Perspectives on High-Energy Physics

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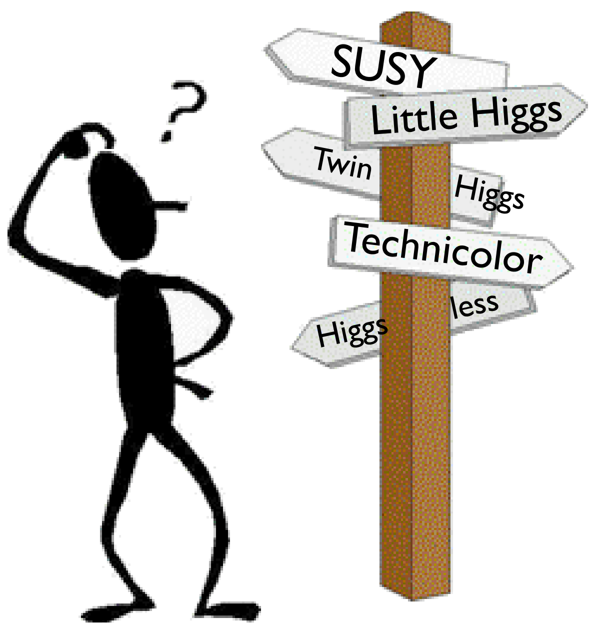
Michigan State University



Topical Seminar on Frontier of Particle Physics 2006:

Beyond the Standard Model

Beijing, China, August 7-11, 2006

Topics:
- Precision Tests
- Collider Physics
- Electroweak Symmetry Breaking and Flavor Physics
- Physics with Extra Dimension and Deconstruction
- Supersymmetry, Dark Matter and Grand Unification
- Experimental Searches for New Particles
- Perspective of the High Energy Physics

Invited Lecturers:
- Howard A. Baer (FSU, USA)
- R. Sekhar Chivukula (MSU, USA)
- Kaoru Hagiwara (KEK, Japan)
- Michael Schmitt (Northwestern, USA)
- Elizabeth H. Simmons (MSU, USA)
- Maria Spiropulu (CERN, Geneva)
- Masaharu Tanabashi (Tohoku, Japan)

Organizing Committee:
- S. Chen (Tsinghua U)
- Y. N. Gao (Tsinghua U)
- T. Han (Wisconsin & Tsinghua U)
- H. J. He (Tsinghua U)
- S. Jin (IHEP)
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- S. H. Zhu (Peking U)

Sponsors:
- Asia Pacific Center for Theoretical Physics (APCTP)
- China Center for Advanced Science and Technology (CCAST)
- Institute of High Energy Physics (IHEP)
- National Natural Science Foundation of China (NSFC)
- Tsinghua University(TU)

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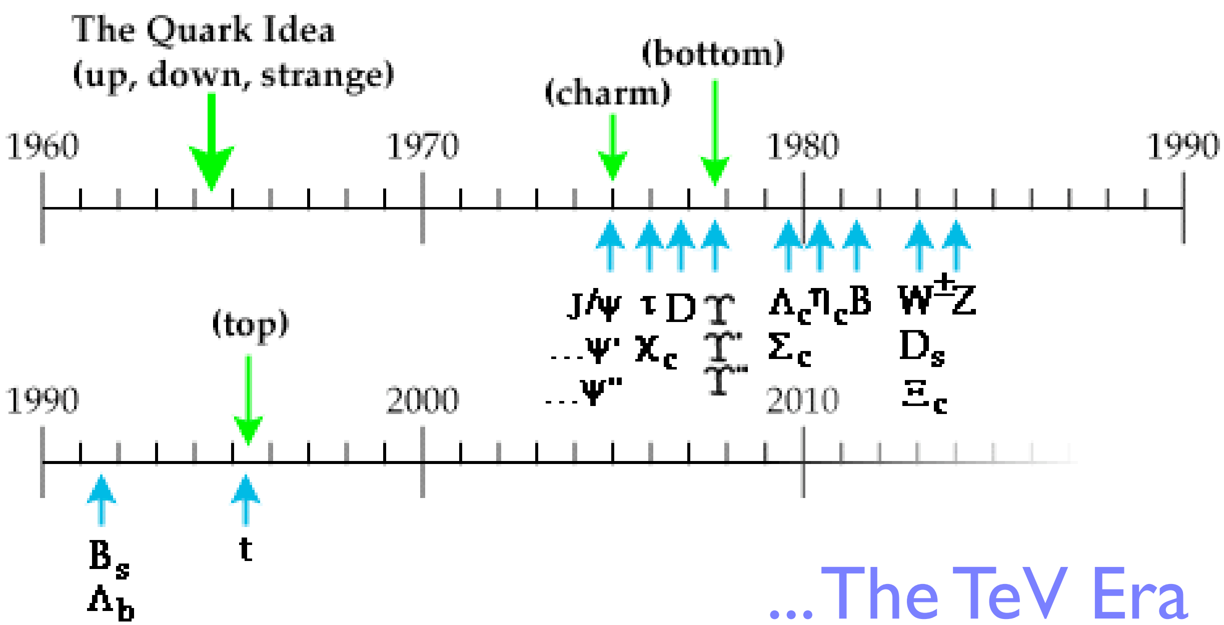
Where we are ...

The SM Age...



...The TeV Era

ν oscillation and dark energy

Dark Matter: Zwicky 1933!

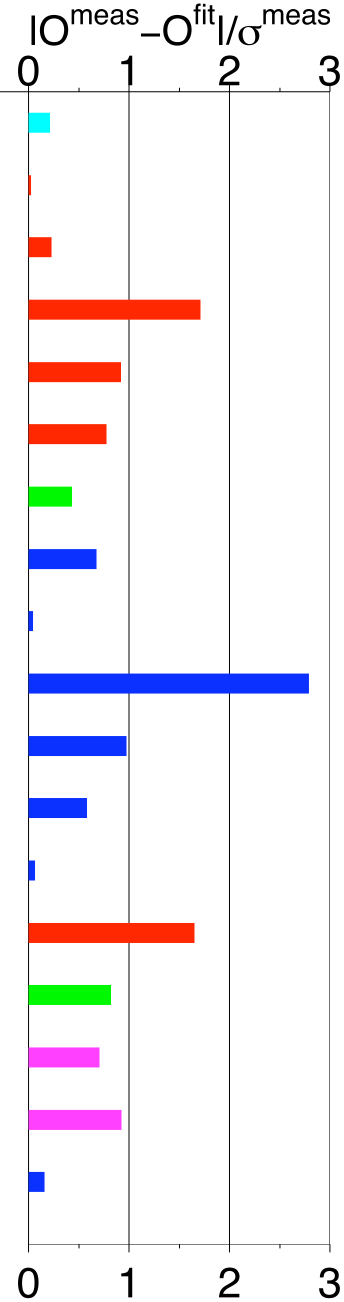
the Standard Model...

Status of SM Summer '06

X^2/dof=17.8/13 (16.6%)

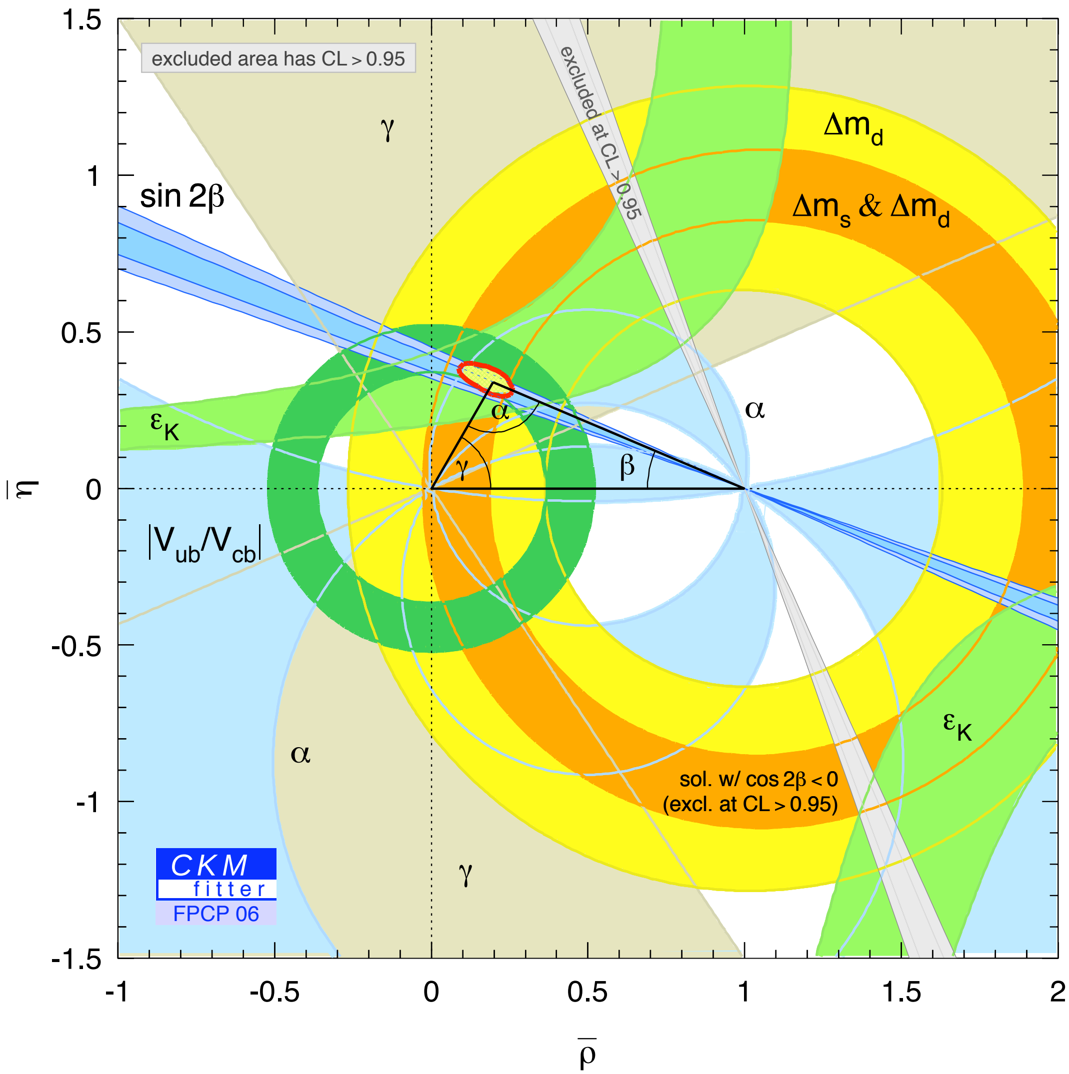
Not bad??

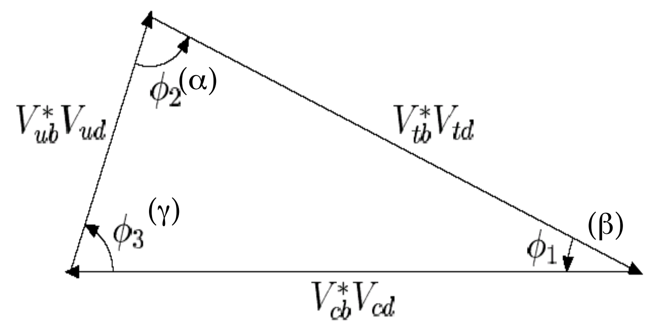
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



Tanabashi Lectures

SM Flavor : CKM and CP-violation

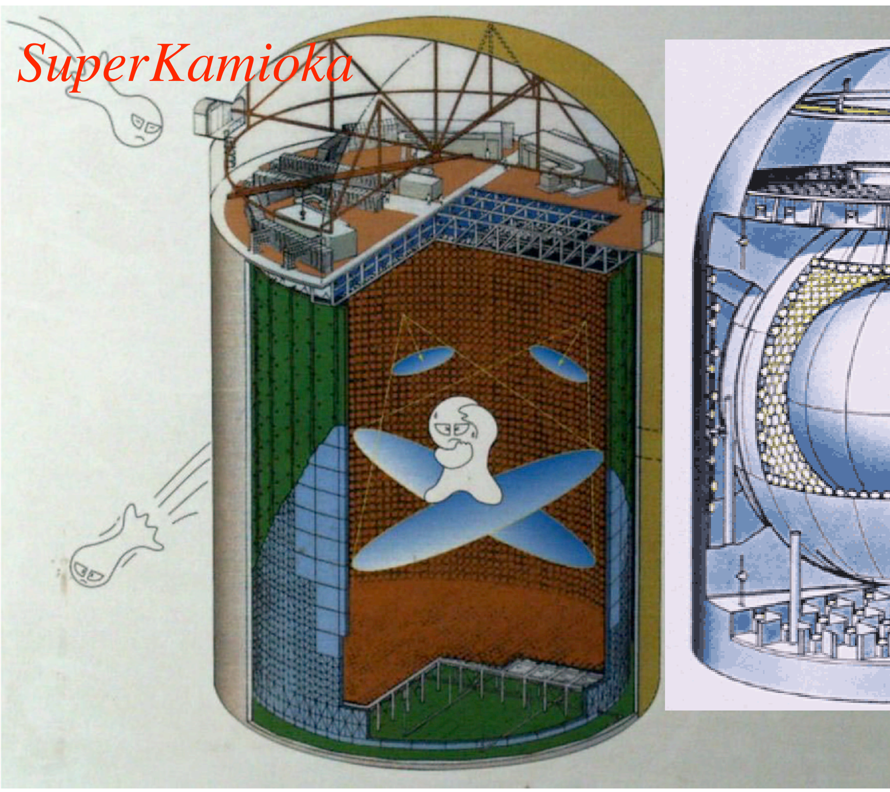


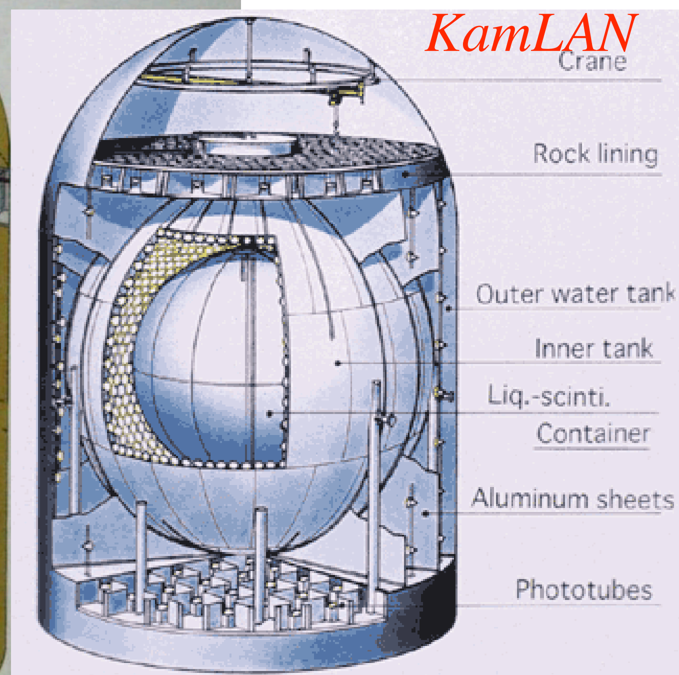


No hint of physics BSM yet!

... the sky is beginning to fall ...

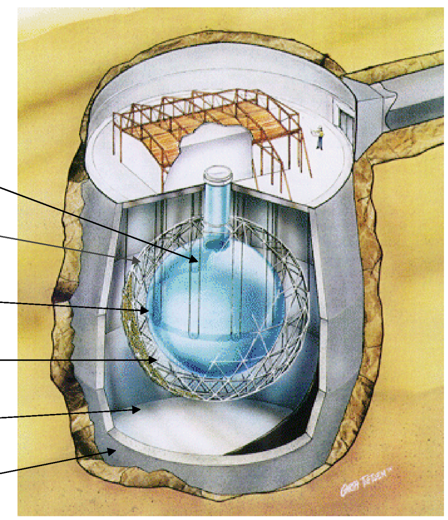
ν-Oscillations



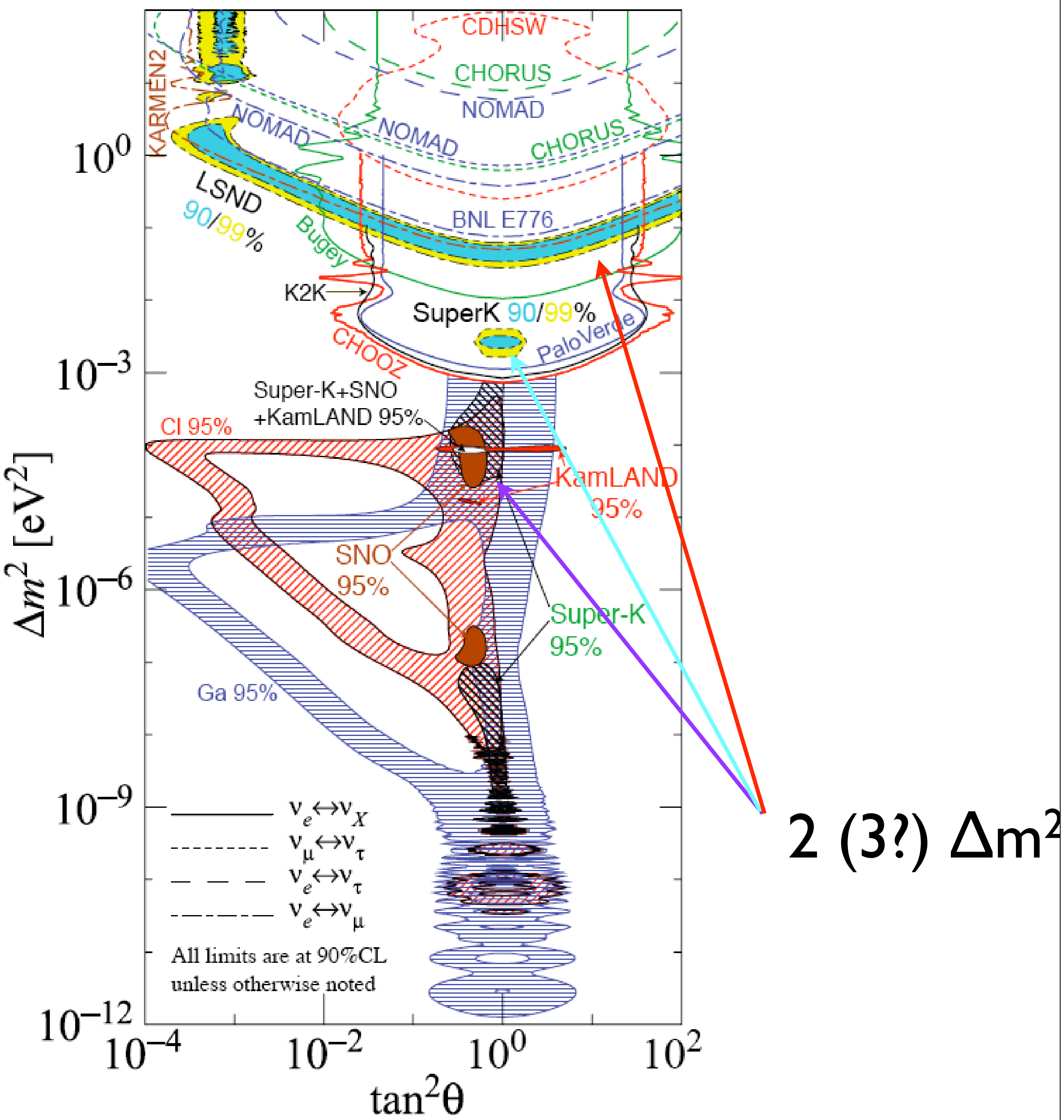


SNO

Sudbury Neutrino Observatory

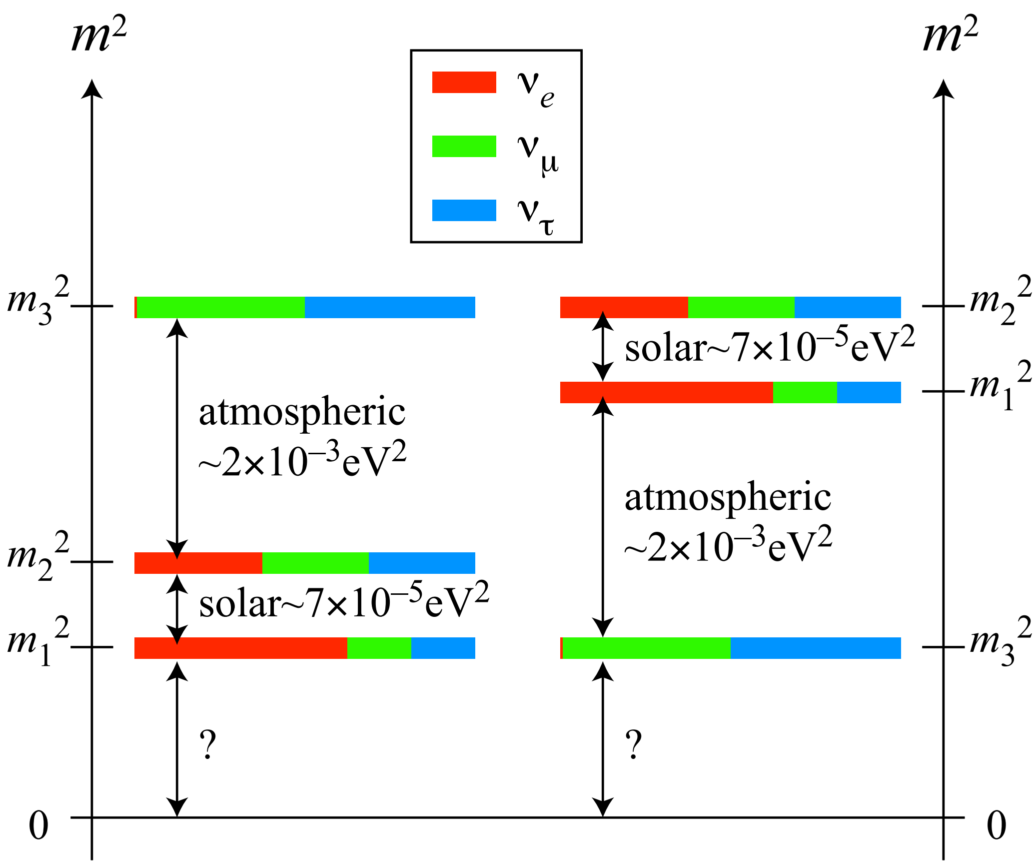


Summary of current results:



B. Kayser, RPP2006

ν-Questions



What is absolute scale of Δm^2?

Are these masses Dirac or Majorana?

How is this related to EWSB?

Dark Matter

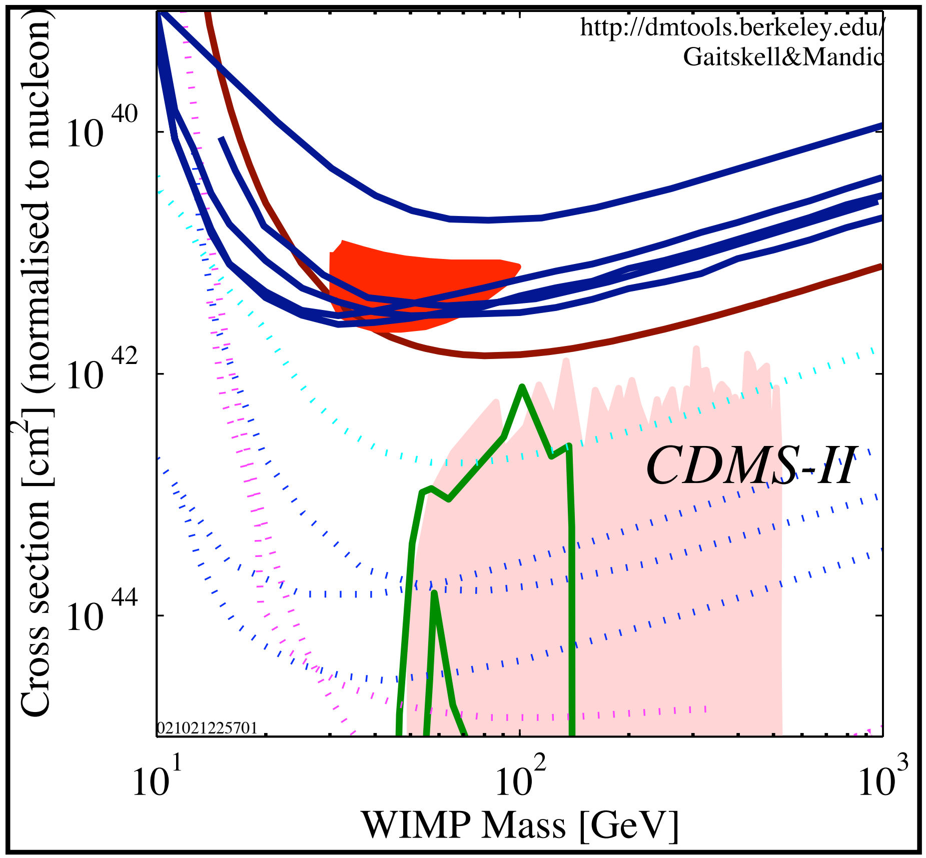
For WIMP's in thermal equilibrium after inflation the density is:

$$\boxed{\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle}}$$

can work for typical weak cross-sections!!!

Dark Matter Searches

- Detect Dark Matter to
  see it is there.
- Produce Dark Matter
  in an accelerator to
  see what it is.



Search for galactic halo dark matter
through energy deposition in detector

BSM Physics & Dark Matter

There is a very broad connection between models of beyond the standard model physics (particularly those addressing the hierarchy problem) and dark matter

- Almost any model involves new particles at the TeV scale, related to the SM particles through symmetries (SUSY partners, KK partners, extra gauge and scalar partners, ...)
- Typically, to avoid things like proton decay and precision EW tests, an extra symmetry is required (R-parity, KK-parity, T-parity, ...).
- This symmetry renders stable some new particle at the weak scale

Often, this stable new particle is an ideal WIMP candidate!

...Including Technicolor

For example, in the last week:

High Energy Physics - Phenomenology, abstract hep-ph/0608055

```
From: Sannino Francesco [view email]
Date: Fri, 4 Aug 2006 13:55:28 GMT   (85kb)
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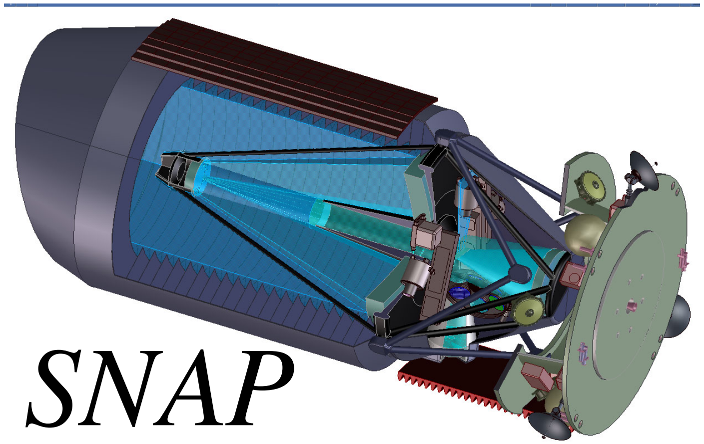
Dark Matter from new Technicolor Theories

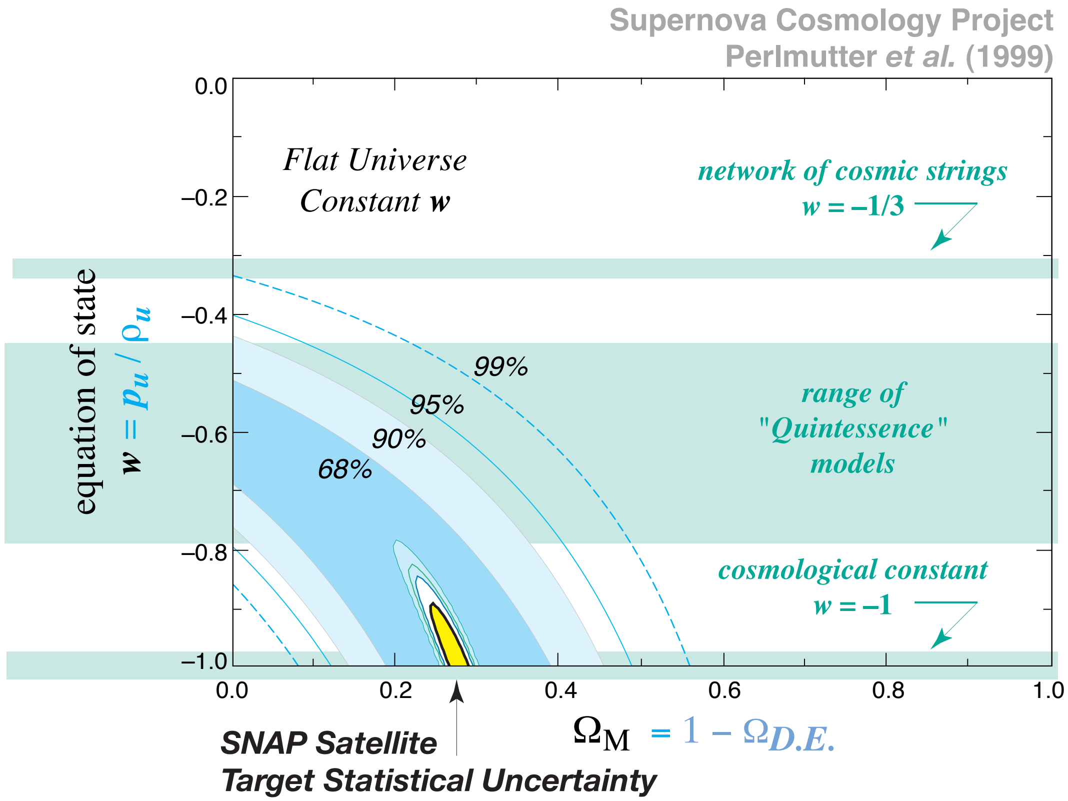
Authors: **Sven Bjarke Gudnason**, **Chris Kouvaris**, **Francesco Sannino**, **(Bohr Institute)**
Comments: 21 pages, 5 figures. RevTeX

What is Dark Energy?

New ground and space-based observations of geometry of universe

Measure EOS!

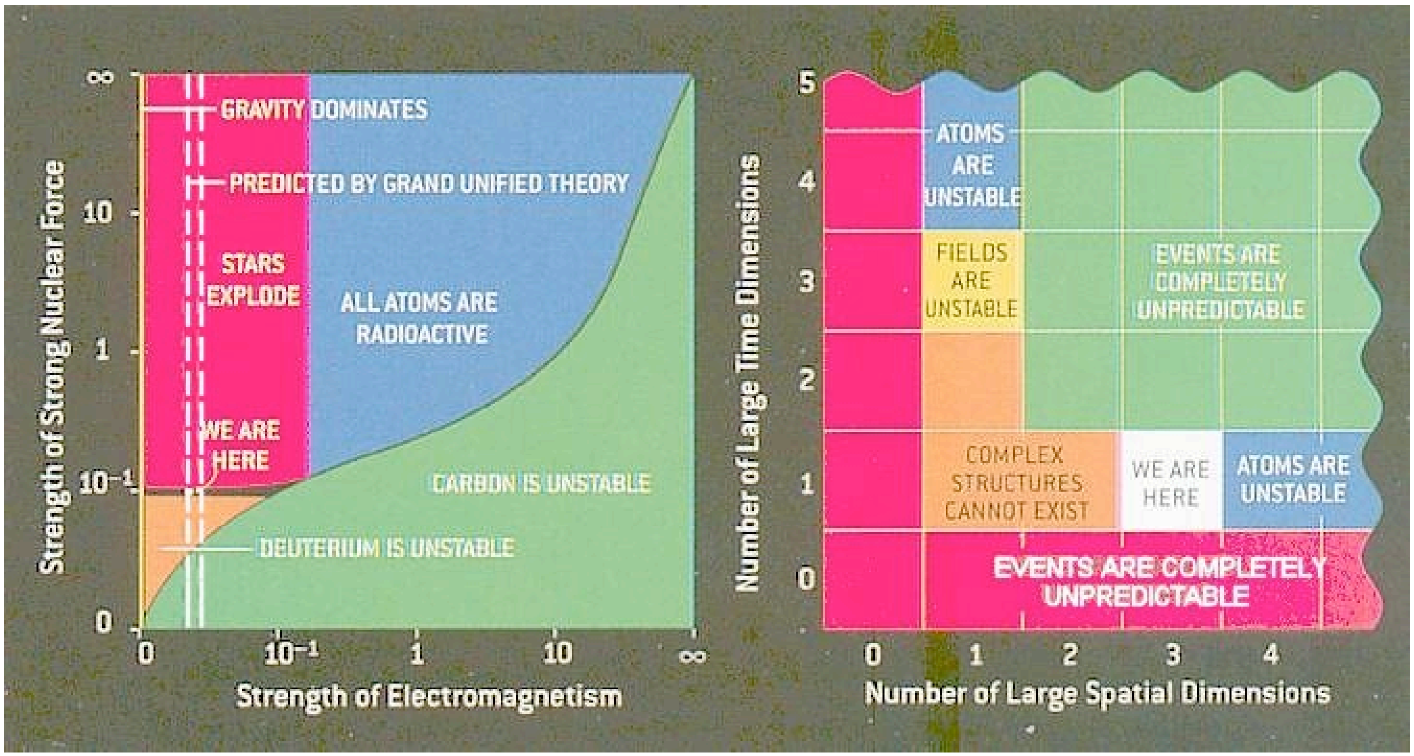


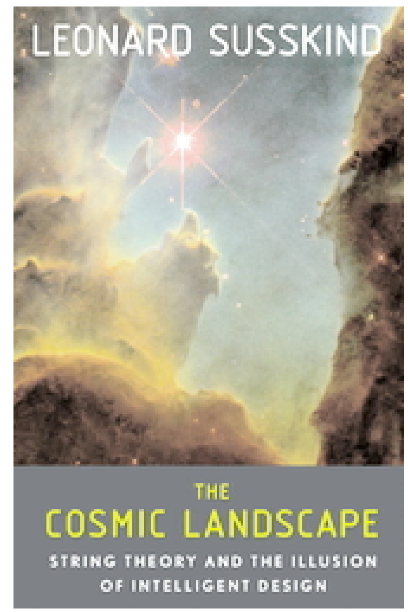


Good Ideas about Dark Energy:

(Your idea goes here ...)

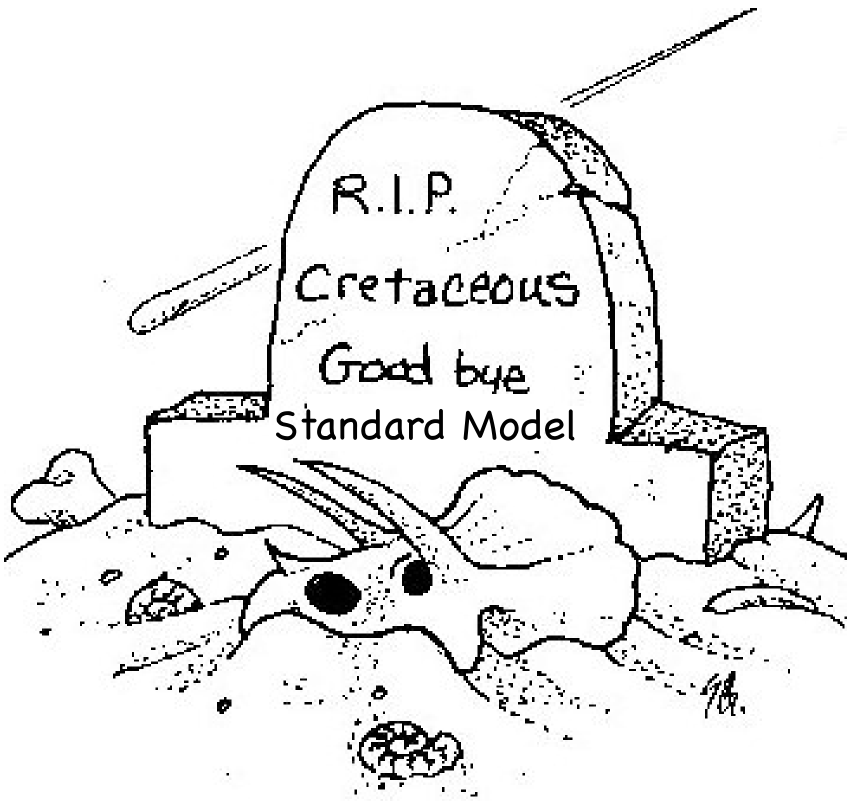
Accomodate Dark Energy?





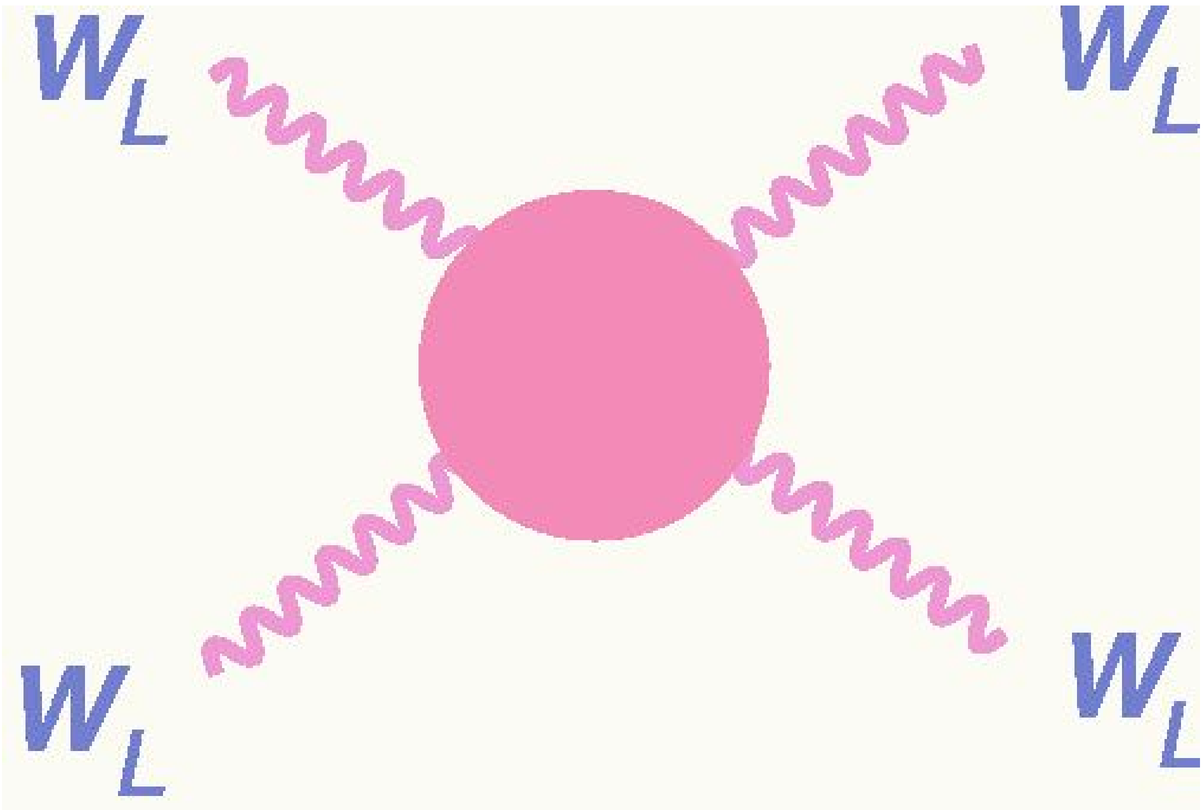
The String Landscape and the Anthropic Principle

... the TeV Era



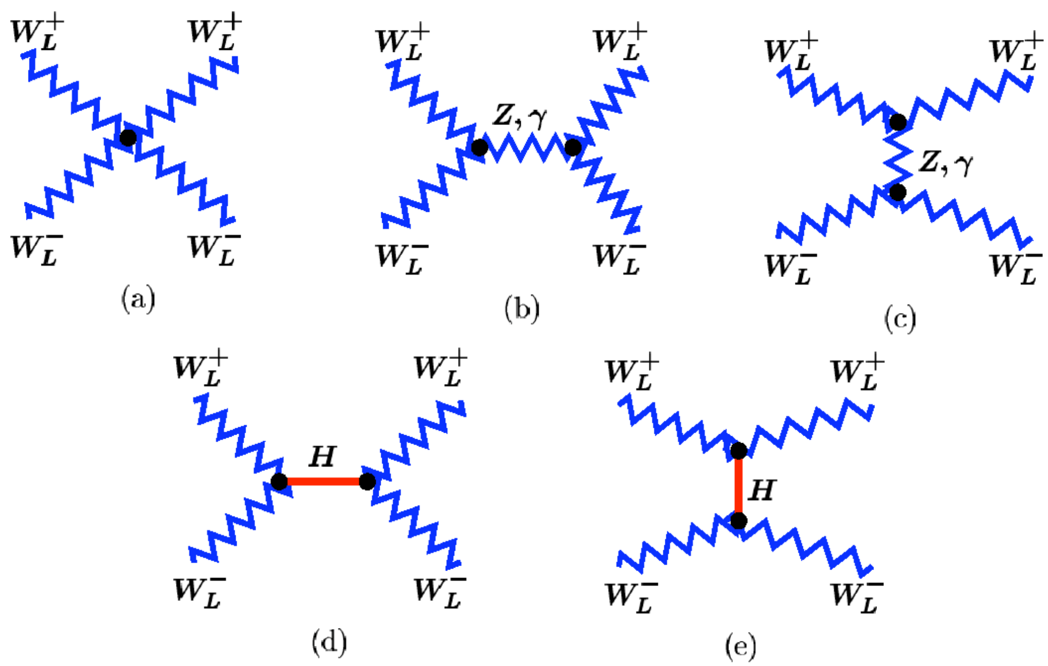
Why Worry About the TeV-scale?

Loss of Unitarity in



All Lectures!

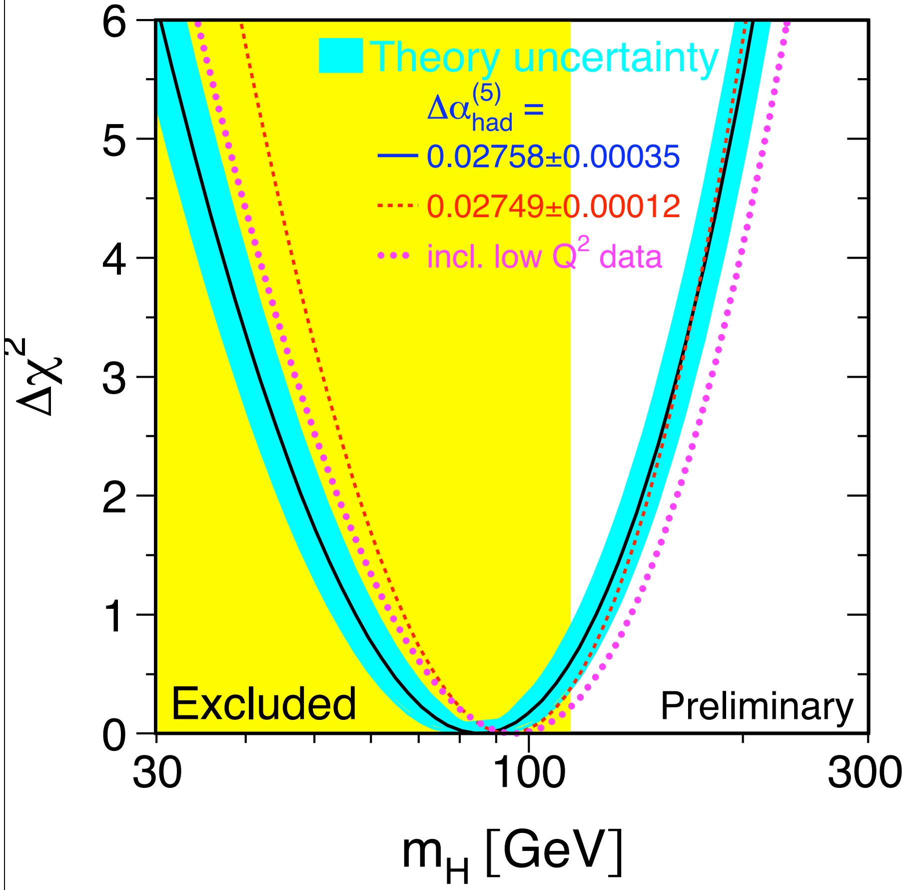
SU(2) x U(1) @ E^2

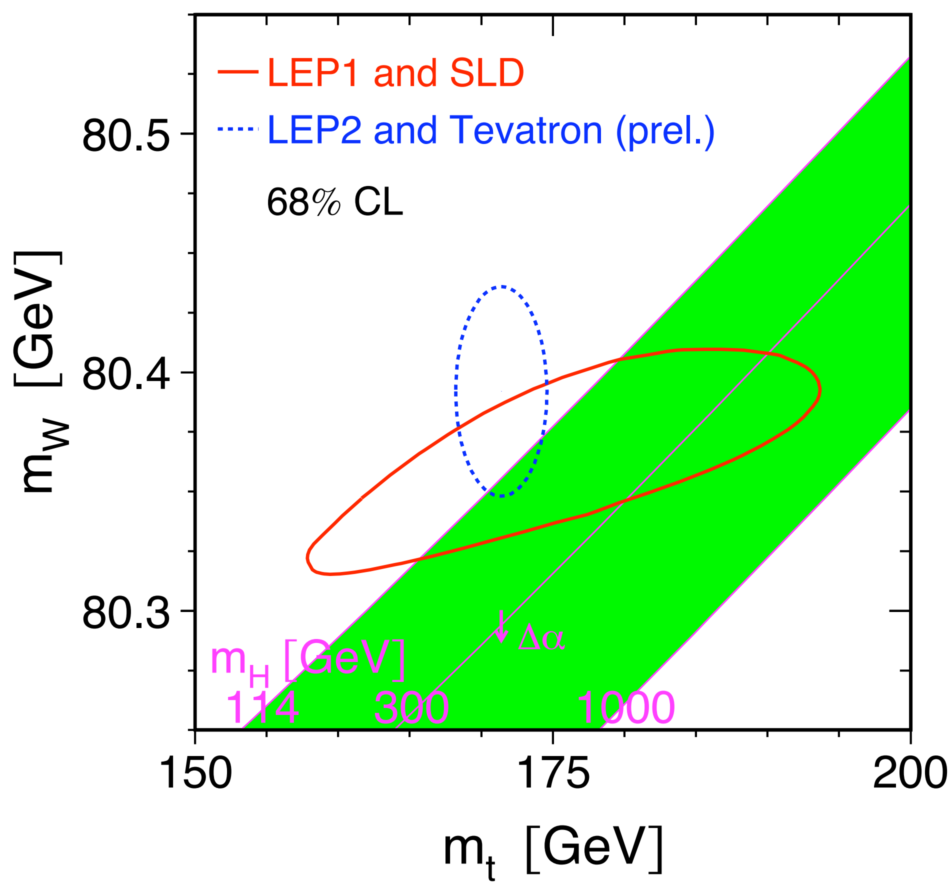


Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2-6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2}+\frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2}-\frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

- ▶ $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- ▶ If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow \; E < \sqrt{4\pi}\, v \simeq 0.9$ TeV

Is all well with the SM?

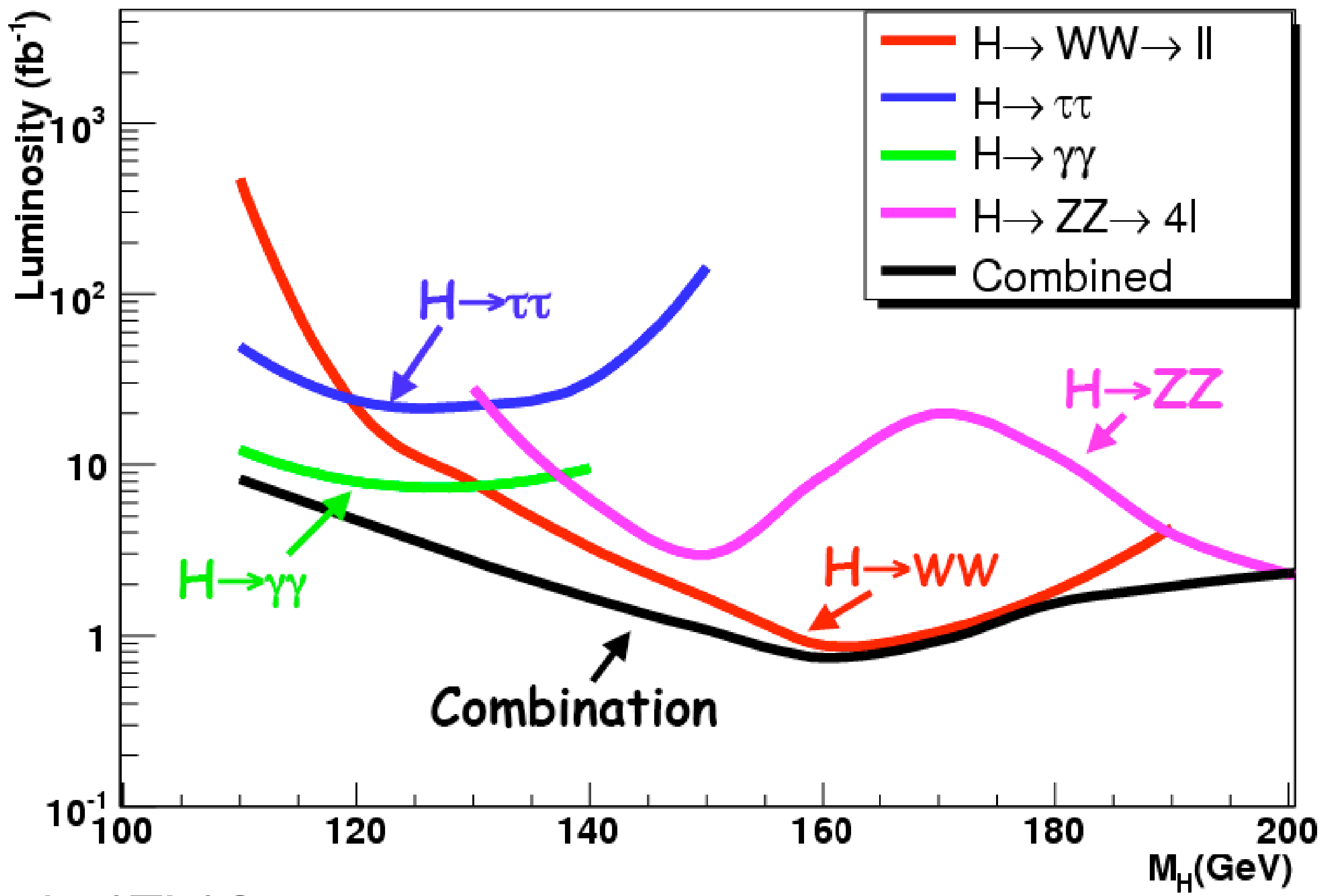




"Lies, d***d lies, and statistics!" - Twain/Disraeli

Higgs Hunting at LHC

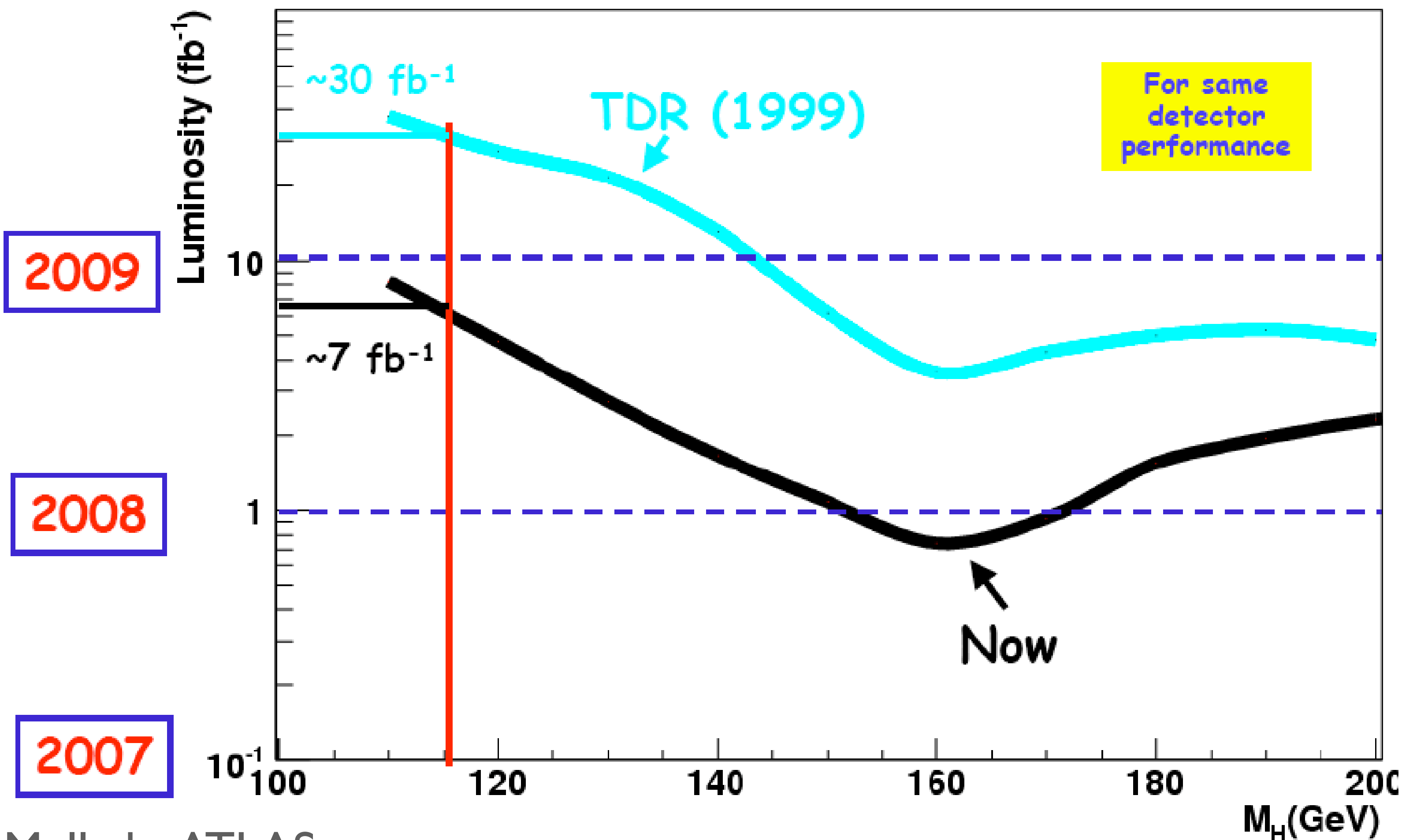
- Combination of strongest channels in terms of luminosity required for 5σ observation (ATLAS)



Bruce Mellado, ATLAS

Higgs at LHC

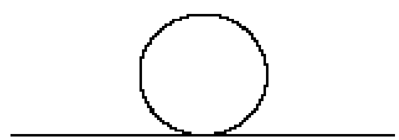
- Strong enhancement of sensitivity w.r.t. to ATLAS physics TDR (1999) mostly due to addition of H+jets



Bruce Mellado, ATLAS

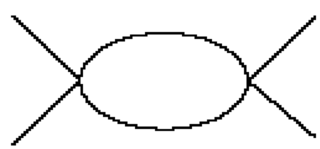
Problems with a fundamental Higgs Boson

- No fundamental scalars observed in nature!
- No explanation of Electroweak Symmetry Breaking
- Hierarchy and Naturalness Problem



$$\Rightarrow \; m_H^2 \propto \Lambda^2 \; .$$

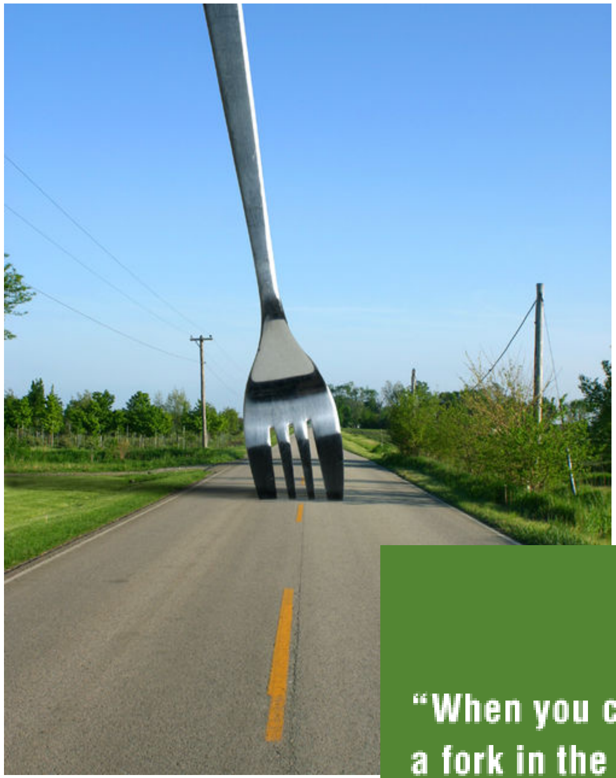
- Triviality Problem



$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0 \quad .$$

A Fork in the Road...

- Make the Higgs Natural: Supersymmetry
- Make the Higgs Composite
  - Little Higgs
  - (Higgs as A_5)
  - Twin Higgs
- Eliminate the Higgs
  - Technicolor
  - “Higgsless” Models



“When you come to a fork in the road, take it!”
— Yogi Berra

Supersymmetry

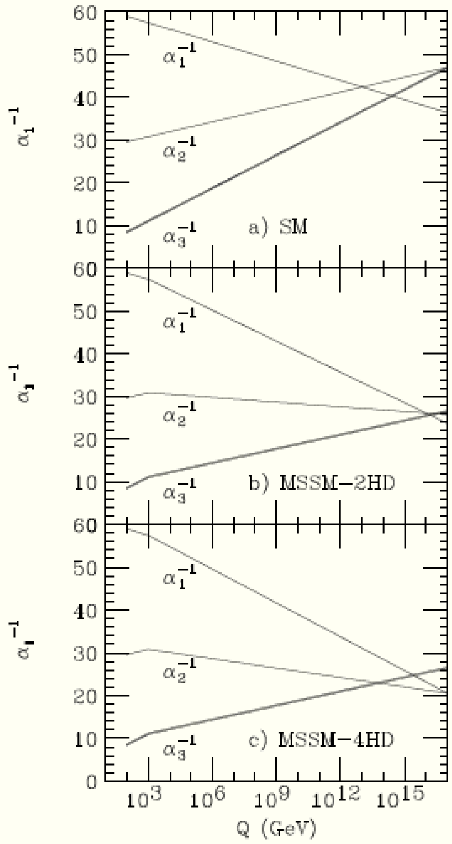
The MSSM: summary

- ⋆ The MSSM includes the SM as a sub-theory, but also includes many new states of matter
- ⋆ Unlike the SM, the MSSM is free of quadratic divergences in the scalar sector
- ⋆ Thus, the MSSM can accommodate vastly different mass scales, *e.g.* M_{weak} and M_{GUT} or M_{string}
- ⋆ The 124 parameter MSSM is likely to be the low energy effective theory of some more fundamental theory, perhaps one linked to GUTs or strings
- ⋆ The MSSM provides for us the possible physical states and Feynman rules needed for making predictions of physical phenomena
- ⋆ The MSSM parameters are highly constrained by bounds from FCNCs, CP-violation, etc.

More than double number of states...

Supersymmetry

Gauge coupling evolution

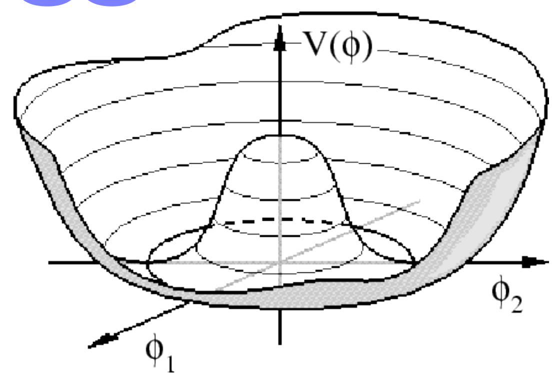


!

OR . . .

Composite Higgs

Higgs as (Pseudo-)Goldstone Boson:



Hard to do!

$$V(h) = \frac{Cg^2}{16\pi^2}\left(-\eta_2 f^2 |h|^2 + \eta_4 \frac{|h|^4}{2} + \dots\right)$$

$g \ll 1$

Decay Constant

Yields: $\langle h \rangle^2 \simeq \frac{\eta_2}{\eta_4} f^2$

But, EWPT: $f > 4 - 5\,\mathrm{TeV}$

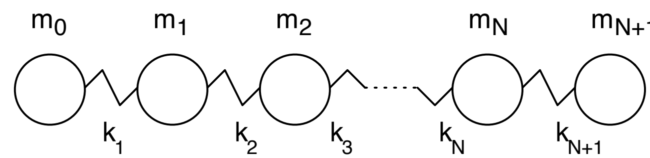
Must suppress η_2 without suppressing η_4

Georgi & Kaplan; Banks

Chacko et. al., hep-ph/0510273

The Little Higgs

Collective Symmetry Breaking:



For weak springs, masses at end very weakly coupled!

In practice: $\frac{\eta_2}{\eta_4} \simeq \frac{g^2}{16\pi^2}$ $m_h^2 \simeq \frac{g^2}{16\pi^2} f^2$

Global Symmetries	Gauge Symmetries	triplet	# Higgs
$SU(5)/SO(5)$	$[SU(2)\times U(1)]^2$	Yes	1
$SU(3)^8/SU(3)^4$	$SU(3)\times SU(2)\times U(1)$	Yes	2
$SU(6)/Sp(6)$	$[SU(2)\times U(1)]^2$	No	2
$SU(4)^4/SU(3)^4$	$SU(4)\times U(1)$	No	2
$SO(5)^8/SO(5)^4$	$SO(5)\times SU(2)\times U(1)$	Yes	2
$SU(9)/SU(8)$	$SU(3)\times U(1)$	No	2
$SO(9)/[SO(5)\times SO(4)]$	$SU(2)^3\times U(1)$	Yes	1

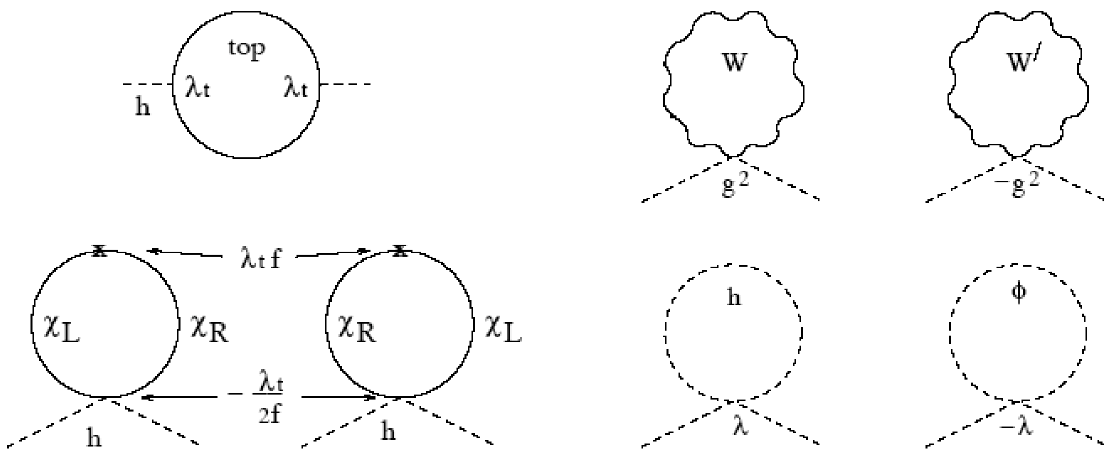
Arkani-Hamed, Cohen, Georgi

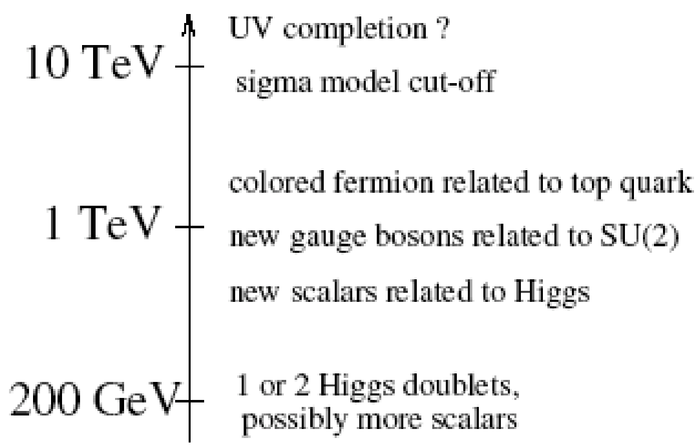
Meade, hep-ph/0402036

Global Symmetry Extended to Third Generation

- Top Yukawa Large and breaks chiral symmetries
- Extra singlet quarks added
- Top mass results from seesaw like mixing between doublet and singlet fermions
- EWSB: radiatively induced

Little Higgs : The Hierarchy





Cancellation of divergences by particles of same spin!

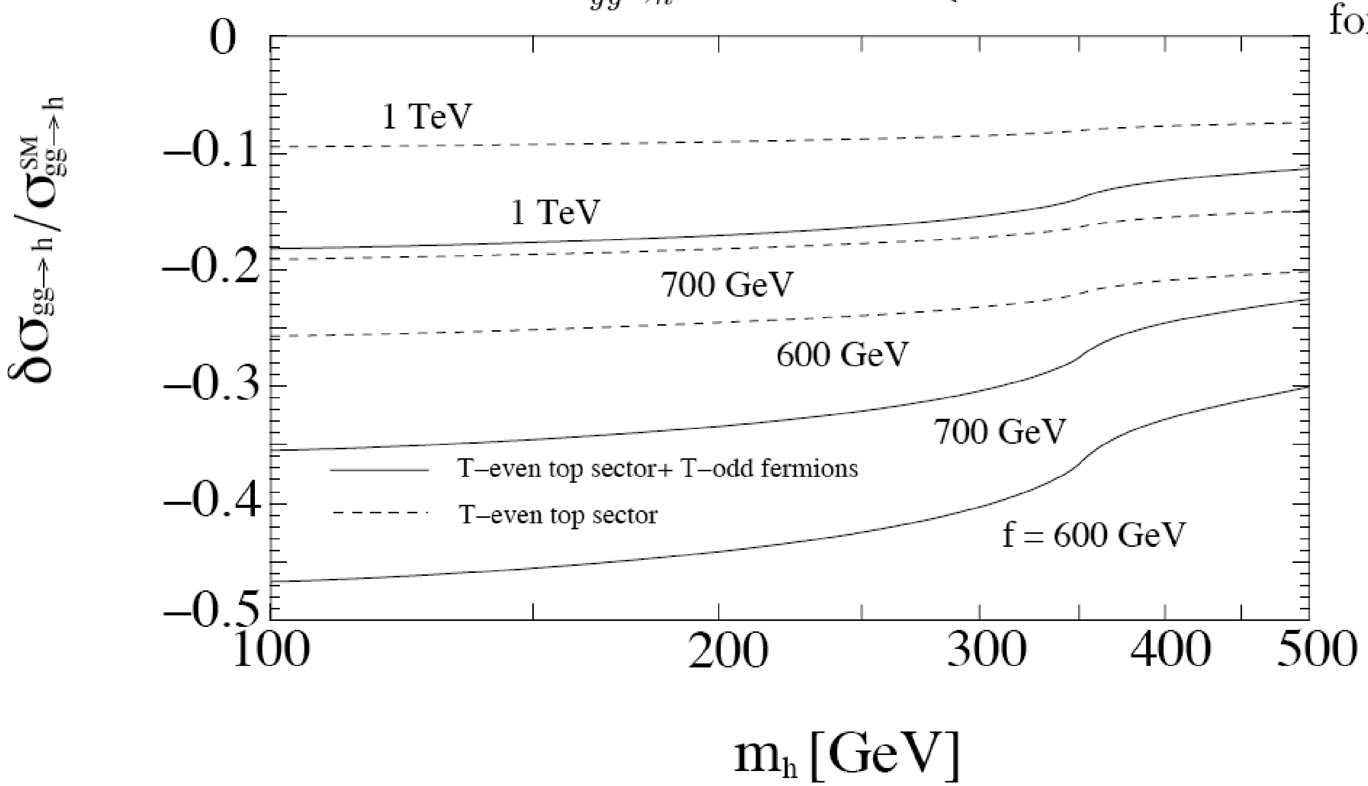
Schmaltz hep-ph/0210415

Correction to Higgs production cross section via gluon fusion process

$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \quad (\text{where } \delta\sigma_{gg\to h} = \sigma^{\rm LH}_{gg\to h} - \sigma^{\rm SM}_{gg\to h})$$

$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\rm SM}_{gg\to h}} \simeq -3\frac{v^2_{SM}}{f^2} \simeq \begin{cases} -37\% \text{ for } f = 700 \text{ GeV}, \\ -18\% \text{ for } f = 1000 \text{ GeV}. \end{cases}$$

for small m_h



The production cross section can be significantly suppressed

Chen, Tobe, Yuan

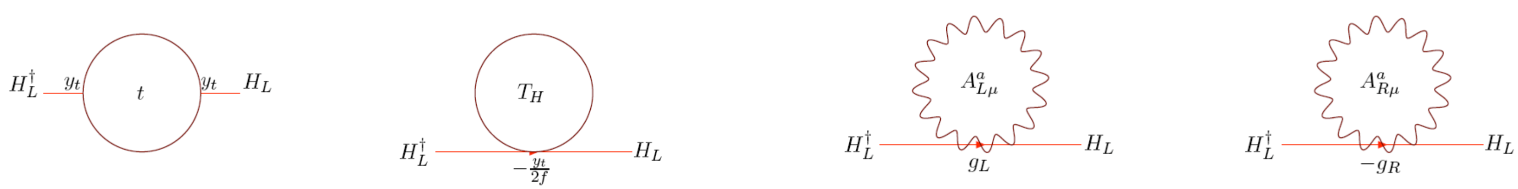
Twin Higgs

- Global SU(4) Symmetry, H in fundamental
  - $V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$
  - <H>, SU(4) breaks to SU(3); 7 GBs
- Weakly Gauge $SU(2)_W$ x $SU(2)_H$, $H=(H_W,H_H)$
  - 3 GBs eaten, 4 remaining are "higgs"
  - $\Delta V^{(2)} = \frac{9g_A^2\Lambda^2}{64\pi^2} H_W^\dagger H_W + \frac{9g_B^2\Lambda^2}{64\pi^2} H_H^\dagger H_H$
- Z_2 symmetry: $g_A=g_B$
  - Accidental SU(4) symmetry of $\Delta V^{(2)}$
  - No mass generated for higgs boson to $O(g^2)$

Chacko, Go, and Harnick hep-ph/0506256

Twin Higgs (cont'd)

- Self-coupling $\Delta V^{(4)} \propto \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda}{gf}\right) \left(|H_W|^4 + |H_H|^4\right)$
- Extend SU(4) global symmetry to top-quark sector
- EWSB: Radiatively induced
- Hierarchy : like Little Higgs



Goh, Argonne Workshop 2006

OR ...

Eliminate the Higgs...

Technicolor: Higgsless since 1976!

Eliminate Scalars: Electroweak gauge symmetry broken by the nonzero expectation value of a fermion bilinear, driven by new strong interactions.

Understanding of strongly-interacting gauge theories is extremely limited $\Rightarrow$ theories constructed by analogy!

Simmons Lectures

Technicolor Limits:

- Model Dependent

- Just Reaching interesting range!

- Run II & LHC will extend limits substantially

No Run II limits yet?

Narain, Womersley, RSC
PDG review

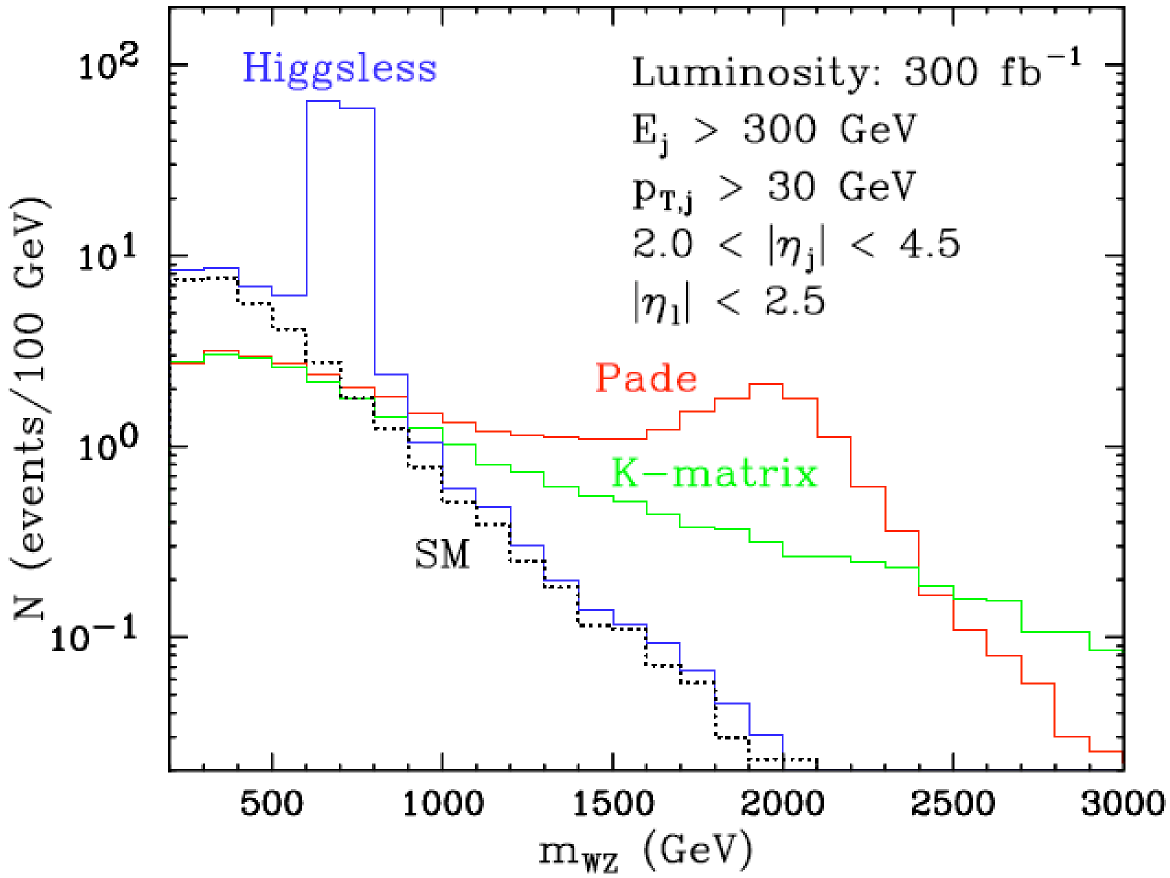
Process	Excluded mass range	Decay channels	Ref.
$p\bar{p} \to \rho_T \to W\pi_T$	$170 < m_{\rho_T} < 190$ GeV for $m_{\pi_T} \approx m_{\rho_T}/2$	$\rho_T \to W\pi_T$; $\pi_T^0 \to b\bar{b}$ $\pi_T^\pm \to b\bar{c}$	[16]
$p\bar{p} \to \omega_T \to \gamma\pi_T$	$140 < m_{\omega_T} < 290$ GeV for $m_{\pi_T} \approx m_{\omega_T}/3$ and $M_T = 100$ GeV	$\omega_T \to \gamma\pi_T$; $\pi_T^0 \to b\bar{b}$; $\pi_T^\pm \to b\bar{c}$	[18]
$p\bar{p} \to \omega_T/\rho_T$	$m_{\omega_T} = m_{\rho_T} < 203$ GeV for $m_{\omega_T} < m_{\pi_T} + m_W$ or $M_T > 200$ GeV	$\omega_T/\rho_T \to \ell^+\ell^-$	[19]
$e^+e^- \to \omega_T/\rho_T$	$90 < m_{\rho_T} < 206.7$ GeV; $m_{\pi_T} < 79.8$ GeV	$\rho_T \to WW$, $W\pi_T$, $\pi_T\pi_T$, $\gamma\pi_T$, hadrons	[20]
$p\bar{p} \to \rho_{T8}$	$260 < m_{\rho_{T8}} < 480$ GeV	$\rho_{T8} \to q\bar{q}$, gg	[22]
$p\bar{p} \to \rho_{T8} \to \pi_{LQ}\pi_{LQ}$	$m_{\rho_{T8}} < 510$ GeV	$\pi_{LQ} \to c\nu$	[25]
	$m_{\rho_{T8}} < 600$ GeV	$\pi_{LQ} \to b\nu$	[25]
	$m_{\rho_{T8}} < 465$ GeV	$\pi_{LQ} \to \tau q$	[24]
$p\bar{p} \to g_t$	$0.3 < m_{g_t} < 0.6$ TeV for $0.3 m_{g_t} < \Gamma < 0.7 m_{g_t}$	$g_t \to b\bar{b}$	[30]
$p\bar{p} \to Z'$	$m_{Z'} < 480$ GeV for $\Gamma = 0.012 m_{Z'}$; $m_{Z'} < 780$ GeV for $\Gamma = 0.04 m_{Z'}$	$Z' \to t\bar{t}$	[31]

What about the S-parameter?

Why are we still talking about technicolor?

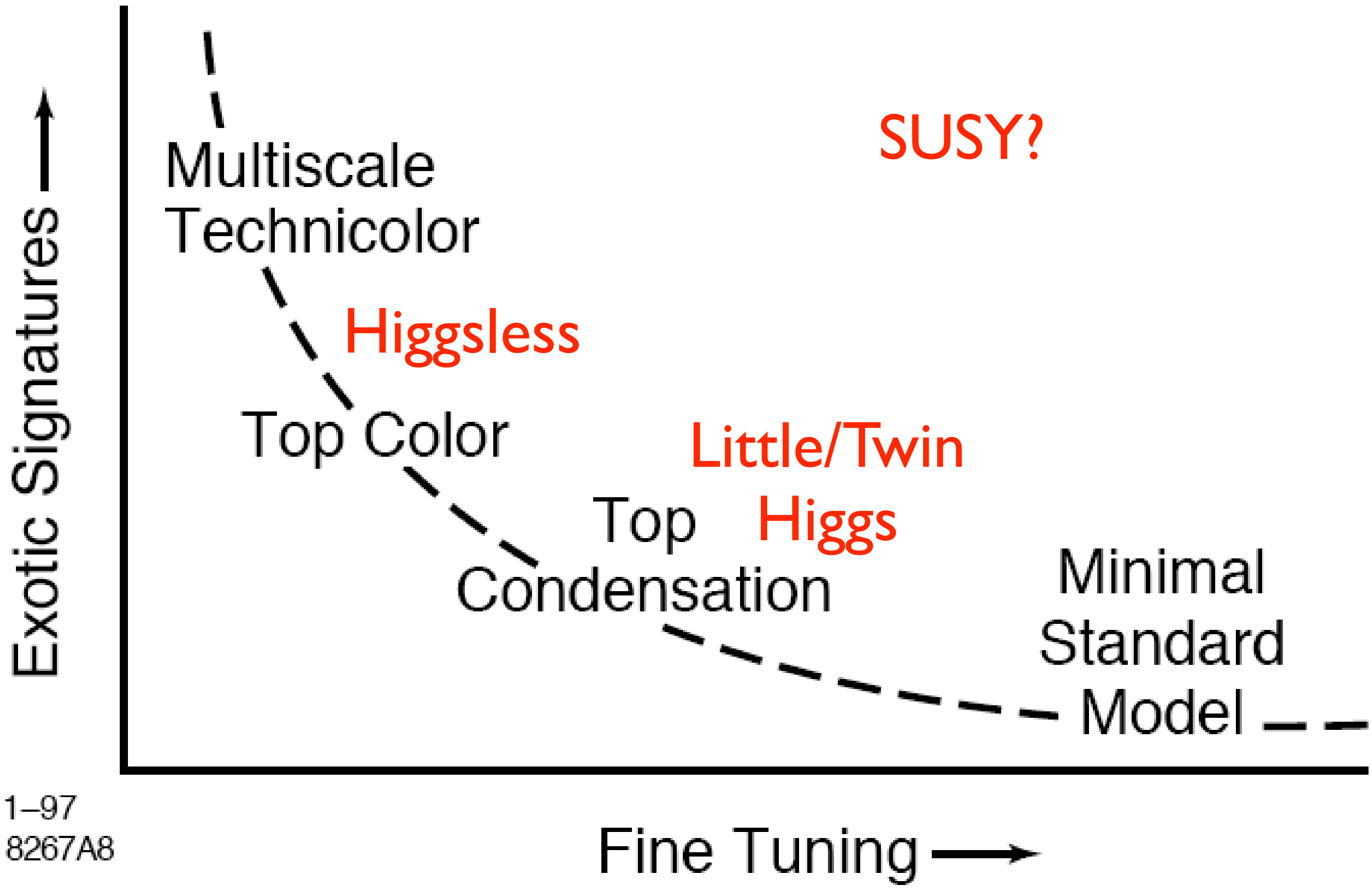
- Technicolor may be there
  - No "computations" of S in non-QCD like theories
- Technicolor has interesting experimental signatures
  - Complementary to other BSM theories
- AdS/CFT Correspondence:
  - Some 4D strongly-coupled theories "dual" to weakly-coupled 5D theories
  - New model building ideas
  - Address S parameter issues

LHC Phenomenology



Birkedal, et.al., hep-ph/0412278

The Terning Plot



BSM: Observations

- Our standards have changed
  - We are content with a low-energy effective theory valid to ~ few TeV
  - This is a good thing in preparation for the LHC ...
- Fine-tuning is in the eye of the beholder
  - S=O(1) in QCD-like technicolor; experimental bound O(0.1) - hence need 10% fine-tuning?
  - Dynamics matters: Inflation makes fine-tuning of flatness problem irrelevant.

Interim Conclusions

- Three mechanisms to address hierarchy problem
  - SUSY
  - Composite/Little/Twin Higgs (Higgs as A_5)
  - Higgsless Models/Technicolor
- All predict new TeV Scale particles
  - SUSY Partners or
  - Extended Electroweak Gauge Symmetries and
  - Extended Fermion Sector
- Much Phenomenology Left to be done!

Our Future: the LHC

LHC Schedule

- Low luminosity at 900 GeV at end 2007: Start debugging detectors
- Some months at beginning of 2008 to commission remaining LHC components
- 14 TeV Physics run in 2008. Significant luminosity is expected
- "Low luminosity" achieved (2 10**33)
- Operation in this mode
- Ramp up to full luminosity in 2010?

Hinchliffe, SSI 2006

Physics Program

- Start by "rediscovering standard model" in new energy regime and new detectors
- Some QCD needed for "engineering" of Monte Carlo: e.g. Min bias and underlying events
- Top and W/Z production are well understood theoretically, start with inclusive and move to exclusive states that are harder for theory
- Some important results will come as soon as detectors are understood sufficiently
- Theorists should pay attention during this phase: which predictions are poor and why? If you wait for "new physics" you may be too late
- Don't believe new "pink elephant" discovery if SM is not understood

What will we see?

Murayama

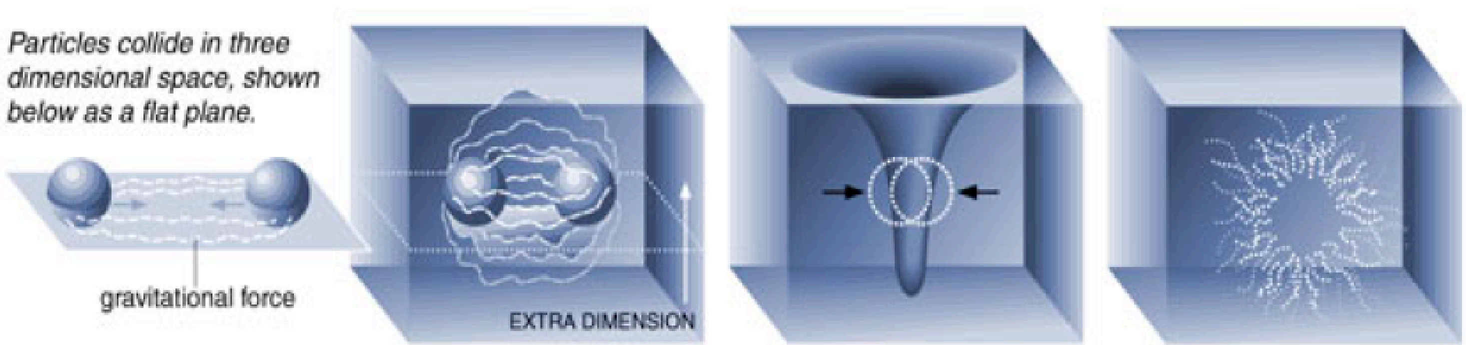
Black Holes in LED?

Black Holes on Demand

NYT, 9/11/01

The New York Times on the Web

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

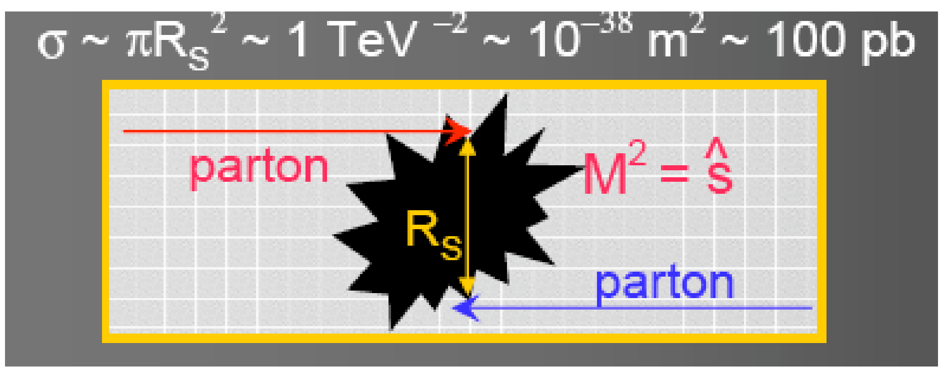


As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

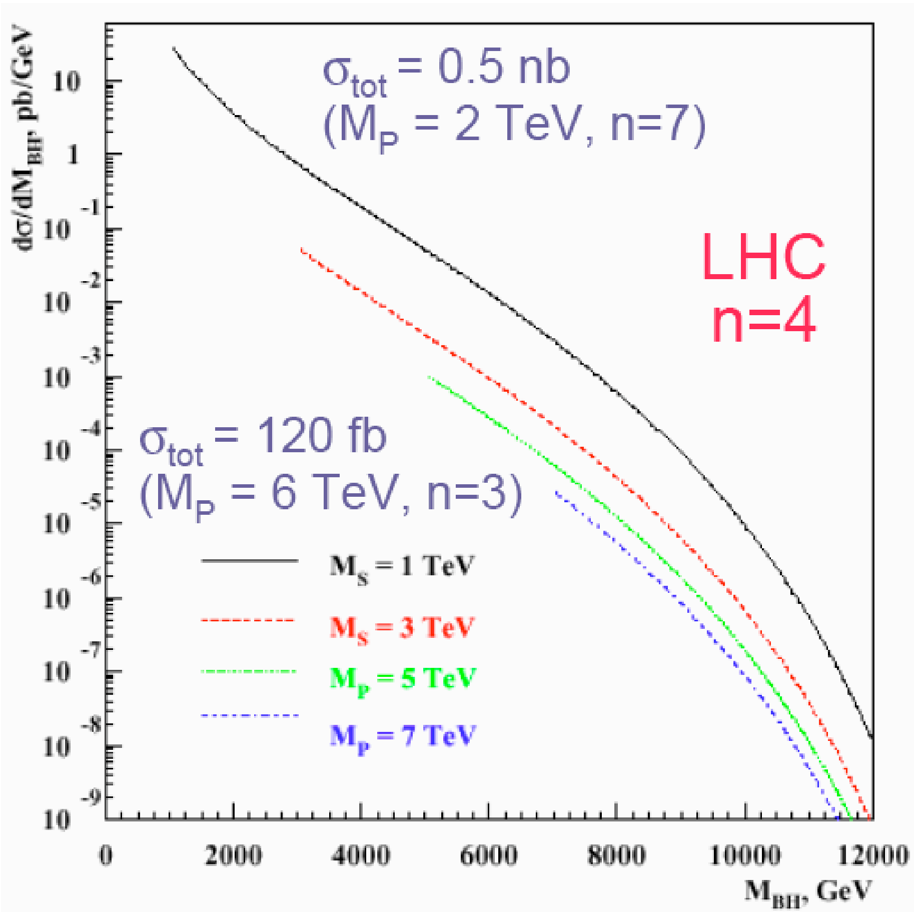
When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

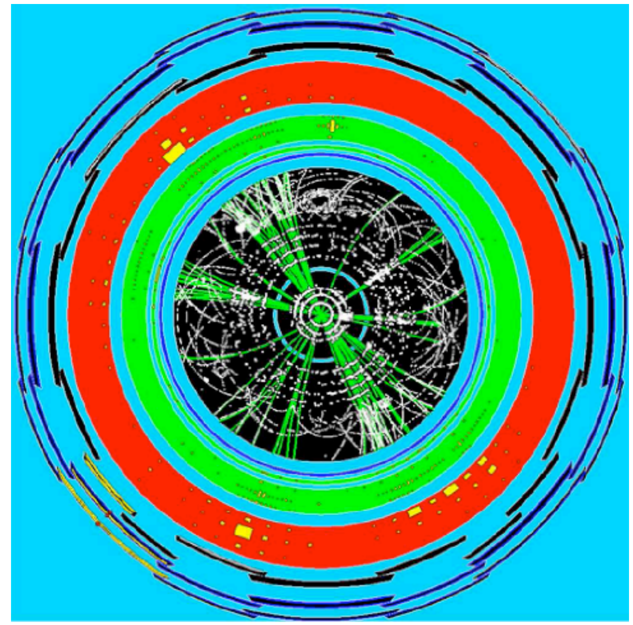


Black Holes @ LHC



Dimopoulos and Landsberg

ATLAS



- High Multiplicity
- High ΣE_T
- High Sphericity
- High Missing P_T
- Democratic Decay

To find out
... return in 2010!

- Thanks to ...
  - Students and Lecturers
  - Sponsors, Organizers, and Staff
  - Profs. Yu-Ping Kuang & Hong-Jian He

... for a wonderful workshop!