Title: Quantum gravity from fakeons

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Abstract: A new quantization prescription is able to endow quantum field theory with a new type of â€œparticleâ€•, the fakeon (fake particle), which mediates interactions, but cannot be observed. A massive fakeon of spin
2 (together with a scalar field) allows us to build a theory of quantum gravity that is both renormalizable and unitary, and basically unique.
After presenting the general properties of this theory, I discuss its classical limit, which carries important remnants of the fakeon quantization prescription. I also discuss the implications for cosmology and the possibility that the Higgs boson might be a fakeon.

# Quantum gravity from fakeons

*Damiano Anselmi*

- The idea of fake particle ("fakeon") allows us to make sense of higher-derivative theories (under certain assumptions)
- It can also be applied to non-higher-derivative theories
- It amounts to a novel quantization prescription (alternative to the Feynman $i\epsilon$)
- It leads to an essentially unique theory of quantum gravity

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Summary of the talk :

- Brief introduction to the theory
- Physical implications and predictions
- Classical limit
- Non-perturbative aspects of the classical limit
- FLRW solution

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- The fakeon simulates a physical particle in many situations, but does not belong to the physical spectrum of asymptotic states
- It must be introduced and later projected away (like the Faddeev-Popov ghosts), to have unitarity
- The fakeon prescription/projection does <u>not</u> follow from a gauge principle
- It leads to the violation of microcausality

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CAUTION

The problem of quantum gravity is to make it renormalizable and unitary at the same time

$$\frac{1}{(p^2-m_1^2)(p^2-m_2^2)} = \frac{1}{m_1^2-m_2^2}\left[\frac{1}{p^2-m_1^2} - \frac{1}{p^2-m_2^2}\right]$$

Higher derivatives lead to renormalizability, but violate unitarity $\quad S^\dagger S = 1$

$$\sum_{|n\rangle} \langle a|S^\dagger|n\rangle\langle n|S|b\rangle = \langle a|b\rangle$$

Unless...

Propagator: $\pm \frac{1}{p^2 - m^2}$

Feynman: $\pm \frac{1}{p^2 - m^2 + i\epsilon}$ $\pm \delta(p^2 - m^2)$

Fakeon: 1) $\pm \frac{p^2 - m^2}{(p^2 - m^2)^2}$

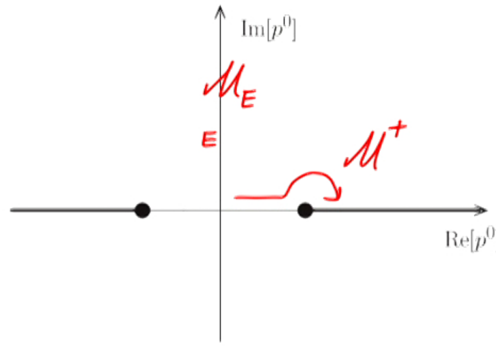
2) $\pm \frac{p^2 - m^2}{(p^2 - m^2)^2 + \mathcal{E}^4}$ ( $= 0$ on shell ! )

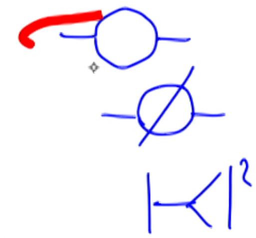
$\rightarrow 0 \cdot \delta(p^2 - m^2)$

3) follow a certain procedure in loop diagrams

## Beyond tree level:

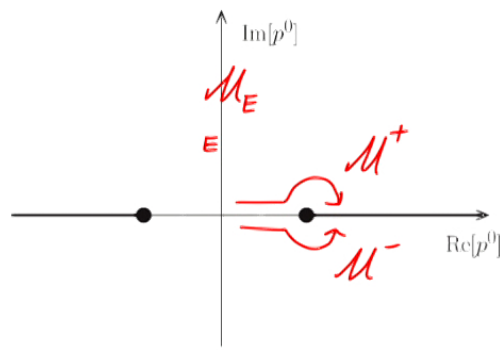
Feynman
analytic continuation




Im. part

fakeon




Result: average continuation $\frac{1}{2}\left(\mathcal{M}^+ + \mathcal{M}^-\right)$

The so-defined theory IS UNITARY

D. Anselmi, Fakeons and Lee-Wick models, J. High Energy Phys. 02 (2018) 141, 18A1 Renormalization.com and arXiv:1801.00915 [hep-th].

# Quantum gravity

Consider the (renormalizable) higher-derivative action

$$S_{\mathrm{QG}} = -\frac{1}{2\kappa^2}\int \sqrt{-g}\left[2\Lambda_C + \zeta R + \alpha\left(R_{\mu\nu}R^{\mu\nu} - \frac{1}{3}R^2\right) - \frac{\xi}{6}R^2\right] + S_{\mathrm{m}}(g,\Phi)$$

$\zeta, \alpha, \xi > 0$

Standard Model

If quantized as usual, this theory has a ghost

Solution: quantize the would-be ghost as a fakeon

D. Anselmi, On the quantum field theory of the gravitational interactions, J. High Energy Phys. 06 (2017) 086, 17A3 Renormalization.com and arXiv: 1704.07728 [hep-th].

Eliminate the higher derivatives by means of extra fields.

$$S_{\rm QG}(g,\phi,\chi,\Phi) = S_{\rm H}(g) + S_\chi(g,\chi) + S_\phi(\tilde{g},\phi) + S_{\rm m}(\tilde{g}\mathrm{e}^{\kappa\phi},\Phi)$$

where $\tilde{g}_{\mu\nu} = g_{\mu\nu} + 2\chi_{\mu\nu}$

$$S_{\rm H}(g) = -\frac{\zeta}{2\kappa^2}\int\sqrt{-g}R, \qquad S_\phi(g,\phi) = \frac{3\zeta}{4}\int\sqrt{-g}\left[\nabla_\mu\phi\nabla^\mu\phi - \frac{m_\phi^2}{\kappa^2}\left(1-\mathrm{e}^{\kappa\phi}\right)^2\right]$$

$$S_\chi(g,\chi) = S_{\rm H}(\tilde{g}) - S_{\rm H}(g) - 2\int\chi_{\mu\nu}\frac{\delta S_{\rm H}(\tilde{g})}{\delta g_{\mu\nu}} + \frac{\zeta^2}{2\alpha\kappa^2}\int\sqrt{-g}(\chi_{\mu\nu}\chi^{\mu\nu} - \chi^2)\Big|_{g\to\tilde{g}}.$$

D. Anselmi and M. Piva, Quantum gravity, fakeons and microcausality, J. High Energy Phys. 11 (2018) 21, 18A3 Renormalization.com and arXiv:1806.03605 [hep-th].

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Now, the $\chi_{\mu\nu}$ action has the wrong overall sign :

$$S_\chi(g,\chi) = -\frac{\zeta}{\kappa^2} S_{\rm PF}(g,\chi,m_\chi^2) - \frac{\zeta}{2\kappa^2}\int \sqrt{-g}R^{\mu\nu}(\chi\chi_{\mu\nu} - 2\chi_{\mu\rho}\chi_\nu^\rho) + S_\chi^{(>2)}(g,\chi)$$

where $S_{PF}$ is the covariantized Pauli-Fierz action

This means that $\chi_{\mu\nu}$ MUST be quantized as a fakeon. This way, we have both renormalizability and unitarity.

Instead, $\phi$ can be quantized either as a fakeon or as a physical particle

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Graviton multiplet : $\{h_{\mu\nu}, \phi, \chi_{\mu\nu}\}$

$m_\chi = \frac{\zeta}{\alpha}$

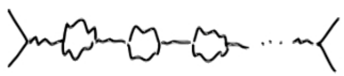
$m_\phi = \frac{\zeta}{\xi}$

$g_{\mu\nu} = \eta_{\mu\nu} + 2\kappa h_{\mu\nu}$

fluctuation of the metric

massive scalar

spin-2 fakeon of mass $m_\chi$



Fakeon width :

$$\Gamma_\chi = -\alpha_\chi C m_\chi \qquad C = \frac{N_s + 6N_f + 12N_v}{120}$$

$\Gamma_\chi < 0$ : causality is violated by $\chi_{\mu\nu}$

$$\alpha_\chi = \left(\frac{m_\chi}{M_{Pl}}\right)^2$$

D. A. and M. Piva, The ultraviolet behavior of quantum gravity, J. High Energy Phys. 05 (2018) 027 and arxiv:1803.0777 [hep-th]

D. A. and M. Piva, ~~Quantum gravity, fakeons and microcausality~~, arxiv:1806.03605 [hep-th] JHEP 11 (2018) 21

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$$\frac{i}{E - m + i\frac{\Gamma}{2}} \longrightarrow \mathrm{sgn}(t)\,\theta(\Gamma t)\cdot \exp\left(-imt - \frac{\Gamma t}{2}\right)$$

$$\equiv G_{BW}(t)$$

$$\varphi(x) = \int d^4y\; G_{BW}(x-y)\, J(y)$$

$\Gamma < 0$:

$$\varphi(t) = -\int_t^{\infty} dt'\, e^{-im(t-t') - \frac{\Gamma}{2}(t-t')}\, J(t')$$

The violation is short-range $\Delta t \simeq \frac{1}{m}, \frac{1}{|\Gamma|}$

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PROJECTION

$$Z_{\rm pr}(J) = \int [\mathrm{d}\varphi \mathrm{d}\chi] \exp\left( iS(\varphi,\chi) + i\int J\varphi \right) = \exp\left(iW_{\rm pr}(J)\right)$$

NO SOURCE $J_\chi$ FOR $\chi$

Projection = integrating out the fakeons with the fakeon prescription

At the level of generating functionals: $\Gamma(\varphi, \chi)$

$\varphi$ = physical fields

$\chi$ = fakeons

Solve $\delta\Gamma(\varphi,\chi)/\delta\chi = 0$ by means of the fakeon prescription

Let $\langle\chi\rangle$ denote the solution

Projected functionals: $\Gamma_{\rm pr}(\varphi) = \Gamma(\varphi, \langle\chi\rangle)$

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## Classical limit

The action

$$S_{\mathrm{QG}}(g,\phi,\chi,\Phi) = S_{\mathrm{H}}(g) + S_{\chi}(g,\chi) + S_{\phi}(\tilde{g},\phi) + S_{\mathrm{m}}(\tilde{g}\mathrm{e}^{\kappa\phi},\Phi)$$

is NOT the classical limit, because it is unprojected

Unprojected field equations :

$g_{\mu\nu}$ : $$R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R = \frac{\kappa^2}{\zeta}\left[\mathrm{e}^{3\kappa\phi} f T^{\mu\nu}_{\mathrm{m}}(\tilde{g}\mathrm{e}^{\kappa\phi},\Phi) + f T^{\mu\nu}_{\phi}(\tilde{g},\phi) + T^{\mu\nu}_{\chi}(g,\chi)\right]$$

$\phi$ : $$-\frac{1}{\sqrt{-\tilde{g}}}\,\partial_\mu\left(\sqrt{-\tilde{g}}\tilde{g}^{\mu\nu}\partial_\nu\phi\right) - \frac{m_\phi^2}{\kappa}\left(\mathrm{e}^{\kappa\phi} - 1\right)\mathrm{e}^{\kappa\phi} = \frac{\kappa\mathrm{e}^{3\kappa\phi}}{3\zeta} T^{\mu\nu}_{\mathrm{m}}(\tilde{g}\mathrm{e}^{\kappa\phi},\Phi)\tilde{g}_{\mu\nu}$$

$\chi_{\mu\nu}$ : $$\frac{1}{\sqrt{-g}}\frac{\delta S_\chi(g,\chi)}{\delta\chi_{\mu\nu}} = \mathrm{e}^{3\kappa\phi} f T^{\mu\nu}_{\mathrm{m}}(\tilde{g}\mathrm{e}^{\kappa\phi},\Phi) + f T^{\mu\nu}_{\phi}(\tilde{g},\phi),$$

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At the tree level, the subtleties about integration paths and average continuations are not important, so we can take

$$\frac{p^2 - m^2}{(p^2 - m^2)^2 + \mathcal{E}^4} = \mathcal{P}\frac{1}{p^2 - m^2}$$

Use it to solve the fakeon equations

The projected classical action is then

$$\mathcal{S}_{\mathrm{QG}}(g, \phi, \Phi) = S_{\mathrm{H}}(g) + S_\chi(g, \langle\chi\rangle) + S_\phi(\bar{g}, \phi) + S_{\mathrm{m}}(\bar{g}\mathrm{e}^{\kappa\phi}, \Phi)$$

where $\langle \chi \rangle$ is the solution $\qquad \bar{g}_{\mu\nu} = g_{\mu\nu} + 2\langle\chi_{\mu\nu}\rangle$

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Example : $\mathcal{L}_{\text{HD}} = \frac{m}{2}(\dot{x}^2 - \tau^2 \ddot{x}^2) + xF_{\text{ext}}(t)$

$$m\frac{d^2}{dt^2}\underbrace{\left(1+\tau^2\frac{d^2}{dt^2}\right)}x = F_{ext}$$

$\longrightarrow$ invert with $\mathcal{P}\frac{1}{1+\tau^2\frac{d^2}{dt^2}}$

The projected equation is

$$m\ddot{x} = \int_{-\infty}^{\infty} \mathrm{d}u \, \frac{\sin(|u|/\tau)}{2\tau} F_{\text{ext}}(t-u)$$

$\longrightarrow$ violation of microcausality

$\cancel{F = ma}$ $\quad \langle F \rangle = ma$ !!

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<u>But</u> in general the projection is defined perturbatively (since it comes from quantum gravity, which is defined perturbatively)

→ The classical equations are defined perturbatively : one may have to face asymptotic series and nonperturbative effects (just to <u>write</u> the equations)

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Example:

$$\mathcal{L}_{\mathrm{HD}} = \frac{m}{2}(\dot{x}^2 - \tau^2\ddot{x}^2) - V(x,t) \qquad V = \frac{\lambda}{4!}x^4$$

Unprojected equations of motion:

$$m\,\frac{d^2}{dt^2}\underbrace{\left(1+\tau^2\frac{d^2}{dt^2}\right)}\,x = -\frac{\lambda}{3!}x^3$$

Projected equations of motion:

$$m\ddot{x} = -\frac{\lambda}{3!}\langle x^3\rangle$$

$\langle \cdots \rangle$ = same average as before

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By iterating the projection, we get

$\omega = 0 \quad \tilde{\lambda} \equiv \lambda/m$

$$\ddot{x} = -\frac{\tilde{\lambda}x}{6}\left(x^2 - 6\tau^2\dot{x}^2\right) - \frac{\tilde{\lambda}^2\tau^2 x}{12}\left(x^4 - 48\tau^2x^2\dot{x}^2 + 372\tau^4\dot{x}^4\right)$$
$$-\frac{\tilde{\lambda}^3\tau^4 x}{6}\left(x^6 - 156\tau^2x^4\dot{x}^2 + 4572\tau^4x^2\dot{x}^4 - 31152\tau^6\dot{x}^6\right) + \mathcal{O}(\tilde{\lambda}^4)$$

$$\frac{\mathcal{L}}{m} = \frac{\dot{x}^2}{2} - \frac{\tilde{\lambda}x^2}{4!}\left(x^2 + 12\tau^2\dot{x}^2\right) + \frac{\tau^2\tilde{\lambda}^2x^2}{72}\left(x^4 - 54\tau^2x^2\dot{x}^2 + 372\tau^4\dot{x}^4\right) + \mathcal{O}(\tilde{\lambda}^3)$$

Growth of the coefficients:

$c_{nm} x^n \dot{x}^m$

| $n$ | 5 | 10 | 15 | 20 | 25 |
|---|---|---|---|---|---|
| $c_{n,0}$ | $10^0$ | $10^6$ | $10^{13}$ | $10^{22}$ | $10^{32}$ |
| $c_{n,n}$ | $10^9$ | $10^{28}$ | $10^{52}$ | $10^{78}$ | $10^{107}$ |

!!

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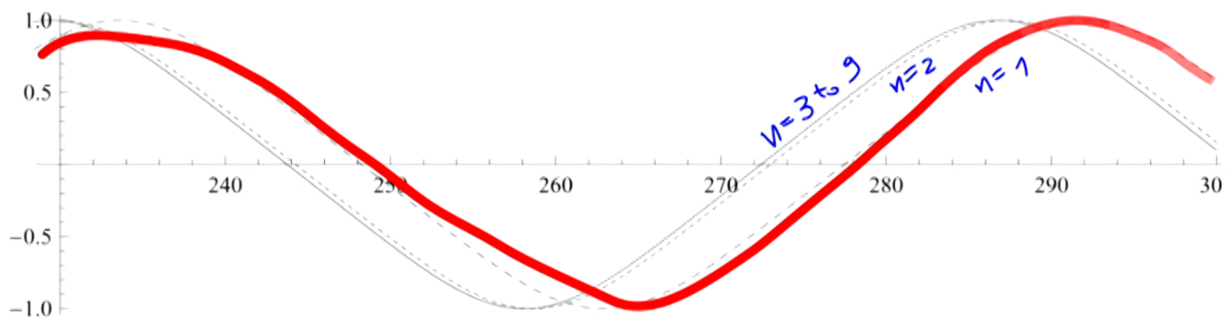
Solution with $x(0)=1$, $\dot{x}(0)=0$, $m=\tau=1$, $\lambda=\frac{1}{10}$




$n=1$ : fairly good

$n=2$ : good

$n=3$ to $n=9$ : excellent

$n>9$ : meaningless $\qquad n_{max} \simeq \left[\frac{1}{|\lambda|}\right]$

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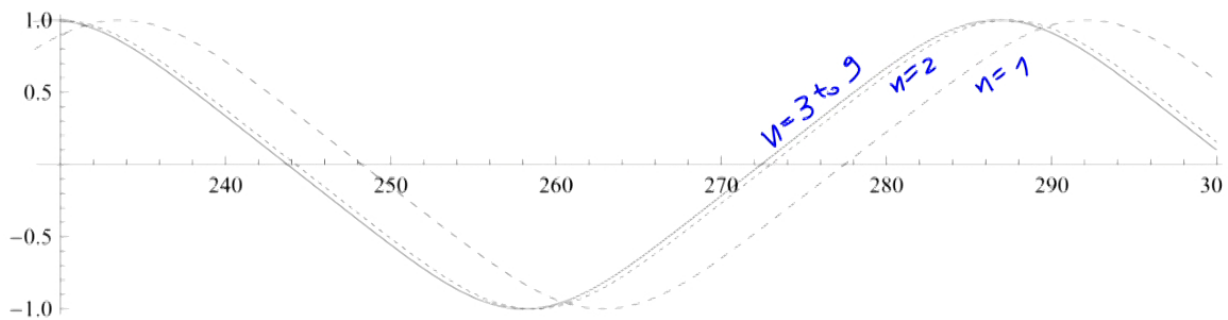
Solution with $x(0) = 1$, $\dot{x}(0) = 0$, $m = \tau = 1$, $\lambda = \frac{1}{10}$

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The FLRW metric

$$ds^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \qquad \mathrm{d}t^2 - a^2(t)\mathrm{d}\sigma^2$$

$g_{\mu\nu}$, $\phi$, $\cancel{\chi_{\mu\nu}}$

fakeon

$$\mathrm{d}\sigma^2 = \frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\,\mathrm{d}\phi^2$$

Unprojected equations $\left( \frac{\mathcal{L}}{\sqrt{-g}} \sim R + \frac{1}{m_\phi^2} R^2 \right)$

$$\Sigma\left(\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right) = \frac{4\pi G}{3}(\rho - 3p), \qquad \Upsilon\left(\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2} - \frac{k}{a^2}\right) = -4\pi G(\rho + p),$$

where

$$\Sigma = 1 + \frac{1}{m_\phi^2}\left(3\frac{\dot{a}}{a} + \frac{\mathrm{d}}{\mathrm{d}t}\right)\frac{\mathrm{d}}{\mathrm{d}t}, \qquad \Upsilon = \Sigma + \frac{2}{m_\phi^2}\left[\frac{k}{a^2} + 3\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\dot{a}}{a}\right)\right].$$

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Projection. Define $\langle A\rangle_X \equiv \frac{1}{2}\left[\left.\frac{1}{X}\right|_{\rm rit} + \left.\frac{1}{X}\right|_{\rm adv}\right] A$

and use it to define $\frac{1}{\Sigma}$ and $\frac{1}{\Upsilon}$

(Partially) projected equations :

(it is NOT over yet .... !! )

$$\frac{\ddot a}{a} + \frac{\dot a^2}{a^2} + \frac{k}{a^2} = \frac{4\pi G}{3}\langle \rho - 3p\rangle_\Sigma$$

$$\frac{\ddot a}{a} - \frac{\dot a^2}{a^2} - \frac{k}{a^2} = -4\pi G\langle \rho + p\rangle_\Upsilon$$

OR :

$$\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = \frac{8\pi G}{3}\tilde{\rho},$$

$$2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = -8\pi G\tilde{p}.$$

where

$$\tilde{\rho} = \frac{1}{4}\langle \rho - 3p\rangle_\Sigma + \frac{3}{4}\langle \rho + p\rangle_\Upsilon$$

$$\tilde{p} = \frac{1}{4}\langle \rho + p\rangle_\Upsilon - \frac{1}{4}\langle \rho - 3p\rangle_\Sigma$$

The projection can be handled exactly for radiation combined with the vacuum energy:

$$p = \frac{\rho}{3} + p_0$$

$p_0$ = constant

Exact solution: $\rho_0 = 3\sigma^2/(8\pi G)$ $\tilde{p} = (\tilde{\rho} - 4\rho_0)/3$

$\sigma$, $\sigma'$ = constants

$$\rho(t) = \frac{3}{8\pi G}\left(\sigma^2 + \frac{\sigma''^2}{4a^4}\right), \qquad \sigma''^2 = \sigma'^2\left(1 + \frac{4\sigma^2}{m_\phi^2}\right) \qquad \tilde{\rho}(t) = \frac{3}{8\pi G}\left(\sigma^2 + \frac{\sigma'^2}{4a^4}\right)$$

$$a(t) = \sqrt{\frac{\sinh(\sigma t)}{\sigma}\left(\sigma' \cosh(\sigma t) - \frac{k}{\sigma}\sinh(\sigma t)\right)}$$

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<u>But</u> in general the projection is defined perturbatively (since it comes from quantum gravity, which is defined perturbatively)

$\longrightarrow$ The classical equations are defined perturbatively : one may have to face asymptotic series and nonperturbative effects (just to <u>write</u> the equations)

Example: cosmic dust ($p=0$) or $p = w\rho$ $w \neq \frac{1}{3}, -1$

# Causality

- The relation between higher-derivatives and the violation of microcausality has been known since the Abraham-Lorentz force of classical electrodynamics

~~runaway solution~~ $\rightarrow$ violation of microcausality

$$F = ma - \tau m \dot{a} \quad \Rightarrow$$

$$= m\left(1 - \tau \frac{d}{dt}\right)a$$

$$ma = \langle F \rangle = \frac{1}{\tau}\int_t^{\infty} dt' \, e^{(t-t')/\tau} F(t')$$

[J.D. Jackson, Classical electrodynamics, chap. 17]

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The Feynman-Wheeler electrodynamics could contain the classical massless fakeon with propagator

$$\mathcal{P}\,\frac{1}{p^2}$$

However, this option violates causality at large, so Feynman and Wheeler developed an "emitter-absorber theory" to eliminate the massless fakeon and recover causality

J.A. Wheeler and R.P. Feynman, Interaction with the absorber as the mechanism of radiation, Rev. Mod. Phys. 17 (1945) 175;

J.A. Wheeler and R.P. Feynman, Classical electrodynamics in terms of direct inter-particle action, Rev. Mod. Phys. 21 (1949) 425.

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't Hooft - Veltman, Diagrammar, CERN 73-09, §6.1

Every diagram, when multiplied by the appropriate source functions and integrated over all x contributes to the S-matrix. The contribution to the T-matrix, defined by

$$S = 1 + iT \tag{6.7}$$

is obtained by multiplying by a factor -i. Unitarity of the S-matrix implies an equation for the imaginary part of the so defined T matrix

$$T - T^{+} = iT^{+}T \,. \tag{6.8}$$

The T-matrix, or rather the diagrams, are also constrained by the requirement of causality. As yet nobody has found a definition of causality that corresponds directly to the intuitive notions; instead formulations have been proposed involving the off-mass-shell Green's functions. We will employ the causality requirement in the form proposed by Bogoliubov that has at least some intuitive appeal and is most suitable in connection with a diagrammatic analysis. Roughly speaking Bogoliubov's condition can be put as follows: if a space-time point $x_1$ is in the future with respect to some other space-time point $x_2$, then the diagrams involving $x_1$ and $x_2$ can be rewritten in terms of functions that involve positive energy flow from $x_2$ to $x_1$ only.

The trouble with this definition is that space-time points cannot be accurately pinpointed with relativistic wave packets corresponding to particles on mass-shell. Therefore this definition cannot be formulated as an S-matrix constraint. It can only be used for the Green's functions.

Other definitions refer to the properties of the fields. In particular there is the proposal of Lehmann, Symanzik and Zimmermann that the fields commute outside the light cone. Defining fields in terms of diagrams, this definition can be shown to reduce to Bogoliubov's definition. The formulation of Bogoliubov causality in terms of cutting rules for diagrams will be given in Section 6.4.

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Personal position:

- it is hard to elevate micro causality to a fundamental physical principle
- quantum gravity does not allow it at small distances
- micro causality is probably a blunder, due to our limited insight and poor experimental accuracy

Downgraded to: unusual form of the equations, fuzziness of the input/output relation ...

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Comments on alternative approaches to the problem of quantum gravity

--- **string theory** is criticized for being nonpredictive. Moreover, its calculations often require mathematics that is not completely understood

--- **loop quantum gravity** is even more challenging, because it is at an earlier stage of development

--- **holography** (AdS/CFT correspondence) do not admit a weakly coupled expansion

--- **asymptotic safety** in nonperturbative as well.

**None is as close to the standard model as the solution based on the fakeon idea, which is a quantum field theory, admits a perturbative expansion in terms of Feynman diagrams and allows us to make calculations with a comparable effort. It can be coupled to th standard model straightforwardly.**

**Our solution bests its competitors in calculatibity, predictivity and falsifiability. It is also rather rigid, because it contains only two new parameters. It could turn out to be the most predictive theory ever.**

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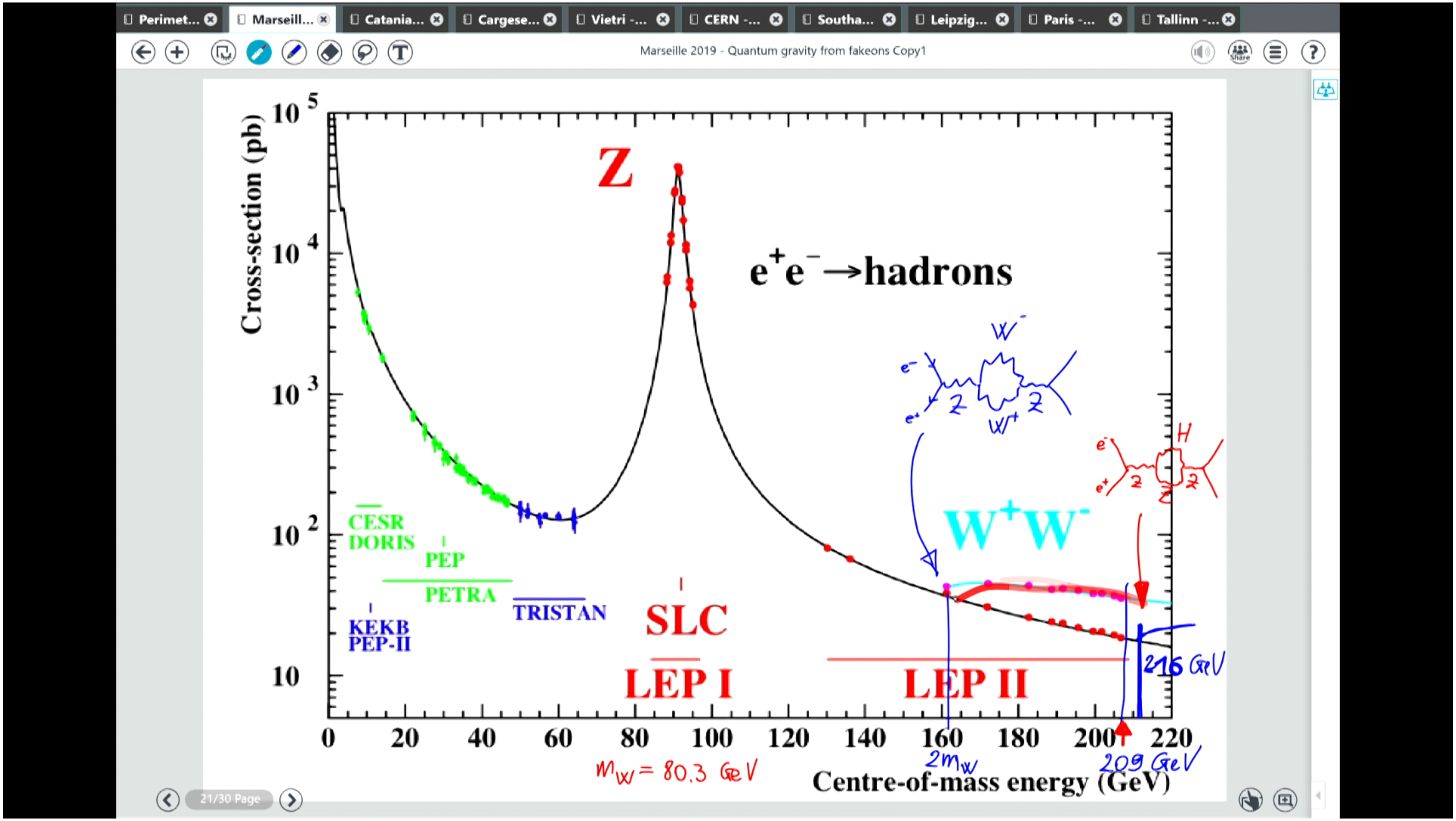
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