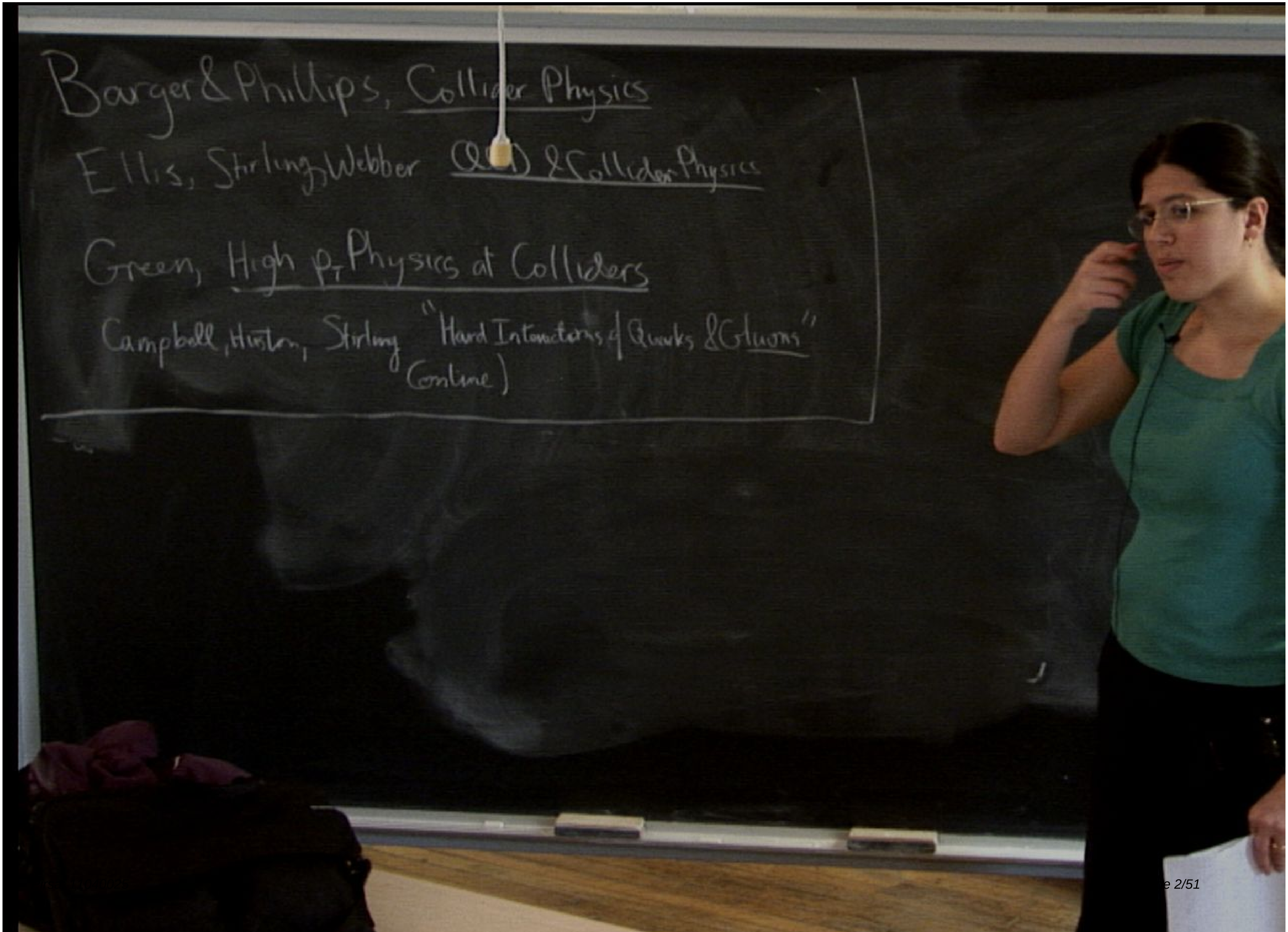
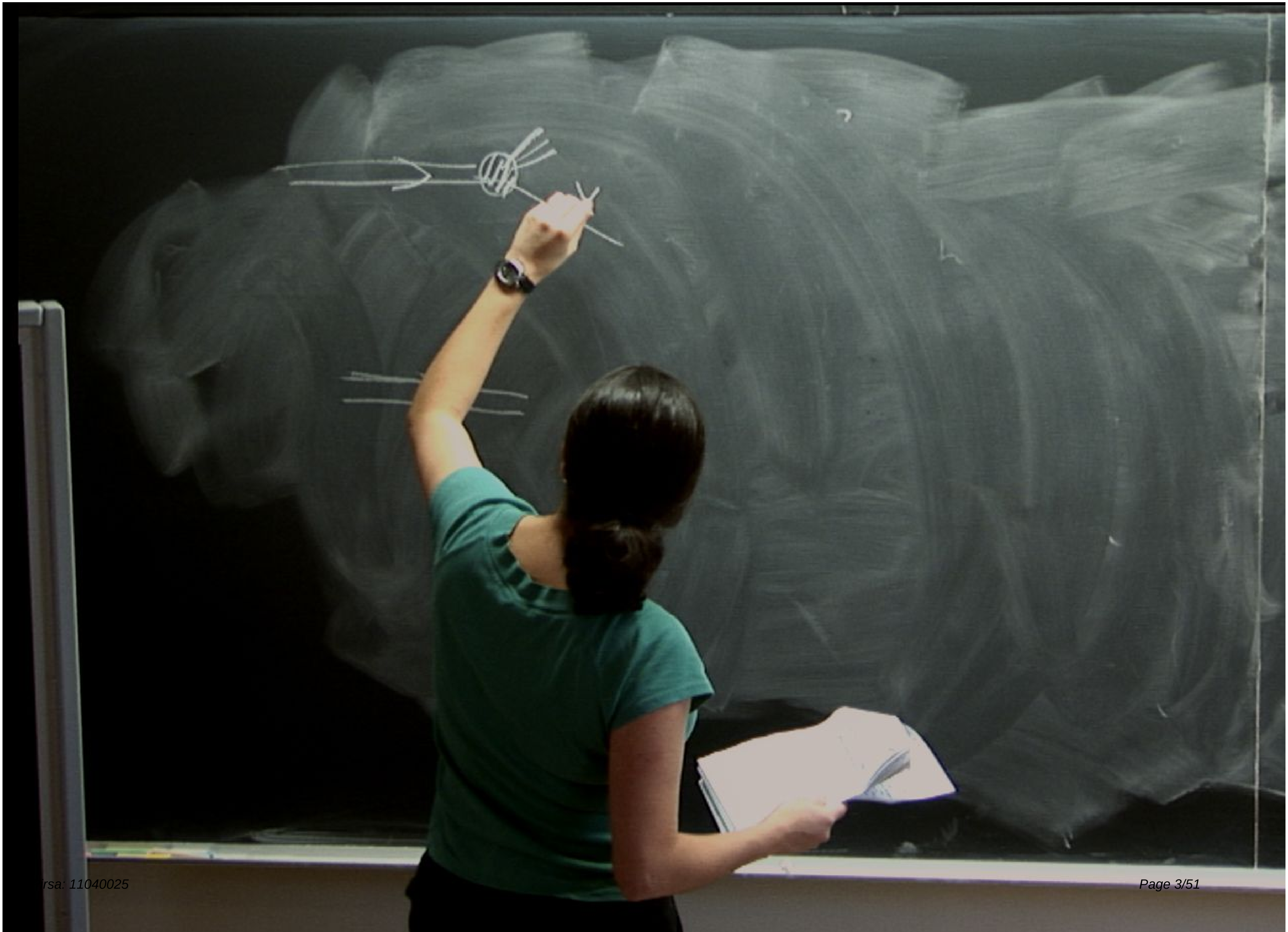
Title: Explorations in Particle Theory - Lecture 5

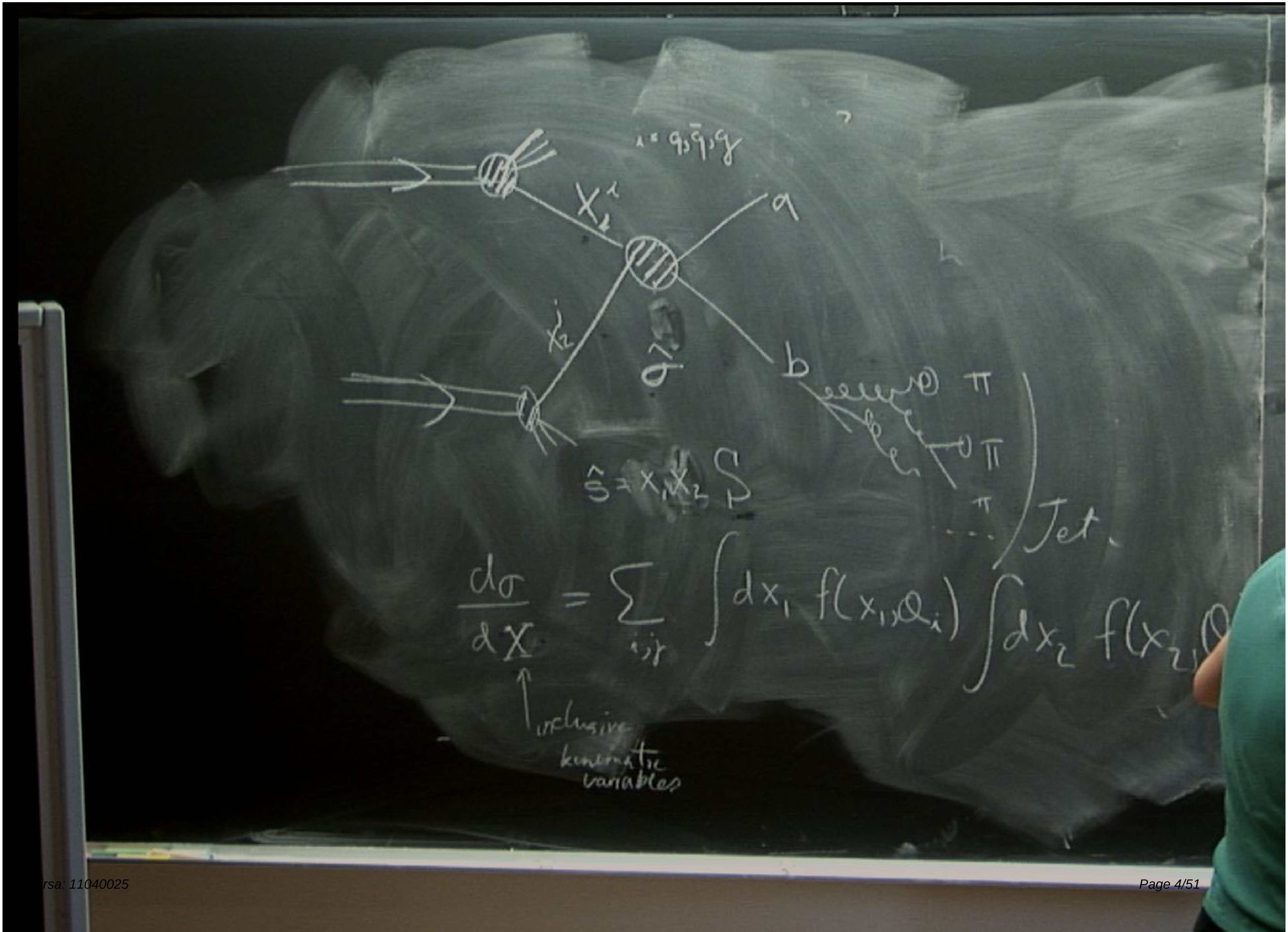
Date: Apr 08, 2011 10:15 AM

URL: http://pirsa.org/11040025

Abstract:


Barger & Phillips, Collider Physics
Ellis, Stirling, Webber QCD & Collider Physics
Green, High p_T Physics at Colliders
Campbell, Huston, Stirling "Hard Interactions of Quarks & Gluons" (online)



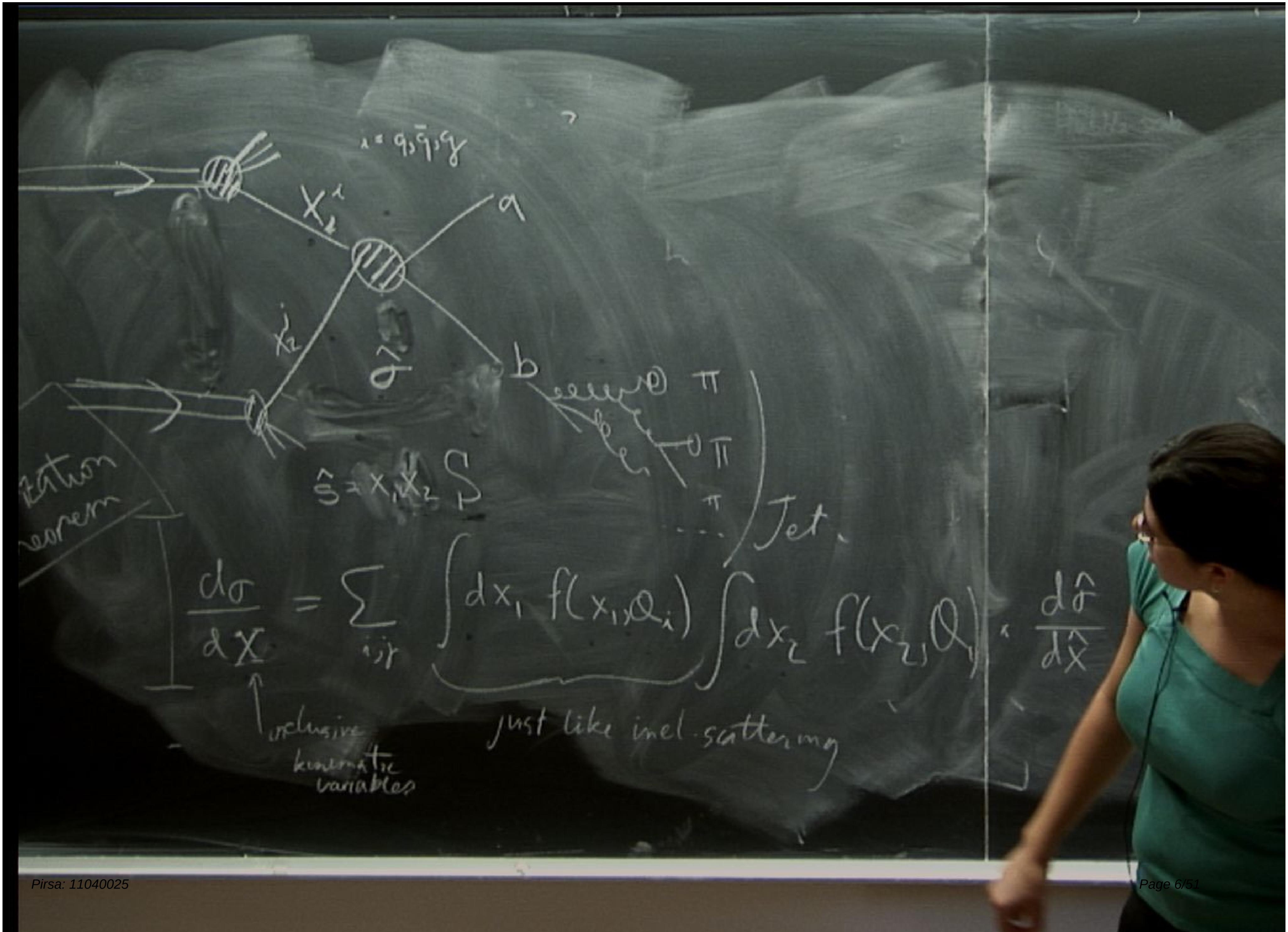

i = q, q̄, g
x₁ⁱ
a
x₂ʲ
σ̂
b
π
π
π
Jet.
ŝ = x₁x₂S
dσ/dX = Σᵢ,ⱼ ∫dx₁ f(x₁, Qᵢ) ∫dx₂ f(x₂,
inclusive
kinematic
variables

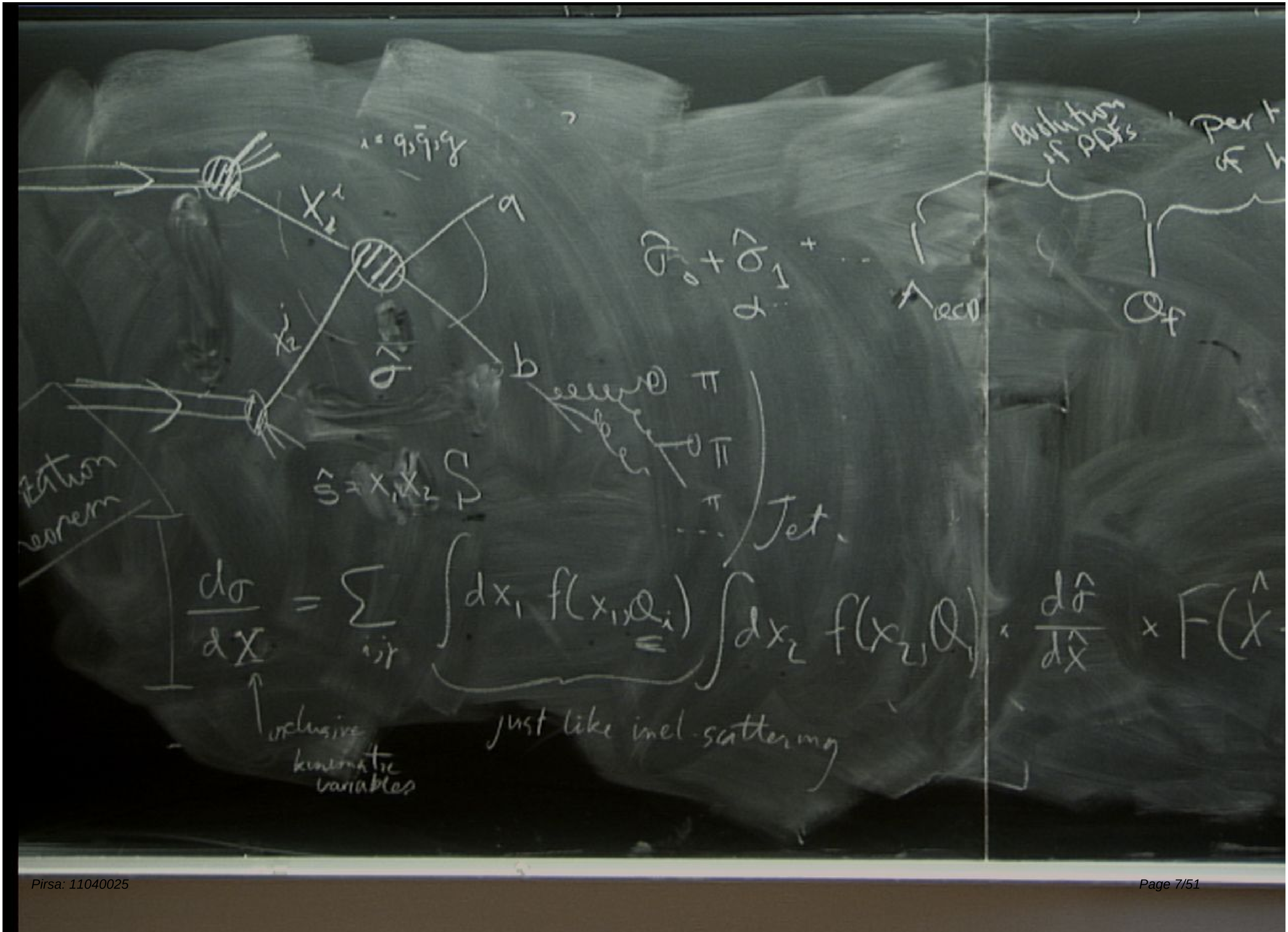
$= q, \bar{q}, g$

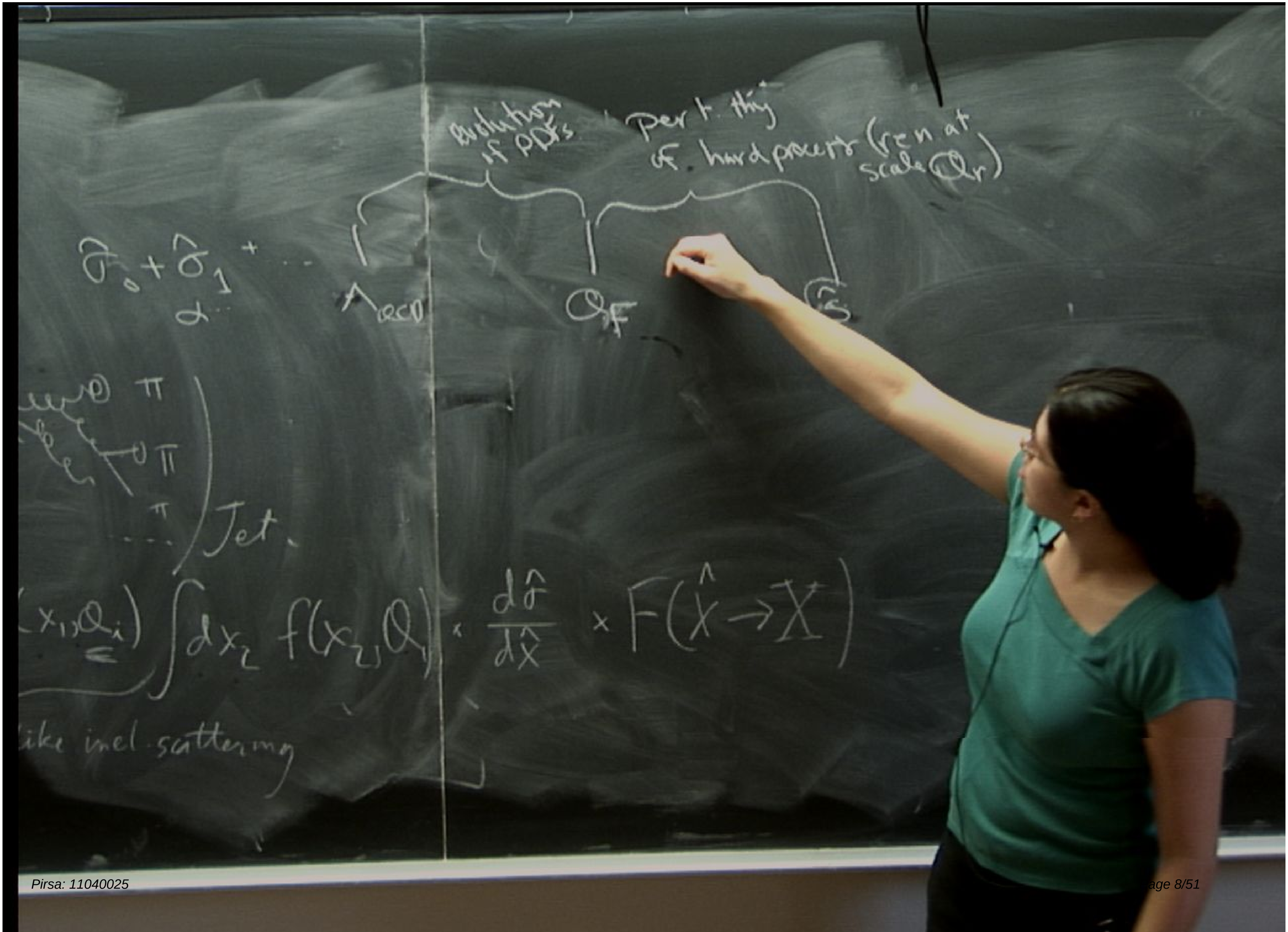
$x_1 x_2 S$

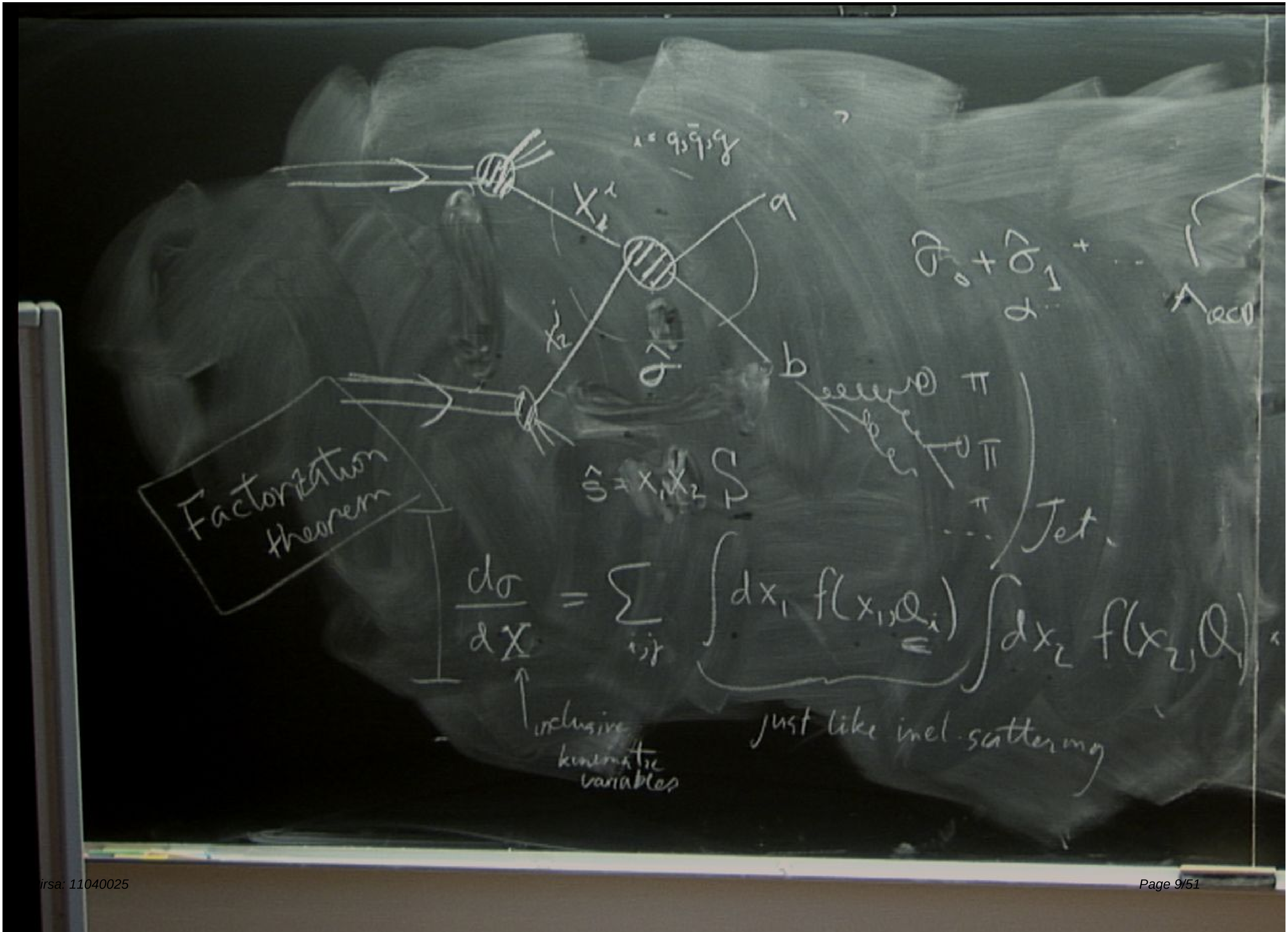
$$\int dx_1\, f(x_1, Q_i) \int dx_2\, f(x_2, Q_i) \times \frac{d\hat{\sigma}}{d\hat{X}} \times F(\hat{X} \to X)$$

just like inel. scattering


i = q, q̄, g
a
b
Jet.
ŝ = x1 x2 S
dσ/dX = Σ_{i,j} ∫dx1 f(x1, Q_i) ∫dx2 f(x2, Q_j) · dσ̂/dX̂
just like inel. scattering
inclusive kinematic variables


i = q, q̄, g
x_1^i
a
b
x_2^j
σ̂
π
π
π
Jet.
ŝ = x_1 x_2 S
σ̂_0 + σ̂_1 + ...
α
Λ_QCD
Q_f
Evolution of PDFs
per
of h
theorem
dσ/dX = Σ_{i,j} ∫dx_1 f(x_1, Q_i) ∫dx_2 f(x_2, Q_i) × dσ̂/dX̂ × F(X̂
inclusive kinematic variables
just like inel. scattering


evolution of PDFs
pert. thy of hard process (ren at scale Q_r)
σ̂_0 + σ̂_1 + ...
Λ_QCD
Q_F
Jet
d σ̂ / d X̂ × F(X̂ → X)
like inel. scattering

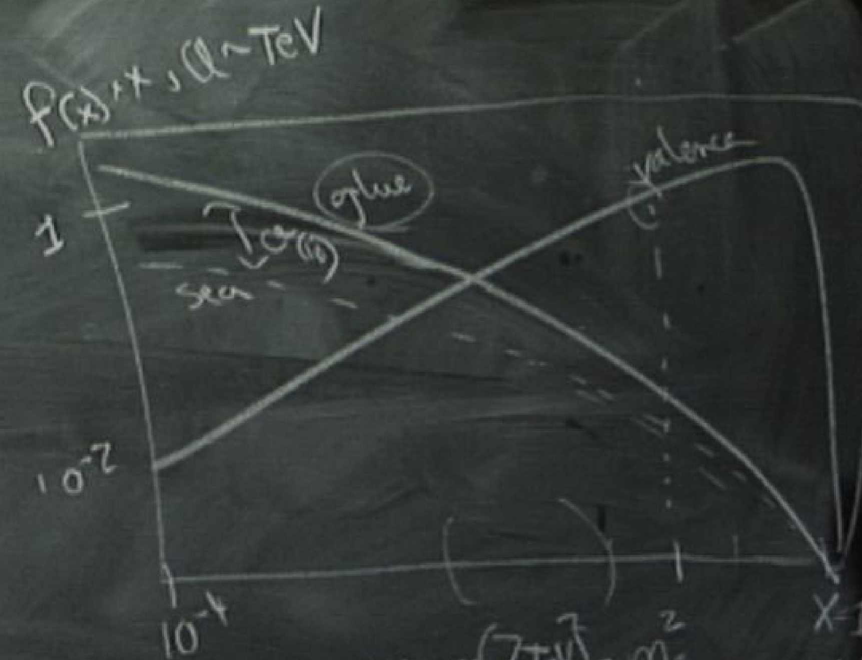

i = q, q̄, g
a
b
π
π
π
Jet
ŝ = x₁x₂S
σ̂₀ + σ̂₁ + ...
Factorization theorem
dσ/dX = Σ_{i,j} ∫dx₁ f(x₁, Qᵢ) ∫dx₂ f(x₂, Q)
inclusive kinematic variables
just like inel. scattering

...olution of PDFs

pert. thy of hard process (ren at scale Q_r)

Q_F

$\sqrt{\hat{s}}$



$x_1 \times x_2 \times (7\,\text{TeV})^2 = m_Z^2$

7 TeV

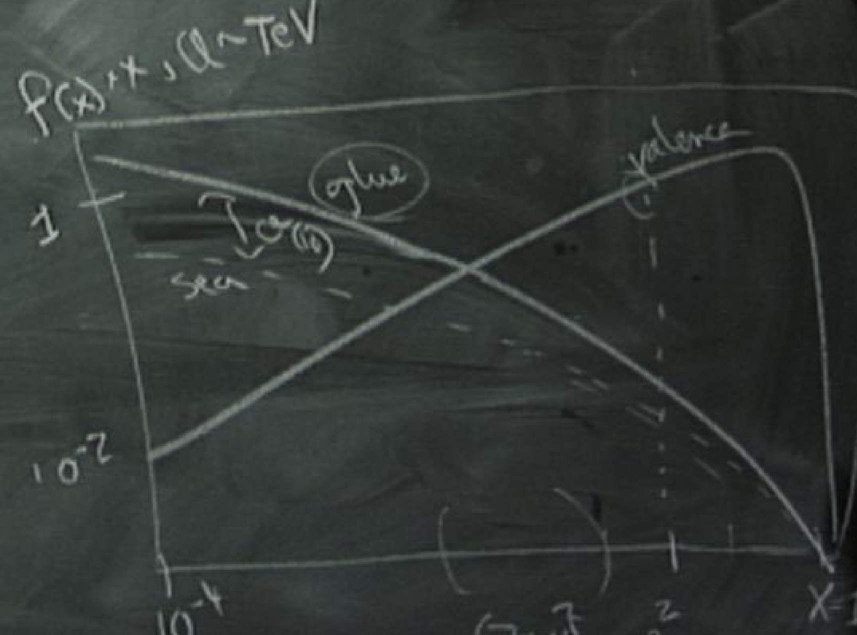
$x_i \sim \frac{m_Z}{7\,\text{TeV}} \sim 1\%$

$\frac{1}{20}$

$$\frac{d\hat{\sigma}}{d\hat{X}} \times F(\hat{X} \to X)$$

olution of PDFs — pert. thy of hard process (ren at scale Q_r)

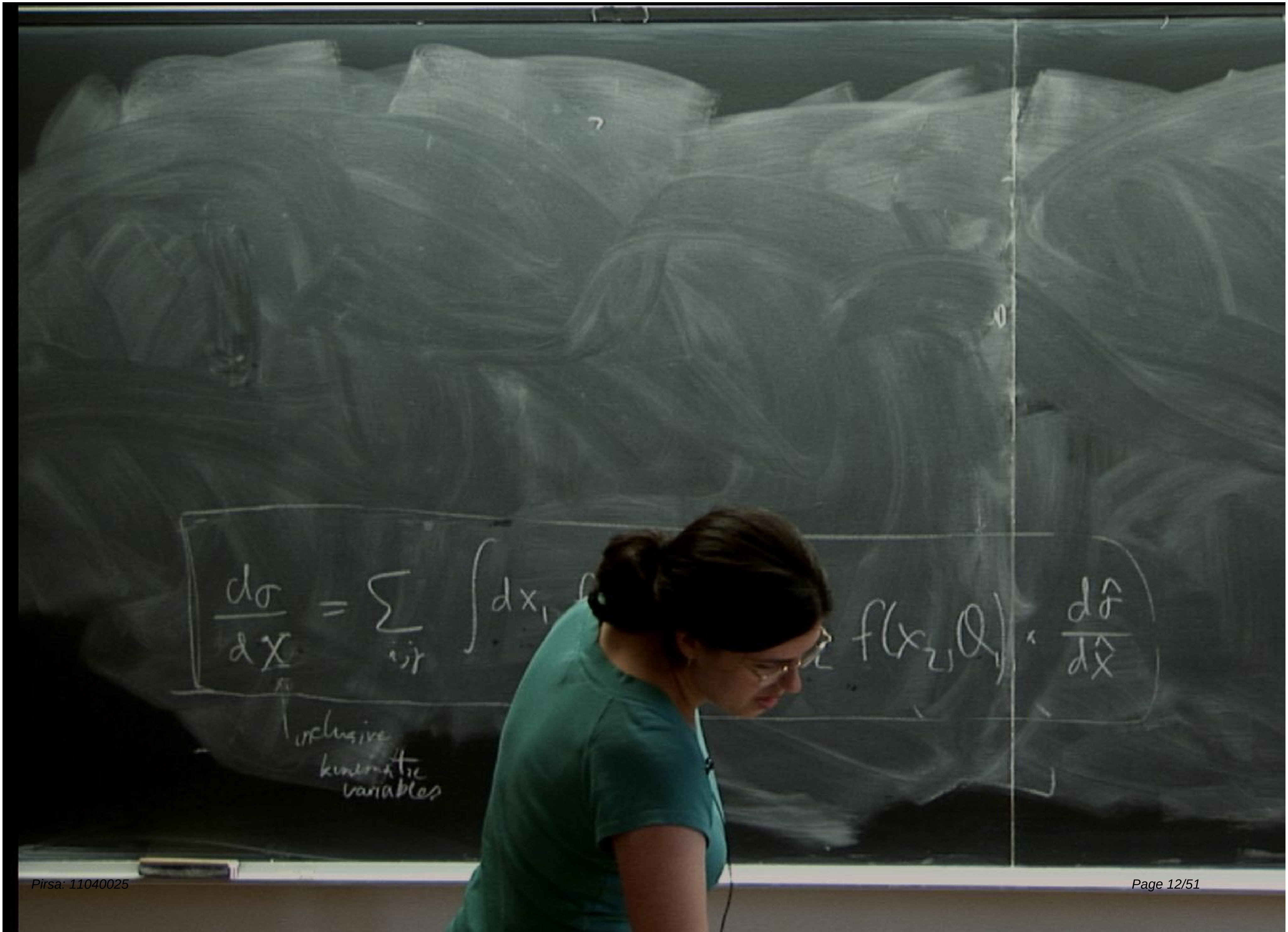
$$\underbrace{\text{olution of PDFs}}_{Q_F} \quad \underbrace{\text{pert. thy of hard process (ren at scale } Q_r)}_{\sqrt{\hat{s}}}$$

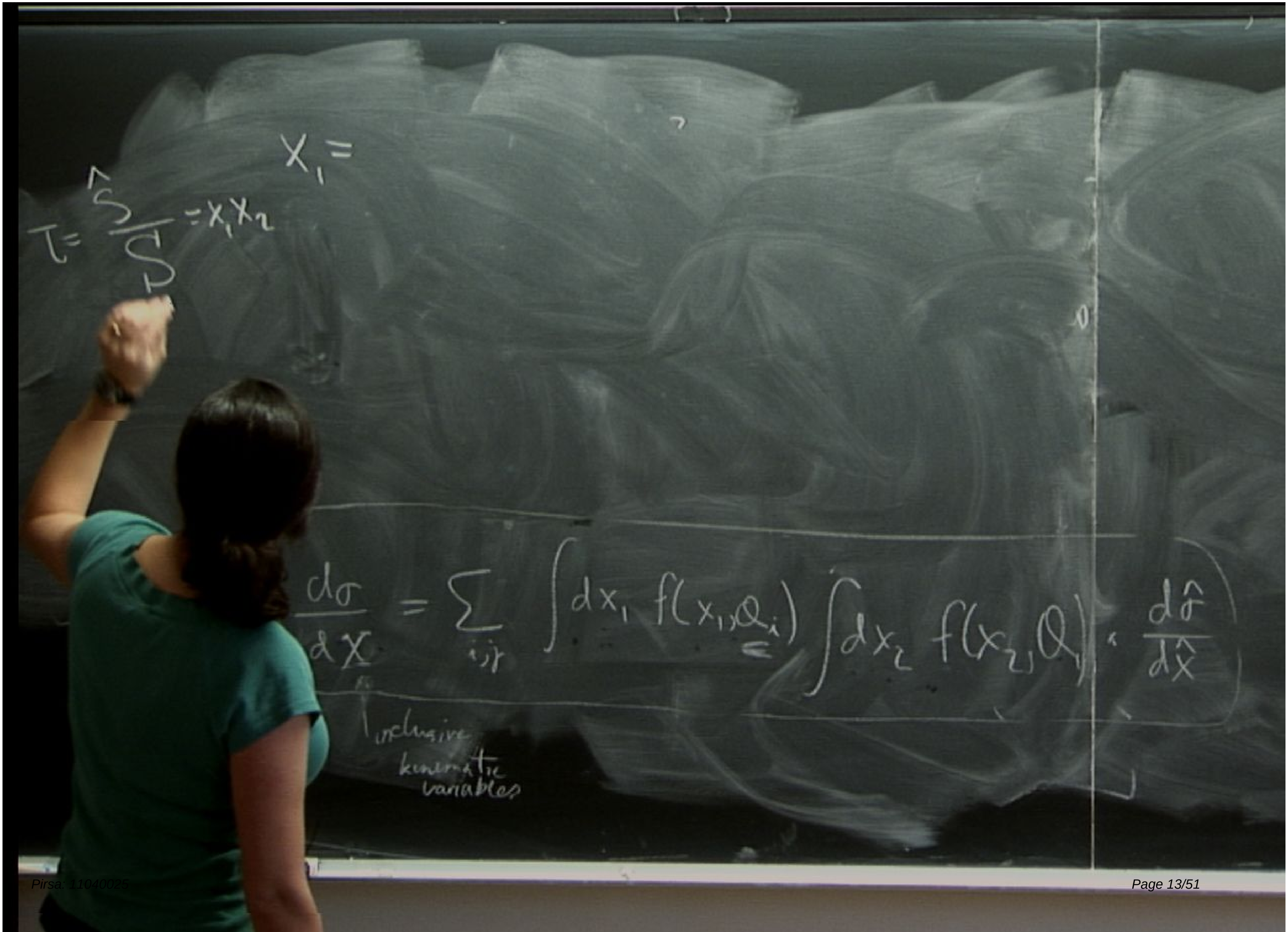


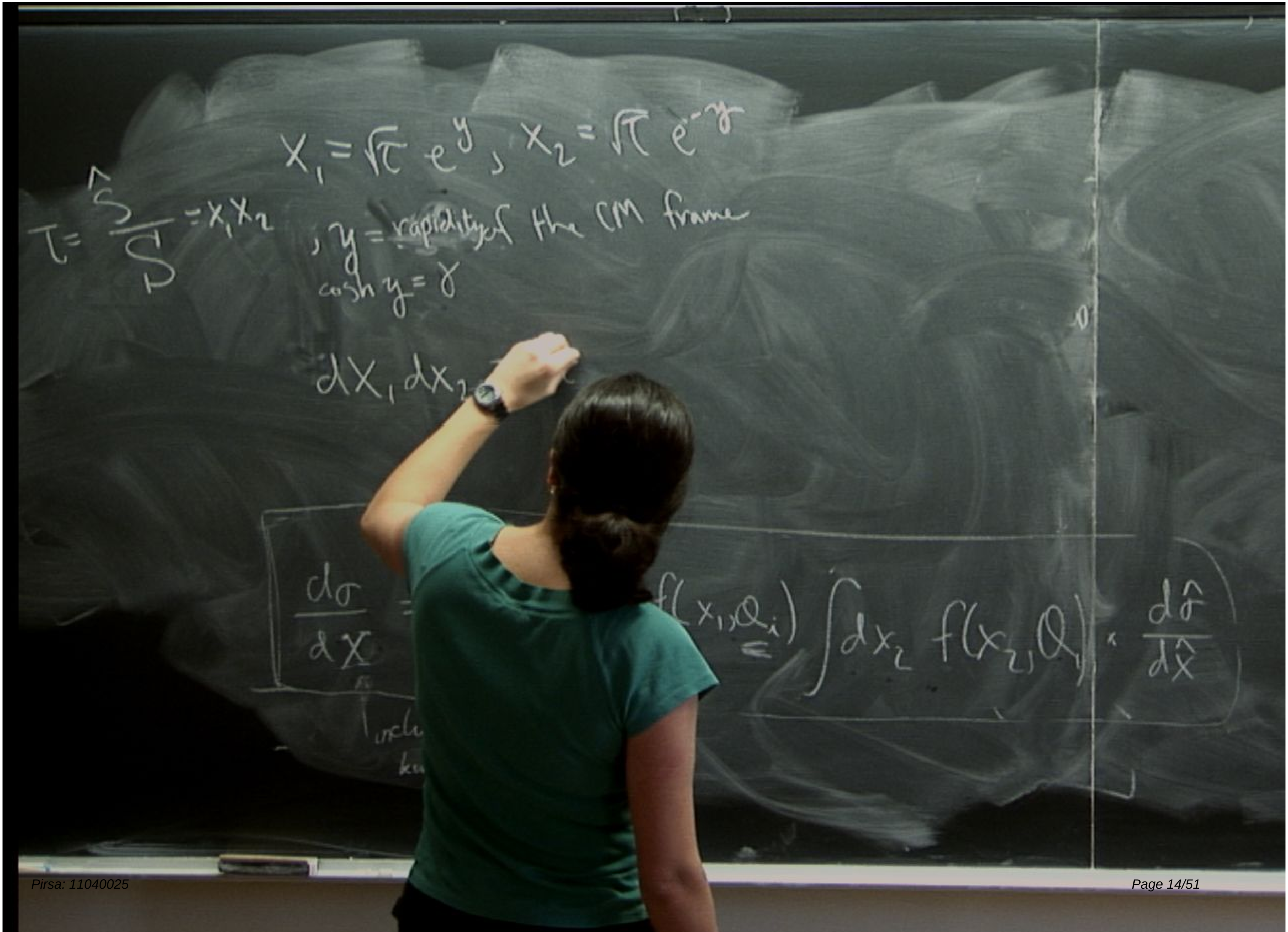
$$x_1 \times x_2 \times (7\,\text{TeV})^2 = m_Z^2 \qquad 7\,\text{TeV}$$

$$x_i \sim \frac{m_Z}{7\,\text{TeV}} \sim 1\% \qquad \frac{1}{20}$$

$$\frac{d\hat{\sigma}}{d\hat{X}} \times F(\hat{X} \to X)$$


$\frac{d\sigma}{dX} = \sum_{i,j} \int dx_1$
$f(x_2, Q_1) \times \frac{d\hat{\sigma}}{d\hat{X}}$
inclusive
kinematic
variables


x1 =
τ = ŝ/s = x1 x2
dσ/dX = Σi,j ∫dx1 f(x1,Qi) ∫dx2 f(x2,Qi) · dσ̂/dX̂
inclusive
kinematic
variables


x1 = √τ e^y , x2 = √τ e^-y
τ = ŝ/S = x1 x2
, y = rapidity of the CM frame
cosh y = γ
dx1 dx2
dσ/dX
f(x1,Q1) ∫dx2 f(x2,Q1) × dσ̂/dX̂

$$x_1 = \sqrt{\tau}\, e^{y}\,,\quad x_2 = \sqrt{\tau}\, e^{-y}$$

$$\tau = \frac{\hat{s}}{s} = x_1 x_2 \,,\quad y = \text{rapidity of the CM frame}$$

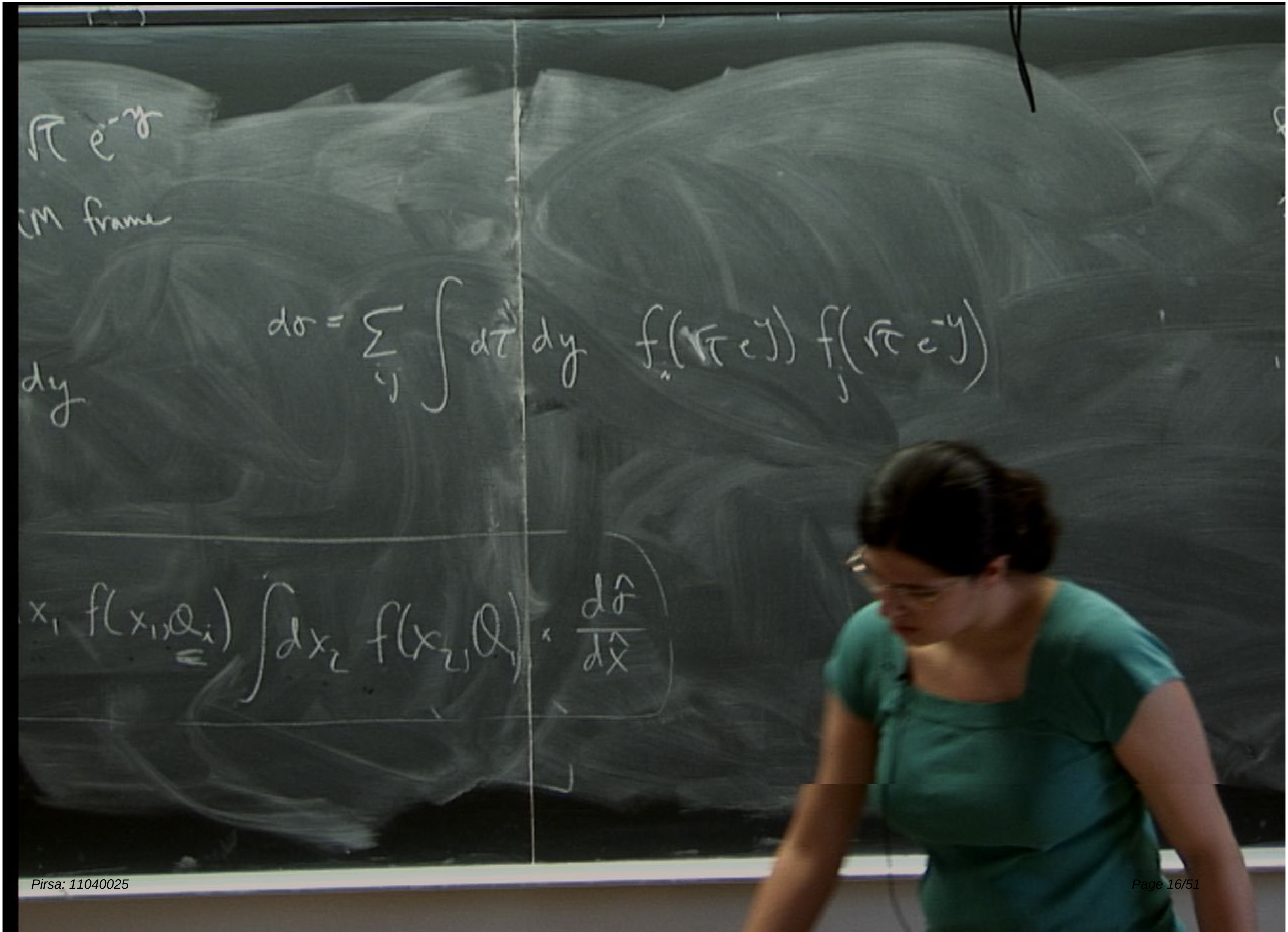
$$\cosh y = \gamma$$

$$dx_1\, dx_2 = d\tau\, dy$$

$$d\sigma = \sum_{i,j} \int d\tau\, dy \quad f($$

$$\boxed{\frac{d\sigma}{dX} = \sum_{i,j} \int dx_1\, f(x_1, Q_i) \int dx_2\, f(x_2, Q_j) \cdot \frac{d\hat{\sigma}}{d\hat{X}}}$$

inclusive kinematic variables


$\sqrt{\tau}\, e^{-y}$
cm frame
$d\sigma = \sum_{i,j} \int d\tau\, dy \;\; f_i(\sqrt{\tau}\, e^{y})\, f_j(\sqrt{\tau}\, e^{-y})$
dy
$x_1\, f(x_1, Q_i) \int dx_2\, f(x_2, Q_i) \times \frac{d\hat{\sigma}}{d\hat{X}}$

$x_1 = \sqrt{\tau}\, e^{y}$, $x_2 = \sqrt{\tau}\, e^{-y}$

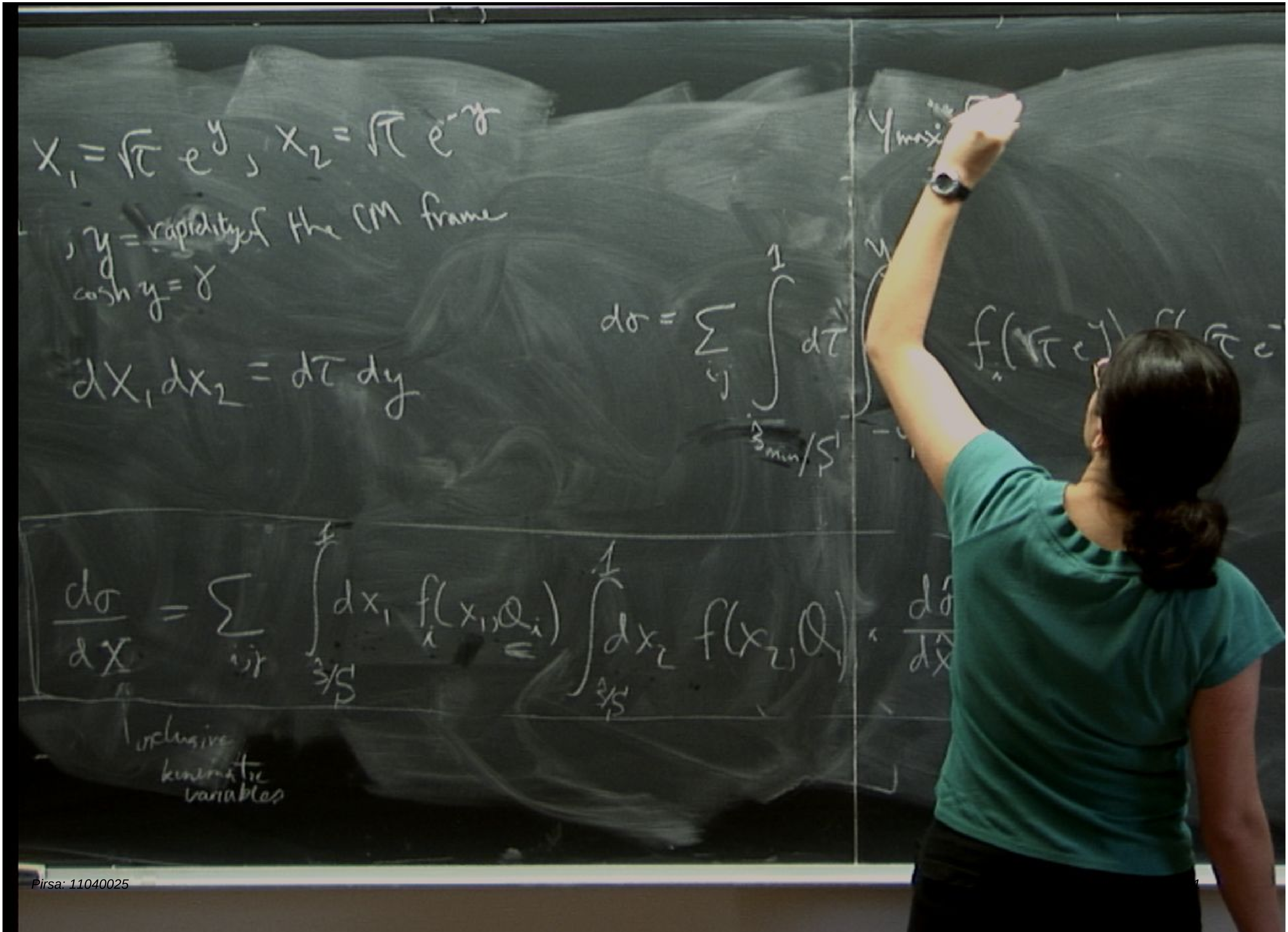
, y = rapidity of the CM frame

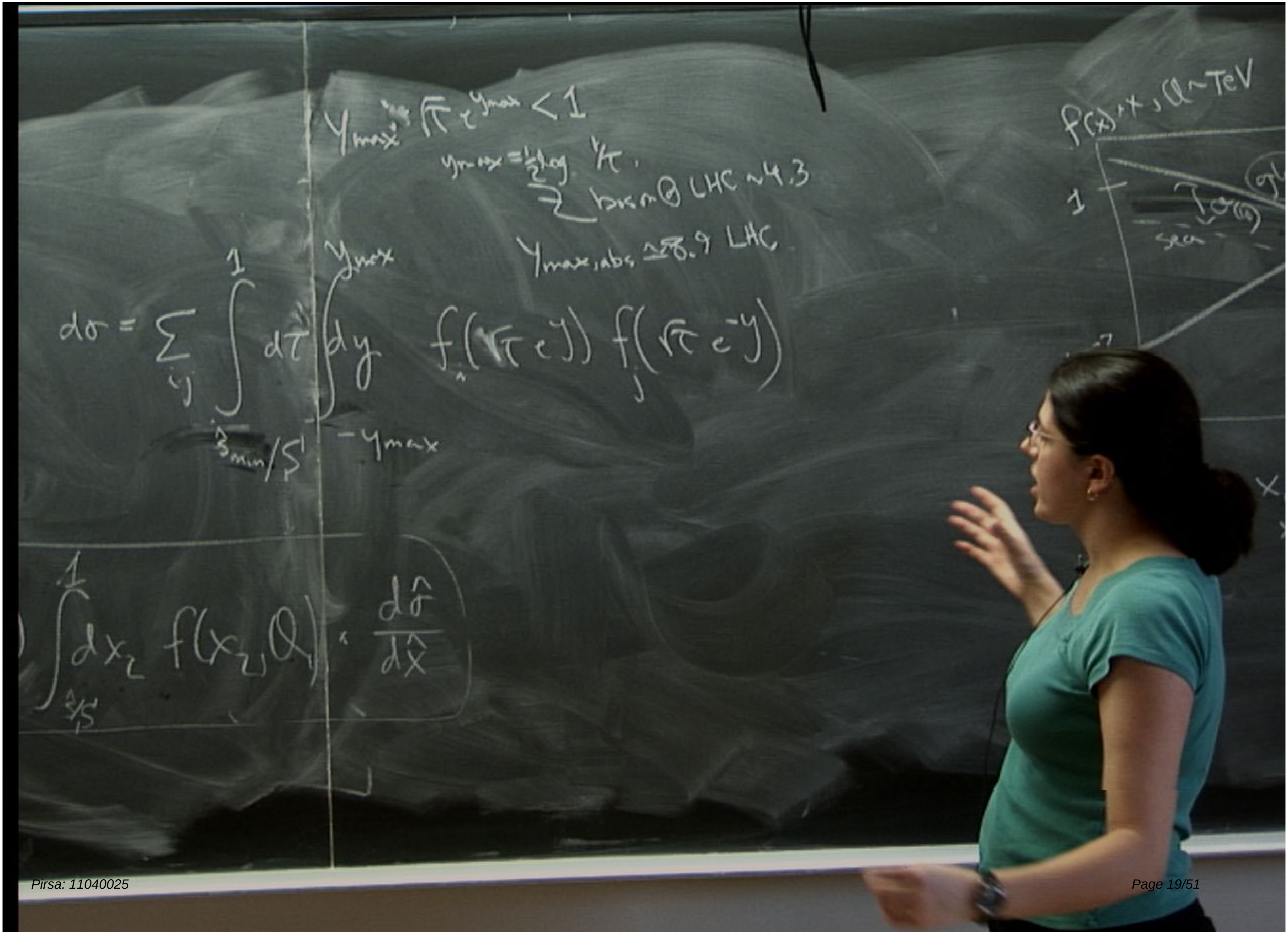
$\cosh y = \gamma$

$$dx_1\, dx_2 = d\tau\, dy$$

$$d\sigma = \sum_{i,j} \int d\tau \int dy \quad f_i(\sqrt{\tau}\, e^{y})\, f_j(\sqrt{\tau}\, e^{-}$$

$$\sum_{i,j} \int_{3/S}^{1} dx_1\, f_i(x_1, Q_i) \int^{1} dx_2\, f(x_2, Q_i) \times \frac{d\hat{\sigma}}{d\hat{x}}$$


x1 = √τ e^y , x2 = √τ e^-y
, y = rapidity of the CM frame
cosh y = γ
dx1 dx2 = dτ dy
dσ = Σ i,j ∫ 3min/S 1 dτ
f i(√τ e^y) f(√τ e
ymax
dσ/dX = Σ i,j ∫ 3/S 1 dx1 f i(x1,Qi) ∫ 3/S 1 dx2 f(x2,Qi) × dσ̂/dX̂
inclusive kinematic variables


y_{max}: $\sqrt{\tau}\, e^{y_{max}} < 1$
$y_{max} = \frac{1}{2}\log 1/\tau$
LHC ~4.3
$y_{max,abs} \simeq 8.9$ LHC
$d\sigma = \sum_{ij} \int_{\hat{s}_{min}/S}^{1} d\tau \int_{-y_{max}}^{y_{max}} dy \; f_i(\sqrt{\tau}\, e^{y})\, f_j(\sqrt{\tau}\, e^{-y})$
$\int_{\hat{s}/S}^{1} dx_2 \, f(x_2, Q) \times \frac{d\hat{\sigma}}{d\hat{X}}$
f(x), x, Q ~ TeV
1
sea

y_{max}: $\sqrt{\tau}\, e^{y_{max}} < 1$

$y_{max} = \frac{1}{2}\log 1/\tau$

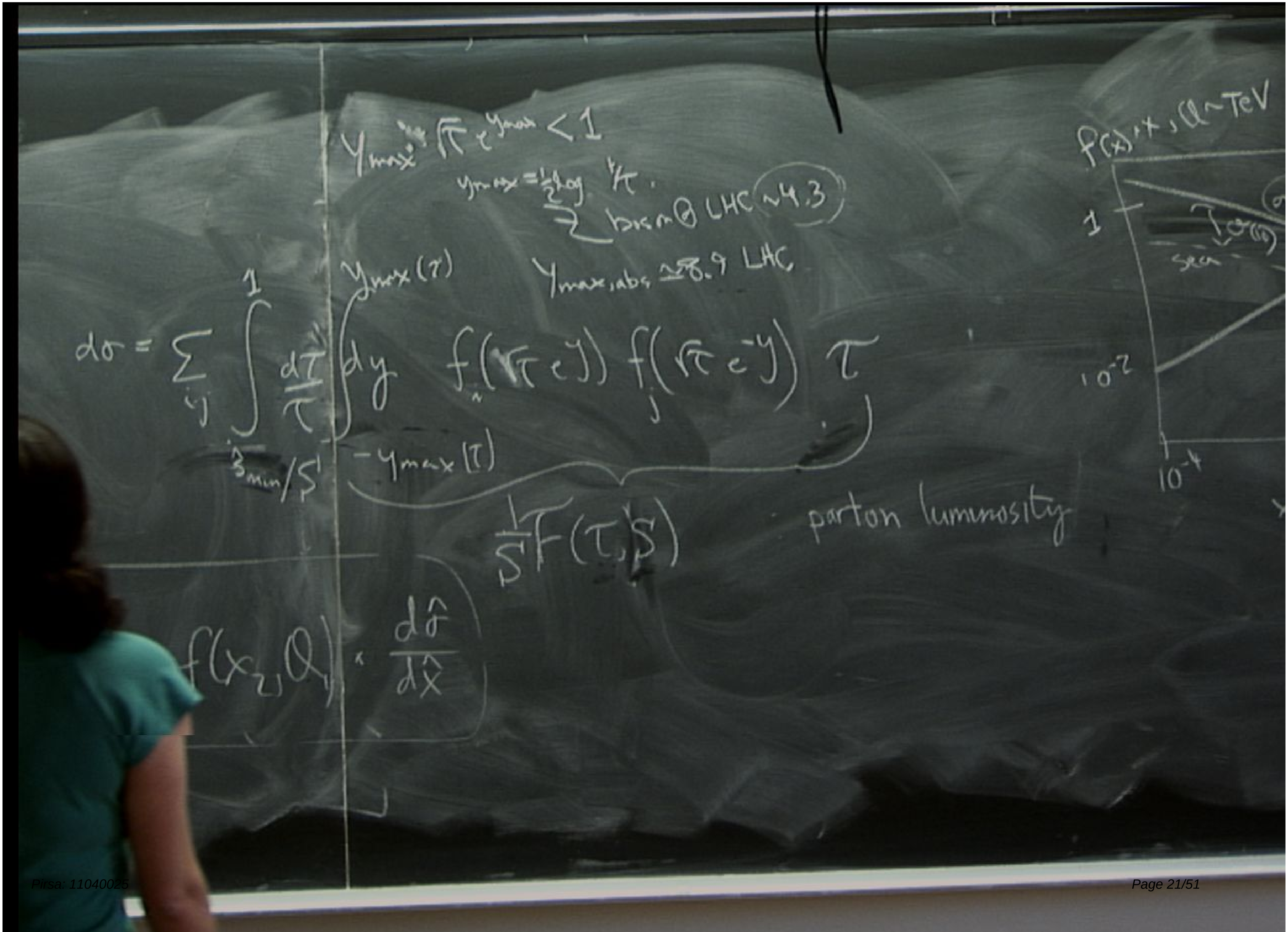
$\sum$ bins in θ LHC ~ 4.3

$y_{max,abs} \simeq 8.9$ LHC

$$d\sigma = \sum_{ij} \int_{\hat{s}_{min}/S}^{1} d\tau \int_{-y_{max}}^{y_{max}} dy \quad f_i(\sqrt{\tau}\, e^{y})\, f_j(\sqrt{\tau}\, e^{-y})$$

$$\int_{\hat{s}/S}^{1} dx_2\, f(x_2, Q) \times \frac{d\hat{\sigma}}{d\hat{x}}$$

$f(x) \cdot x$, $Q \sim$ TeV


y_{max}: $\sqrt{\tau}\, e^{y_{max}} < 1$
$y_{max} = \frac{1}{2}\log 1/\tau$
$\gtrsim$ b/c m @ LHC ~4.3
$y_{max}(\tau)$
$y_{max,abs} \simeq 8.9$ LHC
$d\sigma = \sum_{ij} \int_{\hat{s}_{min}/S}^{1} \frac{d\tau}{\tau} \int_{-y_{max}(\tau)}^{y_{max}(\tau)} dy\; f_i(\sqrt{\tau}e^{y})\, f_j(\sqrt{\tau}e^{-y})\, \tau$
$\frac{1}{S} F(\tau, S)$
parton luminosity
$f(x_2, Q) \times \frac{d\hat{\sigma}}{d\hat{x}}$
$f(x) \cdot x$, $Q \sim$ TeV
1
10^{-2}
10^{-4}
sea

y_{max}: $\sqrt{\tau}\, e^{y_{max}} < 1$

$y_{max} = \frac{1}{2}\log 1/\tau$.

$\gtrsim$ bins @ LHC ~4.3

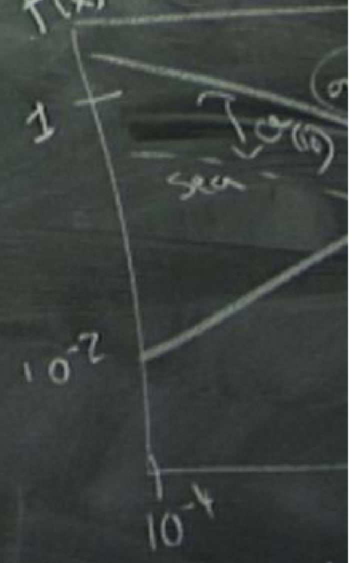
$y_{max}(\tau)$ $\quad y_{max,abs} \simeq 8.9$ LHC

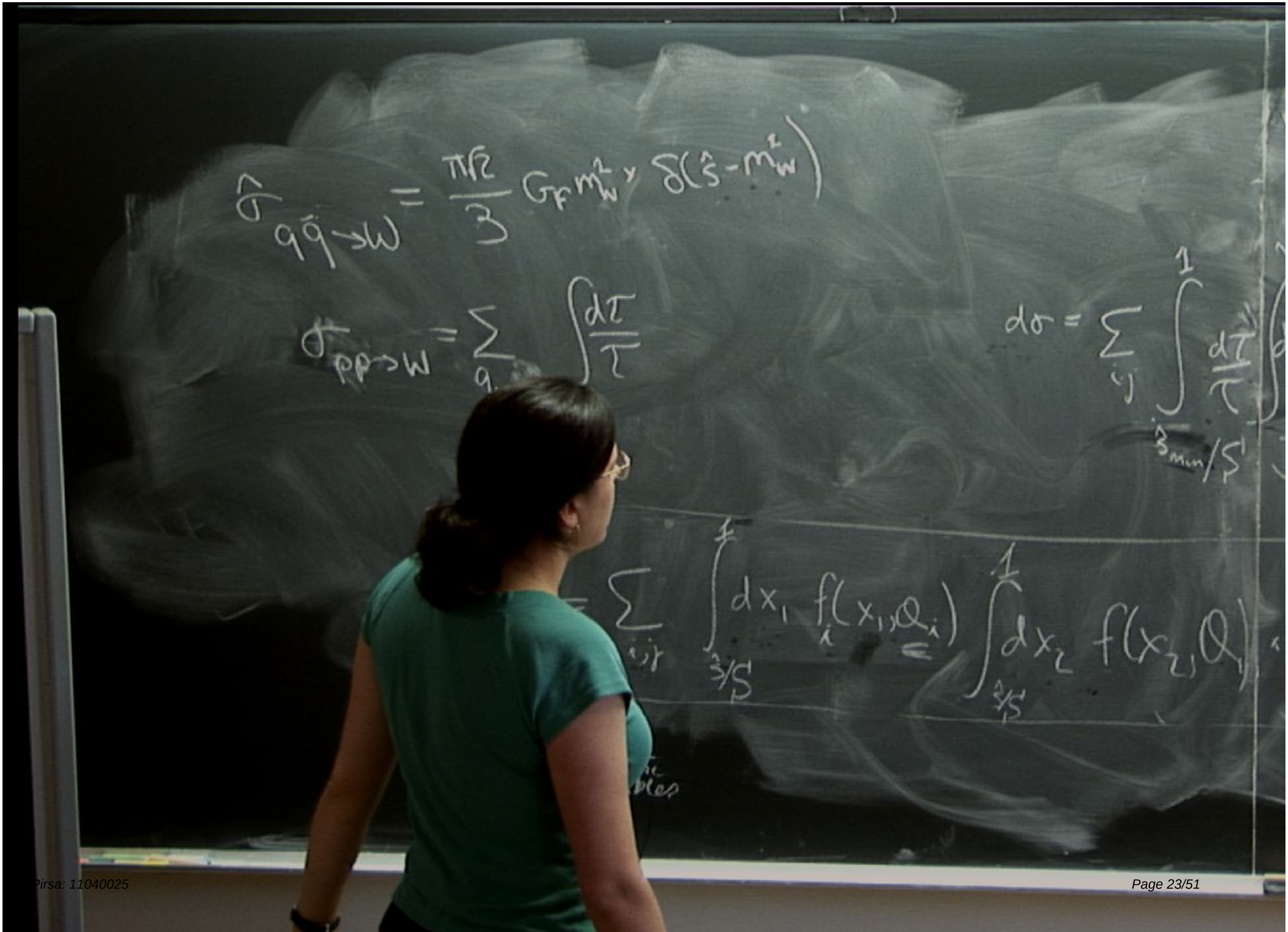
$$d\sigma = \sum_{ij} \int_{\hat{s}_{min}/S}^{1} \frac{d\tau}{\tau} \underbrace{\int_{-y_{max}(\tau)}^{y_{max}(\tau)} dy \; f_i(\sqrt{\tau}\, e^{y})\, f_j(\sqrt{\tau}\, e^{-y})\; \tau}_{\frac{1}{S}F(\tau, S)}$$

parton luminosity

$$) \int_{\hat{s}/S}^{1} dx_2 \; f(x_2, Q) \times \frac{d\hat{\sigma}}{d\hat{x}}$$

$f(x)\cdot x$, $Q \sim$ TeV



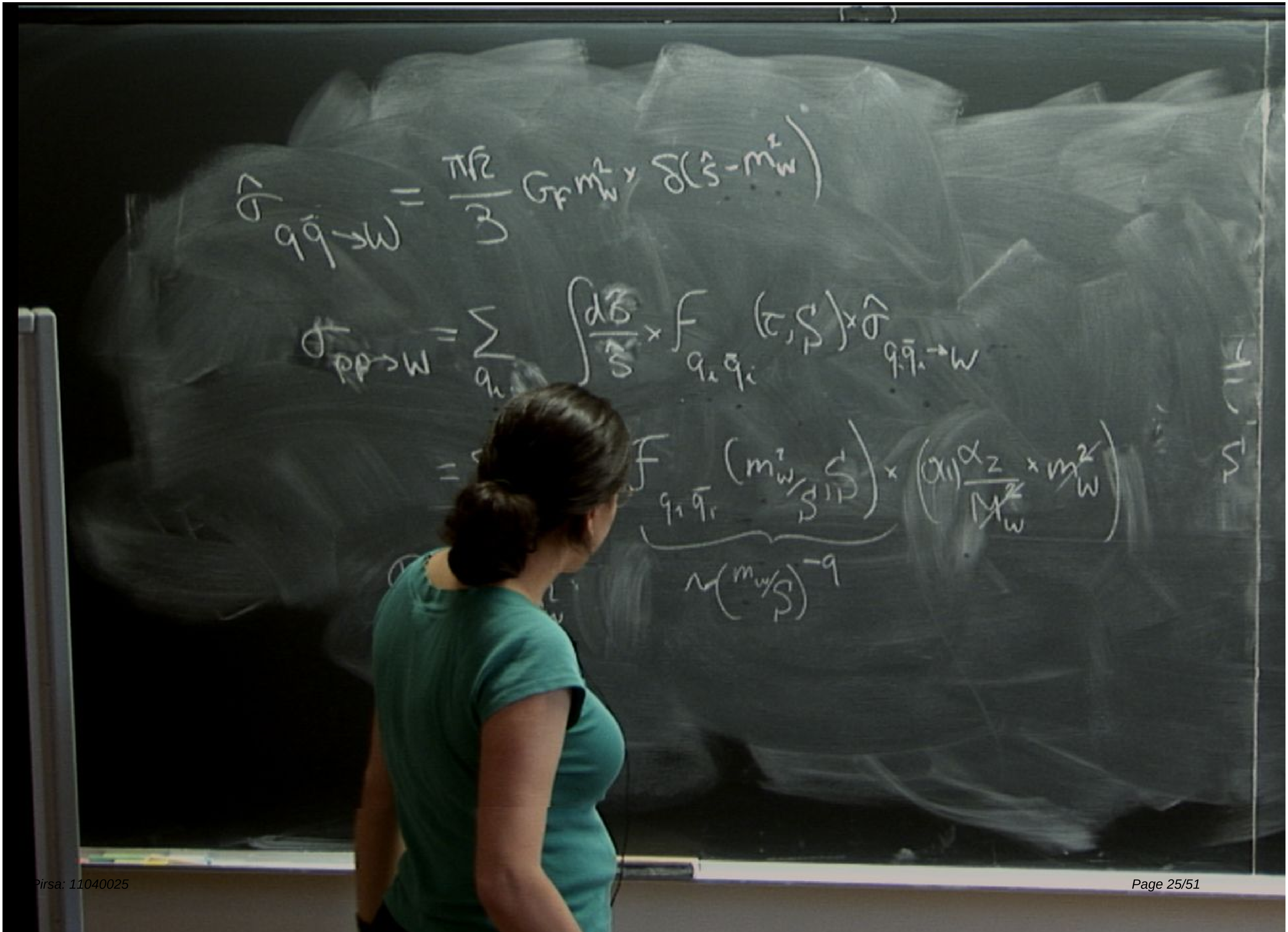

$\hat{\sigma}_{q\bar{q}\to W} = \frac{\pi\sqrt{2}}{3} G_F m_W^2 \times \delta(\hat{s} - m_W^2)$
$\sigma_{pp\to W} = \sum_{q} \int \frac{d\tau}{\tau}$
$d\sigma = \sum_{i,j} \int_{\hat{s}_{min}/S}^{1} \frac{d\tau}{\tau}$
$\int_{\hat{s}/S}^{1} dx_1 \, f_i(x_1, Q_i) \int_{\hat{s}/S}^{1} dx_2 \, f(x_2, Q)$

$$\hat{\sigma}_{q\bar{q}\to W} = \frac{\pi\sqrt{2}}{3} G_F m_W^2 \times \delta(\hat{s} - m_W^2)$$

$$\sigma_{pp\to W} = \sum_{q_i} \int \frac{d\hat{s}}{\hat{s}} \times F_{q_i \bar{q}_i}(\tau, S) \times \hat{\sigma}_{q_i\bar{q}_i \to W}$$

$$\boxed{\frac{d\sigma}{dX} = \sum_{i,j} \int_{\hat{s}/S}^{1} dx_1 \, f_i(x_1, Q_i) \int_{\hat{s}/S}^{1} dx_2 \, f(x_2, Q_i) \times}$$

inclusive kinematic variables


$\hat{\sigma}_{q\bar{q}\to W} = \frac{\pi\sqrt{2}}{3} G_F m_W^2 \times \delta(\hat{s} - m_W^2)$
$\sigma_{pp\to W} = \sum_{q_i} \int \frac{d\hat{s}}{\hat{s}} \times F_{q_i\bar{q}_i}(\tau, s') \times \hat{\sigma}_{q_i\bar{q}_i\to W}$
$F_{q_i\bar{q}_i}(m_W^2/s', s') \times \left(\alpha_1 \frac{\alpha_2}{M_W^2} \times m_W^2\right)$
$\sim (m_W/s)^{-9}$

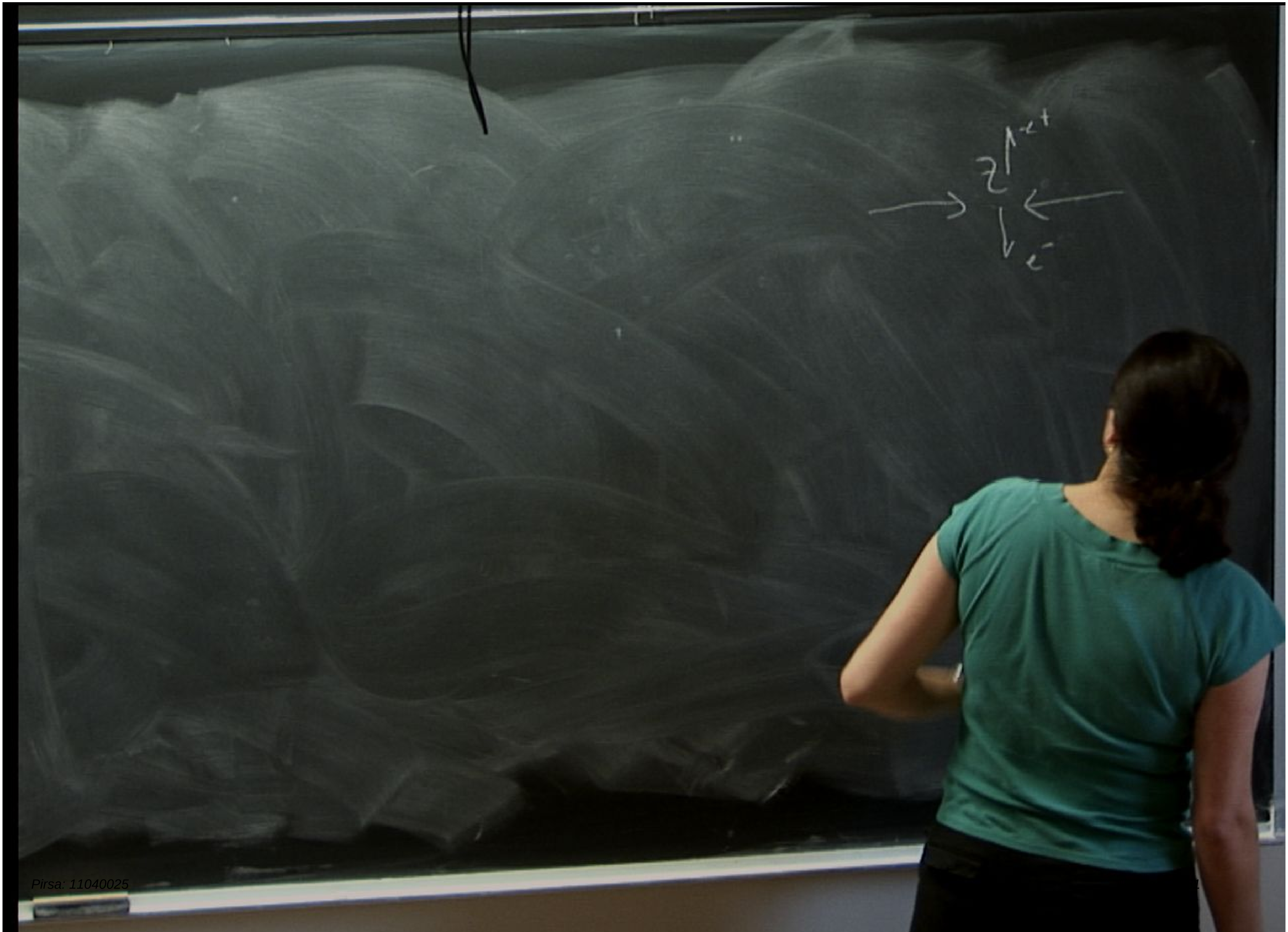
$$\hat{\sigma}_{q\bar{q}\to W} = \frac{\pi\sqrt{2}}{3} G_F m_W^2 \times \delta(\hat{s} - m_W^2)$$

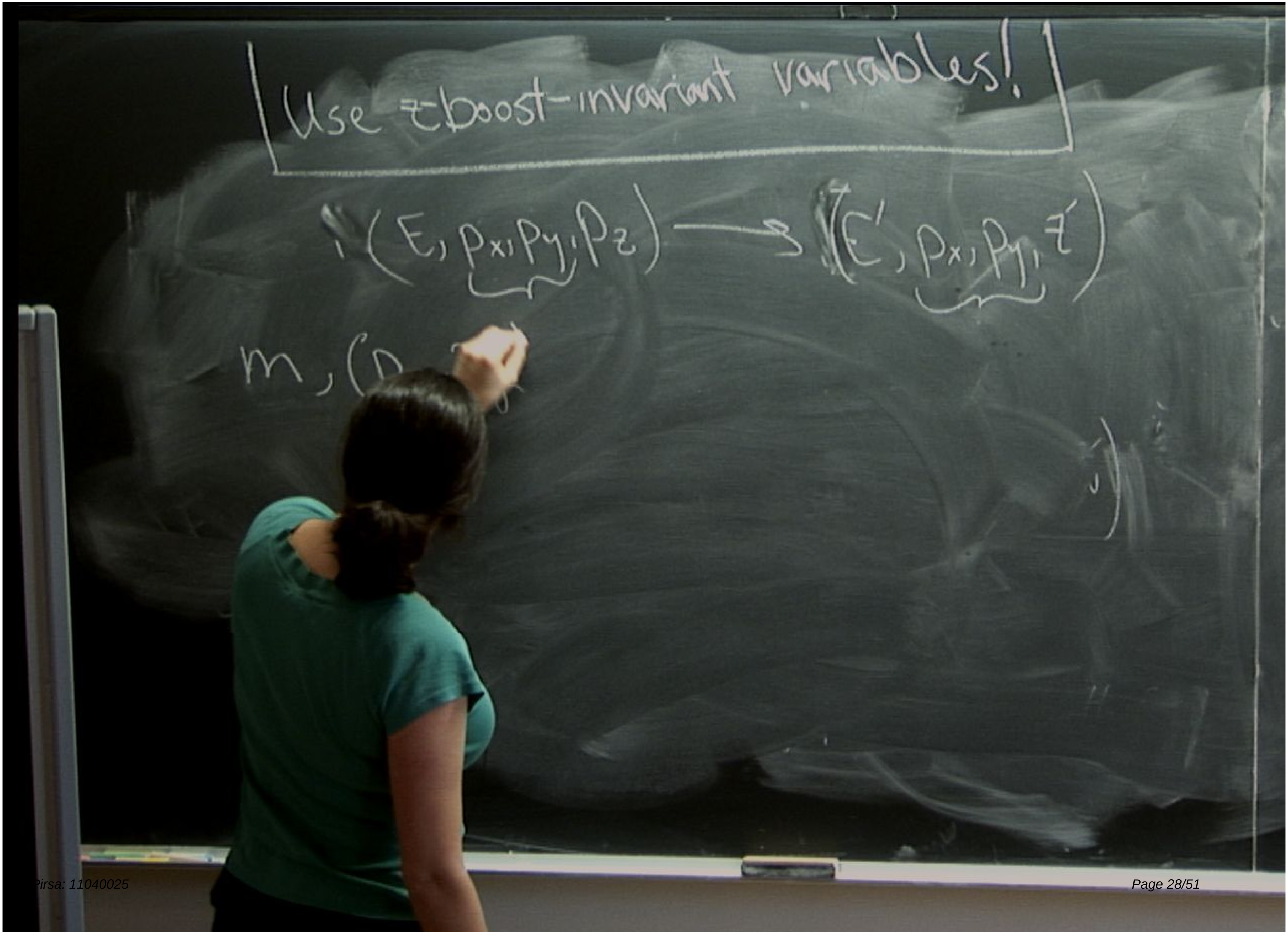
$$\sigma_{pp\to W} = \sum_{q_i} \int \frac{d\hat{s}}{\hat{s}} \times F_{q_i \bar{q}_i}(\tau, S) \times \hat{\sigma}_{q_i\bar{q}_i \to W}$$

$$= \sum_{q_i} \frac{1}{m_W^2} \underbrace{F_{q_i \bar{q}_i}\left(m_W^2/S^{11}, S\right)}_{\sim (m_W/S)^{-q}} \times \left((\alpha_1) \frac{\alpha_2}{\cancel{M_W^2}} \times \cancel{m_W^2} \right)$$

$$\sigma = \frac{\alpha_2}{m_W^2}$$

$$\sigma \sim \alpha_2 \frac{S^q}{m_W^{2+q}} \quad \text{grows with } S$$

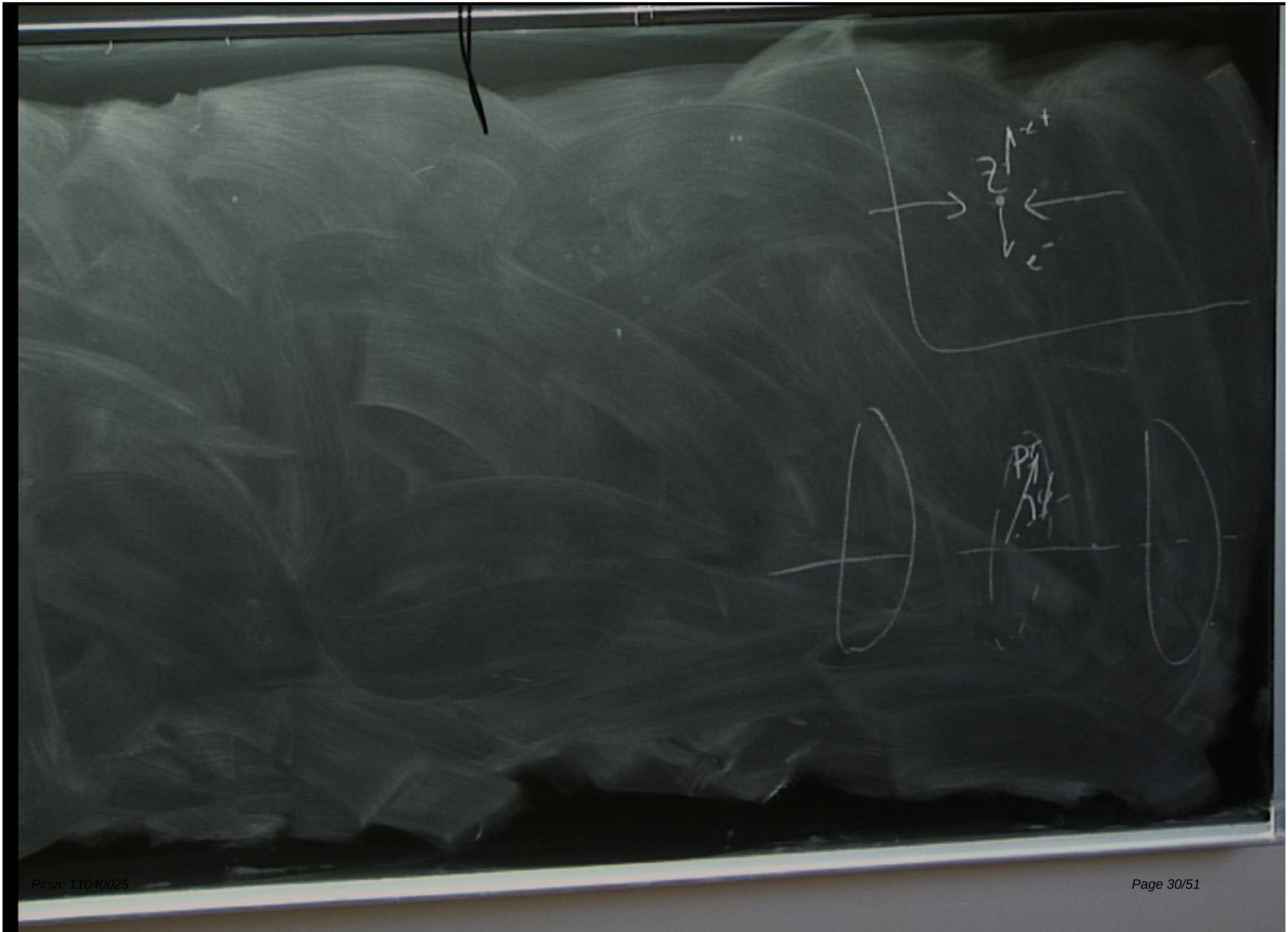

Z
e+
e-


Use z-boost-invariant variables!
(E, px, py, pz) → (E', px, py, z')
m, (p

$$\boxed{\text{Use } z\text{-boost-invariant variables!}}$$

$$(E, \underbrace{p_x, p_y}, p_z) \longrightarrow (E', \underbrace{p_x, p_y}, z')$$

$$m, (p_x, p_y) \longrightarrow p_T, \phi$$

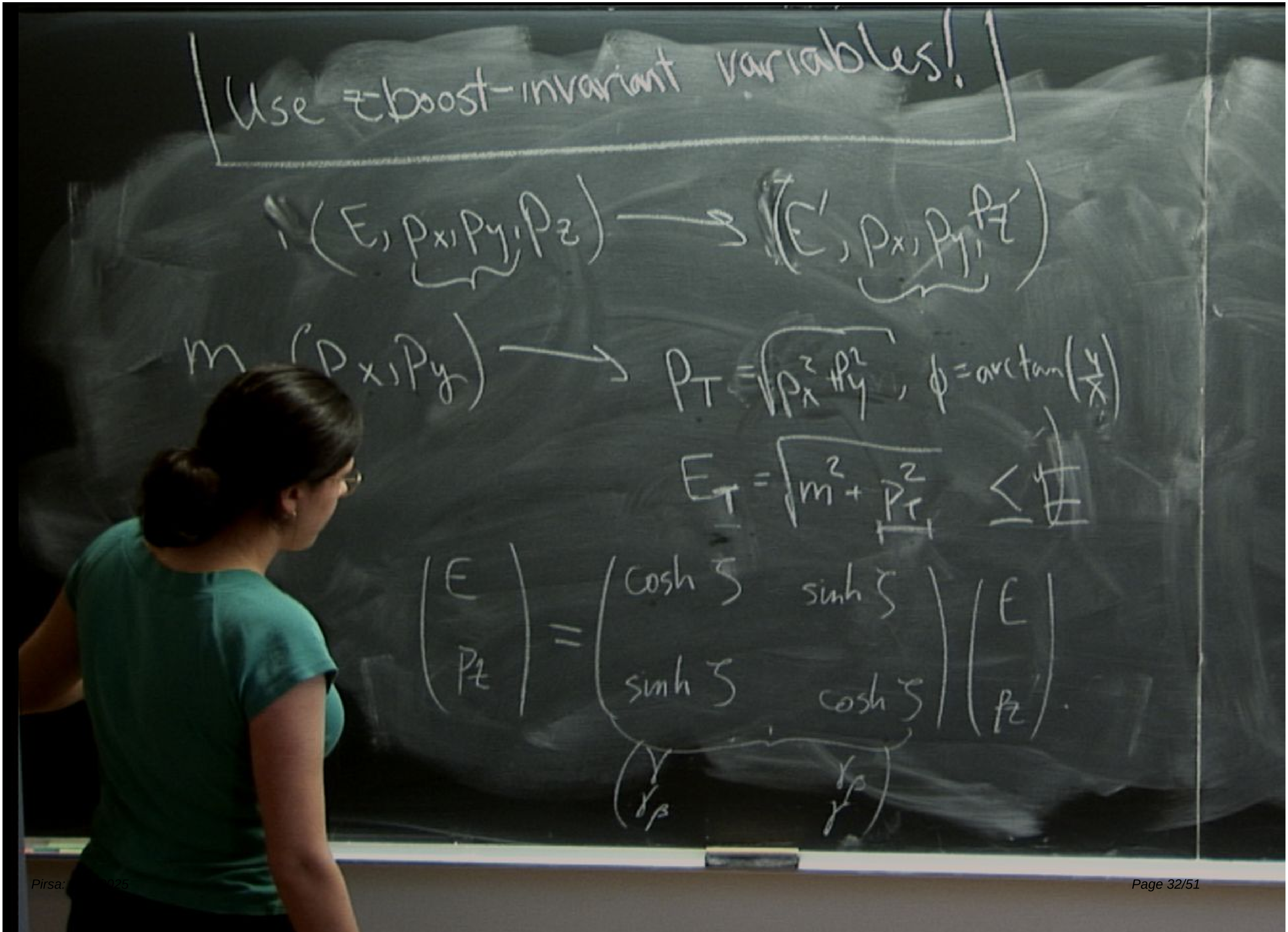

Z
e+
e-

$\boxed{\text{Use } z\text{-boost-invariant variables!}}$

$$(E, \underbrace{p_x, p_y}, p_z) \longrightarrow (E', \underbrace{p_x, p_y}, z')$$

$$m, (p_x, p_y) \longrightarrow p_T = \sqrt{p_x^2 + p_y^2}, \ \phi = \arctan\left(\frac{y}{x}\right)$$

$$E_T = \sqrt{m^2 + p_T^2}$$


Use z-boost-invariant variables!
(E, px, py, pz) → (E', px, py, pz')
m (px, py) → pT = √(px² + py²), φ = arctan(y/x)
ET = √(m² + pT²)
(E, pz) = (cosh ζ, sinh ζ; sinh ζ, cosh ζ) (E, pz).
(γ, γβ; γβ, γ)

$$\boxed{\text{Use } z\text{-boost-invariant variables!}}$$

$$(E, \underbrace{p_x, p_y}, p_z) \longrightarrow (E', \underbrace{p_x, p_y}, p_z')$$

$$m, (p_x, p_y) \longrightarrow p_T = \sqrt{p_x^2 + p_y^2}, \quad \phi = \arctan\left(\frac{y}{x}\right)$$

$$E_T = \sqrt{m^2 + p_T^2} \leq E$$

$\cosh \zeta = \gamma$

$\sinh^2 \zeta = \cosh^2 \zeta - 1$

$= (\gamma^2 - 1)$

$$\begin{pmatrix} E' \\ p_z' \end{pmatrix} = \underbrace{\begin{pmatrix} \cosh \zeta & \sinh \zeta \\ \sinh \zeta & \cosh \zeta \end{pmatrix}}_{\begin{pmatrix} \gamma & \gamma\beta \\ \gamma\beta & \gamma \end{pmatrix}} \begin{pmatrix} E \\ p_z \end{pmatrix}$$

...st-invariant variables!

$$(\ldots p_y, p_z) \longrightarrow (E', \underbrace{p_x, p_y}, p_z')$$

$$\ldots) \longrightarrow p_T = \sqrt{p_x^2 + p_y^2}, \quad \phi = \arctan\left(\frac{y}{x}\right)$$

$$E_T = \sqrt{m^2 + p_T^2} \le E$$

$$\begin{pmatrix} E' \\ p_z' \end{pmatrix} = \underbrace{\begin{pmatrix} \cosh\zeta & \sinh\zeta \\ \sinh\zeta & \cosh\zeta \end{pmatrix}}_{\begin{pmatrix} \gamma & \gamma_\beta \\ \gamma_\beta & \gamma \end{pmatrix}} \begin{pmatrix} E \\ p_z \end{pmatrix}.$$

$$E^2 - p_z^2 = A^2$$

$$E_T^2 = A^2,$$

$$\frac{E}{E_T}$$

$$E = A\cosh y$$

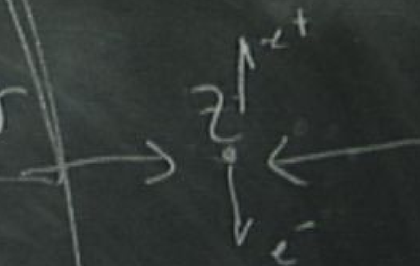
$$p_z = A\sinh y$$

$$\cosh y \to \cosh(y + \zeta)$$

$$E^2 - p_z^2 = A^2$$

$$E_T^2 = A^2,$$

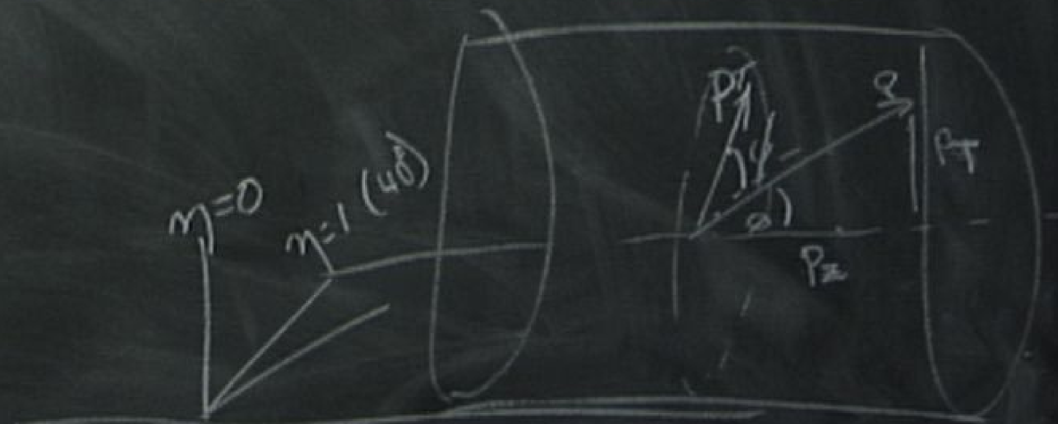
$$\boxed{\frac{E}{E_T} = \cosh y, \quad \frac{p_z}{E_T} = \sinh y}$$



~~Masses~~ $\frac{p}{p_T} = \cosh y = \frac{1}{\cos\theta}, \quad \frac{p_z}{p_T} = \sinh y = \frac{1}{\tan\theta}$

$$\left(y = -\ln \tan \theta/2 \right)$$

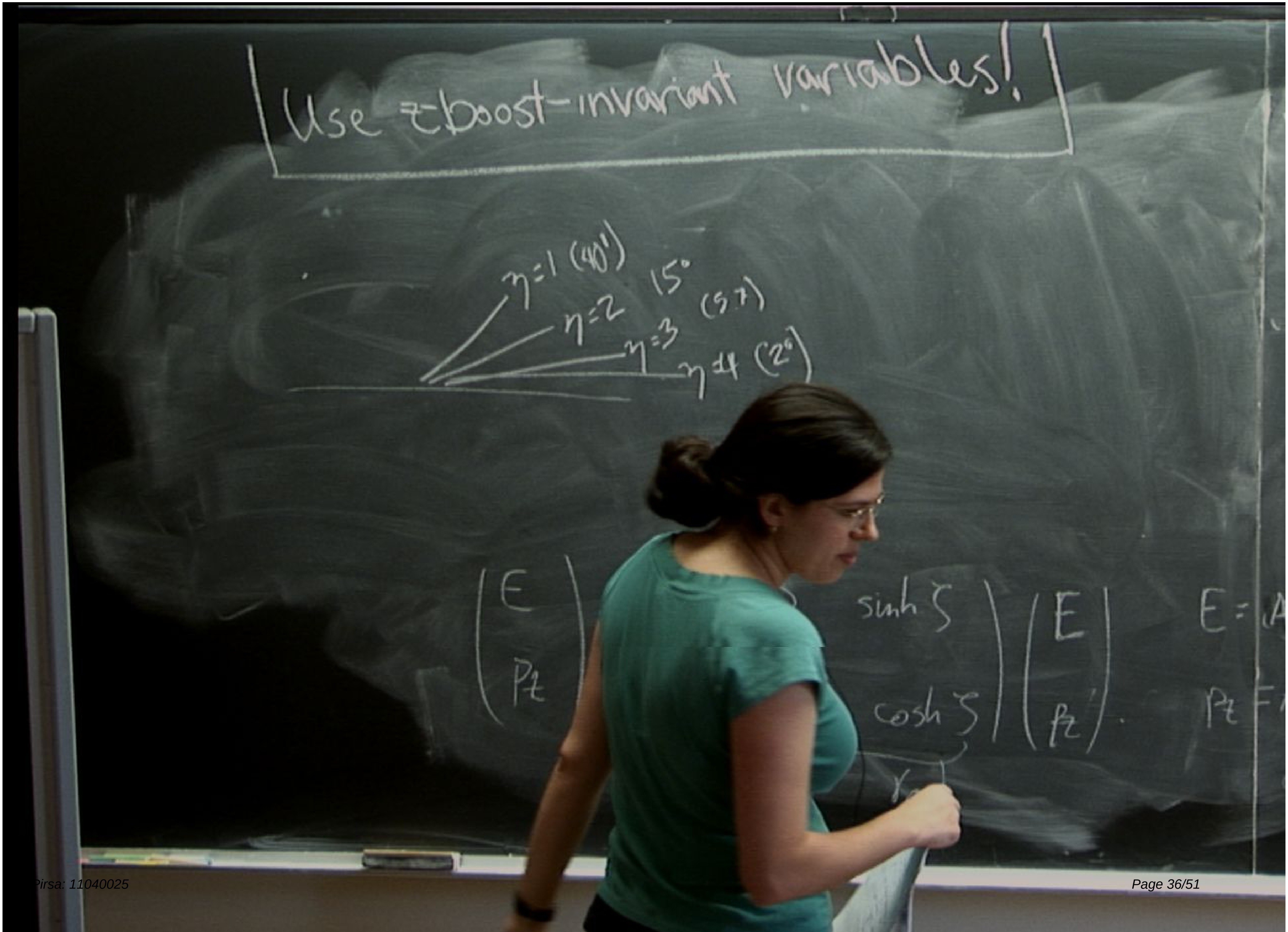
$$\left(\eta \equiv -\ln \tan \frac{\theta}{2} \right)$$

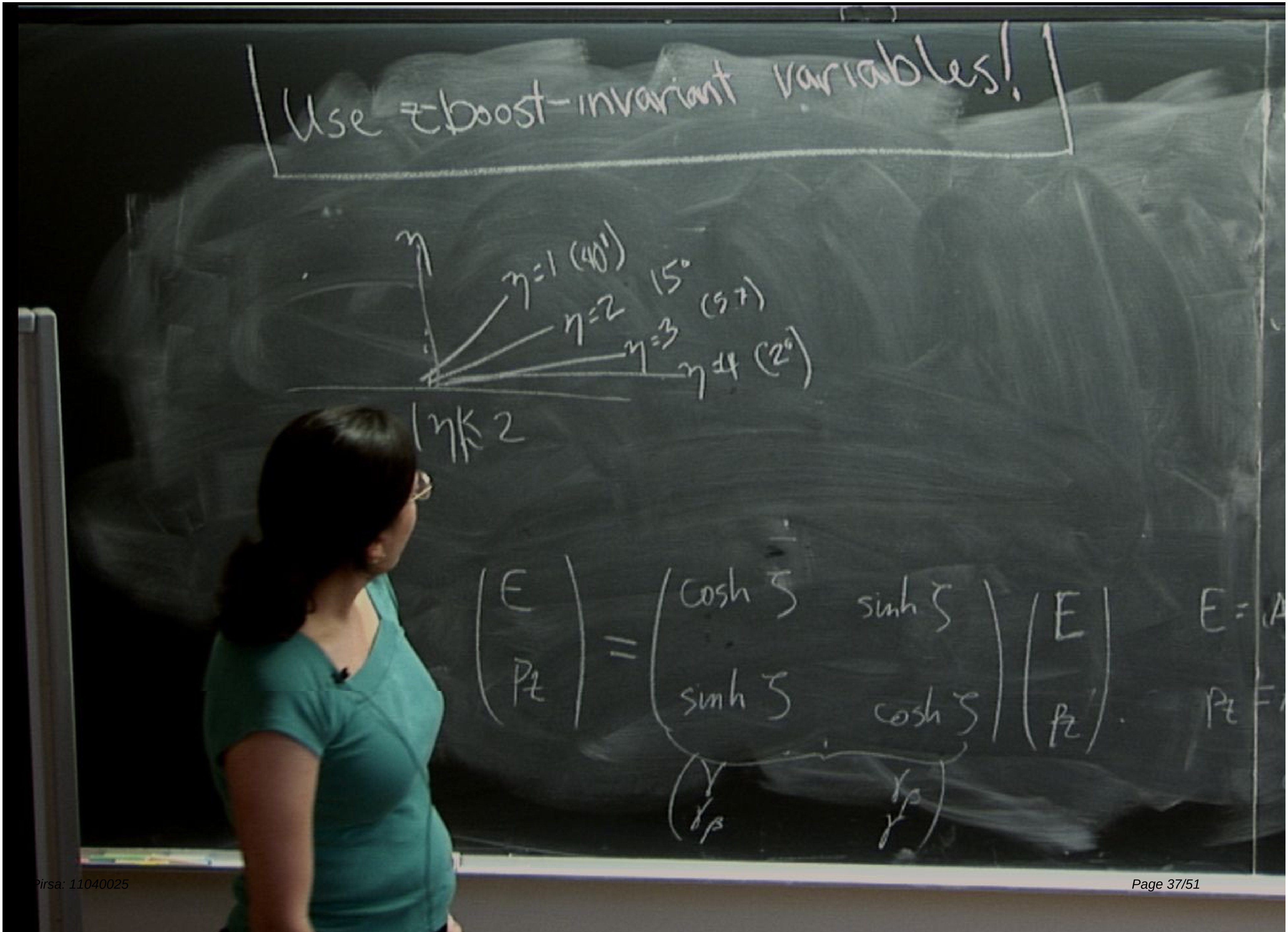


$\cosh y$

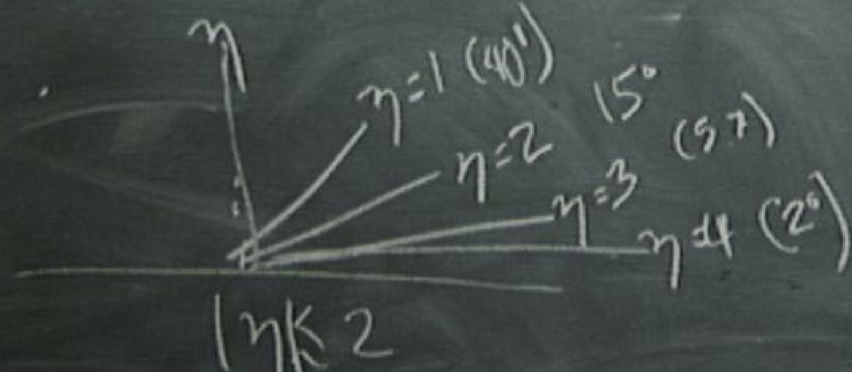
$A \sinh y$

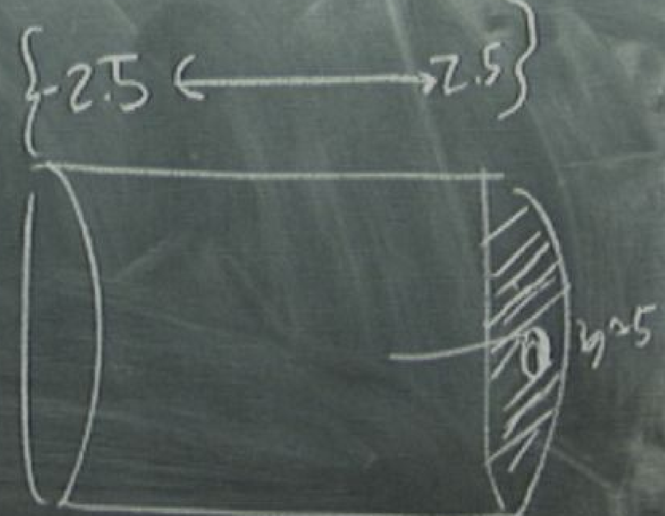
$\cosh y \to \cosh(y+\xi)$


Use z-boost-invariant variables!
η=1 (40°)
η=2 15°
(5.7)
η=3
η=4 (2°)
E
pz
sinh ζ
cosh ζ
E
pz'
E =
pz


Use z-boost-invariant variables!
η
η=1 (40°)
15°
η=2
η=3
η=4 (2°)
|η|< 2
E
pz
=
cosh ζ
sinh ζ
sinh ζ
cosh ζ
E
pz
γ
γβ
γβ
γ

Use z-boost-invariant variables!





$$\begin{pmatrix} E \\ p_z \end{pmatrix} = \begin{pmatrix} \underbrace{\cosh\zeta}_{\gamma} & \sinh\zeta \\ \underbrace{\sinh\zeta}_{\gamma\beta} & \underbrace{\cosh\zeta}_{\gamma} \end{pmatrix} \begin{pmatrix} E \\ p_z \end{pmatrix}.$$

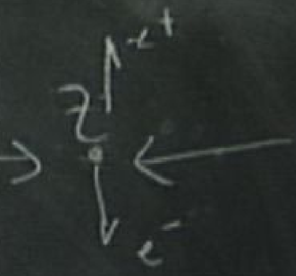
$E = A$

$p_z =$

$$E^2 - p_z^2 = A^2$$

$$E_T^2 = A^2,$$

$$\boxed{\frac{E}{E_T} = \cosh y, \quad \frac{p_z}{E_T} = \sinh y}$$

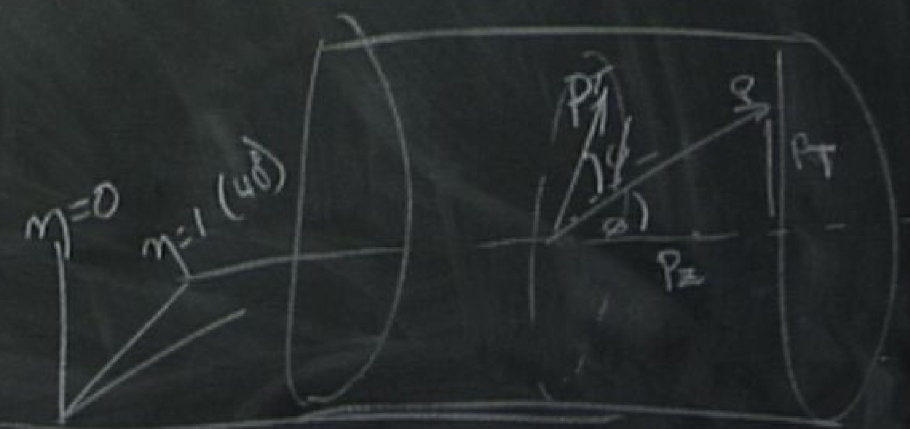


~~Massless~~ $$\frac{p}{p_T} = \cosh y = \frac{1}{\cos\theta}, \quad \frac{p_z}{p_T} = \sinh y = \frac{1}{\tan\theta}$$

→ $\eta \geq 2.5$

$$(y = -\ln \tan\theta/2)$$

$$\left(\eta \equiv -\ln \tan\frac{\theta}{2}\right)$$



$\cosh y$

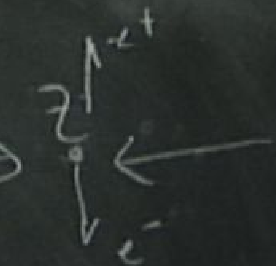
$A \sinh y$

$\cosh y \to \cosh(y+\xi)$

$$E^2 - p_z^2 = A^2$$

$$\boxed{\frac{E}{E_T} = \cosh y, \quad \frac{p_z}{E_T} = \sinh y}$$

$$E_T^2 = A^2,$$



Massless

$$\frac{p}{p_T} \Rightarrow \cosh y \Leftarrow \frac{1}{\cos\theta}, \quad \frac{p_z}{p_T} \Rightarrow \sinh y \Leftarrow \frac{1}{\tan\theta}$$

$\eta > 2.5$

$$\left(y \Rightarrow -\ln \tan\theta/2 \right)$$

$$\left(\eta \equiv -\ln \tan\frac{\theta}{2} \right)$$

$\cosh y$

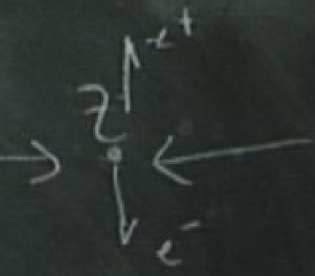
$A \sinh y$

$\cosh y \to \cosh(y+\xi)$

$$E^2 - p_z^2 = A^2$$

$$E_T^2 = A^2,$$

$$\boxed{\frac{E}{E_T} = \cosh y,\quad \frac{p_z}{E_T} = \sinh y}$$



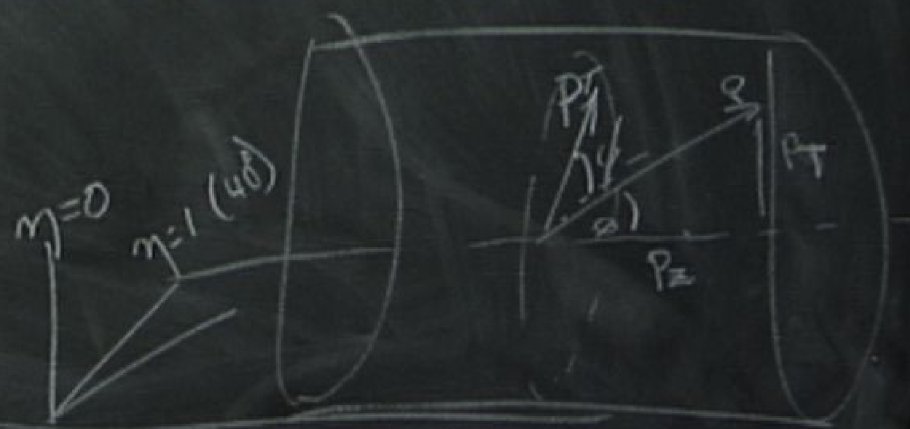
Massless

$$\frac{p}{p_T} \to \cosh y \leftarrow \frac{1}{\cos\theta}, \quad \frac{p_z}{p_T} \to \sinh y \leftarrow \frac{1}{\tan\theta}$$

$\eta \gg 5$

$$\left(y \Rightarrow -\ln \tan \theta/2 \right)$$

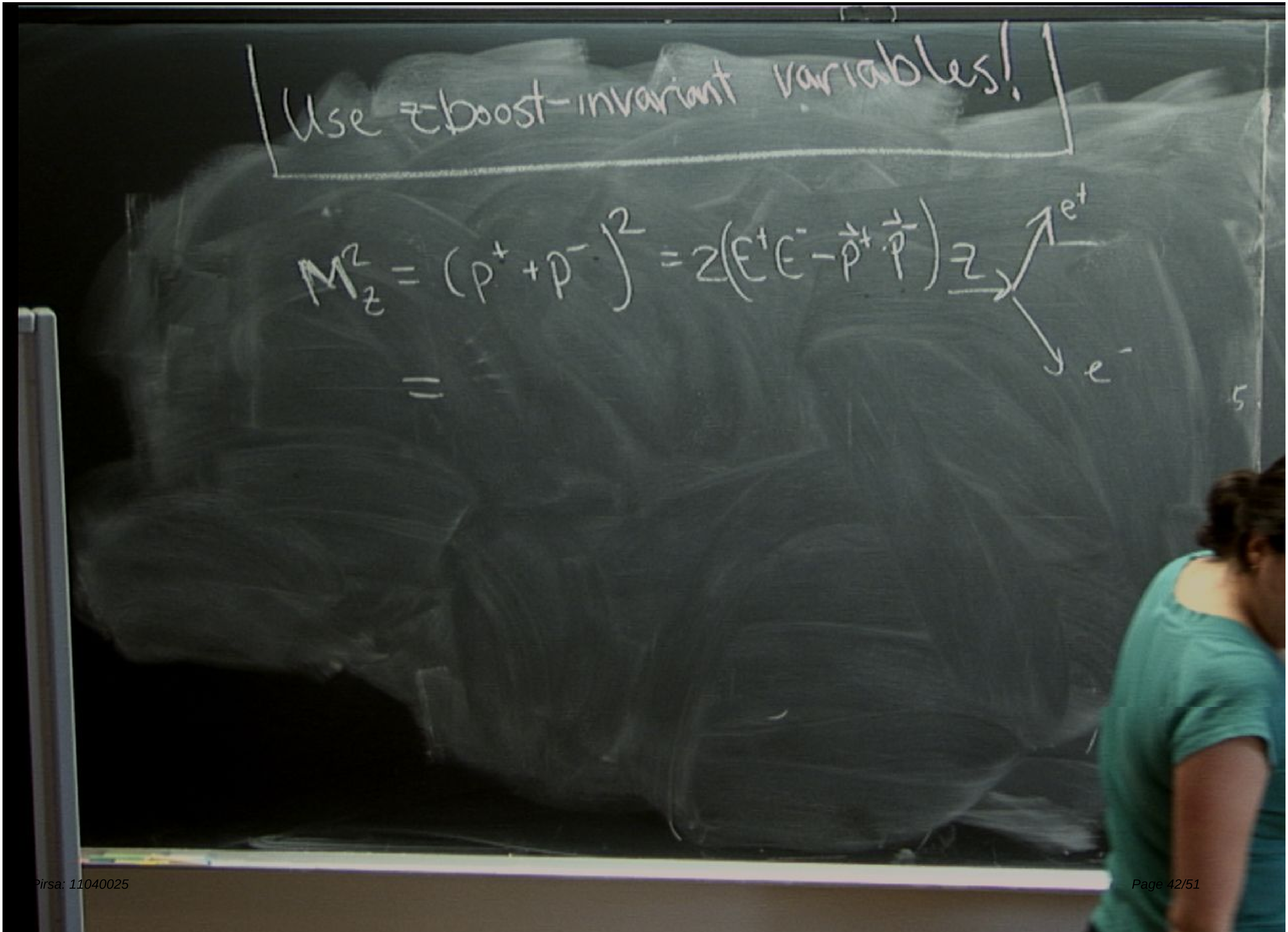
$$\left(\eta \equiv -\ln \tan \frac{\theta}{2} \right)$$

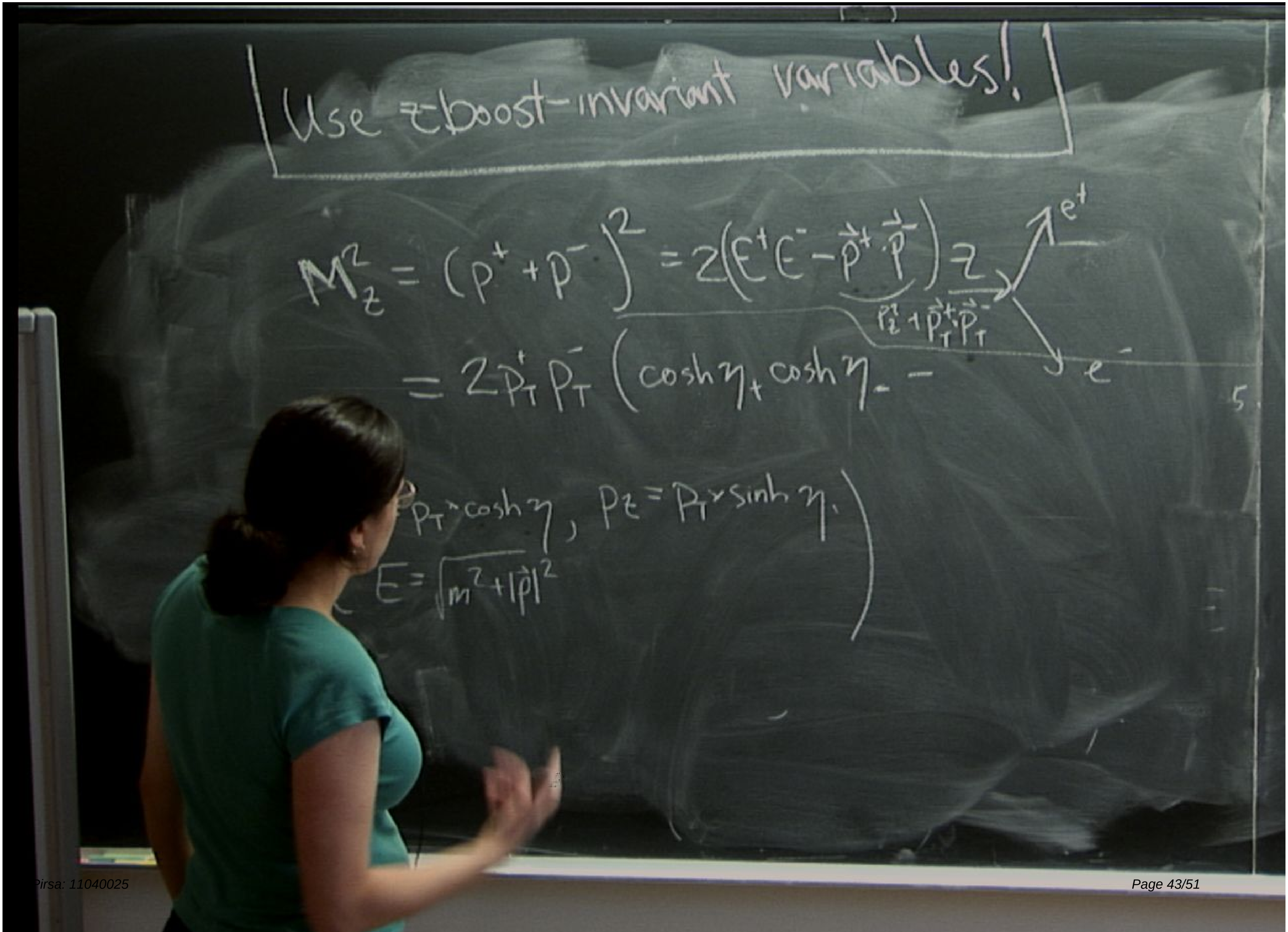


$\cosh y$

$A \sinh y$

$\cosh y \to \cosh(y+\xi)$


Use z boost-invariant variables!
$M_Z^2 = (p^+ + p^-)^2 = 2(E^+E^- - \vec{p}^+ \cdot \vec{p}^-)$
Z
e^+
e^-
=
5


Use z boost-invariant variables!
$M_Z^2 = (p^+ + p^-)^2 = 2(E^+E^- - \vec{p}^+\cdot\vec{p}^-)$
$p_z^+ p_z^- + \vec{p}_T^+\cdot\vec{p}_T^-$
$= 2 p_T^+ p_T^- (\cosh\eta_+ \cosh\eta_- -$
Z
e^+
e^-
5
$p_T \times \cosh\eta, \; p_z = p_T \times \sinh\eta.$
$E = \sqrt{m^2 + |\vec{p}|^2}$

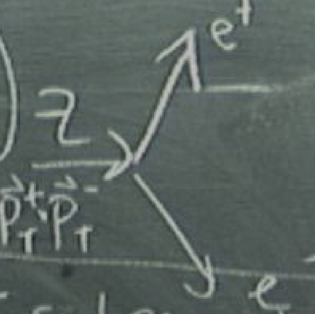
Use z-boost-invariant variables!

$$M_Z^2 = (p^+ + p^-)^2 = 2\left(E^+E^- - \underbrace{\vec{p}^{\,+}\cdot\vec{p}^{\,-}}_{p_z^+ p_z^- + \vec{p}_T^{\,+}\cdot\vec{p}_T^{\,-}}\right)$$

$$= 2p_T^+p_T^-\left(\underbrace{\cosh\eta_+\cosh\eta_- - \sinh\eta_+\sinh\eta_-}_{\cosh(\eta_+-\eta_-)} - \cos\Delta\phi\right)$$ 5

$$\boxed{M_Z^2 = 2p_T^+p_T^-\left(\cosh(\Delta\eta) - \cos\Delta\phi\right)}$$

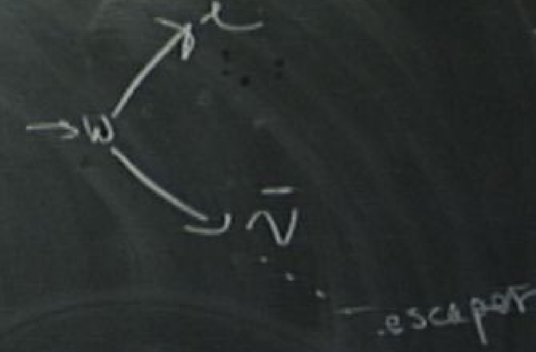
$$\boxed{\text{Use } z \text{ boost-invariant variables!}}$$

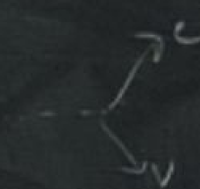


$$M_Z^2 = (p^+ + p^-)^2 = 2\big(E^+E^- - \underbrace{\vec{p}^+\cdot\vec{p}^-}_{p_z^+p_z^- + \vec{p}_T^+\cdot\vec{p}_T^-}\big)$$

$$= 2p_T^+p_T^-\big(\underbrace{\cosh\eta_+\cosh\eta_- - \sinh\eta_+\sinh\eta_-}_{\cosh(\eta_+-\eta_-)} - \cos\Delta\phi\big)$$

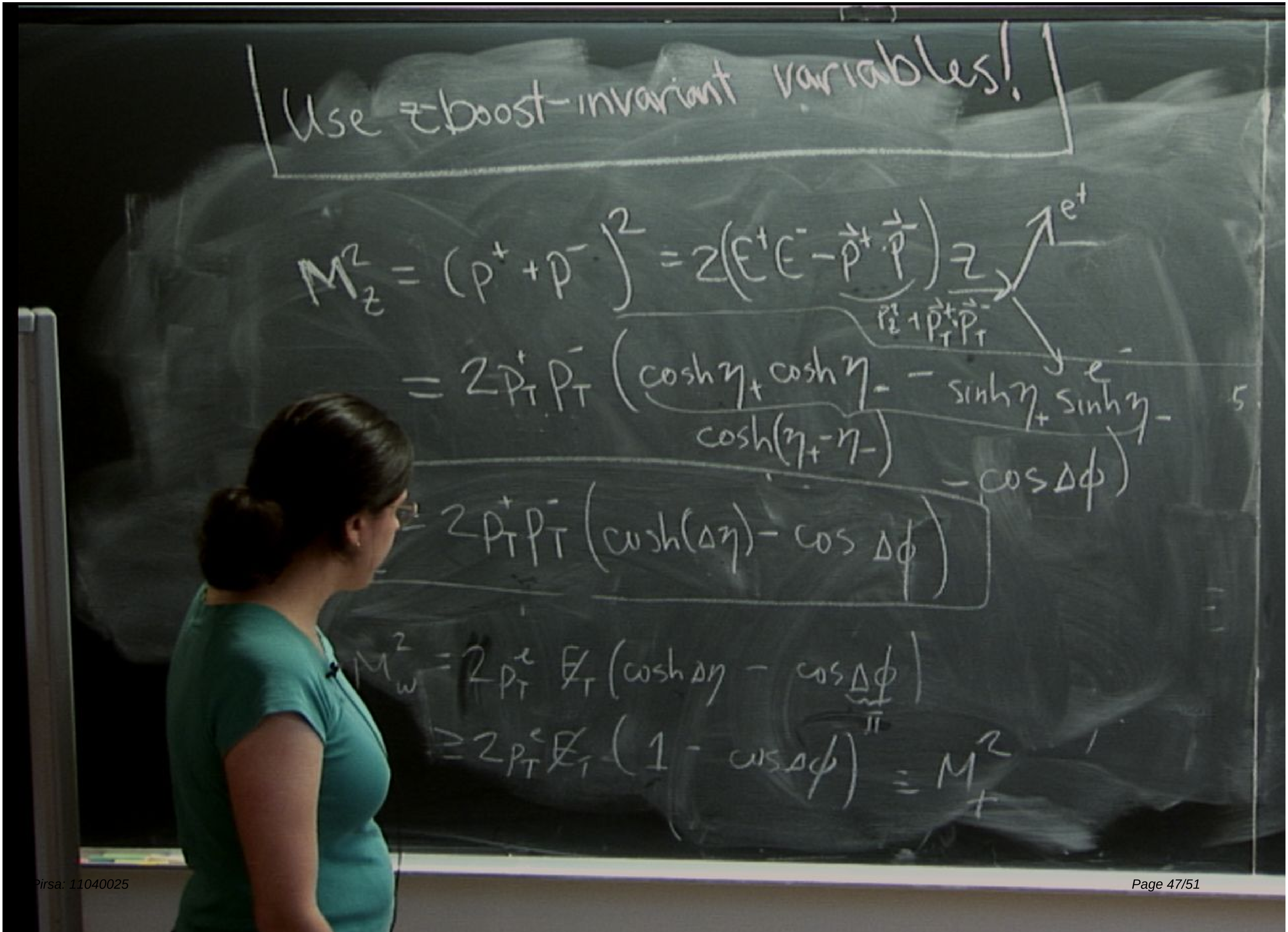
$$\boxed{M_Z^2 = 2p_T^+p_T^-\big(\cosh(\Delta\eta) - \cos\Delta\phi\big)}$$





$$\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,e}$$

η^ν unknown.


Use z boost-invariant variables!
$M_Z^2 = (p^+ + p^-)^2 = 2(E^+E^- - \vec{p}^+ \cdot \vec{p}^-)$
$p_z^+ p_z^- + \vec{p}_T^+ \cdot \vec{p}_T^-$
z
e^+
e^-
$= 2 p_T^+ p_T^- (\cosh\eta_+ \cosh\eta_- - \sinh\eta_+ \sinh\eta_- - \cos\Delta\phi)$
$\cosh(\eta_+ - \eta_-)$
5
$= 2 p_T^+ p_T^- (\cosh(\Delta\eta) - \cos\Delta\phi)$
$M_W^2 = 2 p_T^e \not{E}_T (\cosh\Delta\eta - \cos\Delta\phi)$
$\geq 2 p_T^e \not{E}_T (1 - \cos\Delta\phi) = M_T^2$

Use z boost-invariant variables!

$$M_Z^2 = (p^+ + p^-)^2 = 2(E^+E^- - \vec{p}^+\cdot\vec{p}^-)$$

$$p_z^+ + \vec{p}_T^+\cdot\vec{p}_T^-$$

$$Z \to e^+ e^-$$

$$= 2p_T^+ p_T^- \left(\underbrace{\cosh\eta_+\cosh\eta_- - \sinh\eta_+\sinh\eta_-}_{\cosh(\eta_+ - \eta_-)} - \cos\Delta\phi\right)$$

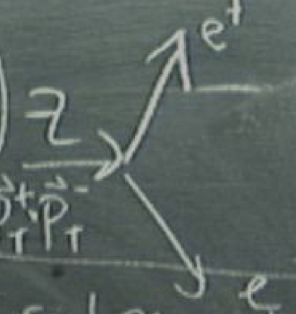
$$\boxed{M_Z^2 = 2p_T^+ p_T^- \left(\cosh(\Delta\eta) - \cos\Delta\phi\right)}$$

$$M_W^2 = 2p_T^e \not{E}_T \left(\cosh\Delta\eta - \cos\Delta\phi\right)$$

$$\geq 2p_T^e \not{E}_T (1 - \cos\Delta\phi) \equiv M_T^2$$

$$\boxed{\text{Use } z \text{ boost-invariant variables!}}$$

$$M_Z^2 = (p^+ + p^-)^2 = 2(E^+E^- - \underbrace{\vec{p}^{\,+}\cdot\vec{p}^{\,-}}_{p_z^+p_z^- + \vec{p}_T^{\,+}\cdot\vec{p}_T^{\,-}})$$

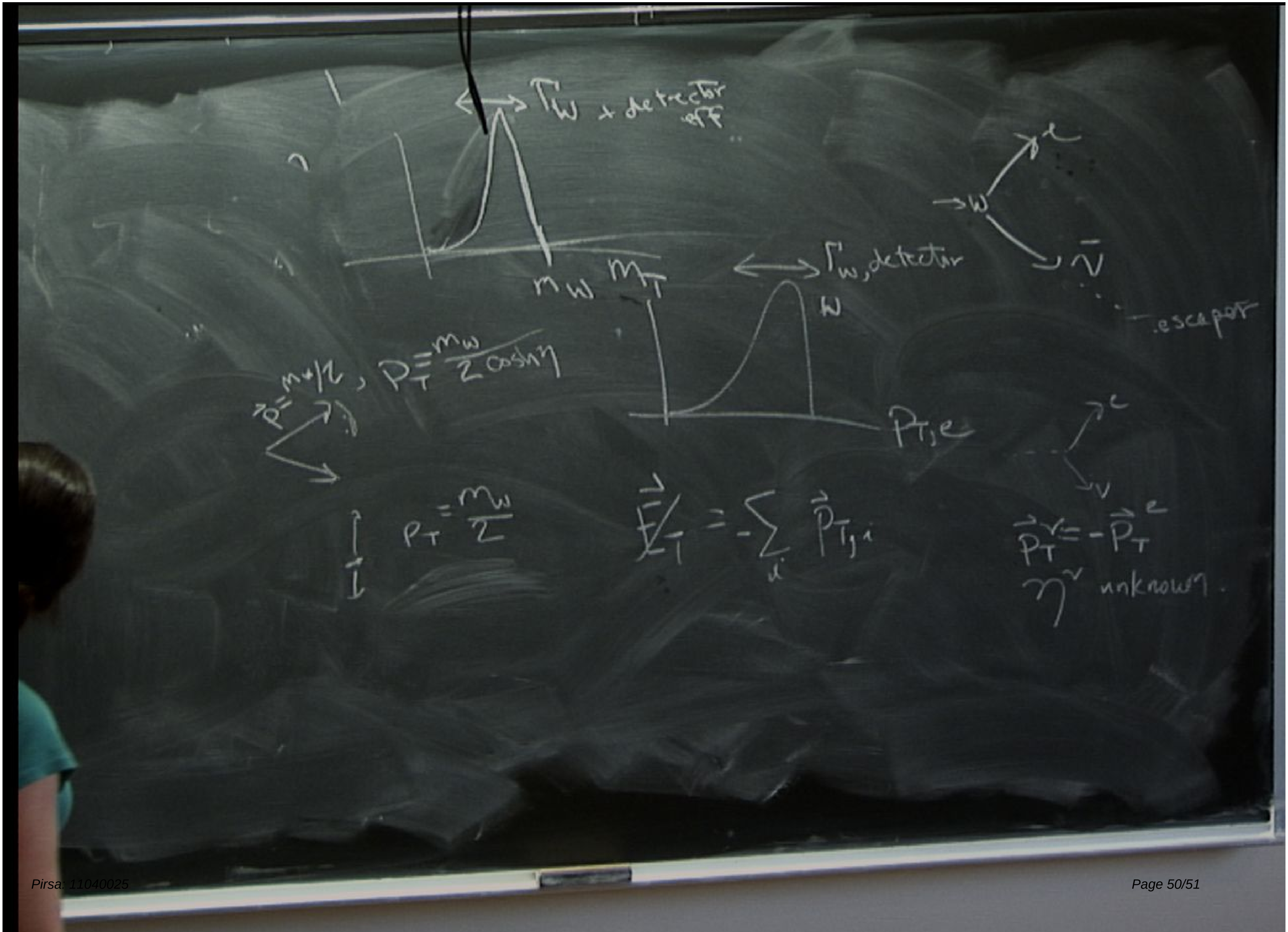


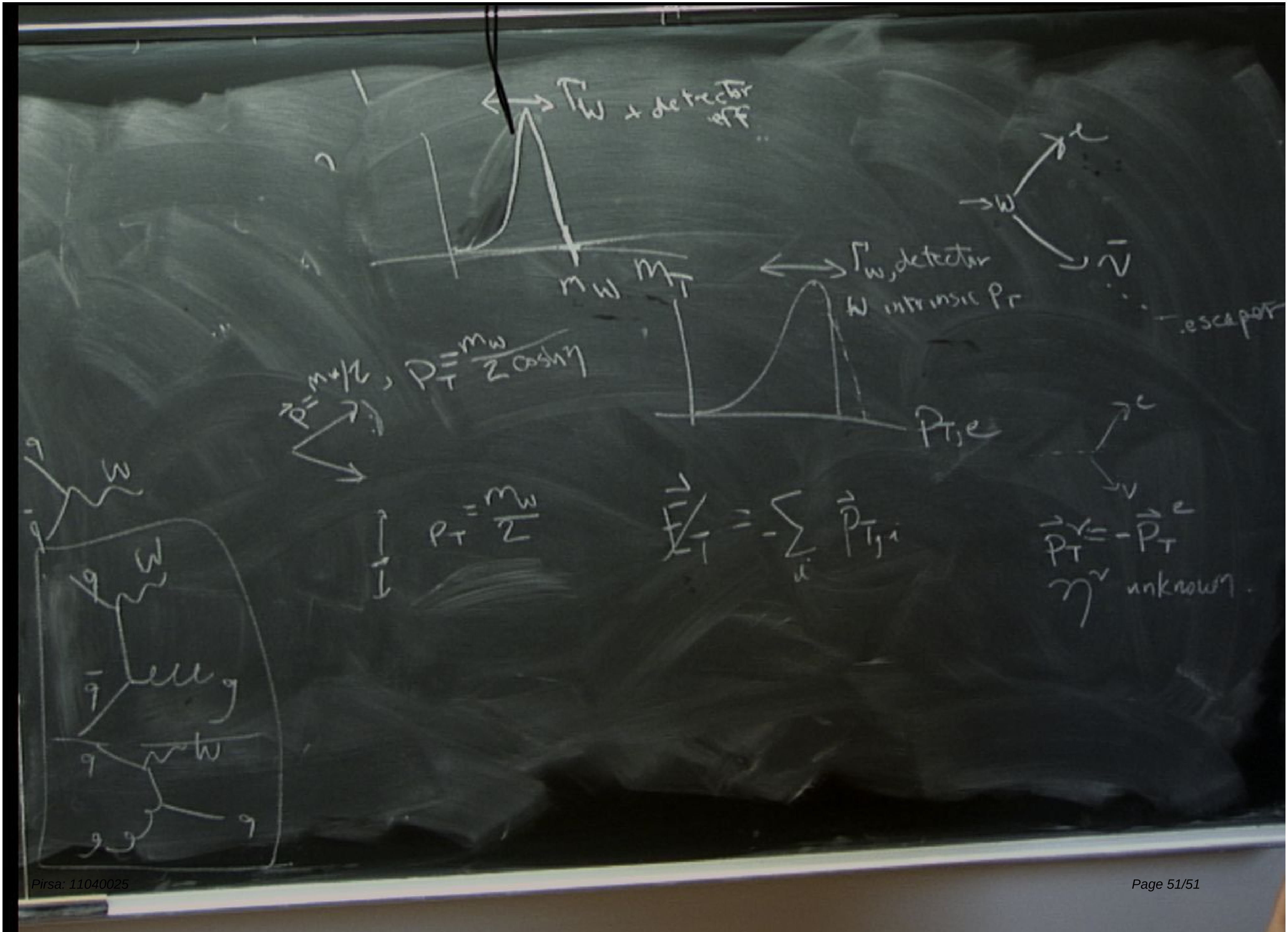
$$= 2p_T^+p_T^-\left(\underbrace{\cosh\eta_+\cosh\eta_- - \sinh\eta_+\sinh\eta_-}_{\cosh(\eta_+-\eta_-)} - \cos\Delta\phi\right)$$

$$\boxed{M_Z^2 = 2p_T^+p_T^-\left(\cosh(\Delta\eta) - \cos\Delta\phi\right)}$$

$$M_W^2 = 2p_T^e \not{E}_T\left(\cosh\Delta\eta - \cos\Delta\phi\right)$$

$$\geq 2p_T^e \not{E}_T\left(1 - \cos\Delta\phi\right) = M_T^2$$


Γ_W + detector eff
m_W M_T
Γ_W, detector
W
$p_{T,e}$
W
e
$\bar{\nu}$
escapes
$\vec{p} = m_W/2$, $p_T = \frac{m_W}{2\cosh\eta}$
$p_T = \frac{m_W}{2}$
$\vec{\not{E}}_T = -\sum_i \vec{p}_{T,i}$
e
ν
$\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,e}$
η^ν unknown.


Γ_W + detector eff
m_W M_T
Γ_W, detector
W intrinsic p_T
$W \to e$, $\bar{\nu}$
escapes
$p = m_W/2$, $p_T = \frac{m_W}{2\cosh\eta}$
$p_{T,e}$
$p_T = \frac{m_W}{2}$
$\vec{\not{E}}_T = -\sum_i \vec{p}_{T,i}$
$\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,e}$
η^ν unknown
q, $\bar{q}$, W, g