Physics Landscapes:
The Energy Frontier

Marcela Carena

Theoretical Physics Dept.

Fermilab

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Physics Landscapes: The Energy Frontier

- Introduction:
  Physics Landscape $\Longrightarrow$ Certainties and Unknowns
- The role of the Tevatron in shaping the next decade

– Precision Measurements
– Discovery of new particles or new bosonic or fermionic (SUSY) dimensions

- The LHC:

– Largest Potential in Direct Searches for New Particles
⋆ SM and extended Higgs sectors ⋆ Supersymmetry
⋆ Extended Gauge sectors ⋆ Strong Dynamics
⋆ Extra Dimensions ⋆ Exotic Fermions

– Some precision measurements

- The LC:

– good discovery potential in heavy weakly interacting particles or particles with un-tagged jet final states.
– Precision measurements testing Properties of New particles
⋆ Particle masses ⋆ Couplings ⋆ Branching ratios ⋆ Spin ⋆ Parity

- Outlook

Introduction

• Standard Model $\Longrightarrow$ the pillar of particle physics that explains data collected in the past several years and provides description of physical processes up to energies of $\approx$ 100 GeV.

However, it is only an effective theory.

• Many open questions

- ⋆ origin of EWSB
- ⋆ generation of stabilization of hierarchies: M_{weak} Vs M_{Planck}
- ⋆ connection of electroweak and strong interactions with gravity
- ⋆ generation of fermion masses and mixings
- ⋆ explanation of baryon asymmetry of the universe
- ⋆ dark matter

$\Longrightarrow$ crucial to get the complete picture valid up to higher energies, M_{Pl}

• **Collider Experiments**: Tevatron LHC, LC (TeV reach)
our most robust handle to reveal the new physics that should answer these questions

EWSB occurs at the TeV scale

In the absence of big fine-tuning of scales,

$\Longrightarrow$ New Phenomena should lie in the TeV range or below, within reach of LHC/LC

Numerous theories have been proposed:

two broad classes:

- weakly coupled dynamics
- strongly coupled dynamics

• Standard Model $\rightarrow$ example of weak EWSB

one extra physical state left in the spectrum $\equiv$ HIGGS Boson

Present Data $\rightarrow$ no direct evidence of Higgs [$m_h > 114.4$ GeV (LEP2)]

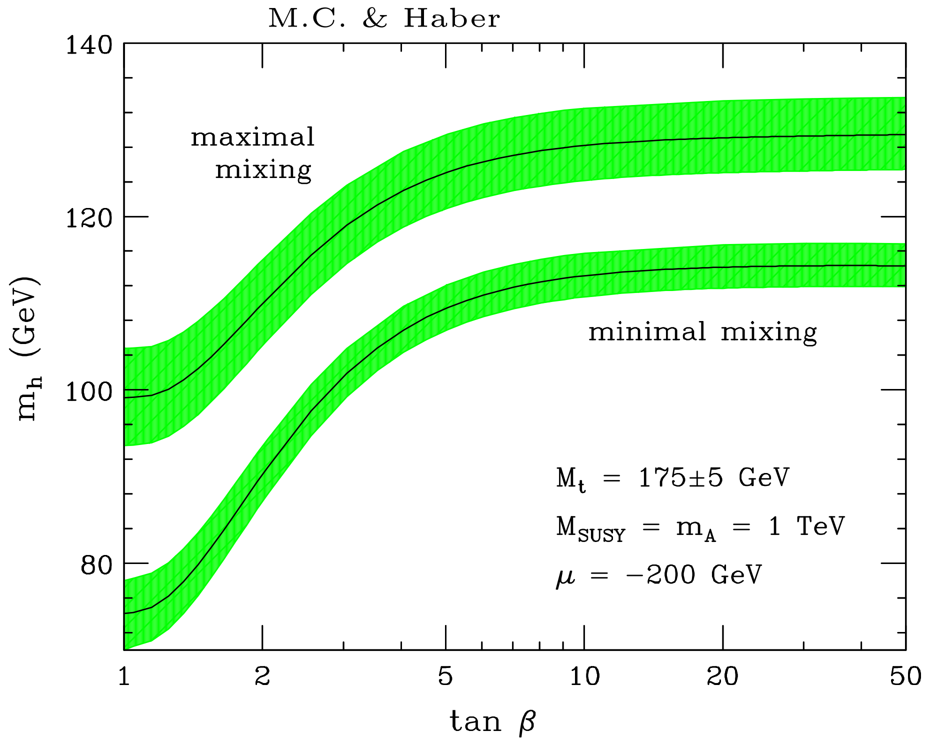
- SM with weakly coupled Higgs is in excellent agreement with precision data $\Longrightarrow$ $m_{H_{SM}} \leq 210$ GeV at 95 % C.L.

• In weakly coupled approach, SM most probably embedded in SUSY theory

fermion-boson symmetry $\rightarrow$ stabilization of hierarchy: quadratic sensitivity to M_{pl} replaced by quadratic sensitivity to superpartner masses

SUSY Theories $\Longrightarrow$
larger Higgs sector with lightest Higgs having (usually) SM-like properties and
$m_h \leq 200$ GeV

MSSM: simplest extension
($m_h \leq 135$ GeV)



- SUSY must be broken in the ground state – SUSY partners heavier than SM particles

However, if SUSY exists, many of its most important motivations

- ⋆ solve hierarchy problem
- ⋆ play central role in unification of gauge couplings
- ⋆ provide a good dark matter candidate
- ⋆ provide a possible solution to baryogenesis

demand some SUSY particles at the TeV range or below

The mechanism of SUSY breaking is not well understood.

$\Downarrow$

Different SUSY breaking scenarios $\longrightarrow$ crucially different patterns of low energy spectrum –production and decays–

- Important to develop a comprehensive search strategy to explore the main signals in different SUSY breaking scenarios.

SUGRA Scenarios

Supersymmetric particles odd under R-parity: $R_p = (-1)^{3B+L+2S}$

- If R-parity Conserved: Lightest Supersymmetric Particle (LSP) Stable
  $\Longrightarrow$ lots of $\not{E}_T \rightarrow$ distinctive SUSY signature

- LSP Stable $\Longrightarrow$ good Dark Matter candidate.

Best candidate: Neutralino $\Longrightarrow$ SUSY partner of the neutral Higgs or gauge bosons

- Strongly interacting particles (due to RG effects) tend to be heavier than weakly interacting ones.

Gauge-Mediated Low-energy SUSY Breaking Scenarios

- Special feature $\longrightarrow$ LSP: light (gravitino) Goldstino: $m_{\tilde{G}} \sim 10^{-6} - 10^{-9}\text{GeV}$

If R-parity conserved, heavy particles cascade to lighter ones and

NLSP $\longrightarrow$ SM partner + $\tilde{G}$ $\quad$ *e.g.*, $\tilde{\chi}_1^0 \to (h, Z, \gamma)\,\tilde{G}$; $\quad \tilde{\ell}^{\pm} \to \ell^{\pm}\,\tilde{G}$; $\quad \tilde{q} \to q\,\tilde{G}$

Superpartner masses proportional to their gauge couplings.

- Signatures: decay length $\quad L \sim 10^{-2}\text{cm}\left(\frac{m_{\tilde{G}}}{10^{-9}\text{GeV}}\right)^2 \times \left(\frac{100\text{GeV}}{M_{\text{NLSP}}}\right)^5$

  ⋆ NLSP can have prompt decays:

  Signature of SUSY pair: 2 hard photons, (H's, Z's) + $\not{E}_T$ from $\tilde{G}$

  ⋆ macroscopic decay length but within the detector:

  displaced photons; high ionizing track with a kink to a minimum ionizing track

  (smoking gun of low energy SUSY)

  ⋆ decay well outside the detector: $\not{E}_T$ like SUGRA

Anomaly-Mediated SUSY Breaking Scenarios

- SUSY breaking masses determined by beta functions, proportional to gauge couplings

- Striking signature at colliders: $\quad \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \pi^{\pm}$

  at tree level, $M_{\tilde{\chi}_1^{\pm}} \approx M_{\tilde{\chi}_1^0}$ – mass degeneracy lifted by radiative corrections

  by about 150 MeV $\longrightarrow$ very soft pion (decay length of order 1 cm)

Strongly Coupled Dynamics

(a) Models which do not require a Higgs Boson

⟹ Strong interactions at the TeV scale: Technicolor, Topcolor

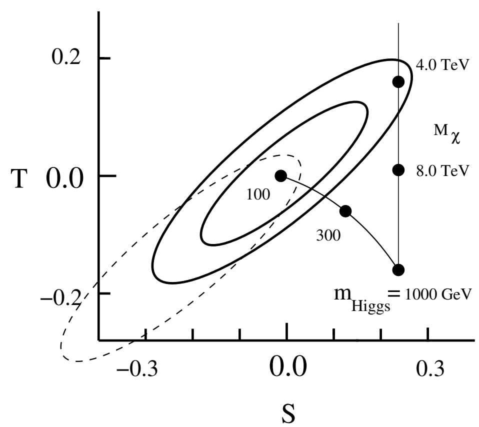
Robust prediction: vector resonance with mass $\leq$ 2 TeV (unitarizes WW scattering)

Key components: Strong WW scattering; Anomalous gauge couplings;
Extra scalars → composites of underlying strongly coupled fermions

(b) Strong interactions above TeV scale give rise to bound states

⟹ including Higgs boson: Composite Higgs Models

He, Hill & Tait



Top quark seesaw theory:

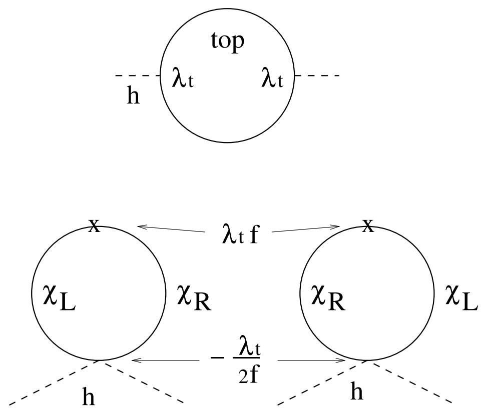
- Higgs is a bound state of left-handed top and right-handed component of a new vector-like fermion: $m_H \simeq 500$ GeV.
- New contributions from additional quarks bring agreement with precision electroweak measurements.

possible low energy signatures:

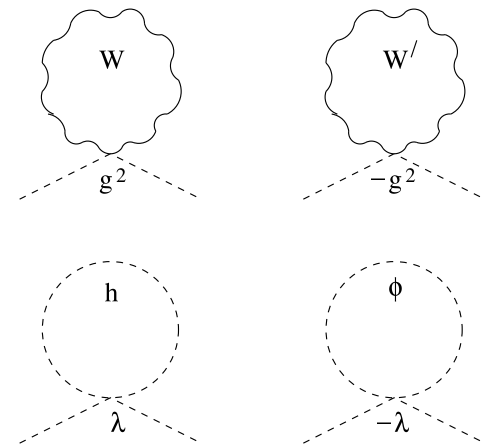
Extended Higgs sector at TeV scale or below → mixing can bring the SM-like Higgs down to 200 GeV; Extra Fermions; Heavy vector bosons.

(c) Little Higgs Models:

- Higgs is a pseudo-Goldstone boson from global symmetry breaking at scale 10–30 TeV. New Dynamics needed above that scale.
- Higgs acquires mass only through collective breaking of global symmetry.
- Non-linearly realized symmetry yields cancellation of quadratically divergent quantum corrections between fields of the same spin.



A fermion loop cancels a fermion loop.



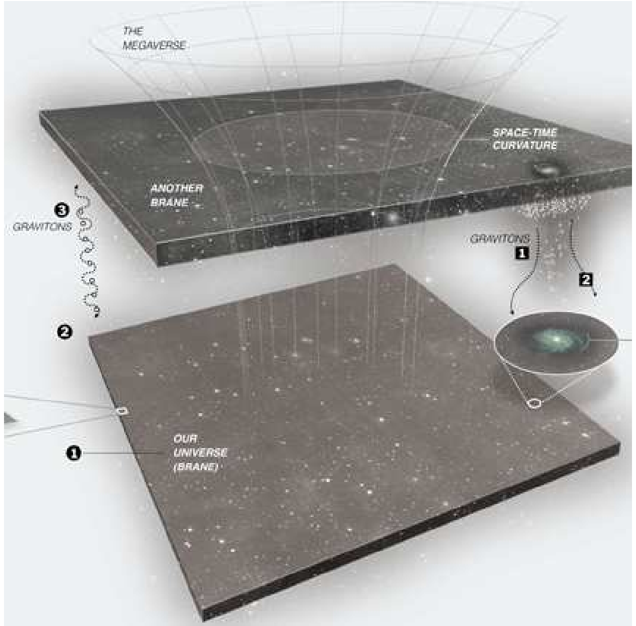
The gauge and Higgs loops are canceled by diagrams with new bosons in loops.

Cancellation of quadratic divergences works at one loop.

$\Longrightarrow$ new fermionic partners for SM quarks and leptons and new gauge boson partners for SM gauge fields at the TeV scale.

- LHC should discover some of them;
- LC: precision measurement of heavy gauge boson couplings to fermions via polarized cross sections and asymmetries.

A daring alternative: Extra Dimensions



- If seen by SM particles, they should be quite small:
  $R \leq 10^{-17} cm \approx 1\ \text{TeV}^{-1}$
- If not seen by SM particles, only by gravity
  $\longrightarrow$ they can be larger: $R \leq 1mm$

<u>Generic Feature:</u> (KK modes in 4-D)
excited states with the same quantum numbers
as the graviton and the SM particles

- If gravity propagates in the extra dimensions

$\Longrightarrow$ Newton's law modified: $M_{Pl}^2 = (M_{Pl}^{\text{fund.}})^{2+d}\, R^d$

$\Longrightarrow$ this lowers the fundamental Planck scale, depending on the size & number of ED.

Signatures

- Coupling of gravitons to matter with $1/M_{Pl}$ strength
  $1/R \simeq 10^{-2}$ GeV $(d=6)$; $1/R \simeq 10^{-4}$ eV $(d=2)$;

(a) Emission of KK graviton tower states: $G_n \Longleftrightarrow \not{E}_T$
(emitted gravitons appear as continuous mass distribution)

(b) Graviton exchange in $2 \to 2$ scattering – deviations for SM cross sections or new decays

(c) If SUSY also present $\Longrightarrow$ KK tower of gravitinos as well,
$\longrightarrow$ important in light gravitino SUSY breaking scenarios

Warped Extra Dimensions

Metric: $ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ $\Longrightarrow$ Solution to 5d Einstein eqs.

5d Planck mass relates to M_{Pl}: $M_{Pl}^2 = \frac{(M_{Pl}^{\text{fund.}})^3}{2k}(1 - e^{-2kL})$

fundamental scales: $M_{Pl} \sim M_{Pl}^{\text{fund.}} \sim v \sim k$ (k is the 'warp factor')

$\Longrightarrow$ Physical Higgs v.e.v. suppressed by e^{-kL} $\Longrightarrow$ $\tilde{v} = v\, e^{-kL} \simeq M_{Pl}\, e^{-kL}$

$kL \approx 34 \Longrightarrow$ good solution to the hierarchy problem.

Signatures

- Graviton KK modes have 1/TeV coupling strength to SM fields and unequally spaced masses starting with a few hundred GeV.
- KK graviton states produced as resonances or may contribute to $f\bar{f}$ production.

SM fields propagating in ED: TeV-scale or warped ED

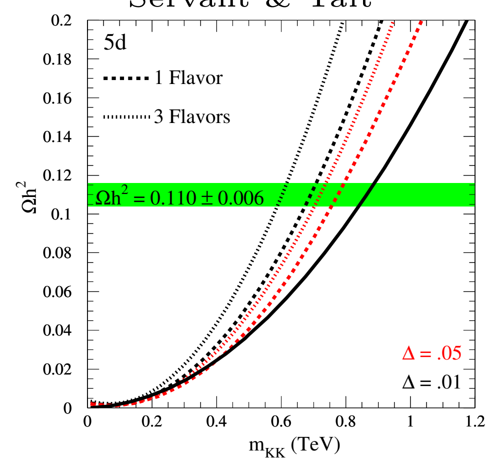
- Gauge bosons and/or fermions in the bulk $\Longrightarrow$ new particles may be within reach of LHC.

Universal Extra Dimensions (flat ED):

All fields in the bulk – no wall or branes
$\Longrightarrow$ momentum conserved in ED.

- KK modes produced by pairs
- Lightest Kaluza-Klein Particle (LKP)
  $\longrightarrow$ good dark matter candidate

Servant & Tait



What Can We Learn from RUN 2?

– Precision measurements:

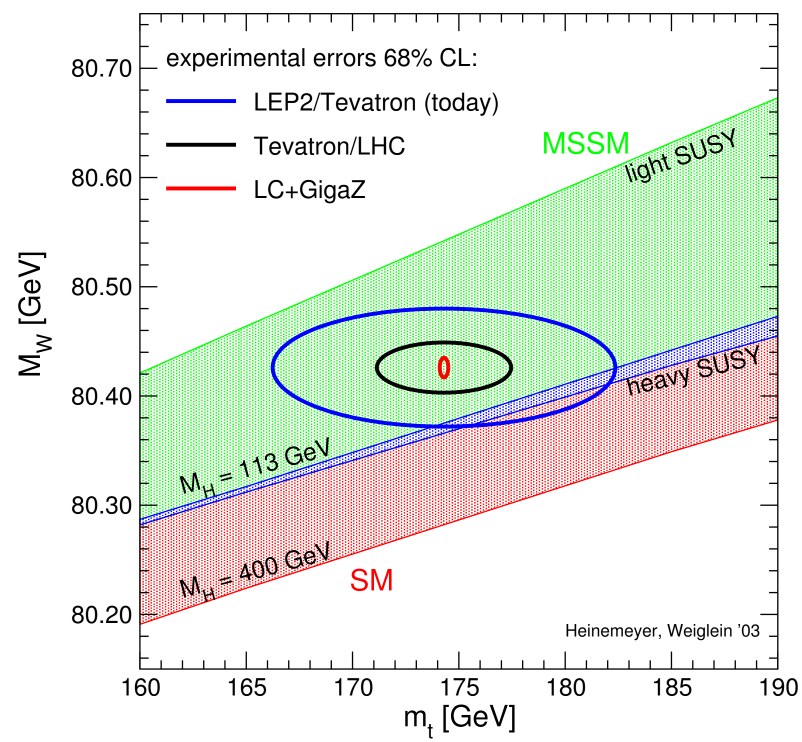
- top quark mass: $\delta M_t \simeq 3$ GeV with 2 fb^{-1}
- W mass: $\delta M_W \simeq 30$ MeV with 2 fb^{-1}

high precision for M_t is important to
$\Longrightarrow$ exploit precision on M_W in the context of electroweak precision measurements

M_t–M_W–M_H Correlation

- direct M_t and M_W measurements from LEP and the Tevatron
- Indirect M_t and M_W determination from SM fit to precision data (LEP, SLD, νN)
- SM relationship for M_t–M_W–M_H
  $\Longrightarrow$ crucial information on M_H

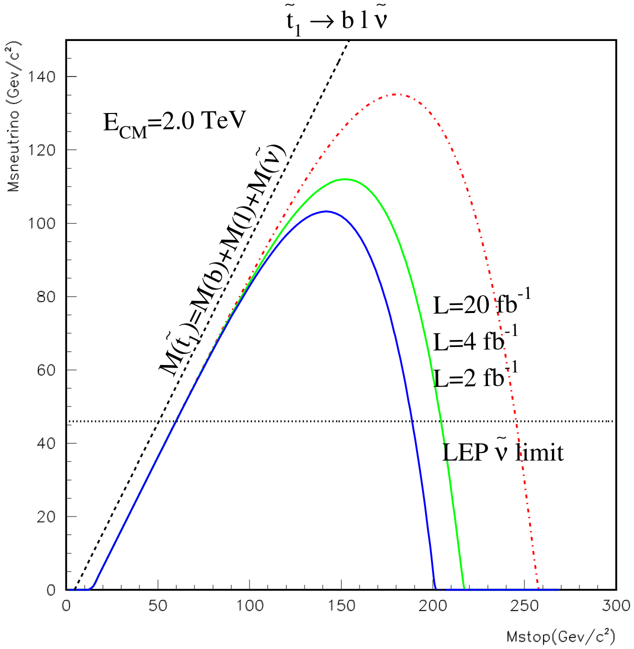
$\Longrightarrow$ A light SM Higgs Boson strongly favored by data



Stop and Sbottom Searches

In many models (MSUGRA, extended Gauge– and Anomaly–Mediated) $\longrightarrow$ $\tilde{t}$'s and $\tilde{b}$'s can be quite light

Demina, Lykken, Matchev & Nomerotski



prospects: with $\int \mathcal{L}\, dt = 4$ fb^{-1}

$m_{\tilde{t}_1} \leq$	200/210	in $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} / \tilde{t}_1 \rightarrow bl\tilde{\nu}$
$m_{\tilde{t}_1} \leq$	180	in $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$
$m_{\tilde{b}_1} \leq$	230	in $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$

generic squark & gluinos: 350–450 GeV

New Studies: jets + photons + $\not\!\!E_T$ with 4 fb^{-1} M.C., Choudhury, Logan, Diaz & Wagner

$\longrightarrow$ possible signature of gauge-mediated scenarios

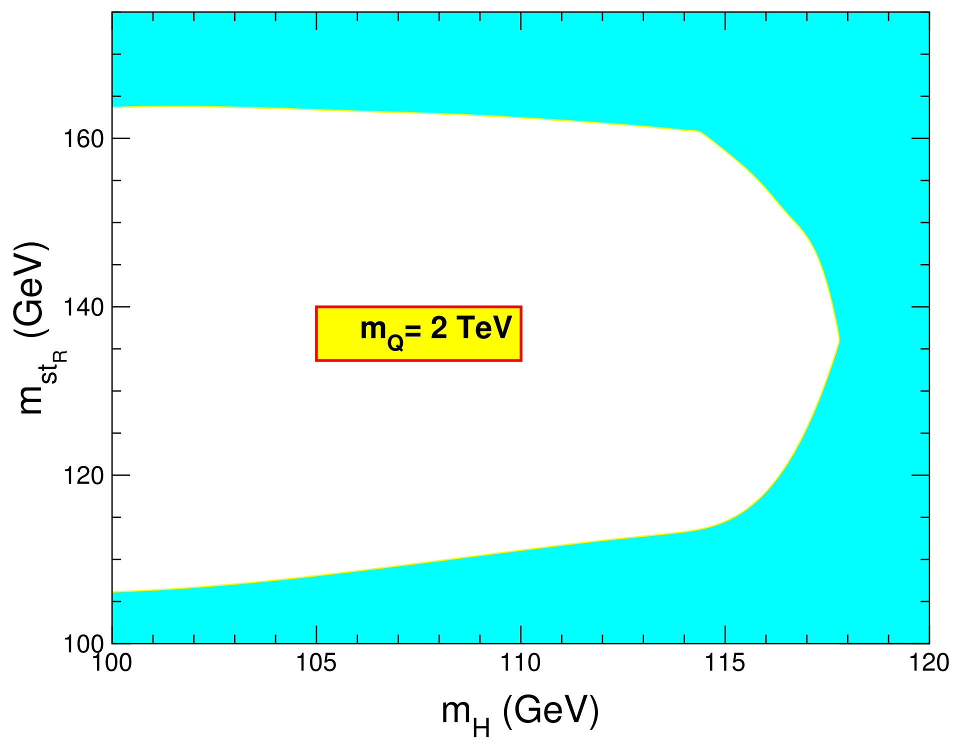
In the cases $\tilde{t} \rightarrow c\gamma\tilde{G}$ and $\tilde{t} \rightarrow bW\gamma\tilde{G}$, sensitivity up to $m_{\tilde{t}_1} \leq 300$ GeV

For generic squark production, $\tilde{q} \rightarrow q\gamma\tilde{G}$, sensitivity up to $m_{\tilde{q}} \leq 400$ GeV

An Interesting Highlight $\longrightarrow$ **Electroweak Baryogenesis**

predicts light right-handed stops $m_{\tilde{t}_R} \sim 150$ GeV

and MSSM Higgs bosons in the range $m_h \sim 100$-118 GeV



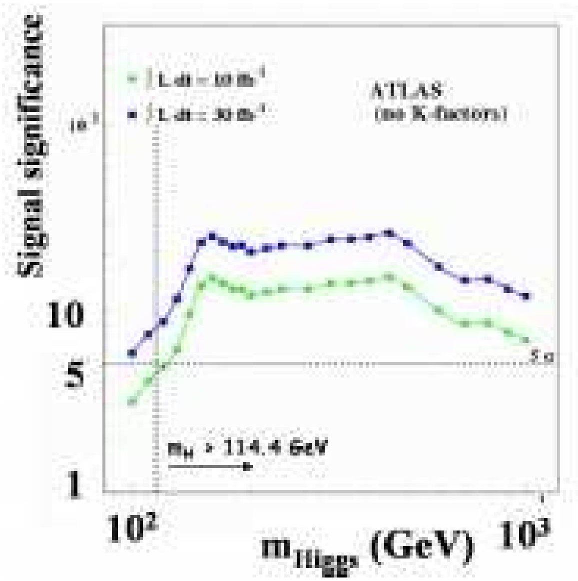
M.C., Quiros & Wagner

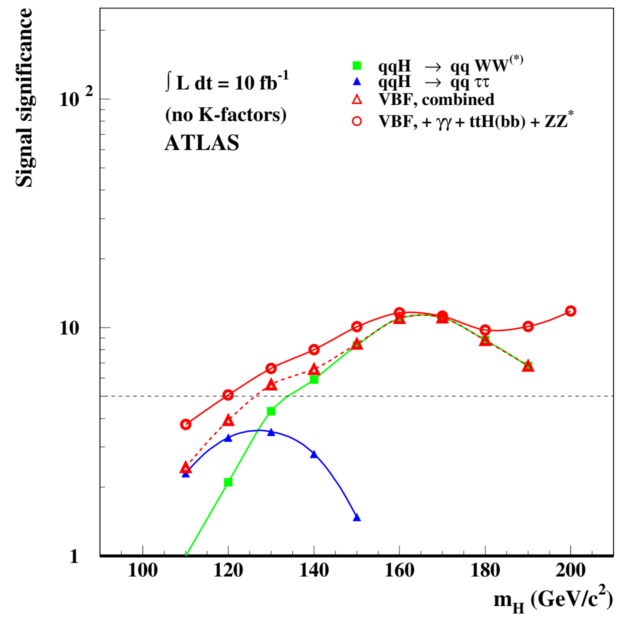
Tevatron Run II reach for Higgs and stops probes Baryogenesis at the Electroweak scale!

What Will We Know by the End of the Decade?

After the first run period of the LHC $\longrightarrow$ 10–30 fb^{-1} collected

- *If the SM Higgs exists, it will be discovered at the LHC.*





mass regions –

- m_H in the range $2\,M_Z$ – 600 GeV
  best channel is $H \to ZZ \to 4\ell$
- $m_H > 600$ GeV
  $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and
  $H \to WW \to \ell\nu JJ$

more demanding :

$m_H < 2\,M_Z$ (esp. below 130 GeV)
need combination of three channels:

$H \to \gamma\gamma$, $\quad H\,t\bar{t} \to b\bar{b}\,t\bar{t}$,
$q\bar{q}\,H \to q\bar{q}\,\tau^+\tau^-/WW^*$

to achieve 5σ discovery with 10 fb^{-1} ($\sim$ 1 year)

Higgs Bosons in the

Minimal Supersymmetric Extension of the Standard Model (MSSM)

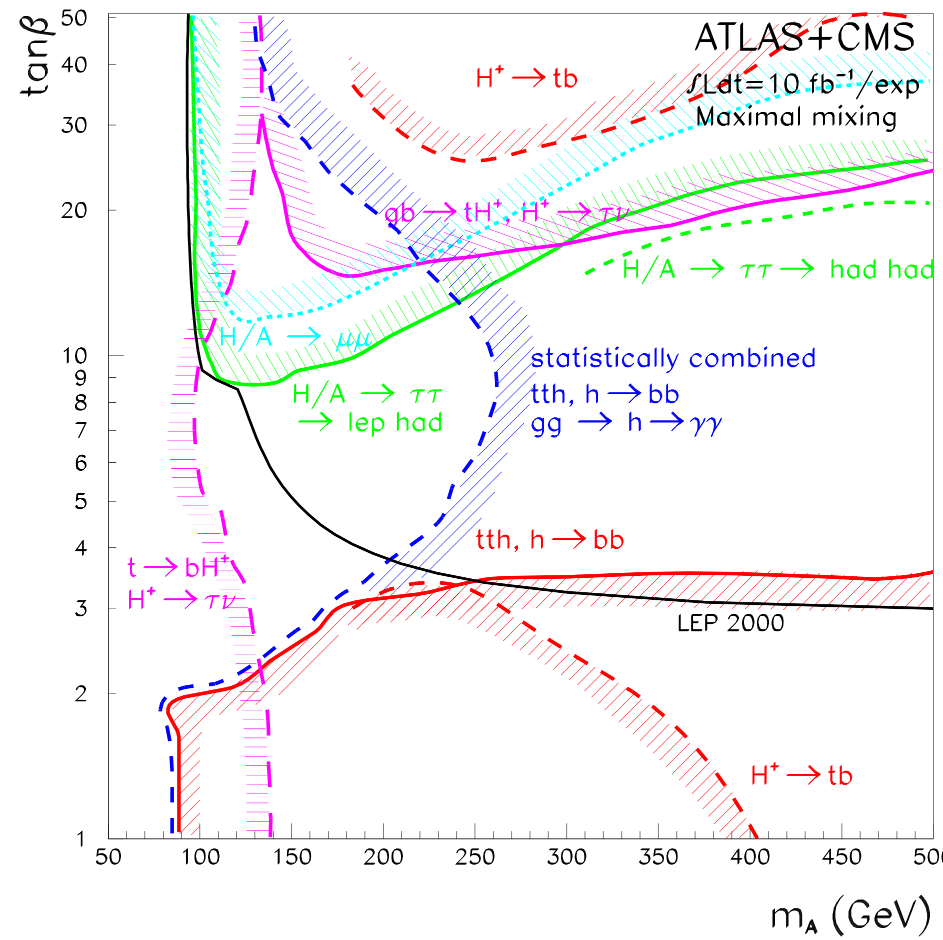
- many different channels for H, A & $H^{\pm}$

- full coverage assured only for h

Vector Boson Fusion

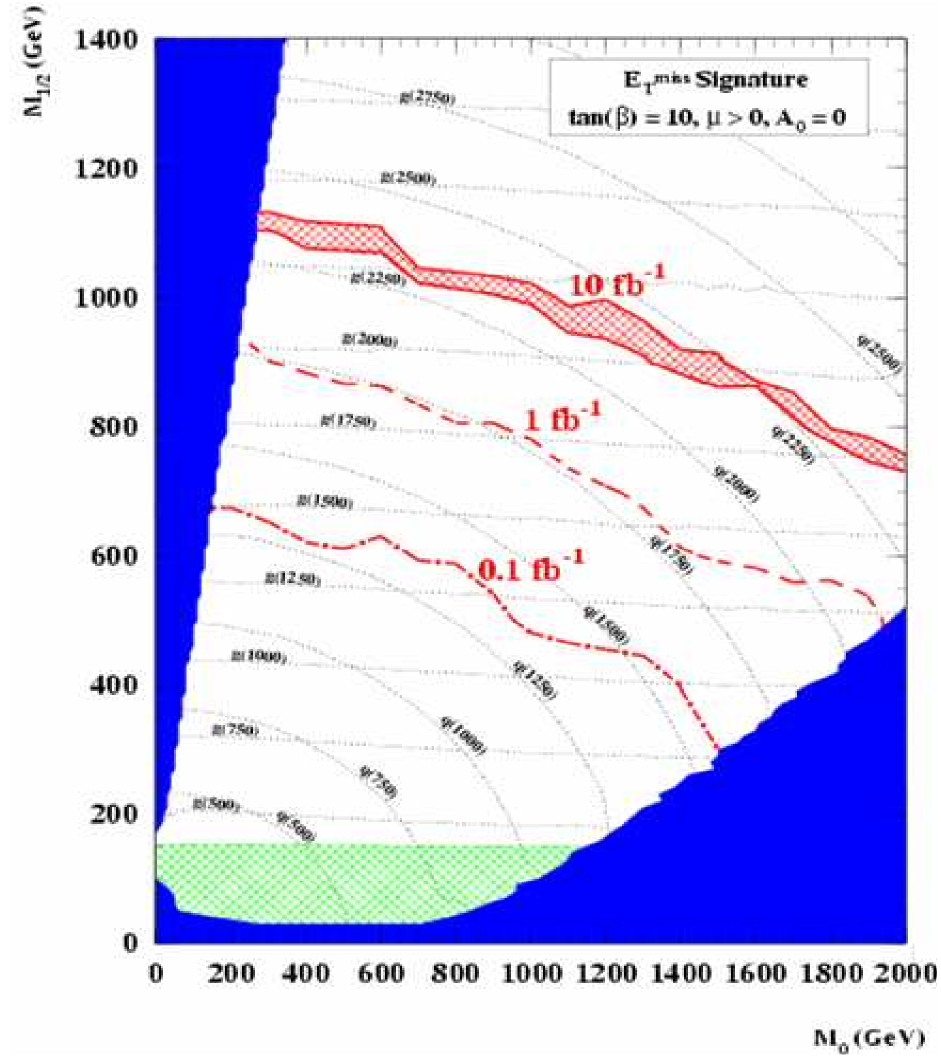
$$q\bar{q}\,h/H \to q\bar{q}\,\tau^+\tau^-/WW^*$$

essential for MSSM coverage with 10 fb^{-1}



SUSY

LHC: SUSY particles, especially strongly interacting ones, are produced at large rates.



- most likely types of signatures:
  - ‘mSUGRA’ type –
    high E_T jets and $\not{E}_T$ (maybe leptons)
  - ‘GMSB’ type –
    hard photons & $\not{E}_T$; heavily ionizing tracks

reach: $M_{\tilde{q}}$ and $M_{\tilde{g}}$ up to $\sim$2 TeV with 10 fb^{-1}

If low-energy SUSY is there, we expect to see some of its signature(s) by the end of this decade.

The Energy Frontier During the Next Decade

LHC: high luminosity, up to 300 fb^{-1}

- Continue Exploration of Higgs Physics
- Measurement of Higgs Parameters –

– Mass

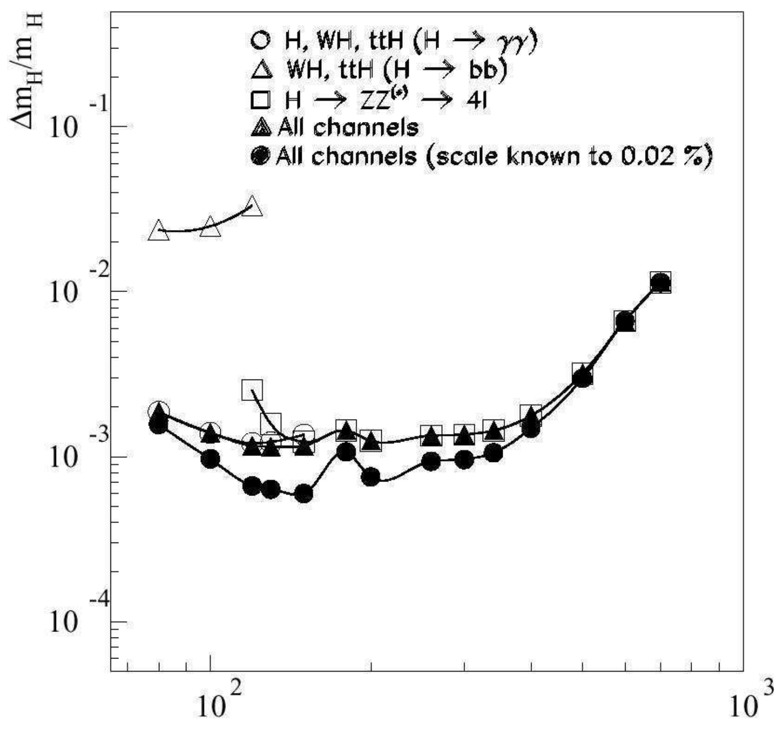
δm_H to 0.1% (leptonic & photonic modes)
1% ($b\bar{b}$ final states)

– Branching Ratios & Couplings

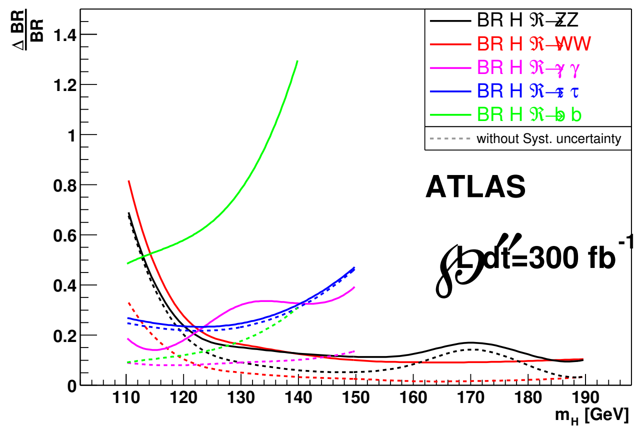
$\delta Br(H \to ZZ)/Br \sim$ 10–20% ($m_H >$ 125 GeV)

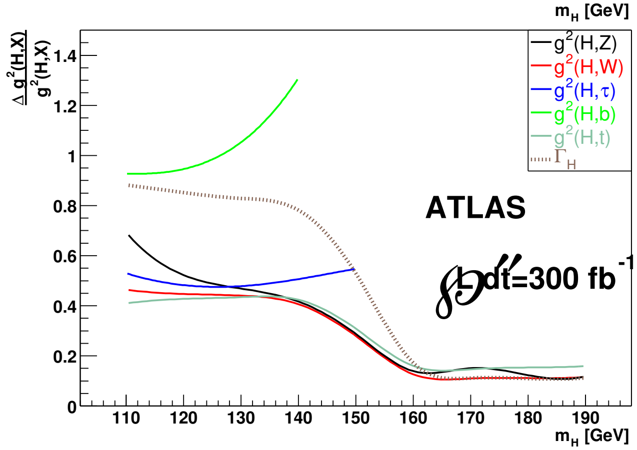
$\delta Br(H \to b\bar{b})/Br \sim$ 50% ($m_H \sim$ 120 GeV)

$\delta g^2/g^2$ ~20% for $H \to Z, W, \tau, t$ if $m_h >$ 150 GeV



ATLAS, 300 fb^{-1}

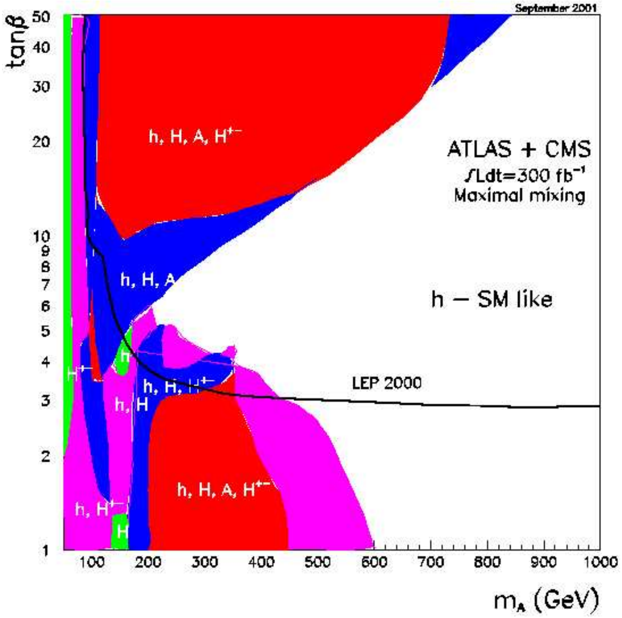




MSSM Higgs

– higher luminosity allows access to many additional channels

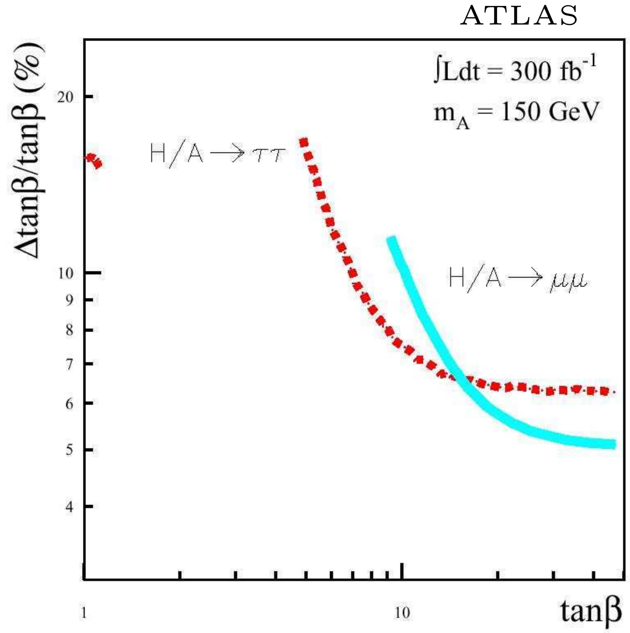
$\longrightarrow$ better coverage of H, A, $H^{\pm}$, h



- still some regions where only h is visible
- some prospects to cover part of this region

  if $H, A \to \tilde{\chi}^0_2 \tilde{\chi}^0_2$; use $\tilde{\chi}^0_2 \to \ell^+ \ell^- \tilde{\chi}^0_1$

– $\tan\beta$ determination from $H/A \to \mu^+\mu^- / \tau^+\tau^-$ to precision 5–15%



⋆ radiative corrections $\Longrightarrow$ other information will be crucial in order to know what we are measuring!!

Higgs Physics $\longrightarrow$ LHC will have a great shot at it.

⋆ Kaluza-Klein Modes from Extra Dimensions

• Flat Extra Dimensions

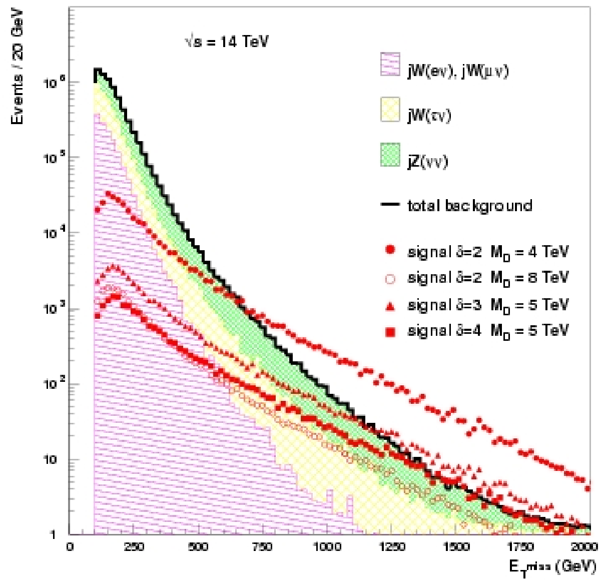
– emission of KK graviton tower states

• $p\bar{p} \to g\, G_N \;(G_N \to \not{E}_T) \longrightarrow \text{jet}+\not{E}_T$

cross section summed over full KK towers

$\Longrightarrow \sigma \propto (\sqrt{S}/M_{\rm Pl}^{\rm fund})^{2+d}$

emitted graviton appears as
a continuous mass distribution



5σ discovery limit for $M_{\rm Pl}^{\rm fund}$ (TeV)

δ	100 fb^{-1}	1000 fb^{-1}
2	9	12
3	7	8
4	6	7

Exciting Possibility:

TeV-scale Production of Black Holes

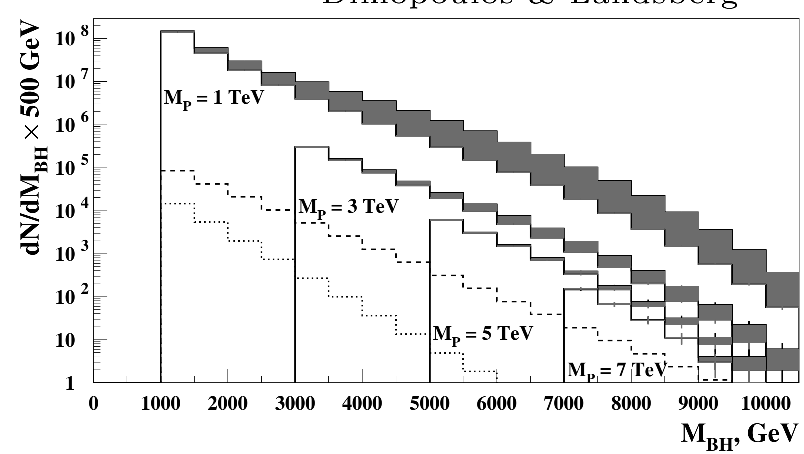
If $M_{BH} \gg M_{\rm Pl}^{\rm fund} \Longrightarrow$ BH prop. understood:

• two partons: $\sqrt{\hat{s}} \equiv M_{BH}$ moving in oppo. dir:
if impact parameter smaller than
Schwarzschild radius $\Longrightarrow$ BH forms

• $M_{\rm Pl}^{\rm fund} \sim 1$ TeV $\Longrightarrow$
more than 10^7 BH per year at the LHC !!

• Signal: sprays of SM particles in equal abundances;
$\longrightarrow$ look for hard, prompt leptons & photons;

Dimopoulos & Landsberg



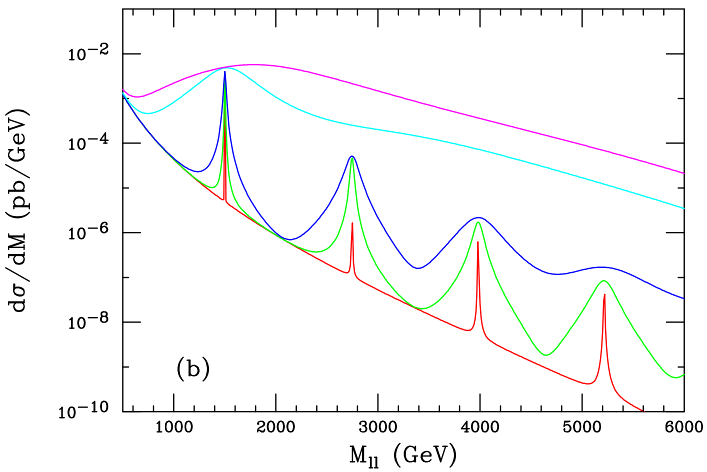
Maybe the first signal of TeV-scale Quantum Gravity!

• Warped Extra Dimensions

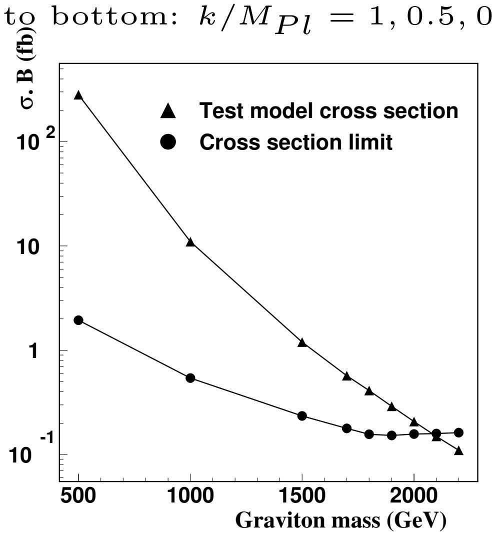
Narrow Graviton Resonances

$pp \to G_N \to e^+e^-$

Hewett & Rizzo



from top to bottom: $k/M_{Pl} = 1, 0.5, 0.1, 0.05, 0.01$



ATLAS, 100 fb^{-1}

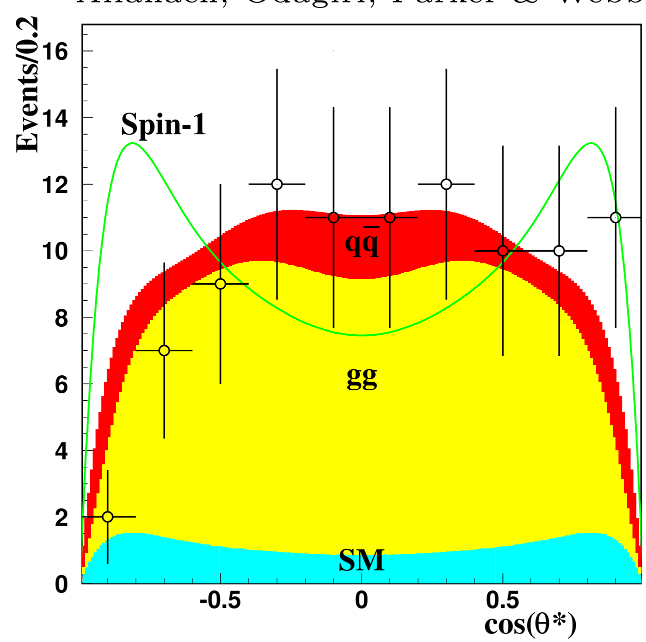
smallest detectable $\sigma \times Br$

Probe up to $M_{\tilde{g}} \sim 2100$ GeV

– to demonstrate that the resonance is a graviton and not another exotic object (spin-1 Z', ...)

$\Longrightarrow$ use angular distributions to determine the spin of the resonance

Allanach, Odagiri, Parker & Webber



construct a likelihood function to quantify angular distribution information

$\Longrightarrow$ spin can be determined with 90% CL for $M_G \sim 1700$ GeV (100 fb^{-1})

High Energy Linear Colliders

- High Luminosity LHC –
  - lots of new information on precise Higgs measurements.
  - some information on SUSY parameters.
  - explore our ideas of space and time.
  - uncover other new particles & interactions

However, a LC will add uniquely to this program.

- Higgs physics

- If kinematically accessible, LC can observe Higgs bosons independent of their decay patterns using the recoil mass method. $\sigma(e^+e^- \to Z\phi) \Longrightarrow g_{\phi ZZ}$

  This is the most powerful feature unique to the LC.

- W boson fusion: $\sigma(\phi\nu_e\bar{\nu}_e) \Longrightarrow g_{\phi WW}$ ratio $\frac{g_{\phi WW}}{g_{\phi ZZ}}$ tests SU(2) symmetry

- $\sigma(e^+e^- \to \phi t\bar{t}) \Longrightarrow g_{\phi t\bar{t}}$ direct measure of Yukawa coupling

- Higgs Decay Width: from cross sections + observed decay modes

$$\Gamma_H = \Gamma_W / Br(\phi \to WW)$$

• Accuracy on Branching Ratios $\delta Br/Br$

LC typical precision $\sim$ 2–10%

for $m_H \sim$ 110–150 GeV

LHC $\longrightarrow$ 10–50% in same mass range

10–20% if $m_H >$ 150 GeV

• Accuracy on couplings $\delta g/g$

LC typical precision $\rightarrow$ 1–5%

for $m_H \sim$ 110–150 GeV

LHC $\longrightarrow$ 15–25% in same mass range

5–10% if $m_H >$ 150 GeV

Super-LHC with 3000 fb^{-1} will improve precision by about a factor 2.

<u>Prec. Meas. of Br's & Γ's</u>

- distinguish MSSM/SM Higgs
- indir. evidence for m_A beyond kin. reach
- info on SUSY vertex corr. to bottom Yuk. coupl.

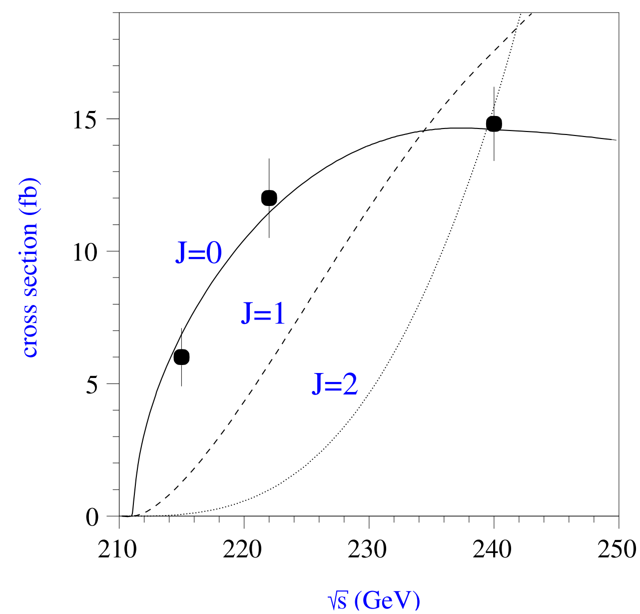
• Precision Measurement of Higgs Mass

$\delta m_h \sim$ 50 MeV (LHC: 100-150 MeV)

• Higgs quantum numbers: spin and parity

- threshold dependence of excitation curve
- angular distributions

$e^+e^- \rightarrow Z\phi; \quad e^+e^- \rightarrow f\bar{f}\phi$



One can determine unambiguously spin & parity of the particle produced.

⋆ Supersymmetry

(a) Measurements of SUSY particles masses

$\Longrightarrow$ sleptons, charginos, neutralinos
with an accuracy of 1% or less

If any visible SUSY particle produced,
$\longrightarrow \delta M_{\tilde{\chi}_1^0} \sim 1\% \Longrightarrow$ important for LHC meas.

(b) Measurement of SUSY parameters

- $\tilde{\chi}_i^{\pm}$, $\tilde{\chi}_i^0$ production & decay
  $\longrightarrow$ param. of mixing mass matrix to 1%
  $\longrightarrow$ determine composition in terms of SUSY partners of γ, Z, W, H
- slepton and squark mixing angles from cross sections with polarized beams

(c) Spin of SUSY particles:

Simplicity of production reactions allows spin determination from angular distributions

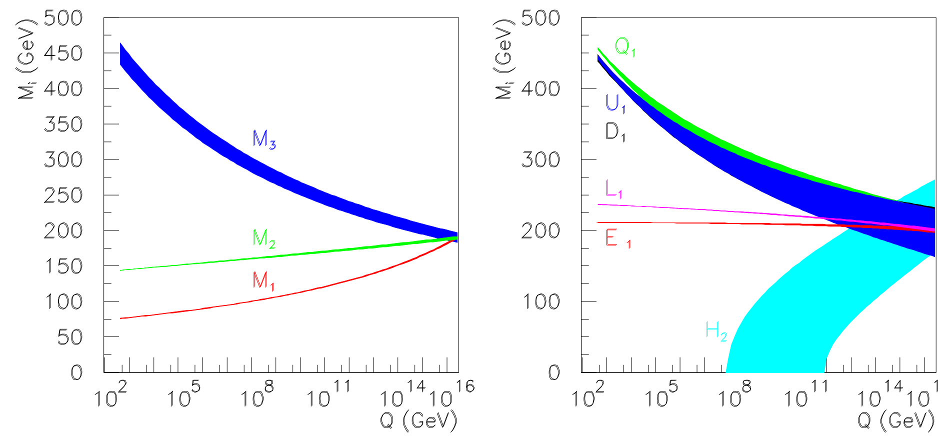
(d) Tests of SUSY $\longrightarrow$ coupling relations:

gauge coupling are equal to gaugino-fermion-sfermion couplings

(departures at loop level: non-decoupling effects provide a rare window to heavy sfermions)

Precise SUSY measurements at LC
+ LHC input on gluinos/squarks
$\Longrightarrow$ allow for precise extrapolation of SUSY parameters at high energies

Test type of SUSY theory at high energies.



Porod, Blair, Zerwas

Linear Collider and the Cosmos

– Weak-interacting particles with weak-scale masses naturally provide $\Omega_{\rm DM}$.

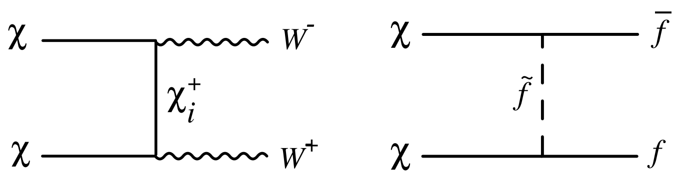
$\Rightarrow$ A coincidence or DM provides fundamental motivation for new particles at EW scale.

$\star$ Understanding what DM is made of demands Collider & Astrophysical/Cosmological input.

• If the LSP is found to be a stable neutralino

$\rightarrow$ accurate meas. of $\tilde{\chi}^0_1$ mass & composition

$\Longrightarrow$ Comput. of $\tilde{\chi}^0_1 \tilde{\chi}^0_1$ annih. cross section



$\Longrightarrow$ determined thermal relic density assuming SM evolution of the universe

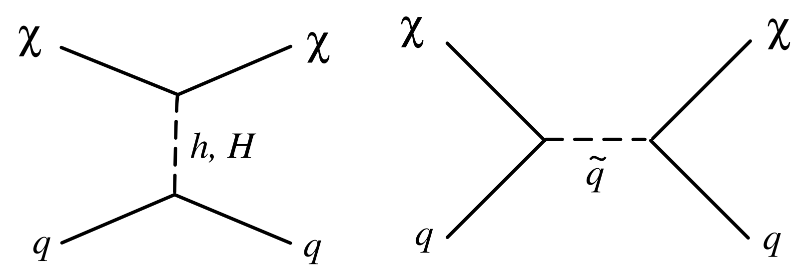
• comparing this result with $\Omega_{\rm DM}$ from Astrophysical/Cosmological input

$\Longrightarrow$ new insights into history of our universe

– Dark Matter Detection:

• Direct: depends on $\tilde{\chi}^0_1\, N$ scattering

$\longrightarrow$ input from both collider and conventional DM experiments



• Indirect: through annih. decay products ($\tilde{\chi}^0_1\, \tilde{\chi}^0_1 \rightarrow \gamma$'s in galactic center, e^+'s in halo, anti-protons, ν's in centers of Earth & Sun)

$\Longrightarrow$ $\tilde{\chi}^0_1\, N$ scattering not necessarily in one-to-one correspondence with DM detection rates

$\Longrightarrow$ LC will provide important info about DM halo densities and velocity distributions.

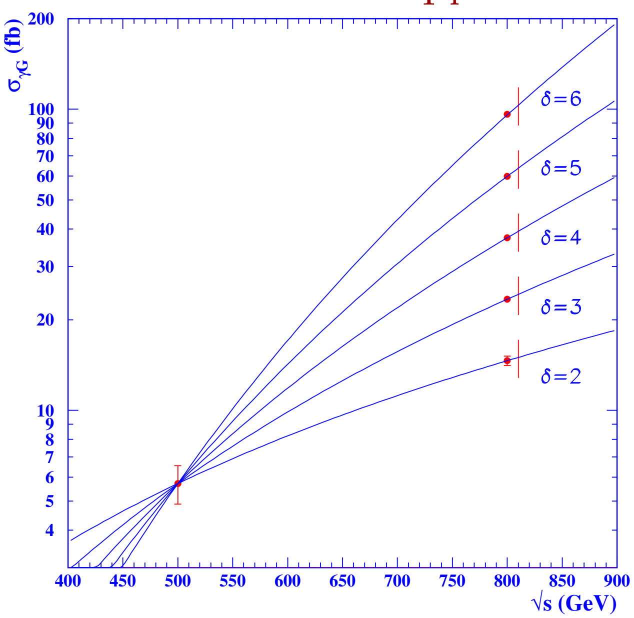
Extra Dimensions

Flat ED:

graviton emission: $e^+e^- \to \gamma\, G_N$

• if signal observed, reach on $M_{\rm Pl}^{\rm fund}$ comparable to LHC if beams partially polarized

• varying $\sqrt{s}$ one can determine values of fundamental parameters: $M_{\rm Pl}^{\rm fund}$ & δ



graviton exchange in $2 \to 2$ processes:

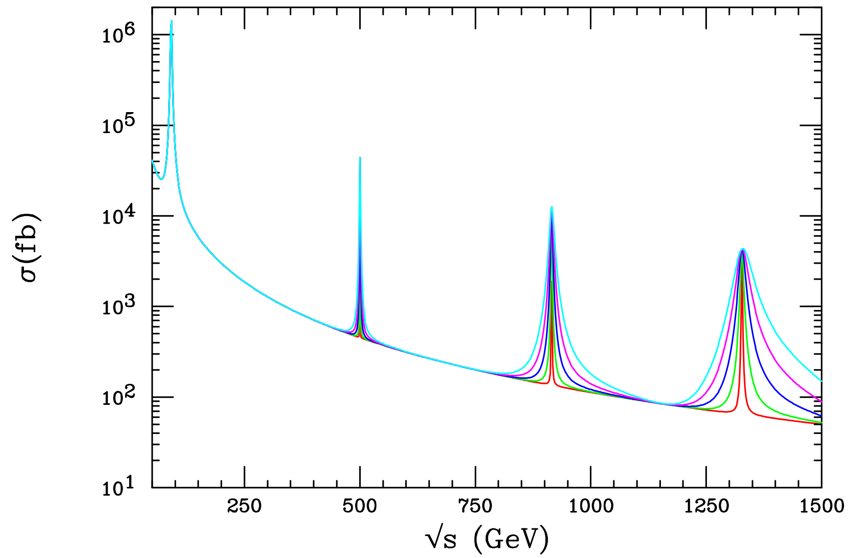
• deviations for $e^+e^- \to f\bar{f}$ or

new decays with hh or $\gamma\gamma$

• ability to determine spin-2 nature

Warped ED:

• Given sufficient center-of-mass energy, KK graviton states produced as resonances:



$\sigma(e^+e^- \to \mu^+\mu^-)$ as a function of $\sqrt{s}$, including KK graviton exchange, $m_1 = 500$ GeV, $k/M_{Pl} = 0.01$–0.05 range.

Energy Frontier – Outlook

By the End of This Decade

- **Tevatron**
  - will have measured M_t, M_W to unprecedented accuracy
    $\longrightarrow$ indirect constraints on $M_{H_{\rm SM}}$
  - If Nature is kind, discovery of new particles.
- **LHC**
  - If Higgs & SUSY are there, we will find out.
  - If Nature is kind, we will know exactly which type of SUSY is there.

Over the Next Decade

- **LHC**
  - A *sure* window to new physics:
    ⋆ Higgs ⋆ SUSY ⋆ New Dimensions ⋆ New Particles & Interactions
  - A SLHC would broaden the scope of physics.
- **LC**
  - unique capabilities which complement LHC physics
  - unique connection with Cosmology

To make FERMILAB a premier LHC Lab, we must pursue several courses:

⋆ Accelerator R&D ⋆ Detector R&D ⋆ Advanced Computing Projects

⋆ CMS Physics Analysis Center ⋆ LHC Theory Center

Synergy between theory and experiment can give us the extra edge –

(LHC Open Session Sep. 4, 2003)

By the end of this decade, Tevatron and LHC will put us in a position to make a successful push for the LC $\Longrightarrow$ We need to be ready.

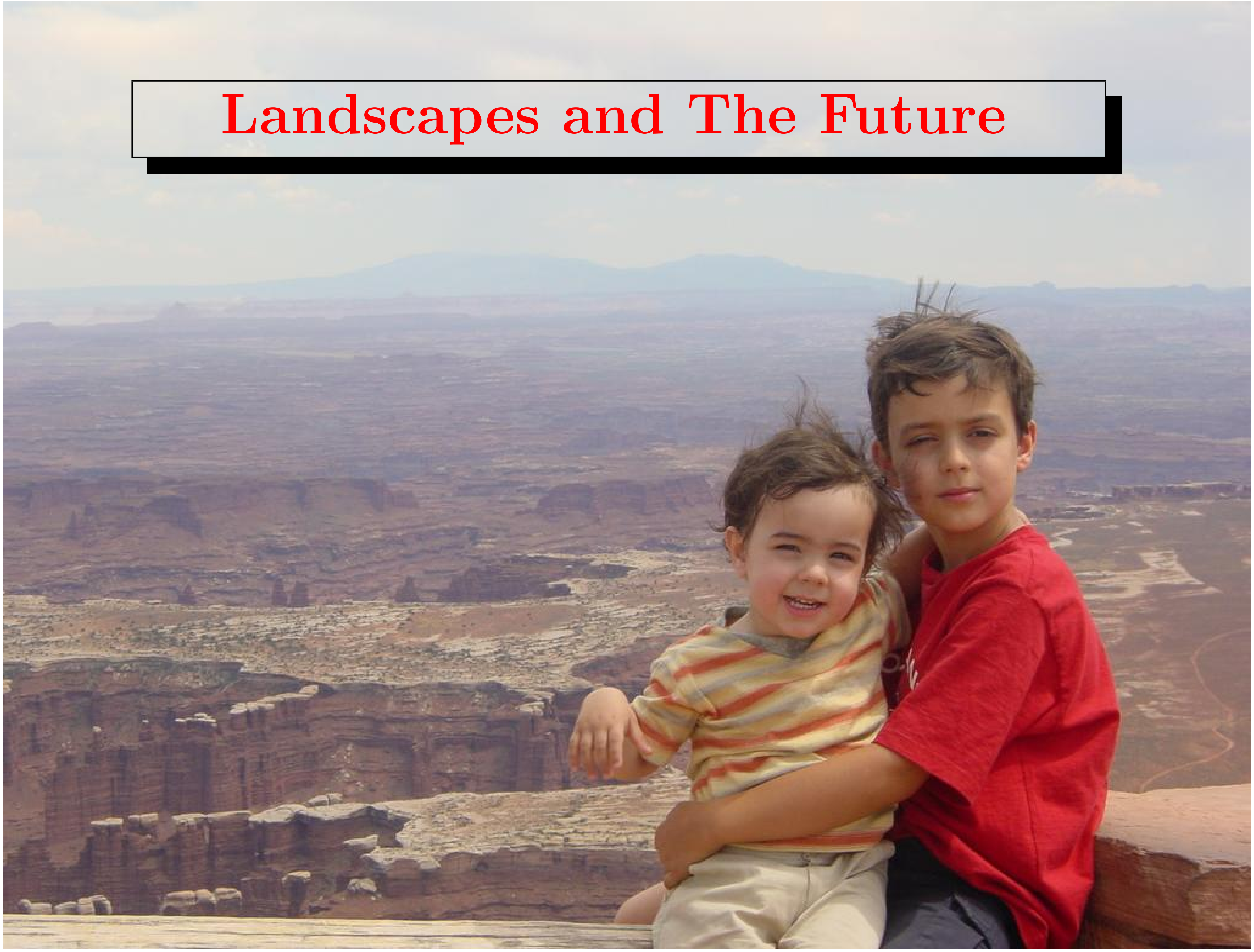
Fermilab must take a proactive role in this process!

In the Next Decade –

Great Challenges $\Longleftrightarrow$ *Great Discoveries*

$\Longrightarrow$ **Shed light on most of the fundamental open questions of Physics and Cosmology!**

Landscapes and The Future



extras

More on Top Physics (explore hints for NP)

• top electroweak and strong interactions

– accurate measurement of $\sigma_{t\bar{t}}$ (10 %)

$\Longrightarrow$ precision test of SM QCD; or if $\sigma_{t\bar{t}} > \sigma_{t\bar{t}}^{SM}$ $\Longrightarrow$ non-SM prod. mechanism

Search for $t\bar{t}$ resonances in the invariant mass ($M_{t\bar{t}}$) spectrum:

$\rightarrow$ resonant topcolor Z', multiscale technicolor...

– measurement of CKM matrix element $|V_{tb}|$ (10 %):

best via measurement of $\Gamma(t \rightarrow bW)$ in single top production

• test SM production mechanisms and decays or find hints for new physics

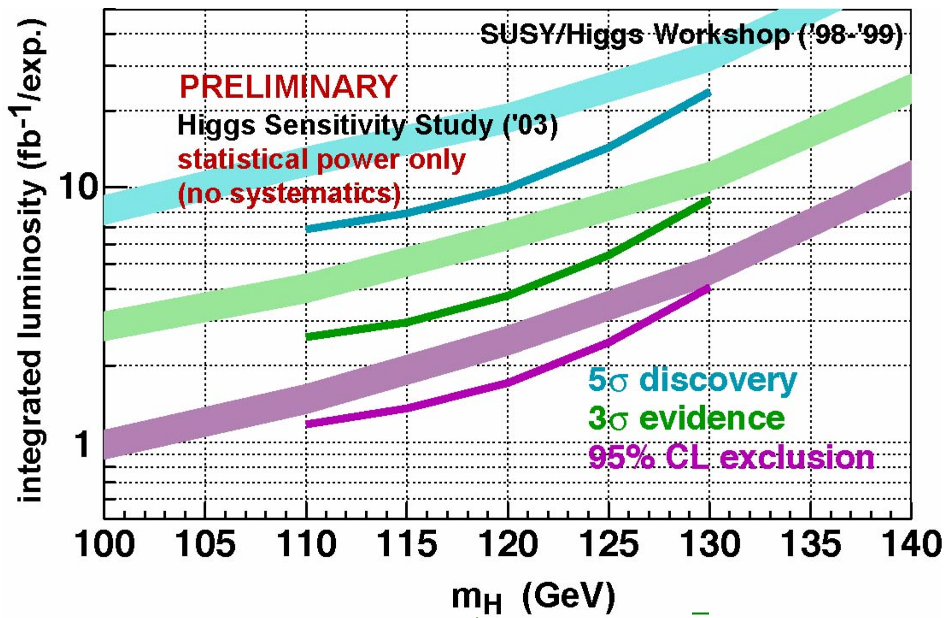
– probe EW top couplings via W polarization in top decays

– search for anomalously large rare top decays: $t \rightarrow c\gamma, \ldots$
and non-SM decays: $t \rightarrow H^{\pm}b$, $t \rightarrow \tilde{t}\tilde{\chi}$ ...

Tevatron Higgs Searches

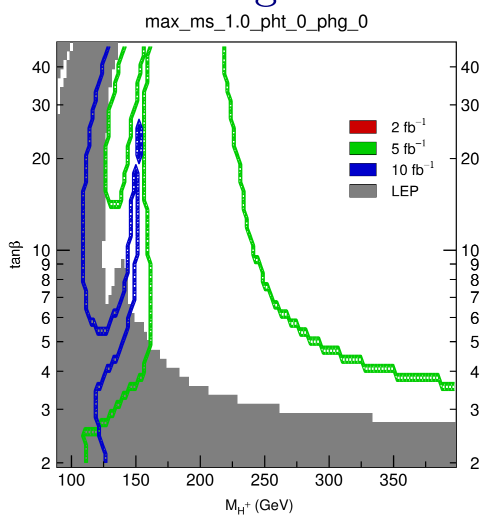
⋆ recent results from CDF+DØ

Higgs Sensitivity Studies:

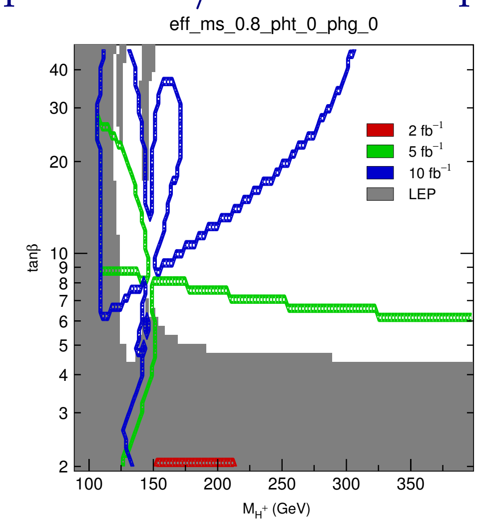


What regions of MSSM parameter space can be excluded? $p\bar{p} \to Vh/VH \to Vb\bar{b}$:

max. mixing scenario:



suppressed $h/H \to b\bar{b}$ couplings:



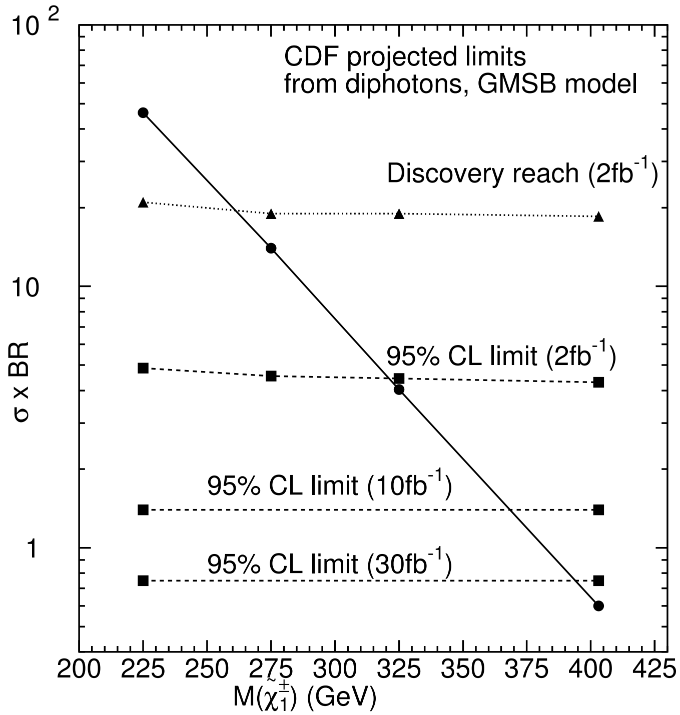
M.C., Mrenna, Wagner

Gauge-Mediated Tevatron Reach

- Bino-like NLSP: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

  Signal: $\gamma\gamma X \not\!\!E_T$

  $X = \ell$'s and/or jets



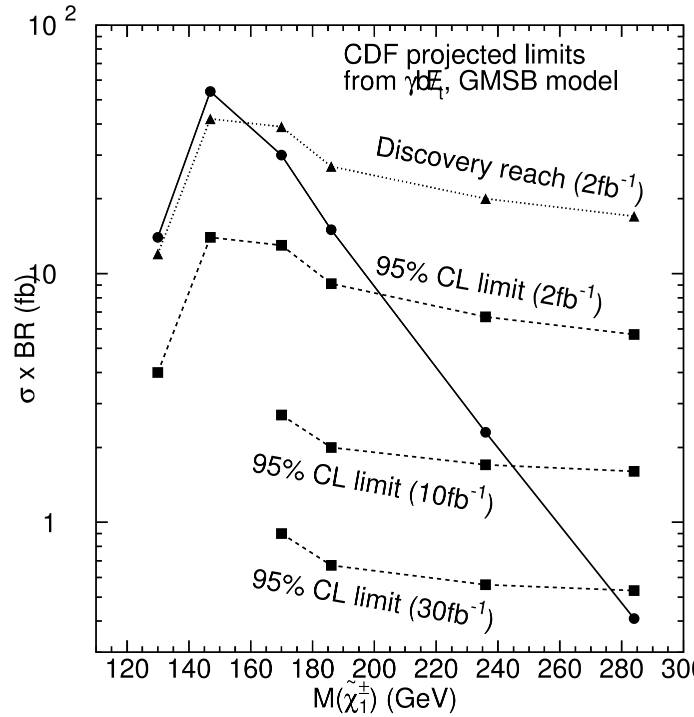
$M_{\tilde{\chi}^\pm} \sim 325$ GeV *(exclusion)* &

~ 260 GeV *(discovery)*

- Higgsino-like NLSP: $\tilde{\chi}_1^0 \rightarrow (h, Z, \gamma)\tilde{G}$

  Signal: γ b $\not\!\!E_T X$

  diboson signatures $(Z \rightarrow \ell\ell/\text{jj};\ h \rightarrow b\bar{b})\not\!\!E_T$



$M_{\tilde{\chi}_1^\pm}$ sensitivity ~ 200 GeV for 2 fb^{-1}

Tevatron Searches for KK Gravitons

Flat ED

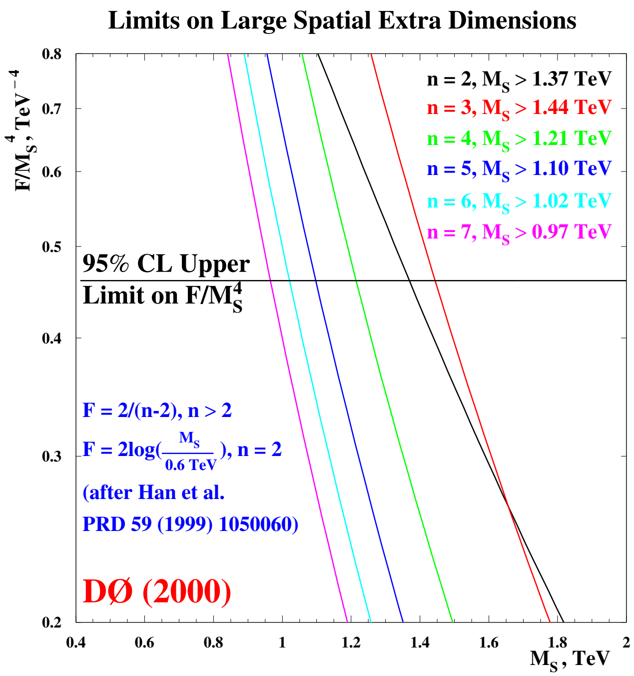
⋆ direct: $p\bar{p} \longrightarrow$ jets $+\not{E}_T$

$n = 2 \quad M_{\rm Pl}^{\rm fund} > 1.5$ TeV

$n = 6 \quad > 0.8$ TeV

at 95% CL

⋆ Drell-Yan and di-photons

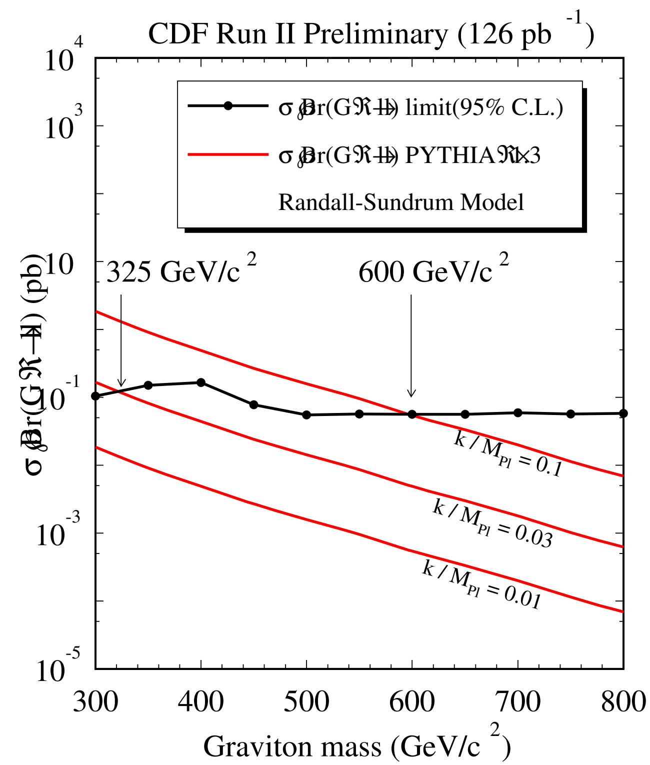


Run 2:

$M_{\rm Pl}^{\rm fund}$ sensitivity ≈ 1.3–2.5 TeV

Warped ED

⋆ $p\bar{p} \longrightarrow \ell^+\ell^- \qquad \ell = e$ and μ



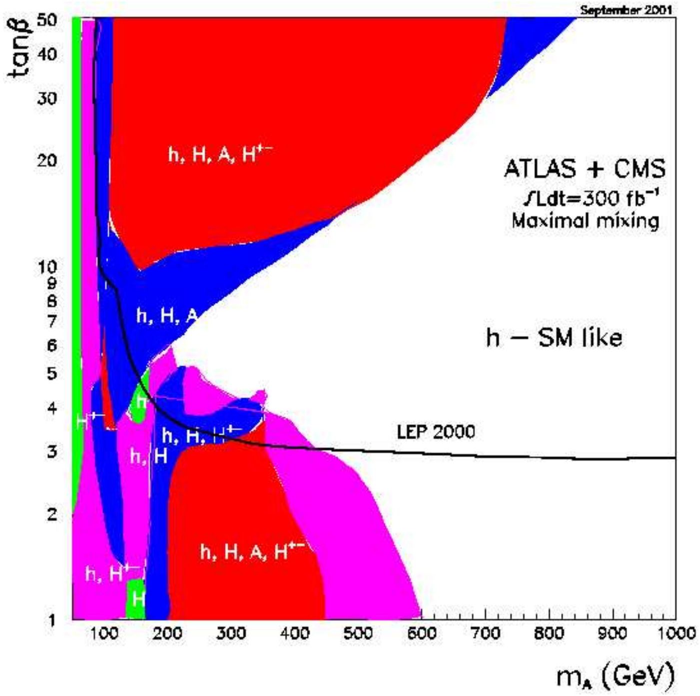
$\longrightarrow$ with 2 fb^{-1},
expected reach is in the few TeV range

SUSY after a high luminosity run

– MSSM Higgs:

access to many additional channels

$\longrightarrow$ better coverage of H, A, $H^{\pm}$, h



• still some regions where only h is visible

• some prospects to cover part of this region

if $H, A \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$;   use $\tilde{\chi}_2^0 \to \ell^+ \ell^- \tilde{\chi}_1^0$

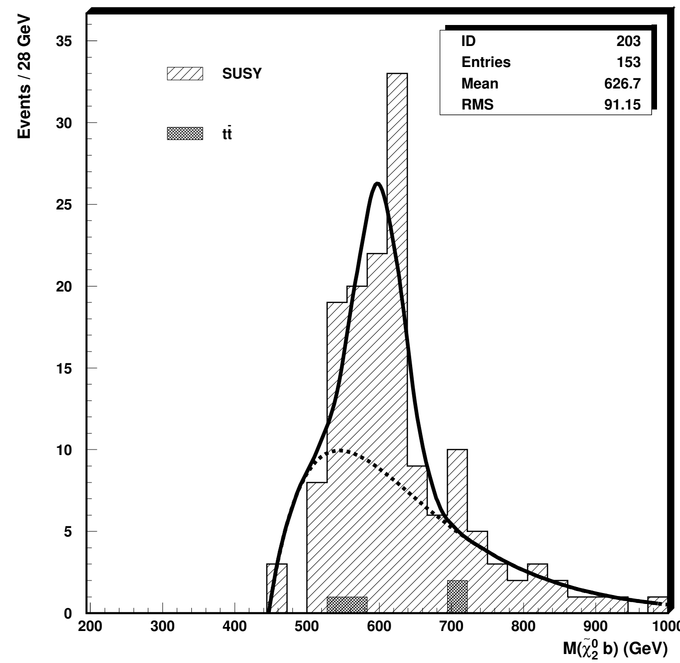
• $\tan\beta$ determination to precision 5–15%

from $H/A \to \mu^+\mu^-/\tau^+\tau^-$

LHC will have a great shot at Higgs Physics.

In some cases, one can reconstruct decay chains.

ex: $\tilde{g} \to \tilde{b} b$; $\tilde{b} \to b \tilde{\chi}_2^0$; $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\pm} \ell^{\mp}$; $\tilde{\ell}^{\pm} \to \ell^{\pm} \tilde{\chi}_1^0$;



Directly measure $M_{\tilde{b}}$ and $M_{\tilde{g}}$ to 10%

High $\tan\beta$ demands high luminosity.

If SUSY is there, depending on the signal, info about mass patterns will enable us to constrain models of SUSY breaking

SUSY after a high luminosity run

- estimation of SUSY mass scale, $M_{\rm SUSY}$, from the jets+$\not\!\!E_T$ signal

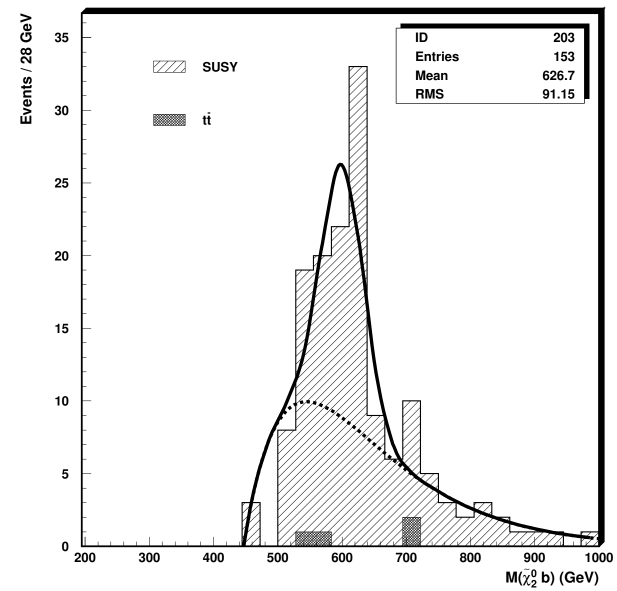
- $M_{\rm SUSY}^{\rm eff} = (M_{\rm SUSY} - M_{\tilde{\chi}}^2/M_{\rm SUSY})$ takes into account a heavy LSP – reduces the number and p_T of observed jets

- a precision of 10 (30)% can be obtained on $M_{\rm SUSY}^{\rm eff}$ after 100 fb^{-1}

– use correlation between $M_{\rm SUSY}^{\rm eff}$ and $\sigma_{\rm SUSY}$ to discriminate different models

In some cases, can reconstruct decay chains.

ex: $\tilde{g} \to \tilde{b} b$; $\tilde{b} \to b\tilde{\chi}_2^0$; $\tilde{\chi}_2^0 \to \tilde{\ell}_R^\pm \ell^\mp$; $\tilde{\ell}^\pm \to \ell^\pm \tilde{\chi}_1^0$;



Directly measure $M_{\tilde{b}}$ and $M_{\tilde{g}}$ to 10%

High $\tan\beta$ requires high luminosity.

If SUSY is there, depending on the signal, info about mass patterns will enable us to constrain models of SUSY breaking

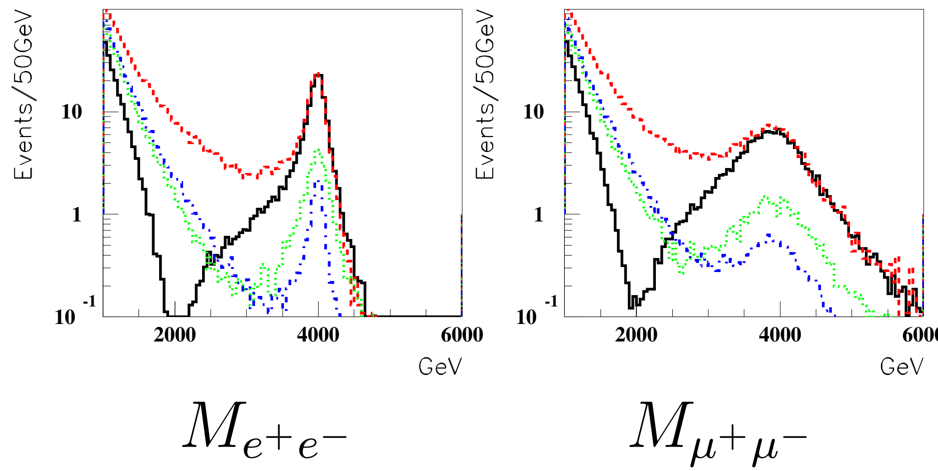
KK Excitations of Gauge Bosons

γ/Z excitations in TeV scale extra dimensions –

- detect peak in $\ell^+\ell^-$ invariant mass for $M_{\rm Pl}^{\rm fund} < 5.8$ TeV (100 fb^{-1})

no peak $\Longrightarrow M_{\rm Pl}^{\rm fund} > 12$ TeV (300 fb^{-1})

study lepton angular distributions $\Longrightarrow$ distinguish KK excitations & alternatives



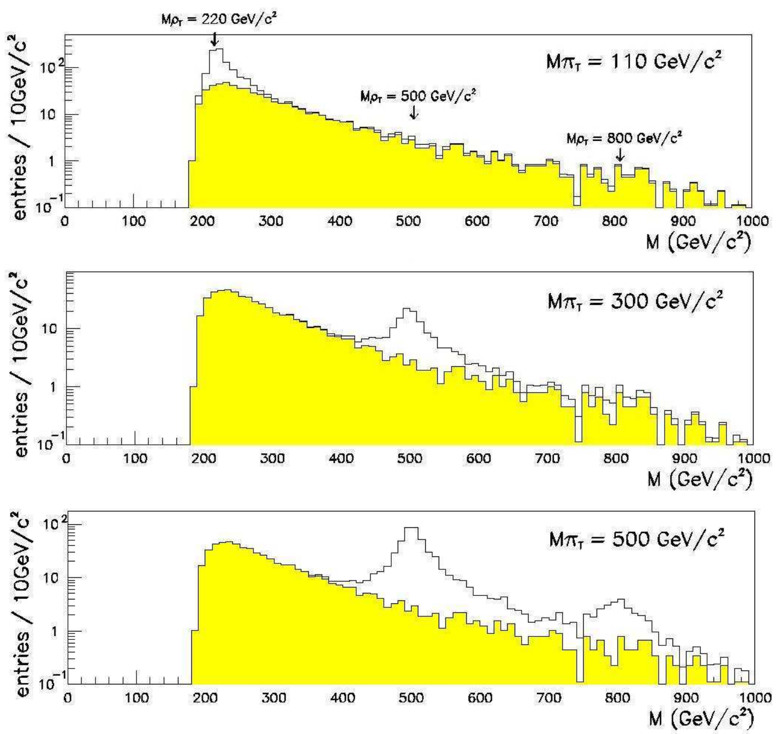
Strong Dynamics

- Technicolor-type models

$\Rightarrow$ detect ρ_T up to the TeV range

best channel:

$$\rho_T^{\pm} \rightarrow W^{\pm} Z \rightarrow \ell^{\pm} \nu \ell^{+} \ell^{-}$$



ATLAS, 30 fb^{-1}

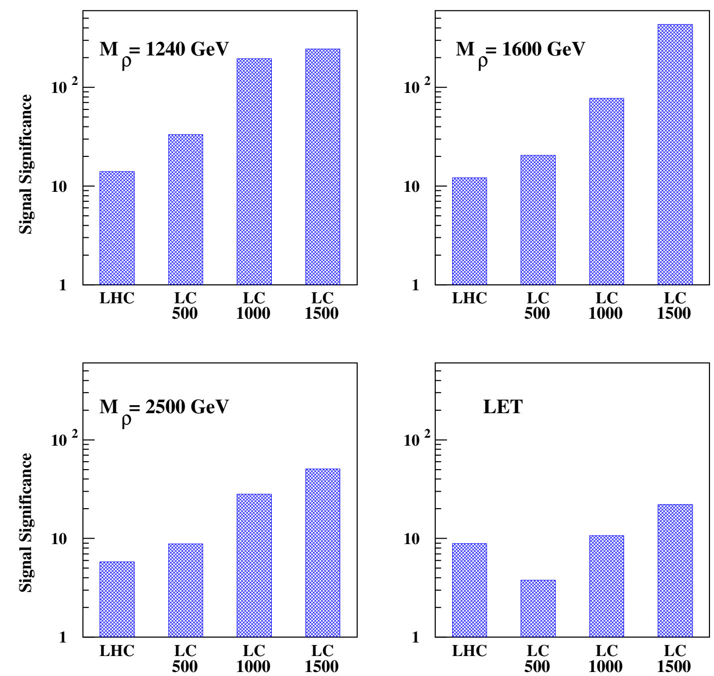
- Strongly Coupled Vector Boson Scattering

(strongly coupled resonances)

- LC $\longrightarrow e^+e^- \rightarrow \nu\bar{\nu}W^+W^-/ZZ$

  LHC, 300 fb^{-1}: bump in W^+W^- scattering

  (LET $\rightarrow$ enhancement in σ_{SM})



Latest ATLAS study shows sensitivity to longitudinal gauge vector boson scattering only for SLHC luminosities ($\sim$ 3000 fb^{-1})

⋆ SM Fields in the Bulk

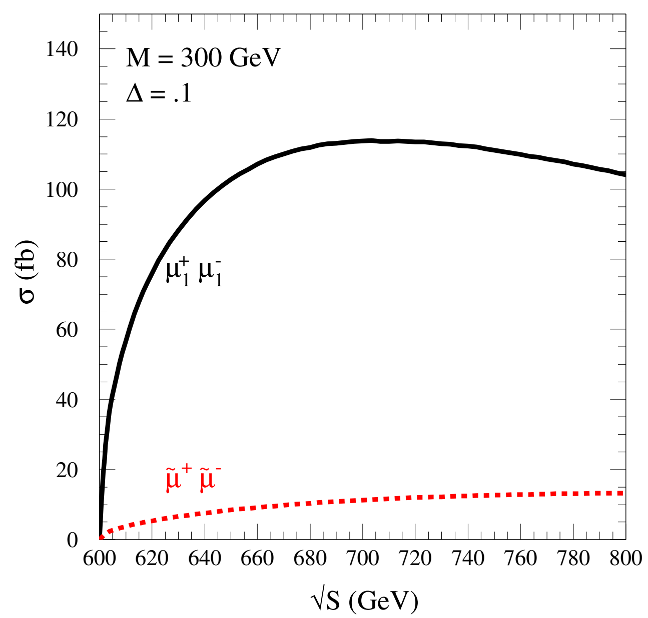
- Universal Extra Dimensions (UED)

Important property: Spectrum of 1st KK excitations can mimic a SUSY spectrum, though particles have different spin

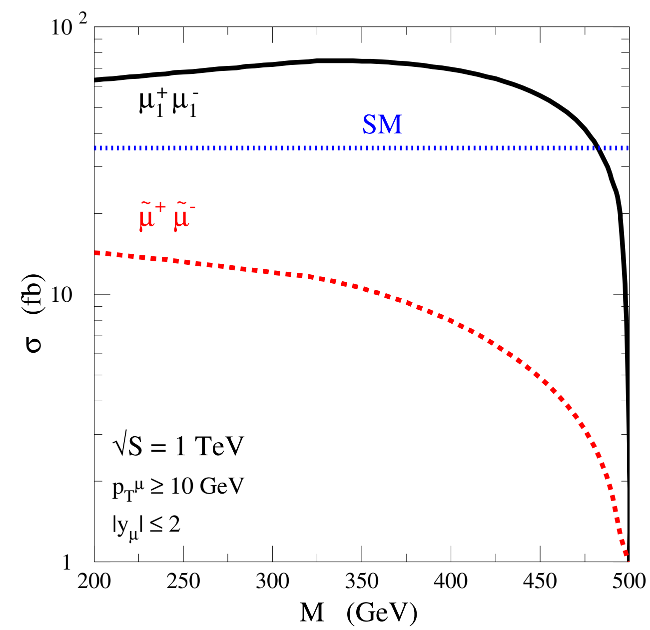
LC has the unique opportunity of distinguishing SUSY from UED: examine p- versus s-wave production

Comparison of cross section production for smuon pairs Vs first KK mode muon pairs.

(Tait et al. in prep.)



$e^+e^- \to \mu_1^+\mu_1^-(\tilde{\mu}^+\tilde{\mu}^-)$ as a function of $\sqrt{s}$, for $M = 300$ GeV.



$e^+e^- \to \mu_1^+\mu_1^-(\tilde{\mu}^+\tilde{\mu}^-)$, as a function of M, at a 1 TeV LC

Top Seesaw Model

• Extended SM fermion content: a vector pair of quarks, $\chi_{L,R}$ with the same quantum numbers as t_R

• The dynamics of the model yields mixing between the right & left-handed top & heavy quark components. $\Longrightarrow$ the left mixing has a direct influence on the interaction of the physical top with the weak bosons:

• Modification of left-handed top coupling

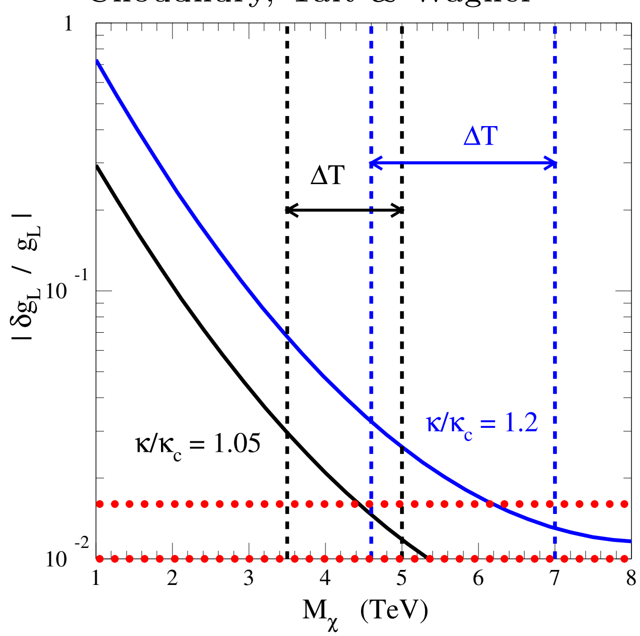
with $s_L \simeq \mu_{t\chi}/m_{\chi\chi}$

$$\frac{\delta g_L}{g_L} = \frac{s_L^2}{1 - 4\sin^2\theta_W/3}.$$

$m_{\chi\chi} \longrightarrow$ heavy quark mass constrained by EW data $\longrightarrow$ 3.8–7 TeV

$\mu_{t\chi} \sim 700$ GeV to reproduce physical m_t

Choudhury, Tait & Wagner



• A LC can test the Top Seesaw model via accurate determination of top-vector boson couplings at the level of 1.5%.

• It can also measure directly the heavy Higgs associated to this model and hence determine a range of acceptable χ masses.