# QUANTIZATION OF A GAUGE THEORY : CASE OF QED (ABELIAN)

$\Rightarrow$ QUANTIZATION

QM : $[\hat{x}, \hat{p}_x]_- = i\hbar$

FIELD THEORY : FIELDS $\phi_r(\bar{x}, t)$

$\downarrow$

CANONICALLY CONJUGATE 'MOMENTUM' FIELDS $\Pi_r(\bar{x}, t)$

$$\Pi_r(\bar{x}, t) \equiv \frac{\partial \mathcal{L}}{\partial(\partial^0 \phi_r(\bar{x}, t))}$$

$$\left\{ \begin{array}{l} [\phi_r(\bar{x}, t), \phi_s(\bar{x}', t)]_- = 0 \\ [\Pi_r(\bar{x}, t), \Pi_s(\bar{x}', t)]_- = 0 \\ [\phi_r(\bar{x}, t), \Pi_s(\bar{x}', t)]_- = \delta_{rs}\, i\, \delta^3(\bar{x} - \bar{x}') \end{array} \right.$$

$\hookrightarrow$ EQUAL TIME COMMUTATION RELATIONS (ETCR)

⇒ QED

$$\boxed{\mathcal{L} = \bar{\Psi}\,(i\gamma^\mu \partial_\mu - m)\,\Psi - \underbrace{e\,\bar{\Psi}\gamma^\mu\Psi}_{J^\mu}\,A_\mu \underbrace{- \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu}}_{\mathcal{L}_{em}}}$$

↓

- FIELD EQUATIONS FOR $A^a$ $\qquad (\Phi_r = A^\nu)$

$$\frac{\partial \mathcal{L}}{\partial \Phi_r} - \partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \Phi_r)} = 0$$

$$-J^\nu + \tfrac{1}{2}\partial_\mu F^{\mu\nu} \cdot 2 = 0$$

$$\Downarrow$$

$$\underline{\underline{\partial_\mu F^{\mu\nu} = J^\nu}}$$

$$\underline{\underline{\Box A^\nu - \partial^\nu(\partial_\mu A^\mu) = J^\nu}}$$

- GAUGE INVARIANCE

$$A^\mu \rightarrow A^\mu - \partial^\mu \chi \qquad , \quad \Psi \rightarrow \exp(ie\,\chi)\,\Psi$$

$$\Downarrow$$

FREEDOM TO CONSTRAIN $A^\mu$ :

POSSIBLE CHOICES ARE

$\partial_\mu A^\mu = 0$ : LORENTZ GAUGE (COVARIANT)

$\bar{\nabla} . \bar{A} = 0$ COULOMB GAUGE (NON- COVARIANT)

$n_\mu A^\mu = 0$ AXIAL GAUGE WITH $n_\mu n^\mu = -1$

e.g. $n_\mu\,(0,0,0,1)$

e.g. FOR LORENTZ GAUGE :

FIELD EQUATIONS REDUCE TO

$$\square A^\nu = J^\nu$$

$$\partial_\nu A^\nu = 0 \qquad \text{( CONSTRAINT )}$$

( NOTE THAT THE EQS. ARE CONSISTENT IF $\partial_\nu J^\nu = 0$ : CURRENT CONSERVATION )

$\Rightarrow$ QUANTISE THEORY IN PRESENCE OF CONSTRAINT

$$A^\mu \longrightarrow \Pi^\mu \equiv \frac{\partial \mathcal{L}}{\partial \dot{A}_\mu} = - F^{0\mu}$$

$$\begin{cases} \Pi^0 = 0 \\ \Pi^i = - F^{0i} = + E^i \quad \text{( ELECTRIC FIELDS )} \end{cases}$$

FOR $A^i$ $i = 1,2,3$ OK

FOR $A^0$ , WE CANNOT IMPOSE ETCR AS $\Pi^0 = 0$

PROBLEM 1

# ➾ PHOTON PROPAGATOR

- KLEIN - GORDON

$$(\Box + m^2)\phi = 0$$

$$\downarrow$$

$$(-k^2 + m^2)\phi = 0$$

SCALAR PROPAGATOR $\frac{i}{k^2 - m^2}$ : 'INVERSE' OF OPERATOR IN $\overbrace{\ }^{\text{FREE}}$ FIELD EQUATION

$$\overset{\longrightarrow}{k}$$

- FREE FIELD EQUATION FOR $A^\nu$

$$\Box A^\nu - \partial^\nu(\partial_\mu A^\mu) = 0$$

$$\underbrace{(-k^2 g^{\mu\nu} + k^\mu k^\nu)}\, A_\mu = 0$$

$$\downarrow \text{ INVERSE}$$

$$(-k^2 g^{\mu\nu} + k^\mu k^\nu)(A g_{\nu\lambda} + B k_\nu k_\lambda) = g^\mu_\lambda$$

$$-Ak^2 g^\mu_\lambda + A k^\mu k_\lambda - \cancel{Bk^2 k^\mu} k_\lambda + \cancel{Bk^2} k^\mu k_\lambda = g^\mu_\lambda$$

$$\left.\begin{aligned} -Ak^2 &= 1 \\ A &= 0 \end{aligned}\right\} \quad \text{IMPOSSIBLE FOR ANY } A$$

↳ PROBLEM 2 : OPERATOR IN FIELD EQ. FOR $A^\nu$ HAS NO INVERSE

## ⇒ SOLUTION TO ABOVE PROBLEMS

CONSIDER ALTERNATIVE $\mathcal{L}$

$$\mathcal{L}_{em} \rightarrow \boxed{\mathcal{L}_{em}' = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \underbrace{\frac{1}{2}(\partial_\mu A^\mu)^2}_{\text{GAUGE FIXING TERM}}}$$

- EQUATIONS OF MOTION :

$$\partial_\mu F^{\mu\nu} + \partial^\nu(\partial_\mu A^\mu) = 0$$

$$\square A^\nu - \cancel{\partial^\nu(\partial_\mu A^\mu)} + \cancel{\partial^\nu(\partial_\mu A^\mu)} = 0$$

$$\square A^\nu = 0$$

i.e. FIELD EQ. FOLLOWING FROM $\mathcal{L}_{em}'$

CORRESPOND WITH CHOICE OF LORENTZ GAUGE

- CANONICAL MOMENTA

$$\pi^\mu = - F^{0\mu} - (\partial_\alpha A^\alpha)\, g^{0\mu}$$

$$\begin{cases} \pi^0 = - \partial_\alpha A^\alpha \\ \pi^i = - F^{0i} \end{cases}$$

OK PROBLEM 1

IF $\partial_\alpha A^\alpha$ is CONSIDERED AS OPERATOR CONDITION

⇓

ETCR
$$\begin{cases} [A^\mu(\bar{x},t), A^\nu(\bar{x}',t)]_- = 0 \\ [\pi^\mu(\bar{x},t), \pi^\nu(\bar{x}',t)]_- = 0 \\ [A^\mu(\bar{x},t), \pi^\nu(\bar{x}',t)]_- = i\, g^{\mu\nu}\, \delta^3(\bar{x}-\bar{x}') \end{cases}$$

$$\rightsquigarrow \quad \Big[ A^\mu(\bar{x},t)\,,\ \underbrace{\Pi^0(\bar{x}',t)}_{-\partial_\alpha A^\alpha} \Big]_- = i g^{\mu 0}\, \delta^3(\bar{x}-\bar{x}')$$

$$= - \big[ A^\mu(\bar{x},t)\,,\ \dot{A}^0(\bar{x}',t) \big]_- + \bar{\nabla}_{x'} \underbrace{\cancel{\big[ A^\mu(\bar{x},t)\,,\ \bar{A}(\bar{x}',t) \big]_-}}_{0}$$

$$\rightsquigarrow \quad \Big[ A^\mu(\bar{x},t)\,,\ \underbrace{\Pi^i(\bar{x}',t)}_{-\dot{A}^i + \partial^i A^0} \Big]_- = i g^{\mu i}\, \delta^3(\bar{x}-\bar{x}')$$

$$= - \big[ A^\mu(\bar{x},t)\,,\ \dot{A}^i(\bar{x}',t) \big]_- + \partial^i_{x'} \underbrace{\cancel{\big[ A^\mu(\bar{x},t)\,,\ A^0(\bar{x}',t) \big]_-}}_{0}$$

$$\therefore \quad \big[ A^\mu(\bar{x},t)\,,\ \dot{A}^\nu(\bar{x}',t) \big]_- = - i g^{\mu\nu}\, \delta^3(\bar{x}-\bar{x}')$$

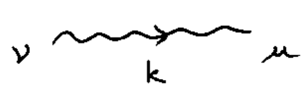
$$\boxed{\begin{array}{l} \big[ A^\mu(\bar{x},t)\,,\ \dot{A}^0(\bar{x}',t) \big]_- = - i\, \delta^3(\bar{x}-\bar{x}') \\ \big[ A^\mu(\bar{x},t)\,,\ \dot{A}^i(\bar{x}',t) \big]_- = + i\, \delta^3(\bar{x}-\bar{x}') \end{array}} \quad \begin{array}{l} \text{FOR } \mu = 0 \\ \text{FOR } \mu = i \end{array}$$

- PHOTON PROPAGATOR

$$\Box A^\nu = 0$$

$$-k^2 A^\nu = 0$$

INVERSE EXISTS $\Rightarrow$ PHOTON PROPAGATOR (IN LORENTZ GAUGE)




$$\frac{-i g^{\mu\nu}}{k^2}$$

OK PROBLEM 2.

$\Rightarrow$ CAN GAUGE CONDITION $\partial_\mu A^\mu = 0$ BE CONSIDERED AS OPERATOR CONDITION WHEN THEORY IS QUANTIZED ?

i.e. FIELDS $A^\mu \longrightarrow$ FIELD OPERATORS $\hat{A}^\mu$

QUANTIZATION $\Rightarrow$ NORMAL MODE EXPANSION FOR $\hat{A}^\mu$

$$\hat{A}^\mu(\bar{x},t) = \int \frac{d^3\bar{k}}{\sqrt{(2\pi)^3 2\omega_{\bar{k}}}} \sum_{\lambda=0}^{3} \left\{ a(\bar{k},\lambda)\, \varepsilon^\mu(\bar{k},\lambda)\, e^{-ikx} + a^+(\bar{k},\lambda)\, \varepsilon^{\mu *}(\bar{k},\lambda)\, e^{+ikx} \right\}$$

$$\omega_{\bar{k}} = |\bar{k}|$$

WITH POLARIZATION VECTORS $\varepsilon^\mu(\bar{k},\lambda)$

e.g. IF $k\,(|\bar{k}|, 0, 0, |\bar{k}|)$

↳ CONVENIENT CHOICE

SCALAR POL. $\leftarrow \varepsilon(\bar{k},\lambda=0) = (1,0,0,0)$

TRANSVERSE POL $\begin{cases} \varepsilon(\bar{k},\lambda=1) = (0,1,0,0) \\ \varepsilon(\bar{k},\lambda=2) = (0,0,1,0) \end{cases}$

LONG. POL. $\leftarrow \varepsilon(\bar{k},\lambda=3) = (0,0,0,1)$

$$\varepsilon^\mu(\bar{k},\lambda)\,\varepsilon^*_\mu(\bar{k},\lambda') = -\zeta_\lambda \delta_{\lambda\lambda'}$$

$$\begin{cases} \zeta_0 = -1 \\ \zeta_i = +1 \end{cases}$$

$a(\bar{k},\lambda)$ : ANNIHILATION OPERATOR FOR PHOTON WITH MOMENTUM $\bar{k}$ & POLARIZATION $\lambda$

$a^+(\bar{k},\lambda)$ : CREATION OPERATOR

$$\int d^3\bar{x}\ e^{-i\bar{k}.\bar{x}}\ A^\mu(\bar{x},t)$$

$$= \frac{(2\pi)^{3/2}}{\sqrt{2\omega_{\bar{k}}}} \sum_{\lambda=0}^{3} \Big\{ a(\bar{k},\lambda)\, \varepsilon^\mu(\bar{k},\lambda)\, e^{-i\omega_k t} + a^+(-\bar{k},\lambda)\, \varepsilon^{\mu *}(-\bar{k},\lambda)\, e^{i\omega_{\bar{k}} t} \Big\}$$

$$\Downarrow$$

$$\rightsquigarrow \int d^3\bar{x}\ e^{-i\bar{k}.\bar{x}} \Big\{ A^\mu(\bar{x},t) + \frac{i}{\omega_{\bar{k}}} \dot{A}^\mu(\bar{x},t) \Big\}$$

$$= 2\, \frac{(2\pi)^{3/2}}{\sqrt{2\omega_{\bar{k}}}} \sum_{\lambda=0}^{3} a(\bar{k},\lambda)\, \varepsilon^\mu(\bar{k},\lambda)\, e^{-i\omega_k t}$$

$$\rightsquigarrow \int d^3\bar{x}\ e^{-i\bar{k}.\bar{x}} \Big\{ A^\mu(\bar{x},t) - \frac{i}{\omega_{\bar{k}}} \dot{A}^\mu(\bar{x},t) \Big\}$$

$$= 2\, \frac{(2\pi)^{3/2}}{\sqrt{2\omega_k}} \sum_{\lambda=0}^{3} a^+(-\bar{k},\lambda)\, \varepsilon^{\mu *}(-\bar{k},\lambda)\, e^{i\omega_k t}$$

$$\therefore \quad a(\bar{k},\lambda) = -\zeta_\lambda e^{i\omega_k t} \sqrt{\frac{\omega_k}{2(2\pi)^3}} \int d^3\bar{x}\ e^{-i\bar{k}.\bar{x}}\, \varepsilon^*_\mu(\bar{k},\lambda) \Big\{ A^\mu + \frac{i}{\omega_k} \dot{A}^\mu \Big\}$$

$$a^+(\bar{k},\lambda) = -\zeta_\lambda\, e^{-i\omega_k t} \sqrt{\frac{\omega_k}{2(2\pi)^3}} \int d^3\bar{x}\ e^{+i\bar{k}.\bar{x}}\, \varepsilon_\mu(\bar{k},\lambda) \Big\{ A^\mu - \frac{i}{\omega_k} \dot{A}^\mu \Big\}$$

ET COMMUTATION RELATIONS FOR FIELD OPERATORS $\hat{A}^\mu$ IMPLY COMMUTATION RELATIONS FOR CREATION & ANNIHILATION OPERATORS :

$$\left[ a(\bar{k},\lambda) \, , \, a^+(\bar{k}',\lambda') \right]_-$$

$$= \zeta_\lambda \zeta_{\lambda'} \, e^{i\omega_k t} e^{-i\omega_{k'} t} \, \frac{\sqrt{\omega_k \omega_{k'}}}{2\,(2\pi)^3} \, \mathcal{E}^*_\mu(\bar{k},\lambda) \, \mathcal{E}_\nu(\bar{k}',\lambda')$$

$$\cdot \int d^3\bar{x} \int d^3\bar{x}' \, e^{-i\bar{k}.\bar{x}} \, e^{+i\bar{k}'.\bar{x}'}$$

$$\underbrace{\left[ A^\mu(\bar{x},t) + \frac{i}{\omega_k} \dot{A}^\mu(\bar{x},t) \, , \, A^\nu(\bar{x}',t) - \frac{i}{\omega_{k'}} \dot{A}^\nu(\bar{x}',t) \right]_-}_{-\frac{1}{\omega_{k'}} g^{\mu\nu} \delta^3(\bar{x}-\bar{x}') \; - \frac{1}{\omega_k} g^{\mu\nu} \delta^3(\bar{x}-\bar{x}')}$$

$$= \zeta_\lambda \zeta_{\lambda'} \, e^{i(\omega_k - \omega_{k'})t} \, \frac{\sqrt{\omega_k \omega_{k'}}}{2\,(2\pi)^3} \, \mathcal{E}^*_\mu(\bar{k},\lambda) \, \mathcal{E}^\mu(\bar{k}',\lambda')$$

$$\cdot \underbrace{\int d^3\bar{x} \; e^{-i(\bar{k}-\bar{k}').\bar{x}}}_{(2\pi)^3 \, \delta^3(\bar{k}-\bar{k}')} \left( -\frac{1}{\omega_{k'}} - \frac{1}{\omega_k} \right)$$

$$= -\zeta_\lambda \zeta_{\lambda'} \, \underbrace{\mathcal{E}^*_\mu(\bar{k},\lambda) \, \mathcal{E}^\mu(\bar{k},\lambda')}_{-\zeta_\lambda \delta_{\lambda\lambda'}} \, \delta^3(\bar{k}-\bar{k}')$$

$$= \zeta_\lambda \, \delta_{\lambda\lambda'} \, \delta^3(\bar{k}-\bar{k}')$$

$$\boxed{\begin{array}{l} [a(\vec{k},\lambda),\ a^+(\vec{k}',\lambda')]_- = \zeta_\lambda\, \delta_{\lambda\lambda'}\, \delta^3(\vec{k}-\vec{k}') \\ \text{AND ANALOGOUSLY} \\ [a(\vec{k},\lambda),\ a(\vec{k}',\lambda')]_- = 0 \\ [a^+(\vec{k},\lambda),\ a^+(\vec{k}',\lambda')]_- = 0 \end{array}}$$

FOR $\lambda = 1, 2, 3$

$$[a(\vec{k},i),\ a^+(\vec{k}',j)]_- = \delta_{ij}\, \delta^3(\vec{k}-\vec{k}')$$

FOR $\lambda = 0$ ( "SCALAR" PHOTON POLARIZATION)

$$[a(\vec{k},0),\ a^+(\vec{k}',0)]_- = \underset{\Uparrow}{-}\ \delta^3(\vec{k}-\vec{k}')$$

$\rightsquigarrow$ DEFINE : VACUUM IS STATE WITHOUT PHOTONS

$$a(\vec{k},\lambda)\,|0\rangle = 0 \qquad , \quad \lambda = 0,1,2,3$$

$\rightsquigarrow$ CONSIDER STATE WITH 1 SCALAR PHOTON

$$|\gamma, \lambda=0\rangle = \int d^3\vec{k}\ f(\vec{k})\ a^+(\vec{k},0)\,|0\rangle$$

↳ WAVE PACKET $\int d^3\vec{k}\,|f(\vec{k})|^2 < \infty$

$\Downarrow$

NORM $\langle \gamma, \lambda=0 \,|\, \gamma, \lambda=0\rangle$

$$\int d^3\vec{k} \int d^3\vec{k}'\, f^*(\vec{k})\, f(\vec{k}') \langle 0 |\, a(\vec{k},0)\, a^+(\vec{k}',0)\,|\,0\rangle$$

$$= -\int d^3\vec{k}\ |f(\vec{k})|^2 \langle 0|0\rangle \quad < 0 \quad \text{( NEGATIVE NORM !)}$$

⤳ HAMILTONIAN

$$H = \int d^3\bar{k} \;\; \omega_k \left\{ - a^+(\bar{k},0)\, a(\bar{k},0) + \sum_{i=1}^{3} a^+(\bar{k},i)\, a(\bar{k},i) \right\}$$

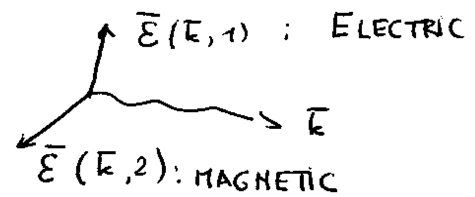
↑

STATES WITH $\lambda = 0$
LEAD TO NEGATIVE ENERGY

PHYSICALLY : ONLY 2 INDEPENDENT COMPONENTS FOR
FREE MAXWELL FIELD

$\varepsilon(\bar{k},1)$ , $\varepsilon(\bar{k},2)$

$\bar{k}\cdot\bar{\varepsilon} = 0$




WE WANT CONDITION TO GET RID OF $\lambda = 0,3$ STATES IN QUANTUM THEORY
↓
SHOULD NOT APPEAR IN PHYSICAL STATES.

LORENTZ CONDITION AS OPERATOR RELATION IS TOO STRONG
↓
LEADS TO NEGATIVE NORM, ENERGY STATES

⇓

WEAKER CONDITION , WE ONLY REQUIRE LORENTZ CONDITION
FOR PHYSICAL STATES OF THEORY

$|\Psi\rangle$ GROUND STATE (PHYSICAL VACUUM)

i.e. $$\boxed{\partial_\mu A^{\mu\,(+)}\, |\Psi\rangle = 0}$$

+ FREQUENCY PART (i.e. ANNIHILATING PART)

$$\partial_\mu A^{\mu(+)} |\Psi\rangle = 0$$

$$\Downarrow$$

$$\partial_\mu \int \frac{d^3\bar{k}}{\sqrt{(2\pi)^3 2\omega_k}} \sum_\lambda a(\bar{k},\lambda)\, e^{-ikx}\, \varepsilon^\mu(\bar{k},\lambda)\, |\Psi\rangle = 0$$

$$\int \frac{d^3\bar{k}}{\sqrt{(2\pi)^3 2\omega_k}} \sum_\lambda (-i)\, a(\bar{k},\lambda)\, e^{-ikx}\, \underbrace{k_\mu \varepsilon^\mu(\bar{k},\lambda)}\, |\Psi\rangle = 0$$

$$\omega_k\, \varepsilon^0(\bar{k},\lambda) - \bar{k}\cdot\bar{\varepsilon}(\bar{k},\lambda)$$

$$= \omega_k\, \delta_{\lambda 0} - |\bar{k}|\, \delta_{\lambda 3}$$

$$= \omega_k\, (\delta_{\lambda 0} - \delta_{\lambda 3})$$

$$\Downarrow$$

$$\therefore \quad \boxed{\left( a(\bar{k},0) - a(\bar{k},3) \right) |\Psi\rangle = 0} \qquad \forall\, \bar{k}$$

SCALAR POL.

LONGITUDINAL POL.

$$\langle \Psi | \underbrace{a^\dagger(\bar{k},3)\, a(\bar{k},3)}_{\text{number of long. photons}} |\Psi\rangle = \langle \Psi | \underbrace{a^\dagger(\bar{k},0)\, a(\bar{k},0)}_{\text{number of scalar photons}} |\Psi\rangle$$

VACUUM CONTAINS EQUAL ADMIXTURES OF L & S PHOTONS

- CHANGE IN NUMBER OF LONG, SCALAR PHOTONS IS EQUIVALENT TO GAUGE TF.
- THEIR COMBINED ENERGY IS ZERO

# $\Rightarrow$ MORE GENERAL GAUGES

$$\boxed{\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2\xi} (\partial_\mu A^\mu)^2}$$

$\xi = 1 \Rightarrow$ LORENTZ GAUGE

$\downarrow$

FIELD EQUATIONS

$$\Box A^\nu - \partial^\nu (\partial_\mu A^\mu) + \frac{1}{\xi}\partial^\nu(\partial_\mu A^\mu) = 0$$

$$\boxed{\Box A^\nu - \left(1 - \frac{1}{\xi}\right) \partial^\nu (\partial_\mu A^\mu) = 0}$$

$\rightsquigarrow$ CANONICAL MOMENTA

$$\Pi^\mu = - F^{0\mu} - g^{0\mu} \frac{1}{\xi}(\partial_\alpha A^\alpha)$$

$\rightsquigarrow$ PROPAGATOR

$$\left[ - k^2 g^{\mu\nu} + \left(1 - \frac{1}{\xi}\right) k^\mu k^\nu \right] A_\nu = 0$$

PROPAGATOR: INVERSE $\sim A g_{\nu\lambda} + B k_\nu k_\lambda$

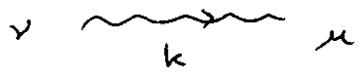
$$\left[-k^2 g^{\mu\nu} + \left(1 - \frac{1}{\xi}\right) k^\mu k^\nu\right] \left( A g_{\nu\lambda} + B k_\nu k_\lambda \right) = g^\mu_\lambda$$

$$(- A k^2) g^\mu_\lambda + \underbrace{\left[-k^2 B + \left(1 - \frac{1}{\xi}\right) A + B k^2 \left(1 - \frac{1}{\xi}\right)\right]}_{k^\mu k_\lambda} = g^\mu_\lambda$$

$$\begin{cases} A = -1/k^2 \\ \left(1 - \frac{1}{\xi}\right) A - \frac{B k^2}{\xi} = 0 \end{cases}$$

$$B = -\frac{(1-\xi)}{k^2} A$$

## PHOTON PROPAGATOR




$$\boxed{\begin{array}{c} i D^{\mu\nu}(k) \\ D^{\mu\nu} = \frac{1}{k^2}\left(-g^{\mu\nu} + (1-\xi)\frac{k^\mu k^\nu}{k^2}\right) \end{array}}$$

GAUGE-FIXING TERM

SOME WELL KNOWN GAUGES :

$\xi = 1$ : LORENTZ GAUGE / FEYNMAN GAUGE

$\xi = 0$ : LANDAU GAUGE $\left( k_\mu D_L^{\mu\nu} = k_\nu D_L^{\mu\nu} = 0 \right)$

PHYSICAL RESULTS ARE GAUGE INDEPENDENT

$\downarrow$

INDEPENDENT OF $\xi$