SUSY: GMSB

GMSB

- Model assumes SUSY broken at scale $F^{1/2}$ in sector containing non-SM (heavy) particles
  - This sector couples to SM via "messengers" of mass M
  - Loops involving messengers $\rightarrow$ mass to s-partners
    - Advantage of model; mass from gauge interactions $\rightarrow$ no FCNC (which can cause problems in SUGRA)
- Phenomenology: lightest SP is gravitino ($\tilde{G}$)
  - SUGRA: M($\tilde{G}$)~O(1)TeV, phenomenologically irrelevant
  - GMSB: NSLP decays to $\tilde{G}$; unstable $\rightarrow$ NLSP can be charged
    - Lifetime of NLSP "free": $O(\mu\text{m}) < c\tau < O(\text{km})$
  - Neutral NLSP: lightest combination of higgsinos and gauginos $\rightarrow$ behaves like SUGRA LSP (except for its decay…)
  - Charged NLSP: $\tilde{\lambda}_R$; low tanβ: degenerate $\tilde{e}_R, \tilde{m}_R, \tilde{t}_R$; high tan$\beta$: $\tilde{t}_R$ is lightest slepton, others decay to it

GMSB parameters

- SUSY breaking scale: $\Lambda = F/M$
  - N_5: # messenger fields
  - $\tan\beta$ (ratio of Higgs vev's)
  - $s(\mu)$ ($|\mu|$ fixed from M(Z))
  - C_{grav} ($\tilde{G}$ mass scale factor)
    - $\tau_{NLSP} \sim (C_{grav})^2$
- GMSB "points"*
  - G1: NLSP is $\tilde{\chi}_1^0$
    - G1a: $c\tau$ is short (1.2mm)
    - G1b: $c\tau$ is long (1km)
  - G2: NLSP is $\tilde{\tau}_1$
    - G2a: $\tilde{e}_R$, $\tilde{\mu}_R$, $\tilde{\tau}_1$ short-lived
    - G2b: long-lived (all)

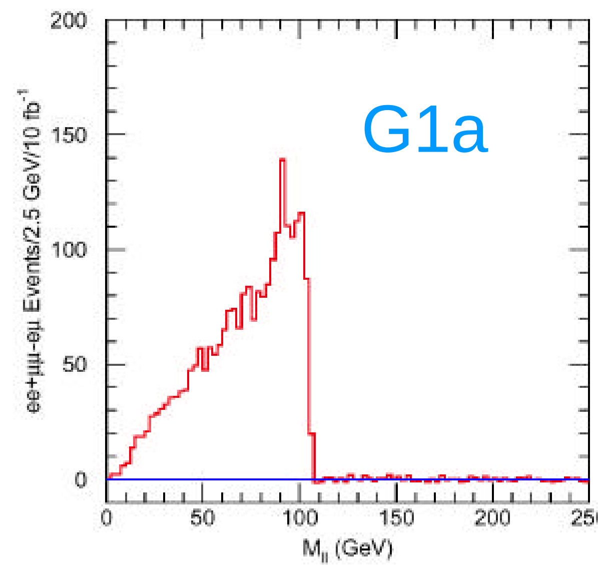
P	*L (TeV)*	*M_m (TeV)*	*N_5*	*C_{grav}*
G1a	90	500	1	1.0
G1b	90	500	1	10^3
G2a	30	250	3	1.0
G2b	30	250	3	5×10^3

$\tan\beta$: 5.0; $s(\mu)$=+

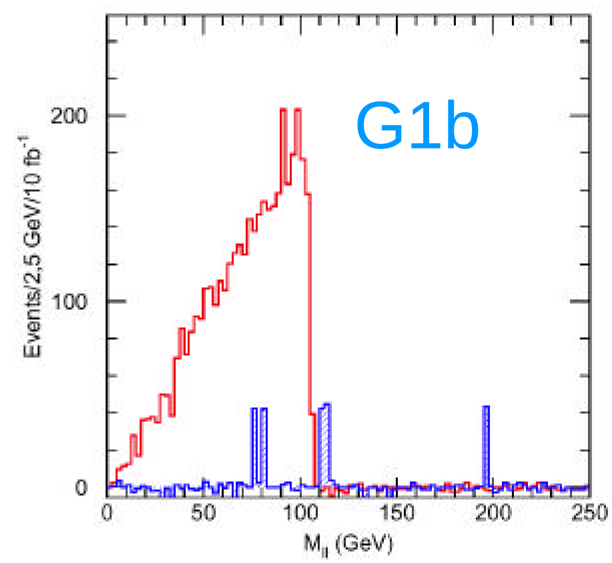
* Hinchliffe & Paige, Phys.Rev. D60 (1999) 095002; hep-ph/9812233

GMSB observation

- Example: G1a; same dilepton edge
  - Decay observed:
    $\tilde{c}_2^{0} \rightarrow \tilde{\lambda}^{\pm}\lambda^{\mu} \rightarrow \tilde{c}_1^{0}\, \lambda^{\pm}\lambda^{\mu} \rightarrow \tilde{G} g \lambda^{+}\lambda^{-}$
  - Selection is simple:
    - M_{eff}>400 GeV
    - $E_T^{miss}>0.1M_{eff}$
    - Demand same-flavor leptons
    - Form $e^+e^- + \mu^+\mu^- - e^{\pm}\mu^{\mu}$



- G2b: very similar to SUGRA
  - c_1^0 is long-lived, escapes
  - Decay observed:
    $\tilde{c}_2^{0} \rightarrow \tilde{\lambda}^{\pm}\lambda^{\mu} \rightarrow \tilde{c}_1^{0}\, \lambda^{+}\lambda^{-}$
  - M_{eff}>1 TeV; rest of selection as in G1a



SUSY parameter measurements (G1a)

- G1a: endpoint in M(λλ) → 3 parameters

$$M_{\max}^{\lambda^+\lambda^-} = M(\tilde{c}_2^0)\sqrt{1-\left(\frac{M(\tilde{\lambda}_R)}{M(\tilde{c}_2^0)}\right)^2}\sqrt{1-\left(\frac{M(\tilde{c}_1^0)}{M(\tilde{\lambda}_R)}\right)^2}$$

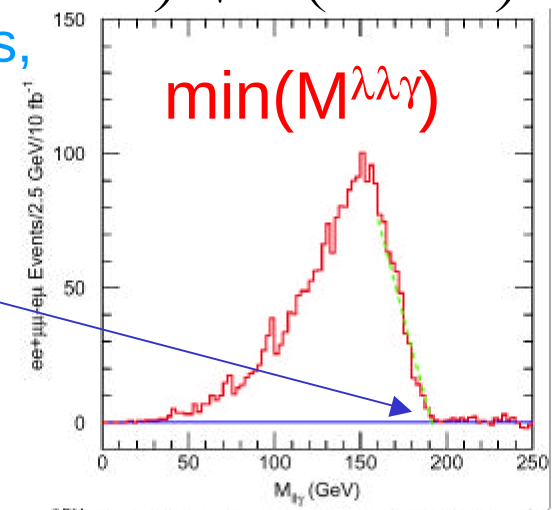
  - Events with two leptons and two photons, plot min(M(λλγ)) yields second relation:

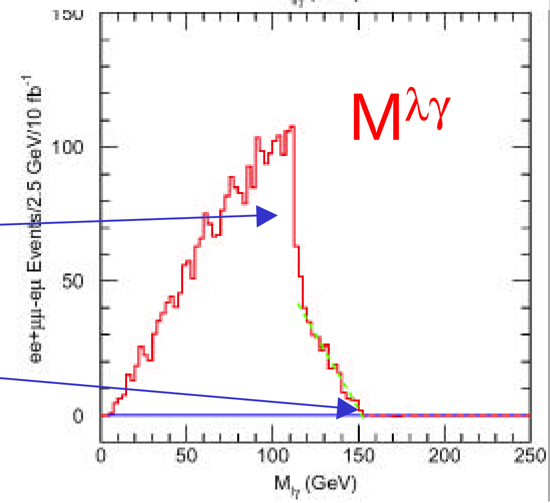
$$M_{\max}^{\lambda^+\lambda^- g} = \sqrt{M^2(\tilde{c}_2^0)-M^2(\tilde{c}_1^0)}$$

  - Next: evts with only one M(λλγ) smaller than endpoint mass
    - Unambiguous id of c_2^0 *decay*
    - Plot lepton-photon mass, two more structures:

$$\sqrt{M^2(\tilde{\lambda}_R)-M^2(\tilde{c}_1^0)} = 112.7\,\mathrm{GeV}$$

$$\sqrt{M^2(\tilde{c}_2^0)-M^2(\tilde{\lambda}_R)} = 152.6\,\mathrm{GeV}$$

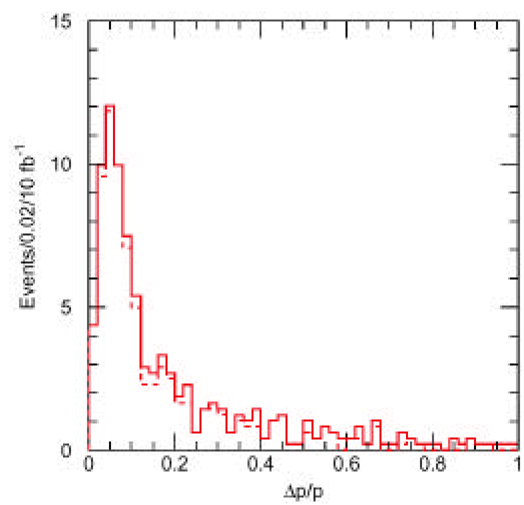




SUSY mass measurements (G1a)

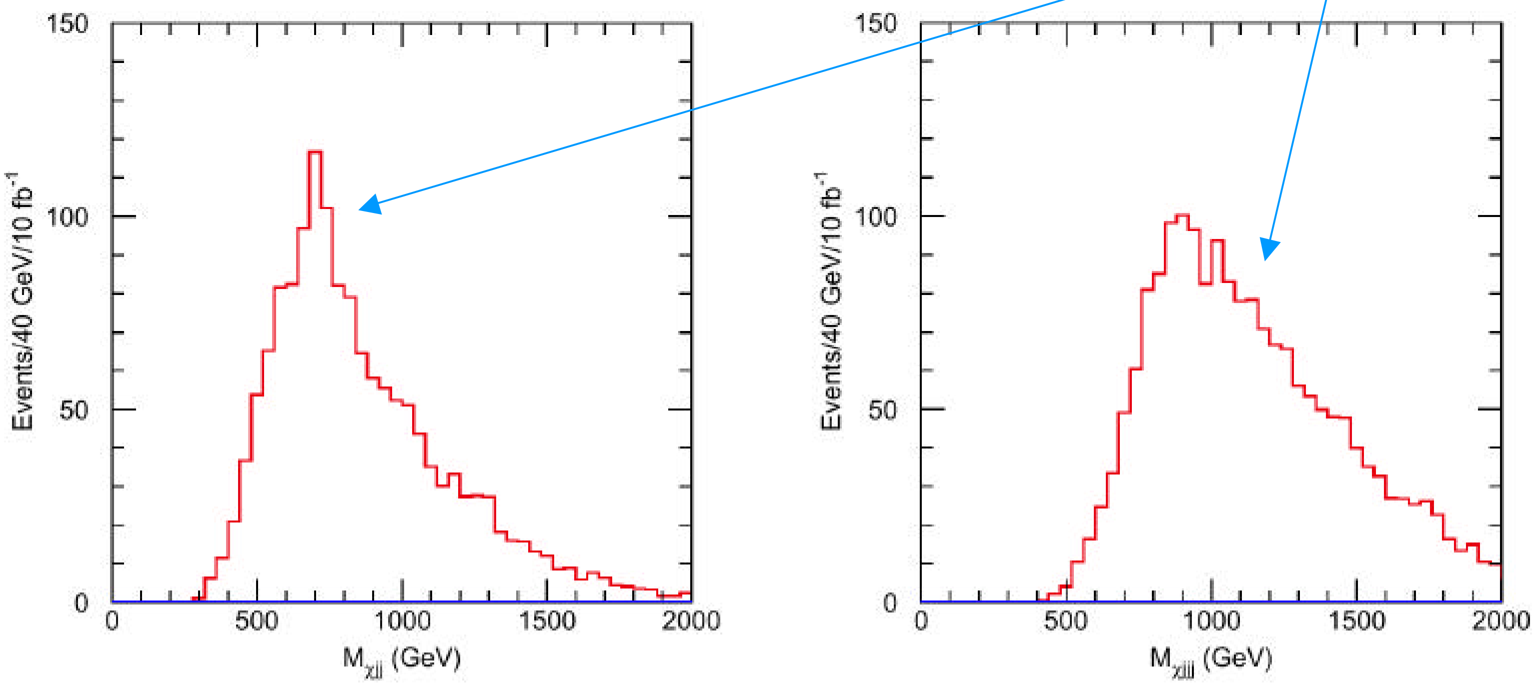
- Measurement of edge positions: very accurate
  - Worse resolution on linear fit (e.g. min(M(λλγ)) →
    - Low luminosity: ±0.5 GeV; High lumi: ±0.2 GeV (syst).
  - One can extract masses of $\tilde{c}_2^0$, $\tilde{c}_1^0$, $\tilde{\lambda}_R$
    - Model-independent (except for decay, rate and interpretation of slepton mass as mass of $\tilde{\lambda}_R$)
- Next step: reconstruct G momentum
  - Motivation: can then build on $\tilde{c}_2^0$ to reconstruct M_q and M_g
    - 0C fit to $\tilde{c}_2^0 \rightarrow \tilde{G} g \lambda^+ \lambda^-$ (with $M_{\tilde{G}}$=0)
      - Momentum to 4-fold ambiguity
    - Use evts with 4 leptons + 2 photons
      - E_T^{miss} fit to resolve solns: min(χ^2):

$$c^2 = \left(\frac{E_x^{miss} - P_{1x} - P_{2x}}{\Delta E_x^{miss}}\right)^2 + \left(\frac{E_y^{miss} - P_{1y} - P_{2y}}{\Delta E_y^{miss}}\right)^2$$



G1a: masses of squarks and gluinos (I)

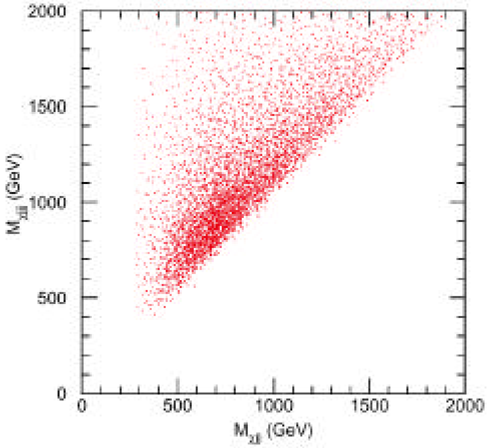
- Decay sought: $\tilde{q}$ ® $\tilde{g}q$ ® $\tilde{c}_2^0 q\bar{q}q$
  - Select evts with ≥ 4 jets (P_T>75)
  - Combine each fully-reconstructed $\tilde{c}_2^0$ with 2 and 3 jets



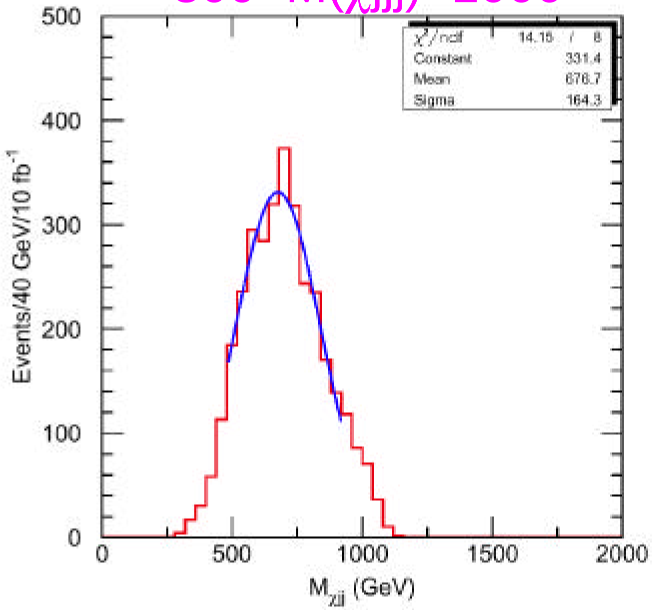
  - This yields peaks at gluino and squark mass (direct)
    - Peak position not a function of jet cut…

G1a: masses of squarks and gluinos (II)

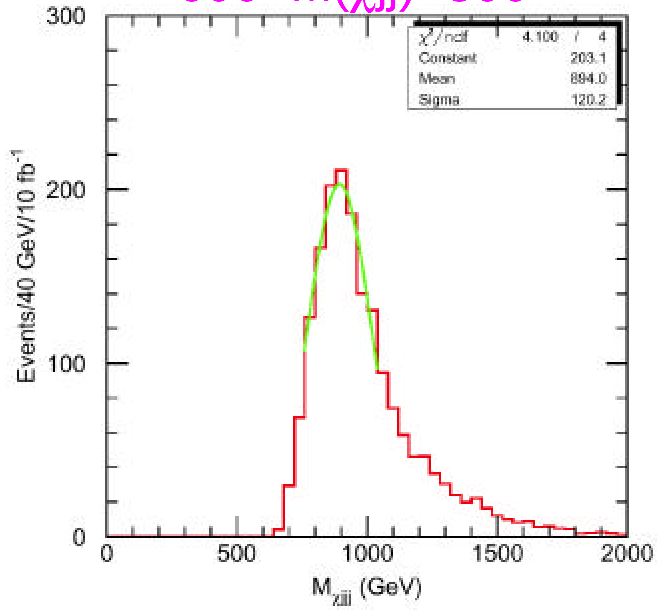
- Mass distributions can be sharpened
  - Use correlations in M(χjj) vs M(χjjj)
  - Statistical errors small
    - Expect syst. dominance (jet energy scale)



800<M(χjjj)<1000



600<M(χjj)<800

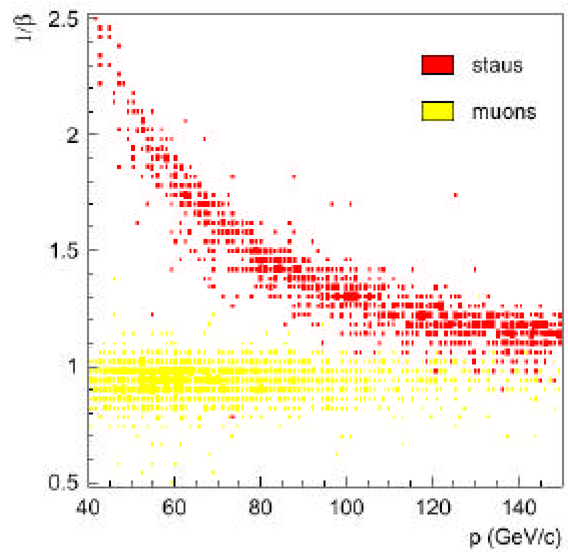


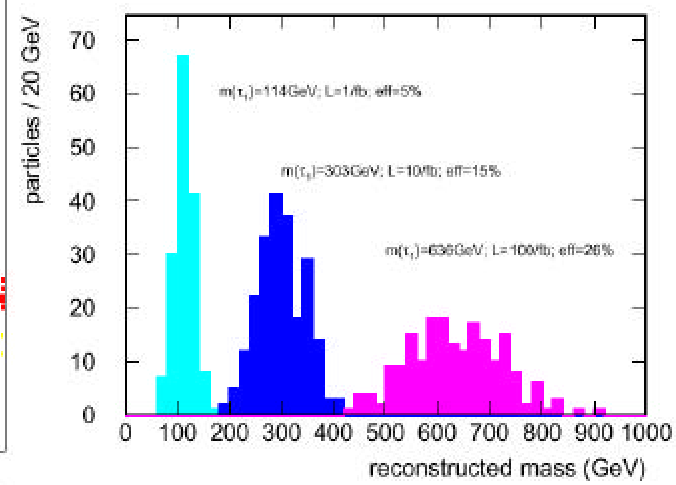
SUSY parameters: GMSB

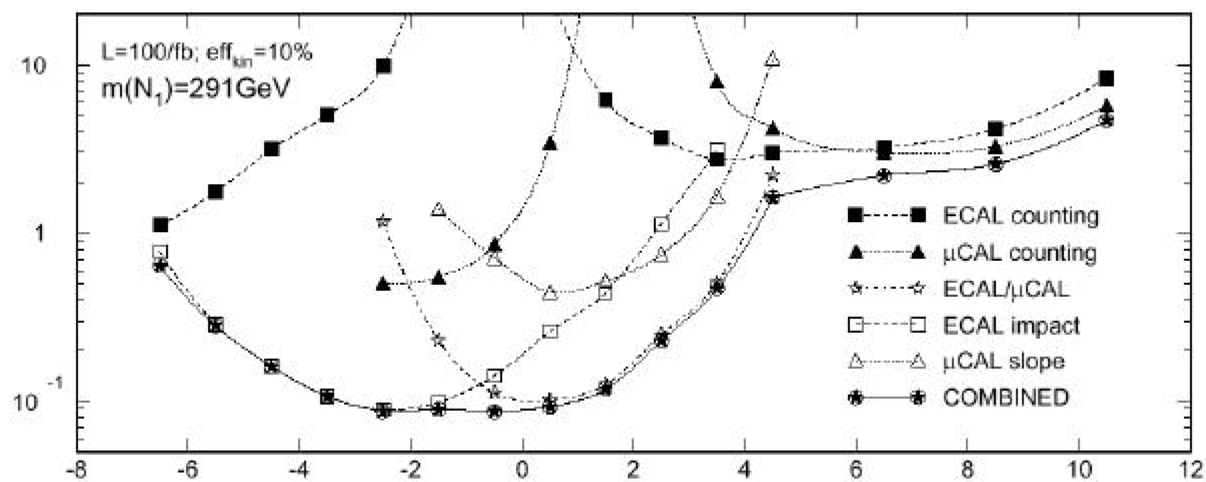
Point/Lumi	Λ (TeV)	M_m (TeV)	$\delta(\tan\beta)$	N_5
G1a @10fb^{-1}	90±1.8	500±150	±1.5	1±0.012
G1a @100fb^{-1}	90±0.6	500±80	±0.3	1±0.008
G1b @10fb^{-1}	90±0.9(ΛN_5)		+1.9 –1.3	
G1b @100fb^{-1}	90±8.1	<7x10^5 (95%CL)	+1.9 –1.3	
G2a @10fb^{-1}	30±0.4	250±44	±0.7	3±0.036
G2b @10fb^{-1}	30±0.18	250±25	±0.21	3±0.014

GMSB: NLSP and c_1^0 lifetime

- If NLSP=τ_1, use TOF (σ~1ns) (good for high lifetimes)
- Detecting the $\tilde{c}_1^0$ ® $\tilde{G}g$ decay
  - Off-pointing photons + c_1^0 decays in muon chambers







SUSY Summary

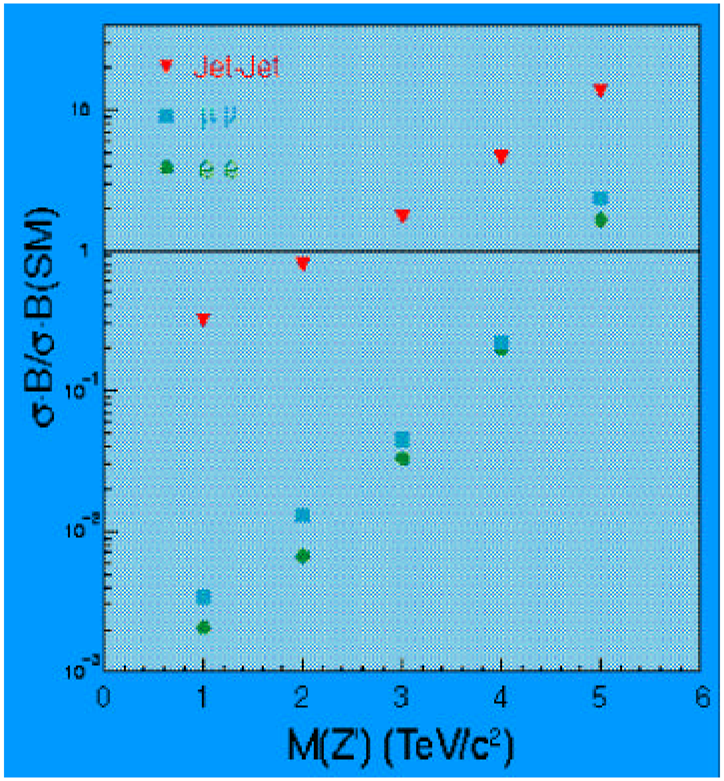
- SUSY discovery easy and fast
  - Expect very large yield of events in clean signatures (dilepton, diphoton).
    - Establishing mass scale is also easy (M_{eff})
- Squarks and gluinos can be discovered over very large range in SUGRA space (M_0,$M_{1/2}$)~(2,1)TeV
  - Discovery of charginos/neutralinos depends on model
  - Sleptons difficult if mass > 300 GeV
- Measurements: mass differences from edges, squark and gluino masses from combinatorics
- Can extract SYSY parameters with ~(1-10)% accuracy

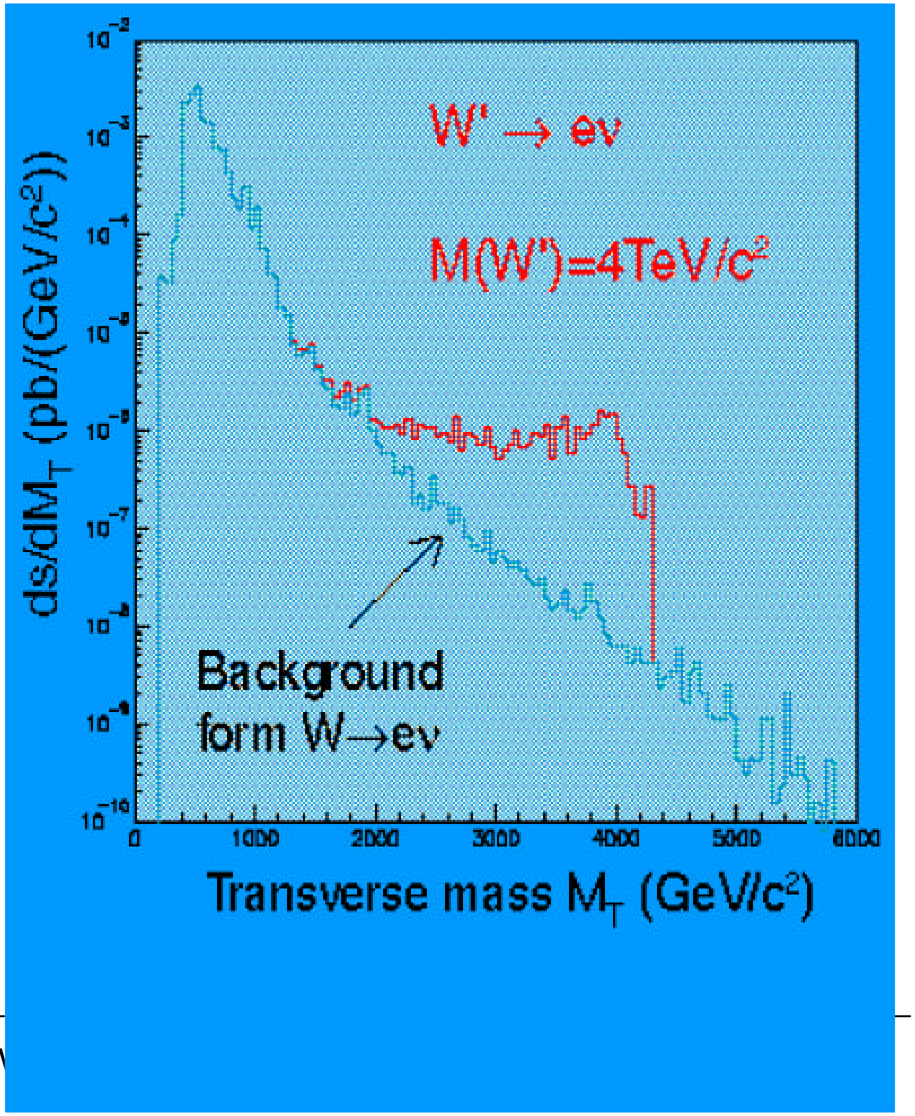
Other new Physics BSM

Other resonances/signatures (I)

- New vector bosons

Z’ reach



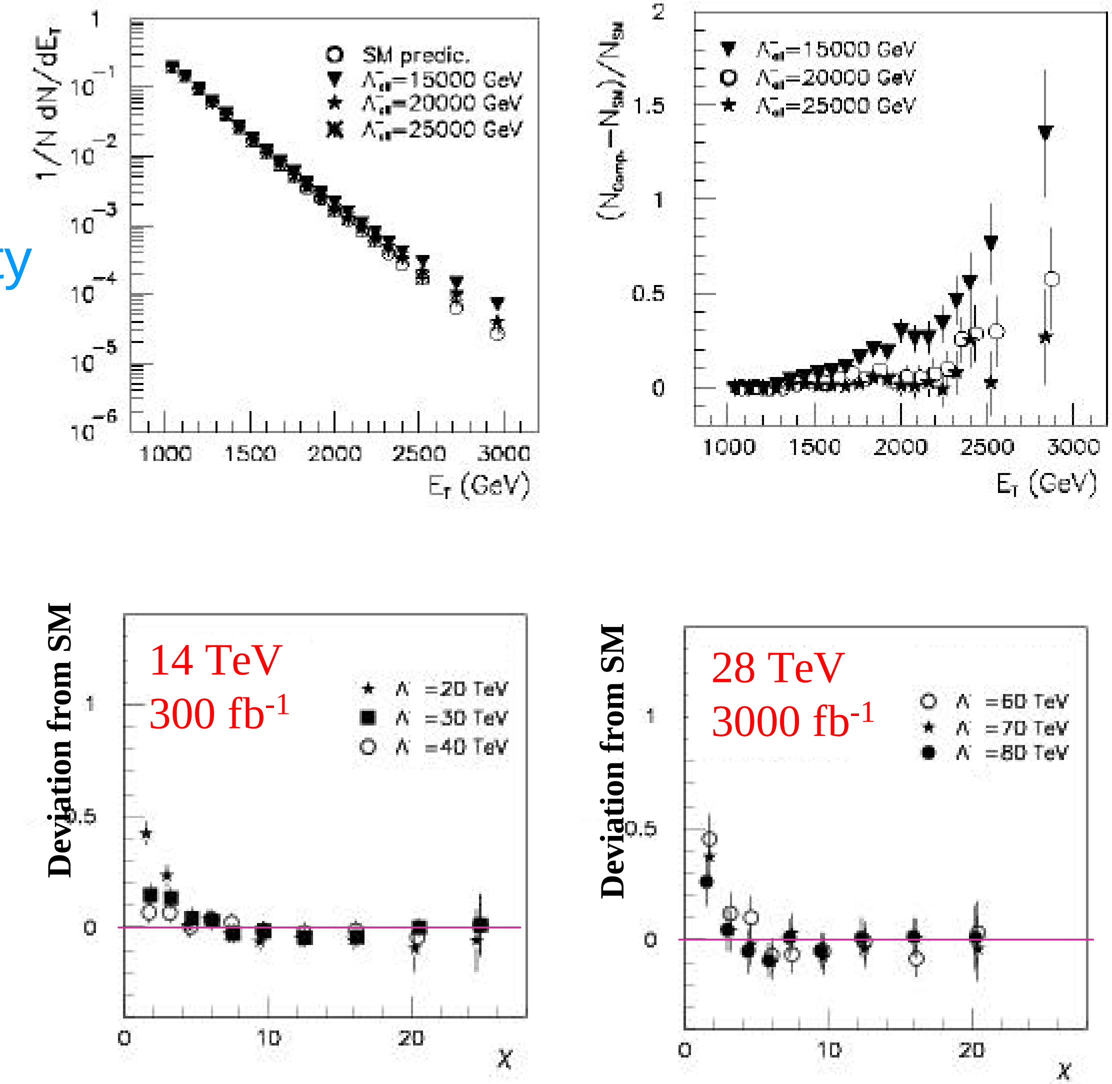


Compositeness

- Usual excess @ high P_T(jet) expected
  - Tricky issue: calorimeter (non)linearity
  - Analysis proceeds via angular distribution

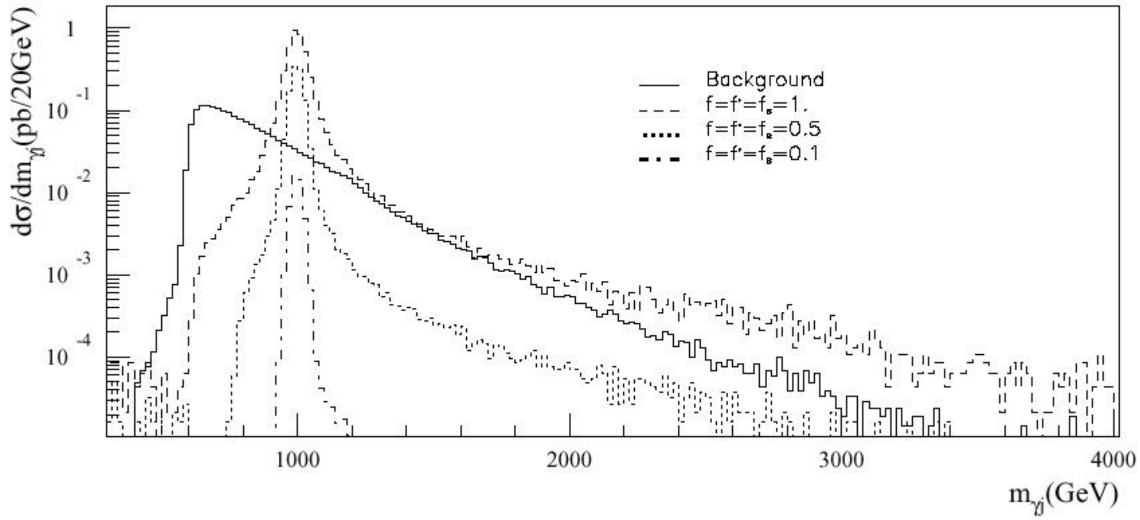
$$c = \frac{1 + |\cos q^*|}{1 - |\cos q^*|}$$

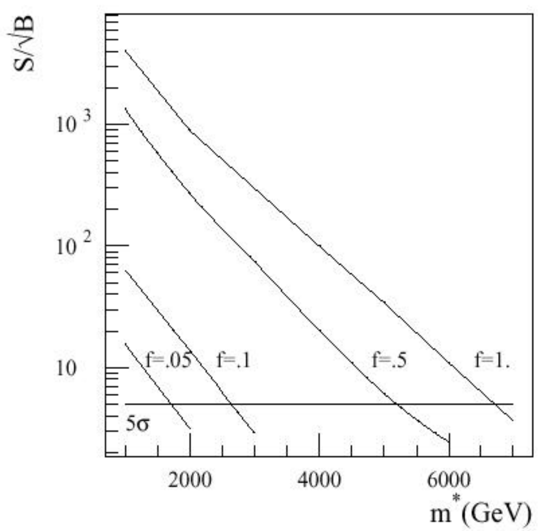
  - Ultimate reach: Λ_{comp} ~ 40 TeV (depends on understanding non-linearity @ 1-2% level)

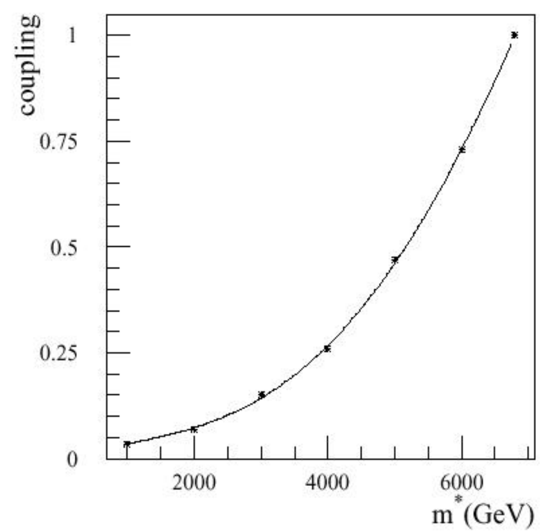


Excited quarks

- Search for q*→qγ

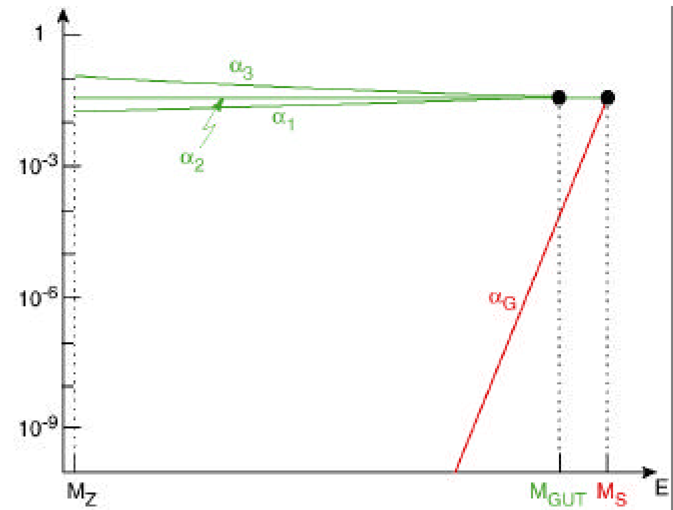






Gravity

- Traditional picture: gravity VERY weak
  - Coupling runs as E^2/M_{pl}^2 ;
    - scale set by M_{pl} given by $G^{-1/2}$
    - Weakness "explained" by large value of M_{pl}
- Attempts to include gravity:
  - So far: modify Standard Model
- Novel idea
  - Change gravity instead
    - (Antoniadis, Lykken, Arkani-Hamed/Dimopoulos/Dvali)

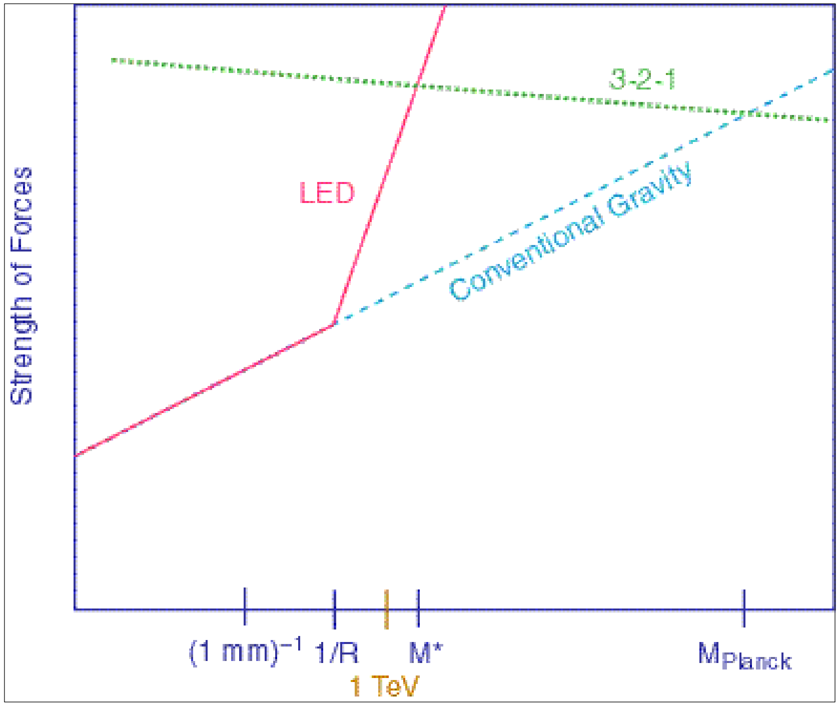


$$V(r) = -\int dr_1 \int dr_2 \frac{G_N r(r_1) r(r_2)}{r_{12}} \left(1 + e_G \exp\left(-r_{12} / l_G\right)\right)$$

- Experimental limits on ε_G deteriorate fast with small λ_G.

Gravity (II)

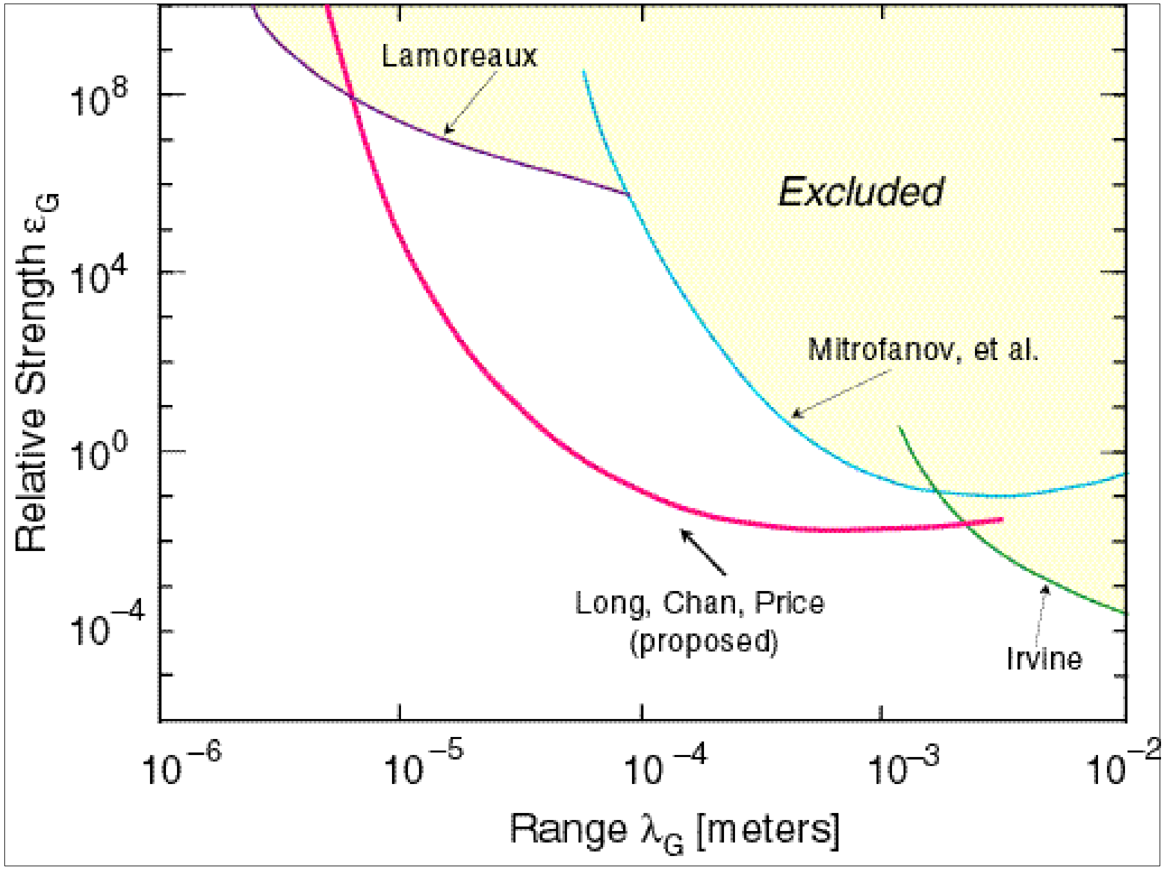
- If gravity does change at some mass scale 1/R, the Planck mass is a "mirage"



  - It's an artifact, given by $M_{pl} = M^*(M^*R)^{n/2}$

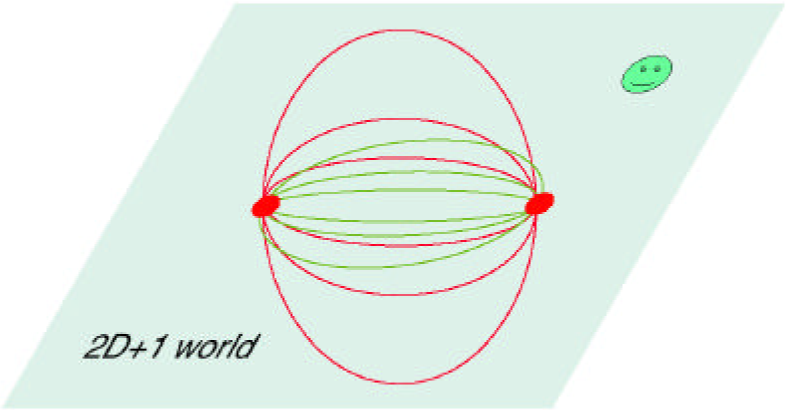
Gravity tests

- Experimental Limits on ε_G-λ_G:



Forces and number of dimensions

- Number (D) of space-time dimensions $\rightarrow$ form of force observed
  - E+M: $F \sim 1/r^2$ because D=3+1
  - For "ants" living in D=2+1 dimensions, E+M is actually a $F \sim 1/r$ force



- Side Conclusion: the running of the force changes in the presence of additional dimensions

Modifying Gravity

- Suppose extra dimensions do exist in nature
  - e.g. could be curled up

  - Then, at distance scales close to the radius, the familiar law would get modified:

$$D = 4;\ F = G\frac{m_1 m_2}{r^2} \qquad D = 4 + d;\ F = k\frac{m_1 m_2}{r^{2+n}}$$

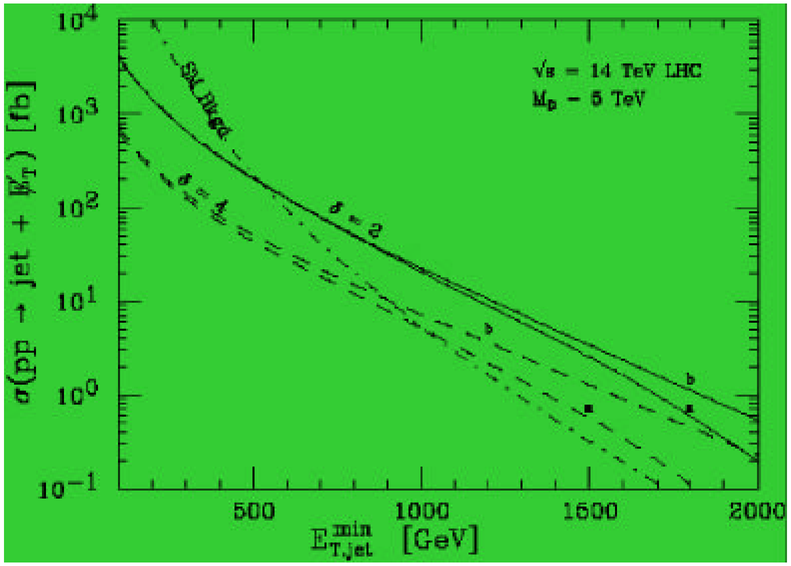
- Fundamental scale for quantum gravity: M_D
  - Dimensions of k: [k] = $M^{-\delta+2}$
  - Equating the forces at a distance scale R we get

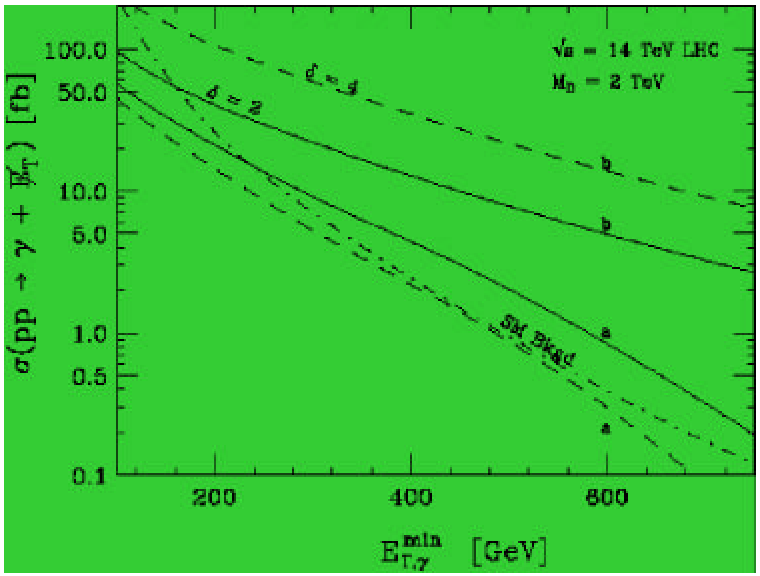
$$\frac{1}{G} \sim R^d M_D^{\ d+2} \Rightarrow R \sim \frac{1}{M_D}\left(\frac{M_{pl}}{M_D}\right)^{2/d}$$

- Scenario with M_D~1 TeV:
  - $\delta=2 \rightarrow$ R ~ 0.4 mm; $\delta=4 \rightarrow$ R ~ 10^{-5} μm

Extra (large) dimensions

- Two basic signatures:
  - Channels with missing E_T: E_T^{miss}+(jet/γ) (back-to-back)
    - Results from theory papers based on similar signatures (e.g. gravitino searches); instrumental bkg: same signature
  - Direct reconstruction of KK modes
    - Essentially a W', Z' search

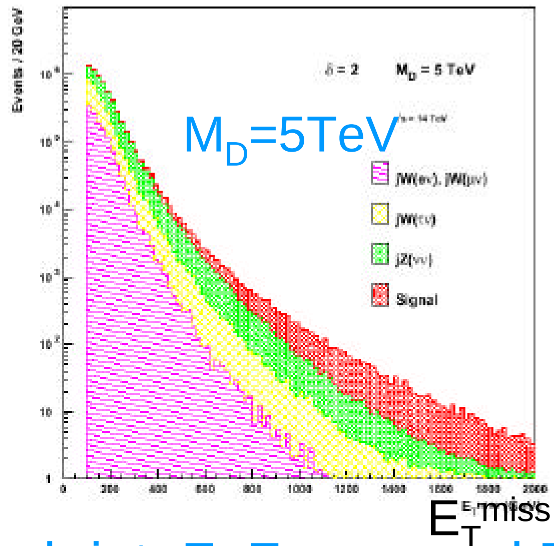


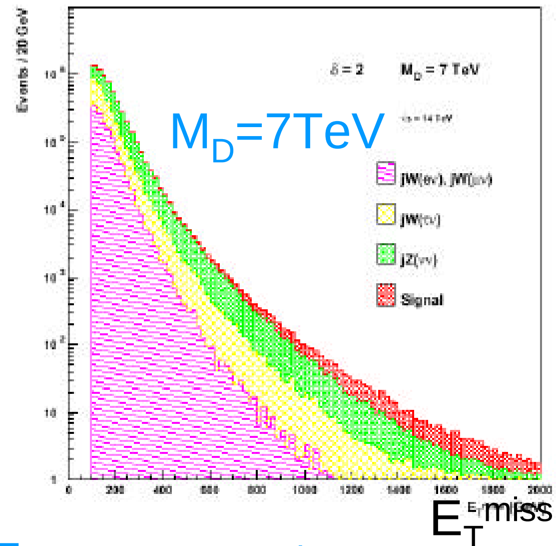


Giudice, Ratazzi, Wells (hep-ph/9811291)

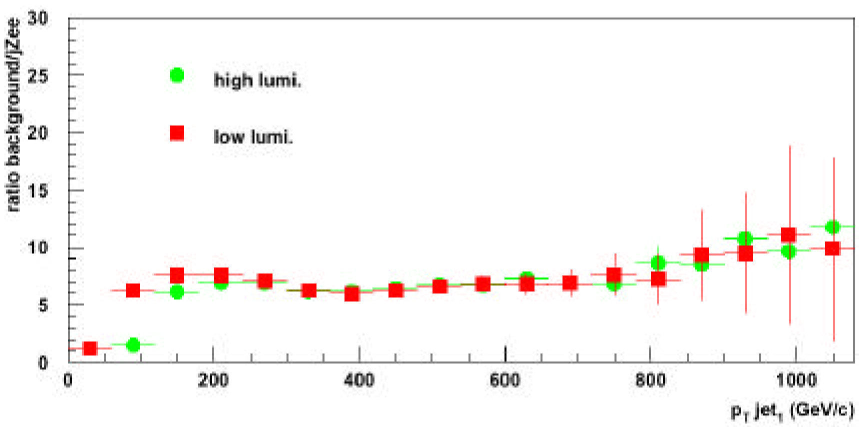
Extra dimensions (I): E_T^{miss}+Jet

- Issue: signal & bkg topologies same; must know shape of bkg vs e.g. E_T^{miss}
  - Bkg: jet+W/Z; $Z\rightarrow\nu\nu$; $W\rightarrow\lambda\nu$.





  - Bkg normalized through jet+Z, $Z\rightarrow ee$ and $Z\rightarrow\mu\mu$ event

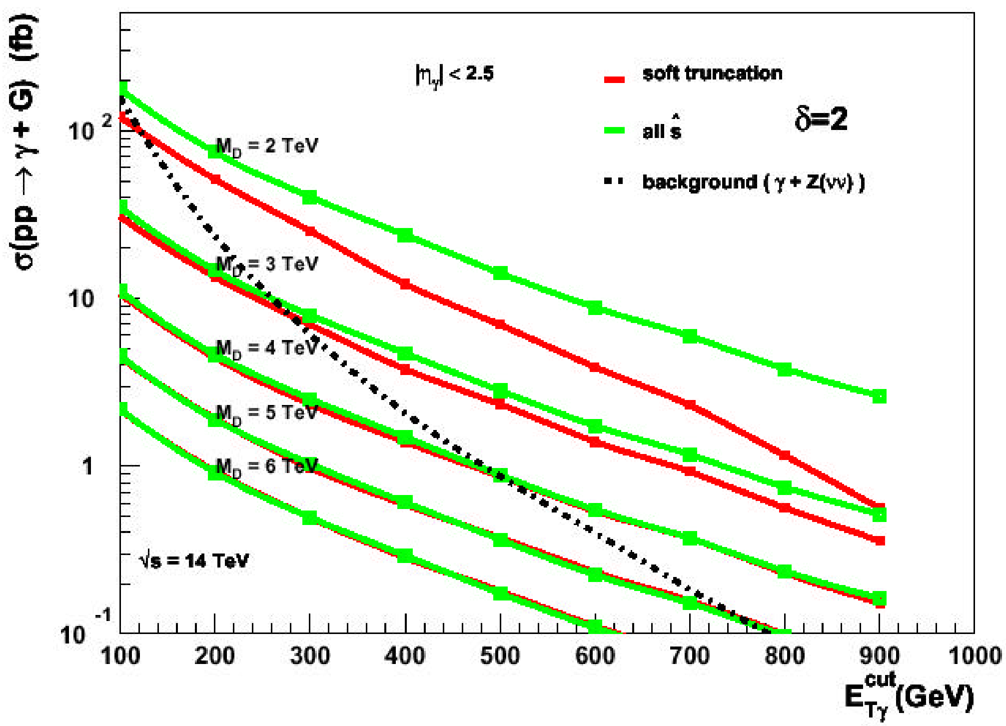


Reach @ 5σ

d	M_D (TeV)	R_D
2	7.5	10 μm
3	5.9	200 pm
4	5.3	1 pm

Extra dimensions (II): E_T^{miss}+photon

- Rates much lower than for jet case
  - Channel could be a “confirmation” one
  - Bkgs: γ+Z, Z$\rightarrow\nu\nu$ & γ+W, W $\rightarrow\tau\nu$; calibrated to Z$\rightarrow\mu\mu$,ee
    - (Z in Bkg)/(Z in $\mu\mu$,ee) ~ 6

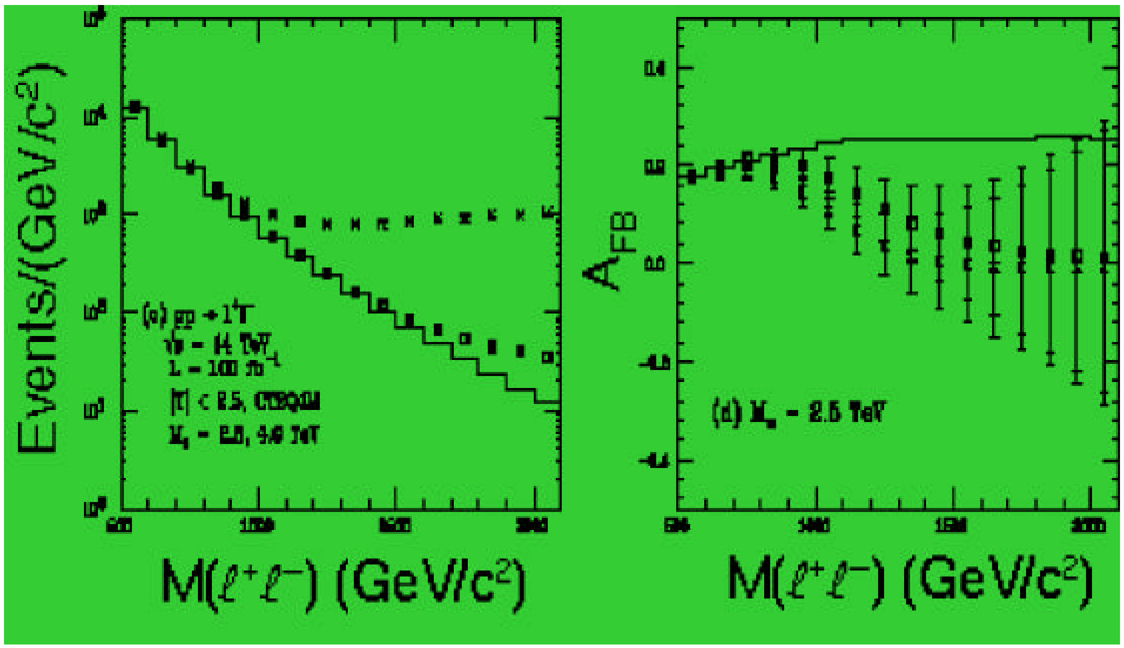


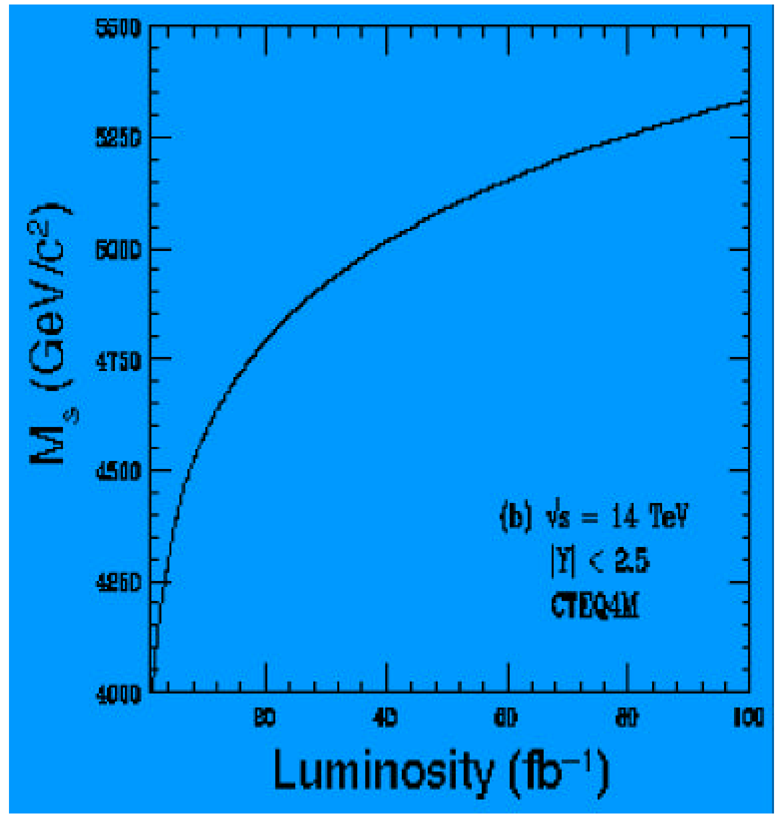
Reach @ 5σ

d	M_D (TeV)	R_D
2	3.7	30 μm

Extra dimensions (III): Dileptons

- Indirect signal: Drell-Yan
  - Leptons very clean; composite-ness-like signature; forward-backward asymmetry as well
    - Also $\gamma\gamma$ production

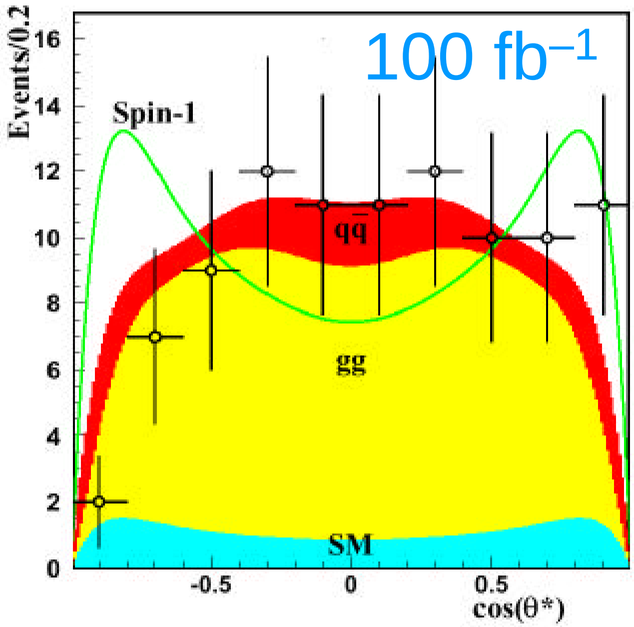


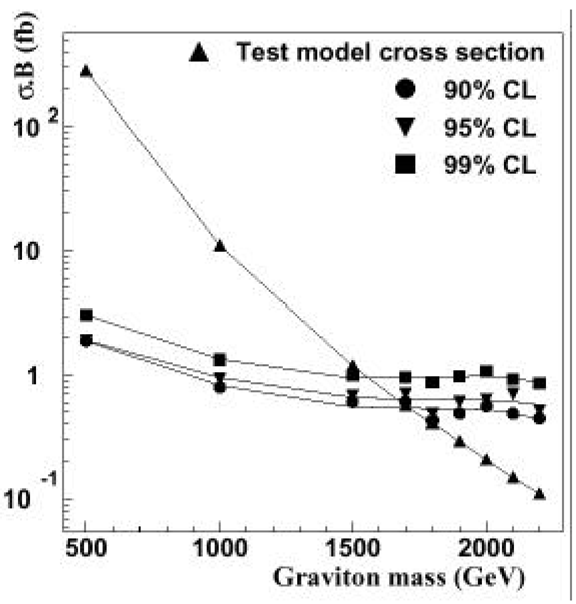


Hewett (hep-ph/9811356)

Extra dimensions: angular analysis

- If graviton excitations present, essentially a Z' search.
  - Added bonus: spin-2 (instead of spin-1 for Z)
    - Case shown*: $G \rightarrow e^+e^-$ for M(G)=1.5 TeV
    - Extract minimum s.B for which spin-w hypothesis is favored (at 90-95%CL)





* B.Allanach,K.Odagiri,M.Parker,B.Webber JHEP09 (2000)019

Summary

- SUSY (if there) will be seen
  - It will be very difficult to not see SUSY if today's "natural" parts of SUSY space are natural indeed
  - Can determine parameters over fairly large part of SUSY space
    - Can perform a few precise measurements
- Large com energy: new thresholds
  - Compositeness, new bosons, excited quarks, etc; Λ ~ 40 TeV
- Large extra dimensions
  - Can see them for M_D up to ~ 5-10 TeV and δ=2-4

Beyond the LHC

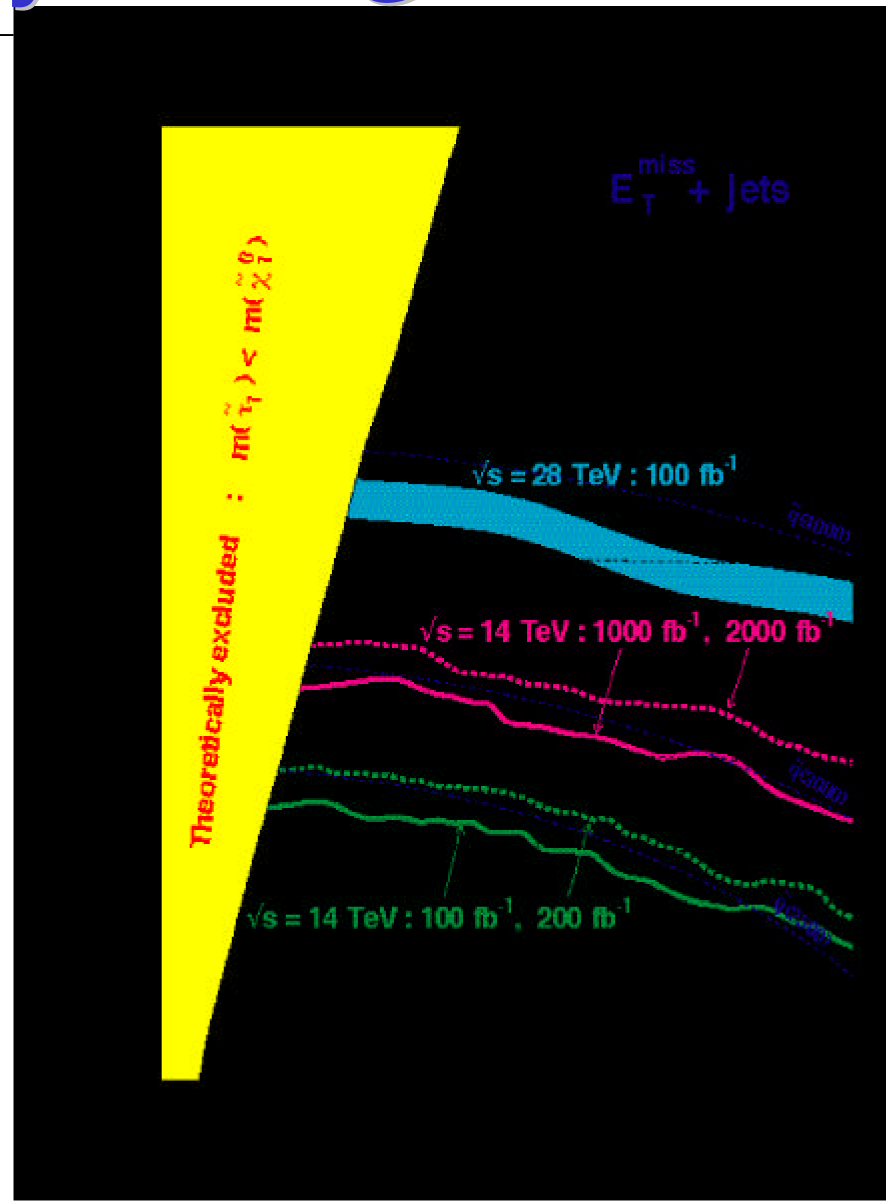
LHC++

Beyond LHC; LHC++?

- Two options being entertained (beyond Linear and muon colliders)
  - LHC at $10^{35}cm^{-2}s^{-1}$; LHC at 28 TeV; LHC with both upgrades
  - First look at effect of these upgrades
    - Triple Gauge Couplings
    - Extra large dimensions
    - New resonances (Z')
    - SUSY
    - Strong VV scattering
  - Preliminary: energy is better than luminosity
    - Detector status at 10^{35} needs careful evaluation

Supersymmetry reach @ LHC++

- mSUGRA scenario
  - Assume R_P conservation
  - Generic E_T^{miss}+Jets
  - Cuts are optimized to get best $S^2_{SUSY}/(S_{SUSY}+B_{SM})$
    - In some cases 0-2 leptons could be better
  - Shown: reach given
    - $A_0 = 0$; $\tan\beta=10$; $\mu>0$
  - For 28 TeV @ 10^{34}cm^{-2}s^{-1} probe squarks & gluinos up to ~ 4 TeV/c^2
  - For 14 TeV @ 10^{35}cm^{-2}s^{-1} reach is ~ 3 TeV/c^2

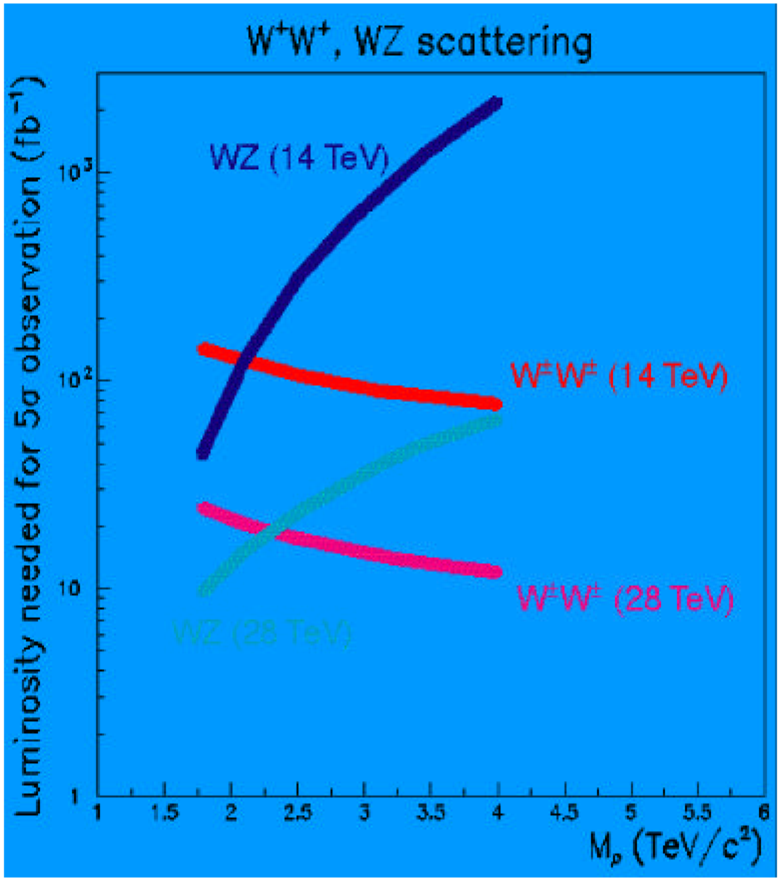


Strong WW/WZ scattering

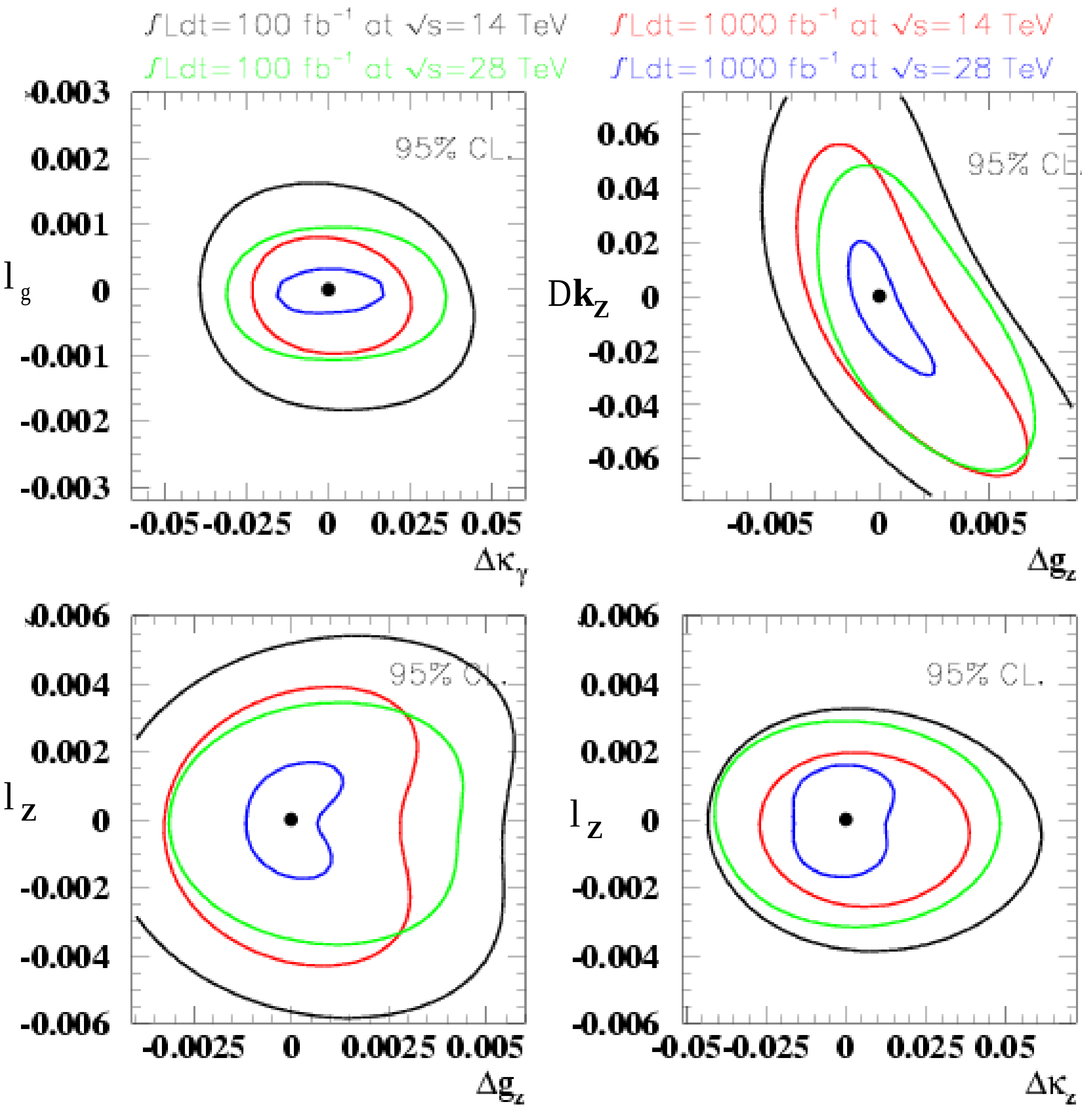
- "Golden modes" considered (leptonic decays; e/μ only)
  - Numerous channels (WW, WZ, ZZ). Worst-case (signal vs backgrounds) channel is WZ
  - Only $L=10^{34}cm^{-2}s^{-1}$ considered because analysis requires:
    - forward tagging jets and
    - central jet vetoes

    large effect from pileup at $L=10^{35}cm^{-2}s^{-1}$

- Like-sign WW & WZ:
  - luminosity needed for 5σ observation



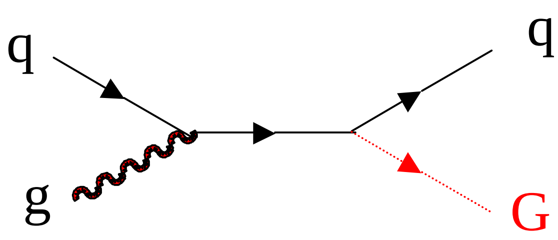
Triple Gauge Couplings @ LHC++



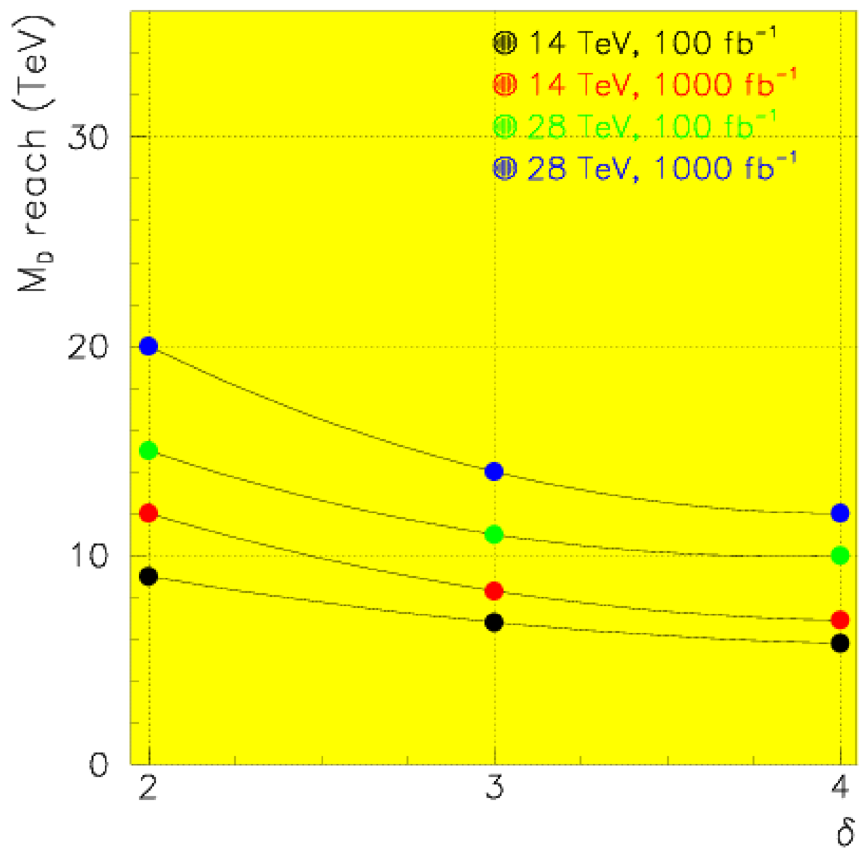
Machine Energy/Lum	Δk_Z x10^{-3}	λ_Z x10^{-3}
NLC 0.5 TeV 500 fb^{-1}	1.6	1.3
LHC 14 TeV 100 fb^{-1}	40	1.4
LHC 14 TeV 1000 fb^{-1}	34	0.6
LHC 28 TeV 1000 fb^{-1}	13	0.2

Extra (large) dimensions @ LHC++

- Signatures: the same
  - Bonus: can extract M_D and δ from σ(28 TeV) / σ(14 TeV) (since $\sigma \sim M_D^{-(\delta+2)}$)



  - Topology used here: Jet+missing E_T

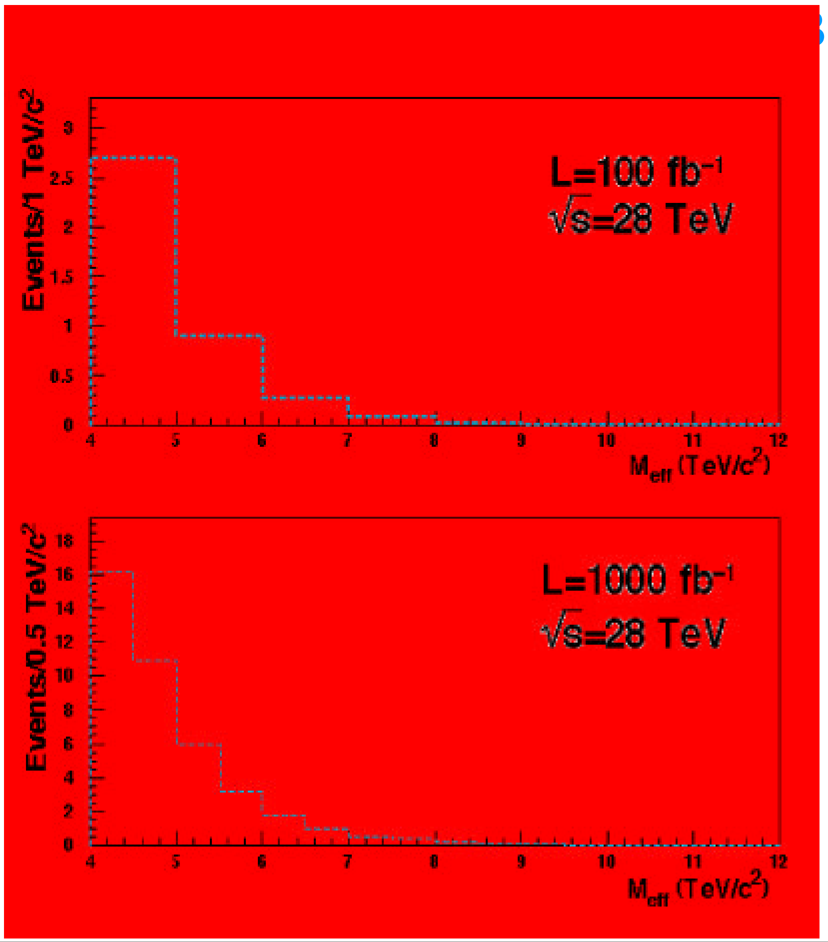


Z' reach in LHC++

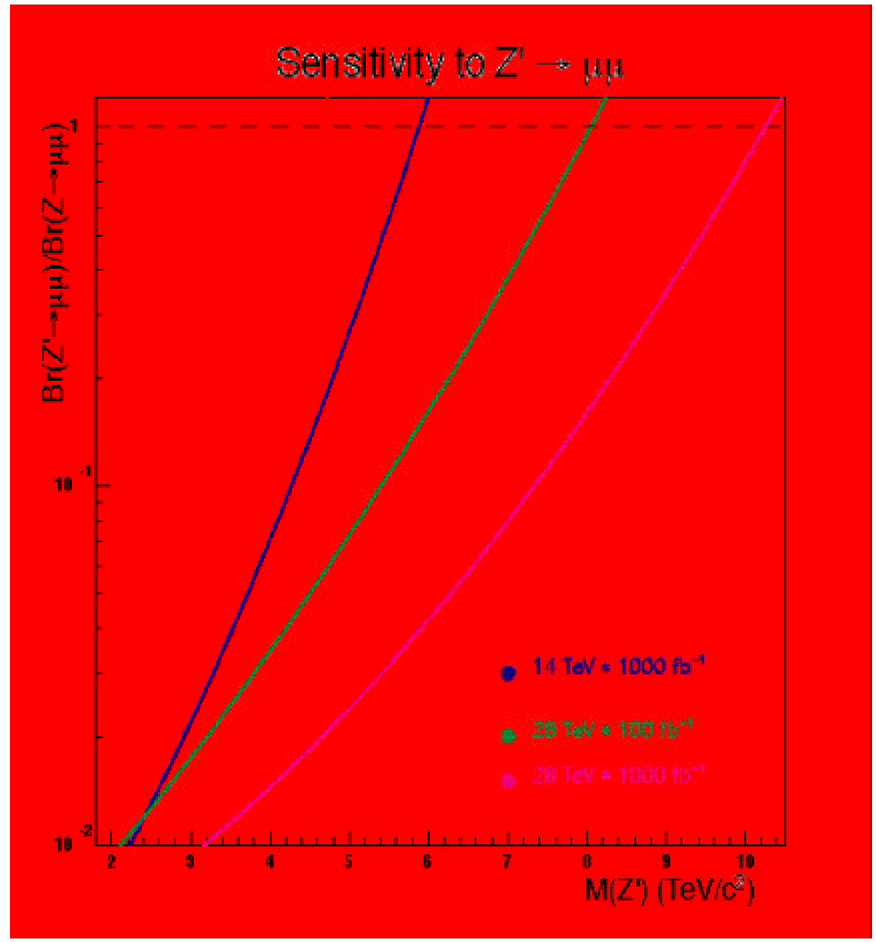
Only $Z' \rightarrow \mu^+\mu^-$ considered

M(Z')=8 TeV/c^2

signal vs Drell-Yan background

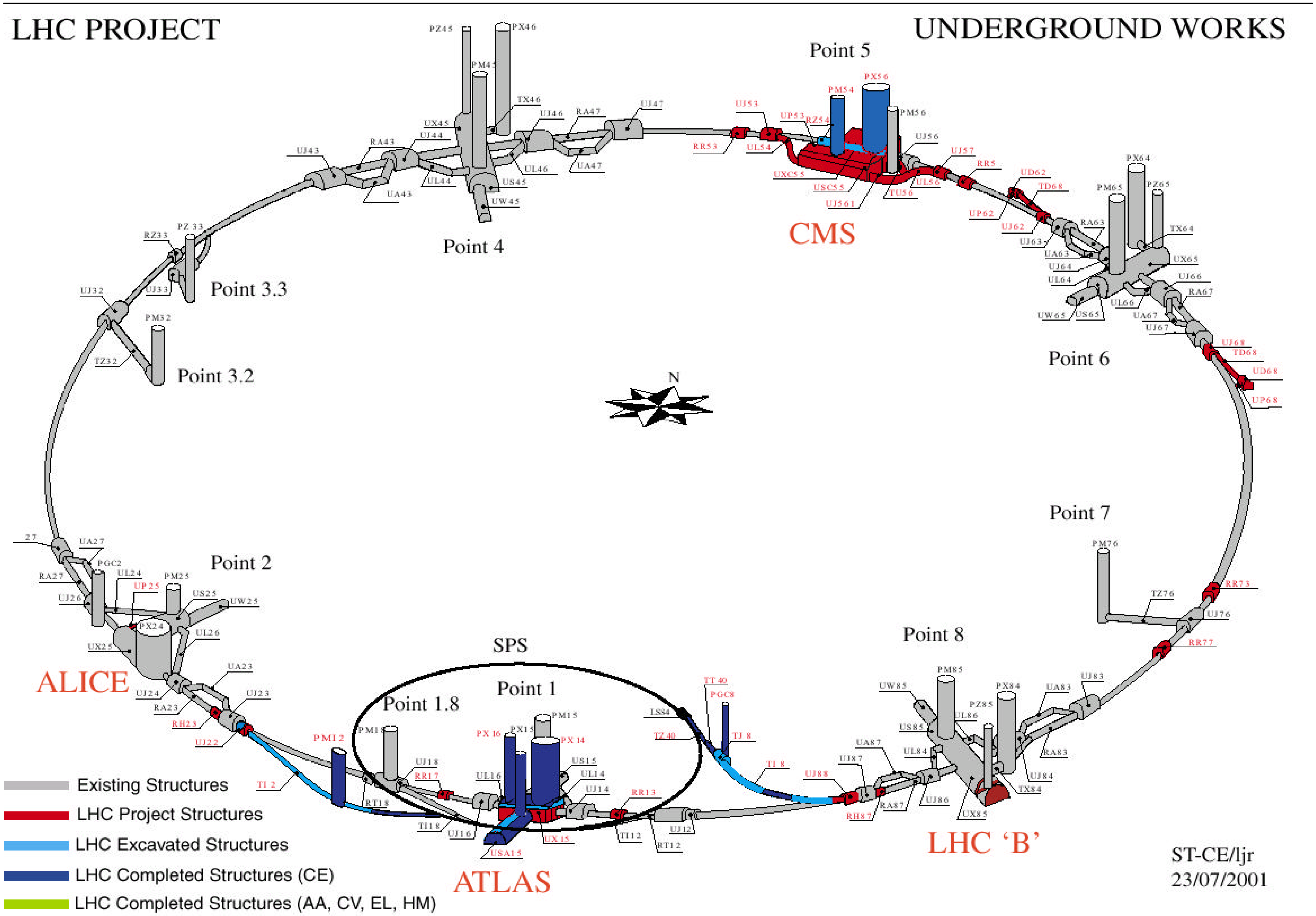


Reach in M(Z') is a function of $Br(Z' \rightarrow \mu\mu)$



Accelerator and experiments: current status & schedules

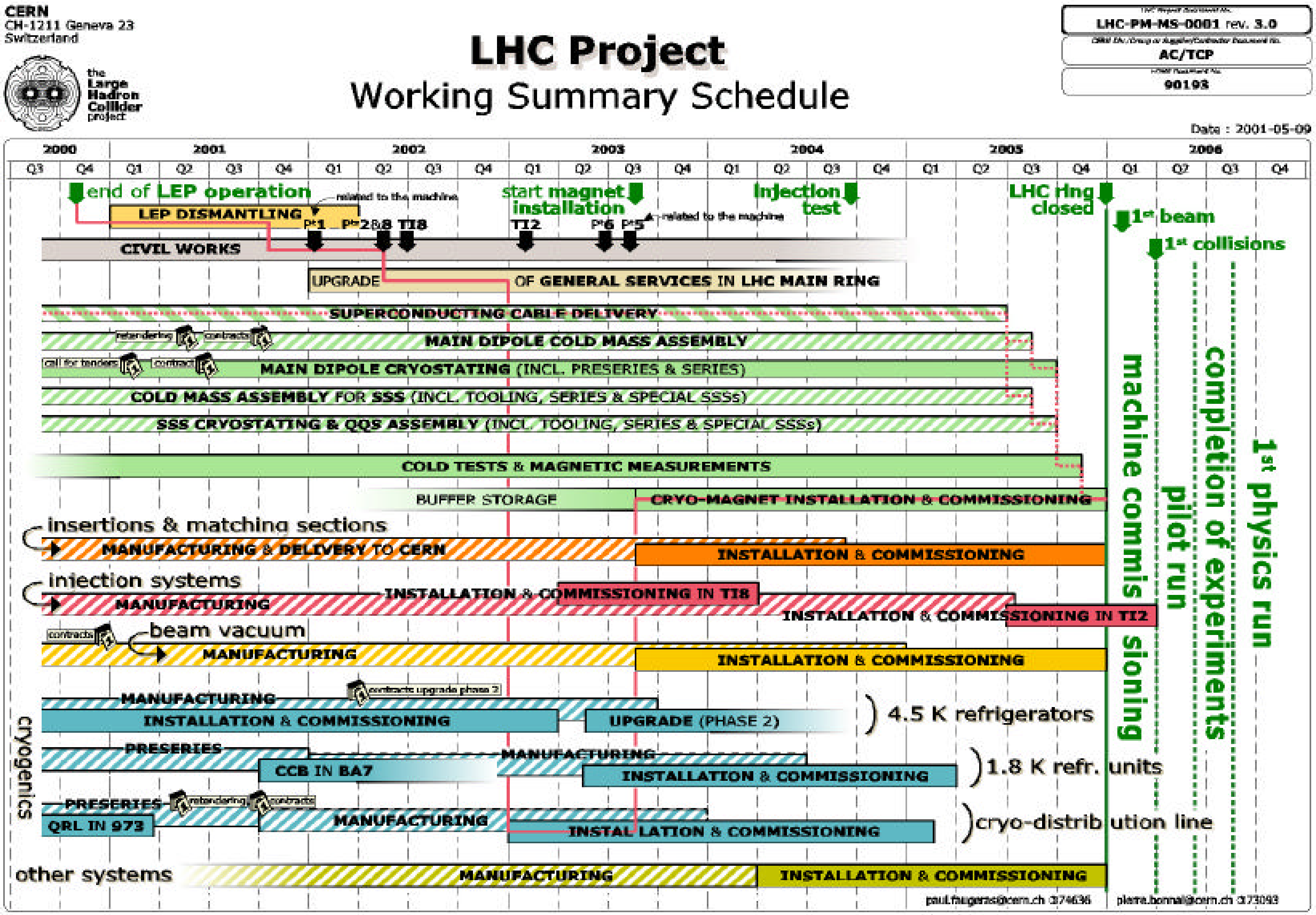
LHC: civil engineering status



LHC Schedule

01/04/04 to 30/09/04	Octant test	
31/03/05	Last dipole delivered	
31/12/05	Ring closed and cold	Full access to experimental caverns
01/01/06 to 31/01/06	Full machine commissioning Beam pipes in place	Full access to experimental caverns
01/02/06 to 31/03/06	1 beam (2 months)	Restricted access to experimental caverns
01/04/06 to 30/04/06	First Collisions 1 month Pilot run	Luminosity: $5x10^{32}$ to $2x10^{33}$
01/05/06 to 31/07/06	Shutdown	Full access to experimental caverns
01/08/06 to 28/02/07	Physics run: 7 months	Luminosity: $=2x10^{33}$ (goal: $=10\ fb^{-1}$)
01/03/07 to 12/04/07	Lead ion run, 6 weeks	

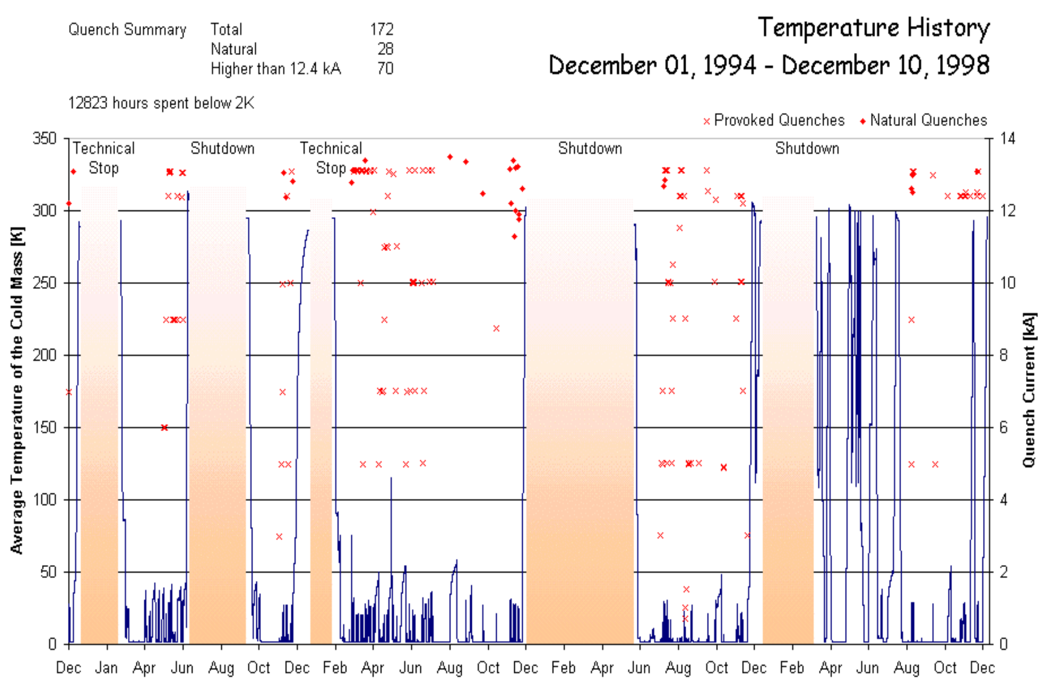
LHC Schedule

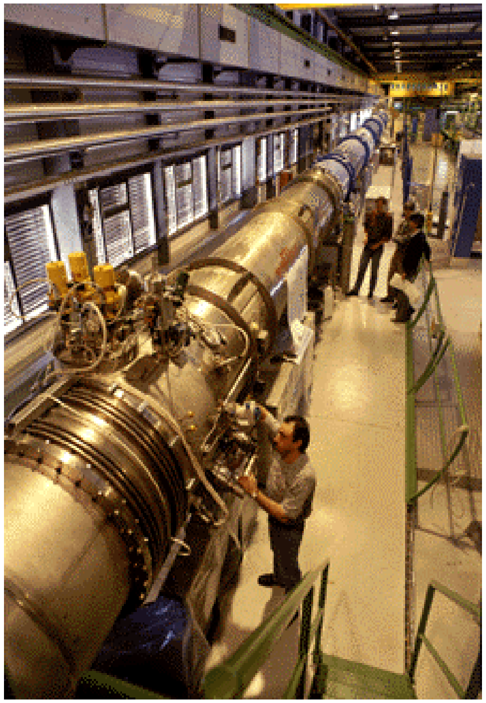


LHC status: LEP dismantling

LHC string tests

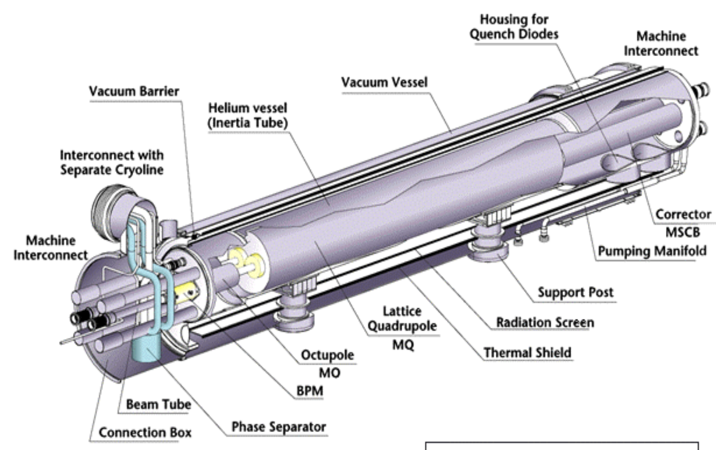
- Quench = Resistive Transition
  - E_{tot}~1.4 GJ ? How to handle this energy?
  - Protection system required (avoid excessive temperatures and voltages)
- String 1 test: 3 10m dipoles+1 quad
  - Operated for equivalent of 10yrs @ LHC; Completed 12/98





LHC status: magnets

- 4 dipoles (10m); 1 dipole (15m) build
  - Operated above 8.3T; reassembled after accidental quench
  - Reached 9T without problems
  - Pre-production contract for 30 magnets being finalized
- String 2: early 2001
  - Full LHC cell
    - 6 dipoles + 4 quads
  - Last tests before commissioning
  - String 2 has the same layout as a LHC c arc and follows the curvature of the tun with a Short Straight Section (SSS), wh cryogenic line and is followed by three simplified cryogenic scheme, the secon the cryogenic line.

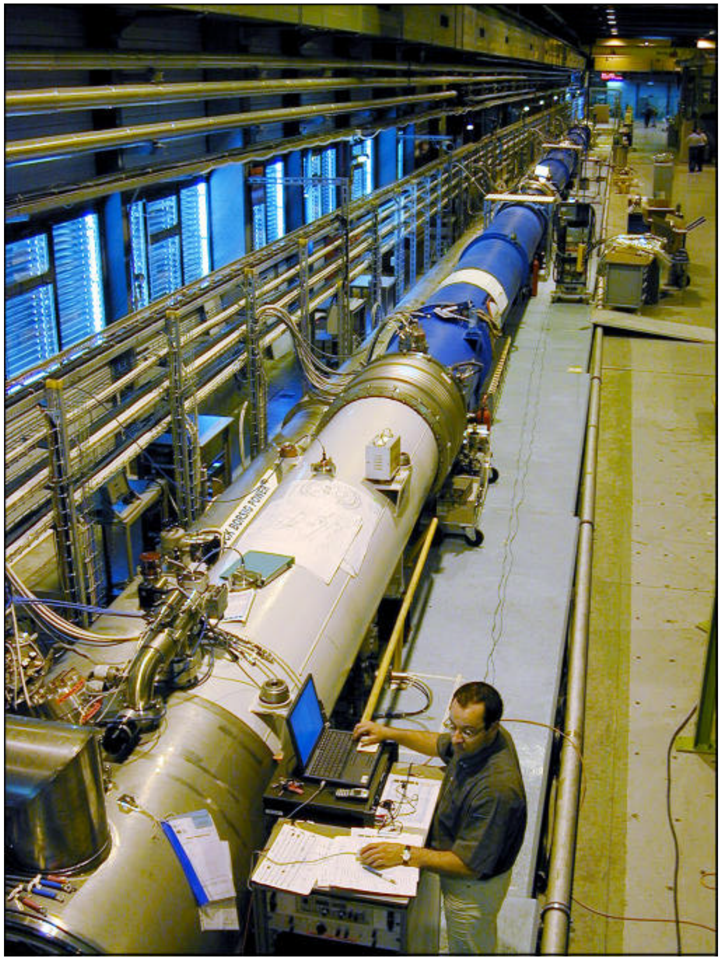


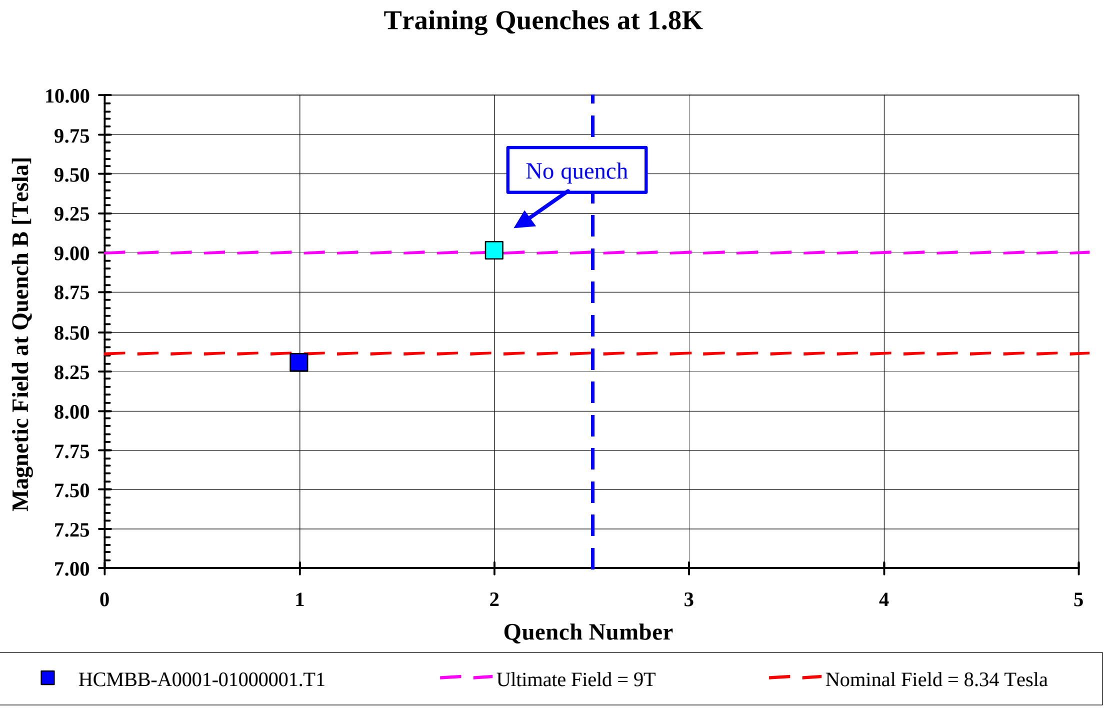
Short straight section assembly

LHC dipole

- Alstom LHC dipole No. 1 on the test bench in the SM18

String 2





Training Quenches at 1.8K
No quench
Magnetic Field at Quench B [Tesla]
10.00
9.75
9.50
9.25
9.00
8.75
8.50
8.25
8.00
7.75
7.50
7.25
7.00
0
1
2
3
4
5
Quench Number
HCMBB-A0001-01000001.T1
Ultimate Field = 9T
Nominal Field = 8.34 Tesla

LHC status: transfer lines

- From SPS to LHC (transfer line)
  - Overall: on schedule

Small prb: slower progress through the rock (6m/day instead of 30m/day)

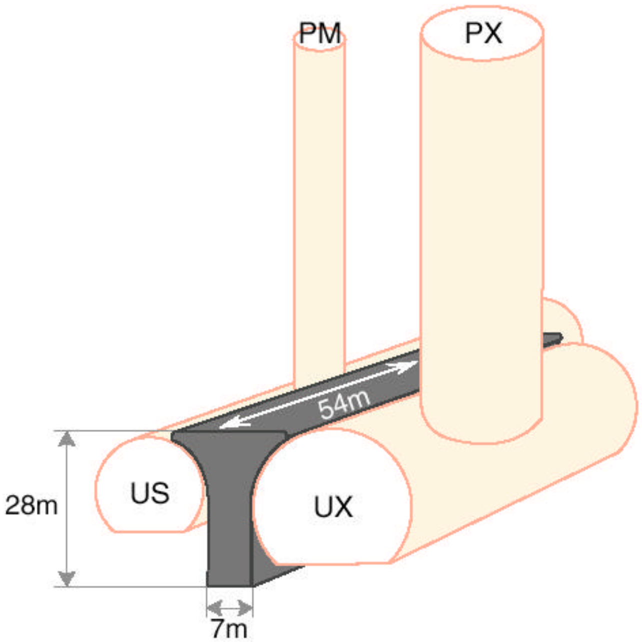
ATLAS & CMS experimental sites

- Civil engineering
  - Proceeding; some problems with water at Point 5 (CMS)
    - ATLAS cavern: 2002;
    - CMS in 2003

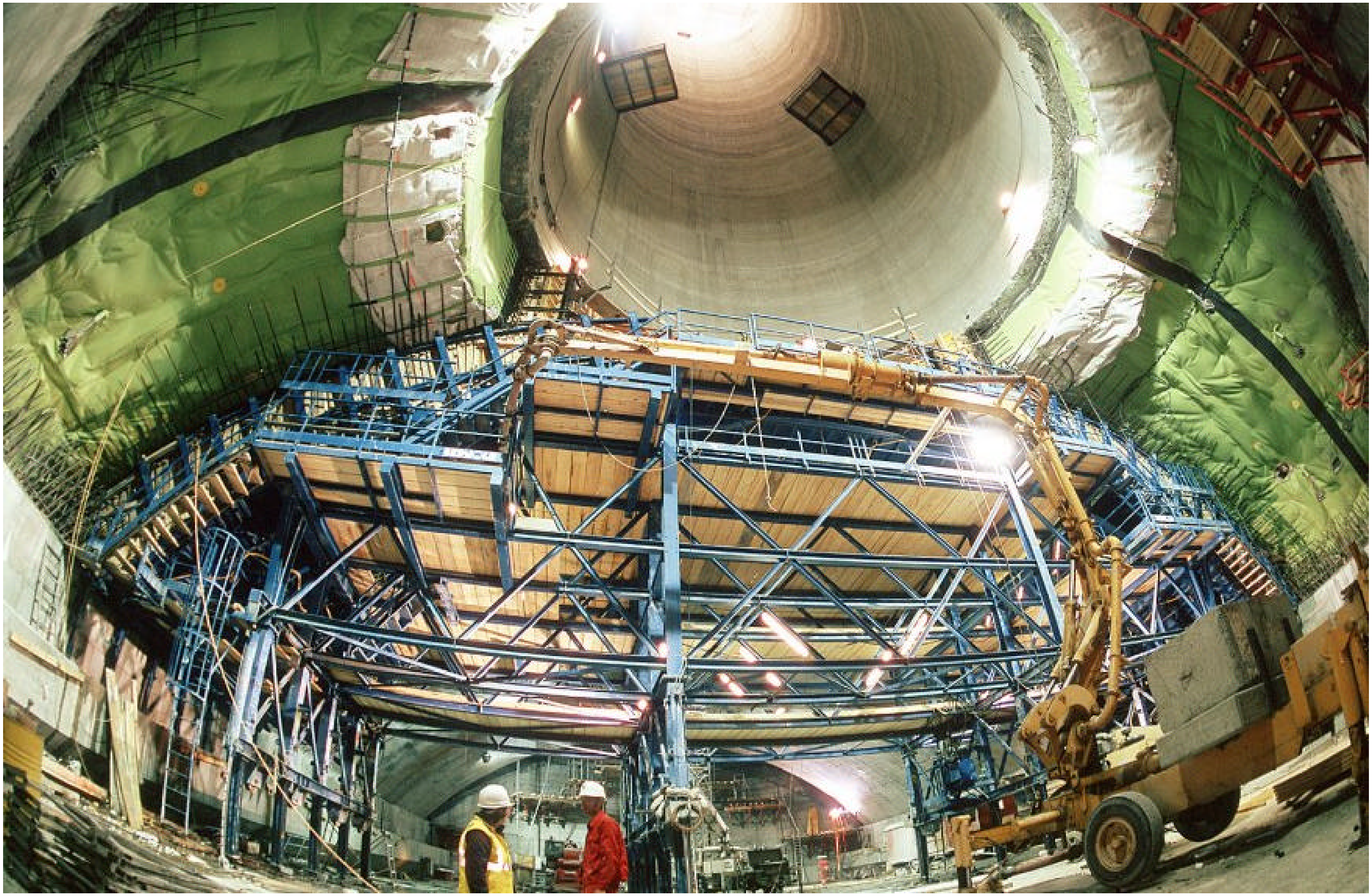
Point 1 (ATLAS pit)

Civil engineering (underground @ CMS)

Excavation of the Pillar



Civil engineering (@ATLAS)



ATLAS coil

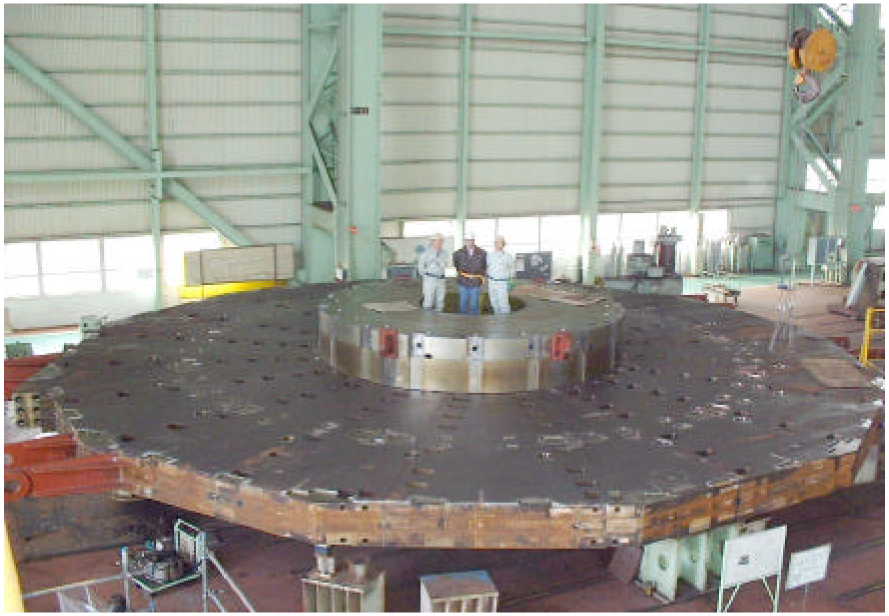
- Completed solenoid and cryogenics chimney during tests at Toshiba (for KEK)

ATLAS torroids

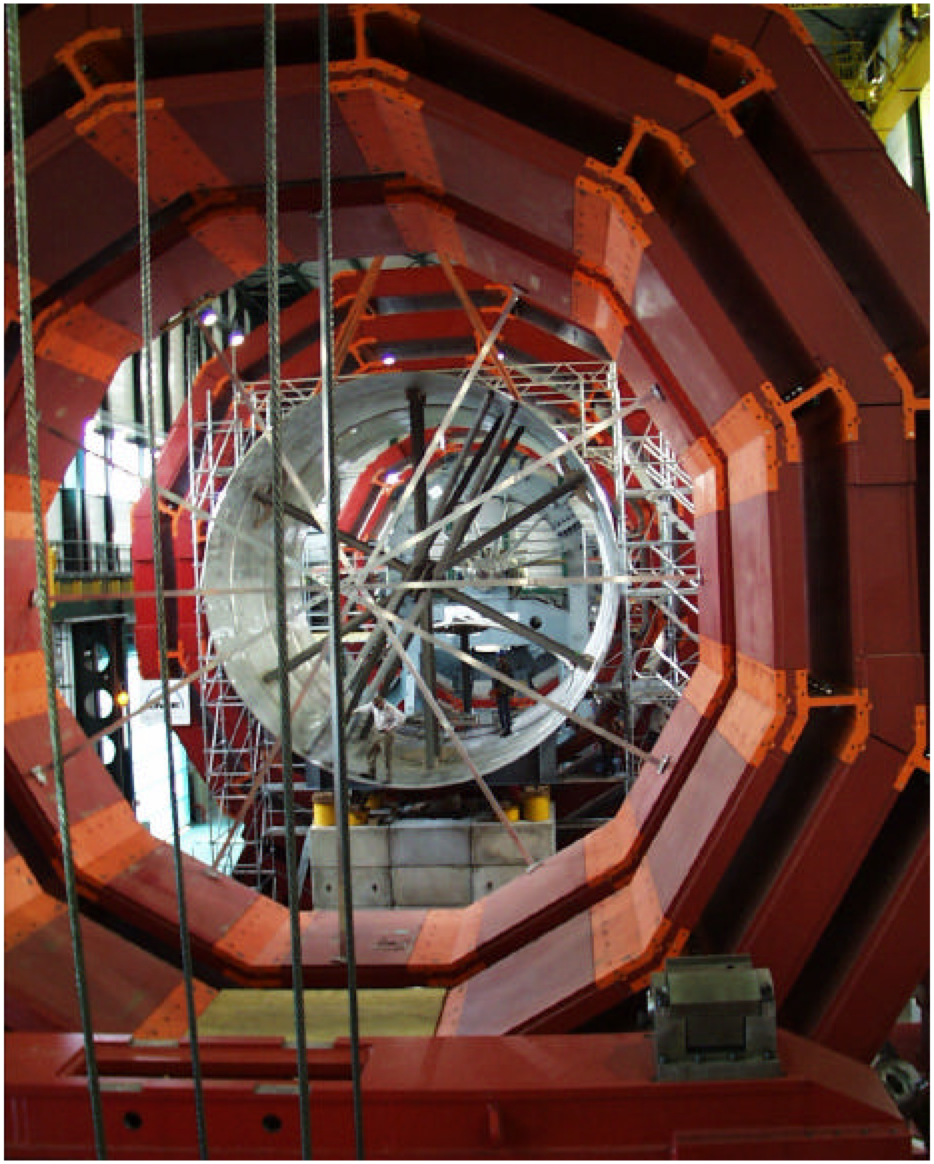
- Left: B0 coil connected to the barrel toroid test stand in Hall 180 at CERN
- Right: First impregnated double pancake Barrel Toroid coil

CMS magnet

YE-1 & nose trial assembly Nov ‘00
In Kawasaki (Japan)



YB-2, YB-1, YB0 ready, YB1 started.
Central wheel YB0, supporting the vacuum tank. Web camera: http://cmsdoc.cern.ch/outreach/



CMS coil

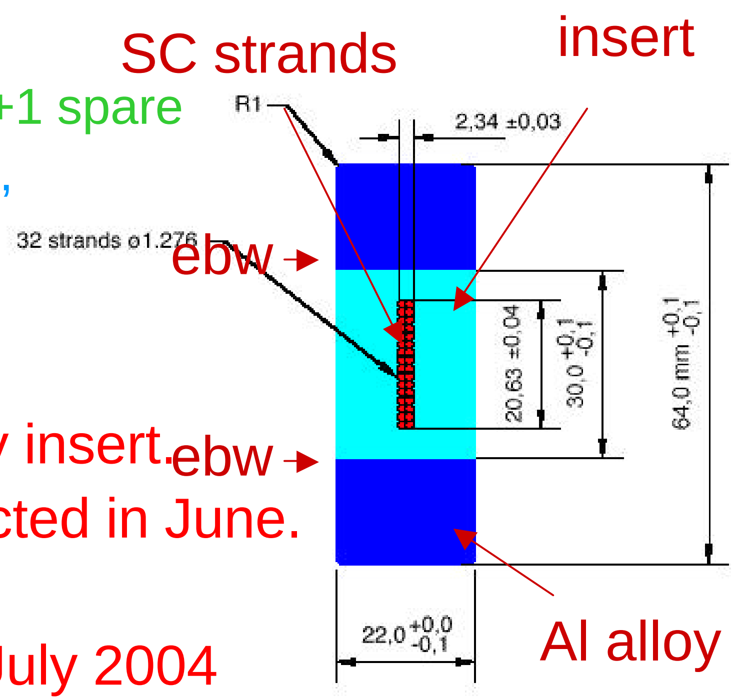
- Most of the major contracts have been placed (86% of budget committed, 104 MCHF).
  - Estimated total cost of the magnet (122.9 MCHF) unchanged
- YOKE Status
  - 3 of the 5 barrel yoke rings assembled at Point 5
  - 1st endcap disk: assembly started 4/01 (2nd endcap@CERN in 9/01)
- COIL Status
  - SC cable: Need 21 lengths of 2.65km

    coil has 5 sections, 4 lengths/section+1 spare
  - Produced: 8 cables worth of sc strands,

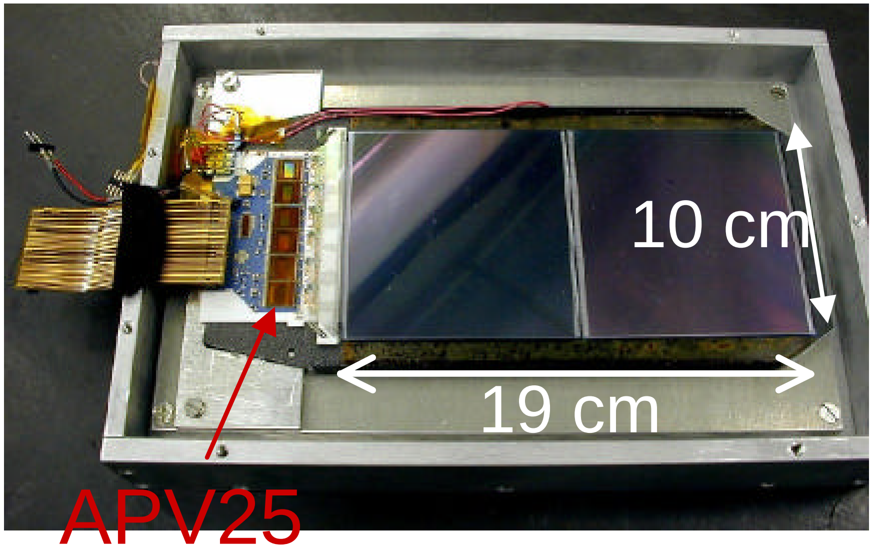
    5x2.65km of Rutherford cable,

    4x2.65km of real insert,

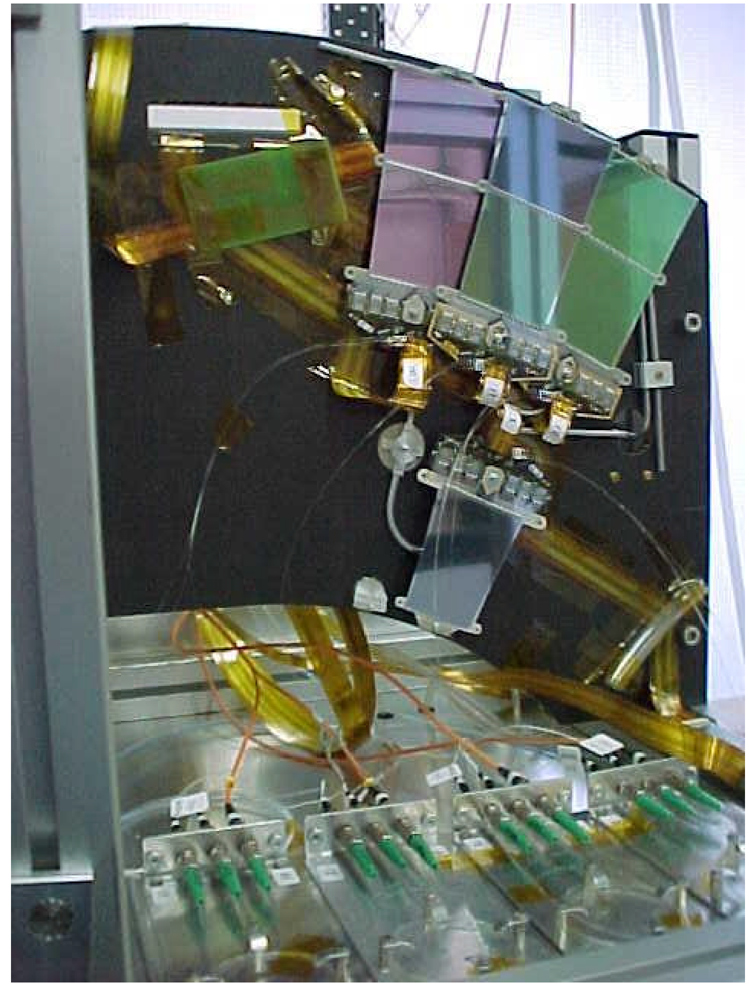
    20 out of 40 lengths of Al alloy.
- EBW reinforcement tested with dummy insert.
- First full length of final conductor expected in June.
- Tests of winding machine started
- Finish Magnet Test on the surface by July 2004



Tracking detectors



CMS: tracker TOB with final hybrid

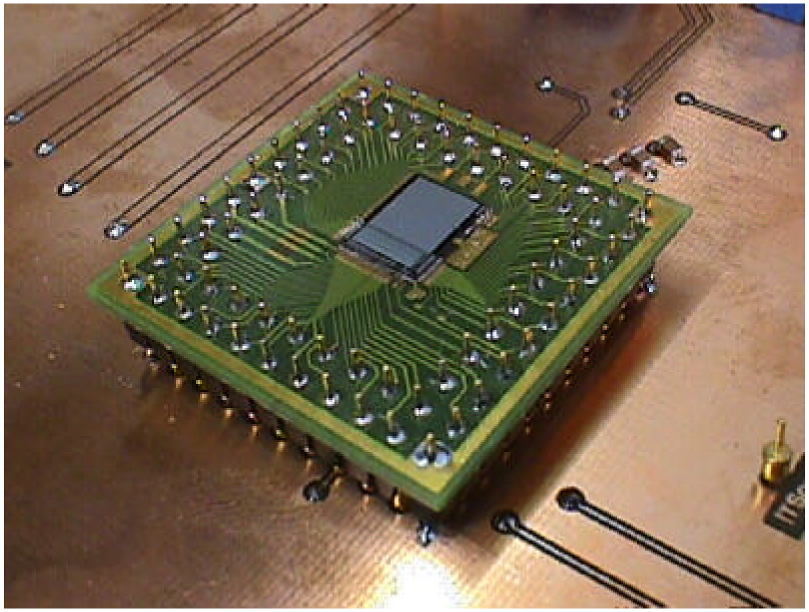


ATLAS: SCT end-cap system test

Pixel Readout Chip

- PSI41 pixel chip (DMILL) with final architecture received 03/2001. Testing just begun.
- Design of full size (52x53pixel), final architecture ROC (DM_PSI43) mostly finished. Submission only after careful checking of PSI41. ~ July 2001
- Allows construction of first full size Pixel modules at end 2001.
- Translation of ROC into ¼ µm CMOS after submission (Aug. 2001).
- Allows probably smaller pixel size.

→ e.g. (125µm x 125 µm)



- 36x40 pixel chip
- 150µm pixel size
- Size: 8.4mm x 6.3mm
- # transistors ~ 240K
- ~ 450 chips in hand

CMS HCAL: HB-1 Complete

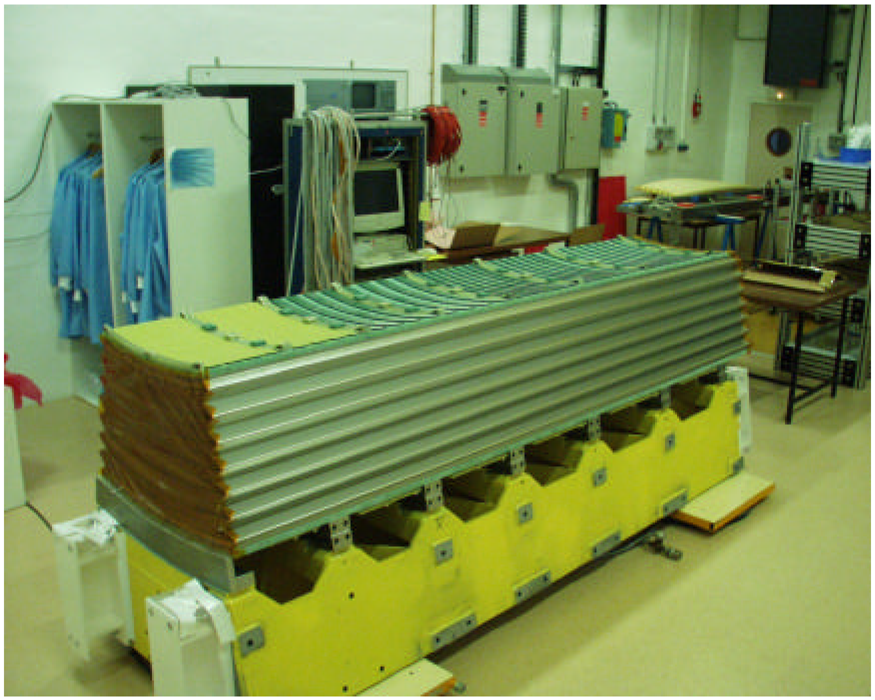
27 October 2000

Reception of HB-1 at Felguera, Oviedo (Spain)

2nd half barrel (HB+1) will be trial-assembled in July 2001.

ATLAS ECAL

First completely stacked series LAr EM barrel module at Saclay



Storage of barrel and extended barrel Tile Calorimeter modules

Muon (3) assembly lines at CIEMAT

Goal is 3 SL's in 2 weeks. Achieved: 3 SL's in 3 weeks

CSC installation fixture

Design and construction completed. Installation demonstrated.
Counterweight movement keeps balance w/ or w/o chamber
Chamber can rotate at any angle

Status: summary

- Roughly on schedule
  - Have lost about 6 months
  - Startup I snow defined as $2x10^{33}$ in August 2006
  - Expect:
    - SUSY within a week/month
    - Higgs within three months
  - Otherwise, a push to higher luminosity
- Now turning to computing (resources etc.)

(Grand) Summary

- Higgs is still missing
  - Symmetry Breaking in the SM (and beyond!) still not understood
  - LHC and ATLAS/CMS designed to find it
  - Numerous challenges, mostly "solved"
- Physics at the LHC will be extremely rich
  - SM Higgs (if there) in the pocket
    - Now turning to measurements of couplings, etc.
  - Supersymmetry (if there) ditto
    - Can perform numerous accurate measurements
  - Large com energy: new thresholds
    - Compositeness, new bosons, large extra dimensions within reach
  - LHC++?
- Just need to build machine/experiments.