Physics Cases For Muon Colliders

Joint Presentation by

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Continued

Muon Colliders Physics Workshop

(Telluride, June 27–July 1, 2011)

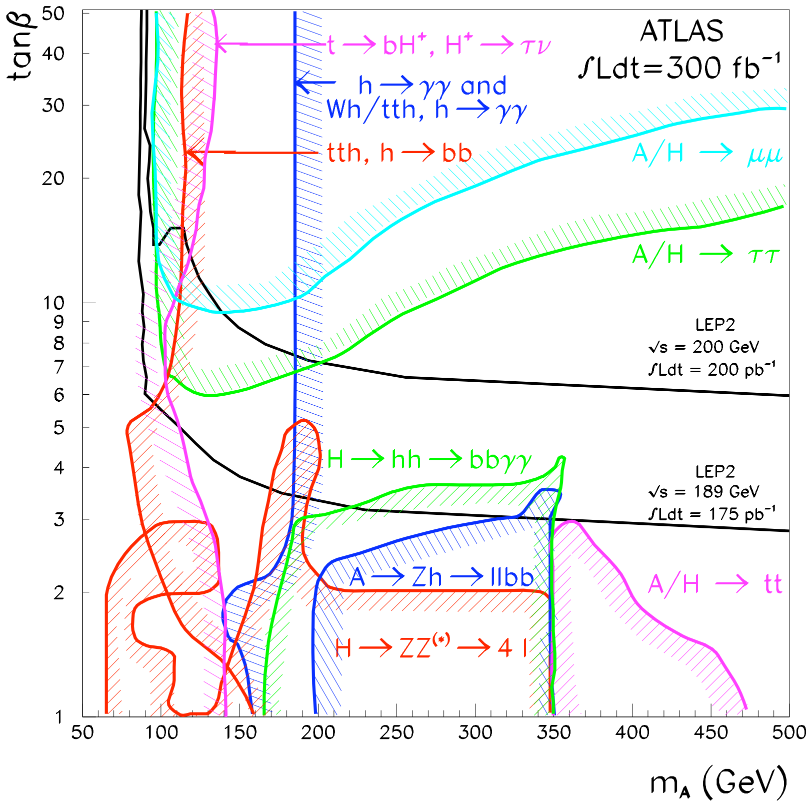
Higgs Physics

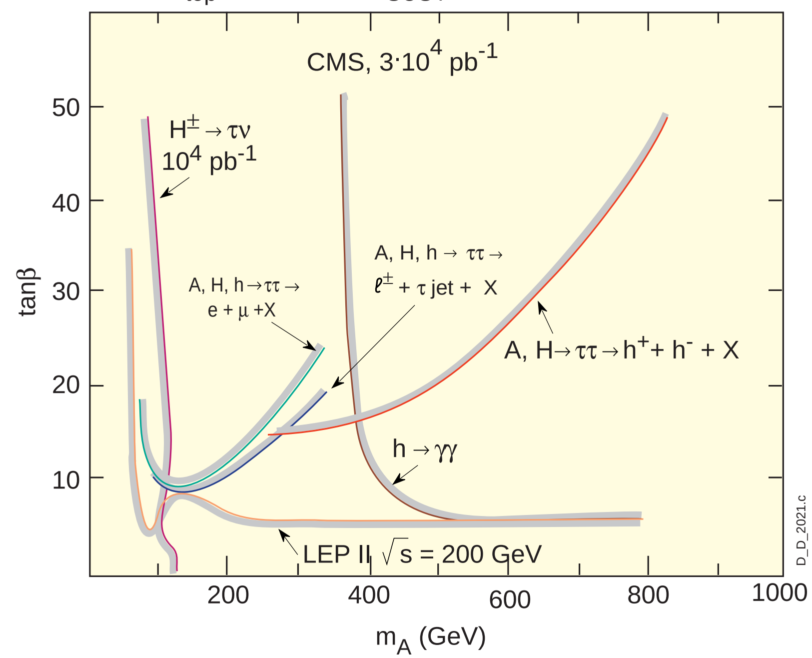
At the LHC, the h fully covered, but the H and A ... At $\sqrt{s} = 14$ GeV, still a large hole, especially $M_{H,A} > 500$ GeV:

Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels

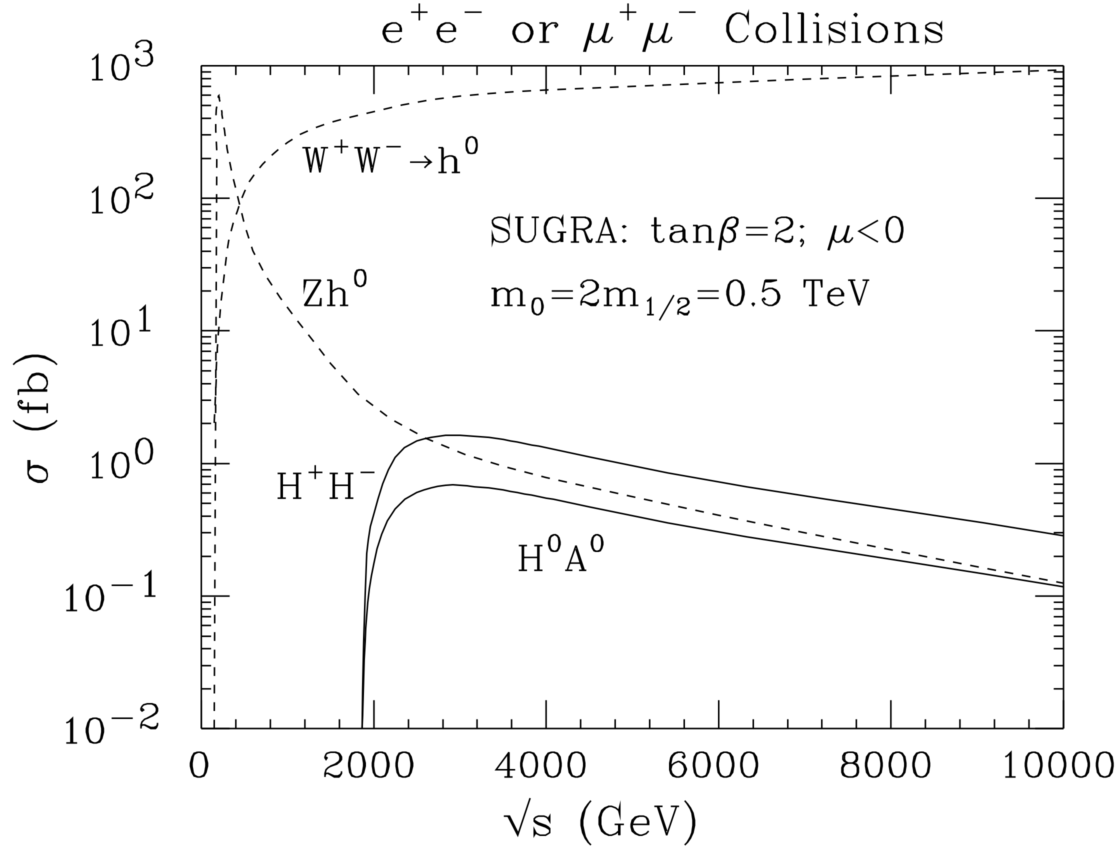
- 5 σ significance contours
- two-loop / RGE-improved radiative corrections
- m_{top} = 175 GeV, m_{SUSY} = 1 TeV, no stop mixing ;





The status of $t\bar{t}h, h \to b\bar{b}$ is still under discussion.

At lepton colliders, pair production rather robust:



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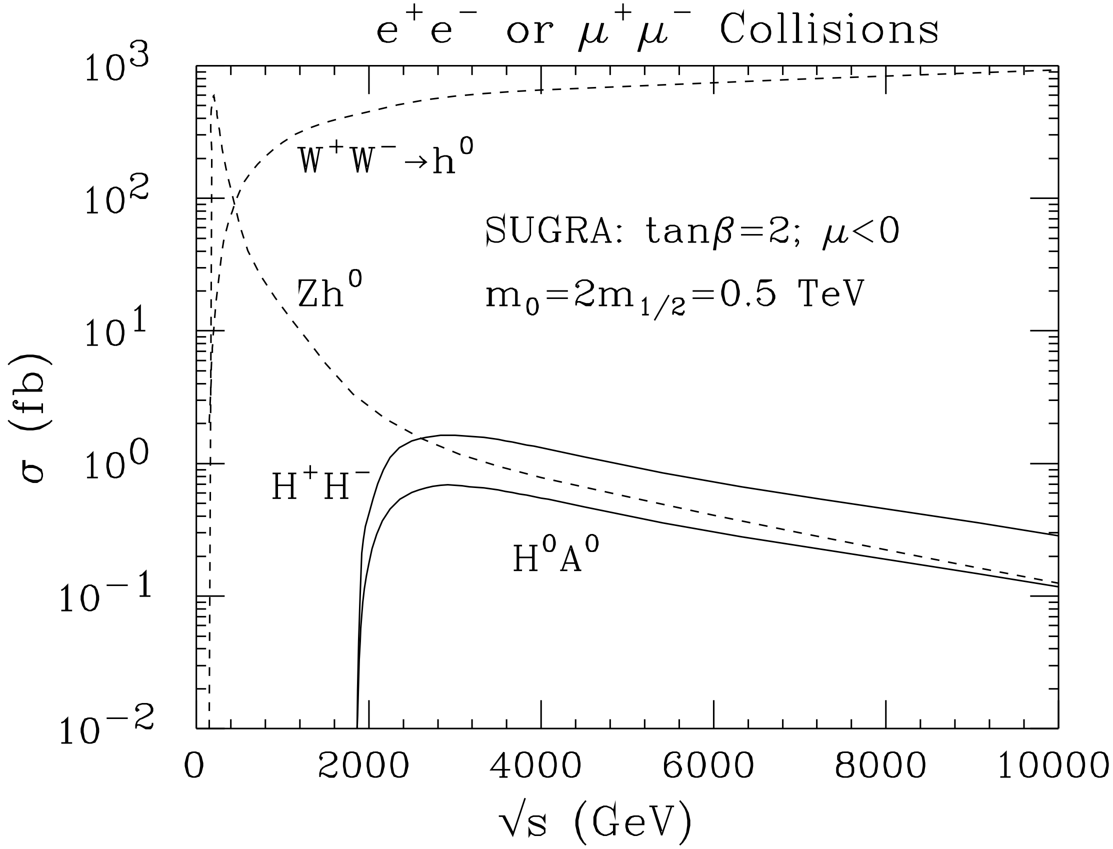

Once crossing the pair threshold, observation straightforward.
(rather model-independent, like in THDM etc.)

Most unique of all at a μC:
The s-channel resonant production.

$$\sigma(\mu^+\mu^- \to H, A \to X) = \frac{4\pi\Gamma(H, A \to \mu^+\mu^-)\ \Gamma(H, A \to X)}{(s - M_H^2)^2 + \Gamma_H^2 M_H^2}$$

$$\overline{\sigma}(s) = \int d\sqrt{s}\ \sigma(\mu^+\mu^- \to H, A \to X)\ \frac{dL}{d\sqrt{s}}$$

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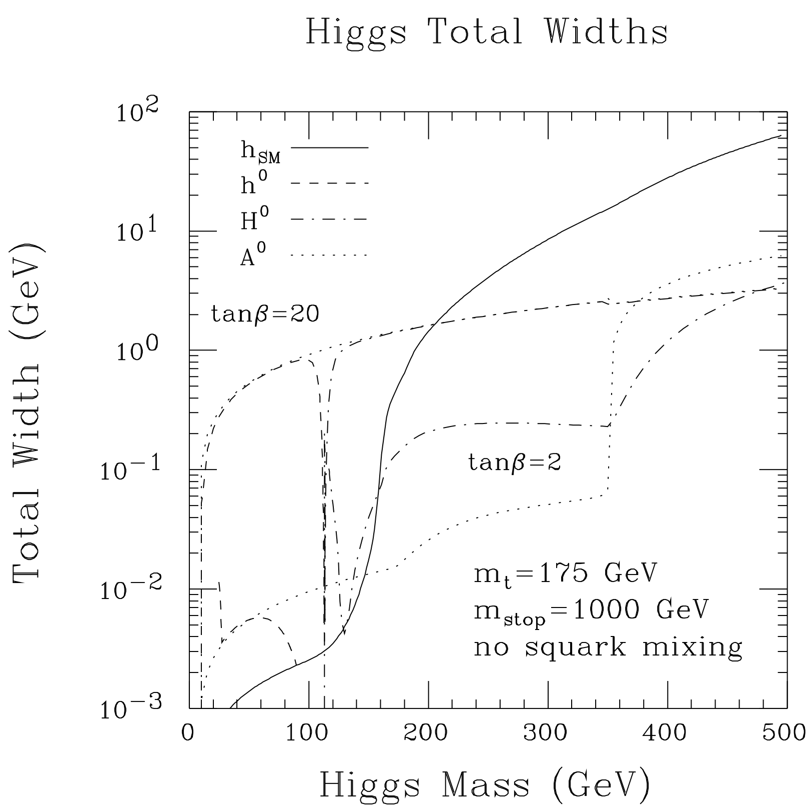
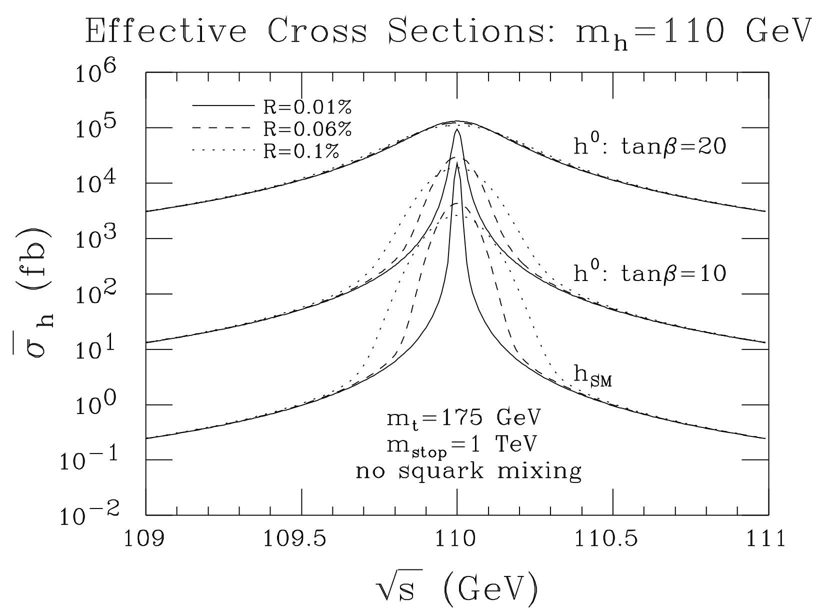
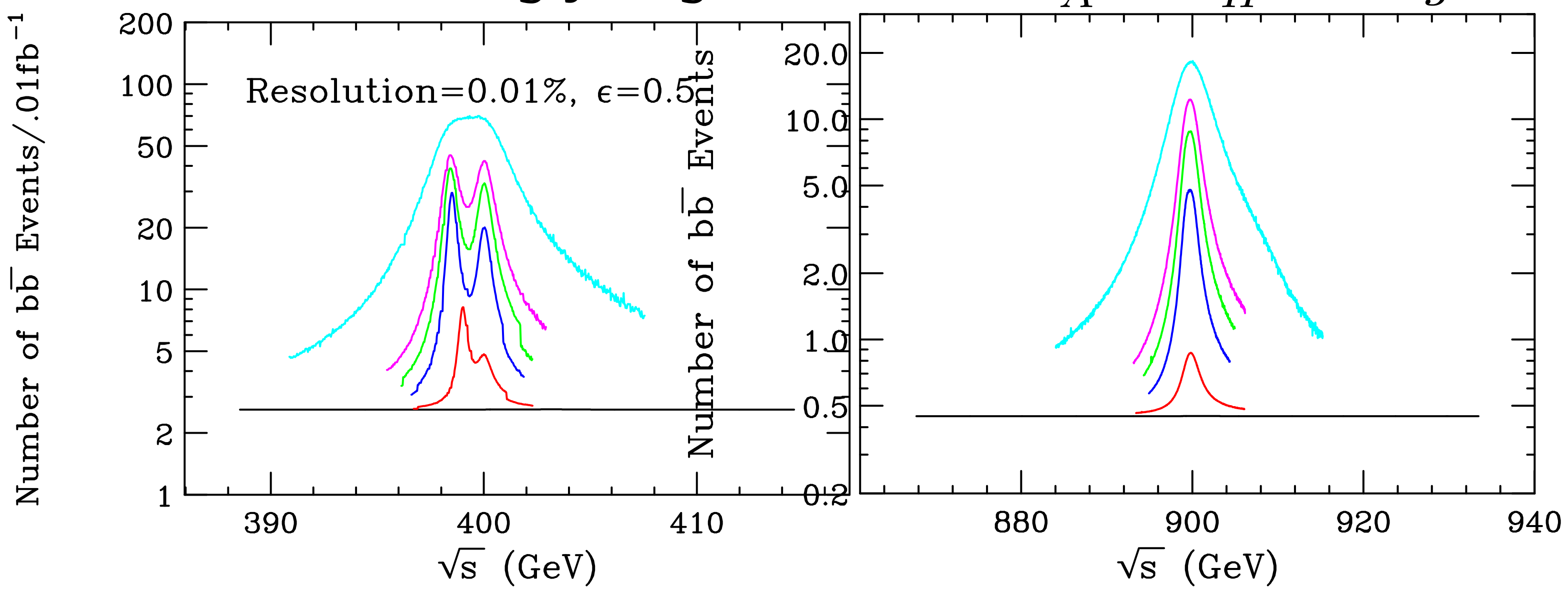




Muon collider sufficient to resolve H, A.

Increasingly degenerate as $m_A \sim m_H \to large$



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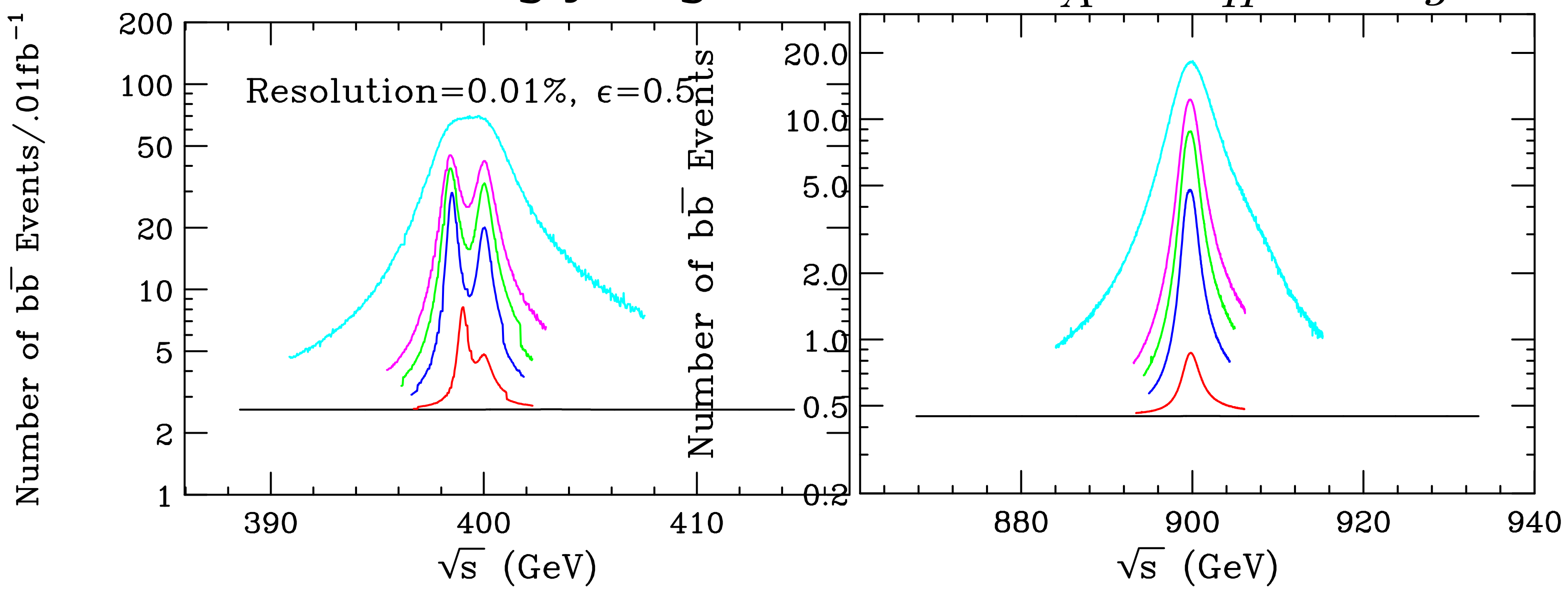

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$$\overline{\sigma}^{measured}(b\bar{b},\ t\bar{t},\ \tau\tau) \ \Rightarrow \ \frac{4\pi\Gamma(H,A\rightarrow\mu^+\mu^-)\ \Gamma(H,A\rightarrow X)}{\Gamma^2_{tot}M^2_H}.$$

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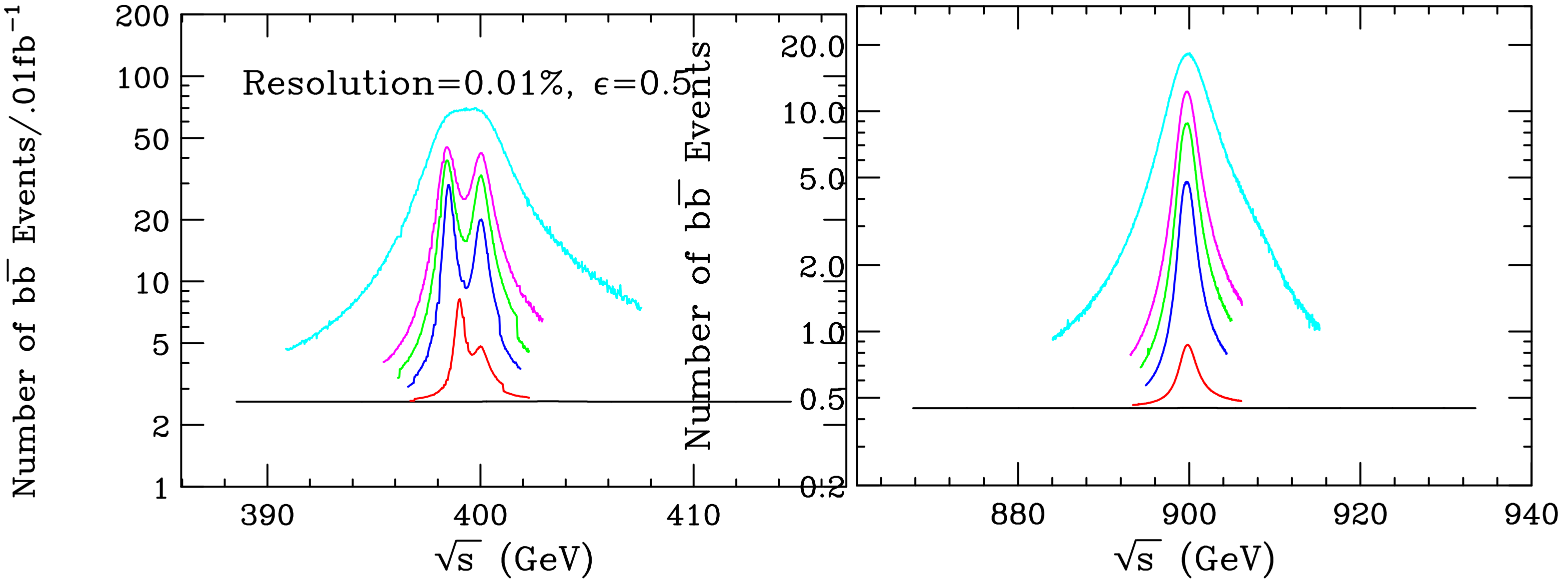

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- M_H: peak, accurate!
- Γ_{tot}: profile, accurate by scanning!
- $\overline{\sigma}^{measured}$: $(b\bar{b})/(t\bar{t}) \approx m_b^2/m_t^2 \tan^4\beta$, $(b\bar{b})/(\tau\tau) \approx m_b^2/m_\tau^2$ upto radiative corrections.
- $\overline{\sigma}^{tot} = (b\bar{b}) + (t\bar{t})+$(smaller ones) $\Rightarrow \Gamma(\mu^+\mu^-)$! upto missing channels.

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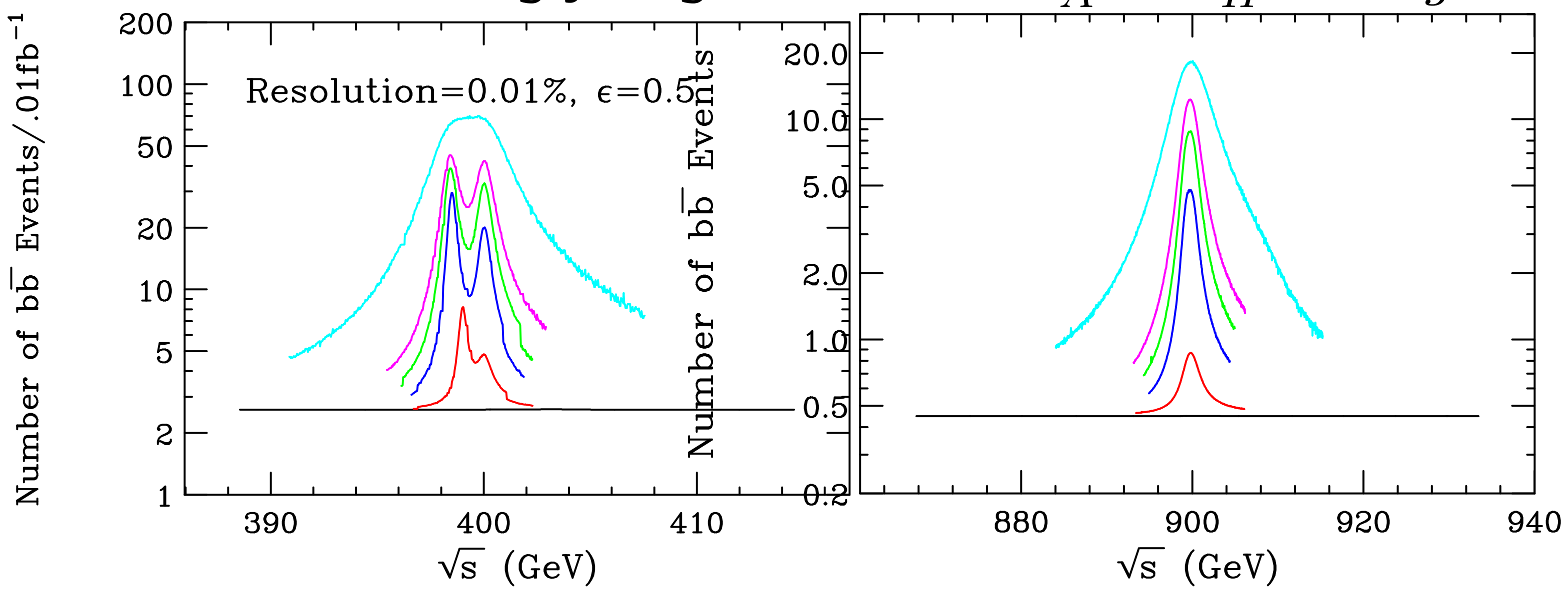

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- Compare with theory: $\Gamma(H,A\to\mu^+\mu^-)$, learn how many H,A's contributing.
- If $t\bar{t},\ \tau\tau$ decays reconstructed, hope to see CP violation!

Strong electroweak dynamics

$W_L W_L$ scattering

If no $h_i/SUSY$ found at the LHC, $W_L W_L$ Scattering must reveal new dynamics

- Unitarity scale: $\Lambda_{EW}(W_L W_L \to W_L W_L) \sim \sqrt{8\pi}\, v \sim$1.2 TeV.

$$\sqrt{s_W} \sim 2 \text{ TeV} \Rightarrow \sqrt{s_f} \sim 4 \text{ TeV}$$

$$\frac{\sigma(W_L^+ W_L^- \to W_L^+ W_L^-)}{\sigma(W_L^+ W_L^- \to Z_L Z_L)} \begin{cases} \sim 2 & \text{scalar } H^0, \\ \gg 1 & \text{vector } \rho^0_{TC}, \\ \sim 2/3 & \text{LET } \sqrt{s} \ll M. \end{cases}$$

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So, consider $\mu^+\mu^- \to \nu\nu W^+W^-,\ \nu\nu ZZ,\ \nu\nu t\bar{t}$ via $H,\ \rho_{TC}$ or non-resonance.

Scalar pairs

EW states that could be (easily) missed at the LHC):

$$\mu^+\mu^- \to \tilde{H}^+\tilde{H}^-,\ \tilde{H}^0\tilde{H}^0,\ \tilde{\ell}\tilde{\ell}.$$

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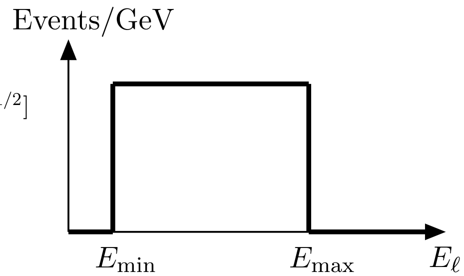
Decay edges: $\mu^+\mu^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^- + E^{miss}\ (\tilde{\chi}_0\tilde{\chi}_0)$

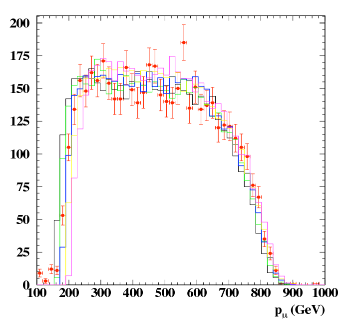
LHC -MC synergy

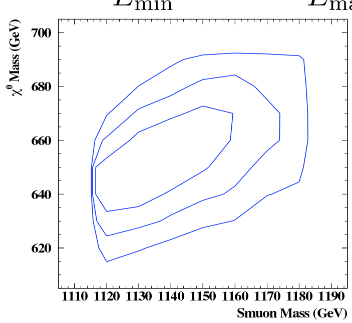
MC gives access to particle masses, couplings, widths, mixing angles

$$E_{\rm max,min} = \frac{\sqrt{s}}{4}(1 - m^2_{\tilde{N}_1}/m^2_{\tilde{\ell}})[1 \pm (1 - 4m^2_{\tilde{\ell}}/s)^{1/2}]$$

$$\mu^+\mu^- \to \tilde{\ell}^+\tilde{\ell}^- \to \ell^+\ell^-\tilde{N}_1\tilde{N}_1$$

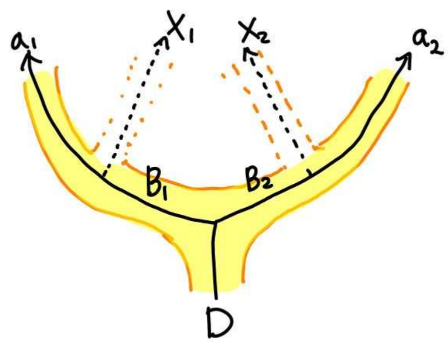


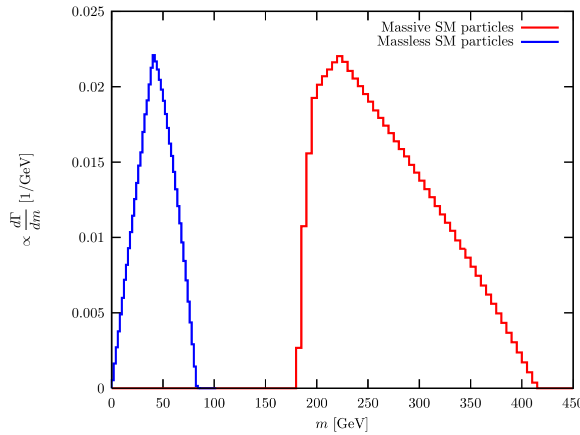




Special topology: "Antler decay" $\mu^+\mu^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^- + E^{miss}$

CLIC, μC: $e^+e^-,\ \mu^+\mu^- \to B_1 + \bar{B}_2 \to a_1 X_1 + a_2 X_2.$





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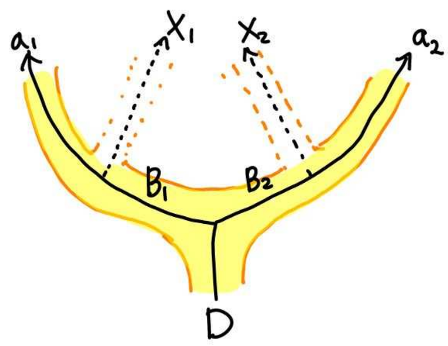

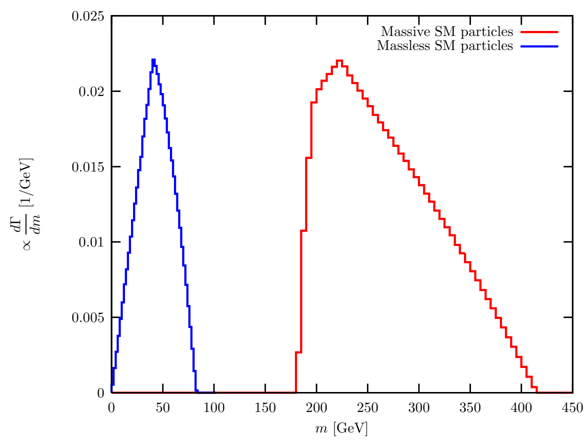

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The end-point, instead of being $M_{aa}^{\text{max}} = m_D - 2m_X$, becomes

$$M_{aa}^{\text{max}} = m_B \left(1 - \frac{m_X^2}{m_B^2}\right) e^{\eta},$$

$$M_{aa}^{\text{cusp}} = m_B \left(1 - \frac{m_X^2}{m_B^2}\right) e^{-\eta}.$$

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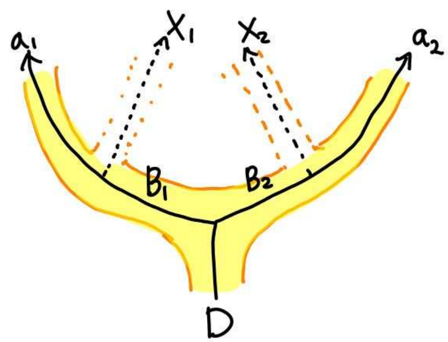

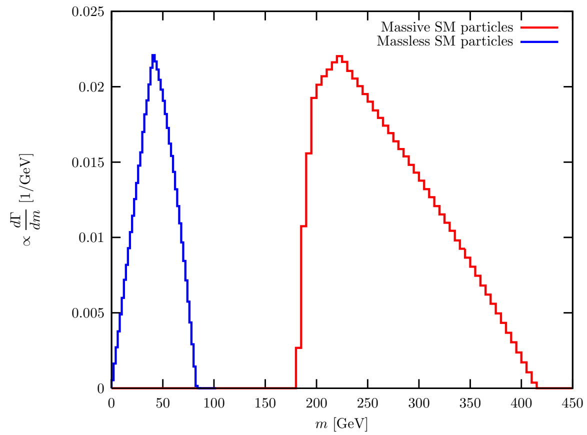

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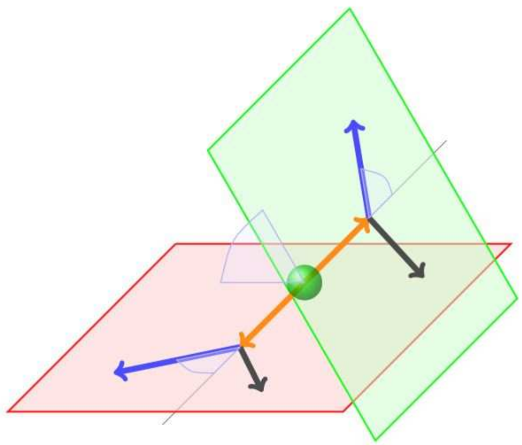
Thus,

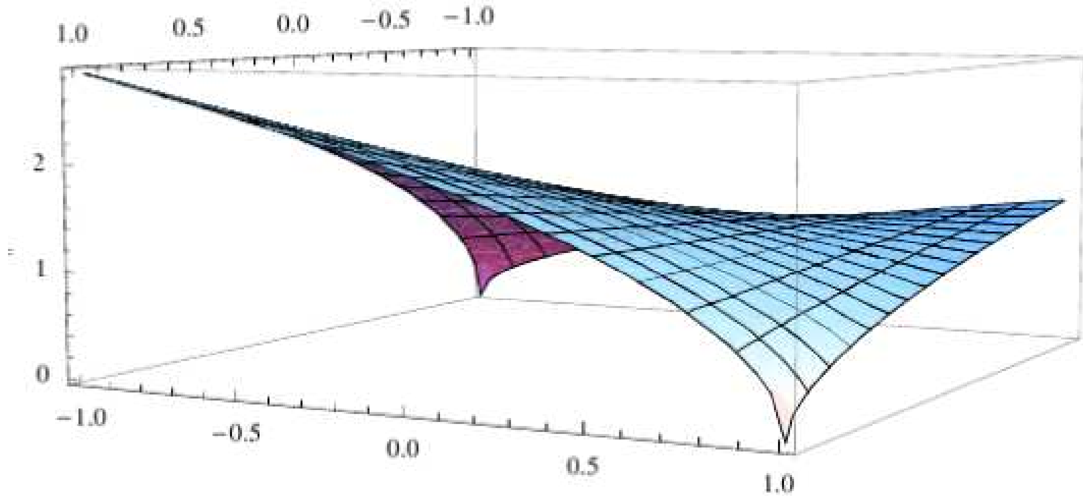
$$M_{aa}^{\max}/M_{aa}^{\text{cusp}} = e^{2\eta}, \quad (D \to B)$$

$$M_{aa}^{\max} M_{aa}^{\text{cusp}} = m_B^2 \left(1 - \frac{m_X^2}{m_B^2}\right)^2. \quad (B \to X)$$

Origin of the cusps:

$a_2 X_2 \leftarrow B_2 \ \Leftarrow D \Rightarrow \ B_1 \rightarrow a_1 X_1$





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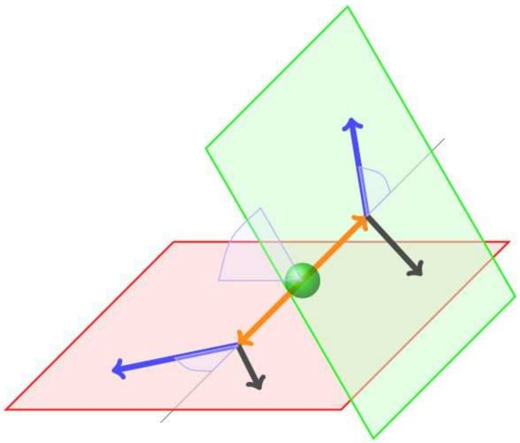

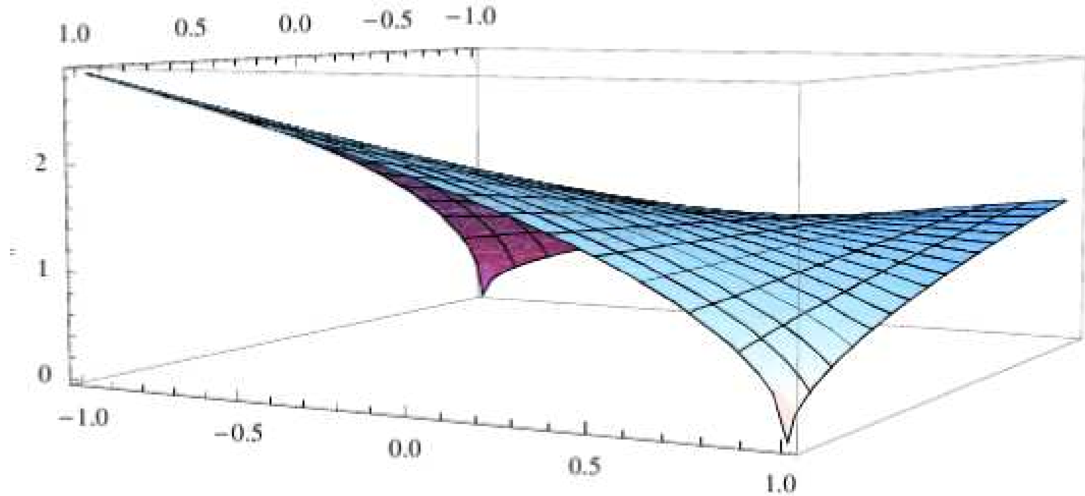

Limiting cases (at the corners):

- Back-to-back: $(\cos\theta_1, \cos\theta_2) = (+1, +1)$ $\quad \Leftarrow + \Rightarrow$
  Maximum M_{aa} configuration.
- Parallel: $(\cos\theta_1, \cos\theta_2) = (\pm 1, \mp 1)$ $\quad \Rightarrow + \Rightarrow, \quad \Leftarrow + \Leftarrow$
  Zero M_{aa} configurations.
- Head-on: $(\cos\theta_1, \cos\theta_2) = (-1, -1)$ $\quad \Rightarrow + \Leftarrow$
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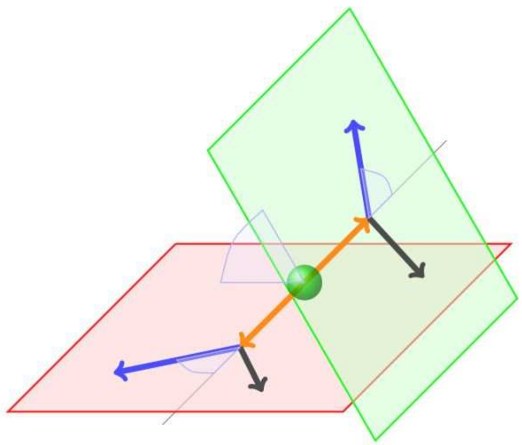

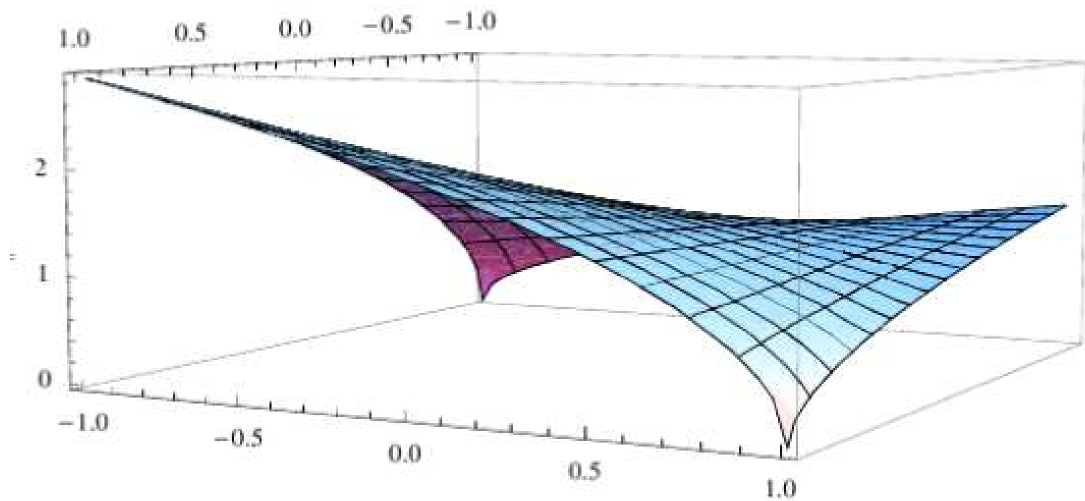

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- Upon variable projection (losing info), singularities may be developed.
- It is purely kinematical, and new (rigorous singularity theorems in math).

Comparative Remarks:

Physics reach:

	Higgs(es)	SUSY	Strong Dynamics	Exotics	Astro/Cosmo
(s)LHC $E_{qq} \approx 1.5 - 3$ TeV 300 fb^{-1}	$\surd$ partial	$\surd$ partial	$\surd\times$ non-resonance?	$\surd\surd$ ΔL	$\surd\times$ missing mass? CP-V ?
CLIC $(1-2)\times 10^{34}$	$\surd\surd$ H potential	$\surd$	$\surd$	$\surd$ e flavor	$\surd$ CP-V
μ-Collider	$\surd\surd\surd$ H resonances CP-V	$\surd$	$\surd$	$\surd$ μ flavor	$\surd$ CP-V

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The main difference between CLIC and μC:

1. s-channel resonance production, especially Higgs-like.
2. Flavor dependent physics.

Experimentation:

	Higgs(es)	SUSY	Strong Dynamics	Exotics	Astro/Cosmo
(s)LHC	ECal, p_μ $\eta \sim 5$, b/τ tag	HCal, E_T^{miss} b/τ tag	high p_T e,μ $b's$, $W's$, $t's$	...	... E_T^{miss}
CLIC	$b/c/\tau$ tag $\theta \sim 12^\circ$	threshold scan 80% pol.	...	$A_{FB,LR}$ pol.	scan
μ-Collider	$R_E \sim 0.1\%$ $\theta \sim 20^\circ$, pol$_T$?	scan? pol.$_L$?	...	A_{FB} 10% pol.	scan
μ-Collider	threshold scan				

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The main difference between CLIC and μC:

CLIC: 1. beam polarization;

2. low machine backgrounds

μC: 1. beam energy resolution;

2. machine/detector backgrounds (in low E_T, p_T).

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BUT, seems to me that the machine backgrounds are NOT a problem for our physics signal identifications. only become a problem for precision measurements.