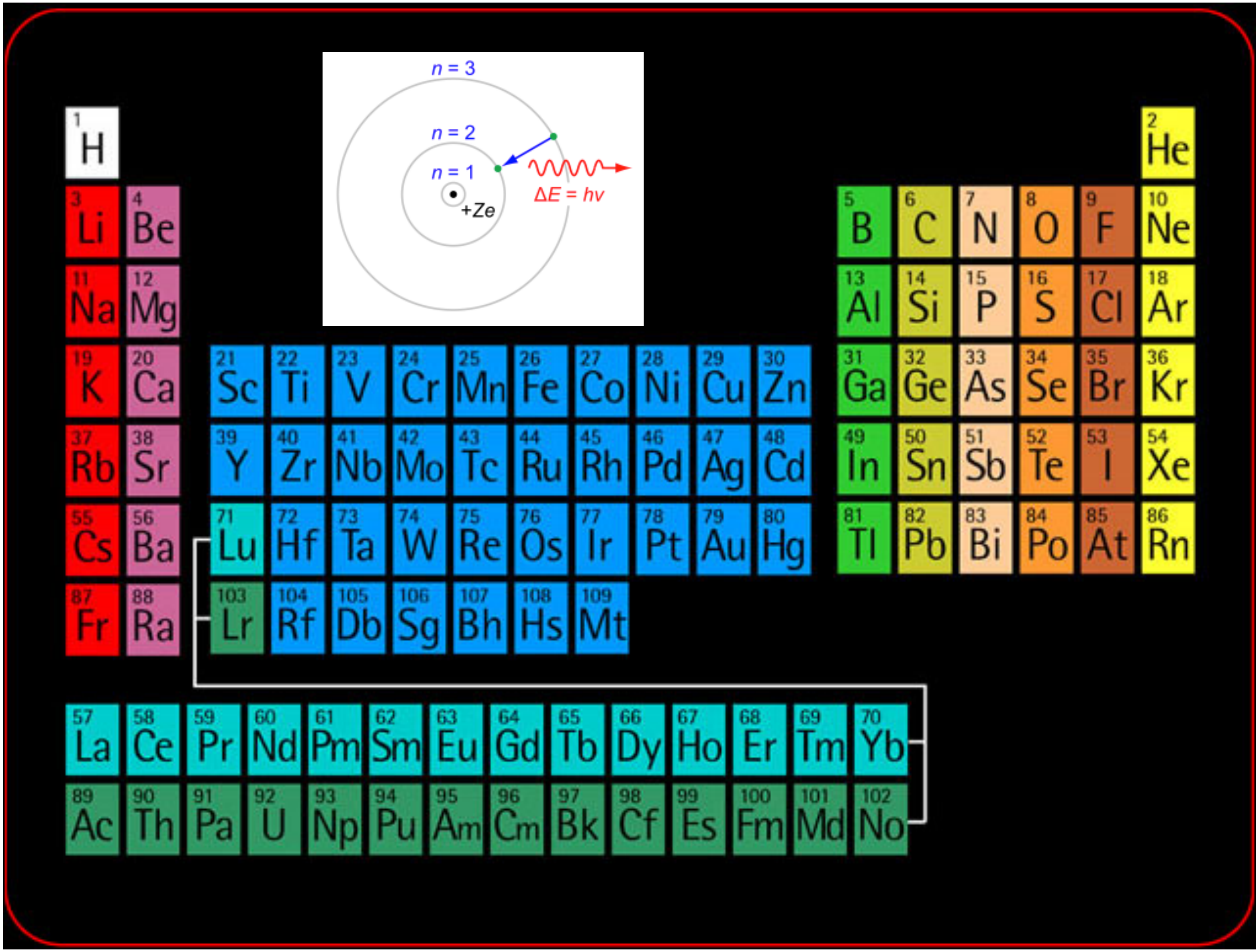
Nuclear Physics School 2018

Chueng-Ryong Ji
North Carolina State University

Third Lecture

Light-Front Quark Model

June 29, 2018


n = 3
n = 2
n = 1
+Ze
ΔE = hν
1 H
2 He
3 Li 4 Be
5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg
13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No

H-atom Spectra

$$\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137.036}$$

$$E_n = -\alpha^2 mc^2 (\frac{1}{2n^2})$$
$$\approx -13.6eV / n^2.$$

$$\Delta E_{fs} = \Delta E_{rel} + \Delta E_{so}$$

$$= -\alpha^4 mc^2 \frac{1}{4n^4}\left(\frac{2n}{j+\frac{1}{2}} - \frac{3}{2}\right)$$

Relativistic Correction

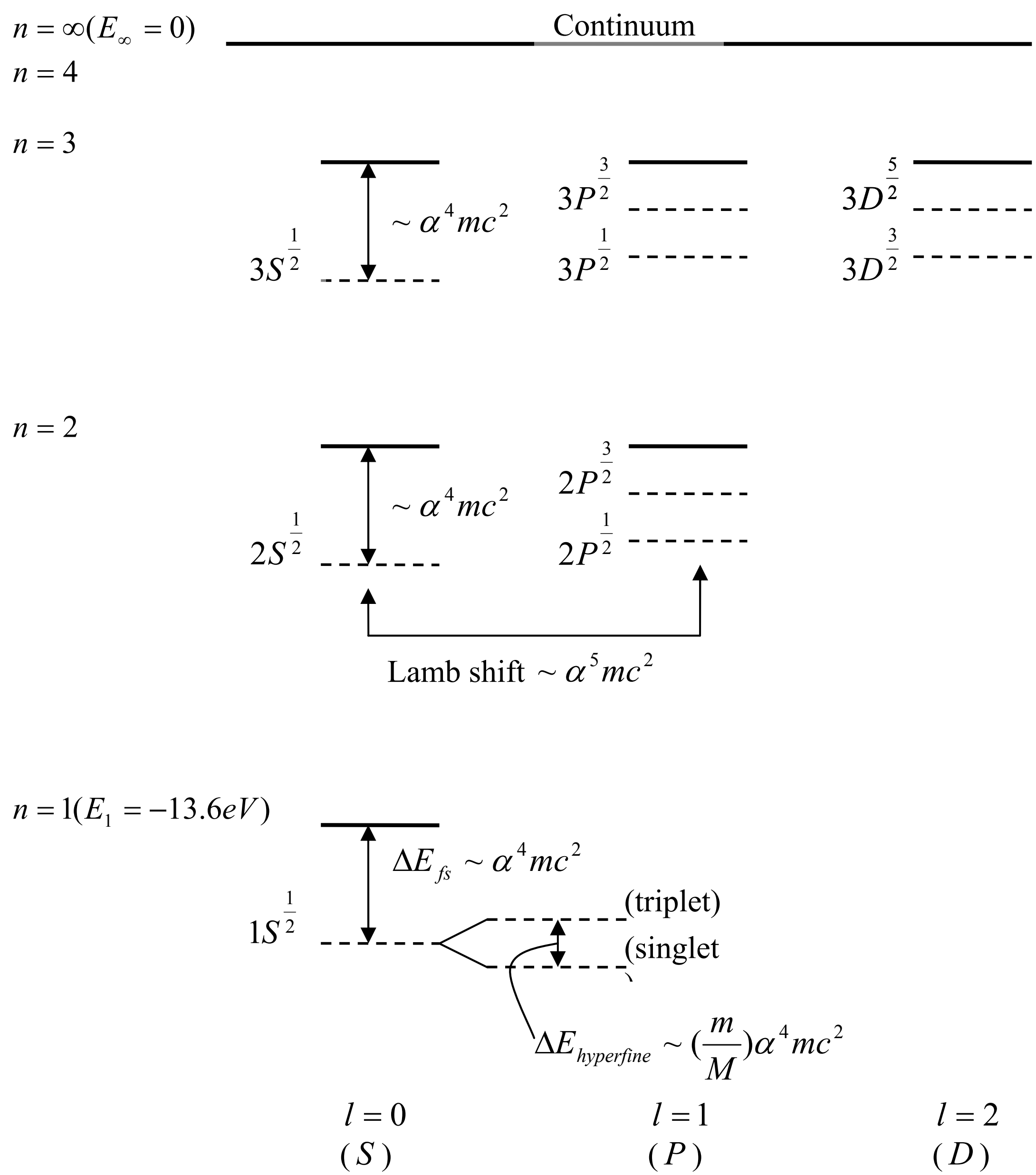
$$T = (\gamma - 1)mc^2$$
$$= \frac{1}{2}m\vec{v}^2 + \frac{3}{8}m\frac{\vec{v}^4}{c^4} + \cdots$$
$$= \frac{\vec{p}^2}{2m} - \frac{\vec{p}^4}{8m^3c^2} + \cdots,$$

$$\Delta E_{rel} = -\alpha^4 mc^2 \frac{1}{4n^4}\left(\frac{2n}{\ell+\frac{1}{2}} - \frac{3}{2}\right)$$

Spin-Orbit Coupling

$$\Delta H_{so} = \frac{e^2}{2m^2c^2r^3}\vec{L}\cdot\vec{s}$$

$$\langle \Delta E_{so} \rangle = \alpha^4 mc^2 \frac{\left\{ j(j+1) - \ell(\ell+1) - \frac{3}{4} \right\}}{4n^3 \ell \left(\ell + \frac{1}{2}\right)(\ell+1)}$$



The solid line spectra($E_n=-\alpha^2mc^2(\frac{1}{2n^2})$) are without corrections. The masses of electron and proton are denoted by m and M respectively.

For the positronium, m/M = 1:

the reduced mass effect, i.e. $m_{red} = \frac{m}{2}$,

Thus, there is no distinction between the fine structure and the hyperfine structure in the positronium system.

The hyperfine structure is at the same order as the fine structure in the positronium system and the degeneracy of $2S_{1/2}$ and $2P_{1/2}$ states is already broken in the level of fine and hyperfine combined structure.

Therefore, the Lamb shift which breaks the degeneracy of $2S_{1/2}$ and $2P_{1/2}$ states is less interesting in the positronium system.

$$E_n^{positronium} = -\alpha^2 m_{red} c^2 \left(\frac{1}{2n^2} \right)$$

$$= \frac{1}{2} E_n^{hydrogen},$$

i.e.

$$E_1^{positronium} = \frac{13.6eV}{2} = 6.8eV,$$

and

$$a^{positronium} = \frac{\hbar^2}{m_{red} e^2}$$

$$= 2a^{hydrogen}$$

$$= 1.06x10^{-8}\, cm.$$

The second one is the electron-positron annihilation effect which modifies the interaction Hamiltonian. In some cases, the positronium decays into two or three photons depending on the positronium state. The energy level correction due to the annihilation effect occurs at the same order as the fine structure, i.e.

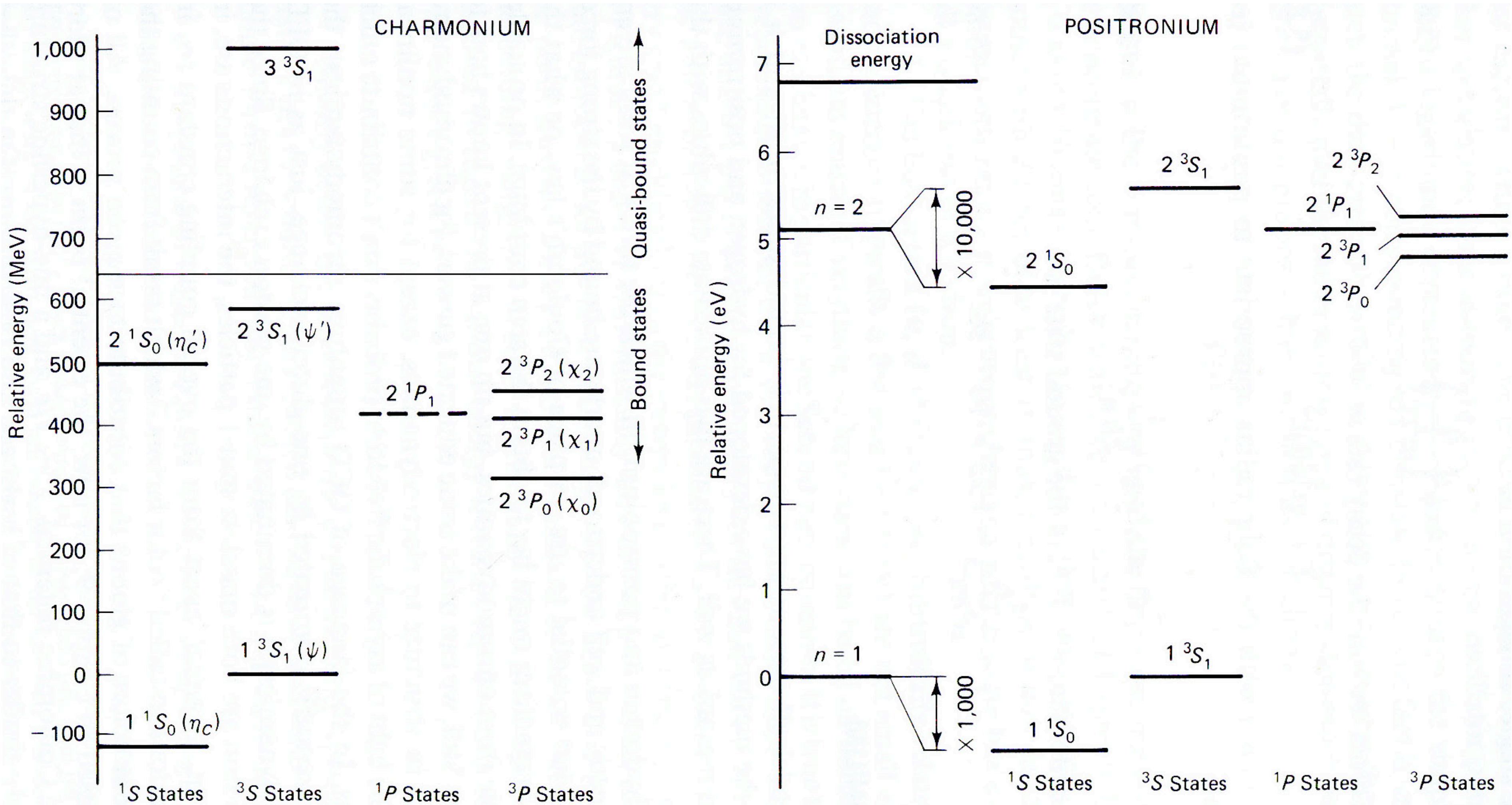
$$\Delta E_{annihilation} \sim \alpha^4 mc^2 .$$

$\ell = 0$ $\quad$ $c = (-1)^{\ell+s}$ $\quad$ $c_\gamma = -1$

$$\tau(^1S_0 \to 2\gamma) = 1.25x10^{-10} \sec \qquad s=0$$

and

$$\tau(^3S_1 \to 3\gamma) = 1.45x10^{-7} \sec . \qquad s=1$$


CHARMONIUM
Relative energy (MeV)
1,000
900
800
700
600
500
400
300
200
100
0
−100
3 ³S₁
2 ³S₁ (ψ′)
2 ¹S₀ (η′c)
2 ¹P₁
2 ³P₂ (χ₂)
2 ³P₁ (χ₁)
2 ³P₀ (χ₀)
1 ³S₁ (ψ)
1 ¹S₀ (ηc)
Quasi-bound states
Bound states
¹S States
³S States
¹P States
³P States
POSITRONIUM
Relative energy (eV)
Dissociation energy
7
6
5
4
3
2
1
0
n = 2
× 10,000
n = 1
× 1,000
2 ¹S₀
2 ³S₁
2 ¹P₁
2 ³P₂
2 ³P₁
2 ³P₀
1 ³S₁
1 ¹S₀
¹S States
³S States
¹P States
³P States

$$V = -\frac{e^2}{r} \longrightarrow (\Delta E)_{positronium} \sim eV$$

$$V(r) = -\frac{4}{3}\frac{\alpha_s \hbar c}{r} + F_o r \longrightarrow (\Delta E)_{quarkonium} \sim 100 MeV$$

splitting of the energy level for n=1 state, i.e. 1^1S_0 and 1^3S_1

singlet $(^1S_0)$	triplet $(^3S_1)$
pseudoscalar meson octet	vector meson octet

the mass difference between π and ρ mesons

$$M = m_1 + m_2 + A\frac{\vec{s}_1 \cdot \vec{s}_2}{m_1 m_2}$$

$$\vec{s}_1 \cdot \vec{s}_2 = \frac{\vec{s}^{\,2} - \vec{s}_1^{\,2} - \vec{s}_2^{\,2}}{2}$$

$$= \frac{s(s+1) - \frac{3}{4} - \frac{3}{4}}{2}\hbar^2 \begin{cases} s = 0; & -\frac{3}{4}\hbar^2 \\ s = 1; & \frac{1}{4}\hbar^2. \end{cases}$$

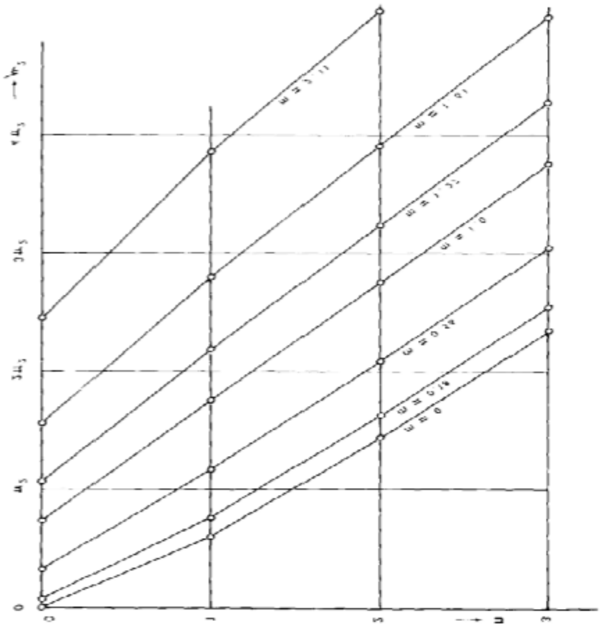
$$M = m_1 + m_2 + A\frac{\vec{s}_1 \cdot \vec{s}_2}{m_1 m_2}$$

	Eq. (3.101)	Experiment
π	140	138
K	484	496
η	559	549
ρ	780	776
ω	780	783
K *	896	892
ϕ	1032	1020

$$m_u = m_d = 310 MeV/c^2, \qquad m_s = 483 MeV/c^2$$

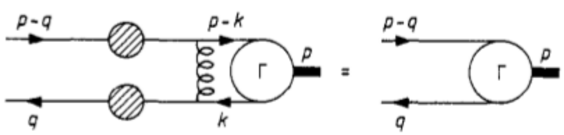
$$A = \left(\frac{2m_u}{\hbar}\right)^2 160 MeV/c^2$$

Meson spectroscopy in QCD_{1+1}

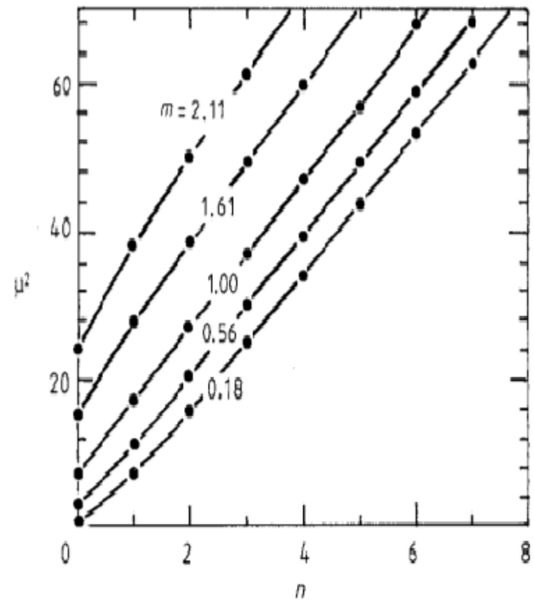


G. 't Hooft, Nucl. Phys. B75, 461 (1974)

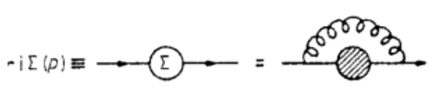
LFD ⇦



IFD ⇨



Li, Wilets and Birse, J. Phys. G:Nucl. Phys. 13, 915 (1987)



Dynamical quark/gluon mass generation and color confinement in QCD should be understood further.

Effective Constituent Quark Model for Low Q^2

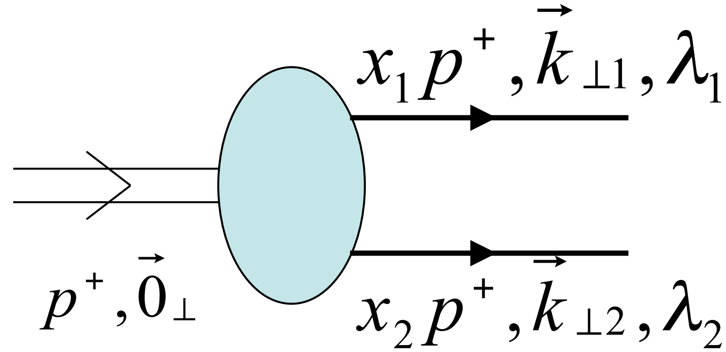
$$\left|Meson\right\rangle = \psi_{q\bar{q}}\left|q\bar{q}\right\rangle + \psi_{q\bar{q}g}\left|q\bar{q}g\right\rangle + \ldots$$

$$\approx \Psi_{Q\bar{Q}}\left|Q\bar{Q}\right\rangle,$$

where

$$\left|Q\right\rangle = \psi^{Q}_{q}\left|q\right\rangle + \psi^{Q}_{qg}\left|qg\right\rangle + \ldots$$

$$\left|\bar{Q}\right\rangle = \psi^{\bar{Q}}_{\bar{q}}\left|\bar{q}\right\rangle + \psi^{\bar{Q}}_{\bar{q}g}\left|\bar{q}g\right\rangle + \ldots$$



$$\Psi_{Q\bar{Q}}(x_i, \vec{k}_{\perp i}, \lambda_i) = \Phi(x_i, \vec{k}_{\perp i})\chi(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Radial
(Dependent on the model potential)

H = T + V
V includes Coulomb, Confinement, Spin-Spin,Spin-Orbit interactions.

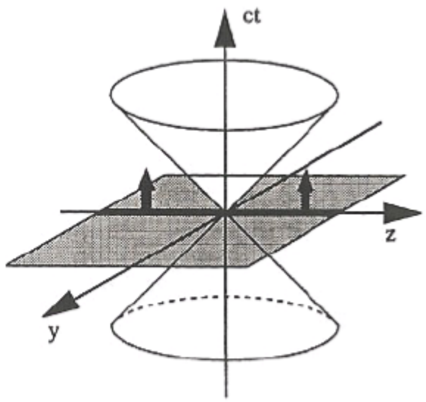
Spin-Orbit
(Interaction independent Melosh transformation)

$J^{PC} = 0^{++}(f_0, a_0, \ldots)$

$0^{-+}(\pi, K, \eta, \eta', \ldots)$

$1^{--}(\rho, K^*, \omega, \phi, \ldots)$

...



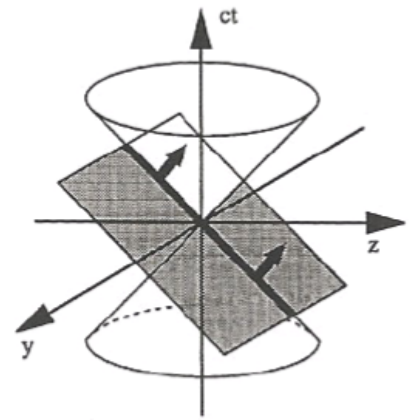
The instant form

Equal t $\quad\quad$ *Equal τ*

$$p^0 \leftrightarrow p^- = p^0 - p^3$$

$$(p^1, p^2) \leftrightarrow \vec{p}_\perp$$

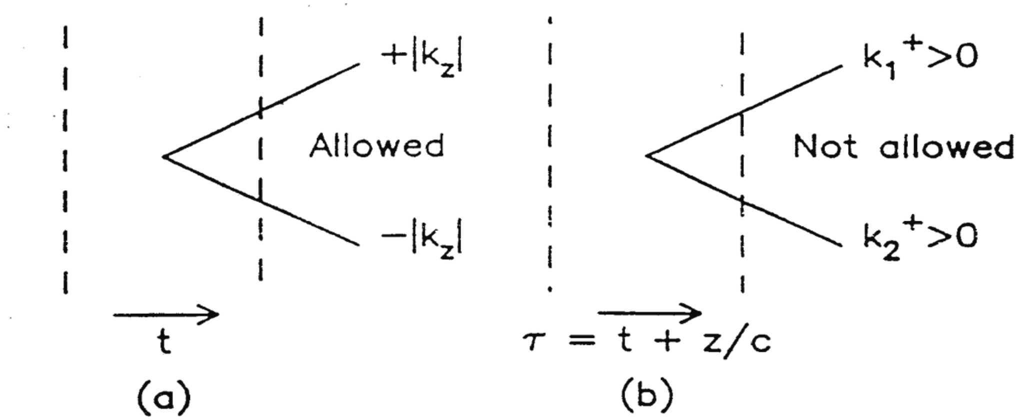
$$p^3 \leftrightarrow p^+ = p^0 + p^3$$



The front form

Energy-Momentum Dispersion Relations

$$p^0 = \sqrt{\vec{p}^{\,2} + m^2} \qquad\qquad p^- = \frac{\vec{p}_\perp^{\,2} + m^2}{p^+}$$

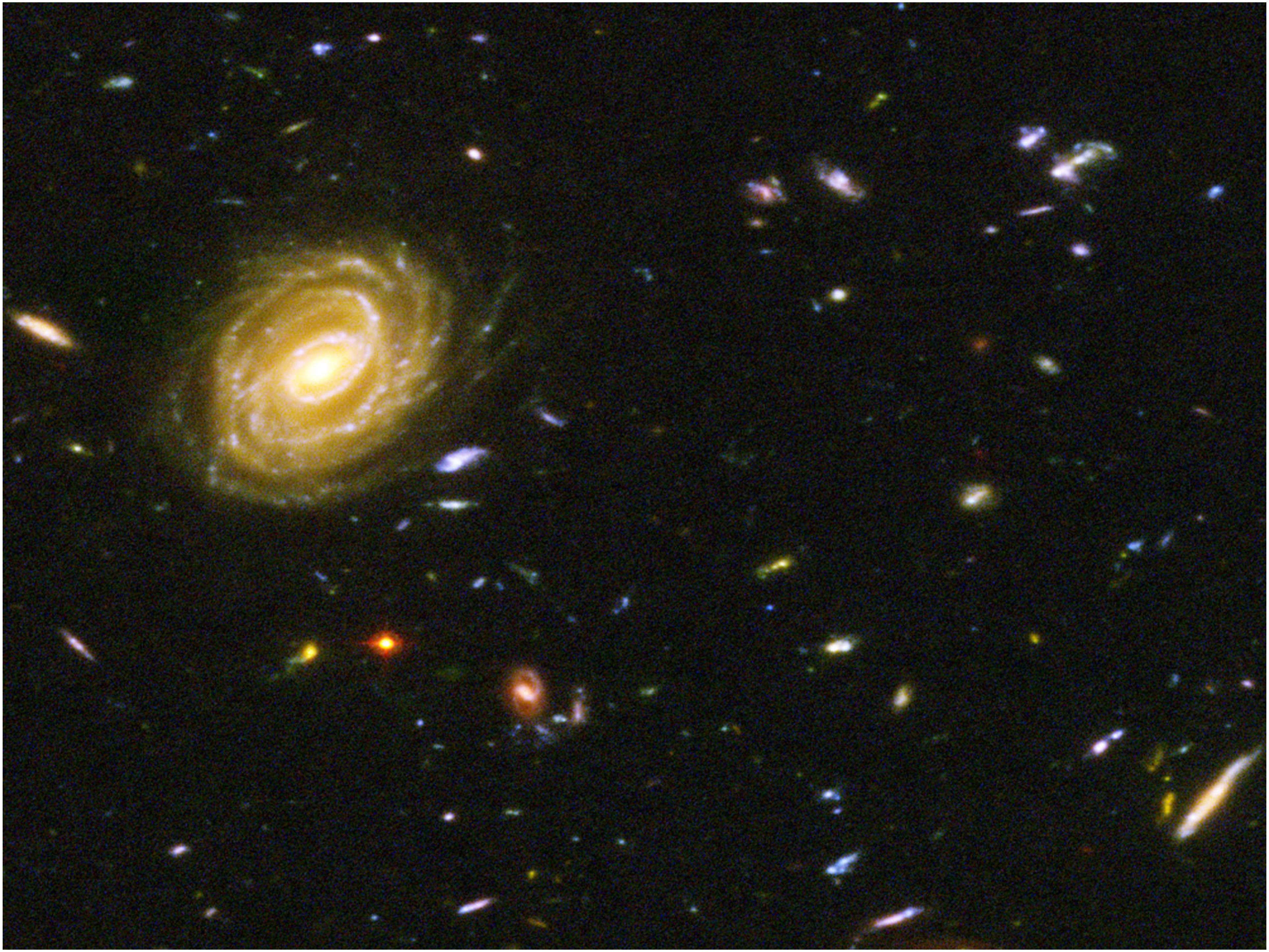


Zero-modes

$k_1^+ = 0$, $k_2^+ = 0$

Stability Group

6 $\qquad$ 7 (maximum)



PHYSICAL REVIEW C **92**, 055203 (2015)

Variational analysis of mass spectra and decay constants ···

Ho-Meoyng Choi,[1] Chueng-Ryong Ji,[2] Ziyue Li,[2] and Hui-Young Ryu[1]

[1]*Department of Physics, Teachers College, Kyungpook National University, Daegu, Korea 702-701*

[2]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695-8202, USA*

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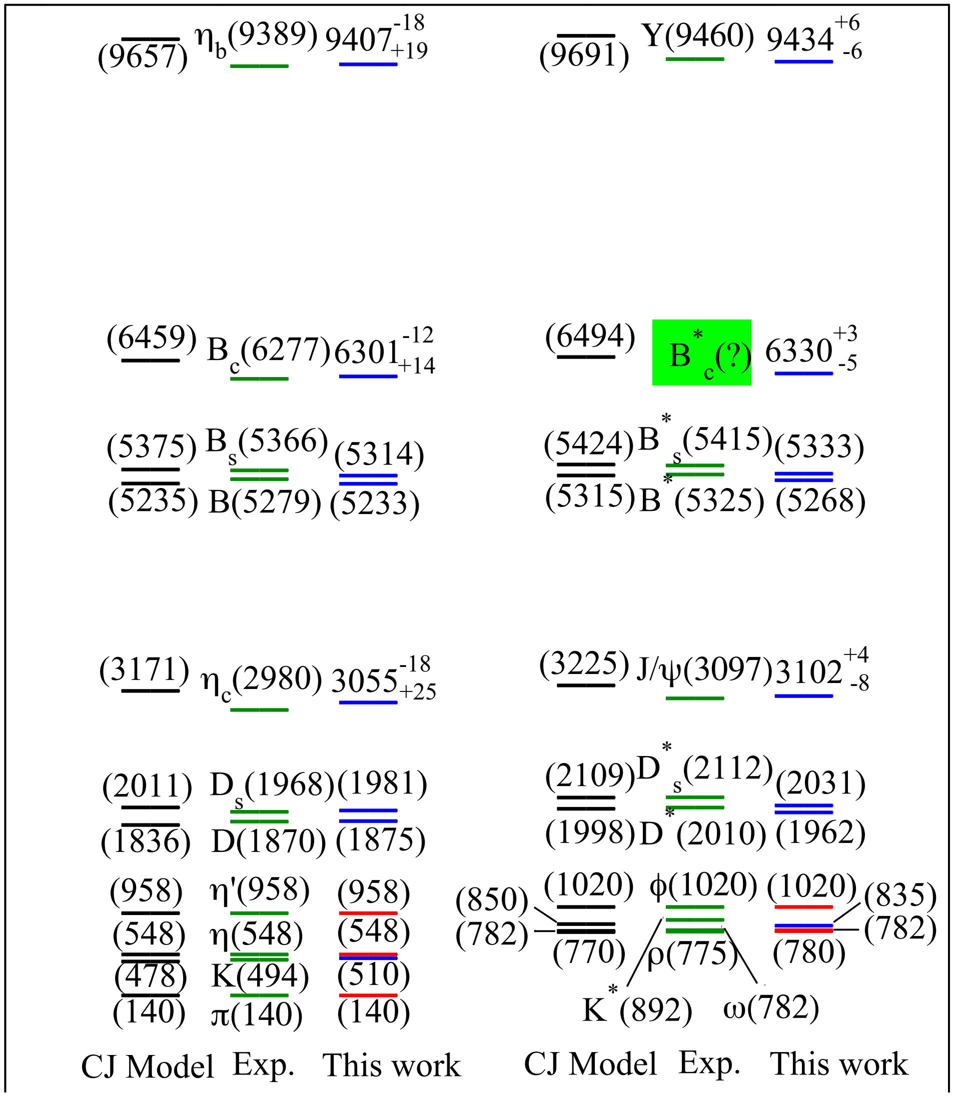
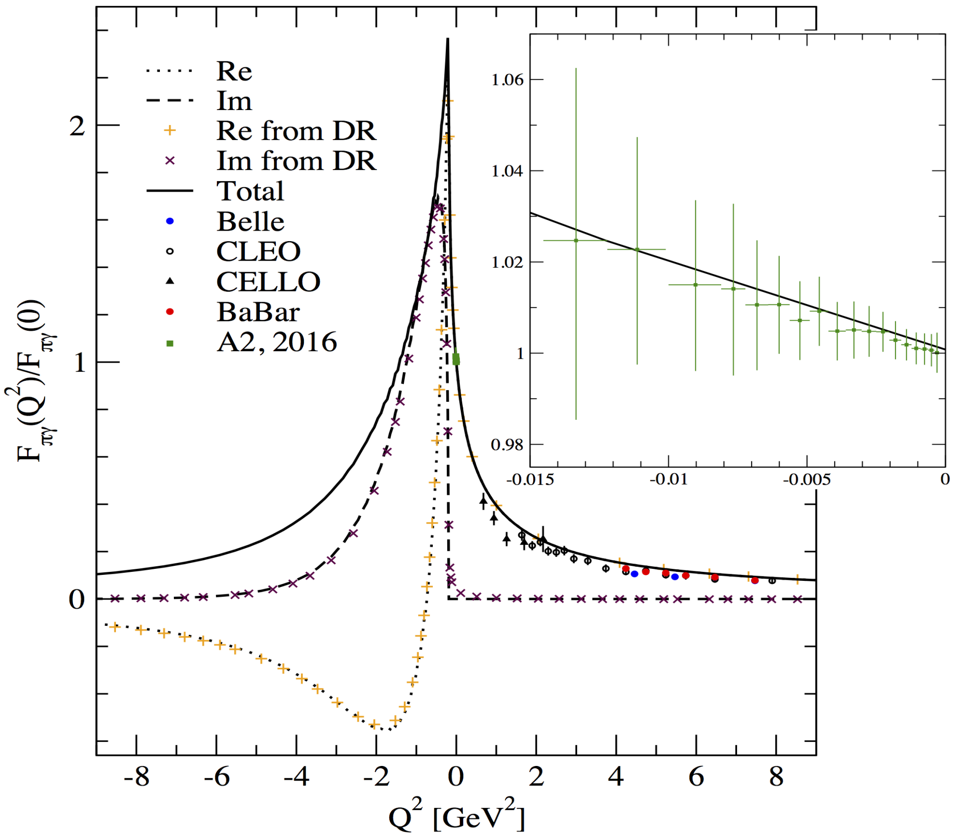
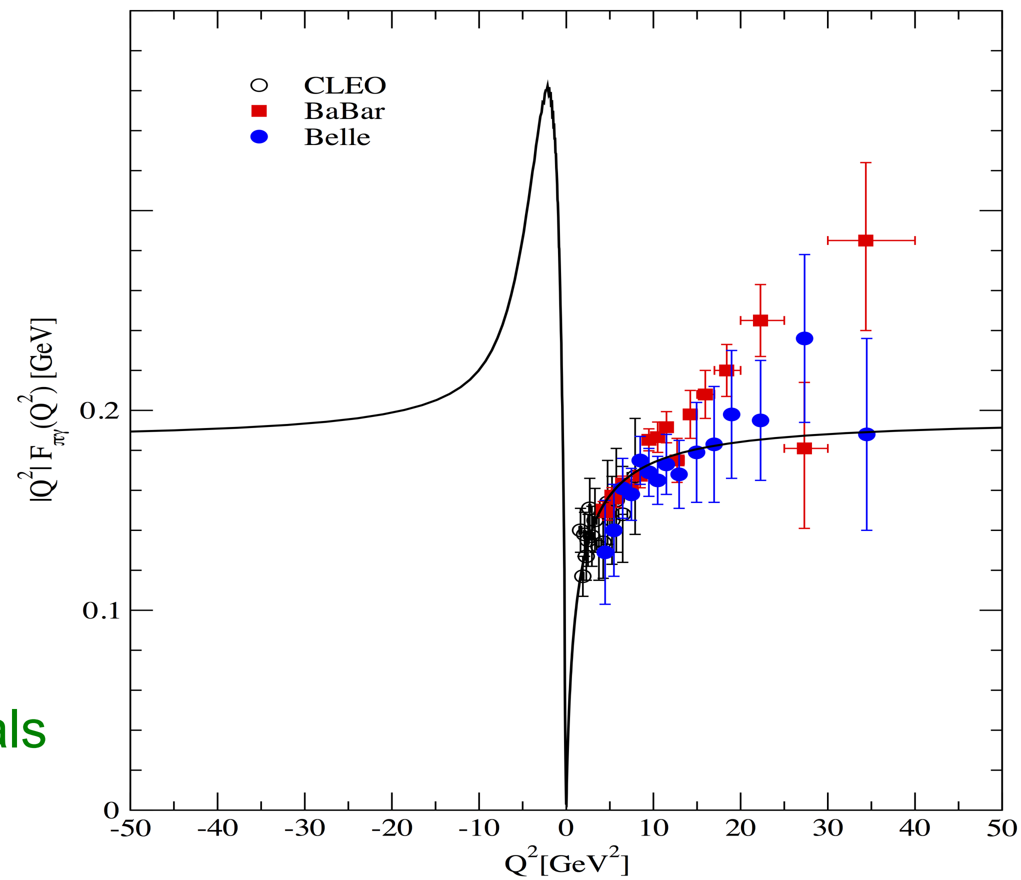




Both spacelike and timelike form factors can be computed in LFQM.

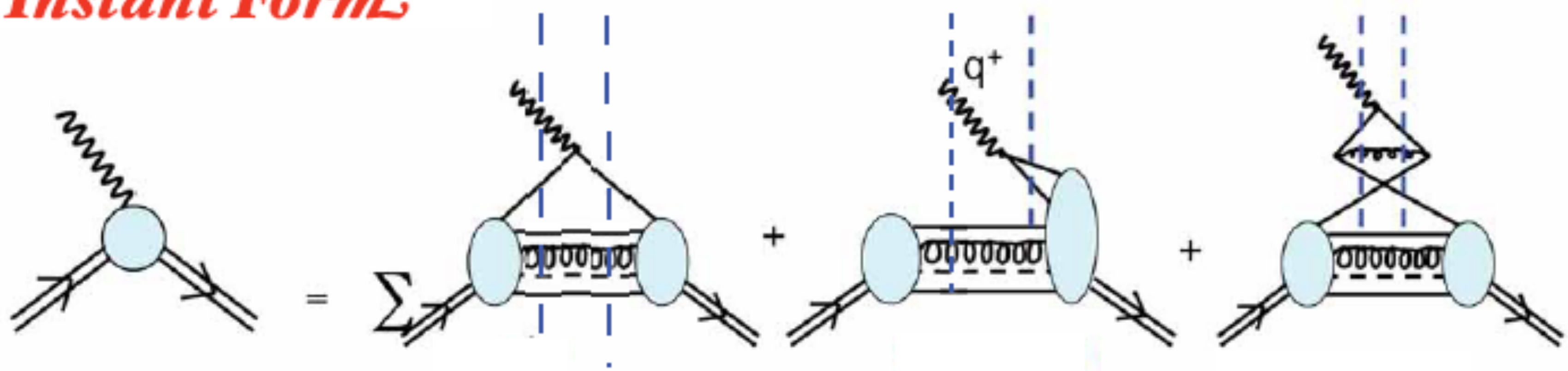


H.-M. Choi, H.-Y. Ryu, C.-R.Ji, PRD96, 056008 (2017)

LFQM applications since 1997
~ 28 papers in peer reviewed journals

Calculation of Form Factors in Equal-Time Theory

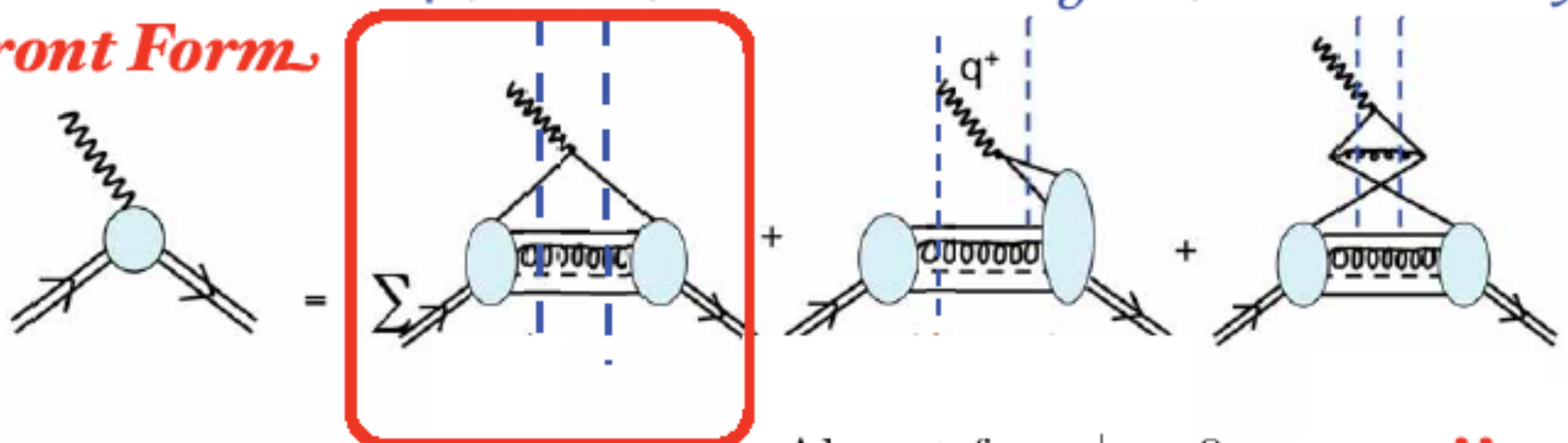
Instant Form



Need vacuum-induced currents

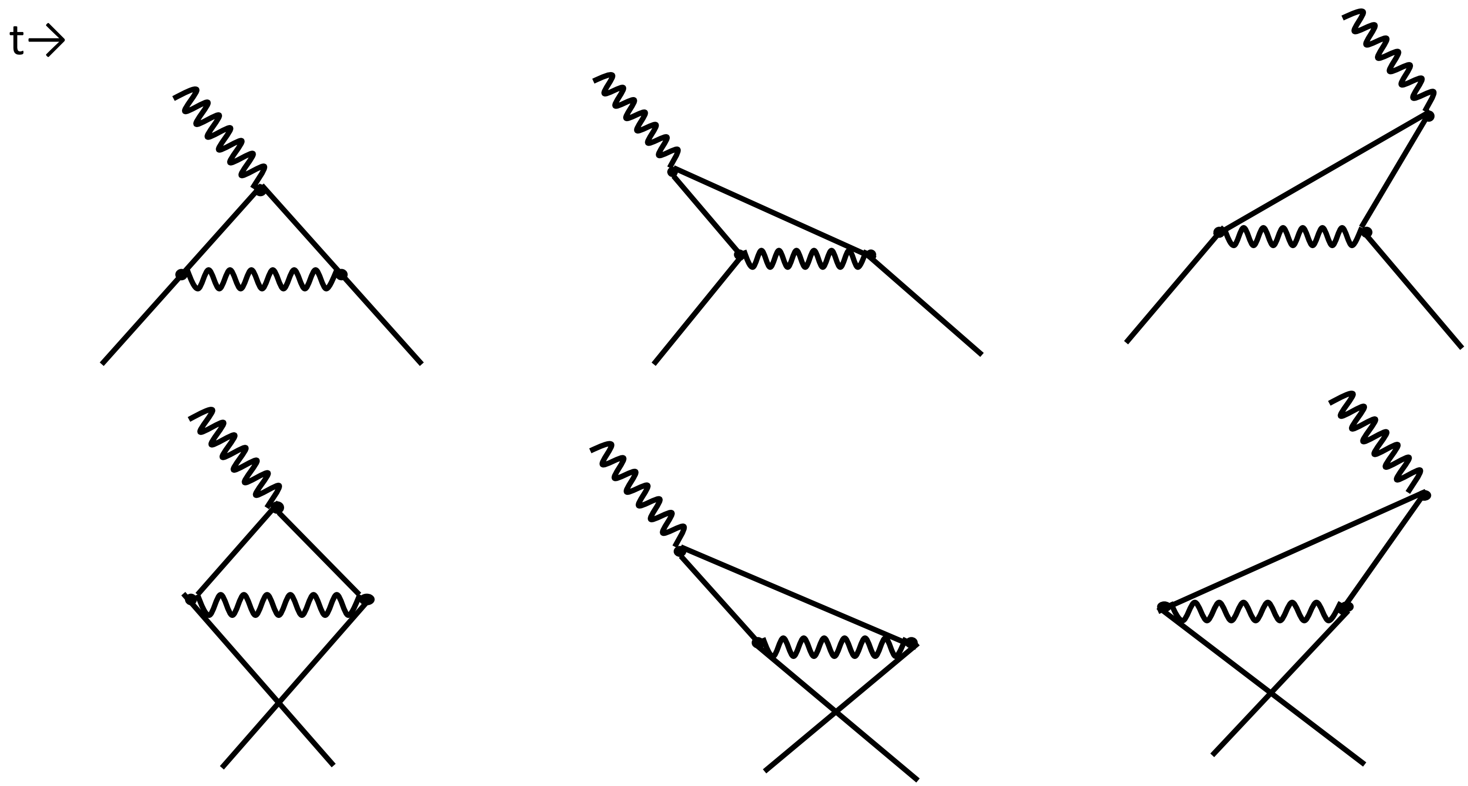
Calculation of Form Factors in Light-Front Theory

Front Form

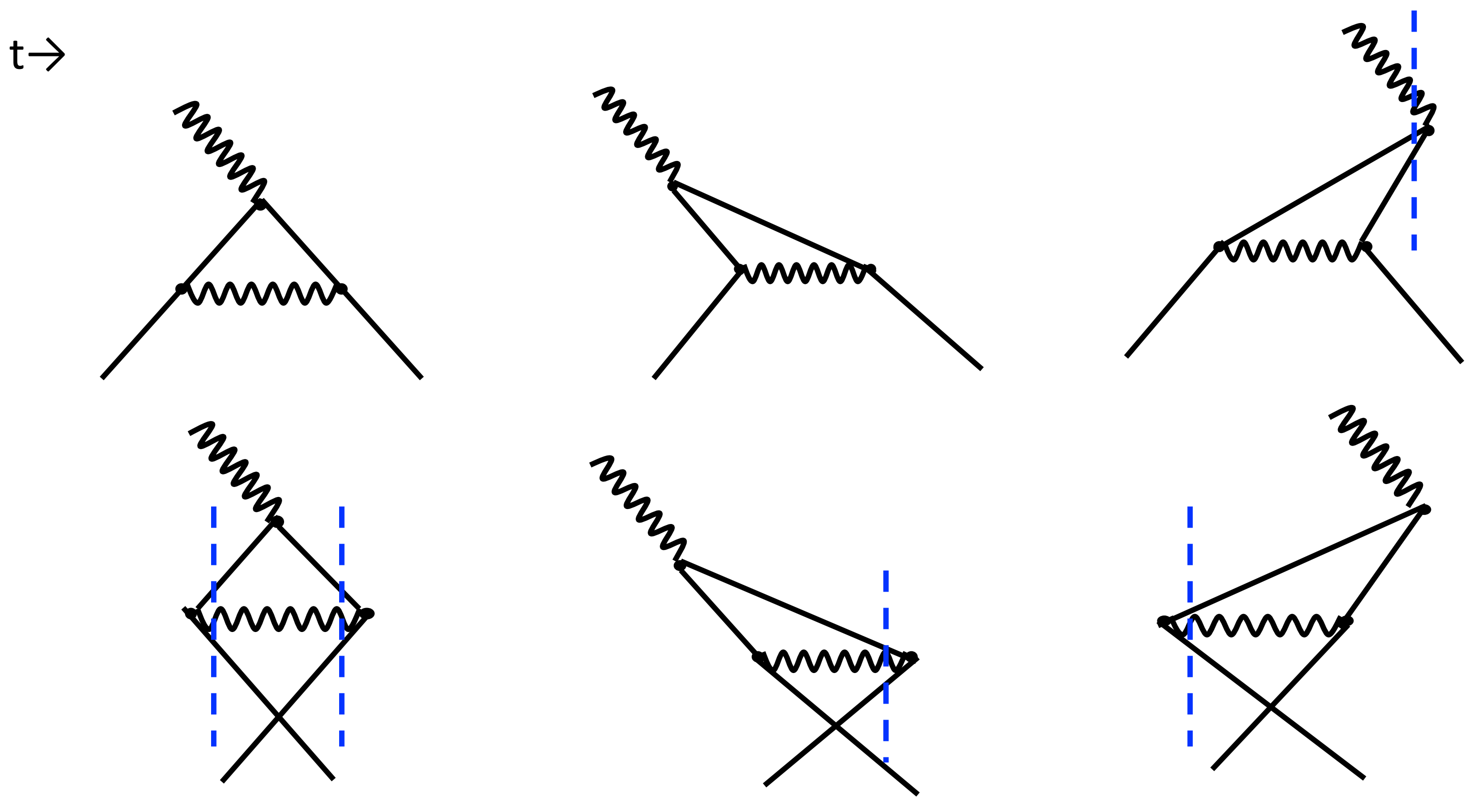


Absent for $q^+ = 0$ **zero !!**

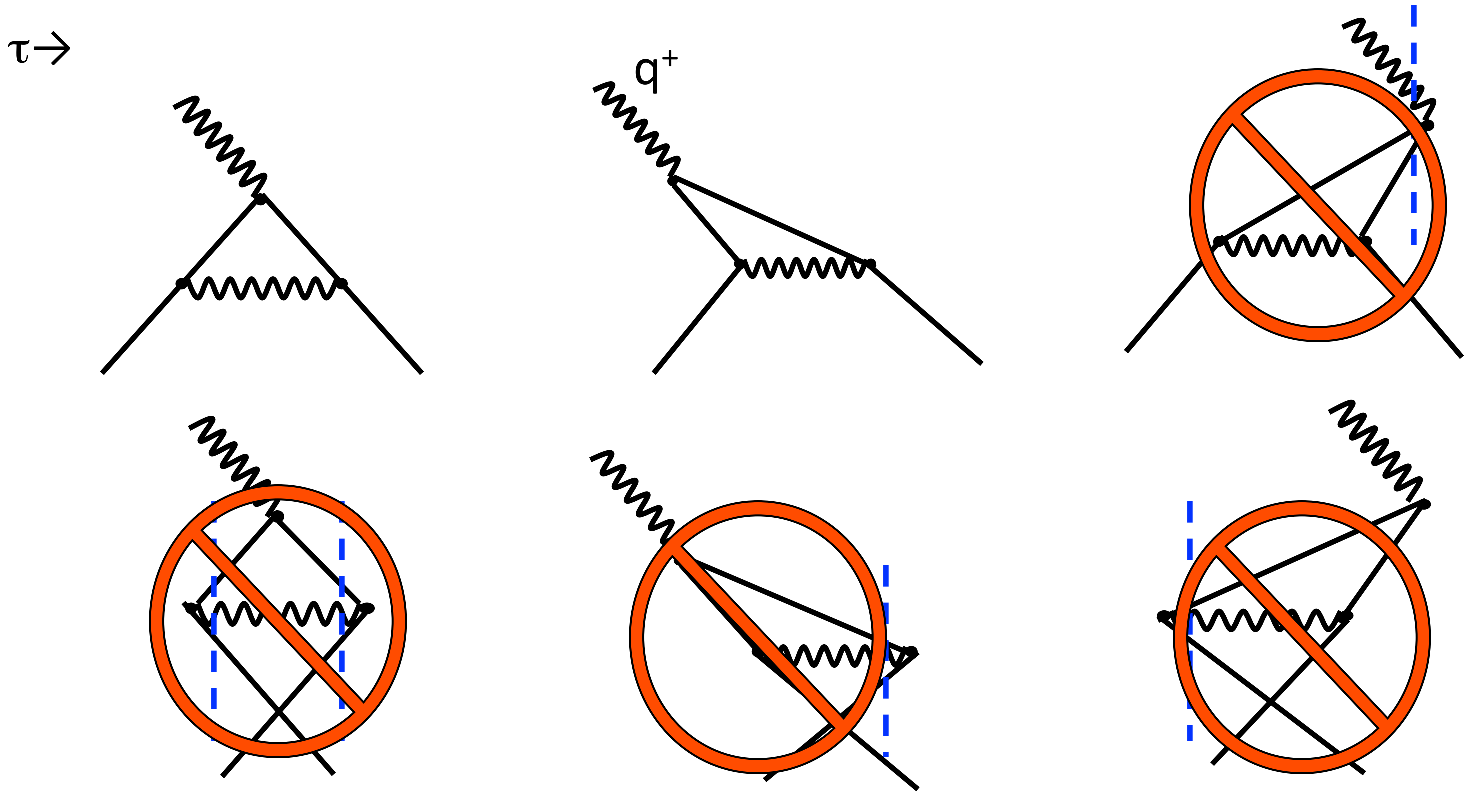
g-2 calculation



g-2 calculation

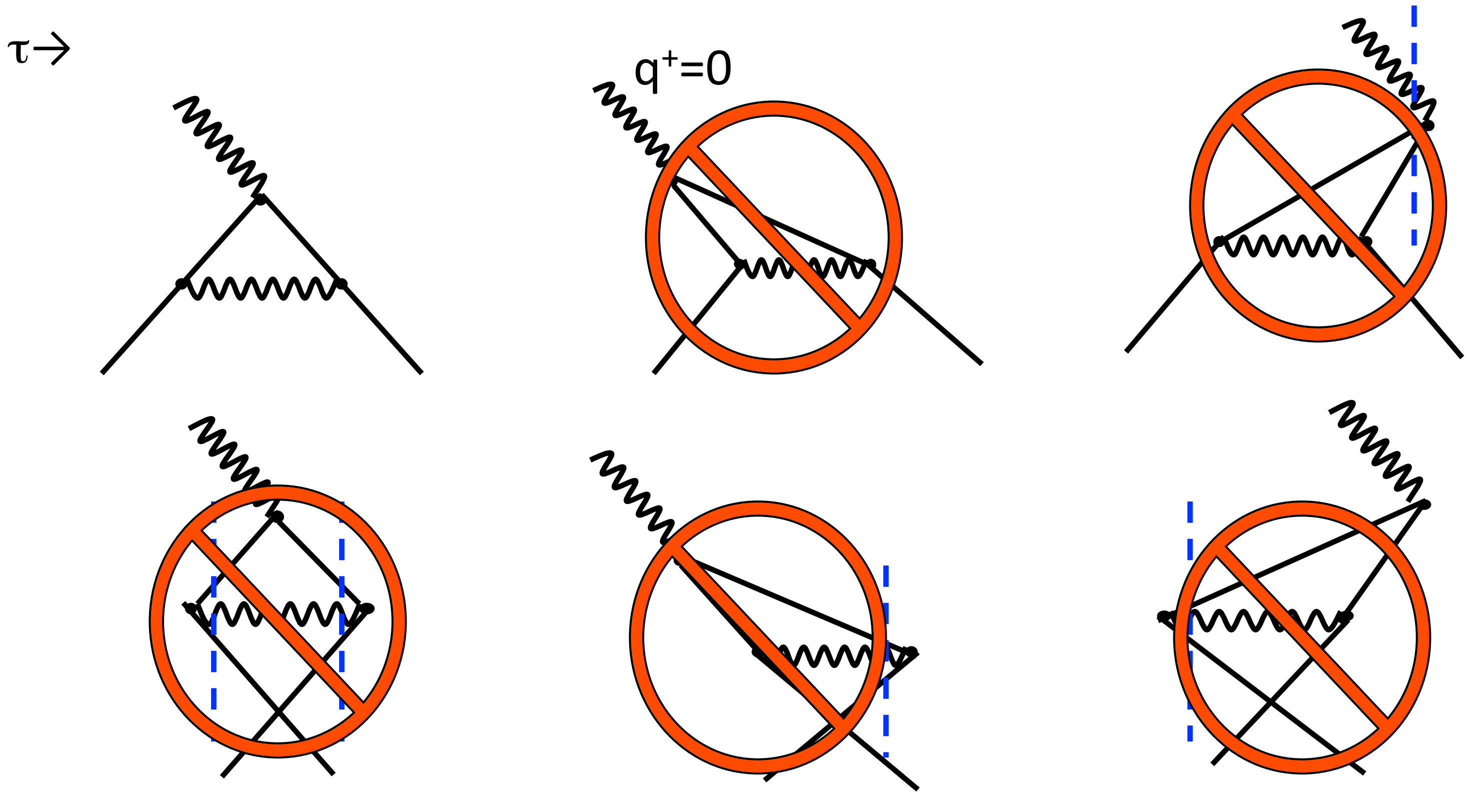


g-2 calculation



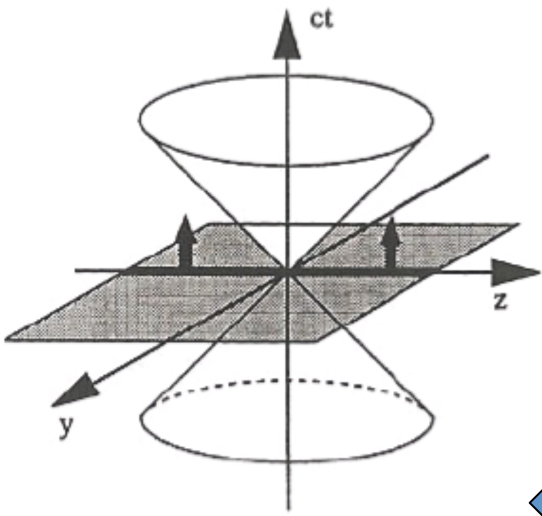
- Vacuum fluctuations are suppressed in LFD and clean hadron phenomenology is possible.

g-2 calculation



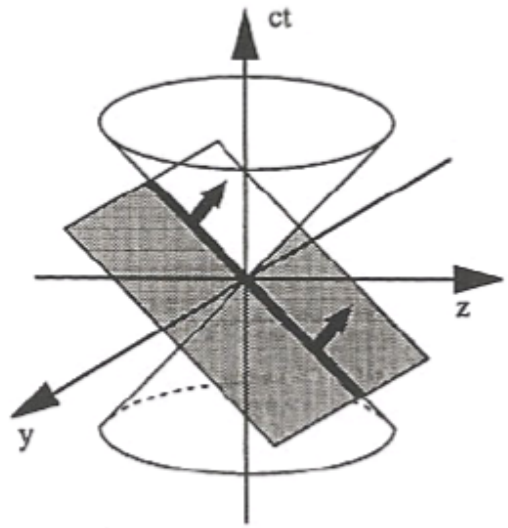
- Vacuum fluctuations are suppressed in LFD and clean hadron phenomenology is possible.

Dirac's Proposition



The instant form

1949



The front form

Can they be linked?

Traditional approach
evolved from NR dynamics

Innovative approach
for relativistic dynamics

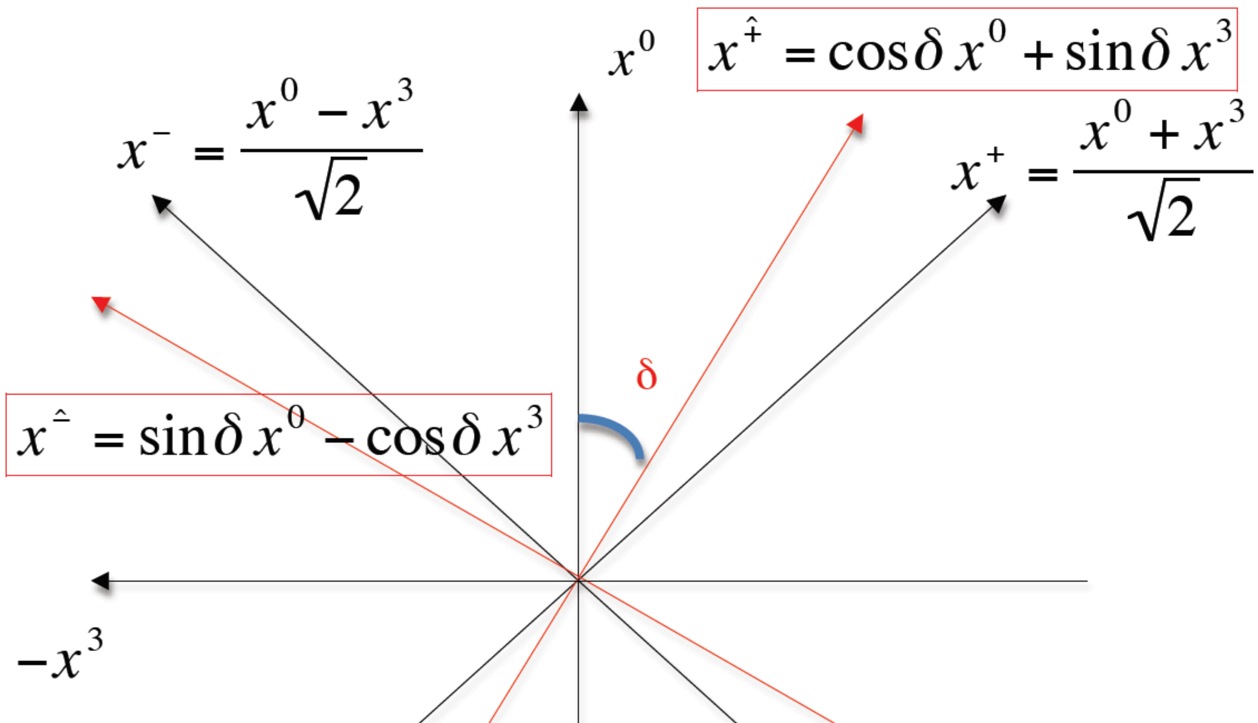
Close contact with
Euclidean space

Strictly in Minkowski space

T-dept QFT, LQCD, IMF, etc.

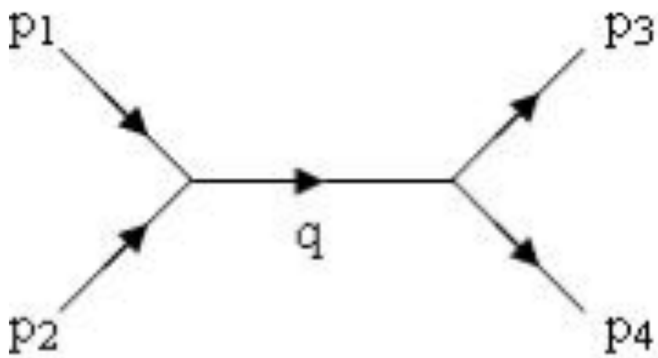
DIS, PDFs, DVCS, GPDs, etc.

Interpolation between Instant and Front Forms



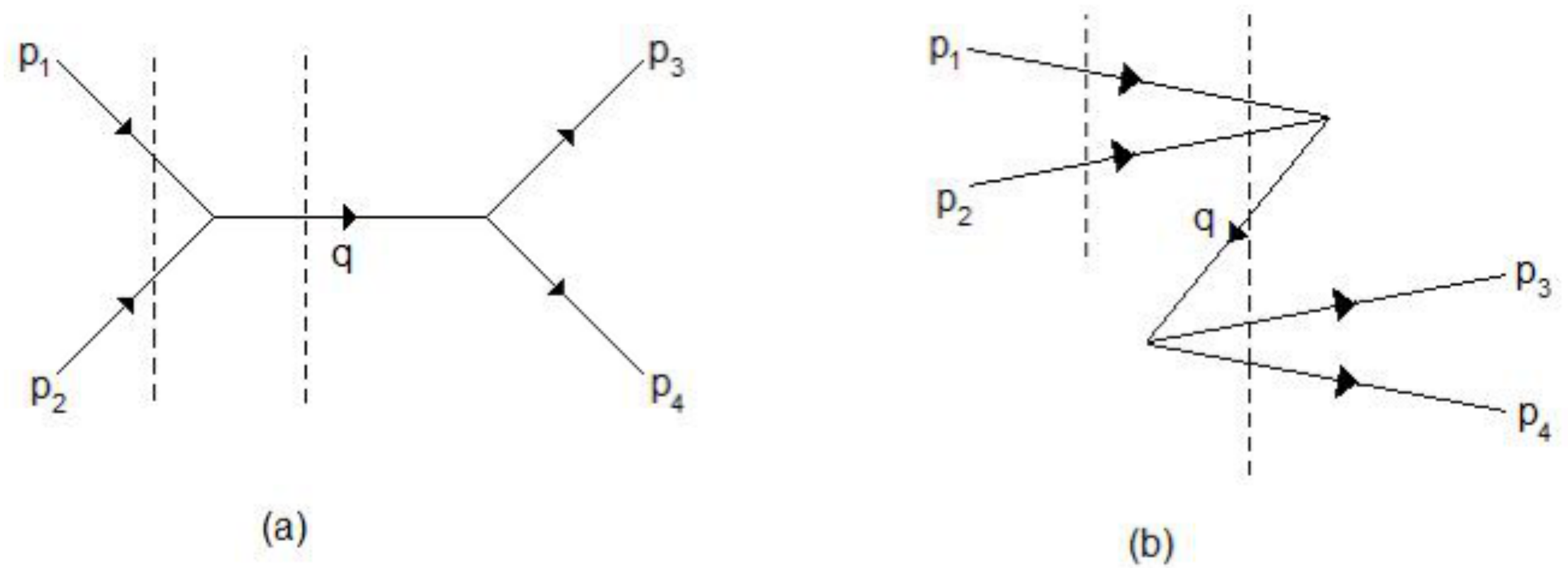
K. Hornbostel, PRD45, 3781 (1992) – RQFT
C.Ji and S.Rey, PRD53,5815(1996) – Chiral Anomaly
C.Ji and C. Mitchell, PRD64,085013 (2001) – Poincare Algebra
C.Ji and A. Suzuki, PRD87,065015 (2013) – Scattering Amps
C.Ji, Z. Li and A. Suzuki, PRD91, 065020 (2015) – EM Gauges
Z.Li, M. An and C.Ji, PRD92, 105014 (2015) – Spinors
C.Ji, Z.Li, B.Ma and A.Suzuki, arXiv:1805.06599 – QED

$$\text{“}e^+e^- \to \mu^+\mu^-\text{”}$$



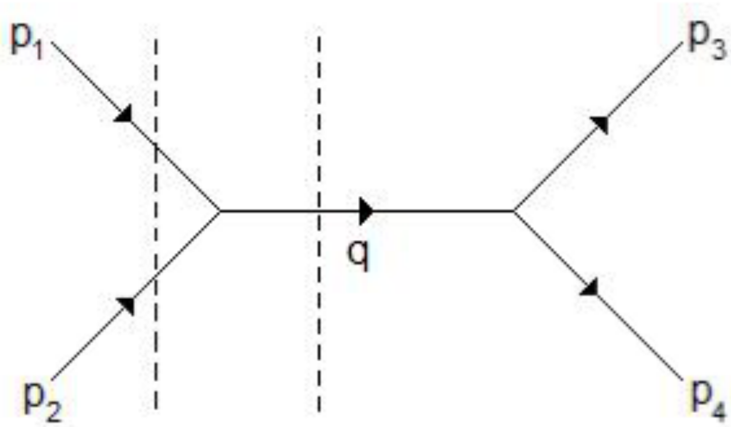
$$= \frac{1}{q^2 - m^2} = \frac{1}{s - m^2}$$

Feynman Diagram: Invariant under all Poincaré generators



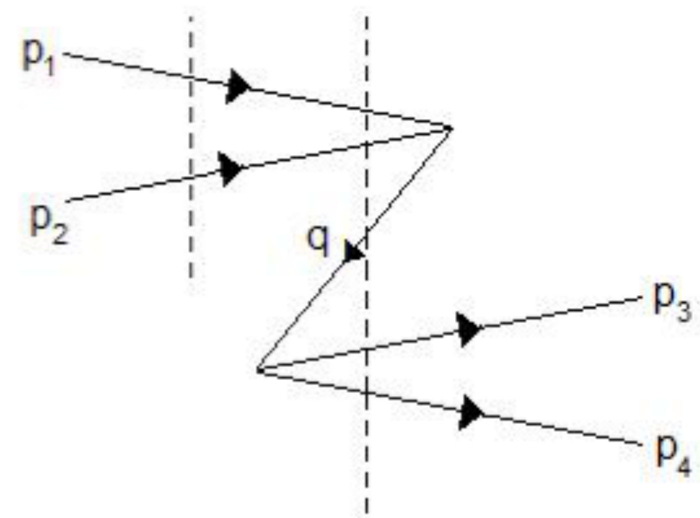
Individual Time-Ordered Diagrams: Invariant under stability group

Kinematic vs. Dynamic Generators



(a)

$$\frac{1}{E_1 + E_2 - Eq}$$



(b)

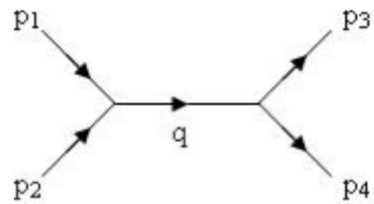
$$-\frac{1}{Eq + E_3 + E_4}$$

$$= -\frac{1}{Eq + E_1 + E_2}$$

$$\rightarrow \quad 0$$

S.Weinberg, PR158,1638(1967)
"Dynamics at Infinite Momentum"

Note however this is still in the instant form.



$\delta = 0$

$p_0 = p^0$

$-p_3 = p^3$

$0 < \delta < \pi/4$

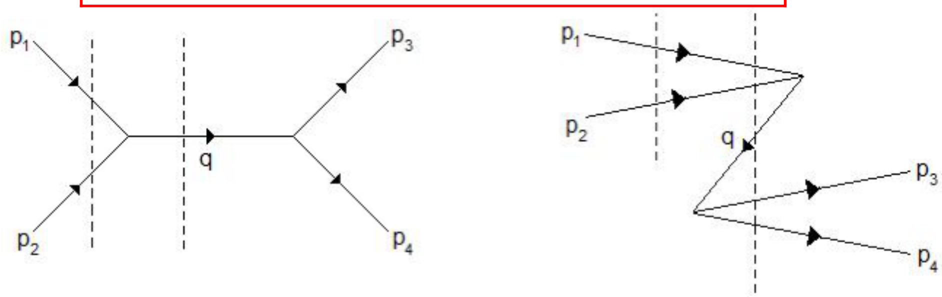
$p_{\hat{+}} = p^0 \cos\delta - p^3 \sin\delta$

$p_{\hat{-}} = p^0 \sin\delta + p^3 \cos\delta$

$\delta = \pi/4$

$p_+ = p^-$

$p_- = p^+$



(a) (b)

$$\frac{1}{2q^0}\left(\frac{1}{p_1^0 + p_2^0 - q^0} - \frac{1}{p_1^0 + p_2^0 + q^0}\right)$$

$$\frac{1}{2\omega_q}\left(\frac{1}{P_{\hat{+}} + \frac{\mathbb{S}q_{\hat{-}} - \omega_q}{\mathbb{C}}} - \frac{1}{P_{\hat{+}} + \frac{\mathbb{S}q_{\hat{-}} + \omega_q}{\mathbb{C}}}\right)$$

$$\omega_q = \sqrt{q_{\hat{-}}^2 + \mathbb{C}\left(\vec{\mathbf{q}}_{\perp}^2 + m^2\right)}$$

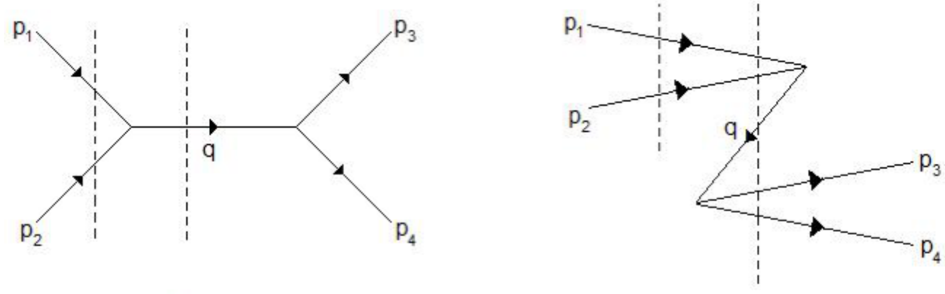
$$\mathbb{C} = \cos 2\delta$$

$$\mathbb{S} = \sin 2\delta$$

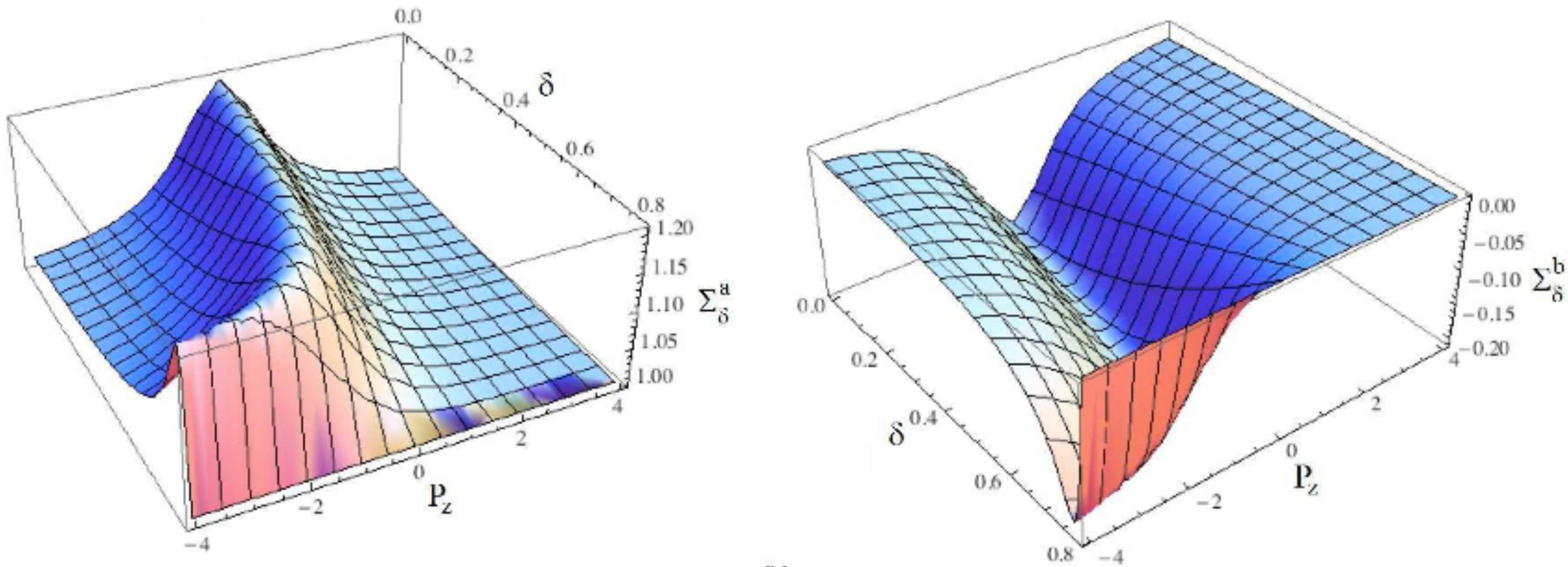
$$\frac{1}{P^+}\frac{1}{\left\{P^- - \frac{(\vec{\mathbf{P}}_{\perp}^2 + m^2)}{2P^+}\right\}}$$

$$\frac{\mathbb{S}q_{\hat{-}} + \omega_q}{\mathbb{C}} \to \frac{2}{\mathbb{C}} - \frac{\vec{\mathbf{q}}_{\perp}^2 + m^2}{2q_{\hat{-}}} + \mathcal{O}(\mathbb{C})$$

$$\to \infty \quad \text{as } \mathbb{C} \to 0$$



(a) (b)

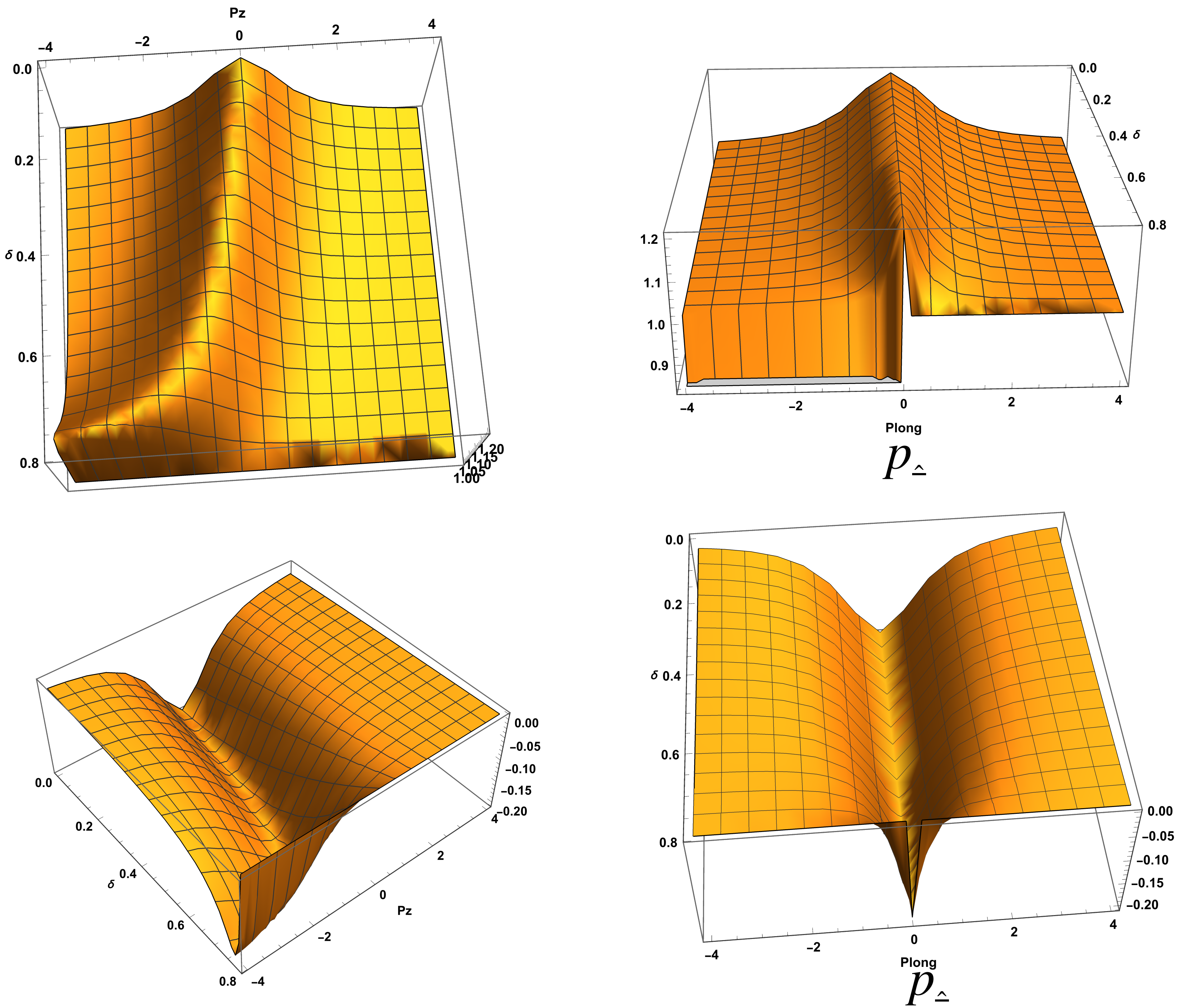


(a) (b)

Σ(a)+Σ(b)=1/(s-m²) ; s=2 GeV², m=1GeV

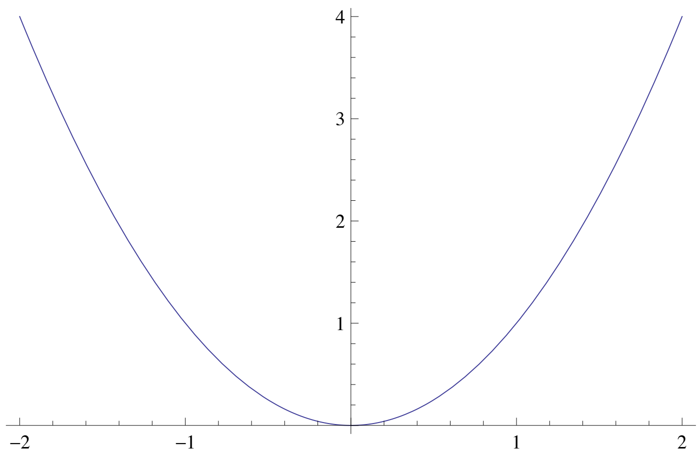
J-shape peak & valley : $P_z = -\sqrt{\frac{s(1-C)}{2C}}$; $C = \cos(2\delta)$

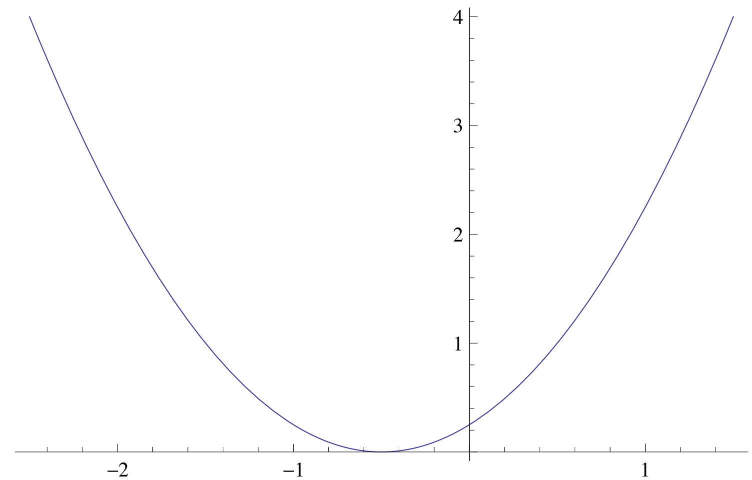
As C → 0, $P^+ = P^0 + P_z \to 0$ leads to LF Zero-modes.



Pz
δ
Plong
δ
$p_{\hat{}}$
δ
Pz
δ
Plong
$p_{\hat{}}$

Symmetry Breaking





$$\phi \longrightarrow \phi' = \phi + \nu$$

$$L \longrightarrow L' = L - m^2 \nu \phi - \frac{1}{2} m^2 \nu^2$$

$$P_{\hat{+}} \longrightarrow P'_{\hat{+}} = P_{\hat{+}} + \frac{\left(m^3 \ell\right)^{1/2} \nu}{C^{1/4}} (a_0 + a_0^+)$$, where $C = \cos 2\delta$

Nontrivial Vacuum State

$$|0> \rightarrow |\Omega>$$

Translation in scalar field: $\phi \rightarrow \phi' = \phi + v$

$$|\Omega> = \exp\left(i \int_{-\ell}^{+\ell} dx^{\hat{-}} v\, \pi(x^{\hat{-}}) \right) |0>$$

$$\pi(x^{\hat{+}} = 0, x^{\hat{-}}) = -i \sum_{n=-\infty}^{\infty} \left(\frac{\pi}{\ell} \right) \sqrt{\frac{\omega_n}{4\pi}} \left[a_n e^{-i\left(\frac{n\pi}{\ell}\right)x^{\hat{-}}} - a_n^{+} e^{i\left(\frac{n\pi}{\ell}\right)x^{\hat{-}}} \right]$$

$$|\Omega> = \exp\left[-(C^{1/2} m\ell) \frac{v^2}{2} \right] \exp\left[-(C^{1/2} m\ell)^{1/2} v a_0^{+} \right] |0>$$

Condensation of Zero-Modes

Vacuum Energy

$$P_{\hat{+}}\,|\Omega>=E_{\Omega}\,|\Omega>$$

$$a\,e^{\alpha a^{+}}\,|0>=\alpha\,e^{\alpha a^{+}}\,|0>$$

$$P_{\hat{+}}\,|\Omega>\longrightarrow\left[\frac{m\nu}{C^{1/2}}a_0^{+}a_0+\frac{\left(m^3\ell\right)^{1/2}\nu}{C^{1/4}}(a_0+a_0^{+})\right]\exp\left[-(C^{1/2}m\ell)^{1/2}\nu a_0^{+}\right]|0>$$

$$=(-m^2\nu^2\ell)\exp\left[-(C^{1/2}m\ell)^{1/2}\nu a_0^{+}\right]|0>$$

$$E_{\Omega}=-m^2\nu^2\ell=\int_{-\ell}^{+\ell}(-\frac{1}{2}m^2\nu^2)\,dx^{\hat{-}}$$

Independent of interpolation angle!

Recovery of Trivial Vacuum in LFD?

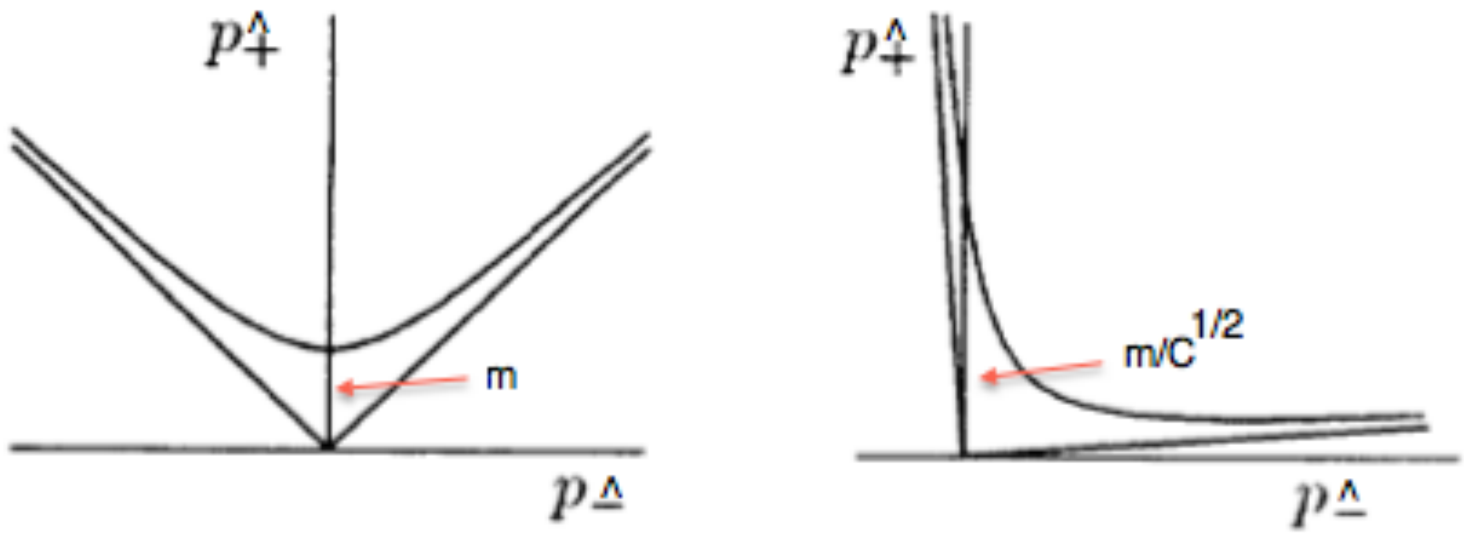
$$|\Omega> = \exp\left[-(C^{1/2}m\ell)\frac{\nu^2}{2}\right]\exp\left[-(C^{1/2}m\ell)^{1/2}\nu a_0^+\right]|0>$$

$$|\Omega> \rightarrow |0> \quad as \quad C \rightarrow 0$$

However, E_Ω and $<\Omega|\phi(x)|\Omega> = -\nu$

are still independent of interpolation angle!

What is going on?

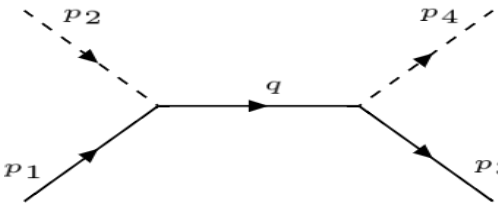


$$< \Omega | \phi(x) | \Omega >$$

$$= < 0 | \exp\left[(C^{1/2} m\ell)^{1/2} v (a_0^+ - a_0)\right] \left(\frac{a_0 + a_0^+}{2(C^{1/2} m\ell)^{1/2}} \right) \exp\left[-(C^{1/2} m\ell)^{1/2} v (a_0^+ - a_0)\right] | 0 >$$

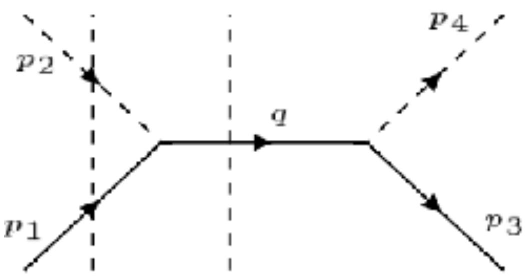
$$= -v$$

Complication is transferred from vacuum to operator.

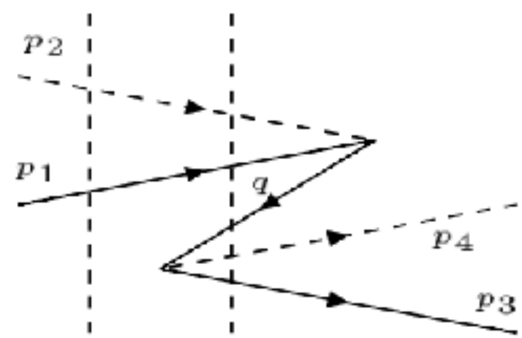


Constrained Degrees of Freedom of Fermion in Light-Front Dynamics

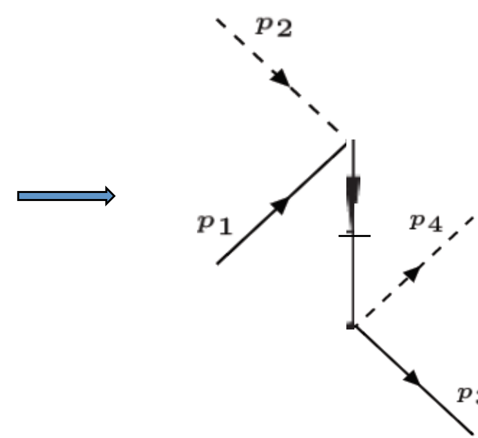
Fermion Propagator



(a)



(b)



$$\Sigma_a^{\mathrm{IFD}} + \Sigma_b^{\mathrm{IFD}} = \frac{1}{2q^0_{on}}\left(\frac{\not{q}+m}{q^0-q^0_{on}} - \frac{\not{q}+m}{q^0+q^0_{on}}\right) = \frac{1}{2q^0_{on}}\frac{2q^0_{on}(\not{q}+m)}{(q^0)^2-(q^0_{on})^2} = \frac{\not{q}+m}{q^2-m^2}$$

$$\Sigma_{a,\delta\to\frac{\pi}{4}} = \frac{\not{q}_{on}+m}{q^2-m^2}$$

$$\Sigma_{b,\delta\to\frac{\pi}{4}} = \frac{\gamma^+}{2q^+}$$

S.-J.Chang and T.-M.Yan, PRD7,1147(1973)

$$\frac{1}{\not{q}-m} = \frac{\sum_s u(q,s)\bar{u}(q,s)}{q^2-m^2} + \frac{\gamma^+}{2q^+}$$

$$A^{\hat{+}} = 0,\ \partial_{\hat{-}} A_{\hat{-}} + \boldsymbol{\partial}_\perp \mathbf{A}_\perp \mathbb{C} = 0 \quad (\mathbb{C} = \cos 2\delta)$$

$\delta \to 0$ $(\mathbb{C} \to 1)$

$\delta \to \pi/4$ $(\mathbb{C} \to 0)$

C.Ji, Z. Li, and A. T. Suzuki, PRD91, 065020(2015)

$$A^0 = 0,\ \nabla \cdot \mathbf{A} = 0$$

Coulomb Gauge

$$A^+ = 0$$

Light-front Gauge

$$\sum_{\lambda=\pm} \epsilon^*_{\hat{\mu}}(\lambda)\epsilon_{\hat{\nu}}(\lambda) = -g_{\hat{\mu}\hat{\nu}} + \frac{(q\cdot n)(q_{\hat{\mu}} n_{\hat{\nu}} + q_{\hat{\nu}} n_{\hat{\mu}})}{\mathbf{q}_\perp^2 \mathbb{C} + q_{\hat{-}}^2} - \frac{\mathbb{C} q_{\hat{\mu}} q_{\hat{\nu}}}{\mathbf{q}_\perp^2 \mathbb{C} + q_{\hat{-}}^2} - \frac{q^2 n_{\hat{\mu}} n_{\hat{\nu}}}{\mathbf{q}_\perp^2 \mathbb{C} + q_{\hat{-}}^2}$$

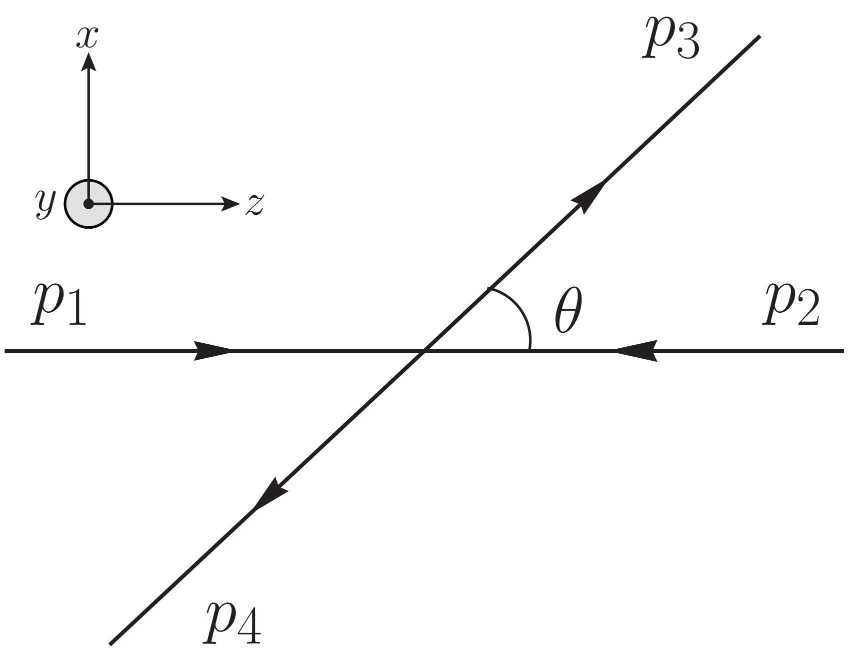
LFD

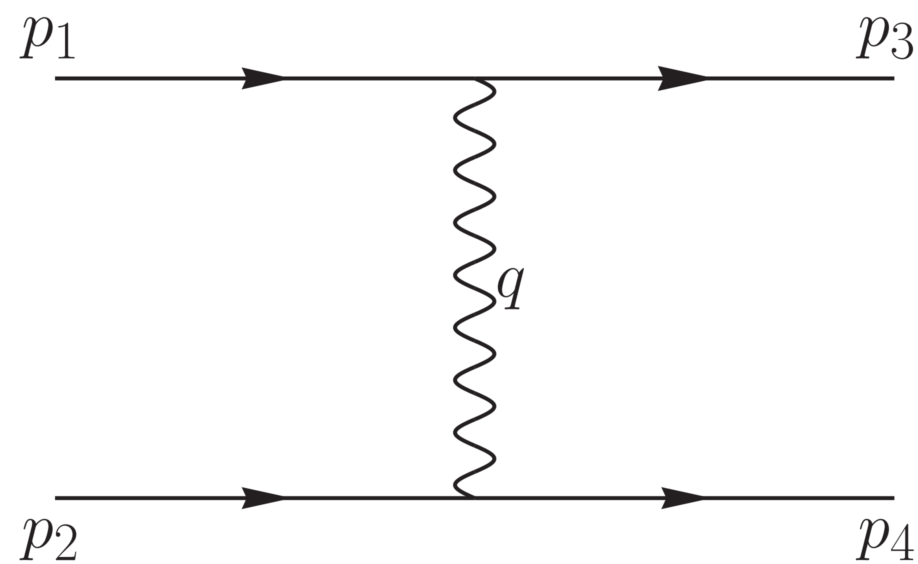
$$-g_{\mu\nu} + \frac{(q\cdot n)(q_\mu n_\nu + q_\nu n_\mu)}{(q\cdot n)^2} - \frac{q^2 n_\mu n_\nu}{(q\cdot n)^2}$$

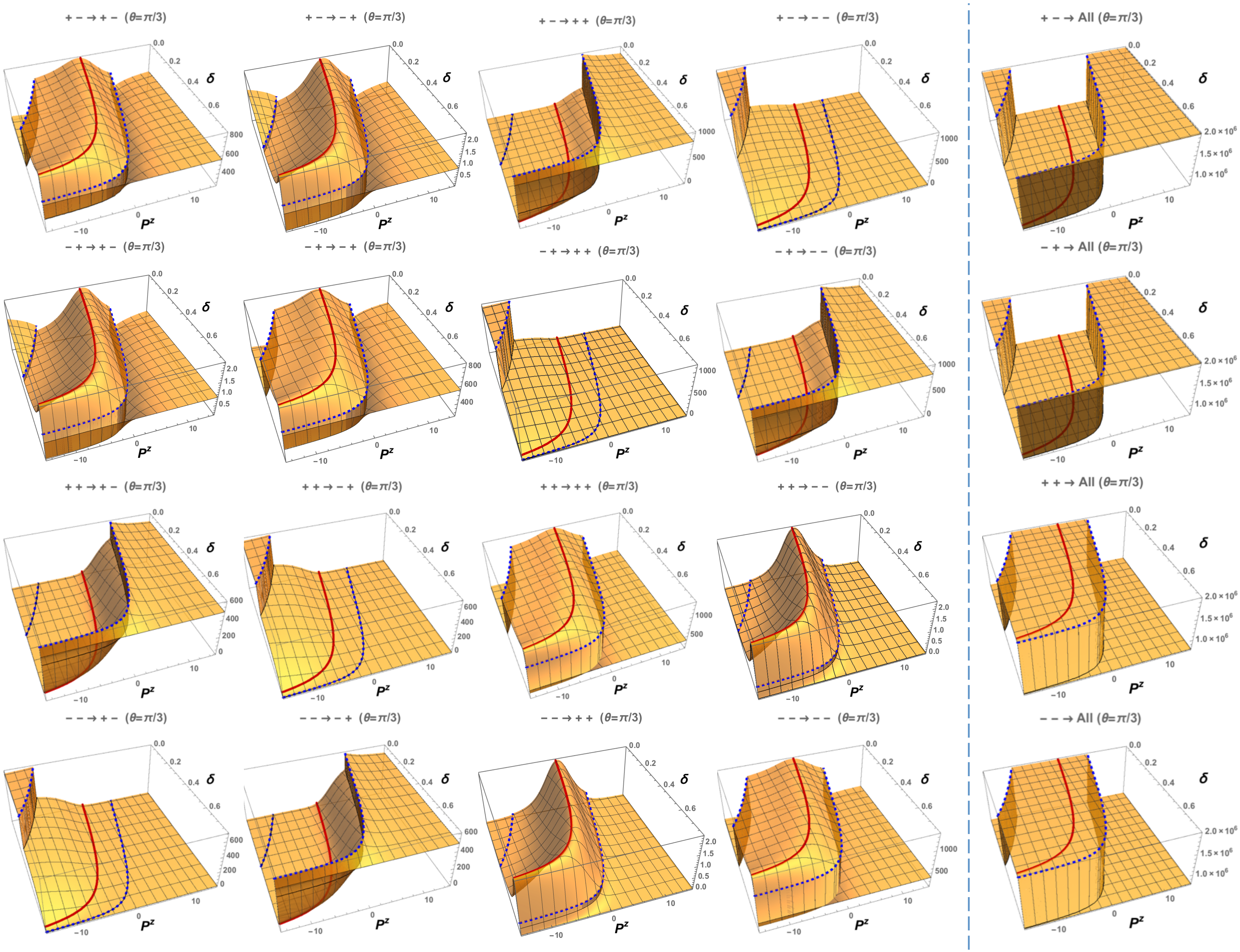
P.Srivastava and S. Brodsky, PRD64,045006(2001)

IFD

$$-\eta_{\mu\nu} + \frac{(q\cdot n)(q_\mu n_\nu + q_\nu n_\mu)}{(q\cdot n)^2 - q^2} - \frac{q_\mu q_\nu}{(q\cdot n)^2 - q^2} - \frac{q^2 n_\mu n_\nu}{(q\cdot n)^2 - q^2}$$


x
y
z
p_1
p_2
p_3
p_4
θ


p_1
p_3
q
p_2
p_4


+ − → + − (θ=π/3)
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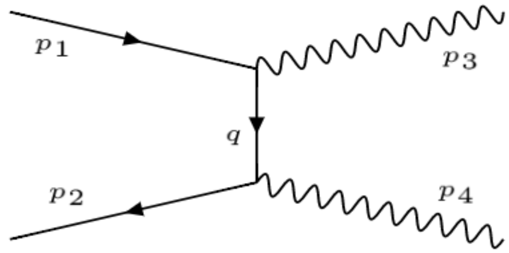
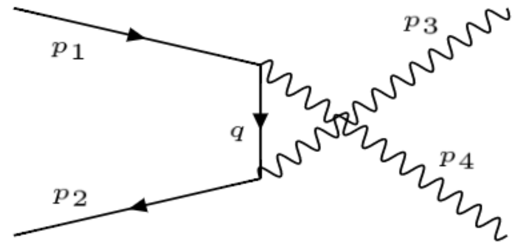
+ + → − − (θ=π/3)
+ + → All (θ=π/3)
− − → + − (θ=π/3)
− − → − + (θ=π/3)
− − → + + (θ=π/3)
− − → − − (θ=π/3)
− − → All (θ=π/3)
δ
P^z

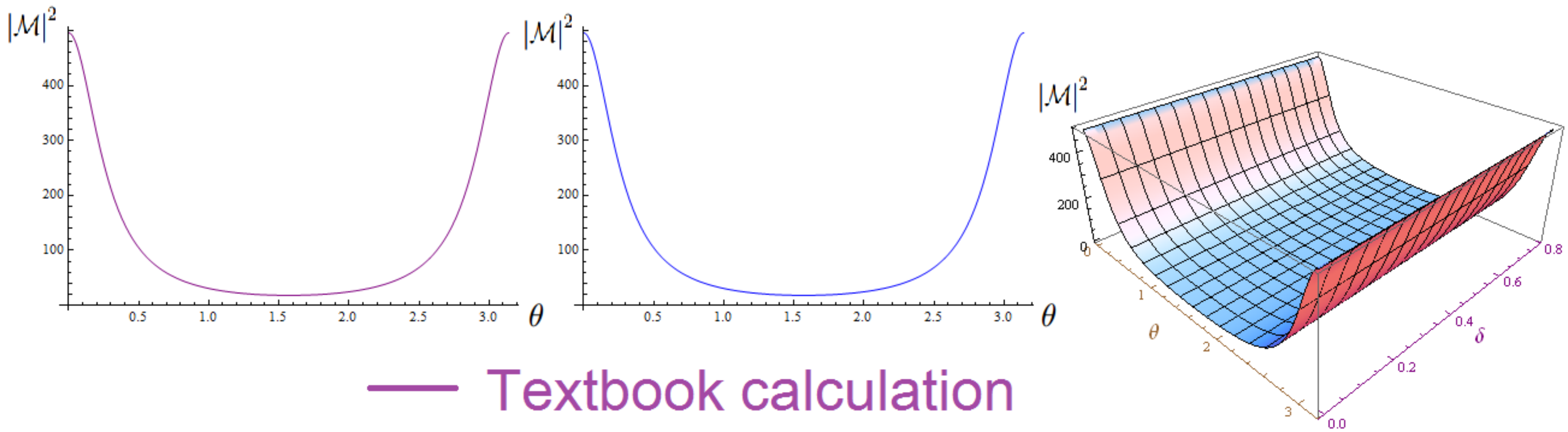


Direct Diagram



Exchanged Diagram

Including electron mass



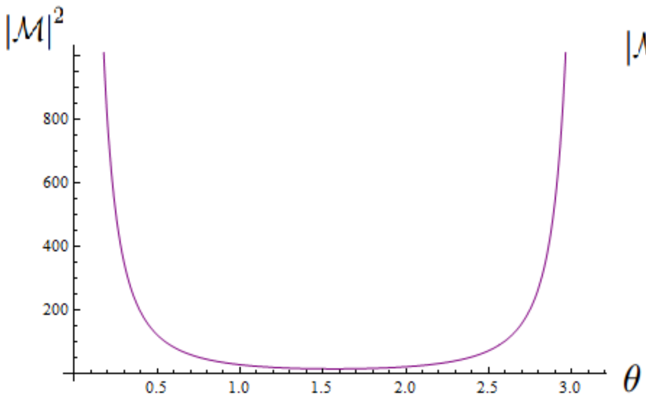
Textbook calculation

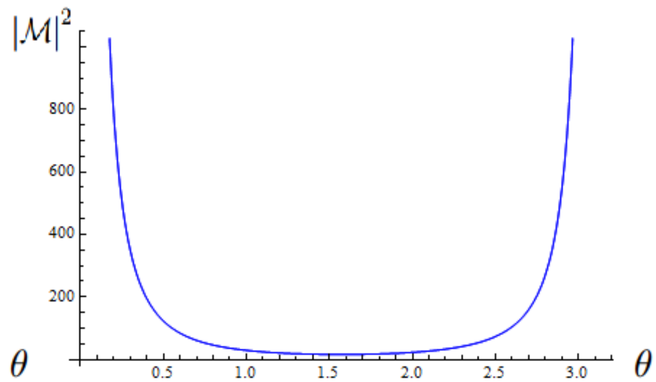
Our interpolation method

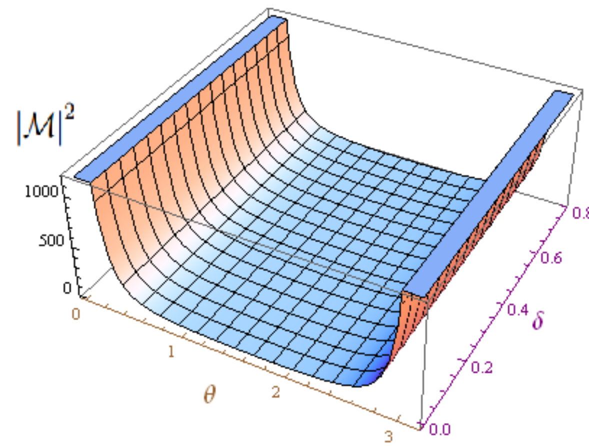
$$|\mathcal{M}|^2 = 2e^4\left[\frac{u_m}{t_m} + \frac{t_m}{u_m} + 2m^2\left(\frac{s_m}{t_m u_m} - \frac{1}{t_m} - \frac{1}{u_m}\right) - 4m^4\left(\frac{1}{{t_m}^2} + \frac{1}{{u_m}^2}\right)\right]$$

where $t_m \equiv t - m^2$, $u_m \equiv u - m^2$, and $s_m \equiv s - 4m^2$.

Taking electron mass zero





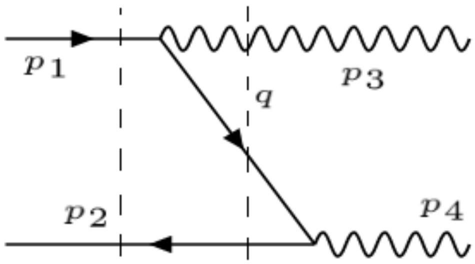


Textbook calculation

Our interpolation method

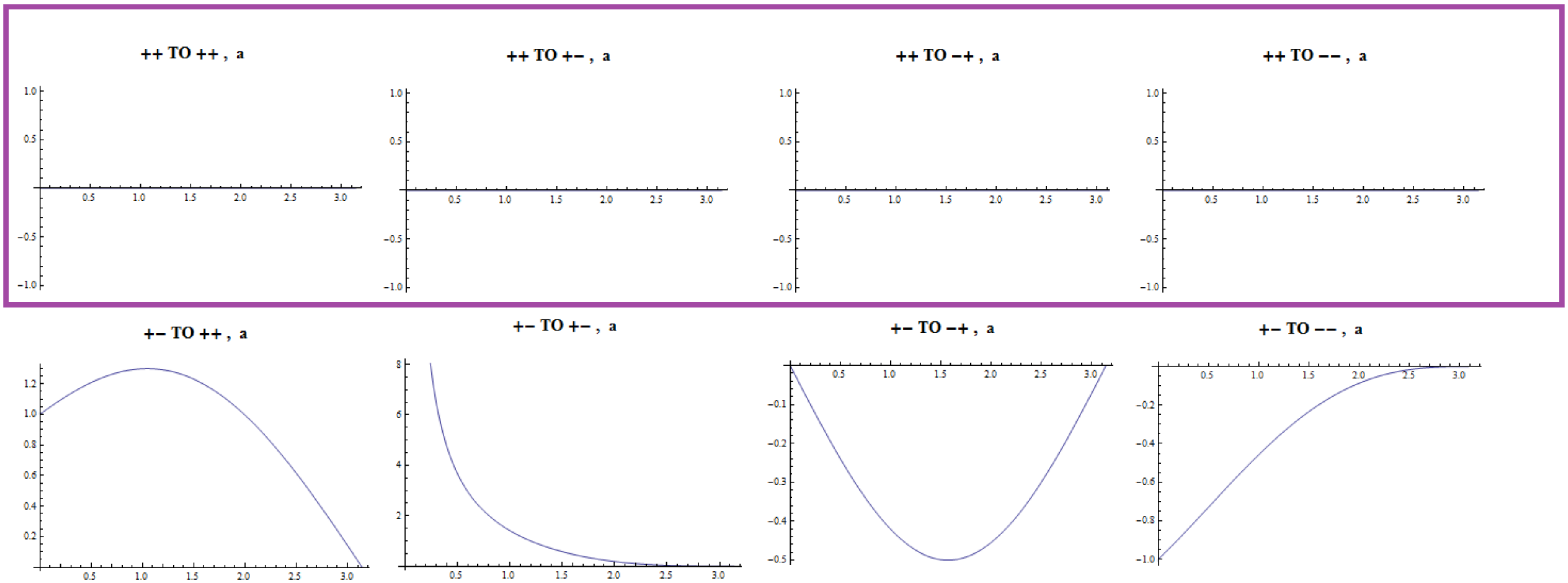
$$|\mathcal{M}|^2 = 2e^4\left(\frac{u}{t} + \frac{t}{u}\right)$$

Scattering Angle Dependence of the Annihilation Amplitudes: Chirality

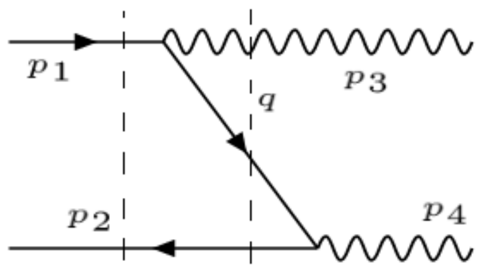


(a)

When m_e=0, chirality is conserved.

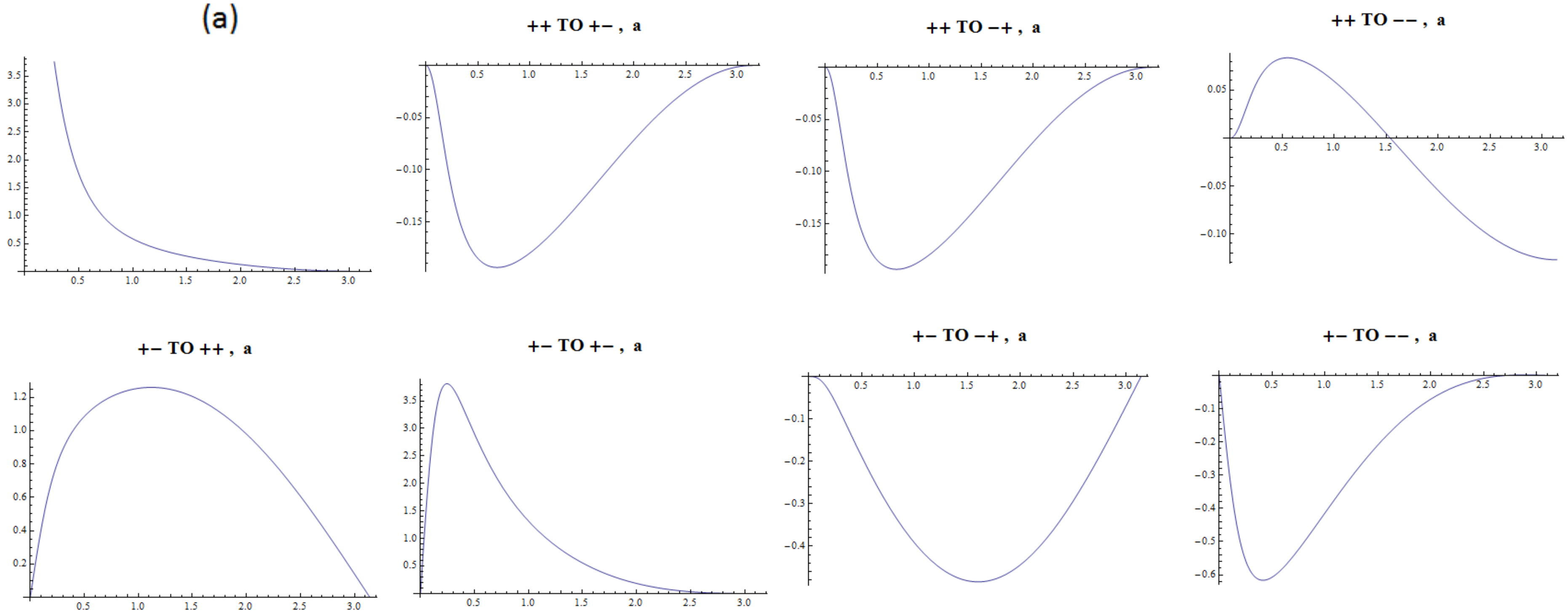


Scattering Angle Dependence of the Annihilation Amplitudes: Chirality



(a)

When $m_e \neq 0$, no such property.



Outlook

- “A method is more important than a discovery, since the right method will lead to new and even more important discoveries.” - Lev Landau
- LFQM saves a lot of dynamical effort in the hadron spectroscopy and structure study.
- Correspondence between IFD and LFD may shed more light on bridging the LFQM and the QCD.