Hadronic Light-by-Light Scattering in Muon $g-2$: from the INT Seattle HLbL Workshop

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Abstract

A summary of the “INT Workshop on The Hadronic Light-by-Light Contribution to the Muon Anomaly” held at INT Seattle, February 28 - March 4, 2011. Goal of the WS was working out a “White Paper” in support of the new $g-2$ experiment planned (and approved) at Fermilab.

Working groups:

❖Models for HLbL: de Rafael, Bijnens, Nyffeler, Vainshtein, and others

❖HLbL from lattice QCD: Blum, Jansen, Hashimoto, Kronfeld

❖Data for HLbL: J., Denig, Morriciani, Eidelman, Czyż

Original idea for the WS: previous attempts to get funding for an upgraded BNL muon $g-2$ experiment failed also because experts raised doubts whether theory is able to predict HLbL for Muon $g-2$. Lee Roberst spokesperson of E989 Collaboration got upset about HLbL theoreticians. David Herzog proposes INT WS to work out convincing evidence that theory is able to provide reliable estimates of a_μ(HLbL). Decision for the shutdown of TEVATRON, changed situation for particle physics in US: muon $g-2$ at Fermilab now first priority, second is support for super KEK B,...

Topics of Talk:

- ❖The hadronic LbL: setup and problems
- ❖Models and Controversies
- ❖Data constrain Models
- ❖A role for lattice QCD
- ❖Present & Future

The Good News first:

Fermilab E989: Approved January 2011

- Re-locate the $(g - 2)$ storage ring to Fermilab
- Use the many proton storage rings to form the ideal proton beam
- Use one of the antiproton rings as a 900 m decay line to produce a pure muon beam
- Accumulate 21 times the statistics
- Improve the systematic errors
- Final goal: At least a factor of 4 more precise over E821

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The adventure:

Sikorsky S64F 12.5 T hook weight (Outer coil/cryostat 8T)

- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.

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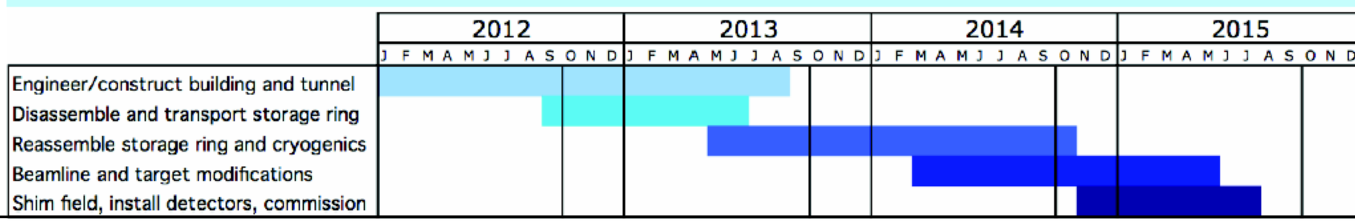
Timeline presented to DOE this week



On this timescale it's essential that the theory improve

- Lowest-order hadronic
  - BaBar and Belled have additional unanalyzed data
    - especially important for multihadron channels
  - VEPP2000 at Novosibirsk
    - CMD3
    - SND
- HLBL
  - Agreement among theorists and additional work
  - KLOE 2 photon physics
  - BES, Mainz

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The new muon $g-2$: Fermilab E989

- $\delta a_\mu = 16 \times 10^{-11}$ by 2015
- Magnetic field: $\frac{\delta \langle B \rangle_\mu}{\langle B \rangle_\mu} \leq 2 \times 10^{-8}$
- Requires 10% error on HLbL
- HLbL white paper in progress

Present:

- $a_\mu^{\rm exp} = 116\,592\,089(63) \times 10^{-11}$; $a_\mu^{\rm SM} = 116\,591\,793 \pm 51 \times 10^{-11}$

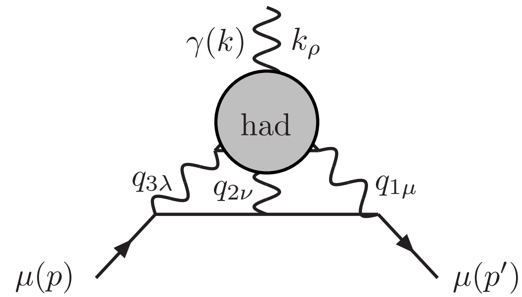
E989: statistics $21\times$; total error factor 4 more precise

$$\left.\begin{array}{l}\sigma_{\rm stat} = 0.1 \text{ ppm} \\ \sigma_{\rm syst} = 0.1 \text{ ppm}\end{array}\right\} \sigma_{\rm tot} = 0.14 \text{ ppm}$$

- $a_\mu^{\rm exp} = 116\,59x\,xxx(16) \times 10^{-11}$

The hadronic LbL: setup and problems

Hadrons in $\langle 0|T\{A^\mu(x_1)A^\nu(x_2)A^\rho(x_3)A^\sigma(x_4)\}|0\rangle$



Key object full rank-four hadronic vacuum polarization tensor

$$\Pi_{\mu\nu\lambda\rho}(q_1,q_2,q_3) = \int d^4x_1\, d^4x_2\, d^4x_3\, e^{i\,(q_1x_1+q_2x_2+q_3x_3)} \times\langle\, 0\,|\,T\{j_\mu(x_1)\,j_\nu(x_2)\,j_\lambda(x_3)\,j_\rho(0)\}\,|\,0\,\rangle\ .$$

- non-perturbative physics
- general covariant decomposition involves 138 Lorentz structures of which
- 32 can contribute to $g-2$

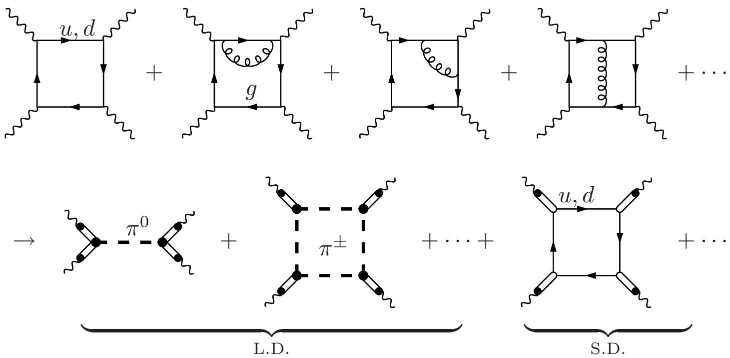
- fortunately, dominated by the pseudoscalar exchanges $\pi^0, \eta, \eta', ...$ described by the effective Wess-Zumino Lagrangian

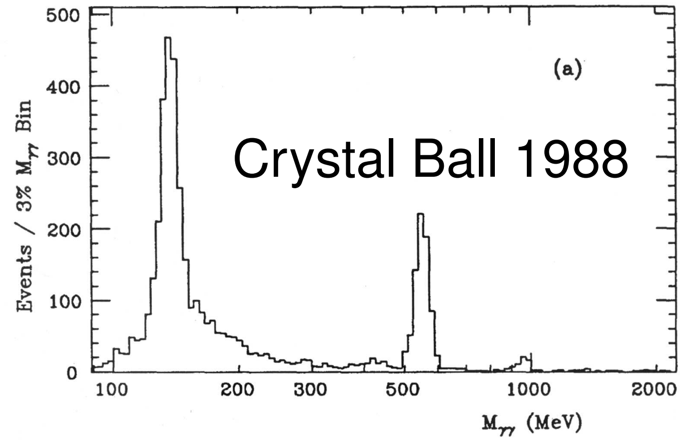
- generally, pQCD useful to evaluate the short distance (S.D.) tail

- off-shell form factors needed not directly accessible to experiment!

- the dominant long distance (L.D.) part must be evaluated using some low energy effective model which includes the pseudoscalar Goldstone bosons as well as the vector mesons which play a dominant role (vector meson dominance mechanism); HLS, ENJL, general RLA, large N_c inspired ansätze, and others

Need appropriate low energy effective theory ⇒amount to calculate the following type diagrams

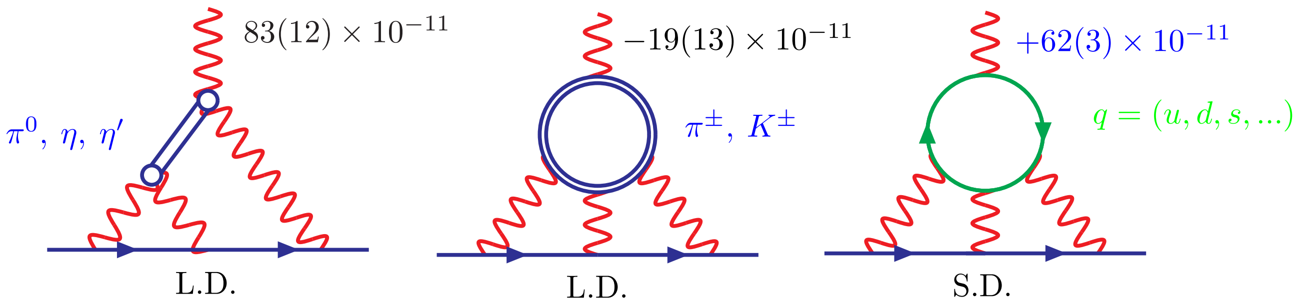




Data show almost background free spikes of the PS mesons! Substantial background form quark loop is absent (seems to contradict large quark-loop contribution as obtained in SDA). Clear message from data: fully non-perturbative, evidence for PS dominance. However, no information about axial mesons (Landau-Yang theorem). Illustrates how data can tell us where we are.

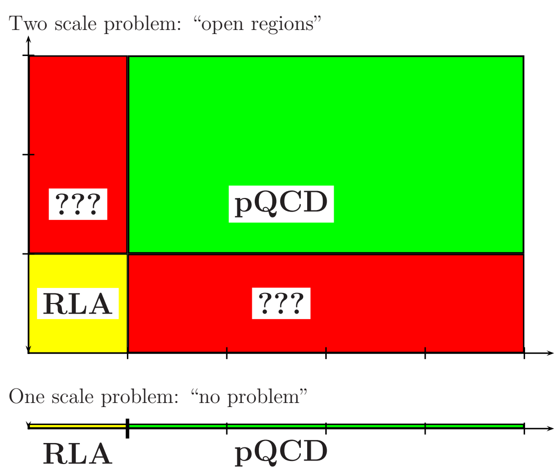
Low energy expansion in terms of hadronic components: theoretical models vs experimental data

➠ KLOE, KEDR, BES, BaBar, Belle, ?



LD requires low energy effective hadronic models: simplest case $\pi^0\gamma\gamma$ vertex

Basic problem: (s, s_1, s_2)–domain of $\mathcal{F}_{\pi^{0*}\gamma^*\gamma^*}(s, s_1, s_2)$; here $(0, s_1, s_2)$–plane



??? – Data, effective Lagrangians, OPE,
– QCD factorization,
– Brodsky-Lepage approach

Models and Controversies

❒ Low energy effective field theory

Traditional approach: low energy effective Lagrangians: HLS, ENJL (resonance chiral theory) Kinoshita et al., Bijnens et al, ➠matching and double counting problems

❒ Large N_c QCD inspired approach

Novel approach: refer to quark–hadron duality of large-N_c QCD, hadron spectrum known, infinite series of narrow spin 1 resonances 't Hooft 79 ⇒no matching problem (resonance representation has to match quark level representation) De Rafael 94, Knecht, Nyffeler 02

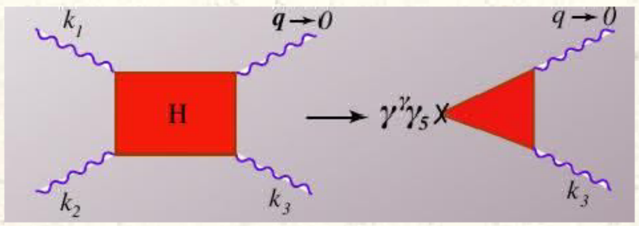
❒ other new approaches:

- HLbL from string theory
  Cappiello, Catá, D' Ambrosio
- QCD based numeric Schwinger-Dyson/Bethe-Salpeter equations approach
  Goecke, Fischer, Williams

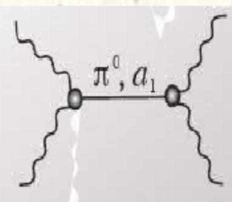
The Melnikov-Vainshtein constraint and model

The model that fits the box

- We simplify the problem by picking up a particular part in the phase-space $q_1^2 \gg q_2^2 \gg q_3^2 \gg \Lambda^2_{\mathrm{QCD}}$ However, we require that in that part of the phase-space the amplitude is reproduced ``exactly"



$$\mathcal{M} = \alpha^2 N_c \,\mathrm{Tr}\,[\hat{Q}^4]\,\mathcal{A}$$



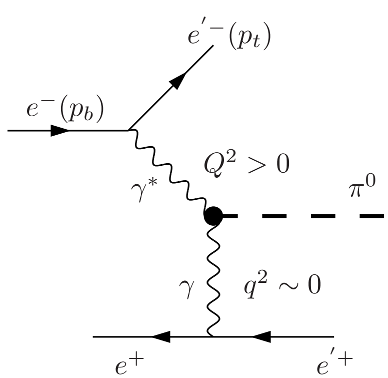
$$\mathcal{A}_{\pi^0} = -\frac{N_c W^{(3)}}{2\pi^2 F_\pi^2}\,\frac{F_{\pi\gamma^*\gamma^*}(q_1^2,q_2^2)}{q_3^2+m_\pi^2}\{f_2\tilde{f}_1\}\{\tilde{f}f_3\}$$

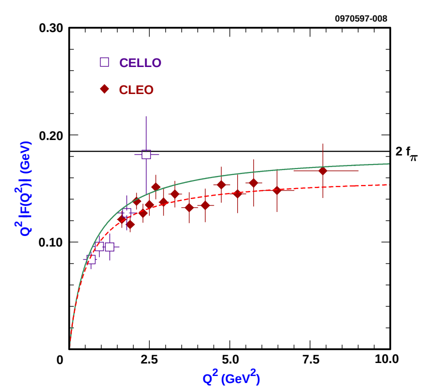
$$\mathcal{A} = \frac{4}{q_3^2\,\hat{q}^2}\{f_2\tilde{f}_1\}\{\tilde{f}f_3\} - \frac{4}{q_3^2\,\hat{q}^4}\Big(\{q_2 f_2\tilde{f}_1\tilde{f}f_3 q_3\} + \{q_1 f_1\tilde{f}_2\tilde{f}f_3 q_3\} + \frac{q_1^2+q_2^2}{4}\{f_2\tilde{f}_1\}\{\tilde{f}f_3\}\Big) + \cdots$$

Constraints for on-shell pions (pion pole approximation)

- The constant $e^2 \mathcal{F}_{\pi^0\gamma\gamma}(m_\pi^2, 0, 0) = \frac{e^2 N_c}{12\pi^2 f_\pi} = \frac{\alpha}{\pi f_\pi} \approx 0.025$ GeV^{-1} well determined by $\pi^0 \to \gamma\gamma$ decay rate (from Wess-Zumino Lagrangian); experimental improvement needed!

- Information on $\mathcal{F}_{\pi^0\gamma^*\gamma}(m_\pi^2, -Q^2, 0)$ from $e^+e^- \to e^+e^-\pi^0$ experiments





CELLO and CLEO measurement of the π^0 form factor $\mathcal{F}_{\pi^0\gamma^*\gamma}(m_\pi^2, -Q^2, 0)$ at high space–like Q^2. outdated now by BaBar?

Brodsky–Lepage interpolating formula gives an acceptable fit.

$$\mathcal{F}_{\pi^0\gamma^*\gamma}(m_\pi^2, -Q^2, 0) \simeq \frac{1}{4\pi^2 f_\pi} \frac{1}{1 + (Q^2/8\pi^2 f_\pi^2)} \sim \frac{2 f_\pi}{Q^2}$$

Inspired by pion pole dominance idea this FF has been used mostly (HKS,BPP,KN) in the past, but has been criticized recently (MV and FJ07).

❒ Melnikov, Vainshtein: in chiral limit vertex with external photon must be non-dressed! i.e. use $\mathcal{F}_{\pi^0\gamma^*\gamma}(0,0,0)$, which avoids eventual kinematic inconsistency, thus no VMD damping ⇒result increases by 30% !

❒ In $g-2$ external photon at zero momentum ⇒ only $\mathcal{F}_{\pi^{0*}\gamma^*\gamma}(-Q^2, -Q^2, 0)$ not $\mathcal{F}_{\pi^0\gamma^*\gamma}(m_\pi^2, -Q^2, 0)$ is consistent with kinematics. Unfortunately, this off–shell form factor is not known and in fact not measurable and CELLO/CLEO constraint does not apply!. Obsolete far off-shell pion (in space-like region).

Can we check such questions experimentally or in lattice QCD?

Present status:

Pseudoscalar exchanges

Model for $\mathcal{F}_{P^{(*)}\gamma^*\gamma^*}$	$a_\mu(\pi^0) \times 10^{11}$	$a_\mu(\pi^0, \eta, \eta') \times 10^{11}$
modified ENJL (off-shell) [BPP]	59(9)	85(13)
VMD / HLS (off-shell) [HKS,HK]	57(4)	83(6)
LMD+V (on-shell, $h_2 = 0$) [KN]	58(10)	83(12)
LMD+V (on-shell, $h_2 = -10$ GeV^2) [KN]	63(10)	88(12)
LMD+V (on-shell, constant FF at ext. vertex) [MV]	77(7)	114(10)
nonlocal χQM (off-shell) [DB]	65(2)	—
LMD+V (off-shell) [N]	72(12)	99(16)
AdS/QCD (off-shell ?) [HoK]	69	107
AdS/QCD/DIP (off-shell) [CCD]	65.4(2.5)	—
DSE (off-shell) [FGW]	58(7)	84(13)
[PdRV]	—	114(13)
[JN]	72(12)	99(16)

BPP = Bijnens, Pallante, Prades '95, '96, '02 (ENJL = Extended Nambu-Jona-Lasinio model); HK(S) = Hayakawa, Kinoshita, Sanda '95, '96; Hayakawa, Kinoshita '98, '02 (HLS = Hidden Local Symmetry model); KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; DB = Dorokhov, Broniowski '08 (χQM = Chiral Quark Model); N = Nyffeler '09; HoK = Hong, Kim '09; CCD = Cappiello, Catà, D'Ambrosio '10 (used AdS/QCD to fix parameters in DIP (D'Ambrosio, Isidori, Portolés) ansatz); FGW = Fischer, Goecke, Williams '10, '11 (Dyson-Schwinger equation)

Reviews on LbyL: PdRV = Prades, de Rafael, Vainshtein '09; JN = Jegerlehner, Nyffeler '09

A. Nyffeler, Seattle

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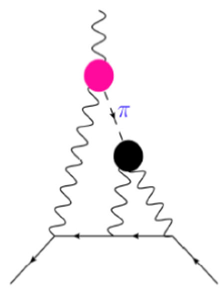
Data constrain Models

Details in Seattle talks:

Dario Morriciani	KLOE small angle tagger (low energy $\pi^0\gamma\gamma$)
Achim Denig	BaBar and BES results and plans
Simon Eidelman	Belle and KEDR results and plans [work in progress]
Henryk Czyż	EKHARA a Monte Carlo for $\gamma^*\gamma^*$ physics

Pion exchange in hadronic LbL



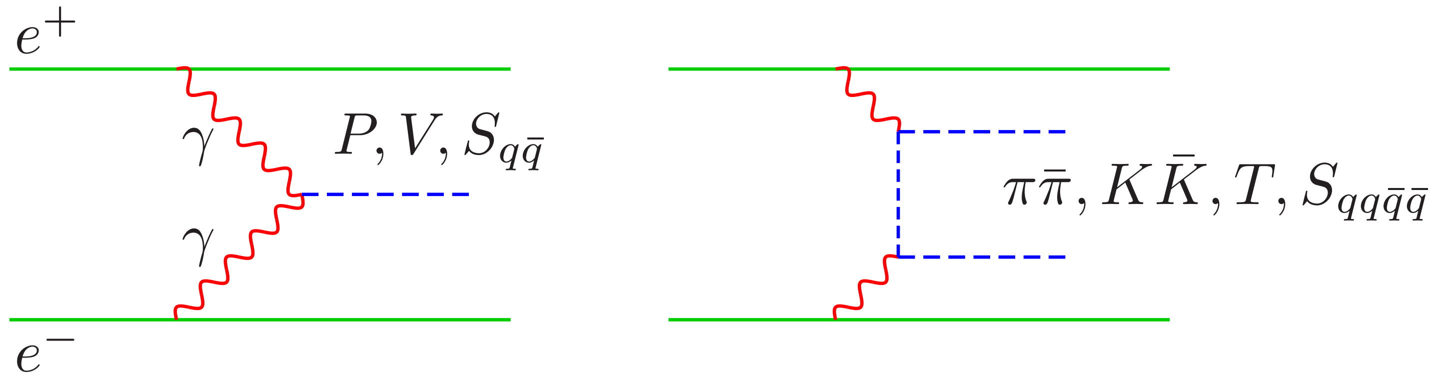
$F_{\pi^*\gamma^*\gamma^*}$ form factors are key objects

- external vertex : $F_{\pi\gamma\gamma}(t_\pi, t_\pi, 0^2)$
  - ¿ ✓ far off-shell pion ¿
  - ✓ zero-energy photon
- internal vertex : $F_{\pi\gamma\gamma}(t_\pi, t_1, t_2)$
  - ✓ totally off-shell object

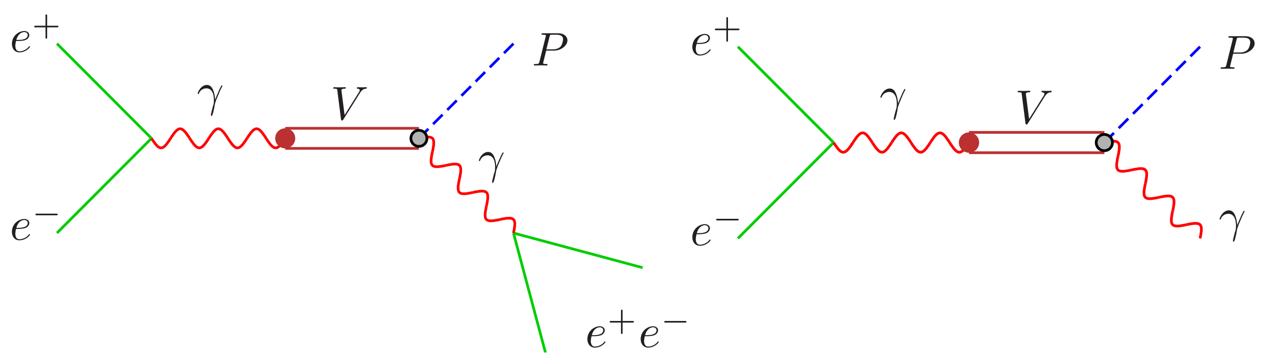
These form factors were never measured

H. Czyż, IF, UŚ, Katowice, EKHARA 2.0+ ... 3

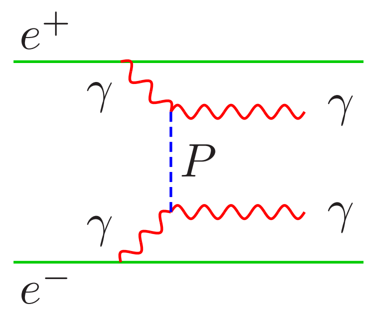
Overview (Eidelman incl progress report for Belle,KEDR):



mostly single-tag events: KLOE, KEDR (taggers), BaBar, Belle, BES III (high luminosity)



Dalitz-decays: $\rho, \omega, \phi \to \pi^0(\eta)e^+e^-$ Novosibirsk, NA60,JLab, Mainz, Bonn, Jülich, BES

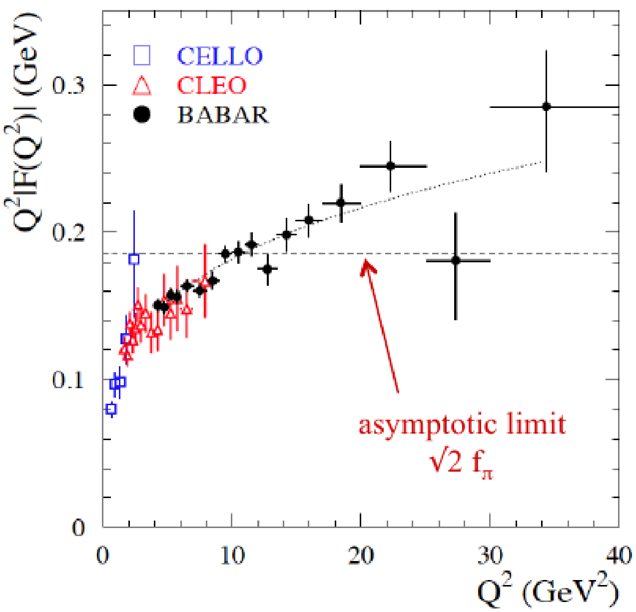


would be interesting, but is buried in the background

BaBar

The π^0 Transition Form Factor

Comparison with world data set and QCD



- In Q^2 range 4-9 GeV^2 BaBar results are in a reasonable agreement with CLEO and CELLO
- Expectation: >10 GeV^2 reach asymptotic limit for $Q^2 F(Q^2) = \sqrt{2} f_\pi = 0.185$ GeV predicted by Brodsky-Lepage in 1979

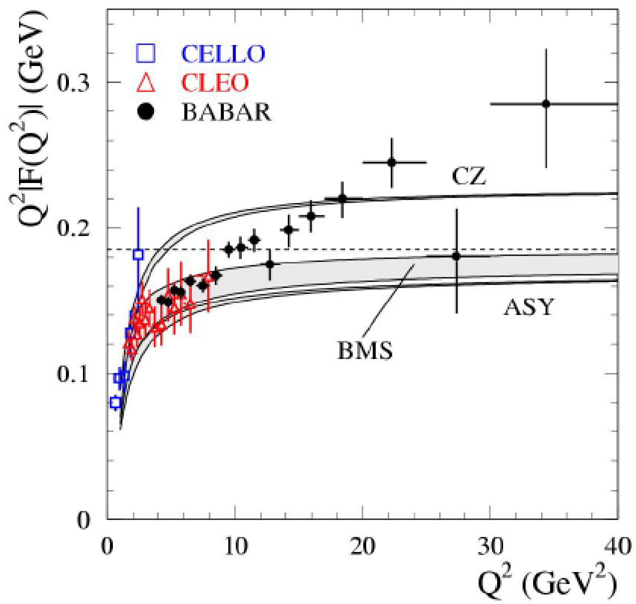
PRD22,2157

Data exceed asymptotic limit $Q^2 > 10$ GeV^2

Achim Denig *Meson Transition FFs at BaBar*

The π^0 Transition Form Factor

Comparison with world data set and QCD



- Several DAs to confront theory vs. experiment:

  CZ: Chernyak-Zhitnitsky DA

  ASY: Asymptotic DA

  BMS: Bakulev-Mikhailov-Stefanis

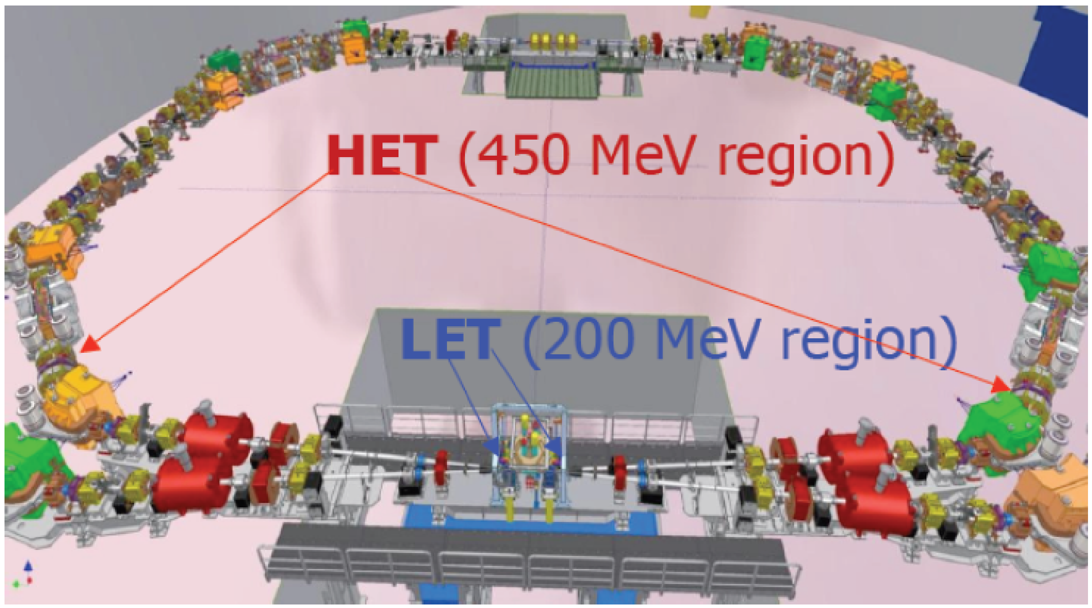
Models for DA do not describe data
→ Is the DA for pions not known ?

- Use Bakulev-Mikhailov-Stefanis light-cone sum rule theory at NLO pQCD + twist-4 power corrections PRD 67, 074012

Need for higher order pQCD corrections ?!

Start of new KLOE-2 experiment under way:

KLOE-2 experiment $\gamma\gamma \to \pi^0, \eta, \cdots$



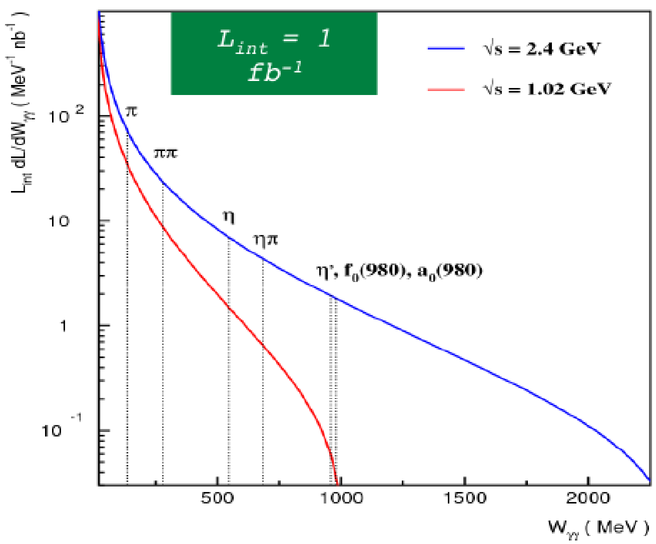
The $\phi(1020)$ meson factory DAΦNE (Frascati)
+ KLOE detector + small angle taggers

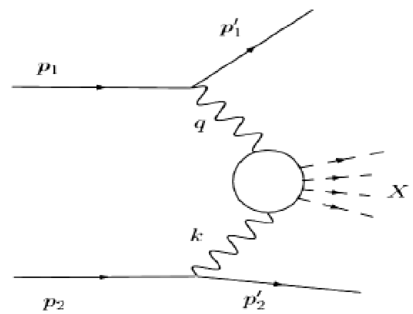
Sergiy IVASHYN (Katowice, Kharkov) $\pi^0\gamma\gamma$ 21 / VI / 2010 @ Mainz 28 / 66

$\gamma\gamma$ - physics

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

$$\frac{dN_X}{dW_{\gamma\gamma}} = L_{int} \frac{dL}{dW_{\gamma\gamma}} \; \sigma \; (\gamma\gamma \to X)$$





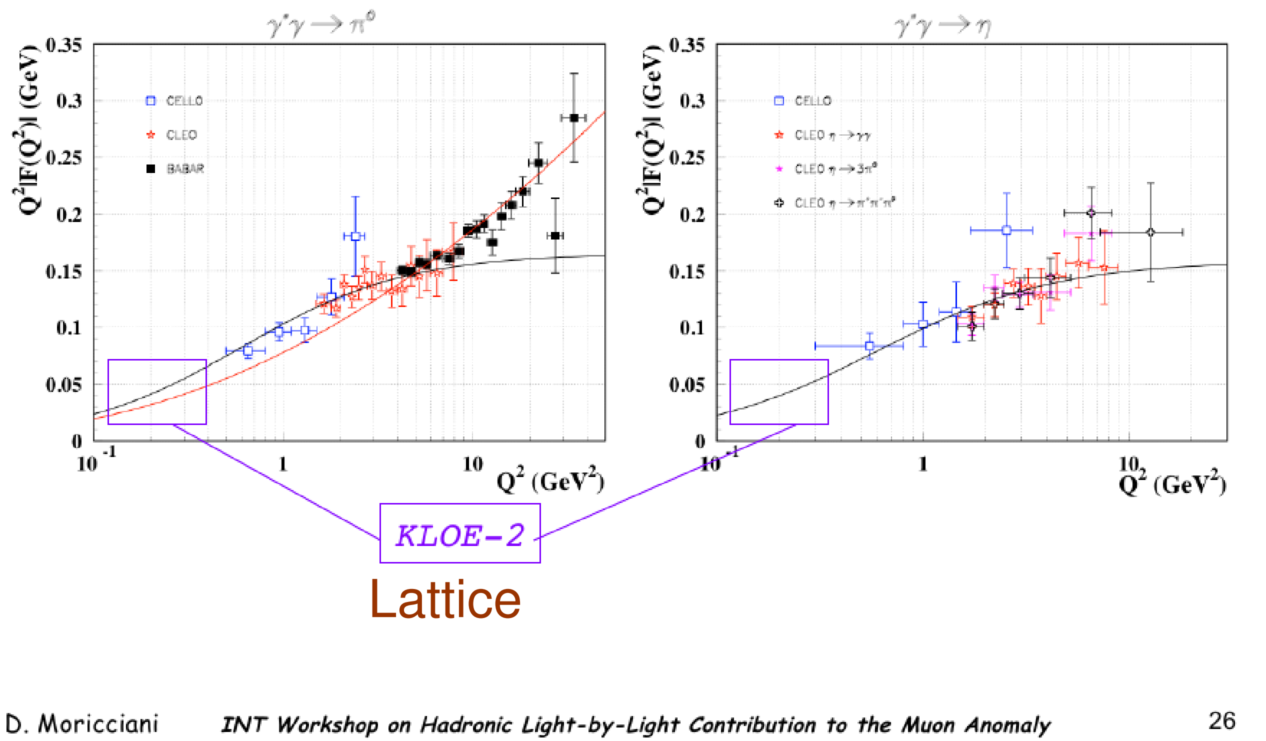
$X \equiv \pi\pi$ → σ meson, ChPT tests

$X \equiv \pi^0, \eta$ → 2-photon widths, transition FFs @ low q^2

$(W_{\gamma\gamma} = M_X)$

D. Moricciani *INT Workshop on Hadronic Light-by-Light Contribution to the Muon Anomaly* 19

KLOE-2 contribution ??



Lattice (Shoij Hashimoto)

MC Simulation with EKHARA Generator

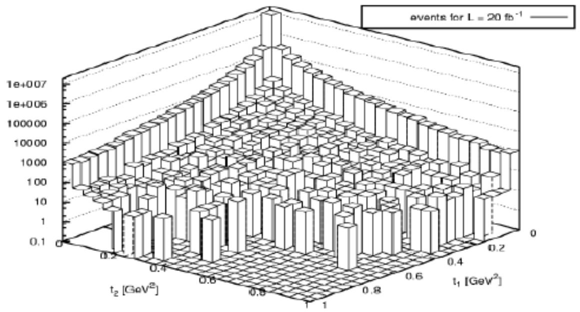
H. Czyż, S. Ivashyn et al. [http://prac.us.edu.pl/˜ekhara]

Tagging:

- single tagging LET: tagged invariant t_1 close to zero, promising range 0.05 GeV$^2 < t_2 < 0.4$ GeV^2
- LET-LET and LET-HET double tagging is not possible
- LET + central: promising range 0.18 GeV$^2 < t_2 < 0.4$ GeV^2
- single tagging HET: tagged invariant t_1 close to zero $\Rightarrow$ t_2 also close to zero
- HET-HET double tagging is possible but both photons quasi-real $\Rightarrow$ good for measurement of $\pi^0 \to \gamma\gamma$ width, pion practically at rest

BES-III at small Q^2

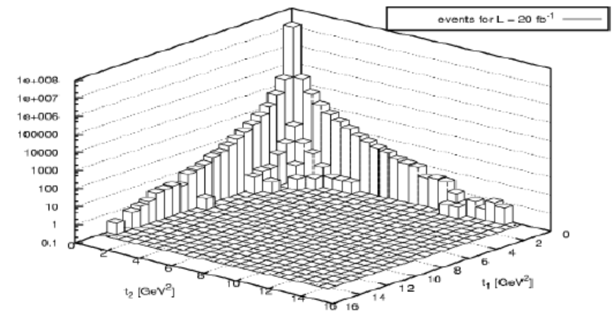
example: no cuts



- $\sqrt{s} = 3$ GeV, $\int \mathscr{L} dt = 20$ fb^{-1} (~ 9 months at $\mathscr{L} = 10^{33}$ cm^{-2} s^{-1})

BES-III at high Q^2

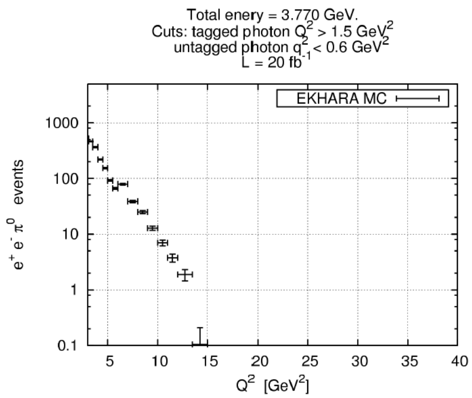
example: no cuts



- $\sqrt{s} = 3.770$ GeV, $\int \mathscr{L} dt = 20$ fb$^{-|1}$ (~ 9 months at $\mathscr{L} = 10^{33}$ cm^{-2} s^{-1})

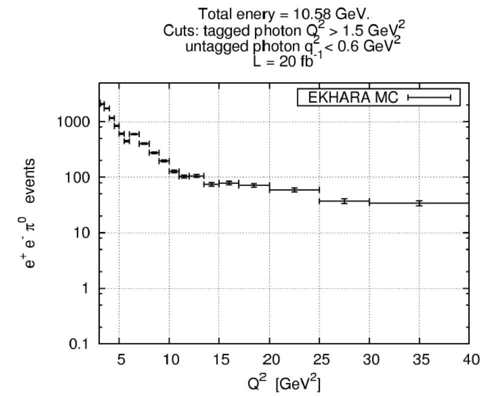
Single-tag measurement at BES-III

e.g. for extraction of the form-factor $F(m_\pi^2, Q^2, 0)$



cf. Single-tagging at BaBar energy

for illustration: the same integrated luminosity



Cross check of BABAR only possible by *Belle* [work in progress]!

Sergiy IVASHYN (Katowice, Kharkov) $\pi^0\gamma\gamma$ 21 / VI / 2010 @ Mainz 52 / 66

Sergiy IVASHYN (Katowice, Kharkov) $\pi^0\gamma\gamma$ 21 / VI / 2010 @ Mainz 53 / 66

Axial exchanges: a_1, f_1', f_1

Axial exchanges

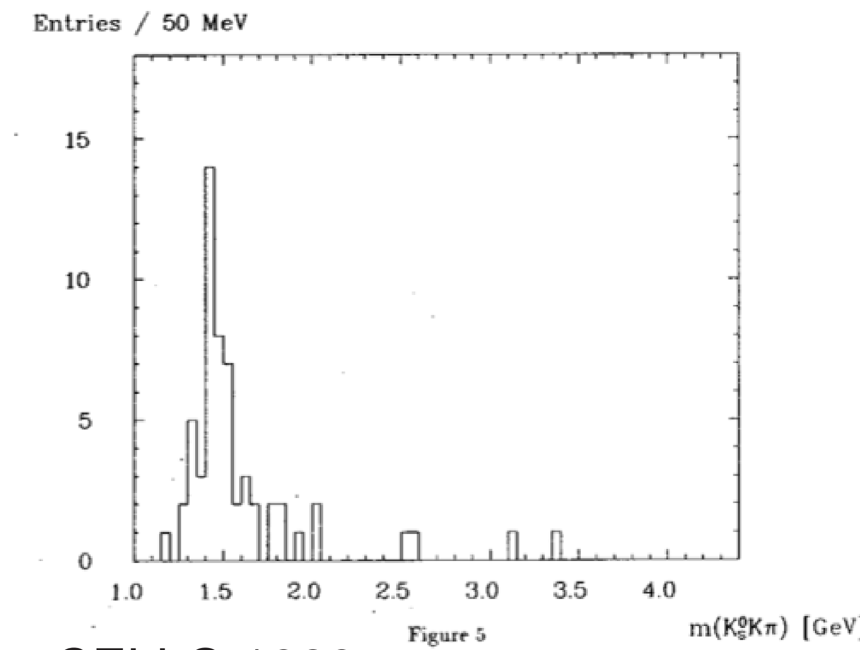
Landau-Yang Theorem: $\mathcal{A}$ (axial meson $\to \gamma\gamma$)=0

e.g. $Z^0 \not\to \gamma\gamma$, while $Z^0 \to \gamma e^+ e^-$ ✓

Why $a_\mu[a_1, f_1', f_1] \sim 25 \times 10^{-11}$ so large?

- ❒ untagged $\gamma\gamma \to A$ no signal!
- ❒ single-tag $\gamma^*\gamma \to A$ strong peak is $Q^2 \gg m_f^2$

$$\sigma(\gamma^*\gamma \to f_1 \to K_s^0 K\pi)$$



CELLO 1989

Sparse data so far, new measurements important; in particular momentum dependent $\Gamma(a_1 \to \gamma\gamma^*)$, $\Gamma(f_1(1285) \to \gamma\rho)$ (factor 5 too large) etc.
Expected contribution from axial mesons:

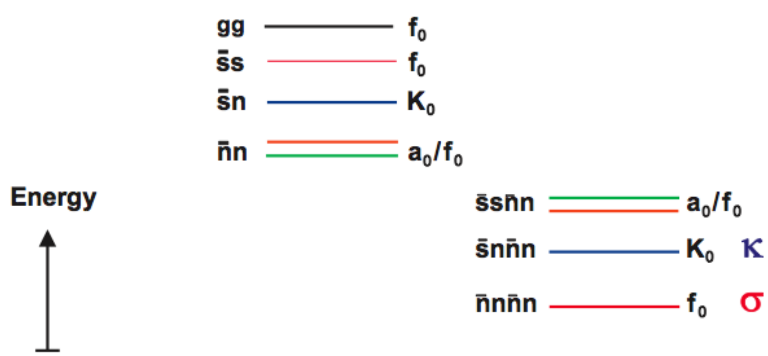
$$a_\mu[a_1, f_1', f_1] \sim (28.13 \pm 5.63) \times 10^{-11}$$

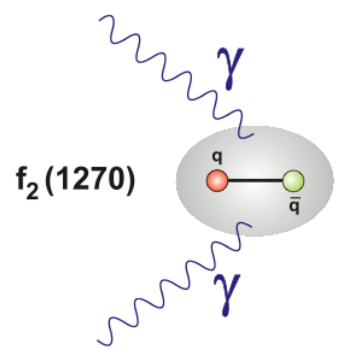
Scalar exchanges: $a_0, f_0', f_0, \cdots$

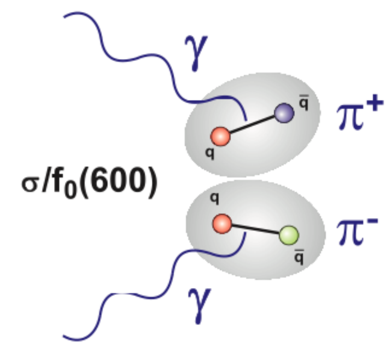
Mesons: $M(q\bar{q})$, $M(qq\bar{q}\bar{q})$, glueballs mixing

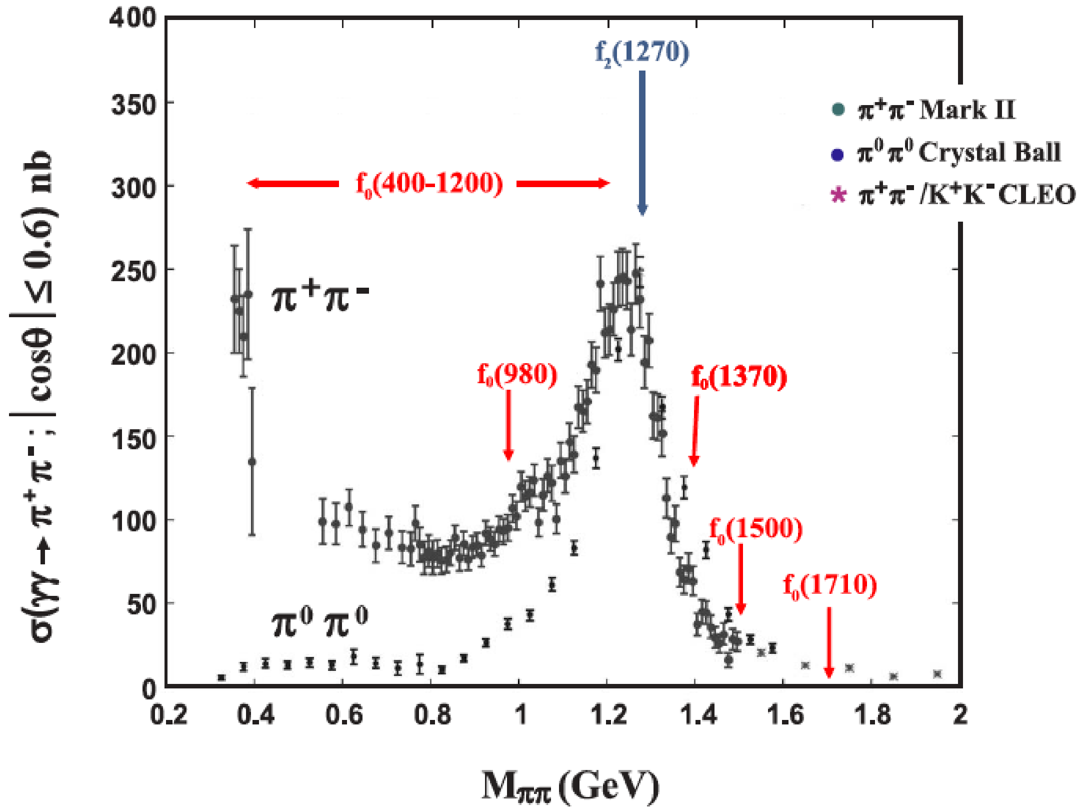
Experimental: Crystal Ball, Mark II, Belle!

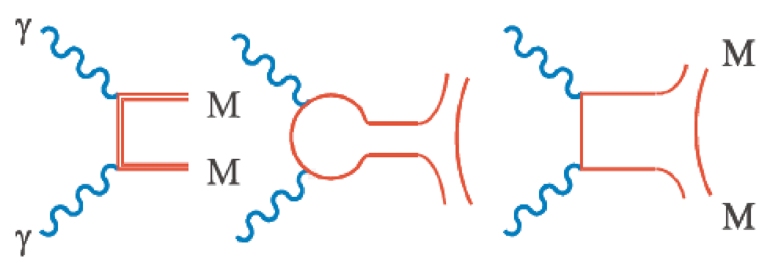
Theory: Mennessier, Pennington et al., Mousallam et al., Achasov et al., ...








400
350
300
250
200
150
100
50
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
σ(γγ → π⁺π⁻; |cosθ| ≤ 0.6) nb
M_ππ (GeV)
f₂(1270)
f₀(400-1200)
f₀(980)
f₀(1370)
f₀(1500)
f₀(1710)
π⁺π⁻
π⁰ π⁰
π⁺π⁻ Mark II
π⁰π⁰ Crystal Ball
π⁺π⁻/K⁺K⁻CLEO


γ
γ
M
M
M
M

Strong tensor meson resonance in $\pi\pi$ channel $f_2(1270)$

So: expect usual pion-loop in HLbL plays role like pion-loop in VP. i.e. like missing the ρ.
➠ Need to explicitly include tensor mesons

Scalars everywhere. Many scalars many small contributions may sum up to substantial effect!

Expected contribution from $q\bar{q}$ scalars:

$$a_\mu[a_0, f_0', f_0] \sim (-5.98 \pm 1.20) \times 10^{-11}$$

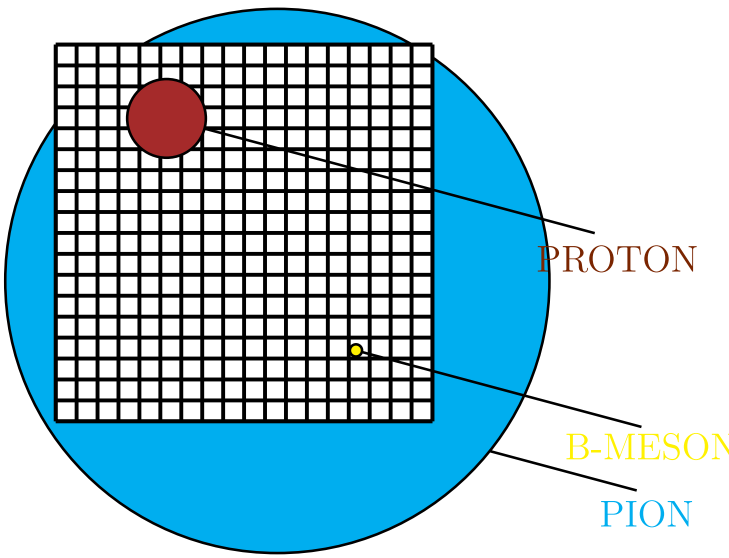
So far nobody has evaluated $qq\bar{q}\bar{q}$ in $SU(3)$ sector $[u, d, s\ ]$ many possible states, which individually are expected rather small

A role for lattice QCD

- Hadronic contributions to $g-2$ = integrals over physical cross sections or hadronic amplitudes

- in fact all can be represented as integrals over space-like "form-factors"

➠directly accessible to lattice QCD : $\langle j^{\mu}_{\rm em}(x_1)\; j^{\nu}_{\rm em}(x_2)\; j^{\rho}_{\rm em}(x_3)\; j^{\sigma}_{\rm em}(x_4)\rangle$ or integral of it.



$a \ll 1/m \ll L$ ➠ HLbL multiscale problem: VP+3

Hadronic LbL difficult, challenging long term project:

HLbL Blum et al.

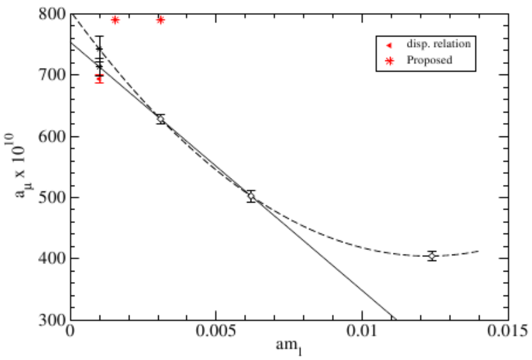
Summary/Outlook: light-by-light contributions ($O(\alpha^3)$)

- Pure QED calculation on the lattice roughly reproduces the perturbative result. Encouraging.
- Full hadronic contribution is $O(10^2)$ times smaller, still swamped by the statistical noise
- Small volumes, poor statistics. Try
  - Volume (low-mode) averaging for the loop
  - Larger volumes
  - More statistics, i.e. more QED configurations per QCD configuration
  - conventional calculation using "all-to-all" propagator
- multi-quark loops not yet attempted

The test case hadronic VP:

VP – Aubin & Blum:

The order α^2 hadronic contribution to g-2



Extrapolate $m_l \to m_{u,d}$

Simple linear and quadratic chiral extrapolations consistent with $e^+e^- \to$ hadrons result

$a_\mu^{HLO} = (713 \pm 15) \times 10^{-10}$ (linear)
$a_\mu^{HLO} = (742 \pm 21) \times 10^{-10}$ (quad)
(statistical errors only).

[Aubin, Blum, Phys. Rev. D, 2006]

Fit	quenched	$am_l = 0.0124$	$am_l = 0.0062$	$am_l = 0.0031$
Poly 3	381 (63)	370(49)	445(43)	542(24)
Poly 4	588 (142)	410(91)	639(123)	729(59)
A	366.6 (7.0)	412.3 (7.8)	516.0 (9.5)	646.9 (8.1)
B		403.9 (7.8)	502.1 (9.5)	628.0 (8.1)
C		403.9 (7.8)	502.1 (9.5)	628.0 (8.1)

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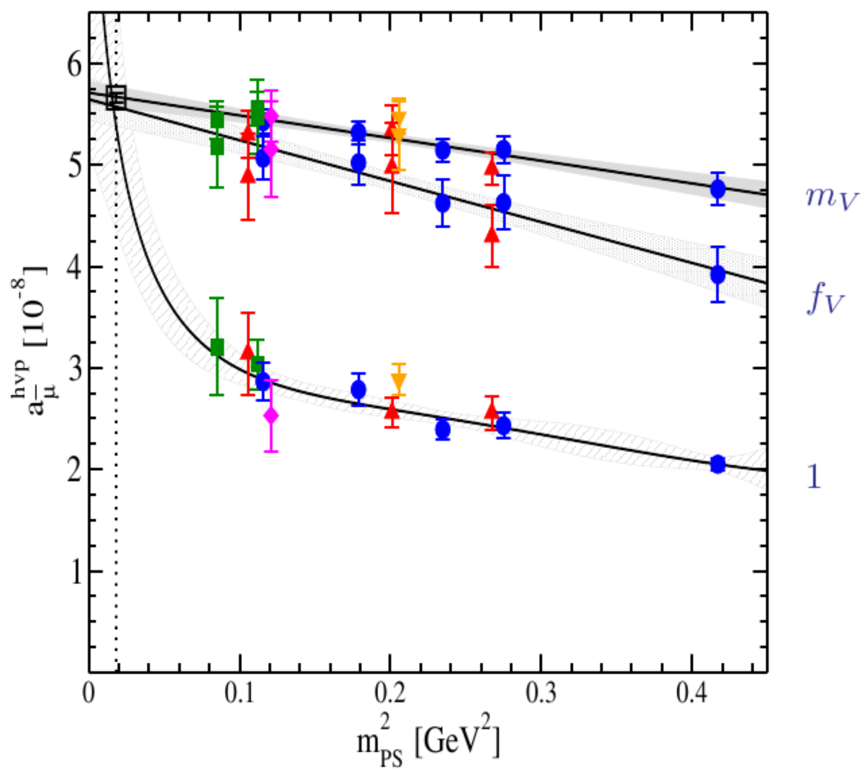
The problem of extrapolation: VP Jansen et al

comparison using r_1, r_2, r_3



a_μ direct, as a function of M_ρ and of f_ρ

Some preliminary numbers

- experimental value: $a_{\mu,N_f=2}^{\mathrm{hvp,exp}} = 5.66(05)10^{-8}$
- from our old analysis: $a_{\mu,N_f=2}^{\mathrm{hvp,old}} = 2.95(45)10^{-8}$

$\rightarrow$ misses the experimental value
$\rightarrow$ order of magnitude larger error

- from our new analysis: $a_{\mu,N_f=2}^{\mathrm{hvp,new}} = 5.66(11)10^{-8}$

$\rightarrow$ error (including systematics) almost matching experiment

looks like very promising progress!

Present & Future

- Role of Melnikov-Vainshtein constraint still under debate (is virtual photon dressed or undressed at external $\pi^0\gamma\gamma$ vertex?)

- Role of quark loop: is it an independent contribution? solving Schwinger-Dyson equation approach yields very large value.

- Large Q^2 behavior of $\mathcal{F}_{\pi^{0*}\gamma\gamma^*}(m_\pi^2, -Q^2, 0)$ from BaBar shows much weaker fall-off than expected by theory

- New muon $g-2$ experiment is on its way !!!

    - Need to improve accuracy for the hadronic light-by-light contribution.

    - New input form $\gamma\gamma$ physics to constrain theoretical models for HLbL (KLOE-2,BES,MAINZ)

    - Challenge for theory: radiative corrections needed

- Question of asymptotic behavior seen by BaBar, will likely be settled by Belle

- Can we check controversial dressed/undressed (i.e damping or not?) at external vertex? Can Primakoff-effect plus DR help?

❒ Lattice QCD makes big progress: we may expect relevant results for constraining models

❒ Not to forget: urgent improvement of VP mandatory [lattice QCD may become competitive] (Novosibirsk: CMD3, SND, unanalised data from BaBar & Belle?)

Viva $g-2$! Let's go to work!