FISICA DE LAS INTERACCIONES FUNDAMENTALES

1ER CUATRIMESTRE 2026

CLASE 9

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CLASE 9: Teoría de perturbaciones.

Temas: Perturbación covariante, propagadores, electrodinámica

formalismo no relativista:

$$E_n \phi_n = H_0 \phi_n \qquad\qquad \int d^3x \, \phi_m^* \phi_n = \delta_{mn}$$

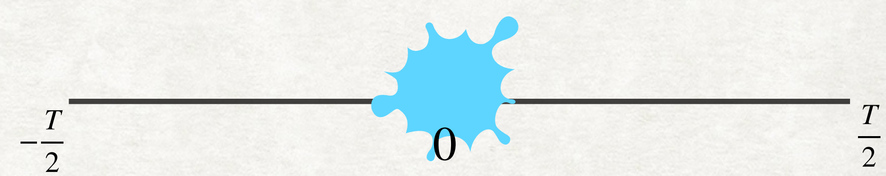
$$i \frac{\partial \psi}{\partial t} = \left(H_0 + V(\vec{x}, t)\right) \psi \qquad\qquad \psi(\vec{x}, t) = \sum_n a_n(t)\, \phi_n(\vec{x})\, e^{-iE_n t} \qquad a_n(t)$$

$$i \sum_n \frac{da_n}{dt} \phi_n(\vec{x})\, e^{-iE_n t} + \sum_n E_n\, a_n(t)\, \phi_n(\vec{x})\, e^{-iE_n t} = \sum_n E_n\, a_n(t)\, \phi_n(\vec{x})\, e^{-iE_n t} + \sum_n a_n(t)\, V(\vec{x}, t)\, \phi_n(\vec{x})\, e^{-iE_n t}$$

mult. m.a.m por ϕ_f^*

$$\frac{da_f}{dt} = -i \sum_n a_n(t) \int d^3x\, \phi_f^*\, V(\vec{x}, t)\, \phi_n(\vec{x})\, e^{i(E_f - E_n)t} \simeq -i \int d^3x\, \phi_f^*\, V(\vec{x}, t)\, \phi_i(\vec{x})\, e^{i(E_f - E_i)t}$$

supongamos que a $t_i = -\frac{T}{2} \sim \phi_i \qquad a_i(-\frac{T}{2}) = 1 \qquad a_n(-\frac{T}{2}) = 0 \quad \forall n \neq i$



$$a_f(t) \simeq -i \int_{-\frac{T}{2}}^{t} dt' \int d^3x\; \phi_f^*(\vec{x})\, V(\vec{x}, t')\, \phi_i(\vec{x})\, e^{i(E_f - E_i)t'}$$

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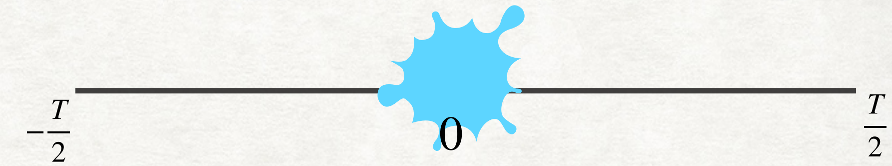
formalismo no relativista:

$$a_f(t) \simeq -i \int_{-\frac{T}{2}}^{t} dt' \int d^3x \; \phi_f^*(\vec{x})\, V(\vec{x}, t')\, \phi_i(\vec{x})\, e^{i(E_f - E_i)t'}$$



$$T_{fi} \equiv a_f(\frac{T}{2}) = -i \int_{-\frac{T}{2}}^{\frac{T}{2}} dt' \int d^3x \; \left(\phi_f e^{-iE_f}\right)^* \; V(\vec{x}, t') \; \left(\phi_i\, e^{-iE_i t'}\right) \;\; = -i \int d^4x \; \Phi_f^*(x^\mu)\, V\, \Phi_i(x^\mu)$$

si $V \sim cte$ $\qquad T_{fi} = -i\, V_{fi} \int dt\, e^{i(E_f - E_i)t}$ $\qquad V_{fi} \equiv \int d^3x \phi_f^*(\vec{x})\, V\, \phi_i(\vec{x})$

si $T \to \infty$ $\qquad T_{fi} = -2\pi i\, V_{fi}\, \delta(E_f - E_i)$ $\qquad E_f = E_i$ sólo si $T \to \infty$!!

probabilidad de transición
por unidad de tiempo

$$W \equiv \lim_{T \to \infty} \frac{|T_{fi}|^2}{T}$$

$$W = \lim_{T \to \infty} 2\pi \frac{|V_{fi}|^2}{T} \delta(E_f - E_i) \int_{-\frac{T}{2}}^{\frac{T}{2}} dt\, e^{i(E_f - E_i)t} = \lim_{T \to \infty} 2\pi \frac{|V_{fi}|^2}{T} \delta(E_f - E_i) \int_{-\frac{T}{2}}^{\frac{T}{2}} dt$$

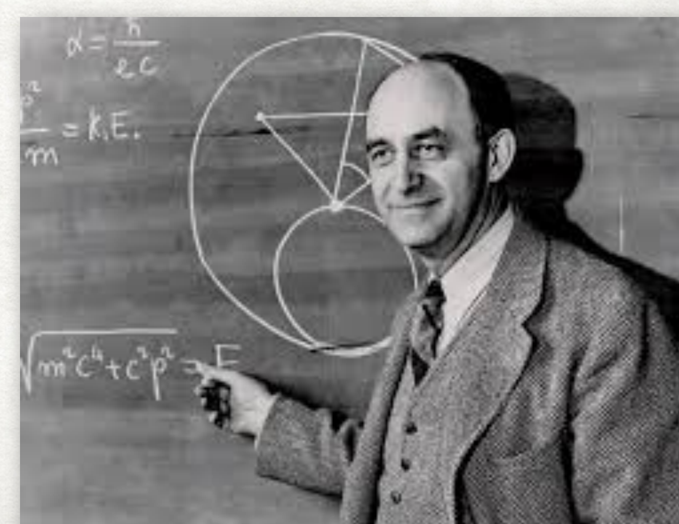
$$= 2\pi\, |V_{fi}|^2\, \delta(E_f - E_i)$$

para un estado inicial fijo i
y un continuo de estados
finales $\rho(E_f)$

$$W_{if} = 2\pi \int dE_f\, \rho(E_f)\, |V_{fi}|^2\, \delta(E_f - E_i) = 2\pi\, \rho(E_i)\, |V_{fi}|^2$$

$\rho(E_f)$ número de estados
entre E_f y $E_f + dE_f$

"regla de oro de Fermi"



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formalismo no relativista:

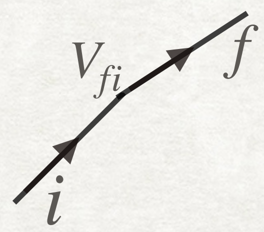
$$a_f^{(1)}(t) \simeq -\, i\, V_{fi} \int_{-\frac{T}{2}}^{t} dt'\, e^{i(E_f - E_i)t'} \qquad \frac{da_f}{dt} = -i \sum_n a_n(t)\, V_{fn}\, e^{i(E_f - E_n)t} \qquad a_n(t) \simeq 0 \quad \forall n \neq i$$

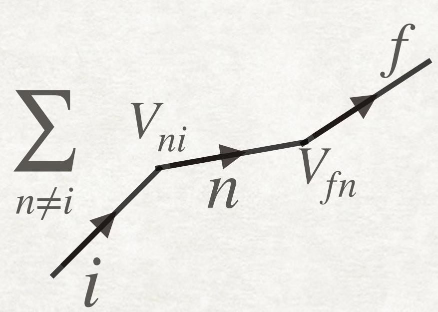
$$\frac{da_f^{(2)}}{dt} \simeq \underbrace{-i\, V_{fi}\, e^{i(E_f - E_i)t}}_{n=i} \quad \underbrace{+(-i) \sum_{n \neq i} \overbrace{(-i) V_{ni} \int_{-\frac{T}{2}}^{t} dt'\, e^{i(E_n - E_i)t'}}^{a_n^{(1)}}\, V_{fn}\, e^{i(E_f - E_n)t}}_{n \neq i}$$

$$T_{fi} \equiv a_f(\frac{T}{2}) = -\, 2\pi i\, V_{fi}\, \delta(E_f - E_i) - \sum_{n \neq i} V_{fn} V_{ni} \int_{-\frac{T}{2}}^{\frac{T}{2}} dt\, e^{i(E_f - E_n)t} \int_{-\frac{T}{2}}^{t} dt'\, e^{i(E_n - E_i)t'}$$

$$\int_{-\frac{T}{2}}^{t} dt'\, e^{i(E_n - E_i)t'} \xrightarrow[T \to \infty]{} i\, \frac{e^{i(E_n - E_i)t}}{E_i - E_n}$$

$$T_{fi} = -\, 2\pi i\, V_{fi}\, \delta(E_f - E_i) - 2\pi i \sum_{n \neq i} \frac{V_{fn} V_{ni}}{E_i - E_n}\, \delta(E_f - E_i)$$





$E_f = E_i$ sólo si $T \to \infty$!!

$$\frac{1}{E_i - E_n}$$ "propagador"

CLASE 9: Teoría de perturbaciones.

formalismo relativista:

$$H_0 = \alpha\cdot p + \beta m \qquad \left(\gamma_\mu p^\mu - m\right)\psi = 0$$

$$H = \alpha\cdot p + \beta m + V \qquad \left(\gamma_\mu p^\mu - m - \gamma^0 V\right)\psi' = 0$$

$$-\gamma^0 V = e\gamma_\mu A^\mu \qquad V = -\,e\gamma^0\gamma_\mu A^\mu$$

$$p^\mu \to p^\mu + e\,A^\mu \qquad \left(\gamma_\mu p^\mu - m + e\gamma_\mu A^\mu\right)\psi' = 0$$

$$T_{fi} = -\,i\int d^4x\,\Phi_f^*(x^\mu)\,V\,\Phi_i(x^\mu) \longrightarrow -\,i\int d^4x\,\psi_f^\dagger(x^\mu)\,V\,\psi_i(x^\mu) = -\,i\int d^4x\,\psi_f^\dagger(x^\mu)\,(-e\gamma^0\gamma_\mu A^\mu)\,\psi_i(x^\mu)$$

$$= -\,i\int d^4x\,(-e)\,\overline{\psi}_f(x^\mu)\,\gamma_\mu\,\psi_i(x^\mu)\,A^\mu$$

$$= -\,i\int d^4x\,J_\mu^{fi}\,A^\mu$$

$$J_\mu^{fi} \equiv -\,e\,\overline{\psi}_f\,\gamma_\mu\,\psi_i = -\,e\,\overline{u}_f\gamma_\mu\,u_i\,e^{i(p^f-p^i)_\mu x^\mu}$$

$$= -\,e\,(p_\mu^f - p_\mu^i)\;e^{i(p^f-p^i)_\mu x^\mu}$$

$$\Box A^\mu = J^\mu \qquad J^\mu = -\,e\,(p_d^\mu - p_c^\mu)\;e^{i(p^d-p^c)_\mu x^\mu}$$

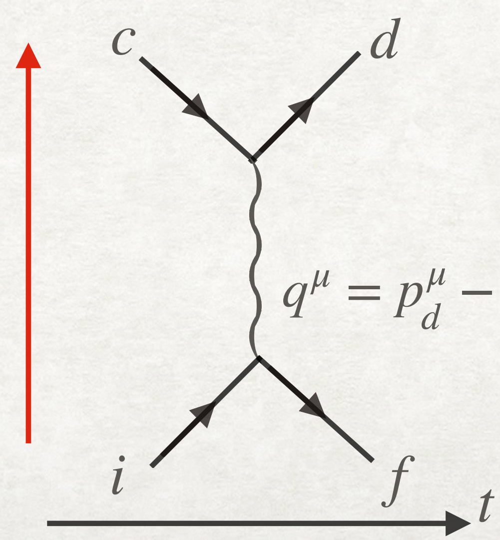
$$\Box\, e^{iq\cdot x} = -\,q^2 e^{iq\cdot x} \qquad (q^2 = q_\mu q^\mu)$$

$$A^\mu = -\frac{1}{q^2}J^\mu \qquad q^\mu = p_d^\mu - p_c^\mu$$

$\overline{u}_f \to \overline{v}_f$
$u_c \to v_c$

"aniquilación"

$i + \bar{f} \to \bar{c} + d$



$$q^\mu = p_d^\mu - p_c^\mu = p_f^\mu - p_i^\mu$$

$$T_{fi} = -\,i\int d^4x\,J_\mu^{fi}\left(-\frac{1}{q^2}\right)J_{dc}^\mu$$

"scattering" $\quad i + c \to f + d$

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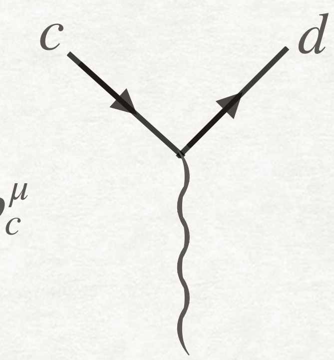
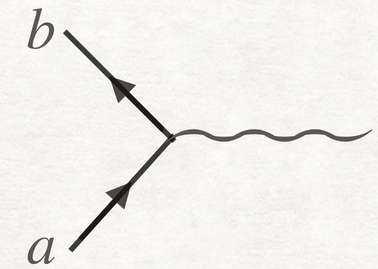
propagadores:

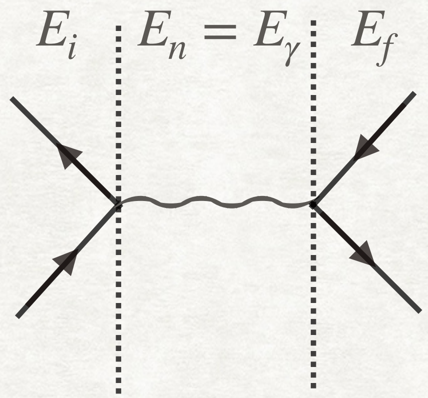
$$\frac{1}{E_i - E_f} \longrightarrow -\frac{1}{q^2}$$

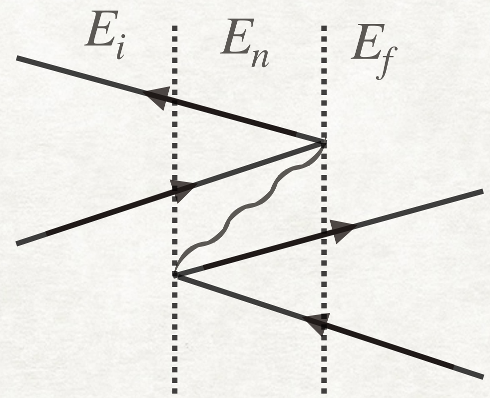
$$q^\mu = p_d^\mu - p_c^\mu$$



$$q^\mu = p_a^\mu + p_b^\mu$$







$$E_n = E_i + E_f + E_\gamma$$
$$= 2E_i + E_\gamma$$

$$T \sim V_{fn}\frac{1}{E_i - E_\gamma}V_{ni} + V_{fn}\frac{1}{E_i - 2E_i - E_\gamma}V_{ni} = V_{fn}\,\frac{-2E_i}{E_i^2 - E_\gamma^2}\,V_{ni}$$

$$-E_i - E_\gamma$$

en términos de p_a y p_b

$$p^2 = E^2 - \vec{p}^{\,2}$$

$$E_i^2 = (p_a + p_b)^2 + (\vec{p_a} + \vec{p_b})^2$$

$$E_\gamma^2 = m_\gamma^2 + \vec{p}_\gamma^{\,2}$$

$$\frac{1}{E_i^2 - E_\gamma^2} = \frac{1}{(p_a + p_b)^2 - m_\gamma^2} = \frac{1}{q^2 - m_\gamma^2}$$

$-\frac{1}{q^2}$ propagador de un mediador de m=0

(incluyendo todos los ordenamientos)

q^2 sería el cuadri-impulso al cuadrado del fotón si se conservara la energía en cada vértice

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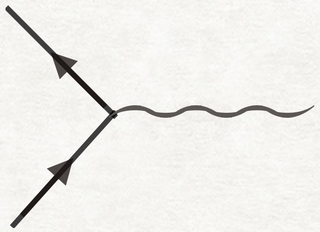
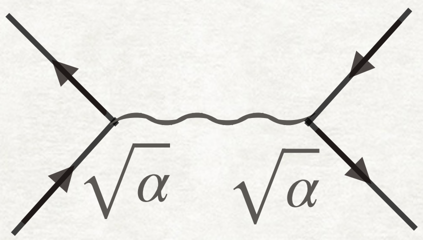
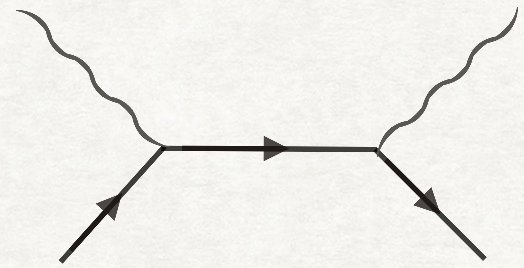
electrodinámica (QED):

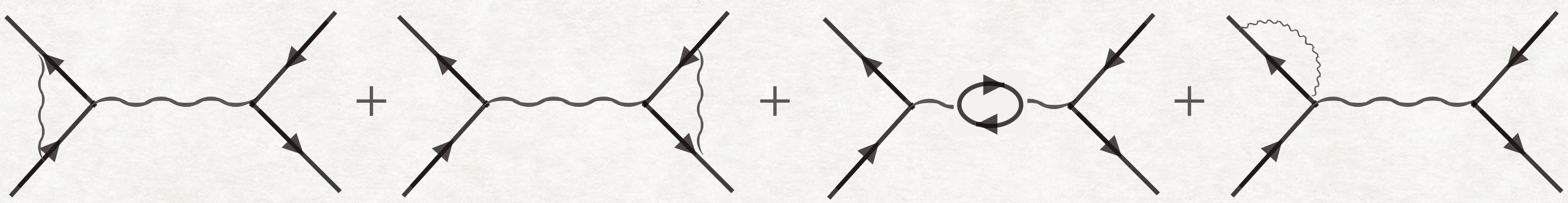


$\mathscr{A} \propto \sqrt{\alpha_{QED}}$ $\qquad \alpha_{QED} = \dfrac{e^2}{\hbar c} \simeq \dfrac{1}{137}$



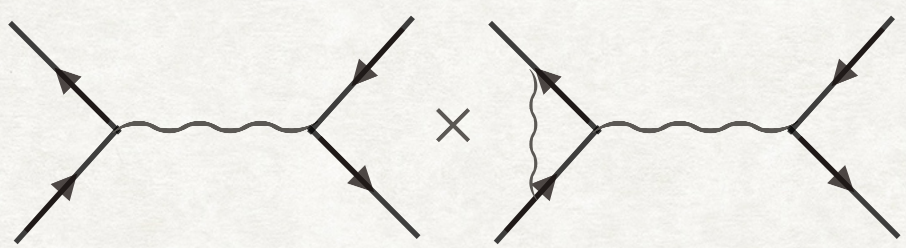
$\mathscr{A} \propto \alpha \qquad \sigma \propto \alpha^2$



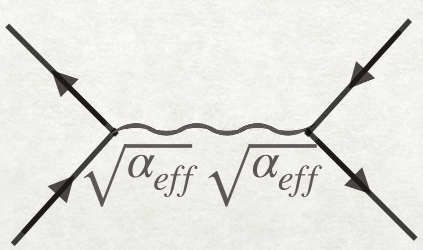


$\cdots \qquad \sigma \propto \alpha^4$

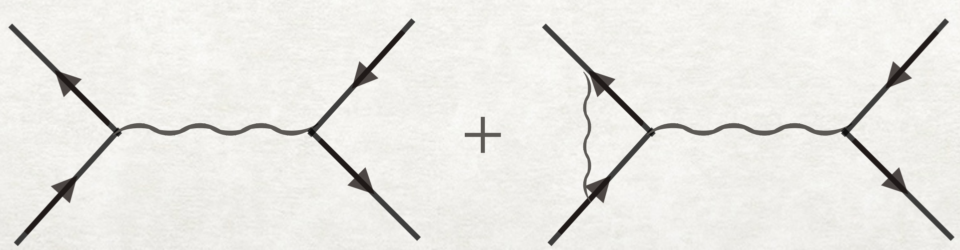
$\sigma \sim \left| \sum \mathscr{A}_i \right|^2$



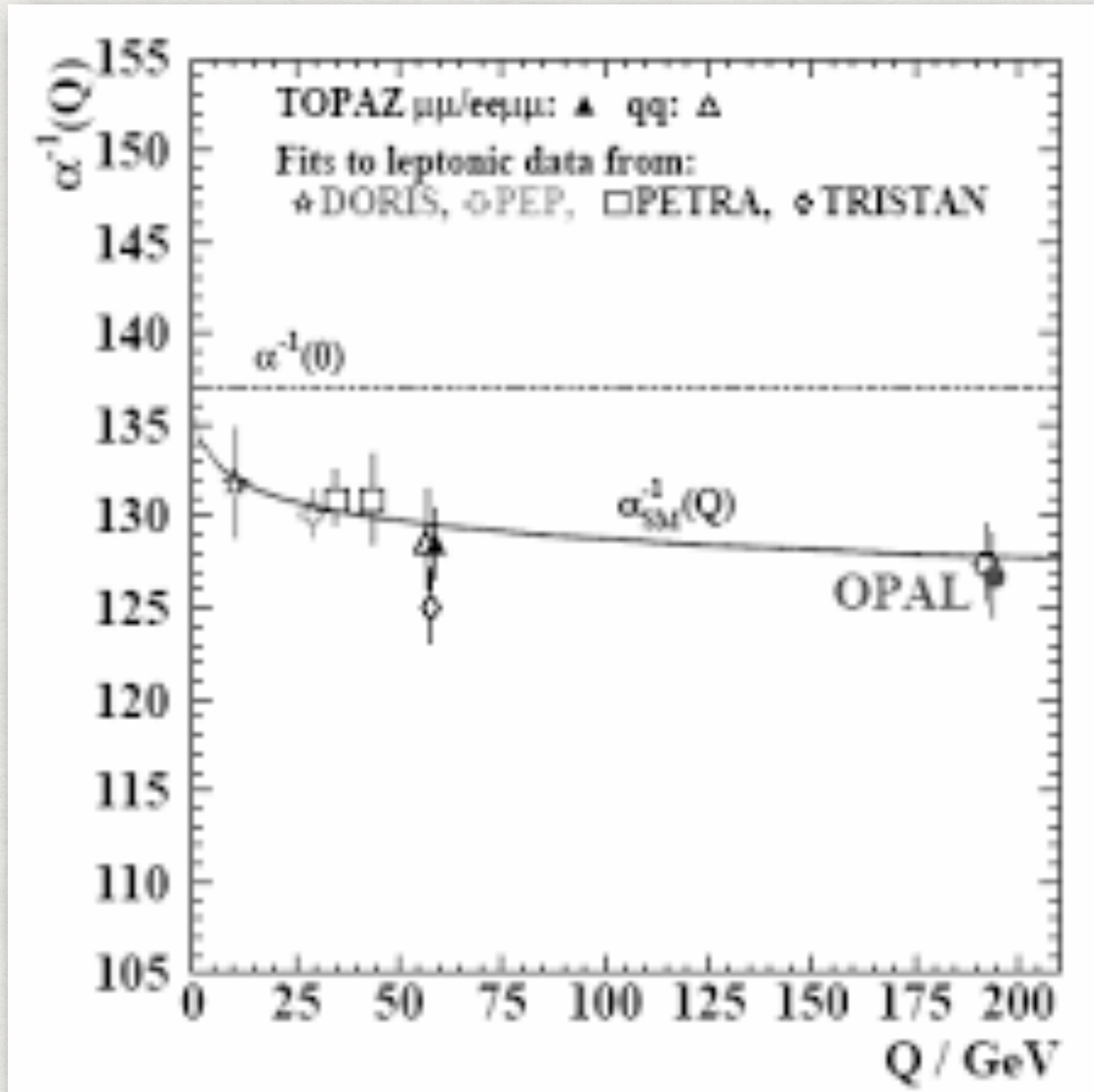
$\sigma \propto \alpha^3$

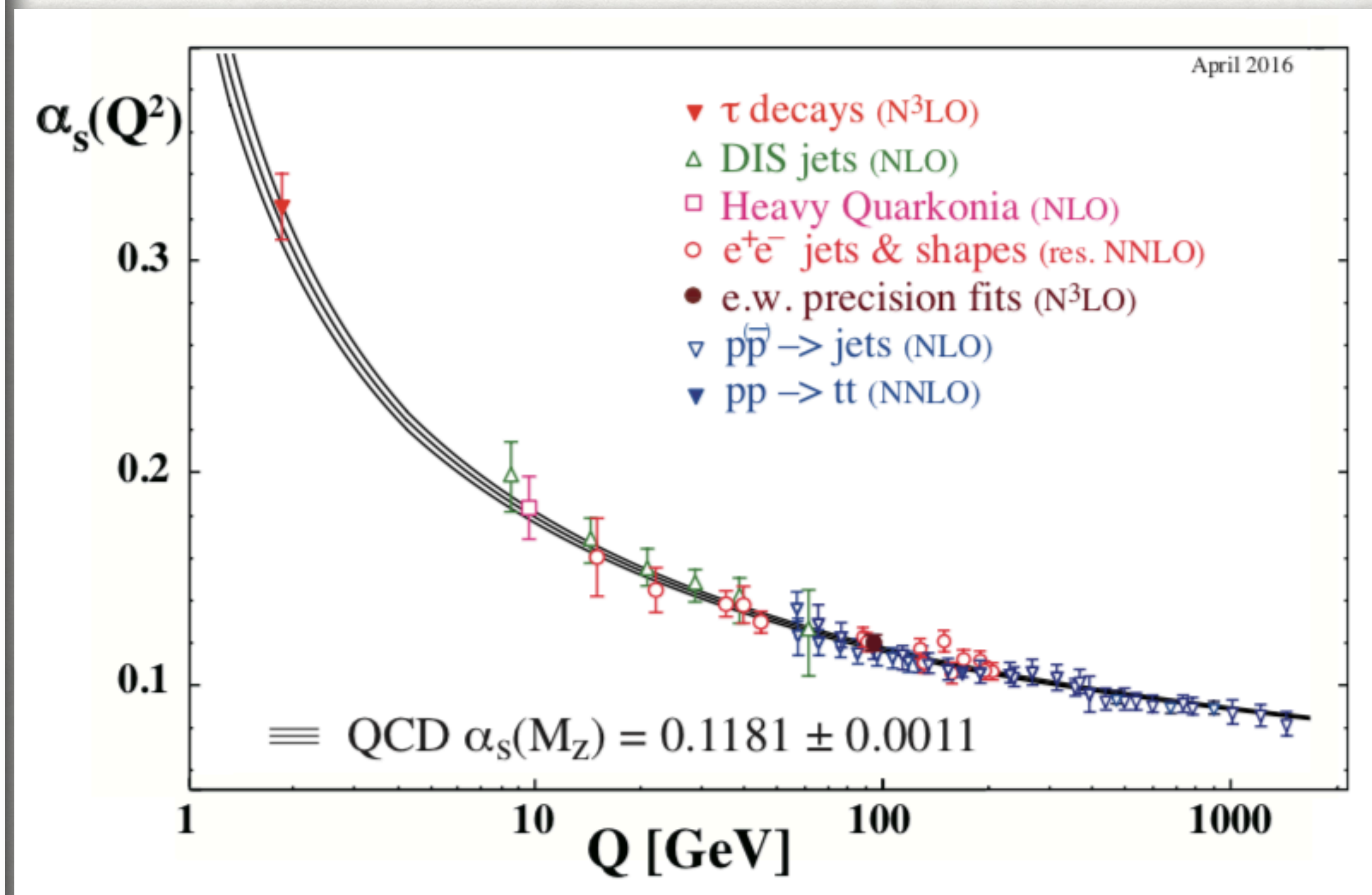


$\equiv$



$+ \cdots \qquad \alpha_{eff}(E) \qquad \dfrac{1}{137} \to \dfrac{1}{128}$


$\alpha^{-1}(Q)$
155
150
145
140
135
130
125
120
115
110
105
TOPAZ μμ/eeμμ: ▲ qq: △
Fits to leptonic data from:
DORIS, PEP, PETRA, TRISTAN
$\alpha^{-1}(0)$
$\alpha^{-1}_{SM}(Q)$
OPAL
0 25 50 75 100 125 150 175 200
Q / GeV


April 2016
$\alpha_s(Q^2)$
τ decays (N³LO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e⁺e⁻ jets & shapes (res. NNLO)
e.w. precision fits (N³LO)
pp̄ –> jets (NLO)
pp –> tt (NNLO)
0.3
0.2
0.1
QCD $\alpha_s(M_Z)$ = 0.1181 ± 0.0011
1 10 100 1000
Q [GeV]