Physics Landscape

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Fermilab

Where We Stand

- The Standard Model (SM) - Gauge interactions with fermions
  - QCD - SU(3) gauge interactions
    - color octet gluons (g) and color triplet quarks $(u,d,s,c,b,t)_{(L,R)}$
  - Electroweak - $SU(2)_L X U(1)$ gauge interactions:
    - $SU(2)_L$ triplet gauge bosons: $(W^\pm, W^0)$ and a $U(1)_Y$ gauge boson B
    - quarks: $SU(2)_L$ doublets: (u_L,d_L), (c_L,s_L), (t_L, b_L); and singlets: q_R
    - leptons $SU(2)_L$ doublets: (ν_e, e^-_L), (ν_μ, μ^-_L), (ν_τ, τ^-_L); and singlets l_R
- Electroweak Symmetry Breaking
  - Introduce a $SU(2)_L$ complex doublet scalar field Φ, with self interactions
    - $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2$ with EWSB -> $< \Phi^\dagger\Phi > = v^2 = -\mu^2 /\lambda$; one physical Higgs boson (mass $m_H^2=2\lambda v^2$)
  - Gauge interactions
    - $D^\mu\Phi^\dagger D_\mu\Phi$ with EWSB -> massive $W^\pm$, Z^0 and massless photon γ
  - Yukawa couplings to fermions
    - $\Gamma_{ij}\psi_{iL}^\dagger\psi_{jR}\Phi$ + h.c. with EWSB -> fermion masses and mixing of flavor eigenstates into mass eigenstates. CKM matrix for quarks.
- All data consistent with Standard Model - but incomplete
  - dark matter; neutrino masses and mixing -> new fields or interactions; baryon asymmetry -> more CP violation

Where We Stand

Theoretical questions

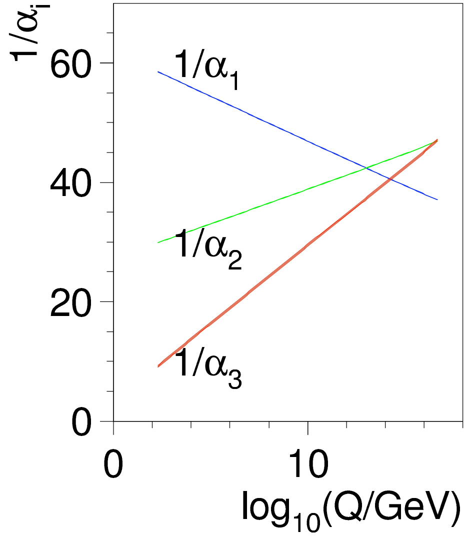
- The issue of naturalness and the origin of mass;
  - $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2 + \Gamma_{ij}\psi_{iL}^\dagger\psi_{jR}\Phi + \text{h.c.}$

$m_H^2/M^2_{planck} \approx 10^{-34}$
Hierarchy problem

vacuum
stability

large range of
fermion masses

- gauge unification -> new interactions;
- gravity: strings and extra dimensions

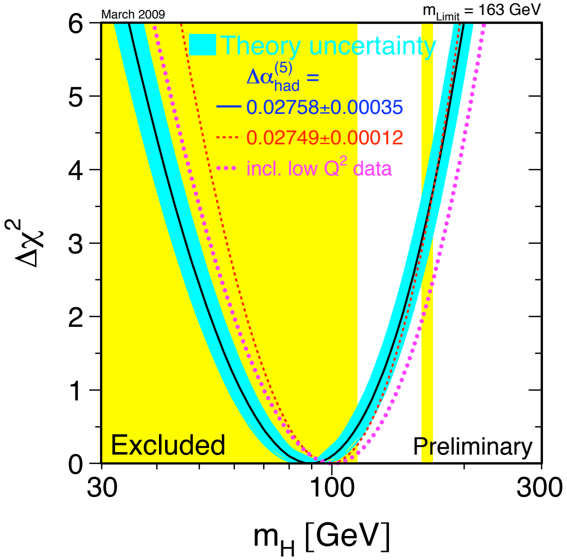


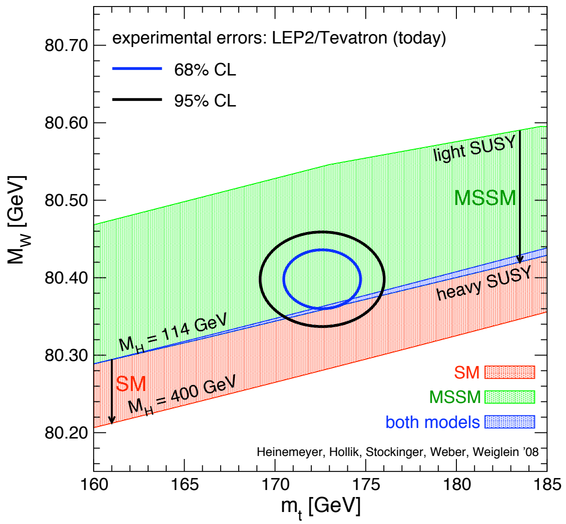
Experimental hints for new physics

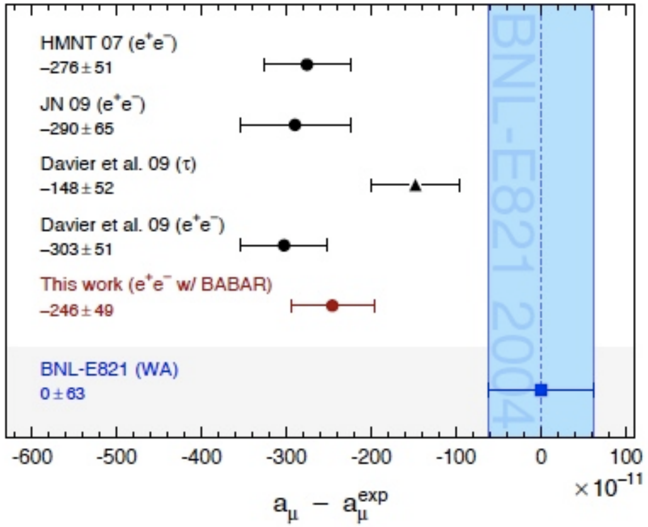
LEP: $m_H > 114$ (95 % CL)
CDF/D0: $m_H = 165$ excluded (95% CL)

indirect

muon (g-2)





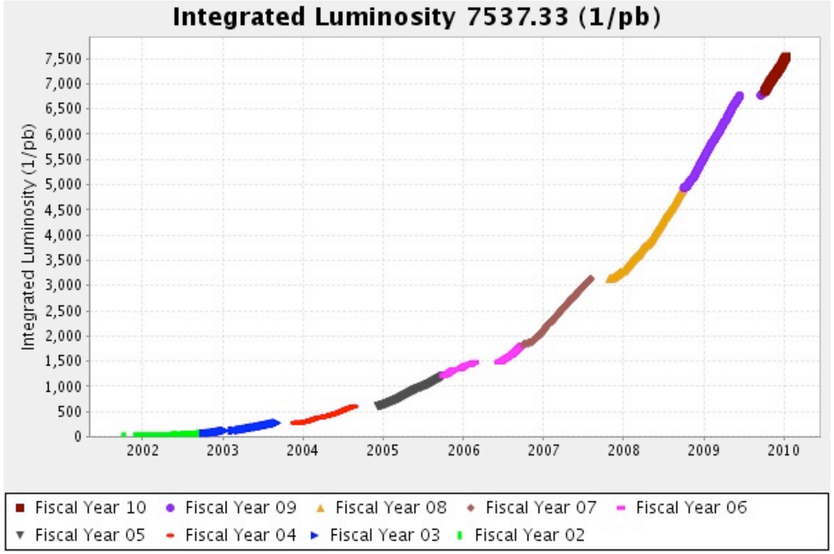


Where We Stand

Energy Frontier Accelerators

Tevatron - Operating well

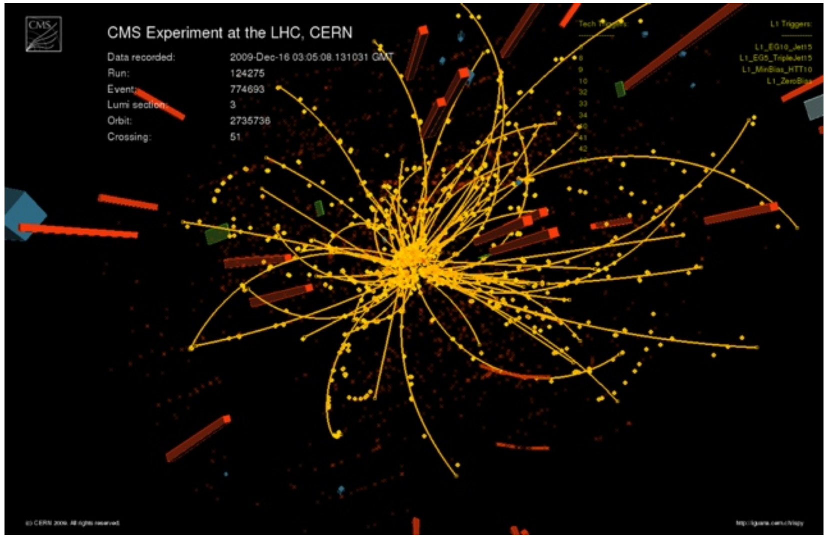
$\sqrt{s}$ = 1.96 TeV   pbar p
Luminosity - 3.52×10^{32} cm^{-2} sec^{-1} (peak)
7.5 fb^{-1} (to date Run II)
CDF, D0



LHC - Coming online $\sqrt{s}$ = 2.36 TeV   p p
Luminosity - 10^{27} cm^{-2} sec^{-1}

$\sqrt{s}$ = 14 TeV   p p
Luminosity - 10^{34} cm^{-2} sec^{-1}

ATLAS, CMS, LHCb, ALICE

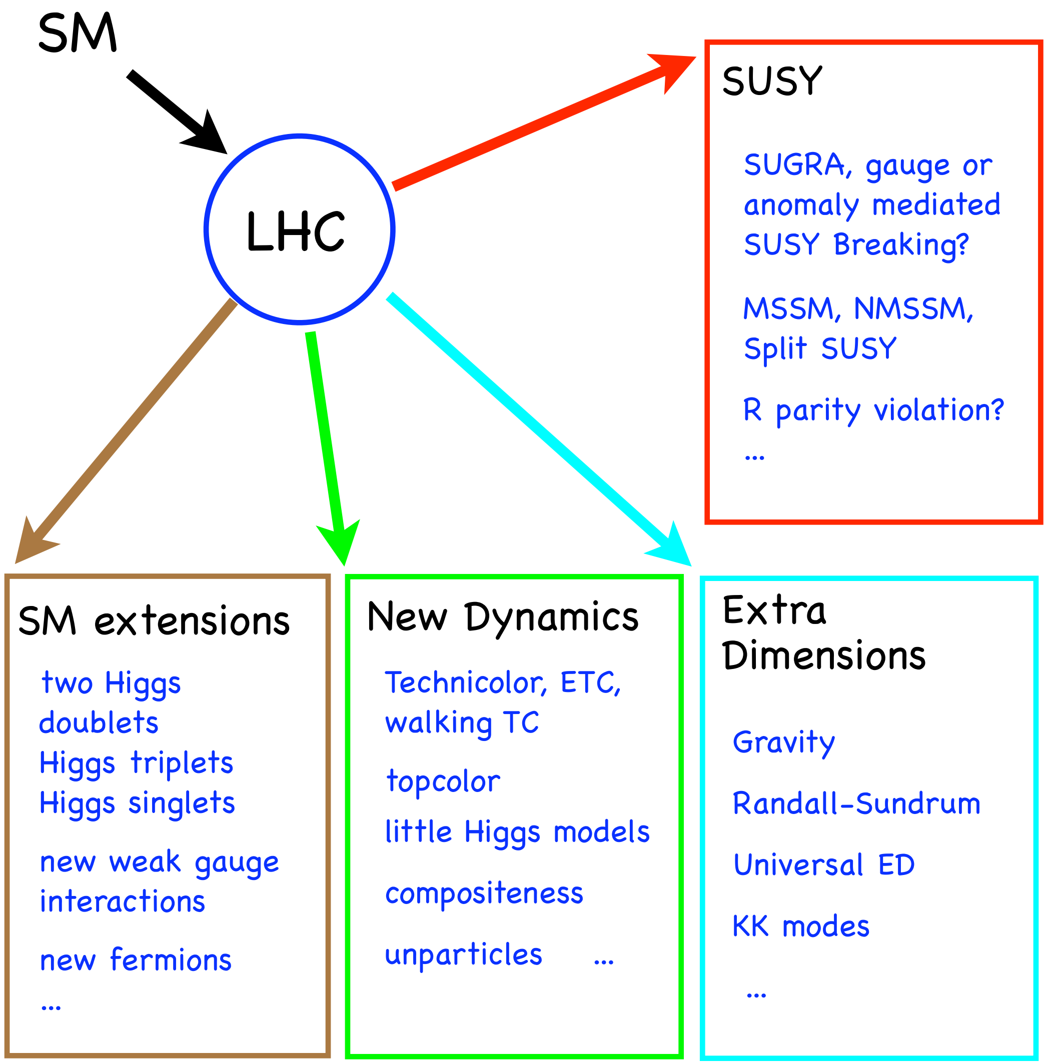


Neutrino Experiments

Accelerators: MiniBooNE, SciBooNE, MINOS, OPERA, NOvA, T2K, ...
Reactors: Double CHOOZ, Daya Bay, ...
Double Beta Decay, Super Beams, Beta Beams, Astrophysical Sources

Crossroad In Theoretical Physics

- Existing facilities in 2025:
  - LHC with luminosity or energy upgrade
- Options:
  - low energy lepton collider: ILC (500 GeV) (upgradable) or muon collider - Higgs Factory
  - lepton collider in the multi-TeV range: CLIC or muon collider
  - hadron collider in hundred TeV range: VLHC
- High energy lepton collider likely required for full study of Tevascale physics.



SM

LHC

SUSY

SUGRA, gauge or anomaly mediated SUSY Breaking?

MSSM, NMSSM, Split SUSY

R parity violation?

…

SM extensions

two Higgs doublets

Higgs triplets

Higgs singlets

new weak gauge interactions

new fermions

…

New Dynamics

Technicolor, ETC, walking TC

topcolor

little Higgs models

compositeness

unparticles …

Extra Dimensions

Gravity

Randall-Sundrum

Universal ED

KK modes

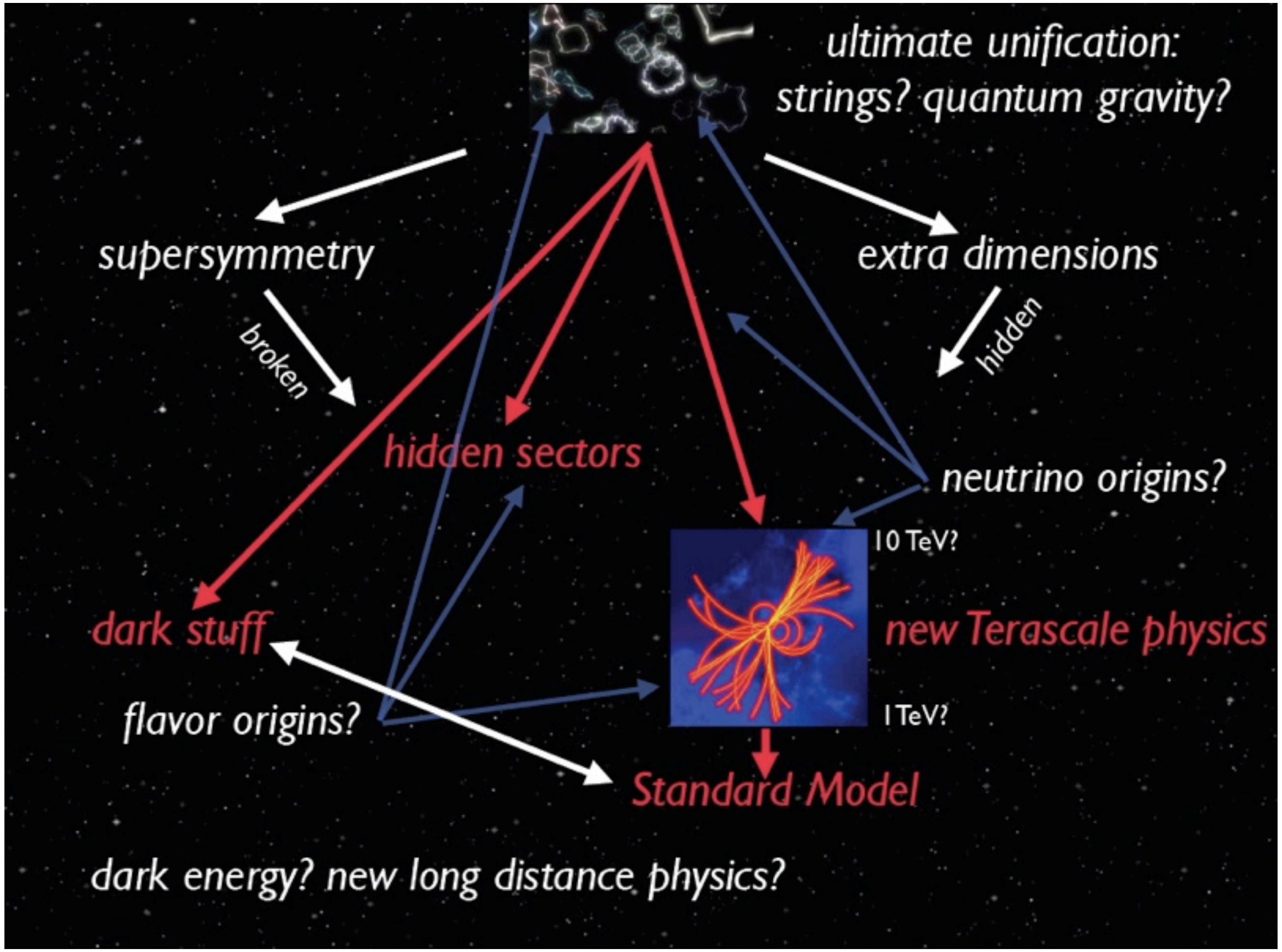
…

Theorists' grand visions

- New Scales and Symmetry Breaking

Physics	Symmetry	Scale
EW	$SU(2)_L \times U_Y(1)$ --> $U_{EM}(1)$	M_W/g
QCD	confinement	$m_{glueball}$
	χ SB	m_{proton}

What is the origin and scale of fermion masses?



Lykken's talk at the "Muon Collider Physics, Detectors and Backgrounds Workshop"

A Muon Collider

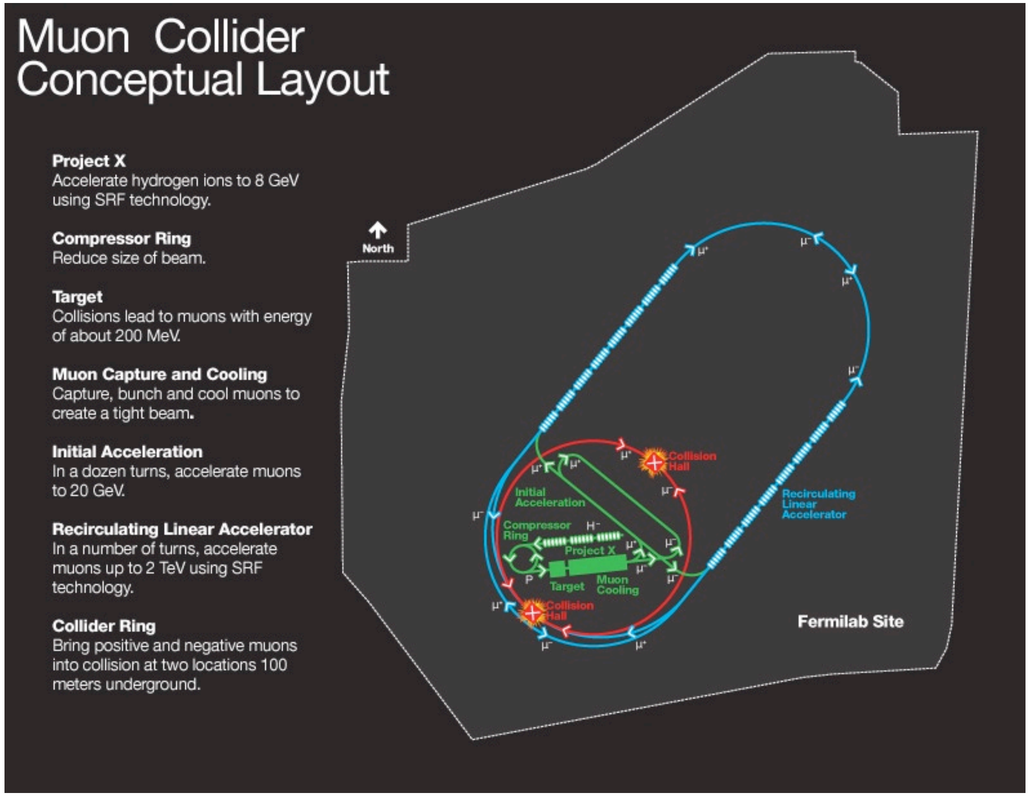
- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 5 TeV (focus 3 TeV)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (focus 400 fb^{-1} per year)

Abridged Parameter List

Machine	1.5-TeV $\mu^+\mu^-$	3.0-TeV $\mu^+\mu^-$	CLIC 3 TeV
$\mathcal{L}_{\text{peak}}$ [cm^{-2} s^{-1}]	7×10^{34}	8.2×10^{34}	8×10^{34} $_{\text{tot}}$
$\mathcal{L}_{\text{avg}}$ [cm^{-2} s^{-1}]	3.0×10^{34}	3.5×10^{34}	3.1×10^{34} $_{99\%}$
$\Delta p/p$ [%]	1	1	0.35
$\beta^\star$	0.5 cm	0.5 cm	35 μm
Turns / lifetime	2000	2400	
Rep. rate [Hz]	65	32	
Mean dipole field	10 T	10 T	
Circumference [m]	2272	3842	33.2 km site
Bunch spacing	0.75 μs	1.28 μs	0.67 ns

A Muon Collider

- Compact Facility



Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

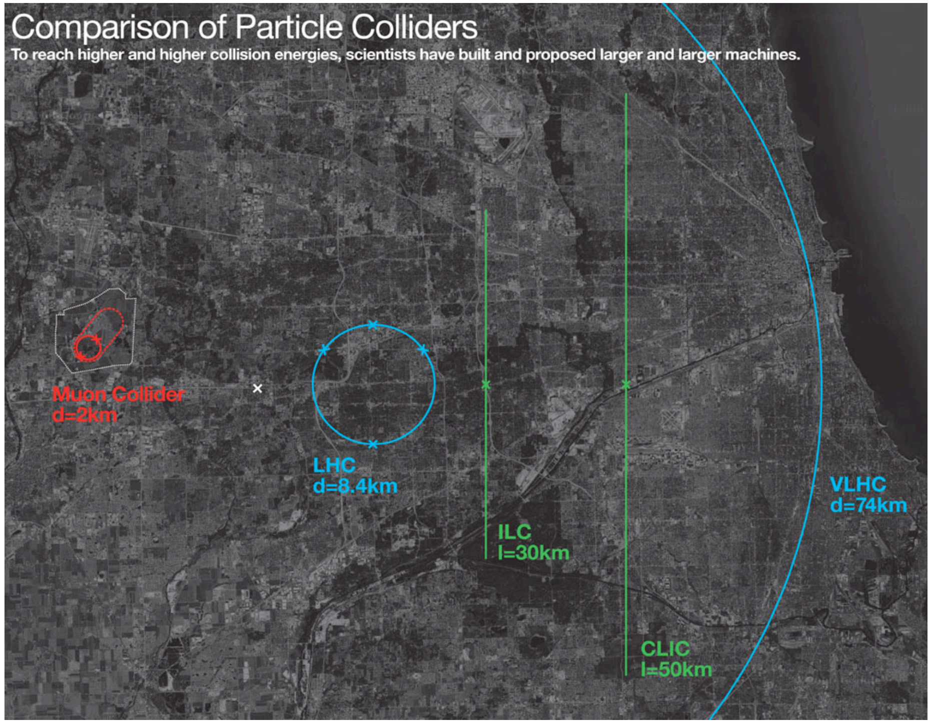
Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.

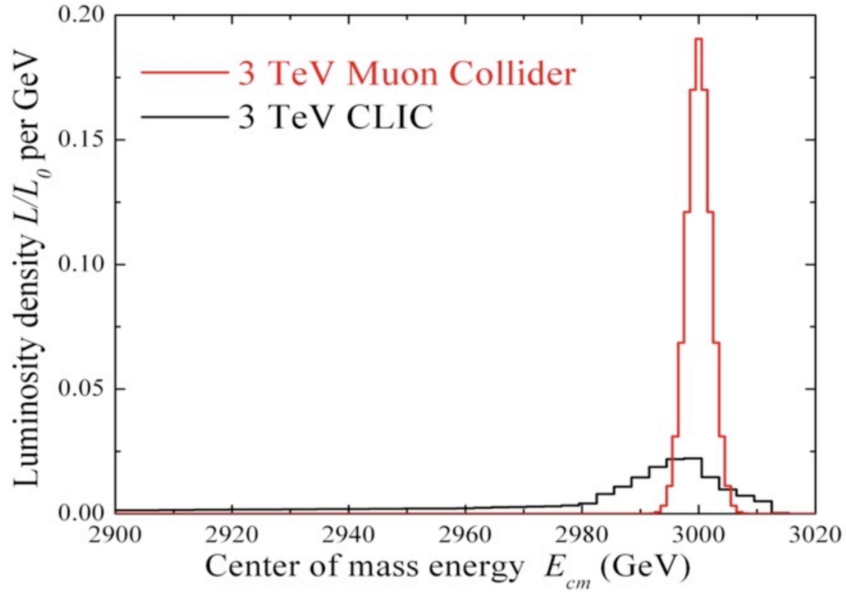


Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.

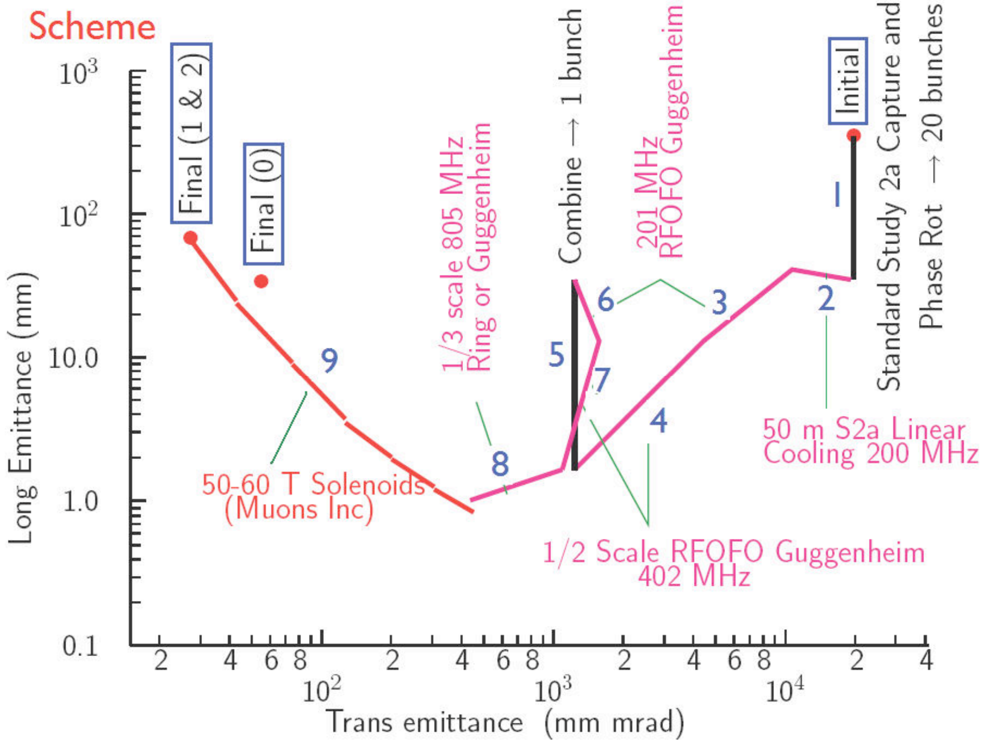
- Superb Energy Resolution
  - MC: 95% luminosity in dE/E ~ 0.1%
  - CLIC: 35% luminosity in dE/E ~ 1%

    Beamstrahlung in e+e- collider $\delta E/E \sim \gamma^2$



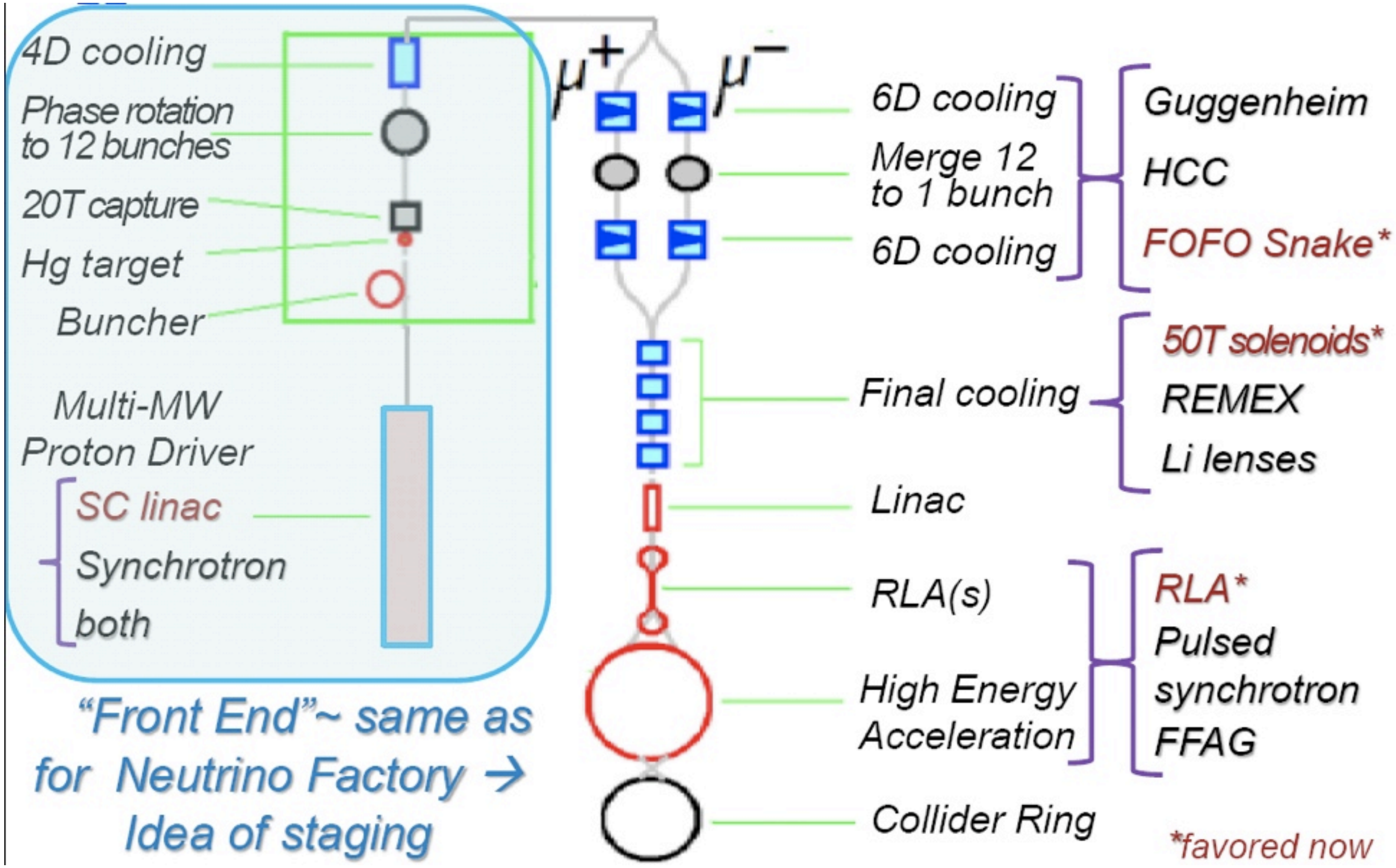
A Muon Collider

- Muons decay:
  - muon lifetime: (2.197034 ± 0.000021) × 10^{-6} sec
  - *A 3 GeV muon travels 18.7 km in one lifetime*
  - *A 1.5 TeV muon travels 9,300 km in this time -> More than 2000 turns in final collider ring.*
  - The muon beams must be accelerated and cooled in phase space (factor ≈ 10^6) rapidly -> ionization cooling
  - requires a complex cooling scheme
  - The decay products (μ^- -> $\nu_\mu \bar{\nu}_e$ e^-) high energies.



Muon Collider Facility

- Present options for technologies:

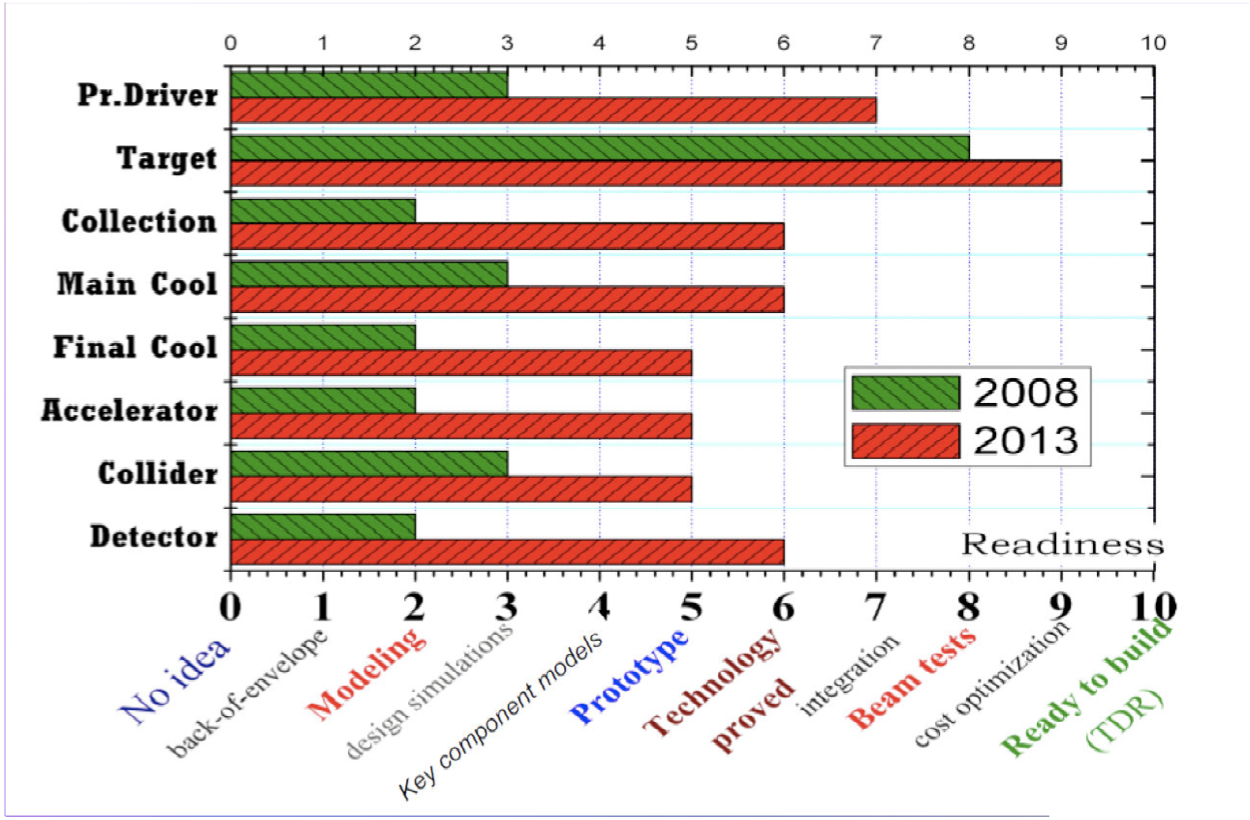


"Front End"~ same as for Neutrino Factory → Idea of staging

*favored now

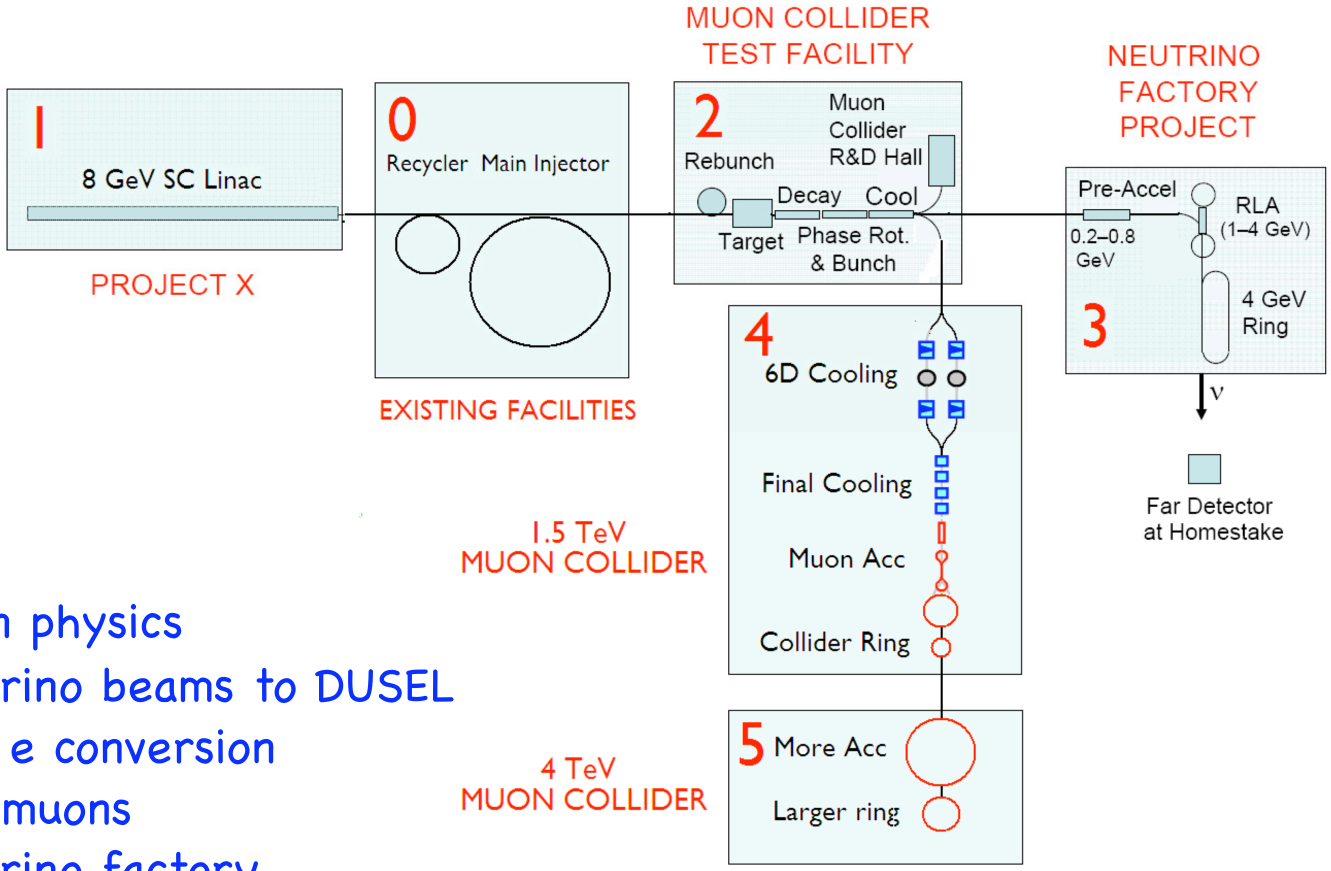
Many Elements Need R&D

- Five Year Plan R&D



Path to Muon Collider Facility

☐ A flexible scenario with physics at each stage:



- Kaon physics
- Neutrino beams to DUSEL
- μ -> e conversion
- cold muons
- Neutrino factory
- Muon collider - Higgs factory ✓
- Multi-TeV Muon Collider ✓

Low Energy Muon Collider Basics

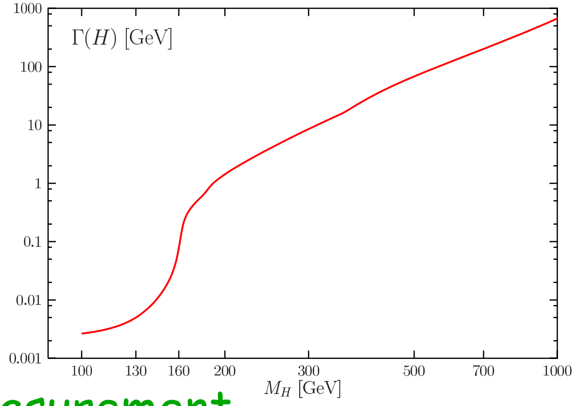
- For $\sqrt{s} < 500$ GeV lepton collider
  - SM threshold regions:
    top pairs; W^+W^-; Z^0Z^0; Z^0h production

- For low energy muon collider
  - s-channel Higgs production
    - Coupling ∝ lepton mass

$$\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^{4}$$

    - Narrow width

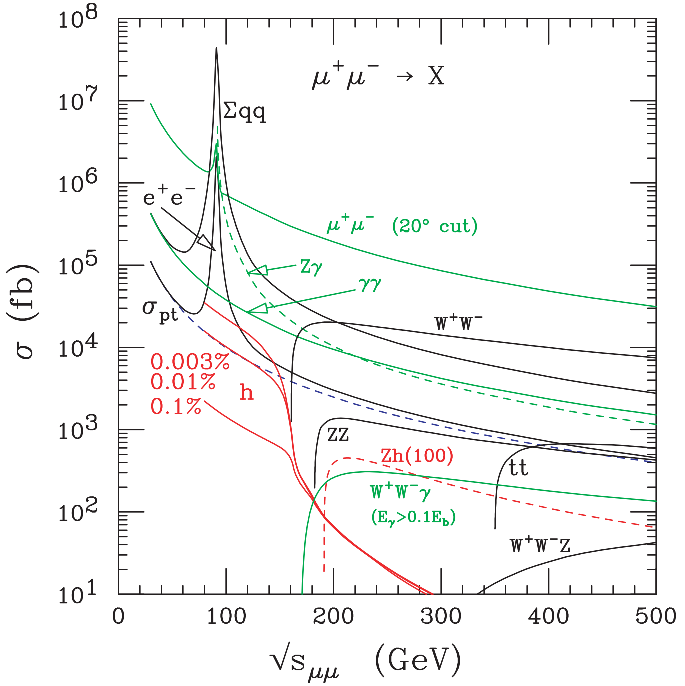
$$\begin{aligned} \Gamma &= 3.6 \text{ MeV} \\ (m_h &= 120 \text{ GeV}) \end{aligned}$$



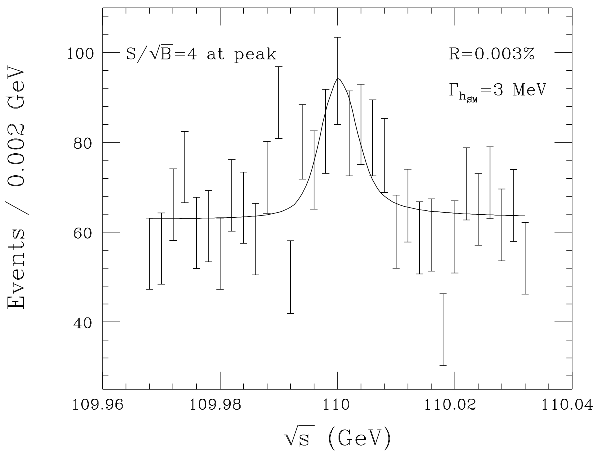
    - Direct width measurement

$$\Delta E/E \approx 0.003\% \quad \text{and } 100\ pb^{-1}$$

Standard Model Cross Sections

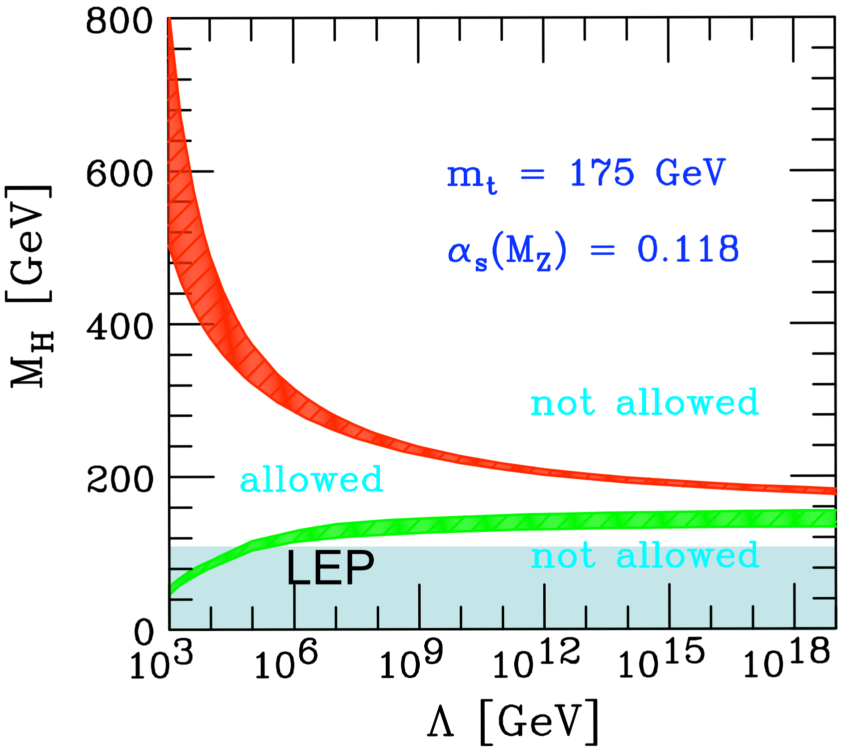


$m_{h_{SM}}$ = 110 GeV, εL=0.00125fb^{-1} per bin

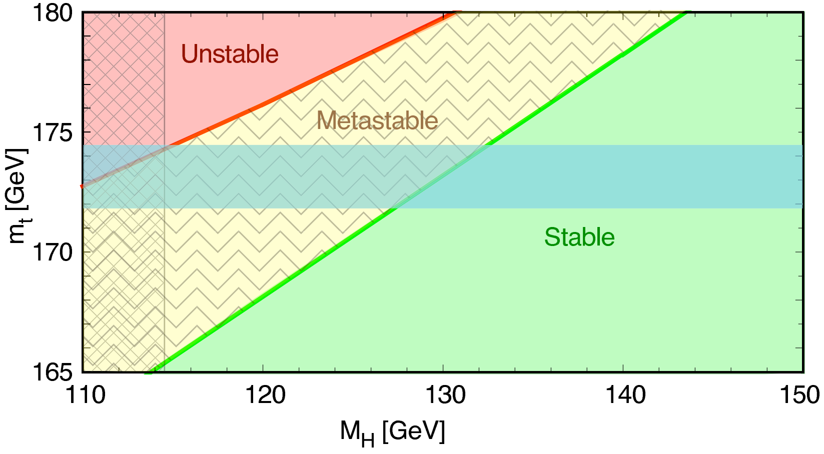


Constraints on Standard Model Higgs

- Theoretical Constraints:
  - The standard model with an elementary Higgs scalar is only self-consistent up to some maximum energy scale (Λ).
  - Upper bound - A large Higgs mass requires a large higgs self-coupling term. This coupling increases with the scale Λ until perturbative theory breaks down.
  - Lower bound - For small Higgs mass, the quantum corrections can lead to vacuum instability.
  - Planck Chimney: SM self-consistent to Planck scale ($\approx 10^{19}$ GeV)

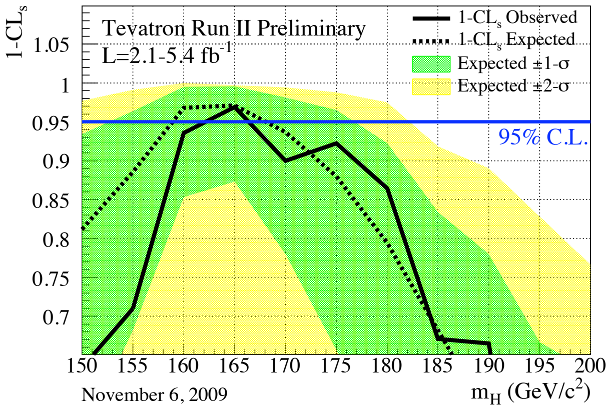


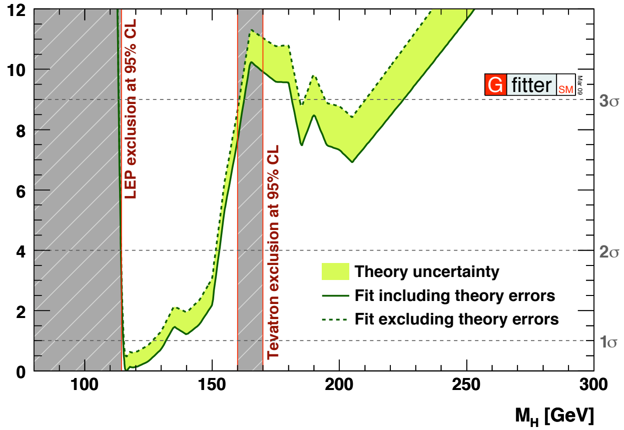
Lower bounds for Planck chimney



Observing the Standard Model Higgs

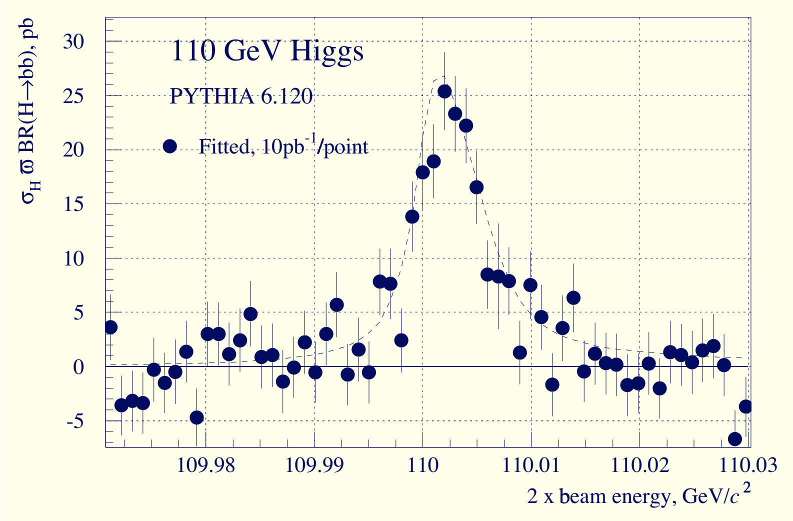
- Experimental Constraints:
  - Direct: LEP $m_H > 114.7$ GeV (95% CL)
    CDF/D0 $m_H < 162$ or > 167 GeV (95% CL)
  - Indirect: LEP/SLC $m_H < 190$ GeV (95% CL)
  - Combined all information: Gfitter
    $113.8 < m_H < 152.5$ GeV (95% CL)





H. Flaecher *et al.*, "Gfitter - Revisiting the Global Electroweak Fit of the Standard Model and Beyond," arXiv:0811.0009 [hep-ph], cern.ch/gfitter.

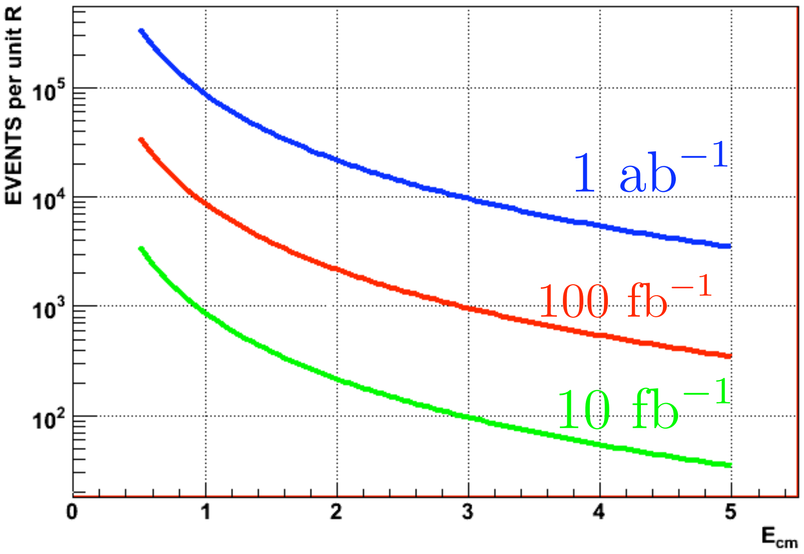
- LHC will discover the SM Higgs. If Higgs mass is not in the Planck chimney (130-190), new physics "nearby".
- Large Higgs mass implies a strong Higgs self interaction and presumably a nearby strong interaction.
- For a low mass Higgs, the new physics can be perturbative. This case is favored by the present indirect Higgs bounds. Many of the Higgs couplings could be measured at the LHC.
- The ILC(500) allows detailed study of the light Higgs properties.
- Only a low energy Muon Collider can directly measure Higgs width.



J. Gunion, MC workshop (2008)

Multi-TeV Muon Collider Basics

- For $\sqrt{s}$ > 500 GeV
  - Above SM pair production thresholds:
    $R \equiv \sigma/\sigma_{QED}(\mu^+\mu^- \to e^+e^-)$ flat
- Luminosity Requirements



R at $\sqrt{s}$ = 3 TeV

$O(\alpha_{em}^2)$ $O(\alpha_s^0)$

$\mu^+\mu^-(20^o\ \mathrm{cut}) = 100$

$W^+W^- = 19.8$

$\gamma\gamma = 3.77$

$Z\gamma = 3.32$

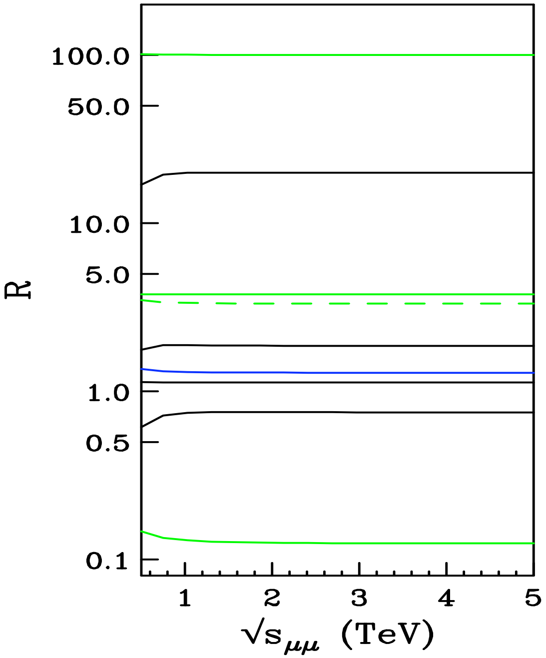
$t\bar{t} = 1.86$

$b\bar{b} = 1.28$

$e^+e^- = 1.13$

$ZZ = 0.75$

$Zh(120) = 0.124$



(one unit of R)

$$\sigma_{\rm QED}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \mathrm{fb}}{s(\mathrm{TeV}^2)}$$

For example: $\sqrt{s} = 3.0$ TeV $\Rightarrow$ 965 events/unit of R

$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

$$\to 100\ \mathrm{fb}^{-1}\mathrm{year}^{-1}$$

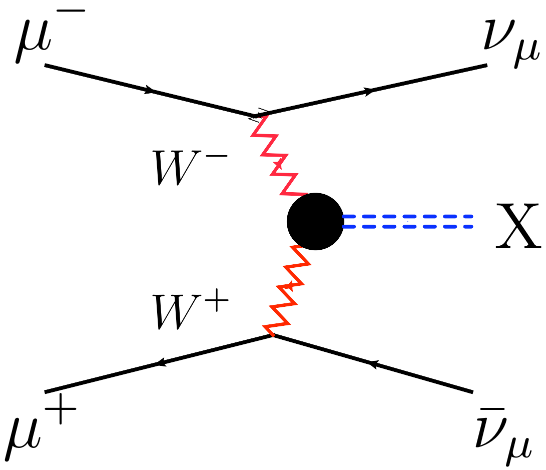
Processes with R ≥ 0.1 can be studied

Total - 128 K SM events per year

Fusion Processes

- Large cross sections
- Increase with s.
- Important at multi-Tev energies
- $M_X^2 < s$

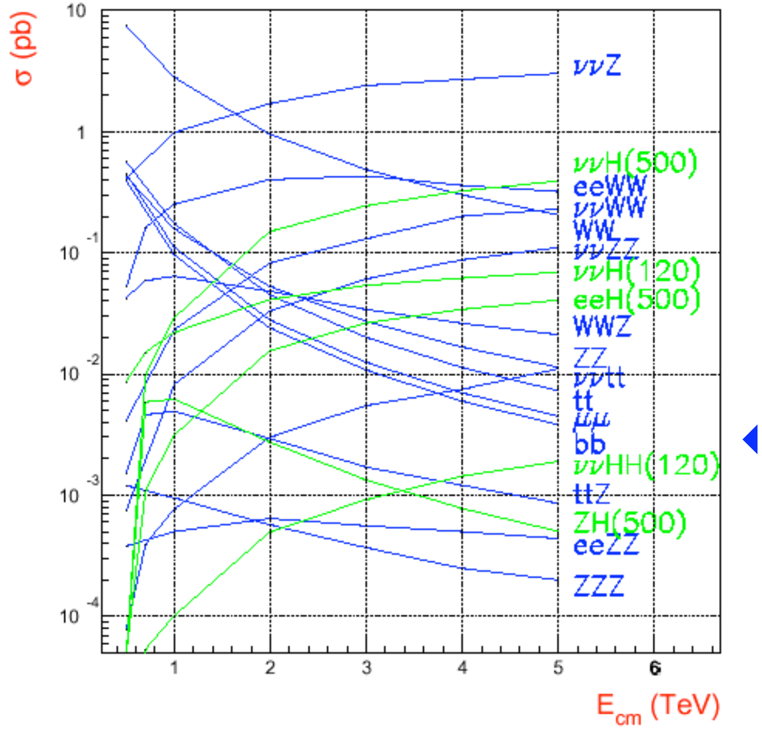
- Backgrounds for SUSY processes
- t-channel processes sensitive to angular cuts



$$\sigma(s) = C\ln(\frac{s}{M_X^2}) + \dots$$

☐ An Electroweak Boson Collider

CLIC (or MC e<->μ)

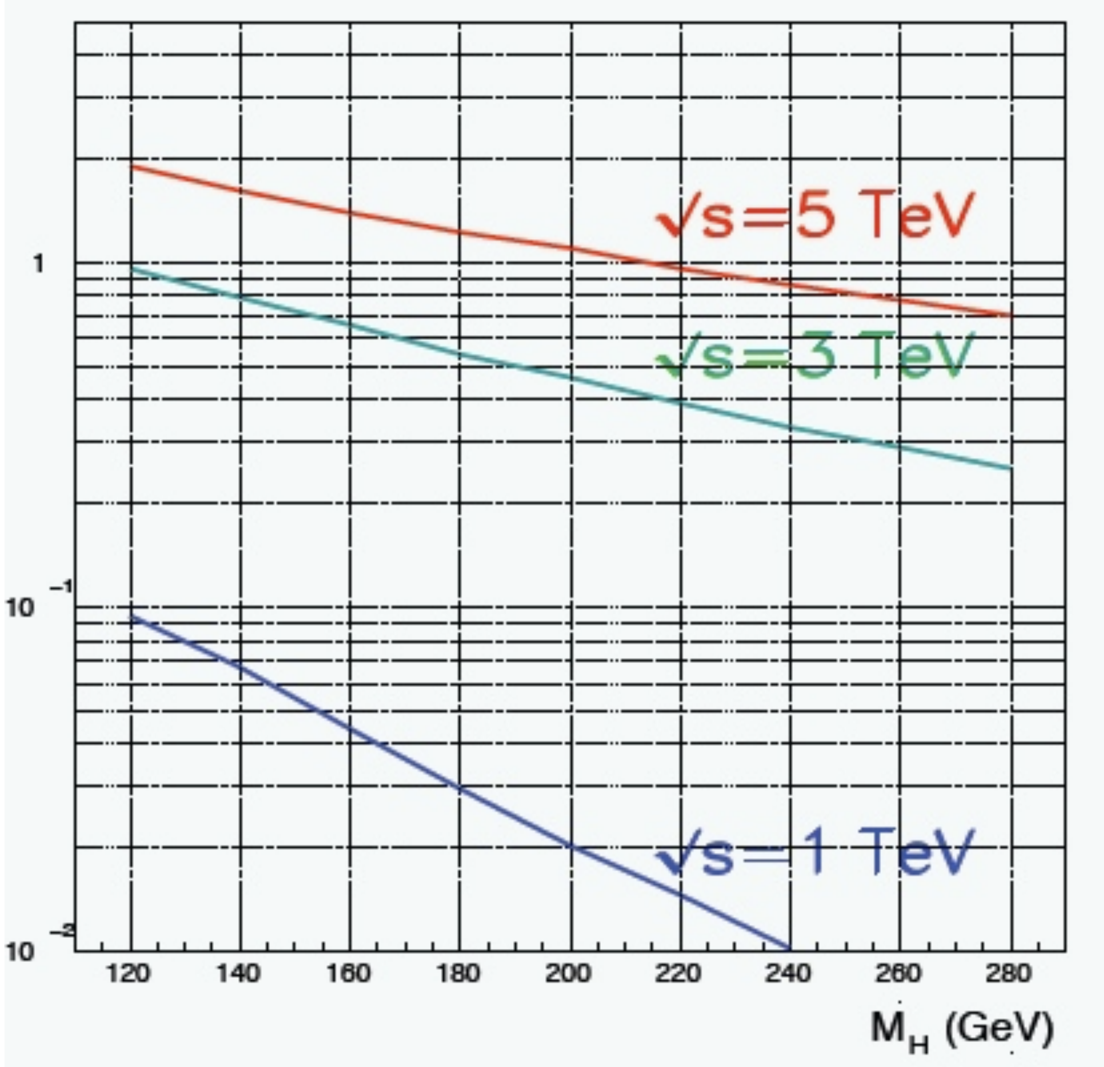


X	R (@ 3 TeV)
Z^0	230
$h^0(500)$	25
W^+W^-	19.8
Z^0Z^0	5.8
$h^0(120)$	5.5
$t\bar{t}$	0.6
$h^0h^0(120)$	0.1

Fusion Processes

☐ Double Higgs from WW fusion : $\sigma(\mu^+\mu^- \to \nu\nu HH)$

σ (fb)



Minimum Luminosity for Muon Collider

- Universal behavior for s-channel resonance

$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left[\frac{\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4} \right] B_{in} B_{out}$$

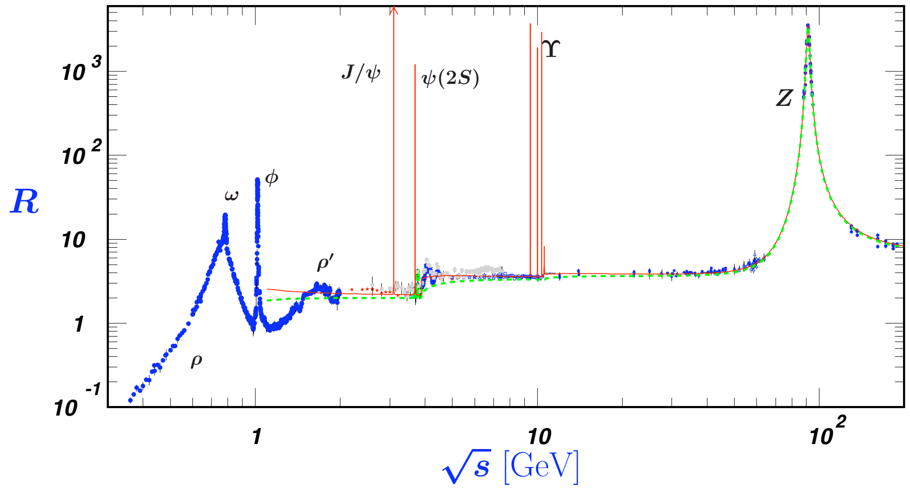
Convolute with beam resolution ΔE.

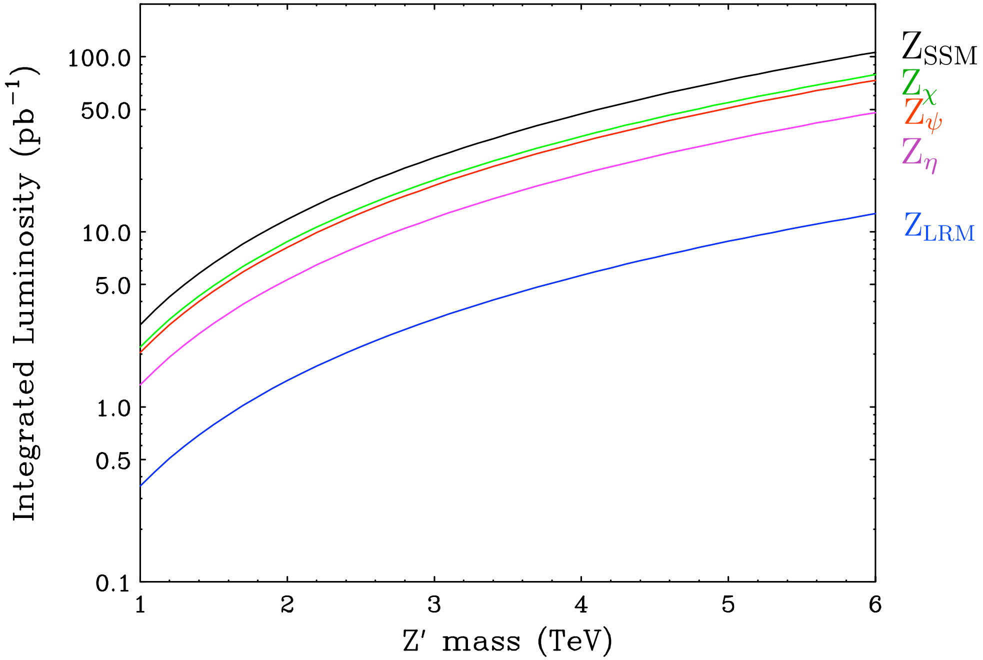
If $\Delta E \ll \Gamma$

$$\boxed{R_{\text{peak}} = (2J+1) 3 \frac{B(\mu^+\mu^-) B(visible)}{\alpha_{\text{EM}}^2}}$$

- Can use to set minimum required luminosity
    - Likely new physics candidates:
        - scalars: h, H^0, A^0,...
        - gauge bosons: Z'
        - new dynamics: bound states
        - ED: KK modes
    - Example - new gauge boson: Z'
        - SSM, E6, LRM
        - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

Minimum luminosity at Z' peak:
$\mathcal{L} = 0.5\text{–}5.0 \times 10^{30}$ cm^{-2} sec^{-1}
for M(Z') -> 1.5–5.0 TeV





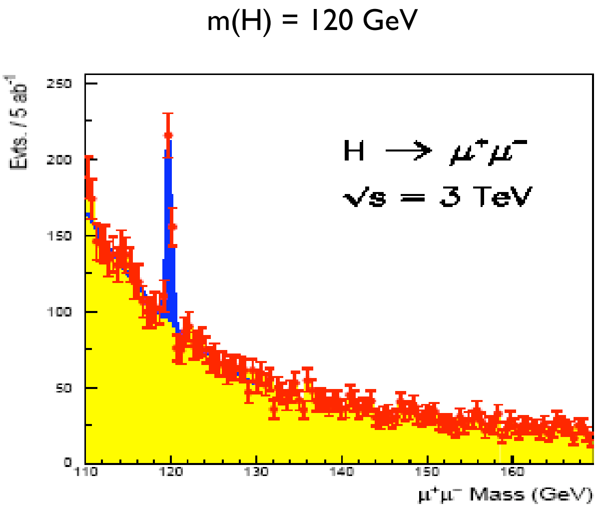
The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z' events on the peak

Studying the Higgs Boson

- Theoretical issues after discovery of Higgs
  - Higgs boson couplings SM?
  - Scalar interaction self-coupling SM?
  - Any additional scalars? EW doublets, triplets or singlets ?
  - Where's the next scale? GUT?

- Various processes available for studying the Higgs at a multi-TeV muon collider
  - associated production: Zh^0 MC or CLIC
    - $R \sim 0.12$
    - search for invisible h^0 decays
  - Higgsstrahlung: $t\bar{t}h^0$ MC or CLIC: needs 10 ab^{-1} !!
    - $R \sim 0.01$
    - measure top coupling
  - W*W* fusion : $\nu_\mu \bar{\nu}_\mu h^0$
    - $R \sim 1.1\, s \ln(s)$ (s in TeV^2) ($m_h = 120$ GeV)
    - study some rare decay modes
    - measure Higgs self coupling

MC or CLIC:
good benchmark process



Two Higgs Doublets (MSSM)

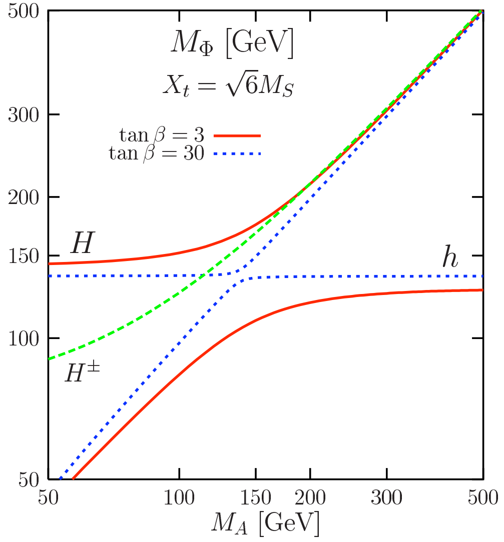
- decay amplitudes depend on two parameters:

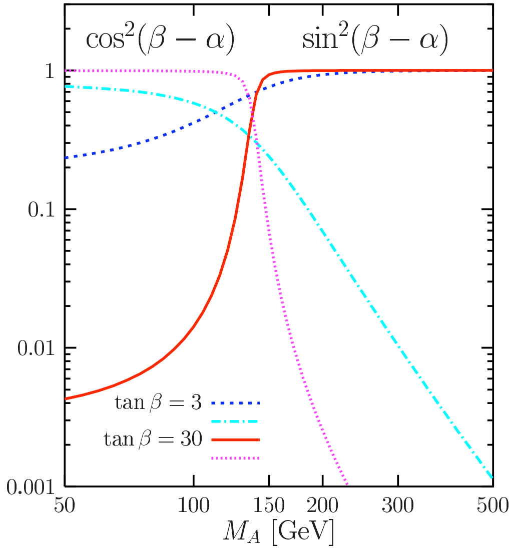
	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	ZZ, W^+W^-	ZA^0
h^0	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
H^0	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$
A^0	$-i\gamma_5\tan\beta$	$-i\gamma_5/\tan\beta$	0	0

$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\tan 2\beta .$$

- decoupling limit $m_{A^0} \gg m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings to top quarks suppressed by $1/\tan\beta$ factor.

- good energy resolution is needed for H^0 and A^0 studies:
  - for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at $\tan\beta = 20$.
  - nearby in mass need good energy resolution to separate H and A.
  - can use bremsstrahlung tail to see states using bb decay mode.





good benchmark process

New Fermions and Gauge Bosons

- Present CDF/D0 bounds on W′, Z′, and new quarks effectively rule out production at ILC(500).

State	CDF/D0 Limit (GeV)
Quark: (W,Z,h) + jet	325
Z′ (SM)	923
W′ (SM)	860

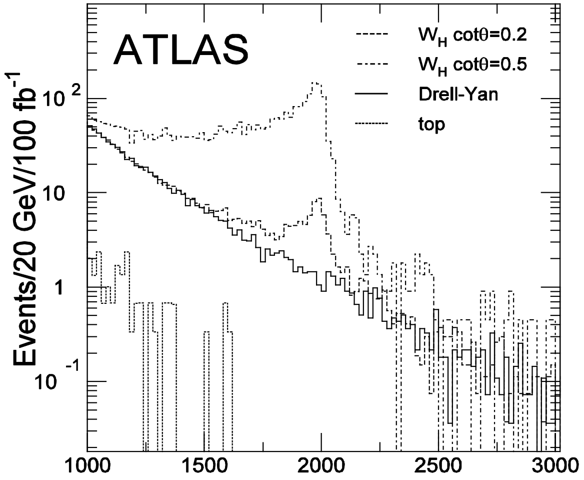
- Littlest Higgs Model: good benchmark processes

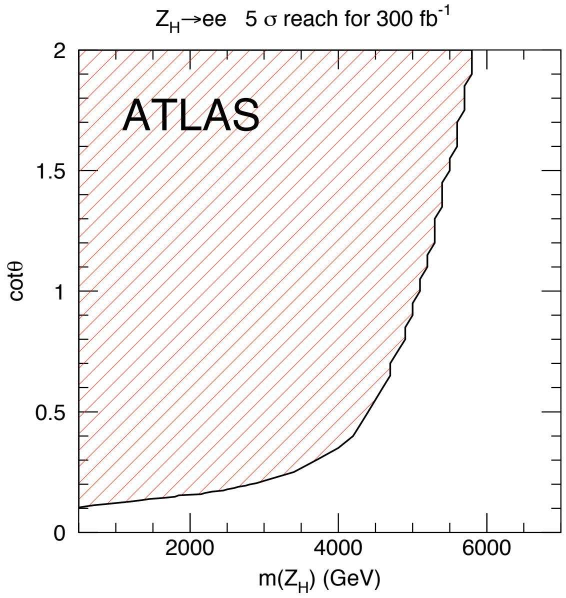
  charge (2/3) quark T (EW singlet),
  new W, Z, and A gauge bosons, Higgs triplet

  At the LHC, T observable for m(T) < 2.5 TeV
  For W, Z, and A dependent on mixing parameters

- Muon collider will allow detailed study.
  Requires high luminosity 1 ab^{-1} for T

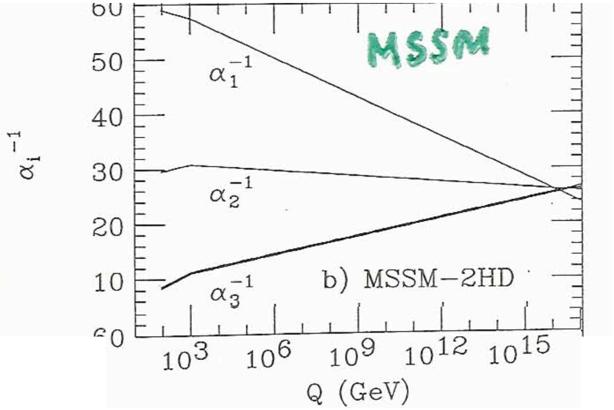
ATLAS study LHC [hep-ph/0402037]





Supersymmetry

- Supersymmetry
  - Q_{susy} |boson> = |fermion>: gluon -> gluino ,... ; W boson -> wino; higgs -> higgino, ...
    Q_{susy} |fermion>=|boson>: top quark -> top squark (L,R), ...; electron -> selectron(L,R), ...
    - spin 1/2 symmetry charges $\{\bar{Q}_{susy}, Q_{susy}\} = 2\,\gamma^{\mu} P_{\mu}$; Q_{susy} H|state> = H Q_{susy}|state>
  - supersymmetry dictates the couplings between particles and sparticles
  - supersymmetry is broken $M_{sparticle} \neq M_{particle}$



- Solves the hierarchy and GUT unification problems

- Theoretical issues after discovery at the LHC :

- What is the spectrum of superpartner masses?
- Dark matter candidates?
- Are all the couplings correct?
- What is the structure of flavor mixing interactions?
- Are there additional CP violating interactions?
- Is R parity violated?
- What is the mass scale at which SUSY is restored?
- What is the mechanism of SUSY breaking?
- ...

Names		spin 0	spin 1/2	$SU(3)_c$, $SU(2)_L$, $U(1)_y$
squarks, quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$\mathbf{3}$, $\mathbf{2}$, 1/3
(× 3 families)	$\bar{u}$	$\tilde{\bar{u}}_L(\tilde{u}_R)$	$\bar{u}_L \sim (u_R)^c$	$\bar{\mathbf{3}}$, $\mathbf{1}$, -4/3
	$\bar{d}$	$\tilde{\bar{d}}_L(\tilde{d}_R)$	$\bar{d}_L \sim (d_R)^c$	$\bar{\mathbf{3}}$, $\mathbf{1}$, 2/3
sleptons, leptons	L	$(\tilde{\nu}_{eL}, \tilde{e}_L)$	(ν_{eL}, e_L)	$\mathbf{1}$, $\mathbf{2}$, -1
(× 3 families)	$\bar{e}$	$\tilde{\bar{e}}_L(\tilde{e}_R)$	$\bar{e}_L \sim (e_R)^c$	$\mathbf{1}$, $\mathbf{1}$, 2
higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$\mathbf{1}$, $\mathbf{2}$, 1
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$\mathbf{1}$, $\mathbf{2}$, -1

Table 1: Chiral supermultiplet fields in the MSSM.

Names	spin 1/2	spin 1	$SU(3)_c$, $SU(2)_L$, $U(1)_y$
gluinos, gluons	$\tilde{g}$	g	$\mathbf{8}$, $\mathbf{1}$, 0
winos, W bosons	$\widetilde{W}^{\pm}, \widetilde{W}^0$	$W^{\pm}$, W^0	$\mathbf{1}$, $\mathbf{3}$, 0
bino, B boson	$\tilde{B}$	B	$\mathbf{1}$, $\mathbf{1}$, 0

Table 2: Gauge supermultiplet fields in the MSSM.

Supersymmetry

- Minimal Supersymmetric Standard Model (MSSM)
  - Supersymmetry dictates the couplings between particles and sparticles
  - The masses of the superpartners depends on the pattern of SUSY breaking
  - The most studied model is mSUGRA (others are mGMSB and mAMSB)
    - requires two Higgs doublets for consistency ($h^0 \to h^0, H^0, H^\pm, A^0$)
    - one set of scalar doublets have Yukawa couplings to up fermions and the other to down fermions. (Φu ,Φd)
  - Setting soft breaking couplings equal at the GUT scale (mSUGRA -> cMSSM)
  - Five new parameters for cMSSM:
    - m_0 (soft breaking mass parameter for spin zero sparticles)
    - $m_{1/2}$ (soft breaking mass parameter for spin 1/2 sparticles)
    - tan β (ratio of vacuum expectation values $\langle\Phi u\rangle / \langle\Phi d\rangle$)
    - A/m_0 (parameter for triplet scalar couplings)
    - sign(μ) (sign of higgino mass parameter)

cMSSM

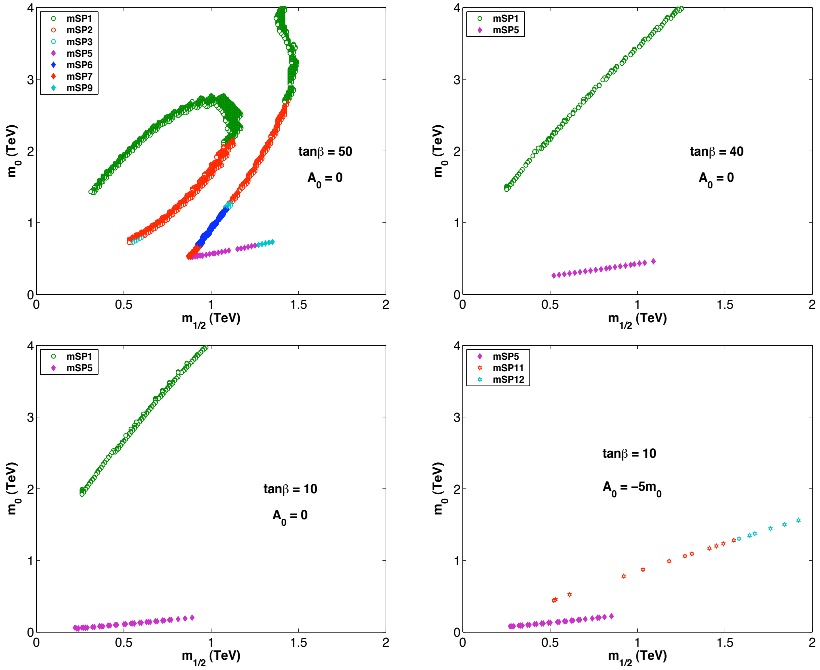
- Many studies of constraints on cMSSM
  - Present experimental constraints
    - Direct limit (LEP, CDF, Dzero): $m_{h^0}, m_{\chi^+}, m_{\tilde{t}}, \ldots$
    - Electroweak precision observables (EWPO): $M_W^2, \sin^2\theta_{sw}, (g-2)_\mu, \ldots$
    - B physics observables (BPO): $b \to s + \gamma,\ \mathrm{BR}(B_s \to \mu^+\mu^-), \ldots$
    - Cold dark matter (CDM): $\Omega_{DM} = .23 \pm .04$
  - Allowed regions are narrow filaments in parameter space
  - Theoretical fine tuning

$M_{h0} > 113.8 \Rightarrow$ large m_{stop}

requires large cancellations in the Higgs potential
$\Rightarrow$ fine tuning (to a few %)

Monte Carlo searches of parameter space

J. Ellis, S. Heinemeyer, K.A. Olive, A.M. Weber, G. Wieglein
[arXiv:0706.0652] ;
D. Feldman, Zuowei Lui and Pran Nath,
PRL 99, 251802 (07); [arXiv:0802.4085] ; ...



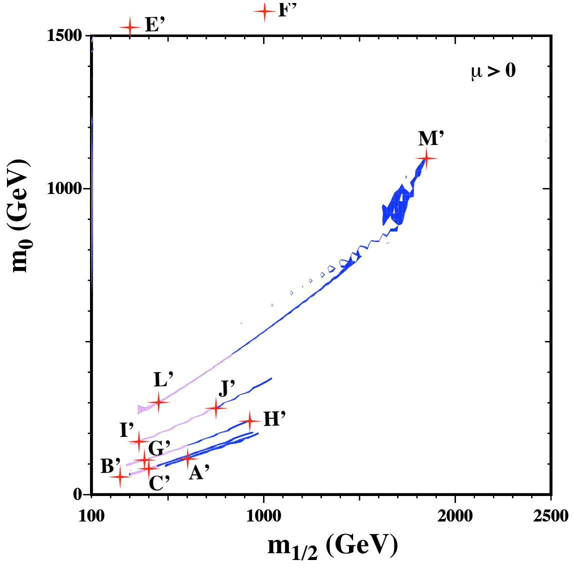
tree 1-loop

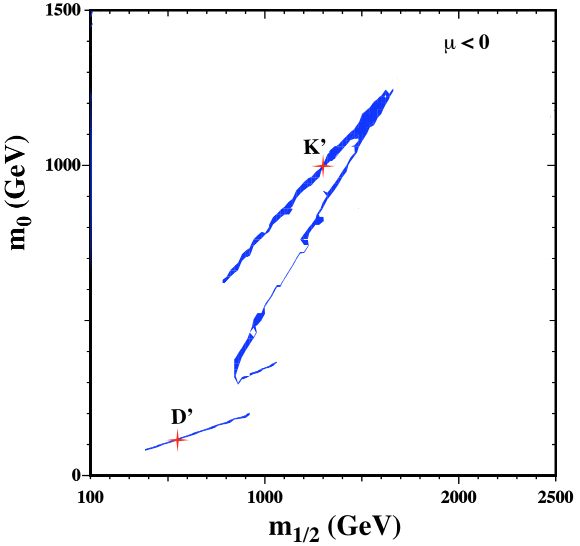
$$M_{h^0}^2 = m_Z^2\cos^2(2\beta) + \frac{3}{4\pi^2}\sin^2\beta\, y_t^2\Big[m_t^2\ln\left(m_{\tilde{t}_1}m_{\tilde{t}_2}/m_t^2\right) + c_{\tilde{t}}^2 s_{\tilde{t}}^2(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)\ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2)$$
$$+ c_{\tilde{t}}^4 s_{\tilde{t}}^4\Big\{(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4)\ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2)\Big\}/m_t^2\Big].$$

LHC + multiTeV lepton collider

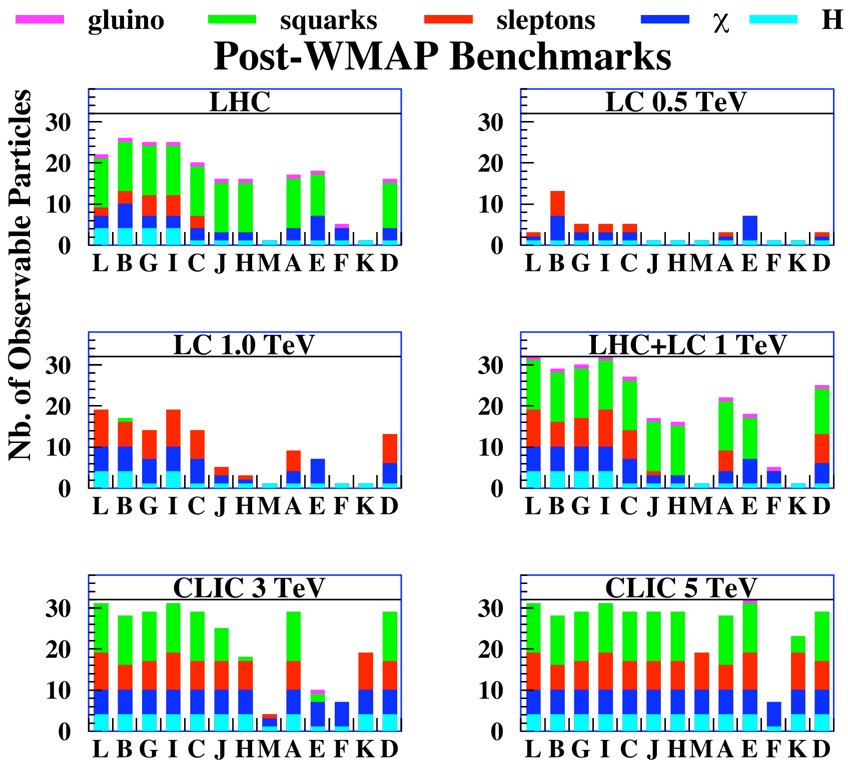
- A multi-TeV lepton collider needed for full coverage of SUSY spectrum.

Allowed regions and sample points





2004 CLIC study SUSY reach



Similar Conclusion for MC

"Supersymmetry at a Muon Collider", Anupama Atre,
Low Emittance Muon Collider Workshop
Fermilab, April 2008

cMSSM, mGMSB, mAMSB Studies

- More generally, full coverage likely requires a multi TeV lepton collider

S. Heinemeyer, X. Miao, S. Su, G. Wieglein [arXiv:0805.2359]
(using only EWPO, BPO and LEP)

Second lightest neutralino:

m($\tilde{\chi}_2$) < 900 GeV for $\Delta\chi^2 < 4$
Heavy for LHC - possibly in decay chain ?
Lepton collider: $\chi_2^0 \rightarrow \chi_1^0 + X$

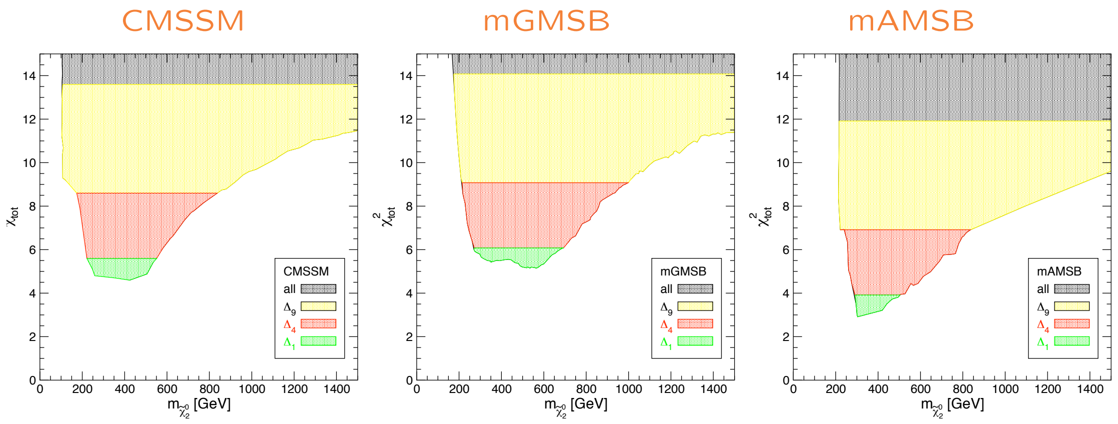
Lightest chargino:

m($\tilde{\chi}_1^+$) < 800, 900, 300 GeV for $\Delta\chi^2 < 4$
Heavy for LHC - possibly in decay chain ?
Lepton collider: Observable at ILC for mAMSB

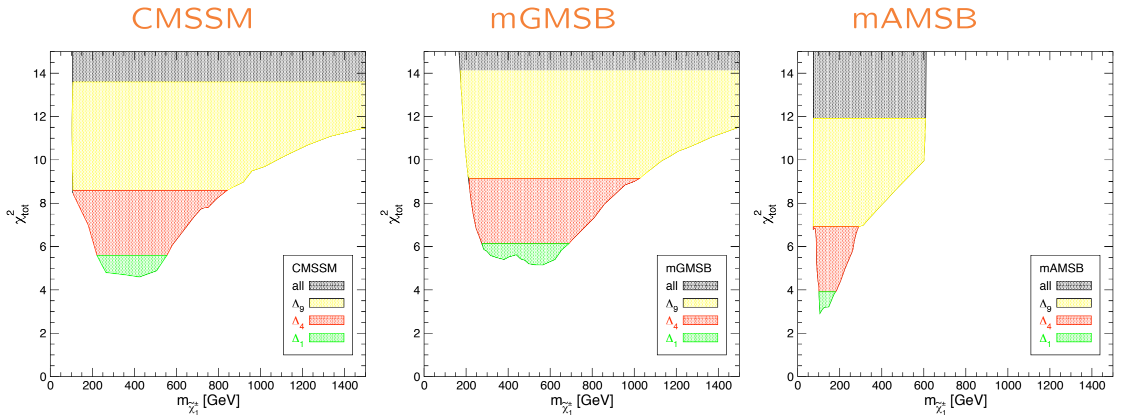
Lightest stop, sbottom and gluino:

m($\tilde{t}_1$) > 500 for $\Delta\chi^2 < 4$
Easy for LHC up to 2 TeV
Lepton collider: Detailed study?

Second lightest neutralino



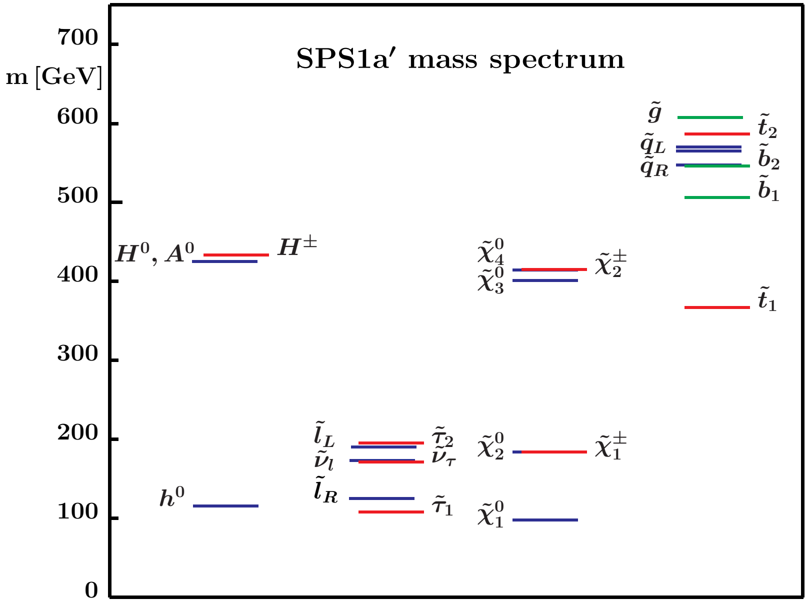
Lightest chargino



Modifying cMSSM

- Fine tuning problems in the cMSSM - Allow non universal $m_{1/2}$

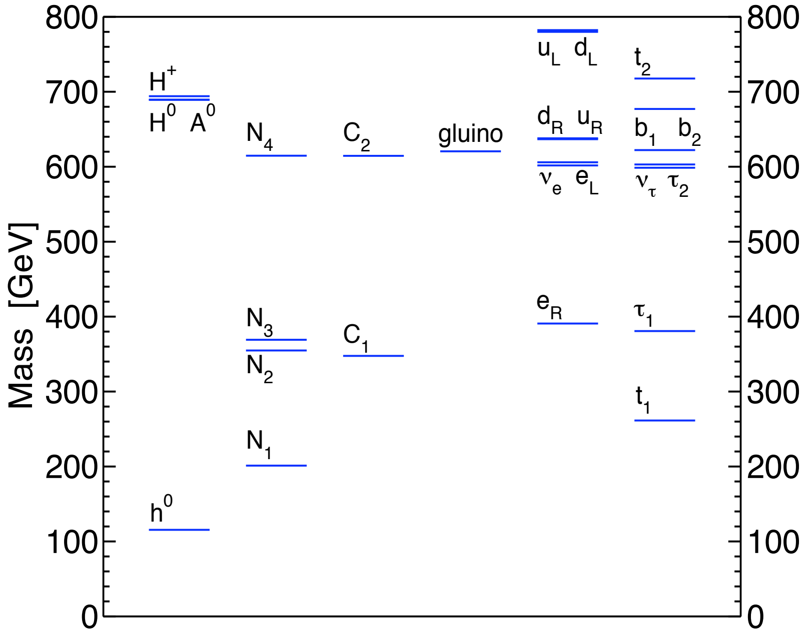
cMSSM ILC Benchmark



Many visible superpartners within reach of the ILC (500 GeV).
All pair production thresholds are below 1.2 TeV.

Compressed SUSY

S. Martin [PR D75:115005,2007]

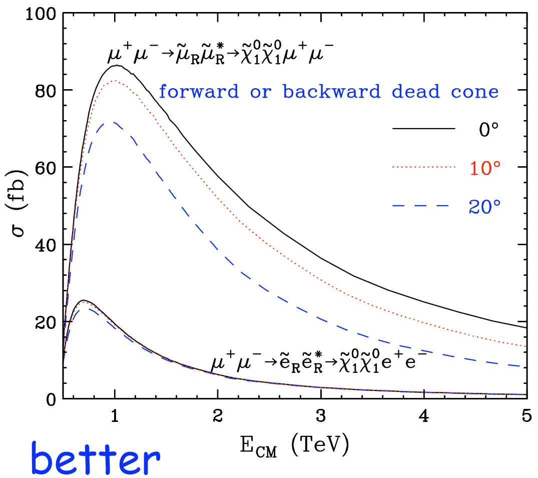


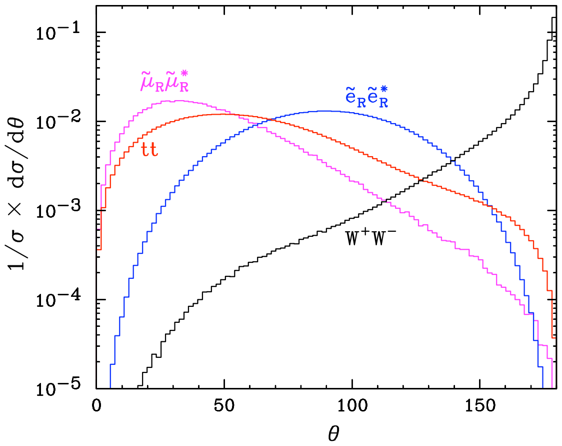
No visible superpartners within reach of the ILC (500 GeV).
All pair production thresholds are below 1.6 TeV.

Supersymmetry provides strong case for a multi-TeV lepton collider

Example Process at Muon Collider

$$\mu^+\mu^- \to \tilde{e}_1^+\tilde{e}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-$$





- ☐ Angular cut at 20° from beam direction:
  50% reduction for smuon pair,
  20% reduction for selectron pair

- ☐ Mass measurements using edge method better for MC than CLIC:

$$E_{\max/\min} = \frac{1}{2}M_{\tilde{e}}\left[1-\frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{e}}}\right]\gamma(1\pm\beta)$$

Effect of beamstrahlung

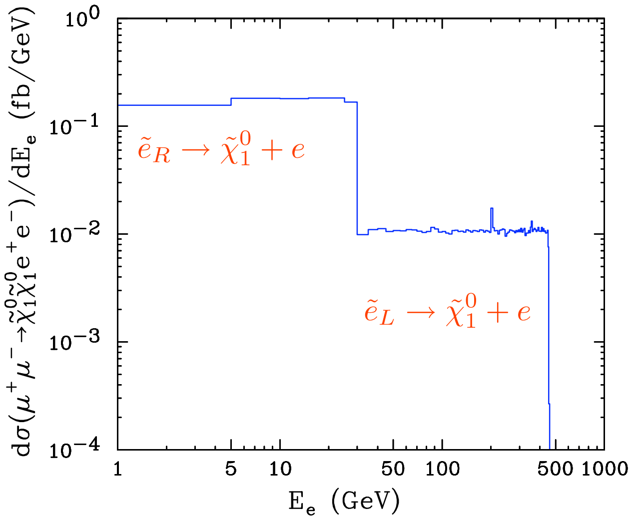
Kong, Winter (MC)

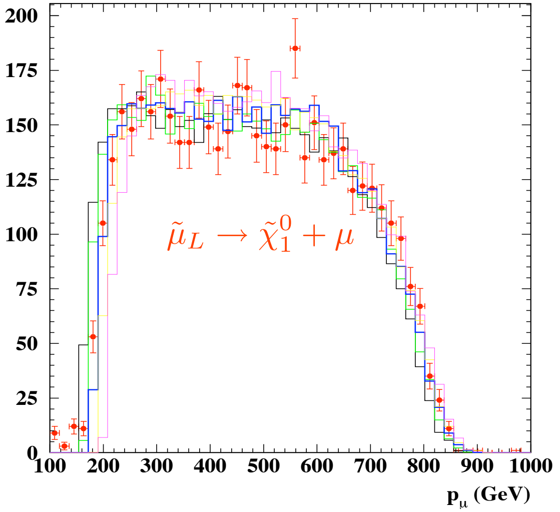
$m_{\tilde\chi_1^0} = 212;\ m_{\tilde e_R} = 222;\ m_{\tilde e_L} = 374$ GeV

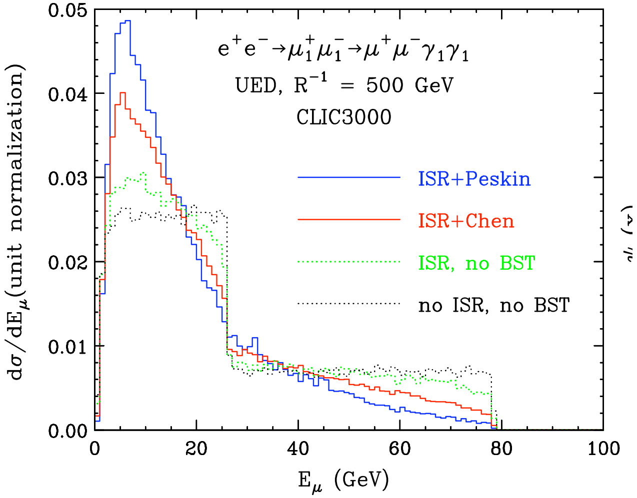
CLIC report (2004)

$m_{\tilde\chi_1^0} = 660$ GeV$;\ m_{\tilde\mu_L} = 1150$ GeV

Datta, Kong and Matchev
[arXiv:hep-ph/0508161]







New Strong Dynamics

☐ Solves the Naturalness Problem: Electroweak Symmetry Breaking is generated dynamically at a nearby scale. May or may not be a light Higgs boson.

Theoretical issues

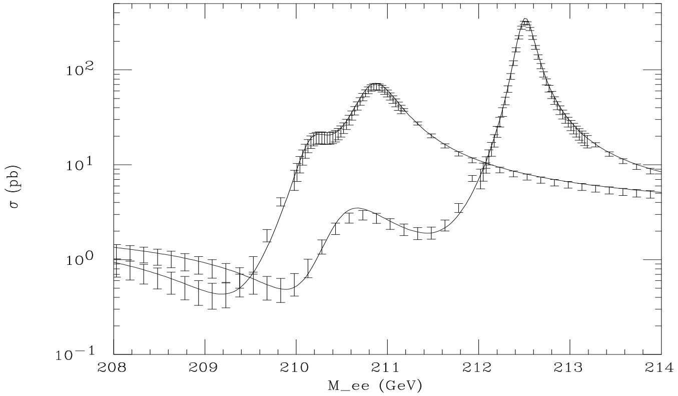
- What is the spectrum of low-lying states?
- What is the ultraviolet completion? Gauge group? Fermion representations?
- What is the energy scale of the new dynamics?
- Any new insight into quark and/or lepton flavor mixing and CP violation?
- ...

Technicolor, ETC, Walking TC, Topcolor , ...

For example with a new strong interaction at TeV scale expect:

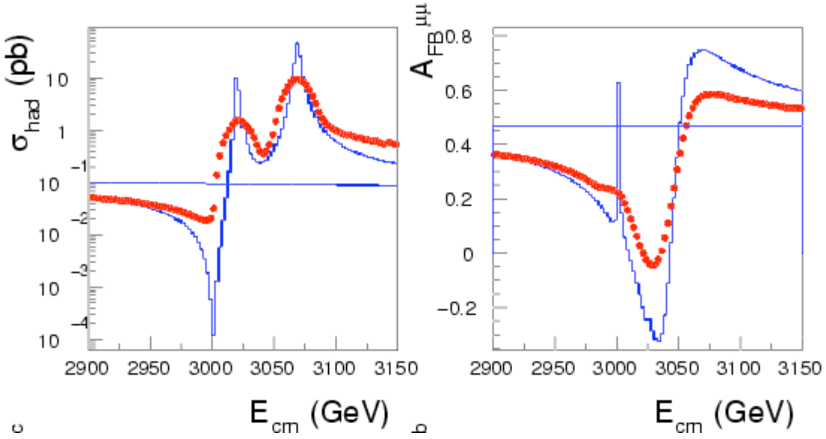
- Technipions - s channel production (Higgs like)
- Technirhos - Nearby resonances (ρ_T,ω_T)- need fine energy resolution of muon collider.

Eichten, Lane, Womersley PRL 80, 5489 (1998)
$M(\rho_T)$ = 210 GeV $M(\omega_T)$ = 211, 209 GeV
MC 40 steps (total 1 fb^{-1})



good benchmark processes

CLIC - D-BESS model (resolution 13 GeV)



Contact Interactions

- Solves the Naturalness Problem: The SM theory is only an effective theory valid below the compositeness scale.
  - New interactions (at scales not directly accessible) give rise to contact interactions.

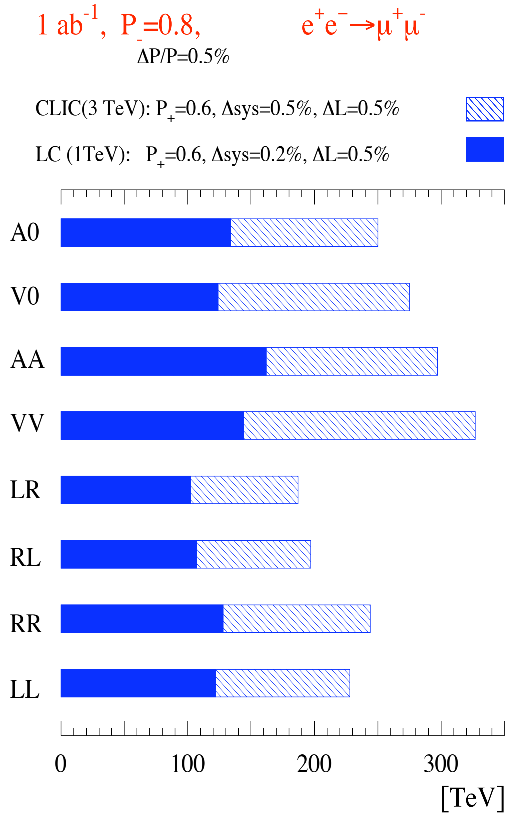
$$\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{\Psi}\Gamma\Psi)(\bar{\Psi}\Gamma'\Psi)$$

  - Muon collider is sensitive to contact interaction scales over 200 TeV as is CLIC.
  - Cuts on forward angles for a muon collider not an issue.
  - Polarization useful to disentangle the chiral structure of the interaction. (CLIC)

good benchmark process

Muon Collider Study
E.Eichten, S.~Keller, [arXiv:hep-ph/9801258]

CLIC Study



Extra Dimensions

☐ Solves the Naturalness Problem: The effective GUT scale is moved closer.

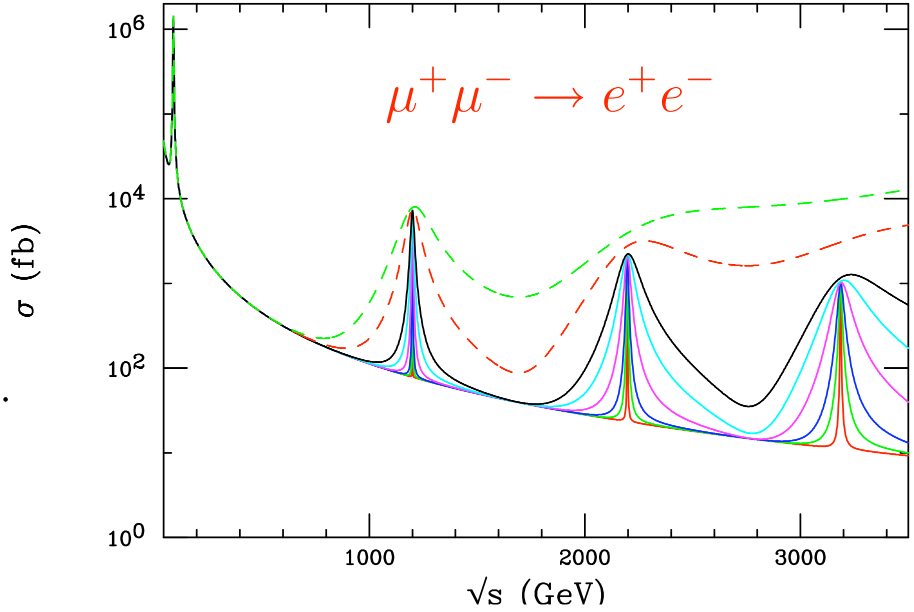
Theoretical issues

- How many dimensions?
- Which interactions (other than gravity) extend into the extra dimensions?
- At what scale does gravity become a strong interaction?
- What happens above that scale?
- ...

Randall-Sundrum model:
warped extra dimensions

- two parameters:
  - mass scale ∝ first KK mode;
  - width ∝ 5D curvature / effective 4D Planck scale.

possible KK modes



LHC discovery - Detailed study at a muon collider

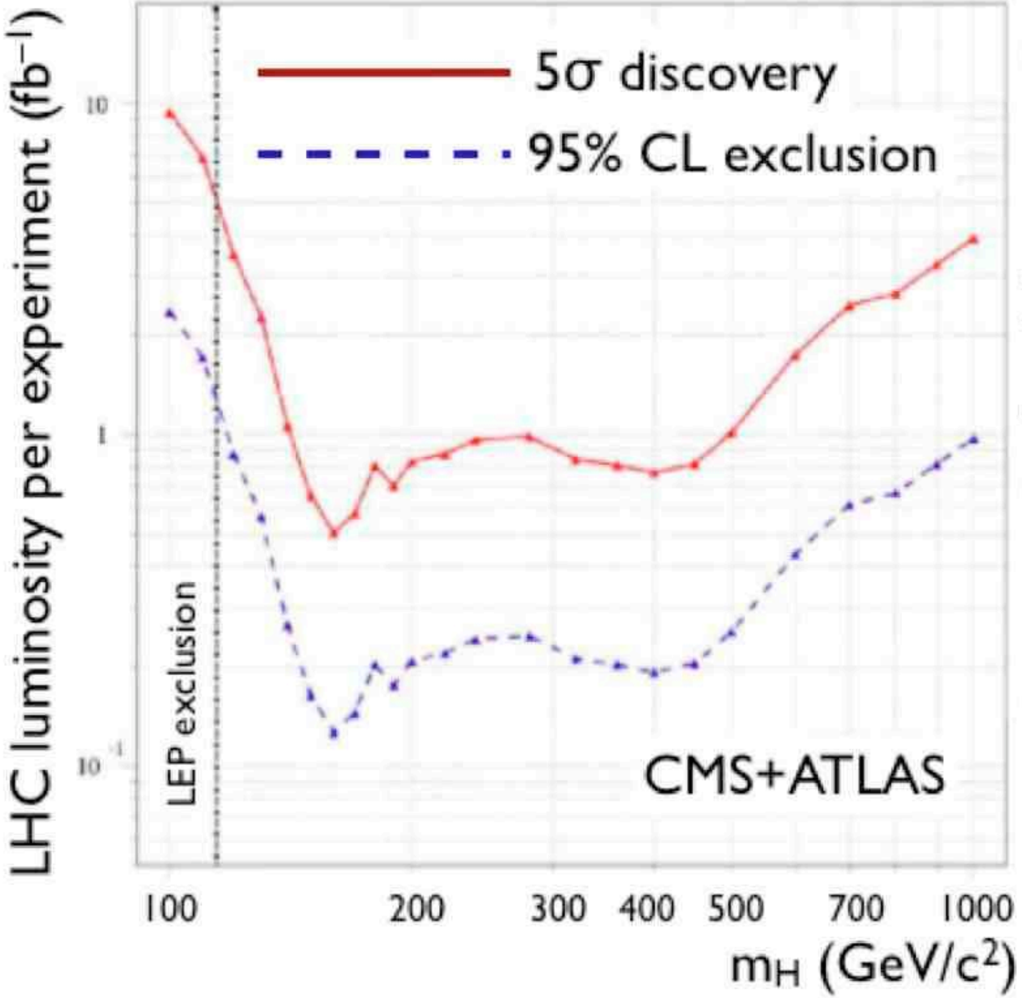
Summary

- A multiTeV lepton collider is required for full coverage of Tevascale physics.
- The physics potential for a muon collider at $\sqrt{s} \sim 3$ TeV and integrated luminosity of 1 ab^{-1} is outstanding. Particularly strong case for SUSY and new strong dynamics.
- Narrow s-channel states played an important role in past lepton colliders. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics. Sets the minimum luminosity scale.
- Precise knowledge of the neutrino sector has wide impact from cosmology (dark matter, baryon asymmetry, ...) to the nature of gauge unification near the Planck scale. A staged Muon Collider would provide a Neutrino Factory to fully disentangle neutrino physics.
- A detailed study of physics case for 1.5-4.0 TeV muon collider has began:
  Workshop on "Muon Collider Physics, Detectors and Backgrounds", Fermilab, Nov. 10-12 (2009)
  http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-muoncollider.html
  - Identify benchmark processes: pair production (slepton; new fermion), Z' pole studies, h^0 plus missing energy, resolving nearby states (H^0-A^0; ρ_T-ω^0_T), ...
  - Dependence on initial beam [electron/muon, polarization and beam energy spread] as well as luminosity should be considered.
  - Estimates of collision point environment and detector parameters needed.
  - Must be able to withstand the real physics environment after ten years of running at the LHC.

Next workshop this summer. Your all encouraged to get involved.

Backup Slides

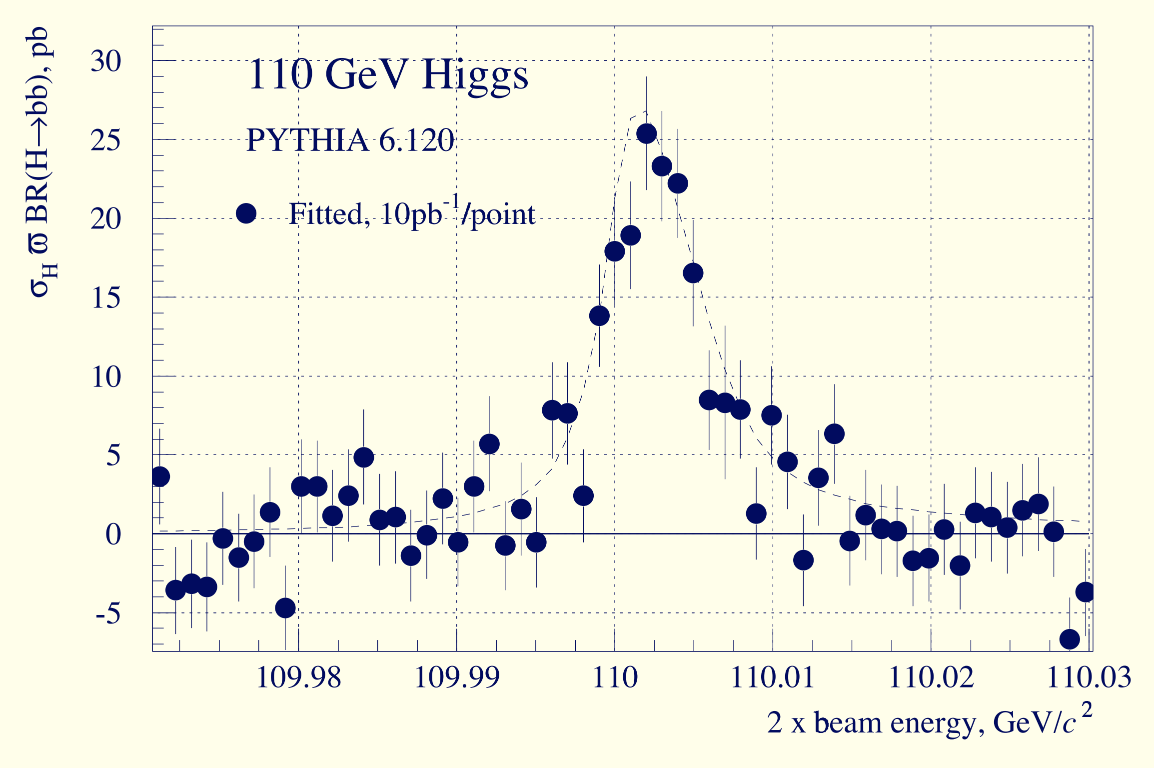
LHC - Discovery of the SM Higgs



Higgs study at MC

ΔE/E = 0.03%   10 pb-1/point

Easier for large tanβ SUSY Higgs



J. Gunion

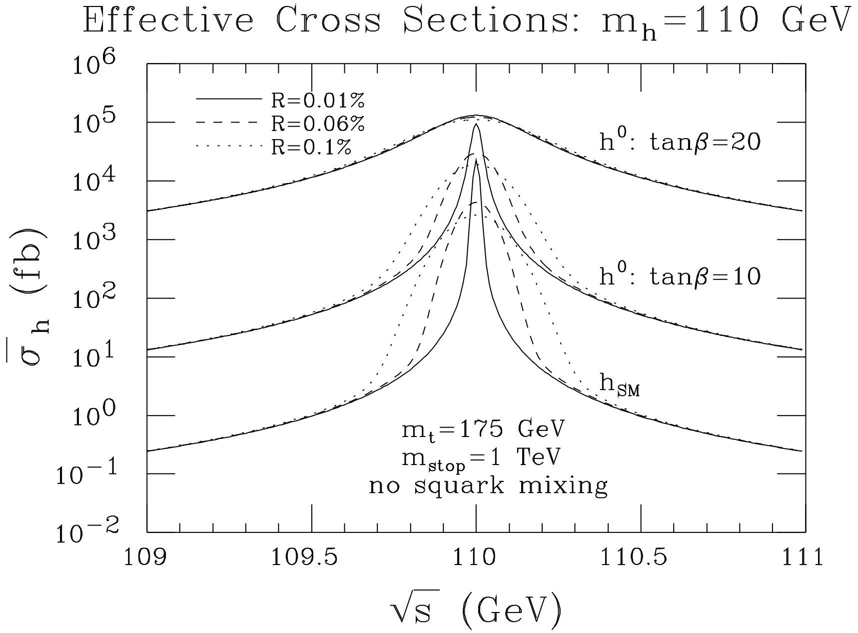


Figure 7: The effective cross section, $\overline{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$, is plotted as a function of $\sqrt{s}$ taking $m_h = 110$ GeV. Results are displayed in the cases: h_{SM}, h^0 with $\tan\beta = 10$, and h^0 with $\tan\beta = 20$. In the MSSM h^0 cases, two-loop/RGE-improved radiative corrections have been included for Higgs masses, mixing angles, and self-couplings assuming $m_{\widetilde{t}} = 1$ TeV and neglecting squark mixing. The effects of bremsstrahlung are not included in this figure.

Good energy resolution is needed for H^0 and A^0 studies:

- for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at $\tan\beta = 20$.
- nearby in mass need good energy resolution to separate H and A
- can use bremsstrahlung tail to see states using bb decay mode

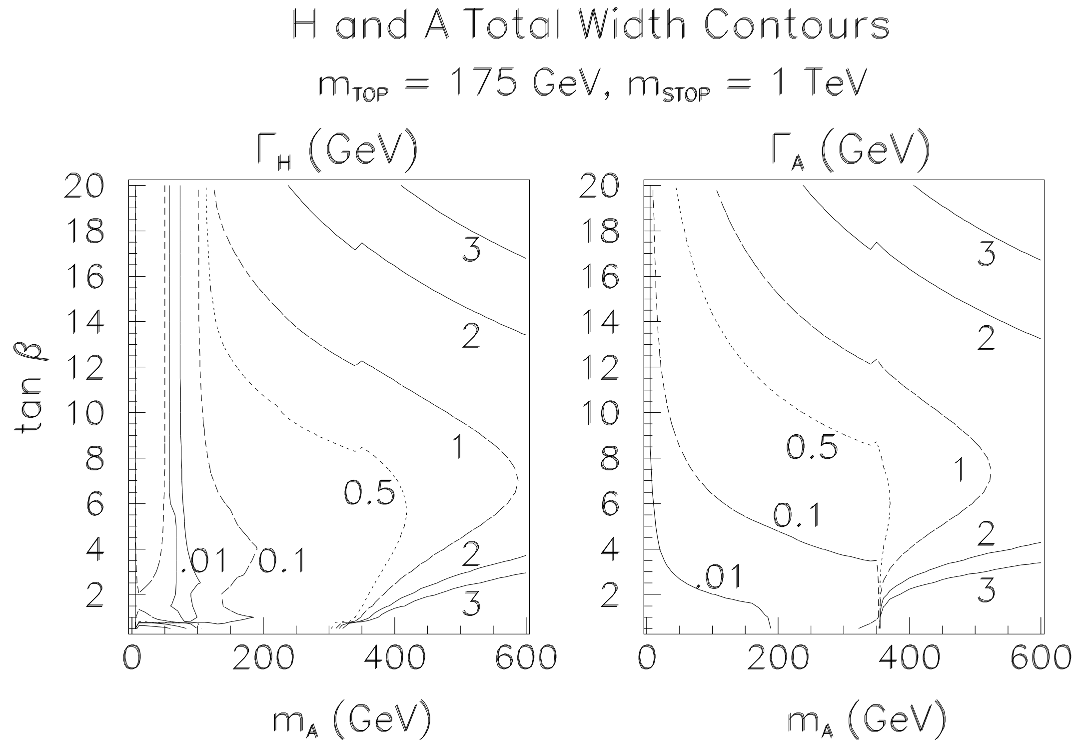
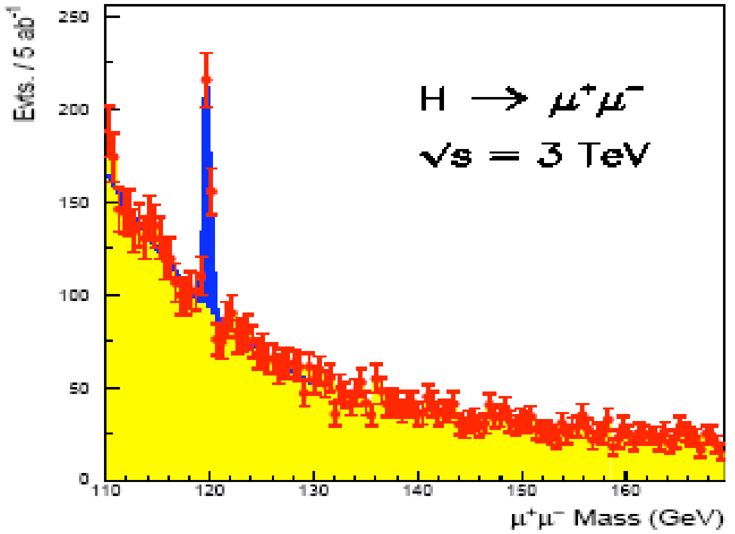


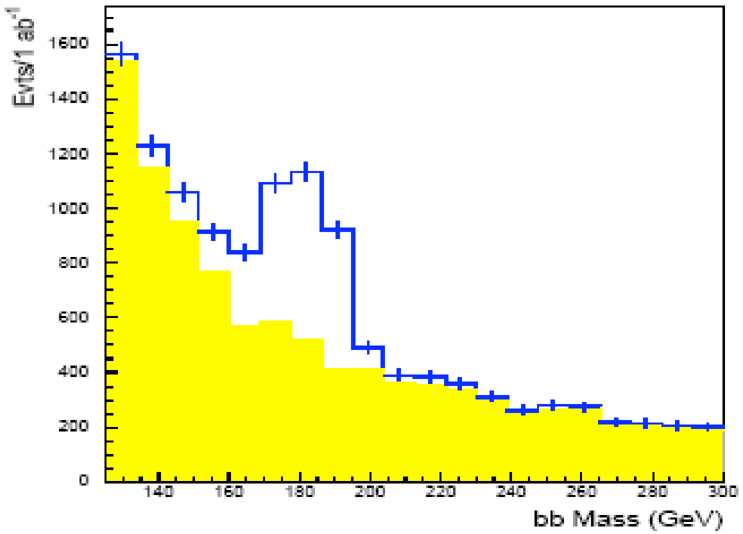
Figure 20: Contours of H^0 and A^0 total widths (in GeV) in the $(m_{A^0}, \tan\beta)$ parameter space. We have taken $m_t = 175$ GeV and included two-loop/RGE-improved radiative corrections using $m_{\tilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decay channels are assumed to be absent.

ZH (CLIC)

m(H) = 120 GeV



m(H) = 200 GeV



W*W* fusion

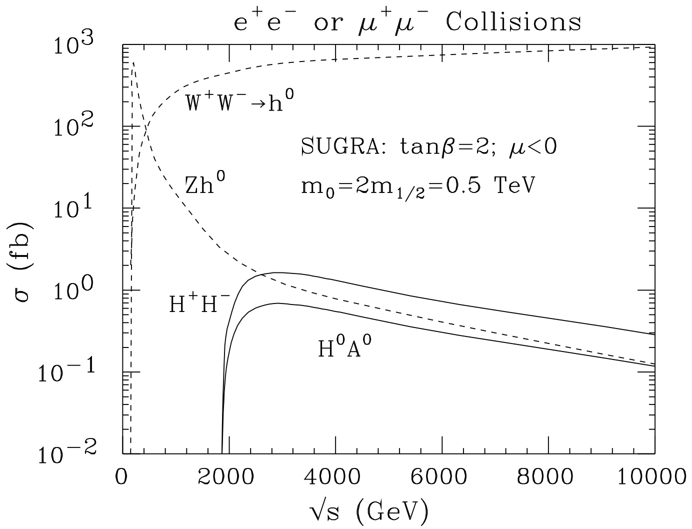


FIGURE 6. Pair production of heavy Higgs bosons at a high energy lepton collider. For comparison, cross sections for the lightest Higgs boson production via the Bjorken process $\mu^+\mu^- \to Z^* \to Zh^0$ and via the WW fusion process are also presented.

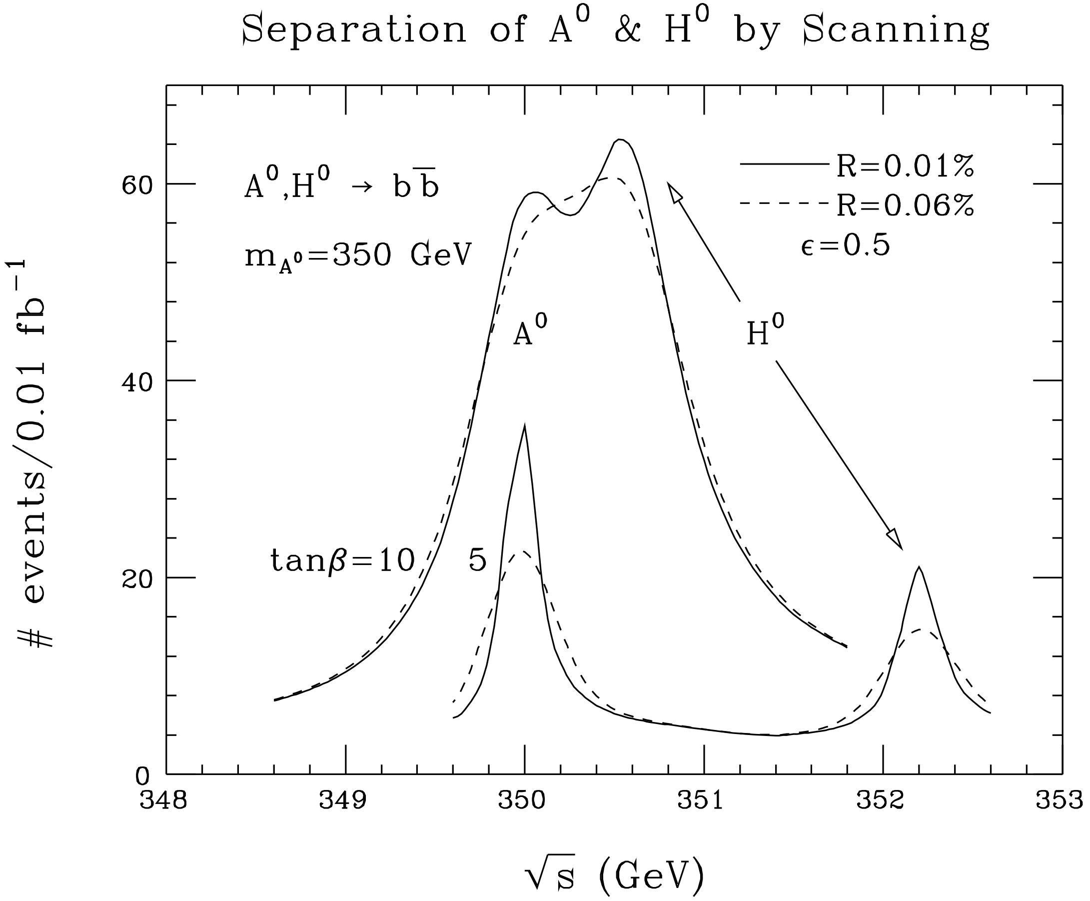


FIGURE 4. Plot of $b\bar{b}$ final state event rate as a function of $\sqrt{s}$ for $m_{A^0} = 350$ GeV, in the cases $\tan\beta = 5$ and 10, resulting from the H^0, A^0 resonances and the $b\bar{b}$ continuum background. We have taken $L = 0.01$ fb^{-1} (at any given $\sqrt{s}$), efficiency $\epsilon = 0.5$, $m_t = 175$ GeV, and included two-loop/RGE-improved radiative corrections to Higgs masses, mixing angles and self-couplings using $m_{\widetilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decays are assumed to be absent. Curves are given for two resolution choices: $R = 0.01\%$ and $R = 0.06\%$

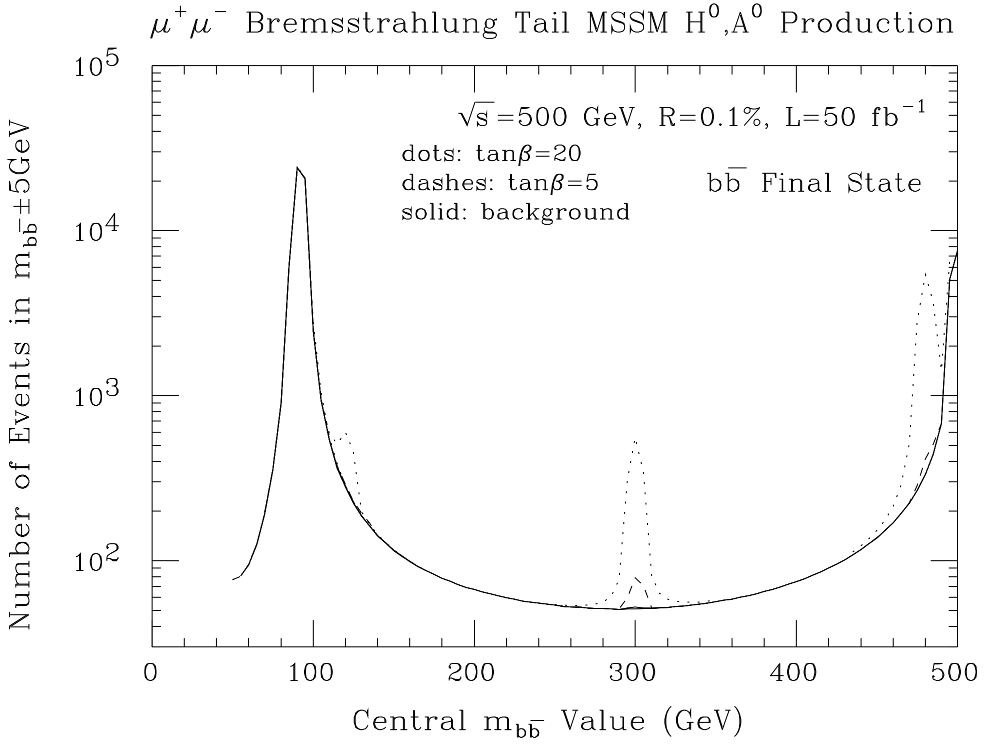


FIGURE 5. Taking $\sqrt{s} = 500$ GeV, integrated luminosity $L = 50$ fb^{-1}, and $R = 0.1\%$, we consider the $b\bar{b}$ final state and plot the number of events in the interval $[m_{b\bar{b}} - 5\text{ GeV}, m_{b\bar{b}} + 5\text{ GeV}]$, as a function of the location of the central $m_{b\bar{b}}$ value, resulting from the low $\sqrt{\hat{s}}$ bremsstrahlung tail of the luminosity distribution. MSSM Higgs boson H^0 and A^0 resonances are present for the parameter choices of $m_{A^0} = 120$, 300 and 480 GeV, with $\tan\beta = 5$ and 20 in each case. Enhancements for $m_{A^0} = 120$, 300 and 480 GeV are visible for $\tan\beta = 20$; $\tan\beta = 5$ yields visible enhancements only for $m_{A^0} = 300$ and 480 GeV. Two-loop/RGE-improved radiative corrections are included, taking $m_t = 175$ GeV, $m_{\widetilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decay channels are assumed to be absent.

CMSSM - Soft breaking couplings set equal at GUT scale.
Fewest parameters (aka mSUGRA)

- Detailed study benchmark points for CLIC - CERN report 2004

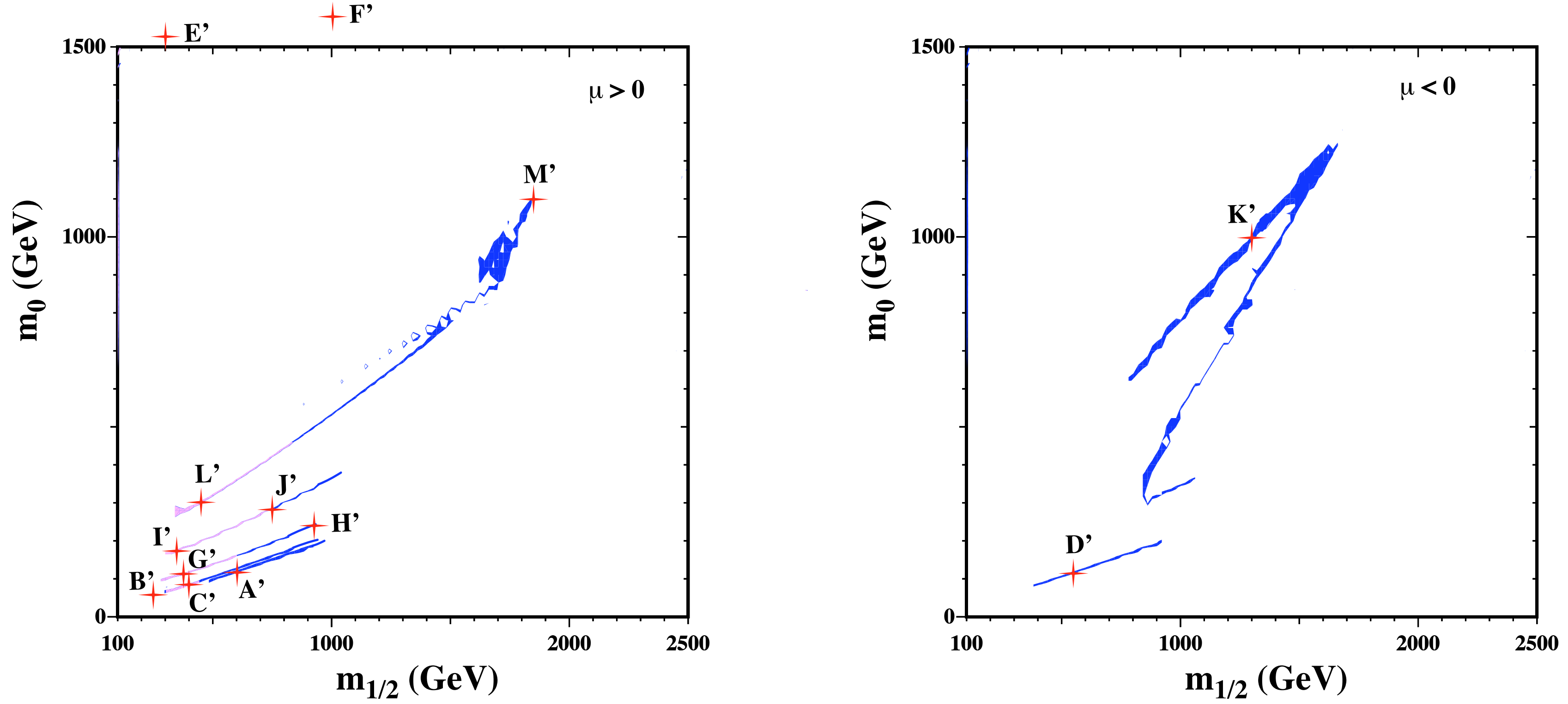


Fig. 5.2: Overview of the updated proposed CMSSM benchmark points in the $(m_0, m_{1/2})$ planes, superposed on the strips allowed by laboratory limits and the relic density constraint, for $\mu > 0$ and $\tan\beta$ = 5, 10, 20, 35, 50, and for $\mu < 0$ and $\tan\beta$ = 10, 35 [8]

○ Fine tuning problems in the cMSSM

M(h^0) > 113.8 GeV (95% cl) LEP combined bound]

$\tan\beta$ = v_u/v_d

top squark
masses: $m_{\tilde t_1}, m_{\tilde t_2}$
mixing: $c_{\tilde t}, s_{\tilde t}$

tree 1-loop

$$M^2_{h^0} = m^2_Z\cos^2(2\beta) + \frac{3}{4\pi^2}\sin^2\beta\, y_t^2\Big[m_t^2\ln\left(m_{\tilde t_1}m_{\tilde t_2}/m_t^2\right) + c^2_{\tilde t}s^2_{\tilde t}(m^2_{\tilde t_2}-m^2_{\tilde t_1})\ln(m^2_{\tilde t_2}/m^2_{\tilde t_1}) + c^4_{\tilde t}s^4_{\tilde t}\Big\{(m^2_{\tilde t_2}-m^2_{\tilde t_1})^2 - \frac{1}{2}(m^4_{\tilde t_2}-m^4_{\tilde t_1})\ln(m^2_{\tilde t_2}/m^2_{\tilde t_1})\Big\}/m_t^2\Big]. + \ldots$$

with measured top mass and $\tan\beta$ constraints,

need large top squark mass. BUT

$$m_Z^2 = -2\left(|\mu|^2 + m^2_{H_u}\right) - \frac{1}{v_u}\frac{\partial}{\partial v_u}\Delta V + \mathcal{O}(1/\tan^2\beta).$$

soft SUSY breaking mass term
in higgs field coupling to top

loop part of effective potential

the largeness the soft SUSY breaking mass term
means a fine tuned cancellation between the μ^2 and
m^2_H terms to more than a few percent.

Relax the soft breaking restrictions at the GUT scale ?

Technicolor, ETC, Walking TC, Topcolor, ...

Technipions:

S channel production - higgs like

$$\frac{d\sigma(\mu^+\mu^- \to \pi_T^0 \,\mathrm{or}\, \pi_T^{0\prime} \to \bar{f} f)}{dz} = \frac{N_f}{2\pi}\left(\frac{C_\mu C_f m_\mu m_f}{F_T^2}\right)^2 \frac{s}{(s - M_{\pi_T}^2)^2 + s\,\Gamma_{\pi_T}^2}\,,$$

$$\frac{d\sigma(\mu^+\mu^- \to \pi_T^{0\prime} \to gg)}{dz} = \frac{C_{\pi_T}}{32\pi^3}\left(\frac{C_\mu m_\mu \alpha_S N_{TC}}{F_T^2}\right)^2 \frac{s^2}{(s - M_{\pi_T}^2)^2 + s\,\Gamma_{\pi_T}^2}\,.$$

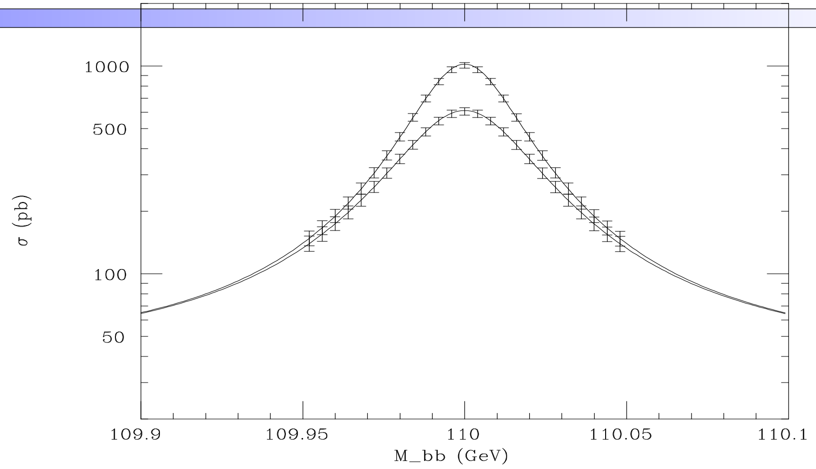


Figure 1: Cross sections for $\mu^+\mu^- \to \pi_T^0 \to \bar{b}b$ (upper curve) and $\pi_T^{0\prime} \to \bar{b}b$. Statistical errors only are shown for a luminosity of $1\,\mathrm{pb}^{-1}$ per point. Cuts and efficiencies are described in the text. The solid lines are the theoretical cross sections (perfect resolution).

Technirhos:

Can have nearby vector resonances that interfere:

Would need the fine resolution to disentangle states

Common case with new strong dynamics

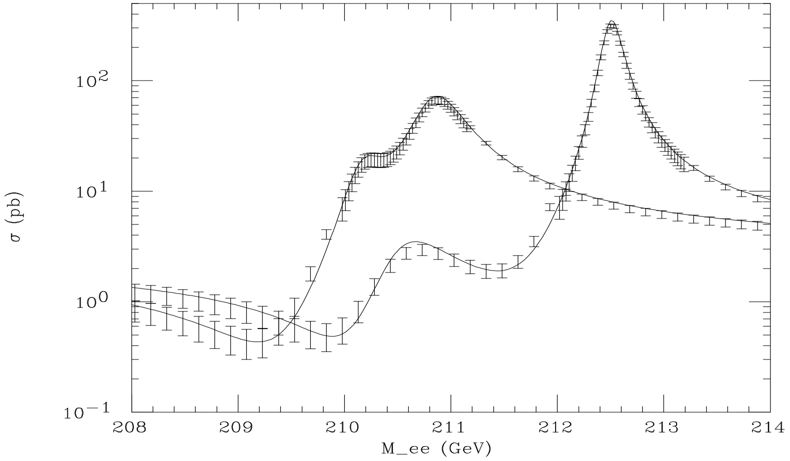


Figure 2: Cross sections for $\mu^+\mu^- \to \rho_T, \omega_T \to e^+e^-$ for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 211\,\mathrm{GeV}$ (higher-peaked curve) and 209 GeV. Statistical errors only are shown for resolutions and luminosities described in the text. The solid lines are the theoretical cross sections (perfect resolution).

Neutrino Physics

☐ SM leptons: $\mathrm{L}_e = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_\mathrm{L}$ $\mathrm{L}_\mu = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_\mathrm{L}$ $\mathrm{L}_\tau = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_\mathrm{L}$ $\mathrm{R}_{e,\mu,\tau} = e_\mathrm{R}, \mu_\mathrm{R}, \tau_\mathrm{R}$

No ν_R needed. Singlet under $SU(3)_c \times SU(2)_L \times U(1)_Y$
Lepton number conserved.

☐ Observation of neutrino flavor mixing drastically changes the picture

☐ Flavor mixing ⇒ neutrino masses

$$\Delta m^2_\mathrm{solar} << \Delta m^2_\mathrm{atm}$$

Simple two flavor (α,β) case: with mass eigenstates (i,j)

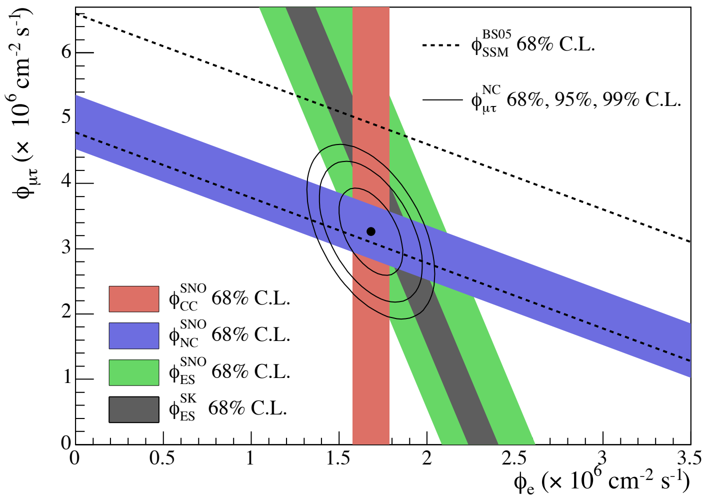
$$\nu_\alpha = \nu_i \cos\theta + \nu_j \sin\theta$$

$$\nu_\beta = -\nu_i \sin\theta + \nu_j \cos\theta$$

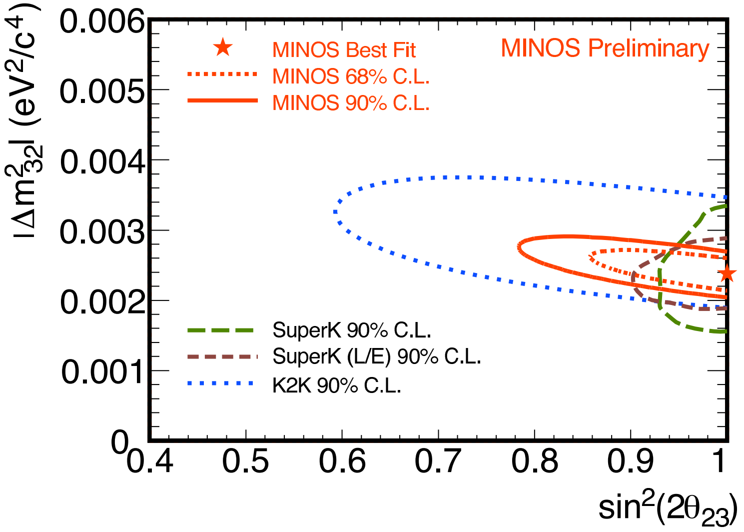
$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(\Delta m^2 L/4E\right)$$

Oscillation probability (P) for energy (E) and distance (L)

Solar

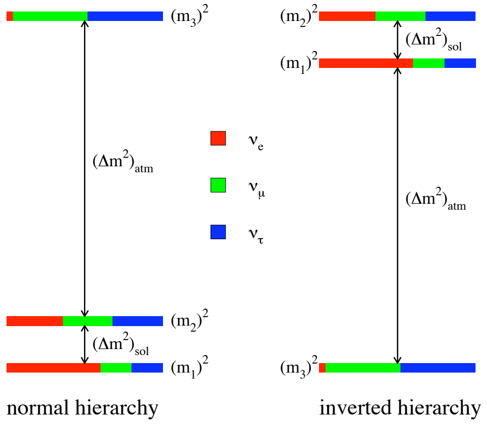


Atmospheric



Theoretical Issues

- Normal or Inverted Mass Hierarchy?



- Majorana or Dirac particles?

Usual Dirac fermion can be expressed as a left-handed particle χ and its charge conjugate (C) particle ϕ

$$\psi_D = \begin{pmatrix} \chi \\ \sigma_2 \phi^* \end{pmatrix} \qquad C = \begin{pmatrix} -\sigma_2 & 0 \\ 0 & \sigma_2 \end{pmatrix} \qquad \psi_D^c = C\bar{\psi}_D^T = \begin{pmatrix} \phi \\ \sigma_2 \chi^* \end{pmatrix}$$

A majorana fermion is its own charge conjugate.

Dirac fermion is equivalent to two Majorana fermions with equal mass.

Majorana fermions: ρ_1 ρ_2

$$\phi \equiv \frac{1}{2}(\rho_2 + i\rho_1)$$
$$\chi \equiv \frac{1}{2}(\rho_2 - i\rho_1)$$

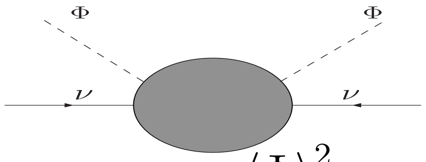
Dirac mass term: $\bar{\psi}_D m \psi_D = m(\phi\sigma_2\chi + h.c) = \frac{m}{2}\sum_{\alpha=1,2} \rho_\alpha \sigma_2 \rho_\alpha + h.c.$

Majorana: no ν_R - mass term violates lepton number conservation

$$\mathcal{L}_{\text{mass}} = \bar{\nu}_L^c M_L \nu_L + h.c.$$

Dirac: ν_R

$$\mathcal{L}_{\text{mass}} = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}^\dagger \mathcal{M} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + h.c.$$



$$m_\nu = \lambda_0 \frac{\langle \Phi \rangle^2}{M_X}$$

ν_R has no SM gauge interactions.
Does it have new gauge interactions?

Pure Dirac: $\mathcal{M} = \begin{pmatrix} 0 & M \\ M^\dagger & 0 \end{pmatrix}$

Seesaw I: $\mathcal{M} = \begin{pmatrix} 0 & M \\ M^\dagger & M_R \end{pmatrix}$

Seesaw II: $\mathcal{M} = \begin{pmatrix} M_L & M \\ M^\dagger & M_R \end{pmatrix}$

Theoretical Issues

- Three generation mixing matrix PMNS

Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

Three angles: $\theta_{12}, \theta_{23}, \theta_{13}$

CP phases: δ(Dirac) (α,β,δ) (Majorana)

$c_{ij} = \cos(\theta_{ij})$ $s_{ij} = \sin(\theta_{ij})$

$$U_{PMNS} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} diag(1, e^{i\alpha/2}, e^{i\beta/2})$$

Atmos. L/E $\mu \rightarrow \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \rightarrow \mu, \tau$

500km/GeV 15km/MeV

The additional Majorana CP phases appear in lepton number violating interactions: eg. neutrinoless double beta decay.

- Matter effects:

Interactions in matter EW flavor dependent and differ for neutrino/antineutrino. (Compare K_L-K_S)
Induces new terms in mixing formulae.

Appearance probabilities in long baseline neutrino oscillation experiments

$$P(\nu_\mu \rightarrow \nu_e) \quad = \quad X_+ \sin\theta_{13}^2 + Y_+ \sin\theta_{13}\cos(\Delta_{13}+\delta) + P_{\rm sol}$$
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \quad = \quad X_- \sin\theta_{13}^2 - Y_- \sin\theta_{13}\cos(\Delta_{13}+\delta) + P_{\rm sol}$$

where

(normal hierarchy)

$$X_\pm = 4\sin^2\theta_{23}\left[\frac{\Delta_{31}\sin(aL\mp\Delta_{31})}{(aL\mp\Delta_{31})}\right]^2$$
$$Y_\pm = \pm 2\sqrt{X_\pm P_{\rm sol}}$$
$$P_{\rm sol} = \cos^2\theta_{23}\sin^2 2\theta_{12}\left[\frac{\Delta_{21}\sin(aL)}{aL}\right]^2$$
$$\Delta_{ij} \equiv |\Delta m_{ij}^2| L/4E$$

and the index of refraction in matter is:

J. Burguet-Castell et.al.
NP B608 (2001) 301

$$a = G_F N_e/\sqrt{2}$$

Note that the interference term is the only term that depends on CP phase δ. Also the only term that differs for neutrino/antineutrino beside matter effects.

Experimental Status

Present status

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

KamLAND
K2K,
MINOS
SNO
SuperK
CHOOZ

T. Schwetz, M. Tortola and J. Valle
[arXiv:0808.2016v2]

$\sin^2\theta_{13}$, δ
not measured yet

Reactor Neutrinos: Daya Bay

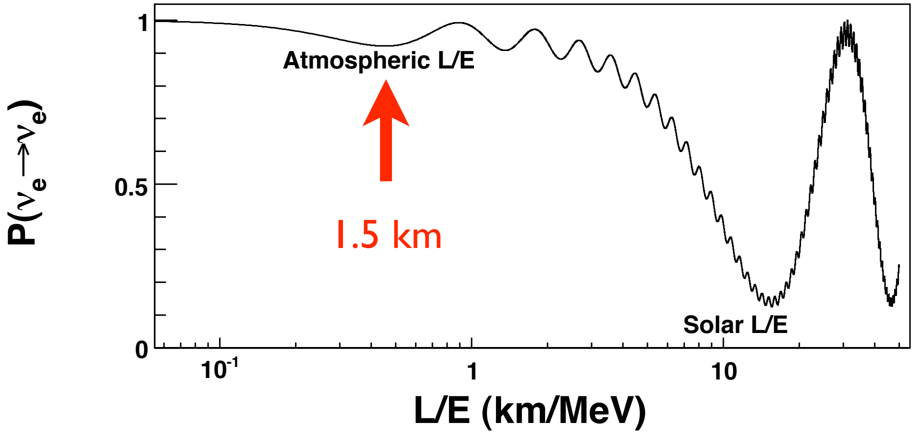
$$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$$

$$P(\bar\nu_e \to \bar\nu_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$- \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

< 0.002

$$\approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

Daya Bay sensitivity ≈ 0.01



Experimental Status

Nova and T2K

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{solar}}|^2$$

where

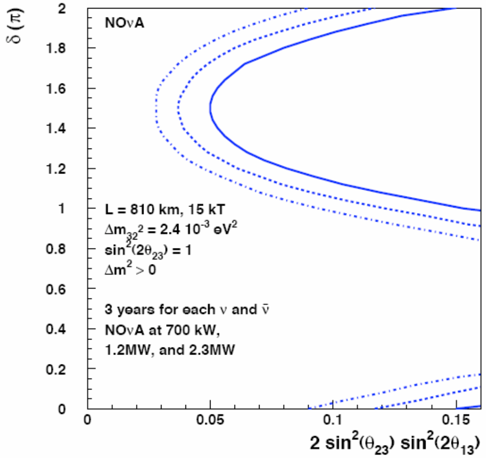
$$\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{13}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}$$

$$\sqrt{P_{solar}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{(aL)}\Delta_{21}$$

and the matter effect parameter

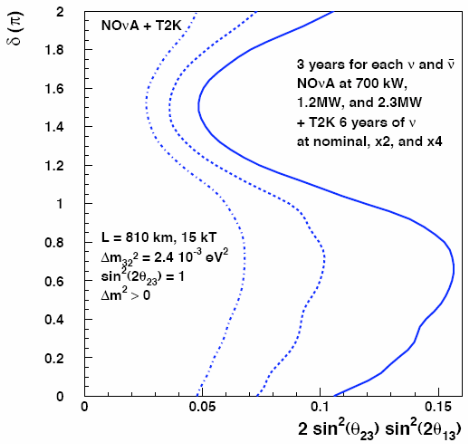
$$a = G_F N_e/\sqrt{2} = (4000\ \mathrm{km})^{-1}$$

95% CL Resolution of the Mass Ordering
NOνA Alone



Normal Ordering

95% CL Resolution of the Mass Ordering
NOνA Plus T2K



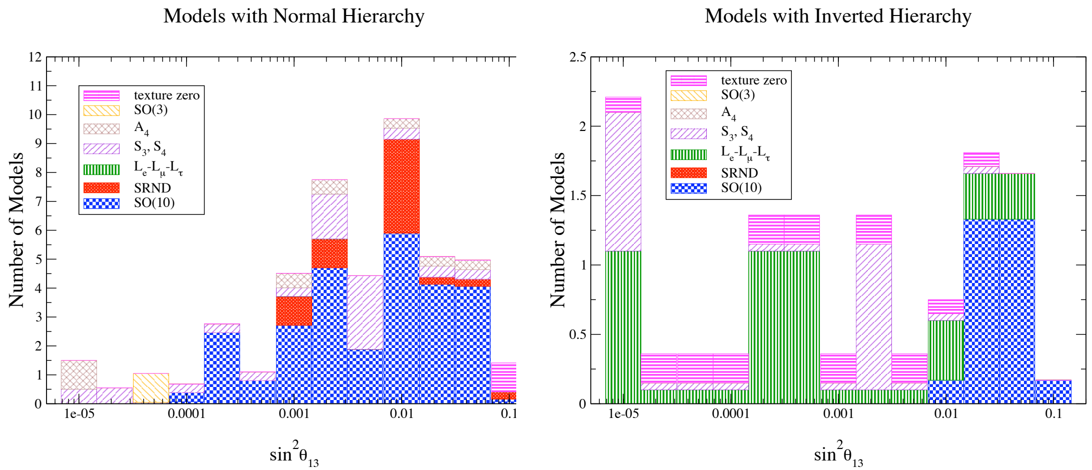
Normal Ordering

S. Parke [NFMCC 2009 (1/25/2009) LBNL]

for Inverted Hierarchy $\delta \to \pi - \delta$

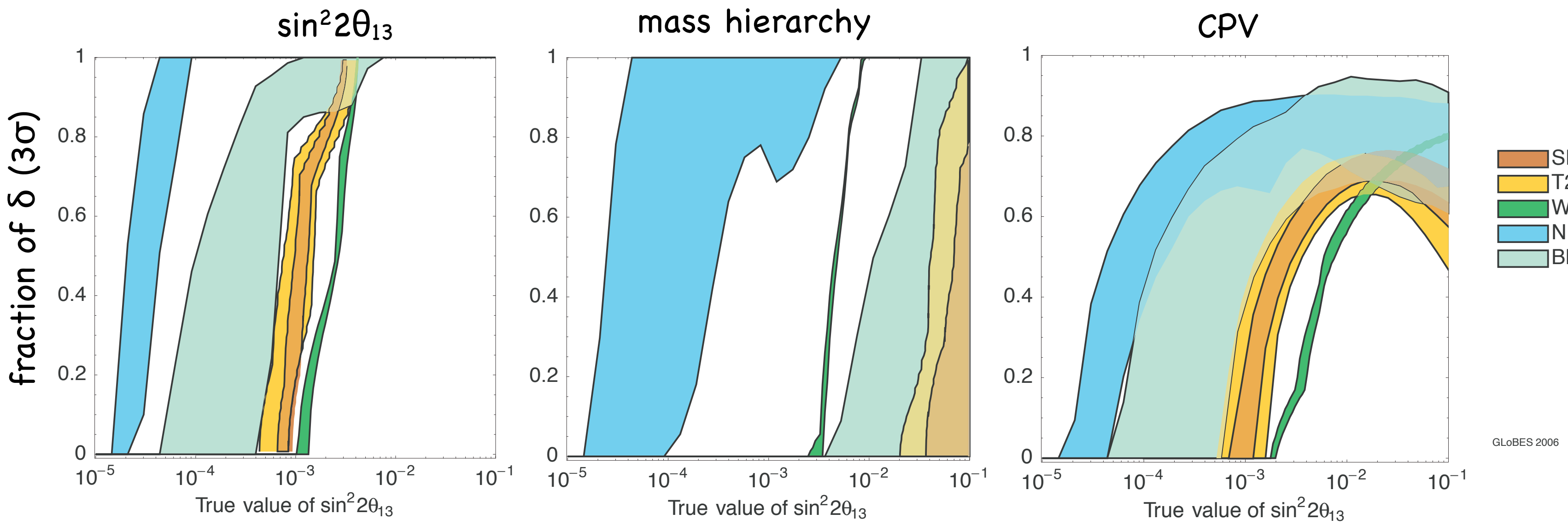
Neutrino Factory

- Expected $\sin^2 2\theta_{13}$ for a variety of theoretical models
- Neutrino factory:
  - Muon storage ring: $\sqrt{s}$ = 50 GeV
  - Long straight sections
  - High intensity: 10^{21} muon decays /yr



ISS Physics Working Group [arXiv:0710.4947]

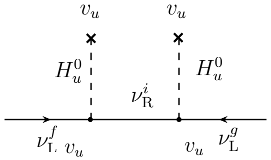
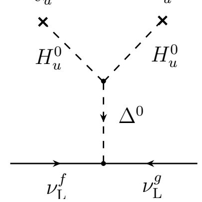
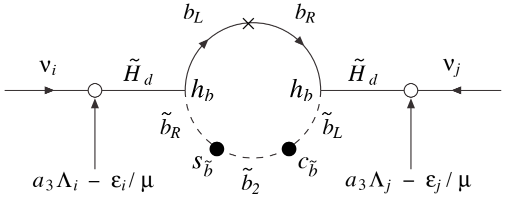
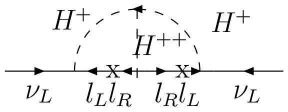
- Discovery reach for various proposed facilities.



Very likely Neutrino Factory needed to disentangle θ_{13}, mass hierarchy, and measure CPV parameter.

Non-Standard Neutrino Interactions

- A plethora of theoretical models:

Model	Interaction	New Particles	Comments
(1-2-3) Seesaw I		ν_R, Majoron	Very light majoron dark matter candidate
(1-2-3) Seesaw II		heavy higgs triplet	
L-R Seesaw SU(3)×SU(2)×SU(2)×U(1)	Both types	new gauge bosons	No majoron B-L Terascale physics
SUSY models		SUSY partners	Calculable in terms of Smasses and Smixings. R parity violating
Babu model		charged $SU(2)_L$ singlet scalars	H^{++} scalar
Texture models, ...			

Goals of Neutrino Program

☐ Basic goals

(a) Determine Dirac or Majorana nature of neutrinos.

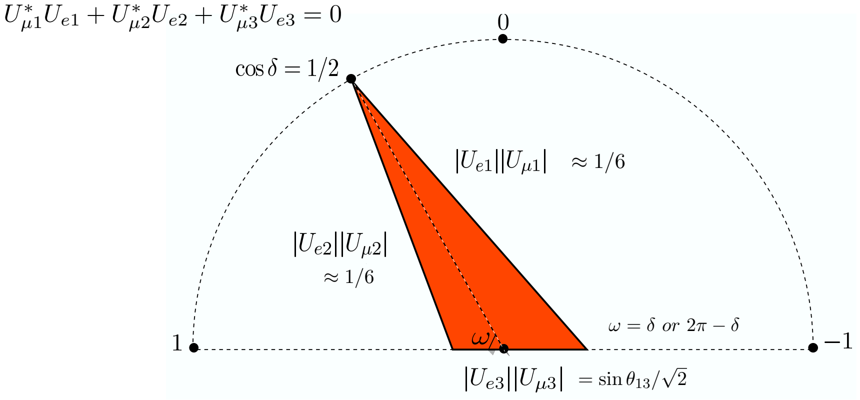
(b) Determine the mass hierarchy.

(c) Measure θ_{13}, δ and improve θ_{12}, θ_{23} measurements

(d) Study unitarity of PMNS matrix.

(e) Are there additional mixing or CPV from new particles or interactions?

Unitarity Triangle:



$$|J| = 2 \times Area$$

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta$$

☐ Why is this important?

(a) Neutrino masses are very small. Theoretical models for these masses predict new particles at the Terascale or a new scale beyond.

(b) Potential source of lepton number violation and CP violation. Leptogenesis might be responsible the observed baryon asymmetry in the universe.

(c) Contributions to dark matter and cosmological evolution.

(d) Complimentary to energy frontier physics (LHC)

☐ Why a Neutrino Factory?

(a) Large $\sin^2(2\theta_{13})$ (≥ 0.005) - can explore new physics as subleading effects.

(b) Small $\sin^2(2\theta_{13})$ - provides unmatched sensitivity.