Hadron structure in the covariant confined quark model

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Overview

- Covariant confined quark model
- Applications in the meson sector
- (Light baryons and their electromagnetic structure)
- Semileptonic decays of heavy baryons
- Summary

Recent Coworkers

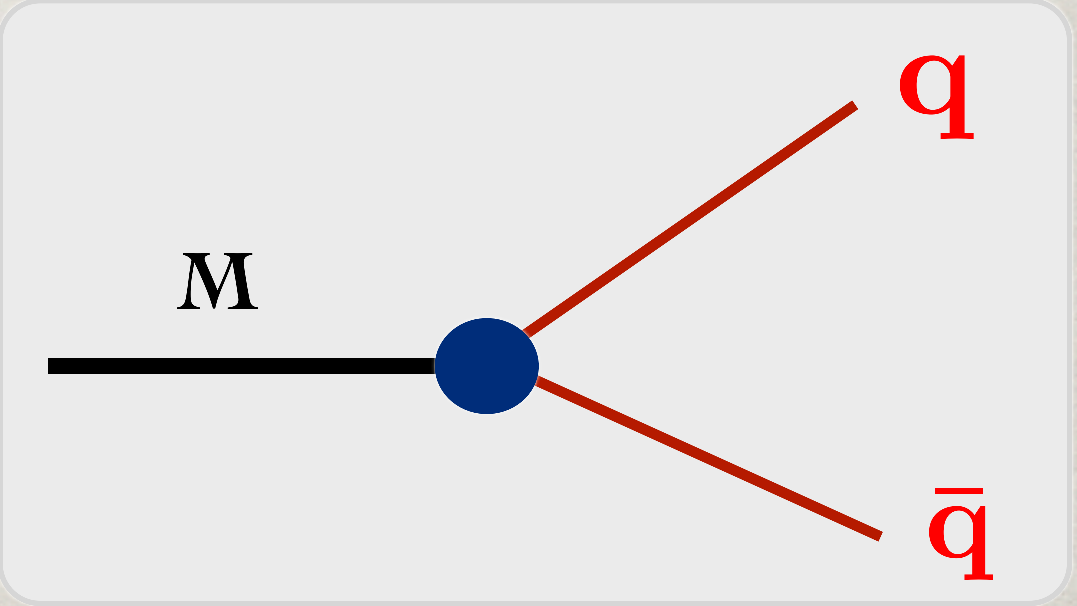
- Tübingen: V. Lyubovitskij
- Dubna: M. Ivanov
- Mainz: J. Körner
- Napoli: P. Santorelli
- Almaty: N. Habyl

Covariant quark model

- main assumption: hadrons interact by quark exchange
- quantum field theory tool: interaction Lagrangian for coupling between composite hadron and its constituents

Coupling of a meson M(x) to the $q\bar{q}$ constituents

$$\mathcal{L}_{\rm int}^{\rm str}(x) = g_M M(x) \cdot J_M(x)$$



with the non-local quark current

$$J_M(x) \;=\; \int dx_1 \int dx_2 F_M(x,x_1,x_2)\,\bar{q}_1(x_1)\,\Gamma_M\,\lambda_M\,q_2(x_2) + \text{h.c.}$$

Vertex function — Spin — Flavor

compositeness condition

Salam 1962, Weinberg 1963

- composite field M and quarks are introduced as elementary particles
- non-local interaction between M and its constituents
- field renormalization constant Z:
  matrix element between physical and bare state
- Quasi-particle M is a stable composite bound state with

$$Z_M^{1/2} = < M_{bare} | M_{dressed} > = 0$$

compositeness condition

compositeness condition leads to self-consistent determination of the hadron-constituents coupling.

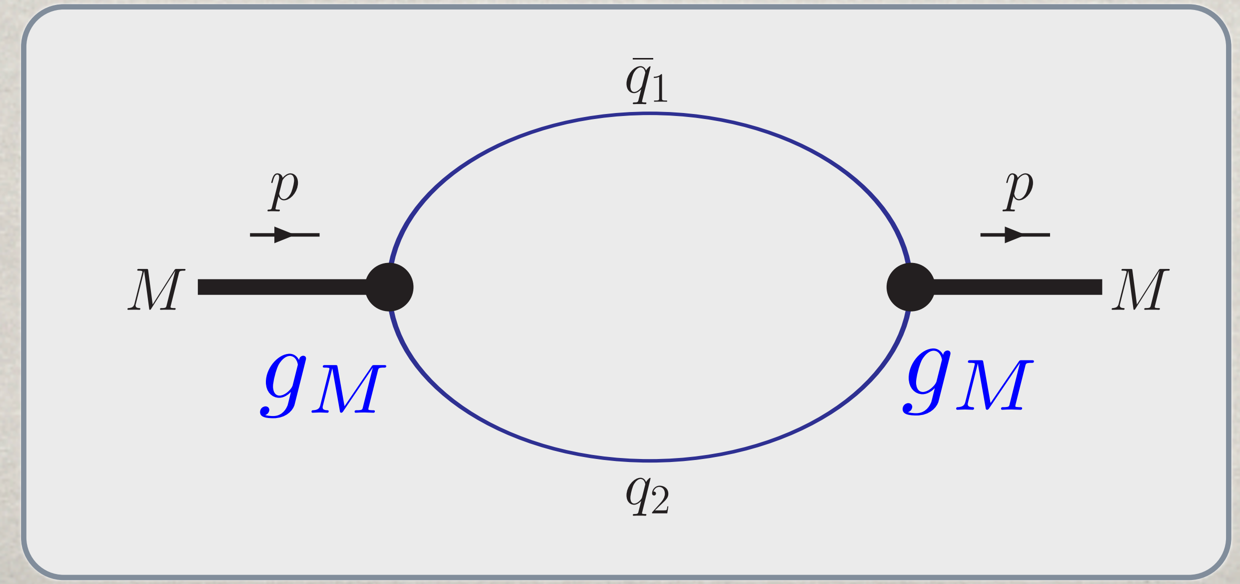
coupling g_M is determined by the condition

$$Z_M = 1 - \Sigma'_M(m_M^2) = 0$$

with the derivative of the mass operator

Exp. input

$$\Sigma'_M(m_M^2) = g_M^2 \Pi'_M(m_M^2) = g_M^2 \frac{d\Pi_M(p^2)}{dp^2}\bigg|_{p^2=m_M^2}$$



vertex function and propagators

- vertex function characterizes finite size of hadron:

$$F_M(x, x_1, x_2) = \delta^{(4)}(x - \sum_{i=1}^{2} w_i x_i)\, \Phi_M\Big((x_1 - x_2)^2\Big)$$

with $w_i = m_i / \sum m_i$ and
translational invariance for any 4-vector a with

$$F_M(x + a, x_1 + a, x_2 + a) = F_M(x, x_1, x_2)$$

often choose simple Gaussian form with

$$\Phi_M(y^2) = \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot y} \tilde{\Phi}(-k^2), \qquad \tilde{\Phi}(-k_E^2) = exp\left(-k_E^2/\Lambda_M^2\right)$$

- constituent quark propagator

$$S_q(k) = \frac{1}{m_q - \not{k} - i\epsilon}$$

with effective mass m_q

inclusion of photons or gauging the non-local Lagrangian

Strong interaction Lagrangian is non-local

Gauged by applying gauge field exponential with

$$q_i(x_i) \to e^{-ie_{q_i} I(x_i,x,P)} q_i(x_i) \text{ with } I(x_i,x,P) = \int_x^{x_i} dz_\mu A^\mu$$

Mandelstam (1961), Terning (1991)

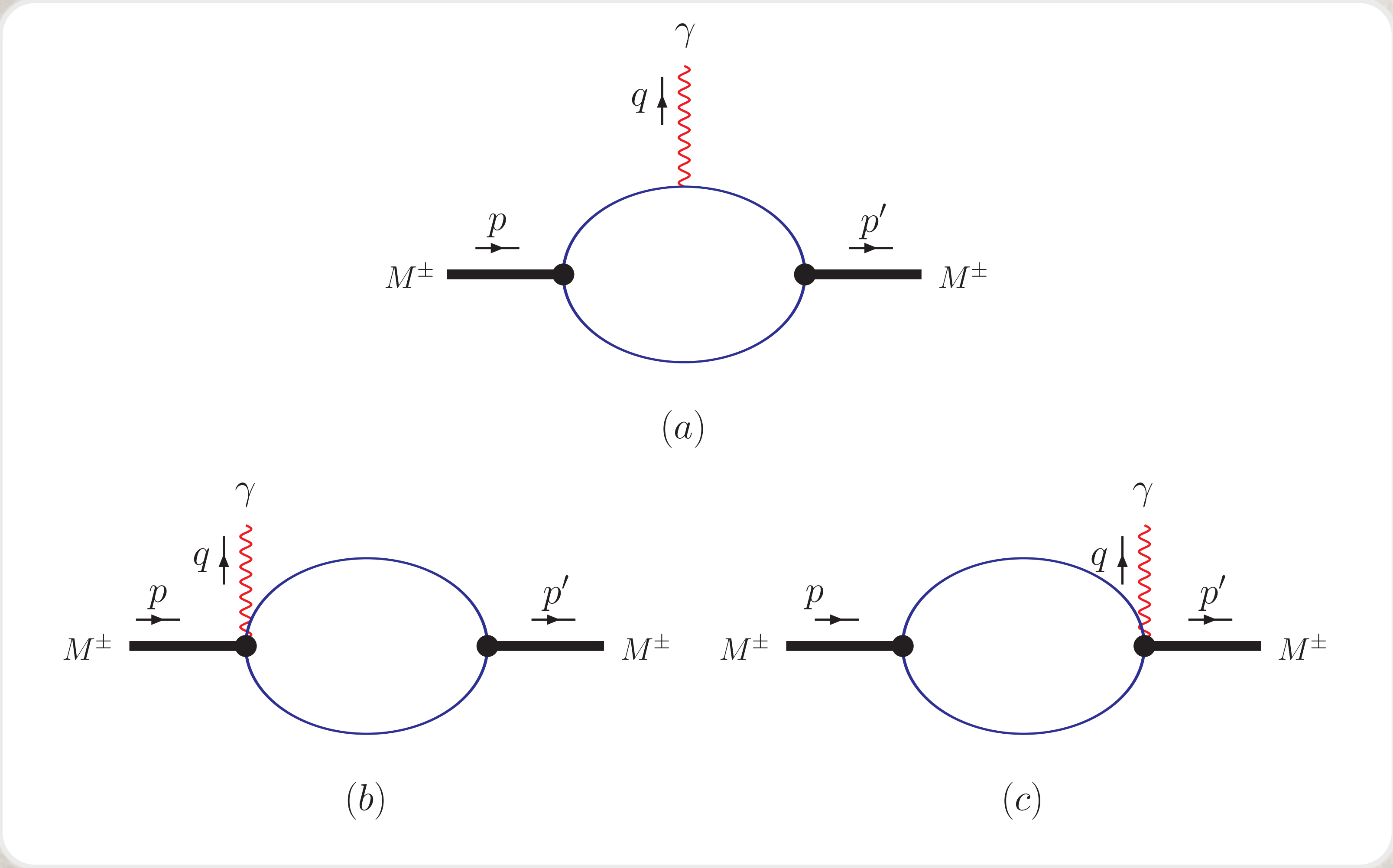
Expansion of gauged Lagrangian with

$$\mathcal{L}_{\rm int}^{\rm str;em}(x) = g_M M(x) \int dx_1 \int dx_2 F_M(x,x_1,x_2)$$

$$\times \bar{q}_1(x_1) e^{ie_{q_1} I(x_1,x,P)} \Gamma_M \lambda_M e^{-ie_{q_2} I(x_2,x,P)} q_2(x_2)$$

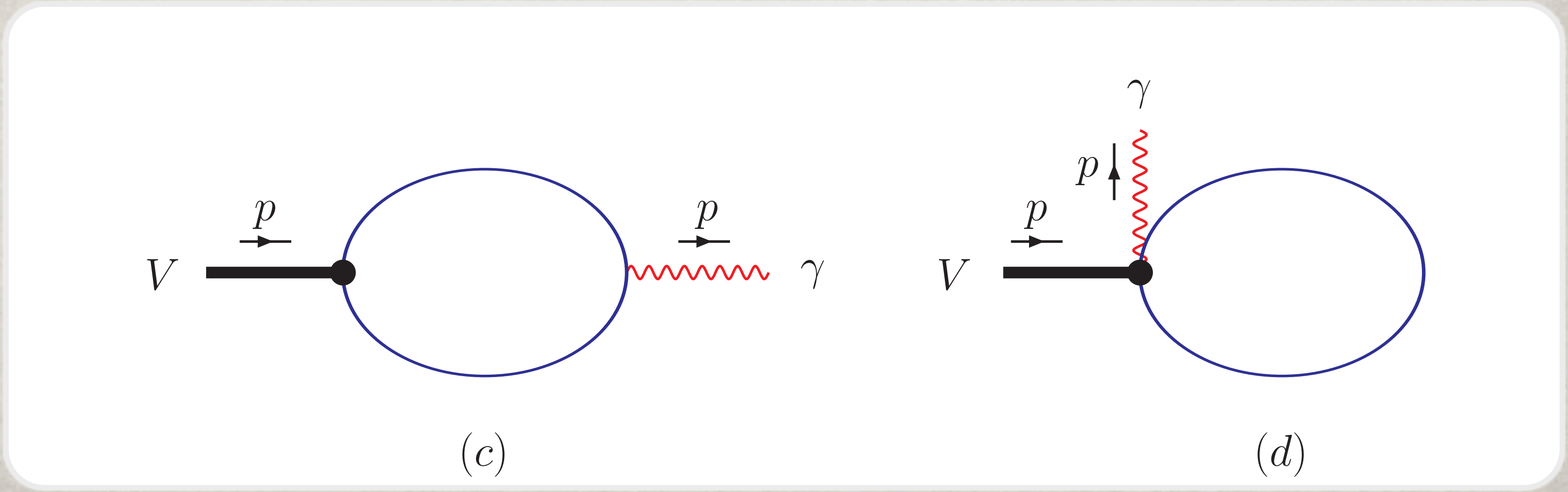
in powers of $\mathbf{A}_\mu$ leads to:

inclusion of photons or gauging the non-local Lagrangian



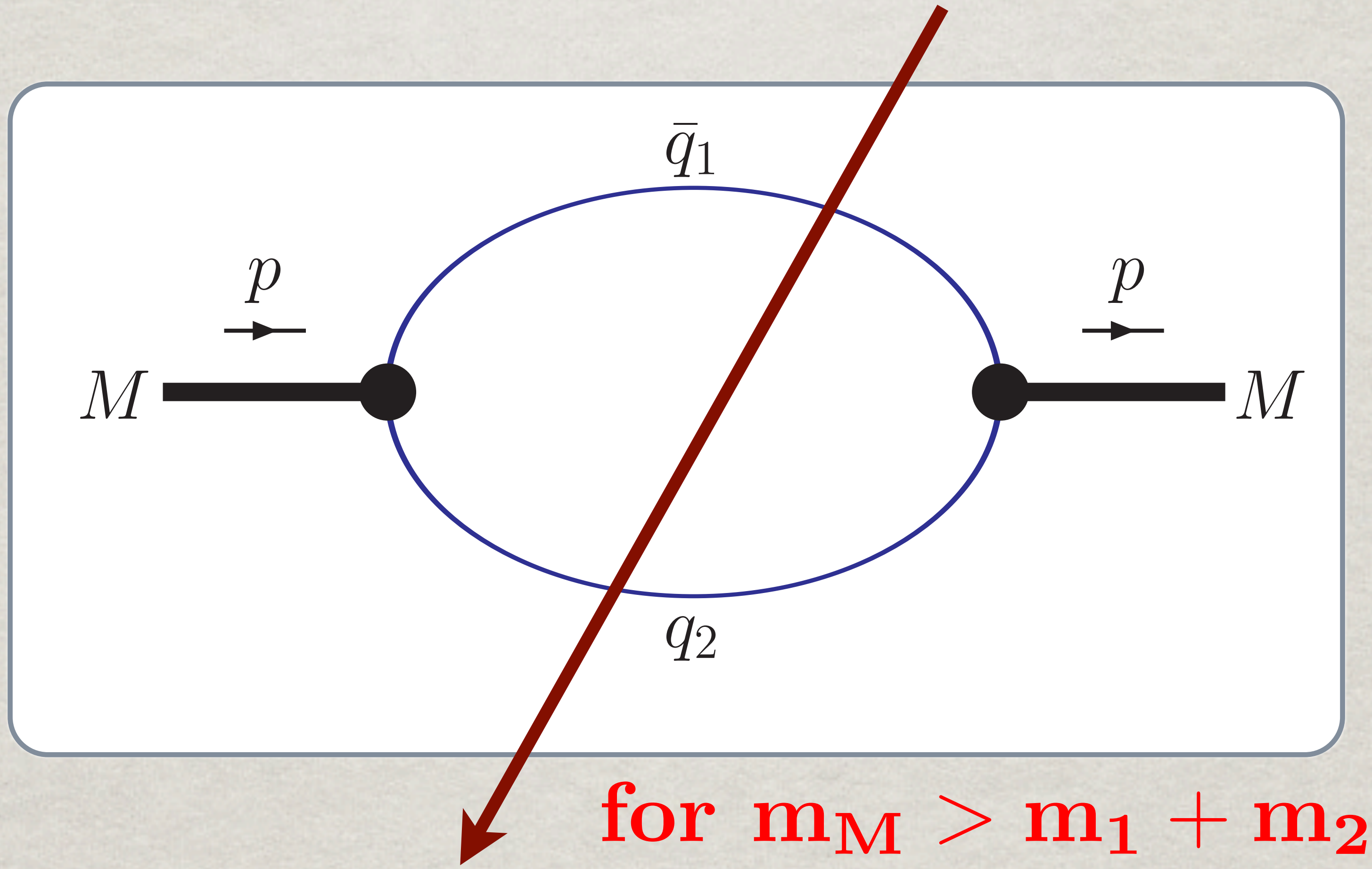
electromagnetic vertex function

vector meson
$V \to \gamma$ transition



infrared confinement

up to now applications limited to hadrons with $m_M < m_1 + m_2$.



reason: free quark propagator,
threshold singularities with free quarks

---> confinement = absence of quark poles

infrared confinement

Idea: consider scalar one-pole propagator

$$\frac{1}{m^2-p^2} = \int_0^\infty d\alpha \exp[-\alpha(m^2-p^2)]$$

in the Schwinger representation.

Introduce integration limit with the infrared confinement scale: λ with mass dimension (m)

$$\int_0^{1/\lambda^2} d\alpha \exp[-\alpha(m^2-p^2)] = \frac{1-\exp[-(m^2-p^2)/\lambda^2]}{m^2-p^2}$$

entire function, confined propagator

(similar to NJL (Ebert 1996), constant self-dual field Leutwyler/Efimov (1995))

Consider general l-loop diagram with n propagators:

$$\Pi(p_1,\ldots,p_n) = \int\limits_0^\infty d^n\alpha \int [d^4k]^l \, \Phi \, \exp[-\sum_{i=1}^n \alpha_i(m_i^2 - p_i^2)]$$

numerator: product of propagators and vertices

after loop integration

$$\Pi = \int\limits_0^\infty d^n\alpha \, F(\alpha_1,\ldots,\alpha_n)$$

complete structure of diagram

with the identity $1 = \int\limits_0^\infty dt \, \delta(t - \sum_{i=1}^n \alpha_i)$ we get

$$\Pi = \int\limits_0^\infty dt t^{n-1} \int\limits_0^1 d^n\alpha \, \delta\Big(1 - \sum_{i=1}^n \alpha_i\Big) \, F(t\alpha_1,\ldots,t\alpha_n)$$

confinement: introduce infrared cut-off at $\mathbf{1/\lambda^2}$

$$\Pi^c = \int\limits_0^{\mathbf{1/\lambda^2}} dt t^{n-1} \int\limits_0^1 d^n\alpha \, \delta\Big(1 - \sum_{i=1}^n \alpha_i\Big) F(t\alpha_1, \ldots, t\alpha_n)$$

consequences:

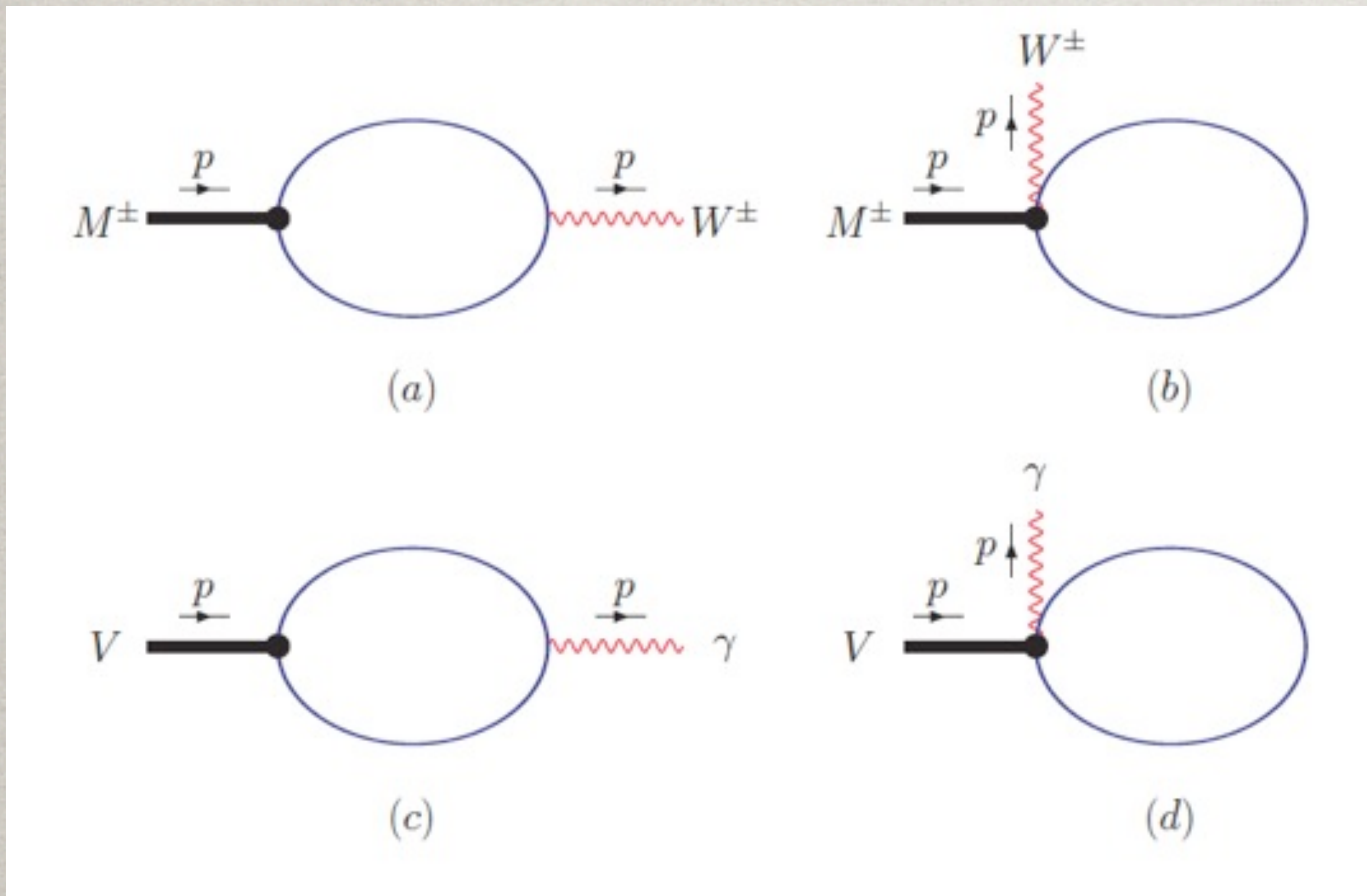
- all thresholds are removed in the quark-loop diagram
- infrared cut-off $\mathbf{1/\lambda^2}$ is universal -- same for all physical processes

T. Branz, A. Faessler, TG, M. Ivanov, J. Körner, V. Lyubovitskij, PRD D81, 034010 (2010)

first fits and parameters

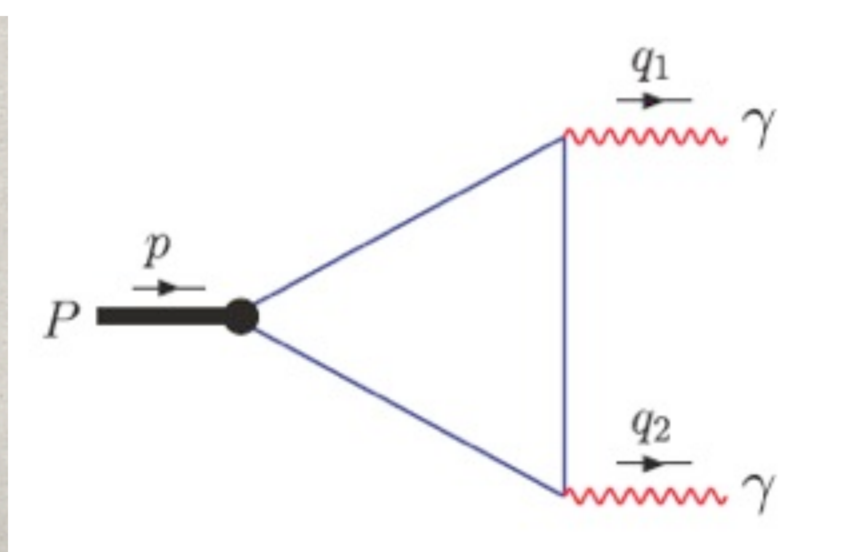
see T. Branz, A. Faessler, TG, M. Ivanov, J. Körner, V. Lyubovitskij, PRD D81, 034010 (2010)
update in M. Ivanov et al., PRD D85, 034004 (2012)

π and ρ properties:

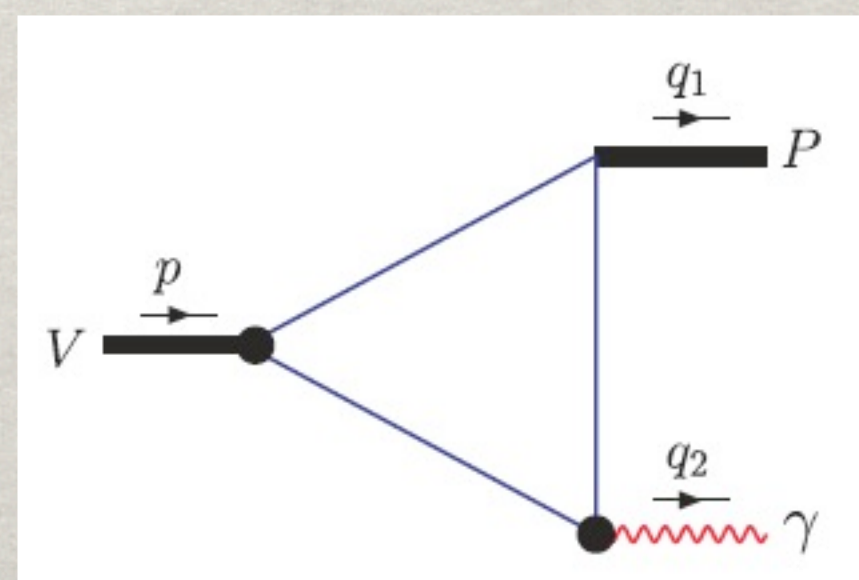


$\rightarrow \mathbf{f}_\pi$

$\rightarrow \mathbf{g}_{\rho\gamma}$



$\rightarrow \mathbf{g}_{\pi\gamma\gamma}$



$\rightarrow \mathbf{g}_{\rho\pi\gamma}$

first fits and parameters

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π and ρ properties:

Quantity	Our	Data (PDG)
f_π, MeV	130.2	$130.4 \pm 0.04 \pm 0.2$
$g_{\pi\gamma\gamma}$, GeV^{-1}	0.23	0.276
$g_{\rho\gamma}$	0.2	0.2
$g_{\rho\pi\gamma}$, GeV^{-1}	0.75	0.723 ± 0.037

Infrared cut-off

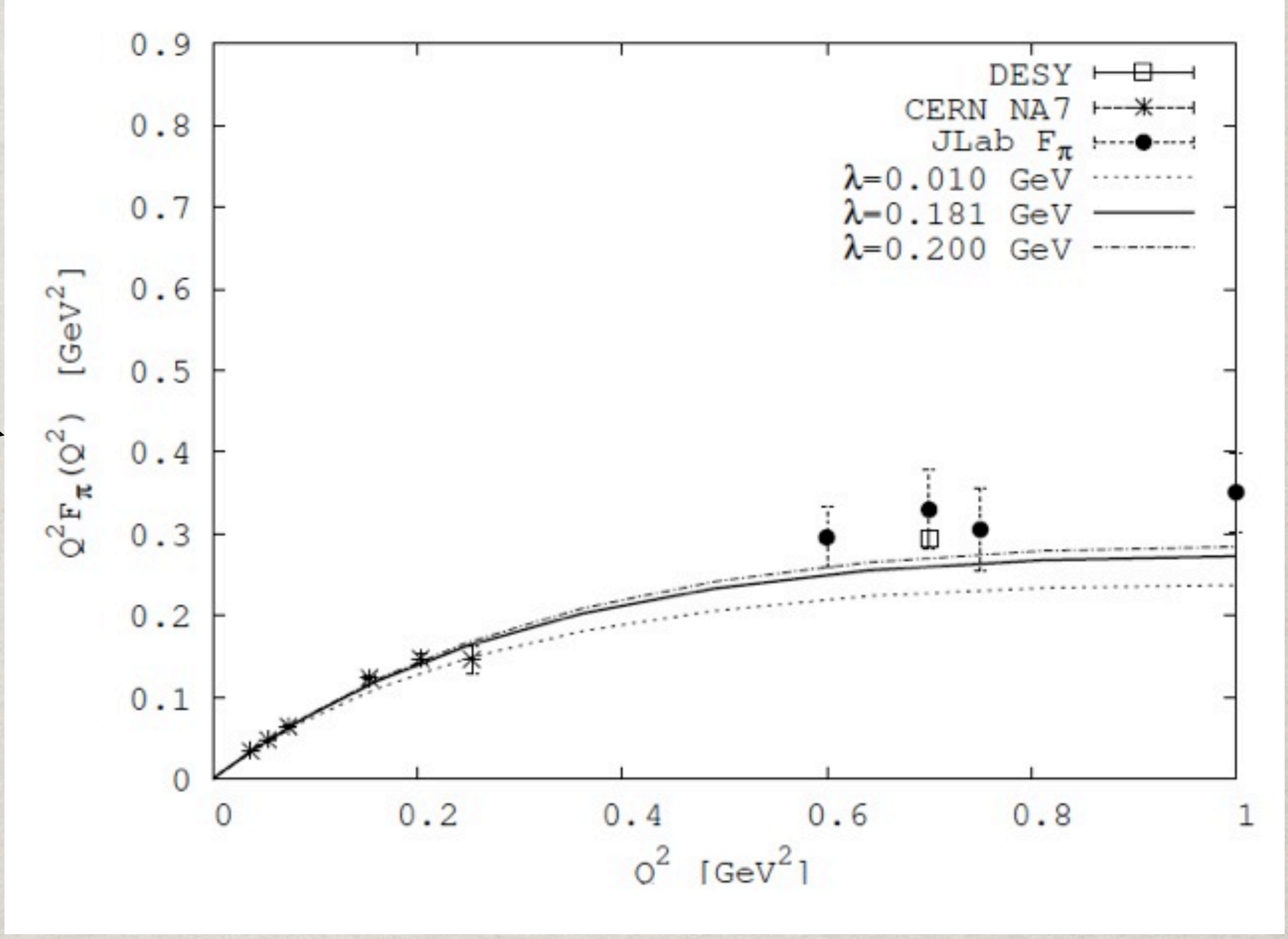
m	Λ_π	Λ_ρ	λ	
0.217	0.711	0.295	0.181	GeV

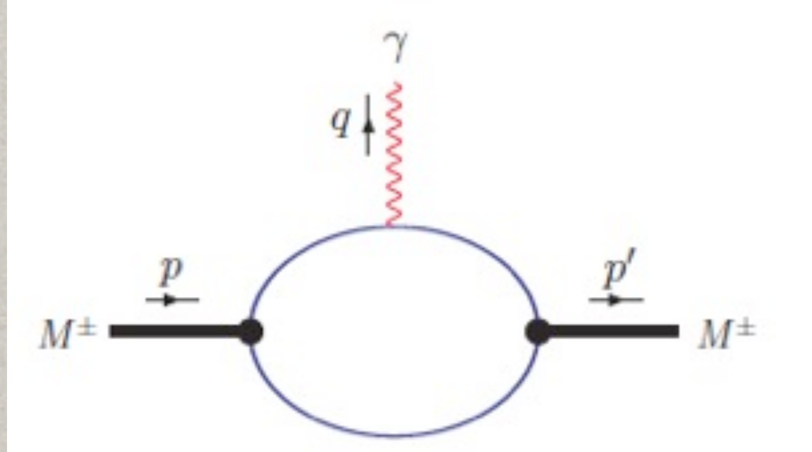
$\mathbf{m_u = m_d}$

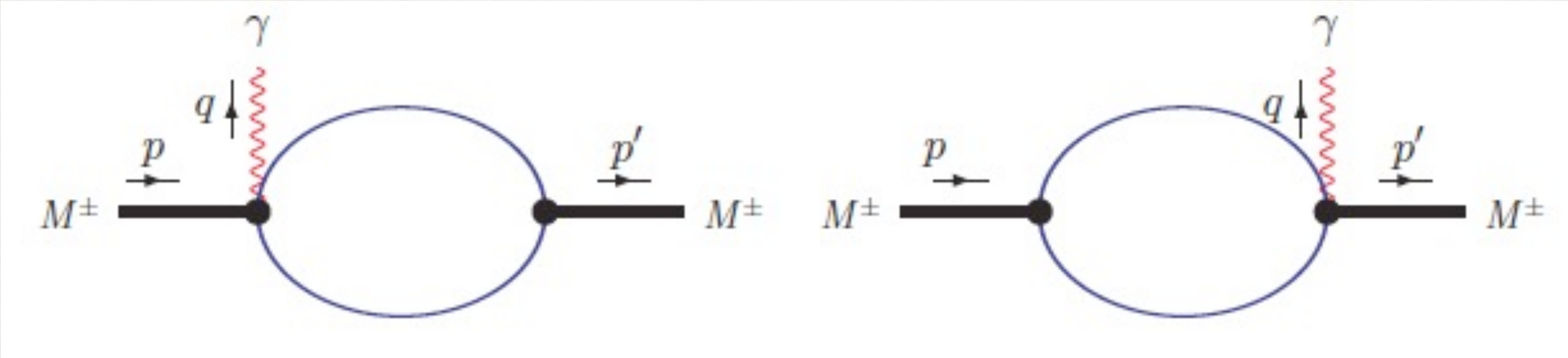
parameters

form factor $\pi^\pm \to \pi^\pm \gamma^*$ for space-like photon momentum Q^2

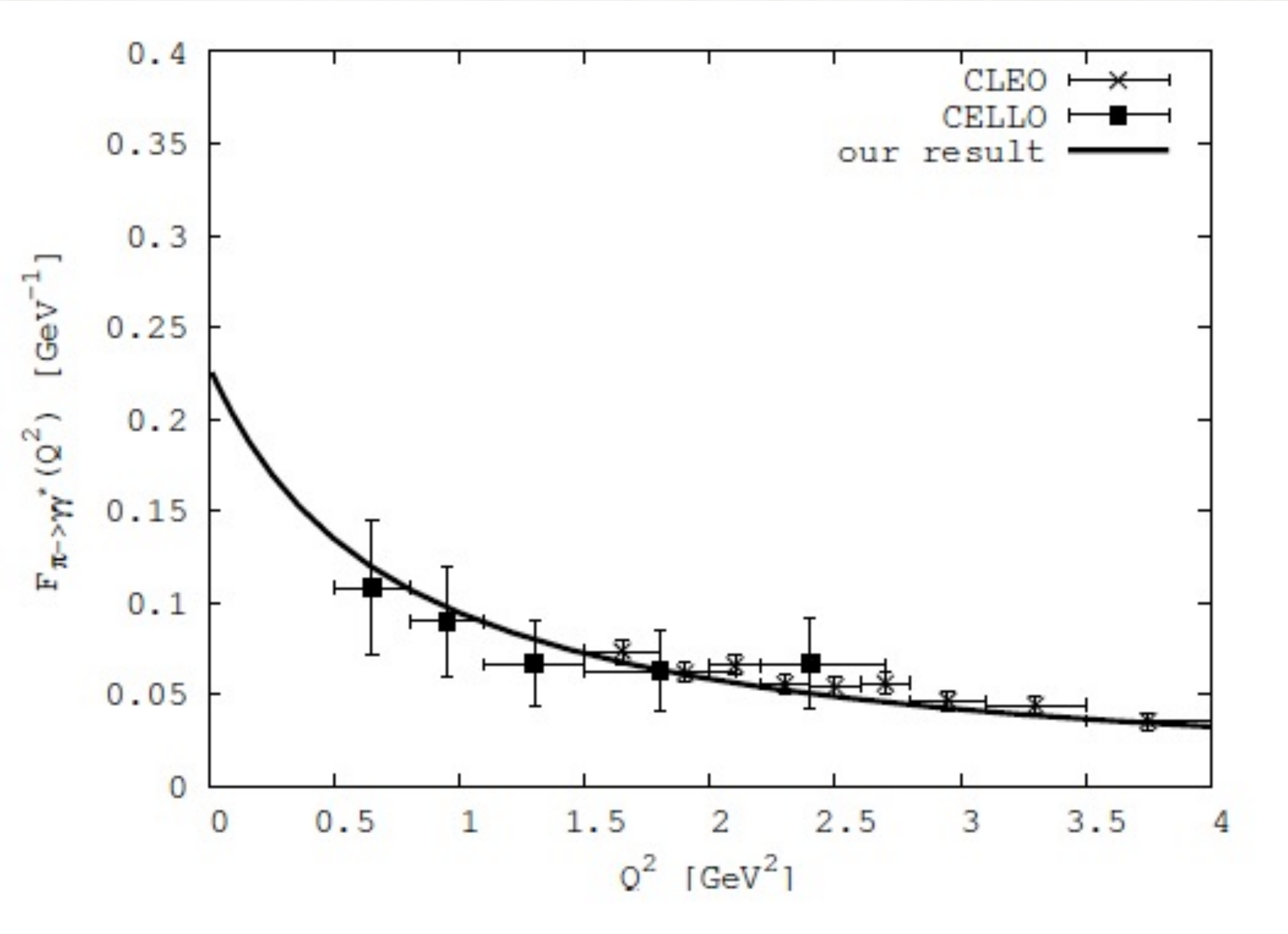
variation in infrared cut-off

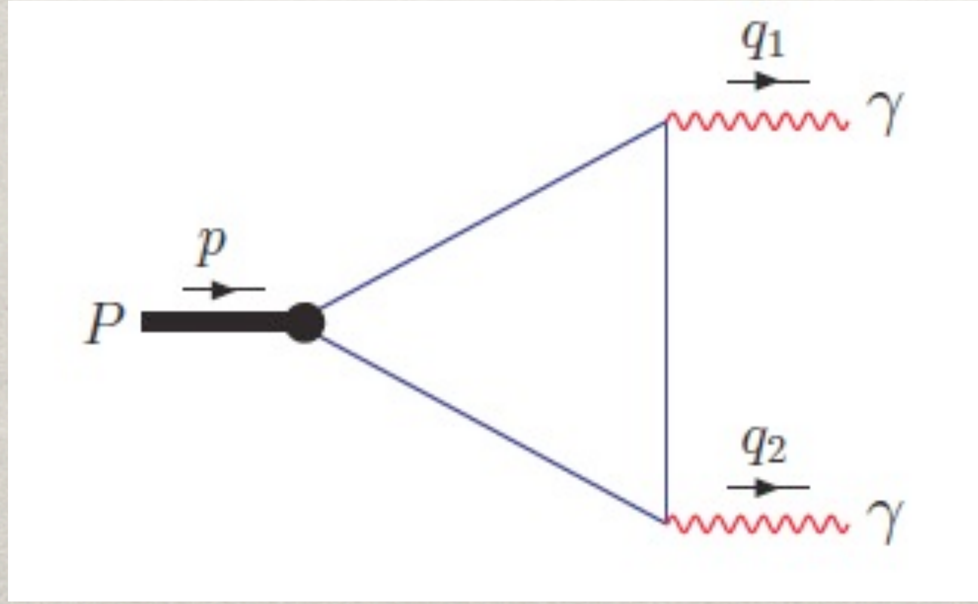






transition form factor $\gamma\gamma^* \to \pi^0$ for space-like photon momentum Q^2





+ „nonlocal“ graphs

further model parameters: basic electroweak properties

m_s	m_c	m_b	
0.360	1.6	4.8	GeV

$\Lambda_{\rho/\omega/\phi}$	Λ_η	Λ_η^s	$\Lambda_{\eta'}$	$\Lambda_{\eta'}^s$	Λ_K	Λ_{K^*}	Λ_D	Λ_{D^*}	Λ_{D_s}	$\Lambda_{D_s^*}$	Λ_{B/B^*}	Λ_{B_s/B_s^*}	$\Lambda_{J/\psi}$	Λ_{η_c/B_c}	Λ_Υ	Λ_{η_b}	
0.295	0.70	0.85	0.27	0.45	0.87	0.30	1.4	2.3	1.95	2.6	3.35	4.4	3.3	3.0	5.07	5.0	GeV

TABLE II: Weak leptonic decay constants $f_{P(V)}$ in MeV.

Meson	Our	Data [15]
π^-	130.2	$130.4 \pm 0.04 \pm 0.2$
K^-	155.4	$155.5 \pm 0.2 \pm 0.8$
D^+	206.2	205.8 ± 8.9
D_s^+	273.7	273 ± 10
B^-	216.4	216 ± 22
B_s^0	250.2	$253 \pm 8 \pm 7$
B_c	485.2	$489 \pm 5 \pm 3$ [23]
ρ^+	209.3	210.5 ± 0.6 [15]
D^{*+}	187.0	$245 \pm 20^{+3}_{-2}$ [24]
D_s^{*+}	213	$272 \pm 16^{+3}_{-20}$ [25]
B^{*+}	210.6	$196 \pm 24^{+39}_{-2}$ [24]
B_s^{*0}	264.6	$229 \pm 20^{+41}_{-16}$ [24]

Electromagnetic leptonic decay constants f_V

Meson	Our	Data [15]
ρ^0	148.0	154.7 ± 0.7
ω	51.7	45.8 ± 0.8
ϕ	76.3	76 ± 1.2
J/ψ	277.4	277.6 ± 4
$\Upsilon(1s)$	238.4	238.5 ± 5.5

in MeV

TABLE IV. Electromagnetic and leptonic decay widths in keV.

Process	Ours	Data [15]
$\pi^0 \to \gamma\gamma$	5.40×10^{-3}	$(7.7 \pm 0.6) \times 10^{-3}$
$\eta \to \gamma\gamma$	0.51	0.510 ± 0.026
$\eta' \to \gamma\gamma$	4.27	4.28 ± 0.19
$\eta_c \to \gamma\gamma$	4.55	$7.2 \pm 0.7 \pm 2.0$
$\eta_b \to \gamma\gamma$	0.43	
$\rho^0 \to e^+e^-$	6.33	7.04 ± 0.06
$\omega \to e^+e^-$	0.76	0.60 ± 0.02
$\phi \to e^+e^-$	1.27	1.27 ± 0.04
$J/\psi \to e^+e^-$	5.54	$5.55 \pm 0.14 \pm 0.02$
$\Upsilon \to e^+e^-$	1.34	1.34 ± 0.018
$\rho^\pm \to \pi^\pm\gamma$	72.42	68 ± 7
$\rho^0 \to \eta\gamma$	63.25	62 ± 17
$\omega \to \pi^0\gamma$	682.71	703 ± 25
$\omega \to \eta\gamma$	7.63	6.1 ± 2.5
$\eta' \to \omega\gamma$	12.44	9.06 ± 2.87
$\phi \to \eta\gamma$	51.72	$58.9 \pm 0.5 \pm 2.4$
$\phi \to \eta'\gamma$	0.41	0.27 ± 0.01
$K^{*\pm} \to K^\pm\gamma$	40.86	50 ± 5
$K^{*0} \to K^0\gamma$	122.04	116 ± 10
$D^{*\pm} \to D^\pm\gamma$	0.62	1.5 ± 0.8
$D^{*0} \to D^0\gamma$	20.27	$<0.9 \times 10^3$
$D_s^{*\pm} \to D_s^\pm\gamma$	0.30	$<1.8 \times 10^3$
$B^{*\pm} \to B^\pm\gamma$	0.36	
$B^{*0} \to B^0\gamma$	0.12	
$B_s^{*0} \to B_s^0\gamma$	0.12	
$J/\psi \to \eta_c\gamma$	1.89	1.58 ± 0.37
$\Upsilon \to \eta_b\gamma$	0.02	

further predictions in the meson sector

physics of heavy baryons: motivation

- origin of flavor and CP violations
- determination of CKM matrix elements
- weak decays of heavy hadrons containing a b- or c-quark
- experimental possibilities at LHCb
- signals for new physics beyond the Standard Model
- models of heavy flavor decays (nonperturbative hadronic effects)
- new exotic states

recent work on heavy baryons:

TG, M. Ivanov, J. Körner, V. Lyubovitskij, P. Santorelli and N.Habyl:

PRD 91, 074001 (2015) $\mathbf{\Lambda_b} \to \mathbf{\Lambda_c} + \tau^- + \bar{\nu}_\tau$

PRD 90, 114033 (2014) $\mathbf{\Lambda_b} \to \mathbf{p} + \ell^- + \bar{\nu}_\ell$ and $\mathbf{\Lambda_c} \to \mathbf{n} + \ell^+ + \nu_\ell$

PRD 88, 114018 (2013) $\mathbf{\Lambda_b} \to \mathbf{\Lambda}(\to \mathbf{p}\pi^-) + \mathbf{J}/\mathbf{\Psi}(\to \ell^+\ell^-)$

PRD 87, 074031 (2013) $\mathbf{\Lambda_b} \to \mathbf{\Lambda}\ell^+\ell^-$ $(\ell = \mathbf{e}, \mu, \tau)$ and $\mathbf{\Lambda_b} \to \mathbf{\Lambda}\gamma$

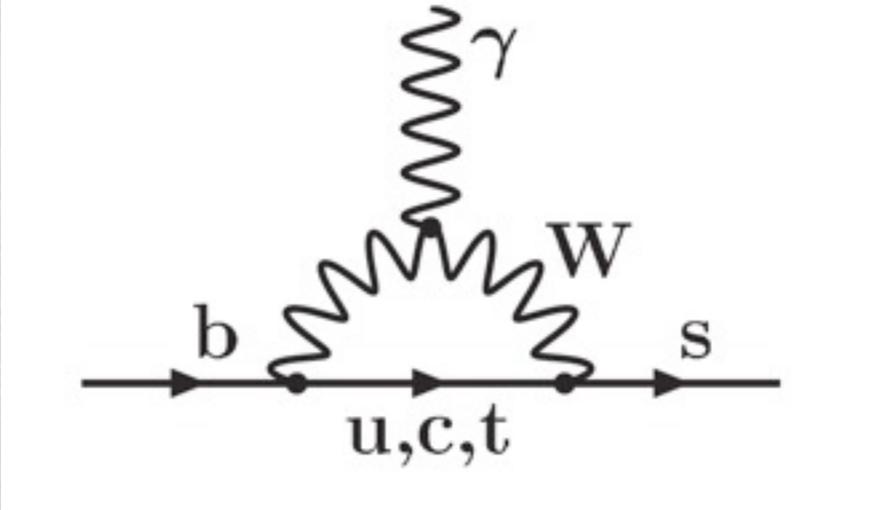
PRD 86, 074013 (2012) **el.magn. structure of light baryons**

Rare baryon decays:
$\Lambda_b \to \Lambda \ell^+ \ell^-$ $(\ell = e, \mu, \tau)$ and $\Lambda_b \to \Lambda\gamma$

TG, M. Ivanov, J. Körner, V. Lyubovitskij, P. Santorelli, PRD 87, 074031 (2013)

- flavor-changing neutral currents - FCNC, like

$b \to s\gamma$



(forbidden at tree level, =0 for degenerate up-type masses)

- loop induced processes: sensitivity to „new physics"
- extraction of CKM matrix elements
- exclusive and inclusive decays of the form

$$b \to s\gamma \text{ and } b \to s\ell^+\ell^-$$

- **rare baryon decays complementary to** $B \to K^{(*)}\ell^+\ell^-$

Rare baryon decays: $\Lambda_b \to \Lambda \ell^+ \ell^-$ $(\ell = e, \mu, \tau)$ and $\Lambda_b \to \Lambda \gamma$

- naive factorization, based on OPE in local operators
- separation of short-distance SM dynamics from long-distance hadronic effects
- nonperturbative determination of hadronic matrix elements ----> form factors
- $b \to s \ell^+ \ell^-$ contains lots of information through
  - lepton invariant mass
  - lepton energy spectra
  - forward-backward asymmetries .....
- data

$\Gamma(\Lambda \mu^+ \mu^-)/\Gamma_{total}$

VALUE (units 10^{-7})	DOCUMENT ID		TECN	COMMENT
10.8±2.8 OUR AVERAGE				
9.6±1.6±2.5	[40] AAIJ	13AJ	LHCB	pp at 7 TeV
17.3±4.2±5.5	AALTONEN	11AI	CDF	$p\bar{p}$ at 1.96 TeV

Lagrangian and 3-quark current

$$\mathcal{L}_{\rm int}^{\Lambda}(x) = g_\Lambda\,\bar\Lambda(x)\cdot J_\Lambda(x) + g_\Lambda\,\bar J_\Lambda(x)\cdot\Lambda(x)$$

$$J_\Lambda(x) = \int\!dx_1\!\int\!dx_2\!\int\!dx_3\,F_\Lambda(x;x_1,x_2,x_3)\,J_{3q}^{(\Lambda)}(x_1,x_2,x_3)$$

$$J_{3q}^{(\Lambda)}(x_1,x_2,x_3) = \epsilon^{a_1a_2a_3}\,Q^{a_1}(x_1)\,u^{a_2}(x_2)\,C\,\gamma^5\,d^{a_3}(x_3)$$

$Q = s, c, b$ $\qquad$ $(ud)_{^1S_0}$

Vertex function of the form

$$F_\Lambda(x;x_1,x_2,x_3) = \delta^{(4)}(x - \sum_{i=1}^{3} w_i x_i)\,\Phi_\Lambda\Big(\sum_{i<j}(x_i - x_j)^2\Big)$$

with $\quad w_i = m_i/(m_1 + m_2 + m_3)$

Effective Hamiltonian for the quark amplitudes

see Buchalla, Buras, Lautenbacher, Rev. Mod. Phys. 68 (1996)

$\mathbf{b \to s}\ell^+\ell^-$

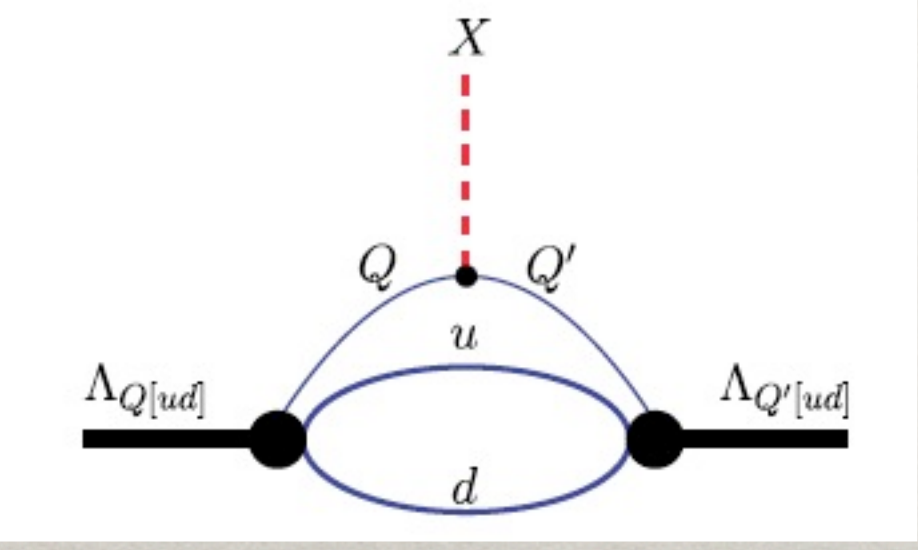
$$M(b \to s\ell^+\ell^-) = \frac{G_F}{\sqrt{2}}\frac{\alpha\lambda_t}{2\pi}\Big\{C_9^{\rm eff}(\bar{s}O^\mu b)(\bar{\ell}\gamma_\mu\ell) + C_{10}(\bar{s}O^\mu b)(\bar{\ell}\gamma_\mu\gamma_5\ell) - \frac{2}{q^2}C_7^{\rm eff}[m_b(\bar{s}i\sigma^{\mu q}(1+\gamma^5)b) + m_s(\bar{s}i\sigma^{\mu q}(1-\gamma^5)b)](\bar{\ell}\gamma_\mu\ell)\Big\}.$$

long-distance $c\bar{c}$ contributions

$\mathbf{b \to s}\gamma$

$\sigma^{\mu q} = \sigma^{\mu\nu}q_\nu$ $\quad \lambda_t \equiv V_{ts}^\dagger V_{tb}$

$$M(b \to s\gamma) = -\frac{G_F}{\sqrt{2}}\frac{e\lambda_t}{4\pi^2}C_7^{\rm eff}[m_b(\bar{s}i\sigma^{\mu q}(1+\gamma^5)b) + m_s(\bar{s}i\sigma^{\mu q}(1-\gamma^5)b)]\epsilon_\mu$$



$$\Lambda_{Q[ud]} \to \Lambda_{Q'[ud]} + X$$

$$X = \ell^-\bar{\nu}_\ell, \ell^+\ell^- \text{ or } \gamma$$

Hadronic matrix elements and form factors

$$\langle B_2|\bar{s}\gamma^\mu b|B_1\rangle = \bar{u}_2(p_2)[f_1^V(q^2)\gamma^\mu - f_2^V(q^2)i\sigma^{\mu q}/M_1 + f_3^V(q^2)q^\mu/M_1]u_1(p_1),$$

$$\langle B_2|\bar{s}\gamma^\mu\gamma^5 b|B_1\rangle = \bar{u}_2(p_2)[f_1^A(q^2)\gamma^\mu - f_2^A(q^2)i\sigma^{\mu q}/M_1 + f_3^A(q^2)q^\mu/M_1]\gamma^5 u_1(p_1),$$

$$\langle B_2|\bar{s}i\sigma^{\mu q}/M_1 b|B_1\rangle = \bar{u}_2(p_2)[f_1^{TV}(q^2)(\gamma^\mu q^2 - q^\mu \not{q})/M_1^2 - f_2^{TV}(q^2)i\sigma^{\mu q}/M_1]u_1(p_1),$$

$$\langle B_2|\bar{s}i\sigma^{\mu q}\gamma^5/M_1 b|B_1\rangle = \bar{u}_2(p_2)[f_1^{TA}(q^2)(\gamma^\mu q^2 - q^\mu \not{q})/M_1^2 - f_2^{TA}(q^2)i\sigma^{\mu q}/M_1]\gamma^5 u_1(p_1)$$

with $q = p_1 - p_2$ and $q_1 = q/M_1$

Fit parameters

- quark masses and infrared cut-off as in meson sector
- set of size parameters:

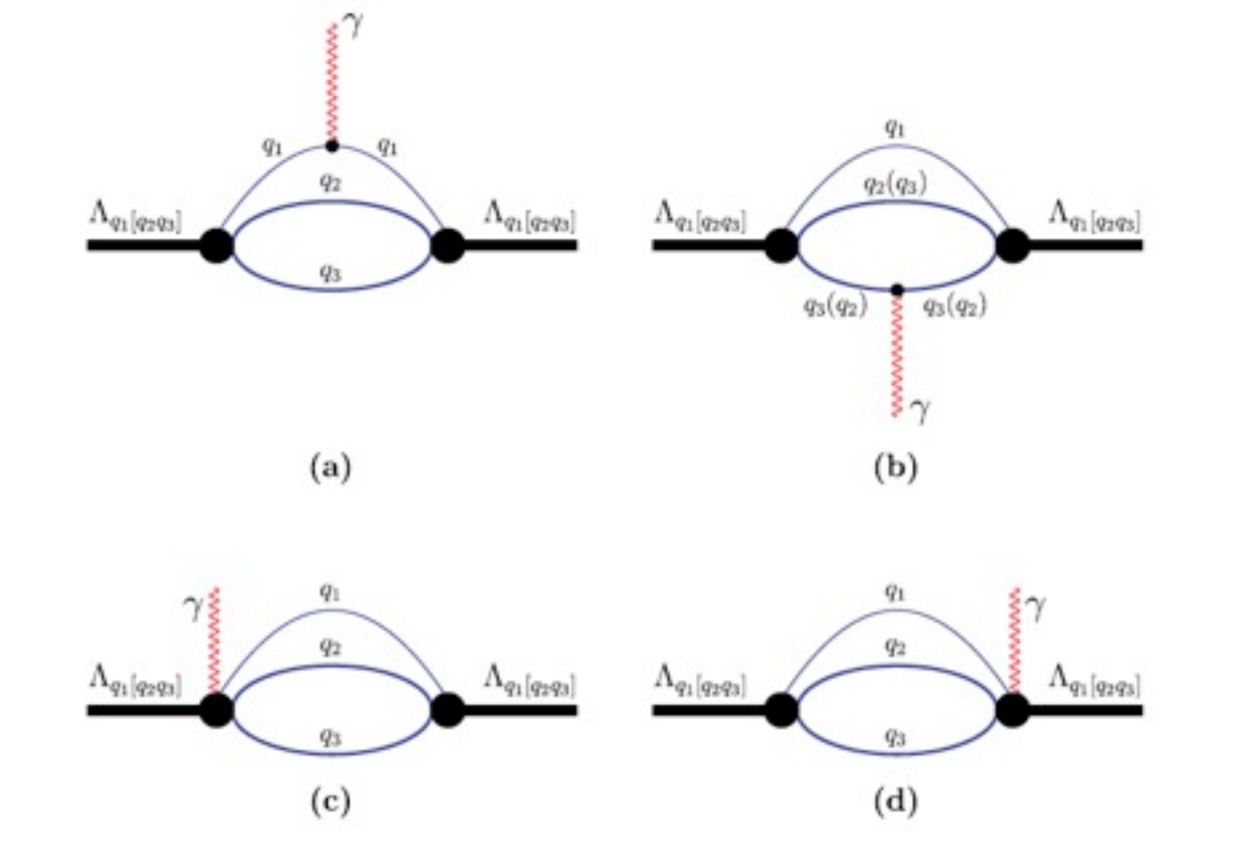
$$\Lambda_{\Lambda_s} = 0.490 \text{ GeV}, \ \Lambda_{\Lambda_c} = 0.864 \text{ GeV and } \Lambda_{\Lambda_b} = 0.569 \text{ GeV}$$

- fit to magnetic moments of Lambda-hyperon:

$$\mu_{\Lambda_s} = -0.73, \quad \mu_{\Lambda_c} = 0.39, \quad \mu_{\Lambda_b} = -0.06,$$

in n.m.

$$\mu_{\Lambda_s}^{\text{expt}} = -0.613 \pm 0.004$$



- and to leading semileptonic decays

TABLE IV. Branching ratios of semileptonic decays of heavy baryons (in %).

Mode	Our results	Data [52]
$\Lambda_c \to \Lambda e^+ \nu_e$	2.0	2.1 ± 0.6
$\Lambda_c \to \Lambda \mu^+ \nu_\mu$	2.0	2.0 ± 0.7
$\Lambda_b \to \Lambda_c e^- \bar{\nu}_e$	6.6	$6.5^{+3.2}_{-2.5}$
$\Lambda_b \to \Lambda_c \mu^- \bar{\nu}_\mu$	6.6	
$\Lambda_b \to \Lambda_c \tau^- \bar{\nu}_\tau$	1.8	

TABLE V. Asymmetry parameter α in the semileptonic decays of heavy baryons.

Mode	Our results	Data [52]
$\Lambda_c \to \Lambda e^+ \nu_e$	0.828	0.86 ± 0.04
$\Lambda_c \to \Lambda \mu^+ \nu_\mu$	0.825	
$\Lambda_b \to \Lambda_c e^- \bar{\nu}_e$	0.831	
$\Lambda_b \to \Lambda_c \mu^- \bar{\nu}_\mu$	0.831	
$\Lambda_b \to \Lambda_c \tau^- \bar{\nu}_\tau$	0.731	

Rare baryon decays: $\Lambda_b \to \Lambda \ell^+ \ell^-$ $(\ell = e, \mu, \tau)$ and $\Lambda_b \to \Lambda\gamma$

our result: $\mathbf{BR(\Lambda_b \to \Lambda\mu^+\mu^-) = 1.0 \cdot 10^{-6}}$

recent LHCb result:

$\Gamma(\Lambda\mu^+\mu^-)/\Gamma_{total}$

VALUE (units 10^{-7})		DOCUMENT ID		TECN	COMMENT
10.8±2.8 OUR AVERAGE					
9.6±1.6±2.5	40	AAIJ	13AJ	LHCB	pp at 7 TeV
17.3±4.2±5.5		AALTONEN	11AI	CDF	$p\bar{p}$ at 1.96 TeV

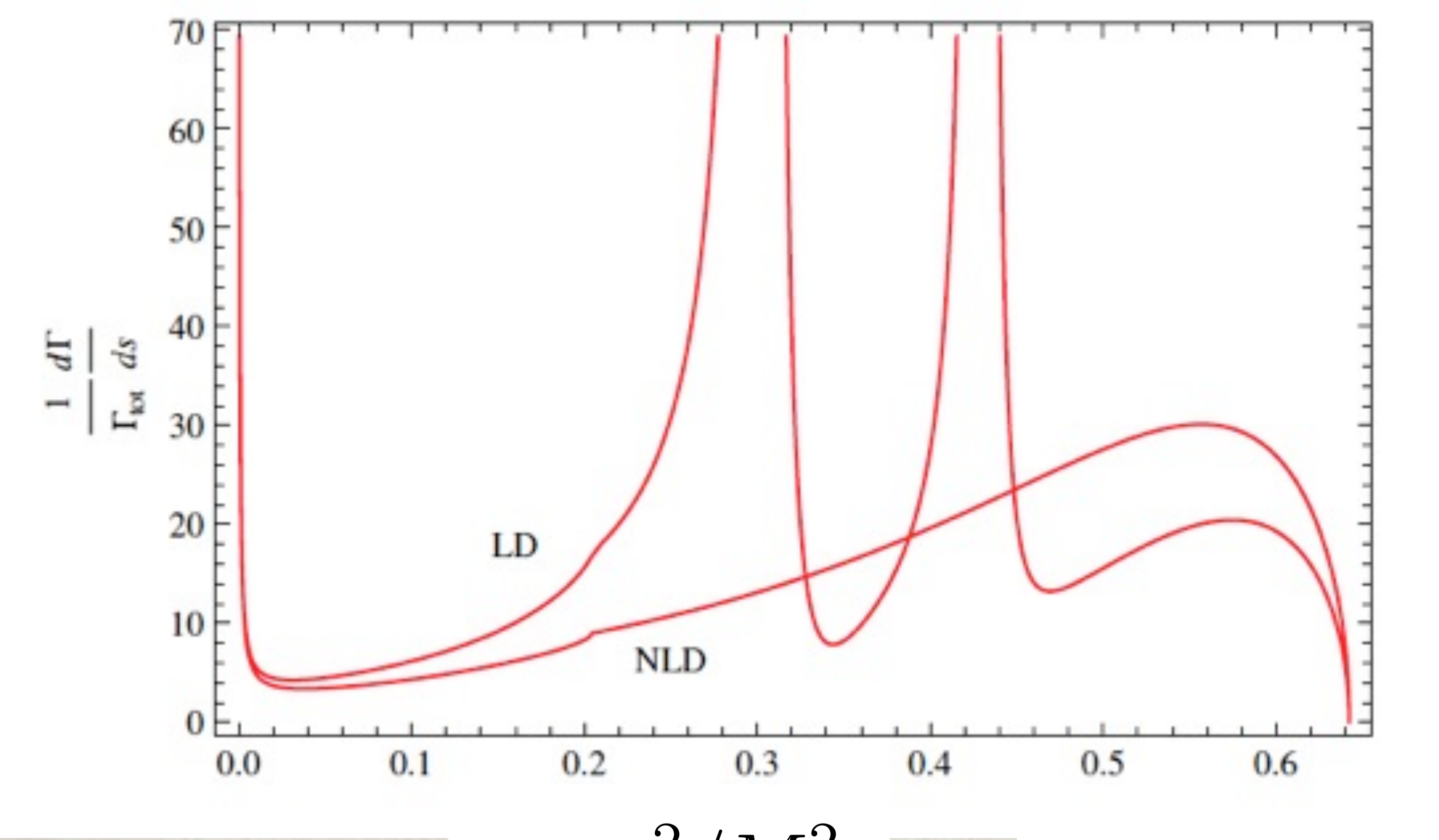
and the prediction: $\mathbf{BR(\Lambda_b \to \Lambda\gamma) = 0.4 \cdot 10^{-5}}$

compared to:

$\Gamma(\Lambda\gamma)/\Gamma_{total}$

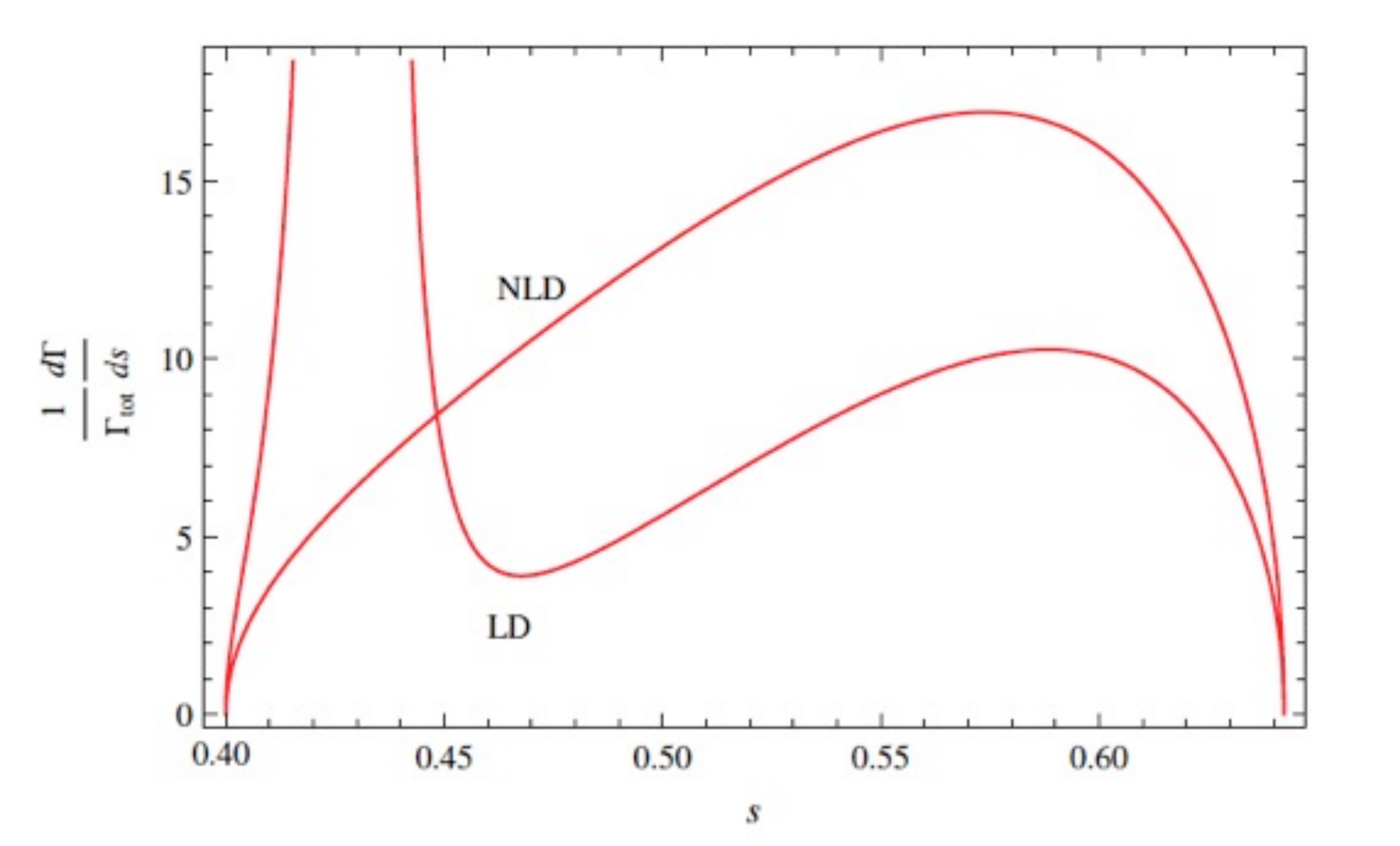
VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.3 \times 10^{-3}$	90	ACOSTA	02G	CDF	$p\bar{p}$ at 1.8 TeV

differential rate $\frac{1}{\Gamma_{Tot}} \frac{d\Gamma(\Lambda_b \to \ell^+ \ell^-)}{ds}$



$s \equiv q^2/M_{\Lambda_b}^2$

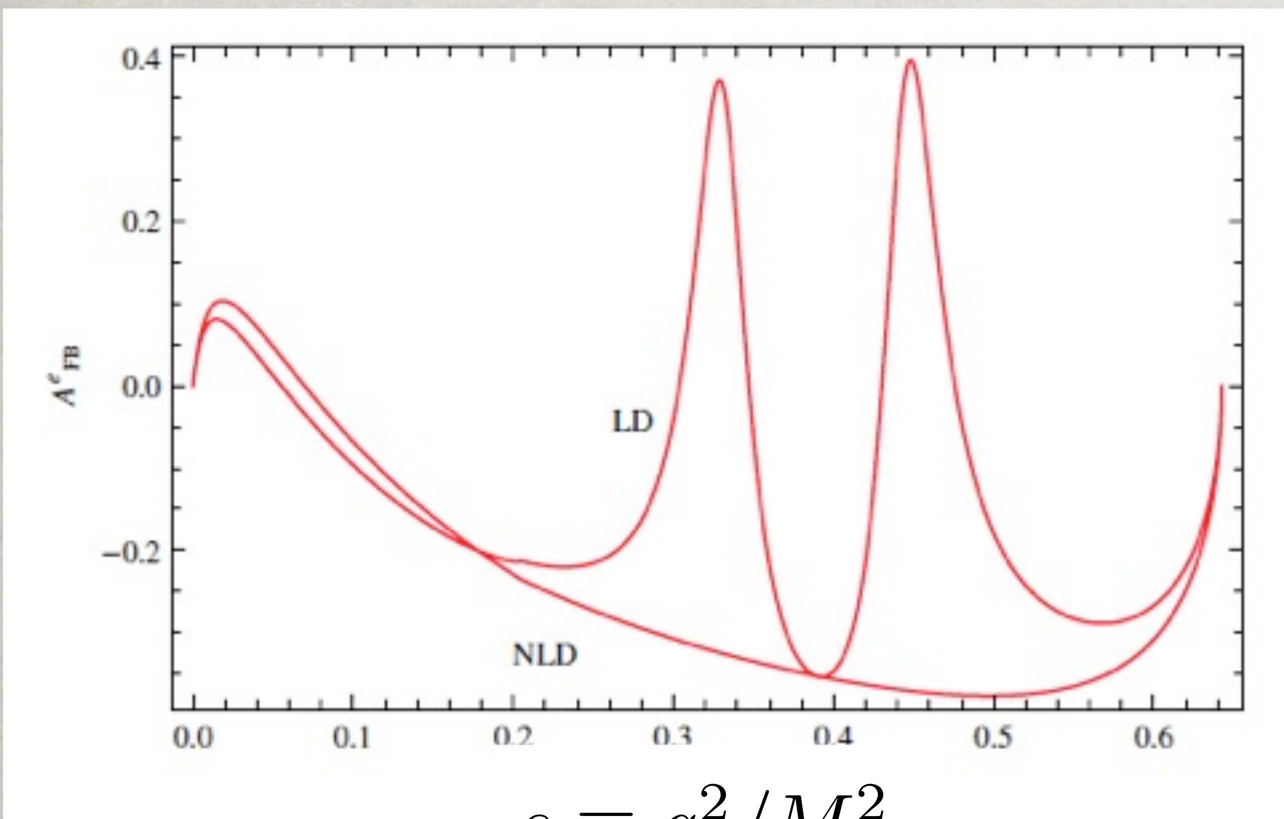
e^+e^-



$\tau^+\tau^-$

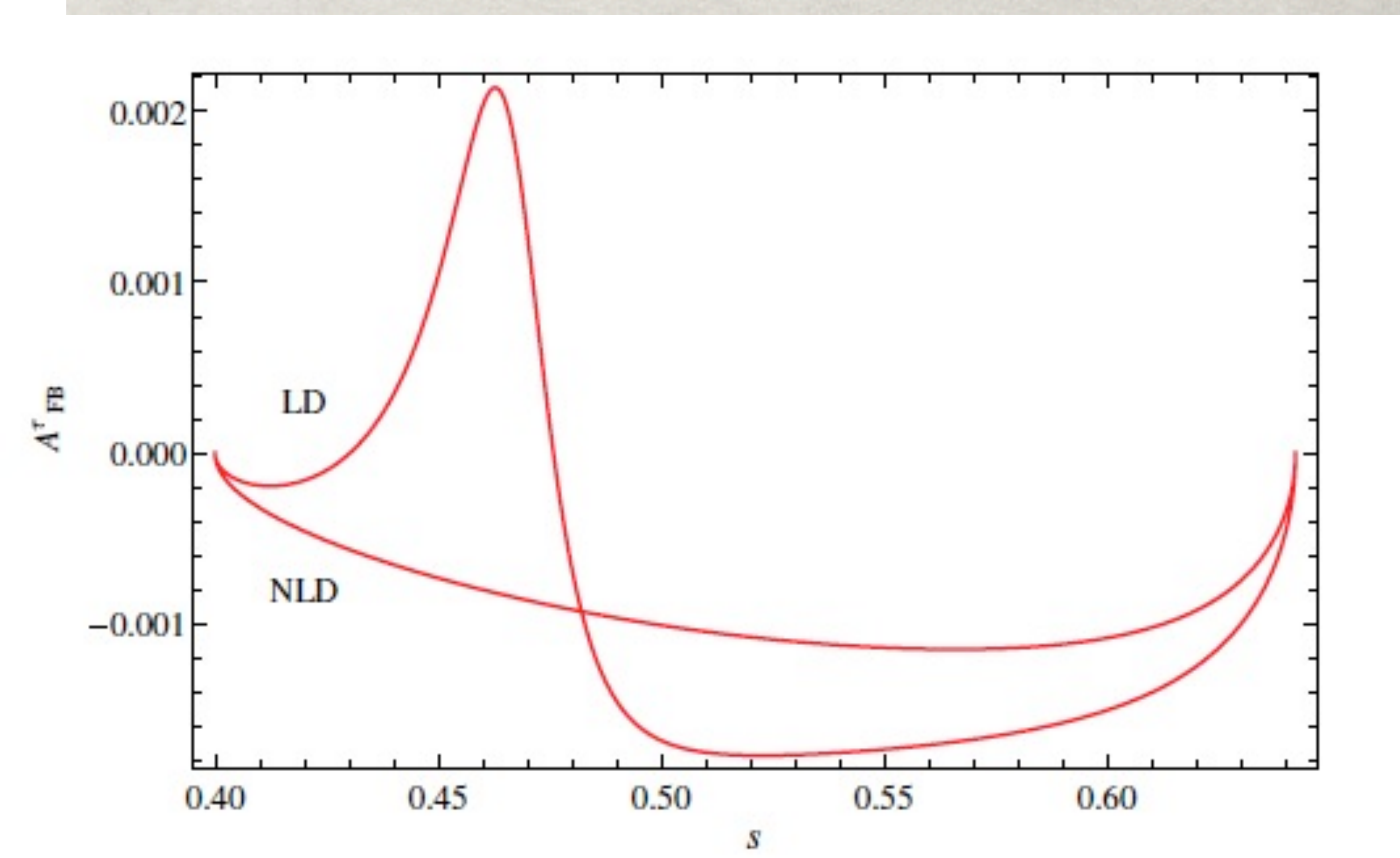
forward-backward asymmetry

$$A_{FB} = \frac{\int_0^1 d(\cos\vartheta) - \int_{-1}^0 d(\cos\vartheta)}{\int_0^1 d(\cos\vartheta) + \int_{-1}^0 d(\cos\vartheta)}$$



$s \equiv q^2/M^2_{\Lambda_b}$

$\mathbf{e^+e^-}$



$\tau^+\tau^-$

Focus on semileptonic decay: $\Lambda_b \to \Lambda_c + \tau^- + \bar{\nu}_\tau$

TG, M. Ivanov, J. Körner, V. Lyubovitskij, P. Santorelli, N. Habyl, PRD 91, 074001 (2015)

- tests of a key property of the SM: lepton flavor universality
- deviations would signal possible NP
- contraints on NP are weaker for the third generation
- discrepancies with SM results in B decays:

$$R(\mathcal{D}) \equiv \frac{\mathrm{Br}(\bar{B} \to \mathcal{D}\tau^-\bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to \mathcal{D}\ell^-\bar{\nu}_\ell)}$$

$(\mathcal{D} = D, D^*; \ell = e, \mu)$

$$R(D) = \begin{cases} 0.305 \pm 0.012 & \mathrm{SM} \\ 0.421 \pm 0.058 & BABAR \text{ \& Belle}, \end{cases}$$

$$R(D^*) = \begin{cases} 0.252 \pm 0.004 & \mathrm{SM} \\ 0.337 \pm 0.025 & BABAR \text{ \& Belle}. \end{cases}$$

$0.336 \pm 0.027 \pm 0.030$ LHCb 2015

Λ_b with spin 1/2 has a complex angular distribution

Mode	Our results	Data
$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	2.72	2.74 ± 0.82
$\Lambda_b^0 \to \Lambda_c^+ e^- \bar{\nu}_e$	6.9	$6.5^{+3.2}_{-2.5}$
$\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$	2.0	

rates in %

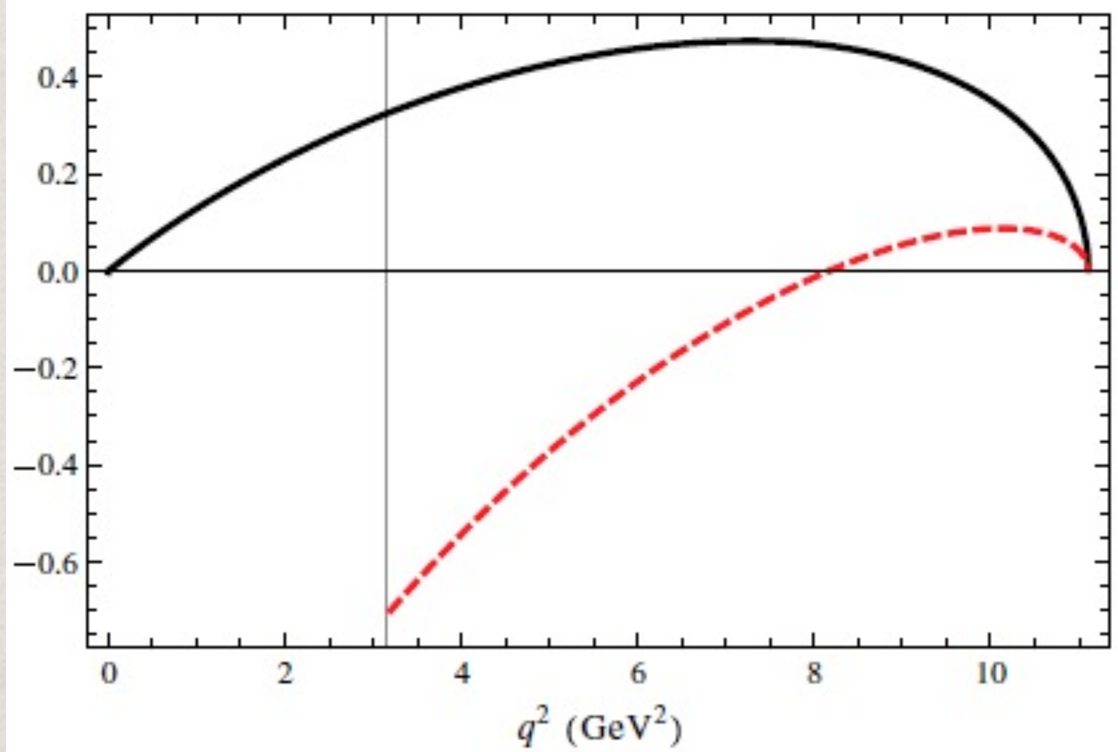


FIG. 5 (color online). The q^2 dependence of the lepton-side forward-backward asymmetry $A^\ell_{FB}(q^2)$ for the e^- (solid) and τ^- (dashed) modes.

forward-backward asymmetries

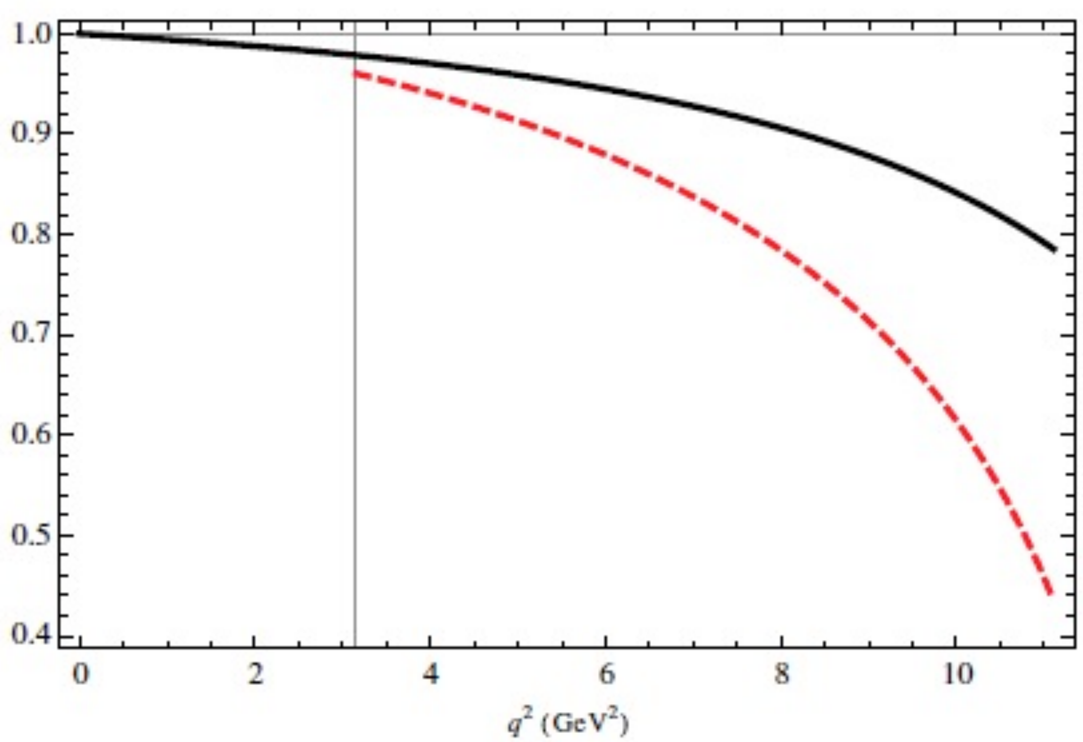


FIG. 9 (color online). The q^2 dependence of the total Λ_c polarization $|\vec{P}^h|(q^2) = \sqrt{(P^h_x)^2 + (P^h_z)^2}$ for the e^- (solid) and τ^- (dashed) modes.

polarization observables

finally

- quark model: „old-fashioned" but reliable tool in describing conventional hadron structure

- here: covariant confined quark model, quantum field theory tool for analyzing hadronic properties

- light hadron sector

- heavy hadrons -- lab to constrain SM and BSM physics

- looking forward to LHCb among others

- extension to multiquark configurations