The search for physics Beyond the Standard Model

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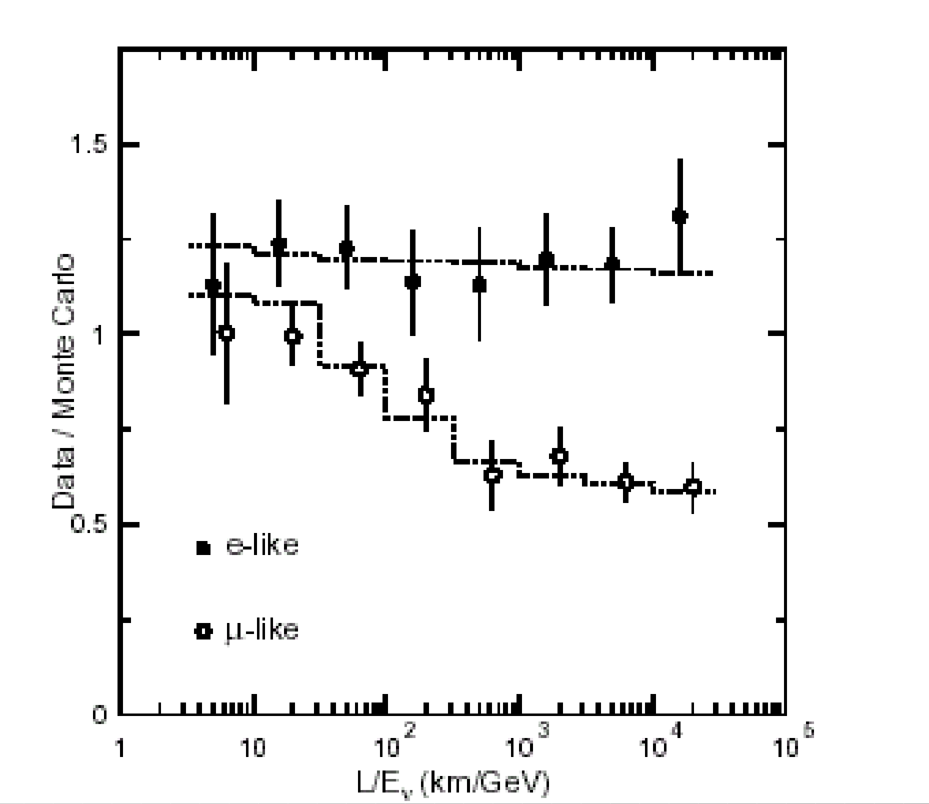
We are already in the era of Beyond the SM physics!

neutrino oscillations

with this plot from SuperK in 1998, everybody started believing in atmospheric ν oscillations



neutrino oscillations

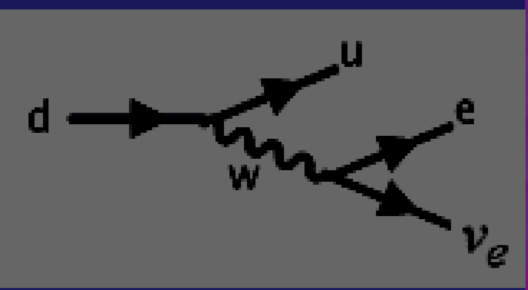
neutrino masses imply new physics:
need right-handed ν's and/or violate lepton number

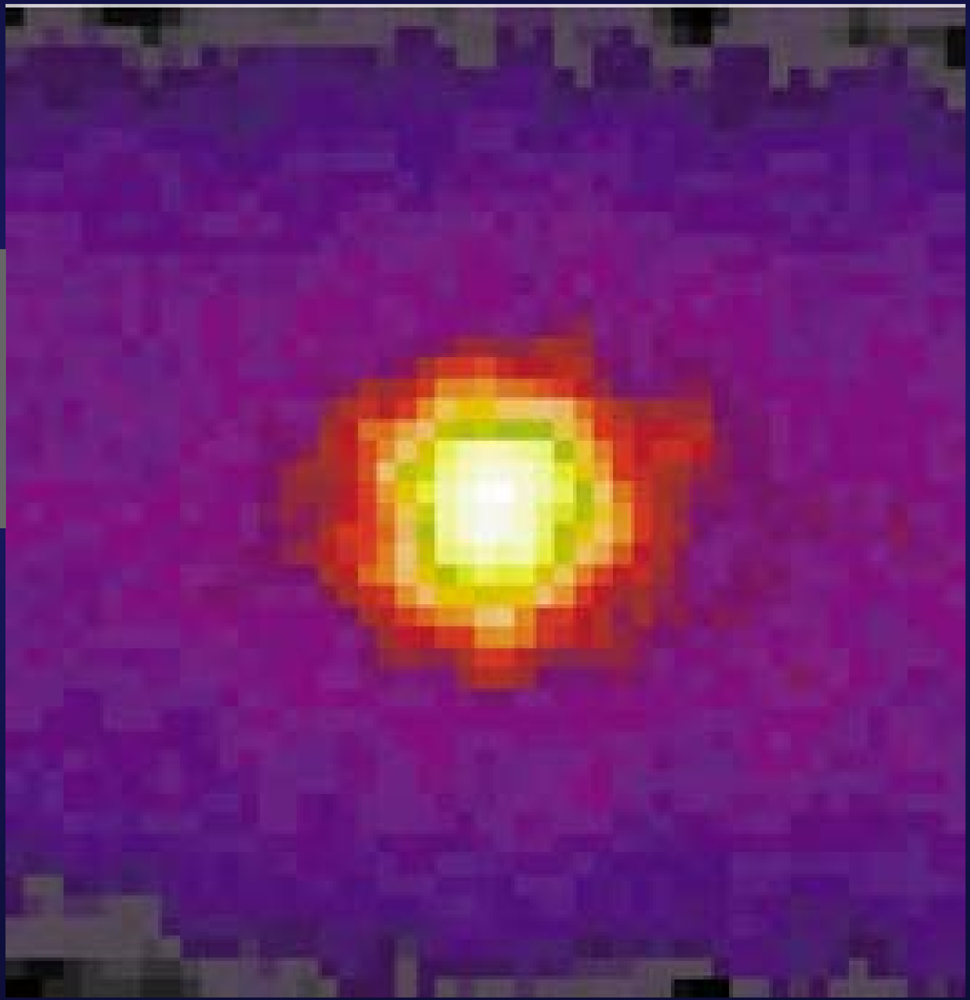
this is great!

but the situation with solar neutrino oscillations
was more confused…

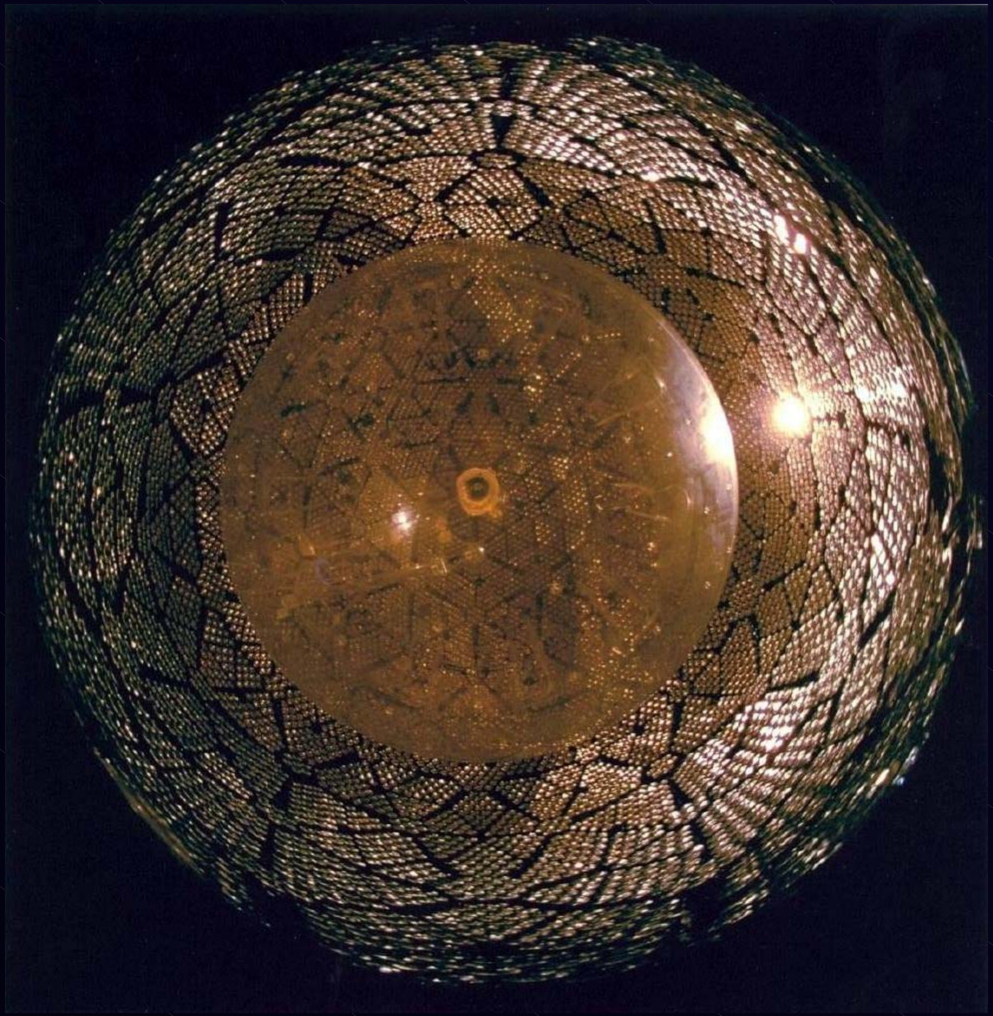
and the LSND result was even less convincing.

solar neutrinos





New results from SNO



- direct evidence for flavor conversion of solar ν's
- observation of day/night effect

ν Reactions in SNO

CC $\nu_e + d \Rightarrow p + p + e^-$

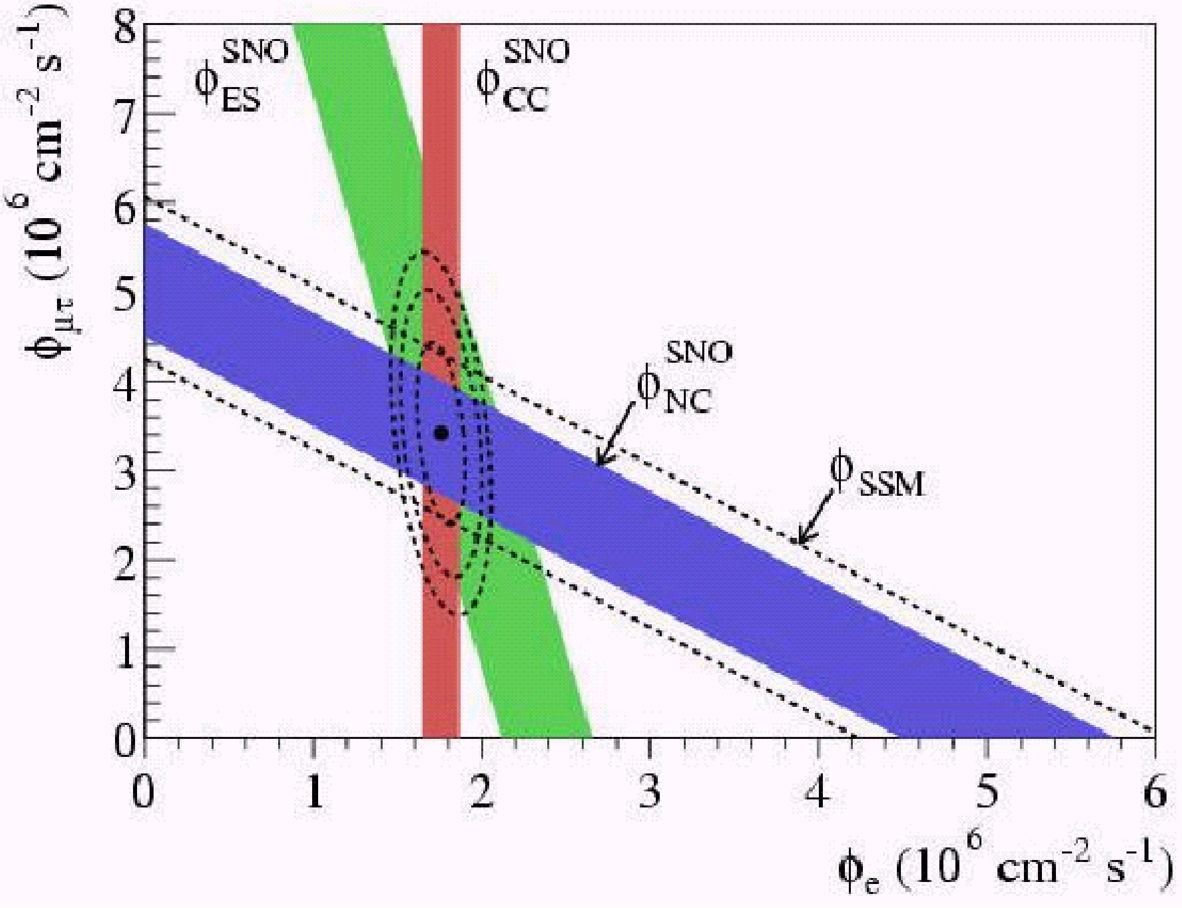
-Good measurement of ν_e energy spectrum
-Weak directional sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- Equal cross section for all ν types
- Measure total ^{8}B ν flux from the sun.

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

-Low Statistics
-Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
-Strong directional sensitivity



ϕ^{SNO}_{ES}
ϕ^{SNO}_{CC}
ϕ^{SNO}_{NC}
ϕ_{SSM}
$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8

Shape Constrained Neutrino Fluxes

Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES}. $E_{Theshold} > 5$ MeV

$$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05}\,(\text{stat.})\,^{+0.09}_{-0.09}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23}\,(\text{stat.})\,^{+0.12}_{-0.12}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43}\,(\text{stat.})\,^{+0.46}_{-0.43}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

Signal Extraction in Φ_e, $\Phi_{\mu\tau}$.

$$\Phi_e = 1.76^{+0.05}_{-0.05}\,(\text{stat.})\,^{+0.09}_{-0.09}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}\,(\text{stat.})\,^{+0.48}_{-0.45}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

Purely sterile oscillations excluded at 5.4 σ

global solar data favors LMA, disfavors SMA at nearly 4σ

Solution	Δm^2	$\tan^2(\theta)$	$f_{B,best}$	χ^2_{min}	g.o.f.
LMA	5.0×10^{-5}	4.2×10^{-1}	1.07	45.5	49%
LOW	7.9×10^{-8}	6.1×10^{-1}	0.91	54.3	19%
VAC	4.6×10^{-10}	1.8×10^{0}	0.77	52.0	25%
SMA	5.0×10^{-6}	1.5×10^{-3}	0.89	62.7	5.1%
Just So^2	5.8×10^{-12}	1.0×10^{0}	0.46	86.3	~ 0%
Sterile VAC	4.6×10^{-10}	2.3×10^{0}	0.81	81.6	~ 0%
Sterile Just So^2	5.8×10^{-12}	1.0×10^{0}	0.46	87.1	~ 0%
Sterile SMA	3.7×10^{-6}	4.7×10^{-4}	0.55	89.3	~ 0%

Bahcall, Gonzalez-Garcia, Pena-Garay, hep-ph/0204314
Barger *et al*, hep-ph/0204253

are we converging on a
STANDARD MODEL of ν oscillations?

NO

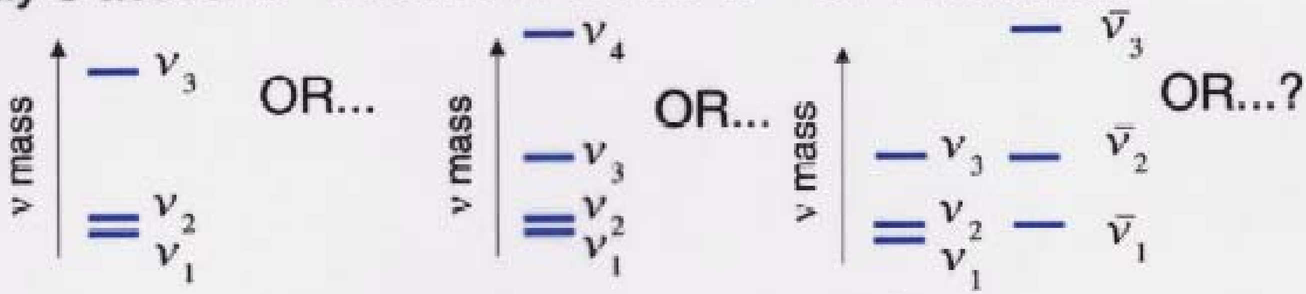
two big mysteries:

- is the LSND result correct?
- where do ν masses and mixings come from?

is the LSND result correct?

With the latest results on solar, atmospheric, and accelerator ν–oscillation searches (3 Δm^2s), we have an interesting situation:

Only 3 active ν: 3 active+1 sterile ν: CPT violation:



Only 3 active ν	3 active+1 sterile ν	CPT violation
solar: $\nu_e \rightarrow \nu_\mu$	*solar:* $\nu_e \rightarrow \nu_\mu, \nu_\tau$	*solar:* $\nu_e \rightarrow \nu_\mu$
atmos: $\nu_\mu \rightarrow \nu_e, \nu_\tau$	*atmos:* $\nu_\mu \rightarrow \nu_\tau$	*atmos:* $\nu_\mu \rightarrow \nu_\tau$
LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \rightarrow \bar{\nu}_e$	*LSND:* $\bar{\nu}_\mu \rightarrow \bar{\nu}_s \rightarrow \bar{\nu}_\mu$	*LSND:* $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
– not a good fit to data	– possible(?)	– possible(?)

Need to definitively check the LSND result!

Rex Tayloe, Indiana U.
Neutrino 2002, 5/02

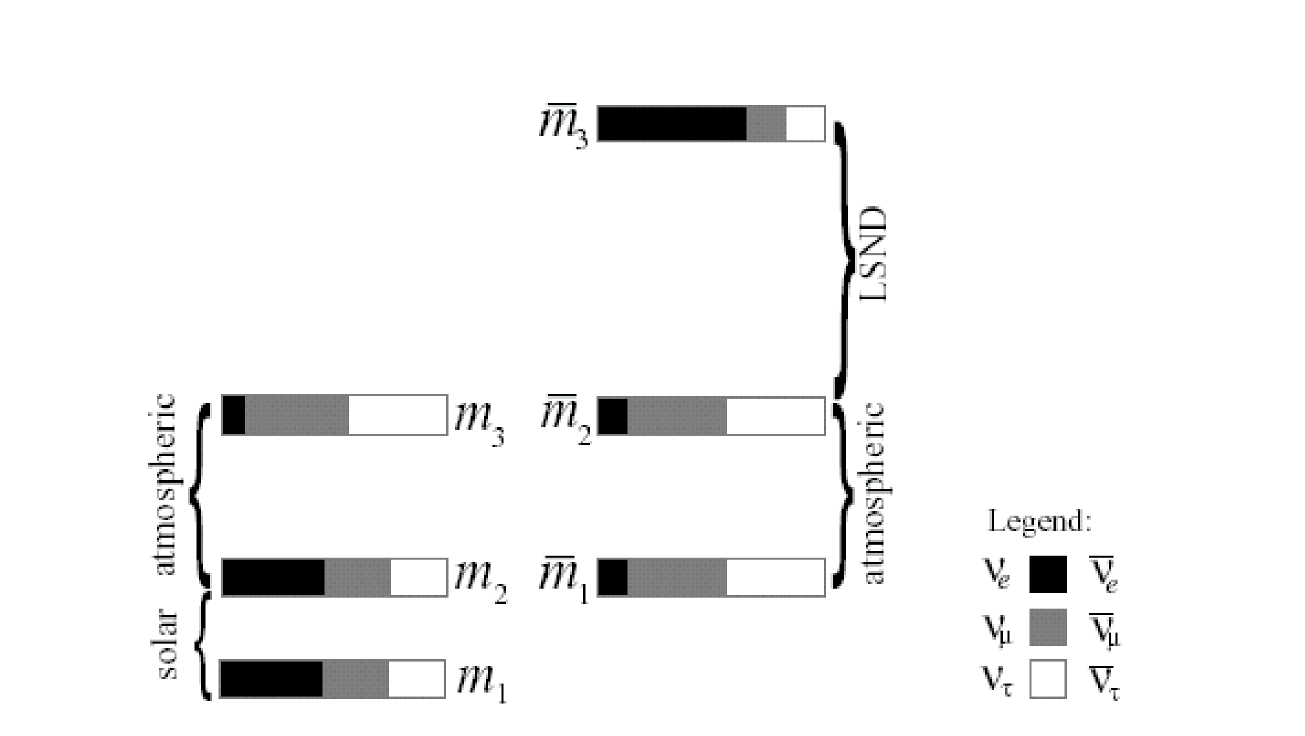
miniBooNE:

Goal: to definitively test the LSND signal.
First, with a
$\nu_\mu \rightarrow \nu_e$ appearance search.
Then, with a
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance search.
Then, if a signal is seen, with a 2nd detector.

Dec. 1997:
Proposal submitted
June 2002:
experiment begins

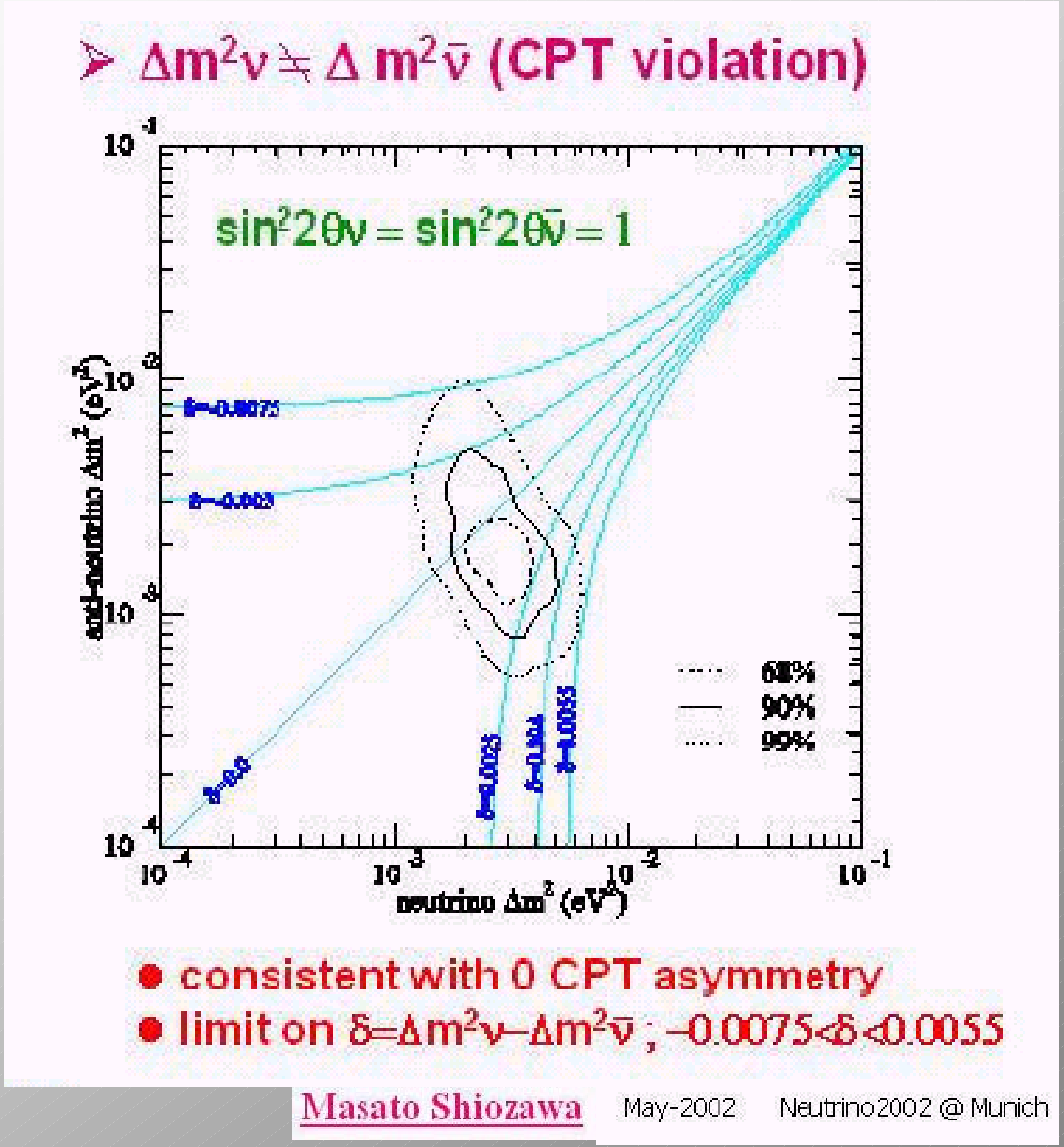
ν's violate CPT? look for it now:

- SuperK atmospheric data
- KamLAND reactor antineutrinos



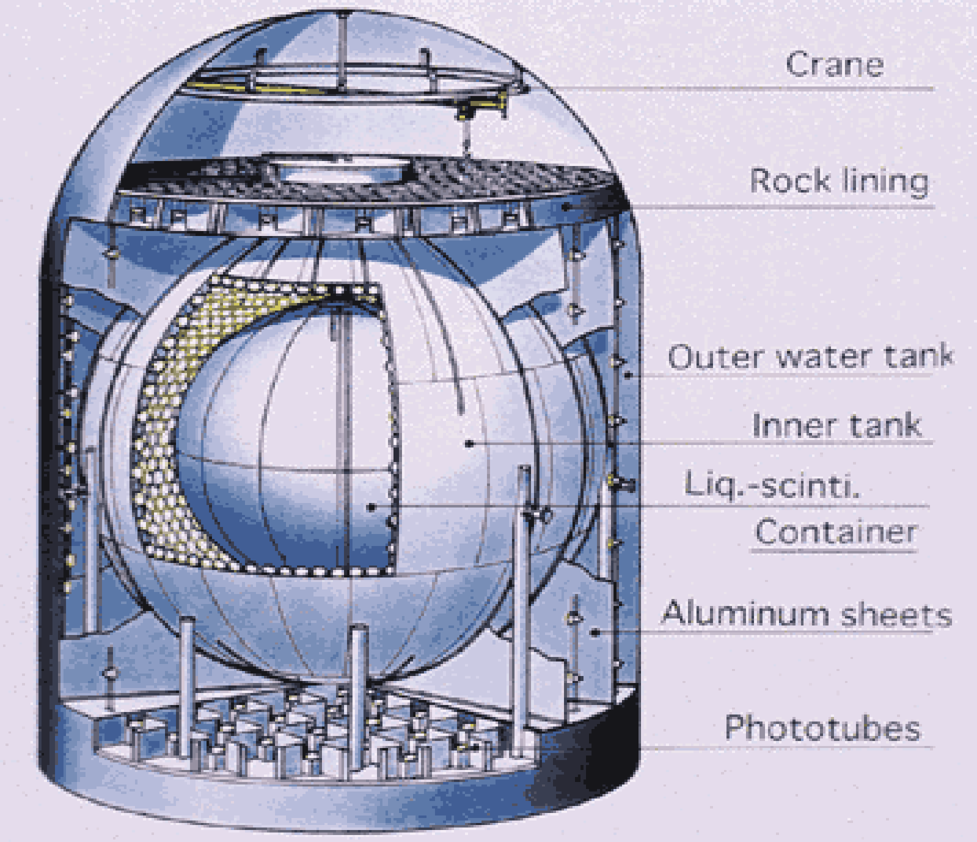
Barenboim, Borissov, JL, Smirnov, hep-ph/0108199

SuperK atmospheric data is happy with CPT or without it



KamLAND is looking for LMA "solar" oscillations in reactor *antineutrinos*.

In CPT violating scenario, KamLAND does not see oscillations!



Motivations for BSM physics scenarios

- To address some theoretical deficiency or gap in the SM
- To explain some anomaly in somebody's data
- Because it isn't forbidden, and we know how to look for it

Motivations for BSM physics scenarios

- To address some theoretical deficiency or gap in the SM

Prime example: the naturalness and hierarchy problems of the SM:

- **what stabilizes the separation between the electroweak breaking scale and higher scales e.g. the Planck scale?**
- **why is the gap between these scales so large (~16 orders of magnitude)?**

Prime example: the naturalness and hierarchy problems of the SM

3 competing BIG IDEAS to solve these problems:

- Supersymmetry (with weak scale soft breakings)
- new Strong Dynamics (technicolor, topcolor)
- Extra Dimensions (large, warped, etc)

Note: as far as we know, **strings**

are happy with all 3 of these!

- Supersymmetry (with weak scale soft breakings)
- new Strong Dynamics (technicolor, topcolor)
- Extra Dimensions (large, warped, etc)

Motivations for BSM physics scenarios

- To explain some anomaly in somebody's data

Prime examples:

- **the neutrino anomalies**
- **anomalies in b production at LEP, Tevatron**

Motivations for BSM physics scenarios

- Because it isn’t forbidden, and we know how to look for it

Examples:

Z primes, leptoquarks, magnetic monopoles, etc.

Prime example: the naturalness and hierarchy problems of the SM

3 competing BIG IDEAS to solve these problems:

- Supersymmetry (with weak scale soft breakings)
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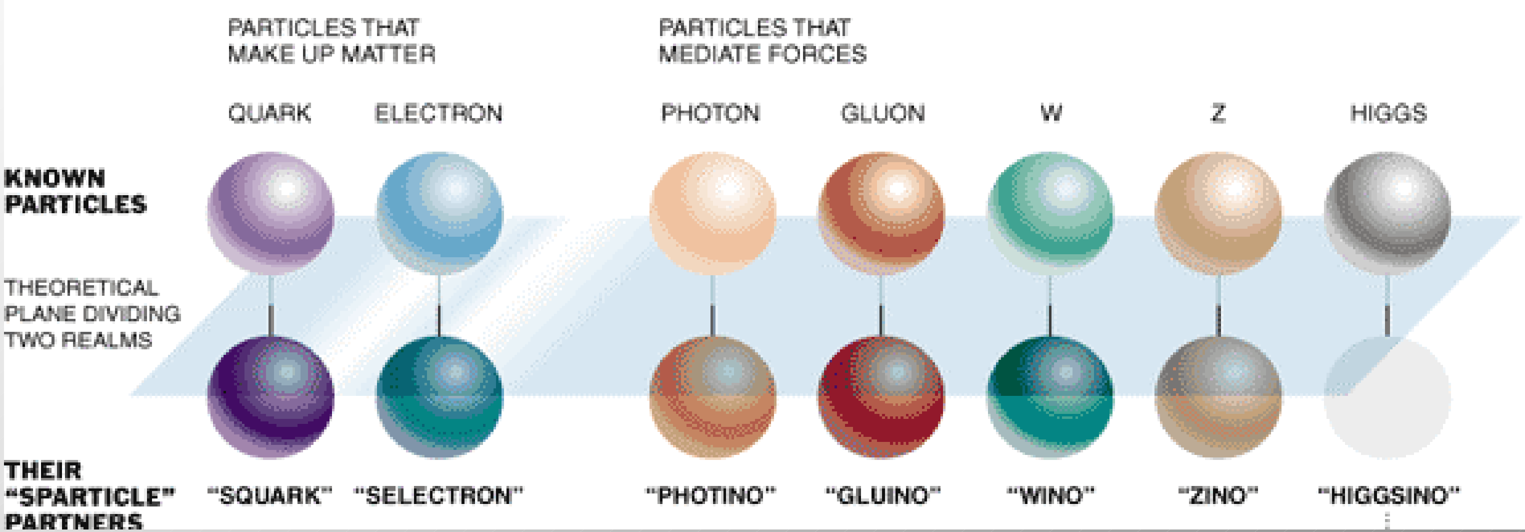
Supersymmetry

fermions ⟷ bosons



- none of the sparticles have been discovered yet
- most of the dark matter in the universe maybe the lightest sparticle

Why else do we like SUSY?

- only possible extension of spacetime symmetries
- gauge coupling unification
- radiative electroweak breaking if top is heavy
- MSSM predicts light Higgs boson < 130 GeV

MSSM = Minimal Supersymmetric SM
= supersymmetrize the SM with *minimal* Higgs sector

SUSY is a framework, not a model

Basic idea:

- There is a hidden sector where SUSY is spontaneously broken at some scale.
- soft SUSY breaking is communicated to the MSSM via some “messengers”.
- if R-parity is conserved, the lightest superpartner particle (LSP) is stable.

Classify SUSY models by choice of messenger:

- SUGRA models: supergravity mediated SUSY breaking
- Gauge mediated models: SUSY breaking mediated by some new gauge interactions
- Anomaly mediation, Gaugino mediation, Radion mediation, etc.

Minimal SUGRA (mSUGRA)

Universal soft breaking terms at the GUT scale:

- $m_{1/2}$ = common gaugino mass
- m_0^2 = common scalar mass^2
- A_0 = common ratio of scalar^3 couplings to Yukawa couplings
- $\tan\beta$ = ratio of Higgs VEVs
- Arg[μ] = phase of the μ term

next few slides stolen from Steve Martin

mSUGRA sparticle spectra

- Use RGEs to run down to the weak scale
- Usually Bino LSP

Sfermions

Squarks $m_{\tilde{Q}}^2 = m_0^2 + 5m_{1/2}^2$

Sleptons $m_{\tilde{\ell}_L}^2 = m_0^2 + 0.5m_{1/2}^2$

$m_{\tilde{\ell}_R}^2 = m_0^2 + 0.15m_{1/2}^2$

Gauginos

Gluino $M_{\tilde{g}} = 3m_{1/2}$

Winos $M_{\tilde{W}^\pm}, M_{\tilde{W}^0} = 0.8\, m_{1/2}$

Bino $M_{\tilde{B}^0} = 0.4\, m_{1/2}$

$M_1 : M_2 : M_3 :: 0.5 : 1 : 3.3$

Warning: mSUGRA is simple, but probably *too* simple

e.g. gaugino mass relations may be wrong!

Phenomenological argument: the electroweak scale looks more natural if M_3 is relatively smaller.

Bastero-Gil, Kane, King, hep-ph/9910506

For a typical "supergravity" model with fixed $\tan\beta$, sgn(μ):

$$M_Z^2 = -1.7\mu^2 + 7.2M_{\tilde{g}}^2 - 0.24M_{\tilde{W}}^2 + 0.014M_{\tilde{B}}^2 + \ldots$$

Reason: Renormalization effects feed (gluino mass) $\rightarrow$ (top squark mass) $\rightarrow$ (Higgs mass) $\rightarrow$ Weak scale.

Required cancellation is easier if $M_{\tilde{g}}$ is not so big.

Most expt. searches have assumed mSUGRA

What are the expt signatures?

In every case: $\tilde{N}_1$ neutralino LSP escapes, yields $\not{E}_T$.

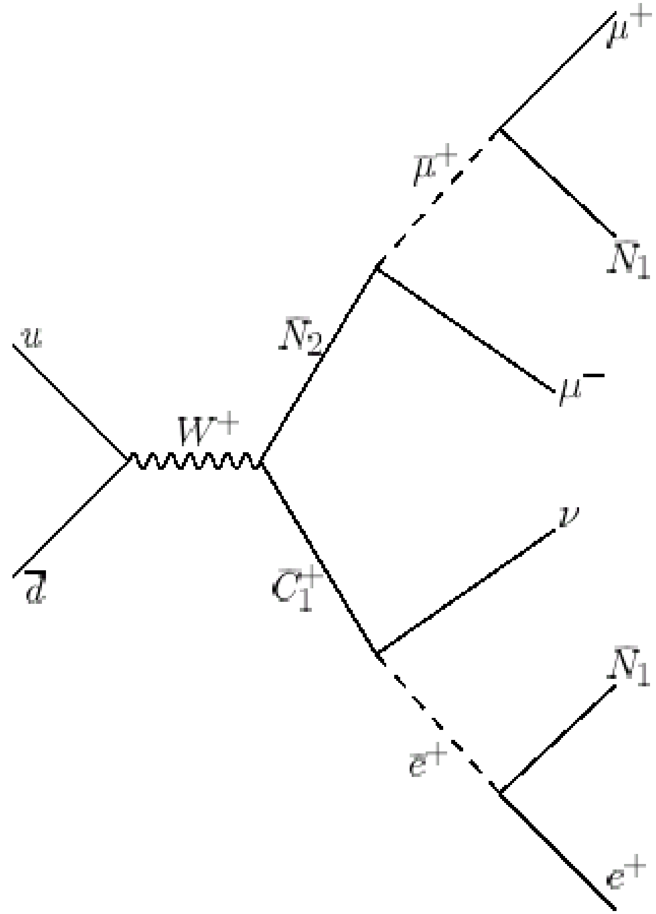
- Trileptons:
  $\ell\ell\ell + \not{E}_T$ + [possibly jets]
  - From Chargino+Neutralino Production:

$$p\overline{p} \to \tilde{C}_1^{\pm}\tilde{N}_2 \to \left\{ \begin{array}{l} \tilde{C}_1^{\pm} \to \ell^{\pm}\nu\tilde{N}_1 \\ \tilde{N}_2 \to \ell^{+}\ell^{-}\tilde{N}_1 \end{array} \right\} \to \ell^{\pm}\ell'^{+}\ell'^{-}\not{E}_T$$

  - From Gluino, Squark production:

$$p\overline{p} \to \tilde{g}\tilde{g},\ \tilde{g}\tilde{Q},\ \tilde{Q}\tilde{Q} \to \text{jets} + \tilde{C}_1^{\pm}\tilde{N}_2 \to \text{jets} + \ell^{\pm}\ell'^{+}\ell'^{-}\not{E}_T$$

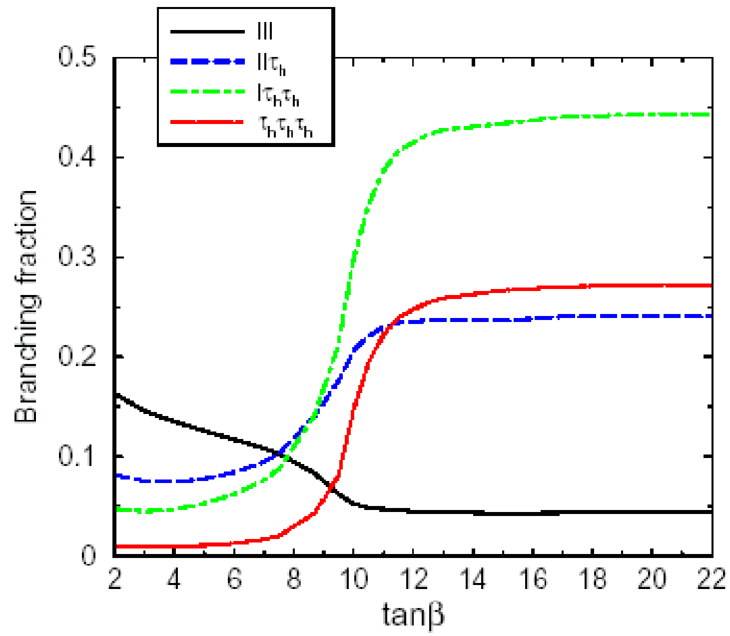
  - Standard Model backgrounds are small.



μ^+
$\tilde{\mu}^+$
$\tilde{N}_1$
u
$\tilde{N}_2$
μ^-
W^+
ν
$\bar{d}$
$\tilde{C}_1^+$
$\tilde{N}_1$
$\tilde{e}^+$
e^+

The Importance of Taus for Run II:

Branching fraction of Chargino+Neutralino $\tilde{C}_1^{\pm}\tilde{N}_2$ into final states with leptons or hadronic taus and $\not{E}_T$:



τ_h means a hadronic tau decay.

l means an electron or muon (direct, or from a leptonic τ decay).

For $\tan\beta \gtrsim 8$, the two-body decays

$$\tilde{N}_2 \to \tau^{\pm}\tilde{\tau}^{\mp}$$
$$\tilde{C}^{\pm} \to \nu\tilde{\tau}^{\pm}$$

begin to go on shell, so final states dominated by τ's.

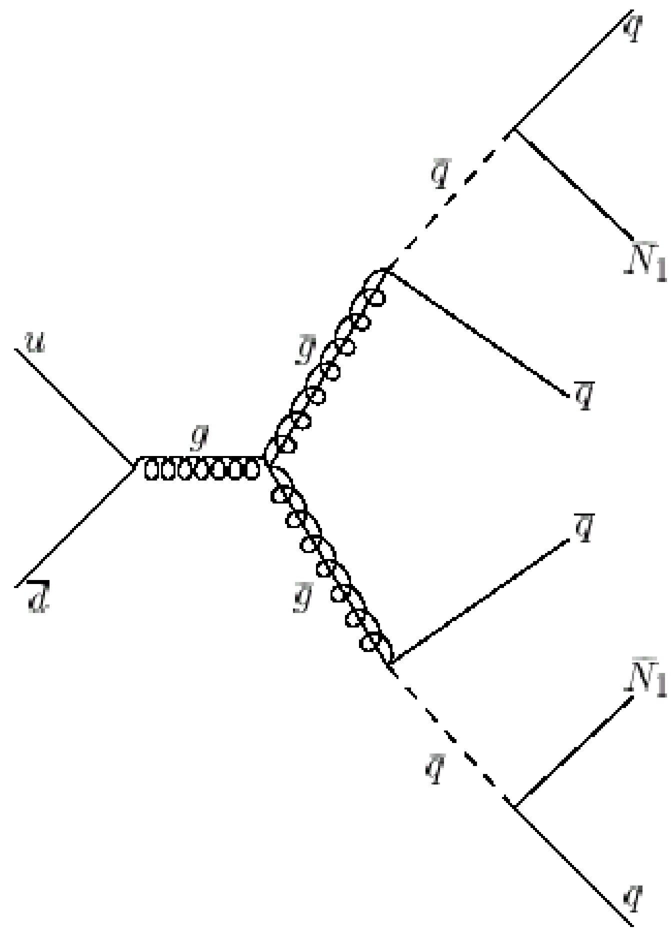
- **Missing Transverse Energy:**
  Multi-Jets + $\not{E}_T$ + [isolated lepton veto]
  - From Gluino, Squark production:

    $$p\bar{p} \to \tilde{g}\tilde{g}, \tilde{g}\tilde{Q}, \tilde{Q}\tilde{Q} \to \left\{ \begin{array}{c} \tilde{g} \to jj\tilde{N}_i \text{ or } jj\tilde{C}_i \\ \tilde{Q} \to j\tilde{N}_i \text{ or } j\tilde{C}_i \end{array} \right\} \to \text{jets} + \not{E}_T$$

    (b-tag is optional)
  - From Chargino,Neutralino Production:

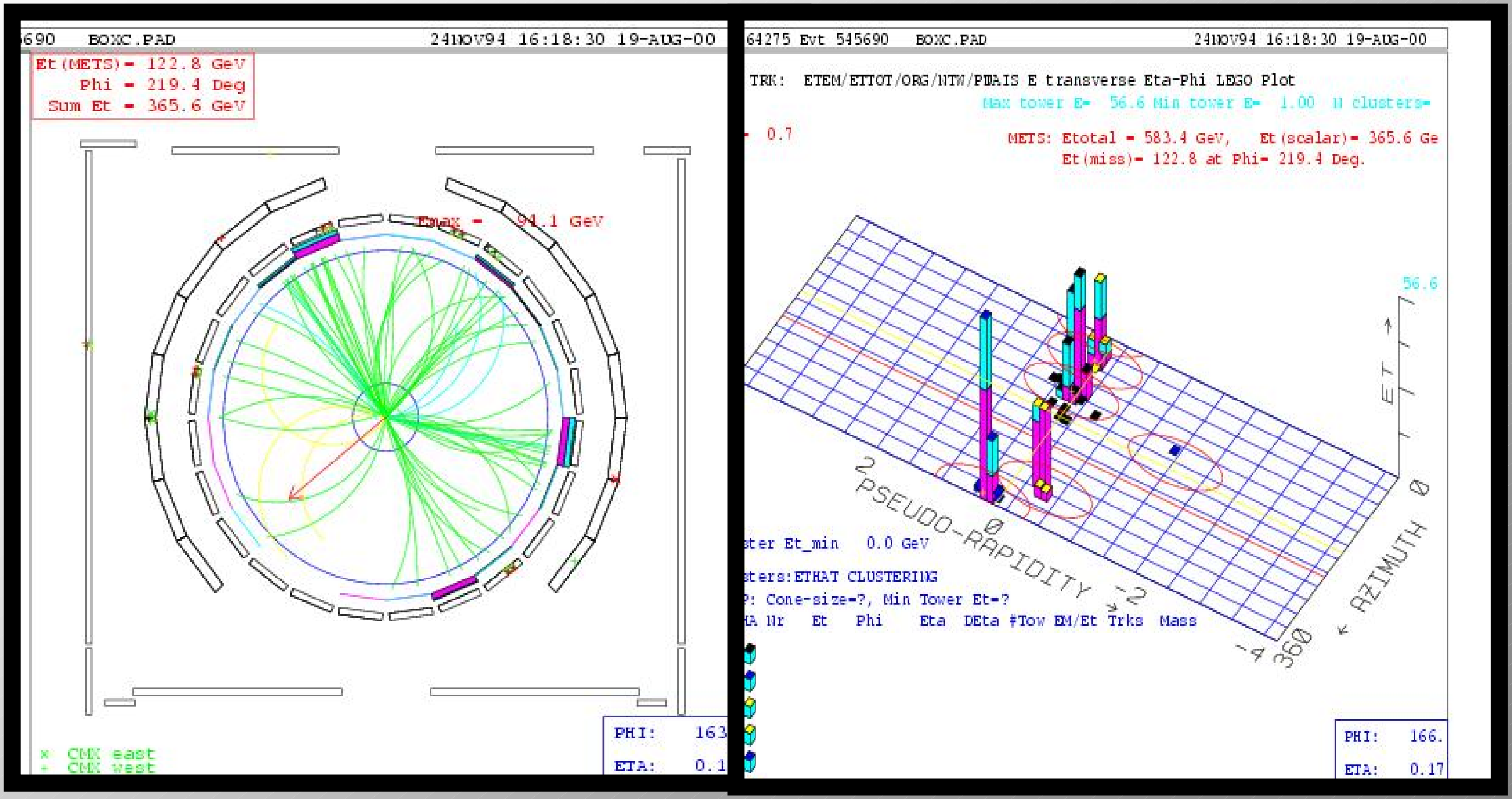
    $$p\bar{p} \to \tilde{C}_1^{\pm}\tilde{N}_2, \tilde{C}_1^{+}\tilde{C}_1^{-} \to \left\{ \begin{array}{c} \tilde{C}_1^{\pm} \to jj\tilde{N}_1 \\ \tilde{N}_2 \to jj\tilde{N}_1 \end{array} \right\} \to \text{jets} + \not{E}_T$$

  - Veto leptons to kill background from $W \to \ell\nu$



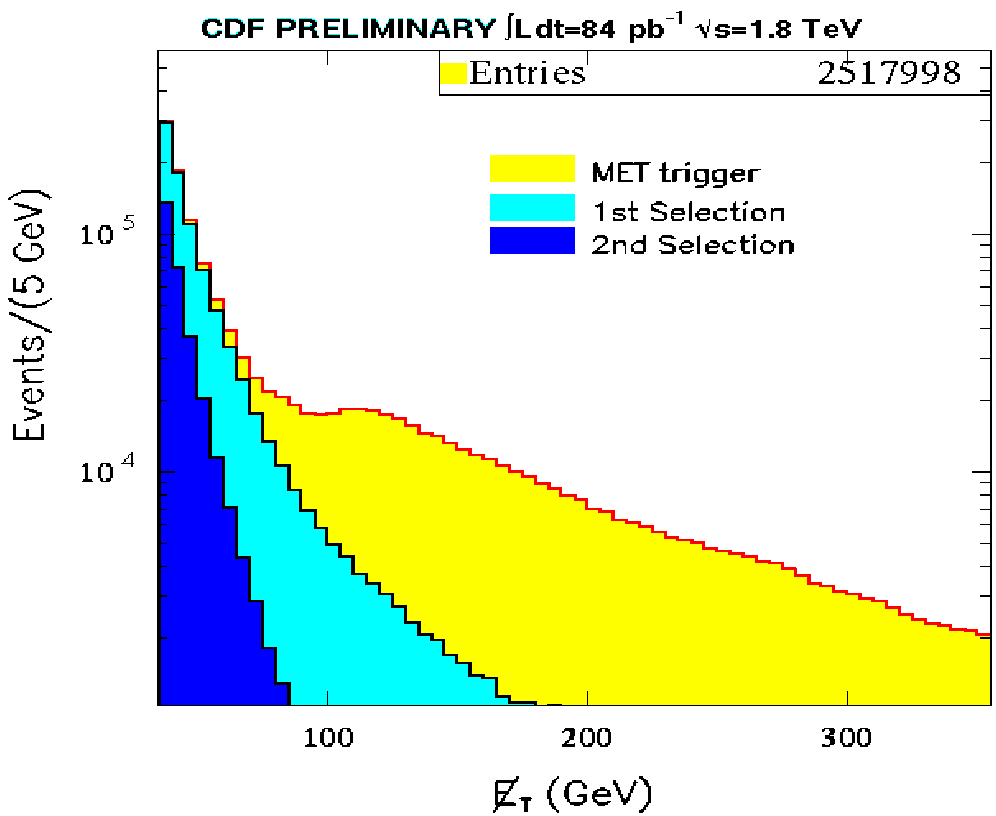
q
$\bar{q}$
$\bar{N}_1$
u
$\tilde{g}$
g
q
q
d
$\tilde{g}$
$\bar{N}_1$
$\bar{q}$
q

gluino candidate event



next few slides stolen from Maria Spiropulu

$\not{E}_T$ + jets search



MISSING ENERGY + MULTIJET STANDARD MODEL COMPONENT

$Z(\to ll) + jets$

$W(\to l\nu) + jets$

$t\bar{t}$, single top

Diboson

QCD multijet

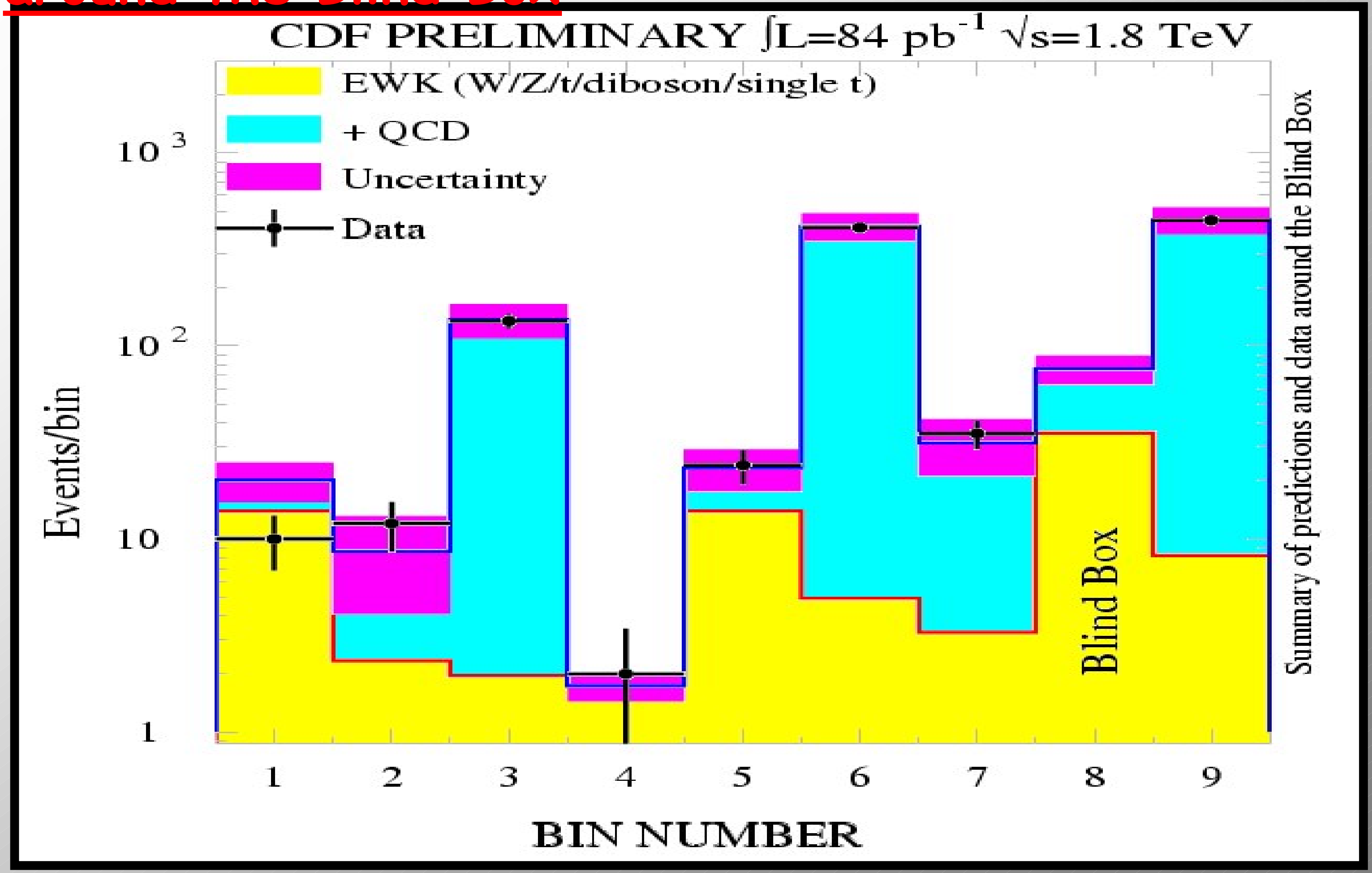
EWK

Note: The missing energy is a QCD sample

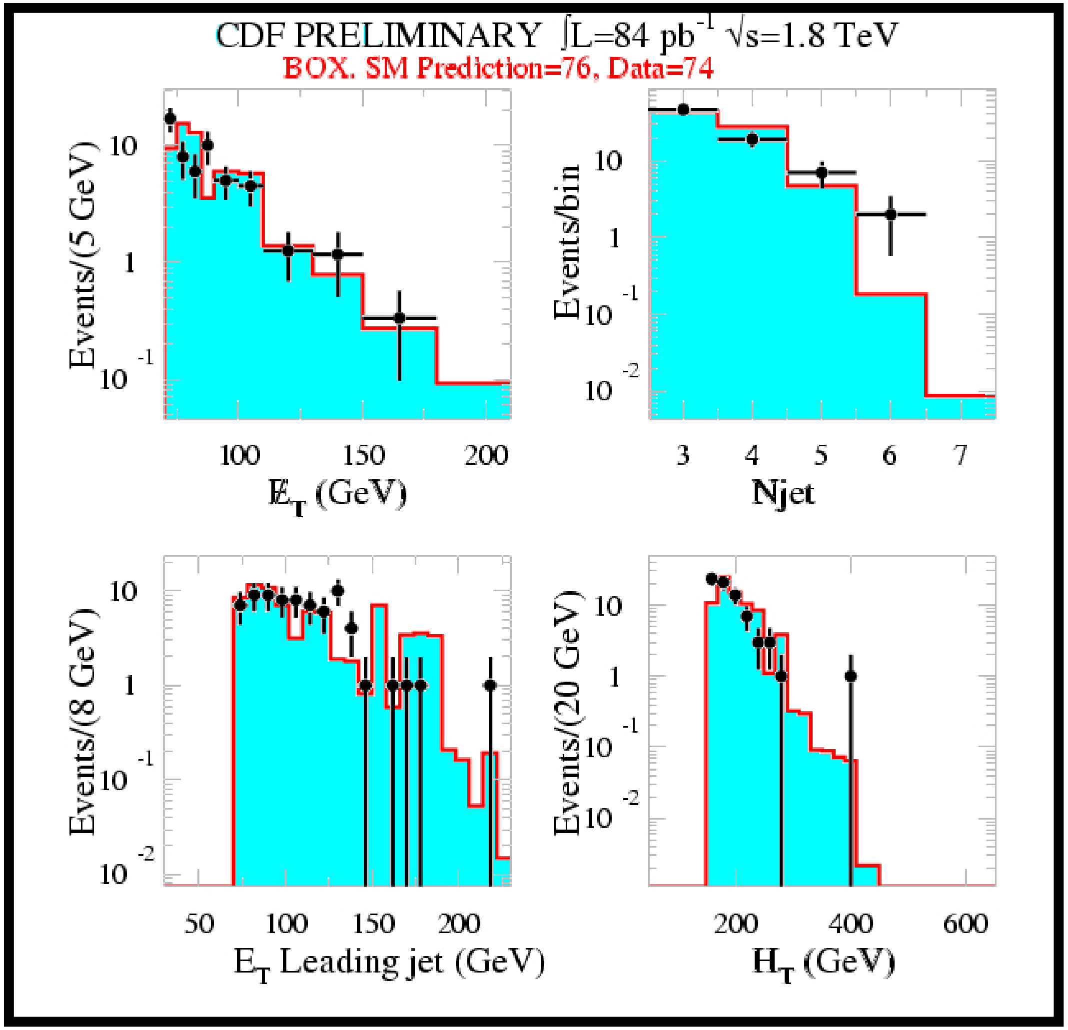
Comparisons SM predictions-Data around the Blind Box

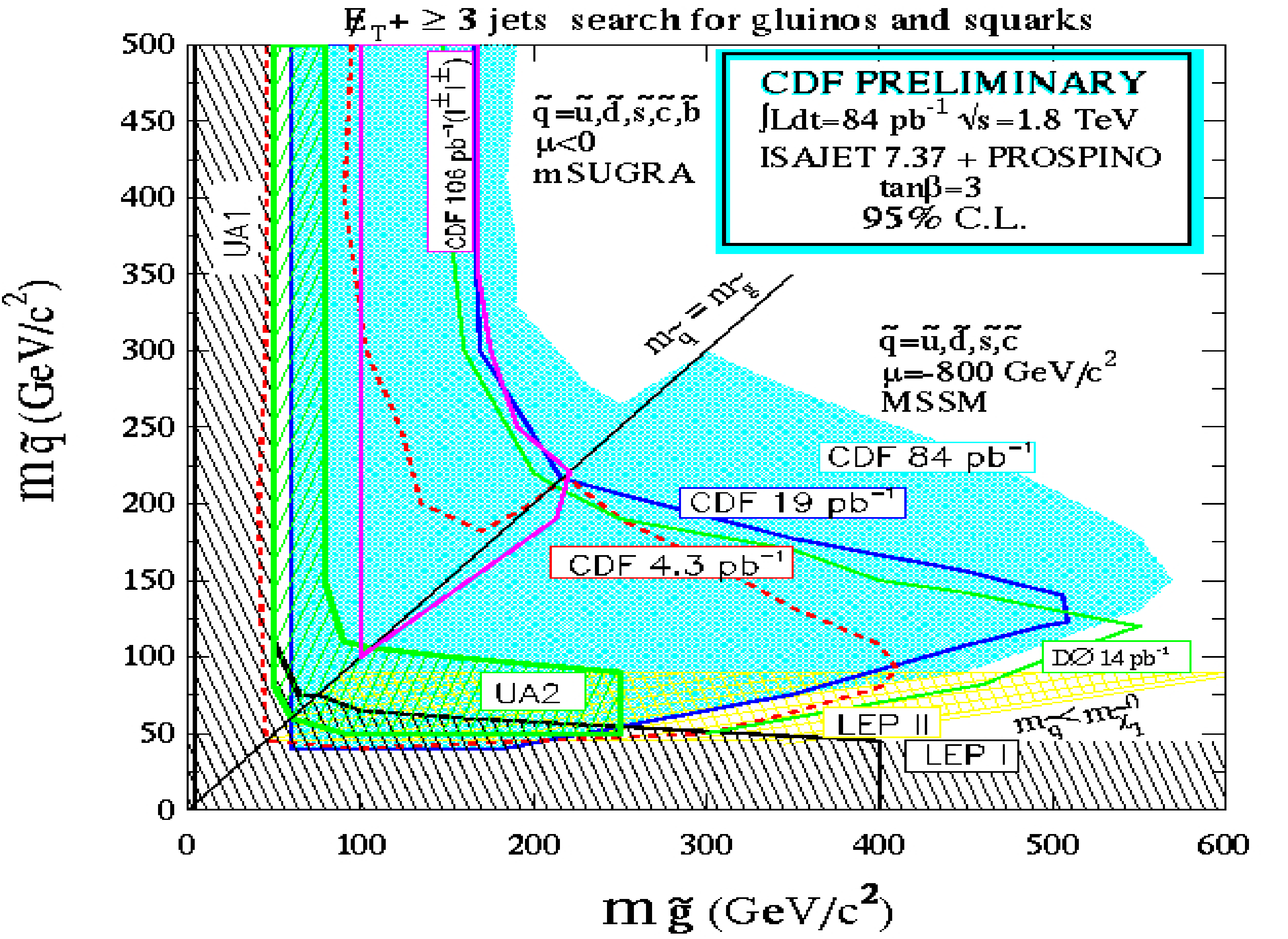
Description	EWK	QCD	All	Data
$\not\!\!E_T \geq 70, H_T \geq 150, N_{trk}^{iso} > 0$	13.9	6.26	20.2±4.7	10
$\not\!\!E_T \geq 70, H_T < 150, N_{trk}^{iso} = 0$	2.3	6.26	8.6±4.5	12
$35 < \not\!\!E_T < 70, H_T > 150, N_{trk}^{iso} = 0$	1.95	134.6	136.5±27.8	134
$\not\!\!E_T > 70, H_T < 150, N_{trk}^{iso} > 0$	1.73	0	1.73±0.3	2
$35 < \not\!\!E_T < 70, H_T > 150, N_{trk}^{iso} > 0$	13.95	9.39	23.34±5.7	24
$35 < \not\!\!E_T < 70, H_T < 150, N_{trk}^{iso} = 0$	4.9	413.16	418.1±68.8	410
$35 < \not\!\!E_T < 70, H_T < 150, N_{trk}^{iso} > 0$	3.3	28.17	31.4±10.2	35
$\not\!\!E_T > 70, H_T > 150, N_{trk}^{iso} = 0$	35.3	40.69	76.02±12.8	?
$35 < \not\!\!E_T < 70, H_T < 150$	8.2	441.3	449.5±72	445

Comparisons SM predictions-Data around the Blind Box



$\not{E}_T$ + jets search



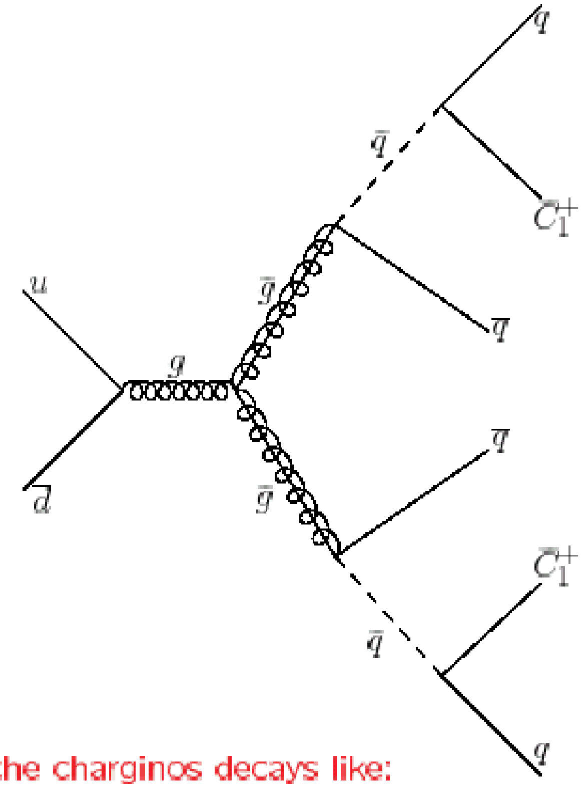


E̸T + ≥ 3 jets search for gluinos and squarks
CDF PRELIMINARY
∫Ldt=84 pb-1 √s=1.8 TeV
ISAJET 7.37 + PROSPINO
tanβ=3
95% C.L.
q̃=ũ,d̃,s̃,c̃,b̃
μ<0
mSUGRA
q̃=ũ,d̃,s̃,c̃
μ=-800 GeV/c2
MSSM
CDF 106 pb-1(l±l±)
UA1
UA2
CDF 84 pb-1
CDF 19 pb-1
CDF 4.3 pb-1
DØ 14 pb-1
LEP II
LEP I
mq̃ = mg̃
mq̃ < mχ̃01
mq̃ (GeV/c2)
mg̃ (GeV/c2)
0
50
100
150
200
250
300
350
400
450
500
0
100
200
300
400
500
600

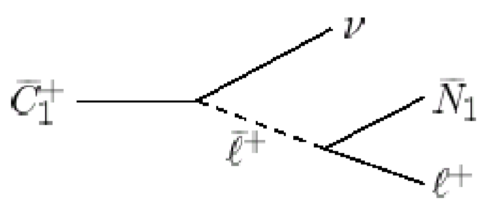
- Like-charge Dileptons:
  $\ell^\pm \ell^\pm + \not{E}_T + \text{[jets]}$
  - From Chargino+Neutralino Production:
    (same as trilepton, but with opposite-charge lepton missed or ignored)
  - From Gluino, Squark production:

$$p\overline{p} \to \tilde{g}\tilde{g} \to \left\{ \begin{array}{l} \tilde{g} \to jj\tilde{C}_1^\pm \to jj\ell^\pm \tilde{N}_1 \\ \tilde{g} \to jj\tilde{C}_1^\pm \to jj\ell^\pm \tilde{N}_1 \end{array} \right\} \to \ell^\pm \ell^\pm + \text{jets} + \not{E}_T$$

(Gluinos are Majorana, decays are independent and don't prefer a charge.)



Each of the charginos decays like:



Gauge mediated models

Goldstino is the LSP; classify models by NLSP

Neutralino NLSP Scenario

- Prompt decays $\tilde{N}_1 \to \gamma \tilde{G}$
  Superpartners $\to \gamma\gamma + \not{E}_T + X$
  Both photons have very high p_T.

- Delayed decays $\tilde{N}_1 \to \gamma \tilde{G}$
  One or two displaced photon vertices $+ \not{E}_T + X$

- Decay outside the detector
  Same as usual "Minimal Supergravity" signatures

Slepton (including Stau) NLSP Scenario

- Prompt decay $\tilde{\ell} \to \ell \tilde{G} \to$ High p_T leptons + $\not{E}_T$.
- Decay inside detector $\tilde{\ell} \to \ell \tilde{G} \to$ Decay Kink
  Impact parameter
- Decay outside the detector "Stable" slepton $\tilde{\ell}$
  - Highly Ionizing Tracks (HIT) (slow, $\beta\gamma \lesssim 0.85$)
  - Time of Flight (slow, $\beta\gamma \lesssim ???$)
  - Fake "muon" (fast, $\beta\gamma \gtrsim 0.85$)

new Strong Dynamics

1. Technicolor

- weak doublet technifermions condense at ~ TeV scale due to new strong interaction; breaks EW symmetry dynamically.

- not popular these days due to problems with phenomenology.

new Strong Dynamics

2. Topcolor

- at high energies, top quark sees a different, stronger SU(3) color than the lighter quarks

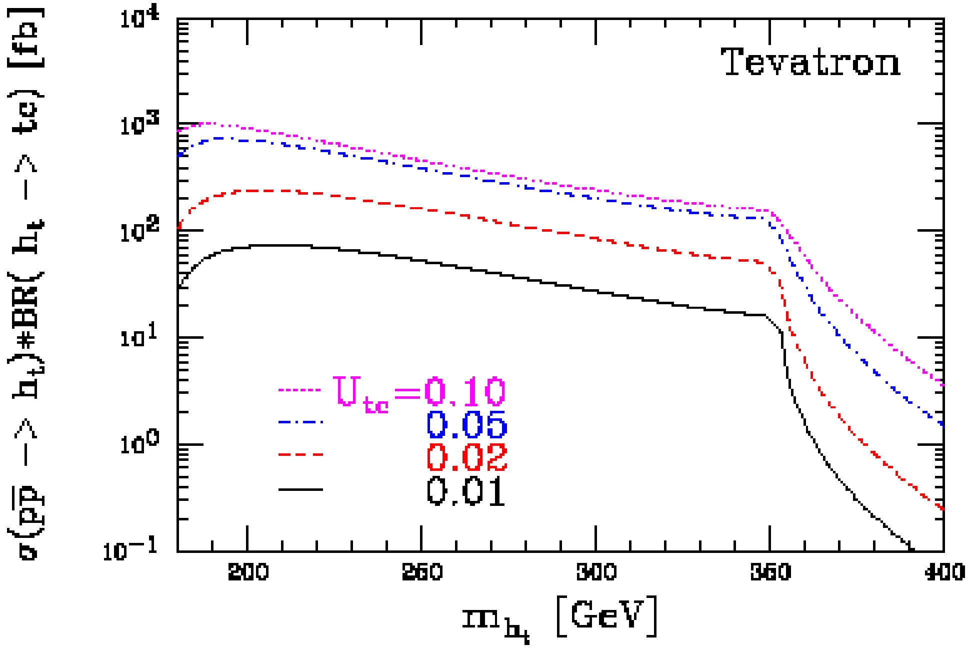
- top condensate forms, plays role of a Higgs

phenomenology of Topcolor

- **new heavy particles: pseudoscalar "top-pions" and scalar "top-higgs"; decay to $\bar{t}c$**

- **"colorons": extra octet of massive gluons**

top-higgs at the Tevatron in Run II



extra dimensions

see tomorrow's lecture

the whole concept of getting to "beyond the SM" physics is wrong on two counts:

- we need to devote *more* resources to understanding SM physics, not less
- we need to attack *the big questions,* not just add epicycles to the SM

attacking the Big questions

- what is the dark matter?

- what is the structure of spacetime?

what is the dark matter?

- stable weakly interacting massive particles (WIMPS) are attractive CDM candidates

- for large portions of the parameter space of R-parity conserving SUSY models, the weakly interacting massive *neutralino* is the stable LSP

How do we test this?

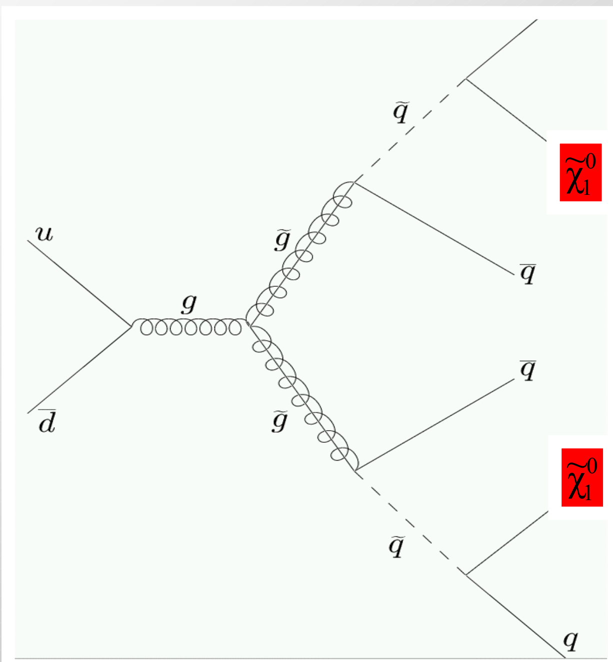
what is the dark matter?

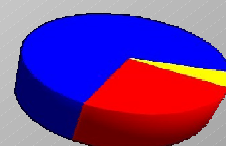
a 5-pronged attack:

- study DM distributions, clustering
- look for high energy gamma rays from neutralino annihilation in the cosmos
- look for high energy neutrinos from neutralino annihilation in the Sun
- detect DM particles coming from space

- **produce neutralinos in colliders!**

what is the dark matter?





Is this the
dark matter?

We will have a definitive answer within about 5 years!

what is the structure of spacetime?

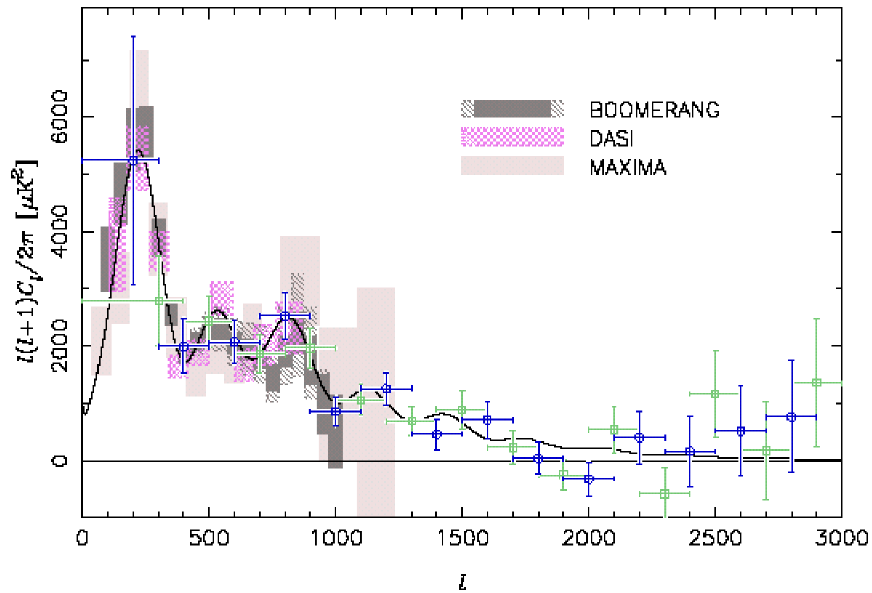
Really many questions, all hard:

- large-scale structure of spacetime?
- microscopic structure of spacetime?
- extra dimensions of spacetime?
- quantum dynamics of spacetime?

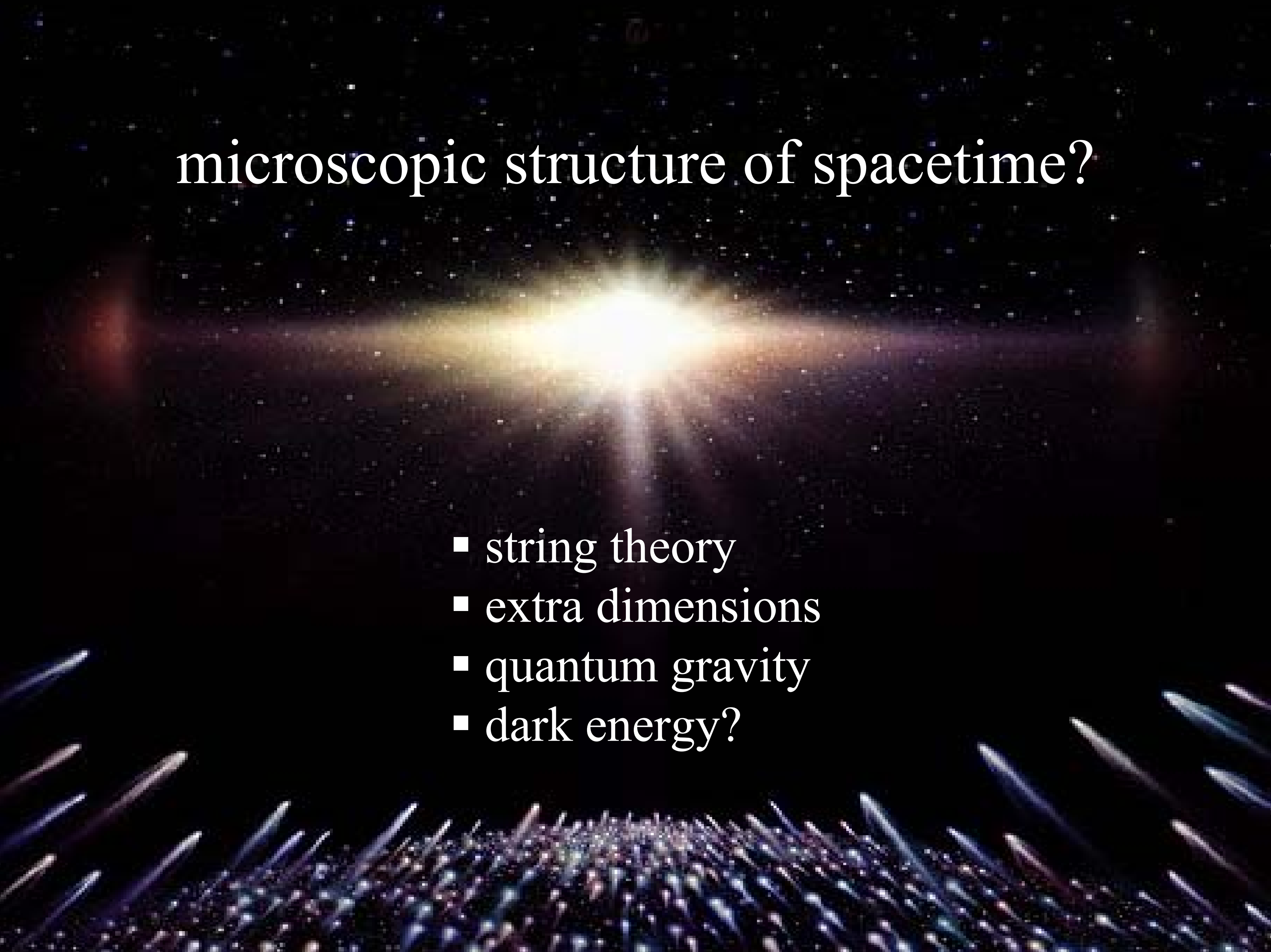
large-scale structure of spacetime

We are getting lots of information about the cosmological parameters!

Biggest discovery in cosmology of past 5 years is real error bars!



Priors	Ω_{tot}	n_s	$\Omega_b h^2$	$\Omega_{cdm} h^2$	Ω_Λ	Ω_m	Ω_b	h	Age	τ_c
wk-h	$1.05^{0.05}_{0.05}$	$1.02^{0.06}_{0.07}$	$0.023^{0.003}_{0.003}$	$0.13^{0.03}_{0.02}$	$0.54^{0.12}_{0.13}$	$0.52^{0.15}_{0.15}$	$0.080^{0.023}_{0.023}$	$0.55^{0.09}_{0.09}$	$15.0^{1.1}_{1.1}$	$0.16^{0.18}_{0.13}$
wk-h+LSS	$1.03^{0.03}_{0.04}$	$1.00^{0.06}_{0.06}$	$0.023^{0.003}_{0.003}$	$0.12^{0.02}_{0.02}$	$0.61^{0.09}_{0.10}$	$0.42^{0.12}_{0.12}$	$0.067^{0.018}_{0.018}$	$0.60^{0.09}_{0.09}$	$14.7^{1.2}_{1.2}$	$0.09^{0.12}_{0.07}$
wk-h+SN	$1.01^{0.04}_{0.03}$	$1.03^{0.06}_{0.06}$	$0.024^{0.003}_{0.003}$	$0.12^{0.02}_{0.02}$	$0.68^{0.06}_{0.07}$	$0.33^{0.07}_{0.07}$	$0.055^{0.014}_{0.014}$	$0.67^{0.07}_{0.07}$	$13.9^{1.0}_{1.0}$	$0.14^{0.17}_{0.11}$
wk-h+LSS+SN	$1.00^{0.03}_{0.02}$	$1.03^{0.06}_{0.06}$	$0.024^{0.003}_{0.003}$	$0.12^{0.02}_{0.02}$	$0.69^{0.04}_{0.06}$	$0.32^{0.06}_{0.06}$	$0.052^{0.011}_{0.011}$	$0.68^{0.06}_{0.06}$	$13.8^{0.9}_{0.9}$	$0.13^{0.14}_{0.10}$



microscopic structure of spacetime?

- string theory
- extra dimensions
- quantum gravity
- dark energy?