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CP-violation in charged Higgs boson production at LHC

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This talk is based on the results from work in progress in collaboration with E. Christova, INRNE, Sofia & H. Eberl, Institut Fuer Hocherergiephysik, Vienna

Outline

- The subprocess $bg \to H^{\pm}t$
- LHC process $pp \to H^{\pm}t$
- $H^{\pm}$ production and decay at the LHC
- Numerical analysis
- Conclusions

Our process: charged Higgs boson production associated with a t-quark production at LHC

- The main production process at LHC:
  $pp \to H^{\pm} t + X$
- At parton level the reaction proceeds through:
  - Gluon-gluon fusion $gg \longrightarrow H^+ \bar{t} b$
  - Bottom-gluon fusion $\bar{b} g \longrightarrow H^+ \bar{t}$

Concerning CP-violation...

- We consider the charge conjugate processes:

$$b_r(p_b) + g_\mu^\alpha(b_g) \longrightarrow t_s(p_t) + H^-(p_{H^-})$$

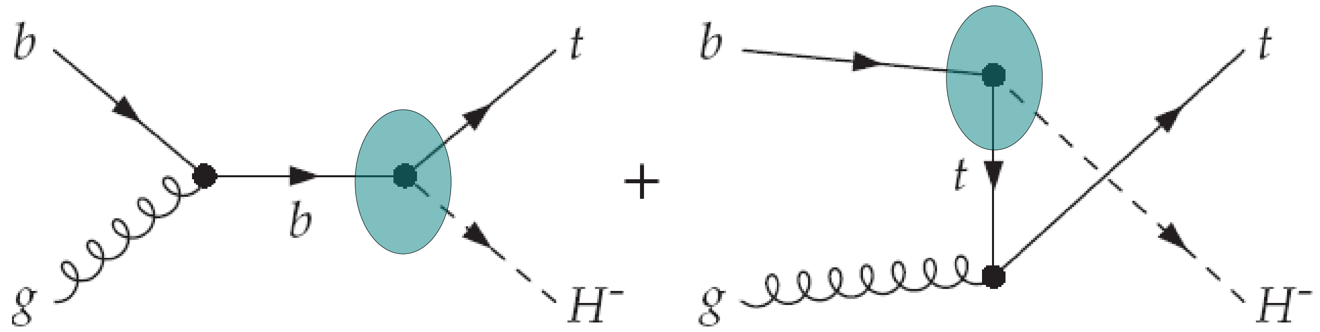
$$\bar{b}_r(p_{\bar{b}}) + g_\mu^\alpha(b_g) \longrightarrow \bar{t}_s(p_{\bar{t}}) + H^+(p_{H^+})$$

in the Minimal Supersymmetric Standard Model (MSSM) with complex phases

The subprocess b g → t $H^{\pm}$

- At tree-level the process b g → t $H^{\pm}$ has two channels:

  s-channel t-channel



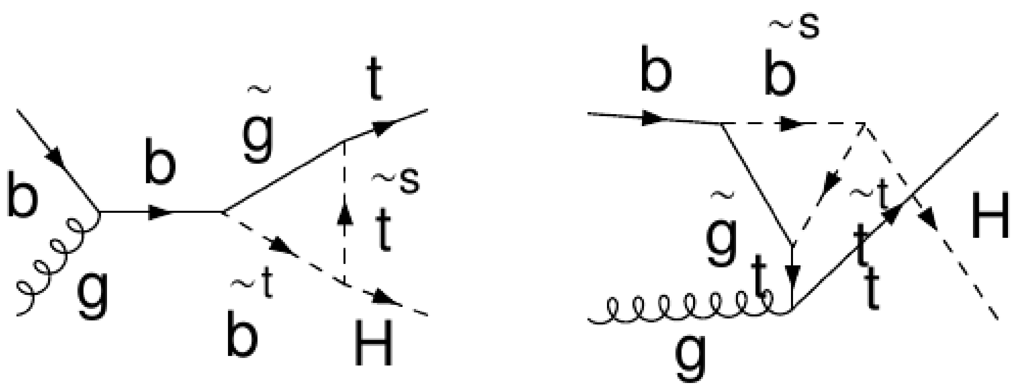
$$\hat{s} = (p_b + p_g)^2, \qquad t = (p_t - p_g)^2 = (p_b - p_{H^+})^2$$

- Effects of CP-violation appear at next-to-leading order, when adding loop corrections with SUSY particles in the $H^{\pm}$tb-vertices of both s- and t-channels

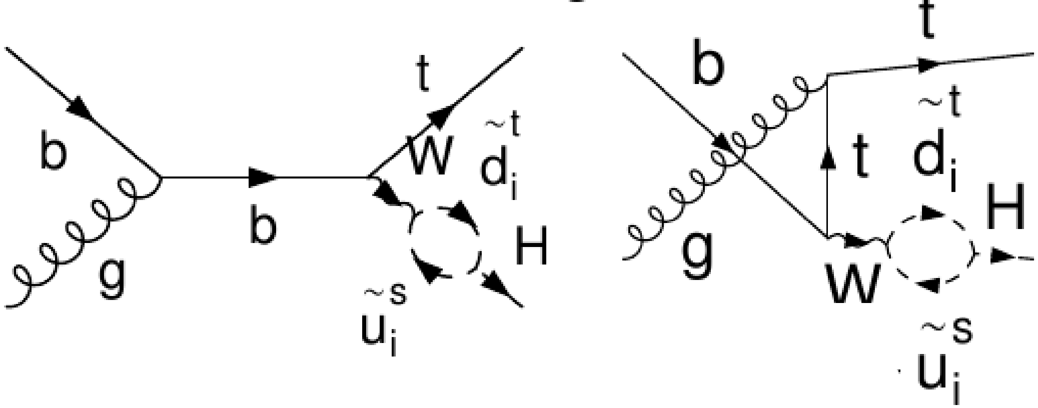
Sources of CP-violation in MSSM

- The (main) contributions to CP-violating asymmetry comes from:

  ✓vertex graphs



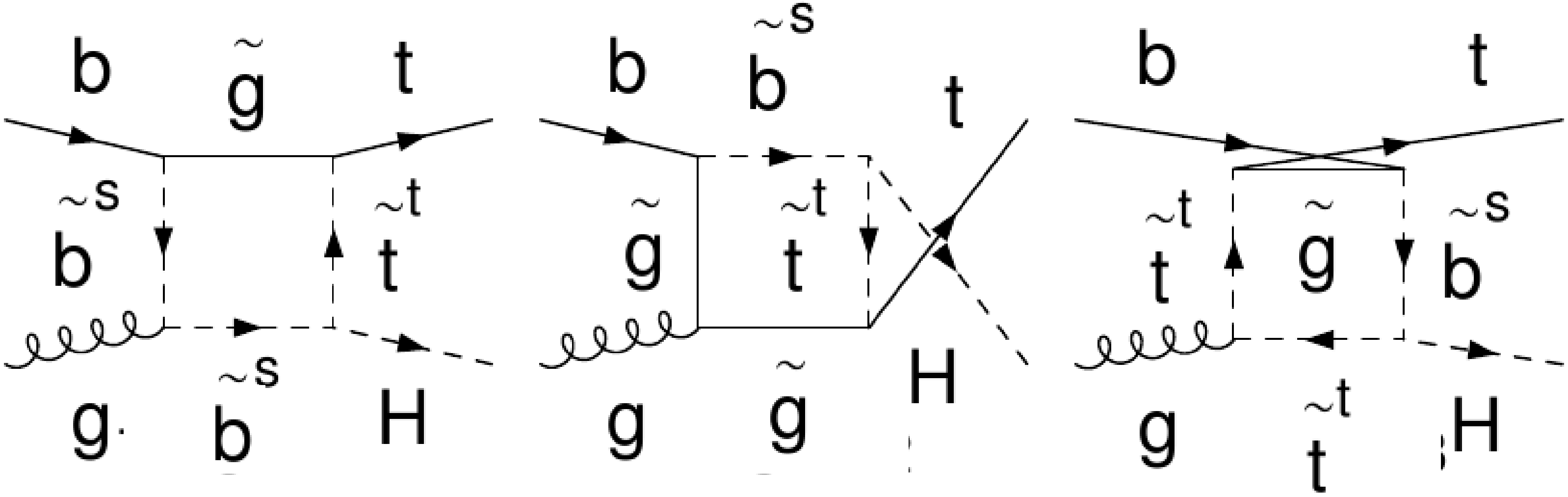
  ✓self-energy graphs



- On the same argumentation as in the case of the decay, only these two types of corrections are further considered analytically

Sources of CP-violation in MSSM

✓box graphs*



The s- and t-channel amplitudes

- The loop-corrected amplitudes[1] have a different structure in comparison with the decay case – one of the quarks is always off-shell:

$$\mathcal{M}^s = i\frac{g_s}{\hat{s}}\bar{u}_s(p_t)\Big\{[(y_t + \delta\tilde{Y}_t^s)P_L + (y_b + \delta\tilde{Y}_b^s)P_R](\not{p}_b + \not{p}_g) + $$

$$+\hat{s}[f_{RR}^{s,2}P_L + (f_{LL}^{s,2} - \tilde{f}_{LL})P_R]\Big\}T_{sr}^{\alpha}\gamma^{\mu}u_r(p_b)\epsilon_{\mu}^{\alpha}(p_g)$$

$$\mathcal{M}^t = i\frac{g_s}{t - m_t^2}\bar{u}_s(p_t)\epsilon_{\mu}^{\alpha}(p_g)\gamma^{\mu}T_{sr}^{\alpha}\Big\{(\not{p}_t - \not{p}_g + m_t)[(y_t + \delta\tilde{Y}_t^t)P_L + (y_b + \delta\tilde{Y}_b^t)P_R]$$

$$+(t - m_t^2)[(f_{LL}^{t,1} + \tilde{f}_{LL})P_L + f_{RR}^{t,1}P_R]\Big\}u_r(p_b)\,,$$

$$\delta\tilde{Y}_t^s = m_{\tilde{g}}f_{RL}^{s,0} + m_t(f_{LL}^{s,1} + \tilde{f}_{LL})\,, \qquad \delta\tilde{Y}_b^s = m_{\tilde{g}}f_{LR}^{s,0} + m_t f_{RR}^{s,1}\,,$$

$$\delta\tilde{Y}_t^t = m_{\tilde{g}}f_{RL}^{t,0} + m_t(f_{LL}^{t,1} + \tilde{f}_{LL})\,, \qquad \delta\tilde{Y}_b^t = m_{\tilde{g}}f_{LR}^{t,0} + m_t f_{RR}^{t,1}$$

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1) Given here for H^- production

Cross section

- The couplings have real and imaginary parts

$$f^{\pm}_{LR} = \mathrm{Re}(f_{LR}) \pm i\mathrm{Im}(f_{LR})\,, \qquad f_{LR} \equiv f^{-}_{LR}$$

as well as the PV-integrals ⇒ we write the cross sections as a sum $\hat{\sigma}^{\pm} = \hat{\sigma}^{inv} \pm \hat{\sigma}^{CP}$, where

$$\hat{\sigma}^{inv} = \hat{\sigma}^{tree} - \frac{\alpha_s}{24\hat{s}^2}\Big\{\mathcal{A}^{s,inv}\int_{t_{min}}^{t_{max}}(\mathcal{X}_1 + \mathcal{X}_{12} + \mathcal{U}\mathcal{V})\,dt$$

$$+ \int_{t_{min}}^{t_{max}}\mathcal{A}^{t,inv}(\mathcal{X}_{12} + \mathcal{X}_2 - \mathcal{U}\mathcal{V})\,dt - \int_{t_{min}}^{t_{max}}(\mathcal{B}^{s,inv} + \mathcal{B}^{t,inv})(1 + \mathcal{Y} - \mathcal{V})\,dt\Big\}$$

$$\hat{\sigma}^{CP} = \frac{\alpha_s}{24\hat{s}^2}\Big\{\mathcal{A}^{s,CP}\int_{t_{min}}^{t_{max}}(\mathcal{X}_1 + \mathcal{X}_{12} + \mathcal{U}\mathcal{V})\,dt$$

$$+ \int_{t_{min}}^{t_{max}}\mathcal{A}^{t,CP}(\mathcal{X}_{12} + \mathcal{X}_2 - \mathcal{U}\mathcal{V})\,dt - \int_{t_{min}}^{t_{max}}(\mathcal{B}^{s,CP} + \mathcal{B}^{t,CP})(1 + \mathcal{Y} - \mathcal{V})\,dt\Big\}$$

$$t_{min,max} = \frac{1}{2}\Big(m_t^2 + m_{H^+}^2 - \hat{s} \mp \lambda^{1/2}(\hat{s}, m_t^2, m_{H^+}^2)\Big)$$

Gauge invariance

- One should be careful with the gauge invariance of the process!
  For the gluon helicity spin summation we use

$$\sum_{\lambda=1}^{2} \epsilon_{\mu}^{\alpha *}(k,\lambda)\epsilon_{\nu}^{\beta}(k,\lambda) = \delta^{\alpha\beta}\Big(- g_{\mu\nu} - \frac{\eta^2 k_\mu k_\nu}{(\eta.k)^2} + \frac{\eta_\mu k_\nu + \eta_n u k_\mu}{\eta.k}\Big)$$

  At one loop level in this massless case it is gauge dependent. In the cross section the η-dependence should cancel ultimately.

CP-violating asymmetry

- The CP-violating asymmetry at parton level is defined as

$$\hat{A}_P^{CP} = \frac{\hat{\sigma}^+(\bar{b}g \to \bar{t}H^+) - \hat{\sigma}^-(bg \to tH^-)}{\hat{\sigma}^+(\bar{b}g \to \bar{t}H^+) + \hat{\sigma}^-(bg \to tH^-)}$$

- In our terms $$\hat{A}_P^{CP} = \frac{\hat{\sigma}^{CP}}{\hat{\sigma}^{inv}}$$

The LHC process pp $\rightarrow$ t $H^{\pm}$

- At hadron level: $p\,(P_A) + p\,(P_B) \longrightarrow t(p_t) + H^{\pm}(p_{H^{\pm}})$
  with $s = (P_A + P_B)^2$, for LHC $\sqrt{s} = 14$ TeV

- The cross sections including PDFunctions:

$$\sigma^{\pm}(pp \longrightarrow tH^{-}) = 2\int_0^1 f_b(x_b)\int_0^1 f_g(x_g)\hat{\sigma}^{\pm}(x_b x_g s)\theta(x_b x_g s - s_0)dx_b dx_g$$

CP-violating asymmetry

- The CP-violating asymmetry is defined as:

$$A_P^{CP} = \frac{\sigma^+(pp \to \bar{t}H^+) - \sigma^-(pp \to tH^-)}{\sigma^+(pp \to \bar{t}H^+) - \sigma^-(pp \to tH^-)}$$

In our terms:

$$A_P^{CP} = \frac{\sigma^{CP}}{\sigma^{inv}} = \frac{\alpha_s}{12\sigma^{tree}} \int dx_b dx_g f_b(x_b) f_g(x_g) \frac{1}{(x_b x_g \hat{s})^2} \left\{ \frac{2\alpha_s}{3\pi} \mathcal{C}_s + \frac{3\alpha_\omega}{8\pi} \mathcal{C}_w \right\}$$

$$\begin{aligned} \mathcal{C}_s &= [\mathrm{Im}(f_{RL}) y_t + \mathrm{Im}(f_{LR}) y_b] \mathcal{I}_1 + [\mathrm{Im}(f_{LL}) y_t + \mathrm{Im}(f_{RR}) y_b] \mathcal{I}_2 \\ \mathcal{C}_\omega &= \mathrm{Im}(f_{LL}) y_t \mathcal{I}_3 \end{aligned}$$

Production and decay process at LHC: $pp \to tH^{\pm} \to \ldots$

- The full CP-violating asymmetry in the production and the particular decay $H^{\pm} \to tb$ is defined as:

$$A^{CP} = \frac{\sigma^{+}(pp \to \bar{t}H^{+} \to t\bar{b}) - \sigma^{-}(pp \to tH^{-} \to \bar{t}b)}{\sigma^{+}(pp \to \bar{t}H^{+} \to t\bar{b}) + \sigma^{-}(pp \to tH^{-} \to \bar{t}b)}$$

- Analogical definition can be made for any subsequent decay, e.g. $H^{\pm} \to \tau\nu$
- In narrow width approximation, the CP-asymmetry is a direct sum from the CP-asymmetry in the production and the CP-asymmetry in the relevant decay:

$$A^{CP} = A_{P}^{CP} + \delta_{D}^{CP}$$

Numerical analysis

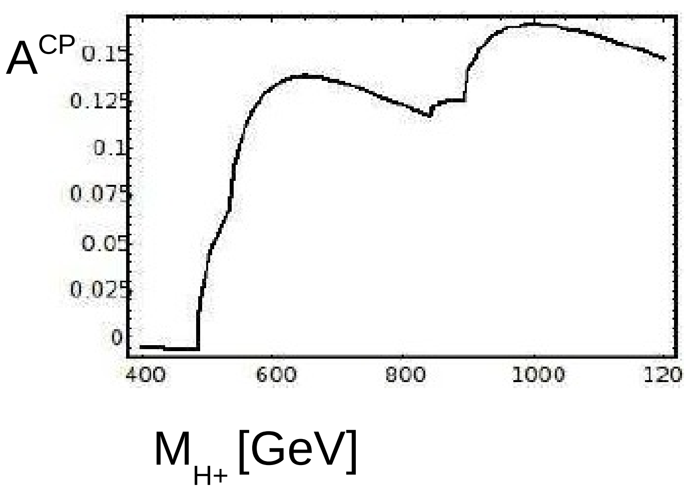
- Production process at parton level:

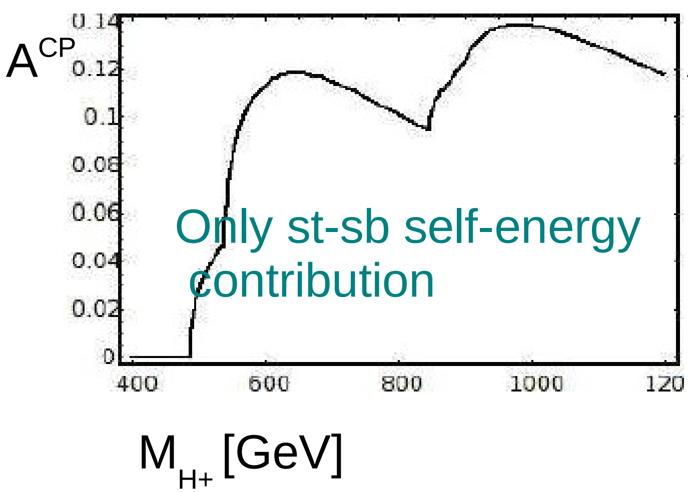
► Parameter space:

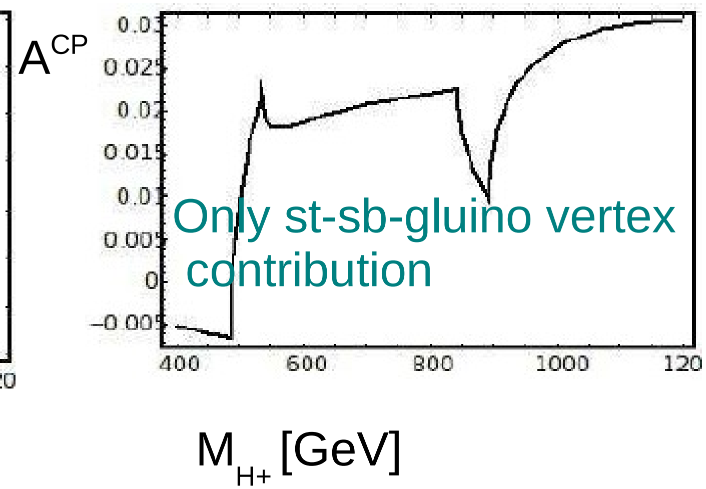
$$M_2 = 300 \text{ GeV}, \quad M_{\tilde{U}} = M_{\tilde{Q}} = M_{\tilde{D}} = M_E = M_L = 350 \text{ GeV},$$
$$\mu = -700 \text{ GeV}, \quad |A_t| = |A_b| = |A_\tau| = 700 \text{ GeV}$$

- CP-violating asymmetry

$$\tan\beta = 5, \ \phi_\mu = 0$$
$$\phi_{A_t} = \pi/2, \phi_{A_b} = 0$$

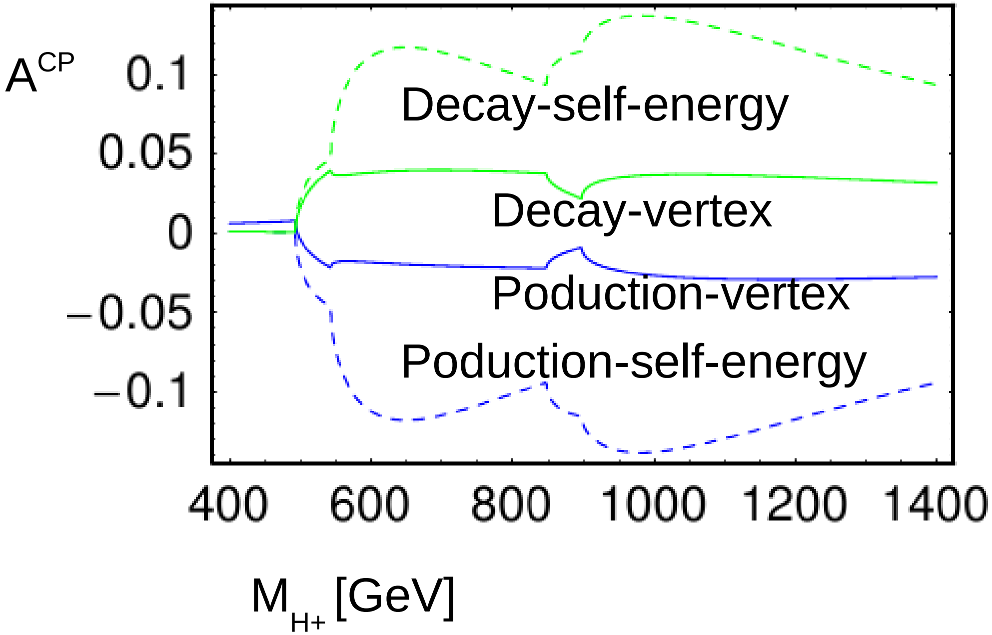






Numerical analysis

- Production and decay $pp \to tH^{\pm} \to tb$ process at parton level



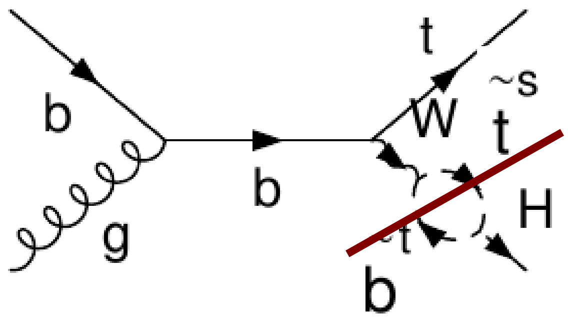
$$\sqrt{\hat{s}} = 2\ \mathrm{TeV}$$

? … ? … ☹

Numerical analysis

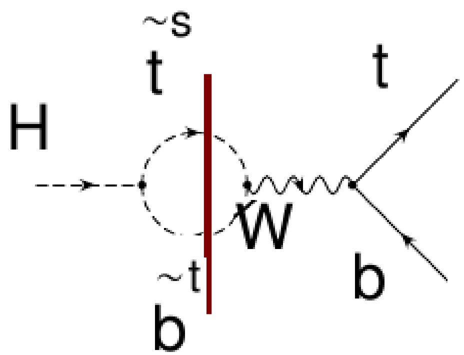
- What happens actually?

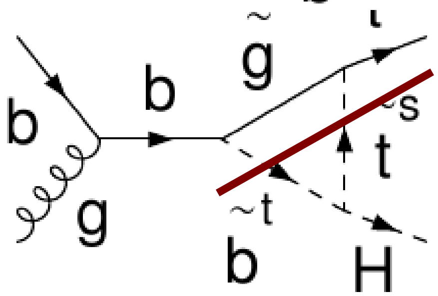
s-channel



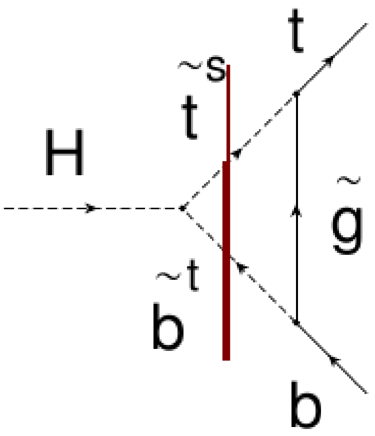
Cancel

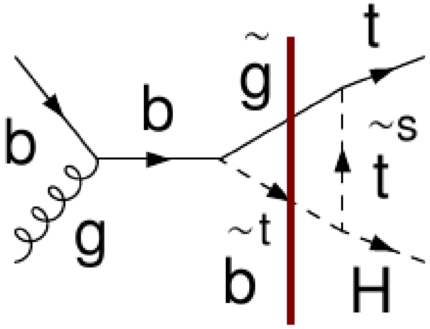
$\longleftrightarrow$





~ Im[PV($\hat{s}$)-PV(m_b^2)]



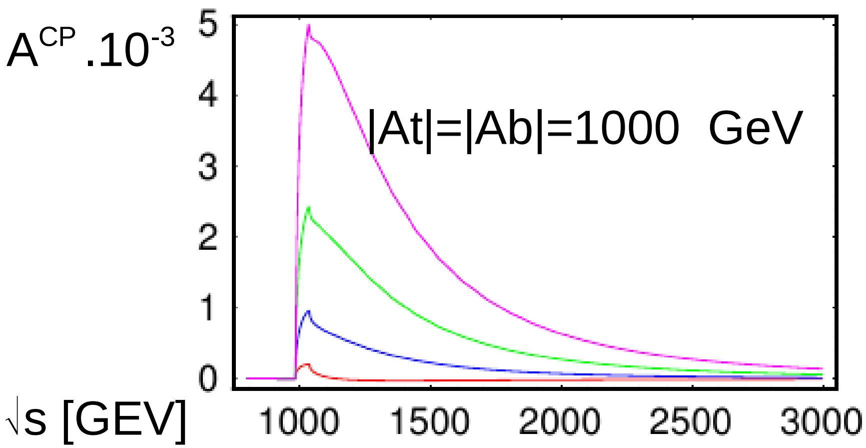


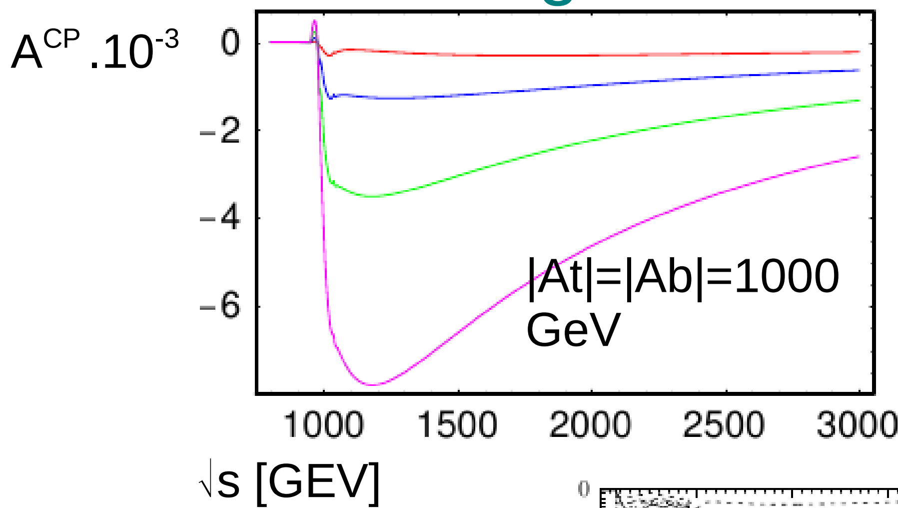
Remain

... + the same for the t-channel...

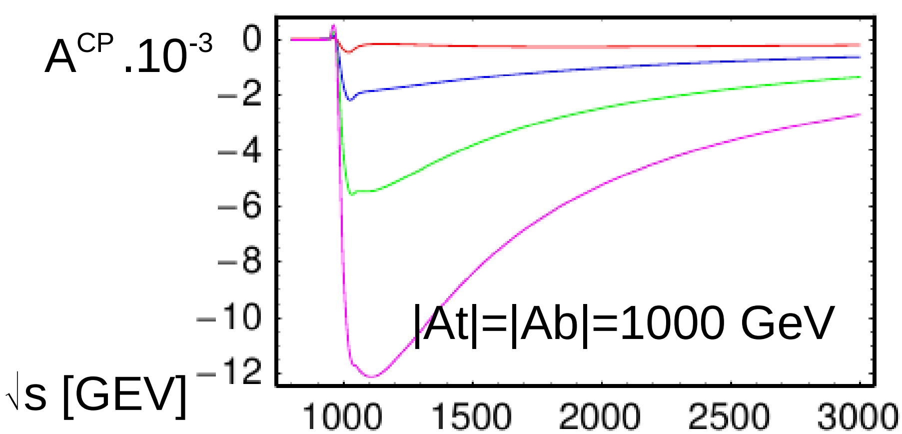
Numerical analysis

- Check for other parameter space: sps1a point:
- Only vertex diagrams → Both together

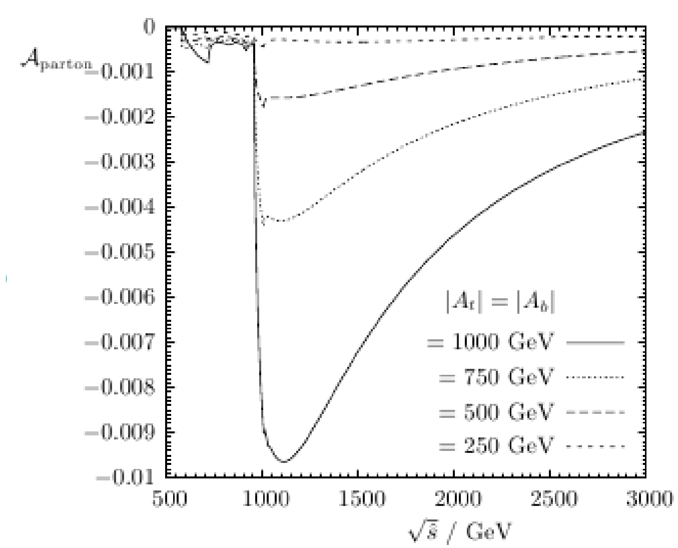




- Only box diagrams



check:
hep-ph/060807
J. Williams



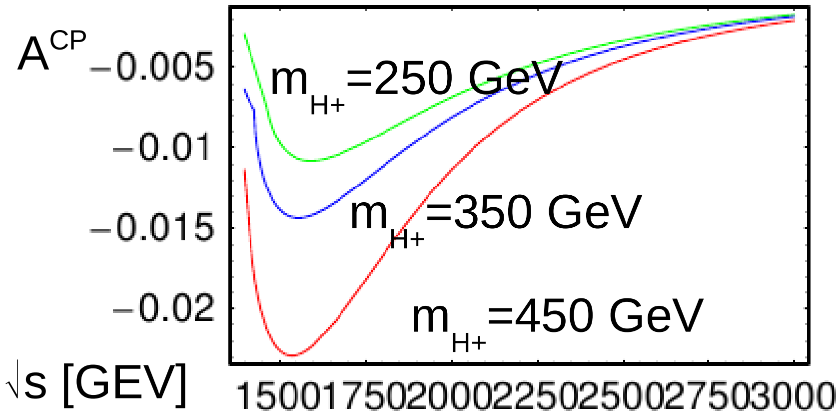
Numerical analisys

- What is left?

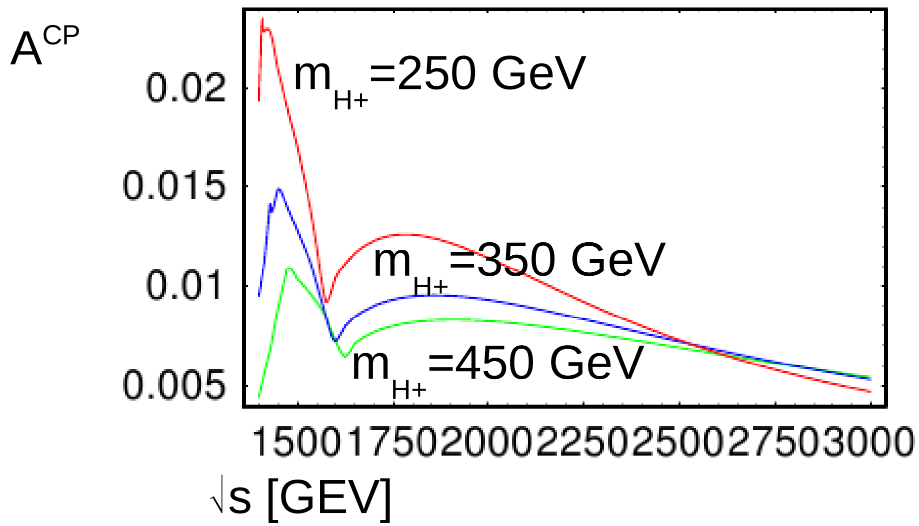
“Low” charged Higgs masses, below the stop-sbottom threshold, Br($H^{\pm} \rightarrow tb$) ~ 1, the CP-violation remains what it is only in the production.

Numerical analysis

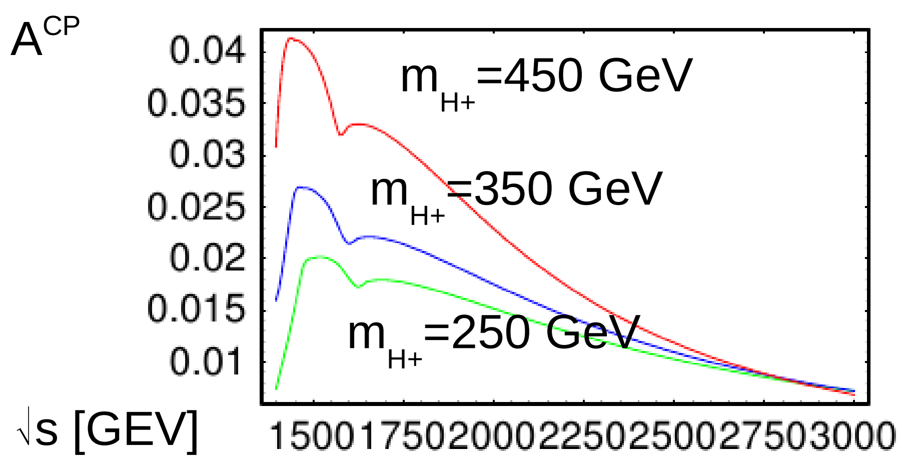
- Including only vertex diagrams



→Both together



- Including only box diagrams



Heavy chargino & neutralino scenario

$\tan\beta = 5, \mu = 1000\ \text{GeV}, m_{H^\pm} = 350\ \text{GeV},$

$|A_t| = 700, |A_b| = 3000, \phi_{A_t} = \phi_{A_b} = \frac{\pi}{2}$

$\text{Br}(H^\pm \to tb) = 0.961807003$

Summary

- The CP-violating asymmetry in the production process $pp \rightarrow H^{\pm}t$ can be rather large at a particular parameter point
- As the the CP-asymmetry in the decay $H^{\pm} \rightarrow tb$ adds to this asymmetry, it becomes very small due to cancelation of the main contribution
- The resulting CP-asymmetry in the production and decay process can reach hardly 2%, which is almost impossible to be observed at LHC, according to the big background of the process

Thank you! ☺