High1-2014 KIAS-NCTS Joint workshop on Particles Physics, String theory and Cosmology.

Searching on lepton-jet, photon-jet signature for the Weinberg's Goldstone Boson Model at the LHC.

張蓉 Jung Chang Taiwan, Natl. Tsing Hua U.

2014.2.11 (Tue)

Work In Progress With
Prof. Kingman Cheung (Taiwan, Natl. Tsing Hua U. & Konkuk U.)
Prof. Shih-Chieh Hsu (University of Washington & Taiwan, Natl. Tsing Hua U.)
Chih-Ting Lu (Taiwan, Natl. Tsing Hua U. & Konkuk U.)

OutLine

- Weinberg's Goldstone Boson Model
- Collider Signature
    - lepton jet Channel : signal and BG
    - Experimental Constraints
    - Numerical Results
- Conclusion & Future Work

OutLine

- Weinberg's Goldstone Boson Model
- Collider Signature
  - lepton jet Channel : signal and BG
  - Experimental Constraints
  - Numerical Results
- Conclusion & Future Work

Goldstone Boson

- spontaneous breakdown of some exact or nearly-exact global continuous symmetry in Nature
- exactly or nearly massless
- i.e. pion in the SM
  (the Goldstone boson of spontaneous breakdown of the chiral SU(2)×SU(2) symmetry.)

Reference:
S. Weinberg, Phys. Rev. Lett. 110, 241301 (2013)
[arXiv:1305.1971 [astro-ph.CO]].

Kingman Cheung, Wai-Yee Keung and Tzu-Chiang Yuan, ”Collider Signatures of Goldstone Bosons“ arXiv:1308.4235v2 [hep-ph]

Wai-Yee Keung, Kin-Wang Ng, Huitzu Tu, and Tzu-Chiang Yuan, “Supernova Bounds on Weinberg’s Goldstone Bosons“ arXiv:1312.3488v1 [hep-ph]

Reference:
•S. Weinberg, Phys. Rev. Lett. 110, 241301 (2013) [arXiv:1305.1971 [astro-ph.CO]].

•Kingman Cheung, Wai-Yee Keung and Tzu-Chiang Yuan, arXiv:1308.4235v2 [hep-ph]

•Wai-Yee Keung, Kin-Wang Ng, Huitzu Tu, and Tzu-Chiang Yuan, arXiv: 1312.3488v1 [hep-ph]

•G. Hinshaw et al. [WMAP collaboration], arXiv: 1212.5226

•P. A. R. Ade et al. [Planck collaboration], arXiv: 1303.5076

Weinberg's Goldstone Boson Model

- Correlations of temperature fluctuations in the cosmic microwave background depend on the effective number of neutrino species (Neff)

total radiation energy density : $\rho_\nu = N_{eff}\frac{7}{8}(\frac{4}{11})^{\frac{4}{3}}\rho_\gamma$

- WMAP9 +eCMB : Neff = 3.89 ± 0.67
Planck+WP+highL : Neff = 3.36±0.34

both at the 68% confidence level.

- Weinberg suggest :
nearly massless weakly interacting particle as a fractional cosmic neutrino?
⇒ the Goldstone bosons !

√spontaneous breakdown of some exact or nearly-exact global continuous symmetry in Nature
√exactly or nearly massless

Goldstone Boson as fractional Cosmic Neutrinos

Reference:
- S. Weinberg, Phys. Rev. Lett. 110, 241301 (2013) [arXiv:1305.1971 [astro-ph.CO]].
- Kingman Cheung, Wai-Yee Keung and Tzu-Chiang Yuan, arXiv:1308.4235v2 [hep-ph]
- Wai-Yee Keung, Kin-Wang Ng, Huitzu Tu, and Tzu-Chiang Yuan, arXiv: 1312.3488v1 [hep-ph]
- G. Hinshaw et al. [WMAP collaboration], arXiv: 1212.5226
- P. A. R. Ade et al. [Planck collaboration], arXiv: 1303.5076

Weinberg's Goldstone Boson Model

- Goldstone bosons could remain in thermal equilibrium in the early Universe until they went out of equilibrium at a temperature above but not much above the muon mass.
  ⇒ A neutral Goldstone boson might look like (1/2)/(7/8) = 4/7 of a neutrino

  * If Goldstone bosons went out of equilibrium much earlier, then neutrinos but not Goldstone bosons would have been heated by the annihilation of the various species of particles of the Standard Model, and the contribution of Goldstone bosons to Neff would be much less than 4/7.

- Suppose GB decoupled not far above muon annihilation, from that time on, GB is then free propagating across the Universe with constant Ta.
  (T : temperature, a_B is the radiation energy constant)

  cosmic entropy density
  just before muon annihilation : $s = \frac{4a_B T^3}{3}(1+\frac{7}{4}+\frac{7}{4}+\frac{21}{8})$ ~ $57/8\, T^3$
  right after muon annihilation : $s = \frac{4a_B T^3}{3}(1+\frac{7}{4}+\frac{21}{8})$ ~ $43/8\, T^3$

- the contribution of Goldstone bosons to Neff would be :
  Neff = $(4/7) * (43/57)^{4/3} = 0.39$

Weinberg's Goldstone Boson Model

•S. Weinberg, Phys. Rev. Lett. 110, 241301 (2013) [arXiv:1305.1971 [astro-ph.CO]].

- logical possibility Goldstone Boson can be :
presence of a global hidden symmetry that the usual SM particles do not experience

- simplest choice : global hidden U(1) symmetry (with nonzero W qn)
all the hidden particles carry non-vanishing W charges
all SM particles are neutral W=0

- Add a complex U(1) scalar singlet S to SM :

GB weak interactions with the SM particles via a Higgs portal

$$\mathcal{L} = (\partial_\mu S^\dagger)(\partial^\mu S) + \mu^2 S^\dagger S - \lambda (S^\dagger S)^2 - \boxed{g(S^\dagger S)(\Phi^\dagger \Phi)} + \mathcal{L}_{sm}$$

$$\mathcal{L}_{sm} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) + \mu_{sm}^2 \Phi^\dagger \Phi - \lambda_{sm} (\Phi^\dagger \Phi)^2$$

$$S(x) = \frac{1}{\sqrt{2}}(< r > + \underline{r(x)}) e^{i2\underline{\alpha(x)}}$$

Goldstone Boson

Radial Field

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ < \phi > + \underline{\phi(x)} \end{pmatrix}$$

SM Higgs

S(x) is a complex singlet scalar field neutral under the SM symmetries with a nonzero W qn, and Φ is the SM Higgs doublet with W = 0.

Weinberg's Goldstone Boson Model

•S. Weinberg, Phys. Rev. Lett. 110, 241301 (2013) [arXiv:1305.1971 [astro-ph.CO]].

SM & Dark Higgs Mixing : $\begin{pmatrix} H(x) \\ \sigma(x) \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi(x) \\ r(x) \end{pmatrix}$

$$< \phi >^2 = \frac{4\lambda\mu_{sm}^2 - 2g\mu^2}{4\lambda\lambda_{sm} - g^2}$$

$$< r >^2 = \frac{4\lambda_{sm}\mu^2 - 2g\mu_{sm}^2}{4\lambda\lambda_{sm} - g^2}$$

$$\theta \ll 1, m_\sigma \ll m_H :$$

Higgs mass & mixing angle :

$$m_H^2 \approx 2\lambda_{sm} < \phi >^2$$

$$m_\sigma^2 \approx 2\lambda < r >^2$$

$$\theta \approx \frac{g < r >< \phi >}{m_H^2 - m_\sigma^2}$$

Higgs & GB Couplings :

$$\mathcal{L}_{H\alpha\alpha} = \frac{\theta}{< r >} H(\partial_\mu \alpha)(\partial^\mu \alpha)$$

$$\mathcal{L}_{\sigma\alpha\alpha} = \frac{1}{< r >} \sigma(\partial_\mu \alpha)(\partial^\mu \alpha)$$

$$\mathcal{L}_{H\sigma\sigma} = -\frac{g}{2} < \phi > H\sigma^2$$

Reference:
[1]S. Weinberg, Phys. Rev. Lett. 110, 241301 (2013) [arXiv:1305.1971 [astro-ph.CO]].

[2]Kingman Cheung, Wai-Yee Keung and Tzu-Chiang Yuan, arXiv:1308.4235v2 [hep-ph]

[3]Wai-Yee Keung, Kin-Wang Ng, Huitzu Tu, and Tzu-Chiang Yuan, arXiv: 1312.3488v1 [hep-ph]

Constraints on Weinberg's GB model

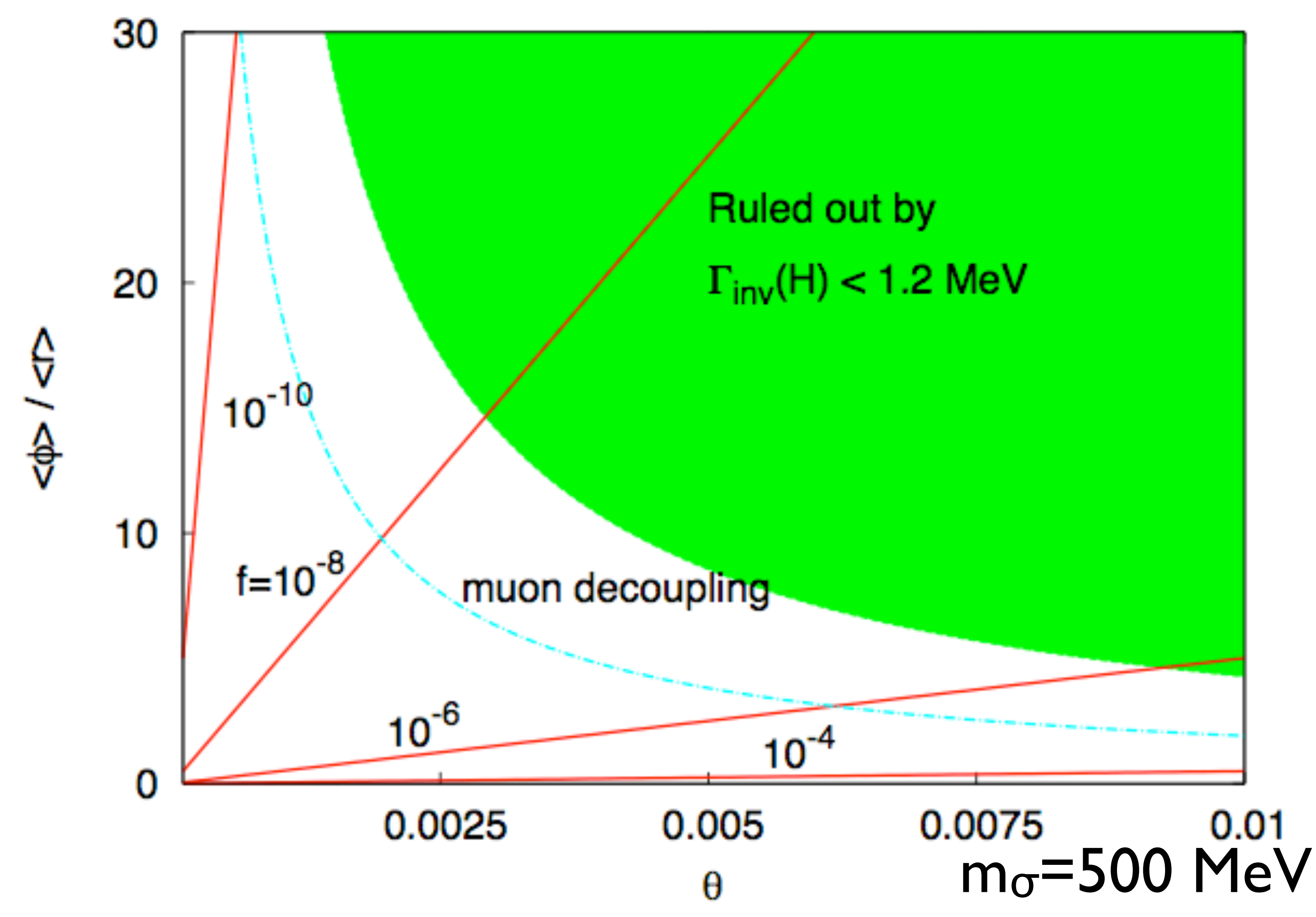
- Higgs Invisible Width $\theta \frac{<\phi>}{<r>} \leq 0.043$ [2] , $|g| < 0.009$ [1]
  - non- standard decay width of the Higgs boson to be less than 1.2 MeV (BR ~ 22%) at 95% CL.

small mixing angle, $m_H >> m_\sigma$
small mixing angle, $<r> < 7$ TeV

- Muon Decoupling $\frac{g^2 m_\mu^7 m_{PL}}{m_\sigma^4 m_H^4} \approx 1$ [1] if g=0.005, m_H=125 GeV, then m_σ=500 MeV
  - the annihilation rate of αα ↔μ+μ− must be of the same order of the Hubble expansion rate at the temperature $k_BT \approx m_\mu$

- Supernova Bounds $|g| \lesssim 0.011(m_r/500MeV)^2$ [3]
  - calculate by energy loss rates through the emission of GB in a post-collapse supernova core

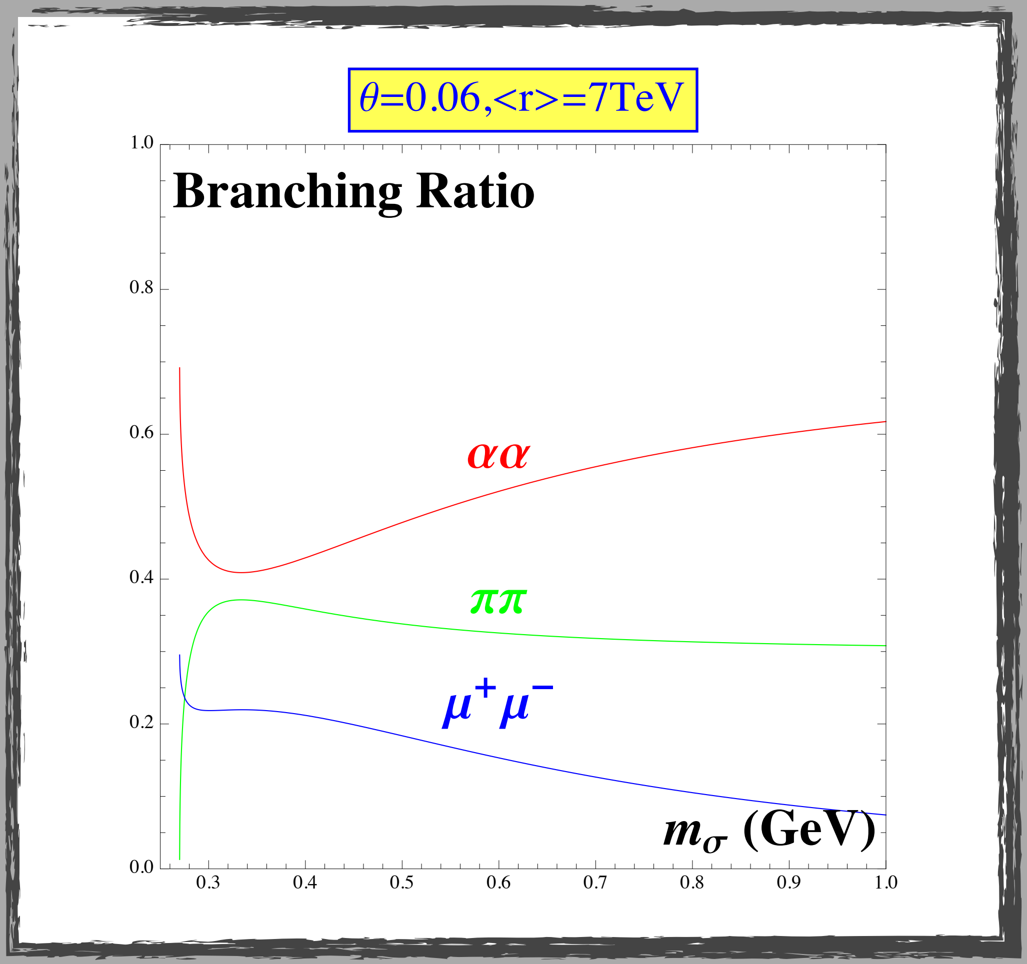
Parameter Space

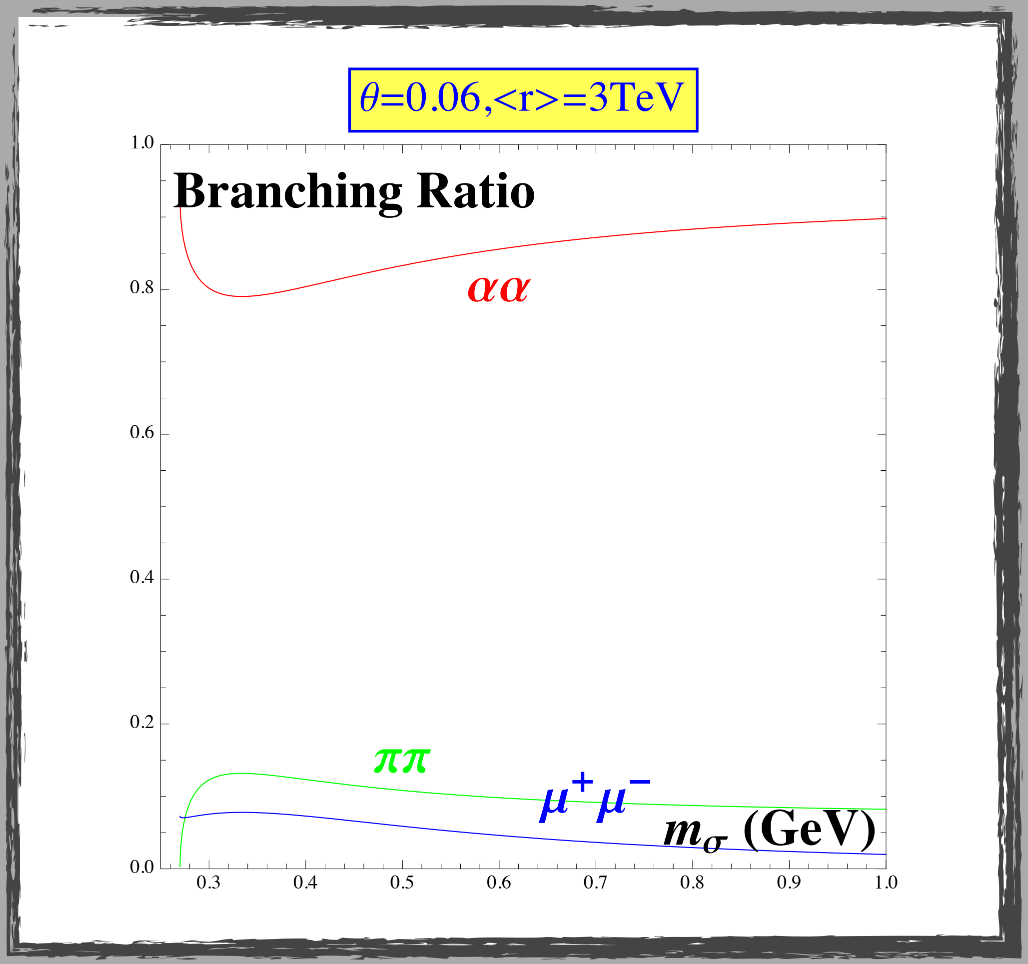


m_σ=500 MeV

Reference:
Kingman Cheung, Wai-Yee Keung and Tzu-Chiang Yuan, arXiv:1308.4235v2 [hep-ph]

Branch Ratio of σ



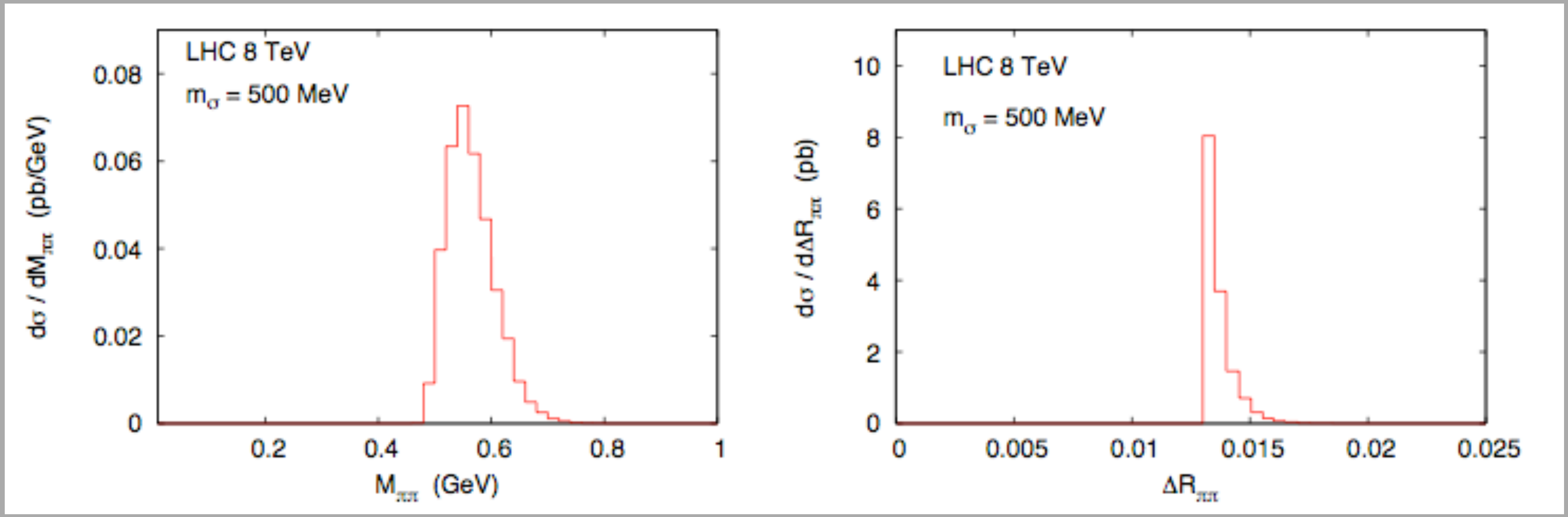


For the m_σ is small, dR of σ decay particles is small.
σ mostly will decay into mET (αα) then ππ and μμ.
Consider the σ→π0 π0 (π0 ~100% decay into ϒϒ)

If the σ field is much lighter than the Higgs boson, e.g. in sub-GeV region, we can have the lepton-jet or photon-jet signatures.

IM and ΔR example :

$$pp \to h, h \to \sigma\sigma, \sigma \to \pi\pi$$



Angular separation between the two pions are very small

$$\sim 2m_\sigma/p_{T\sigma} = 1GeV/60GeV \approx 0.015$$

Reference:
Kingman Cheung, Wai-Yee Keung and Tzu-Chiang Yuan, arXiv:1308.4235v1 [hep-ph]

OutLine

- Weinberg’s Goldstone Boson Model
- Collider Signature
  - lepton jet Channel : signal and BG
  - Experimental Constraints
  - Numerical Results
- Conclusion & Future Work

lepton jet Channel : signal and BG

Signal

Gluon Fusion :

2μ + mET $pp \to h, h \to \sigma\sigma, \sigma \to \alpha\alpha, \sigma \to \mu^+\mu^-$

4μ $pp \to h, h \to \sigma\sigma, \sigma \to \mu^+\mu^-$

There can be associated production or other production mechanism, here we first focus on the gluon fusion production and the lepton jet final states.

BG

2μ + mET

$$\mathrm{BG1}: \; pp \to \mu^+\mu^-\nu\overline{\nu}$$

$$\mathrm{BG2}: \; pp \to h, h \to WW^*, \qquad W, W^* \to \mu\nu$$

4μ

$$\mathrm{BG1}: \; pp \to \mu^+\mu^-\mu^+\mu^-$$

$$\mathrm{BG2}: \; pp \to h, h \to ZZ, Z \to \mu^+\mu^-$$

Experimental Constraints

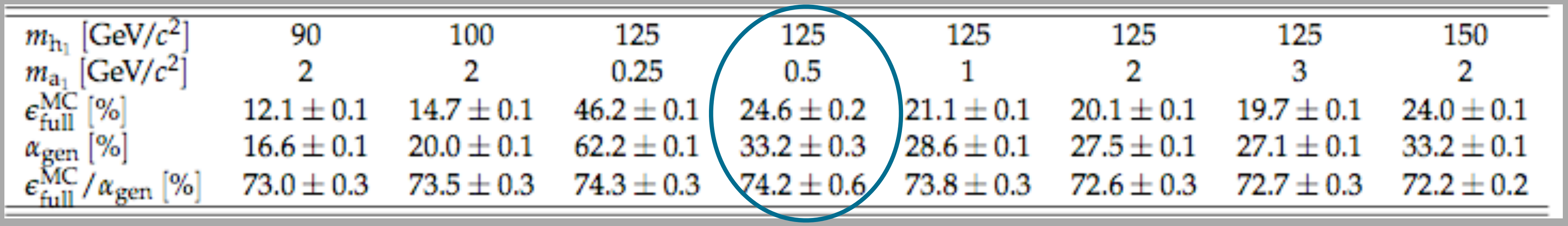
One Lepton jet + X

Two Lepton jet + X

$$2m_\mu < m_a < 2m_\tau$$

$$\sigma(pp \rightarrow 2a + X)Br(a \rightarrow \mu\mu)^2\alpha_{gen} < 0.24fb$$

$$Br(h \rightarrow aa)Br(a \rightarrow \mu\mu)^2 < 1.2 \times 10^{-5}$$



m_{h_1} [GeV/c^2]	90	100	125	125	125	125	125	150
m_{a_1} [GeV/c^2]	2	2	0.25	0.5	1	2	3	2
ϵ_{full}^{MC} [%]	12.1 ± 0.1	14.7 ± 0.1	46.2 ± 0.1	24.6 ± 0.2	21.1 ± 0.1	20.1 ± 0.1	19.7 ± 0.1	24.0 ± 0.1
α_{gen} [%]	16.6 ± 0.1	20.0 ± 0.1	62.2 ± 0.1	33.2 ± 0.3	28.6 ± 0.1	27.5 ± 0.1	27.1 ± 0.1	33.2 ± 0.1
$\epsilon_{full}^{MC}/\alpha_{gen}$ [%]	73.0 ± 0.3	73.5 ± 0.3	74.3 ± 0.3	74.2 ± 0.6	73.8 ± 0.3	72.6 ± 0.3	72.7 ± 0.3	72.2 ± 0.2

α_{gen} : geometric and kinematic acceptances

Reference:
CMS Collaboration, S. Chatrchyan et. al., Search for Light Resonances Decaying into Pairs of Muons as a Signal of New Physics, JHEP 1107 (2011) 098, [arXiv:1106.2375].

Search for a non-standard-model higgs boson decaying to a pair of new light bosons in four-muon final states, Tech. Rep. CMS-PAS-HIG-13-010, CERN, Geneva, 2013.

David Curtin, Rouven Essig, Stefania Gori, Prerit Jaiswal, Andrey Katz, Tao Liu, Zhen Liu, David McKeen, Jessie Shelton, Matthew Strassler, Ze'ev Surujon, Brock Tweedie and Yi-Ming Zhong1, "Exotic Decays of the 125 GeV Higgs Boson" arXiv:1312.4992v1 [hep-ph]

Numerical Results

Signal

(1) case1 :
mixing angle $\theta = 0.06$
$< r >= 7TeV$
$m_\sigma = 500MeV$

(2) case2 :
mixing angle $\theta = 0.06$
$< r >= 6TeV$
$m_\sigma = 500MeV$

(3) case3 :
mixing angle $\theta = 0.06$
$< r >= 5TeV$
$m_\sigma = 500MeV$

(4) case4 (Consider for 13 TeV):
mixing angle $\theta = 0.06$
$< r >= 4TeV$
$m_\sigma = 500MeV$

BG & Signal are generated with MG5
Detector simulation with Delphes 3
Significance estimate with :

$$S = \frac{N_S}{\sqrt{N_{B1} + N_{B2} + dN_{B1}^2 + dN_{B2}^2}}$$

Numerical Results

$2\mu + missing\ E_T$ final state :

For $\sqrt{s} = 8TeV$, $L = 20fb^{-1}$:
Basic cuts :
(1) $20GeV < P_{T_{l_1}} < 150GeV$, $10GeV < P_{T_{l_2}} < 150GeV$, $|\eta_{l_1-2}| < 2.5$
(2) $50GeV < mET < 150GeV$
Special cut :
$M_{\mu^+\mu^-} < 1GeV$

For $\sqrt{s} = 13TeV$, $L = 10fb^{-1}$:
Basic cuts :
(1) $20GeV < P_{T_{l_1}} < 150GeV$, $10GeV < P_{T_{l_2}} < 150GeV$, $|\eta_{l_1-2}| < 2.5$
(2) $50GeV < mET < 200GeV$
Special cut :
$M_{\mu^+\mu^-} < 1GeV$

8 TeV			
s1	s2	s3	
5.33	4.53	3.33	
13 TeV			
s1	s2	s3	s4
5.87	5.02	3.84	2.18

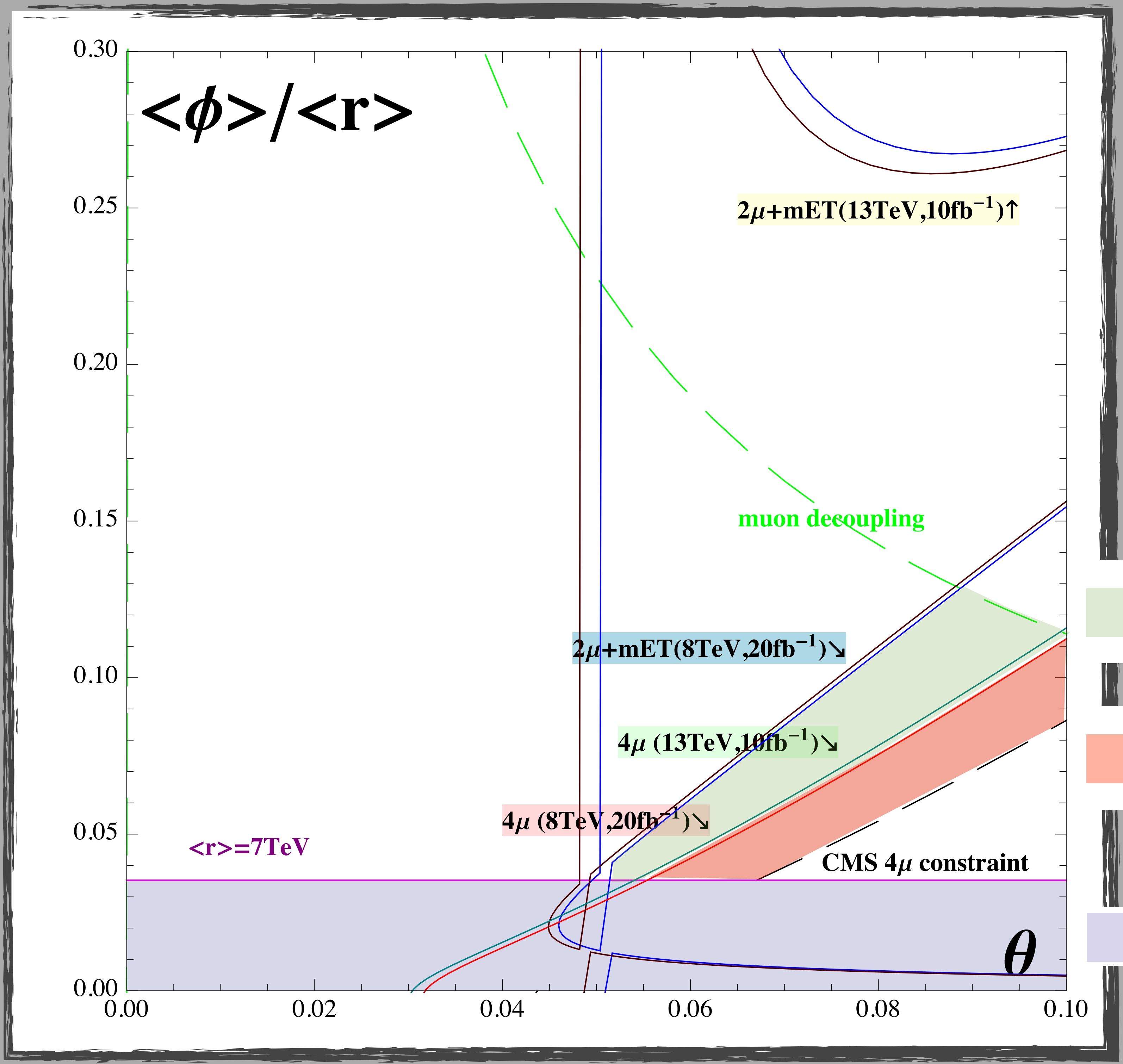
4μ final state :

For $\sqrt{s} = 8TeV$, $L = 20fb^{-1}$:
Basic cuts :
(1) $20GeV < P_{T_{\mu_1}} < 150GeV$, $10GeV < P_{T_{\mu_2}} < 150GeV$, $|\eta_{\mu_1-2}| < 2.5$
Which μ represents for both μ^+ and μ^-. (The cuts had applied on all 4 muons, $\mu_1 : \mu_1^+, \mu_1^-$, $\mu_2 : \mu_2^+, \mu_2^-$.)
Special cut :
$|M_{\mu^+\mu^-\mu^+\mu^-} - 126| < 15GeV$
$M_{\mu^+\mu^-} < 1GeV$
(the μ pair are select by opposite charged muon with the minimal $|dR(\mu_1, \mu_2)| + |dR(\mu_3, \mu_4)|$ and the smallest $|IM(\mu_1, \mu_2) - 0.5| + |IM(\mu_3, \mu_4) - 0.5|$ from the combination of 4 muon.)

For $\sqrt{s} = 13TeV$, $L = 10fb^{-1}$:
Same as 8 TeV.

8 TeV			
s1	s2	s3	
3.43	2.17	1.11	
13 TeV			
s1	s2	s3	s4
4.17	2.66	1.36	0.51

Conclusion for the numerical results



🟩 allowed region for 8TeV search for 2μ+mET

🟥 allowed region for 8TeV search for 4μ & 2μ+mET

🟪 small mixing angle ⇒ limit <r> < 7 TeV region

OutLine

- Weinberg's Goldstone Boson Model
- Collider Signature
    - lepton jet Channel : signal and BG
    - Experimental Constraints
    - Numerical Results
- Conclusion & Future Work

Conclusion

- The interesting lepton jet signature (4μ, 2μ + mET) of Weinberg's Goldstone Boson model, still got search potential even with the LHC-8, $\mathscr{L}$=20 fb^{-1}.

Future Work

- The Photon jet channel Analysis
  i.e. $pp \to h, h \to \sigma, \sigma \to \pi^0\pi^0, \pi^0 \to \gamma\gamma$
- Collider Signature with other Production channel
  i.e. associated production,...

Thanks for your attention!

張蓉 Jung Chang Taiwan, Natl.Tsing Hua U.

2014.2.11 (Tue)

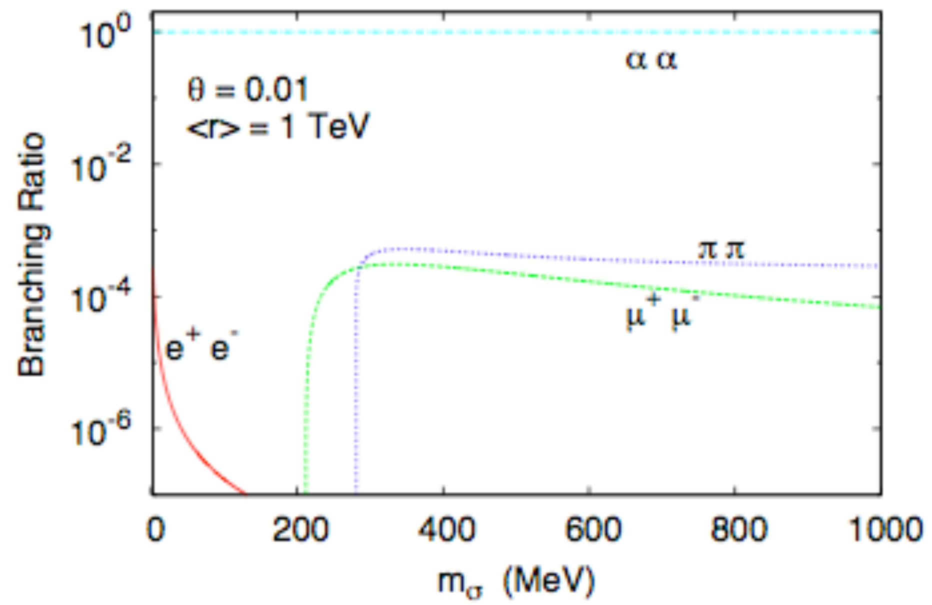
High1-2014 KIAS-NCTS Joint workshop on Particles Physics, String theory and Cosmology.

Backup Slides

2014.2.11 (Tue)

Branch Ratio of σ

For small mixing Angle (0.01)



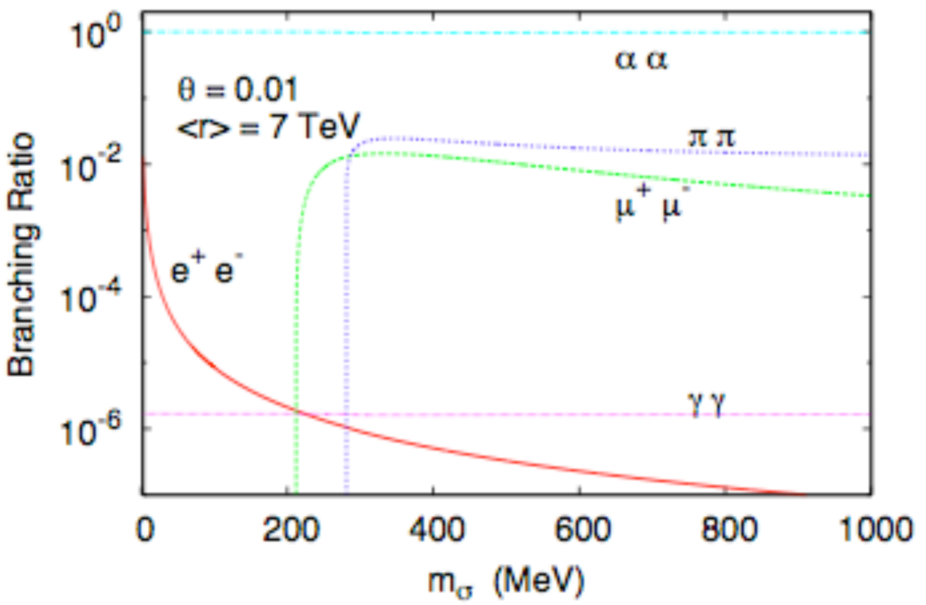


FIG. 2. Decay branching ratios for the σ field for (a) $\langle r \rangle = 1$ TeV and (b) $\langle r \rangle = 7$ TeV. The mode $\pi\pi$ includes $\pi^+\pi^-$ and $\pi^0\pi^0$. The mixing parameter θ is set at 0.01.

Reference:
Kingman Cheung, Wai-Yee Keung and Tzu-Chiang Yuan, arXiv:1308.4235v2 [hep-ph]