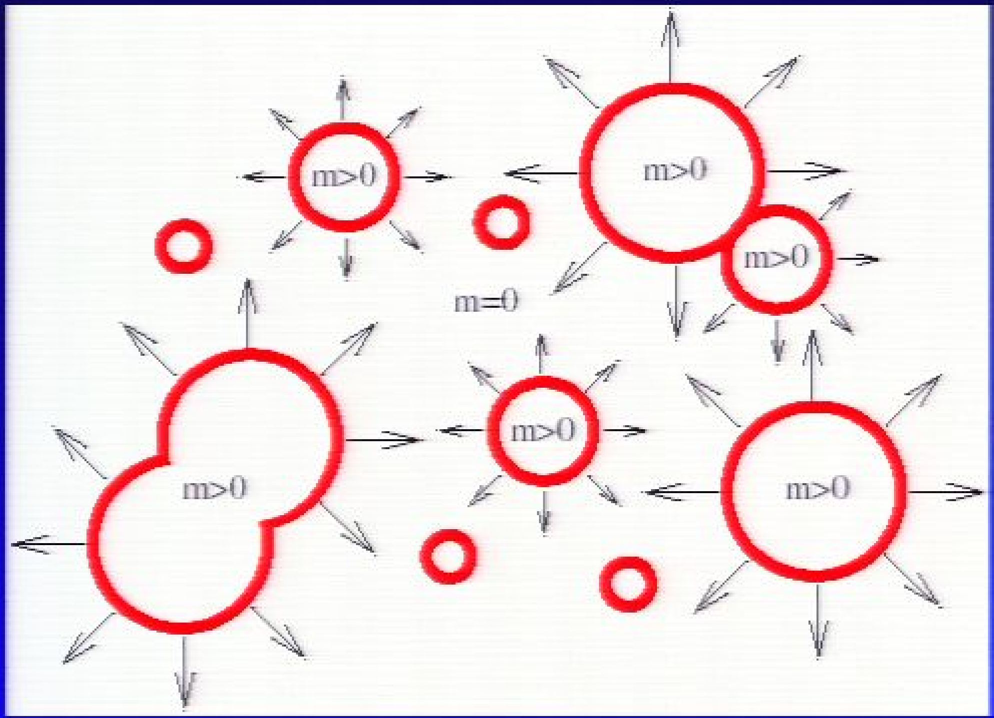
Title: Two Higgs doublet models/Baryogenesis and LHC

Date: Dec 07, 2010 03:40 PM

URL: http://pirsa.org/10120030

Abstract: TBA

DØ dimuon anomaly and electroweak baryogenesis



Jim Cline (McGill U. and PI)

with Kimmo Kainulainen (Jyväskylä) and Mike Trott (PI)

PI-ATLAS LHC day, 7 Dec. 2010

New source of CP violation?

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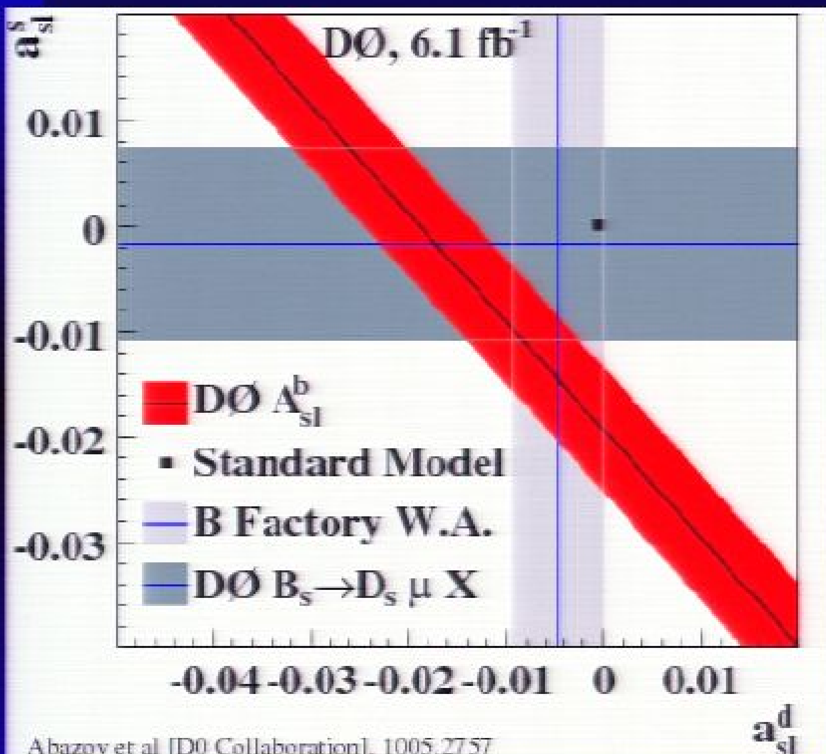

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from semileptonic B decays

$$B_{d,s} \to \mu^\pm X$$

(a^d_{sl} and a^s_{sl} are respective contributions from $B_{d,s}$)

$B_s \to J/\psi\,\phi$ and $B^- \to \tau\nu$ also deviate from SM.

Evidence for new CP violation beyond SM

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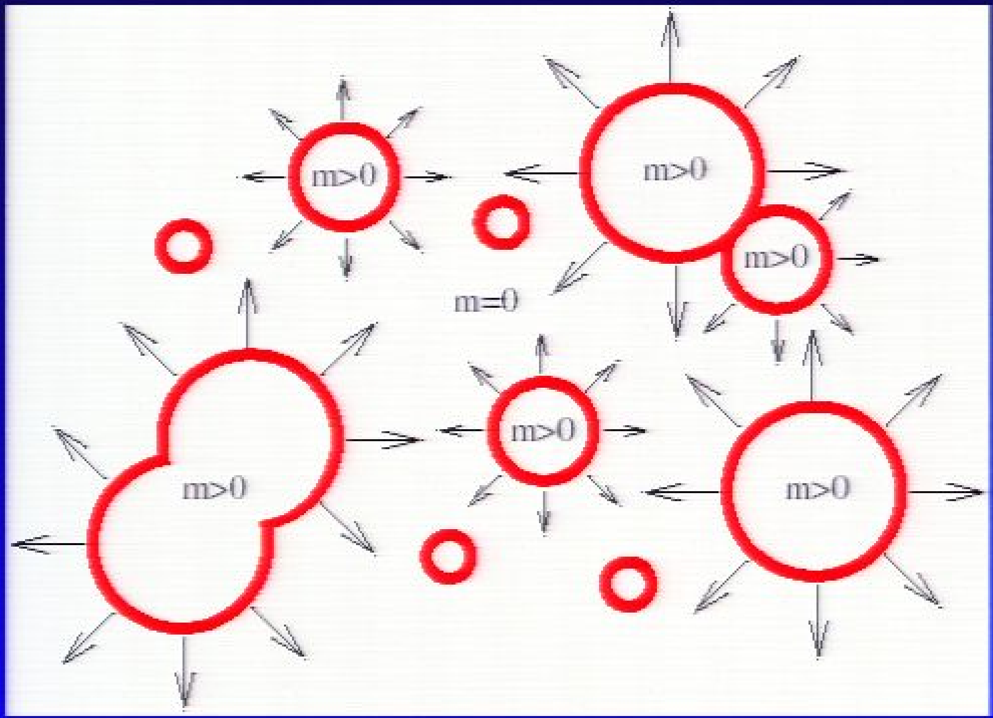

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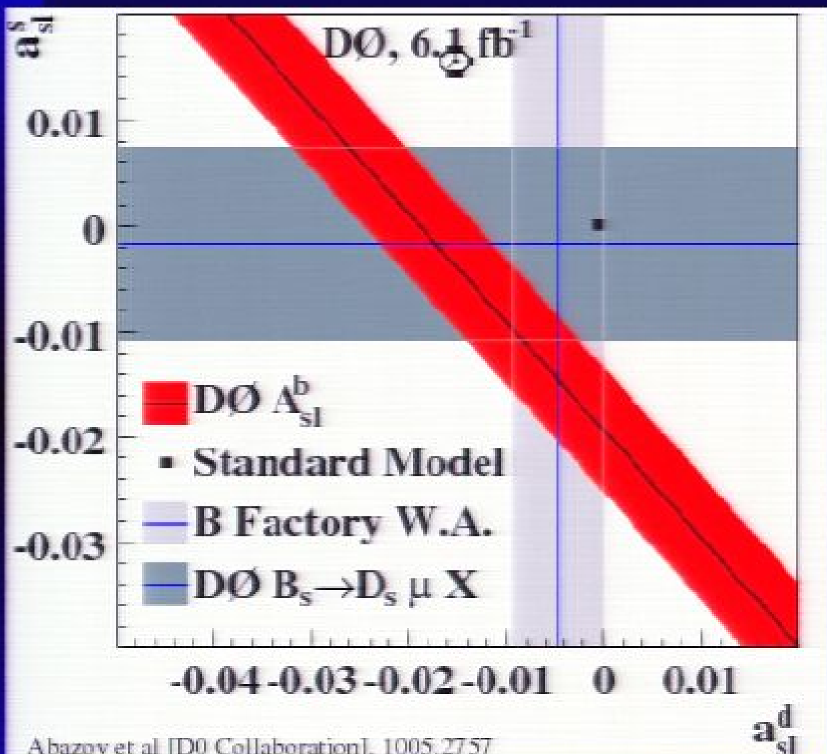

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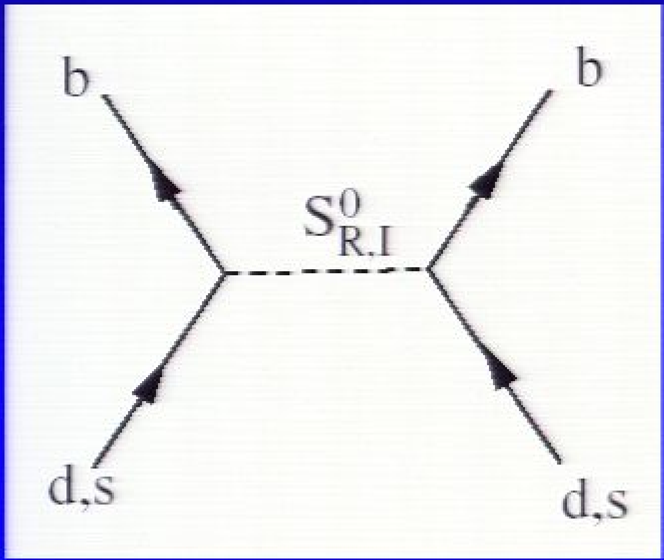
A simple model

Two Higgs doublets (H, S) with minimal flavor violation (MFV) Trott, Wise 1009.2813

New Higgs S^0 FCNC couplings to b (and t) are CKM-suppressed:

$$y_b\,\bar{b}_L\left(H^0\delta_{bi} + (\eta_D\delta_{bi} + \eta'_D V_{tb}V^*_{ti})S^0\right)q^i_R$$



$$\sim {\eta'_D}^2 y_b^2 \frac{m^2_{S_R} - m^2_{S_I}}{m^4_S}(V_{tb}V^*_{ti})^2$$

same CKM structure as SM box diagram contribution

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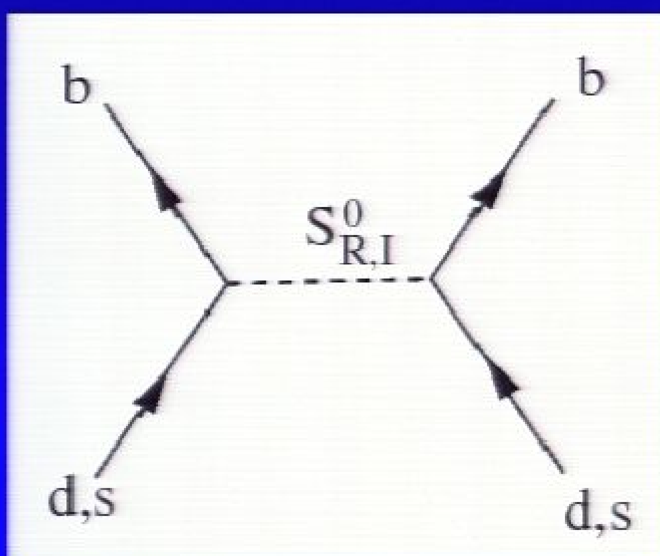

CP violating couplings

$$\sim \eta'^2_D \, y_b^2 \frac{m^2_{S_R} - m^2_{S_I}}{m^4_S} (V_{tb} V^*_{ti})^2$$

same CKM structure as SM box diagram contribution

New $\not{C}\not{P}$ couplings

In addition to $\not{C}\not{P}$ Yukawa couplings η_U, η'_U, η_D, η'_D, scalar potential has new $\not{C}\not{P}$ couplings,

$$\begin{aligned} V &= \lambda\left(H^{\dagger i}H_i - \tfrac{1}{2}v^2\right)^2 + m_1^2\,(S^{\dagger i}S_i) \\ &+ \left(\underline{m_2^2}\;H^{\dagger i}S_i + \text{h.c.}\right) + \lambda_1\,(H^{\dagger i}H_i)\,(S^{\dagger j}S_j) \\ &+ \lambda_2\,(H^{\dagger i}H_j)\,(S^{\dagger j}S_i) + \left[\underline{\lambda_3}\,H^{\dagger i}H^{\dagger j}S_iS_j + \text{h.c.}\right] \\ &+ \left[\underline{\lambda_4}\,H^{\dagger i}S^{\dagger j}S_iS_j + \underline{\lambda_5}\,S^{\dagger i}H^{\dagger j}H_iH_j + \text{h.c.}\right] \\ &+ \lambda_6(S^{\dagger i}S_i)^2 \end{aligned}$$

of which 2 can be removed by field redefinitions.

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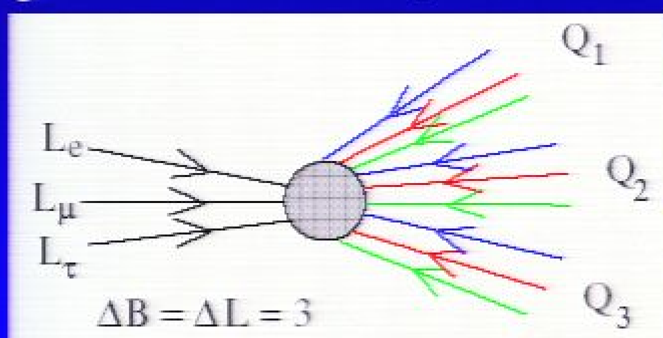
$\not{CP}$ and baryogenesis

People like to say that new $\not{CP}$ is exciting because of baryogenesis. Electroweak baryogenesis might be testable at LHC. Can we put these together?

Necessary ingredients:

- new $\not{CP}$ ✔
- baryon violation $\not{B}$ ✔

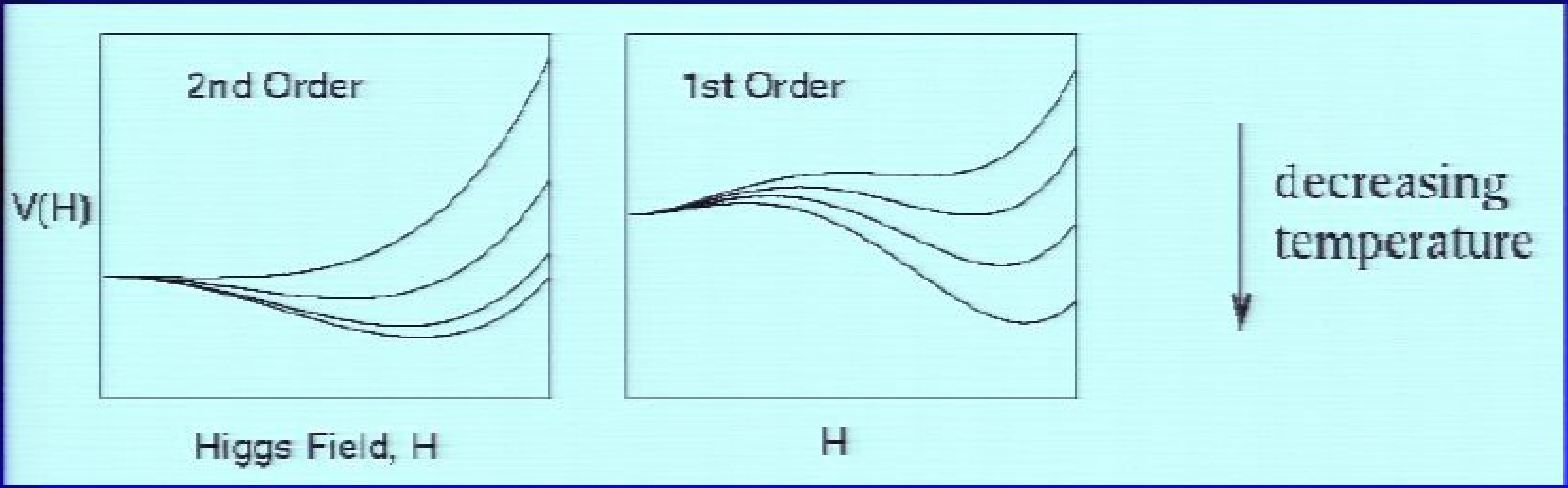


SM provides anomalous $\not{B}$ at high temperature through sphalerons

- getting out of thermal equilibrium ?

Electroweak Baryogenesis

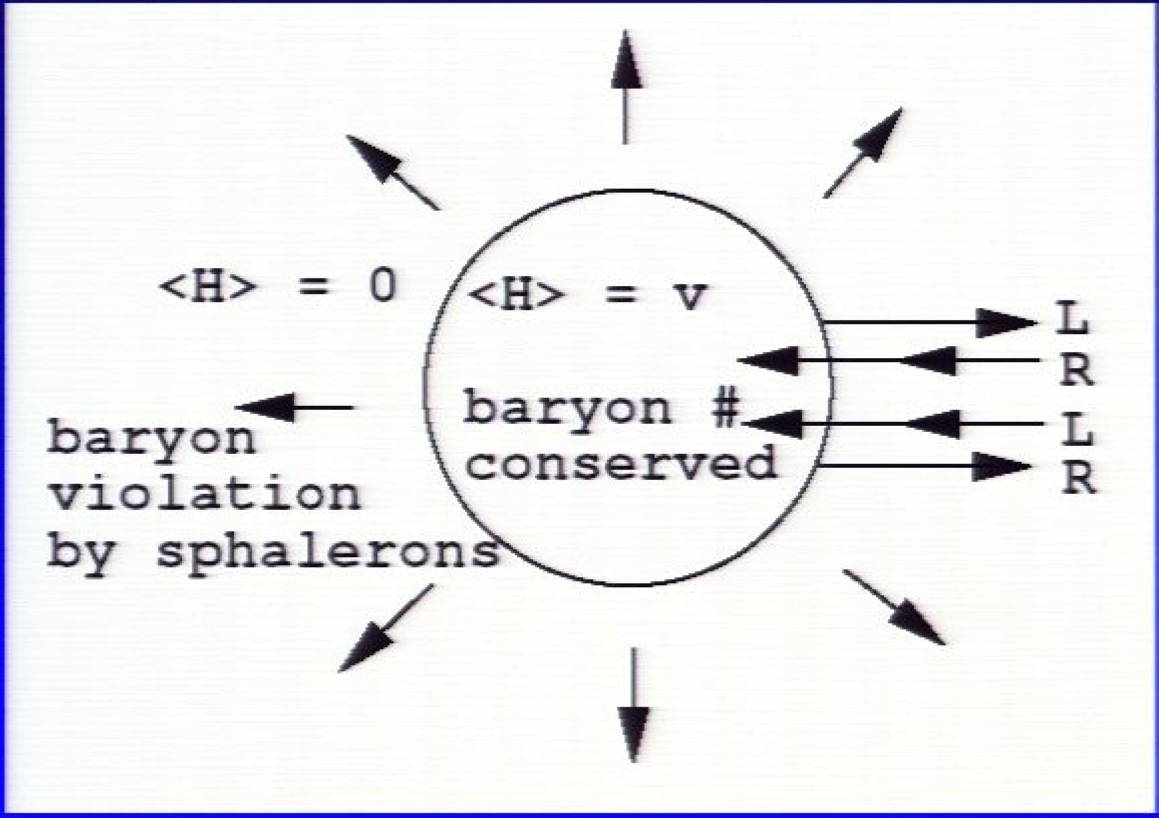
- Sakharov: must go out of thermal equilibrium to make baryon asymmetry.
- Getting out of equilibrium can be achieved in a first order electroweak phase transition.



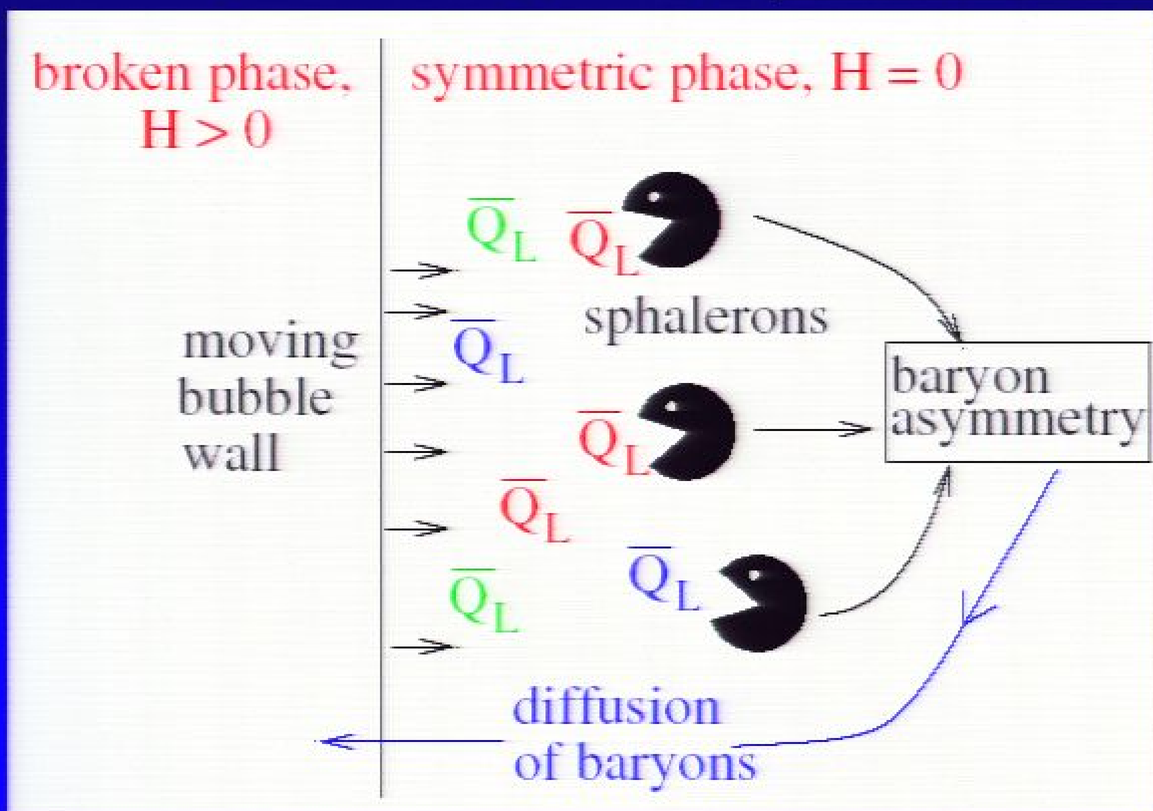
- Phase transition is too weak in Standard Model, need new Higgs physics ✔

How it works

- At critical temperature $T_c \sim 100$ GeV, bubbles of true vacuum ($\langle H \rangle \neq 0$) form and start expanding.
- Particles reflect off wall in a CP violating way.
- Baryon asymmetry forms inside the bubble.



- Sphalerons eat excess left-handed antiquarks in front of wall
- baryon asymmetry is created
- baryons diffuse back inside expanding bubble
- sphalerons must be ineffective inside bubble, otherwise baryons decay away: need $\langle H \rangle > T_c$



EWBG in 2HDM

Electroweak baryogenesis has been previously considered in 2 Higgs doublet models. But our analysis is different:

- MFV couplings of quarks to Higgses instead of discrete symmetries to avoid FCNC's

$$\mathcal{L}_{\bar{q}Hq} = \bar{u}_R\, y_u\, QH + \bar{d}_R\, y_d\, QH^\dagger$$
$$+\bar{u}_R(\eta_u y_u + \eta'_u y_u y_u^\dagger y_u)QS + \bar{d}_R(\eta_d y_d + \eta'_d y_d y_u^\dagger y_u)QS^\dagger$$

- Explain dimuon + B decay anomalies

- Respect numerous particle physics constraints: R_b, EWPO, LEP/Tevatron mass limits, $b \to s\gamma$, neutron EDM, vacuum stability, Landau poles

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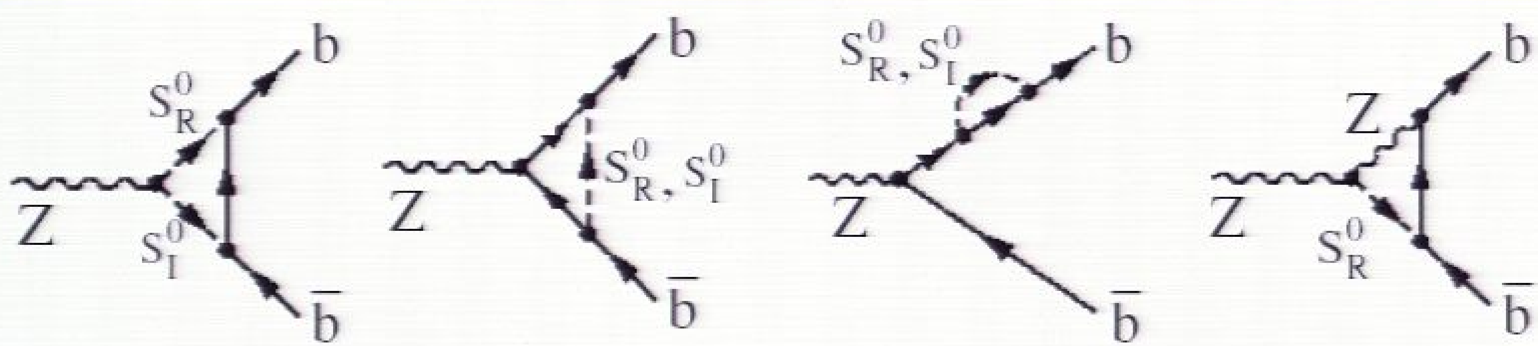

adapted from Haber & Logan, hep–ph/9909335

go like $|\eta_D|^2$;
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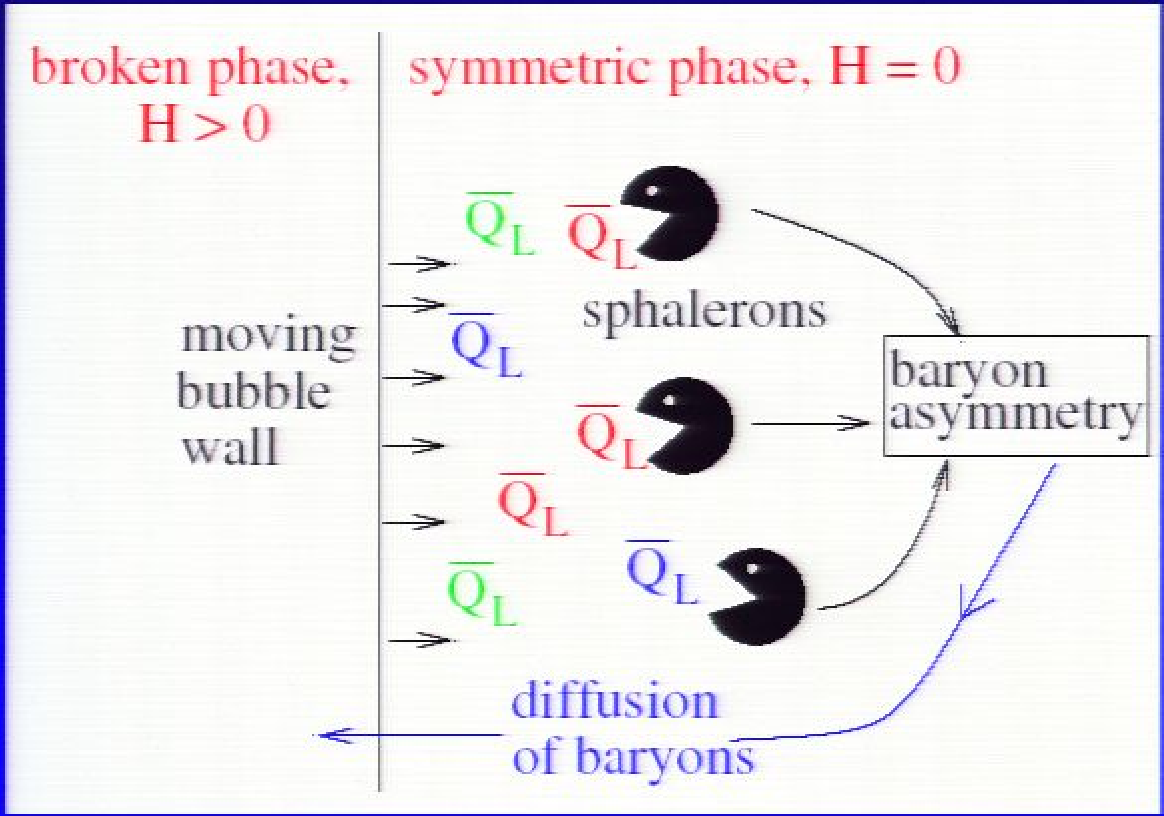

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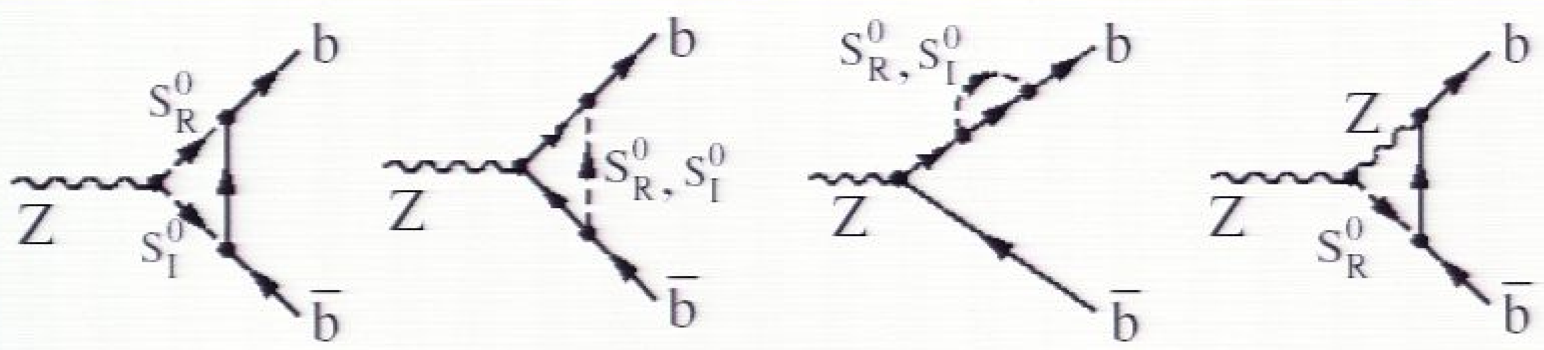

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Pheno constraints are stringent

We find it hard to satisfy particle physics constraints and get a strong phase transition.

1. Search grid in $\{m_h, m_1, \lambda_1, \lambda_2, \lambda_3\}$ space for strong phase transitions. Then filter with pheno constraints. All examples excluded by EWPO and dimuons $+R_b$!

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m_h (GeV)	# start	# strong p.t.
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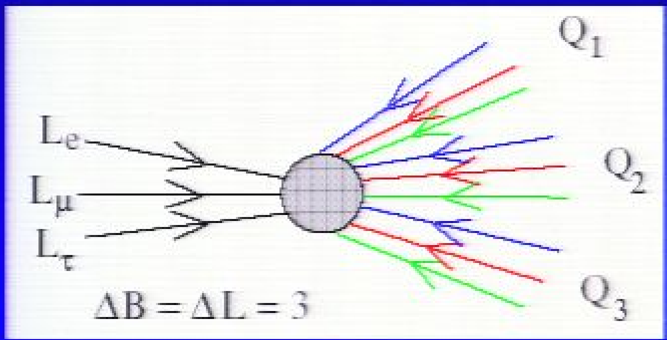

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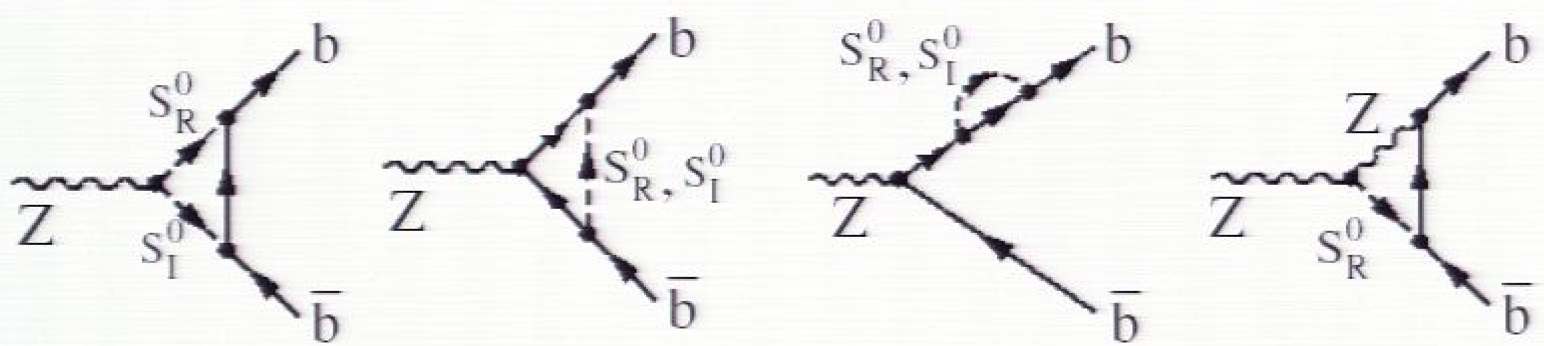

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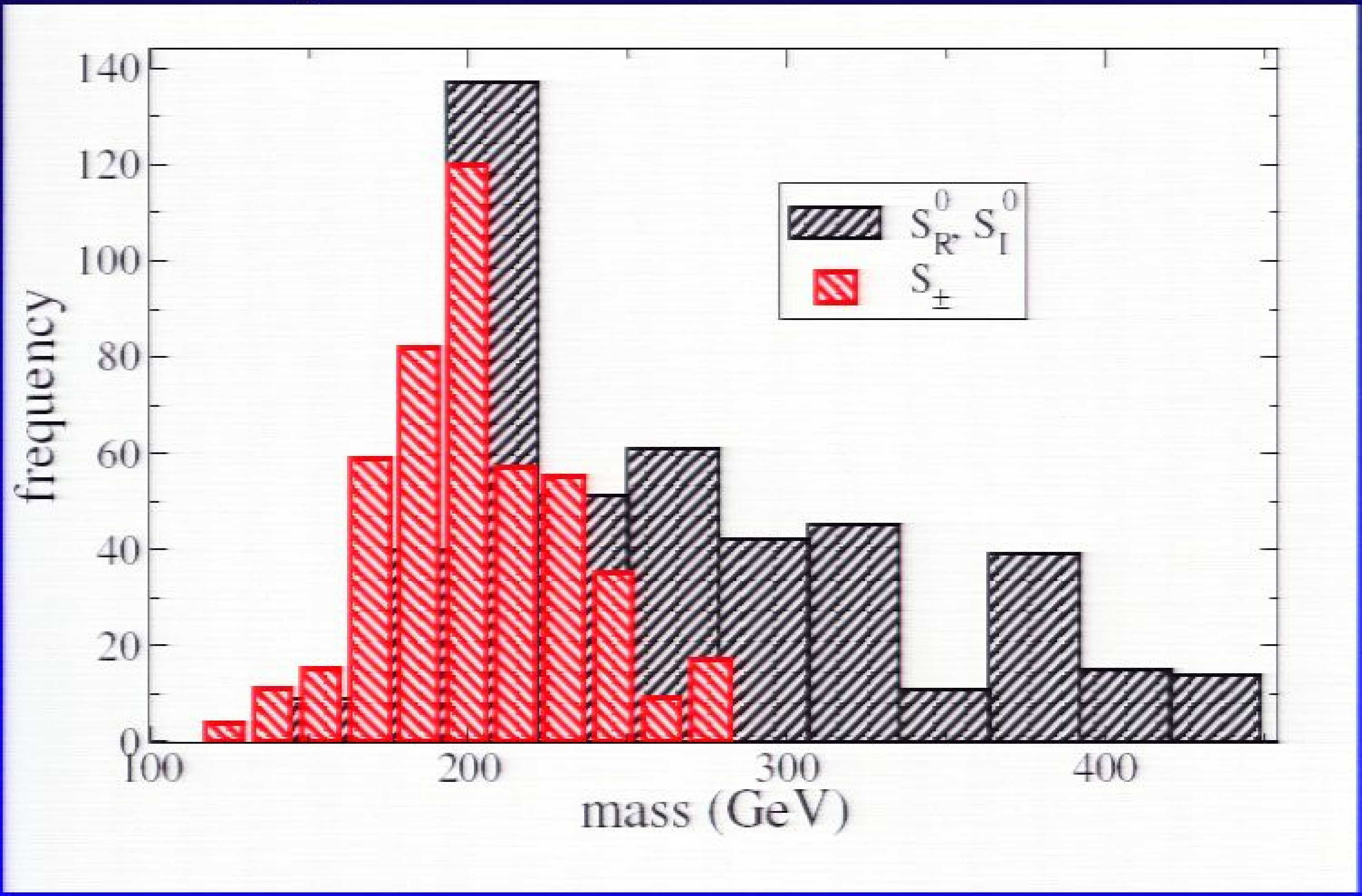

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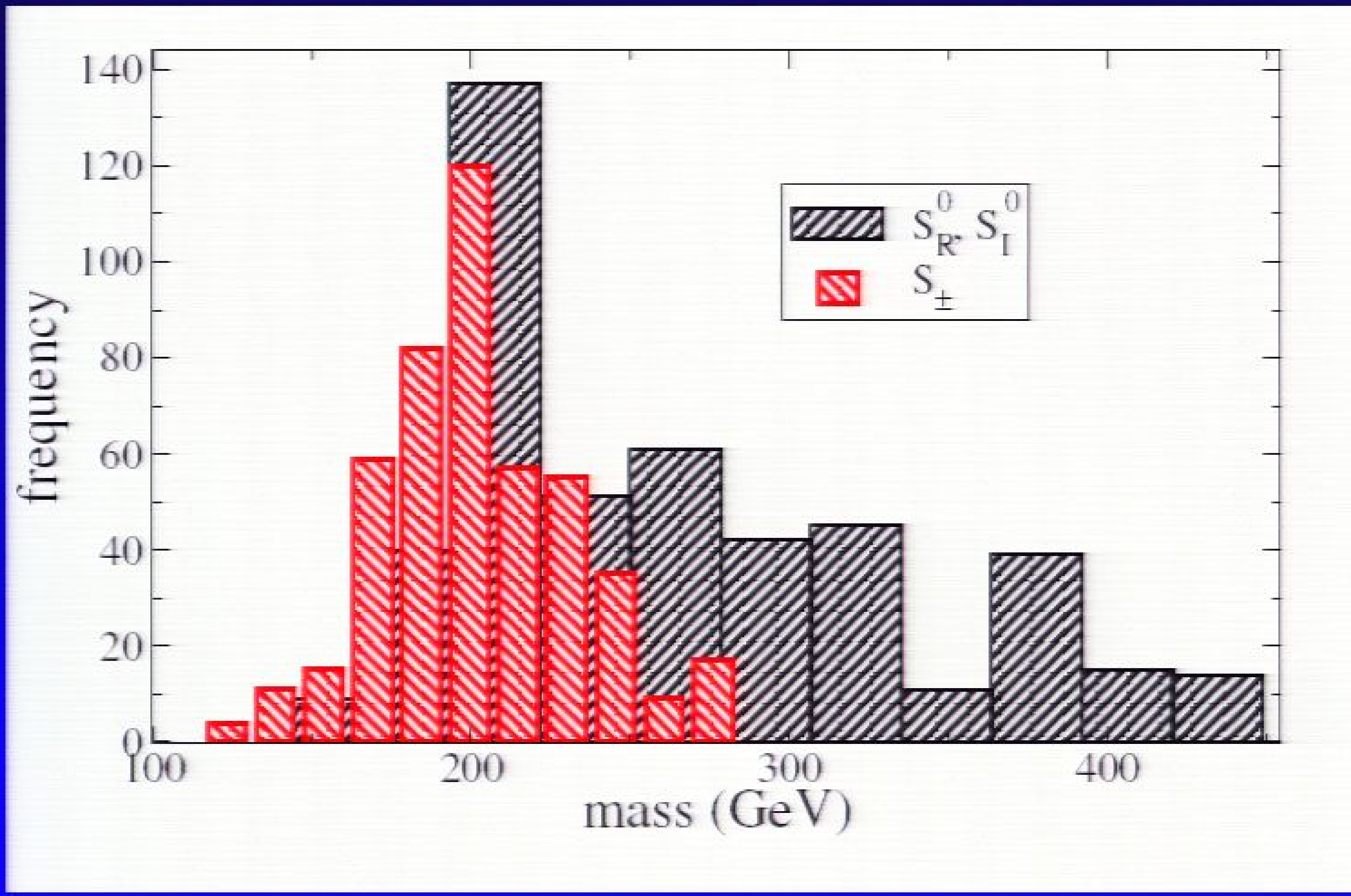

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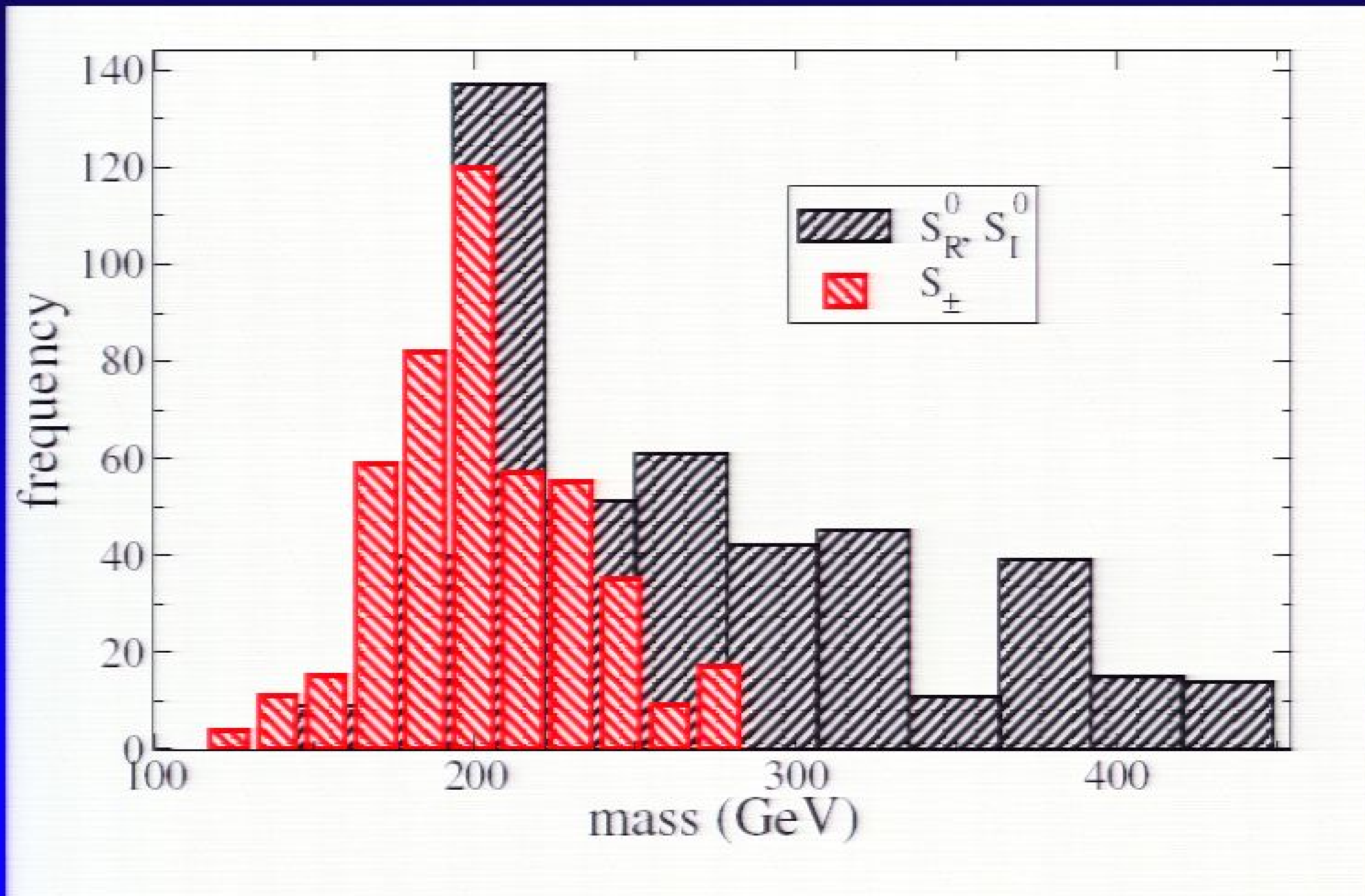

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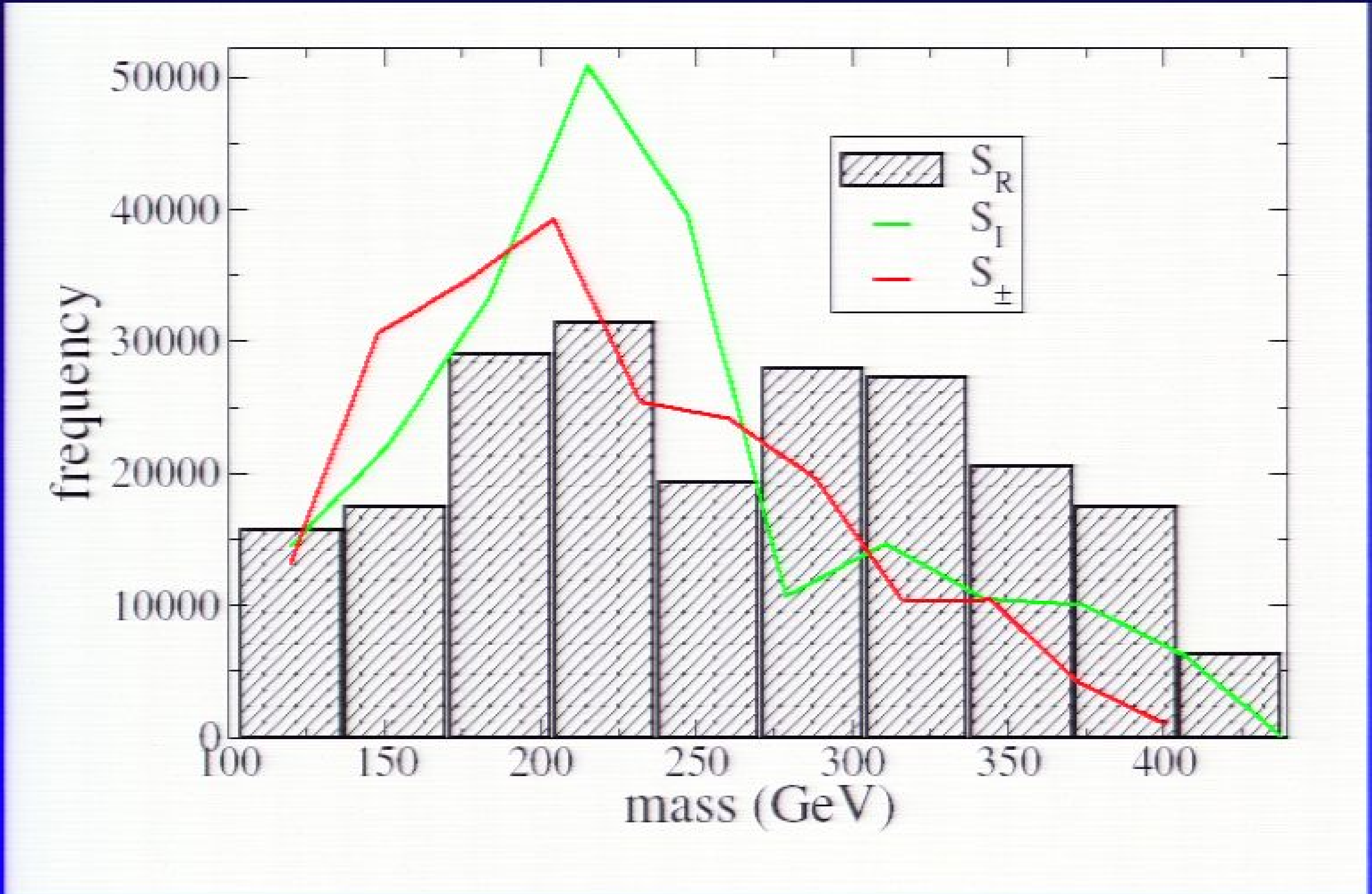

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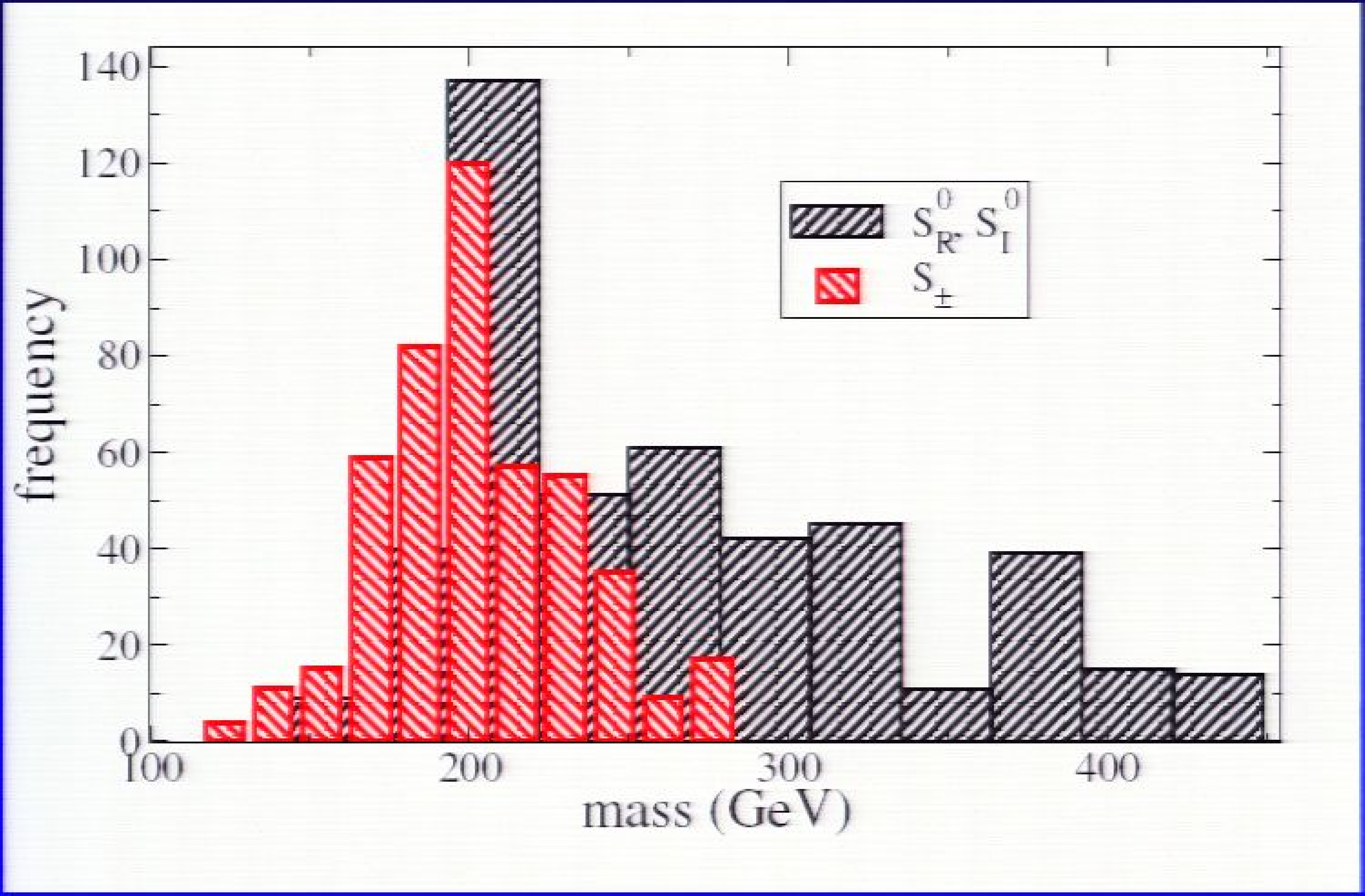

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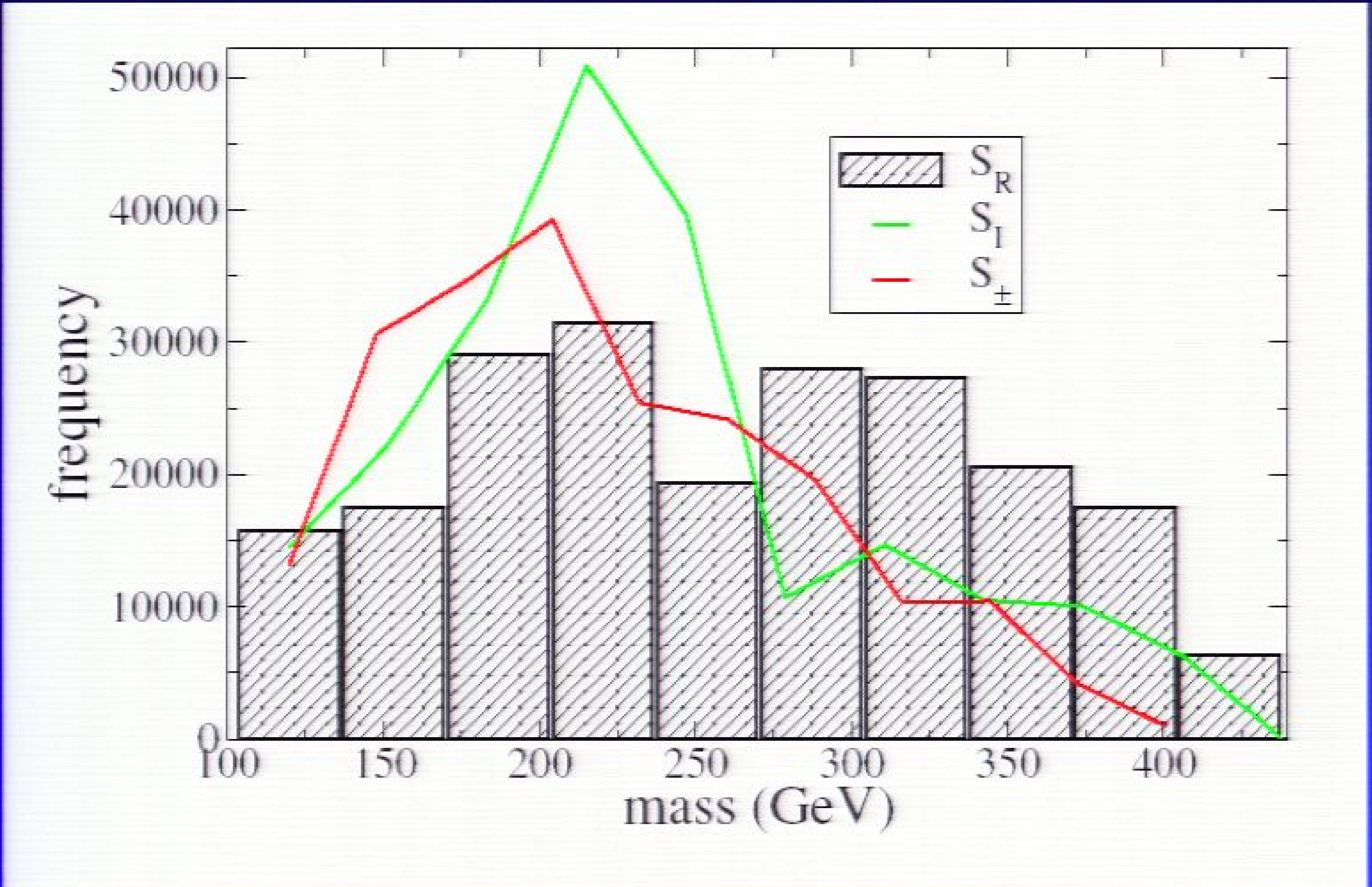

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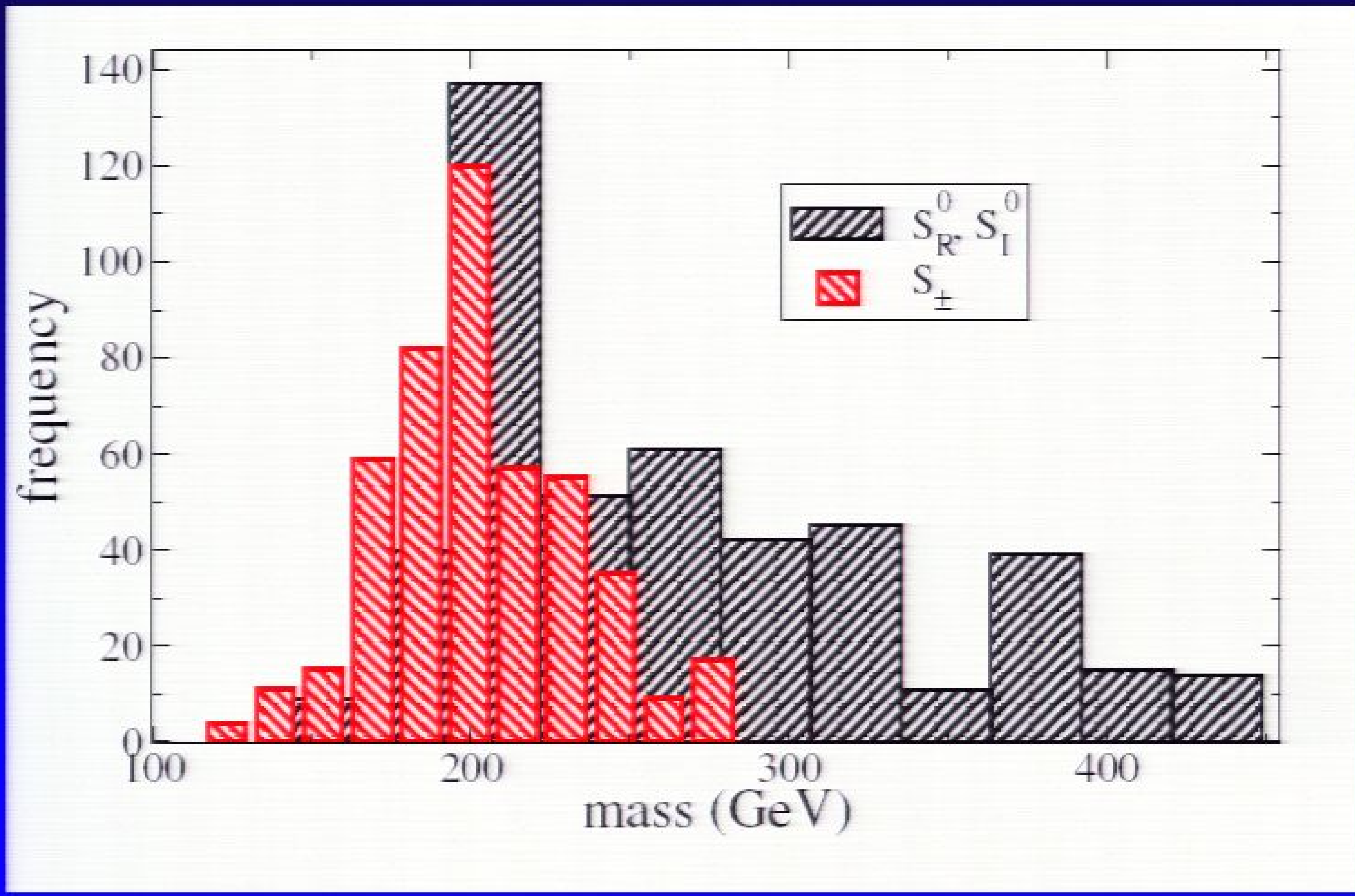

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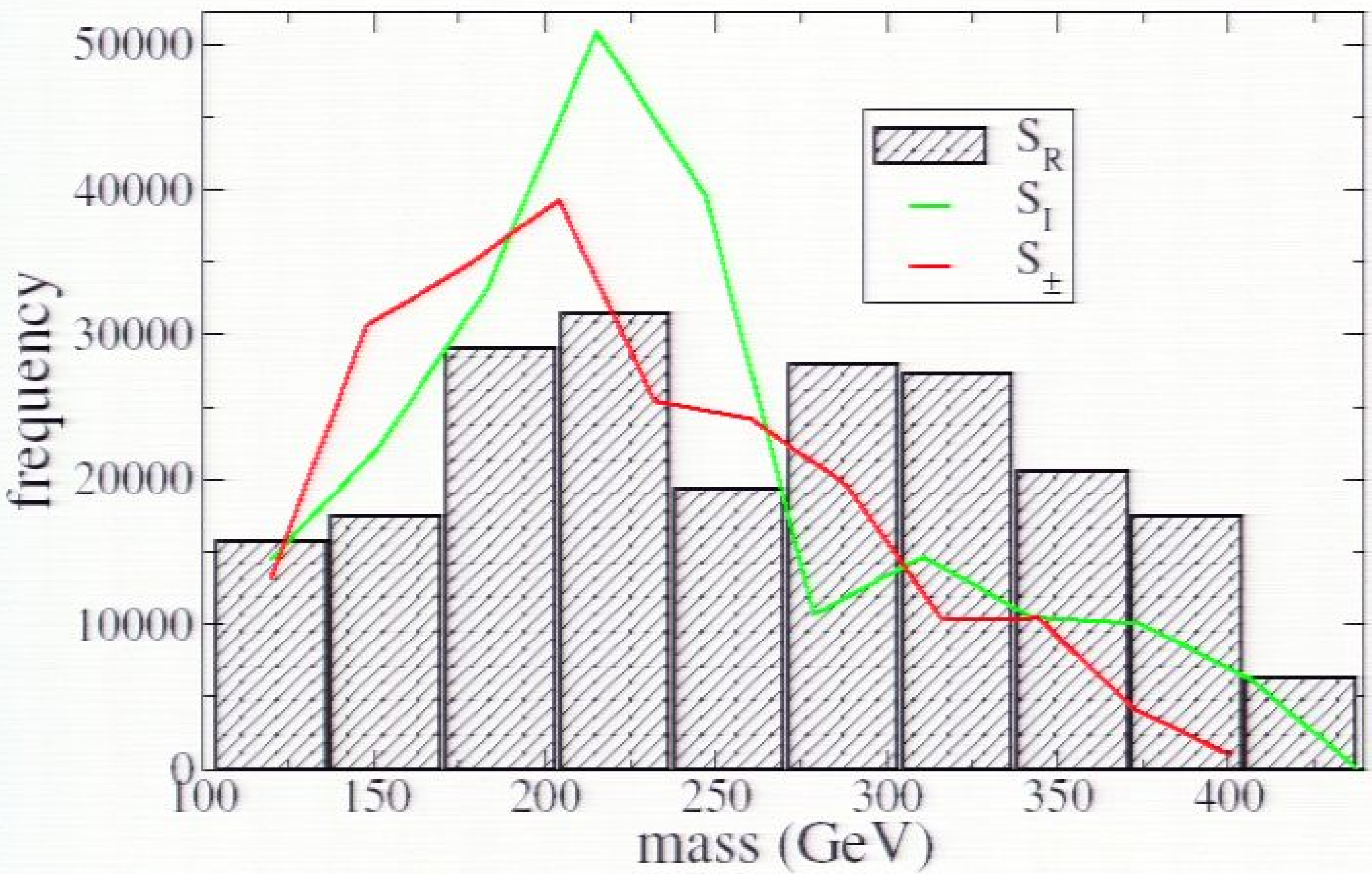

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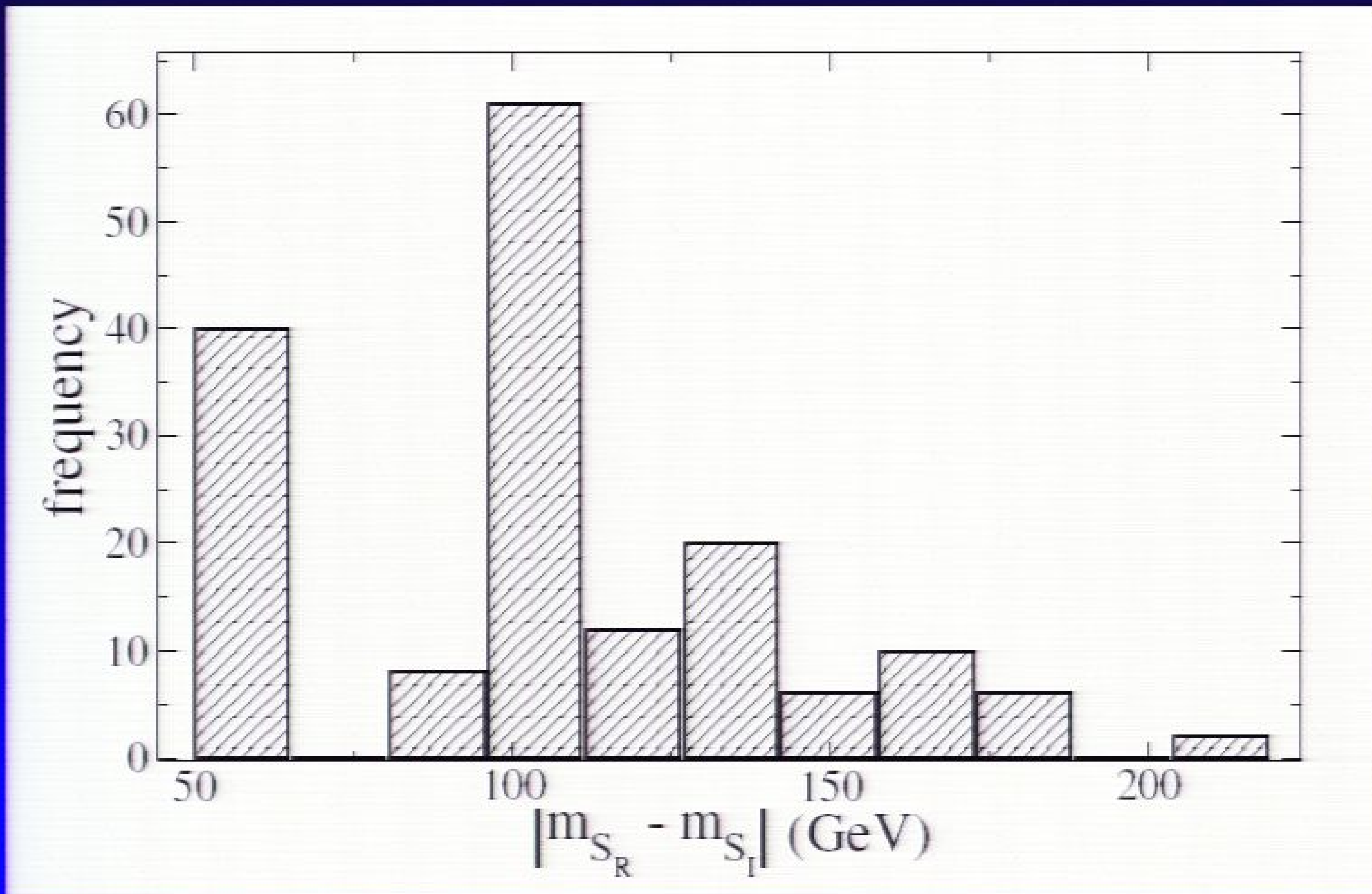
Distribution of S_I^0-S_R^0 mass splittings:



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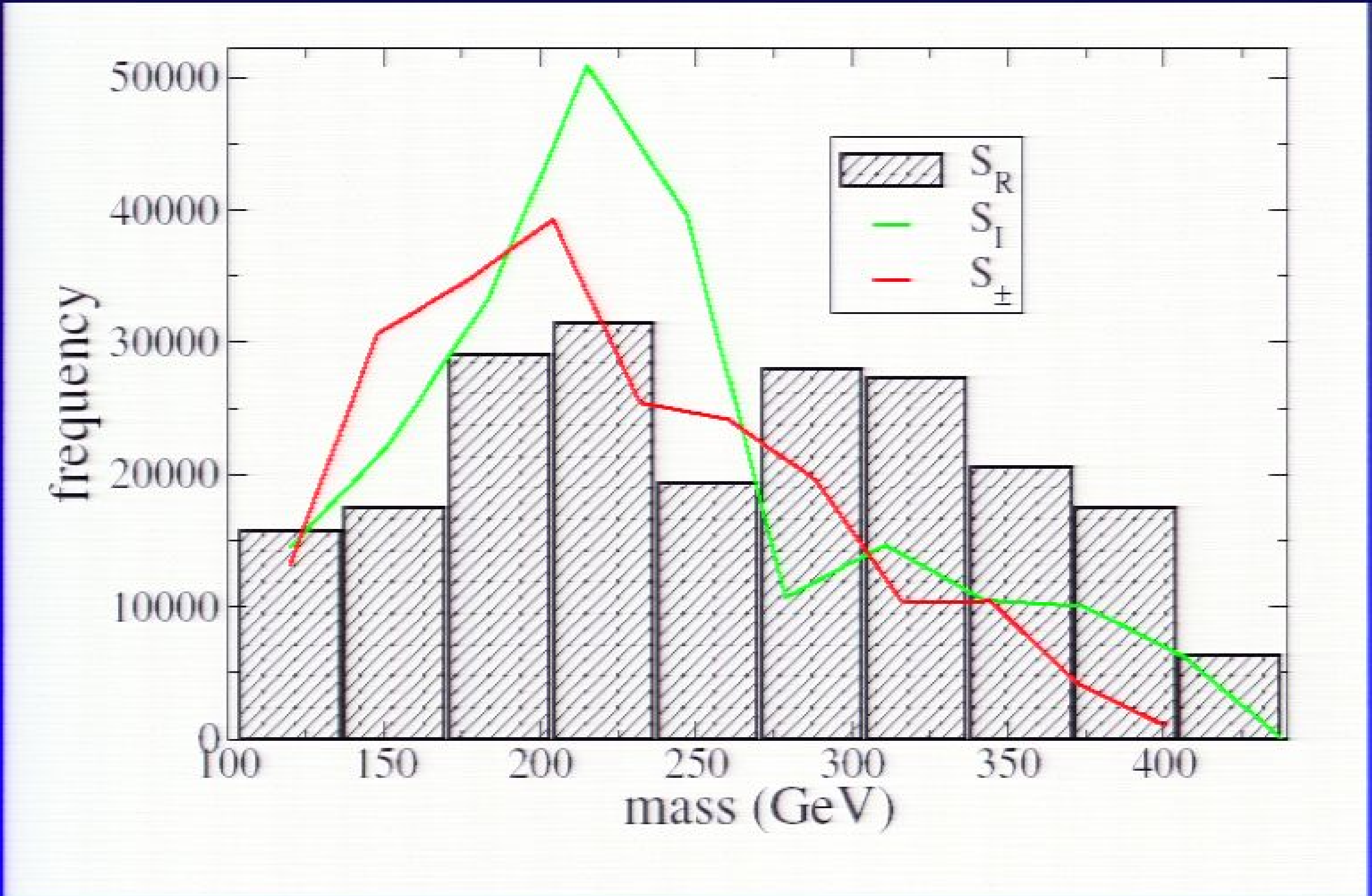

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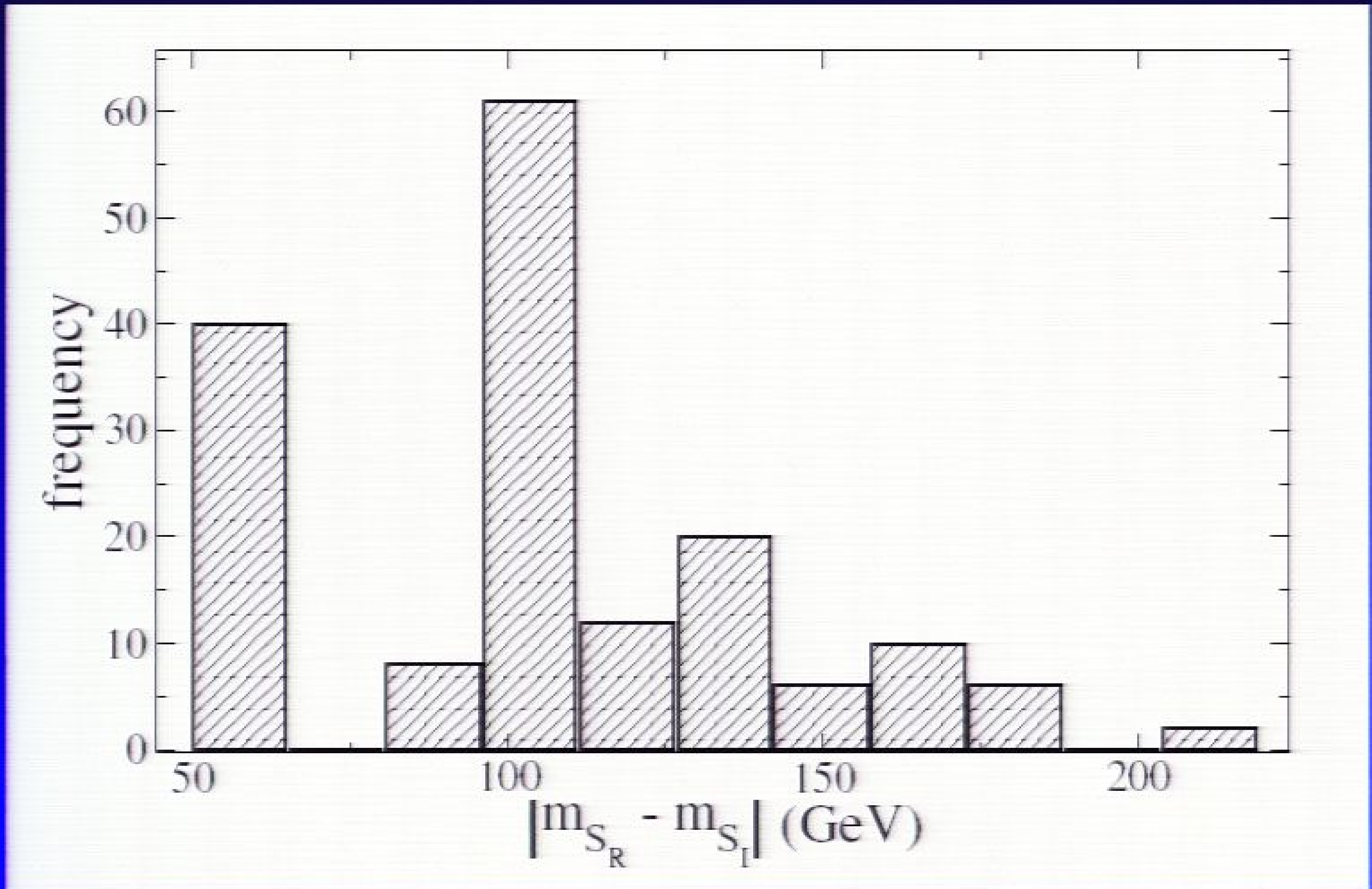

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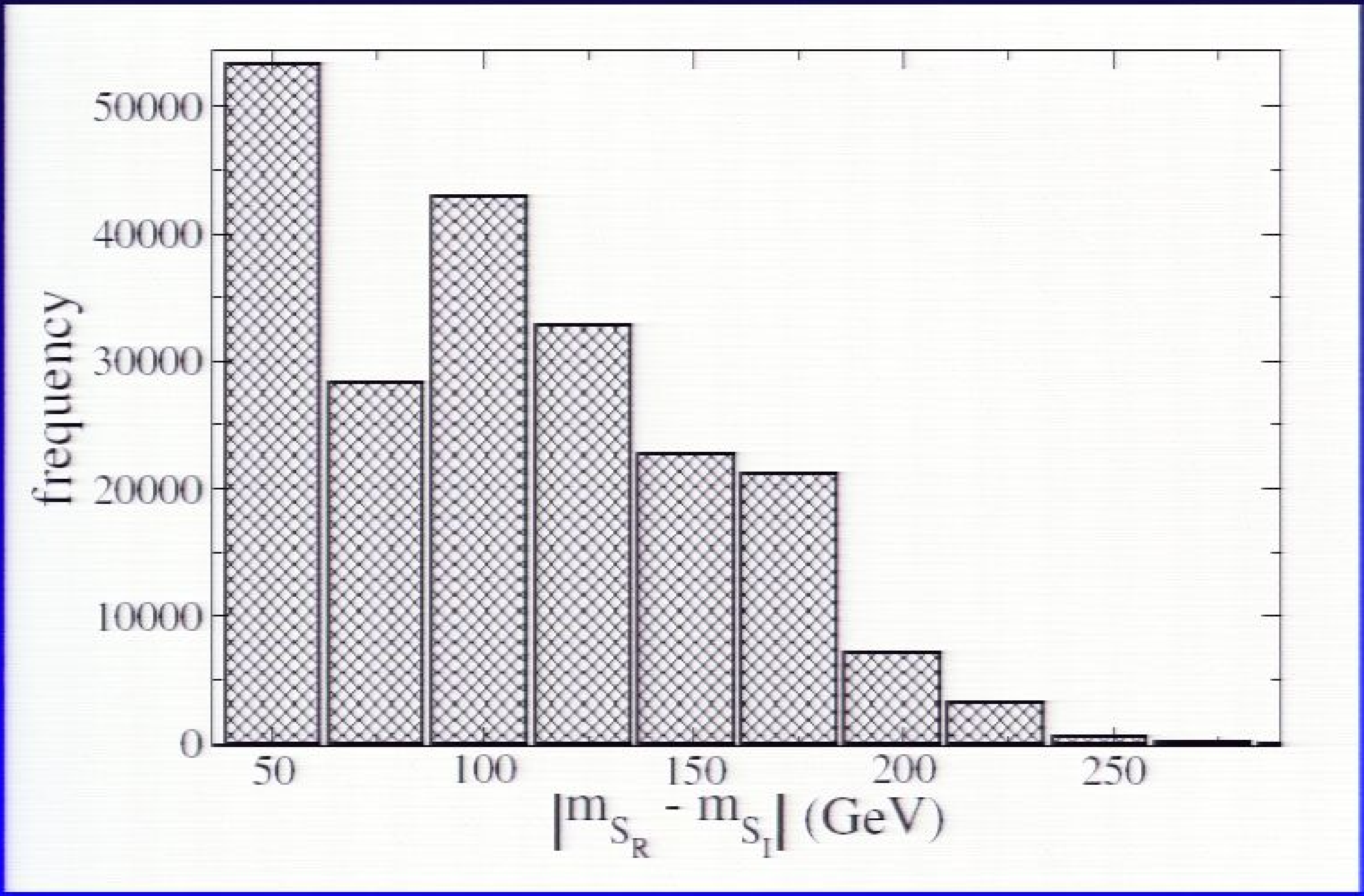

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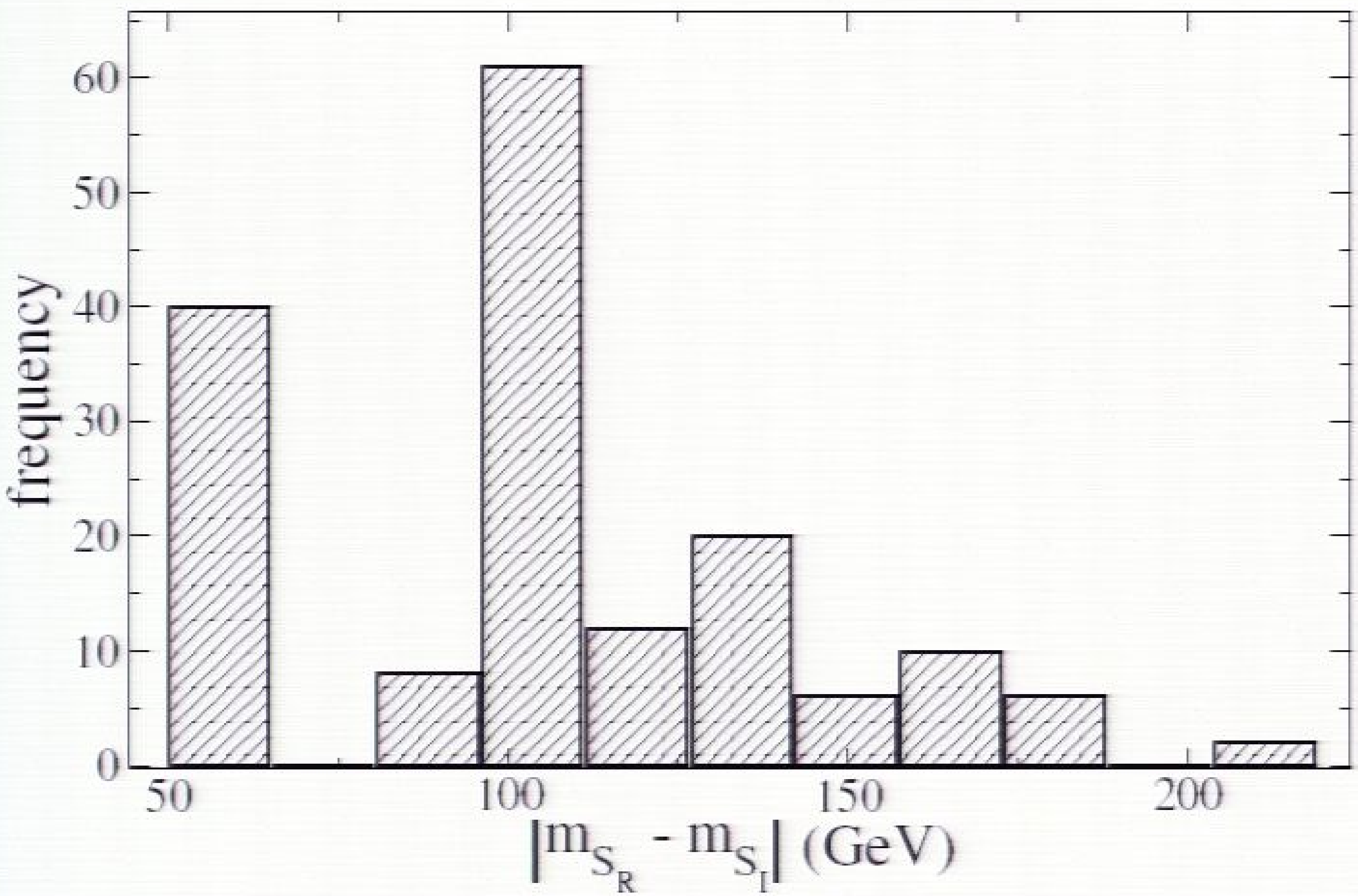

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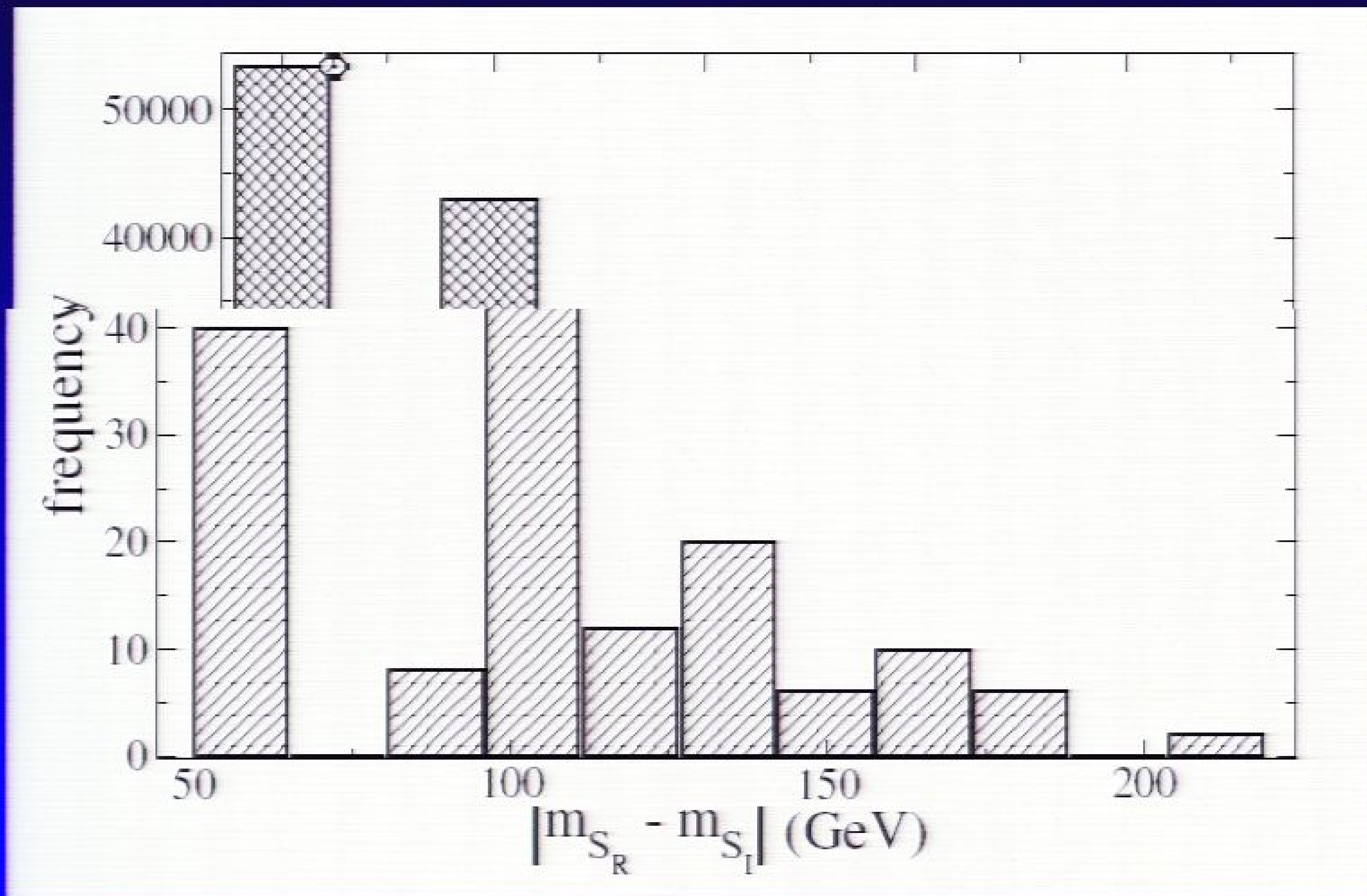

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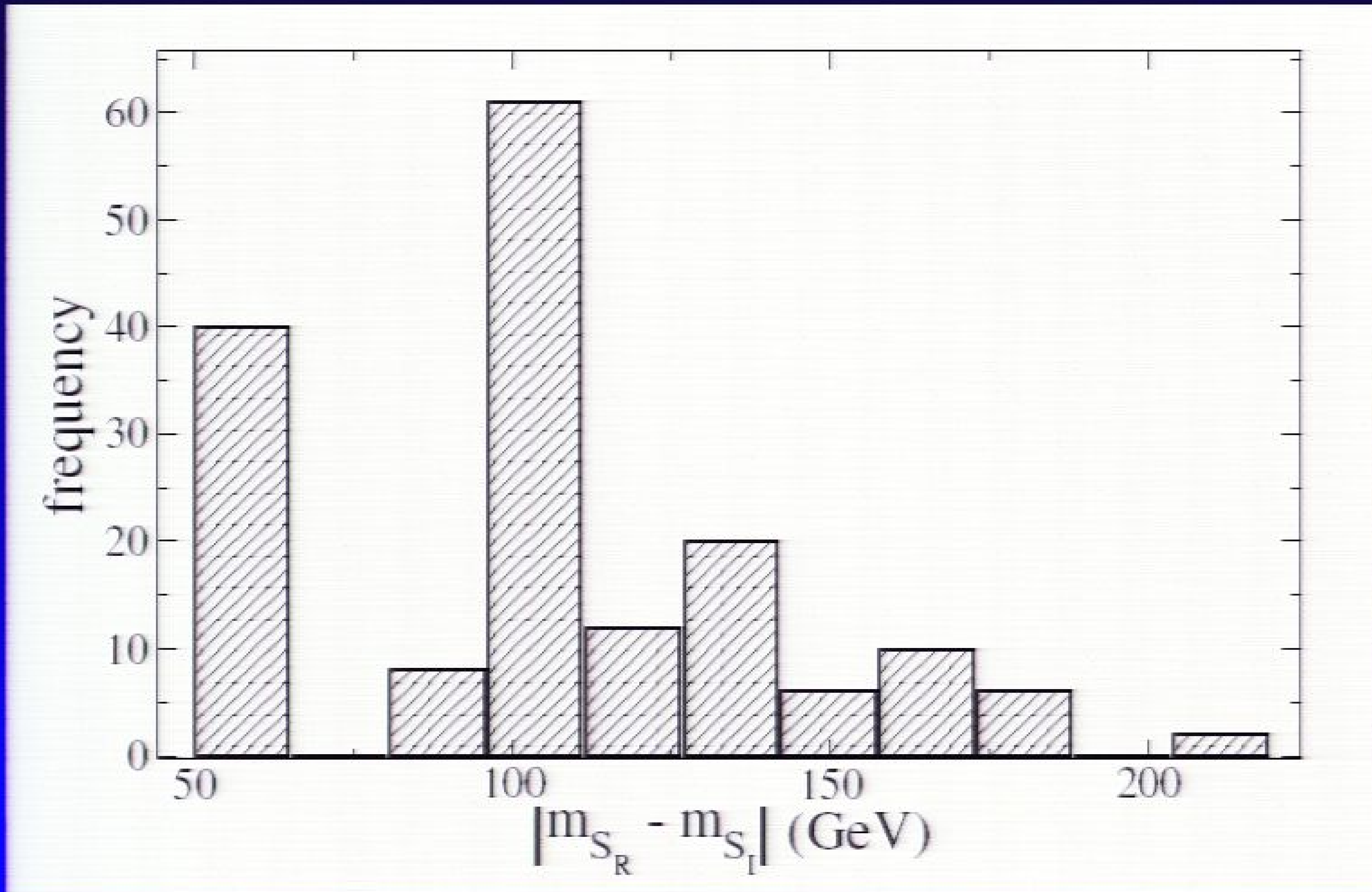

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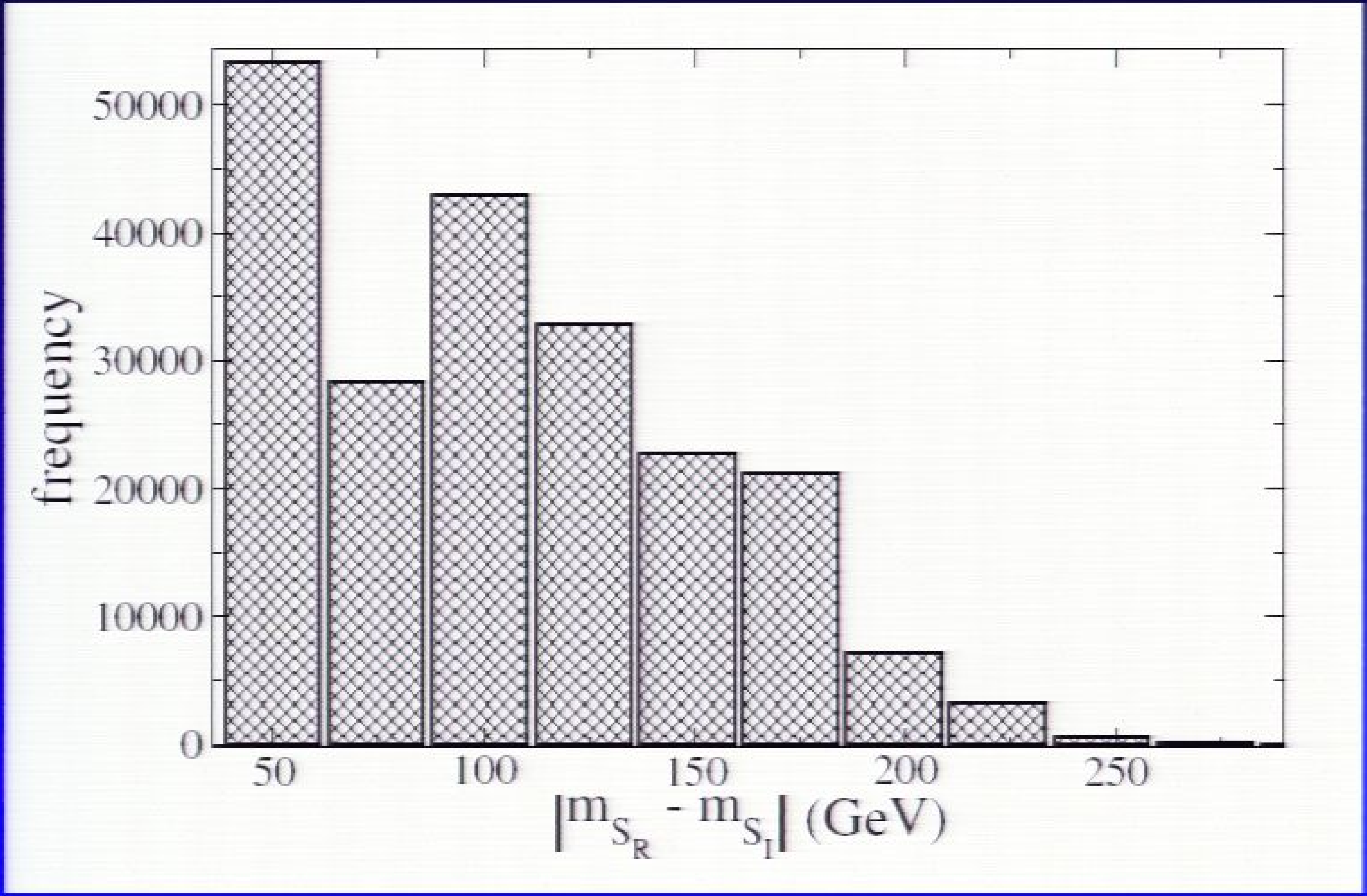

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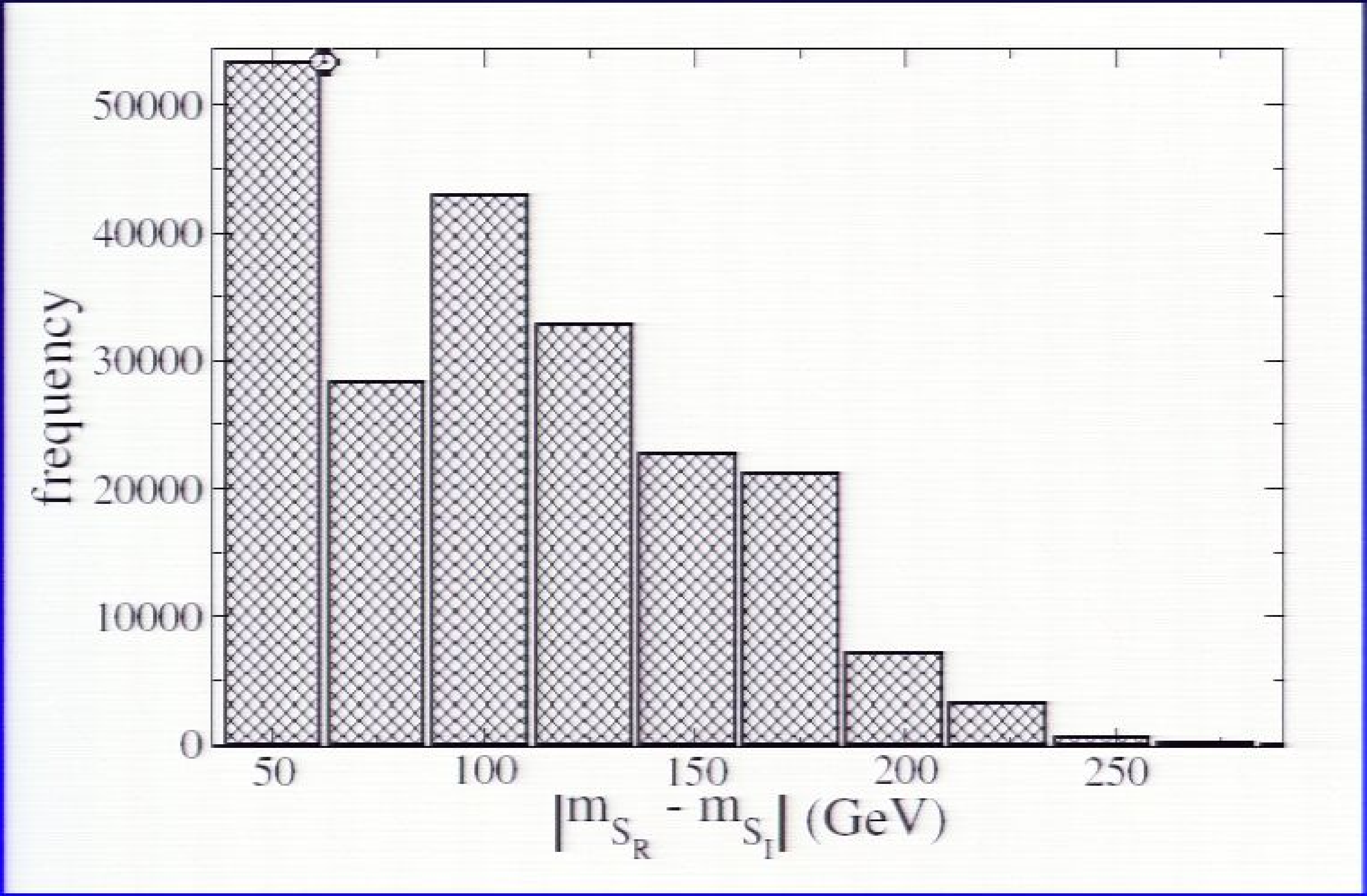

Collider signatures

Parameter η'_D is large, $\sim 5 - 10$; appears in

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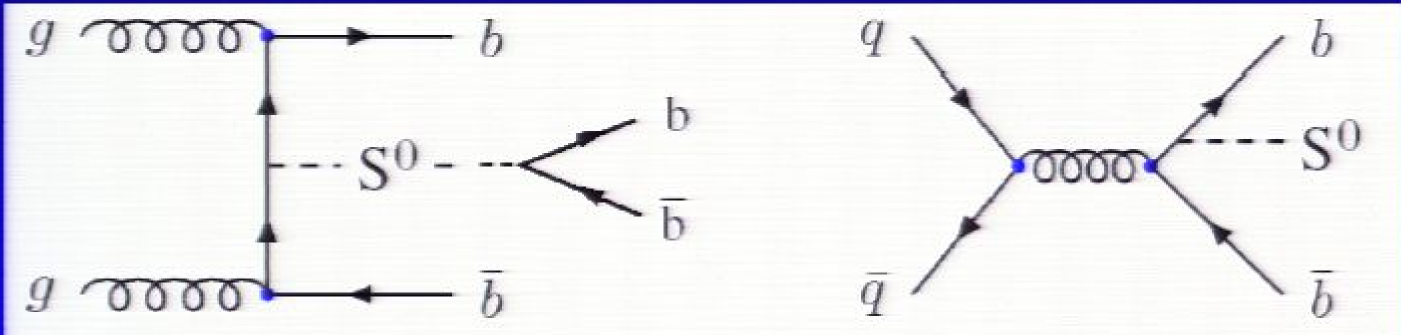

adapted from Dawson et al., hep–ph/0508293

Resulting $4b$ events have higher p_T, lower rapidity than SM background, plus resonance in one $b\bar{b}$ pair.

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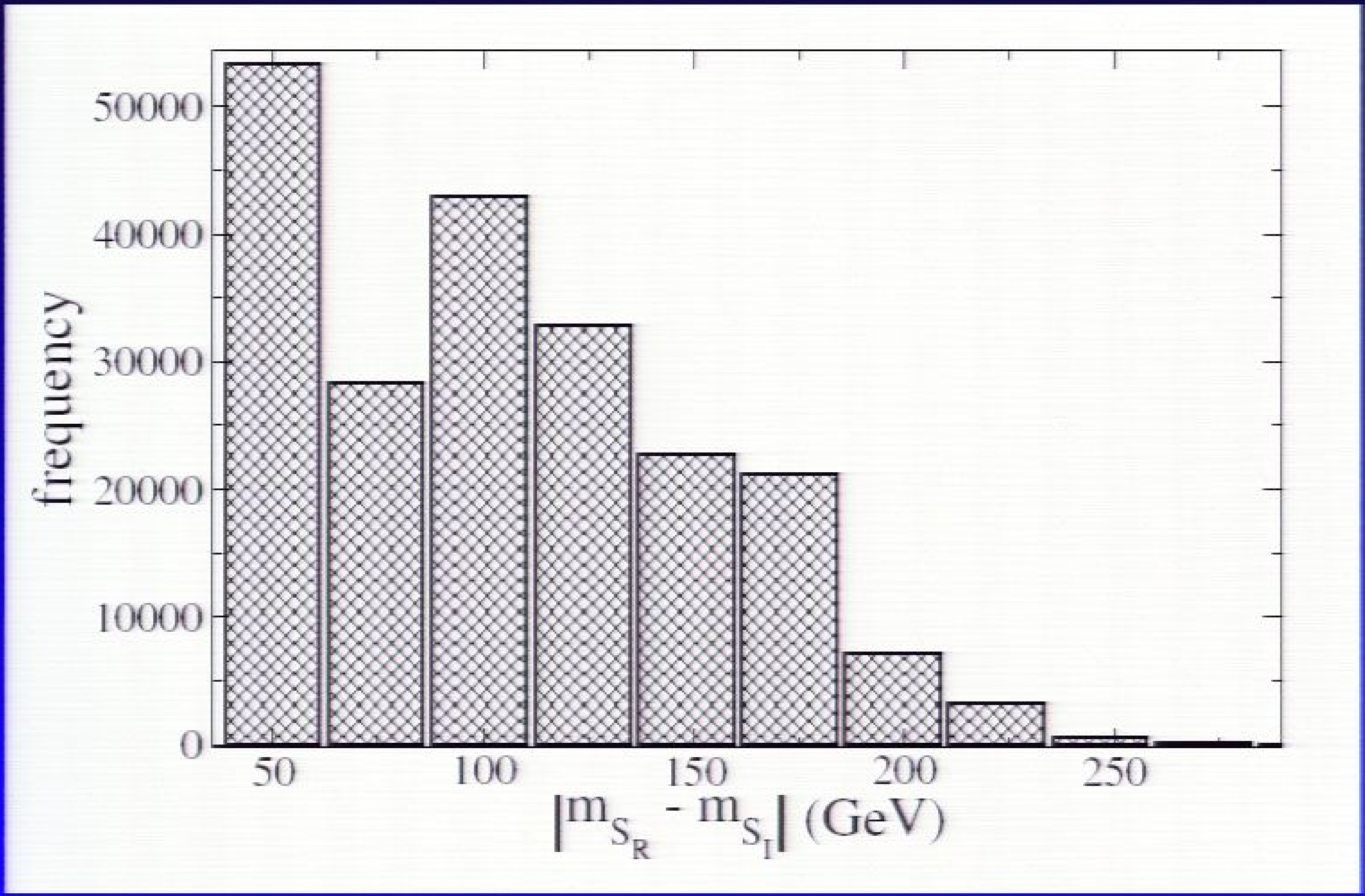

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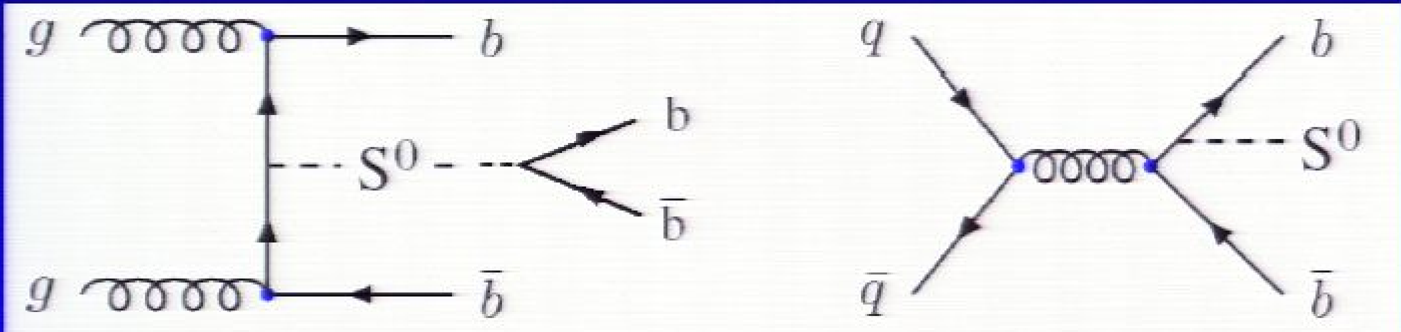

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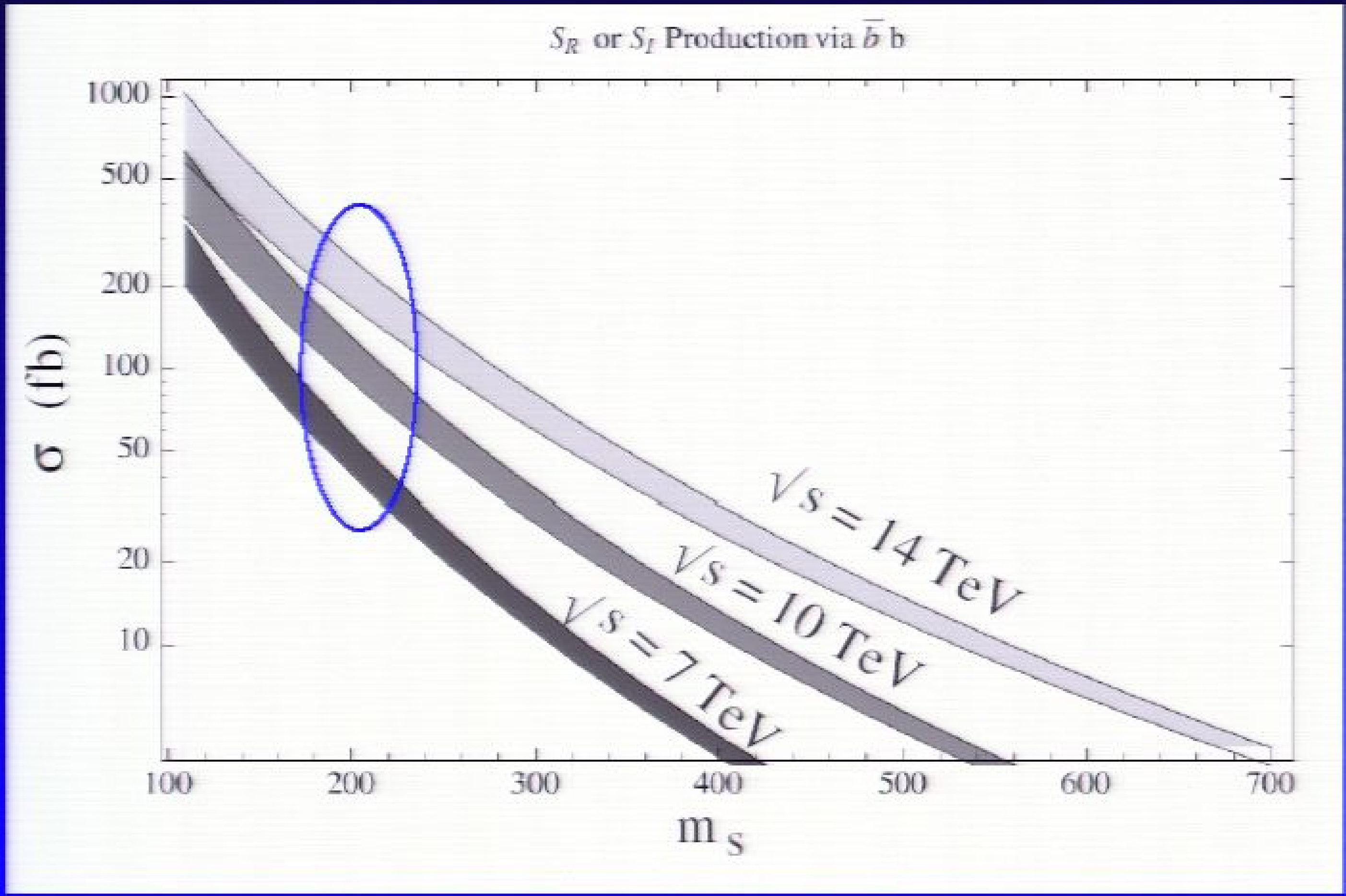
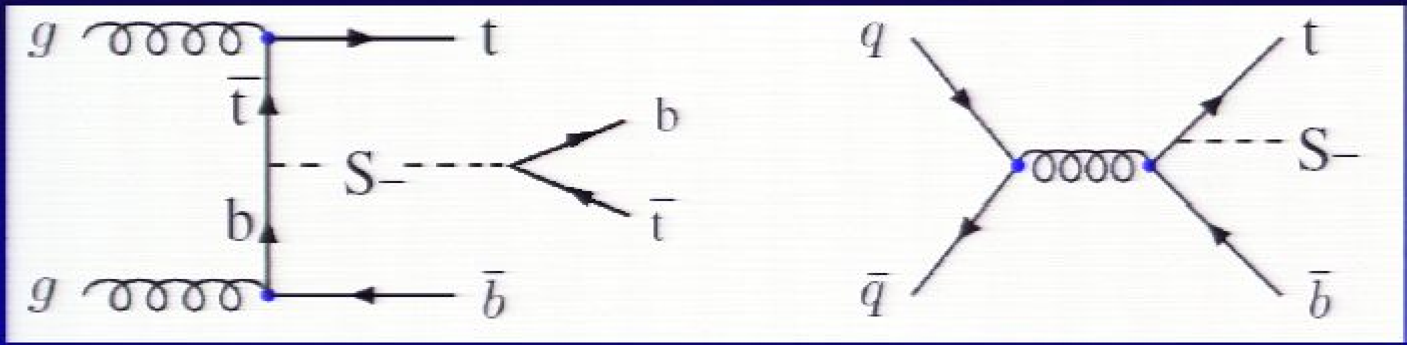
S^0 production cross section

From Trott & Wise (1009.2813)



$2b$-$2t$ events

We also predict production of $t\bar{b} + S_-$



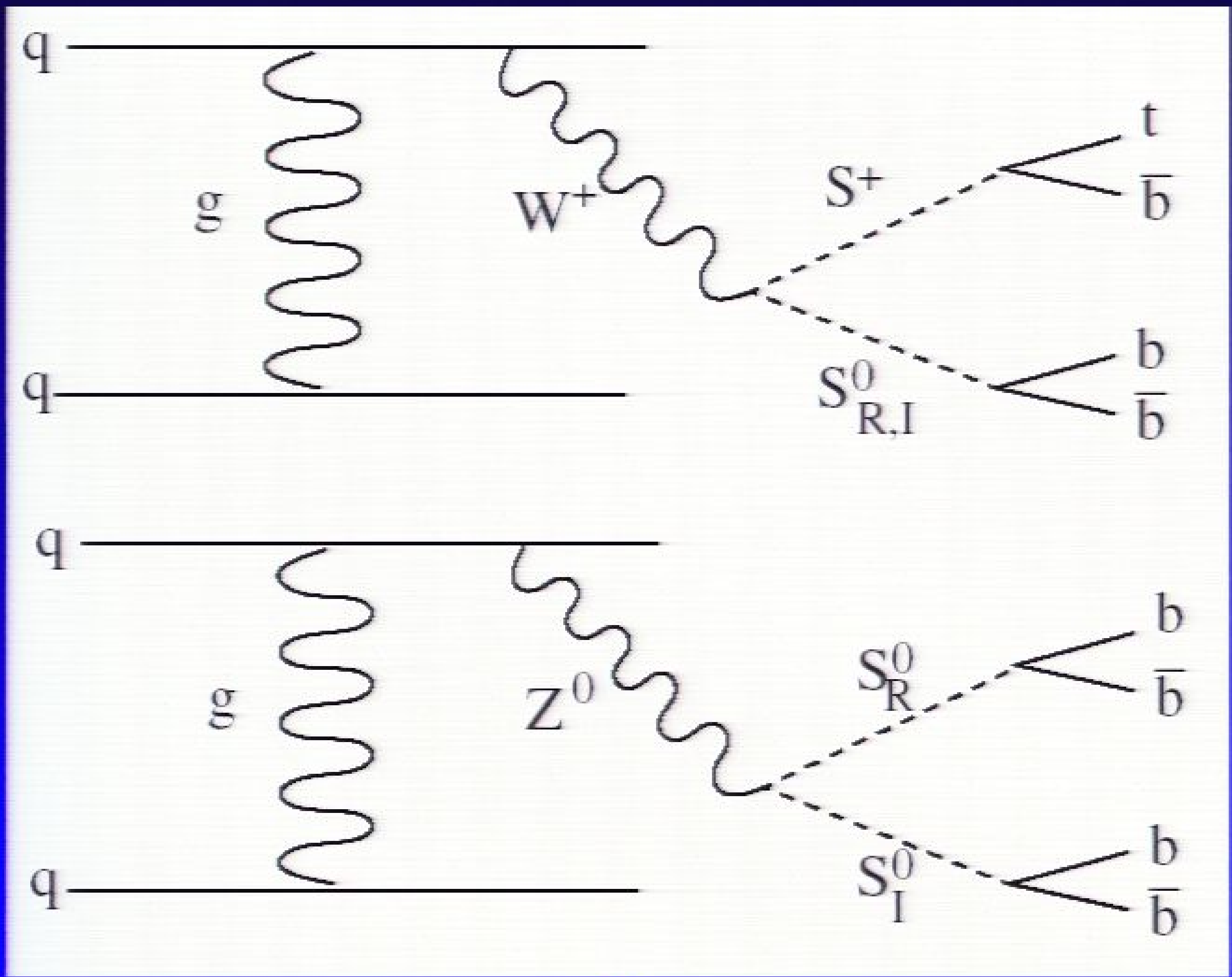
followed by $S_- \to b\bar{t}$.

Is this as promising as $4b$ channel, or more so?

Is production cross section greatly suppressed?

Production via W, Z

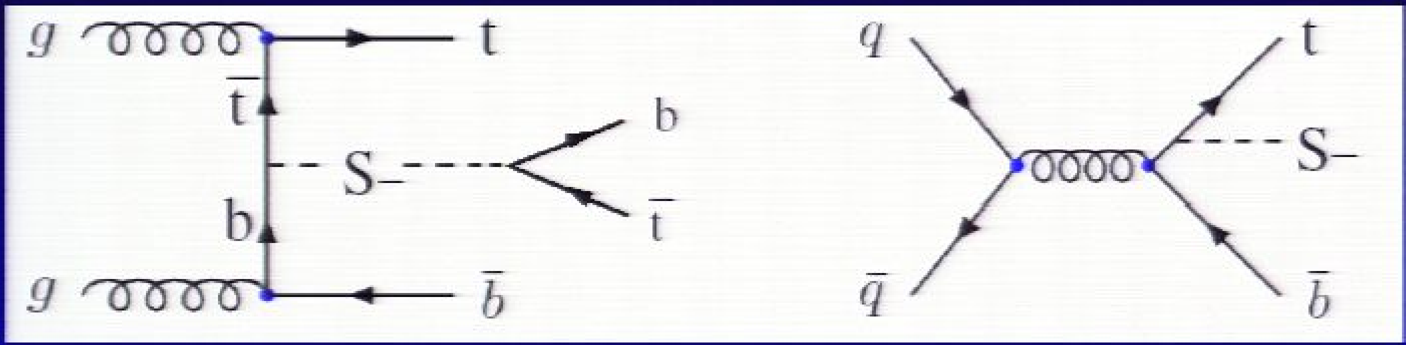
What about



?

$2b$-$2t$ events

We also predict production of $t\bar{b} + S_-$



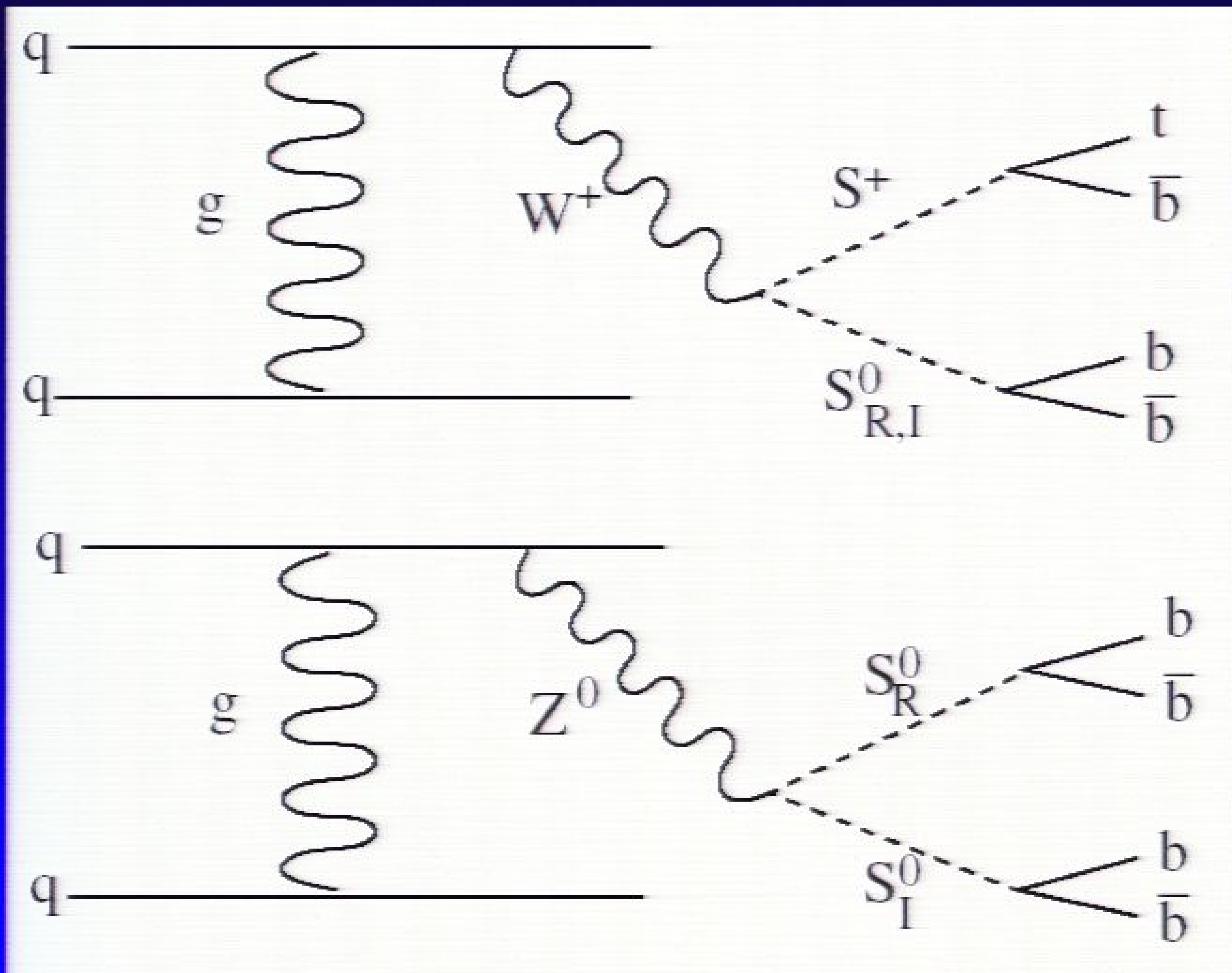
followed by $S_- \to b\bar{t}$.

Is this as promising as $4b$ channel, or more so?

Is production cross section greatly suppressed?

Production via W, Z

What about



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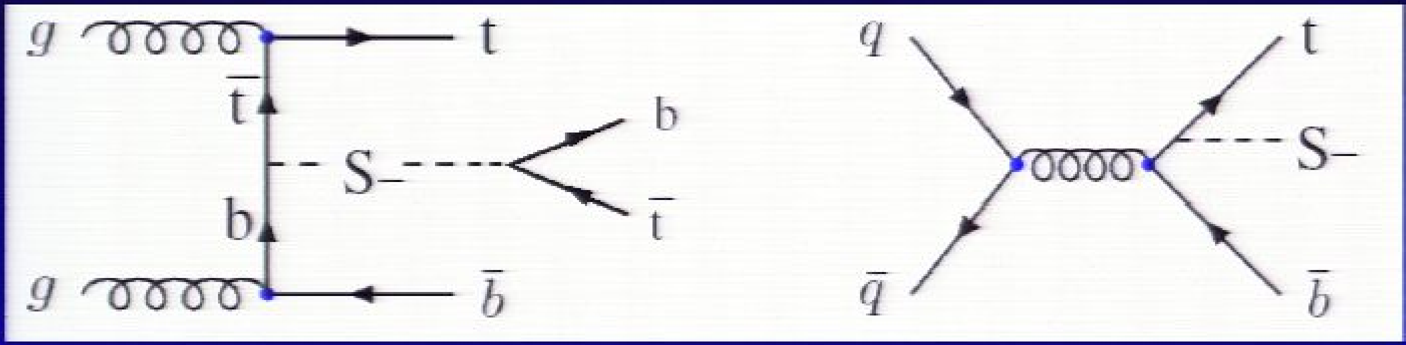

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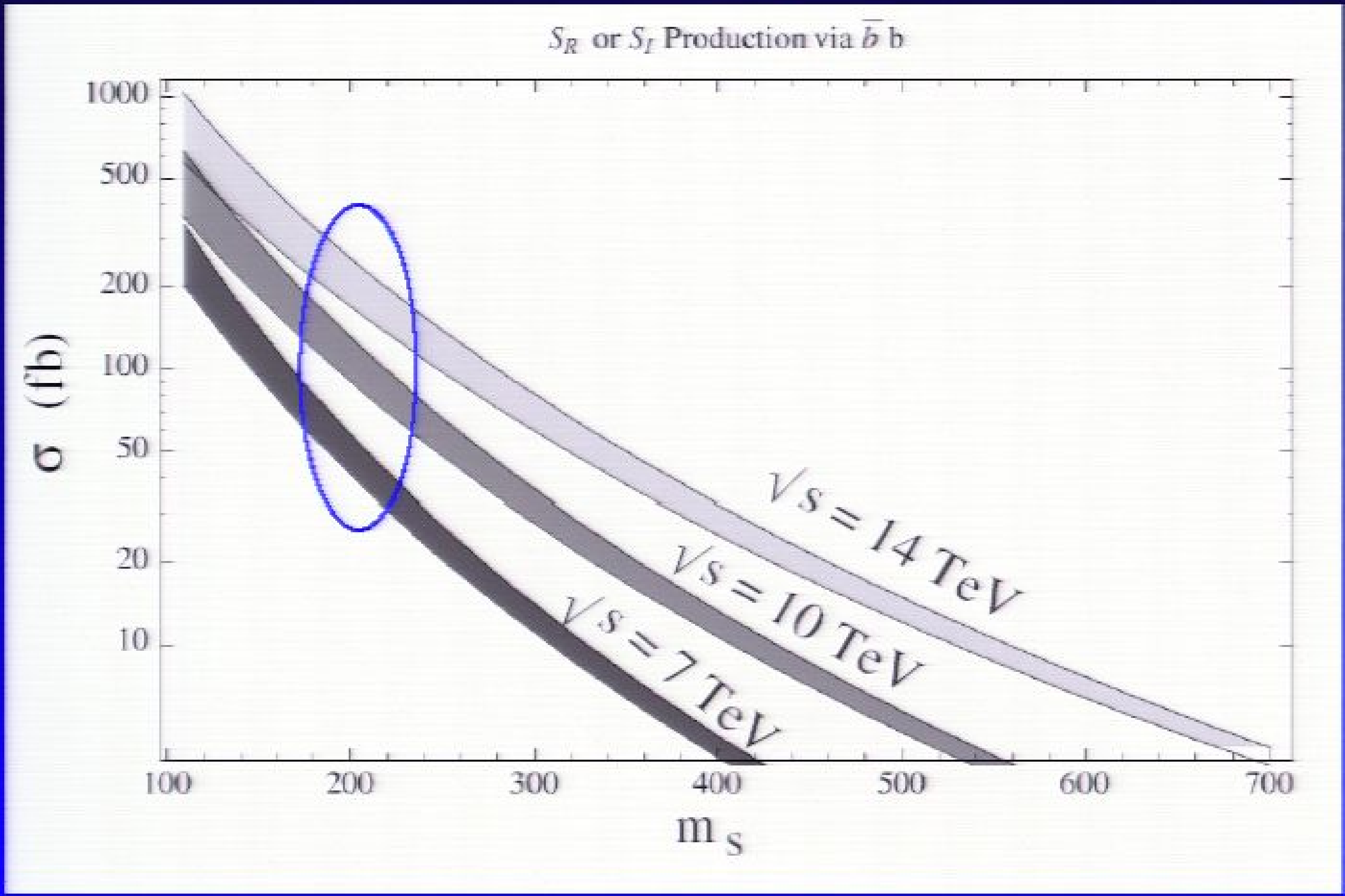
S^0 production cross section

From Trott & Wise (1009.2813)

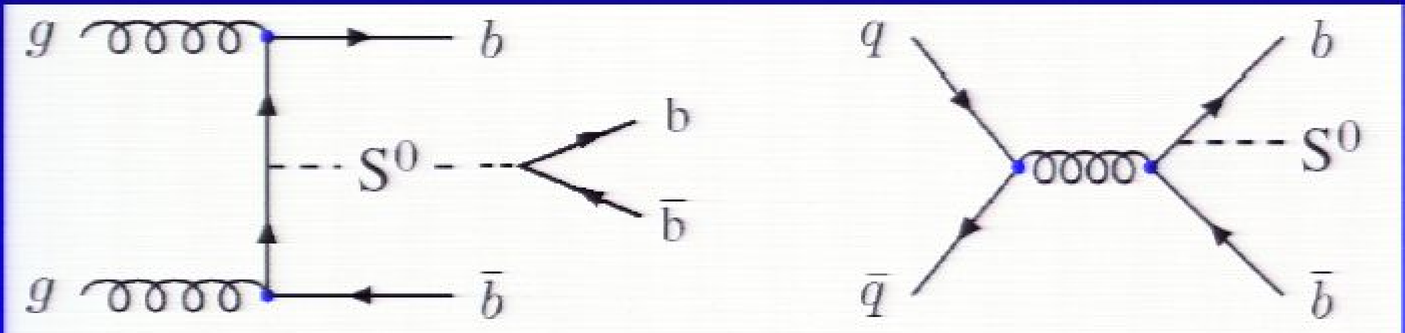


Collider signatures

Parameter η'_D is large, $\sim 5-10$; appears in

$$\eta'_D y_b \, \bar{b} Q S^\dagger$$

Trott & Wise (1009.2813) suggest collinear gluon splitting + b quark fusion, followed by $S^0 \to b\bar{b}$, as main discovery channel at LHC.



adapted from Dawson et al., hep–ph/0508293

Resulting $4b$ events have higher p_T, lower rapidity than SM background, plus resonance in one $b\bar{b}$ pair.

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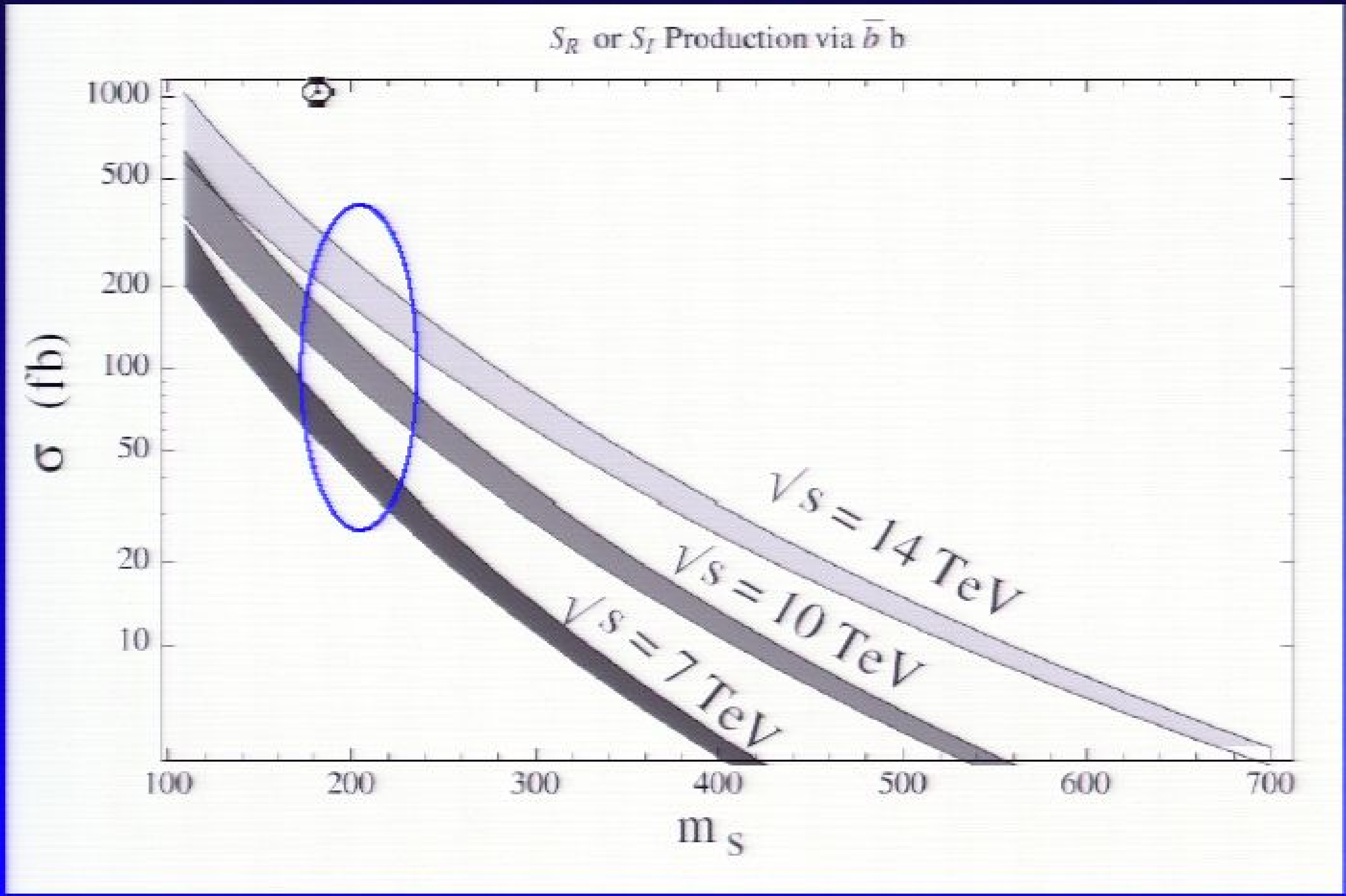


The challenge of baryogenesis

So far we only included necessity of strong phase transition, $\langle h\rangle/T_c > 1$.

Getting enough baryogenesis is even more rare.

Case study that yields observed baryon asymmetry:

$$m_h = 115,\ m_{S_R} = 318,\ m_{S_I} = 201,\ m_\pm = 219 \text{ GeV}$$

Baryogenesis is sensitive to values of

$$\lambda_4 = 0.23I, \quad \lambda_5 = 0, \quad \eta_U = 0.125$$

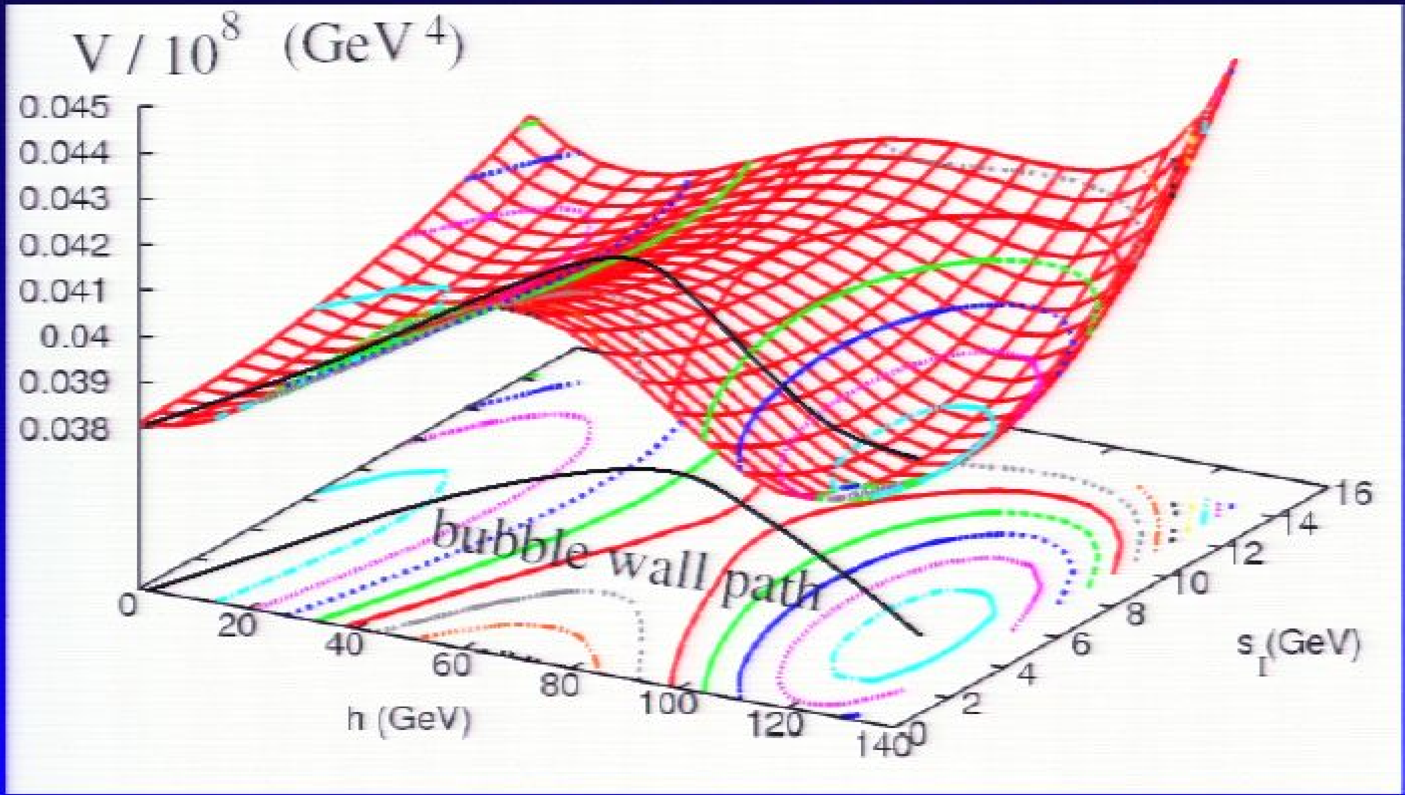
which impact complex t quark mass in bubble wall,

$$m_t(z) \cong \frac{y_t}{\sqrt{2}}\left(h(z) + \eta_U s(z)\right)$$

$\frac{d}{dz}\mathrm{Im}(m_t(z))$ must be nonnegligible in bubble wall.

Potential barrier + top mass phase

Phase of $m_t(z)$ comes from $\langle s_I(z) \rangle$ induced by $\mathrm{Im}(\lambda_4)$ in bubble wall: $\arg(m_t(z)) \sim \eta_U \, s_I(z)/h(z)$



We saturate $|\eta_U| \leq 0.125$, the 1-σ upper limit from R_b.

Tuning λ_4, λ_5, $\arg(\eta_U)$ gives barely large enough baryon asymmetry!

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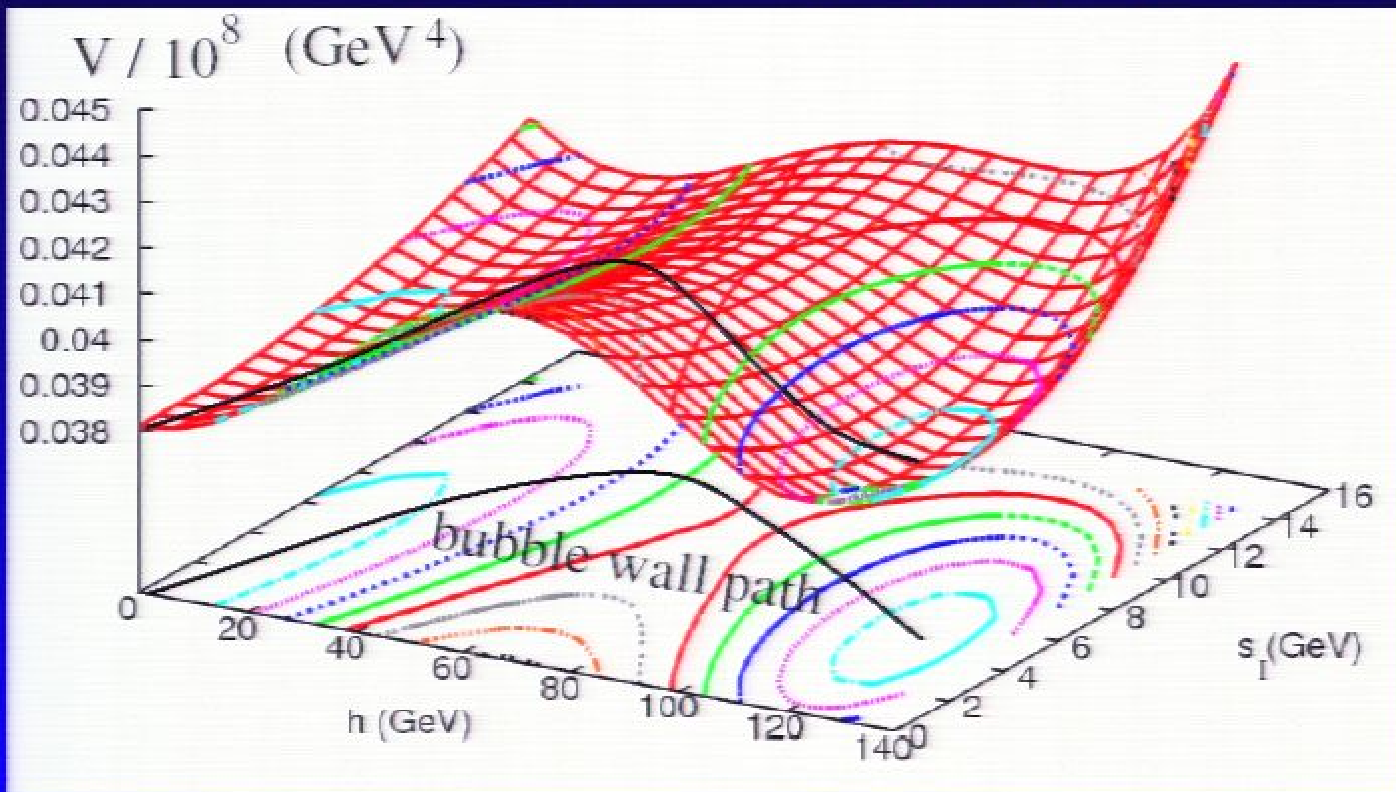

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Why is it so difficult?

Naively, increasing $\text{Im}(\lambda_5)$ increases $\text{Im}(m_t(z))$ in bubble wall, good for baryogenesis.

Nonzero λ_5 makes it easier to explain dimuon anomaly with smaller η'_D, good for R_b

$$C^{\rm NP}(m_t) = (\eta'_D)^2 \left(\frac{\sqrt{2}m_t}{v}\right)^4 \left[\frac{\lambda_3\, m_b^2}{m_S^4 - \lambda_3^2 v^4} + \frac{(\lambda_5^R)^2\, v^2\, m_b^2}{2\,(m_s^2 + \lambda_3\, v^2 - m_h^2)\,(m_s^4 - \lambda_3^2\, v^4)} + \frac{(\lambda_5^R)^2\, v^2\, m_b^2}{2\,(m_s^2 + \lambda_3\, v^2 - m_h^2)^2\, m_h^2}\right]$$
$$+ (\eta'_D)^2 \left(\frac{\sqrt{2}m_t}{v}\right)^4 \left[-\frac{(\lambda_5^I)^2\, v^2\, m_b^2}{2\,(m_s^2 - \lambda_3\, v^2 - m_h^2)\,(m_s^4 - \lambda_3^2\, v^4)} + \frac{(\lambda_5^I)^2\, v^2\, m_b^2}{2\,(m_s^2 - \lambda_3\, v^2 - m_h^2)^2\, m_h^2}\right].$$

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Integrating out S gives

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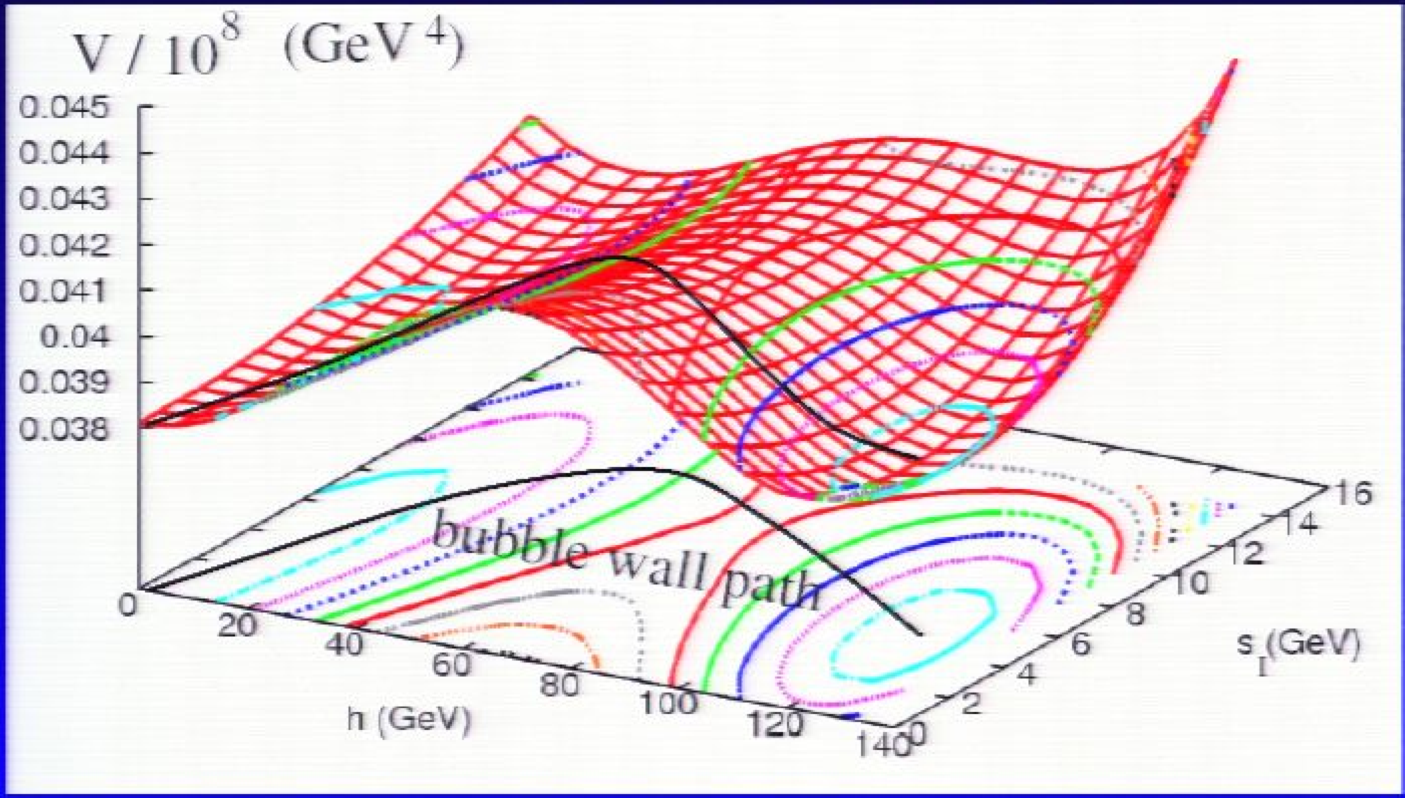

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Why is it so difficult?

Also, $\mathrm{Im}(m_t) \sim \eta_U$ must be small due to neutron EDM and R_b constraints

Further challenges

Baryon asymmetry depends on network of Boltzmann equations for all species of particles near bubble wall

(Fromme, Huber, Seniuch, hep-ph/0605242)

$$
\begin{aligned}
3v_w K_{1,t}\mu'_{t,2} + 3v_w K_{2,t}(m_t^2)'\mu_{t,2} + 3u'_{t,2} \\
-3\Gamma_y(\mu_{t,2} + \mu_{t^c,2} + \mu_{h,2}) - 6\Gamma_m(\mu_{t,2} + \mu_{t^c,2}) - 3\Gamma_W(\mu_{t,2} - \mu_{b,2}) \\
-3\Gamma_{ss}[(1 + 9K_{1,t})\mu_{t,2} + (1 + 9K_{1,b})\mu_{b,2} + (1 - 9K_{1,t})\mu_{t^c,2}] &= 0
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source term, $\theta = \text{Im}(m_t)$:

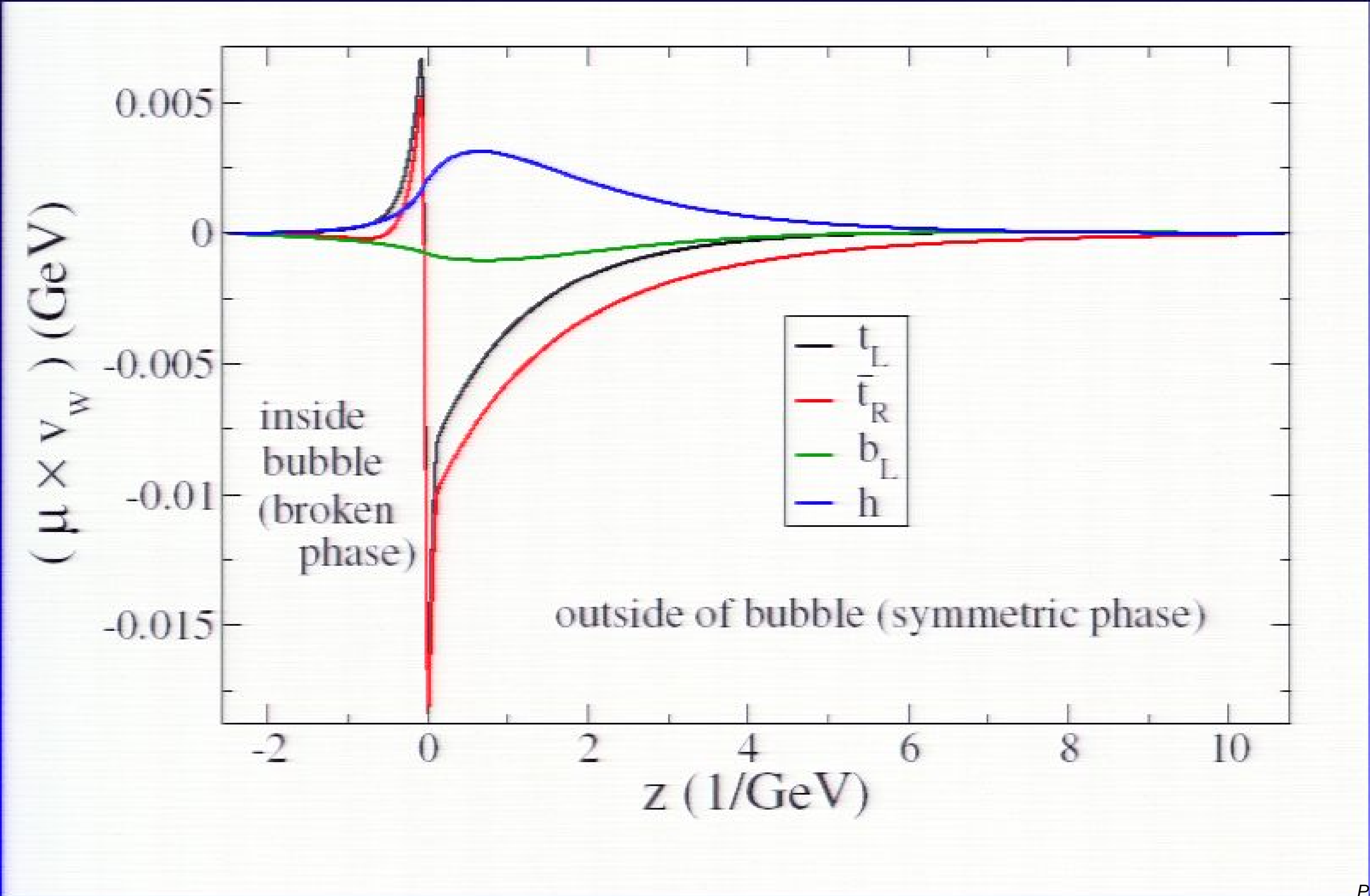
$$S_t = -v_w K_8(m_t^2\theta'_t)' + v_w K_9\theta'_t m_t^2(m_t^2)'.$$

To simplify network, FHS follow t_L, t_R, b_L, h (assuming all Higgses have same asymmetry).

Results depend upon how many species are explicitly followed; investigation in progress.

Solution of Boltzmann equations

Chemical potentials for t_L, $\bar{t}_R$, b_L, h near bubble wall:



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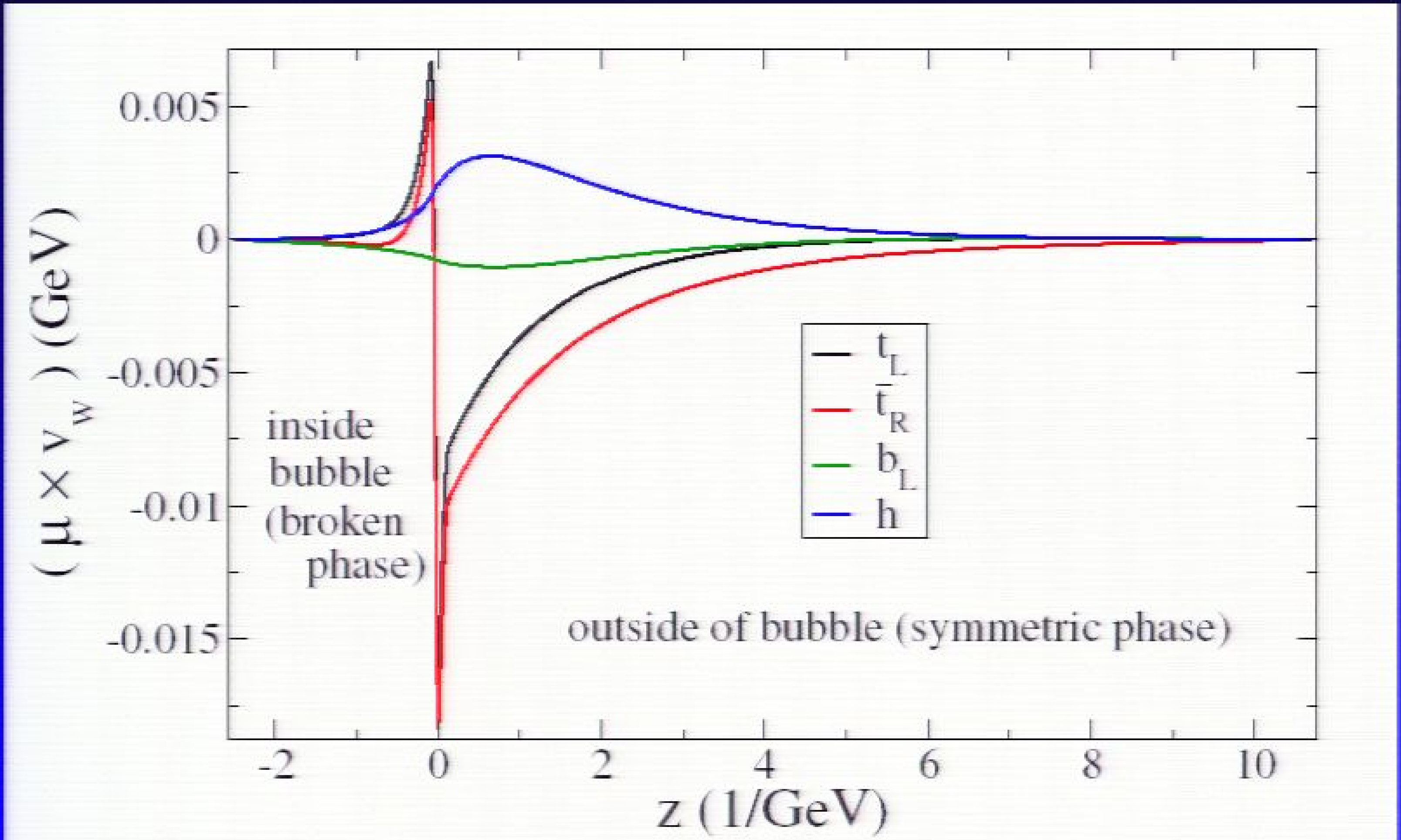

Summary

- MFV 2HDM gives good account of new CP violation indicated in B mixing from DØ dimuons and deviations in $B_s \to J/\psi\,\phi$ and $B^- \to \tau\nu$.

- Same model can give baryogenesis; highly constrained.

- Unfortunately new phase in B mixing is not the one responsible for baryogenesis; model has 6 new $\not{CP}$ phases.

- η_U should be as large as possible; more sensitive measurements of R_b might see a deviation

- Predict light Higgs and new Higgses $m_{S_I,S_R} \lesssim 450$ GeV, $m_\pm \lesssim 300$ GeV; these may become sharper

- $4b$ or $2b$-$2t$ discovery channels possible for LHC