Muon Collider as a Higgs Factory

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* Tao Han and Zhen Liu, arXiv: 1210.7803

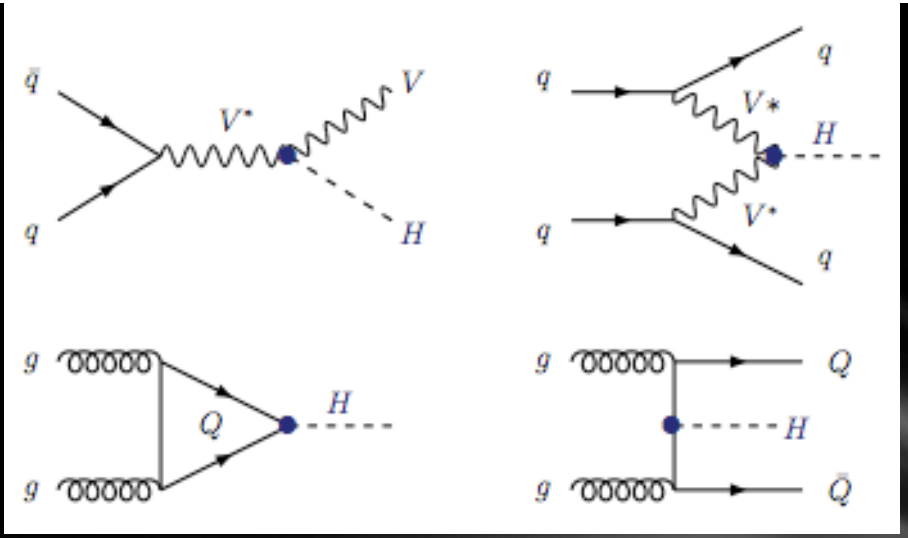
In celebrating the discovery of a SM-like Higgs boson, it is high time to start a Higgs factor program:

- Precision determination of mass
- Spin, CP properties
- BR's, partial widths

  probe fundamental interactions
- Total width

  count for all modes, including invisible…

The measurements of the partial widths & the total width:



At the LHC

- inaccurate knowledge of parton energy
- Inadequate energy/momentum resolutions

Impossible to determine the total width (~ MeV)

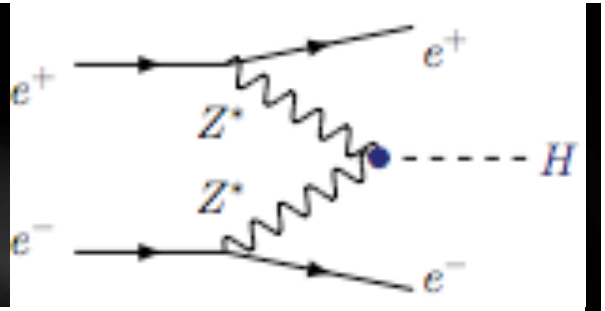
nor a partial width: $\sigma \sim \Gamma_i \Gamma_f / \Gamma_h$

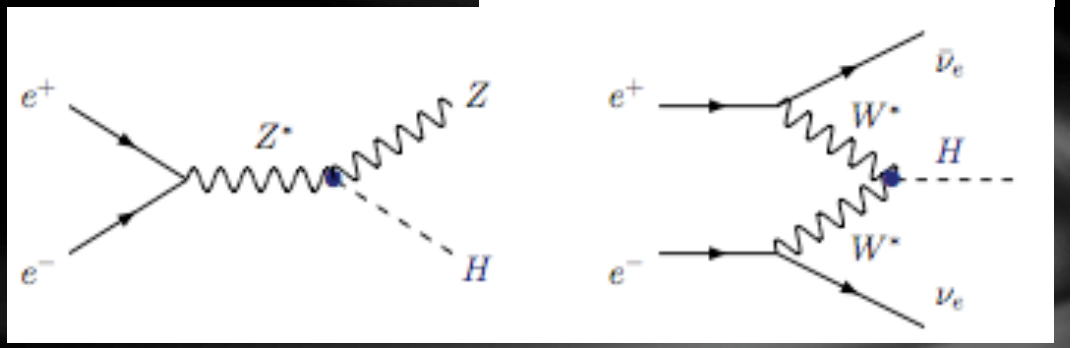
Commonly assume SM-like,* or relations+

* M. Duhrssen, hep-ph/0406323.

\+ M. Peskin, arXiv: 1207.2516; Dobrescu+Lykken, arXiv: 1210.3342.

The measurements of the partial widths & the total width:





At an ILC

- Accurate knowledge of beam energy
- "recoil mass technique" to obtain inclusive signal

$$m^2(\text{recoil}) = (p_{i1} + p_{i2} - p_{f1} - p_{f2})^2 = m_h^2$$

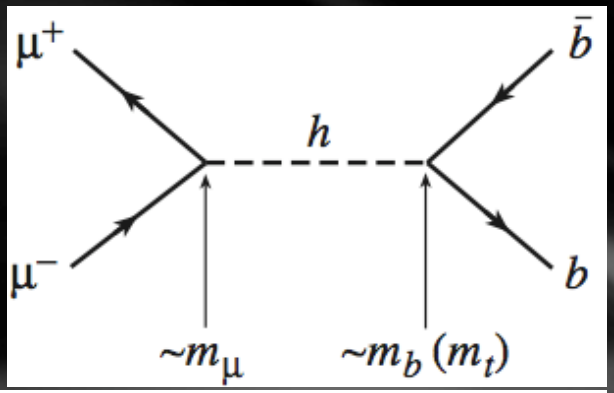
→ g_{ZZH} to 1.5% @ 250 GeV/250 fb^{-1}.*
Thus, partial width Γ_{ZZH} calculated

→ $\Gamma(H) = \Gamma_{ZZH} / BR_{ZZH}$ calculated at 10% - 20%.

* James Brau et al., arXiv: 1210.0202

s-channel production most beneficial

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}

Muon Collider as a Higgs Factory

S-Channel 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 m_h=126 GeV, Γ_h = 4.2 MeV

Convoluted with energy profile:

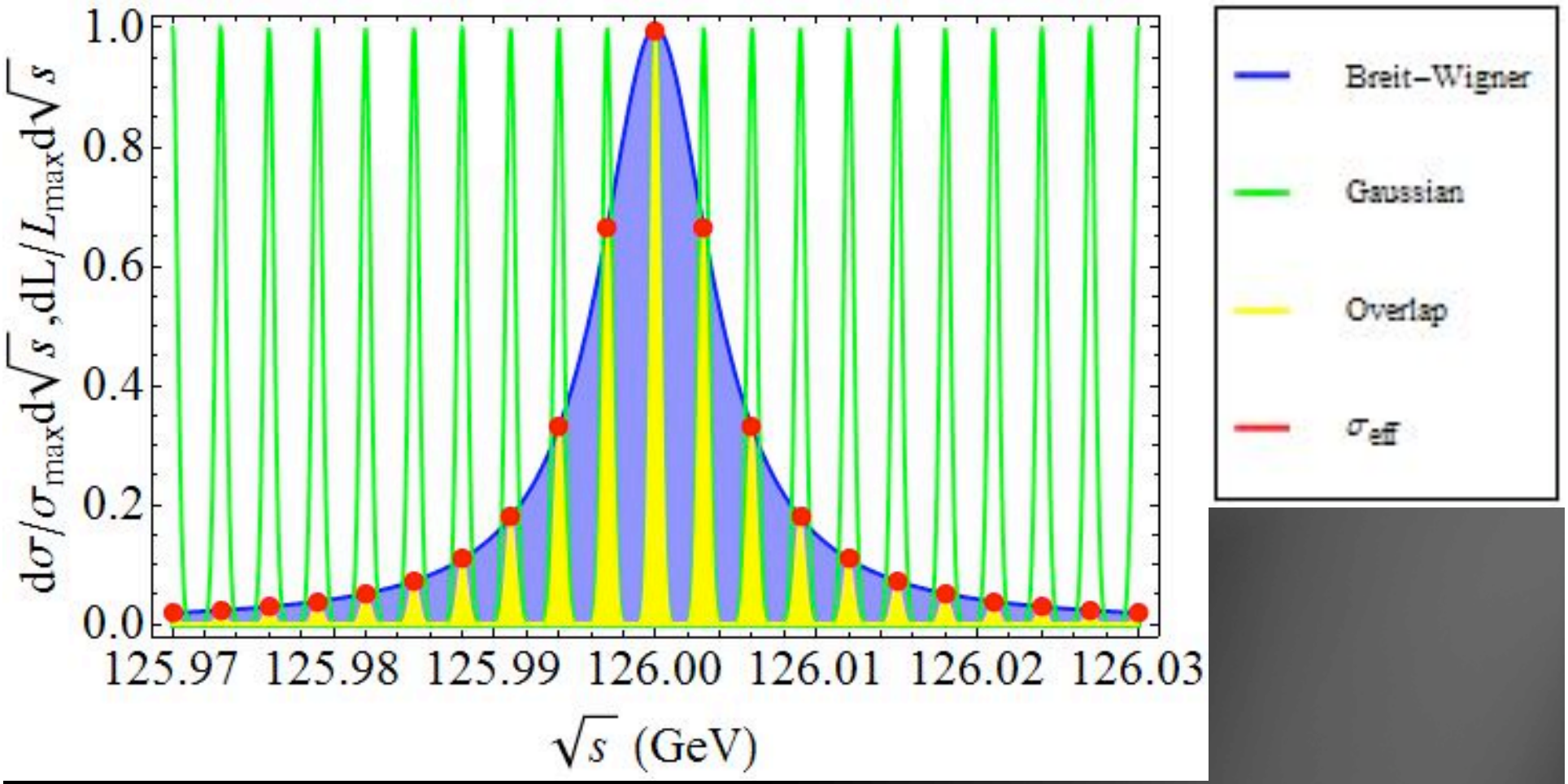
$$\sigma_{\mathrm{eff}}(s) = \int d\sqrt{\hat{s}}\ \frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\sigma(\mu^+\mu^- \to h \to X)$$

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

Extreme (good) Case:

Energy Spread much smaller than the physical width:

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

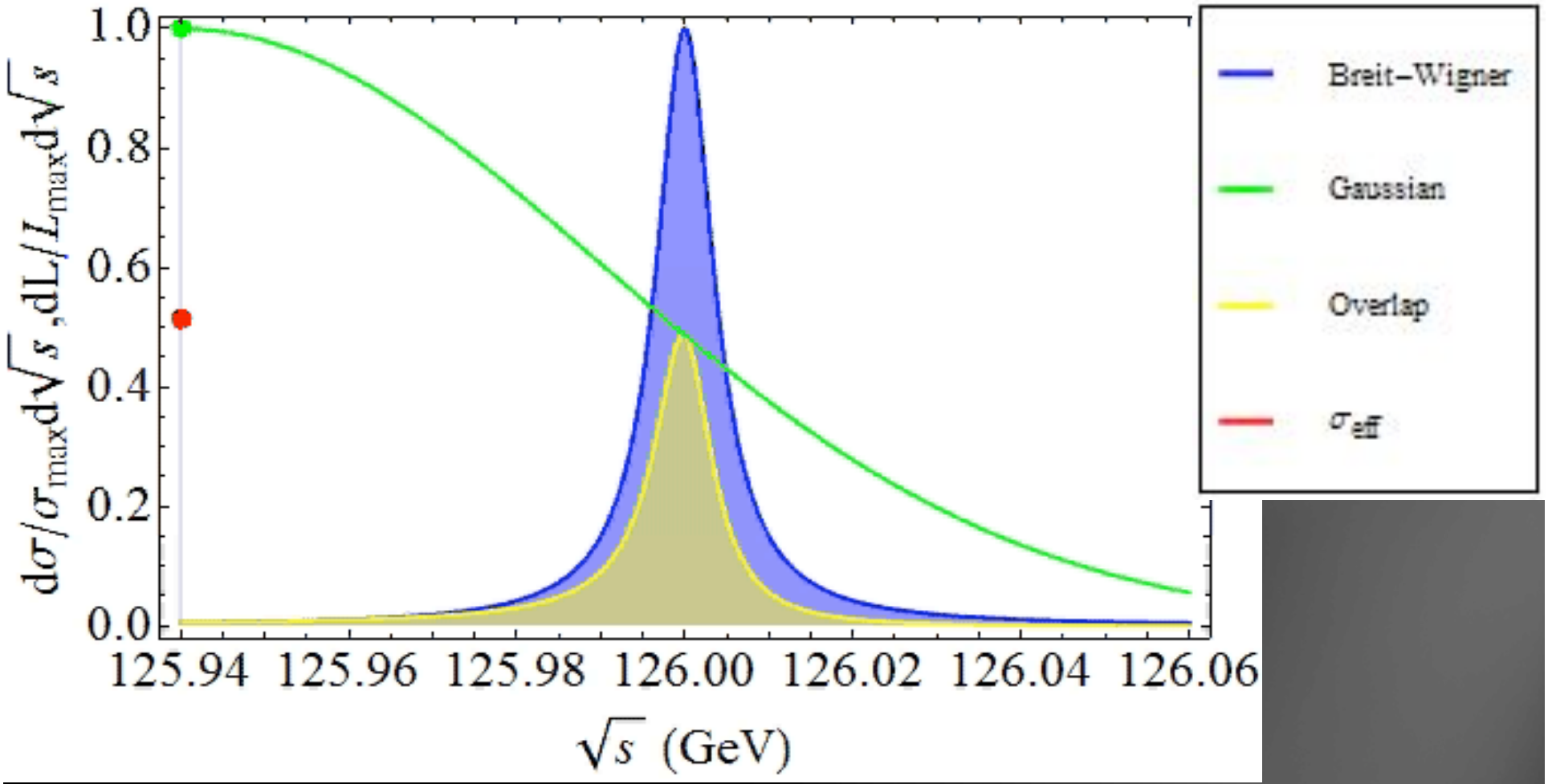


Recall: Z line shape with $\Gamma_Z \approx$ 2.5 GeV

Extreme (bad) Case:

Energy Spread much larger than the physical width:

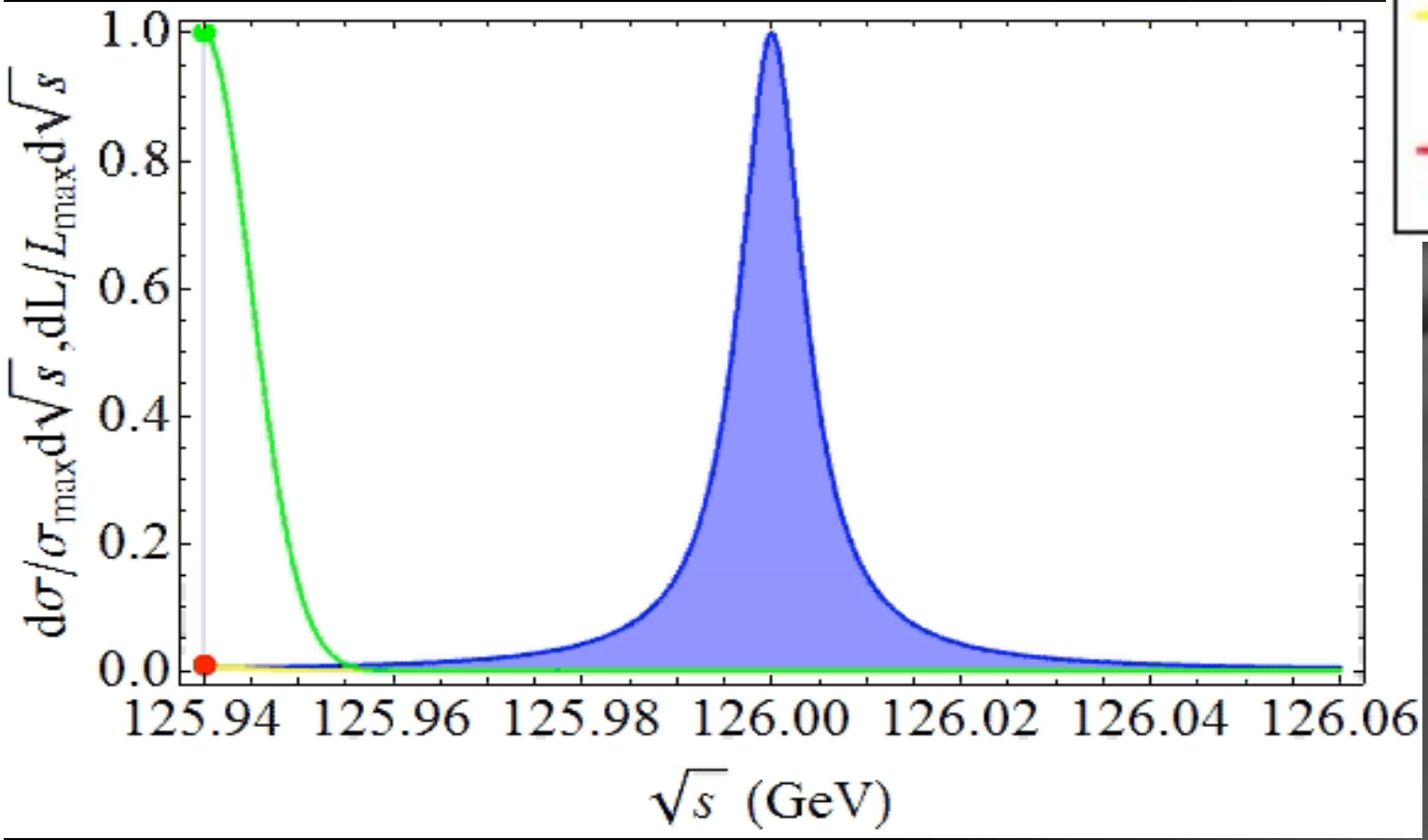
(Δ = 50 MeV, $\Gamma_h \approx 4.2$ MeV)

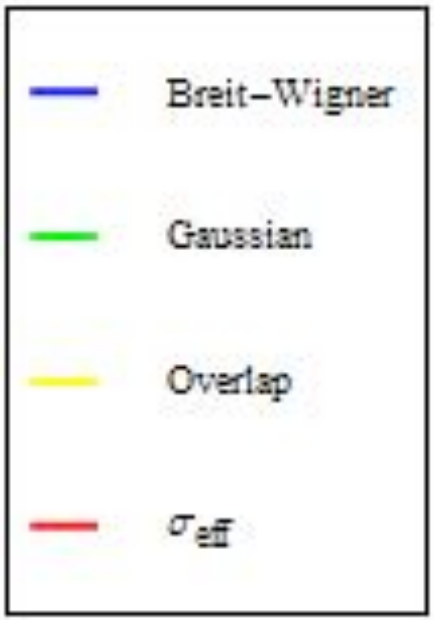


Recall: J/ψ scan $\Gamma \approx 93$ keV

"Normal" (ideal) case:

Energy Spread=5 MeV





An optimal fitting would reveal Γ_h

Realistic studies:

* TH and Z. Liu, arXiv: 1210.7803.

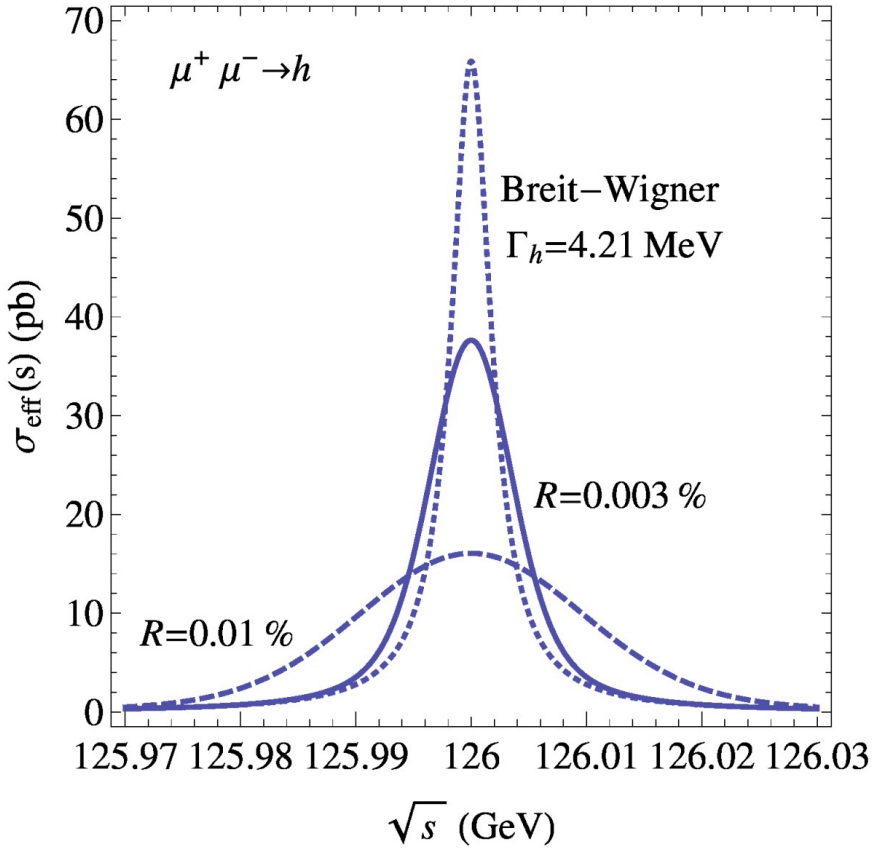


FIG. 1: Effective cross section for $\mu^+\mu^- \to h$ versus the

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

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

Leading signals and background rates

the SM Higgs and a broader Higgs

Width (MeV)		R (%)	$\mu^+\mu^- \to h$	$h \to b\bar{b}$		$h \to WW^*$	
$\mathrm{Br}_{b\bar{b}}$	Br_{WW^*}		σ_{eff} (pb)	σ_{Sig}	σ_{Bkg}	σ_{Sig}	σ_{Bkg}
SM: 4.2 [9]		0.01	16	7.6	15	3.7	0.051
56%	23%	0.003	38	18		5.5	
Exotic: 42		0.01	18	2.6		1.3	
18%	7.3%	0.003	20	3.0		1.5	

TABLE I: Effective cross sections (in pb) at the resonance $\sqrt{s} = m_h$ for two choices of beam energy resolutions R and two leading decay channels. The SM Higgs and exotic Higgs width, as well as the branching fractions in the SM are also listed.

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

For the broad Higgs, we have kept the LHC signal rate unchanged.

Profile for SM Higgs

- Leading channels
- Sig+Bkg
- Randomize
- Step choice

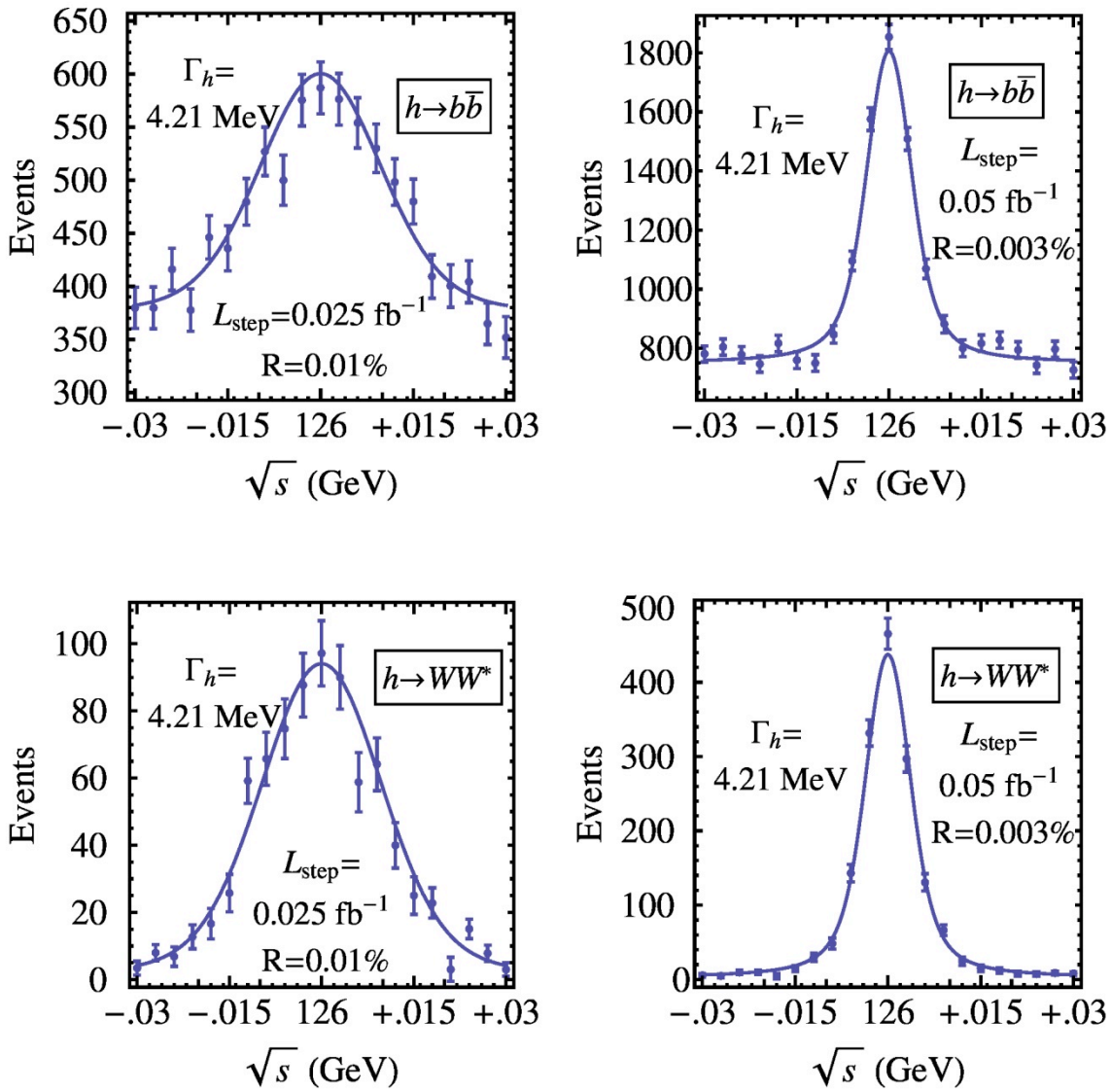


FIG. 2: Number of events of the Higgs signal plus backgrounds and statistical errors expected for Cases A and B as a function of the collider energy $\sqrt{s}$ in $b\bar{b}$ and WW^* final states with a SM Higgs $m_h = 126$ GeV and $\Gamma_h = 4.21$ MeV.

Fitting procedure:

- Three Parameters Fitting
  - Width
  - Mass
  - Cross Section

- Minimize χ^2 over bins
- Estimate standard deviation of fitting via $\chi^2_{min}+1$

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

Fitting the SM Higgs

$\Gamma_h = 4.21$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	$\delta m_h(MeV)$
Case A	0.005	1.5	13%	0.51
$R = 0.01\%$	0.025	0.85	6.1%	0.32
	0.2	0.34	2.2%	0.13
Case B	0.01	0.61	8.3%	0.40
$R = 0.003\%$	0.05	0.30	3.8%	0.13
	0.2	0.17	2.0%	0.10

TABLE II: Fitting accuracies for one standard deviation range of $\delta\Gamma_h$, δB and δm_h of the SM Higgs with the scanning scheme as specified in Eq. (7) for three representative luminosities per step.

Furthermore, Superb beam energy resolution would help for other resonant studies:

MSSM Decoupling region: $M_A \approx M_H > 2M_Z$

Or, Non-decoupling: $M_A \approx m_h \approx M_Z$ *

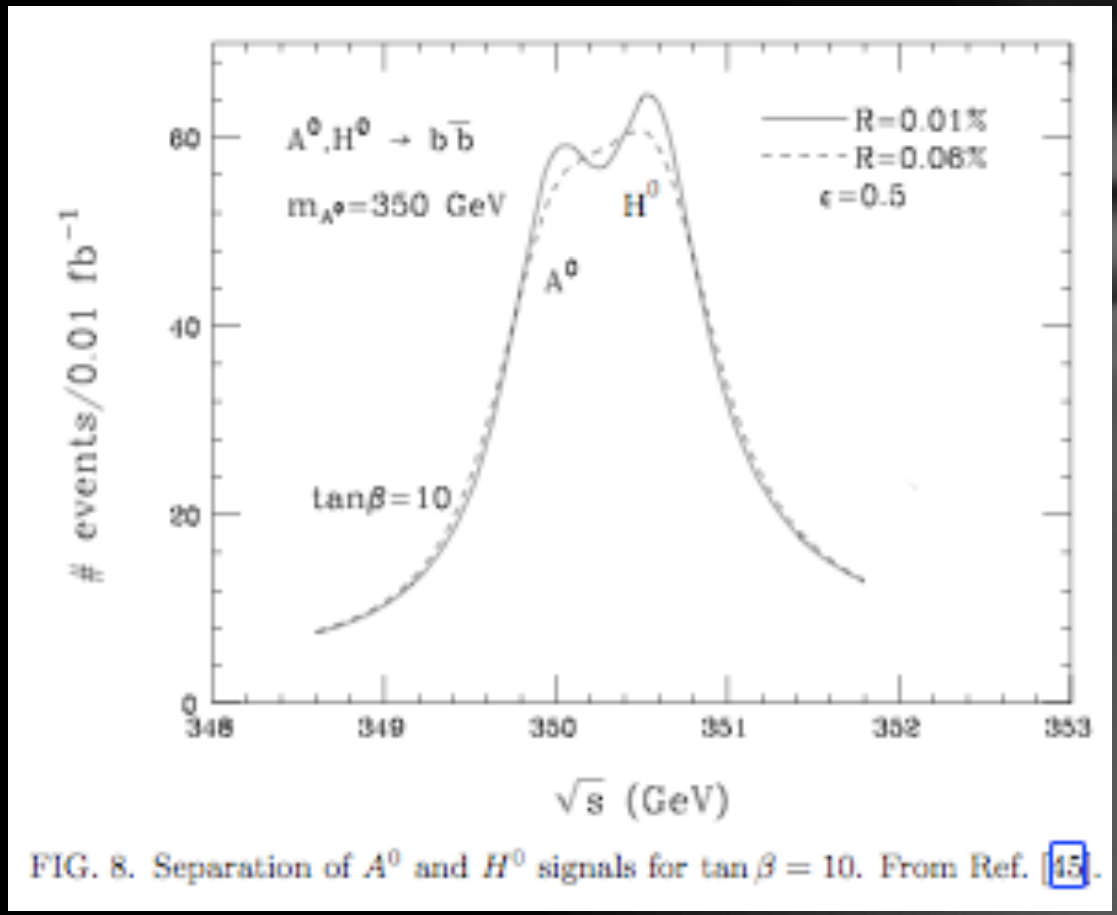
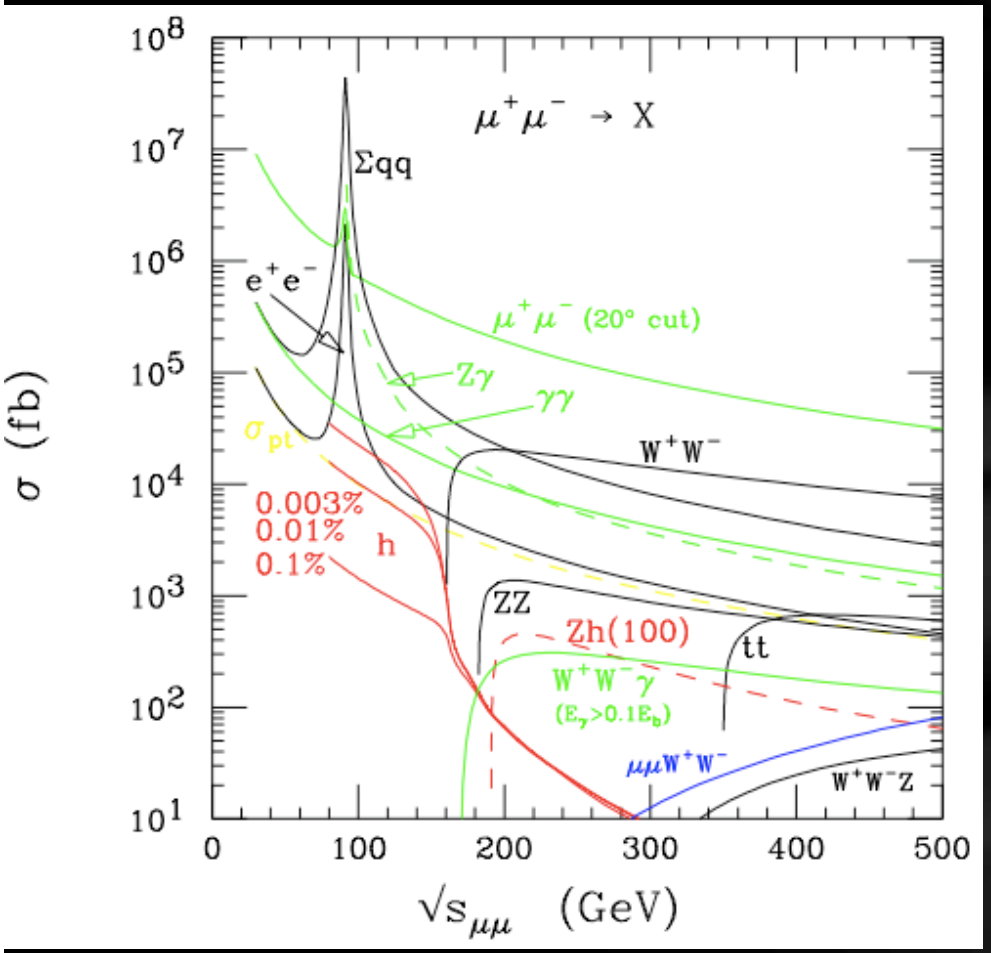


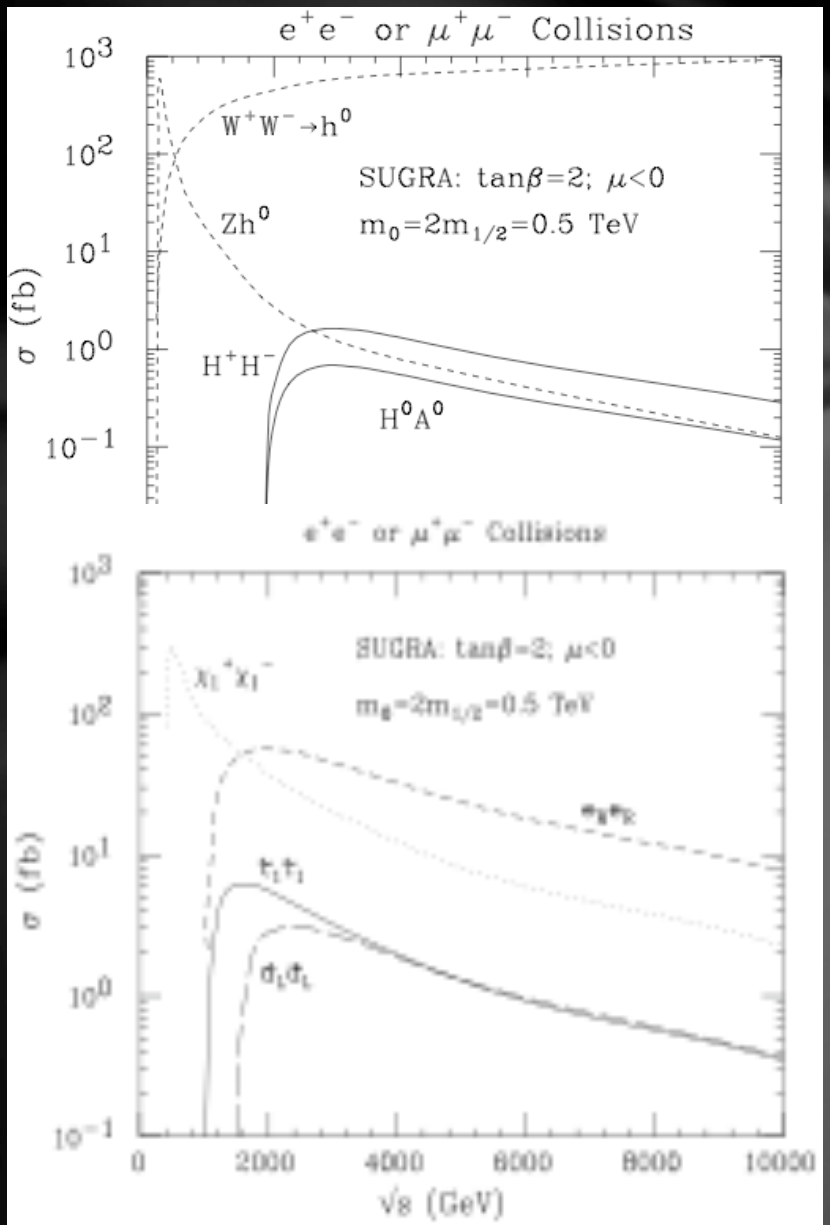
FIG. 8. Separation of A^0 and H^0 signals for $\tan\beta = 10$. From Ref. [13].

* TH, Christensen, Su, arXiv: 1203.3207

Still can do the bread & butter physics

And beyond





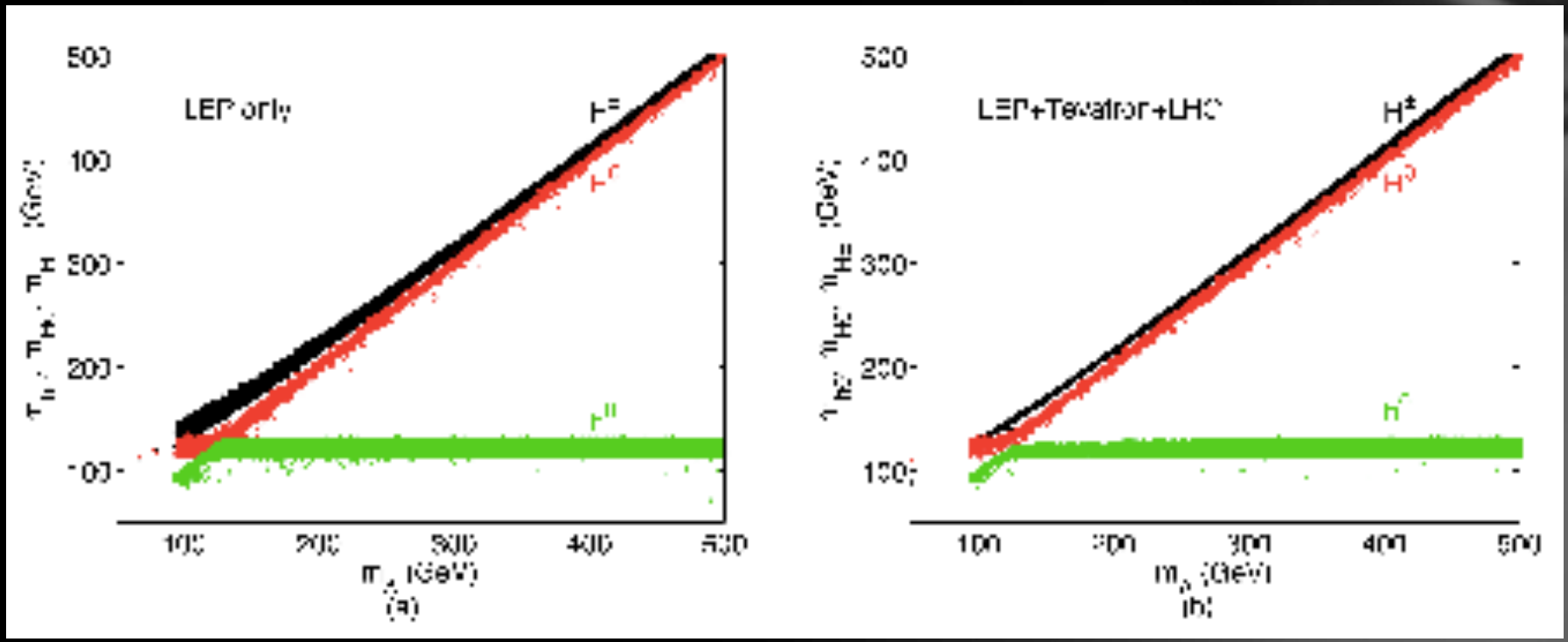
Conclusions

A Muon Collider Higgs Factory

- Unique, Direct, model-independent measurement of the Higgs width
- Achievable precision

  for the SM Higgs $\delta\Gamma_h \approx 0.3 - 0.8$ MeV.
- Energy resolution, luminosity: crucial.
- Energy extension for other new physics.

Backup slides



Fitting the SM Higgs

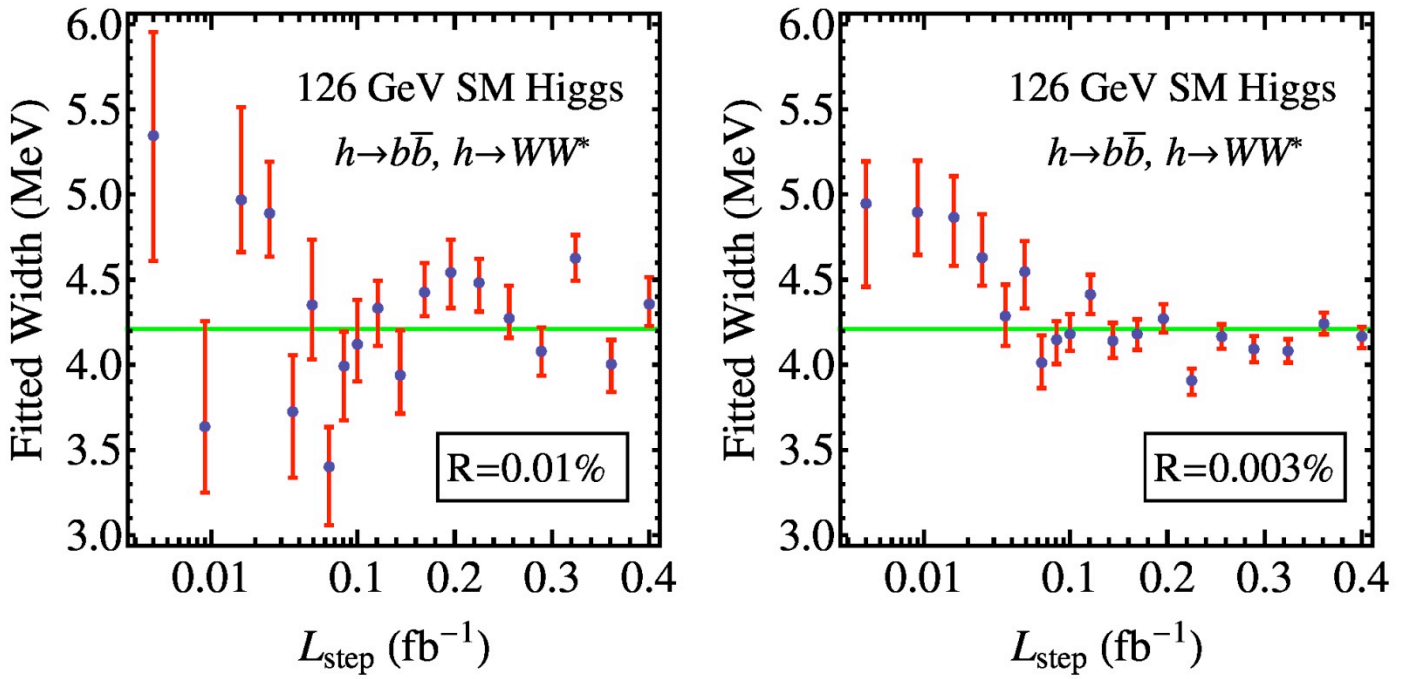


FIG. 3: Fitted values and errors for the SM Higgs width versus the luminosity per step with the scanning scheme as specified in Eq. (7).

Profile for Broader Higgs

- Leading channels
- Sig+Bkg
- Randomize
- Step choice

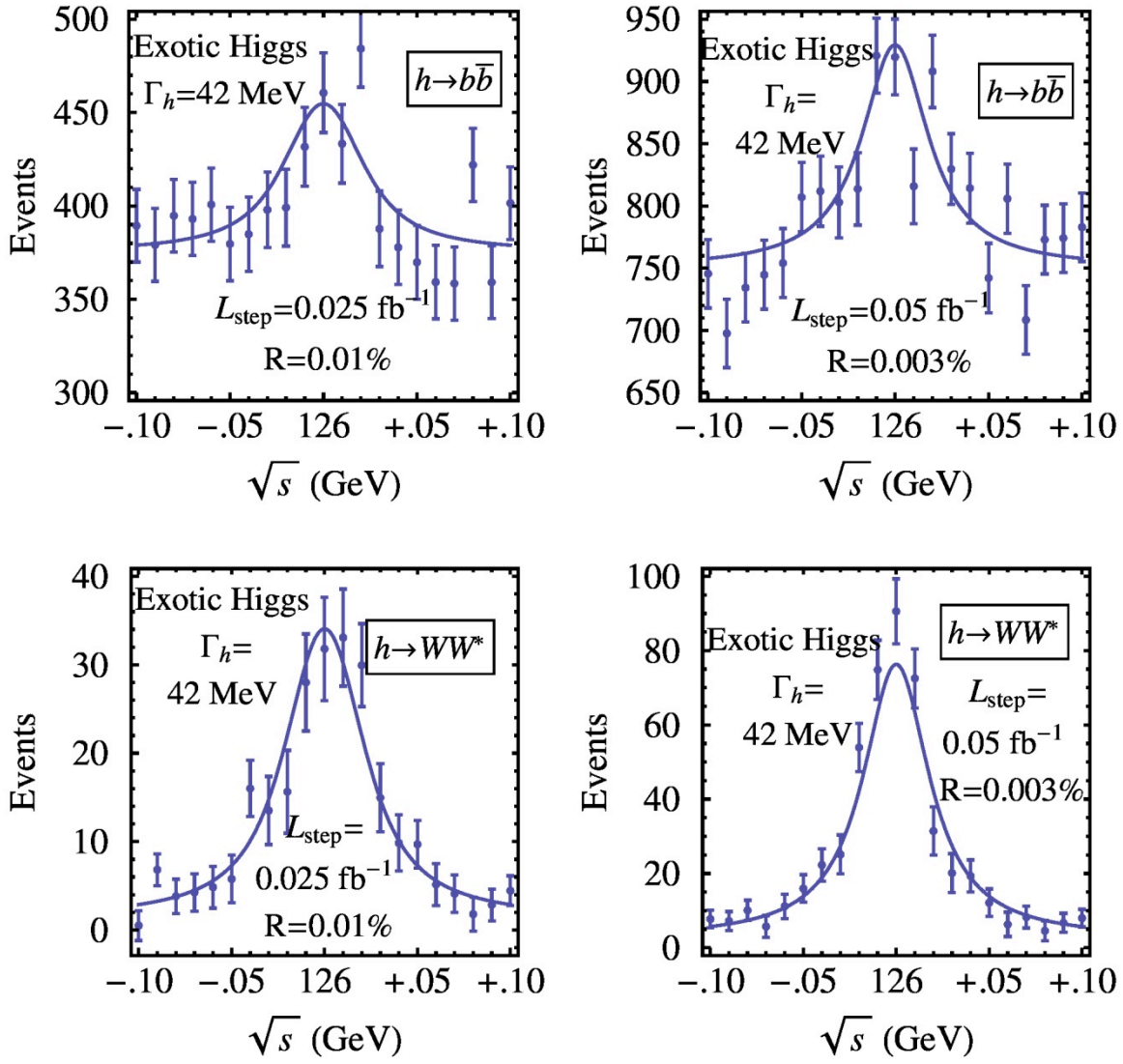
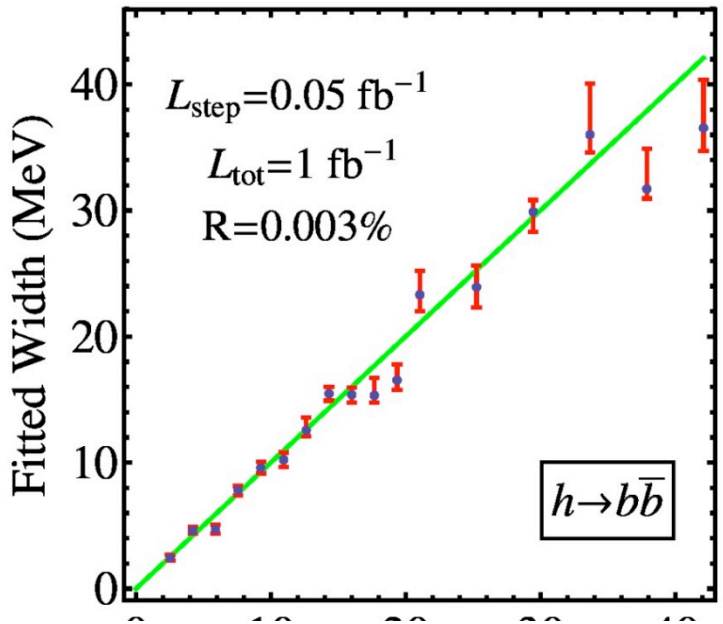
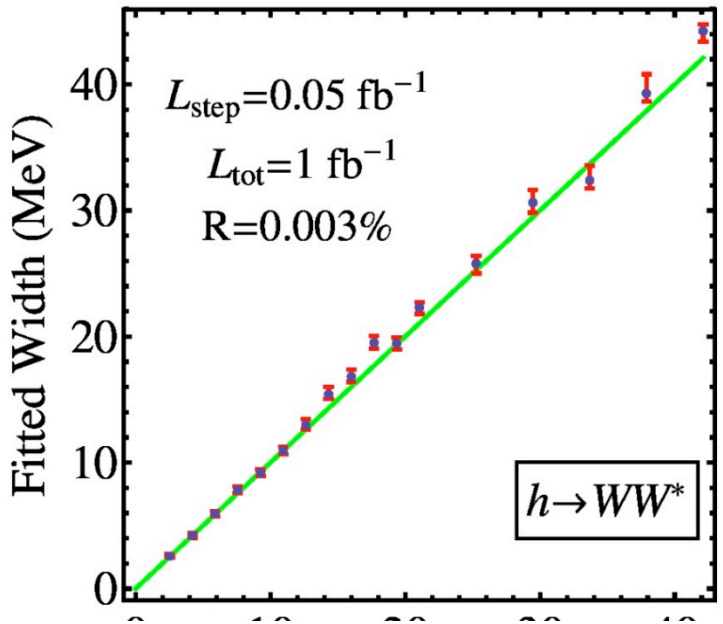


FIG. 4: Number of events of the Higgs signal plus backgrounds and statistical errors expected for Cases A and B as a function of the collider energy $\sqrt{s}$ in $b\bar{b}$ and WW^* final states with an exotic Higgs $m_h = 126$ GeV and $\Gamma_h = 42$ MeV.

Fitting a Broader Higgs





$\Gamma_h = 2.5 - 42$ MeV	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$b\bar{b}$	$0.5 - 6.8$	$6\% - 20\%$	$0.2 - 2$
WW^*	$0.3 - 1.3$	$5\% - 10\%$	$0.1 - 1$

TABLE III: Fitting accuracies for the exotic Higgs properties. The scanning scheme is the same as in Fig. 5.

Profile for a Broader Higgs

A Broader Higgs is and will be consistent with LHC data

- Flat initial state energy profile
- Narrow width of this Higgs
- ->Narrow Width Approximation

  The measured rate:

$$\sigma \propto \Gamma_h BR_{ini} BR_{fin}$$

- LHC indirectly with assumptions

  ILC indirectly through inclusive mode