Title: Standard Model - Review (PHYS 622) - Lecture 5

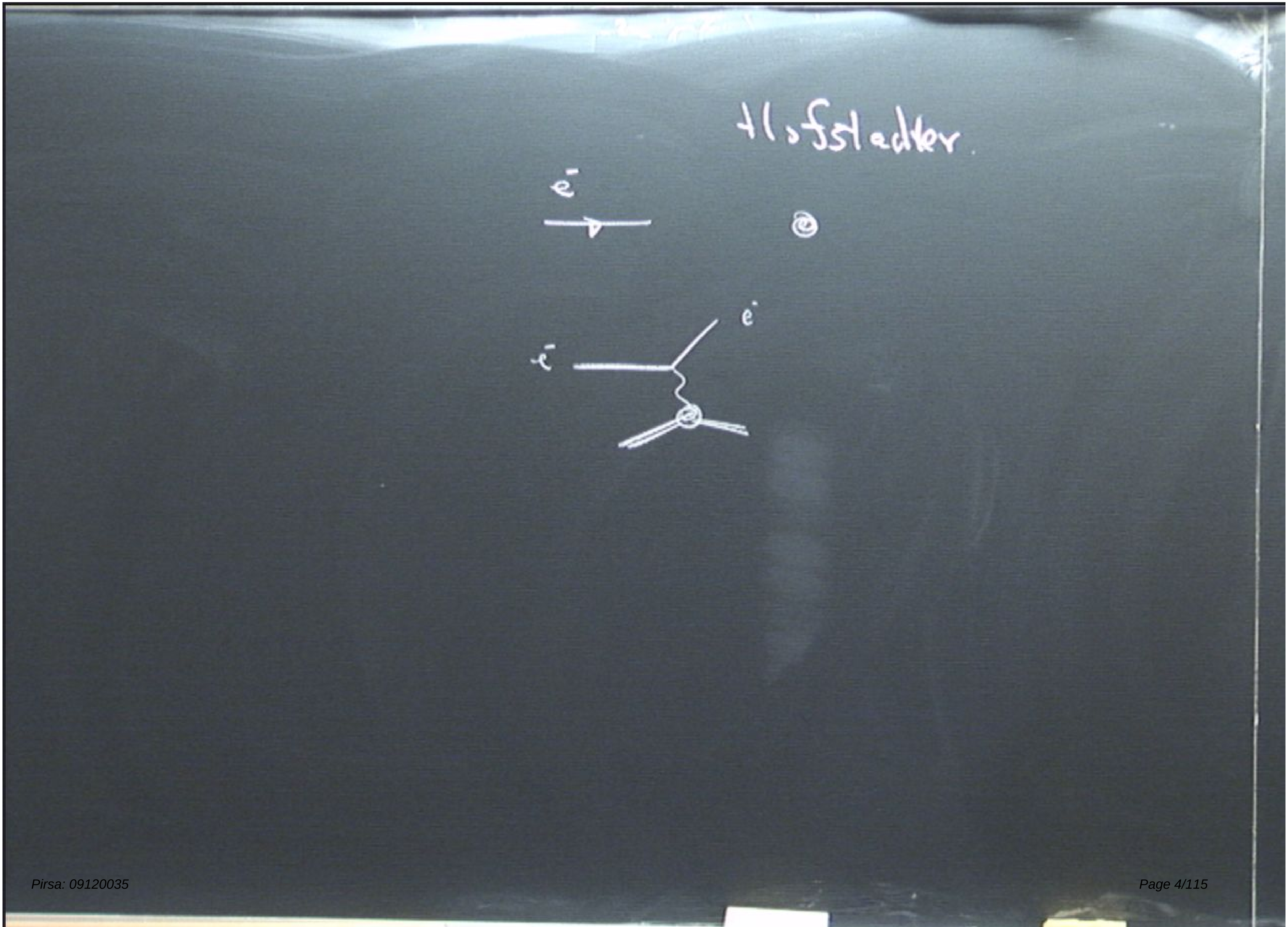
Date: Dec 04, 2009 09:00 AM

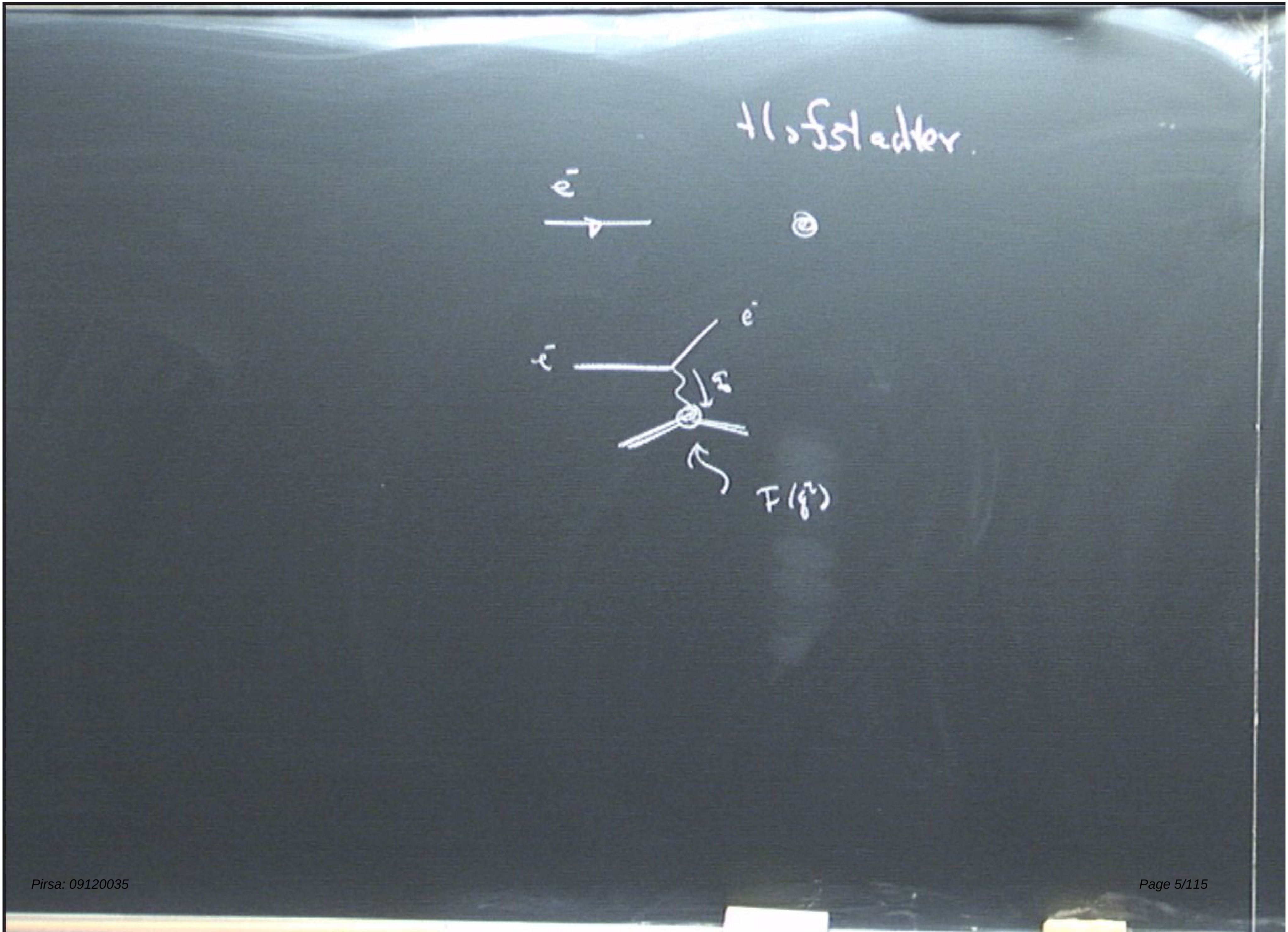
URL: http://pirsa.org/09120035

Abstract:

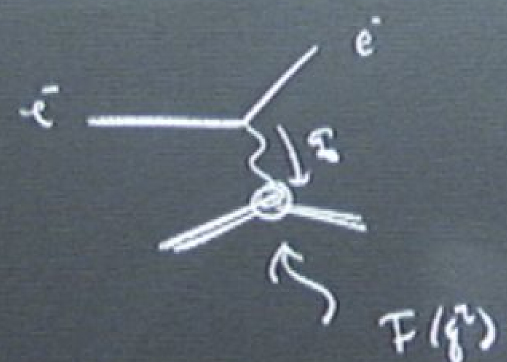
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Hofstadter.


Hofstadter
e⁻
e⁻
e⁻

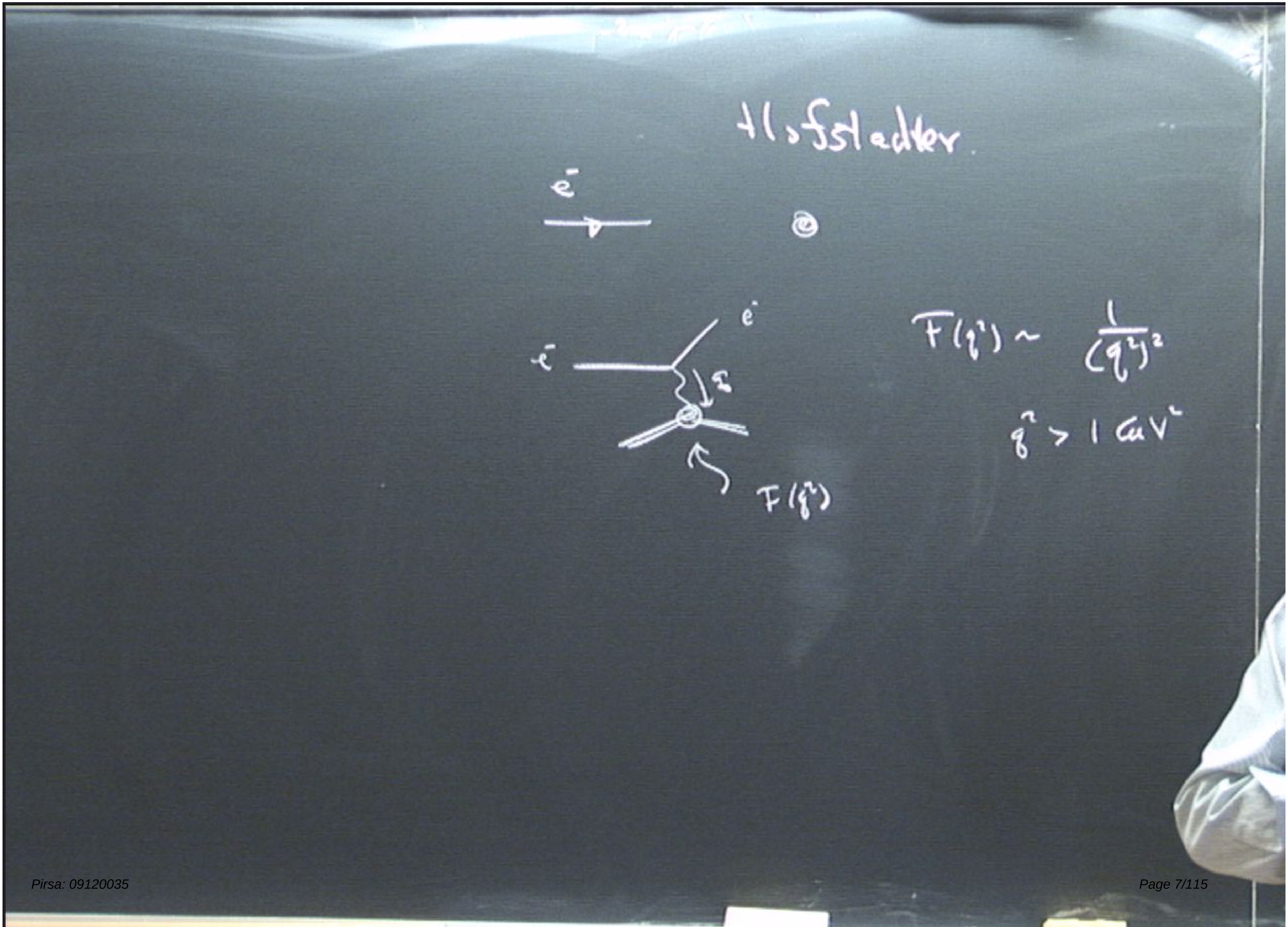

Hofstadter.
e⁻
e⁻
e⁻
q
F(q²)

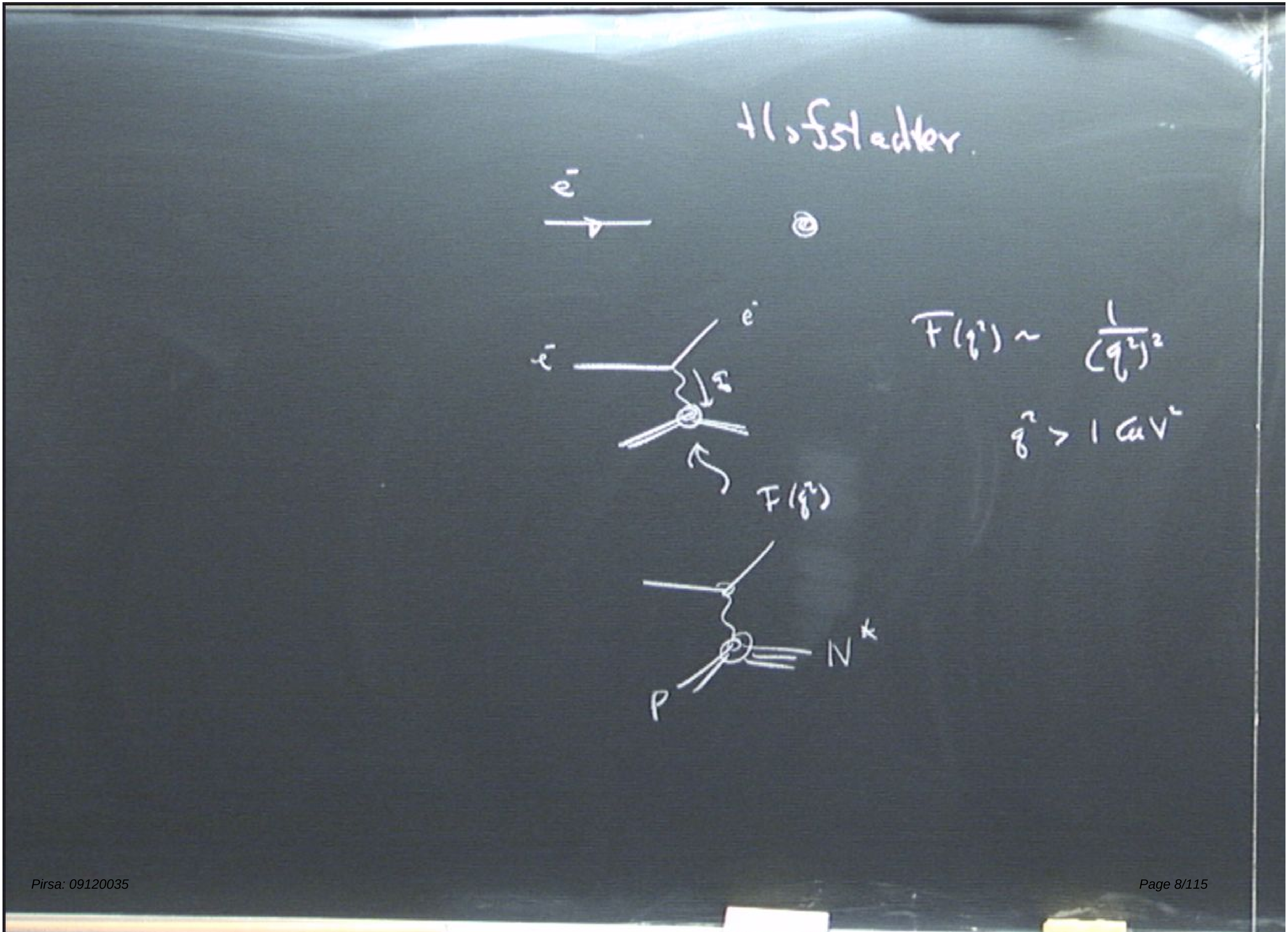
Hofstadter

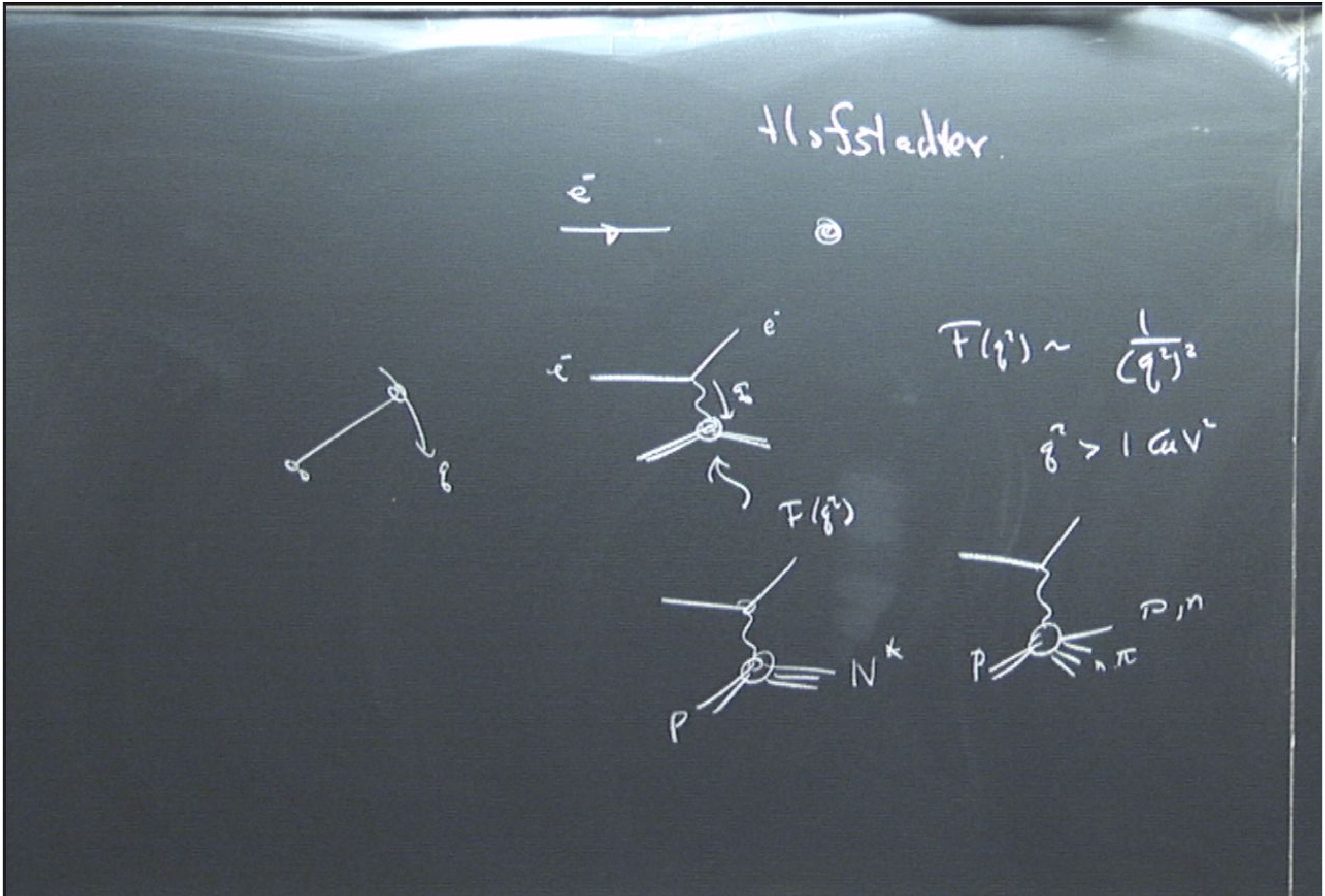


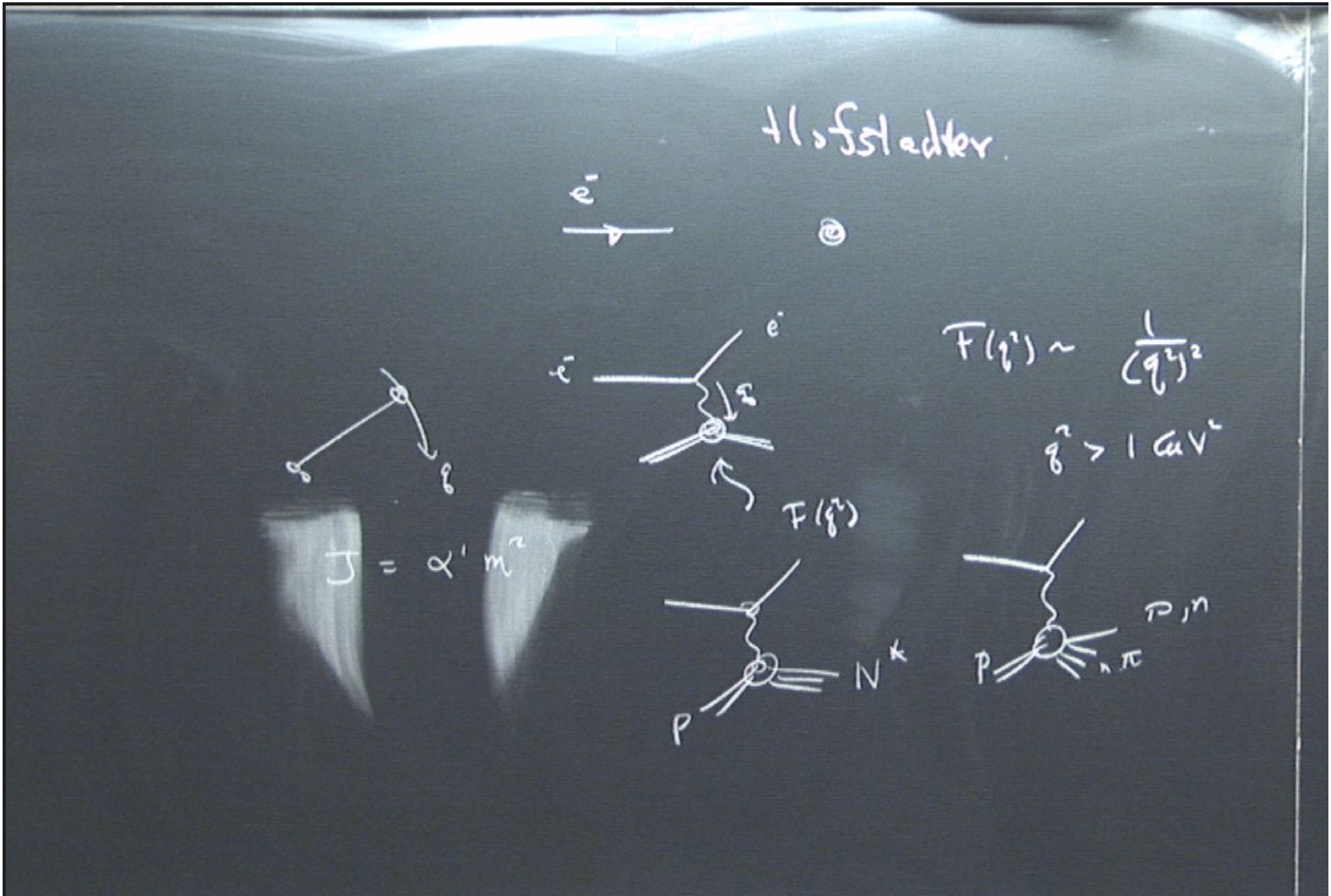
$$F(q^2) \sim \frac{1}{(q^2)^2}$$

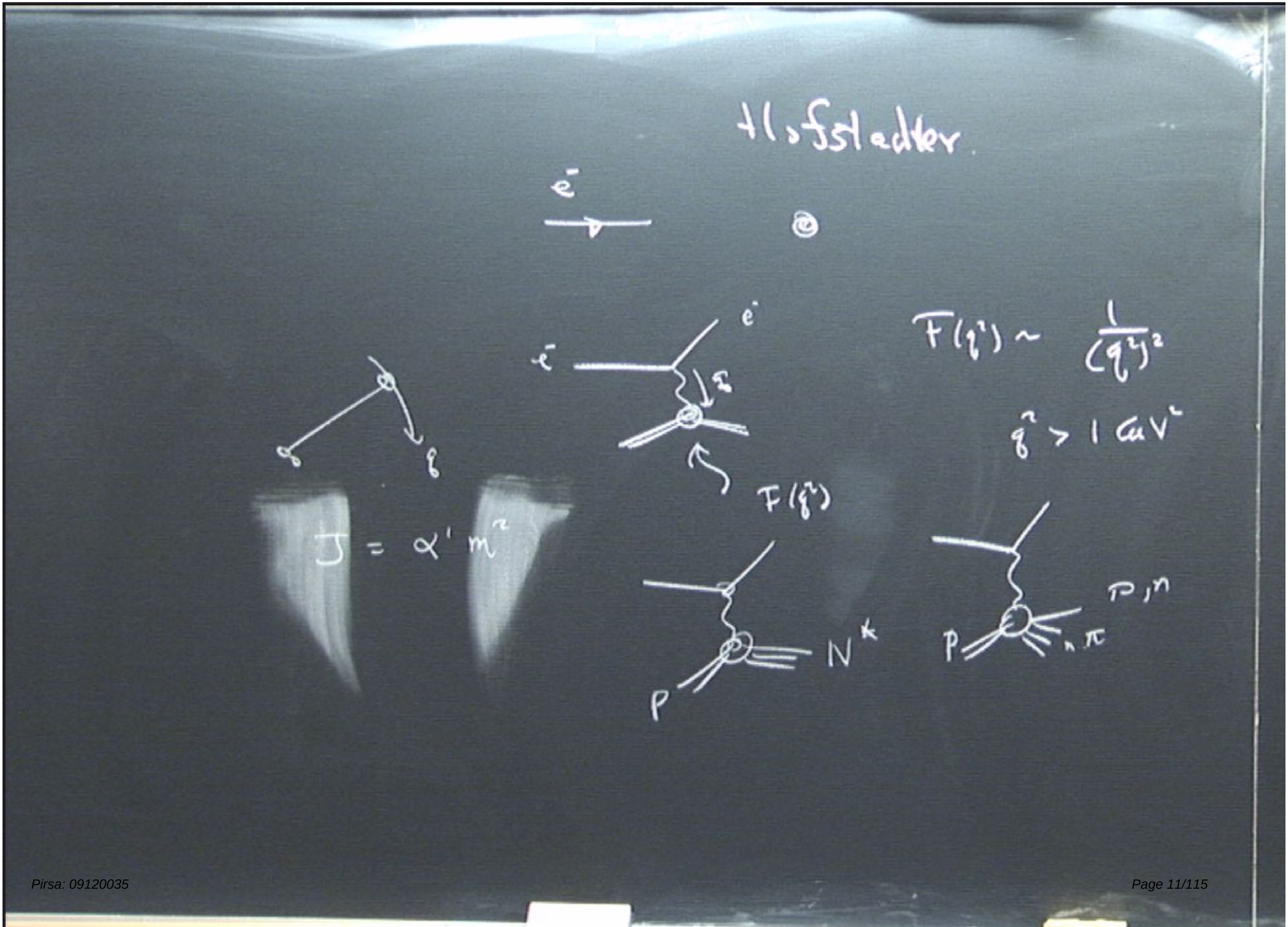
$$q^2 > 1\ \text{GeV}^2$$

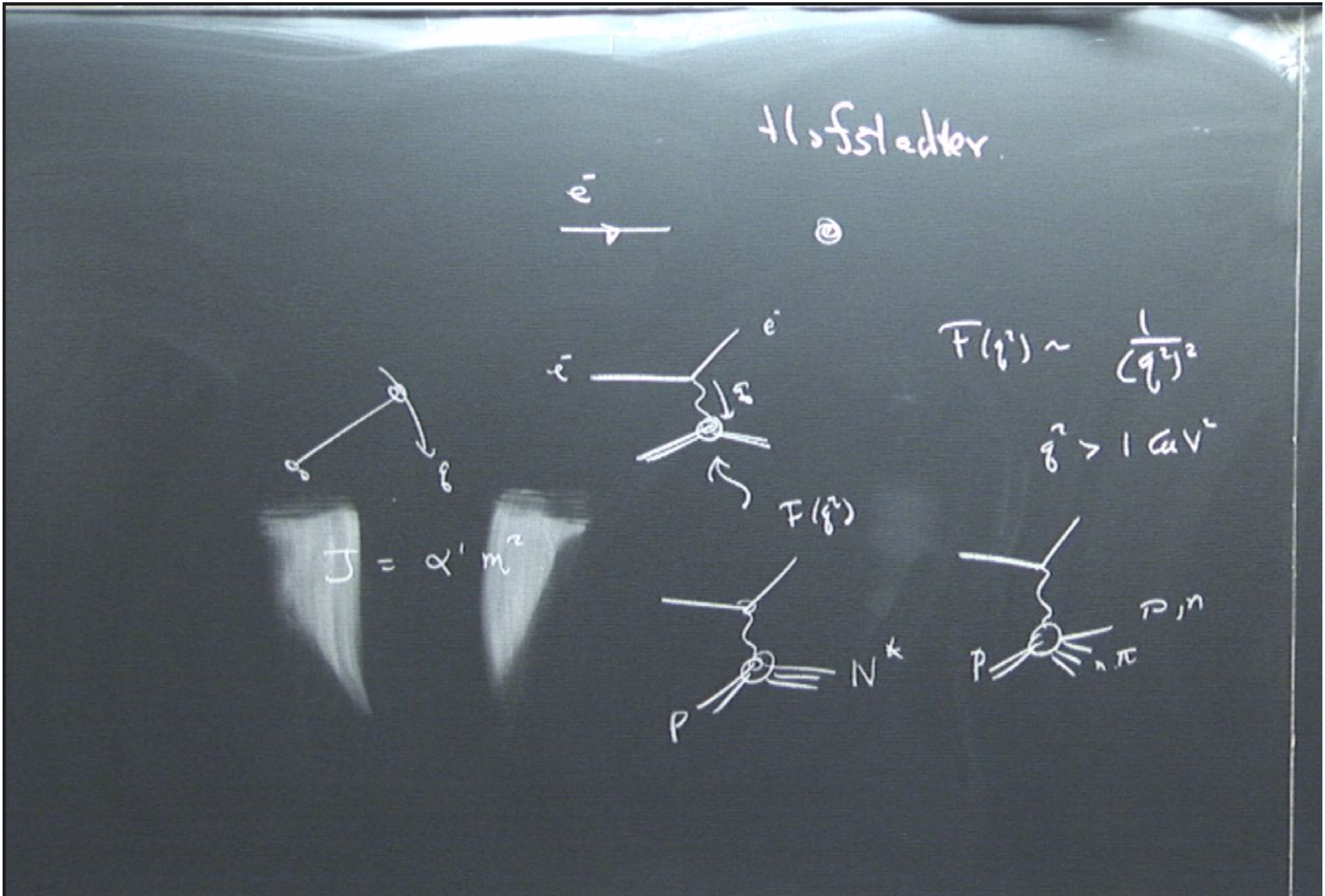

Hofstadter
e^-
e^-
e^-
γ
$F(q^2)$
$F(q^2) \sim \frac{1}{(q^2)^2}$
$q^2 > 1\ GeV^2$

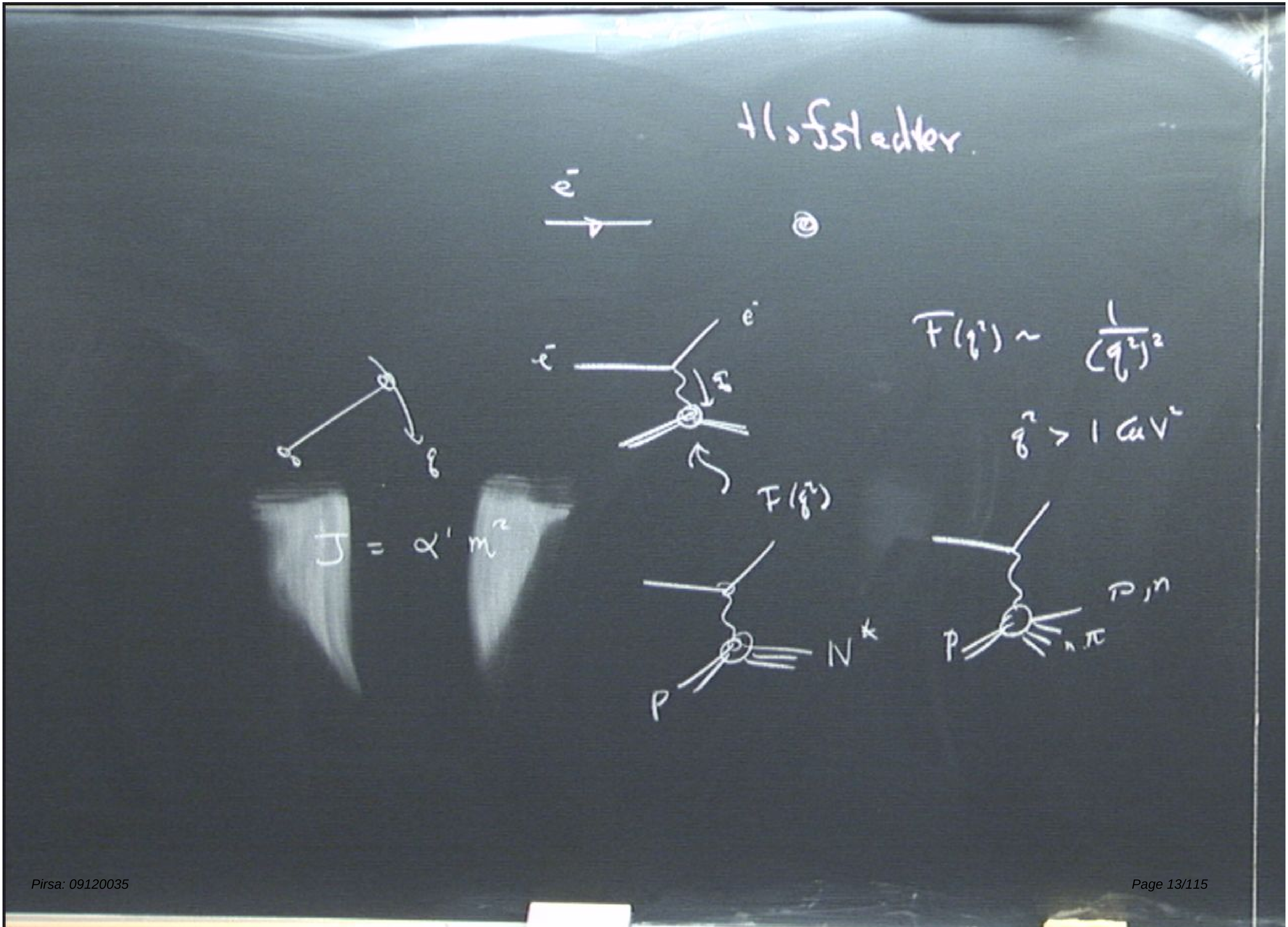

Hofstadter
e⁻
e⁻
e⁻
γ
F(q²) ~ 1/(q²)²
q² > 1 GeV²
F(q²)
N*
P

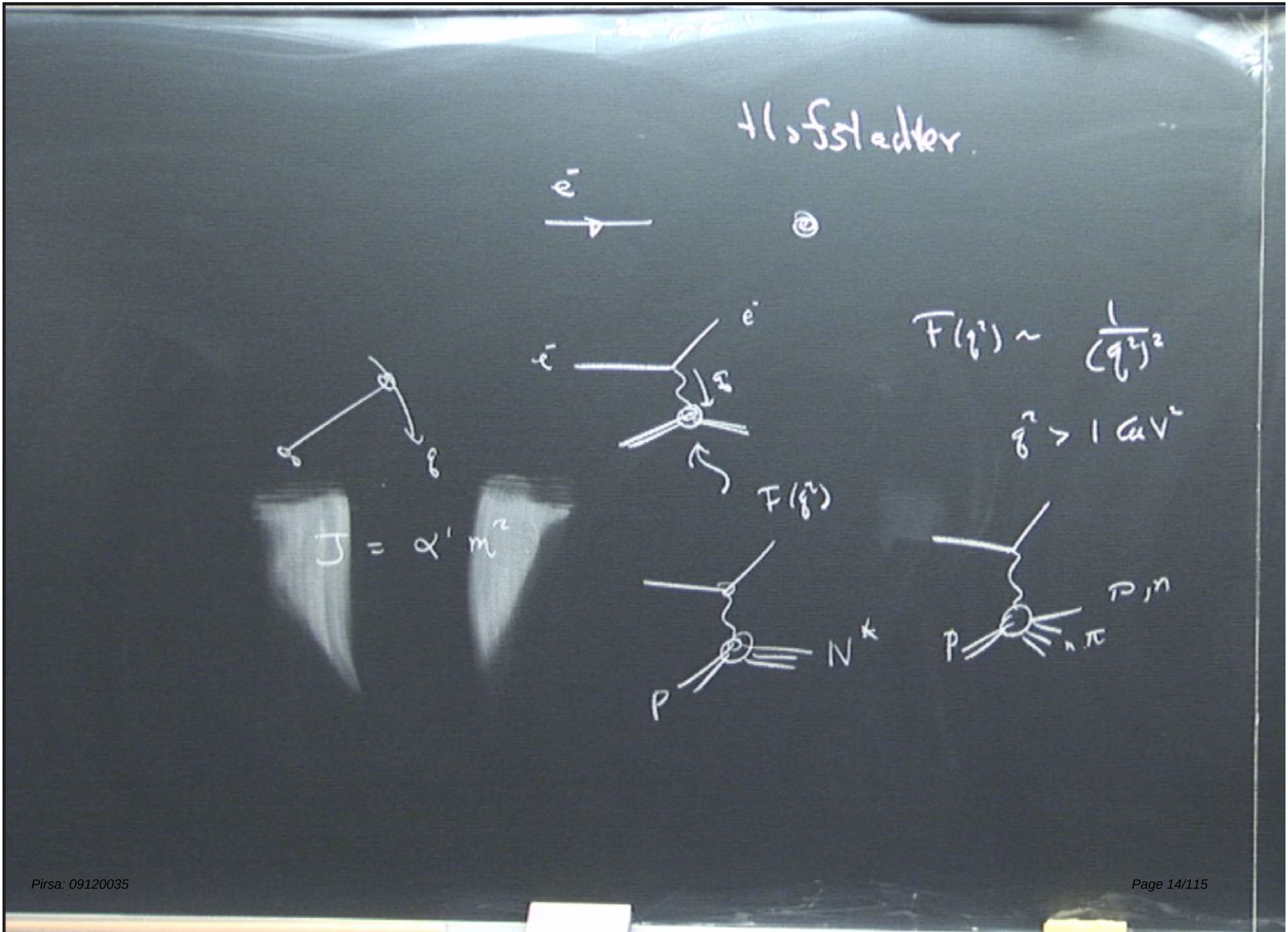

Hofstadter
e⁻
e⁻
e⁻
q
q
q
F(q²) ~ 1/(q²)²
q² > 1 GeV²
F(q²)
N*
P
P
π, n
n π

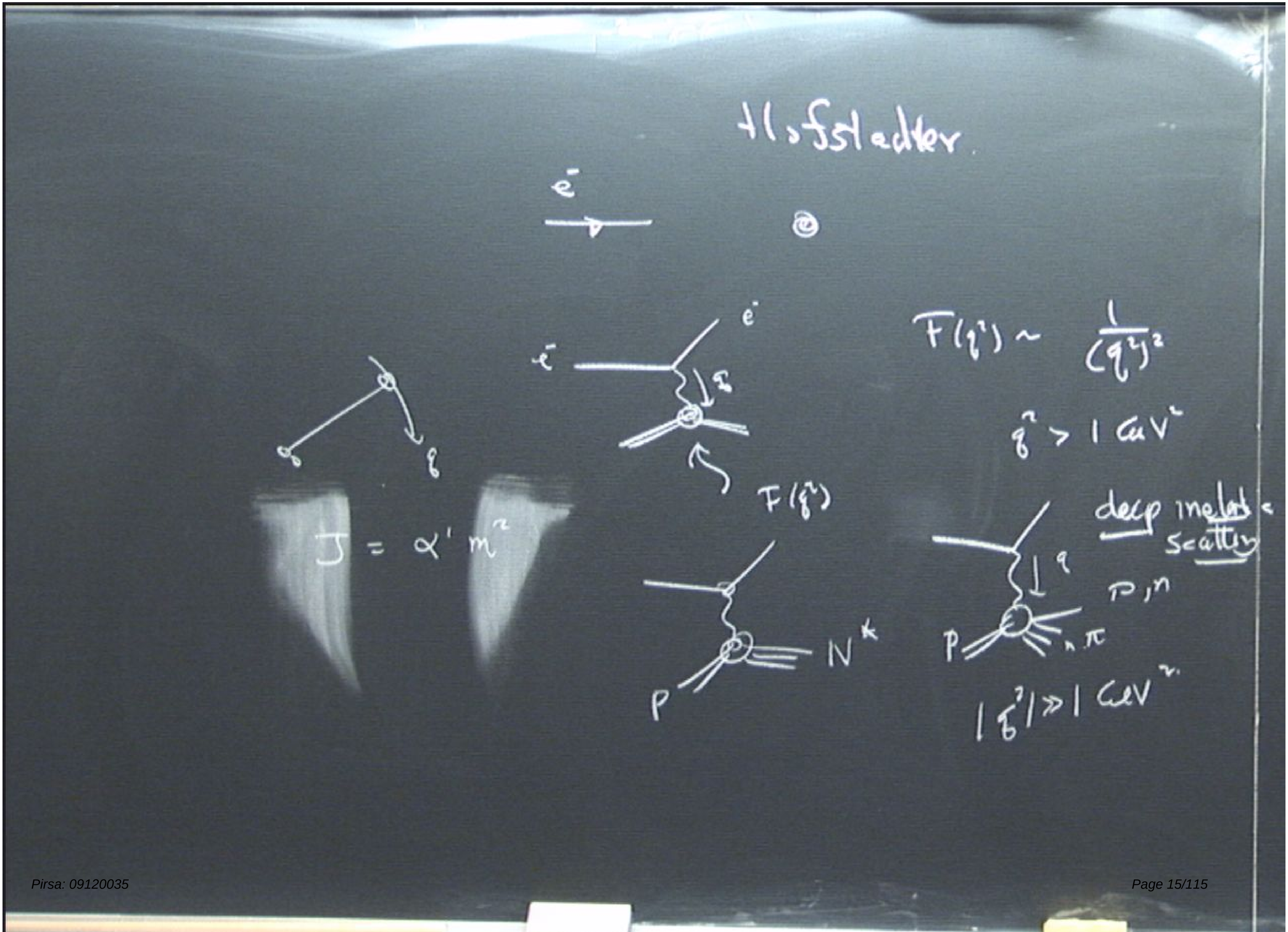

Hofstadter
e⁻
e⁻
e⁻
q
q
q
F(q²) ~ 1/(q²)²
q² > 1 GeV²
J = α' m²
F(q²)
p
N*
p
p, n
n π

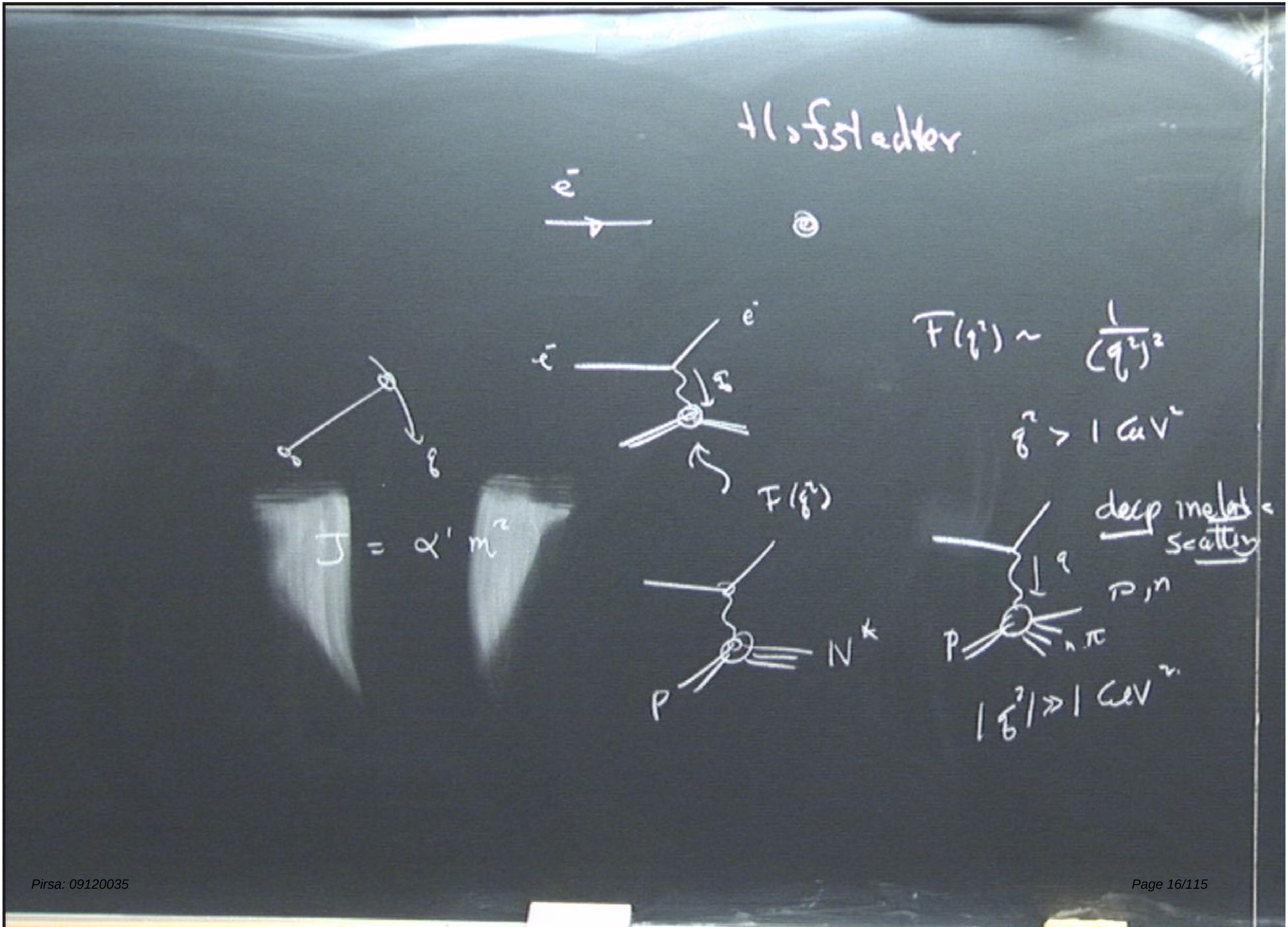

Hofstadter
e⁻
e⁻
e⁻
q
F(q²) ~ 1/(q²)²
q² > 1 GeV²
q
q
J = α' m²
F(q²)
N*
P
P
p, n
n π

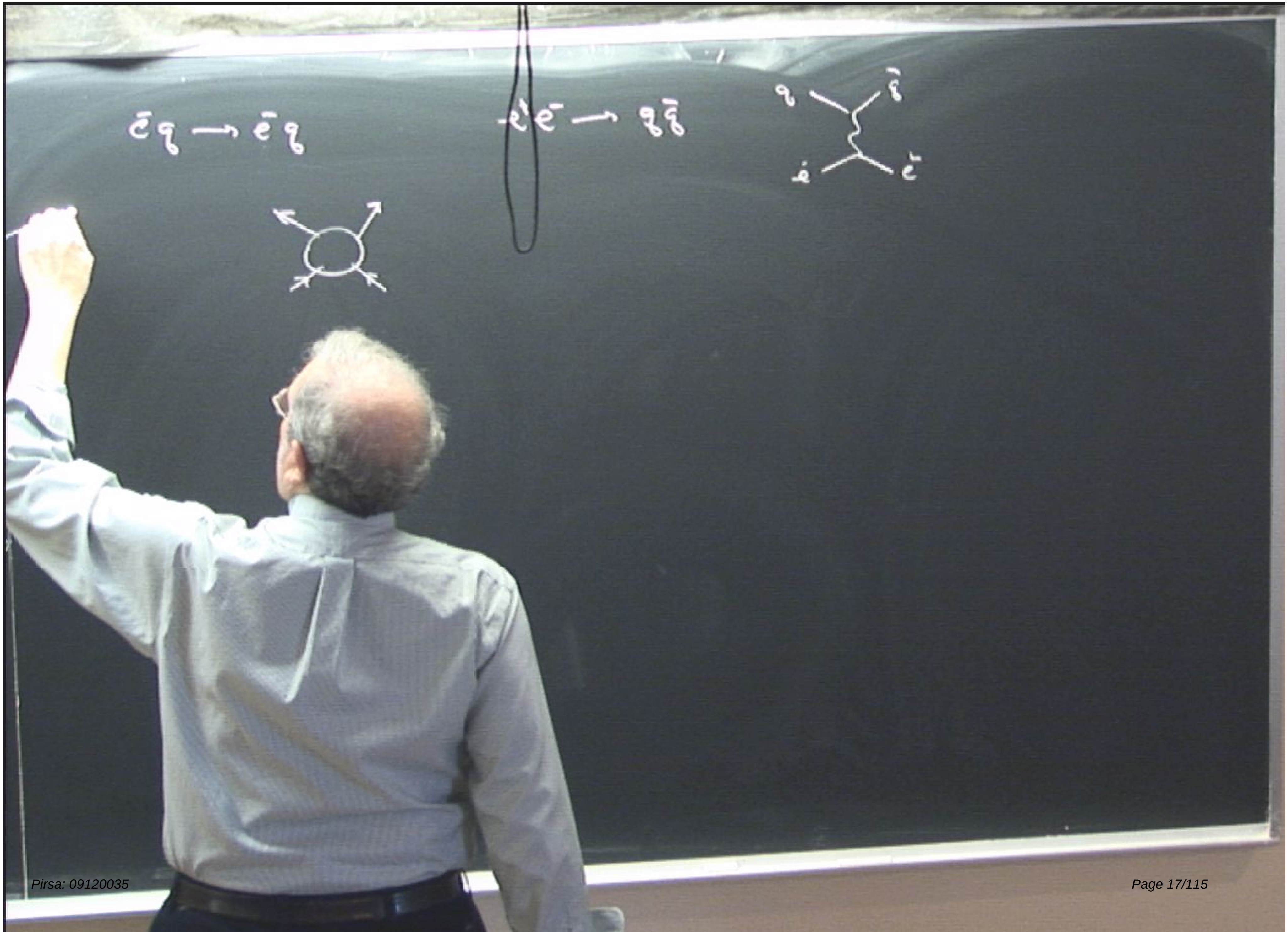

Hofstadter
e⁻
F(q²) ~ 1/(q²)²
q² > 1 GeV²
J = α' m²
F(q²)
N*
p
p, n
n, π

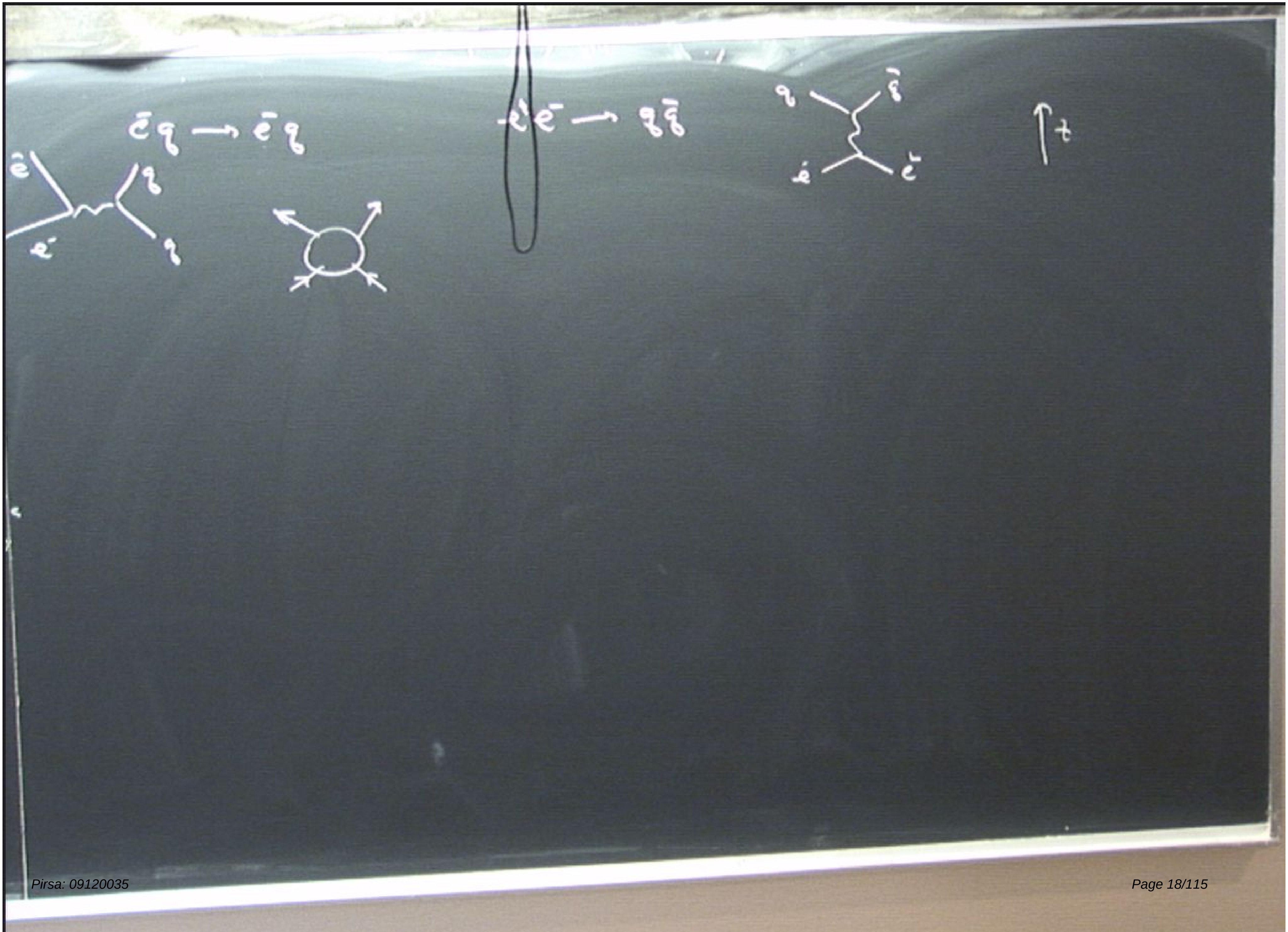

Hofstadter
e⁻
e⁻
e⁻
q
q
q
F(q²) ~ 1/(q²)²
q² > 1 GeV²
F(q²)
J = α' m²
N*
P
P
p, n
n π


Hofstadter
e⁻
e⁻
e⁻
q
F(q²) ~ 1/(q²)²
q² > 1 GeV²
F(q²)
q
q
J = α' m²
N*
P
P
p, n
n, π

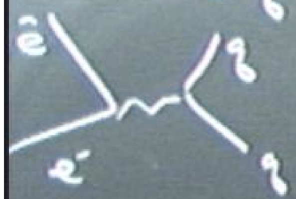

Hofstadter
e⁻
e⁻
e⁻
F(q²) ~ 1/(q²)²
q² > 1 GeV²
F(q²)
deep inelastic scattering
p, n
N*
P
P
n π
|q²| ≫ 1 GeV²
J = α' m²

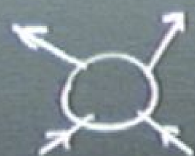

Hofstadter
e⁻
e⁻
e⁻
q
F(q²) ~ 1/(q²)²
q² > 1 GeV²
F(q²)
J = α' m²
N*
P
deep inelastic scattering
p, n
n, π
|q²| ≫ 1 GeV²


ēq → ēq
e⁺e⁻ → qq̄
q
q̄
e
e

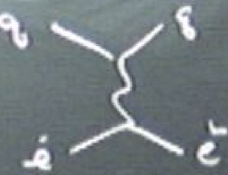

ēq → ēq
e⁺e⁻ → qq̄
t

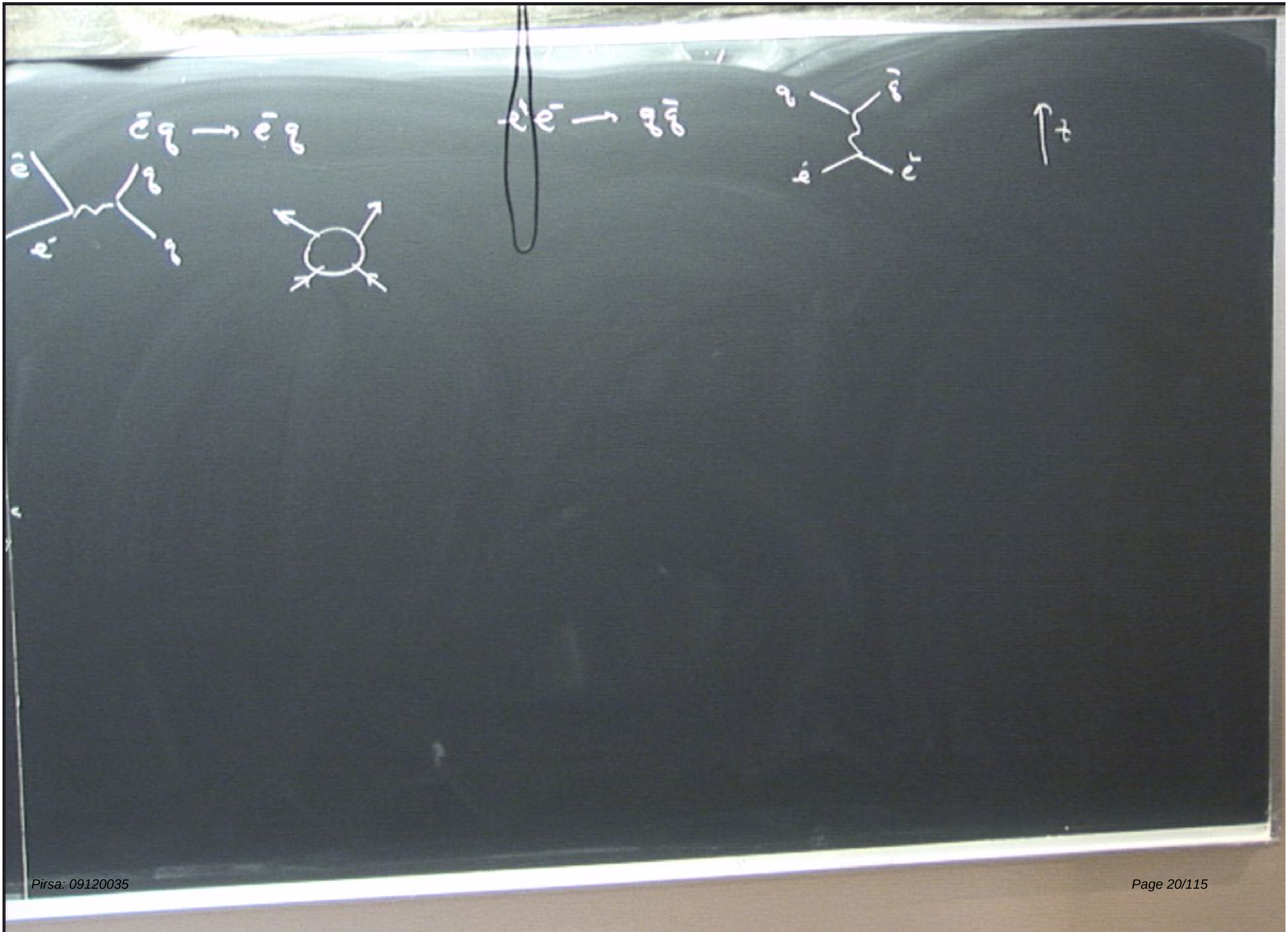
$\bar{e}q \longrightarrow \bar{e}q$





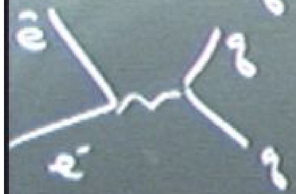
$e^+e^- \longrightarrow q\bar{q}$



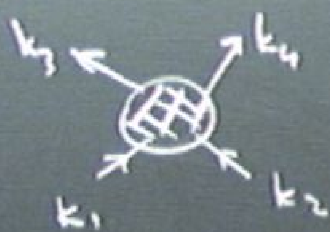

ēq → ēq
e⁺e⁻ → qq̄
t

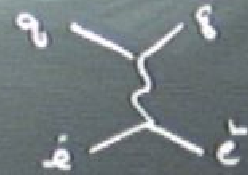
$\bar{e} q \to \bar{e} q$

$e^+ e^- \to q\bar{q}$



$2 \to 2$

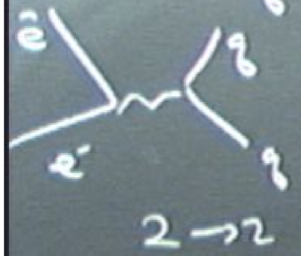


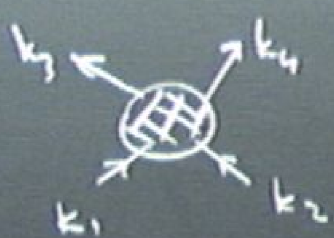


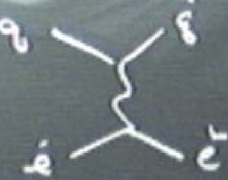
$\uparrow t$

$$s = (k_1+k_2)^2 + (k_3+k_4)^2 = E_{cm}^2$$

$\bar{e} q \to \bar{e} q$ $\qquad$ $e^+ e^- \to q\bar{q}$



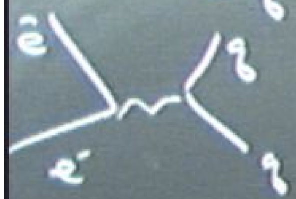




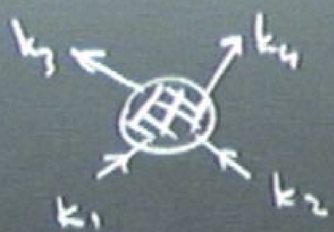
$\uparrow t$

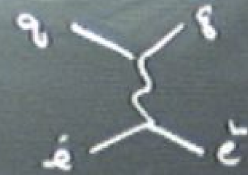
$$s = (k_1+k_2)^2 = (k_3+k_4)^2 = E_{cm}^2$$
$$t = (k_3-k_1)^2 = (k_4-k_2)^2$$
$$u = (k_4-k_1)^2 = (k_3-k_2)^2$$

$\bar{e} q \longrightarrow \bar{e} q$ $\qquad$ $e^+ e^- \longrightarrow q \bar{q}$



$2 \to 2$





$\uparrow t$

$$s = (k_1 + k_2)^2 = (k_3 + k_4)^2 = E_{cm}^2$$

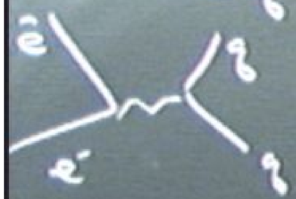
$$t = (k_3 - k_1)^2 = (k_4 - k_2)^2$$

$$u = (k_4 - k_1)^2 = (k_3 - k_2)^2$$

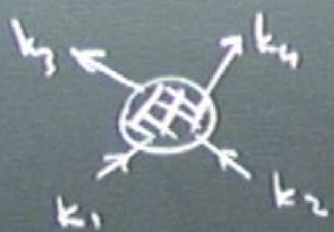
$$2(s + t + u) = 3(k_1^2 + k_2^2 + k_3^2 + k_4^2)$$

$\bar{e} q \to \bar{e} q$

$e^+ e^- \to q \bar{q}$



$2 \to 2$



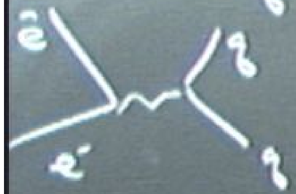
$$s = (k_1 + k_2)^2 = (k_3 + k_4)^2 = E_{cm}^2$$

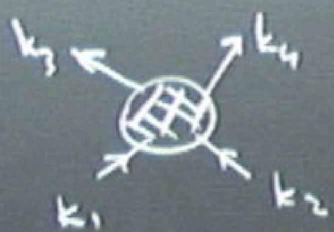
$$t = (k_3 - k_1)^2 = (k_4 - k_2)^2$$

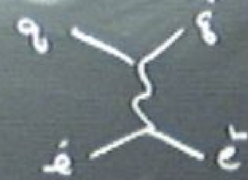
$$u = (k_4 - k_1)^2 = (k_3 - k_2)^2$$

$$2(s + t + u) = 3(k_1^2 + k_2^2 + k_3^2 + k_4^2) + 2(k_1 k_2 + k_3 k_4 - k_1 k_3 \cdots)$$

$\bar{e} q \to \bar{e} q$ $\qquad$ $e^+ e^- \to q \bar{q}$







$\uparrow t$

$2 \to 2$

$$s = (k_1 + k_2)^2 = (k_3 + k_4)^2 = E_{cm}^2$$

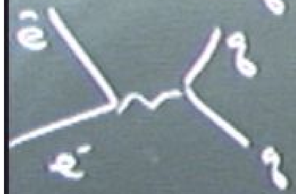
$$t = (k_3 - k_1)^2 = (k_4 - k_2)^2$$

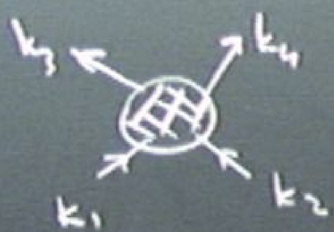
$$u = (k_4 - k_1)^2 = (k_3 - k_2)^2$$

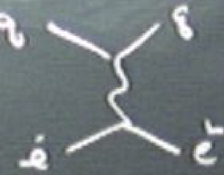
$$2(s + t + u) = 3(k_1^2 + k_2^2 + k_3^2 + k_4^2) + 2(k_1 k_2 + k_3 k_4 - k_1 k_3 \cdots)$$

$$= (k_1 + k_2 - k_3 - k_4)^2 + 2(k_1^2 + k_2^2 + k_3^2 + k_4^2)$$

$\bar{e} q \to \bar{e} q$ $\qquad$ $e^+ e^- \to q\bar{q}$







$\uparrow t$

$2 \to 2$

$$\boxed{s+t+u = \sum m_i^2}$$

$$s = (k_1+k_2)^2 = (k_3+k_4)^2 = E_{cm}^2$$

$$t = (k_3-k_1)^2 = (k_4-k_2)^2$$

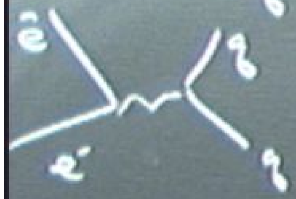
$$u = (k_4-k_1)^2 = (k_3-k_2)^2$$

$$2(s+t+u) = 3(k_1^2+k_2^2+k_3^2+k_4^2) + 2(k_1k_2 + k_3k_4 - k_1k_3 \cdots)$$

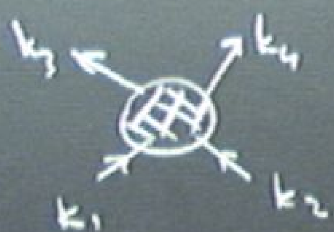
$$= (k_1+k_2-k_3-k_4)^2 + 2(k_1^2+k_2^2+k_3^2+k_4^2)$$

$$= (k_1 + k_2$$

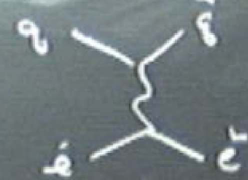
$\bar{e} q \to \bar{e} q$



$2 \to 2$



$e^+ e^- \to q\bar{q}$



$\uparrow t$

$$\boxed{s + t + u = \sum m_i^2}$$

$$s = (k_1+k_2)^2 = (k_3+k_4)^2 = E_{cm}^2$$

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$$u = (k_4-k_1)^2 = (k_3-k_2)^2$$

$$2(s+t+u) = 3(k_1^2+k_2^2+k_3^2+k_4^2) + 2(k_1k_2 + k_3k_4 - k_1k_3 \cdots)$$

$$= (k_1+k_2-k_3-k_4)^2 + 2(k_1^2+k_2^2+k_3^2+k_4^2)$$

$$\underline{k^2 = m^2}$$

at mass = 0

$k_1 = (E, 0\ 0\ k)$ $k_2 = (E, 0\ 0\ {-k})$

$k_3 = (E, \sin\theta, 0\ \cos\theta)$ $k_4 = (E, -\sin\theta, 0, -\cos\theta)$

$z \uparrow$

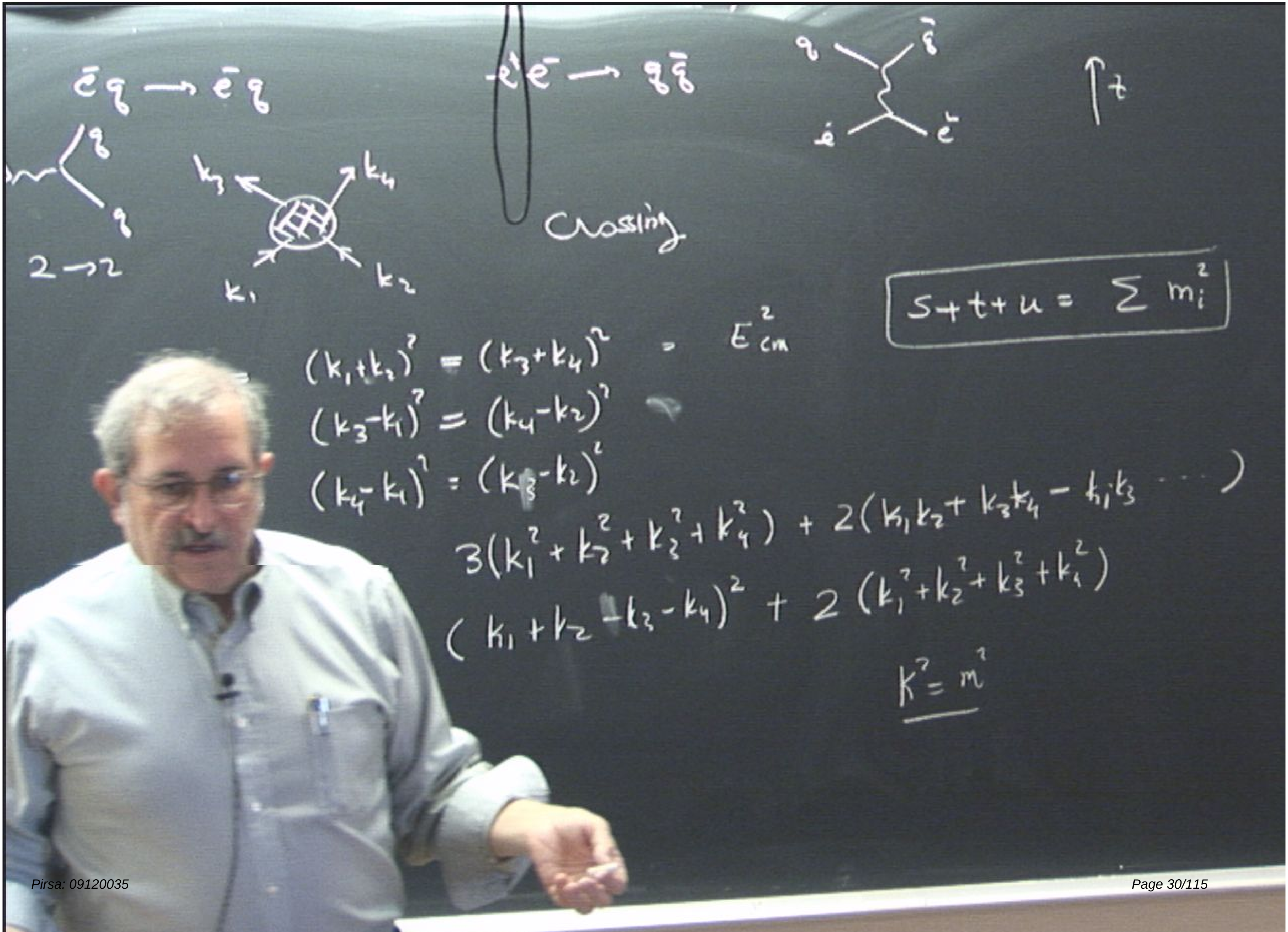
at mass = 0

$k_1 = (E, 0\ 0\ k)$ $\quad k_2 = (E, 0\ 0\ -k)$

$k_3 = (E, \sin\theta, 0\ \cos\theta)$ $\quad k_4 = (E, -\sin\theta, 0, -\cos\theta)$

$s = 4E^2 \qquad t = -2E(1 - \cos\theta)$

$u = \quad -2E(1 + \cos\theta)$


ēq → ēq
e⁺e⁻ → qq̄
2 → 2
k1 k2 k3 k4
Crossing
s+t+u = Σ m_i^2
(k1+k2)^2 = (k3+k4)^2 = E_cm^2
(k3−k1)^2 = (k4−k2)^2
(k4−k1)^2 = (k3−k2)^2
3(k1^2+k2^2+k3^2+k4^2) + 2(k1k2+k3k4 − k1k3 ...)
(k1+k2−k3−k4)^2 + 2(k1^2+k2^2+k3^2+k4^2)
k^2 = m^2

at mass = 0

$$k_1 = (E, 0\ 0\ k) \qquad k_2 = (E, 0\ 0\ -k)$$

$$k_3 = (E, E\sin\theta, 0, E\cos\theta) \qquad k_4 = (E, -E\sin\theta, 0, E\cos\theta)$$

$$s = 4E^2 \qquad t = -2E^2(1-\cos\theta)$$

$$u = -2E^2(1+\cos\theta)$$

at mass = 0

$$k_1 = (E, 0, 0, E) \qquad k_2 = (E, 0, 0, -E)$$

$$k_3 = (E, E\sin\theta, 0, E\cos\theta) \qquad k_4 = (E, -E\sin\theta, 0, E\cos\theta)$$

$$s = 4E^2 \qquad t = -2E^2(1-\cos\theta)$$

$$u = -2E^2(1+\cos\theta)$$

at mass = 0

$$k_1 = (E, 0\ 0\ E) \qquad k_2 = (E, 0\ 0\ {-E})$$

$$k_3 = (E, E\sin\theta, 0, E\cos\theta) \qquad k_4 = (E, -E\sin\theta, 0, -E\cos\theta)$$

$$s = 4E^2 \qquad t = -2E^2(1-\cos\theta)$$

$$u = -2E^2(1+\cos\theta)$$

$$|\mathcal{M}|^2 = \mathrm{tr}\left[(\not{k}+m)\gamma^\mu(\not{\bar{k}}-m)\gamma^\nu\right] \cdots$$

at mass = 0

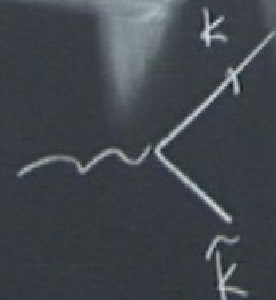
$k_1 = (E, 0\;0\;E)$ $\quad k_2 = (E, 0\;0\;-E)$

$k_3 = (E, E\sin\theta, 0, E\cos\theta)$ $\quad k_4 = (E, -E\sin\theta, 0, E\cos\theta)$

$s = 4E^2 \qquad t = -2E^2(1-\cos\theta)$

$u = -2E^2(1+\cos\theta)$

$|\mathcal{M}|^2 = \mathrm{tr}\left[(\not{k}+m)\gamma^\mu(\not{\bar{k}}-m)\gamma^\nu\right]$



$|\mathcal{M}|^2 = \mathrm{tr}\left[(\not{k}+m)\gamma^\mu(\not{\tilde{k}}+m)\gamma^\nu\right]$

at mass = 0

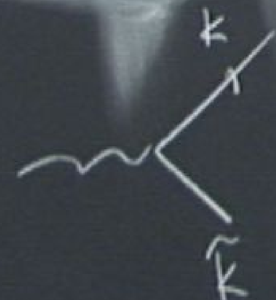
$k_1 = (E, 0\, 0\, E)$ $\quad k_2 = (E, 0\, 0\, -E)$

$k_3 = (E, E\sin\theta, 0, E\cos\theta)$ $\quad k_4 = (E, -E\sin\theta, 0, -E\cos\theta)$

$s = 4E^2 \qquad t = -2E^2(1-\cos\theta)$

$u = -2E^2(1+\cos\theta)$

$|\mathcal{M}|^2 = \mathrm{tr}\left[(\not{k}+m)\gamma^\mu(\not{\bar{k}}-m)\gamma^\nu\right] \ldots$



$|\mathcal{M}|^2 = \mathrm{tr}\left[(\not{k}+m)\gamma^\mu(\not{\tilde{k}}+m)\gamma^\nu\right]$

$\bar{k} \to -\tilde{k}$

at mass = 0

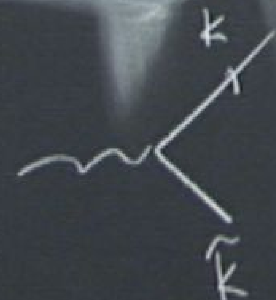
$k_1 = (E, 0\ 0\ E)$ $\quad k_2 = (E, 0\ 0\ -E)$

$k_3 = (E, E\sin\theta, 0\ E\cos\theta)$ $\quad k_4 = (E, -E\sin\theta, 0, -E\cos\theta)$

$s = 4E^2 \qquad t = -2E^2(1-\cos\theta)$

$u = -2E^2(1+\cos\theta)$

$|\mathcal{M}|^2 = \mathrm{tr}\,[(\not{k}+m)\gamma^\mu(\not{\bar{k}}-m)\gamma^\nu] \cdots$



$|\mathcal{M}|^2 = \mathrm{tr}\,[(\not{k}+m)\gamma^\mu(\not{\tilde{k}}+m)\gamma^\nu]$

$\bar{k} \to -\tilde{k} \quad (-1)\,f\ldots$

at mass = 0

$k_1 = (E, 0\ 0\ E)$ $\quad k_2 = (E, 0\ 0 -E)$

$k_3 = (E, E\sin\theta, 0, E\cos\theta)$ $\quad k_4 = (E, -E\sin\theta, 0, -E\cos\theta)$

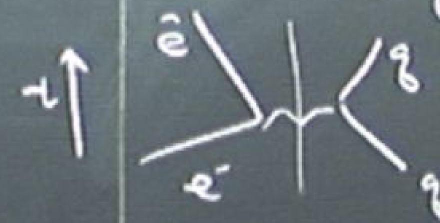
$s = 4E^2 \qquad t = -2E^2(1-\cos\theta)$

$u = -2E^2(1+\cos\theta)$

$|\mathcal{M}|^2 = \mathrm{tr}\,[(\not{k}+m)\gamma^\mu(\not{\bar{k}}-m)\gamma^\nu] \ \ldots$

$|\mathcal{M}|^2 = \mathrm{tr}\,[(\not{k}+m)\gamma^\mu(\not{\tilde{k}}+m)\gamma^\nu]$

$\bar{k} \to -\tilde{k}$ $\quad (-1)$ for each fermion



$\bar{e}\,q$

$2 \to 2$

$2(s$

at mass = 0

$k_1 = (E, 0, 0, E)$ $\quad k_2 = (E, 0, 0, -E)$

$k_3 = (E, E\sin\theta, 0, E\cos\theta)$ $\quad k_4 = (E, -E\sin\theta, 0, -E\cos\theta)$

$$s = 4E^2 \qquad t = -2E^2(1-\cos\theta)$$

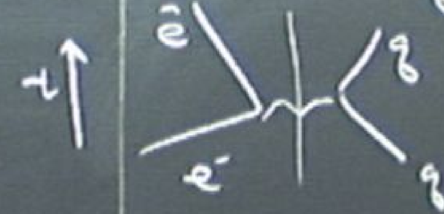
$$u = -2E^2(1+\cos\theta)$$

$$|M|^2 = \mathrm{tr}[(\not{k}+m)\gamma^\mu(\not{\bar{k}}-m)\gamma^\nu] \cdot \mathrm{tr}[\ \gamma^\mu\ \gamma^\nu]$$

$$|M|^2 = \mathrm{tr}[(\not{k}+m)\gamma^\mu(\not{\tilde{k}}+m)\gamma^\nu]$$

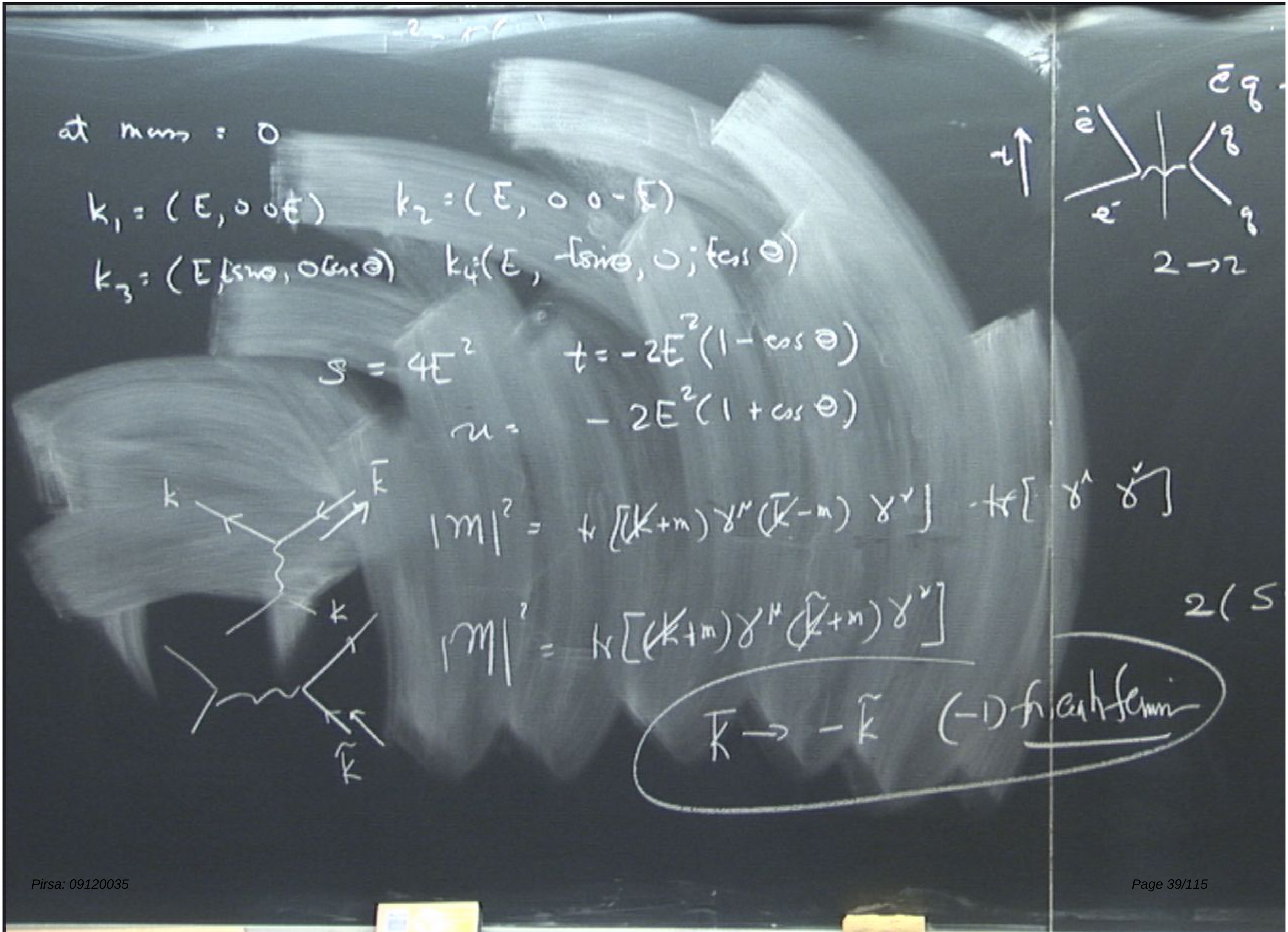
$\bar{k} \to -\tilde{k}$ $\quad (-1)$ for each fermion

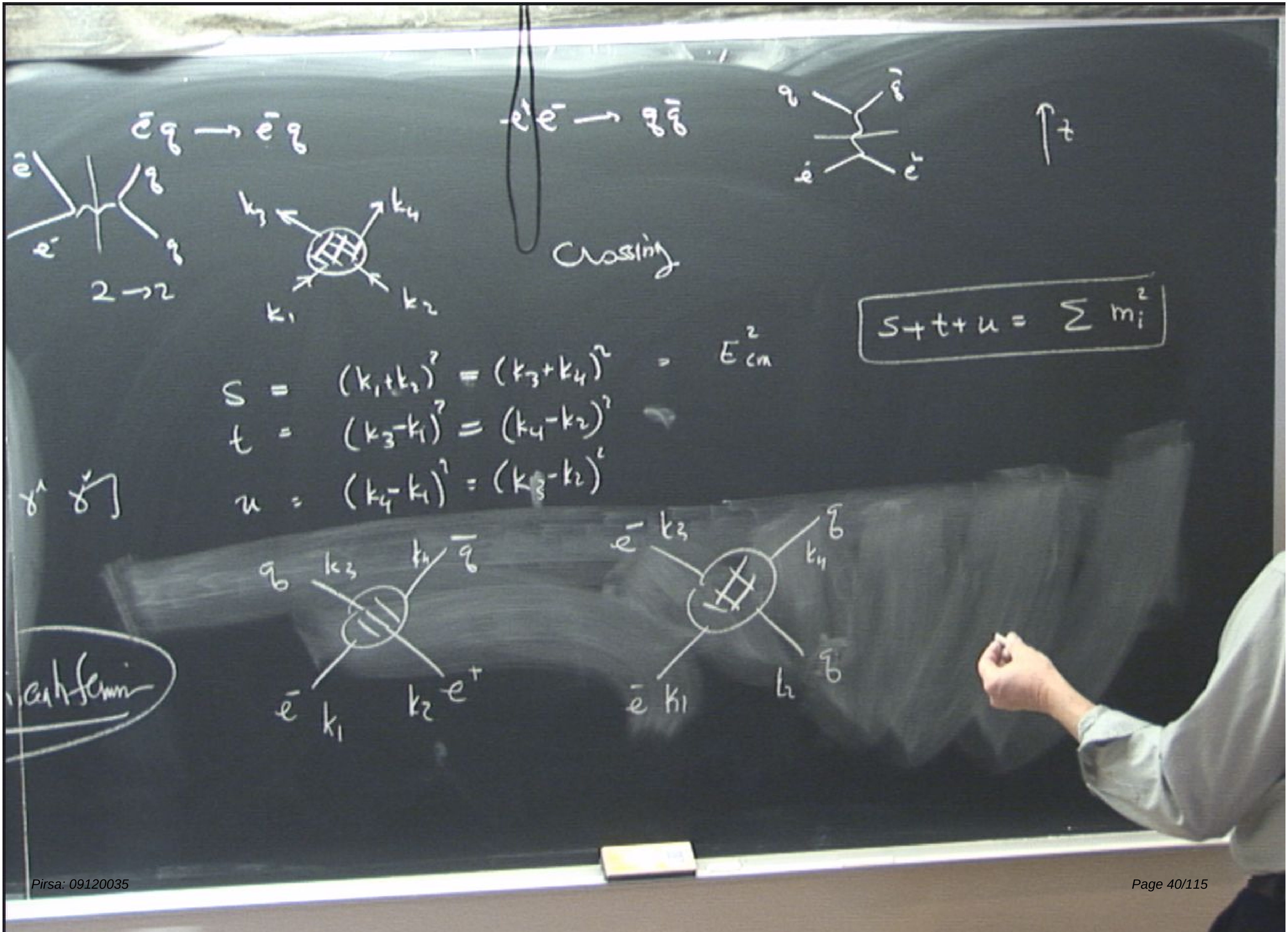
$\bar{e}q$

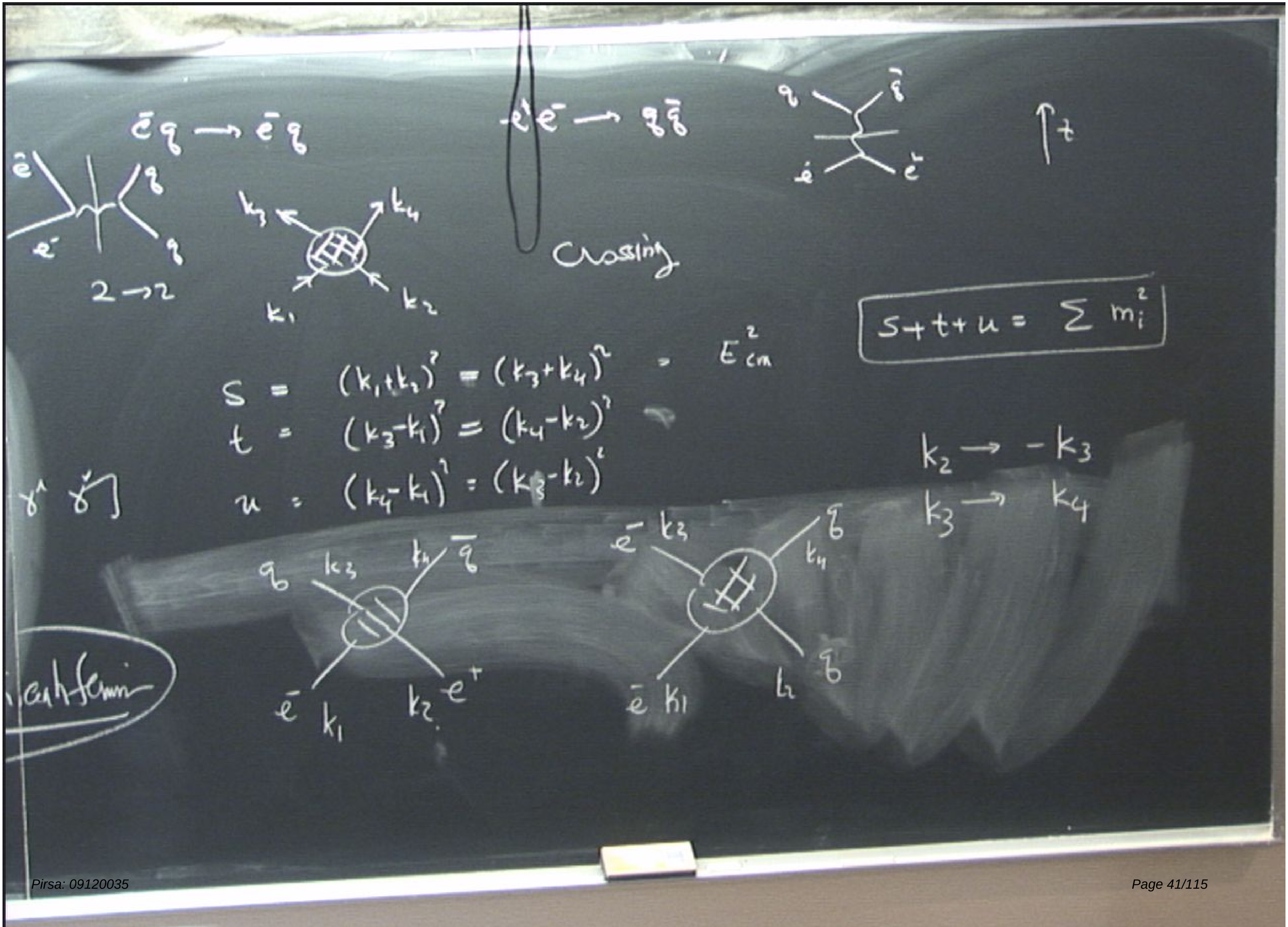


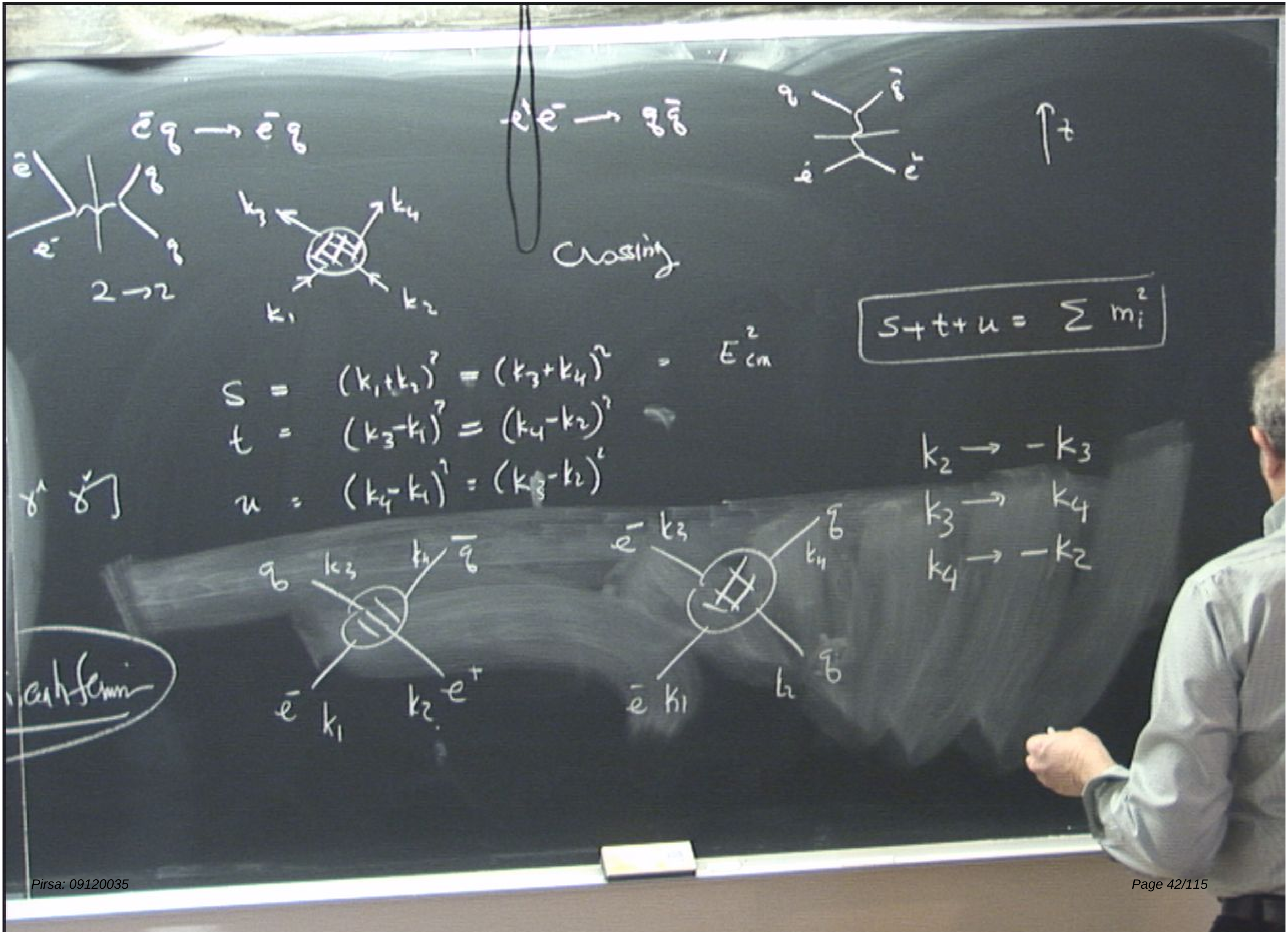
$2 \to 2$

$2(s$


at mass = 0
k1 = (E, 0 0 E)   k2 = (E, 0 0 -E)
k3 = (E, E sinθ, 0 E cosθ)   k4 (E, -E sinθ, 0, -E cosθ)
s = 4E^2   t = -2E^2 (1 - cos θ)
u = - 2E^2 (1 + cos θ)
|M|^2 = tr [(k + m) γ^μ (k̄ - m) γ^ν]   tr [γ^μ γ^ν]
|M|^2 = tr [(k + m) γ^μ (k̃ + m) γ^ν]
k̄ → - k̃   (-1) for each fermion
2 → 2
ē q
e⁻
q
2 (S

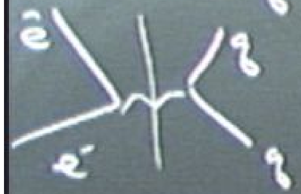

ēq → ēq
e⁺e⁻ → qq̄
2 → 2
k1 k2 k3 k4
Crossing
s + t + u = Σ m_i²
s = (k1+k2)² = (k3+k4)² = E_cm²
t = (k3−k1)² = (k4−k2)²
u = (k4−k1)² = (k3−k2)²


ē q → ē q
e⁺e⁻ → q q̄
2 → 2
k3 k4 k1 k2
Crossing
↑ t
s + t + u = Σ m_i²
s = (k1+k2)² = (k3+k4)² = E_cm²
t = (k3−k1)² = (k4−k2)²
u = (k4−k1)² = (k3−k2)²
k2 → −k3
k3 → k4

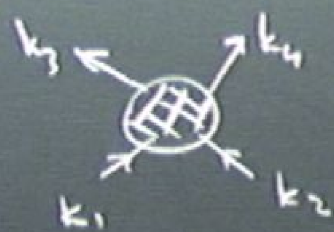

ēq → ēq
e⁺e⁻ → qq̄
↑t
2→2
k₃ k₄ k₁ k₂
Crossing
s+t+u = Σ m_i²
s = (k₁+k₂)² = (k₃+k₄)² = E_cm²
t = (k₃−k₁)² = (k₄−k₂)²
u = (k₄−k₁)² = (k₃−k₂)²
k₂ → −k₃
k₃ → k₄
k₄ → −k₂
q k₃ k₄ q̄
e⁻ k₁ k₂ e⁺
e⁻ k₃ k₄ q̄
e⁻ k₁ k₂ q̄

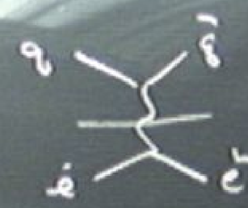
$\bar{e} q \longrightarrow \bar{e} q$

$e^+ e^- \longrightarrow q \bar{q}$



$2 \to 2$





$\uparrow t$

Crossing

$$s + t + u = \sum m_i^2$$

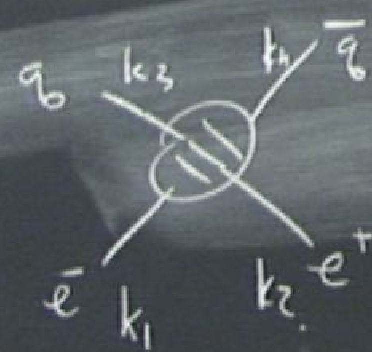
$$s = (k_1 + k_2)^2 = (k_3 + k_4)^2 = E_{cm}^2$$
$$t = (k_3 - k_1)^2 = (k_4 - k_2)^2$$
$$u = (k_4 - k_1)^2 = (k_3 - k_2)^2$$

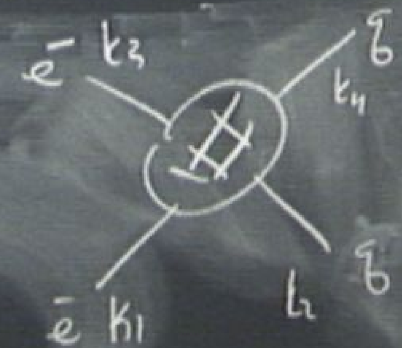
$k_2 \longrightarrow -k_3 \qquad s \to t$

$k_3 \longrightarrow k_4 \qquad t \to u$

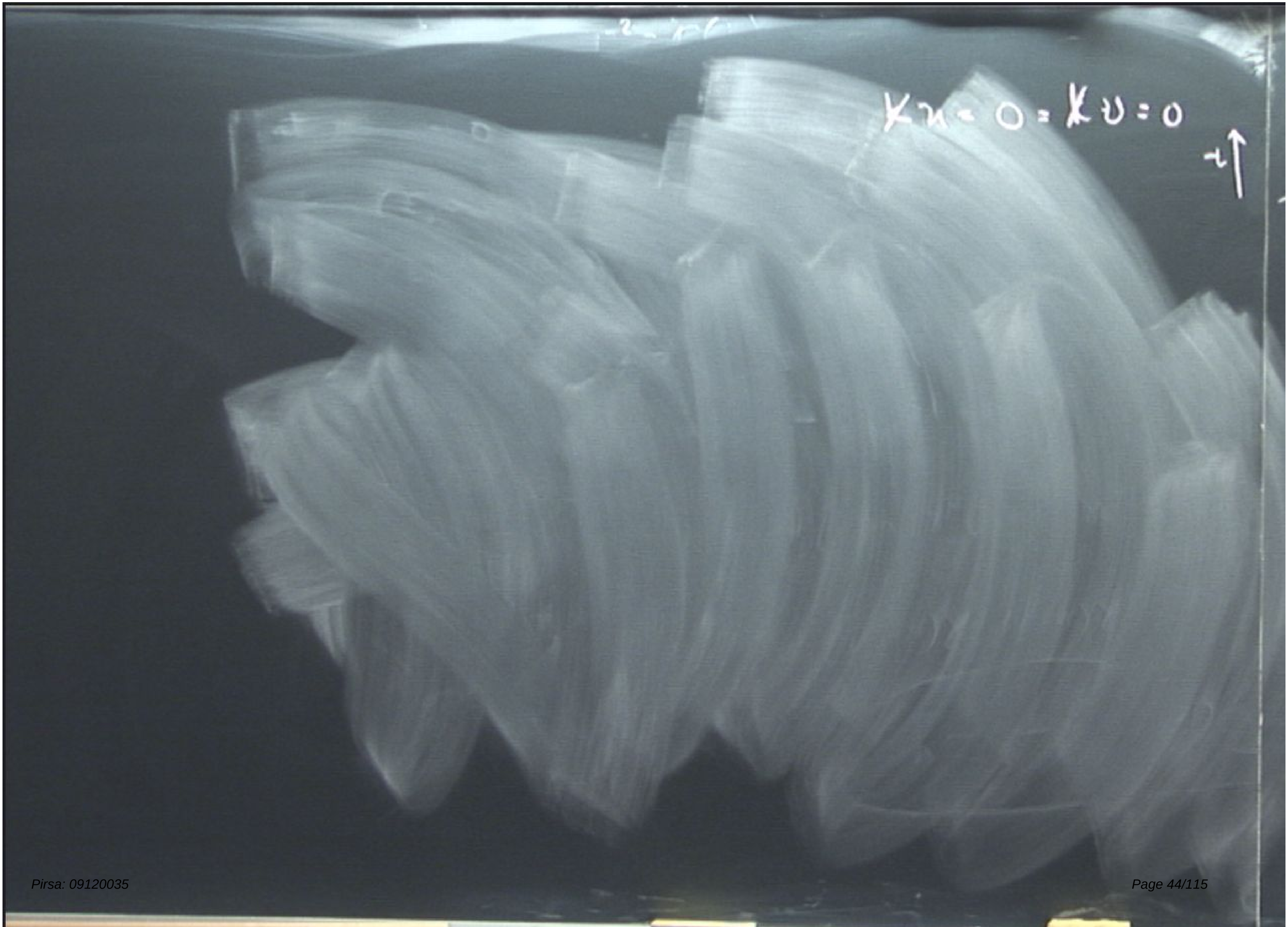
$k_4 \longrightarrow -k_2 \qquad u \to s$

$\gamma^\mu \; \gamma^\nu]$





...ach fermi...

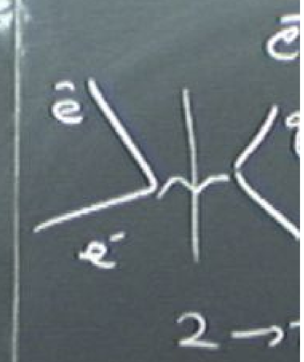

Ku = 0 = Kv = 0

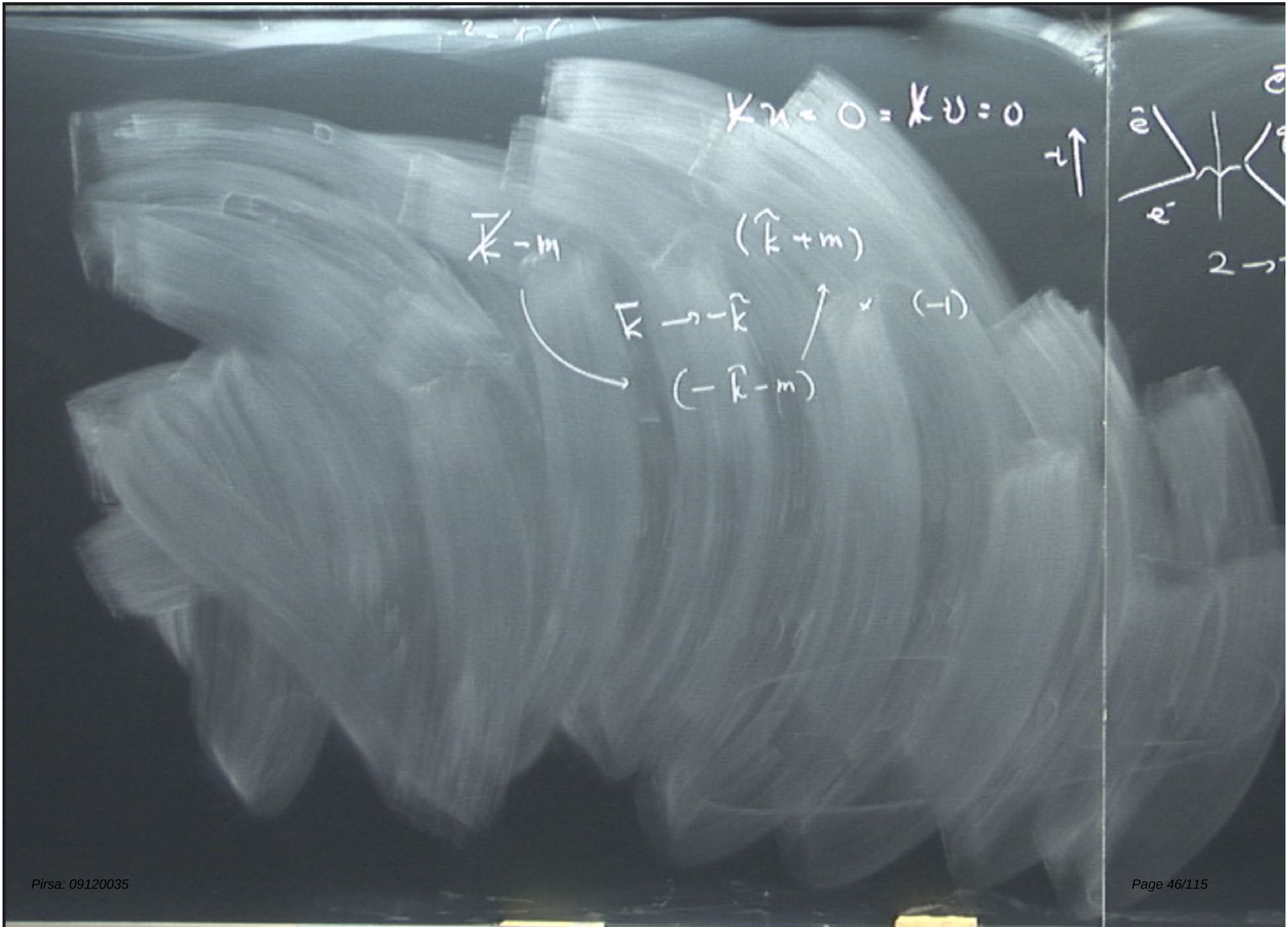
$\not{k}\, u = 0 = \not{k}\, v = 0$

$-i \uparrow$

$\not{k} - m$ $(\hat{k} + m)$

$\bar{k} \to -\hat{k}$ $\times (-1)$



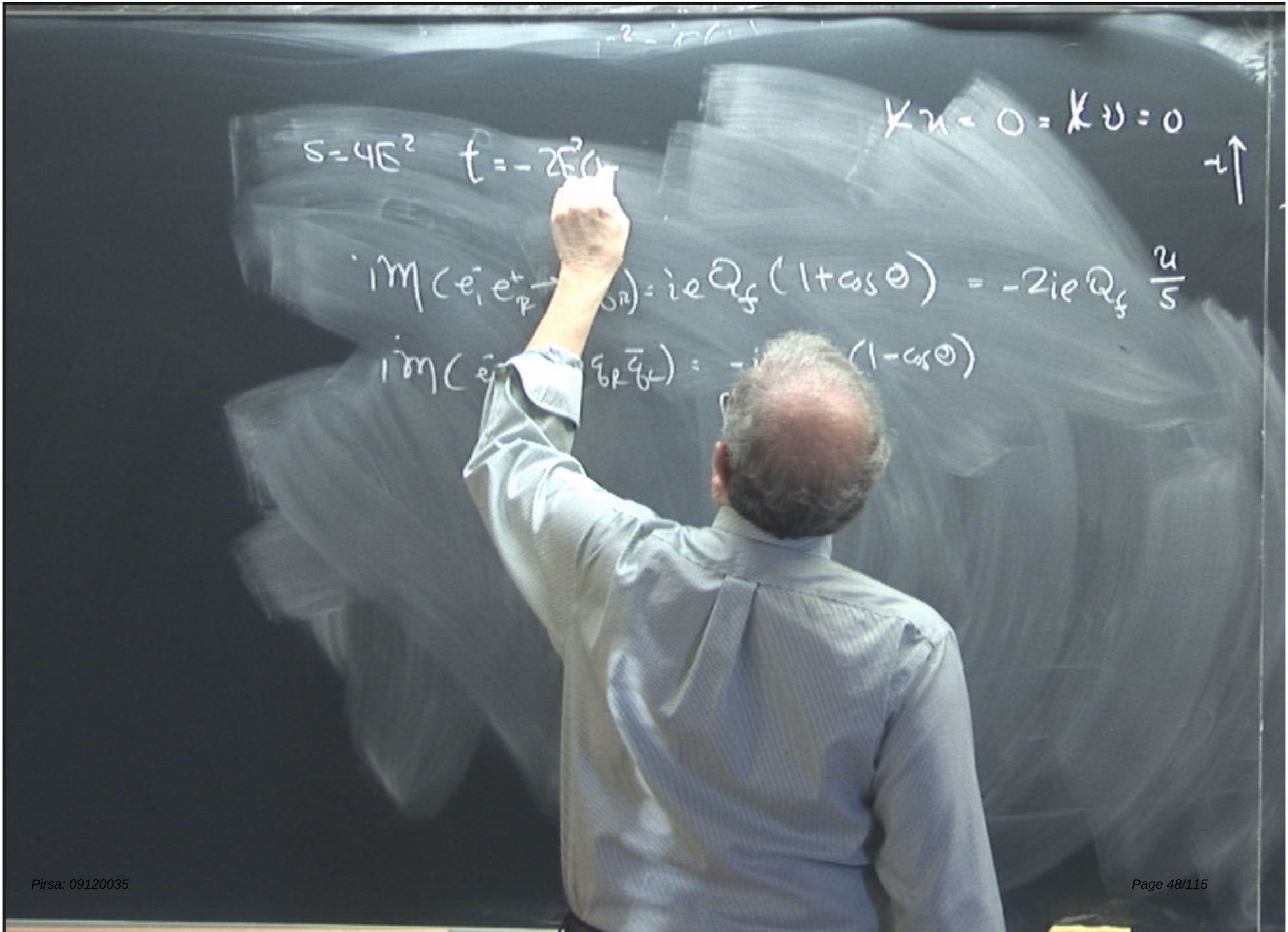

k̸u = 0 = k̸v = 0
k̸ − m
(k̂ + m)
k̸ → −k̂
× (−1)
(−k̂ − m)
e⁻
2 →

$\not{k}\, u = 0 = \not{k}\, v = 0$

$-i \uparrow$

$$i\mathcal{M}(e^-_L e^+_R \to q_L \bar{q}_R) = ie Q_f (1+\cos\theta) =$$

$$i\mathcal{M}(e^-_L e^+_R \to q_R \bar{q}_L) = -ie Q_f (1-\cos\theta)$$


s = 4E²   t = -2E²(1
k̸u = 0 = k̸v = 0
iM(e⁻ e⁺_R →) = ieQ_f (1+cosθ) = -2ieQ_f u/s
iM(e⁻ q_R q̄_L) = - (1-cosθ)

$\not{k} \cdot x = 0 = \not{k} \cdot v = 0$

$-1 \uparrow$

$s = 4E^2 \quad t = -2E^2(1-\cos\theta) \quad u = -2E(1+\cos\theta)$

$$i\mathcal{M}(e^-_L e^+_R \to q_L \bar{q}_R) = ieQ_f(1+\cos\theta) = -2ieQ_f \frac{u}{s}$$

$$i\mathcal{M}(e^-_L e^+_R \to q_R \bar{q}_L) = -ieQ_f(1-\cos\theta)$$

$\not{k}\, u = 0 = \not{k}\, v = 0$

$s = 4E^2 \quad t = -2E^2(1-\cos\theta) \quad u = -2E(1+\cos\theta)$

$i\mathcal{M}(e^-_L e^+_R \to q_L \bar{q}_R) = ie Q_f (1+\cos\theta) = -2ie^2 Q_f \frac{u}{s}$

$i\mathcal{M}(e^-_L e^+_R \to q_R \bar{q}_L) = -ie Q_f (1-\cos\theta) = 2ie^2 Q_f \frac{t}{s}$

$\not k \cdot u = 0 = \not k \cdot v = 0$

$s = 4E^2 \quad t = -2E^2(1-\cos\theta) \quad u = -2E^2(1+\cos\theta)$

$i\mathcal{M}(e^-_L e^+_R \to q_L \bar{q}_R) = ie^2 Q_f (1+\cos\theta) = -2ie^2 Q_f \frac{u}{s}$

$i\mathcal{M}(e^-_L e^+_R \to q_R \bar{q}_L) = -ie^2 Q_f (1-\cos\theta) = 2ie^2 Q_f \frac{t}{s}$

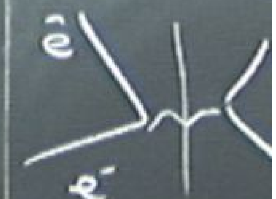
$i\mathcal{M}(e^-_L q_L \to e^-_L q_L) = -2ie^2 Q_f \frac{s}{t}$

$i\mathcal{M}(e^-_L q_R \to e^-_L q_R) = +2ie^2 Q_f \frac{u}{t}$

$\not k u = 0 = \not k v = 0$

$s = 4E^2 \quad t = -2E^2(1-\cos\theta) \quad u = -2E^2(1+\cos\theta)$

$-t \uparrow$



$2 \to$

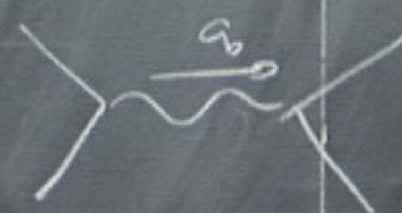
$$i\mathcal{M}(e^-_L e^+_R \to q_L \bar q_R) = ie Q_f (1+\cos\theta) = -2ie^2 Q_f \frac{u}{s}$$

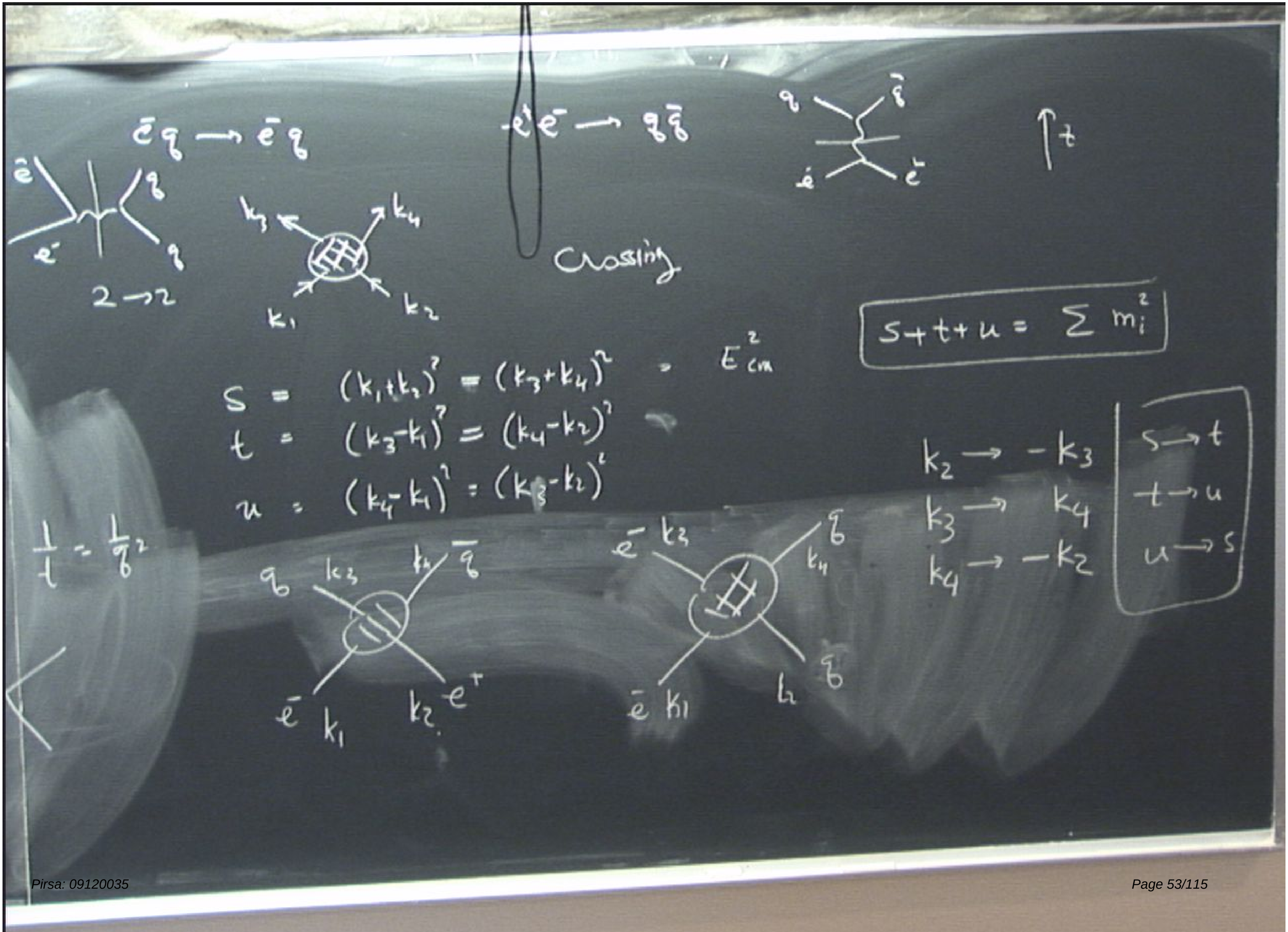
$$i\mathcal{M}(e^-_L e^+_R \to q_R \bar q_L) = -ie Q_f (1-\cos\theta) = 2ie^2 Q_f \frac{t}{s}$$

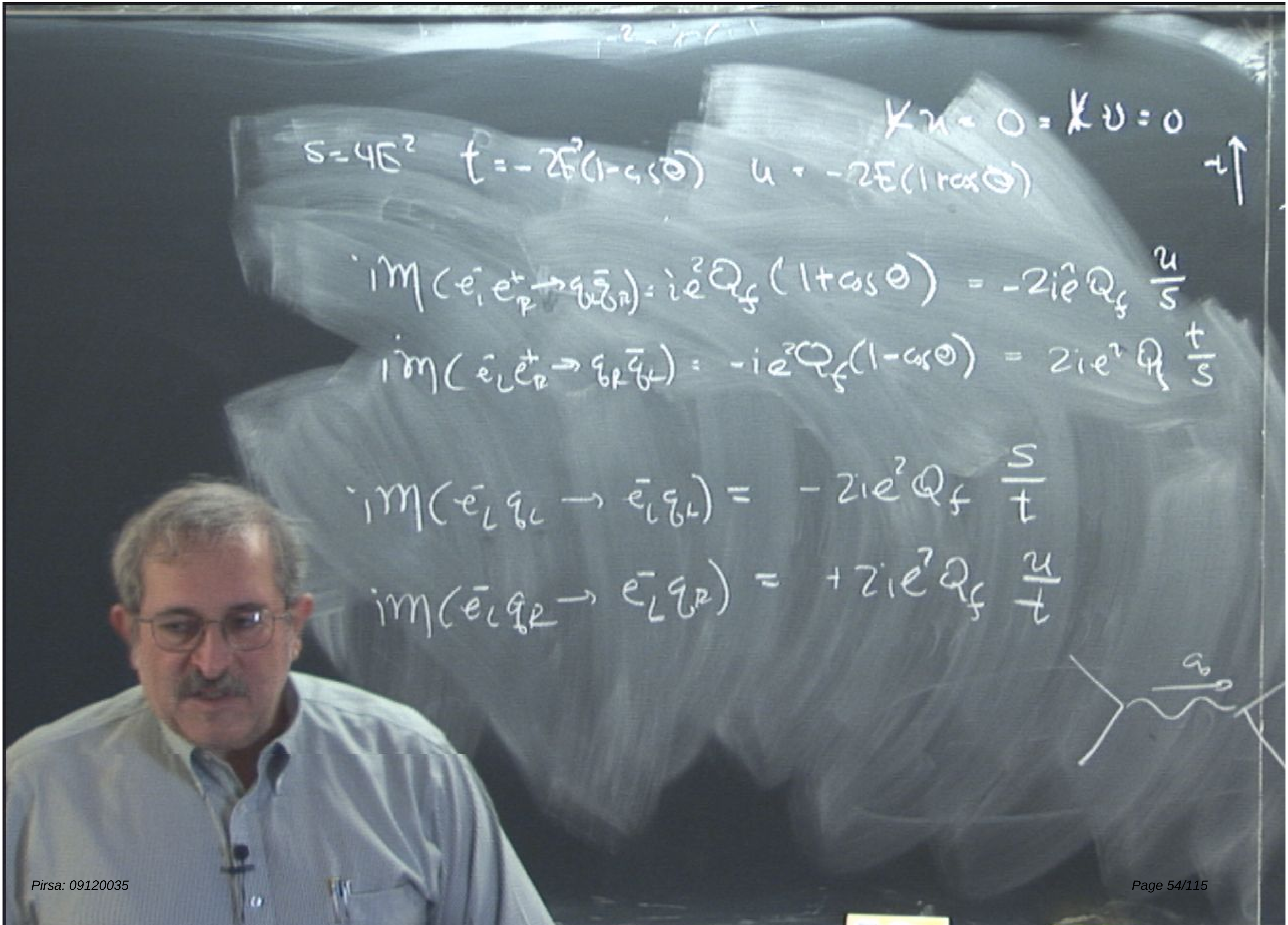
$$i\mathcal{M}(e^-_L q_L \to e^-_L q_L) = -2ie^2 Q_f \frac{s}{t}$$

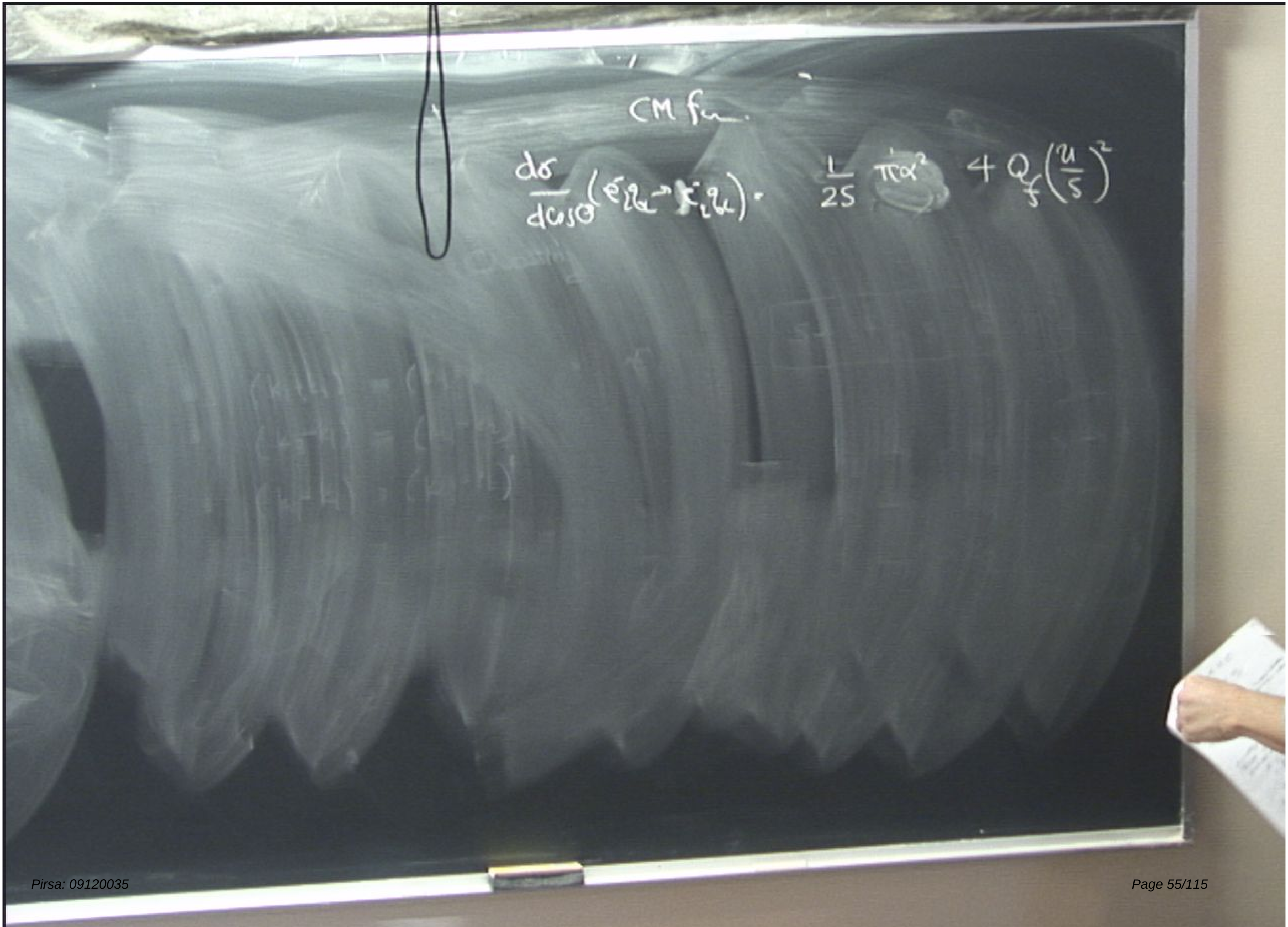
$$i\mathcal{M}(e^-_L q_R \to e^-_L q_R) = +2ie^2 Q_f \frac{u}{t}$$

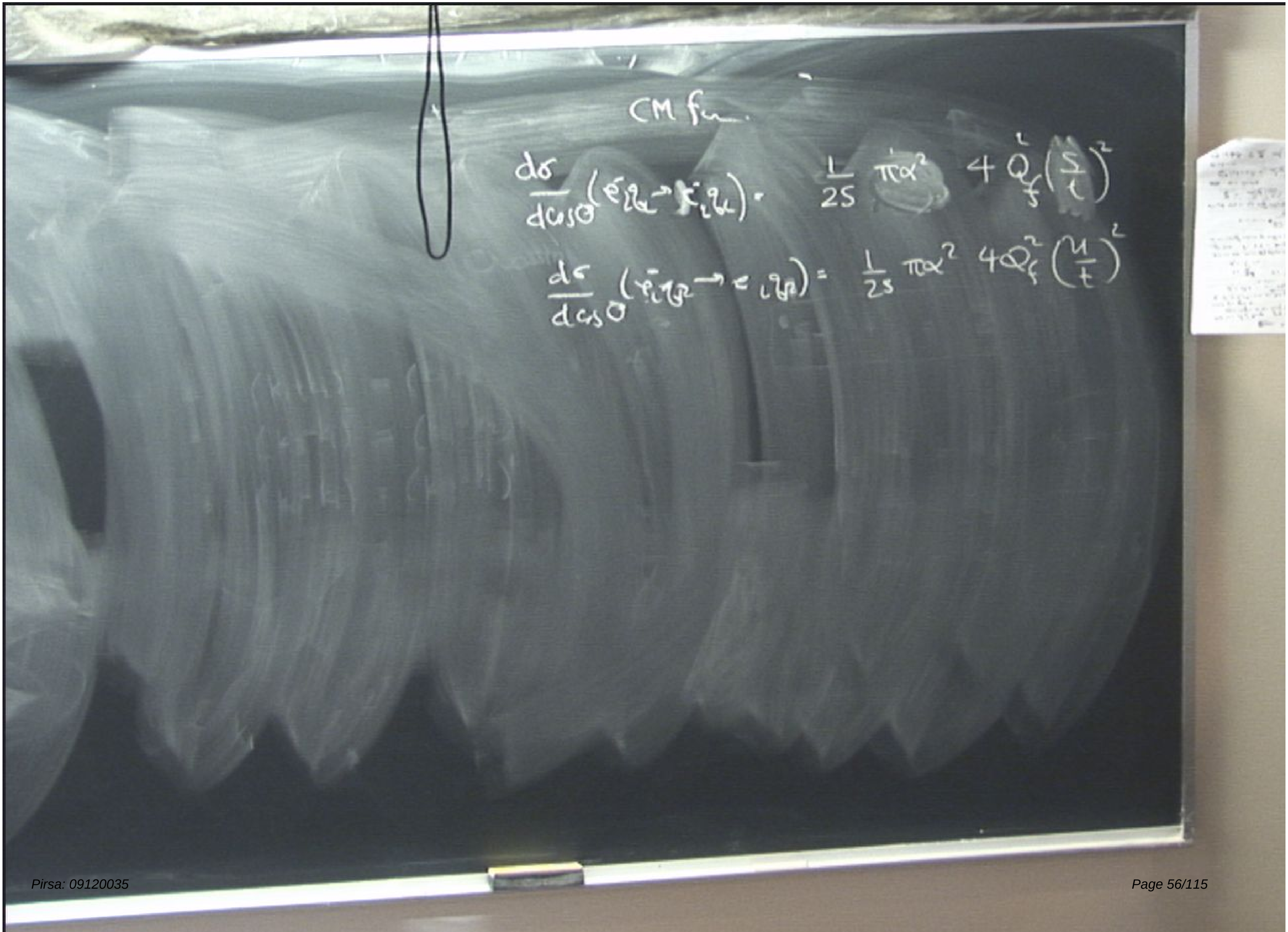
$\frac{1}{t} = \frac{1}{q^2}$




$\bar{e} q \to \bar{e} q$
$e^+ e^- \to q \bar{q}$
$\uparrow t$
$2 \to 2$
k_1 k_2 k_3 k_4
Crossing
$s + t + u = \sum m_i^2$
$s = (k_1 + k_2)^2 = (k_3 + k_4)^2 = E_{cm}^2$
$t = (k_3 - k_1)^2 = (k_4 - k_2)^2$
$u = (k_4 - k_1)^2 = (k_3 - k_2)^2$
$\frac{1}{t} = \frac{1}{q^2}$
$k_2 \to -k_3$
$k_3 \to k_4$
$k_4 \to -k_2$
$s \to t$
$t \to u$
$u \to s$


s = 4E²   t = -2E²(1-cosθ)   u = -2E(1+cosθ)
iM(e⁻_L e⁺_R → q_L q̄_R) = ie²Q_f (1+cosθ) = -2ie²Q_f u/s
iM(e⁻_L e⁺_R → q_R q̄_L) = -ie²Q_f(1-cosθ) = 2ie²Q_f t/s
iM(e⁻_L q_L → e⁻_L q_L) = -2ie²Q_f s/t
iM(e⁻_L q_R → e⁻_L q_R) = +2ie²Q_f u/t


CM fr.
dσ/dcosθ (e⁻_L q_L → e⁻_L q_L) = 1/2s πα² 4 Q_f (u/s)²

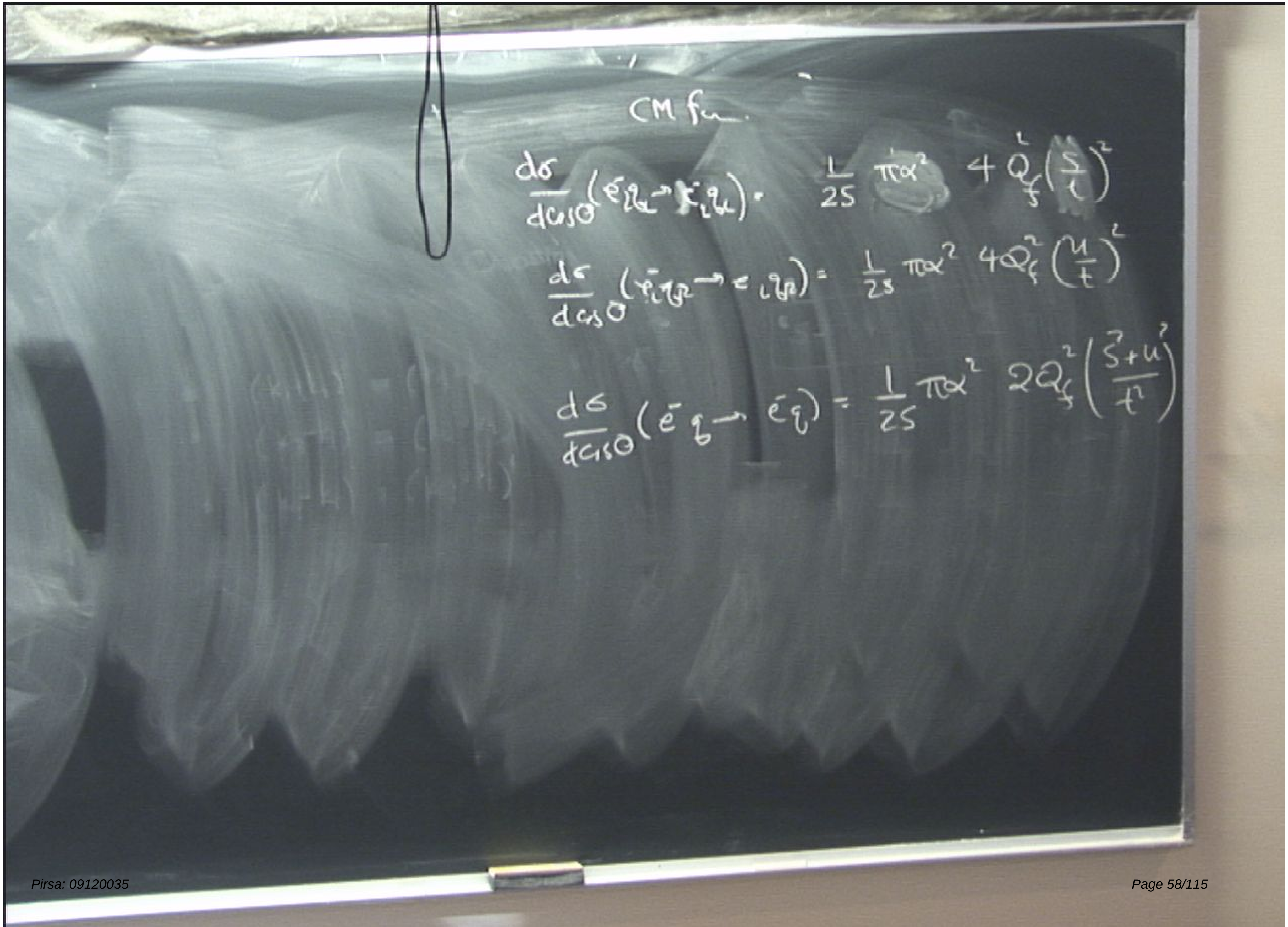

CM fr
$\frac{d\sigma}{d\cos\theta}(e^-_L q_R \to e^-_L q_R) = \frac{1}{2s}\pi\alpha^2\, 4Q_f^2 \left(\frac{s}{t}\right)^2$
$\frac{d\sigma}{d\cos\theta}(e^-_L \bar{q}_R \to e^-_L \bar{q}_R) = \frac{1}{2s}\pi\alpha^2\, 4Q_f^2 \left(\frac{u}{t}\right)^2$

CM fr.

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_L \to e^-_L q_L) = \frac{1}{2s}\pi\alpha^2\, 4\, Q_f^2 \left(\frac{s}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_R \to e_L q_R) = \frac{1}{2s}\pi\alpha^2\, 4 Q_f^2 \left(\frac{u}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^- q \to e^- q) = \frac{1}{2s}\pi\alpha^2\, 2 Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$


CM fr
dσ/dcosθ (e⁻_L q_L → e⁻_L q_L) = 1/2s πα² 4 Q_f² (s/t)²
dσ/dcosθ (e⁻_L q_R → e⁻_L q_R) = 1/2s πα² 4Q_f² (u/t)²
dσ/dcosθ (e⁻ q → e⁻ q) = 1/2s πα² 2Q_f² ((s²+u²)/t²)

CM fr.

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_L \to e^-_L q_L) = \frac{1}{2s}\pi\alpha^2 \, 4 Q_f^2 \left(\frac{s}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_R \to e^-_L q_R) = \frac{1}{2s}\pi\alpha^2 \, 4 Q_f^2 \left(\frac{u}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^- q \to e^- q) = \frac{1}{2s}\pi\alpha^2 \, 2 Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

$$dt = 2E^2 \, d\cos\theta = \tfrac{1}{2} s \, d\cos\theta$$

CM fr...

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_L \to e^-_L q_L) = \frac{1}{2s}\pi\alpha^2\, 4 Q_f^2 \left(\frac{s}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_R \to e^-_L q_R) = \frac{1}{2s}\pi\alpha^2\, 4 Q_f^2 \left(\frac{u}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^- q \to e^- q) = \frac{1}{2s}\pi\alpha^2\, 2 Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

$$dt = 2E^2\, d\cos\theta = \tfrac{1}{2} s\, d\cos\theta$$

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha^2}{s} Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

CM fr...

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_L \to e^-_L q_L) = \frac{1}{2s}\pi\alpha^2 \; 4 Q_f^2 \left(\frac{s}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_R \to e_L q_R) = \frac{1}{2s}\pi\alpha^2 \; 4 Q_f^2 \left(\frac{u}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^- q \to e^- q) = \frac{1}{2s}\pi\alpha^2 \; 2 Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

$$dt = 2E^2 \, d\cos\theta = \tfrac{1}{2} s \, d\cos\theta$$

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha^2}{s^2} Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

CM fr.

$$\frac{d\sigma}{d\cos\theta}(\bar{e}_R q_R \to \bar{e}_L q_L) = \frac{1}{2s}\pi\alpha^2\, 4Q_f^2\left(\frac{s}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(\bar{e}_L q_R \to \bar{e}_L q_R) = \frac{1}{2s}\pi\alpha^2\, 4Q_f^2\left(\frac{u}{t}\right)^2$$

add

$\bar{e}_R q_L \to \bar{e}_R q_R$

$$\frac{d\sigma}{d\cos\theta}(\bar{e} q \to \bar{e} q) = \frac{1}{2s}\pi\alpha^2\, 2Q_f^2\left(\frac{s^2+u^2}{t^2}\right)$$

$$dt = 2E^2\, d\cos\theta = \tfrac{1}{2}s\, d\cos\theta$$

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha^2}{s^2}\, Q_f^2\left(\frac{s^2+u^2}{t^2}\right)$$

CM fr.

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_L \to e^-_L q_L) = \frac{1}{2s}\pi\alpha^2\, 4 Q_f^2 \left(\frac{s}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_R \to e_L q_R) = \frac{1}{2s}\pi\alpha^2\, 4 Q_f^2 \left(\frac{u}{t}\right)^2$$

add

$e^-_R q_R \to e^-_R q_R$

$$\frac{d\sigma}{d\cos\theta}(e^- q \to e^- q) = \frac{1}{2s}\pi\alpha^2\, 2 Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

$$dt = 2E^2\, d\cos\theta = \tfrac{1}{2} s\, d\cos\theta$$

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha^2}{s^2} Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

CM fr...

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_L \to e^-_L q_L) = \frac{1}{2s}\pi\alpha^2 \, 4 Q_f^2 \left(\frac{s}{t}\right)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L q_R \to e^-_L q_R) = \frac{1}{2s}\pi\alpha^2 \, 4 Q_f^2 \left(\frac{u}{t}\right)^2$$

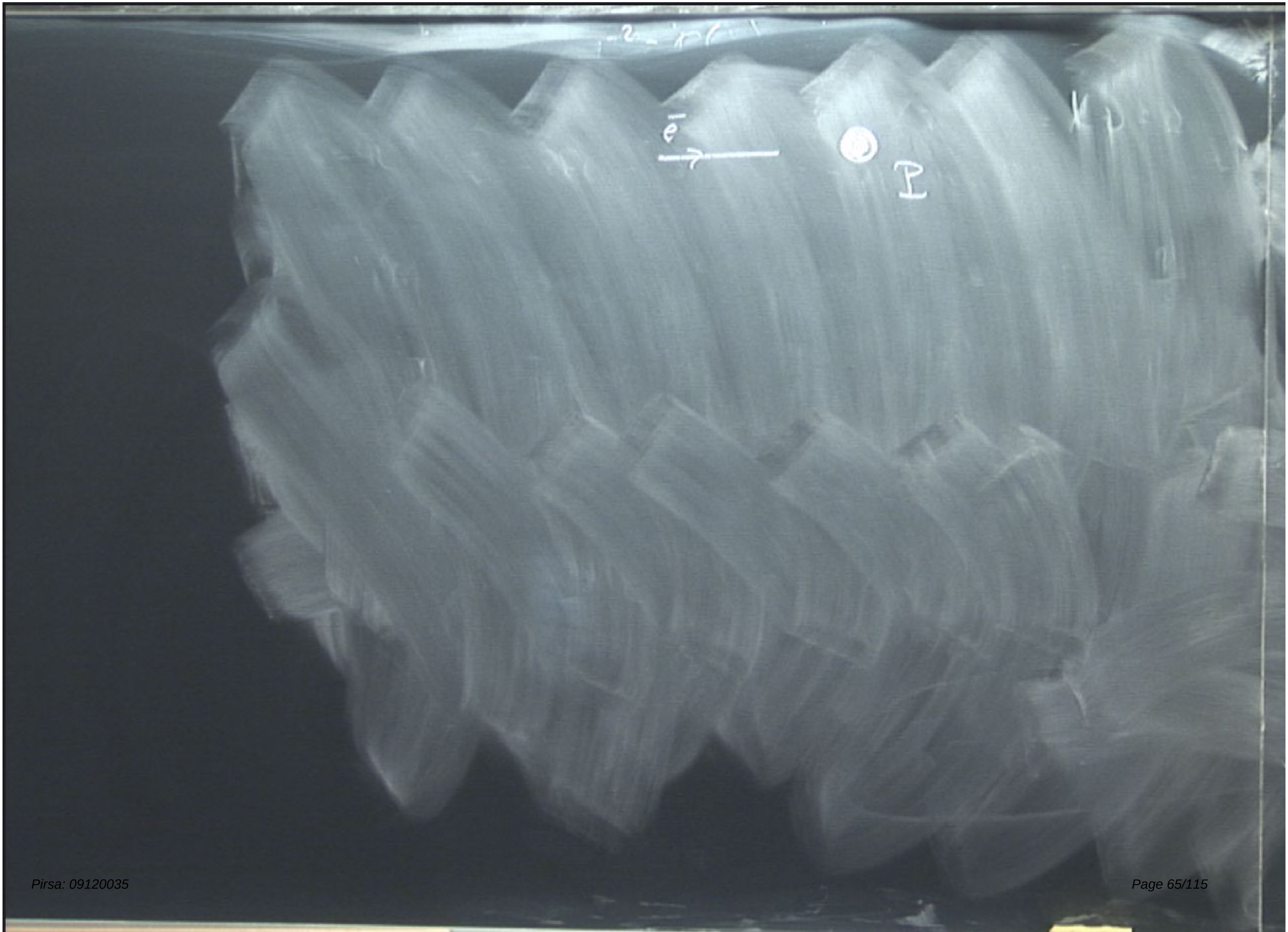
add

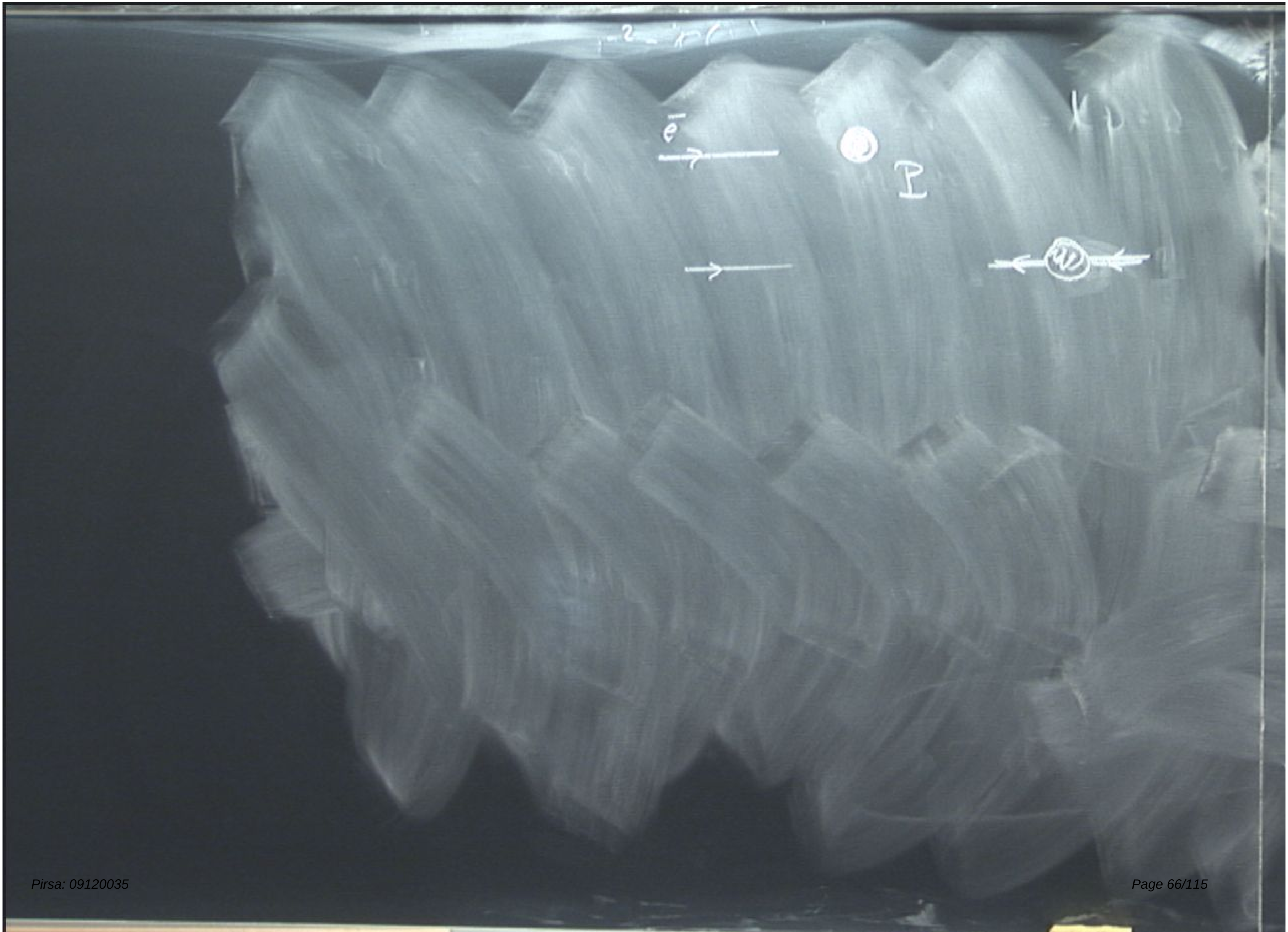
$e^-_R q_R \to e^-_R q_R$

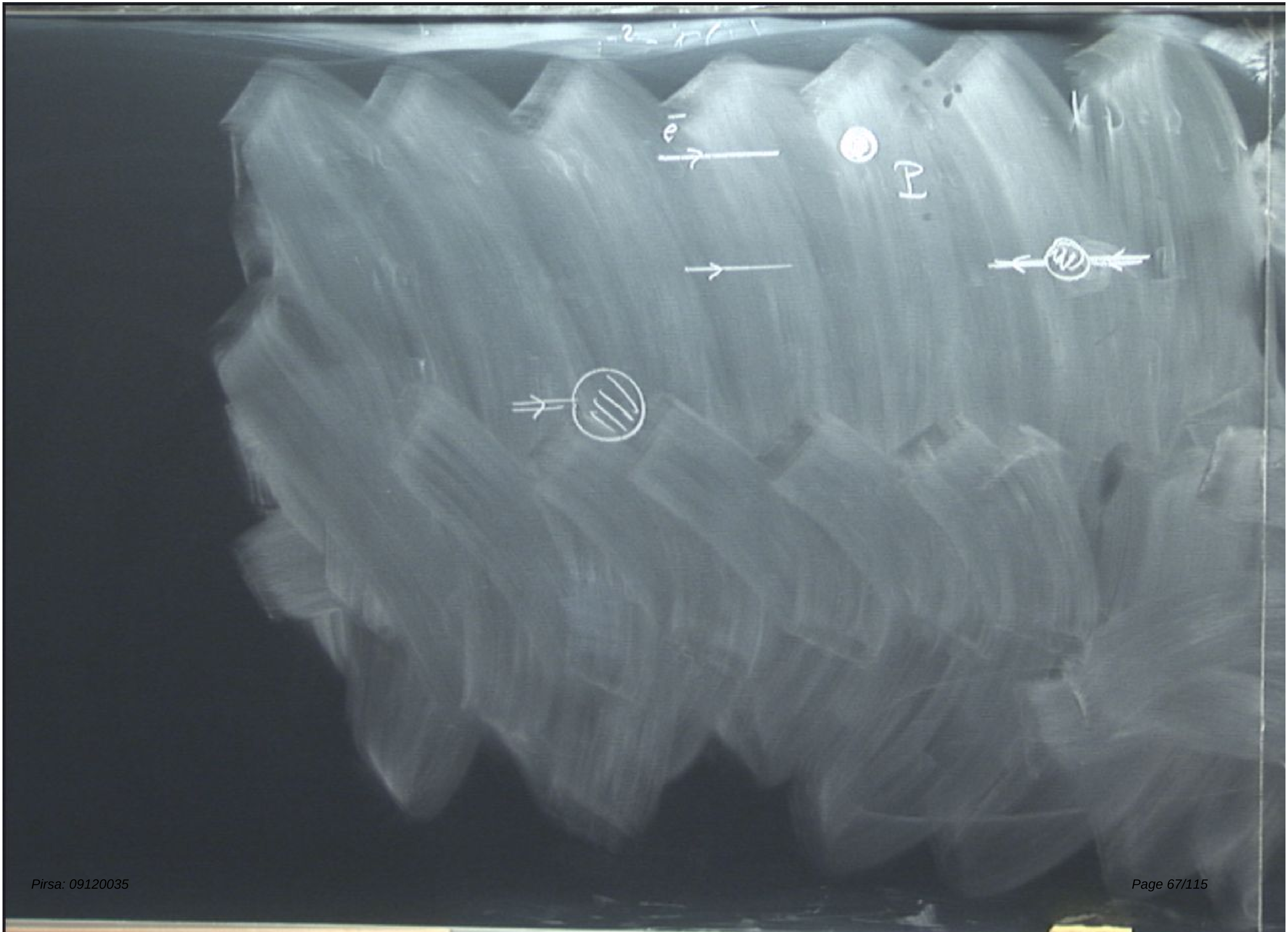
$$\frac{d\sigma}{d\cos\theta}(e^- q \to e^- q) = \frac{1}{2s}\pi\alpha^2 \, 2 Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

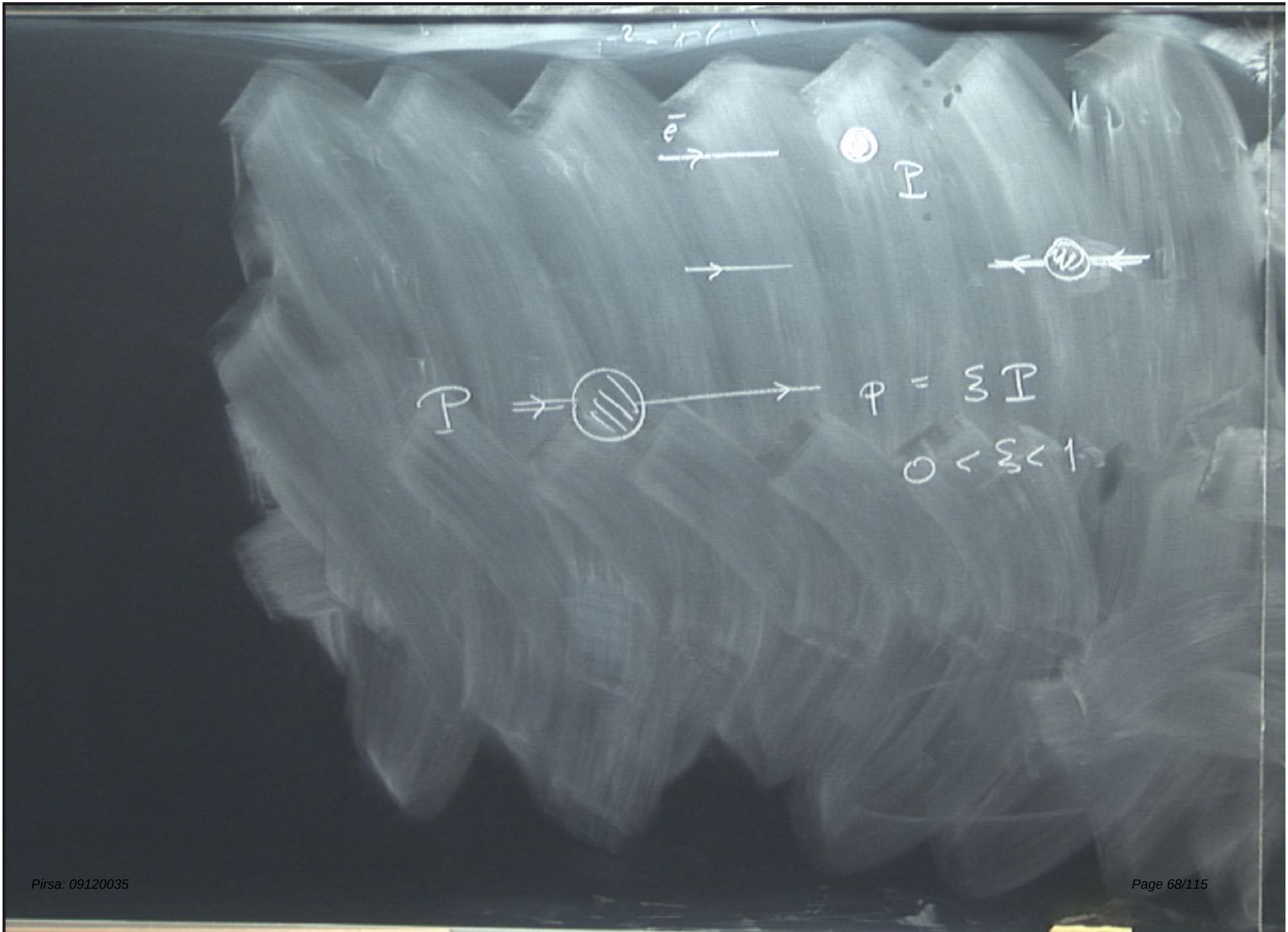
$$dt = 2E^2 \, d\cos\theta = \tfrac{1}{2} s \, d\cos\theta$$

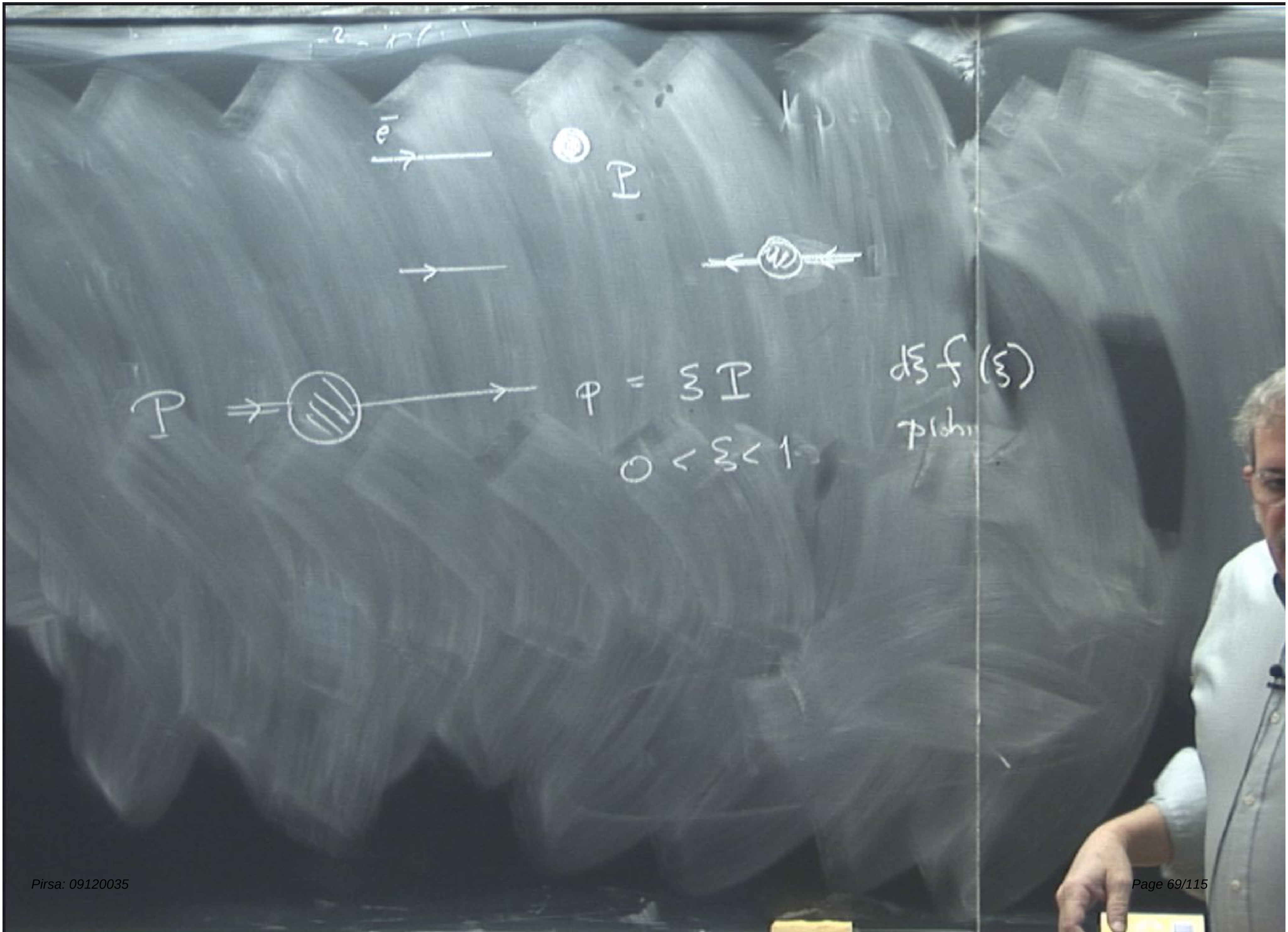
$$\frac{d\sigma}{dt} = \frac{2\pi\alpha^2}{s^2} Q_f^2 \left(\frac{s^2+u^2}{t^2}\right)$$

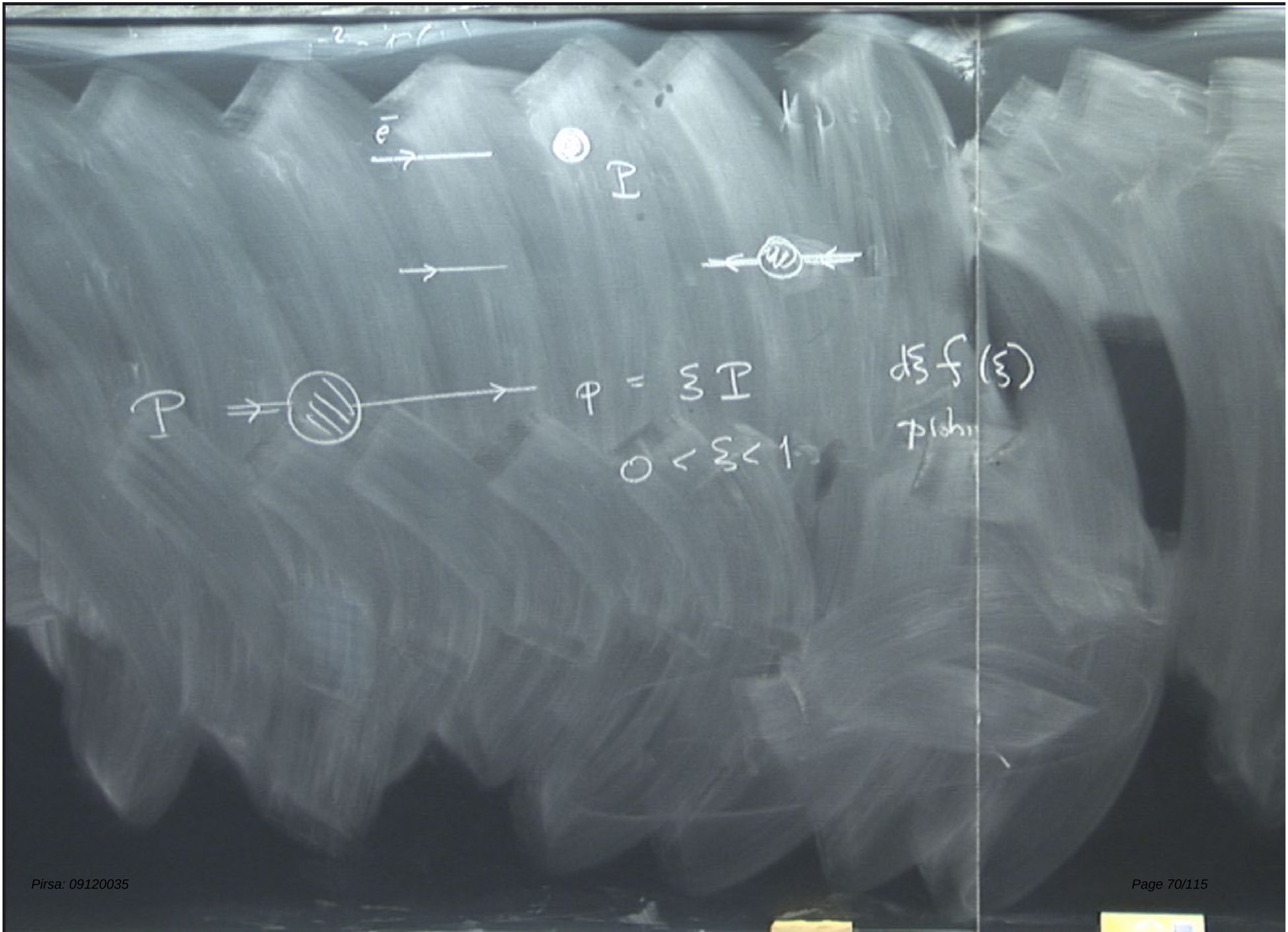

e^-
P


e⁻
P

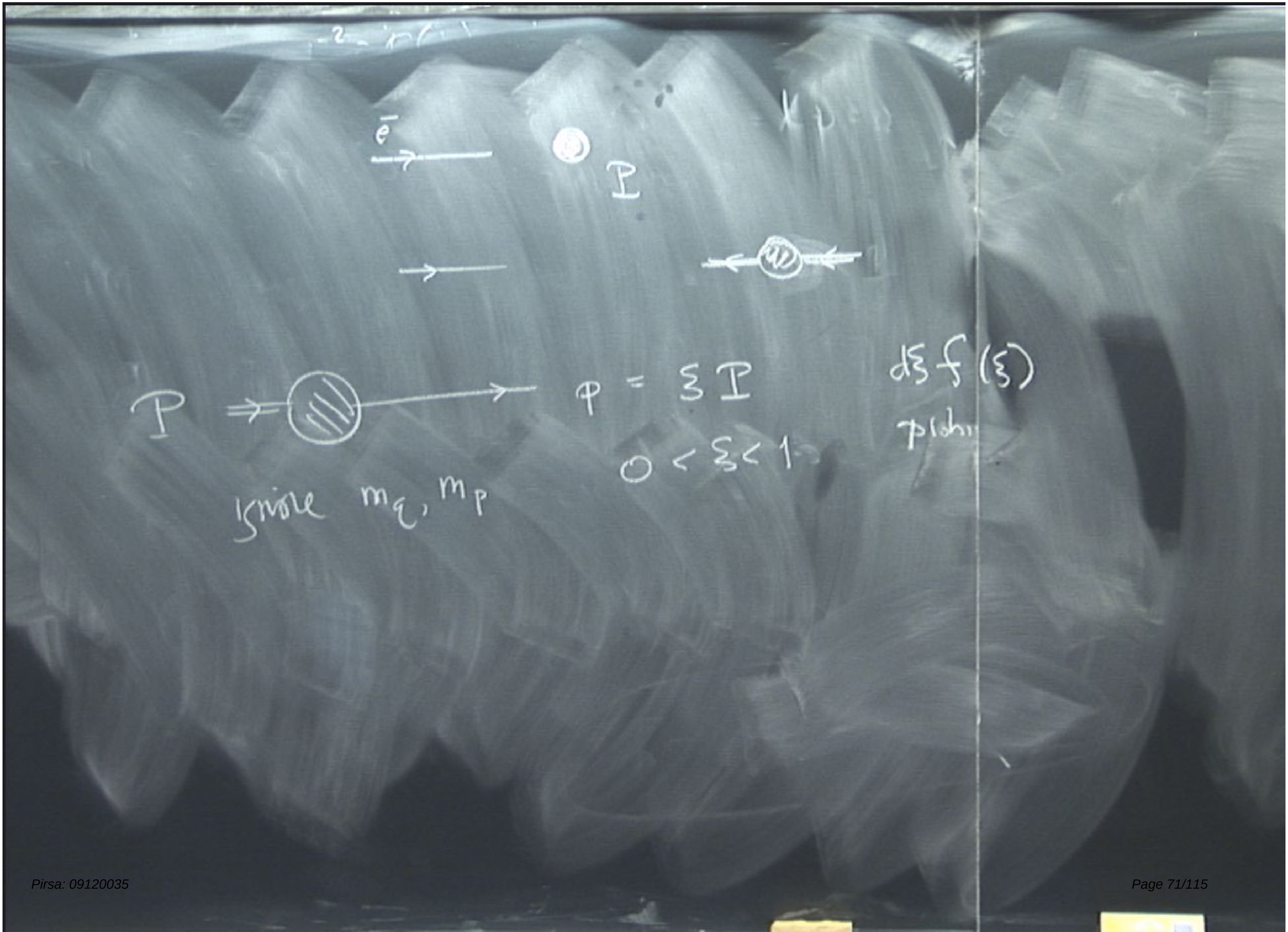

P

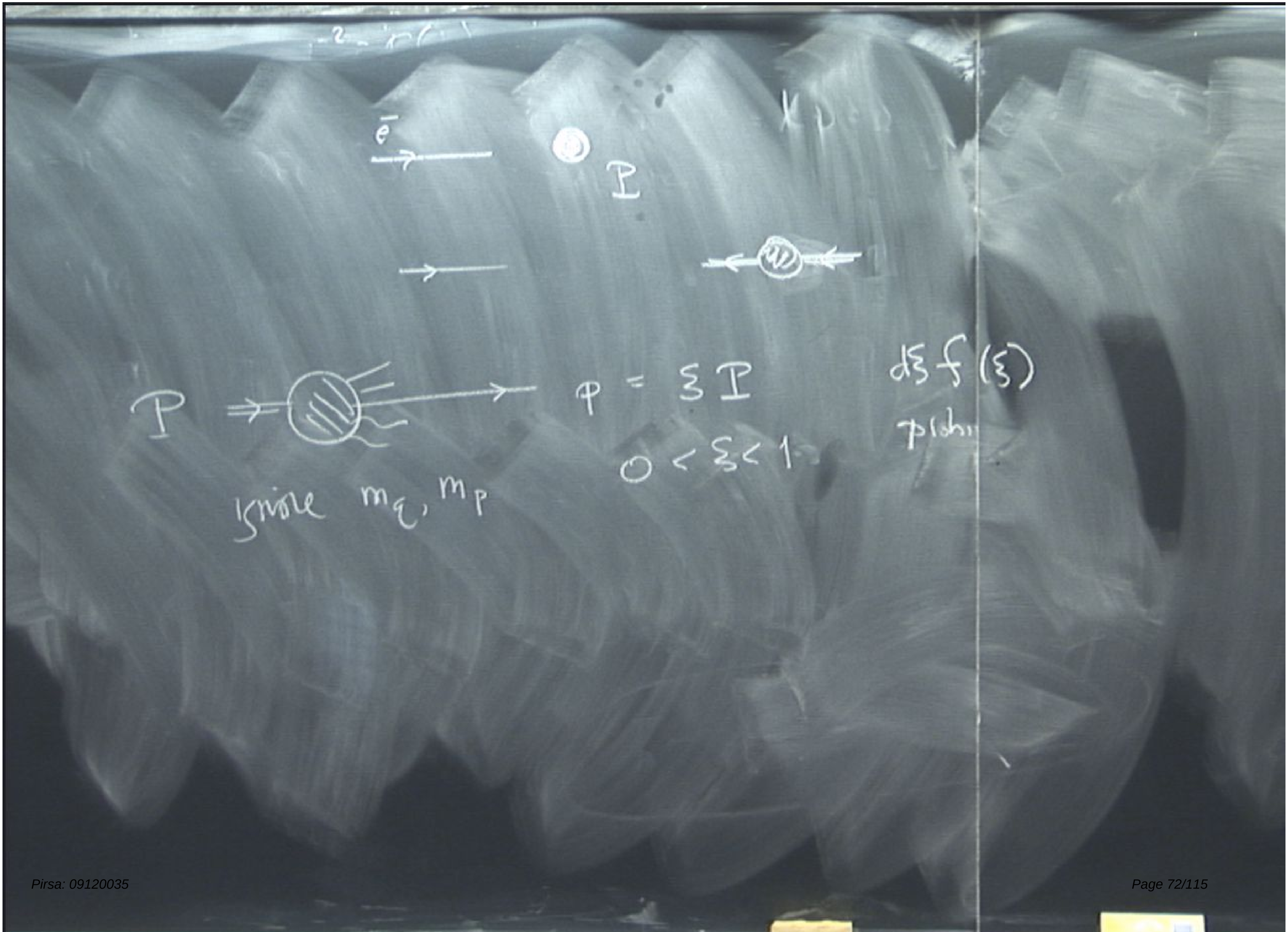

e⁻
P
P
p = ξ P
0 < ξ < 1

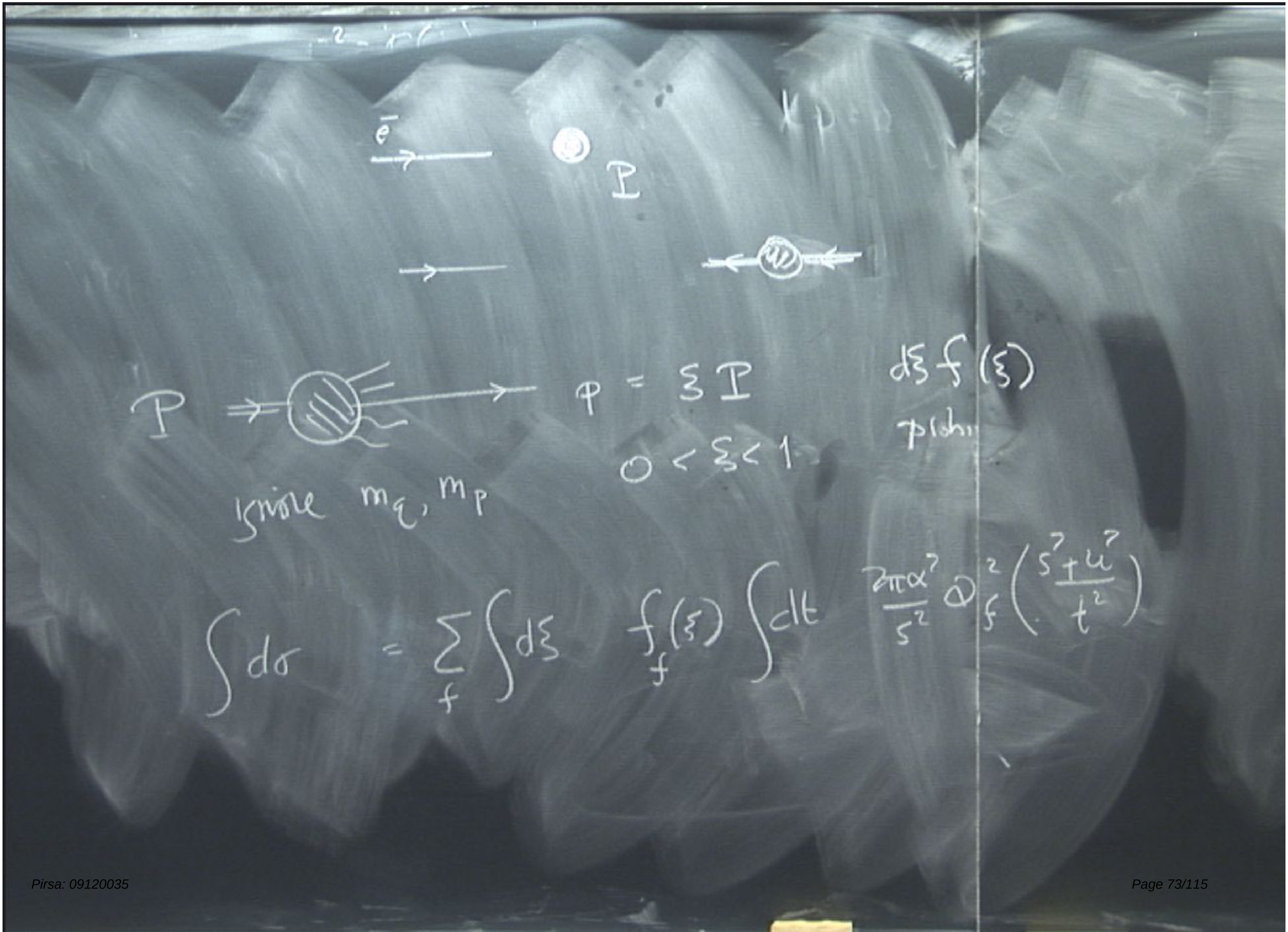

P
p = ξ P
0 < ξ < 1
dξ f (ξ)



e⁻
P
P
p = ξ P
0 < ξ < 1
dξ f (ξ)


P
P
p = ξ P
0 < ξ < 1
dξ f (ξ)
ignore m_q, m_p


P
P
p = ξ P
0 < ξ < 1
dξ f (ξ)
ignore m_q, m_p


ē
P
P
p = ξ P
0 < ξ < 1
dξ f(ξ)
prob..
ignore m_q, m_p
∫dσ = Σ_f ∫dξ f_f(ξ) ∫dt (2πα²/s²) Q_f² ((s² + u²)/t²)

$p = \xi P$

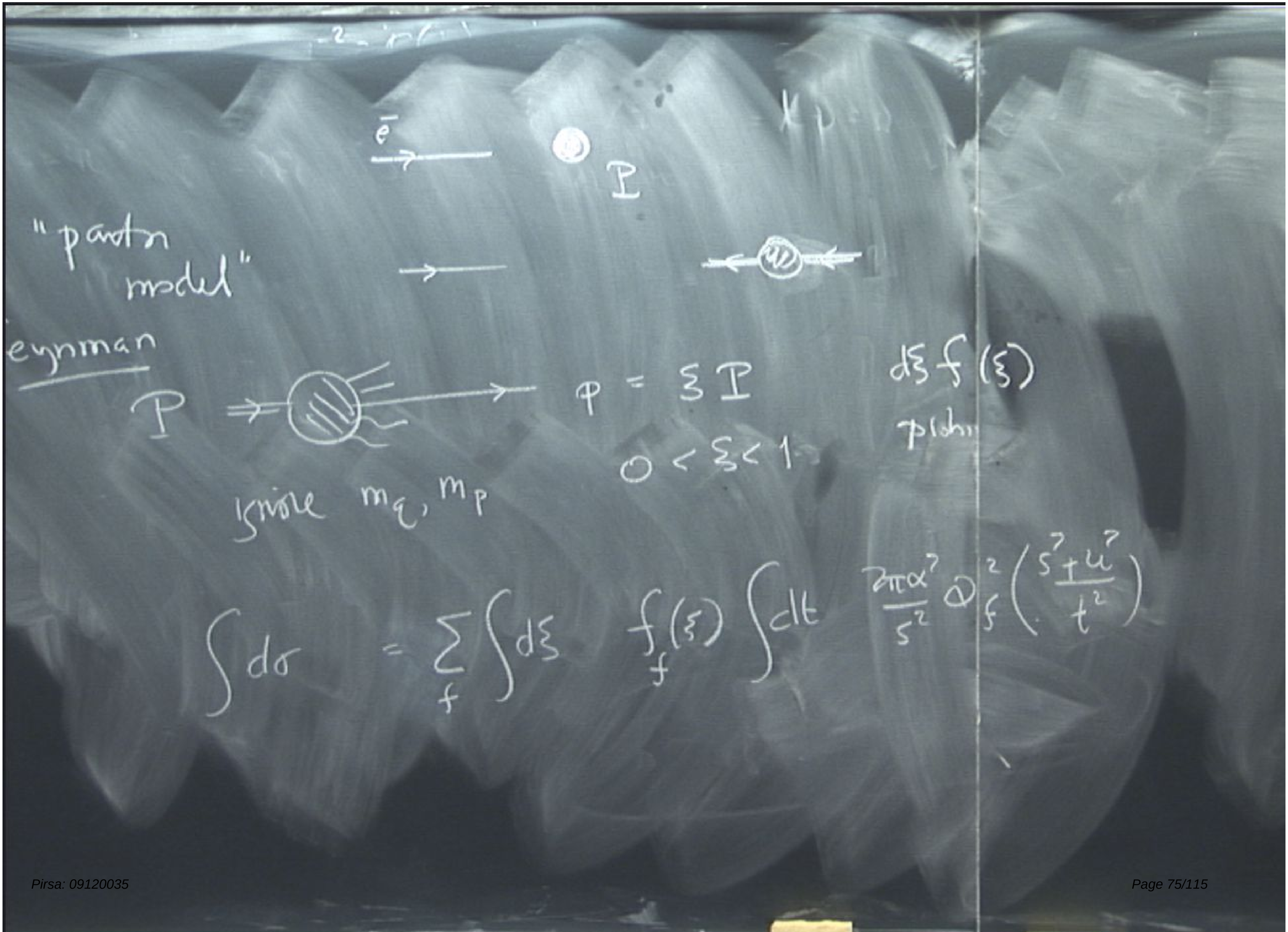
$0 < \xi < 1$

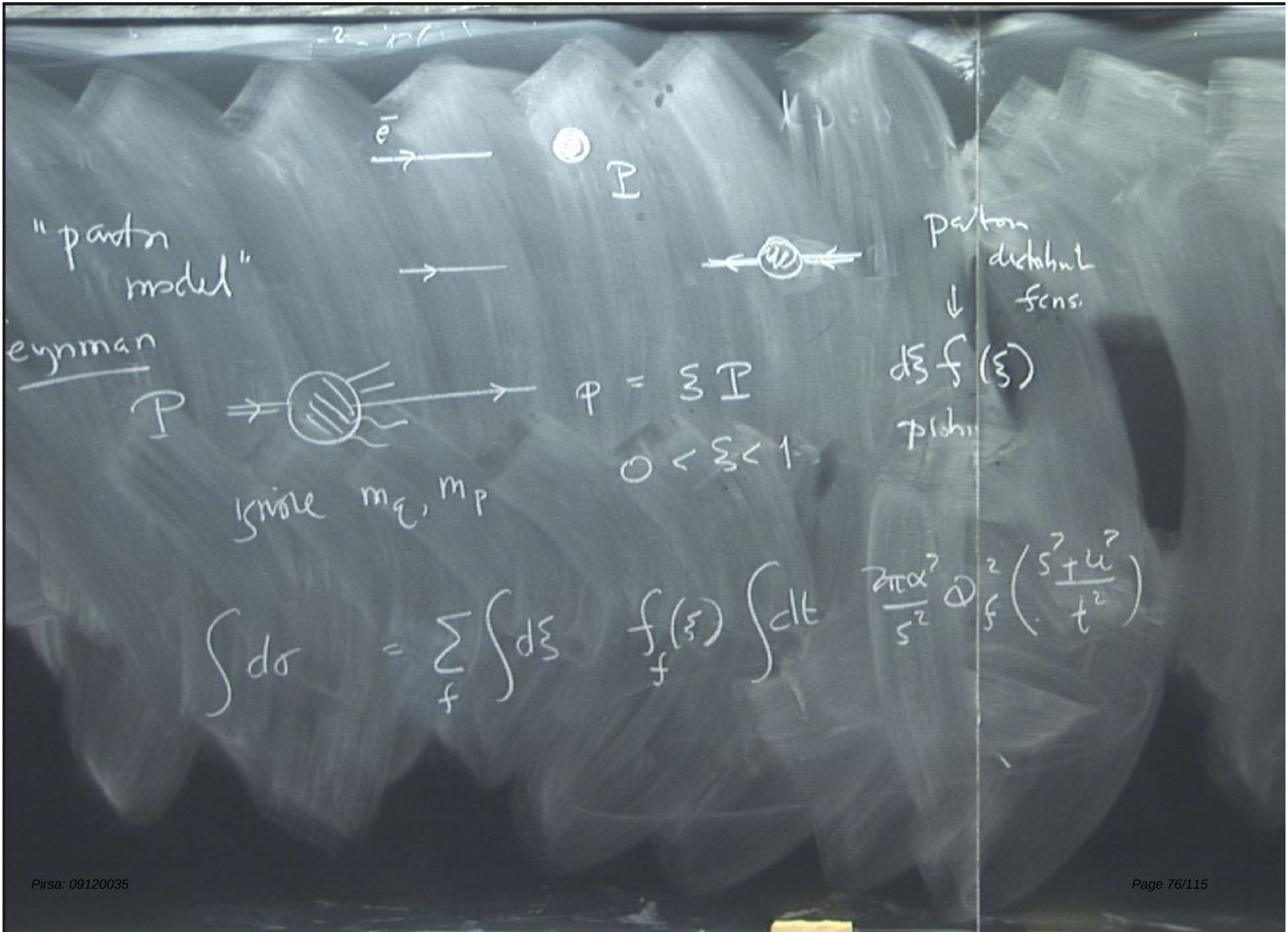
$d\xi \, f(\xi)$

prob..

ignore m_q, m_p

$$\int d\sigma = \sum_f \int d\xi \; f_f(\xi) \int dt \; \frac{2\pi\alpha^2}{s^2} Q_f^2 \left(\frac{s^2+u^2}{t^2} \right)$$


"parton model"
eynman
P
p = ξ P
0 < ξ < 1
dξ f(ξ)
prob
ignore m_q, m_p
∫dσ = Σ_f ∫dξ f_f(ξ) ∫dt (2πα²/s²) Q_f² ((s² + u²)/t²)


ē
P
"parton model"
Feynman
P
p = ξ P
0 < ξ < 1
ignore m_q, m_p
parton distribut fcns.
dξ f(ξ)
prob
∫dσ = Σ_f ∫dξ f_f(ξ) ∫dt (2πα²/s²) Q_f² ((s² + u²)/t²)

"parton model"

Feynman

parton distribution fcns.

↓

$d\xi\, f(\xi)$

prob.

P 

$p = \xi P$

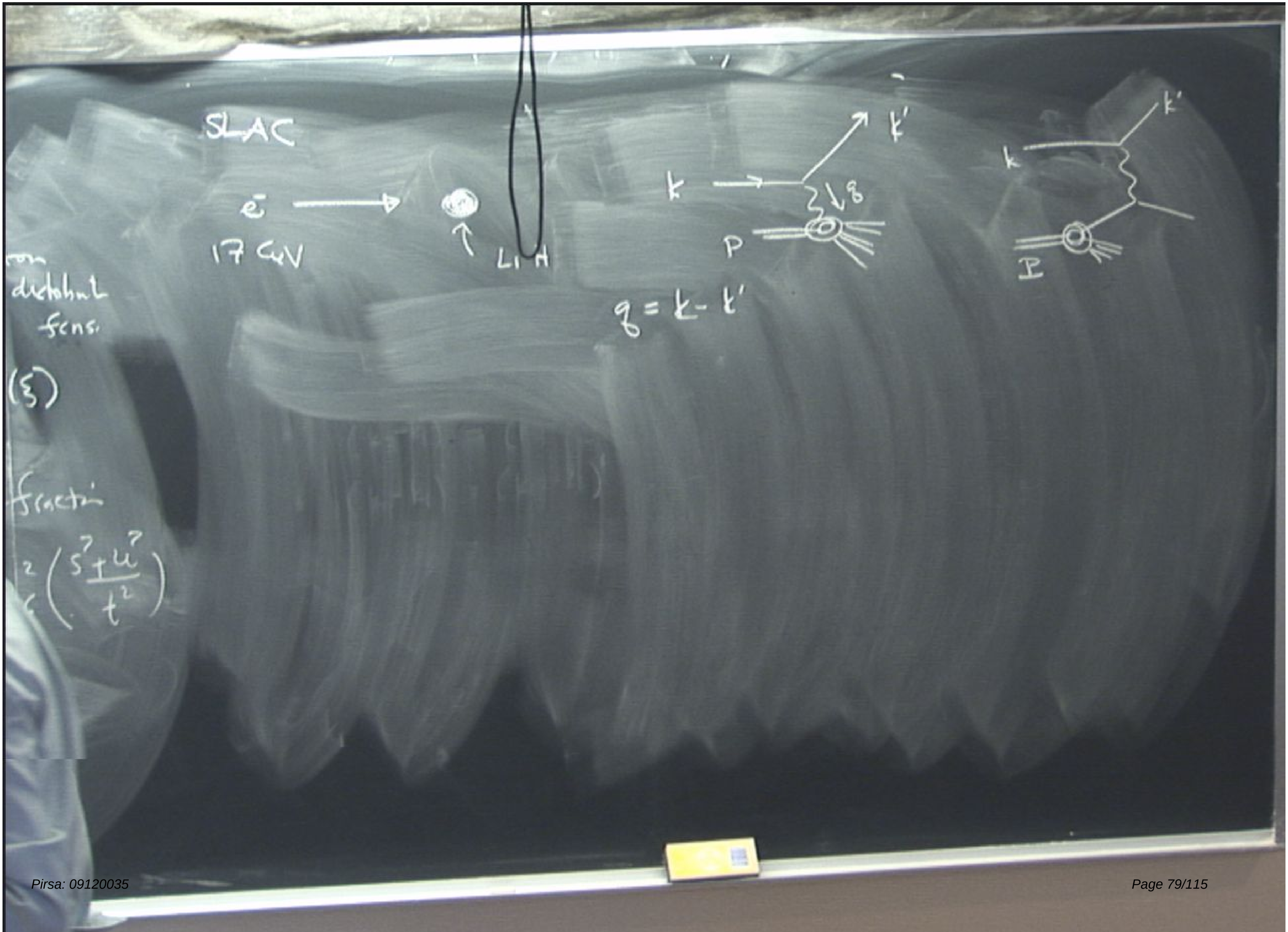
$0 < \xi < 1$

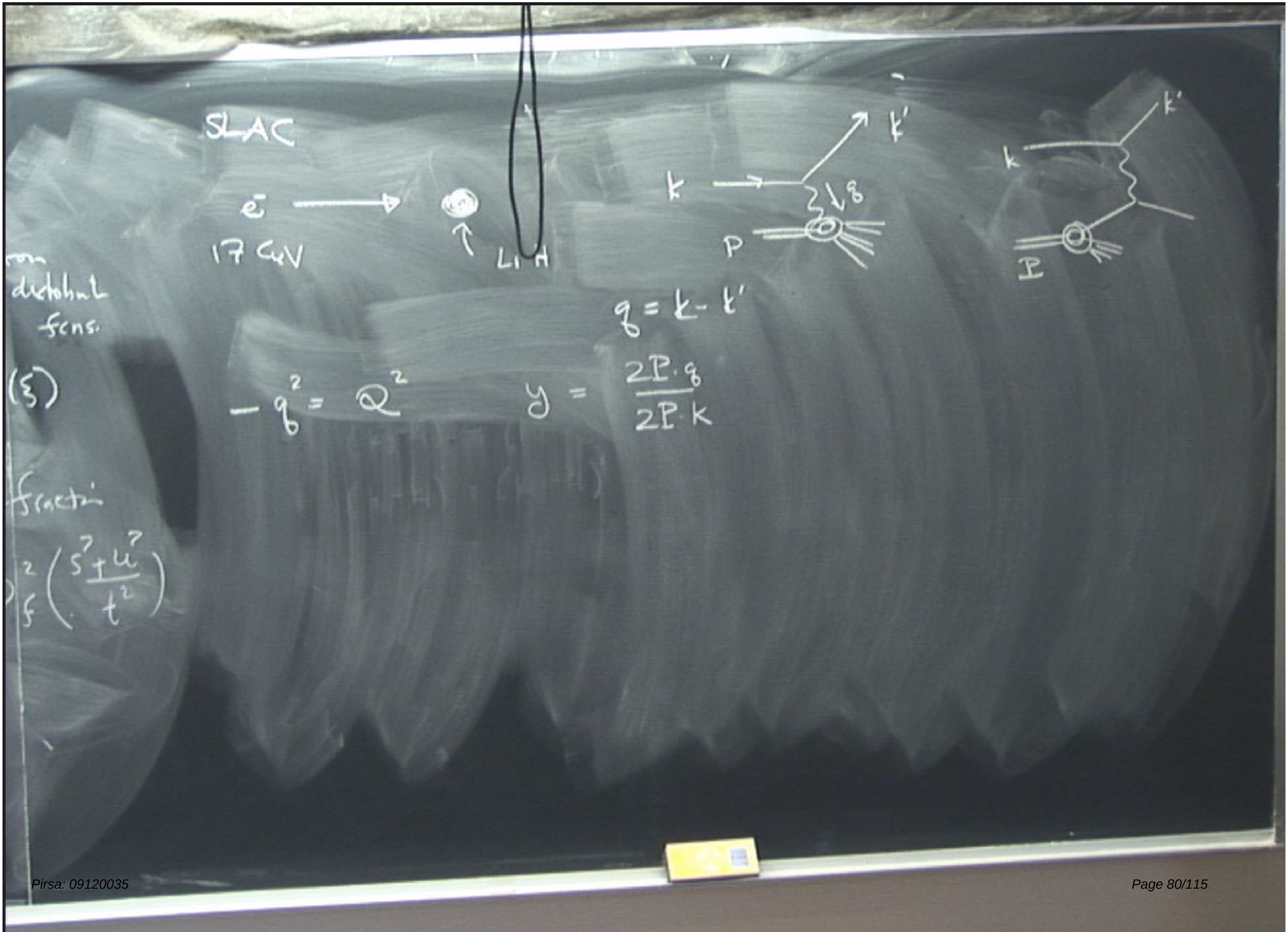
↑ "longitudinal fraction"

ignore m_q, m_p

$$\int d\sigma = \sum_f \int d\xi \; f_f(\xi) \int dt \; \frac{2\pi\alpha^2}{s^2} Q_f^2 \left(\frac{s^2+u^2}{t^2} \right)$$


SLAC
17 GeV
LiH
k
k′


SLAC
e⁻
17 GeV
Li H
k
k'
P
q = k − k'
fraction


SLAC
e⁻
17 GeV
Li H
k
k'
q
P
q = k − k'
−q² = Q²
y = 2P·q / 2P·k
(ξ)

...ion
distribution
fcns.

(ξ)

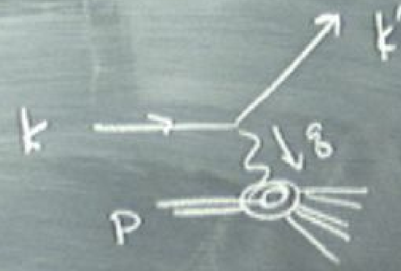
fraction

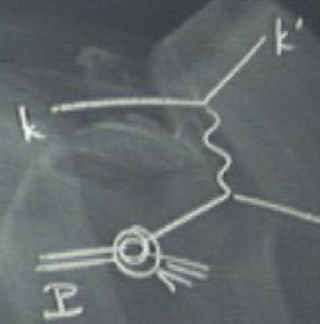
$f^2\left(\frac{s^2+u^2}{t^2}\right)$

SLAC

$e^- \longrightarrow$ ●

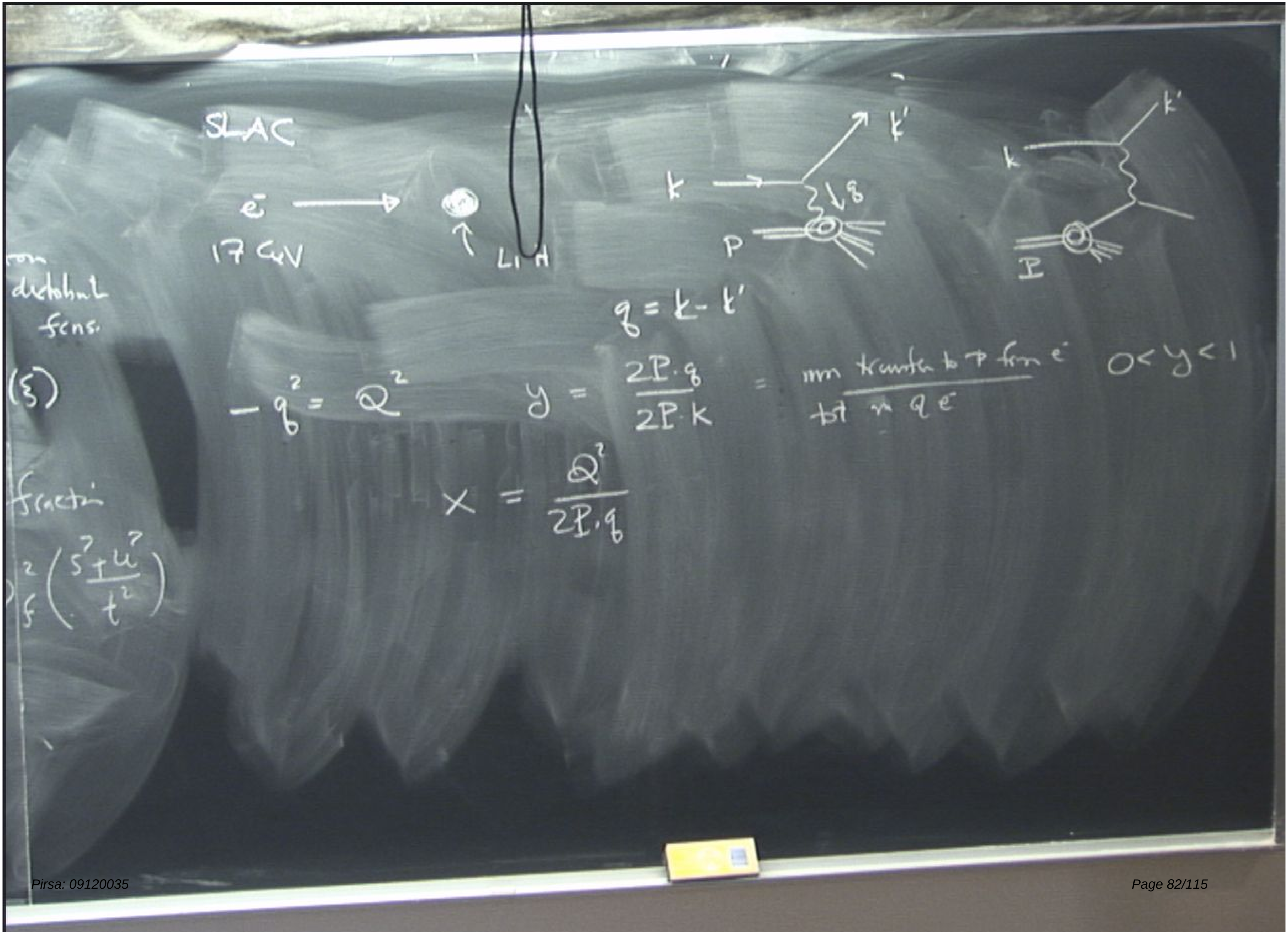
17 GeV ↑ LiH





$q = k - k'$

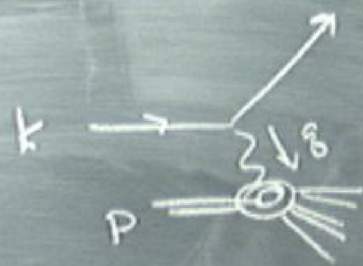
$-q^2 = Q^2 \qquad y = \frac{2P\cdot q}{2P\cdot k} = \frac{\text{mom transfer to p from } e^-}{\text{tot mom } e^-} \qquad 0<y<1$

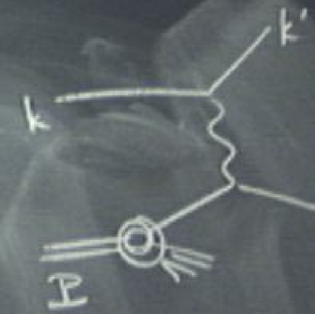

SLAC
e⁻
17 GeV
LiH
k
k'
q
P
q = k − k'
−q² = Q²
y = 2P·q / 2P·k
0 < y < 1
x = Q² / 2P·q
fcns.
fraction

SLAC

e^- ⟶ ● Li H

17 GeV





$q = k - k'$

$-q^2 = Q^2$ $\qquad y = \dfrac{2P\cdot q}{2P\cdot k} = \dfrac{\text{mm transfer to p from } e^-}{\text{tot mm } e^-}$ $\qquad 0<y<1$

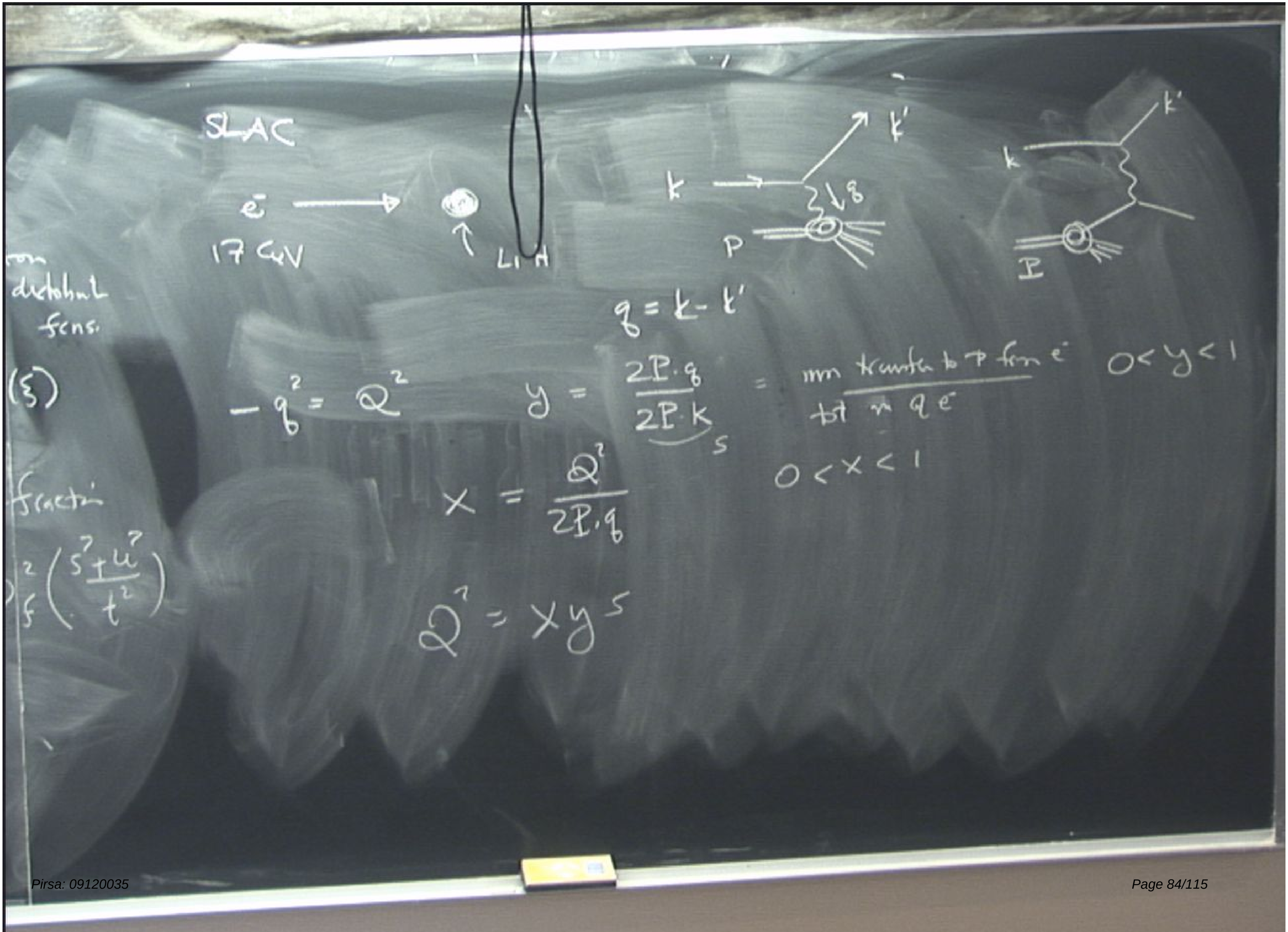
$x = \dfrac{Q^2}{2P\cdot q}$ $\qquad 0<x<1$

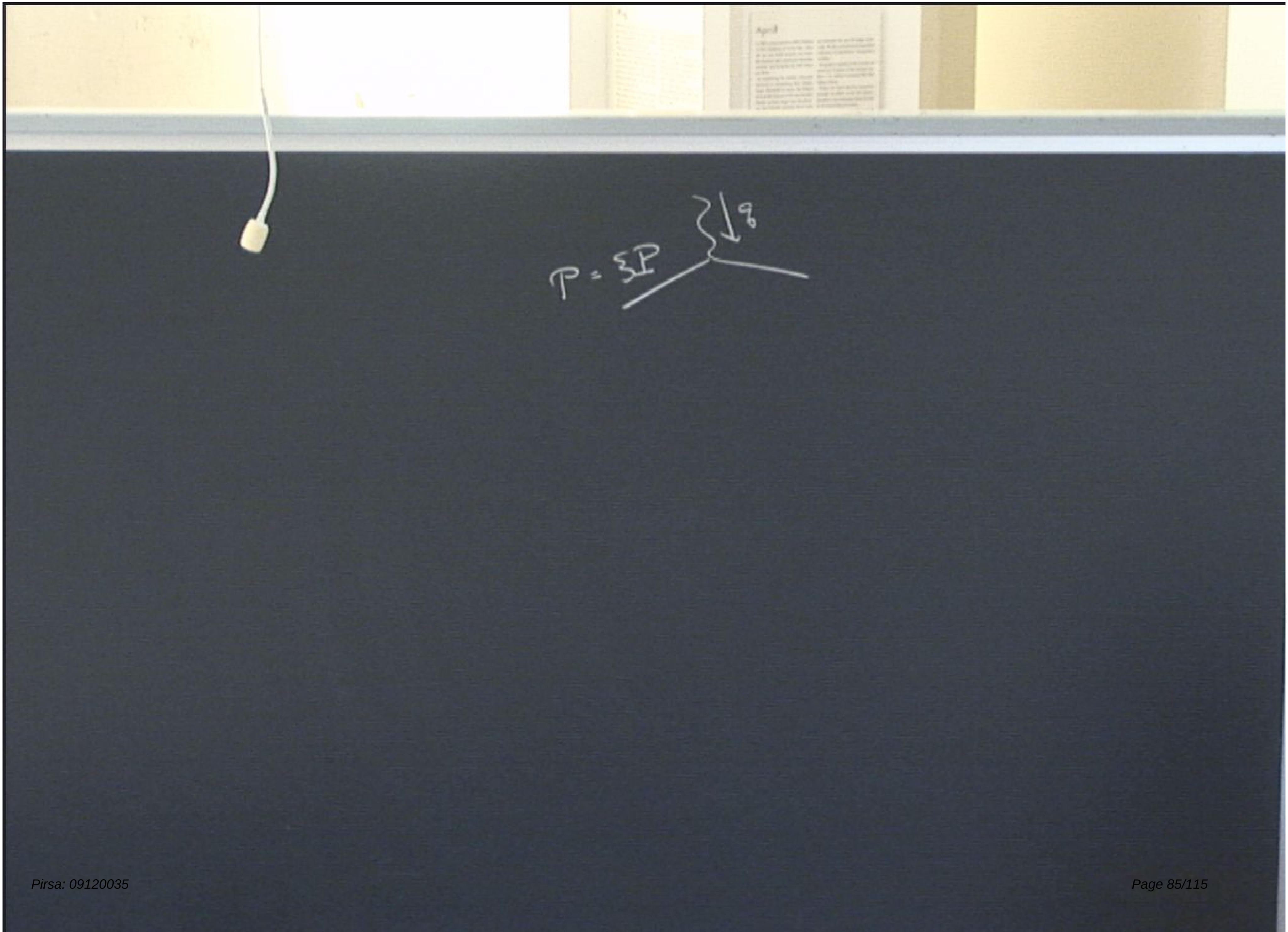
dist. fcns.

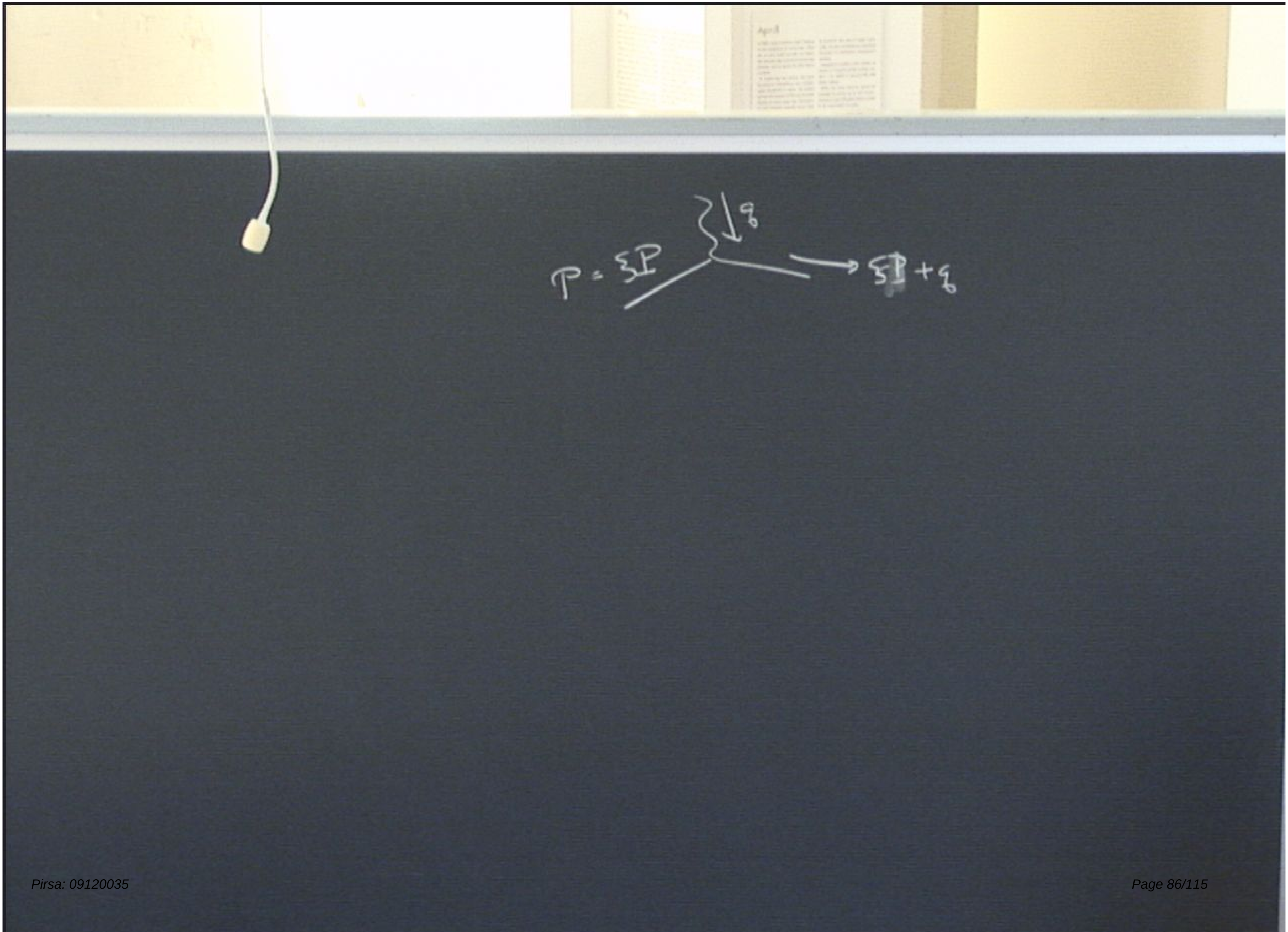
(ξ)

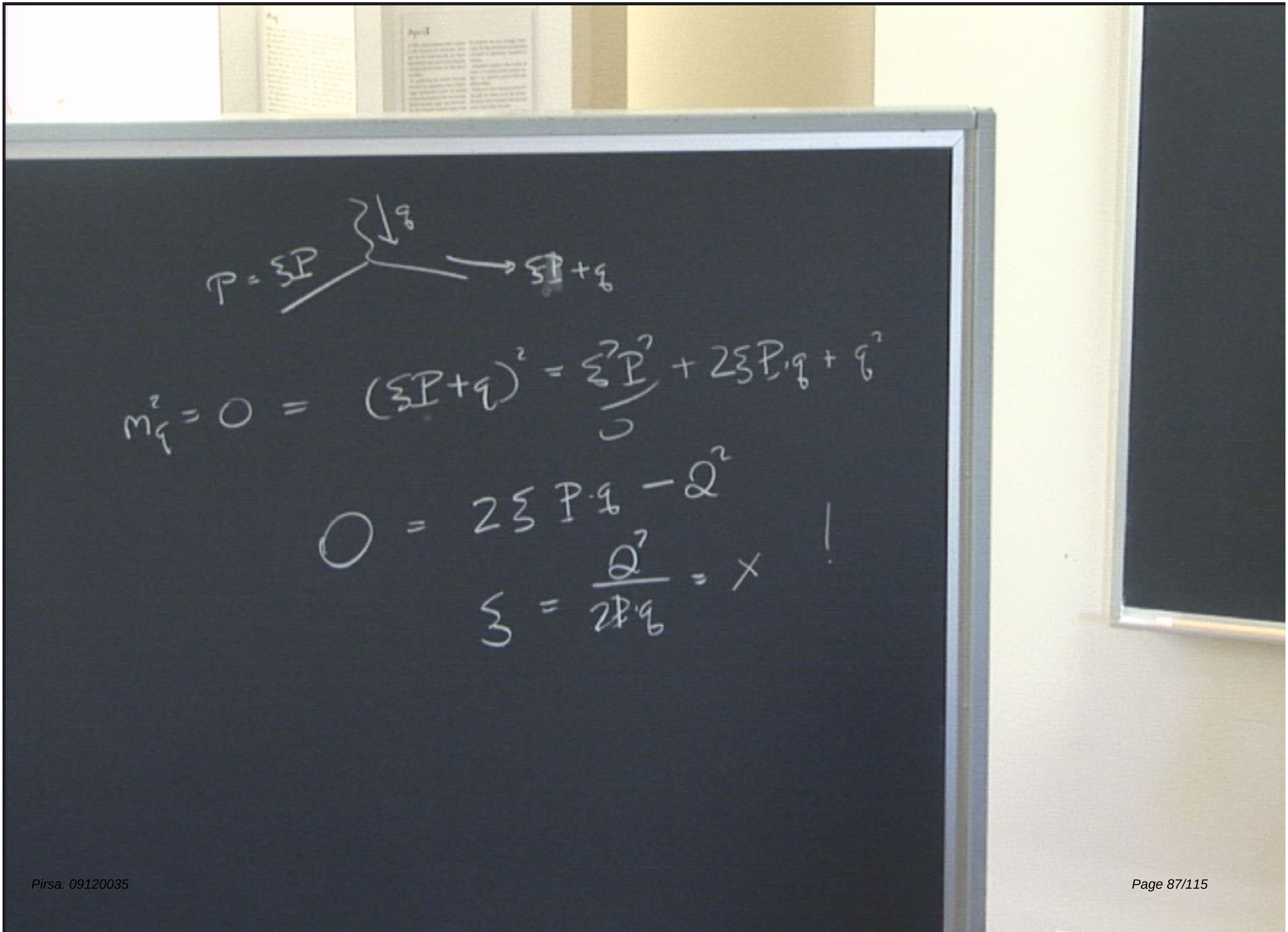
fraction

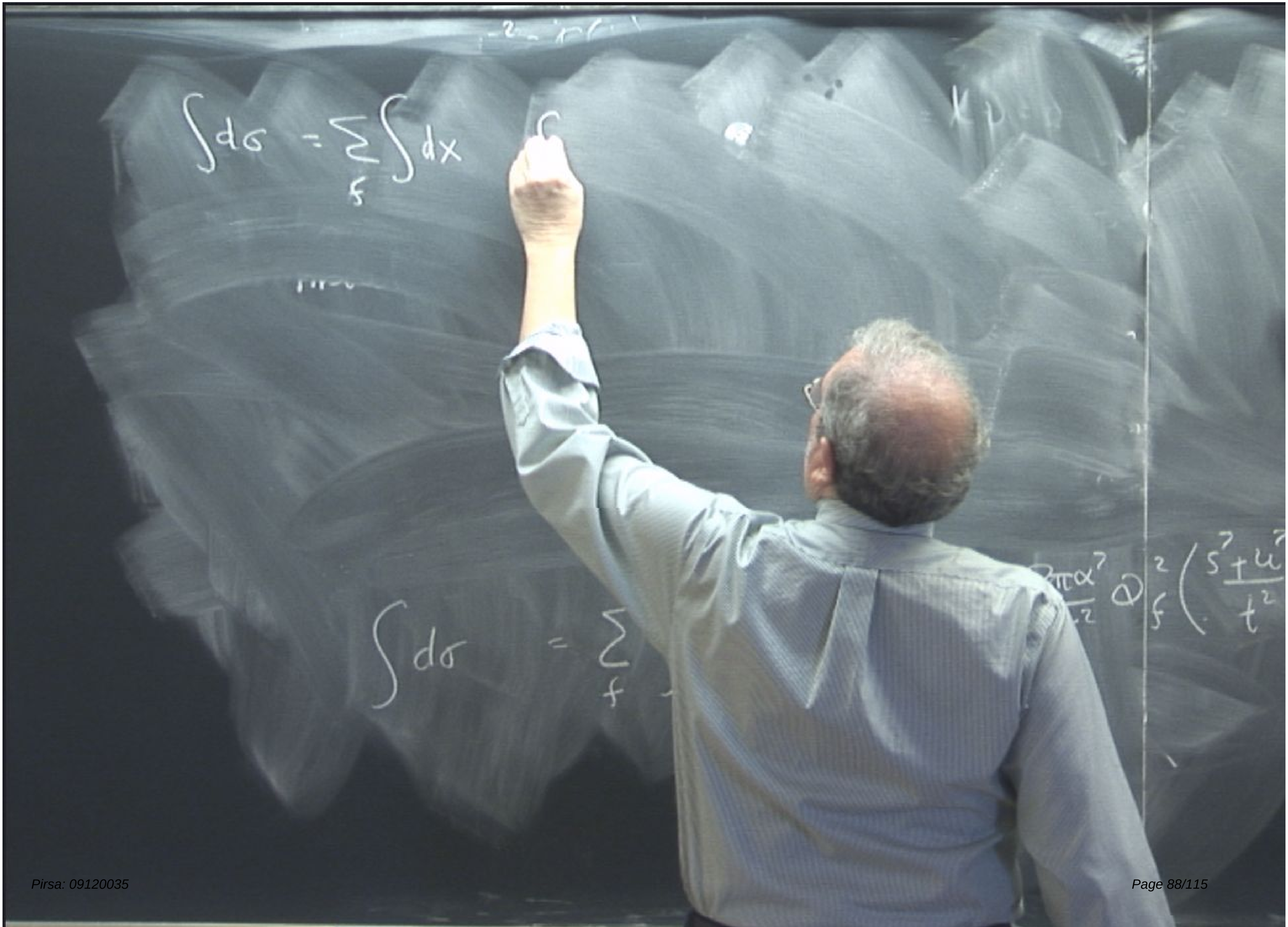
$\left(\dfrac{s^2+u^2}{t^2}\right)$


SLAC
e⁻
17 GeV
k
k'
q
P
q = k − k'
− q² = Q²
y = 2P·q / 2P·k
0 < y < 1
s
0 < x < 1
x = Q² / 2P·q
Q² = xys

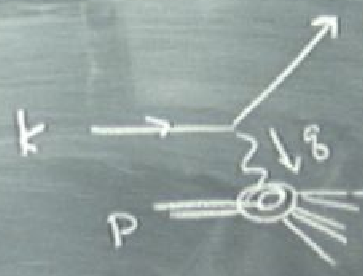

P = ξP
q

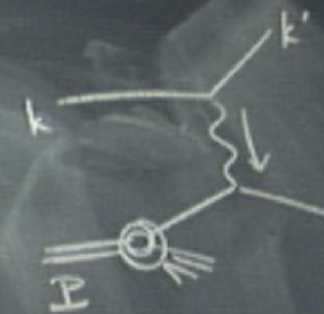

P = ξP
q
ξP + q


$P = \xi P$
q
$\xi P + q$
$m_q^2 = 0 = (\xi P + q)^2 = \xi^2 P^2 + 2\xi P \cdot q + q^2$
$0 = 2\xi P \cdot q - Q^2$
$\xi = \frac{Q^2}{2P \cdot q} = x$!


∫dσ = Σ_f ∫dx
∫dσ = Σ_f

SLAC





$$q = k - k'$$

$$-q^2 = Q^2 \qquad y = \frac{2P\cdot q}{2P\cdot k} = \frac{\text{mom transfer to P from } e^-}{\text{tot mom of } e^-} \qquad 0 < y < 1$$

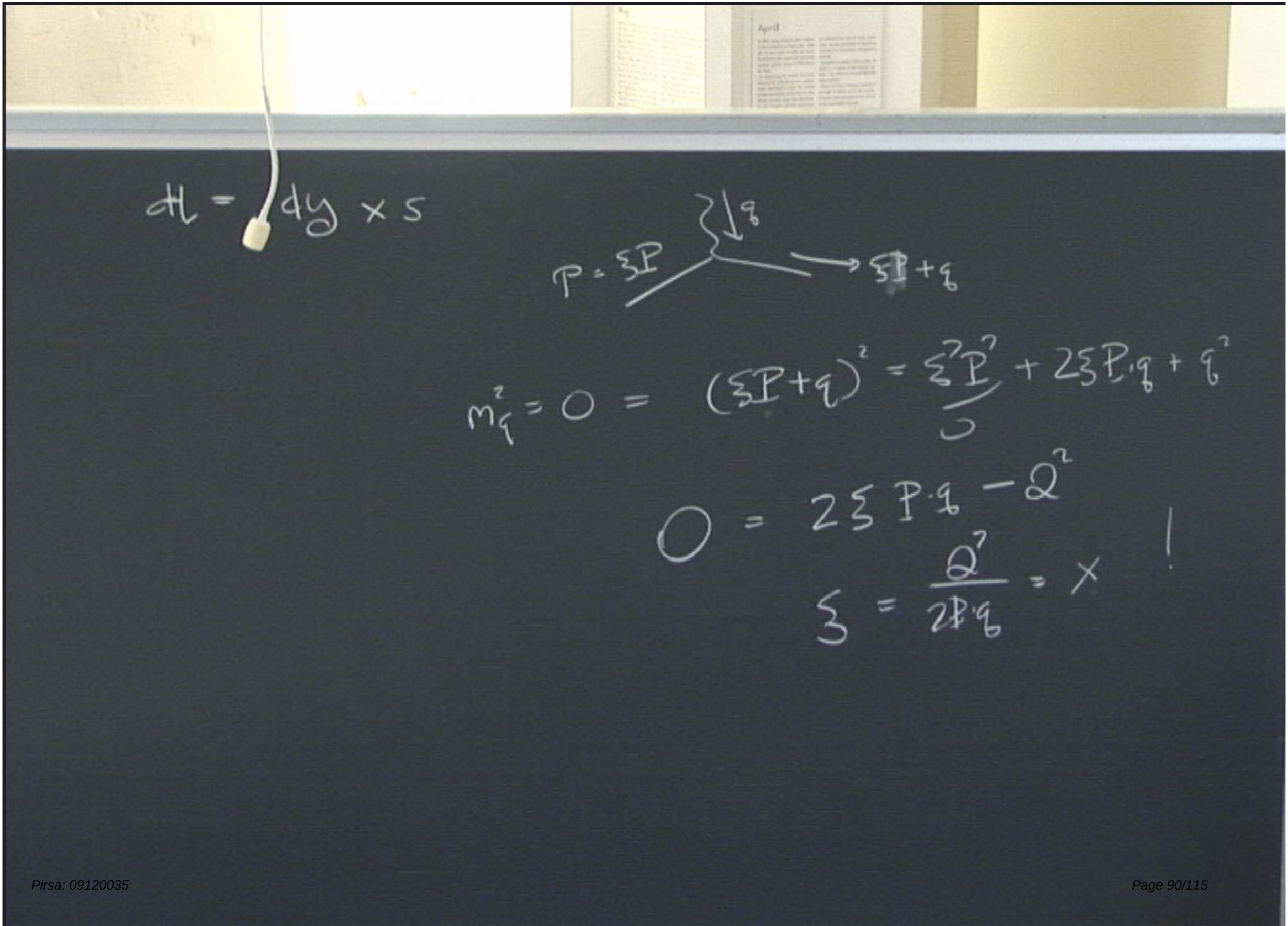
($2P\cdot k = s$)

$$x = \frac{Q^2}{2P\cdot q} \qquad 0 < x < 1$$

$$t = Q^2$$

$$f^2\left(\frac{s^2+u^2}{t^2}\right)$$

$$Q^2 = xys$$


dt = dy × 5
q
P = ξP
ξP + q
m_q^2 = 0 = (ξP+q)^2 = ξ^2P^2 + 2ξP·q + q^2
0
0 = 2ξ P·q − Q^2
ξ = Q^2 / 2P·q = x !

$$= \sum_f \int dx \quad f_f(x) \quad \int dy \times S$$

SLAC

e^- ⟶ ●

17 GeV

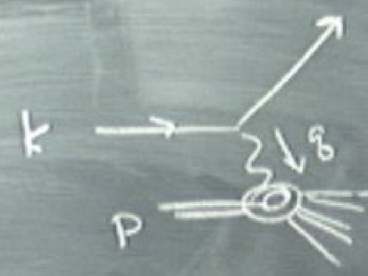
$$-q^2 = Q^2$$

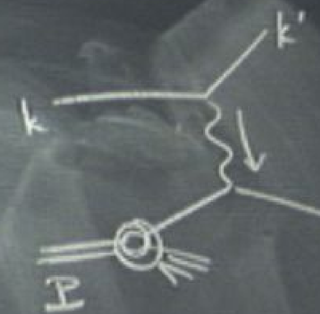
$$x =$$

$$\int d\sigma = \sum_f \int d\xi \quad f_f(\xi) \int dt \quad \frac{2\pi\alpha^2}{\hat{s}^2} Q_f^2 \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \right)$$

$$Q^2 =$$

SLAC





$$q = k - k'$$

$$-q^2 = Q^2 \qquad y = \frac{2P\cdot q}{2P\cdot k} = \frac{\text{mom transfer to p from } e^-}{\text{tot m q } e^-} \qquad 0 < y < 1$$

($2P\cdot k = s$)

$$x = \frac{Q^2}{2P\cdot q} \qquad 0 < x < 1$$

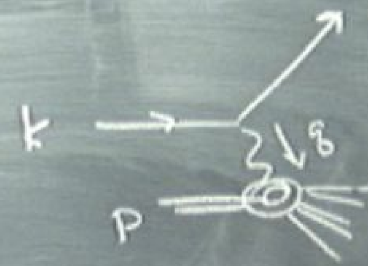
$$\hat{t} = Q^2 = xys$$

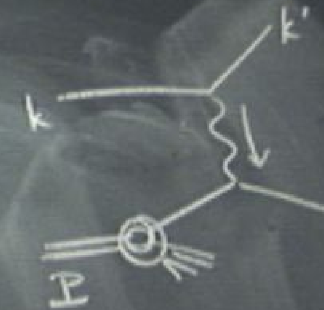
$$\hat{s} =$$

$$Q^2 = xys$$

$$f^2\left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}\right)$$

SLAC





$$q = k - k'$$

$$-q^2 = Q^2 \qquad y = \frac{2P\cdot q}{2P\cdot k} = \frac{\text{mom transfer to p from } e^-}{\text{tot mom of } e^-} \qquad 0 < y < 1$$

$$2P\cdot k = s$$

$$x = \frac{Q^2}{2P\cdot q} \qquad 0 < x < 1$$

$$\hat{t} = Q^2 = xys$$

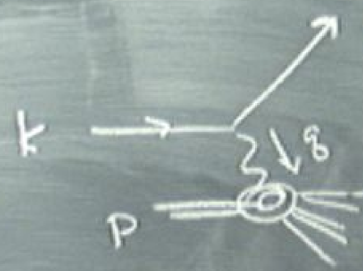
$$\hat{s} = 2p\cdot k = \xi s = xs$$

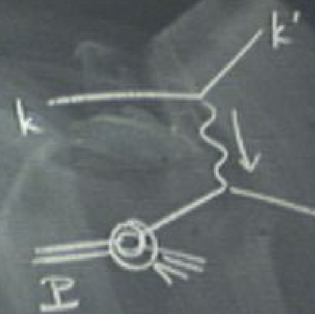
$$Q^2 = xys$$

$$\hat{u} =$$

$$\left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}\right)$$

SLAC





$q = k - k'$

$-q^2 = Q^2$ $\qquad y = \frac{2P\cdot q}{2P\cdot k}$ ($2P\cdot k = s$) $=$ mom transfer to p from e^- / tot mom of e^- $\qquad 0 < y < 1$

$x = \frac{Q^2}{2P\cdot q}$ $\qquad 0 < x < 1$

$Q^2 = xys$

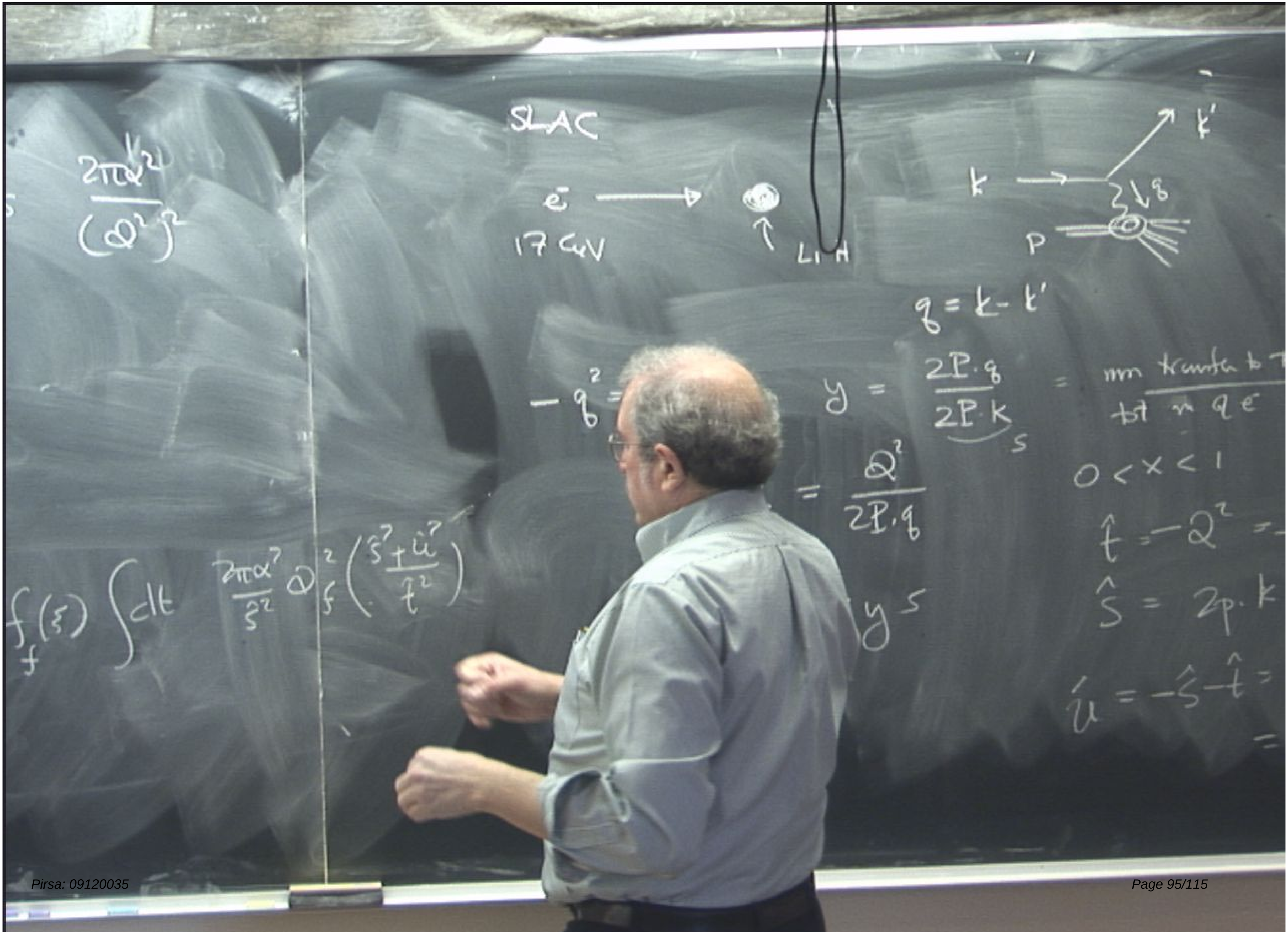
$\hat{t} = -Q^2 = -xys$

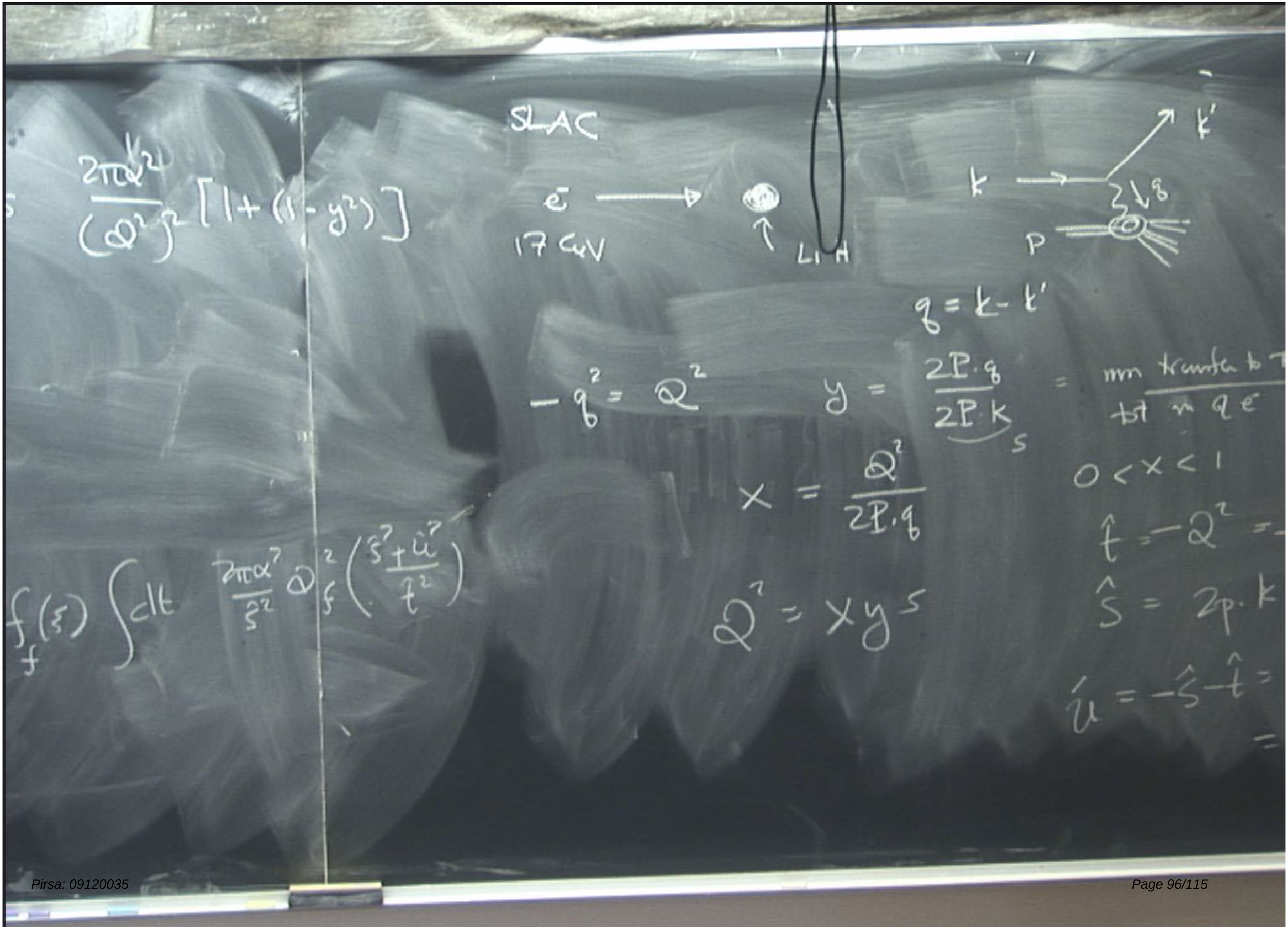
$\hat{s} = 2p\cdot k = \xi s = xs$

$\hat{u} = -\hat{s} - \hat{t} = -(xs - xys)$

$= xs(1-y)$

$f^2\left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}\right)$


SLAC
e⁻
17 GeV
LiH
k
k'
q
P
q = k − k'
y = 2P·q / 2P·k
0 < x < 1


SLAC
e⁻
17 GeV
LiH
k
k'
q
P
q = k − k'
−q² = Q²
y = 2P·q / 2P·k
0 < x < 1
x = Q² / 2P·q
Q² = xys
ŝ = 2p·k

$$\int d\sigma = \sum_f \int dx \quad f_f(x) \int dy \times s \quad \frac{2\pi\alpha^2}{(Q^2)^2} \left[1 + (1 - \right.$$

$$\frac{d\sigma}{dx\,dy}$$

$$\int d\sigma = \sum_f \int d\xi \quad f_f(\xi) \int dt \quad \frac{2\pi\alpha^2}{\hat{s}^2} Q_f^2$$

$$\int d\sigma = \sum_f \int dx \; f_f(x) \int dy \times s \; \frac{2\pi\alpha^2}{(Q^2)^2} \left[1 + (1-y)^2 \right]$$

$$\frac{d\sigma}{dx\,dy} = \left[\sum_f Q_f^2 \, x \, f_f(x) \right] \left[\frac{2\pi\alpha^2 s}{Q^2} \left[1 + (1-y)^2 \right] \right]$$

$$\int d\sigma = \sum_f \int d\xi \; f_f(\xi) \int dt \; \frac{2\pi\alpha^2}{\hat{s}^2} Q_f^2 \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \right)$$

$$\int d\sigma = \sum_f \int dx \; f_f(x) \int dy \times s \; \frac{2\pi\alpha^2}{(Q^2)^2} \left[1 + (1-y^2)\right]$$

$$\frac{d\sigma}{dx\,dy} = \underbrace{\left[\sum_f Q_f^2 \, x \, f_f(x)\right]}_{F_2(x,Q^2)} \left[\frac{2\pi\alpha^2 s}{Q^2}\left[1 + (1-y^2)\right]\right]$$

$$\int d\sigma = \sum_f \int d\xi \; f_f(\xi) \int dt \; \frac{2\pi\alpha^2}{\hat{s}^2} Q_f^2 \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}\right)$$

$$\int d\sigma = \sum_f \int dx \; f_f(x) \int dy \times s \; \frac{2\pi\alpha^2}{(Q^2)^2} \left[1 + (1 - y^2) \right]$$

SLAC

e^-

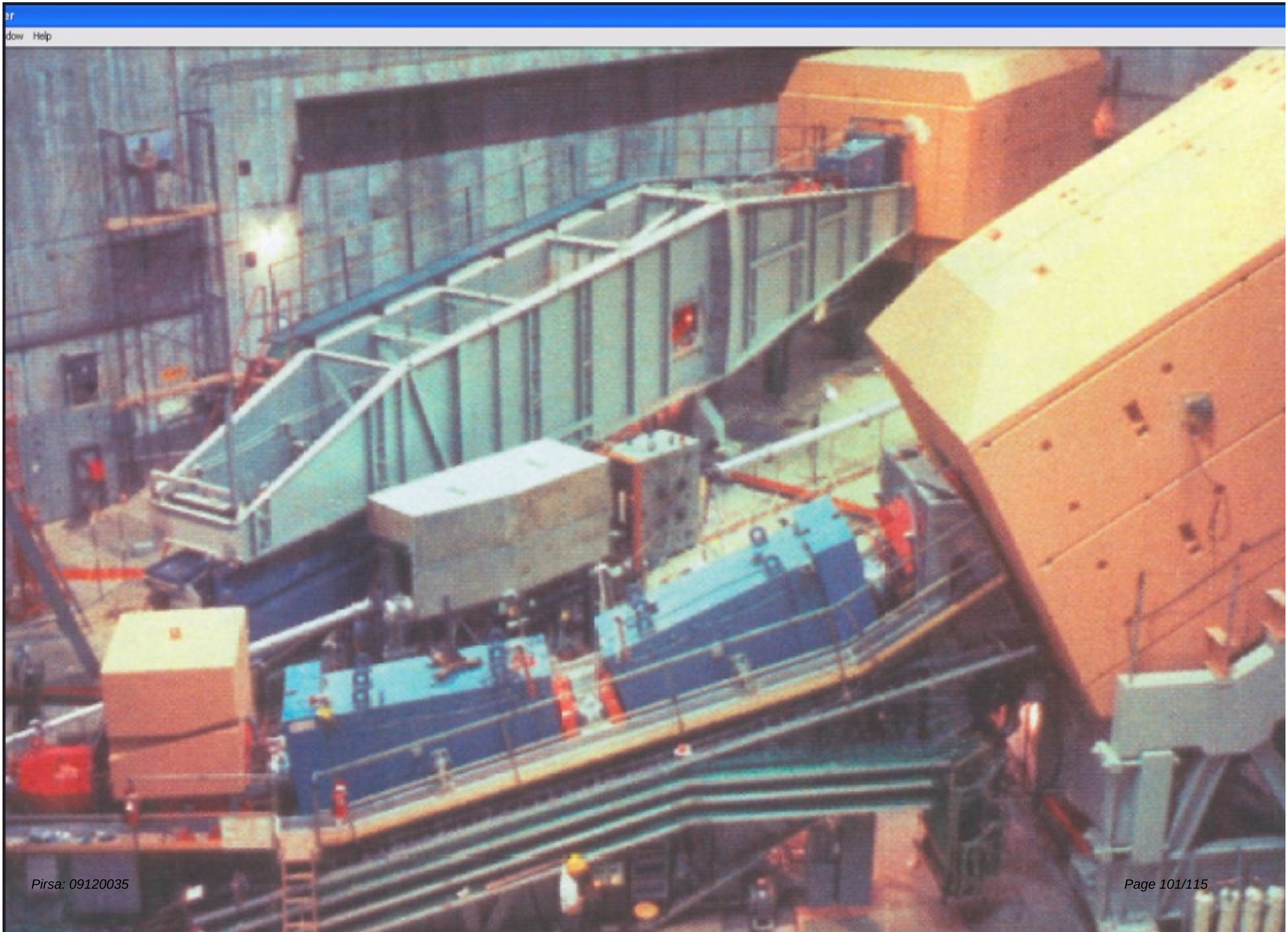
17 ...

$$\frac{d\sigma}{dx\,dy} = \left[\sum_f Q_f^2 \, x f_f(x) \right] \left[\frac{2\pi\alpha^2 s}{Q^2} \left[1 + (1 - y^2) \right] \right]$$

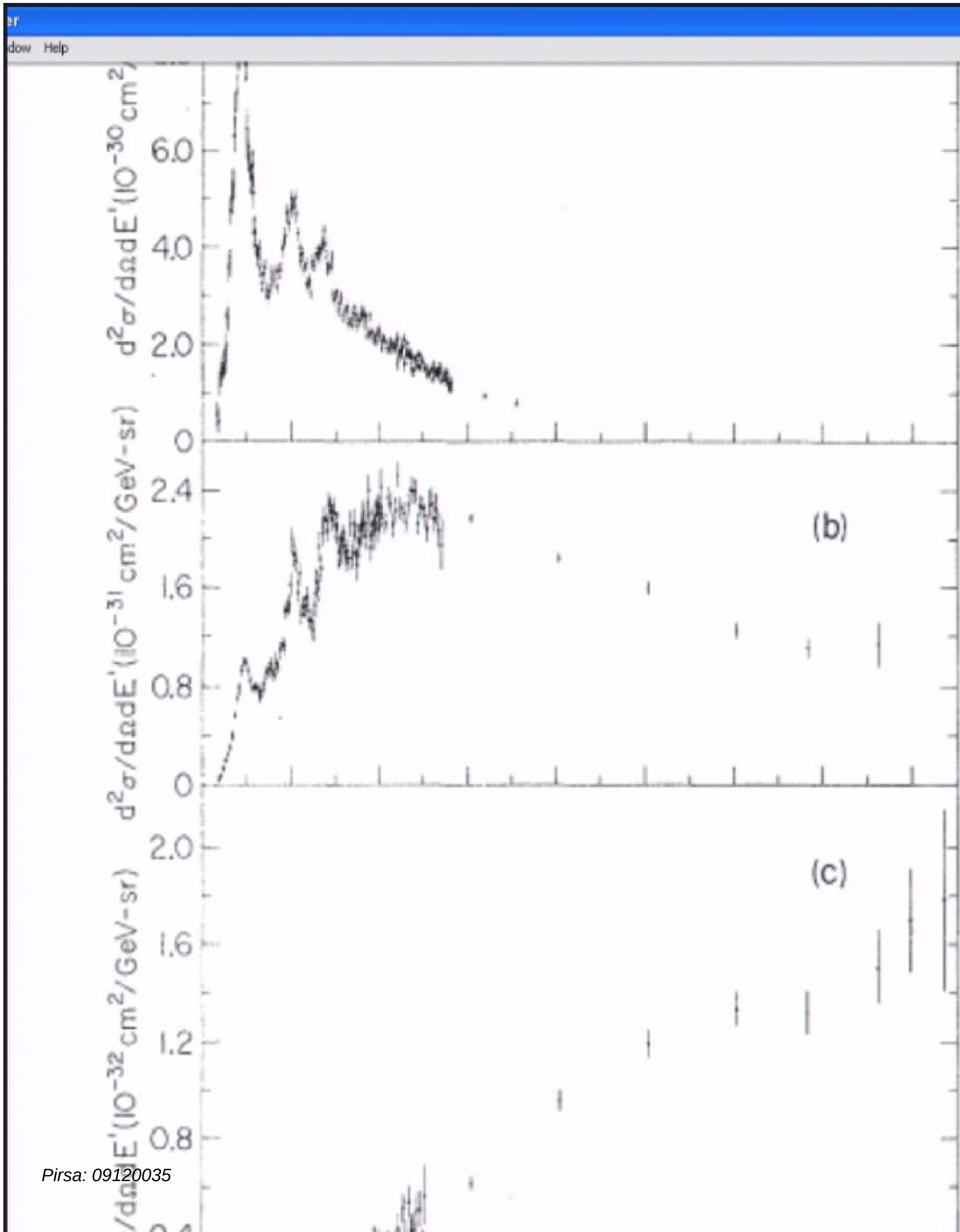
$F_2(x, Q^2)$

Bjorken scaling

$$\int d\sigma = \sum_f \int d\xi \; f_f(\xi) \int dt \; \frac{2\pi\alpha^2}{\hat{s}^2} Q_f^2 \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \right)$$


dow Help

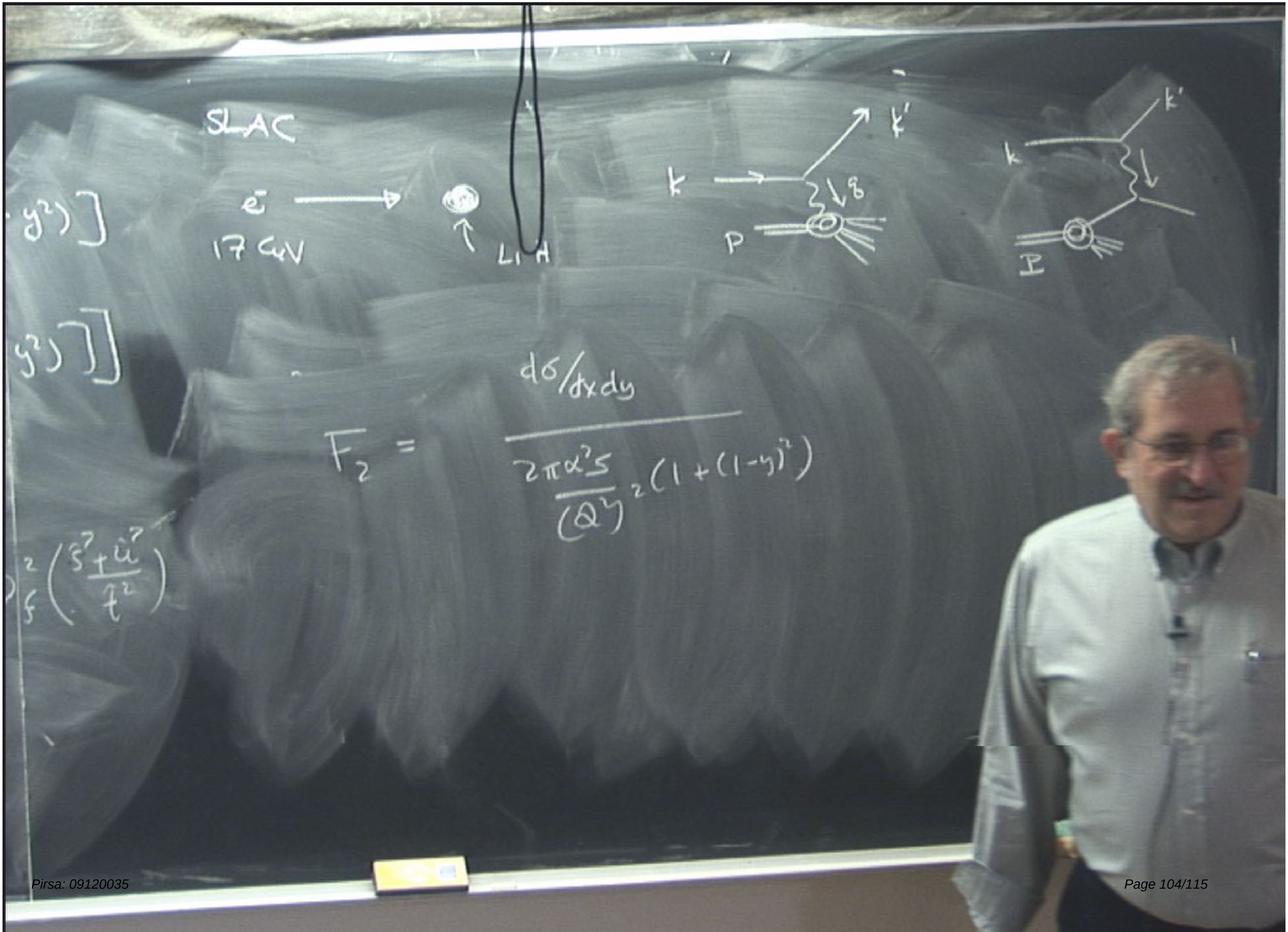

dow Help



$$\theta = 6^\circ,\ E = 7\ \text{GeV}$$

$$\theta = 6^\circ,\ E = 16\ \text{GeV}$$

$$\theta = 10^\circ,\ E = 17.7\ \text{G}$$

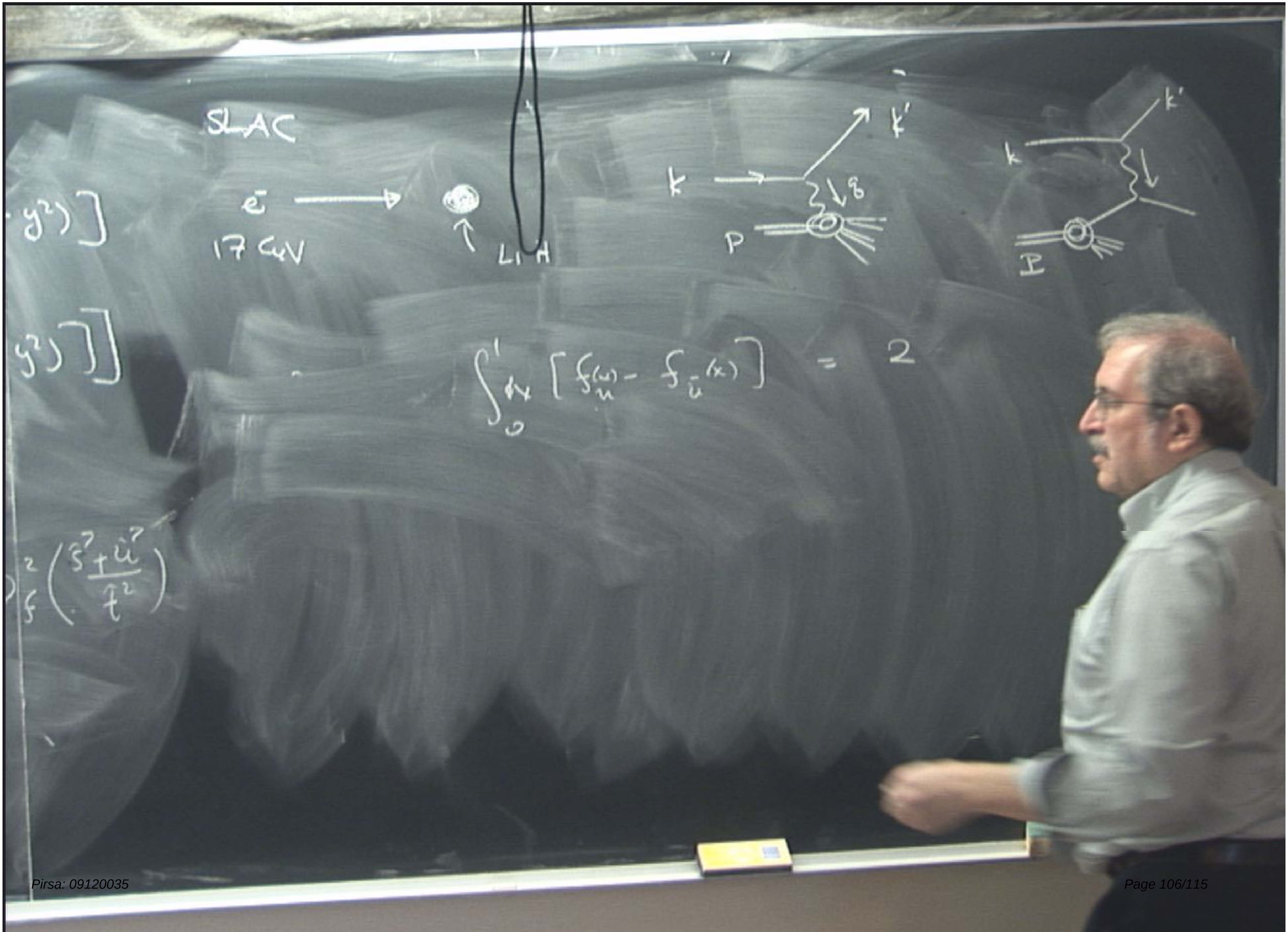

SLAC
e⁻
17 GeV
LiH
k
k'
p
F₂ = dσ/dx dy / (2πα²s/(Q²)² (1+(1−y)²))

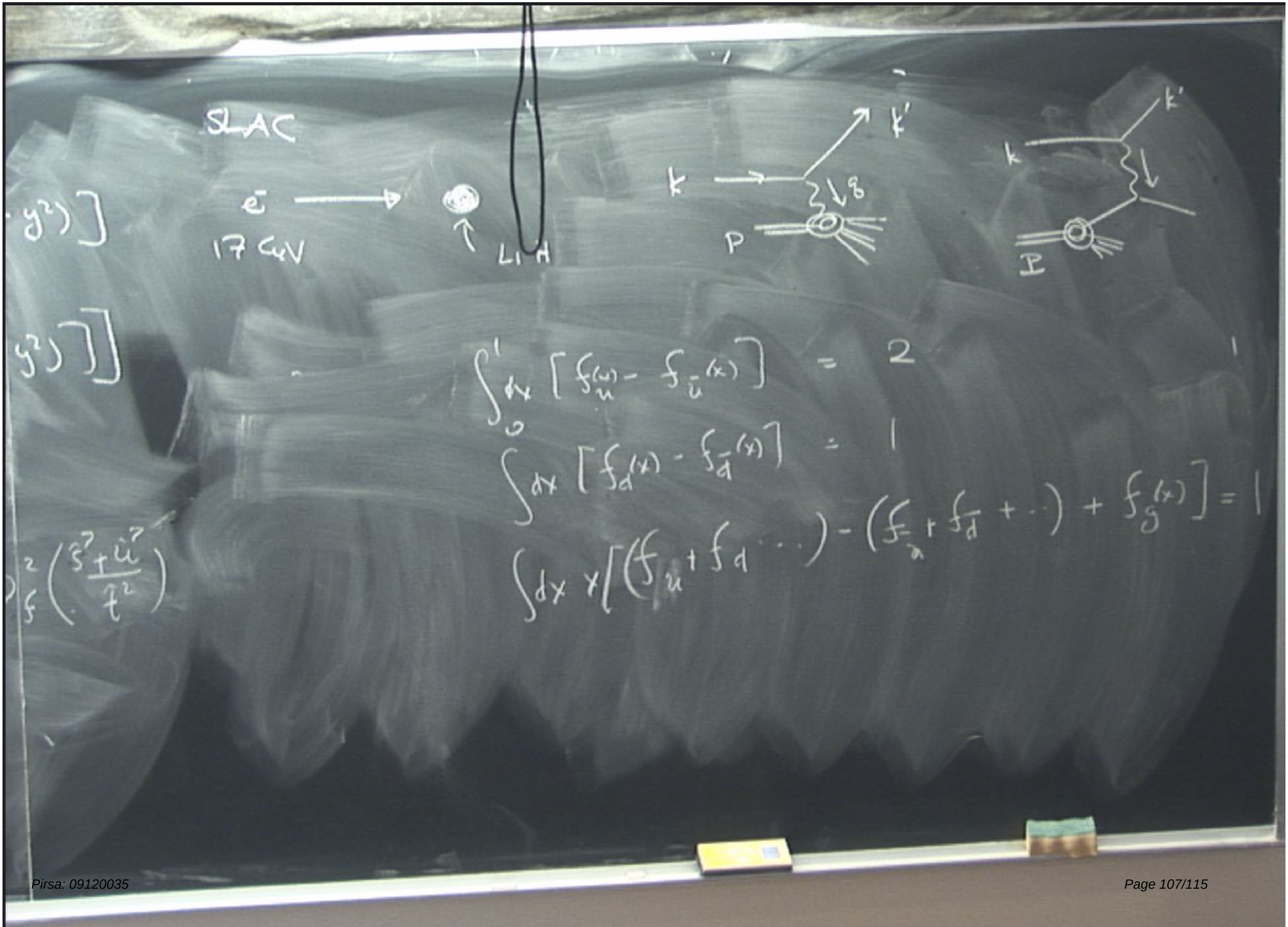
$$\int d\sigma = \sum_f \int dx \; f_f(x) \int dy \; x\, s \; \frac{2\pi\alpha^2}{(Q^2)^2}\left[1+(1-\ldots\right.$$

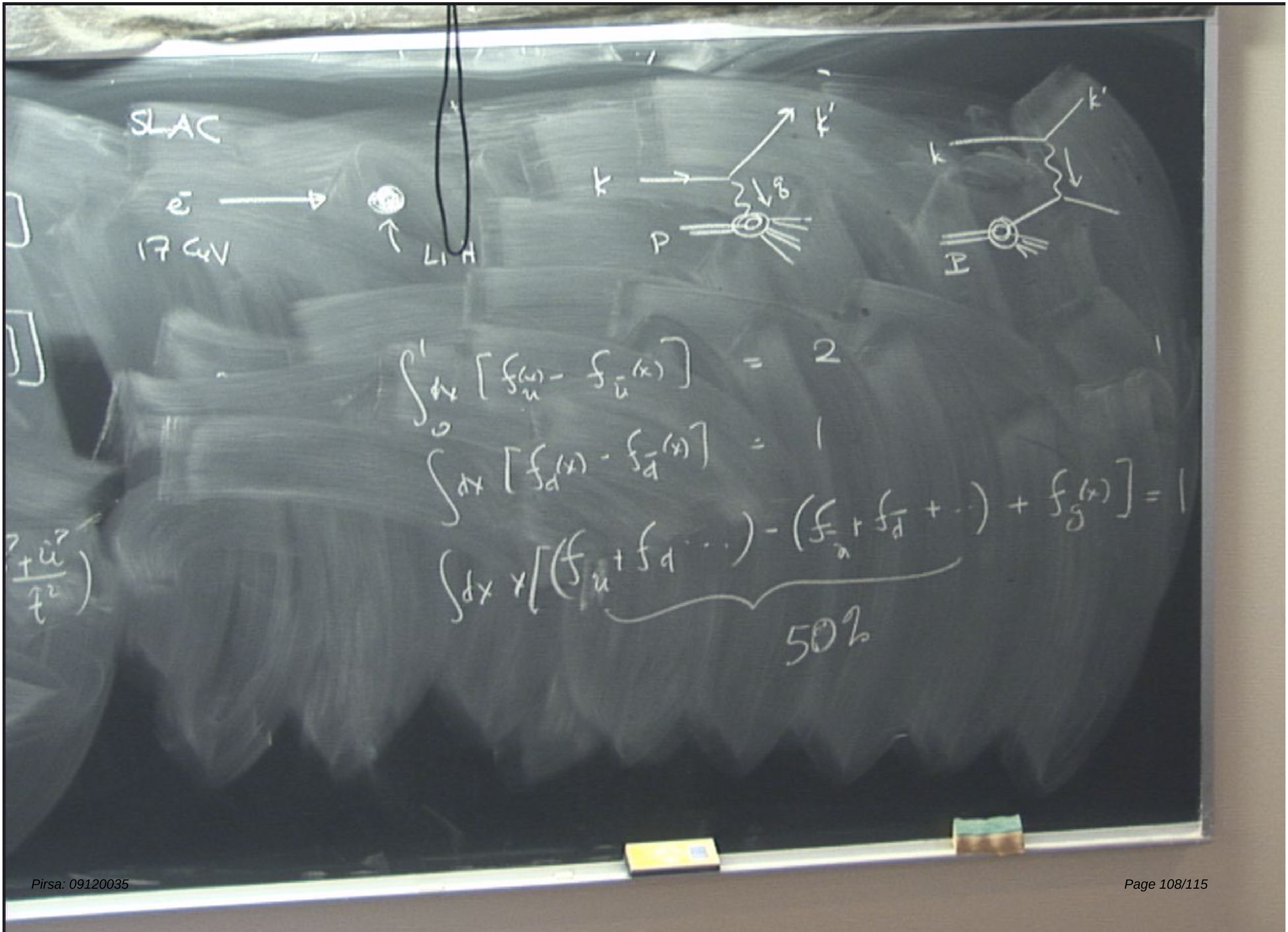
$$\frac{d\sigma}{dx\,dy} = \Big[\underbrace{\sum_{f=q,\bar{q}} Q_f^2 \, x \, f_f(x)}_{F_2(x,\,\not{Q^2})}\Big]\Big[\frac{2\pi\alpha^2 s}{Q^2}\left[1+(1-\ldots\right.$$

Bjorken scaling

$$\int d\sigma = \sum_f \int d\xi \; f_f(\xi) \int dt \; \frac{2\pi\alpha^2}{\xi^2} Q_f^2 \ldots$$


SLAC
17 GeV
LiH
k
k'
P
2

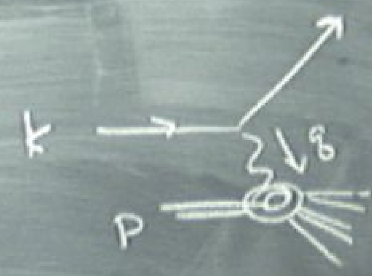

SLAC
e⁻
17 GeV
LiH
k
k'
P
q
$\int_0^1 dx\,[f_u(x) - f_{\bar{u}}(x)] = 2$
$\int dx\,[f_d(x) - f_{\bar{d}}(x)] = 1$
$\int dx\, x\,[(f_u + f_d \cdots) - (f_{\bar{u}} + f_{\bar{d}} + \cdots) + f_g(x)] = 1$

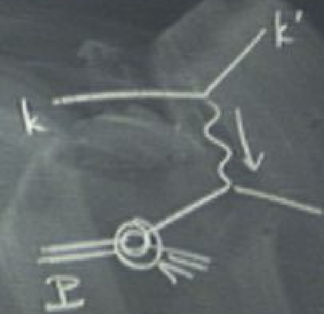

SLAC
e^-
17 GeV
LiH
k
k'
P
γ
$\int_0^1 dx\,[f_u(x) - f_{\bar{u}}(x)] = 2$
$\int dx\,[f_d(x) - f_{\bar{d}}(x)] = 1$
$\int dx\, x[(f_u + f_d \cdots) - (f_{\bar{u}} + f_{\bar{d}} + \cdots) + f_g(x)] = 1$
50%

SLAC

e^- ⟶ ● ← LiH

17 GeV





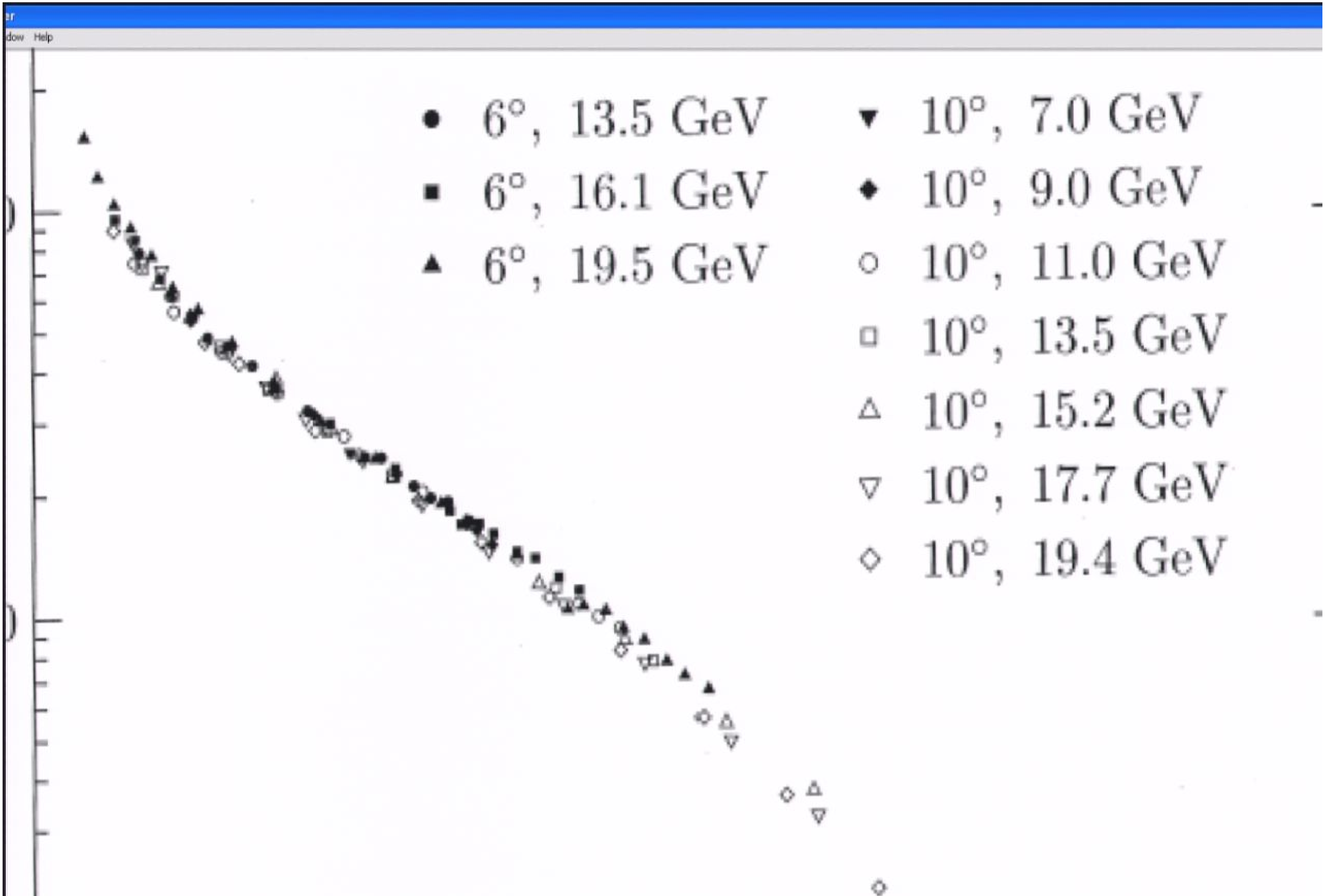
HERA

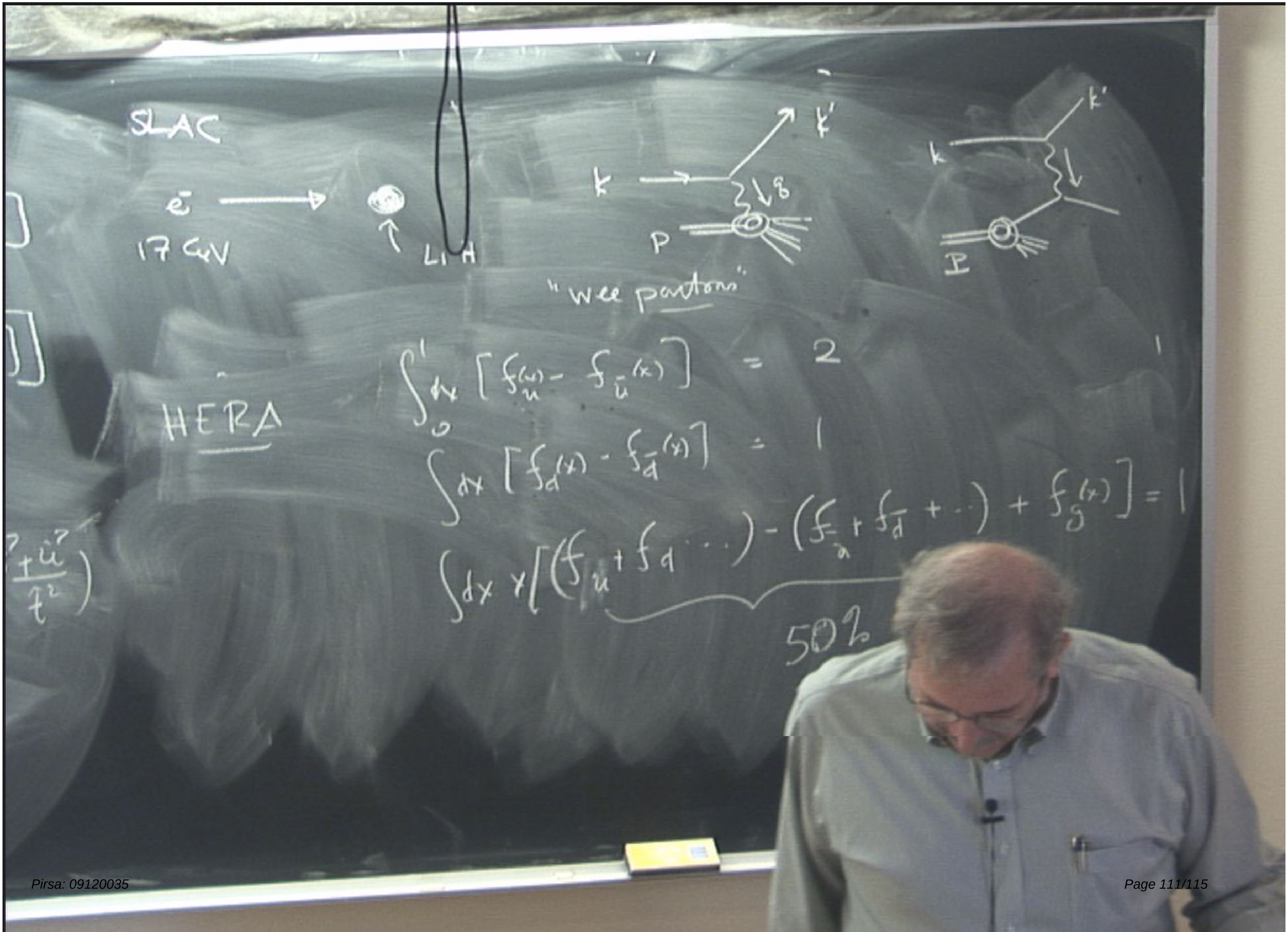
$$\int_0^1 dx\,[f_u(x) - f_{\bar u}(x)] = 2$$

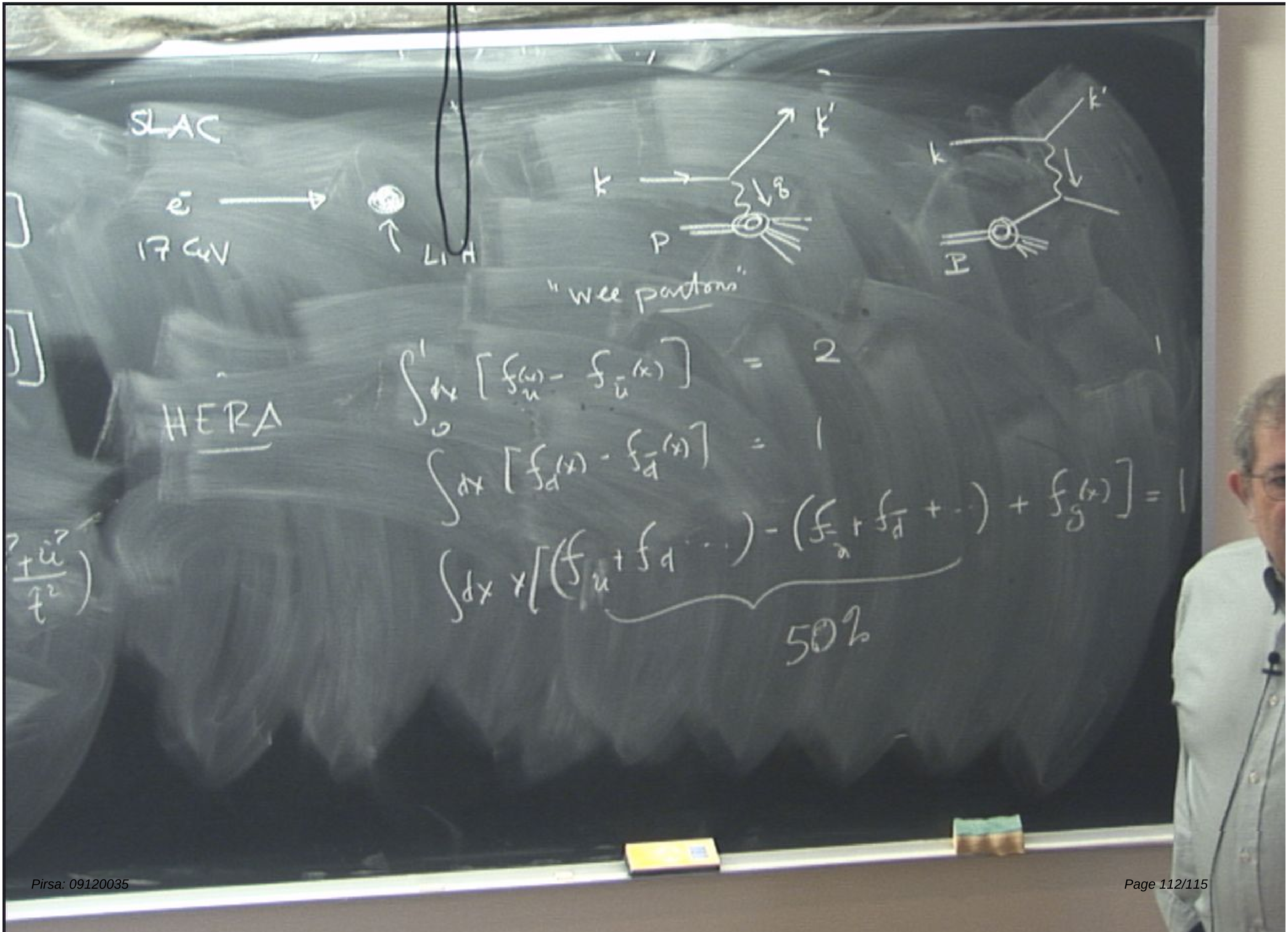
$$\int dx\,[f_d(x) - f_{\bar d}(x)] = 1$$

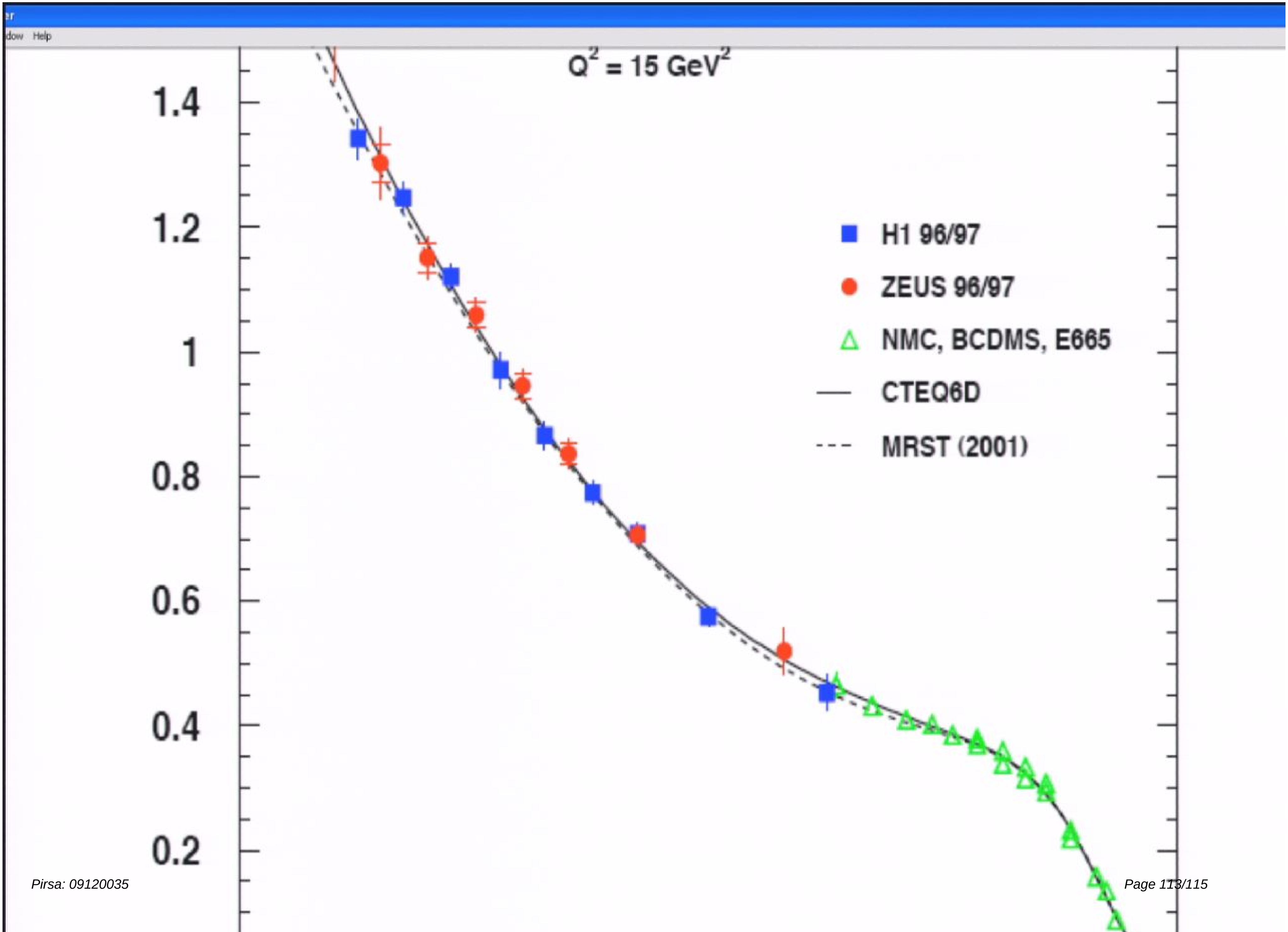
$$\int dx\, x\Big[\underbrace{(f_u + f_d \dots) - (f_{\bar u} + f_{\bar d} + \dots)}_{50\%} + f_g(x)\Big] = 1$$

$\frac{\dots + u^2}{t^2})$

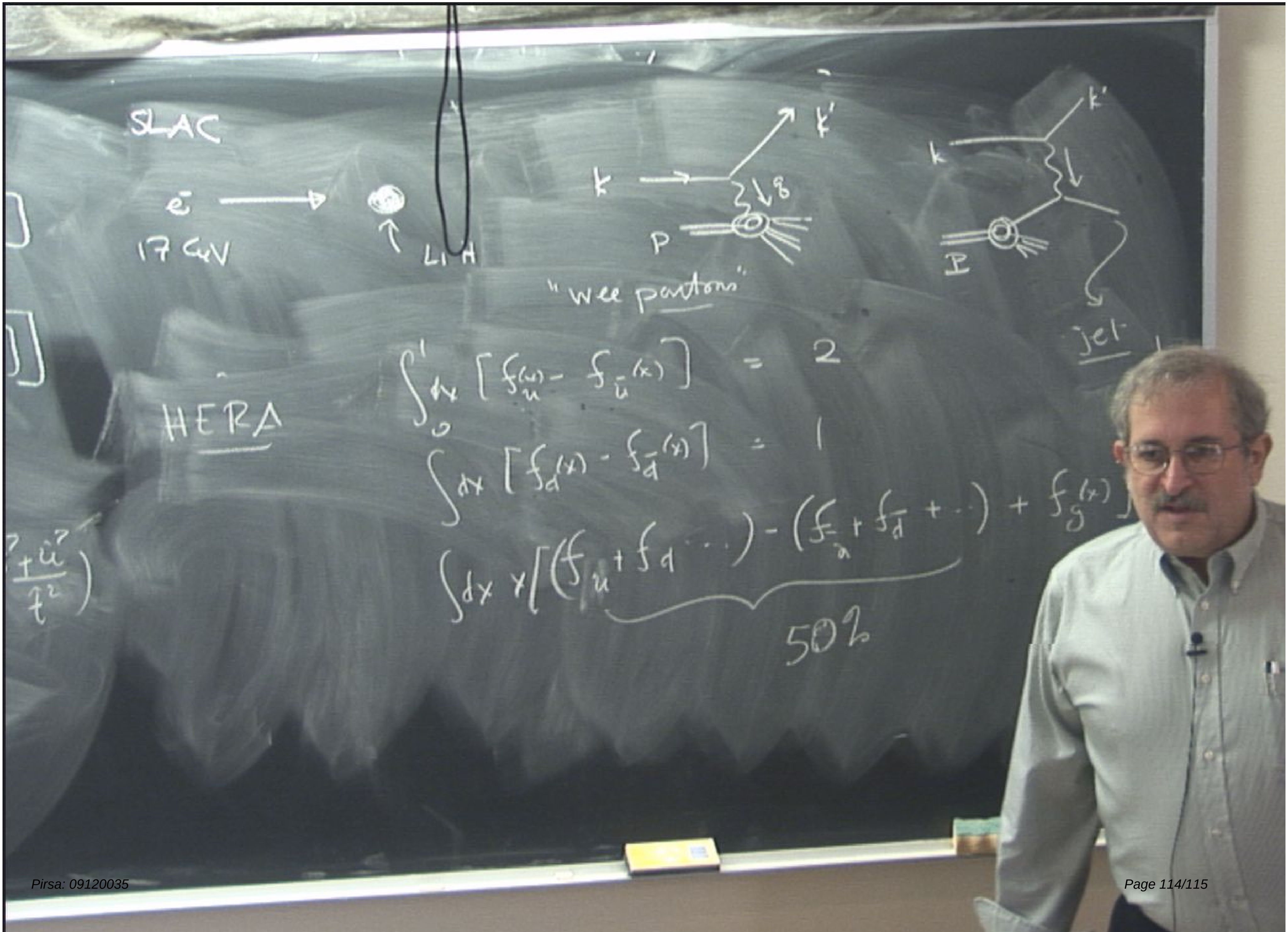

dow Help
● 6°, 13.5 GeV
■ 6°, 16.1 GeV
▲ 6°, 19.5 GeV
▼ 10°, 7.0 GeV
◆ 10°, 9.0 GeV
○ 10°, 11.0 GeV
□ 10°, 13.5 GeV
△ 10°, 15.2 GeV
▽ 10°, 17.7 GeV
◇ 10°, 19.4 GeV

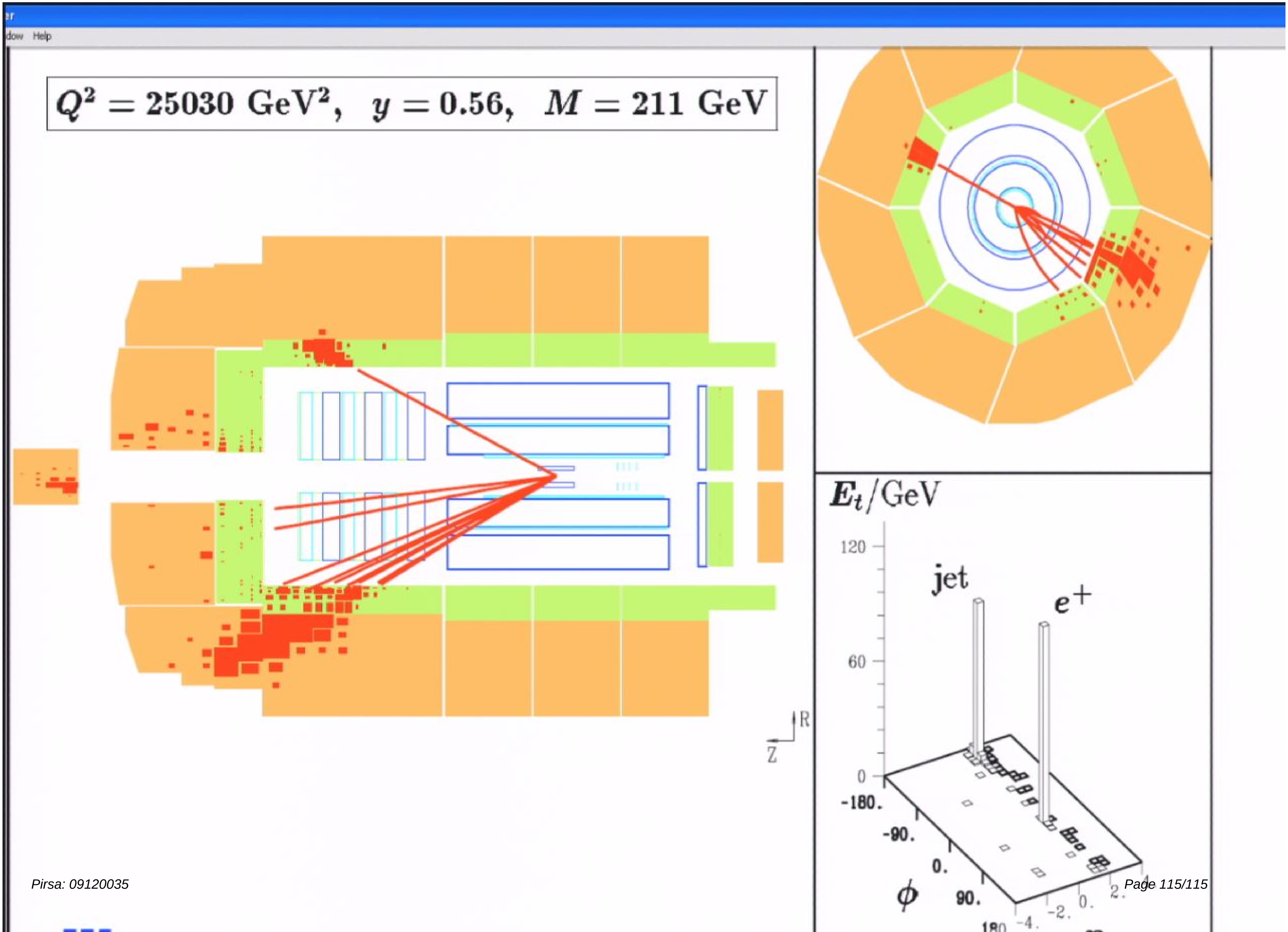

SLAC
e⁻
17 GeV
LiH
k
k'
p
P
"wee partons"
HERA
= 2
= 1
50%


SLAC
e⁻
17 GeV
LH
k
k'
P
"wee partons"
HERA
∫₀¹ dx [f_u(x) − f_ū(x)] = 2
∫ dx [f_d(x) − f_d̄(x)] = 1
∫ dx x [(f_u + f_d ...) − (f_ū + f_d̄ + ...) + f_g(x)] = 1
50%



Q^2 = 15 GeV^2
1.4
1.2
1
0.8
0.6
0.4
0.2
H1 96/97
ZEUS 96/97
NMC, BCDMS, E665
CTEQ6D
MRST (2001)


SLAC
e⁻
17 GeV
LiH
k
k'
P
"wee partons"
jet
HERA
∫₀¹ dx [f_u(x) − f_ū(x)] = 2
∫ dx [f_d(x) − f_d̄(x)] = 1
∫ dx x [(f_u + f_d …) − (f_ū + f_d̄ + …) + f_g(x)]
50%


dow Help
$Q^2 = 25030$ GeV^2, $y = 0.56$, $M = 211$ GeV
R
Z
E_t/GeV
120
60
0
jet
e^+
-180.
-90.
0.
90.
ϕ
-4.
-2.
0.
2.