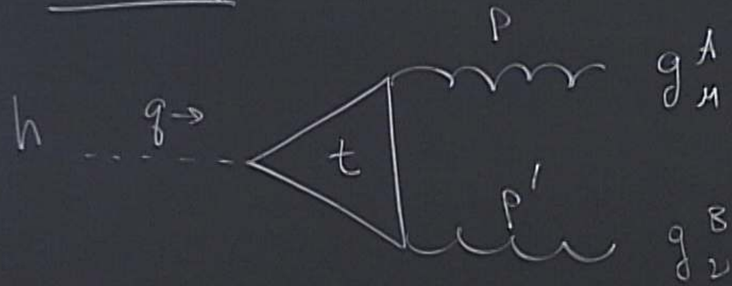
Title: PSI 2016/2017 Standard Model (Review) - Lecture 10

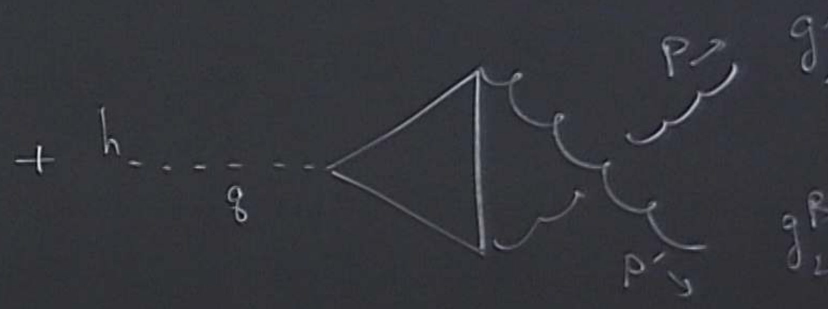
Date: Jan 16, 2017 09:00 AM

URL: http://pirsa.org/17010014

Abstract:

<u>$h \to gg$</u>





$$i\mathcal{M} = i\mathcal{M}_1 + i\mathcal{M}_2$$

$$i\mathcal{M}_1 = -\frac{i}{16\pi^2}\frac{g_s^2}{v}\,\mathrm{Tr}(T^A T^B)\,\varepsilon_\mu(p)\,\varepsilon_\nu(p')\left(4p^\nu p'^\mu -\right.$$

$$\times \int_0^1 dx \int_0^{1-x} dz \, \frac{1-4xz}{1-xz\,(m_h^2/m_t^2)}$$

Consider: $m_t^2 \gg m_h^2$

$$i\mathcal{M}_1 = -\frac{i}{16\pi^2}\frac{g_s^2}{v}\,\mathrm{Tr}(T^A T^B)\,\varepsilon_\mu(p)\,\varepsilon_\nu(p')\left(4p^\nu p'^\mu - \right.$$

$$\times \int_0^1 dx \int_0^{1-x} dz \,\frac{1-4xz}{1-xz\,(m_h^2/m_t^2)}$$

Consider: $m_t^2 \gg m_h^2$

$$\rightarrow \int_0^1 dx \int_0^{1-x} dz\,(1-4xz) = \frac{1}{3}$$

$$\frac{g_s^2}{V} \mathrm{Tr}(T^A T^B)\, \varepsilon_\mu(p)\, \varepsilon_\nu(p') \left(4 p^\nu p'^\mu - 2 m_h^2 \eta^{\mu\nu} \right)$$

$$\times \int_0^1 dx \int_0^{1-x} dz \, \frac{1 - 4xz}{1 - xz\,(m_h^2/m_t^2)}$$

$$m_t^2 \gg m_h^2$$

$$\int_0^1 dx \int_0^{1-x} dz \, (1 - 4xz) = \frac{1}{3}$$

$$\mathrm{Tr}\left(T^A T^B\right) = \frac{1}{2}\,\delta^{AB}$$

$$i\mathcal{M}_2 = i\mathcal{M}_1$$

$$i\mathcal{M} = -i\,\frac{\alpha_s}{3\pi v}\,\varepsilon_\mu(p)\,\varepsilon_\nu(p')\left(p^\nu p'^\mu - \frac{m_h^2}{2}\eta^{\mu\nu}\right)\delta^{AB}$$

Check: $\varepsilon_\mu(p) \to p_\mu$

$\varepsilon_\nu(p') \to p'_\nu$

$$\sum |\mathcal{M}|^2 = \left(\frac{\alpha_s}{3\pi v}\right)^2 \underbrace{\delta_{AB}\,\delta^{AB}}_{8} \left(p^\nu p'^\mu - \frac{m_h^2}{2}\eta^{\mu\nu}\right)\left(p_\nu p'_\mu - \frac{m_h^2}{2}\right.$$

$$= \frac{8\alpha_s^2}{9\pi^2 v^2}\left(-2\,\frac{m_h^2}{2}\,p\cdot p' + \frac{m_h^4}{4}\cdot 4\right) =$$

$$)^2 \; \underbrace{\delta_{AB}\,\delta^{AB}}_{8} \left(p^{\nu} p'^{\mu} - \frac{m_h^2}{2} \eta^{\mu\nu} \right) \left(p_{\nu} p'_{\mu} - \frac{m_h^2}{2} \eta_{\mu\nu} \right)$$

$$2 p \cdot p' = m_h^2$$

$$\frac{\alpha_s^2}{\ldots \pi^2 v^2} \left(-2 \frac{m_h^2}{2} p \cdot p' + \frac{m_h^4}{4} \cdot 4 \right) = \frac{4 \alpha_s^2 m_h^4}{9 \pi^2 v^2}$$

$$\Gamma(h \to gg) = \frac{\alpha_s^2 m_h^3}{64\pi^3 v^2}$$

Needed to divide by 2 to avoid
identical final state gluons.

$$\simeq 0.23 \text{ MeV} \qquad (5.7\%)^*$$

*QCD corrections enhance

Needed to divide by 2 to avoid double-counting identical final state gluons.

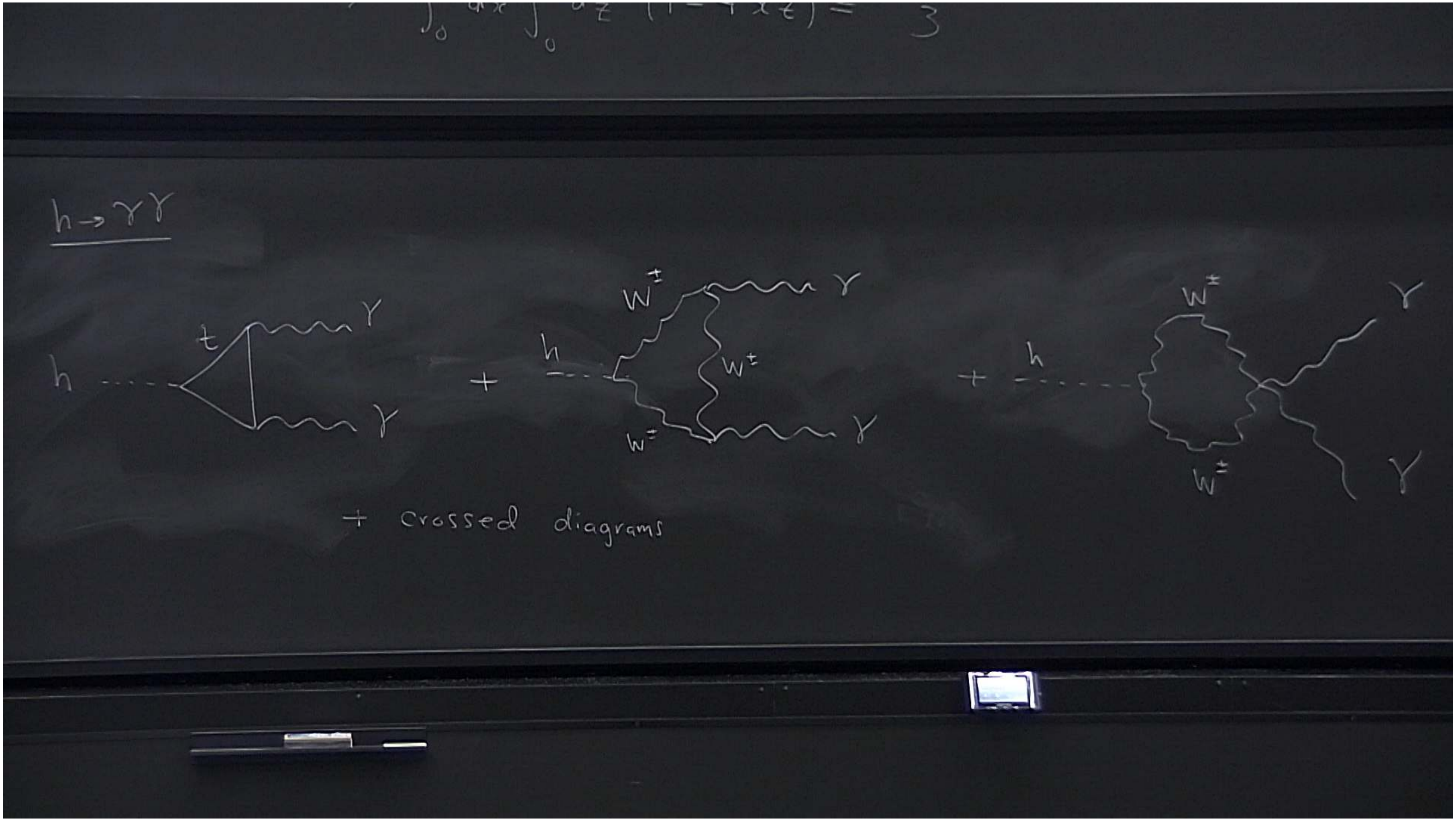
$(5.7\%)^*$ $\quad$ *QCD corrections enhance $\Gamma(h \to gg)$ by $\sim 60\%$

Light quarks: $m_q = m_u, m_d, m_s, m_c, m_b \ll m_h$

$$\int_0^1 dx \int_0^{1-x} dz \, \frac{1-4xz}{1-xz\left(m_h^2/m_q^2\right)} = \begin{cases} 1/3 & \text{if } m_q \gg m_h \quad (q=t) \\ \frac{1}{2}\frac{m_q^2}{m_h^2}\log^2\left(m_h^2/m_q^2\right) & m_q \ll m_h \end{cases}$$

$m_u, m_d, m_s, m_c, m_b << m_h$

$$\frac{1-4xz}{1-xz(m_h^2/m_q^2)} = \begin{cases} 1/3 & \text{if} \quad m_q >> m_h \quad (q=t) \\ \frac{1}{2}\frac{m_q^2}{m_h^2}\log^2\left(m_h^2/m_q^2\right) & m_q << m_h \quad (q=u,d,s,c,b) \end{cases}$$


h → γγ
t
h
γ
γ
+
h
W±
W±
W±
γ
γ
+
h
W±
W±
γ
γ
+ crossed diagrams

$\ldots 2 m_h^2 \eta^{\mu\nu})$

$$= \frac{-i}{k^2 - m_W^2}\left(\eta_{\mu\nu} - \frac{k_\mu k_\nu}{m_W^2}\right)$$

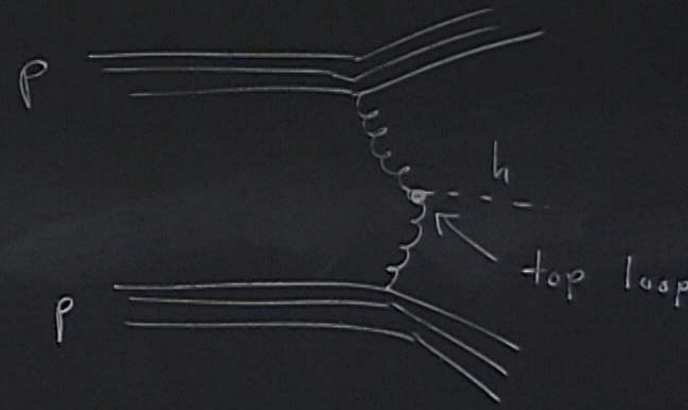
Higgs production at colliders

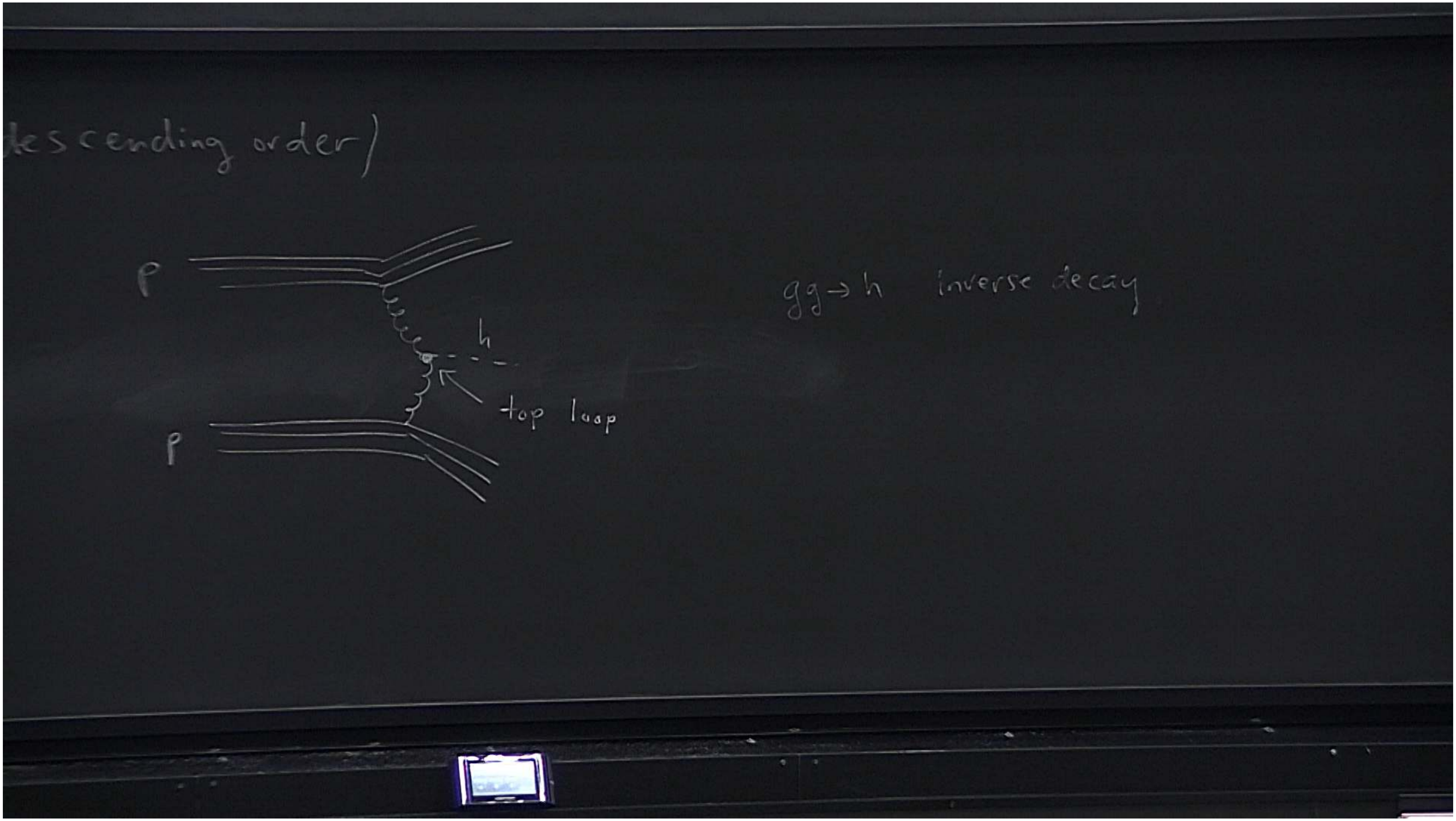
LHC: pp collider at $\sqrt{s} = 7, 8, 13$ TeV

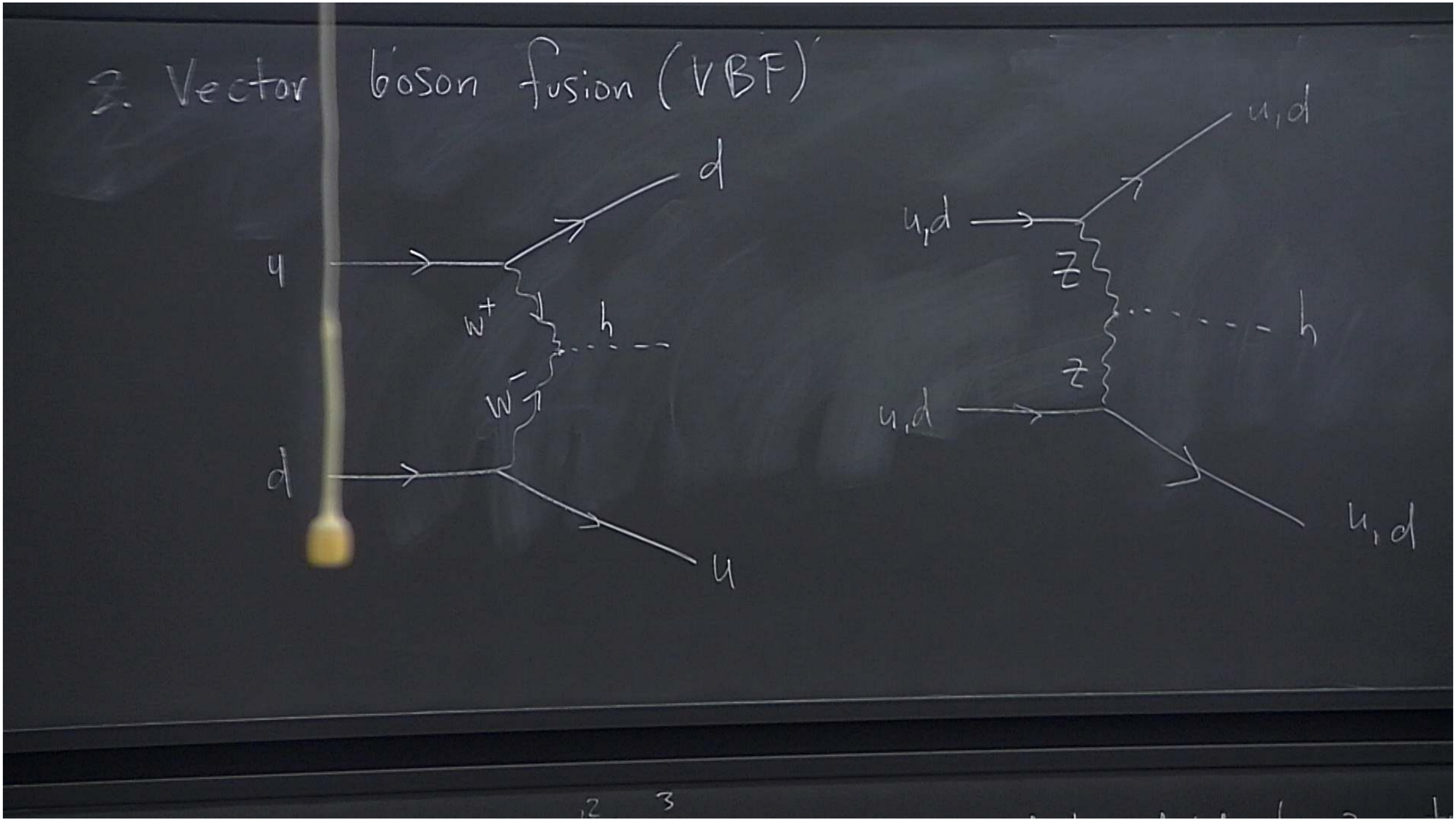
What is cross section? How many h produced?

Production mechanisms (descending order)

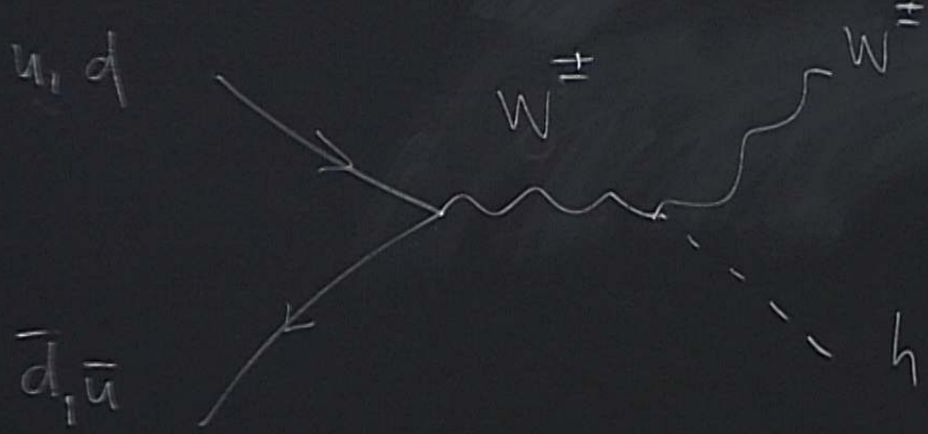
1. gluon-gluon fusion (ggF)

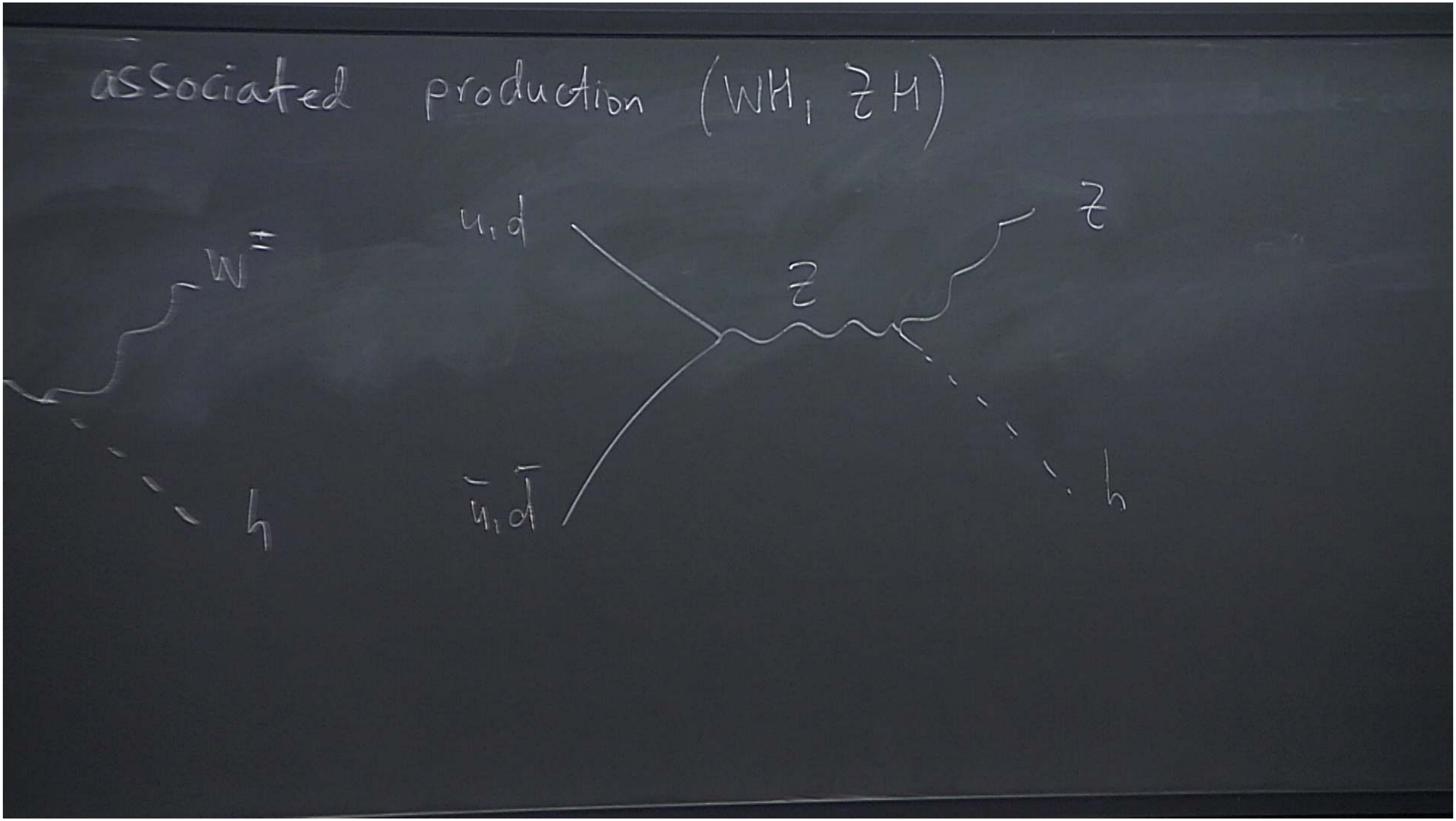


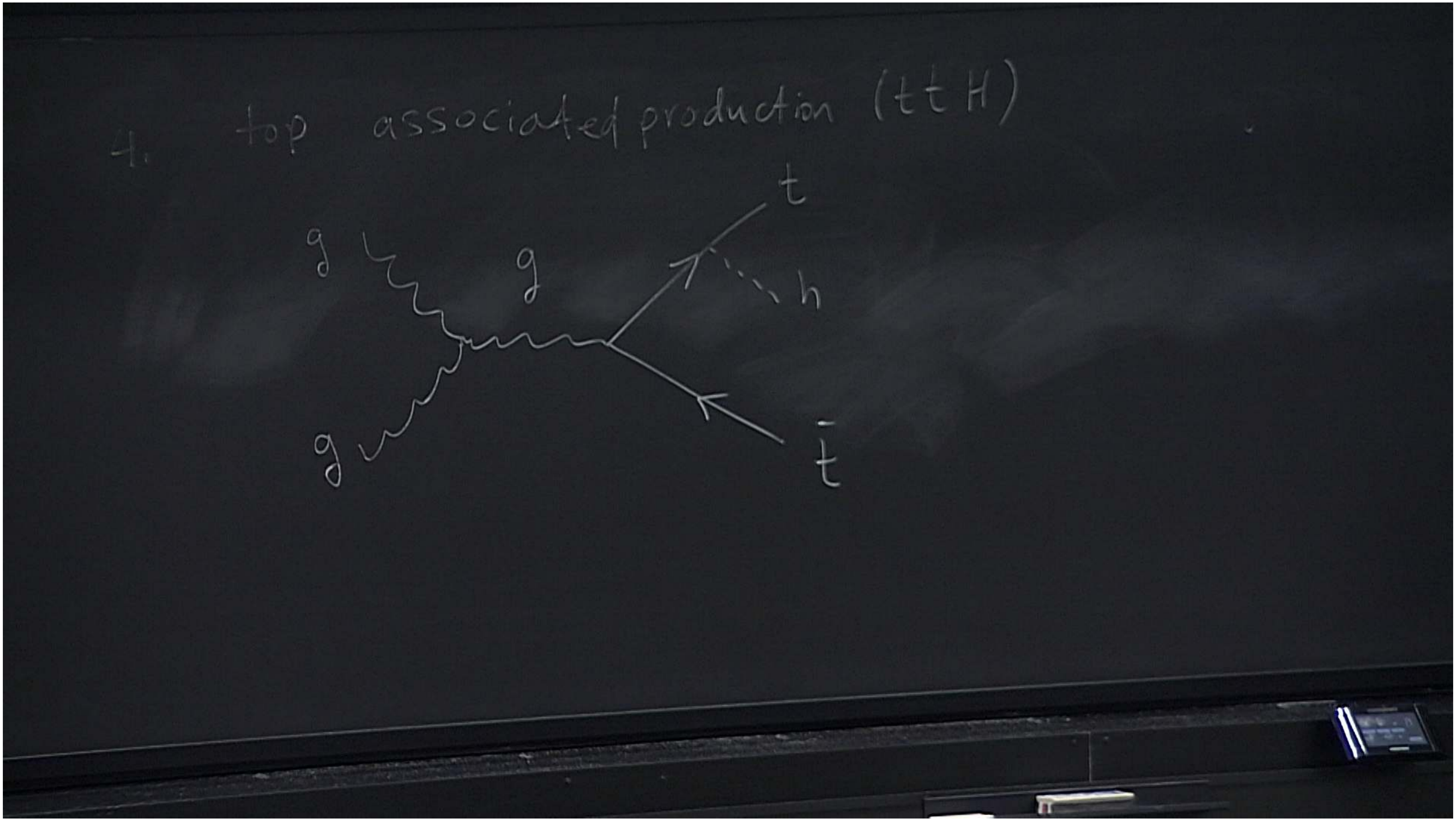

escending order)
p
p
h
top loop
gg→h inverse decay

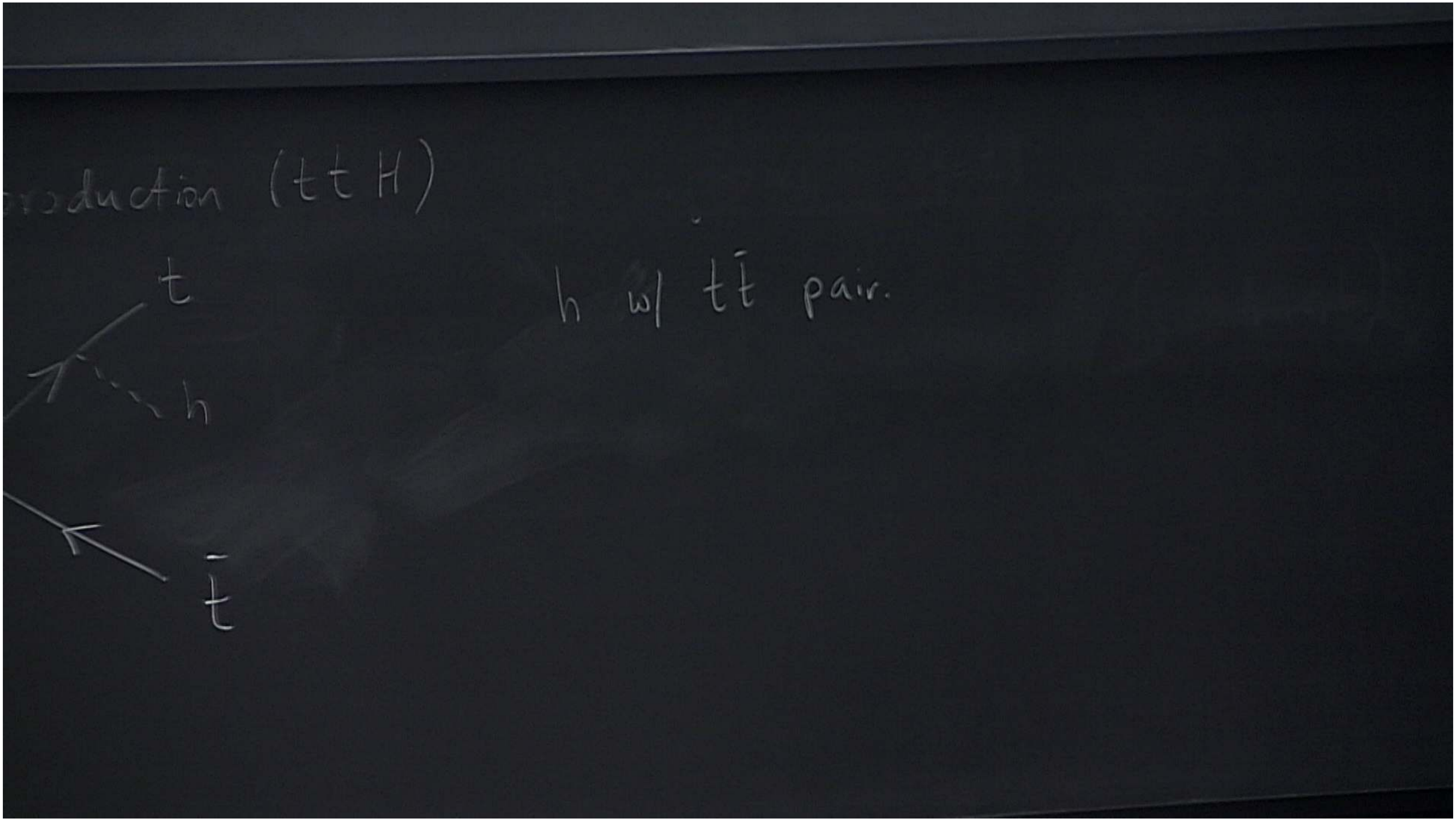

2. Vector boson fusion (VBF)
u
d
d
u
W^+
W^-
h
u,d
u,d
Z
Z
h
u,d
u,d

3. vector boson (W, Z) associated production (WH, ZH)




associated production (WH, ZH)
$W^{\pm}$
h
u, d
$\bar{u}, \bar{d}$
Z
Z
h


4. top associated production ($t\bar{t}H$)
g
g
g
t
h
$\bar{t}$


roduction (tt̄H)
t
h
t̄
h w/ tt̄ pair.

$$\hat{\sigma}(gg \to h) = \frac{1}{2E_1 \cdot 2E_2 \, |\underline{v}_{rel}|} \int \frac{d^3 q}{(2\pi)^3} \frac{1}{2E_q} (2\pi)^4 \delta^4(p_1 + p_2 - q)$$

$$(2\pi)^4 \, \delta^4(p_1 + p_2 - q) \quad \left(\frac{1}{2\cdot 8}\right)^2 \sum_{\substack{\text{spins,}\\ \text{colors.}}} |\mathcal{M}(gg \to h)|^2$$

$$\hat{\sigma}(gg \to h) = \frac{1}{2E_1 \cdot 2E_2\, |\underline{v}_{rel}|} \int \frac{d^3q}{(2\pi)^3} \frac{1}{2E_q} (2\pi)^4\, \delta^4(p_1 + p_2 - q$$

CM frame: $|\underline{v}_{rel}| = 2$, $4E_1E_2 = \hat{s}$, $E_q = m_h$

$$\hat{\sigma}(gg \to h) = \frac{1}{2\hat{s}} \frac{1}{2m_h} (2\pi)\, \delta(m_h - E_1 - E_2) \frac{1}{16^2}$$

$$(2\pi)^4 \, \delta^4(p_1 + p_2 - q) \quad \left(\frac{1}{2\cdot 8}\right)^2 \sum_{\substack{\text{spins,}\\ \text{colors.}}} |\mathcal{M}(gg \to h)|^2$$

$$E_q = m_h$$

$$(m_h - E_1 - E_2) \quad \frac{1}{16^2} \quad 2 \sum |\mathcal{M}(h \to gg)|^2$$

$$\hat{\sigma}(gg \to h) = \frac{1}{2E_1 \cdot 2E_2 \, |\underline{v}_{rel}|} \int \frac{d^3 q}{(2\pi)^3} \frac{1}{2E_q} (2\pi)^4 \delta^4(p_1 + p$$

CM frame: $|\underline{v}_{rel}| = 2$, $4E_1 E_2 = \hat{S}$, $E_q = m_h$

$$\hat{\sigma}(gg \to h) = \frac{1}{2\hat{S}} \frac{1}{2m_h} (2\pi)\, \delta(m_h - E_1 - E_2) \quad \frac{1}{16}$$

$$\Gamma(h \to gg) = \frac{1}{16\pi m_h} \sum |\mathcal{M}(h \to gg)|^2$$

$$\hat{\sigma}(gg \to h) = \frac{2 \cdot 8\pi^2 \, \Gamma(h \to gg)}{16^2 \, \hat{s}} \, \delta\Big(m_h - \underbrace{(E_1 + E_2)}_{\sqrt{\hat{s}}}\Big)$$

$$= \frac{\pi^2 \, \Gamma(h \to gg)}{16^2 \, \hat{s}} \, \delta\left(\sqrt{\hat{s}} - m_h\right)$$

$$\delta(\sqrt{\hat{s}} - m_h) = \delta(\hat{s} - m_h^2)\, 2\sqrt{\hat{s}} = 2m_h\, \delta(\hat{s} - m_h^2)$$

$$\hat{\sigma}(gg \to h) = \frac{2 \cdot 8\pi^2 \, \Gamma(h \to gg)}{16^2 \, \hat{s}} \, \delta\Big(m_h - \underbrace{(E_1 + E_2)}_{\sqrt{\hat{s}}}\Big)$$

$$= \frac{\pi^2 \, \Gamma(h \to gg)}{16 \, \hat{s}} \, \delta\left(\sqrt{\hat{s}} - m_h\right)$$

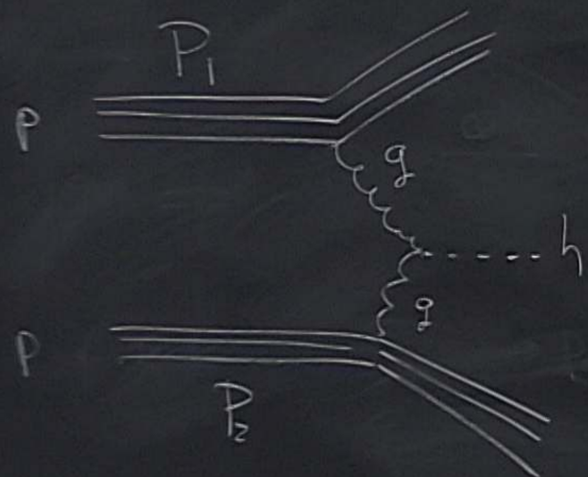
$$= \frac{\pi^2 \, \Gamma(h \to gg)}{8 m_h} \, \delta\left(\hat{s} - m_h^2\right)$$

$$\delta(\sqrt{\hat{s}} - m_h) = \delta(\hat{s} - m_h^2)\, 2\sqrt{\hat{s}} = 2m_h\, \delta(\hat{s} - m_h^2)$$

$$\hat{s} = m_h^2$$

δm_h

Hadron level cross section: $pp \to h \underbrace{X}_{\text{anything}}$ in hadronic final states.



$pp \to h\underbrace{X}_{\text{anything}}$ in hadronic final states.

$$\sigma(pp \to hX) = \int_0^1 dx_1 \int_0^1 dx_2 \; f_g(x_1)\, f_g(x_2)\, \hat{\sigma}(gg \to h)$$

$P_{1,2}$ = initial proton momenta.

$p_{1,2}$ = initial parton (gluon) momenta.

$x_{1,2}$ = momentum fractions $\quad p^\mu_{1,2} = x_{1,2} P^\mu_{1,2}$

Relate $\hat{s}$ to $s = (P_1 + P_2)^2 = 2 P_1 \cdot P_2$

$$= x_1 x_2 \underbrace{2 p_1 \cdot p_2}_{\hat{s}} = x_1 x_2 \hat{s}$$

Relate $\hat{s}$ to $s = (P_1 + P_2)^2 = 2 P_1 \cdot P_2$ (neg

$= x_1 x_2 \underbrace{2 p_1 \cdot p_2}_{\hat{s}} = x_1 x_2 \hat{s}$

$$\sigma(pp \to hX) = \int_0^1 dx_1 \, f_g(x_1) \int_0^1 dx_2 \, f_g(x_2) \quad \frac{\pi^2 \Gamma(h \to gg)}{8 m_h}$$

$\hat{s}$ to $\hat{s} = (p_1 + p_2)^2 = 2\, p_1 \cdot p_2$ (neg

$= x_1 x_2 \underbrace{2 P_1 \cdot P_2}_{s} = x_1 x_2 s$

$\to hX) = \int_0^1 dx_1\, f_g(x_1) \int_0^1 dx_2\, f_g(x_2) \quad \dfrac{\pi^2\, \Gamma(h \to gg)}{8 m_h}$

$$\underbrace{2P_1 \cdot P_2}_{s} = x_1 x_2 s$$

$$\int_0^1 dx_2 \, f_g(x_2) \, \frac{\pi^2 \Gamma(h \to gg)}{8 m_h} \, \delta\left(\underbrace{x_1 x_2 s}_{\hat{s}} - m_h^2 \right)$$

production (WH, ZH)

Define $\tau = m_h^2/s$.

$$\delta(x_1 x_2 s - m_h^2) = \frac{1}{s}\,\delta(x_1 x_2 - \tau) = \frac{1}{s x_1}\,\delta\left(x_2 - \frac{\tau}{x_1}\right)$$

Must have: $0 \le x_2 \le 1 \;\rightarrow\; 0 \le \frac{\tau}{x_1} \le 1 \;\rightarrow\; 0 \le \tau \le x_1$

In general: $0 \le x_1 \le 1 \;\longrightarrow\; \tau \le x_1 \le 1$

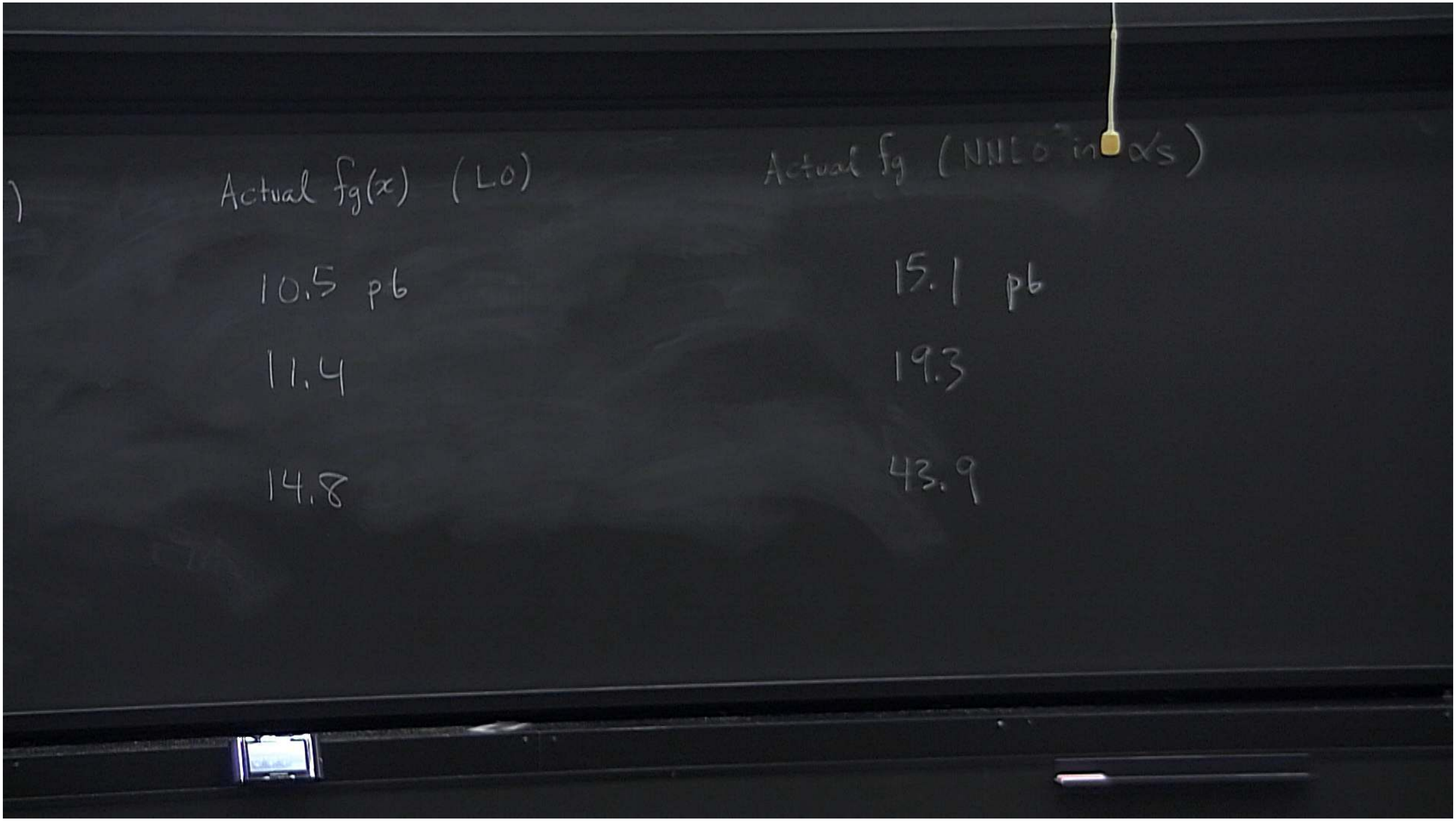
$$\sigma(pp \to hX) = \int_\tau^1 \frac{dx_1}{x_1}\, f_g(x_1)\, f_g(\tau/x_1)\, \frac{\pi^2\, \Gamma(h \to gg)}{8 m_h s}$$

$f_g(x)$ fit to data.

$$f_g(x) = \frac{8}{x}(1-x)^7$$

Peskin & Schroeder ansatz.

At LHC (pp)	P&S ansatz (LO)	Actual $f_g(x)$ (LO)
$\sqrt{s}$ = 7 TeV	5.3 pb	10.5 pb
8 TeV	6.8 pb	11.4
13 TeV	15.7 pb	14.8



Actual fg(x) (LO)
10.5 pb
11.4
14.8
Actual fg (NNLO in αs)
15.1 pb
19.3
43.9

(pp)

P&S ansatz (LO) Actual $f_g(x)$ (LO)

TeV 5.3 pb 10.5 pb

6.8 pb 11.4

TeV

15.7 pb 14.8

TeV

1 barn = $10^{-24}\,\mathrm{cm}^2$, pb = 10^{-12} barn = $10^{-36}\,\mathrm{cm}^2$