Physics at the LHC

(Large Hadron Collider)

by Kaoru Hagiwara (KEK, SOKENDAI)

2006. 8. 5 @ Wakate S.S.
2006. 8. 9 @ BSM2006, Beijing

LHC countdown schedule

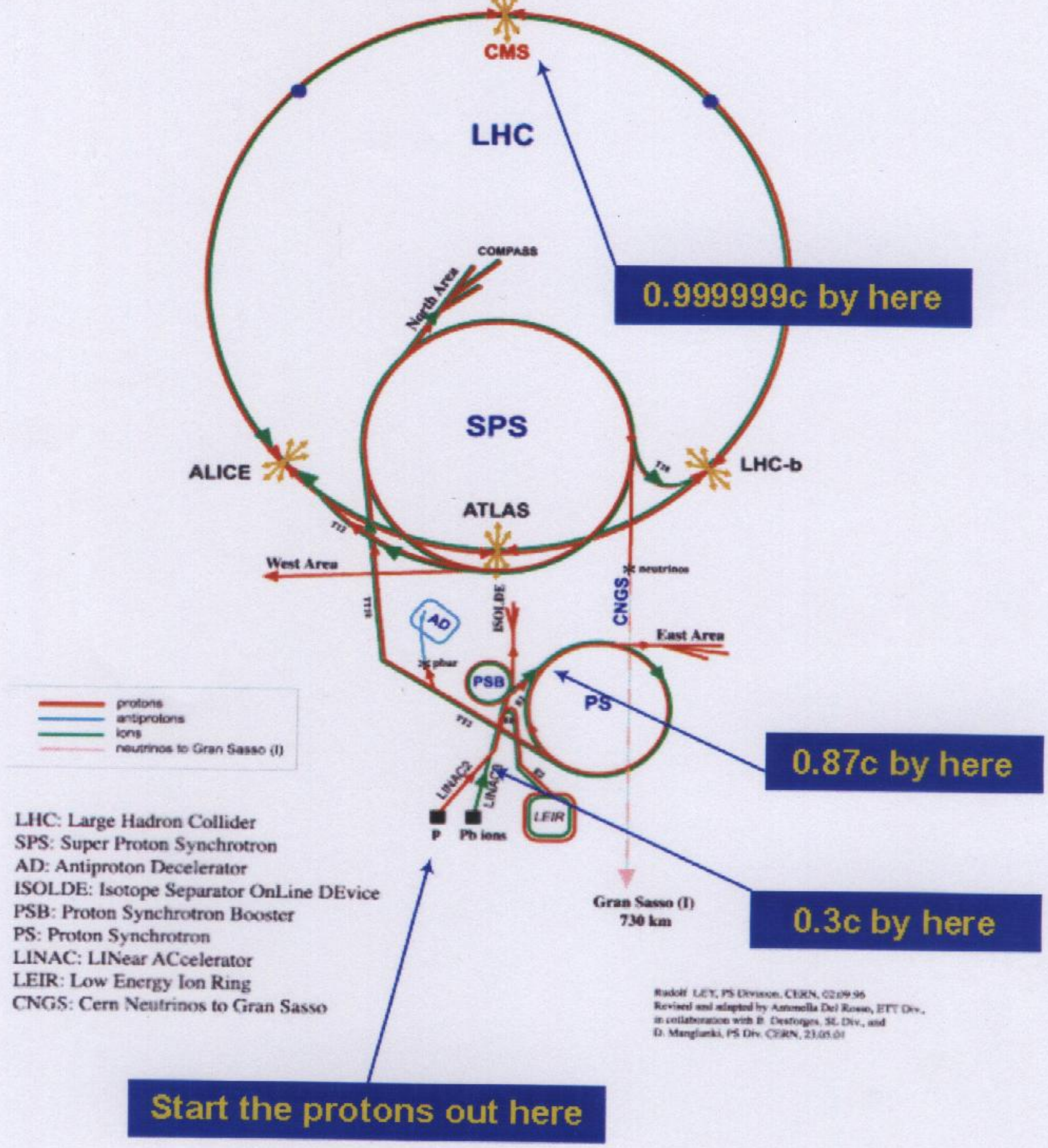
2006.12 all the magnets are tested.

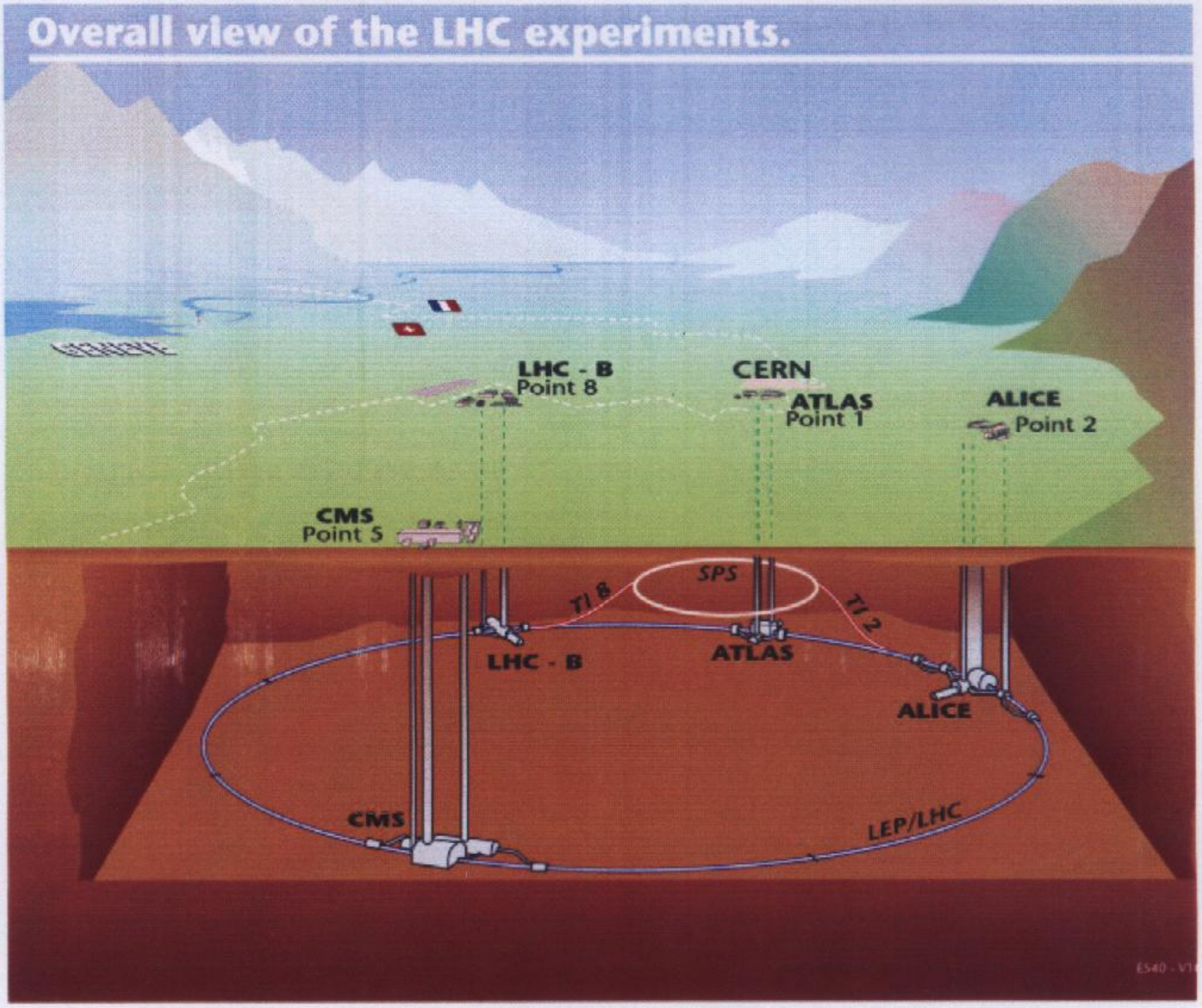
2007.3 all the magnets are installed in the LHC ring.

2007.8 beam tests

- 2007.11 first collisions @ $\sqrt{s} \sim 1$ TeV !
- 2008. spring collisions @ $\sqrt{s} \sim 14$ TeV !!
- 2008. summer first news from the LHC !!!

CERN Accelerators
(not to scale)




Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

Success, defects, limitations of the SM of Elementary Particles

✓ strong, weak, electromagnetic interactions of all the EP's are understood at the quantum level.

✓ classification of all the EP's

$(3,2,\frac{1}{6}) + (3,1,-\frac{1}{3}) + (3,1,\frac{2}{3}) + (1,2,-\frac{1}{2}) + (1,1,-1) + (1,1,0)$ fermions

$(8,1,0) + (1,3,0) + (1,1,0)$ gauge bosons

$[(1,3,0)$ Nambu-Goldstone bosons$]$

✓ $m_W^2/m_Z^2 = g_W^2/(g_W^2+g_Y^2)$ of the minimal SM with 1 Higgs doublet

✓ $\cancel{P}$ from chiral $SU(2)_L \times U(1)_Y$

✓ $\cancel{CP}$ from the KM phase of 3×3 V_{CKM}, Flavor 'conservation'

✓ B & L conservation (up to $SU(2)_L$ instanton & possible See-Saw m_ν)

✓ Dark Matter of the Universe ⇒ new stable particle *

✓ Baryogenesis ⇒ new $\cancel{CP}$ *

✓ $\theta_{QCD} \lesssim 10^{-9}$ ⇒ $U(1)_{PQ}$ or CP, ...

✓ $m_\nu/m_e \lesssim 10^{-9}$, $m_\nu/m_t \lesssim 10^{-12}$ ⇒ See-saw, ...

✓ $U(1)_Y$ charge quantization $\frac{1}{6}\times 6 + \frac{1}{3}\times 3 + (-\frac{2}{3})\times 3 + (-\frac{1}{2})\times 2 + 1\times 1 = 1+1-2-1+1 = 0$

$(\frac{1}{6})^3\times 6 + (\frac{1}{3})^3\times 3 + (-\frac{2}{3})^3\times 3 + (-\frac{1}{2})^3\times 2 + 1^3\times 1 = \frac{1+4-32-9+36}{36} = 0$

⇒ quark-lepton unification

✓ $g_3^2 \gg g_2^2 > g_1^2$ why? ⇒ GUT with " *

* ✓ Higgs : fundamental scalar or composite state of new strong int.?

✓ Why $(3,2,\frac{1}{6}) + (3,1,-\frac{1}{3}) + (3,1,\frac{2}{3}) + (1,2,-\frac{1}{2}) + (1,1,-1) + (1,1,0)$ for fermions?

* ✓ Why $(1,2,\pm\frac{1}{2})$ for 'Higgs'?

✓ Why $SU(3)\times SU(2)\times U(1)$?

✓ Why 3 generations?

* ✓ Why $SU(2)_L \times U(1)_Y \to U(1)_{EM}$ @ $v \approx 256$ GeV?

* ✓ What do q & l masses and mixings tell us? q (6 masses, 3 angles, 1 phase) l (6 masses, 3 angles, 1+2 phases)

$*$ ⇛ TeV physics ⇛ Physics beyond the SM ⇛ $*$

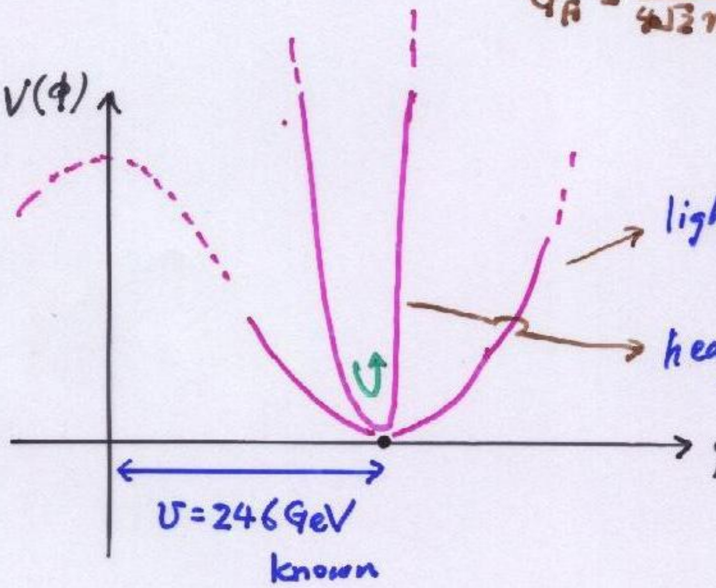
EWSB (Higgs)

⇛ new questions

Why is the EWSB (Higgs) physics at the TeV scale?

$$\left.\begin{array}{l} m_W = \frac{g_W}{2} v \\ m_Z = \frac{\sqrt{g_W^2 + g_Y^2}}{2} v \end{array}\right\} \Rightarrow \quad v = 246\ \text{GeV} \quad \text{known}$$

$$G_F = \frac{g_W^2}{4\sqrt{2}\, m_W^2} = \frac{1}{\sqrt{2}\, v^2}$$



light Higgs → flatter $> 115\,\text{GeV}$ LEP

heavy Higgs → steeper

⇓

new strong interactions

⇓

composite states

$\lesssim 1\ \text{TeV}$ Lattice Higgs th.

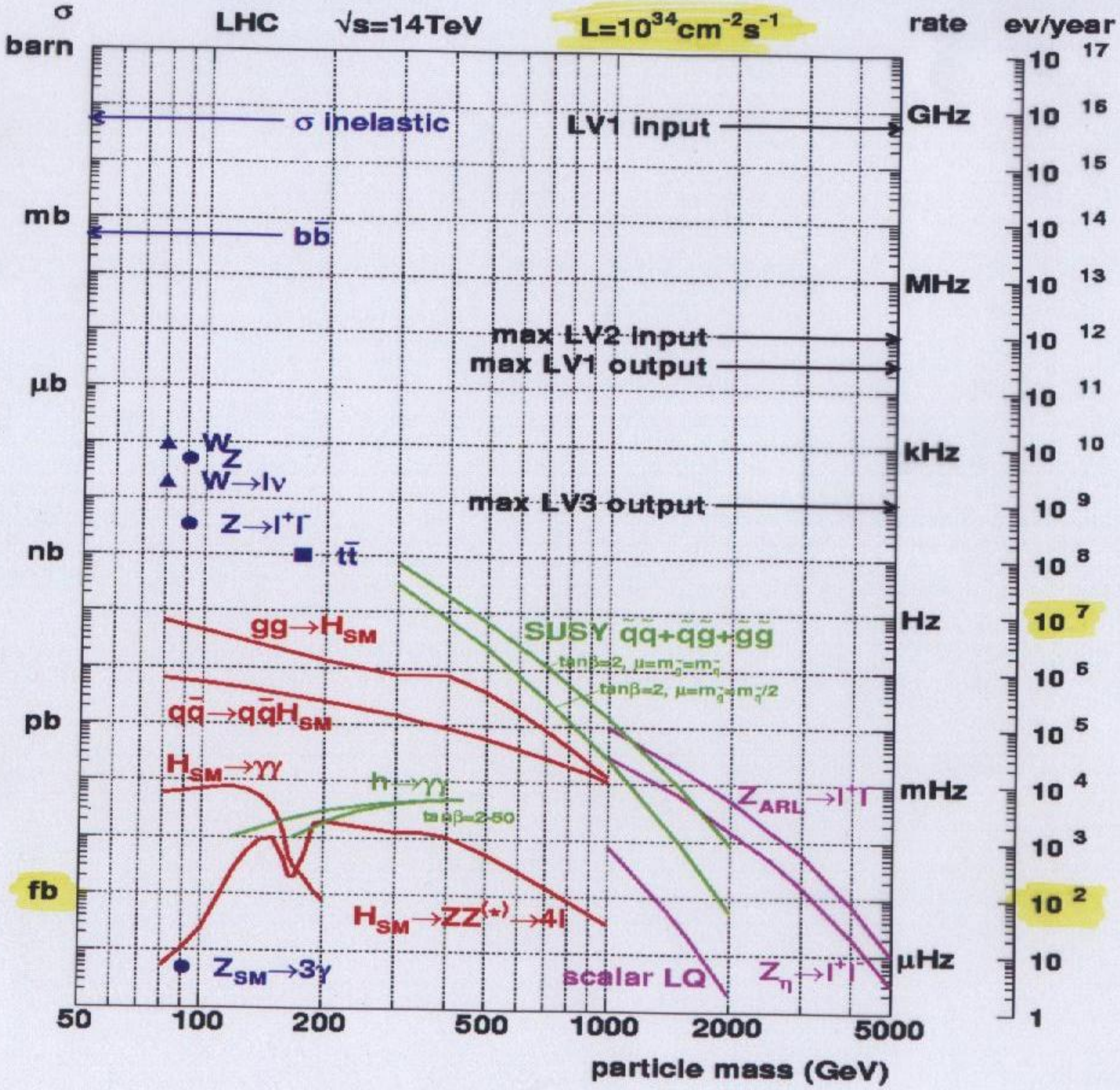
We can hence uncover the physics of EWSB by a collider which has elementary collisions at TeV energies.

LHC $\quad pp$ @ $\sqrt{s} = 14\ \text{TeV}$

ILC $\quad e^+e^-$ @ $\sqrt{s} = 0.5 \sim 1\ \text{TeV}$

$\quad$ ($\gamma\gamma$ @ $\sqrt{s} = 0.4 \sim 0.8\ \text{TeV}$) PLT option

Cross sections @ the LHC



"Well known"processes, don't need to keep all of them …

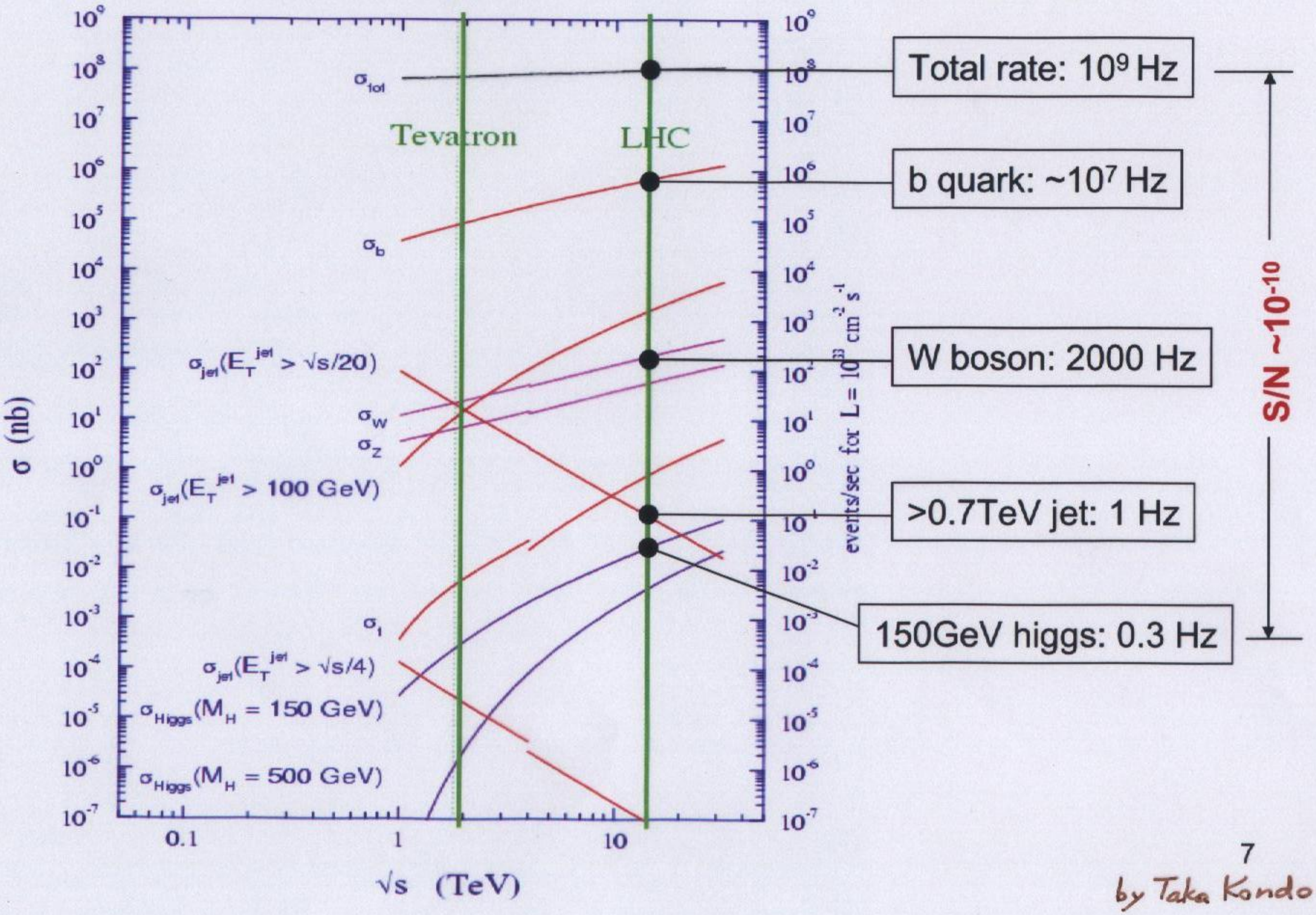
New Physics!!

This we want to keep!!

Filip Moortgat, CERN

pp interactionでの
いろいろな生成断面積

L=10^{34}cm^{-2}s^{-1}でのrate



by Taka Kondo

length $\quad 1\,\text{mm} = 10^{-3}\,\text{m}$

$1\,\mu = 10^{-6}\,\text{m}$

$1\,\text{nm} = 10^{-9}\,\text{m}$

$1\,\text{pm} = 10^{-12}\,\text{m}$

$1\,\text{fm} = 10^{-15}\,\text{m} \quad \approx$ size of hadrons $\approx \underbrace{(0.2\,\text{GeV})}_{\approx 1.4\, m_\pi}{}^{-1}$

cross sections

$$\sigma \sim \pi R^2 \sim \pi (1\,\text{fm})^2 = \underbrace{\pi \cdot 10\,\text{mb}} \approx \text{hadronic cross sections}$$

$$10^{-30}\,\text{m}^2 = 10^{-26}\,\text{cm}^2 = 10\,\text{mb}$$
$$10^{-27}\,\text{cm}^2 = 1\,\text{mb}$$
$$10^{-30}\,\text{cm}^2 = 1\,\mu\text{b}$$
$$10^{-33}\,\text{cm}^2 = 1\,\text{nb}$$
$$10^{-36}\,\text{cm}^2 = 1\,\text{pb}$$
$$10^{-39}\,\text{cm}^2 = 1\,\text{fb}$$

$\text{GeV}^2 \cdot \text{mb}$ $\quad (10^{-15}\,\text{m})^2 = 10^{-26}\,\text{cm}^2 = 10\,\text{mb} \approx \dfrac{1}{(0.2\,\text{GeV})^2} = \dfrac{1}{0.04} \cdot \dfrac{1}{\text{GeV}^2}$

$$\frac{1}{\text{GeV}^2} \approx 0.4\,\text{mb}$$
$$\frac{1}{\text{TeV}^2} \approx 0.4\,\text{nb} = 400\,\text{pb} = 4 \times 10^5\,\text{fb}$$

Luminosity

$$[\underbrace{\mathcal{L} = 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}}_{\text{LHC } (\sim 3\text{yrs})}] \times [\underbrace{10^7\,\text{s}}_{\substack{\approx \frac{1}{3}\text{ year} \\ \approx 1 \text{ machine operation year}}}] = 10^{40}\,\text{cm}^{-2}/\text{year} = 10\,\text{fb}^{-1}/\text{year}$$

$$[\underbrace{\mathcal{L} = 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}}_{\text{LHC } (>4\text{yrs})}] \times [10^7\,\text{s}] = 10^{41}\,\text{cm}^{-2}/\text{year} = 100\,\text{fb}^{-1}/\text{year}$$

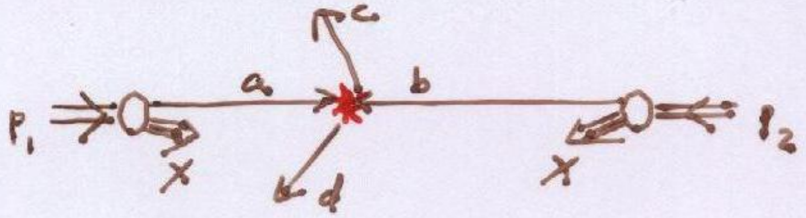
\# of collisions $\quad [\mathcal{L} = 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}] \times [\sigma_{pp}^{tot} \approx 100\,\text{mb}] = 10^8$ collisions/second

$[\mathcal{L} = 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}] \times [\quad " \quad] = 10^9$ collisions/second

$= 1$ event$/10^{-9}$ second

$pp \to (ab \to cd)\,X$ [$pp \to cdX$ in the parton model]

= the Leading Order (LO) of the QCD perturbation theory with factorization of collinear singularities.



$$d\sigma(pp\to cdX) = \sum_{a\,b}\int_0^1 dx_1\int_0^1 dx_2\, D_{a/p}(x_1,Q^2)\,D_{b/p}(x_2,Q^2)\, d\hat\sigma(ab\to cd;\ \hat s = s\,x_1x_2)$$

factorization scale

$Q^2 \approx \hat s$ … $\hat s$-channel process

$Q^2 \approx |\hat t|$ … $\hat t$-channel process

$$\hat s = (p_a+p_b)^2 = (E_a+E_b)^2 - (\vec p_a + \vec p_b)^2$$
$$= \left(\frac{\sqrt{s}}{2}\right)^2 \left\{ (x_1+x_2)^2 - (x_1-x_2)^2 \right\}$$
$$= \frac{s}{4}\cdot 4x_1x_2 = s\,x_1x_2 \equiv s\,\tau$$

$$\left.\begin{array}{l} x_1 = \sqrt{\tau}\,e^{y} \\ x_2 = \sqrt{\tau}\,e^{-y} \end{array}\right\} y = \frac{1}{2}\ln\frac{x_1}{x_2} = \frac{1}{2}\ln\frac{(x_1+x_2)+(x_1-x_2)}{(x_1+x_2)-(x_1-x_2)}$$

… rapidity of $a+b = c+d$ system

$$dx_1\,dx_2 = \frac{dx_1}{x_1}\, d(x_1x_2)$$
$$= d\ln x_1\, d\tau$$
$$= d\tau\, dy$$

$$d\sigma(pp\to cdX) = \sum_{a\,b}\int_0^1 d\tau \cdot \underbrace{\int_{-\ln(1/\sqrt{\tau})}^{\ln(1/\sqrt{\tau})} dy\, D_{a/p}(\sqrt{\tau}e^{y},Q^2)\,D_{b/p}(\sqrt{\tau}e^{-y},Q^2)}_{\equiv \left(\frac{dL}{d\tau}\right)_{ab}} \cdot d\hat\sigma(ab\to cd;\ \hat s)$$

$\equiv \left(\frac{dL}{d\tau}\right)_{ab}$ … $a+b$ collision luminosity @ $\tau = x_1x_2$

most important to understand the LHC phenomenology

[$ab = gg,\ uu,\ ud,\ dd,\ q\bar q,\ (q\bar q)^{up},\ b\bar b,\ qg,\ ug,\ dg,\ bg$, $(q\bar q)^{down}$

@ $\sqrt{\hat s} = 120\,\text{GeV},\ 300\,\text{GeV},\ 1\,\text{TeV},\ 3\,\text{TeV}$

$Q = \sqrt{\hat s},\ m_W$]

12×4 Table $\times 2$

$$\left(\frac{dL}{d\tau}\right)_{ab} = \int_{\ln\sqrt{\tau}}^{-\ln\sqrt{\tau}} dy\, D_{a/p}(\underbrace{\sqrt{\tau}e^{y}}_{x_1}, Q)\, D_{b/p}(\underbrace{\sqrt{\tau}e^{-y}}_{x_2}, Q) + \begin{pmatrix} a \leftrightarrow b \\ \text{if } a \neq b \end{pmatrix}$$

a • b	$\sqrt{\hat{s}} = 120\,\text{GeV}$	300 GeV	1 TeV	3 TeV
	$\tau = 7.3\times10^{-5}$	4.6×10^{-4}	0.0051	0.046
	$\sqrt{\tau} = 0.0086$	0.021	0.071	0.21
g • g $(Q = m_W)$	2260000.	74300.	422.	0.680
$(Q = \sqrt{\hat{s}})$	2330000.	72400.	284.	0.224
g • (q + $\bar{q}$)				
g • u	279000.	13700.	216.	1.75
	291000.	13900.	166.	0.777
g • d	133000.	6110.	78.9	0.448
	139000.	6150.	59.4	0.189
g • (b + $\bar{b}$)				
u • u	45000.	8320.	117.	3.46
	47500.	3550.	106.	2.09
u • d	87900.	6170.	182.	3.73
	92700.	6600.	161.	2.14
d • d	27000.	1770.	44.8	0.654
	28400.	1870.	38.8	0.360
u • $\bar{u}$ + c • $\bar{c}$				
d • $\bar{d}$ + s • $\bar{s}$				
b • $\bar{b}$				

by CTEQ5M1

PDF (Parton Distribution Function)

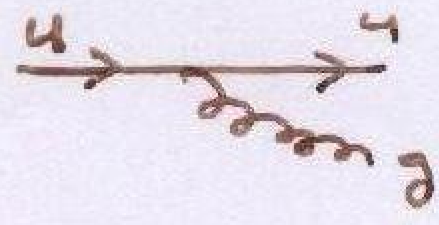
parton model sum rules

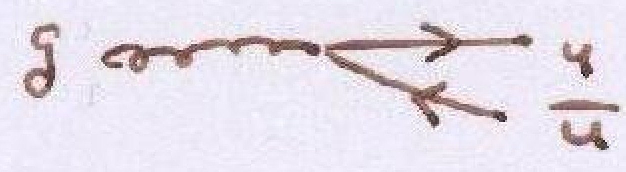
$$\sum_{\substack{a=g,u,d,s,c,b\\ \bar{u},\bar{d},\bar{s},\bar{c},\bar{b}}} \int_0^1 dx \; x\, D_{a/p}(x, Q^2) = 1 \qquad \text{energy sum rule}$$

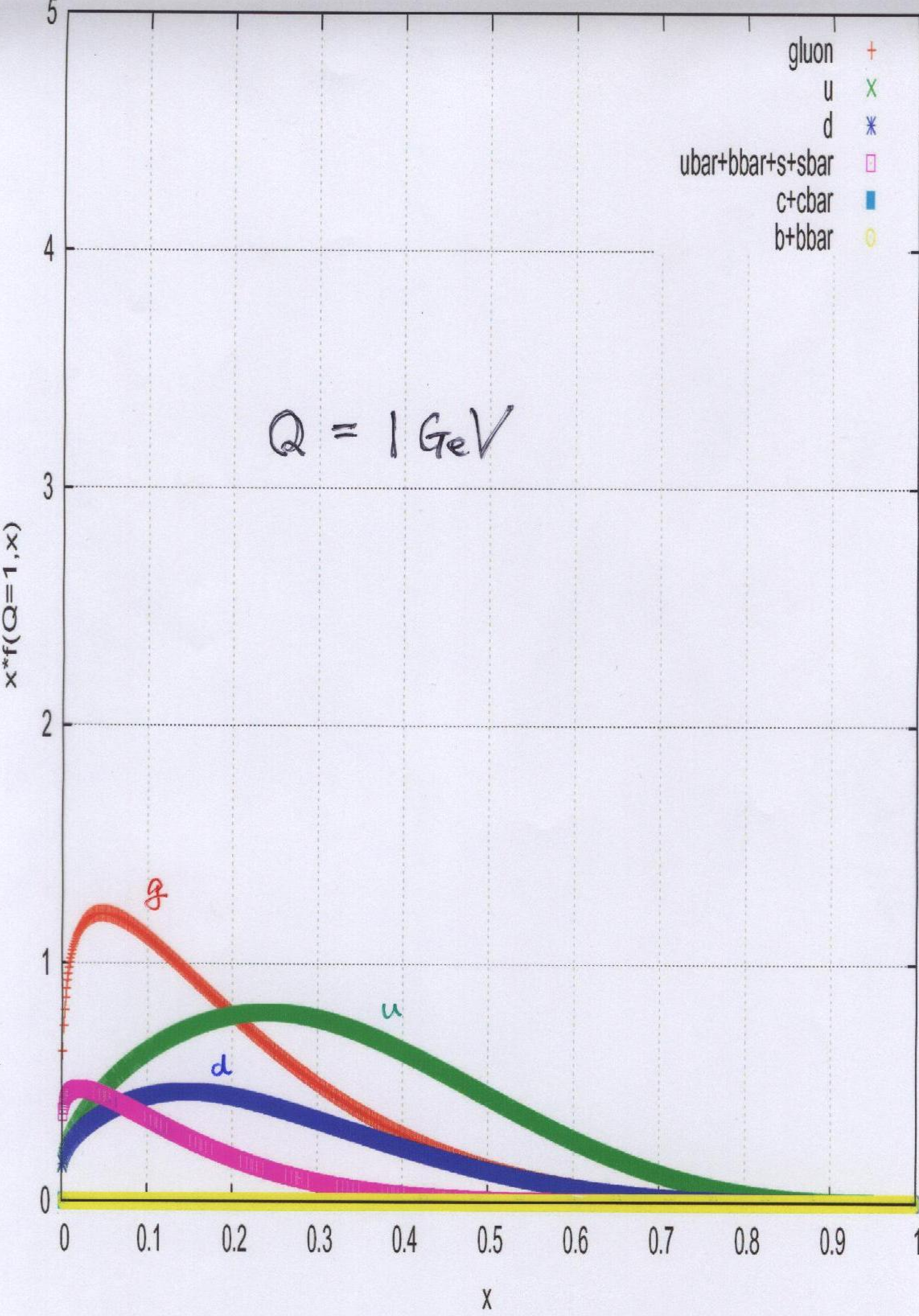
		$Q = 2\,\text{GeV}$	$Q = m_W$	$Q = 1\,\text{TeV}$
g:	$\int_0^1 dx\; x\,D_{g/p}(x, Q^2) \approx$	0.41	0.47	0.48
u:	$\int_0^1 dx\; x\,D_{u/p}(x, Q^2) \approx$	0.32	0.22	0.20
d:	$\int_0^1 dx\; x\,D_{d/p}(x, Q^2) \approx$	0.16	0.12	0.11
$\bar{u} + \bar{d} + s + \bar{s}$	$\approx$	0.10	0.13	0.14
$c + \bar{c}$	$\approx$	0.009	0.037	0.045
$b + \bar{b}$	$\approx$	0	0.023	0.033
Sum	$\approx$	1.00	1.00	1.00

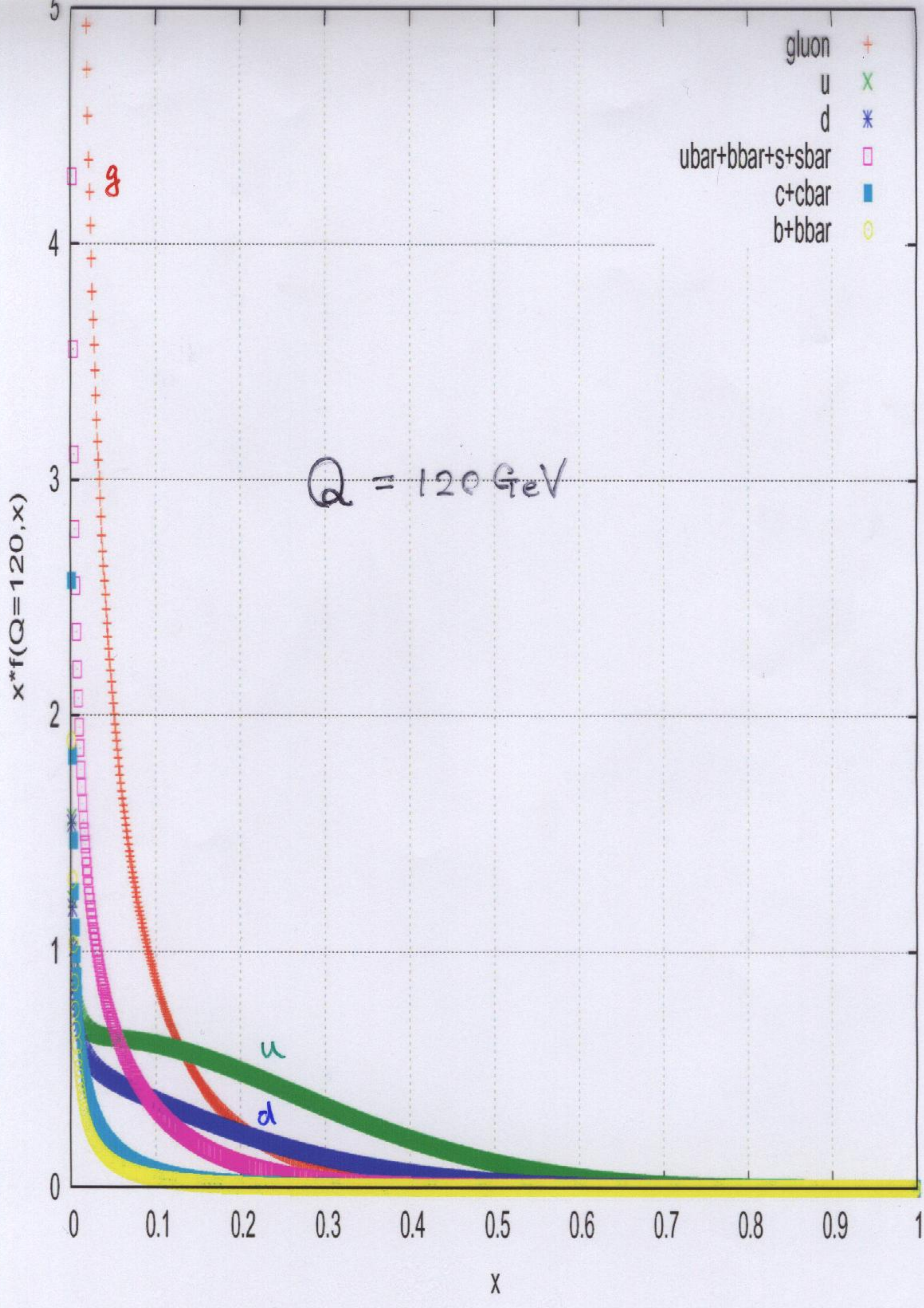
by CTEQ5M1

$$\left.\begin{aligned} &\int_0^1 dx \left[D_{u/p}(x, Q^2) - D_{\bar{u}/p}(x, Q^2) \right] = 2 \\ &\int_0^1 dx \left[D_{d/p}(x, Q^2) - D_{\bar{d}/p}(x, Q^2) \right] = 1 \end{aligned}\right\} \text{valence-quark sum rules}$$

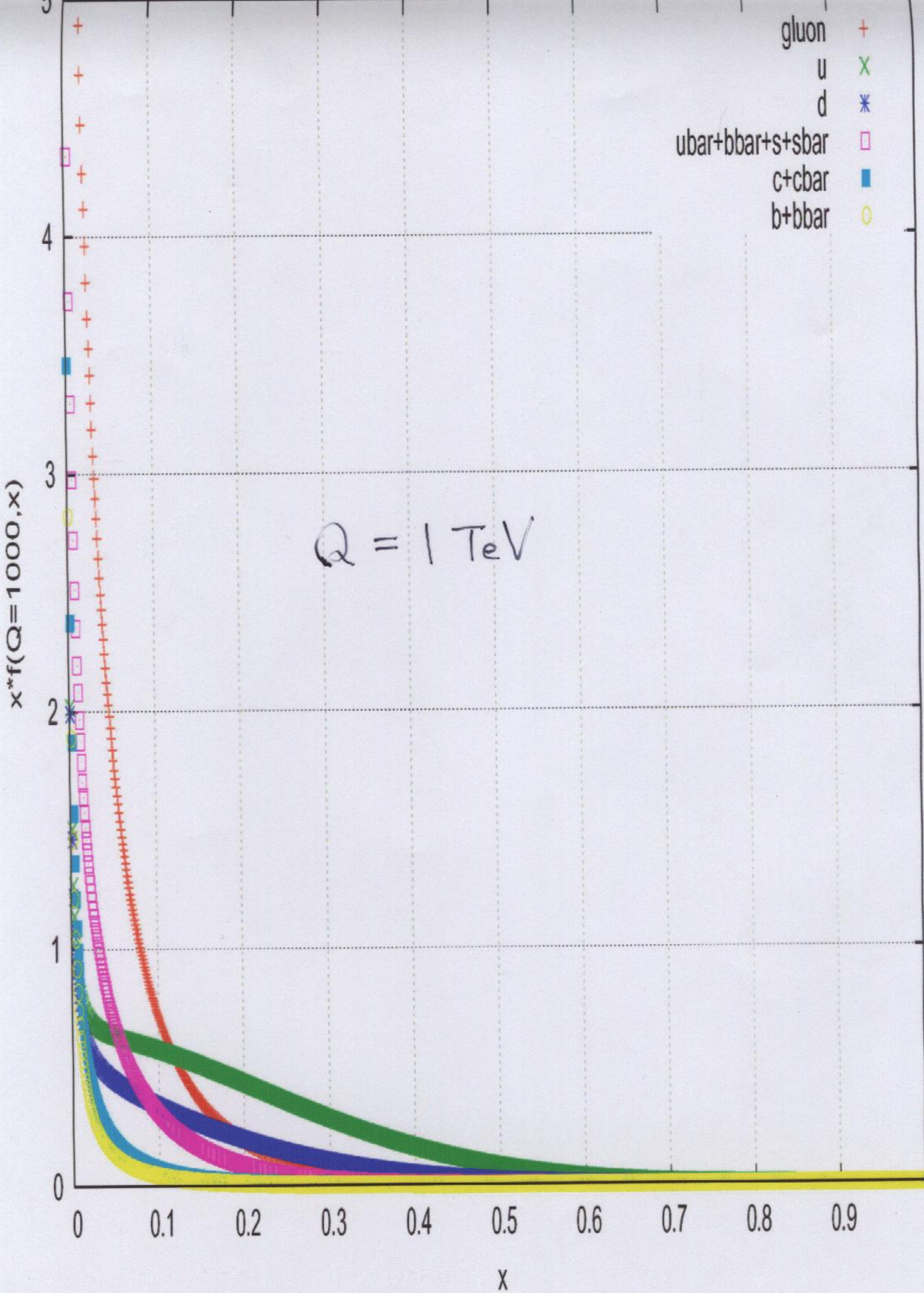





gluon
u
d
ubar+bbar+s+sbar
c+cbar
b+bbar
Q = 1 GeV
g
u
d
x*f(Q=1,x)
x
0
1
2
3
4
5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



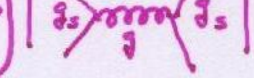
gluon
u
d
ubar+bbar+s+sbar
c+cbar
b+bbar
g
Q = 120 GeV
u
d
x*f(Q=120,x)
x
0
1
2
3
4
5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


gluon
u
d
ubar+bbar+s+sbar
c+cbar
b+bbar
Q = 1 TeV
x*f(Q=1000,x)
x
0
1
2
3
4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

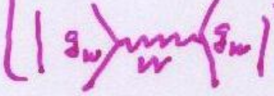
Hard (short-distance) cross section

$2 \to 2$

$$\hat\sigma(ab \to cd) \approx \underbrace{\frac{1}{2\hat s}}_{\text{flux}} \; \underbrace{|M|^2} \; \underbrace{\frac{1}{8\pi}}_{\text{2 body phase space}}$$



$$\Big|\ \ \Big|^2 \sim (g_s^2)^2 = (4\pi\alpha_s)^2 = 16\pi^2\alpha_s^2$$



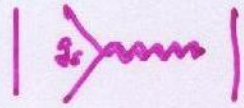
$$\Big|\ \ \Big|^2 \sim (g_w^2)^2 = (4\pi\alpha_w)^2 = 16\pi^2\alpha_w^2$$

$$\approx \frac{\pi}{(1\,\text{TeV})^2} \begin{Bmatrix} \alpha_s^2 \\ \alpha_w^2 \end{Bmatrix} \frac{1}{(\sqrt{\hat s}/\text{TeV})^2}$$

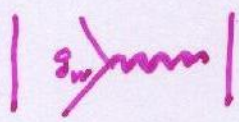
$$\approx \frac{10^3\,\text{fb}}{(\sqrt{\hat s}/\text{TeV})^2} \begin{Bmatrix} \alpha_s^2 \sim 10^{-2} \\ \alpha_w^2 \sim 10^{-3} \end{Bmatrix}$$

$2 \to 1$

$$\hat\sigma(ab \to e) \approx \underbrace{\frac{1}{2\hat s}}_{\text{flux}} \; \underbrace{|M|^2} \; \underbrace{2\pi\delta(sx_1x_2 - m_e^2)}_{\text{1 body phase space}}$$



$$\Big|\ \ \Big|^2 \sim g_s^2\,\hat s = 4\pi\alpha_s \cdot \hat s$$



$$\Big|\ \ \Big|^2 \sim g_w^2\,\hat s = 4\pi\alpha_w \cdot \hat s$$

$$\approx (2\pi)^2 \begin{Bmatrix} \alpha_s \\ \alpha_w \end{Bmatrix} \delta(sx_1x_2 - m^2)$$

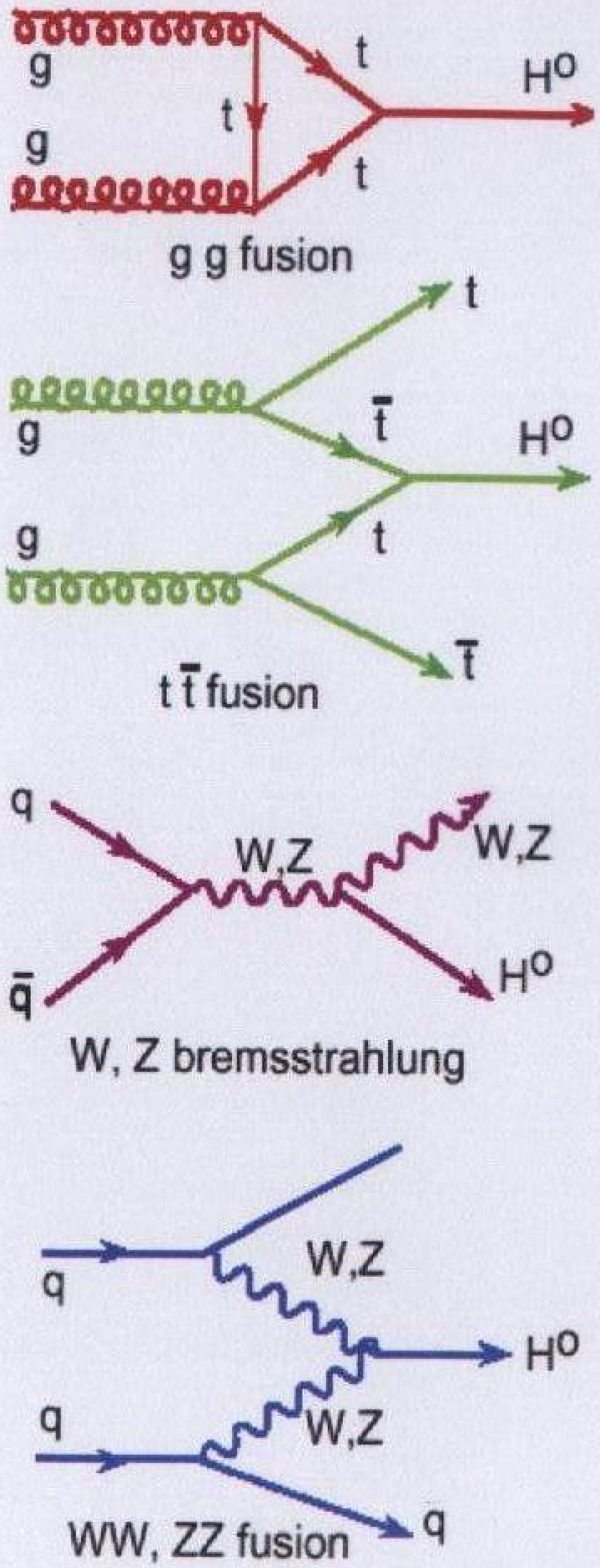
$$= \left(\frac{2\pi}{\sqrt{s} = 14\,\text{TeV}}\right)^2 \begin{Bmatrix} \alpha_s \\ \alpha_w \end{Bmatrix} \delta\left(x_1x_2 - \frac{m^2}{s}\right)$$

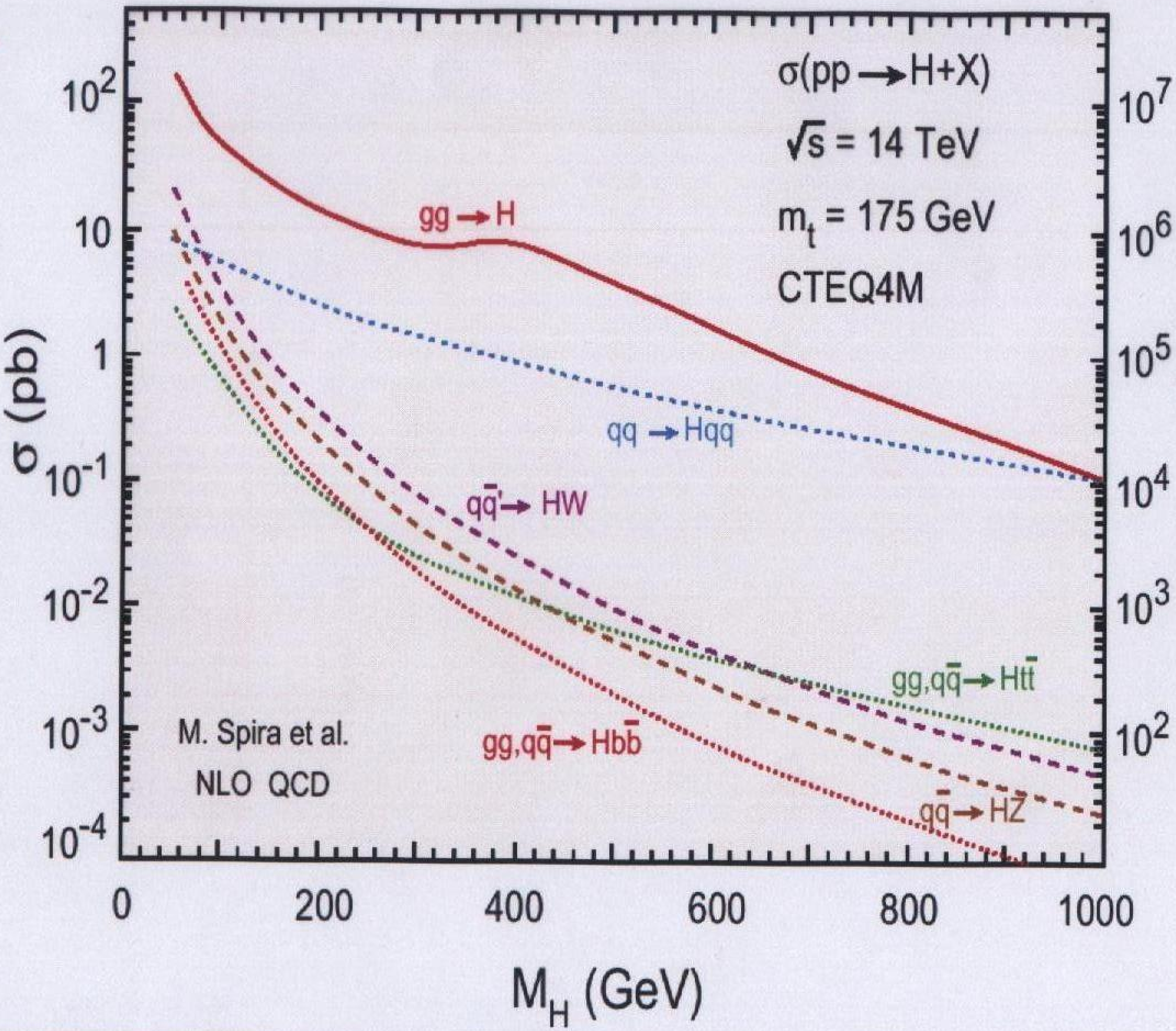
$$\approx 10^5\,\text{fb} \begin{Bmatrix} \alpha_s \sim 0.1 \\ \alpha_w \sim 0.3 \end{Bmatrix} \delta\Big(x_1x_2 - \underbrace{\frac{m^2}{s}}_{=\tau}\Big)$$

[× Branching fraction of $c \to$ observed modes]

6

Higgs Production at LHC





The table of $\left(\frac{dL}{d\tau}\right)_{ab}(\tau, Q^2)$ will help us identify

- the most important channel for $pp \to SX$ (signal)
- the most relevant <u>backgrounds</u> for the signal
- the possible large NLO QCD corrections to the cross section.

Higgs (SM)

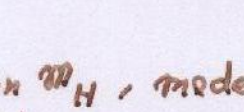
	$\overbrace{\quad S \quad}$		N (noise = B.G.)	S/N $_{m_H = 120\,\mathrm{GeV}}$
$pp \to HX \to b\bar{b}X \to$	$b\bar{b}$	X	$b\bar{b}X$, bjX, jjX, …	—
$\tau^+\tau^- X \to$	$\ell^+\ell^- \not{p}_T$	X	$\tau^+\tau^- X$, $W^+W^- X$, …	—
$\mu^+\mu^- X \to$	$\mu^+\mu^-$	X	$\mu^+\mu^- X$, …	—
$WW^{(*)} X \to$	$\ell^+\ell^- \not{p}_T$	X	$W^+W^- X$, ZX, …	—
$ZZ^{(*)} X \to$	$\ell^+\ell^-\ell^+\ell^-$	X	ZZX, …	—
$\gamma\gamma X \to$	$\gamma\gamma$	X	$\gamma\gamma X$, γjX, jjX, …	✓
$t\bar{t} X \to$	$\ell^+\ell^- b\bar{b} \not{p}_T$	X	$W^+W^- jj$, …	—
$pp \to HVX \to b\bar{b}VX \to$	$b\bar{b}(\ell^+\ell^-)_Z$	X	$b\bar{b}Z$, bjZ, jjZ, …	—
$V = W/Z$ $\tau^+\tau^- VX \to$	$\ell^+\ell^-(\ell^+\ell^-)_Z$	X	$\ell^+\ell^- Z$, $W^+W^- Z$, …	
$WW^* VX \to$	$\ell^+\ell^-(\ell^+\ell^-)_Z$	X	$\ell^+\ell^- Z$, $W^+W^- Z$, …	
$\gamma\gamma VX \to$	$\gamma\gamma(\ell^+\ell^-)_Z$	X	$\gamma\gamma Z$, γjZ, jjZ, …	—
$pp \to Hjj X \to b\bar{b}jjX \to$	$b\bar{b}jj$	X	$b\bar{b}jj$, $bjjj$, $jjjj$, …	—
$\tau^+\tau^- jjX \to$	$\ell^+\ell^- \not{p}_T jj$	X	$\ell^+\ell^- jj$, $W^+W^- jj$, …	✓
$WW^* jjX \to$	$\ell^+\ell^- \not{p}_T jj$	X	$\ell^+\ell^- jj$, $W^+W^- jj$, …	✓
$\gamma\gamma jjX \to$	$\gamma\gamma jj$	X	$\gamma\gamma jj$, γjjj, $jjjj$, …	✓

H production cross sections (depends on m_H, models)

$ab \to H$ $gg \to H$

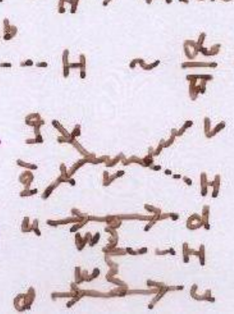
$\sim \frac{\alpha_s}{\pi}\frac{m_t}{v}$ $c\bar{c}, b\bar{b} \to H \sim \frac{m_q}{v}$

$ab \to HV$ $q\bar{q} \to HZ$, $u\bar{d} \to HW^+$



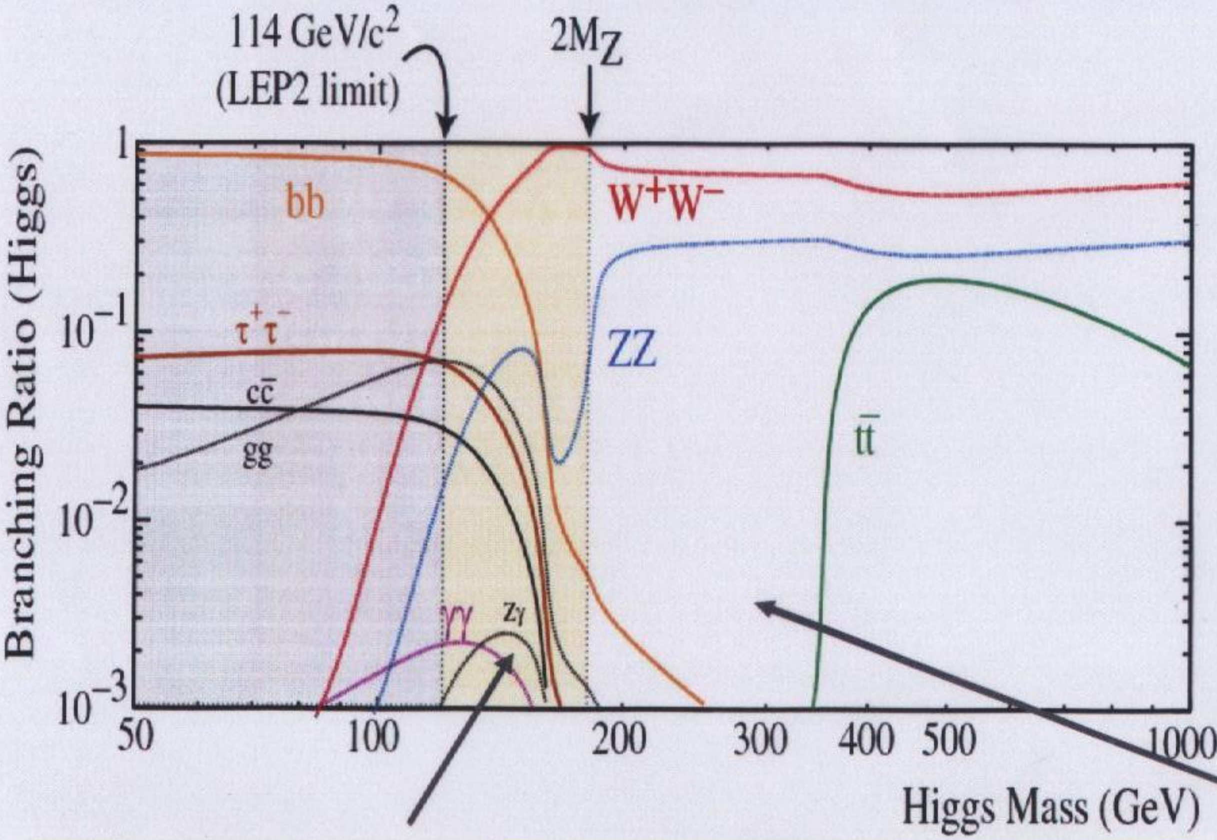
$\sim g_w^2$

$ab \to Hjj$ $ud \to duH$, $qq \to qqH$



$2 \to 3$, $p_T^q \sim p_T^H \sim m_W$, Δy_{gap}.

Search for Higgs at LHC



Dominant BR for $m_H < 2m_Z$:
σ (H → bb) ≈ 20 pb;
σ (bb) ≈ 500 μb
for m(H) = 120 GeV
→ no hope to trigger or extract fully hadronic final states
→ look for final states with ℓ, γ (ℓ = e,μ)

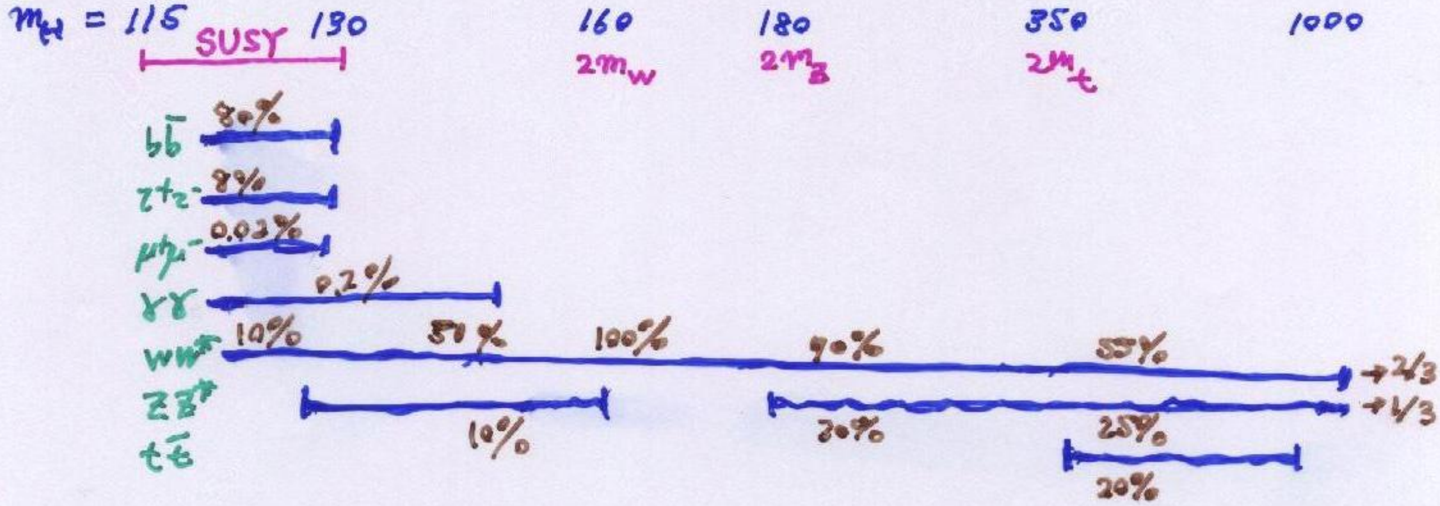
Low mass region: m(H) < 2 m_Z :

H → γγ : small BR, but best resolution
H → bb : good BR, poor resolution: ttH, WH
H → ZZ* → 4ℓ
H → WW* → ℓνℓν or ℓνjj : via VBF
H → ττ : via VBF

m(H) > 2 m_Z :

H → ZZ → 4ℓ
qqH → ZZ → ℓℓ νν
qqH → ZZ → ℓℓ jj
qqH → WW→ ℓνjj

H decay branching fractions (depends on m_H, models)



Signals need high p_T e, μ, γ / high p_T jets / high $\not{p}_T$ } for triggering of events

Noize (backgrounds) should depend on details of signals

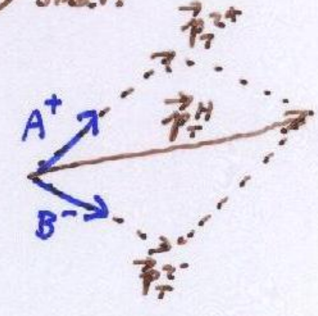
m_H peak: $b\bar{b}$ $\gamma\gamma$ $\mu^+\mu^-$ $ZZ^* \to \ell^+\ell^-\ell^+\ell^-$

$\mu^+\mu^-$, ZZ^* → very small B.R. for $m_H < 130$ GeV ⇒ 100 fb^{-1}/yr

$\gamma\gamma$ ← $\gamma\gamma, \gamma j, jj$ → $S/\sqrt{S+N} \gtrsim 5$ because $P_{\gamma/j} \lll 1$

$b\bar{b}$ ← $b\bar{b}, bj, jj$ → $S/\sqrt{S+N} < 1$ because $P_{b/j}$ not very small!

m_H peak when p_T^H large: $\tau^+\tau^- \to A^+B^-\not{p}_T$



$Z\,\tau^+\tau^- \to (\ell^+\ell^-)_Z\, A^+B^-\not{p}_T$

$jj\,\tau^+\tau^- \to jj\,\ell^+\ell^-\not{p}_T$, $jj\,\ell^\pm\pi^\mp\not{p}_T$, ...

Δy gap of hadron jets $qq \to qqH$ ↳ $\tau^+\tau^-$, $\gamma\gamma$ ✓, WW^* ✓

10 fb^{-1}/yr $\ell^+\ell^-\not{p}_T$, $\ell^\pm\pi^\mp\not{p}_T$, ... ✓

$\tan^2\beta \lesssim (50)^2$ enhancement $gg \to b\bar{b}H$ ↳ $b\bar{b}$, $\tau^+\tau^-$

Comments on the Higgs search @ the LHC

Inclusive modes (m_H peak search)

$H \to \gamma\gamma$ $\quad B \sim 10^{-3}$ $\quad (m_H < 140\,\text{GeV})$

$J \neq 1$ $\quad \sigma \cdot B \sim 70\,\text{fb}$ $\quad S \sim 700$ $(L = 10\,\text{fb}^{-1})$

Yang's Th.

$$\left(\frac{d\sigma}{dm_{\gamma\gamma}}\right)_{q\bar{q}\to\gamma\gamma} \sim \underbrace{200\,\text{fb/GeV}}$$

a few GeV resolution!

$$\left(\frac{d\sigma}{dm_{\gamma j}}\right)_{qg\to q\gamma} \sim \underbrace{2\times10^{5}\,\text{fb/GeV}}$$

$P_{\gamma/j} < 10^{-3}$ rejection needed!

$$\left(\frac{d\sigma}{dm_{jj}}\right)_{gg\to gg} \sim \underbrace{6\times10^{8}\,\text{fb/GeV}}$$

$(P_{\gamma/j})^2 < 10^{-6}$ rejection

If $B \sim (200\,\text{fb/GeV}) \times \underbrace{3\,\text{GeV}}_{\text{resolution}} \times \underbrace{3}_{\text{fakes}} \times 10\,\text{fb}^{-1}$

$B \sim 18000$

$$S/\sqrt{B+S} = 700/\sqrt{18700}$$

$$\simeq 700/137$$

$$\simeq 5.1$$

$H \to \mu^+\mu^-$ $\quad B \sim 10^{-5}$ $\quad (m_H < 130\,\text{GeV})$

$\sigma \cdot B \sim 0.7\,\text{fb}$ $\quad S \sim 7$ $(L = 10\,\text{fb}^{-1})$

$S \sim 70$ $(L = 100\,\text{fb}^{-1})$

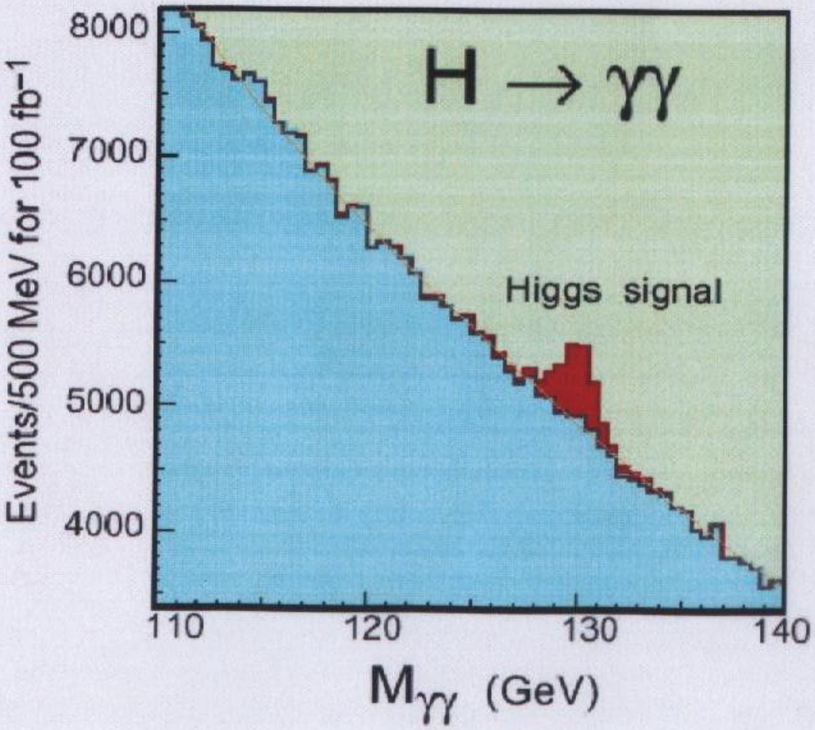
B ?

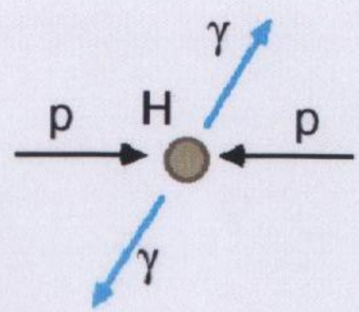
Light Higgs search (1)

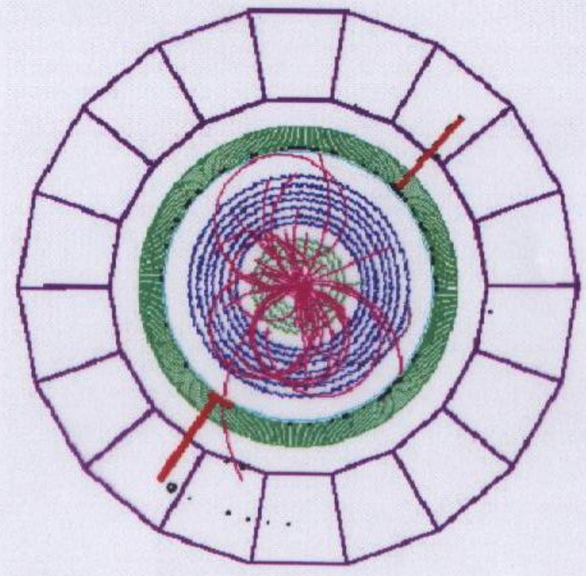
If $m_h < 140$ GeV : $gg \rightarrow h \rightarrow \gamma\gamma$ most promising channel, although BR only 10^{-3} …

Full Analysis

→ motivation for high resolution ECAL ($PbWO_4$ crystals: 1% at 100 GeV)







$H \to ZZ^{(*)} \to \mu^+\mu^-\mu^+\mu^-$ B ~ significant for $m_H > 180$ GeV

J, CP

$\sigma \cdot B \gtrsim 10$ fb $m_H = 180 - 400$ GeV $S > 100$

$\sigma \cdot B \gtrsim 1$ fb $m_H = 130 - 800$ GeV $S > 10$

($L = 10\,fb^{-1}$)

If $m_H = 180 - 400$ GeV, $S = 10$ events @ $L = 1\,fb^{-1}$.

⇒ early discovery

⇒ early exclusion

Typical coverage of the detectors

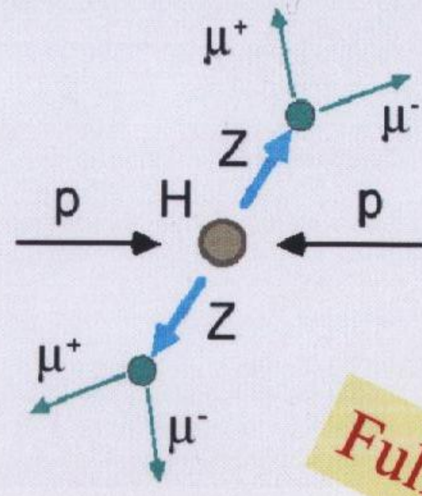
$|\eta_{\gamma, e, \mu}| < 2.5$

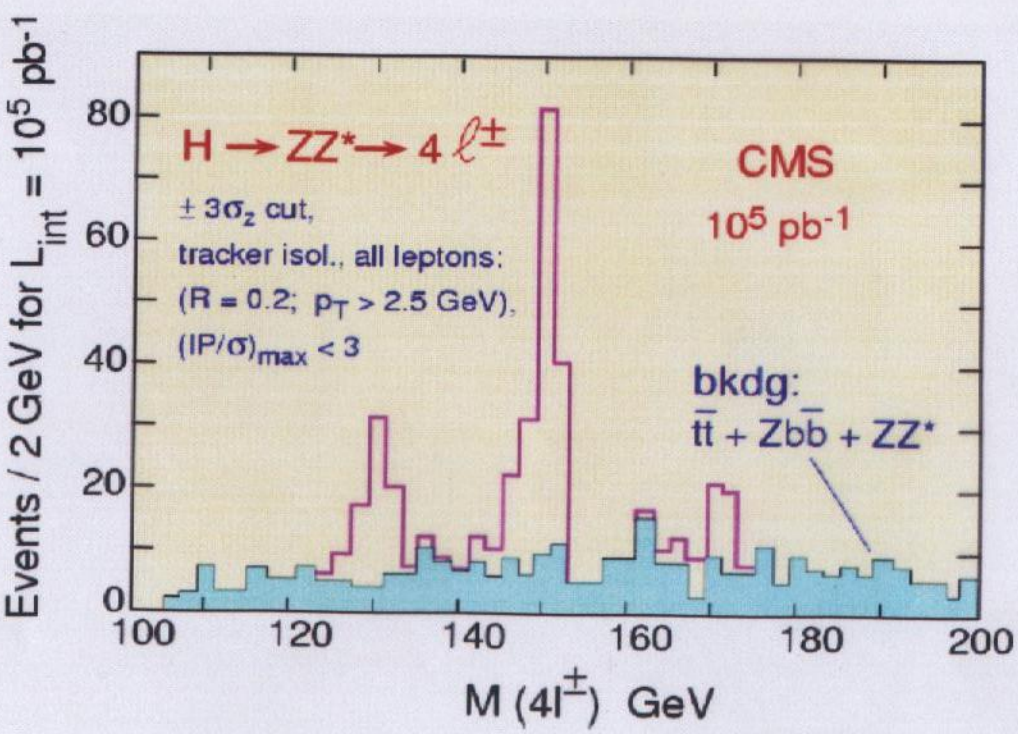
$p_{T\,\gamma, e, \mu} > 30$ GeV   (smaller p_T for μ for b-jet ID)

$|\eta_j| < 5$

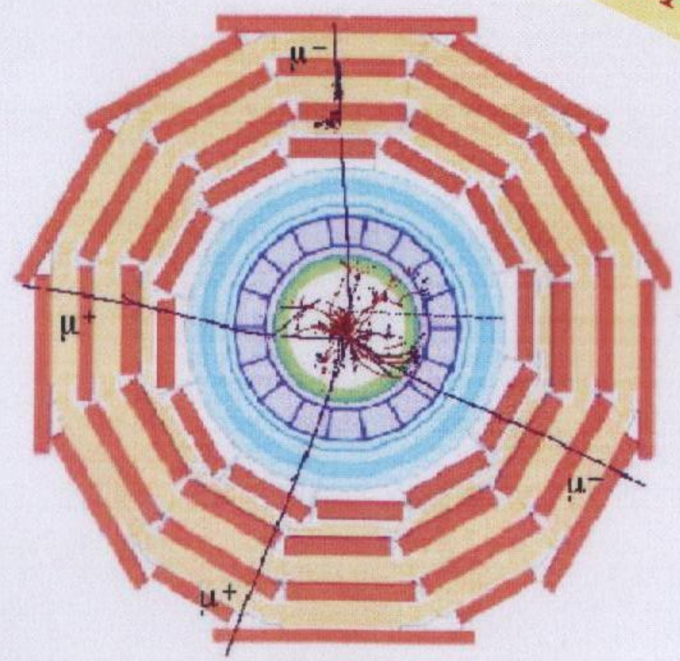
$H \to ZZ^{(*)} \to 4$ leptons

- clean signal, mass resolution 1%
- mass range: 130 GeV < M_H < 500 GeV





Full Analysis



$l\,(= e, \mu) + \text{jets}$

$$qq \to \underbrace{q'q'}\, H$$

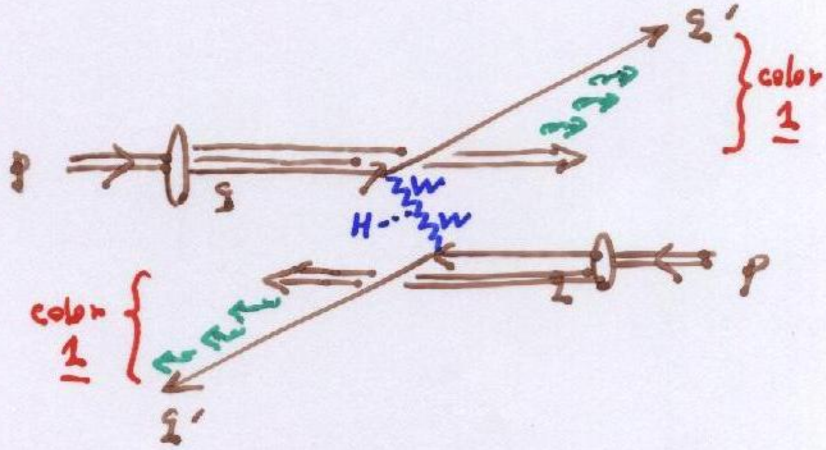
$$H \to \begin{cases} \gamma\gamma & m_{\gamma\gamma} \text{ peak} \\ \tau^+\tau^- \to l^\pm \pi^\mp \vec{\not{p}}_T & m_{\tau^+\tau^-} \text{ peak} \\ WW^* \to l^+ l^- \vec{\not{p}}_T & m_T(l^+l^-, \not{p}_T) \text{ peak} \end{cases}$$

2 forward jets

$\left(\begin{array}{c}\text{very energetic} \\ p_T \sim m_W/2\end{array}\right)$

+

rapidity gap



$$gg \to \underbrace{t\,\bar{t}}\; H, \quad H \to b\bar{b}$$

$$t\bar{t} \to \underbrace{l^\pm \not{p}_T}_{W}\; b\bar{b}\; \underbrace{jj}_{m_W}$$

Look for m_{jj} peak

in the $(t\bar{t}) + \underbrace{2j}_{\text{b-selection}}$ events

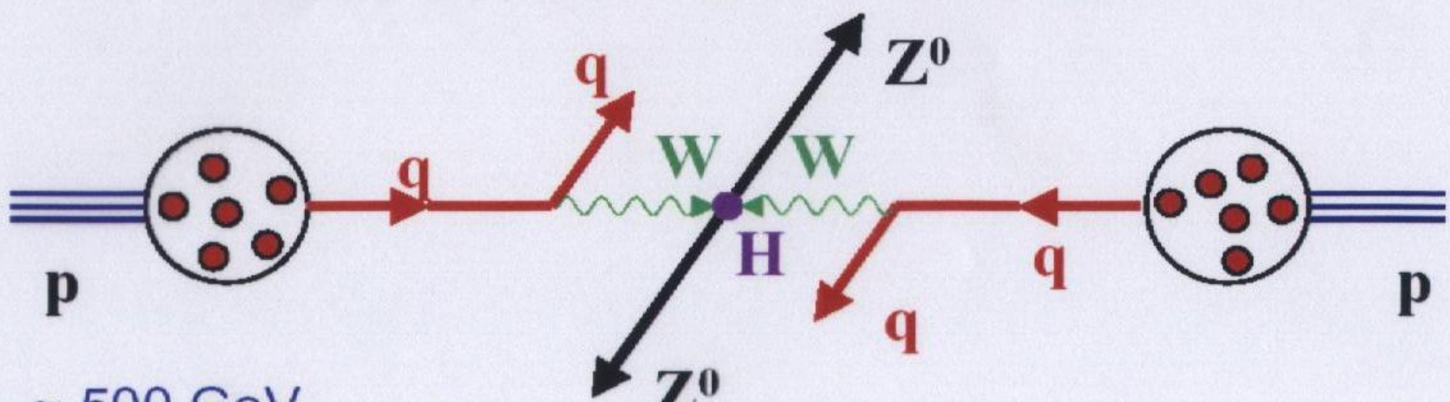
$$(l^\pm, \gamma, \not{p}_T) + 2j,\ 3j,\ \cdots,\ 6j$$

SM BG with $\begin{cases} \text{valid normalization} & \text{NLO, NNLO (Inclusive)} \\ \text{valid kinematical correlations} & \text{Exact M.E.} \end{cases}$

Design goals of the LHC

Hadron colliders are broad-band exploratory machines

May need to study W_L-W_L scattering at a cm energy of ~ 1 TeV



- ⇨ E_W ~ 500 GeV
- ⇨ E_{quark} ~ 1 TeV
- ⇨ E_{proton} ~ 6 TeV

⇨ pp collisions at 7 + 7 TeV ⟶ **14 TeV collider**

Event Rate = L.σ.BR ⟶ **$L \sim 10^{34}\ cm^{-2}\ s^{-1}$**

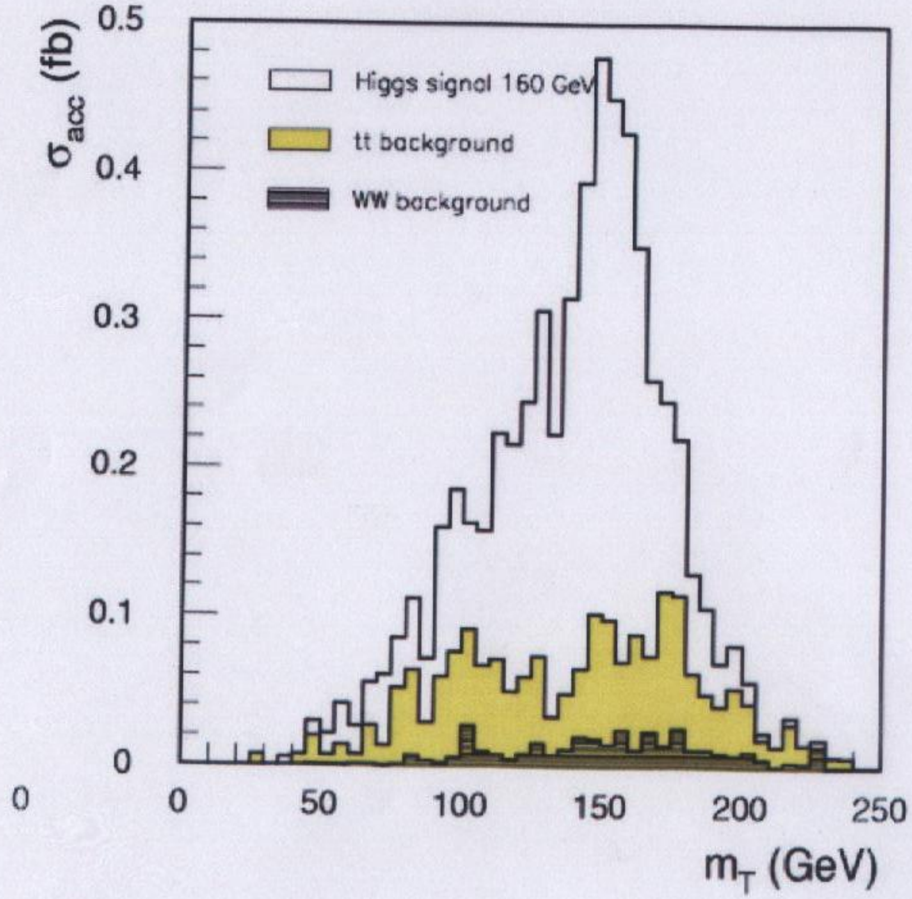
e.g. H(1 TeV) → ZZ → 2e+2μ or 4e or 4μ

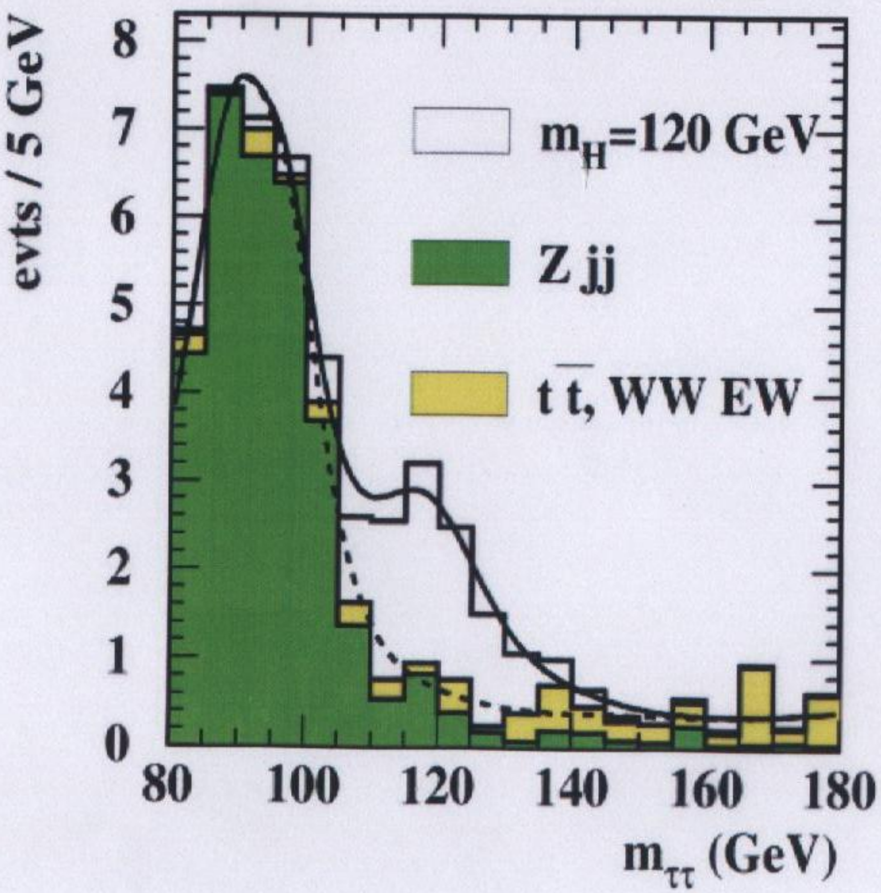
For L ~10^{34}, Evts/yr = **10^{34}** $10^{-37}.10^{-3}.10^{7}$ ~ 10 /yr !!

Search for Higgs at LHC

$qq\,H \rightarrow qq\,WW^*$
$\rightarrow qq\,l\,\nu\,l\,\nu$

$qq\,H \rightarrow qq\,\tau\,\tau$
$\rightarrow qq\;l\,\nu\,\nu\,l\,\nu\,\nu$
$\rightarrow qq\;l\,\nu\,\nu\,h\,\nu$





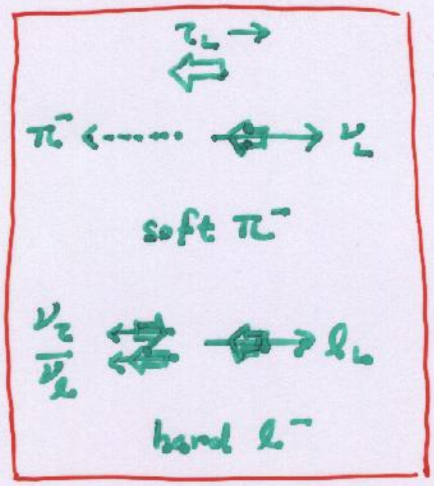
$\boxed{J_H = 0 \text{ @ LHC}}$

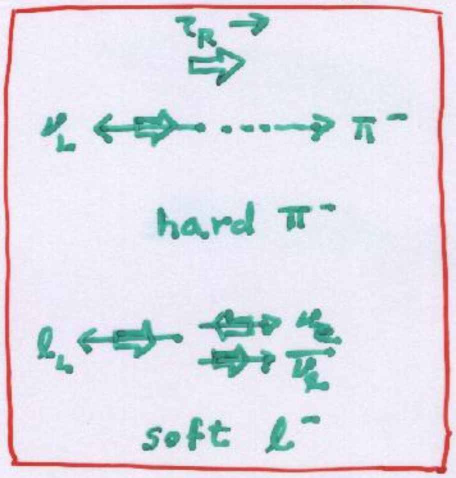
$H \to \tau^+\tau^-$ vs $Z \to \tau^+\tau^-$

$$H \to \begin{cases} \tau_L^-\,\tau_L^+ & (\tau_L\,\bar{\tau}_R) \\ \tau_R^-\,\tau_R^+ & (\tau_R\,\bar{\tau}_L) \end{cases} \qquad Z \to \begin{cases} \tau_L^-\,\tau_R^+ & (\tau_L\,\bar{\tau}_L) \\ \tau_R^-\,\tau_L^+ & (\tau_R\,\bar{\tau}_R) \end{cases}$$

chirality flip — chirality conservation

τ_L vs τ_R



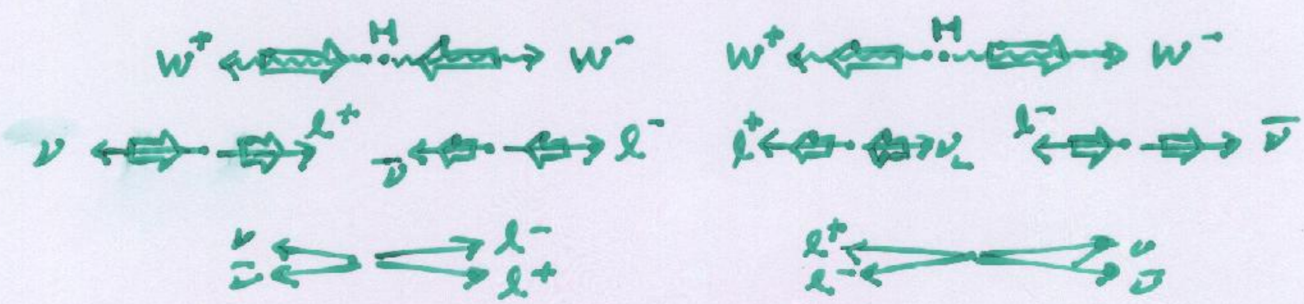


$$Z \to \begin{cases} \tau_L\,\bar{\tau}_L & \text{soft } \pi^\pm \times \text{hard } \ell^\mp \\ \tau_R\,\bar{\tau}_R & \text{hard } \pi^\pm \times \text{soft } \ell^\mp \end{cases}$$

$$H \to \begin{cases} \tau_L\,\bar{\tau}_R & \text{soft } \pi^\pm \times \text{soft } \ell^\mp \\ \tau_R\,\bar{\tau}_L & \text{hard } \pi^\pm \times \text{hard } \ell^\mp \end{cases}$$

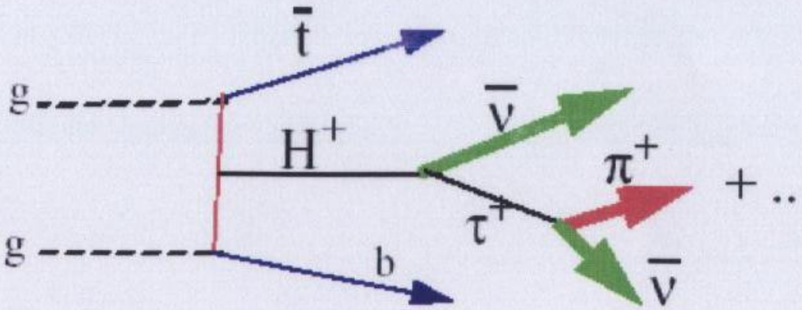
$\Leftarrow$ high acceptance

$H \to W^- W^{+*} \to \ell^+\ell^-\nu\bar{\nu}$



small $m_{\ell^+\ell^-}$, large $\not{p}_T$

$H^{\pm} \rightarrow \tau\nu$



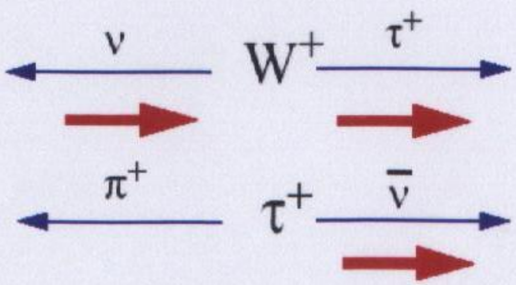
Strategy:

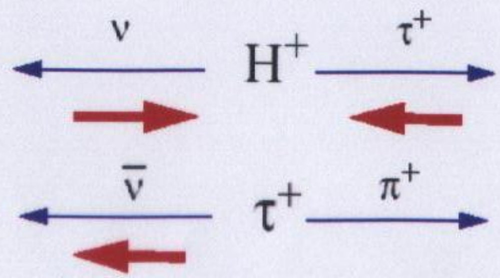
- reconstruct hadronic τ
- reconstruct hadronic top ($t \rightarrow bjj$)

Main backgrounds: $t\bar{t}$, Wtb, W + jets

W and $H^{\pm}$ have different spin $\rightarrow$ exploit τ polarization effects !!

(*D.P. Roy*)





$\rightarrow$ harder pions from $H^{\pm}$ …

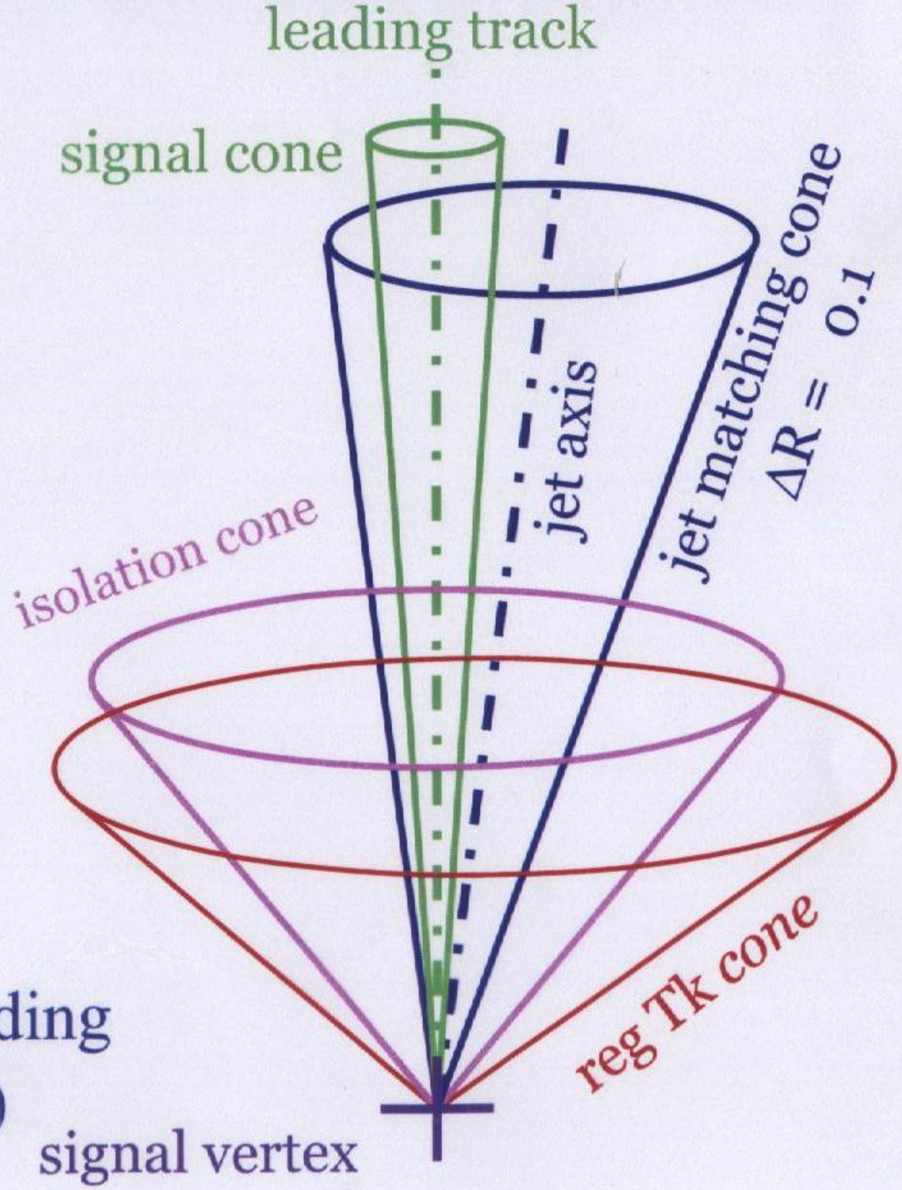
Tau-jet selection

- remember τ branching ratios:
  - $\tau \rightarrow l\, \nu_l\, \nu_\tau$: 35%
  - $\tau \rightarrow \pi^\pm + n\, \pi^0$'s : 50%
  - $\tau \rightarrow 3\pi^\pm + n\, \pi^0$'s : 15%

- prefer hadronic decays (for mass rec.) but QCD background is huge

CMS has developed
dedicated τ trigger for this!!

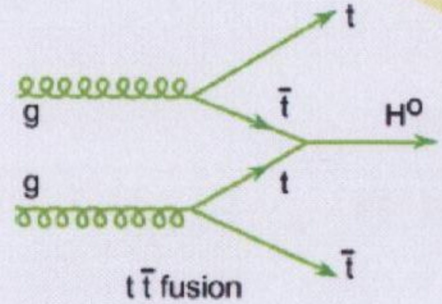
→ look for narrow jet (L1) with leading charged track ($\pi^\pm$) (L3)



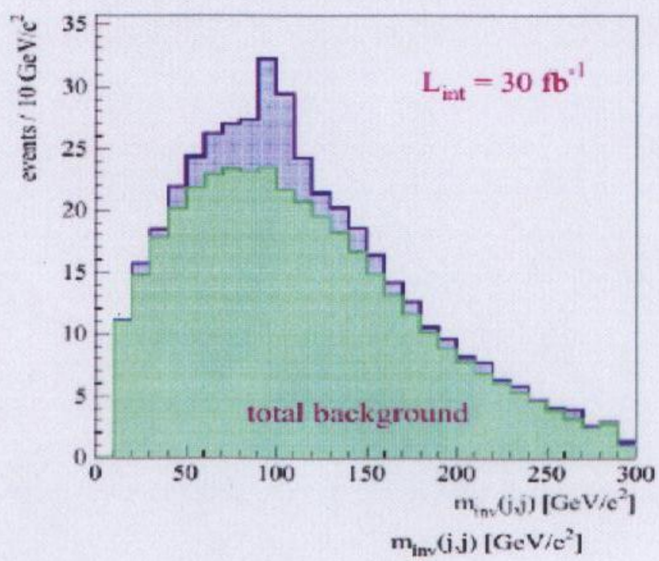
Light Higgs search (2)

Full Analysis

- $H \to b\bar{b}$ in $t\bar{t}H$ production
  - σ.Br=300 fb
  - Backgrounds:
    - ➔ Wjjjj, $Wjjb\bar{b}$
    - ➔ $t\bar{t}jj$
    - ➔ Signal (combinatorics)
  - Tagging the t quarks helps a lot
    - ➔ Trigger: $t \to b(e/\mu)\nu$
    - ➔ Reconstruct both t quarks
  - In mass region $90GeV<M(b\bar{b})<130GeV$, S/B =0.3



$t\bar{t}H^0$: $S + B\,(100\;GeV)$



Discovery of new physics @ LHC needs

very exotic signals e.g. extremely long lived heavy charged particles ($\tilde{\tau} \to \tau \tilde{G}$)

$\underline{S} / \sqrt{N+S} > 5$ over the SM B.G.

$\left(\begin{array}{l} \text{high } p_T \text{ isolated } \gamma, e, \mu \\ \cancel{p_T}, \; p_{Tj} \text{ large} \end{array} \right)$

$(\gamma, e, \mu)'_s + \cancel{p_T} + nj$

Urgent & most important $\Rightarrow$

$$\boxed{\begin{array}{l} (\gamma, Z, W) + nj \\ (\gamma\gamma, \gamma Z, \gamma W, ZW, ZZ, WW) + nj \\ t\bar{t} + nj \end{array}}$$

Both the normalization and the kinematical correlations among all the final state particles should be valid.

NLO, NNLO

inclusive

$\left(\begin{array}{c} V + X \\ VV + X \\ t\bar{t} + X \end{array} \right)$

c.f. $qq \ell\nu + X$

by J-D-Z

m_{ej}, m_{ejj}, m_{jj}, m_{jjj}, …

$y_e - y_j$, $y_{j_1} - y_{j_2}$, …

R_{ej}, $R_{j_1 j_2}$, …

….

$\Downarrow$

Matching of the exact ME & Shower MC

kinematical correlations

$\sigma_{1j} : \sigma_{2j} : \sigma_{3j} \cdots$

$\Sigma \sigma_{nj} = \sigma_{LO}$

NLO ?

c.f. CKKW; JHEP 0111, 063 (2001) SHERPA

MLM : JHEP 07, 001 (2003) ALPGEN

Strategy for understanding the SM BG for new physics signals

		$0.1\ fb^{-1}$	$1\ fb^{-1}$	$10 fb^{-1}$
$\sigma(p_{T\gamma} > 30\,GeV)$	$\sim 20nb$	2×10^6	2×10^7	2×10^8
$\sigma(W\to\ell\nu)$	$\sim 20nb$	2×10^6	2×10^7	2×10^8
$\sigma(Z\to\ell\bar{\ell})$	$\sim 3nb$	3×10^5	3×10^6	3×10^7
$\sigma(t\bar{t}\to\ell\nu b\bar{b}jj)$	$\sim 0.5nb$	5×10^4	5×10^5	5×10^6

Inclusive distributions $\frac{d\sigma}{dy\,dp_T}$ (y, p_T of $\gamma, W, Z, t\bar{t}$)

$\Rightarrow$ compare with NLO QCD predictions

$\Rightarrow$ adjust K factors, PDF's, scales (μ, Q), etc

$\Downarrow$

for a given region of (y, p_T)

study 1j, 2j, 3j, 4j, ...

and correlations ($V+j_1$, $V+j_2$, $V+j_1+j_2$, j_1+j_2 ...)

$\Downarrow$

adjust parameters of the shower MC

which has built-in matching of ME + SMC

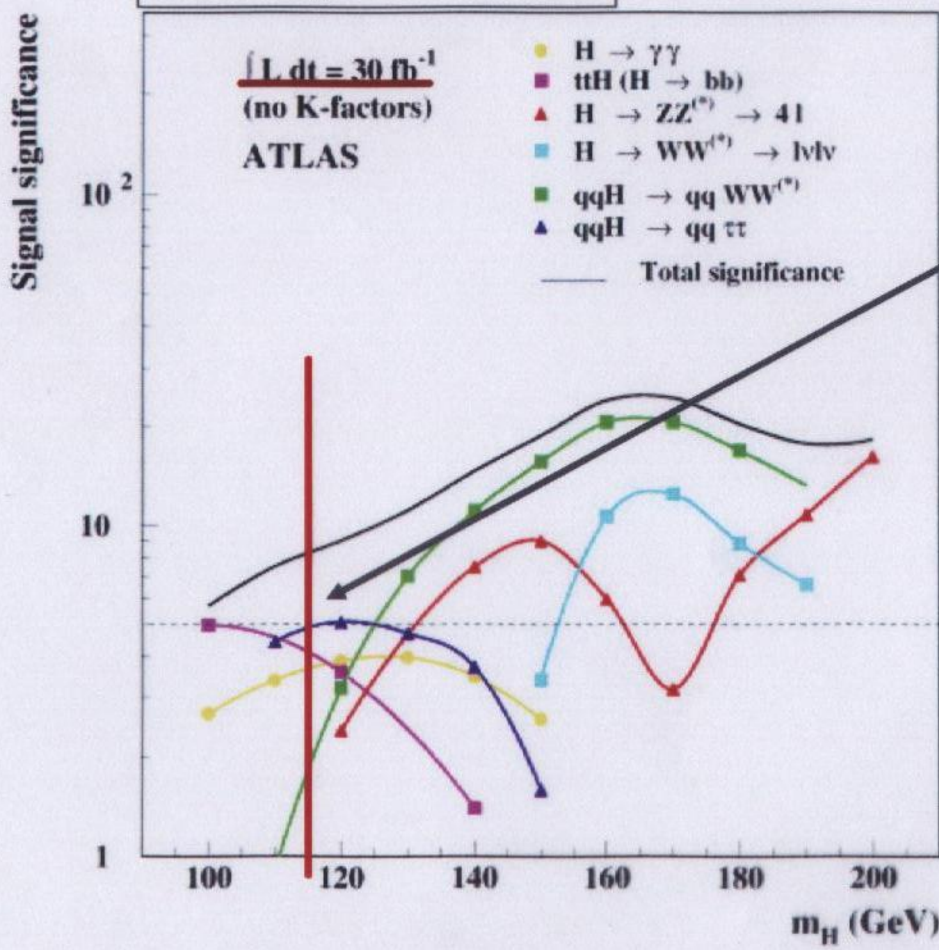
otherwise it is impossible to adjust all the important correlations

Only after this exercise, $\Downarrow$

we can Extrapolate to the Signal region!

Higgs Discovery Potential at LHC

LEP : m_H > 114.1 GeV



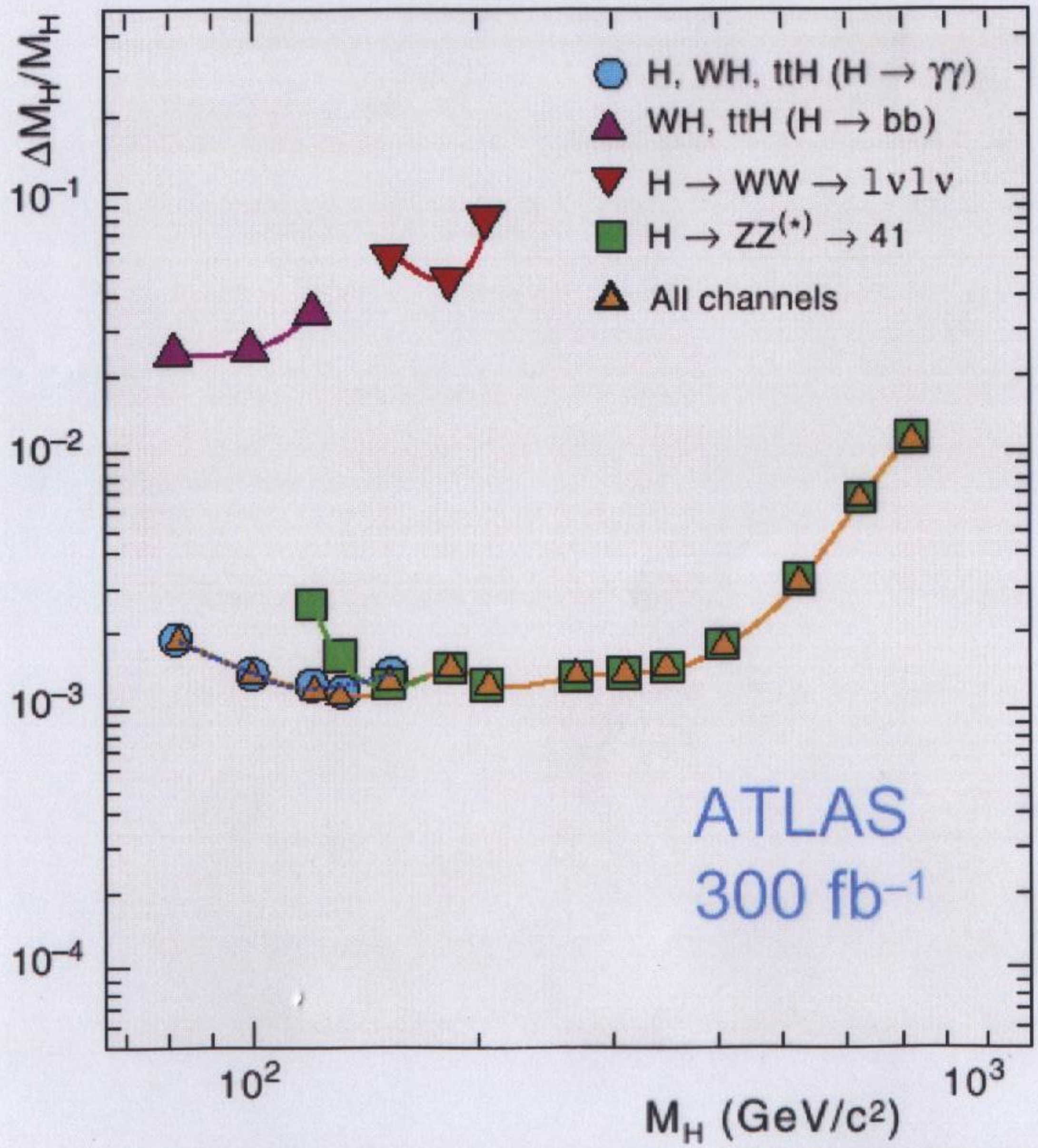
$m_H \sim 115$ GeV

10 fb^{-1}

	$H \to \gamma\gamma$	$ttH \to ttbb$	$qqH \to qq\tau\tau$ ($\ell\ell + \ell$-had)
S	150	15	~ 10
B	3900	45	~ 10
S/B	0.04	0.33	
Sig.	2.4	2.1	3.5
CLb	9×10^{-3}	2×10^{-2}	4×10^{-3}

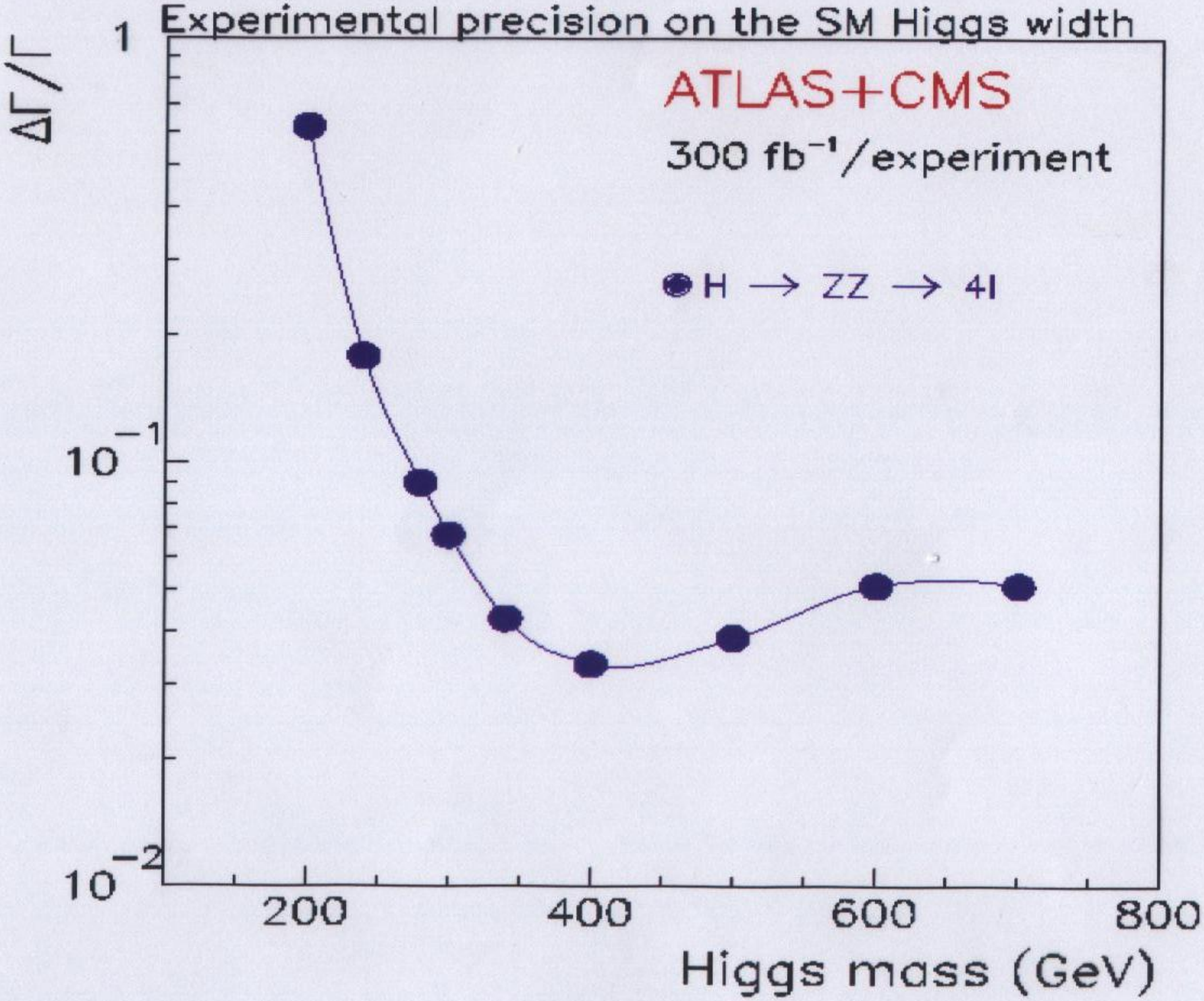
Total S/ $\sqrt{B}$ for 10 fb^{-1} and complete detector: ~ 4.2 σ

Higgs mass measurement

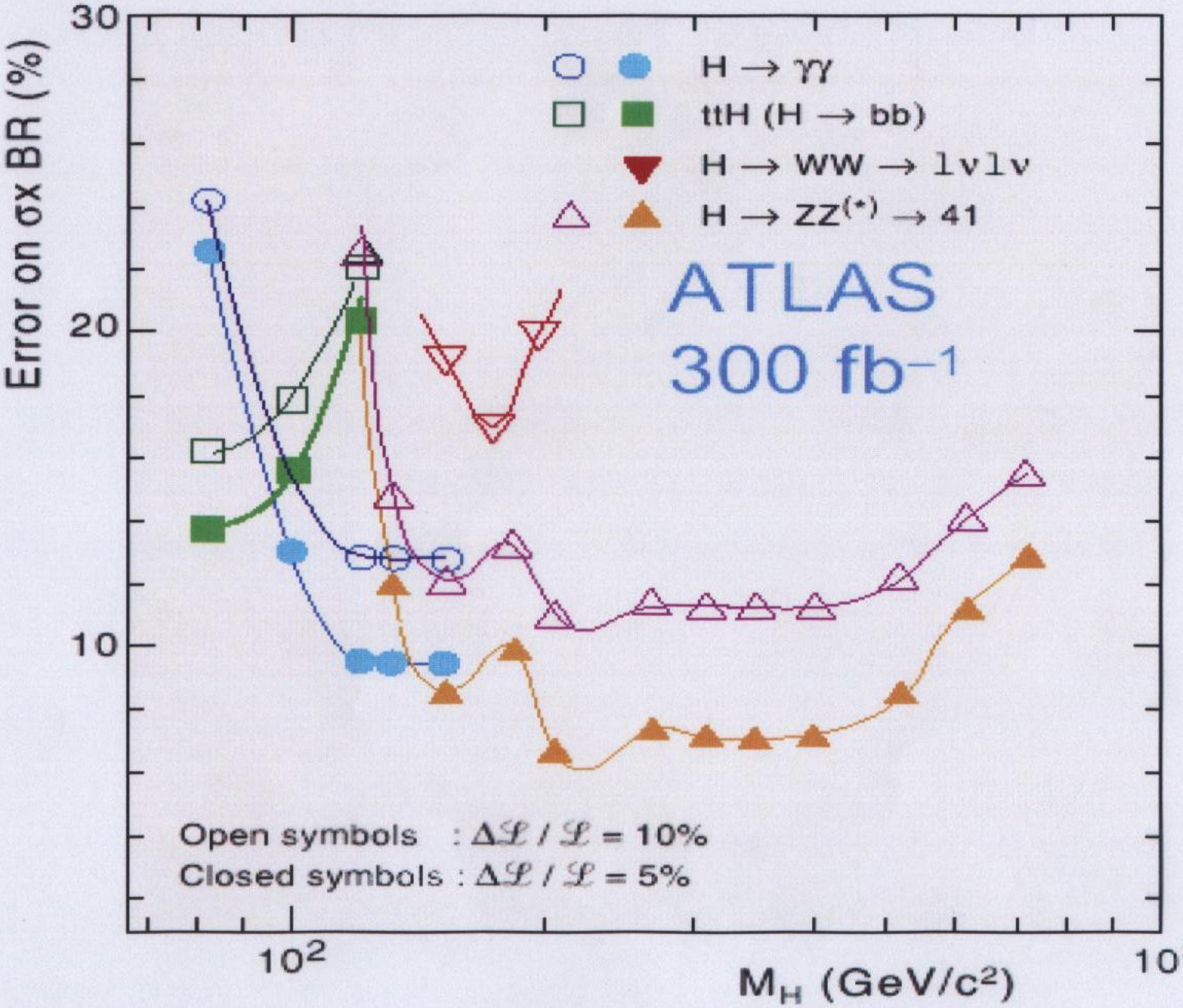


Higgs boson mass can be measured with a precision of 0.1% over a large mass range (130 - ~450 GeV / c^2)

SM Higgs Decay Width



Higgs Branching Fractions



What I would like to encourage you to do now

in order to prepare yourself for the LHC era

1. Try to imagin what kind of new physics should be in the TeV region.
   [physics that breaks the $SU(2)_L \times U(1)_Y$ symmetry]

2. " what kind of signals we should expect at the LHC.

3. " what kind of backgrounds we should face before the signals.

4. " if there is a way to beat the backgrounds for the discovery.
   [or, for constraining the new physics models.]

5. Try to examine if there are hints or constraints on the new physics models from the other experiments/observations such as

   - precision electroweak physics — $S, T, U, (g-2)_\mu, \cdots$
   - FCNC processes — K, D, B rare decays, mixings, $\mu \to e\gamma$, $\tau \to \mu\gamma$, $e \leftrightarrow \mu, \cdots$
   - $\cancel{CP}$ observables — K, B decays, EDM's, ...
   - $\cancel{B}$ constraints — p, n decays, n-$\bar{n}$ oscillation, ...
   - astrophysics/cosmology — Dark Matter, Nucleosynthesis, Baryogenesis, ...

6. New observation ?, or, go back to 1.