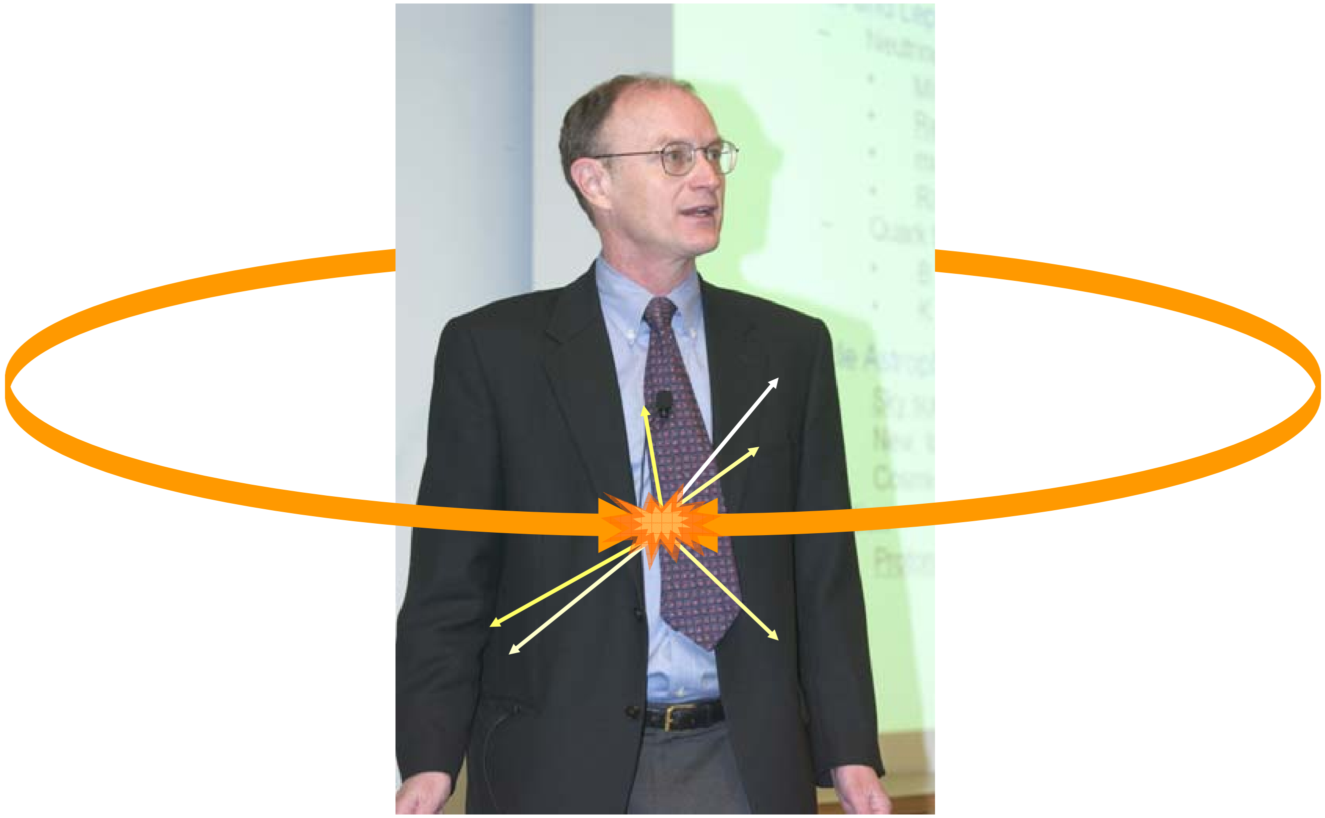
Collider Physics
The Witherell Years



John Womersley – July 14, 2005

What is the universe made of?

- A very old question, and one that has been approached in many ways
  - The only <u>reliable</u> way to answer this question is by directly enquiring of nature, through experiments
- We live in a cold and empty universe: only the stable relics and leftovers of the big bang remain. The unstable particles have decayed away with time, and the symmetries have been broken as the universe has cooled.

  But every kind of particle that ever existed is still there, in the quantum fluctuations of the vacuum. The vacuum "knows" about all the degrees of freedom and all the symmetries.
- We use colliders to pump sufficient energy into the vacuum to re-create the particles and uncover the symmetries that existed in the earliest universe.
- Accelerators, which were invented to study the structure of matter, are also tools to study the structure of the vacuum – the space-time fabric of the universe itself


On this revolutionary anniversary...

Revolution is coming

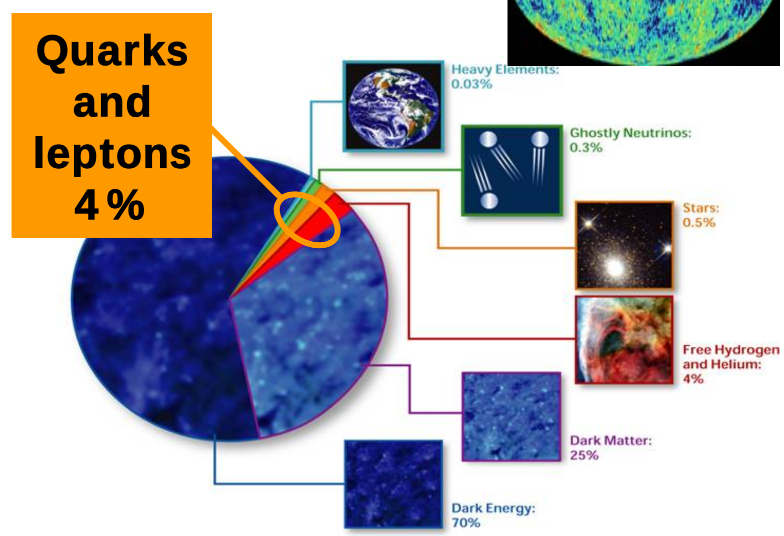
- The standard model makes precise and accurate predictions
- It provides an understanding of what nucleons, atoms, stars, you and me are made of
- But (like capitalism!) it contains the seeds of its own destruction

- Its spectacular success in describing phenomena at energy scales below 1 TeV is based on
  - At least one unobserved ingredient
    - the SM Higgs
  - Whose mass is unstable to loop corrections
    - requires something like supersymmetry to fix
  - And which has an energy density 10^{60} times too great to exist in the universe we live in

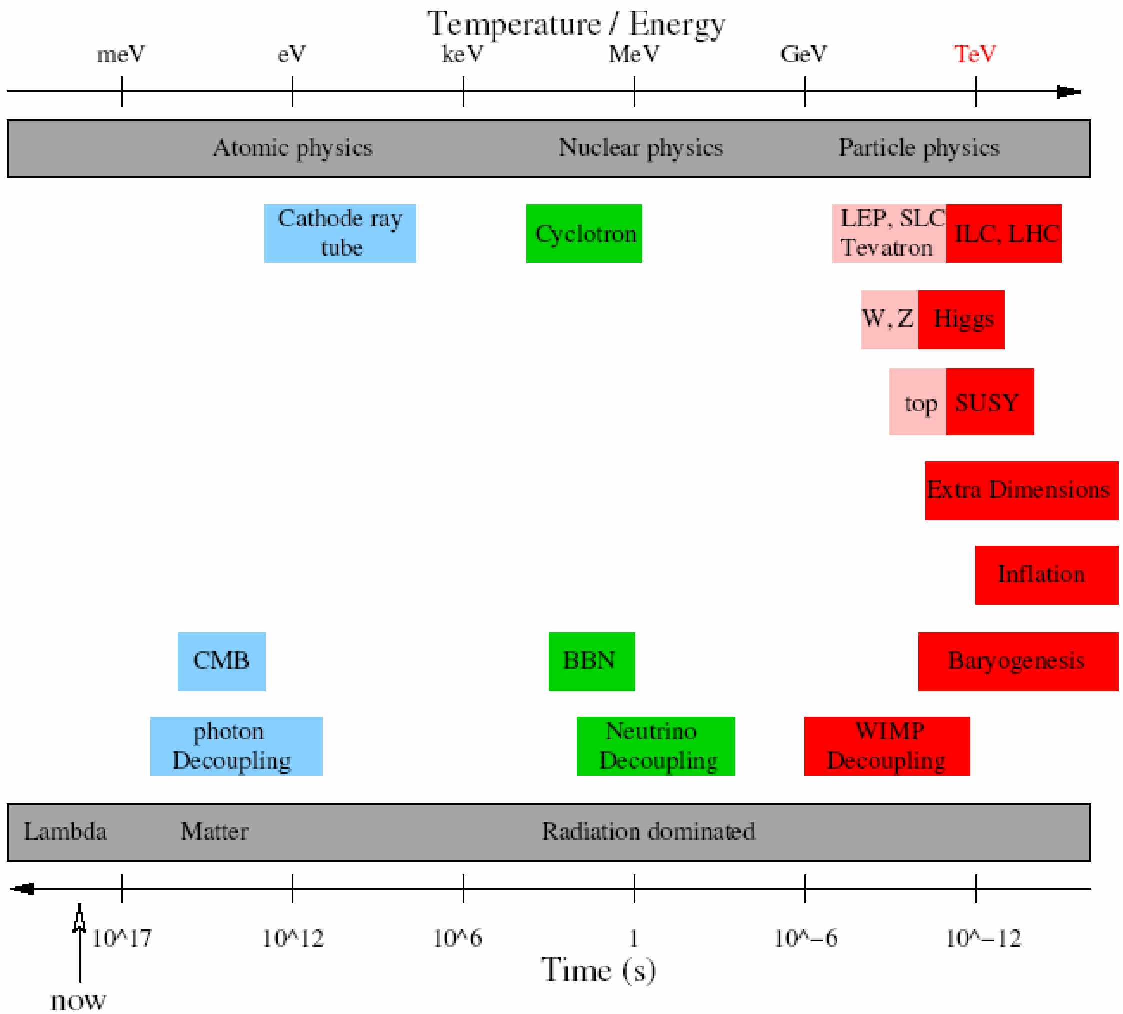
- The way forward is through experiment (and only experiment)
  - tantalizing – we know the answers are accessible
  - frustrating – we have known this for 20 years…

Meanwhile, back in the universe ...

- What shapes the cosmos?
  - Old answer: the mass it contains, through gravity
- But we now know
  - There is much more mass than we'd expect from the stars we see, or from the amount of helium formed in the early universe
    - Dark matter
  - The velocity of distant galaxies shows there is some kind of energy driving the expansion of the universe, as well as mass slowing it down
    - Dark Energy
- We do not know what 96% of the universe is made of!

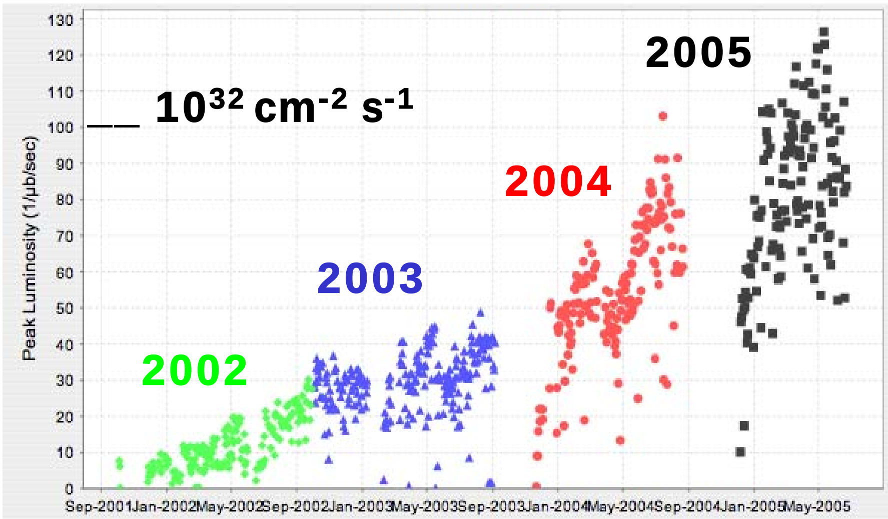


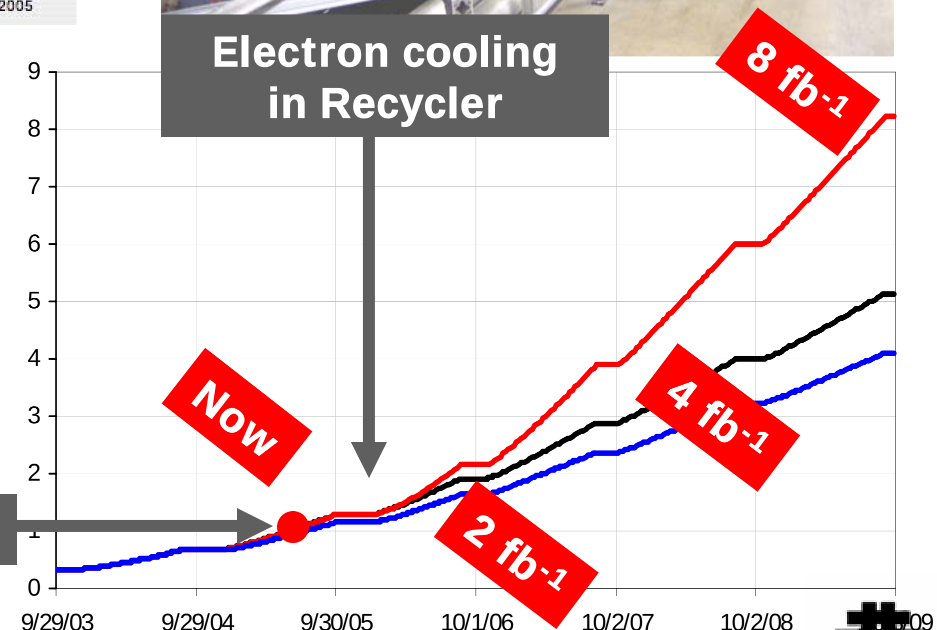
These questions come together at the TeV scale



We are exploring what the universe contained ~ 1ps after the big bang!

Tevatron Status

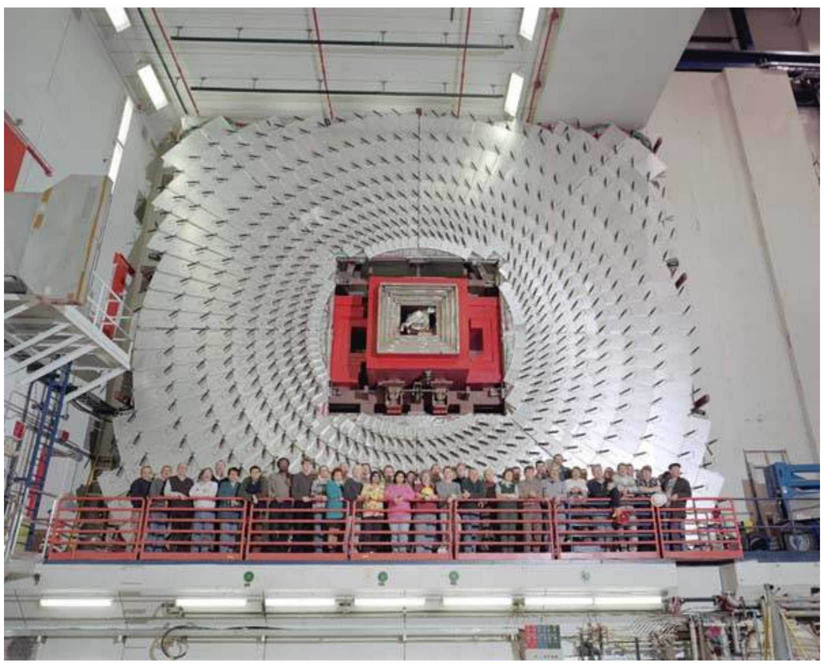


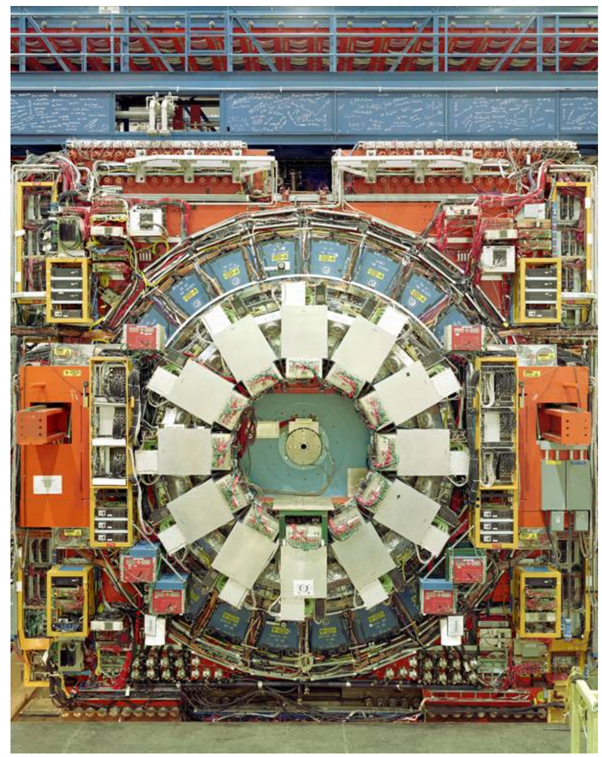


John Womersley

CDF

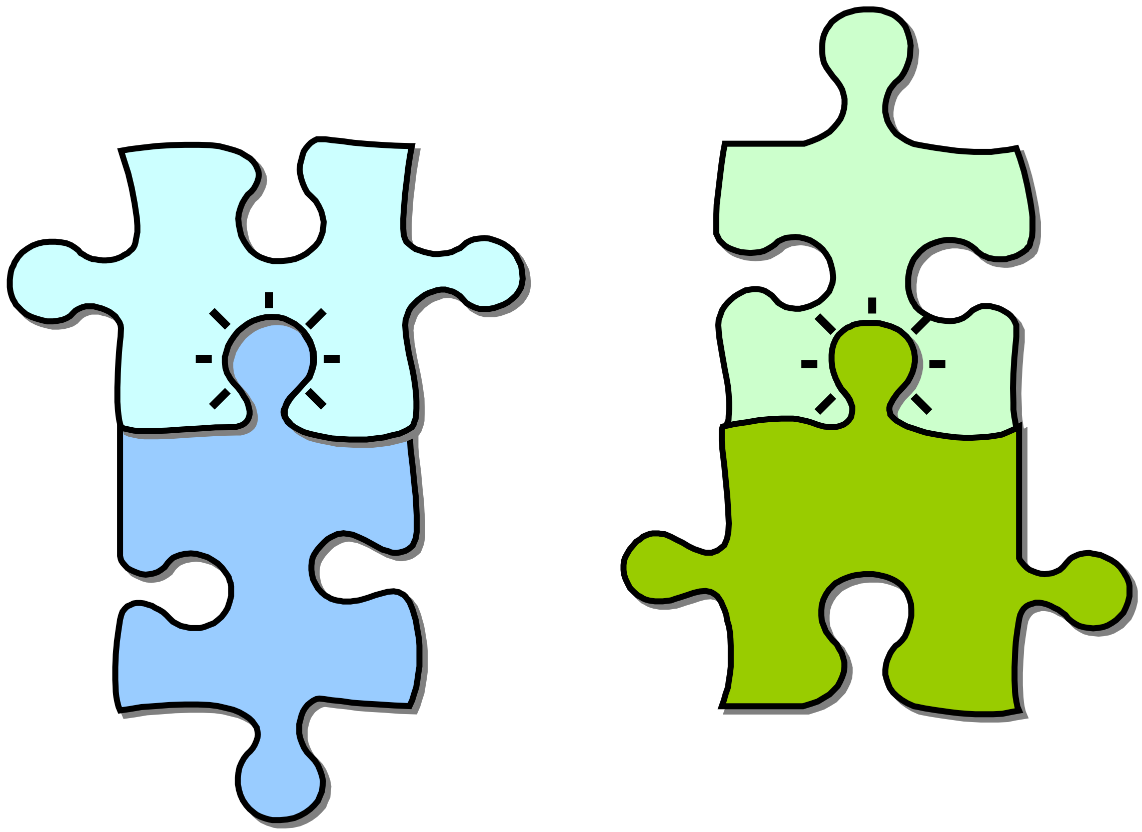
DØ





Particle
Physics
Experiments
Accelerators
Underground

Quantum
Field
Theory
(Standard
Model)



Astronomy
Experiments
Telescopes
Satellites

Standard
Cosmology
Model

10^{-18} m

10^{26} m

Describing the Universe

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Field
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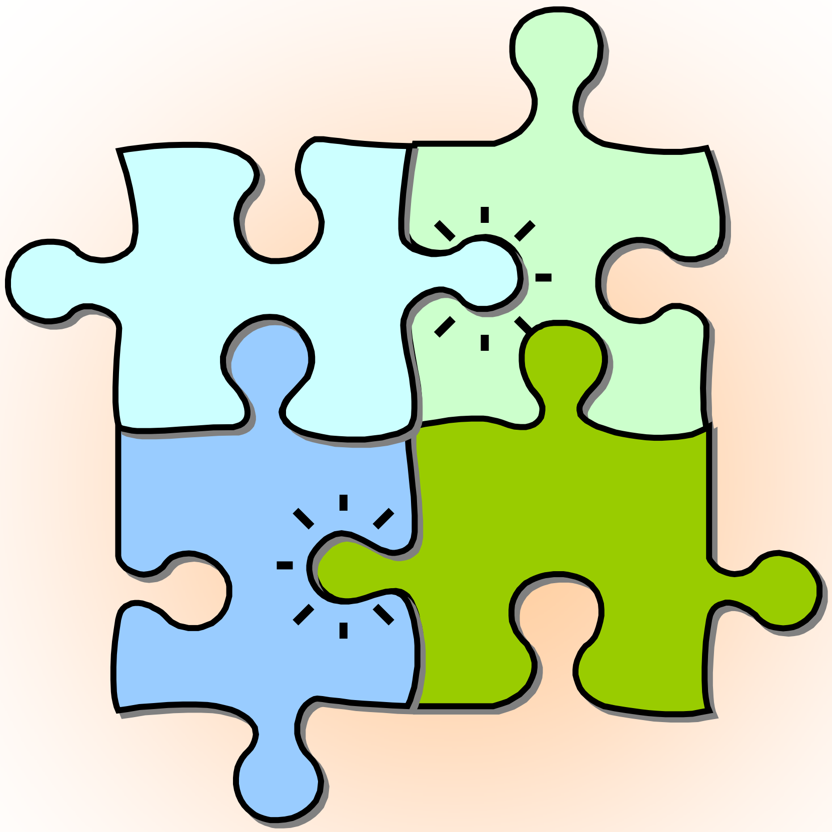

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Consistent understanding?

10^{-18} m

10^{26} m

Describing the Universe

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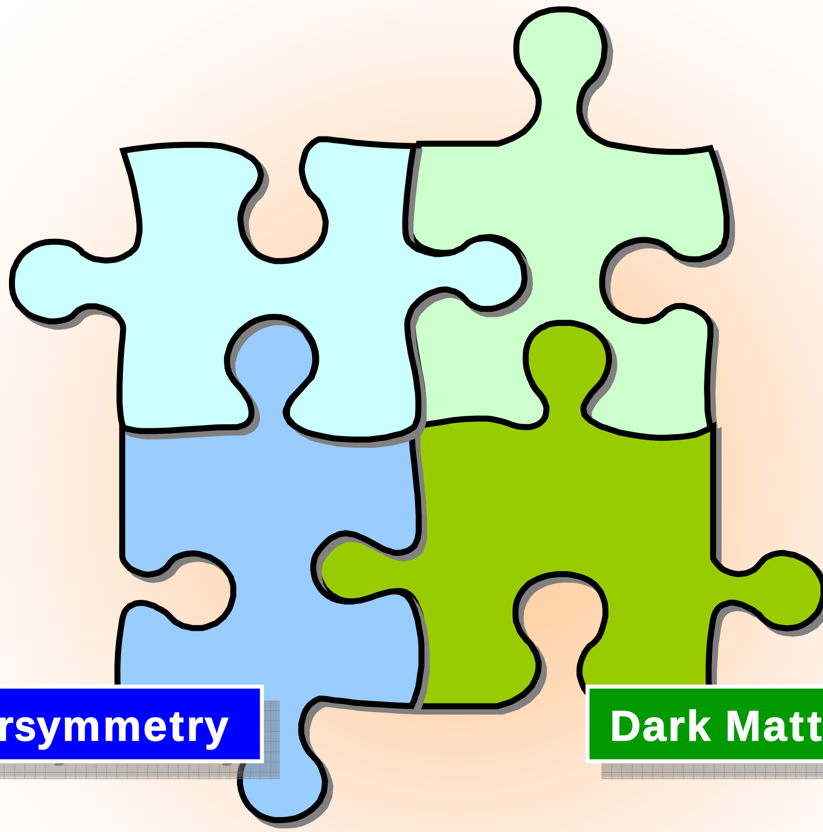

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Consistent understanding?

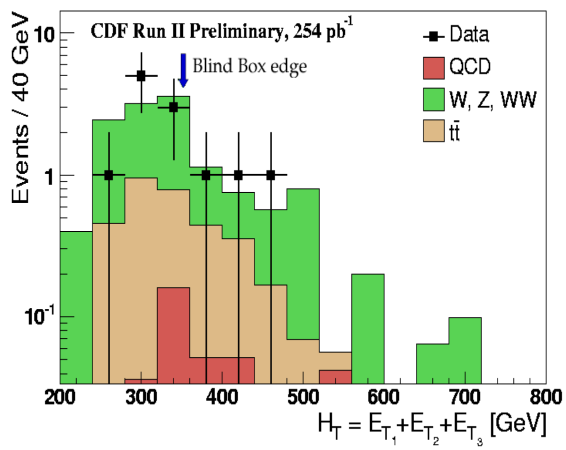
?

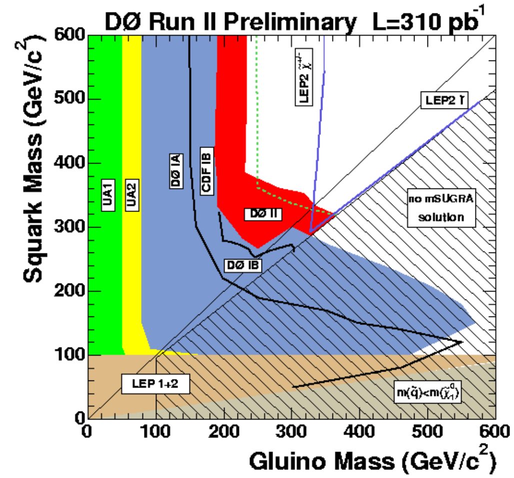
Goals for hadron colliders
- can we discover supersymmetry? Something else?
- is it consistent with cosmic dark matter?

Tevatron supersymmetry searches

Two classic search modes:

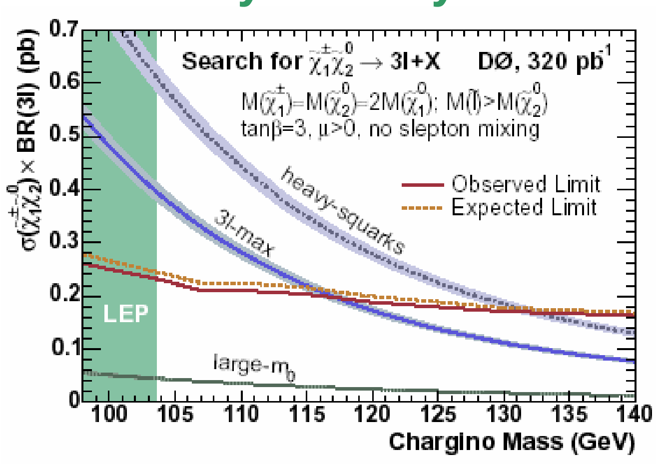
1. **Squarks / Gluinos → jets + missing E_T**

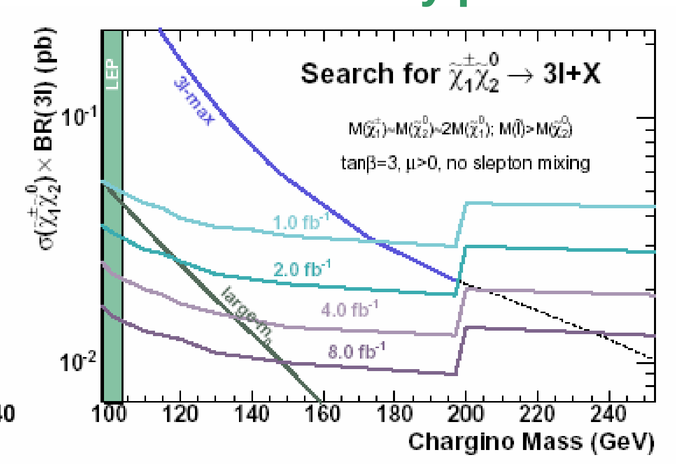




2. **Chargino + Neutralino → trileptons + missing E_T signature**

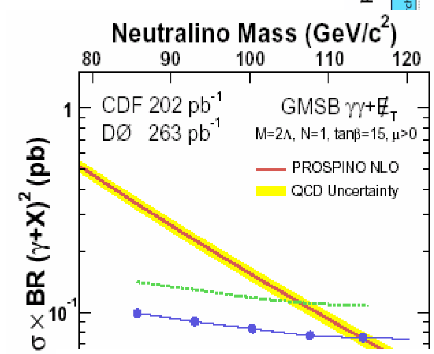
Sensitivity now beyond LEP… … discovery potential

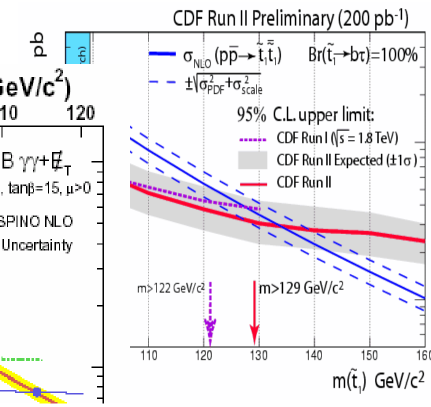


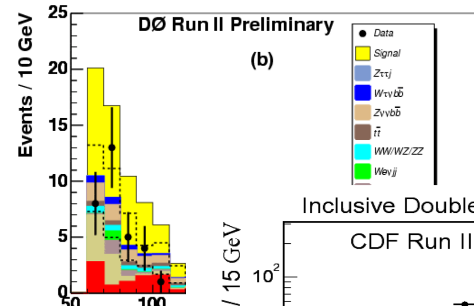


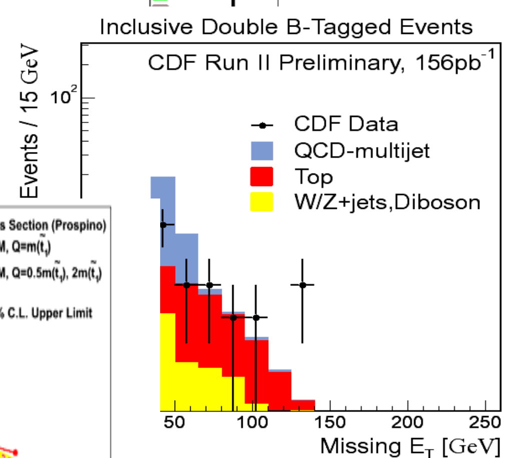
Many other SUSY searches ongoing…

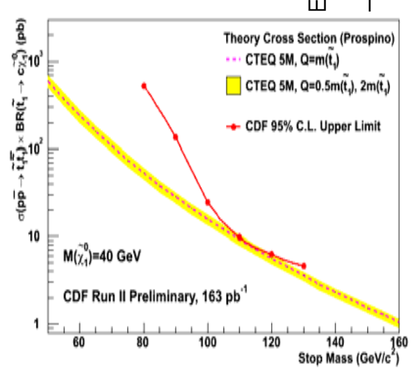
- gluino $\rightarrow$ sbottom + bottom
- sbottom pair production
- stop pair production
- gauge mediated SUSY
  - photons + missing E_T signature
- R-parity violation
  - multileptons from LLE coupling
  - jets + muons from LQD coupling
  - neutralino $\rightarrow$ eμ, ee, $\mu\mu$, $\tau\tau$
  - stop pairs $\rightarrow$ bτ bτ
- charged massive (quasi-)stable particles
  - e.g. stau or chargino

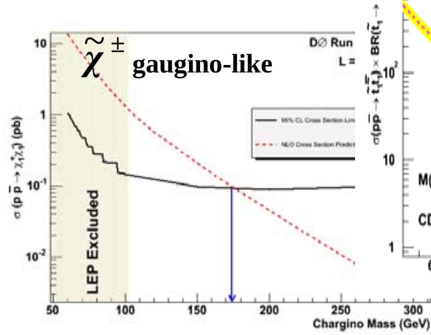






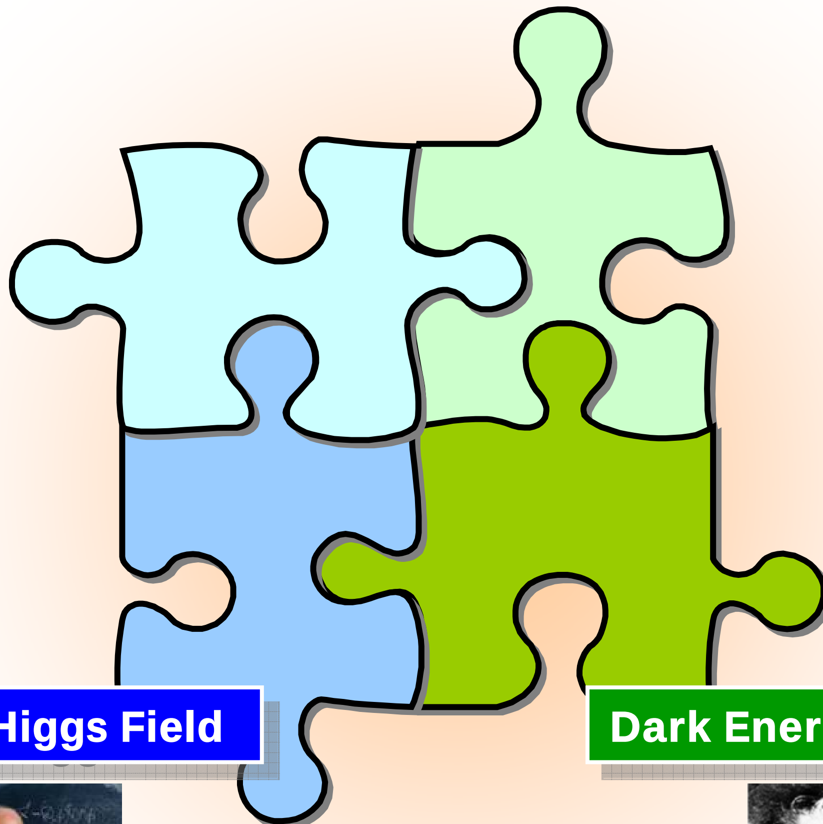






Particle Physics Experiments Accelerators Underground

Quantum Field Theory (Standard Model)

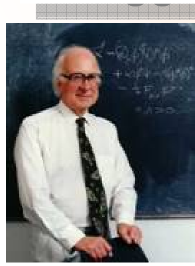


Astronomy Experiments Telescopes Satellites

Standard Cosmology Model

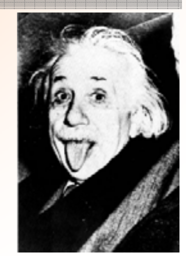
Higgs Field

Dark Energy



Consistent understanding?

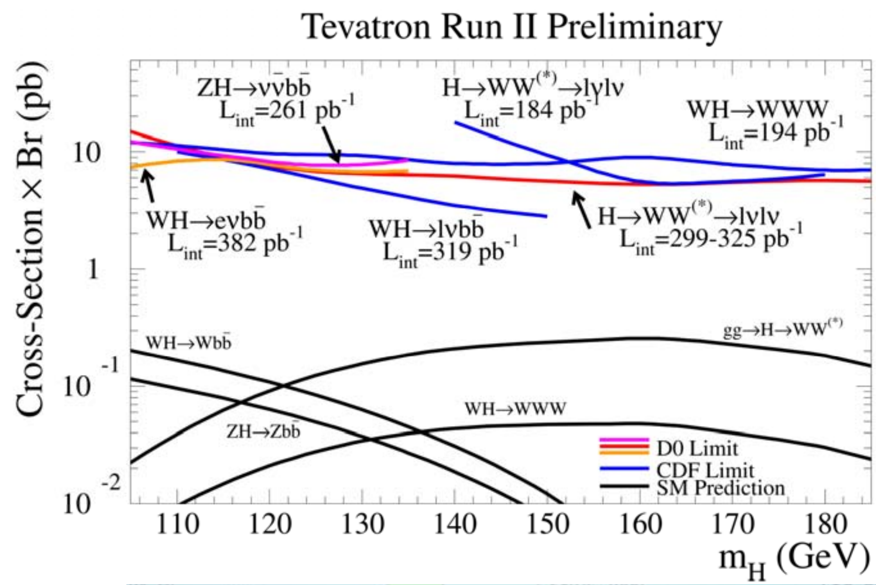
NO! > 10^{60}

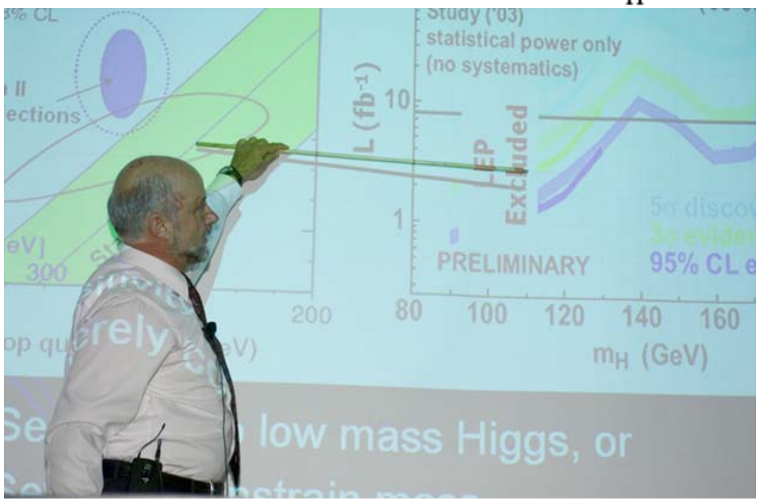


Goals for hadron colliders
- **what can we learn about the Higgs field?**
- **from direct searches, and indirectly from the top quark?**

Higgs at the Tevatron

- **Many analyses being carried out**
- **Limits obtained with ~300pb^{-1} are 20-100 times higher than SM cross section**
- **Experiments have quantified the improvements in sensitivity needed to reach projections**
  - **EM coverage**
  - **EM efficiency**
  - **Dijet mass resolution**
  - **b-tagging**
  - **...**
- **No one said this would be easy!**

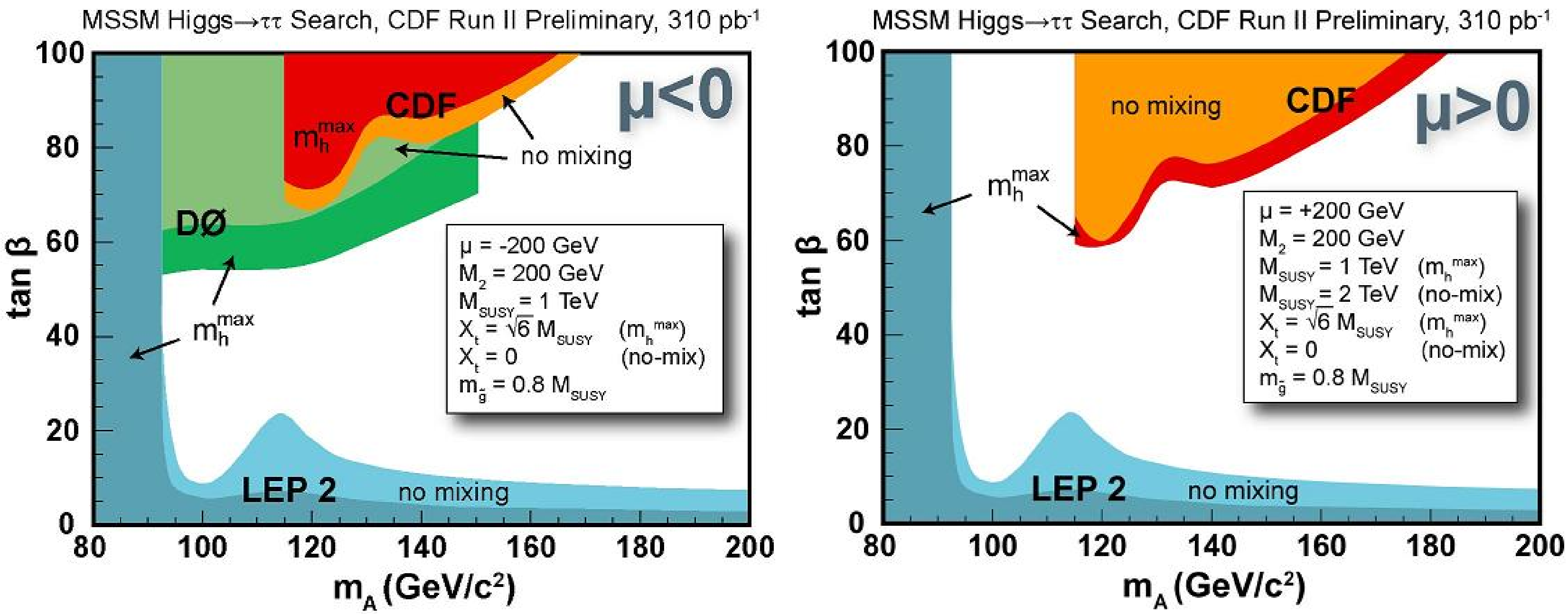




Pier Oddone at National Academies EPP2010 Panel
May 2005

Supersymmetric Higgs at the Tevatron

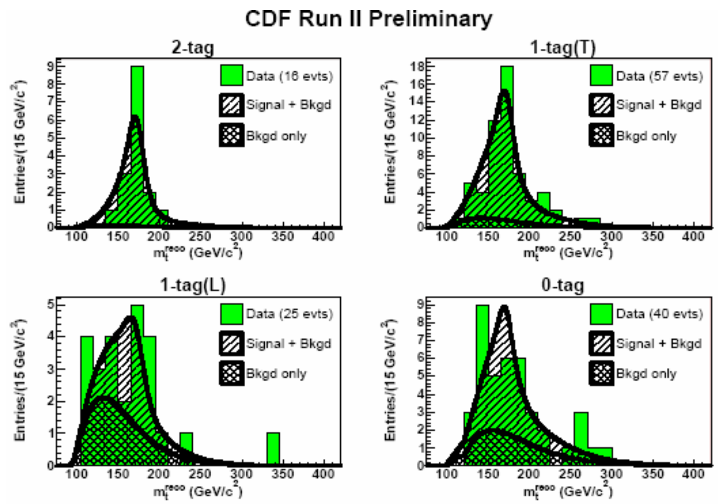
- **H / h / A $\rightarrow \tau\tau$ and $b\bar{b}$**

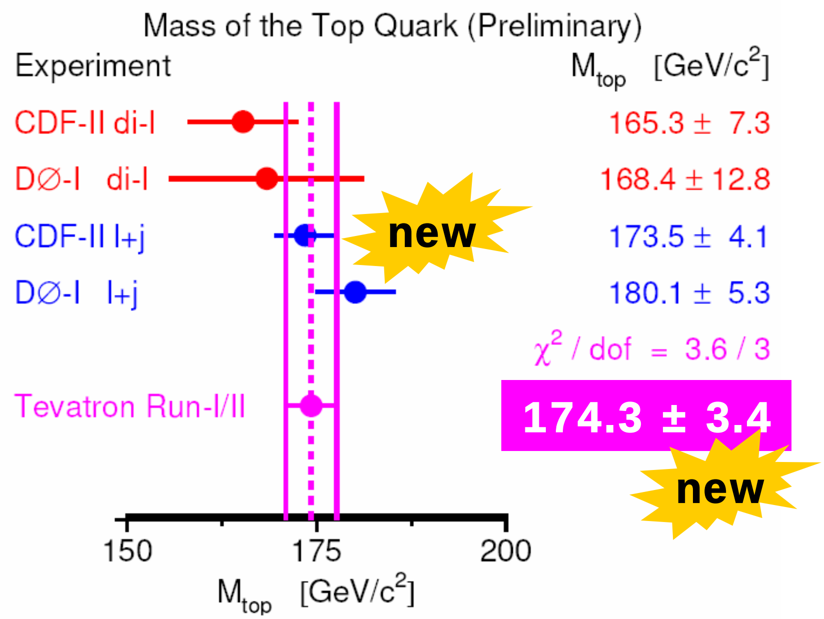


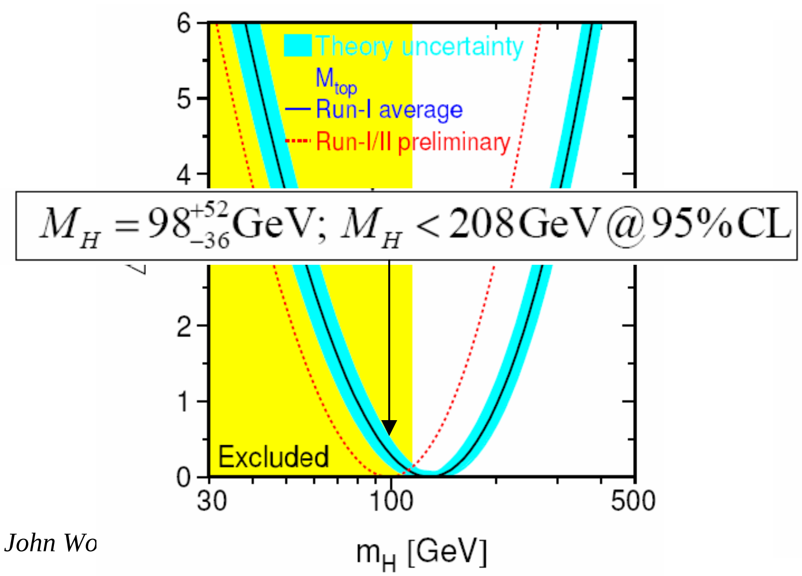
- **Already constraining models at large tan β**
- **Georg Weiglein at HCP 2005:**
  "Tevatron has the potential to rule out mSUGRA, GMSB, AMSB scenarios! Could have big impact on search strategies at LHC."

Top Mass

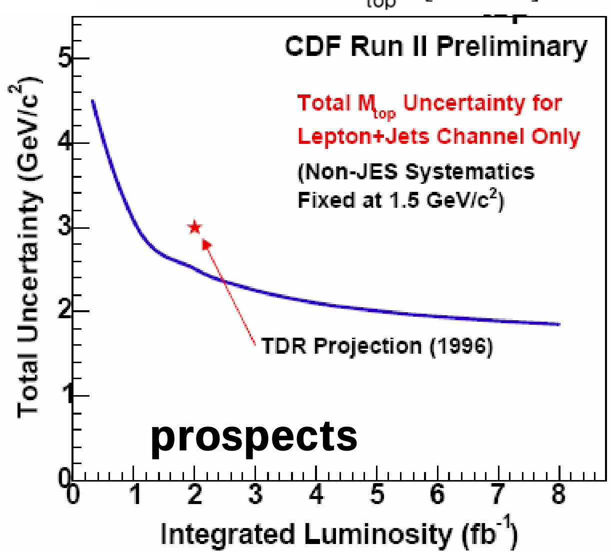
- **New CDF Run II mass (lepton + jets)**







$$M_H = 98^{+52}_{-36}\,\mathrm{GeV};\ M_H < 208\,\mathrm{GeV} @ 95\%\mathrm{CL}$$



Will have a new DØ result soon

How does top decay?

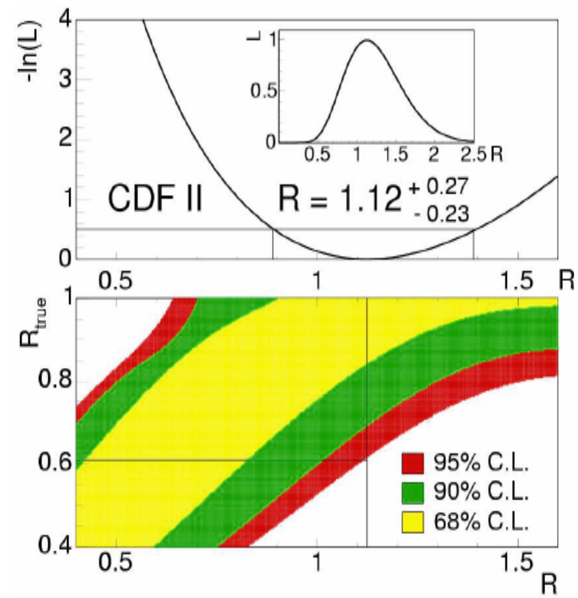
- In the SM, top decays almost exclusively to a W and a b-quark, but in principle it could decay to other down-type quarks too
- Can test by measuring

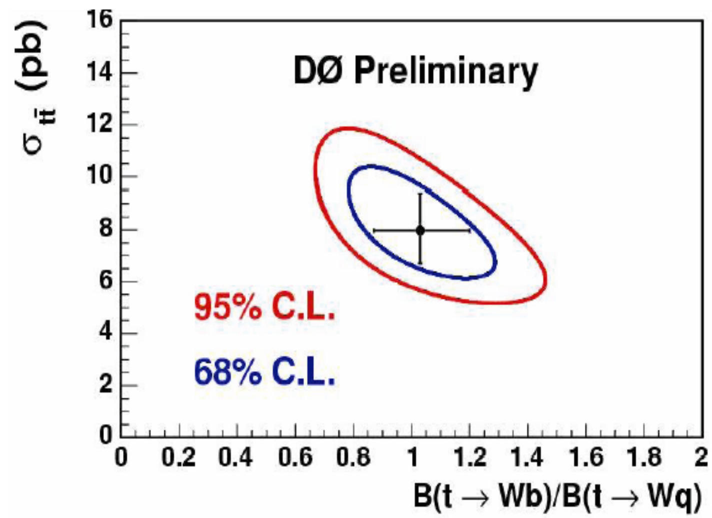
  $R = B(t \to b) / B(t \to q)$
- Compare number of double b-tagged to single b-tagged events

All consistent with R = 1 (SM)
i.e. 100% top $\to$ b

Also CDF searches for top $\to \tau\nu$, top $\to$ charged Higgs

Top charge determination soon





Spin in Top decays

- Because its mass is so large, the top quark is expected to decay very rapidly (~ yoctoseconds)
- No time to form a top meson
- Top → Wb decay then preserves the spin information
  - reflected in decay angle and momentum of lepton in the W rest frame
- DØ finds the fraction of RH W's to be

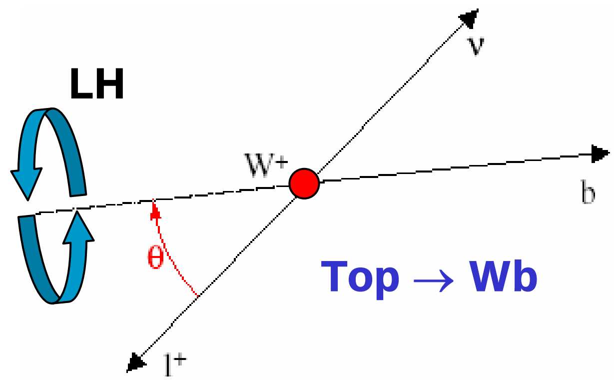
  $F_+ < 0.25$ (95% CL)

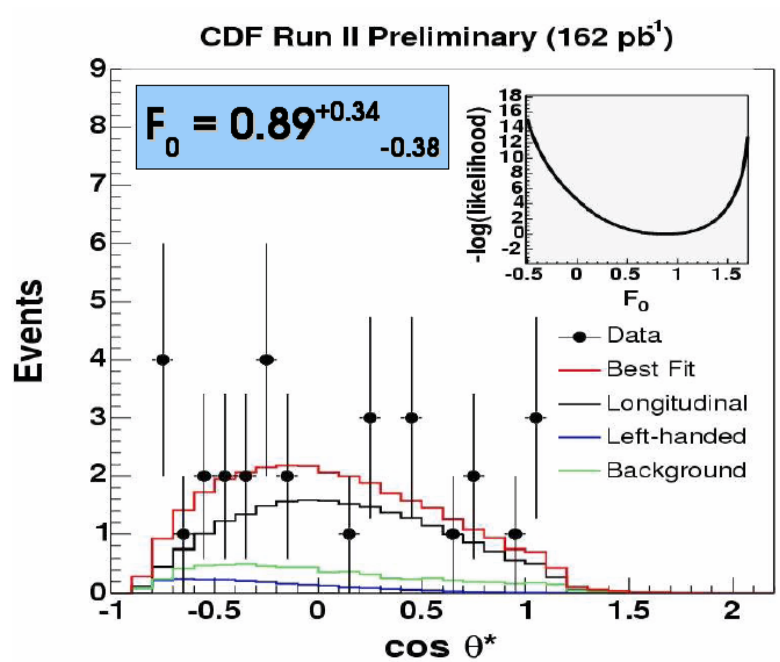
- CDF finds the fraction of longitudinal W's to be

  $F_0 = \; 0.27 \; +0.35 \; -0.24$ (lepton p_T)

  $0.89 \; +0.34 \; -0.38$ ($\cos\theta^*$)

In the SM, $F_+ \approx 0$ and $F_0 \sim 0.7$

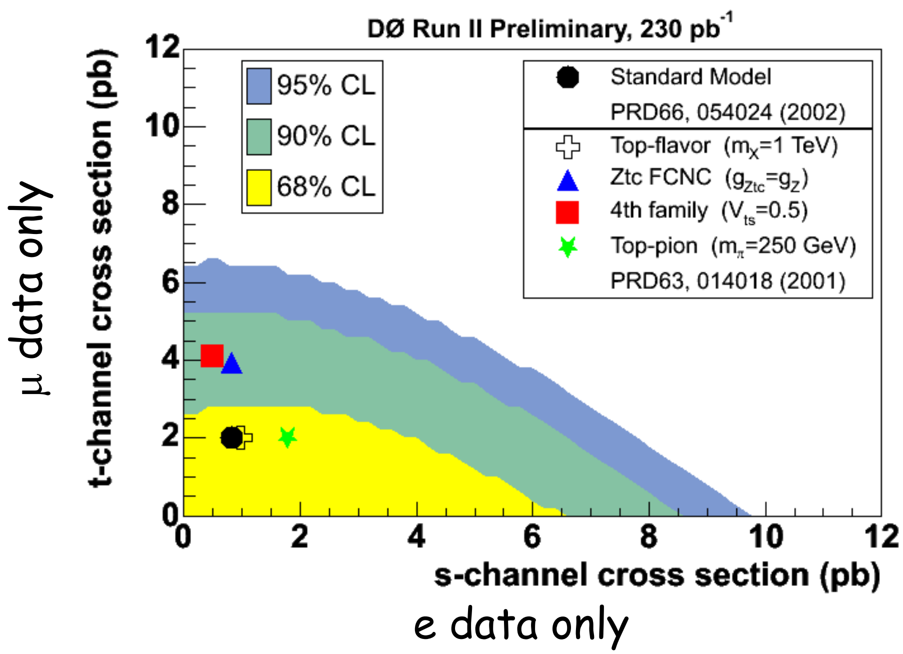




All consistent with the SM

Single Top

- Probes the electroweak properties of top
- Good place to look for new physics connected with top
  - Desirable to separate s and t-channel production



Channel	CDF (162 pb^{-1})	DØ (230 pb^{-1})
s+t	<17.8 (13.6)	
s	<13.6 (12.1)	<6.4 (4.5)
t	<10.1 (11.2)	<5.8 (5.0)

95% CL observed (expected)

- Not yet sensitive to SM, but starting to be sensitive to some models
- With current DØ analysis, would require ~ 2.5fb^{-1} for a 3σ signal in the t-channel
  - So it will happen in Run II – but improvements still desirable!

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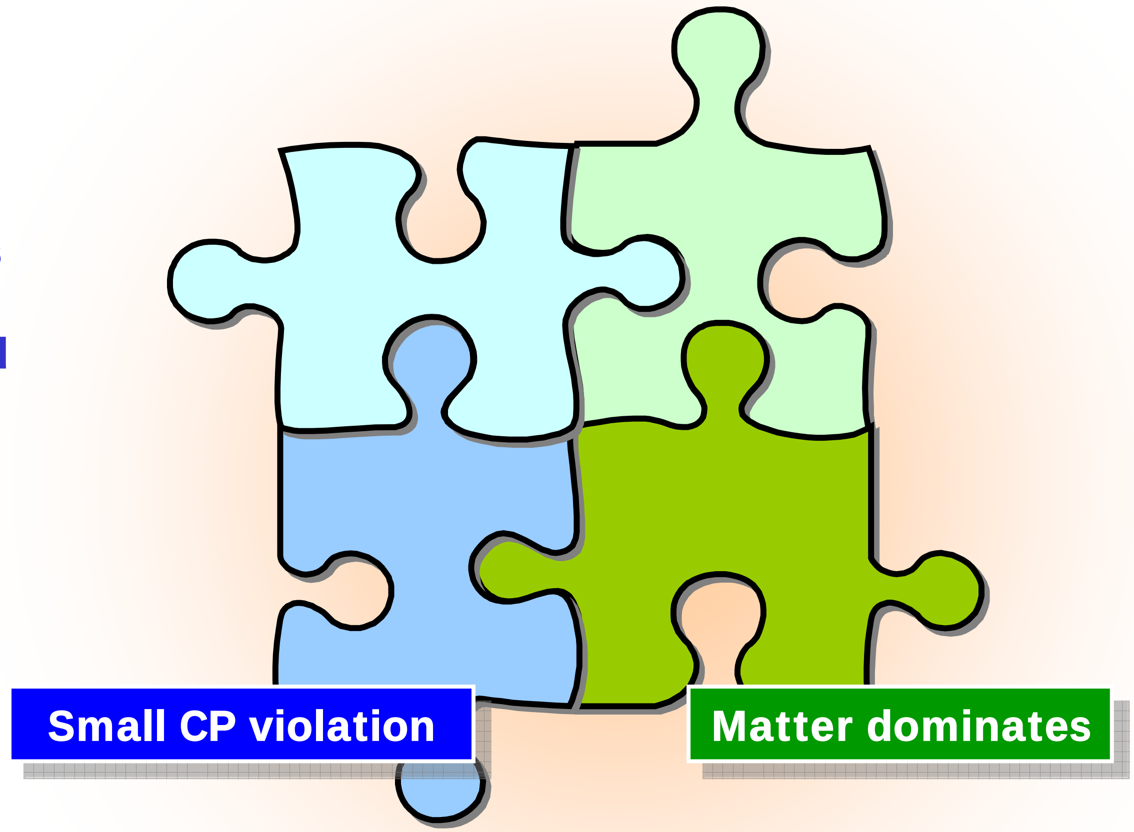


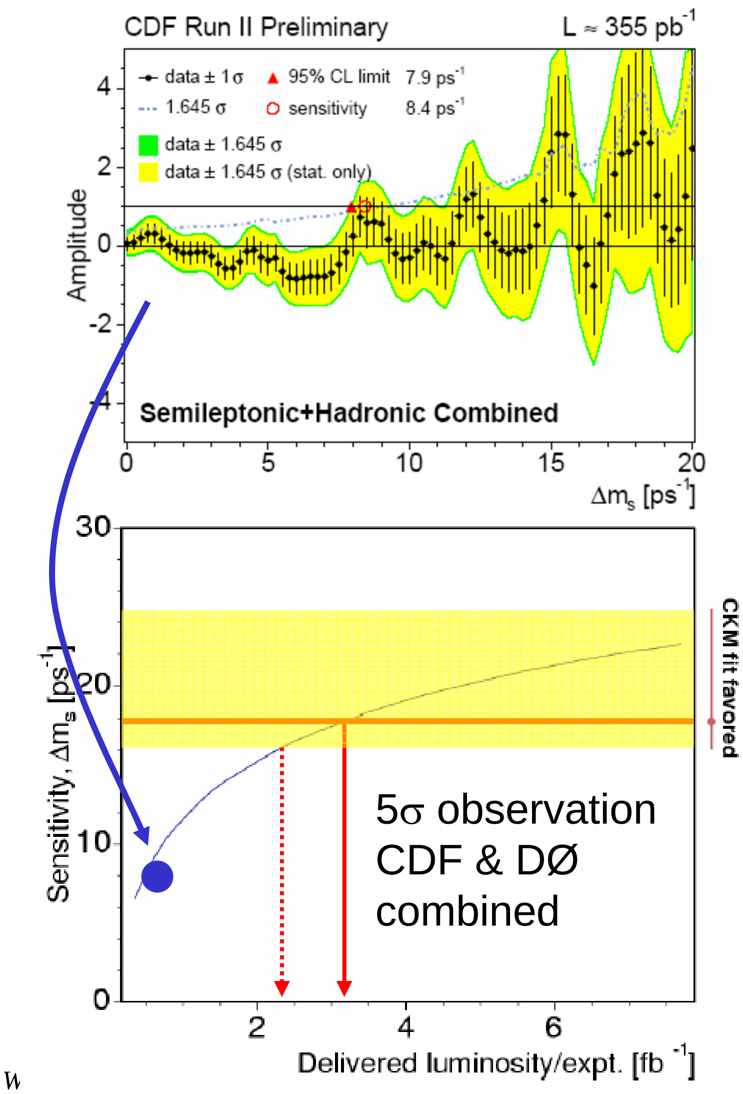
Consistent understanding?

Not really

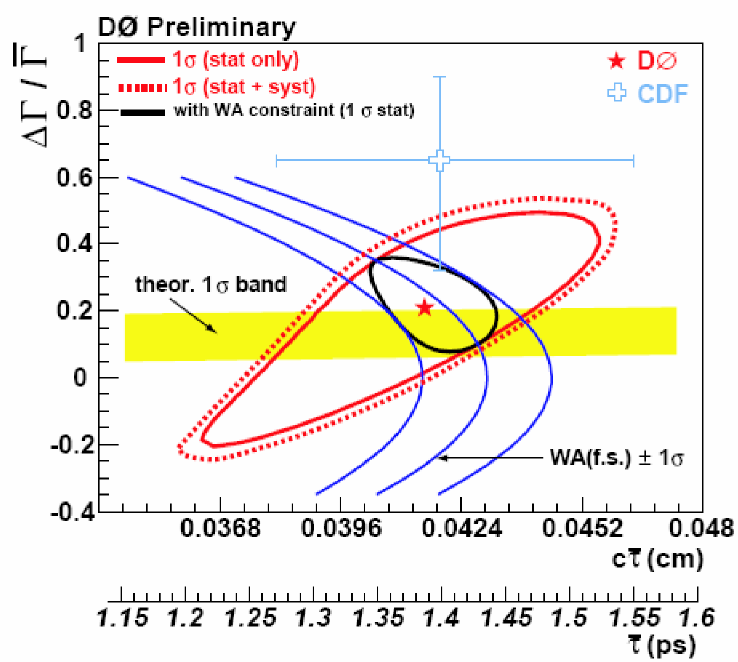
Goals for hadron colliders
- complement the B-factories in exploring CP violation
- search for new sources and use B as probe of new physics

B^0_s oscillations and width difference

- Δm_s > 7.9 ps^{-1} (CDF)



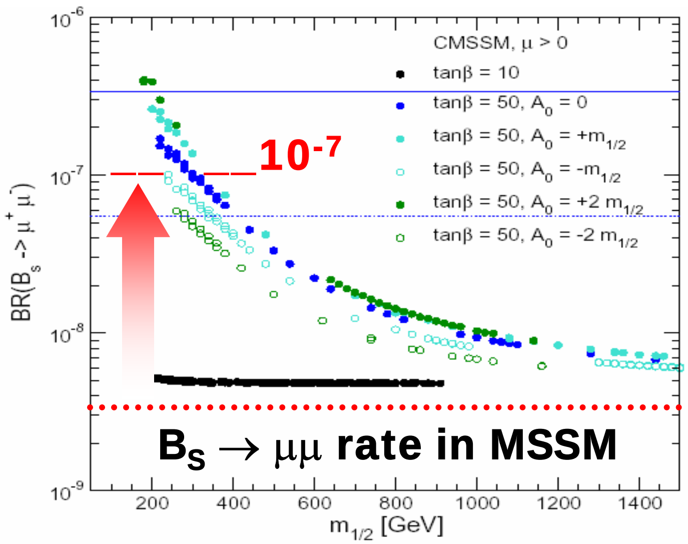
- $\Delta\Gamma_s/\Gamma$ from CDF larger than expected; central value would imply large Δm_s (and new physics?)

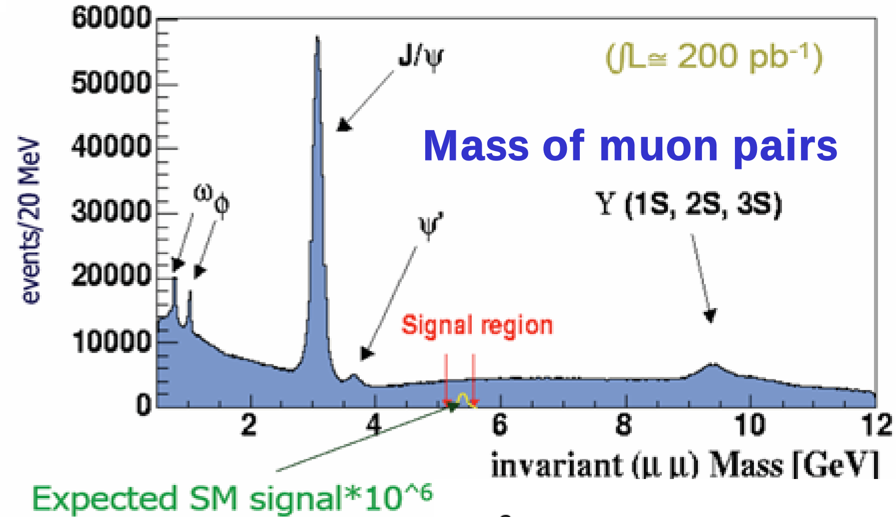


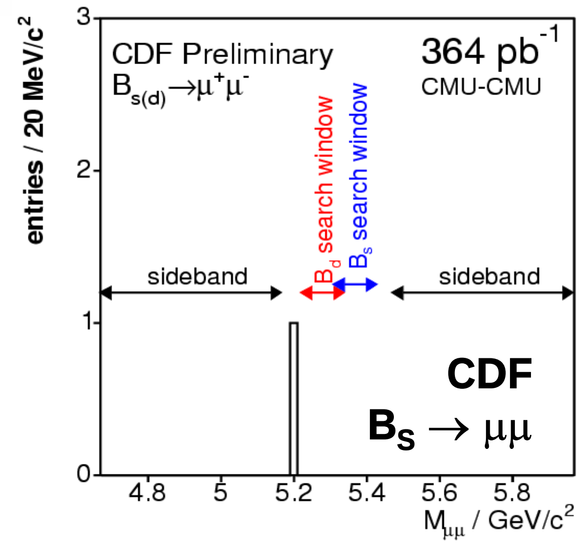
- Combined DØ + CDF consistent with SM

Indirect searches for new physics

- New particles (e.g. SUSY) can substantially increase branching ratios of rare B decays







Decay Mode	CDF (364/336pb^{-1})	DØ (300 pb^{-1})	SM Prediction
$B_s \to \mu^+ \mu^-$	$< 2.0 \times 10^{-7}$	$< 3.7 \times 10^{-7}$	$3.4 \pm 0.4 \times 10^{-9}$
$B_d \to \mu^+ \mu^-$	$< 4.9 \times 10^{-8}$	—	$1.5 \pm 0.9 \times 10^{-10}$
$B_s \to \mu^+ \mu^- \phi$	—	$< 4.1 \times 10^{-6}$	$1.6 \pm 0.5 \times 10^{-6}$
	(95% CL)	(95% CL)	

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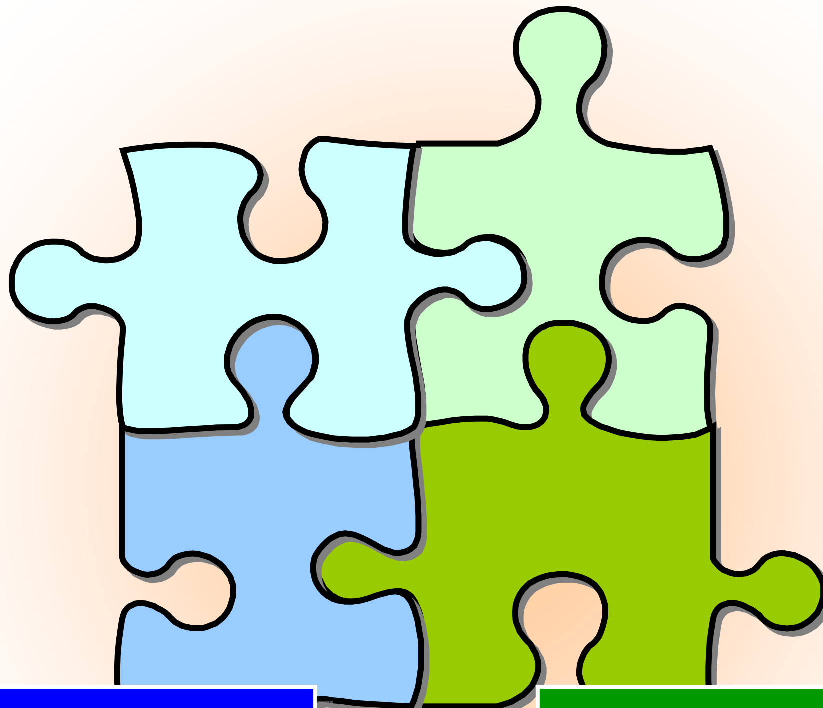

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Supersymmetry
Extra Dimensions

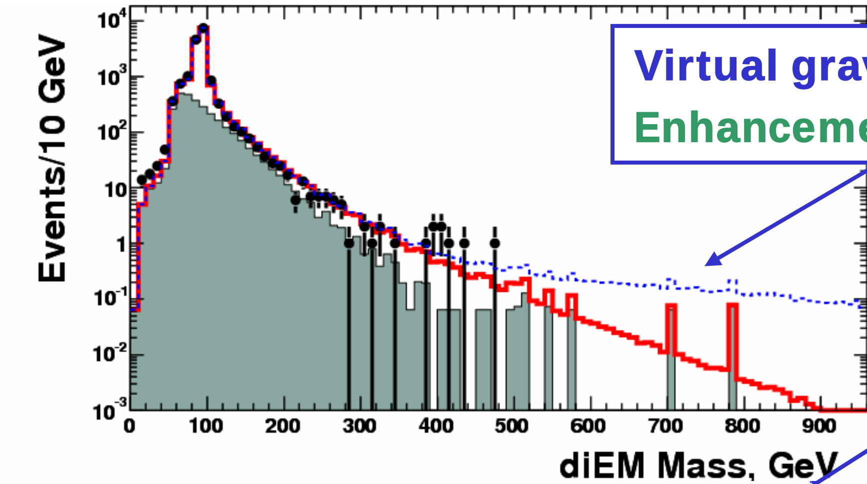
Quantum Gravity
Inflation

Consistent understanding?

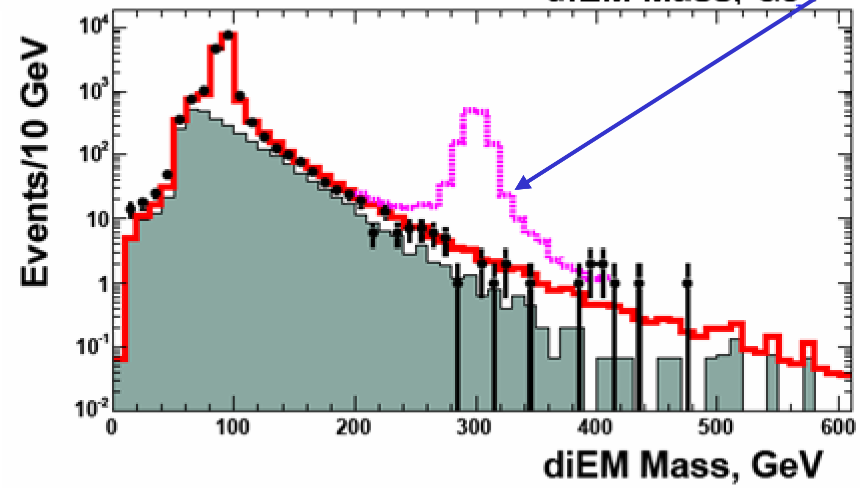
Superstrings!

Goals for hadron colliders
– can we see evidence of extra dimensions?

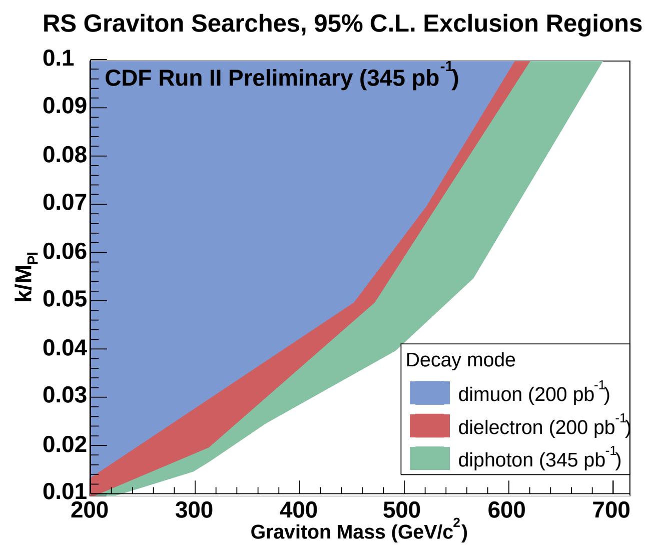
Measuring the shape of space-time



Virtual graviton exchange, e.g. in ADD framework
Enhancement to photon / electron-pair production



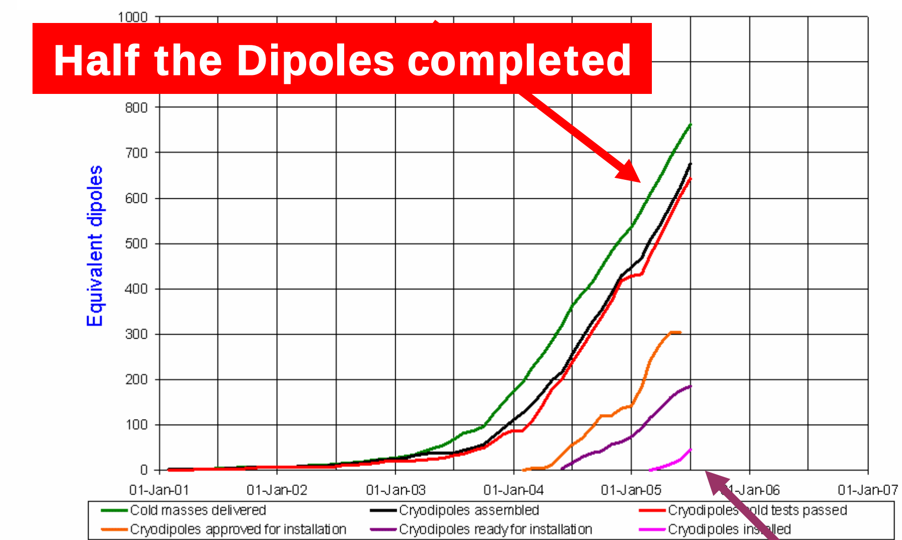
KK excitation of the graviton, e.g. in Randall-Sundrum framework
Assumed to couple to $\gamma\gamma$, ee, $\mu\mu$

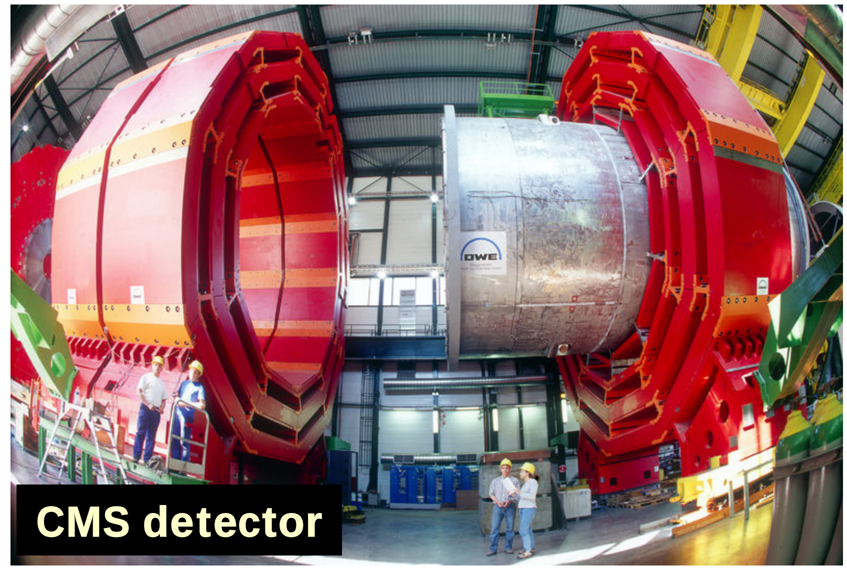


- **See no deviation from 3+1 dimensions**
- **Set limits on the size and properties of extra dimensions**

The Large Hadron Collider

Half the Dipoles completed





Dipoles being installed

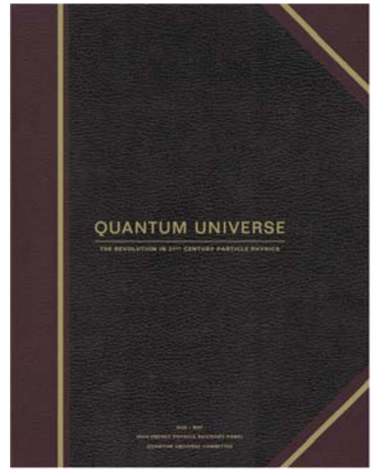
Beam in 2007 - Physics in 2008

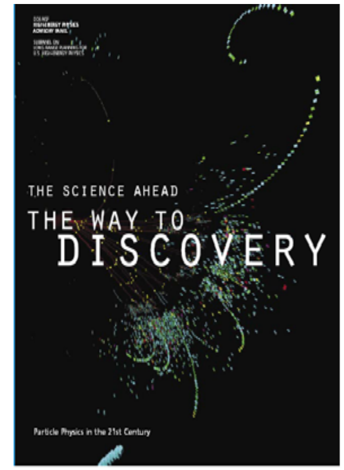
LHC at Fermilab

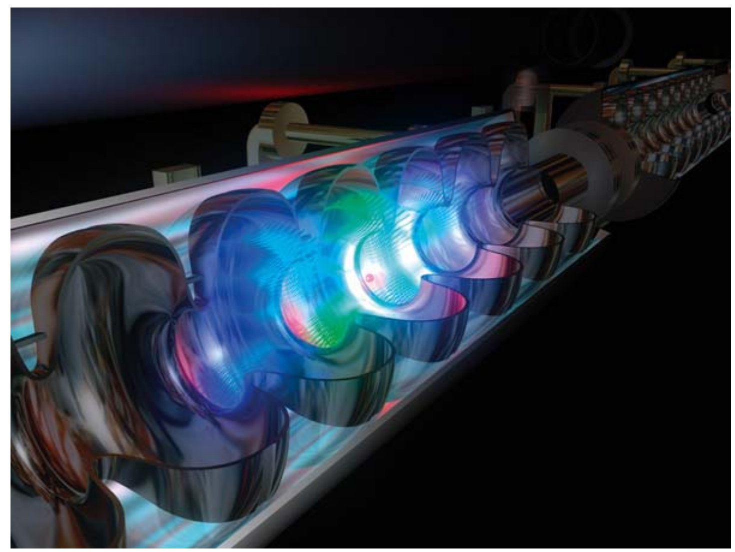
- We confidently expect that the LHC will throw open the door to TeV-scale physics
- Fermilab has long been a key player in both the CMS detector and computing, and the US contribution to the accelerator
- A transition is now underway from construction to operations and analysis
- Concerns
  - How to manage the transition of people from Tevatron to LHC
  - How to ensure full US participation in the physics analysis
- LHC Physics Center at Fermilab is an attempt to address both issues, at least for CMS
  - Support US universities – give access to a critical mass of physicists for LHC analysis without going to CERN
  - Build on Tier I center
  - Share resources with Tevatron experiments

The International Linear Collider

- **Discoveries at the Tevatron or LHC will leave us more questions than answers:**
  - **Have we really discovered the Higgs**
    - **Is it a scalar particle?**
    - **Does it couple to mass?**
  - **Have we really discovered supersymmetry?**
    - **Same coupling, different spin?**
  - **Have we really discovered dark matter?**
    - **Does it have the right properties?**
- **The ILC is the way to answer these questions**

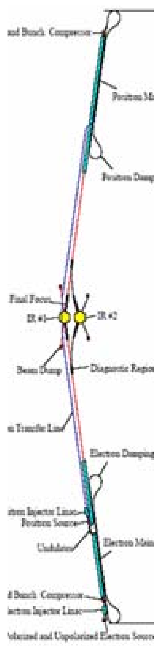


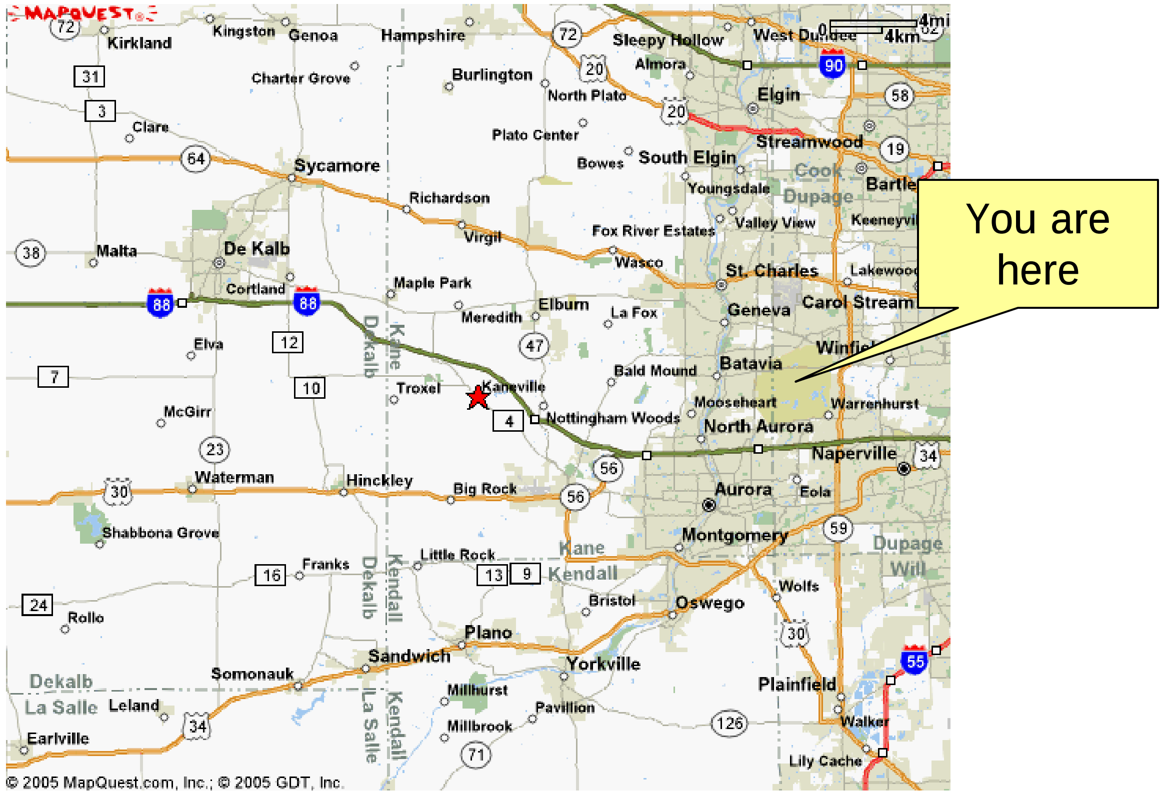




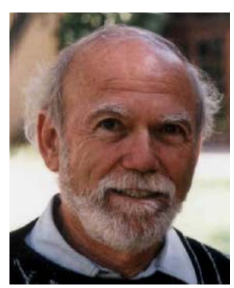
- **Just to show the scale:**

US options study 47 km long





- **Fermilab's role in paving the way towards ILC is critical and growing**
  - R&D in superconducting RF
  - Global Design Effort
  - ...



Conclusions

Axiom

- **The lab director gets the blame for everything that goes badly**

Corollary

- **The lab director deserves at least some credit for everything that goes well**

Mike leaves a solid legacy in collider physics:

- **Run II is on track to be an outstanding physics success**
  - A flood of papers coming out
  - Will see new SM processes e.g. single top, B_S mixing
  - Will constrain – hopefully discover – physics beyond the SM
- **When the energy frontier moves to CERN, Fermilab is well placed to continue to play a strong role**
  - LPC – a new partnership with the universities
- **Worldwide consensus on ILC is matched by a growing feeling, both inside the lab and out, that it belongs here**

Thanks – and good luck!