Discovering New Physics with Early LHC Data

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BROWN UNIVERSITY

CMS

Loopfest VII

SUNY @ Buffalo

May 14, 2008

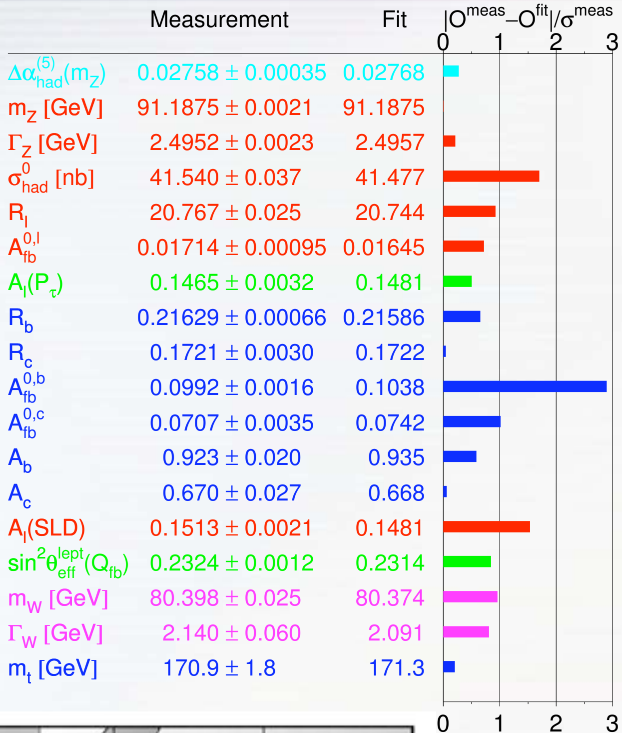
Outline

- Why looking beyond the Standard Model?
  – You know the answer!
- The machine, the detectors
- Discovering new physics with early LHC data*
- Conclusions

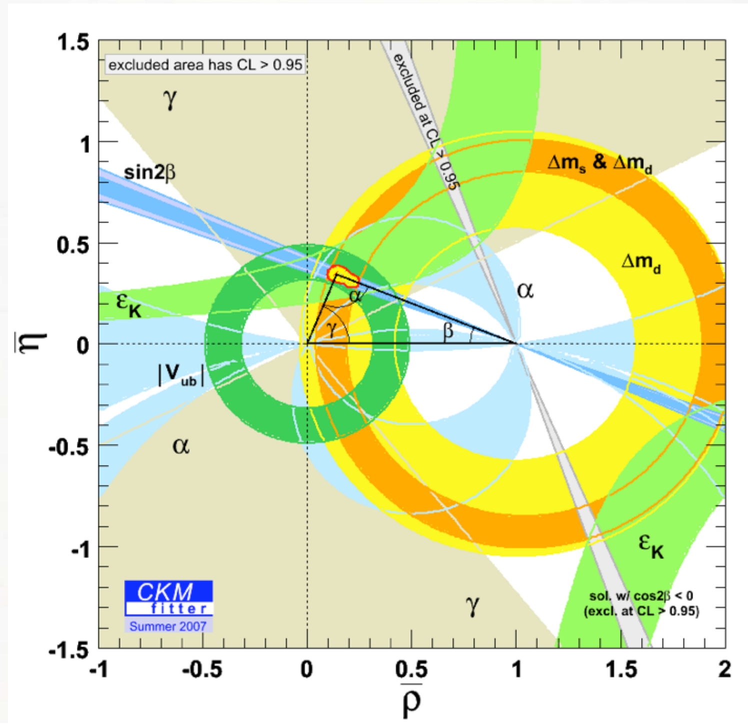
*) Chose to focus on a few characteristic examples, rather than being too inclusive

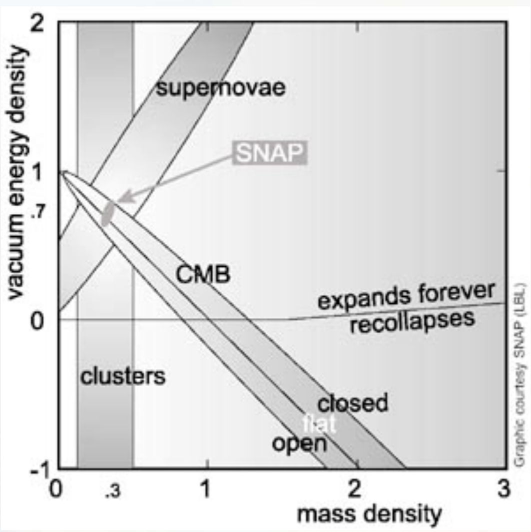
I would like to thank the organizers for a kind invitation and a great workshop!

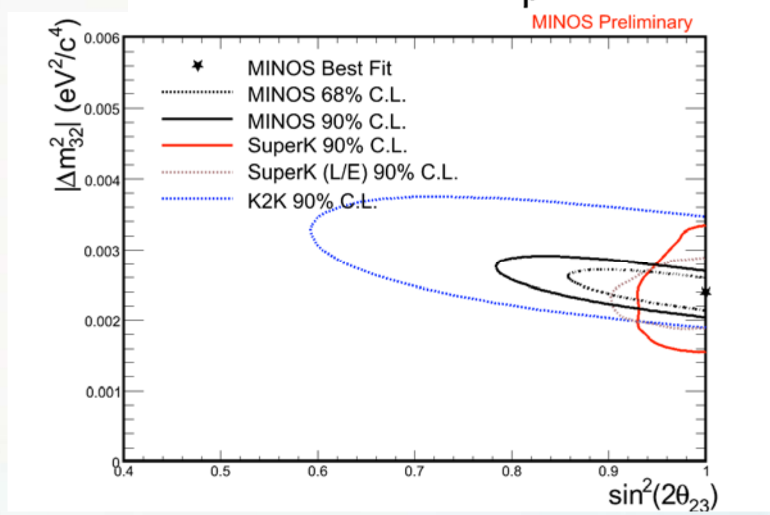
We Live in Precision Times…



	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1875	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	
σ^0_{had} [nb]	41.540 ± 0.037	41.477	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21586	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.374	
Γ_W [GeV]	2.140 ± 0.060	2.091	
m_t [GeV]	170.9 ± 1.8	171.3	







We Still Have Things to Do…

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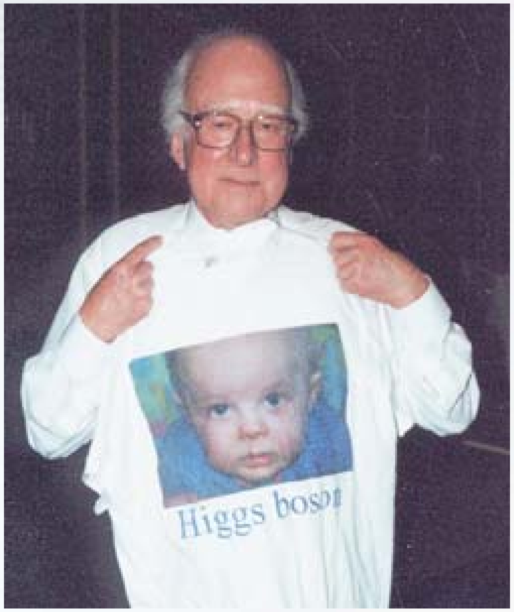
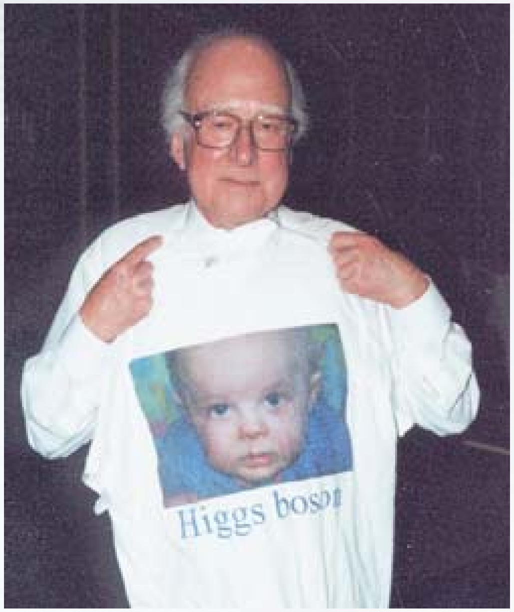


The only Higgs observed in Nature

We Still Have Things to Do…



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The only stop decay observed in Nature

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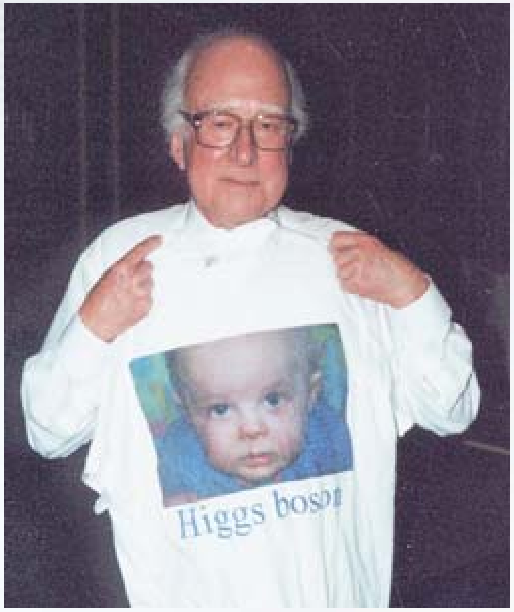

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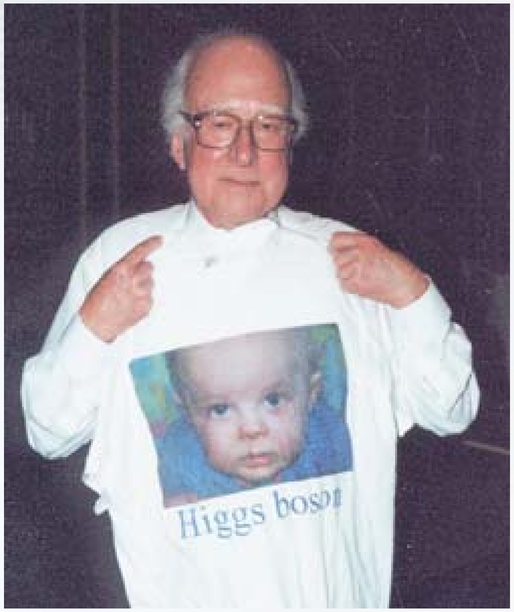

The only Higgs observed in Nature

The only dark matter observed in Nature

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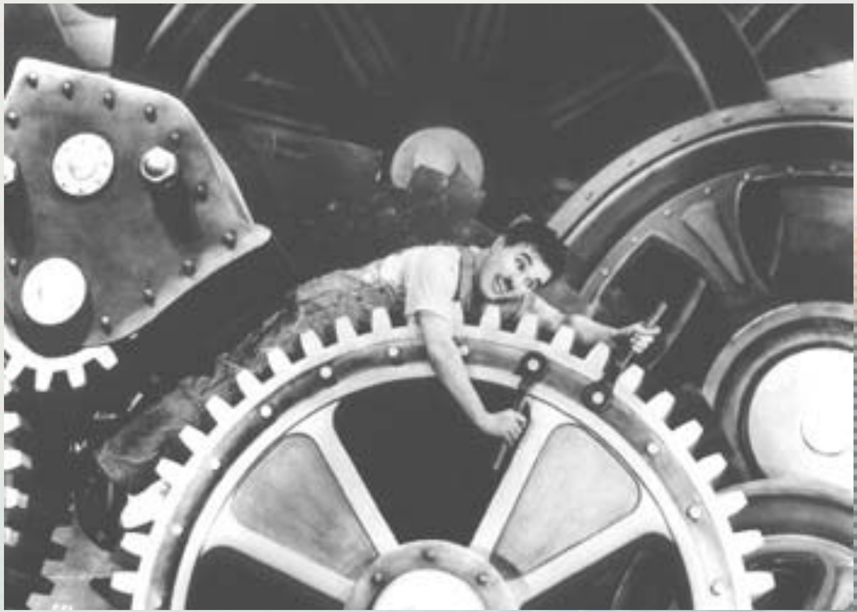
A lot of dark energy...

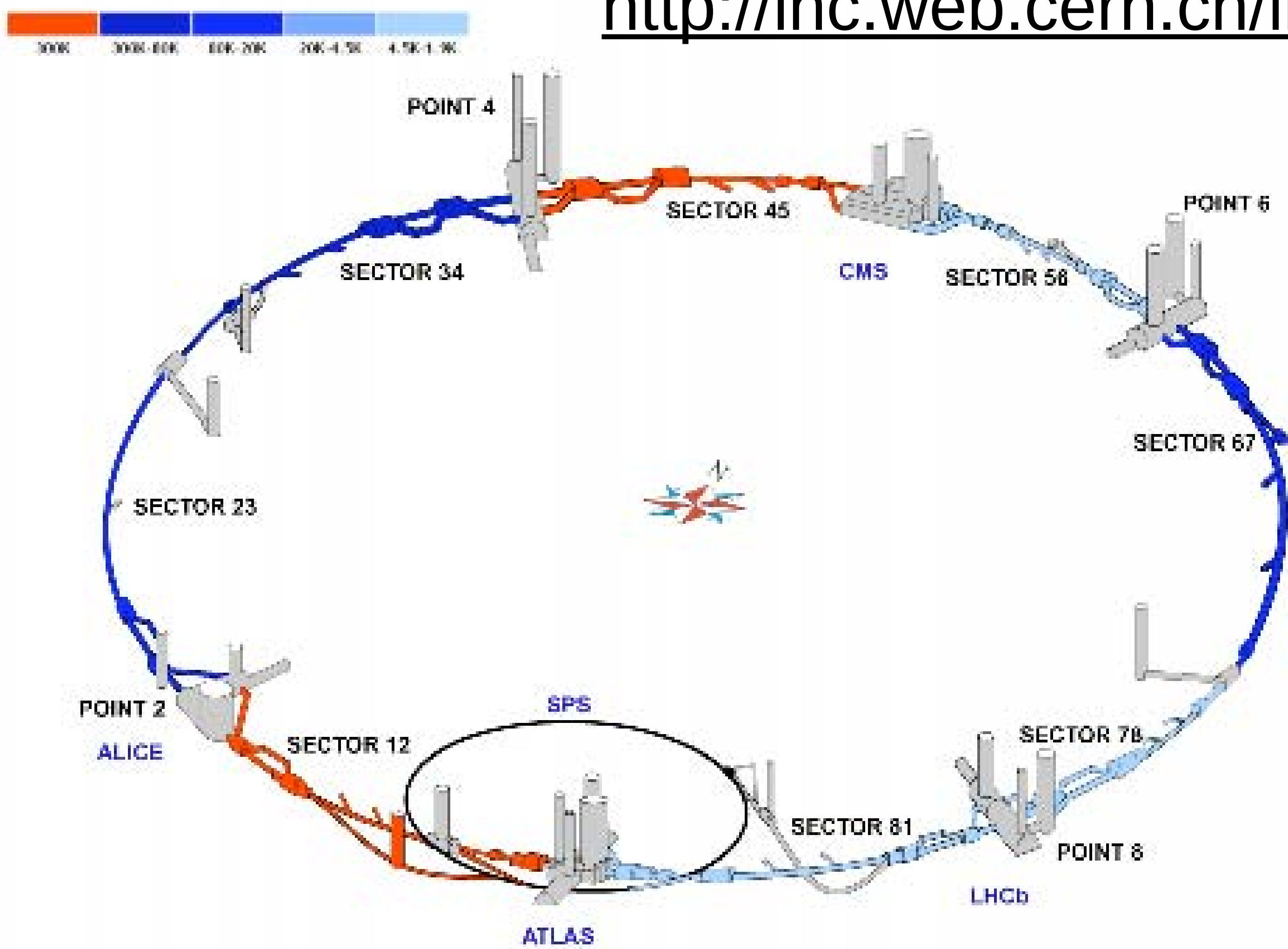
The Machine

The LHC



LHC Cooldown Status

http://lhc.web.cern.ch/lhc

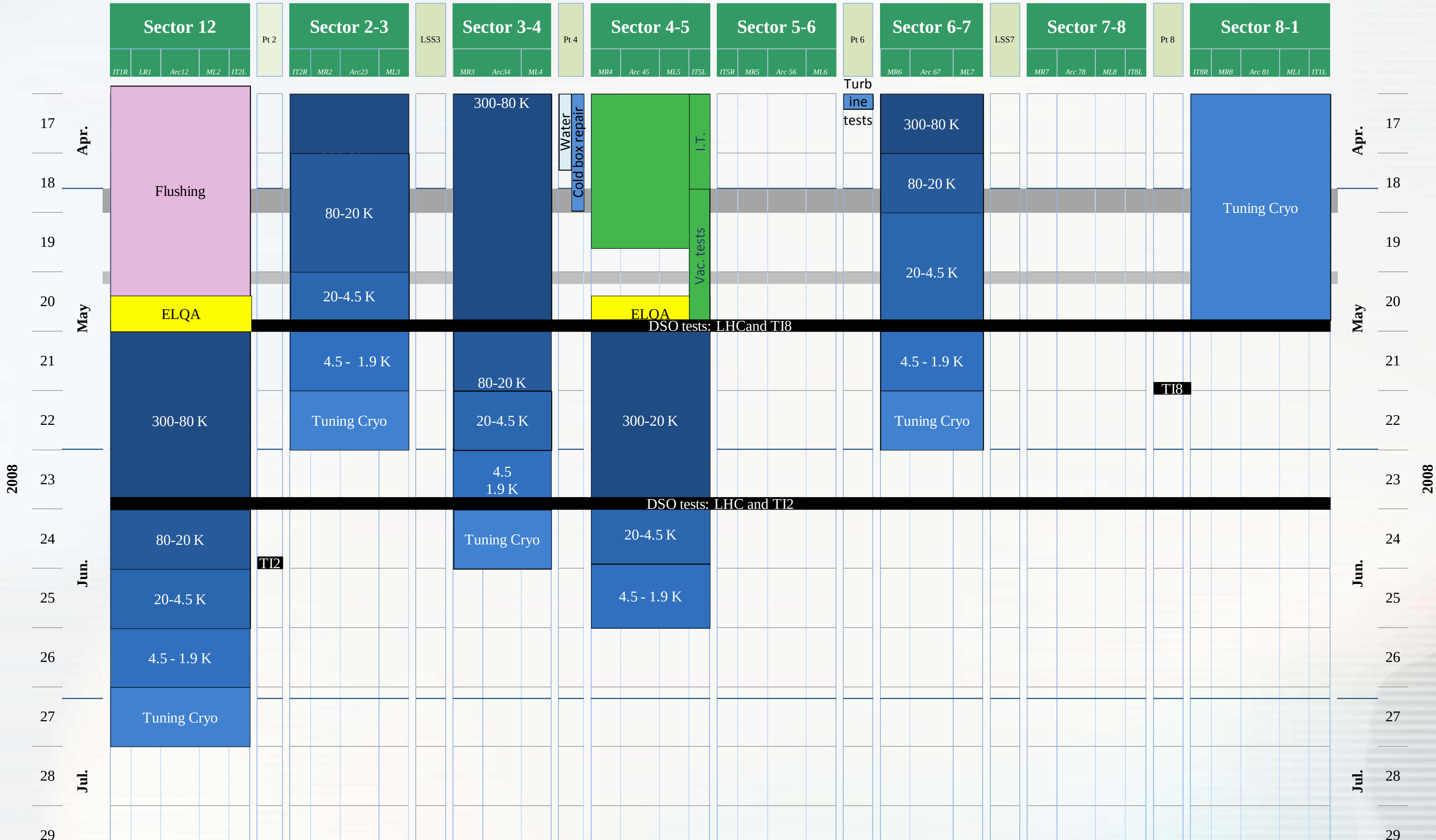


The LHC Schedule

K. Foraz - TS/ICC

General Coordination Schedule - wk.10 (update wk. 19)

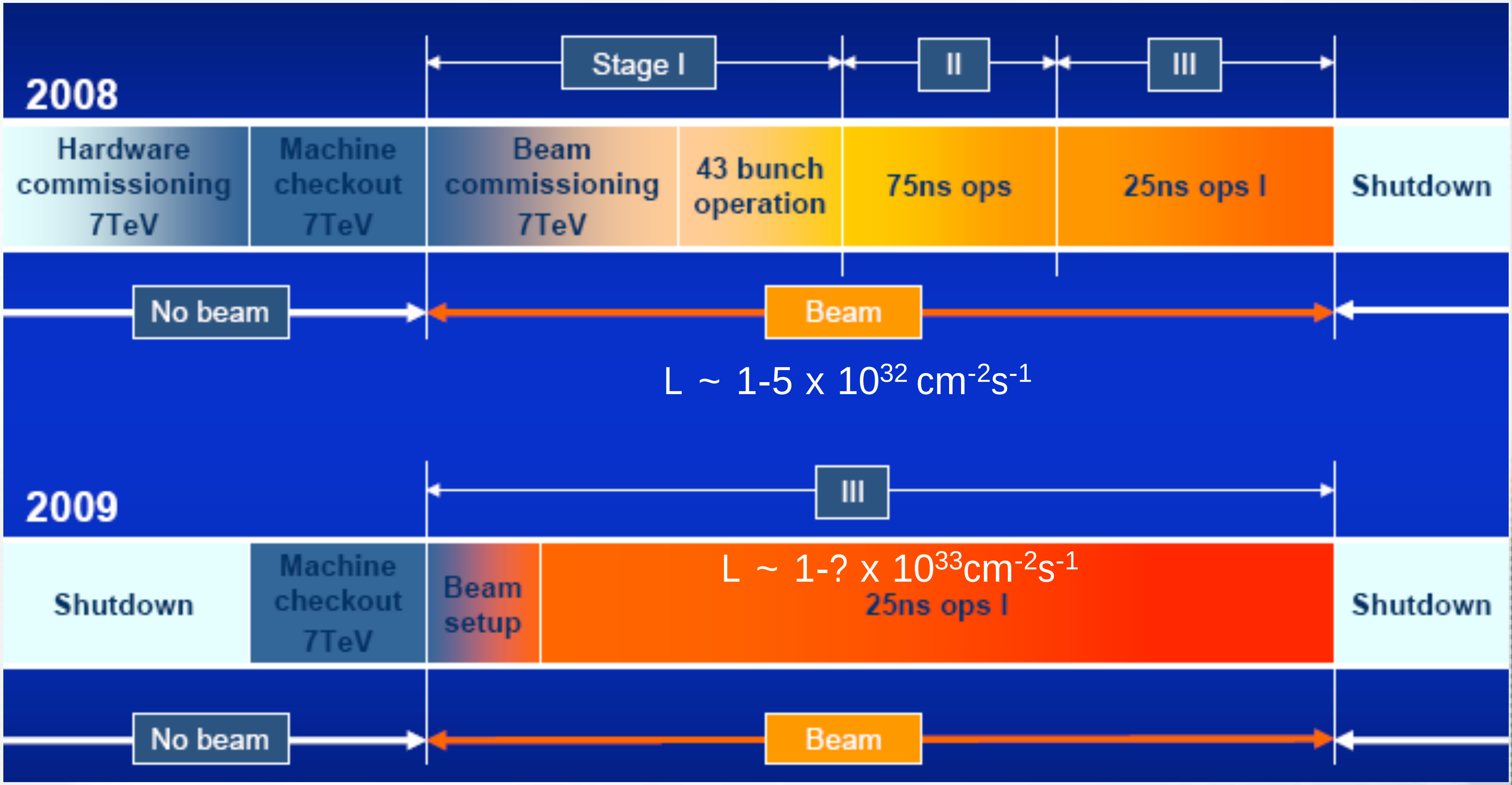
May 13, 2008



Despite a few annoying problems, the schedule has not changed!

The LHC Operation Stages

- First 10 TeV Collisions: ~ Fall 2008
- Effective ATLAS/CMS running time/year: ~1000 hours ~ 4 x 10^6 s ~ 4 x 10^{39} cm^{-2} = 4 x 10^{15} b^{-1} = 4 fb^{-1} @ 10^{33} $cm^{-2}s^{-1}$
- Expected luminosity: ~10-100 pb^{-1} in 2008; a few fb^{-1} in 2009



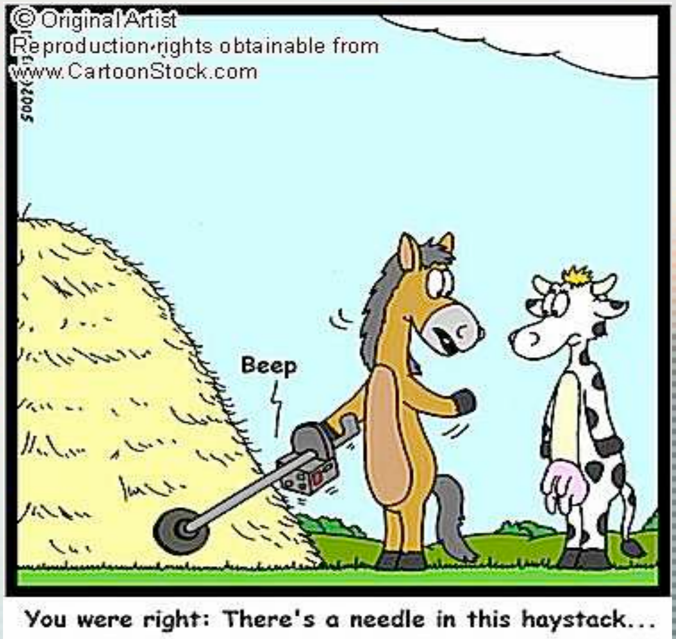
LHC Parameter Evolution

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

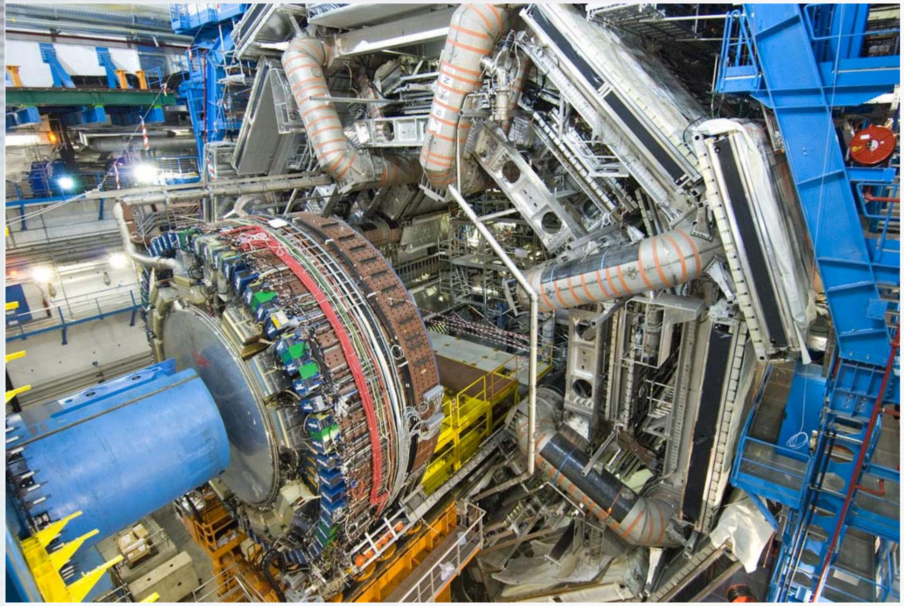
$$Eventrate / Cross = \frac{L \sigma_{TOT}}{k_b f}$$

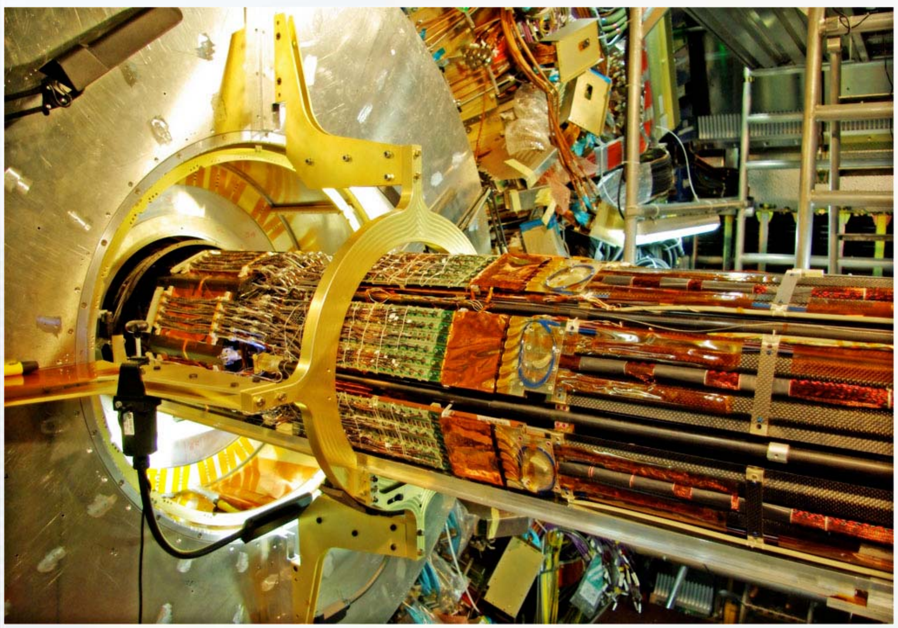
	Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
	k_b	N	β^* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
5 TeV	43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	1.4	$8.0\ 10^{29}$	<< 1	Depend on the configuration of collision pattern	
5 TeV	43	$4\ 10^{10}$	3	$1.7\ 10^{12}$	1.4	$2.9\ 10^{30}$	0.36		
5 TeV	156	$4\ 10^{10}$	3	$6.2\ 10^{12}$	5	$1.0\ 10^{31}$	0.36		
5 TeV	156	$9\ 10^{10}$	3	$1.4\ 10^{13}$	11	$5.4\ 10^{31}$	1.8		
7 TeV	936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
7 TeV	936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
7 TeV	936	$6\ 10^{10}$	2	$5.6\ 10^{13}$	63	$2.9\ 10^{32}$	1.6	$6.0\ 10^{31}$	0.34
7 TeV	936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76
7 TeV	2808	$4\ 10^{10}$	11	$1.1\ 10^{14}$	126	$7.2\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
7 TeV	2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
7 TeV	2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
7 TeV	2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24

The Detectors

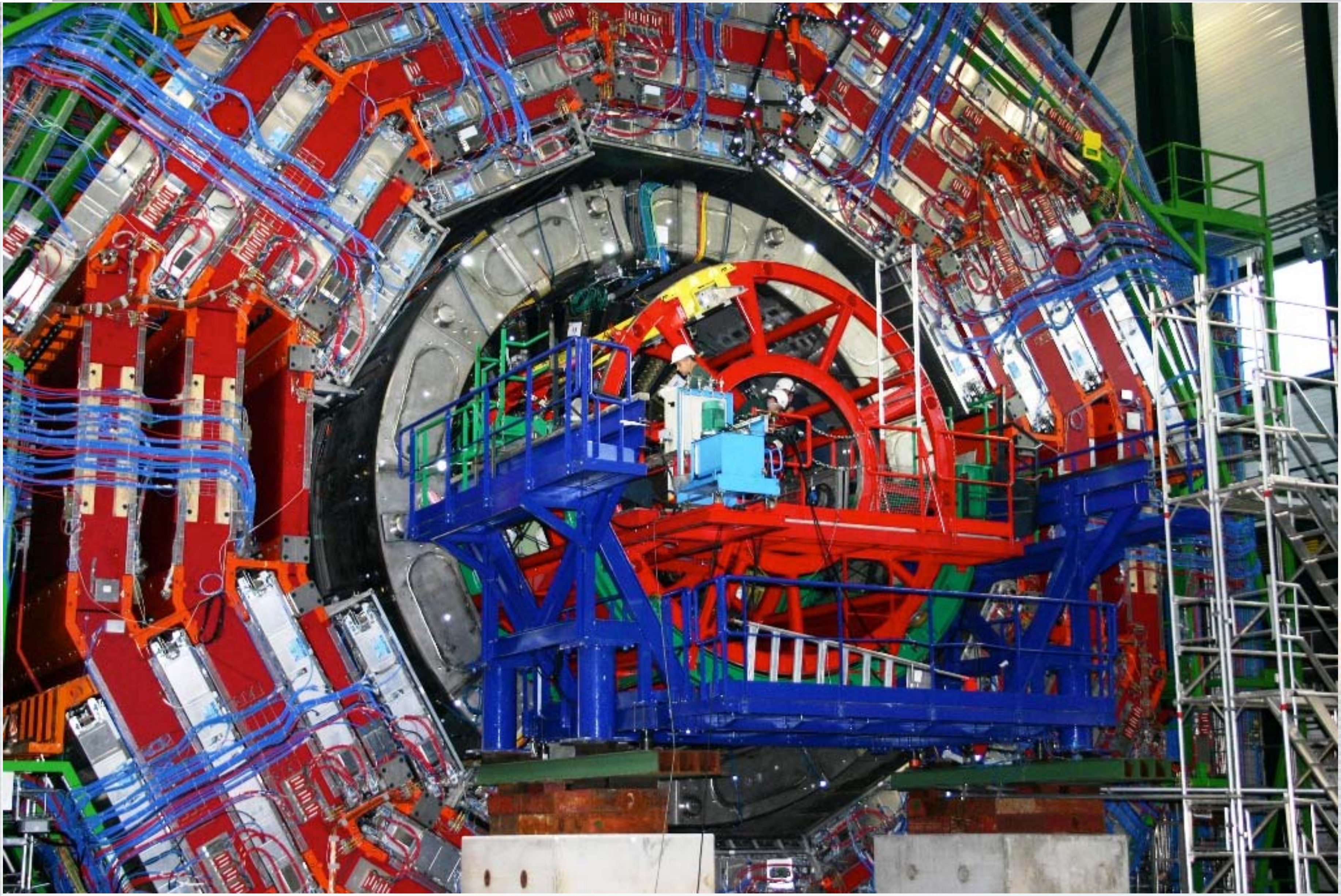


ATLAS Now

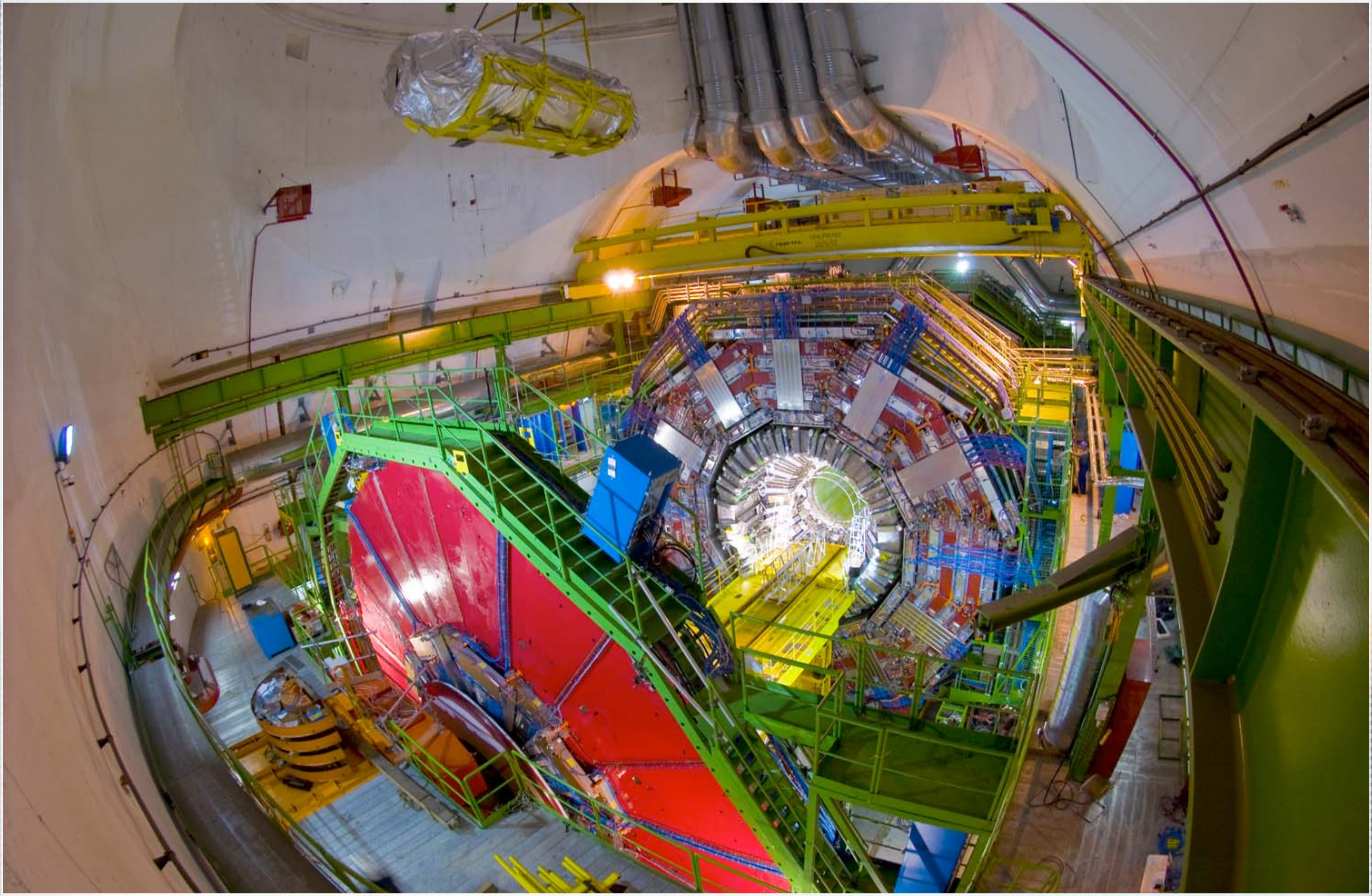




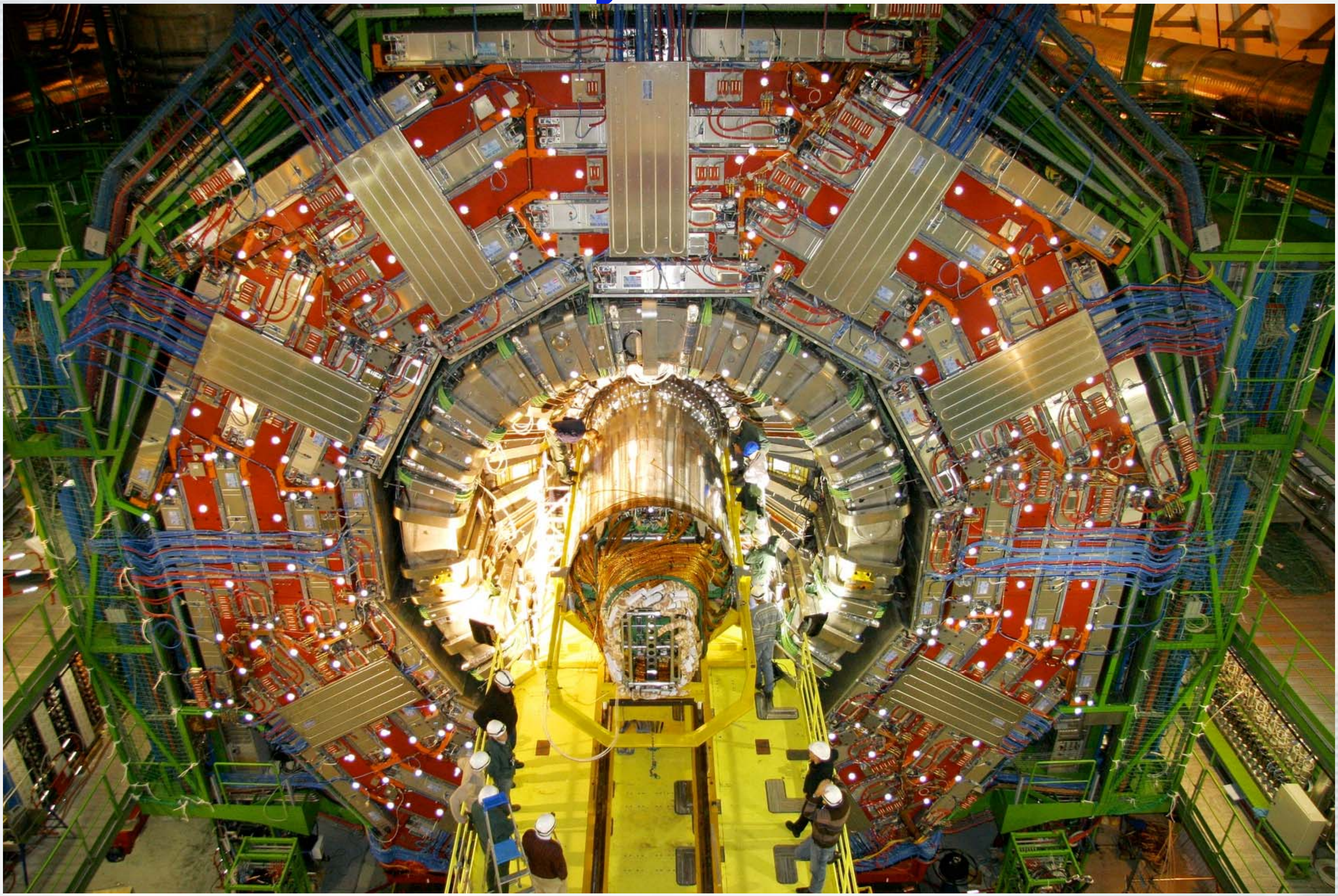
CMS - 2006



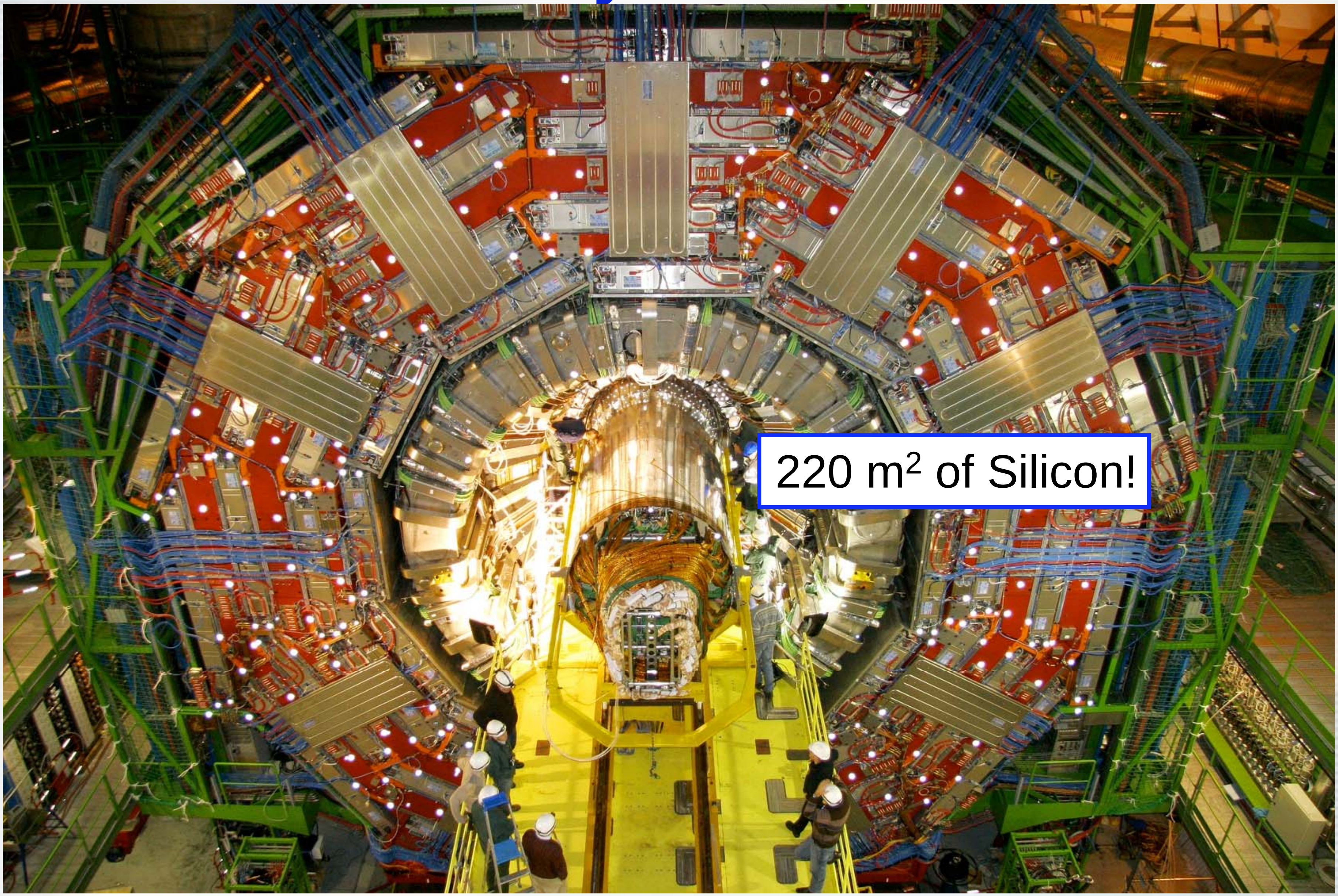
CMS in December, 2007



CMS in January

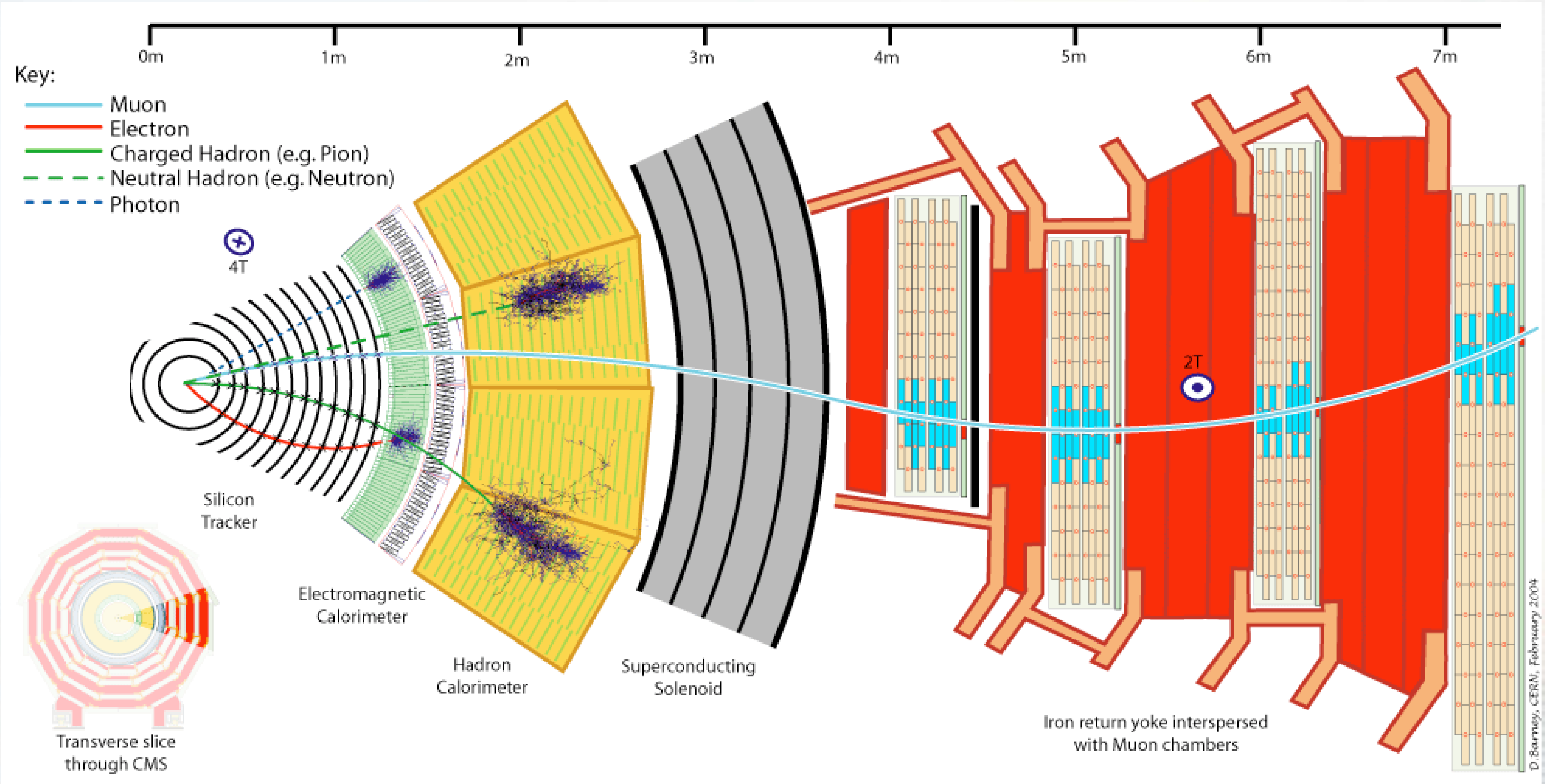


CMS in January



Detector Concept

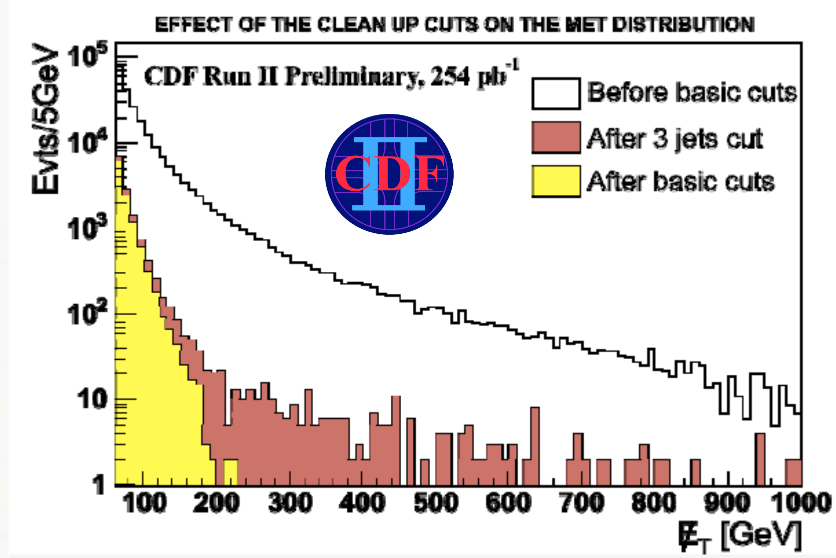
- Nearly 4π, hermetic, redundant, Russian-doll design

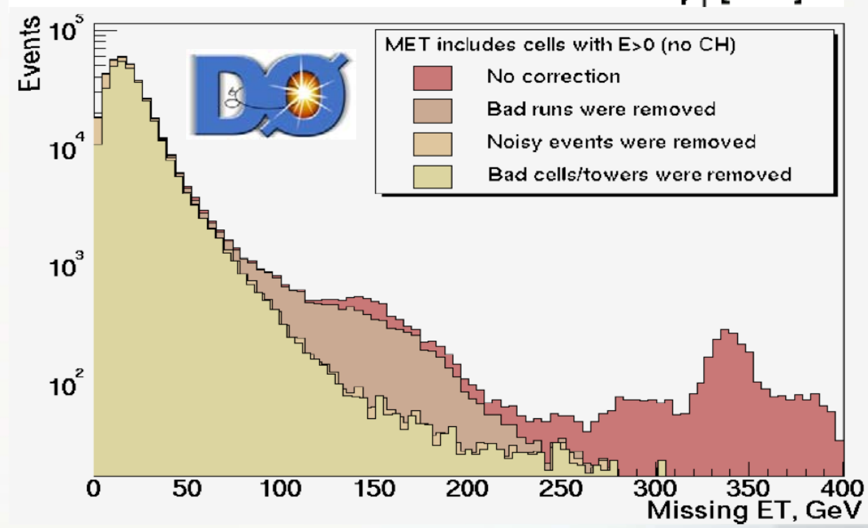


The Tale of ME_T

Why ME_T is Tough?

- Fake ME_T appears naturally in multijet events, which have enormous rate at the LHC
- Jets tend to fluctuate wildly:
  - Large shower fluctuation
  - Fluctuations in the e/h energy ratio
  - Non-linear calorimeter response
  - Non-compensation (i.e., $e/h \neq 1$)
- Instrumental effects:
  - Dead or "hot" calorimeter cells
  - Cosmic ray bremsstrahlung
  - Poorly instrumented area of the detector
- Consequently, it will be a challenge to use in early LHC running
- Nevertheless, MET is one of the most prominent signatures for new physics and thus must be pursued





- Raw ME_T spectrum at the Tevatron and that after thorough clean-up

ME_T Reconstruction and Performance

- Missing E_T is based on the calorimeter information and defined as a 2D-vector sum of transverse energy deposits in the calorimeter cells:

$$\vec{\not{E}}_T = -\sum_n (E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) = -\not{E}_x \hat{\mathbf{i}} - \not{E}_y \hat{\mathbf{j}}$$

- In case of muons in the event, it receives an additional correction:

$$\vec{\not{E}}_T = -\sum_{i=1}^{\text{towers}} \vec{E}_T^i - \sum^{\text{muons}} \vec{p}_T^{\,\mu} + \sum_{i=1}^{\substack{\text{deposit}\\ \text{towers}}} \vec{E}_T^i.$$

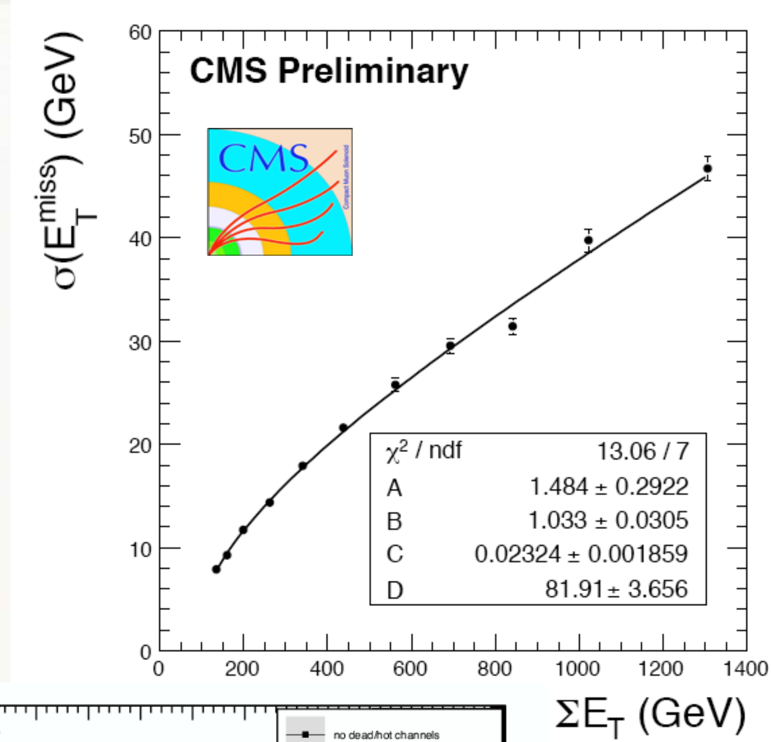
- ME_T resolution in QCD events depends on total energy deposit in the calorimeter and is often parameterized as a function of scalar E_T sum over the calorimeter cells, or S_T:

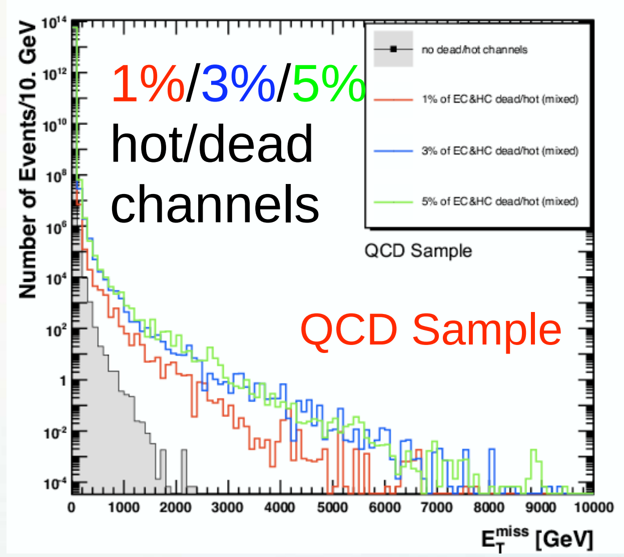
$$\sigma(\not{E}_T) = A \oplus B\sqrt{\Sigma E_T - D} \oplus C(\Sigma E_T - D)$$

Noise Stochastic Constant Offset

ME_T in CMS

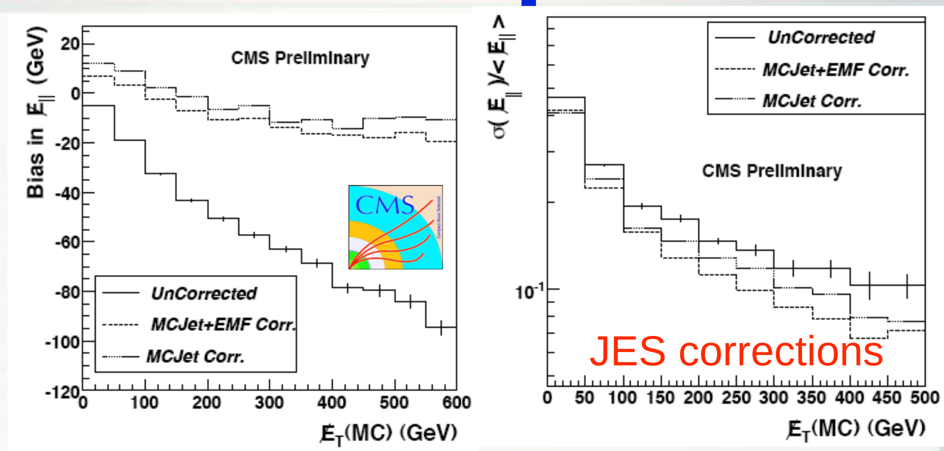
- Parameters:
  - A = 1.48 GeV
  - B = 1.03 GeV$^{1/2}$
  - C = 0.023 (dominates at large S_T)
  - D = 82 GeV
- Apart from the resolution an important characteristic is the non-Gaussian tails
- Very hard to simulate; will have to wait for real data to see how large the effect is
  - A few special cases have been looked at already, e.g. the effect of hot/dead channels

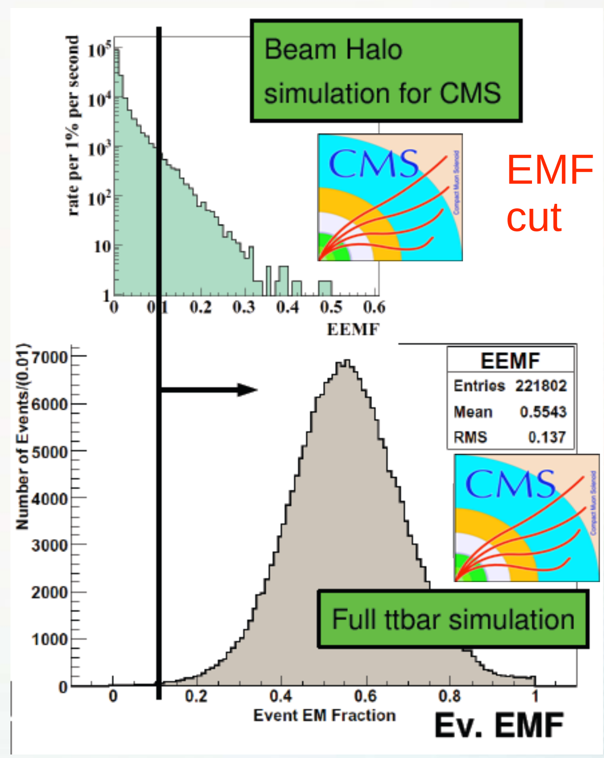




ME_T Corrections and Clean-Up

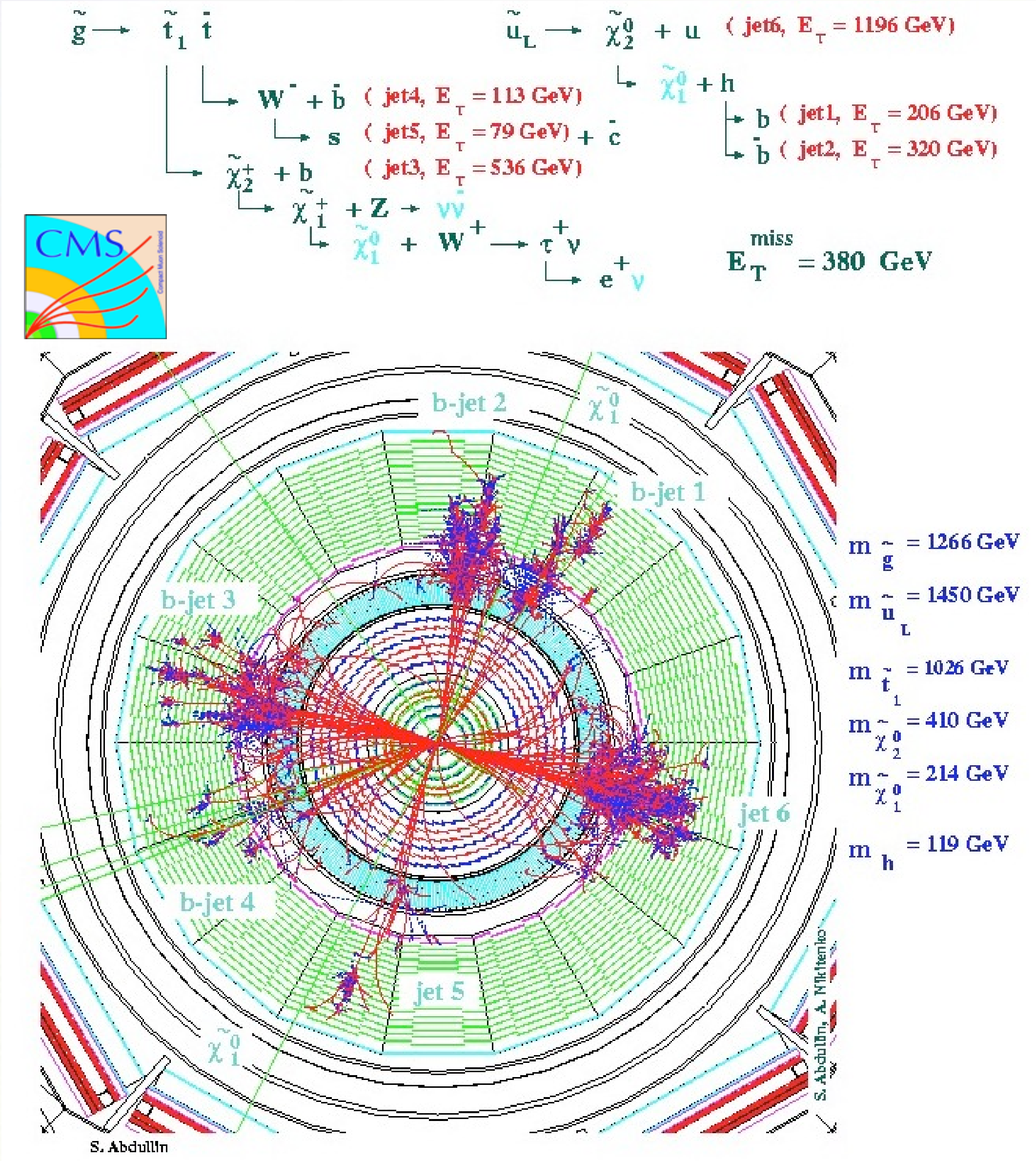
- To improve the resolution and remove possible bias for events with true ME_T, we correct ME_T for
  - Jet energy scale
  - Hadronic tau's
  - Muons
- The non-Gaussian tails are reduced by jet quality cuts, e.g. p_T/E_T or EMF
- Philosophy: make ME_T look as good as possible





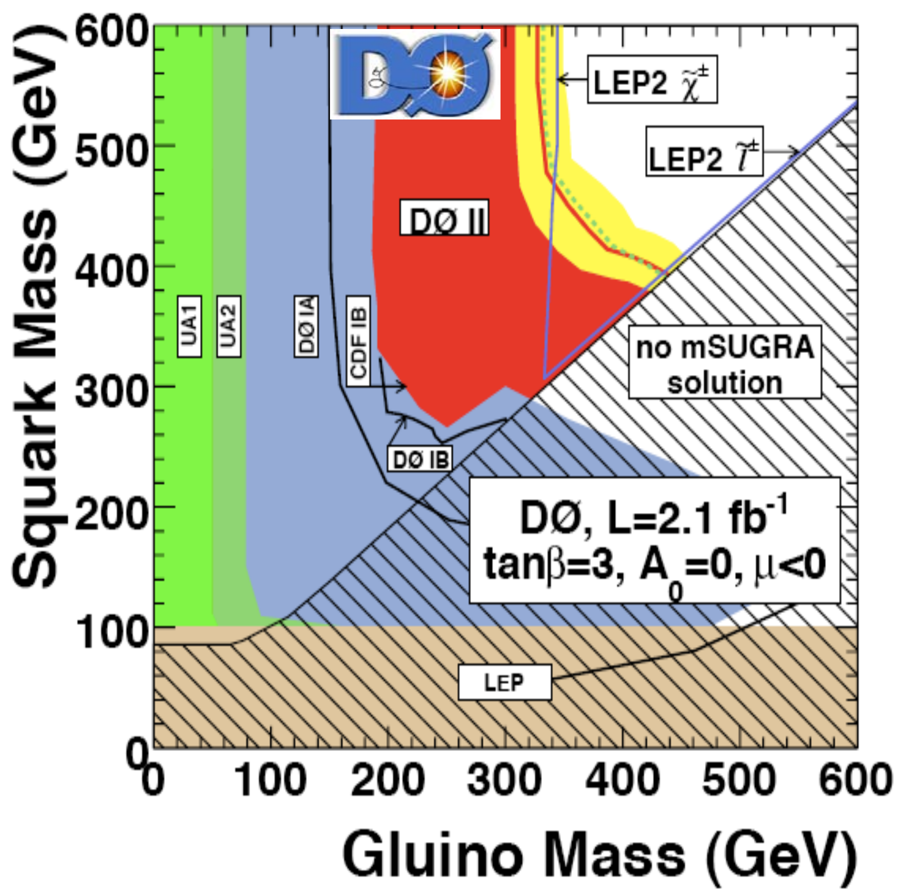
Example 1: SUSY in Jets + ME_T

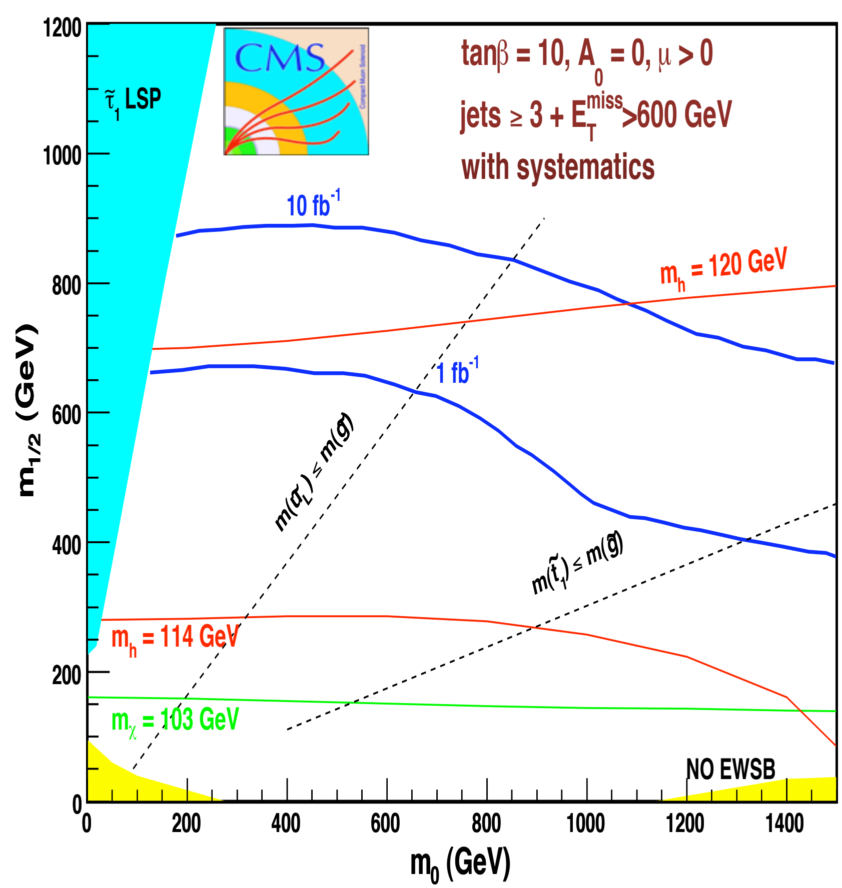
Strong Production, Complicated Events



Possibility for an Early Discovery

- Even with a handful of statistics the reach will be expanded dramatically compared to the Tevatron limits





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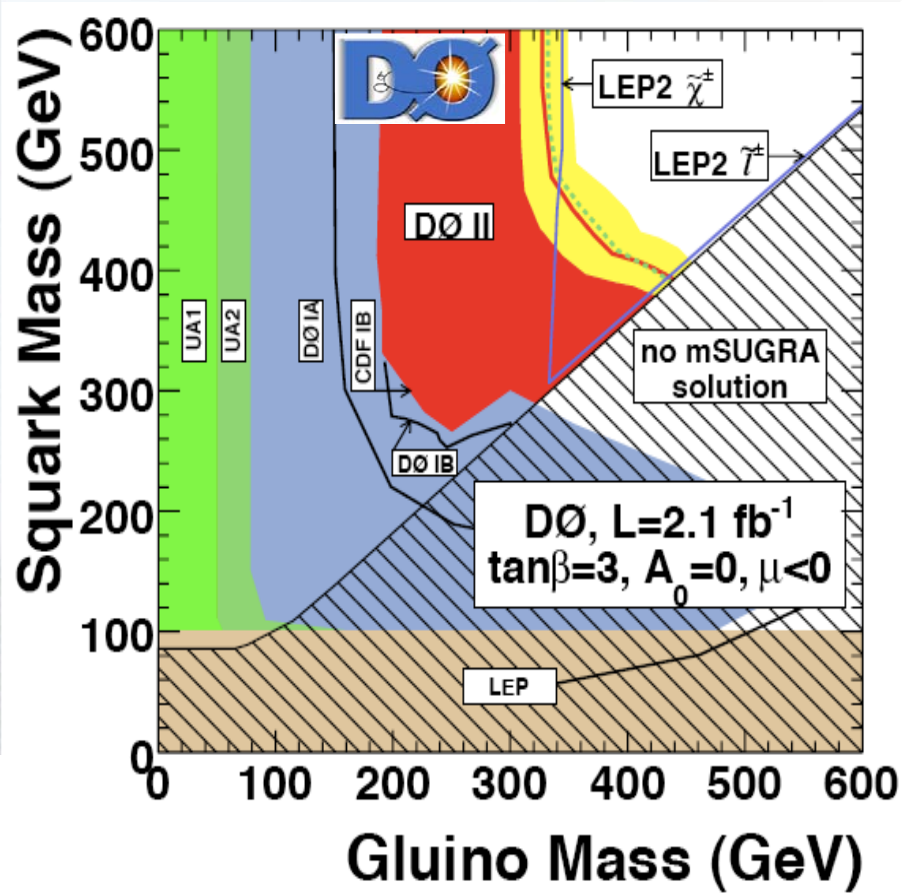
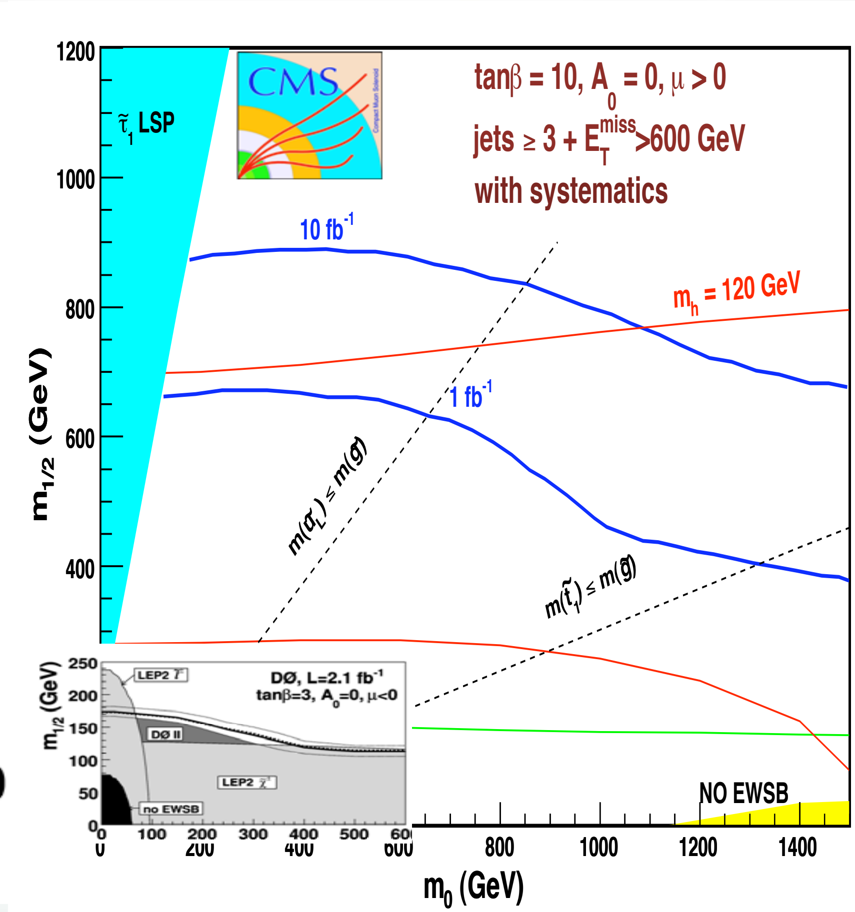
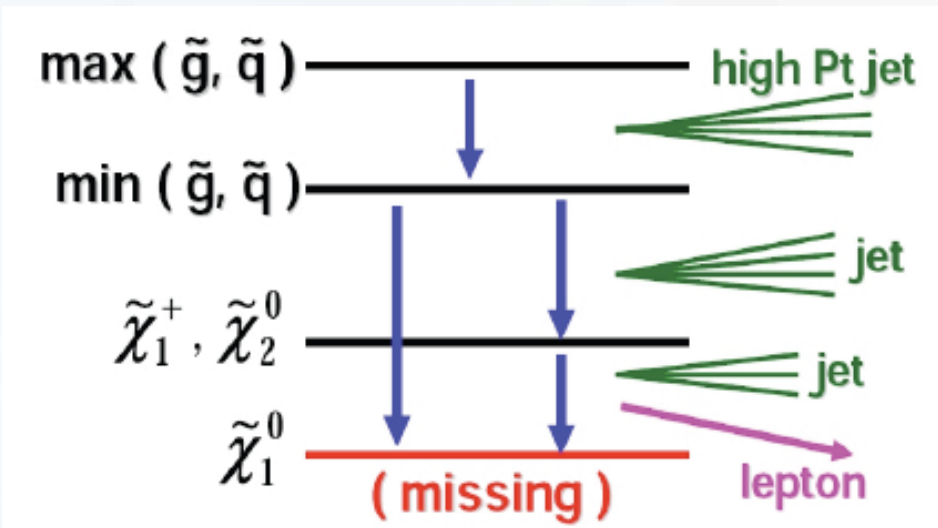
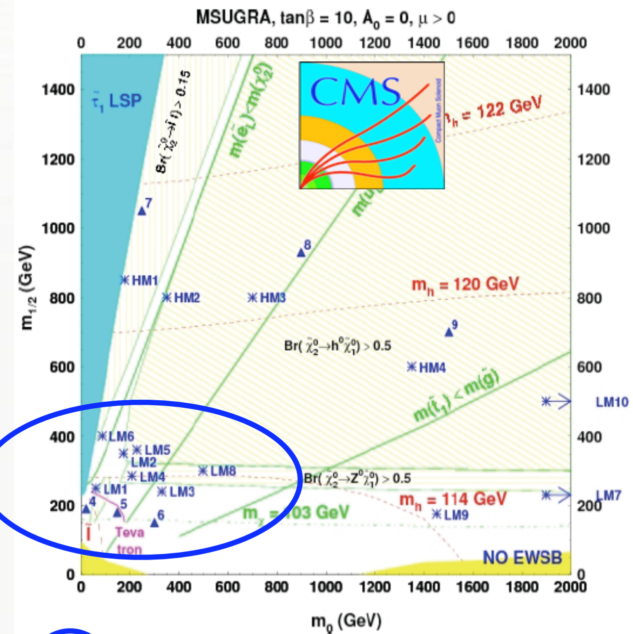




SUSY Event Selection

- Focus on low-mass SUSY points
- Jets and ME_T always present; no hit for leptonic branching fraction



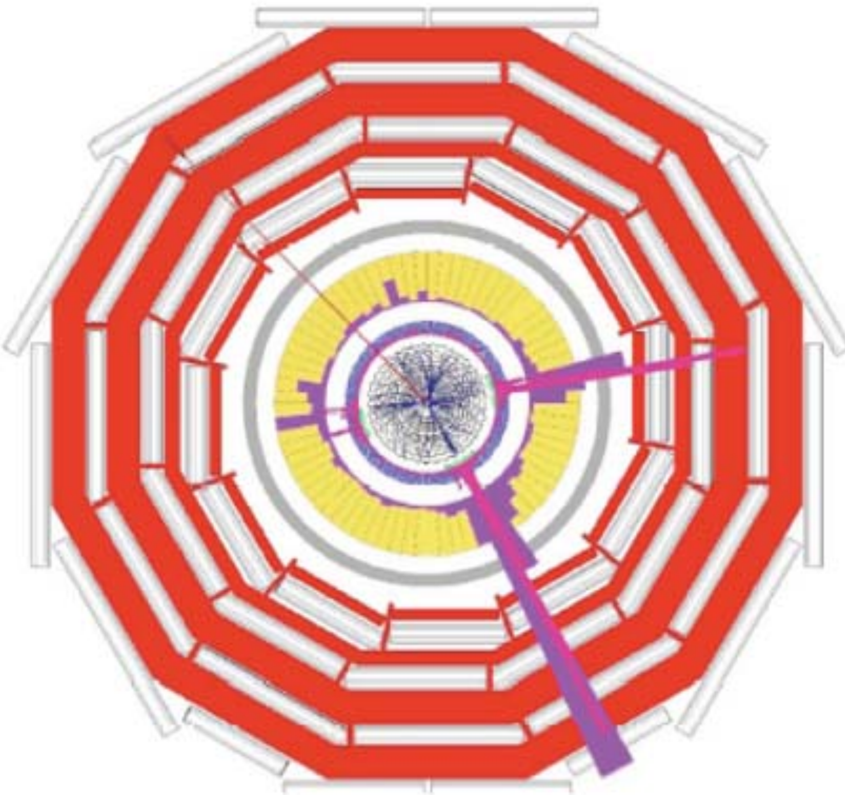


ME_T > 200 GeV

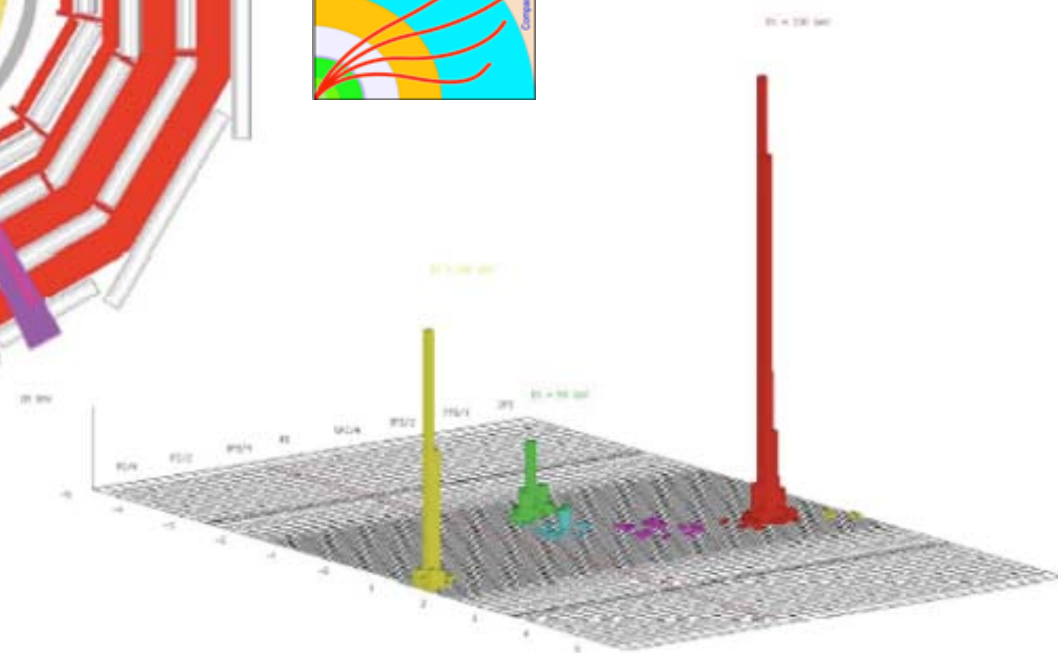
$N_j \geq 3, \lvert\eta_d^{1j}\rvert < 1.7$	signal signature
$\delta\phi_{min}(E_T^{miss} - jet) \geq 0.3$ rad, $R1, R2 > 0.5$ rad, $\delta\phi(E_T^{miss} - j(2)) > 20°$	QCD rejection
$Iso^{lead\ trk} = 0$	ILV (I) $W/Z/t\bar{t}$ rejection
$f_{em(j(1))}, f_{em(j(2))} < 0.9$	ILV (II), $W/Z/t\bar{t}$ rejection
$E_{T,j(1)} > 180$ GeV, $E_{T,j(2)} > 110$ GeV	signal/background optimisation
$H_T \equiv E_{T(2)} + E_{T(3)} + E_{T(4)} + E_T^{miss} > 500$ GeV	signal/background optimisation
SUSY LM1 signal efficiency 13%	

Point	m_0	$m_{1/2}$	$\tan\beta$	sgn(μ)	A_0
LM1	60	250	10	+	0
LM2	185	350	35	+	0
LM3	330	240	20	+	0
LM4	210	285	10	+	0
LM5	230	360	10	+	0
LM6	85	400	10	+	0
LM7	3000	230	10	+	0
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0
LM10	3000	500	10	+	0
HM1	180	850	10	+	0
HM2	350	800	35	+	0
HM3	700	800	10	+	0
HM4	1350	600	10	+	0

A Typical SUSY Event

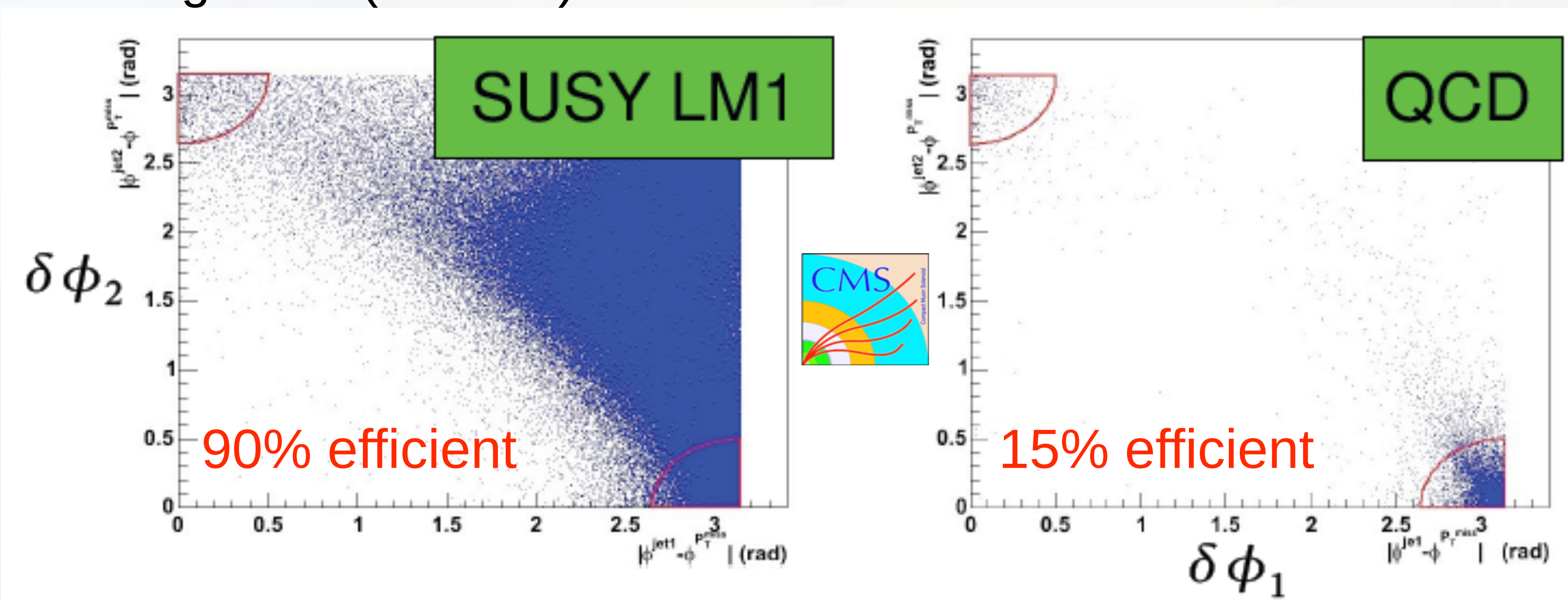


- A SUSY candidate event :
  - Leading jets ET = 330, 140, 60 GeV
  - MET = 360 GeV



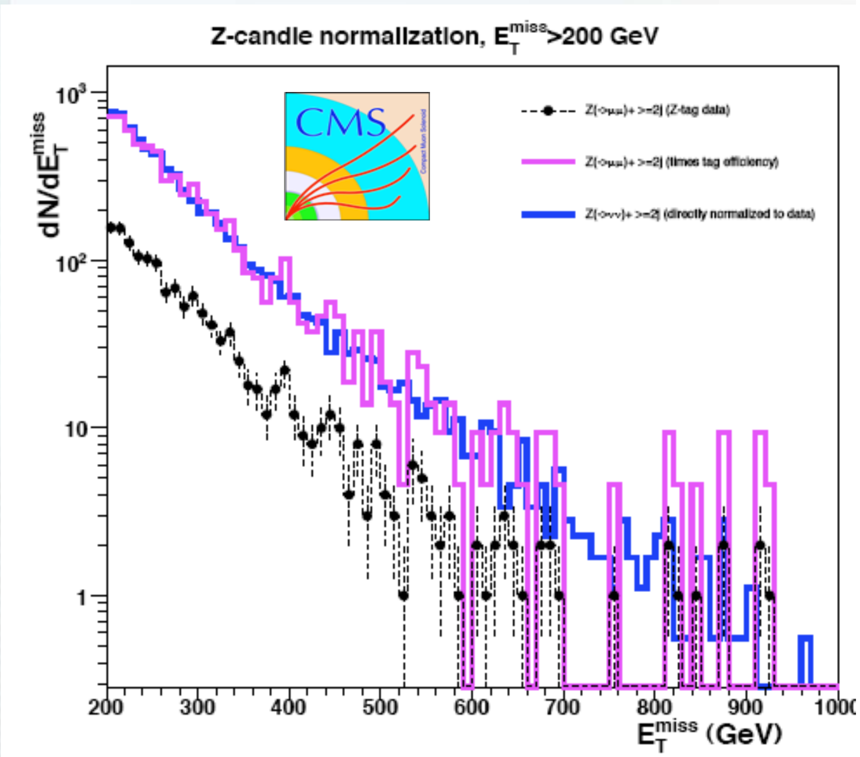
QCD Background Rejection

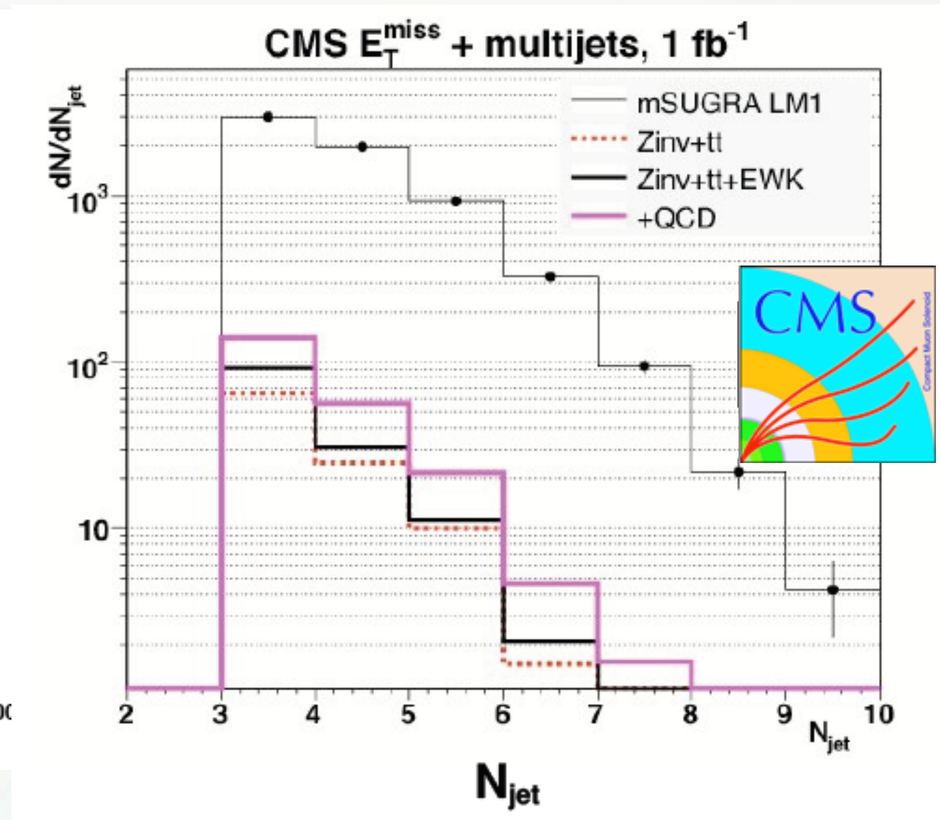
- The dominant background is QCD multijet production with fake ME_T
- Can be effectively reduced by requiring the minimum angular separation between the ME_T vector and the direction of jet 1 (leading) or jet 2 (subleading)
- Use extrapolation from low MET region to estimate residual background (a la DØ)



Z(νν) + Jets: Estimate from Data

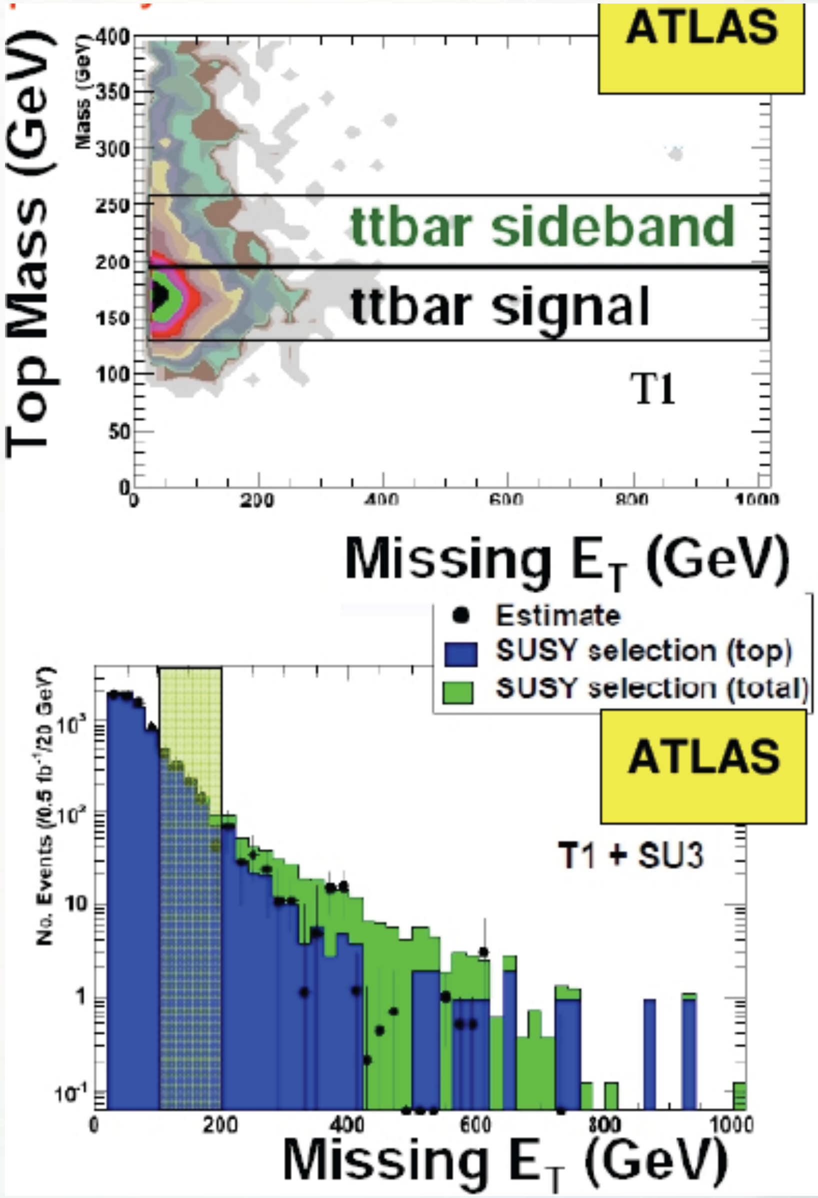
- Use Z(ee) and Z(μμ) + jets for normalization; acceptance corrections via MC
- Necessary since the signal and background shapes are similar





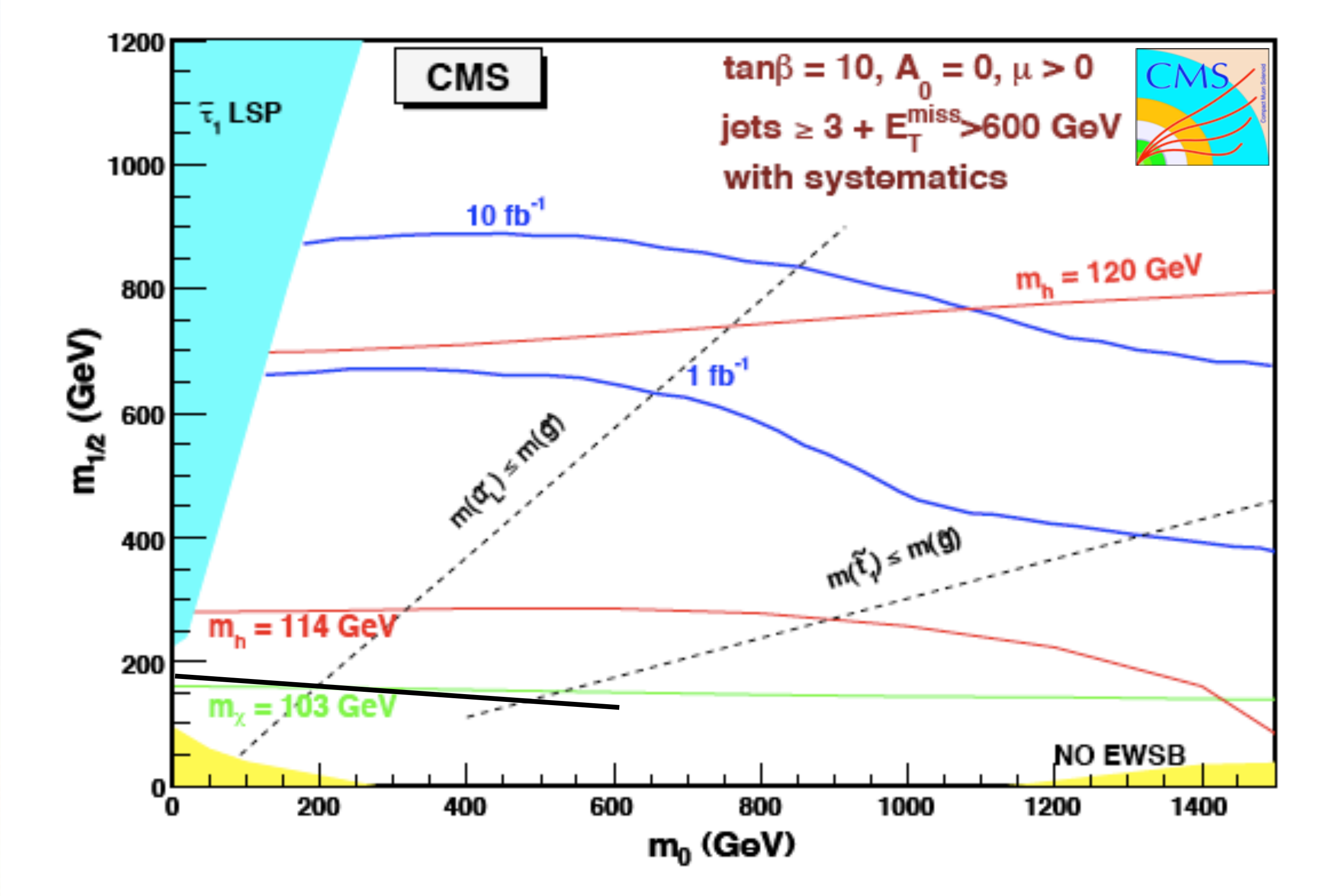
tt Background

- Estimating tt background from data is a high-priority task
- Important to find a variable, reasonably uncorrelated with the ME_T
- Top mass can be used as such a variable (ATLAS method)
- Use upper tt-mass sideband and normalize in the low ME_T region



Reach

- Significant reach with as low as ~100 pb^{-1}



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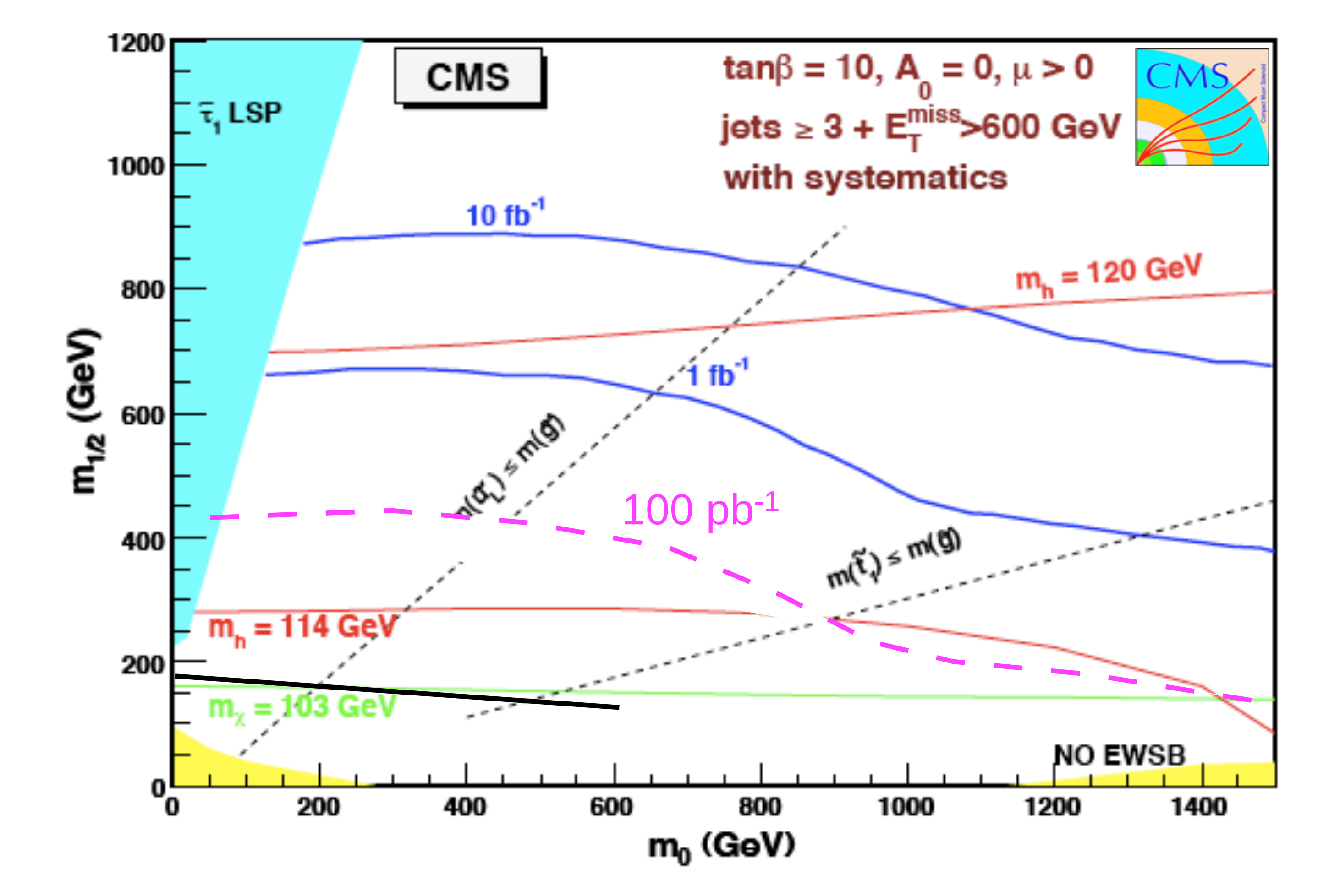
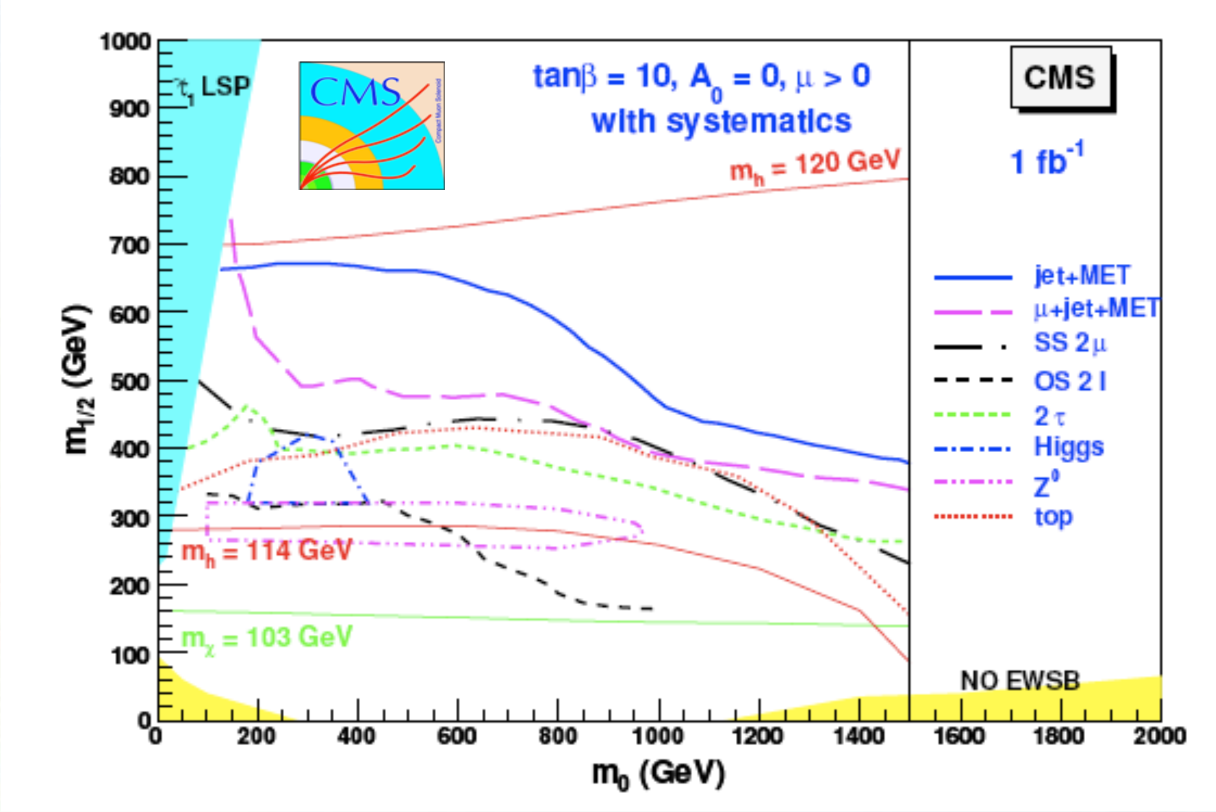
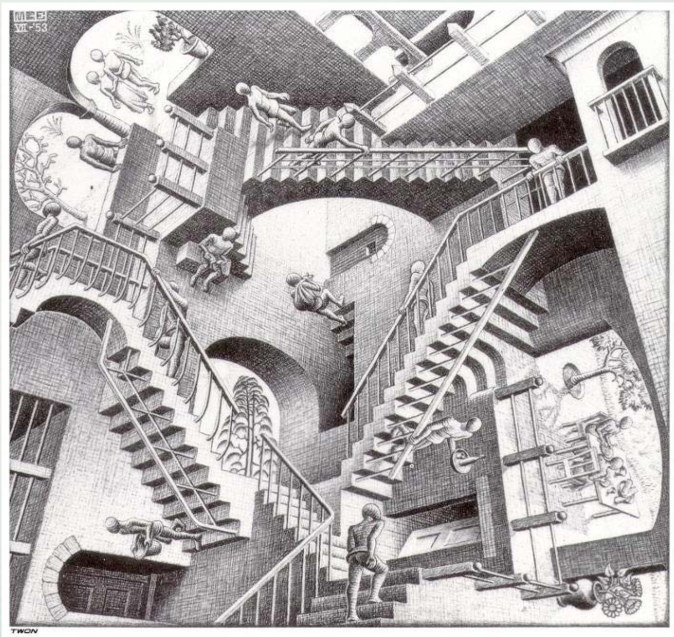


Other SUSY Channels

- Clearly, a number of channels will be investigated in parallel, including lepton+jets, like- and opposite-sign dileptons, channels with tau's, and MSSM Higgs searches
- Sensitivity in all these channels is being reevaluated using most realistic simulation available
- Previous studies suggest that the best reach is achieved in inclusive channels



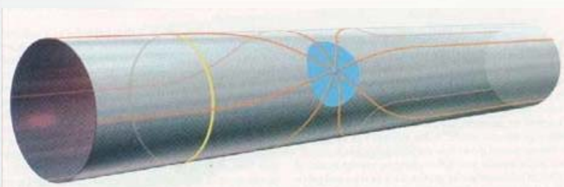
Example 2: Extra Dimensions in Space



Extra Dimensions: a Brief Recap

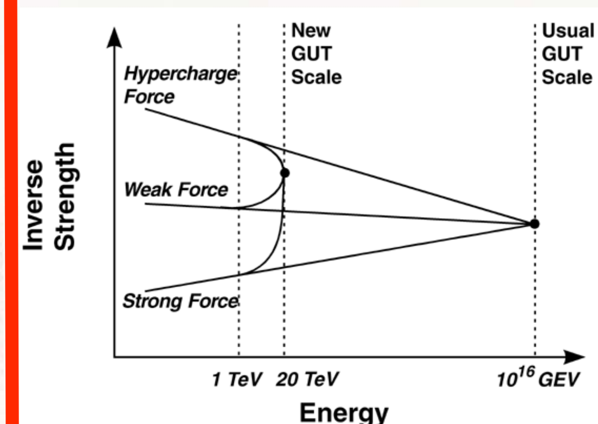
ADD Paradigm:

- Pro: “Eliminates” the hierarchy problem by stating that physics ends at a TeV scale
- Only gravity lives in the “bulk” space
- Size of ED’s (n=2-7) between ~100 μm and ~1 fm
- Black holes at the LHC and in the UHE cosmic rays
- Con: Doesn’t explain why ED are so large



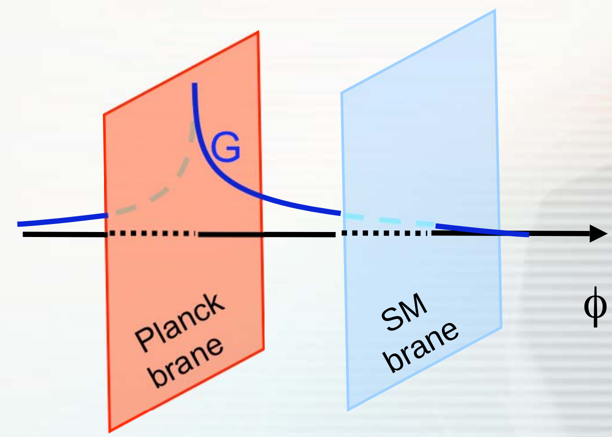
TeV^{-1} Scenario:

- Pro: Lowers GUT scale by changing the running of couplings
- Only gauge bosons (g/γ/W/Z) “live” in ED’s
- Size of ED’s ~1 TeV^{-1} or ~10^{-19} m – i.e., natural EWSB size
- Con: Gravity is not in the picture



RS Model:

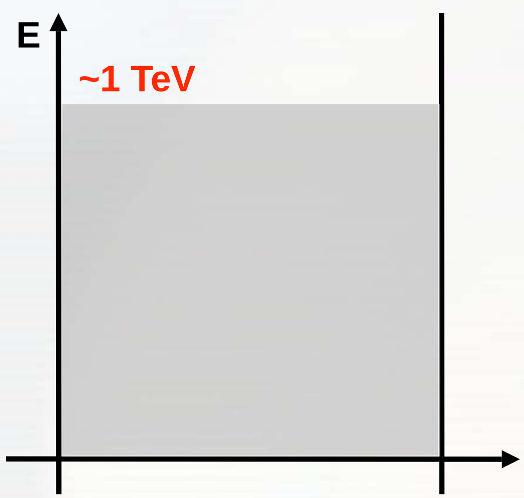
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

ADD Paradigm:

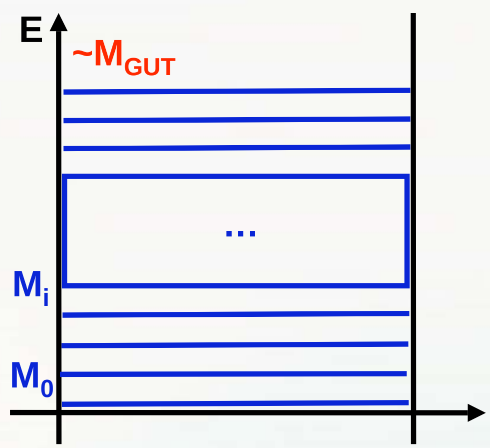
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



TeV^{-1} Scenario:

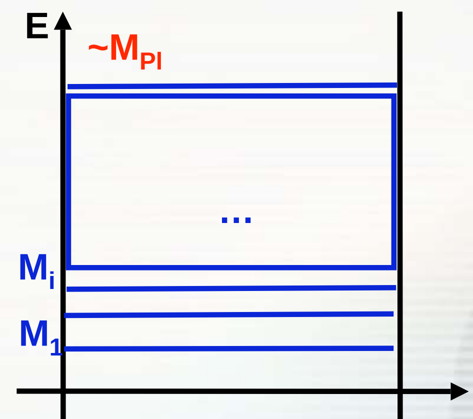
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~ 1 TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_w per mode

$$M_i = \sqrt{M_0^2 + i^2/r^2}$$



RS Model:

- "Particle in a box" with special AdS metric
- Energy eigenvalues are given by the zeroes of Bessel function J_1
- Light modes might be accessible at colliders
- Coupling: G_N for the zero mode; $1/\Lambda_\pi^2$ for the others



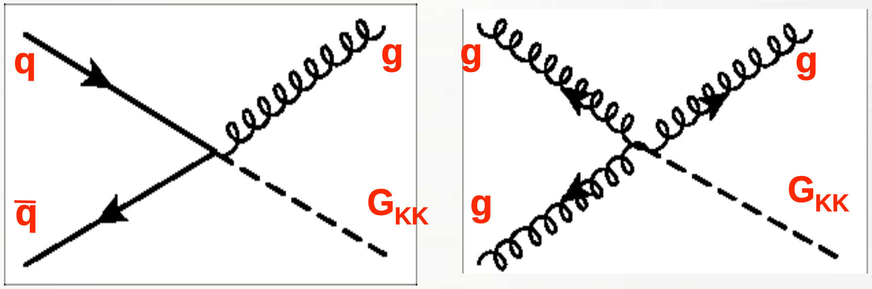
$$M_0 = 0;\; M_i = M_1 \frac{x_i}{x_1} \approx M_1,\; 1.83M_1,\; 2.66M_1,\; 3.48M_1,\; \ldots$$

Collider Signatures for Large ED

- Kaluza-Klein gravitons couple to the energy-momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang [PRD **59**, 105006 (1999)]
  - Giudice, Rattazzi, Wells [NP **B544**, 3 (1999)]
- Graviton emission: direct sensitivity to the fundamental Planck scale M_D
- Virtual effects: sensitive to the ultraviolet cutoff M_S, expected to be ~M_D (and likely < M_D)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders



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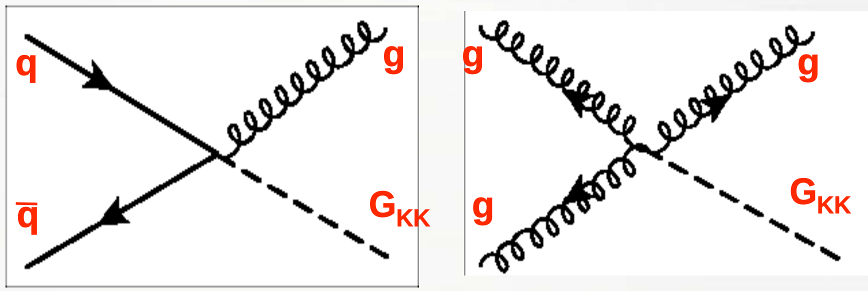
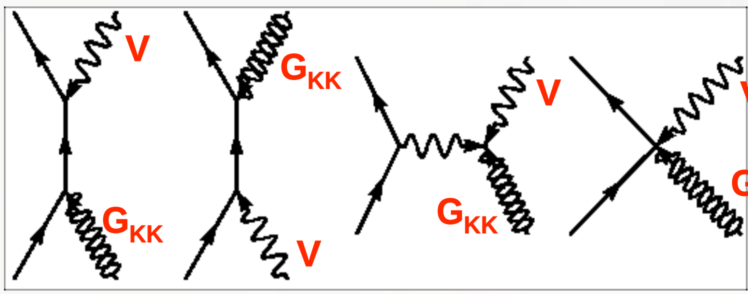


Single VB at hadron or e^+e^- colliders



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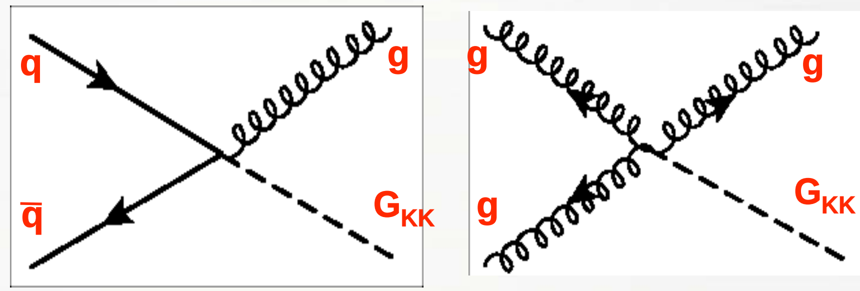

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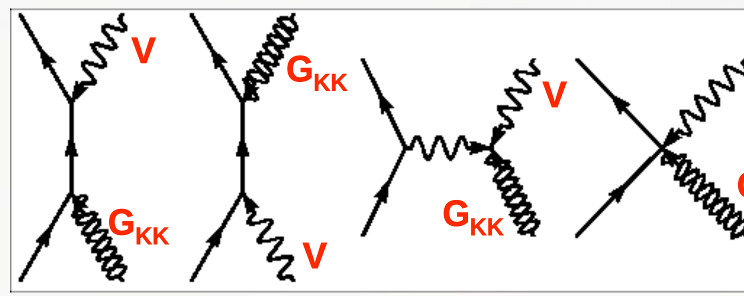
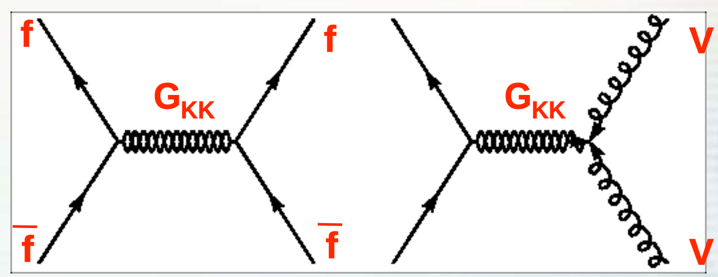


Virtual Graviton Effects

Fermion or VB pairs at hadron or e^+e^- colliders



Monojets: Tainted History

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

[PL, **139B**, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

Abstract

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

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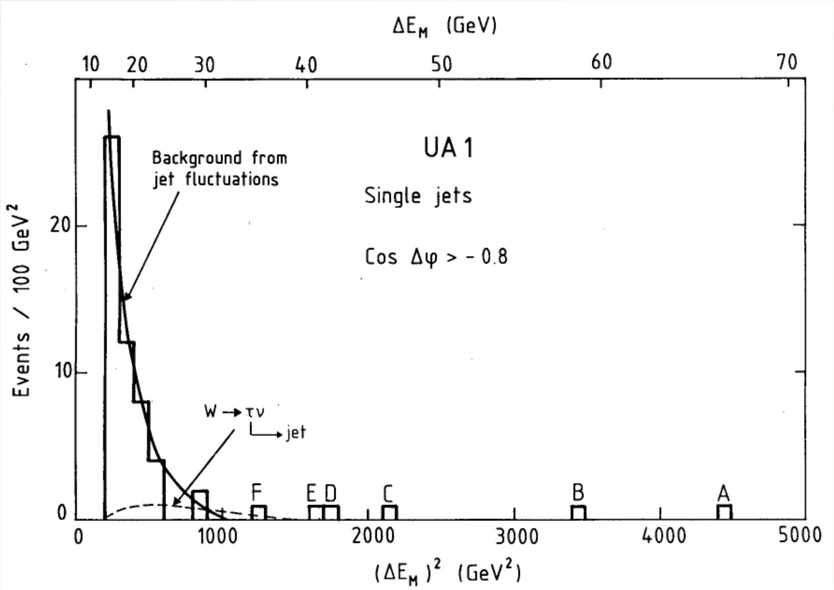
VOLUME 54, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1985

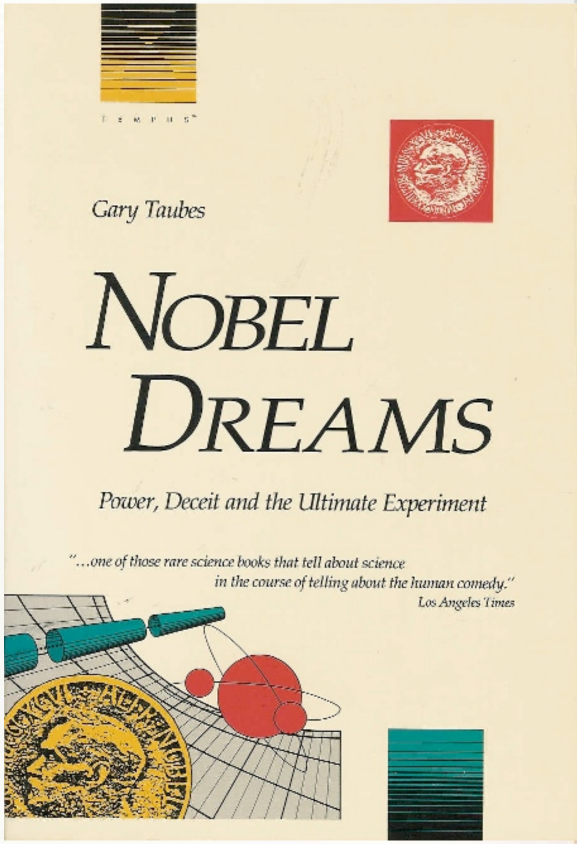
Monojets from *Z* Decay without Extra Neutrinos or Higgs Particles

Stephen F. King
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 26 November 1984)

The recent discovery of monojets by Arnison *et al.*[1] at the CERN $p\bar{p}$ collider has caused ripples of excitement throughout the particle physics world, since they cannot be explained by the minimal standard model.[2]

Monojets: Tainted History

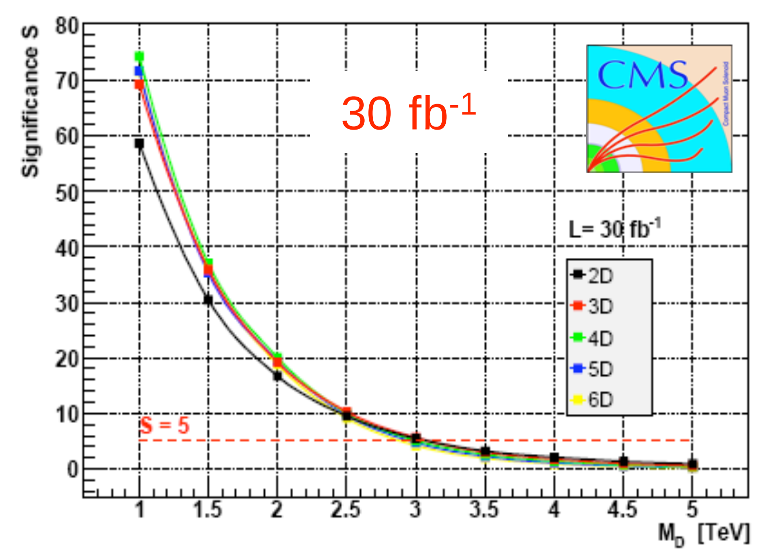




- These monojets turned out to be due to unaccounted background
- The signature was deemed doomed and nearly forgotten
- It took many years for successful monojet analyses at a hadron collider to be completed (CDF/DØ)

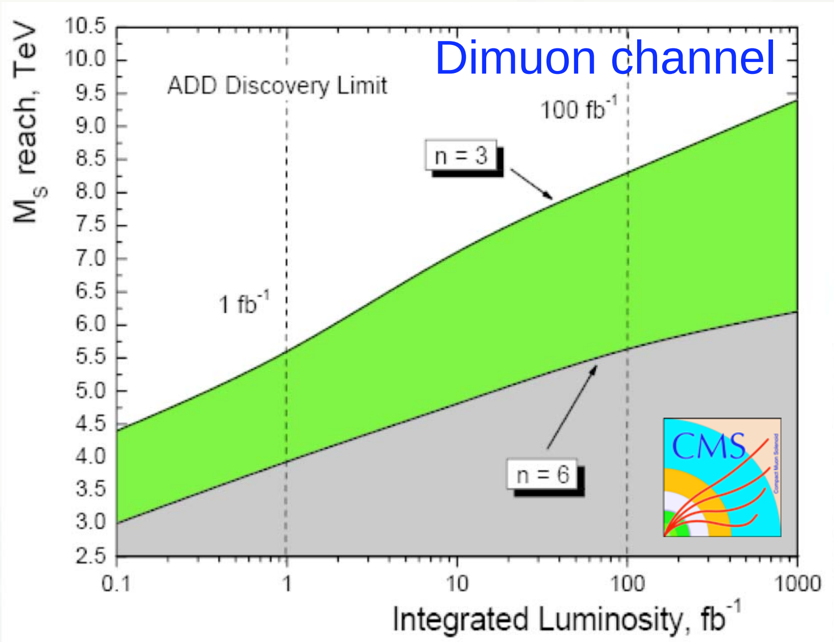
Expectations at the LHC

- Monojets are tough; what about monophotons?
  - CMS simulations only done for 30 fb^{-1} so far, but the luminosity dependence is weak ($\sim L^{1/4}$)



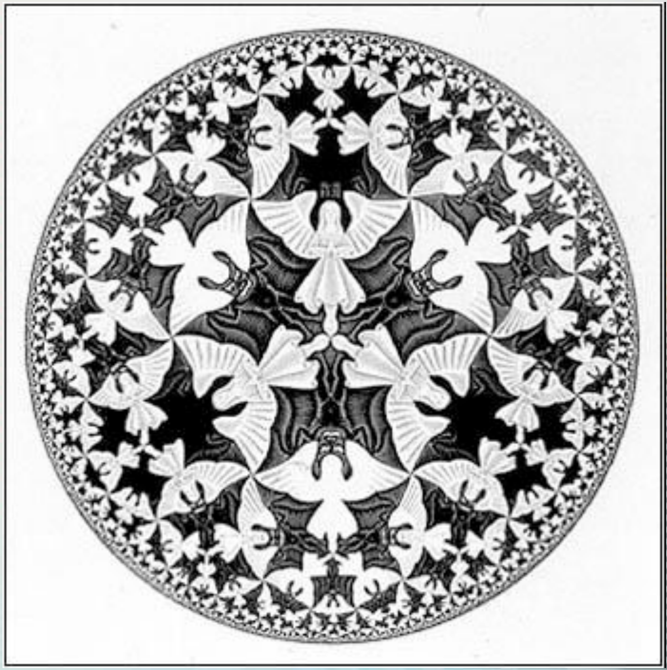
δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

- Virtual graviton exchange offers clean signature, with a huge potential of a quick discovery in dimuon, dielectron, and diphoton channels:
  - Factor of ~3 gain over the Tevatron/ Cosmic Ray limits in just 100 pb^{-1}
  - Will also probe compositeness models with similar increase in sensitivity compared to the existing limits



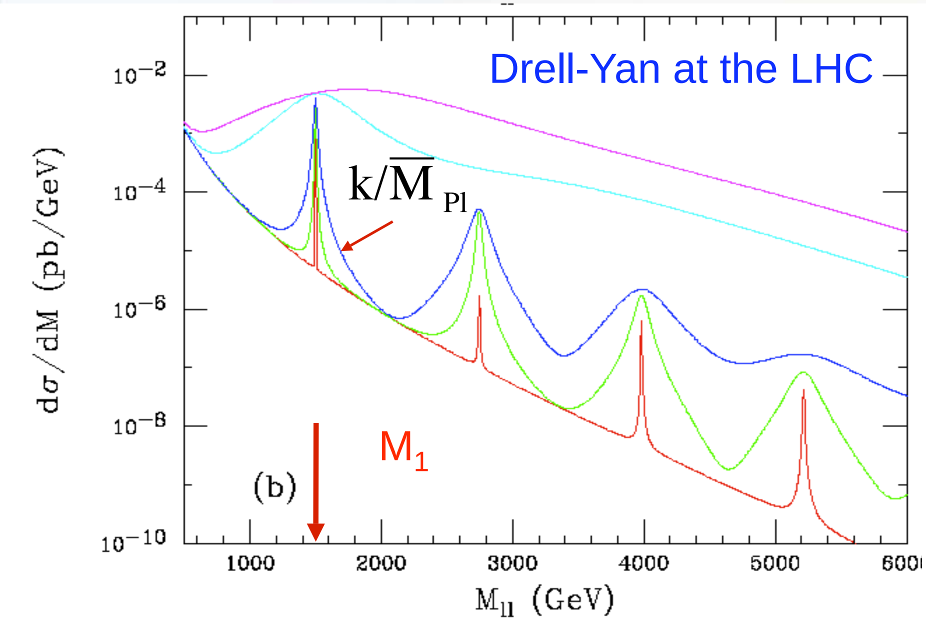
Example 3: Kaluza-Klein Resonances/Z'

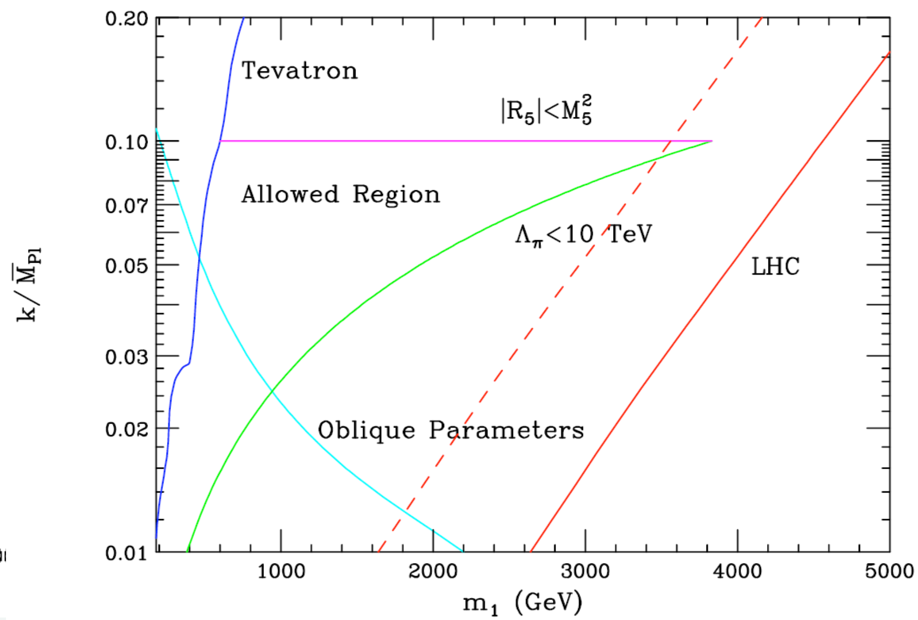
Found in RS, TeV-1 models and in various Z' models



Randall-Sundrum Model Observables

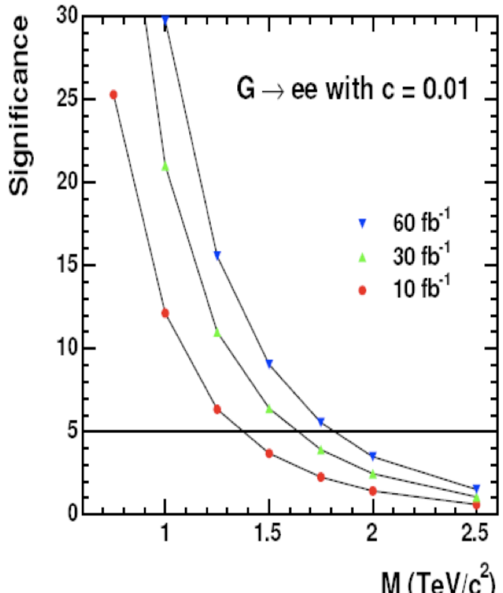
- Need only two parameters to define the model: k and r
- Equivalent set of parameters:
  - The mass of the first KK mode, M_1
  - Dimensionless coupling $k/\overline{M}_{Pl}$, which determines the graviton width
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \le k/\overline{M}_{Pl} \le 0.10$ is the expected range
- Gravitons are narrow
- Similar observables for Z_{KK}/g_{KK} in TeV^{-1} models



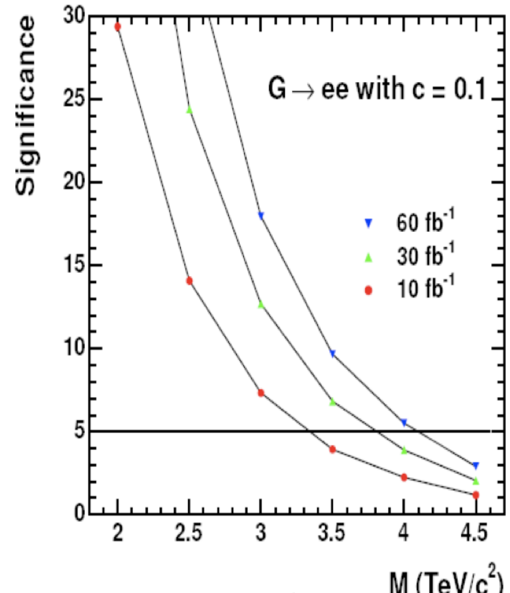


Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

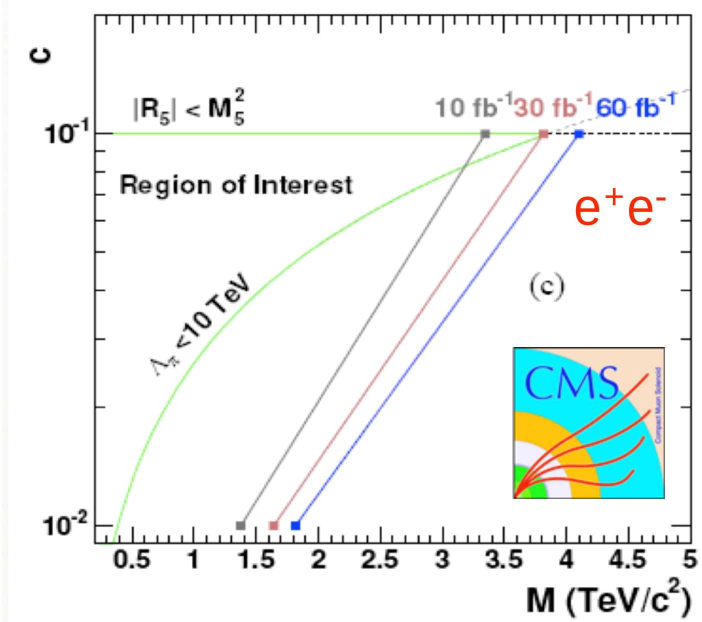
Randall-Sundrum Graviton Reach

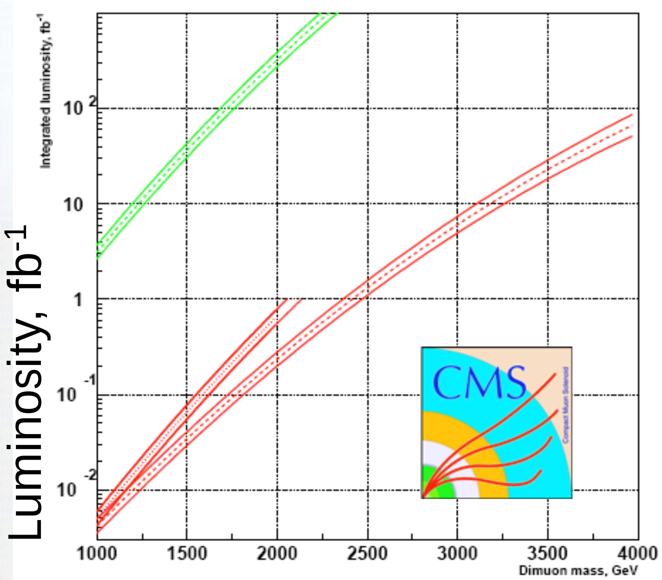


(a)

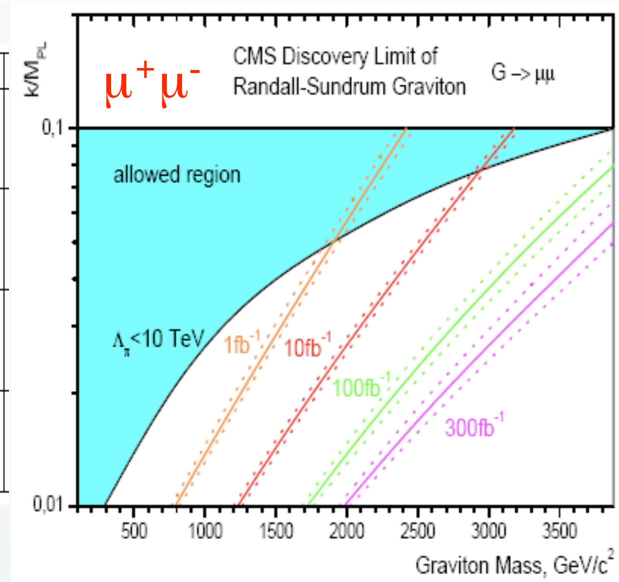


(b)



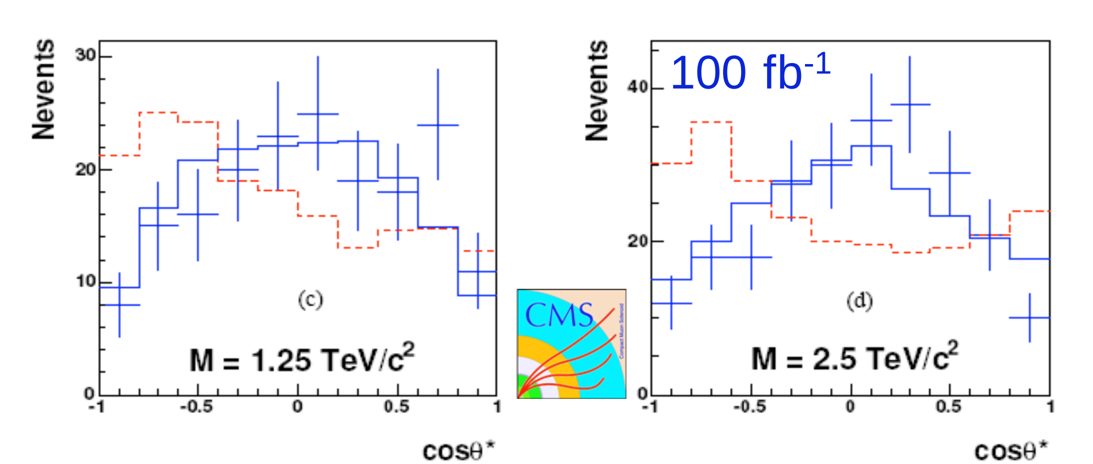


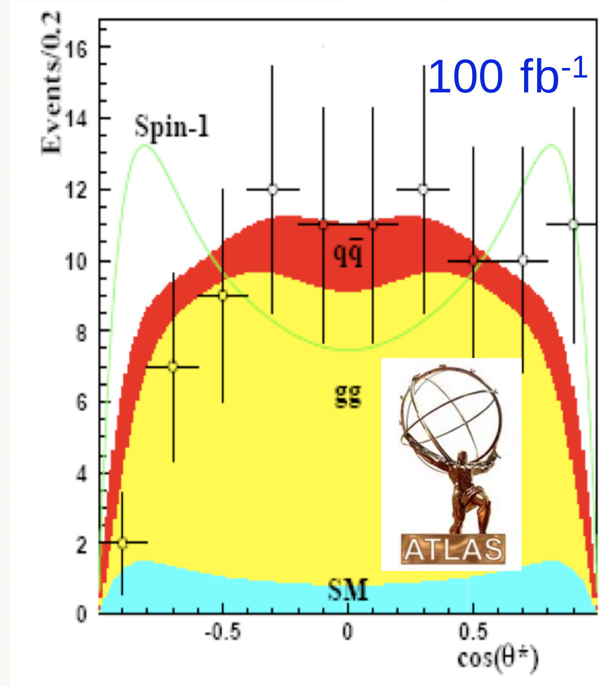
Coupling constant c	Estimator	$1\ \mathrm{fb}^{-1}$	$10\ \mathrm{fb}^{-1}$
0.01	S_{cP}	0.75	1.20
	S_{cL}	0.77	1.21
	S_L	0.78	1.23
0.02	S_{cP}	1.21	1.72
	S_{cL}	1.22	1.72
	S_L	1.22	1.74
0.05	S_{cP}	1.83	2.48
	S_{cL}	1.85	2.49
	S_L	1.85	2.51
0.1	S_{cP}	2.34	3.11
	S_{cL}	2.36	3.13
	S_L	2.36	3.16

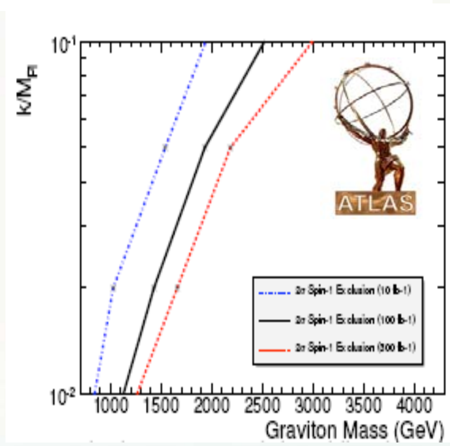


Angular Distributions?

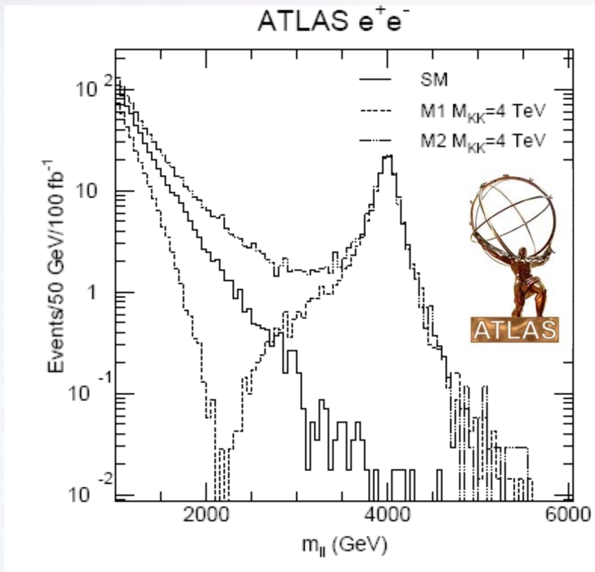
- Not in the early running!
  - "One event – discovery; two events – cross section measurement; three events – angular distributions"
  - Nevertheless observation in the diphoton channel excludes spin 1!

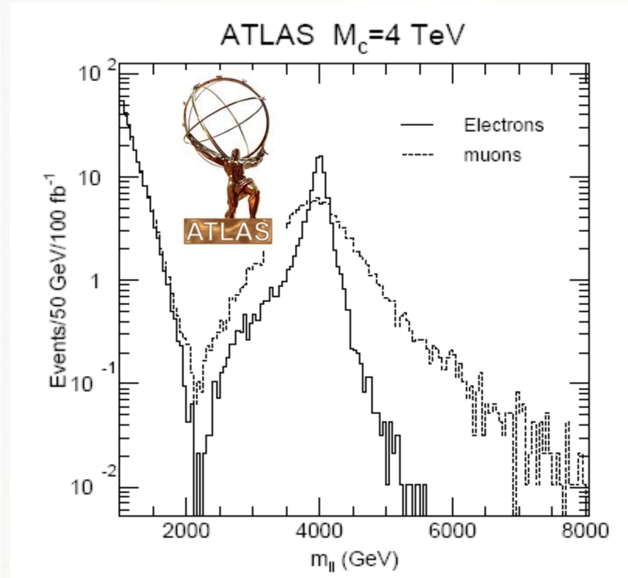


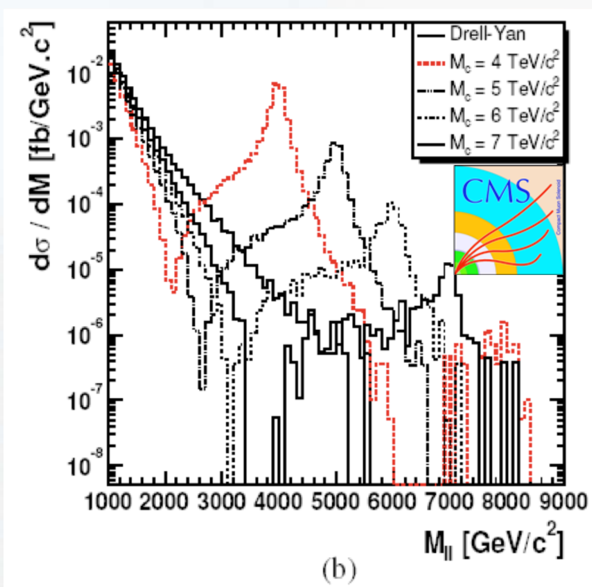


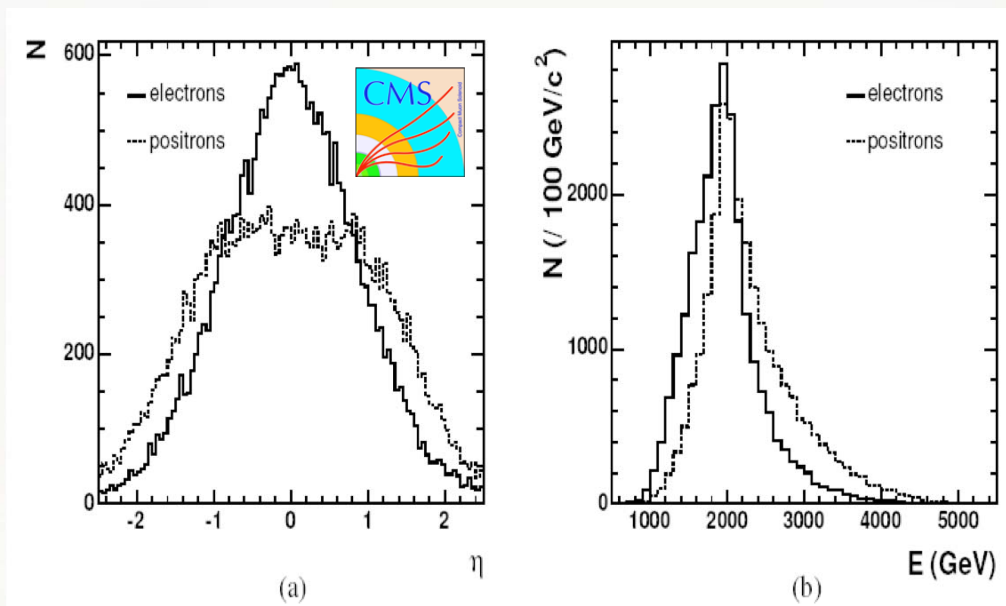


KK Excitations of the Z Boson



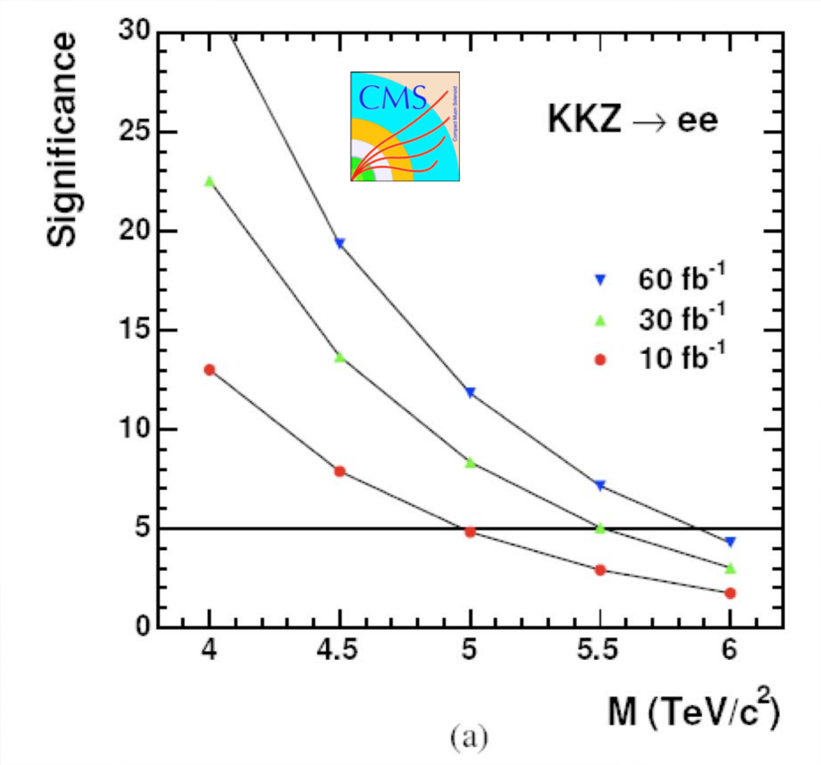


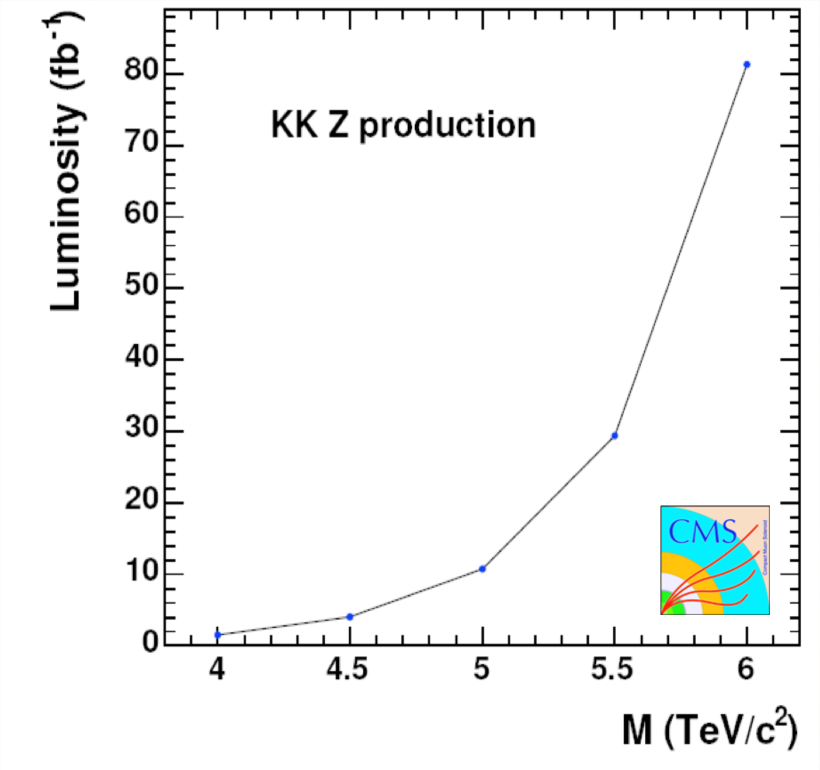




KK Reach

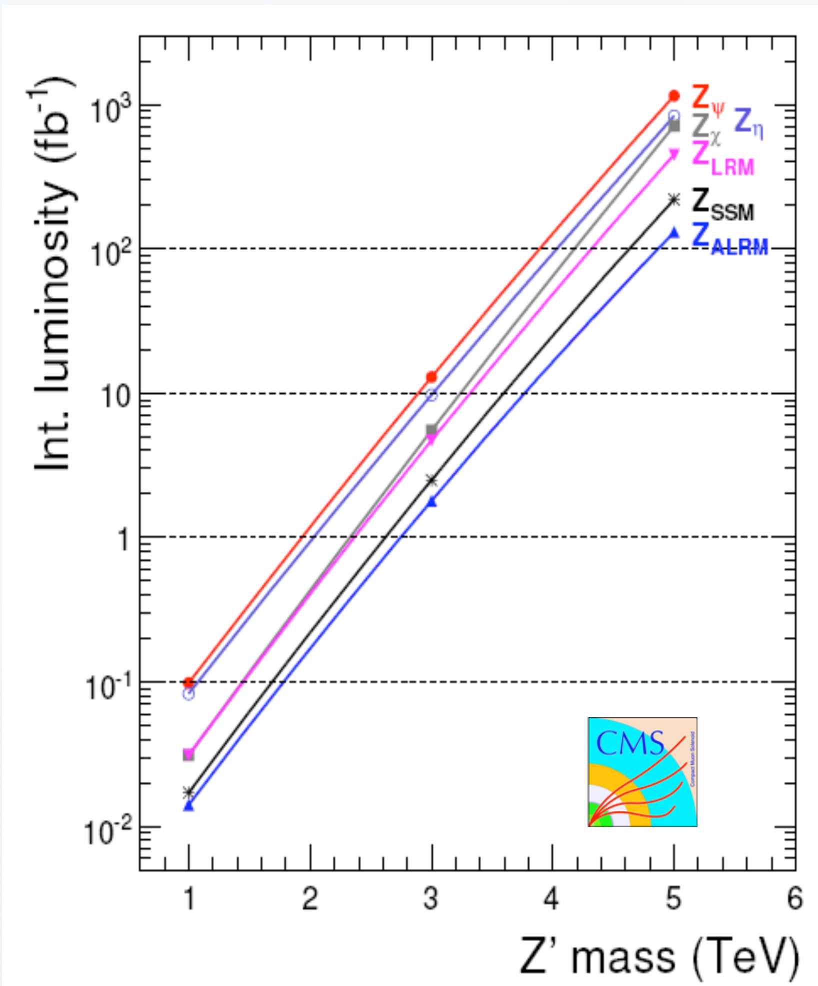
- Dramatic reach even with ~1 fb^{-1}



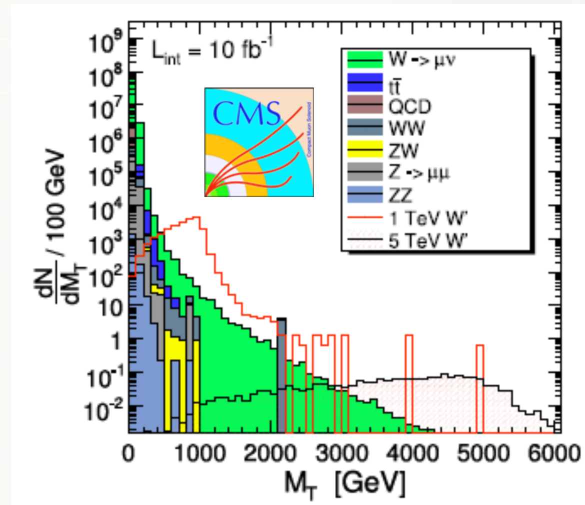


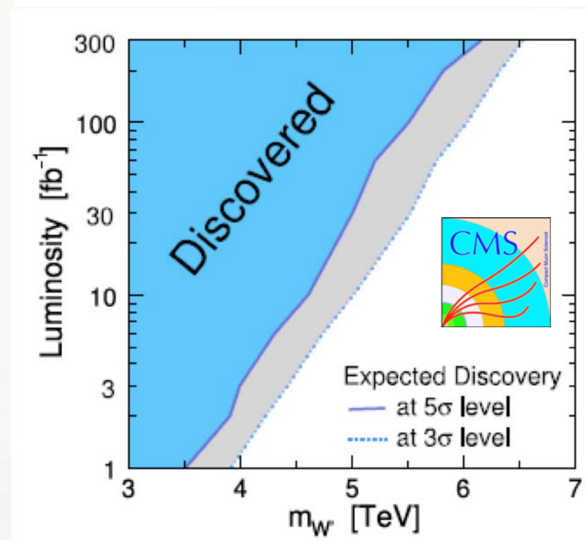
Z' and W' Reach

- Same conclusion applies to Z' in various models, as well as W' seen in μ+ME_T channel



CMS reach in the dimuon channel





Challenges

There will be surprises on the way!

Before One Can Succeed in Searches

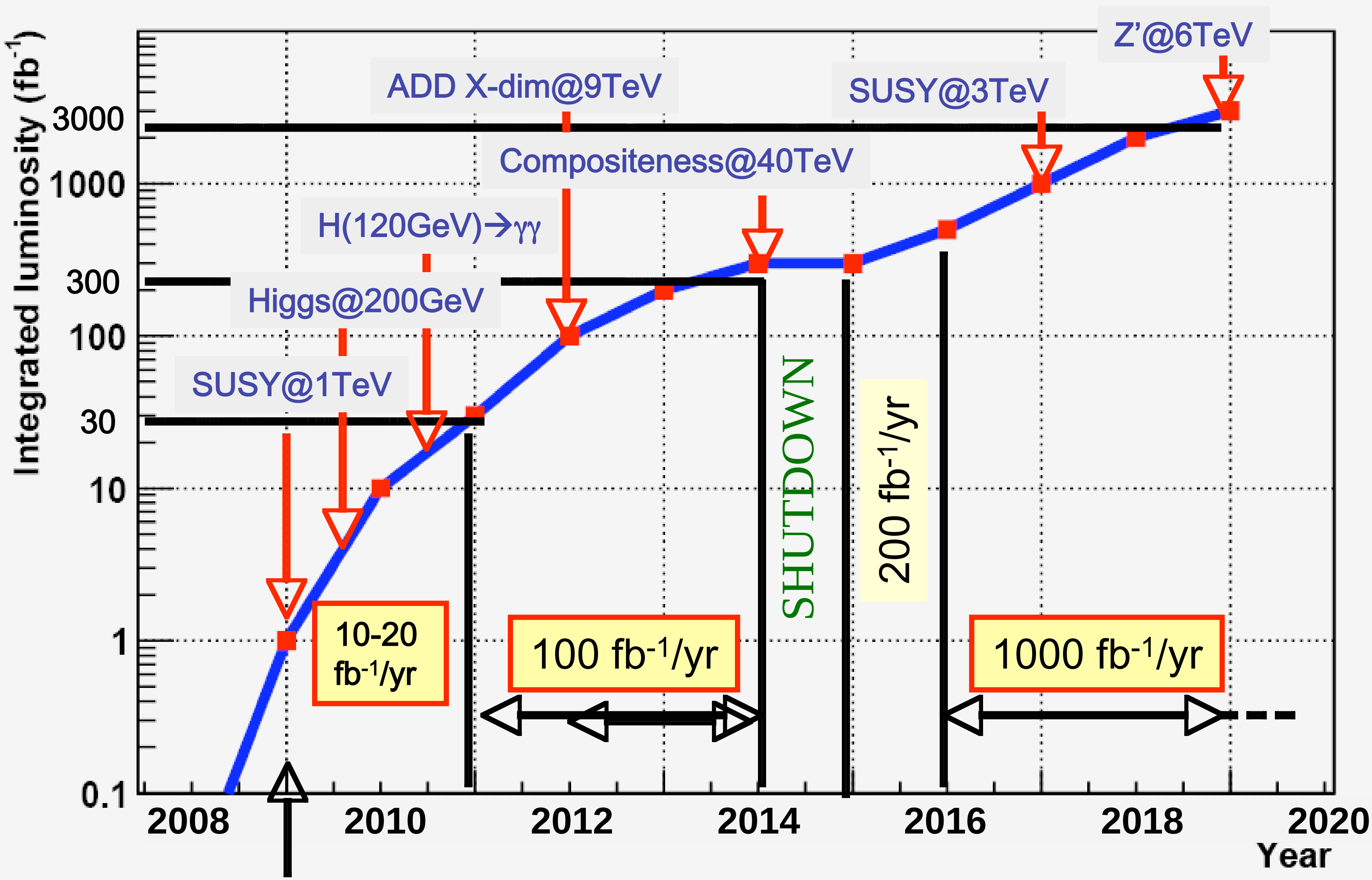
- Proper detector calibration, alignment, and detailed simulation is required
- Taunting task, which easily takes several years
- Searches typically look for one event in a million; that means that the detector often has to be understood to the 10^{-6} level!
- Use calibration samples of well understood nature:
  - Test beams (initial calibration)
  - Cosmic runs (alignment, efficiency)
  - Minbias data (channel-by-channel calibration)
  - "Standard candles" – Z, W, top (efficiency, non-Gaussian tails in resolution, b-tagging)
  - Z(ee) and γ + jets (jet energy calibration and resolution)
  - High-p_T dijets (saturation, ME_T resolution and tails)
- Easily a subject for several dedicated lectures; not covered here in detail:
  - See 2006, 2007 Hadron Collider Physics Summer School proceedings for dedicated talks
- Note: while a few spectacular discoveries may happen as early as 2008, most would require two-three years of accelerator running and operating the detectors!
  - Gear up for a long(er) ride!

Early Discovery Menu from Chez LHC

Early Discovery Menu from Chez LHC

Model	Mass reach	Luminosity (fb^{-1})	Early Systematic Challenges
Contact Interaction	Λ < 2.8 TeV	0.01	Jet Eff., Energy Scale
Z' ALRM SSM LRM E6, SO(10)	 M ~ 1 TeV M ~ 1 TeV M ~ 1 TeV M ~ 1 TeV	 0.01 0.02 0.03 0.03 – 0.1	Alignment
Excited Quark	M ~0.7 – 3.6 TeV	0.1	Jet Energy Scale
Axigluon or Colouron	M ~0.7 – 3.5 TeV	0.1	Jet Energy Scale
E6 diquarks	M ~0.7 – 4.0 TeV	0.1	Jet Energy Scale
Technirho	M ~0.7 – 2.4 TeV	0.1	Jet Energy Scale
ADD Virtual G_{KK}	M_D~ 4.3 - 3 TeV, n = 3-6 M_D~ 5 - 4 TeV, n = 3-6	0.1 1	Alignment
ADD Direct G_{KK}	M_D~ 1.5-1.0 TeV, n = 3-6	0.1	MET, Jet/photon Scale
SUSY Jet+MET+0 lepton Jet+MET+1 lepton Jet+MET+2 leptons	M ~1.5 – 1.8 TeV M ~0.5 TeV M ~0.5 TeV M ~0.5 TeV	1 0.01 0.1 0.1	MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backgrounds
mUED	M ~0.3 TeV M ~ 0.6 TeV	0.01 1	ibid
TeV^{-1} ($Z_{KK}^{(1)}$)	M_{z1} < 5 TeV	1	
RS1 di-jets di-muons	 M_{G1}~0.7- 0.8 TeV, c=0.1 M_{G1}~0.8- 2.3 TeV, c=0.01-0.1	 0.1 1	 Jet Energy Scale Alignment

LHC Discovery Roadmap



Conclusions

If History is a Guide...

- Let's recall a tale of a great discovery of five centuries ago: the discovery of the Americas
- Christopher Columbus was an ideal experimenter:
  - He raised funding
  - He ignored theoretical prejudice
  - He was lucky
  - As a result, he has discovered a WHOLE NEW WORLD!
- We have a thing or two to learn from him...

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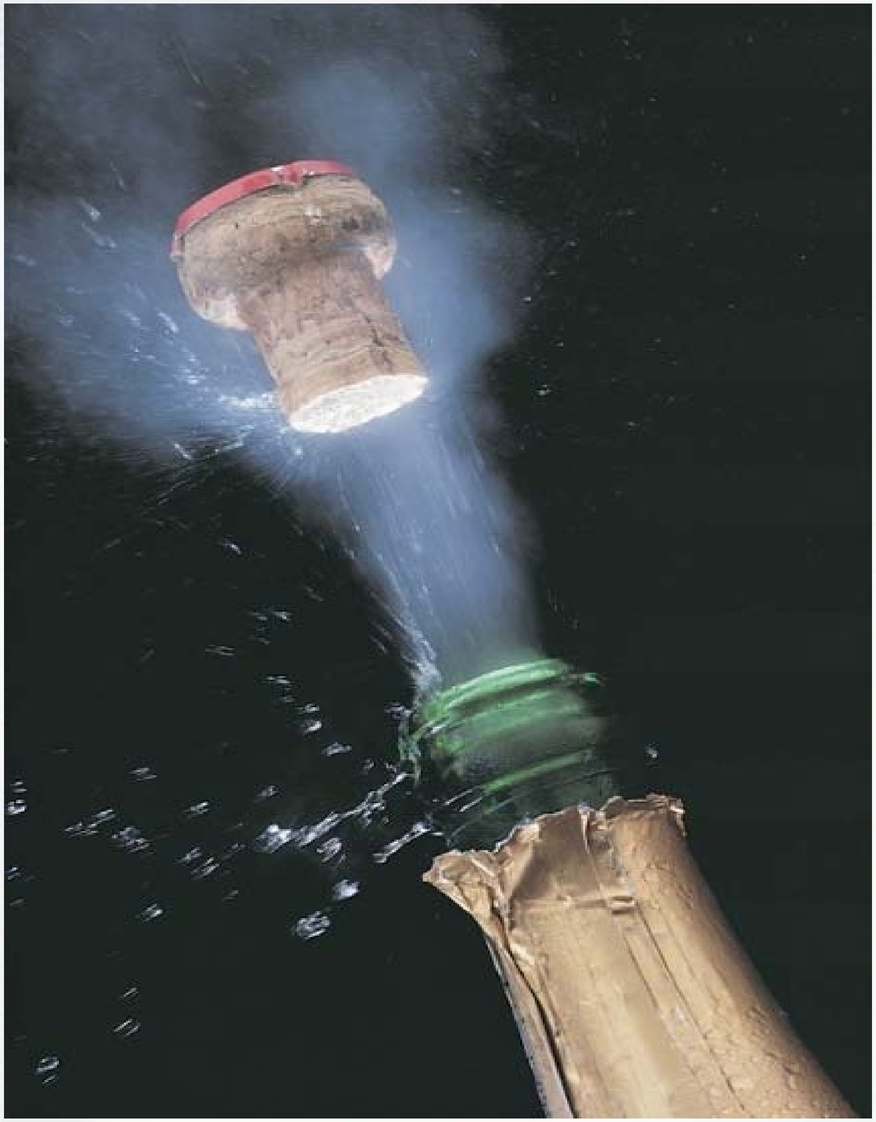

¡Prospero Año Nuevo 2008: el año de LHC!