Lecture II: Higgs Physics at Colliders

A. Higgs Boson Decay

1. Decay to fermions
2. Decay WW, ZZ
3. Decay through loops

B. Higgs Boson Production at the LHC

1. The leading channels
2. The search strategies
3. Signal characteristics

C. Higgs Boson Production at e^+e^- colliders

D. Higgs Boson Production at a muon collider

Pre-requisite formulae:

For a $2 \to n$ scattering process:

$$\sigma(ab \to 1 + 2 + ...n) = \frac{1}{2s} \overline{\sum} |\mathcal{M}|^2 \, dPS_n,$$

$$dPS_n \equiv (2\pi)^4 \, \delta^4 \left(P - \sum_{i=1}^{n} p_i \right) \Pi_{i=1}^{n} \frac{1}{(2\pi)^3} \frac{d^3\vec{p}_i}{2E_i},$$

$$s = (p_a + p_b)^2 \equiv P^2 = \left(\sum_{i=1}^{n} p_i \right)^2,$$

where $\overline{\sum} |\mathcal{M}|^2$: dynamics (dimension $4 - 2n$);

dPS_n: kinematics (Lorentz invariant, dimension $2n - 4$.)

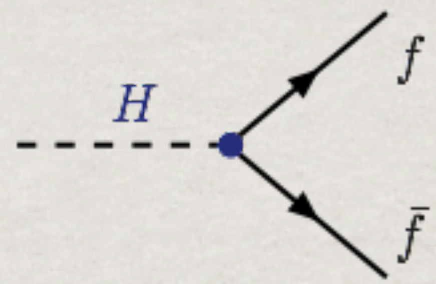
For a $1 \to n$ decay process, the partial width in the rest frame:

$$\Gamma(a \to 1 + 2 + ...n) = \frac{1}{2M_a} \overline{\sum} |\mathcal{M}|^2 \, dPS_n.$$

$$\tau = \Gamma_{tot}^{-1} = (\sum_f \Gamma_f)^{-1}.$$

A. Higgs Boson Decay§

1. Decay to fermions:



$$\Gamma_{\rm Born}(A \to f\bar{f}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H\, m_f^2\, \beta_f$$

$$\Gamma = g^2\ \frac{dPS_2}{2m}\ \sum |M|^2 \propto \frac{g^2}{4\pi}\ m\ \beta^{2\ell+1}$$

The largest higher-order effect is the quark running mass:

$$\begin{aligned} \bar{m}_Q(\mu)_{LO} &= \bar{m}_Q(m_Q)\left(\frac{\alpha_s(\mu)}{\alpha_s(m_Q)}\right)^{\frac{2b_0}{\gamma_0}} \\ &= \bar{m}_Q(m_Q)\left(1 - \frac{\alpha_s(\mu)}{4\pi}\ln\left(\frac{\mu^2}{m_Q^2}\right) + \cdots\right) \end{aligned}$$

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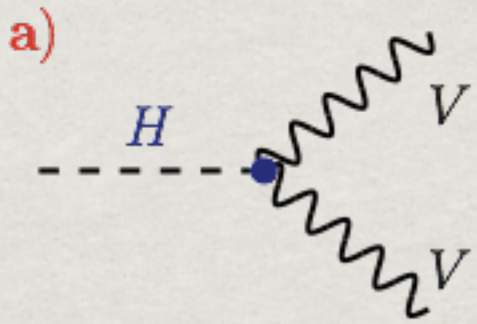
A. Higgs Boson Decay§

2. Decay to WW,ZZ:



$$\Gamma(H \to VV) = \frac{G_\mu M_H^3}{16\sqrt{2}\pi}\,\delta_V\,\sqrt{1-4x}\,(1-4x+12x^2)\ , \quad x = \frac{M_V^2}{M_H^2}$$

$$\Gamma = g^2\ \frac{dPS_2}{2m}\ \sum |M|^2 \propto \frac{g^2}{4\pi}\ m\ \beta^{2\ell+1}$$

The unusual M^3 dependence is due to the V_L: M_H/M_V.

Exercise 8:

Calculate the Higgs decay to polarized pairs V_TV_T, V_LV_T, and V_LV_L.

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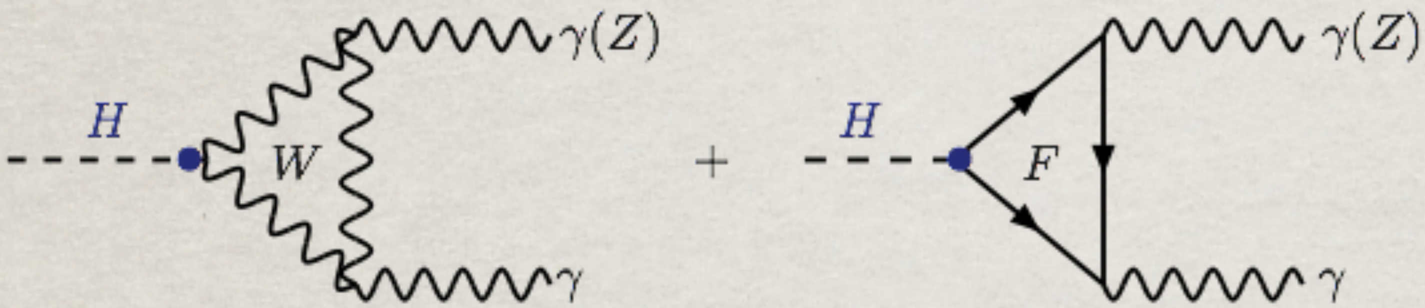
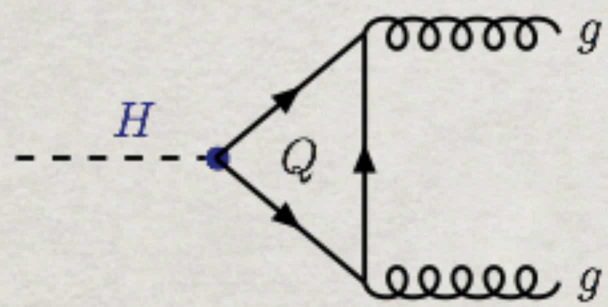
A. Higgs Boson Decay§

3. Decay through loops:

a)



b)



Sensitive to new charged (Q,L), colored (Q) heavy states in loops.

$$\Gamma(H\to\gamma\gamma)=\frac{G_F\alpha^2M_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c^f Q_f^2 A_f^H(\tau_f)+A_W^H(\tau_W)\right|^2$$

$$\Gamma(H\to\gamma Z)=\frac{G_F^2M_W^2\alpha M_H^3}{64\pi^4}\left(1-\frac{M_Z^2}{M_H^2}\right)^3\left|\sum_f A_f^H(\tau_f,\lambda_f)+A_W^H(\tau_W,\lambda_W)\right|^2$$

$$\Gamma(H\to gg)=\frac{G_F\alpha_s^2M_H^3}{36\sqrt{2}\pi^3}\left|\frac{3}{4}\sum_q A_q^H(\tau_q)\right|^2$$

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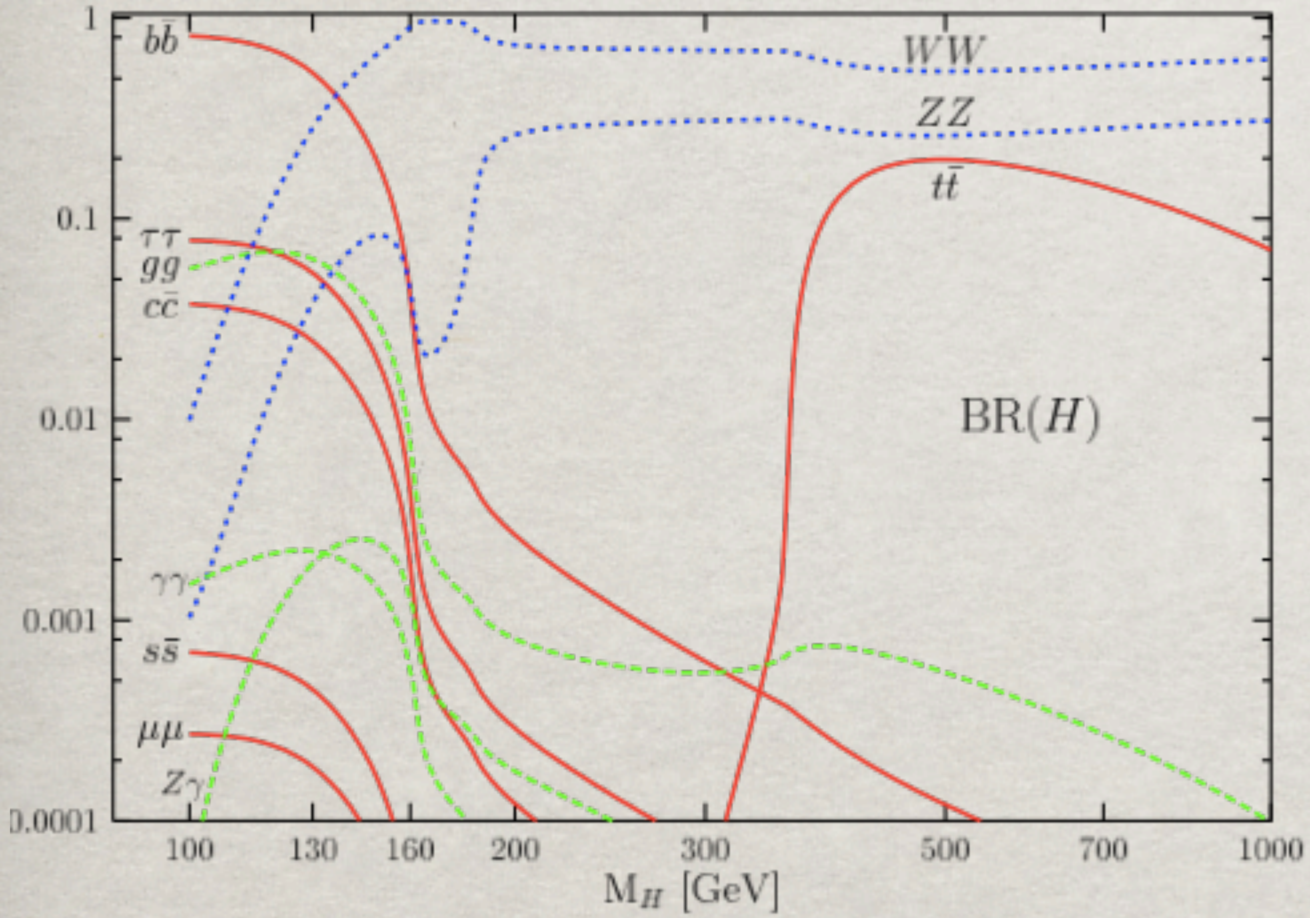
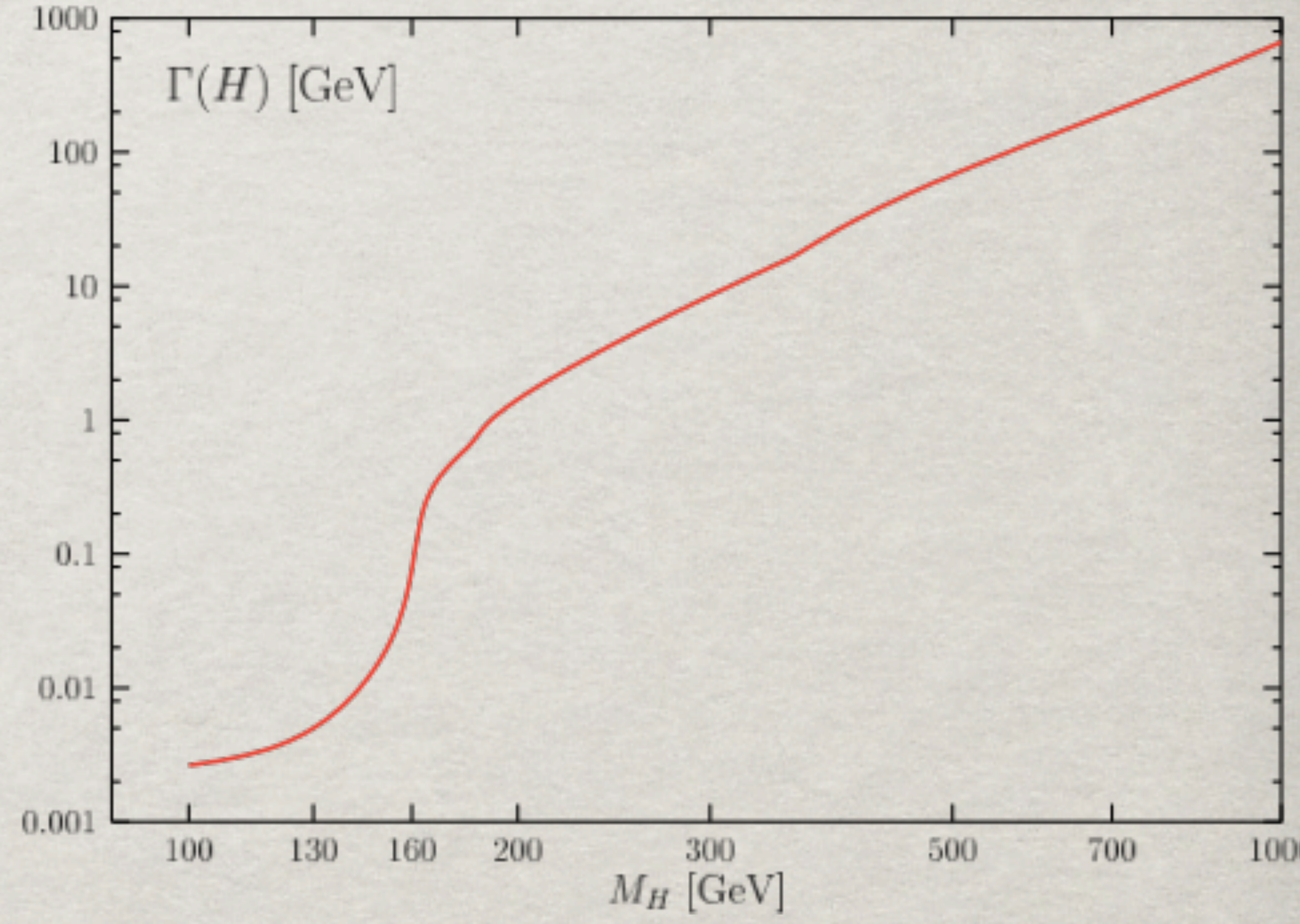
As the results for a SM Higgs: The branching fractions and total width





For m_H = 125 GeV, Γ(total) ≈ 4 MeV

BR(bb) ≈ 60%

BR(ττ) ≈ 8%

BR(WW) ≈ 21%

BR(ZZ) ≈ 2%

BR(gg) ≈ 9%

BR(γγ) ≈ 0.22%

Particle production in hadronic collisions:

The luminosity:

$$\mathcal{L} \propto f n_1 n_2 / a,$$

(a some beam transverse profile) in units of #particles/cm^2/s

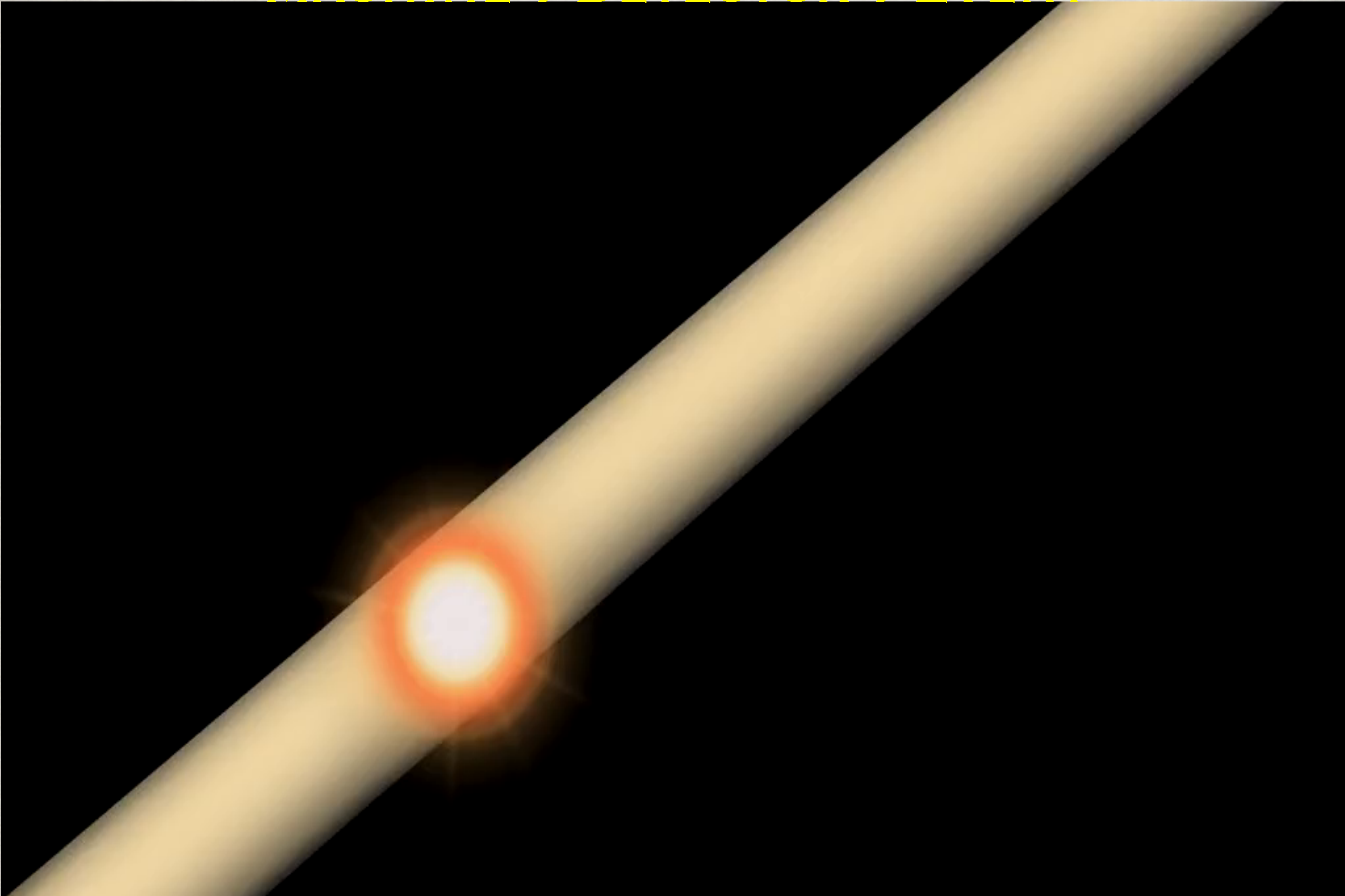
$\Rightarrow 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 1\ \mathrm{nb}^{-1}\ \mathrm{s}^{-1} \approx 10\ \ \mathrm{fb}^{-1}$/year.

Current and future high-energy colliders:

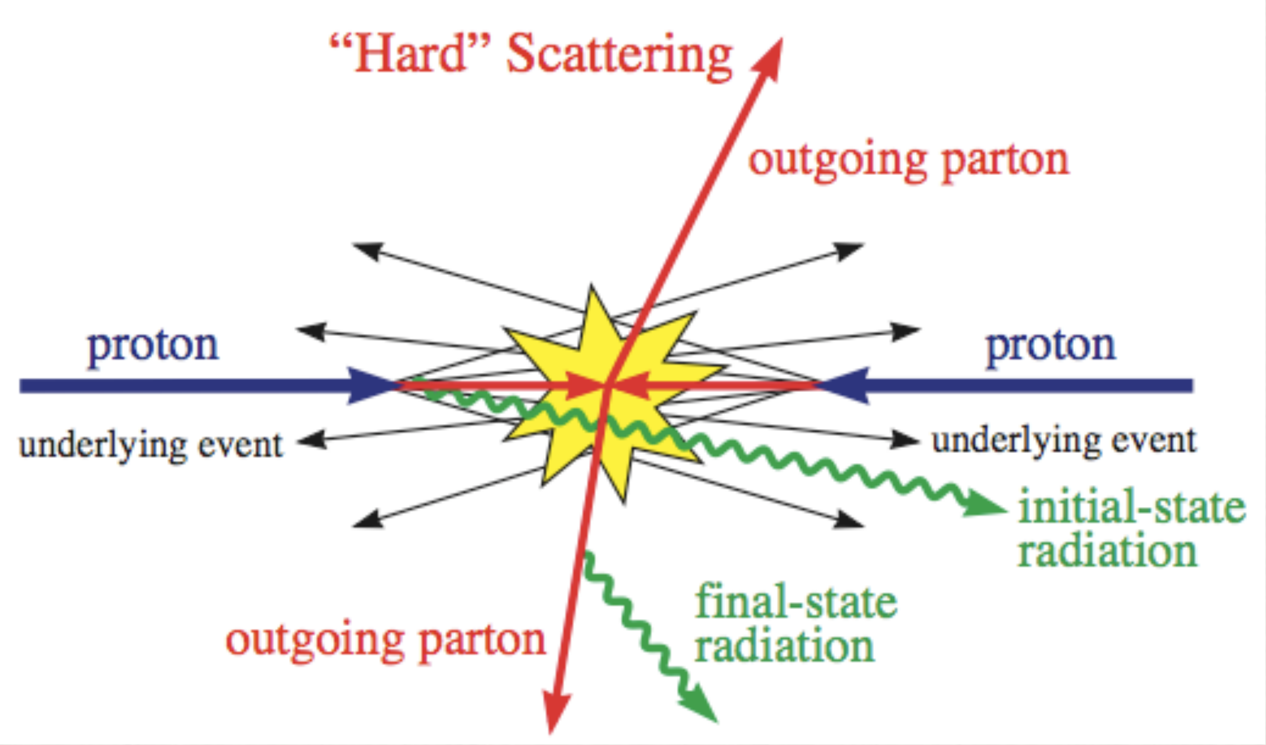
Hadron Colliders	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (cm^{-2}s^{-1})	$\delta E/E$	f (MHz)	#/bunch (10^{10})	L (km)
Tevatron	1.96	2.1×10^{32}	9×10^{-5}	2.5	p: 27, $\bar{p}$: 7.5	6.28
LHC	(7) 14	(10^{32}) 10^{34}	0.01%	40	10.5	26.66

e^+e^- Colliders	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (cm^{-2}s^{-1})	$\delta E/E$	f (MHz)	polar.	L (km)
ILC	0.5–1	2.5×10^{34}	0.1%	3	80, 60%	14 – 33
CLIC	3–5	$\sim 10^{35}$	0.35%	1500	80, 60%	33 – 53

Trapping The Higgs : Machine→Detector→Event



Particle production in hadronic collisions:



In high energy collisions involving a hadron, the total cross sections can be factorized into two factors:

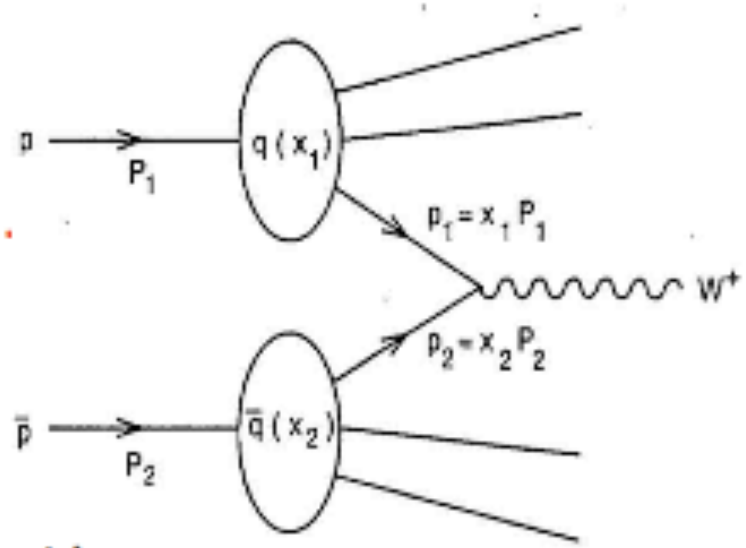
(1). hard subprocess of parton scattering with a large scale $\mu^2 \gg \Lambda^2_{QCD}$;

(2). "parton distribution functions" (hadronic structure with $Q^2 < \mu^2$.)

Observable cross sections at hadron level:

$$\sigma_{pp}(S) = \int dx_1 dx_2 P_1(x_1, Q^2) P_2(x_2, Q^2)\ \hat{\sigma}_{parton}(s).$$

$$= \sum_{ij} \int d\tau \frac{dL_{ij}}{d\tau}\ \sigma_{ij}(s), \quad \tau = s/S$$



† $\hat{\sigma}_{parton}(s)$ is theoretically calculated by perturbation theory (in the SM or models beyond the SM).

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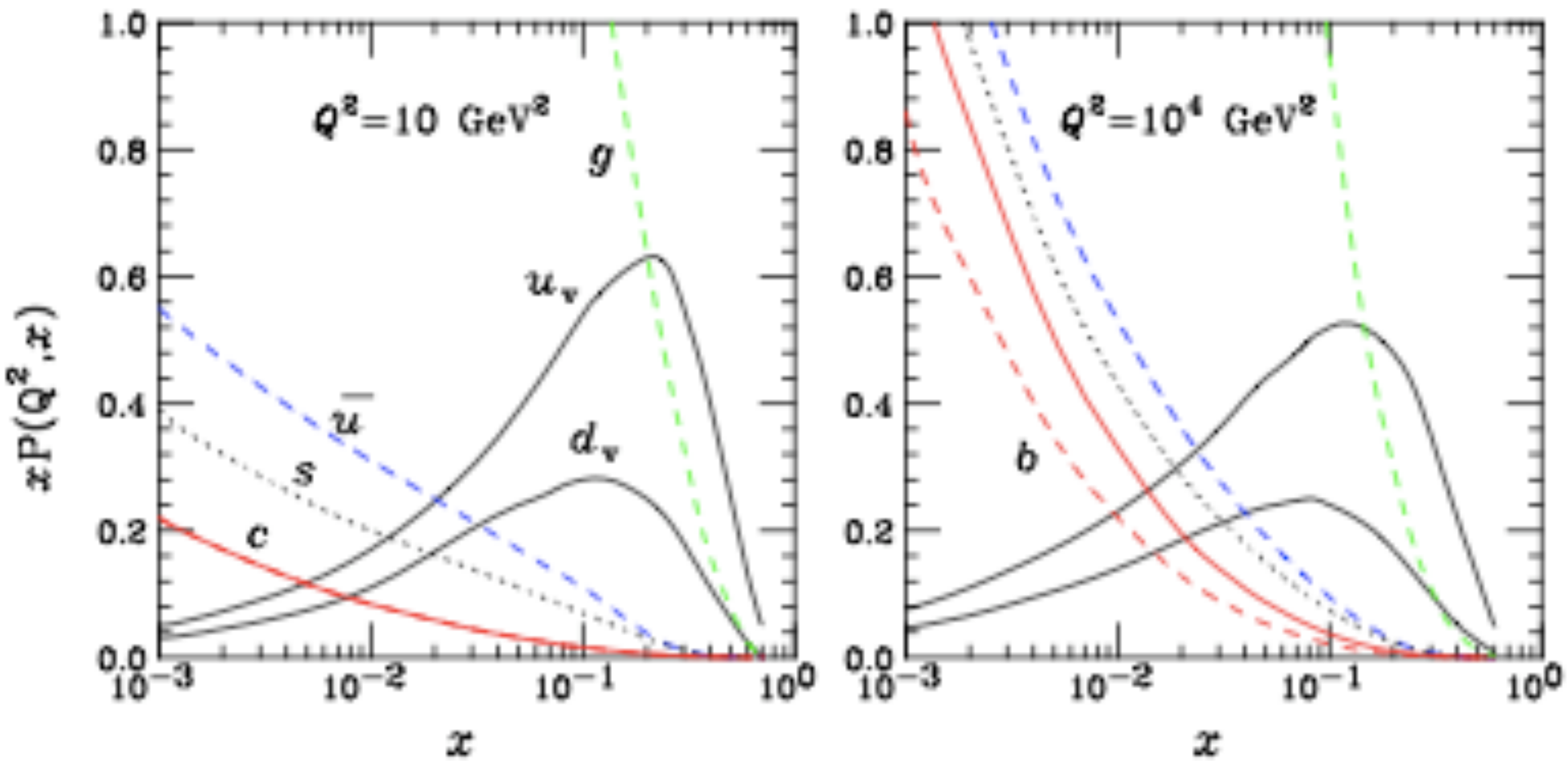
Ultra violet (UV) divergence (beyond leading order) is renormalized;
Infra-red (IR) divergence is cancelled by soft gluon emissions;
Co-linear divergence (massless) is factorized into PDF
– The essence of "factorization theorem".

Typical quark/gluon parton distribution functions $P(x, Q^2)$:

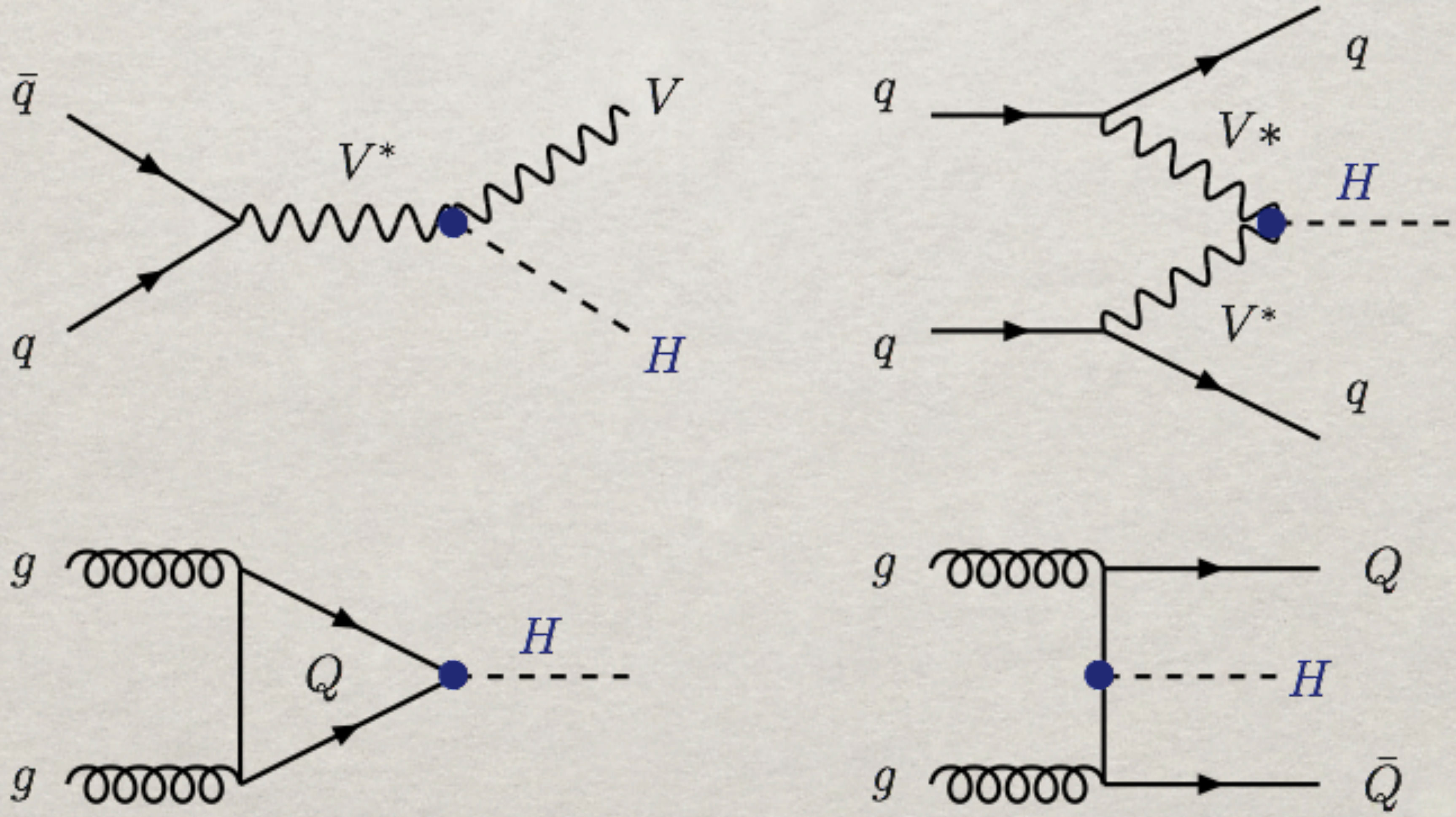


B. Higgs Boson Production at LHC

1. The leading channels:

Recall that the Higgs couples preferably to heavier particles.

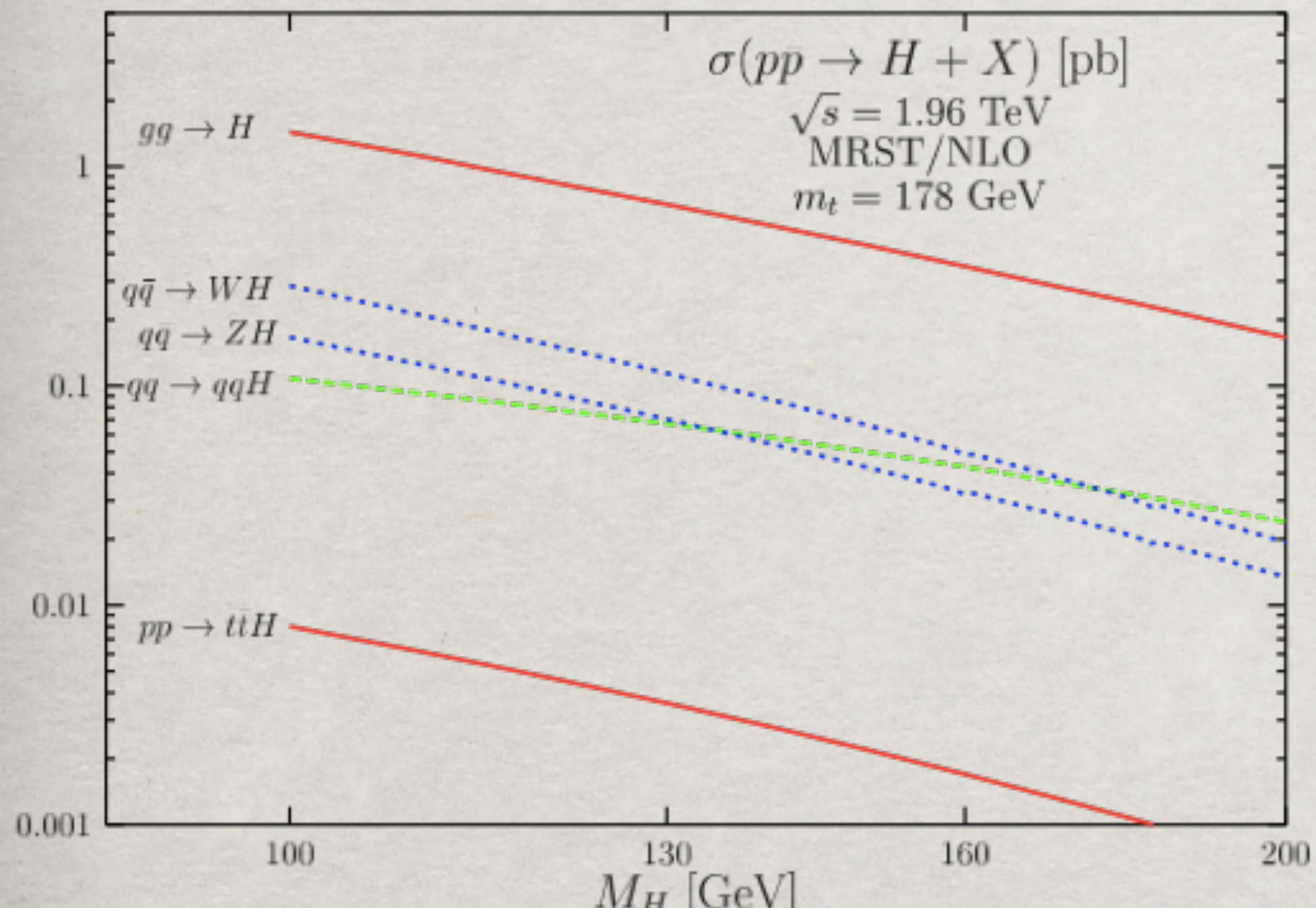
$$
\begin{aligned}
\text{associated production with } W/Z: &\quad q\bar{q} \longrightarrow V + H \\
\text{vector boson fusion}: &\quad qq \longrightarrow V^*V^* \longrightarrow qq + H \\
\text{gluon} - \text{gluon fusion}: &\quad gg \longrightarrow H \\
\text{associated production with heavy quarks}: &\quad gg, q\bar{q} \longrightarrow Q\bar{Q} + H
\end{aligned}
$$

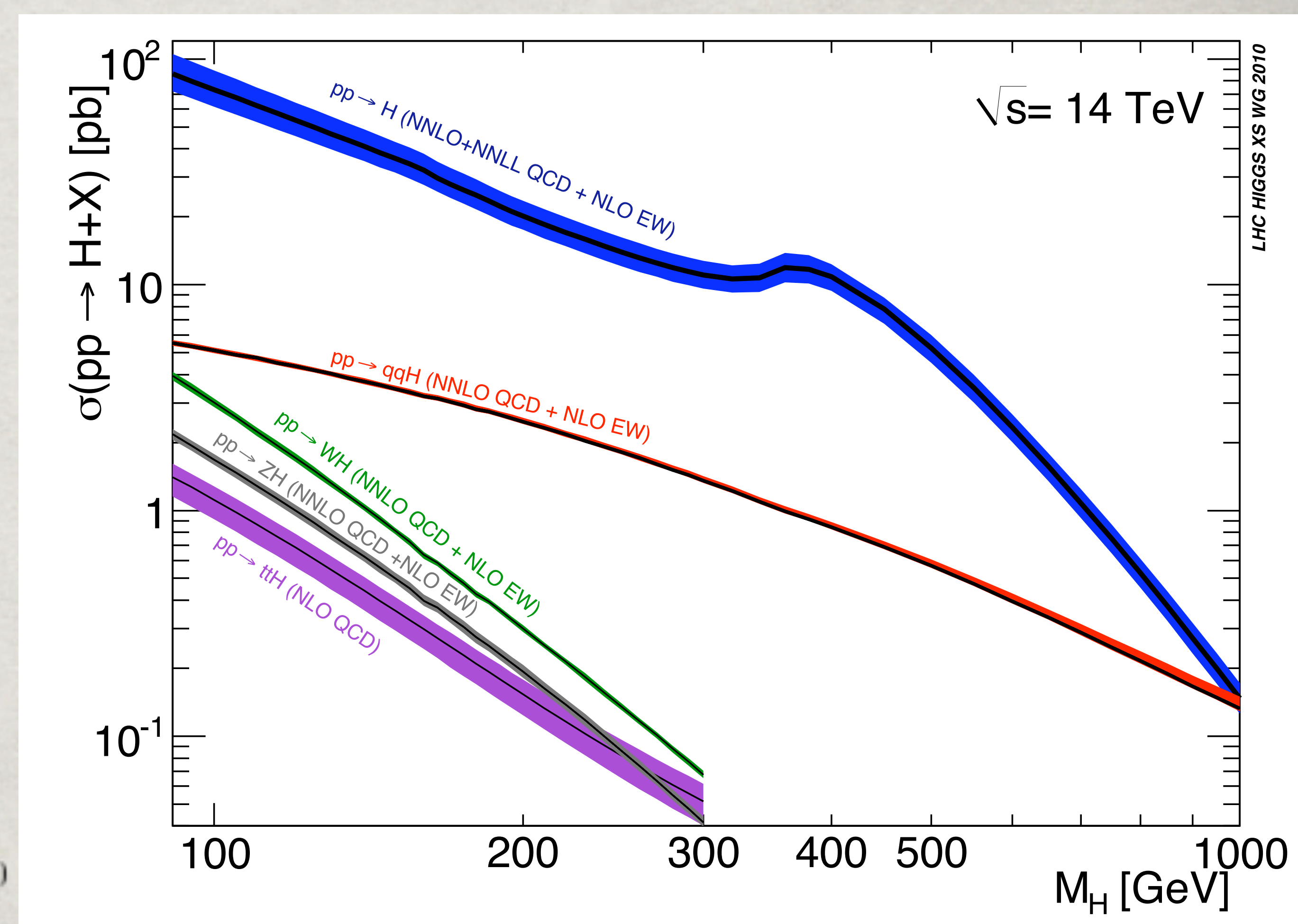


Calculation history and references compiled by Laura Reina

process	$\sigma_{NLO,NNLO}$ by
$gg \to H$	S.Dawson, NPB 359 (1991), A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser *et al.*, JHEP 0212 (2002); V.Ravindran *et al.*, NPB 634 (2002) D. de Florian *et al.*, PRL 82 (1999) R.Harlander, W.Kilgore, PRL 88 (2002) (NNLO) C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNLO) V.Ravindran *et al.*, NPB 665 (2003) (NNLO) S.Catani *et al.* JHEP 0307 (2003) (NNLL), G.Bozzi *et al.*, PLB 564 (2003), NPB 737 (2006) (NNLL) C.Anastasiou, R.Boughezal, F.Petriello, JHEP (2008) (QCD+EW)
$q\bar{q} \to (W,Z)H$	T.Han, S.Willenbrock, PLB 273 (1991) M.L.Ciccolini, S.Dittmaier, and M.Krämer (2003) (EW) O.Brien, A.Djouadi, R.Harlander, PLB 579 (2004) (NNLO)
$q\bar{q} \to q\bar{q}H$	T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992) T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003) M.L.Ciccolini, A.Denner,S.Dittmaier (2008) (QCD+EW) P.Bolzoni, F.Maltoni, S.O.Moch, and M.Zaro (2010) (NNLO)
$q\bar{q}, gg \to t\bar{t}H$	W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003) S.Dawson *et al.*, PRL 87 (2001), PRD 65 (2002), PRD 67,68 (2003)
$q\bar{q}, gg \to b\bar{b}H$	S.Dittmaier, M.Krämer, M.Spira, PRD 70 (2004) S.Dawson *et al.*, PRD 69 (2004), PRL 94 (2005)
$gb(\bar{b}) \to b(\bar{b})H$	J.Campbell *et al.*, PRD 67 (2003)
$b\bar{b} \to H$	D.A.Dicus *et al.* PRD 59 (1999); C.Balasz *et al.*, PRD 60 (1999). R.Harlander, W.Kilgore, PRD 68 (2003) (NNLO)

Production cross sections at hadron colliders:

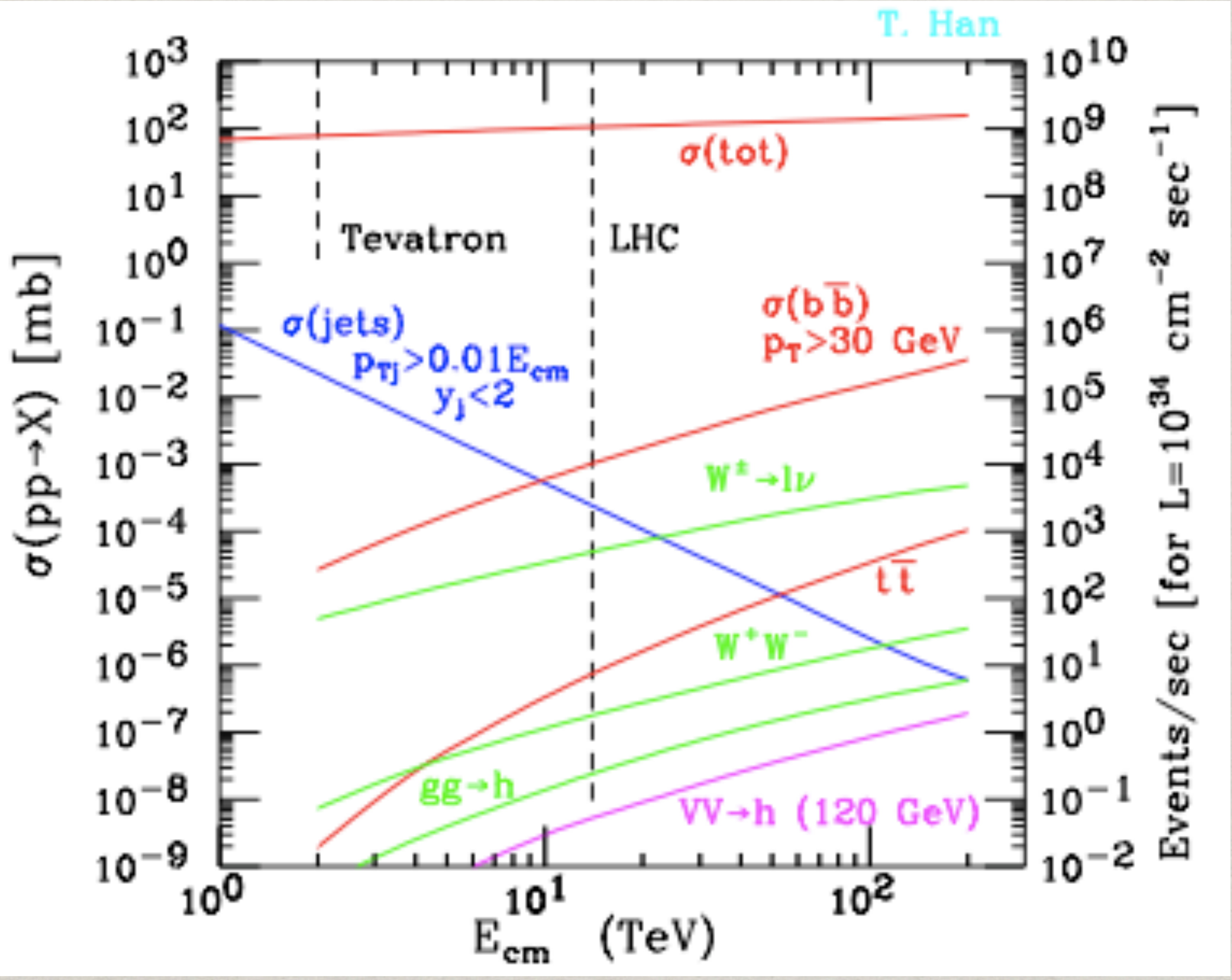




Exercise 9: List three leading processes for SM Higgs pair production and comment on their relative sizes.

§ L. Reina, TASI lectures, 2011.
A. Djouadi, hep-ph/0503172.

Total rates in hadronic collisions:



2. Signal Search Strategy:

Searching for the Higgs boson at the LHC is highly non-trivial!

In theory:

- assume a mass parameter;
- predict the production cross section;
- specify a (good) final state in H decay;
- identify the SM backgrounds;
- calculate the observability by $S/\sqrt{B}$ or alike

In experiments:

- specify a (good) final state from H decay;
- compare with the SM backgrounds;
- assume a mass parameter and compare with theory;
- estimate the sensitivity (μ signal strength, p-value)

Salute to theorists/experimentalists:

We Made It!

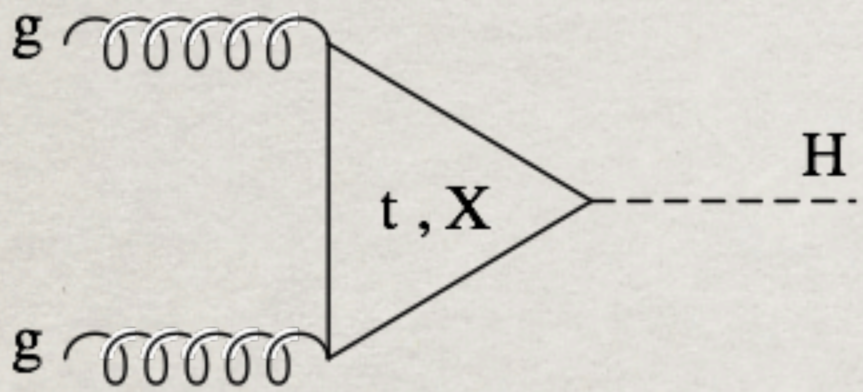
We want to know more (experimentally):

- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
- Couplings as accurate as possible:
  - to verify the SM prediction: Spin, parity …
  - to seek for hints for new physics.

Still a lot of hard, but fun work to do!

3. Signal Characteristics:

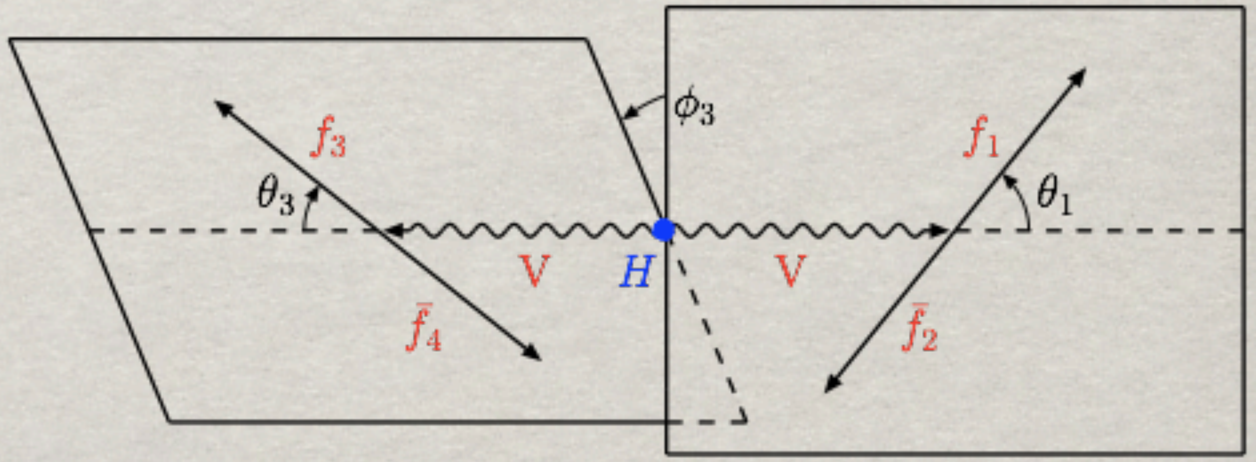
(a). Gluon fusion: The leading production channel



σ(125 GeV@ 8 TeV) ≈ 20 pb
σ(125 GeV@14 TeV) ≈ 40 pb

- Need clean decay modes: γγ, WW, ZZ
- Effects from radiative corrections very large!§
- Sensitive to new colored particles in the loop:

gg → H sensitive to new colored states: Q
H → γγ sensitive to new charged states: Q, L
H → ZZ → 4 leptons
best to study the Higgs
CP properties:



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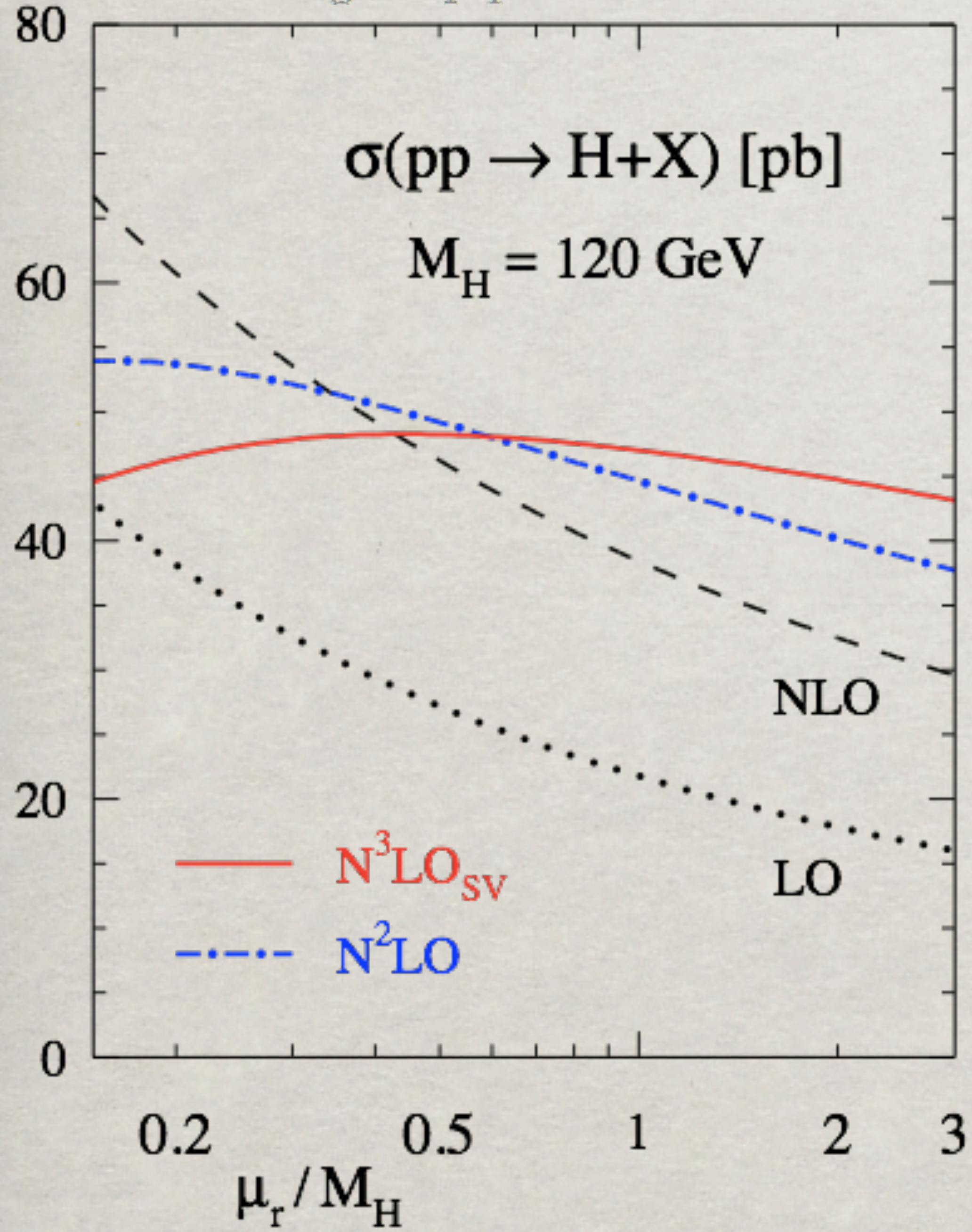
QCD corrections to $gg \to H$

Moch & Vogt, hep-ph/0508265

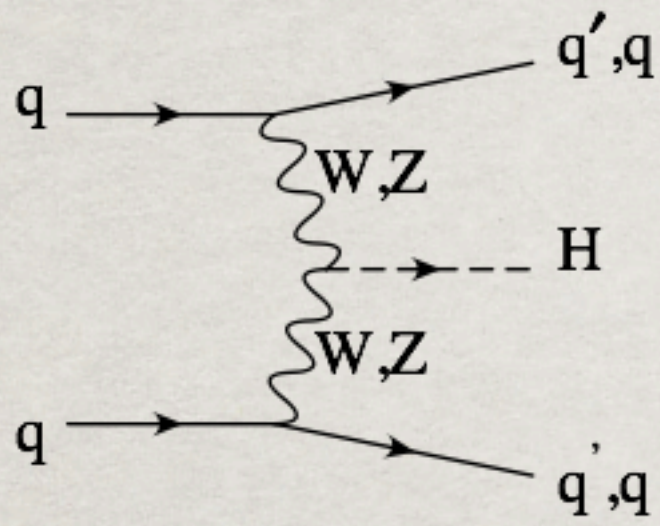


- Large QCD corrections: K-factor of about 2
- Stabilization of scale dependence needs N^3LO or at least NNLO corrections
- Cross section estimate for $m_H = 126$ GeV at 8 TeV from LHC XS WG, determined at NNLL QCD and NLO EW

$$\sigma(gg \to H) = 19.22\,\text{pb} \pm 14.7\%$$

- Error is linear combination of $\approx 7.5\%$ scale uncertainty and $\approx 7.2\%$ from gluon pdf and α_s error
- Additional uncertainty from use of effective hgg vertex (heavy top approximation) is estimated to be below 2%

(b). The Vector Boson Fusion:



$\sigma(14\ \text{TeV}) \approx 4$ pb

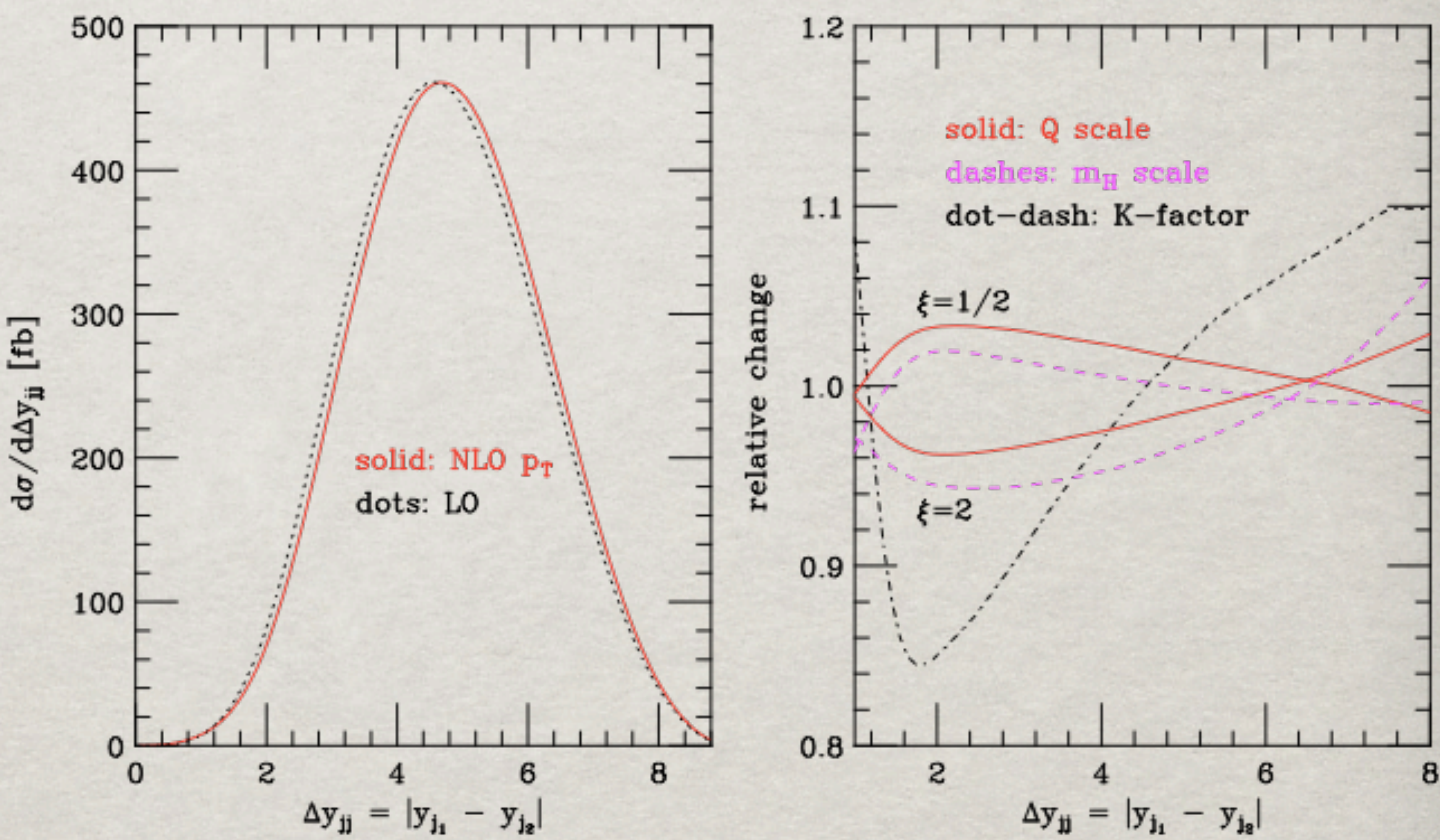
- Need clean decay modes: $\tau\tau$, WW, ZZ, $\gamma\gamma$
- Effects from radiative corrections very small!
  -> color singlet exchange, low jet activities.
- Sensitive to HWW, HZZ couplings
- Good for H → $\tau\tau$, $\gamma\gamma$
- A bit lower rate, but unique kinematics

NLO corrections to VBF

- Small QCD corrections of order 10%
- Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 1\%$ for σ_{total}
- pdf error is below 3% since pdf's are dominated by valence quarks
- $\approx\ -5\%$ EW corrections included

  Ciccolini, Denner, Dittmaier, 0710.4749

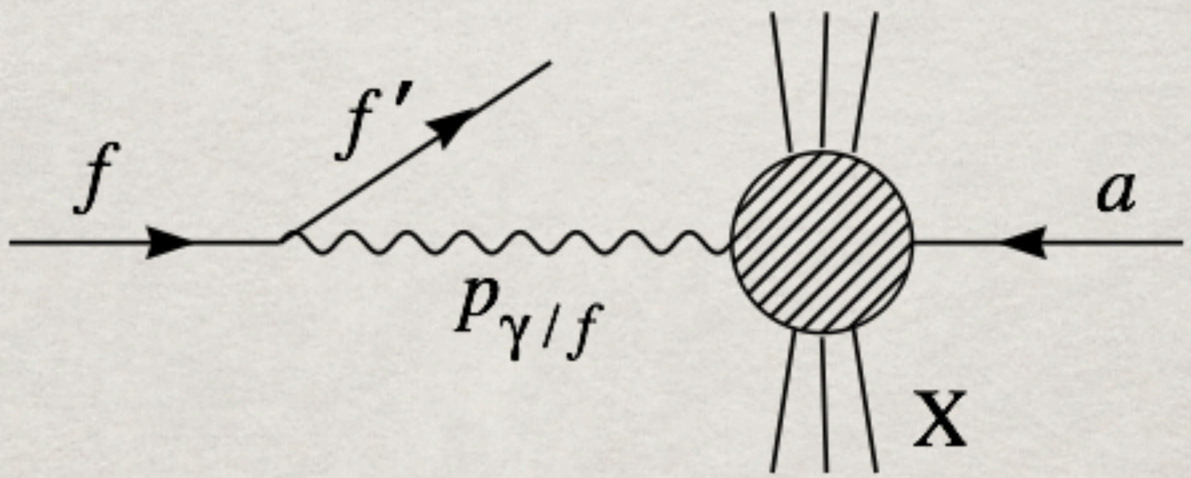
  Figy, Palmer, Weiglein arXiv:1012.4789
- Very small cross section error of about 3% for $m_H = 126$ GeV



$m_H = 120$ GeV, typical VBF cuts

Basic feature: V radiation off a quark

The familiar Weizsäcker-Williams approximation



$$\sigma(fa \to f'X) \approx \int dx\, dp_T^2\, P_{\gamma/f}(x, p_T^2)\, \sigma(\gamma a \to X),$$

$$P_{\gamma/e}(x, p_T^2) = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\left(\frac{1}{p_T^2}\right)\Big|_{m_e}^{E}.$$

Exercise 10: Qualitative feature for V radiation off a quark

- Generalize to massive gauge bosons:

$$P^T_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{8\pi^2}\,\frac{1+(1-x)^2}{x}\,\frac{p_T^2}{(p_T^2+(1-x)M_V^2)^2},$$
$$P^L_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{4\pi^2}\,\frac{1-x}{x}\,\frac{(1-x)M_V^2}{(p_T^2+(1-x)M_V^2)^2}.$$

Special kinematics for massive gauge boson fusion processes:
For the accompanying jets,

At low-p_{jT},

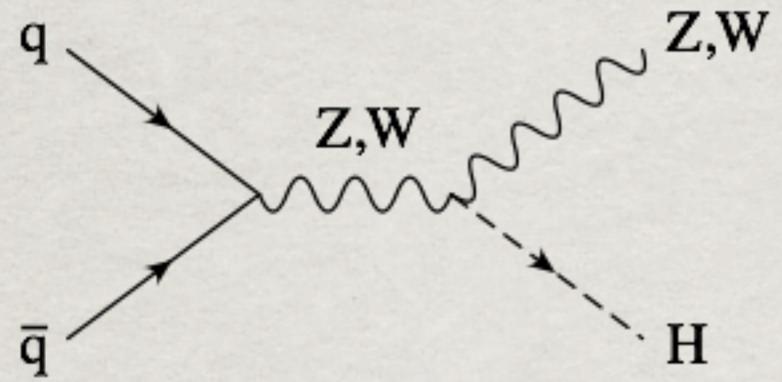
$$\left.\begin{array}{l} p_{jT}^2 \approx (1-x)M_V^2 \\ E_j \sim (1-x)E_q \end{array}\right\}\ \textit{forward jet tagging}$$

At high-p_{jT},

$$\left.\begin{array}{l} \frac{d\sigma(V_T)}{dp_{jT}^2} \propto 1/p_{jT}^2 \\ \frac{d\sigma(V_L)}{dp_{jT}^2} \propto 1/p_{jT}^4 \end{array}\right\}\ \textit{central jet vetoing}$$

has become important tools for Higgs searches, single-top signal etc.

(c). VH Associate production:

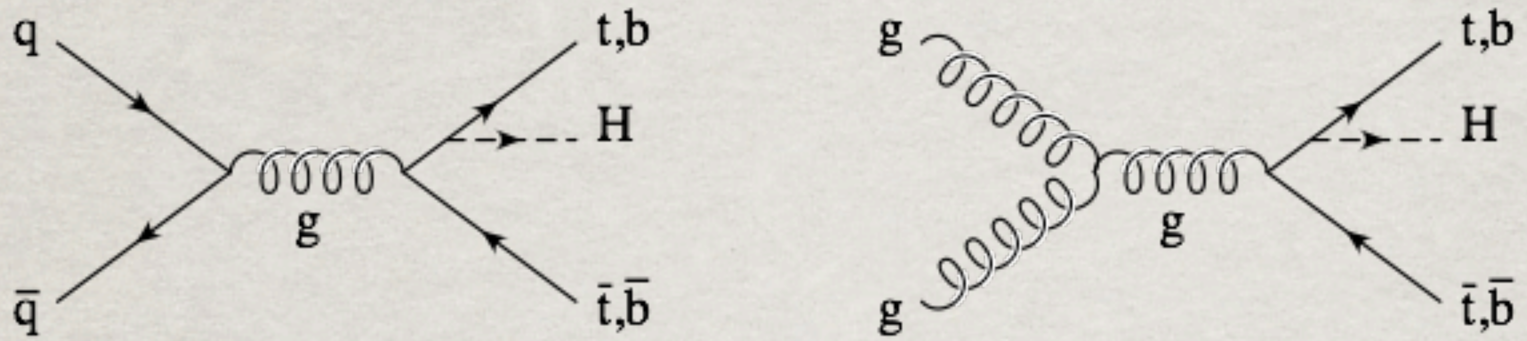


$\sigma(14\ \text{TeV}) \approx 2.2$ pb

- W/Z leptonic decays serve as good trigger.
- Effects from radiative corrections very modest.
- Sensitive to HWW, HZZ couplings
- Do not need clean decay modes: chance for b bbar !

Boosted Higgs helps for the signal ID!

(d). Top quark pair associate production:



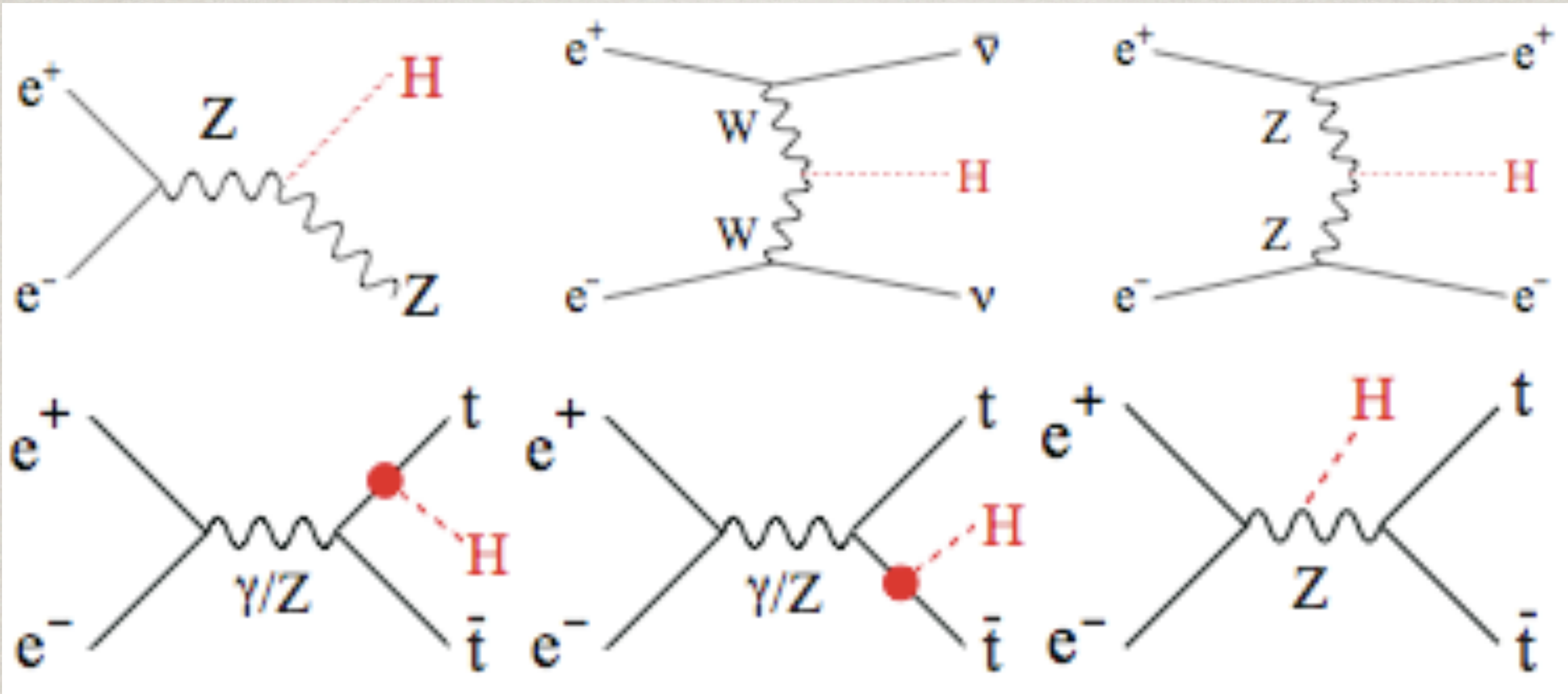
$\sigma(14\ \text{TeV}) \approx 0.6\ \text{pb}$

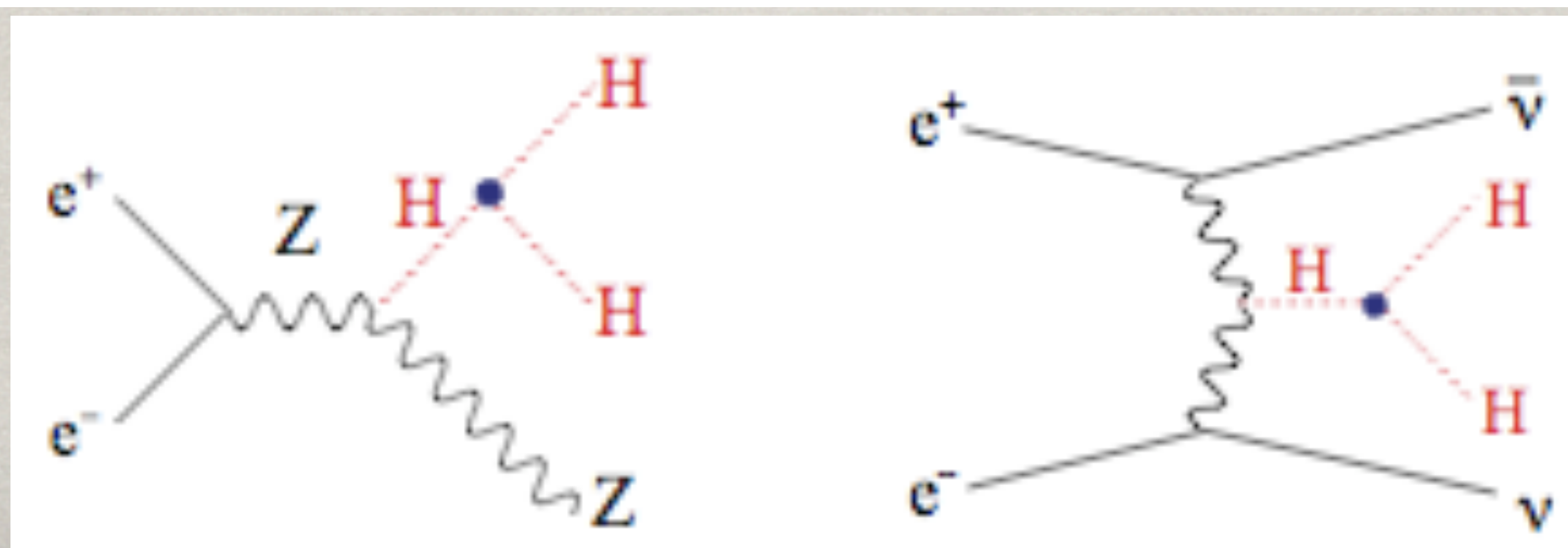
- Top leptonic decays serve as good trigger.
- Effects from radiative corrections can be large.
- Directly sensitive to Htt coupling
- Do not need clean decay modes: chance for b bbar !
- Combinatorics of the 4 b's are difficult to handle...

C. Higgs Boson Production at e^+e^- Colliders

1. The leading channels:

Recall that the Higgs couples preferably to heavier particles.





The idea of a Higgs Factory:

Two Candidate Sites

- Kyushu
  - Sefuri mountains
- Tohoku
  - Kitakami mountains

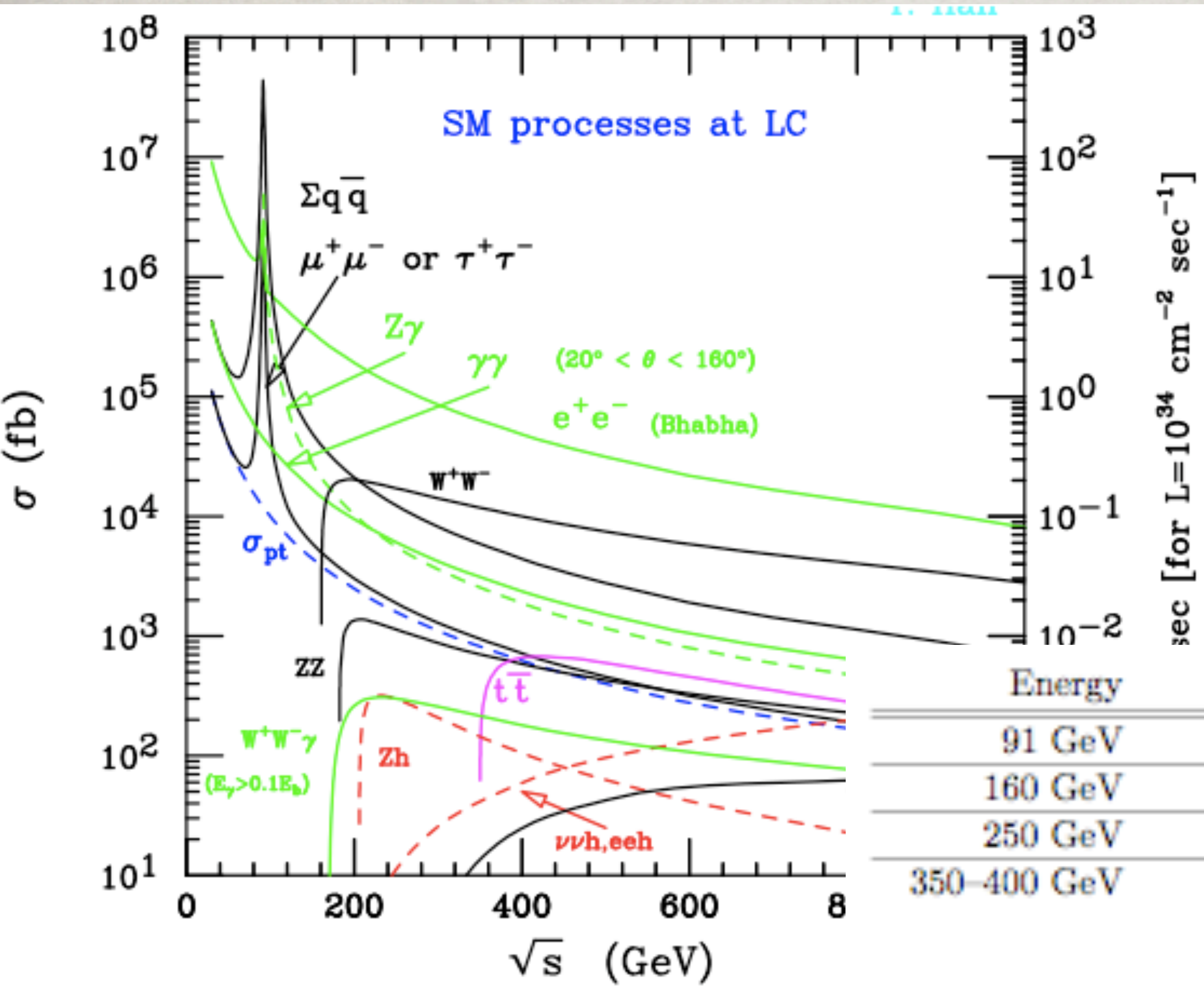
In order to focus the de
one of them will be cho

1. Geology and other techni
2. Infrastructure and econon
3. Political aspects

- Staging
  - A Higgs factory with a CM energy of ~250 GeV to start
  - Upgraded in stages to ~500 GeV (ILC baseline)
  - Technical expandability to ~1 TeV to be secured

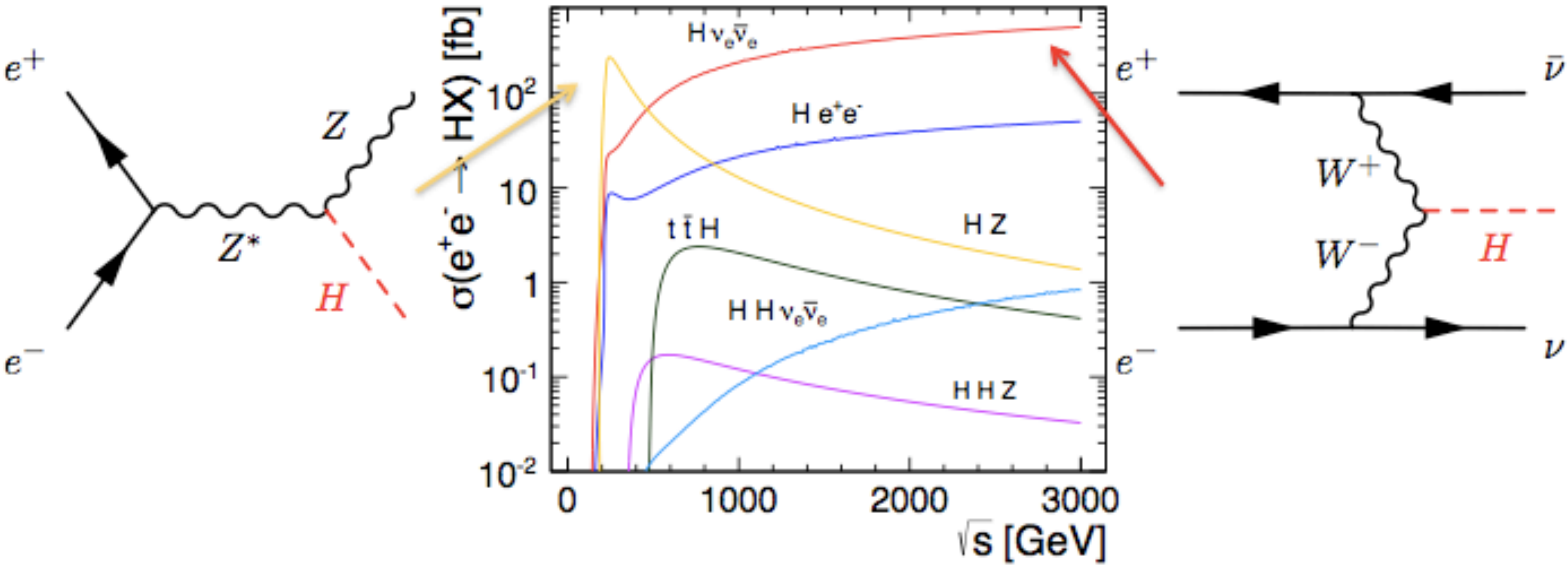
- Guideline for cost sharing
  - The host country to cover 50% of the expenses (construction) of the overall project of the 500 GeV machine.
  - The actual contribution, however, should be left to negotiations among the governments.

Total rates in e⁺e⁻ collisions:



Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

2. Higgs production:



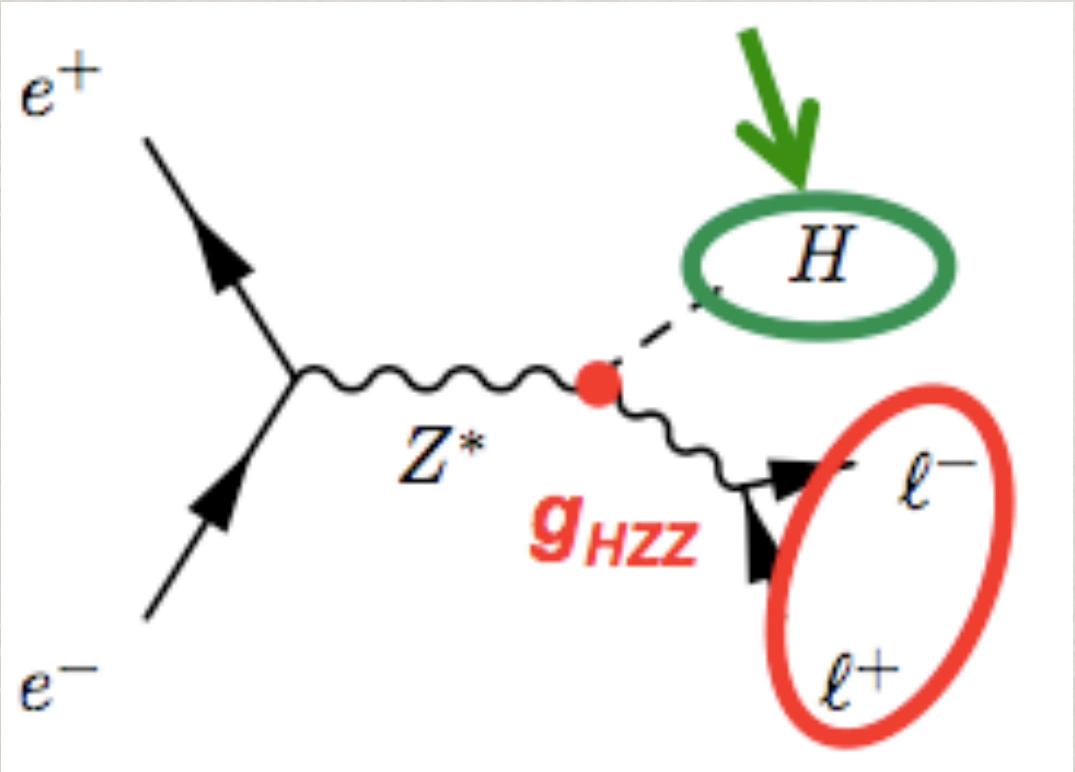
	250 GeV	**350 GeV**	**500 GeV**	**1 TeV**	**1.5 TeV**	**3 TeV**
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to \nu\nu H)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. Luminosity	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1 ab^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# vvH events	2,000	10,500	37,500	210,000	460,000	970,000

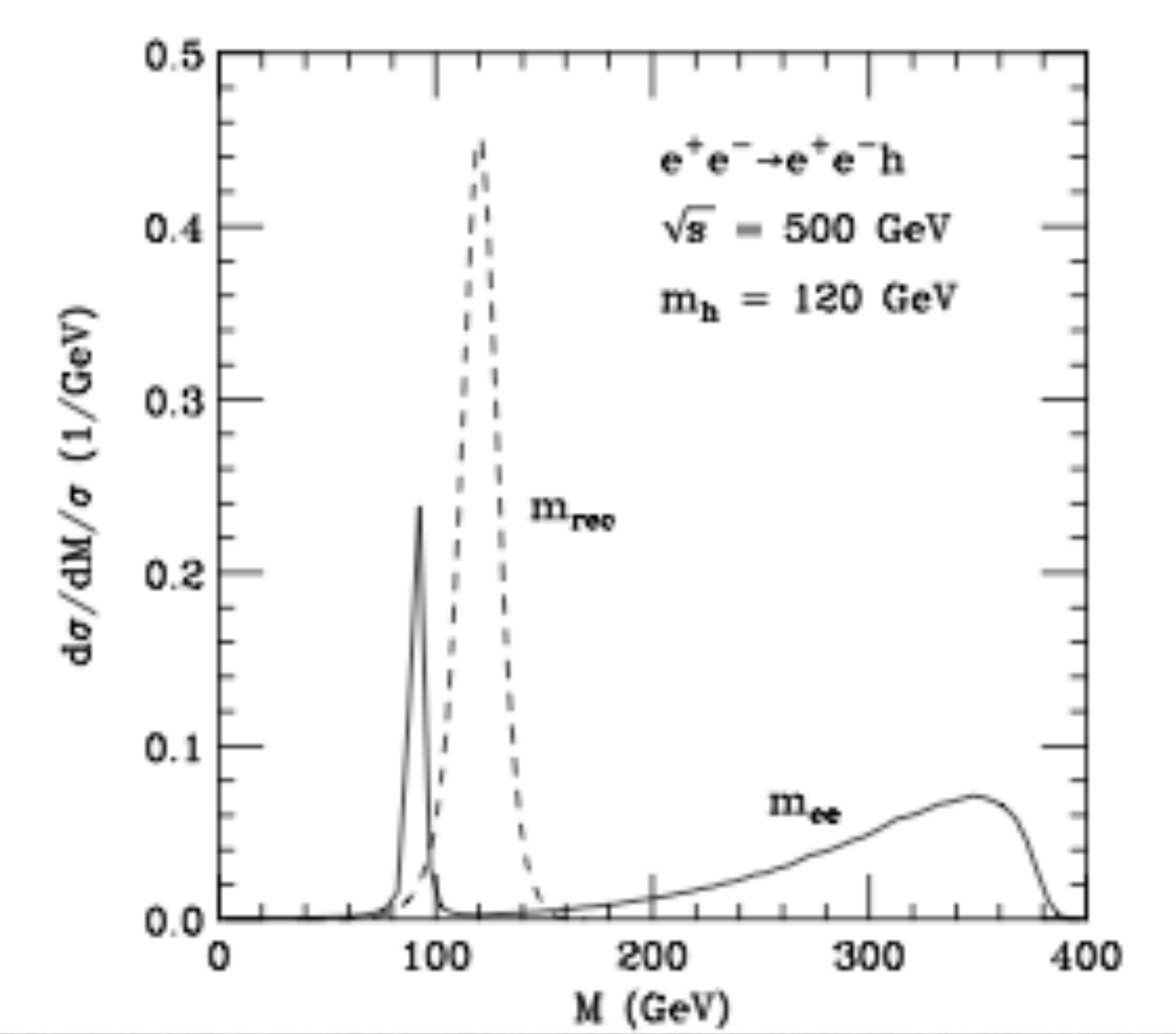
3. Recoil mass technique:

$$e^-(p_1)\, e^+(p_2) \to f(q_1)\, \bar{f}(q_2)\, h(q_3).$$

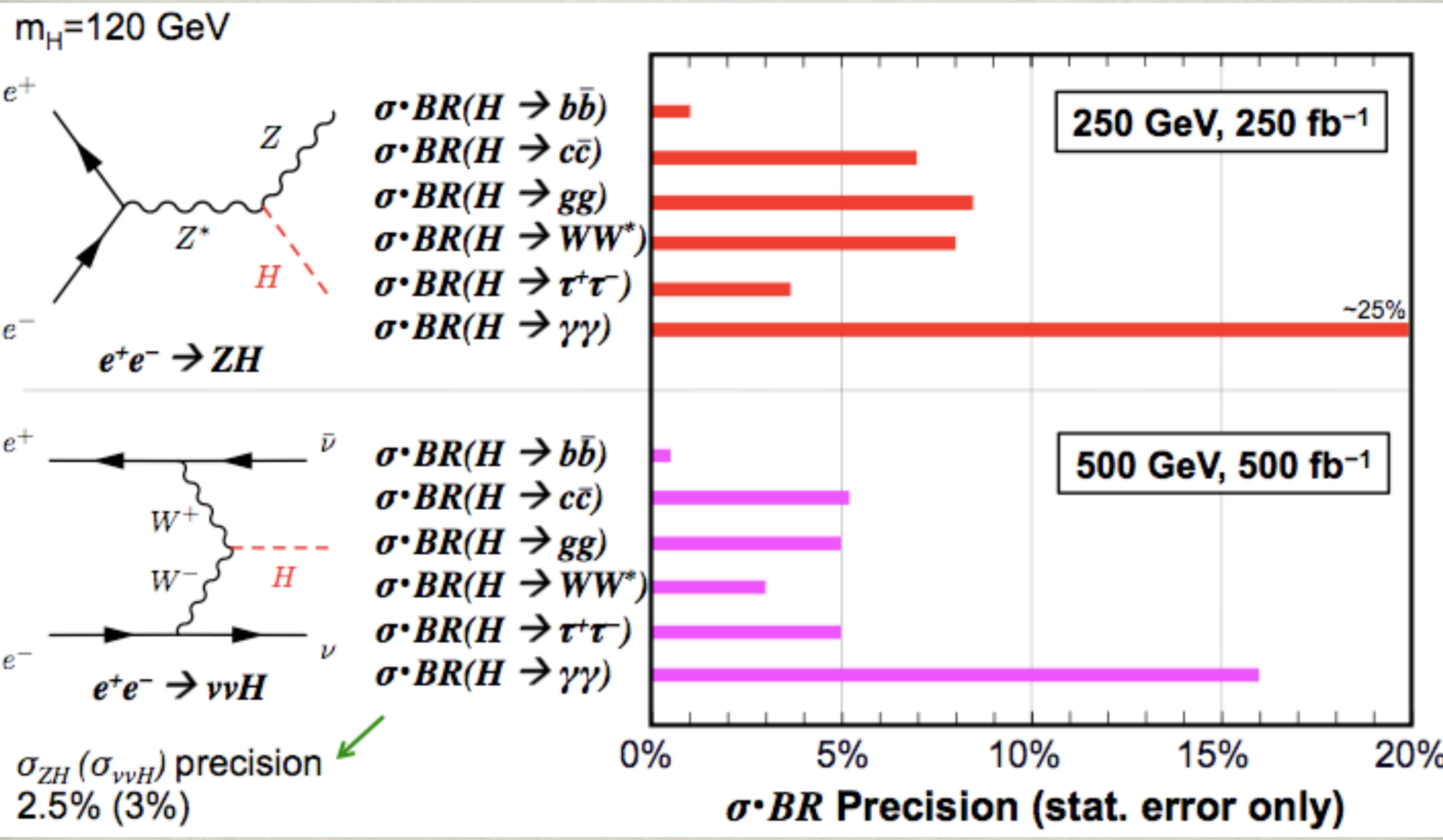
The Higgs boson signal may be best identified by examining the recoil mass variable

$$m_{rec}^2 = (p_1 + p_2 - q_1 - q_2)^2 = s + m_{f\bar{f}}^2 - 2\sqrt{s}(E_f + E_{\bar{f}}),$$





Branching accuracy



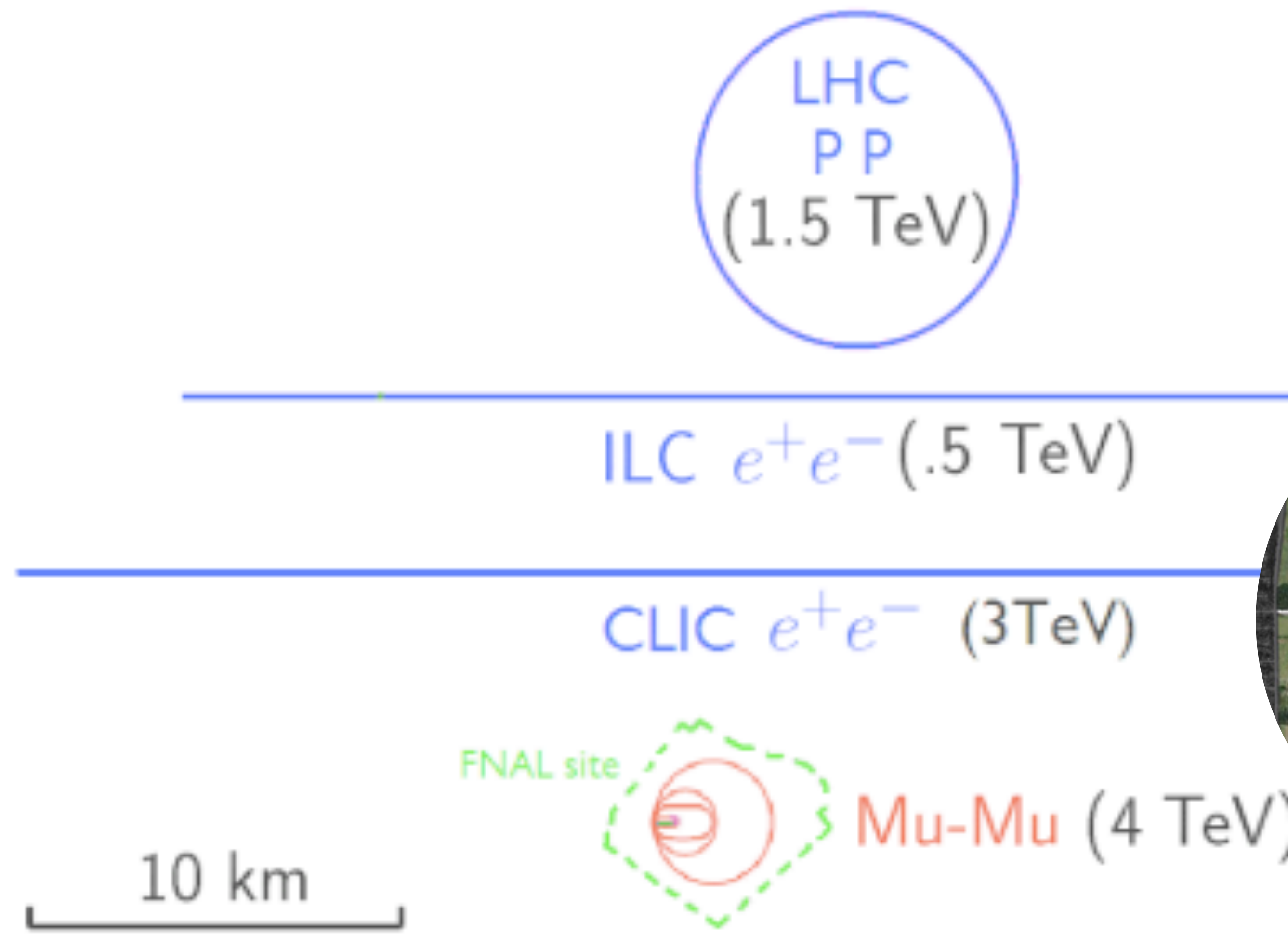
D. Higgs Boson Production at a muon Collider

Advantages of a Muon Collider

(1). Less radiative energy loss

$$\Delta E \sim \gamma^4 = (\frac{E}{m_\mu})^4$$

which allows a higher energy and much smaller machine:*



and a better beam-energy resolution: $\delta p/p \sim 0.1\% - 0.003\%$.

(2). Some natural beam-polarization via $\pi^- \to \mu^- \bar{\nu}$.

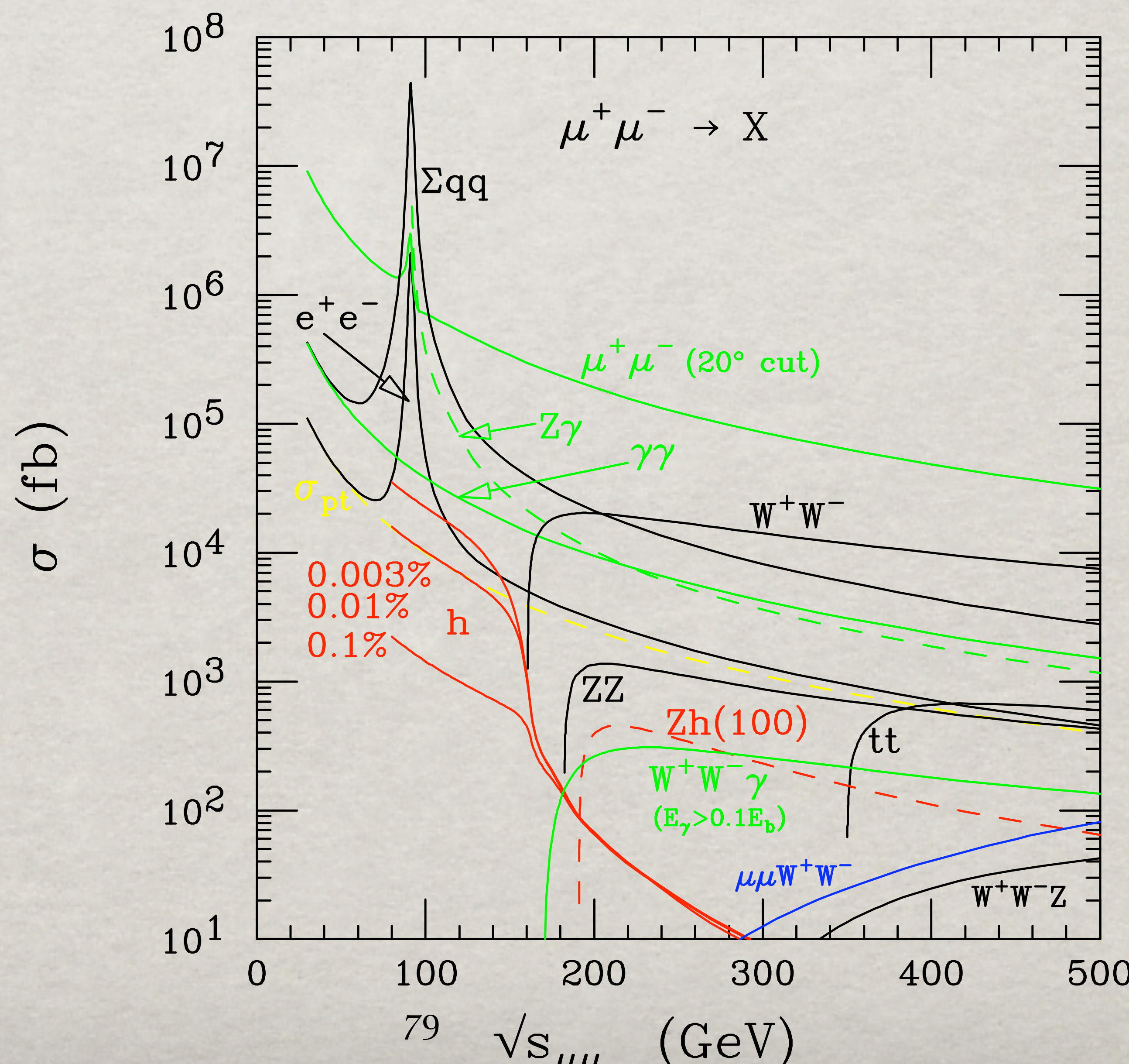
Challenges for a Muon Collider

"Never play with an unstable thing!"

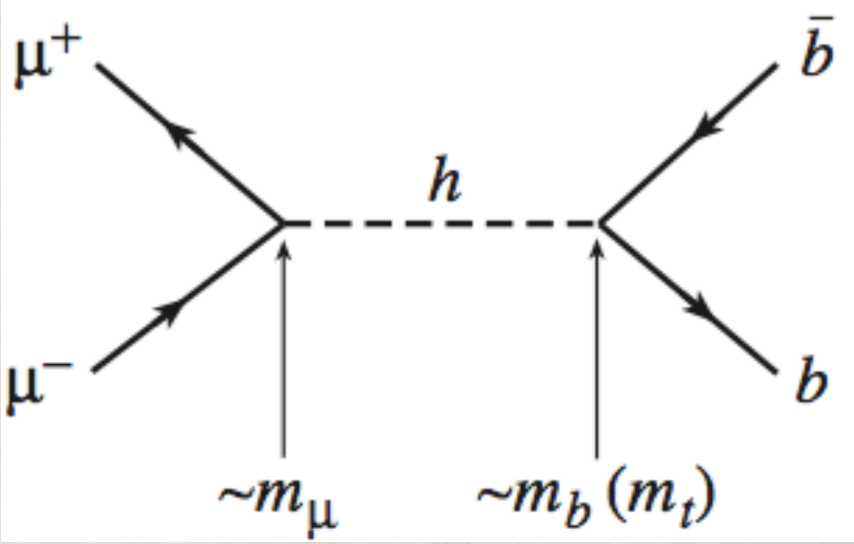
(1). Luminosity: Beam cooling on transverse momentum

(2). Detector backgrounds: Muon decay and re-scattering

(3). Neutrino hazard: When E_{cm} reaching Multi-TeV.



Resonant Production:



$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$

At the peak with a perfect energy resolution:

$$\begin{aligned} \sigma_{peak}(\mu^+\mu^- \to h) &= \frac{4\pi}{m_h^2} BR(h \to \mu^+\mu^-) \\ &\approx 41 \text{ pb at } m_h = 125 \text{ GeV}. \end{aligned}$$

About 40,000 events produced per fb^{-1}

SM Higgs is (very) narrow:

At m_h=126 GeV, Γ_h = 4.2 MeV

Must convolute with energy profile:

$$\frac{dL(\sqrt{\hat{s}})}{d\sqrt{\hat{s}}} = \frac{1}{\sqrt{2\pi}\Delta} \exp[\frac{-(\sqrt{\hat{s}}-\sqrt{s})^2}{2\Delta^2}],$$

$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h\to\mu^+\mu^-)\mathrm{Br}(h\to X)}{(\hat{s}-m_h^2)^2+\Gamma_h^2 m_h^2}.$$

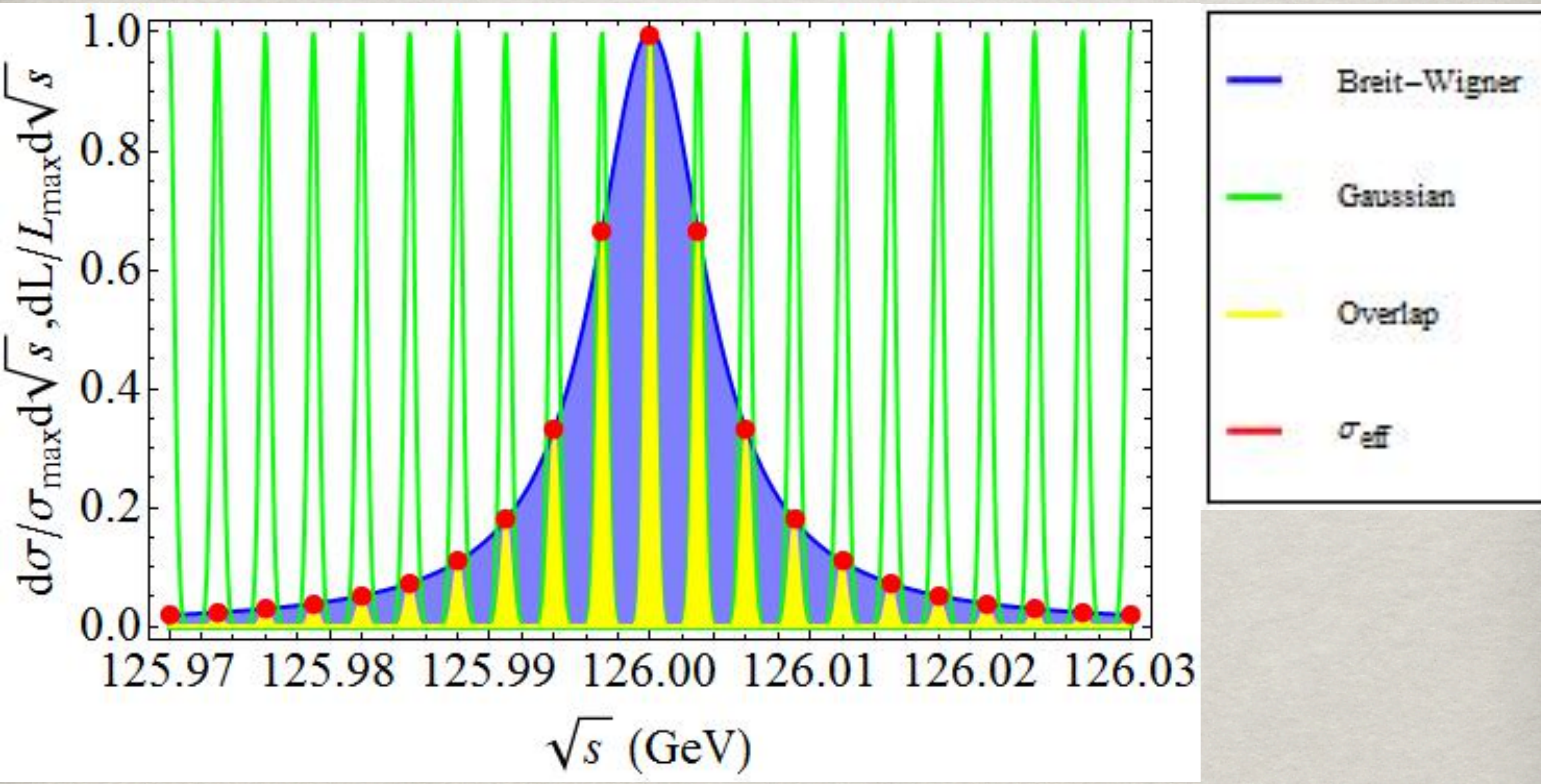
$$\sigma_{\rm eff}(s) = \int d\sqrt{\hat{s}}\,\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\sigma(\mu^+\mu^- \to h \to X)$$

$$\propto \begin{cases} \Gamma_h^2 B/[(s-m_h^2)^2+\Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B\exp[\frac{-(m_h-\sqrt{s})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$

Extreme (good) Case:

Energy Spread much smaller than the physical width:

(Δ = 0.3 MeV, $\Gamma_h \approx 4.2$ MeV)

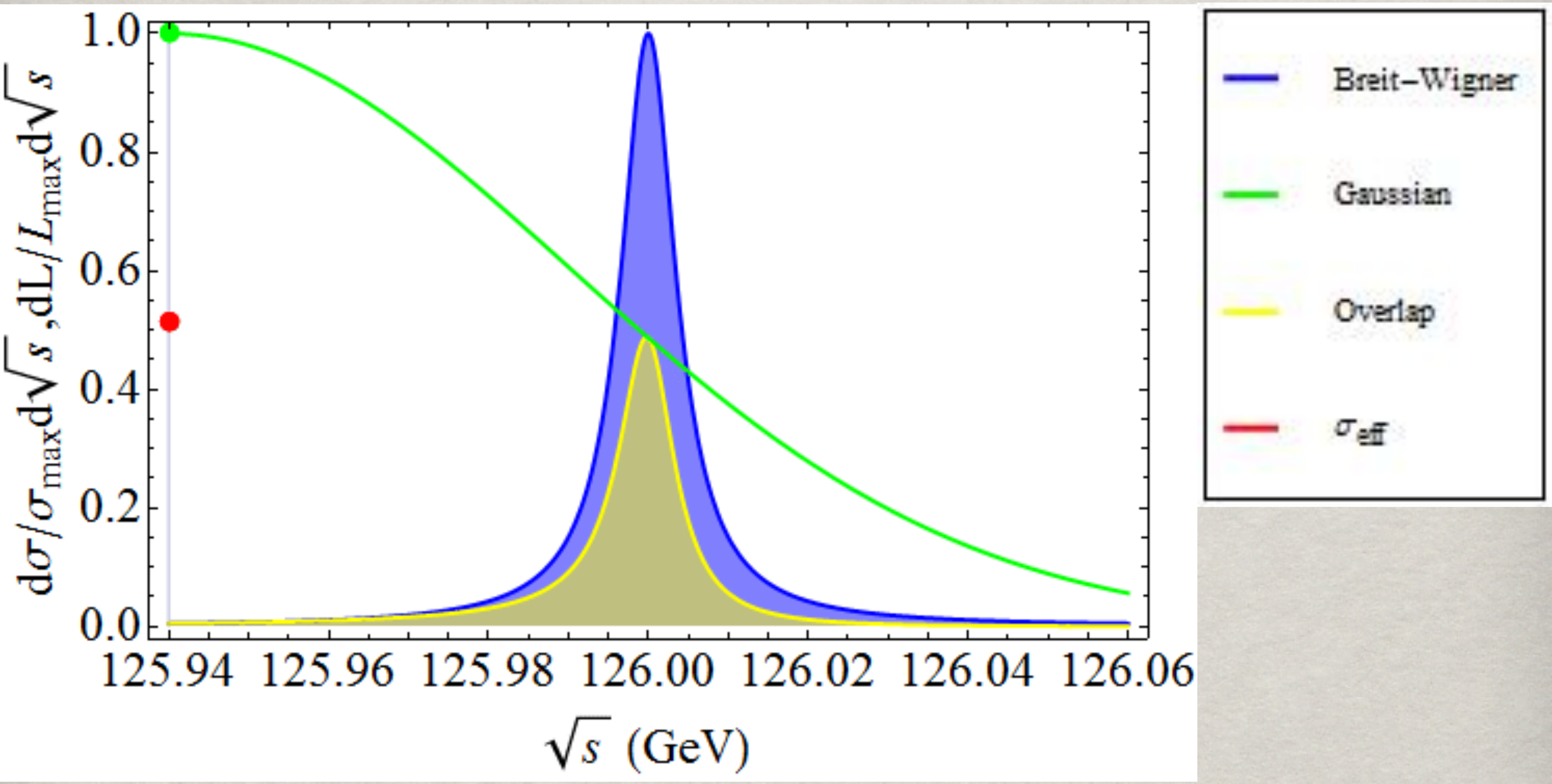


Recall: Z line shape with $\Gamma_Z \approx 2.5$ GeV

Extreme (bad) Case:

Energy Spread much larger than the physical width:

(Δ = 50 MeV, $\Gamma_h \approx 4.2$ MeV)

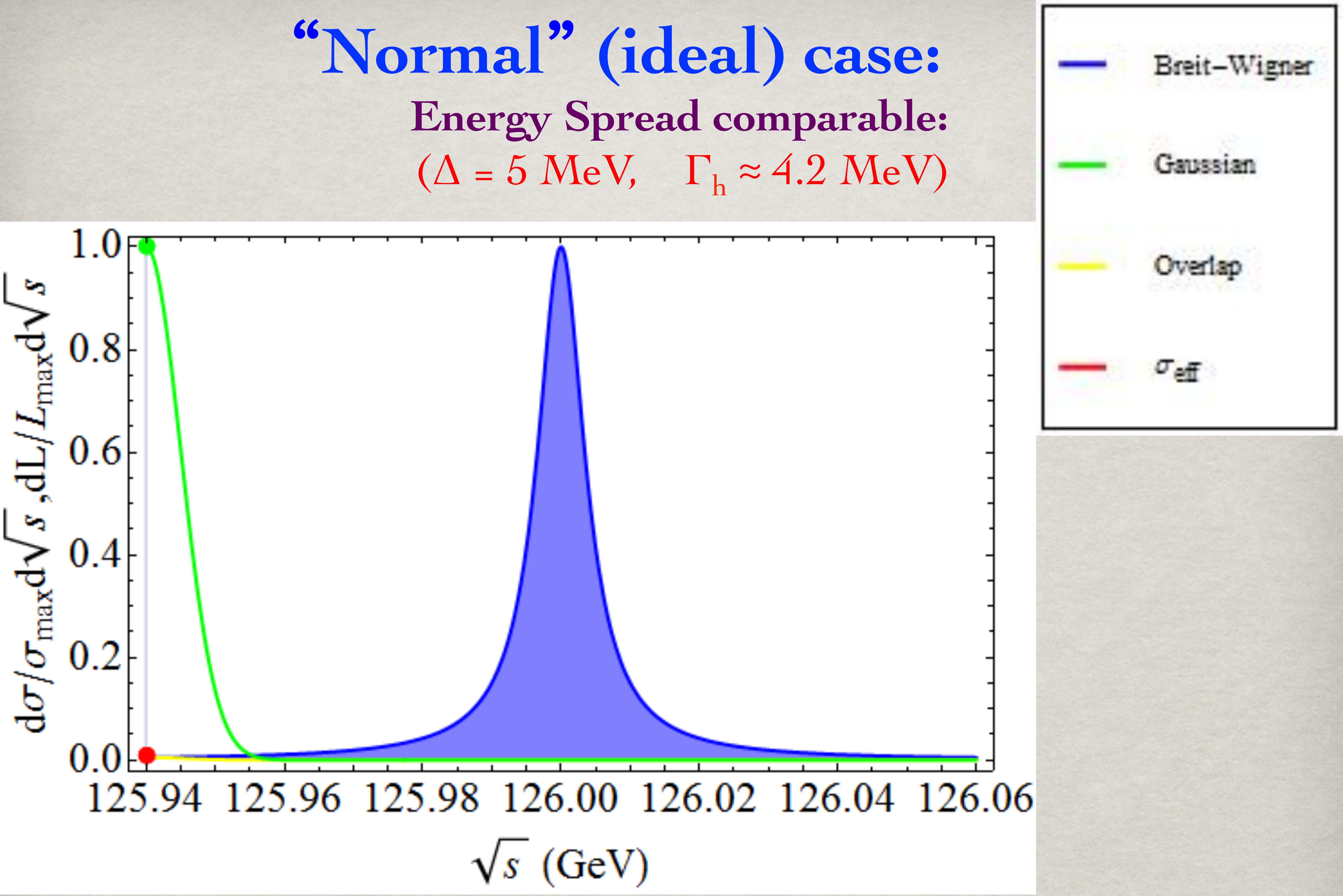


Recall: J/ψ scan $\Gamma \approx 93$ keV

“Normal” (ideal) case:

Energy Spread comparable:

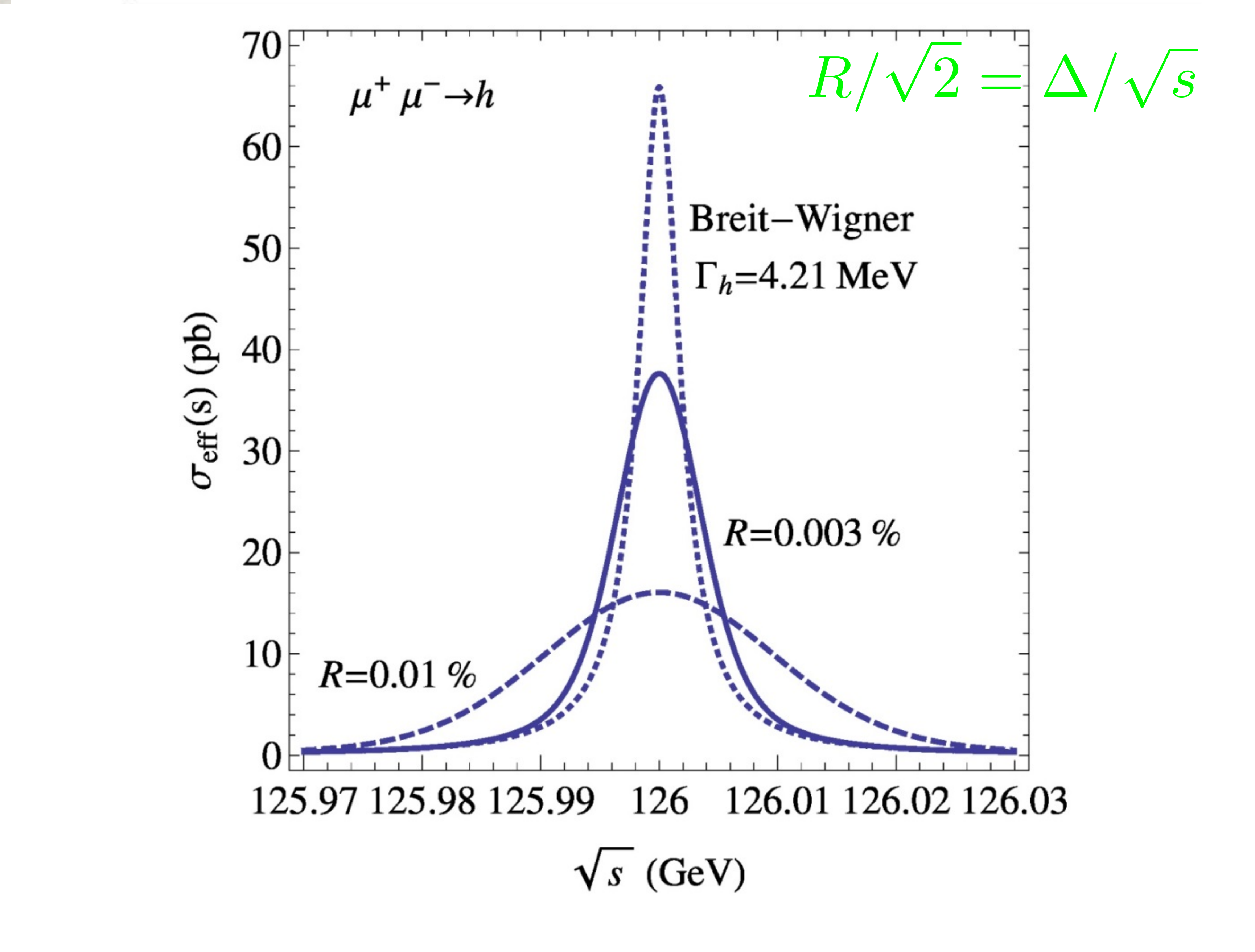
(Δ = 5 MeV, $\Gamma_h \approx 4.2$ MeV)



An optimal fitting would reveal Γ_h

Realistic studies:

- TH and Z. Liu, arXiv: 1210.7803.



$$\text{Case A}: \quad R = 0.01\% \ (\Delta = 8.9\,\text{MeV}), \ L = 0.5 \text{ fb}^{-1},$$

$$\text{Case B}: \quad R = 0.003\% \ (\Delta = 2.7\,\text{MeV}), \ L = 1 \text{ fb}^{-1}.$$

Leading signals and background rates

The SM Higgs

R (%)	$\mu^+\mu^- \to h$ $\sigma_{\rm eff}$ (pb)	$h \to b\bar{b}$		$h \to WW^*$	
		σ_{Sig}	σ_{Bkg}	σ_{Sig}	σ_{Bkg}
0.01	16	7.6	15	3.7	0.051
0.003	38	18		5.5	

With a cone angle cut: $10^o < \theta < 170^o$