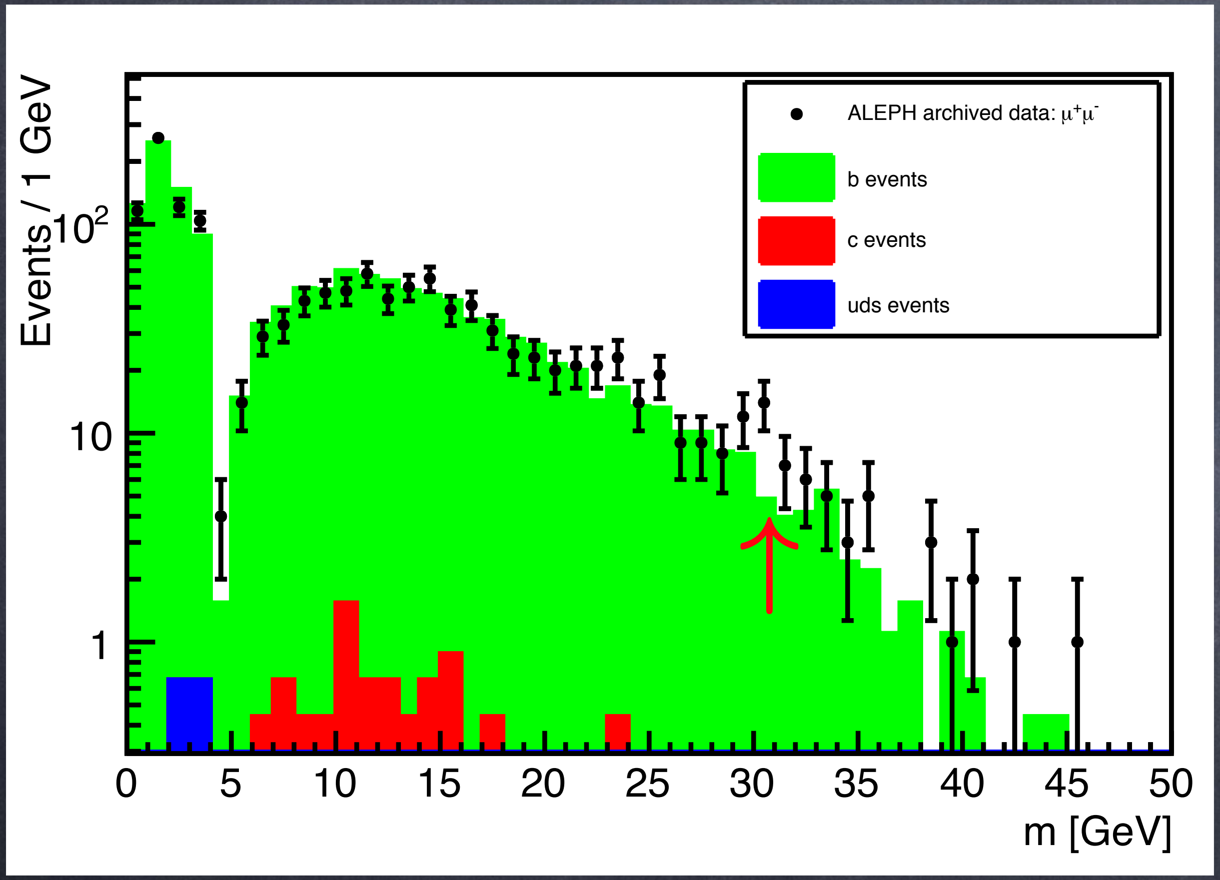
The 30 GeV Dimuon at ALEPH

Kenneth Lane, with Lukas Pritchett
Boston University

- The ALEPH data
- The 2HDM model
- The two options
- The predictions
- The fly in the ointment

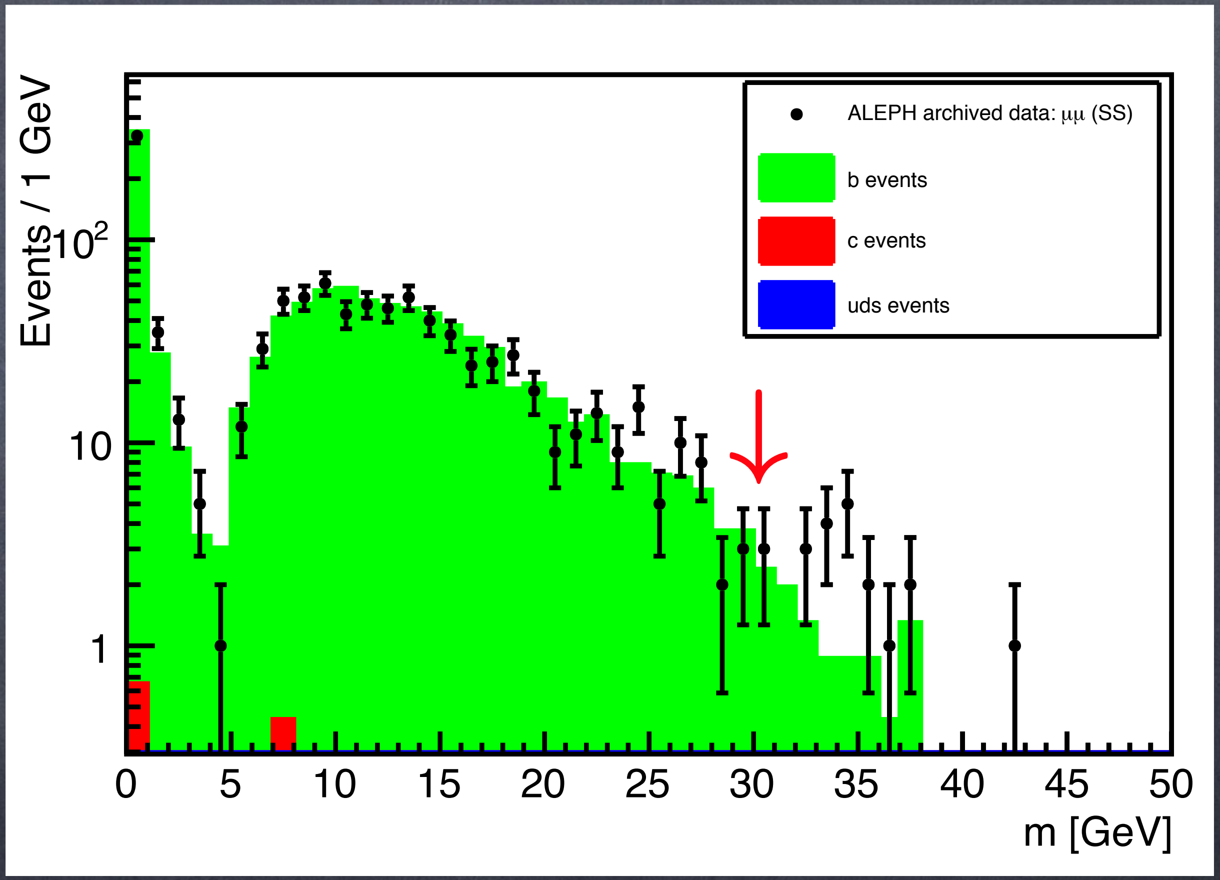
The ALEPH data

From A. Heister, "Observation of an excess at 30 GeV in the opposite sign di-muon spectra of $Z \to b\bar{b} + X$ events by the ALEPH detector at LEP", arXiv:1610.06536



opposite-sign $M_{\mu\mu}$

(from arXiv:1610.06536)



same-sign $M_{\mu\mu}$

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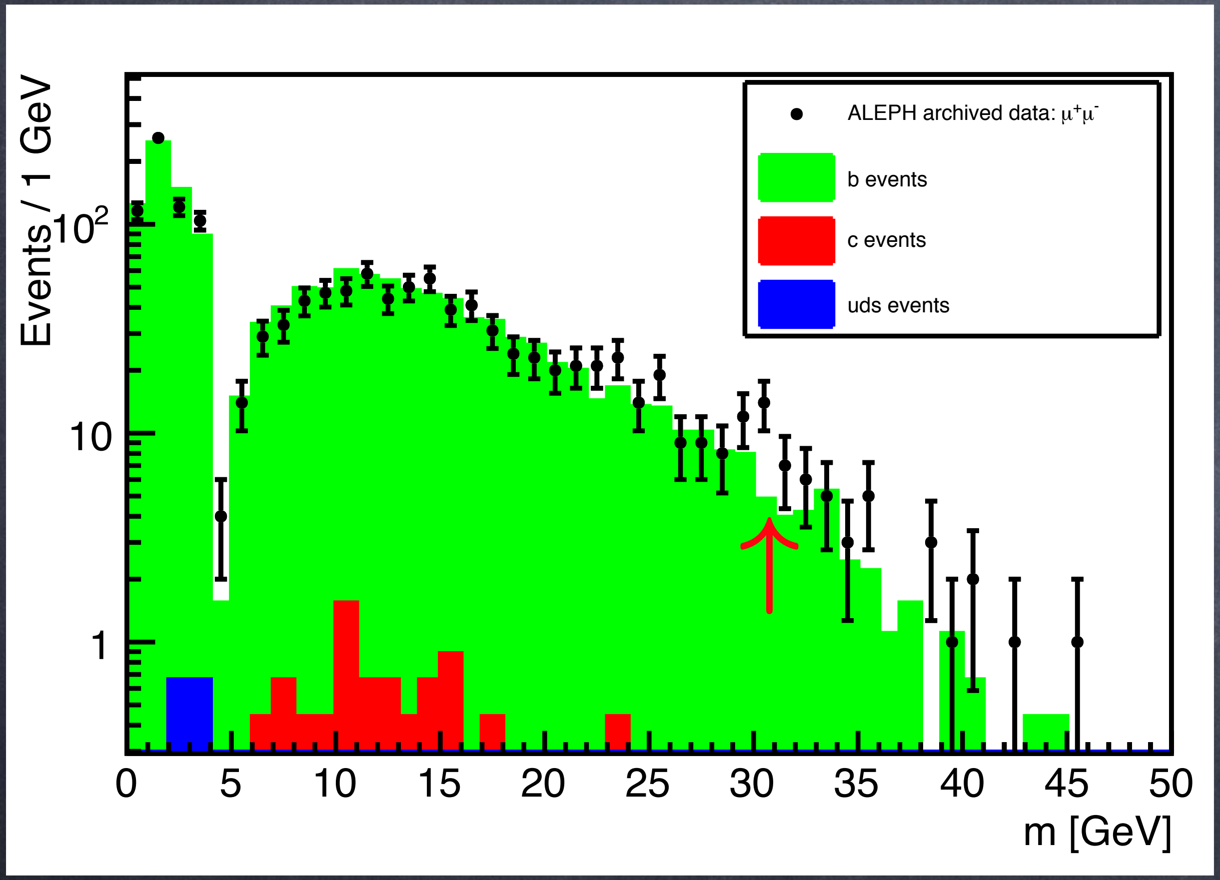
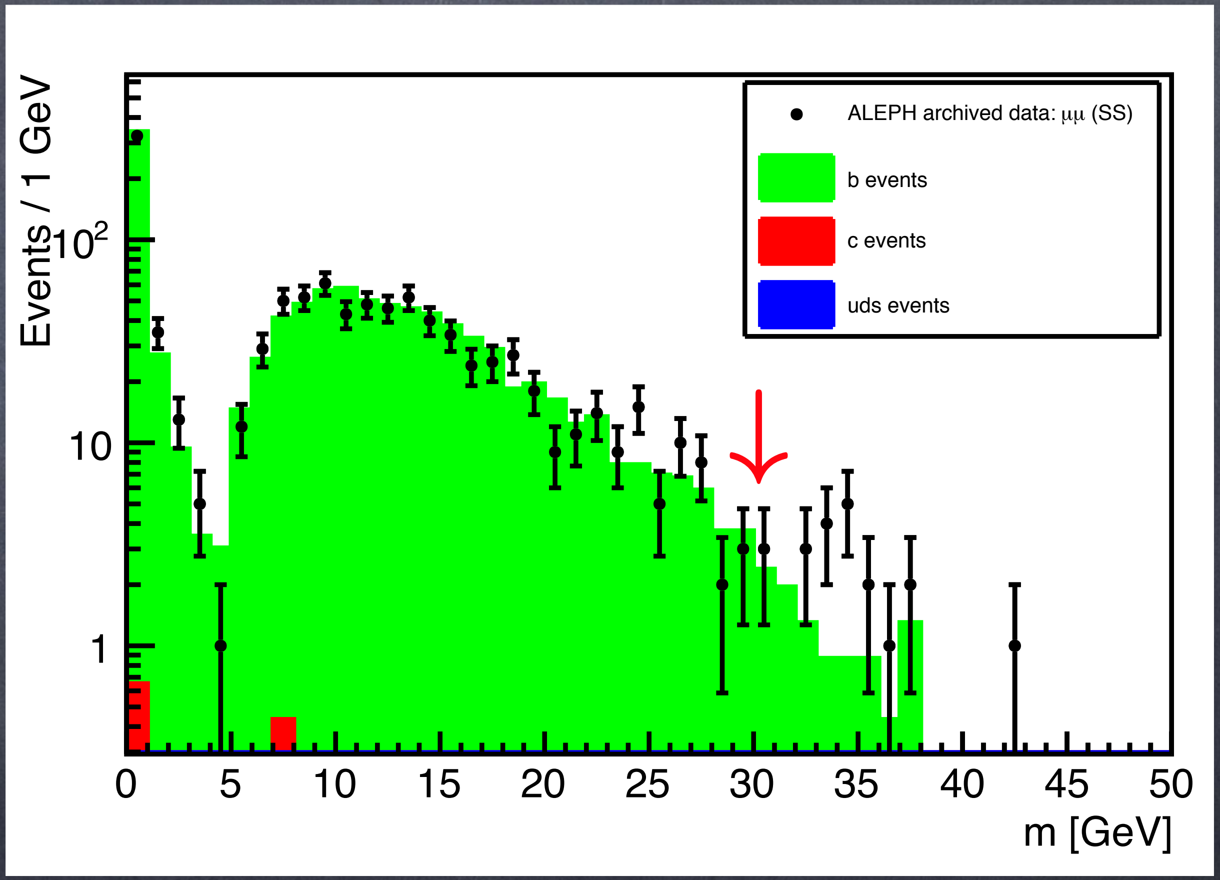


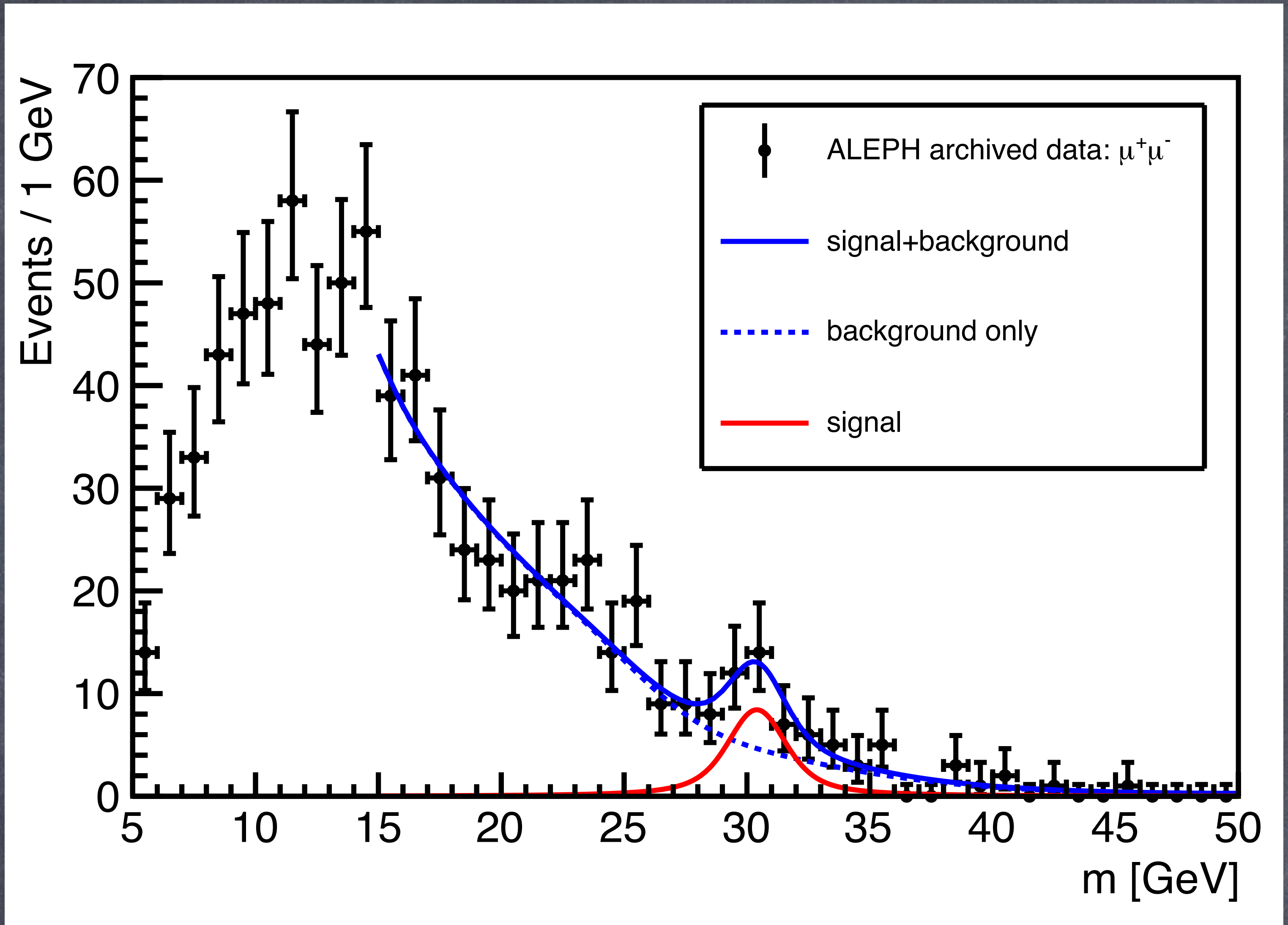


opposite-sign $M_{\mu\mu}$

same-sign $M_{\mu\mu}$

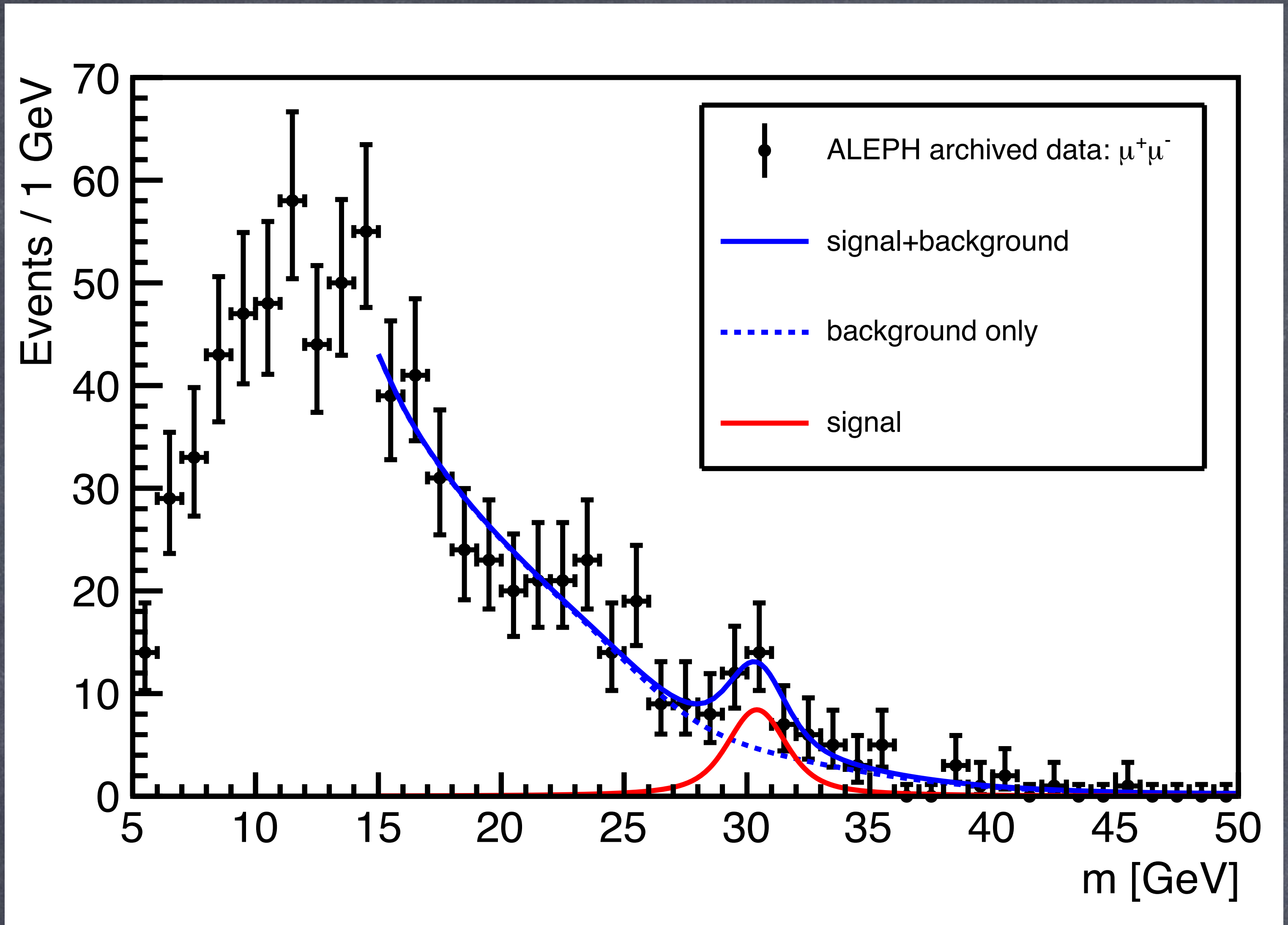
NO MC reproduces this excess!

(from arXiv:1610.06536)



Signal + background model used to extract signal parameters (from arXiv:1610.06536)

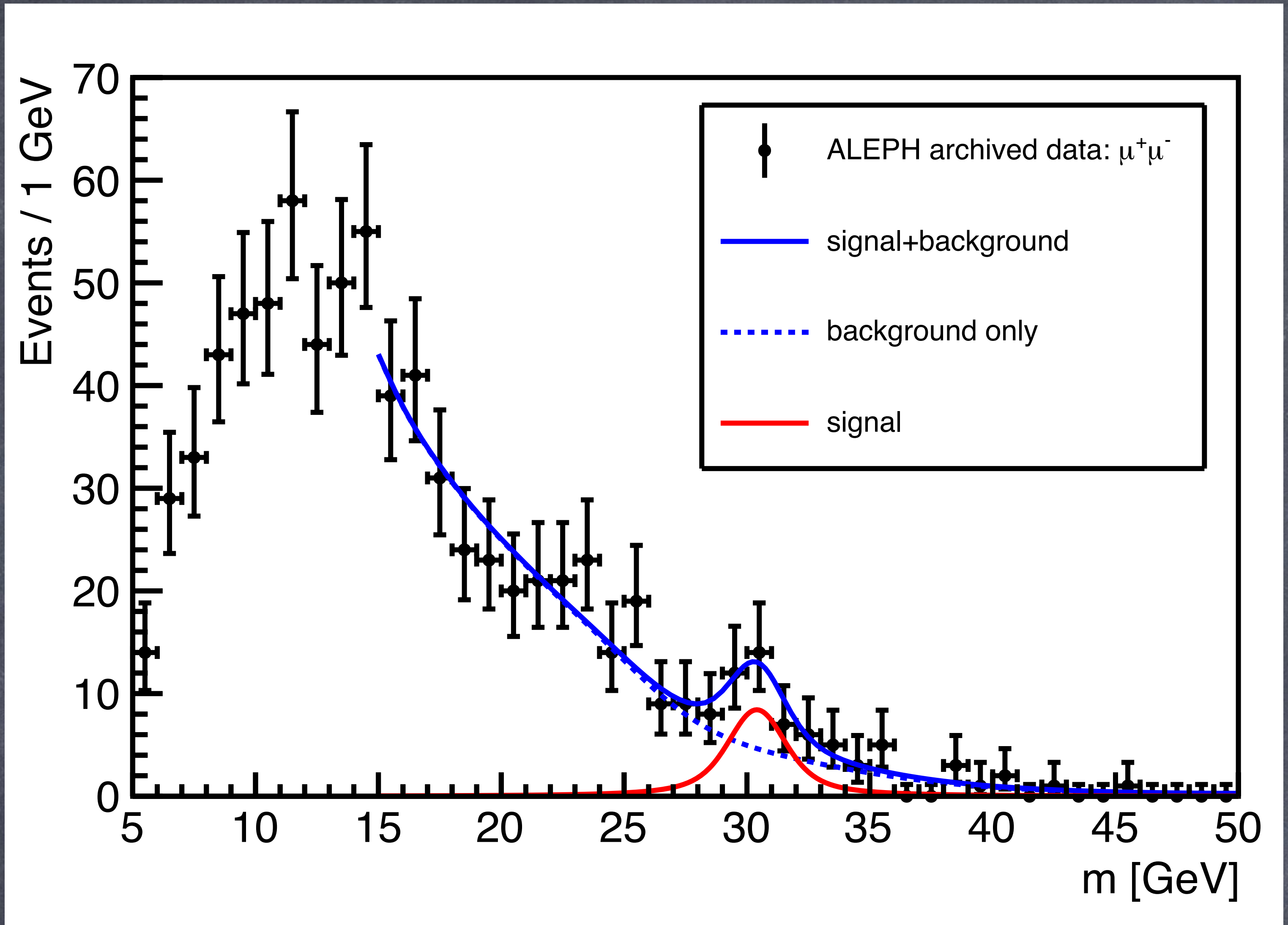
$\mathbf{32 \pm 11}$ **events, significance** $\simeq \mathbf{3}\,\boldsymbol{\sigma}$ (from statistical tools)



Signal + background model used to extract signal parameters (from arXiv:1610.06536)

$$\mathbf{32 \pm 11 \text{ events}, \ \ significance \ \simeq 3\,\sigma}$$

Natural width is (1.78 ± 1.14) GeV, IOW, consistent with zero (again, see 1610.06536)



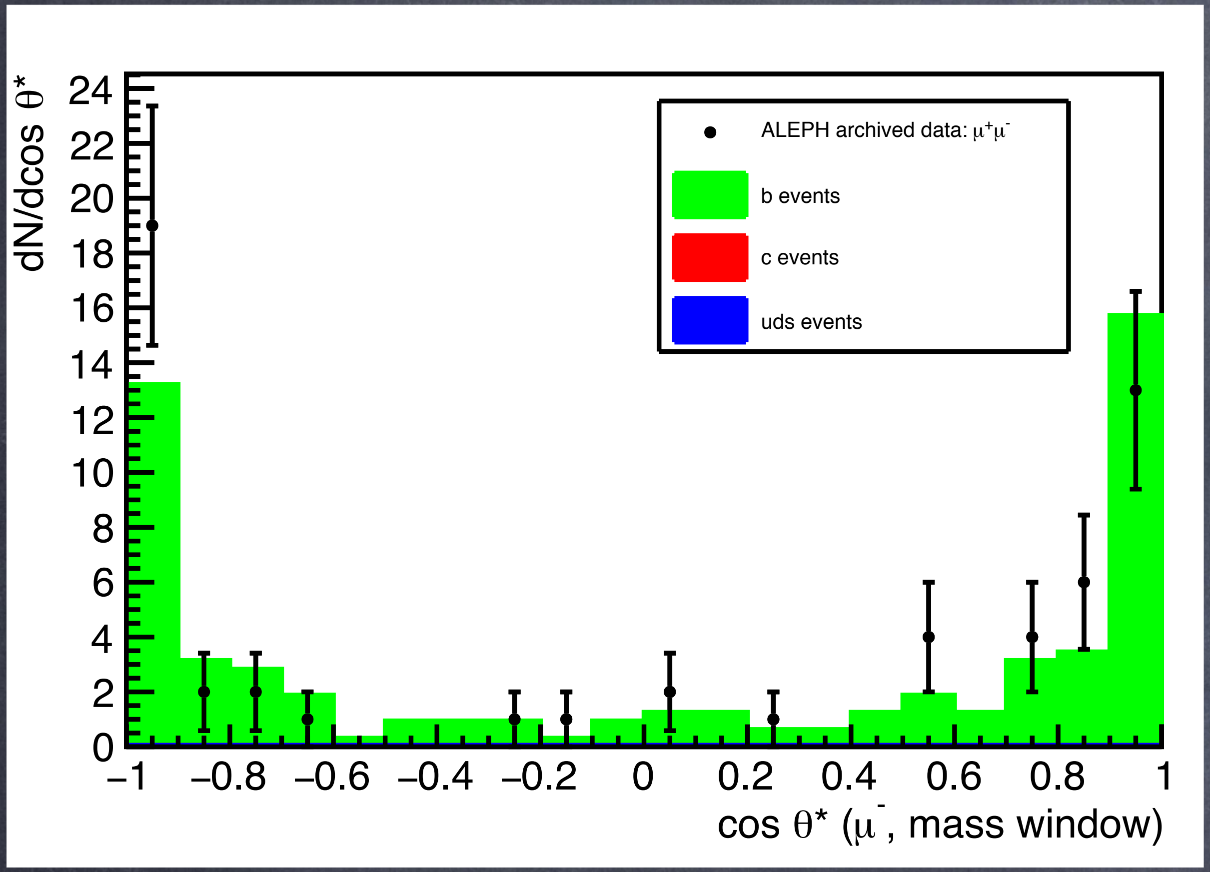
Signal + background model used to extract signal parameters (from arXiv:1610.06536)

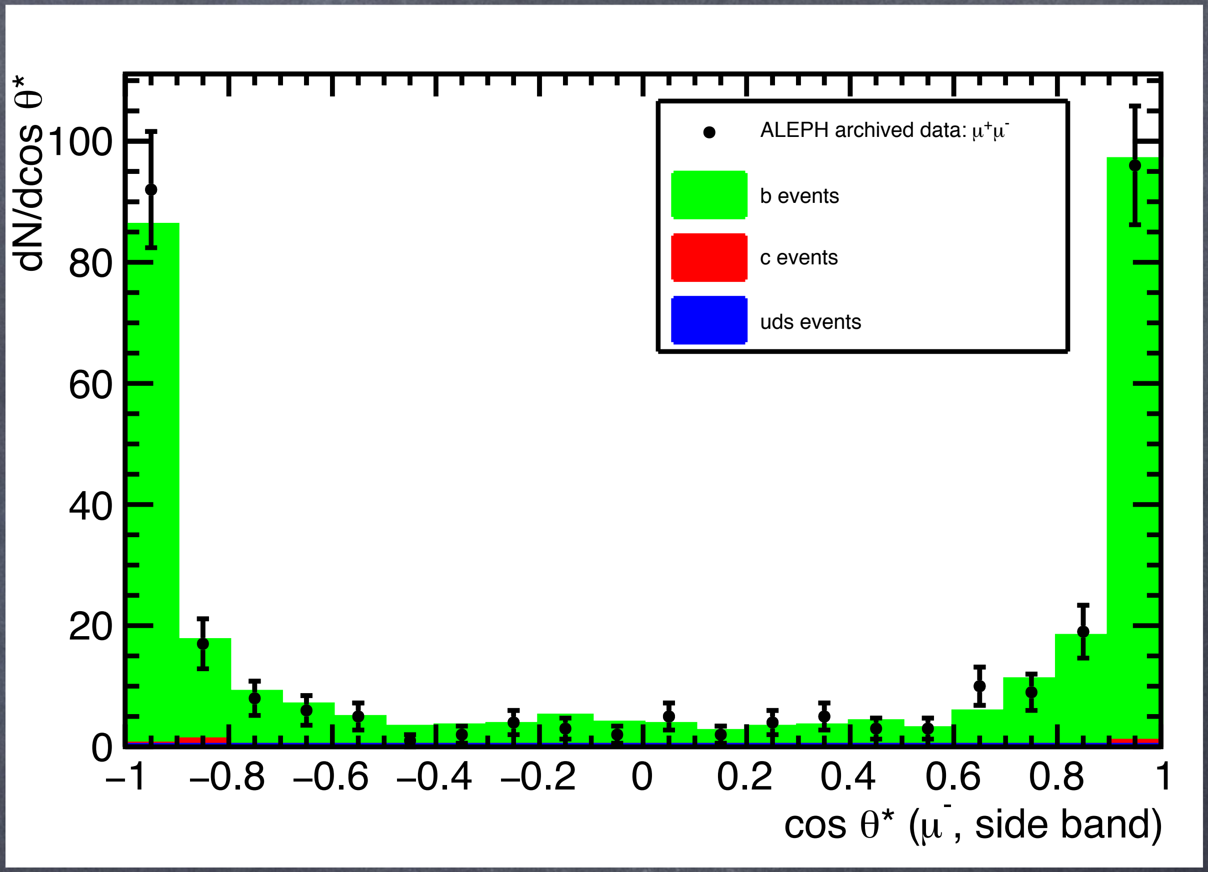
$$\mathbf{32 \pm 11 \ \text{events}, \ \ \text{significance} \ \simeq 3\,\sigma}$$

$$\Longrightarrow \ \boldsymbol{B(Z \to \bar{b}bX(\to \mu^+\mu^-)) = (2.77 \pm 0.95) \times 10^{-4}}$$

μ^- angular distribution in dimuon rest frame (from arXiv:1610.06536)

$$\cos\theta^* = \widehat{p}_{\mu^-} \cdot \widehat{p}_{\mu^+\mu^-}$$





$$M_{\mu^+\mu^-} = (30.40 \pm 3.85)\,\mathrm{GeV}$$

$$M_{\mu^+\mu^-} = 15 - 50\,\mathrm{GeV}$$

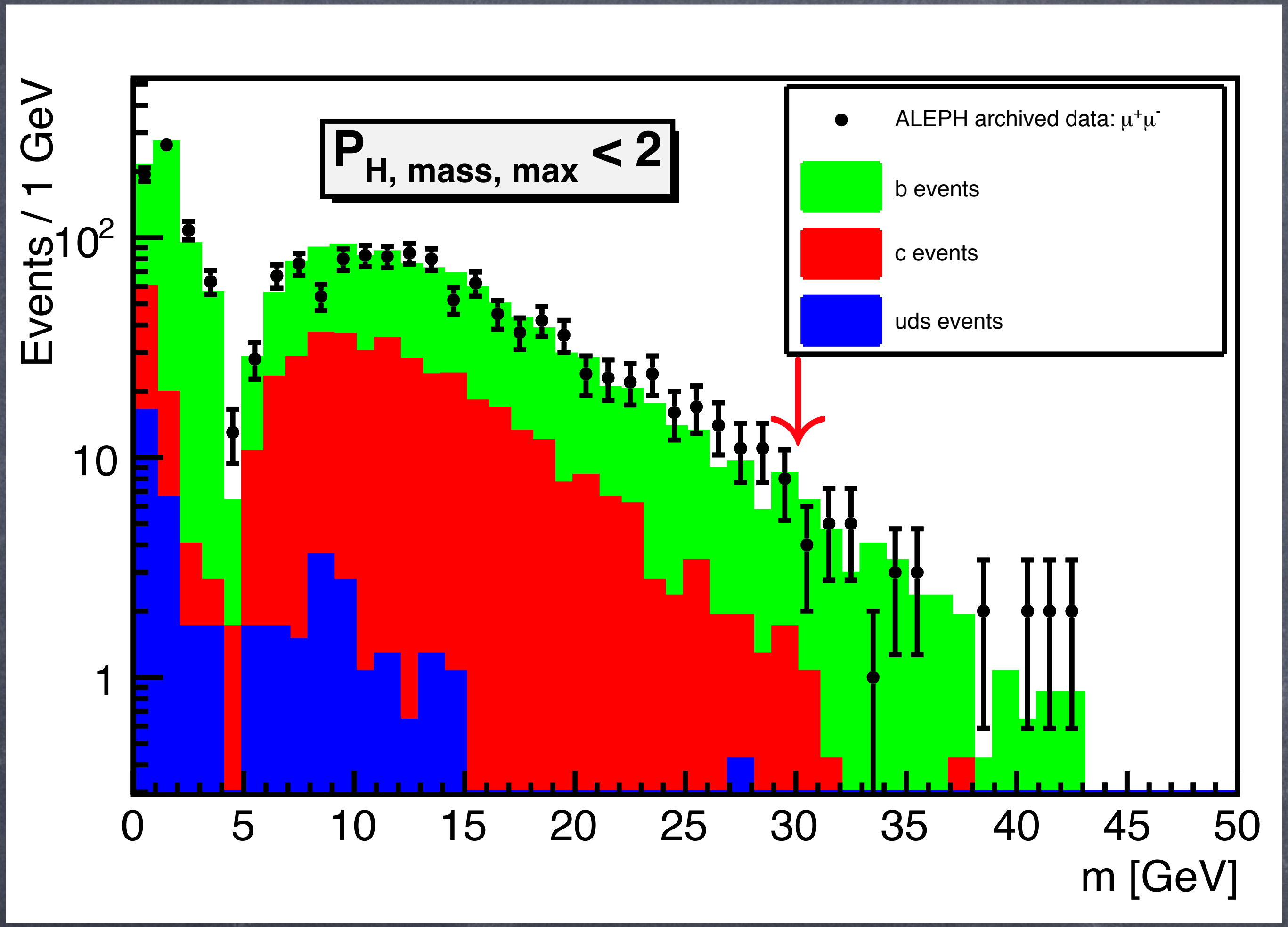
excluding signal region

The "horns" at $\cos\theta^* \cong \pm 1$ are <u>*mostly*</u> $b \to c\mu\nu$

There is a weak (~1-sigma) e+e- near 30 GeV.

I'm going to Fuhgeddaboutit.

Finally, inverting the b-tag shows no evidence of a dimuon excess near 30 GeV:



==> Hypothesis: The dimuon excess near 30 GeV is associated with Z-decays and $\bar{b}b$ production.

The 2HDM model

Impose softly-broken $U(1)_\phi$ symmetry: $(Y_{EW} = \frac{1}{2})$

$$Y_\phi(\phi_1) = 0,\ Y_\phi(\phi_2) = 1\,;$$

$$Y_\phi(q_{Lk}) = Y_\phi\begin{pmatrix} u_{Lk} \\ d_{Lk} \end{pmatrix} = Y_\phi(u_{Rk}) = Y_\phi(d_{Rk}) = 0\,; \quad (k = 1,2,3)$$

$$Y_\phi(L_{Lk}) = Y_\phi\begin{pmatrix} \nu_{Lk} \\ \ell_{Lk} \end{pmatrix} = \tfrac{1}{2}\,, \quad Y_\phi(\ell_{Rk}) = -\tfrac{1}{2}\,; \qquad (k = 1,2)$$

$$Y_\phi(L_{L3}) = Y_\phi(\ell_{R3}) = 0\,.$$

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$$\Gamma_1^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad \Gamma_2^\ell = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\Gamma_1^{u,d} = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad \Gamma_2^{u,d} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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to maintain:

- $\phi_{10} \cong H(125)$ with $\cong$ SM couplings
- $\phi_{20} \cong h,\ \phi_{23} \cong \eta_A$ couple to $\mu^+\mu^-,\ \bar{b}b$ (weakly, thru mixing)
- $\phi_2^\pm \cong h^\pm$ couple to $\mu^\pm\nu_\mu$

Impose <u>softly-broken</u> $U(1)_\phi$ symmetry: $(Y_{EW} = \frac{1}{2})$

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↓

$$V(\phi_1, \phi_2) = -\mu_1^2\,\phi_1^\dagger\phi_1 - \mu_2^2\,\phi_2^\dagger\phi_2 - \mu_3^2\,(\phi_1^\dagger\phi_2 + \phi_2^\dagger\phi_1) + \lambda_1(\phi_1^\dagger\phi_1)^2$$
$$+\lambda_2(\phi_2^\dagger\phi_2)^2 + 2\lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + 2\lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)\,.$$

Impose softly-broken $U(1)_\phi$ symmetry: $(Y_{EW} = \frac{1}{2})$

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$$V(\phi_1, \phi_2) = -\mu_1^2\, \phi_1^\dagger\phi_1 - \mu_2^2\, \phi_2^\dagger\phi_2 - \mu_3^2\, (\phi_1^\dagger\phi_2 + \phi_2^\dagger\phi_1) + \lambda_1(\phi_1^\dagger\phi_1)^2$$

$$+\lambda_2(\phi_2^\dagger\phi_2)^2 + 2\lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + 2\lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)\,.$$

$$\langle\phi_i\rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix} \qquad \text{for } \mu_{1,2,3}^2 > 0\,,\ \lambda_{1,2} > 0\,,\ \lambda_{3,4} \text{ real.}$$

The 2HDM masses

CP-even:

$$M^2(\phi_{10},\phi_{20}) = \begin{pmatrix} \mu_3^2\, v_2/v_1 + 2\lambda_1 v_1^2 & -\mu_3^2 + 2(\lambda_3+\lambda_4)v_1v_2 \\ -\mu_3^2 + 2(\lambda_3+\lambda_4)v_1v_2 & \mu_3^2\, v_1/v_2 + 2\lambda_2 v_2^2 \end{pmatrix},$$

$$H = \phi_{10}\cos\alpha + \phi_{20}\sin\alpha\,, \quad h = -\phi_{10}\sin\alpha + \phi_{20}\cos\alpha\,,$$

$$\text{where } \tan 2\alpha = \frac{2(2(\lambda_3+\lambda_4)v_1v_2 - \mu_3^2)}{\mu_3^2(v_2/v_1 - v_1/v_2) + 2(\lambda_1 v_1^2 - \lambda_2 v_2^2)}\,;$$

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$$H = \phi_{10}\cos\alpha + \phi_{20}\sin\alpha\,, \quad h = -\phi_{10}\sin\alpha + \phi_{20}\cos\alpha\,,$$

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$$M^2(H,h) = \frac{1}{2v_1 v_2}\Big\{\mu_3^2 v^2 + 2(\lambda_1 v_1^2 + \lambda_2 v_2^2)v_1 v_2$$

$$\pm\Big[\big[\mu_3^2 v^2 + 2(\lambda_1 v_1^2 + \lambda_2 v_2^2)v_1 v_2)\big]^2 - 8\big[\mu_3^2(\lambda_1 v_1^4 + \lambda_2 v_2^4)v_1 v_2$$

$$+2\lambda_1\lambda_2 v_1^4 v_2^4 + 2\mu_3^2(\lambda_3+\lambda_4)v_1^3 v_2^3 - 2(\lambda_3+\lambda_4)^2 v_1^4 v_2^4\big]\Big]^{\frac{1}{2}}\Big\}.$$

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$$H = \phi_{10} \cos\alpha + \phi_{20} \sin\alpha\,, \quad h = -\phi_{10} \sin\alpha + \phi_{20} \cos\alpha\,,$$

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$$+ 2\lambda_1 \lambda_2 v_1^4 v_2^4 + 2\mu_3^2(\lambda_3 + \lambda_4) v_1^3 v_2^3 - 2(\lambda_3 + \lambda_4)^2 v_1^4 v_2^4\big]\Big]^{\frac{1}{2}} \Big\}.$$

Aaaarrrrggghhh!

CP-odd:

$$\pi_A = \phi_{13} \cos\beta + \phi_{23} \sin\beta\,, \quad \eta_A = \phi_{13} \sin\beta - \phi_{23} \cos\beta\,,$$

where $\tan\beta = \frac{v_2}{v_1}$;

$$M^2_{\pi_A} = 0\,, \quad M^2_{\eta_A} = \mu_3^2 \frac{v^2}{v_1 v_2}\,.$$

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Charged:

$$\pi^\pm = \phi_1^\pm\cos\beta + \phi_2^\pm\sin\beta\,, \quad h^\pm = \phi_1^\pm\sin\beta - \phi_2^\pm\cos\beta\,,$$

$$M^2_{\pi^\pm} = 0\,, \quad M^2_{h^\pm} = \left(\frac{\mu_3^2}{v_1 v_2} - \lambda_4\right)v^2\,.$$

The 2HDM interactions

Leptons:

$$\mathcal{L}_{Yl} = -\sum_{\ell_k=e,\mu} \frac{m_{\ell_k}}{v\sin\beta}\,\bar{\ell}_k\left[v\sin\beta + H\sin\alpha + h\cos\alpha - i\eta_A\cos\beta\gamma_5\right]\ell_k$$

$$-\frac{m_\tau}{v\cos\beta}\,\bar{\tau}\left[v\cos\beta + H\cos\alpha - h\sin\alpha + i\eta_A\sin\beta\gamma_5\right]\tau$$

$$+h^+\left[\sum_{k=e,\mu}\frac{\sqrt{2}m_{\ell_k}\cot\beta}{v}\,\bar{\nu}_{k_L}\ell_{kR} - \frac{\sqrt{2}m_\tau\tan\beta}{v}\,\bar{\nu}_{\tau L}\,\tau_R\right] + \text{h.c.}$$

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N.B.: These interactions induce **no** detectable charged-lepton flavor violation!

Quarks:

$$\mathcal{L}_{Yq} = -\sum_{d_k=d,s,b} \frac{m_{d_k}}{v\cos\beta}\,\bar{d}_k\left(v\cos\beta + H\cos\alpha - h\sin\alpha - i\gamma_5\eta_A\sin\beta\right)d_k$$

$$-\sum_{u_k=u,c,t} \frac{m_{u_k}}{v\cos\beta}\,\bar{u}_k\left(v\cos\beta + H\cos\alpha - h\sin\alpha + i\gamma_5\eta_A\sin\beta\right)u_k$$

$$-\frac{\sqrt{2}\tan\beta}{v}\sum_{k,l=1}^{3}\left[\bar{u}_{kL}(V\mathcal{M}_d)_{kl}\,h^+\,d_{lR} - \bar{d}_{kL}(V^\dagger\mathcal{M}_u)_{kl}\,h^-\,u_{lR}\right] + \text{h.c.}$$

$$\Longrightarrow \frac{B(\eta_A\to\bar{b}b)}{B(\eta_A\to\mu^+\mu^-)} = \frac{3m_b^2\tan^4\beta}{m_\mu^2}$$

EW bosons:

$$\mathcal{L}_{EW} = \frac{e}{\sin 2\theta_W}\left[(h\cos(\beta-\alpha) - H\sin(\beta-\alpha))\overleftrightarrow{\partial_\mu}\,\eta_A\right]Z^\mu$$

$$+\frac{e}{2\sin\theta_W}\left[(\eta_A \pm ih\cos(\beta-\alpha) \mp iH\sin(\beta-\alpha))\overleftrightarrow{\partial_\mu}\,h^\pm\right]W^{\mp\,\mu}$$

$$+\left[\frac{2e^2}{\sin^2 2\theta_W}Z^\mu Z_\mu + \frac{e^2}{\sin^2\theta_W}W^{+\,\mu}W^-_\mu\right]\left[H\cos(\beta-\alpha) + h\sin(\beta-\alpha)\right].$$

The two options

To be close to SM and consistent with LHC H-data require:

- small α for weak $\phi_{10} - \phi_{20}$ mixing
- small β for weak $\pi_A - \eta_A$ mixing

So...

- $v^2 \cong v_1^2 \gg v_2^2$
- $(\mu_3^2 - 2\lambda_1 v_1 v_2)^2 \gg 8(\lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2)v_2^4$

The two options

To be close to SM and consistent with LHC H-data require:

- small α for weak $\phi_{10} - \phi_{20}$ mixing
- small β for weak $\pi_A - \eta_A$ mixing

$$\Longrightarrow \; M^2(H,h) \cong \begin{cases} \max(2\lambda_1 v_1^2,\, \mu_3^2 v^2/v_1 v_2) \\ \\ \min(2\lambda_1 v_1^2,\, \mu_3^2 v^2/v_1 v_2) \end{cases}$$

i.e., either

(1) $M_H^2 \cong 2\lambda_1 v^2$ and $M_h^2 \cong M_{\eta_A}^2 \cong \mu_3^2 v^2/v_1 v_2$

or

(2) $M_H^2 \cong M_{\eta_A}^2 \cong \mu_3^2 v^2/v_1 v_2$ and $M_h^2 \cong 2\lambda_1 v^2$

Option 1:

$Z \to h\eta_A \to \mu^+\mu^- \, \bar{b}b$ **plus "Higgsstrahlung" :**

$$Z \to Z^* h \text{ with } Z^* \to \bar{b}b, \quad h \to \mu^+\mu^-$$
$$\text{or } Z \to \bar{b}b \text{ with } b(\bar{b}) \to b(\bar{b}) + h/\eta_A \to b(\bar{b})\, \mu^+\mu^-$$

Option 2:

Higgsstrahlung only, with $\mathcal{O}(10^{-10})$ contribution to $Z \to \bar{b}b +$ dimuon.

So, only option 1 is available:

$$B(Z \to h\eta_A \to \bar{b}b\mu^+\mu^-) \cong B(Z \to h\eta_A)\left[B(h \to \bar{b}b)B(\eta_A \to \mu^+\mu^-) + (h \leftrightarrow \eta_A)\right]$$

where

$$B(Z \to h\eta_A) = \frac{2\alpha_{EM}\, p^3}{3M_Z^2 \sin^2 2\theta_W \Gamma_Z} \cos^2(\beta - \alpha)$$

$$= 0.0141 \cos^2(\beta - \alpha) \text{ for } M_H = M_{\eta_A} = 30\,\mathrm{GeV}$$

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$$= 0.0141 \cos^2(\beta - \alpha) \text{ for } M_H = M_{\eta_A} = 30\,\text{GeV}$$

Wait for it!

But... $H \to hh,\ \eta_A\eta_A,\ h^+h^-$??

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- Require $\lambda_4 < 0$ so that
  $M_{h^\pm} > \frac{1}{2}M_H \cong 63\,\mathrm{GeV}$ or
  $M_{h^\pm} > (M_{\tilde{\mu}^\pm})_{\mathrm{limit}} \cong 95\,\mathrm{GeV}$

- Require $|\lambda_3 + \lambda_4| < 5.44 \times 10^{-3}$
  so that $\Gamma(H \to hh),\ \Gamma(H \to \eta_A\eta_A) < \frac{1}{2}\,\mathrm{MeV}$

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  so that $\Gamma(H \to hh)$, $\Gamma(H \to \eta_A\eta_A) < \frac{1}{2}\,\mathrm{MeV}$

(Yes, it's fine tuning, but who cares?)

The predictions

Tables' inputs:

- $M_{h,\eta_A} = 30\,\mathrm{GeV},\;\; M_H = 125\,\mathrm{GeV},\;\; M_{h^\pm} = 65\,\mathrm{GeV}$
- $\lambda_4 = (M^2_{\eta_A} - M^2_{h^\pm})/v^2 = -5.49 \times 10^{-2}$
- $\lambda_3 + \lambda_4 = -3.00 \times 10^{-3}$;
  results insensitive to $|\lambda_3 + \lambda_4| < 5 \times 10^{-3}$.

v_2 (GeV)	β	α	μ_3^2 (GeV^2)	λ_1	λ_2
10	0.04066	-0.348×10^{-2}	36.6	0.1293	0.833×10^{-2}
12.5	0.05084	-0.435×10^{-2}	45.7	0.1294	0.833×10^{-2}
15	0.06101	-0.522×10^{-2}	54.8	0.1295	0.833×10^{-2}
20	0.08139	-0.695×10^{-2}	72.9	0.1299	0.832×10^{-2}

v_2 (GeV)	$B(h \to \mu^+\mu^-)$	$B(h \to \bar{b}b)$	$B(\eta_A \to \mu^+\mu^-)$	$B(\eta_A \to \bar{b}b)$	$B(Z \to \bar{b}b\mu\mu)$
10	0.9999	0.444×10^{-4}	0.9923	0.667×10^{-2}	0.950×10^{-4}
12.5	0.9998	1.085×10^{-4}	0.9814	1.613×10^{-2}	2.297×10^{-4}
15	0.9997	2.249×10^{-4}	0.9622	3.286×10^{-2}	4.673×10^{-4}
20	0.9991	7.105×10^{-4}	0.8889	9.652×10^{-2}	13.67×10^{-4}

The predictions

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1.) **The dimuon signal at LEP and LHC will be observed only in Z-decay and in association with $\bar{b}b$.**

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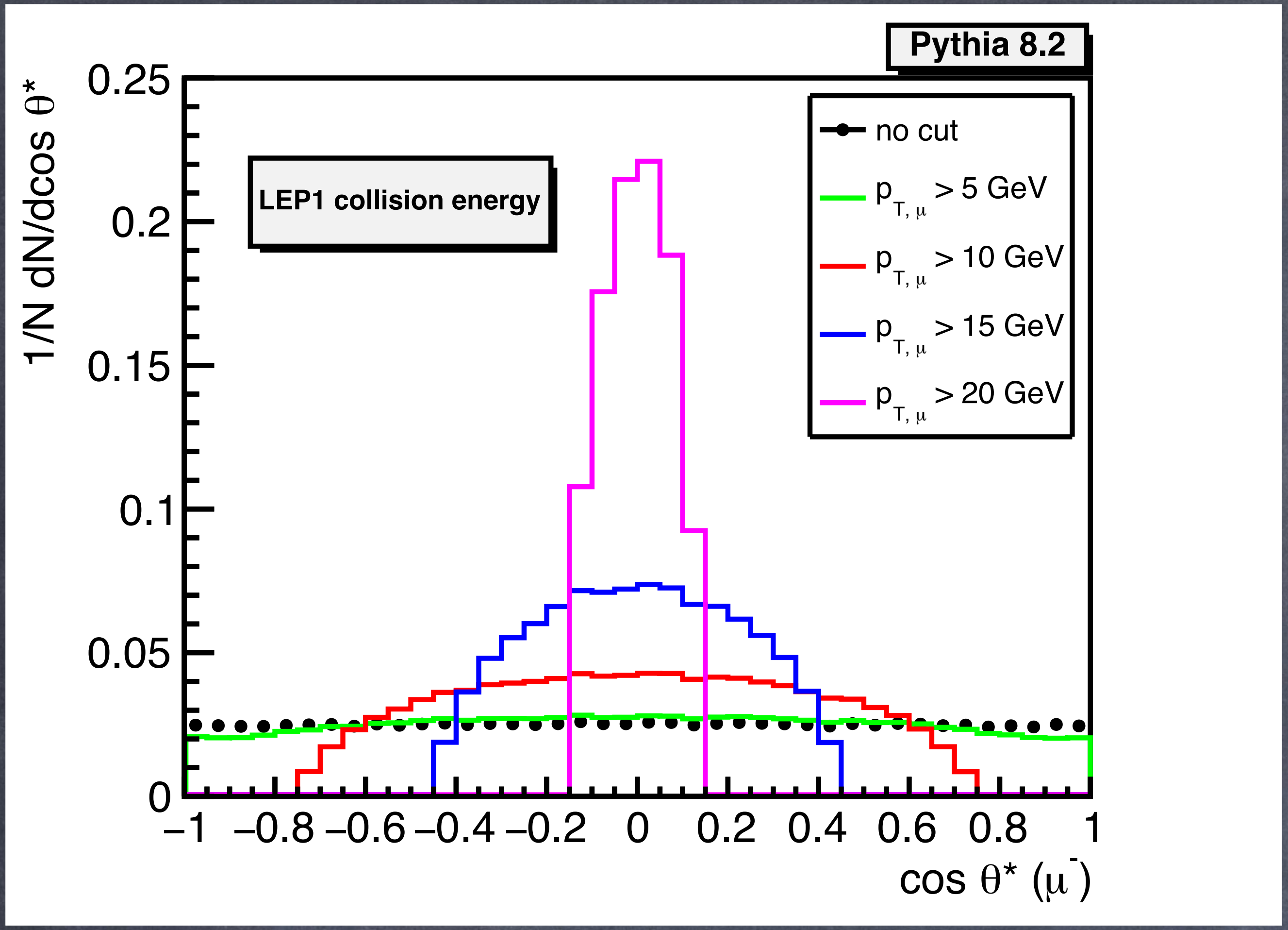
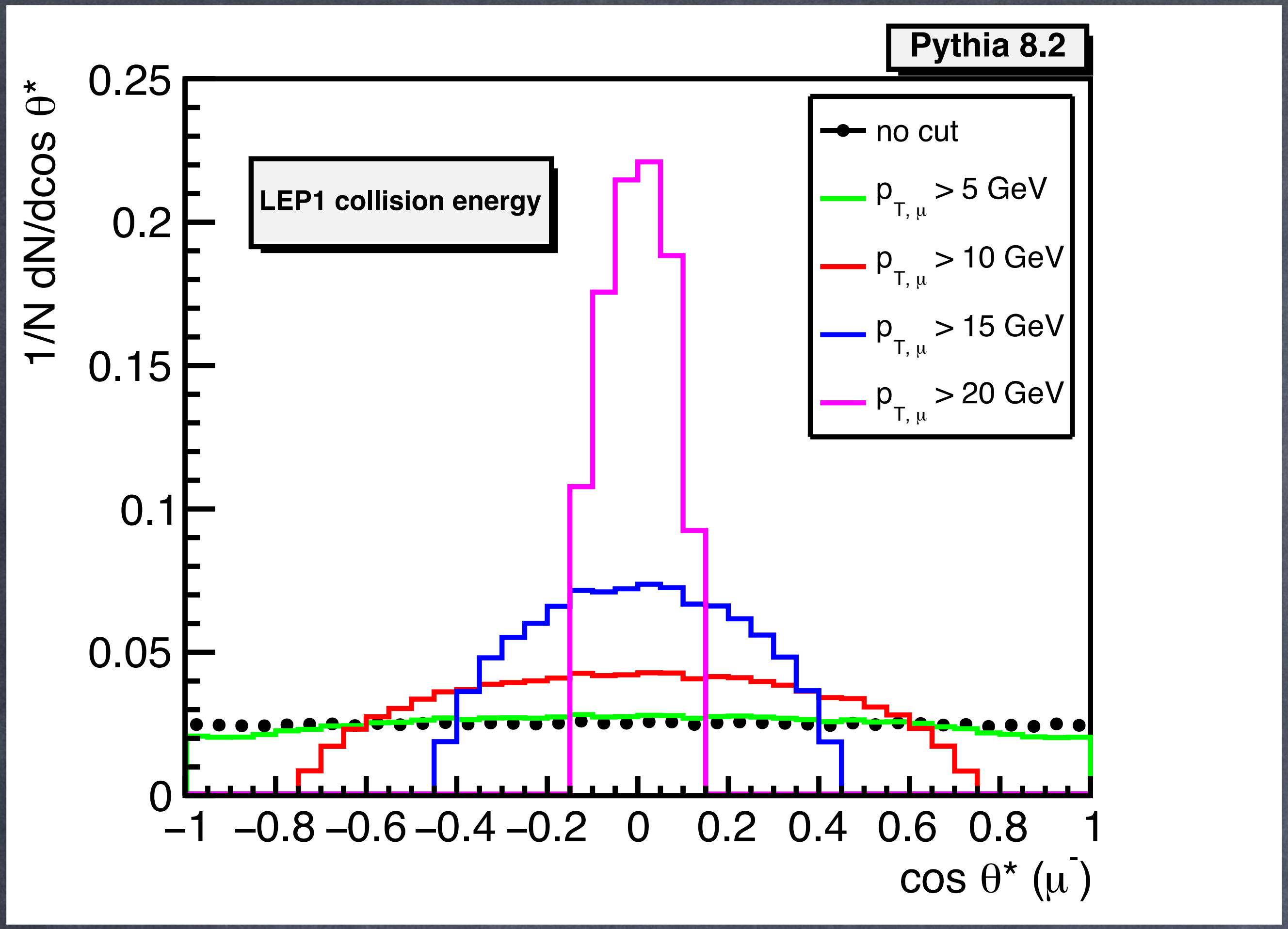
3.) **Signal dimuons have an isotropic $\cos\theta^*$ distribution. Its flat shape is modified to an inverted ~parabola in $\theta_T < \theta^* < \pi - \theta_T$ when there is a $p_T \gtrsim 7\,\mathrm{GeV}$ cut on the muons. (θ_T increases with the p_T cut.) <u>All the signal lies in $|\cos\theta^*| < \cos\theta_T$.</u> (See figures.)**


Pythia 8.2
LEP1 collision energy
no cut
$p_{T,\mu}$ > 5 GeV
$p_{T,\mu}$ > 10 GeV
$p_{T,\mu}$ > 15 GeV
$p_{T,\mu}$ > 20 GeV
1/N dN/dcos θ*
cos θ* (μ⁻)
0.25
0.2
0.15
0.1
0.05
0
−1 −0.8 −0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1

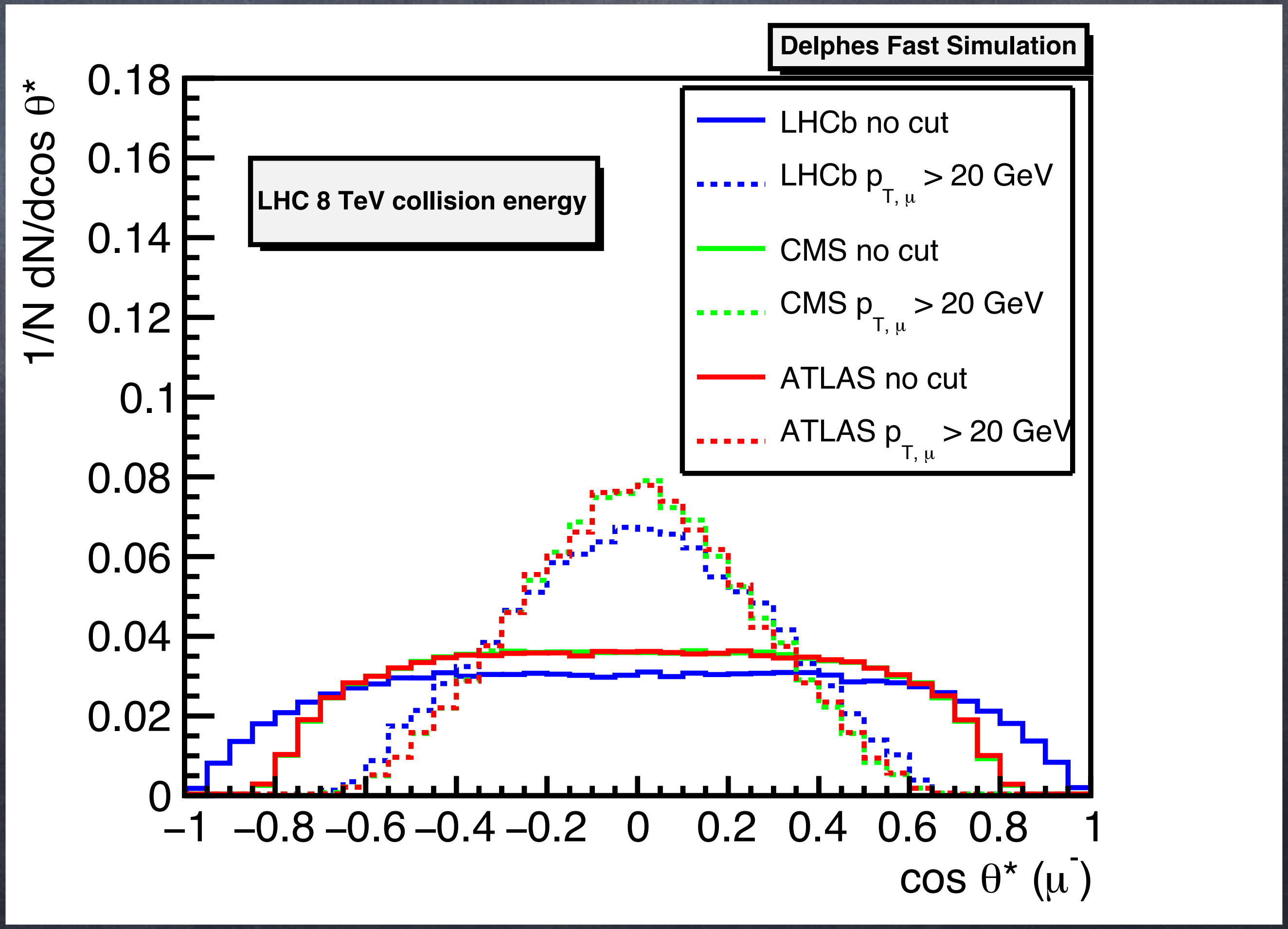
Z's at rest

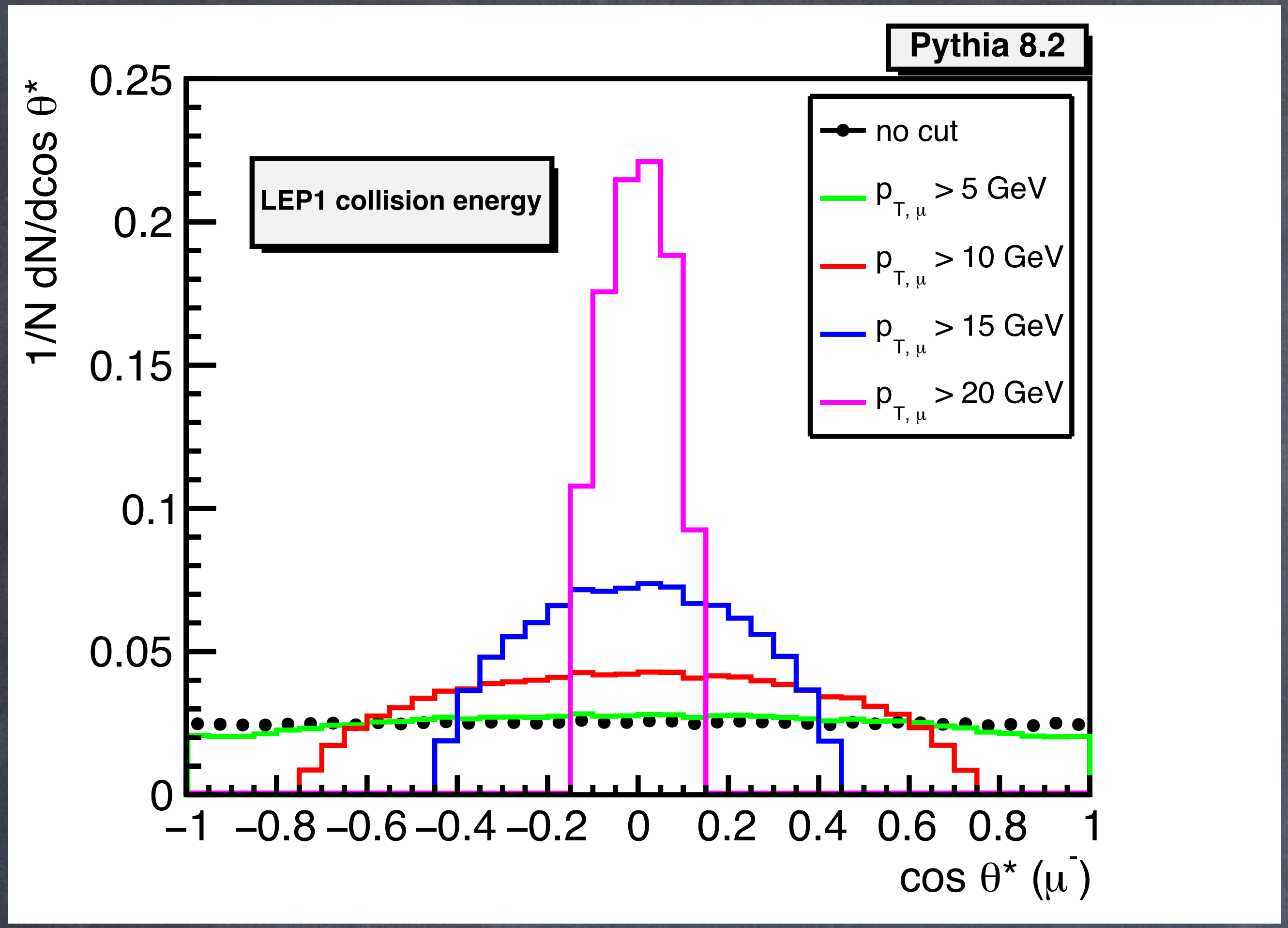


Note: Normalized to unit area!

Z's boosted along beams

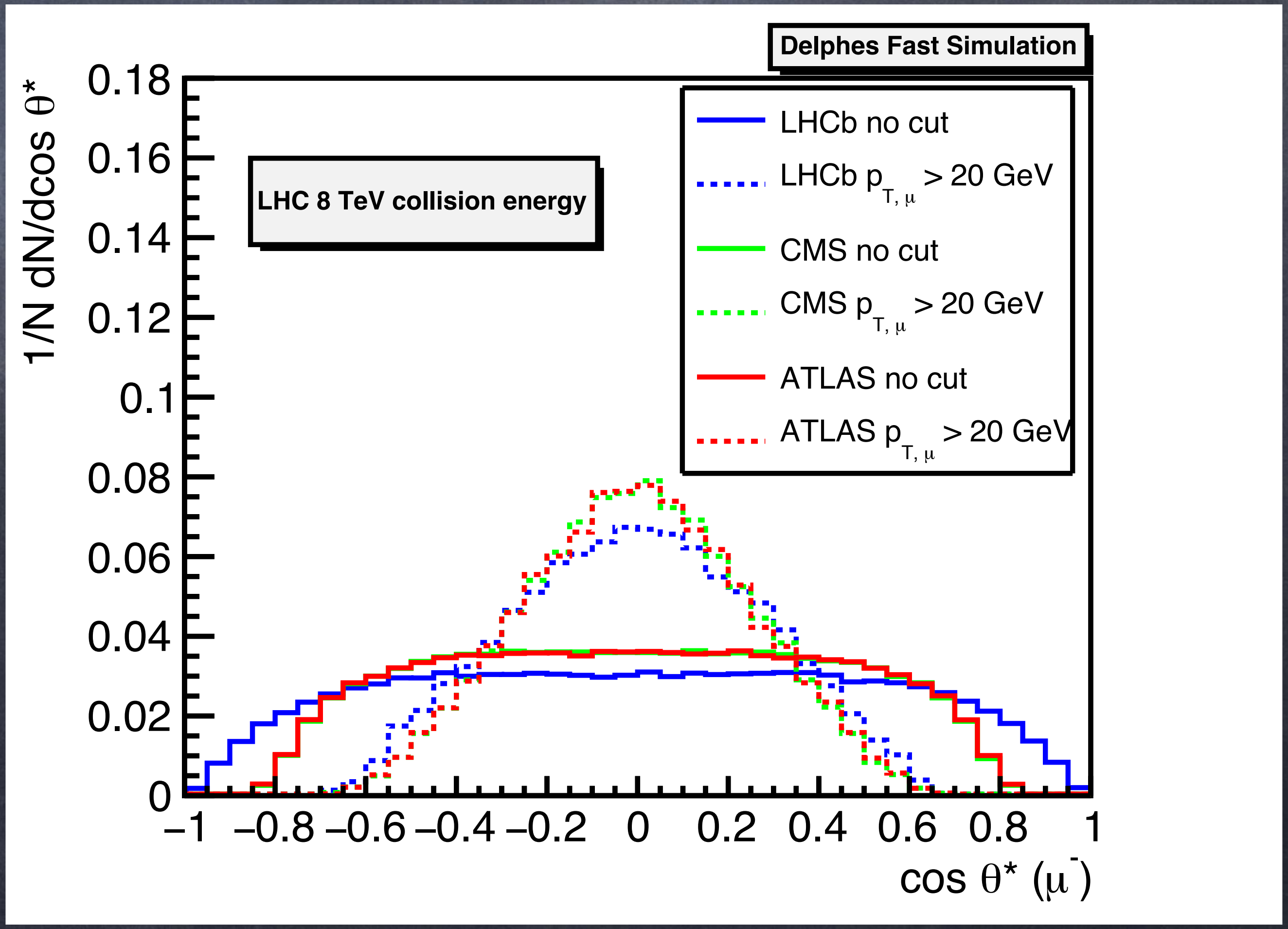
Z's at rest





Low-pT muons have large rapidity & escape

Lose backward-going muons for h at 90°



more predictions

4.) **Signal dimuons will *not* have a strong tendency to follow *b*-jets (in conflict with ALEPH data).**
But, at the LHC, the Z-boost makes muons $\ll$ isolated.
Use $p_T(Z) > 30\,\mathrm{GeV}$ for more muon isolation.

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Most readily sought in $\gamma^*, Z^* \to h^+h^-$ **and** $W^* \to hh^{\pm}$.

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8.) **And *no* $H(125) \to \mu^+\mu^-$ if $(\alpha/\beta)^2 \ll 1$.**

The fly in the ointment

(what you waited for!)

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$$B(h \to \mu^+\mu^-) \cong B(\eta_A \to \mu^+\mu^-) \cong 1$$

$$B(Z \to h\eta_A) = 0.014\cos^2(\beta - \alpha) \text{ with } \beta,\ \alpha \text{ small}$$

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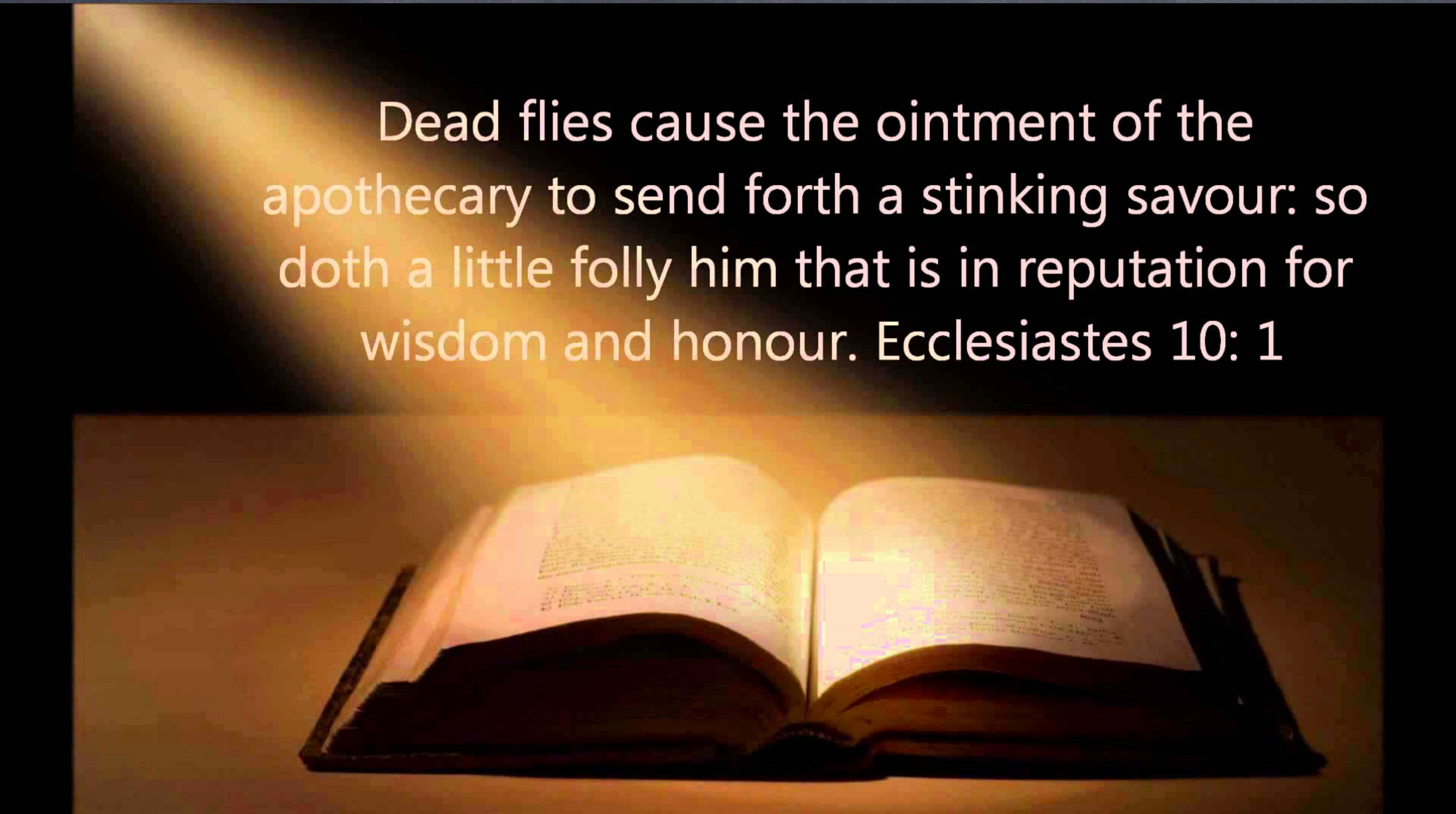
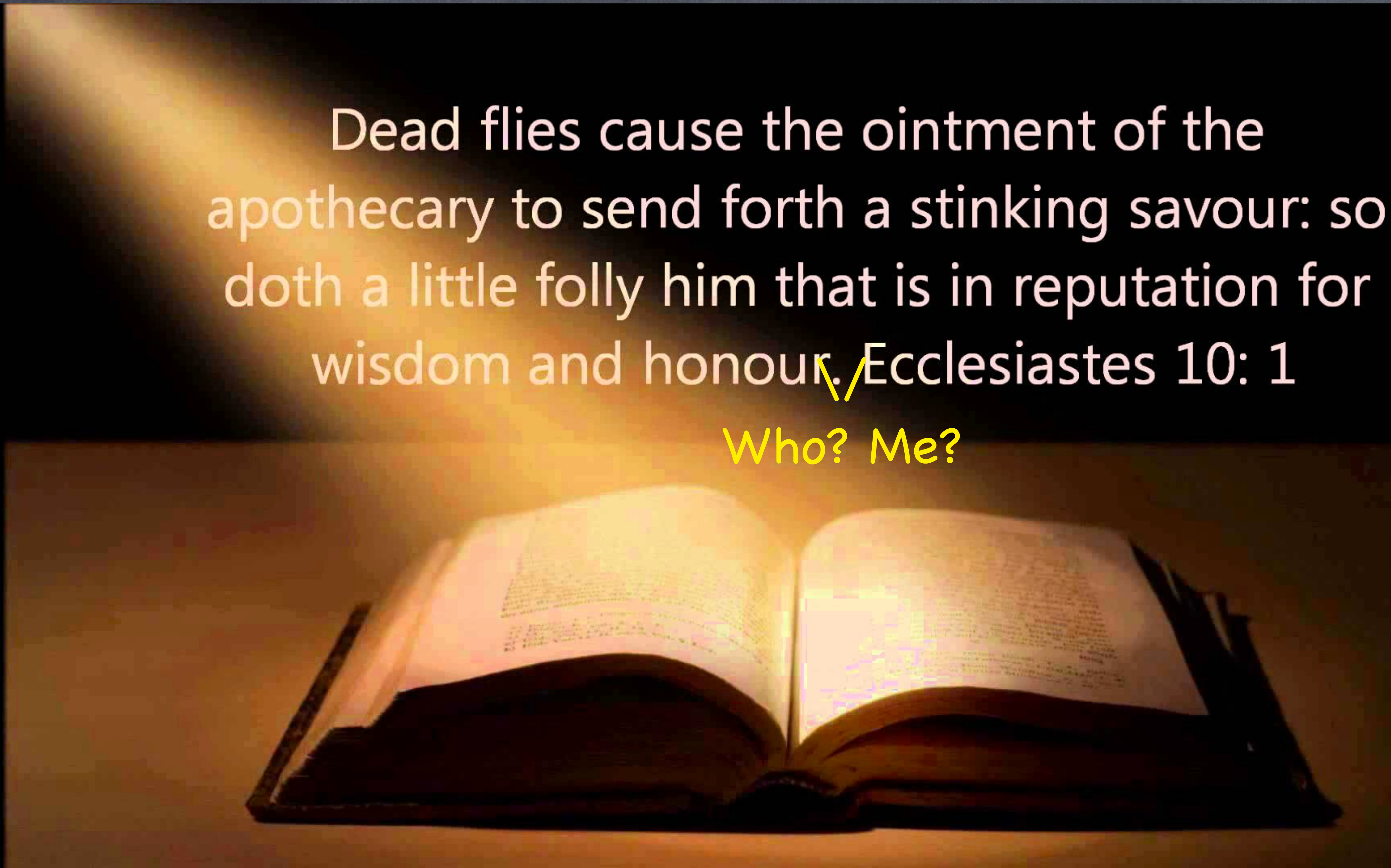
3300 times measured $B(Z \to 4\mu) = 4.2 \times 10^{-6}$**!!**


Dead flies cause the ointment of the apothecary to send forth a stinking savour: so doth a little folly him that is in reputation for wisdom and honour. Ecclesiastes 10: 1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Who? Me?

Some things we tried:

1.) **Cannot raise M_{η_A} or alter**
$(B(h \to \mu^+\mu^-)B(\eta_A \to \bar{b}b) \propto \cos^2\alpha/\cos^2\beta$
nor $B(h \to \bar{b}b)B(\eta_A \to \mu^+\mu^-) \propto \sin^2\alpha/\sin^2\beta$
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2.) **Use the Branco-Grimus-Lavoura (BGL)**
mechanism to dilute $B(h, \eta_A \to \mu^+\mu^-)$.

Here's what we tried for BGL...

BGL: Allow FCNC in 3rd generation of up **or** down-Yukawa's; 4 possibilities:

FCNC:

$$\Gamma_1^{(u\,\mathrm{or}\,d)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}, \quad \Gamma_2^{(u\,\mathrm{or}\,d)} = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix};$$

(or 1 <-> 2)

no FCNC:

$$\Gamma_1^{(d\,\mathrm{or}\,u)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad \Gamma_2^{(d\,\mathrm{or}\,u)} = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

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$\Gamma_{h,\eta_A \bar{t}t}/\Gamma_{H\bar{t}t} \simeq \cot\beta \Longrightarrow h,\eta_A \to gg$ **(!!)**

for d-textures:
$B(h,\eta_A \to \bar{b}b)/B(h,\eta_A \to \mu^+\mu^-) = 3(m_b/m_\mu)^2$
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A no-go theorem?

bj to KL (SLAC, 1977):

There are no no-go theorems!

A challenge to theorists —

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There are no no-go theorems!

A challenge to theorists to repeal and replace this model...

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Especially if the dimuon is also seen in ATLAS, CMS, LHCb, L3...