Title: Leaving Behind N=4 SYM: Why are Three Loops Interesting?

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Abstract:

Leaving behind N=4 SYM: why are three loops interesting?

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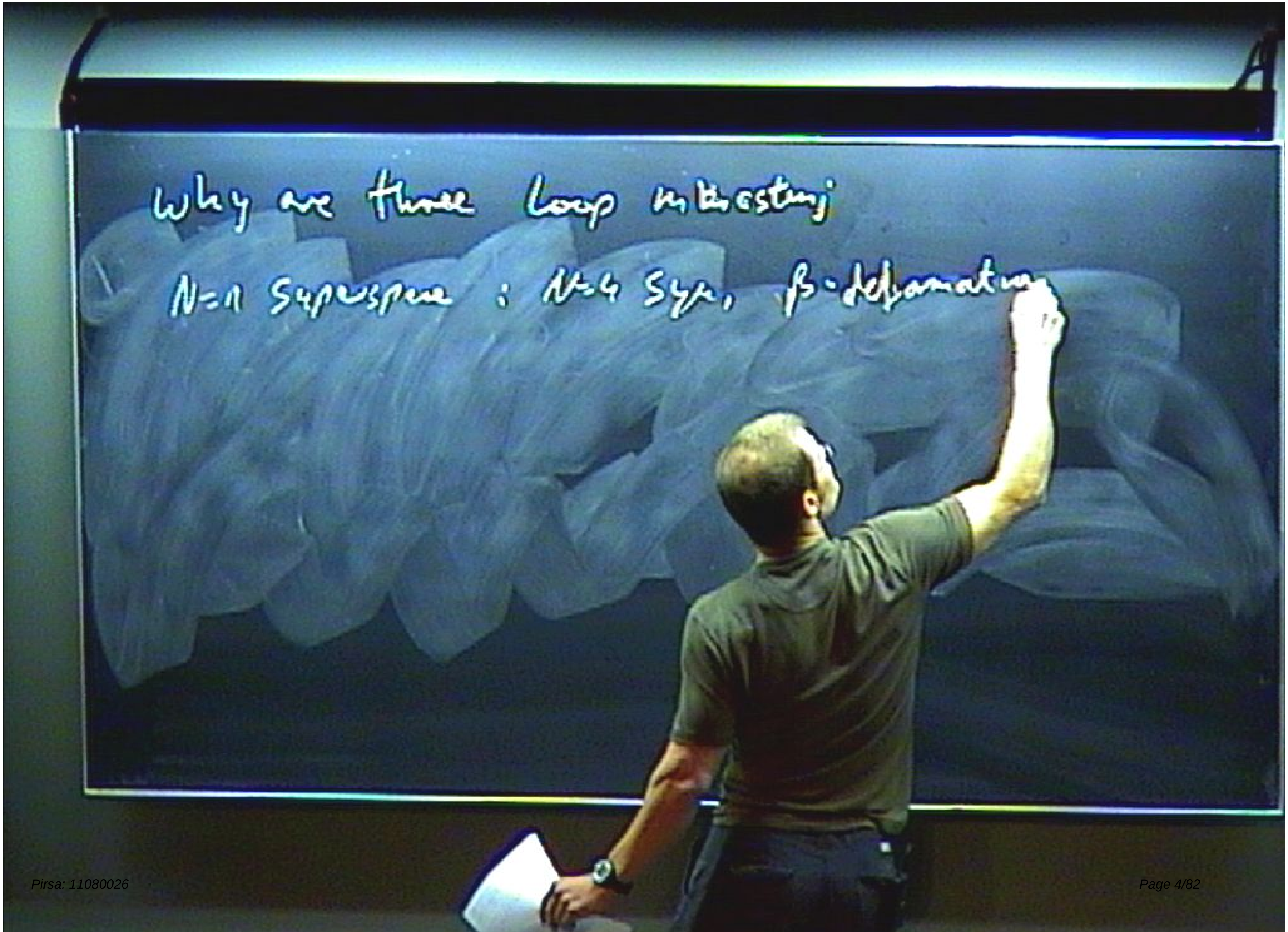
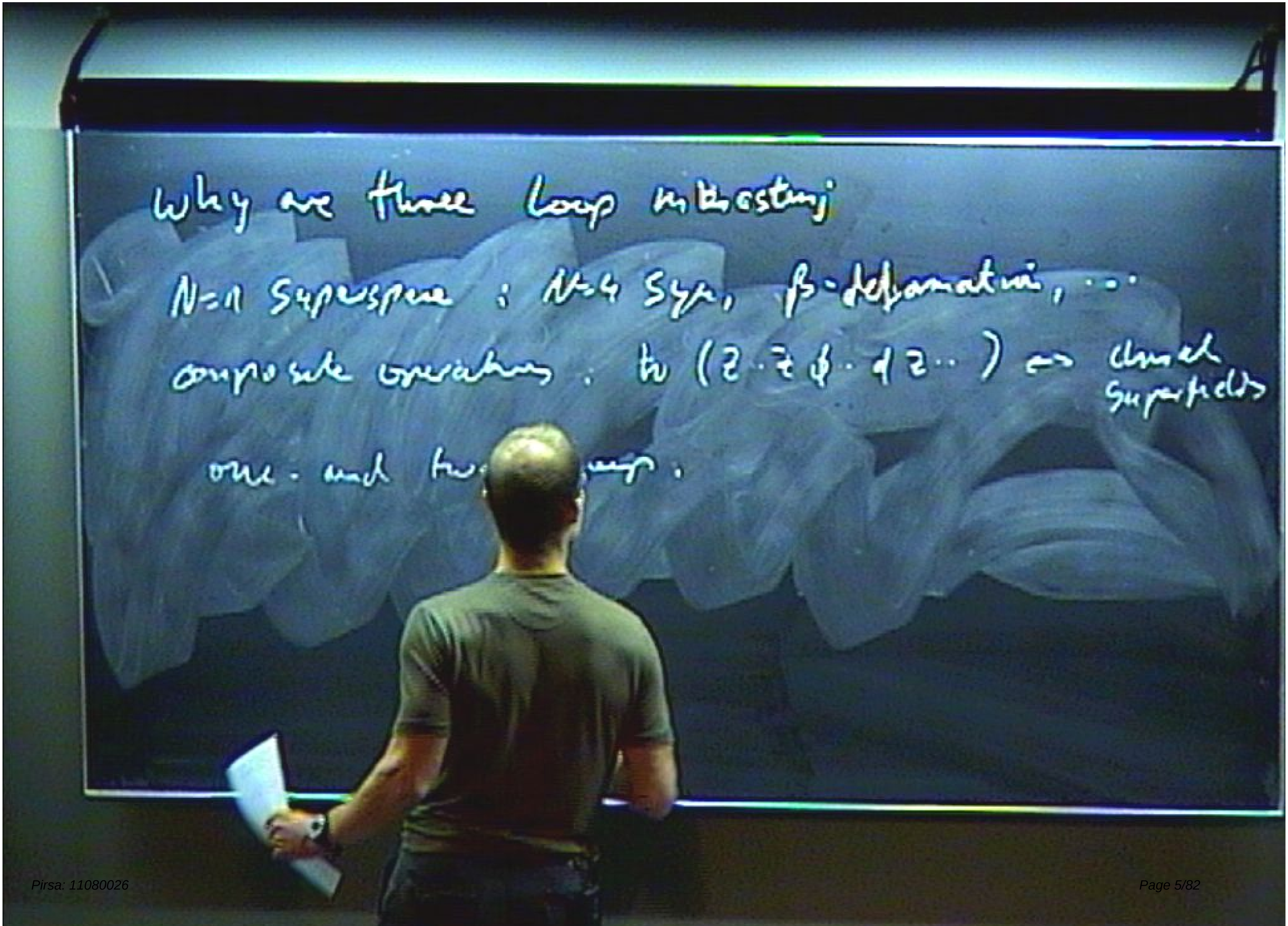
Humboldt University of Berlin

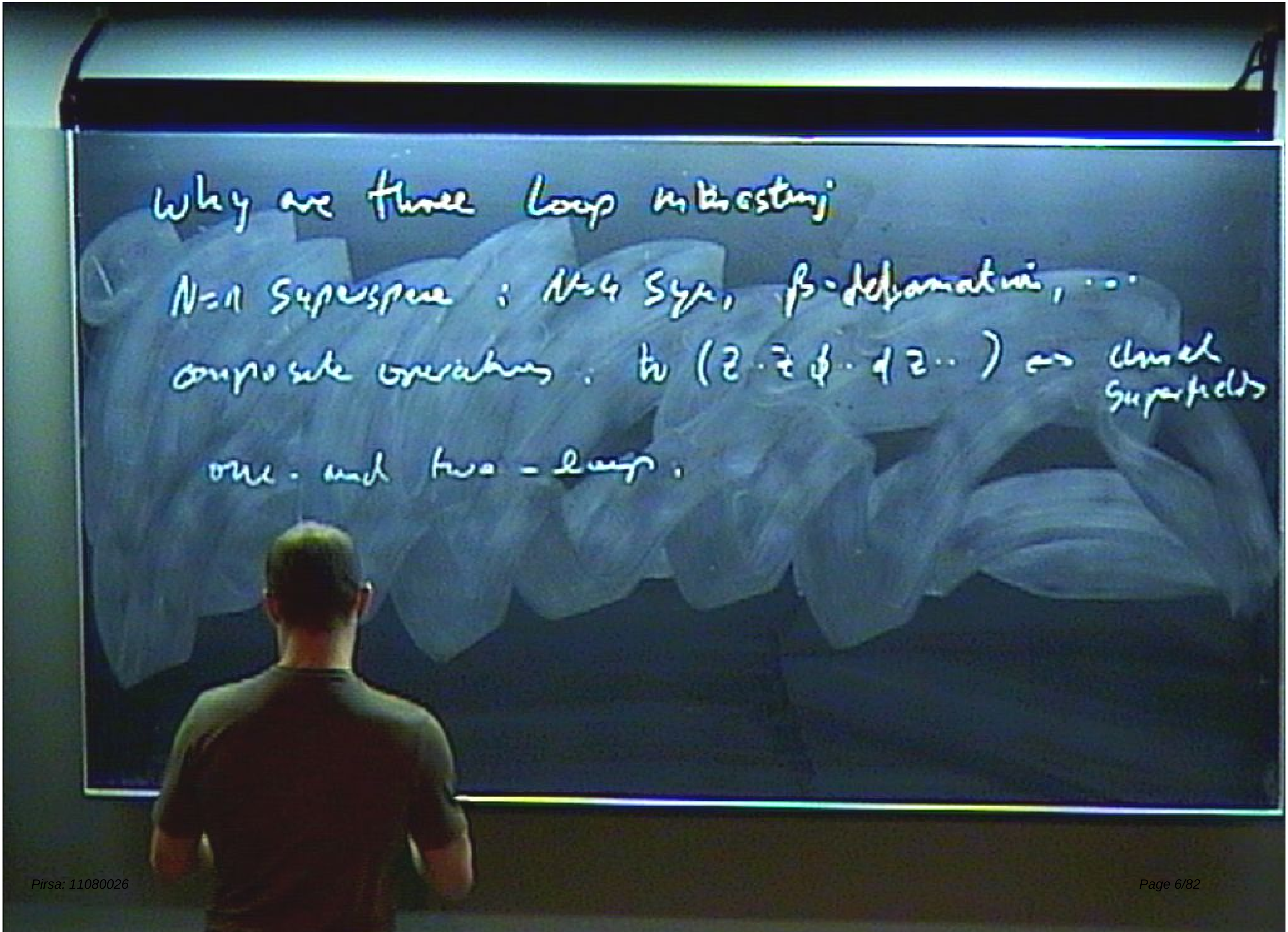
08.08.11, Exact Results in Gauge/Gravity Dualities, PI

C.S.: 1008.3351
E. Pomoni, C.S.: 1105.3487

1. motivation
2. short review of the formalism in $N=4$ SYM
3. the interpolating theory: three tasty results


Why are three loop interesting
N=1 Superspace : N=4 SYM, β-deformation


Why are three loop interesting
N=1 superspace : N=4 SYM, β-deformation, ...
composite operators : tr (Z · Z φ · φ Z ··) as chiral superfields
one- and two-loops.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Why are three loop interesting

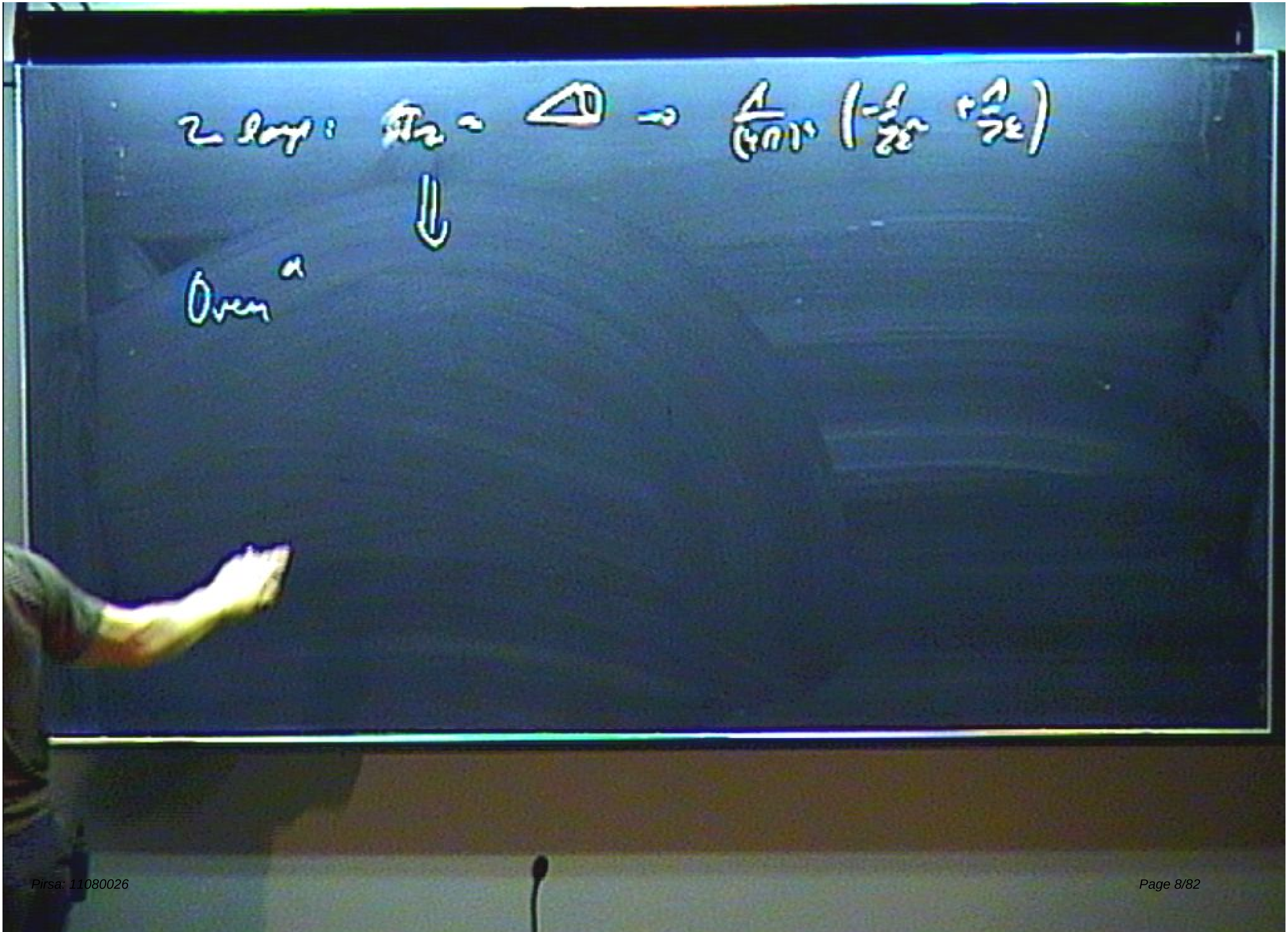
$\mathcal{N}=1$ superspace : $\mathcal{N}=4$ SYM, β-deformation, ...

composite operators : $\mathrm{tr}(Z \cdot Z\, \phi \cdot \phi\, Z \cdots)$ as chiral superfields

one- and two-loop:

- flavor manipulations (chiral functions)

associated with magnon dispersion relation


2 loops:
Oven

2 loops: $\Pi_2 \sim$ → $\frac{1}{(4\pi)^4}\left(-\frac{1}{2\epsilon^2}+\frac{1}{2\epsilon}\right)$

$$\Downarrow$$

$O_{ren}{}^{a} = Z^a{}_b \, O^b_{bare}$ $\qquad Z^a{}_b = \mathbb{1} - \sum$ UV poles

dilatation operator:

2 loops: $\Pi_2 =$  $\rightarrow \frac{1}{(4\pi)^4}\left(-\frac{1}{2\epsilon^2}+\frac{1}{2\epsilon}\right)$

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$$O_{ren}^{\,a} = Z^a{}_b \, O^b_{bare} \qquad Z^a{}_b = \mathbb{1} - \sum \text{UV poles}$$

dilatation operator: $\mathfrak{D} = \mu \frac{\partial}{\partial \mu} \ln Z(g\mu^\epsilon)$.

2 loop: $\delta Z_2 \sim$ $\to \frac{1}{(4\pi)^4}\left(-\frac{1}{2\epsilon^2} + [illegible]\right)$

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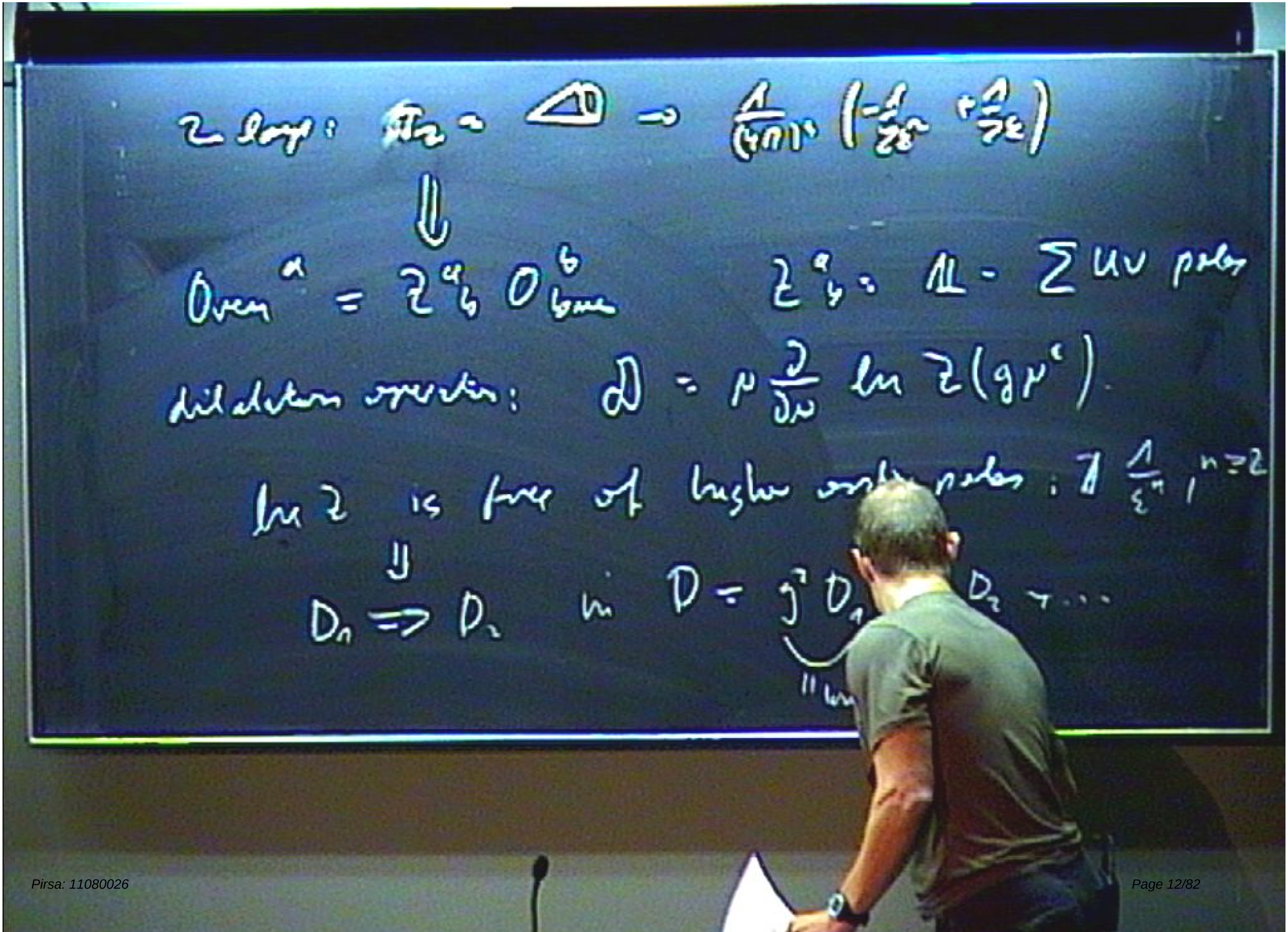
$\ln Z$ is free of higher order poles: $\not\exists\ \frac{1}{\epsilon^n},\ n \geq 2$



2 loops: Π₂ ~ → 1/(4π)⁴ (−1/(2ε²) + 1/(2ε))
⇓
O_ren^a = Z^a_b O^b_bare
Z^a_b = 1 − Σ UV poles
dilatation operator: D = μ ∂/∂μ ln Z(gμ^ε)
ln Z is free of higher order poles: ∄ 1/εⁿ, n ≥ 2
⇓
D₁ ⇒ D₂ in D = g² D₁ + D₂ + ...

2 loops: $\pi_2 \sim$  $\rightarrow \frac{1}{(4\pi)^4}\left(-\frac{1}{2\epsilon^2}+\frac{1}{2\epsilon}\right)$

$\Downarrow$

$O_{ren}^a = Z^a_b \, O^b_{bare}$ $\qquad Z^a_b = \mathbb{1} - \sum$ UV poles

dilatation operator: $\mathcal{D} = \mu \frac{\partial}{\partial \mu} \ln Z(g\mu^\epsilon)$

$\ln Z$ is free of higher order poles: $\nexists \frac{1}{\epsilon^n}, n \geq 2$

$\Downarrow$

$D_1 \Rightarrow D_2$ in $D = \underbrace{g^2 D_1 + g^4 D_2}_{\text{"[illegible]"}} + \dots$

2 loops: $\Pi_2 \sim$  $\to \frac{1}{(4\pi)^4}\left(-\frac{1}{2\varepsilon^2}+\frac{1}{2\varepsilon}\right)$

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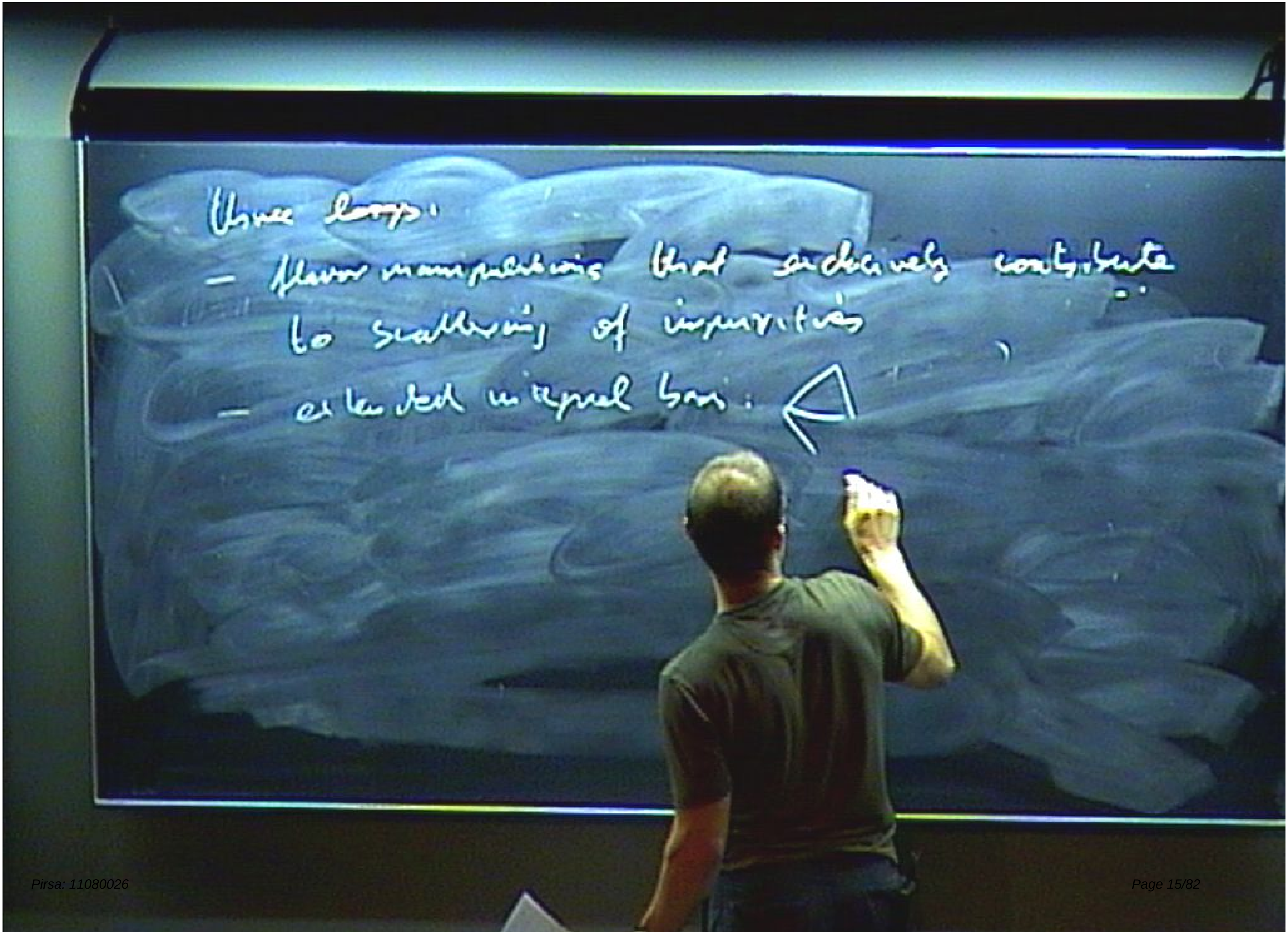
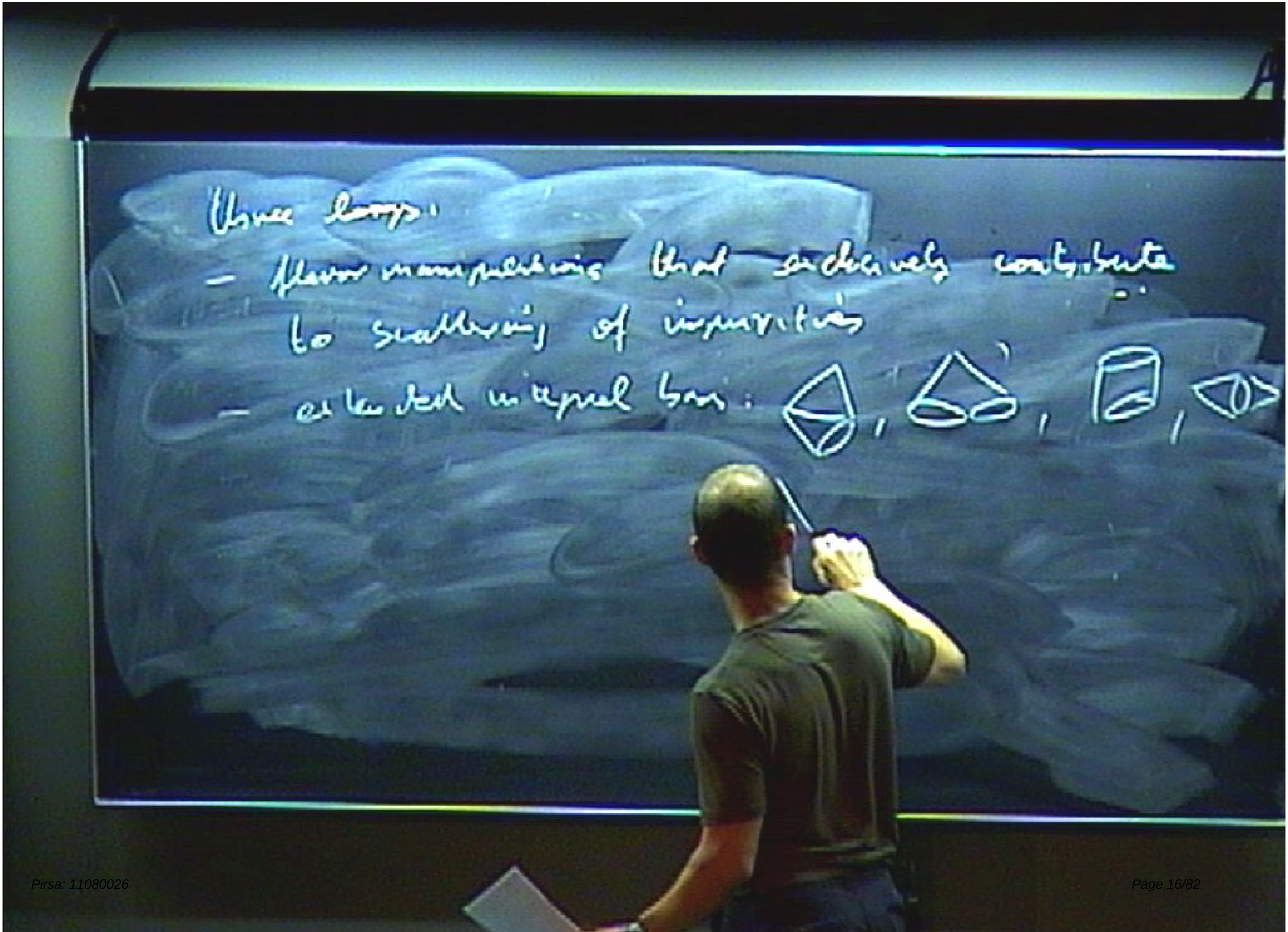

three loops:
– flavor manipulations that exclusively contribute
to scattering of impurities
– extended integral basis: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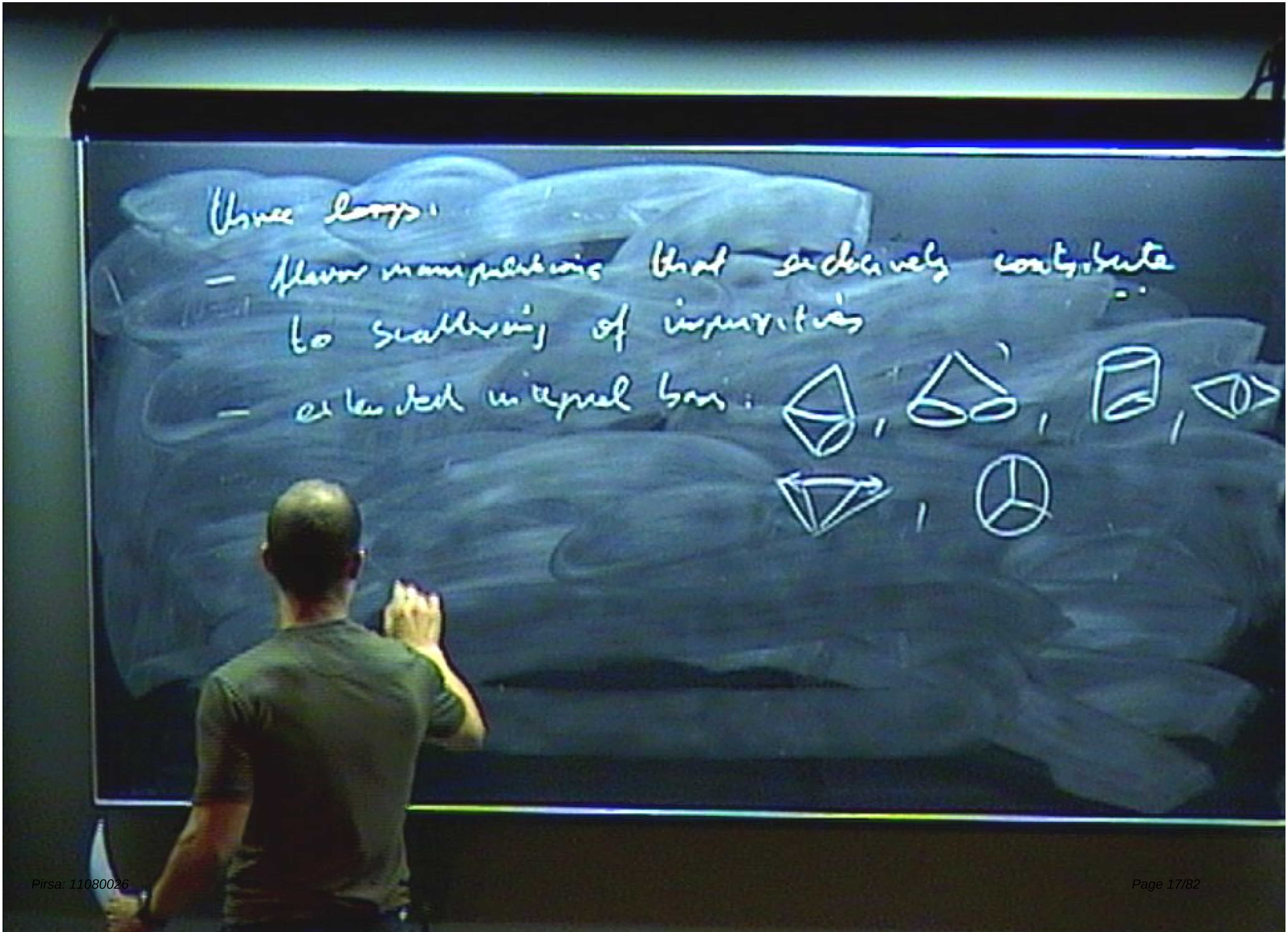
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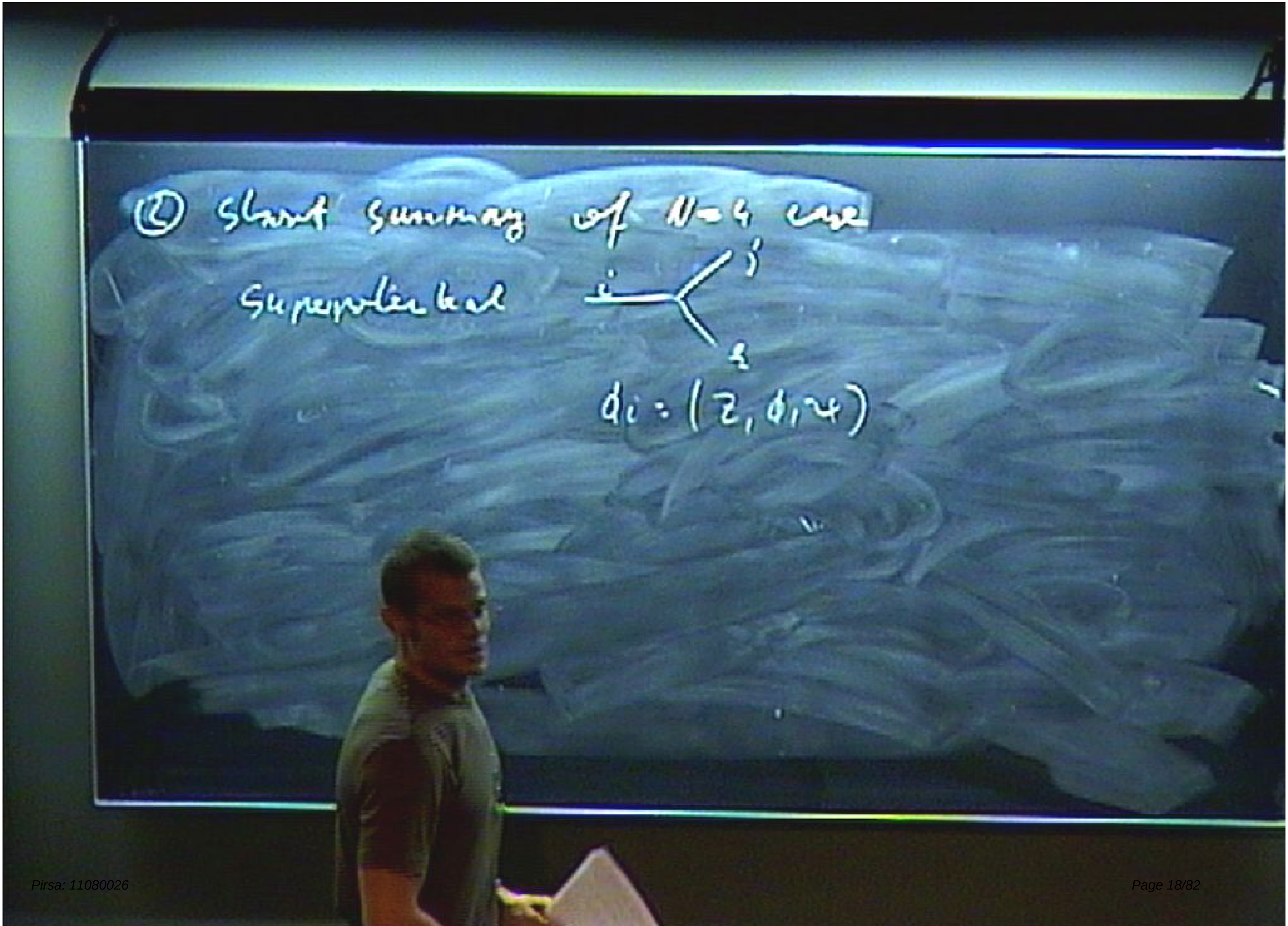
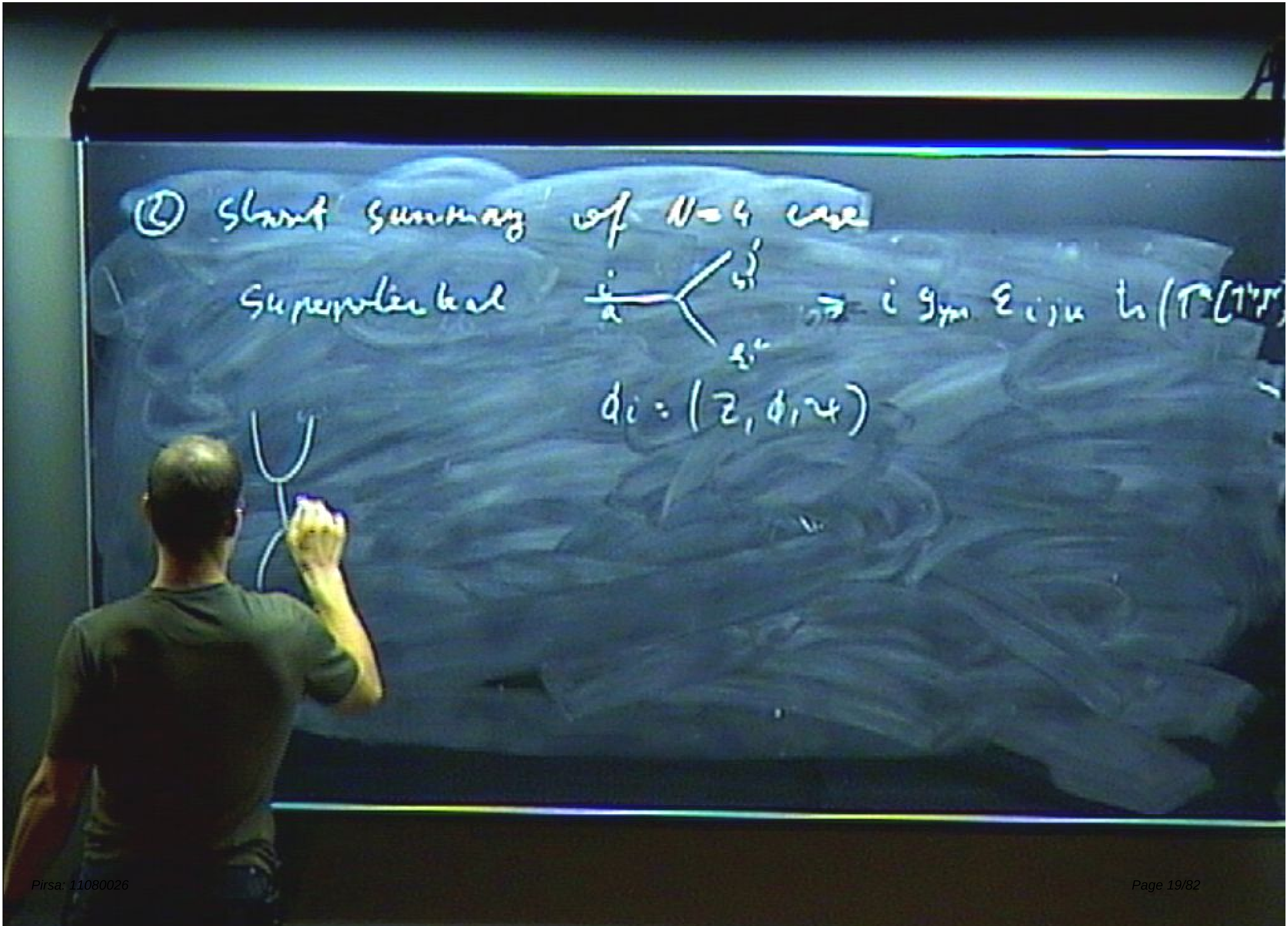
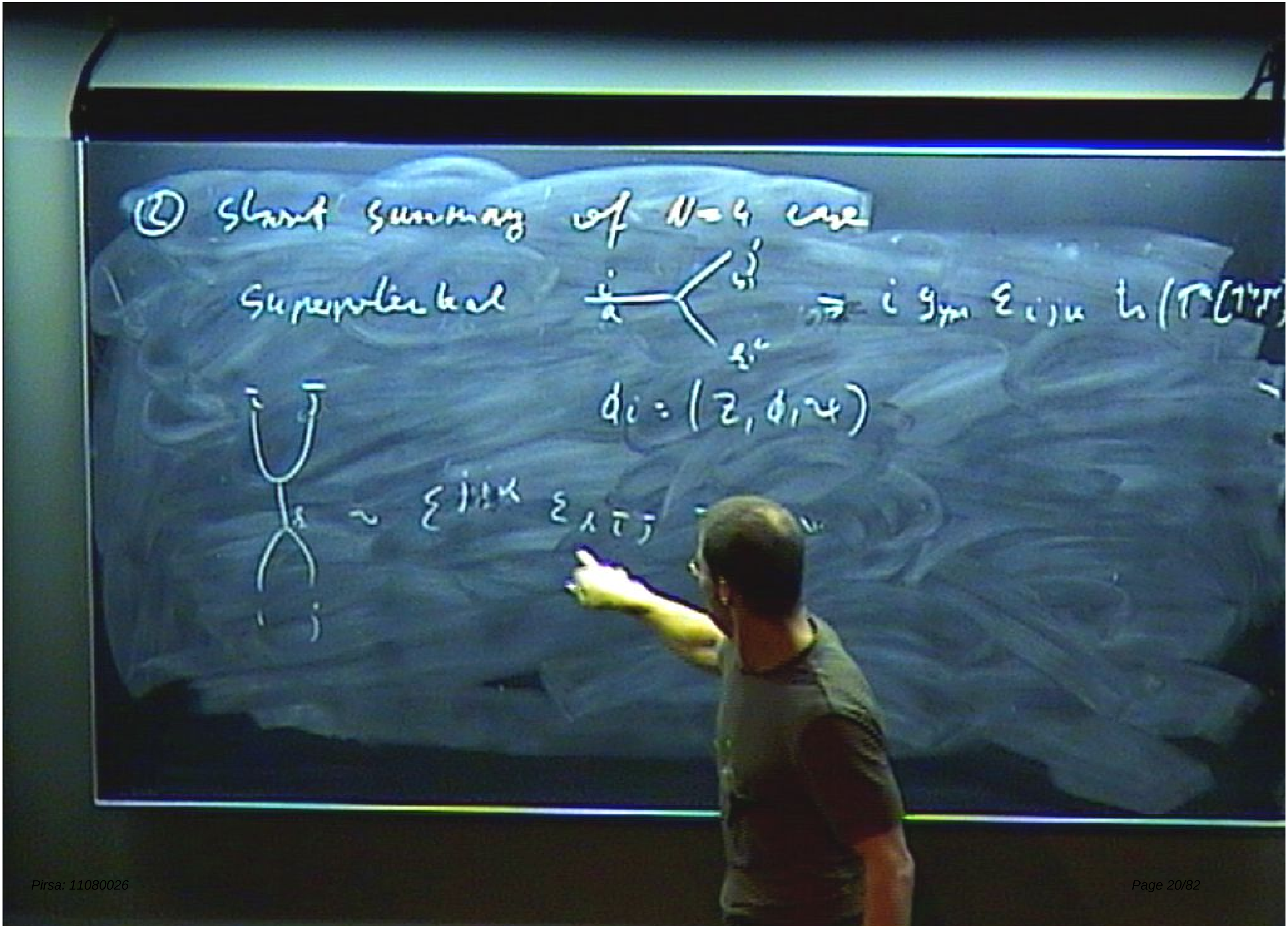

② Short summary of N=4 case
Superpotential
i
j
k
φi = (Z, φ, ψ)



② Short summary of N=4 case
Superpotential
$\Rightarrow i\, g_{YM}\, \varepsilon_{ijk}\, \mathrm{tr}(\Phi^i[\Phi^j, \Phi^k])$
$\phi_i = (Z, \phi, \psi)$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Superpotential
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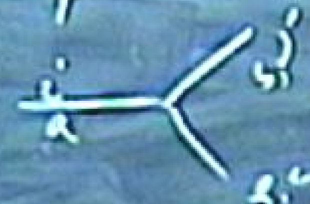
② Short summary of $N=4$ case

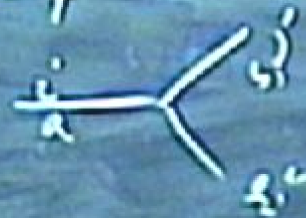
Superpotential  $\Rightarrow i\, g_{ym}\, \varepsilon_{ijk}\, \mathrm{tr}(T^a[T^b T^c]$

$\phi_i = (Z, \phi, \psi)$

$\sim \varepsilon^{ijk}\, \varepsilon_{k\bar{i}\bar{j}} = \delta^{j}_{\bar{i}}\, \delta^{i}_{\bar{j}} - \delta^{i}_{\bar{i}}\, \delta^{j}_{\bar{j}}$

$= \mathbb{P} - \mathbb{1}$

② Short summary of $N=4$ case

Superpotential  $\Rightarrow i\, g_{YM}\, \varepsilon_{ijk}\, \mathrm{tr}(T^a[T^b, T^c])$

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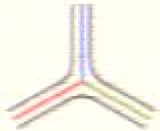
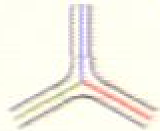
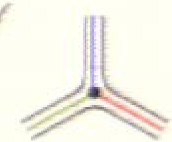
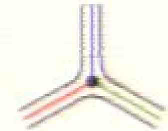
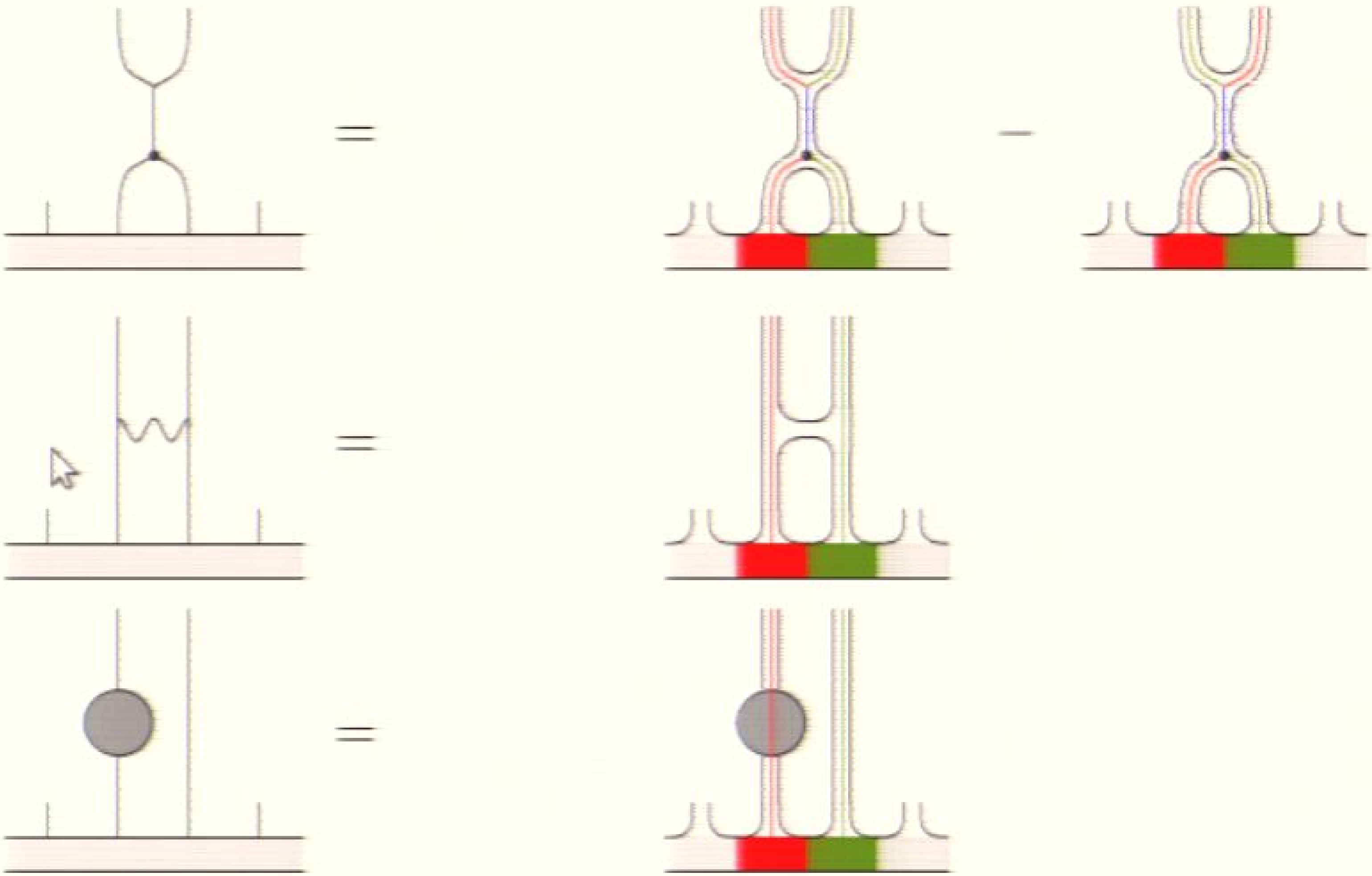
$= \mathbb{P}_1 - \mathbb{1}$

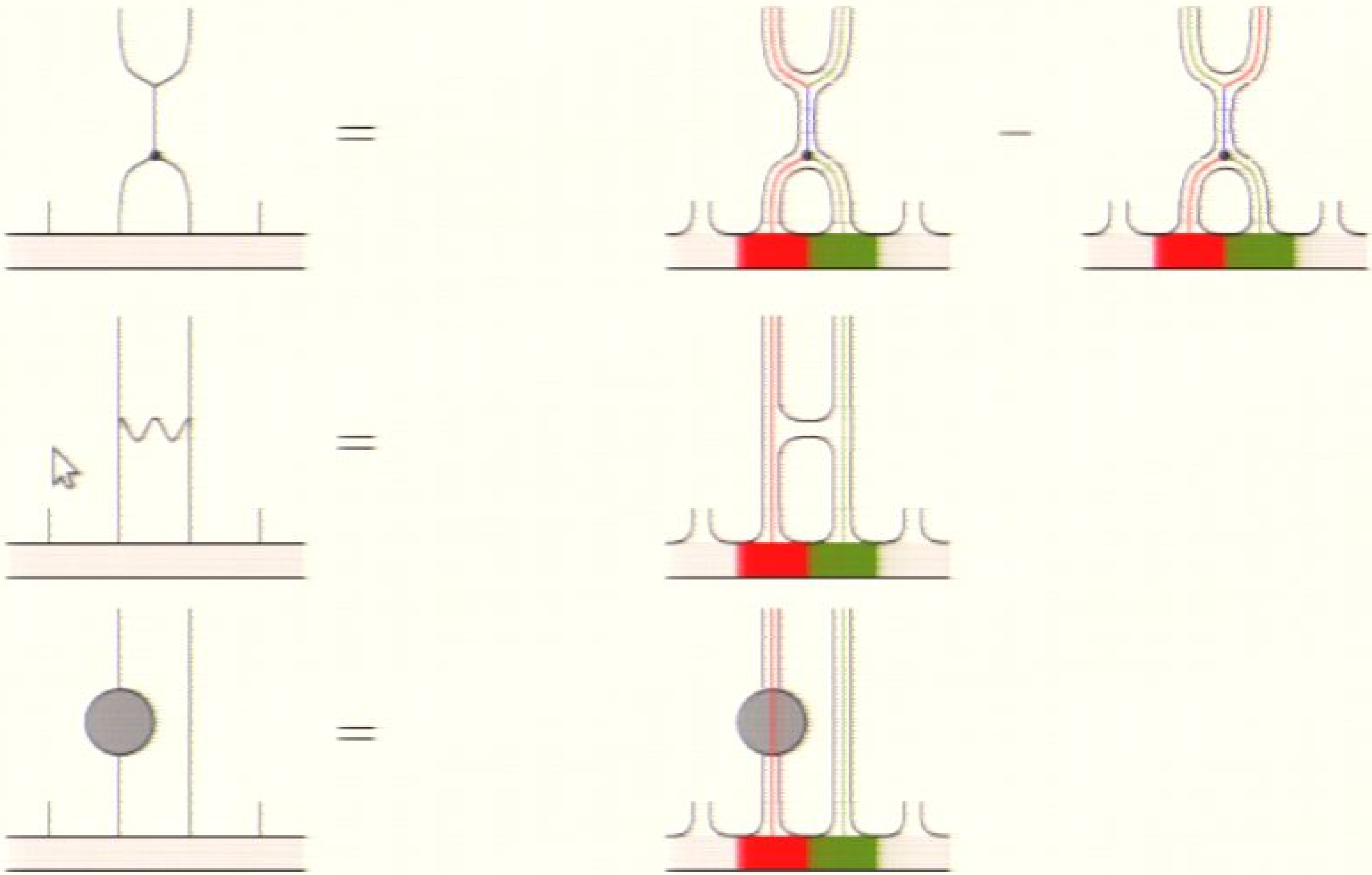
One loop

$\mathrm{tr}(\psi[Z\,,\phi]) = i\Big($  $-$  $\Big)\,, \quad -i\,\mathrm{tr}(\bar{\psi}[\bar{\phi}\,,\bar{Z}]) = -i\Big($  $-$  $\Big)$

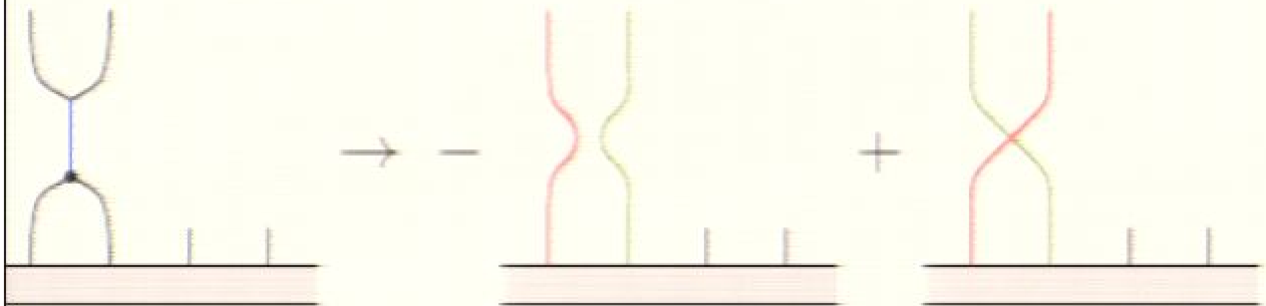


One loop

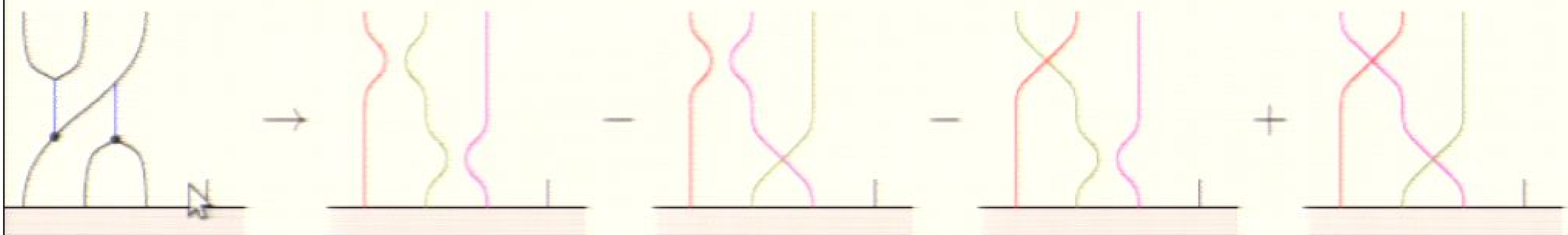
$\mathrm{tr}(\psi[Z\,,\phi]) = i\Big($  $\Big)$, $\quad -i\,\mathrm{tr}(\bar{\psi}[\bar{\phi}\,,\bar{Z}]) = -i\Big($  $\Big)$



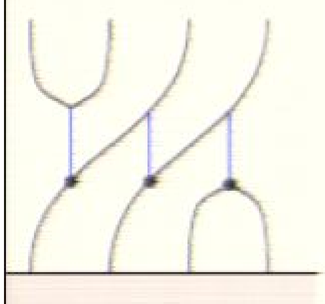
Chiral functions



$$\chi(1) = -\{\} + \{1\}$$



$$\chi(1,2) = \{\} - \{1\} - \{1\} + \{1,2\}$$

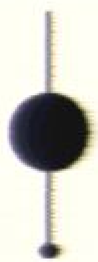
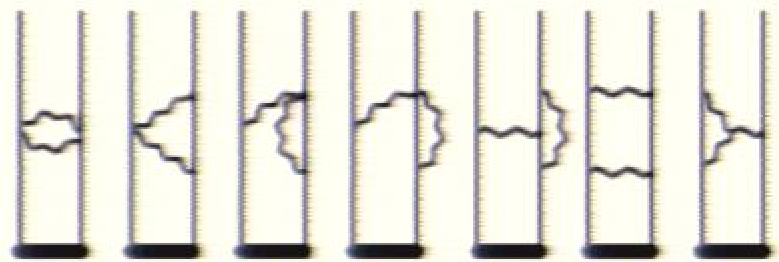
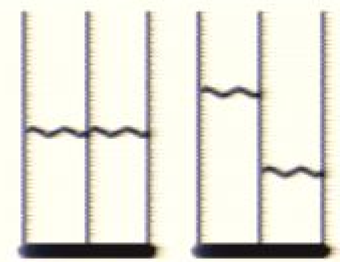
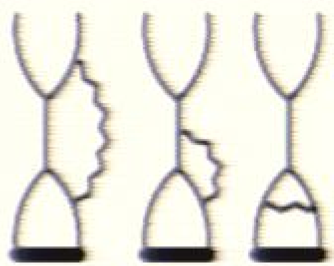
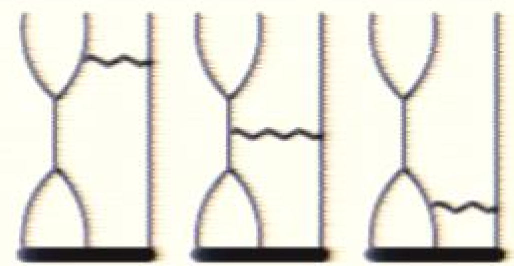
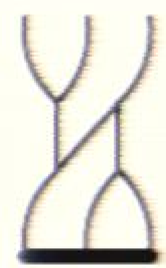


$$\{a_1,\dots,a_n\} = \sum_{i=1}^{L} \mathrm{P}_{i+a_1\; i+a_1+1} \cdots \mathrm{P}_{i+a_n\; i+a_n+1}$$

$$\chi(1,2,3) = -\{\} + 3\{1\} - 2\{1,2\} - \{1,3\} + \{1,2,3\}$$

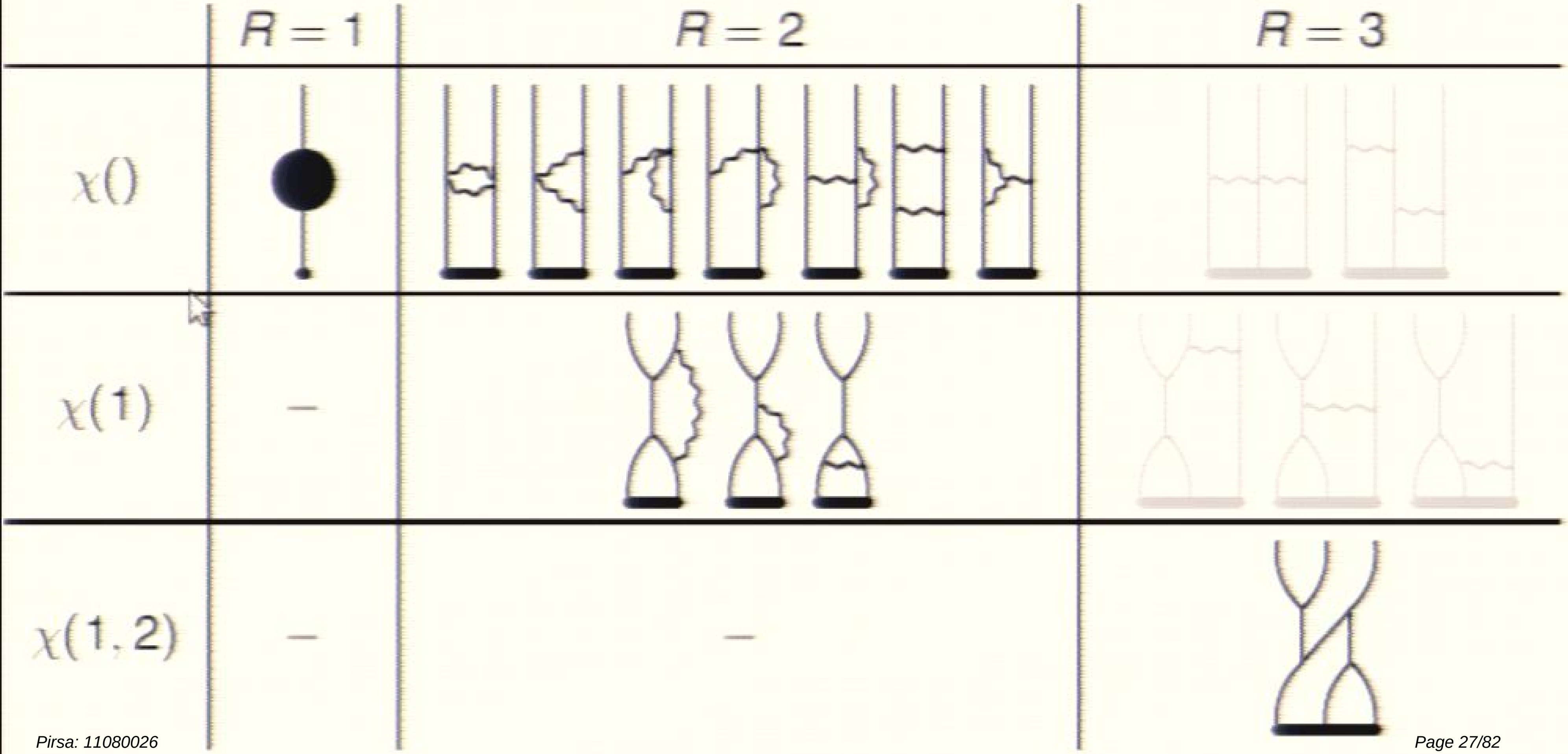
Two loops

- all diagrams (apart from reflections, one-loop wave function ren.)

	$R = 1$	$R = 2$	$R = 3$
$\chi()$			
$\chi(1)$	–		
$\chi(1,2)$	–	–	

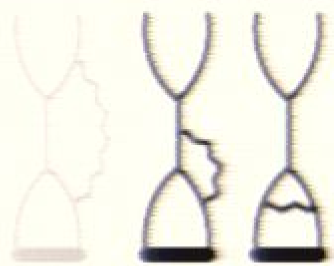
Two loops

- constraints on D-algebra [Fiamberti, Santambrogio, C.S., Zanon]

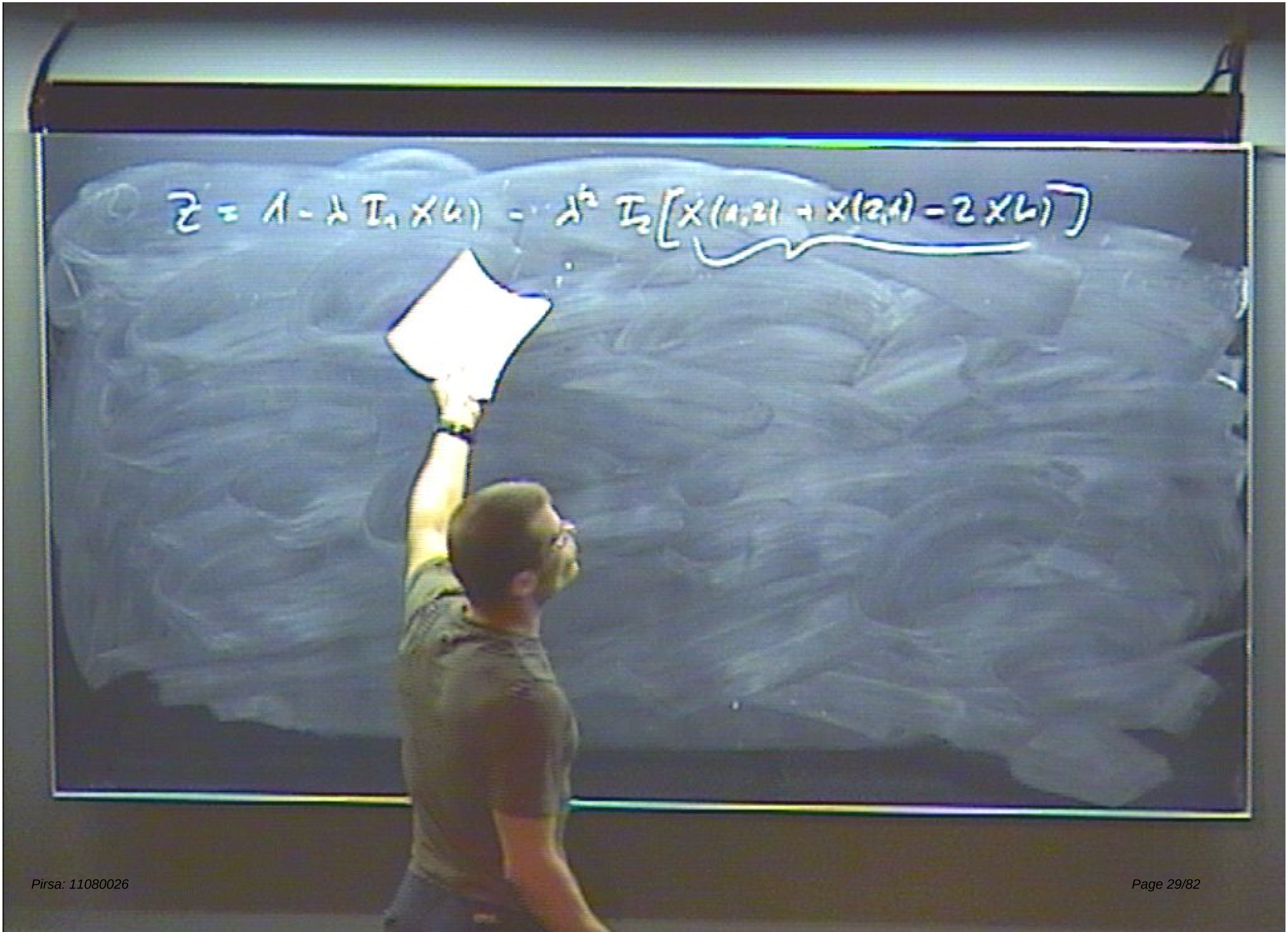


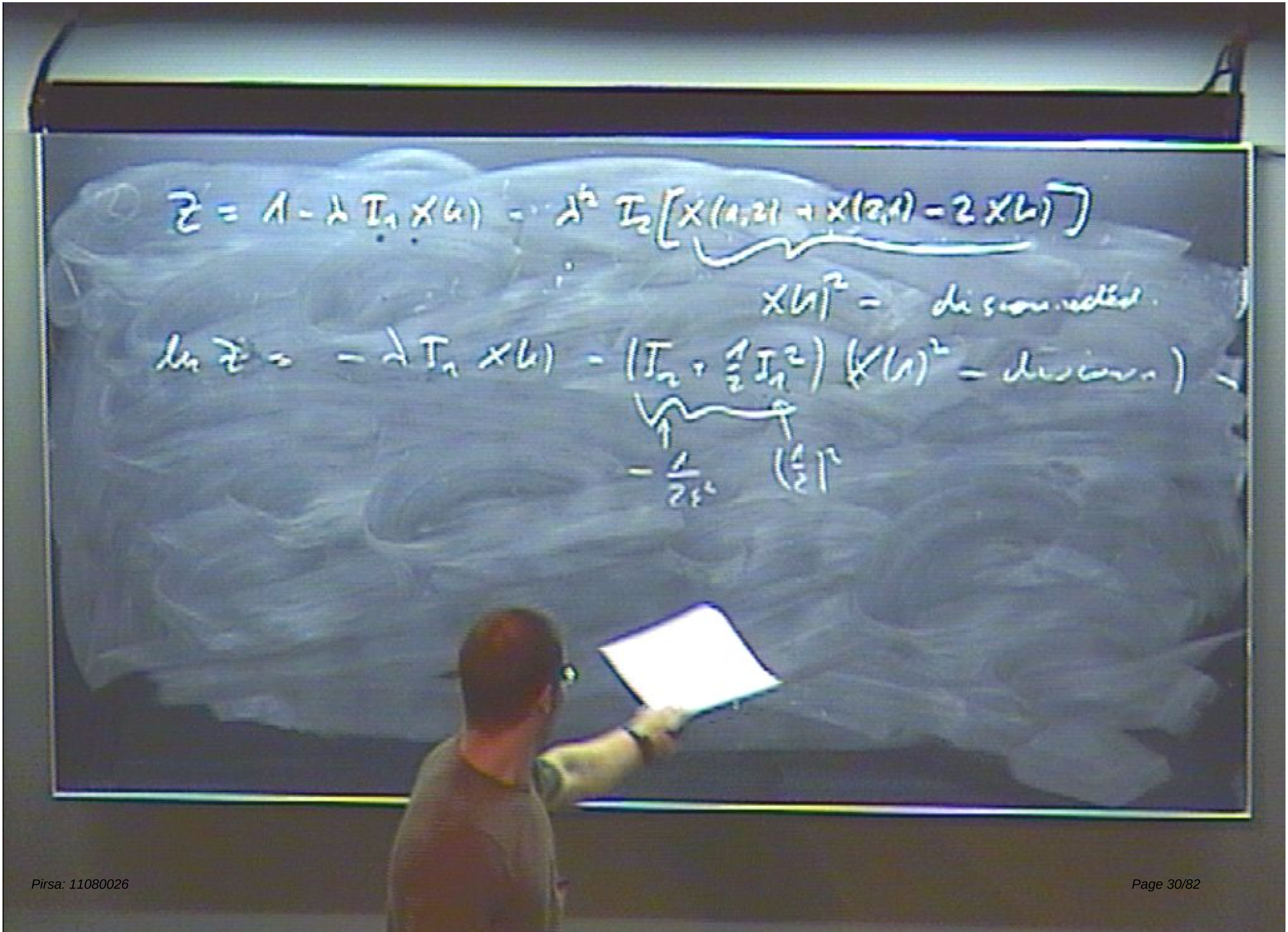
Two loops

- finiteness conditions and finite 2-loop self energy
  $\Rightarrow$ absence of $\chi()$ [C.S.]

	$R=1$	$R=2$	$R=3$
$\chi()$			
$\chi(1)$	–		
$\chi(1,2)$	–	–	

$\mathcal{D}_2 = 4\chi(1) - 2[\chi(1,2) + \chi(2,1)]$


$Z = 1 - \lambda I_1 X(1) - \lambda^2 I_2 [X(1,2) + X(2,1) - 2X(1)]$


X(1)² = disconnected

$$Z = 1 - \lambda I_1 \chi(1) - \lambda^2 I_2 \left[\chi(1,2) + \chi(2,1) - 2\chi(1) \right]$$

$\chi(1)^2 =$ disconnected

$$\ln Z = -\lambda I_1 \chi(1) - \left(I_2 + \tfrac{1}{2} I_1^2 \right) \left(\chi(1)^2 - \text{discon.} \right)$$

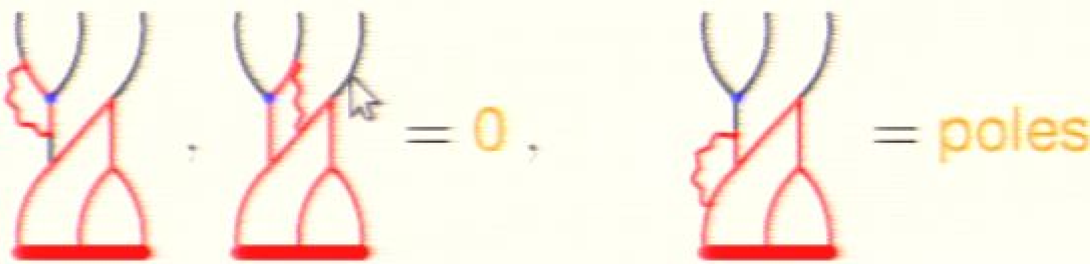
$$-\frac{1}{2\xi^2} \qquad \left(\tfrac{1}{2}\right)^2$$

three loops: feasible thanks to finiteness condition

Finiteness conditions

r all $R \geq 2$ diagrams with $\mathcal{O}_L$ of the $SU(2)$ sector (also beyond?),
o overall UV divergence if at least one of the conditions holds:

. all chiral vertices take part in loops, e.g.:



2. one of its spinor derivatives D_α is brought outside loops
3. for v_0 chiral vertices outside loops:
   more than $2(v_0 - 1)$ spinor derivatives $\bar{\mathrm{D}}_{\dot\alpha}$ are brougth outside loops

- all $R \geq 2$ diagrams with $\chi()$ finite
- cancellations between certain diagrams involving vector fields

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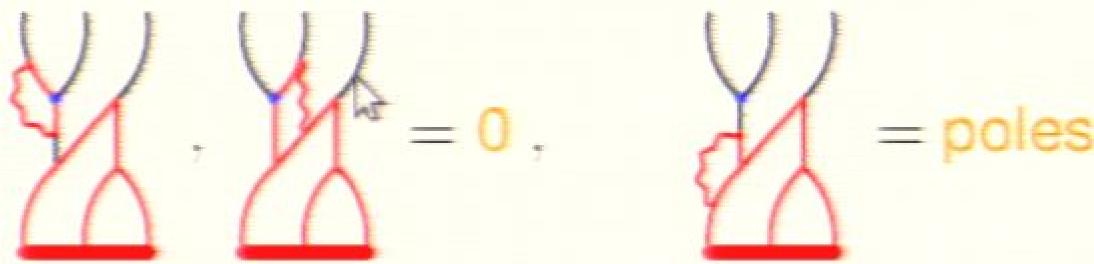

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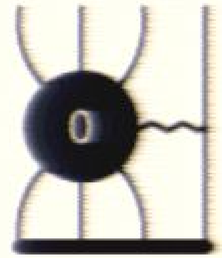
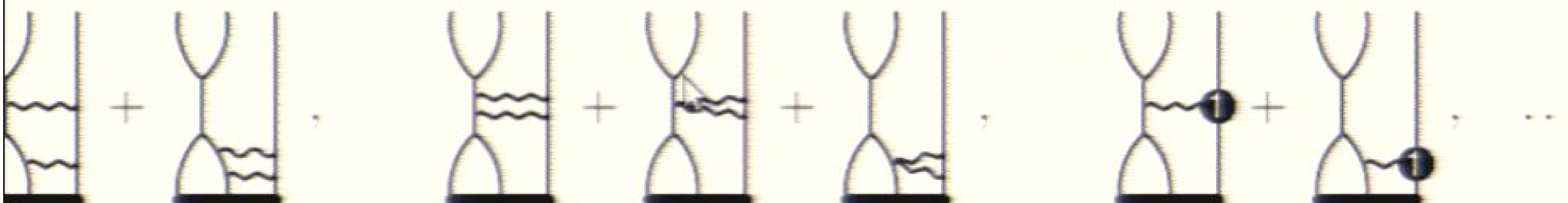
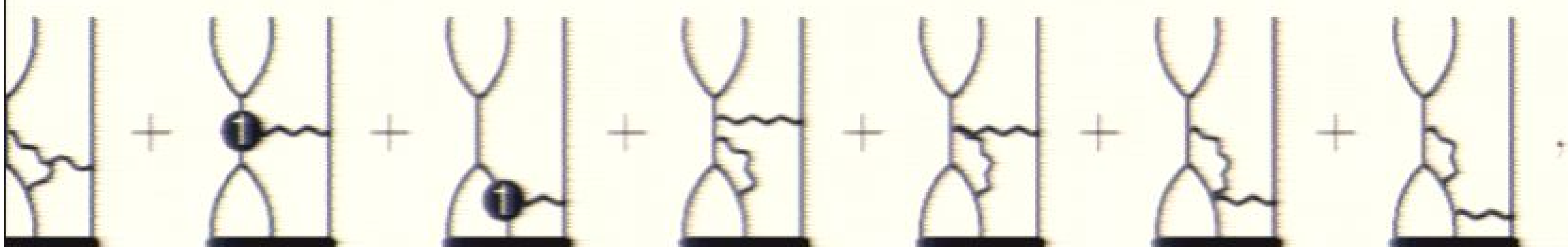
Cancellations

aximum range $R = 4$ diagrams if χ is not of maximum range irrelevant

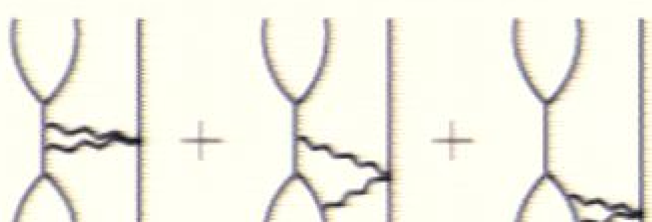


ancellations for next-to-maximum range $R = 3$ diagrams





ut cancellations not complete



$=$ poles

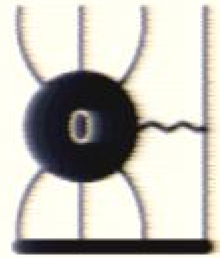
The interpolating theory: field content

[Gadde, Pomoni, Rastelli]

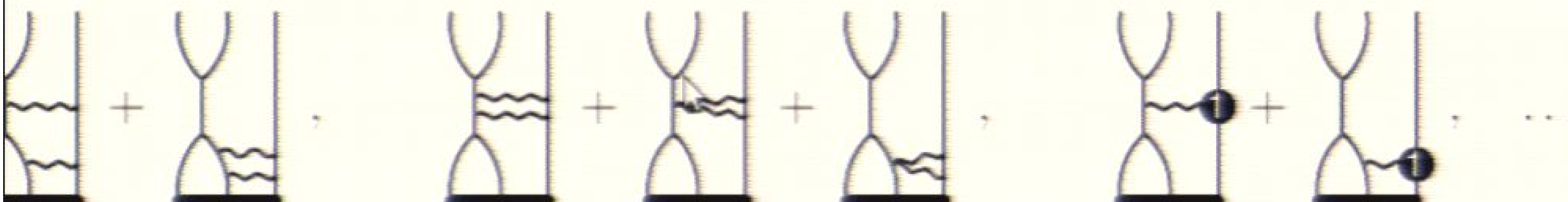
field	$SU(N) \times SU(N)$	$SU(2)_L$	$SU(2)_R$	$U(1)$
V	(adj., 1)	1	1	0
Φ	(adj., 1)	1	1	1
$\bar{\Phi}$	(adj., 1)	1	1	-1
$\hat{V}$	(1, adj.)	1	1	0
$\hat{\Phi}$	(1, adj.)	1	1	1
$\hat{\bar{\Phi}}$	(1, adj.)	1	1	-1
Q_I	$(\square, \bar{\square})$	$\square$	$\square$	0
$\tilde{\bar{Q}}_I$	$(\square, \bar{\square})$	$\square$		0
$\bar{Q}^I$	$(\bar{\square}, \square)$	$\bar{\square}$	$\bar{\square}$	0
$\tilde{Q}^I$	$(\bar{\square}, \square)$	$\bar{\square}$		0

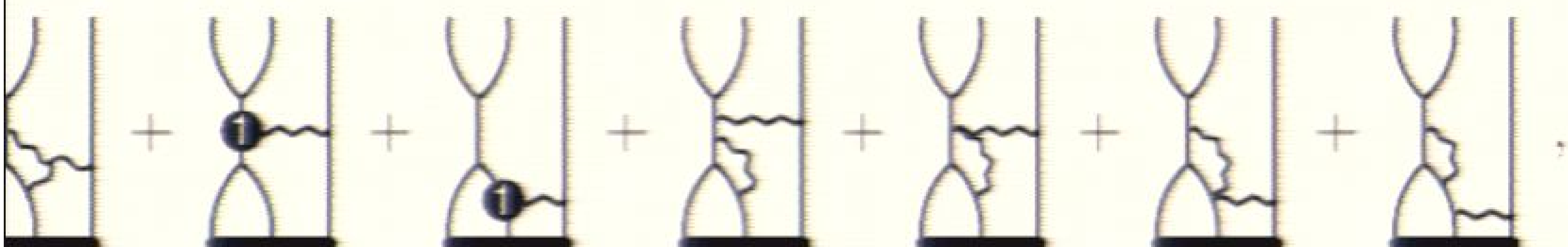
Cancellations

aximum range $R = 4$ diagrams if χ is not of maximum range irrelevant



ancellations for next-to-maximum range $R = 3$ diagrams





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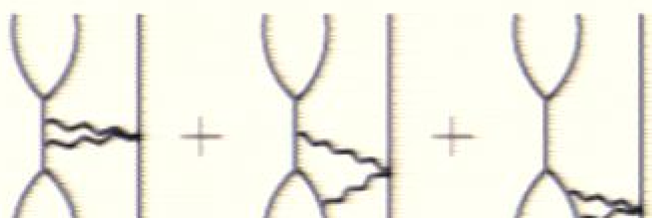
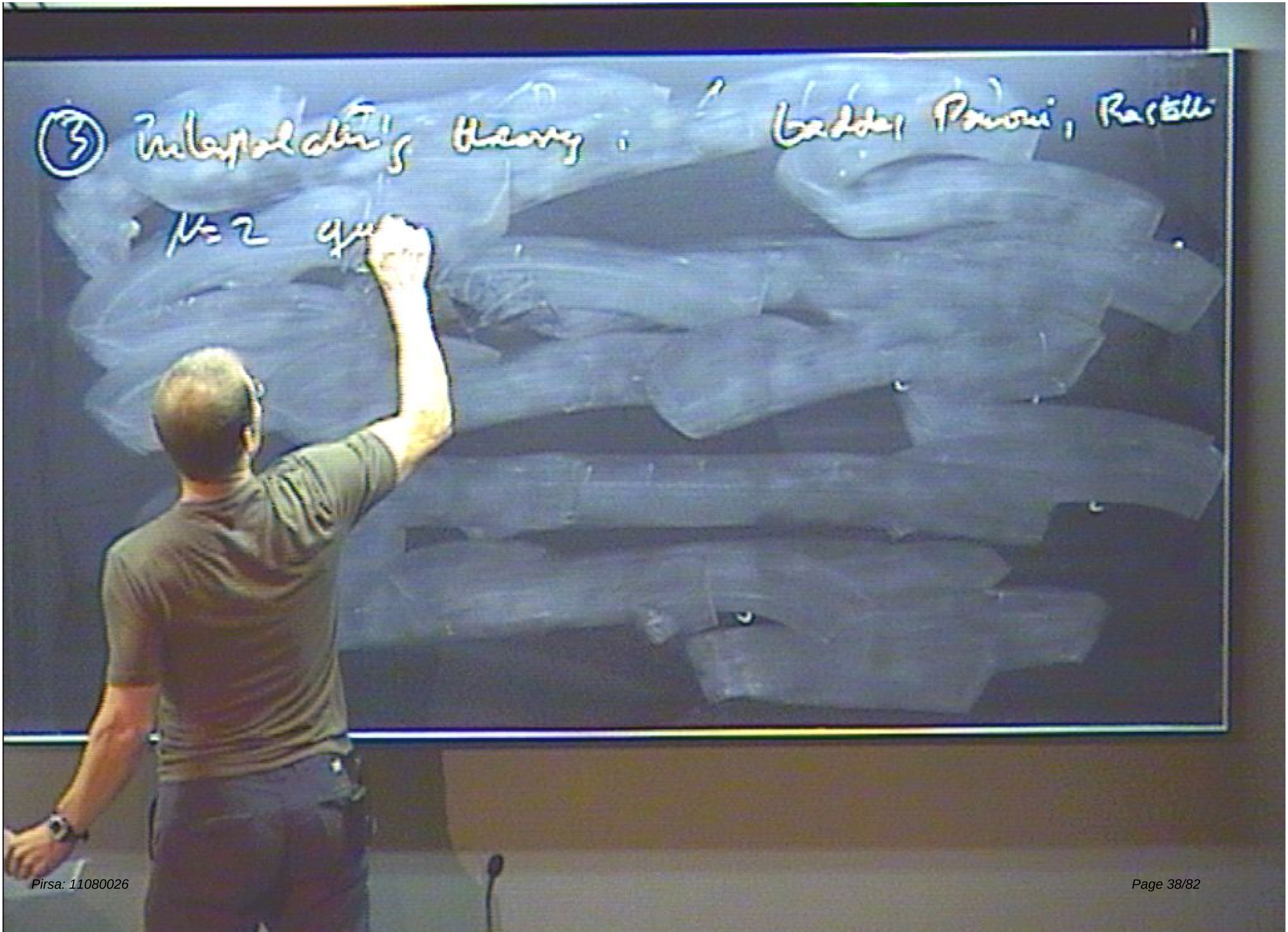
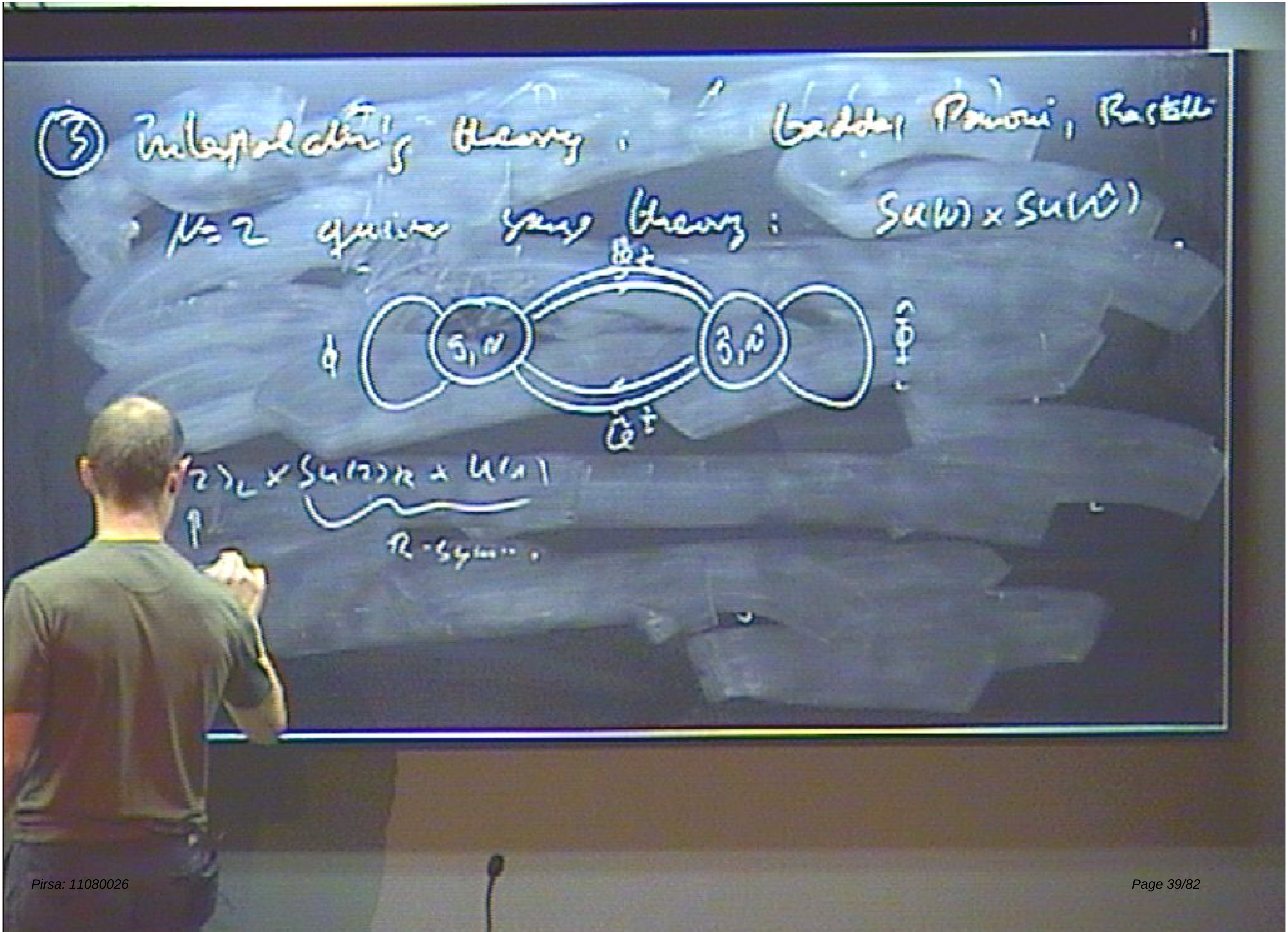


$=$ poles


③ Interpolating theory :


③ Interpolating theory :
Pomoni, Rastelli
• N=2


N=2 quiver gauge theory :
SU(N) × SU(N̂)
R-symm.

③ Interpolating theory : Gadde, Pomoni, Rastelli

• $\mathcal{N}=2$ quiver gauge theory : $SU(N) \times SU(\check{N})$

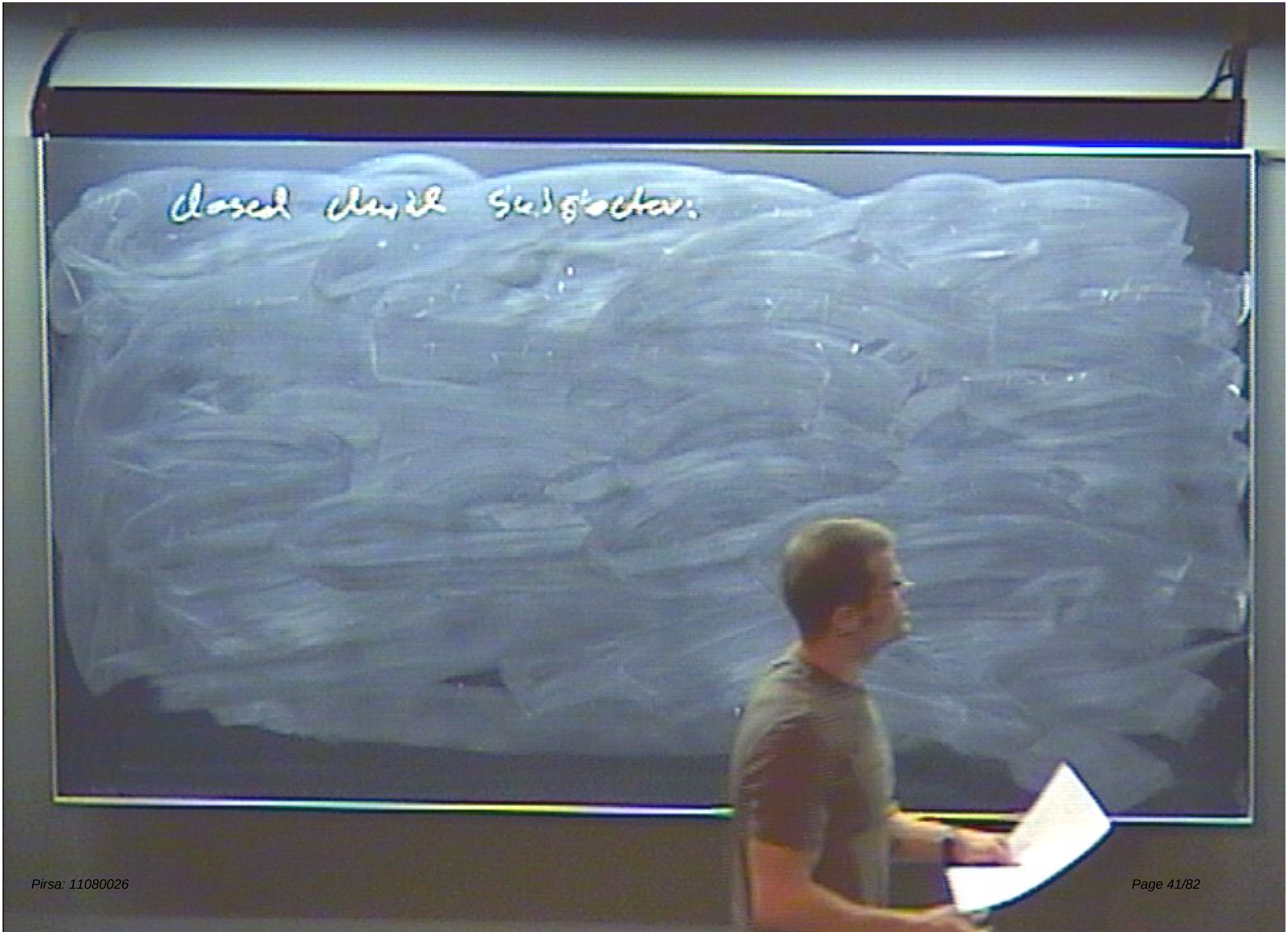
$\underbrace{SU(2)_L \times SU(2)_R \times U(1)}_{R\text{-sym.}}$ $\quad \mathcal{N} = \check{N}$

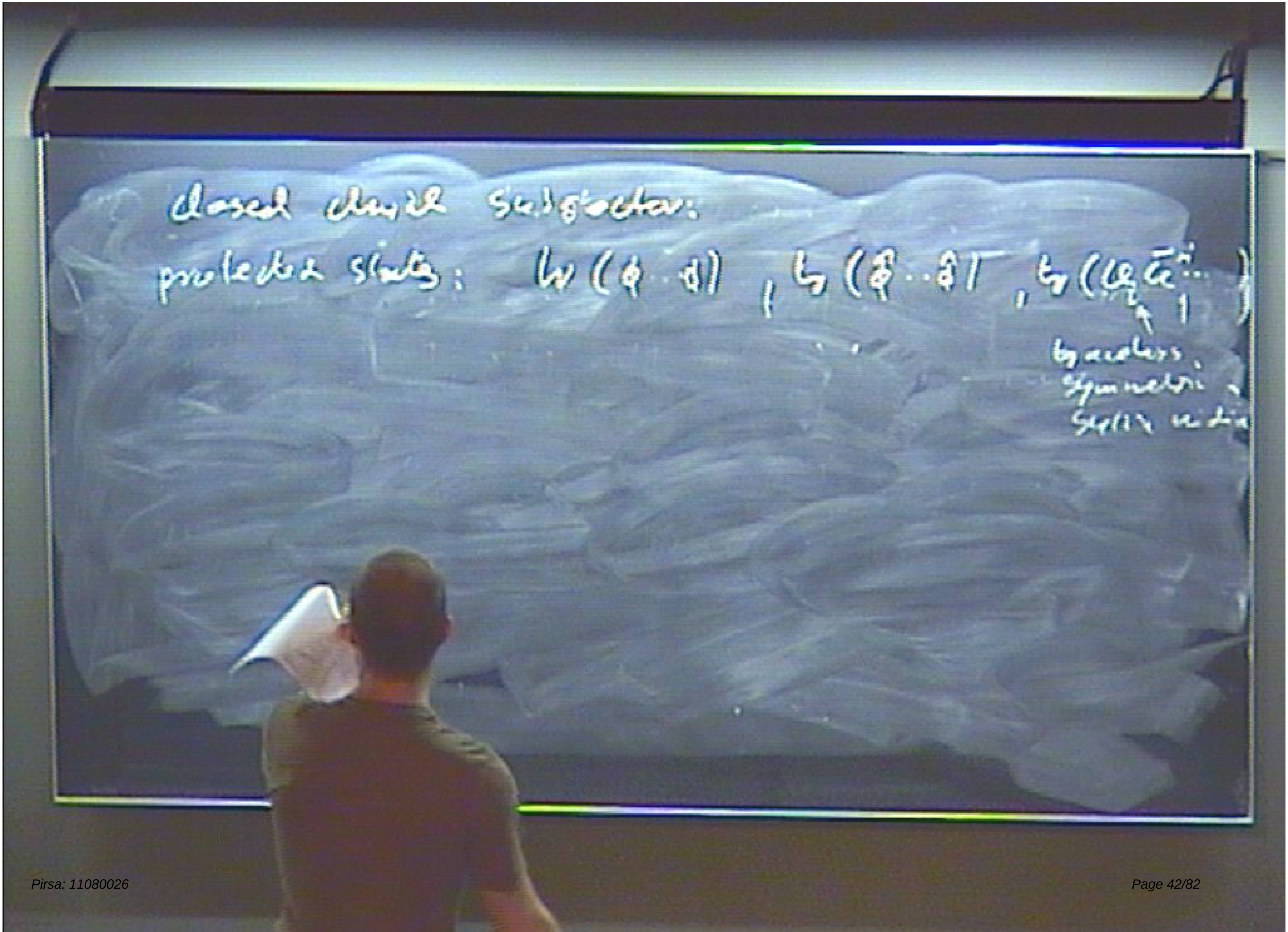
$\updownarrow$

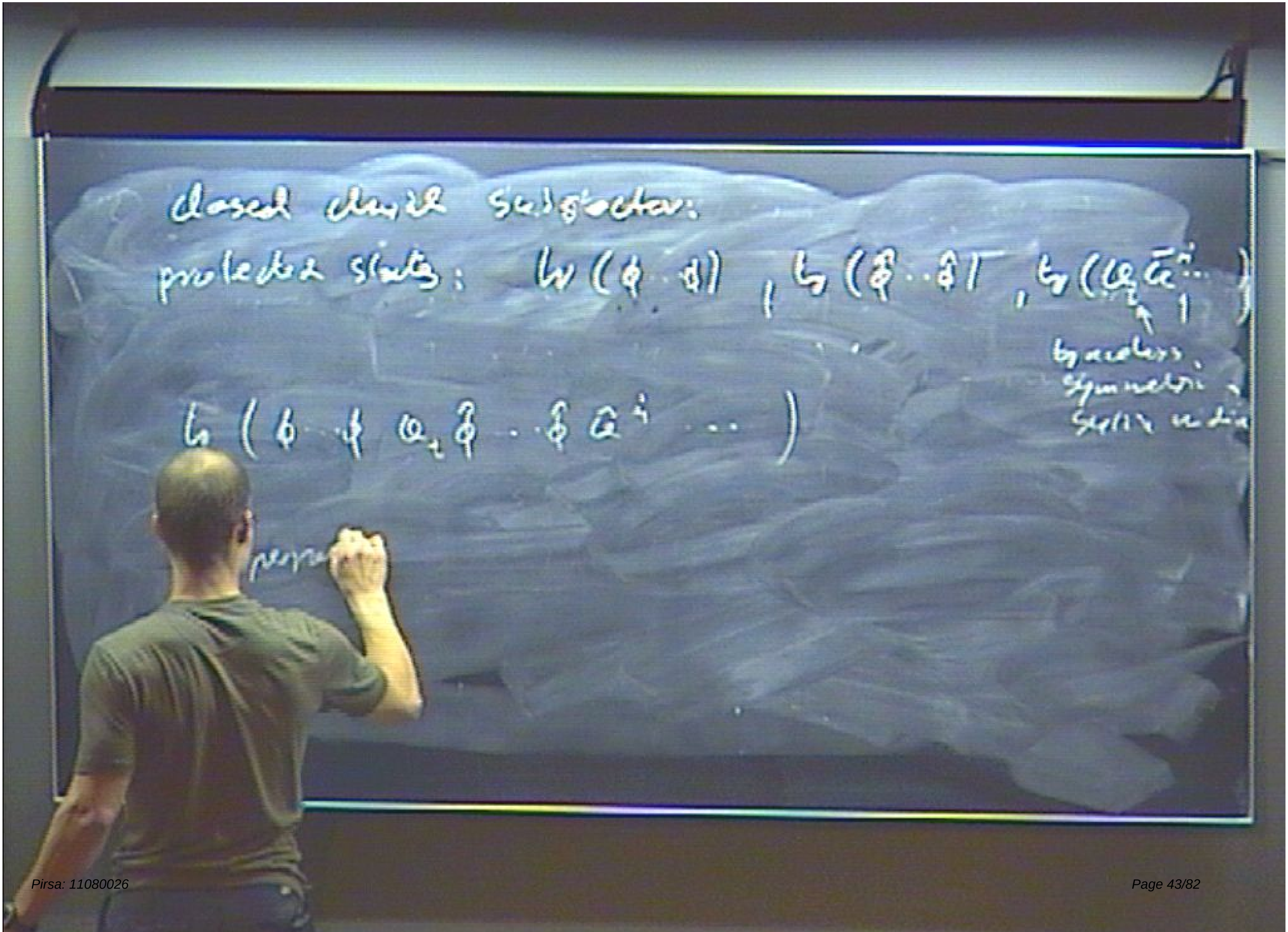
$\leftrightarrow \hat{I}$

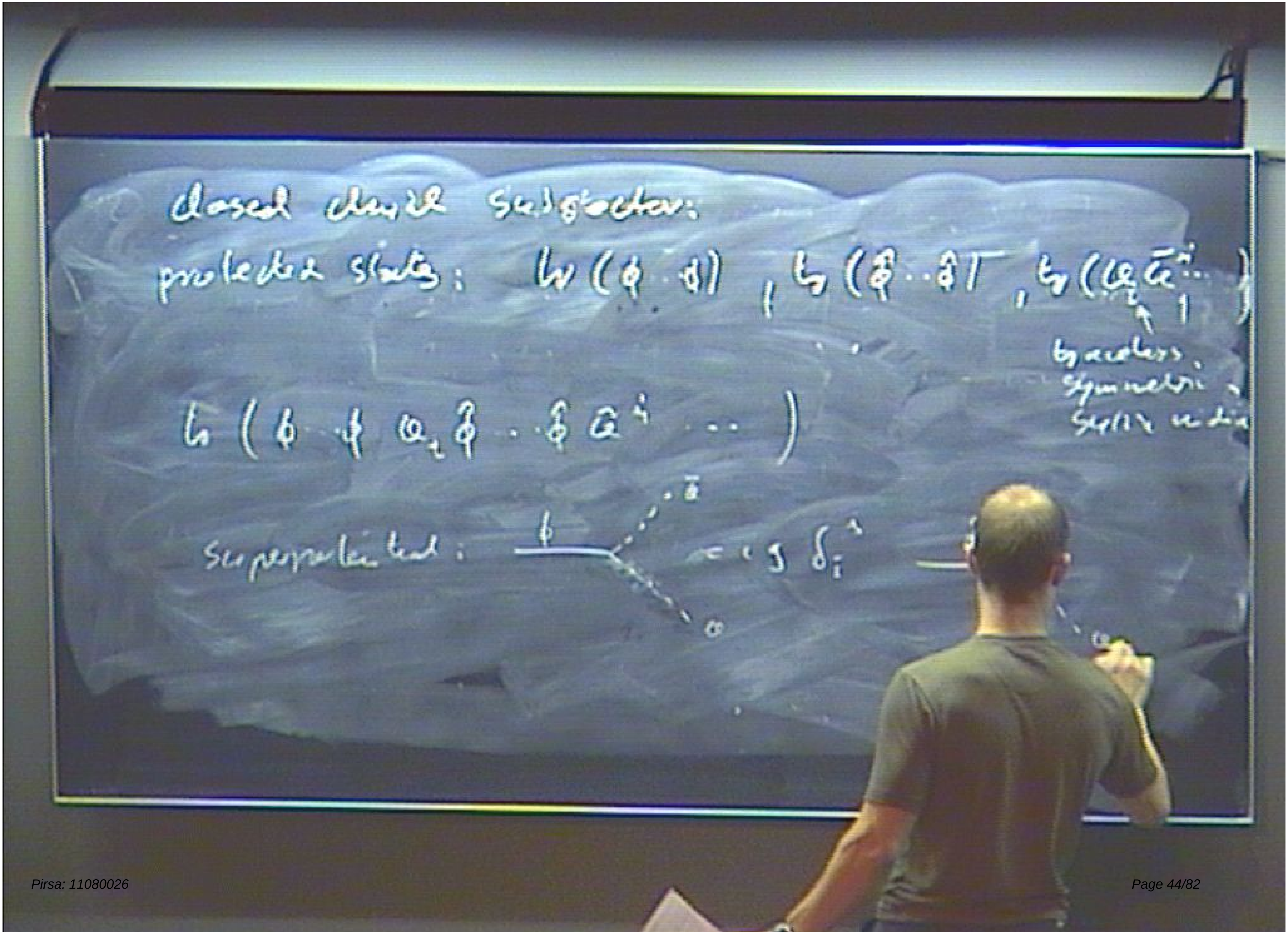
$\check{g} = g$ $\swarrow$ $\qquad \searrow$ $\check{g} = 0$

$\mathbb{Z}_2$ orbifold of $\mathcal{N}=4$ SYM $\qquad$ $\mathcal{N}=2$ SCQCD


closed chiral subsector:


closed chain subsector:
protected states:


closed chain subsector:
protected states:
tr



closed chiral subsector:
protected states:
superpotential:

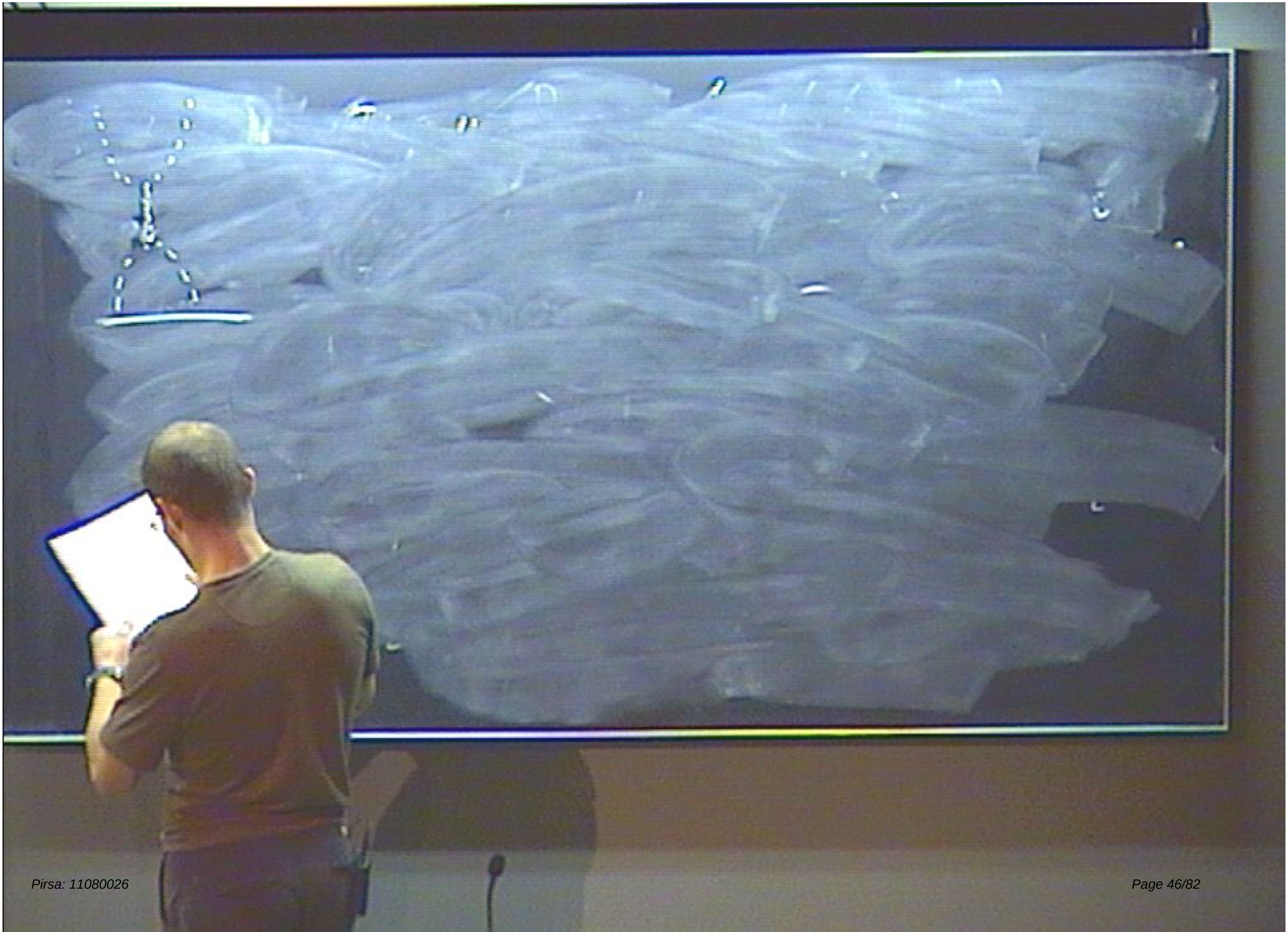
closed chiral subsector:

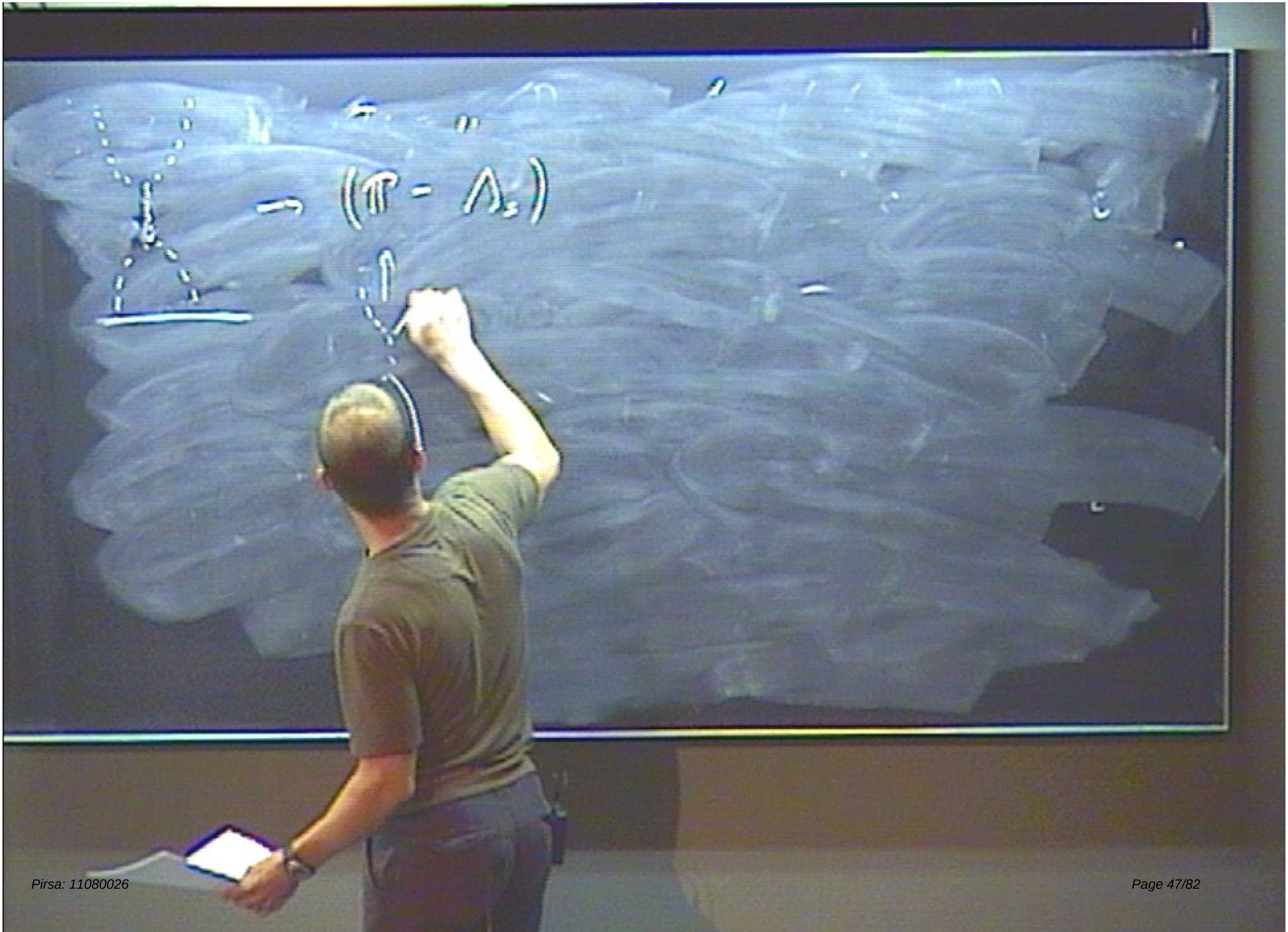
protected states: $\mathrm{tr}(\phi \cdots \phi)$, $\mathrm{tr}(\hat\phi \cdots \hat\phi)$, $\mathrm{tr}(Q_{\hat{\imath}} \tilde{Q}^{i} \cdots)$

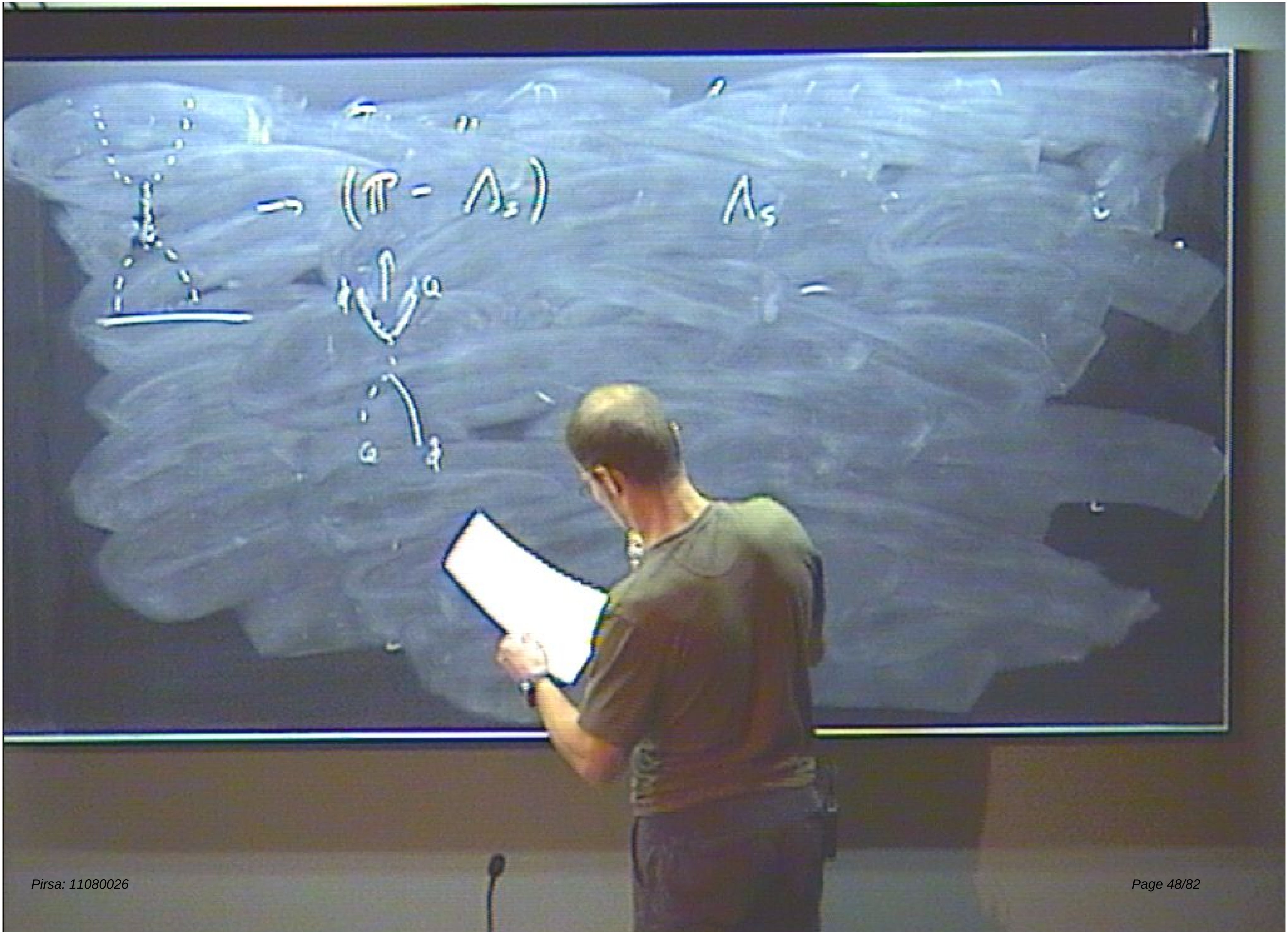
traceless symmetric SU(2) indices

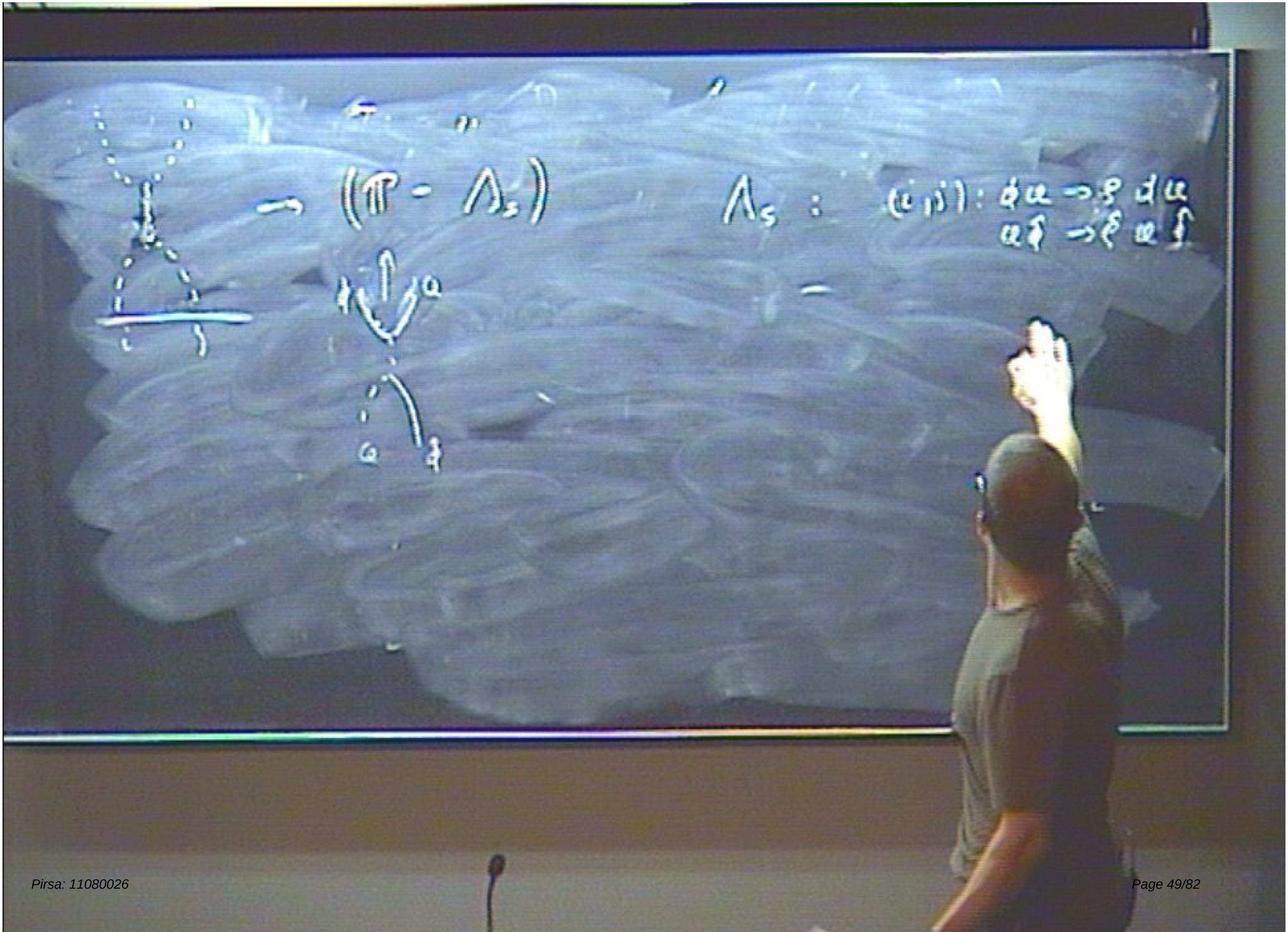
$\mathrm{tr}(\phi \cdots \phi\, Q_{\hat{\imath}}\, \hat\phi \cdots \hat\phi\, \tilde{Q}^{i} \cdots)$

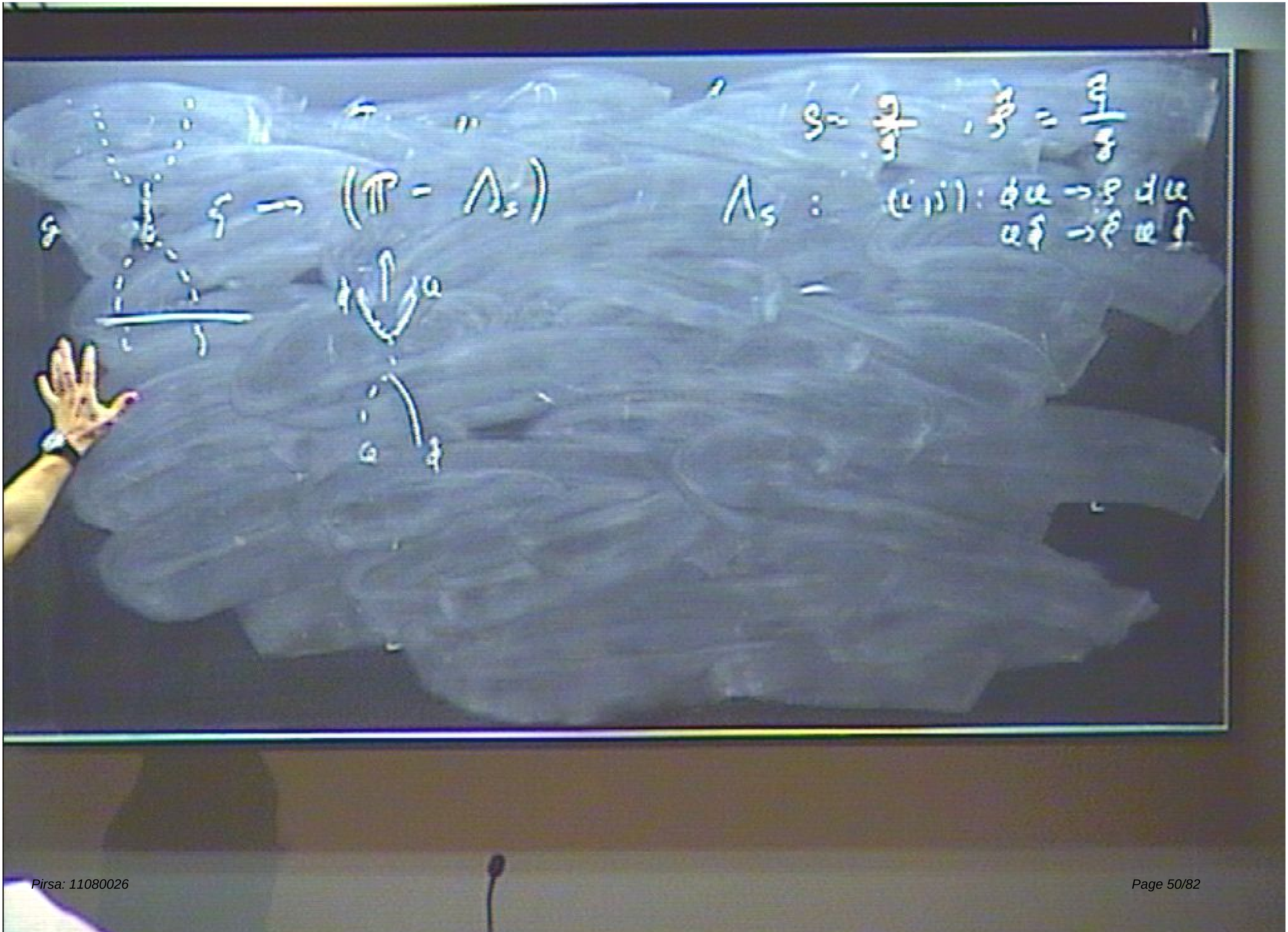
superpotential: ϕ — $\tilde{Q}$, Q $= i g\, \delta_i^{\;i}$, $\hat\phi$ — $Q_{\hat{\imath}}$, $\tilde{Q}^{i}$ $= -i g\, \delta_{\hat{\imath}}^{\;i}$




(π - Λs)


(π - Λs)
Λs

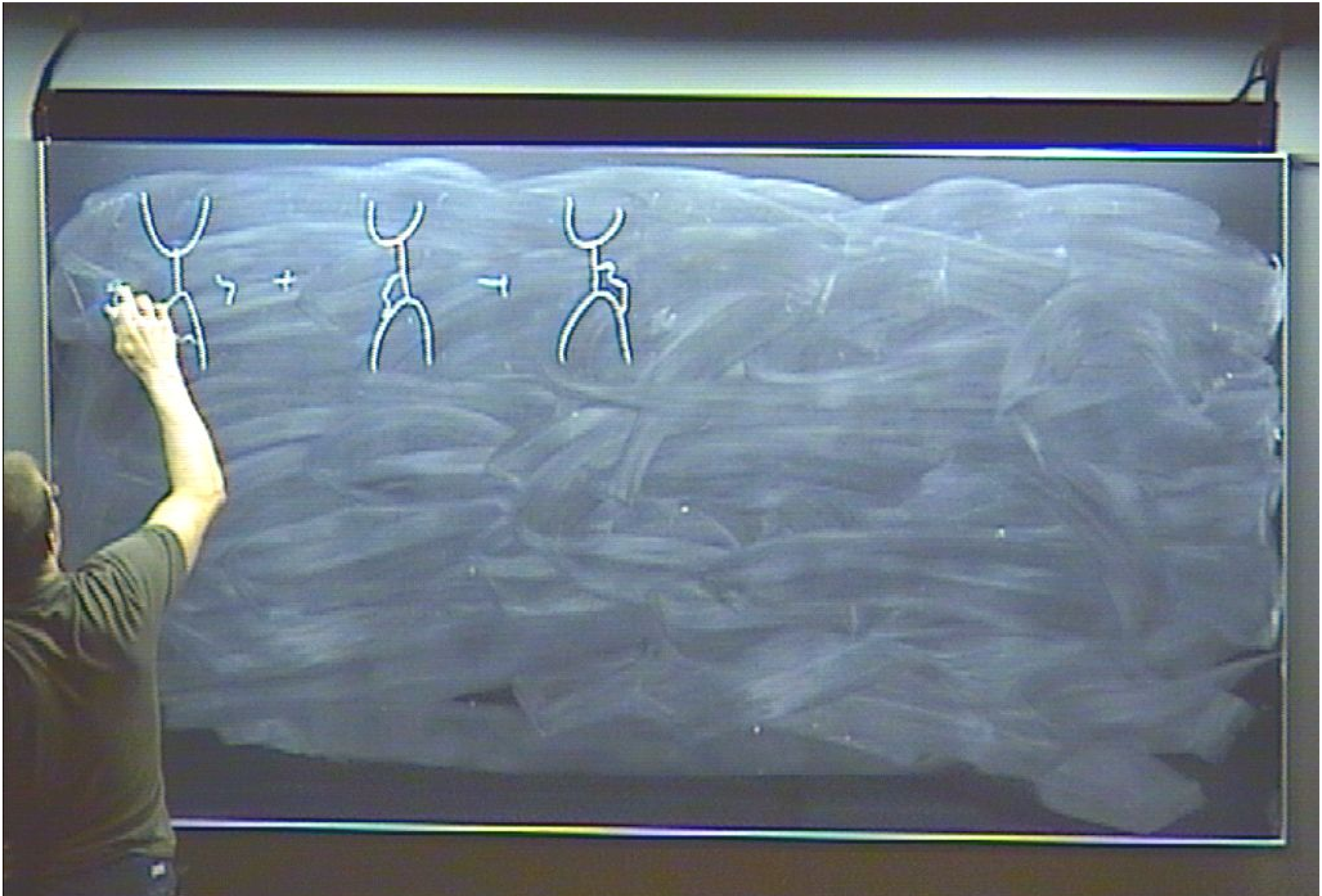

(Π - Λs)
Λs :


(π - Λs)
Λs :

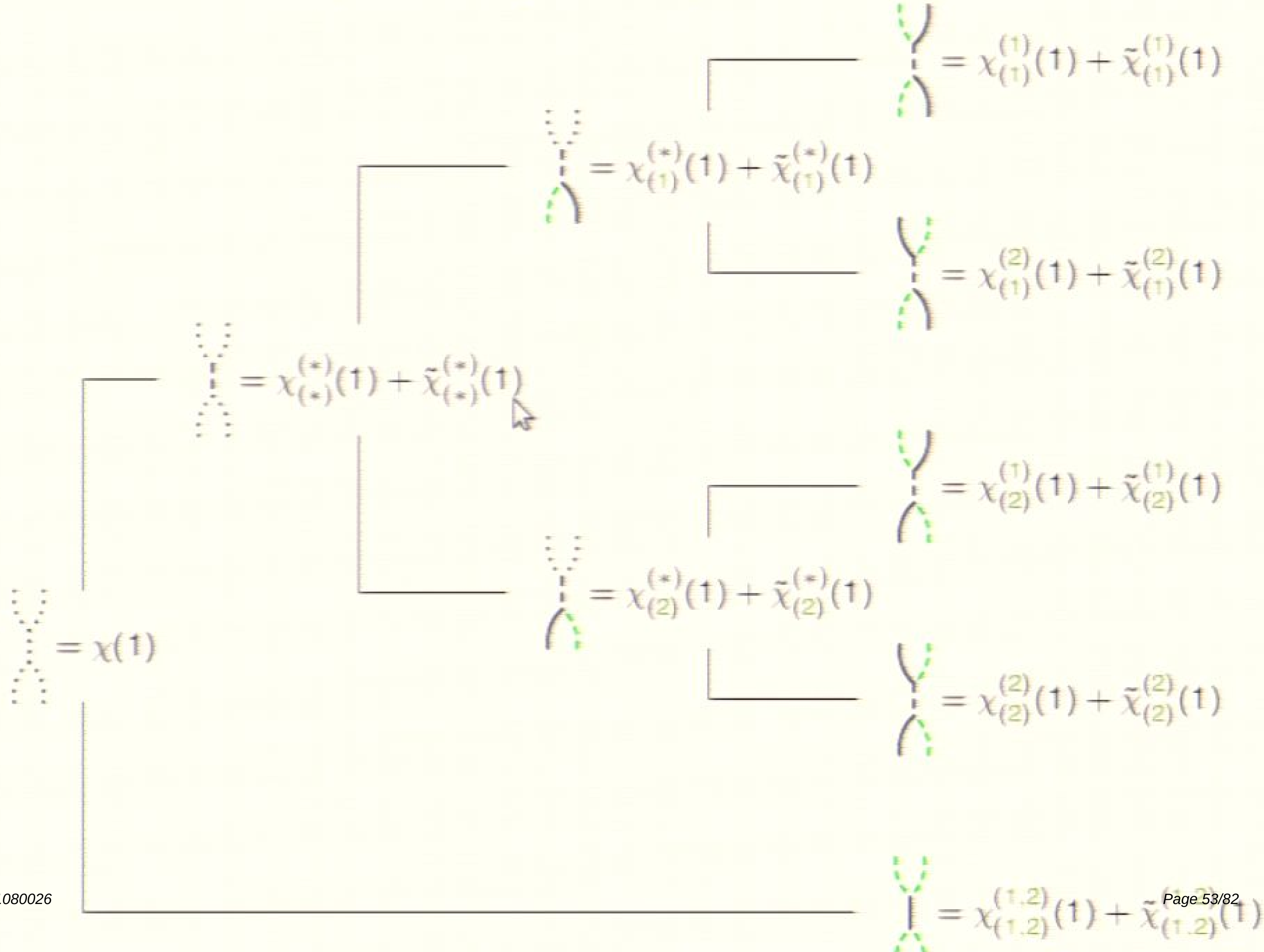
$\varsigma \to (\Pi - \Lambda_\varsigma)$

$$\varsigma = \frac{\bar q}{q}, \quad \bar\varsigma = \frac{q}{\bar q}$$

$$\Lambda_\varsigma : \quad (i,i') : \; \phi u \to \varsigma\, \phi u$$
$$u \bar\phi \to \bar\varsigma\, u \bar\phi$$



The interpolating theory: building block



The interpolating theory: building block

$$= \chi_{(1)}^{(1)}(1) + \tilde{\chi}_{(1)}^{(1)}(1)$$

$$= \chi_{(1)}^{(*)}(1) + \tilde{\chi}_{(1)}^{(*)}(1)$$

$$= \chi_{(1)}^{(2)}(1) + \tilde{\chi}_{(1)}^{(2)}(1)$$

$$= \chi_{(*)}^{(*)}(1) + \tilde{\chi}_{(*)}^{(*)}(1)$$

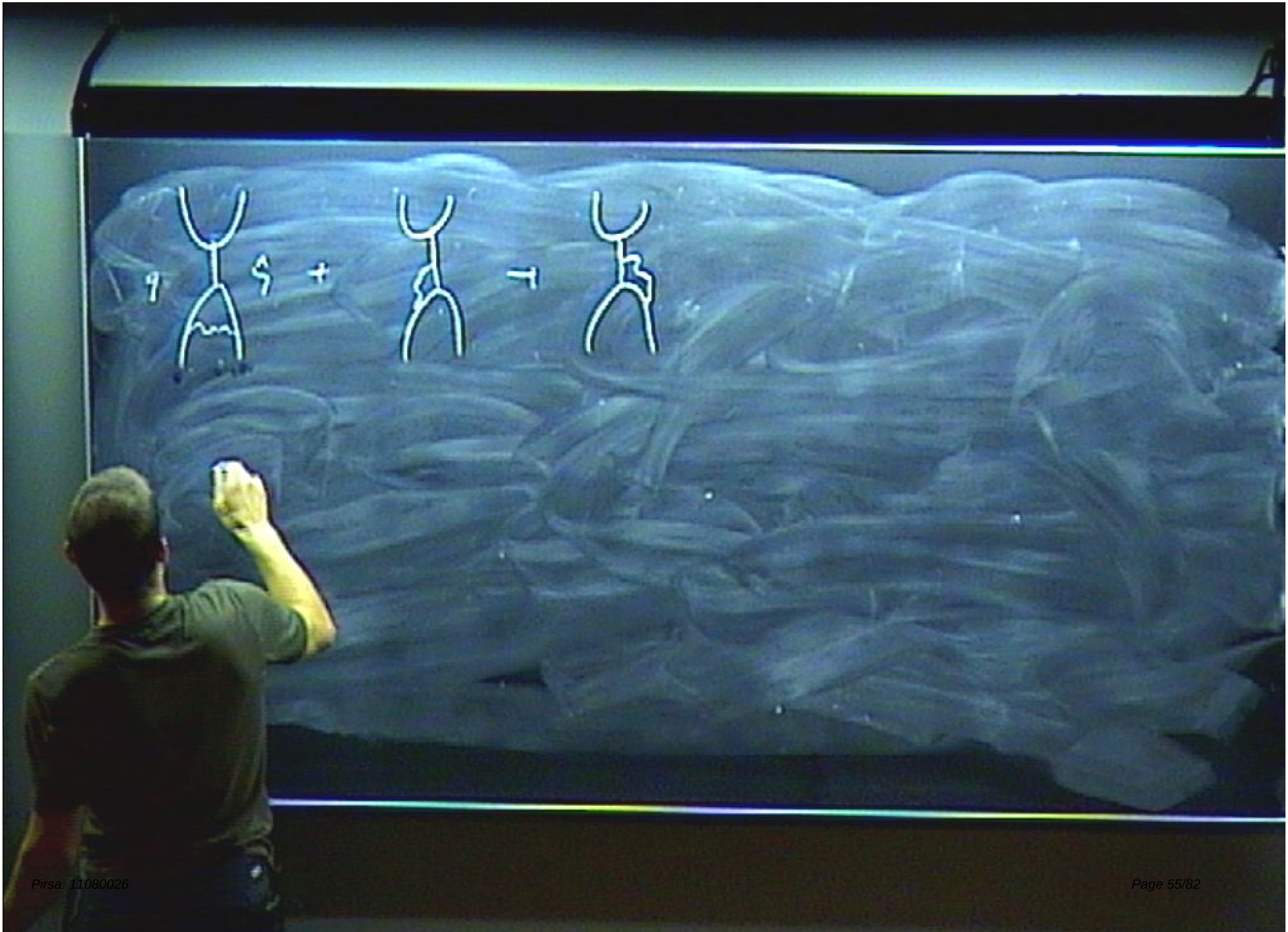
$$= \chi_{(2)}^{(1)}(1) + \tilde{\chi}_{(2)}^{(1)}(1)$$

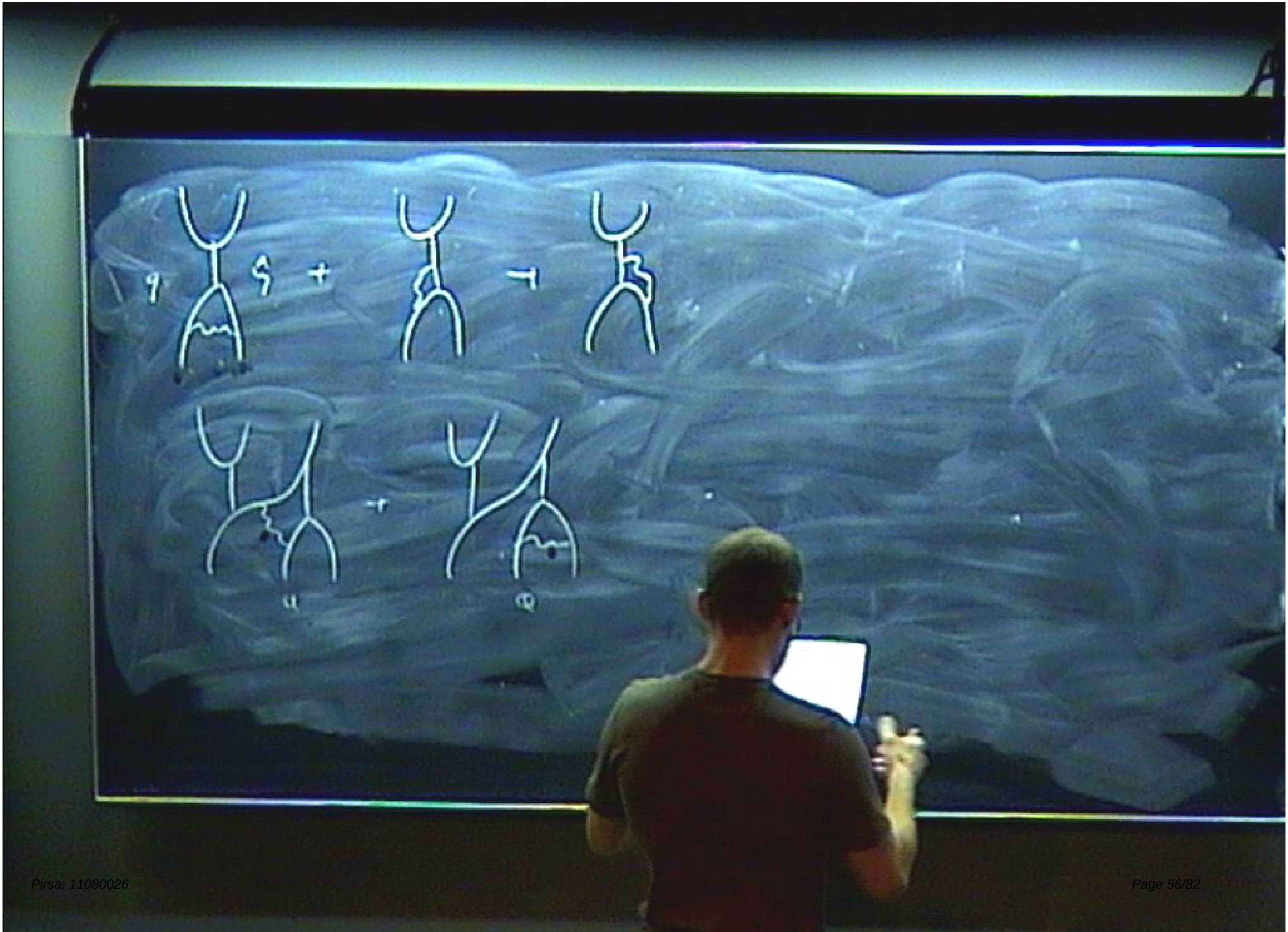
$$= \chi_{(2)}^{(*)}(1) + \tilde{\chi}_{(2)}^{(*)}(1)$$

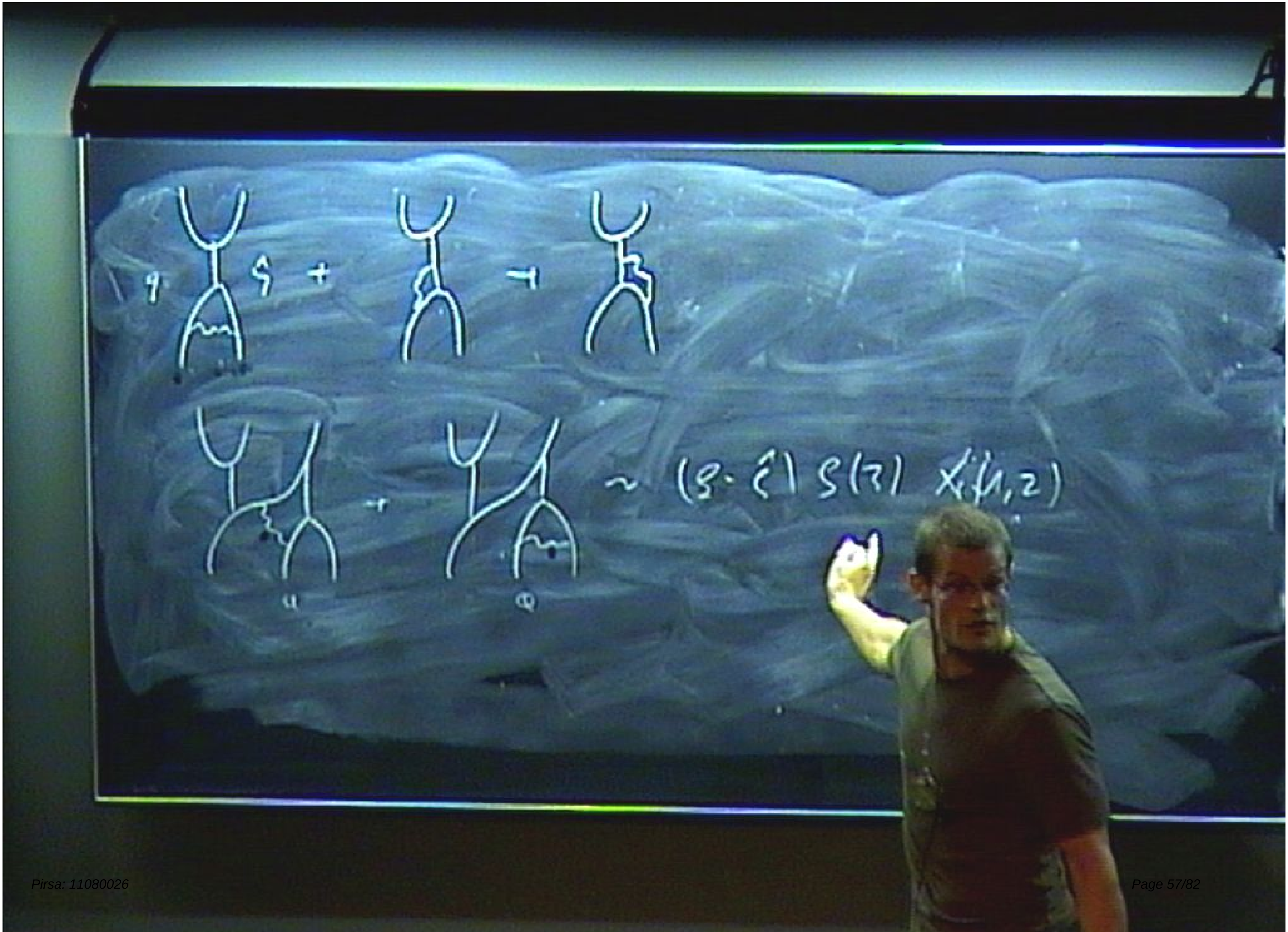
$$= \chi(1)$$

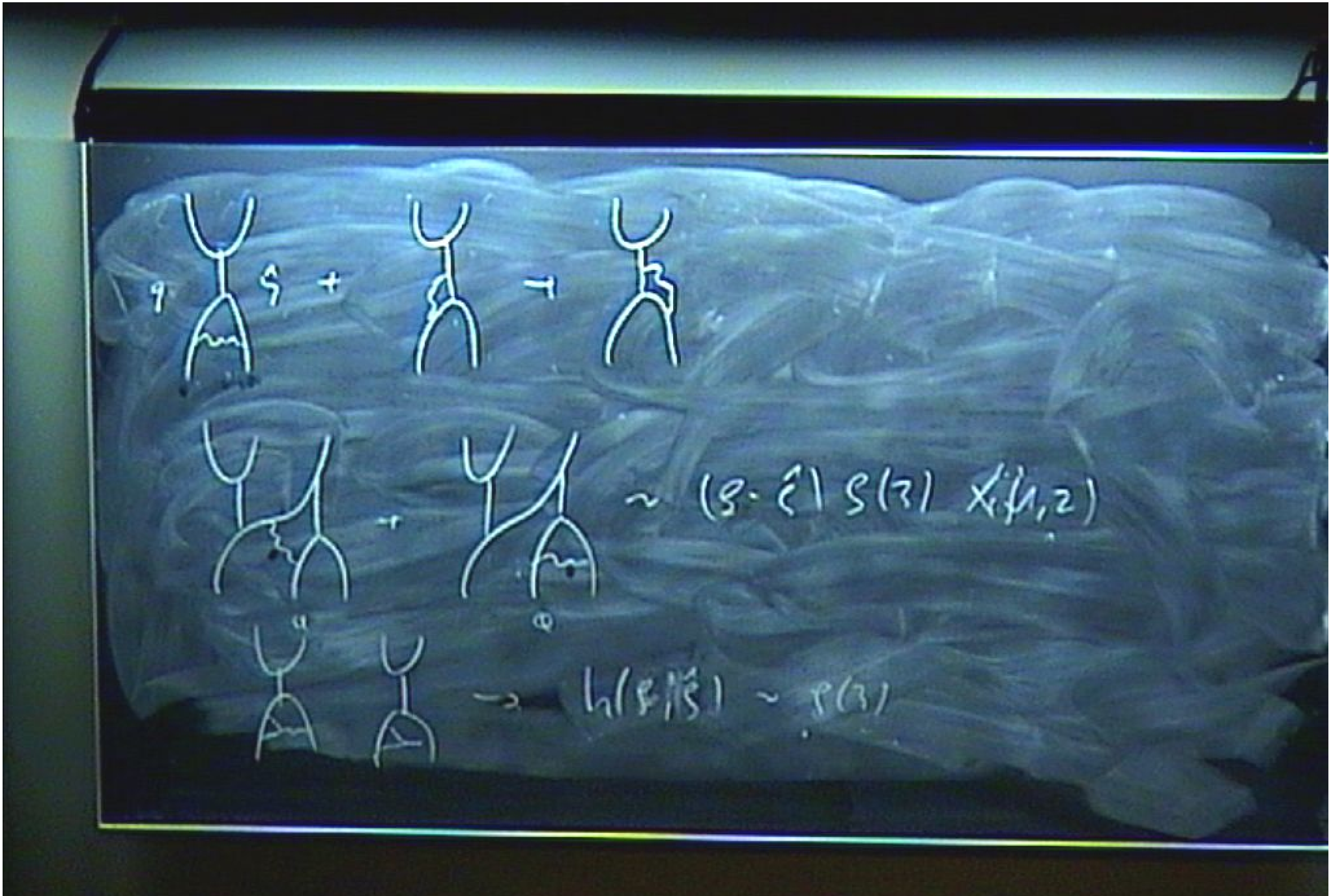
$$= \chi_{(2)}^{(2)}(1) + \tilde{\chi}_{(2)}^{(2)}(1)$$

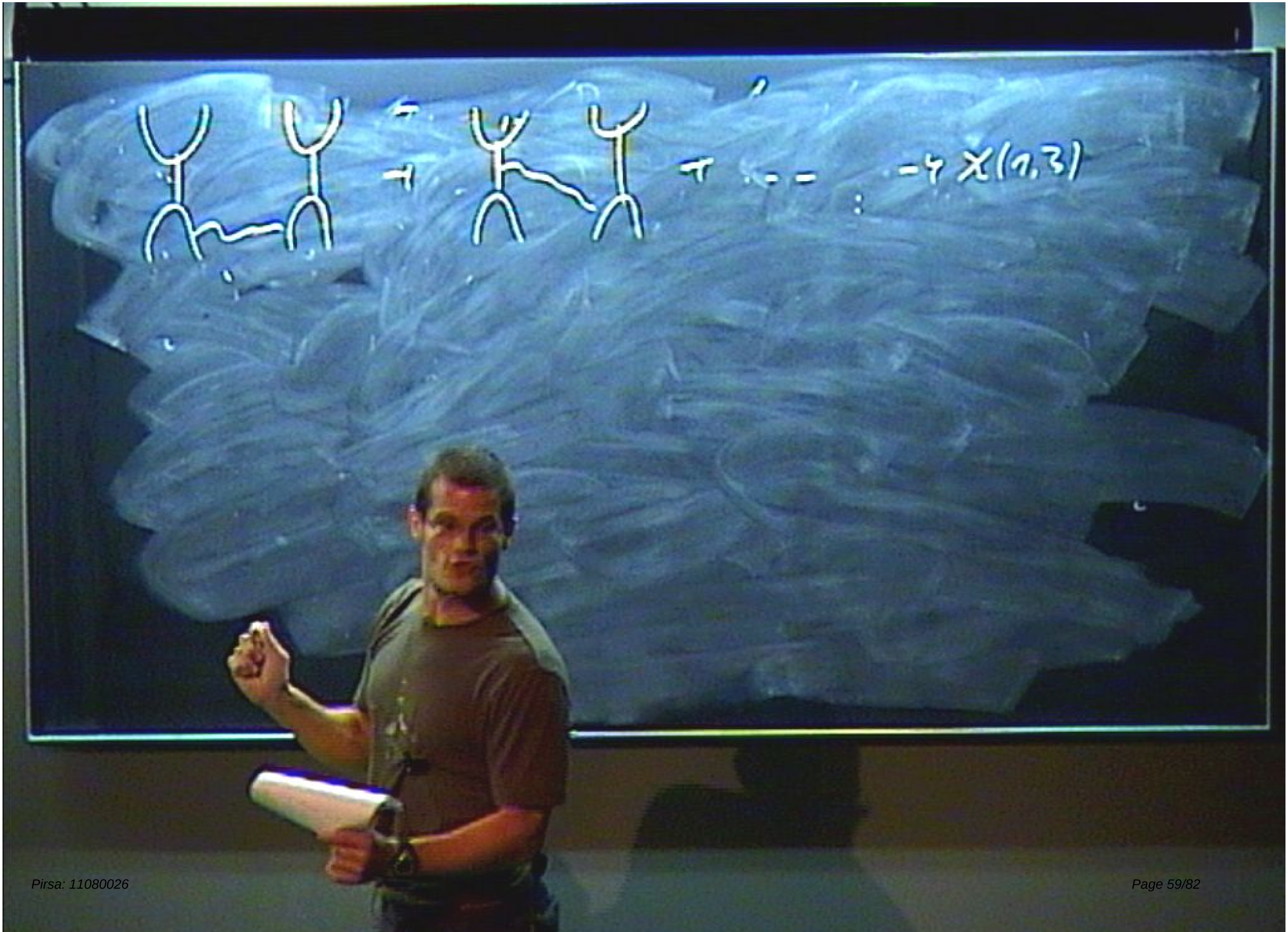
$$= \chi_{(1,2)}^{(1,2)}(1) + \tilde{\chi}_{(1,2)}^{(1,2)}(1)$$










+ + . . . → χ(1,3)

The interpolating theory: dilatation operator

$$D_1 = -2\,\chi(1)\,.$$

The interpolating theory: dilatation operator

$$D_1 = -2\,\chi(1)\,.$$

The interpolating theory: dilatation operator

- deformed pure scattering term
- anti-hermitean contributions: removed by non-unitary similarity trafo

$$D_1 = -2\,\chi(1)\,.$$

$$D_2 = -2(\,\chi(1,2) + \chi(2,1)) + 2(\rho + \hat\rho)\,\chi(1)$$

$$\begin{aligned} D_3 = &-4(\,\chi(1,2,3) + \chi(3,2,1) - 2(\rho+\hat\rho)(\chi(1,2) + \chi(2,1)) \\ &\quad + \chi(1,2,1) + \chi(2,1,2) + (\rho+\hat\rho)^2\,\chi(1)) \\ &- 4(\hat\rho\chi^{(*,*)}_{(*,*)}(1,3) + \rho\tilde\chi^{(*,*)}_{(*,*)}(1,3)) + 2(\,\chi(2,1,3) - \chi(1,3,2)) \\ &+ 2\zeta(3)(\rho-\hat\rho)((\rho-\hat\rho)\,\chi(1) \\ &\qquad - \hat\rho(\chi^{(*)}_{(1)}(1) + \tilde\chi^{(*)}_{(2)}(1)) + \rho(\chi^{(*)}_{(2)}(1) + \tilde\chi^{(*)}_{(1)}(1)) \\ &\qquad - \chi^{(*)}_{(2)}(1,2) + \chi^{(*,3)}_{(1,2)}(1,2) + \chi^{(*)}_{(2)}(2,1) + \chi^{(1,*)}_{(2,3)}(2,1) \\ &\qquad + \tilde\chi^{(*)}_{(2)}(1,2) - \tilde\chi^{(*,3)}_{(1,2)}(1,2) - \tilde\chi^{(*)}_{(2)}(2,1) - \tilde\chi^{(1,*)}_{(2,3)}(2,1)) \end{aligned}$$

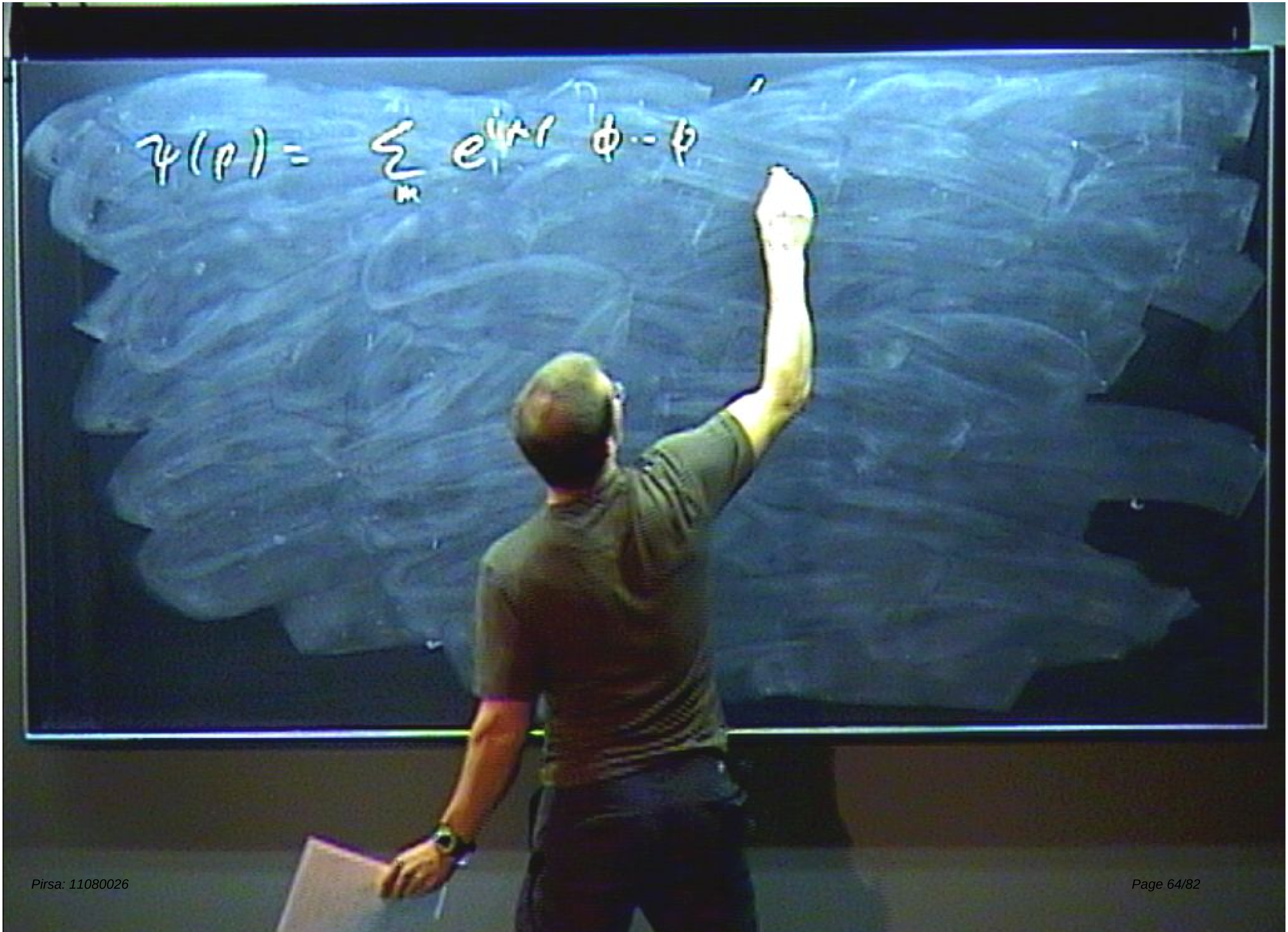
The interpolating theory: dilatation operator

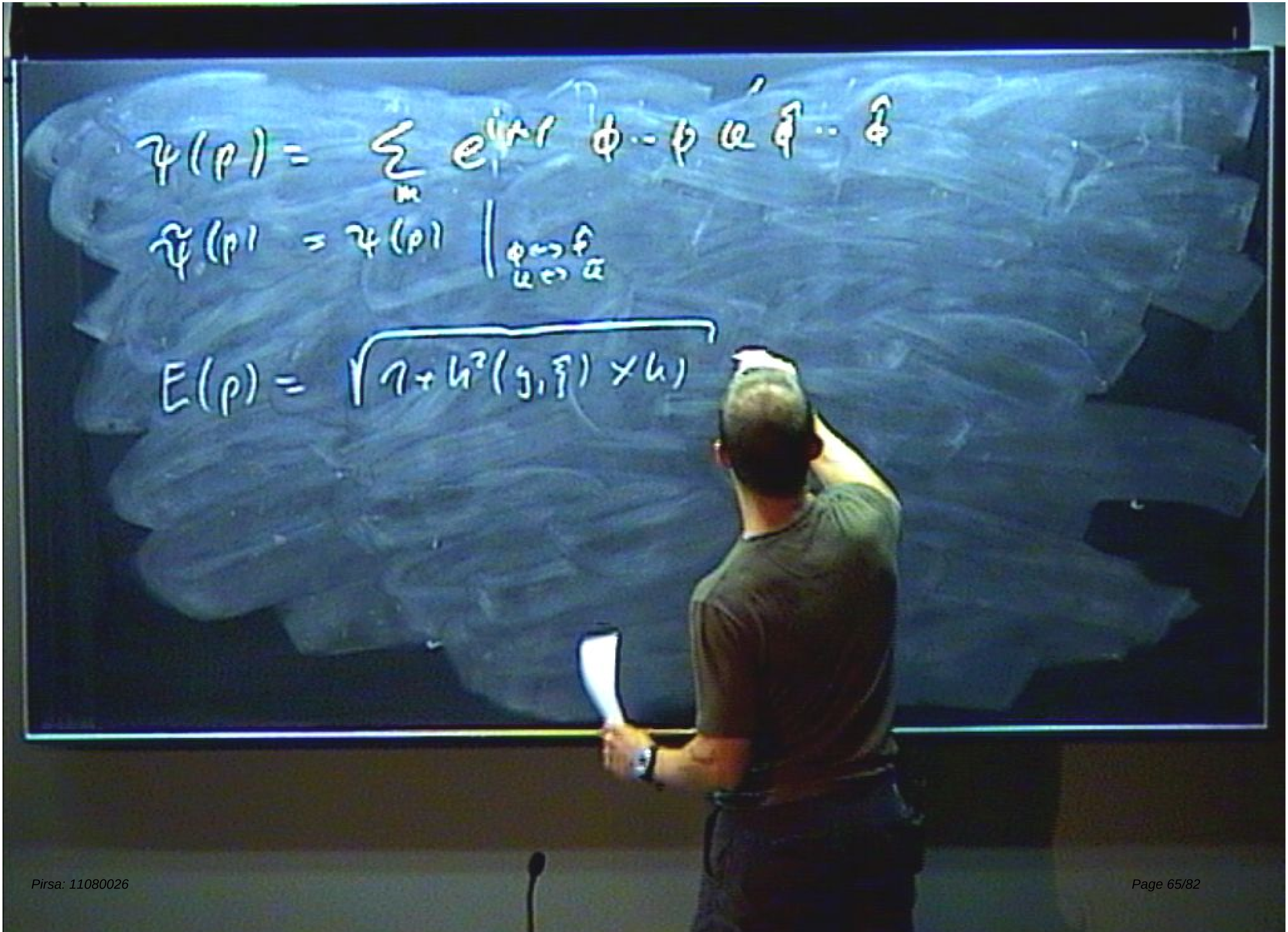
- deformed pure scattering term
- maximal transcendental contributions $\rightarrow h^2(\rho, \hat{\rho})$, $f(\rho, \hat{\rho})$

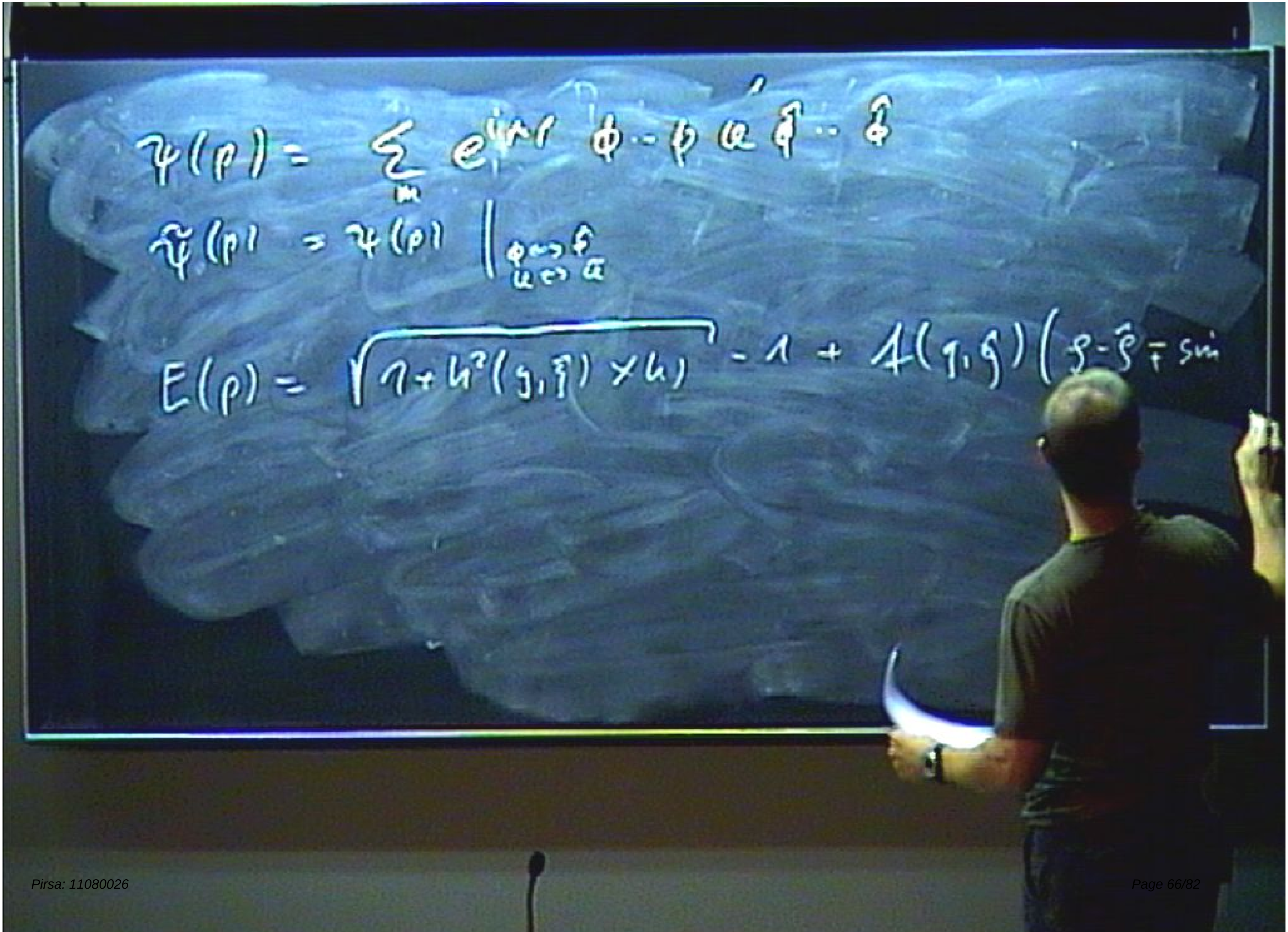
$$\mathcal{D}_1 = -2\,\chi(1)\,,$$

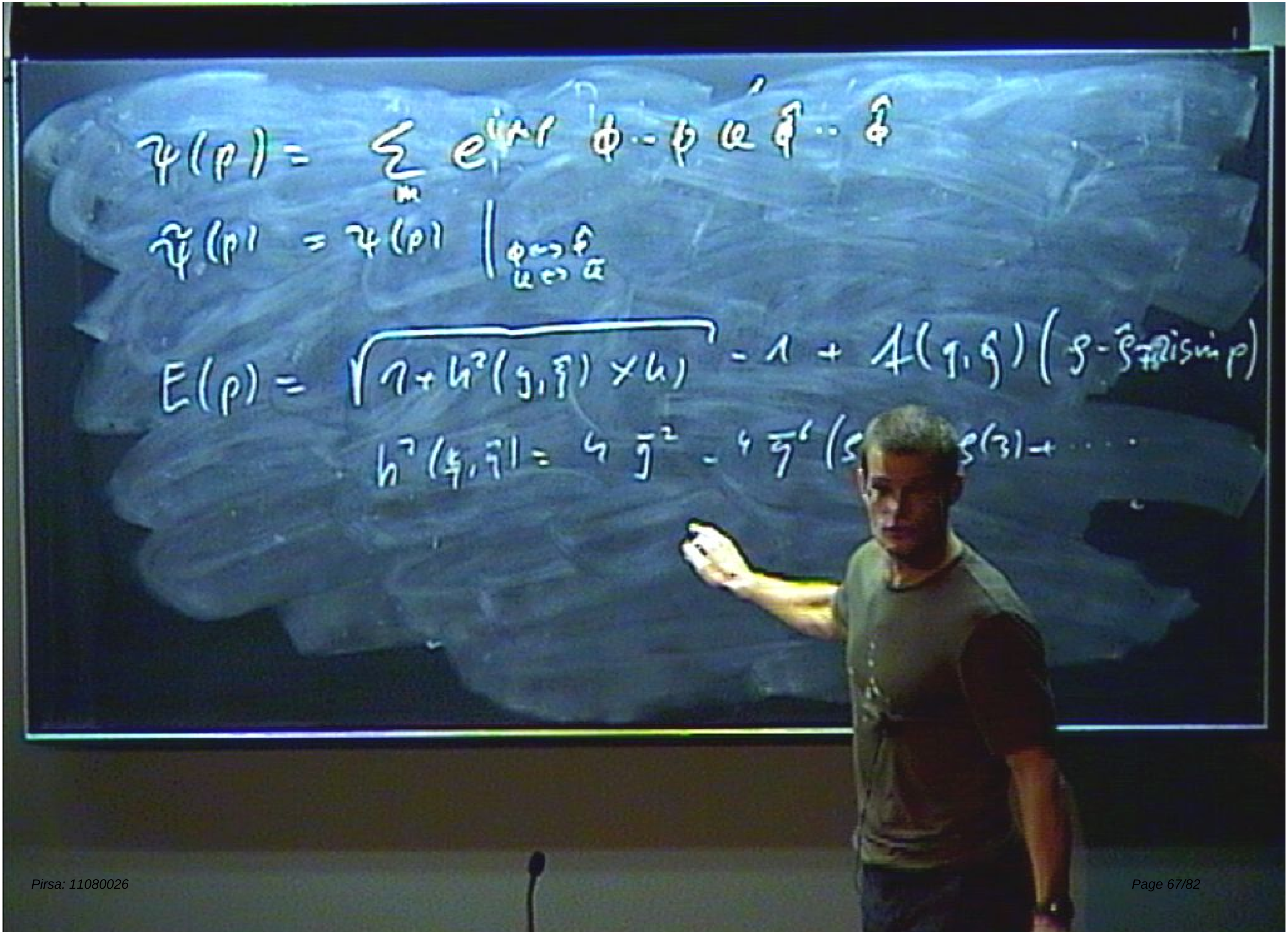
$$\mathcal{D}_2 = -2(\,\chi(1,2) + \chi(2,1)) + 2(\rho + \hat{\rho})\,\chi(1)$$

$$\begin{aligned}\mathcal{D}_3 = &-4(\,\chi(1,2,3) + \chi(3,2,1) - 2(\rho + \hat{\rho})(\chi(1,2) + \chi(2,1)) \\ &\quad + \chi(1,2,1) + \chi(2,1,2) + (\rho + \hat{\rho})^2\,\chi(1)) \\ &-4(\hat{\rho}\chi^{(*,*)}_{(*,*)}(1,3) + \rho\tilde{\chi}^{(*,*)}_{(*,*)}(1,3)) \\ &+2\zeta(3)(\rho - \hat{\rho})((\rho - \hat{\rho})\,\chi(1) \\ &\qquad - (\rho + \hat{\rho})(\chi^{(1)}_{(1)}(1) - \chi^{(2)}_{(2)}(1) - \tilde{\chi}^{(1)}_{(1)}(1) + \tilde{\chi}^{(2)}_{(2)}(1)))\end{aligned}$$

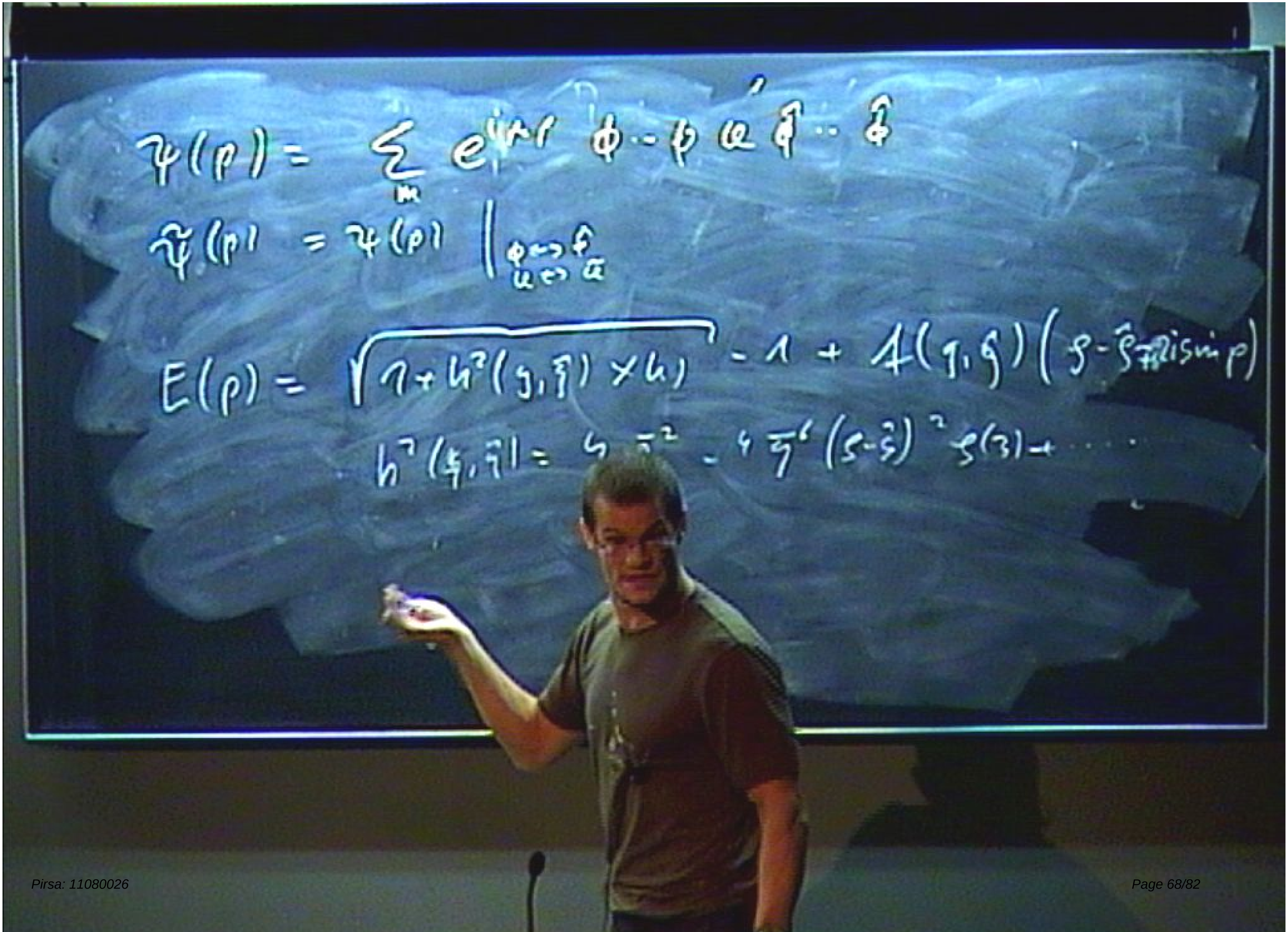



$\psi(p) = \sum_m e^{im\gamma}\, \phi \cdots \phi\, \alpha\, \hat{\phi} \cdots \hat{\phi}$
$\tilde{\psi}(p) = \psi(p) \Big|_{\substack{\phi \leftrightarrow \hat{\phi} \\ \alpha \leftrightarrow \hat{\alpha}}}$
$E(p) = \sqrt{1 + h^2(g, \xi) \times h)}$


$\psi(p) = \sum_m e^{in\gamma} \phi \cdots p \, \alpha' \hat{q} \cdots \hat{q}$
$\tilde{\psi}(p) = \psi(p) \big|_{\phi \leftrightarrow \hat{f},\ \alpha \leftrightarrow \tilde{\alpha}}$
$E(p) = \sqrt{1 + h^2(g,\xi)\, x(u)} - 1 + f(g,g)\,(\xi - \bar{\xi} \mp \sin$



$\psi(p) = \sum_m e^{imp}\, \phi \cdots \phi\; \alpha\; \hat{\phi} \cdots \hat{\phi}$
$\tilde{\psi}(p) = \psi(p) \big|_{\phi \leftrightarrow \hat{\phi},\ \alpha \leftrightarrow \hat{\alpha}}$
$E(p) = \sqrt{1 + h^2(g, \bar{g})\, \kappa(u)} - 1 + f(g, \bar{g})\,(g - \bar{g} \ldots \sin p)$
$h^2(g, \bar{g}) = 4\bar{g}^2 - 4\bar{g}^4 (\ldots \zeta(3) + \cdots$



$$\Psi(p) = \sum_m e^{imp}\, \phi \cdots \phi\, a'\, \hat{\phi} \cdots \hat{\phi}$$

$$\tilde{\Psi}(p) = \Psi(p)\Big|_{\substack{\phi \leftrightarrow \hat{\phi} \\ a \leftrightarrow \hat{a}}}$$

Gadde Rastelli

$$E(p) = \sqrt{1 + h^2(g,\hat{g})\, x(h)} - 1 + f(g,\hat{g})\,(g - \hat{g} \ldots i \sin p)$$

$$h^2(g,\hat{g}) = 4 g^2 - 4 g^6 (g-\hat{g})^2 \zeta(3) + \cdots$$

$$f(g,\hat{g}) = -2 g^6 (g^2 - \hat{g}^2)\, \zeta(3)$$

$$\Psi(p) = \sum_{m} e^{ipm} \phi \cdots \phi \, \mathbb{Q} \, \hat{\phi} \cdots \hat{\phi}$$

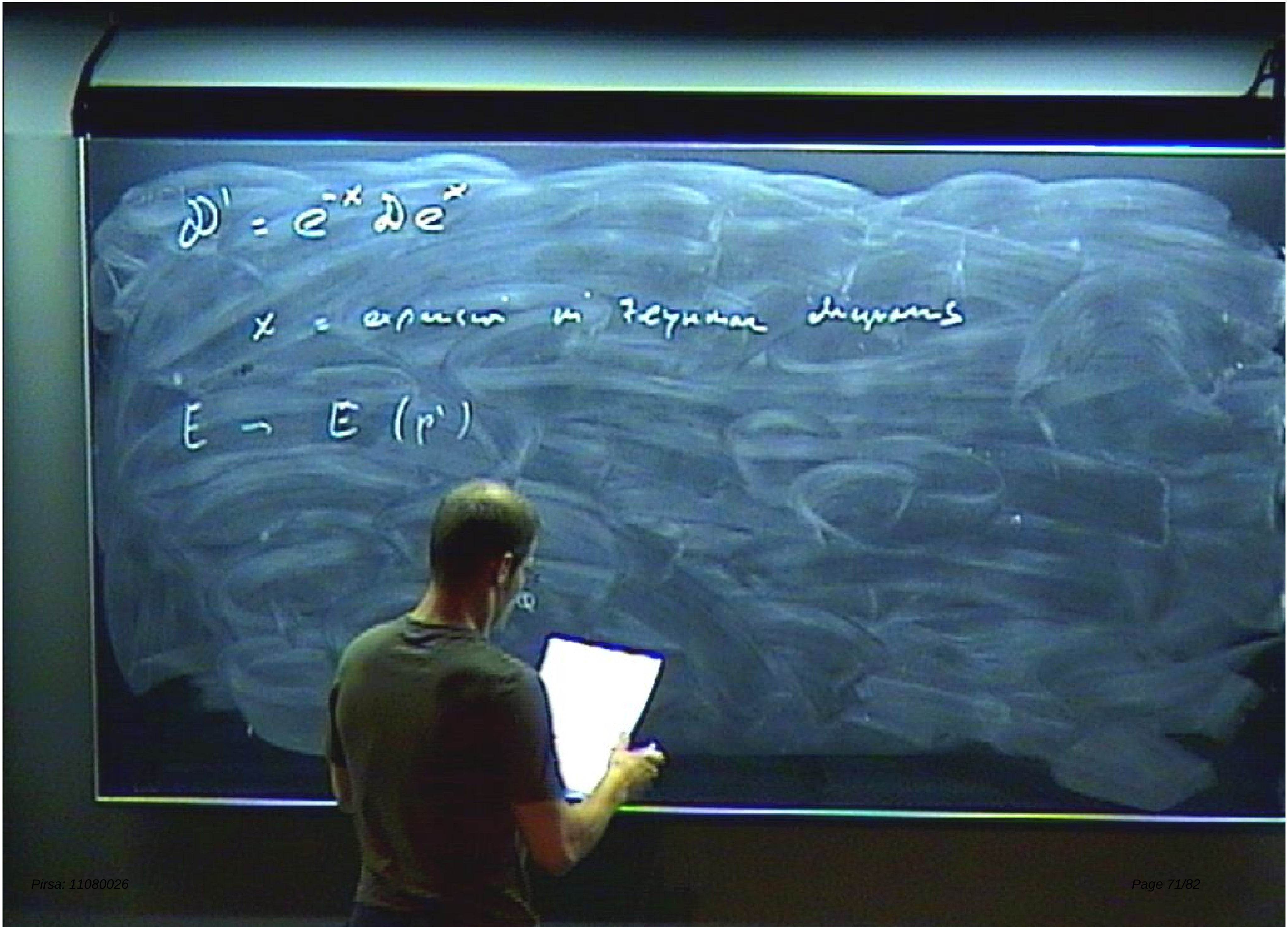
$$\tilde{\Psi}(p) = \Psi(p) \Big|_{\substack{\phi \leftrightarrow \hat{\phi} \\ \mathbb{Q} \leftrightarrow \bar{\mathbb{Q}}}}$$

Gadde Rastelli

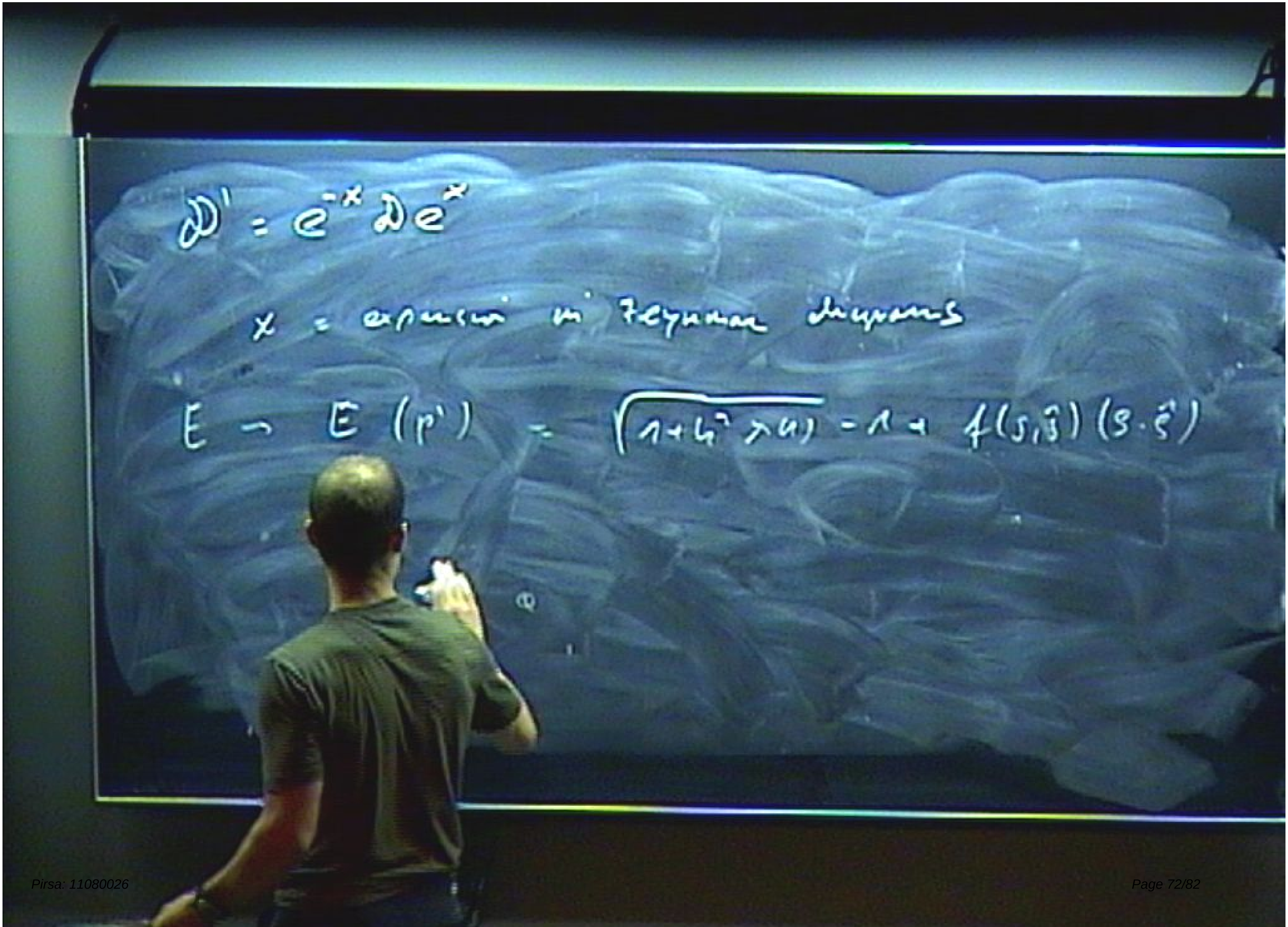
$$E(p) = \sqrt{1 + h^2(g,\hat{g})\, \times h)} - 1 + f(g,\hat{g})\,(g - \hat{g})\, 2 i \sin p$$

$$h^2(g,\hat{g}) = 4 \hat{g}^2 - 4 \hat{g}^6 (g-\hat{g})^2 \zeta(3) + \cdots$$

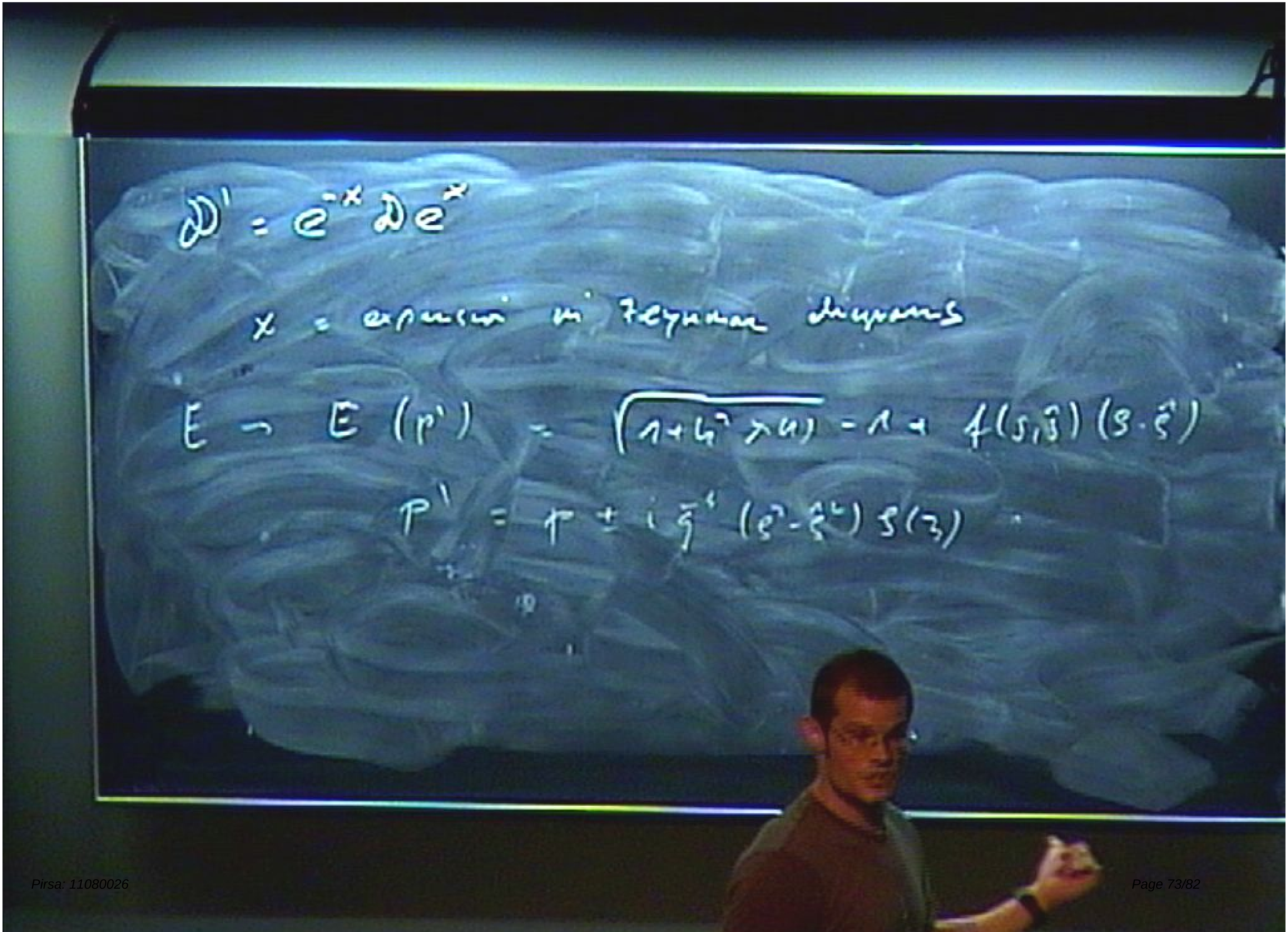
$$f(g,\hat{g}) = -2 \hat{g}^6 (g^2 - \hat{g}^2)\, \zeta(3)$$



D' = e^{-X} D e^{X}
X = expansion in Feynman diagrams
E → E(p')



$\mathcal{D}' = e^{-x} \mathcal{D} e^{x}$
x = expansion in Feynman diagrams



$\mathcal{D}' = e^{-X} \mathcal{D} e^{X}$
X = expansion in Feynman diagrams

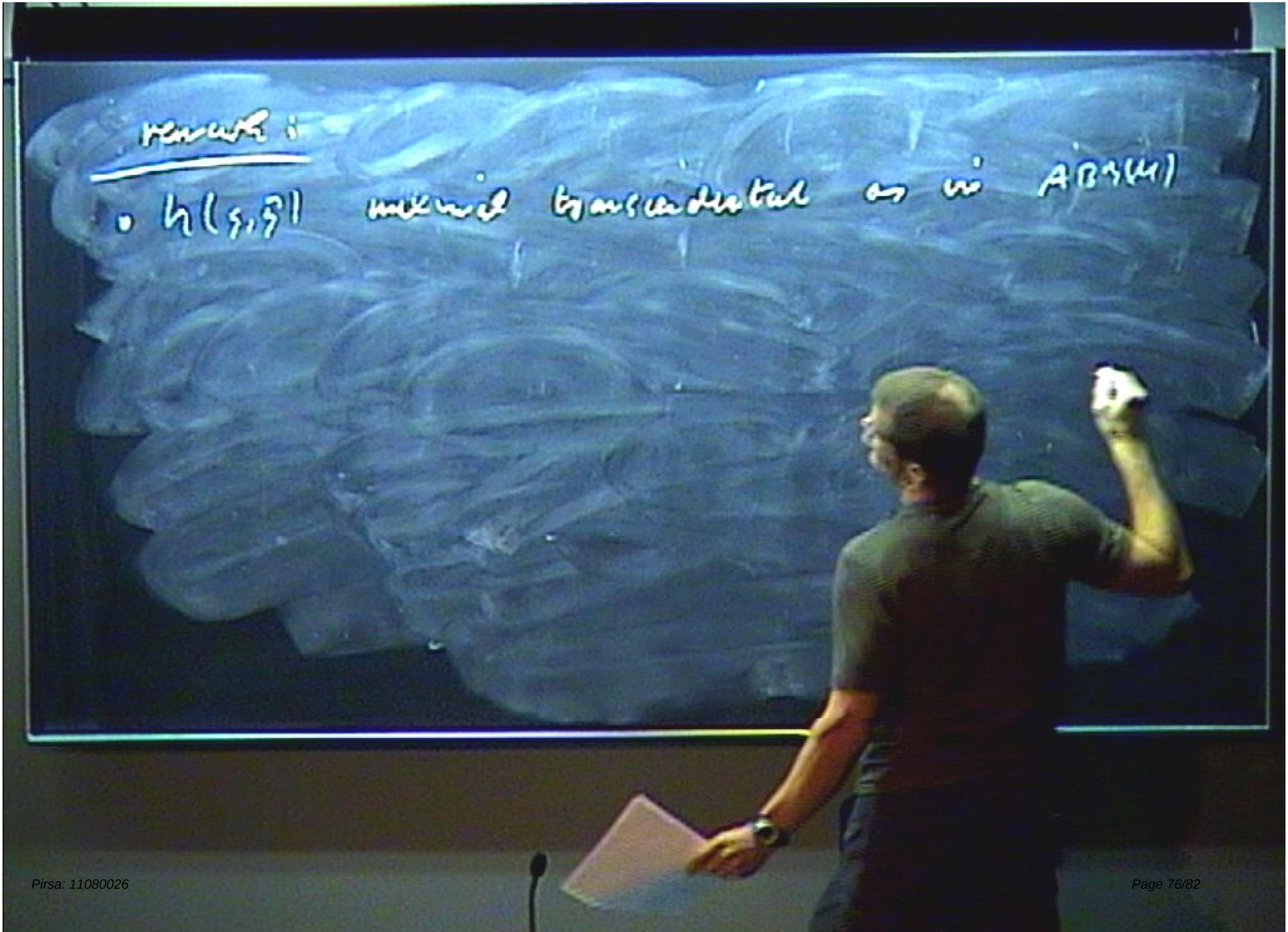
$$\mathcal{D}' = e^{-X}\,\mathcal{D}\,e^{X}$$

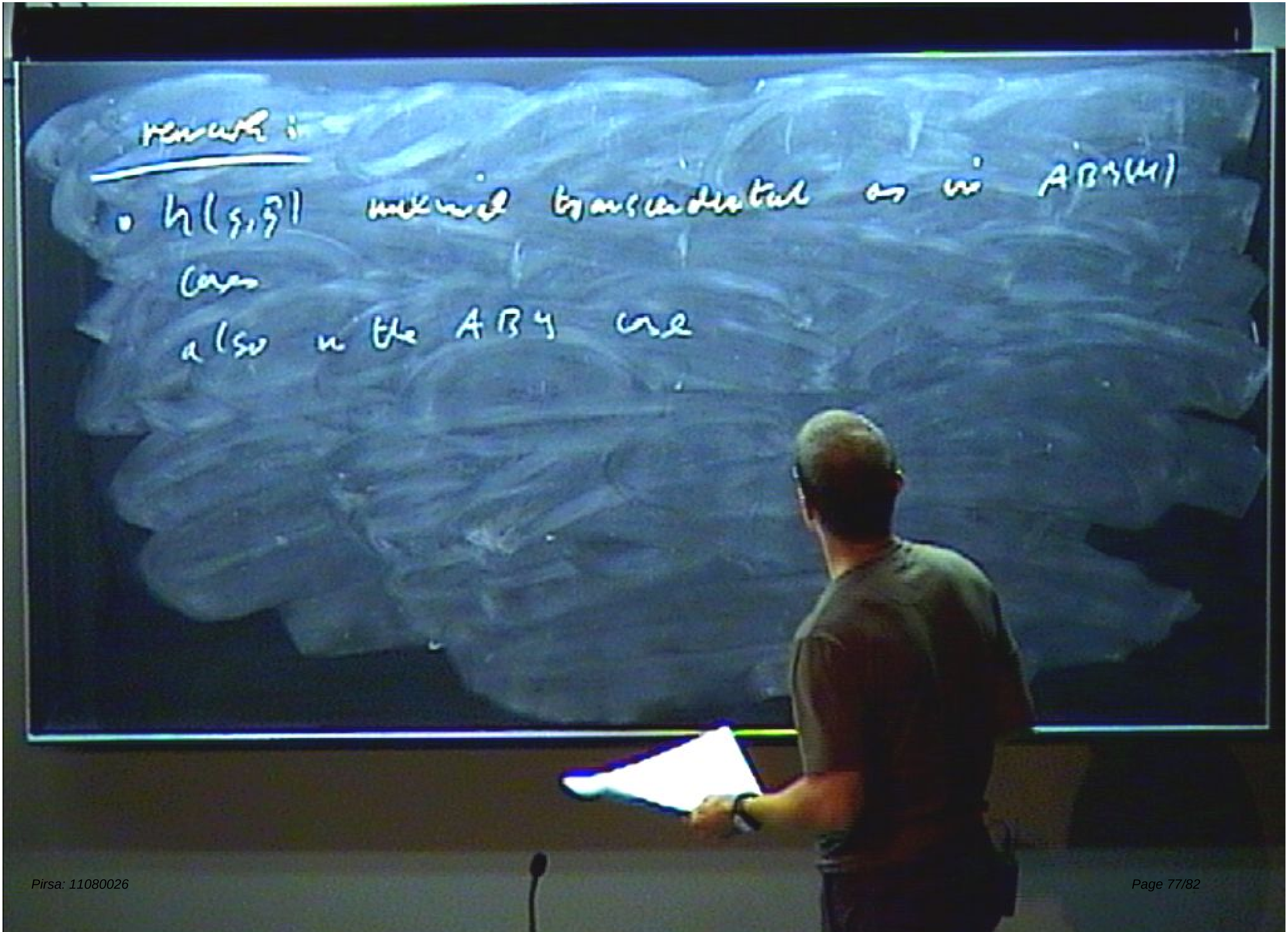
X = expansion in Feynman diagrams

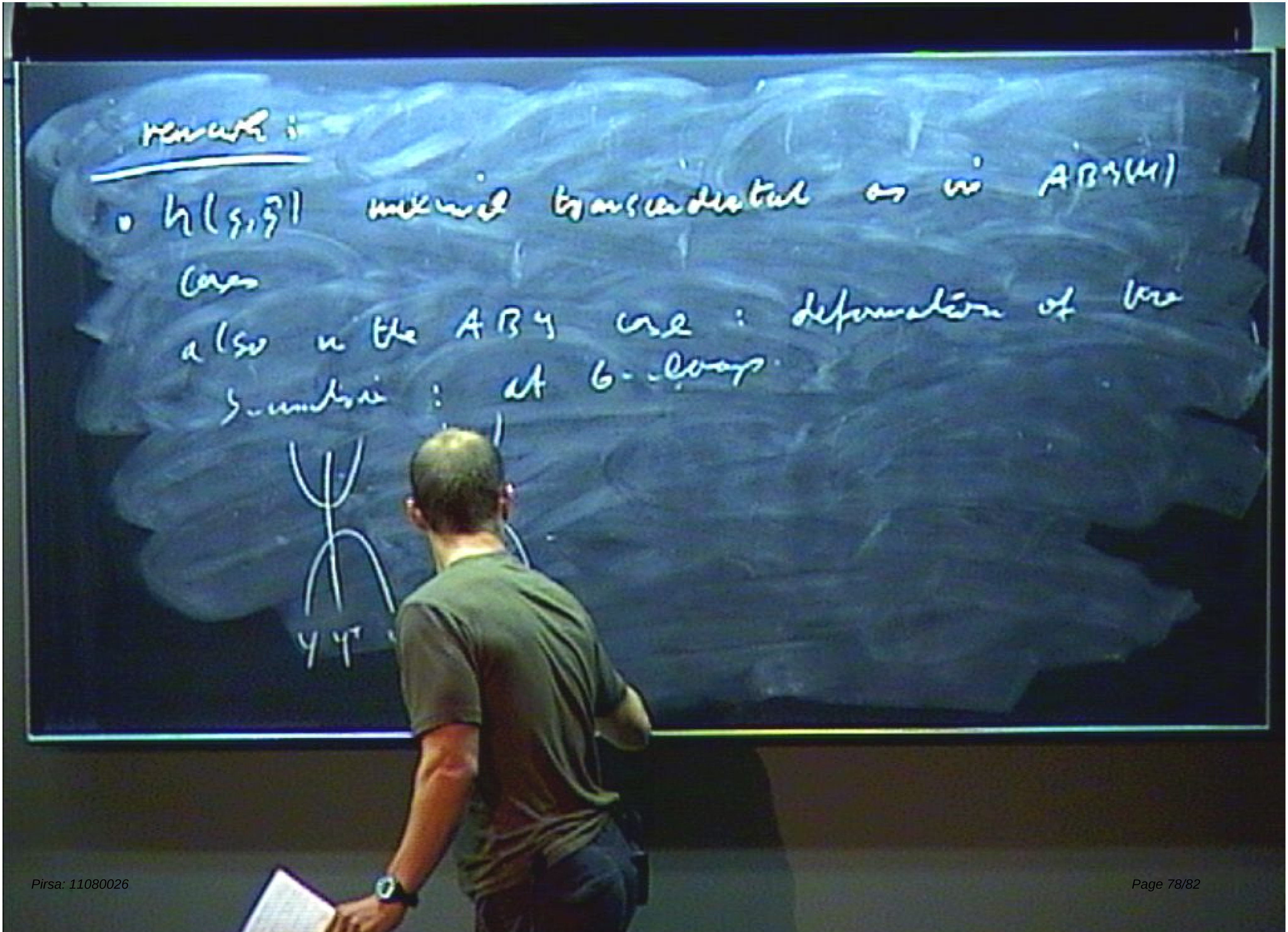
$$E \to E(p') = \sqrt{1+h^2\,\lambda(h)} - 1 + f(S,\bar{S})\,(S\cdot\bar{S}^2)$$

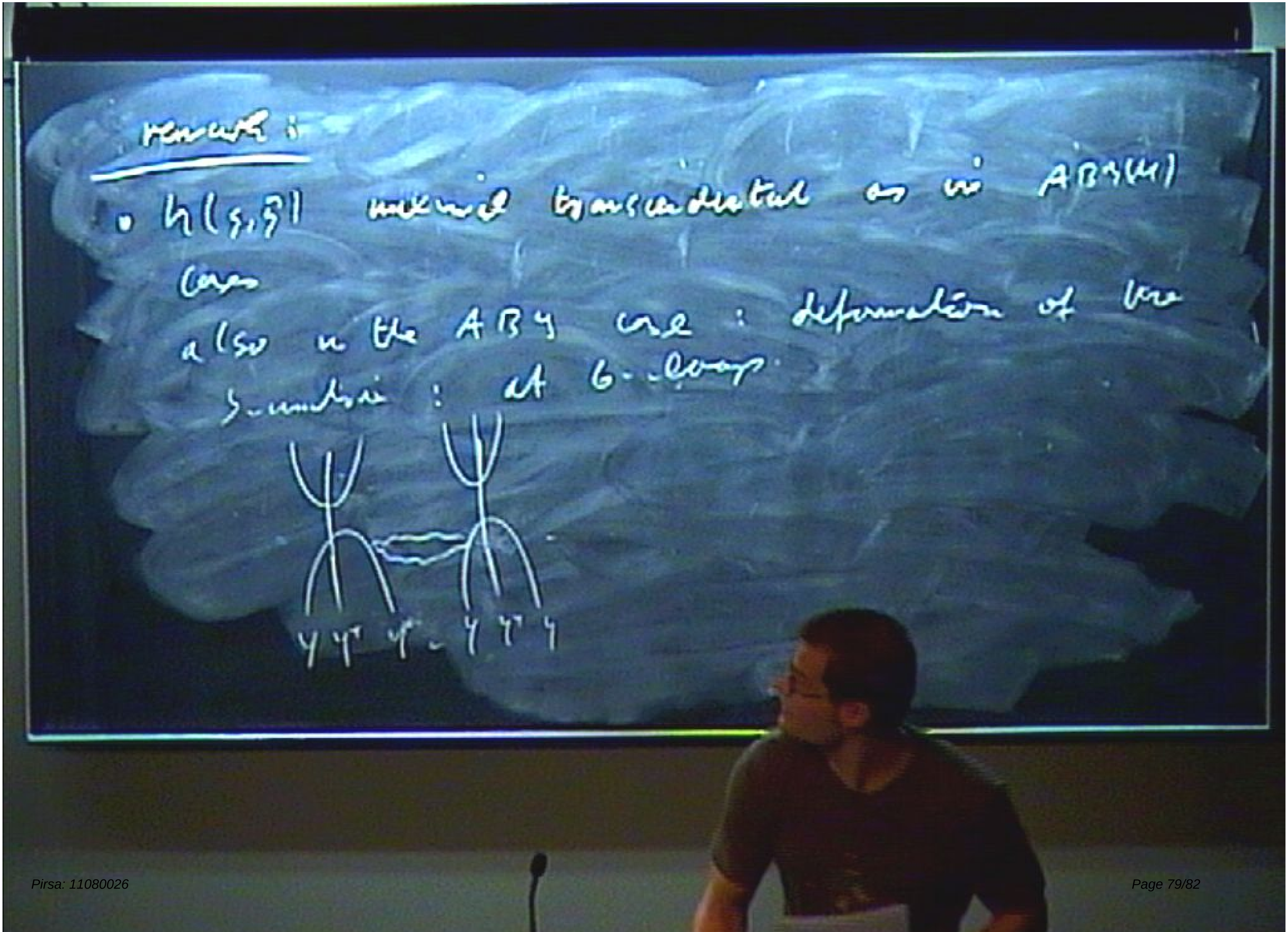
$$p' = p \pm i\,\bar{g}^2\,(S^2-\bar{S}^2)\,S(z)$$

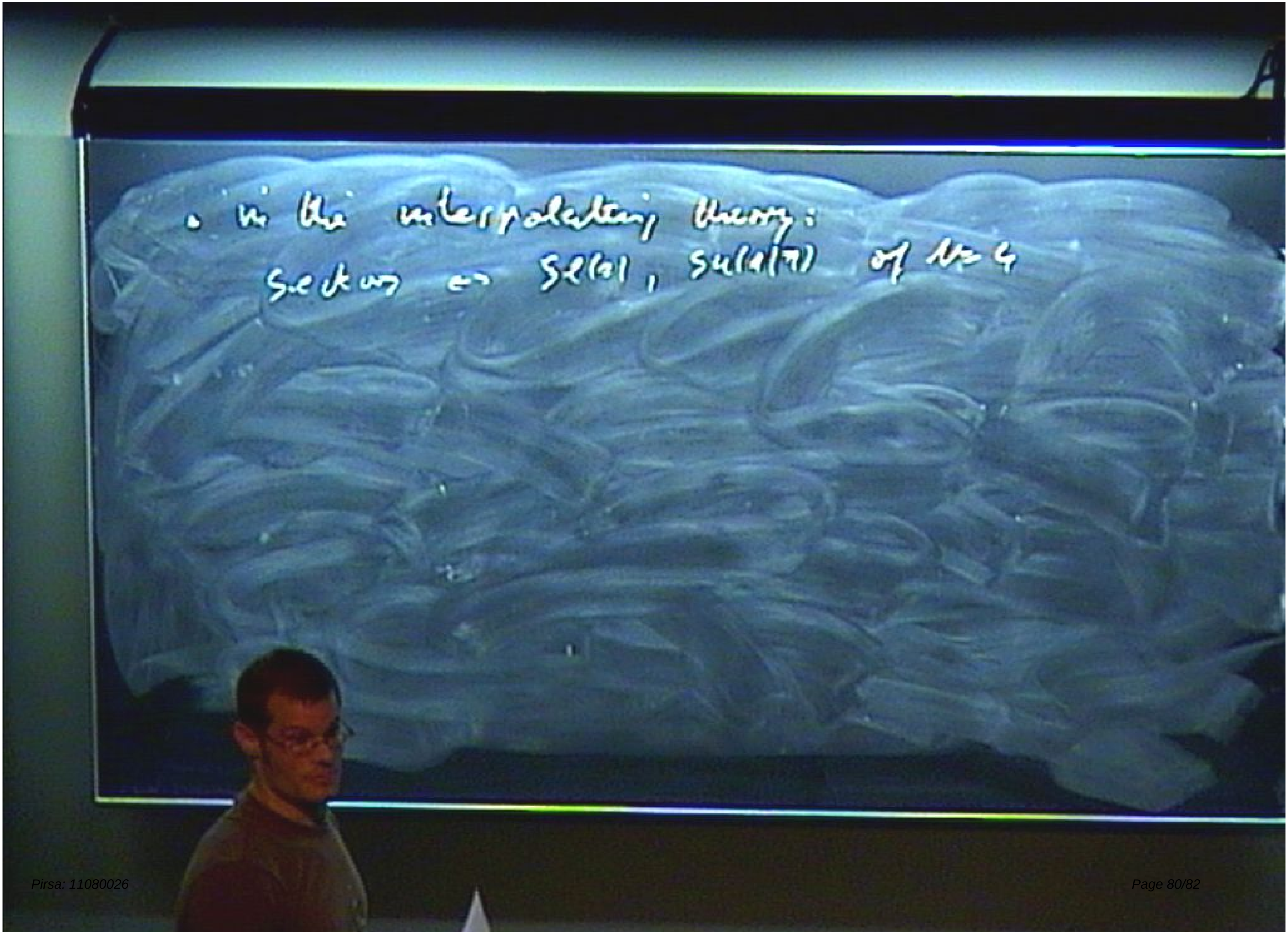

Remark :

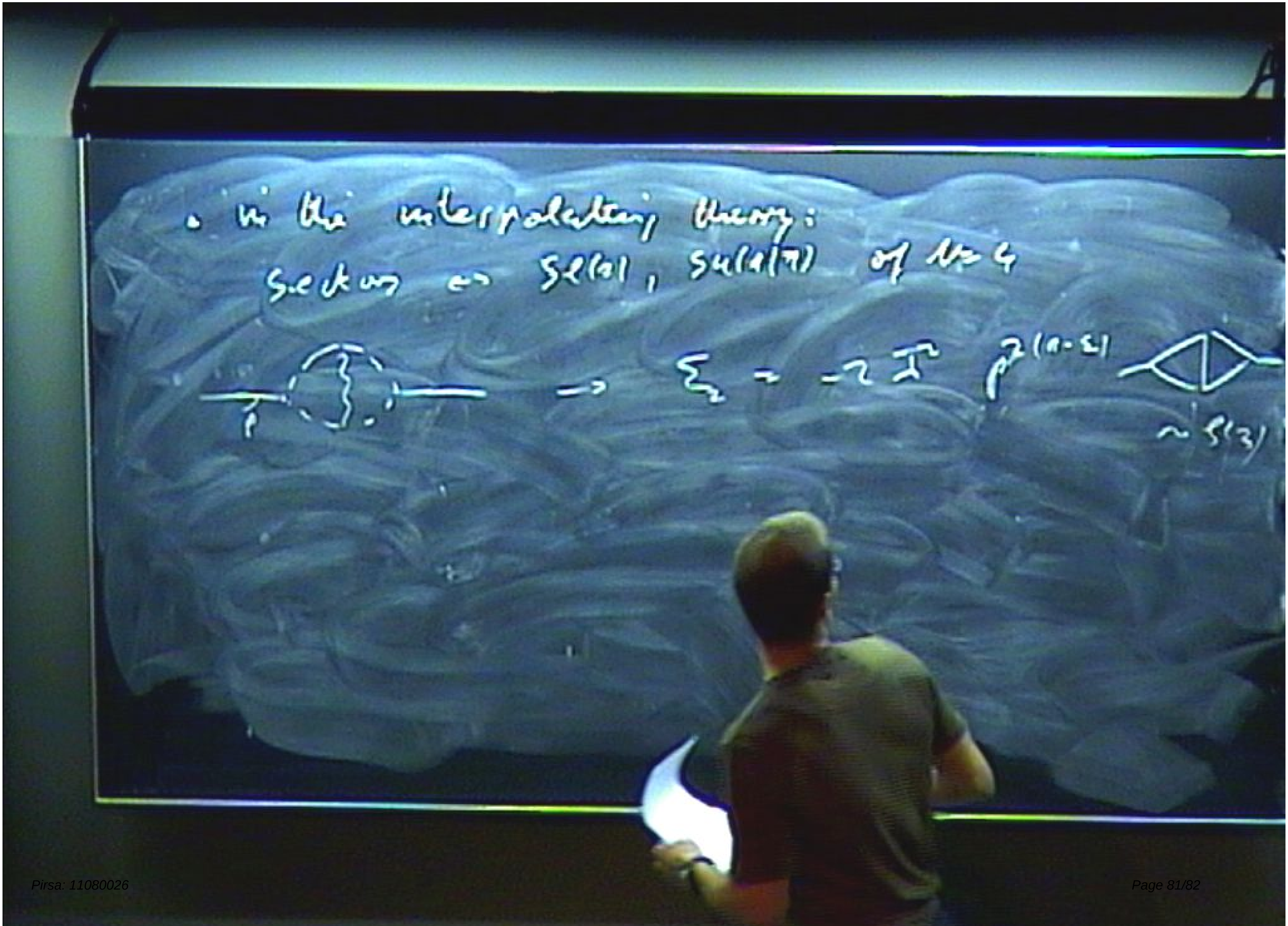

remark :
• h(ς,ς̄) manifest transcendental as in ABJ(M)


remark:
• h(ξ,ξ̄) maximal transcendental as in ABJ(M)
cases
also in the ABJ case


remark:
h(g, ḡ) transcendental as in ABJ(M)
cases
also in the ABJ case: deformation of the
S-matrix: at 6-loops


remark :
• h(ς, ς̄) must be transcendental as in ABJ(M)
case
also in the ABJ case : deformation of the
S-matrix : at 6-loops


• in the interpolating theory:
sectors ↔ SL(2), SU(1|1) of N=4


• in the interpolating theory:
sectors in Sl(2), Su(1|1) of N=4
~ ζ(3)

• in the interpolating theory:

sectors ↔ $SL(2)$, $SU(1|1)$ of $N=4$

 $\longrightarrow$ $\Sigma_2 = -2\,\hat{g}^2\, p^{2(1-\epsilon)}$  $\sim \zeta(3)$

$g \quad g$