Title: Standard Model

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Lecture 3: Electroweak Theory & Tests

gauge theory: $SU(2)_L \times U(1)_Y$ ← hypercharge

$W^1, W^2, W^3 \quad B$

Higgs field $H \rightarrow$ doublet (2)

$Y = \frac{1}{2}$

$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

↳ gets a VEV

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Higgs field $H \rightarrow$ doublet (2) $\quad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$

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↳ gets a VEV $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$, SU(2) gauge theory

$$[T_R^a, T_R^b] = i\,\epsilon^{abc}\,T_R^c$$

reps: doublet (fundamental) $T_F^a = \frac{1}{2}\sigma^a$ ← Pauli spin matrix

adjoint $(T_A^a)^{bc} = -i\,\epsilon^{abc}$

$$D_\mu = \partial_\mu - i g A_\mu^a T_R^a$$

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g\,\epsilon^{abc} A_\mu^b A_\nu^c$$

Gauge sector

$$D_\mu H = \partial_\mu H - i g_Y \left(\frac{1}{2}\right) B_\mu H - i g_W W_\mu^a T_F^a H$$

hypercharge $\frac{1}{2}$

$$\mathcal{L}_H = |D_\mu H|^2 - V(H)$$

Replace $H \to \langle H \rangle$, pick out the mass terms. gauge field

$$D_\mu H \to -i \frac{g_Y}{2}\begin{pmatrix} B_\mu & 0 \\ 0 & B_\mu \end{pmatrix}\begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} - i g_W \begin{pmatrix} \frac{1}{2} W_\mu^3 & \frac{1}{2}(W_\mu^1 - i W_\mu^2) \\ \frac{1}{2}(W_\mu^1 + i W_\mu^2) & -\frac{1}{2} W_\mu^3 \end{pmatrix}\begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$= -i \begin{pmatrix} \frac{1}{2} g_Y B_\mu + \frac{1}{2} g_w W_\mu^3 & \frac{g_w}{2}(W_\mu^1 - i W_\mu^2) \\ \underbrace{\frac{g_w}{2}(W_\mu^1 + i W_\mu^2)}_{\text{multiplied by } 0} & \underbrace{\frac{1}{2} g_Y B_\mu - \frac{1}{2} g_w W_\mu^3}_{\text{multiplied by } \frac{v}{\sqrt{2}}} \end{pmatrix} \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

3 linear combinations get mass.

$$W_\mu^{\pm} = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp i W_\mu^2\right) \qquad M_W = \frac{g_w v}{2}$$

$$= -i \begin{pmatrix} \underbrace{\tfrac{1}{2} g_Y B_\mu + \tfrac{1}{2} g_w W_\mu^3}_{} & \tfrac{g_w}{2}(W_\mu^1 - i W_\mu^2) \\ \underbrace{\tfrac{g_w}{2}(W_\mu^1 + i W_\mu^2)}_{\text{multiplied by } 0} & \underbrace{\tfrac{1}{2} g_Y B_\mu - \tfrac{1}{2} g_w W_\mu^3}_{\text{multiplied by } \frac{v}{\sqrt{2}}} \end{pmatrix} \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$g_w \approx 0.65$

$g_Y \approx 0.3$

3 linear combinations get mass.

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp i W_\mu^2\right)$$

$$Z_\mu = \cos\theta_w W_\mu^3 - \sin\theta_w B_\mu$$

$$\tan\theta_w \equiv \frac{g_Y}{g_w}$$

$$M_W = \frac{g_w v}{2}$$

$$M_Z = \frac{M_W}{\cos\theta_w}$$

Last linear combination is massless:

$$A_\mu = \cos\theta_w B_\mu + \sin\theta_w W^3_\mu$$

↳ photon!

$$SU(2)_L \times U(1)_Y \to U(1)_{EM}.$$

3 eaten Goldstone bosons. → $H^\pm$ eaten by $W^\pm$

$H^0 = h + i a_0$, a_0 eaten by Z

In unitary gauge, $H \to \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}$

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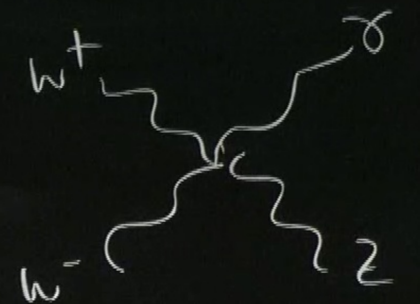

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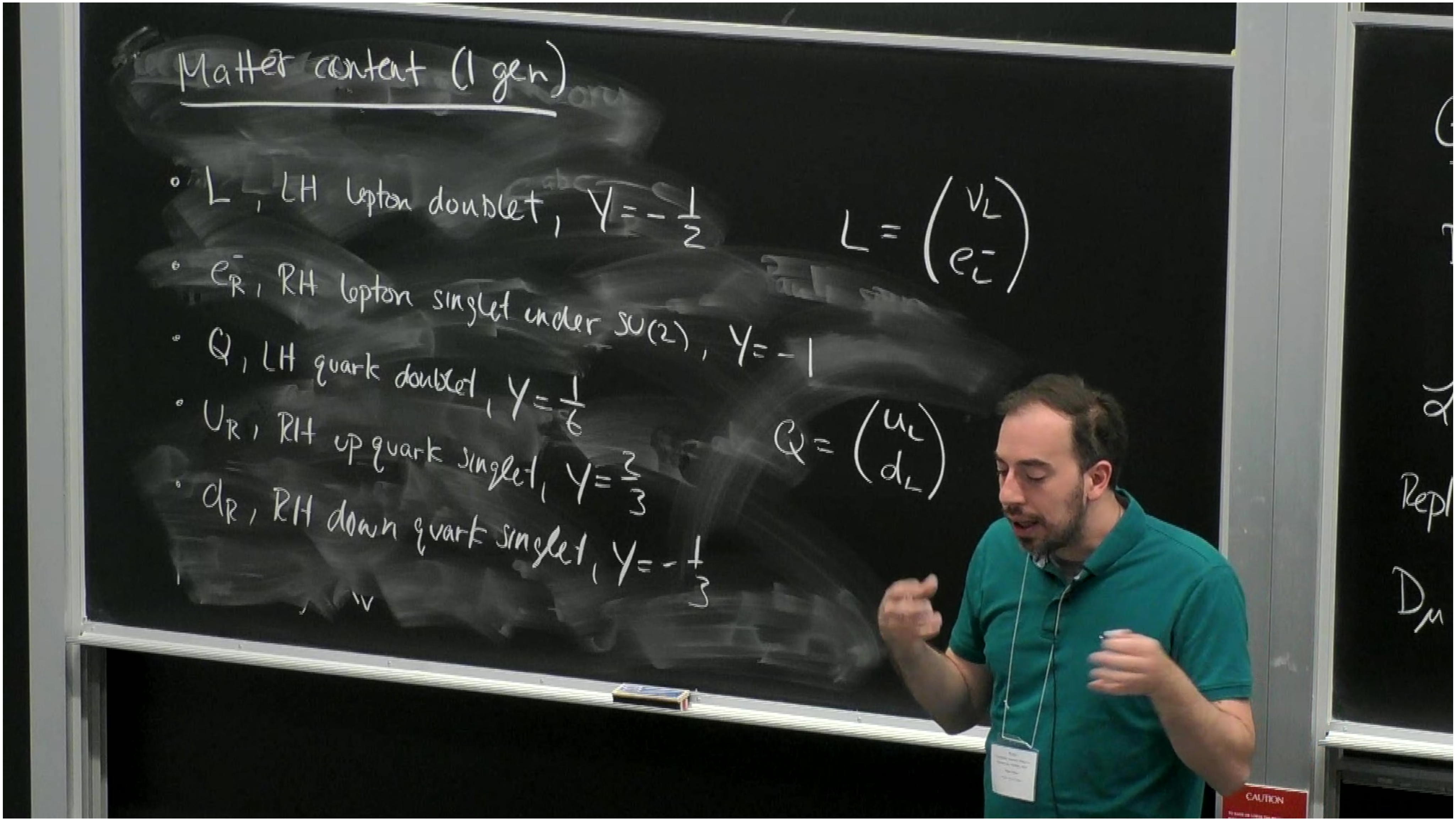
Gauge boson prop: $\dfrac{-i\left(g_{\mu\nu} - \frac{k_\mu k_\nu}{M_W^2}\right)}{k^2 - M_W^2 + i\epsilon}$


Matter content (1 gen)
• L, LH lepton doublet, $Y = -\frac{1}{2}$
• e_R^-, RH lepton singlet under SU(2), $Y = -1$
• Q, LH quark doublet, $Y = \frac{1}{6}$
• u_R, RH up quark singlet, $Y = \frac{2}{3}$
• d_R, RH down quark singlet, $Y = -\frac{1}{3}$
$L = \begin{pmatrix} \nu_L \\ e_L^- \end{pmatrix}$
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
CAUTION

Fermion masses (lepton)

Yukawa coupling for leptons

$$\mathcal{L}_{mass,\ell} = - y_\ell H^* e_R^\dagger L + h.c.$$

$$Y: \quad -\frac{1}{2} + 1 - \frac{1}{2} = 0$$

$$SU(2): \quad H^* = (H^- \ \overline{H}^0)$$

$$H^* L = (H^- \ \overset{v}{\overline{H}^0}) \begin{pmatrix} \nu \\ e_L \end{pmatrix} = \frac{v}{\sqrt{2}} e_L .$$

$$\xrightarrow[\text{gauge}]{\text{unitary}} \quad = -\frac{yv}{\sqrt{2}} e_R^\dagger e_L + h.c.$$

$$\boxed{m_\ell = \frac{y_\ell v}{\sqrt{2}}}$$

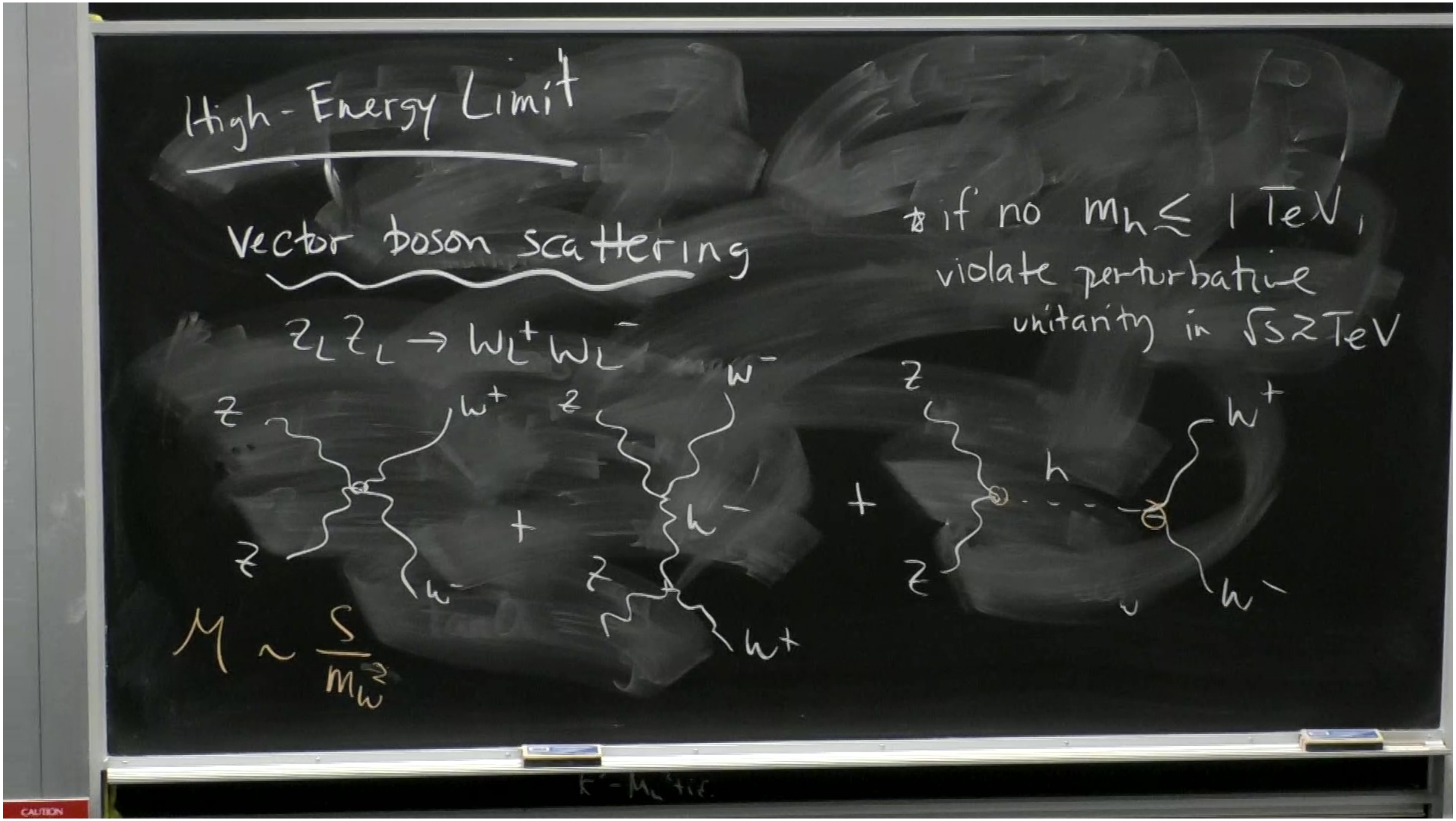
up quark : $\mathcal{L} = - y_u H u_R^\dagger Q + h.c.$

Y : $\frac{1}{2} - \frac{2}{3} + \frac{1}{6} = 0$

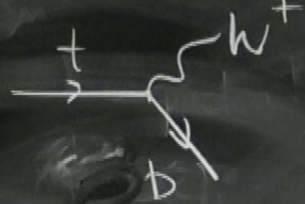
think of QM, spin-$\frac{1}{2}$: how do we get $s = 0$ from $2 \times s = \frac{1}{2}$

$|0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

$|H^+ d\rangle - |H^0 u\rangle$

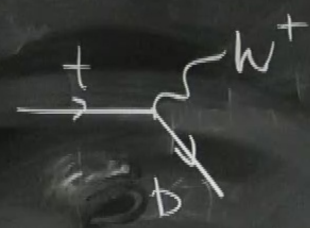

High-Energy Limit
Vector boson scattering
$Z_L Z_L \to W_L^+ W_L^-$
* if no $m_h \lesssim 1$ TeV, violate perturbative unitarity in $\sqrt{s} \gtrsim$ TeV
$\mathcal{M} \sim \frac{s}{m_W^2}$
Z
Z
W+
W-
+
h

Example: top quark decay



$$iM = i\frac{g_w}{\sqrt{2}}\,\bar{u}_b \gamma^\mu P_L u_t\, \epsilon^*_\mu(w)$$

Example: top quark decay



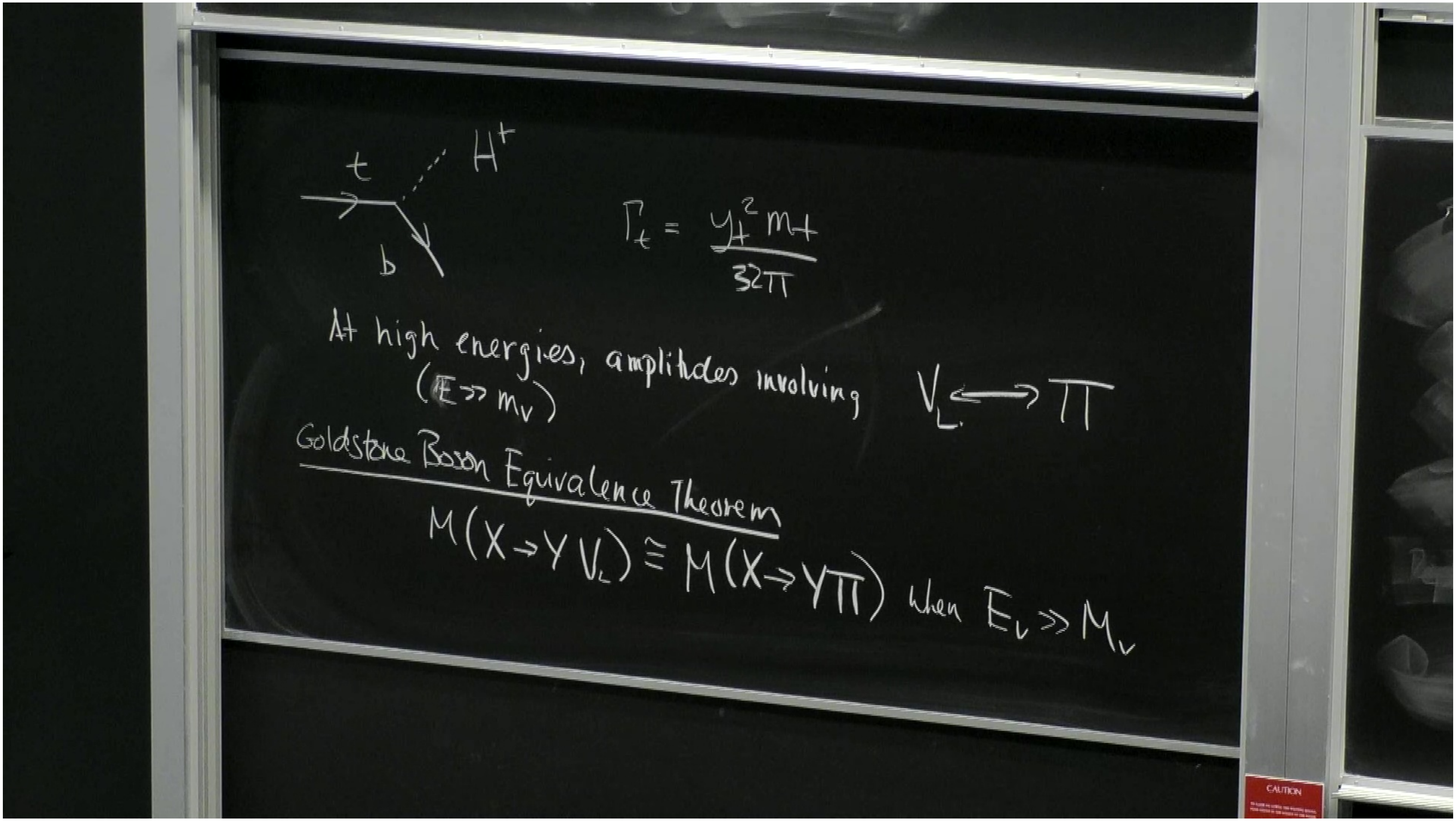
$$iM = \frac{i g_w}{\sqrt{2}} \bar{u}_b \gamma^\mu P_L u_t \, \varepsilon^*_\mu(w)$$

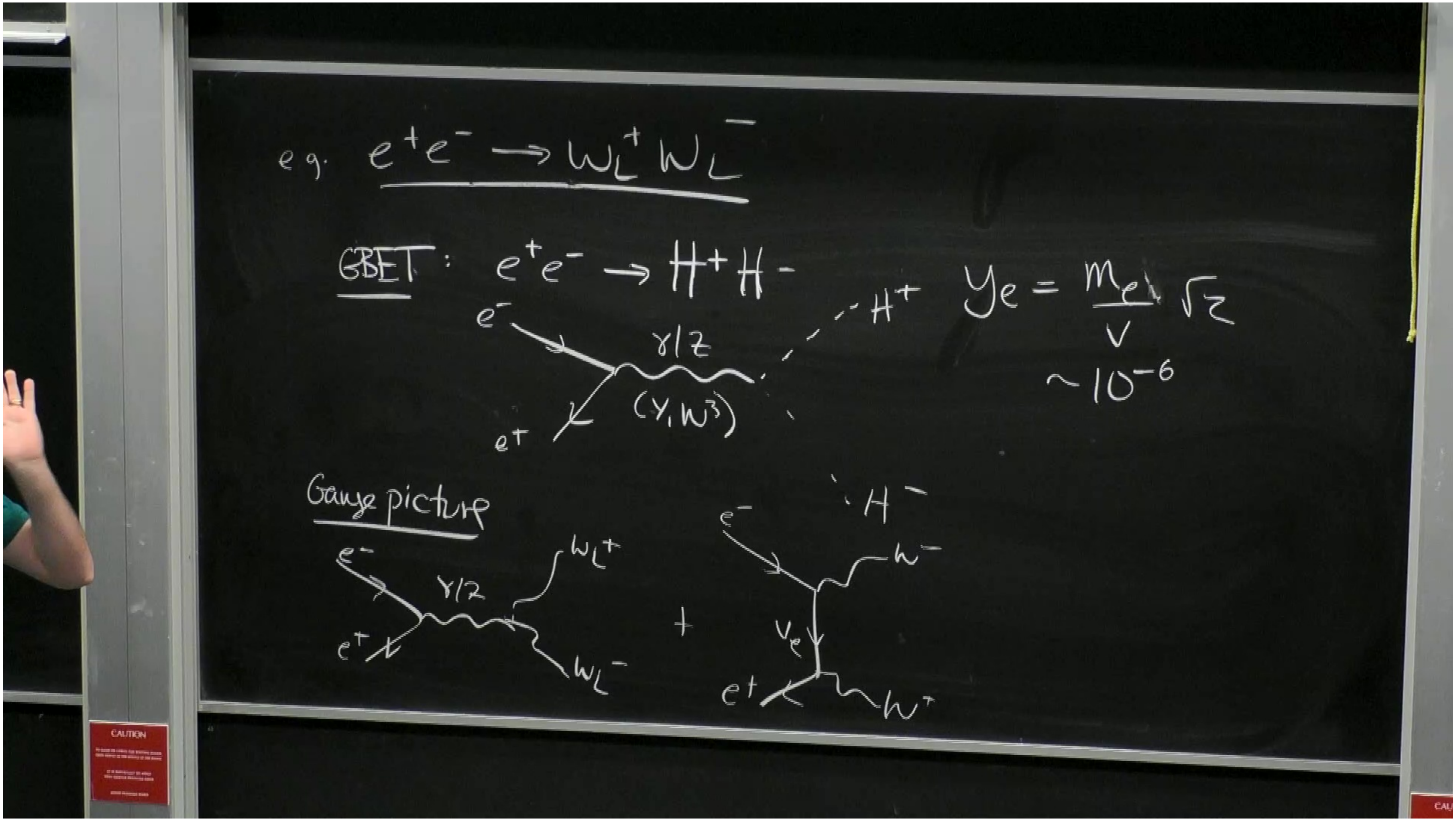
$$\langle |M|^2 \rangle = \frac{g_w^2}{2} \mathrm{Tr}[\cdots] \left(-g_{\mu\nu} + \frac{p_{w\mu} p_{w\nu}}{M_w^2}\right)$$

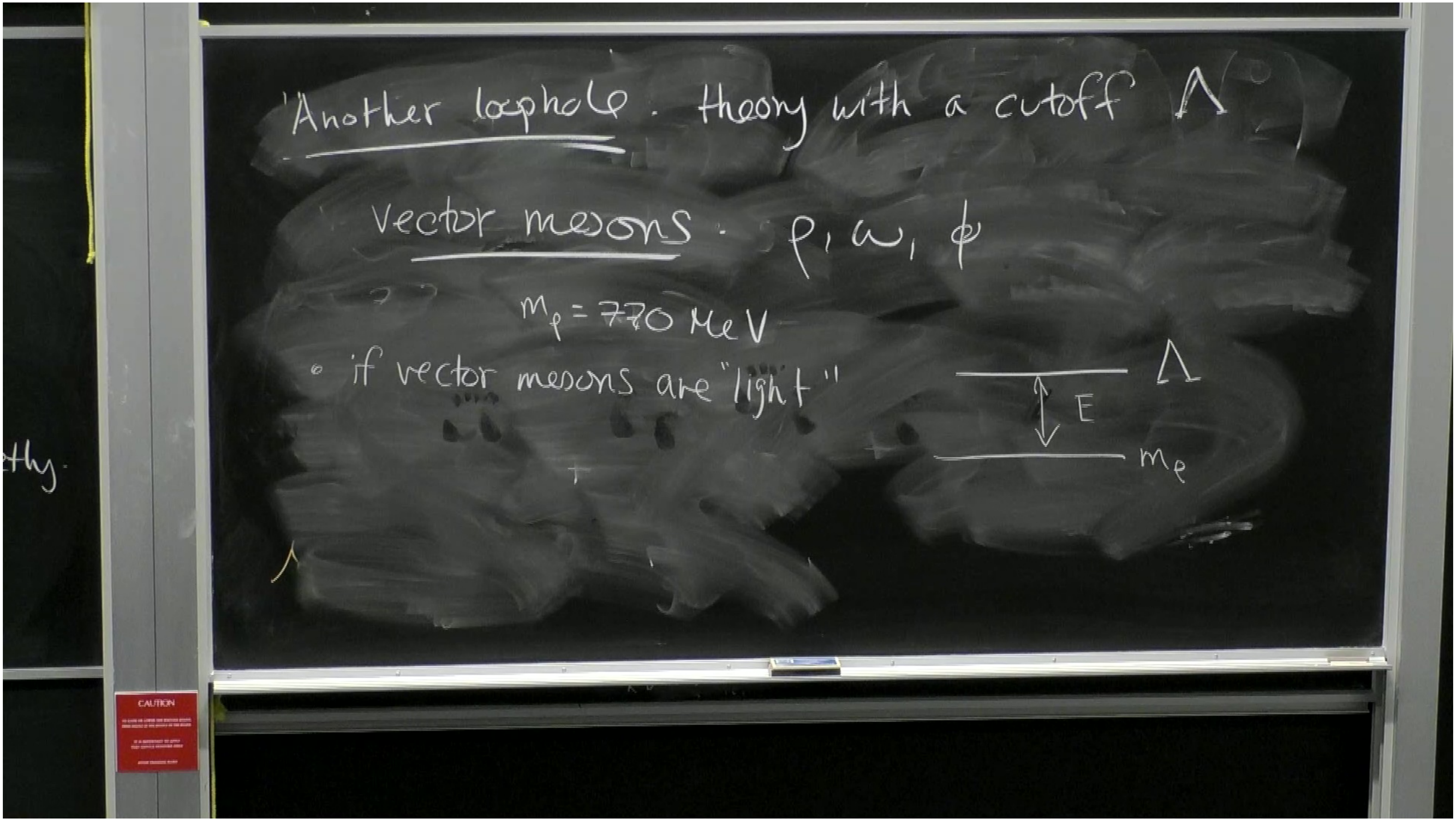
$$\Gamma_t = \frac{g_w^2 m_t^3}{64\pi M_w^2} \qquad (m_t \gg m_w)$$

$$m_t = \frac{y_t v}{\sqrt{2}} \, ; \quad m_w = \frac{g_w v}{2}$$

$$= \frac{\cancel{g_w^2} m_t}{64\pi} \left(\frac{2 y_t^2}{\cancel{g_w^2}}\right) = \frac{y_t^2}{32\pi} m_t$$


t
H^+
b
$\Gamma_t = \frac{y_t^2 m_t}{32\pi}$
At high energies, amplitudes involving $V_L \longleftrightarrow \pi$
$(E \gg m_V)$
Goldstone Boson Equivalence Theorem
$M(X \to Y V_L) \cong M(X \to Y \pi)$ when $E_V \gg M_V$


e.g. $e^+e^- \to W_L^+ W_L^-$
GBET: $e^+e^- \to H^+ H^-$
H^+
$y_e = \frac{m_e}{v}\sqrt{2}$
$\sim 10^{-6}$
e^-
γ/Z
(Y, W^3)
e^+
H^-
Gauge picture
e^-
γ/Z
W_L^+
e^+
W_L^-
+
e^-
W^-
ν_e
e^+
W^+

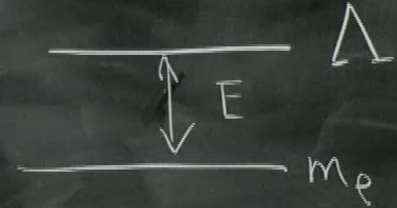

Another loophole: theory with a cutoff Λ
vector mesons: ρ, ω, ϕ
$m_\rho = 770$ MeV
if vector mesons are "light"
Λ
E
m_ρ

Another loophole: theory with a cutoff Λ

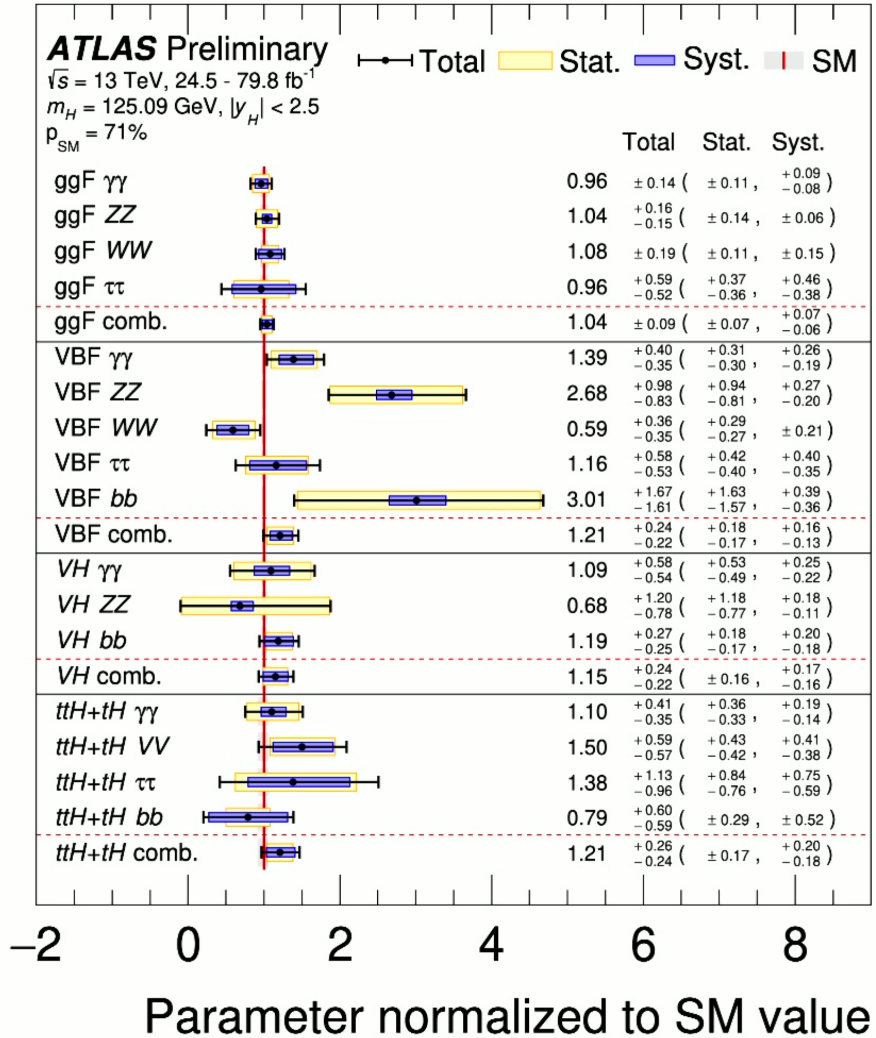
Vector mesons: ρ, ω, ϕ

$$m_\rho = 770 \text{ MeV}$$

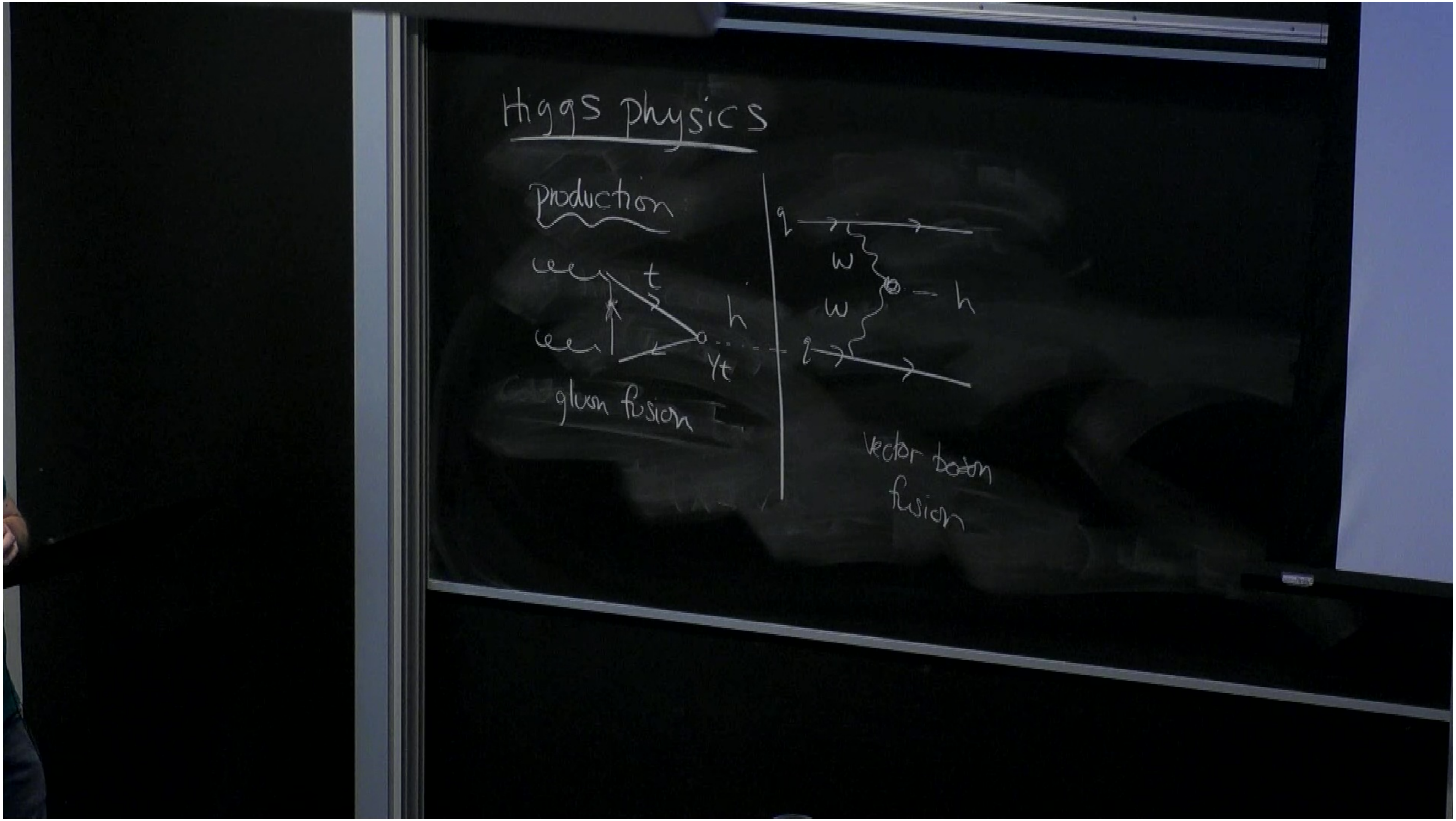
- if vector mesons are "light"
- two interrelated ideas
  - → vector meson dominance

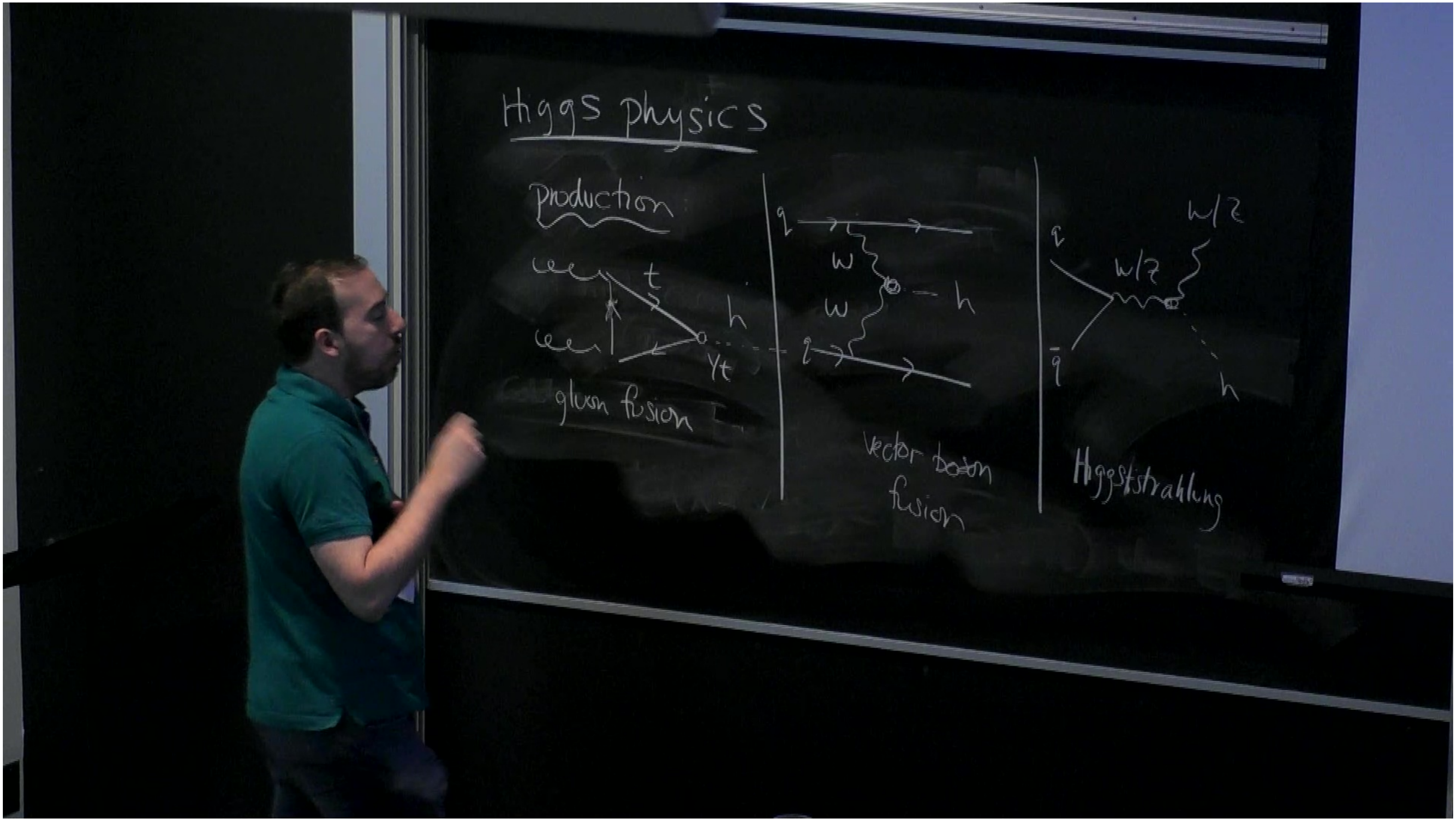


All results from ATLAS-CONF-2019-005

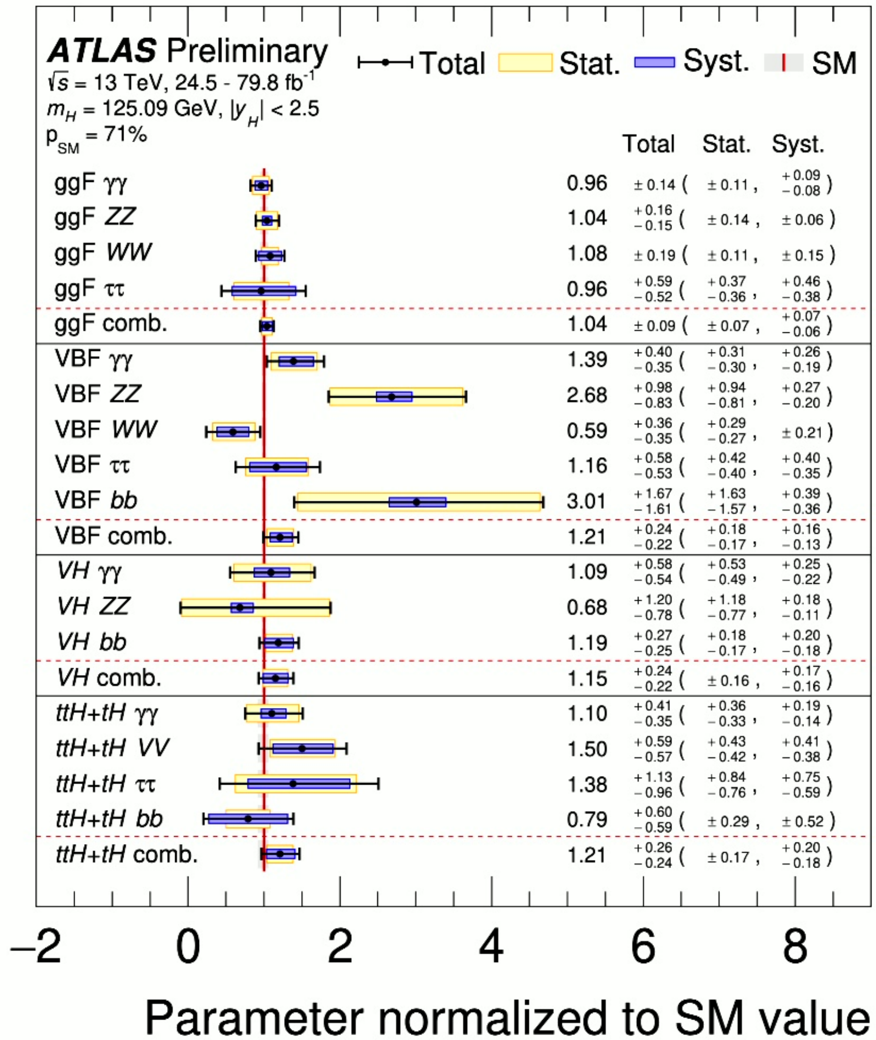


$$\frac{\sigma \times \mathrm{BF}}{\sigma_{\mathrm{SM}} \times \mathrm{BF}_{\mathrm{SM}}}$$


Higgs physics
production
t
h
y_t
gluon fusion
q
W
W
h
q
vector boson
fusion


Higgs physics
production
t
h
y_t
gluon fusion
q
W
W
h
q
vector boson
fusion
q
W/Z
W/Z
$\bar{q}$
h
Higgsstrahlung

All results from ATLAS-CONF-2019-005



$$\frac{\sigma \times \mathrm{BF}}{\sigma_{\mathrm{SM}} \times \mathrm{BF}_{\mathrm{SM}}}$$

nother loophole. theory wit'

vector mesons. ρ,

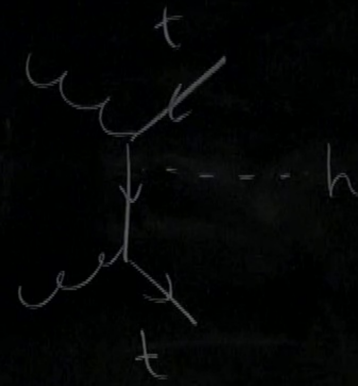
$m_\rho = 770$ MeV

if vector mesons

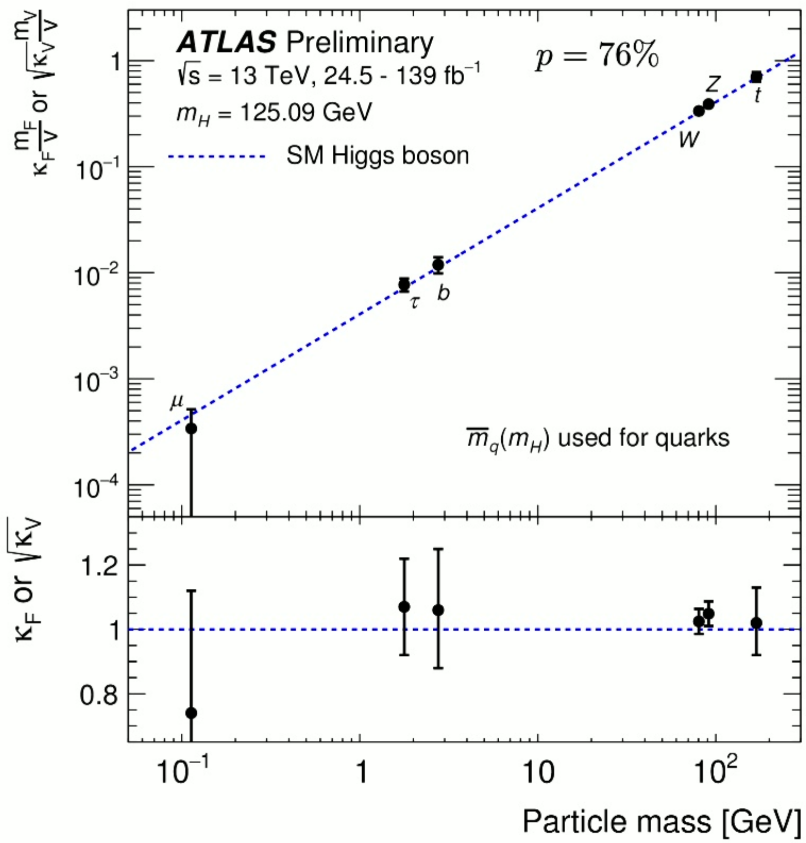
interrelated ideas

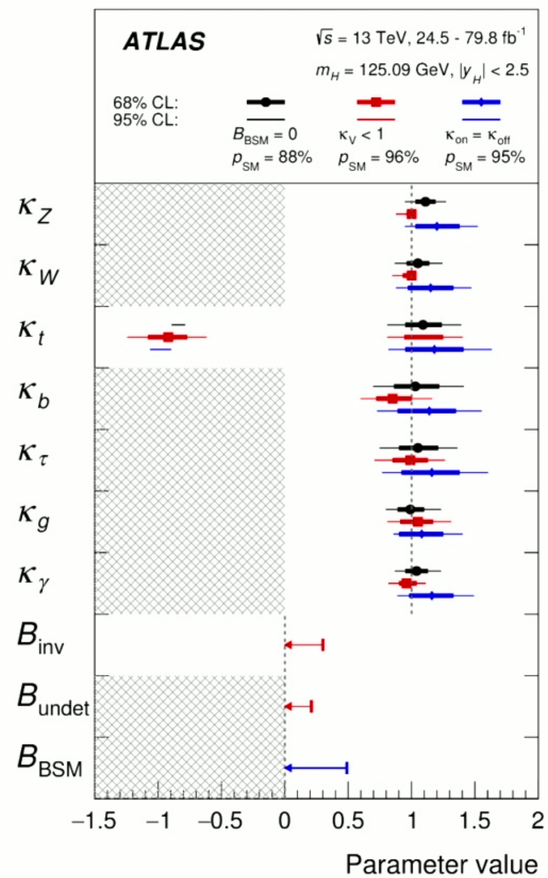
→ vector meson dominance

→ hidden local symmetry (ρ a

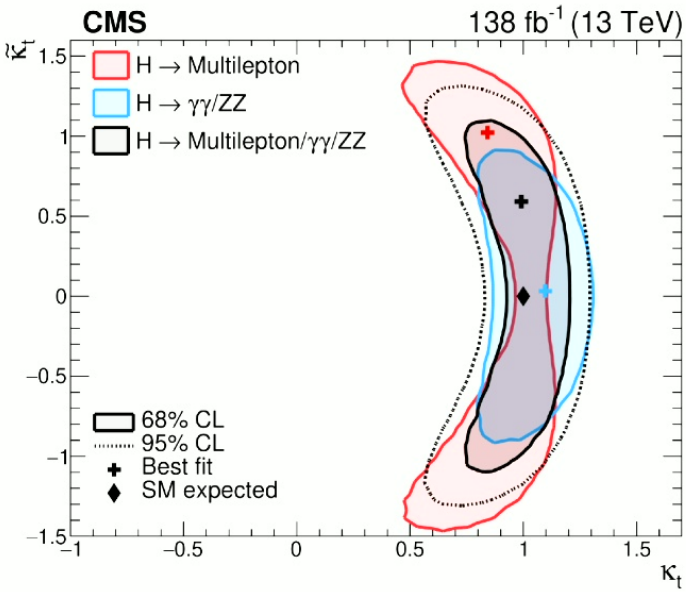


Higgs Coupling Measurements

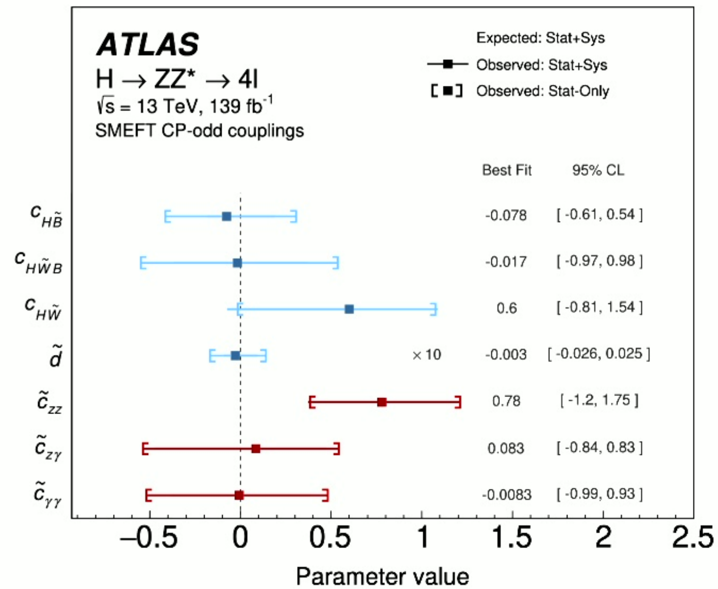



ATLAS
$\sqrt{s}$ = 13 TeV, 24.5 - 79.8 fb^{-1}
m_H = 125.09 GeV, $|y_H|$ < 2.5
68% CL:
95% CL:
B_{BSM} = 0
p_{SM} = 88%
κ_V < 1
p_{SM} = 96%
$\kappa_{on} = \kappa_{off}$
p_{SM} = 95%
κ_Z
κ_W
κ_t
κ_b
κ_τ
κ_g
κ_γ
B_{inv}
B_{undet}
B_{BSM}
−1.5 −1 −0.5 0 0.5 1 1.5 2
Parameter value

CP-violating couplings



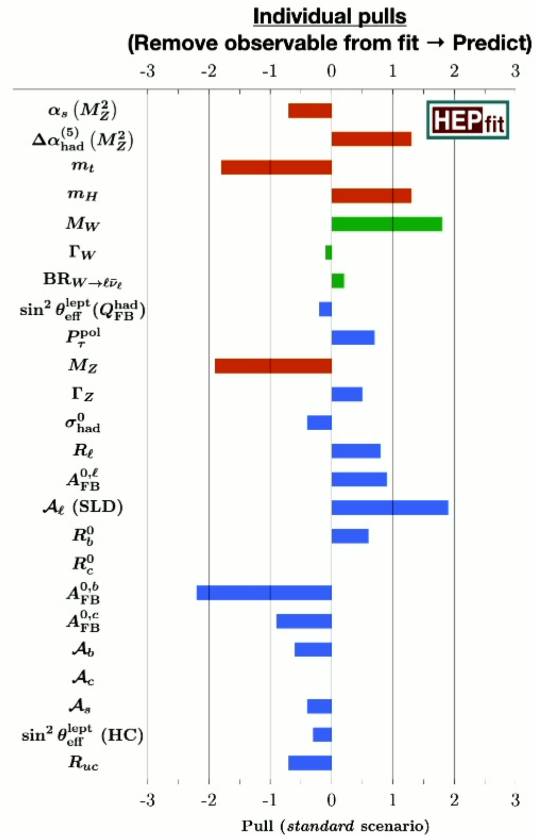
arXiv:2208.02686



arXiv:2304.09612

Electroweak Precision Fits

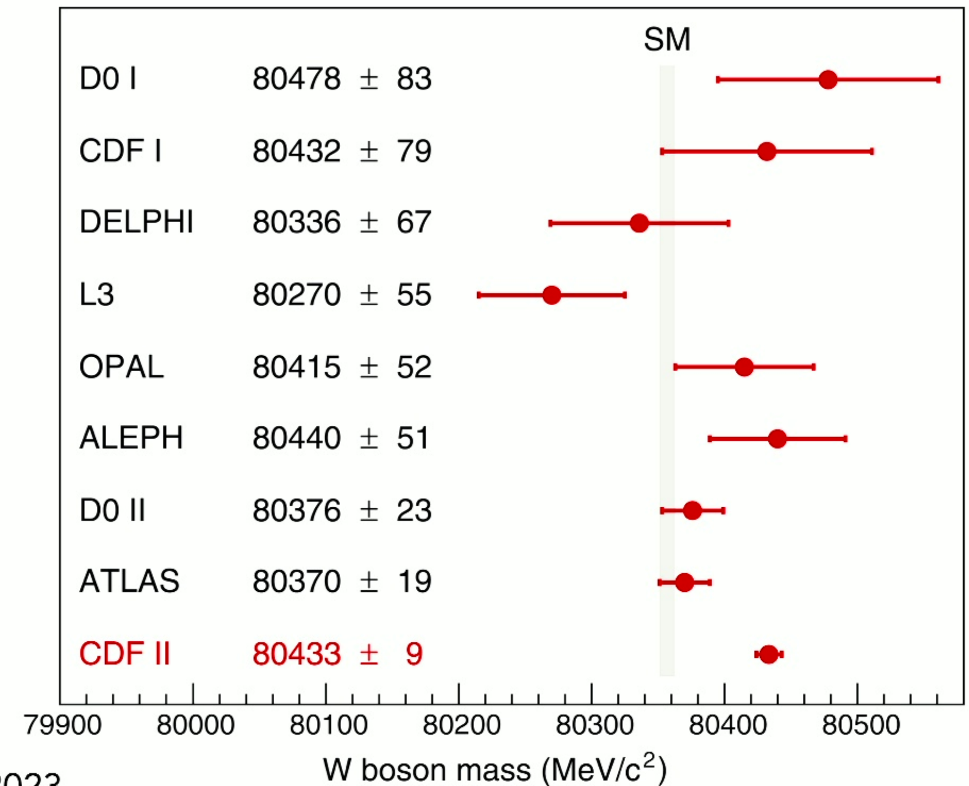
- SM is an over constrained system - perform many measurements and do a global fit!
- Fit from early 2022 data, p-value 0.45



de Blas *et al.*, arXiv:2204.04204

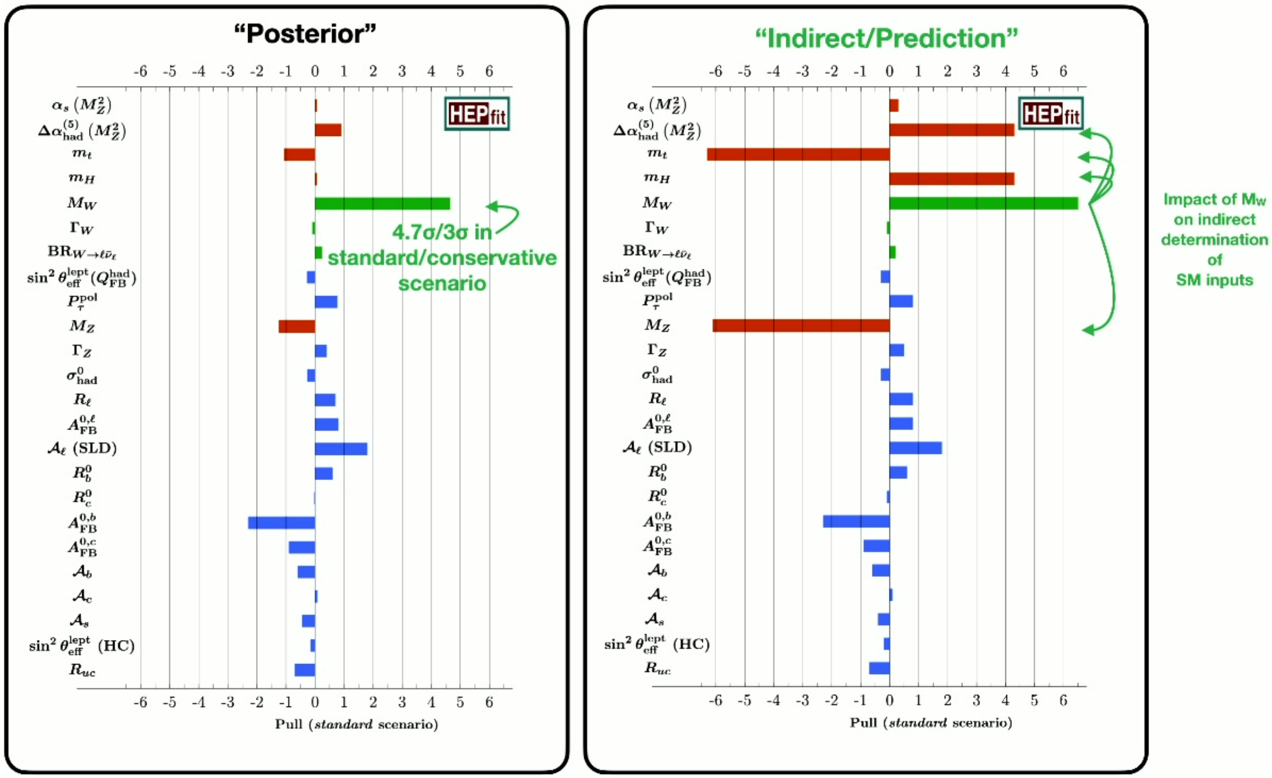
W Mass Anomaly

- Then, in April 2022:



CDF, Science 2023

Updated EW Fits



de Blas *et al.*, arXiv:2204.04204