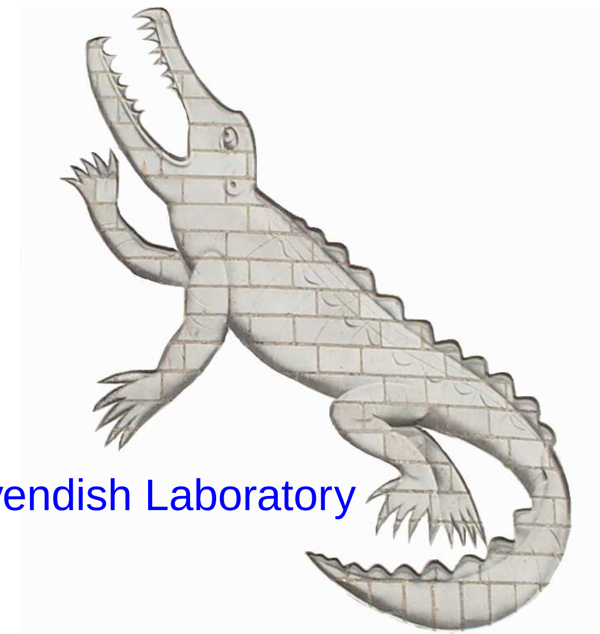
Phenomenology of CP Violation in Supersymmetric Charged Higgs Processes

Jennifer Williams



Cavendish Laboratory

Work done for PhD degree

Plan

- Background
- Production
- Rapidity and Transverse Momentum
- Decay
- Combining Production and Decay
- Outlook at the LHC

Broken Supersymmetry

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★ Write down all possible susy breaking terms:
- keeping gauge invariance
- Lorentz invariance
- no corrections to scalar Higgs mass

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-\mathcal{L}_{\text{soft}} =& \frac{1}{2}\left(m_3\tilde{g}\tilde{g} + m_2\widetilde{W}\widetilde{W} + m_1\widetilde{B}\widetilde{B} + c.c.\right) \\
& \mathbf{m^2_{\tilde{Q}}}\widetilde{Q}^*\widetilde{Q} + \mathbf{m^2_{\tilde{u}}}\tilde{u}^{c*}\tilde{u}^c + \mathbf{m^2_{\tilde{d}}}\tilde{d}^{c*}\tilde{d}^c + \mathbf{m^2_{\tilde{L}}}\widetilde{L}^*\widetilde{L} + \mathbf{m^2_{\tilde{e}}}\tilde{e}^{c*}\tilde{e}^c \\
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Gaugino masses

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Trilinear scalar couplings

Higgs masses

CP Violation

★ Complex phase in couplings (*e.g.* A_t, A_b, m_3, μ)
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- ★ Complex phase in couplings (*e.g.* A_t, A_b, m_3, μ)
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- ★ Not enough to guarantee . . .

$$|\mathcal{M}|^2 = (\text{tree} + \text{loop})^* \ (\text{tree} + \text{loop})$$
$$= |\text{tree}|^2 + 2\,\Re e\,(\text{tree}^* \,\text{loop}) + |\text{loop}|^2$$

- ★ For the CP conjugate state:

$$\left|\mathcal{M}^{\text{CP}}\right|^2 = \left(\text{tree}^{\text{CP}} + \text{loop}^{\text{CP}}\right)^* \ \left(\text{tree}^{\text{CP}} + \text{loop}^{\text{CP}}\right)$$
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$\Longrightarrow$ Need to have:

- tree – loop interference term
- complex loop matrix element

Optical Theorem

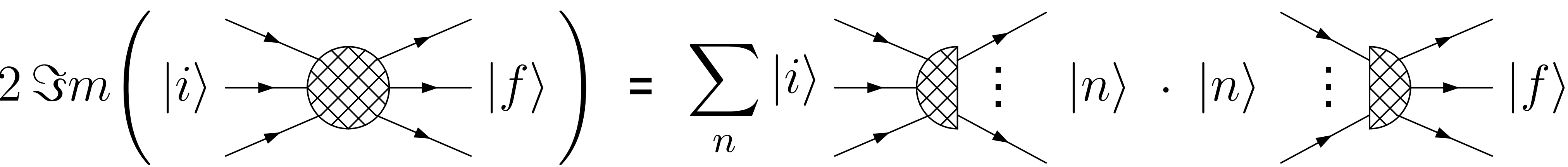
★ In QFT: scattering operator, **S**

$$|f\rangle = \mathbf{S}\,|i\rangle$$

★ **S** is unitary (conservation of probability)

$$\begin{aligned}\mathbf{S} &= \mathbb{I} + i\mathbf{T}\\ \mathbf{S}^\dagger\mathbf{S} &= (\mathbb{I} - i\mathbf{T}^\dagger)(\mathbb{I} + i\mathbf{T})\\ \mathbb{I} &= \mathbb{I} - i(\mathbf{T}^\dagger - \mathbf{T}) + \mathbf{T}^\dagger\mathbf{T}\end{aligned}$$

$$\mathbf{T}^\dagger\mathbf{T} = 2\,\Im m\,\mathbf{T}$$

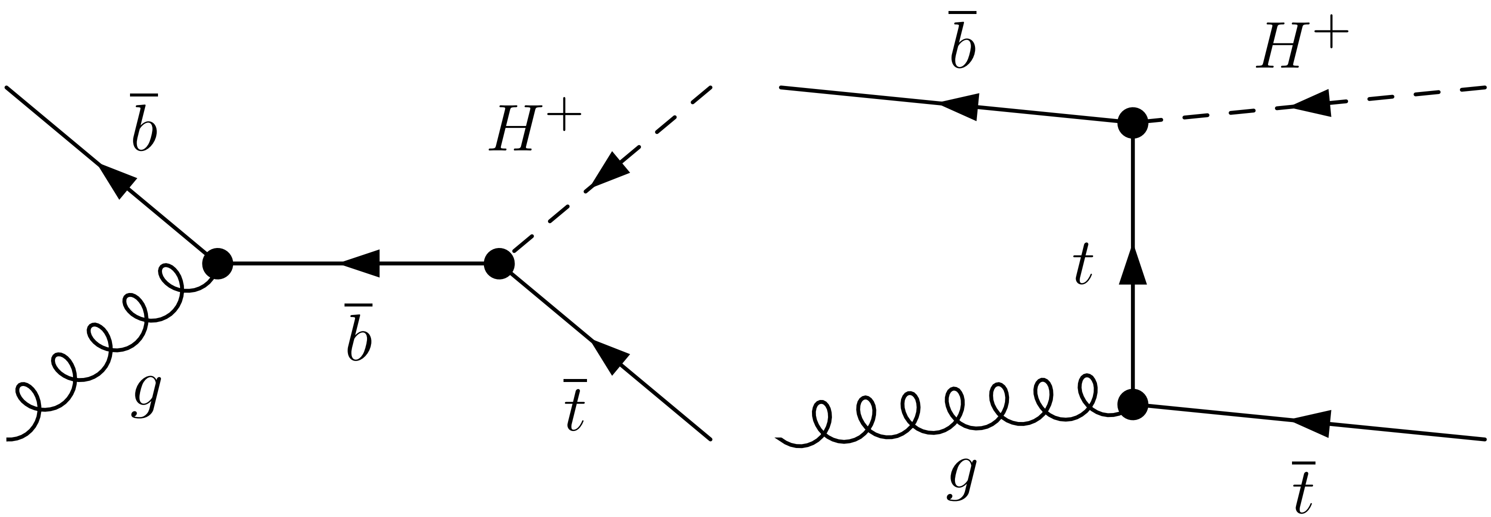


$\Longrightarrow$ Complex $\mathcal{M}$ (CP violation)
IF possible to split diagram into real bits

Production

Dominant production process for charged Higgs is

bottom quark – gluon fusion



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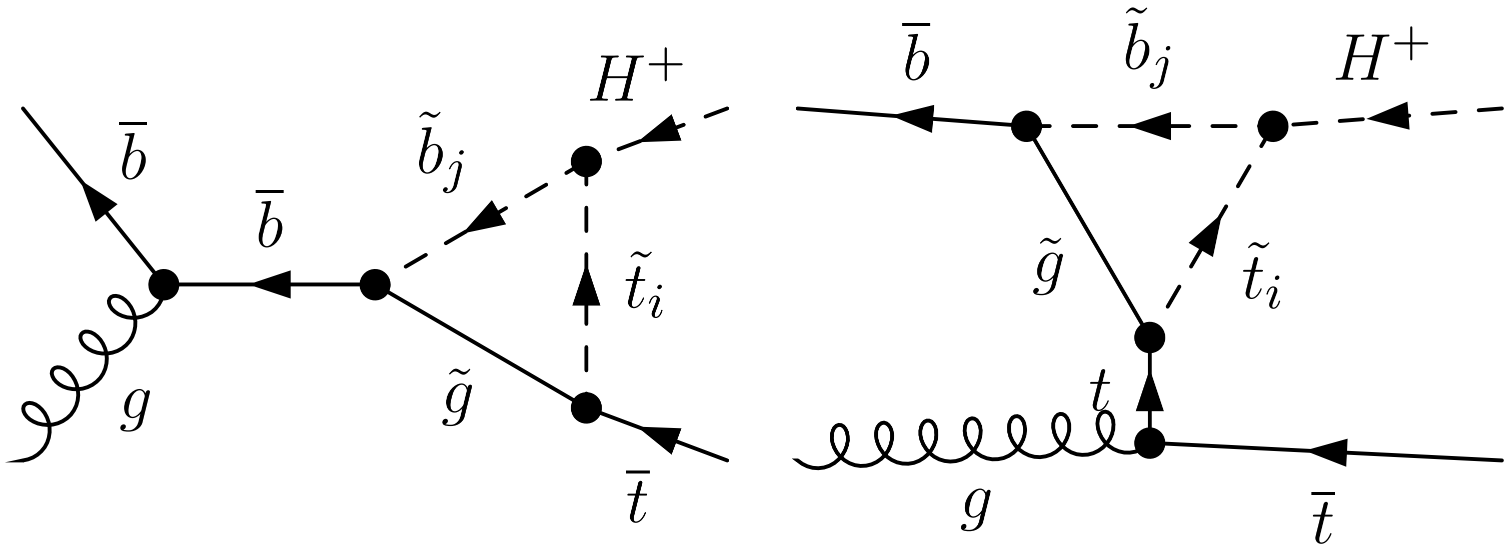

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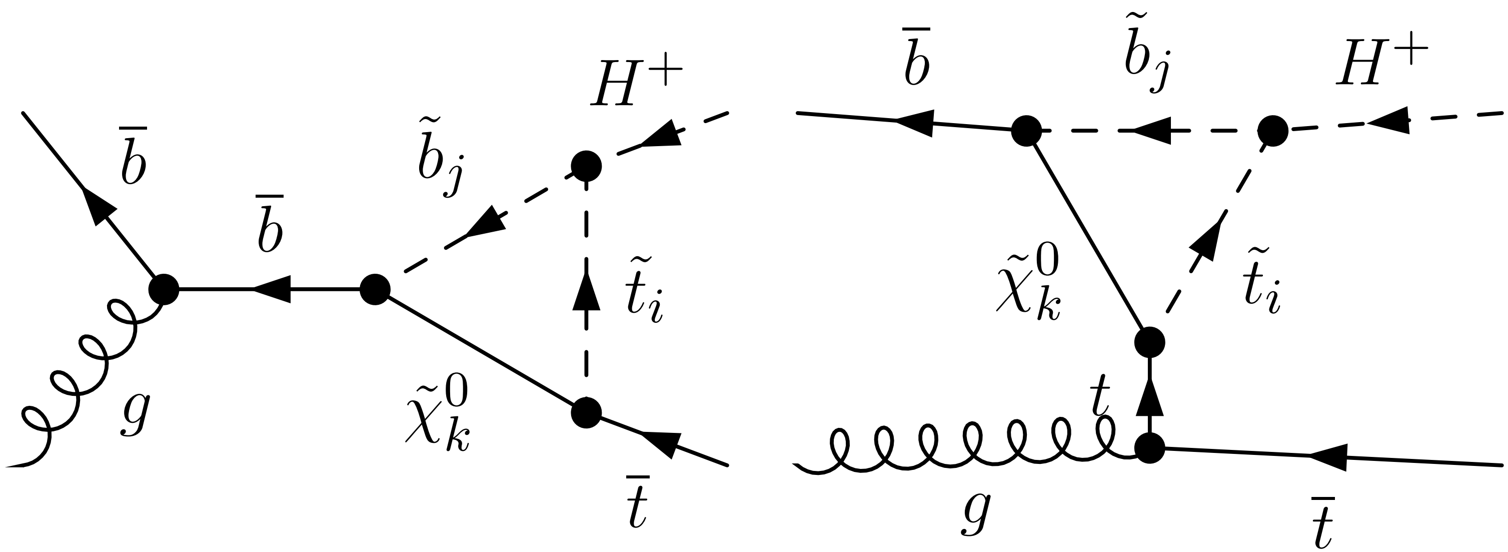

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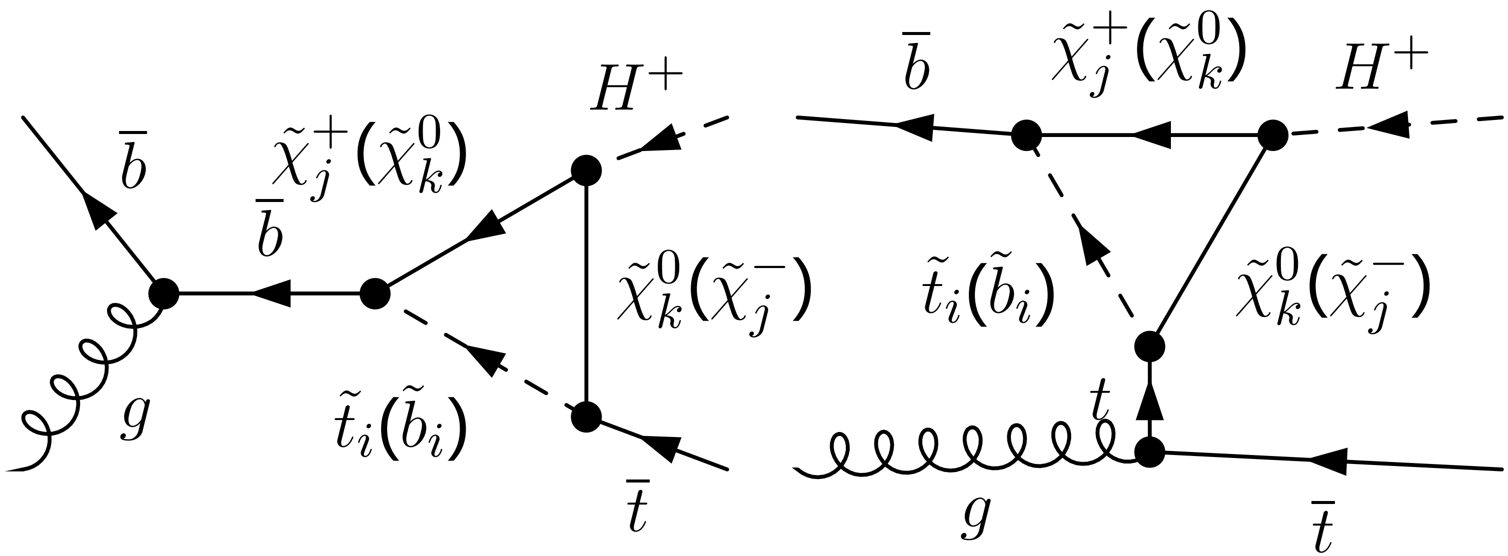

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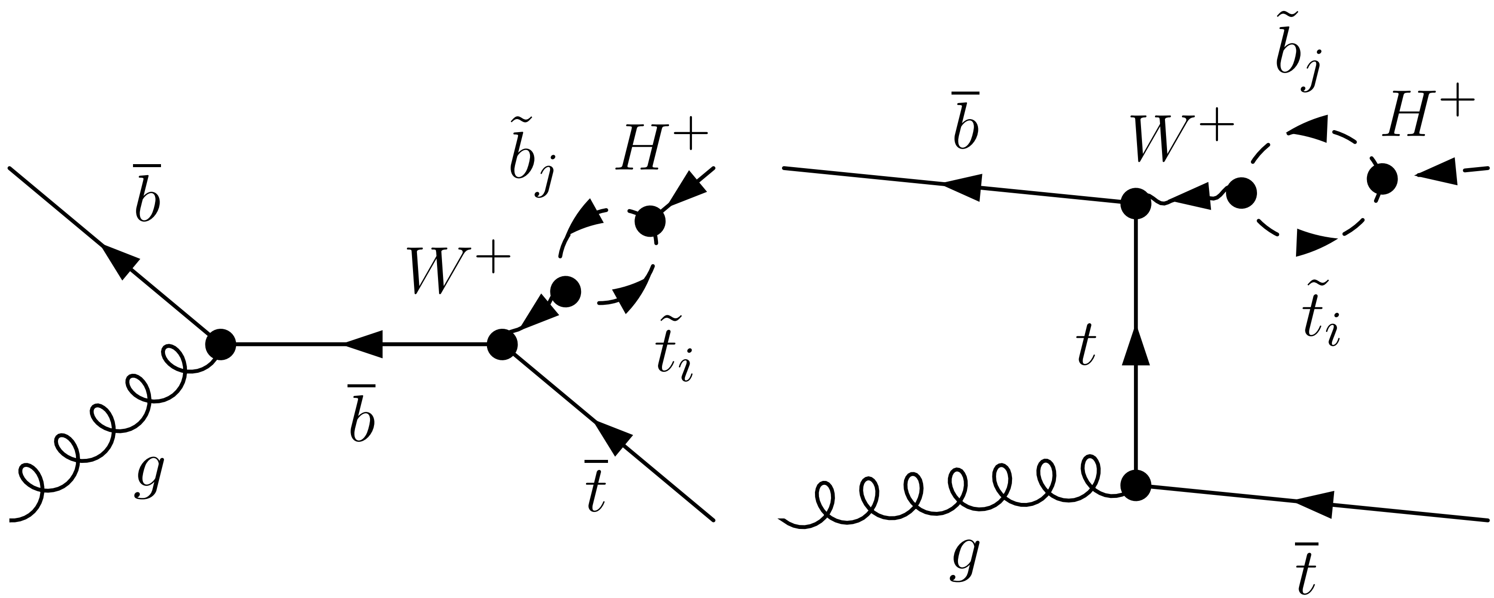

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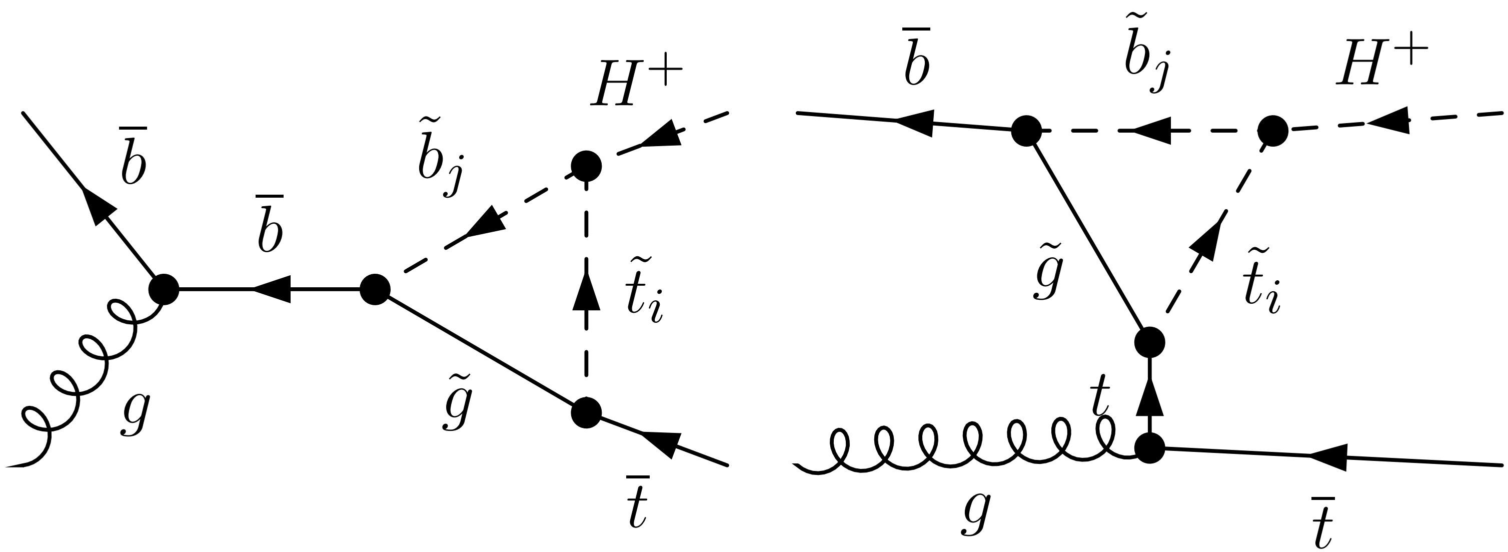
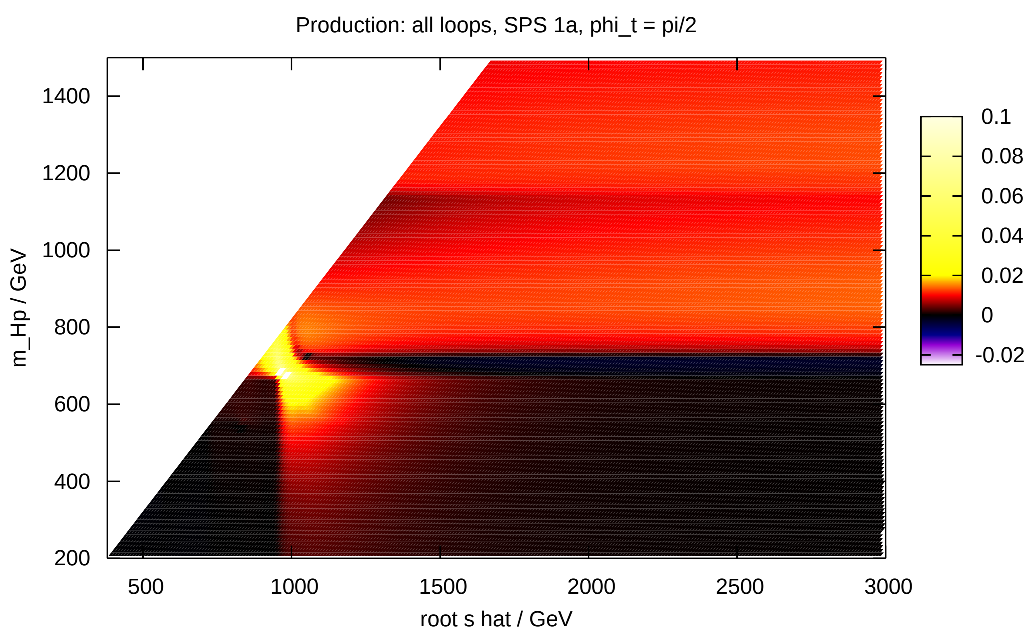


used `FormCalc` to calculate cross section asymmetry:

$$\mathcal{A}_{\text{parton}} = \frac{\hat{\sigma}(\bar{b}g \to H^+\bar{t}) - \hat{\sigma}(bg \to H^-t)}{\hat{\sigma}(\bar{b}g \to H^+\bar{t}) + \hat{\sigma}(bg \to H^-t)}$$

Partonic Production

★ Plot $\mathcal{A}$ vs partonic centre of mass energy, $\sqrt{\hat{s}}$ and charged Higgs mass, $m_{H^\pm}$

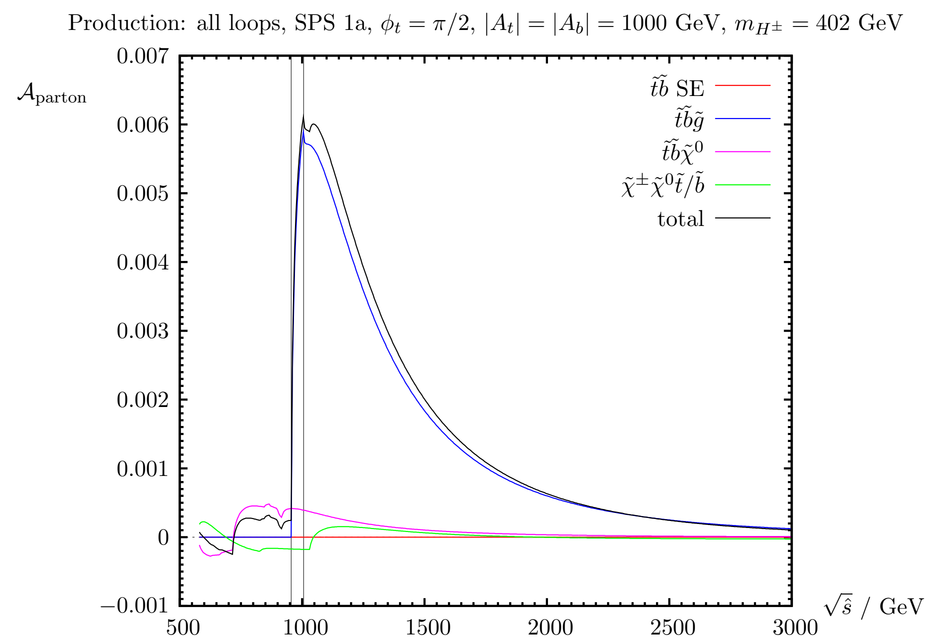


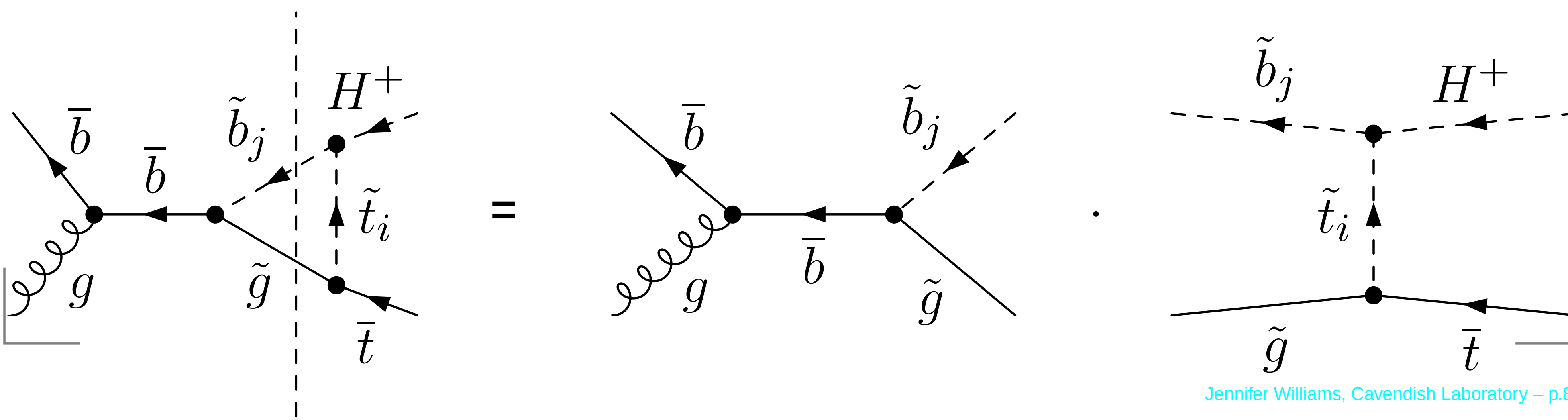
★ Notice the thresholds — remember them!

Partonic Production

★ 2-d plots: sections through 3-d plot:

- vs $\sqrt{\hat{s}}$
- constant $m_{H^\pm} = 402$ GeV
- trilinear scalar coupling:
  $|A_t| = 1000$ GeV
  $\phi_t = \frac{\pi}{2}$





Partonic Production

★ 2-d plots: sections through 3-d plot:

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  range of $|A_t|$
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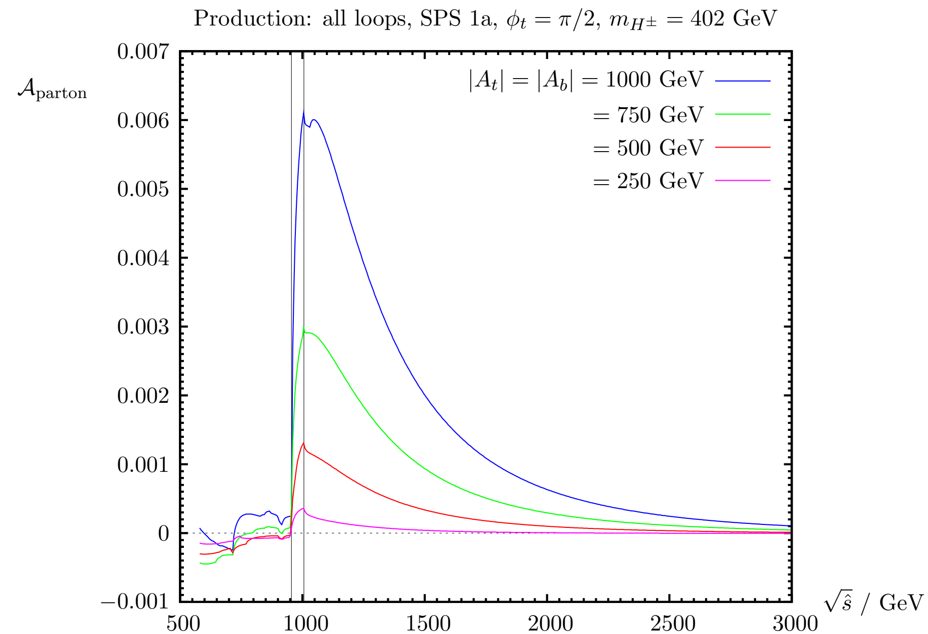

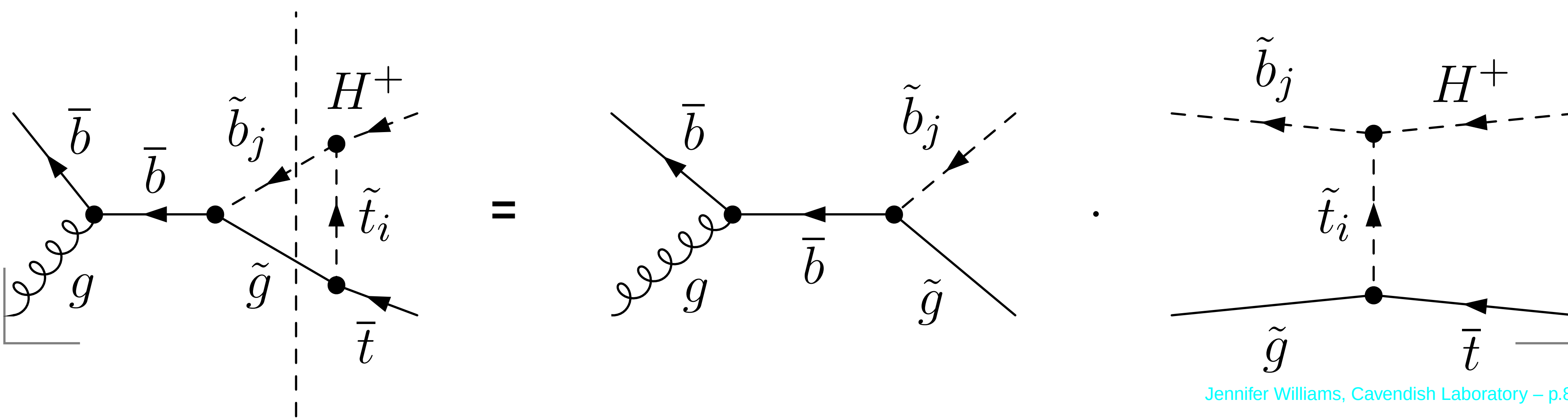

Partonic Production

★ 2-d plots: sections through 3-d plot:

- vs $\sqrt{\hat{s}}$
- constant $m_{H^\pm} = 675$ GeV
- trilinear scalar coupling:
  $|A_t| = 1000$ GeV
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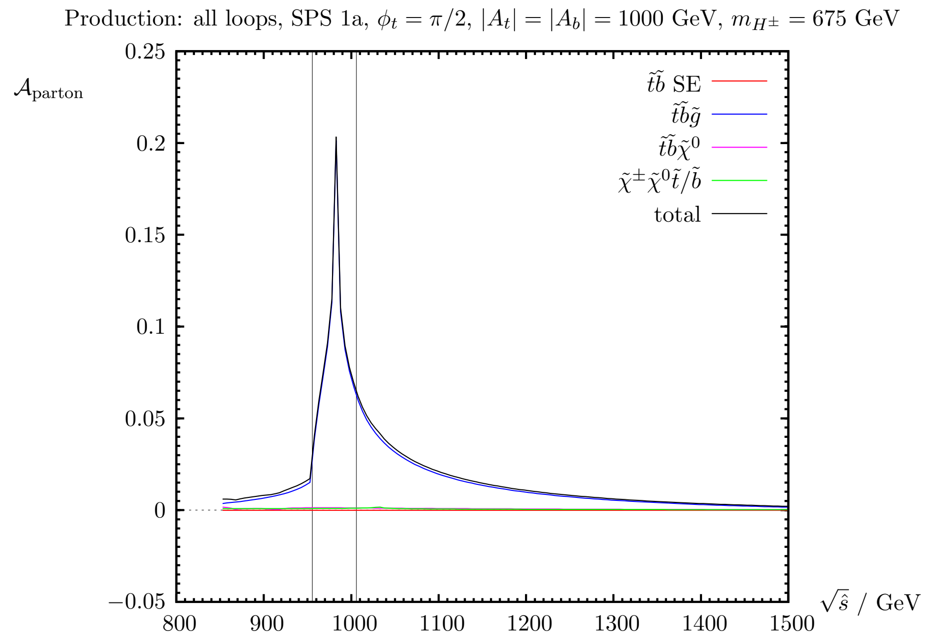

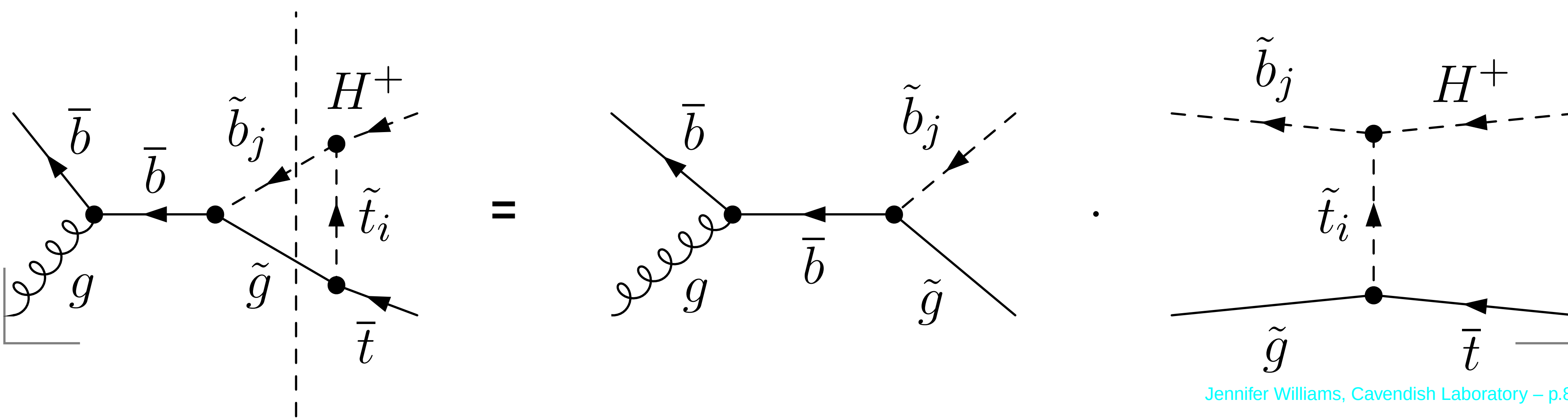

Partonic Production

★ 2-d plots: sections through 3-d plot:

- vs $m_{H^\pm}$
- constant $\sqrt{\hat{s}} = 980$ GeV
- trilinear scalar coupling:
  $|A_t| = 1000$ GeV
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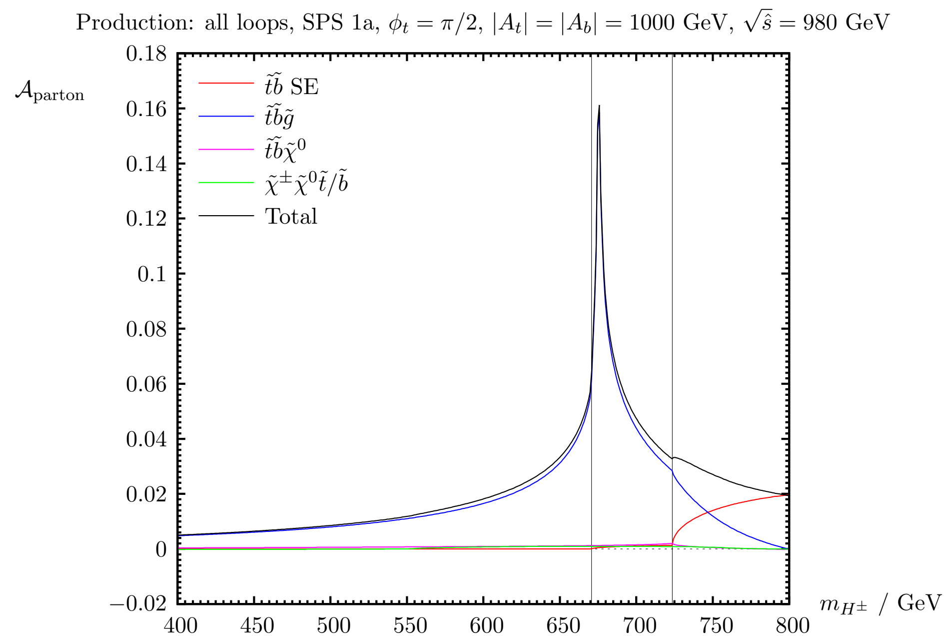

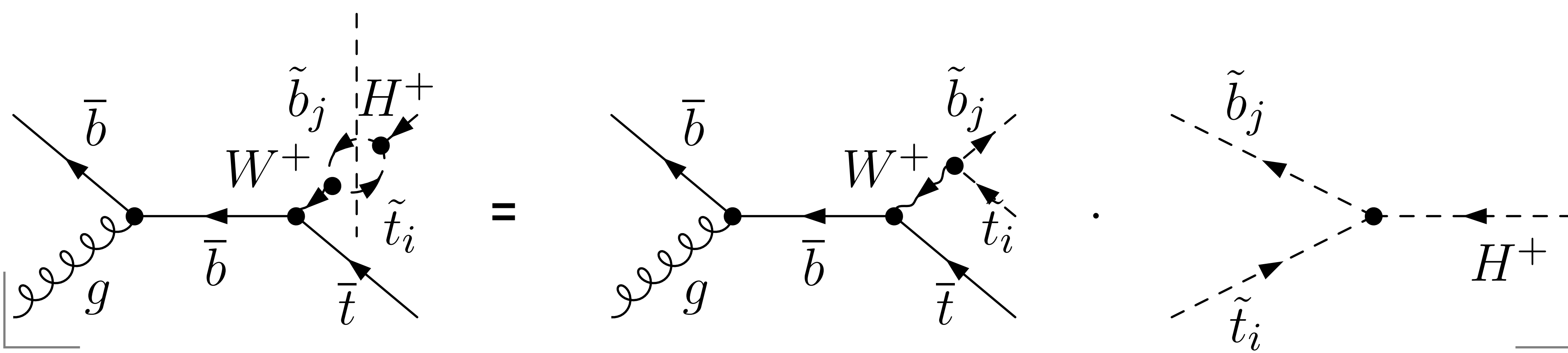

Partonic Production

★ 2-d plots: sections through 3-d plot:

- vs $m_{H^\pm}$
- constant $\sqrt{\hat{s}} = 2000$ GeV
- trilinear scalar coupling:
  $|A_t| = 1000$ GeV
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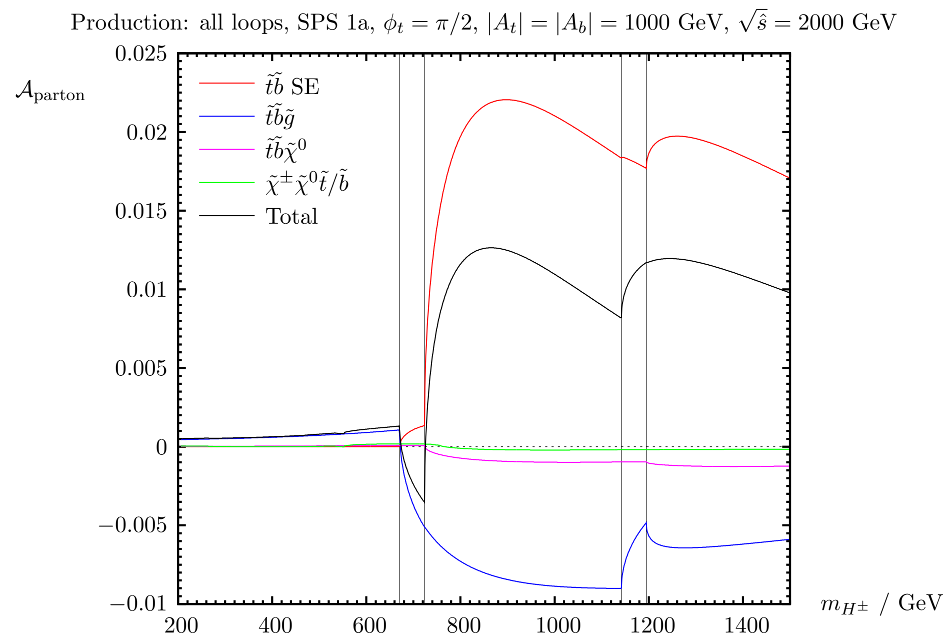
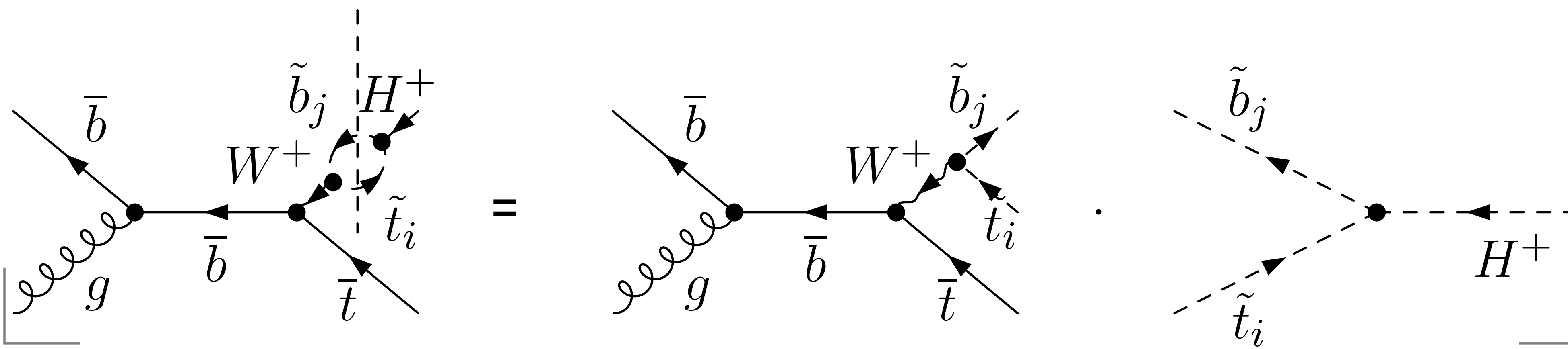
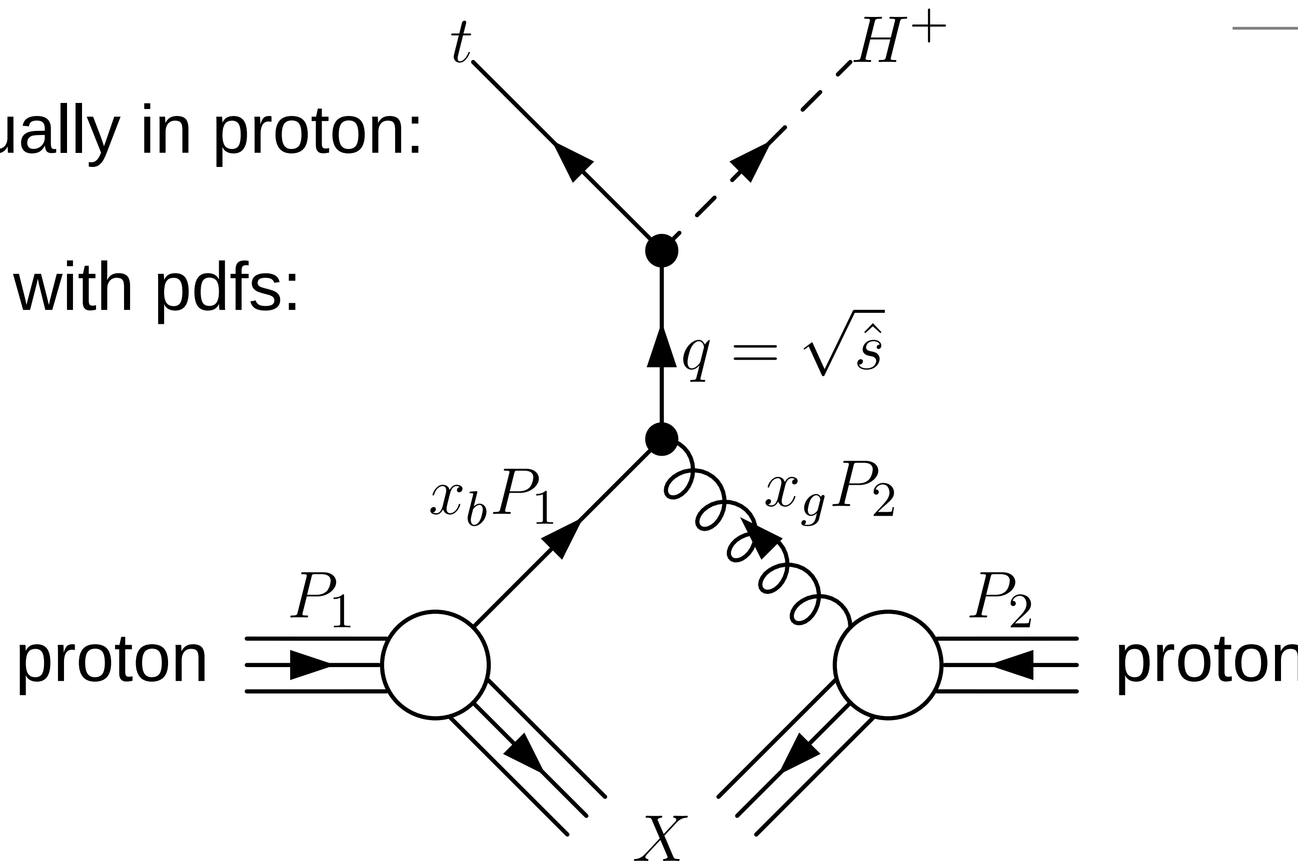




Hadronic Production

- ★ b quark, gluon actually in proton:
- ★ Need to convolute with pdfs:



$$\sigma\left(p\left(P_1\right) + p\left(P_2\right) \longrightarrow b + g \longrightarrow H^{\pm} + t + X\right)$$

$$= \int_0^1 \mathrm{d}x_b \int_0^1 \mathrm{d}x_g f\left(b, x_b\right) f\left(g, x_g\right) \hat{\sigma}\left(b\left(x_b P_1\right) + g\left(x_g P_2\right) \longrightarrow H^{\pm} + t\right)$$

Hadronic Production

★ Convoluting with pdfs integrates over $\sqrt{\hat{s}}$

- vs $m_{H^\pm}$
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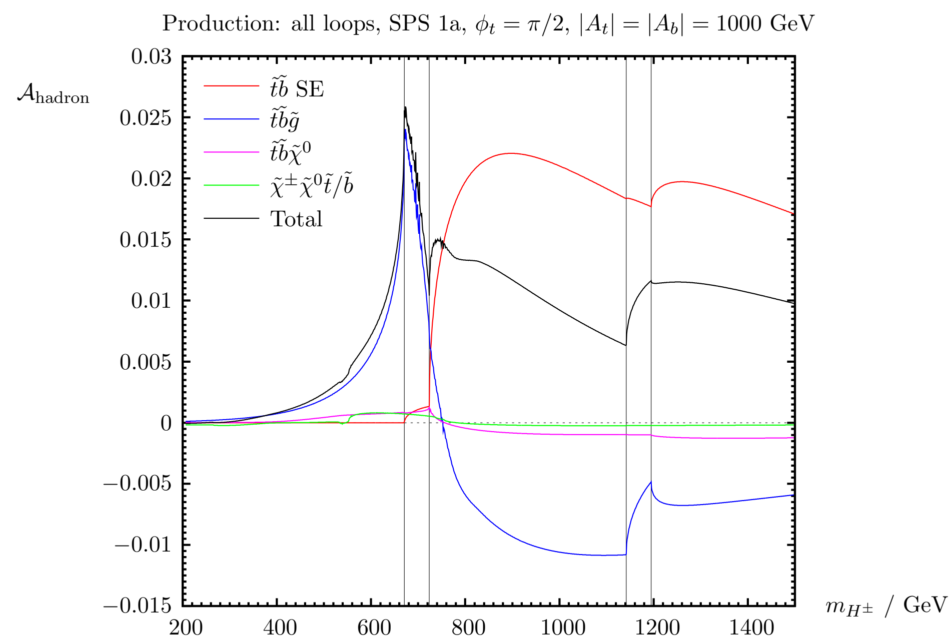

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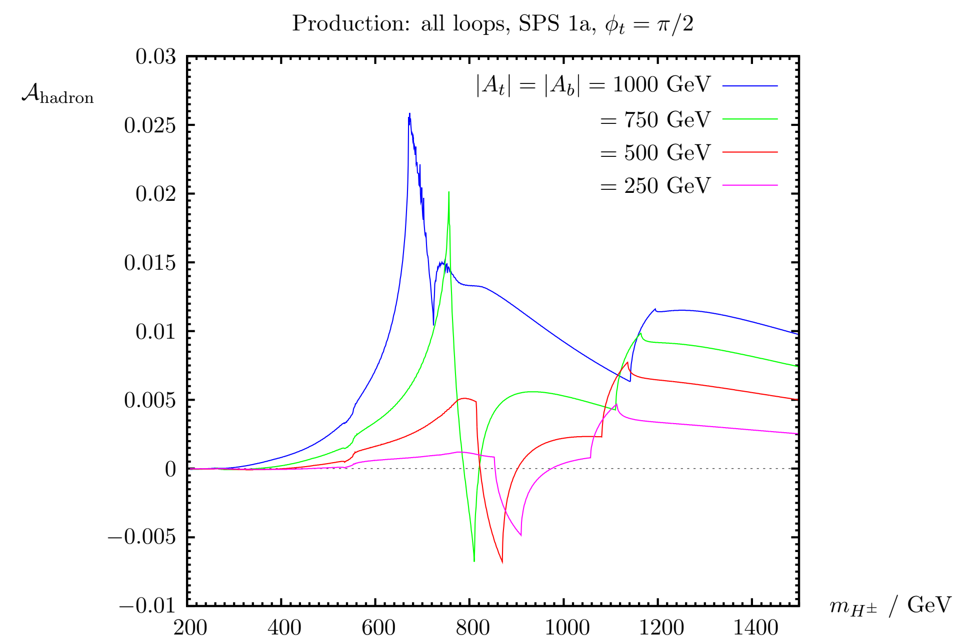

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Rapidity and Transverse Momentum

★ What happens within detector?

- No good if $\mathcal{A}$ all along beampipe!
- Plot $\mathcal{A}$ differentially, vs θ:
  ($H^{\pm}$ production angle, parton c.o.m. frame)

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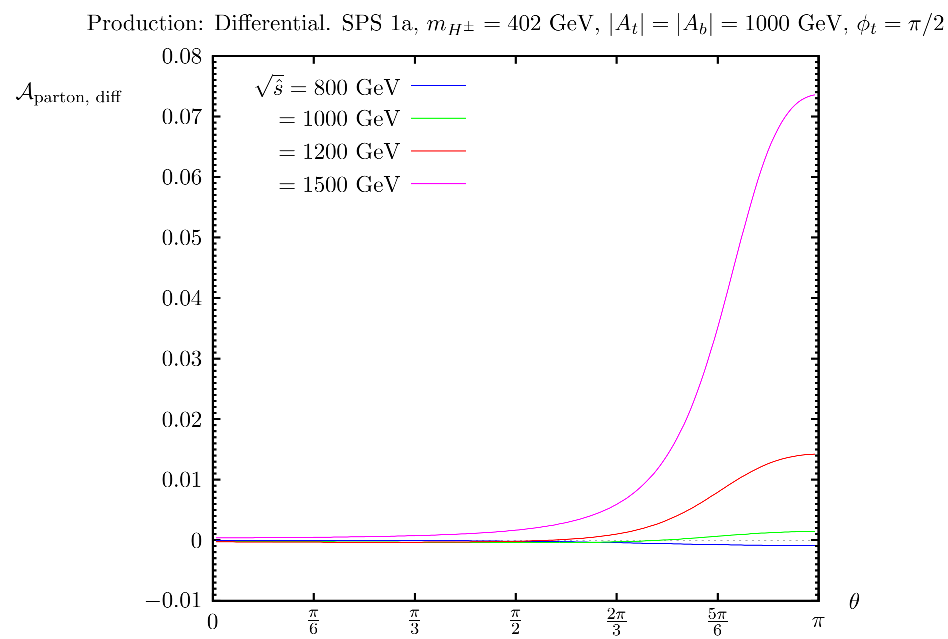

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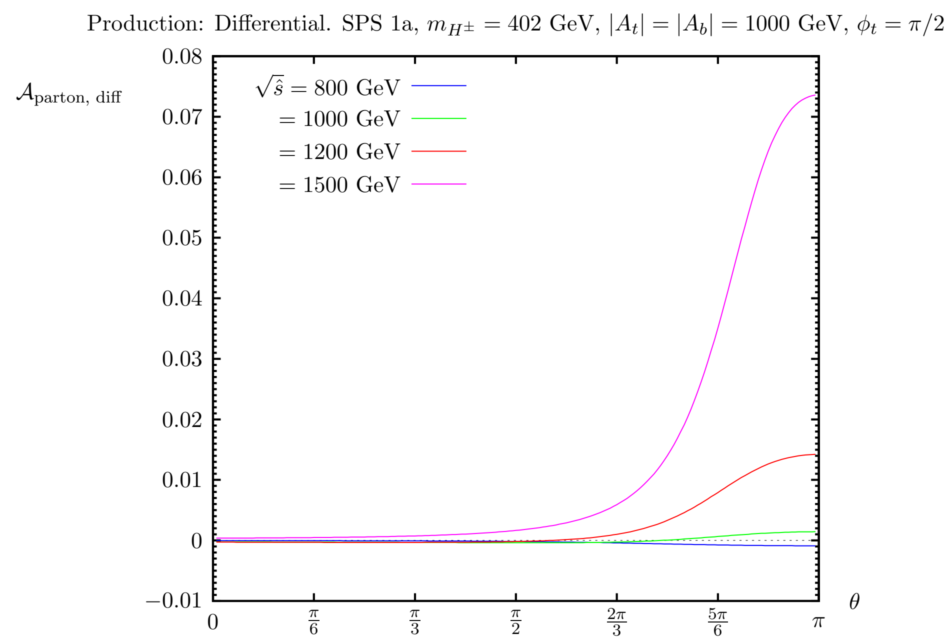
★ $\mathcal{A}$ very backward peaked

BAD NEWS!



Rapidity and Transverse Momentum

- ★ What happens when pdfs are included?
- ★ Use detector variable rapidity
  (Additive under longitudinal boosts)

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) ,$$

- ★ Need kinematics for massive final particles!

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y_H \; \mathrm{d}p_T} = \frac{1}{x_b} F\left(b, x_b\right) \frac{1}{\hat{s}} F\left(g, \frac{\hat{s}}{x_b s}\right) \int \mathrm{d}\theta_* \frac{\mathrm{d}\sigma}{\mathrm{d}\theta_*}\left(\hat{s}\right) \; \left| \frac{\partial\left(\hat{s}, \; x_b\right)}{\partial\left(y_H, \; p_T\right)} \right| .$$

Rapidity and Transverse Momentum

- ★ cross section vs rapidity
- ★ $m_{H^\pm} = 402$ GeV
- ★ trilinear scalar coupling:
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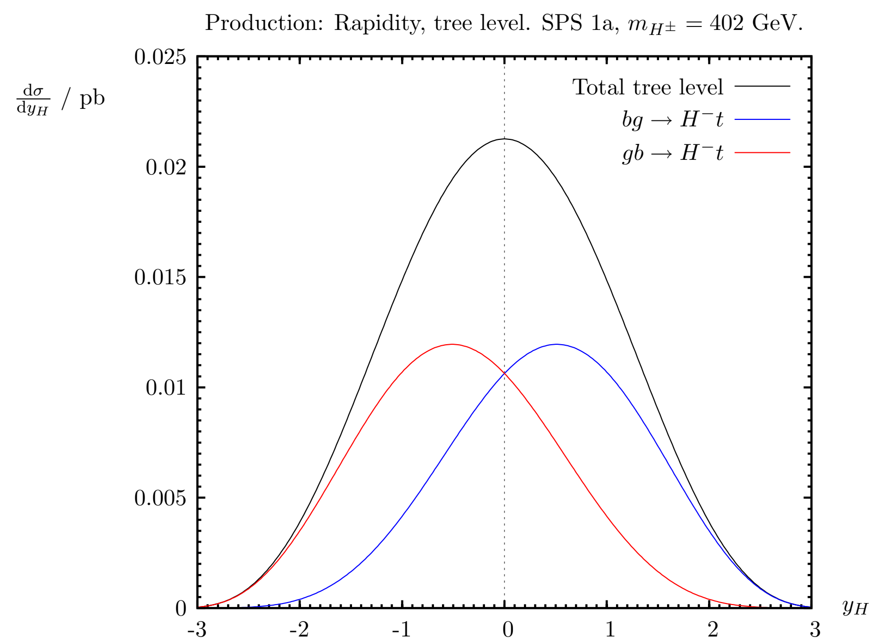

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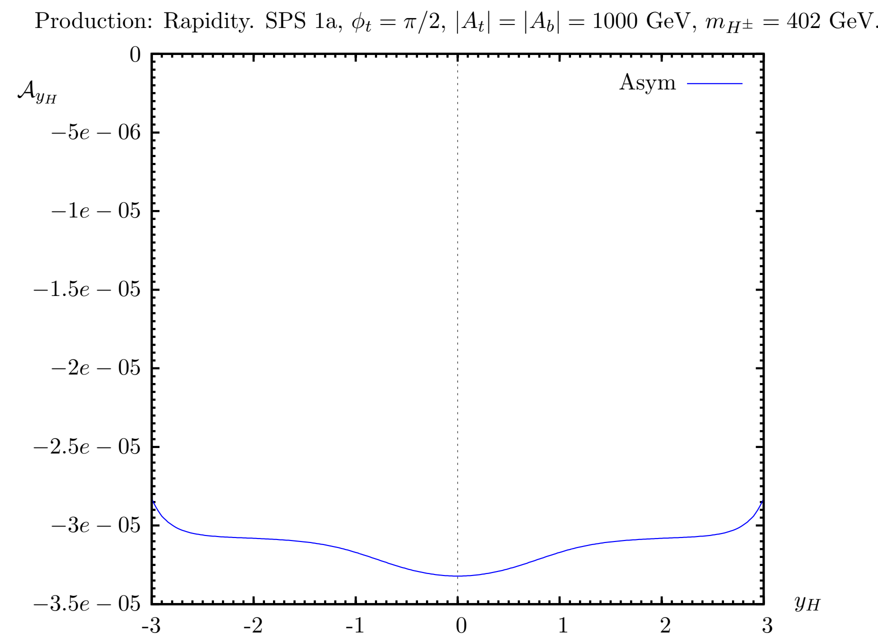

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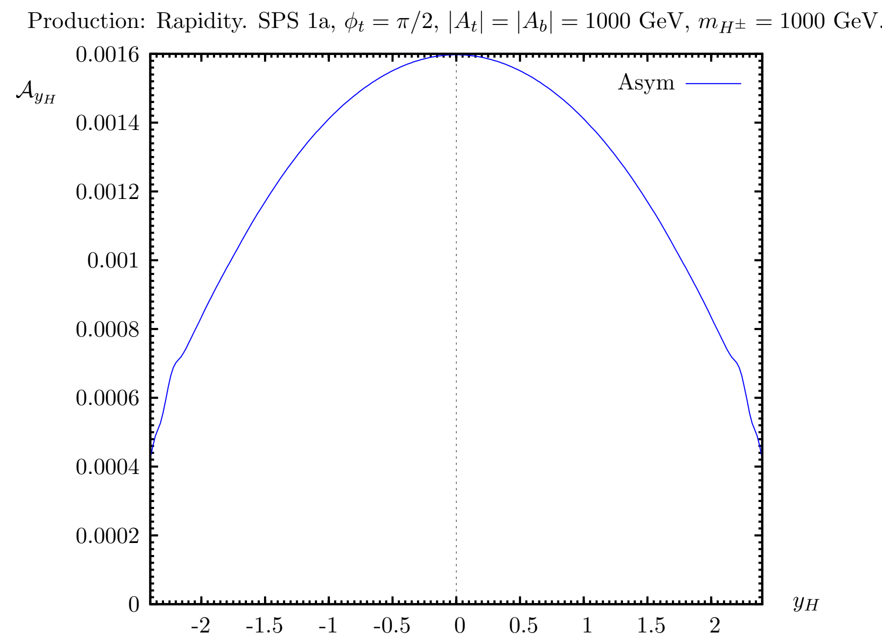

Rapidity and Transverse Momentum

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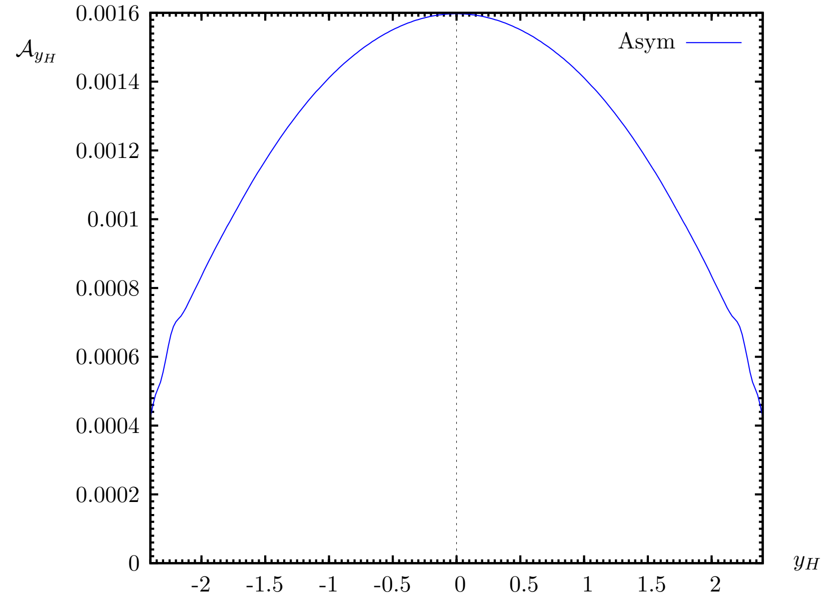
- ★ $m_{H^\pm} = 1000$ GeV
- ★ trilinear scalar coupling:
  $|A_t| = 1000$ GeV
  $\phi_t = \frac{\pi}{2}$
- ★ rather more central

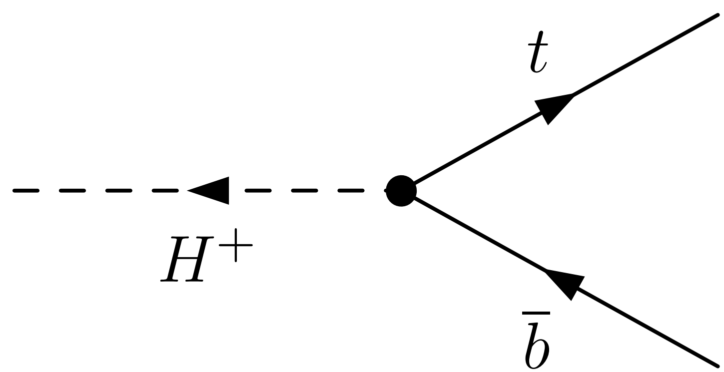
BETTER NEWS!

Production: Rapidity. SPS 1a, $\phi_t = \pi/2$, $|A_t| = |A_b| = 1000$ GeV, $m_{H^\pm} = 1000$ GeV.



Decay

- ★ Consider charged Higgs decay to top and bottom quarks
  Christova *et al* (Nucl. Phys. B639 (2002) 263-280)
- ★ Same loop diagrams —



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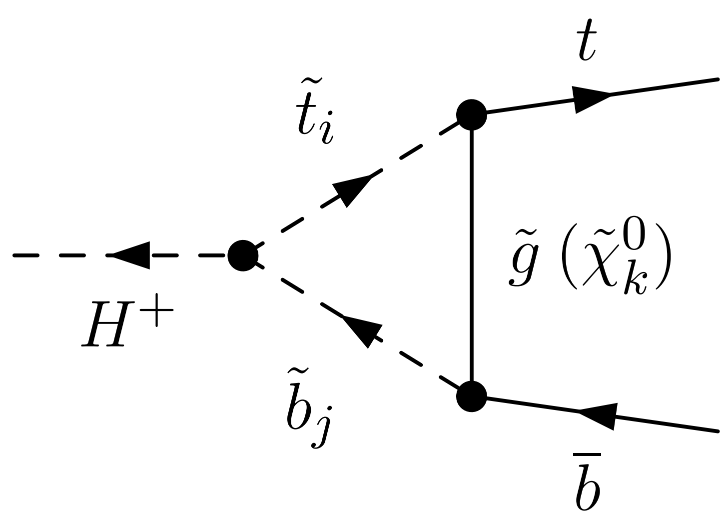

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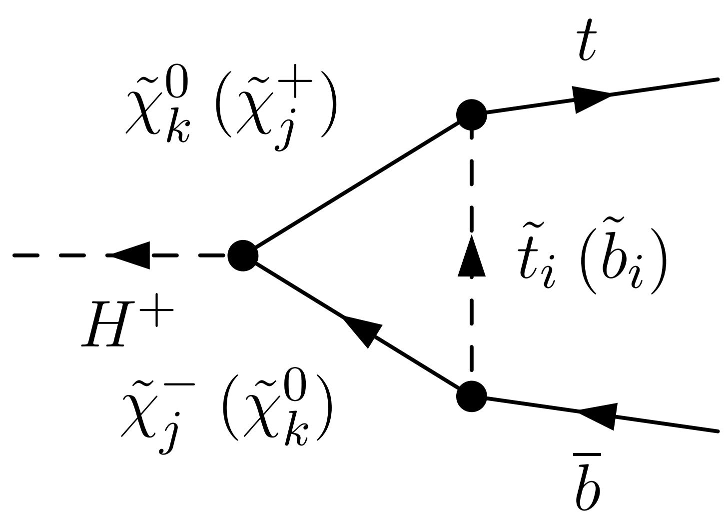

Decay

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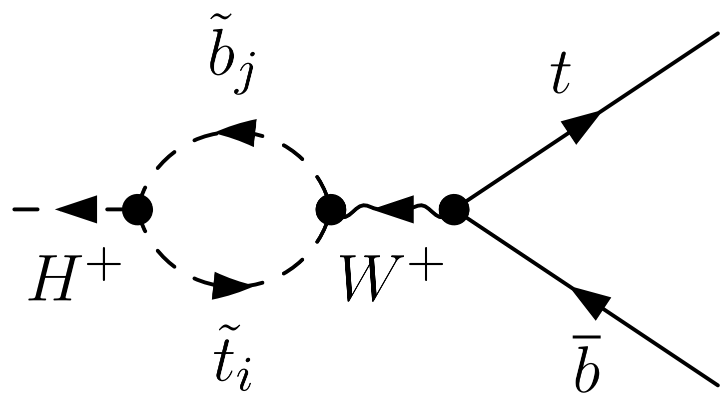

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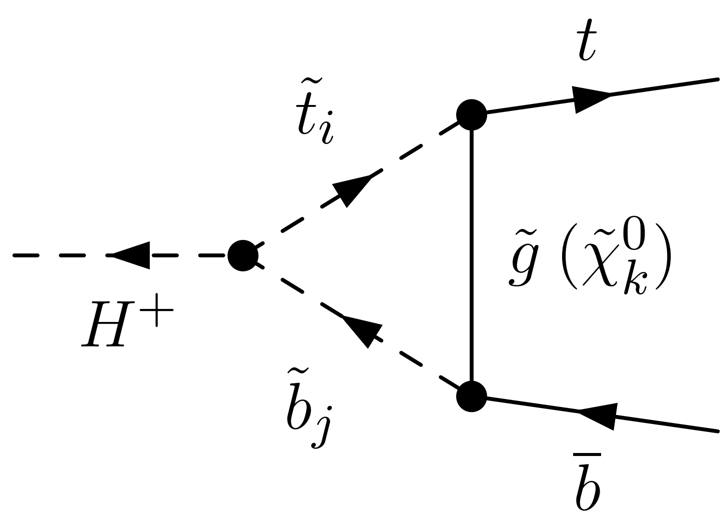


- See similar features to production

- BUT, no thresholds in $\sqrt{\hat{s}}$

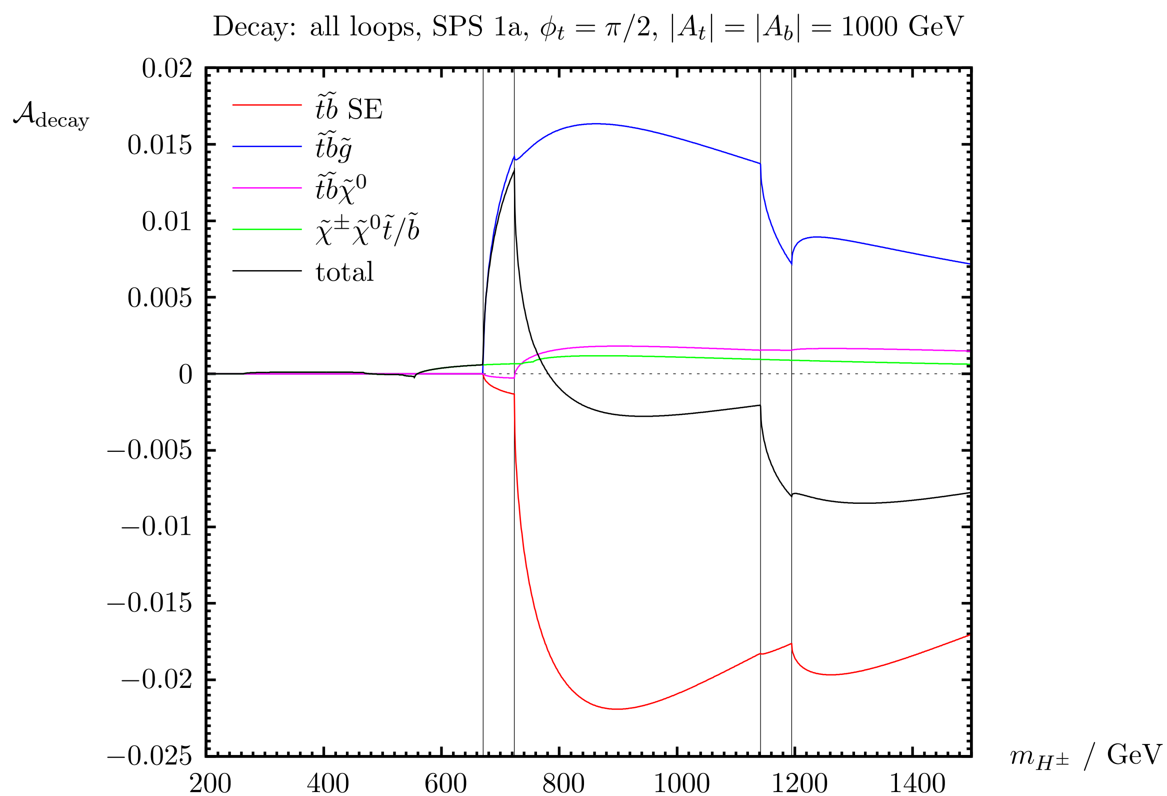
Decay

★ $\mathcal{A}$ vs $m_{H^\pm}$

★ trilinear scalar coupling:

$|A_t| = 1000$ GeV

$\phi_t = \frac{\pi}{2}$



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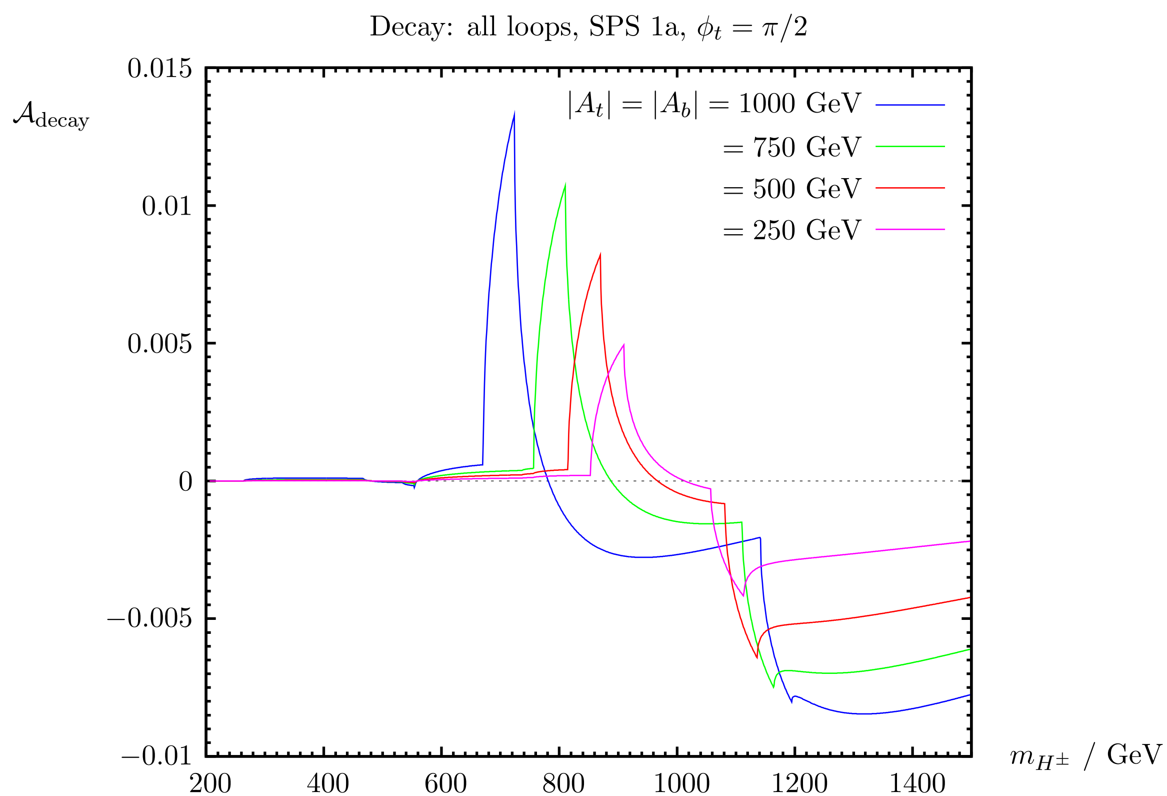

Combining Production and Decay

★ Need cross section $\times$ branching ratio:

(Narrow width approximation,
i.e. charged Higgs is produced and then decays)

$$\mathcal{A}_{\text{total}} = \frac{\sigma\left(H^+\right)\Gamma\left(H^+\right) - \sigma\left(H^-\right)\Gamma\left(H^-\right)}{\sigma\left(H^+\right)\Gamma\left(H^+\right) + \sigma\left(H^-\right)\Gamma\left(H^-\right)}.$$

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- Made simpler because loop contributions are small:

$$\mathcal{A}_{\text{total}} = \mathcal{A}_{\text{hadron}} + \mathcal{A}_{\text{decay}}$$

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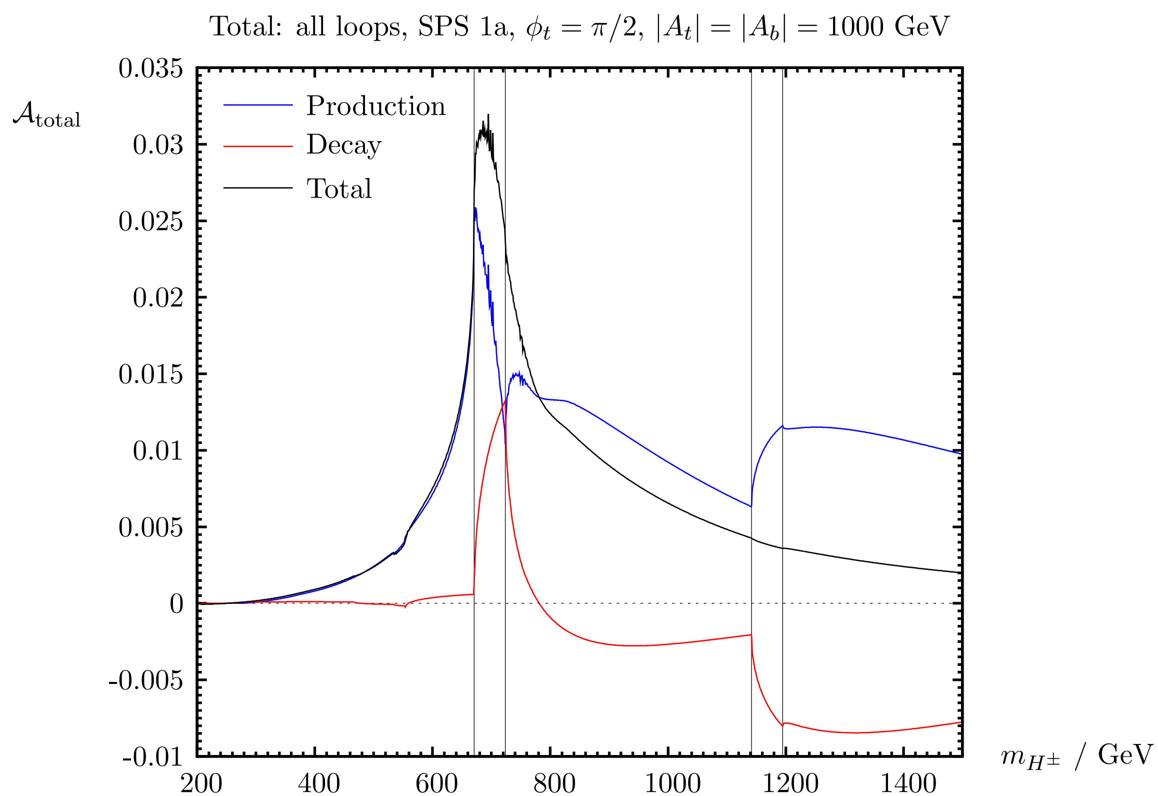

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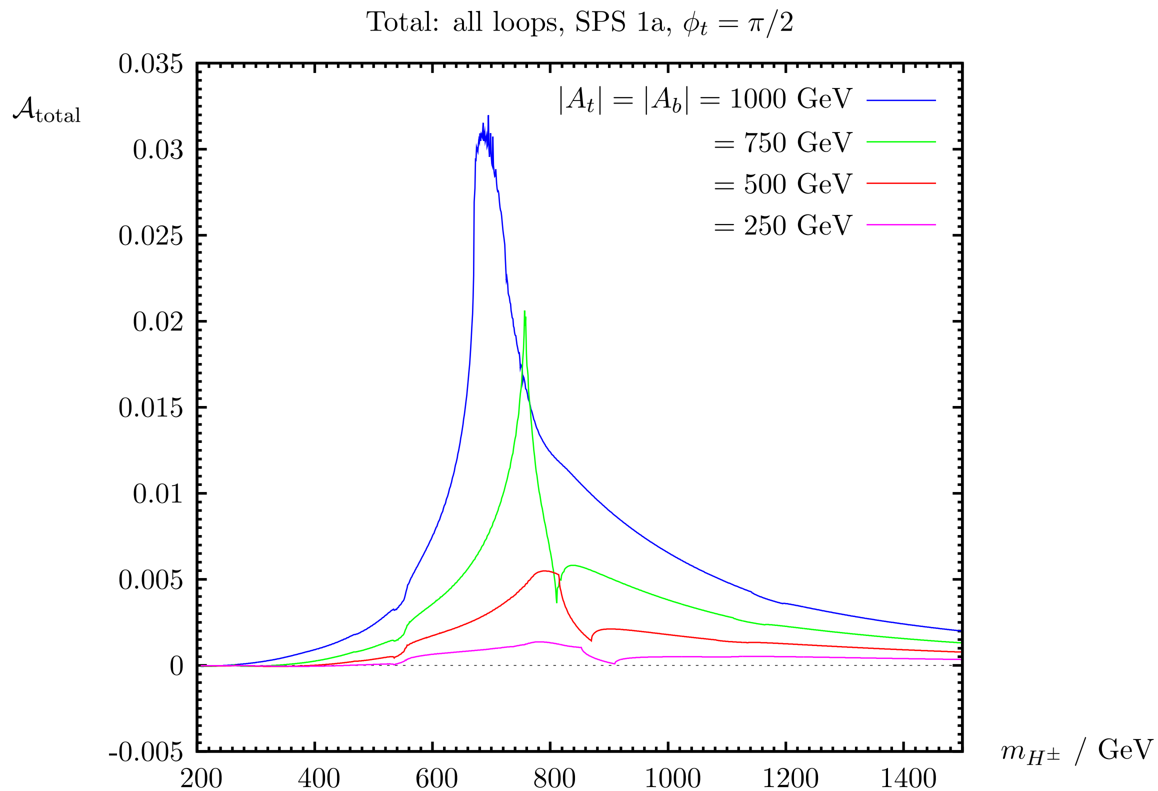

Outlook at the LHC

- ★ Number of Charged Higgs events seen at ATLAS:

$$N = \sigma\left(pp \to bg \to H^{\pm}t\right) \text{BR}\left(H^{\pm} \to tb\right) \times \text{acceptance} \times \text{luminosity}$$

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- acceptance $= 0.05$
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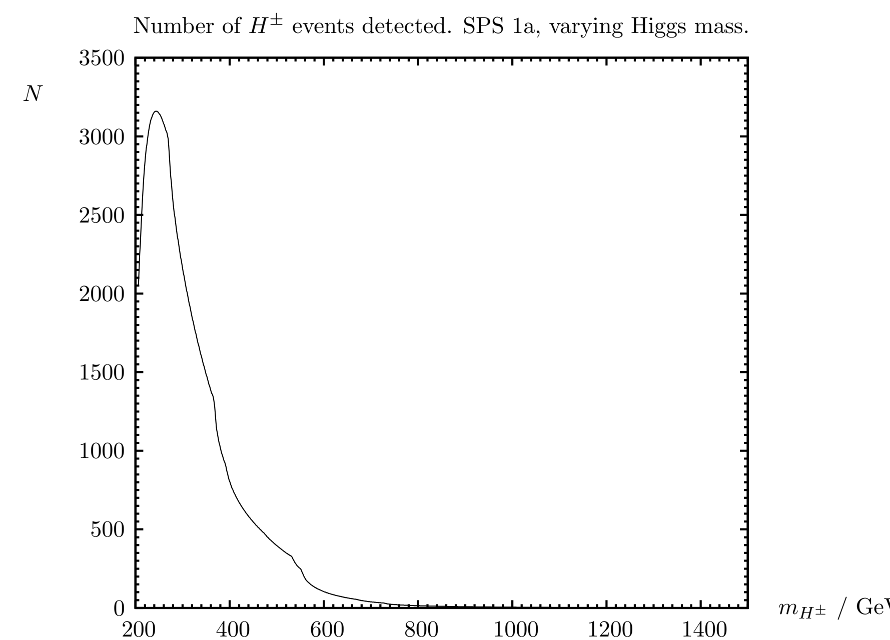

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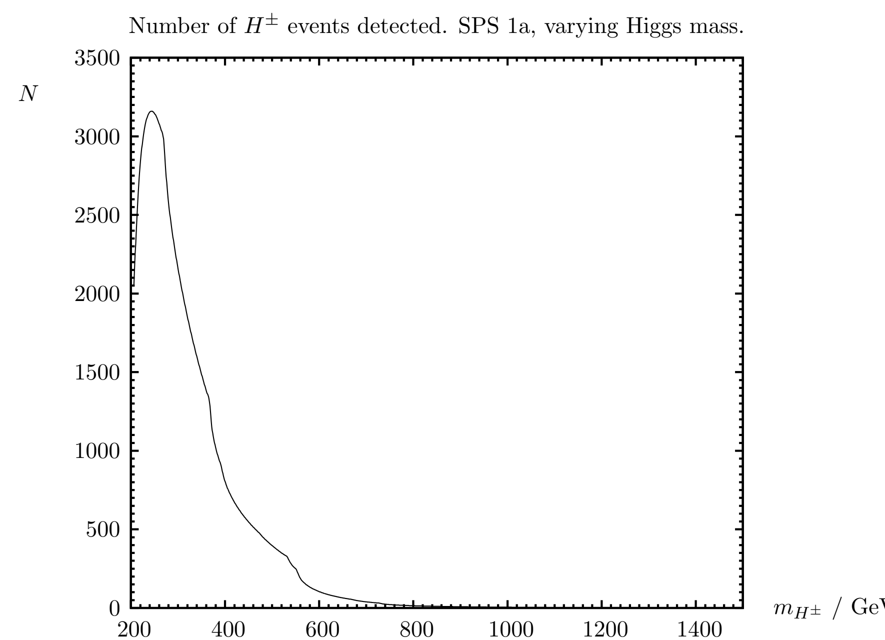

★ Significance of observation:

$$f = \frac{\text{number signal events}}{\sqrt{\text{number background events}}}\ \sigma$$

$$\mathcal{A} = \frac{\text{number events asymmetry signal}}{\text{total number events}}$$

$$f = \sqrt{N}\mathcal{A}$$

Outlook at the LHC

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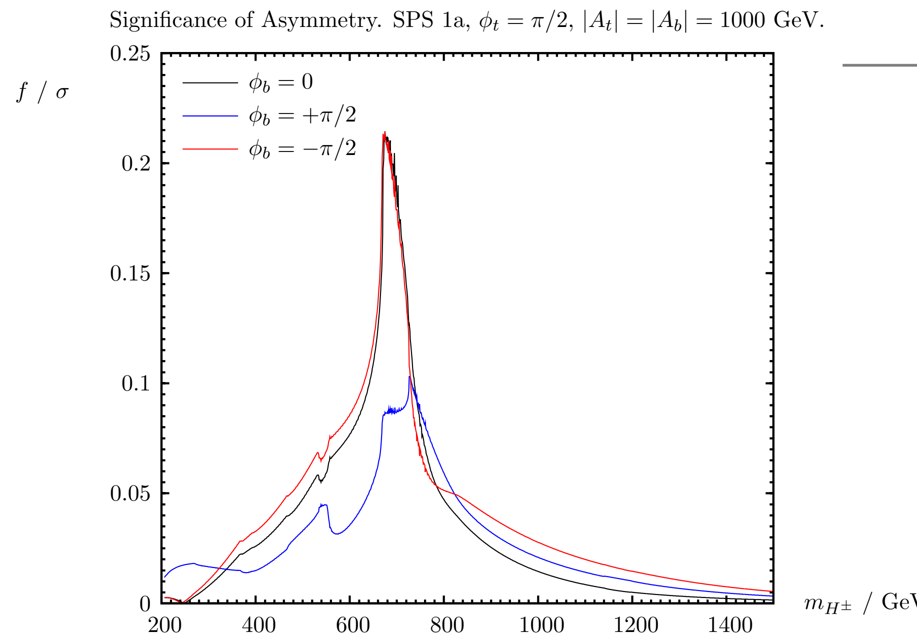
DEPRESSING!



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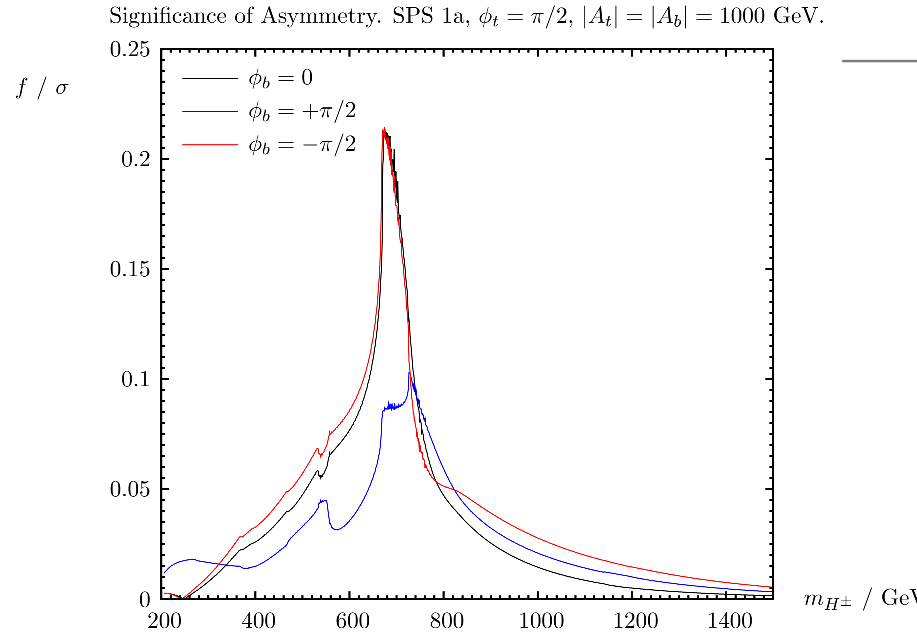

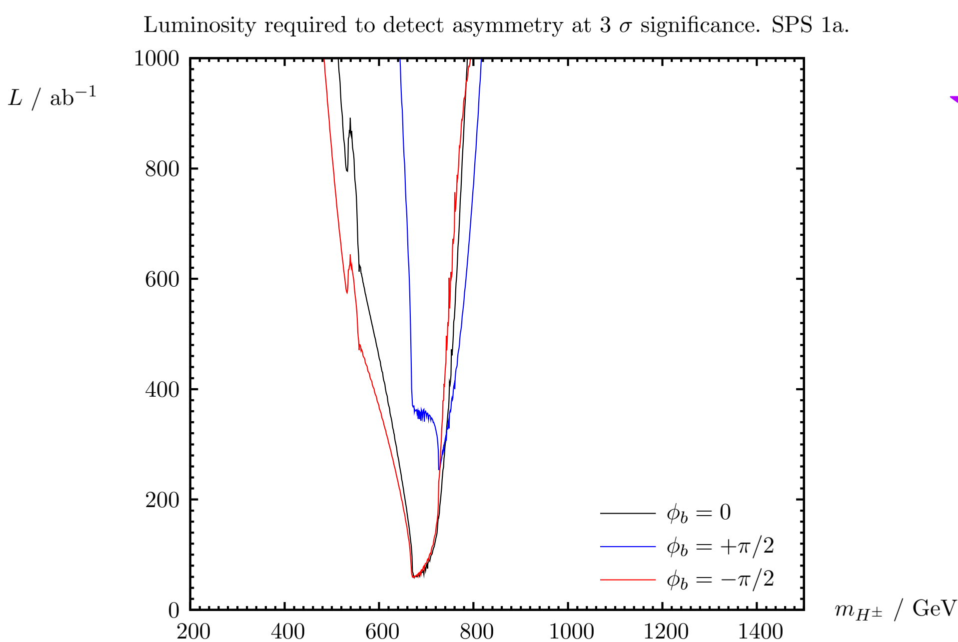

★ How much luminosity?

Scale in ab^{-1}!

EVEN MORE DEPRESSING!

Conclusions

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    (*e.g.* gluon – gluon fusion)
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And finally —

⋆ Thank you . . .

for your helpful input while I have been here!

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⋆ And Goodbye . . .

I'll have to participate remotely in the future!

Varying the Phases

★ Up to now considered maximum phase in A_t, ϕ_t

★ Allow phase to vary

★ As expect - less asym for smaller phase

★ $\mathcal{A}$ vs ϕ_t

- $m_{H^\pm} = 402$
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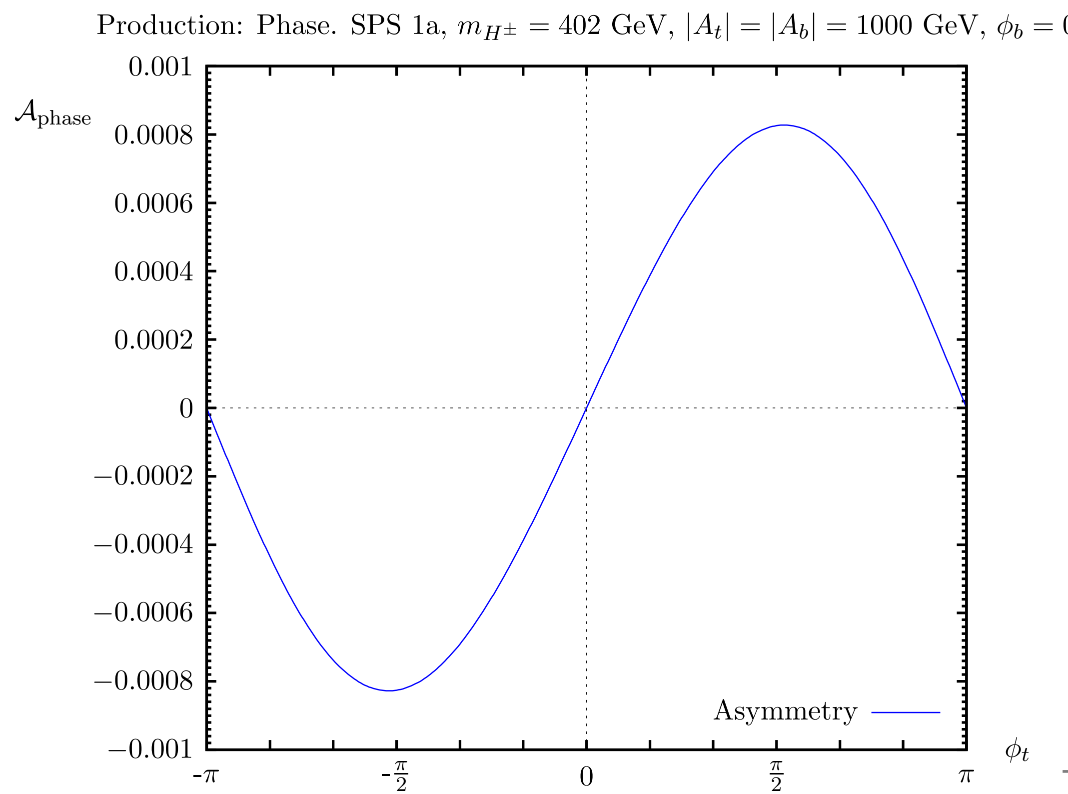

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e.g. A_b, ϕ_b

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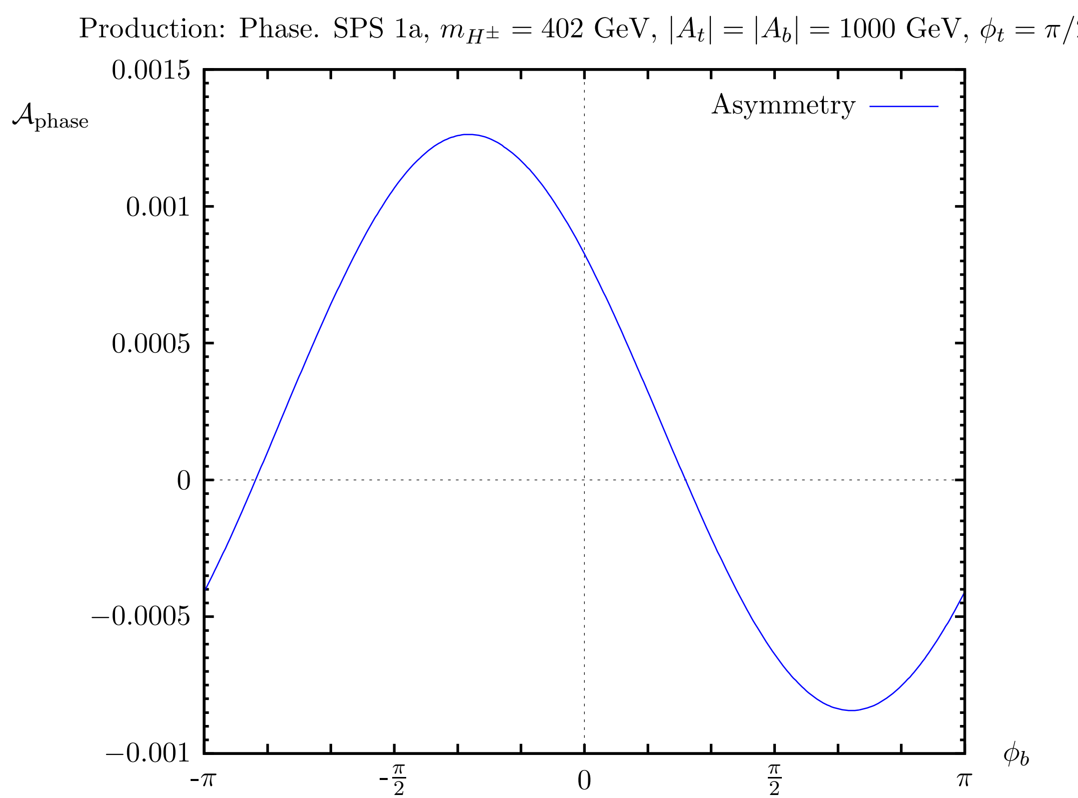

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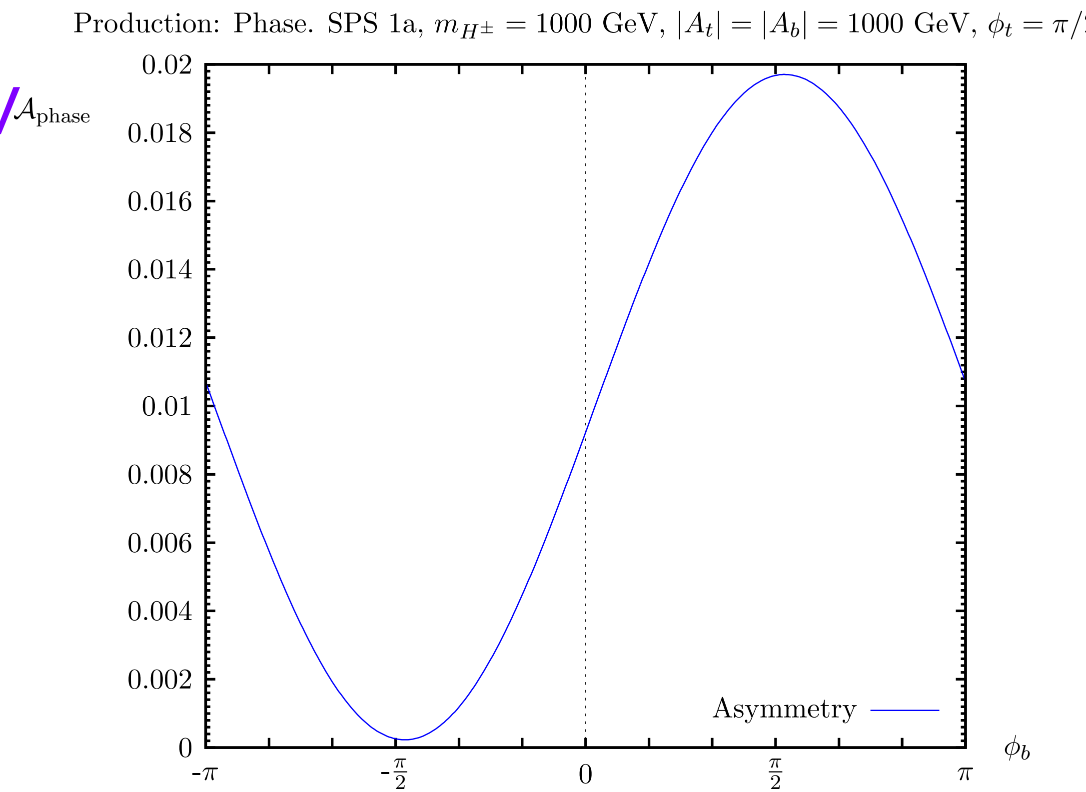

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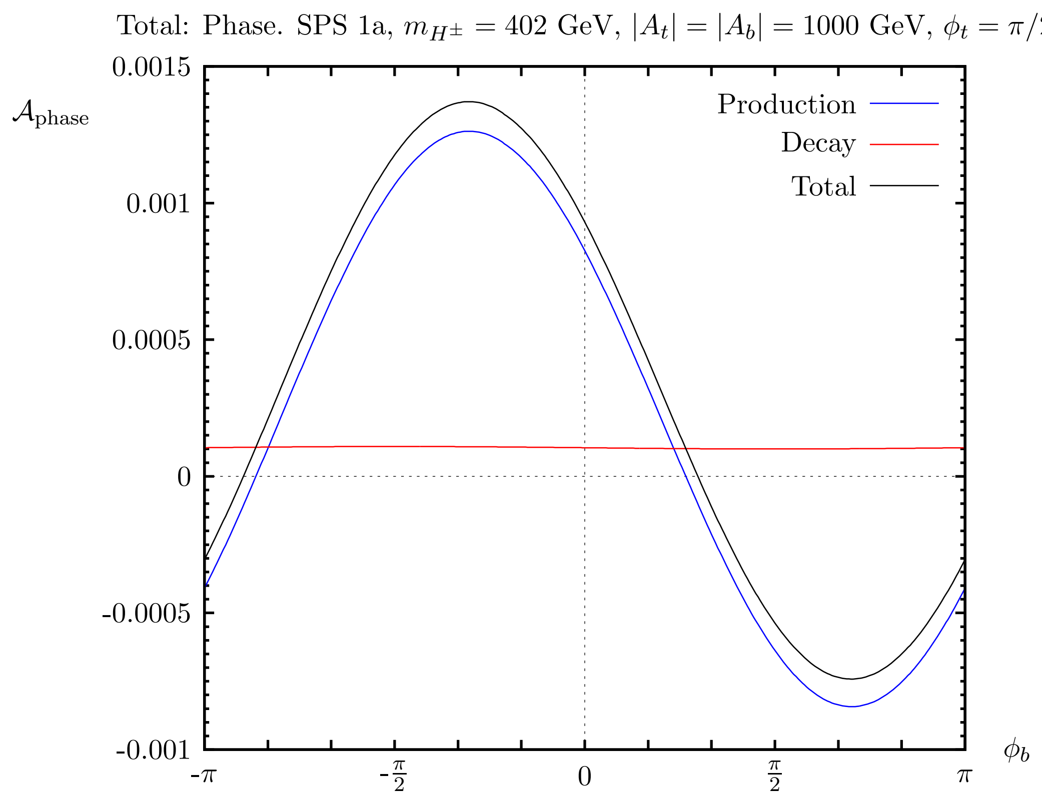

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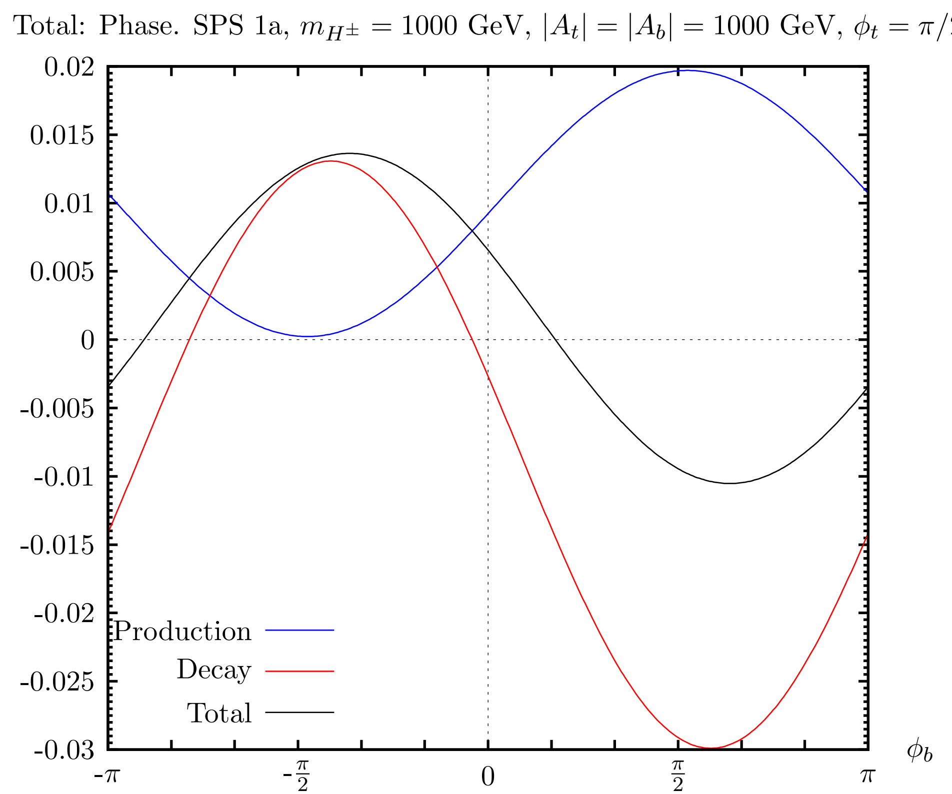

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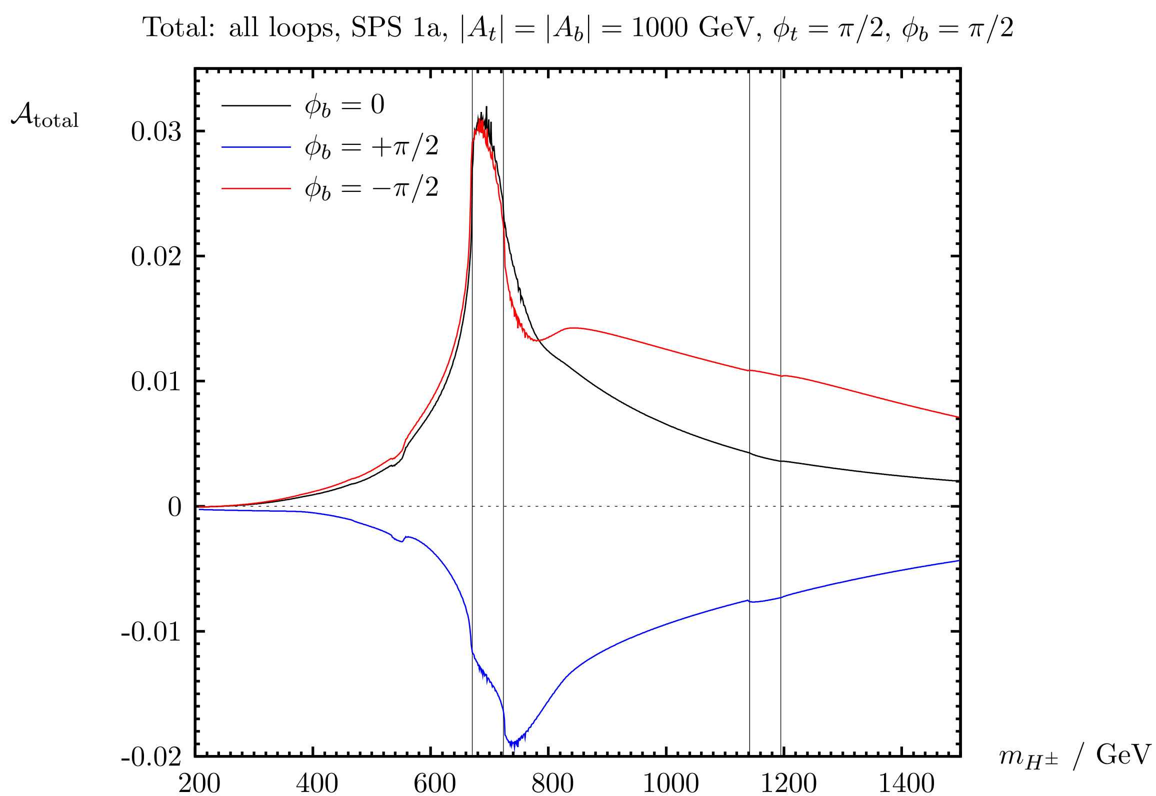

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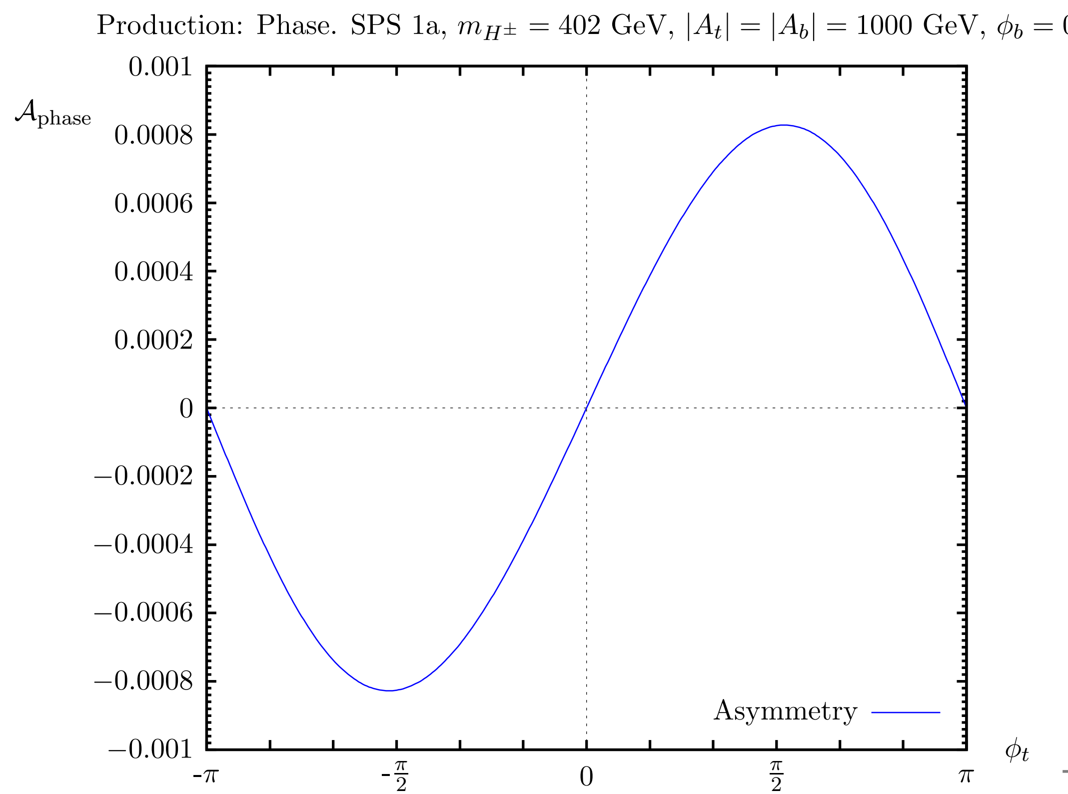

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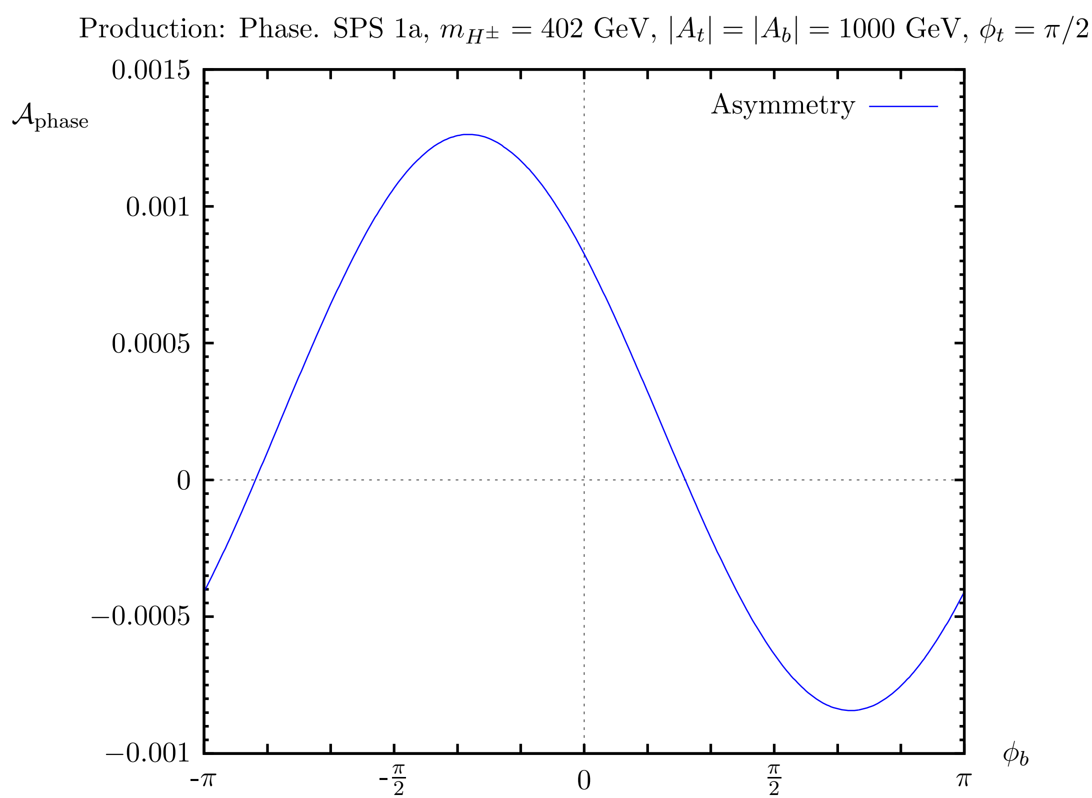

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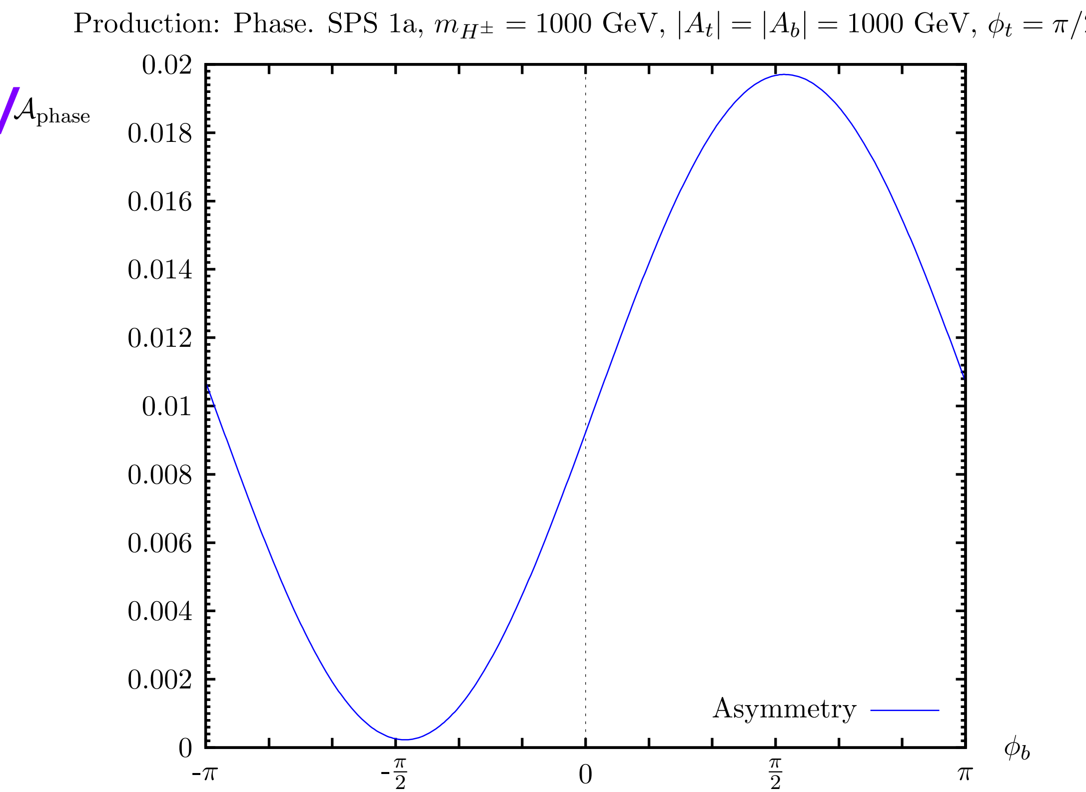

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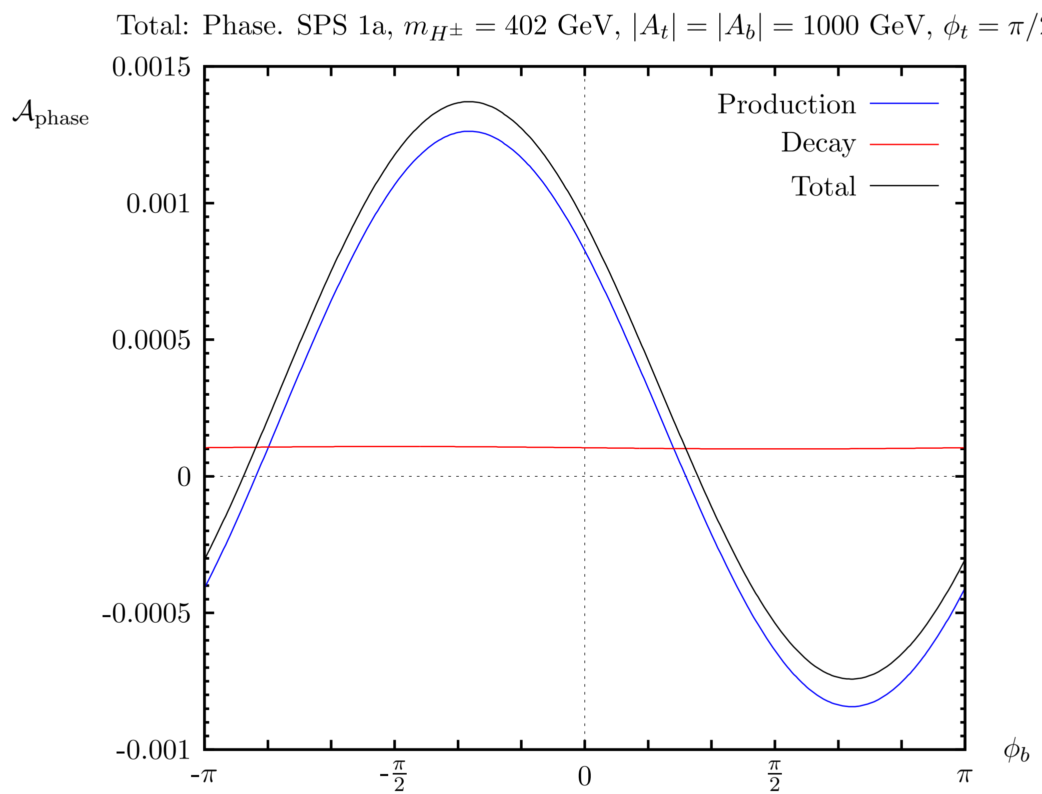

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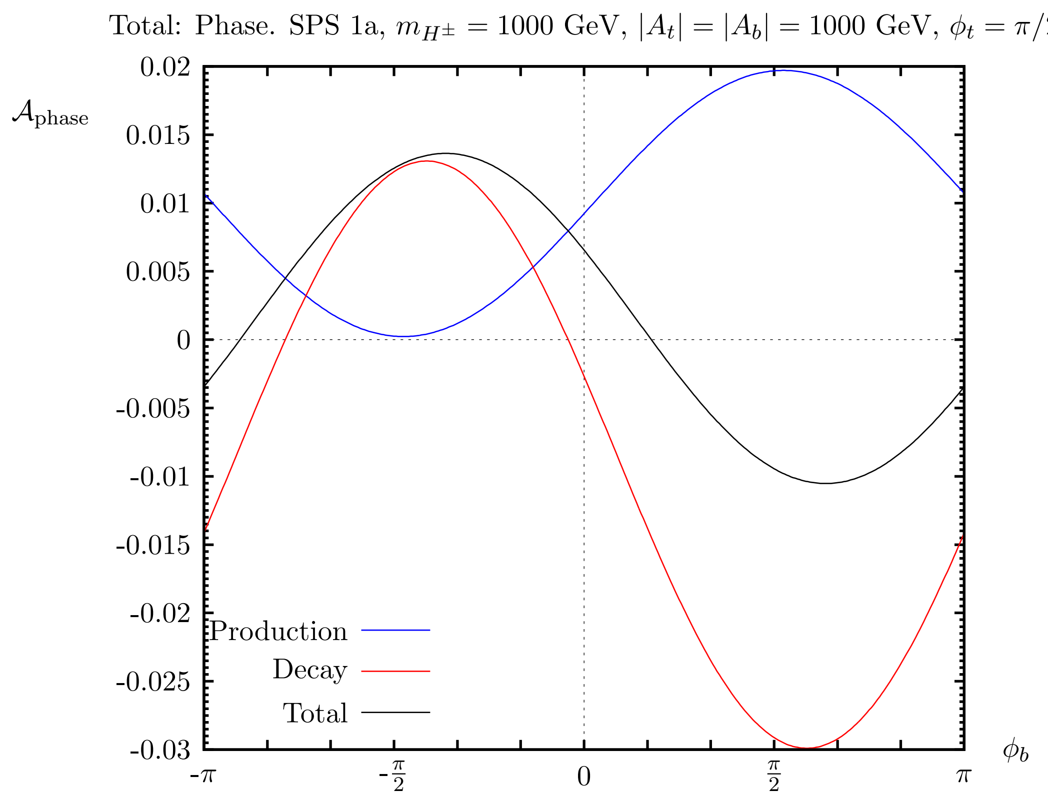

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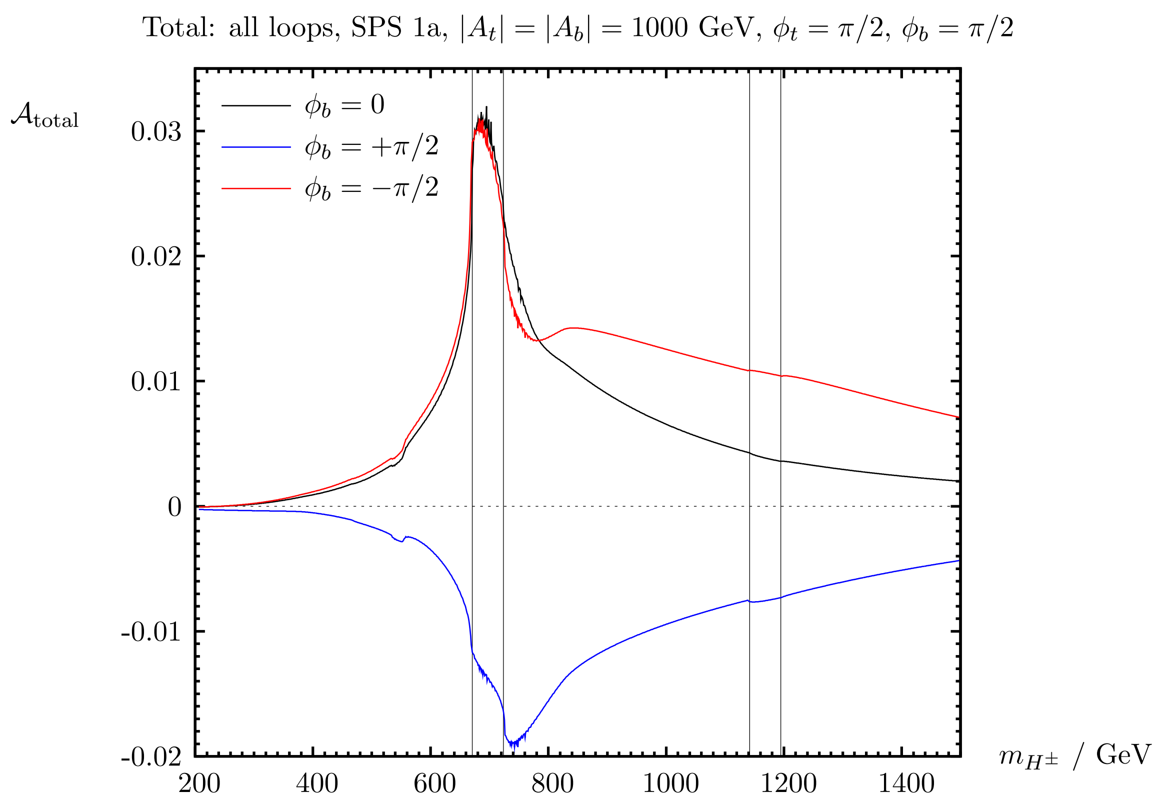

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