PHYSICS AT A MUON COLLIDER

JOSEPH LYKKEN

FERMILAB

MUON COLLIDER PHYSICS WORKSHOP, 10-12 NOV, 2009

MC physics is not a new topic

- *Proceedings of the First Workshop on the Physics Potential and Development of mu+mu- Colliders,* Nucl. Instru. and Meth. A350, 24 (1994).
- V. Barger et al. (The Muon Quartet), Phys. Reports 286, 1 (1997).
- C. Ankenbrandt et al., “Status of muon collider research and development and future plans”, Phys. Rev. ST Accel. Beams 2 (1999)
- http://www.fnal.gov/pub/muon_collider/resources.html

Question: How many U.S. Congressmen does it take to build a muon collider?

Answer:

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Answer: One

Fermi National Accelerator Laboratory

FERMILAB-Conf-95/037

Backgrounds and Detector Performance at
a 2 x 2 TeV $\mu^+\mu^-$ Collider

G. William Foster and Nikolai V. Mokhov

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Short version of this talk

Question: Is it possible to identify the physics targets of the post-LHC energy frontier collider before we have any LHC results?

Answer:

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Question: Is it possible to identify the physics targets of the post-LHC energy frontier collider before we have any LHC results?

Answer: **No**

Discoveries in Physics

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z, W
AGS Brookhaven (1960)	π N interactions	2 kinds of neutrinos, Time reversal non-symmetry, New form of matter (4^{th} Quark)
FNAL Batavia (1970)	Neutrino physics	*5^{th} Quark, 6^{th} Quark*
SLAC Spear (1970)	ep, QED	Partons, 4^{th} Quark, 3^{rd} electron
ISR CERN (1980)	PP	*Increasing PP Cross section*
PETRA Hamburg (1980)	6^{th} Quark	*Gluon*
Super Kamiokande (2000)	Proton decay	Neutrinos have mass
Hubble Space Telescope	Galactic survey	*Curvature of the universe, dark energy*

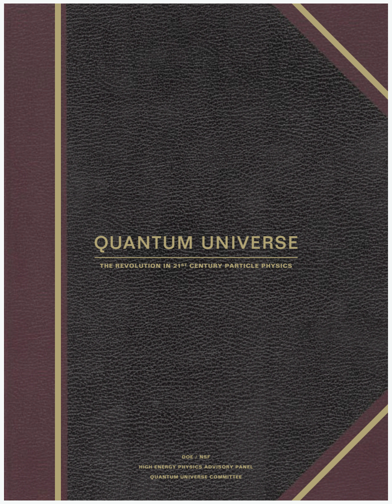
Exploring a new territory with a precision instrument is the key to discovery.

THE BIG QUESTIONS

0. What is the origin of mass for fundamental particles?
1. Are there undiscovered principles of nature: new symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

Based on "The Quantum Universe," *HEPAP 2004*

QUESTIONS



- LHC, Project X, DM and DE programs+... will address these questions, but not answer all of them completely
- More importantly, progress on these questions will raise NEW fundamental questions
- In fact we may discover that many of our current “fundamental” questions are ill-posed, misguided, or peripheral to the real issues

Why do the Sun and the Moon have the same angular diameter?

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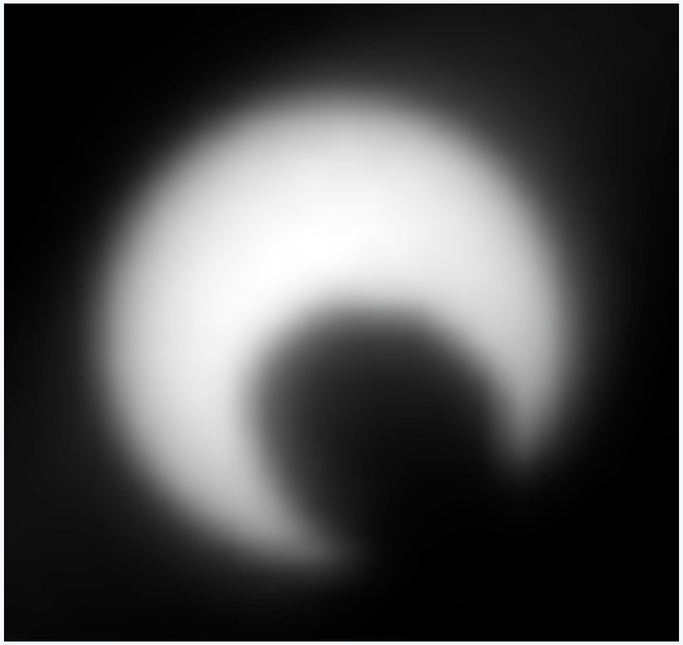
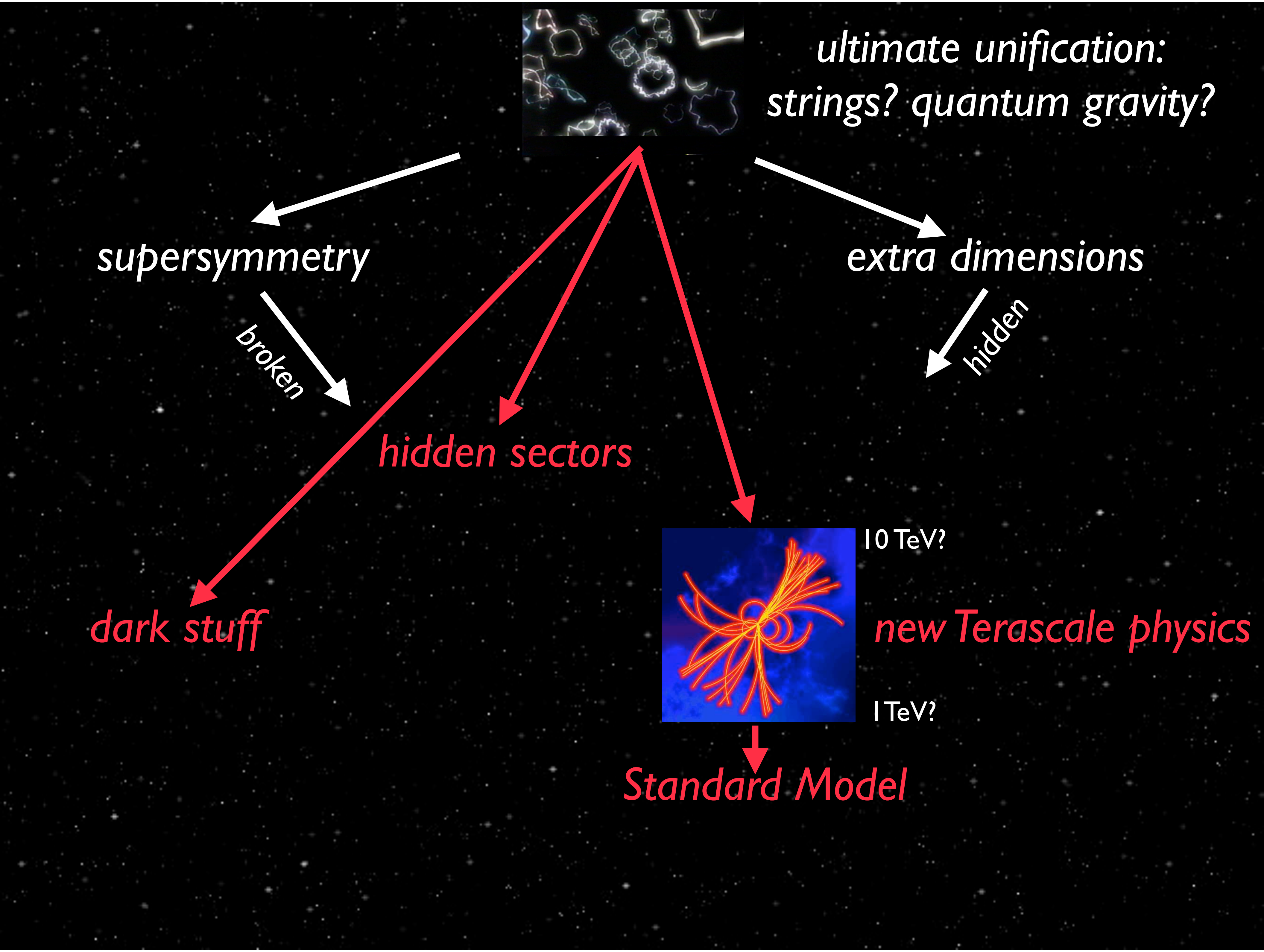
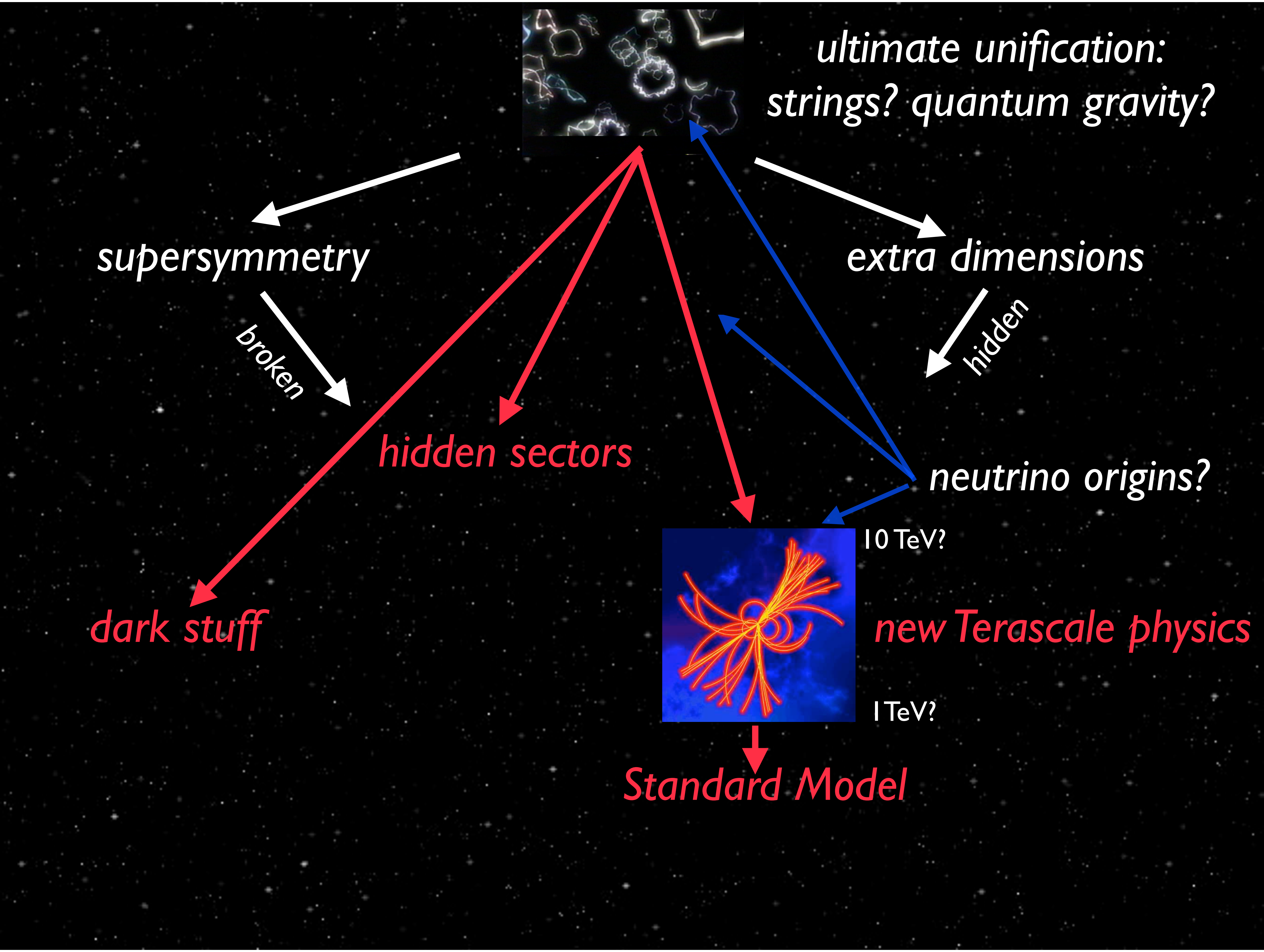


Solar eclipse on Mars, as seen by the Mars Opportunity Rover



ultimate unification:
strings? quantum gravity?
supersymmetry
extra dimensions
broken
hidden
hidden sectors
dark stuff
10 TeV?
new Terascale physics
1 TeV?
Standard Model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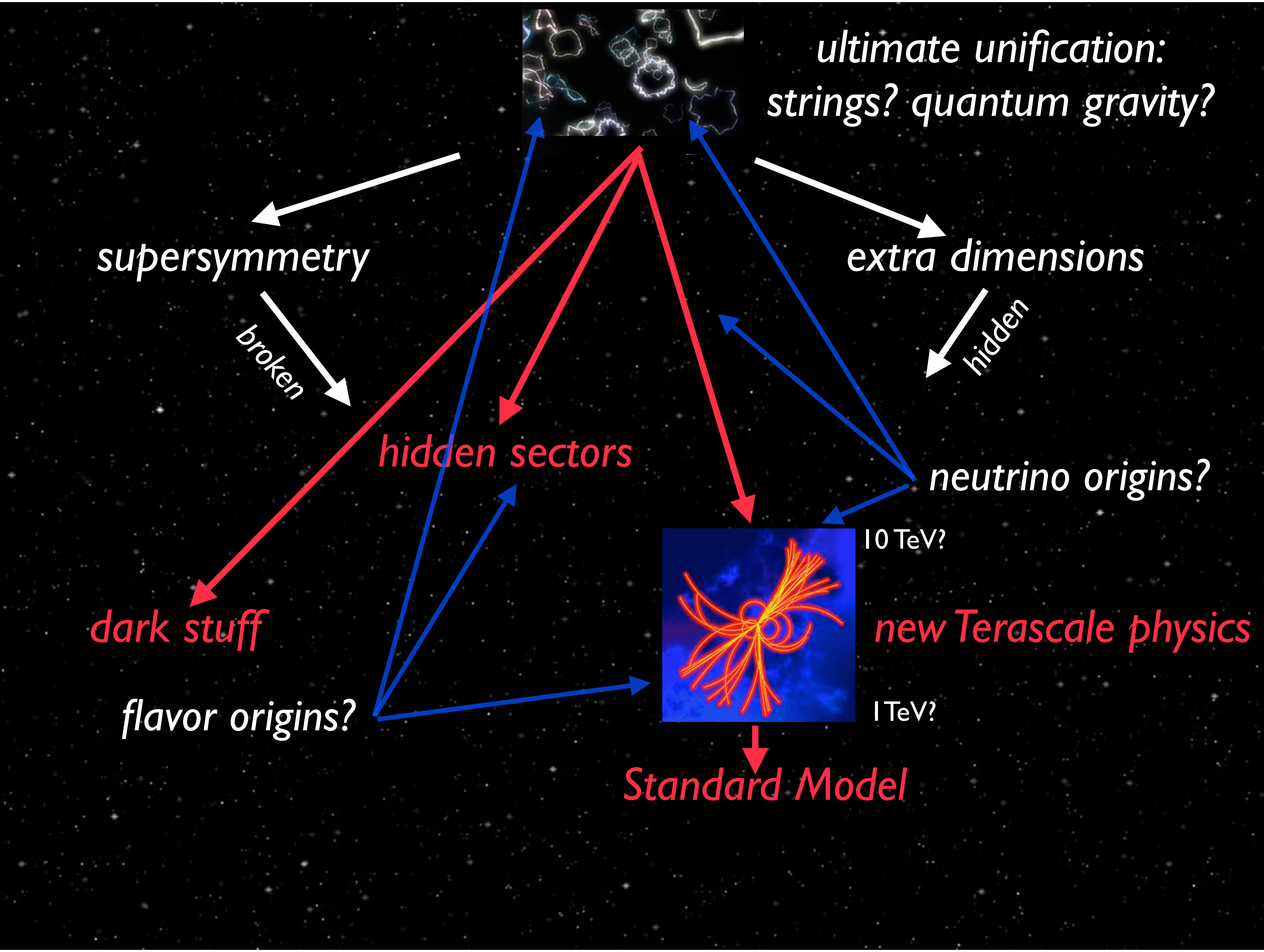
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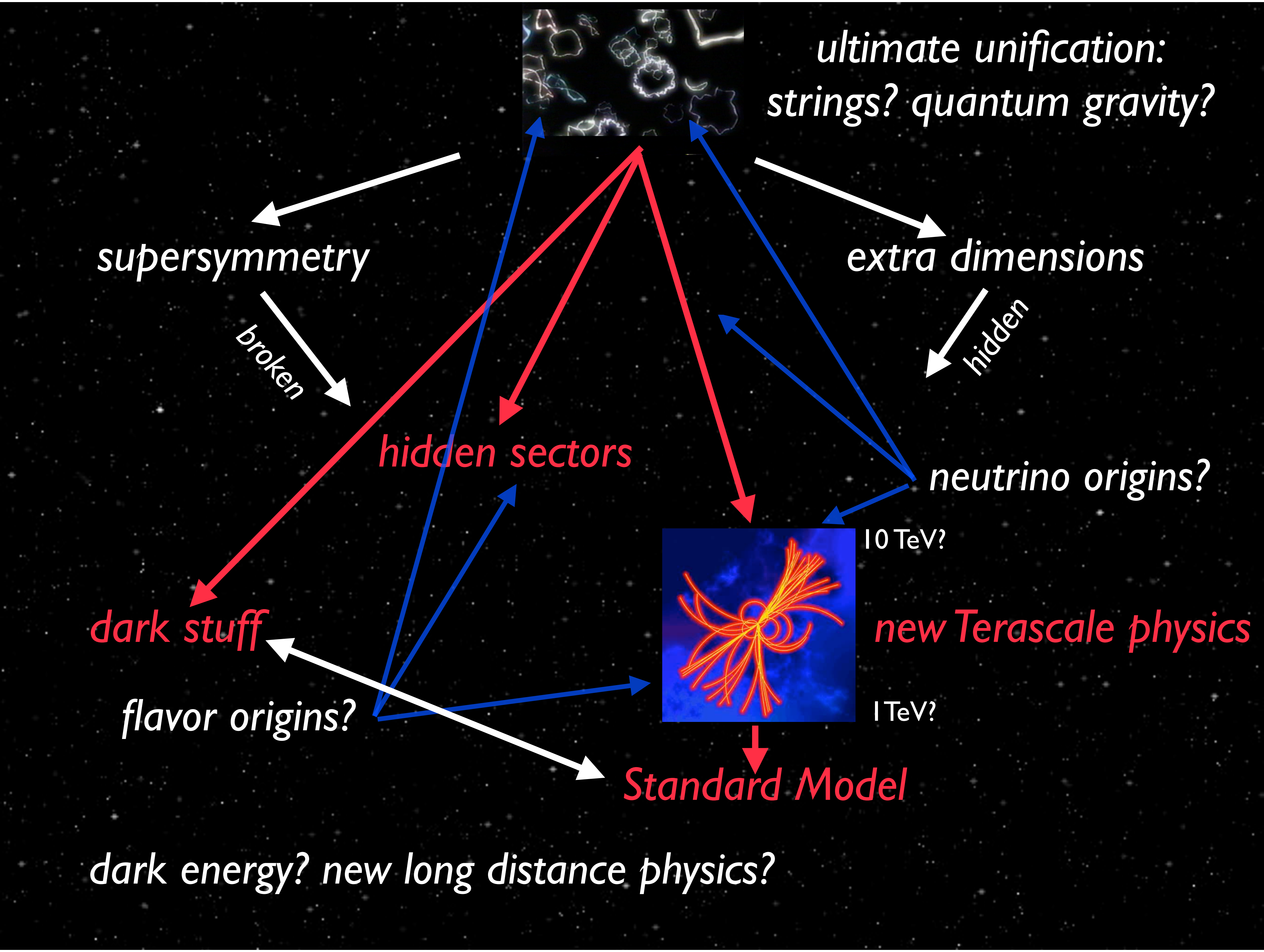
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dark energy? new long distance physics?

How to think about MC physics

Don’t try to motivate MC physics opportunities top-down based on today’s poor guesses about the underlying physics

Figure out more generically what a MC can do

MC physics: the basics

$(1\ \text{ab}^{-1}, \sqrt{s} = 3\ \text{TeV})$

Process	R	Events
$\mu^+\mu^-$ (with 20° cut)	100	9.64×10^5
W^+W^-	19.8	1.91×10^5
$\gamma\gamma$	3.77	3.64×10^4
$Z^0\gamma$	3.32	3.20×10^4
$t\bar{t}$	1.86	1.79×10^4
$b\bar{b}$	1.28	1.23×10^4
e^+e^-	1.13	1.09×10^4
Z^0Z^0	0.75	$7,230$
$Z^0h(120)$	0.124	$1,200$

$$R = \frac{\sigma(\mu^+\mu^- \to X)}{\sigma_{QED}(\mu^+\mu^- \to e^+e^-)}$$

$$\sigma_{QED}(\mu^+\mu^- \to e^+e^-) = \frac{86.8\ \text{fb}}{s\ \text{TeV}^2}$$

Four ways to produce new physics at MC

- **Virtual effects on SM processes**

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- s-channel resonant production of new heavy particles

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How much is specific to MC?

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  same as or worse than ILC, CLIC

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  same as or worse than CLIC

Virtual effects on SM processes

- **Integrate out exchanges of new heavy states at scales >> $\sqrt{\mathbf{s}}$**

- **Parametrize as higher dimension operator suppressed by some large scale $\boldsymbol{\Lambda}$, e.g.**

$$\mathcal{L} = \frac{g^2}{2\Lambda^2}\left[\eta_{LL}\ j_L j_L + \eta_{RR}\ j_R j_R + \eta_{LR}\ j_L j_R\right].$$

- **In the best case, $\mathbf{g^2 = 4\pi}$ with the $\eta_{\mathbf{xx}} \sim \mathbf{1}$**

Virtual effects on SM processes

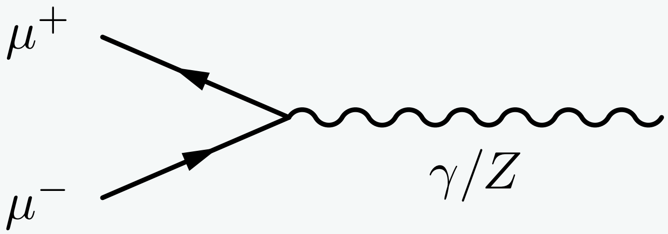
- **For example, look at Bhabha scattering, with a very conservative 37 degree polar angle cut:**

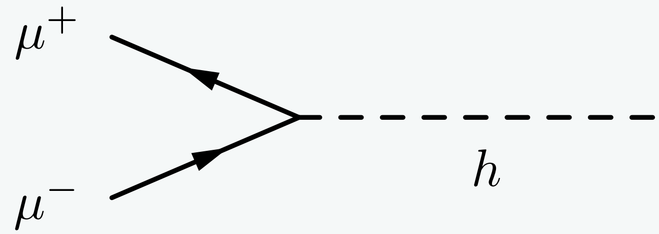
TABLE 2. 95% CL limits (in TeV) for different energies (in GeV) of the muon collider, we used $|\cos\theta| < 0.8$. We also present the expected LEP limits for which we used $|\cos\theta| < 0.95$.

	LEP(91)	LEP(175)	100	200	350	500	4000
$\mathcal{L}(fb^{-1})$	.15	.1	.6	1.	3.	7.	450.
LL	4.0	5.8	4.8	10	20	29	243
RR	3.8	5.7	4.9	10	19	28	228
VV	6.9	12.	12	21	36	54	435
AA	3.8	7.2	12	13	21	32	263

E. Eichten and S. Keller, hep-ph/9801258

s-channel resonances





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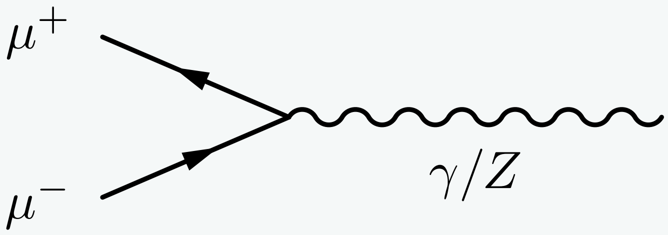

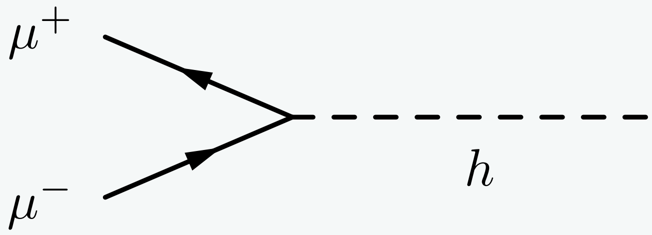

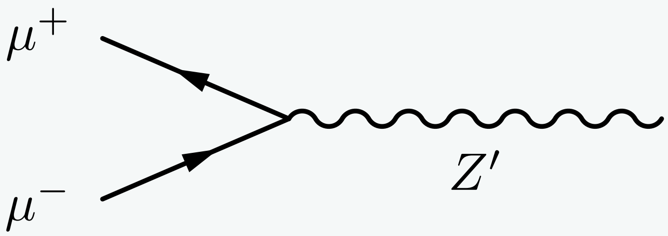

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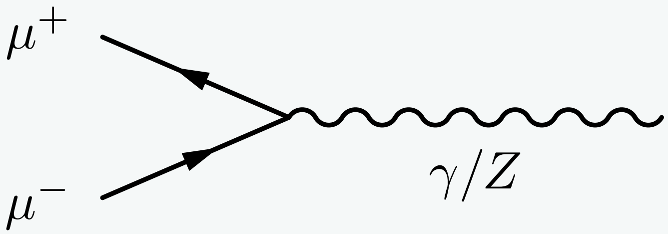

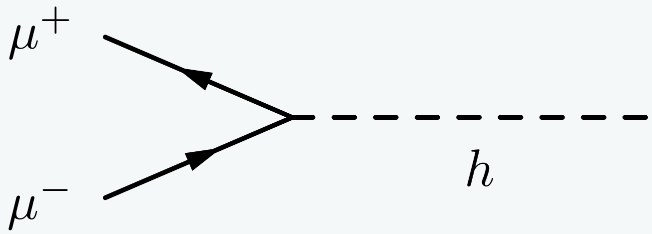

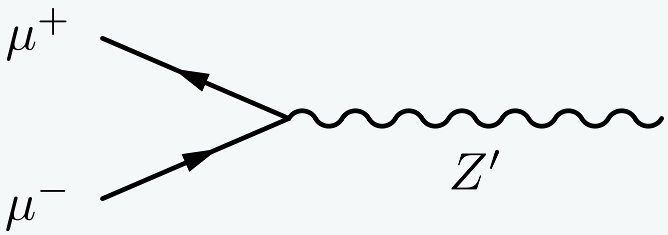

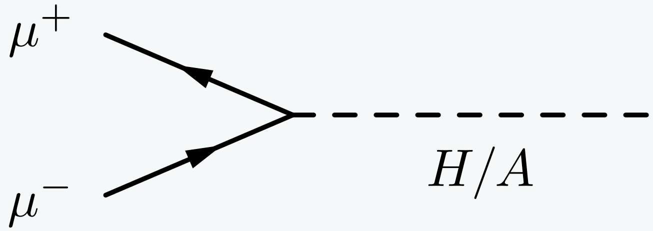

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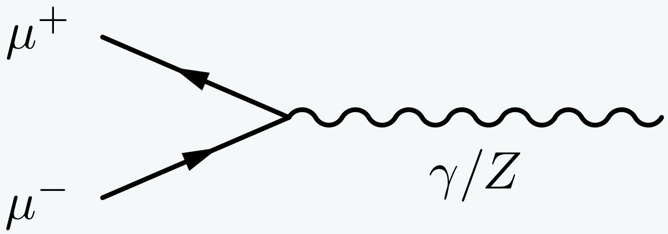

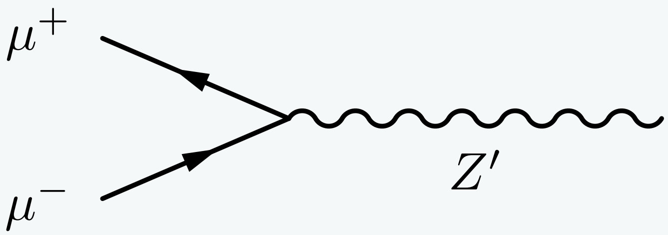

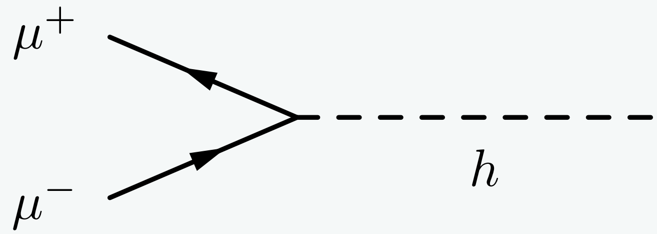

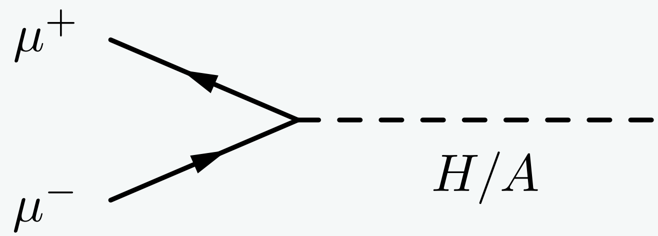

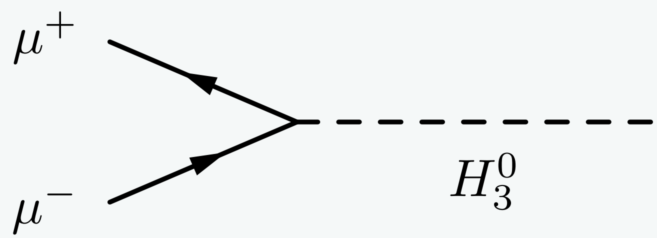

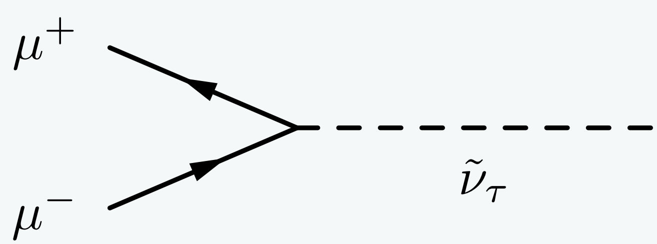

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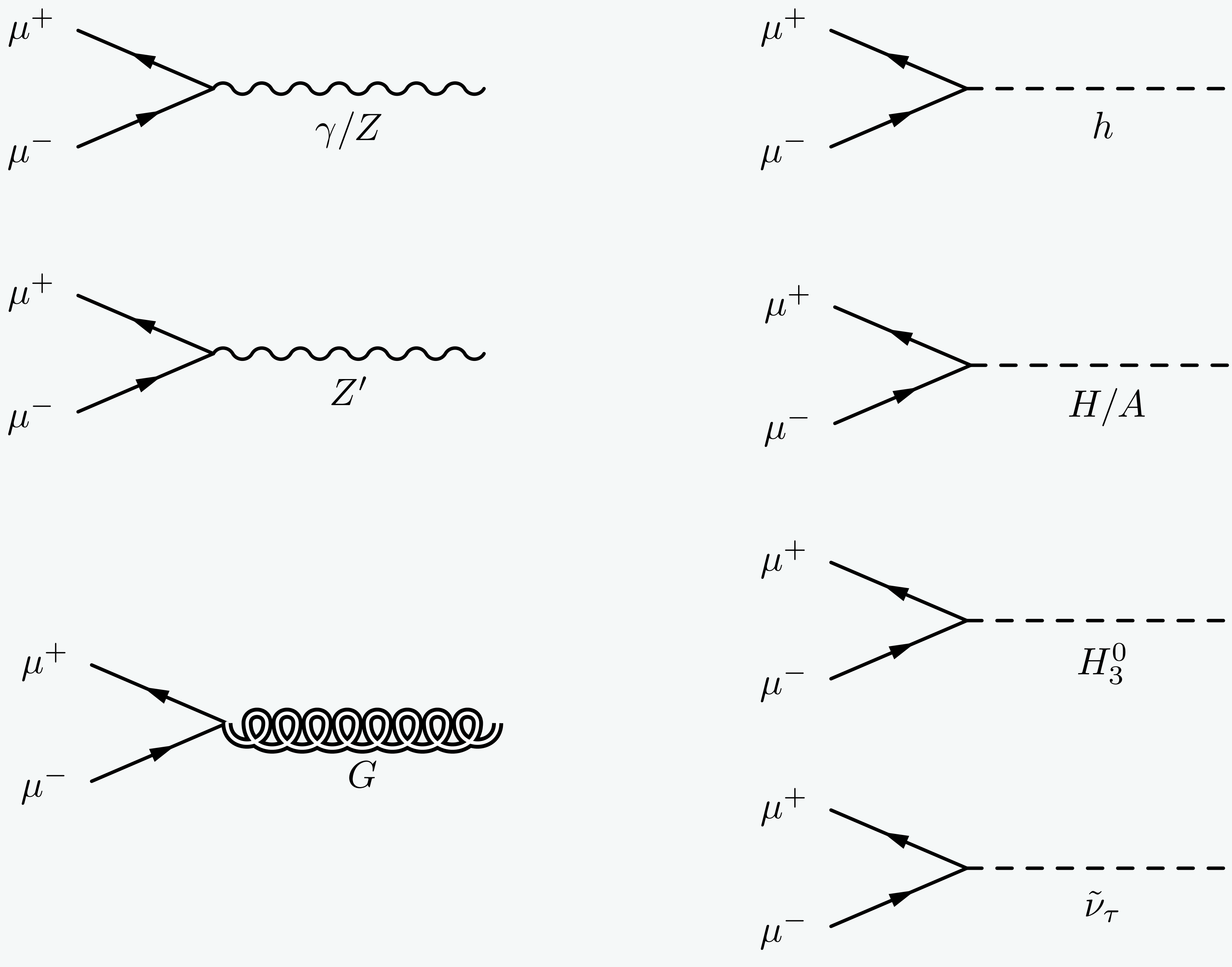


s-channel resonant Higgs production

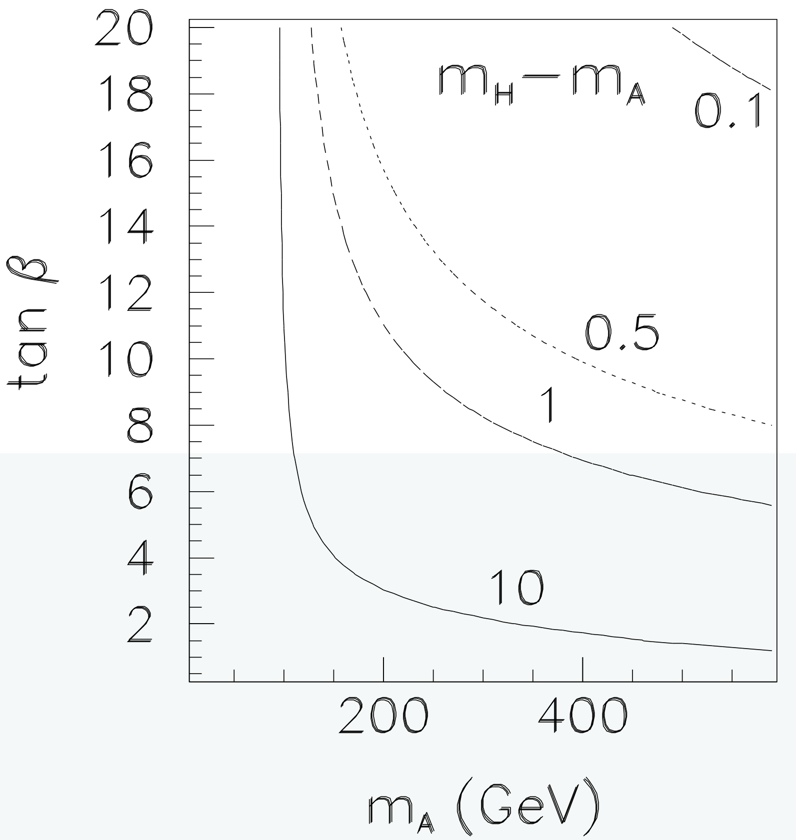
$$\sigma_h(\sqrt{s}) = \frac{4\pi\Gamma(h \to \mu\bar{\mu})\,\Gamma(h \to X)}{\left(s - m_h^2\right)^2 + m_h^2\left(\Gamma_{\rm tot}^h\right)^2}$$

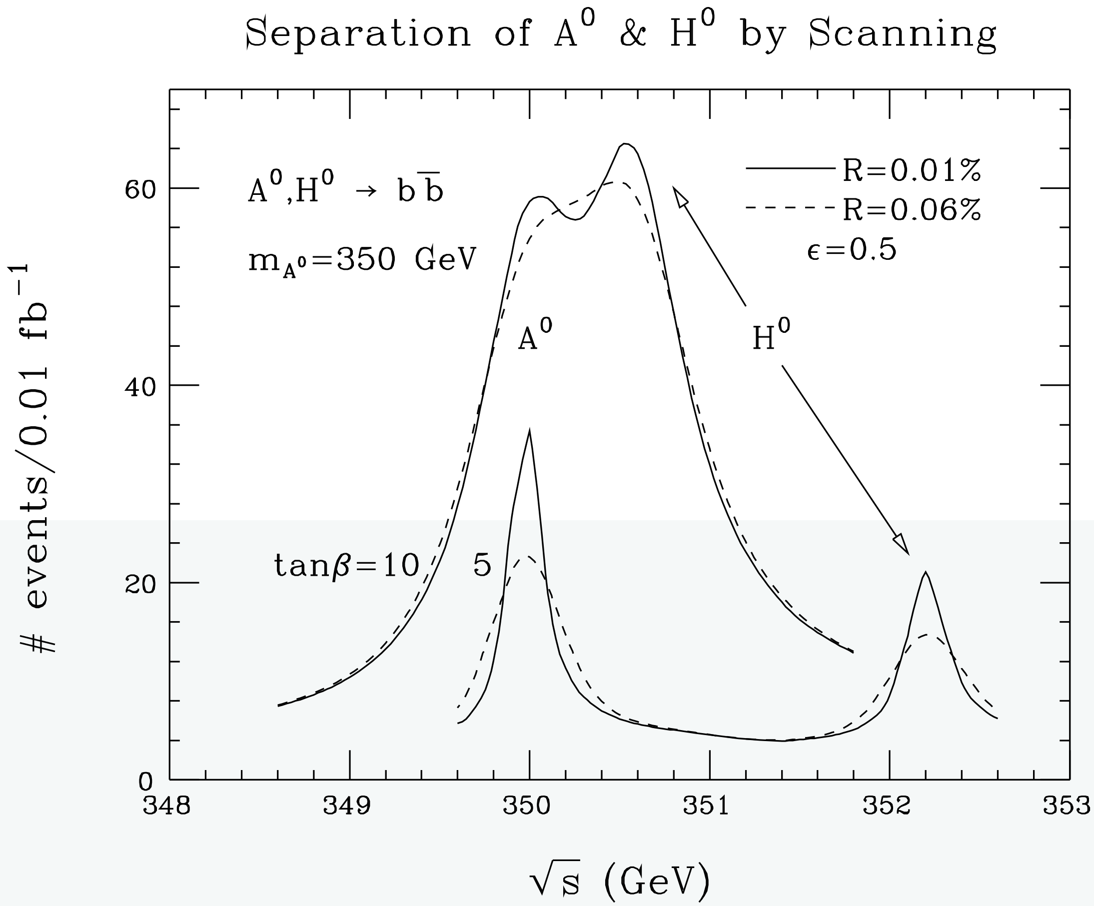
For SM Higgs, this would be a low energy MC and requires > 1 year of scanning to find the peak

M_h (GeV)	$\mathbf{BR}(\mathbf{h} \to \mu^+\mu^-)$	$\Gamma_{\rm total}$ (GeV)
120	0.00026	0.003
140	0.00013	0.008
160	0.000014	0.08
180	0.000002	0.6
200	0.000001	1.4
300	0.00000025	8.4

Multiple heavy scalars, e.g. the MSSM

V. Barger, M. Berger, J. Gunion, T. Han, hep-ph/9602415





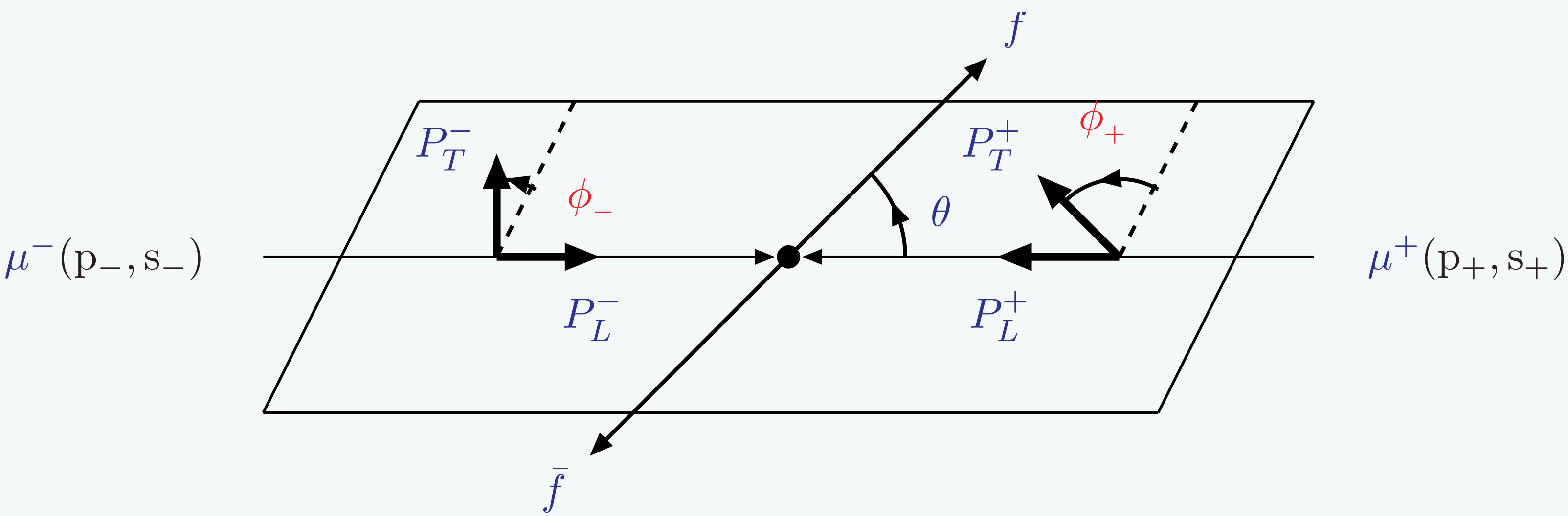
CP even and odd heavy Higgs nearly degenerate for larger values of m_A, $\tan\beta$

In this case, need to push the energy resolution to better than 0.1%

More generally, there may be exotic decays modes, e.g. $H^0 \to h^0 h^0$, $H^0 \to A^0 A^0$, $H^0 \to Z A^0$, $A^0 \to Z h^0$

Detecting CP violation with muon beam polarization

C. Blochinger, M. Carena, J. Ellis, et al., hep-ph/0202199



- Suppose you can get transversely polarized beams (at some cost in luminosity and beam energy spread)
- cross section is a function of the CP even and odd couplings as well as $\phi = \phi^+ - \phi^-$

$$\sigma(\phi) \sim 1 - \frac{g_V^2 - g_A^2}{g_V^2 + g_A^2} \cos\phi + \frac{2 g_V g_A}{g_V^2 + g_A^2} \sin\phi$$

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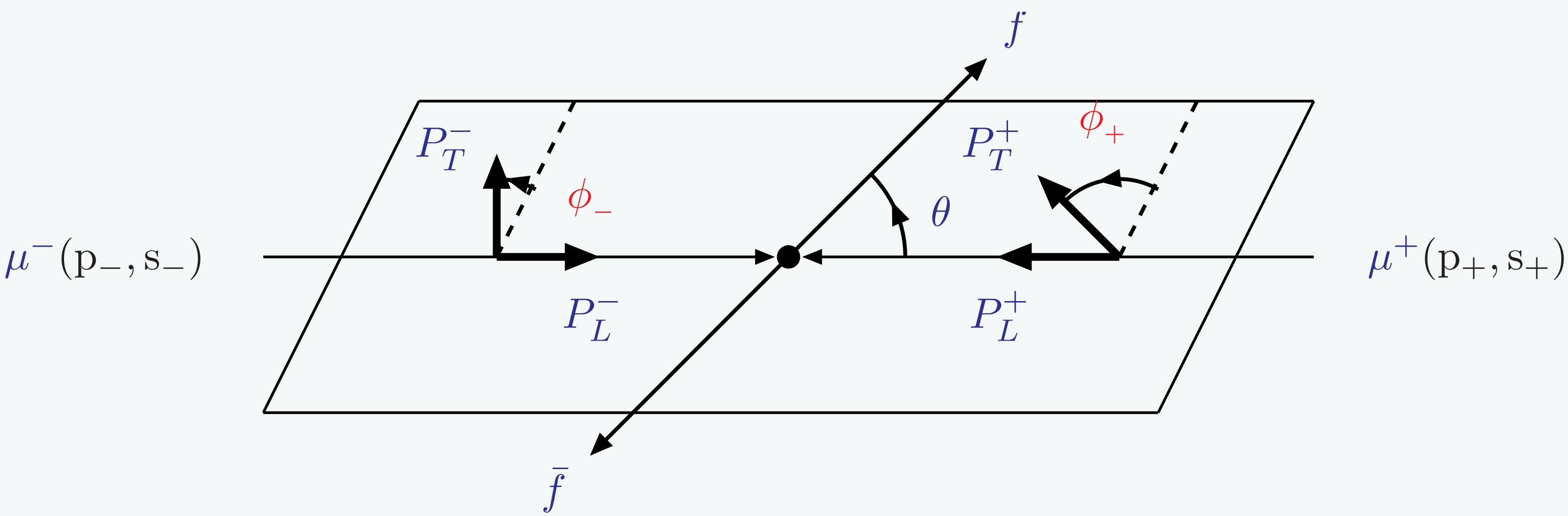
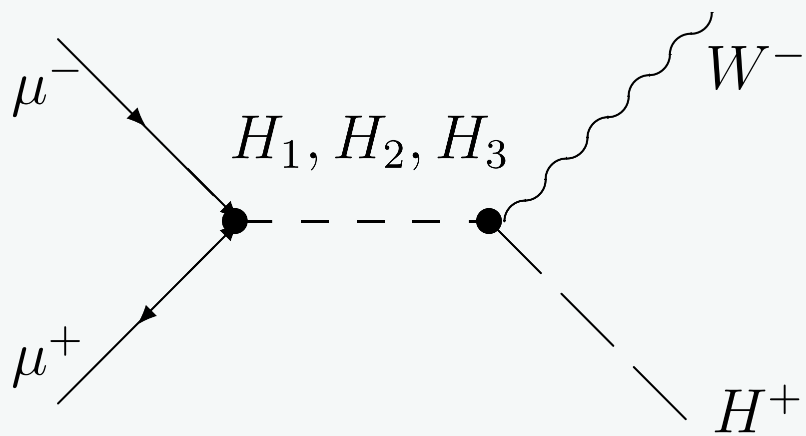


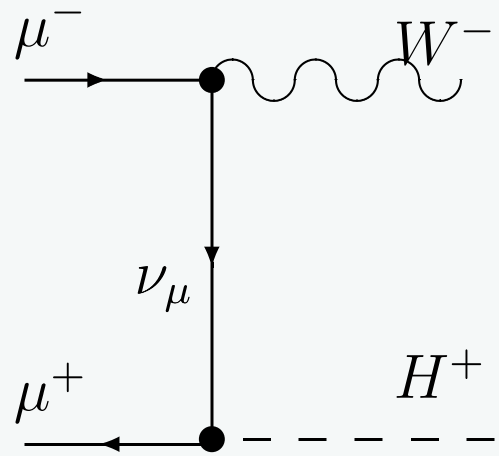
Construct simple asymmetries to extract the CP mixture, e.g.

$$\frac{\sigma(\pi/\mathbf{2}) - \sigma(-\pi/\mathbf{2})}{\sigma(\pi/\mathbf{2}) + \sigma(-\pi/\mathbf{2})}$$

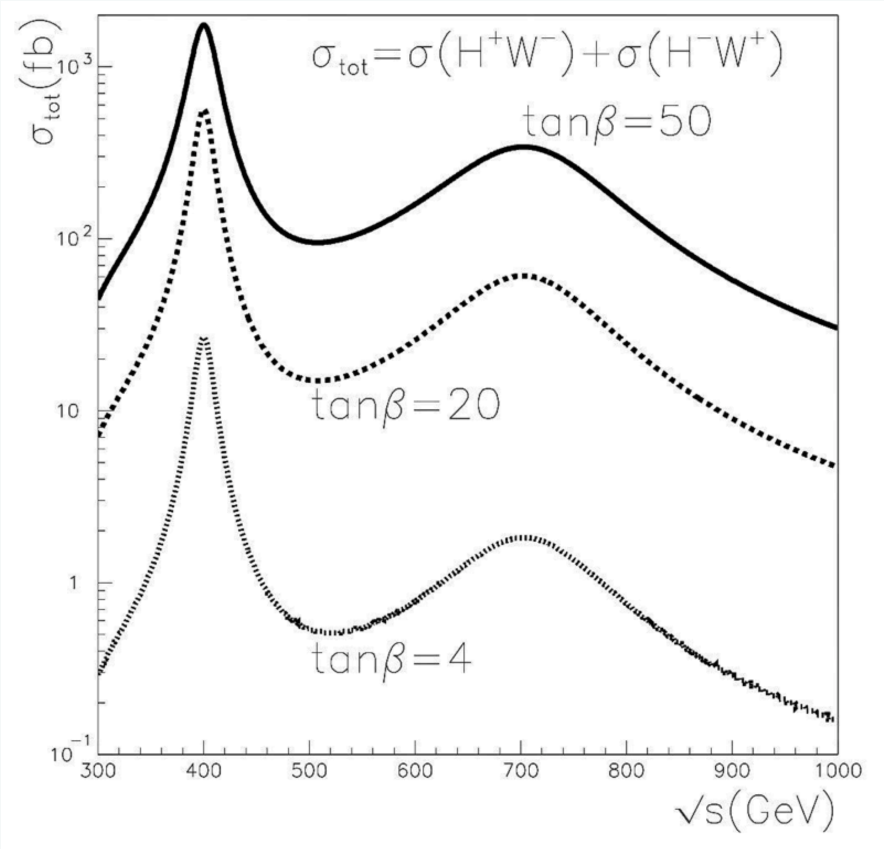
V. Barger et al., hep-ph/9602415

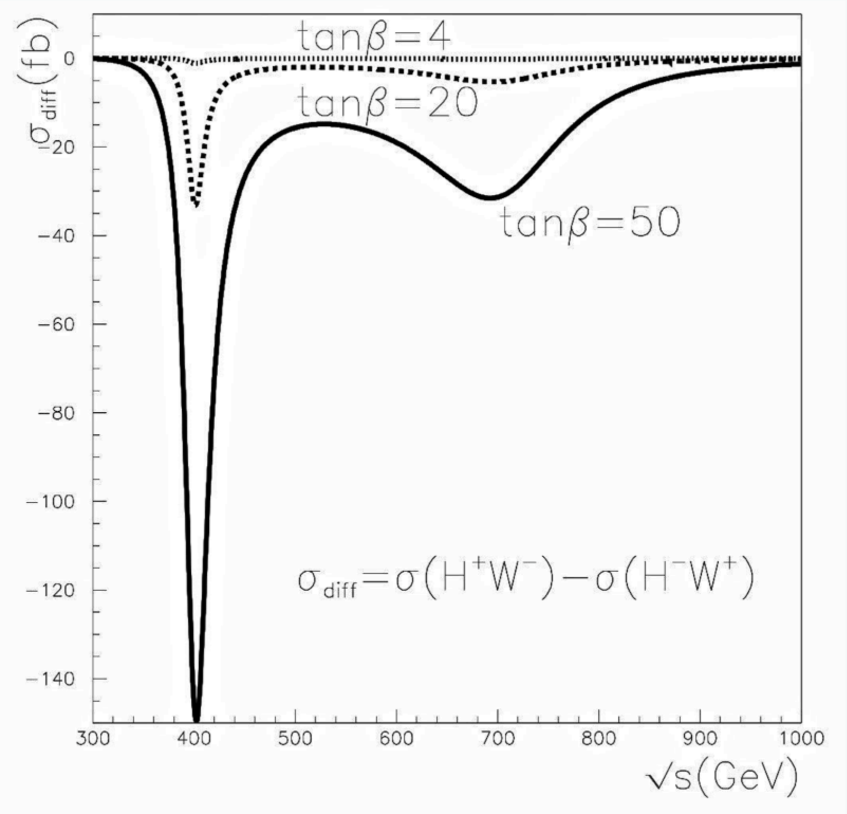
Single production of charged Higgs





- **Both s-channel and t-channel production**





A. Akeroyd and S. Baek, hep-ph/0008286

$$\sigma_{tot} = \sigma(\mu^+\mu^- \to H^+W^-) + \sigma(\mu^+\mu^- \to H^-W^+)$$

$$\sigma_{diff} = \sigma(\mu^+\mu^- \to H^+W^-) - \sigma(\mu^+\mu^- \to H^-W^+)$$

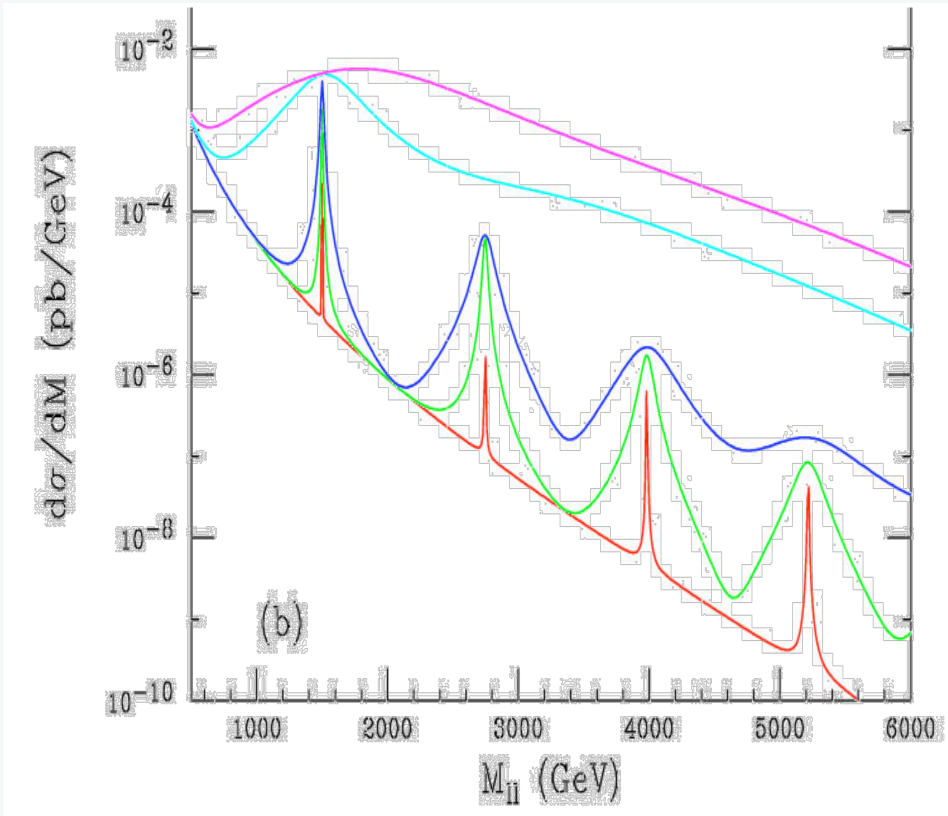
- **Sensitive probe of CP violation in, e.g. general 2HDM**

Is it a Z', or is it M-theory?

- discovery of a heavy dilepton resonance at the LHC will be initially interpreted as a Z'.
- discovery of more than one resonance in the same channel will be interpreted as extra dimensions
- are they spin one, or are they spin two gravitons?
- if they are spin 2, implies warped extra dimensions
- what kind of warped extra dimensions?

- the smoking gun is the mass ratios
- if they are 1, 1.83, 2.66, 3.48, this is locally AdS(5), as you would get from D3 branes of 10-dimensional Type IIB strings
- if they are 1, 1.64, 2.26, 2.88, this is what you would get from M5 branes of 11dimensional M-theory

Bao and JL, hep-ph/0509137



Davoudiasl, Hewett, Rizzo

Pair production of heavy sleptons

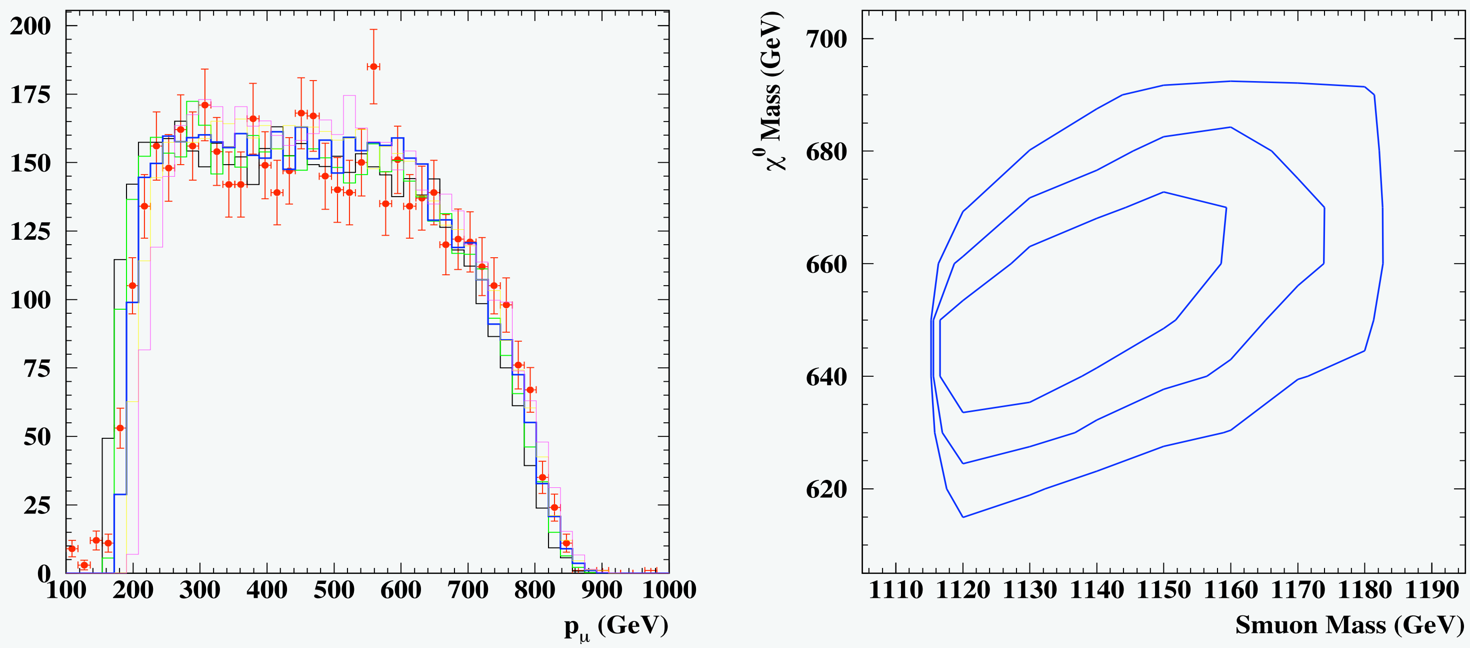


Fig. 5.6: Left panel: Muon energy spectrum in the decay $\tilde{\mu}_L \rightarrow \mu\tilde{\chi}_1^0$ for the benchmark point H, corresponding to $M_{\tilde{\mu}_L}$ = 1150 GeV and $M_{\tilde{\chi}_1^0}$ = 660 GeV, as obtained for $\sqrt{s}$ = 3 TeV, assuming the baseline CLIC luminosity spectrum. Right panel: Accuracy in the determination of the $\tilde{\mu}_L$ and $\tilde{\chi}_1^0$ masses by a two-parameter fit to the muon energy distribution. The lines give the contours at 1σ, 68% and 95% C.L. for 1 ab^{-1} of data at $\sqrt{s}$ = 3 TeV.

$$E_{\max/\min} = \frac{M_{\tilde{\mu}}}{2}\left(1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\mu}}^2}\right) \times \left(1 \pm \sqrt{1 - \frac{M_{\tilde{\mu}}^2}{E_{\mathrm{beam}}^2}}\right)$$

CLIC Physics Working Group, hep-ph/0412251

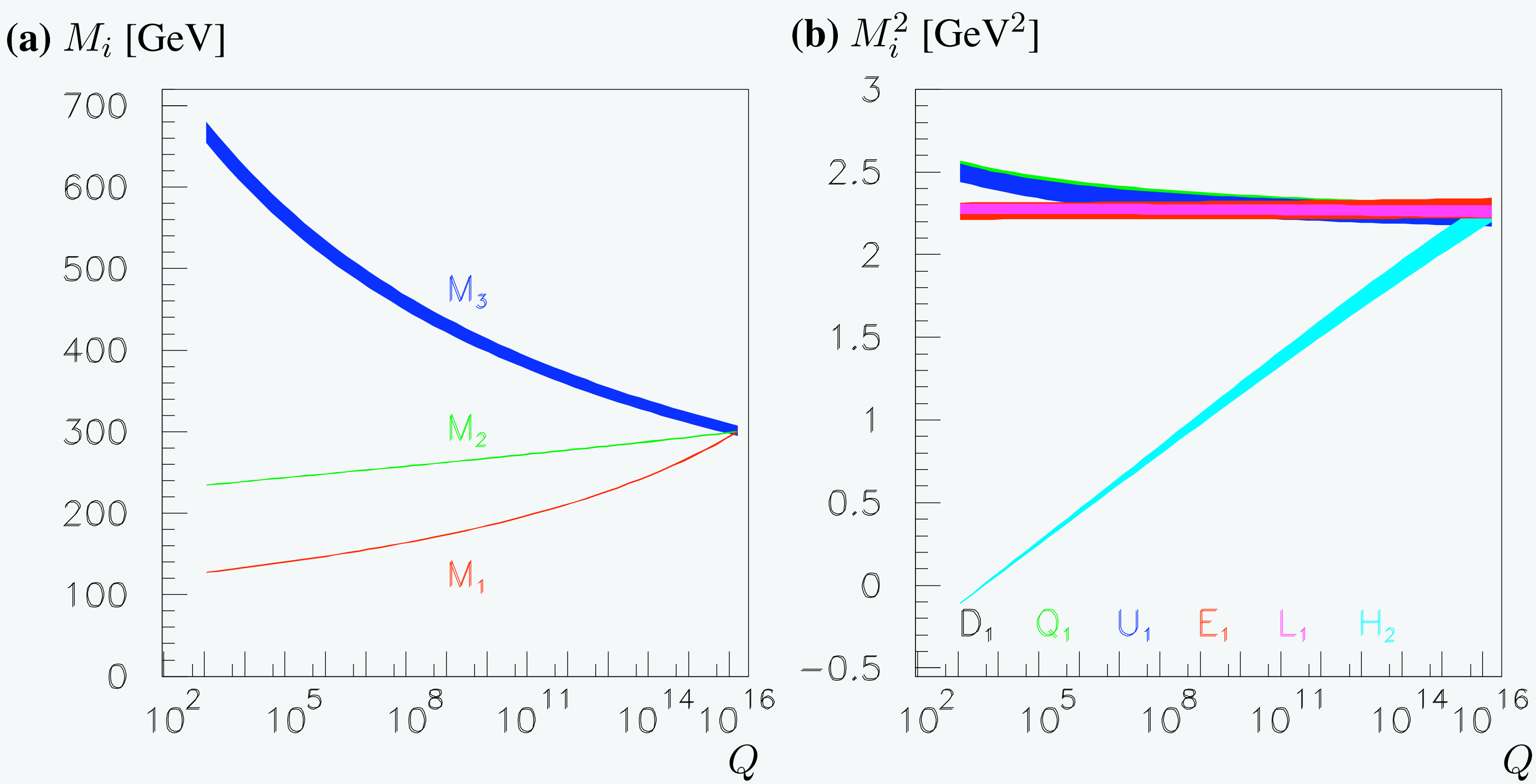
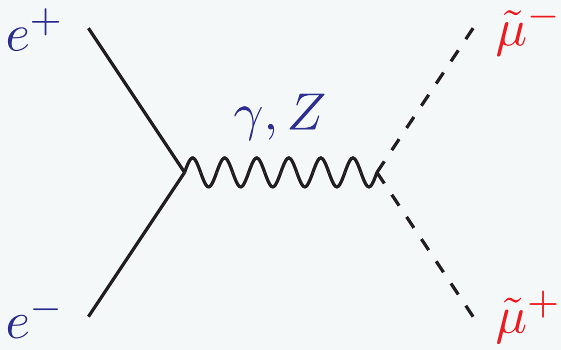
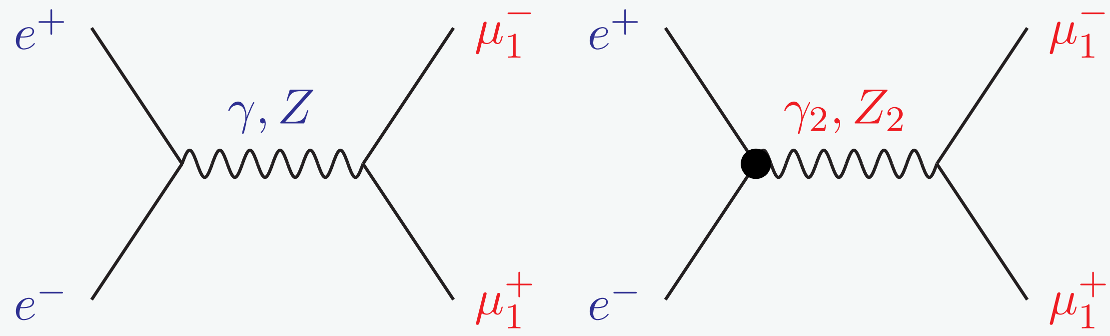


Fig. 5.14: Running of (a) gaugino mass parameters and (b) first-generation sfermion mass parameters and $M^2_{H,2}$ assuming 1% errors on sfermion masses and heavy Higgs boson masses. The width corresponds to 1σ errors.

Is it SUSY, or it it Universal Extra Dimensions?

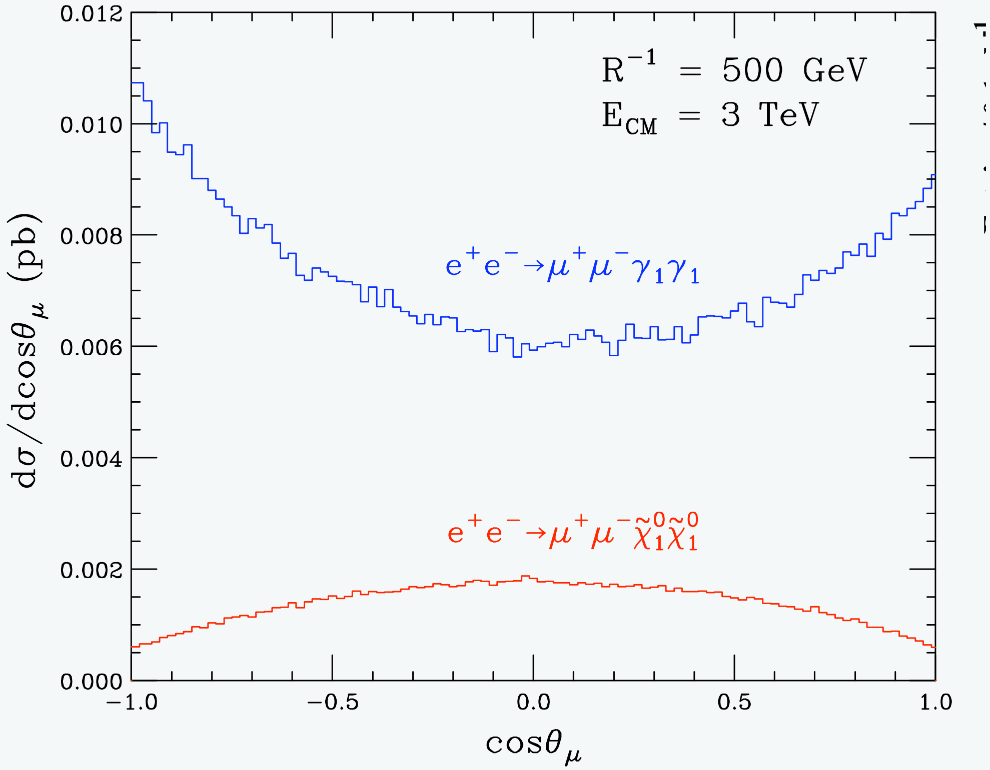




SUSY

Universal Extra Dimensions

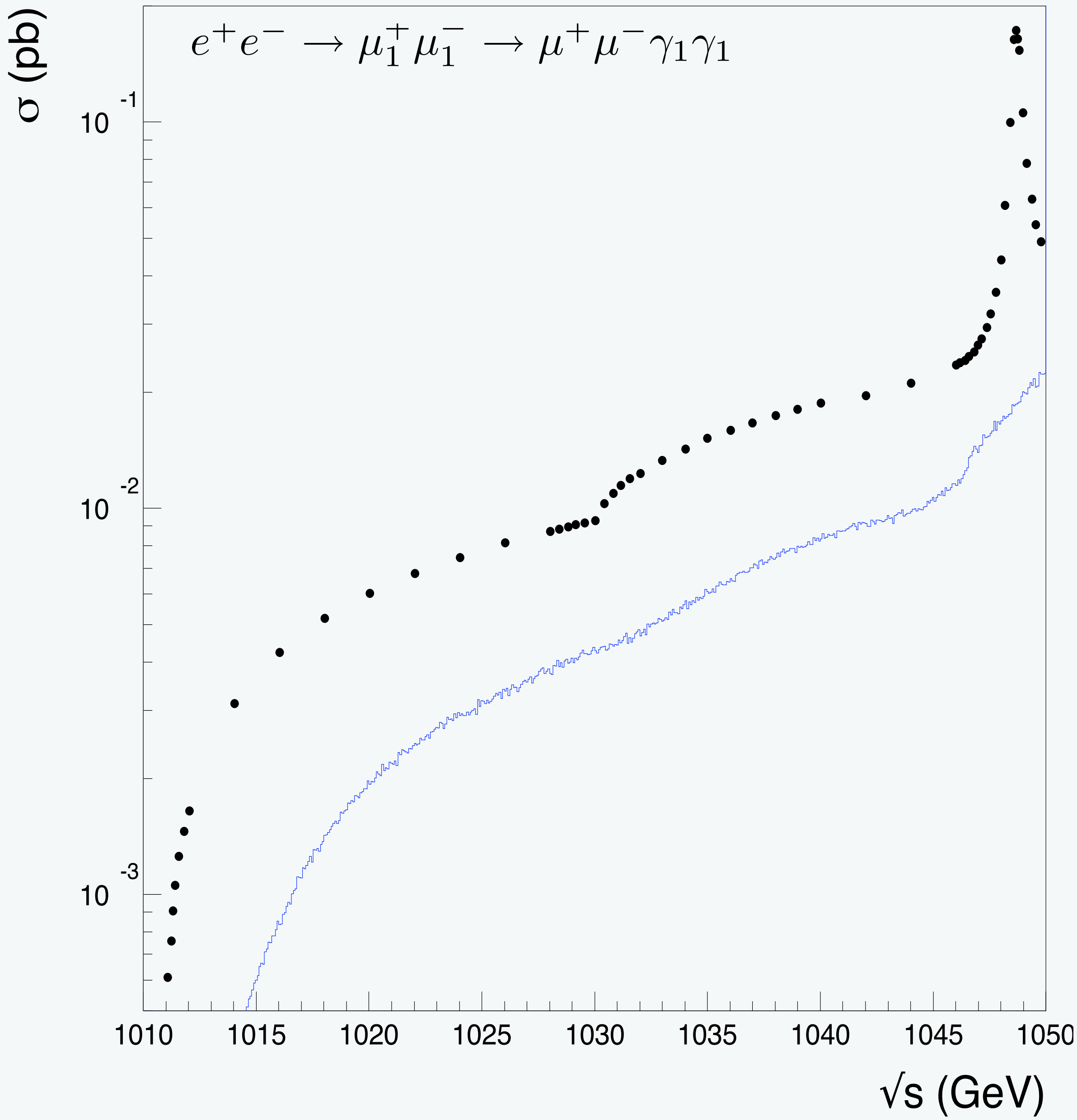
For MC or CLIC, can use angular distributions



Battaglia et al., hep-ph/0502041

Can also use threshold scan, since SUSY pairs turn on like β^3 while UED pairs turn on like β

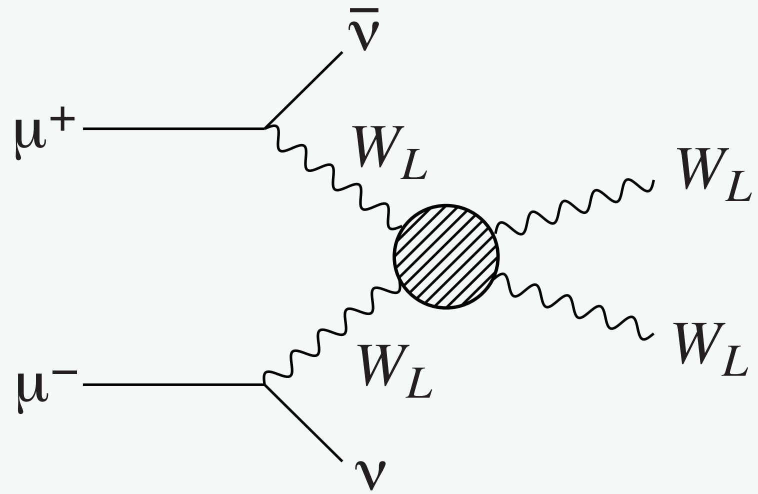
MC has an advantage here over CLIC (how much?)



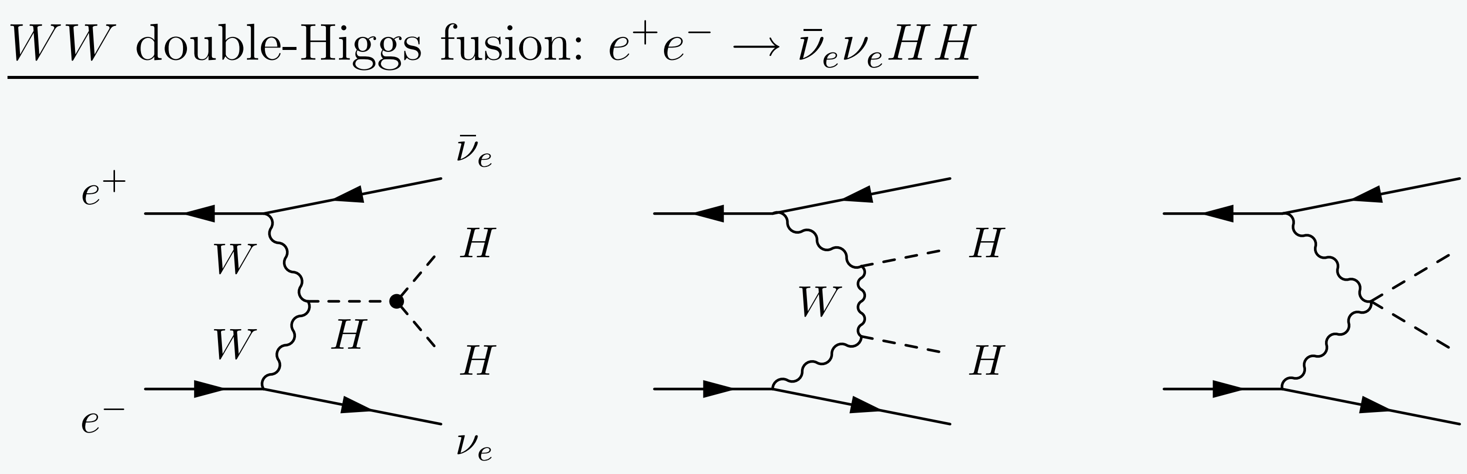
Battaglia et al., hep-ph/0502041

Vector boson fusion at a high energy muon collider

If there is no Higgs (or KK modes) then expect to see ~TeV techni-like resonances in this process



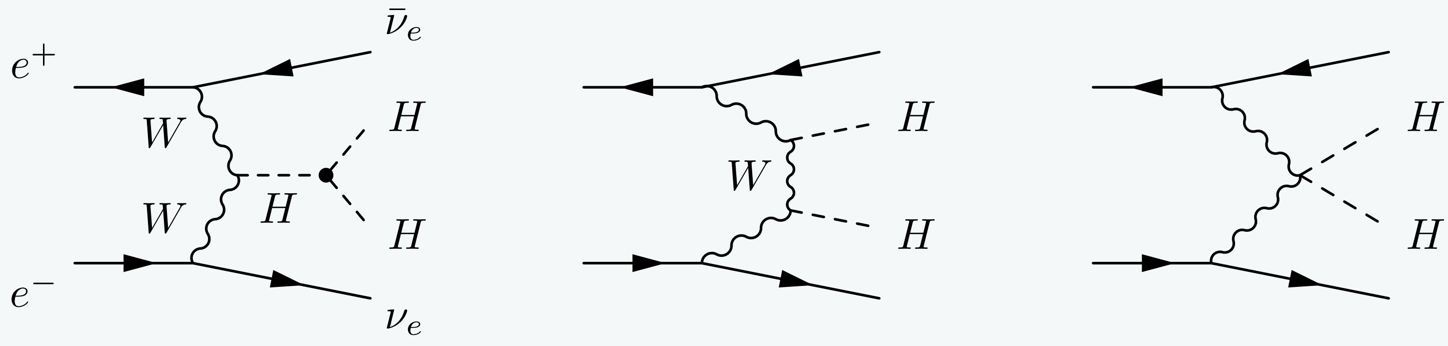
If there is a Higgs, the first diagram below could allow a measurement of the Higgs self-coupling

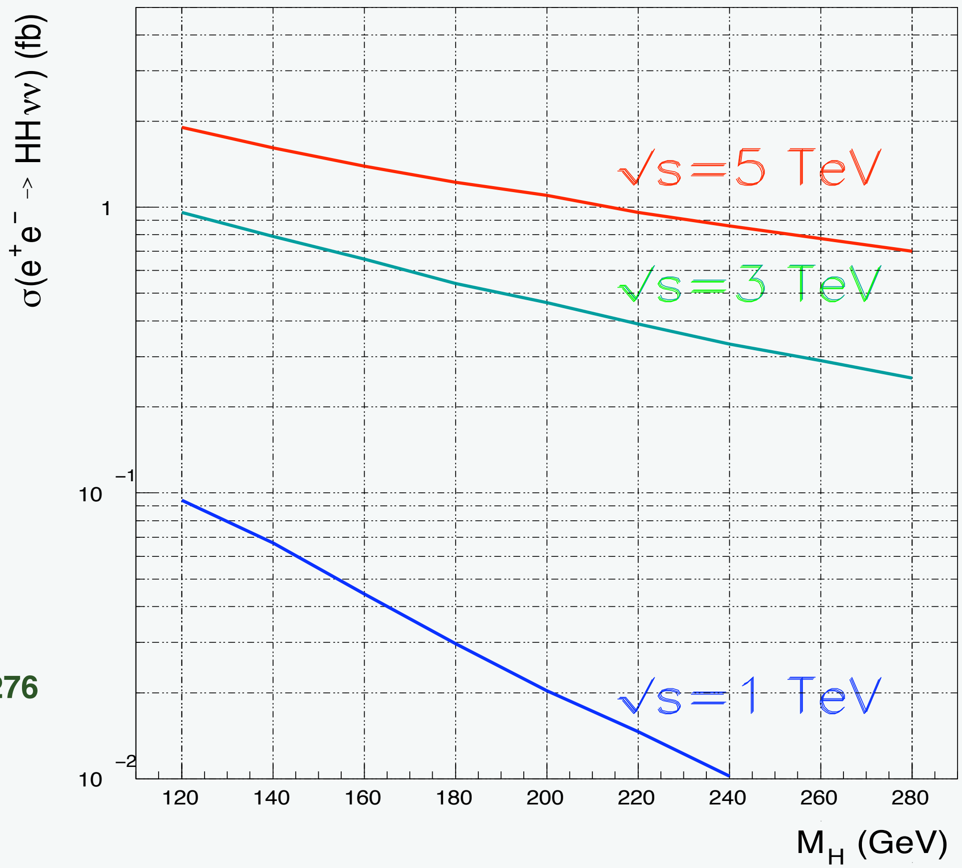


Higgs self-coupling

$\underline{WW \text{ double-Higgs fusion: } e^+e^- \to \bar{\nu}_e \nu_e HH}$

CLIC studies





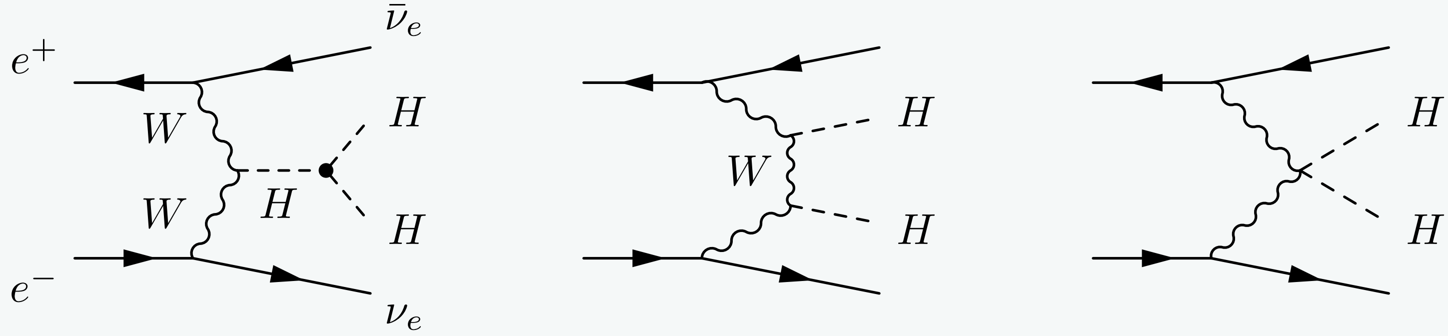
$$\mathbf{R \sim s \log s}$$

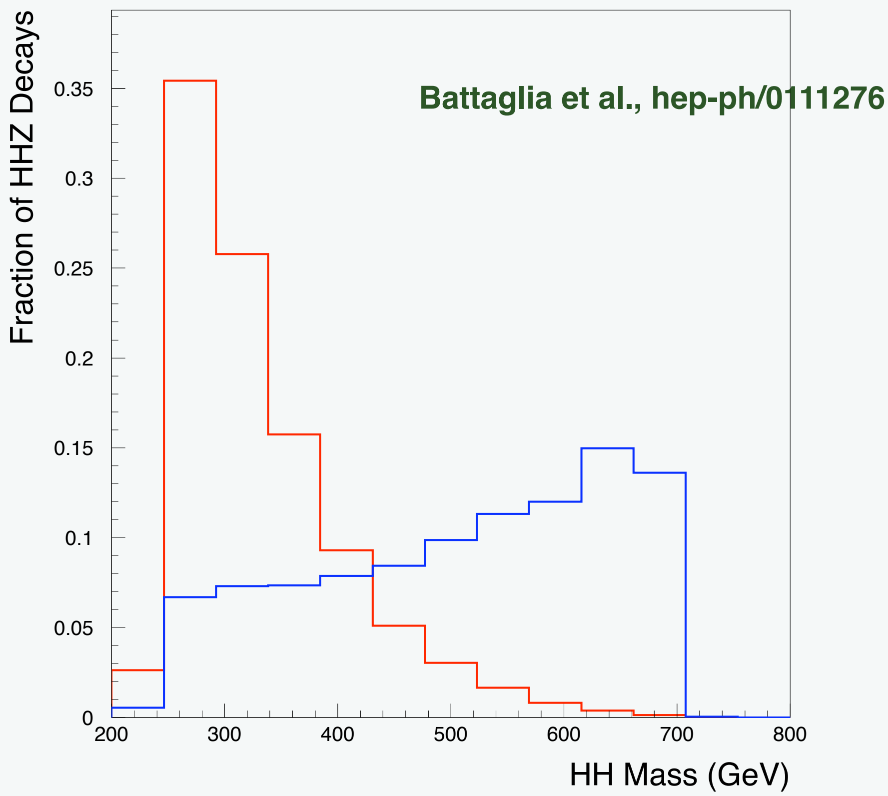
Battaglia et al., hep-ph/0111276

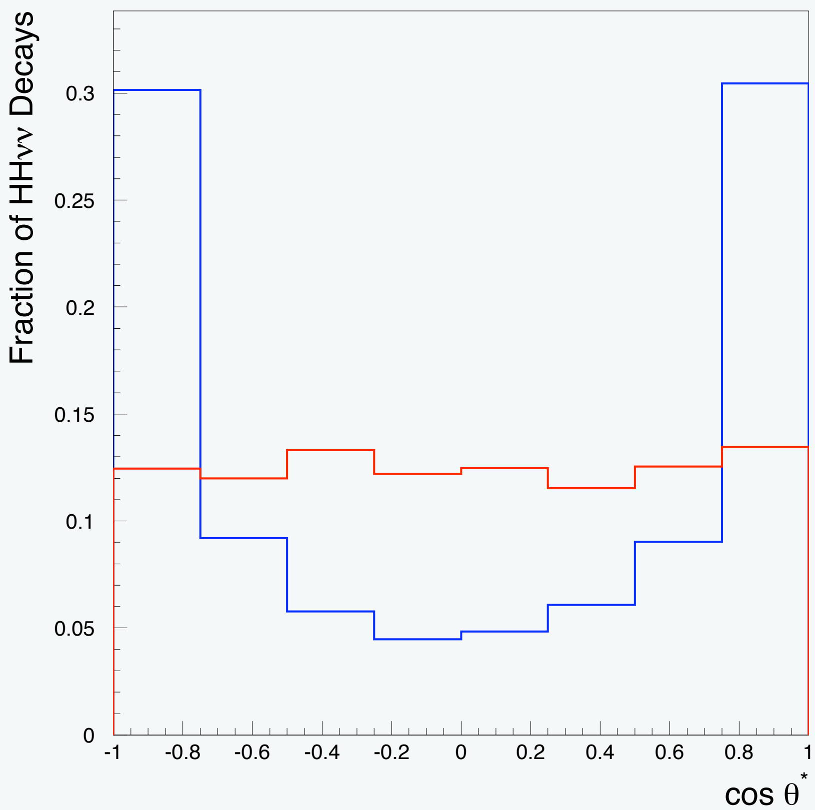
Higgs self-coupling

WW double-Higgs fusion: $e^+e^- \to \bar{\nu}_e \nu_e HH$

CLIC studies







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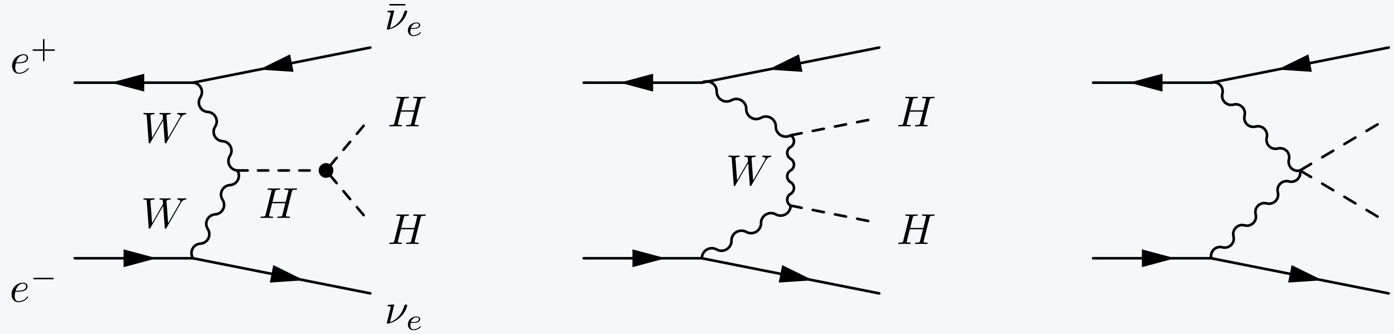

Note: CLIC studies assumed 5 ab-1 integrated luminosity!

Special Bonus Physics
at a High Energy Muon Collider

Special Bonus Physics at a High Energy Muon Collider

Total nuclear disarmament

Special Bonus Physics
at a High Energy Muon Collider

Total nuclear disarmament

Solving the energy crisis

Special Bonus Physics
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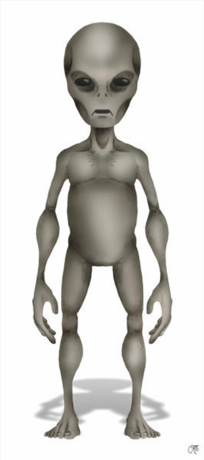
Solving the energy crisis

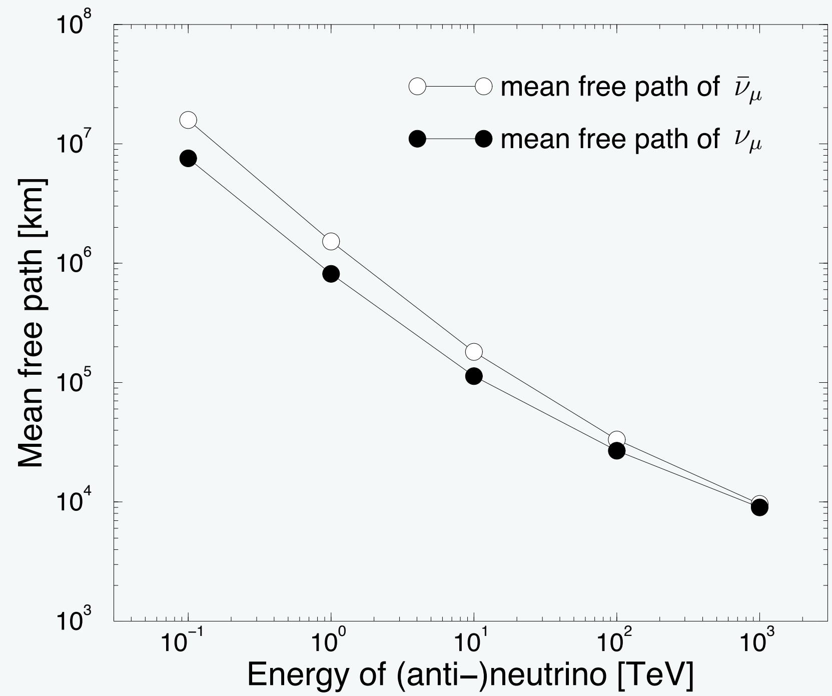


Communicating with extraterrestrials

Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

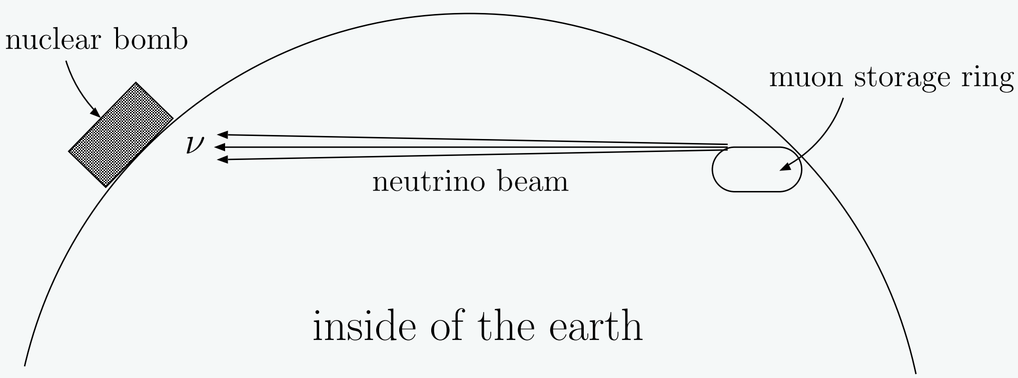
$$r = \frac{m_\mu c^2}{E_\nu} d \simeq \frac{0.1\ (\text{GeV}) \times 10^7\ (\text{m})}{10^6\ (\text{GeV})} = 1\ (\text{m})$$

Hirotaka Sugawara* Hiroyuki Hagura† Toshiya Sanami‡



Abstract

We discuss the possibility of utilizing the ultra-high energy neutrino beam ($\simeq$ 1000 TeV) to detect and destroy the nuclear bombs wherever they are and whoever possess them.



Stau-catalyzed Nuclear Fusion

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Tokyo 113-0033, Japan

[2] *Research Center for the Early Universe, University of Tokyo,*
Tokyo 113-0033, Japan

Abstract

We point out that the stau $\widetilde{\tau}$ may play a role of a catalyst for nuclear fusions if the stau is a long-lived particle as in the scenario of gravitino dark matter. In this letter, we consider dd fusion under the influence of $\widetilde{\tau}$ where the fusion is enhanced because of a short distance between the two deuterons. We find that one chain of the dd fusion may release an energy of $O(10)$ GeV per stau. We discuss problems of making the $\widetilde{\tau}$-catalyzed nuclear fusion of practical use with the present technology of producing stau.

$$t_{\widetilde{\tau}} \simeq 0.2 \text{ years} \left(\frac{m_{3/2}}{10 \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_{\widetilde{\tau}}}\right)^5 \left(1 - \frac{m_{3/2}^2}{m_{\widetilde{\tau}}^2}\right)^{-4} .$$

$$E_{\widetilde{\tau}d+d} \sim \frac{\frac{1}{2}(3.3+4) \text{ MeV}}{\frac{1}{2}(4\times 10^{-4} + 2\times 10^{-5}) \times \kappa} \simeq 20 \text{ GeV}/\kappa.$$

SETI and muon collider

Z. K. Silagadze
Budker Institute of Nuclear Physics and Novosibirsk State University, 630 090, Novosibirsk, Russia

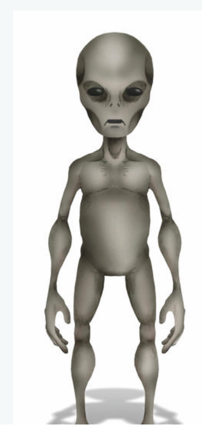
Intense neutrino beams that accompany muon colliders can be used for interstellar communications. The presence of multi-TeV extraterrestrial muon collider at several light-years distance can be detected after one year run of IceCube type neutrino telescopes, if the neutrino beam is directed towards the Earth. This opens a new avenue in SETI: search for extraterrestrial muon colliders.

$$\theta \approx \frac{1}{\gamma} \approx \frac{10^{-4}}{E_\mu[TeV]},$$

Therefore, $E_\mu = 200$ TeV extraterrestrial muon collider operating at the $L = 20$ light-years distance will illuminate with neutrinos a disk of radius $R \approx L\theta \approx 10^8$ km, which is somewhat smaller than the Earth's orbital radius. The neutrino flux on the Earth, assuming the Earth is inside of the neutrino disk, will be $\Phi_\nu \approx 10^5$ year^{-1} km^{-2}, if the neutrino beam intensity at the muon collider is $N_\nu = 3 \times 10^{21}$ year^{-1}.

Therefore, for $S = 1$ km^2 area neutrino detectors, such as IceCube at the South Pole (Ahrens et al., 2004) the expected rate of neutrino events from the hypothetical extraterrestrial muon collider is

$$R = \Phi_\nu S P_{\nu\to\mu} \approx 7 - 10 \text{ year}^{-1}. \quad (1)$$



MC physics studies that have not been done

- sLHC/MC complementarity study, analogous to the 2004 LHC/ILC complementarity study
- MC vs CLIC study, with some reasonable ground rules
- “Physics at a 3-4 TeV Muon Collider” (previous comprehensive studies focused on the “FMC”, a <=500 GeV machine
- Most previous studies of individual channels used the old-fashioned “make some simple cuts” or “make the simplest observable” strategy; need to be re-done using all the information in the events.