Unique Higgs boson signature @ colliders
hep-ph/0611270

朱守华 Shou-hua Zhu
北京大学理论物理研究所
ITP, Peking University
2007/2

1. Where is Higgs boson?

Not found yet!

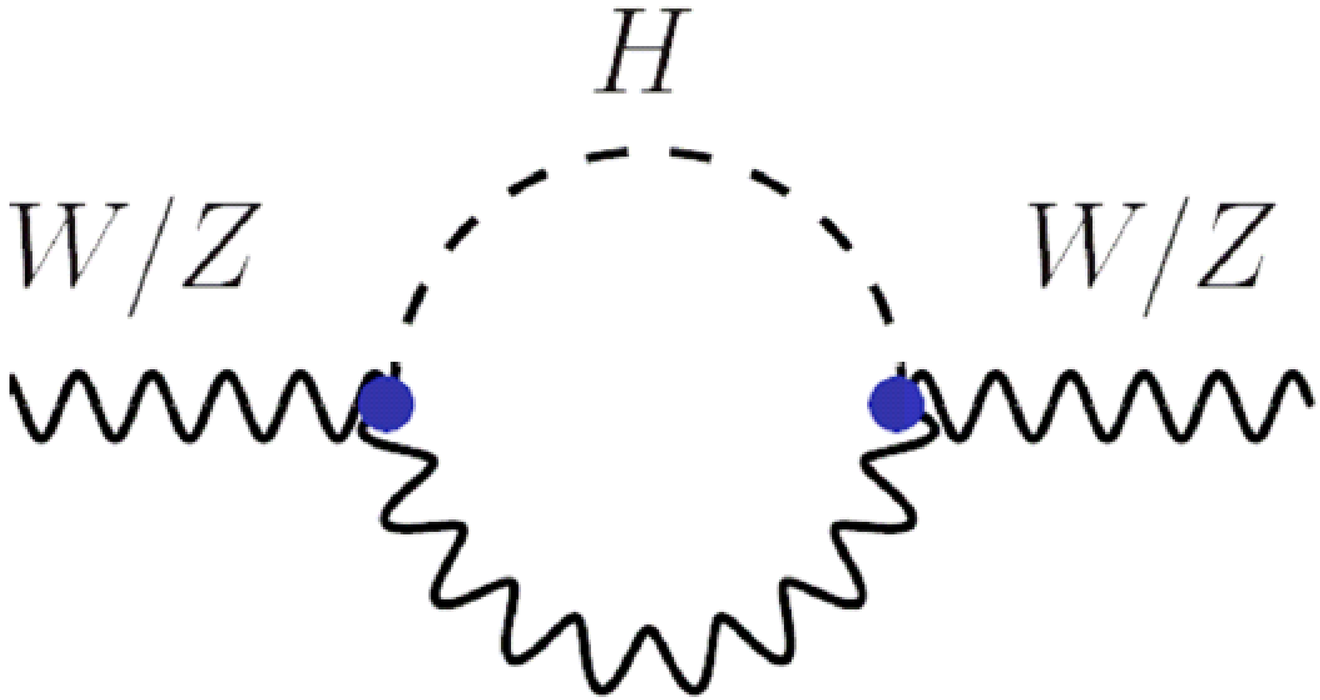
LEP direct search told us

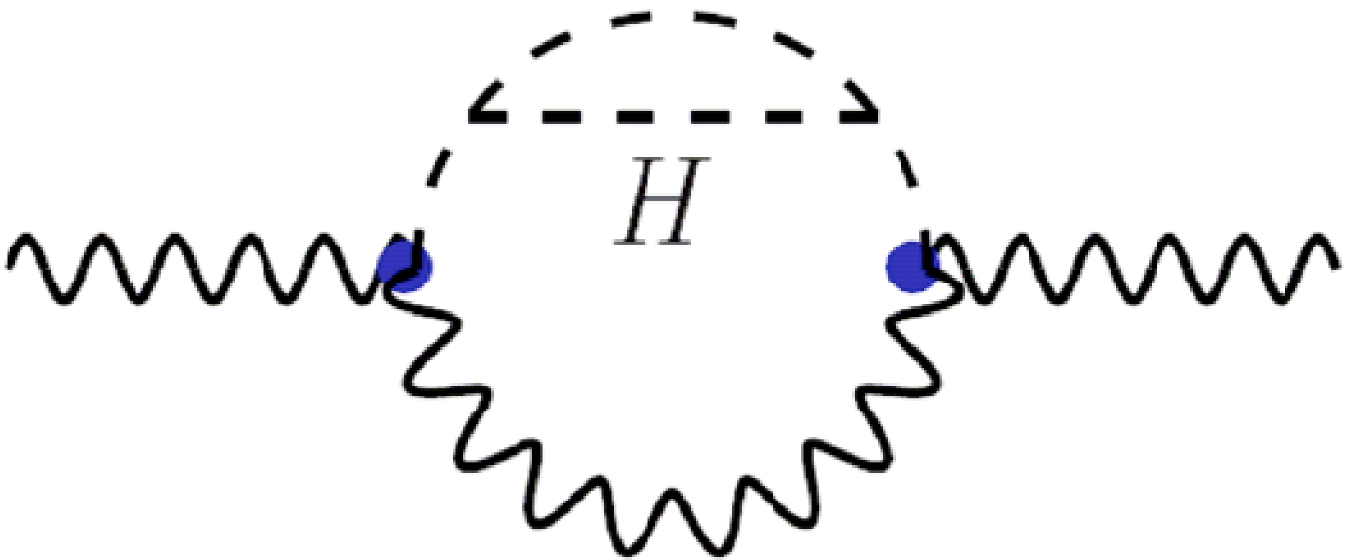
$m_H > 114.4$ GeV@95% CL

in the SM

Alternative approach!

Higgs boson small quantum fluctuations effects can be measured dedicated experiments.


H
W/Z
W/Z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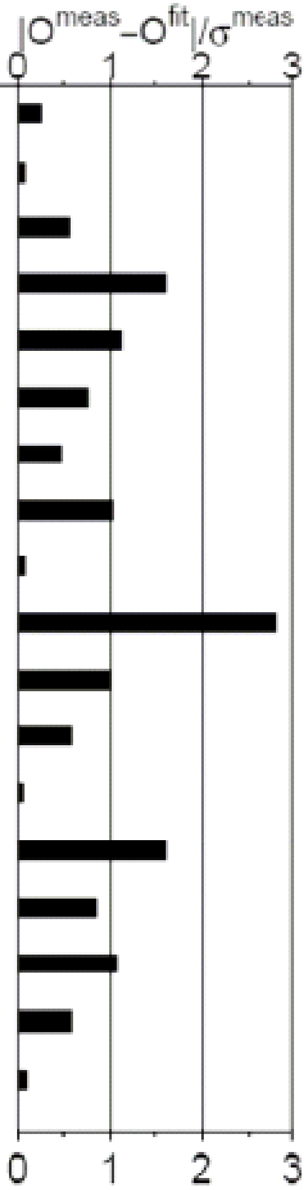
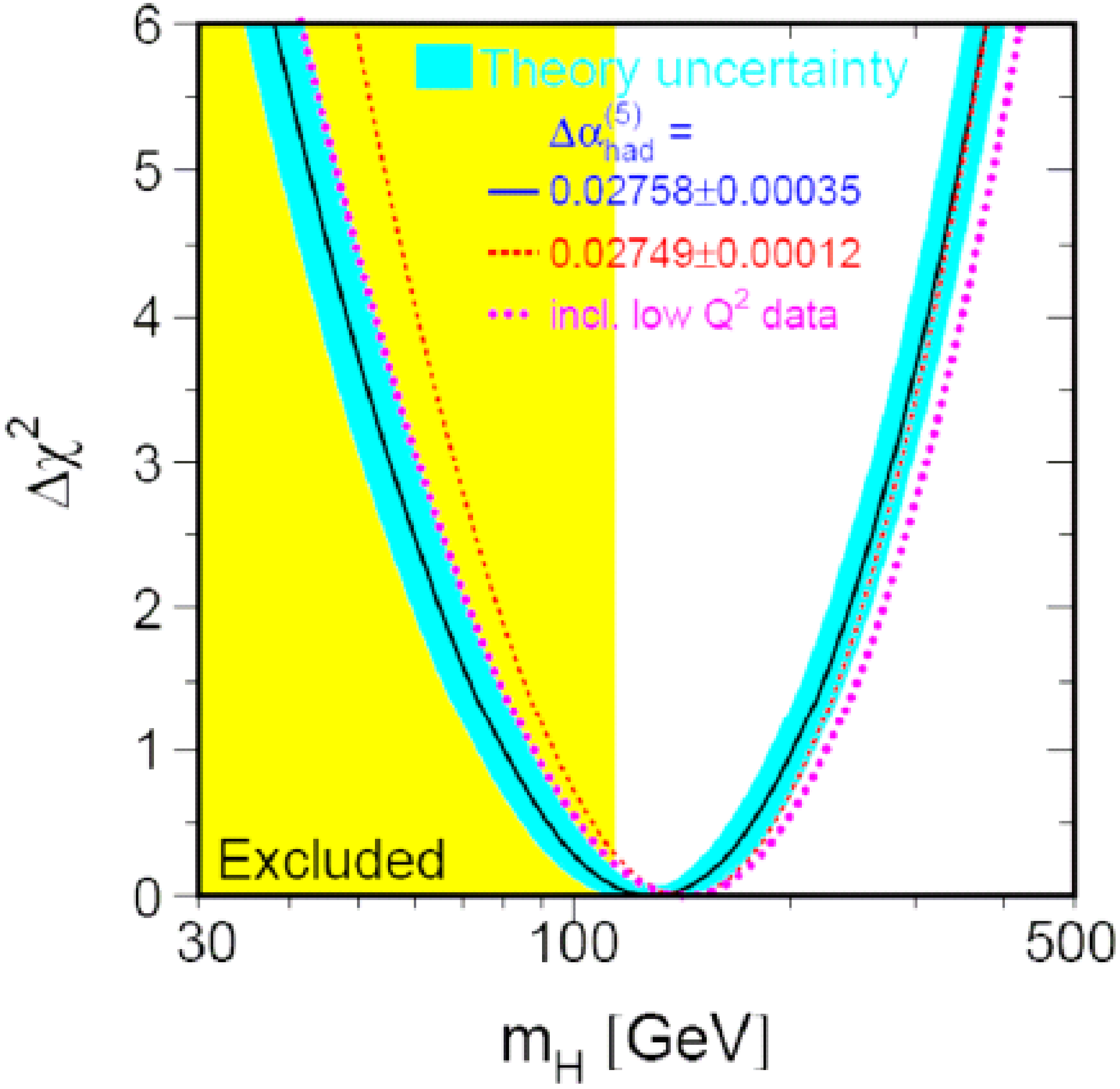
It is claimed that one-Higgs-SM works well with data from LEP, Tevatron, SLC... hep-ex/0509008

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5





Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
$\Delta\chi^2$
0
1
2
3
4
5
6
30
100
500
m_H [GeV]

$$m_t = 174.3 \pm 3.4 \text{ GeV}$$

$$m_H = 98^{+52}_{-36} \text{ GeV}$$

$$m_H < 208 \text{ GeV at } 95\% \text{ CL}$$

2. One puzzle?

VOLUME 87, NUMBER 23 PHYSICAL REVIEW LETTERS 3 DECEMBER 2001

$Z \to \bar{b}b$ Decay Asymmetry: Lose-Lose for the Standard Model

Michael S. Chanowitz

PHYSICAL REVIEW D **66**, 073002 (2002)

Electroweak data and the Higgs boson mass: A case for new physics

Michael S. Chanowitz*

TABLE IV. Results for global fits A–D and for the corresponding fits restricted to m_H-sensitive observables, A′–D′.

	All	$-x_W^{\mathrm{OS}}[\overset{(-)}{\nu} N]$
All	**A**	**B**
	$\chi^2/=27.7/13$, C.L. $=0.010$	18.4/12, 0.10
$-x_W^l[A_H]$	**C**	**D**
	17.4/10, 0.066	6.8/9, 0.65
m_H-sensitive only		
All	**A′**	**B′**
	24.3/8, 0.0020	15.2/7, 0.034
$-x_W^l[A_H]$	**C′**	**D′**
	13.8/5, 0.017	3.45/4, 0.49

TABLE V. SM fit D, to minimal data set, with $x_W^{OS}[\overset{(-)}{\nu} N]$ and three hadronic asymmetry measurements excluded.

	Experiment	SM fit	Pull
A_{LR}	0.1513 (21)	0.1509	0.2
A_{FB}^{l}	0.0171 (10)	0.0171	0.0
$A_{e,\tau}$	0.1465 (33)	0.1509	−1.4
m_W	80.451 (33)	80.429	0.7
Γ_Z	2495.2 (23)	2496.1	−0.4
R_l	20.767 (25)	20.737	1.2
σ_h	41.540 (37)	41.487	1.4
R_b	0.21646 (65)	0.21575	1.1
R_c	0.1719 (31)	0.1722	−0.1
A_b	0.922 (20)	0.9350	−0.7
A_c	0.670 (26)	0.670	0.0
m_t	174.3 (5.1)	175.3	−0.2
$\Delta\alpha_5(m_Z^2)$	0.02761 (36)	0.02761	0.0
$\alpha_S(m_Z)$		0.1168	
m_H		43	

TABLE VII. Confidence levels and Higgs boson mass predictions for global fits A–D. Each entry shows the value of m_H at the χ^2 minimum, the symmetric 90% confidence interval, the χ^2 confidence level, the confidence level for consistency with the search limit, and the combined likelihood P_C from Eq. (1.1).

	All	$-x_W^{\mathrm{OS}}[\overset{(-)}{\nu} N]$
All	**A** $m_H=94$ $37<m_H<193$ $\mathrm{C.L.}(\chi^2)=0.010$ $\mathrm{C.L.}(m_H>114)=0.30$ $P_C=0.0030$	**B** $m_H=81$ $36<m_H<190$ $\mathrm{C.L.}(\chi^2)=0.10$ $\mathrm{C.L.}(m_H>114)=0.26$ $P_C=0.026$
$-x_W^l[A_H]$	**C** $m_H=45$ $14<m_H<113$ $\mathrm{C.L.}(\chi^2)=0.066$ $\mathrm{C.L.}(m_H>114)=0.047$ $P_C=0.0031$	**D** $m_H=43$ $17<m_H<105$ $\mathrm{C.L.}(\chi^2)=0.65$ $\mathrm{C.L.}(m_H>114)=0.035$ $P_C=0.023$

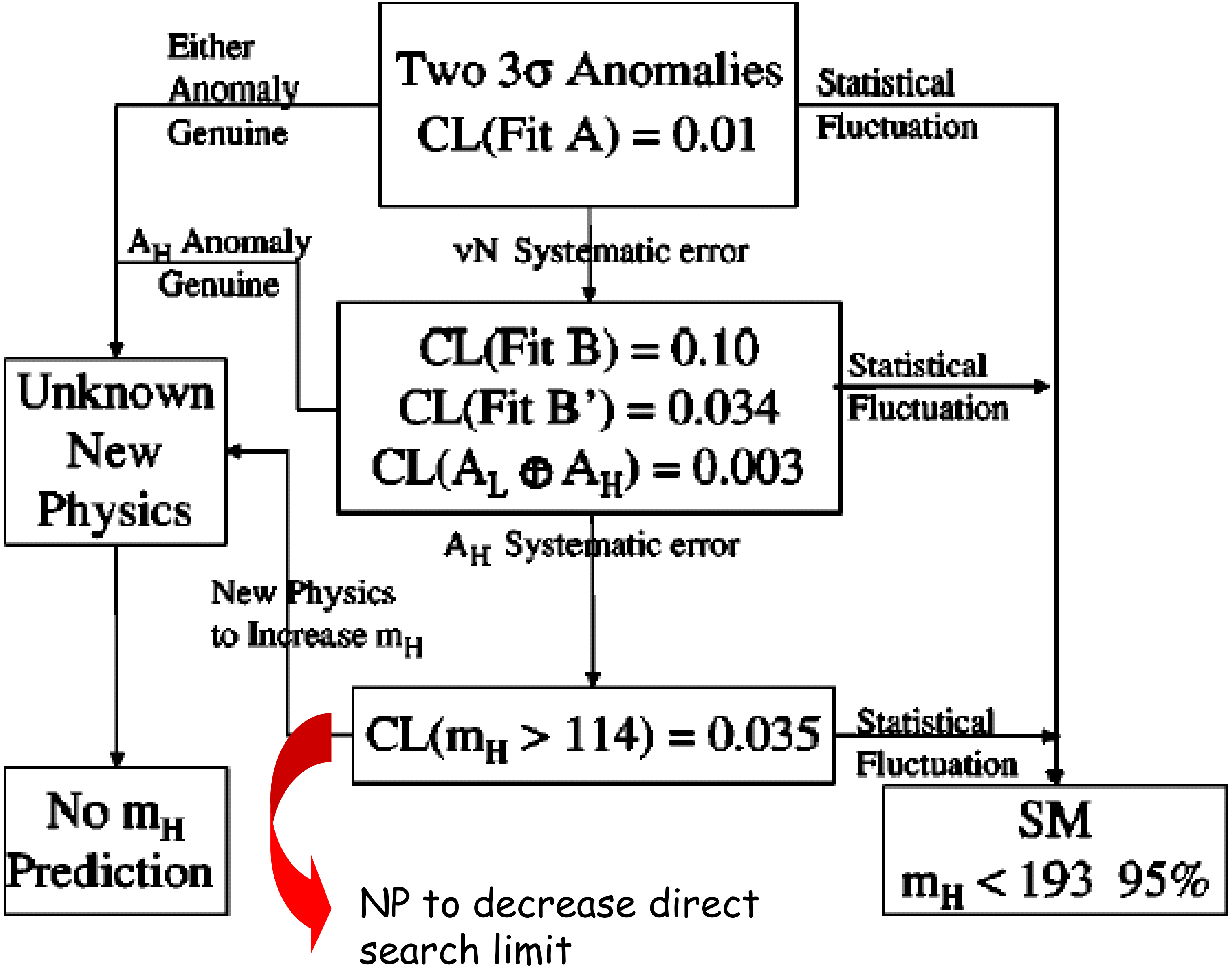


FIG. 14. Electroweak schematic diagram.

3. Then came the HyperCP 3 exotic events in 2005…

Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$

H. K. Park,[8] R. A. Burnstein,[5] A. Chakravorty,[5] Y. C. Chen,[1] W. S. Choong,[2,7] K. Clark,[9] E. C. Dukes,[10] C. Durandet,[10] J. Felix,[4] Y. Fu,[7] G. Gidal,[7] H. R. Gustafson,[8] T. Holmstrom,[10] M. Huang,[10] C. James,[3] C. M. Jenkins,[9] T. Jones,[7] D. M. Kaplan,[5] L. M. Lederman,[5] N. Leros,[6] M. J. Longo,[8,*] F. Lopez,[8] L. C. Lu,[10] W. Luebke,[5] K. B. Luk,[2,7] K. S. Nelson,[10] J.-P. Perroud,[6] D. Rajaram,[5] H. A. Rubin,[5] J. Volk,[3] C. G. White,[5] S. L. White,[5] and P. Zyla[7]

(HyperCP Collaboration)

We report the first evidence for the decay $\Sigma^+ \to p\mu^+\mu^-$ from data taken by the HyperCP (E871) experiment at Fermilab. Based on three observed events, the branching ratio is $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4}(\text{stat}) \pm 5.5(\text{syst})] \times 10^{-8}$. The narrow range of dimuon masses may indicate that the decay proceeds via a neutral intermediate state, $\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-$ with a P^0 mass of $214.3 \pm 0.5\ \text{MeV}/c^2$ and branching ratio $\mathcal{B}(\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-) = [3.1^{+2.4}_{-1.9}(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-8}$.

Theoretical investigations:

[10] X. G. He, J. Tandean and G. Valencia, Phys. Rev. D **72**, 074003 (2005).

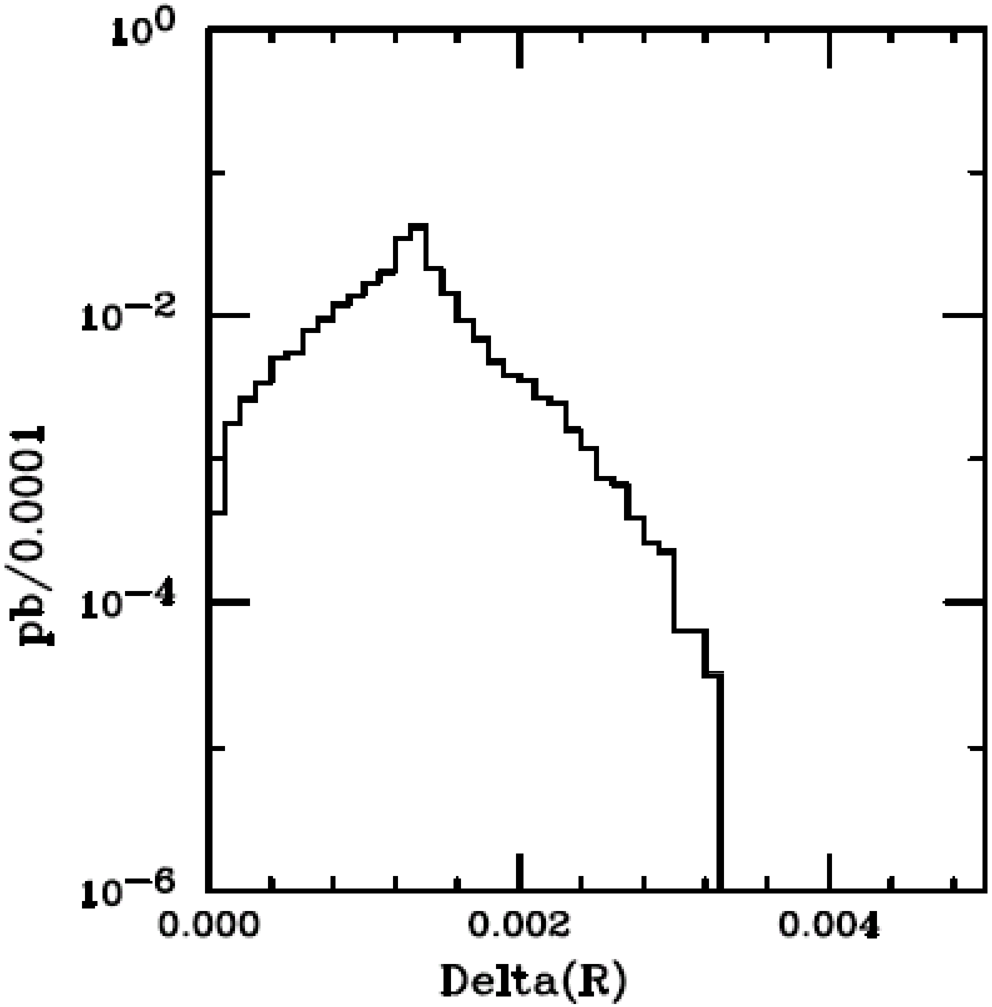
[11] X. G. He, J. Tandean and G. Valencia, Phys. Lett. B **631**, 100 (2005); N. G. Deshpande, G. Eilam and J. Jiang, Phys. Lett. B **632**, 212 (2006); C. Q. Geng and Y. K. Hsiao, Phys. Lett. B **632**, 215 (2006); D. S. Gorbunov and V. A. Rubakov, Phys. Rev. D **73**, 035002 (2006); S. V. Demidov and D. S. Gorbunov, arXiv:hep-ph/0610066; X. G. He, J. Tandean and G. Valencia, arXiv:hep-ph/0610274.

X. G. He, J. Tandean and G. Valencia, arXiv:hep-ph/0610362.

G. Hiller, Phys. Rev. D **70**, 034018 (2004).

- $\sim 2*10^9\ \Sigma$ events
- 3 events in P+dimuon decay mode
- BR can be within SM prediction
- Same di-muon mass (within 0.5 MeV) for 3 events <1% possibility
- Narrow resonance X with mass 214 MeV
- Can't be hadronic state
- Can't be scalar and vector
- Could be pseudo-scalar a in, say NMSSM or sgodstino

4. If a is boosted at high energy colliders: LEP, Tevatron and LHC



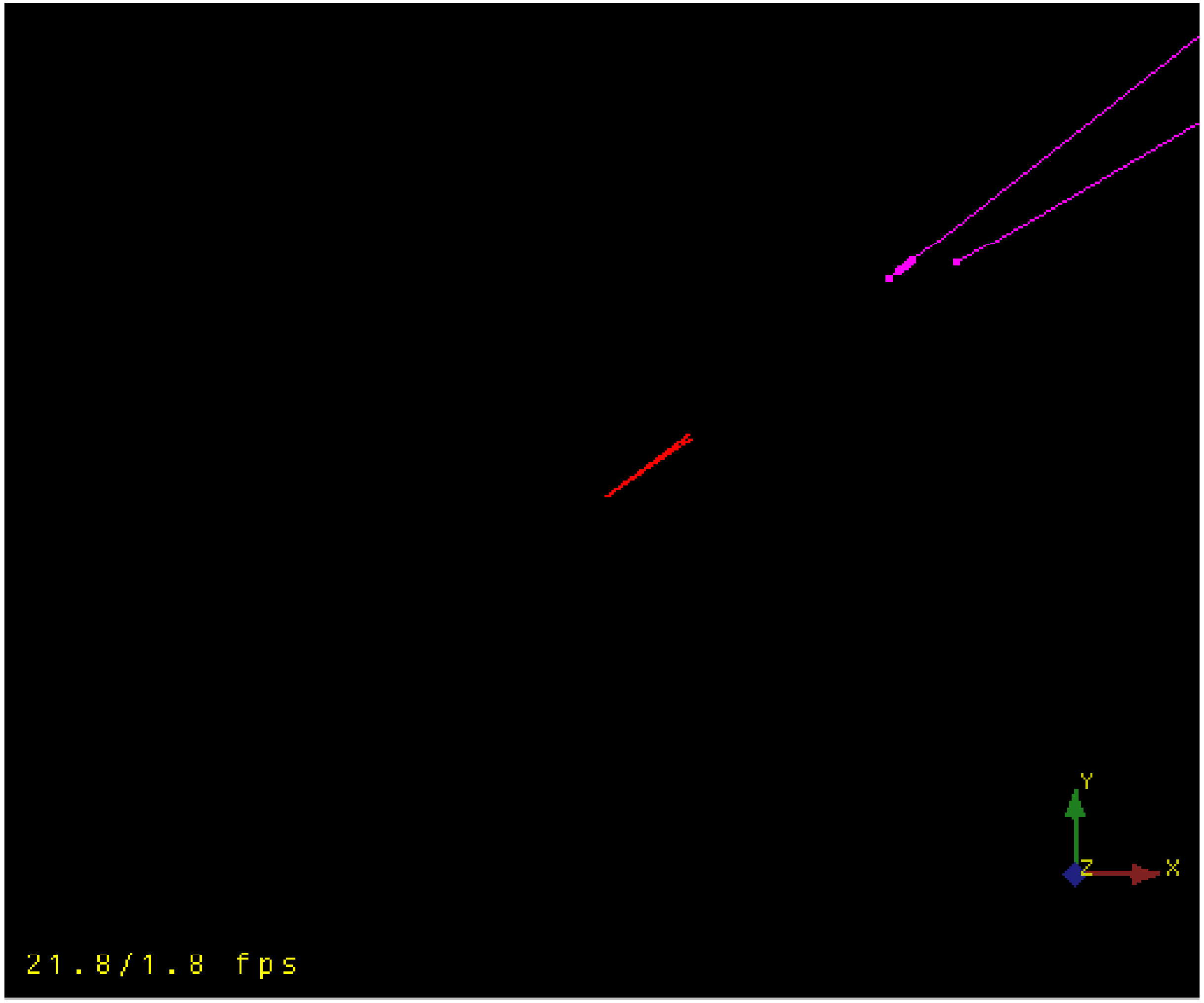
$$m_a = 214.3 \pm 0.5 \text{ MeV}$$

$$2m_\mu \approx 211.3 \text{ MeV}$$

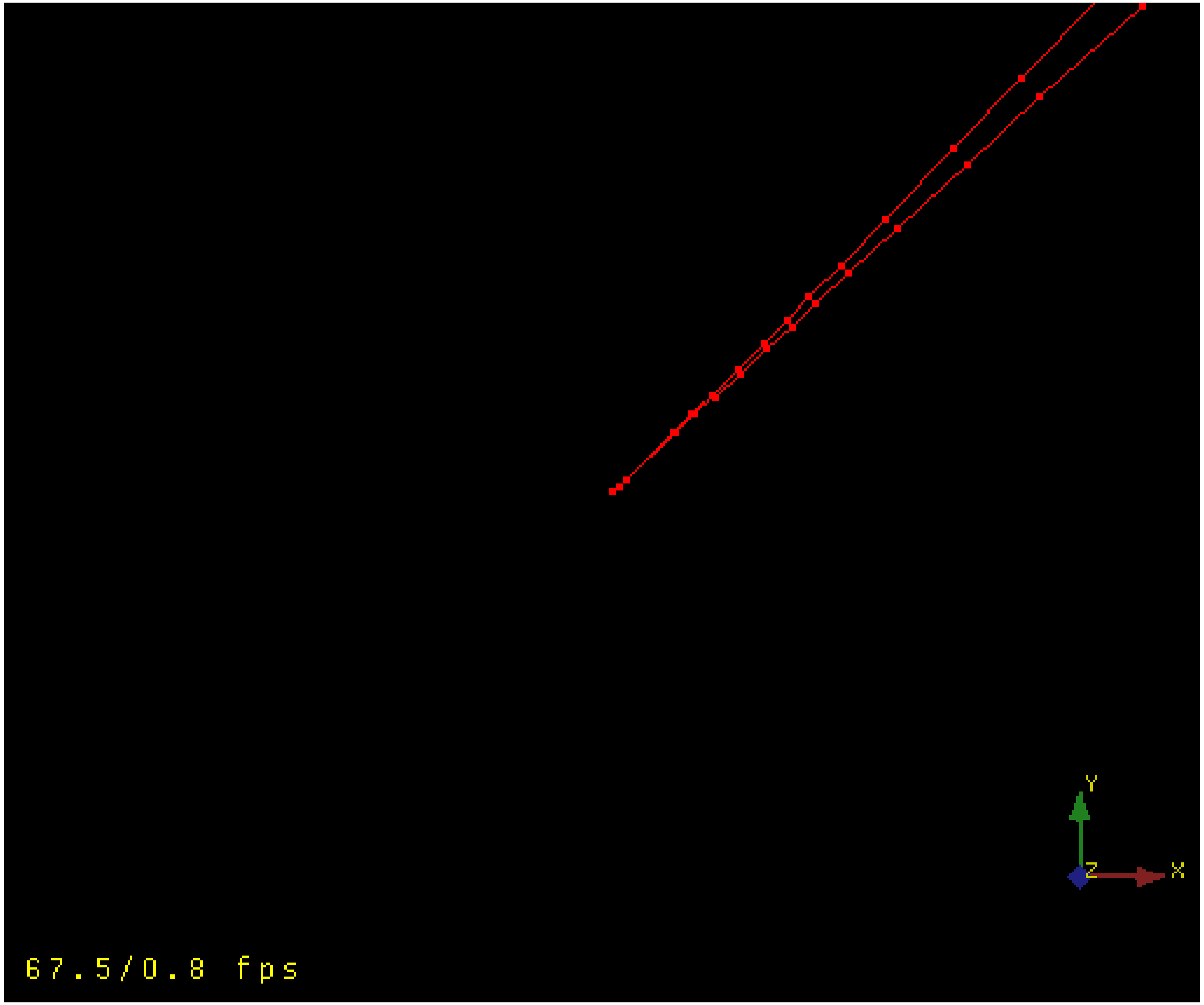
$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

FIG. 1: Distribution of ΔR between $\mu^+\mu^-$ at Tevatron for signal $gg \to h \to aa \to 4\mu$ with "Tevatron basic cuts" of Eq. (4). In all figures of this paper, $m_h = 120$ GeV and $m_a = 0.215$ GeV, except indicated otherwise. The solid (dashed) lines in all figures represent signal (background).

- Unfortunately we overlooked such kind of di-muon in the on-going and past analysis! At ATLAS, Delta(R) >0.01 in order to suppress fake muon!
- However it is possible to reconstruct such di-muon in reasonable efficiency.



Event (a->di-muon) view at CMS detector by Z.C. Yang of Peking University


Y
Z
X
67.5/0.8 fps

At CMS

netic field. The di-muon reconstruction efficiency is still substantial, for example $\sim 64\%$ for $p_T(a) = 50$ GeV.

5. If SM-like h->aa is dominant

the SM. For example, in next-to-minimal supersymmetric model (NMSSM) [5] in which a gauge singlet superfield is introduced, the SM-like CP-even Higgs boson h can mainly decay into light a pair where a is a (mostly singlet) CP-odd Higgs boson [6]. Such light a may due to the approximate R-symmetry [7]. The relevant limit on m_h can be deduced from the measurements of more final states $Zh \to Zaa \to Z\bar{b}b\bar{b}b$ or $Zh \to Zaa \to Z\bar{\tau}\tau\bar{\tau}\tau$. The weaker limit of m_h can be obtained [6] primarily due to dominance of $h \to aa$. Recently the authors of Ref. [8] studied the natural scenario to avoid in electroweak symmetry breaking while satisfying all LEP limits in NMSSM. In this scenario m_h can be lighter than 100 GeV while $Br(h \to aa) > 0.7$ and $m_a < 2m_b$.

[6] R. Dermisek and J. F. Gunion, Phys. Rev. Lett. **95**, 041801 (2005) [arXiv:hep-ph/0502105].

Consequences

- LEP can't find SM-like Higgs boson due to the fault of di-muon reconstruction.
- LEP direct search limit is meaningless in this picture, i.e. SM-like Higgs can be within 17~105 GeV (D data set).
- Tevatron and LHC can't discover Higgs boson either if they don't change analysis methods.

6. Higgs Phenomenology at LEP, Tevatron and LHC if h->4 muon can be reconstructed.

$$haa: \quad \frac{igm_Z}{2\cos\theta_W}\kappa$$

$$Br(h \to aa) \sim 1$$

$$L_{a\bar{f}f} = -\frac{i}{v}\left(l_u m_u \bar{u}\gamma_5 u + l_d m_d \bar{d}\gamma_5 d\right) a + \frac{i g_\ell m_\ell}{v}\bar{\ell}\gamma_5 \ell a$$

$l_d = -g_\ell \sim O(1), l_u = \frac{l_d}{\tan^2\beta}$ in NMSSM

$\tan\beta = 30$ and $l_d = -g_\ell = 1$

$a \to \mu^+\mu^-$ is calculated to be ~ 1

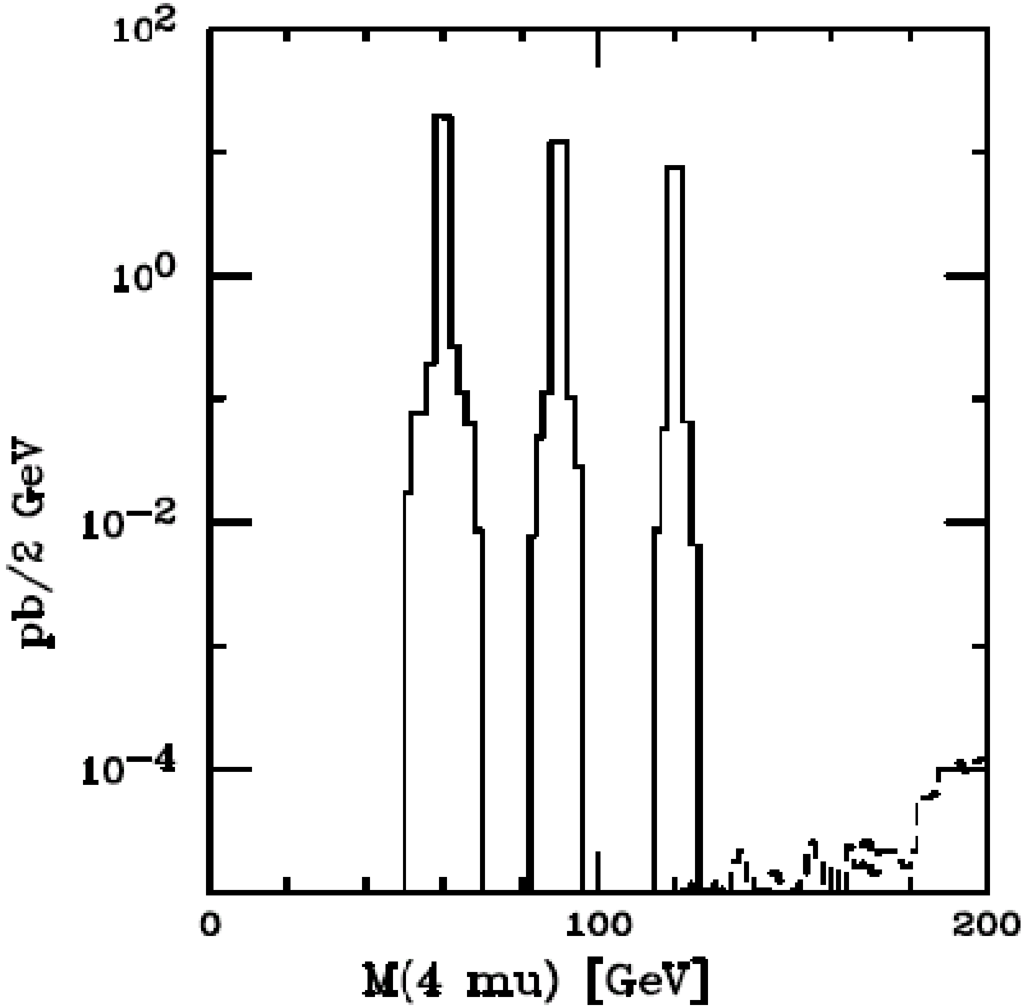


FIG. 3: Distributions of invariant mass of four μ for signal and background at LHC with $\sqrt{s} = 14$ TeV. "LHC basic cuts" are applied. Here the SM-like Higgs boson mass is taken to be 60, 90 and 120 GeV respectively.

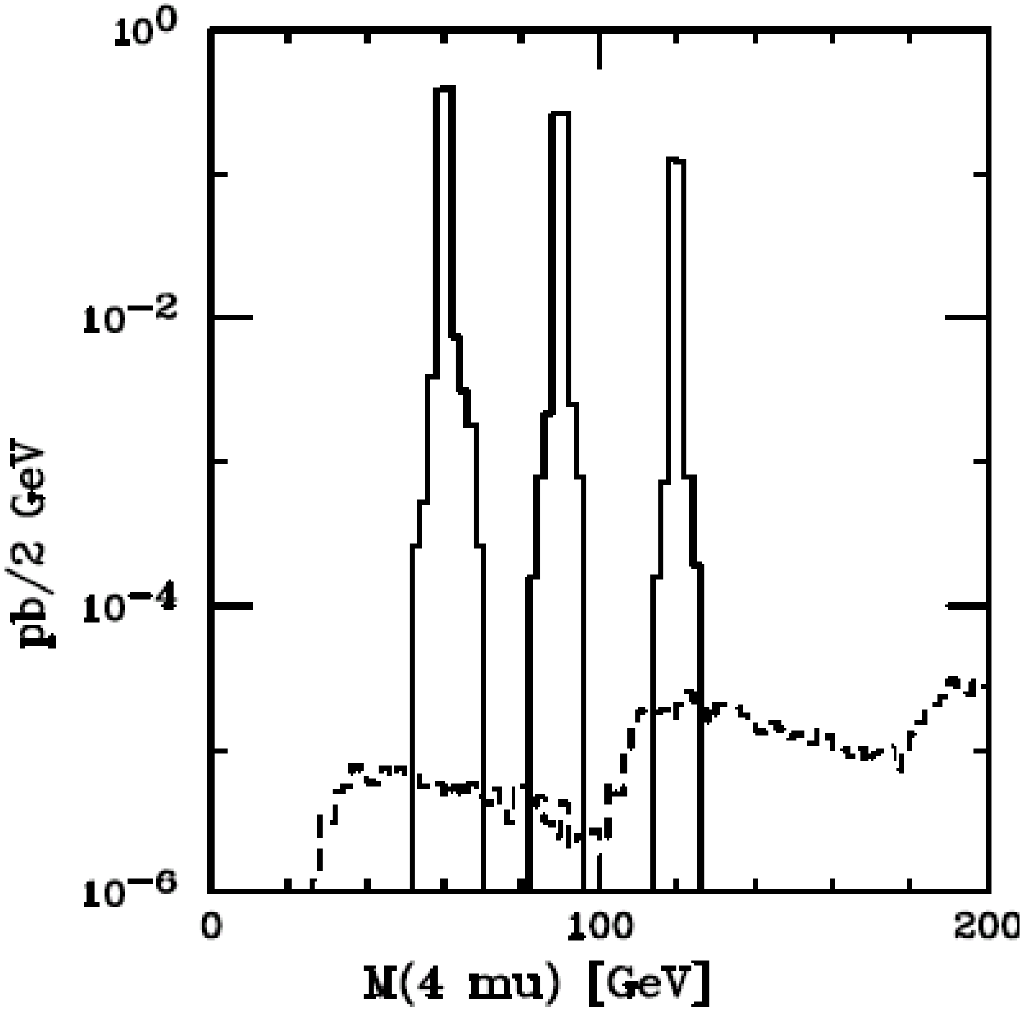


FIG. 4: Same with Fig. 3 but at Tevatron with "Tevatron basic cuts".

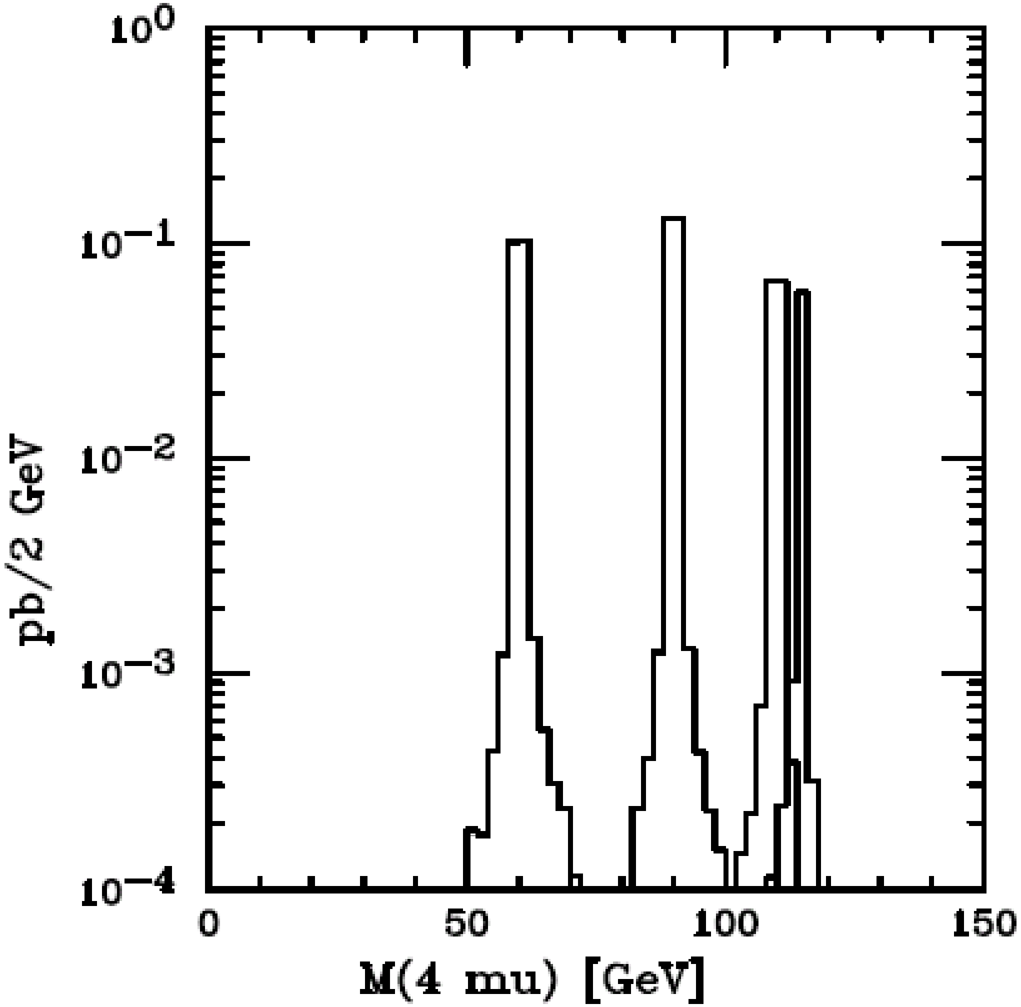


FIG. 5: Distributions of invariant mass of four μ for $e^+e^- \to Zh \to Z + 4\mu$ at LEP with $\sqrt{s} = 208$ GeV. Requirements of Eq.(4) are applied. Here the SM-like Higgs boson mass is taken to be 60, 90 110 and 115 GeV respectively.

At Tevatron

with 1 fb^{-1} integrated luminosity, for $m_h = 120$ GeV, we will have 250 signal events. Even the real efficiency for 4μ reconstruction is 10%, we still have 25 events. At LHC for the same luminosity, Higgs boson mass and reconstruction efficiency, we can have $\sim$ 1500 signal events.

at LEP

4μ from signal. For $\sqrt{s} = 208$ GeV, with 500 pb^{-1} luminosity and 10% efficiency for 4μ reconstruction, we will have about 3, 7, 13 and 10 events for $m_h = 115, 110, 90$ and 60 GeV respectively.

7. Why a is so light (214 MeV)?

Preprint typeset in JHEP style. - HYPER VERSION

Fermilab-Pub-00/134-T
hep-ph/0008192
August 17, 2000

Light Axion within the Next-to-Minimal Supersymmetric Standard Model

Bogdan A. Dobrescu* and Konstantin T. Matchev†

$$W = \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3} \hat{S}^3 \ .$$

$$V = \left| \lambda H_u^\top i\sigma_2 H_d + \kappa S^2 \right|^2 + \lambda^2 \left(|H_u|^2 + |H_d|^2 \right) |S|^2 + V_D + V_{\mathrm{soft}} \ ,$$

$$V_D = \frac{M_Z^2}{2v^2} \left(|H_u|^2 - |H_d|^2 \right)^2 + 2 \frac{M_W^2}{v^2} \left| H_u^\dagger H_d \right|^2 \ ,$$

$$V_{\mathrm{soft}} = M_{H_u}^2 |H_u|^2 + M_{H_d}^2 |H_d|^2 + M_S^2 |S|^2 + \sqrt{2} \left(m_\lambda H_u^\top i\sigma_2 H_d S - \frac{m_\kappa}{3} S^3 + \mathrm{h.c.} \right)$$

3.1 Approximate R-symmetry

The scalar potential V has no global continuous symmetry. However, in the limit where the coefficients of the trilinear terms vanish, $m_\lambda, m_\kappa \to 0$, the potential has a global $U(1)_R$ symmetry under which the S charge, $y_S \neq 0$, is half the charge of $H_u H_d$. This symmetry is spontaneously broken by the VEVs of H_u, H_d and S, so that apparently there is a Nambu-Goldstone boson in the spectrum. In addition, $U(1)_R$ is explicitly broken by the QCD anomaly. To see this, note that the Yukawa terms responsible for quark masses impose constraints on the $U(1)_R$ charges of the quarks such that the $[SU(3)_C]^2 \times U(1)_R$ anomaly is proportional to y_S. Hence the Nambu-Goldstone boson is in fact an axion, and there is a small contribution to its mass from QCD.

$$M_{A_1} = \sqrt{3s}\left(m_\kappa \sin^2\theta_A + \frac{3m_\lambda \cos^2\theta_A}{2\sin 2\beta}\right)^{1/2} + \mathcal{O}(m_{\lambda,\kappa}^{3/2}/\sqrt{v}) \,,$$

8. Conclusions

- Higgs->4mu events may lurk in the existing Tevatron/LEP data!
- LHC need to search such unique Higgs signature!
- Essential part is the 4mu reconstruction efficiency.

Analysis method matters!

- The divorce rate in China "decreases" one-half!
- 中国离婚率“降低”一半

- - Divorce is "a pair", not twice!
- —离婚是“一对”不能算两次!

Jan. 25, 2007, 《Beijing Evening》

谢谢！

Thanks!