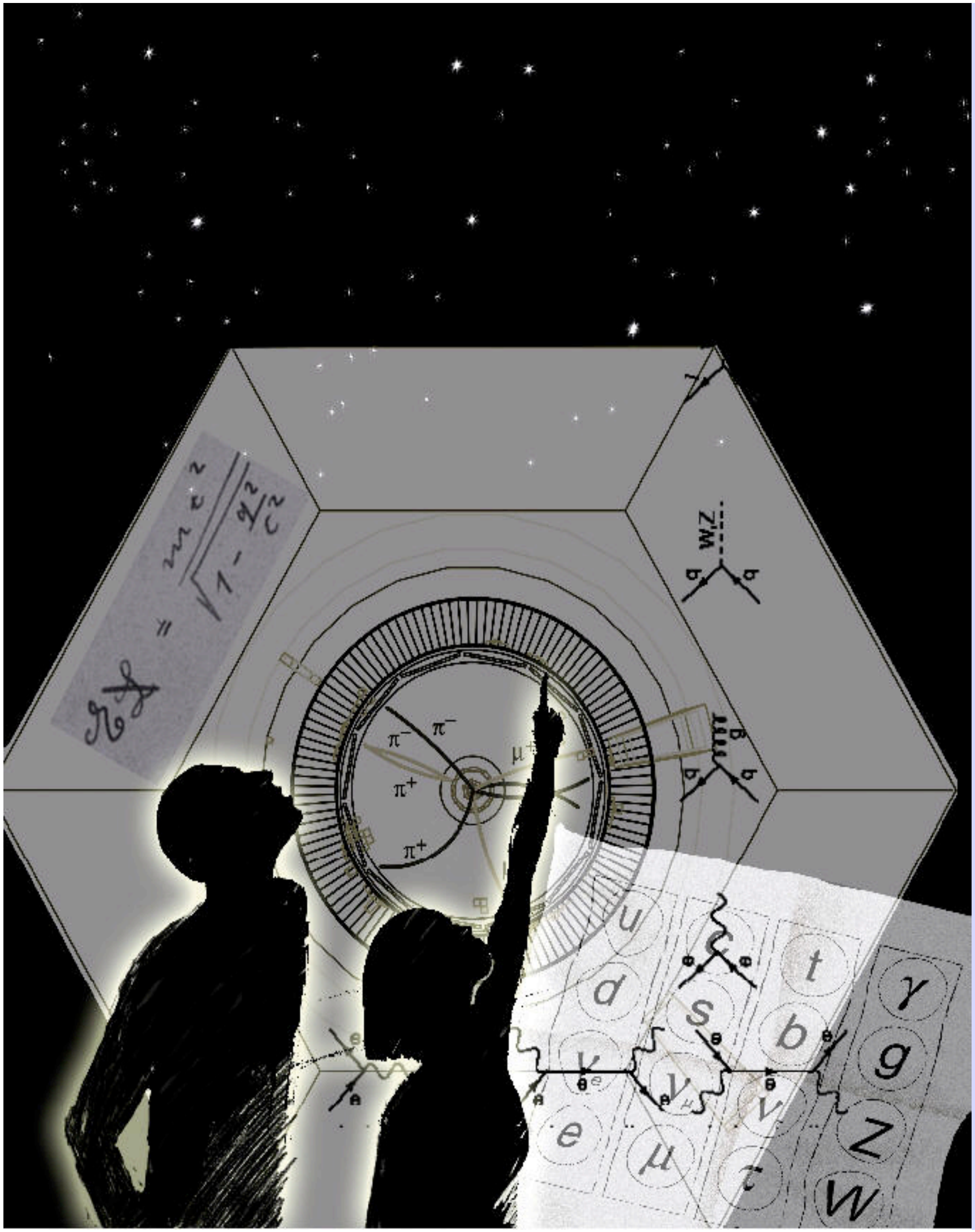
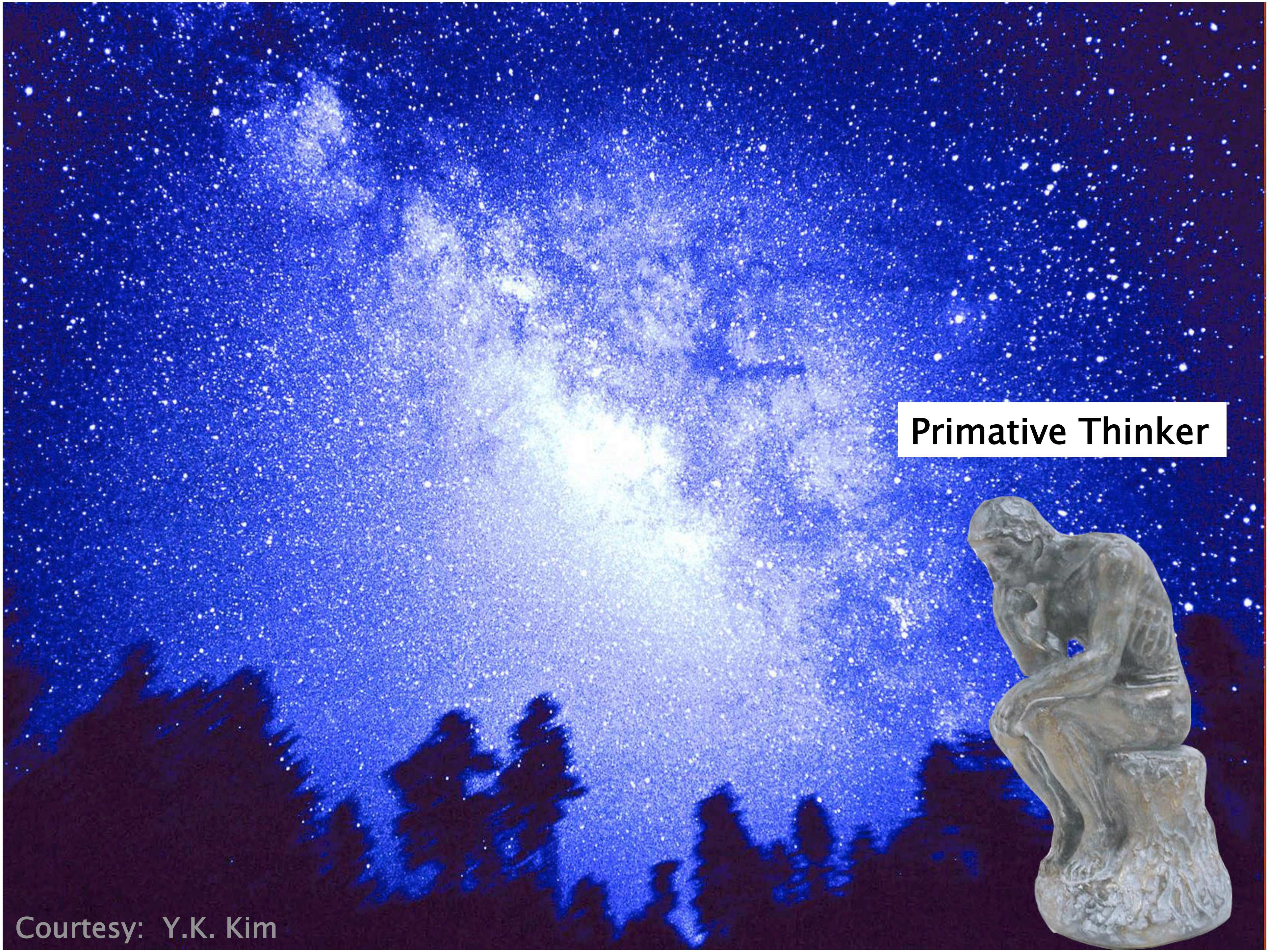


Discovering the Quantum Universe

The Role of Particle Accelerators

J. Hewett

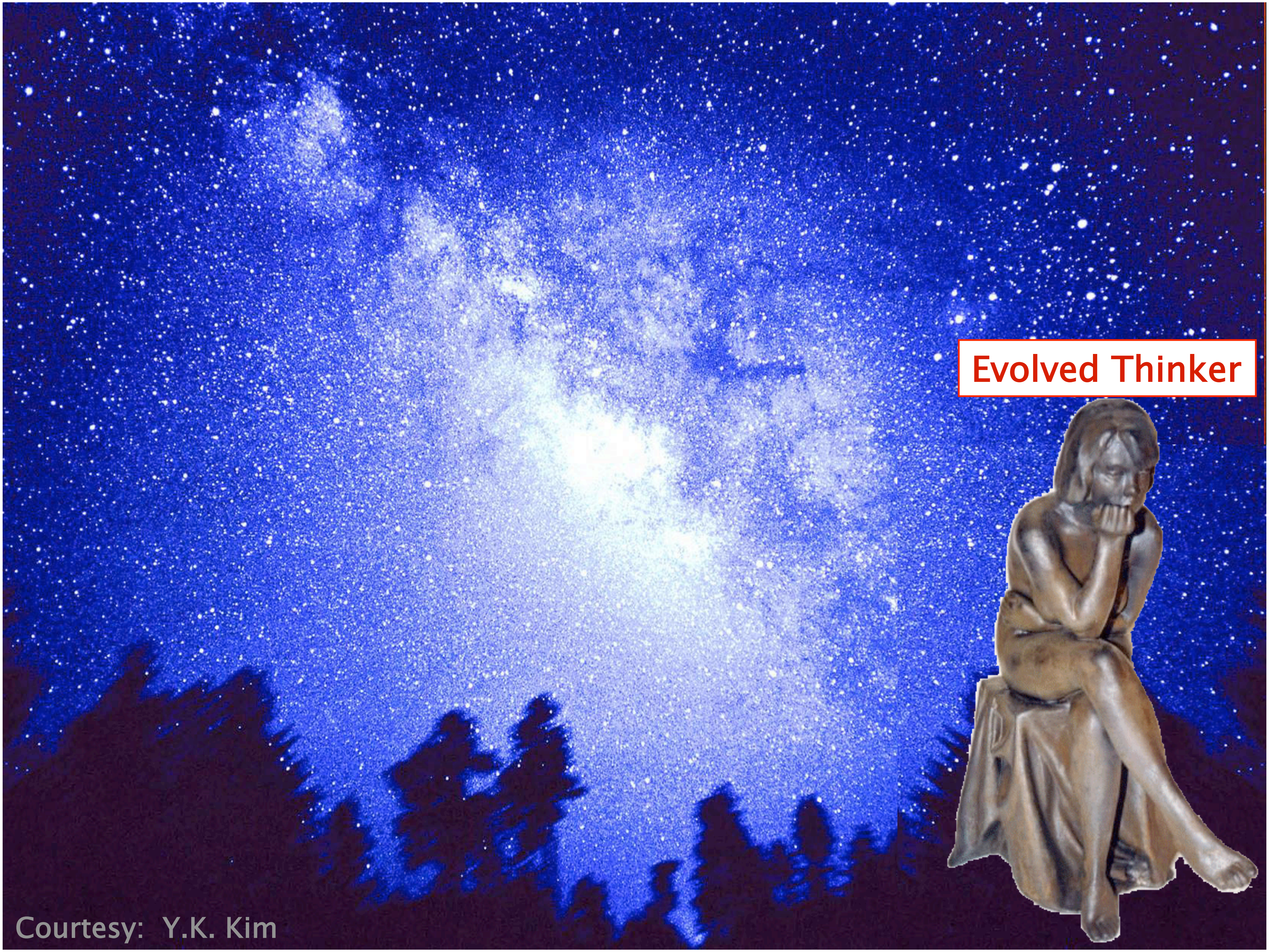


Primative Thinker

Courtesy: Y.K. Kim

What is the world made of?
What holds the world together?
Where did we come from?

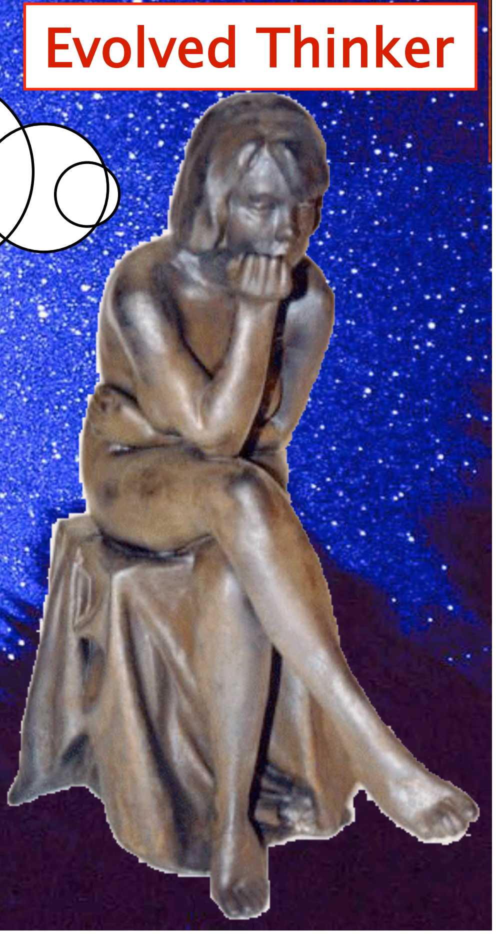
Courtesy: Y.K. Kim



Courtesy: Y.K. Kim

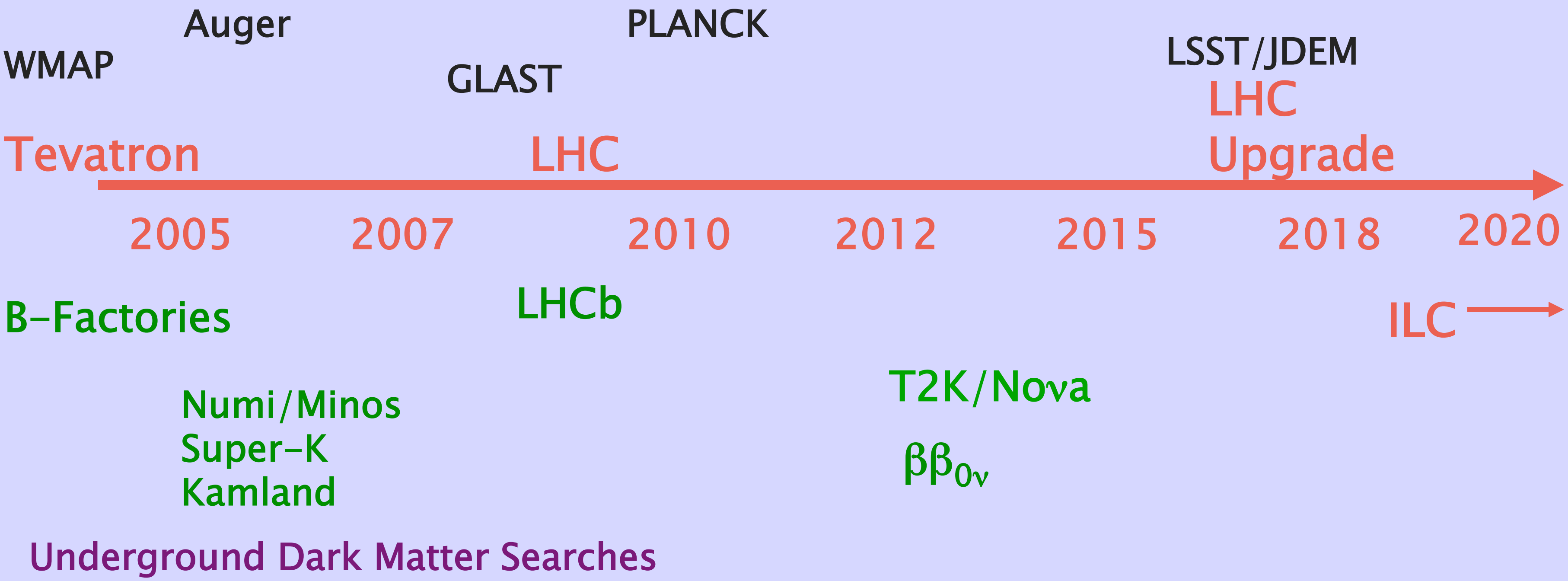
1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter?
   How can we make it in the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

From 'Quantum Universe'



Courtesy: Y.K. Kim

Science Timeline: The Tools



WMAP

Auger

GLAST

PLANCK

LSST/JDEM

Tevatron

LHC

LHC Upgrade

2005 2007 2010 2012 2015 2018 2020

B-Factories

LHCb

ILC →

Numi/Minos
Super-K
Kamland

T2K/Nova

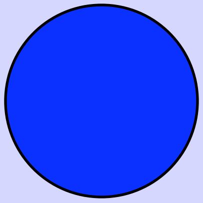
$\beta\beta_{0\nu}$

Underground Dark Matter Searches

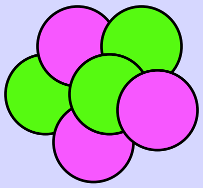
Accelerators are Powerful Microscopes.

They make high energy particle beams
that allow us to see small things

E ~ 1/x



seen by
low energy beam
(poorer
resolution)



seen by
high energy beam
(better resolution)

Accelerators are Time Machines.

They make particles last seen
in the earliest moments of the universe

particle beam

energy

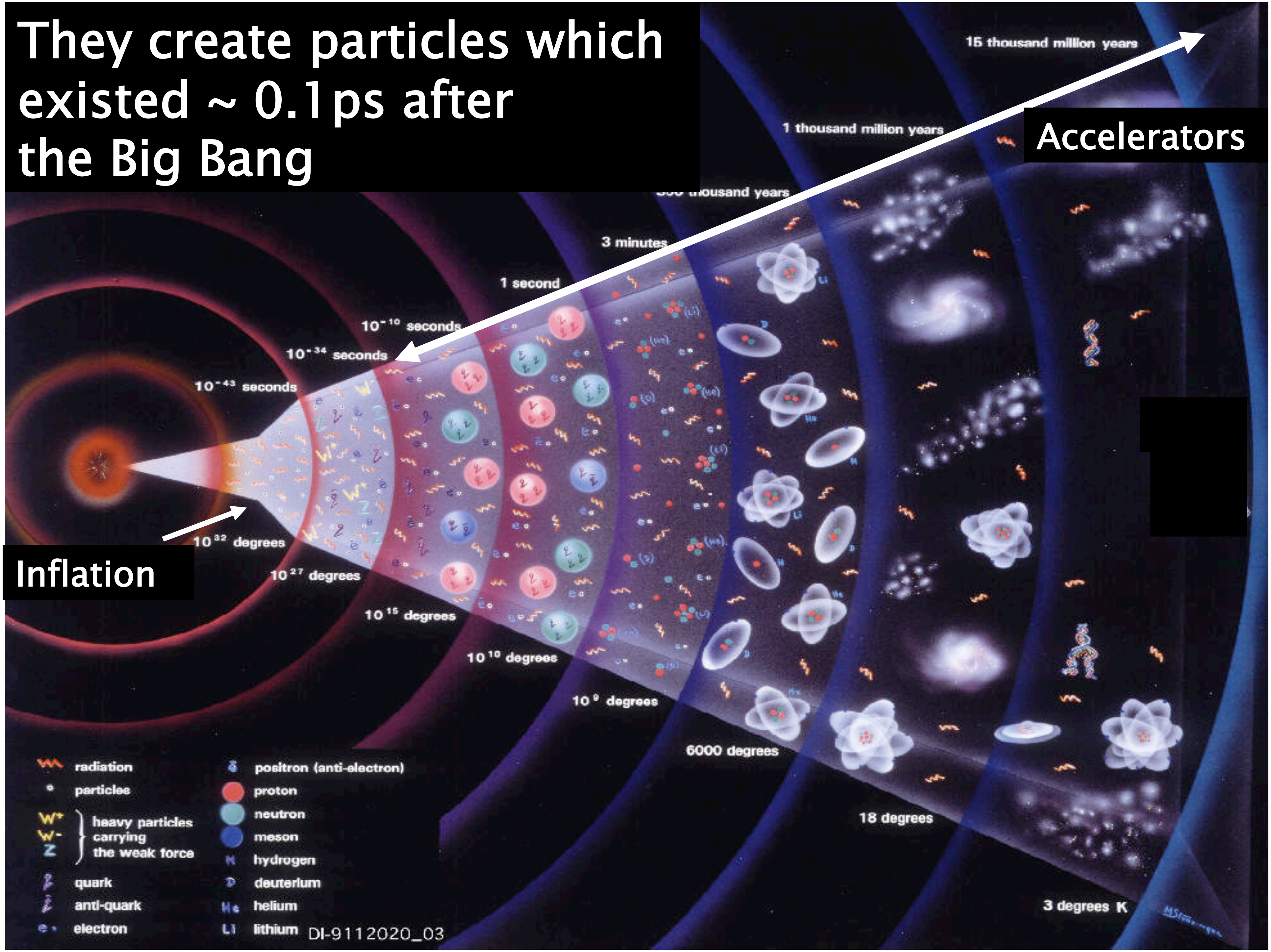
Energy

anti-particle beam

energy

Particle and anti-particle annihilate

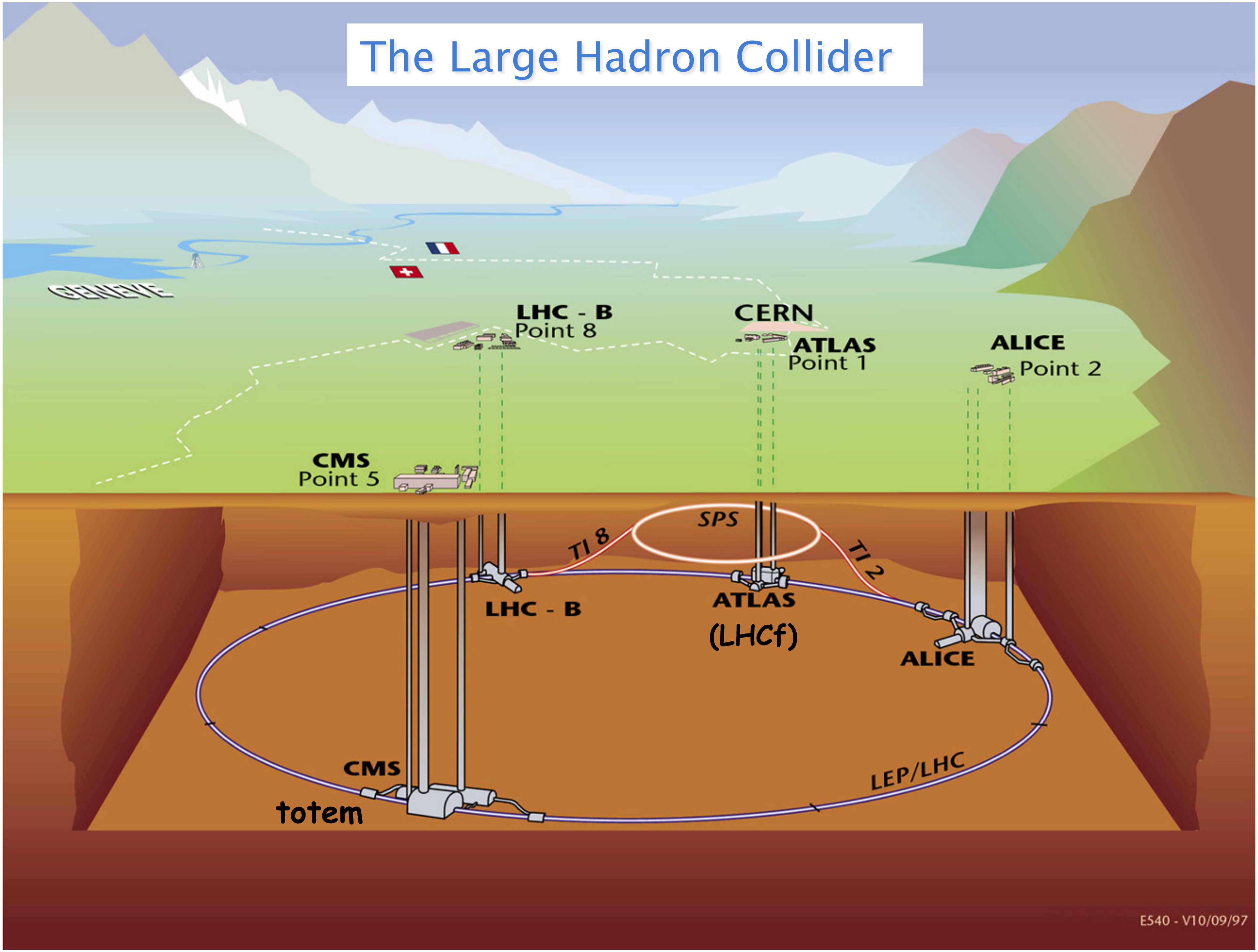
They create particles which existed ~ 0.1ps after the Big Bang



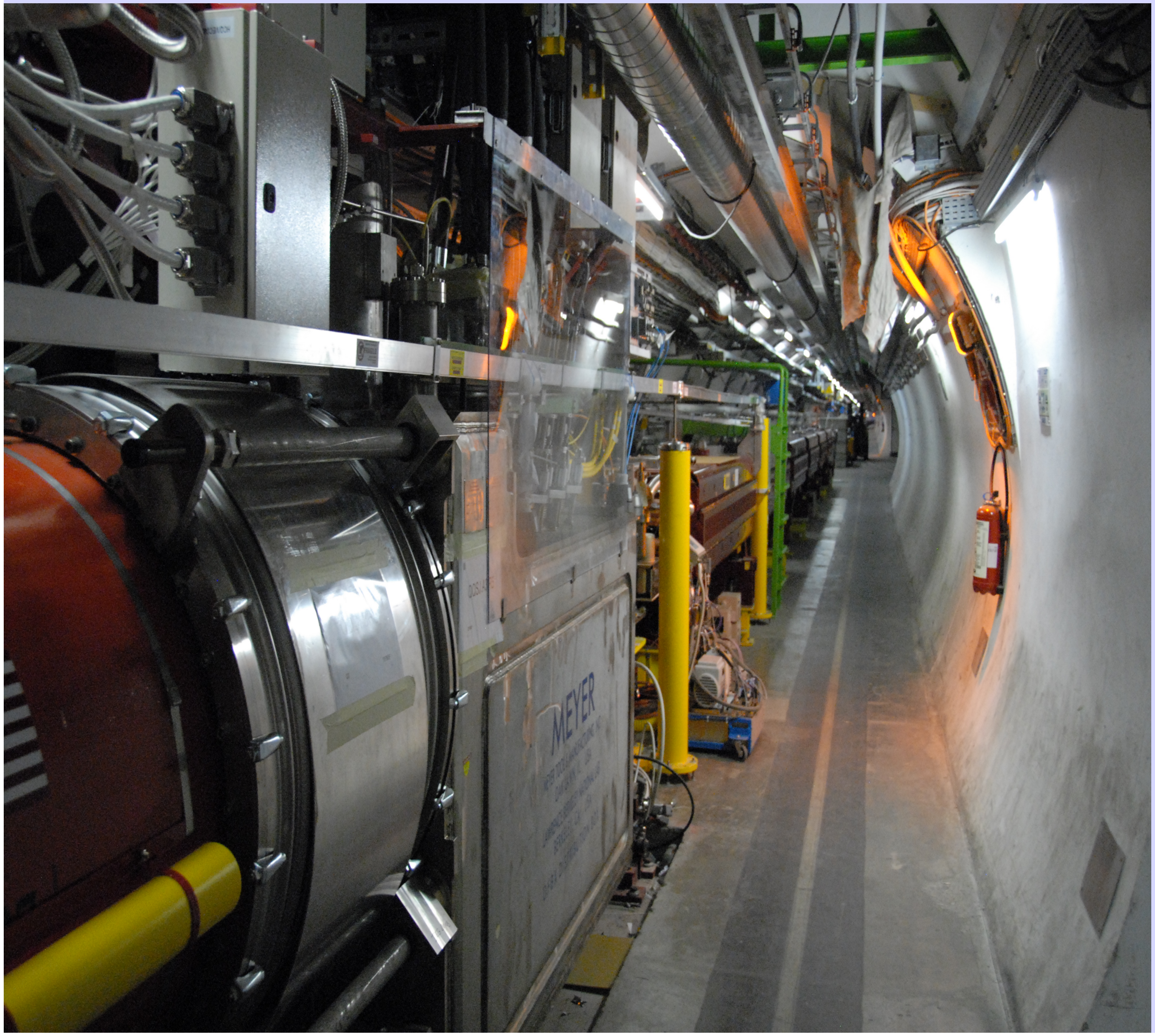
[redacted]

The Large Hadron Collider: CERN, Geneva, Switzerland

The Large Hadron Collider



The LHC is turning on!



The anticipation has fueled many ideas

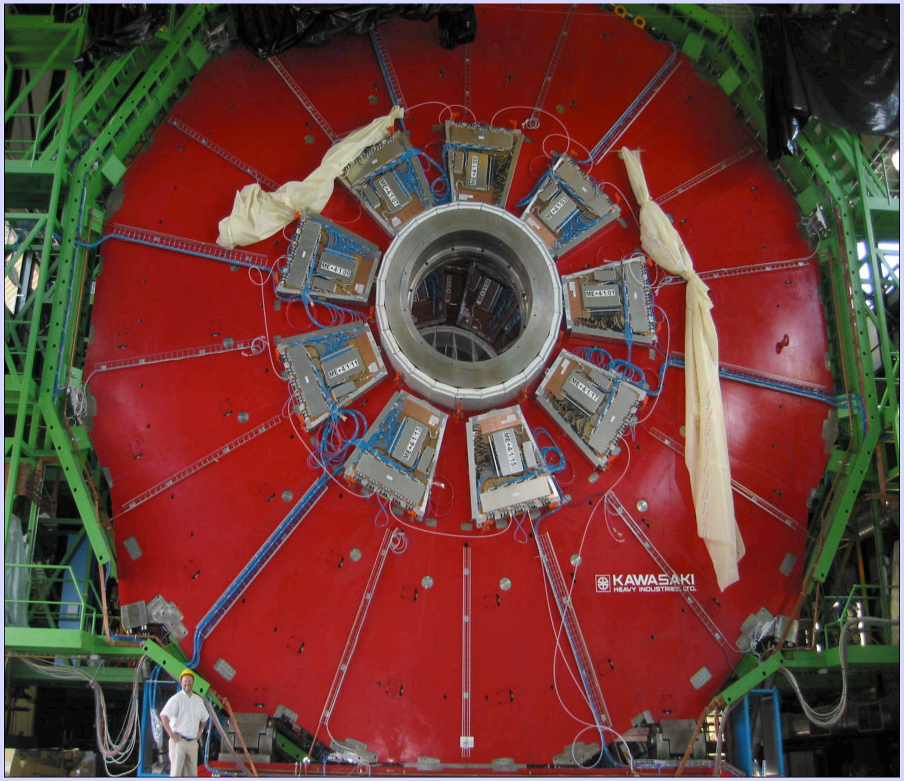
November 2007

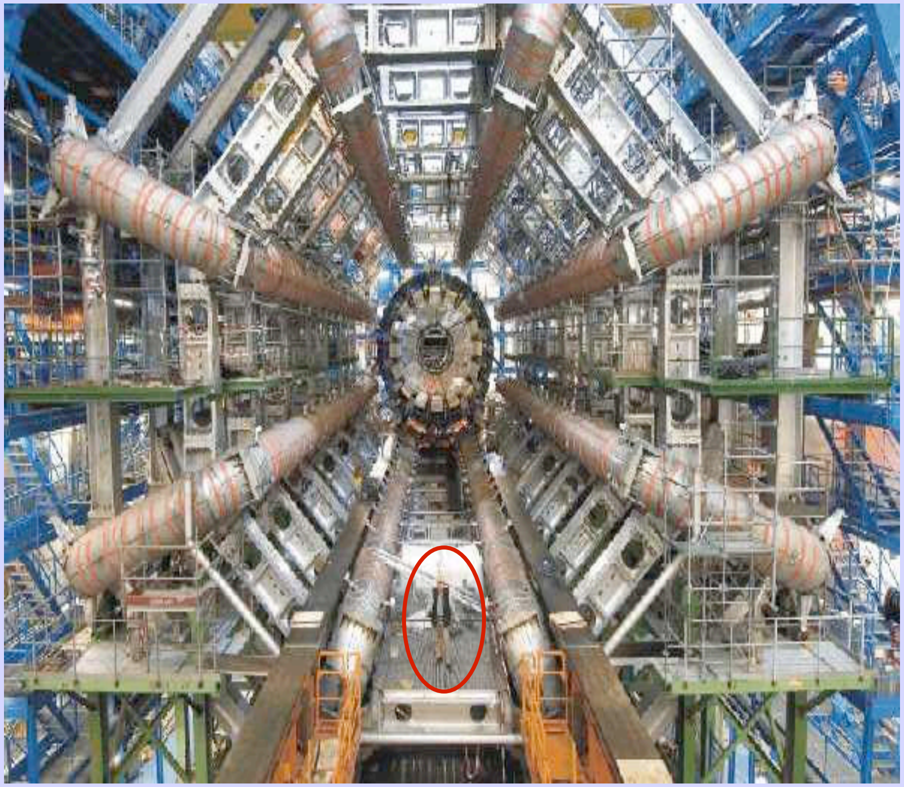
The Experiments are Built

We are terribly excited!!!

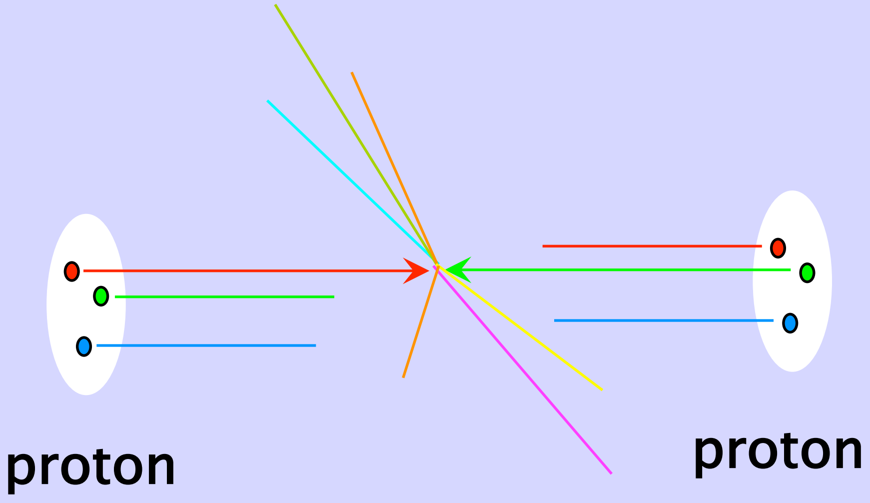
CMS

ATLAS





The LHC: pp collisions @ 14 TeV



Hard scattering occurs between proton's constituents – quarks and gluons

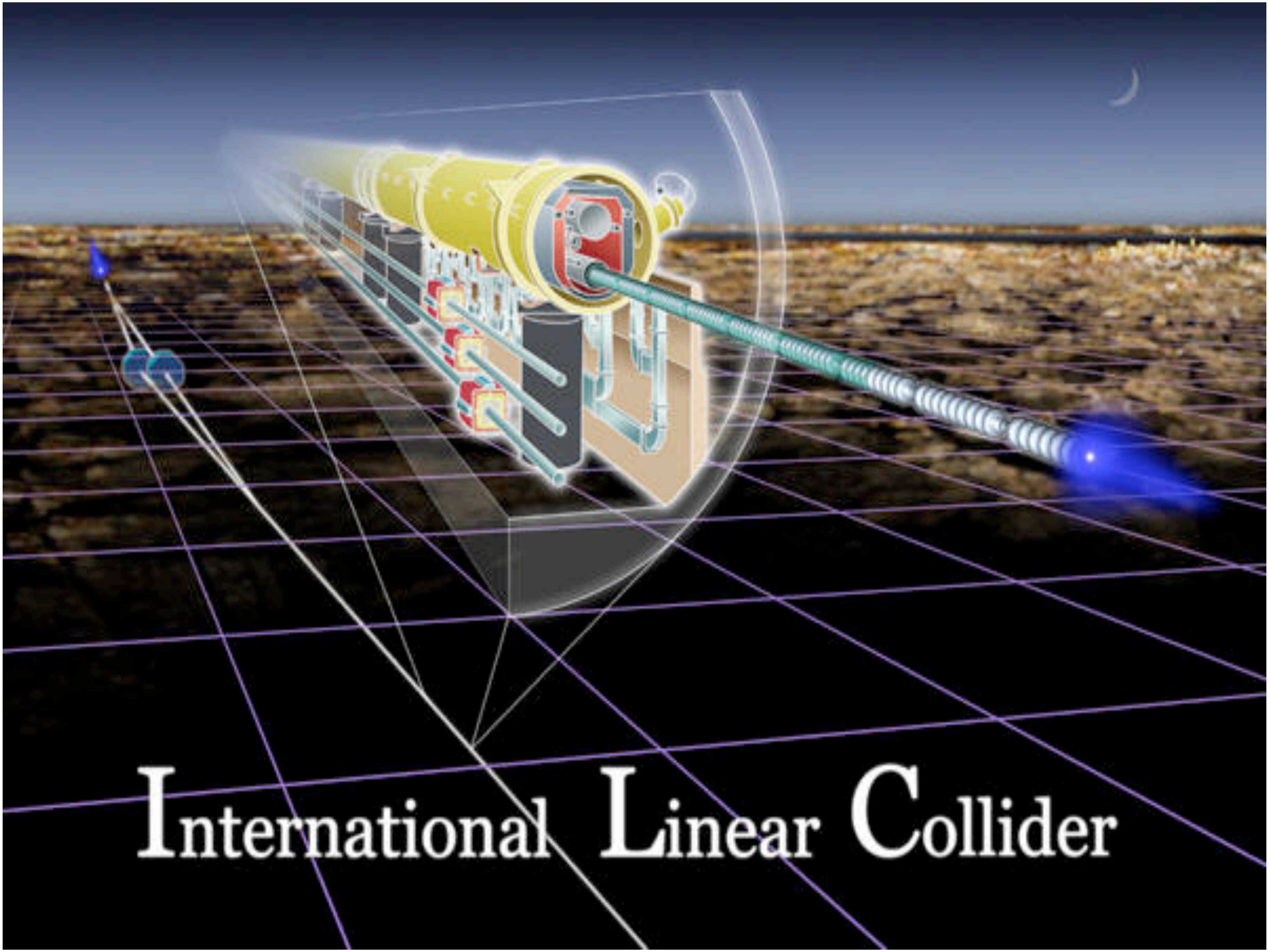
$E_{scatt} \sim 1/9\ E_{CoM} \sim 1–2$ TeV

Current LHC Schedule:

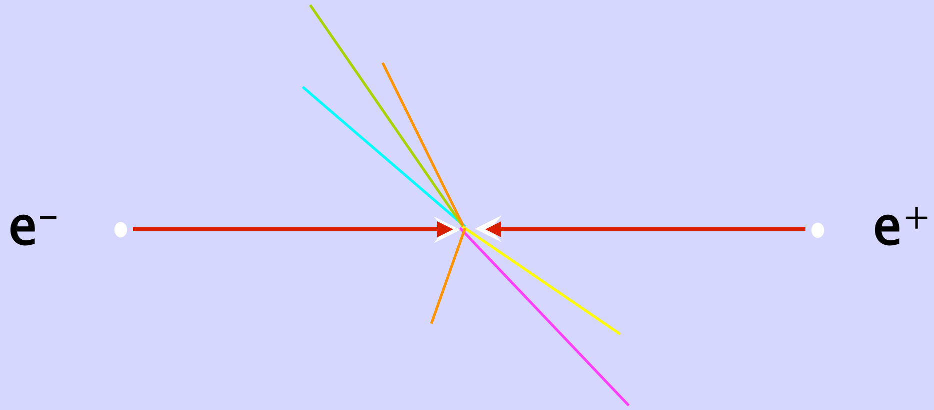
- Closed for beam set-up: August 09
- 1st Beam: Sept 09
- 1st Collisions: Fall 09
- 1st Physics run: 09-10, 100 pb^{-1}
- Physics runs 11 and onwards
  10/20 fb^{-1}/yr ⇒ 100 fb^{-1}/yr

pp Collisions:

- Broad energy reach
- Large event rate
- Complex environment
- Don't know initial state


International Linear Collider

The ILC: e^+e^- Collisions @ 0.5 – 1.0 TeV



Particle beams are fundamental particles

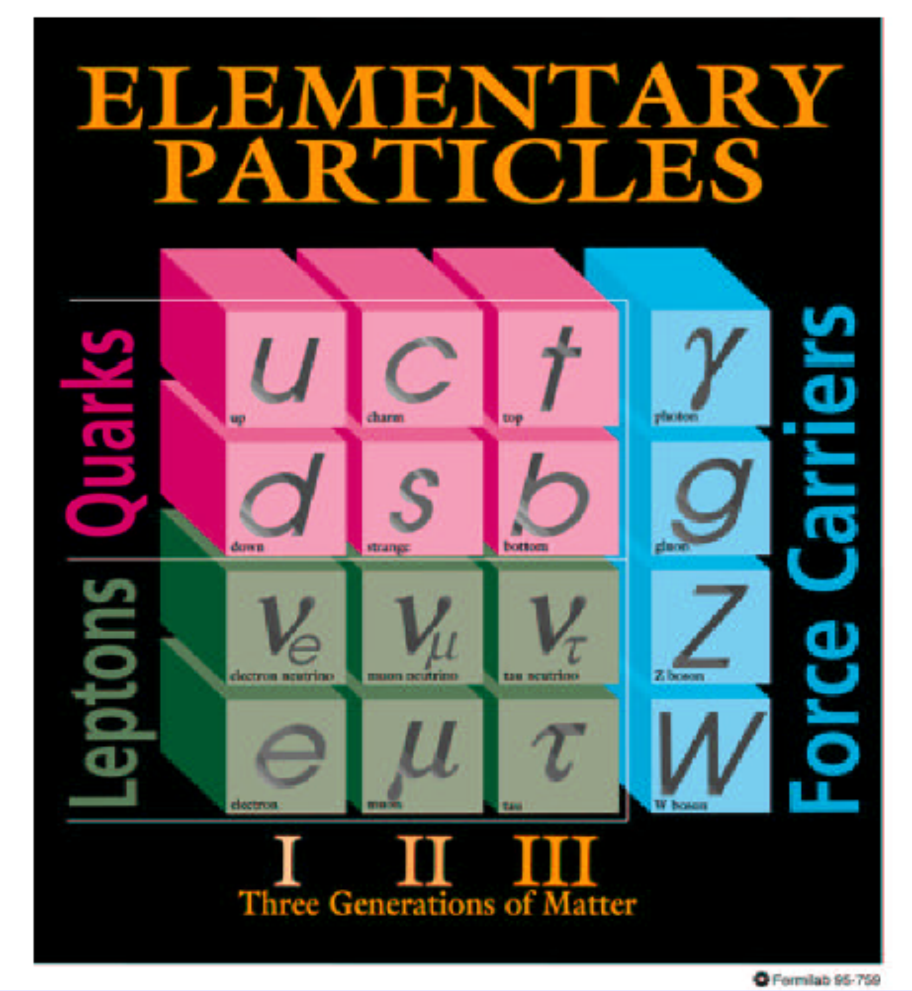
Parameters for the ILC:

- E_{CM} adjustable from 200–500 GeV
- Luminosity = 500 fb^{-1} in 4 yrs
- Ability to scan from 200–500 GeV
- Energy stability below 0.1%
- Electron polarization of at least 80%
- Upgradable to 1 TeV

- e^+e^- Collisions
- Full knowledge of initial quantum state
- Well-defined initial energy and angular momentum (polarization)
- Clean environment
- Can vary CoM

The Standard Model of Particle Physics

Building Blocks of Matter:



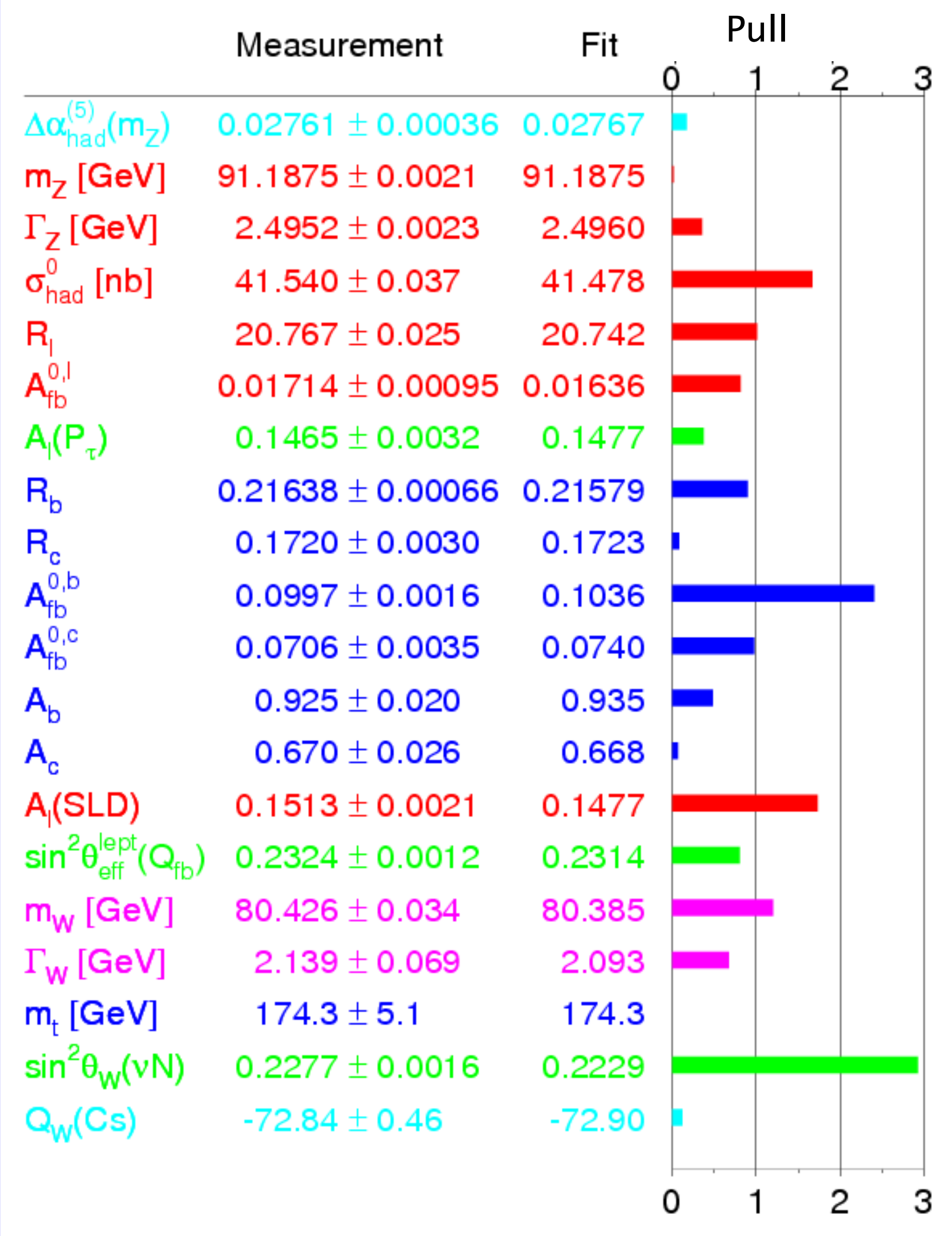
Symmetry:

$$\underbrace{SU(3)_C}_{\text{QCD}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{Electroweak}}$$

↓

Spontaneously Broken
to QED

This structure is experimentally confirmed!



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
$Q_W(Cs)$	-72.84 ± 0.46	-72.90

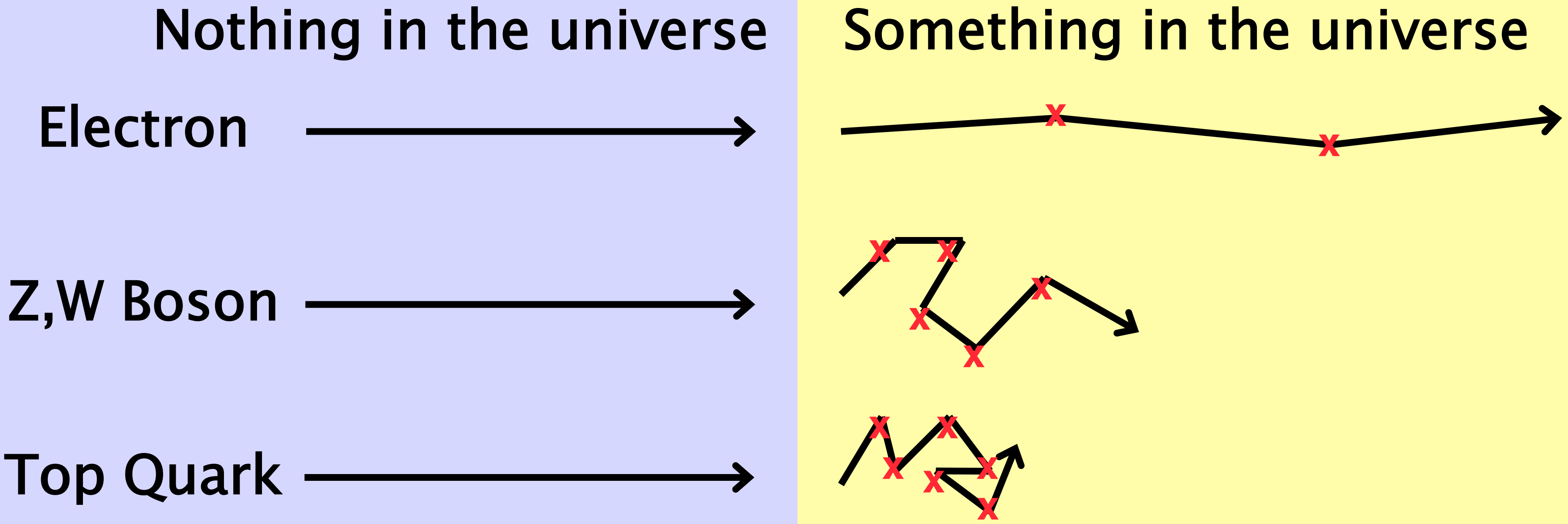
Standard Model predictions well described by data!

… With precision of 0.1% up to energy scales of 100 GeV….

Nonetheless, the Standard Model doesn’t answer the questions listed above!

Origin of Mass:

Something in the universe gives mass to particles



Nothing in the universe

Something in the universe

Electron

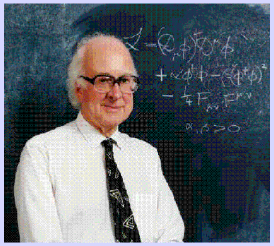
Z,W Boson

Top Quark

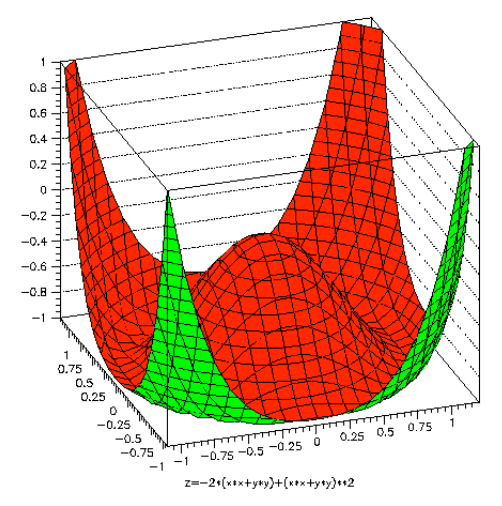
We believe it's a Higgs Field

A particle which couples proportionally to mass

The Standard Model Higgs Boson



Economy: 1 scalar doublet



Higgs Potential:

$V(\phi) = \mu^2\phi^2/2 + \lambda\phi^4/4$

Spontaneous Symmetry Breaking

Chooses a vacuum $v = \langle 0|\phi|0\rangle$

and shifts the field $\chi = \phi - v$

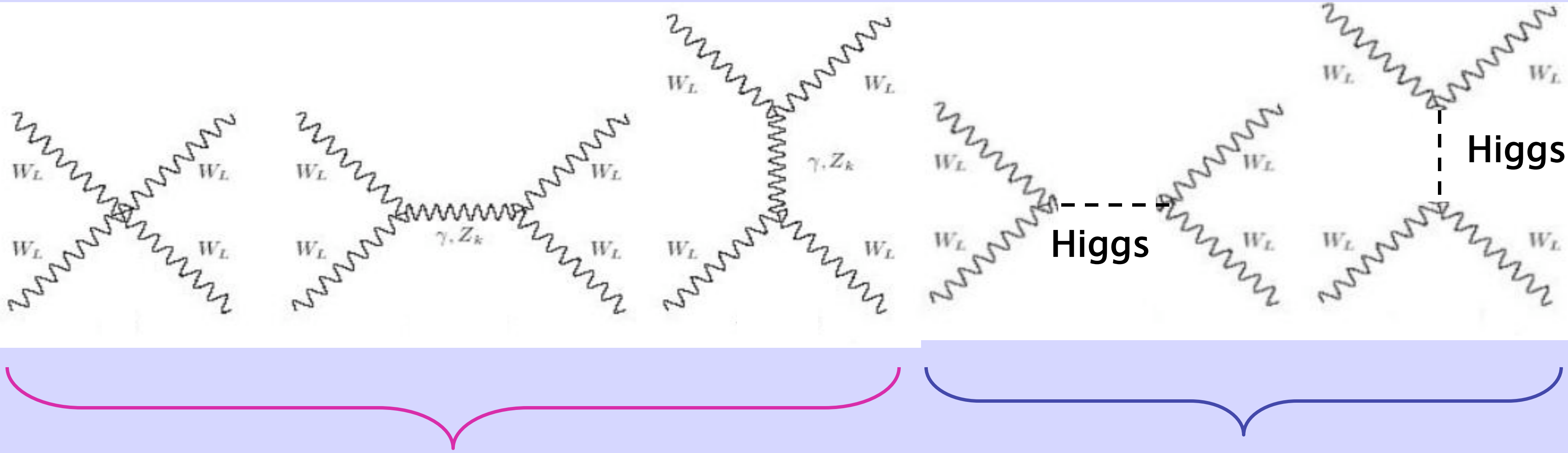
$V(\chi) = m_\chi{}^2\chi^2/2 + \lambda v\chi^3 + \lambda\chi^4/4$

gives 1 physical Higgs scalar with $m_\chi = \sqrt{2}\,\lambda v$

Masses of electroweak gauge bosons proportional to v

We need to discover the Higgs and experimentally test this potential and the Higgs properties!

Higgs Mass Upper Bound: Gauge Boson Scattering



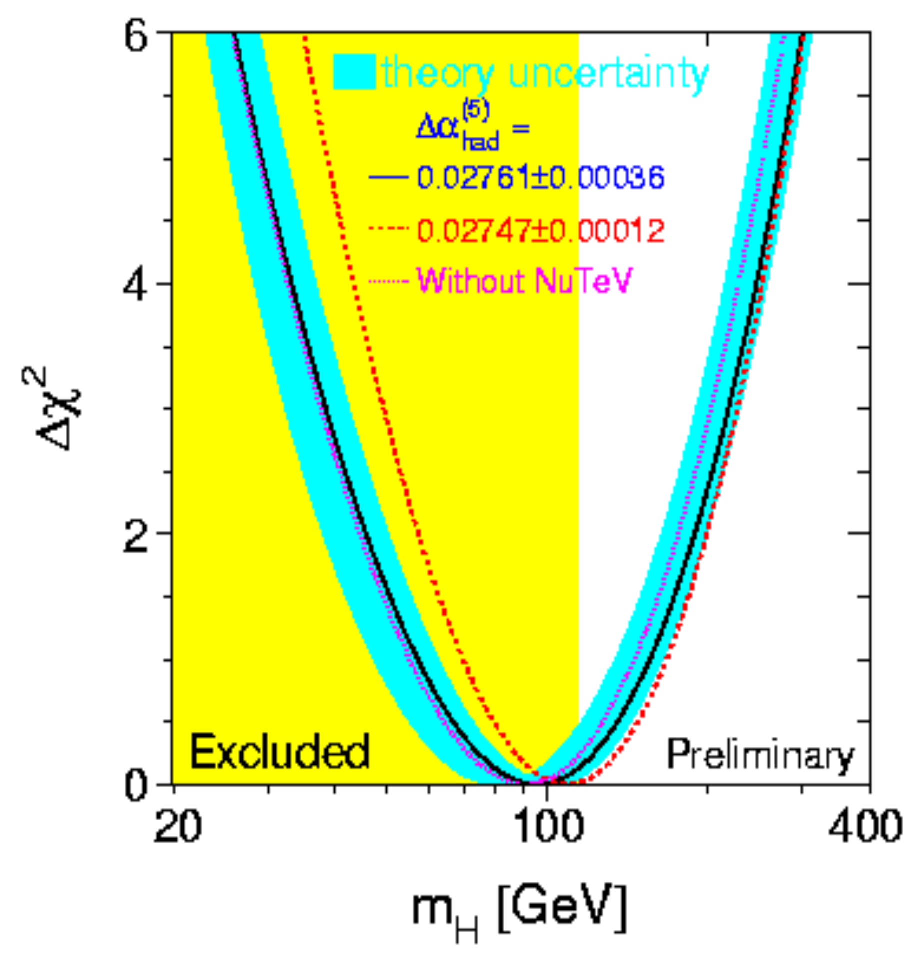
Bad violation of unitarity

Restores unitarity

Expand cross section into partial waves
Unitarity bound (Optical theorem!) $\Rightarrow |\mathrm{Re}\ a_0| < ½$
Gives $m_H < 1$ TeV

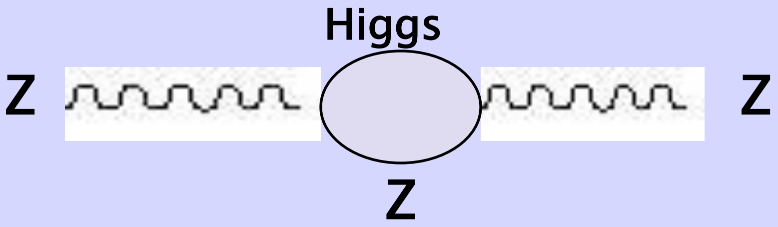
LHC is designed to explore this entire region!

Present Limits:



Direct Searches at LEP:
$m_H > 114.4$ GeV

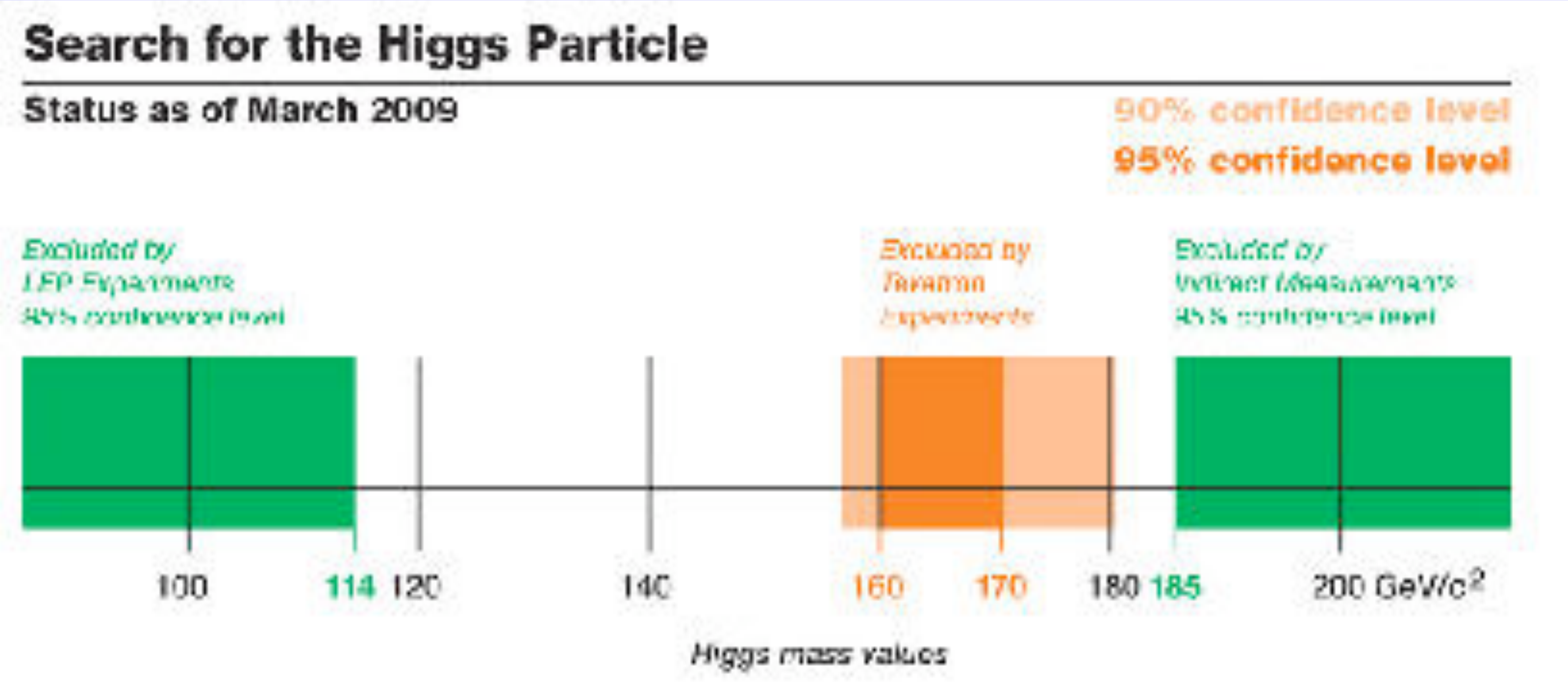
Indirect Searches at LEP/SLC:
$m_H < 185$ GeV @ 95% CL



Direct Higgs Searches @ the Tevatron

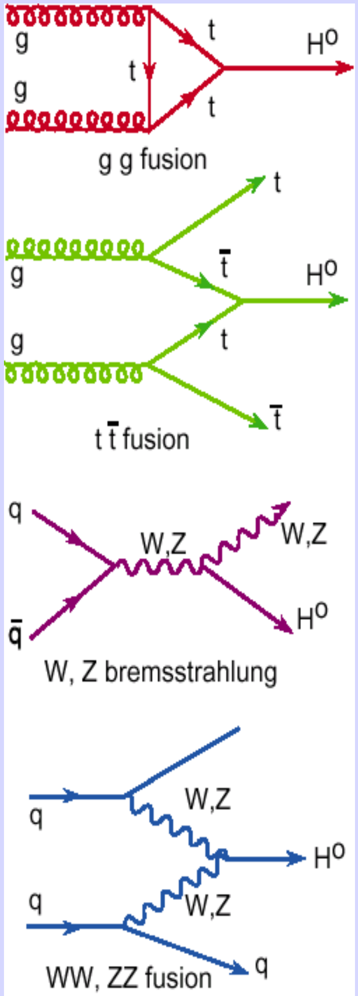
New region excluded from

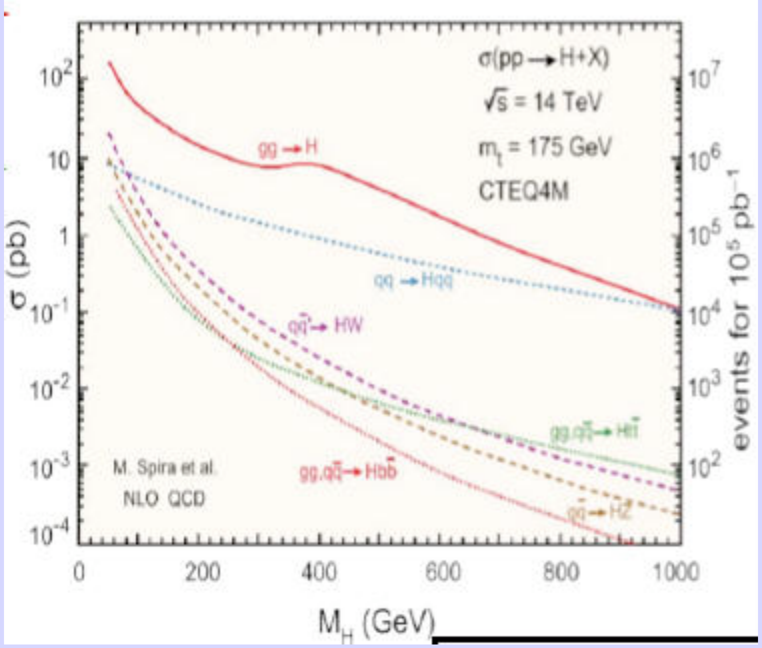
$gg \rightarrow h \rightarrow WW^*$



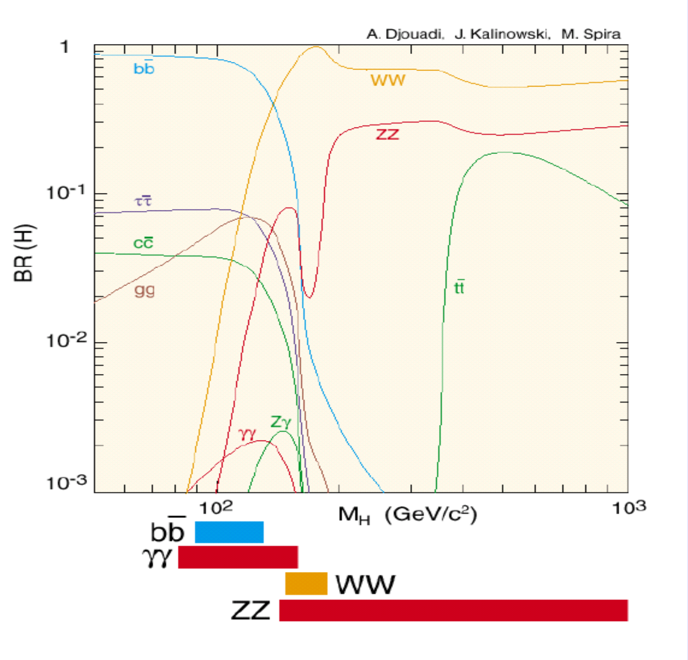
Higgs @ the LHC:

Production mechanisms & rates



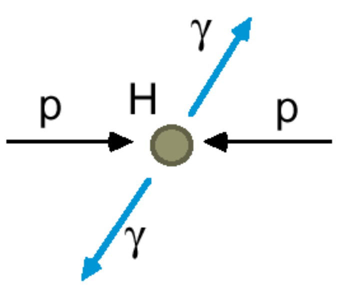


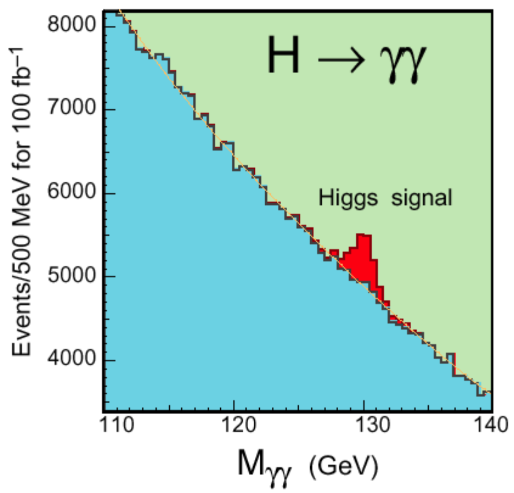
Signal determined by final state versus background

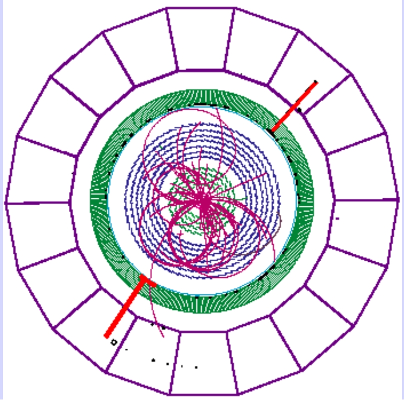


Higgs Search Strategies

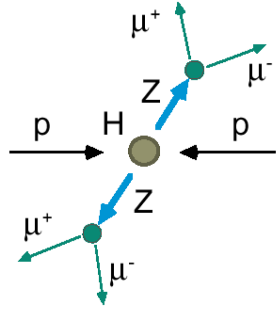
Low: M_H < 140 GeV

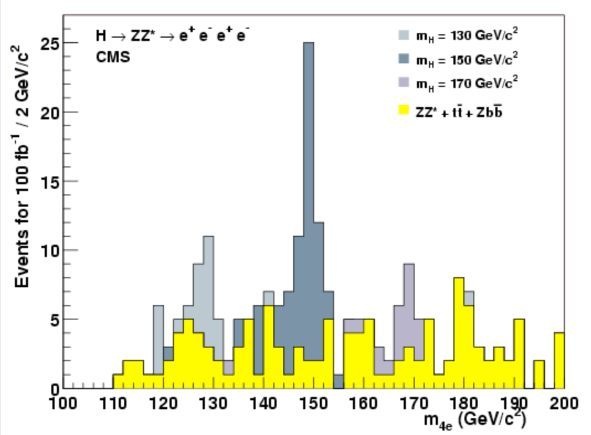


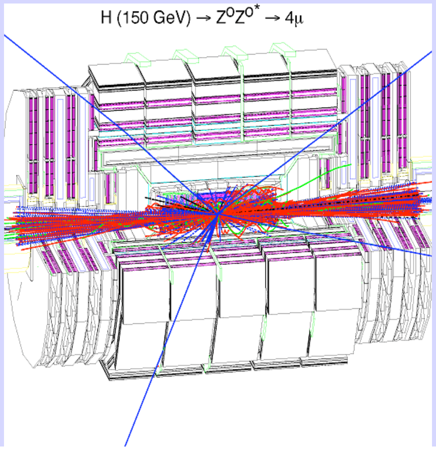




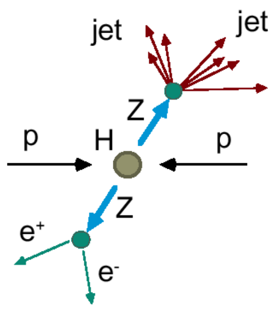
Medium: 130<M_H<500 GeV

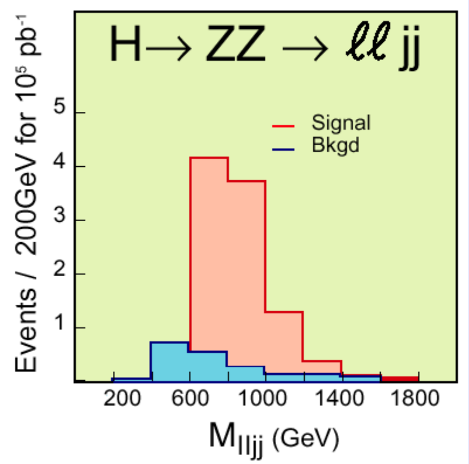


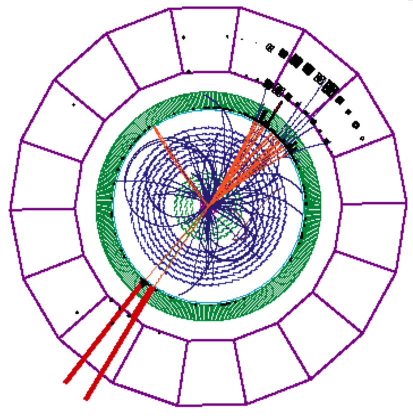


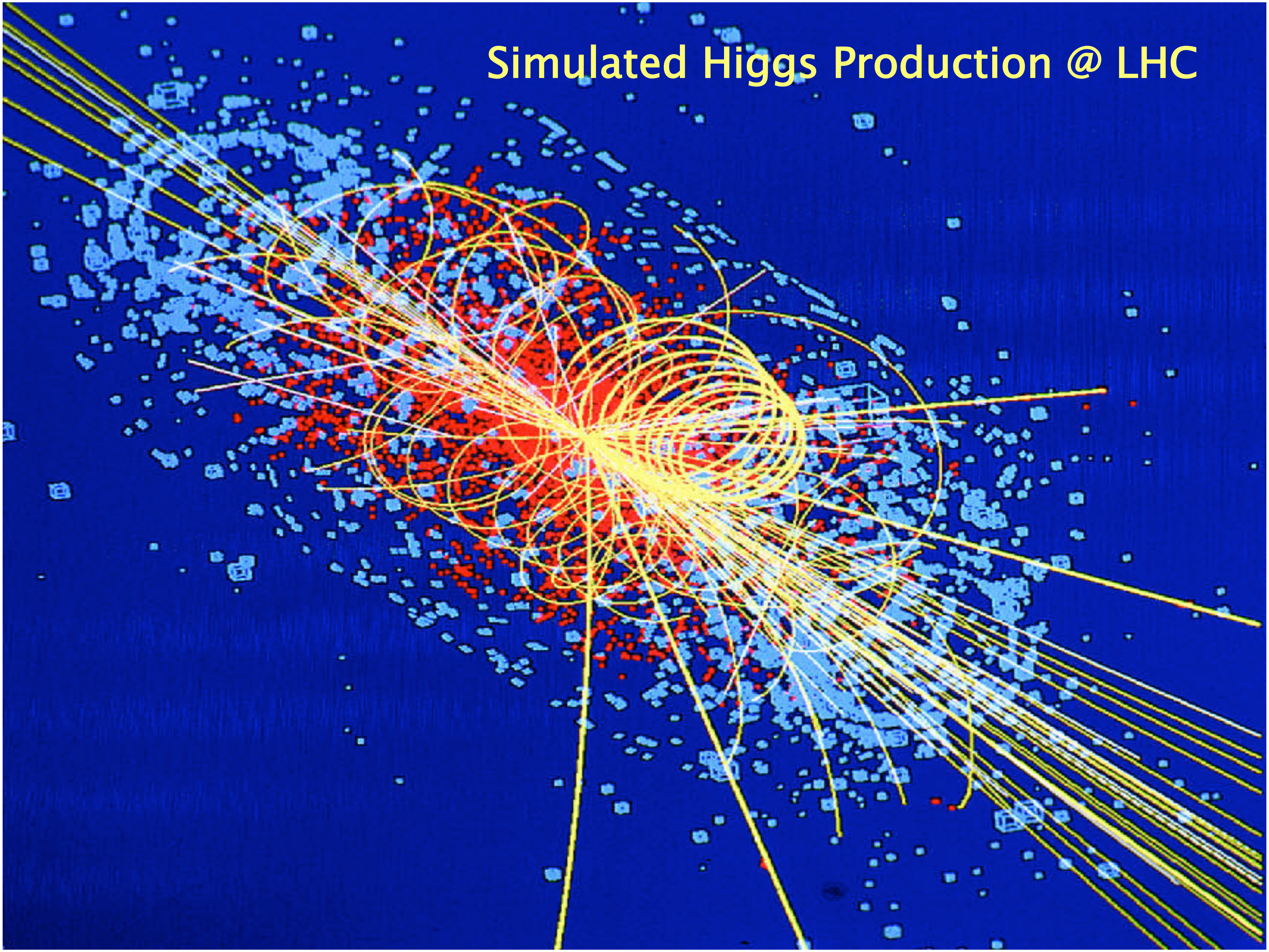


High: M_H > ~500 GeV





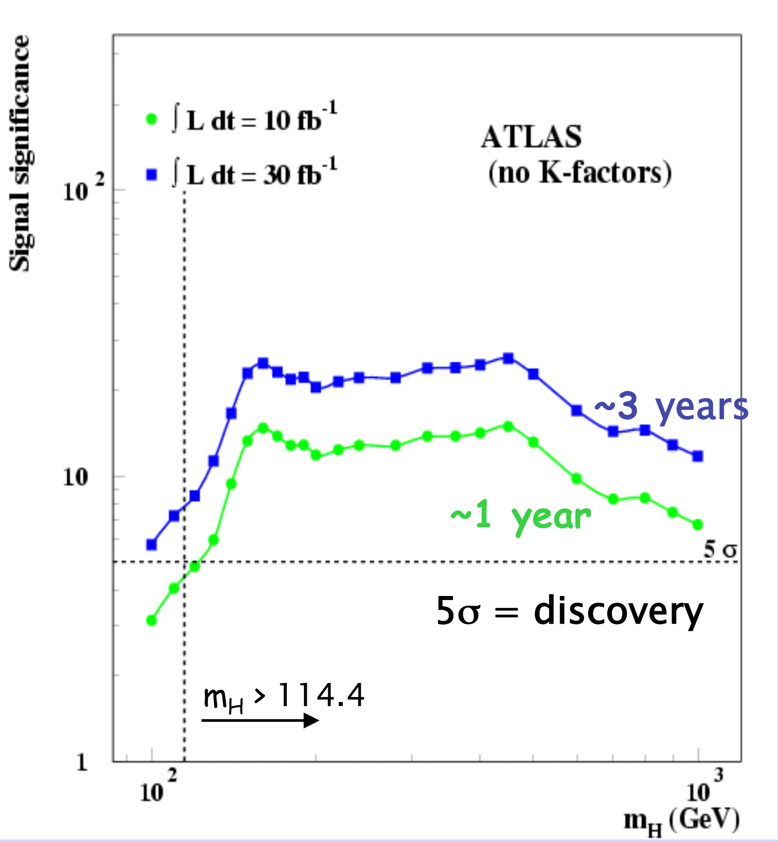


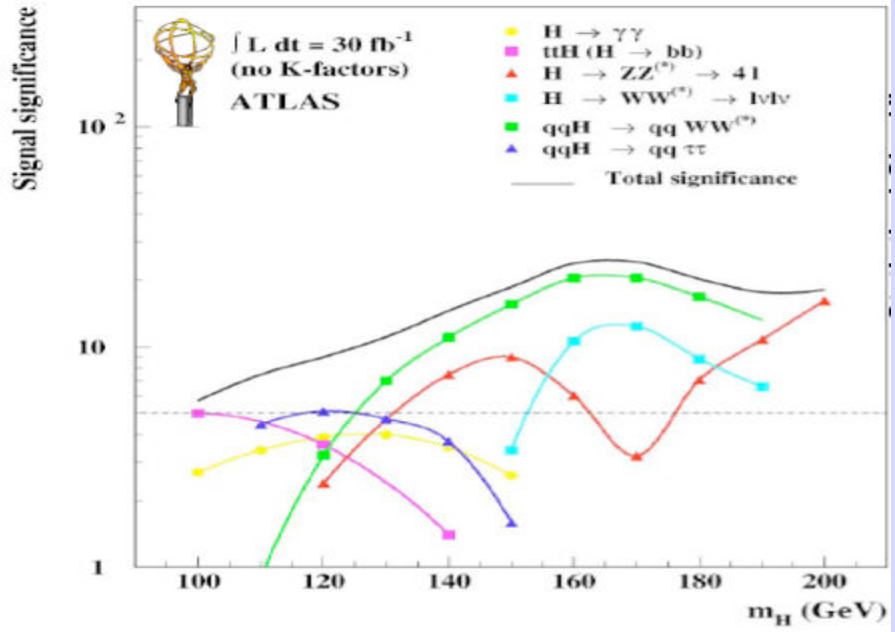


Simulated Higgs Production @ LHC

Higgs Reach

Search reach is complicated convolution of production channels + decay signatures





What the LHC Can and Cannot do:

Can*:

- Discover SM Higgs
- Measure m_H to 0.1–1.0%
- Measure Higgs width to 5–8% for $m_H > 200$ GeV
- Info on spin for $m_H > 200$ GeV
- Measure ratios of branching fractions

Cannot*:

- Discover all scenarios Beyond the Standard Model
- Measure Higgs width and spin for all Higgs masses
- Measure individual branching fractions without model assumptions
- Measure Higgs self-coupling
- Test structure of Higgs potential

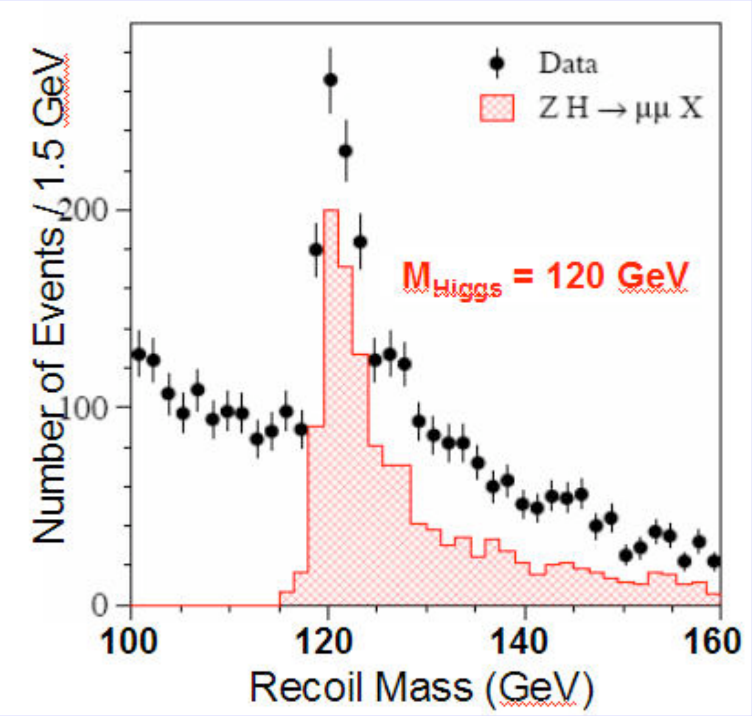
* A. De Roeck, CMS

Higgs at the ILC

- An important Higgs production process is $e^+e^- \rightarrow Z + \text{Higgs}$
- There are many possible final states, depending on how the Z and Higgs decay

Recoil Technique:

In $e+e- \rightarrow Z + \text{Anything}$

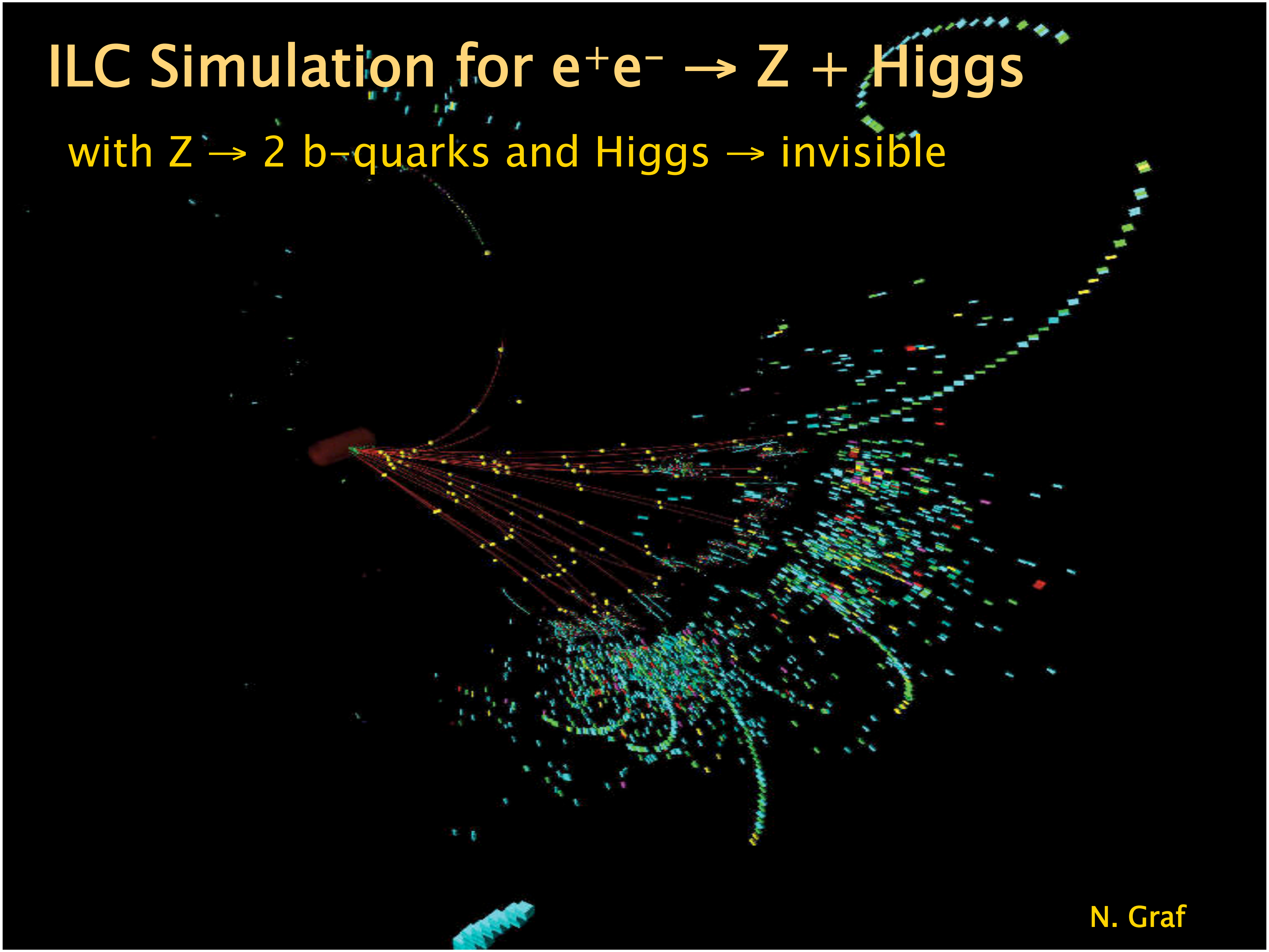


- 'Anything' corresponds to a system recoiling against the Z
- The mass of this system is determined solely by kinematics and conservation of energy
- because we see everything else, we know what is escaping

Peak in Recoil Mass corresponds to 120 GeV Higgs!

ILC Simulation for $e^+e^- \rightarrow Z + \text{Higgs}$

with Z → 2 b-quarks and Higgs → invisible



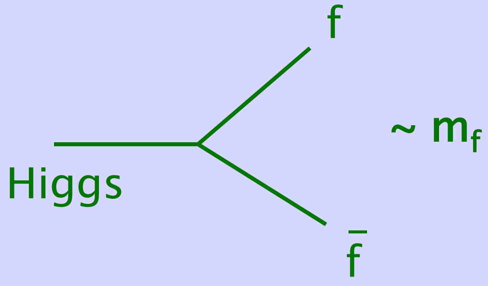
N. Graf

Recoil technique gives precise determination of Higgs properties *Independent* of its decay mode

Even if it decays invisibly…

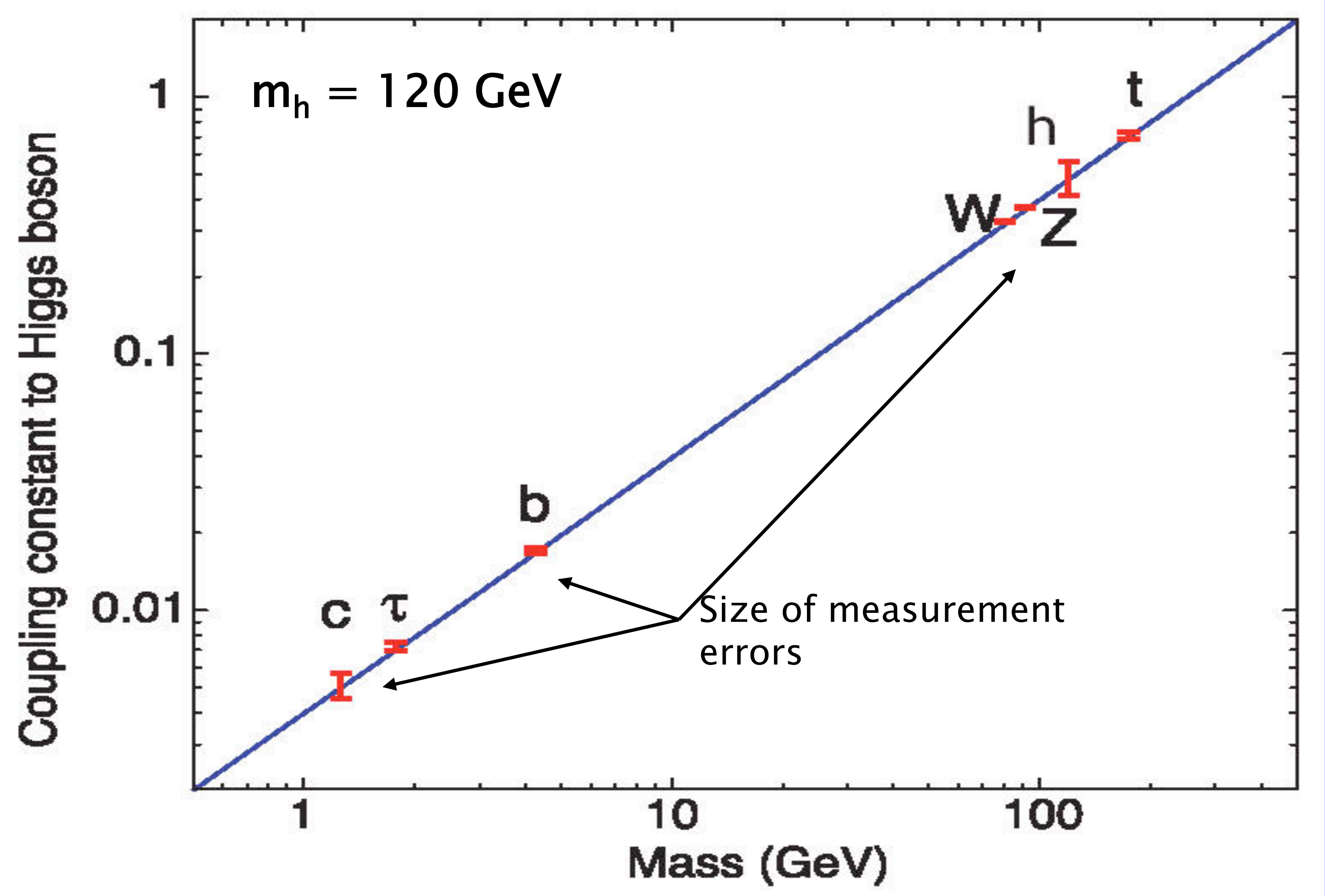
Provides accurate, direct, and *Model Independent* measurements of the Higgs couplings

- The strength of the Higgs couplings to fermions and bosons is given by the mass of the particle
- Within the Standard Model this is a direct proportionality



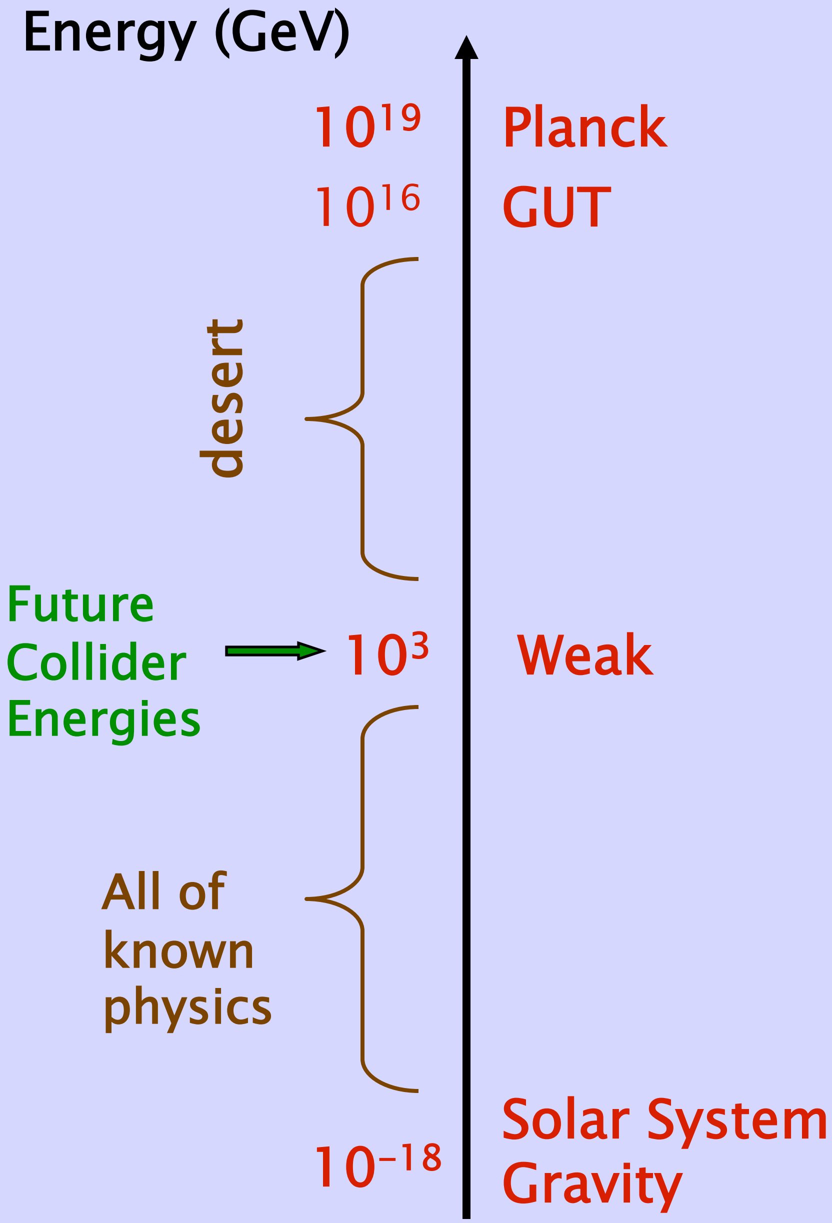
This is a crucial test of whether a particle's mass is generated by the Higgs boson!

ILC will have unique ability to make model independent tests of Higgs couplings at the percent level of accuracy.



Size of measurement errors

The Hierarchy



Energy (GeV)

10^{19} Planck

10^{16} GUT

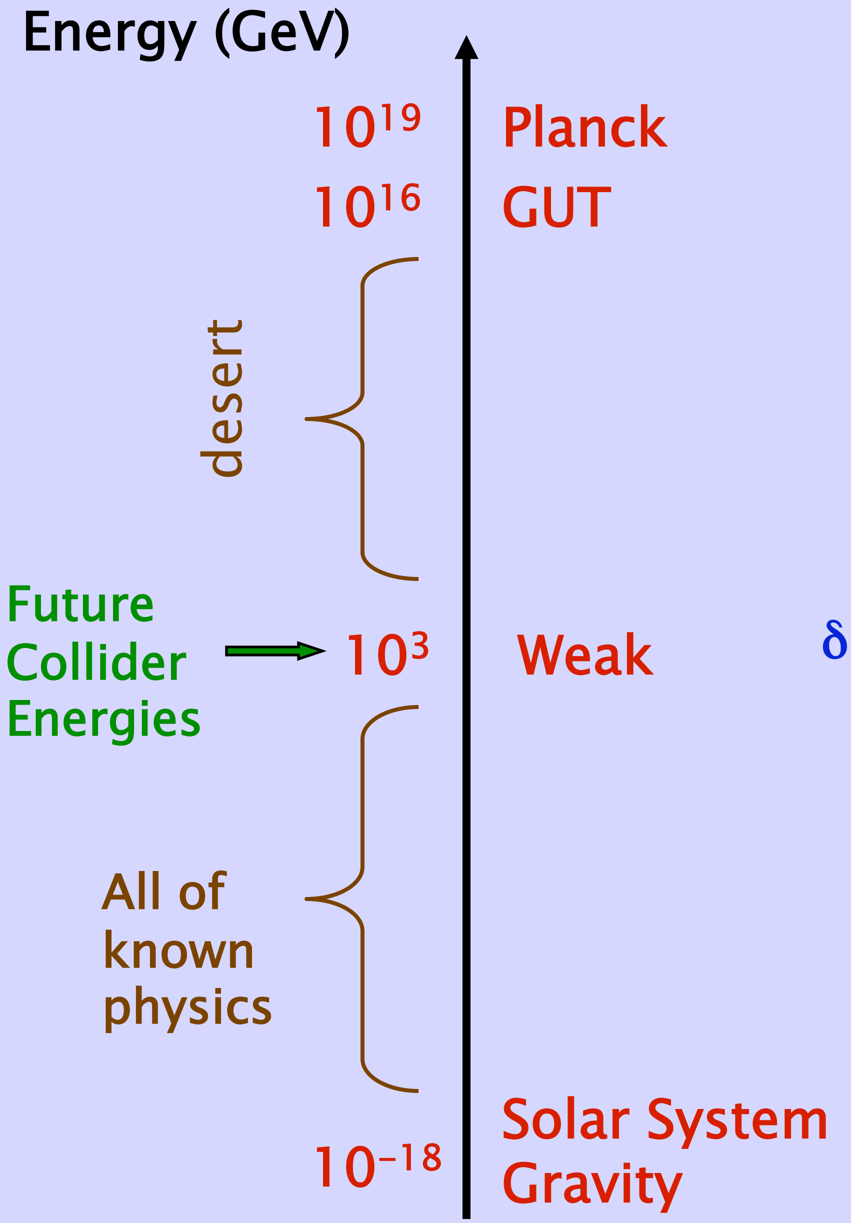
desert

Future Collider Energies → 10^{3} Weak

All of known physics

10^{-18} Solar System Gravity

The Hierarchy Problem



Energy (GeV)

10^{19} Planck

10^{16} GUT

desert

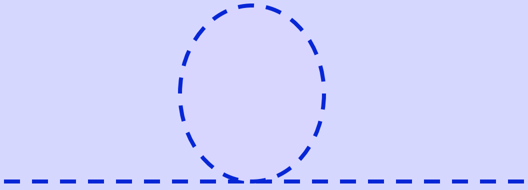
Future Collider Energies → 10^3 Weak

All of known physics

10^{-18} Solar System Gravity

Quantum Corrections:

Virtual Effects drag Weak Scale to M_{Pl}



$$\delta m_H^2 \sim \quad \sim M_{Pl}^2$$

NP @ the Terascale

- Electroweak Symmetry breaks at energies ~ 1 TeV (SM Higgs or ???)
- WW Scattering unitarized at energies ~ 1 TeV (SM Higgs or ???)
- Gauge Hierarchy: Nature is fine-tuned or Higgs mass must be stabilized by New Physics ~ 1 TeV
- Dark Matter: Weakly Interacting Massive Particle must have mass ~ 1 TeV to reproduce observed DM density

All things point to the Terascale!

A Cellar of New Ideas

’67	The Standard Model	a classic! aged to perfection
’77	Vin de Technicolor	better drink now
’70’s	Supersymmetry: MSSM	mature, balanced, well developed – the Wino’s choice
’90’s	SUSY Beyond MSSM	svinters blend
’90’s	CP Violating Higgs	all upfront, no finish lacks symmetry
’98	Extra Dimensions	bold, peppery, spicy uncertain terrior
’02	Little Higgs	complex structure
’03	Fat Higgs	young, still tannic needs to develop
’03	Higgsless	sleeper of the vintage what a surprise!
’04	Split Supersymmetry	finely-tuned
’05	Twin Higgs	double the taste

J. Hewett

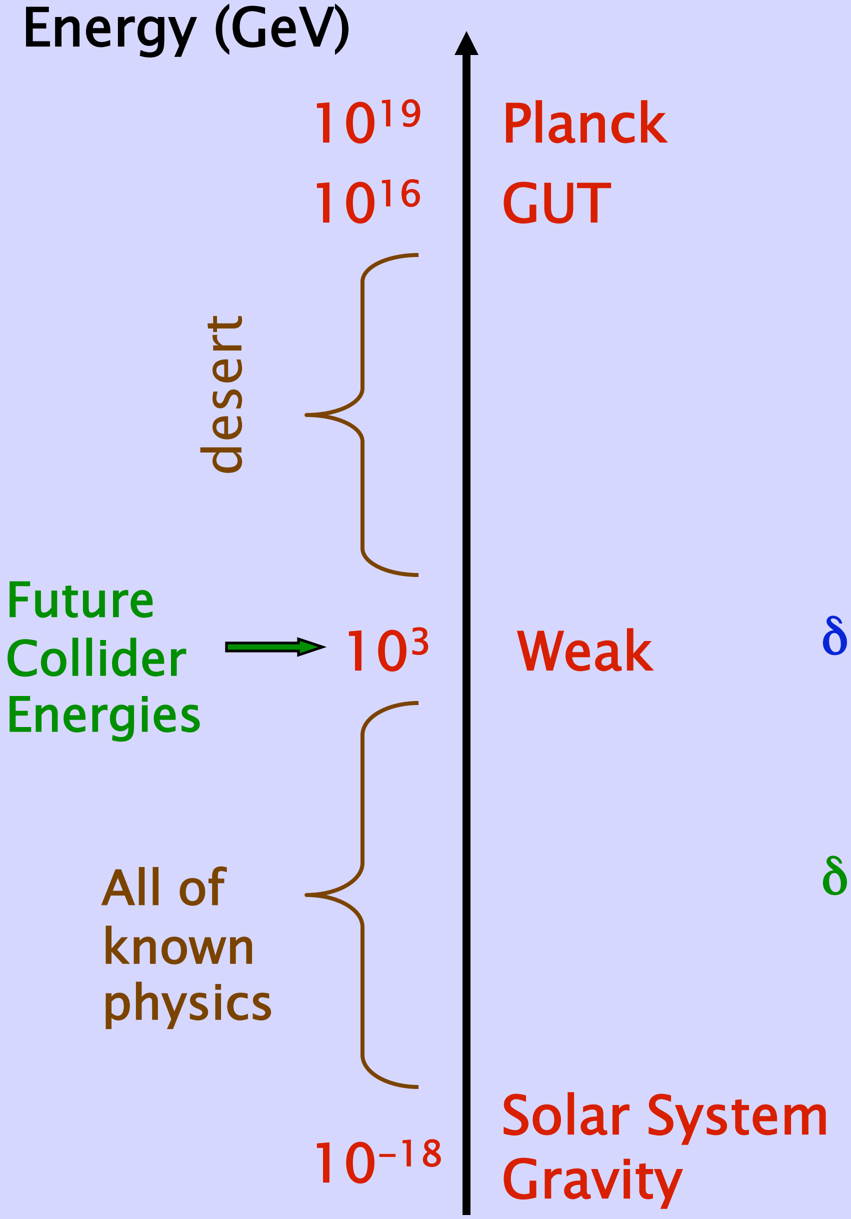
Last Minute Model Building

Anything Goes!

- Non-Communtative Geometries
- Return of the 4th Generation
- Hidden Valleys
- Quirks - Macroscopic Strings
- Lee-Wick Field Theories
- Unparticle Physics
- …..

(We still have a bit more time)

The Hierarchy Problem: Supersymmetry



Energy (GeV)

10^{19} Planck

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Future Collider Energies → 10^3 Weak

All of known physics

10^{-18} Solar System Gravity

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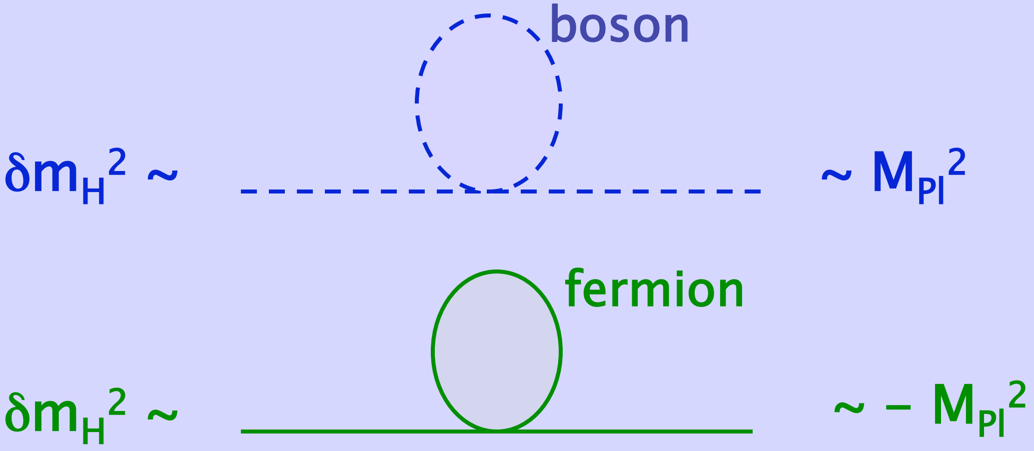
Virtual Effects drag Weak Scale to M_{Pl}



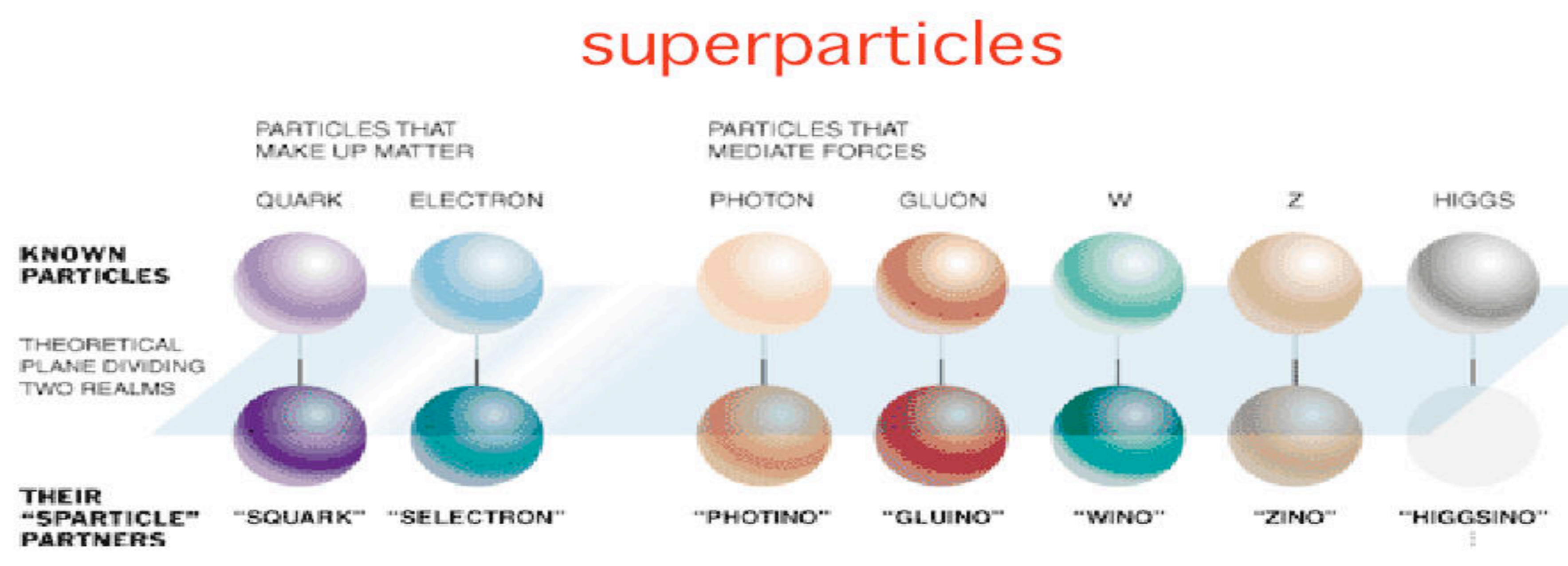
$\delta m_H^2 \sim$ $\sim M_{Pl}^2$

$\delta m_H^2 \sim$ $\sim - M_{Pl}^2$

Large virtual effects cancel order by order in perturbation theory

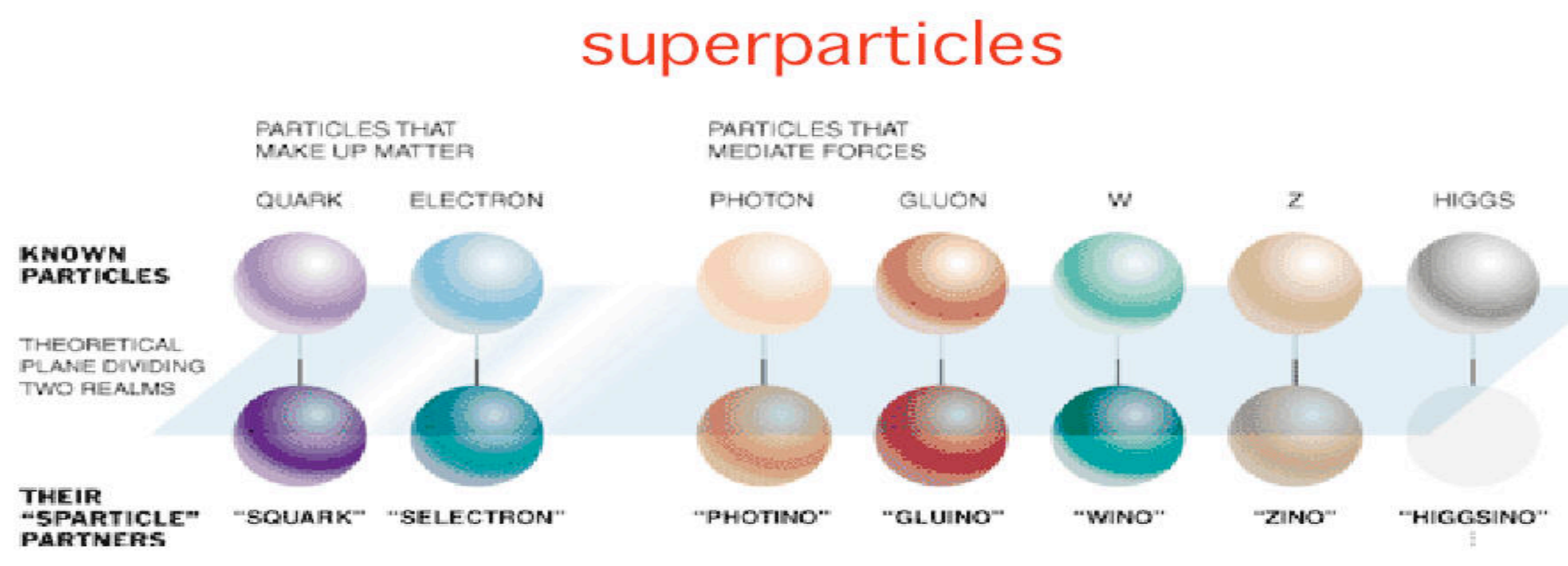
Supersymmetry:

- Symmetry between fermions and bosons
- Predicts that every particle has a superpartner of equal mass
- Suppresses quantum effects
- Can make quantum mechanics consistent with gravity (with other ingredients)



Supersymmetry:

- Symmetry between fermions and bosons
- Predicts that every particle has a superpartner of equal mass (⇒ SUSY is broken: many competing models!)
- Suppresses quantum effects
- Can make quantum mechanics consistent with gravity (with other ingredients)

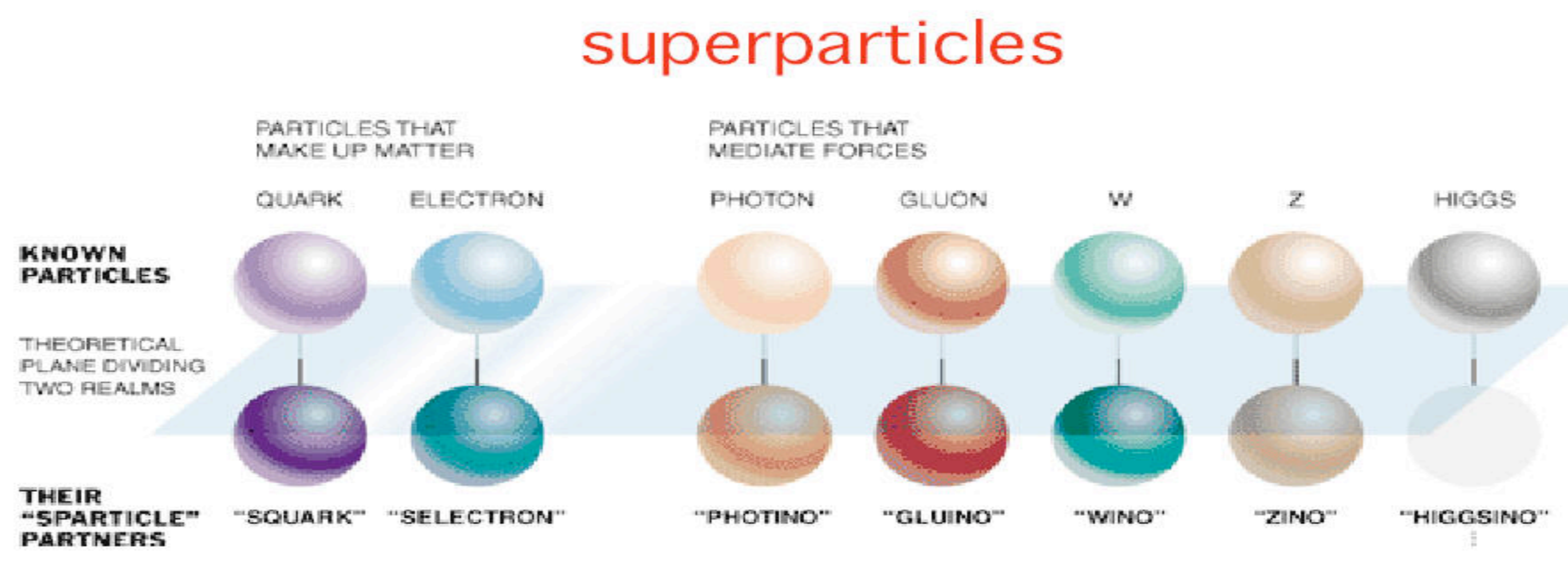


Minimal Supersymmetric Standard Model

Conserved multiplicative quantum number

- Superpartners are produced in pairs
- Heavier Superpartners decay to the Lightest
- Lightest Superpartner is stable

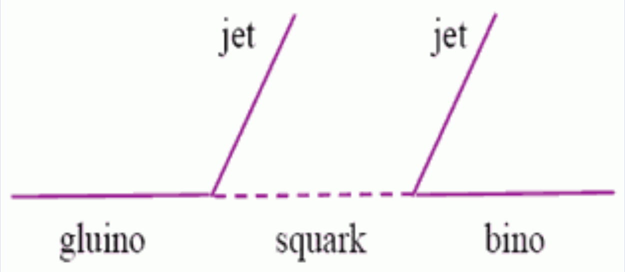
Collider signatures dependent on this assumption and on model of SUSY breaking



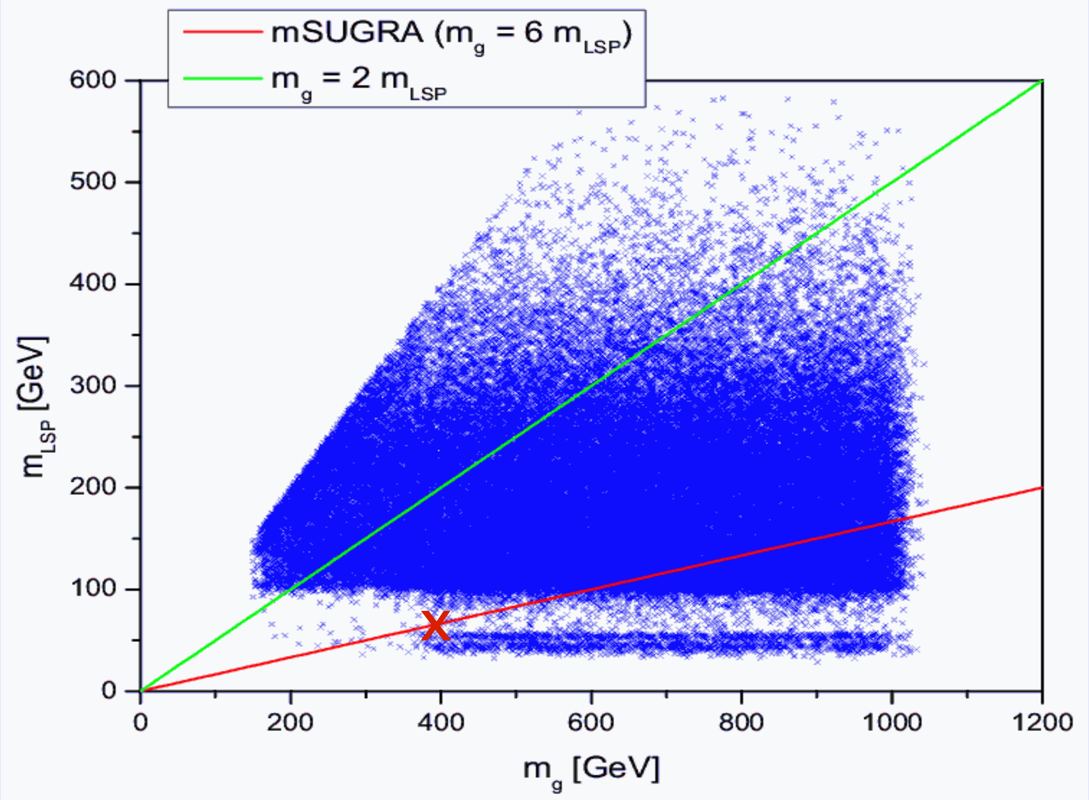
Gluinos at the Tevatron

- Tevatron gluino/squark analyses performed for mSUGRA – constant ratio $m_{gluino} : m_{Bino} \simeq 6 : 1$

Gluino-Bino mass ratio determines kinematics

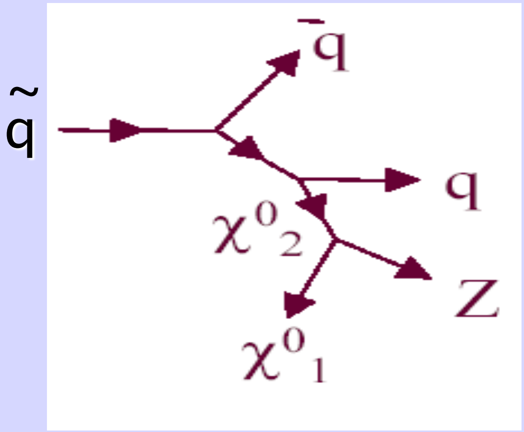


Distribution of Gluino Masses

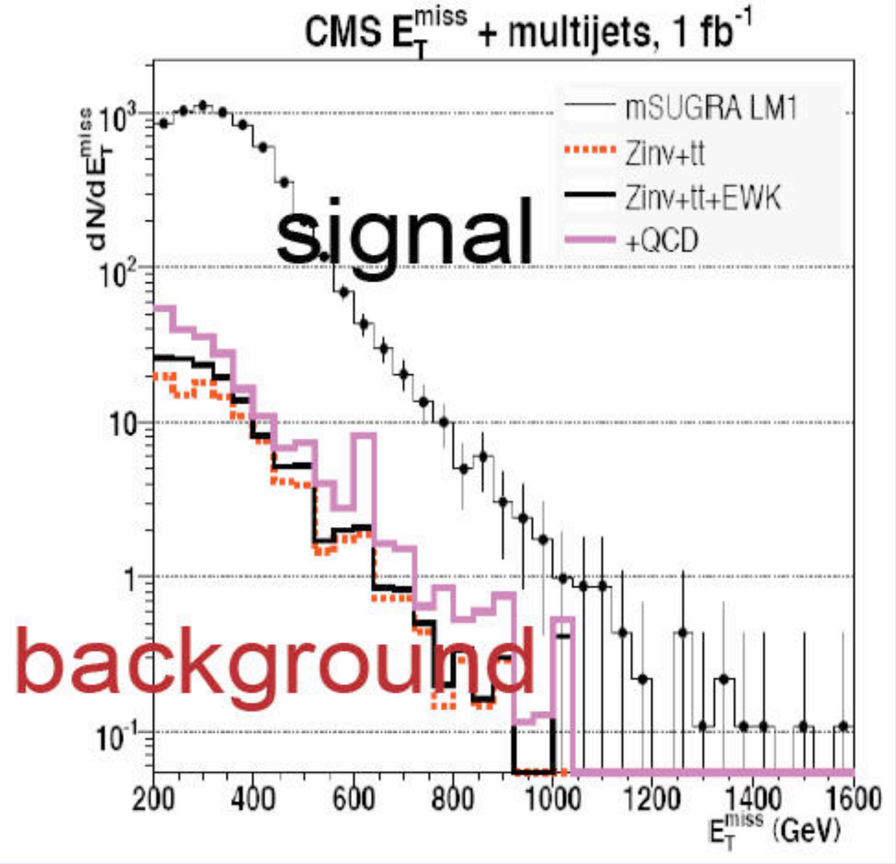


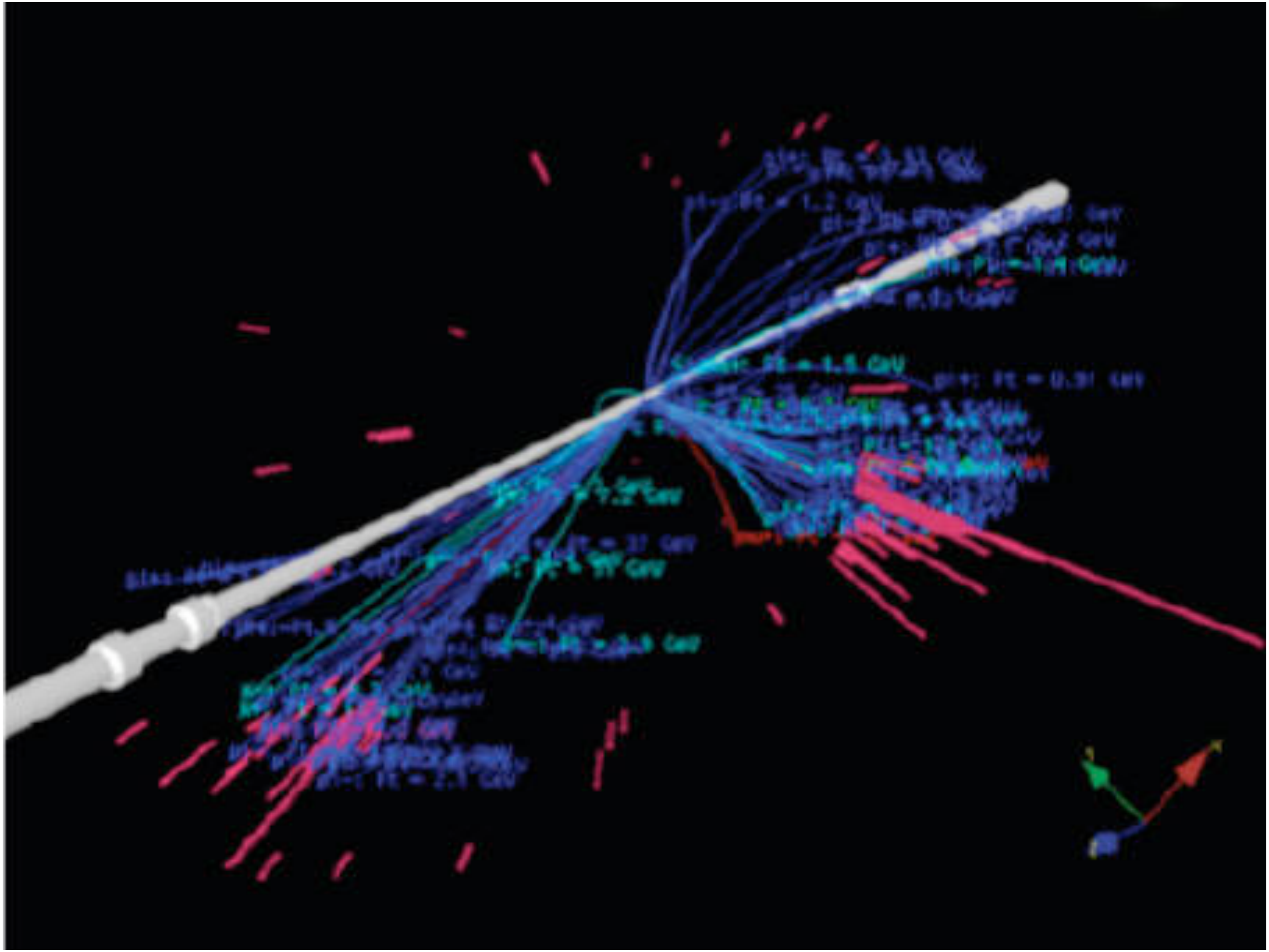
Supersymmetry at the LHC

SUSY discovery generally 'easy' at LHC

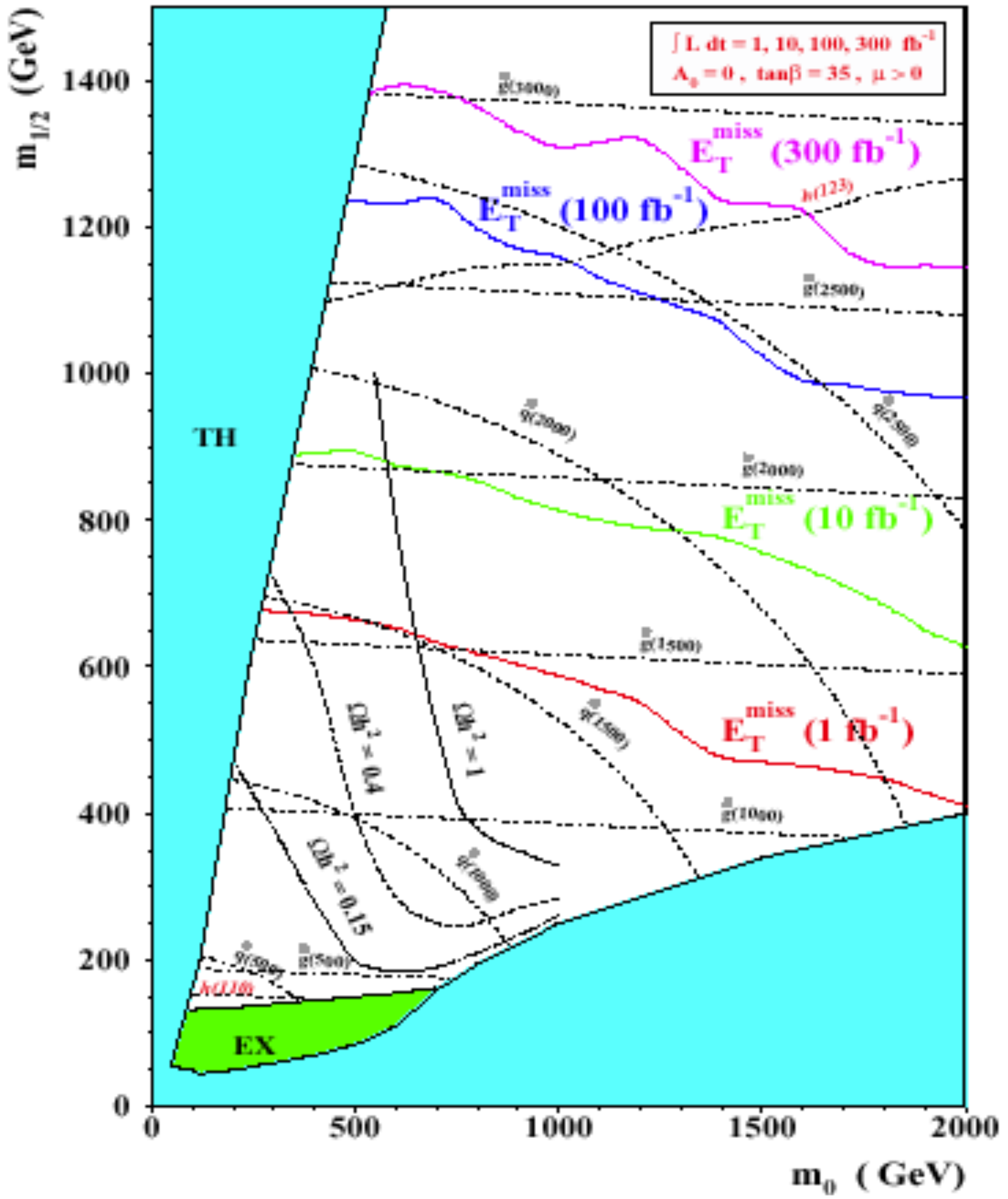


Cut: $E_T^{miss} > 300$ GeV




pi+: Pt = 0.31 GeV

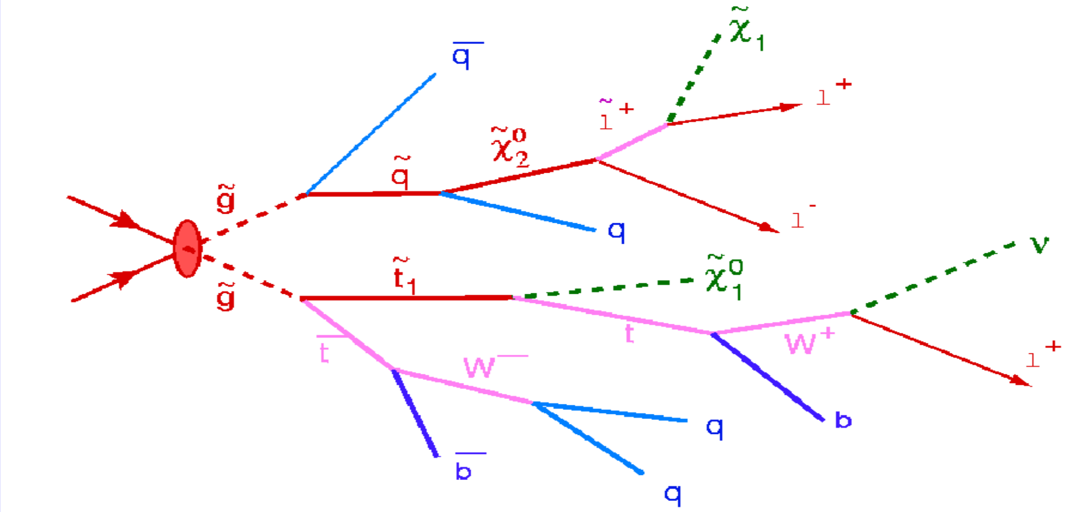
LHC Supersymmetry Discovery Reach



Model where gravity mediates SUSY breaking – 5 free parameters at high energies

Squark and Gluino mass reach is 2.5–3.0 TeV @ 300 fb^{-1}

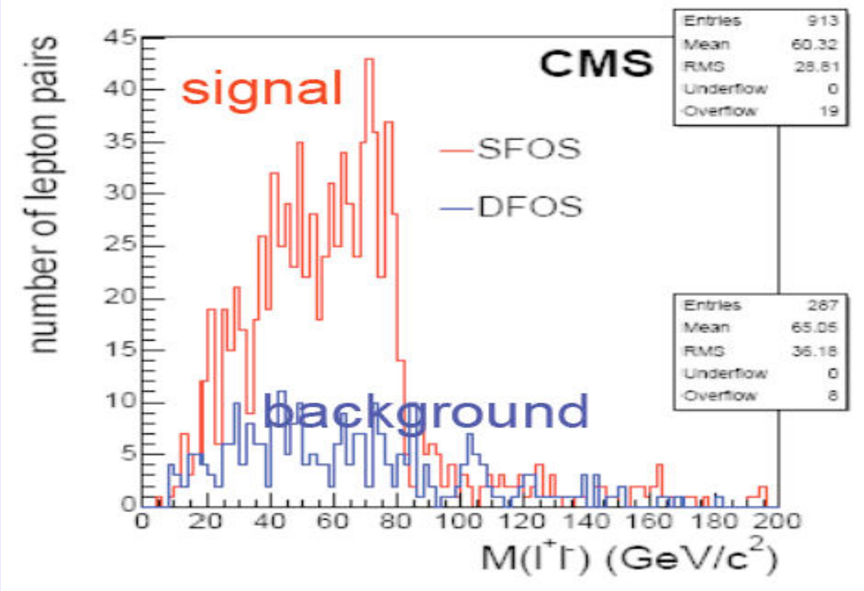
Reconstruction of Sparticle Masses at LHC



Squarks and Gluinos have complicated decay chains

ATLAS and CMS have simulated a benchmark point called SPS1a

Main analysis tool: dilepton edge in $\chi^0_2 \rightarrow \chi^0_1 l^+ l^-$

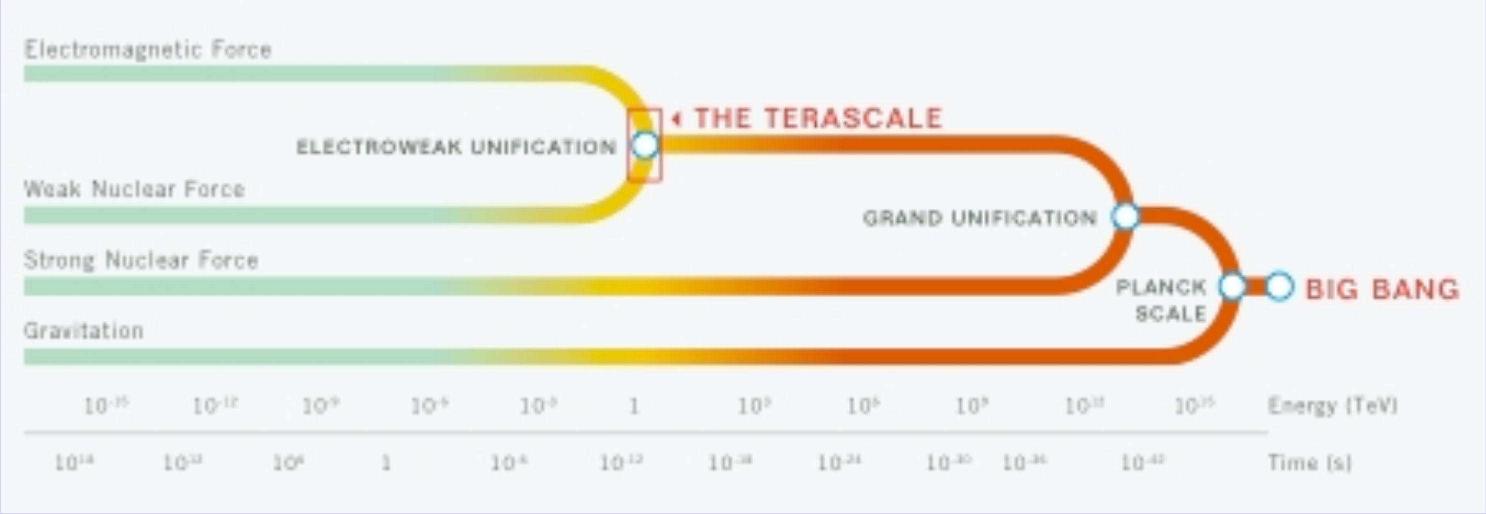


Proportional to Sparticle mass differences

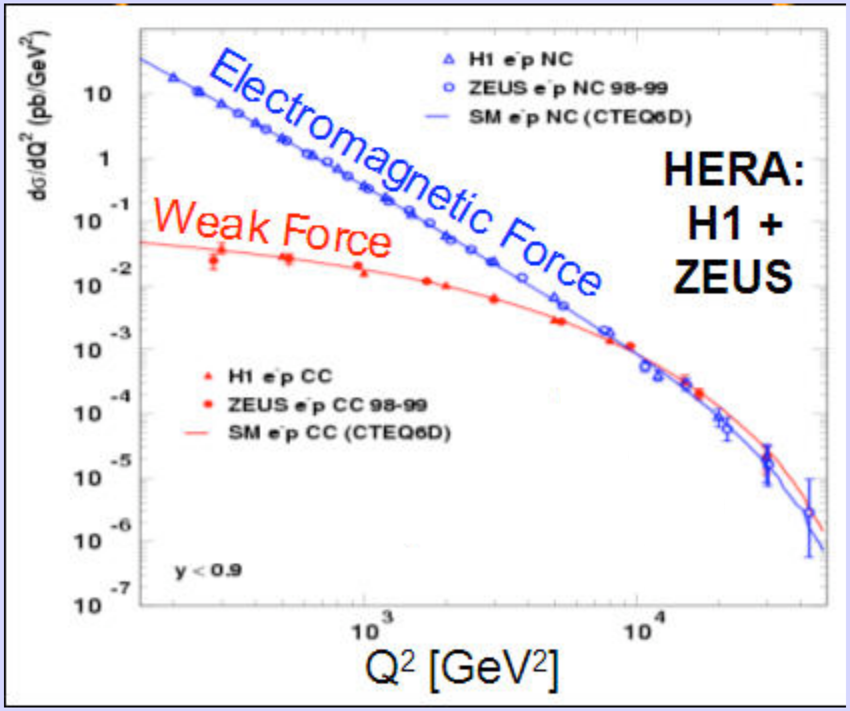
$$m_{ll}^2 = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

Introduces strong mass correlations

Telescope to Unification



Unification of Weak and Electromagnetic forces demonstrated at HERA ep collider at DESY
⇒ Electroweak theory!



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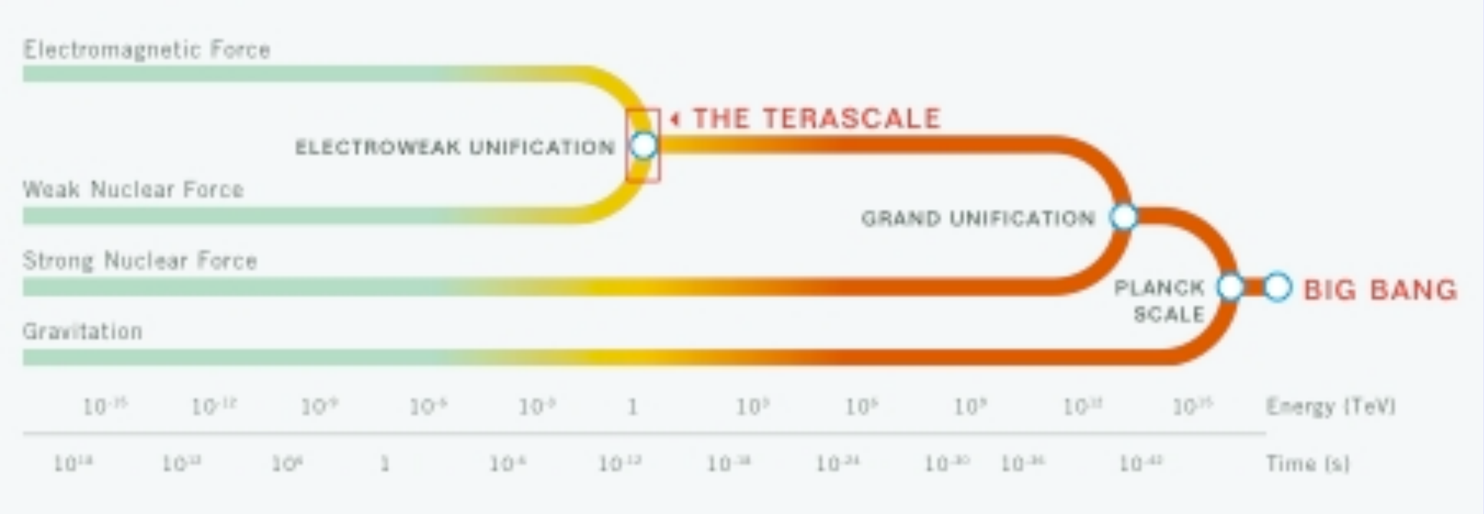
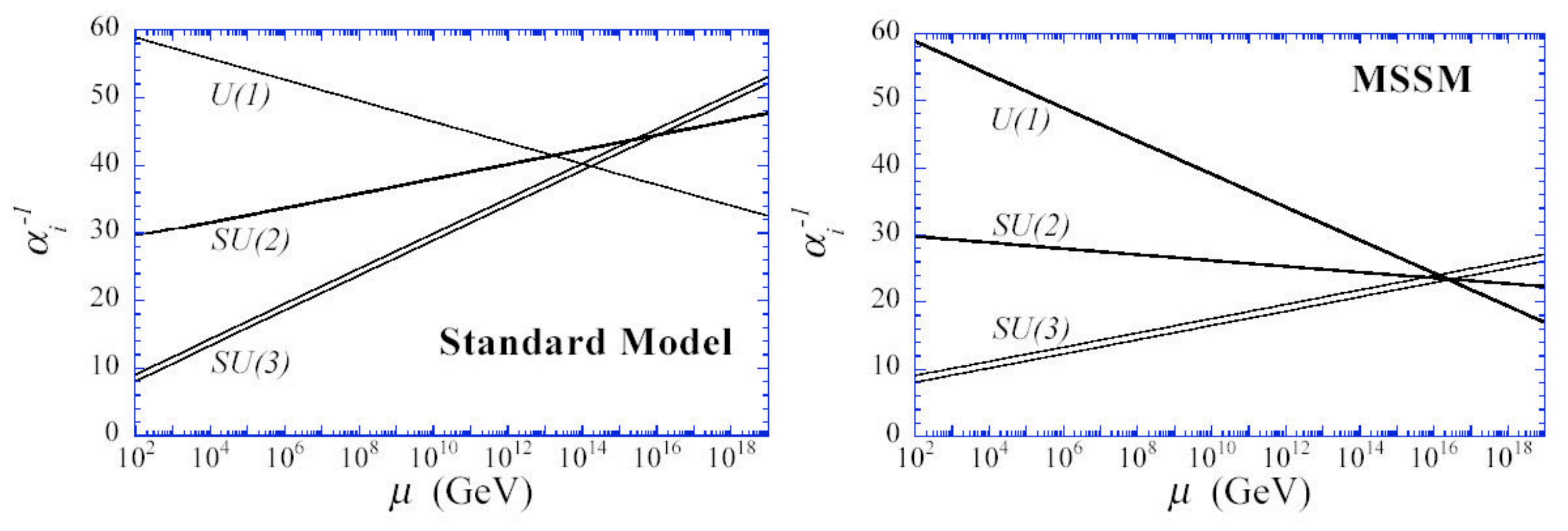
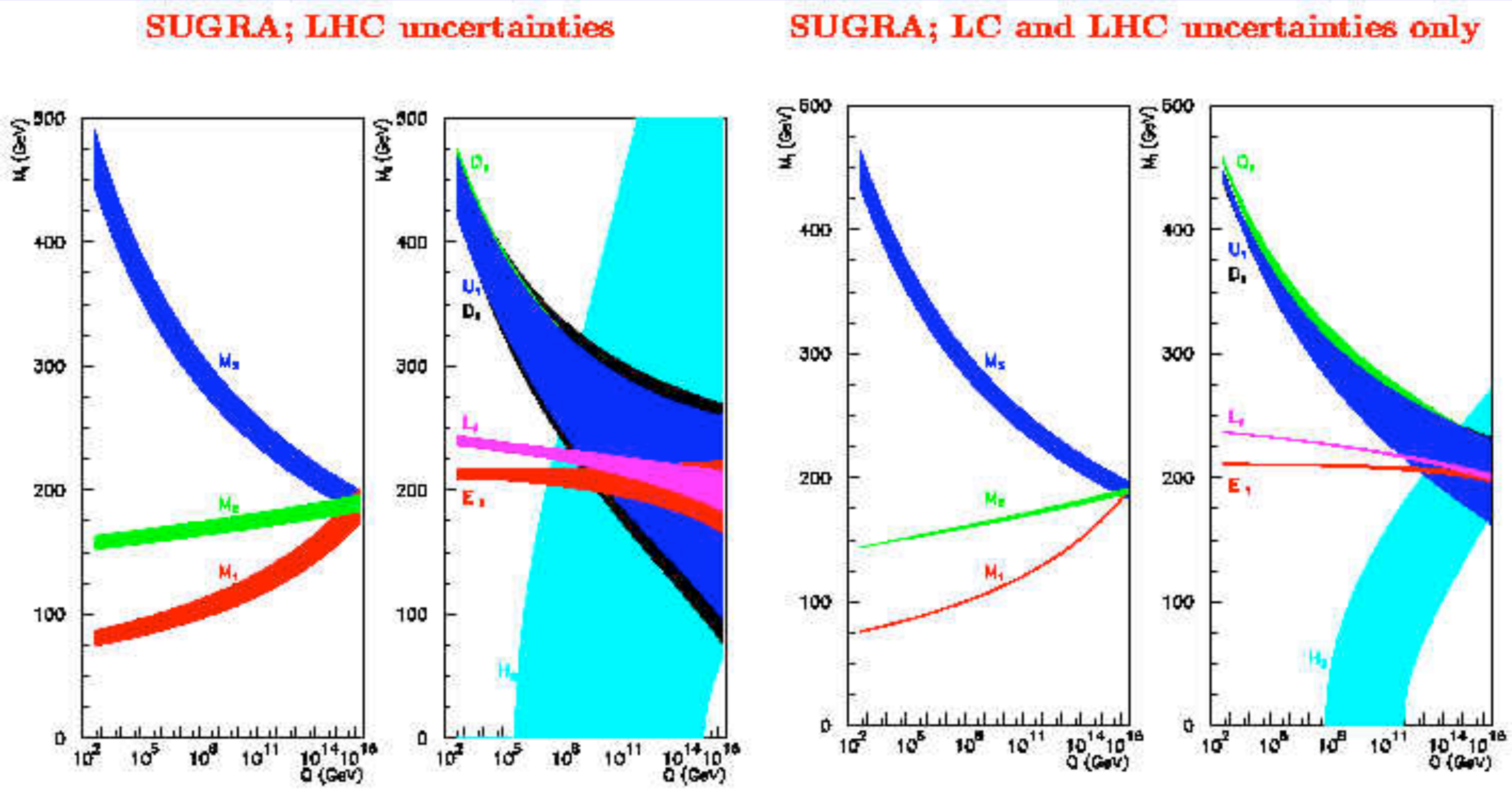




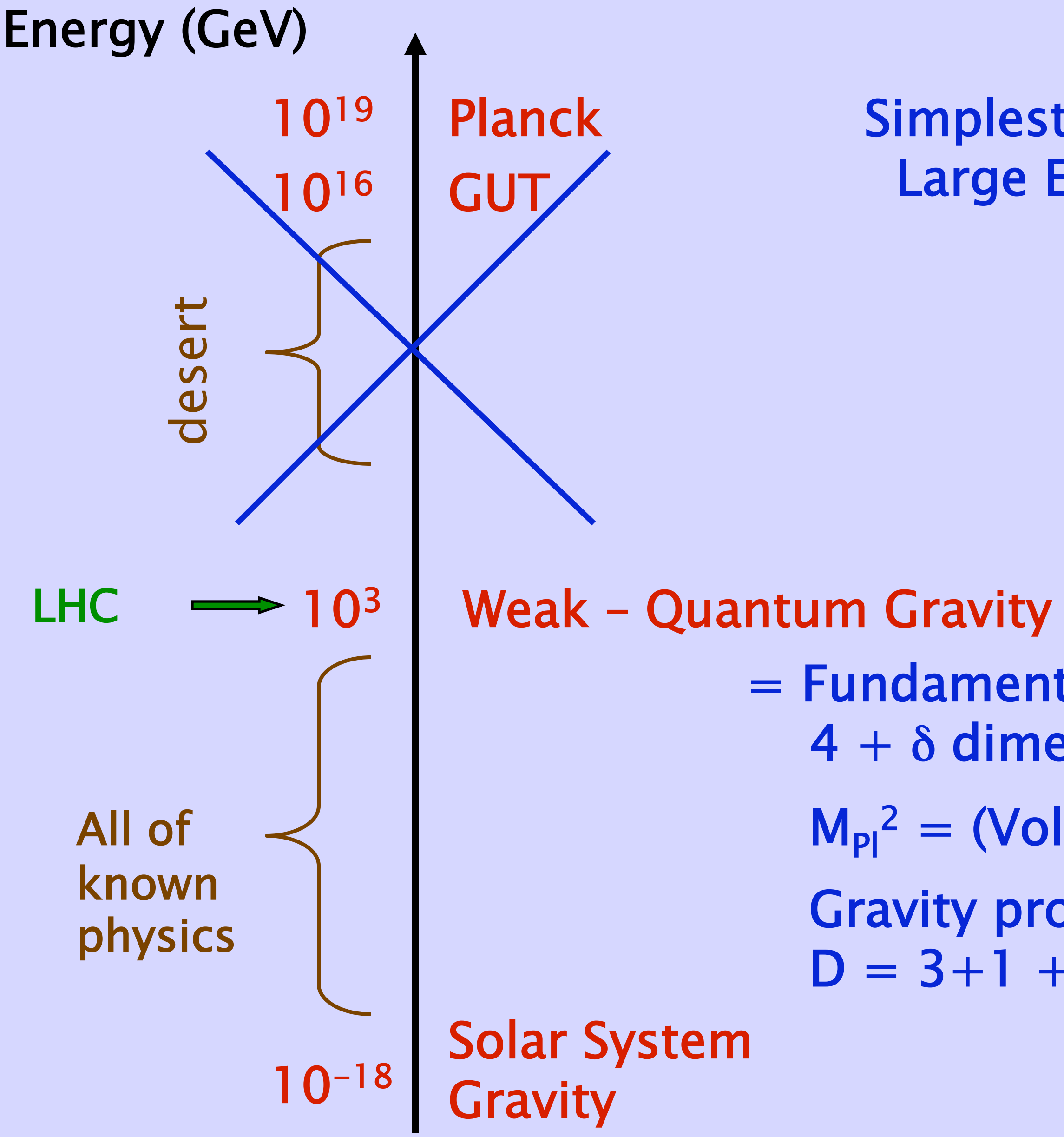
Telescope to Unification

Superpartner mass determinations provide tests for unification

Evolution of superpartner masses to high scale:



The Hierarchy Problem: Extra Dimensions



Energy (GeV)

10^{19} Planck

10^{16} GUT

desert

LHC → 10^3 Weak – Quantum Gravity

All of
known
physics

10^{-18} Solar System
Gravity

Simplest Model:
Large Extra Dimensions

= Fundamental scale in
$4 + \delta$ dimensions

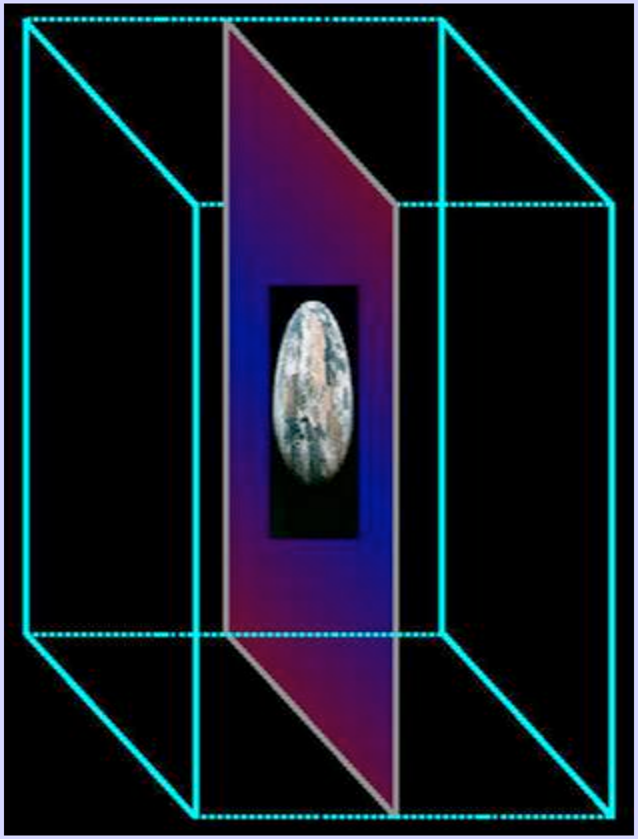
$M_{Pl}^2 = (\text{Volume})_\delta \, M_D^{2+\delta}$

Gravity propagates in
$D = 3+1 + \delta$ dimensions

Arkani-Hamed, Dimopoulis, Dvali

Extra dimensions are difficult to visualize

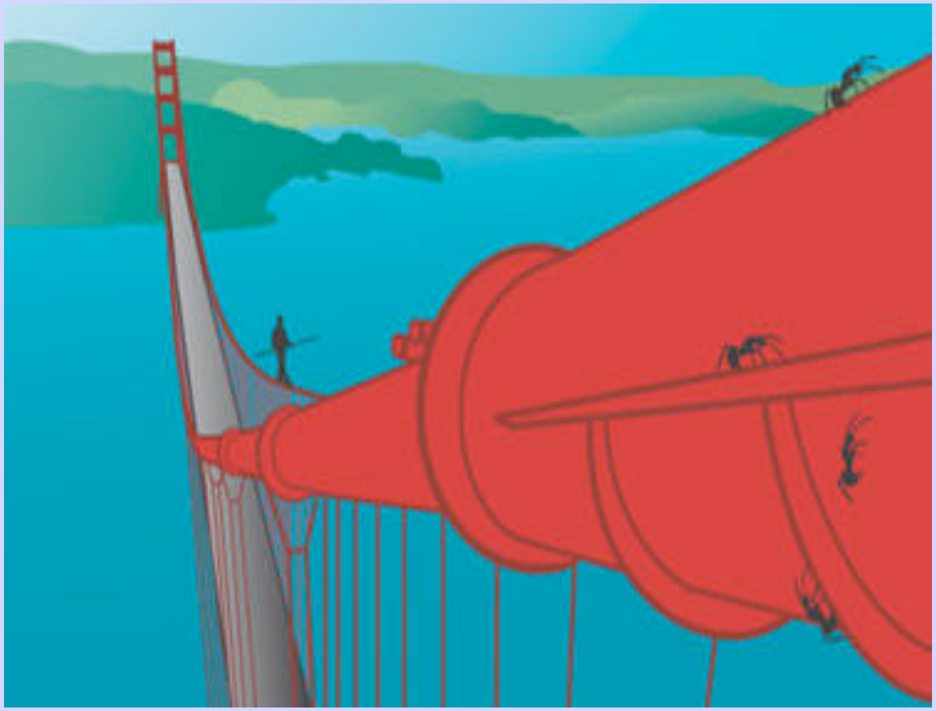
- One picture: the Braneworld scenario



- We are trapped on a 3-dimensional spatial membrane and cannot move in the extra dimensions
- Gravity spreads out and moves in the extra space
- The extra dimensions can be either very small or very large

Extra dimensions are difficult to visualize

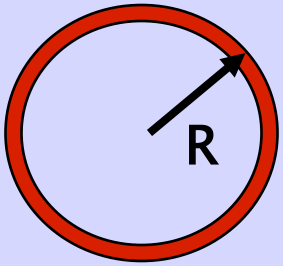
- Another picture: extra dimensions are too small for us to observe ⇒ they are ‘curled up’ and compact



The tightrope walker only sees one dimension: back & forth.

The ants see two dimensions: back & forth and around the circle

Kaluza-Klein particles



- Imagine a particle moving in a single extra dimension of size R
- It has momentum from this motion
- Quantum Mechanics says this momentum comes in steps: it has to be a multiple of 1/R
- $p_{extra} = \frac{n}{R}$ $\qquad n = 0, 1, 2, \ldots$
- “Particle in a Box”

Kaluza-Klein tower of particles

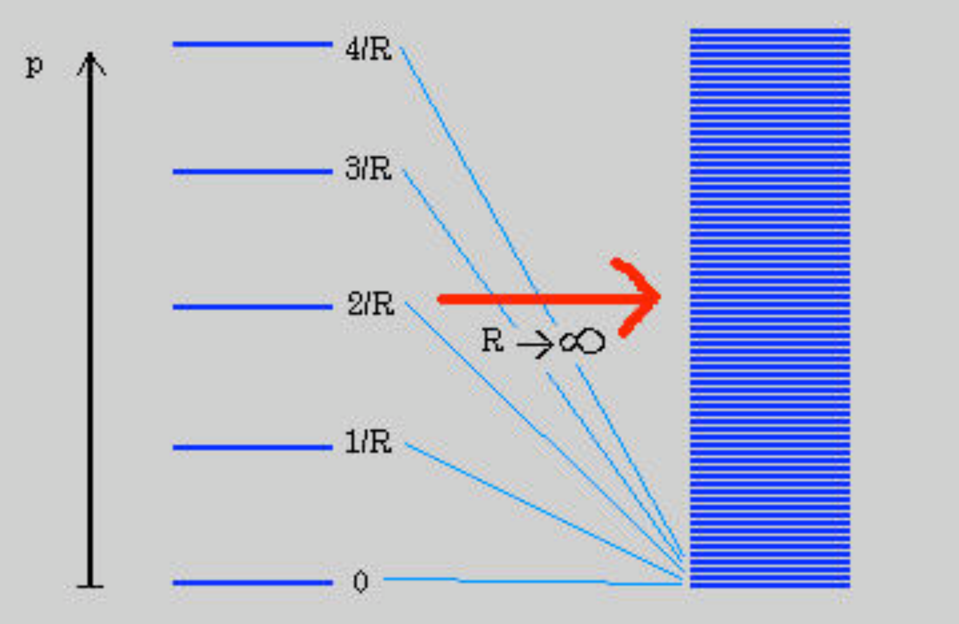
$$E^2 = (p_x c)^2 + (p_y c)^2 + (p_z c)^2 + \underbrace{(p_{extra} c)^2 + (mc^2)^2}$$

Recall $p_{extra} = n/R$

In 4 dimensions,
looks like a mass!

Tower of massive particles

Small radius gives well separated Kaluza-Klein particles



Large radius gives finely separated Kaluza-Klein particles

Small radius

Large radius

An artist's rendition of Kaluza-Klein modes

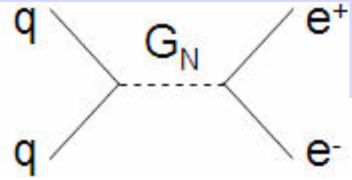
Kaluza-Klein (Invisible Architecture III)

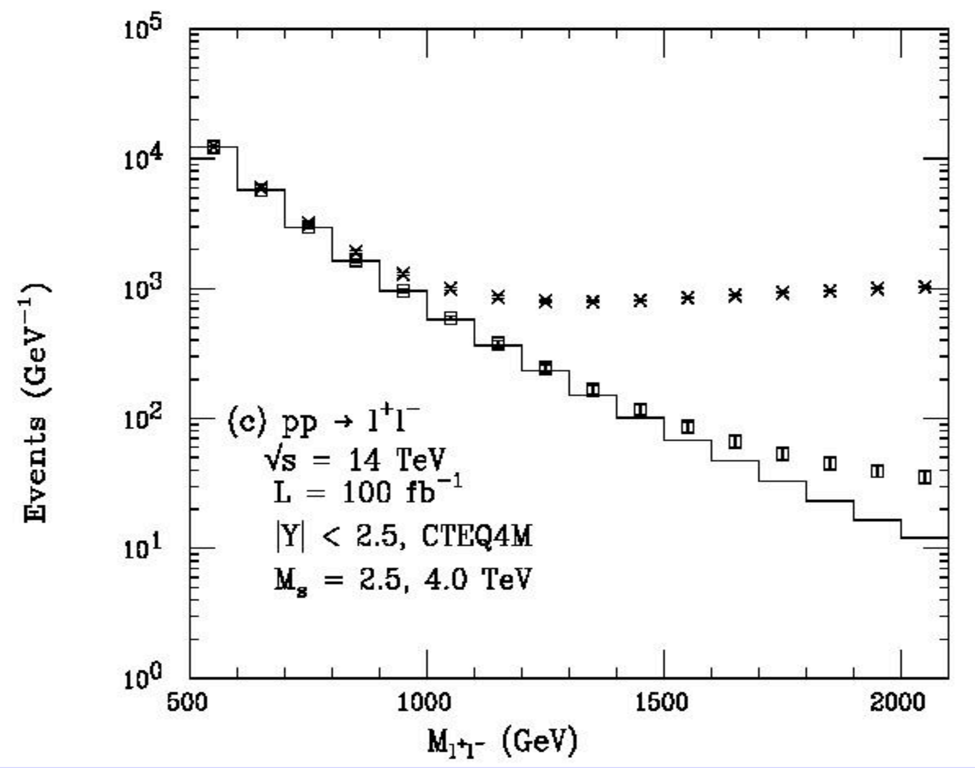
Dawn Meson

The possibility of additional dimensions captivates the imagination of humankind!

Kaluza-Klein Modes in a Detector: I

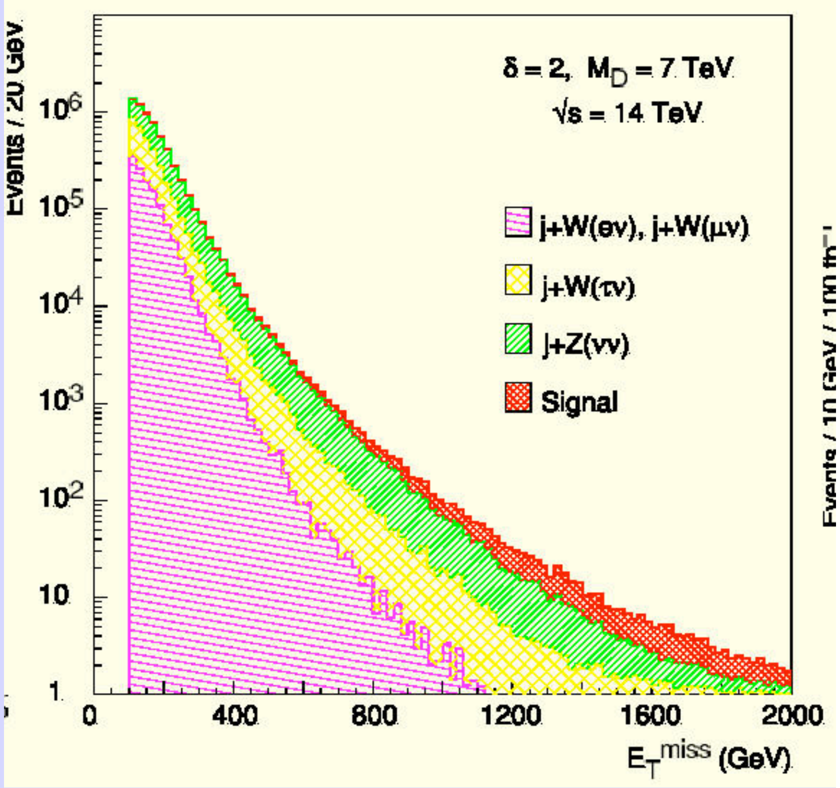
Indirect Signature





Missing Energy Signature

$$pp \rightarrow g + G_n$$

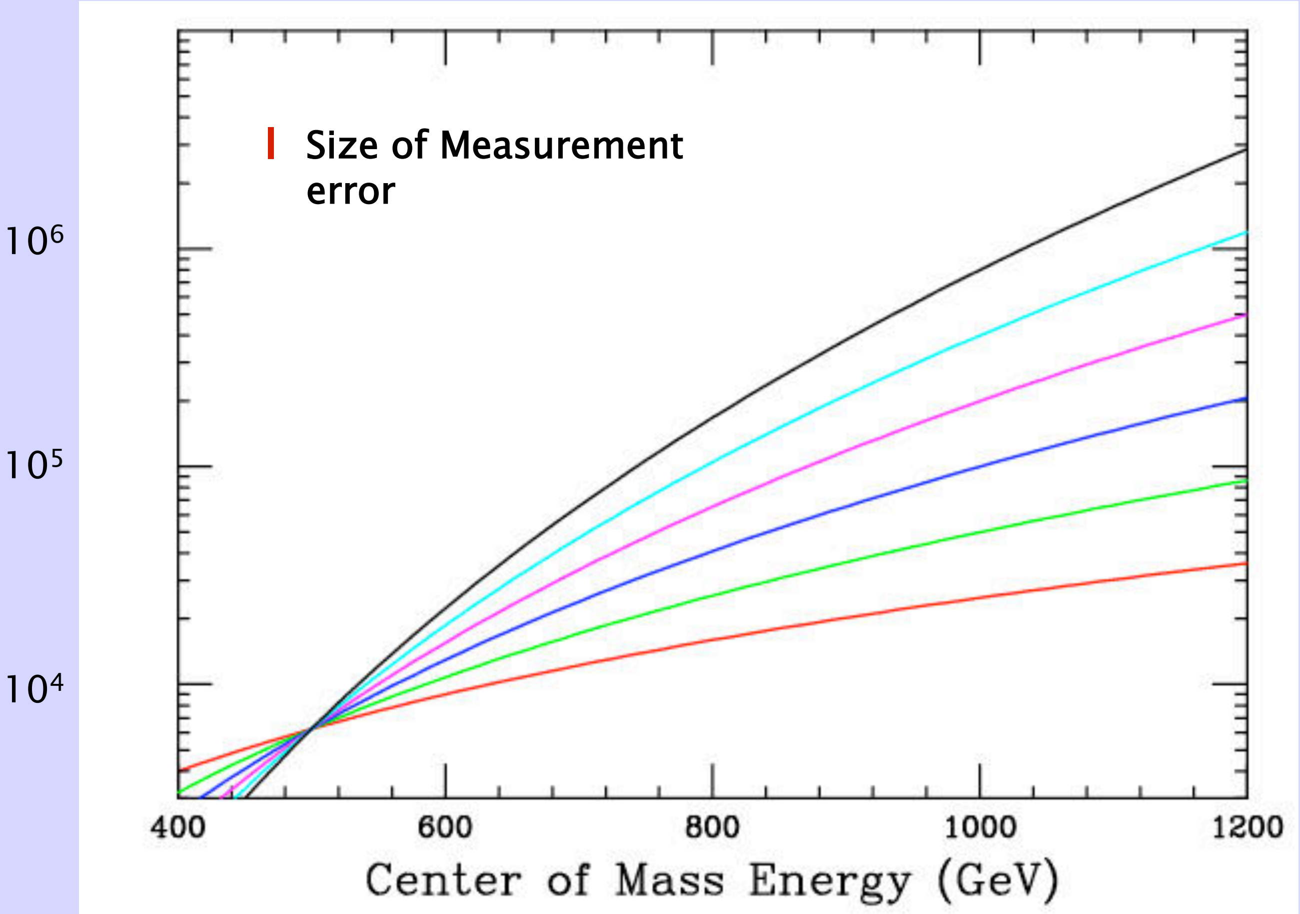


Detailed measurements of the properties of KK modes can determine:

- That we really have discovered additional spatial dimensions
- Size of the extra dimensions
- Number of extra dimensions
- Shape of the extra dimensions
- Which particles feel the extra dimensions
- If the branes in the Braneworld have fixed tension
- Underlying geometry of the extra dimensional space

Example: Production of Graviton Kaluza-Klein modes in flat extra dimensions, probes gravity at distances of ~ 10^{-18} cm

Production rate for $e^+e^- \rightarrow \gamma$ + Graviton



with

7
6
5
4
3
2

Extra Dimensions

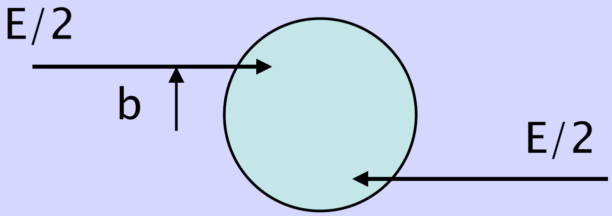
Measurement possible due to well-defined initial state & energy plus clean environment

Black Hole Production @ LHC:

Dimopoulos, Landsberg
Giddings, Thomas

Black Holes produced when $\sqrt{s} > M_*$

Classical Approximation: [space curvature << E]



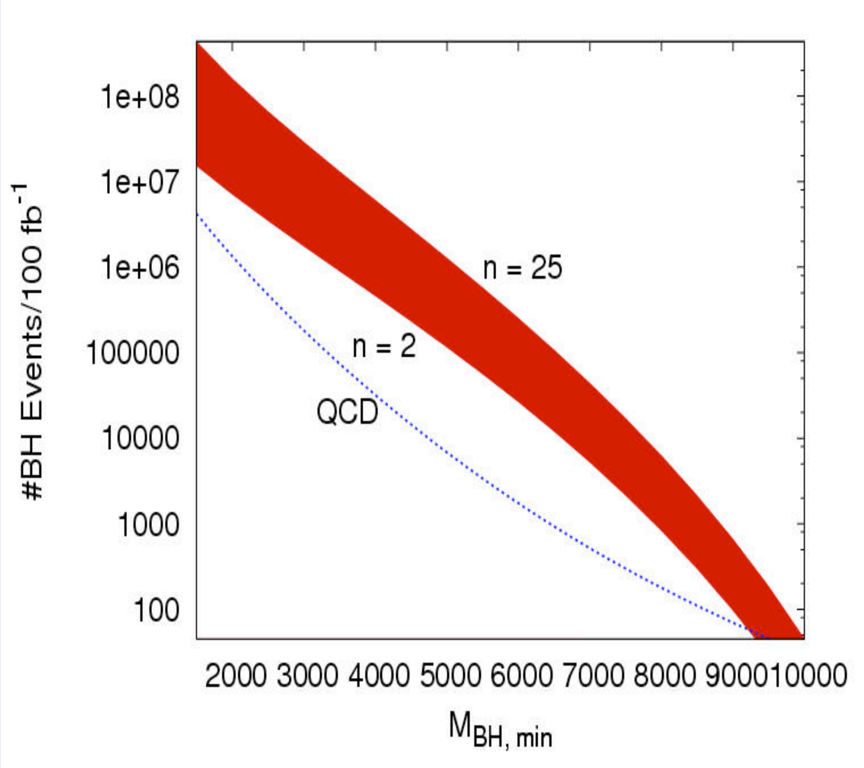
$b < R_s(E) \Rightarrow$ BH forms

$$M_* R_s = \left[\frac{\Gamma(\frac{n+3}{2})}{(n+2)\pi^{(n+3)/2}} \frac{M_{BH}}{M_*} \right]^{1/(n+1)}$$

Geometric Considerations:

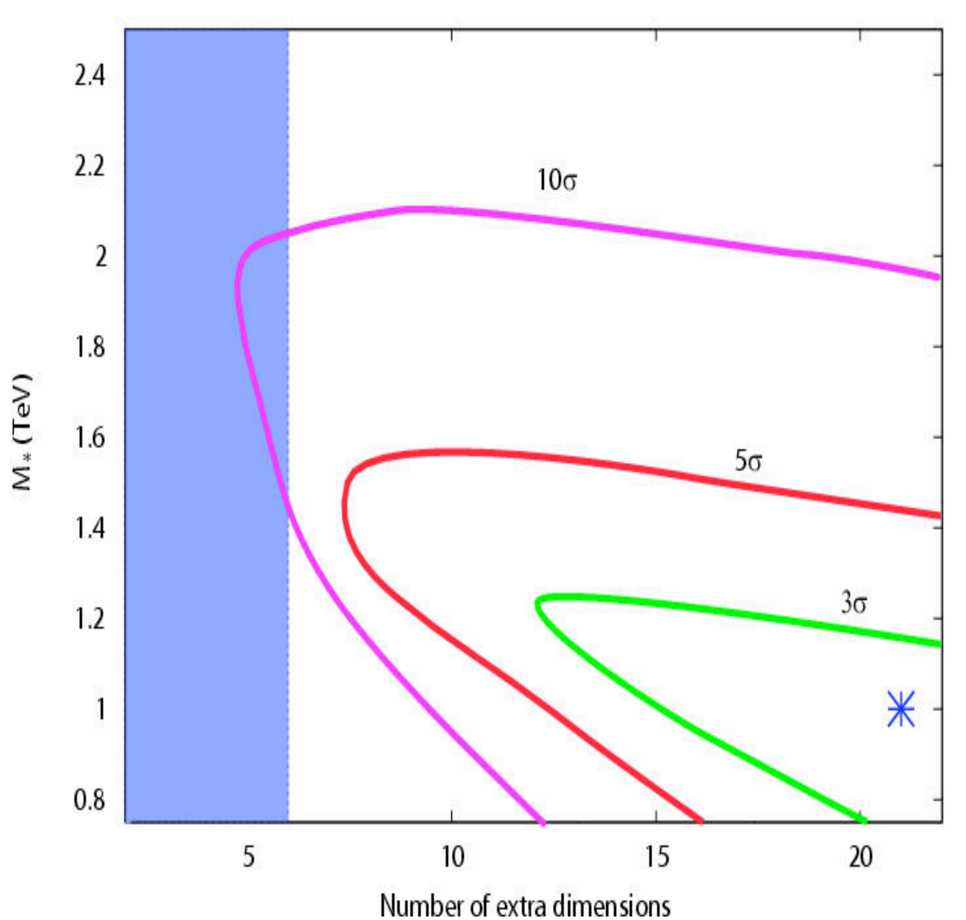
$\sigma_{\text{Naïve}} = \pi R_s^{\,2}(E)$, details show this holds up to a factor of a few

Production rate is enormous!



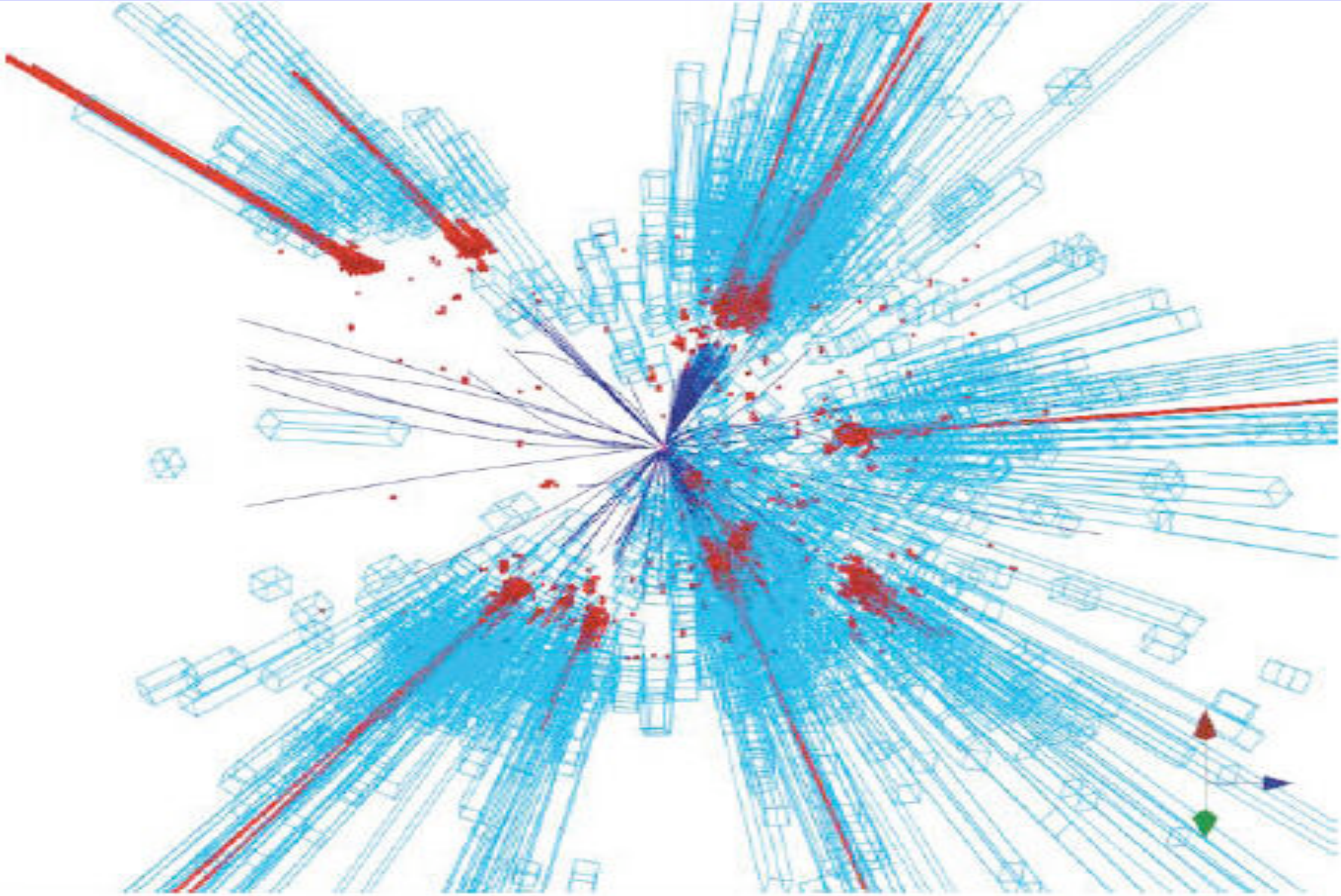
1 per sec at LHC!

Determination of Number of Large Extra Dimensions

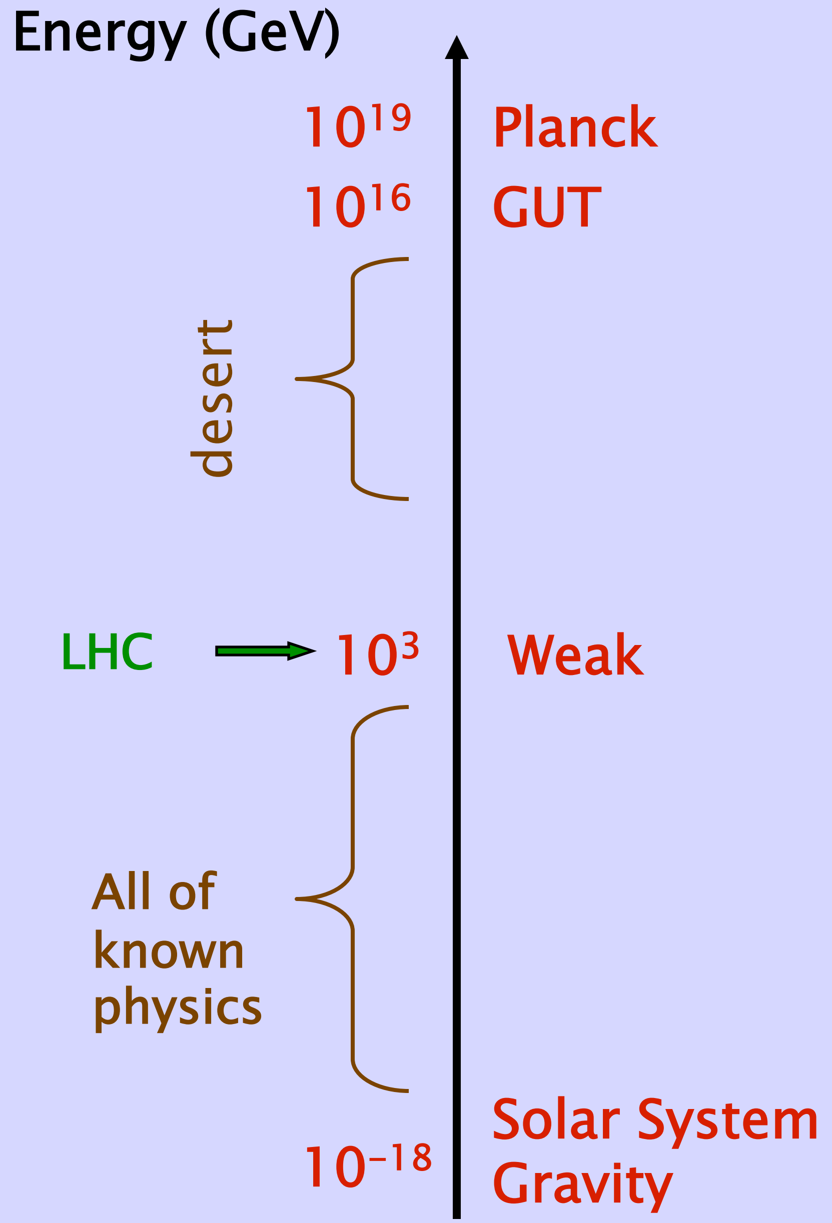


JLH, Lillie, Rizzo
hep-ph/0503178

Black Hole event simulation @ LHC



The Hierarchy Problem: Extra Dimensions



Energy (GeV)

10^{19} Planck

10^{16} GUT

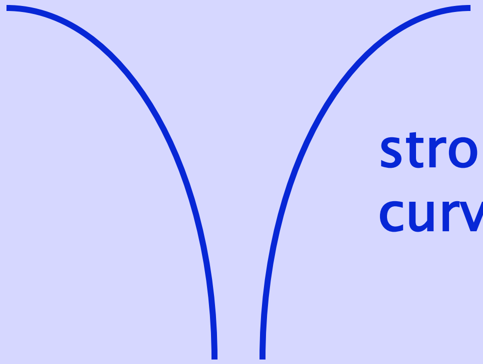
desert

LHC → 10^{3} Weak

All of known physics

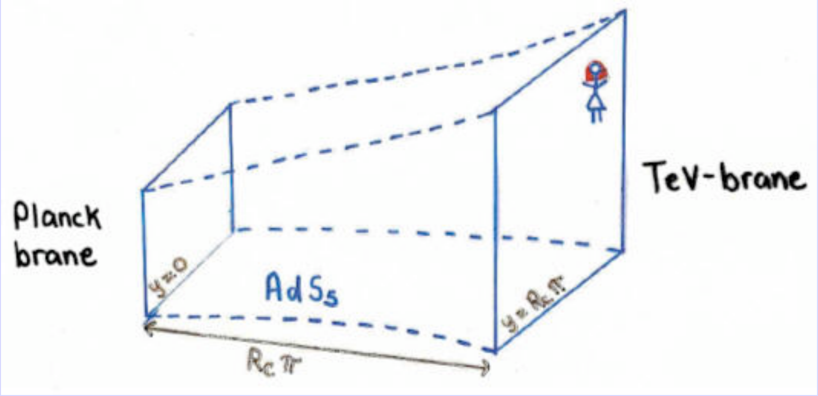
10^{-18} Solar System Gravity

Model II:
Warped Extra Dimensions



strong curvature

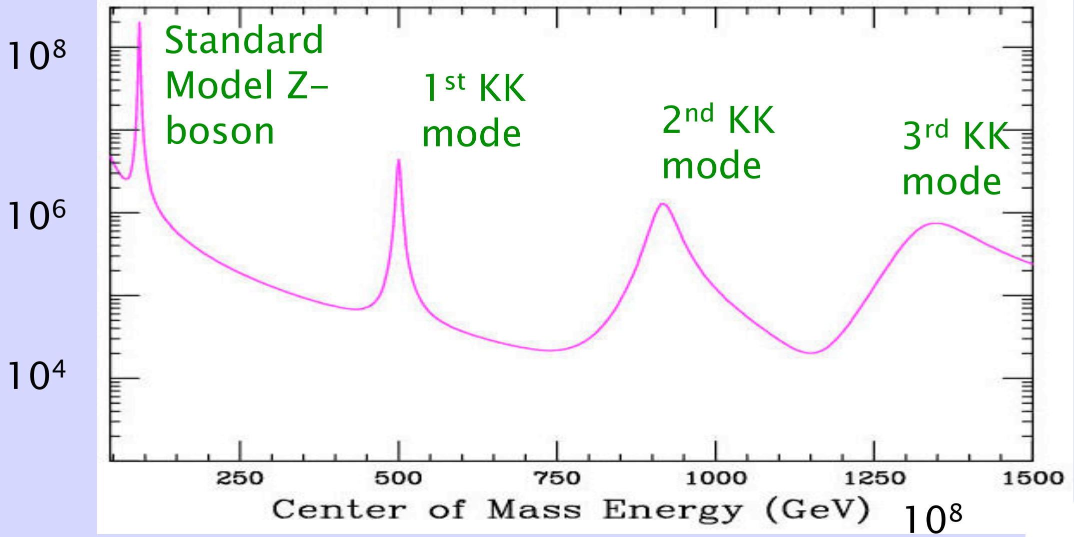
$$\Lambda_{wk} = M_{Pl}\, e^{-kr\pi}$$



Randall, Sundrum

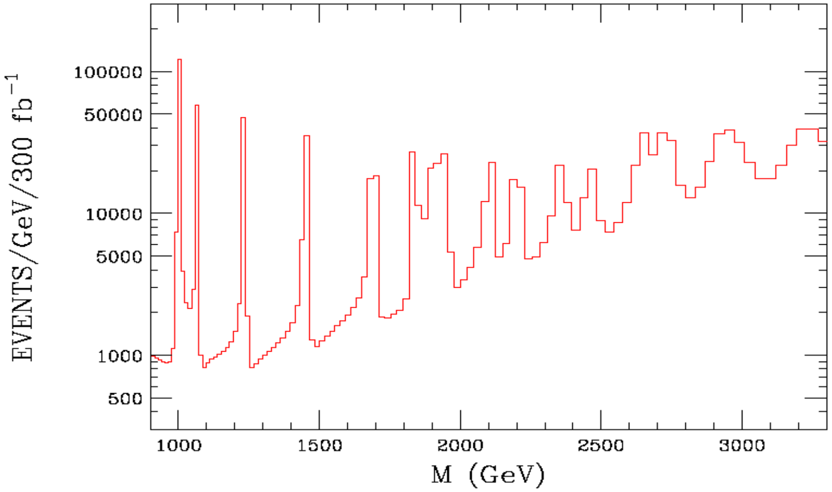
Kaluza–Klein Modes in a Detector: II

Number of Events in $e^+e^- \to \mu^+\mu^-$



For a conventional braneworld model with a single curved extra dimension of size ~ 10^{-17} cm

For this same model embedded in a string theory



Davoudiasl, JLH, Rizzo

This is a Special Time in Particle Physics

- Urgent Questions

  Provocative discoveries lead to urgent questions

- Connections

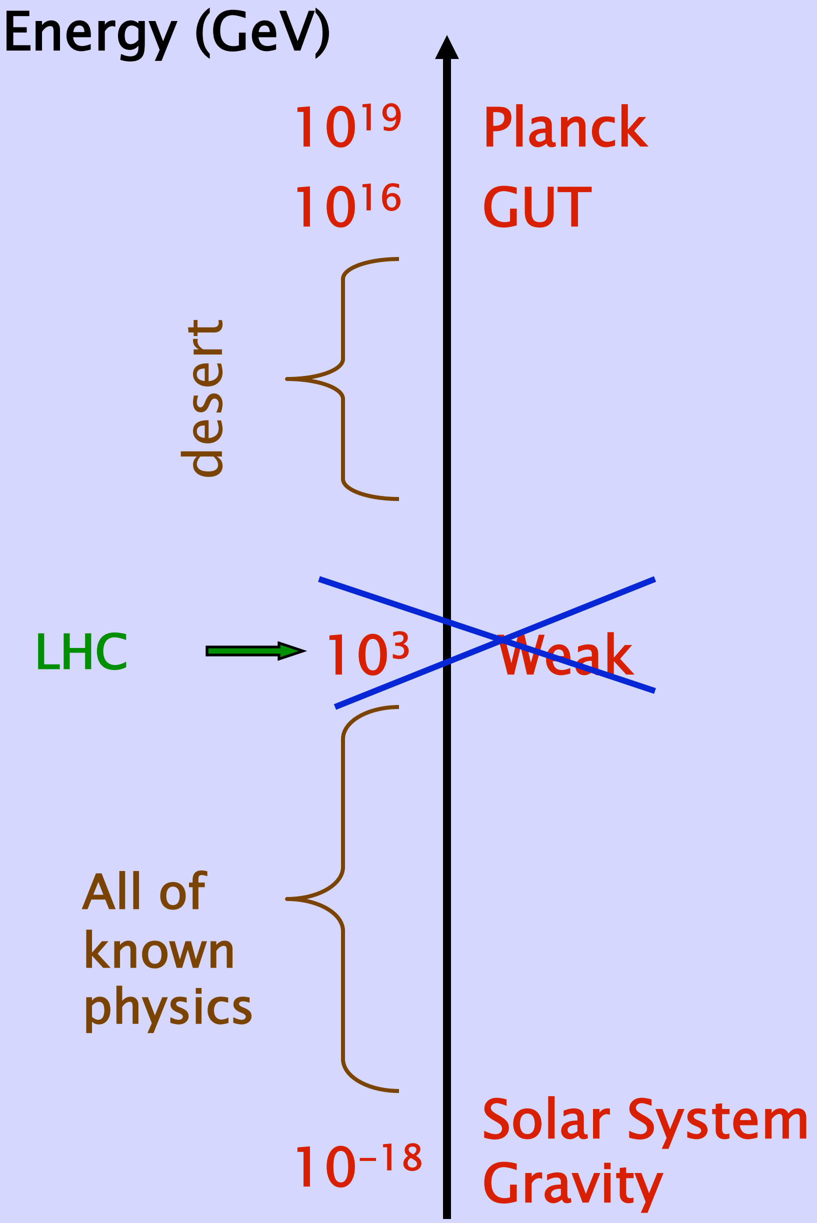
  Questions seem to be related in fundamental, yet mysterious, ways

- Tools

  We have the experimental tools, technologies, and strategies to tackle these questions

We are witnessing a Scientific Revolution in the Making!

The Hierarchy Problem: Higgsless



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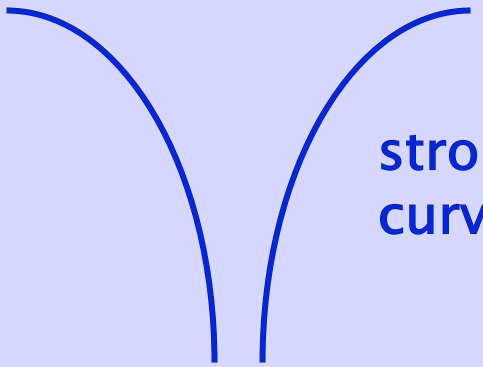
Warped Extra Dimensions



strong curvature

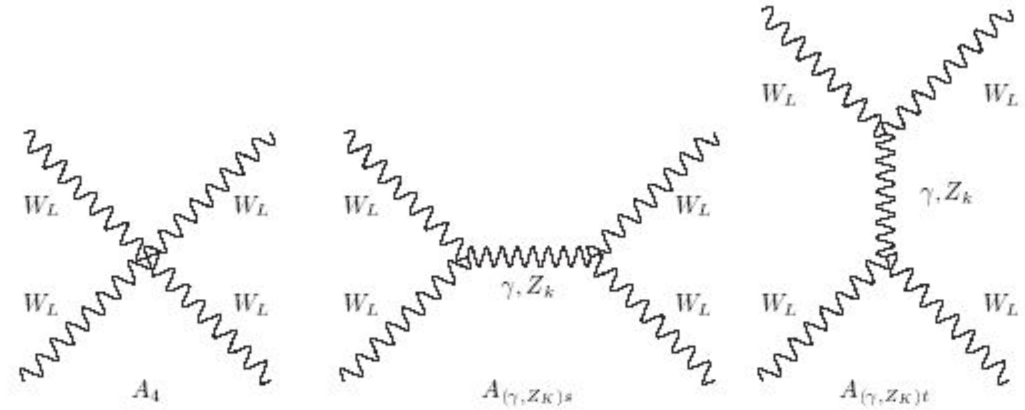
$$\Lambda_{wk} = M_{Pl}\, e^{-kr\pi}$$

With NO Higgs boson!

Csaki, Grojean,Murayama, Pilo, Terning

Unitarity in Gauge Boson Scattering: What do we do without a Higgs?

Exchange gauge
KK towers:



Conditions on KK masses & couplings:

Csaki etal, hep-ph/0305237

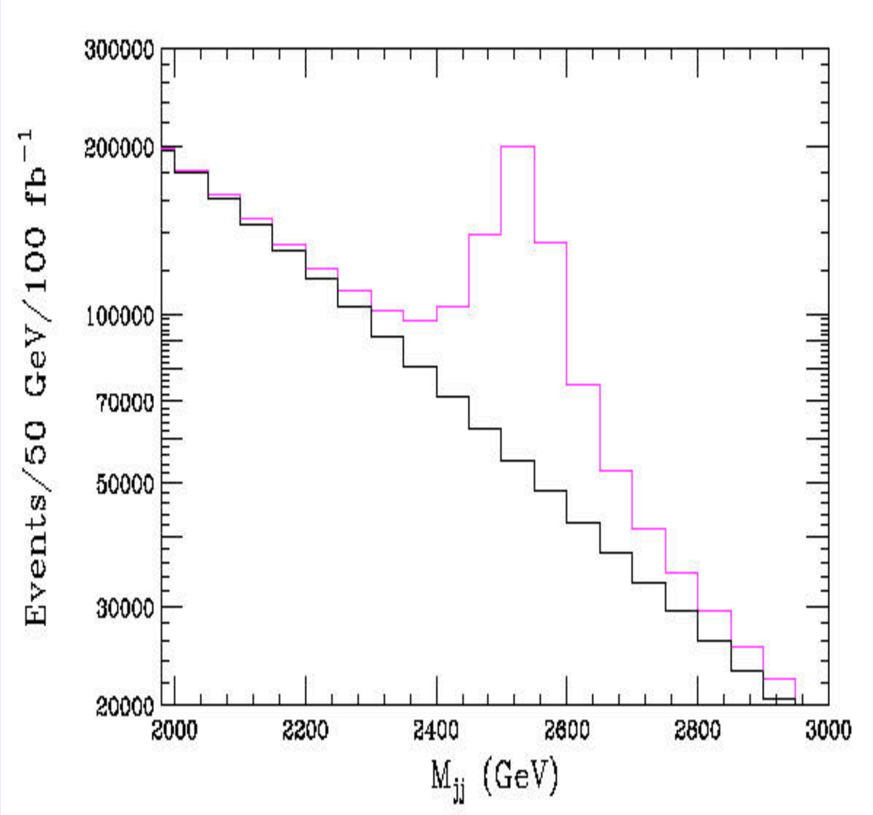
$(g_{1111})^2 = \Sigma_k (g_{11k})^2$

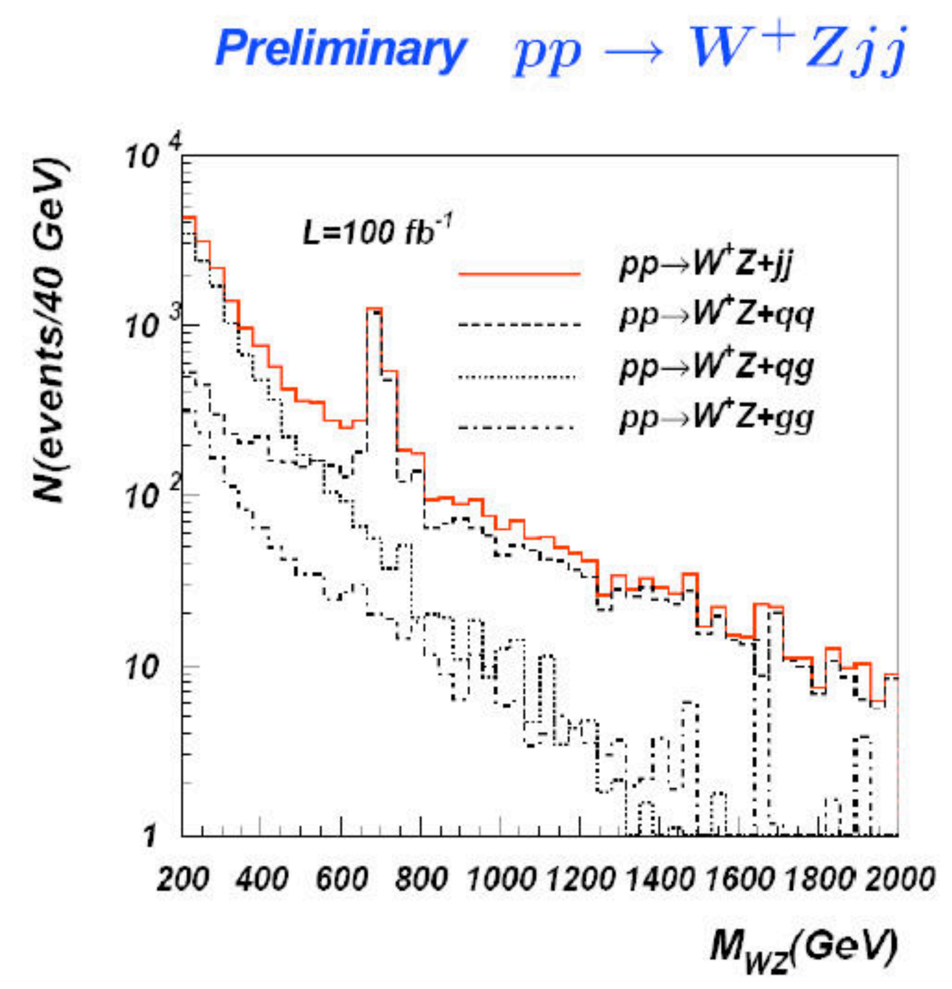
$4(g_{1111})^2 M_1^2 = \Sigma_k (g_{11k})^2 M_k^2$

Necessary, but not sufficient, to guarantee perturbative unitarity!
Some tension with precision EW

Production of Gauge KK States @ LHC

$gg, q\bar{q} \to g_1 \to$ dijets

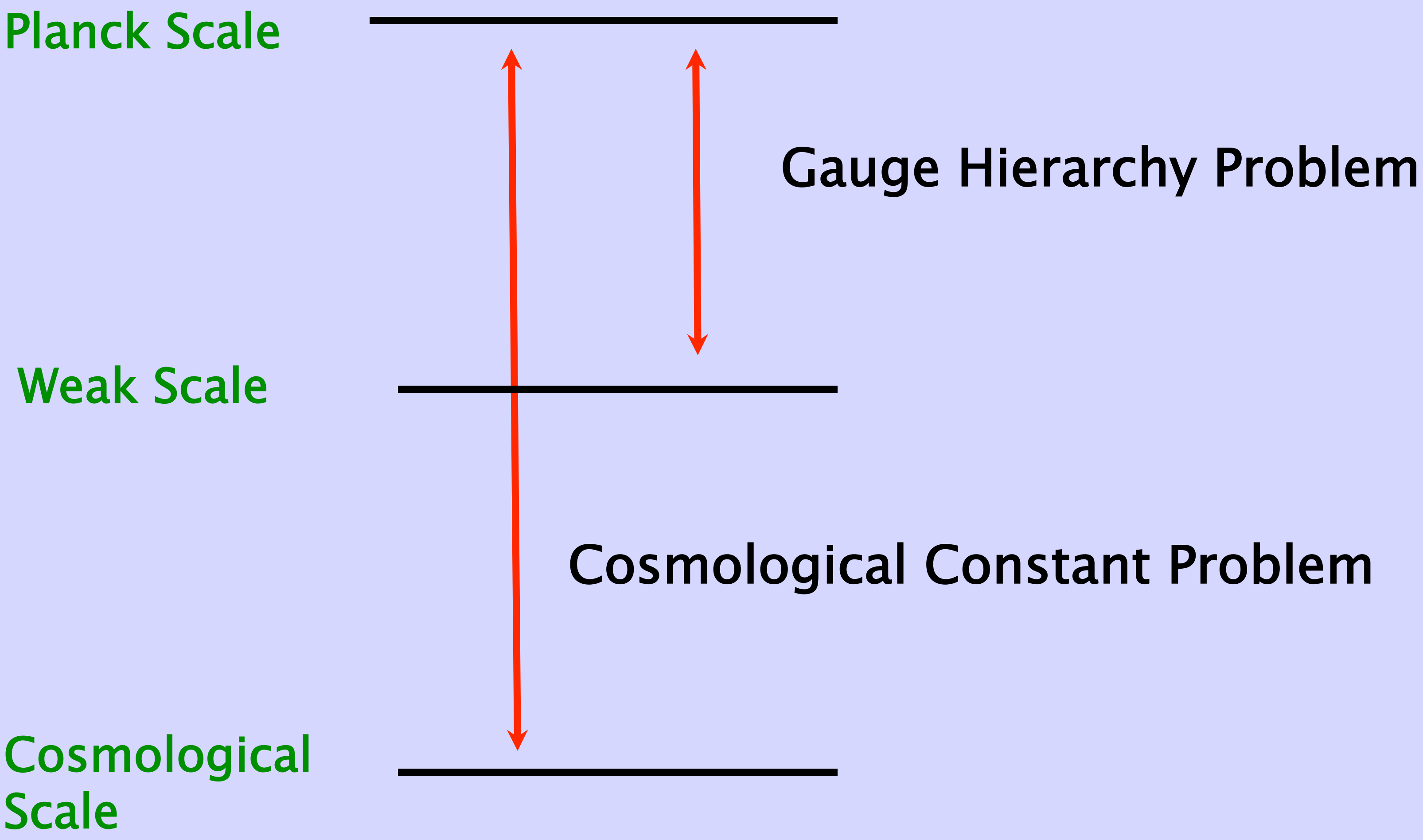




Davoudiasl, JLH, Lilllie, Rizzo

Balyaev, Christensen

The Hierarchy Problem: Who Cares!!



Planck Scale

Gauge Hierarchy Problem

Weak Scale

Cosmological Constant Problem

Cosmological Scale

We have much bigger Problems!

Split Supersymmetry:

Arkani-Hamed, Dimopoulis hep-ph/0405159
Giudice, Romanino hep-ph/0406088

Energy
(GeV)

M_{GUT} ~ 10^{16} GeV

M_S : SUSY broken at high scale ~ 10^{9-13} GeV

Scalars receive mass @ high scale

M_{weak}

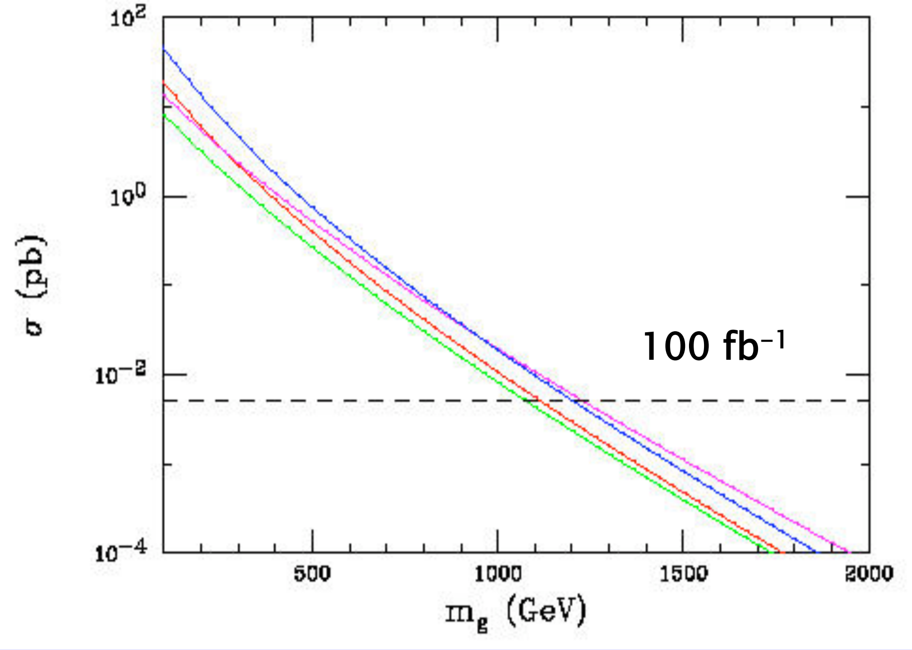
1 light Higgs + Fermions

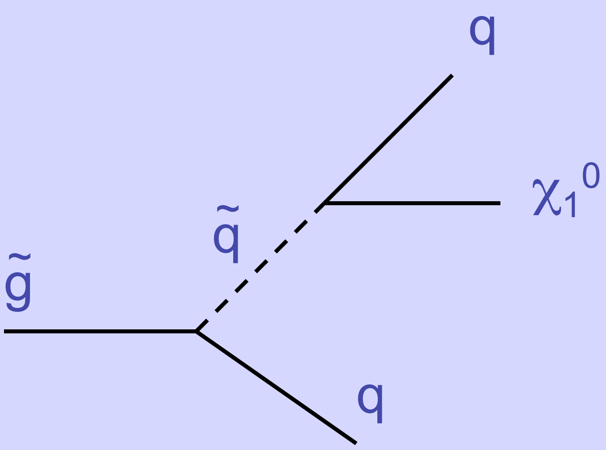
protected by chiral symmetry

Collider Phenomenology: Gluinos

- Pair produced via strong interactions as usual
- Gluinos are long-lived
- No MET signature
- Form R-hadrons

Gluino pair + jet cross section

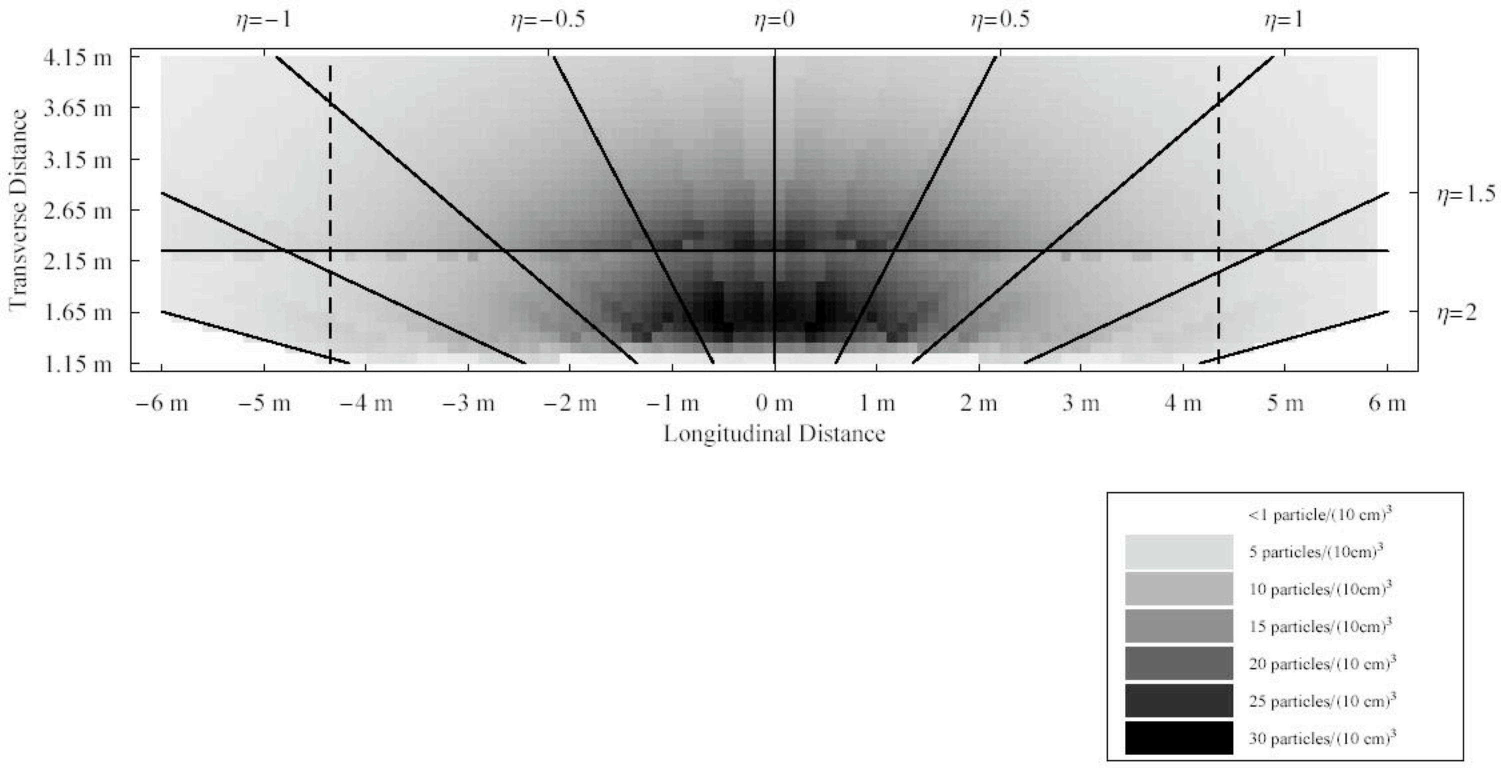




Rate ~ 0, due to heavy squark masses!

JLH, Lillie, Masip, Rizzo hep-ph/0408248

Density of Stopped Gluinos in ATLAS



Arvanitaki, etal hep-ph/0506242

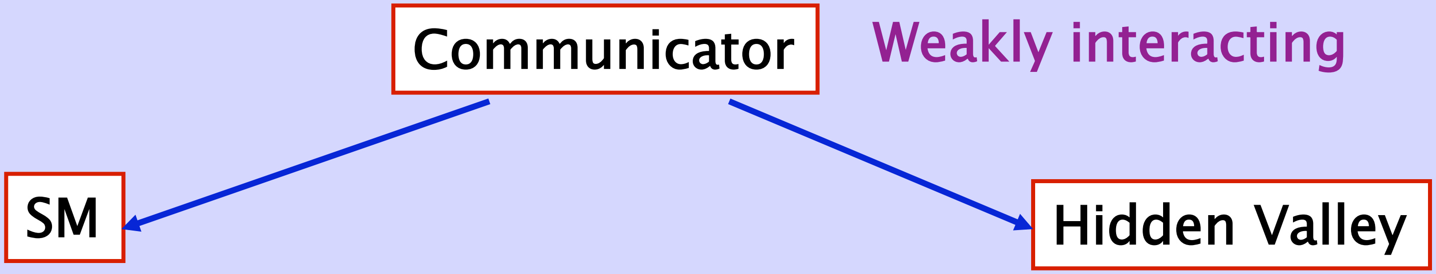
See also ATLAS study, Kraan etal hep-ph/0511014

Hidden Valleys

Strassler, Zurek 2006

Many theories contain new sectors that decouple

Basic structure:



Communicator

Weakly interacting

SM

Hidden Valley

HV Particles have
long lifetimes

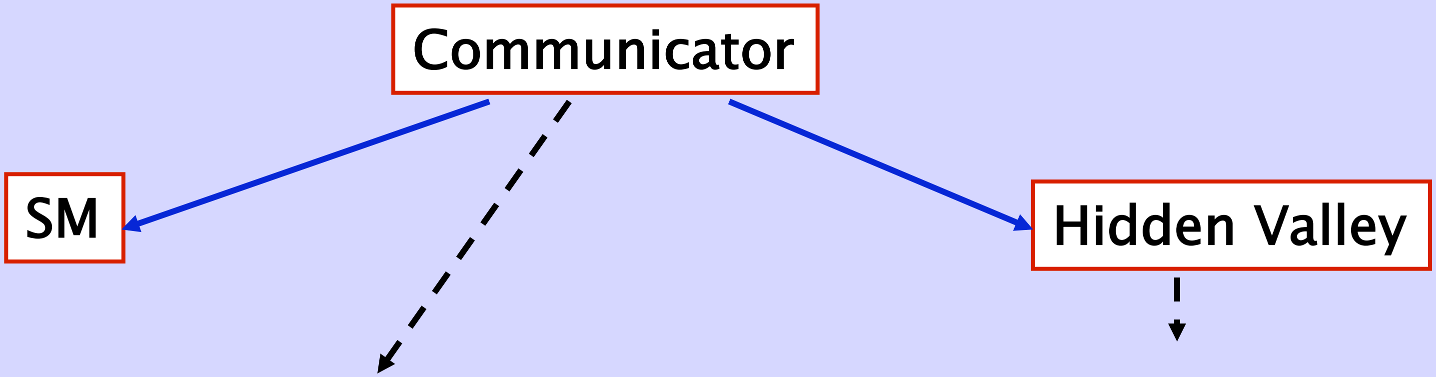
New Physics Sector that doesn’t couple directly to SM

Hidden Valleys

Strassler, Zurek 2006

Many theories contain new sectors that decouple

Basic structure:



Communicator

SM

Hidden Valley

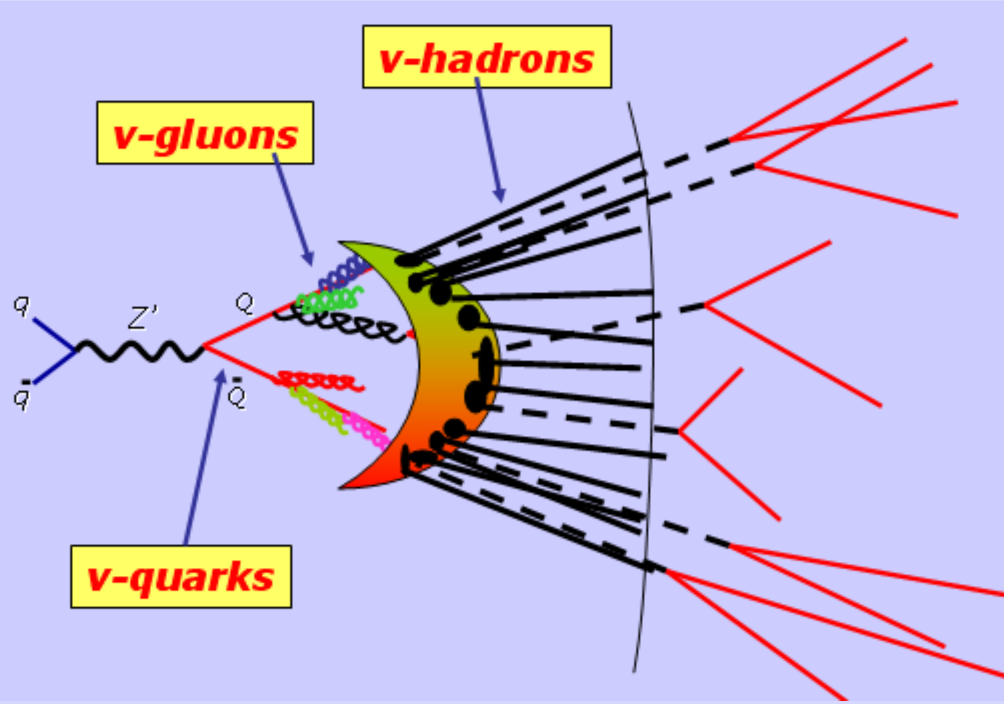
New Z’ from U(1)’
Higgs
LSP
Heavy Sterile ν’s
NP Loops
….

SUSY Breaking
Folded SUSY
Twin Higgs
KS Throats in RS
Multiple Gauge Groups
String Models
ν–QCD …..

Hidden Valley "Typical Signatures"

- Probably complex multi-jet events
- Probably missing energy (maybe a lot)
- Probably heavy flavor (maybe a lot)
- Maybe displaced jets
- Maybe non-isolated lower p_T leptons
- Event to event fluctuations

HV QCD w/ Z' communicator:



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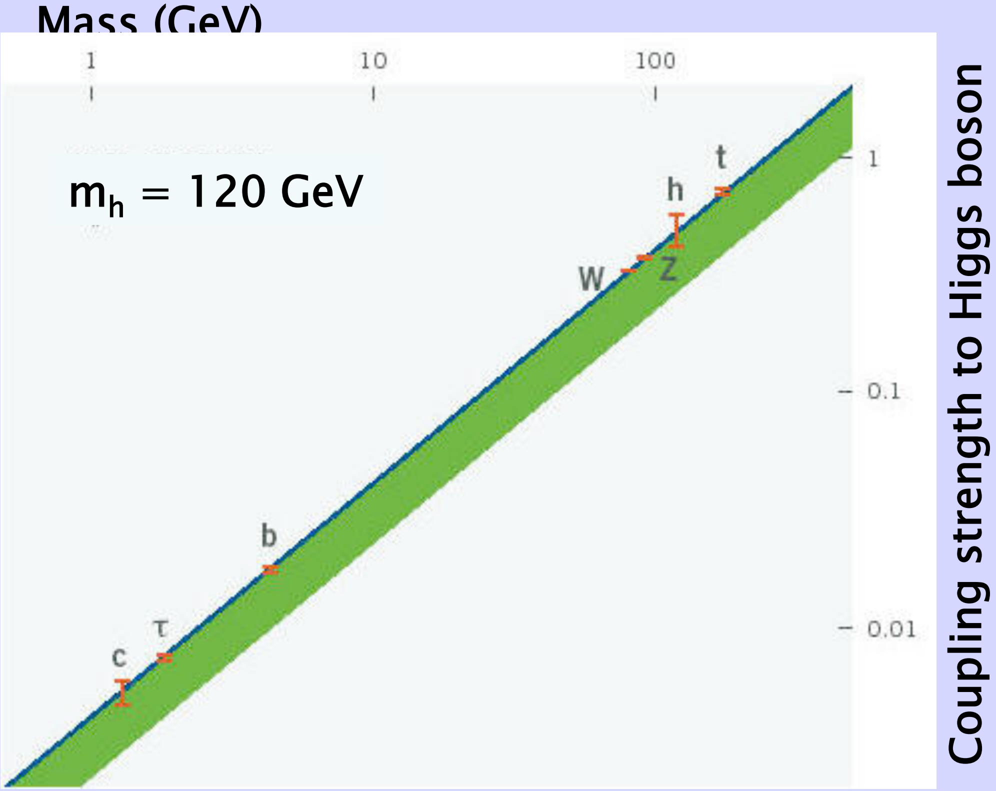
Higgs is *Different!*

First fundamental scalar to be discovered: could be related to many things, perhaps even dark energy

Possible deviations in models with Extra Dimensions

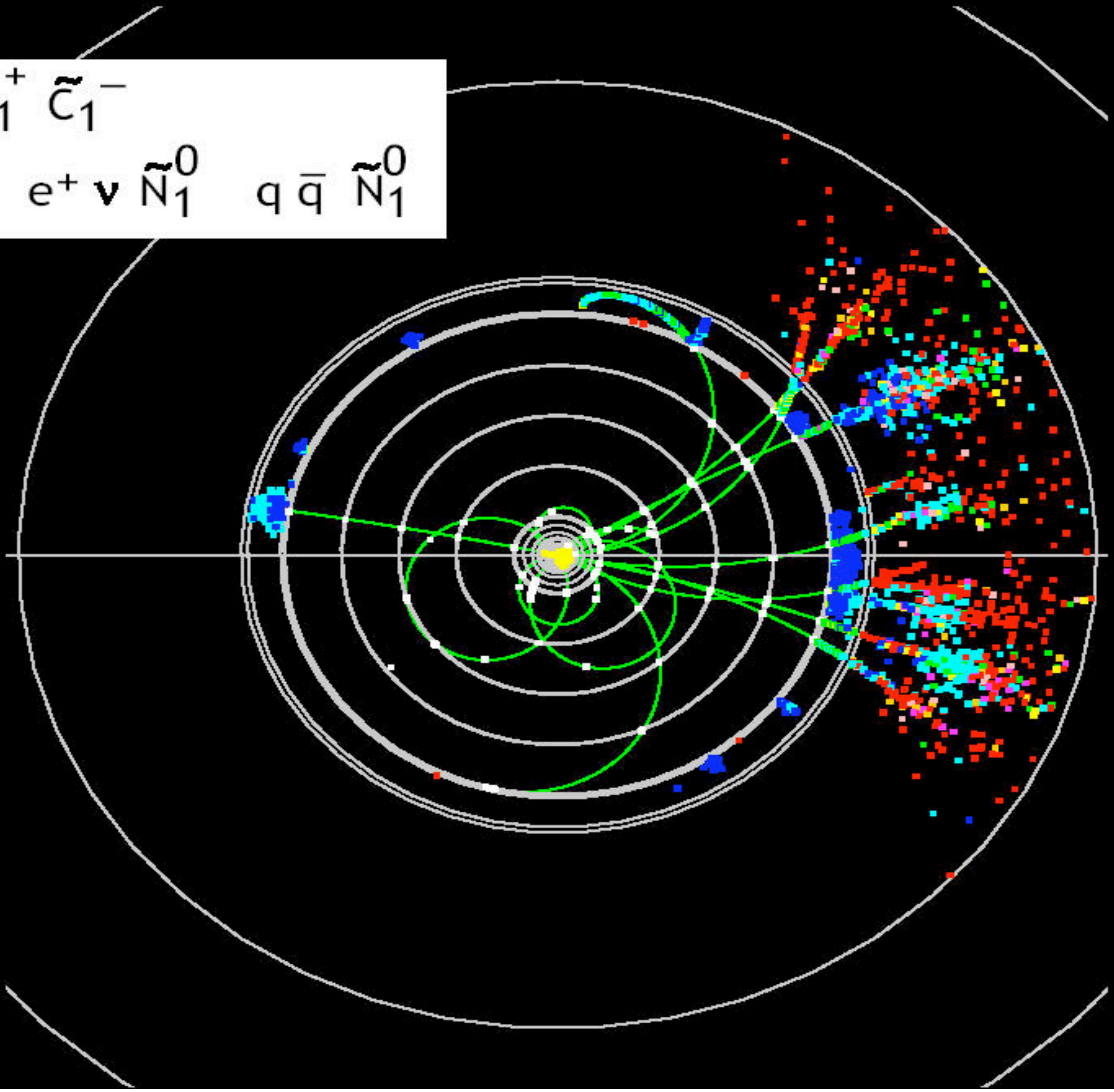


This is the right sensitivity to discover extra dimensions, new sources of CP violation, or other novel phenomena

ILC Detector Simulation of W-Superpartner Production

$$e^+e^- \to \tilde{C}_1^+ \ \tilde{C}_1^-$$

$$\to \quad e^+ \nu \ \tilde{N}_1^0 \quad q \ \bar{q} \ \tilde{N}_1^0$$

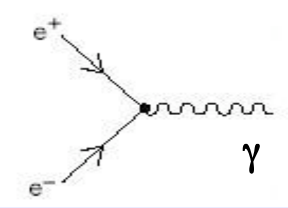


Supersymmetry at the ILC

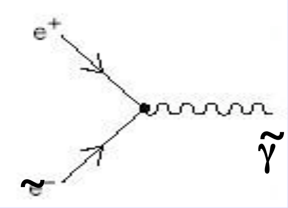
ILC Studies superpartners individually via $e^+e^- \to S\bar{S}$

Determines

- Quantum numbers (spin!)
- Supersymmetric relation of couplings

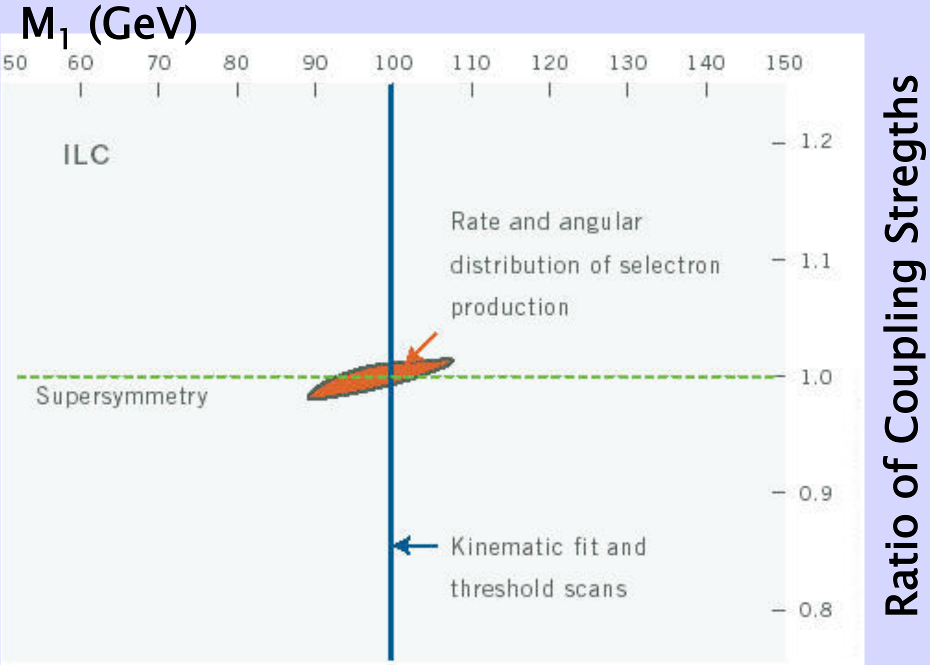


= e



= 2e

Selectron pair production

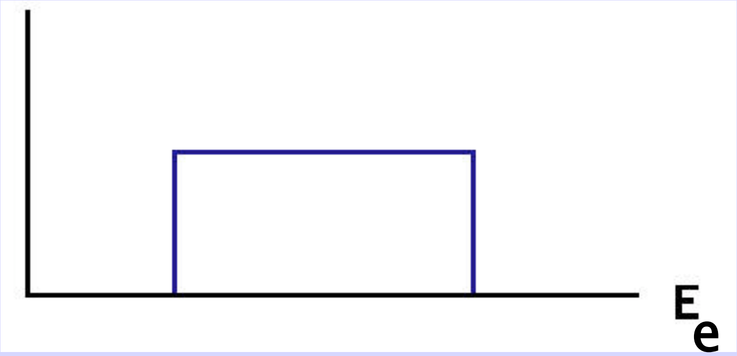


2% accuracy in determination of Supersymmetric coupling strength

Proof that it **IS** Supersymmetry!

Precise Mass Measurements of Superpartners

Example: $\tilde{e} \rightarrow e + \tilde{\gamma}$

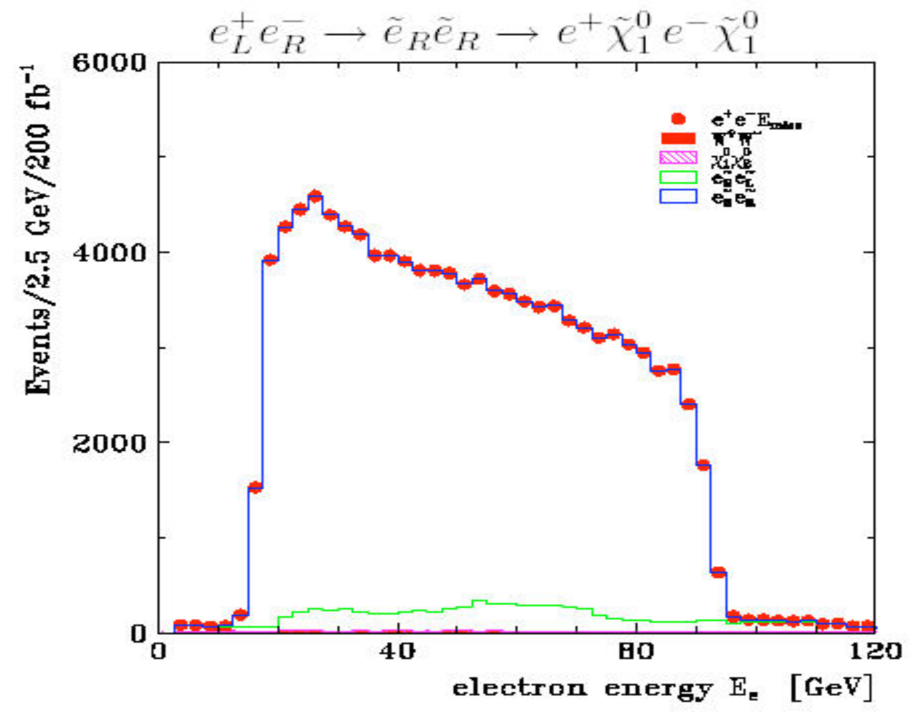


Fixed center of mass energy gives flat energy distribution in the laboratory for final state e^-

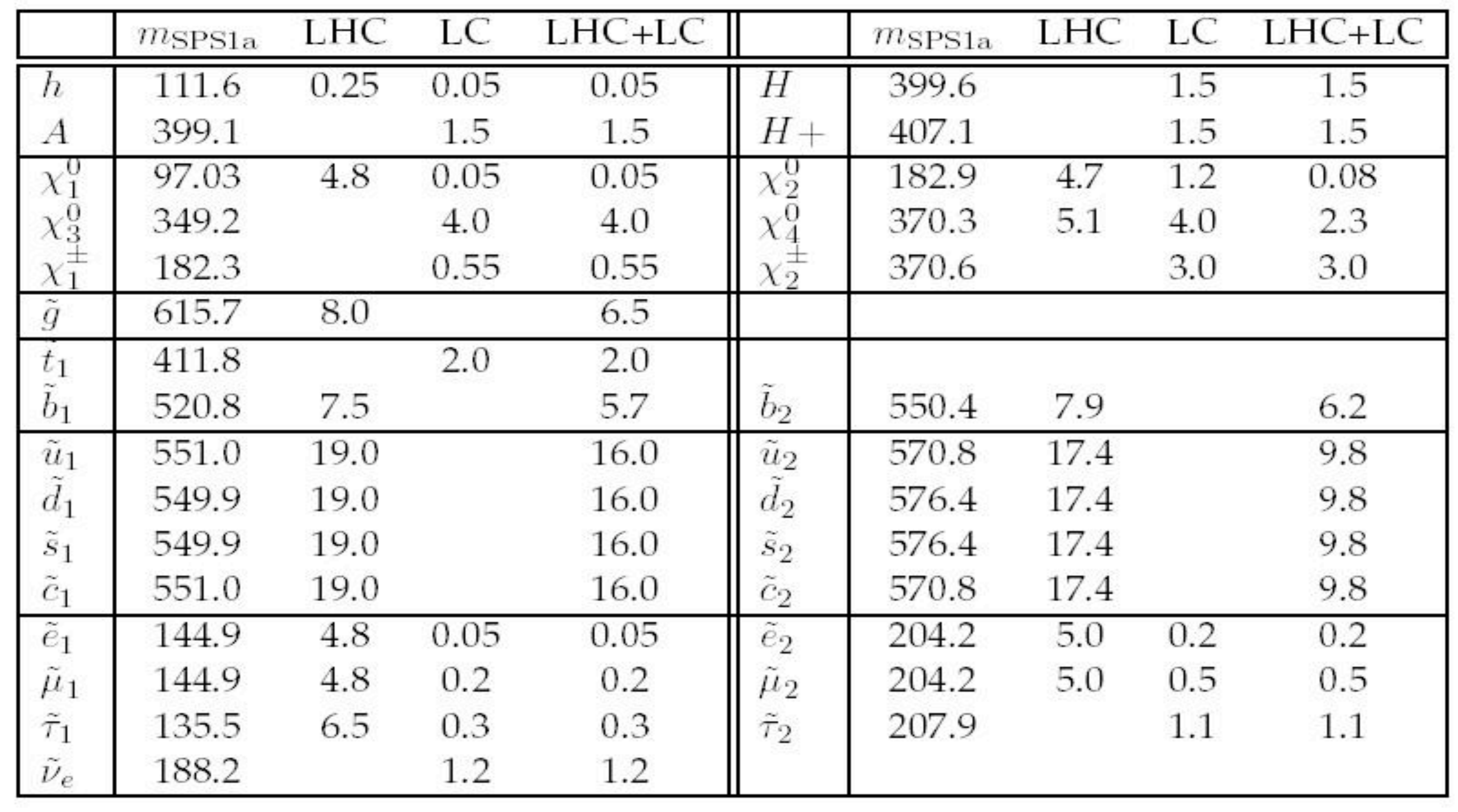
Endpoints can be used to determine superpartner masses to part-per-mil accuracy

A realistic simulation:

Determines Superpartner masses of the electron and photon to 0.05%!



A complicated Table with lots of details that illustrates how ILC results improve upon Superpartner mass measurements at the LHC

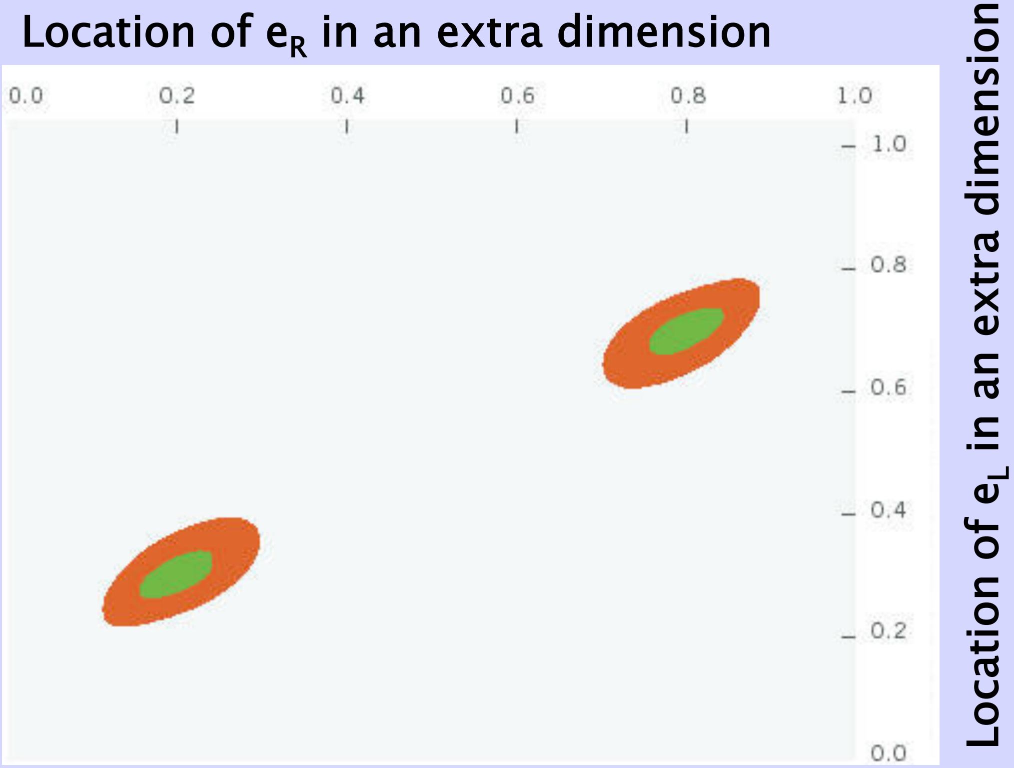


	m_{SPS1a}	LHC	LC	LHC+LC		m_{SPS1a}	LHC	LC	LHC+LC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	549.9	19.0		16.0	$\tilde{s}_2$	576.4	17.4		9.8
$\tilde{c}_1$	551.0	19.0		16.0	$\tilde{c}_2$	570.8	17.4		9.8
$\tilde{e}_1$	144.9	4.8	0.05	0.05	$\tilde{e}_2$	204.2	5.0	0.2	0.2
$\tilde{\mu}_1$	144.9	4.8	0.2	0.2	$\tilde{\mu}_2$	204.2	5.0	0.5	0.5
$\tilde{\tau}_1$	135.5	6.5	0.3	0.3	$\tilde{\tau}_2$	207.9		1.1	1.1
$\tilde{\nu}_e$	188.2		1.2	1.2					

Shows accuracy of mass determinations at LHC and ILC alone and combined

Where particles live in extra dimensions

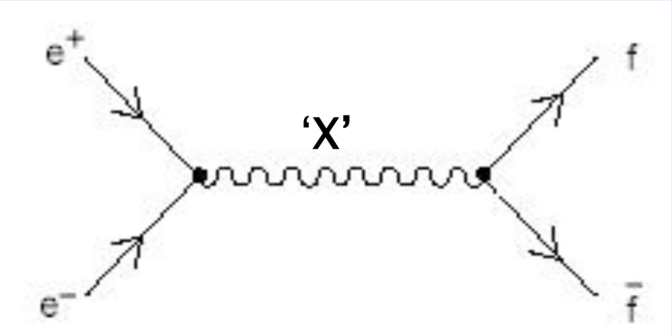
Polarized Bhabha Scattering



Determines location of left- and right-handed electron in extra dimension of size 4 TeV^{-1}

Telescope to Very High Energy Scales

ILC can probe presence of Heavy Objects with Mass > Center of Mass Energy in $e^+e \rightarrow f\bar{f}$



Many tools to detect existence of heavy object 'X':

- Deviations in production rates
- Deviations in production properties such as distribution of angle from beam-line
- Deviations in distributions of angular momentum

For all types of final state fermions!

⇒ Indirect search for New Physics

Footprints of Heavy Particles

Skilled animal trackers can determine:

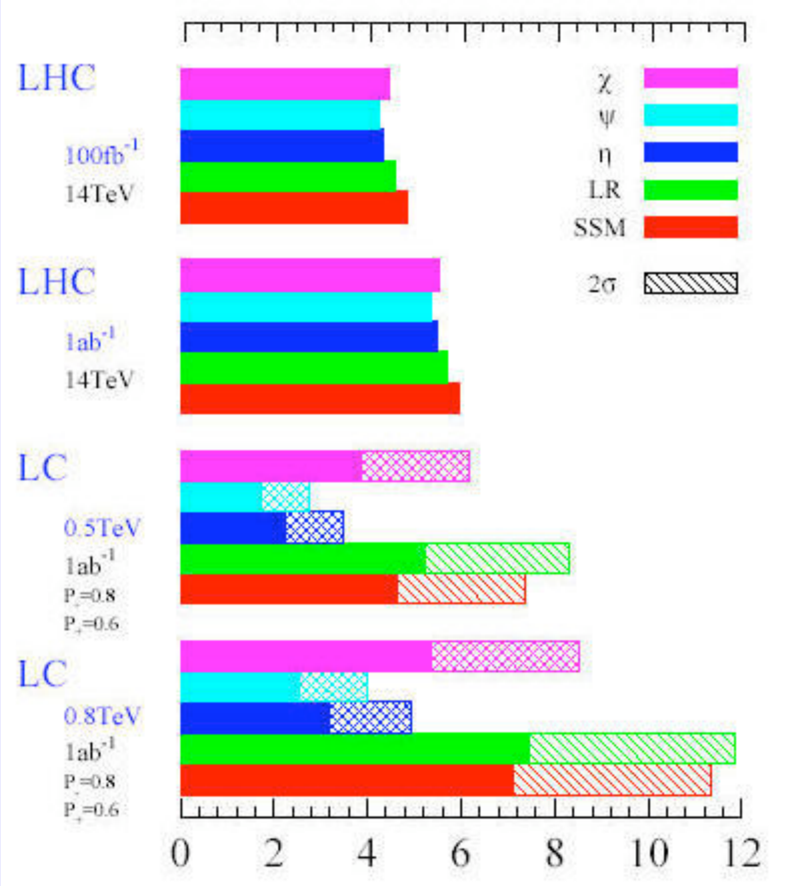
- type of animal
- size of animal
- speed of animal travel
- if animal is injured
- …

Without direct observation of animal!

Information is gathered even if the animal is extinct!

Example: New Heavy Z-like Boson from New Forces

Collider Sensitivity



Mass of Z-like Boson (TeV)

Various Grand Unification Models

95% (=2σ) direct discovery at LHC

For ILC Sensitivity:

Solid = 5σ = standard discovery criteria

Dashed = 2σ

ILC can probe masses many times the machine energy!

Particles Tell Stories:

Discovery of a new particle is the opening chapter of a story. These particles are merely the messengers which reveal a profound story about the nature of matter, energy, space, and time.

Learning the full story involves:

1) Discovery of a new particle
2) Discovery of the theory behind the new particle

It is up to us to find the new particles and to listen to their stories

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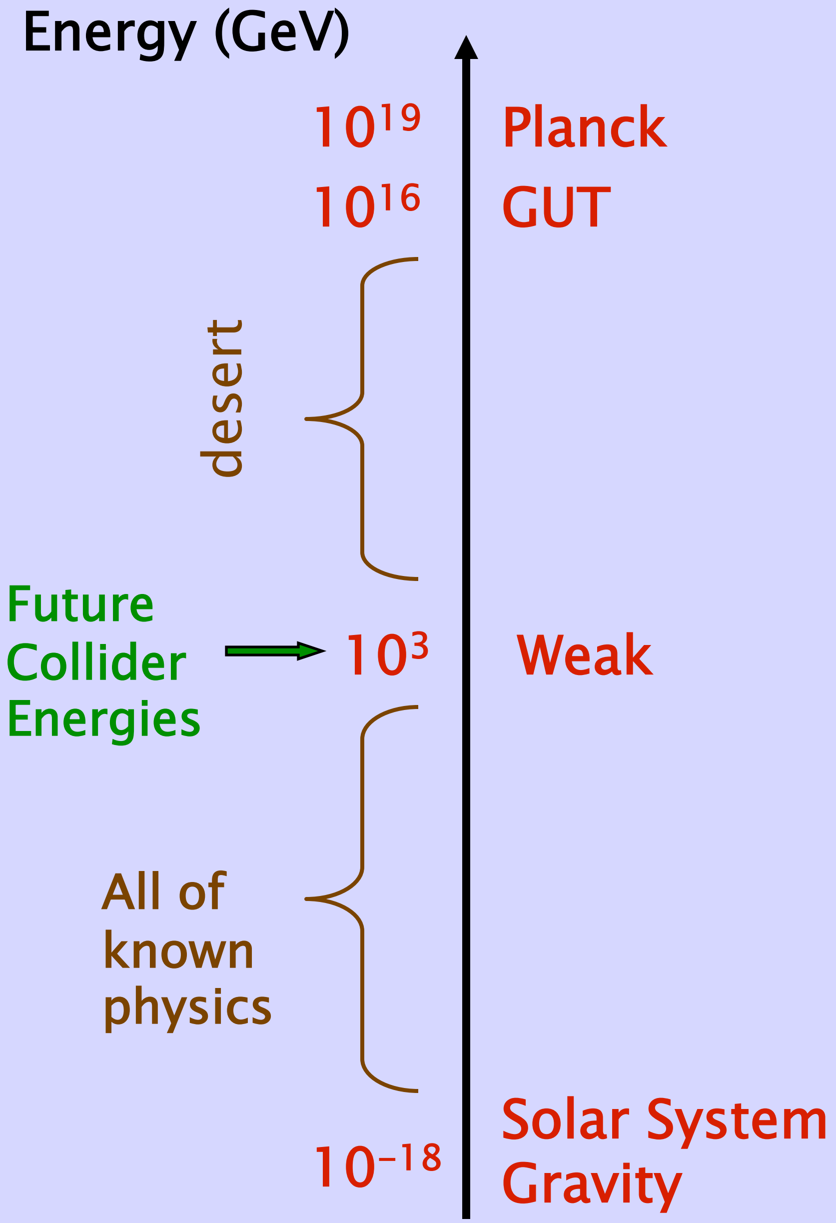
Measurements at the LHC, together with results from the LHC, will identify the full nature of the physics at the TeV scale and reveal its full story

The Hierarchy Problem: Little Hierarchies



Energy (GeV)

10^{19} Planck

10^{16} GUT

desert

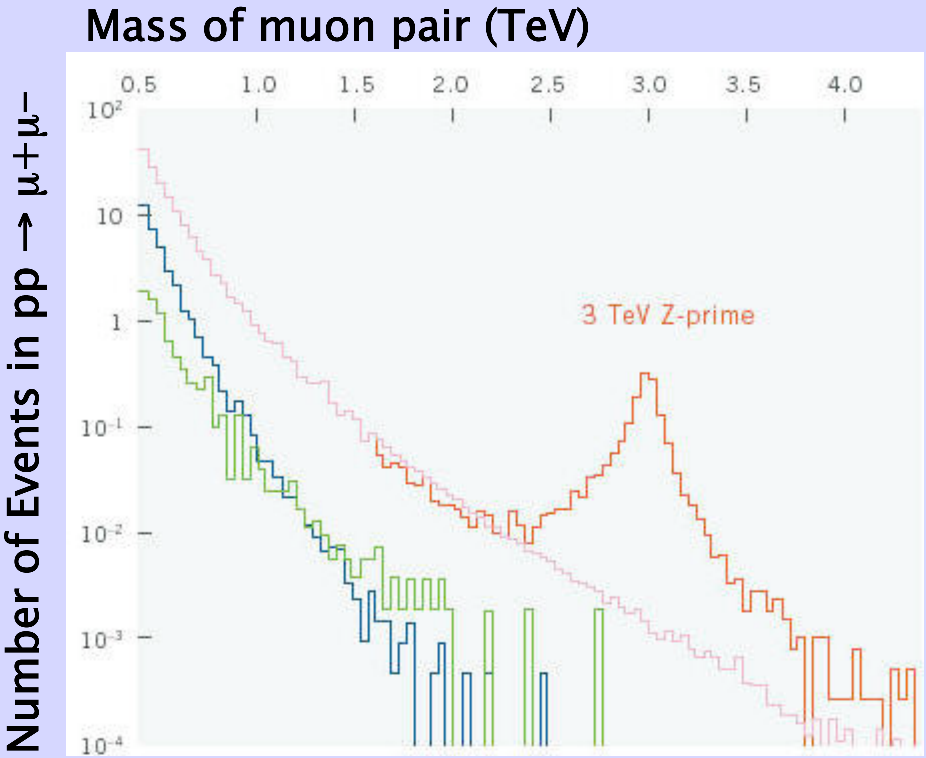
Future Collider Energies → 10^{3} Weak

All of known physics

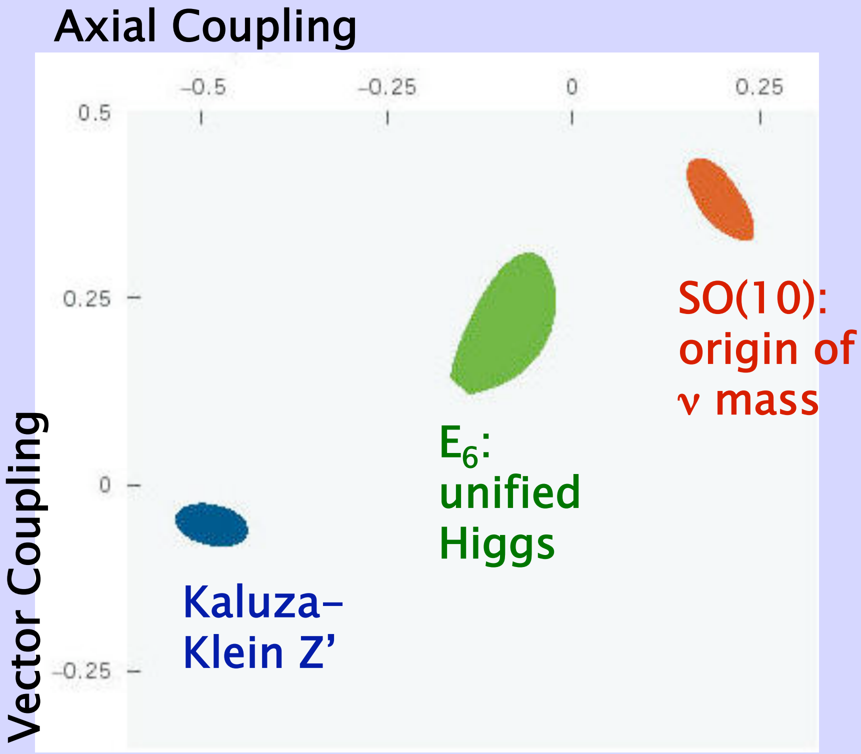
10^{-18} Solar System Gravity

Perhaps the desert is not empty, but is populated with new physics at many different scales.

Drell–Yan distribution at LHC



95% contours for Z’ couplings to leptons at ILC

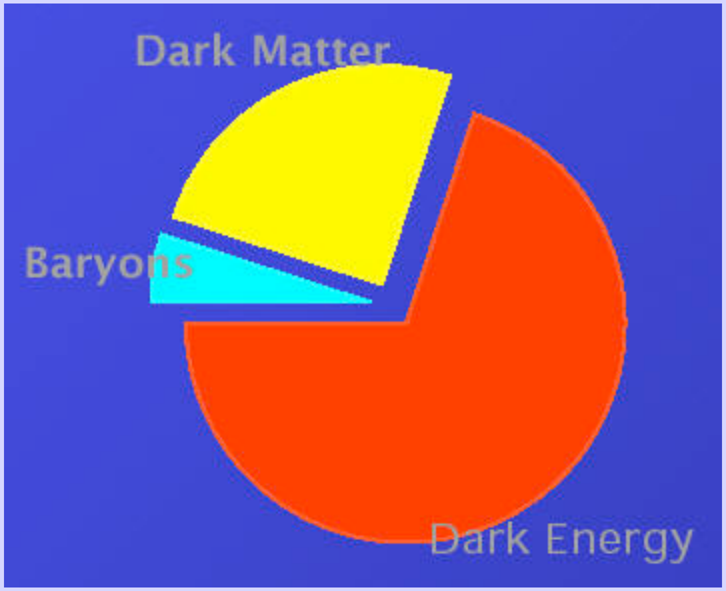


LHC determines mass
ILC determines interactions

Light on Dark Matter

- Dark Matter comprises 23% of the universe
- No reason to think Dark Matter should be simpler than the visible universe ⇒ likely to have many different components
- Dream: Identify one or Dark Matter components and study it in the laboratory

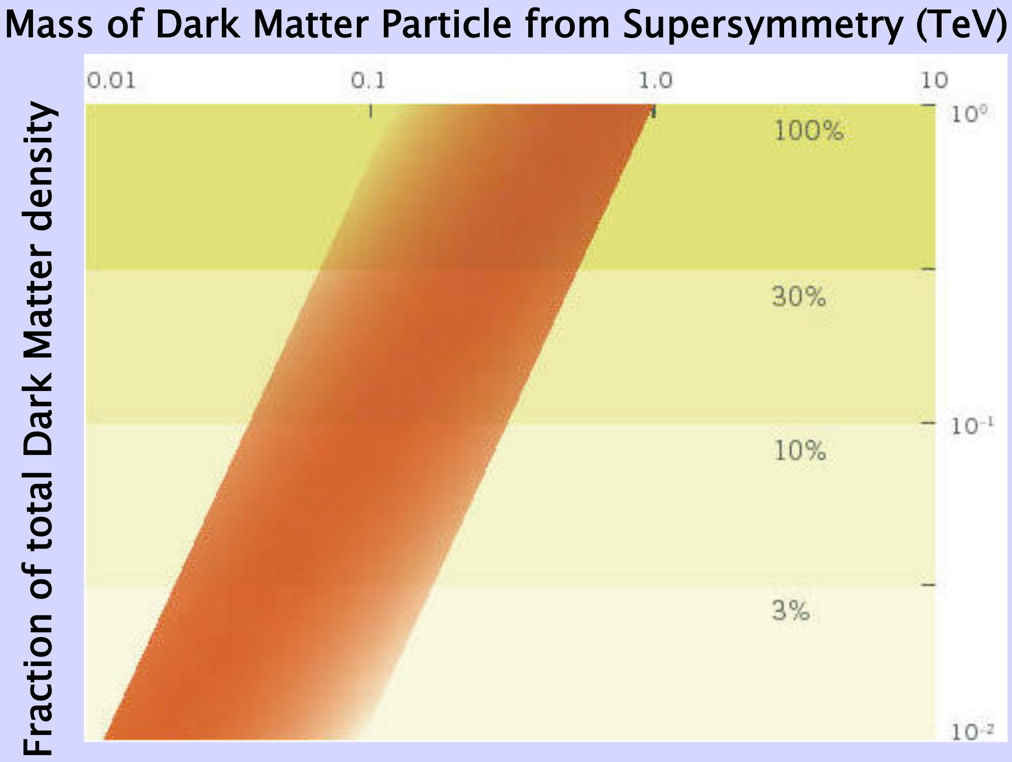
Energy Budget of the Universe



One Possibility: Dark Matter in Supersymmetry

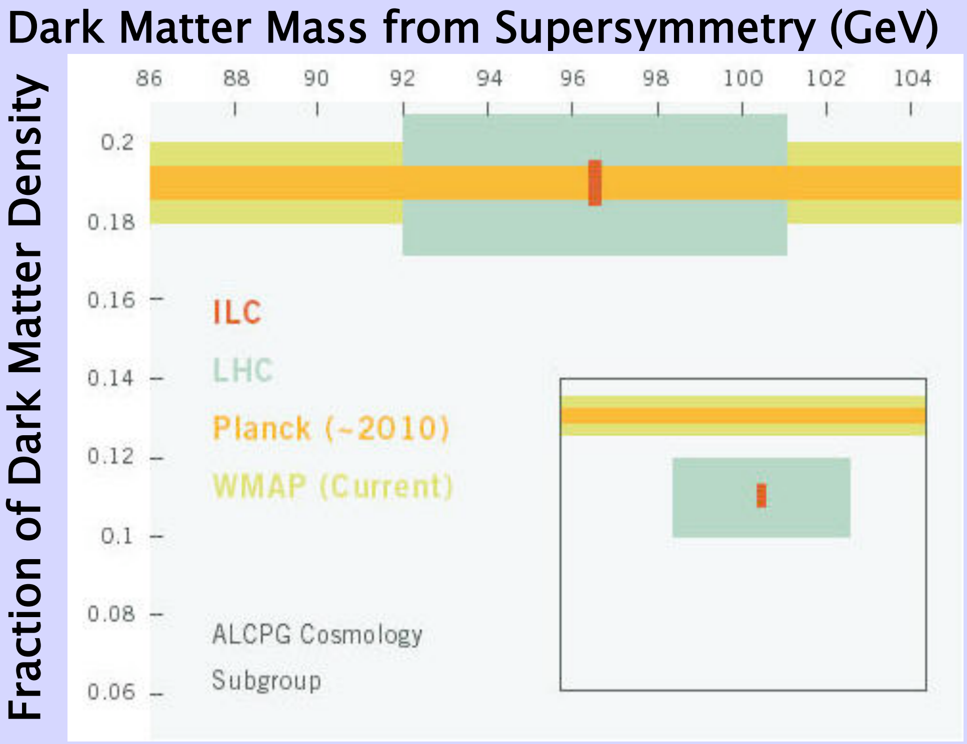
- A component of Dark Matter could be the Lightest Neutralino of Supersymmetry
  - stable and neutral with mass ~ 0.1 – 1 TeV
- In this case, electroweak strength annihilation gives relic density of

$$\Omega_{CDM}\, h^2 \sim \frac{m^2}{(1\ \mathrm{TeV})^2}$$



Comparative precision of Collider measurements (within SUSY)

ILC and Astro measurements



ILC and direct detection