Fictitious Dynamical Effects in Quantum Field Theory

A. Deur

Thomas Jefferson National Accelerator Facility

Work done in collaboration with

S. J. Brodsky.

SLAC National Accelerator Laboratory, Stanford University

Frame independence

Basic scientific principle: Convention choices (frame choice, system of units, renormalization scheme…) made in the study of a physical phenomenon cannot enter its fundamental description.

Classical mechanics's Galilean invariance: the fundamental and minimal description is given in inertial frames. It does not depend on the choice of inertial frame.
Descriptions given in non-inertial frames contain subjective (i.e. observer-dependent) "pseudo-forces" or "fictitious-forces", e.g. centrifugal force.

QFT's Poincaré invariance: physics cannot depend on the Lorentz frame of the observer.

This talk: Just like breaking Galilean invariance yields fictitious dynamics, breaking Poincaré invariance in QFT also leads to fictitious effects.

The framework to discuss Poincaré invariance in dynamical systems is the Dirac Forms of relativistic dynamics.

Dirac Forms of relativistic dynamics

P. A. M. Dirac, Rev. Mod. Phys. 21, 392 (1949)

Poincaré symmetry is a symmetry of the 4D space-time. The 10 symmetries underlying Poincaré's invariance are:

- Spacetime translations (4),
- Spatial rotations (3),
- Lorentz boosts (3).

Poincaré symmetry is dynamical: it mixes space and time.

⇒ Some of the generators of the Poincaré symmetry group involve interaction: dynamical operators, e.g Hamiltonian. Others are kinematical operators: interaction-free.

Dirac Forms of relativistic dynamics

P. A. M. Dirac, Rev. Mod. Phys. 21, 392 (1949)

Poincaré symmetry is a symmetry of the 4D space-time. The 10 symmetries underlying Poincaré's invariance are:

- Spacetime translations (4),
- Spatial rotations (3),
- Lorentz boosts (3).

Poincaré symmetry is dynamical: it mixes space and time.

⇒ Some of the generators of the Poincaré symmetry group involve interaction: dynamical operators, e.g Hamiltonian. Others are kinematical operators: interaction-free.

Dynamical problems are much more complicated to solve than kinematical ones (especially if QCD is involved), we should minimize the number of dynamical operators. Dirac: there are ways to define the 10 generators of the Poincaré group so that interactions are minimally included:

Dirac Forms of relativistic dynamics

P. A. M. Dirac, Rev. Mod. Phys. 21, 392 (1949)

Poincaré symmetry is a symmetry of the 4D space-time. The 10 symmetries underlying Poincaré's invariance are:

- Spacetime translations (4),
- Spatial rotations (3),
- Lorentz boosts (3).

Poincaré symmetry is dynamical: it mixes space and time.

⇒ Some of the generators of the Poincaré symmetry group involve interaction: dynamical operators, e.g Hamiltonian. Others are kinematical operators: interaction-free.

Dynamical problems are much more complicated to solve than kinematical ones (especially if QCD is involved), we should minimize the number of dynamical operators. Dirac: there are ways to define the 10 generators of the Poincaré group so that interactions are minimally included:

- Generators defined with usual coordinate system (t,x,y,z): Instant Form (IF): 4 dynamical operators, 6 kinematical operators.

Dirac Forms of relativistic dynamics

P. A. M. Dirac, Rev. Mod. Phys. 21, 392 (1949)

Poincaré symmetry is a symmetry of the 4D space-time. The 10 symmetries underlying Poincaré's invariance are:

- Spacetime translations (4),
- Spatial rotations (3),
- Lorentz boosts (3).

Poincaré symmetry is dynamical: it mixes space and time.

⇒ Some of the generators of the Poincaré symmetry group involve interaction: dynamical operators, e.g Hamiltonian. Others are kinematical operators: interaction-free.

Dynamical problems are much more complicated to solve than kinematical ones (especially if QCD is involved), we should minimize the number of dynamical operators. Dirac: there are ways to define the 10 generators of the Poincaré group so that interactions are minimally included:

- Generators defined with usual coordinate system (t,x,y,z): Instant Form (IF): 4 dynamical operators, 6 kinematical operators.
- Generators defined with light-cone coordinate system: Front Form (FF): 3 dynamical operators, 7 kinematical operators: smallest number of dynamical operators possible.

Dirac Forms of relativistic dynamics

P. A. M. Dirac, Rev. Mod. Phys. 21, 392 (1949)

Poincaré symmetry is a symmetry of the 4D space-time. The 10 symmetries underlying Poincaré's invariance are:

- Spacetime translations (4),
- Spatial rotations (3),
- Lorentz boosts (3).

Poincaré symmetry is dynamical: it mixes space and time.

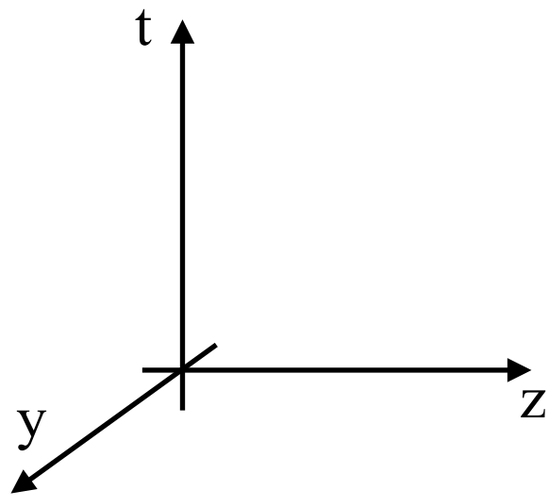
⇒ Some of the generators of the Poincaré symmetry group involve interaction: dynamical operators, e.g Hamiltonian. Others are kinematical operators: interaction-free.

Dynamical problems are much more complicated to solve than kinematical ones (especially if QCD is involved), we should minimize the number of dynamical operators. Dirac: there are ways to define the 10 generators of the Poincaré group so that interactions are minimally included:

- Generators defined with usual coordinate system (t,x,y,z): Instant Form (IF): 4 dynamical operators, 6 kinematical operators.
- Generators defined with light-cone coordinate system: Front Form (FF): 3 dynamical operators, 7 kinematical operators: smallest number of dynamical operators possible.
- 3 others forms (almost never used: involve larger number of dynamical operators).

Instant Form

Usual cartesian system:

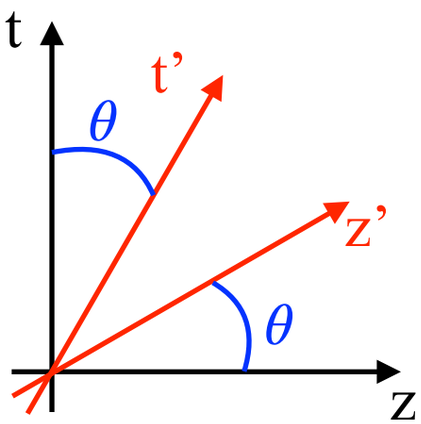


Familiar since our early school days. Intuitive due to its non-relativistic nature.

⇒ Conventionally used in atomic, nuclear, and particle physics.

However, IF is not explicitly Poincaré invariant and using it in relativistic dynamics induces fictitious dynamical effects.

Ex: Lorentz boosts (3 of the 10 generators of the Poincaré group):



⇒ mixes t and z: mix kinematics and dynamics. Fictitious, *viz* frame-dependent, dynamical effects arise.

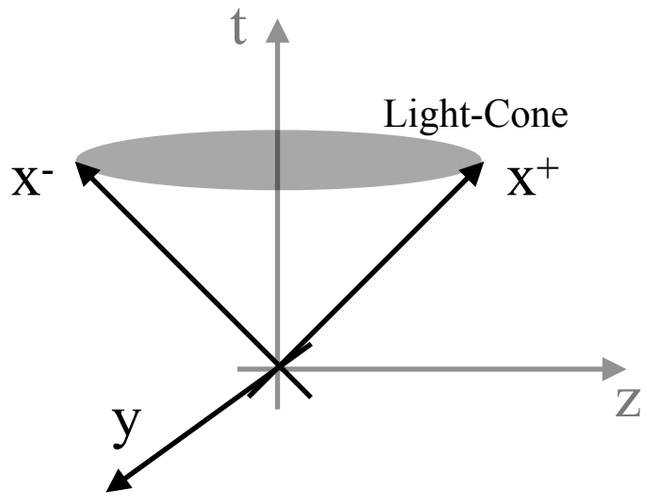
Crucially, boosts are required to describe high energy reactions: for ex. in e + P (p) → e' + P (p + q), the proton is boosted from p to p + q.

⇒ IF description of high energy experiments is subjective.

Front Form

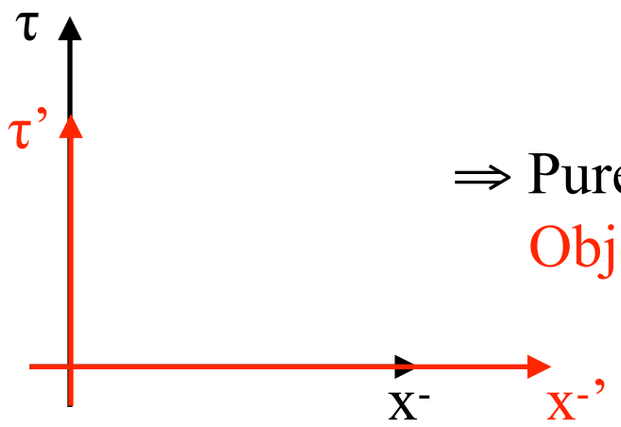
Light-Front system:

$x^+ \equiv t + z = \tau$: FF time
$x^- \equiv t - z$
$\mathbf{x}^\perp \equiv (x,y)$



Relation between (τ, x^-) and (t, z) $\Rightarrow$ physical descriptions on IF and FF not connected by Lorentz transformation.

Ex: Lorentz boosts:



$\Rightarrow$ Purely kinematical operation. No fictitious dynamics appears.
Objective description of high energy phenomenology.

Why is Instant Form not explicitly Poincaré invariant?

Special relativity is one of the two cornerstones of QFT: how can IF not be Poincaré invariant ?

In fact, all Dirac forms of relativistic dynamics, including IF, are constructed to satisfy Poincaré invariance.

However, Poincaré invariance concerns the worldlines of the 4D spacetime. To study a system time-evolution in 3D space, a time variable must be defined (spacetime foliation).

The choice of foliation is the difference between IF and FF.

Why is Instant Form not explicitly Poincaré invariant?

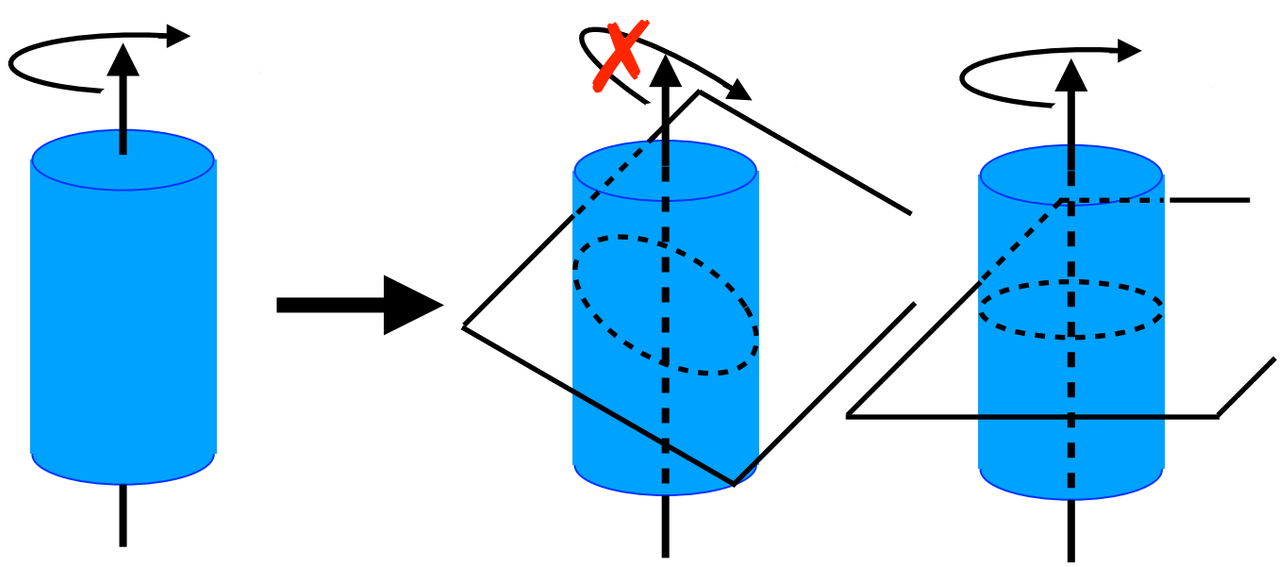
Special relativity is one of the two cornerstones of QFT: how can IF not be Poincaré invariant ?

In fact, all Dirac forms of relativistic dynamics, including IF, are constructed to satisfy Poincaré invariance.

However, Poincaré invariance concerns the worldlines of the 4D spacetime. To study a system time-evolution in 3D space, a time variable must be defined (spacetime foliation).

The choice of foliation is the difference between IF and FF.

Foliation: 4D→(3+1)D, and a space symmetry is not necessarily valid in a sub-space of lower dimension:



⇒IF or FF do not strictly satisfy Poincaré invariance.

However there is a difference on how they break Poincaré invariance.

Instant Form vs Front form

Instant Form

Spacetime translations (E, P_x, P_y, P_z)
Spatial rotations (J_x, J_y, J_z)
Boosts ($\mathcal{K}_x$, $\mathcal{K}_y$, $\mathcal{K}_z$)

} 10 operators of Poincaré algebra

Instant Form vs Front form

Instant Form

Not kinematical
Kinematical

Spacetime translations (~~P_t~~, P_x, P_y, P_z)
Spatial rotations (J_x, J_y, J_z)
Boosts (~~K_x~~, ~~K_y~~, ~~K_z~~)

} 10 operators of Poincaré algebra

Instant Form vs Front form

Instant Form

Not kinematical
Kinematical

Spacetime translations (~~P_-~~, P_x, P_y, P_z)
Spatial rotations (J_x, J_y, J_z)
Boosts (~~Λ_x~~, ~~Λ_y~~, ~~Λ_z~~)

} 10 operators of Poincaré algebra

Operators P_x, P_y, P_z, J_z, and Λ_z express symmetries of the 3D space essential for describing high energy phenomenology (scattering experiments, with the beam along z.).

Spacetime foliation renders the important operator

Λ_z dynamical: a crucial simplification for analyzing high energy phenomenology or relativistic bound states is lost.

Instant Form vs Front form

Instant Form

Not kinematical
Kinematical

Spacetime translations (~~P_-~~, P_x, P_y, P_z)
Spatial rotations (J_x, J_y, J_z)
Boosts (~~K_x~~, ~~K_y~~, ~~K_z~~)

} 10 operators of Poincaré algebra

Operators P_x, P_y, P_z, J_z, and Λ_z express symmetries of the 3D space essential for describing high energy phenomenology (scattering experiments, with the beam along z.).

Spacetime foliation renders the important operator

Λ_z dynamical: a crucial simplification for analyzing high energy phenomenology or relativistic bound states is lost.

⇒ dynamical effects depend on the symmetry parameter; i.e. in the system description, Poincaré invariance is effectively violated.

Instant Form vs Front form

Instant Form

Not kinematical
Kinematical

Spacetime translations (~~P_x~~, P_x, P_y, P_z)
Spatial rotations (J_x, J_y, J_z)
Boosts (~~K_x~~, ~~K_y~~, ~~K_z~~)

} 10 operators of Poincaré algebra

Operators P_x, P_y, P_z, J_z, and Λ_z express symmetries of the 3D space essential for describing high energy phenomenology (scattering experiments, with the beam along z.).

Spacetime foliation renders the important operator

Λ_z dynamical: a crucial simplification for analyzing high energy phenomenology or relativistic bound states is lost.

⇒ dynamical effects depend on the symmetry parameter; i.e. in the system description, Poincaré invariance is effectively violated.

Front form

Spacetime translations (~~P^-~~, P^+, $P^{\perp}_1$, $P^{\perp}_2$)
Spatial rotations (J^-, ~~$J^{\perp}_1$~~, ~~$J^{\perp}_2$~~)
Boosts (Λ^-, $\Lambda^{\perp}_1$, $\Lambda^{\perp}_2$)

} 10 operators of Poincaré algebra

Instant Form vs Front form

Instant Form

Not kinematical
Kinematical

Spacetime translations (~~P^-~~, P_x, P_y, P_z)
Spatial rotations (J_x, J_y, J_z)
Boosts (~~Λ_x~~, ~~Λ_y~~, ~~Λ_z~~)

} 10 operators of Poincaré algebra

Operators P_x, P_y, P_z, J_z, and Λ_z express symmetries of the 3D space essential for describing high energy phenomenology (scattering experiments, with the beam along z.).

Spacetime foliation renders the important operator

Λ_z dynamical: a crucial simplification for analyzing high energy phenomenology or relativistic bound states is lost.

⇒ dynamical effects depend on the symmetry parameter; i.e. in the system description, Poincaré invariance is effectively violated.

Front form

Spacetime translations (~~P^-~~, P^+, $P^{\perp}_1$, $P^{\perp}_2$)
Spatial rotations (J^-, ~~$J^{\perp}_1$~~, ~~$J^{\perp}_2$~~)
Boosts (Λ^-, $\Lambda^{\perp}_1$, $\Lambda^{\perp}_2$)

} 10 operators of Poincaré algebra

- P^-: FF Hamiltonian. Does not express a symmetry of the 3D space.
- $I^{\perp}_1$, $I^{\perp}_2$ rotation operators: usually irrelevant for high-energy scattering.

The operators important to describe high energy phenomenology and relativistic bound states remain kinematical.

Instant Form vs Front form

Instant Form

Not kinematical
Kinematical

Spacetime translations (~~P^-~~, P_x, P_y, P_z)
Spatial rotations (J_x, J_y, J_z)
Boosts (~~Λ_x~~, ~~Λ_y~~, ~~Λ_z~~)

} 10 operators of Poincaré algebra

Operators P_x, P_y, P_z, J_z, and Λ_z express symmetries of the <u>3D space</u> essential for describing high energy phenomenology (scattering experiments, with the beam along z.).

Spacetime foliation renders the important operator

Λ_z dynamical: a crucial simplification for analyzing high energy phenomenology or relativistic bound states is lost.

⇒ dynamical effects depend on the symmetry parameter; i.e. in the system description, Poincaré invariance is effectively violated.

Front form

Spacetime translations (~~P^-~~, P^+, $P^{\perp}_1$, $P^{\perp}_2$)
Spatial rotations (J^-, ~~$J^{\perp}_1$~~, ~~$J^{\perp}_2$~~)
Boosts (Λ^-, $\Lambda^{\perp}_1$, $\Lambda^{\perp}_2$)

} 10 operators of Poincaré algebra

- P^-: FF Hamiltonian. Does not express a symmetry of the 3D space.
- $I^{\perp}_1$, $I^{\perp}_2$ rotation operators: usually irrelevant for high-energy scattering.

The operators important to describe high energy phenomenology and relativistic bound states remain kinematical.

⇒For all intents and purposes, FF dynamics is effectively Poincaré invariant.

Instant Form vs Front form

Instant Form

Not kinematical
Kinematical

Spacetime translations (~~E~~, P_x, P_y, P_z)
Spatial rotations (J_x, J_y, J_z)
Boosts (~~Λ_x~~, ~~Λ_y~~, ~~Λ_z~~)

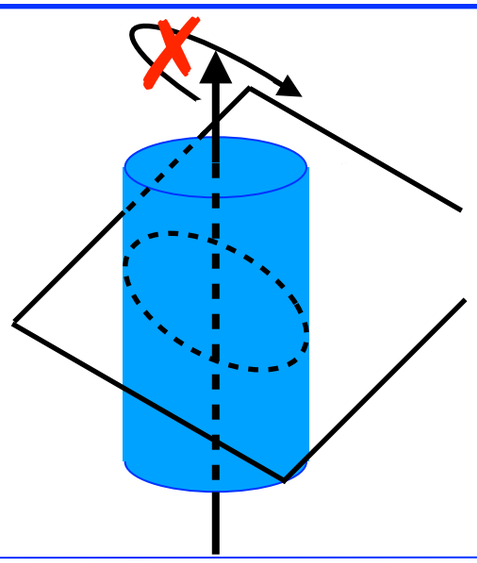
} 10 operators of Poincaré algebra

Operators P_x, P_y, P_z, J_z, and Λ_z express symmetries of the 3D space essential for describing high energy phenomenology (scattering experiments, with the beam along z.).

Spacetime foliation renders the important operator

Λ_z dynamical: a crucial simplification for analyzing high energy phenomenology or relativistic bound states is lost.

⇒ dynamical effects depend on the symmetry parameter; i.e. in the system description, Poincaré invariance is effectively violated.



Front form

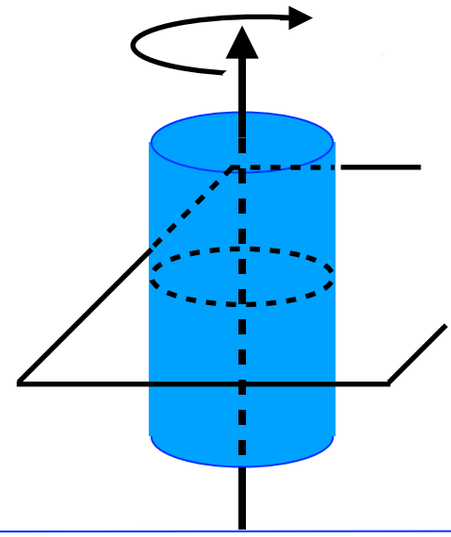
Spacetime translations (~~P^-~~, P^+, $P^{\perp}_1$, $P^{\perp}_2$)
Spatial rotations (J^-, ~~$J^{\perp}_1$~~, ~~$J^{\perp}_2$~~)
Boosts (Λ^-, $\Lambda^{\perp}_1$, $\Lambda^{\perp}_2$)

} 10 operators of Poincaré algebra

- P^-: FF Hamiltonian. Does not express a symmetry of the 3D space.
- $J^{\perp}_1$, $J^{\perp}_2$ rotation operators: usually irrelevant for high-energy scattering.

The operators important to describe high energy phenomenology and relativistic bound states remain kinematical.

⇒For all intents and purposes, FF dynamics is effectively Poincaré invariant.



Instant Form vs Front form

Instant Form

Boosts are dynamical ⇒ induce frame-dependent dynamics: fictitious/pseudo dynamics. Like a centrifugal force in classical dynamics.

Front form

Boosts are purely dynamical.
No fictitious/pseudo effects: description of the dynamics is the same in all frames. For ex. hadron FF wavefunctions are frame independent.

Instant Form vs Front form

Instant Form

Boosts are dynamical ⇒ induce frame-dependent dynamics: fictitious/pseudo dynamics. Like a centrifugal force in classical dynamics.

😈: This could be acceptable in general: IF is more intuitive and familiar than FF. And sometimes it is advantageous to use fictitious forces, e.g. to describe a merry-go-round, so long we keep in mind that centrifugal forces are not fundamental.

Front form

Boosts are purely dynamical.
No fictitious/pseudo effects: description of the dynamics is the same in all frames. For ex. hadron FF wavefunctions are frame independent.

Instant Form vs Front form

Instant Form

Boosts are dynamical ⇒ induce frame-dependent dynamics: fictitious/pseudo dynamics. Like a centrifugal force in classical dynamics.

😈: This could be acceptable in general: IF is more intuitive and familiar than FF. And sometimes it is advantageous to use fictitious forces, e.g. to describe a merry-go-round, so long we keep in mind that centrifugal forces are not fundamental.

😇: Not true in practice for QCD: the pseudo-forces arise from non-perturbative QCD dynamics: calculations are typically not tractable.

Front form

Boosts are purely dynamical.
No fictitious/pseudo effects: description of the dynamics is the same in all frames. For ex. hadron FF wavefunctions are frame independent.

Instant Form vs Front form

Instant Form

Boosts are dynamical ⇒ induce frame-dependent dynamics: fictitious/pseudo dynamics. Like a centrifugal force in classical dynamics.

😈: This could be acceptable in general: IF is more intuitive and familiar than FF. And sometimes it is advantageous to use fictitious forces, e.g. to describe a merry-go-round, so long we keep in mind that centrifugal forces are not fundamental.

😇: Not true in practice for QCD: the pseudo-forces arise from non-perturbative QCD dynamics: calculations are typically not tractable.

Front form

Boosts are purely dynamical.
No fictitious/pseudo effects: description of the dynamics is the same in all frames. For ex. hadron FF wavefunctions are frame independent.

How do these fictitious effects occur in practice?

Example of fictitious force: fictitious spin-orbit force in deuteron

Use the example of the **Gerasimov-Drell-Hearn** (GDH) sum rule. Gerasimov, Yad.Fiz.2,598(1965), Drell & Hearn, PRL 16, 908 (1966)

Fundamental QFT prediction linking spin-dependent photoproduction cross-sections on a particle to that particle anomalous magnetic moment:

Spin-dependent part of the total photoproduction cross-sections

$$\int_{\nu_{thr}}^{\infty} \Delta\sigma \frac{d\nu}{\nu} = \frac{4\alpha S \pi^2 \kappa^2}{M^2}$$

ν: Photon energy; M: Mass; S: spin; κ: anomalous magnetic moment

It applies to any type of particles, point-like and composite ones.

Example of fictitious force: fictitious spin-orbit force in deuteron

Use the example of the **Gerasimov-Drell-Hearn** (GDH) sum rule. Gerasimov, Yad.Fiz.2,598(1965), Drell & Hearn, PRL 16, 908 (1966)

Fundamental QFT prediction linking spin-dependent photoproduction cross-sections on a particle to that particle anomalous magnetic moment:

Spin-dependent part of the total photoproduction cross-sections

$$\int_{\nu_{thr}}^{\infty} \Delta\sigma \frac{d\nu}{\nu} = \frac{4\alpha S \pi^2 \kappa^2}{M^2}$$

anomalous magnetic moment

spin

Mass

Photon energy

It applies to any type of particles, point-like and composite ones.

Basic QFT relation: GDH based on

- Causality,
- Unitarity,
- Lorentz invariance,
- Gauge invariance,
- Physical behavior of the Compton amplitude underlying $\Delta\sigma$. (Cross-section and amplitude decrease fast enough with ν.)

Example of fictitious force: fictitious spin-orbit force in deuteron

Use the example of the **Gerasimov-Drell-Hearn** (GDH) sum rule. Gerasimov, Yad.Fiz.2,598(1965), Drell & Hearn, PRL 16, 908 (1966)

Fundamental QFT prediction linking spin-dependent photoproduction cross-sections on a particle to that particle anomalous magnetic moment:

Spin-dependent part of the total photoproduction cross-sections

$$\int_{\nu_{thr}}^{\infty} \Delta\sigma \frac{d\nu}{\nu} = \frac{4\alpha S \pi^2 \kappa^2}{M^2}$$

anomalous magnetic moment

spin

Photon energy

Mass

It applies to any type of particles, point-like and composite ones.

Basic QFT relation: GDH based on

- Causality,
- Unitarity,
- Lorentz invariance,
- Gauge invariance,
- Physical behavior of the Compton amplitude underlying $\Delta\sigma$. (Cross-sections and amplitude decrease fast enough with ν.)

$\Rightarrow$ The GDH sum rule is always valid[1] (When we test the GDH sum rule, we do not test its general validity, but the whether if inside the particle, a scale for new physics appears that would jeopardize the convergence of the integral in the energy range of the experiment.)

[1] Unless the foundations of QFT are wrong.

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

1967: McGee; Brodsky & Primack: The problem is not with the GDH SR but doing the wrong Lorentz boost (i.e. neglecting IF boost-dependence (fictitious) dynamics).

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

1967: McGee; Brodsky & Primack: The problem is not with the GDH SR but doing the wrong Lorentz boost (i.e. neglecting IF boost-dependence (fictitious) dynamics).

1968: Brodsky & Primack: Derived (IF) GDH SR with Bethe-Salpeter formalism to get proper Lorentz boost (i.e. to account for the (QED-based) fictitious dynamics between p and n): The GDH SR is valid for deuteron.

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

1967: McGee; Brodsky & Primack: The problem is not with the GDH SR but doing the wrong Lorentz boost (i.e. neglecting IF boost-dependence (fictitious) dynamics).

1968: Brodsky & Primack: Derived (IF) GDH SR with Bethe-Salpeter formalism to get proper Lorentz boost (i.e. to account for the (QED-based) fictitious dynamics between p and n): The GDH SR is valid for deuteron.

1969: Brodsky: one should work in the FF: GDH validity for composite particles is straightforward. They could get away with using the IF (although calculations are more difficult than with FF) for p-n bound state because QED is perturbative. Not so for QCD bound-states (hadrons).

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

1967: McGee; Brodsky & Primack: The problem is not with the GDH SR but doing the wrong Lorentz boost (i.e. neglecting IF boost-dependence (fictitious) dynamics).

1968: Brodsky & Primack: Derived (IF) GDH SR with Bethe-Salpeter formalism to get proper Lorentz boost (i.e. to account for the (QED-based) fictitious dynamics between p and n): The GDH SR is valid for deuteron.

1969: Brodsky: one should work in the FF: GDH validity for composite particles is straightforward. They could get away with using the IF (although calculations are more difficult than with FF) for p-n bound state because QED is perturbative. Not so for QCD bound-states (hadrons).

Details:

- Lorentz boost appears because the particle is affected by the probing photon (including $\nu \to \infty$).
- Bethe-Salpeter formalism gives proper IF boost. Mixes QED's p-n interaction in deuteron with kinematical transformation.

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

1967: McGee; Brodsky & Primack: The problem is not with the GDH SR but doing the wrong Lorentz boost (i.e. neglecting IF boost-dependence (fictitious) dynamics).

1968: Brodsky & Primack: Derived (IF) GDH SR with Bethe-Salpeter formalism to get proper Lorentz boost (i.e. to account for the (QED-based) fictitious dynamics between p and n): The GDH SR is valid for deuteron.

1969: Brodsky: one should work in the FF: GDH validity for composite particles is straightforward. They could get away with using the IF (although calculations are more difficult than with FF) for p-n bound state because QED is perturbative. Not so for QCD bound-states (hadrons).

Details:

- Lorentz boost appears because the particle is affected by the probing photon (including $\nu \to \infty$).
- Bethe-Salpeter formalism gives proper IF boost. Mixes QED's p-n interaction in deuteron with kinematical transformation.
- Barton & Dombey assumed independent p and n boosts: it neglected dynamical and kinematical mixing.

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

1967: McGee; Brodsky & Primack: The problem is not with the GDH SR but doing the wrong Lorentz boost (i.e. neglecting IF boost-dependence (fictitious) dynamics).

1968: Brodsky & Primack: Derived (IF) GDH SR with Bethe-Salpeter formalism to get proper Lorentz boost (i.e. to account for the (QED-based) fictitious dynamics between p and n): The GDH SR is valid for deuteron.

1969: Brodsky: one should work in the FF: GDH validity for composite particles is straightforward. They could get away with using the IF (although calculations are more difficult than with FF) for p-n bound state because QED is perturbative. Not so for QCD bound-states (hadrons).

Details:

- Lorentz boost appears because the particle is affected by the probing photon (including $\nu \to \infty$).
- Bethe-Salpeter formalism gives proper IF boost. Mixes QED's p-n interaction in deuteron with kinematical transformation.
- Barton & Dombey assumed independent p and n boosts: it neglected dynamical and kinematical mixing.
- A fictitious spin-orbit force appears during the proper IF boost. Physical origin: Lorentz boost mixes triplet and singlet states of the deuteron.
- Spin-Orbit $\propto$ B-field induced by boosted charged body moving in the external field. $\Rightarrow$ frame-dependent.

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

1967: McGee; Brodsky & Primack: The problem is not with the GDH SR but doing the wrong Lorentz boost (i.e. neglecting IF boost-dependence (fictitious) dynamics).

1968: Brodsky & Primack: Derived (IF) GDH SR with Bethe-Salpeter formalism to get proper Lorentz boost (i.e. to account for the (QED-based) fictitious dynamics between p and n): The GDH SR is valid for deuteron.

1969: Brodsky: one should work in the FF: GDH validity for composite particles is straightforward. They could get away with using the IF (although calculations are more difficult than with FF) for p-n bound state because QED is perturbative. Not so for QCD bound-states (hadrons).

Details:

- Lorentz boost appears because the particle is affected by the probing photon (including $\nu \to \infty$).
- Bethe-Salpeter formalism gives proper IF boost. Mixes QED's p-n interaction in deuteron with kinematical transformation.
- Barton & Dombey assumed independent p and n boosts: it neglected dynamical and kinematical mixing.
- A fictitious spin-orbit force appears during the proper IF boost. Physical origin: Lorentz boost mixes triplet and singlet states of the deuteron.
- Spin-Orbit $\propto$ B-field induced by boosted charged body moving in the external field. $\Rightarrow$ frame-dependent.
- Energy from the external field is (boost-dependently) converted into deuteron internal energy: spin-1 (triplet state) couples with external magnetic field, but not spin-0 (singlet state).

  $\Rightarrow$ IF boost induced apparent dynamical modification: internal energy affected.

Example of fictitious force: fictitious spin-orbit force in deuteron

1965-1966: discovery of the GDH sum rule.

1967: Barton & Dombey computed, on the IF, the GDH SR for deuteron. Found that it seems to be violated.

1967: McGee; Brodsky & Primack: The problem is not with the GDH SR but doing the wrong Lorentz boost (i.e. neglecting IF boost-dependence (fictitious) dynamics).

1968: Brodsky & Primack: Derived (IF) GDH SR with Bethe-Salpeter formalism to get proper Lorentz boost (i.e. to account for the (QED-based) fictitious dynamics between p and n): The GDH SR is valid for deuteron.

1969: Brodsky: one should work in the FF: GDH validity for composite particles is straightforward. They could get away with using the IF (although calculations are more difficult than with FF) for p-n bound state because QED is perturbative. Not so for QCD bound-states (hadrons).

Details:

- Lorentz boost appears because the particle is affected by the probing photon (including $\nu \to \infty$).
- Bethe-Salpeter formalism gives proper IF boost. Mixes QED's p-n interaction in deuteron with kinematical transformation.
- Barton & Dombey assumed independent p and n boosts: it neglected dynamical and kinematical mixing.
- A fictitious spin-orbit force appears during the proper IF boost. Physical origin: Lorentz boost mixes triplet and singlet states of the deuteron.
- Spin-Orbit $\propto$ B-field induced by boosted charged body moving in the external field. $\Rightarrow$ frame-dependent.
- Energy from the external field is (boost-dependently) converted into deuteron internal energy: spin-1 (triplet state) couples with external magnetic field, but not spin-0 (singlet state).

$\Rightarrow$ IF boost induced apparent dynamical modification: internal energy affected.

Classical analogy: fictitious forces mix kinematic and potential energies; e.g., when kinetic energy in inertial frame is converted into the repulsive energy of a centrifugal force in rotating frame.

Example of fictitious force: Extra contribution to elastic scattering

GDH (again): SR derived in several ways:

- Dispersion relation+Low Energy Theorem (Original derivation),
- FF current algebra,
- IF current algebra.

The IF derivation yields a GDH SR (ex. for a proton):

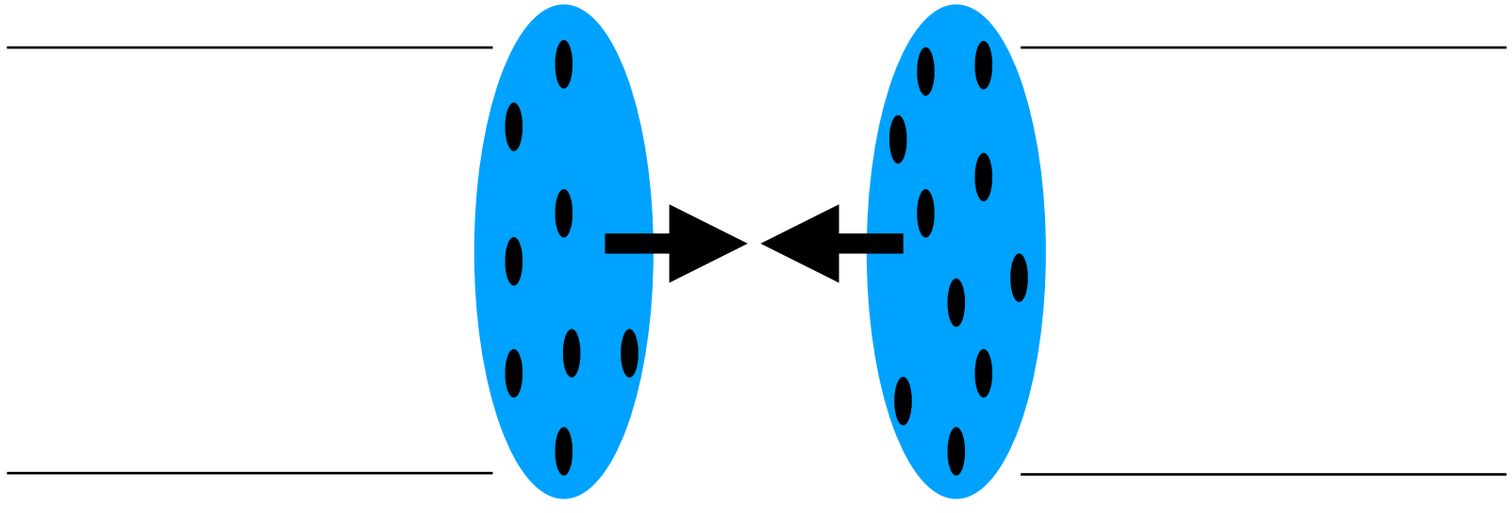
$$\int_{thr}^{\infty} (\Delta\sigma)\frac{d\nu}{\nu} = 2\alpha\pi^2\left(\frac{\kappa^2}{M^2} - \underbrace{\frac{(1+\kappa)^2}{E^2}}\right)$$

Proton initial state energy

Extra term (E explicitly violating Lorentz invariance). Fictitious contribution to Compton scattering.

Proper sum rule recovered in infinite momentum frame (often the case for IF calculations).
But: not acceptable to have to chose one specific frame (inf. mom. frame) to describe an intrinsic property of the particle.

Example of fictitious effect: high energy pancakes



•Often invoked in electron-proton DIS or relativistic heavy-ion collisions.

•Lorentz contraction is subjective: depends on the observer motion relative to the contracted object.
⇒ Not an intrinsic property of the object. Cannot (need not) be used to explain Bjorken's scaling.

•Lorentz contraction not observable in an actual scattering experiment: Terrell-Penrose effect. Lorentz contraction observable only if the finite size object is observed at a single fixed time: either violates causality or requires a technologically unfeasible experiment.

•Not present in the frame-independent FF description.

Example of fictitious effect: complex vacuum

•FF vacuum trivial (appart possibly for the zero-point energy). In the FF, $p^+>0$. Vacuum fluctuations such as $0 \rightarrow q\bar{q}$ are forbidden by FF dynamics. Vacuum fluctuations need $p^+<0$.

Example of fictitious effect: complex vacuum

•FF vacuum trivial (appart possibly for the zero-point energy). In the FF, $p^+>0$. Vacuum fluctuations such as $0 \rightarrow q\bar{q}$ are forbidden by FF dynamics. Vacuum fluctuations need $p^+<0$.

•IF vacuum complexity arises from the fact that IF dynamics includes space-like events. Those can be causally linked in a given frame but not in another one. Unitarity demands that those causality-violating diagrams are compensated by vacuum polarization graphs.

Example of fictitious effect: complex vacuum

•FF vacuum trivial (appart possibly for the zero-point energy). In the FF, $p^+>0$. Vacuum fluctuations such as $0 \rightarrow q\bar{q}$ are forbidden by FF dynamics. Vacuum fluctuations need $p^+<0$.

•IF vacuum complexity arises from the fact that IF dynamics includes space-like events. Those can be causally linked in a given frame but not in another one. Unitarity demands that those causality-violating diagrams are compensated by vacuum polarization graphs.

•IF provides a frame-dependent value of vacuum energy 10^{120} times larger than observed.

Example of fictitious effect: complex vacuum

•FF vacuum trivial (appart possibly for the zero-point energy). In the FF, $p^+>0$. Vacuum fluctuations such as $0 \rightarrow q\bar{q}$ are forbidden by FF dynamics. Vacuum fluctuations need $p^+<0$.

•IF vacuum complexity arises from the fact that IF dynamics includes space-like events. Those can be causally linked in a given frame but not in another one. Unitarity demands that those causality-violating diagrams are compensated by vacuum polarization graphs.

•IF provides a frame-dependent value of vacuum energy 10^{120} times larger than observed.

•The IF complex vacuum is the fictitious mechanism that arises to preserve causality, which would otherwise be broken by doing Poincaré-violating IF dynamics: Fictitious dynamical effects similarly arise in classical mechanics or in IF dynamics to preserve fundamental principles.

Example of fictitious effect: complex vacuum

•FF vacuum trivial (appart possibly for the zero-point energy). In the FF, $p^+>0$. Vacuum fluctuations such as $0 \rightarrow q\bar{q}$ are forbidden by FF dynamics. Vacuum fluctuations need $p^+<0$.

•IF vacuum complexity arises from the fact that IF dynamics includes space-like events. Those can be causally linked in a given frame but not in another one. Unitarity demands that those causality-violating diagrams are compensated by vacuum polarization graphs.

•IF provides a frame-dependent value of vacuum energy 10^{120} times larger than observed.

•The IF complex vacuum is the fictitious mechanism that arises to preserve causality, which would otherwise be broken by doing Poincaré-violating IF dynamics: Fictitious dynamical effects similarly arise in classical mechanics or in IF dynamics to preserve fundamental principles.

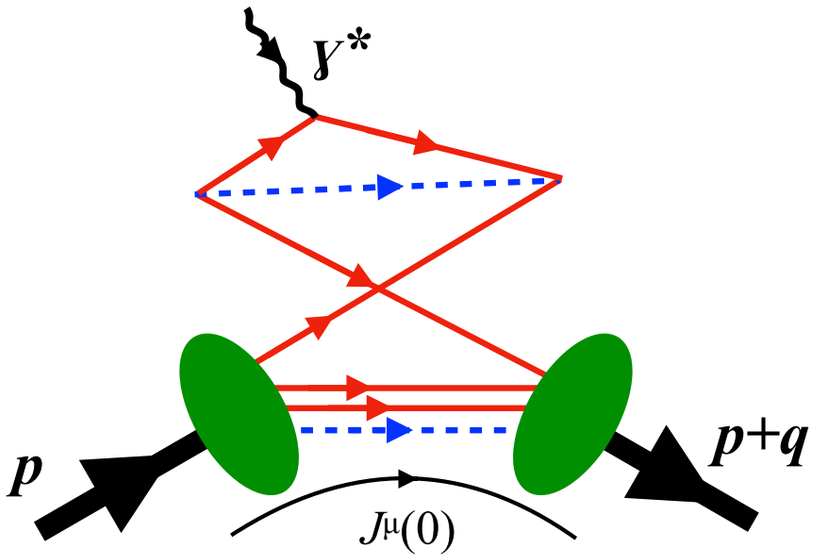
•No vacuum condensates, only in-hadrons condensates. Contribute to hadron mass, not to the cosmological constant.

Brodsky & Shrock, PNAS 108, 45 (2011),
Brodsky, Roberts, Shrock & Tandy, PRC C 82, 022201 (2010), PRC 85, 065202 (2012)

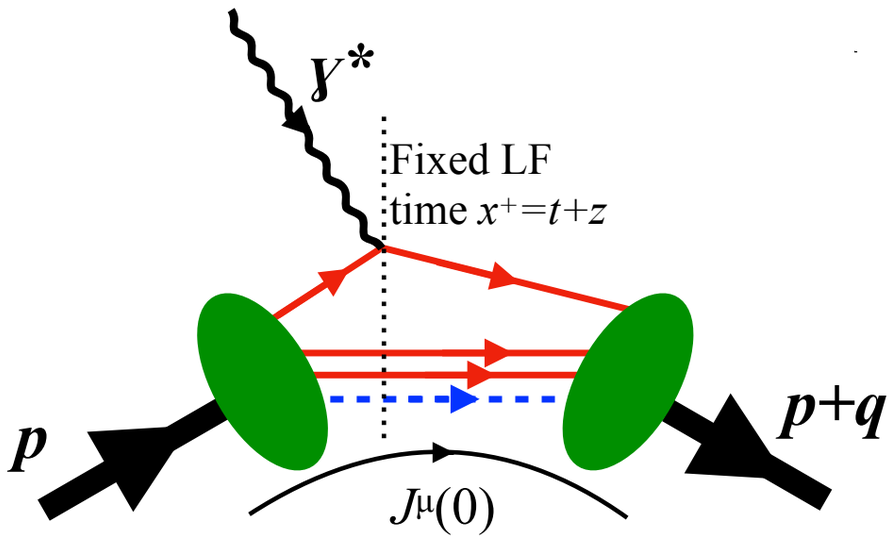
$\Rightarrow$ fictitious origin for the overestimate of the QFT-assessed cosmological constant?

Example of fictitious effect: complex vacuum

Complex vacuum structure complicates hadron wavefunction and requires acausal description. Current is a function of vacuum and bound-state wavefunctions.



Simple vacuum structure with hadron wavefunction describes as a series of Fock states. Causal description. Current is a function of the bound-state wavefunction only.



Summary

- Fundamental descriptions of relativistic dynamics (e.g. high energy scattering) must be done with an effectively Poincaré invariant framework.
- Otherwise, fictitious effects complicate description: Non-minimal description. Subjective. Misleading. Usually harder to compute.
- Poincaré invariance of IF and FF is spoiled by foliation of 4D spacetime into (3+1)D space and time.
  - IF: important operators for high-energy scattering and bound states phenomenology are affected.
  - FF: important operators are not affected: FF effectively Poincaré invariant.
- Just like in classical physics where breaking Galilean invariance induces fictitious forces, breaking Poincaré invariance creates fictitious effects:
  - Extra spin-orbit force in deuteron structure.
  - Extra scattering force in elastic scattering.

  } GDH sum rule
  - Misleading pancakes.
  - Complex vacuum:
    - Complicate calculations of hadron structure.
    - Predicts a cosmological constant 10^{120} times too large.