Model-independent Analysis of Higgs

Spin and CP Properties

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Outline

◇ **Introduction**

◇ **CP properties of the Higgs boson**

- **Observables σ, P_t, A_ϕ to test the Higgs CP parameters**
- **The combined sensitivity**
- **How to tell a spin 0 from a spin 1 particle**

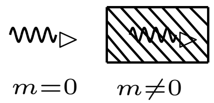
◇ **Conclusions**

Higgs physics at high-energy colliders:
Establish experimentally the Higgs Mechanism

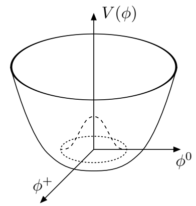
The Higgs mechanism:
Creation of particle masses in a gauge-invariant way

Test of the Higgs mechanism

- Discovery – m
- Spin and CP properties – J^{PC}
- Interaction with the scalar Higgs $\rightsquigarrow$ $g_{HXX} \sim m_X^{(2)}$
  with $v = 246$ GeV$\neq 0$



- EWSB requires Higgs potential $\leftrightarrow$ $\lambda_{HHH}, \lambda_{HHHH}$



The MSSM Higgs Sector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-

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Higgs masses

Ellis et al;Okada et al;Haber,Hempfling; Hoang et al;Carena et al;Heinemeyer et al; Zhang et al;Brignole et al;...

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

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Decoupling limit:

$M_A \sim M_H \sim M_{H^\pm} \gtrsim v$

$M_h \to$ max. value, $\tan\beta$ fixed; h becomes SM-like

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Modified couplings with respect to the SM: (decoupling limit Gunion,Haber)

Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \to 1$	$-s_\alpha/c_\beta \to 1$	$s_{\beta-\alpha} \to 1$
H	$s_\alpha/s_\beta \to 1/\text{tg}\beta$	$c_\alpha/c_\beta \to \text{tg}\beta$	$c_{\beta-\alpha} \to 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

$\tan\beta \uparrow \;\Rightarrow g_{\Phi uu} \downarrow$

$g_{\Phi dd} \uparrow$

$g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{Q}$uantum $\mathcal{N}$umbers

• **Quantum numbers of the Higgs boson:** J^{PC}

J	spin
P	parity
C	charge conjugation

◇ $\gamma\gamma \to H$ or $H \to \gamma\gamma \rightsquigarrow J \neq 1$.

• **CP properties**

∗ SM Higgs $J^{CP} = 0^{++}$; beyond the SM (BSM)

  ◦ more than one spin 0 particle possible

  ◦ CP-even, CP-odd, CP-violating Higgs states

∗ study of CP properties $\rightsquigarrow$ insights in BSM physics

∗ existing and future colliders:
establish CP properties, determine amount of CP-mixing

$\mathcal{D}$etermination of $\mathcal{H}$iggs $\mathcal{Q}$uantum $\mathcal{N}$umbers

- **Spin and CP quantum numbers: threshold effects and angular correlations in**

  - angular correlations in production: Hjj in vector boson fusion, Plehn,Rainwater,Zeppenfeld; Hankele,Klämke,Zeppenfeld

    gluon gluon fusion Odagiri; Klamke,Zeppenfeld; Campanario eal; Del Duca eal; Andersen eal

  - Higgs decays into W and Z pairs Dell'Aquila,Nelson; Barger eal; Kramer,Kühn,Stong,Zerwas; Skjold,Osland; Choi,Kalinowski,Liao,Zerwas Miller,MMM,Zerwas;Bluj; Dova eal; Buszello,Fleck,Marquard,van der Bij; Gao eal:Englert eal: Sancti eal

    observables sensitive to CP-violation Chang eal; Skjold,Osland; Choi eal; Niezurawski,Zarnecki,Krawczyk; Godbole,Kraml;Rindani,Singh Godbole,Miller,MMM; De Rujula eal

  - $\gamma\gamma$ collisions Grzadkowski,Gunion; Asakawa,Choi,Hagiwara; Godbole,Rindani,Singh; Godbole,Kraml,Rindani,Singh

  - Higgs-radiation & VBF at e^+e^- colliders, also Higgs-ZZ coupling
    Godbole,Roy; Hagiwara,Stong; Gounaris,Renard; Rao,Rindani
    Miller,Choi,Eberle,MMM,Zerwas; Skjold,Osland; Hagiwara eal;
    Han,Jiang; Biswal, Godbole, Singh; Biswal, Choudhury, Godbole eal

$\mathcal{D}$etermination of $\mathcal{H}$iggs $\mathcal{Q}$uantum $\mathcal{N}$umbers

- **Problem with pseudoscalar Higgs ZZ coupling:** loop-induced
  $\rightsquigarrow$ suppressed compared to scalar tree-level coupling $\Rightarrow$

- **Study CP-mixing in coupling to photons**
  Grzadkowski,Gunion; Asakawa eal; Godbole eal;Choi eal;Niezurawski eal

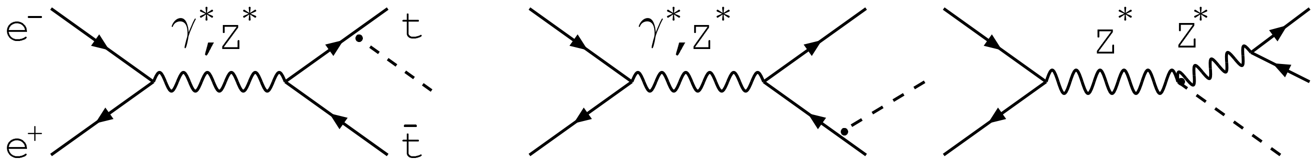
- **Study CP-mixing in coupling to t or τ pair**
  Grzadkowski,Gunion; Bernreuther eal; Atwood eal Gunion,He; Bhupal Dev,Djouadi,Godbole,MMM,Rindani; Huang,Zhu; Khater,Osland; Bower eal; Desch eal

- $\boldsymbol{e^+e^- \longrightarrow t\bar{t}\Phi}$
  Gaemers,Gounaris; Djouadi,Kalinowski,Zerwas; Grzadkowski eal; Dawson,Reina; Dittmaier,Krämer,Liao; Zhu; You eal; Bélanger eal; Denner eal
  - sufficiently high rates Moretti; Juste,Merino; Martinez,Miquel; Desch,Schumacher
  - extract CP information from angular correlations and/or polarisation of the heavy fermions

- **The observables**
  Bhupal Dev,Djouadi,Godbole,MMM,Rindani '07; Godbole,Hangst,MMM '11
  * total cross section σ and its energy dependence
  * top quark polarisation asymmetry P_t
  * up-down asymmetry A_ϕ of $\bar{t}$ $\leftarrow$ can directly probe CP-violation

$\mathcal{T}$he $\mathcal{T}$otal $\mathcal{C}$ross $\mathcal{S}$ection

- **The process $e^+e^- \to t\bar{t}\phi$**



- **Comments**
  - ∗ measurable with $\delta\sigma \sim \mathcal{O}(10\%)$ for $M_H \lesssim 200$ GeV Moretti; Juste,Merino; Martinez,Miquel; Desch,Schumacher
  - ∗ bulk of cxn from $\gamma^* \to t\bar{t}$, last diagram only a few % for $\sqrt{s} \leq 1$ TeV
  - ∗ Several Higgs states: diagrams with CP-even (CP-odd, CP-viol) Higgs splitting into $t\bar{t}$
    - ◦ contributions small for $M_\Phi \leq 2m_t$, remove by cuts on invariant $t\bar{t}$ mass
  - ∗ total cxn is CP-even, not sensitive to possible CP-violation
  - ∗ neglect higher order contributions in first approximation

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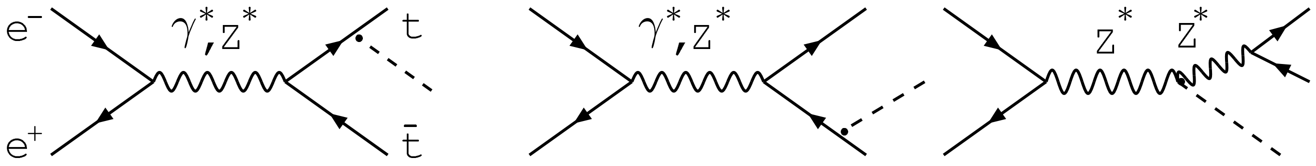
- **The process $e^+e^- \longrightarrow t\bar{t}\phi$**



- **Comments**

  ∗ coupling of a general CP-mixed state Φ to $t\bar{t}$: $a, b \in [-1, .., 1]$

$$C_{tt\Phi} = -i\frac{e}{\sin\theta_W}\frac{m_t}{2M_W}(a + ib\gamma_5) \equiv -ig_{ttH}(a + ib\gamma_5)$$

  ∗ within general 2HDM w/ maximal CP-violation $|ab| \lesssim 2$ fullfills low-energy constraints

    Bernreuther,Brandenburg,Flesch;
    Hayashi,Koide,Matsuda eal

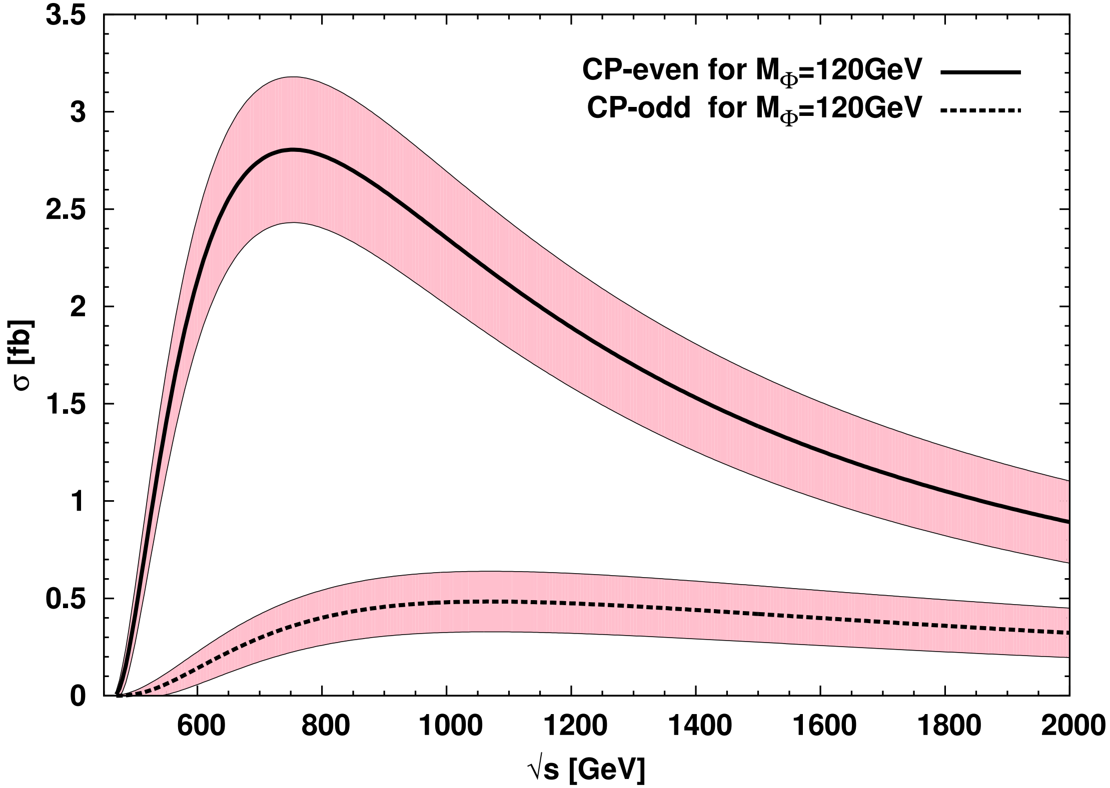
  ∗ the ΦZZ coupling

$$g^{\mu\nu}_{ZZ\Phi} = -ic\,\frac{eM_Z}{\sin\theta_W\cos\theta_W}g^{\mu\nu} \equiv -ic\,g_{ZZH}\,g^{\mu\nu}\ .$$

  c is measurable from other channels, we choose $c = -a$

$\mathcal{T}$he $\mathcal{T}$hreshold $\mathcal{R}$ise

Godbole,Hangst,MMM,Rindani,Sharma



- with $\rho = 1 - 2m_t/\sqrt{s} - M_\Phi/\sqrt{s}$ the threshold rise for CP-even is $\sim \rho^2$, CP-odd $\sim \rho^3$
- for $M_\Phi = 120$ GeV, $\int \mathcal{L} = 500$ fb^{-1} sufficient to distinguish CP-even from CP-odd Higgs (statistical fluctuations only)

$\mathcal{S}$ensitivity $\mathcal{A}$reas

- **Sensitivity of the observable O to the Higgs CP parameters a, b**

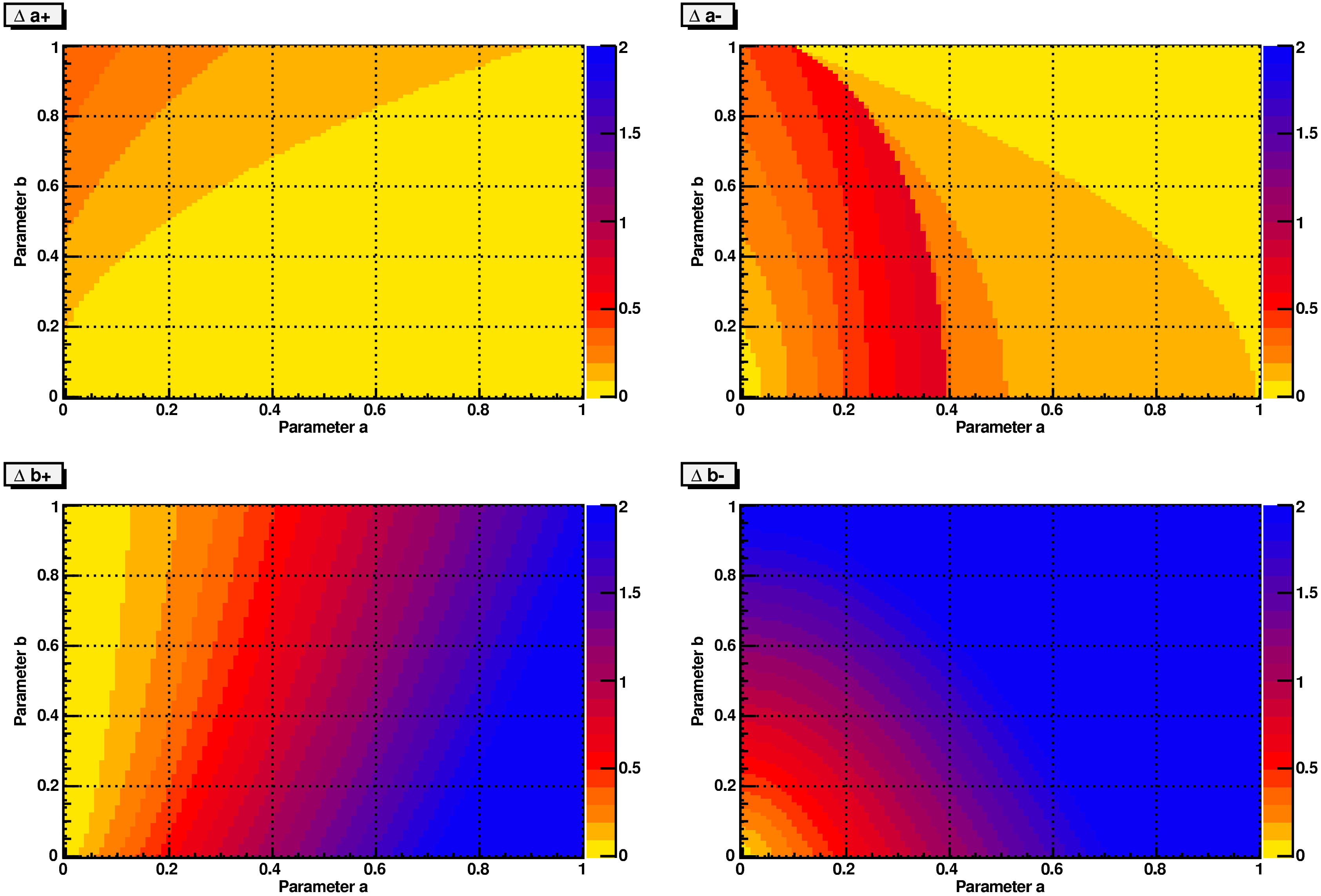
  * sensitivity of O to a, b for a specific parameter point (a_0, b_0): determine the ranges $[a_0 - \Delta a^-, a_0 + \Delta a^+]$ and $[b_0 - \Delta b^-, b_0 + \Delta b^+]$ such that
  * for points outside this region the value of $O(a_0, b_0)$ changes by more than 1σ
  * establishing $O(a_0, b_0)$ at 1σ allows for an extraction of $a_0(b_0)$ with $\Delta a^\pm(\Delta b^\pm)$
  * area in the $a - b$ plane for which the value of the observable $O(a, b)$ cannot be distinguished from the reference value $O(a_0, b_0)$ at a specific point (a_0, b_0) at 1σ:

$$|O(a,b) - O(a_0, b_0)| = \Delta O(a_0, b_0) \; ,$$

  * $\Delta O(a_0, b_0)$ statistical fluctuation in O at $\int \mathcal{L} = 500$ fb^{-1}
  * for the total cross section: $\Delta\sigma = \sqrt{\frac{\sigma}{\mathcal{L}}}$
  * following plots: $\sqrt{s} = 800$ GeV

$\mathcal{A}$ccuracy on Higgs CP parameters from the $\mathcal{T}$otal $\mathcal{C}$ross $\mathcal{S}$ection

Godbole,Hangst,MMM,Rindani,Sharma



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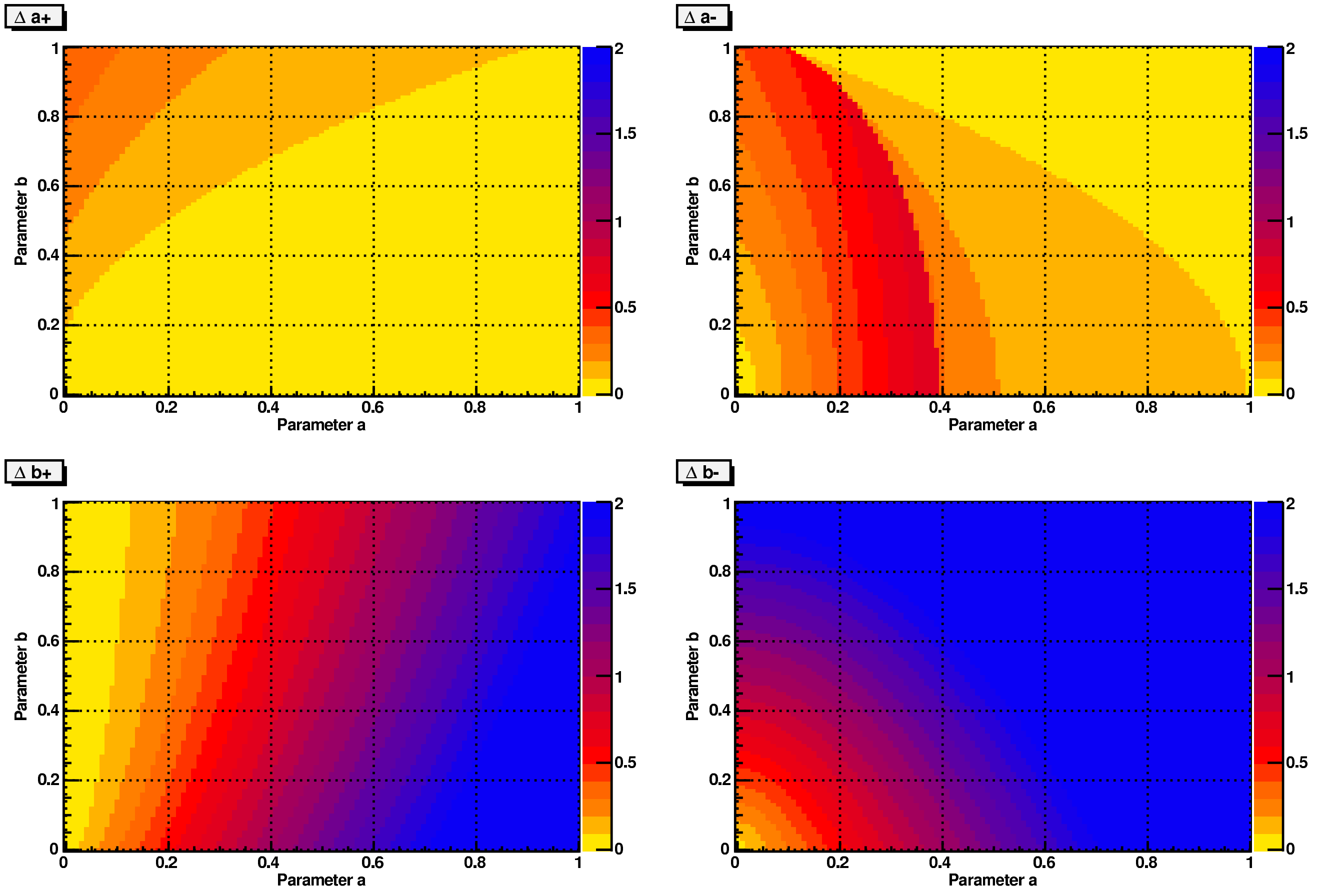


- shows the 1σ errors on a, b; total cxn can be exploited to measure CP-even parameter a
- sensitivity on a improves if b constrained from other observables

$\mathcal{T}$he $\mathcal{P}$olarisation $\mathcal{A}$symmetry of the $\mathcal{T}$op $\mathcal{Q}$uark

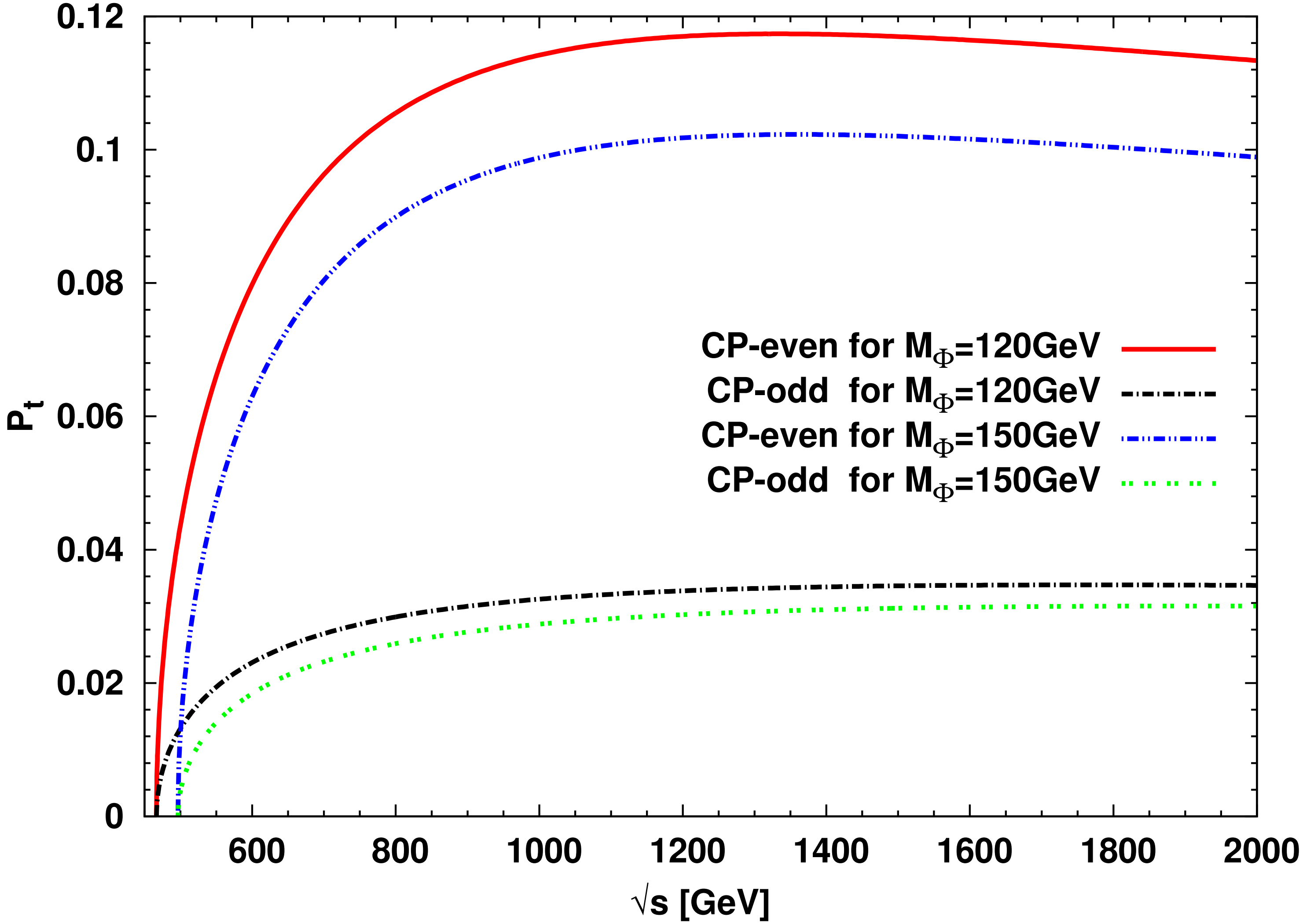
- **Polarisation asymmetry of the top quark**

$$P_t = \frac{\sigma(t_L) - \sigma(t_R)}{\sigma(t_L) + \sigma(t_R)}$$

* lepton angular distribution in $t \to bW \to bl\nu$ not affected by any non-standard effects in the decay vertex $\leadsto$ pure probe of physics of the t productions process $\leadsto$
* P_t probes Higgs CP properties
* threshold rise of P_t approximately the same for scalar and pseudoscalar Higgs $\to$ T
* errors on a, b from P_t larger than 1, polarisation of $e^\pm$ only slightly improves this
* ratios of cxns can be exploited to distinguish CP-even from CP-odd ($\longleftarrow$ cxn threshold rise), but difficult to extract absolute values of a, b

$\mathcal{T}$he $\mathcal{T}$hreshold $\mathcal{R}$ise of P_t

Godbole,Hangst,MMM,Rindani,Sharma



$\mathcal{T}$he CP-violating $\mathcal{U}$p-$\mathcal{D}$own $\mathcal{A}$symmetry

- **The up-down asymmetry A_ϕ of the the antitop**
  - ∗ sensitive to CP-violation
  - ∗ angle ϕ between the antitop direction and the top-electron plane

$$\sin\phi = \frac{\vec{p}_2(\vec{q}_a \times \vec{p}_1)}{|\vec{p}_2||\vec{q}_a \times \vec{p}_1|} \sim \epsilon^{p_1 p_2 q_a q_b}$$

    with $q_{a,b}$ four-momenta of the incoming e^-, e^+, $p_{1,2}$ the four-momenta of the top, antitop

  - ∗ up-down asymmetry

$$A_\phi = \frac{\sigma(\text{up}) - \sigma(\text{down})}{\sigma(\text{up}) + \sigma(\text{down})}$$

    'up' ('down'): integration over ϕ performed for $\phi \in [0,\pi)$ ($\phi \in [\pi, 2\pi)$)

  - ∗ $A_\phi \sim$ interference Higgs rad. off top-quark – Higgs rad. off Z boson

$$A_\phi = \frac{\sigma_{as} bc}{\sigma}$$

  - ∗ a non-vanishing A_ϕ is an unambiguous indicator of CP violation
  - ∗ errors on a, b from A_ϕ larger than the absolute values of a, b

$\mathcal{T}$he $\mathcal{C}$ombined $\mathcal{S}$ensitivity

- **The combined sensitivity**

  * - total cxn good observable to determine a, less good for b
    - top polarisation asymmetry P_t can distinguish CP-even from CP-odd
    - up-down asymmetry A_ϕ tests CP-mixing, but errors on a, b are large

  * accuracy on $a(b)$ substantially improves if $b(a)$ known from some other measurement $\rightsquigarrow$ combine all three observables σ, P_t, A_ϕ

  * for sensitivity areas/error determination for a, b perform a χ^2 test with

$$\chi^2 = \sum_{i=1,2,3} \frac{(O_i(a,b) - O_i(a_0,b_0))^2}{(\Delta O_i(a_0,b_0))^2}$$

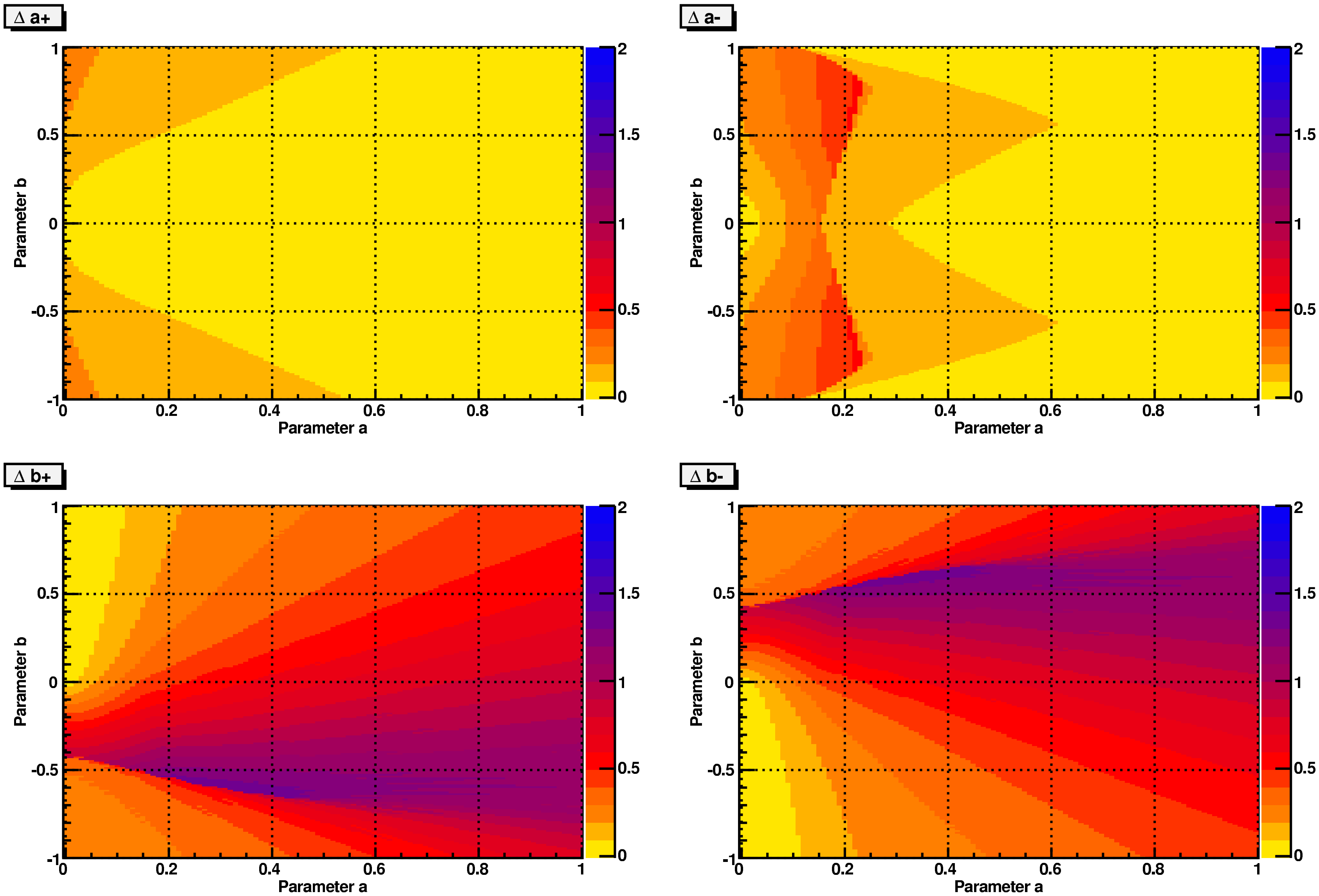
  * errors $\Delta a^\pm, \Delta b^\pm$ determined by the maximal extensions of the insensitive areas

  * polarisation of $e^\pm$ reduces errors on a, b remarkably (it increases σ and P_t) $\longleftarrow$ T

  * Energies $\sqrt{s} = 3 - 5$ TeV: total σ smaller, but higher $\int \mathcal{L} = 3 - 5$ ab^{-1}; P_t approx. the same; A_ϕ increases with $\sqrt{s}$ $\Rightarrow$ all 3 observables contribute significantly to χ^2, mutual interplay $\rightsquigarrow$ small errors $\longleftarrow$ T

$\mathcal{A}$ccuracy on a, b from the $\mathcal{C}$ombined $\mathcal{O}$bservables σ, P_t, A_ϕ

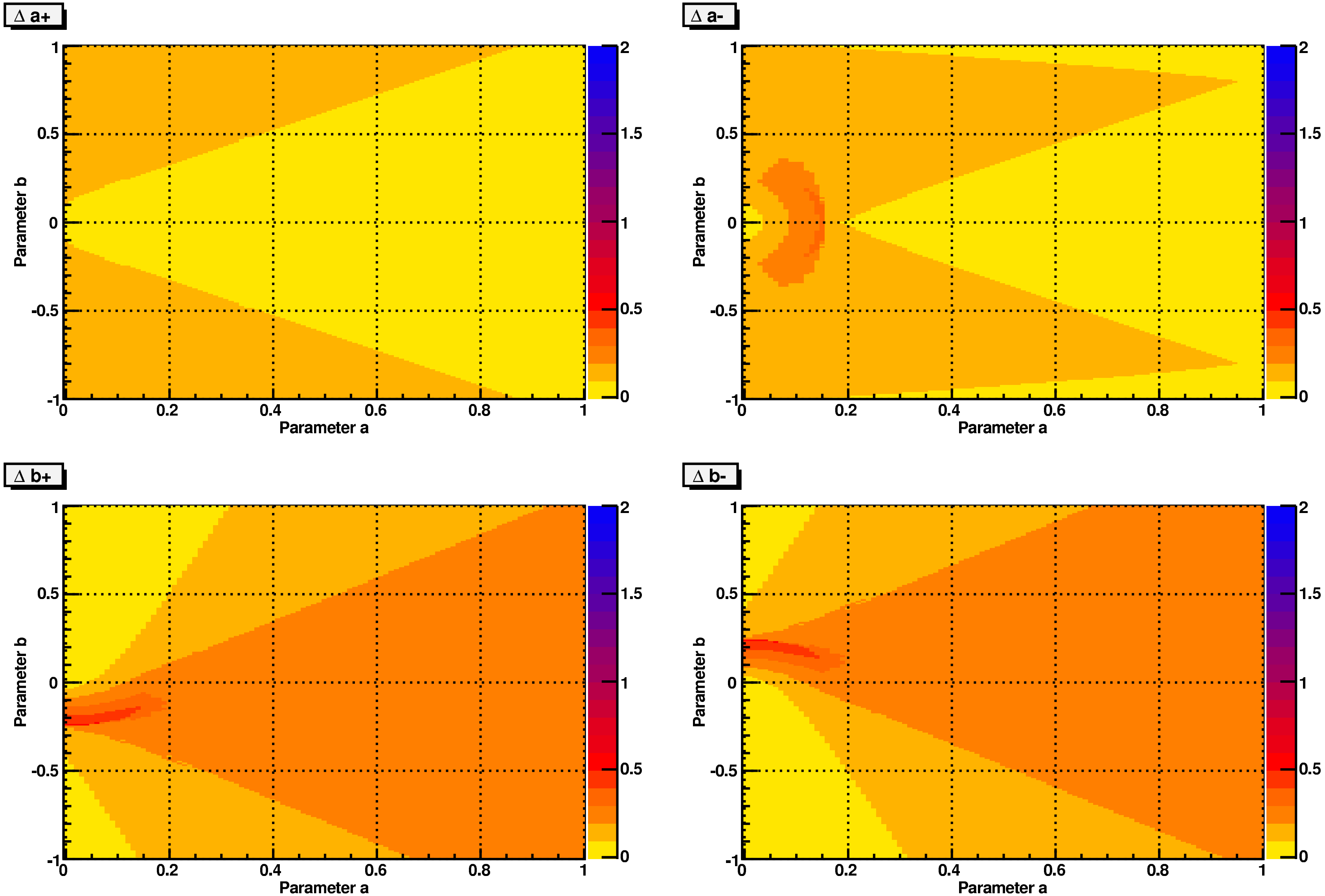
Godbole,Hangst,MMM,Rindani,Sharma



$\sqrt{s} = 800$ GeV, $\int \mathcal{L} = 500$ fb^{-1}, polarised $e^{\pm}$ beams

$\mathcal{A}$ccuracy on a, b from $\mathcal{C}$ombined $\mathcal{O}$bservables σ, P_t, A_ϕ – $\sqrt{s} = 3$ TeV

Godbole,Hangst,MMM,Rindani,Sharma



$\sqrt{s} = 3$ TeV, $\int \mathcal{L} = 3$ ab^{-1}, polarised $e^{\pm}$ beams

$\mathcal{R}$adiation of a $\mathcal{S}$pin 1 $\mathcal{P}$article

- **Question:** To what extent does the spin of the produced particle affect σ and P_t?

- **Motivation**

  * $t\bar{t}Z$ production contributes to irreducible SM bkg of associated Higgs production
  * in numerous New Physics models additional neutral particles Z' with spin 1

- **Model-independent ansatz:** particle couples only to $t\bar{t}$ not e^+e^-;
  first approach: no anomalous vector couplings to $t\bar{t}$ of dimension higher than 4

$$C_{ttZ'} = -ie\gamma_\mu(g_V - g_A\gamma_5)$$

with g_V, g_A of $\mathcal{O}(1)$

$\mathcal{R}$adiation of a $\mathcal{S}$pin 1 $\mathcal{P}$article

- **Question:** To what extent does the spin of the produced particle affect σ and P_t?

- **Can σ and its energy dependence and P_t distinguish spin 0 from spin 1 particle?**

  * $t\bar{t}Z'$ production with $M_{Z'} = M_H = 120$ GeV

  * assume $\sigma(t\bar{t}Z')$ to be equal to $\sigma(t\bar{t}H)$ within 10% ($\leftarrow$ exp error)

  * $\rightsquigarrow$ range $\mathcal{P}$ of values g_V, g_A

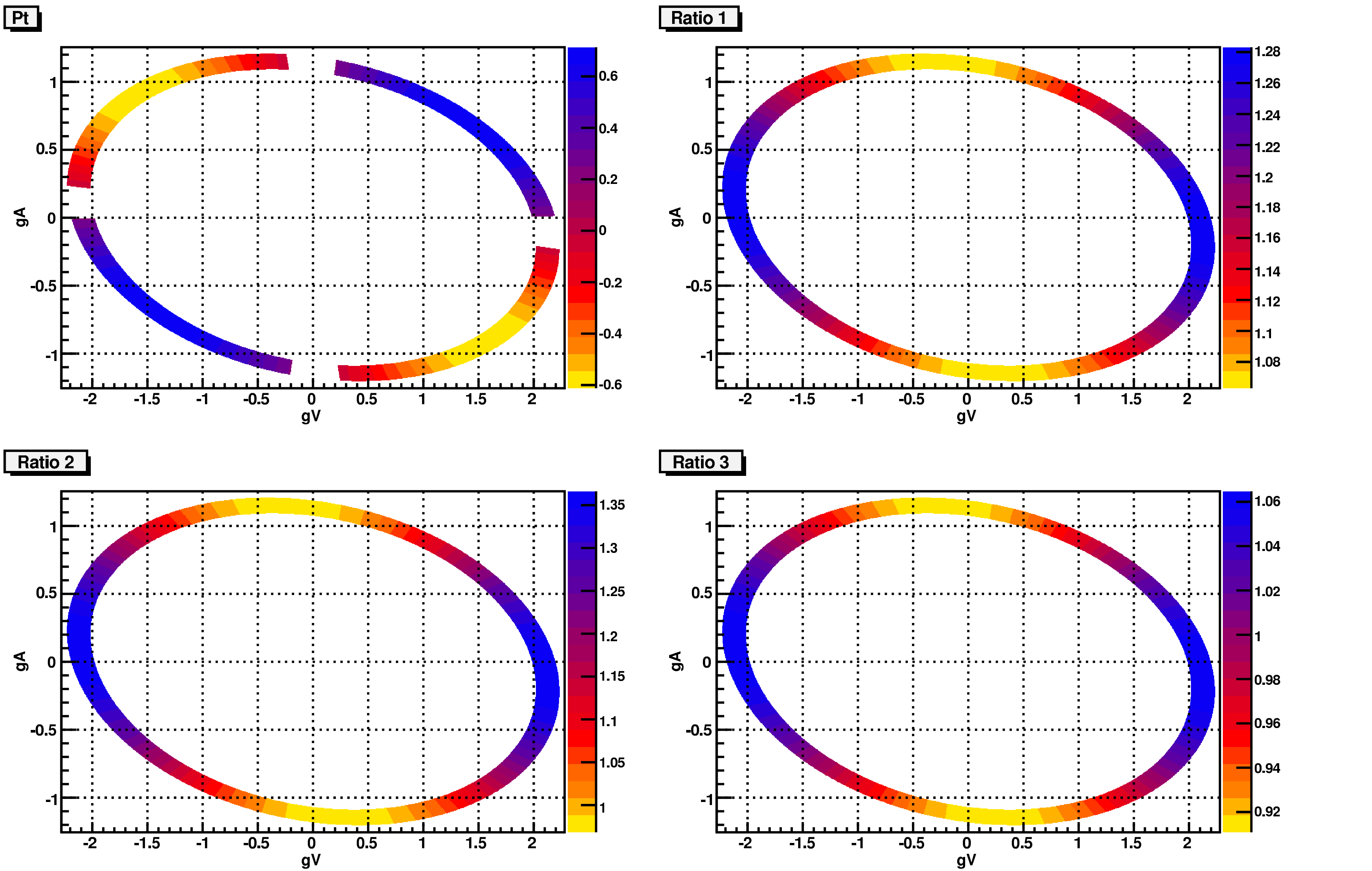
$$g_V, g_A \in \mathcal{P} \quad \Longleftrightarrow \quad \sigma_{t\bar{t}Z'}(g_V, g_A) = \sigma_{t\bar{t}H} \pm 10\%$$

  * calculate P_t, compare to $P_t(t\bar{t}H) = 0.11 \rightarrow$ T

  * ratios of cross sections for 3 different energy combinations:
    $\sigma(1000$ GeV$)/\sigma(800$ GeV$)$, $\sigma(1300$ GeV$)/\sigma(800$ GeV$)$, $\sigma(1300$ GeV$)/\sigma(1000$ GeV$)$,
    compare to corresponding SM ratios $\rightarrow$ T

$\mathcal{P}_t$ Contours and Ratios of Cross Sections Contours

Godbole,Hangst,MMM,Rindani,Sharma



P_t Contours and Ratios of Cross Sections Contours

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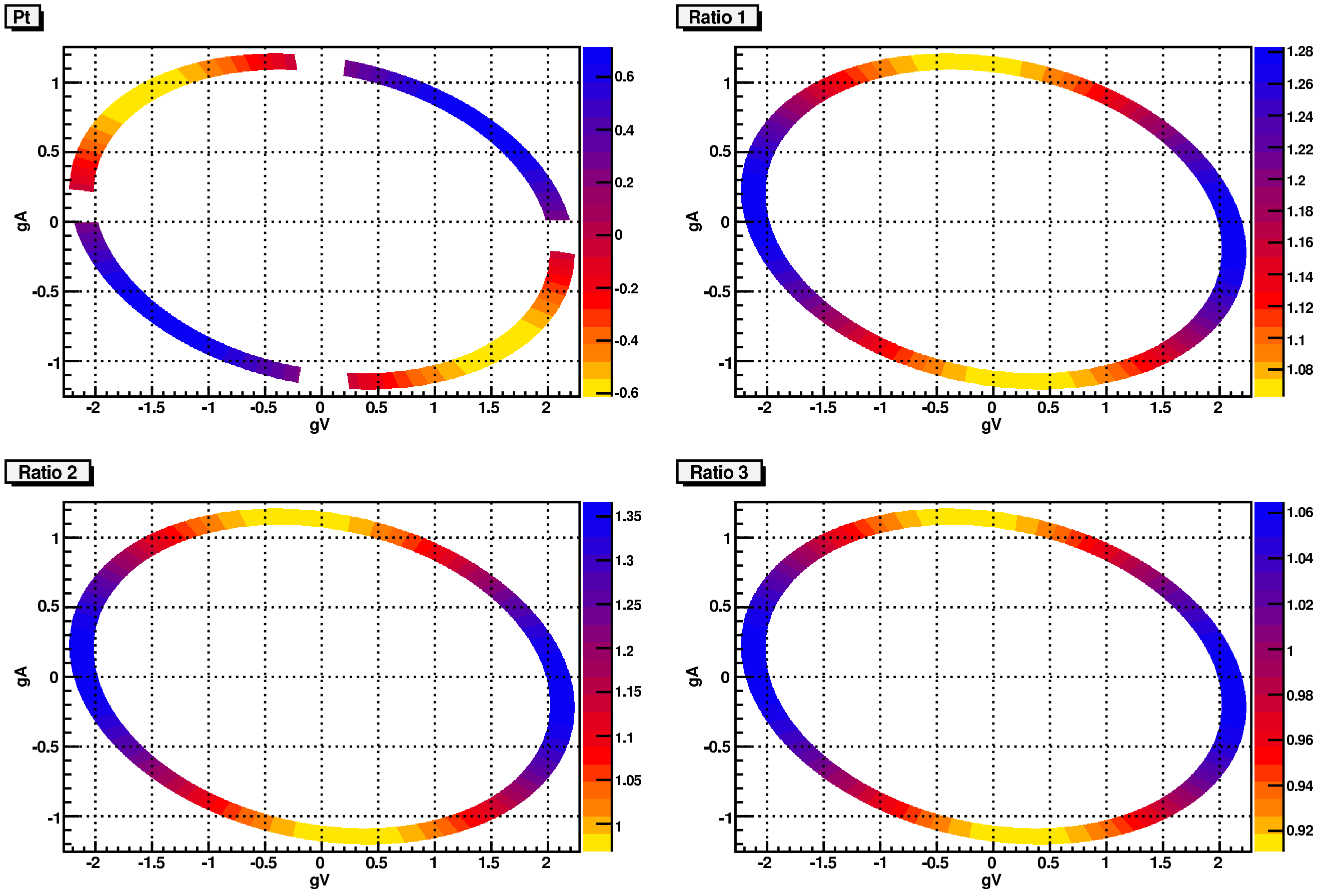


* colour code: magnitude of P_t, cross section ratio, respectively
* white areas: $P_t(t\bar{t}Z')$ differs from $P_t(t\bar{t}H)$ by less than 5σ

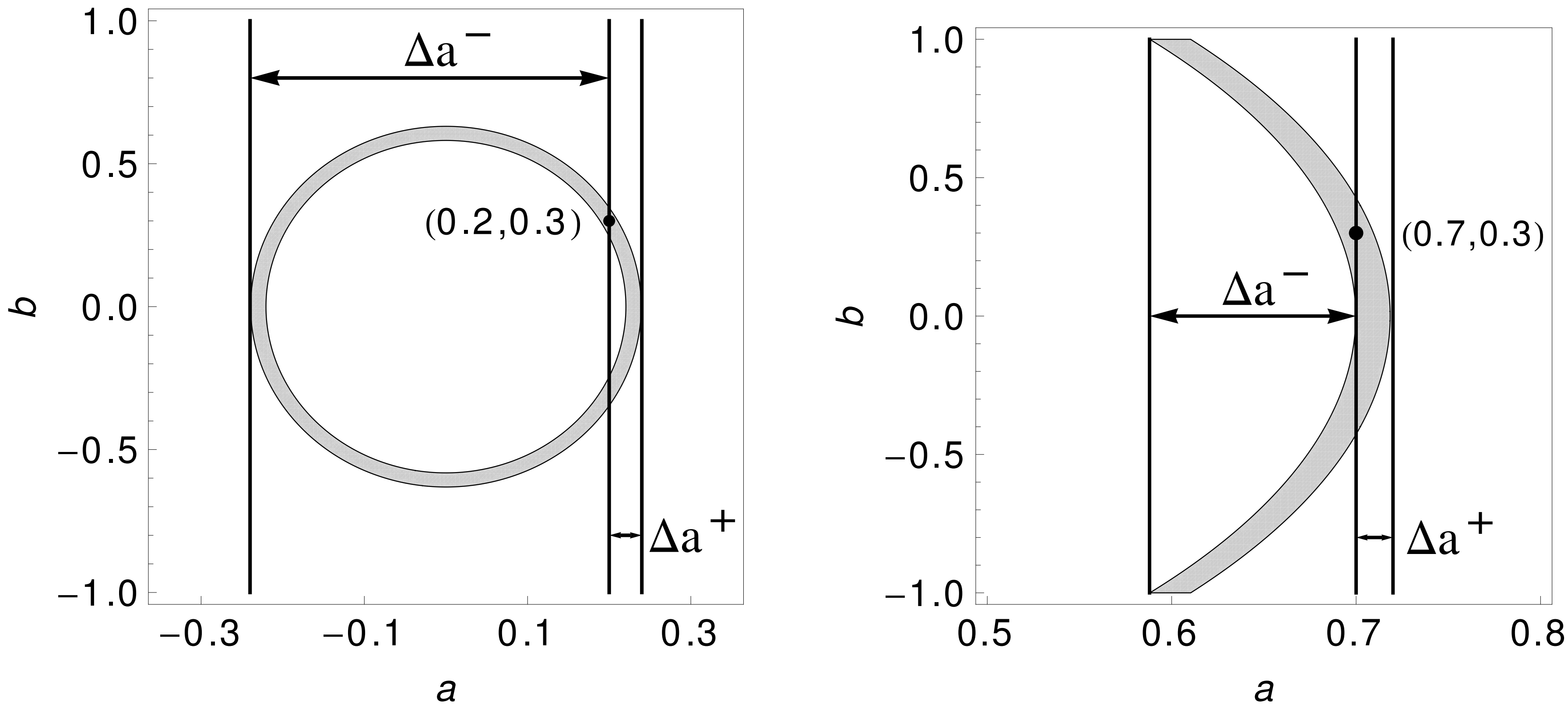
$\mathcal{C}$onclusions

- ◇ Top sector ideal working ground to test Higgs CP properties:
  Various CP-parts of the Higgs boson couple democratically to the top quarks
- ◇ Higgs CP parameters can be determined from σ, P_t, A_ϕ
- ◇ Combination of all three observables:
  Significant reduction of error on a for polarised $e^\pm$ beams
- ◇ P_t and ratios of cross sections at different collider energies:
  Good observables to tell a spin 0 from a spin 1 state

Backup Slides

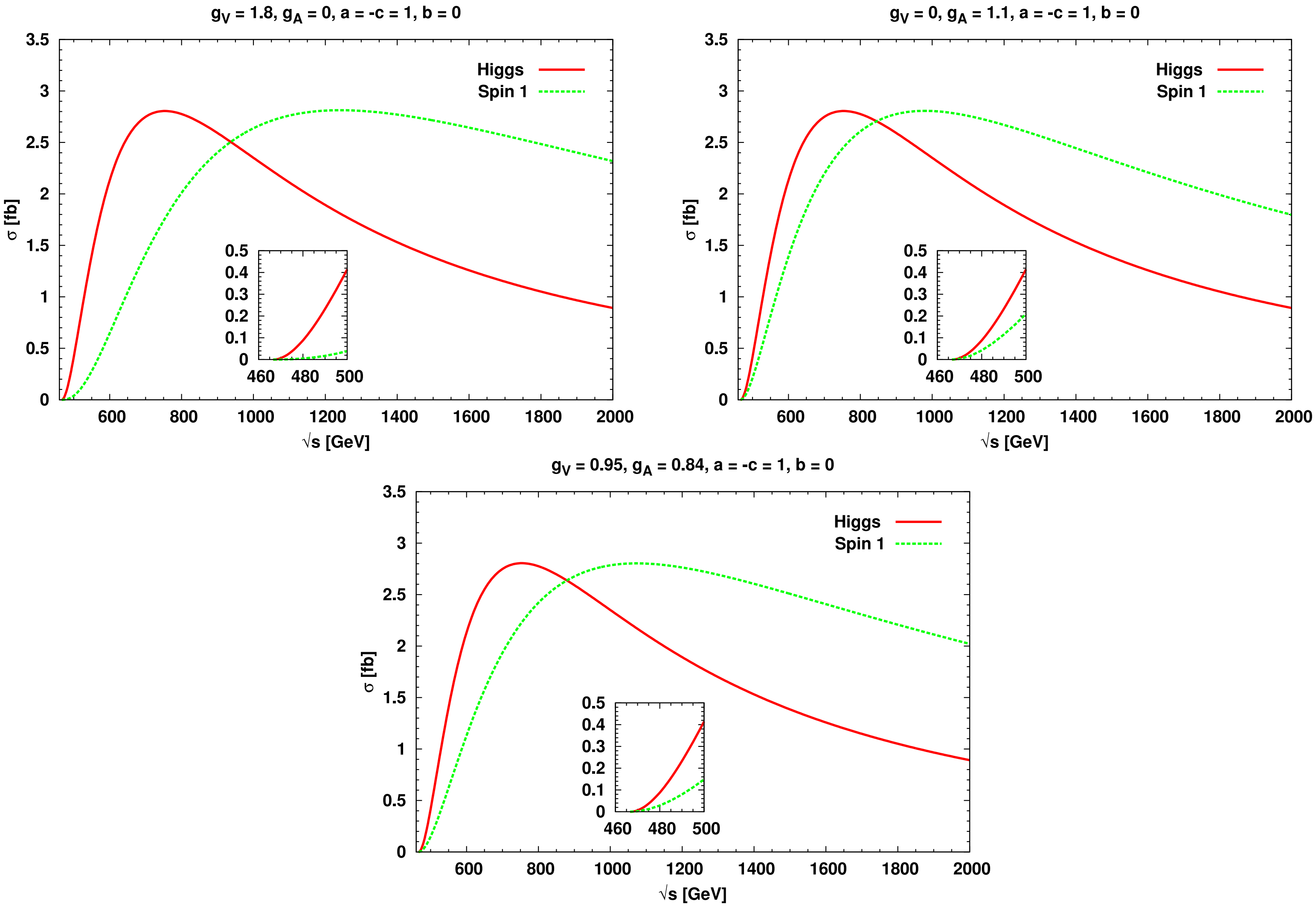
1σ bands of insensitivity

Godbole,Hangst,MMM,Rindani,Sharma



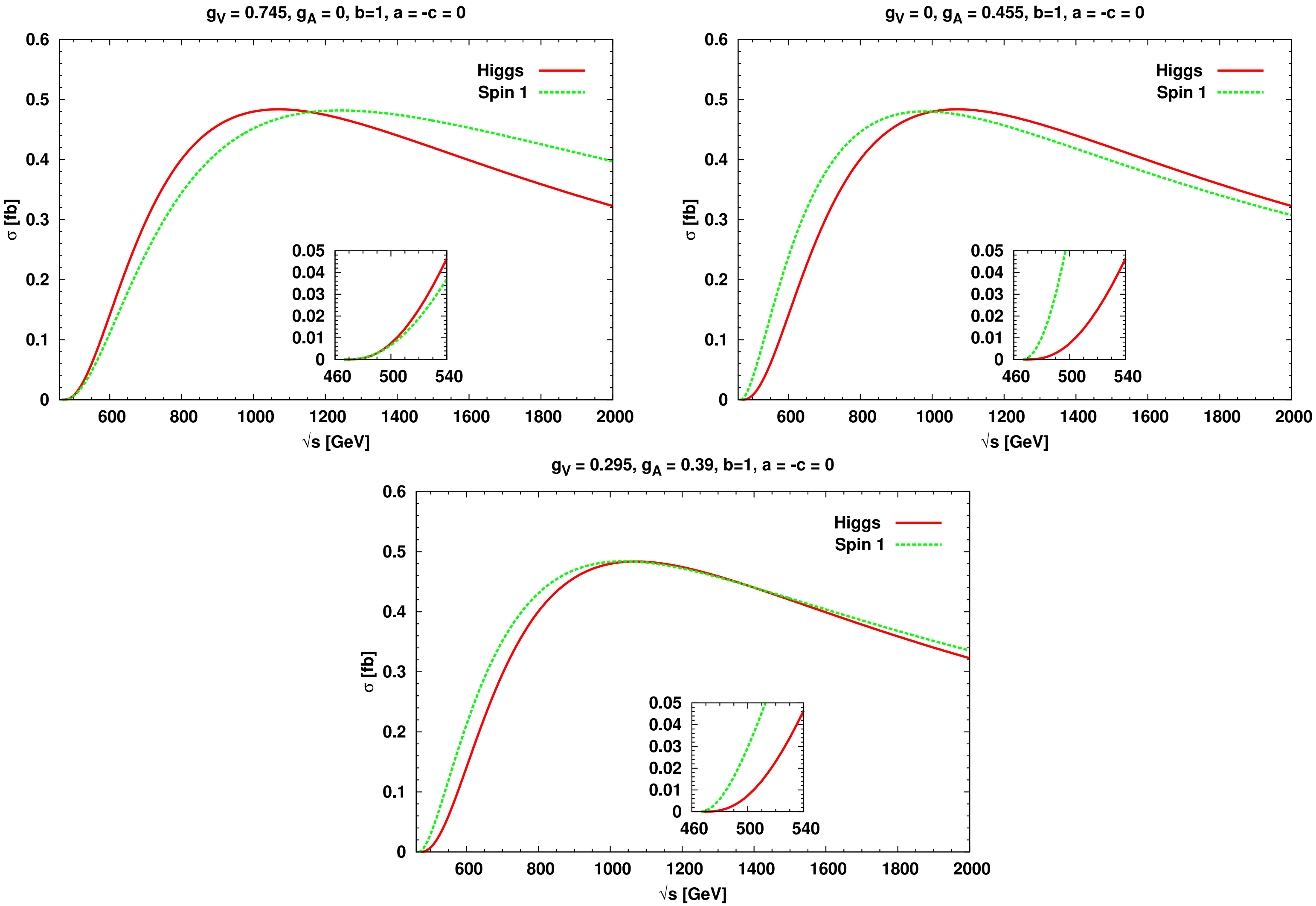
Telling a spin 1 from a CP-even spin 0 Higgs

Godbole,Hangst,MMM,Rindani,Sharma



Telling a spin 1 from a CP-odd spin 0 Higgs

Godbole,Hangst,MMM,Rindani,Sharma



$\mathcal{F}$ormulae

- **The total cross section**

$$\frac{d\sigma}{dx_1 dx_2} = \frac{\alpha^2}{4\pi s}\Bigg\{ \left[Q_e^2 Q_t^2 + \frac{(v_e^2+a_e^2)(v_t^2+a_t^2)}{(1-h_z)^2} + \frac{2Q_eQ_tv_ev_t}{1-h_z}\right]\left(a^2F_1^H + b^2F_1^A\right) + \frac{v_e^2+a_e^2}{(1-h_z)^2}a_t^2\left(a^2F_2^H+b^2F_2^A\right)\Bigg\} g_{ttH}^2$$

where $\alpha^{-1} = \alpha^{-1}(s) \sim 128$, $h_z = M_Z^2/s$ and $v_f = (2I_f^{3L} - 4Q_f s_W^2)/(4s_W c_W), a_f = 2I_f^{3L}/(4s_W c_W)$

- **Statistical fluctuation in P_t**

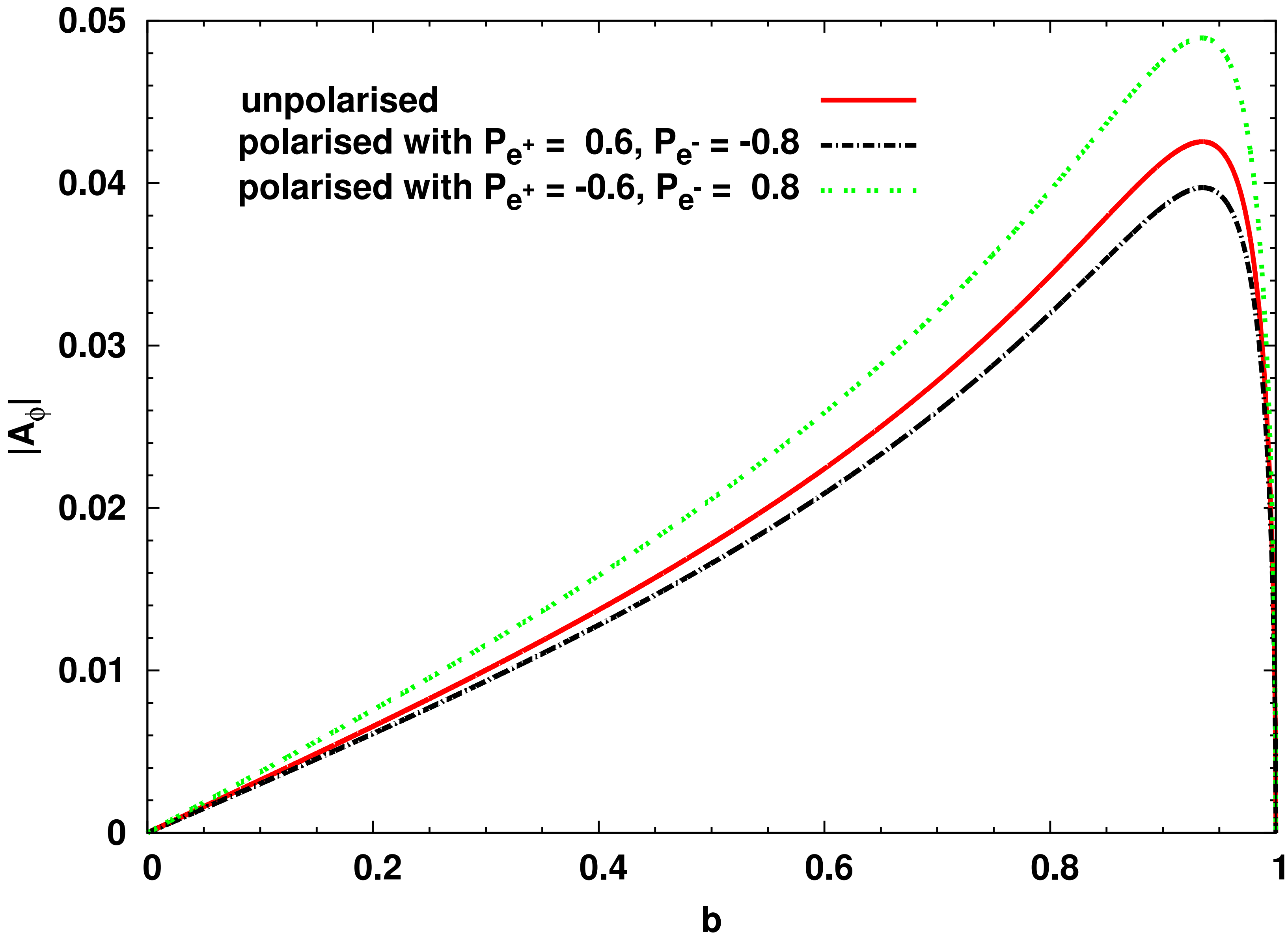
$$\Delta O(a_0, b_0) = \Delta P_t = \frac{1}{\sqrt{\sigma\mathcal{L}}}\sqrt{1-P_t^2}$$

- **Statistical fluctuation in A_ϕ**

$$\Delta O(a_0, b_0) = \Delta A_\phi = \frac{1}{\sqrt{\sigma\mathcal{L}}}\sqrt{1-A_\phi^2}$$

$\mathcal{A}$bsolute $\mathcal{V}$alue of A_ϕ

Godbole,Hangst,MMM,Rindani,Sharma



$a^2 = 1 - b^2$