No contribution from the heavy quark in the limit of an infinitely large mass

J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

Electromagnetic form factors of heavy baryons

Magnetic form factors

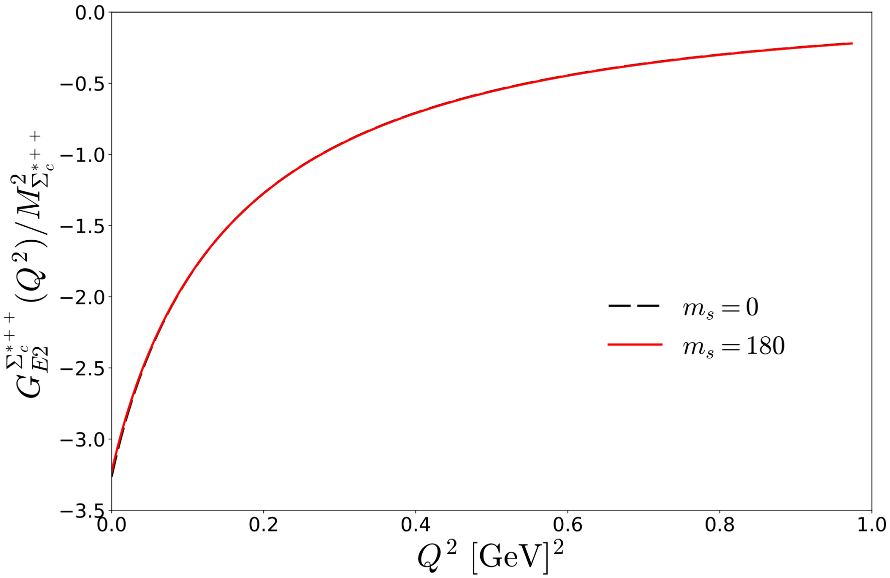


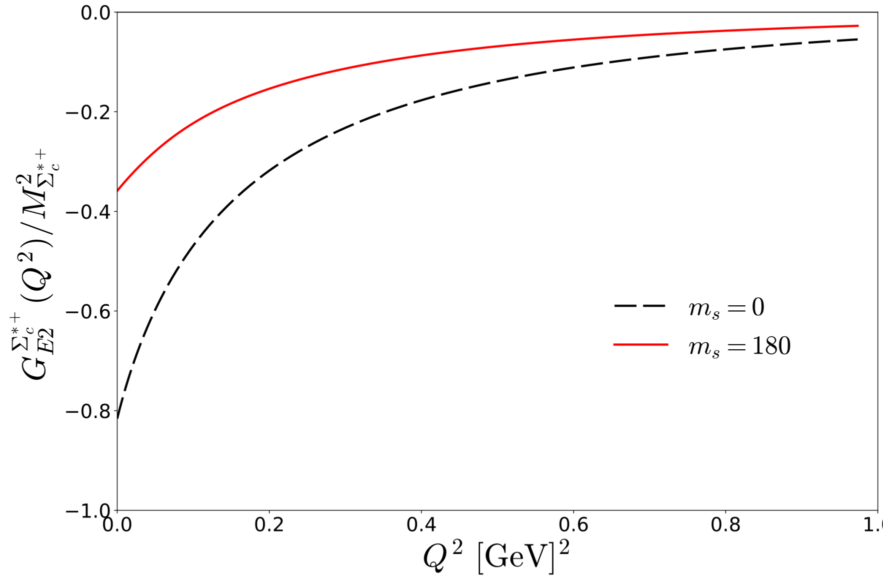


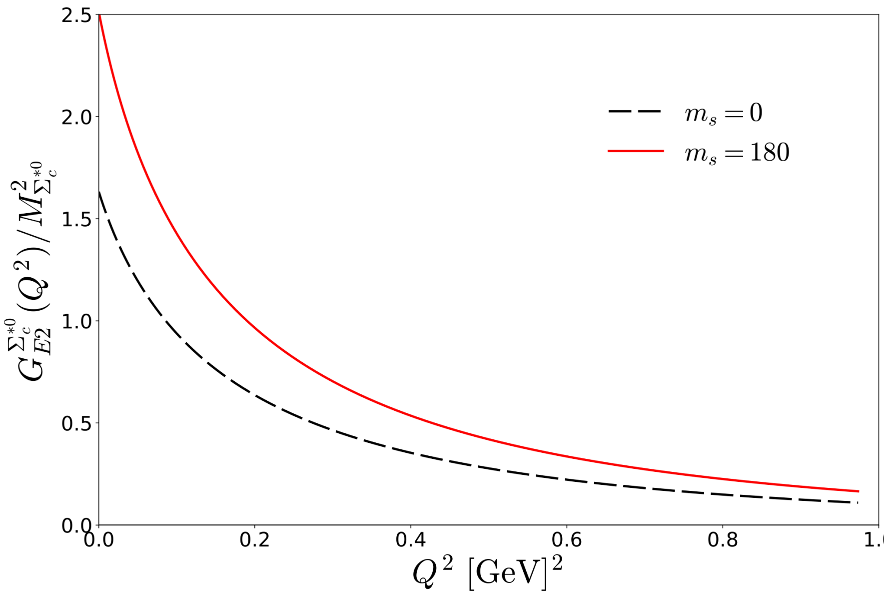
No contribution from the heavy quark in the limit of an infinitely large mass

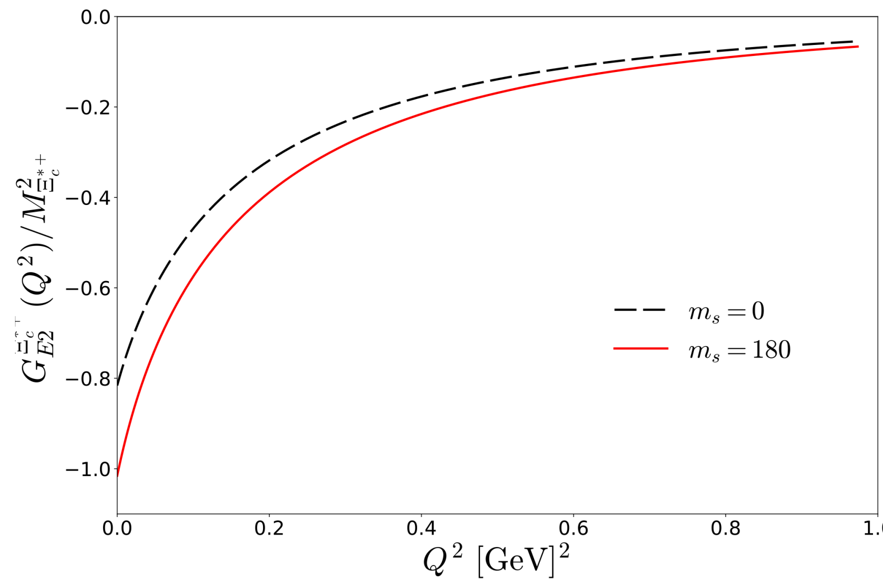
J.-Y. Kim, HChK, Phys.Rev. D97 (2018) 114009

E2 form factors of the sextet (J=3/2)

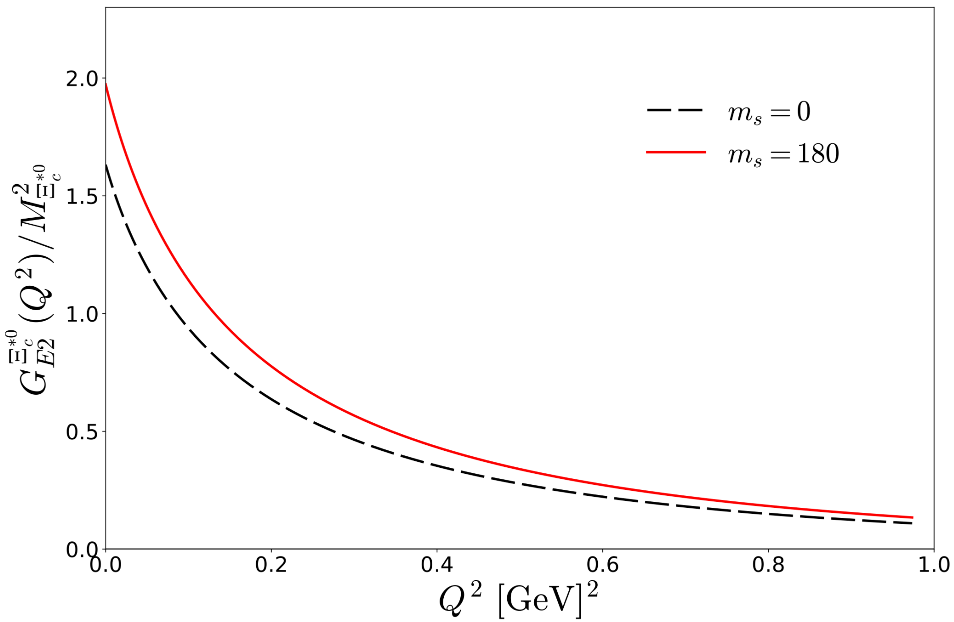


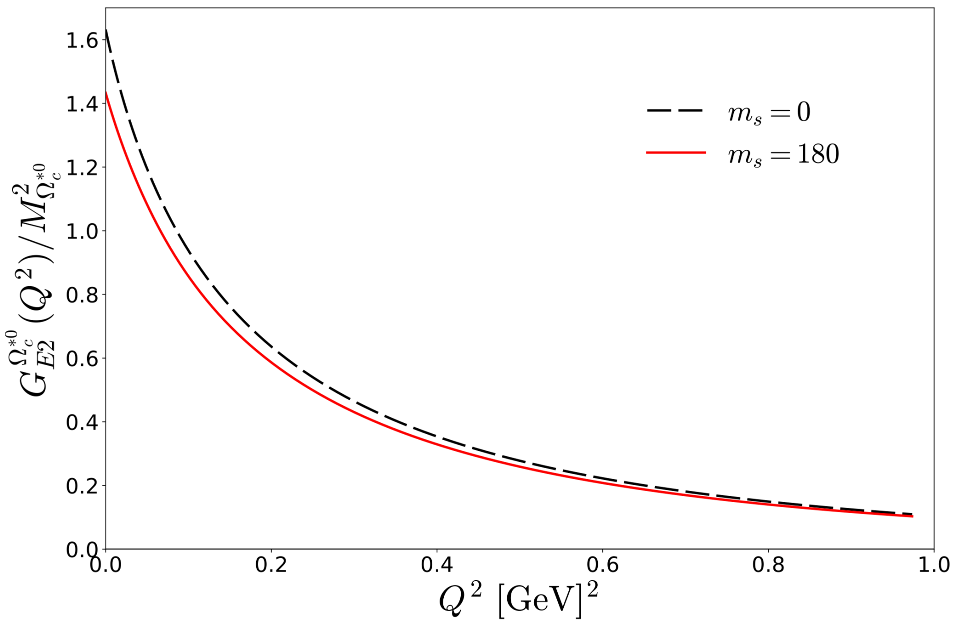






E2 form factors of the sextet (J=3/2)





J.-Y. Kim & HChK, in preparation

Conclusion & Outlook

- We presented a series of recent works on the electromagnetic form factors of the baryon decuplet and heavy baryons, based on a pion mean-field approach.
- Effects of SU(3) symmetry breaking are sizable for both E2 form factors and the EM transition form factors of the baryon decuplet.
- EM form factors of the singly heavy baryons were also discussed.
- Heavy baryons are electrically more compact than the light baryons.

- EM transition form factors of the singly heavy baryons are under way.
- The transverse charge densities of heavy baryons will be also studied.

How to go beyond the mean-field approximation

Conclusion & Outlook

Big Question: How can we go beyond the mean-field approximation?

- Include the meson-loop corrections. $$\frac{\delta^2 S}{\delta\phi^a\delta\phi^b} \neq 0$$

- Include the effects of the quark confinement: excited baryons

- Include the heavy-light quark interactions. $\mathcal{O}(1/m_Q)$

Acknowledgments: I am grateful to my collaborators J.-Y. Kim and Gh.-S. Yang.

Though this be madness,
yet there is method in it.

Hamlet Act 2, Scene 2

Thank you very much!