QCD@LHC for beginners

Lesson 5

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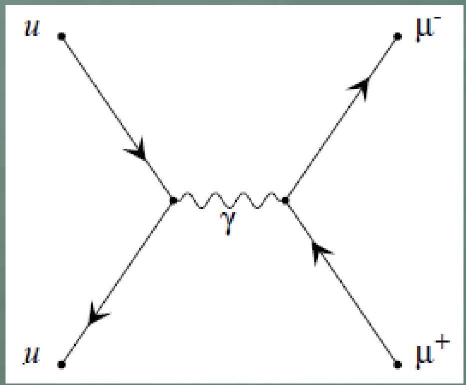
Outline

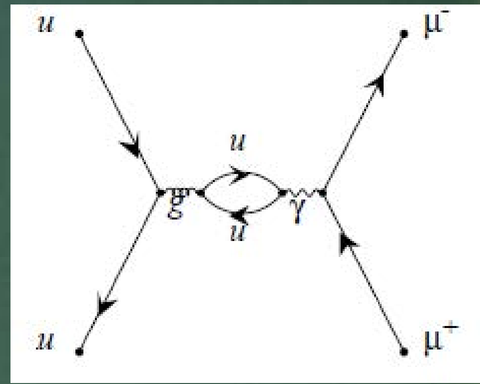
- Lesson 5
  - Examples
    - Drell-Yan process
    - Higgs production/decay
  - Non-perturbative effect
    - Hadronization

Cross section calculations
understand a behavior

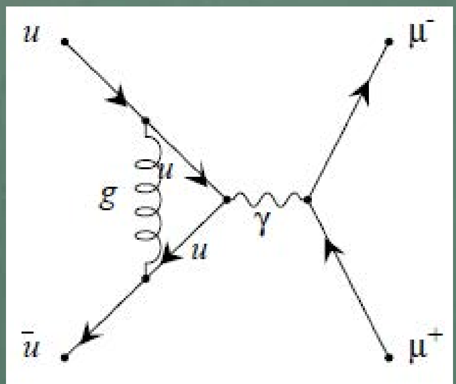
Examples/Drell-Yan



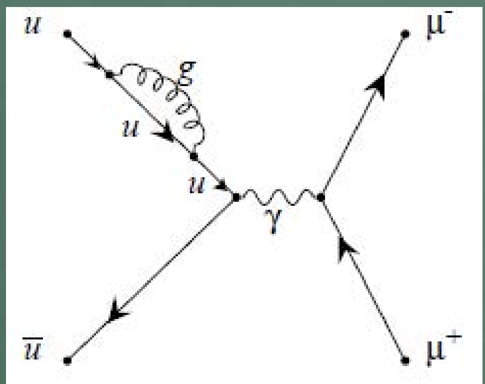
Tree diagram

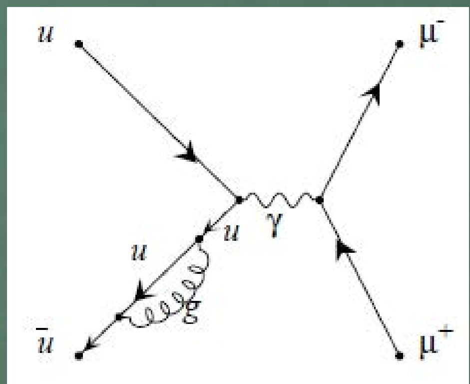


= 0



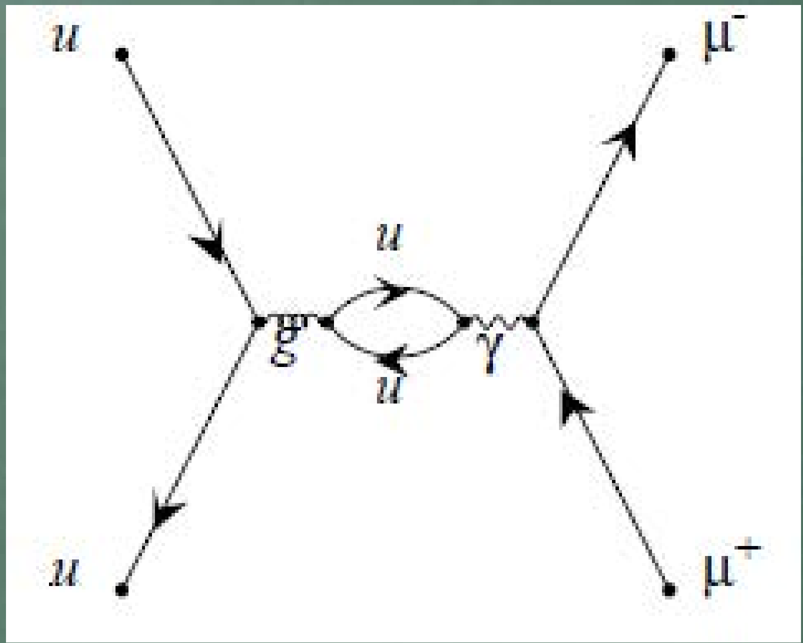
vertex correction





quark self-energy

Examples/Drell-Yan



$= 0$

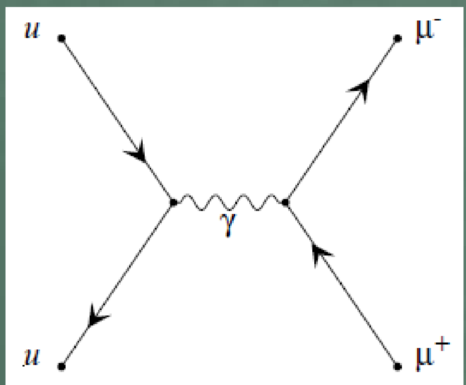
Why?

Examples/Drell-Yan

Tree cross section

$$d\sigma_0 = \frac{1}{4N_c^2}\frac{1}{2s}\left|\mathcal{M}_0\right|^2 d\Phi_2$$

$$d\Phi_2^{(d)}(P \to p_1 + p_2) = \frac{d^{d-1}\vec{p}_1}{(2\pi)^{d-1}2p_1^0}\frac{d^{d-1}\vec{p}_2}{(2\pi)^{d-1}2p_2^0}(2\pi)^d\delta^{(d)}(P - p_1 - p_2)$$



$$\left| \quad \right|^2 = \left|\mathcal{M}_0\right|^2$$

Examples/Drell-Yan

Tree cross section

Phase space:

$$P \to p_1 + p_2, \quad P = (W, \vec{0}^{d-1}), \quad P^2 = W^2$$

$$d\Phi_2^{(d)}(P \to p_1 + p_2) = \frac{d^{d-1}\vec{p}_1}{(2\pi)^{d-1} 2p_1^0} \frac{d^{d-1}\vec{p}_2}{(2\pi)^{d-1} 2p_2^0} (2\pi)^d \delta^{(d)}(P - p_1 - p_2)$$

$$d\Phi_2^{(d)} = \frac{1}{(2\pi)^{d-1}} \frac{d^{d-1}\vec{p}_1}{2p_1^0} 2p_2^0 dp_2^0 \delta(p_2^2 - m_2^2) \frac{d^{d-1}\vec{p}_2}{(2\pi)^{d-1} 2p_2^0} (2\pi)^d \delta^{(d)}(P - p_1 - p_2)$$

$$= \frac{1}{(2\pi)^{d-2}} \frac{d^{d-1}\vec{p}_1}{2p_1^0} \delta(W^2 - 2Wp_1^0 + m_1^2 - m_2^2)$$

=1

$$d^{d-1}\vec{p}_1 = |\vec{p}_1|^{d-2} d|\vec{p}_1| d\Omega_{d-1}$$

d-dim. polar coordinate

angle integration

Examples/Drell-Yan

angle integration

ϕ -symmetry

$$d\Omega_{d-1} = d\theta \sin^{d-3}\theta \, d\Omega_{d-2} = d\theta \sin^{d-3}\theta \frac{2\pi^{\left(\frac{d-2}{2}\right)}}{\Gamma\left(\frac{d-2}{2}\right)}$$

$$d\Phi_2^{(d)} = \frac{1}{(2\pi)^{d-2}} \frac{\pi^{\left(\frac{d-2}{2}\right)}}{\Gamma\left(\frac{d-2}{2}\right)} (p_1^0)^{d-3} \beta_1^{d-3} dp_1^0 \delta(W^2 - 2W p_1^0 + m_1^2 - m_2^2) d\cos\theta (1 - \cos^2\theta)^{\frac{d-4}{2}}$$

p_1^0 integration

0

$$\beta_1 = \frac{|\vec{p}_1|}{p_1^0}$$

Examples/Drell-Yan

p_1^0 integration

$$p_1^0 = \frac{W^2 + m_1^2 - m_2^2}{2W} \qquad \beta = \frac{|\vec{p}_1|}{p_1^0}$$

$$d\Phi_2^{(d)} = \frac{1}{(2\pi)^{d-2}} \frac{\pi^{\left(\frac{d-2}{2}\right)}}{\Gamma\left(\frac{d-2}{2}\right)} (p_1^0)^{d-3} \beta_1^{d-3} \frac{1}{2W} d\cos\theta (1-\cos^2\theta)^{\frac{d-4}{2}}$$

$m_1 = m_2 = 0$

$$d\Phi_2^{(4+2\epsilon_{IR})} = \frac{1}{(16\pi)^{1+\epsilon_{IR}}} \frac{1}{\Gamma(1+\epsilon_{IR})} W^{2\epsilon_{IR}} d\cos\theta (1-\cos^2\theta)^{\epsilon_{IR}}$$

Examples/Drell-Yan

Tree cross section

Phase space:

$$P \to p_1 + p_2, \quad P = (W, \vec{0}^{d-1}), \quad P^2 = W^2$$

$$d\Phi_2^{(d)}(P \to p_1 + p_2) = \frac{d^{d-1}\vec{p}_1}{(2\pi)^{d-1} 2p_1^0} \frac{d^{d-1}\vec{p}_2}{(2\pi)^{d-1} 2p_2^0} (2\pi)^d \delta^{(d)}(P - p_1 - p_2)$$

$m_1 = m_2 = 0$

$$d\Phi_2^{(4+2\epsilon_{IR})} = \frac{1}{(16\pi)^{1+\epsilon_{IR}}} \frac{1}{\Gamma(1+\epsilon_{IR})} W^{2\epsilon_{IR}} d\cos\theta (1-\cos^2\theta)^{\epsilon_{IR}}$$

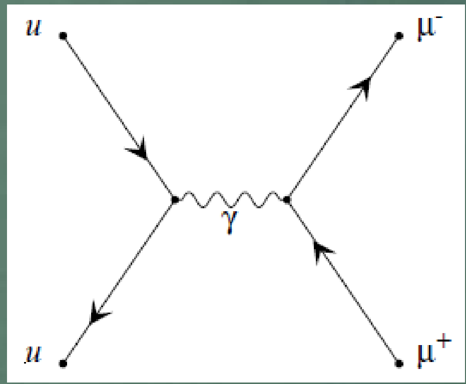
Exercise: Confirm above result.

Examples/Drell-Yan

Tree cross section

Matrix element:

$$\left| \quad \right|^2 = \left|\mathcal{M}_0\right|^2$$



$$\left|\mathcal{M}_0\right|^2 = \frac{e^4}{s^2} Tr[\not{p}_1 \gamma^\mu \not{p}_2 \gamma^\nu] Tr[\not{k}_1 \gamma^\mu \not{k}_2 \gamma^\nu]$$

$$= 4\frac{e^4}{s^2}\left[(d-4)(p_1 \cdot p_2)(k_1 \cdot k_2)\right.$$

$$\left. +2(p_1 \cdot k_1)(p_2 \cdot k_2) + 2(p_1 \cdot k_2)(p_2 \cdot k_1)\right]$$

Examples/Drell-Yan

Tree cross section

$$\int d\Phi_2^d[(d-4)(p_1\cdot p_2)(k_1\cdot k_2)+2(p_1\cdot k_1)(p_2\cdot k_2)+2(p_1\cdot k_2)(p_2\cdot k_1)]$$

$$= \frac{2\,\pi^{3/2}\,s^2\,(\epsilon+1)\,\csc(\pi\,\epsilon)}{\Gamma(-\epsilon-1)\,\Gamma\left(\epsilon+\frac{5}{2}\right)}$$

$$\sigma_0 = \frac{4\pi\alpha^2}{3s}Q_f^2\frac{(1+\epsilon_{IR})^2}{(3+2\epsilon_{IR})}\left(\frac{s}{4\pi}\right)^{\epsilon_{IR}}\frac{1}{\Gamma(1+\epsilon_{IR})}$$

Examples/Drell-Yan

Tree cross section

$$\left|\mathcal{M}_0\right|^2 = \frac{e^4}{s^2} Tr[\not{p}_1 \gamma^\mu \not{p}_2 \gamma^\nu] Tr[\not{k}_1 \gamma^\mu \not{k}_2 \gamma^\nu]$$
$$= 4\frac{e^4}{s^2}\left[(d-4)(p_1\cdot p_2)(k_1\cdot k_2) + 2(p_1\cdot k_1)(p_2\cdot k_2) + 2(p_1\cdot k_2)(p_2\cdot k_1)\right]$$

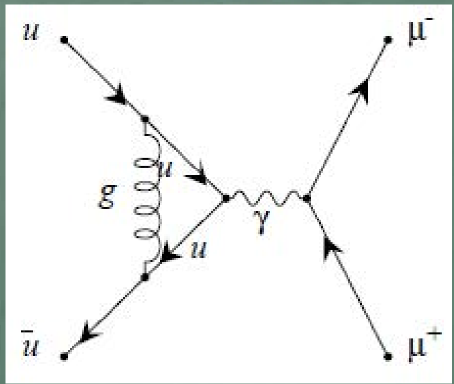
$$\int d\Phi_2^d [(d-4)(p_1\cdot p_2)(k_1\cdot k_2) + 2(p_1\cdot k_1)(p_2\cdot k_2) + 2(p_1\cdot k_2)(p_2\cdot k_1)]$$
$$= \frac{2\,\pi^{3/2}\,s^2\,(\epsilon+1)\,\csc(\pi\epsilon)}{\Gamma(-\epsilon-1)\,\Gamma\left(\epsilon+\frac{5}{2}\right)}$$

$$\sigma_0 = \frac{4\pi\alpha^2}{3s} Q_f^2 \frac{(1+\epsilon_{IR})^2}{(3+2\epsilon_{IR})} \left(\frac{s}{4\pi}\right)^{\epsilon_{IR}} \frac{1}{\Gamma(1+\epsilon_{IR})}$$

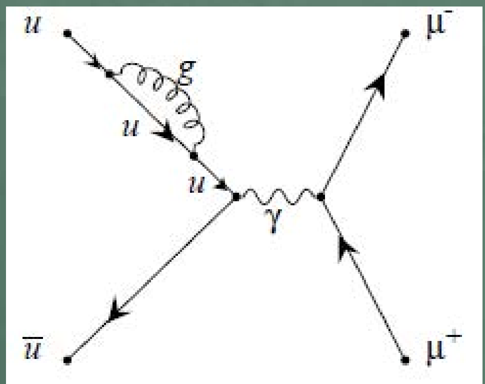
Exercise: Confirm above result.

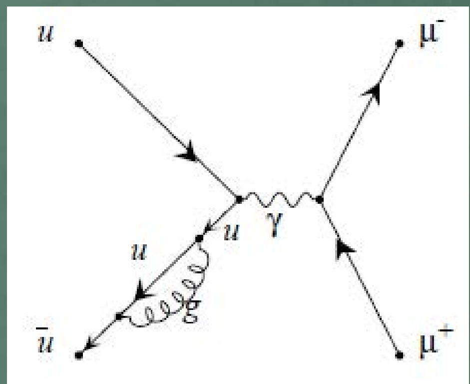
Examples/Drell-Yan

NLO cross section



vertex correction

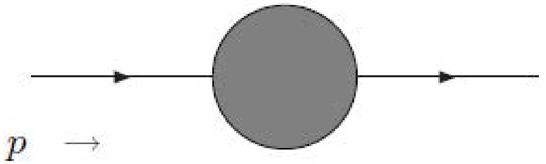




quark self-energy

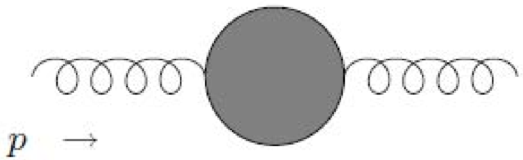
Examples/Drell-Yan

NLO cross section



$$= \Sigma(p^2)$$

on-/off-shell	self-energy
$p^2 \neq 0$	$\Sigma(p^2) = C_F \frac{\alpha_s}{4\pi}(1 - \ln\frac{-p^2}{\mu^2})$
$p^2 = 0$	$\Sigma(0) = C_F \frac{\alpha_s}{4\pi}\frac{1}{\varepsilon_{IR}}$

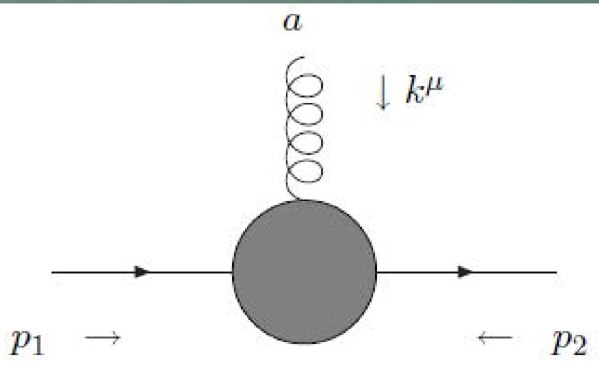


$$= \Pi_G(p^2)$$

on-/off-shell	self-energy
$p^2 \neq 0$	$\Pi_G(p^2) = -C_F \frac{\alpha_s}{4\pi}(\frac{31}{9} - \frac{5}{3}\ln\frac{-p^2}{\mu^2}) + T_R N_f \frac{\alpha_s}{4\pi}(\frac{20}{9} - \frac{4}{3}\ln\frac{-p^2}{\mu^2})$
$p^2 = 0$	$\Pi_G(0) = -C_F \frac{\alpha_s}{4\pi}\frac{1}{\varepsilon_{IR}} + T_R N_f \frac{\alpha_s}{4\pi}\frac{4}{3}\frac{1}{\varepsilon_{IR}}$

Examples/Drell-Yan

NLO cross section



$$= \Lambda^a_\mu(p_1, p_2, k) = \quad g\mathbf{T}^a(C_F - \frac{1}{2}C_G)\frac{\alpha_s}{4\pi}(\mathcal{F}_1^I\gamma^\mu + \mathcal{F}_2^I\frac{p_j^\mu \not{k}}{-p_j^2}) + \quad g\mathbf{T}^a\frac{1}{2}C_G\frac{\alpha_s}{4\pi}(\mathcal{F}_1^I\gamma^\mu + \mathcal{F}_2^I\frac{p_j^\mu \not{k}}{-p_j^2})$$

$k^2 = 0,\ p_i^2 = 0,\ p_j^2 = q^2 \neq 0$, and $L = \ln\frac{-q^2}{\mu^2}$,

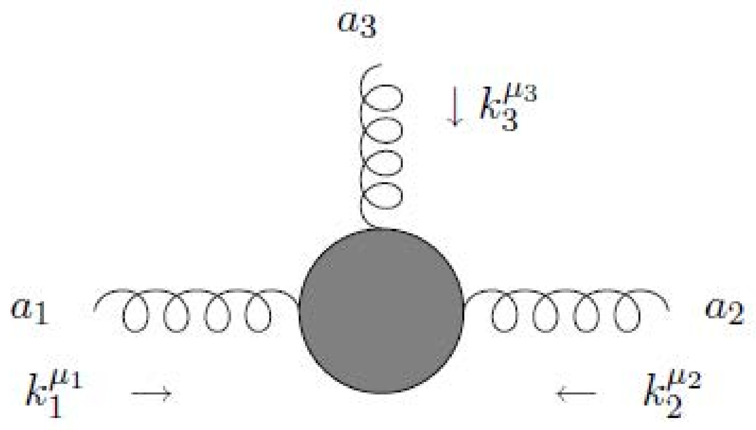
$\mathcal{F}_1^I$	$\frac{2}{\varepsilon_{IR}} + L - 4$
$\mathcal{F}_2^I$	$\frac{4}{\varepsilon_{IR}} + 4L - 10$
$\mathcal{F}_1^{II}$	$-\frac{2}{\varepsilon_{IR}^2} + \frac{3-2L}{\varepsilon_{IR}} + \frac{\pi^2}{6} - L$
$\mathcal{F}_2^{II}$	$-\frac{2}{\varepsilon_{IR}^2} - \frac{2L}{\varepsilon_{IR}} + \frac{12+\pi^2-6L^2}{6}$

$k^2 = q^2,\ p_1^2 = p_2^2 = 0$, and $L = \ln\frac{-q^2}{\mu^2}$.

$\mathcal{F}_1^I$	$-\frac{2}{\varepsilon_{IR}^2} - \frac{2L-4}{\varepsilon_{IR}} - 8 + \frac{\pi^2}{6} + 3L - L^2$
$\mathcal{F}_2^I$	0
$\mathcal{F}_1^{II}$	$\frac{4}{\varepsilon_{IR}} - 2 + L$
$\mathcal{F}_2^{II}$	0

Examples/Drell-Yan

NLO cross section



$$= \Lambda^{a_1 a_2 a_3}_{\mu_1 \mu_2 \mu_3}(k_1, k_2, k_3)$$

$$k_1^2 = k_2^2 = 0, k_3^2 = q^2 \neq 0, L = \ln \frac{-q^2}{\mu^2}$$

$$\Lambda^{a_1 a_2 a_3}_{\mu_1 \mu_2 \mu_3}(k_1, k_2, k_3) = -ig f^{a_1 a_2 a_3} \frac{\alpha_s}{4\pi} \left[\frac{C_G}{2} \left(\mathcal{G}_1 + \mathcal{G}_2 + \mathcal{G}_3 \right) + \frac{N_f}{2} \mathcal{G}_4 \right],$$

$$\mathcal{G}_i = \sum_{j=1}^{3} c_{ij} \mathcal{P}_j$$

$\mathcal{G}_1$:gluon loop, $\mathcal{G}_2$:ghost loop, $\mathcal{G}_3$:gluon loop (fish type), $\mathcal{G}_4$:quark loop

Examples/Drell-Yan

NLO cross section

- $\mathcal{P}_1^{\mu_1\mu_2\mu_3} = (k_1 - k_2)^{\mu_3} g^{\mu_1\mu_2}$
- $\mathcal{P}_2^{\mu_1\mu_2\mu_3} = k_1^{\mu_2} g^{\mu_1\mu_3} - k_2^{\mu_2} g^{\mu_2\mu_3}$
- $\mathcal{P}_2^{\mu_1\mu_2\mu_3} = \frac{k_2^{\mu_1} k_1^{\mu_2} (k_1 - k_2)^{\mu_3}}{q^2}$

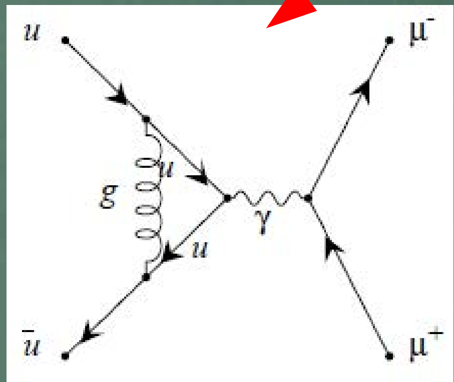
c_{ij}	$j=1$	$j=2$	$j=3$
$i=1$	$-\frac{3}{2\varepsilon_{IR}^2} - \frac{3}{2\varepsilon_{IR}}(-5+L)$ $-\frac{1}{12}(103 - 51L + 9L^2) + \frac{\pi^2}{8}$	$\frac{2}{\varepsilon_{IR}^2} - \frac{1}{2\varepsilon_{IR}}(19-4L)$ $+\frac{1}{3}(19 - 9L + 3L^2) - \frac{\pi^2}{6}$	$-\frac{3}{2}$
$i=2$	$-\frac{11-3L}{36}$	$\frac{8-3L}{18}$	$\frac{1}{6}$
$i=3$	$-\frac{9}{2\varepsilon_{IR}}$	$\frac{2}{2\varepsilon_{IR}} + \frac{18-19L}{2}$	0
$i=4$	$\frac{14-12L}{9}$	$-\frac{40-24}{9}$	$\frac{4}{3}$

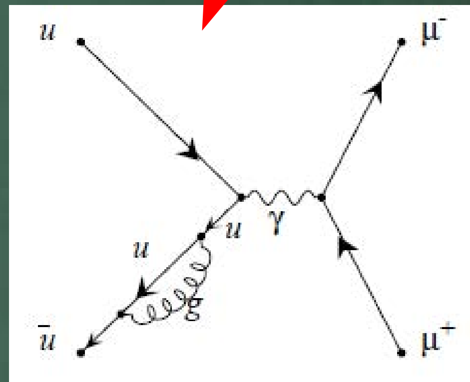
Examples/Drell-Yan

NLO cross section

$$\sigma_{DY}^{loop} = \sigma_{DY}^{0} C_F \frac{\alpha_s(\mu)}{2\pi}\left[-\frac{2}{\epsilon_{IR}^2} - \frac{2L-4}{\epsilon_{IR}} - 8 + \frac{\pi^2}{6} + 3L - L^2 - \frac{1}{\epsilon_{IR}} - \frac{1}{\epsilon_{IR}} \right]$$

$$L = \ln\left(\frac{s}{\mu_F^2}\right)$$





Examples/Drell-Yan

NLO cross section

$$\sigma_{DY}^{loop} = \sigma_{DY}^0 C_F \frac{\alpha_s(\mu)}{2\pi}\Big[-\frac{2}{\epsilon_{IR}^2} - \frac{2L-4}{\epsilon_{IR}} - 8 + \frac{\pi^2}{6} + 3L - L^2 - \frac{1}{\epsilon_{IR}} - \frac{1}{\epsilon_{IR}}\Big]$$

$$\begin{aligned}\sigma_{coll} &= \sigma_0(s)\frac{\alpha_s}{2\pi}C_F\Big[\frac{2}{\varepsilon_{IR}^2} + \frac{2L-3}{\varepsilon_{IR}} - \frac{\pi^2}{2} + L^2\Big] \\ &+ 2\int_0^1 dx\sigma_0(xs)\phi(x,\varepsilon_{IR}) \\ &+ 2C_F\frac{\alpha_s}{2\pi}\int_0^1 dx\sigma_0(xs)\Big[L\frac{1+x^2}{(1-x)_+} + 2\frac{(1+x^2)\ln(1-x)}{(1-x)_+} - \frac{1+x^2}{1-x}\ln x\Big]\end{aligned}$$

$$L = \ln\left(\frac{s}{\mu_F^2}\right)$$

$$\phi(x,\varepsilon_{IR}) = \frac{1}{\varepsilon_{IR}}C_F\frac{\alpha_s}{2\pi}\mathrm{P}(x) = \frac{1}{\varepsilon_{IR}}C_F\frac{\alpha_s}{2\pi}\frac{1+x^2}{(1-x)_+}$$

Examples/Drell-Yan

NLO cross section

$$\sigma_{DY}^{loop} = \sigma_{DY}^{0} C_F \frac{\alpha_s(\mu)}{2\pi}\Big[-\frac{2}{\epsilon_{IR}^2} - \frac{2L-4}{\epsilon_{IR}} - 8 + \frac{\pi^2}{6} + 3L - L^2 - \frac{1}{\epsilon_{IR}} - \frac{1}{\epsilon_{IR}} \Big]$$

$$\begin{aligned} \sigma_{coll} &= \sigma_0(s)\frac{\alpha_s}{2\pi}C_F\Big[\frac{2}{\varepsilon_{IR}^2} + \frac{2L-3}{\varepsilon_{IR}} - \frac{\pi^2}{2} + L^2\Big] \\ &+ 2\int_0^1 dx\sigma_0(xs)\phi(x,\varepsilon_{IR}) \\ &+ 2C_F\frac{\alpha_s}{2\pi}\int_0^1 dx\sigma_0(xs)\Big[L\frac{1+x^2}{(1-x)_+} + 2\frac{(1+x^2)\ln(1-x)}{(1-x)_+} - \frac{1+x^2}{1-x}\ln x\Big] \end{aligned}$$

$$L = \ln\left(\frac{s}{\mu_F^2}\right)$$

$$\phi(x,\varepsilon_{IR}) = \frac{1}{\varepsilon_{IR}}C_F\frac{\alpha_s}{2\pi}\mathrm{P}(x) = \frac{1}{\varepsilon_{IR}}C_F\frac{\alpha_s}{2\pi}\frac{1+x^2}{(1-x)_+}$$

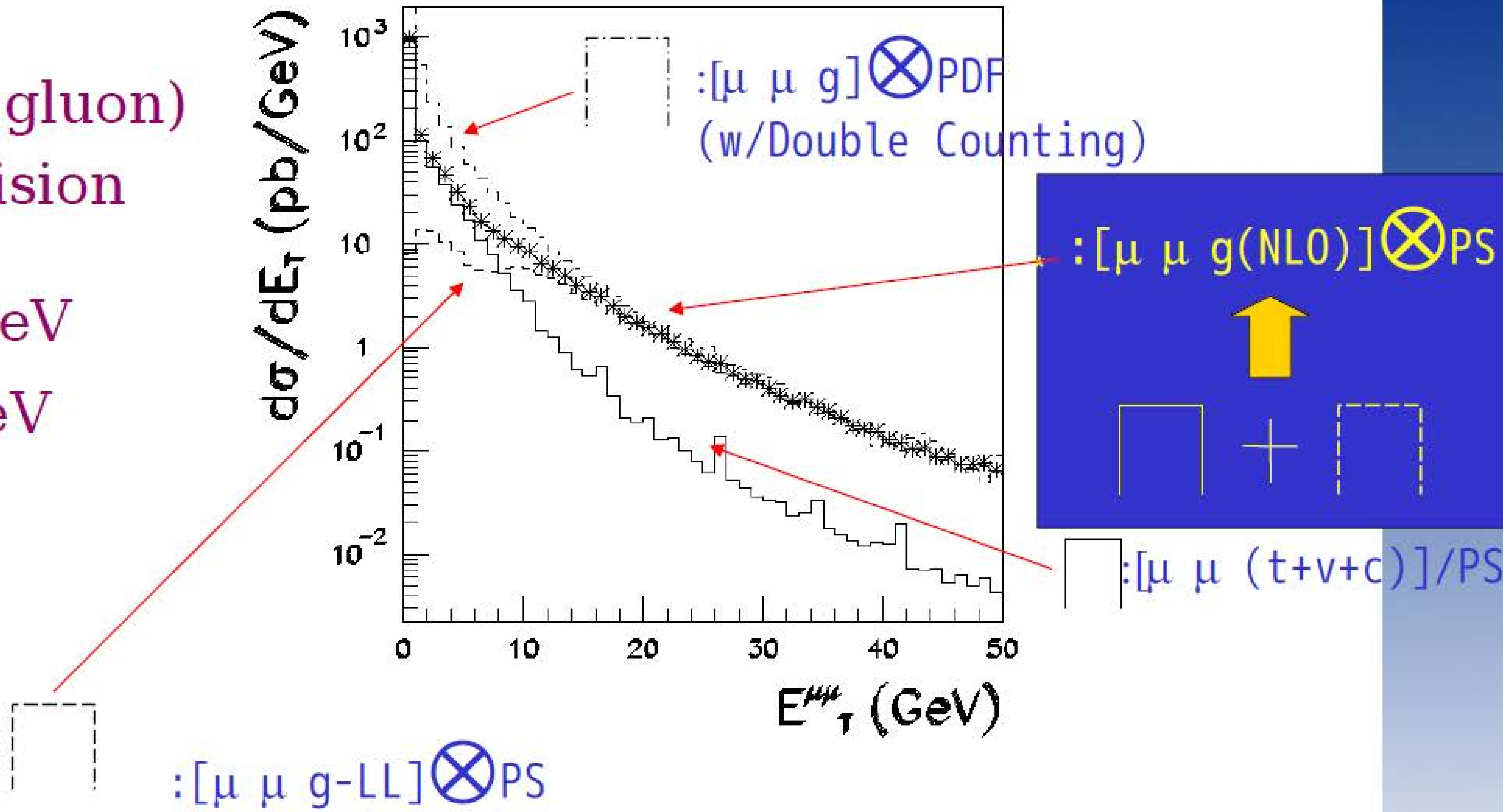
Examples/Drell-Yan

NLO cross section

$$\sigma_{DY}^{NLO} = \sigma_{DY}^{0}\left[1 + C_F \frac{\alpha_s(\mu)}{2\pi}\left(3\ln\left(\frac{s}{\mu_F^2}\right) - \frac{\pi^2}{3} - 8\right)\right]$$

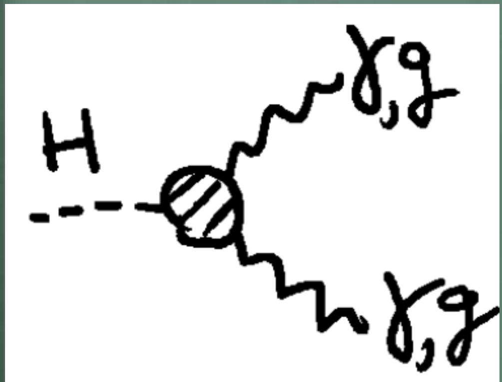
- Process :
  $uu \rightarrow \mu^+\mu^-$(+gluon)
  in pp collision

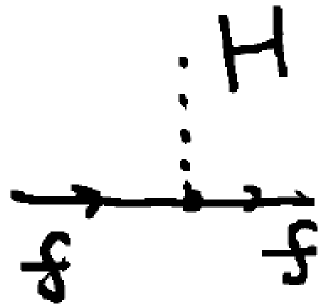
Cuts:
- $\sqrt{s_{\mu\mu}} > 40$GeV
- $k_T^g > 1$ GeV



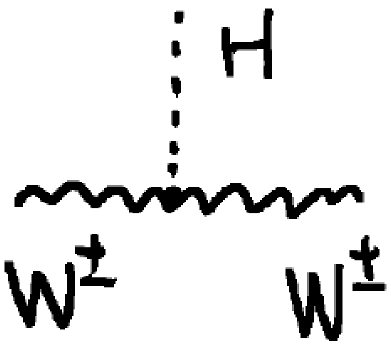
Examples/Higgs → $\gamma\ \gamma$

Feynman Rule

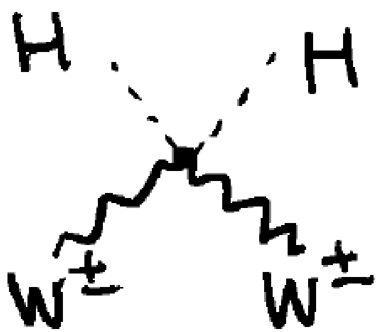




$$= -i\frac{1}{2}\frac{g_W}{m_W}m_f$$



$$= i g_W m_W g^{\mu\nu}$$

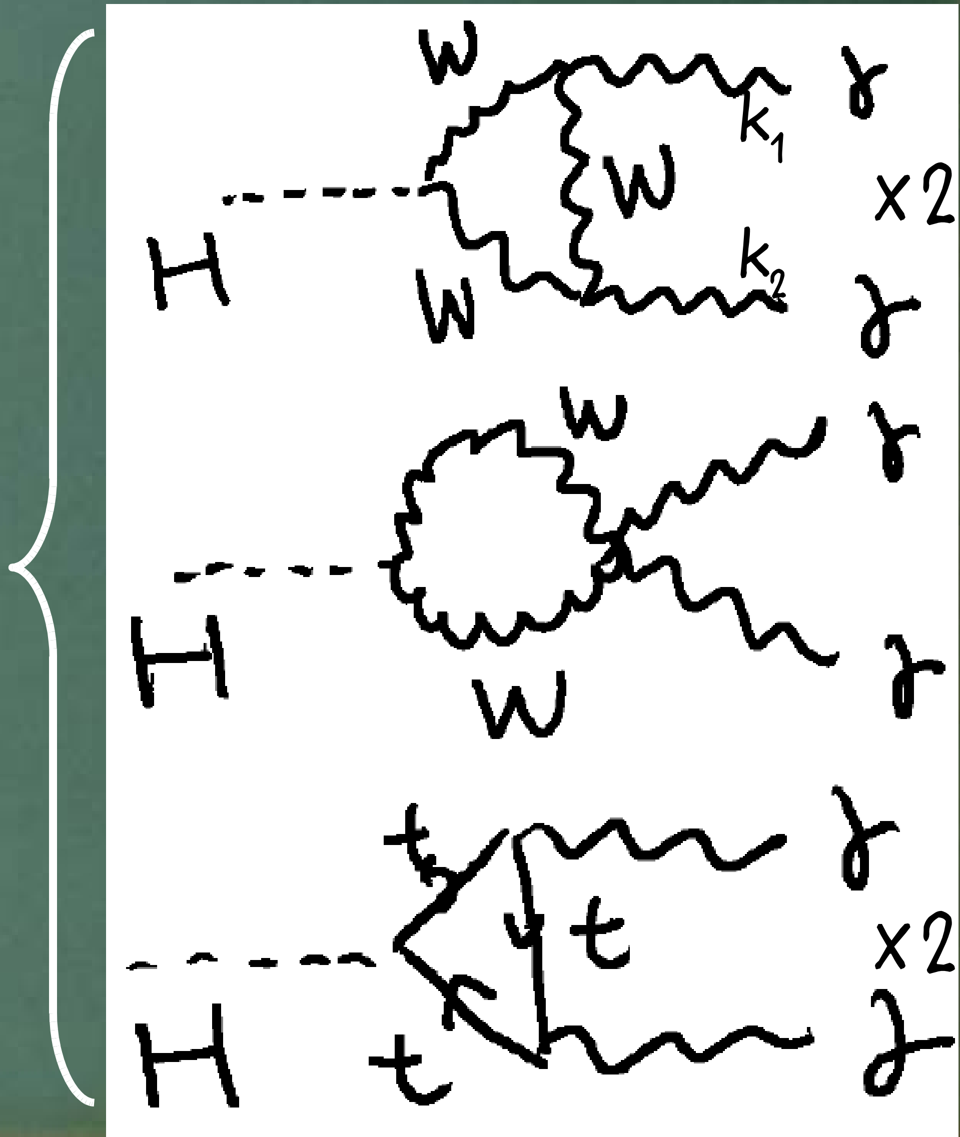


$$= i\frac{g_W^2}{2}g^{\mu\nu}$$

$$g_W = \frac{e}{\sin\theta_W}$$

Examples/Higgs → γ γ

$$\Gamma(H \to \gamma\gamma) = |F|^2 \left(\frac{\alpha}{4\pi}\right)^2 \frac{G_F m_H^3}{8\sqrt{2}\pi}$$



Examples/Higgs → $\gamma\gamma$

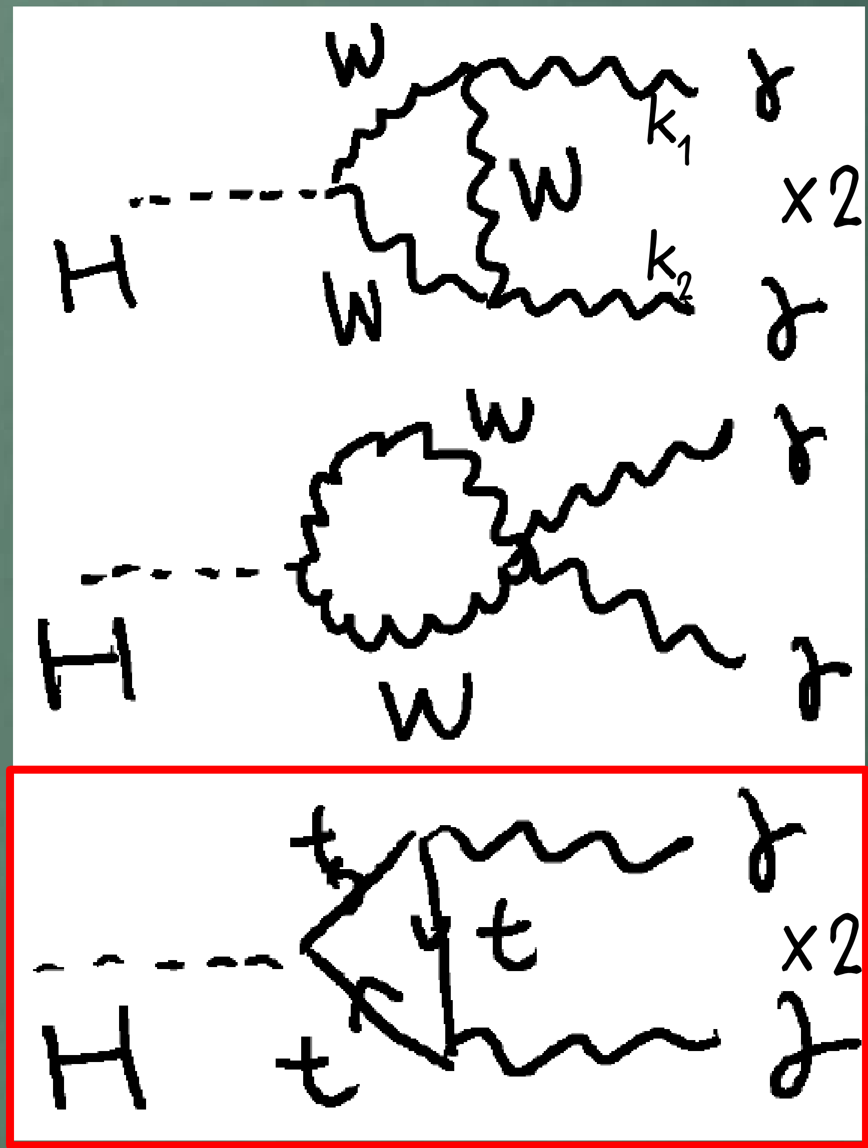
$$F = F_W(\beta_W) + \sum_f N_c Q_f^2 F_f(\beta_f)$$

$$\begin{aligned} F_W(\beta) &= 2 + 3\beta + 3\beta(2-\beta) f(\beta) \\ F_f(\beta) &= -2\beta\left[1 + (1-\beta) f(\beta)\right] \end{aligned}$$

$$\beta_W = \frac{4m_W^2}{m_H^2}, \quad \beta_f = \frac{4m_f^2}{m_H^2}$$

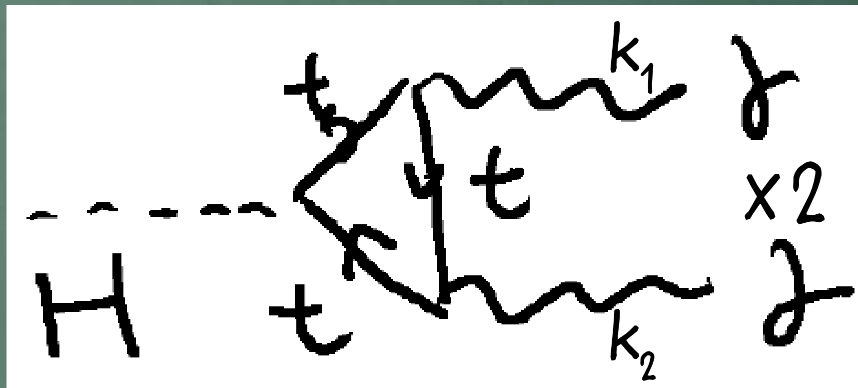
$$f(\beta) = \begin{cases} \arcsin^2(\beta^{-\frac{1}{2}}) & \text{for} \quad \beta \geq 1 \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\beta}}{1-\sqrt{1-\beta}} - i\pi\right]^2 & \text{for} \quad \beta < 1 \end{cases}$$

Examples/Higgs → $\gamma\,\gamma$



Examples/Higgs → γ γ

$$d\Gamma = \frac{(2\pi)^4}{2M} \, |\mathscr{M}|^2 \, d\Phi_n \, (P; \, p_1, \, \ldots, \, p_n)$$

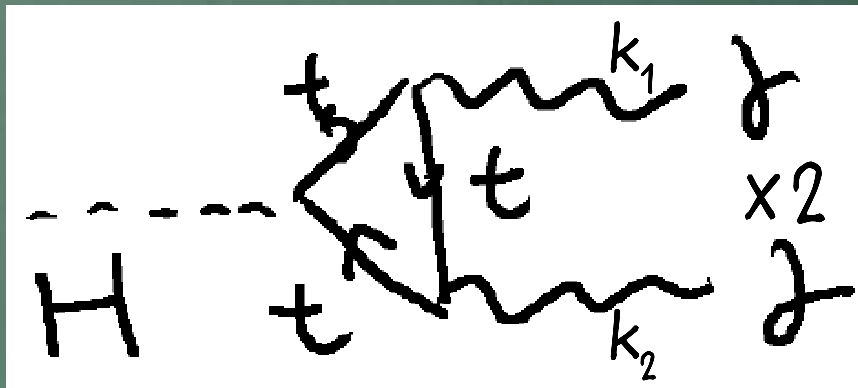


$$2\mathcal{M}_t = -ie^3 \frac{m_t}{m_W \sin\theta_W} \int \frac{d^4k}{(2\pi)^4 i} Tr\left[\frac{i}{\not{k} + \not{k}_1 - m_t} i\not{\epsilon}(k_1) \frac{i}{\not{k} - m_t} i\not{\epsilon}(k_2) \frac{i}{\not{k} + \not{k}_2 - m_t}\right]$$

$$\sim \quad e^3 \frac{m_t}{m_W \sin\theta_W} \int \frac{d^4k}{(2\pi)^4 i} Tr\left[\frac{(\not{k} + m_t)\not{\epsilon}(k_1)(\not{k} + m_t)\not{\epsilon}(k_2)(\not{k} + m_t)}{(k^2 - m_t^2)^3}\right]$$

Examples/Higgs → γ γ

$$d\Gamma = \frac{(2\pi)^4}{2M} \, |\mathscr{M}|^2 \, d\Phi_n \, (P; \, p_1, \, \ldots, \, p_n)$$



$$2\mathcal{M}_t = -ie^3 \frac{m_t}{m_W \sin\theta_W} \int \frac{d^4k}{(2\pi)^4 i} Tr\left[\frac{i}{\not k + \not k_1 - m_t} i\not\epsilon(k_1) \frac{i}{\not k - m_t} i\not\epsilon(k_2) \frac{i}{\not k + \not k_2 - m_t}\right]$$

$$\sim \quad e^3 \frac{m_t}{m_W \sin\theta_W} \int \frac{d^4k}{(2\pi)^4 i} Tr\left[\frac{(\not k + m_t)\not\epsilon(k_1)(\not k + m_t)\not\epsilon(k_2)(\not k + m_t)}{(k^2 - m_t^2)^3}\right]$$

$$\int \frac{d^n k}{(2\pi)^n i} \frac{(k^2)^r}{(k^2 - \mathcal{D})^m} = \frac{(-1)^{r-m}}{(16\pi)^{n/4}} \mathcal{D}^{r-m+n/2} \frac{\Gamma(r + n/2)\Gamma(m - r - n/2)}{\Gamma(n/2)\Gamma(m)}$$

Examples/Higgs → $\gamma\gamma$

$$d\Gamma = \frac{(2\pi)^4}{2M} |\mathscr{M}|^2 \, d\Phi_n\,(P;\, p_1, \ldots, p_n)$$

$$\left\{ e^3 \frac{m_t}{m_W \sin\theta_W} m_t^2 m_H^2 \right\}^2$$

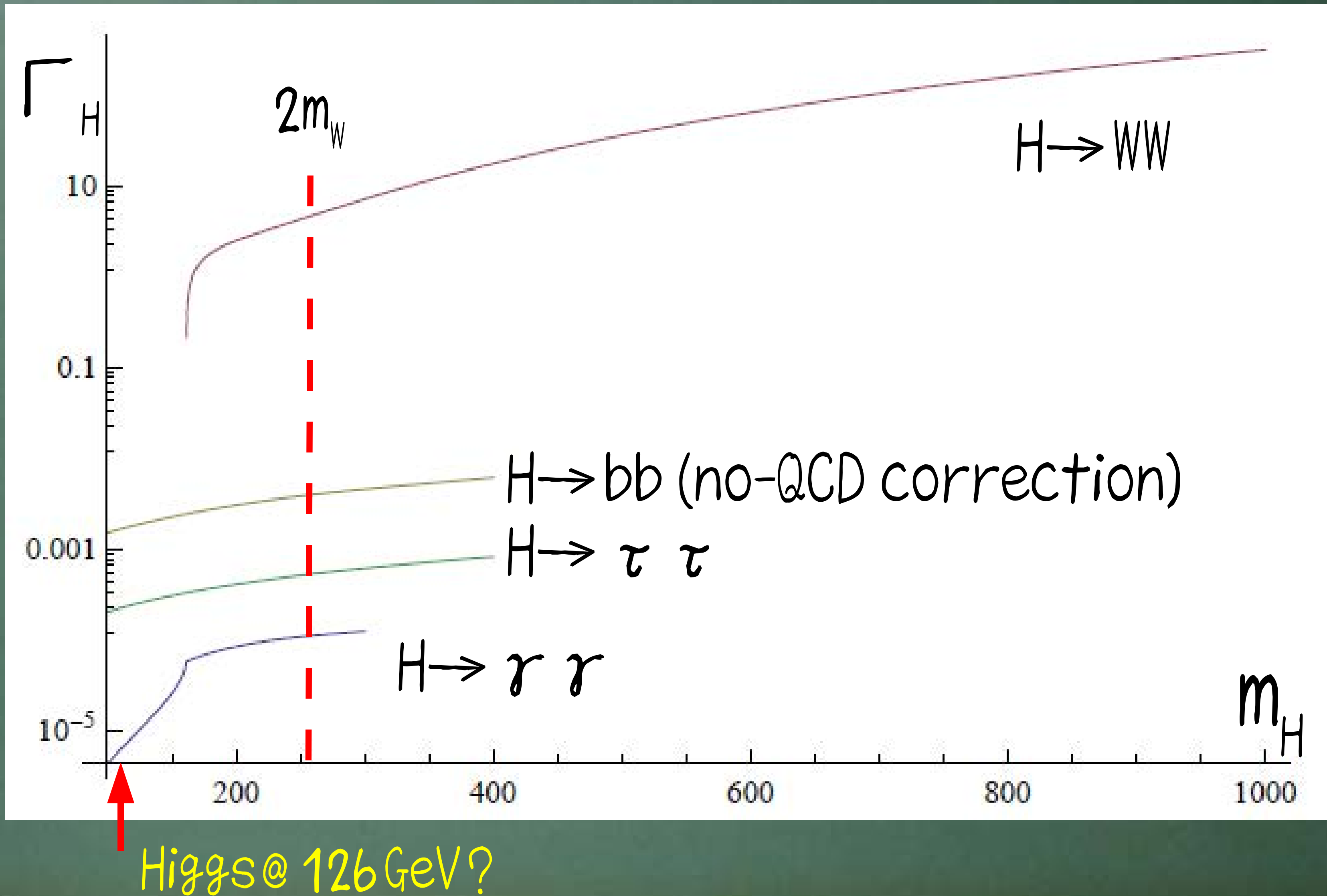
Examples/Higgs → γ γ

$$d\Gamma = \frac{(2\pi)^4}{2M} |\mathscr{M}|^2 \, d\Phi_n \left(P;\, p_1, \ldots, p_n\right)$$

$$\left\{ e^3 \frac{m_t}{m_W \sin\theta_W} m_t^2 m_H^2 \right\}^2$$

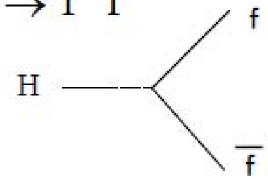
$$\Gamma(H \to \gamma\gamma) = |F|^2 \left(\frac{\alpha}{4\pi}\right)^2 \frac{G_F m_H^3}{8\sqrt{2}\pi}$$

Examples/Higgs → γ γ



Examples/Higgs → $\gamma\ \gamma$

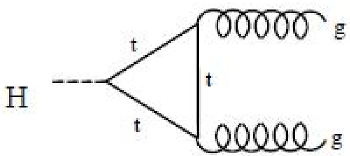
$H \to f\ \bar{f}$



$$\Gamma_{f\bar{f}} = C_f \frac{G_F m_f^2 m_H}{4\pi\sqrt{2}} \beta_f^n, \quad \beta_f = \left(1 - \frac{4m_f^2}{m_H^2}\right)^{1/2}$$

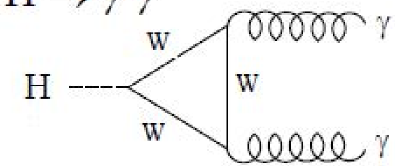
$n = 3$ (scalar) , $n = 1$ (pseudosca lar)

$H \to$ gluon + gluon



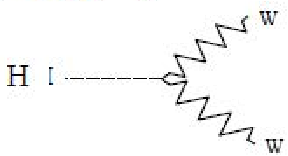
$$\Gamma_{gg} = \frac{G_F m_H^3}{36\pi\sqrt{2}} \left[\frac{\alpha_S\left(m_H^2\right)}{\pi}\right]^2 |I|^2, \ I = 1 \sim 3$$

$H \to \gamma\ \gamma$



$$\Gamma_{\gamma\gamma} = \frac{G_F m_H^3}{8\pi\sqrt{2}} \left[\frac{\alpha}{\pi}\right]^2 |I|^2, \quad I \sim -\frac{1}{2}$$

$H \to W\ \ W$



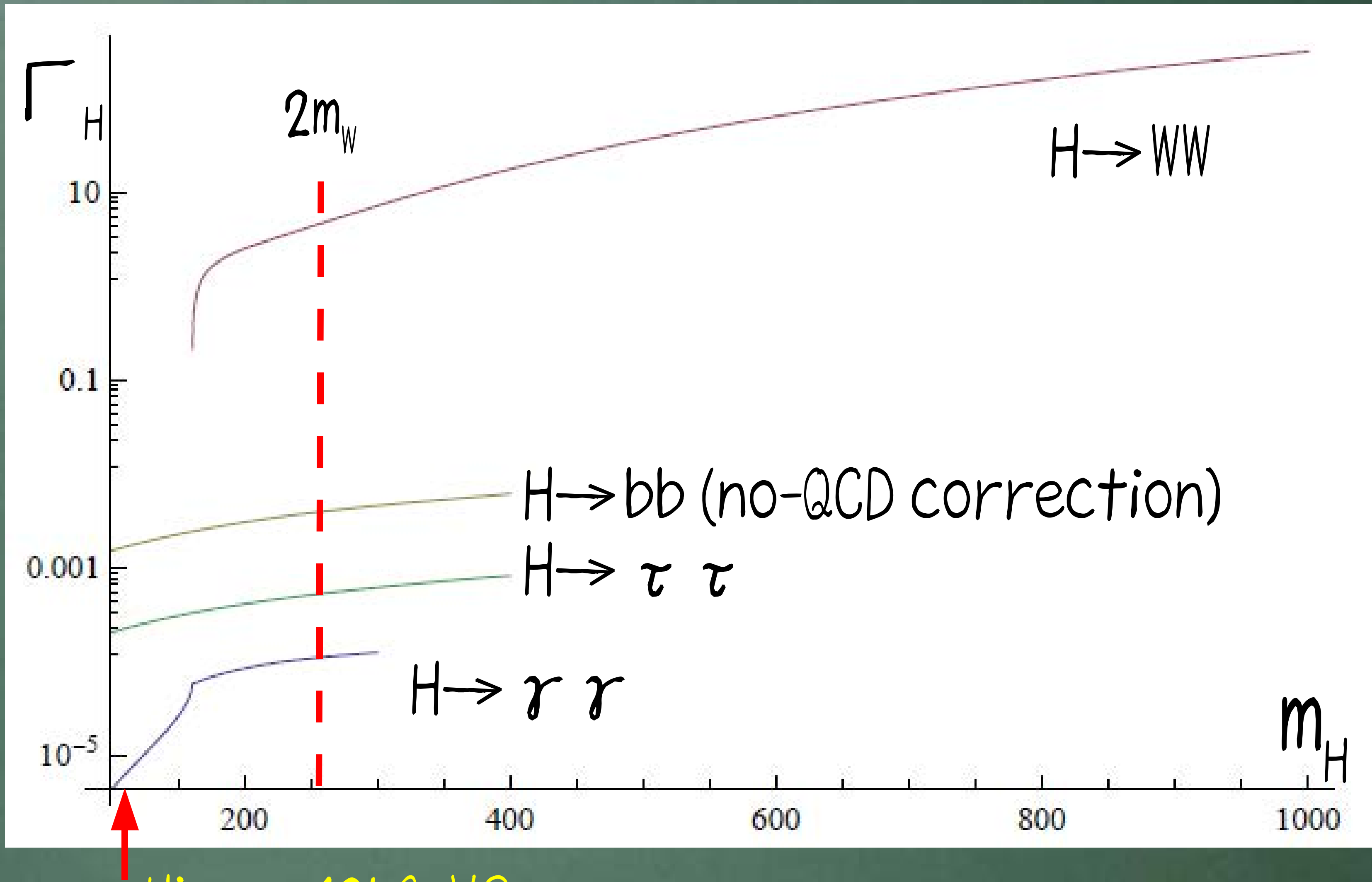
$$\Gamma_{WW} = \frac{G_F m_H^3}{16\pi\sqrt{2}} \delta_V \left(12x^2 - 4x + 1\right)\sqrt{1 - 4x}$$

$$x = \left(m_V / m_H\right)^2, \quad \delta_V = 2\ (\mathrm{W})\ \ 1(\mathrm{Z})$$

[1] Abdelhak Djouadi, Phys.Rept.457:1-216,2008

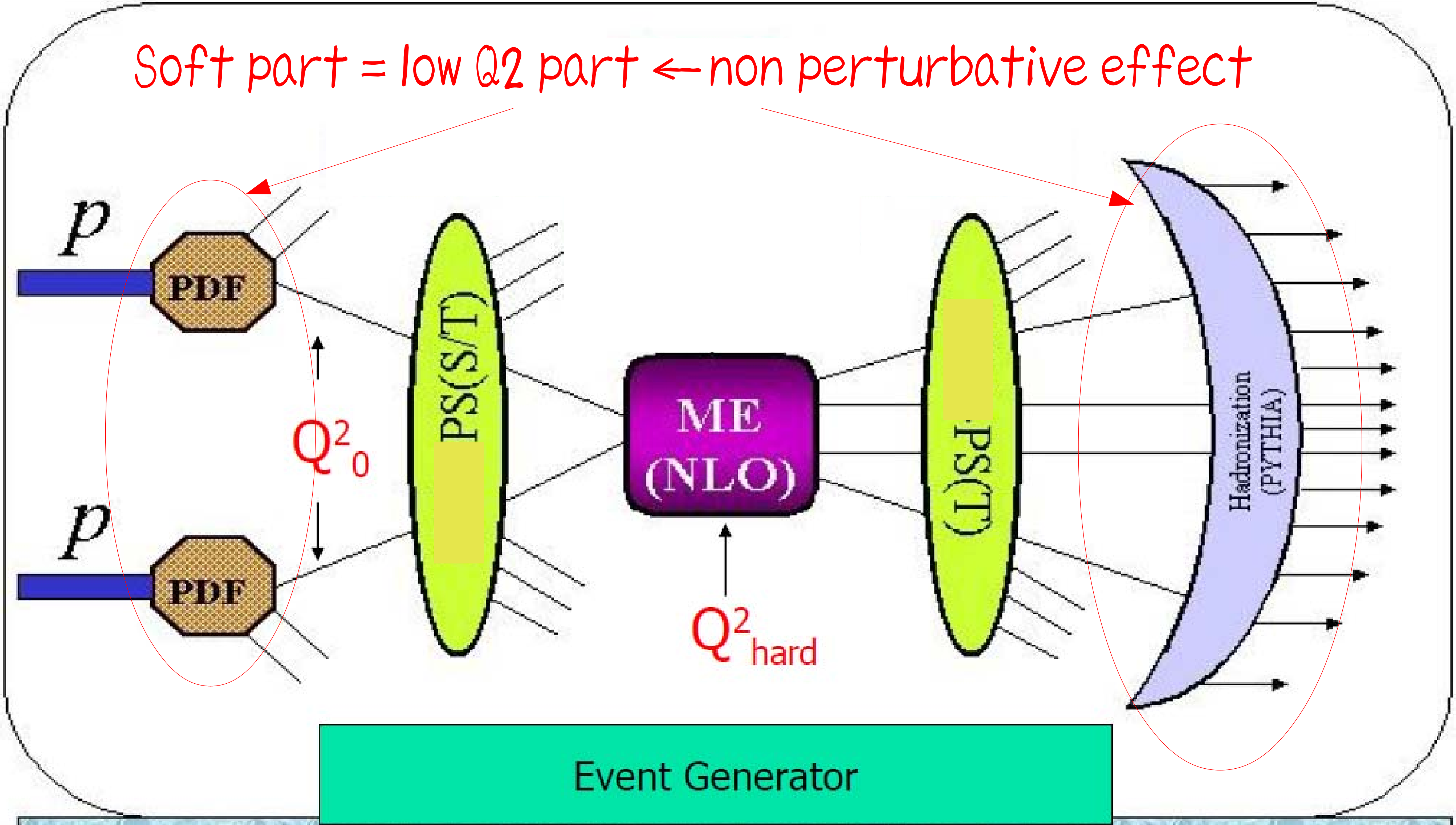
Examples/Higgs → γ γ

Exercise: Draw this plot.



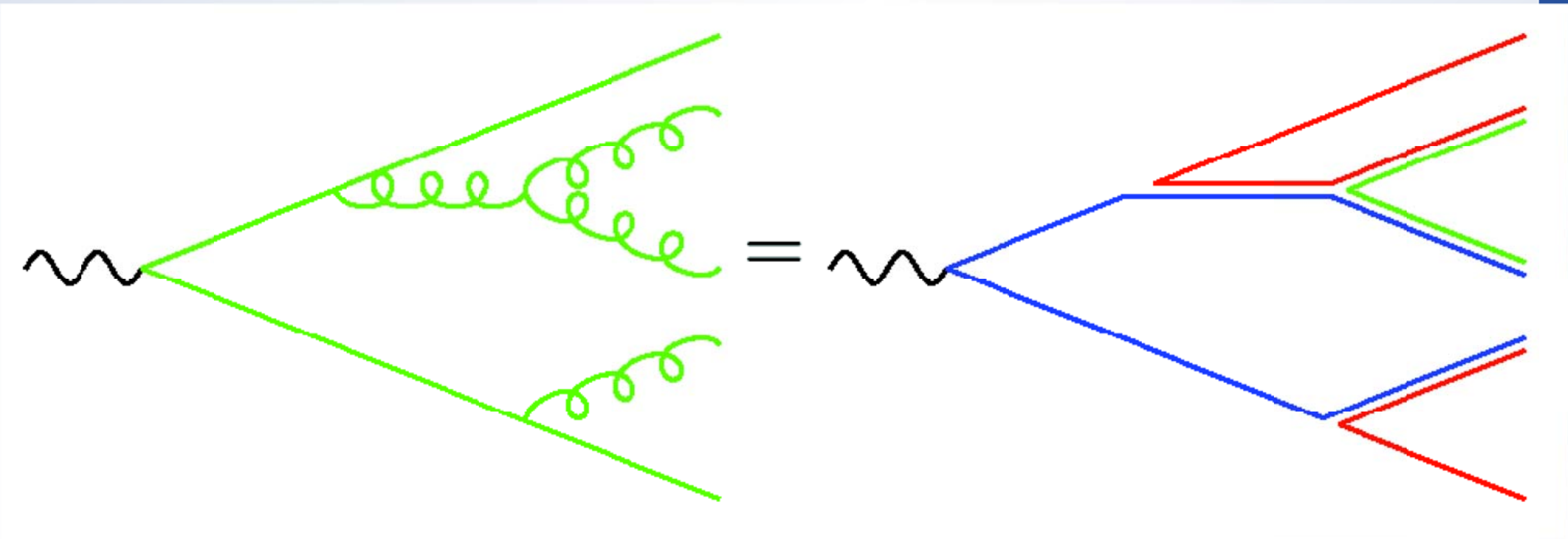
Higgs@ 126 GeV?

non-perturbative effects



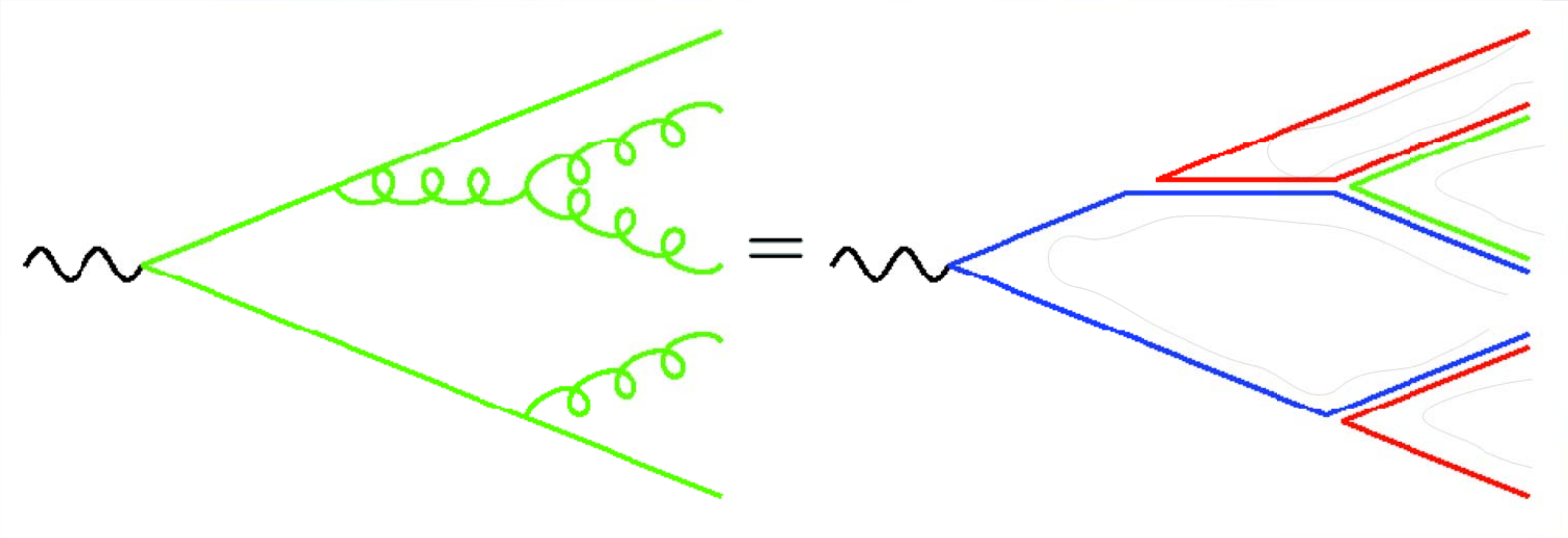
non-perturbative effects/Hadronization String Model

quark, gluon → color line



non-perturbative effects/Hadronization
String Model

quark, gluon → color line



non-perturbative effects/Hadronization
String Model

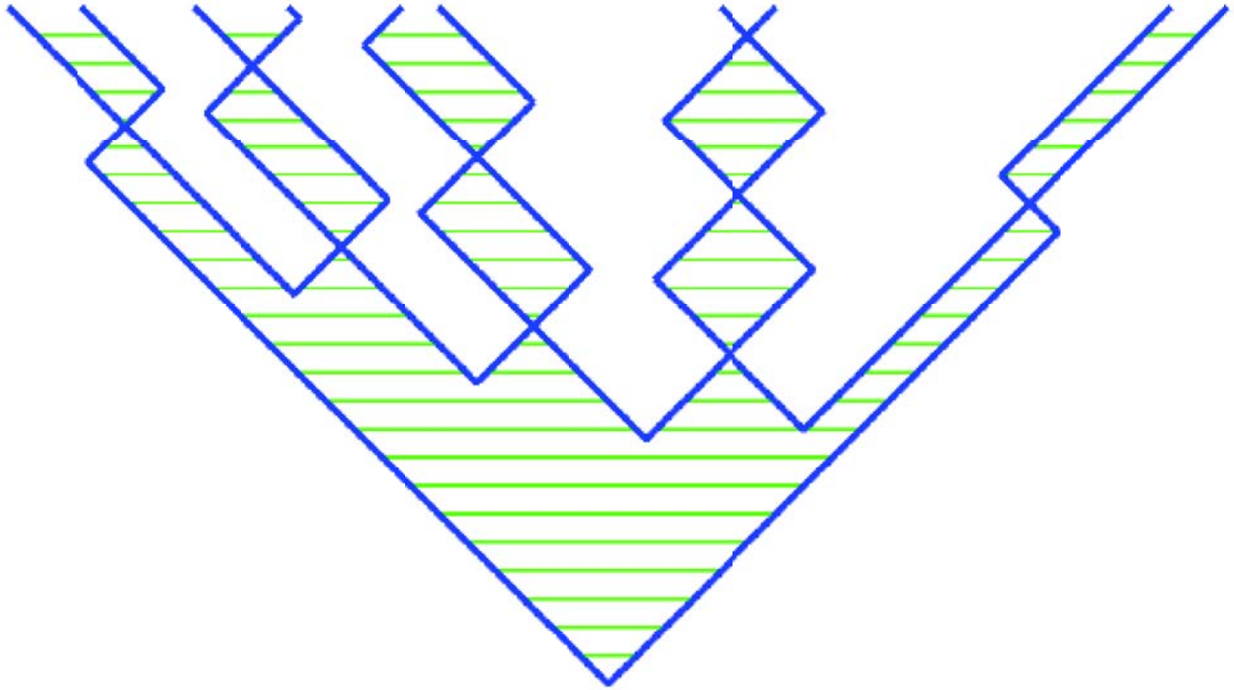
Start by ignoring gluon radiation:

e^+e^- annihilation = pointlike source of $q\bar{q}$ pairs

Intense chromomagnetic field within string → $q\bar{q}$ pairs created by tunnelling. Analogy with QED:

$$\frac{d(\text{Probability})}{dx\ dt} \propto \exp(-\pi m_q^2/\kappa)$$

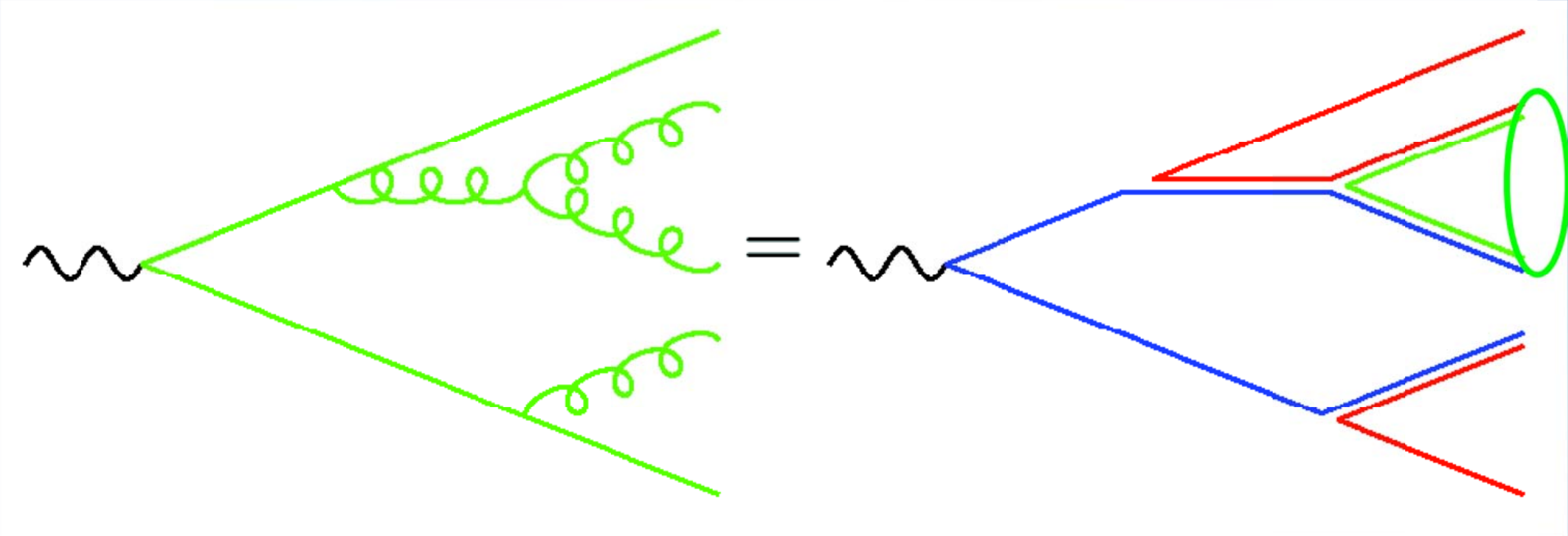
Expanding string breaks into mesons long before yo-yo point.



Event General ... ın Webber

non-perturbative effects/Hadronization
Cluster Model

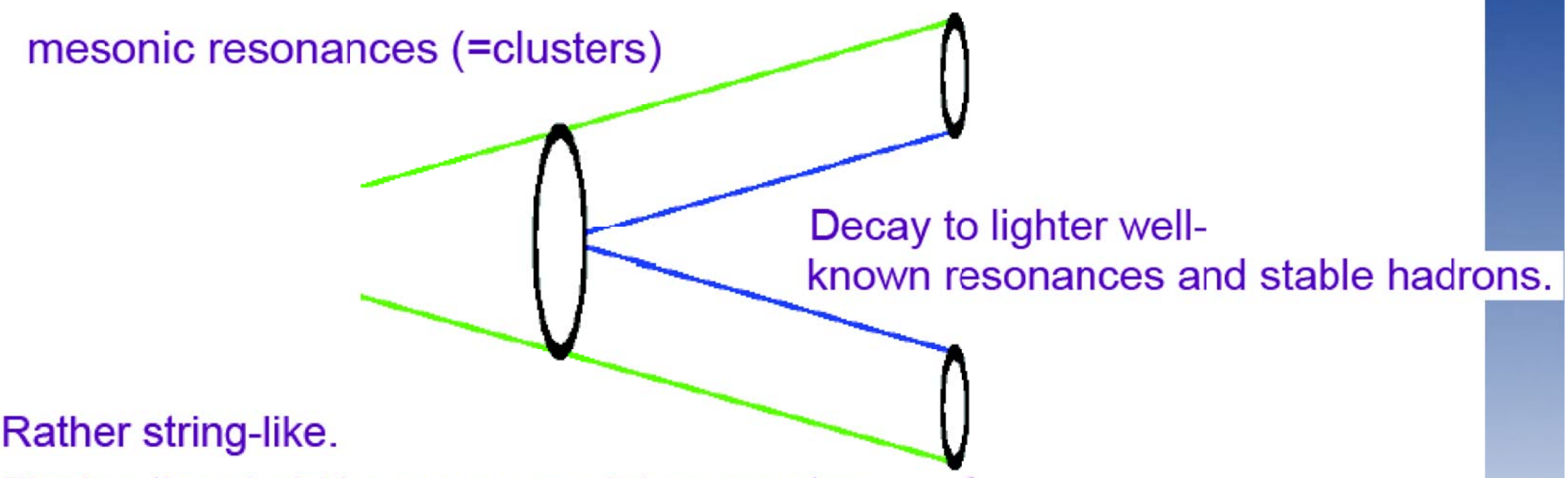
quark, gluon → color line



non-perturbative effects/Hadronization Cluster Model

Although cluster mass spectrum peaked at small m, broad tail at high m.

"Small fraction of clusters too heavy for isotropic two-body decay to be a good approximation" → Longitudinal cluster fission:



Rather string-like.

Fission threshold becomes crucial parameter.

~15% of primary clusters get split but ~50% of hadrons come from them.