



MODELS AND HLbL: DISCONNECTED CONTRIBUTIONS AND FIRST STEPS TOWARDS FINITE VOLUME CORRECTIONS



Johan Bijnens
Lund University



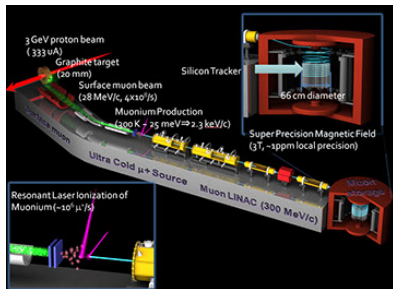
Vetenskapsrådet

bijnens@thep.lu.se
<http://thep.lu.se/~bijnens>
<http://thep.lu.se/~bijnens/chpt/>
<http://thep.lu.se/~bijnens/chiron/>

Why do we do this?



The muon $a_\mu = \frac{g - 2}{2}$ will be measured more precisely



J-PARC



Fermilab

Models and HLbL:
disconnected contributions and first steps towards finite volume corrections

Johan Bijnens

Introduction

To ChPT or not to ChPT
Why models?

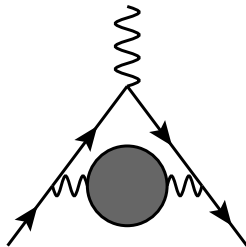
Overview of models

Disconnected/connected

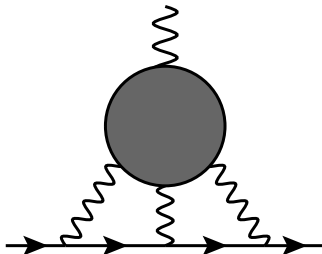
First steps for finite volume

Summary

Hadronic contributions



HVP



HLbL

- The blobs are hadronic contributions
- There are higher order contributions of both types (with photons outside the blobs)
- Extra photons inside the blobs more tricky (not needed at the moment for HLbL)

To ChPT or not to ChPT



LUND
UNIVERSITY

- ChPT = Effective field theory describing the lowest order pseudo-scalar representation
- or the (pseudo) Goldstone bosons from spontaneous breaking of chiral symmetry.
- Describes pions, kaons and etas at low-energies
- It's an effective field theory: new parameters or LECs at each new order
- Recent review of LECs:
[JB, Ecker, Ann.Rev.Nucl.Part.Sci. 64 \(2014\) 149 \[arXiv:1405.6488\]](#)
- a_μ is a very low-energy quantity, why not just calculate it in ChPT?

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

To ChPT or not
to ChPT

Why models?

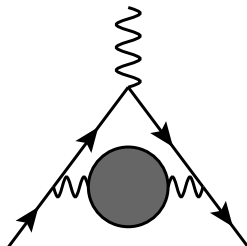
Overview of
models

Disconnected/
connected

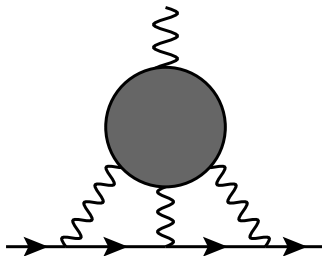
First steps for
finite volume

Summary

To ChPT or not to ChPT



HVP



HLbL

- Fill the blobs with pions and kaons
- Lowest order for both HVP and HLbL:
pure pion loop (or scalar QED): **well defined answer**
- NLO: the blob is nicely finite
but not after the muon/photon integrations
- Needs a counterterm (NLO LEC) **that is the muon $g - 2$**

To ChPT or not to ChPT



LUND
UNIVERSITY

- So need more than ChPT
- Experiment
- Dispersion relations
- lattice QCD
- Models: my talks at Q-park 2017, Capri 2015 and 2017
- I will give some general comments/overview and then restrict to some new results
- ChPT can be used to put constraints, help understanding results and estimate not evaluated parts, . . .

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

To ChPT or not
to ChPT

Why models?

Overview of
models

Disconnected/
connected

First steps for
finite volume

Summary

Why models?



LUND
UNIVERSITY

- **Pro:**
 - Can calculate with them (important in the past)
 - Can use them to understand features of better/more exact calculations
 - Can use them to estimate contributions from regions the other methods do not include
 - Can use them together with better methods to produce better models
- **Con:**
 - They are not the underlying theory or reality (experiment)
 - hard to estimate errors (guesstimates)
 - Beware: just model quark is different from QCD quark
 - Beware: model pion might not be quite the real pion
- **Reminder:**
 - HVP: high precision needed
 - HLbL: “just a bit” better than at present, but need to make sure the error estimate is not way off

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction
To ChPT or not
to ChPT
Why models?

Overview of
models

Disconnected/
connected

First steps for
finite volume

Summary

Requirements for models: **Do as well you can**

- **Constrain as much as possible from experiment**
 - measured states
 - measured form-factors
 - measured relevant scattering processes
- **Constrain as much as possible from theory**
 - include QCD short-distance constraints
 - include long distance constraints from ChPT
- **Use common sense**
 - Vary model parameters
 - Is your model general enough to describe what you want to describe
 - Different regions treated differently: is there some consistency
- **As well as you can** should improve with time

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

To ChPT or not
to ChPT

Why models?

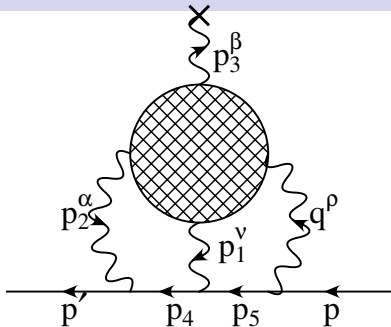
Overview of
models

Disconnected/
connected

First steps for
finite volume

Summary

HLbL: the main object to calculate



- Muon line and photons: well known
- The blob: fill in with hadrons/QCD
- Trouble: low and high energy very mixed
- Double counting needs to be avoided: hadron exchanges versus quarks



A separation proposal: a start

E. de Rafael, "Hadronic contributions to the muon $g-2$ and low-energy QCD,"
Phys. Lett. **B322** (1994) 239-246. [hep-ph/9311316].

- Use ChPT p counting and large N_c
- p^4 , order 1: pion-loop
- p^8 , order N_c : quark-loop and heavier meson exchanges
- p^6 , order N_c : pion exchange

Does not fully solve the problem

only short-distance part of quark-loop is really p^8

but it's a start

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

Overview of
models

Disconnected/
connected

First steps for
finite volume

Summary



A separation proposal: a start

E. de Rafael, "Hadronic contributions to the muon $g-2$ and low-energy QCD,"
Phys. Lett. **B322** (1994) 239-246. [hep-ph/9311316].

- Use ChPT p counting and large N_c
- p^4 , order 1: pion-loop
- p^8 , order N_c : quark-loop and heavier meson exchanges
- p^6 , order N_c : pion exchange

Implemented by two groups in the 1990s:

- Hayakawa, Kinoshita, Sanda: meson models, pion loop using hidden local symmetry, quark-loop with VMD, calculation in Minkowski space (HKS)
- JB, Pallante, Prades: Try using as much as possible a consistent model-approach, ENJL, calculation in Euclidean space (BPP)

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

Overview of
models

Disconnected/
connected

First steps for
finite volume

Summary



- JB, E. Pallante and J. Prades
 - “Comment on the pion pole part of the light-by-light contribution to the muon $g-2$,” Nucl. Phys. B **626** (2002) 410 [arXiv:hep-ph/0112255].
 - “Analysis of the Hadronic Light-by-Light Contributions to the Muon $g - 2$,” Nucl. Phys. B **474** (1996) 379 [arXiv:hep-ph/9511388].
 - “Hadronic light by light contributions to the muon $g-2$ in the large N_c limit,” Phys. Rev. Lett. **75** (1995) 1447 [Erratum-ibid. **75** (1995) 3781] [arXiv:hep-ph/9505251].
- Hayakawa, Kinoshita, (Sanda)
 - “Pseudoscalar pole terms in the hadronic light by light scattering contribution to muon $g - 2$,” Phys. Rev. **D57** (1998) 465-477. [hep-ph/9708227], Erratum-ibid.D66 (2002) 019902[hep-ph/0112102].
 - “Hadronic light by light scattering contribution to muon $g-2$,” Phys. Rev. **D54** (1996) 3137-3153. [hep-ph/9601310].
 - “Hadronic light by light scattering effect on muon $g-2$,” Phys. Rev. Lett. **75** (1995) 790-793. [hep-ph/9503463].



Some main observations: Pseudo-scalar exchange

- The largest contribution is π^0 (and η, η') exchange/pole
- Beware: pole/exchange not quite the same
- Most evaluations are in reasonable agreement
- I will use it for an estimate of disconnected/connected on the lattice
- Point-like VMD: π^0, η and η' give $a_\mu^P = (5.58, 1.38, 1.04) \cdot 10^{-10}$.
- η' large due to charge factors
- Will be discussed in many more talks here (Stoffer, Kubis, Roig, Hashimoto, Gerardin, Chrits, Tu, ...)
- My expectations:
VMD cuts off too fast, short distance constraints on formfactors: final number somewhat higher
- My impression: Generally under control, improve precision



Some main observations: Pion-loop

- The pion loop can be sizable but a large difference between the two evaluations

$$a_{\mu} = (-1.9(BPP), -0.5(HKS)) \cdot 10^{-10}.$$

- Kaon loop is very small
- Pure pion loop, larger numbers proposed Engel, Ramsey-Musolf
- Solved: short-distance constraints lead to BPP more correct, some change when including a_1 for polarizability

JB, Relefors, Zahiri-Abyaneh, 1208.3548, 1208.2554, 1308.2575, 1510.05796

JB, Relefors, JHEP **1609** (2016) 113 [arXiv:1608.01454 [hep-ph]].

$$a_{\mu}^{\pi\text{-loop}} = (-2.0 \pm 0.5) 10^{-10}$$

- Remaining: Rescattering and scalar part
 - Related: dispersive by Colangelo et al. (Stoffer)
 - Related: (Danilkin)
- My impression: Generally under control



Some main observations: Everything else

| Cut-off Λ (GeV) | $a_\mu \times 10^7$ Electron Loop | $a_\mu \times 10^9$ Muon Loop | $a_\mu \times 10^9$ Constituent Quark Loop (q=e) |
|-------------------------------|---|-------------------------------------|--|
| 0.5 | 2.41(8) | 2.41(3) | 0.395(4) |
| 0.7 | 2.60(10) | 3.09(7) | 0.705(9) |
| 1.0 | 2.59(7) | 3.76(9) | 1.10(2) |
| 2.0 | 2.60(6) | 4.54(9) | 1.81(5) |
| 4.0 | 2.75(9) | 4.60(11) | 2.27(7) |
| 8.0 | 2.57(6) | 4.84(13) | 2.58(7) |
| Known Results | 2.6252(4) | 4.65 | 2.37(16) |

- M_Q : 300 MeV (known fully analytically)
- **Slow convergence:**
 - electron: all at 500 MeV
 - Muon: only half at 500 MeV, at 1 GeV still 20% missing
 - 300 MeV quark: at 1 GeV still 50% missing
 - Real charges: about $5 \cdot 10^{-10}$, above 1 GeV about $2.5 \cdot 10^{-10}$

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

Overview of
models

Disconnected/
connected

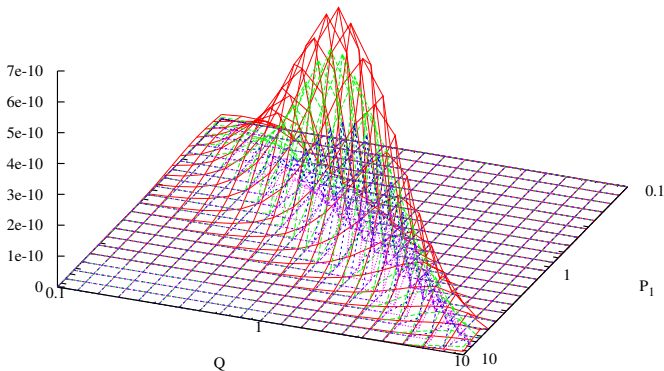
First steps for
finite volume

Summary

Pure quark loop: momentum area

quark loop $m_Q = 0.3 \text{ GeV}$

$P_2 = P_1$ ——— (red)
 $P_2 = P_1/2$ - - - - (green)
 $P_2 = P_1/4$ ····· (blue)
 $P_2 = P_1/8$ ····· (purple)



Most from $P_1 \approx P_2 \approx Q$, sizable large momentum part



Other estimates of the remainder

- BPP: ENJL quark-loop, short-distance quark-loop and a_1 : $2.6 \cdot 10^{-10}$
- BPP: scalar: goes to dispersive pionloop $-0.7 \cdot 10^{-10}$
- Melnikov-Vainshtein: QCD short-distance constraint gives and extra $2.1 \cdot 10^{-10}$ for π^0 exchange
- Melnikov-Vainshtein a_1 probably wrong, all others axials about $2.6 \cdot 10^{-10}$
- Other exchanges come with varying size and typically (much) below $\pm 0.3 \cdot 10^{-10}$
- Guesstimate: remainder will be $(2 - 3) \cdot 10^{-10}$ but need bounds on the errors
- All estimates with larger numbers: use a light quark mass below 1 GeV

Overview of models: conclusions



LUND
UNIVERSITY

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

Overview of
models

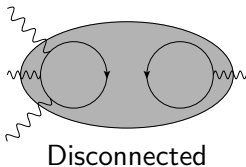
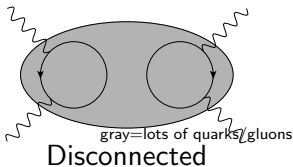
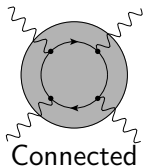
Disconnected/
connected

First steps for
finite volume

Summary

- Present:
 - Pseudo-scalar exchange: $(9-10) \cdot 10^{-10}$
 - Pion-loop+scalar: $-(2-3) \cdot 10^{-10}$
 - Remainder: $(2-4) \cdot 10^{-10}$
- Future:
 - Better approaches are taking over
 - Lattice: we already saw many new numbers
 - Dispersive: one π, η, η' and two pions/kaons will be under control and : errors small enough
 - Future for models: are there large other contributions?
- Present for models: so far no sign we were way off

Disconnected/Connected



- Use the breakup of contributions from previous slide
- Pseudo-scalar exchange: large effects and cancellations
- Pion-loop: reasonable effects and additive
- Rest: small

Disconnected/connected: pion loop and remainder



LUND
UNIVERSITY

- Pion-loop
 - π , ρ , a_1 well described at large N_c
 - Full VMD or similar dispersive will be connected
 - Rescattering is large N_c suppressed estimate via scalar exchange or dispersive estimate without polarizability
 - connected $-2.0 \cdot 10^{-10}$
 - disconnected $-0.7 \cdot 10^{-10}$
 - about 25% of total and additive
- Remainder
 - Short-distance: disconnected needs two-gluon exchange suppressed by α_S^2 and loop factors
 - Resonance exchanges: nonet is usually a decent first approximation
 - So expect: disconnected smaller part of the total

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

Overview of
models

Disconnected/
connected

First steps for
finite volume

Summary

Disconnected/connected: pseudo-scalar exchange



LUND
UNIVERSITY

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

Overview of
models

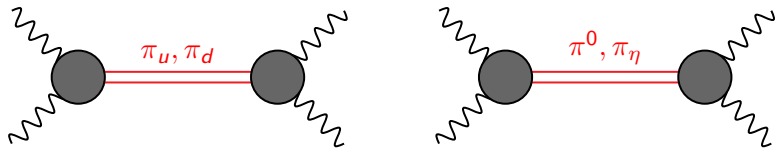
Disconnected/
connected

First steps for
finite volume

Summary

- Connected diagrams only:
 - the gluon exchanges responsible for $U(1)_A$ breaking are not included at all (anomaly is via $G\tilde{G}$)
 - η' becomes light, mainly $(\bar{u}u + \bar{d}d)/\sqrt{2}$
Call it π_η which has the same mass as the pion
 - Or the two-light states are π_u ($\bar{u}u$) and π_d ($\bar{d}d$)
 - η becomes mainly $\bar{s}s$ and much heavier than the pion (and thus small contribution)
- Assume that couplings are not affected (not too bad experimentally)

Disconnected/Connected



- Two flavour case only: up and down quarks (three flavour not more difficult, just more numbers)
- Meson couplings to two-photons is via quark-loop
- Look at charge factors for Connected
 - As “quark-loop”: $q_u^4 + q_d^4 = \frac{17}{81}$
 - As π_u, π_d : $q_u^2 q_u^2 + q_d^2 q_d^2 = \frac{17}{81}$
 - As π^0, π_η : $\left(\frac{q_u^2 - q_d^2}{\sqrt{2}}\right)^2 + \left(\frac{q_u^2 + q_d^2}{\sqrt{2}}\right)^2 = \frac{9}{162} + \frac{25}{162} = \frac{17}{81}$
- Include $U(1)_A$ breaking: π_η heavy
 - π^0 : $\left(\frac{q_u^2 - q_d^2}{\sqrt{2}}\right)^2 = \frac{9}{162}$



- So in this limit:
 - Two-flavour case
 - $U(1)_A$ breaking makes π_η infinitely heavy
 - Full result dominated by pseudo-scalar exchange
 - $U(1)_A$ breaking does not affect couplings

$$\text{Connected: } \frac{34}{162}$$

- Disconnected: $-\frac{25}{162}$

$$\text{Sum: } \frac{9}{162}$$

- All assumptions get corrections but final conclusion stays

The disconnected contribution is expected to be large and of opposite sign with significant cancellations

- Argument used to go from large- N_c to π^0, η, η' in
JB, Pallante, Prades, Nucl. Phys. B **474** (1996) 379 [arXiv:hep-ph/9511388]
- This form: JB, Relefors, JHEP **1609** (2016) 113 [arXiv:1608.01454]

- So in this limit:
 - Two-flavour case
 - $U(1)_A$ breaking makes π_η infinitely heavy
 - Full result dominated by pseudo-scalar exchange
 - $U(1)_A$ breaking does not affect couplings

$$\text{Connected: } \frac{34}{162}$$

- Disconnected: $-\frac{25}{162}$

$$\text{Sum: } \frac{9}{162}$$

- All assumptions get corrections but final conclusion stays

The disconnected contribution is expected to be large and of opposite sign with significant cancellations

- Argument used to go from large- N_c to π^0, η, η' in
JB, Pallante, Prades, Nucl. Phys. B **474** (1996) 379 [arXiv:hep-ph/9511388]
- This form: JB, Relefors, JHEP **1609** (2016) 113 [arXiv:1608.01454]

Disconnected/Connected



LUND
UNIVERSITY

- Let's do numerics and factors for the full VMD case
- Full result: $(5.58 + 1.38 + 1.04 = 8.0) \cdot 10^{-10}$
- Connected: $((5.58(1 + (25/9)) + 0.2) = 22) \cdot 10^{-10}$
- thus disconnected: $-14 \cdot 10^{-10}$
- The other disconnected parts are basically in the error on this number
- disconnected a little over half of the connected and other sign

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

Overview of
models

Disconnected/
connected

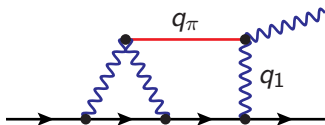
First steps for
finite volume

Summary

Finite volume corrections



- Not much known analytically (at least to me)
- Photons are massless: possibly large corrections
- Idea: put photons (and muons) in larger/infinite volume
- Expect main correction from the π^0 -exchange then, lightest hadronic state
- But: q_π quantized then q_1 as well: photon volume corrections back?

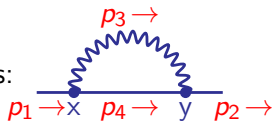


- Need to go back and understand momentum conservation

Simplest case: infinite volume



- Simplest diagram, pointlike couplings:



- Infinite volume (and states normalized accordingly)

$$\int d^d x \int d^d y e^{-ip_1 \cdot x} e^{ip_2 \cdot y} \int \frac{d^d p_3}{(2\pi)^d} \frac{e^{ip_3 \cdot (x-y)}}{p_3^2} \int \frac{d^d p_4}{(2\pi)^d} \frac{e^{ip_4 \cdot (x-y)}}{p_4^2 - m^2}$$

- doing the x and y integrals gives

$$(2\pi)^d \delta^d(p_1 - p_3 - p_4) (2\pi)^d \delta^d(p_3 + p_4 - p_2)$$

- Final

$$(2\pi)^d \delta^d(p_1 - p_2) \int \frac{d^d p_3}{(2\pi)^d} \frac{1}{p_3^2} \frac{1}{(p_3 - p_1)^2 - m^2}$$



Simplest case: finite volume for all

- Time extension infinite, spatial finite extent
- x and y integrals over infinite time but finite spatial
- Propagators: \vec{x} to all $\vec{y} + \vec{n}_y L$ (periodic b.c.)
- States now normalized differently
- $n_y = (0, \vec{n}_y)$

$$\int_{\text{box}} d^d x \int_{\text{box}} d^d y \frac{e^{-ip_1 \cdot x}}{\sqrt{L^3}} \frac{e^{ip_2 \cdot y}}{\sqrt{L^3}}$$

$$\sum_{\vec{n}_y} \int \frac{d^d p_3}{(2\pi)^d} \frac{e^{ip_3 \cdot (x-y-n_y L)}}{p_3^2} \sum_{\vec{m}_y} \int \frac{d^d p_4}{(2\pi)^d} \frac{e^{ip_4 \cdot (x-y-m_y L)}}{p_4^2 - m^2}$$

- Sums make the spatial momentum integrals discrete

Simplest case: finite volume for all

- Shift $\vec{m}_y = \vec{n}_y + \vec{l}_y$ and use $e^{ip_2 \cdot y} = e^{ip_2 \cdot (y + n_y L)}$

$$\int_{\text{box}} d^d x \sum_{\vec{n}_y} \int_{\text{box}} d^d y \frac{e^{-ip_1 \cdot x}}{\sqrt{L^3}} \frac{e^{ip_2 \cdot (y + n_y L)}}{\sqrt{L^3}}$$

$$\int \frac{d^d p_3}{(2\pi)^d} \frac{e^{ip_3 \cdot (x - y - n_y L)}}{p_3^2} \sum_{\vec{l}_y} \int \frac{d^d p_4}{(2\pi)^d} \frac{e^{ip_4 \cdot (x - y - l_y L - n_y L)}}{p_4^2 - m^2}$$

- $\sum_{\vec{n}_y} \int_{\text{box}} d^d y f(y + n_y L) = \int d^d y f(y) \Rightarrow (2\pi)^d \delta^d(p_3 + p_4 - p_2)$
- Time integral over x^0 gives $2\pi \delta(E_1 - E_2)$
- Spatial integral over \vec{x} ($\vec{p}_1, \vec{p}_2, \vec{p}_4$ all discrete): $L^3 \delta_{\vec{p}_1, \vec{p}_2}^{d-1}$
- $(2\pi) \delta(E_1 - E_2) \delta_{\vec{p}_1, \vec{p}_2}^{d-1} \sum_{\vec{l}_y} \int \frac{d^d p_3}{(2\pi)^d} \frac{e^{-ip_3 \cdot l_y}}{p_3^2 ((p_3 - p_1)^2 - m^2)}$
- Discrete sum over p_3 , remove spatial zero mode QED_L

Simplest case: finite volume for massive only

- Only the massive propagator needs the periodicity

$$\int_{\text{box}} d^d x \int_{\text{box}} d^d y \frac{e^{-ip_1 \cdot x}}{\sqrt{L^3}} \frac{e^{ip_2 \cdot y}}{\sqrt{L^3}}$$

$$\int \frac{d^d p_3}{(2\pi)^d} \frac{e^{ip_3 \cdot (x-y)}}{p_3^2} \sum_{\vec{m}_y} \int \frac{d^d p_4}{(2\pi)^d} \frac{e^{ip_4 \cdot (x-y-m_y L)}}{p_4^2 - m^2}$$

- Trick to get one delta function no longer works
- Time integrals x, y give $(2\pi)^2 \delta(E_1 - E_2) \delta(E_1 - E_3 - E_4)$
- $\Delta(z) = \sin(z)/z$ ($\vec{x}, \vec{y} - L/2$ to $L/2$ gives this)

- $(2\pi)^2 \delta(E_1 - E_2) \int \frac{d^d p_3}{(2\pi)^d} L^3 \sum_{\vec{m}_y} \int \frac{d^d p_4}{(2\pi)^d} \frac{e^{-ip_4 \cdot m_y L}}{p_3^2 (p_4^2 - m^2)}$

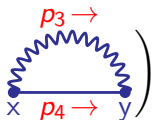
$$\delta(E_1 - E_3 - E_4) \prod_{i=1,2,3} \Delta \left(\frac{(p_1^i - p_3^i - p_4^i)L}{2} \right) \Delta \left(\frac{(p_2^i - p_3^i - p_4^i)L}{2} \right)$$

Simplest case: finite volume for massive only



- **no momentum conservation**
- $\Delta(pL/2)$ is peaked with a width of order $2\pi/L$ in p
- $\Delta(pL/2)$ has a long tail
- No easy way to get a feeling for its behaviour
- No way (for me so far) to check $1/L$ behaviour analytically
- Study an even simpler case numerically
- $p_1 = p_2 = 0$ and take a derivative w.r.t. m^2

- i.e.: $\frac{1}{i} \int \frac{d^d p_3}{p_3^2 (p_3^2 - m^2)^2}$ or $\frac{\partial}{\partial m^2} \left(\text{diagram} \right)$

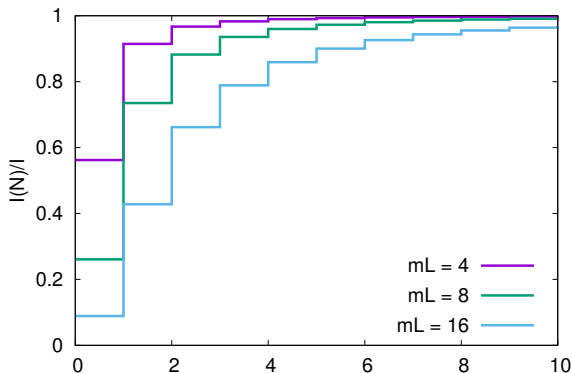


- Infrared and ultraviolet finite
- Infinite volume: $\frac{-1}{16\pi^2 m^2}$



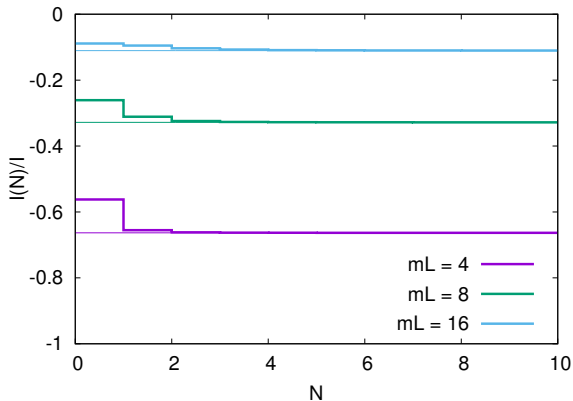
Absolute simplest: infinite volume

- Do the p_3^0 integral analytically for all cases
- Make a grid of $p_4^i = \frac{2\pi}{L}$ up to $\pm N$
(actually done by adding new layers on the cube)
- For infinite volume: set $p_3^i = p_4^i + q^i$ and integrate q^i from $-\pi/L$ to π/L



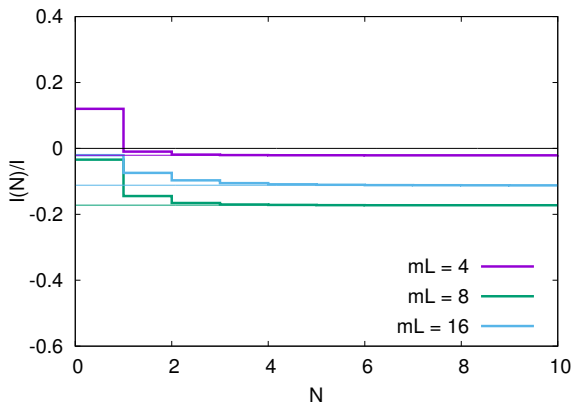
QED_L drops
the first one:
large correc-
tions

Absolute simplest: QED_L



- photon in IV: corrections increases from $mL = 4$ to $mL = 8$
- Then goes back down again

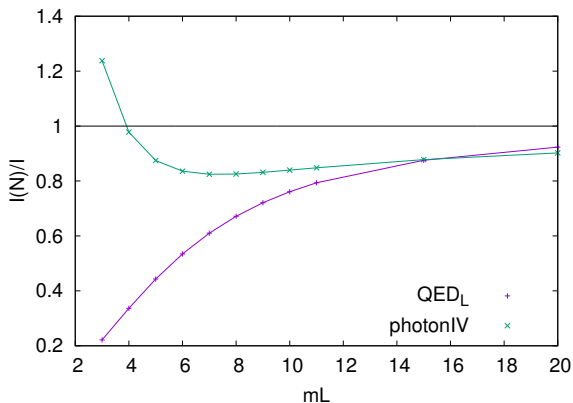
Absolute simplest: photonIV



- QED_L : main correction is from dropping the first bin
- The thin lines are the exact QED_L answers



QED_L and photonIV: comparison



- QED_L bad at small L : main cause zero-bin is large
- But at larger L picture more unclear



- QED_L bad at small L : main cause zero-bin is large
- But at larger L picture more unclear
- Work on other ways in progress
- Finite volume corrections are very quantity dependent
 - Mass electromagnetic corrections: large
Hayakawa-Uno, BMW
 - HVP electromagnetic corrections: small
JB, Boyle, Hermansson Truedsson, Janowski, Juettner, Portelli

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

Introduction

Overview of
models

Disconnected/
connected

First steps for
finite volume

Summary

Conclusions



LUND
UNIVERSITY

Models and
HLbL:
disconnected
contributions
and first steps
towards finite
volume
corrections

Johan Bijnens

See the subconclusions presented after each part

Introduction

Overview of
models

Disconnected/
connected

First steps for
finite volume

Summary