V. Rykov, 07/11/2001
Snowmass-2001

# Could Higgs Physics Be Reachable at RHIC with polarized protons?

**RHIC-Spin current design goals:** (RHIC-500)

$\sqrt{s} = 200-500$ GeV

$\mathcal{L} = (0.8-2) \cdot 10^{32}$ cm$^{-2}$ $\cdot$ s$^{-1}$

$\int \mathcal{L} dt = 320-800$ pb$^{-1}$/year (10 weeks/year running)

Proton polarization: $P_p \simeq 70\%$

**Main focus of the current program:**

Measurement of spin-dependent structure function of proton, particularly gluon structure function.

**First collisions:**

October 2001 at $\sqrt{s} = 200$ GeV, $\mathcal{L} \simeq (5-8) \cdot 10^{30}$ cm$^{-2}$ s$^{-1}$

**Upgrade:** (RHIC-650)

$\sqrt{s} = 650$ GeV

$\mathcal{L} = 5 \cdot 10^{33}$ cm$^{-2}$ $\cdot$ s$^{-1}$

$\int \mathcal{L} dt = 20$ fb$^{-1}$/year (10 weeks/year)

100 fb$^{-1}$/year? (full year ???)

What next for the upgrade?

A. Ogawa, N. Saito and VLR
Spin 2000, October 2000
Osaka, Japan

Current limits for MSSM Higgs:

$M_{h^0} > 88.3$ GeV

$M_{H^0} \gtrsim 113$ GeV

$M_{A^0} > 88.4$ GeV

$M_{H^\pm} > 78.6$ GeV

$\sim 3 \lesssim \tan\beta \lesssim 60$

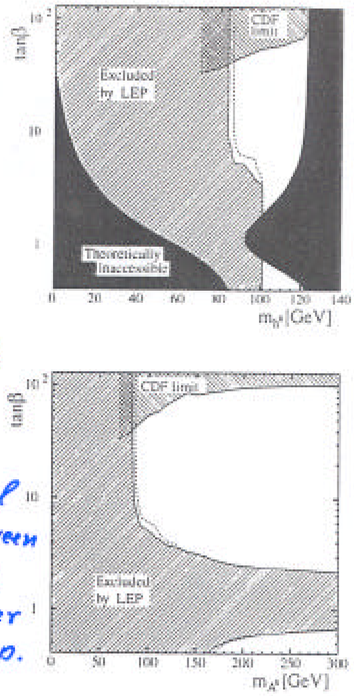



**Figure 6:** The 95% CL bounds on $m_{h^0}$, $m_{A^0}$, and $\tan\beta$, for the case of large mixing, from combining the data of the four LEP experiments up to $\sqrt{s}$ = 196 GeV [29]. The dashed lines indicate the expected limits. The exclusions at large $\tan\beta$ from the CDF experiment [33] are also indicated.

Let us assume for a moment that Higgs was found at

$M \simeq 115$ GeV

At large $\tan\beta$, all 3 neutral scalars would be sitting in between ~100–130 GeV. $H^0$ and $A^0$ are usually pretty close to each other and may significantly overlap. There are models with the physical states to be a mixture of scalar and pseudoscalar, and CP-violation takes place. Interesting interference effects could be observed in collisions of polarized particles with Higgs production

J.F. Gunion et al, PRL 71 (1993) 488

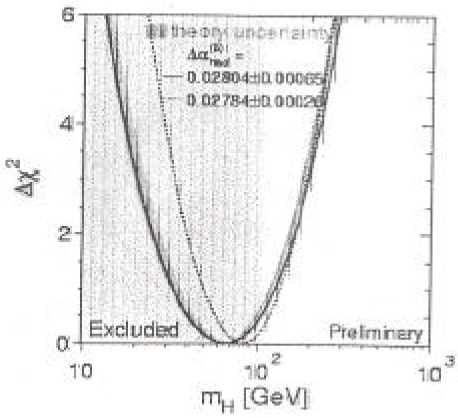
S.Y. Choi et al, hep-ph/9912330

E. Akawa et al, hep-ph/9912373

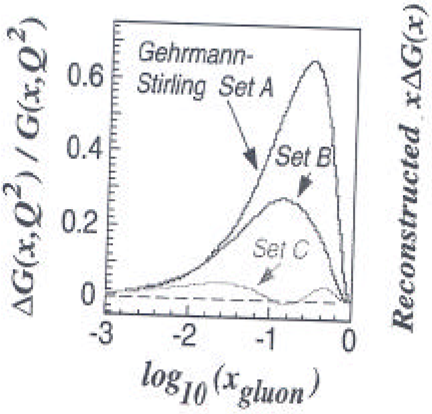
J.I. Ilana, hep-ph/9912467

# Higgs Boson

- Indirect evidence from precision measurement at e+e- colliders suggets:
  - 95-235 GeV at the 95% confidence level



**Gluon Polarization at $Q^2 = 100\ GeV^2$**




$gg \to h$ is the dominant mechanism for Higgs production at hadron colliders.

If gluons are polarized, various spin-dependent asymmetries could potentially be observed.

$$\frac{\Delta G}{G} = \frac{G^+ - G^-}{G^+ + G^-}$$

With $P_p \simeq 70\%$ and $\Delta G/G \simeq 0.6$

$$A_{LL} = \frac{N^{\pm\pm} - N^{\pm\mp}}{N^{\pm\pm} + N^{\pm\mp}} \simeq P_p^2 \left(\frac{\Delta G}{G}\right)^2 \simeq \underline{20\%}$$

$$A_L = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \simeq P_p \cdot \frac{\Delta G}{G} \sim \underline{40\%}$$

HIGLU (M. Spira): $pp$, $\sqrt{s} = 650$ GeV, $M_h \simeq 115$ GeV

SM: $\sigma_h \simeq 0.04$ pb

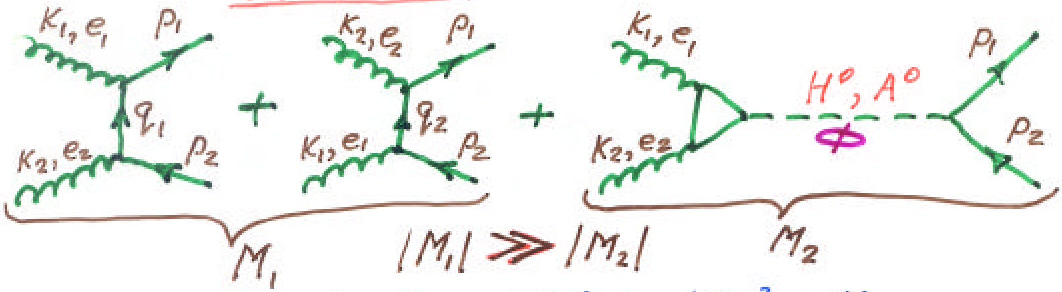
MSSM: $\tan\beta = 30$, $\sigma(H/A) \simeq 0.1 - 0.3$ pb

$\tan\beta = 50$, $\sigma(H/A) \simeq 0.4 - 0.9$ pb

At RHIC-650: $\int L\,dt = 20\ (100)\ fb^{-1}/year$

$N_h \simeq \underline{10^3 - 2\cdot 10^4\ (4\cdot 10^3 - 10^5)\ \text{Higgs/year}}$

## $gg \to b\bar{b}$




$$|M_1| \gg |M_2|$$

$$M_{fi} = M_1 + M_2; \quad |M_{fi}|^2 = |M_1|^2 + |M_2|^2 + M_{12}$$

$$d\hat{\sigma} = \frac{1}{64\pi^2 s}|M_{fi}|^2 d\Omega = d\hat{\sigma}_1 + d\hat{\sigma}_2 + d\hat{\sigma}_{12}; \quad s = (p_1+p_2)^2$$

$$\left.\begin{array}{l} |M_{12}| \lesssim 2|M_1|\cdot|M_2| \\ \text{For } |M_1| \gg |M_2| \end{array}\right\} \Rightarrow \frac{d\hat{\sigma}_{12}}{d\hat{\sigma}_1} \lesssim 2\sqrt{\frac{d\hat{\sigma}_2}{d\hat{\sigma}_1}}$$

### QCD-process

$$M_1 = 16\pi^2\alpha_s \bar{b}_1 \left\{ \not{e}_1 \frac{\not{q}_1 + m_b}{q_1^2} \not{e}_2 + \not{e}_2 \frac{\not{q}_2 + m_b}{q_2^2} \not{e}_1 \right\} b_2$$

Unpolarized gluons (c.m. of $b\bar{b}$ pair)

$$\frac{d\hat{\sigma}_1}{d\Omega} = \frac{16\pi^2\alpha_s^2}{s}\left(\frac{2}{\sin^2\theta} - 1\right)$$

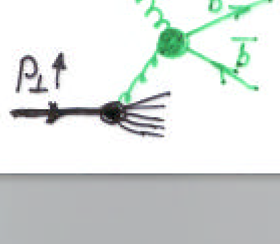
LL and RR polarized gluons

$$\frac{d\hat{\sigma}_1}{d\Omega} = \frac{32\pi^2\alpha_s^2}{s\cdot\sin^2\theta}$$

RL and LR polarized gluons

$$\frac{d\hat{\sigma}_1}{d\Omega} = \frac{32\pi^2\alpha_s^2}{s}\left(\frac{1}{\sin^2\theta} - 1\right)$$

Linearly polarized gluons ??? Not at this time...



# MSSM Higgs coupling to quarks and gluons

$$H^0 \to b\bar{b} = \frac{g\, m_b}{2M_W} \frac{\cos\alpha}{\cos\beta} \bar{b} b \Phi_{H^0}$$

$$A^0 \to b\bar{b} = i \frac{g\, m_b}{2M_W} \tan\beta\, \bar{b} \gamma_5 b \Phi_{A^0}$$

$\Big\}$ $\Gamma_{H^0, A^0} \sim \tan^2\beta$

$$H^0 \to gg = \frac{\alpha_s g}{12\pi M_W} \Big(\sum_i I^i_{H^0}\Big) \Phi_{H^0} \underbrace{\varepsilon^{\mu\nu\alpha\beta} \varepsilon_{\sigma\lambda\alpha\beta} K_{1\mu} e_\nu K_2^\sigma e_2^\lambda}_{h \sim G^{1a}_{\alpha\beta} G^{\alpha\beta}_{2a}}$$

$$\sum_i I^i_{H^0} \simeq C_1^H + C_2^H \frac{m_b}{M_W} \tan\beta$$

$$A^0 \to gg = \frac{\alpha_s g}{12\pi M_W} \Big(\sum_i I^i_{A^0}\Big) \Phi_{A^0} \underbrace{\varepsilon^{\alpha\beta\mu\nu} K_{1\alpha} e_{1\beta} K_{2\mu} e_{2\nu}}_{a \sim G^{1a}_{\alpha\beta} \tilde{G}^{\alpha\beta}_{2a}}$$

$$\sum_i I^i_{A^0} \simeq C_1^A + C_2^A/\tan\beta + C_3^A \frac{m_b}{M_W} \tan\beta$$

Now, let us assume that an eigenstate $\Phi$ at $M_H \simeq 115$ GeV is actually a mixture of $H^0$ and $A^0$: $\Phi = \cos\gamma \cdot \Phi_{H^0} + \sin\gamma \cdot \Phi_{A^0}$. $\Phi$ could be produced as either CP-even or CP-odd, and then forgets about its original CP and then decays to either CP-even or CP-odd $b\bar{b}$-pair.

$$\Phi \to b\bar{b} = \frac{g\, m_b}{2M_W} \Phi \bar{b} (F_+ + i F_- \gamma_5) b$$

$$\Phi \to gg = \frac{\alpha_s g}{12\pi M_W} \Phi (G_+ h + 2 G_- a)$$

$$M_2 = \frac{\alpha_s g^2 m_b}{6 M_W^2 (S - M_H^2 + i M_H \Gamma)} \bar{b}_1 (F_+ + i F_- \gamma_5) b_2 (G_+ h + 2G_- a)$$

In $b\bar{b}$ c.m. system:

$$h = S(\vec{e}_1 \cdot \vec{e}_2) \; ; \qquad a = -\frac{S}{2}\Big(\vec{n}_K [\vec{e}_1 \times \vec{e}_2]\Big) \qquad \vec{n}_K = \frac{\vec{K}_1}{|\vec{K}_1|}$$

RR and LL polarized gluons

$h = S$ ; $\quad a = \pm \frac{iS}{2}$

RL and LR polarized gluons

$h = 0$ ; $\quad a = 0$.

## $gg \to \Phi \to b\bar{b}$ cross section

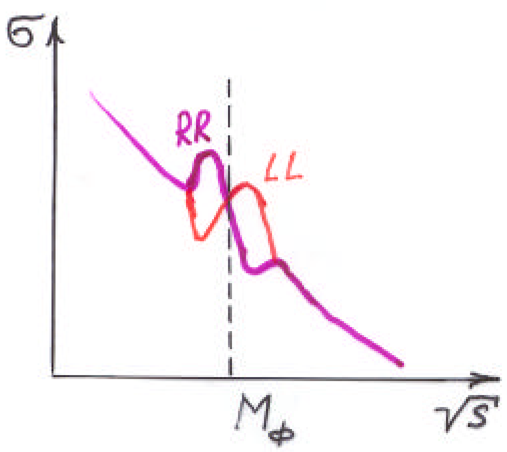
$$\frac{d\hat{\sigma}_2}{d\Omega} = \frac{\alpha_s^2 g^4 m_b^2 S^2 (F_+^2 + F_-^2)}{2304 M_W^4 \left[(S-M_\Phi^2)^2 + M_\Phi^2 \Gamma_\Phi^2\right]} \left\{ \underbrace{(|G_+|^2 + |G_-|^2)(1+\lambda_1\lambda_2)}_{CP\text{-even}} + \underbrace{2\,\mathrm{Im}(G_+ G_-^*)(\lambda_1+\lambda_2)}_{CP\text{-odd}} \right\}$$

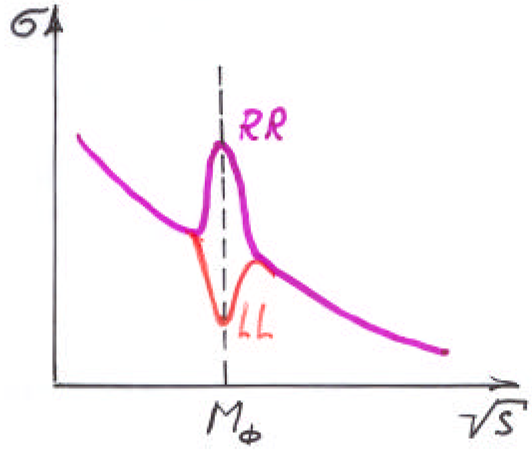
## Interference term

$$\frac{d\hat{\sigma}_{12}}{d\Omega} = \frac{\alpha_s^2 g^2 m_b^2}{3 M_W^2 \sin^2\theta} \left\{ (1+\lambda_1\lambda_2)\sigma^{even} + (\lambda_1+\lambda_2)\sigma^{odd} \right\}$$

$$\sigma^{even} = \frac{(S-M_\Phi^2)(F_+ \mathrm{Re}\,G_+ + F_- \mathrm{Re}\,G_-) + M_\Phi \Gamma_\Phi (F_+ \mathrm{Im}\,G_+ + F_- \mathrm{Im}\,G_-)}{(S-M_\Phi^2)^2 + M_\Phi^2 \Gamma_\Phi^2}$$

$$\sigma^{odd} = \frac{(S-M_\Phi^2)(F_- \mathrm{Im}\,G_+ - F_+ \mathrm{Im}\,G_-) + M_\Phi \Gamma_\Phi (F_+ \mathrm{Re}\,G_- - F_- \mathrm{Re}\,G_+)}{(S-M_\Phi^2)^2 + M_\Phi^2 \Gamma_\Phi^2}$$




$$|M_{12}| \sim \frac{m_b}{\sqrt{s}} |M_1| \cdot |M_2|$$

## Size of the effect: $A \sim \frac{\sigma_2 + \sigma_{12}}{\sigma_1}$

$\sigma_1 \equiv \sigma_{QCD}$ should be taken over $\delta\sqrt{s'} \simeq \pm\,\delta_M$
where $\delta_M$ is mass resolution for $b\bar{b}$ pairs

DØ: $\frac{\delta(E_{jet})}{E_{jet}} \simeq \frac{80\%}{\sqrt{E_{jet}}}$ (B. Abbot et al, Fermilab-Pub 99/357-E)

at $M = 115$ GeV, $\delta_M/M \simeq 7.5\%$, $\delta_M \simeq 8.5$ GeV

PYTHIA: $\sqrt{s'} = 650$ GeV, pp

$\sigma_{QCD}(gg \to b\bar{b}) \simeq 800$ pb at $105\ \text{GeV} < \sqrt{s'} < 125\ \text{GeV}$

$\sigma_{QCD}(q\bar{q} \to b\bar{b}) \simeq 50$ pb

HDECAY/HIGLU (M. Spira) for $gg \to h/H, A$, $\sqrt{s} = 650$ GeV
$M = 115$ GeV pp

| $\tan\beta$ | $\Gamma_{h/H}$, GeV | $\Gamma_A$, GeV | $\sigma_{h/H}$, pb | $\sigma_A$, pb | A |
|---|---|---|---|---|---|
| SM | 0.003 | | 0.04 | | $\sim 0.5\cdot10^{-4}$ |
| 30 | 1.5 | 2.4 | 0.1 | 0.3 | $\sim 0.4\cdot10^{-3}$ |
| 50 | 4.7 | 6.6 | 0.4 | 0.9 | $\sim 1\cdot10^{-3}$ |

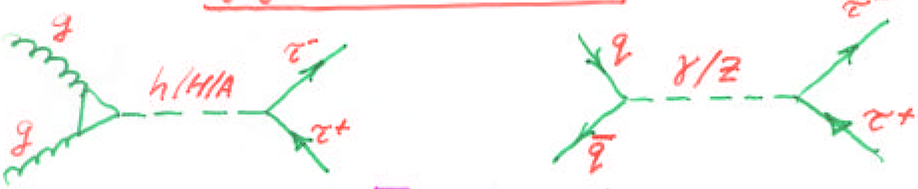
At RHIC-650: $\int L\,dt \simeq 20\,(100)\ fb^{-1}$/year

$N_{tot}^{b\bar{b}} \simeq 800\,pb \cdot 2\cdot10^4\,(10^5)\,pb^{-1} \simeq 1.6\cdot10^7\,(8\cdot10^7)\ b\bar{b}$/year

At detection efficiency 50%: $N_{event} \simeq 0.8\,(4)\cdot10^7\ b\bar{b}$/year

For $P_p \simeq 70\%$, $\Delta G/G \simeq 0.6$: $\sigma_{stat} \simeq 8\,(4)\cdot10^{-4}$

## $gg \to h \to \tau^+\tau^-$




$pp$, $\sqrt{s} = 650$ GeV

HDECAY/HIGLU: $\sigma \cdot Br(gg \to A \to \tau^+\tau^-) \simeq 0.03 - 0.08$ pb $\quad M_A = 115$ GeV, $\tan\beta = 30-50$

PYTHIA: $\sigma(q\bar{q} \to \gamma/Z \to \tau^+\tau^-) \simeq 0.25$ pb $\quad \sqrt{s} = 115(1 \pm 10\%)$ GeV

$S/B \simeq (12-30)\%$

At RHIC-650: $N_{h\to\tau^+\tau^-} \simeq (600-1600)\,(3\cdot10^3 - 8\cdot10^3)$ events/year

At det. eff ~ 20%: $N^{det}_{h\to\tau^+\tau^-} \simeq \underline{(120-320)(600-1600)}$ events/year

Mass resolution for $\tau^+\tau^-$-pairs ???

A. Belyaev (Florida State Univ): $P_T \neq 0$ $\tau^+\tau^-$-pairs

## $gg \to h \to W^+W^- \to 4$ jets

$pp$, $\sqrt{s} = 650$ GeV

HDECAY/HIGLU: $\sigma \cdot Br \simeq 3.5 \cdot 10^{-3}$ pb $\quad$ SM-Higgs, $130\text{ GeV} < M_h < 150\text{ GeV}$

At RHIC-650: $N_{h\to W^+W^-} \simeq \underline{70\,(350)}$ events/year

# Conclusion

Some time in the future after upgrade to RHIC-650, it might be possible to do some limited study of Higgs properties at RHIC with polarized protons, provided:

Nature made: Higgs with the "right" properties was discovered (somewhere else) at the "right" place.

Man made: A full scale HEP detector is built at RHIC (hermeticity, hadron & EM calorimetry, vertex, tracking, etc).