Discussion on the scientific potential of muon beams
18 Nov 2015

Energy frontier - theory

G.F. Giudice

The strength of a μ−beam facility lies in its richness:

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier

Take 1

Get 4 !

μ−colliders can essentially do the HE program of e^+e^- colliders with added bonus (and some limitations)

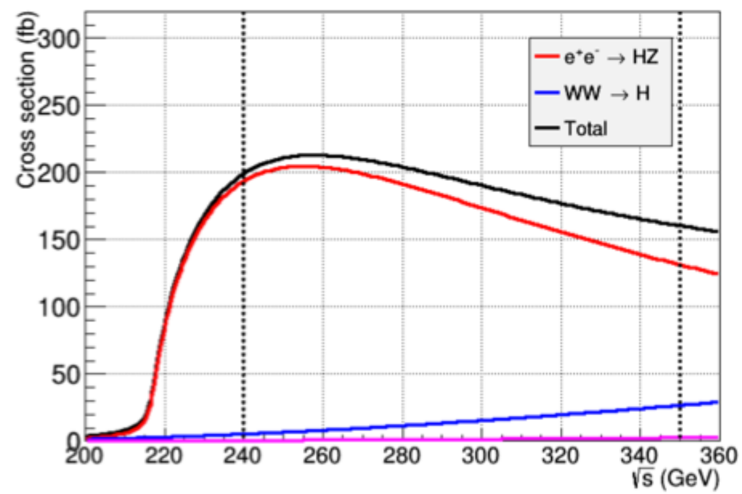
Added value for physics

1. Resonant Higgs production

- $\sigma(\mu^+\mu^- \longrightarrow h)$=41 pb can compensate for lower luminosity (~ 10^{-2} w.r.t. e^+e^-)

  At e^+e^- colliders

  $\sigma(e^+e^- \longrightarrow Zh) < 0.2$ pb



- Unique measurements of m_h and Γ_h

  ($m_h \sim 0.1$ MeV, $\Gamma_h \sim 0.2$ MeV)

- Test of 2nd generation Higgs couplings ($h \longrightarrow \mu^+\mu^-$)

2. Precision in HE measurements & searches

- Studies of threshold pair-production and narrow resonances exploiting the very accurate knowledge of beam-energy spectrum
- Flexibility in the choice of centre-of-mass energy

3. Test of flavour structure

- 2^{nd} generation couplings

Resonant Higgs production

$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2\,\mathrm{Br}(h\to\mu^+\mu^-)\,\mathrm{Br}(h\to X)}{(\hat{s}-m_h^2)^2+\Gamma_h^2 m_h^2}$$

Breit-Wigner ⇒ 3 parameters ⇒ 3 physical observables

peak location ⇔ m_h

peak shape ⇔ Γ_h

peak height ⇔ $\mathrm{Br}(h\to\mu^+\mu^-)\,\mathrm{Br}(h\to X)$

Convolution with Gaussian luminosity distribution + ISR

$$\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}} = \frac{1}{\sqrt{2\pi\Delta}} \exp[\frac{-(\sqrt{\hat{s}} - \sqrt{s})^2}{2\Delta^2}]$$

energy spread

$$\Delta = R\sqrt{s}/\sqrt{2}$$

R = relative energy resolution

$$\sigma_{\text{eff}}(s) = \int d\sqrt{\hat{s}}\, \frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}} \sigma(\mu^+\mu^- \to h \to X)$$

$$\sigma_{\text{peak}} = \sigma(\sqrt{s} = m_H) = \frac{4\pi\, B(H \to \mu^+\mu^-)\, B(H \to X)}{m_H^2}\, \eta\, \pi^{1/2}\, A\, e^{A^2}(1 - \text{Erf}(A))$$

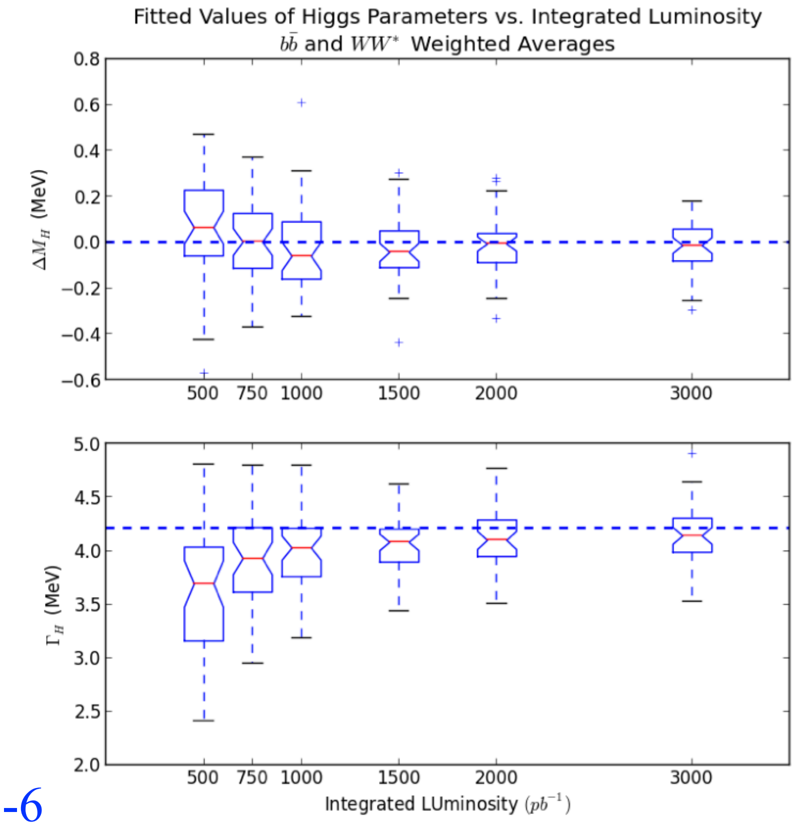
$$A = \frac{\Gamma_h}{2\sqrt{2}\Delta}$$

IRS reduction $\eta = 0.55$

1503.05046
1509.02406

Goal in beam energy resolution $\Delta \sim \Gamma_h = 4.1$ MeV
($R \sim 4\times10^{-5}$)

Excellent precision in Higgs mass and width



1304.5270

$\Delta m_h \sim 0.1$ MeV $\Rightarrow$ $\Delta m_h/m_h \sim 10^{-6}$

Best measured fundamental boson mass

$(\Delta m_Z/m_Z \sim 2\times10^{-5}\ ,\ \Delta m_W/m_W \sim 2\times10^{-4})$

No immediate physical consequences (present and future EW tests, vacuum stability dominated by Δm_t, susy prediction dominated by theoretical uncertainty), but it is a measurement of a fundamental SM parameter.

Higgs width

$\Delta\Gamma_h \sim 0.2$ MeV $\Rightarrow$ $\Delta\Gamma_h/\Gamma_h \sim 5\%$

Test of Higgs couplings and new (hidden) decay modes

Suppose $\Gamma_h = \Gamma_{SM} + \Gamma_{inv}$ $\Rightarrow$
$Br_{inv} = 1 - \Gamma_{SM}/\Gamma$ can be tested $\sim 5\%$

Higgs couplings

Channel	δM_H (MeV)	$\delta\Gamma_H$ (MeV)	$\delta Br(h \to X)$
$b\bar{b}$	0.1	0.4	0.05
WW^*	0.07	0.2	0.01
Combined	0.06	0.18	—

1308.2143

With $\int L \sim 4$ fb^{-1}:

$h \to bb$ with 5% precision

$h \to WW$ with 1% precision

$h \to cc$ visible at 8σ

$h \to \mu\mu$ with few% precision

Error on	μμ Collider
m_H (MeV)	0.06
Γ_H (MeV)	0.17
g_{Hbb}	2.3%
g_{HWW}	2.2%
$g_{H\tau\tau}$	5%
$g_{H\gamma\gamma}$	10%
$g_{H\mu\mu}$	2.1%

With ~ 10 yrs running
(P. Janot, talk at FCC-ee, 24 Sep 2015)

Curiosity: QED RG running of $g_{h\mu\mu}$

$$\frac{\Delta g_{h\mu\mu}}{g_{h\mu\mu}} \equiv \frac{g_{h\mu\mu}(m_\mu) - g_{h\mu\mu}(m_h)}{g_{h\mu\mu}(m_\mu)} \approx \frac{\alpha}{\pi} \ln \frac{m_h}{m_\mu} \approx \text{few } \%$$

Why is it interesting to test 2nd generation Higgs coupling?

The flavour puzzle: why are 1st and 2nd gen. Yukawa small?

Example 1

0804.1753

$$H\bar{\psi}_L^{(3)}\psi_R^{(3)} \quad + \quad \frac{(H^+H)^{n_{ij}}}{\Lambda^{2n_{ij}}} H\bar{\psi}_L^{(i)}\psi_R^{(j)}$$

$$\downarrow \qquad\qquad \downarrow$$

$$m^{(3)} = O(v) \qquad\qquad m^{(ij)} = O\left(\frac{v^{2n_{ij}+1}}{\Lambda^{2n_{ij}}}\right)$$

$$y^{(3)} = \frac{m^{(3)}}{v} \qquad\qquad y^{(ij)} = (2n_{ij}+1)\frac{m^{(ij)}}{v}$$

$$\frac{y^{(3)}}{y_{SM}^{(3)}} = 1 \qquad\qquad \frac{y^{(ij)}}{y_{SM}^{(ij)}} = 2n_{ij}+1$$

Example 2

1508.01501

$$H\overline{\psi}_L^{(3)}\psi_R^{(3)} \quad + \quad \phi\overline{\psi}_L^{(ij)}\psi_R^{(ij)} \quad + \quad \text{small mixing } \phi - H$$

$$\langle H \rangle \approx v \qquad \langle \phi \rangle << v$$

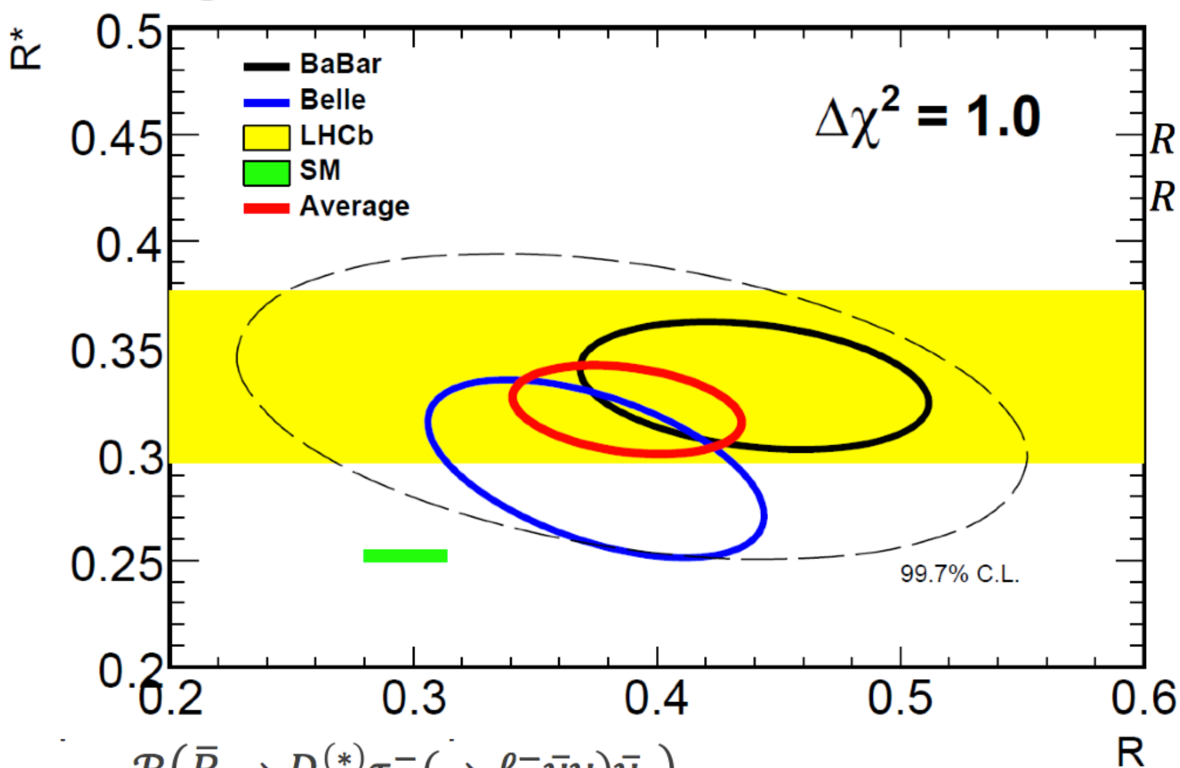
- Suppressed Higgs couplings to light generations (no Higgs resonance in μ collider)
- But $\mu-\phi$ coupling is O(1) (strong new resonance)

Surprises in lepton flavour universality and transitions?

LHCb:

2.6 σ from SM

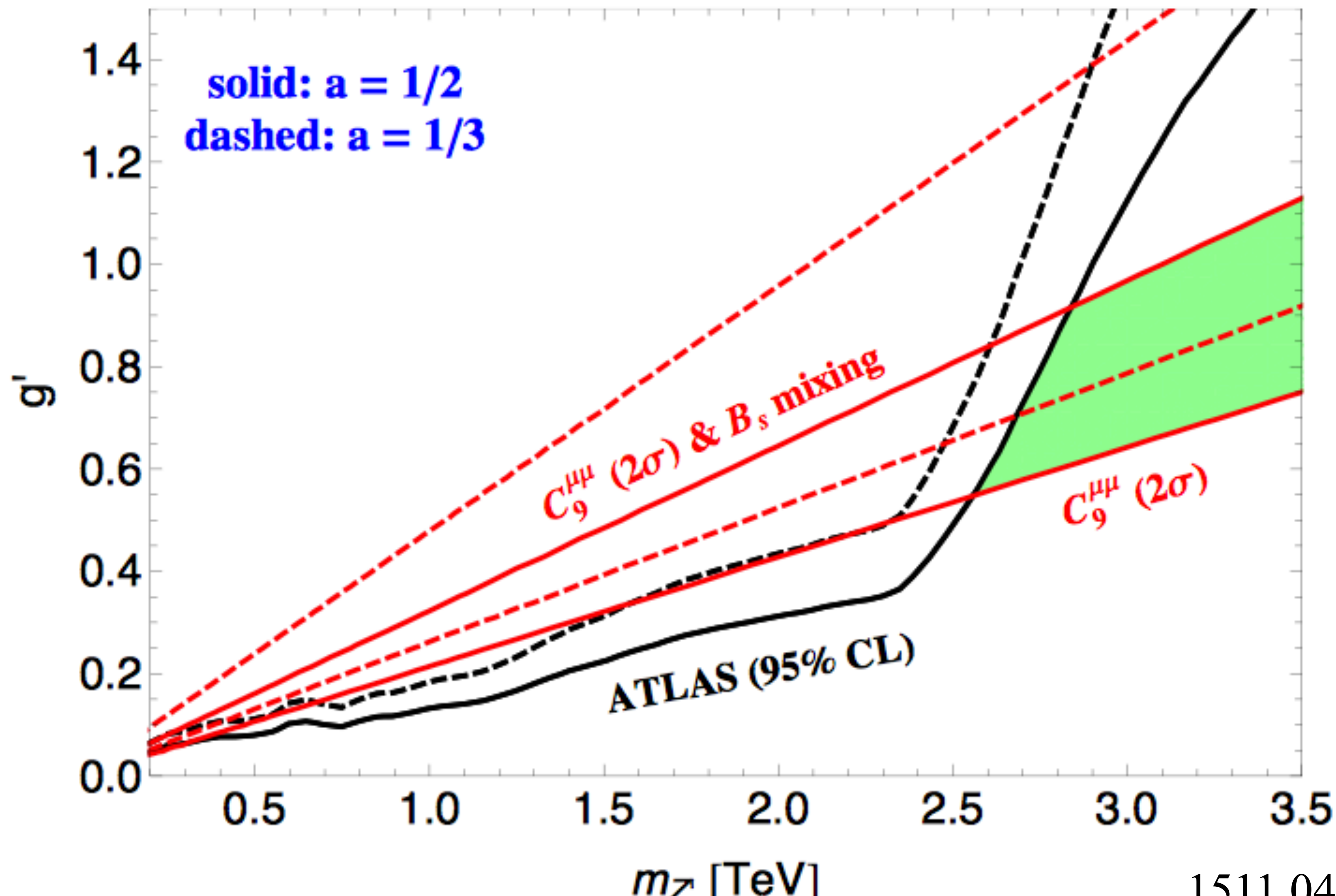
$$\frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} (1 \le q^2 \le 6\, GeV^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$$



$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-(\to \ell^- \bar{\nu}\nu)\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu})}$$

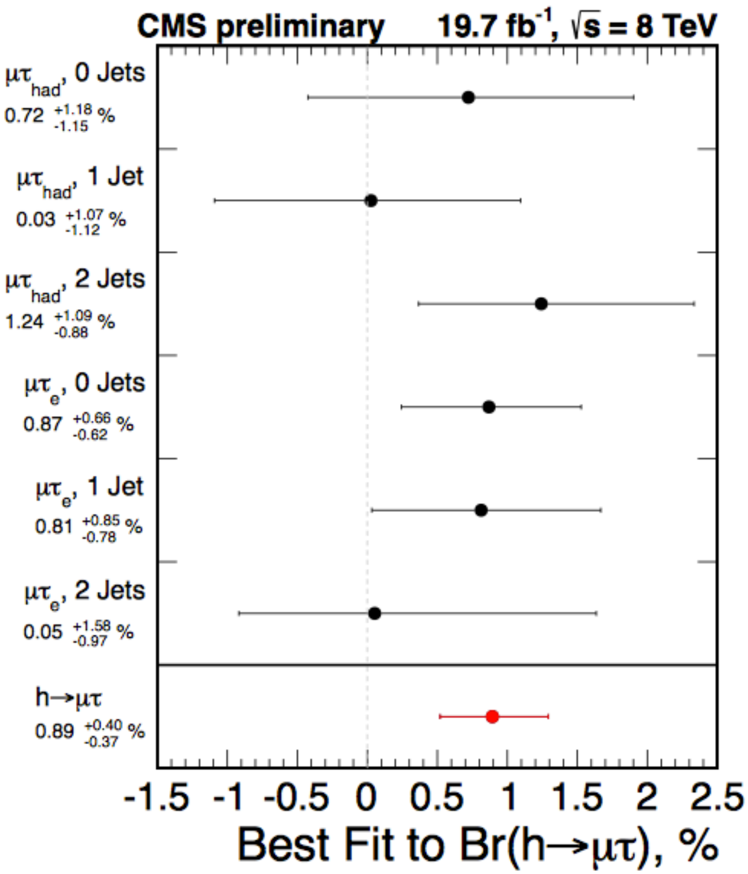
3.9 σ from SM

Z' for $L_\mu - L_\tau$ (and couplings to quarks via mixing of heavy states)? Excellent opportunity for μ collider?



1511.04015

Surprises in the Higgs lepton couplings?



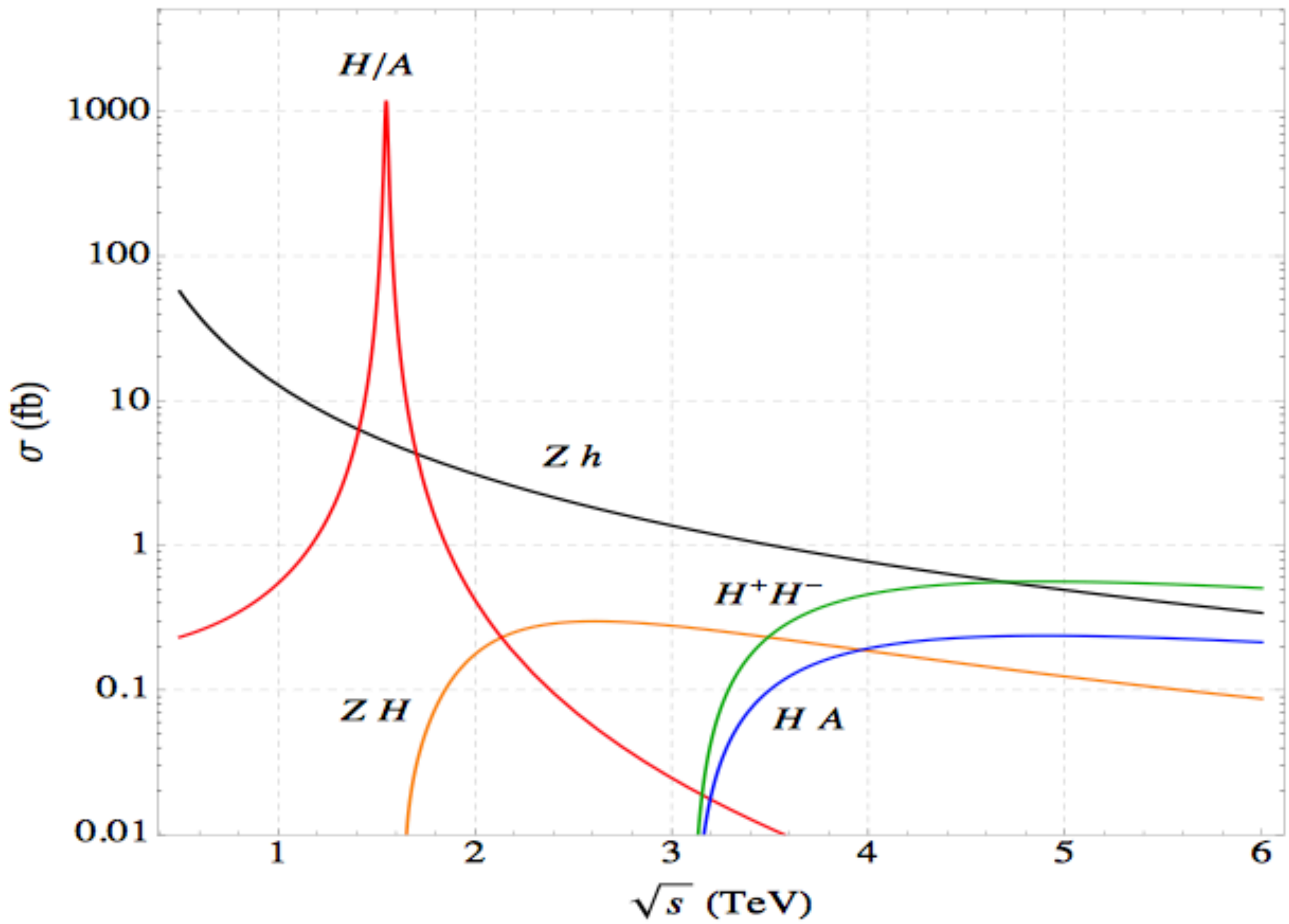
ATLAS

	SR1	SR2	Combined
Expected limit on $\mathrm{Br}(H \to \mu\tau)$ [%]	$1.60^{+0.64}_{-0.45}$	$1.75^{+0.71}_{-0.49}$	$1.24^{+0.50}_{-0.35}$
Observed limit on $\mathrm{Br}(H \to \mu\tau)$ [%]	1.55	3.51	1.85
Best fit $\mathrm{Br}(H \to \mu\tau)$ [%]	$-0.07^{+0.81}_{-0.86}$	$1.94^{+0.92}_{-0.89}$	0.77 ± 0.62

$$h \to \mu\tau$$

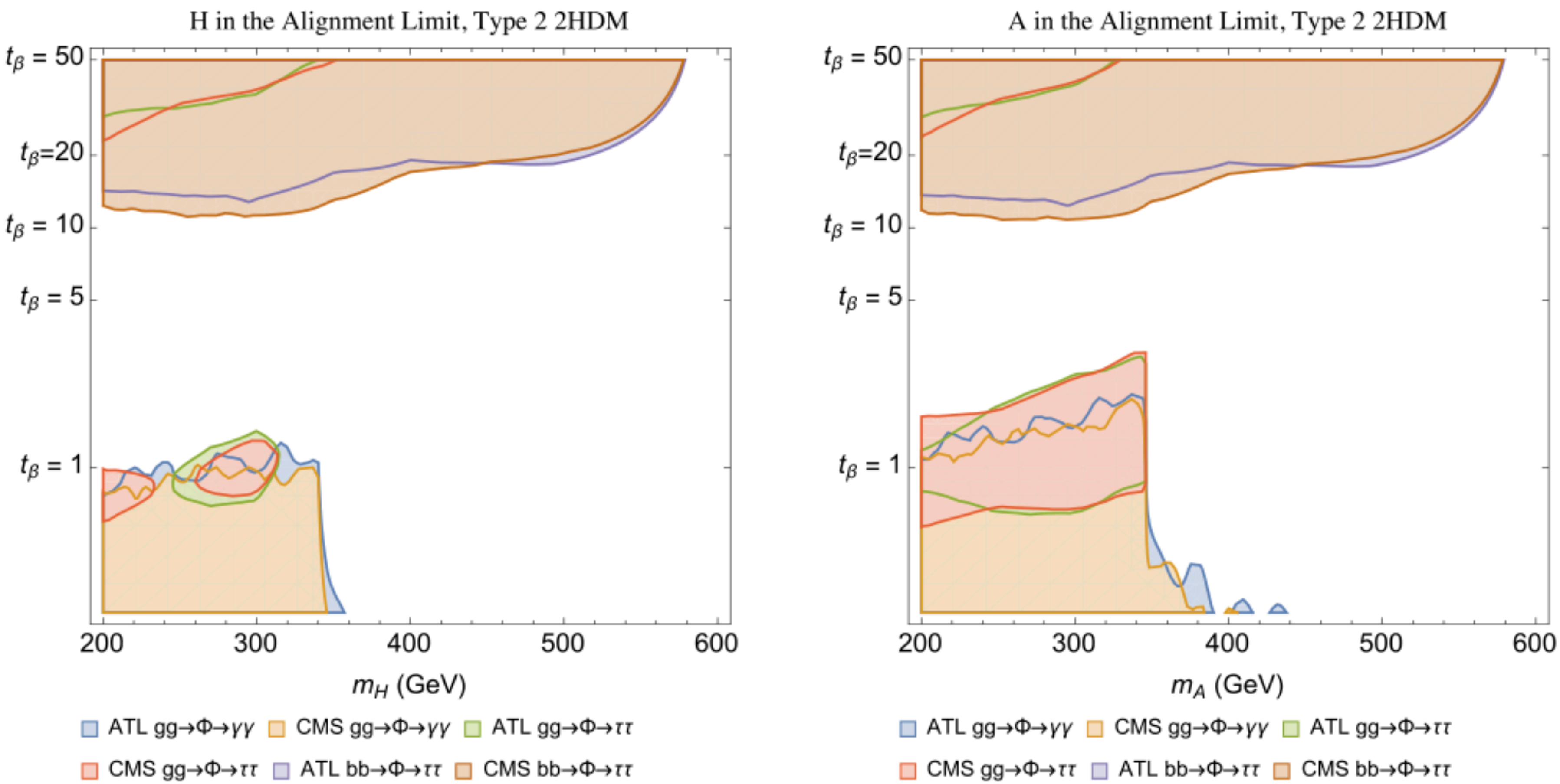
2.4 σ from SM

Beyond the SM Higgs

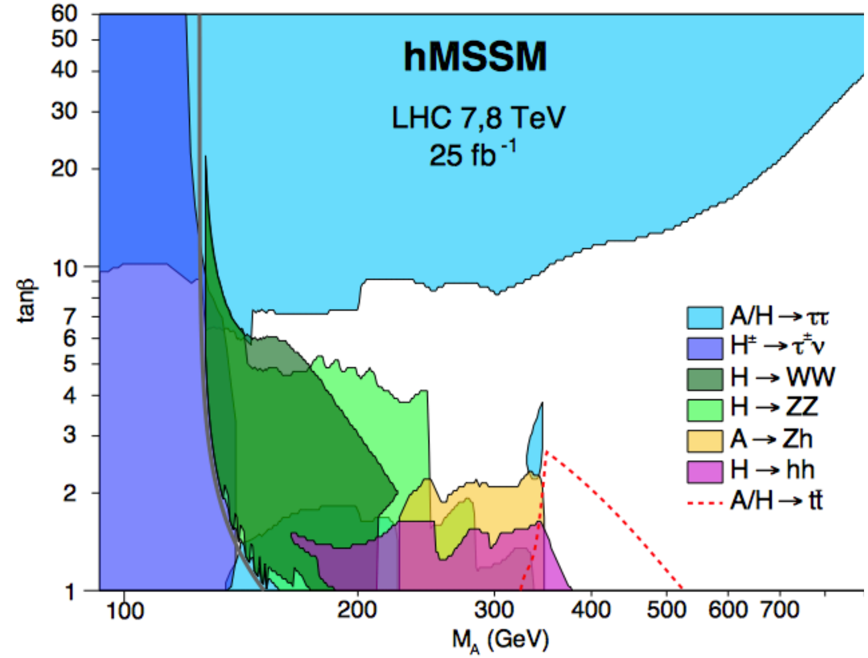


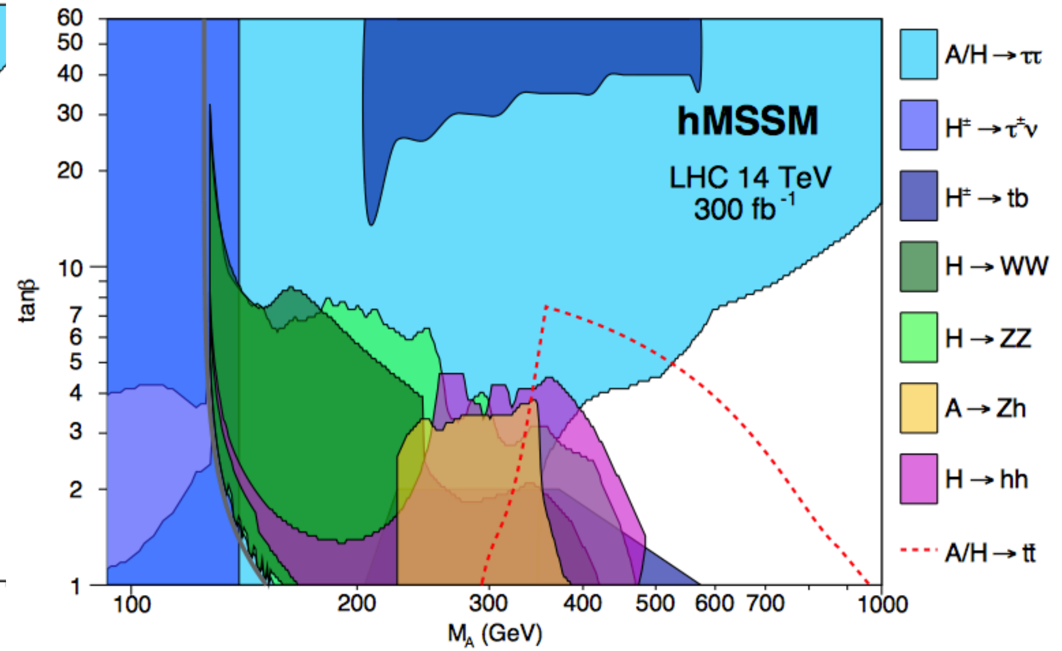
1306.2609

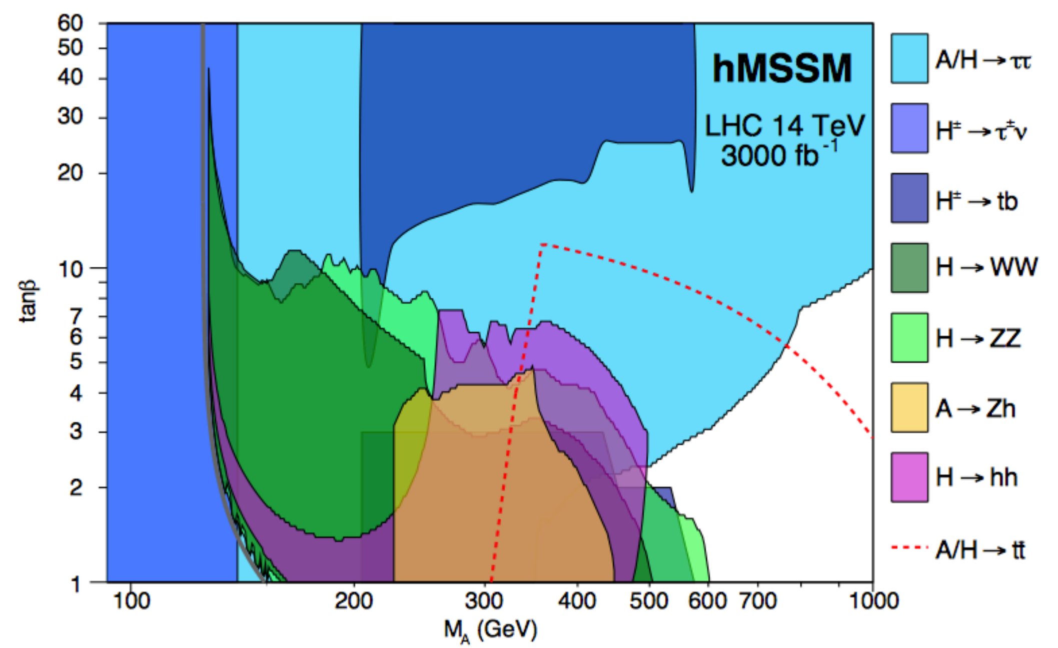
In the decoupling limit ($m_A \to \infty$) alignment of SM Higgs
Yukawa interactions are the only couplings linear in H/A
Production at LHC through b-coupling at large tanβ



1504.04630


hMSSM
LHC 7,8 TeV
25 fb^{-1}
A/H → ττ
H± → τ±ν
H → WW
H → ZZ
A → Zh
H → hh
A/H → tt
tanβ
M$_A$ (GeV)
60
50
40
30
20
10
7
6
5
4
3
2
1
100
200
300
400
500
600
700

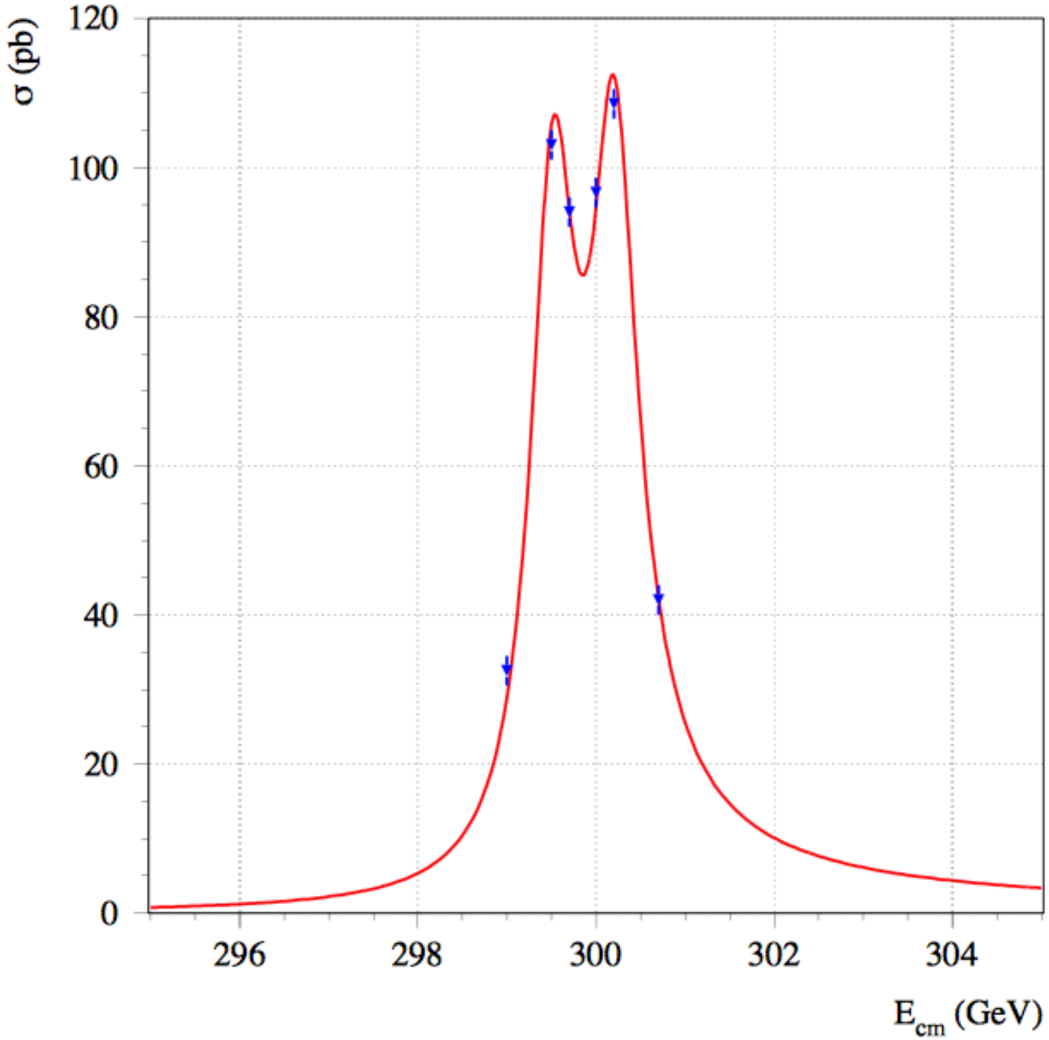

hMSSM
LHC 14 TeV
300 fb^{-1}
A/H → ττ
H± → τ±ν
H± → tb
H → WW
H → ZZ
A → Zh
H → hh
A/H → tt
tanβ
M$_A$ (GeV)
60
50
40
30
20
10
7
6
5
4
3
2
1
100
200
300
400
500
600
700
1000


hMSSM
LHC 14 TeV
3000 fb^{-1}
A/H → ττ
H± → τ±ν
H± → tb
H → WW
H → ZZ
A → Zh
H → hh
A/H → tt
tanβ
M$_A$ (GeV)
60
50
40
30
20
10
7
6
5
4
3
2
1
100
200
300
400
500
600
700
1000

1502.05653

A peculiarity of the Higgs spectrum in the decoupling limit

$$m_H - m_A = \frac{2m_Z^2}{m_A \tan^2\beta} + O\left(\frac{m_Z^4}{m_A^3}\right) \approx \frac{\text{TeV}}{m_A}\left(\frac{20}{\tan\beta}\right)^2 40\ \text{MeV}$$

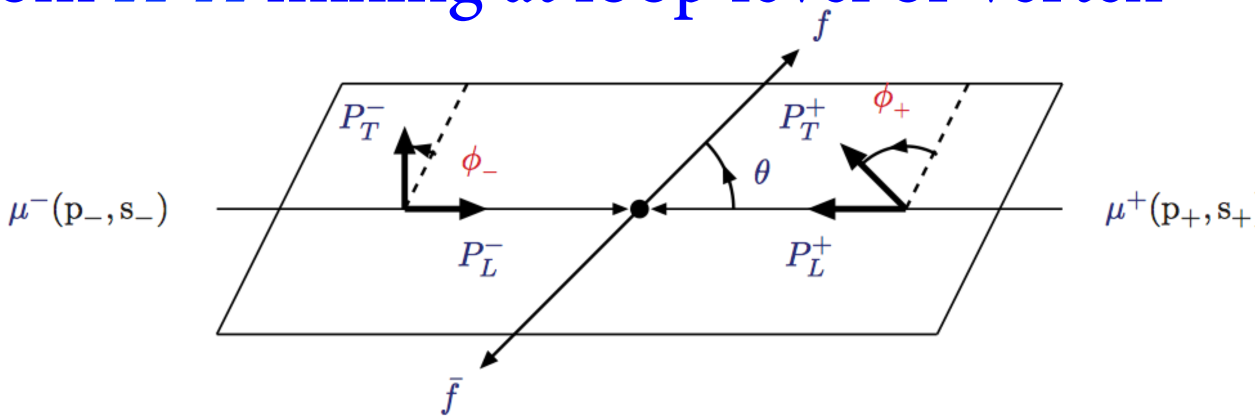


Two-state tests of SM Higgs can also be performed (but today lack strong physics motivation)

YR CERN-99-02

CP violation in the Higgs sector

CP violation from *H-A* mixing at loop level or vertex corrections



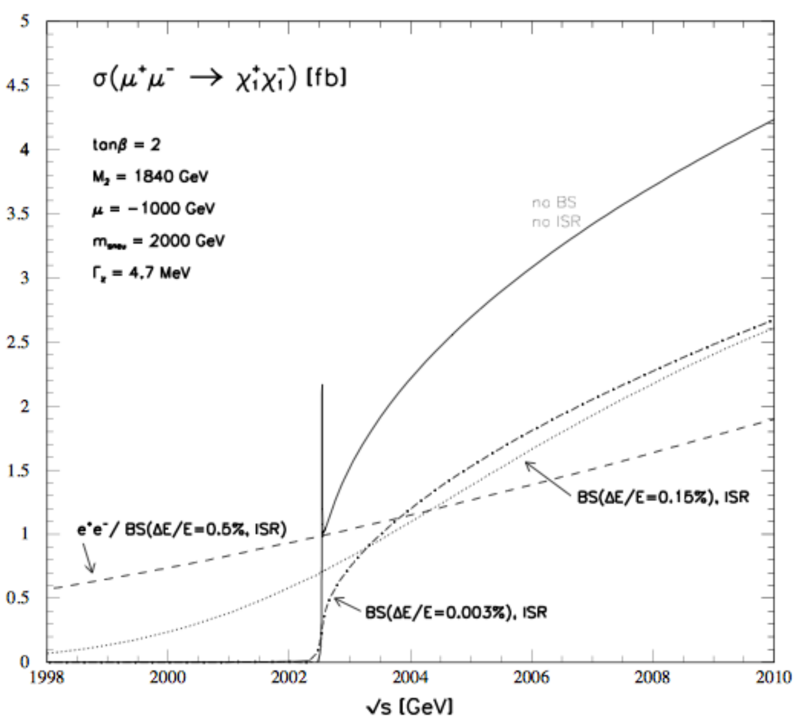
$$\mathcal{A}_{CP}^t = \frac{\sigma(\mu^-(s_x)\mu^+(s_y) \to f\bar{f}) - \sigma(\mu^-(s_x)\mu^+(-s_y) \to f\bar{f})}{\sigma(\mu^-(s_x)\mu^+(s_y) \to f\bar{f}) + \sigma(\mu^-(s_x)\mu^+(-s_y) \to f\bar{f})},$$

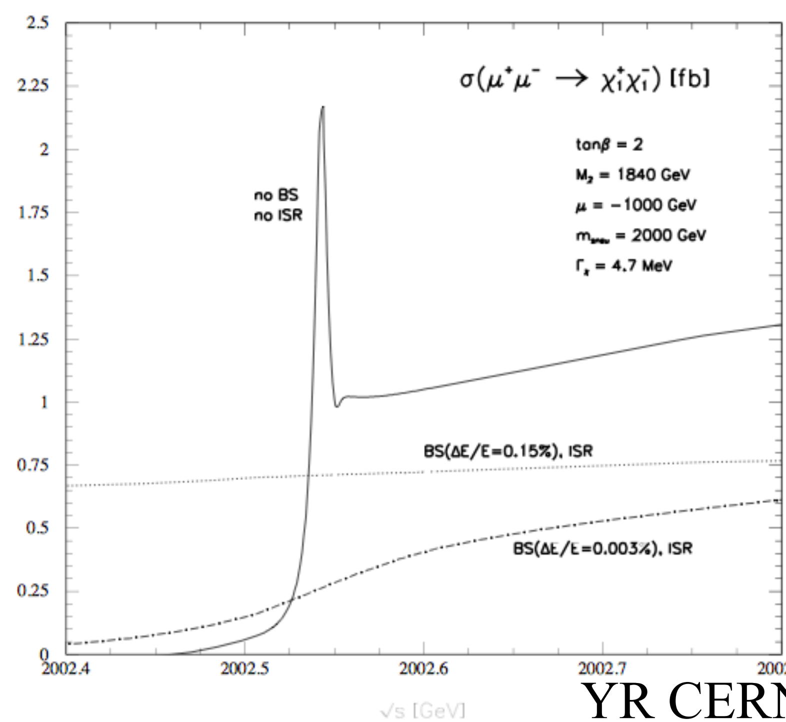
$$\mathcal{A}_{CP}^l = \frac{\sigma(\mu^-(s_z)\mu^+(-s_z) \to f\bar{f}) - \sigma(\mu^-(-s_z)\mu^+(s_z) \to f\bar{f})}{\sigma(\mu^-(s_z)\mu^+(-s_z) \to f\bar{f}) + \sigma(\mu^-(-s_z)\mu^+(s_z) \to f\bar{f})}$$

Without enhanced muon polarization, one can construct CP-violating asymmetries from final state, measuring angular distribution of their decay products

Precise measurements of mass and cross section at threshold pair-production (top or new physics)

- Reduction of ISR and beamstrahlung w.r.t. e^+e^- colliders
- Rapid and accurate beam-energy calibration
- Small beam energy spread





YR CERN-99-02

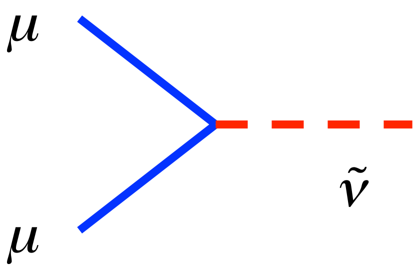
- Now we are focused on Higgs measurements and explorations.
- A new discovery at the LHC may quickly shift the emphasis on precision measurements as the essential strategy to unravel new physics

Muons allow for tests on exotic flavour-dependent physics

Examples: R-parity violation

$\lambda_{ijk} L_i L_j \bar{E}_k$

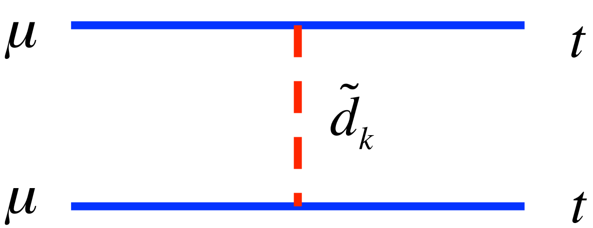
From lepton universality: $\lambda_{(1,3)22} < \frac{\tilde{m}}{2\ \mathrm{TeV}}$



For heavy sleptons, couplings can be sizable

Resonant production with decay into $\mu\mu, \tilde{\ell}^{\pm}\chi^{\mp}, \tilde{\nu}\chi^0$

$\lambda'_{ijk} L_i Q_j \bar{D}_k$



High-energy modification of top-pair production

Conclusions

Muon collider as a Higgs factory

- Very precise determinations of m_h and Γ_h
- Test of Higgs coupling to 2^{nd} generation

Muon collider as exploratory and precision machine in the multi-TeV

- Precise study of resonances (BSM Higgs) and pair-production thresholds (top and new physics)
- Test of new couplings to 2^{nd} generation leptons