PAUL SCHERRER INSTITUT

PRECISION AT FCC$_{ee}$: ELW CORRECTIONS & HIGGS

Michael Spira (PSI)

I Introduction

II ELW Physics

III Higgs Physics

IV Summary

I *INTRODUCTION*

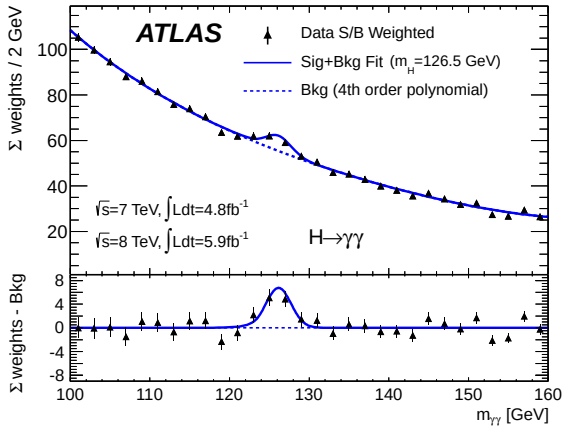
- SM very successful ← precision data [LEP, Tevatron, LHC]

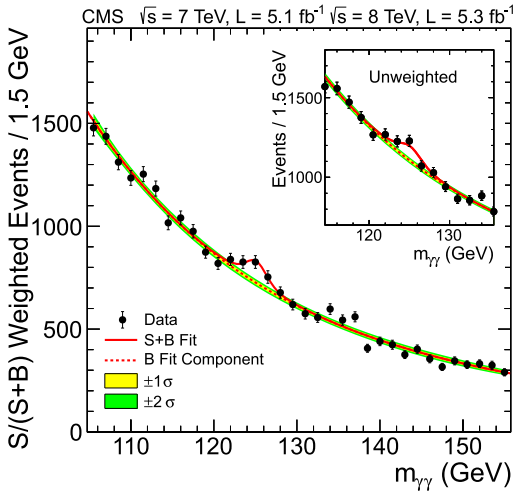
- open problems: – mechanism of electroweak symmetry breaking
  – unification of forces
  – space-time structure @ short distances

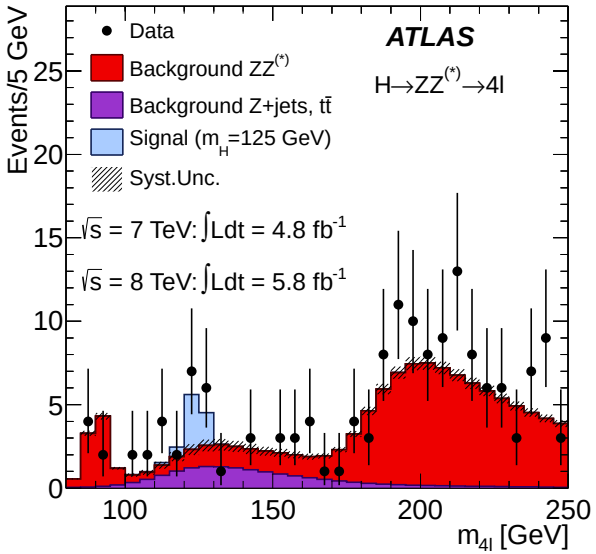
- LHC: fundamental discoveries: Higgs boson(s?)
  Supersymmetry ?
  Extra space dimensions ?

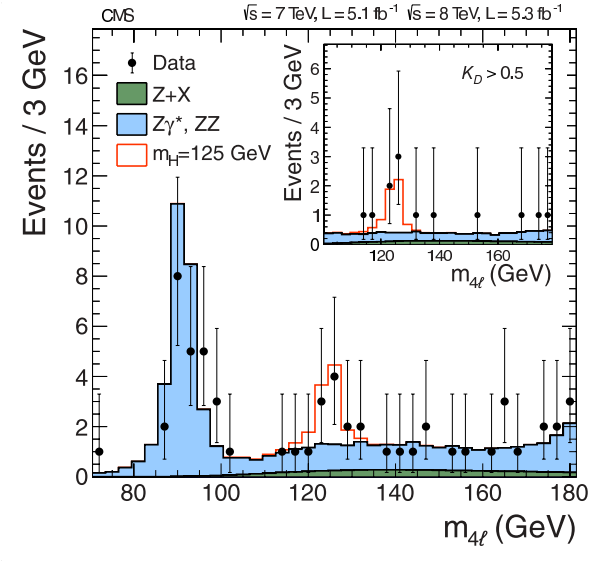
- FCC$_{ee}$: precision measurements → indirect effects
  ← precision calculations

- we have found the Higgs: $M_H \sim 125$ GeV
- $gg \longrightarrow H$ dominant

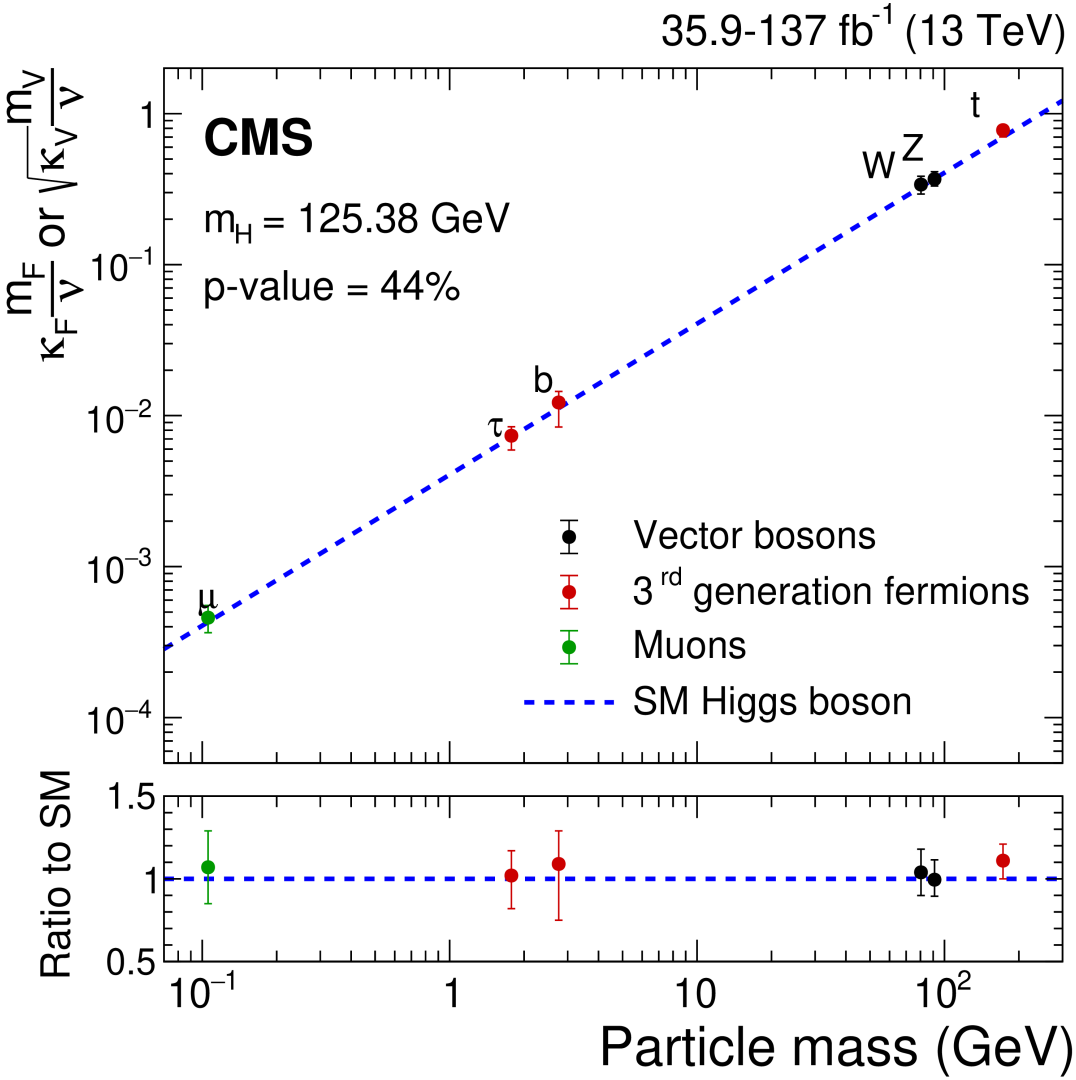






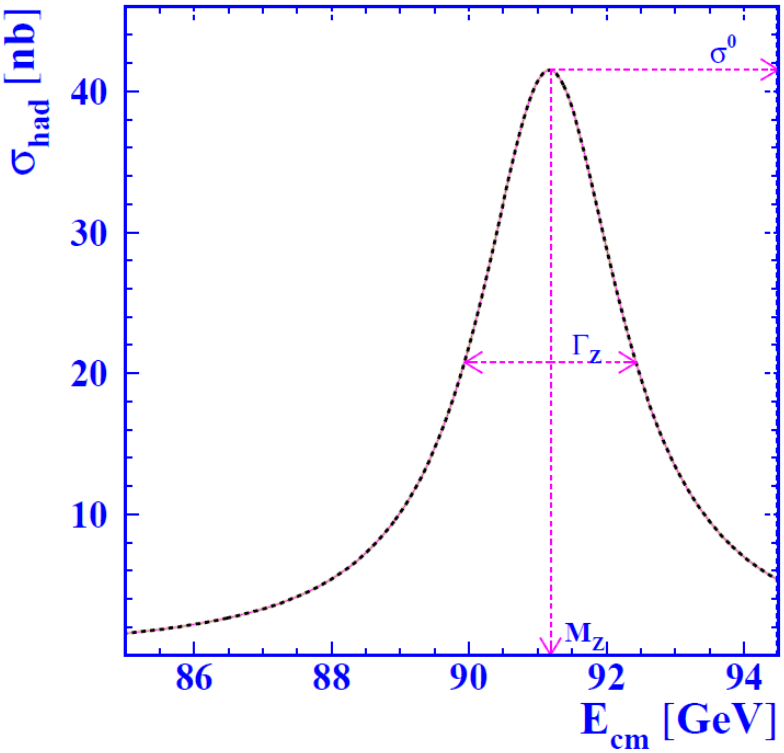


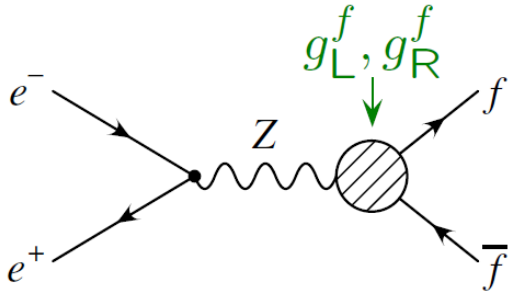
- Discovery: LHC [Tevatron]
  → Higgs mass
  couplings
  spin
  $\mathcal{CP}$
  λ ?



II *ELW PHYSICS*

- Z line shape @ LO





$e^+e^- \to f\bar{f}$ for $\sqrt{s} \sim M_Z$:

$$\sigma^0 \approx \frac{12\pi\Gamma_{ee}\Gamma_{ff}}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2} \to \frac{12\pi}{M_Z^2} R_e R_f$$

$$R_f = \Gamma_{ff}/\Gamma_Z$$

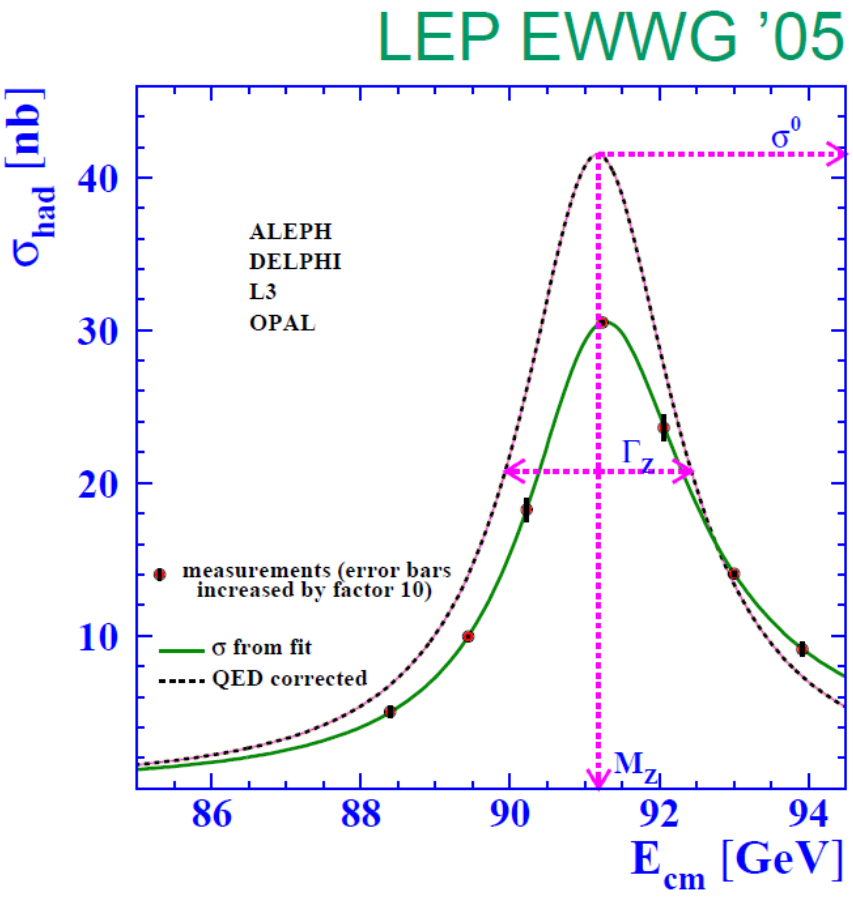
$$\Gamma_Z = \Sigma_f \Gamma_{ff} \;\to\; N_\nu(+X?)$$

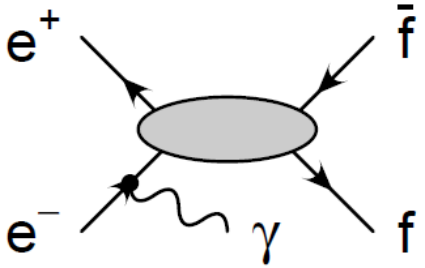
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$\mathcal{A}_f = \frac{2(1-4\sin^2\theta^f_{eff})}{1+(1-4\sin^2\theta^f_{eff})^2}$$

$$\sin^2\theta^f_{eff} = \frac{g^f_R}{2|e_f|(g^f_R - g^f_L)}$$

ISR:





$$\sigma(e^+e^- \to f\bar{f}) = \mathcal{R}_{ISR} \otimes \sigma_{hard}$$

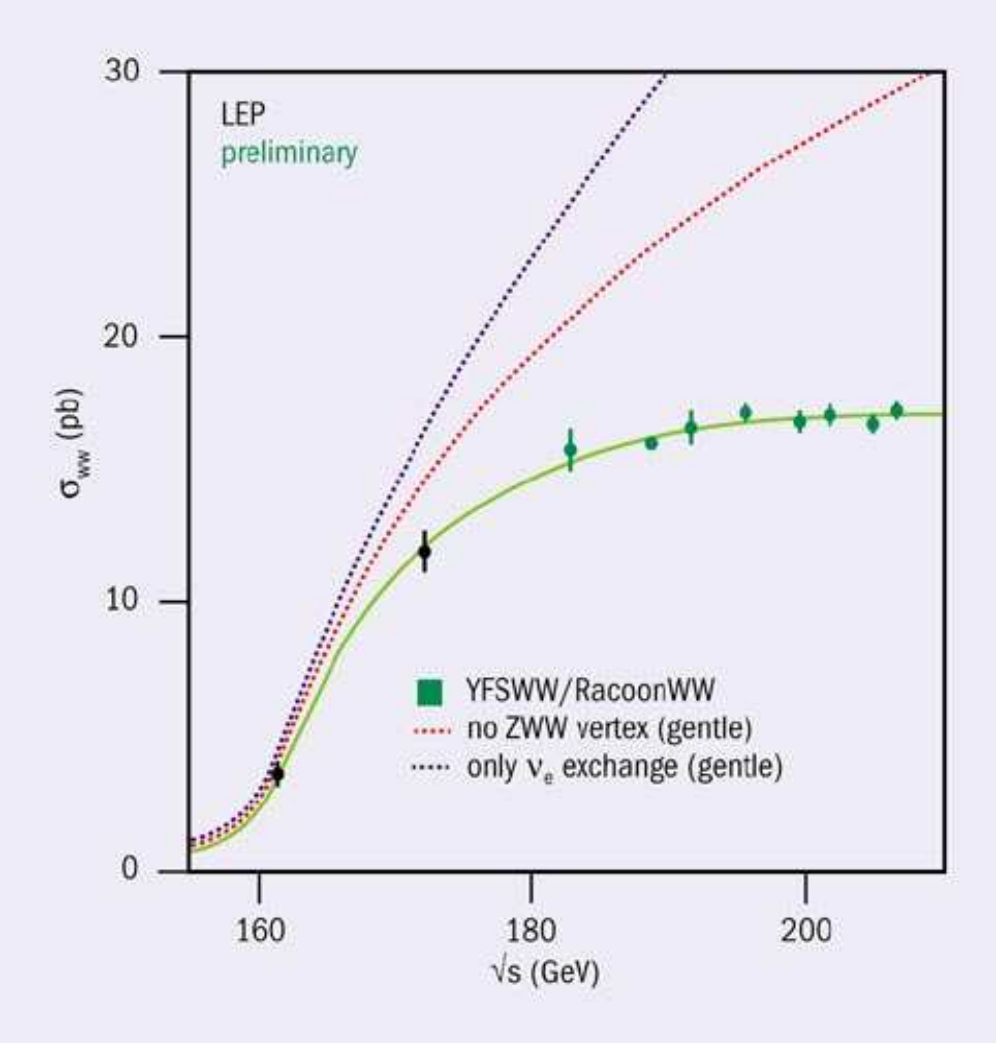
$+$ interference between ISR and FSR

$+ \sigma_{hard}$

$\Rightarrow$ sizeable uncertainties

Kuraev, Fadin
Berends, Burgers, van Neerven
Kniehl, Krawczyk, Kühn, Stewart
Beenakker, Berends, van Neerven
Bardin,. . .
Skrzypek
Montagna, Nicrosini, Piccinini
Ablinger, Blümlein, De Freitas, Schönwald

- $e^+e^- \to WW$



$e^+e^- \to W^+W^-$ near thresh.: M_W, Γ_W

$e^+e^- \to 4f$: full $\mathcal{O}(\alpha)$

Denner, Dittmaier, Roth, Wieders

Coulomb corrections $\propto 1/\beta, \log\beta$

$$\beta \sim \sqrt{\frac{\Gamma_W}{M_W}}$$

EFT expansion in $\alpha \sim \Gamma_W/M_W \sim \beta^2$

Beneke, Falgari, Schwinn, Signer, Zanderighi

NNLO Coulomb corrections

Actis, Beneke, Falgari, Schwinn

NNLO Coul. corr. + NNLO ISR:

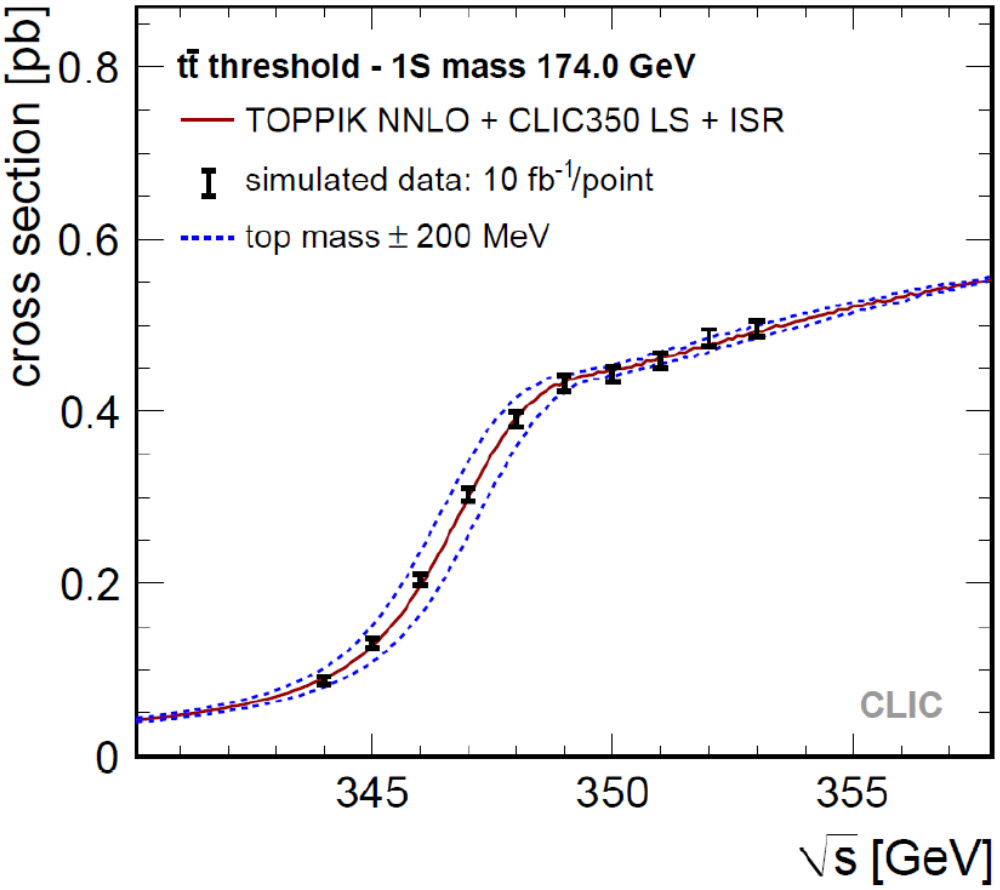
$\delta_{th} M_W \sim 0.6$ MeV

	current exp.	FCC$_{ee}$	current th.	∼3(4)-loop
M_W [MeV]	12	1	4 ($\alpha^3, \alpha^2\alpha_s$)	1
Γ_Z [MeV]	2.3	0.1	0.4 ($\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$)	0.15
R_ℓ [10^{-3}]	25	1	5 ($\alpha^3, \alpha^2\alpha_s$)	1.5
R_b [10^{-5}]	66	6	10 ($\alpha^3, \alpha^2\alpha_s$)	5
$\sin^2\theta^\ell_{eff}$ [10^{-5}]	∼13	0.5	4.5 ($\alpha^3, \alpha^2\alpha_s$)	1.5

Freitas, Heinemeyer, Beneke, Blondel, Dittmaier, Gluza, Hoang, Jadach, Janot, Reuter, Riemann, Schwinn, Skrzypek, Weinzierl

- 3/4-loop: numerical integration? Asymptotic expansions?
  ← convergence? CPU time? grids?

- $e^+e^- \to t\bar{t}$



$e^+e^- \to t\bar{t}$ near threshold: m_t, Γ_t

threshold smeared by Γ_t & Coulomb

$\to$ non-rel. GF Fadin, Khoze

potential-subtracted mass m_t^{PS}

$\leftarrow$ short dist.

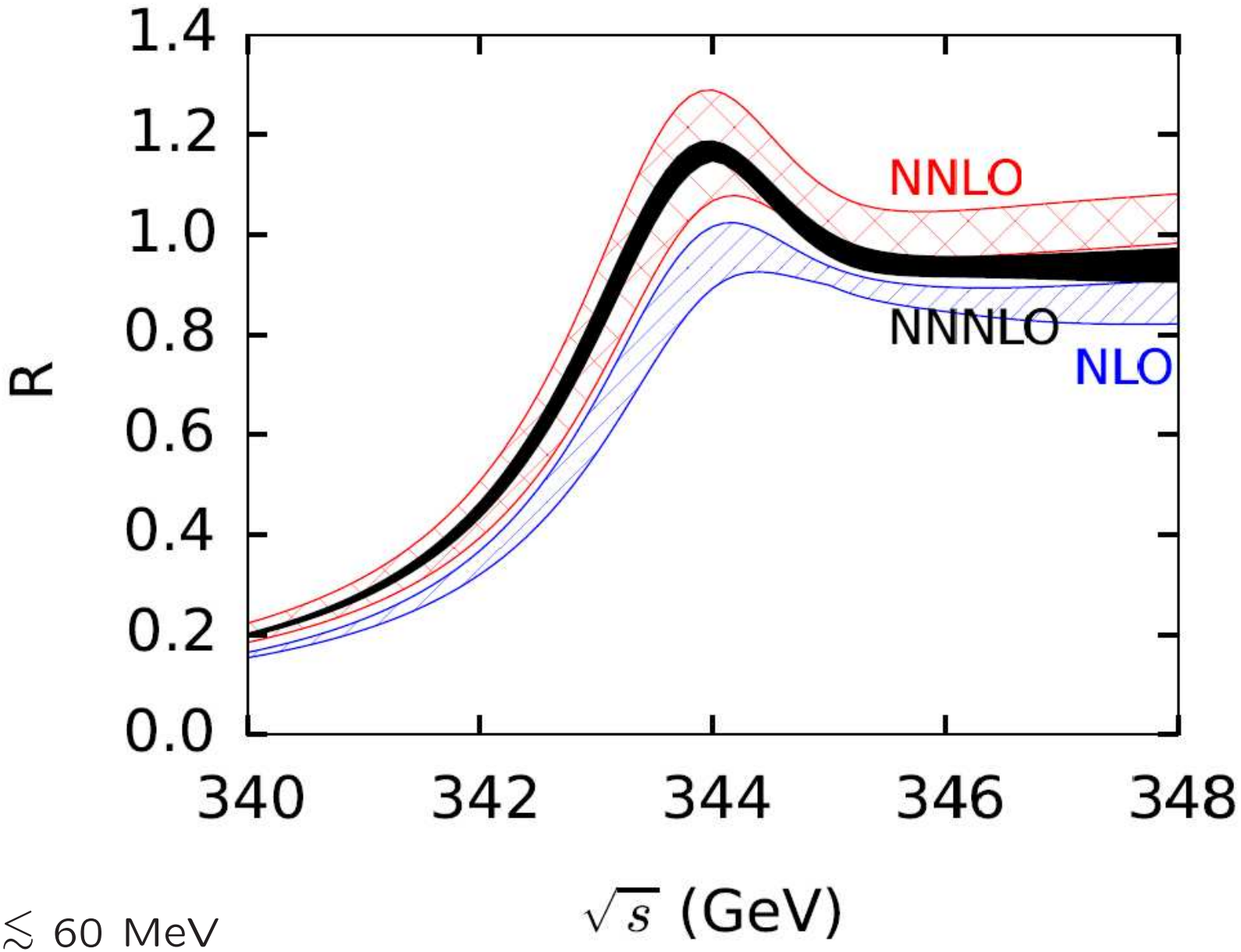
$\Gamma_t \sim 1.3$ GeV

QCD & elw. effects important

ILC/CLIC study: $\delta m_t^{PS} \sim 100$ MeV

$\delta\Gamma_t \sim 30$ MeV

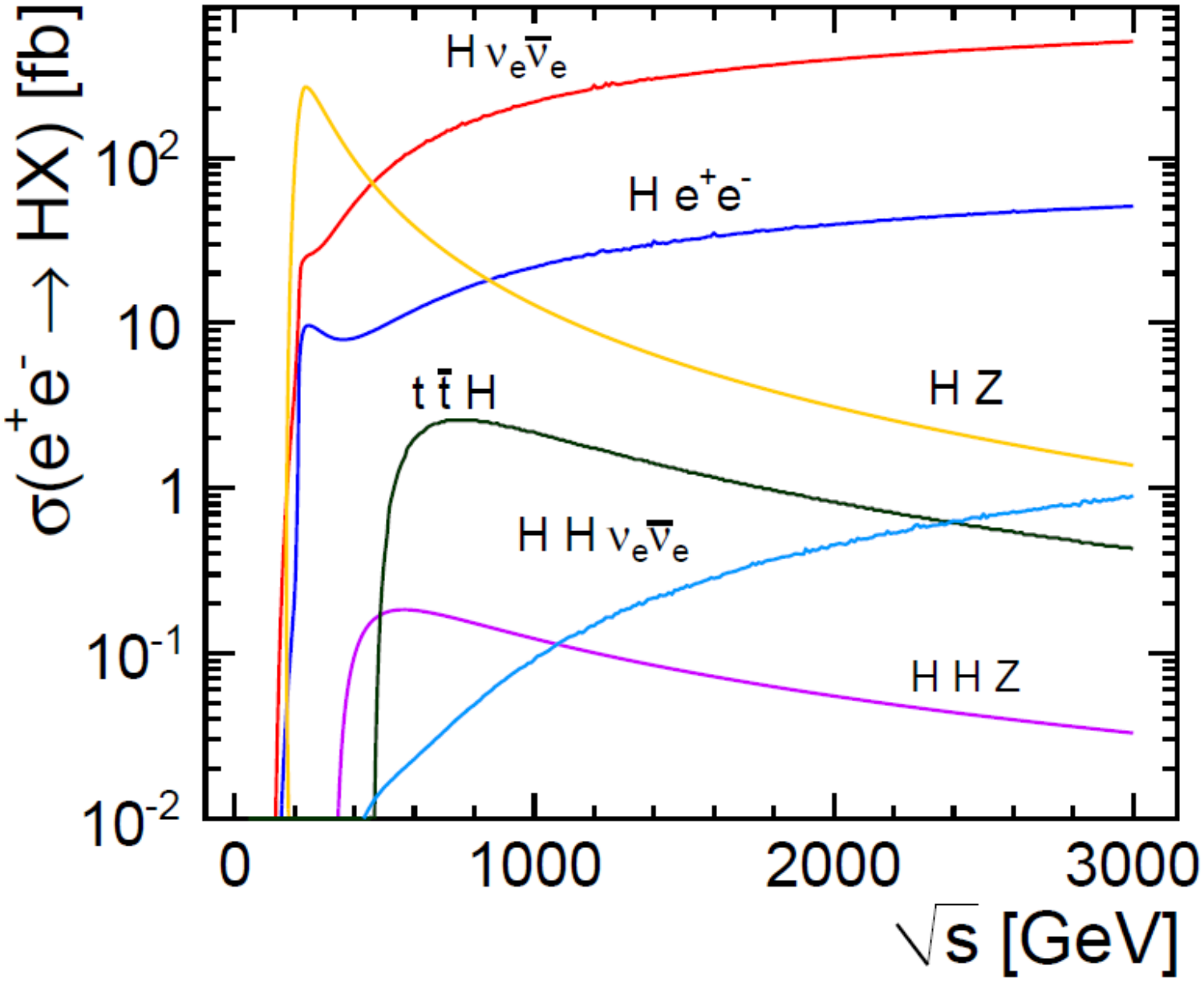
Martinez, Miquel
Seidel, Simon, Tesar, Poss
Horiguchi, Ishikawa, Suehara, Fujii, Sumino, Kiyo, Yamamoto



$\delta m_t \lesssim 60$ MeV

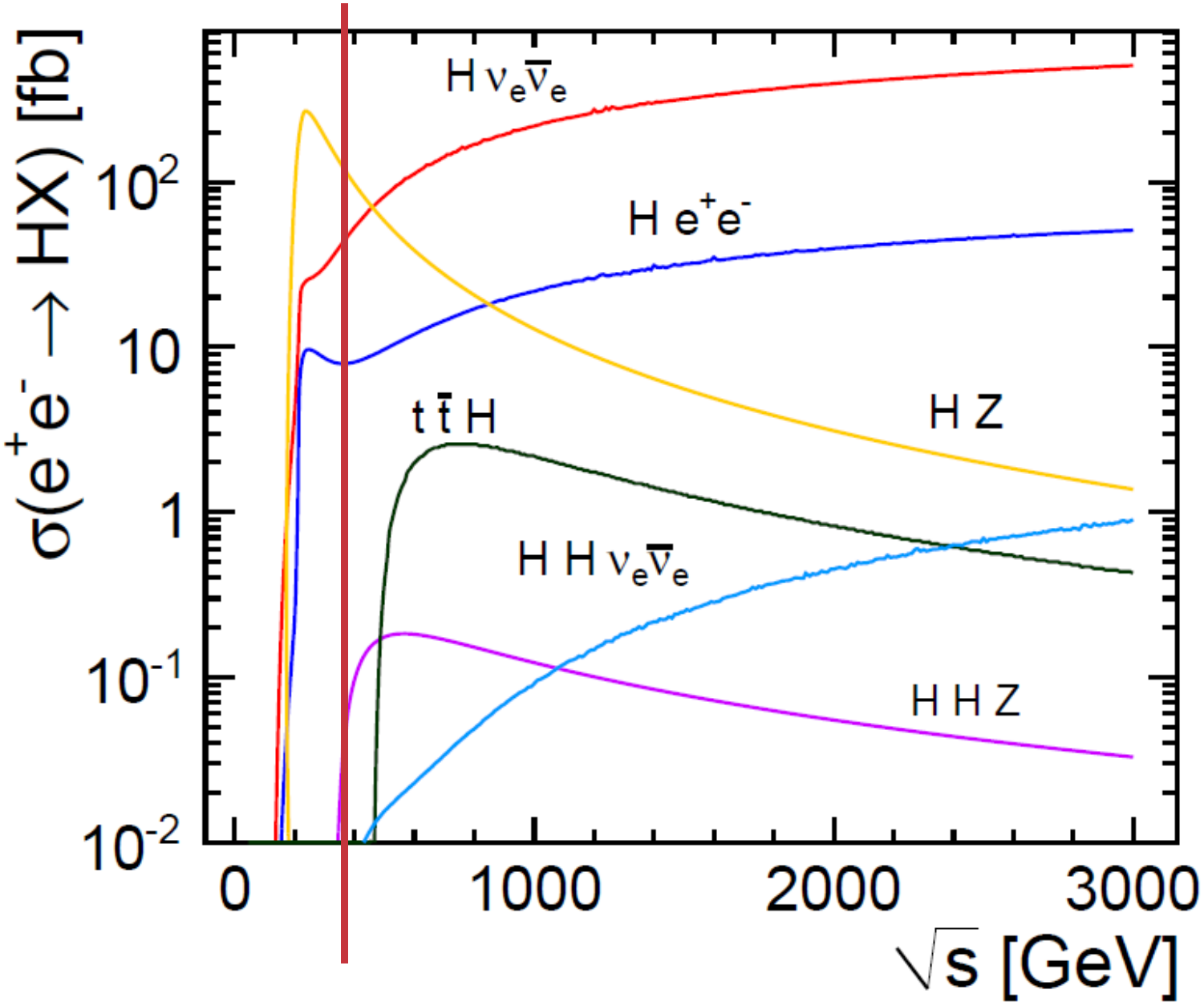
Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser

III *HIGGS PHYSICS*



ILC/CLIC study

III *HIGGS PHYSICS*



ILC/CLIC study

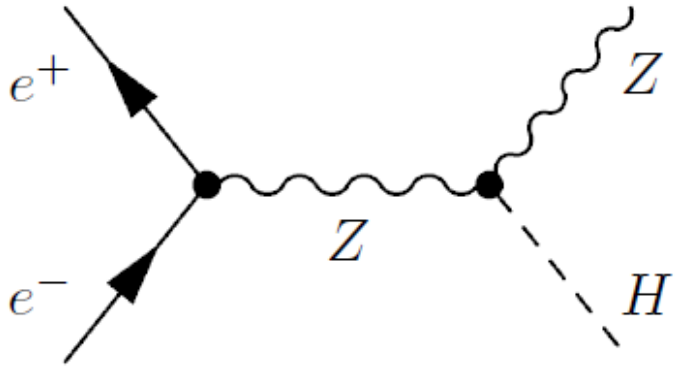
- Higgs-strahlung $e^+e^- \to ZH$ $(\propto g^2_{ZZH})$: Z monoenergetic
  $\Rightarrow M_H^2 = s - 2\sqrt{s}E_Z + M_Z^2 \Rightarrow$ reconstruction from recoil mass

full $\mathcal{O}(\alpha)$ Kniehl; Denner, Küblbeck, Mertig, Böhm

Z decay Consoli,. . . ; Jegerlehner; Akhundov,. . .

$\mathcal{O}(\alpha\alpha_s)$ Gong,. . . ; Chen,. . .

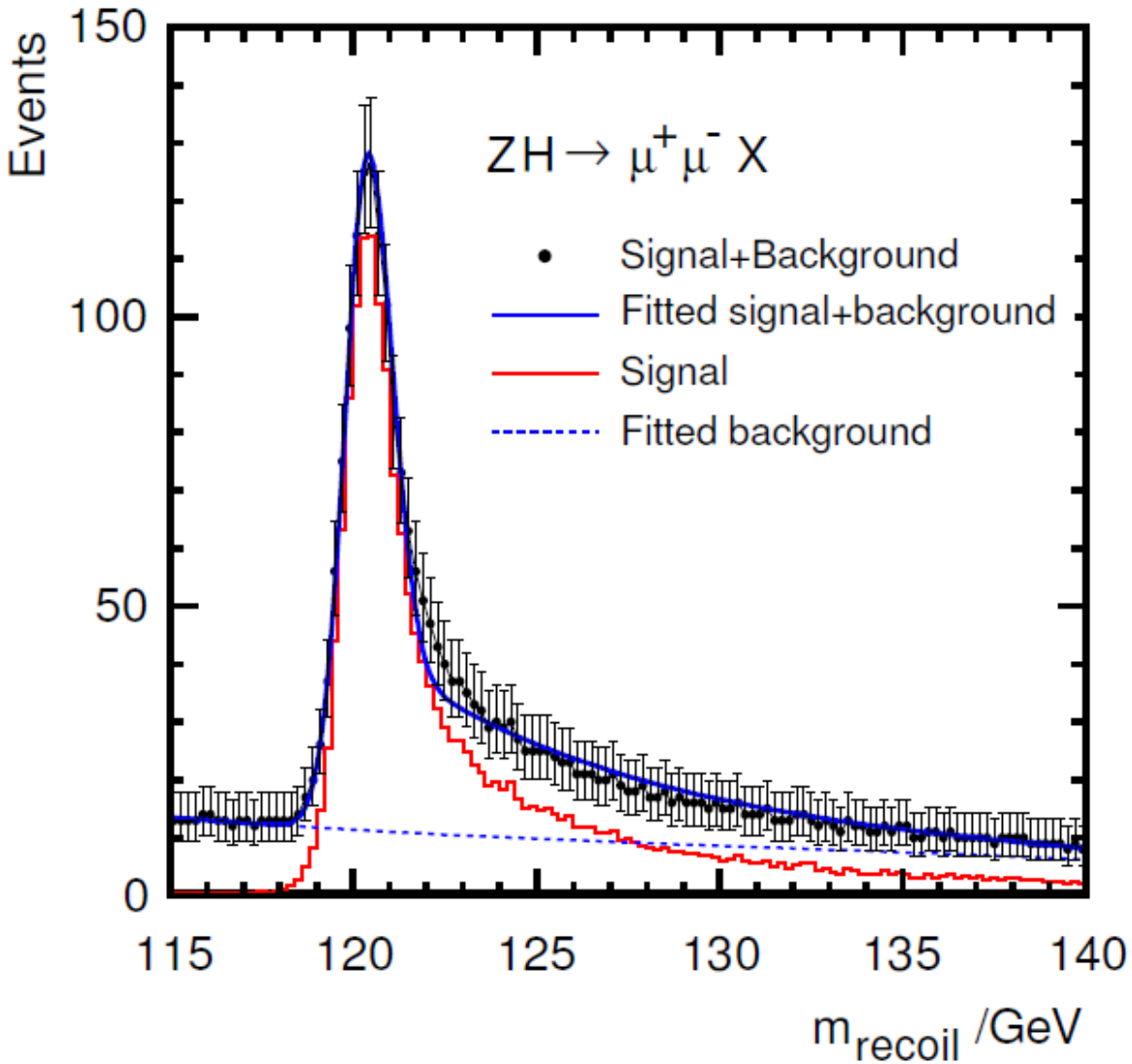
$+$ ISR $\Rightarrow \delta\sigma \sim 1\%$



W fusion $\propto g^2_{WWH}$

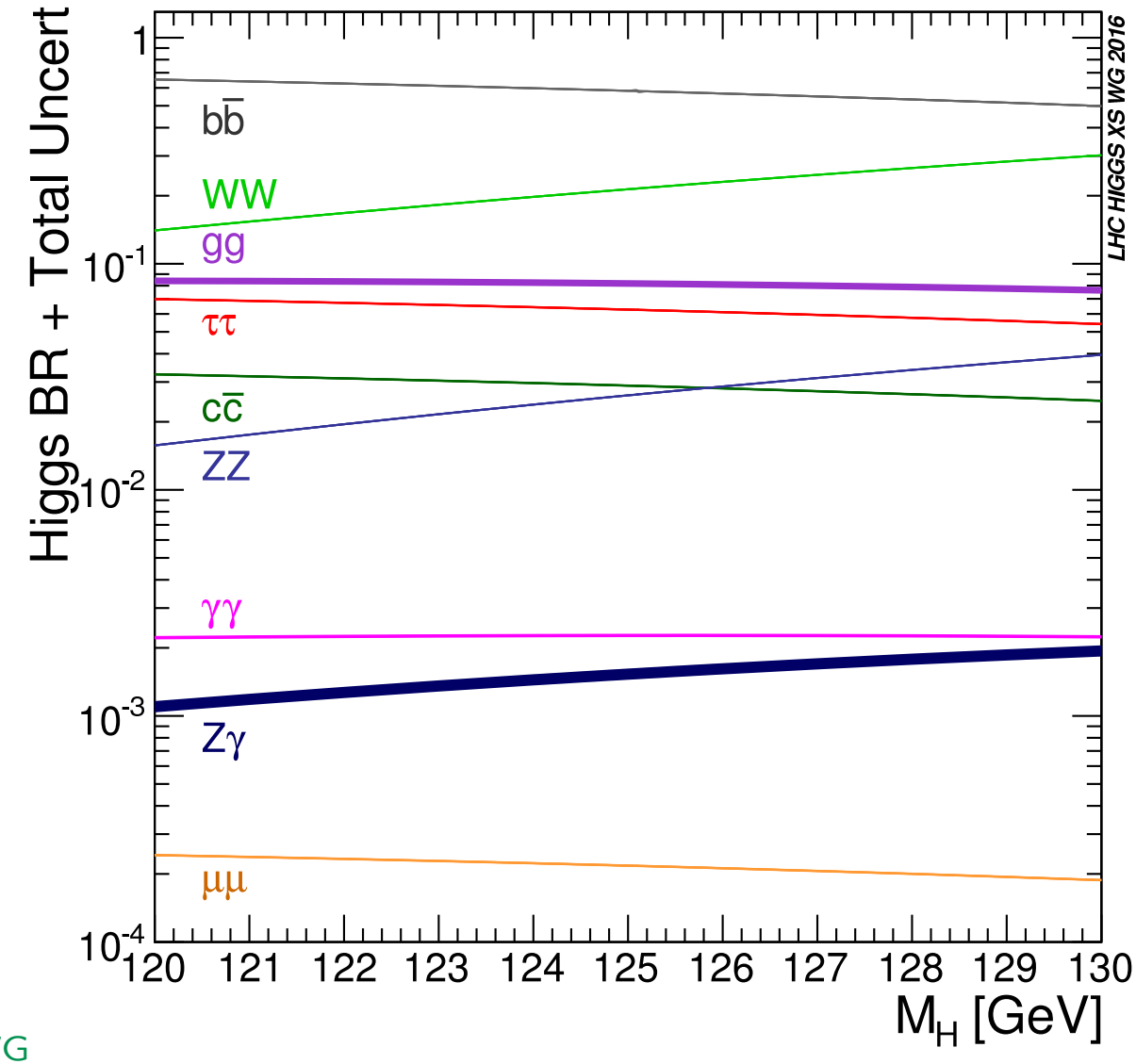
full $\mathcal{O}(\alpha)$ Belanger,. . . ; Denner,. . .

$\delta M_H \lesssim 50$ MeV

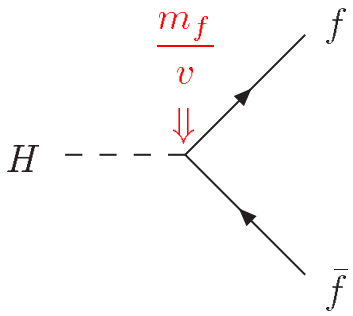


ILC/CLIC study

Higgs Boson BRs



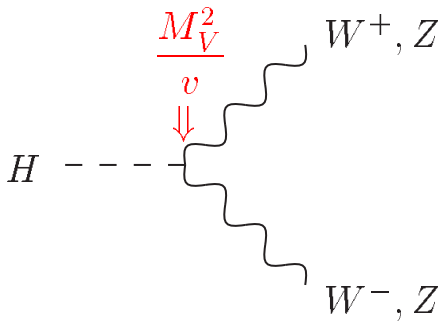
LHC Higgs WG



$$BR(H \to b\bar{b}) \sim 58\%$$
$$BR(H \to \tau^+\tau^-) \sim 6\%$$
$$BR(H \to c\bar{c}) \sim 3\%$$
$$BR(H \to \mu^+\mu^-) \sim 0.02\%$$

$$\Gamma(H \to f\overline{f}) = \frac{N_c G_F M_H}{4\sqrt{2}\pi}\, m_f^2\, (1 + \delta_{\rm QCD} + \delta_t + \delta_{mixed})\,(1 + \delta_{elw})$$

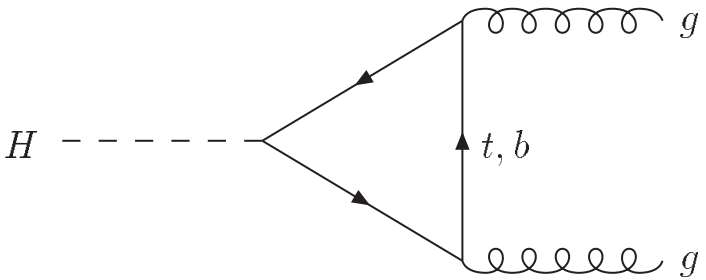
- dominant effect: $m_b \to \overline{m}_b(M_H) \Rightarrow \sim 25\%$ remaining



$$BR(H \to W^{+(*)}W^{-(*)}) \sim 21\%$$
$$BR(H \to Z^{(*)}Z^{(*)}) \sim 3\%$$

below threshold: $H \to V^{(*)}V^*$ important for $M_H \gtrsim M_V$ — Rizzo; Keung, Marciano; Cahn

- elw. corr.: $\sim 5\%$ — Fleischer, Jegerlehner; Bardin,. . . ; Kniehl; Bredenstein, Denner, Dittmaier, Weber

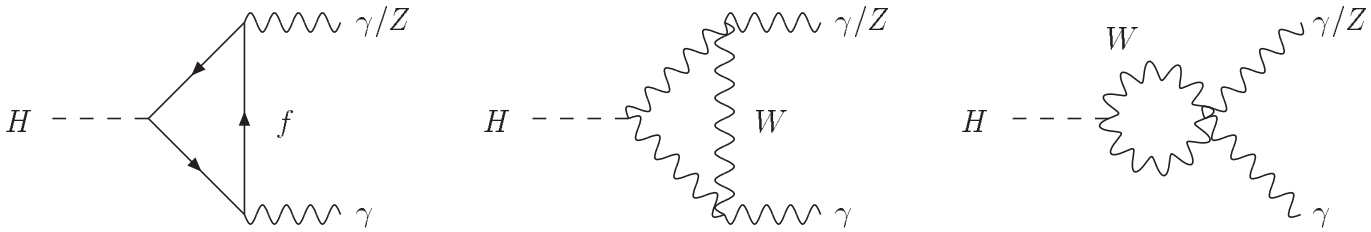


$BR(H \to gg) \sim 8\%$

- large QCD corrections: $\sim +90\%$

Inami, Kubota, Okada
S., Djouadi, Graudenz, Zerwas
Chetyrkin, Kniehl, Steinhauser
Baikov, Chetyrkin
Herzog, Ruijl, Ueda, Vermaseren, Vogt

$$\Gamma\,(H \to gg) \approx \Gamma_{LO}\,\{1 + 0.67 + 0.20 + 0.02\}$$



W–loop dominant

$BR(H \to \gamma\gamma, Z\gamma) \lesssim 2 \times 10^{-3}$

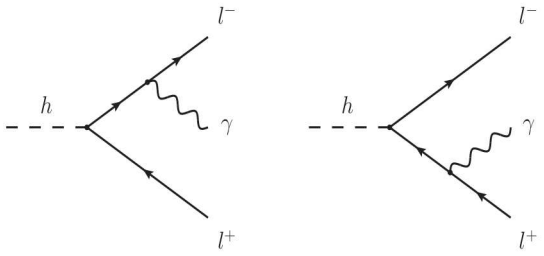
- QCD corrections: $\sim 2\%$ in intermediate mass range

Zheng, Wu
Djouadi, S., Zerwas
Melnikov, Yakovlev
Inoue,. . .

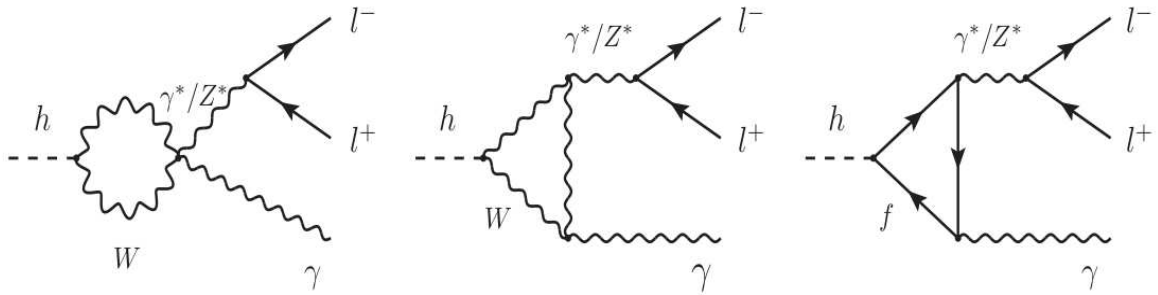
- elw. corr.: $\sim -2\%$

Aglietti, Bonciani, Degrassi, Vicini
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

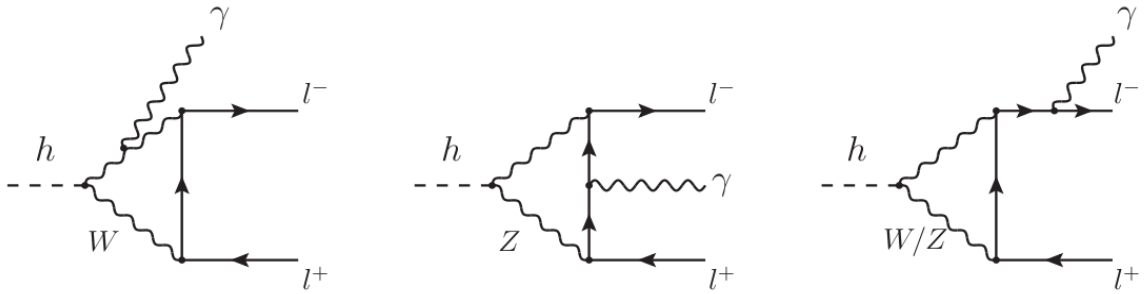
HIGGS DALITZ DECAYS



tree

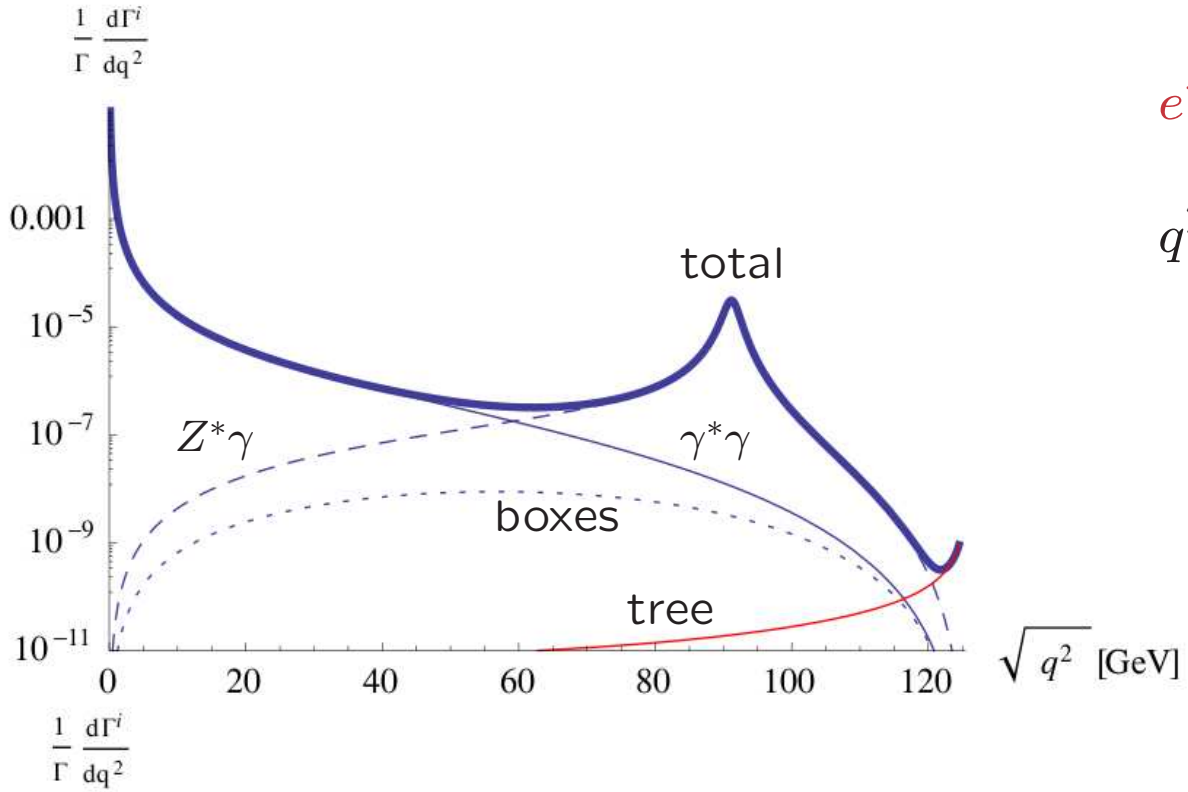


off-shell



boxes

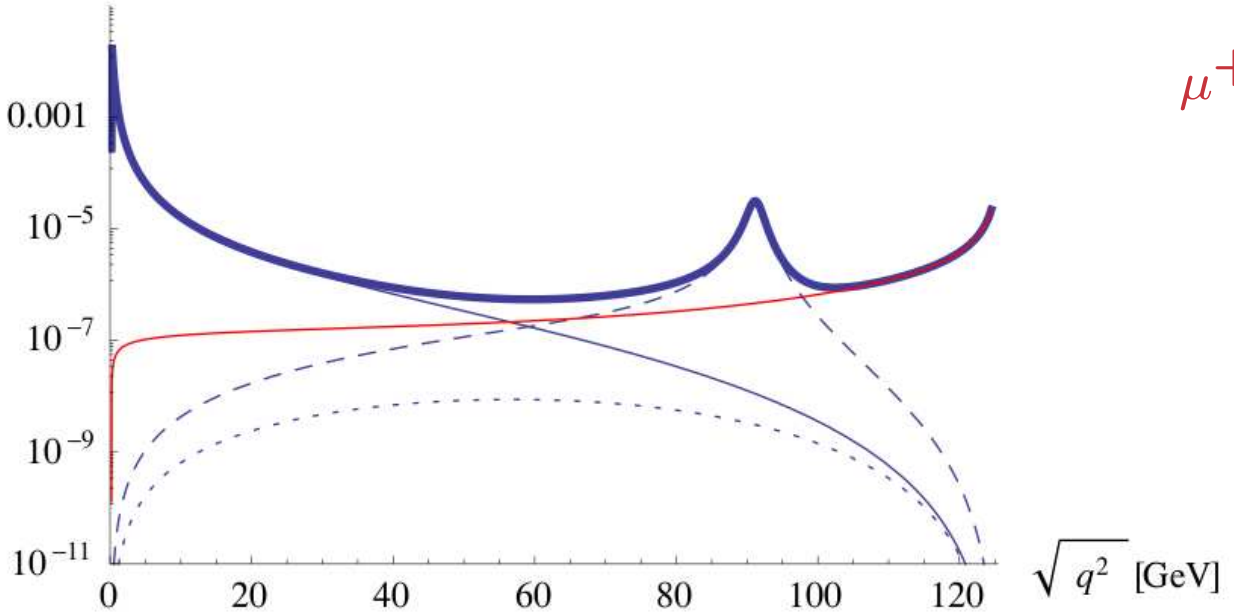
Abbasabadi, Bowser–Chao, Dicus, Repko
Sun, Chang, Gao
Passarino



$e^+e^-\gamma$

$q^2 = M^2_{\ell^+\ell^-}$

Sun, Chang, Gao



$\mu^+\mu^-\gamma$

- Dalitz decays ($H \to Z\gamma \Leftrightarrow H \to \ell^+\ell^-\gamma \Leftrightarrow H \to \gamma\gamma$)

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$	$\sim 0.5\%$	N^{4}LO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$	$\sim 0.5\%$	NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	N^{3}LO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$	(N)NLO

- parametric uncertainties:

  $m_t = 172.5 \pm 1$ GeV $\alpha_s(M_Z) = 0.118 \pm 0.0015$

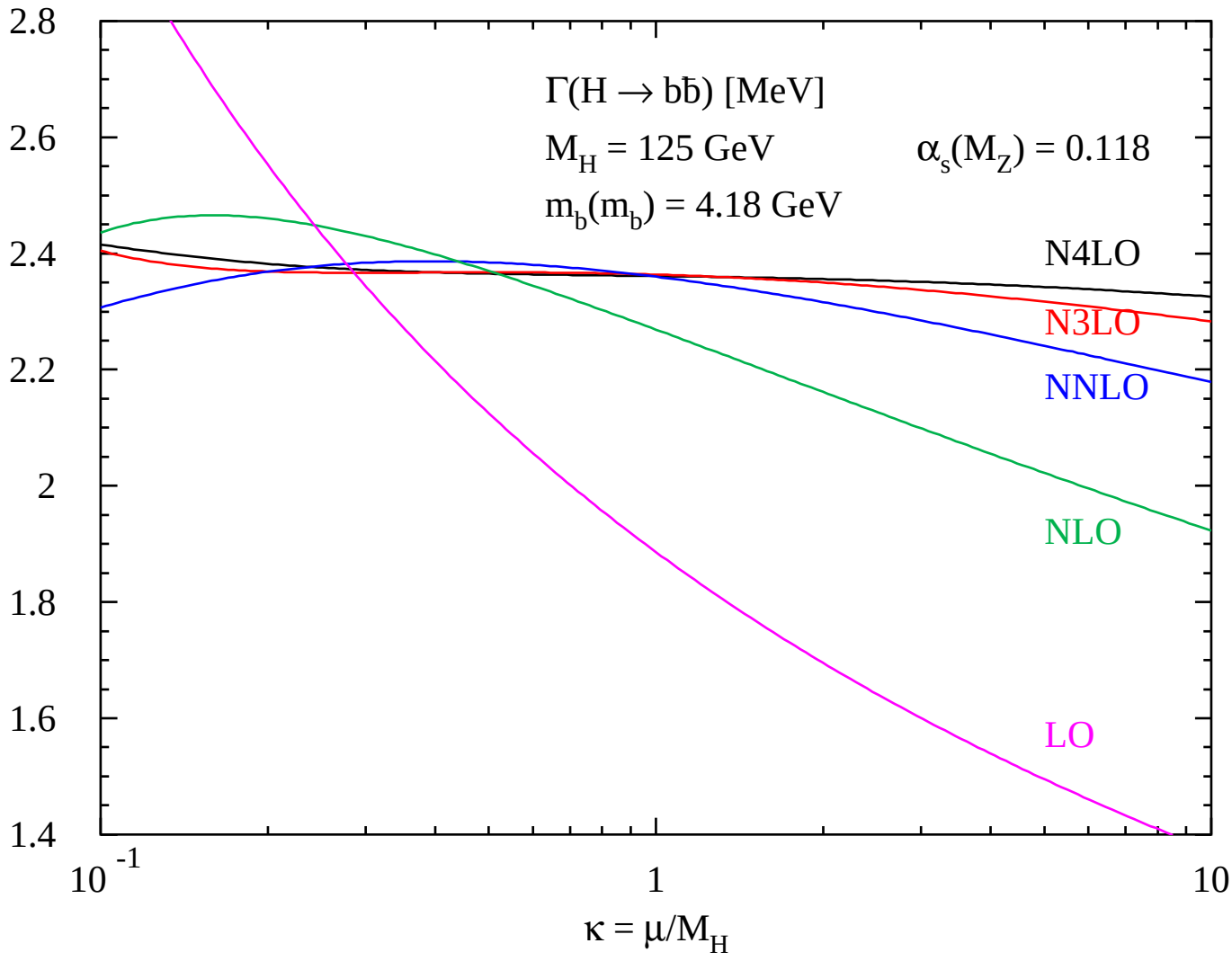
  $m_b(m_b) = 4.18 \pm 0.03$ GeV $m_c(3\text{GeV}) = 0.986 \pm 0.025$ GeV

  different uncertainties added quadratically for each channel

- total uncertainties: parametric & theor. uncertainties added linearly

- dominated by parametric uncertainties: $m_b(b\bar{b}), \alpha_s(gg), m_c(c\bar{c})$

- parametric unc. from M_H small



Braaten, Leveille
Drees, Hikasa
Kataev,. . .
Chetyrkin,. . .
etc.

	FCC$_{ee}$	current th.	current par.
$H \to b\bar{b}$	0.8%	0.5%	2.2%
$H \to c\bar{c}$	1.4%	0.5%	5.5%
$H \to \tau^+\tau^-$	1.1%	0.5%	$< 0.1\%$
$H \to \mu^+\mu^-$	12%	0.5%	$< 0.1\%$
$H \to gg$	1.6%	3.2%	3.0%
$H \to \gamma\gamma$	3.0%	1.0%	$< 0.1\%$
$H \to Z\gamma$	???	5.0%	$< 0.1\%$
$H \to WW$	0.4%	0.5%	$< 0.1\%$
$H \to ZZ$	0.3%	0.5%	$< 0.1\%$

IV *SUMMARY*

- elw/QCD corrections extremely important

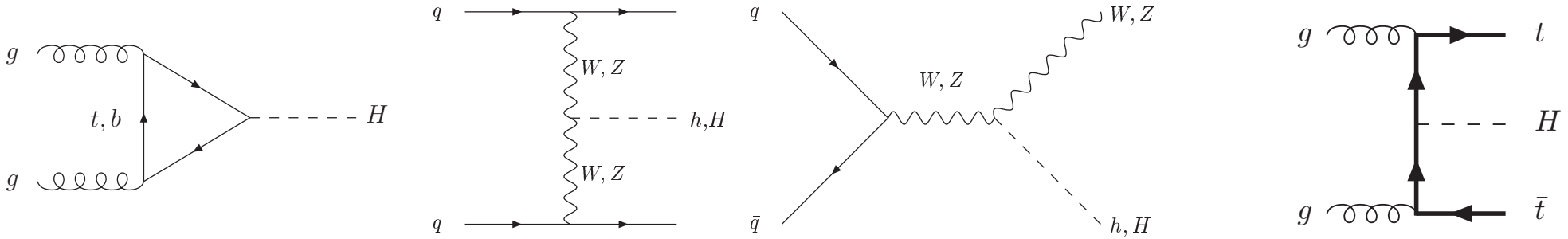
- demands by FCC: beyond present state of the art
  $\Rightarrow$ new techniques (numerical, approx., analytical???)

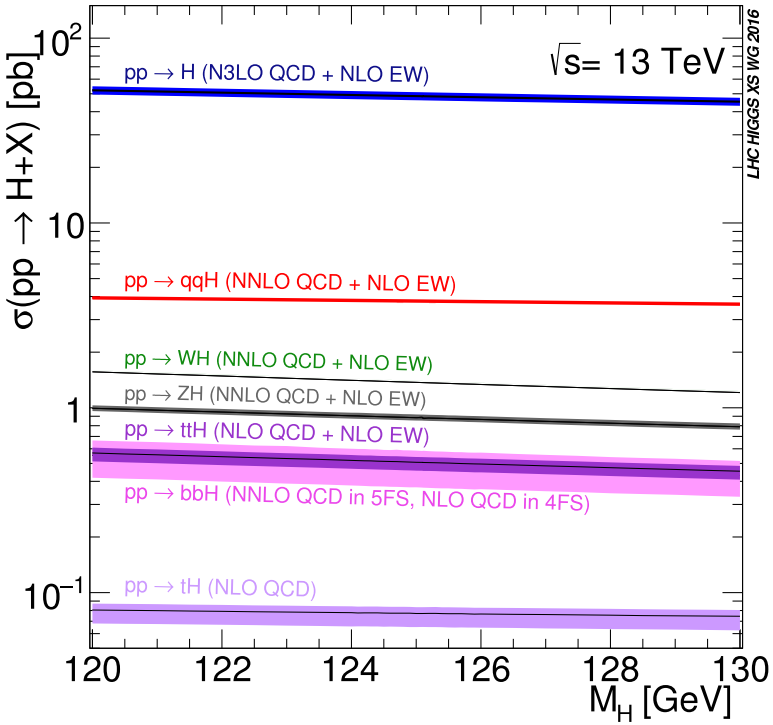
- BSM: $\mathcal{O} = \mathcal{O}_{SM} + \Delta\mathcal{O}_{BSM}$ $\leftarrow \delta\mathcal{O}_{SM}$ limiting factor

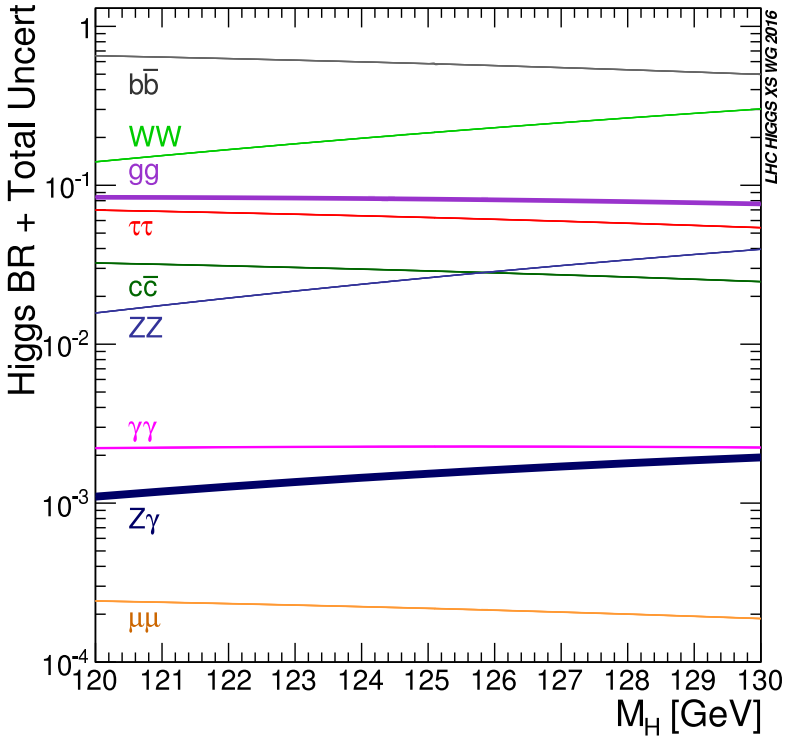
- many improvements needed $\rightarrow$ 30 years (?)

BACKUP SLIDES

- Higgs Boson Production & Decay



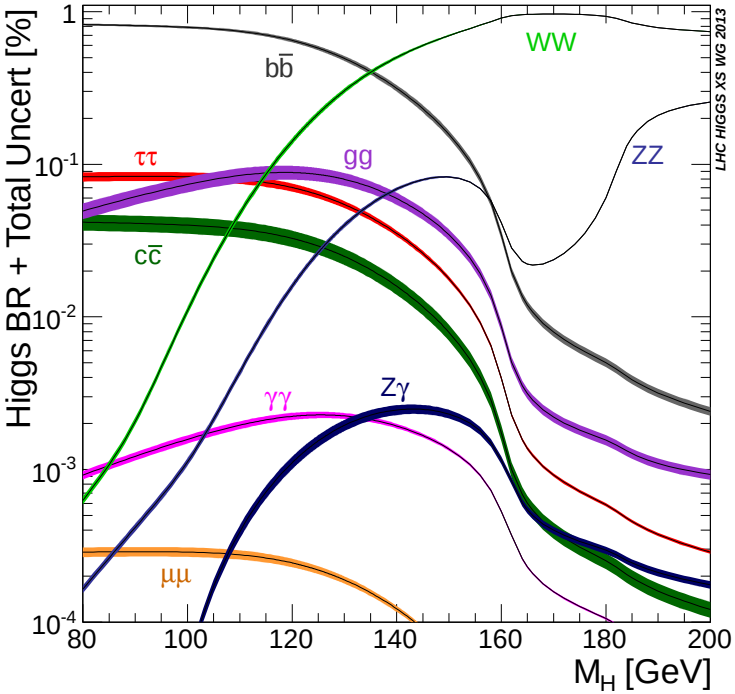




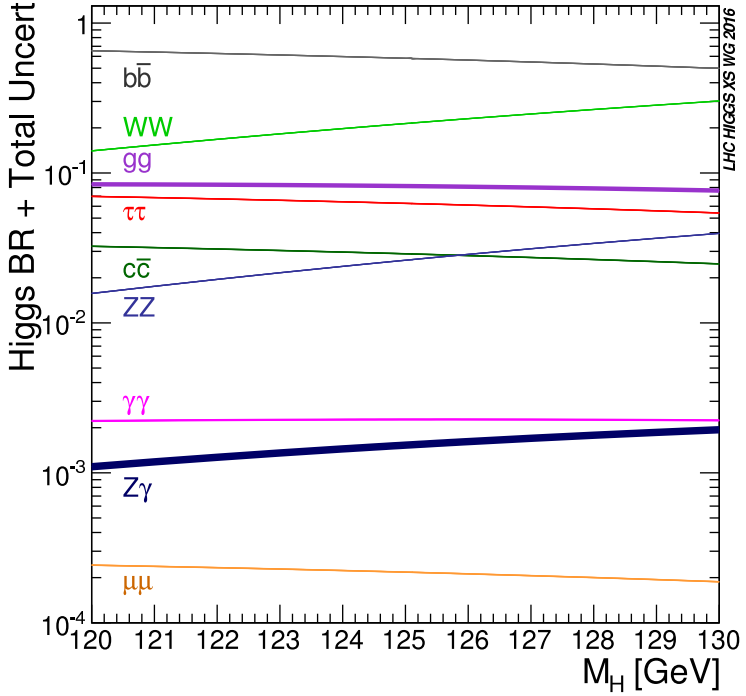
LHC Higgs WG

YR3 (2013) HDECAY & Prophecy4f YR4 (2016)

$\sim$ 10% $\rightarrow$
$\sim$ 10% $\rightarrow$



$\longrightarrow$



Denner, Heinemeyer, Puljak, Rebuzzi, S.

- refinements input parameters
- full NLO elw. corrections to $H \to f\bar{f}$
- NLO quark-mass effects in $H \to gg$