Searches for New Physics with Early LHC Data: Strategies and Challenges

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Physics of the Large Hadron Collider Workshop

Kavli Institute, UCSB

March 21, 2008

Outline

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

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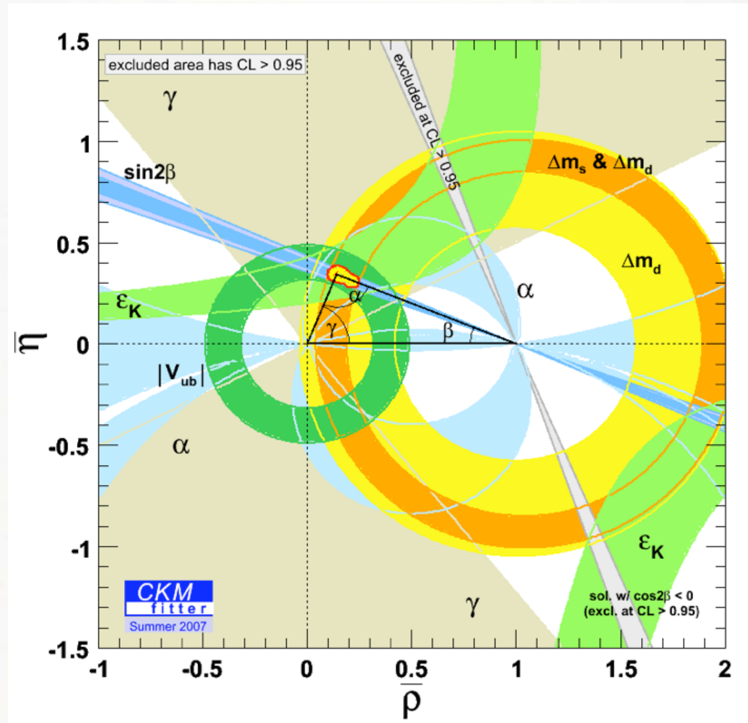
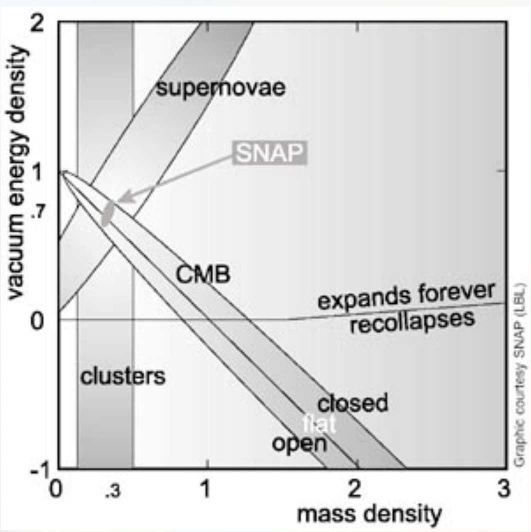
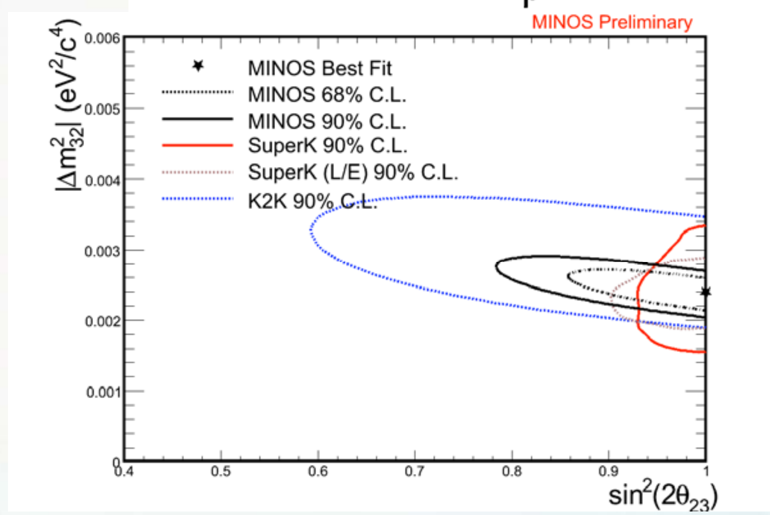
*) Chose to focus on a few characteristic examples, rather than being too inclusive

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

We Live in Precision Times…







We Still Have Things to Do…

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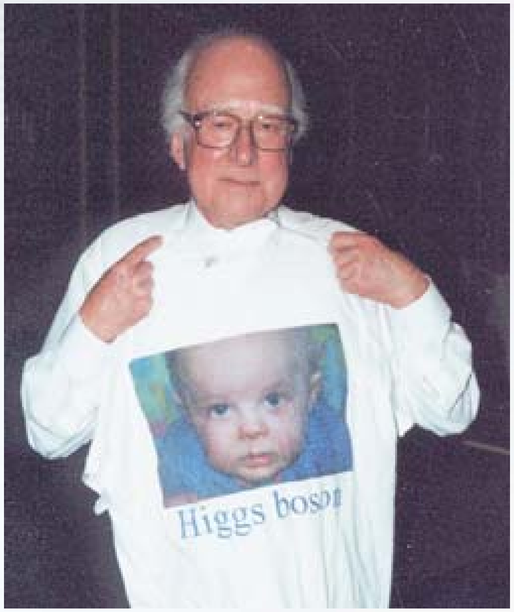

The only Higgs observed in Nature

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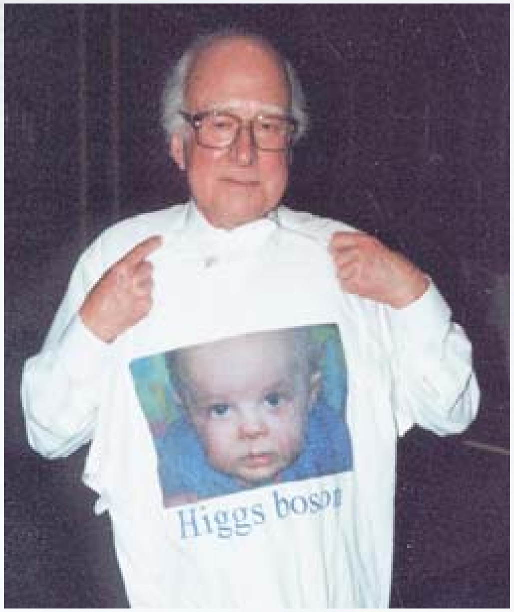

The only Higgs observed in Nature

The only stop decay observed in Nature

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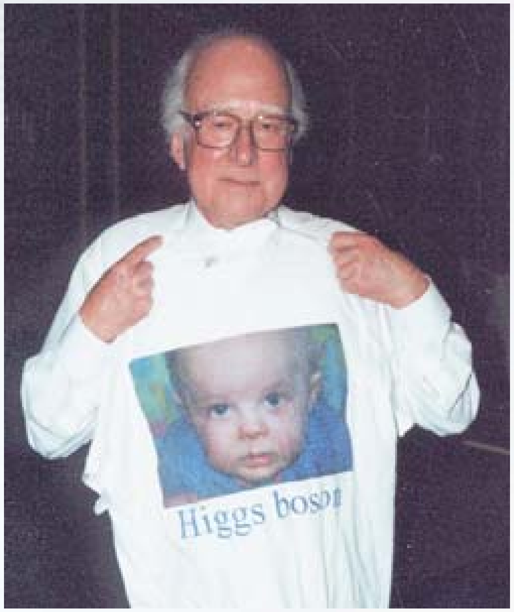

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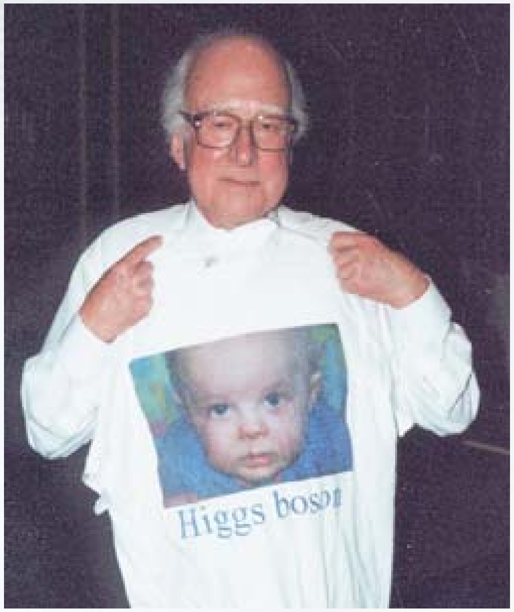


The only Higgs observed in Nature

The only dark matter observed in Nature

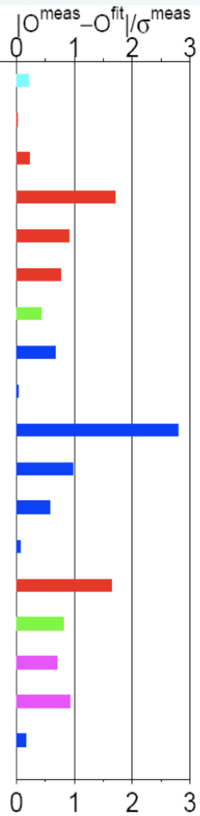
The only stop decay observed in Nature

A lot of dark energy...

Standard Model: Beauty & the Beast

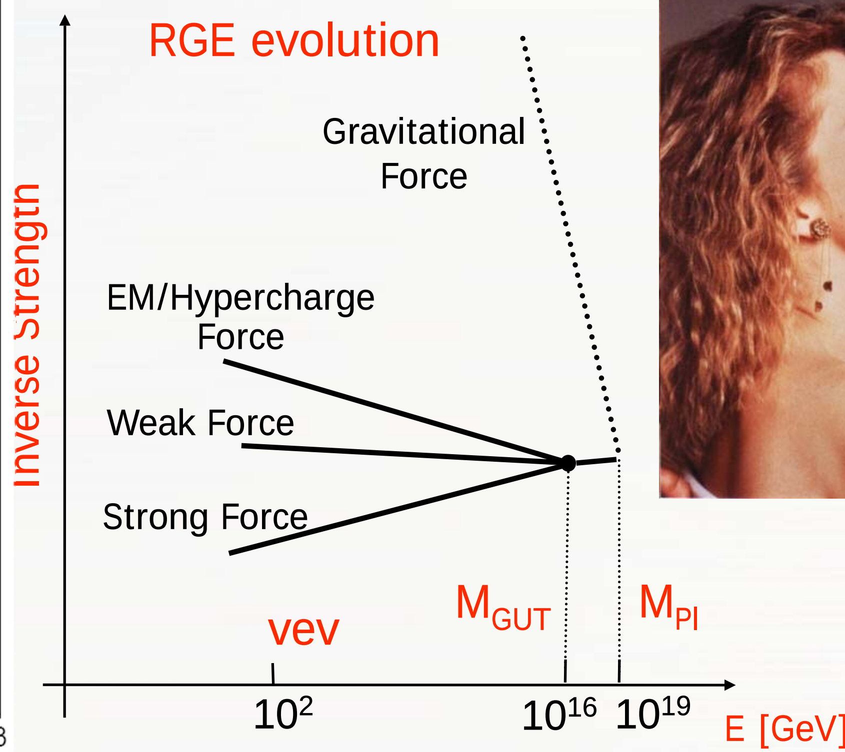
Beauty…

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



Standard Model: Beauty & the Beast

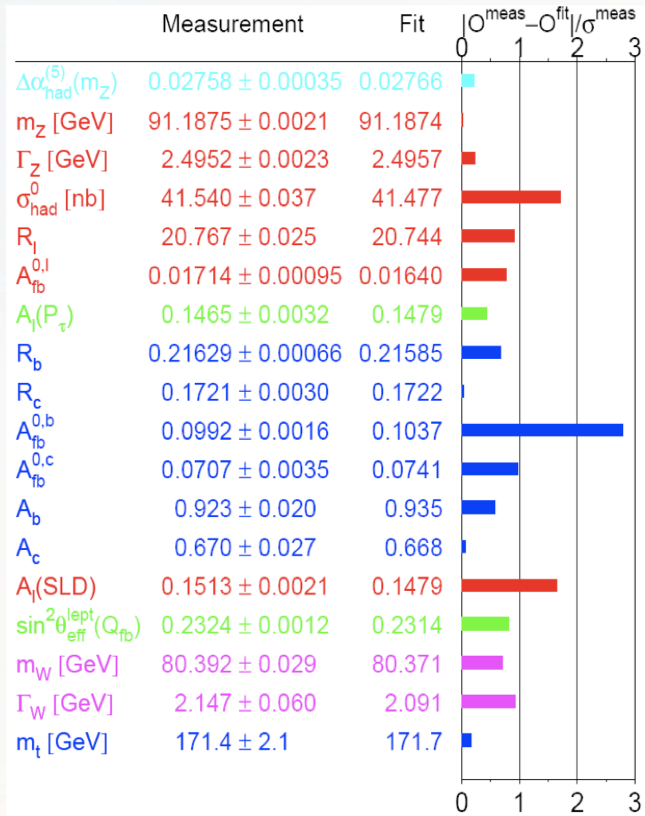
Beauty… and the Beast



M_{GUT}, M_{Pl} » vev

Standard Model: Beauty & the Beast

Beauty…

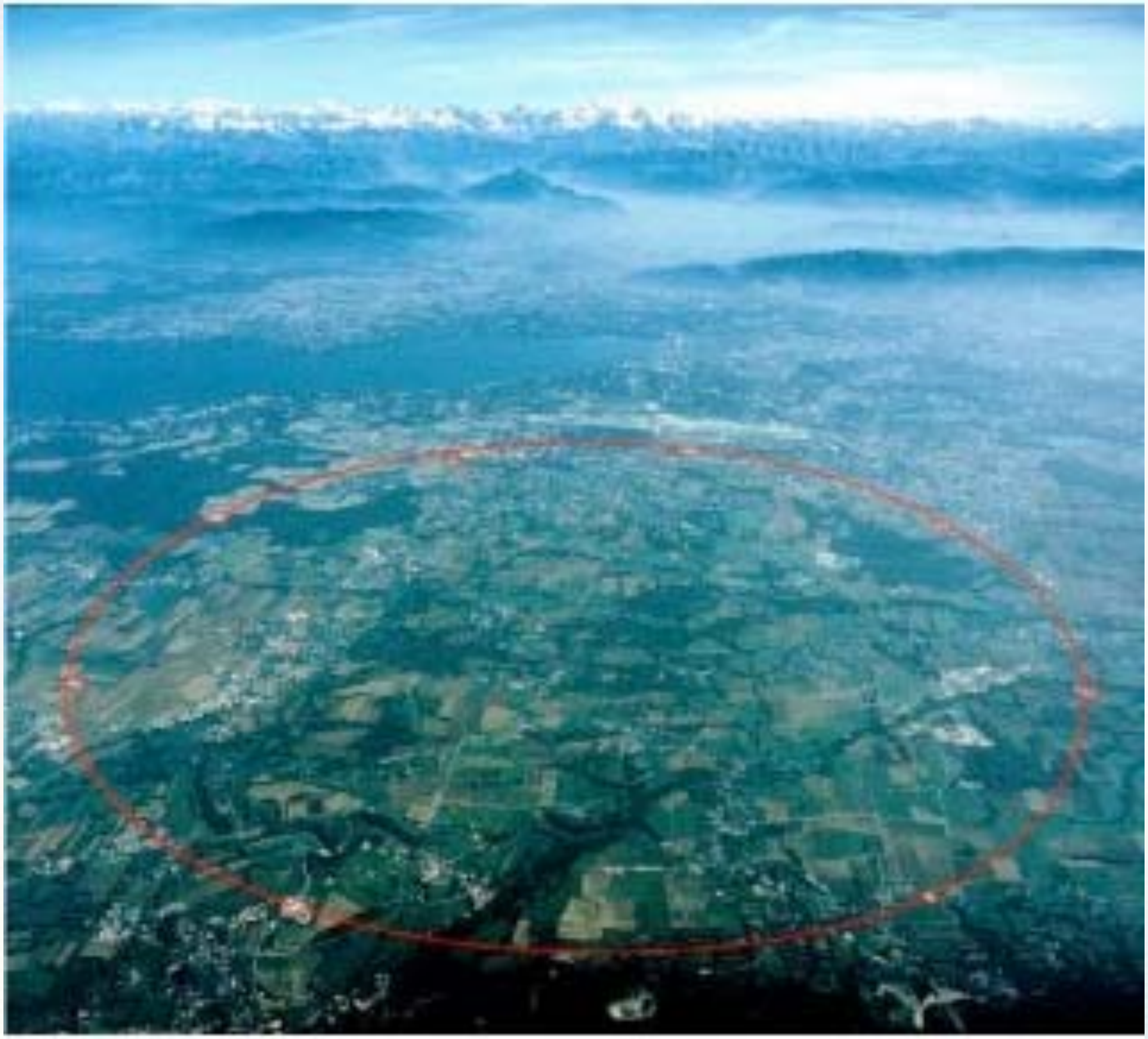


Physics beyond the SM may get rid of the beast while preserving SM's natural beauty!

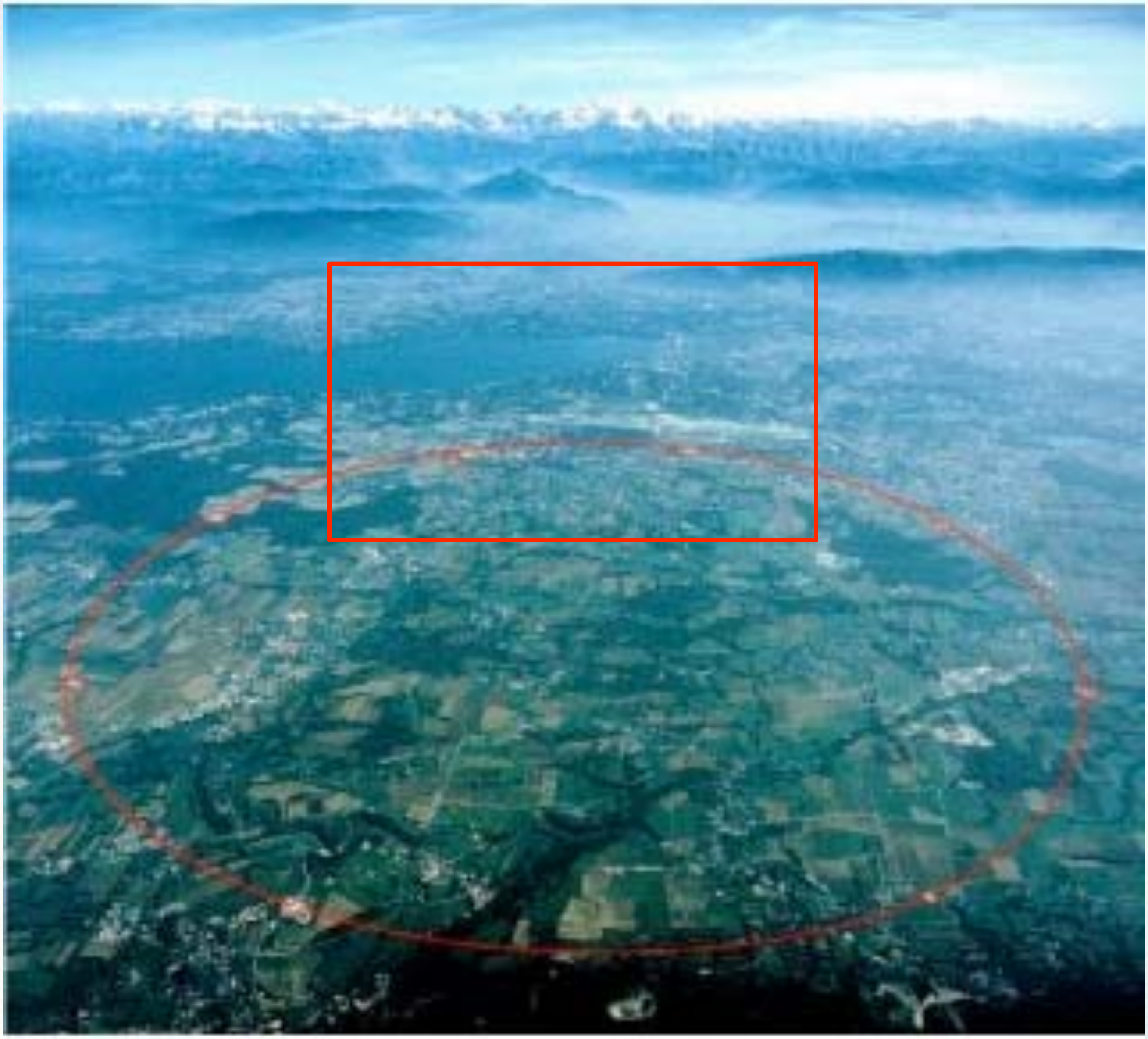
The Machine

The LHC

From Geneva to Santa Barbara

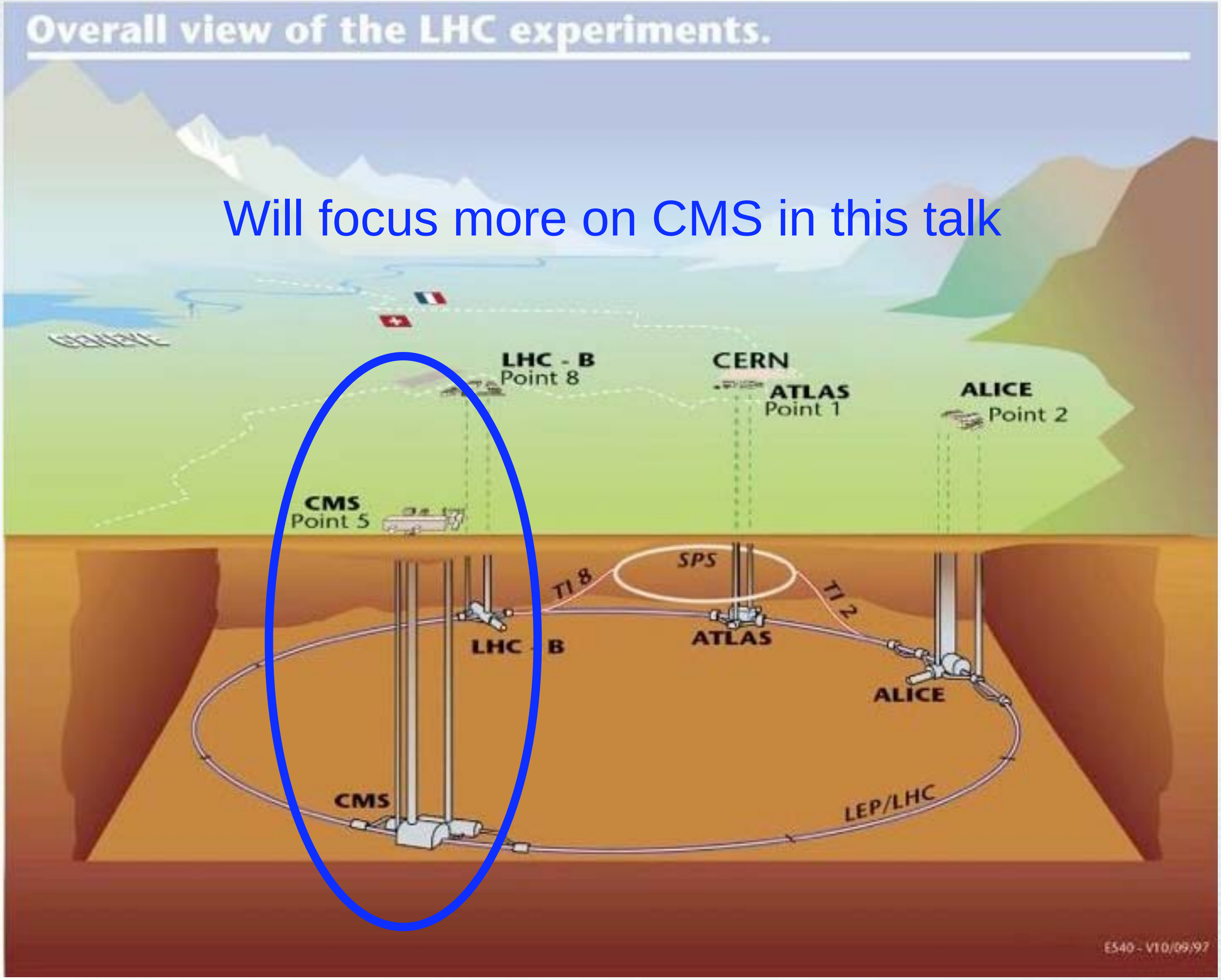


From Geneva to Santa Barbara



From Geneva to Santa Barbara

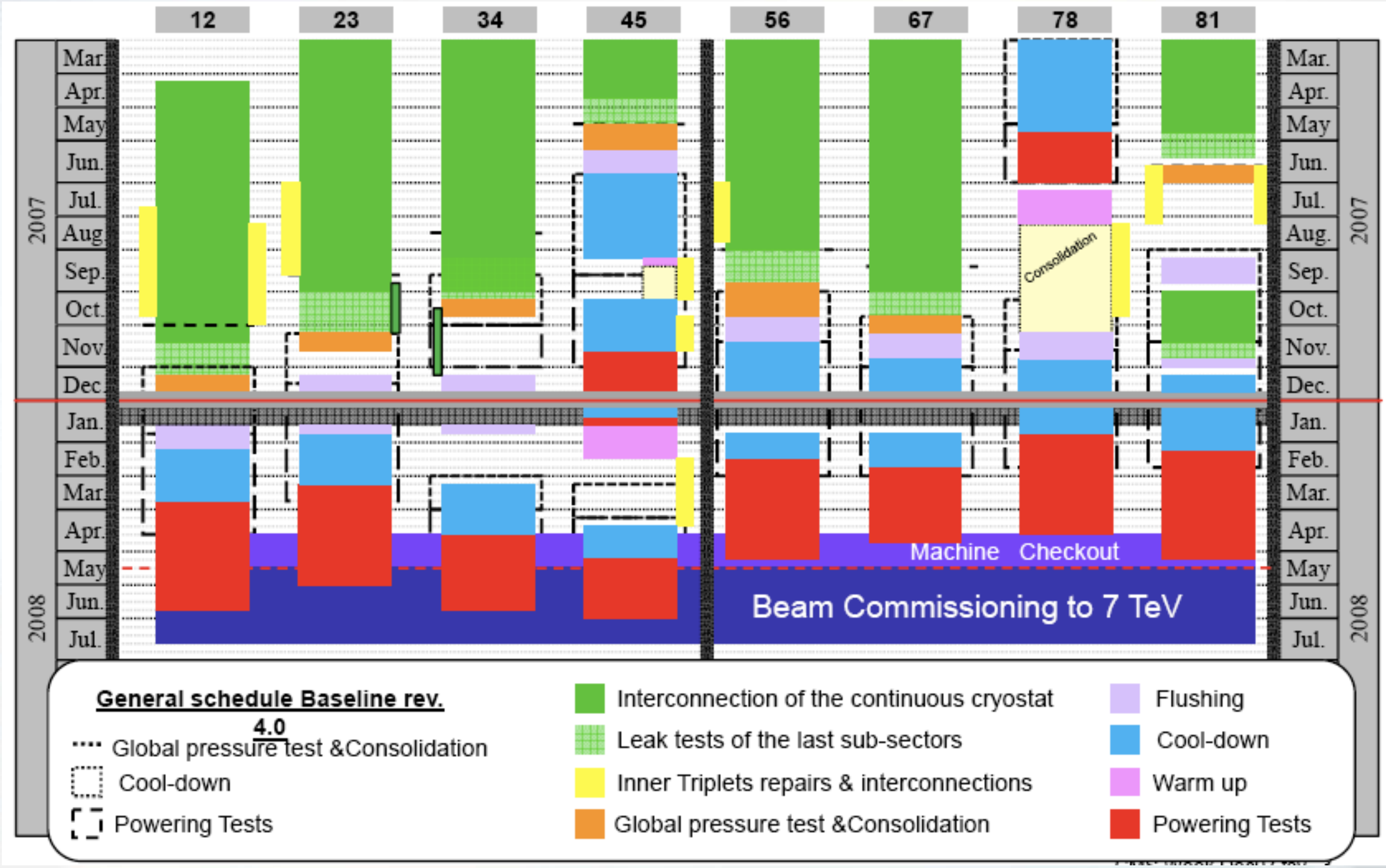
The LHC



Will focus more on CMS in this talk

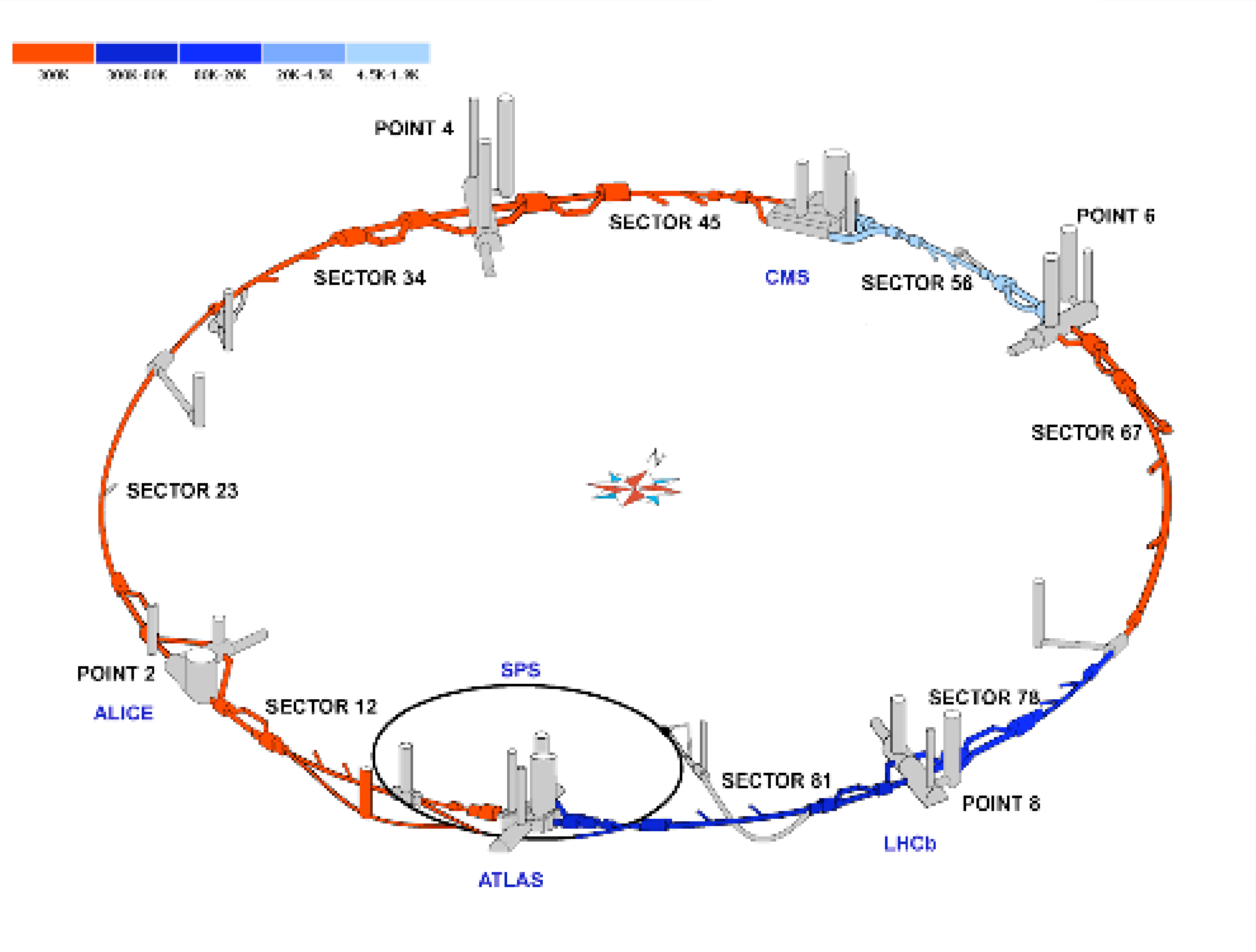
The LHC Schedule

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

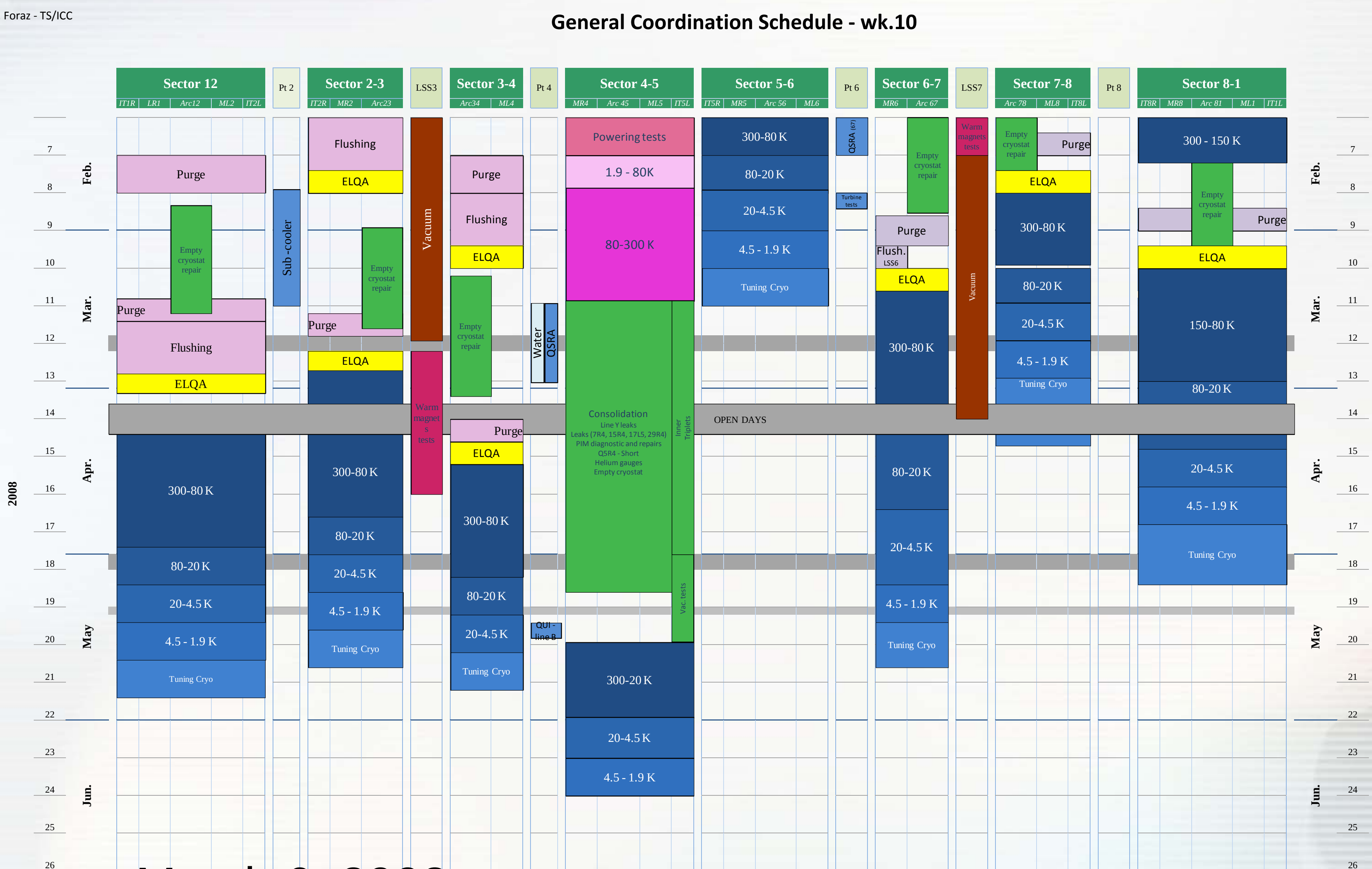


Cooldown Status

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



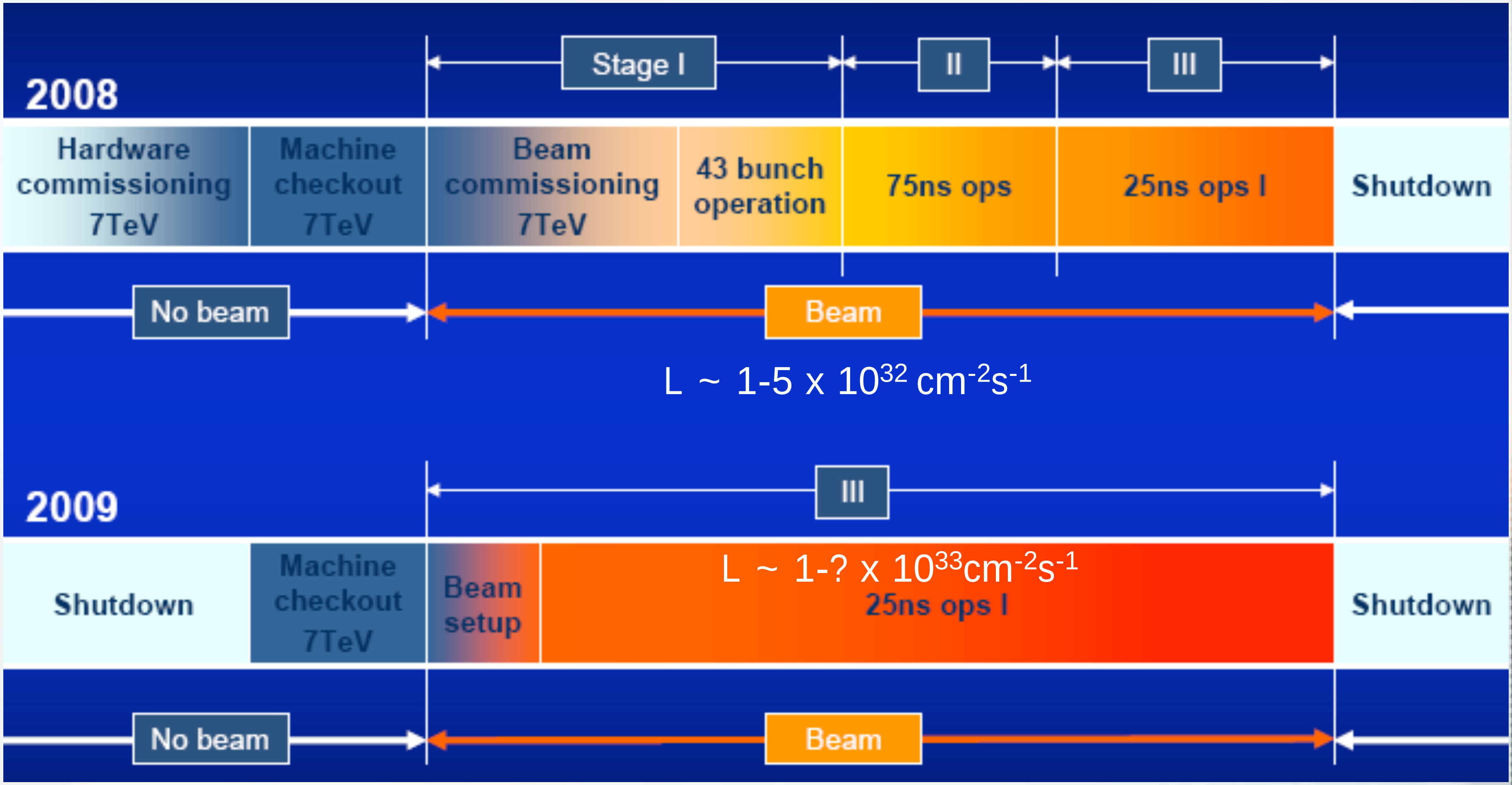
Cooldown Schedule



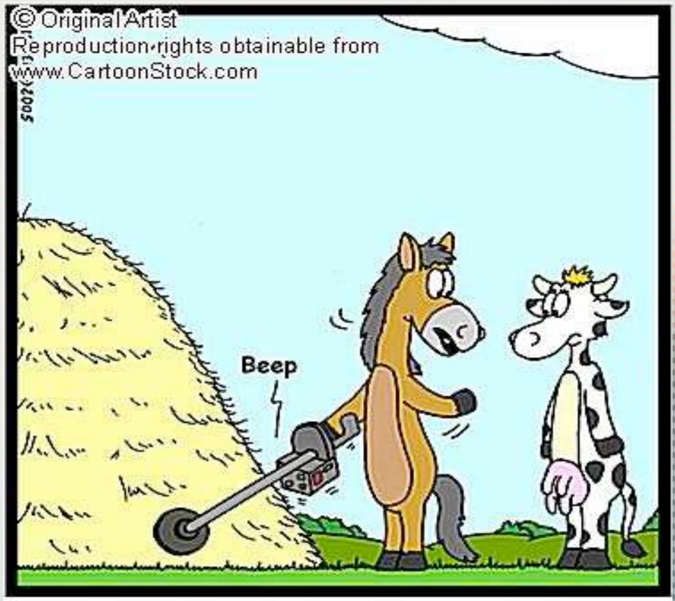
March 6, 2008

The LHC Operation Stages

- First 14 TeV Collisions: ~Summer/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

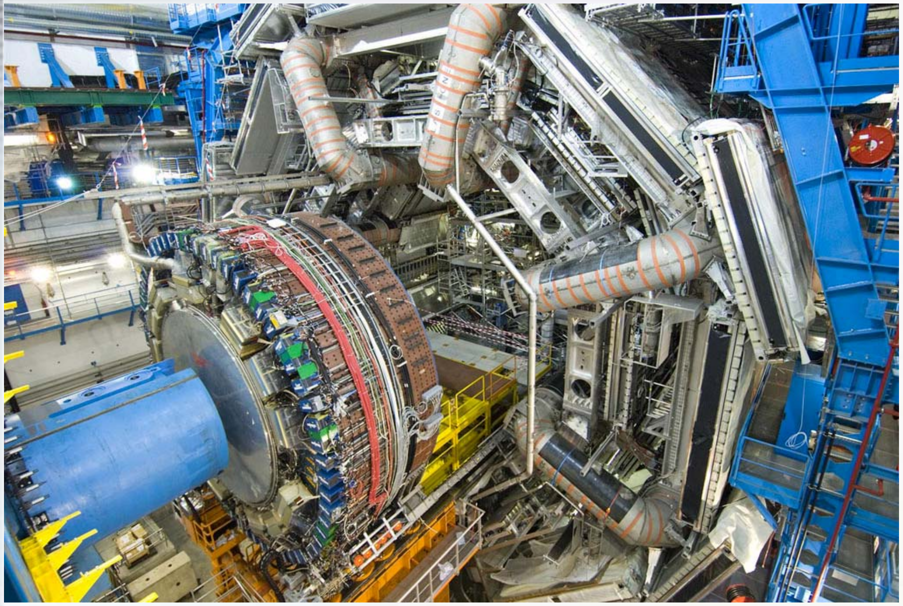


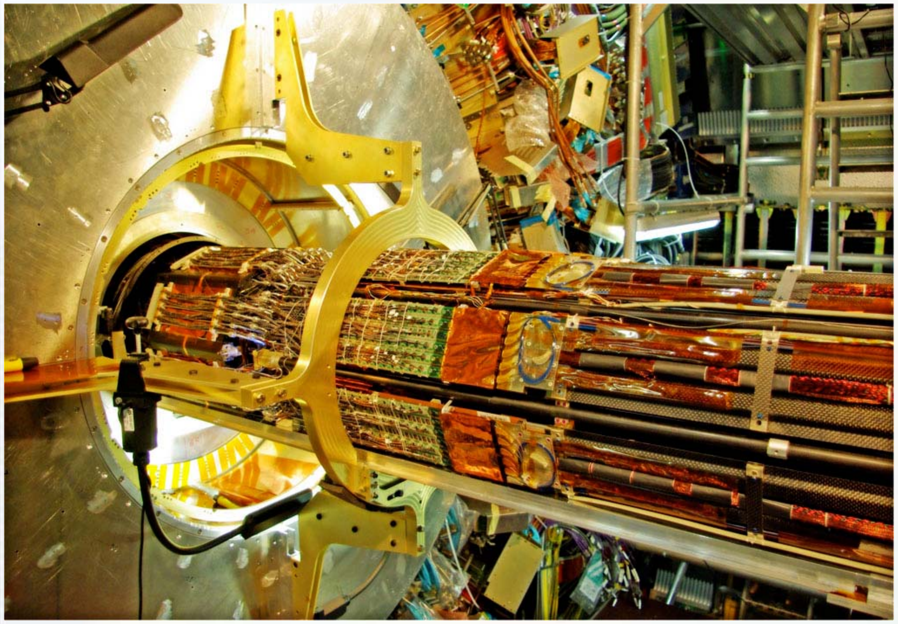
The Detectors



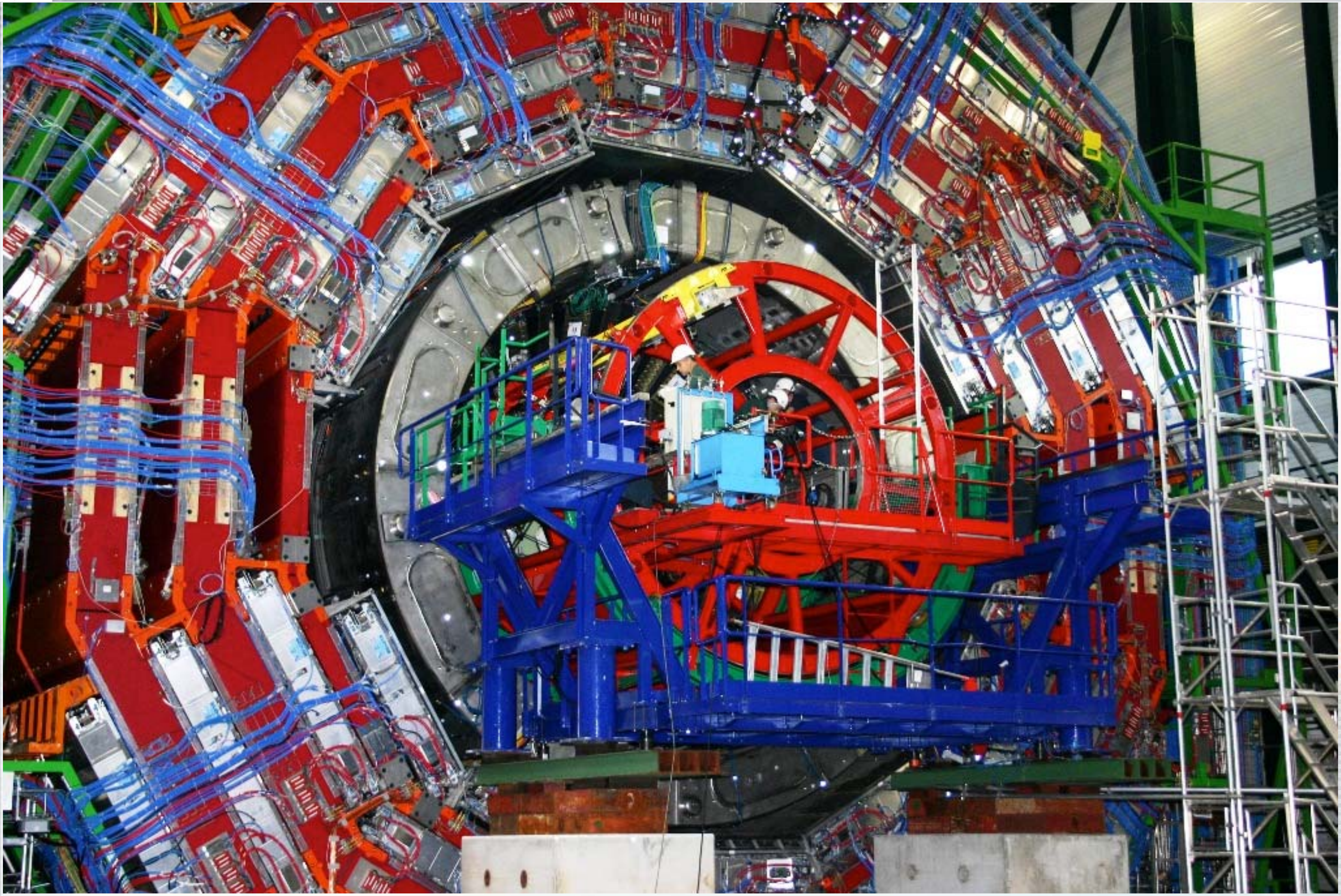
You were right: There's a needle in this haystack...

ATLAS Now

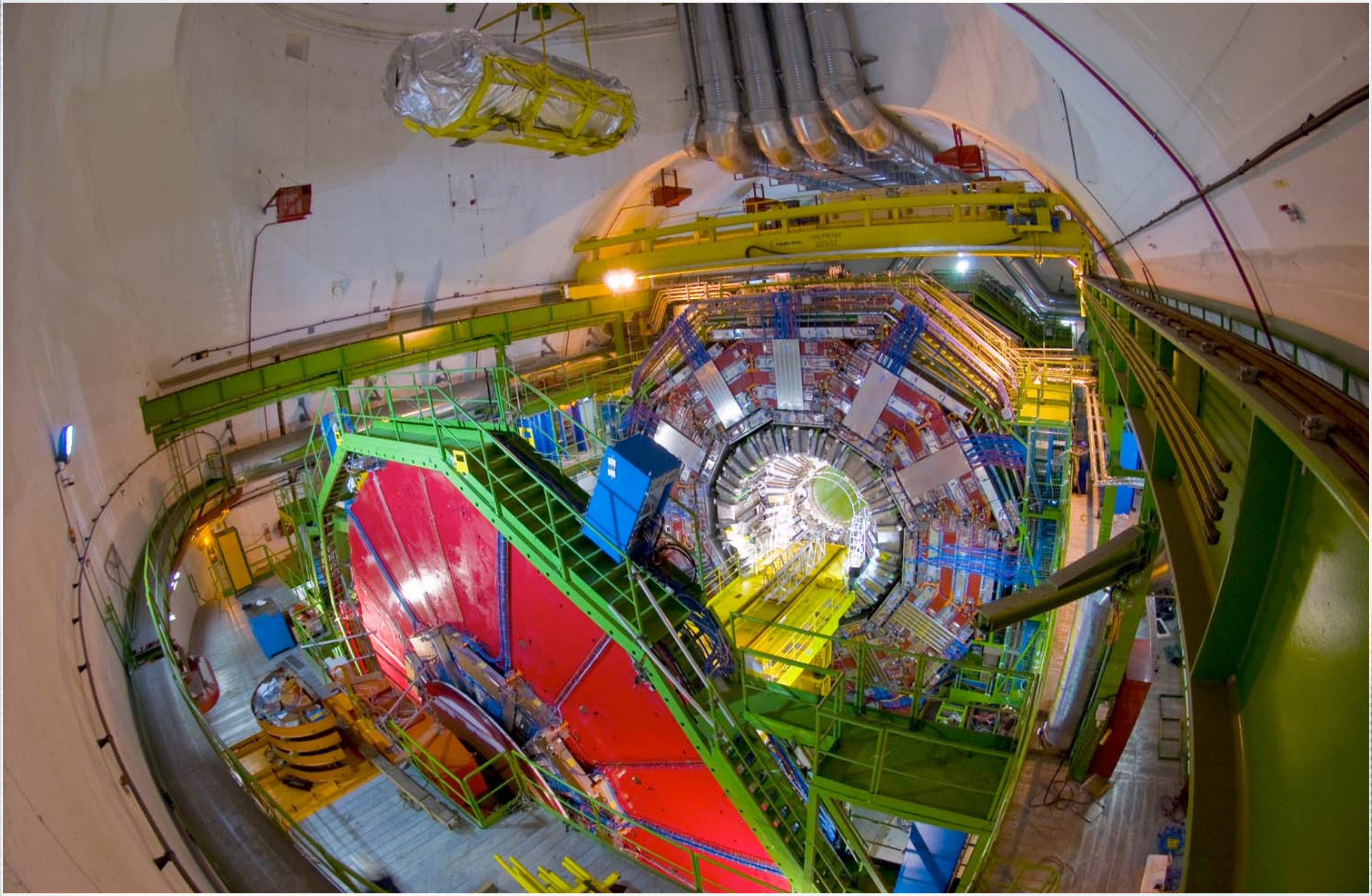




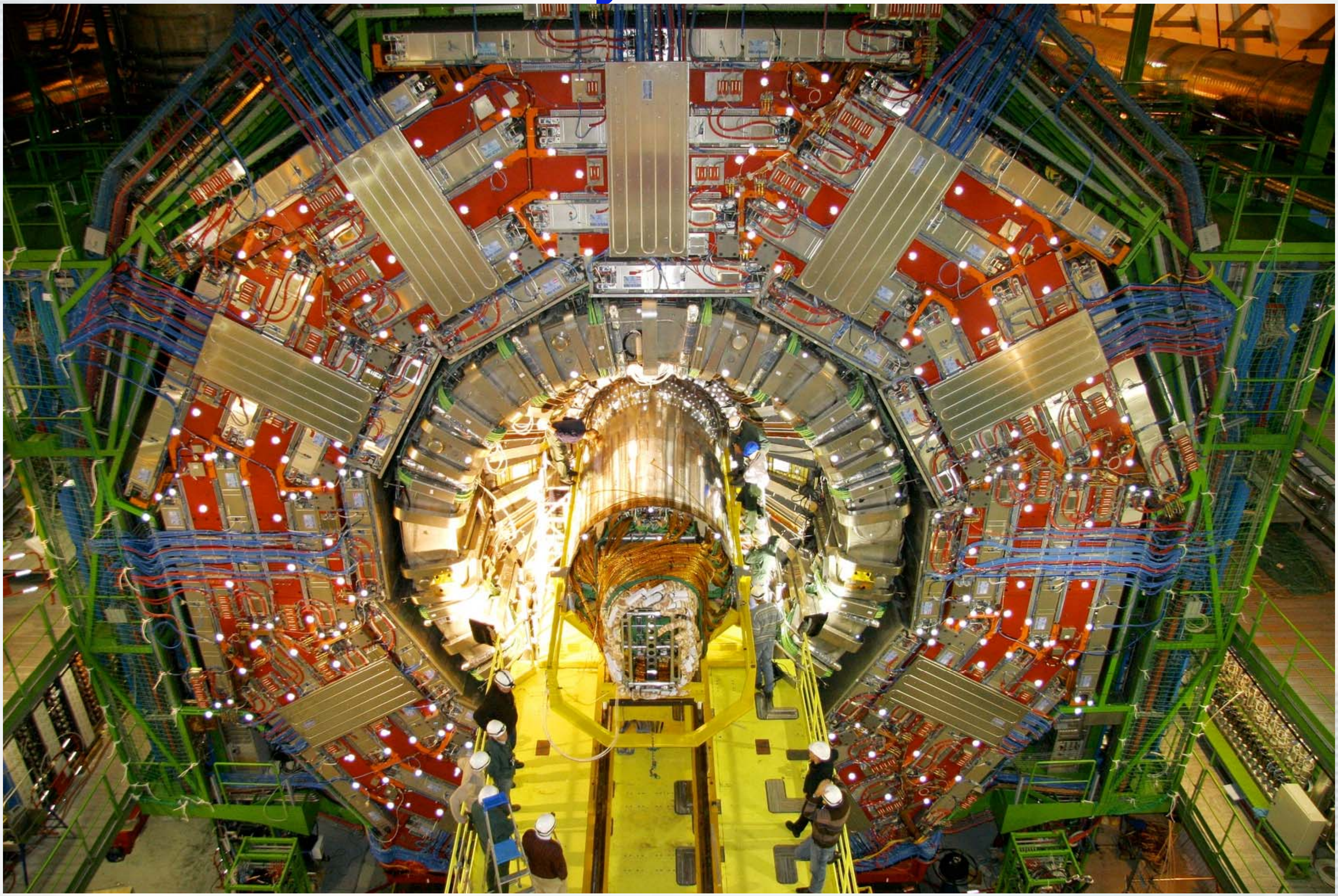
CMS - 2006



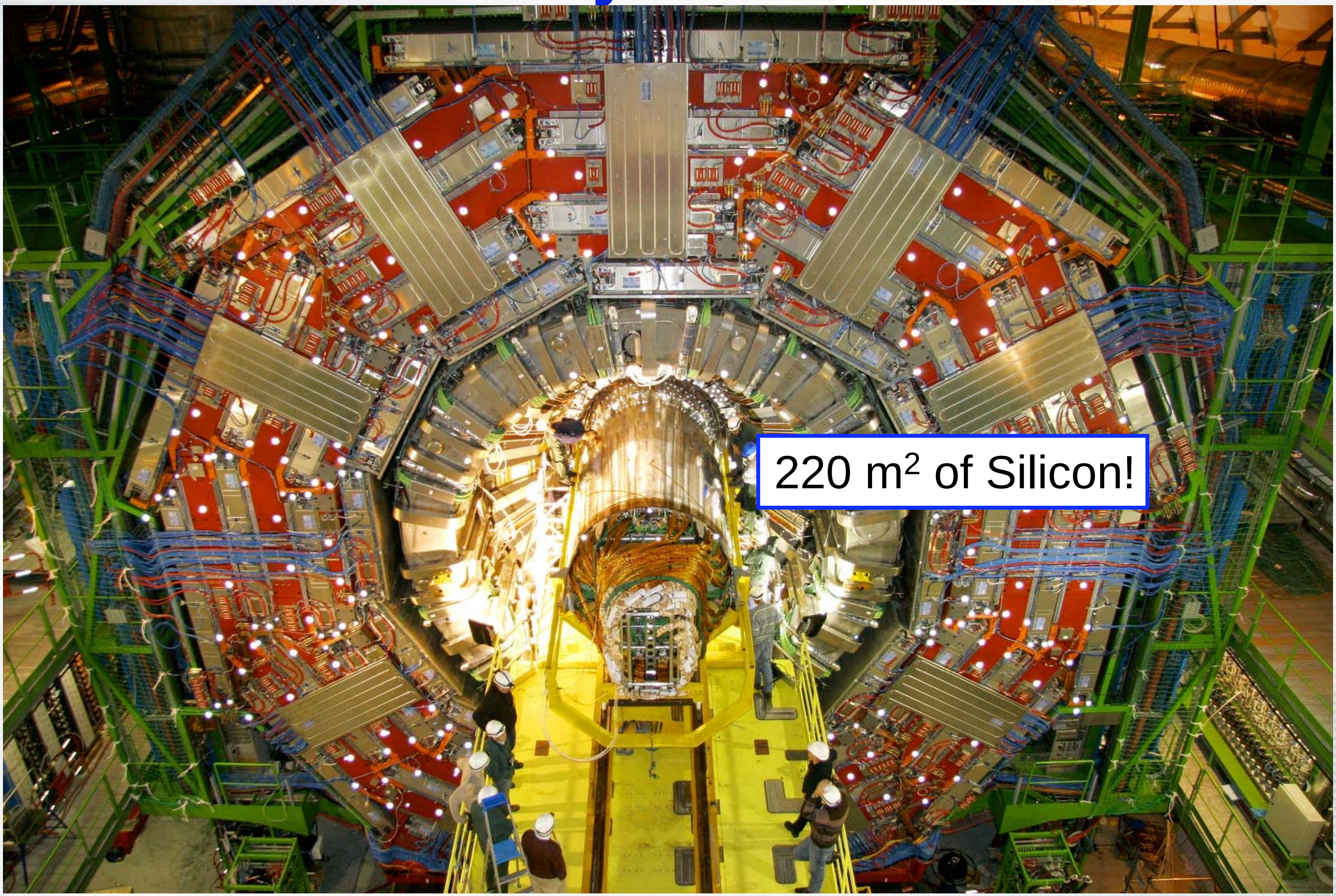
CMS in December, 2007



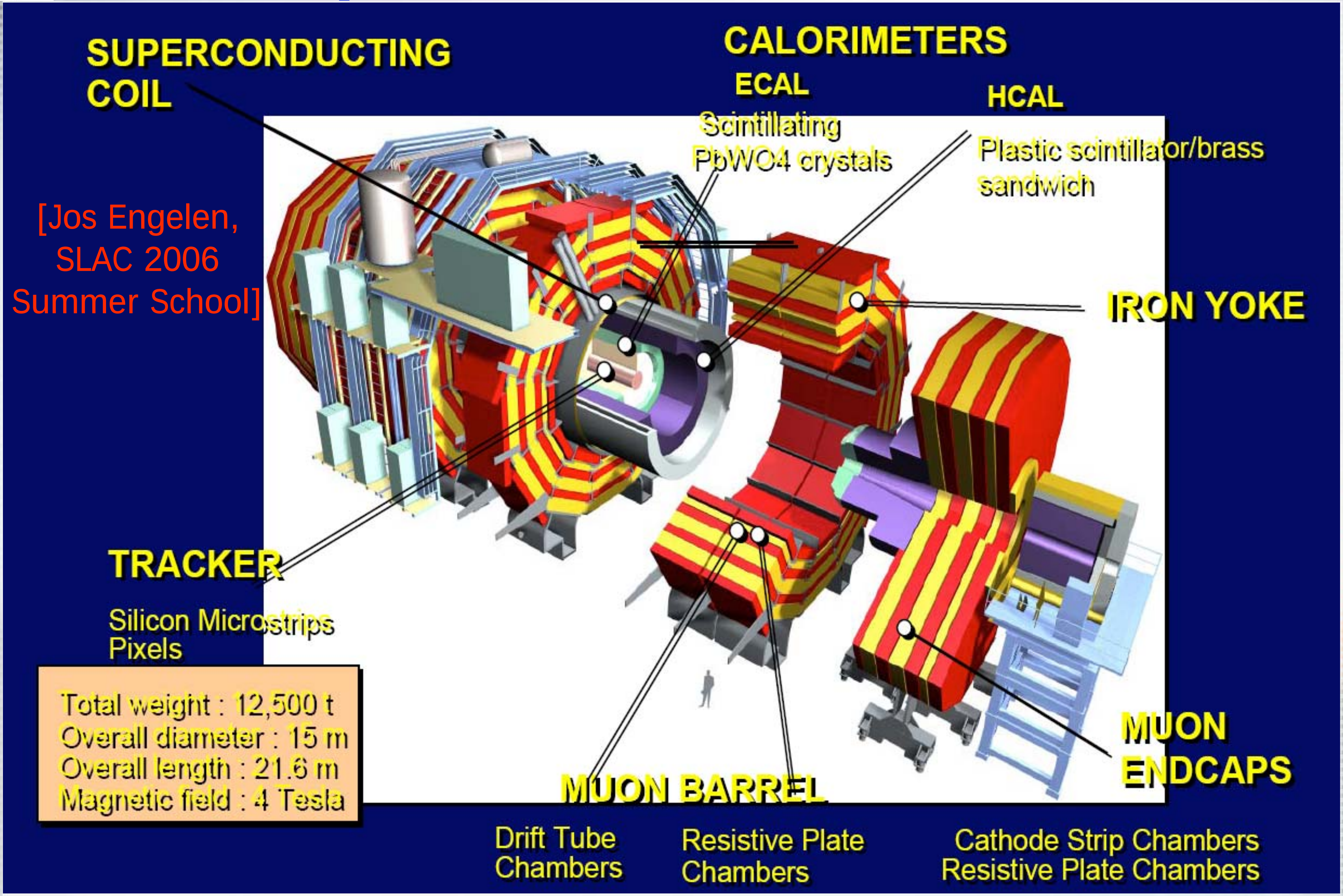
CMS in January



CMS in January



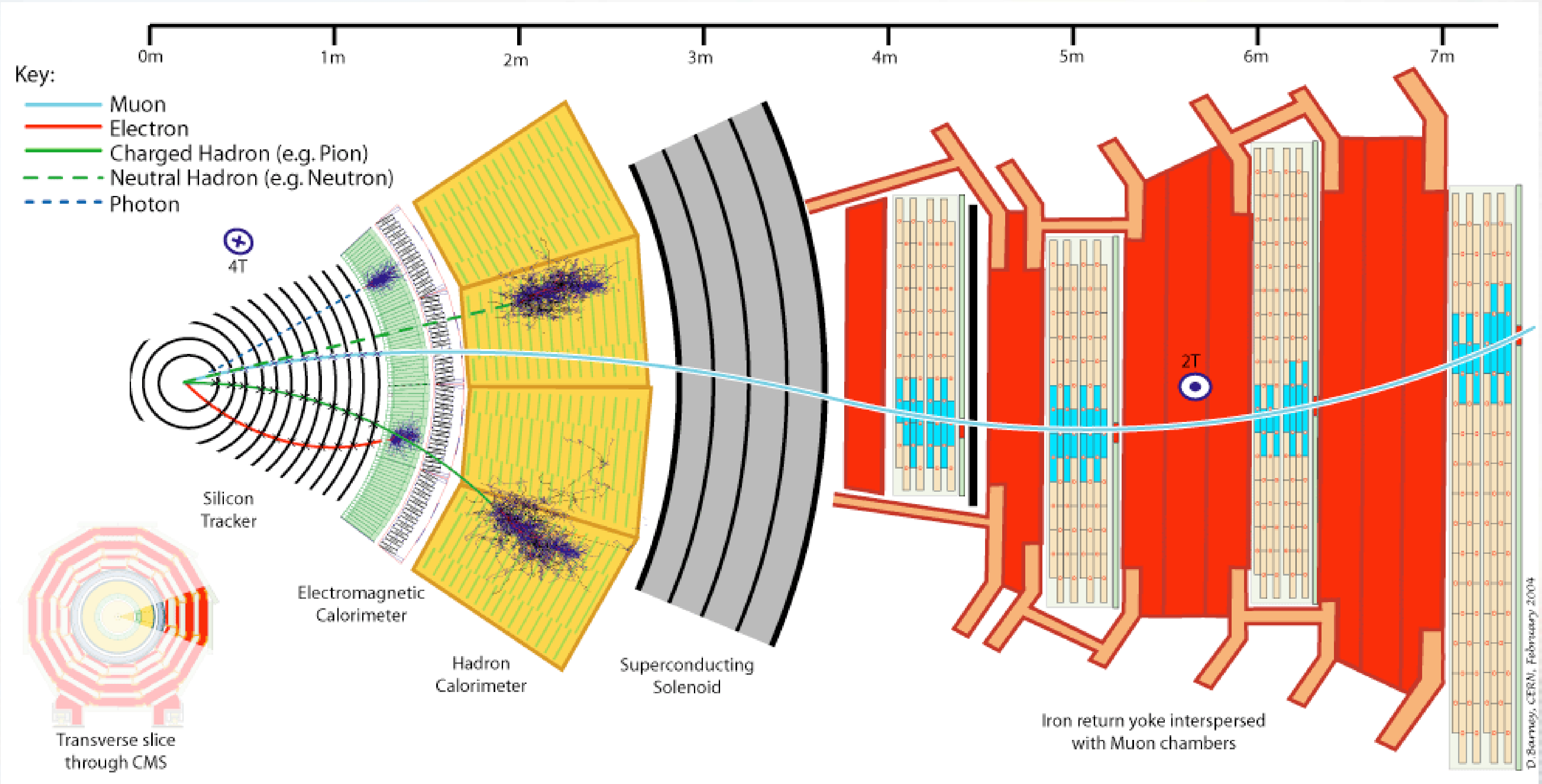
CMS Explained



[Jos Engelen, SLAC 2006 Summer School]

Detector Concept

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



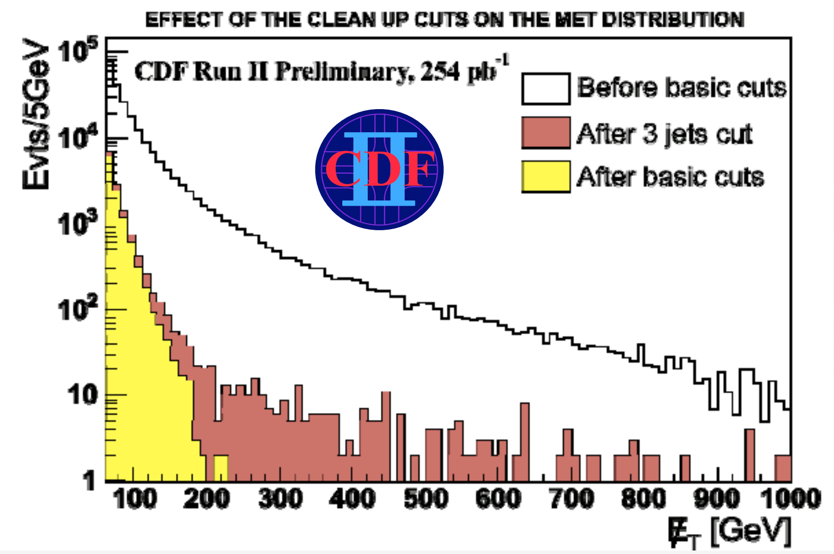
First Physics Roadmap

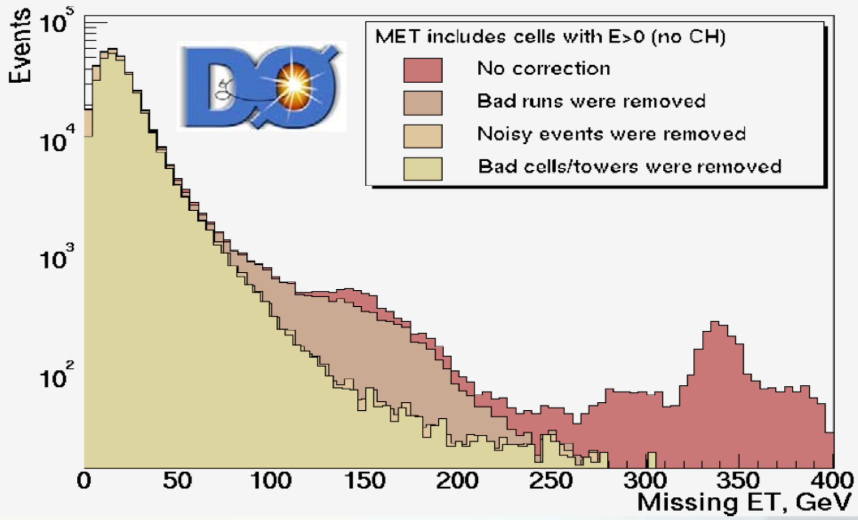
- **Prior to beam: early detector commissioning**
  - Readout & trigger tests, runs with all detectors (cosmics, test beams)
- **Early beam, up to $10 pb^{-1}$:**
  - Detector synchronization, alignment with beam-halo events, minimum-bias events. Earliest in-situ alignment and calibration
  - Commission trigger, start "physics commissioning":
    - Physics objects; measure jet and lepton rates; observe W, Z, top
    - And, first look at possible extraordinary signatures…
- **Physics collisions, $100 pb^{-1}$: measure Standard Model, start search**
  - 10^6 $W \to l \nu$ ($l = e,\mu$); 2×10^5 $Z \to ll$ ($l = e, \mu$); 10^4 $t\bar{t} \to \mu + X$
    - Improved understanding of physics objects; jet energy scale from $W \to j j'$; extensive use (and understanding) of b-tagging
    - Measure/understand backgrounds to SUSY and Higgs searches
  - Initial MSSM (and some SM) Higgs sensitivity
  - Early look for excesses from SUSY& Z′/jj resonances. SUSY hints (?)
- **Physics collisions, $1000 pb^{-1}$: entering Higgs discovery era**
  - Also: explore large part of SUSY and resonances at ~ few TeV

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:

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

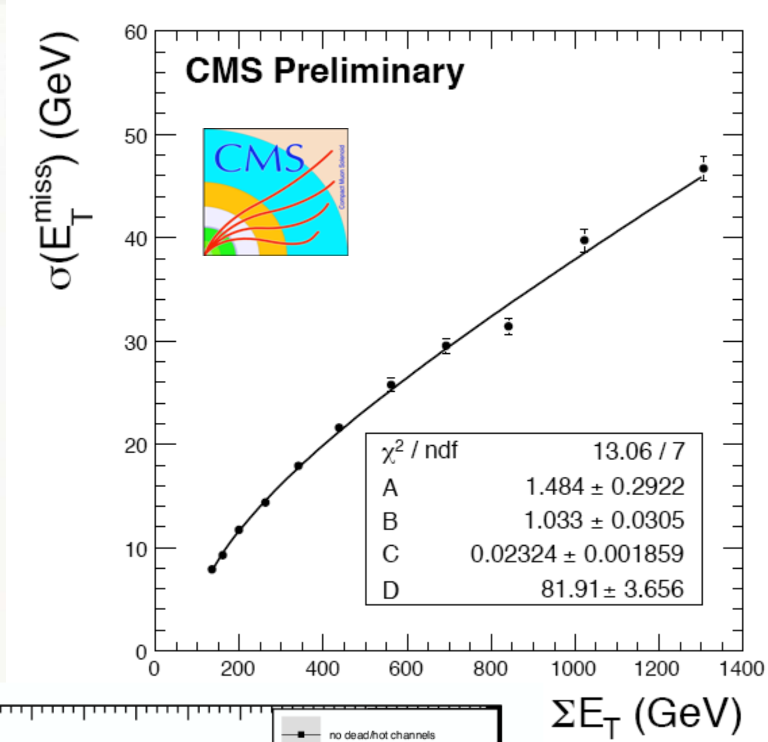
- ME_T resolution in QCD events depends on total energy deposit in the calorimeter and is often parameterized as a function of scalar E_T sum over the calorimeter cells, or S_T:

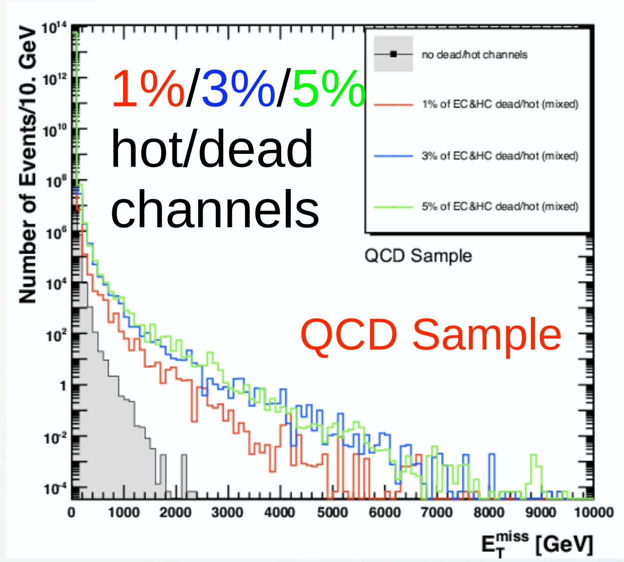
$$\sigma(\not{E}_T) = A \oplus B\sqrt{\Sigma E_T - D} \oplus C(\Sigma E_T - D)$$

Noise Stochastic Constant Offset

ME_T in CMS

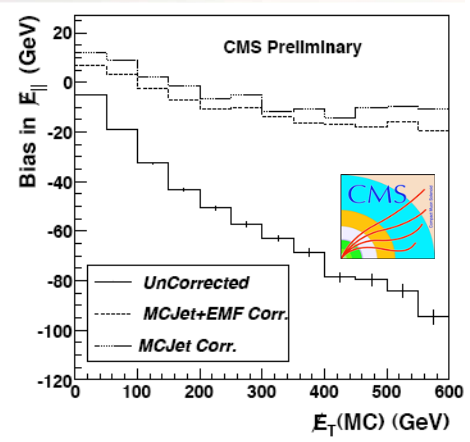
- Parameters:
  - A = 1.48 GeV
  - B = 1.03 GeV$^{1/2}$
  - C = 0.023 (dominates at large S_T)
  - D = 82 GeV
- Apart from the resolution an important characteristic is the non-Gaussian tails
- Very hard to simulate; will have to wait for real data to see how large the effect is
  - A few special cases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

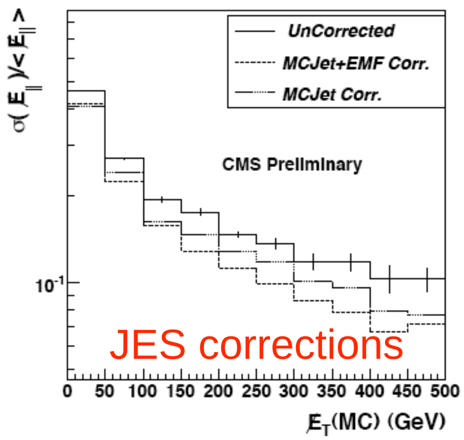


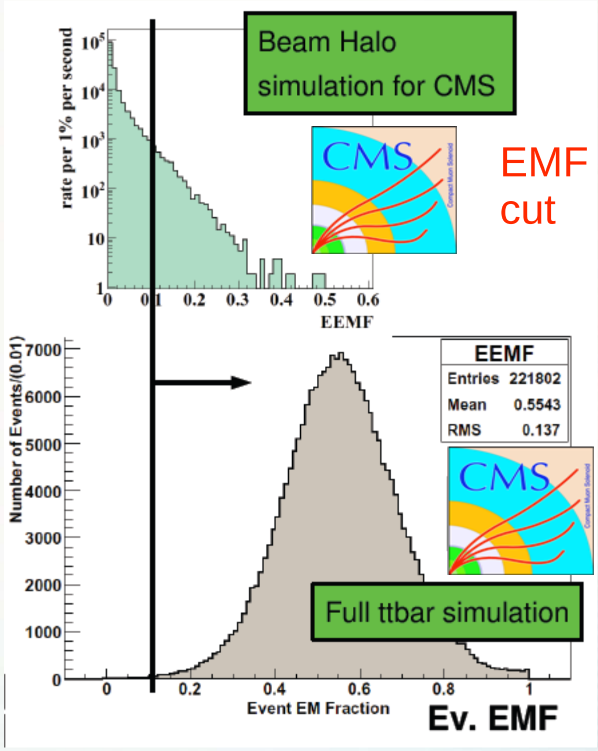


ME_T Corrections and Clean-Up

- 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



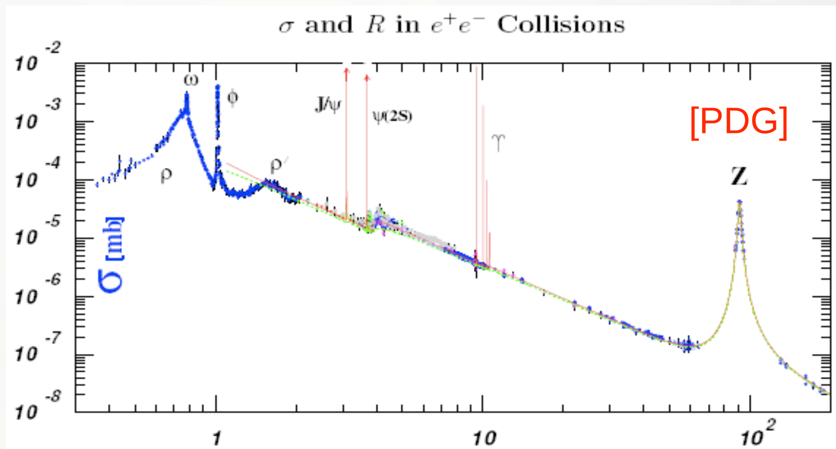


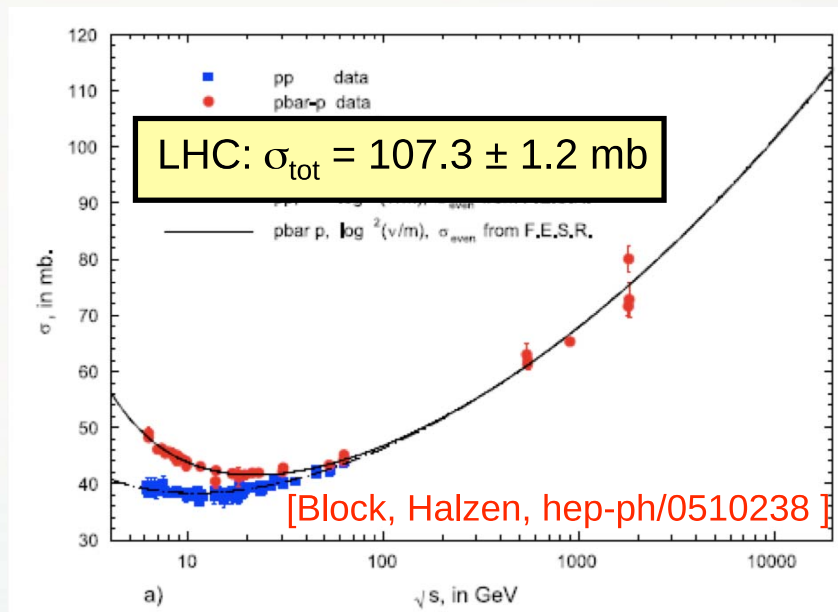


Trigger 101 for Theorists

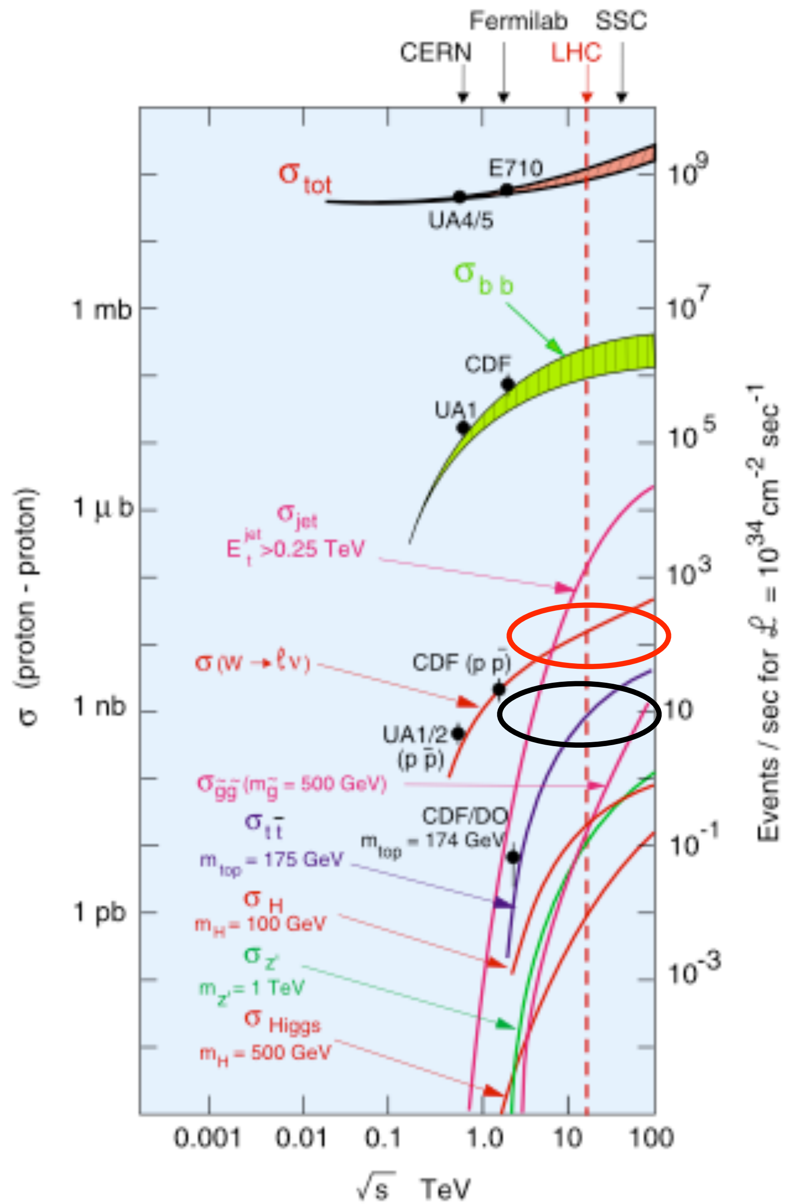
Triggering at Hadron Colliders

- e^+e^- colliders: low total cross section, low rates
  - Trigger pretty much on everything, perhaps with the exception of very forward processes (low-angle Bhabha)
- Hadron colliders: enormous cross section, unattainable rates
  - Trigger is very selective
  - Only small fraction of collisions is written to tape
  - Additional complications due to pile-up
- LHC:
  - σ_{tot} = 110 mb, σ_{in} ~ 70 mb
  - L = 10^{34} $cm^{-2}s^{-1}$ = 10 $nb^{-1}s^{-1}$
  - 25 ns bunch crossing
  - Total rate: ~10^9 s^{-1} or ~20/crossing
- Tevatron:
  - 1.5 smaller cross section; 50 times lower luminosity; 16 times longer crossing time: ~4/crossing





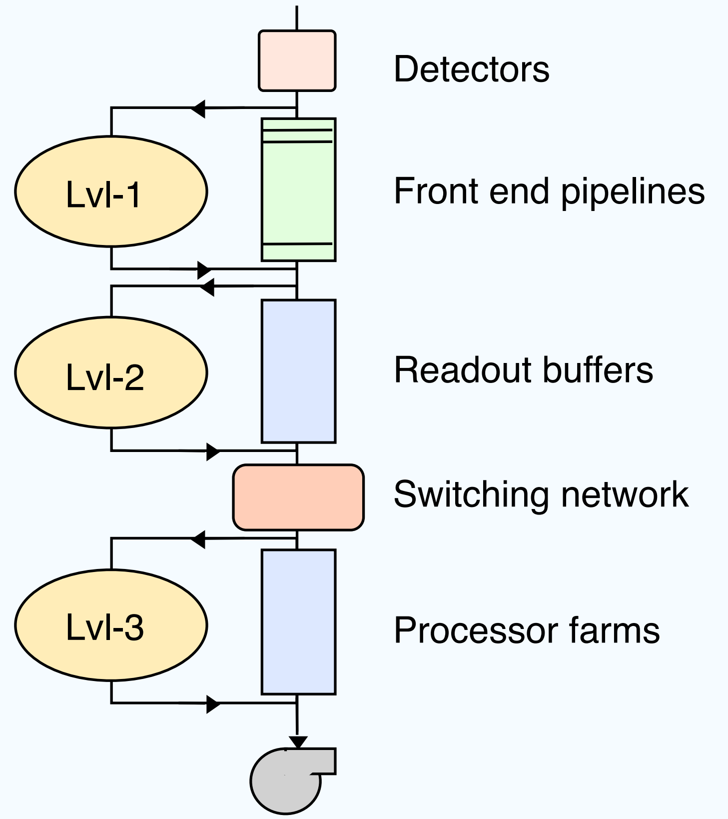
More Trigger Challenges



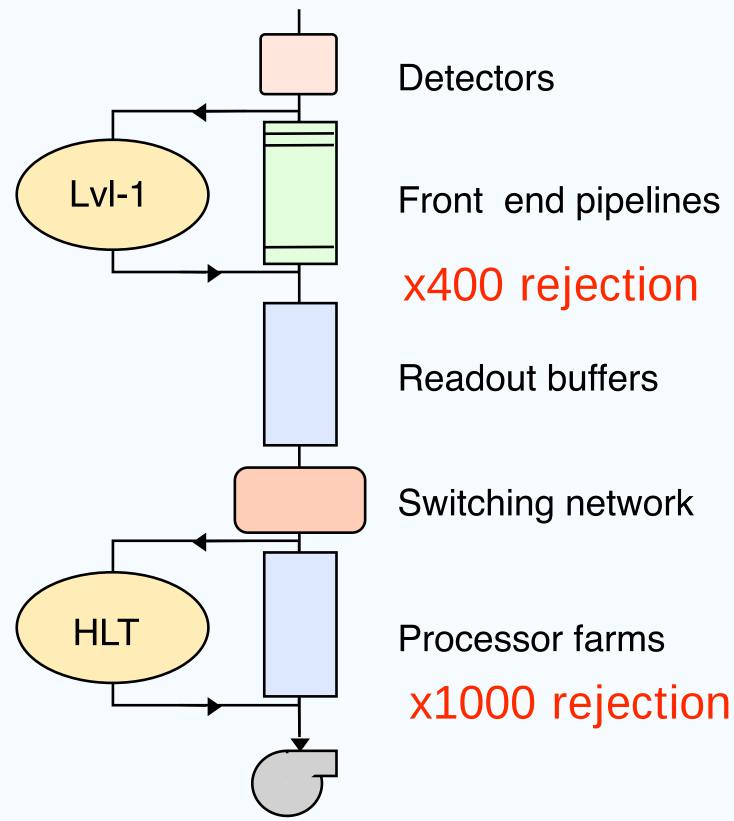
- LHC Physics Demands
  - –EWSB in SM (Higgs, W, Z)
    - Lepton/photons E_T ~ 50 GeV
    - High rate (10 Hz of top events and 200 Hz of W(lν) events!)
  - –TeV scale supersymmetry, UED
    - Multiple leptons, jets and LSPs (missing E_T), E_T < 100 GeV
- QCD Background
  - –Jet E_T ~ 250 GeV, rate ~ 1 kHz
  - –Jet fluctuations ⇒ electron BG
  - –Decays of p, K, B ⇒ muon BG
- Technical challenges
  - –40 MHz input ⇒ fast processing
  - –100 Hz output ⇒ physics selection
  - –10^9 events per year ⇒ ≤10^2 Higgs events
- Benchmark: σ = 100 pb → 1 Hz

Trigger Architecture

- Must reduce 2.5-40 MHz of input interactions to 50-100 Hz
  - Do it in steps/successive approximations: “Trigger Levels”



“Traditional”: 3 physical levels, ATLAS



CMS: 2 physical levels

The 2007 "HLT Exercise"

- Much of the CMS startup trigger development took place during the 2007 "HLT Exercise":
  - CMS AN/2007-009
  - CERN/LHCC 2007-021
- The primary goal was to fit the time budget, so many triggers are not yet optimized for efficiency
- Subsequent optimization is ongoing
- Combination of robust single-object triggers and more efficient multiobject ones
- Backup triggers for crucial physics processes
- Global variable triggers (H_T, S_T, ME_T, etc.)

Available on the CMS information server **CMS AN 2007/009**

CMS Analysis Note

The content of this note is intended for CMS internal use and distribution only

October 29, 2007

CMS High Level Trigger

D. Acosta[30], N. E. Adam[33], J. Alcaraz Maestre[17], N. Amapane[15], L. Apanasevich[31], A. Aurisano[36], A. Avetisyan[26], S. Baffioni[6], R. Bainbridge[25], S. Bansal[7], P. Bargassa[35], C. Battilana[11], R. Bellan[15], U. Berthon[6], A. Bocci[13], T. Bose[26], V. Brigljevic[4], J. Brooke[23], M. Chen[30], L. Christofek[26], B. Dahmes[32], S. Dasu[37], E. Delmeire[18], A. Everett[34], M. Felcini[9], T. M. Frueboes[16], D. Futyan[25], S. Gennai[14], V. Ghete[1], A. Ghezzi[19], D. Giordano[10], S. Goy Lopez[19], S. Greder[25], M. W. Grünewald[9], L. Gray[30], M. F. Hansen[23], G. Heath[23], M. Huhtinen[19], A. Kalinowksi[16], M. Konecki[16], D. Kotlinski[20], V. Krutelyov[28], G. Landsberg[26], D. Lange[32], S. Lehti[5], G. D. Lentdecker[2], J. Leonard[37], C. Leonidopoulos[19], C. Liu[34], B. Mangano[27], K. Mazumdar[8], I. Mikulec[1], M. U. Mozer[3], M. Narain[26], N. Neumeister[34], C.N. Nguyen[36], D. Nguyen[26], A. Nikitenko[25], P. Paganini[6], E. Perez[19], K. Petridis[25], M. Pieri[27], A.N. Safonov[36], S. Sarkar[13], W. Smith[37], T. Speer[22], P. Sphicas[19], W. Sun[29], A. Tapper[25], I.R. Tomalin[24], J.F. de Trocóniz[18], P. Trüb[21], A. Tumanov[35], M. Vander Donckt[19], S. Vanini[12], M. Vazquez Acosta[19], M. Weinberger[36], J. S. Werner[33], L. Wilke[22], M. Wingham[25], G. Wrochna[16], and P. Zotto[12]

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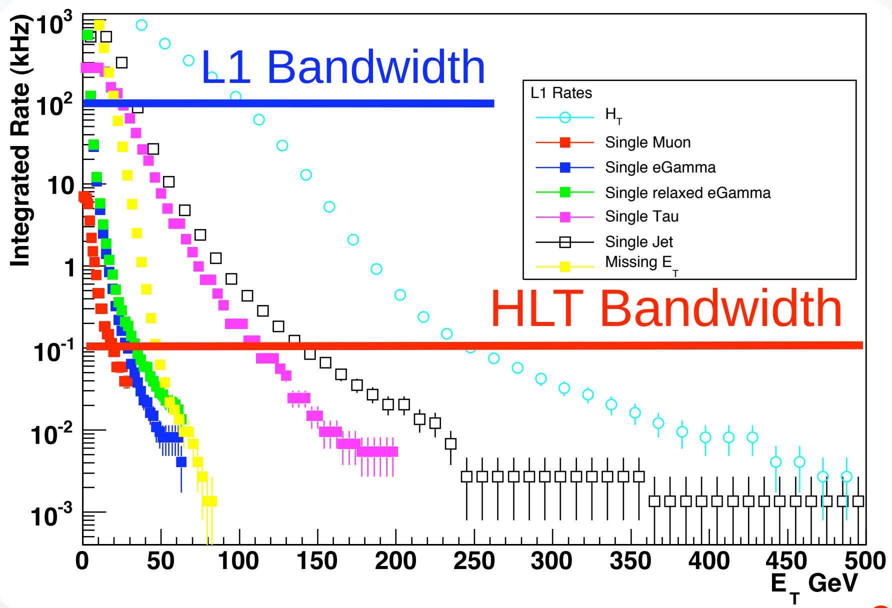
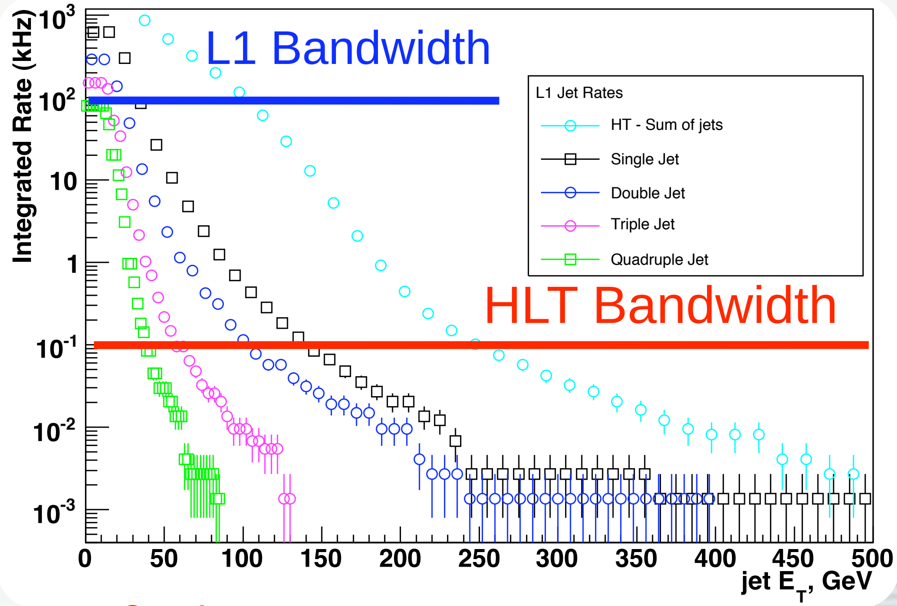
Typical Trigger Rates

- These rate plots give a good idea where one can expect L1 and HLT thresholds for single and multiple-object triggers
  - Caveat: all the rates are known only within a factor of ~3
  - Nevertheless, for low startup luminosity most of processes can be triggered on with either single-object or robust multijet triggers

Single-object triggers



Multijet triggers



$L = 10^{32}\ cm^{-2}s^{-1}$

Example: Jets/ME_T Triggers

- Well-designed suite of Jet/ME_T triggers
- Challenge to keep it at higher luminosities
- ME_T trigger may be very unstable at turn-on
- MH_T trigger is being implemented as a more robust alternative

L1 Triggers

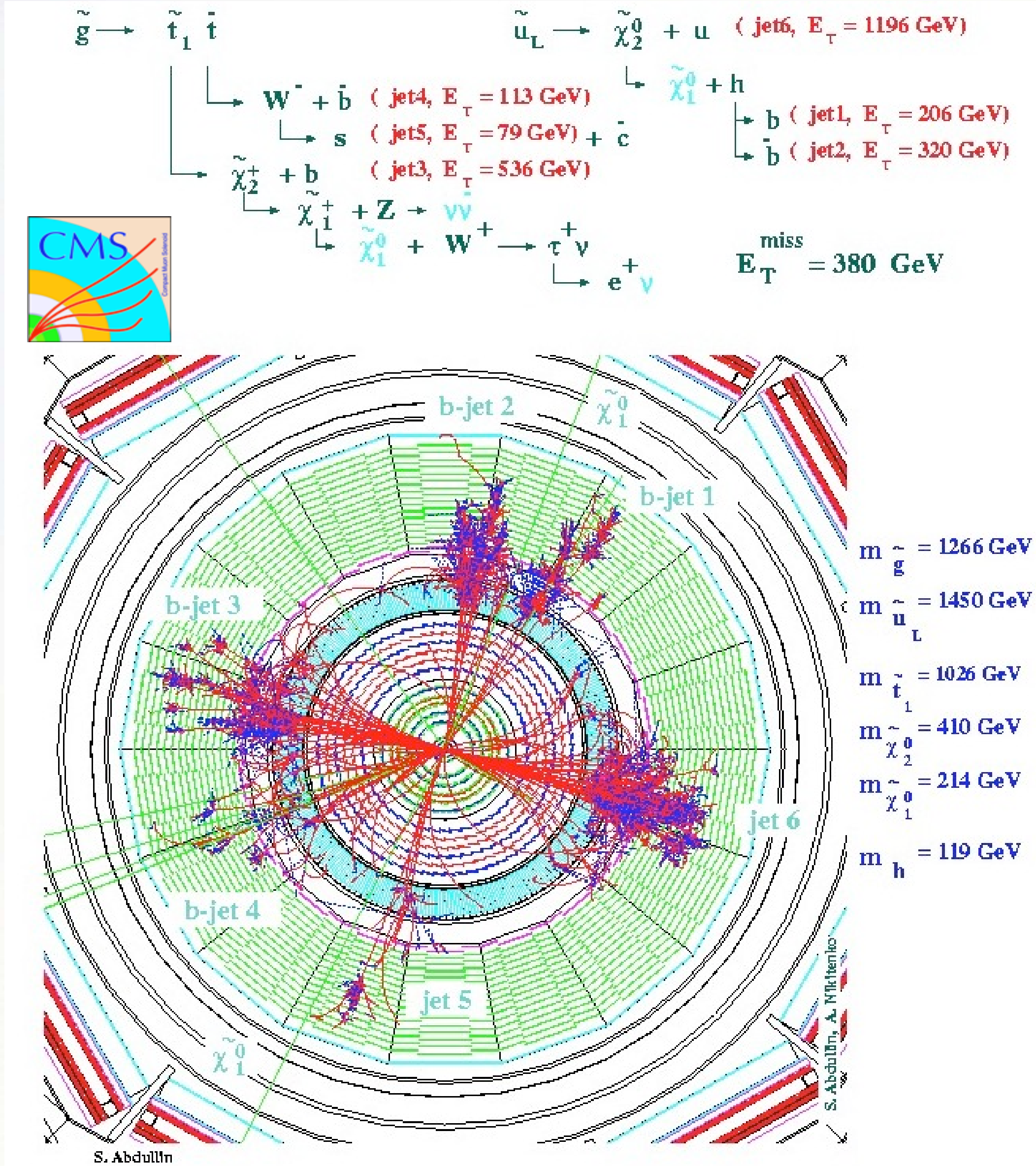
Name	L1 thrsh	Prscl	KHz
A_SingleJet30	30	1000	0.00 ± 0.00
A_SingleJet70	70	100	0.02 ± 0.01
A_SingleJet100	100	10	0.04 ± 0.02
A_SingleJet150	150	1	0.07 ± 0.01
A_SingleJet200	200	1	0.02 ± 0.01
A_HTT250	250	1	2.56 ± 0.06
A_HTT300	300	1	0.65 ± 0.03
A_HTT400	400	1	0.08 ± 0.01
A_HTT500	500	1	0.02 ± 0.00
A_ETM20	20	10000	0.00 ± 0.00
A_ETM30	30	1	5.69 ± 0.09
A_ETM40	40	1	0.40 ± 0.02
A_ETM50	50	1	0.05 ± 0.01
A_ETM60	60	1	0.01 ± 0.00
A_DoubleJet70	70	1	0.58 ± 0.03
A_DoubleJet100	100	1	0.11 ± 0.01
A_TripleJet50	50	1	0.22 ± 0.02
A_QuadJet30	30	1	0.58 ± 0.03

HLT Triggers

Name	L1 Trigger	HLT thrsh	Hz
Single-Jet	A_SingleJet150	200	9.3 ± 0.1
Double-Jet	A_SingleJet150 A_DoubleJet70	150	10.6 ± 0.0
Triple-Jet	†	85	7.5 ± 0.1
Quad-Jet	‡	60	3.9 ± 0.1
$\not\!\!E_T$	A_ETM40	65	4.9 ± 0.7
Acopl. Double-Jet	A_SingleJet150 A_DoubleJet70	125	1.4 ± 0.0
Acopl. Single-Jet + $\not\!\!E_T$	A_ETM30	(100, 60)	1.6 ± 0.0
Single-Jet + $\not\!\!E_T$	A_ETM30	(180, 60)	2.2 ± 0.1
Double-Jet + $\not\!\!E_T$	A_ETM30	(125, 60)	1.0 ± 0.0
Triple-Jet + $\not\!\!E_T$	A_ETM30	(60, 60)	0.6 ± 0.0
Quad-Jet + $\not\!\!E_T$	A_ETM30	(35, 60)	1.2 ± 0.1
$H_T + \not\!\!E_T$	A_HTT300	(350, 65)	4.4 ± 0.1
Single Jet Prescale 10	A_SingleJet100	150	3.5 ± 0.0
Single Jet Prescale 100	A_SingleJet70	110	1.5 ± 0.0
Single Jet Prescale 10^4	A_SingleJet30	60	0.8 ± 0.4
VBF Double-Jet + $\not\!\!E_T$	A_ETM30	(40, 60)	0.2 ± 0.0
SUSY 2-jet+$\not\!\!E_T$	A_ETM30	(80,20,60)	2.0 ± 0.1
Acopl. Double-Jet + $\not\!\!E_T$	A_ETM30	(60, 60)	1.0 ± 0.0

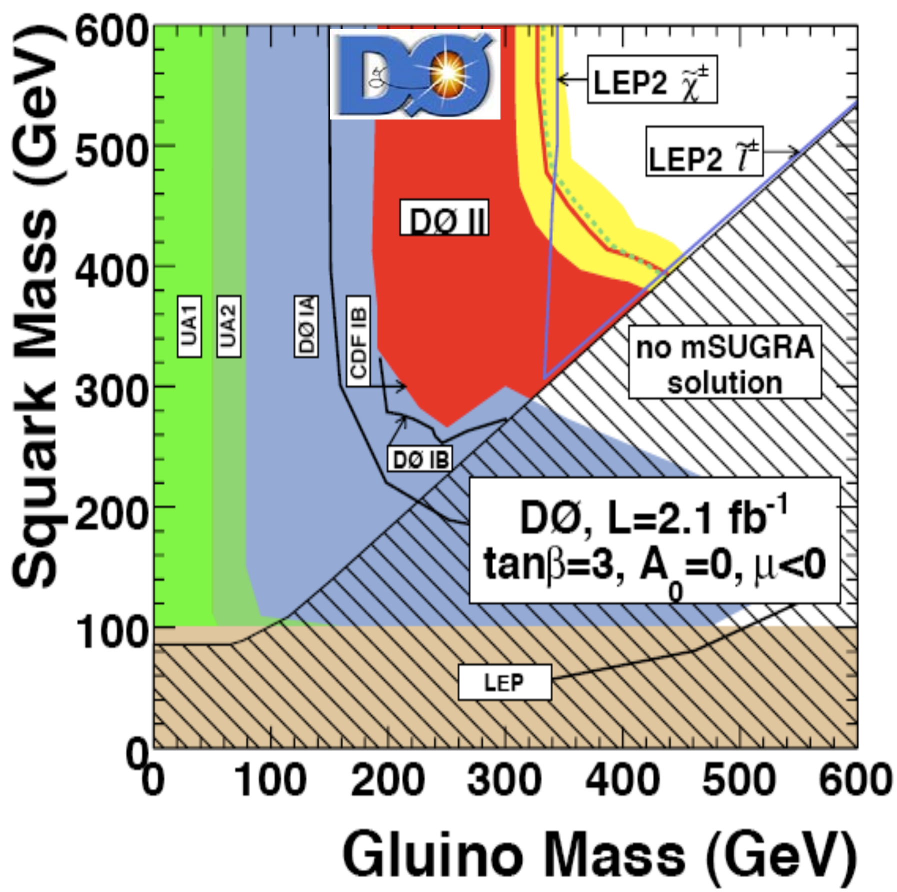
Example 1: SUSY in Jets + ME_T

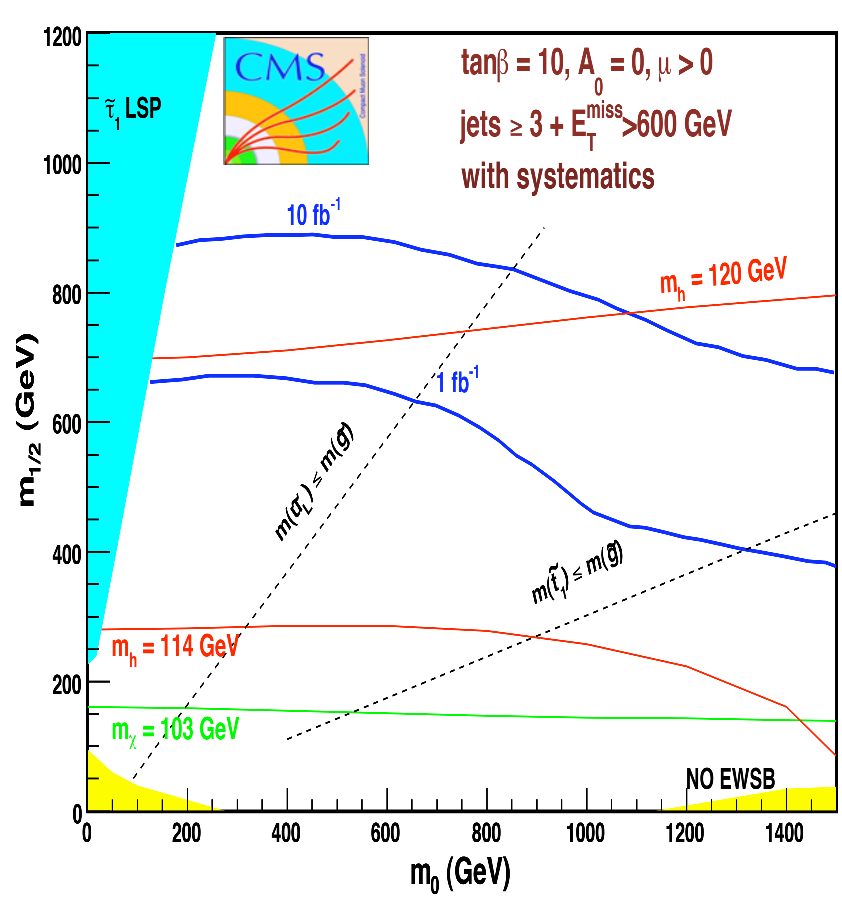
Strong Production, Complicated Events



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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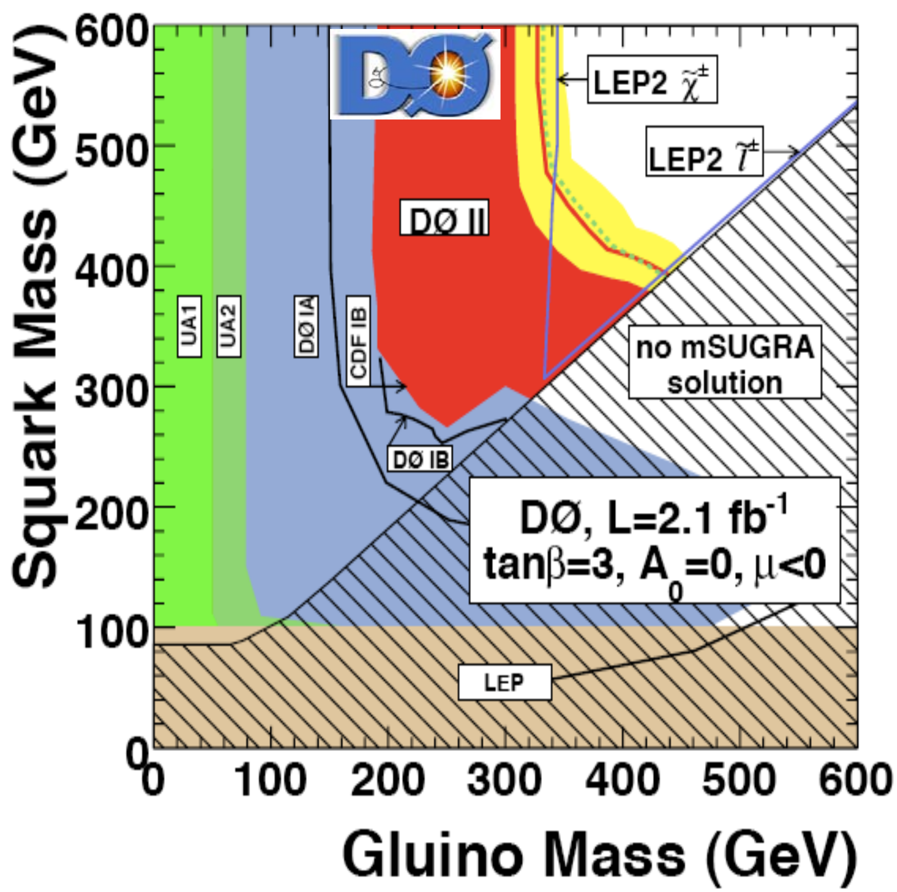
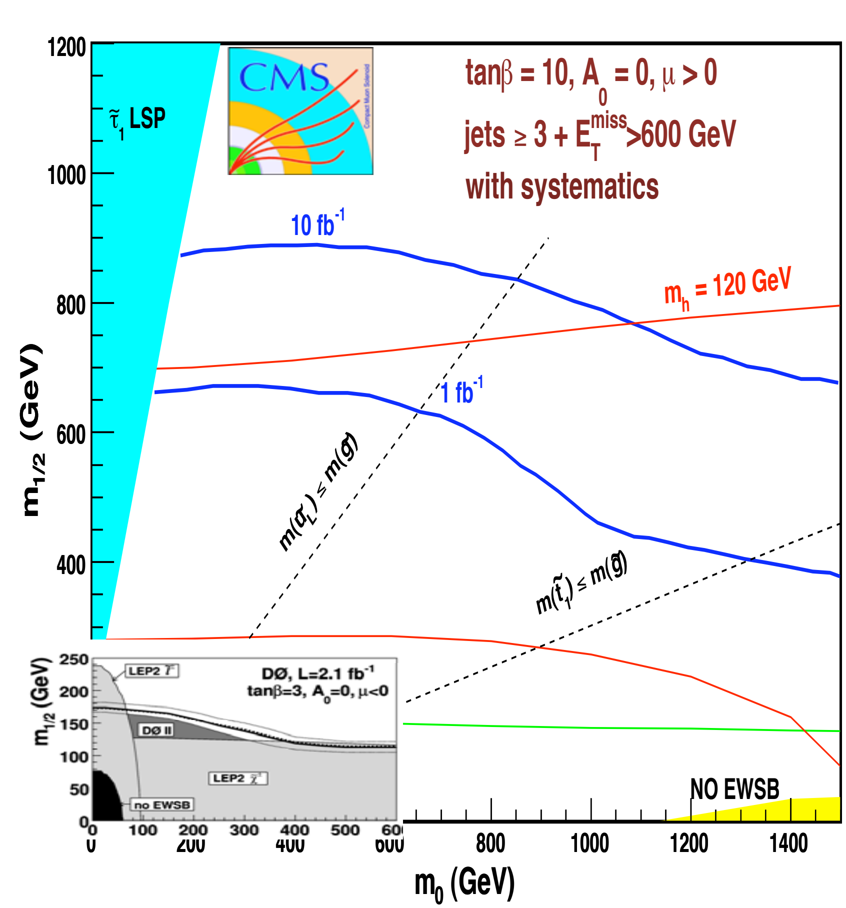
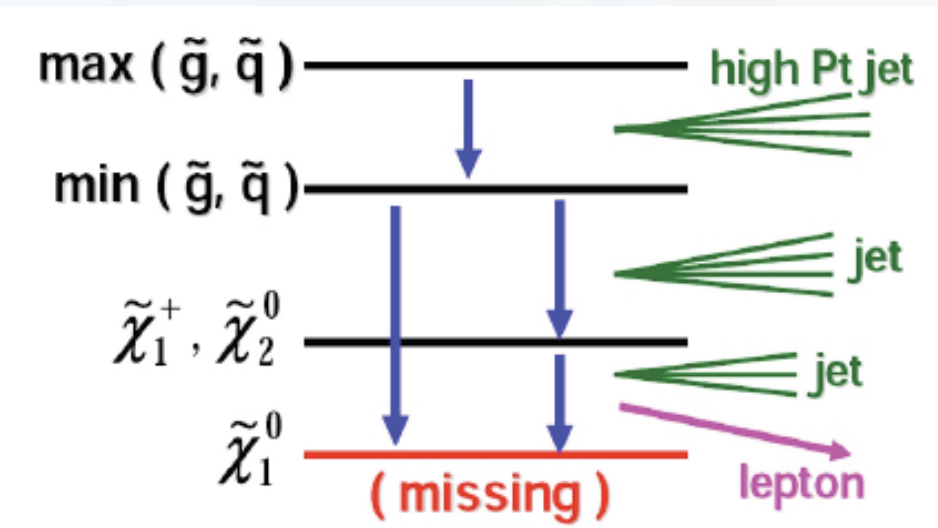
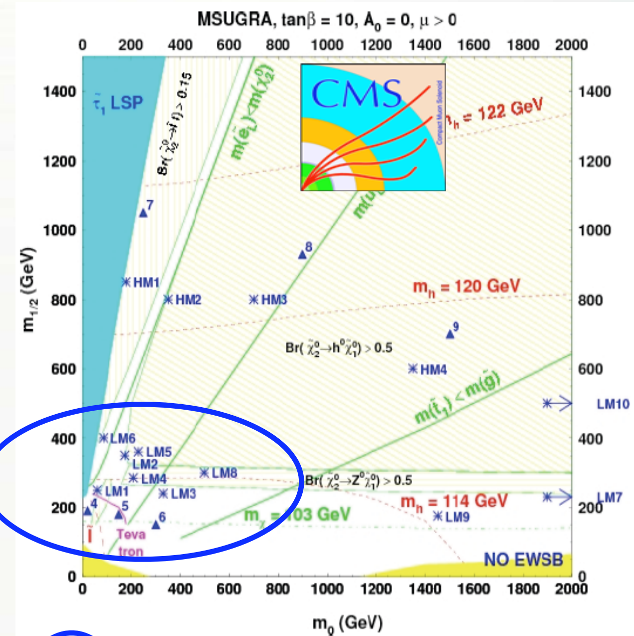




SUSY Event Selection

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



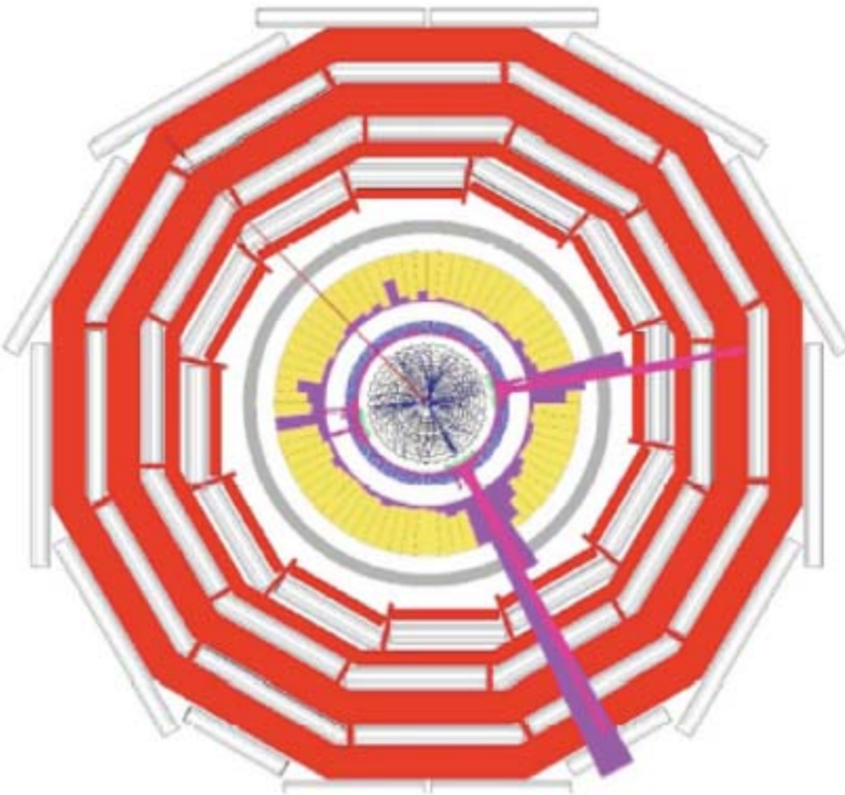


$ME_T > 200$ GeV

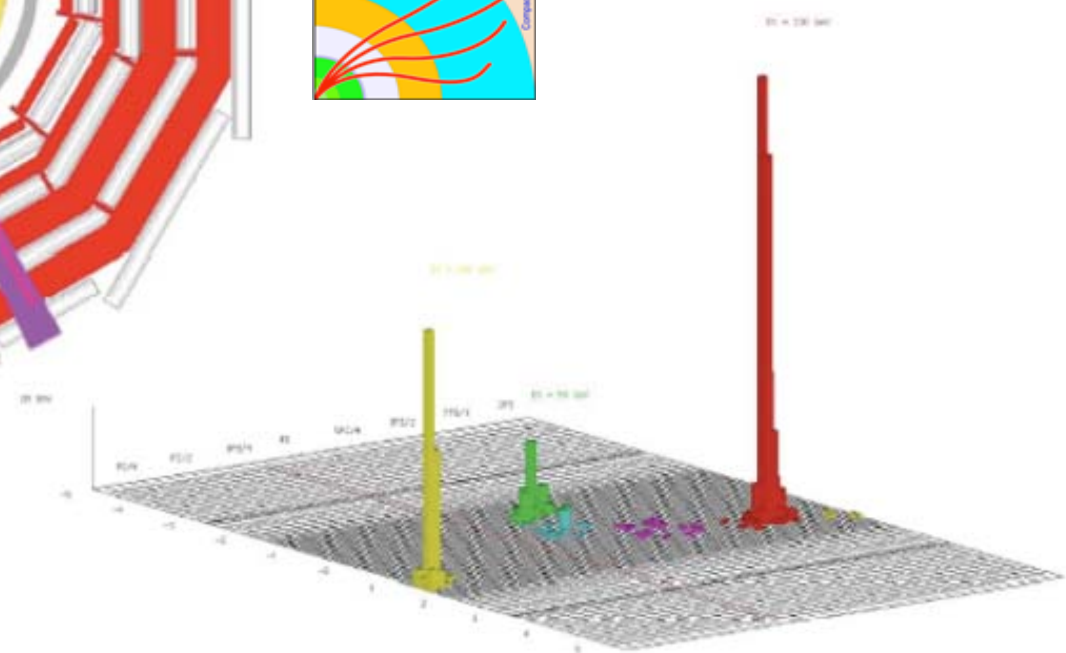
$N_j \geq 3, \lvert\eta_d^{1j}\rvert < 1.7$	signal signature
$\delta\phi_{min}(E_T^{miss} - jet) \geq 0.3$ rad, $R1, R2 > 0.5$ rad, $\delta\phi(E_T^{miss} - j(2)) > 20^\circ$	QCD rejection
$Iso^{lead\ trk} = 0$	ILV (I) $W/Z/t\bar{t}$ rejection
$f_{em(j(1))}, f_{em(j(2))} < 0.9$	ILV (II), $W/Z/t\bar{t}$ 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	$m_{1/2}$	$\tan\beta$	$\mathrm{sgn}(\mu)$	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

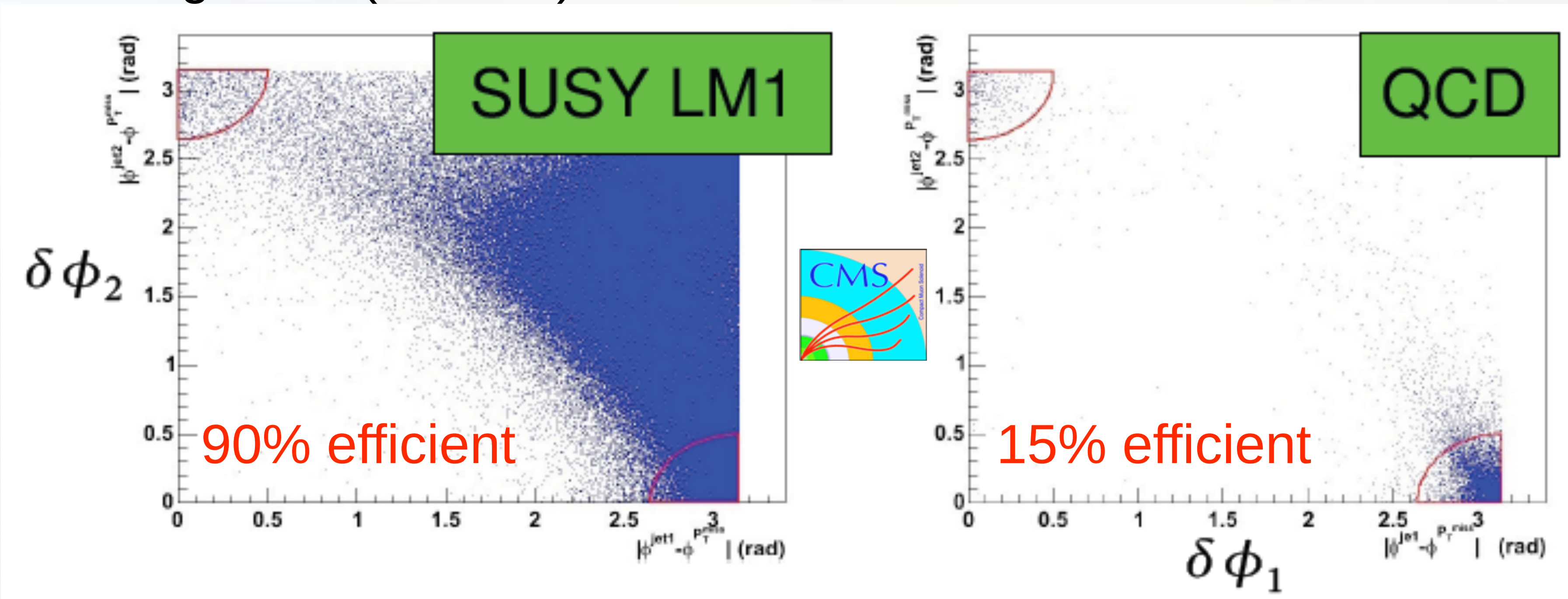


- A SUSY candidate event :
  - Leading jets ET = 330, 140, 60 GeV
  - MET = 360 GeV



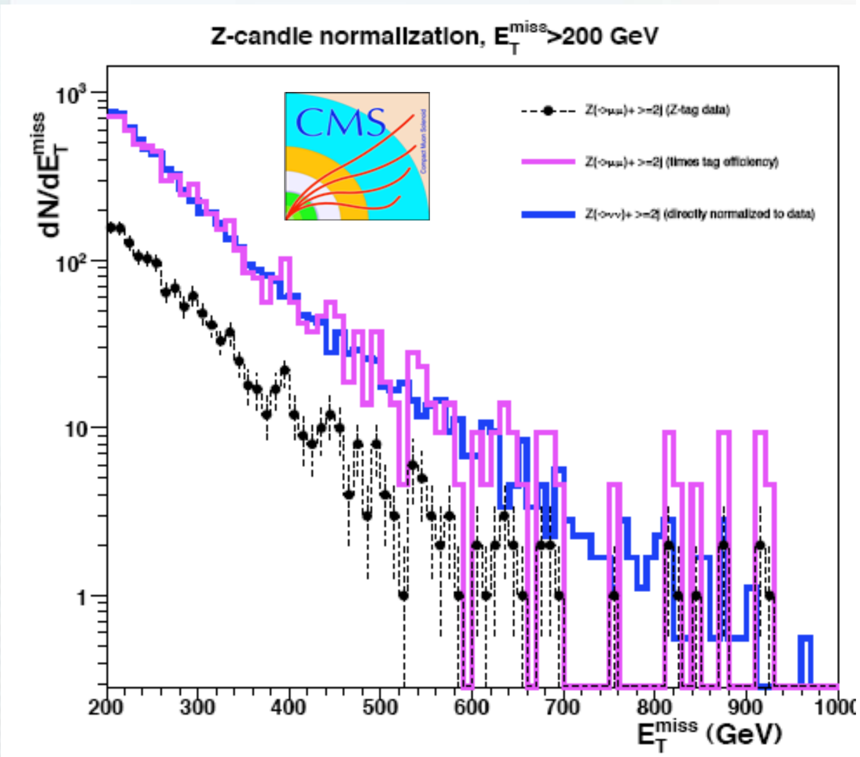
QCD Background Rejection

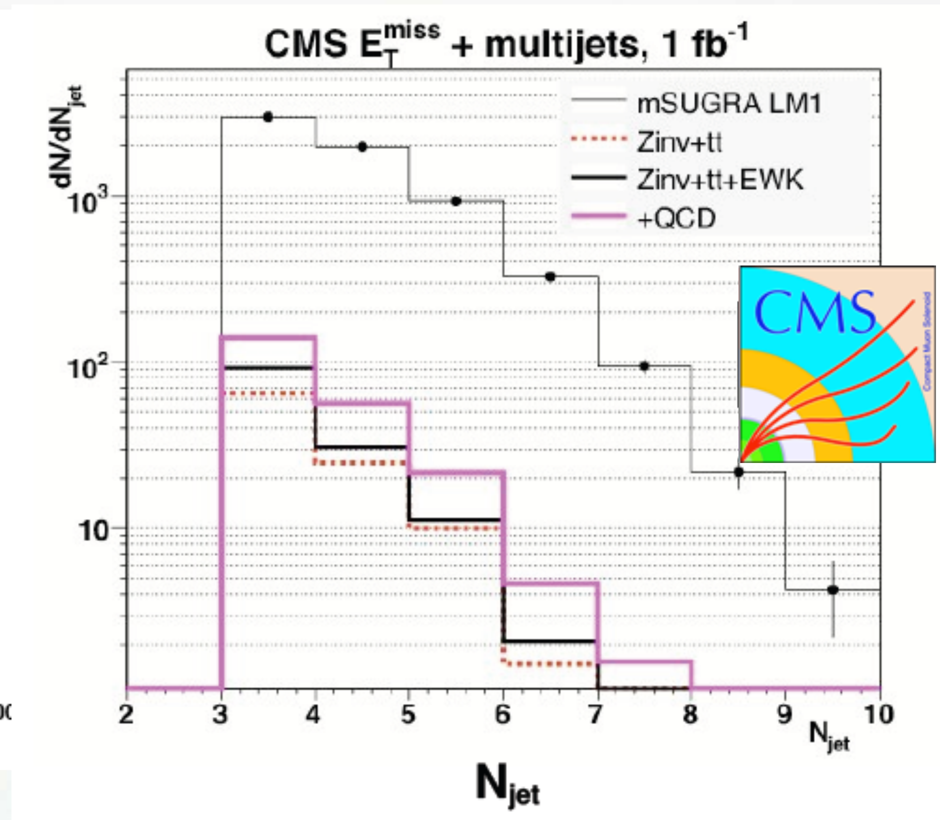
- The dominant background is QCD multijet production with fake ME_T
- Can be effectively reduced by requiring the minimum angular separation between the ME_T vector and the direction of jet 1 (leading) or jet 2 (subleading)
- Use extrapolation from low MET region to estimate residual background (a la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



Z(νν) + Jets: Estimate from Data

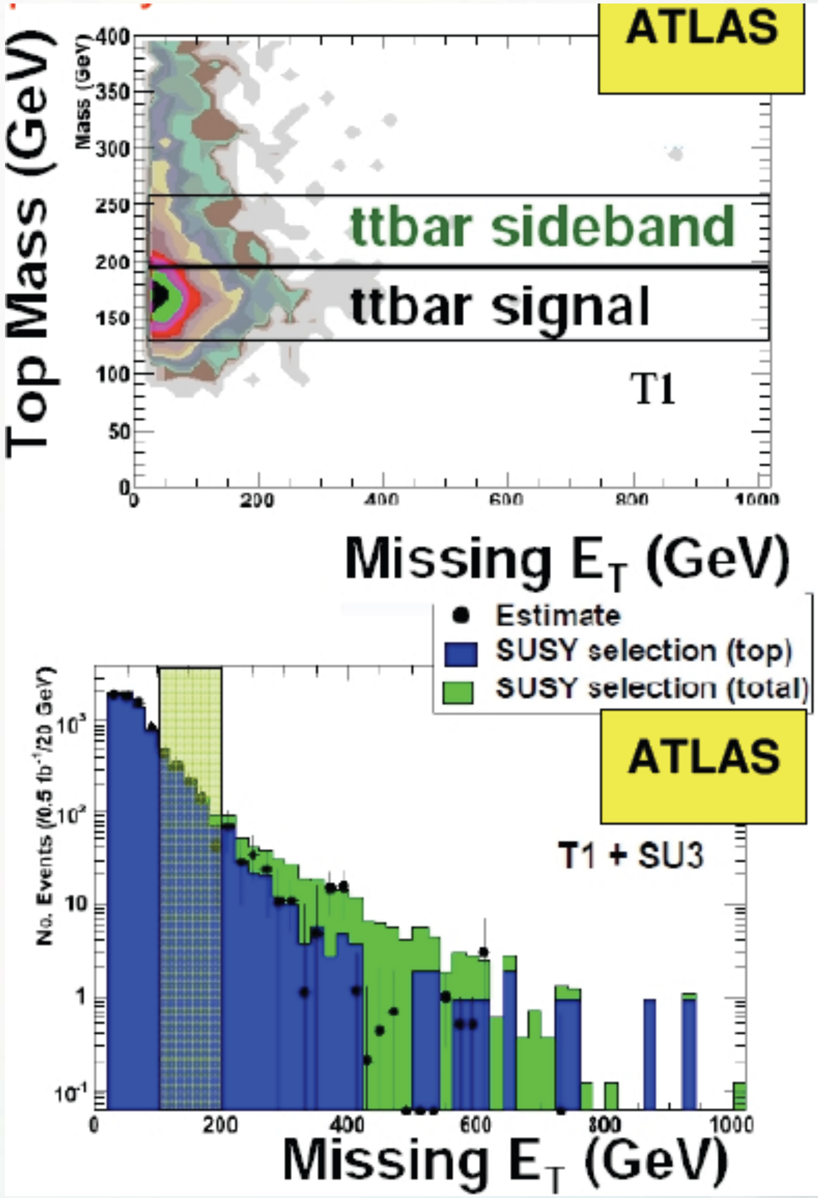
- Use Z(ee) and Z(μμ) + jets for normalization; acceptance corrections via MC
- Necessary since the signal and background shapes are similar





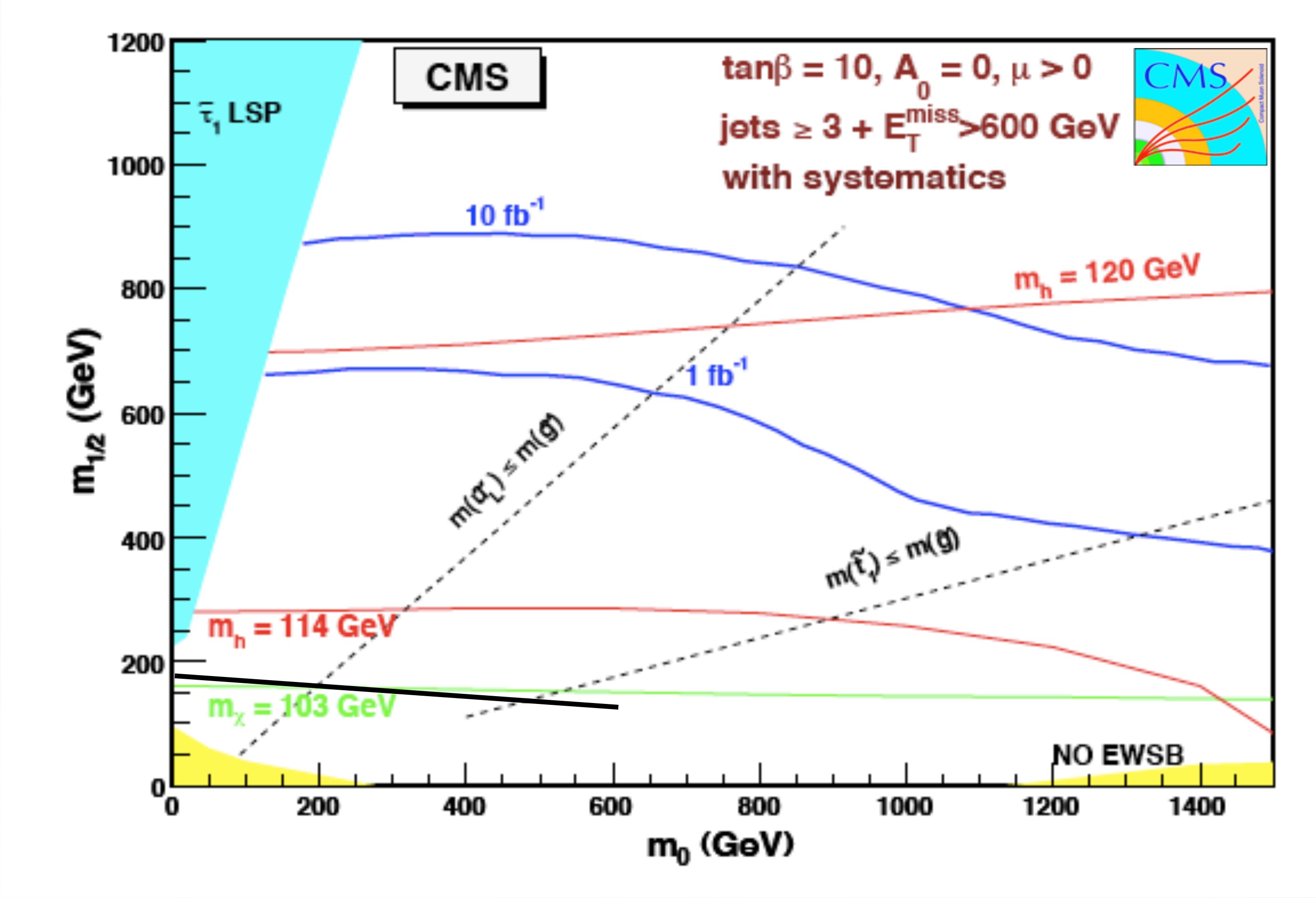
tt Background

- 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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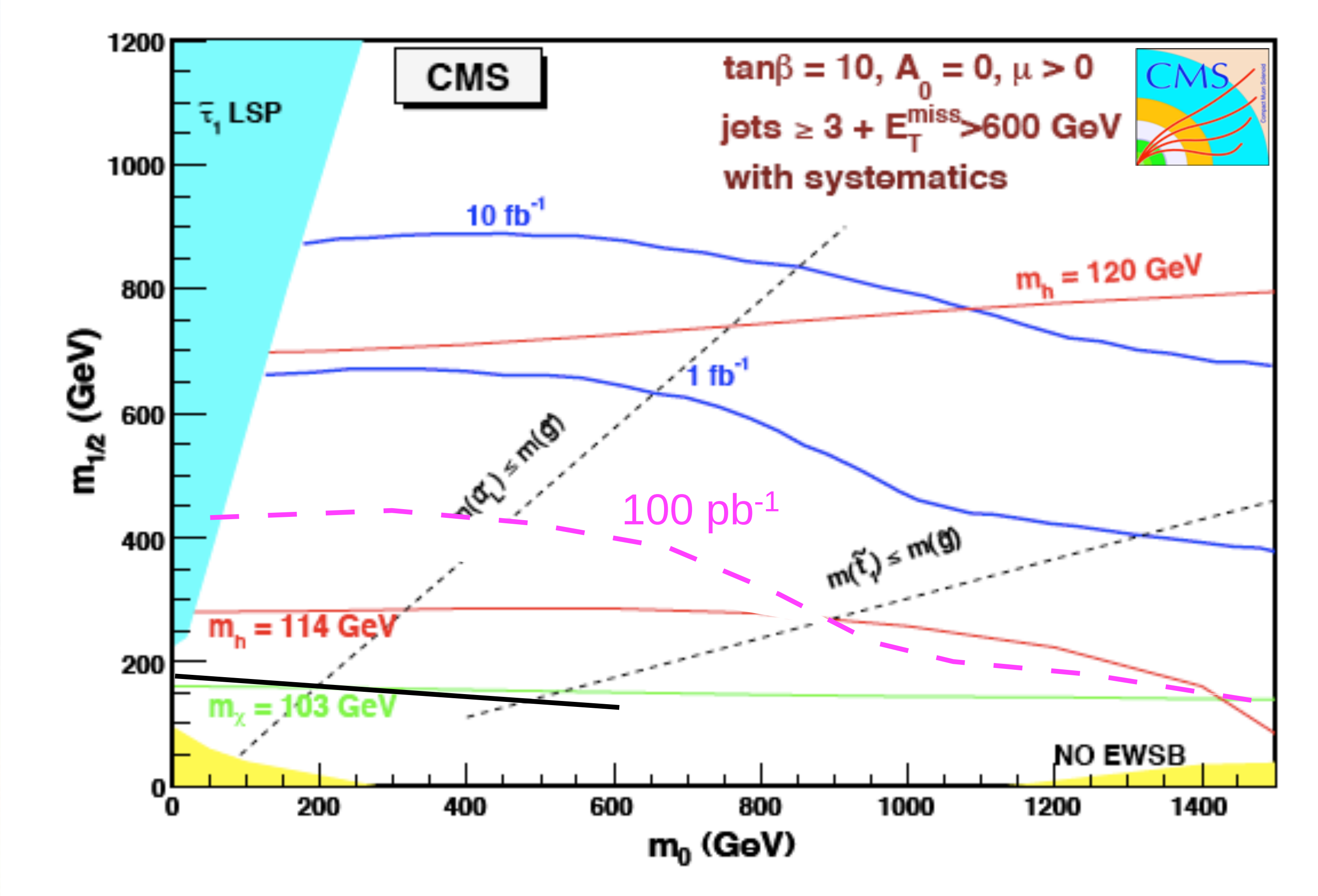
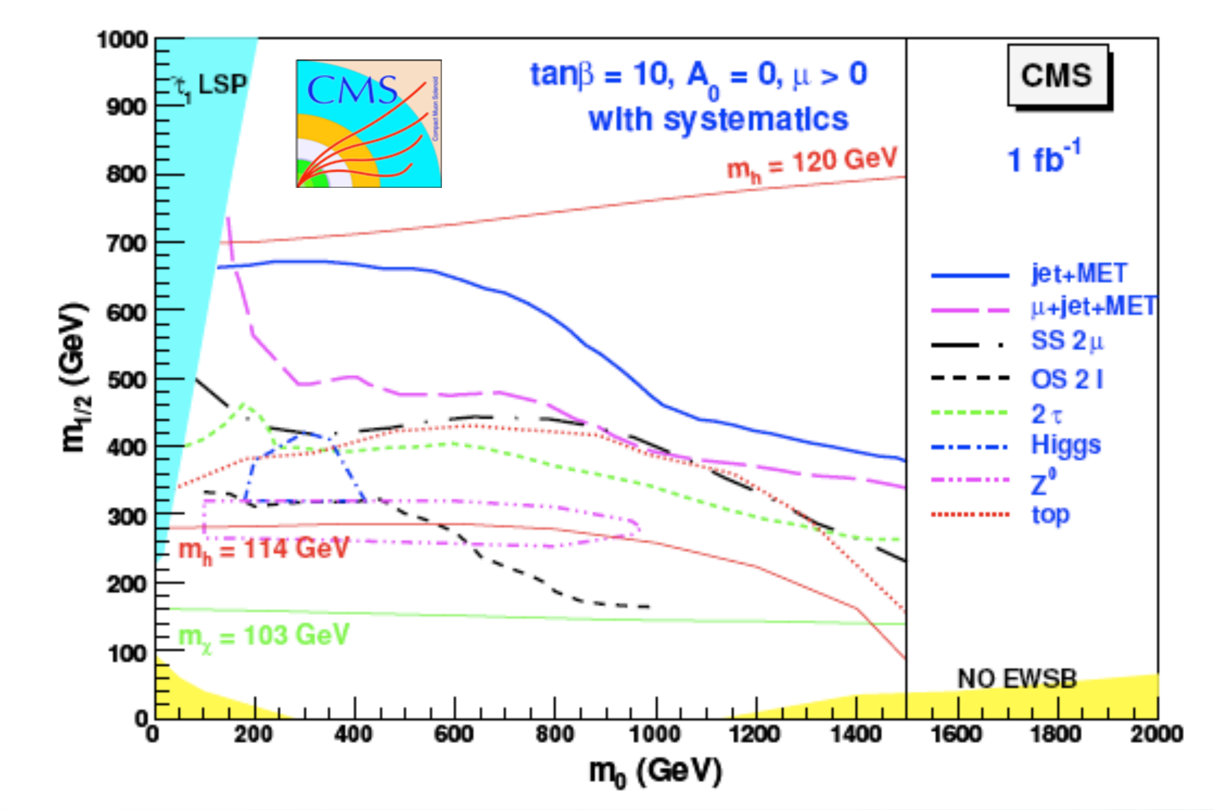


Other SUSY Channels

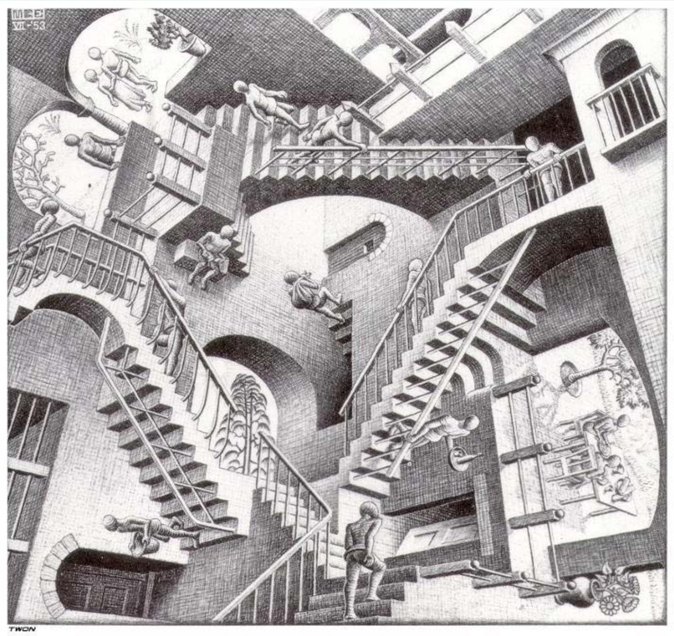
- Clearly, a number of channels will be investigated in parallel, including lepton+jets, like- and opposite-sign dileptons, channels with tau's, and MSSM Higgs searches
- Sensitivity in all these channels is being reevaluated using most realistic simulation available
- Previous studies suggest that the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



(More) Exotic Models

"Particles, particles, particles."

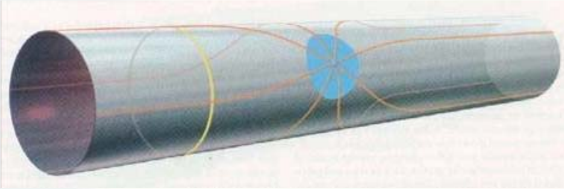
Example 2:
Extra Dimensions in Space



Extra Dimensions: a Brief Recap

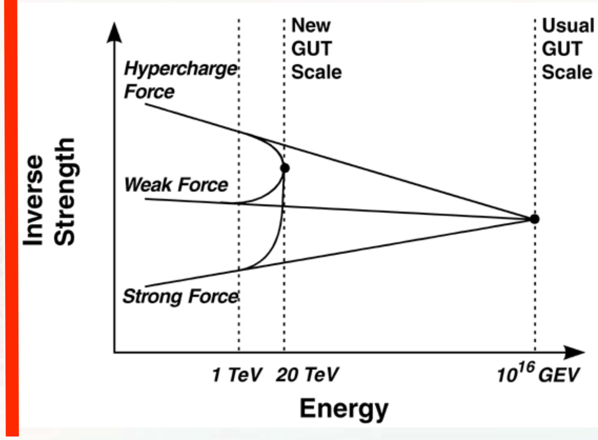
ADD Paradigm:

- 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



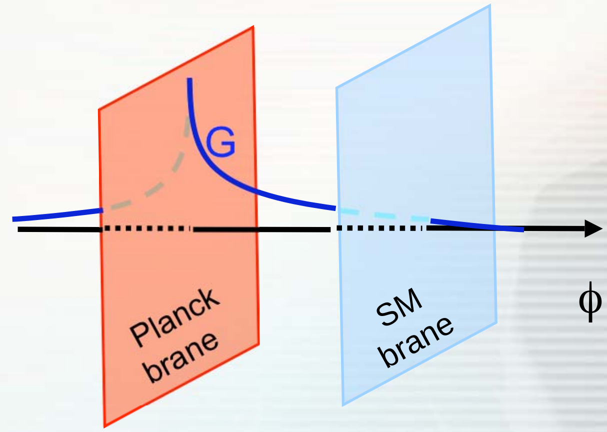
TeV^{-1} Scenario:

- 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:

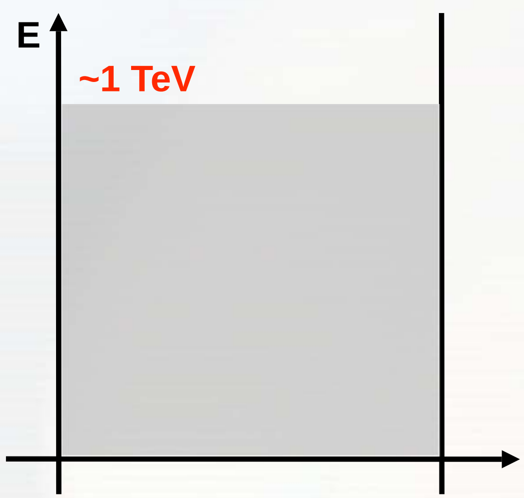
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

ADD Paradigm:

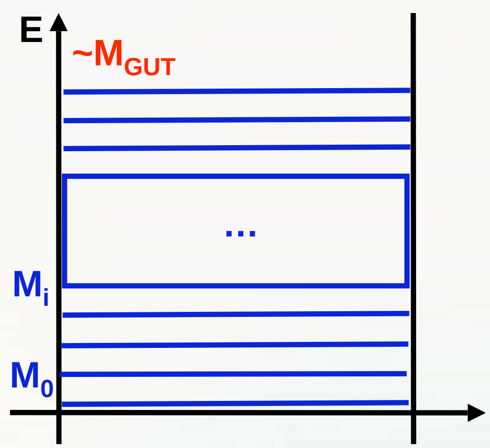
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



TeV^{-1} Scenario:

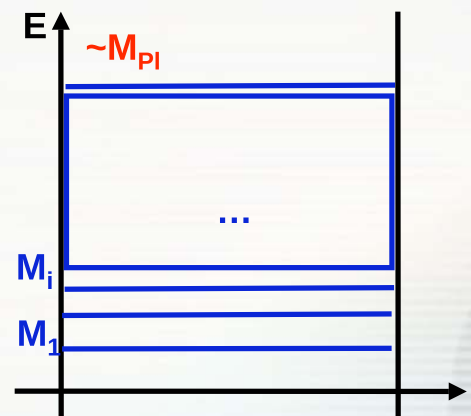
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~ 1 TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_w per mode

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



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



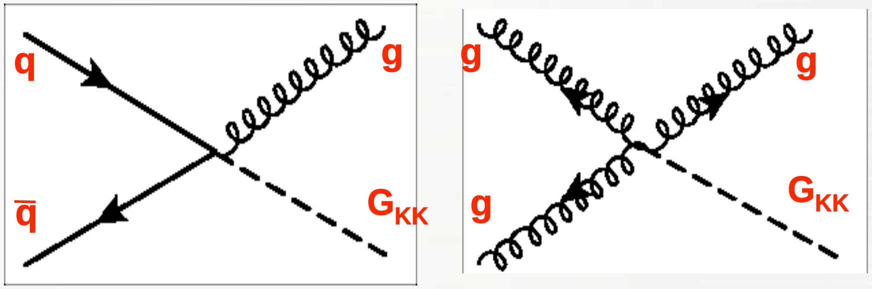
$$M_0 = 0;\ M_i = M_1 \frac{x_i}{x_1} \approx$$
$$M_1,\ 1.83M_1,\ 2.66M_1,\ 3.48M_1,\ \ldots$$

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 $\sim M_D$ (and likely $< M_D$)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders



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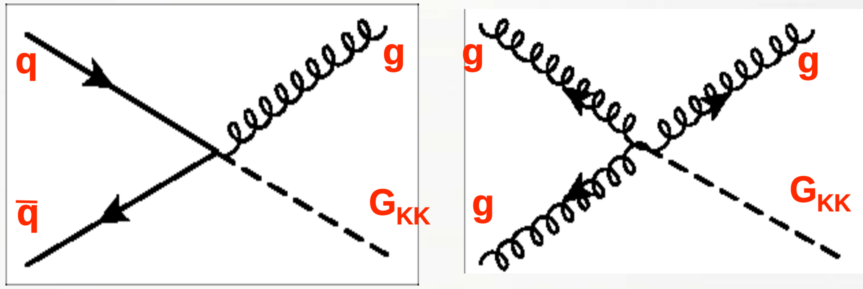
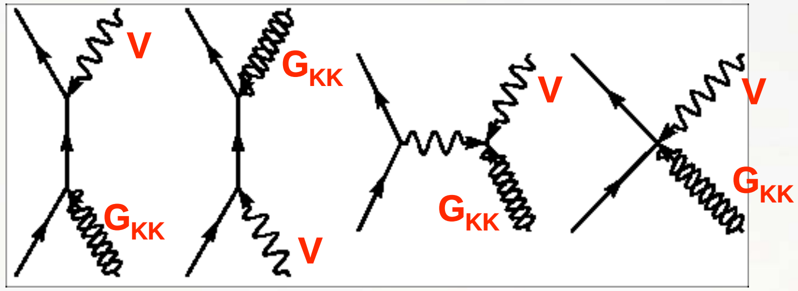


Single VB at hadron or e^+e^- colliders



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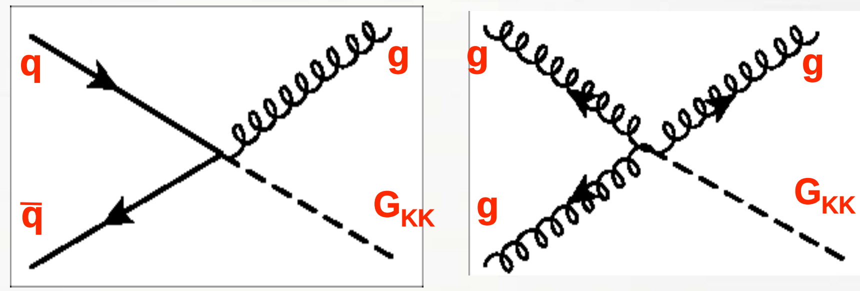

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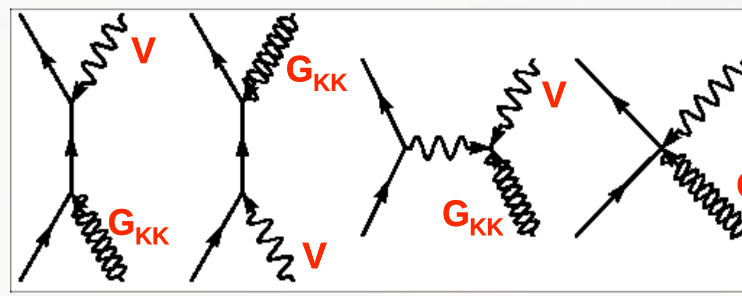
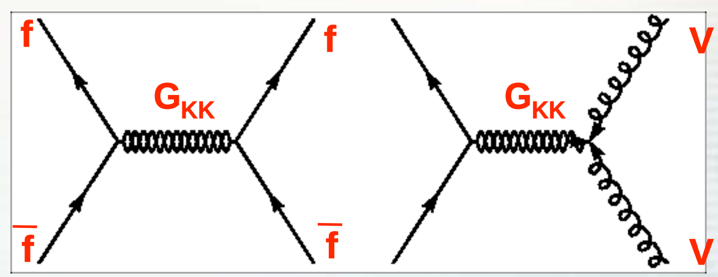
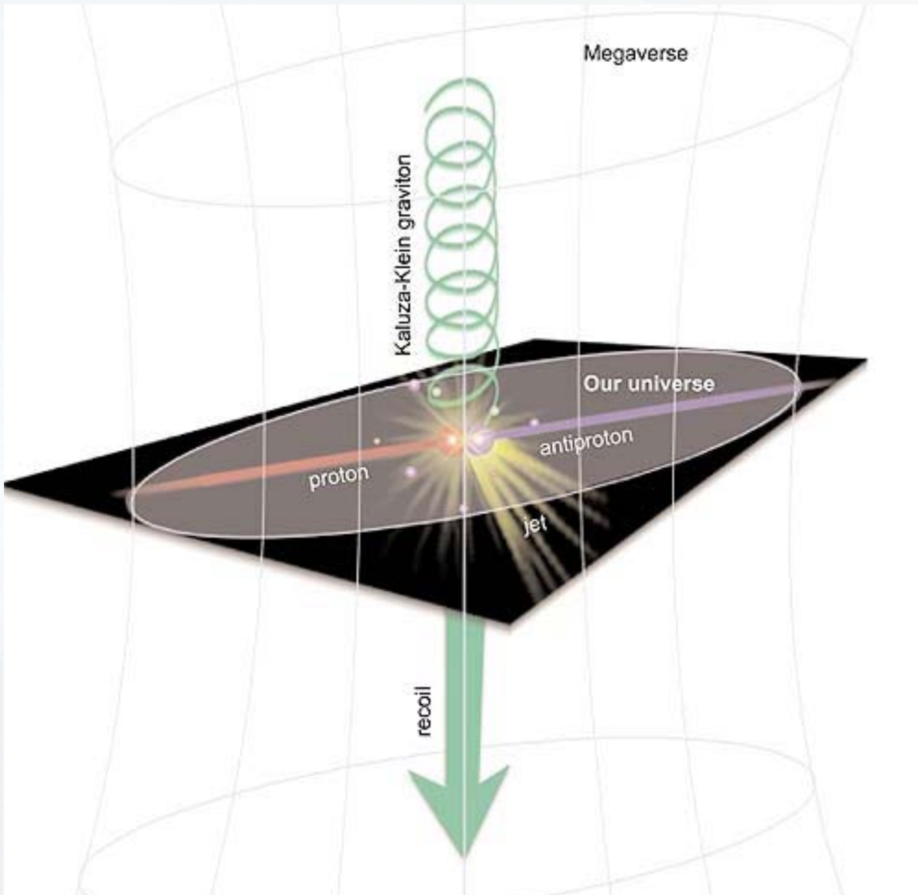


Virtual Graviton Effects

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



Looking for ED at Colliders



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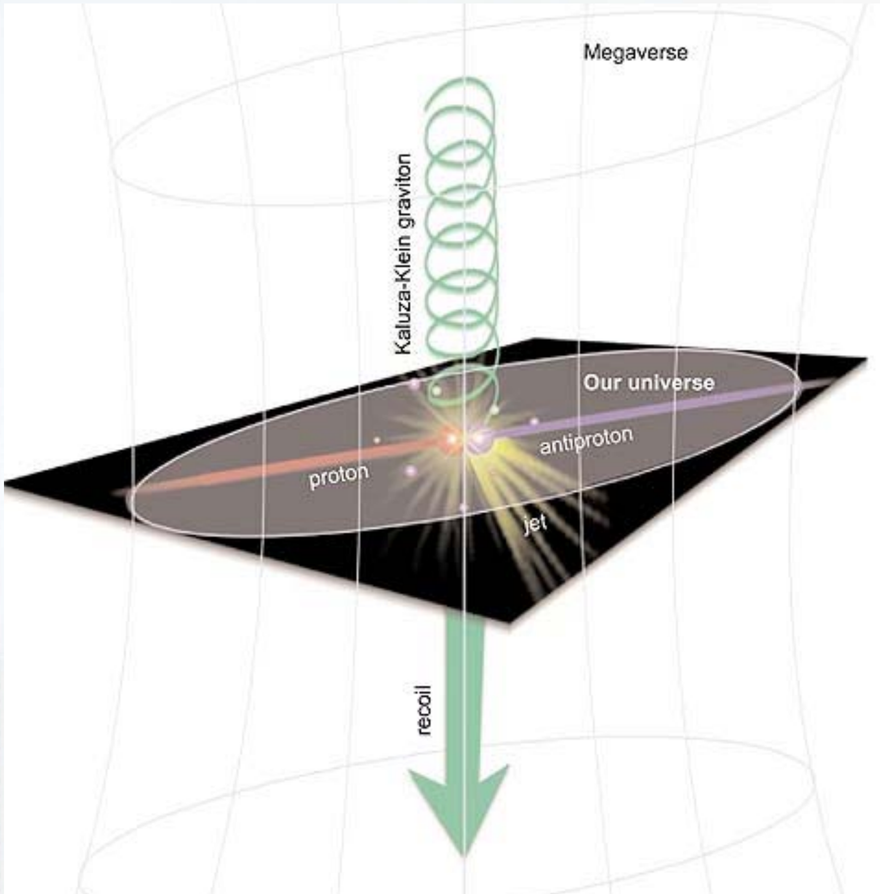

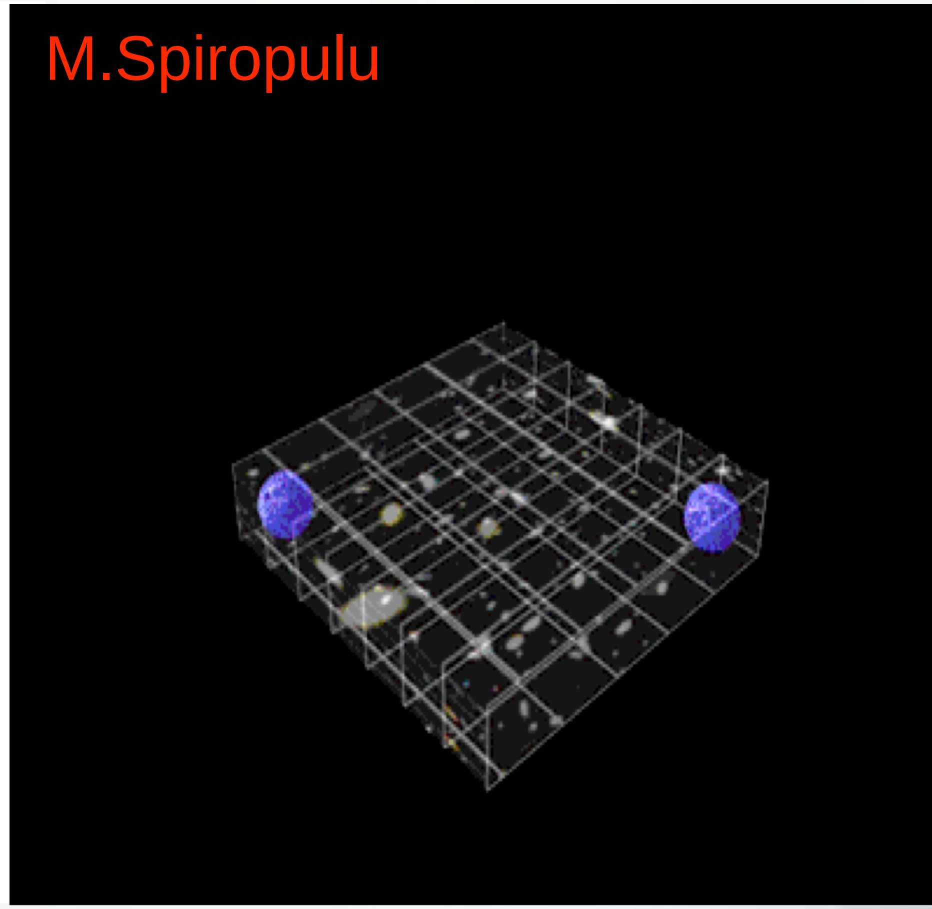

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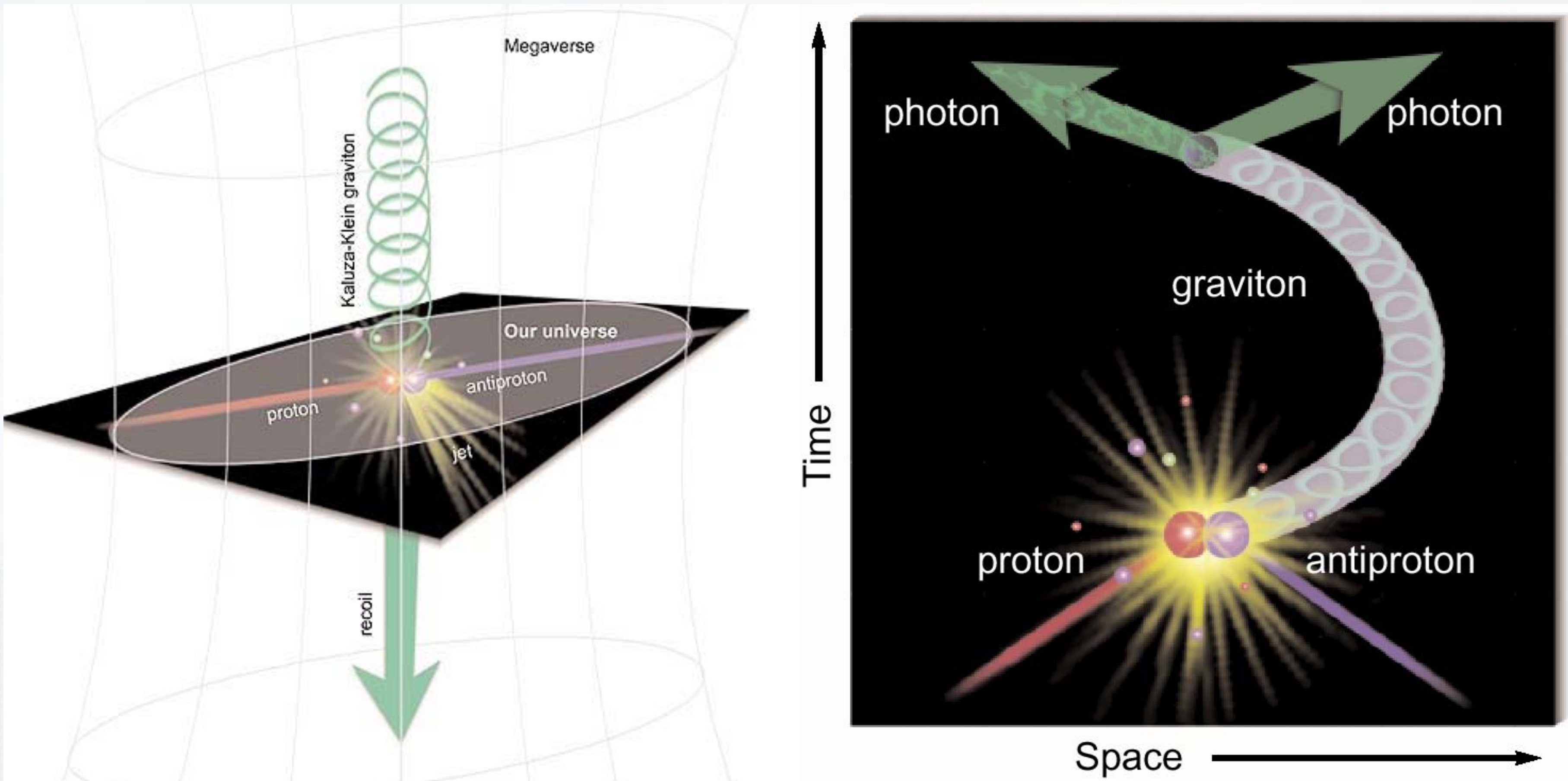

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Monojets: Tainted History

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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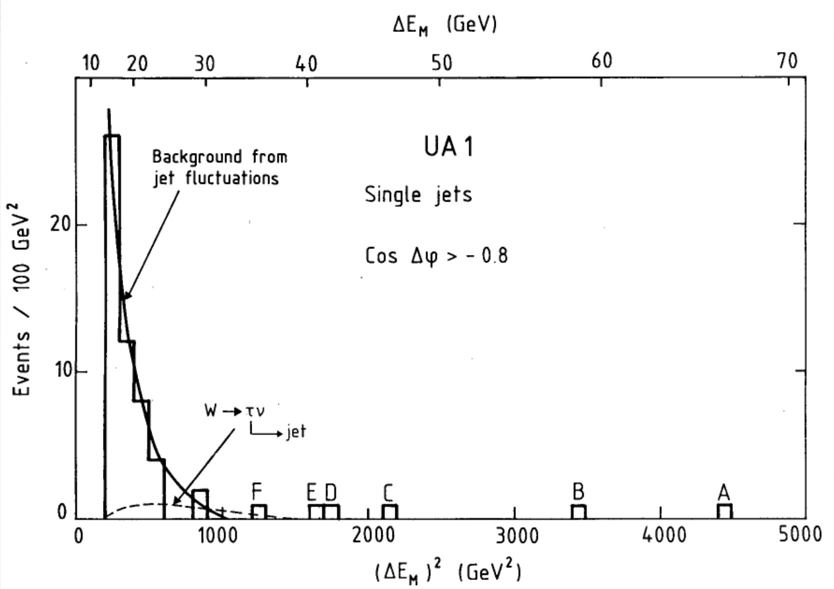
VOLUME 54, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1985

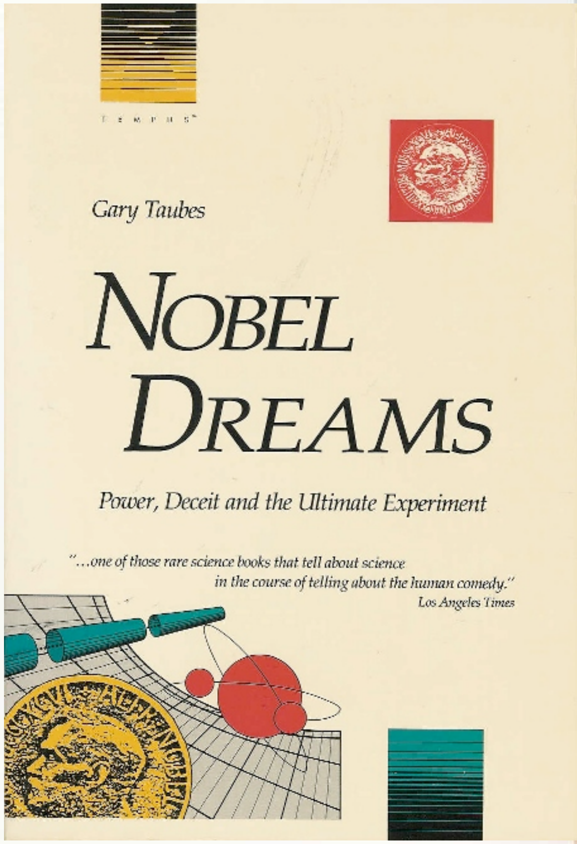
Monojets from *Z* Decay without Extra Neutrinos or Higgs Particles

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

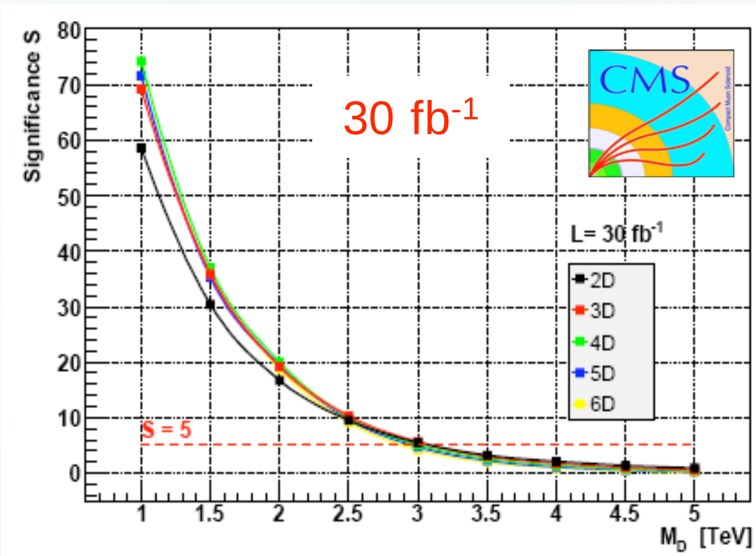




- These monojets turned out to be due to unaccounted background
- The signature was deemed doomed and nearly forgotten
- It took many years for successful monojet analyses at a hadron collider to be completed (CDF/DØ)

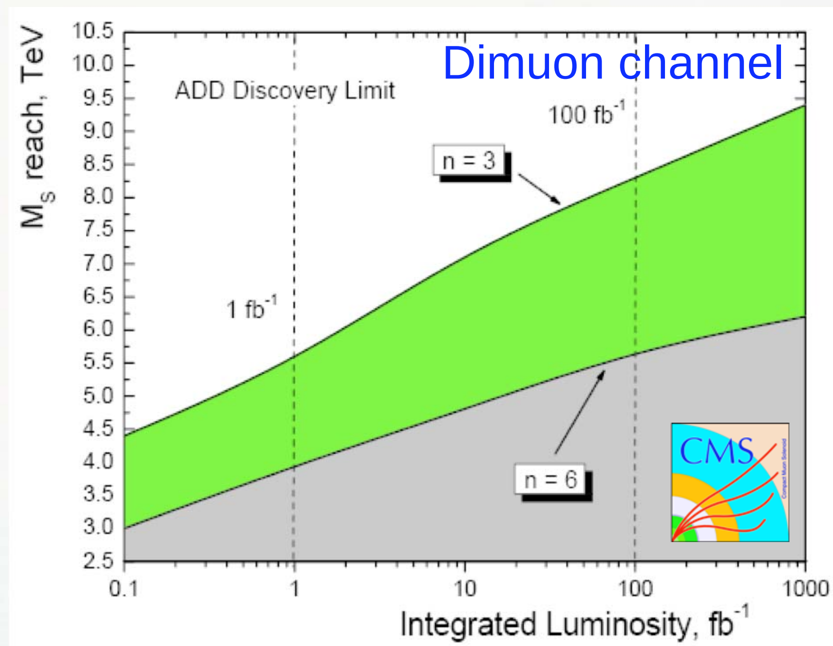
Expectations at the LHC

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



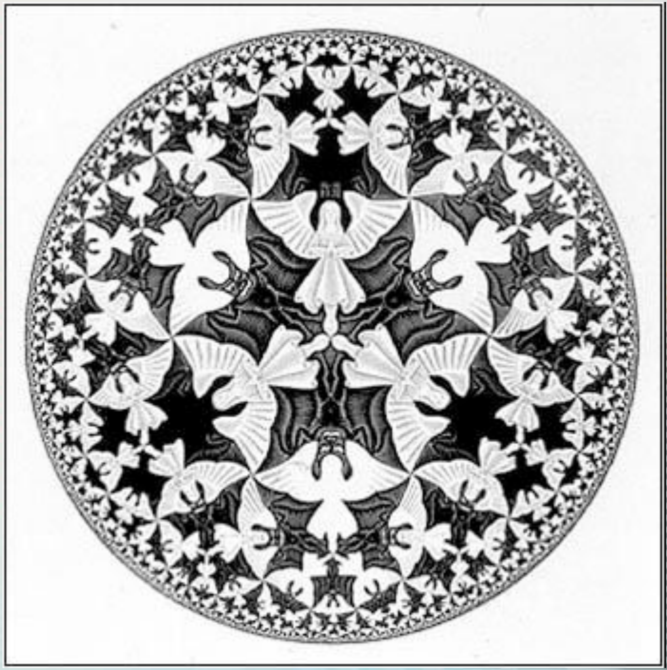
δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

- 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



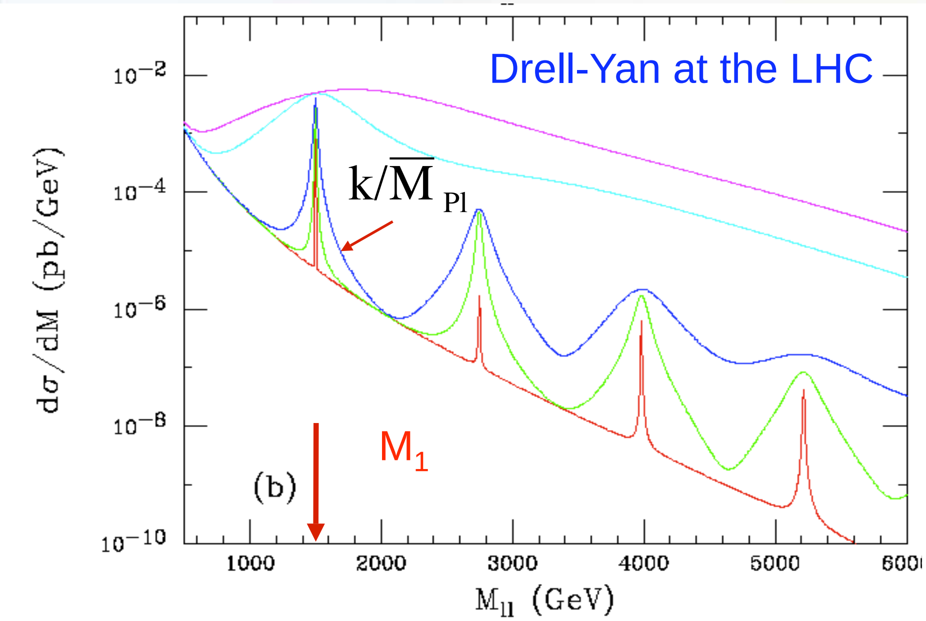
Example 3: Kaluza-Klein Resonances/Z'

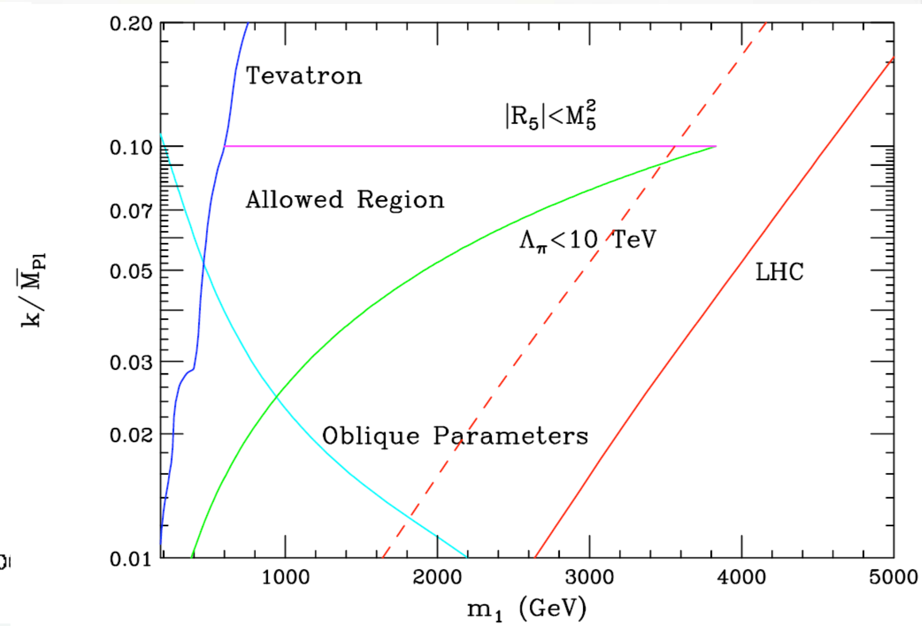
Found in RS, TeV-1 models and in various Z' models



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 $k/\overline{M}_{\rm Pl}$, which determines the graviton width
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \le k/\overline{M}_{\rm Pl} \le 0.10$ 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)]

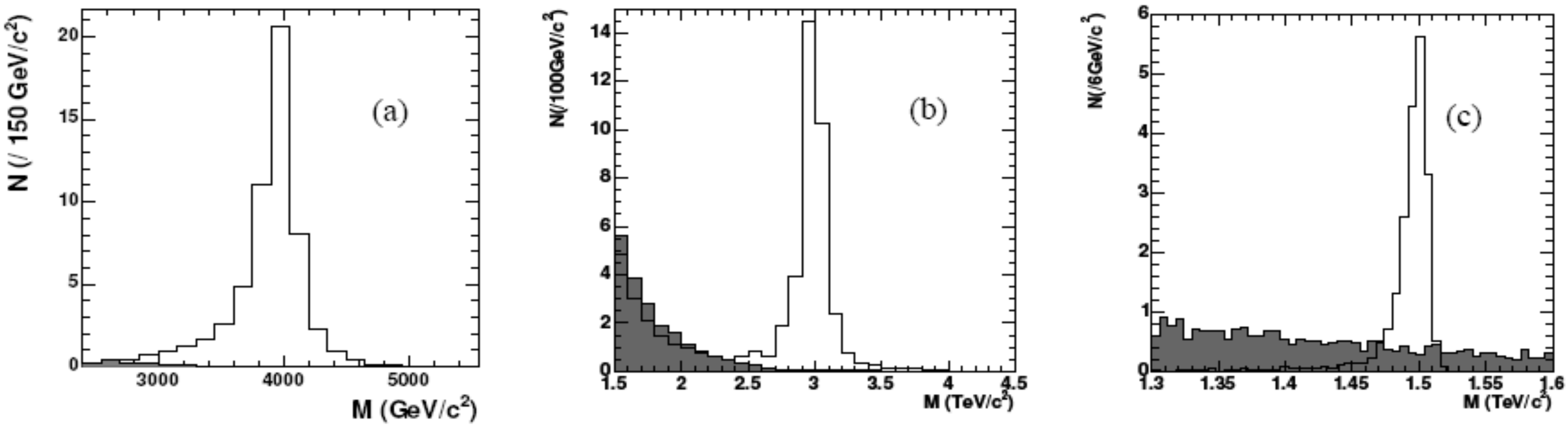
Dielectrons: Discovery Channel

- Excellent resolution 5-10%/sqrt(E, GeV) (calorimeter based) and detection efficiency
- Low background above ~1 TeV

	KK Z		G, $c = 0.01$	G, $c = 0.1$	SSM Z'	
M	4.0	6.0	1.5	3.5	1.0	5.0
M_w	3.5-4.5	5.0-6.7	1.47-1.52	3.30-3.65	0.92-1.07	4.18-5.81
N_s	50.6	1.05	18.8	7.30	72020	0.58
N_b	0.13	0.005	4.16	0.121	85.5	0.025
S	22.5	3.0	6.39	6.83	225	1.63

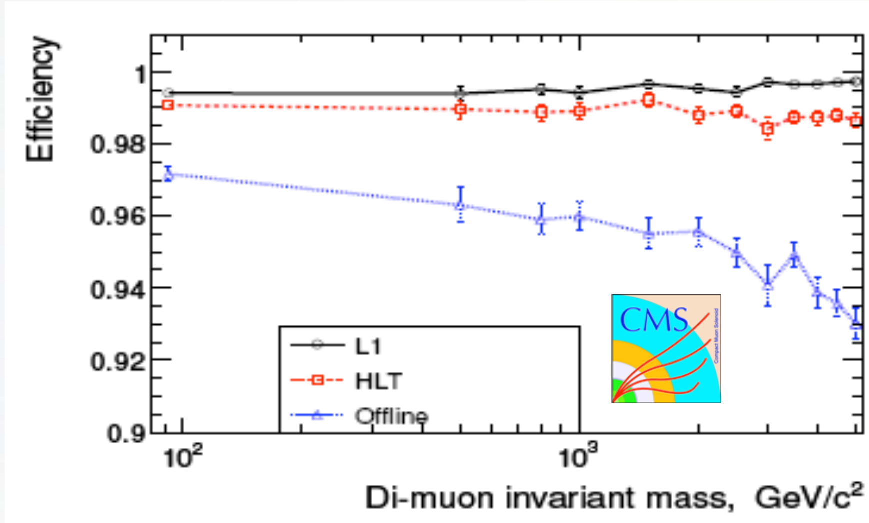
CMS, 30 fb^{-1}

Z_{KK} production

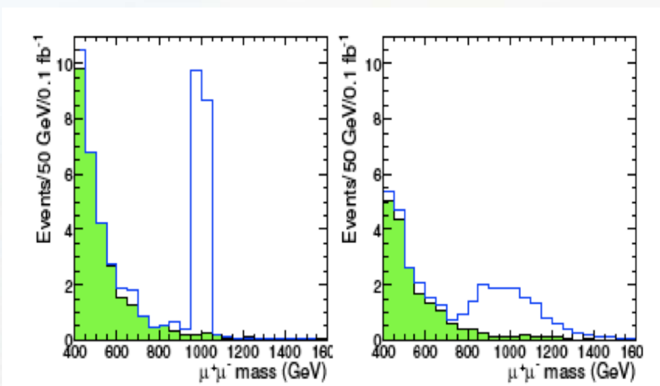


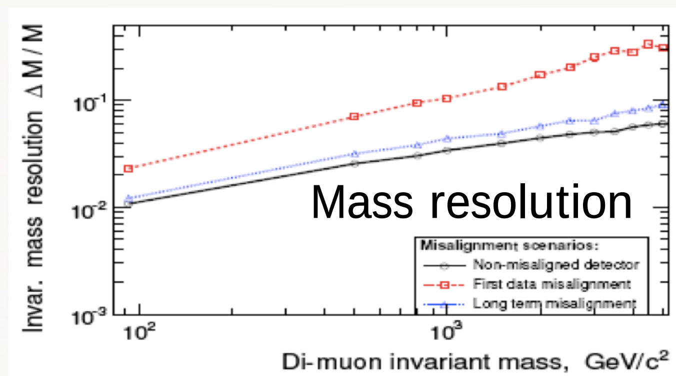
Dimuons: Confirmation Channel?

- Generally worse rapidity coverage, detection efficiency



- Significantly worse momentum resolution than for electrons





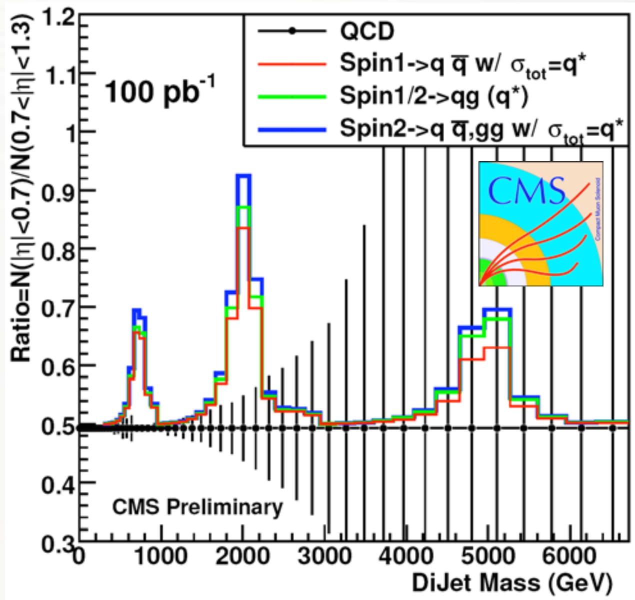
- Nevertheless: generally lower instrumental background may make dimuons a discovery channel along with dielectrons

What about Dijets/Ditaus?

- If jet energy scale is fixed with early data, dijets channel is also sensitive to KK modes
  - CMS 0.1-10 fb^{-1} simulations
  - Caveat: PDF uncertainties are large: poor reach in ADD

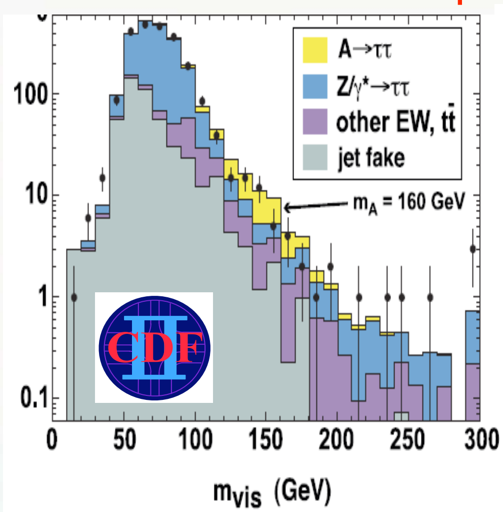
Resonance Model	95% CL Excluded Mass (TeV/c^2)			5σ Discovered Mass (TeV/c^2)		
	100 pb^{-1}	1 fb^{-1}	10 fb^{-1}	100 pb^{-1}	1 fb^{-1}	10 fb^{-1}
Excited Quark	0.7 - 3.6	0.7 - 4.6	0.7 - 5.4	0.7 - 2.5	0.7 - 3.4	0.7 - 4.4
Axigluon or Colouron	0.7 - 3.5	0.7 - 4.5	0.7 - 5.3	0.7 - 2.2	0.7 - 3.3	0.7 - 4.3
E_6 diquarks	0.7 - 4.0	0.7 - 5.4	0.7 - 6.1	0.8 - 2.0	0.8 - 3.7	0.8 - 5.1
Colour Octet Technirho	0.7 - 2.4	0.7 - 3.3	0.7 - 4.3	0.7 - 1.5	0.7 - 2.2	0.7 - 3.1
Randall-Sundrum Graviton	0.7 - 1.1	0.7 - 1.1 1.3 - 1.6	0.7 - 1.1 1.3 - 1.6 2.1 - 2.3	N/A	N/A	N/A
W′	0.8 - 0.9	0.8 - 0.9 1.3 - 2.0	0.8 - 1.0 1.3 - 3.2	N/A	N/A	N/A
Z′	N/A	N/A	2.1 - 2.5	N/A	N/A	N/A

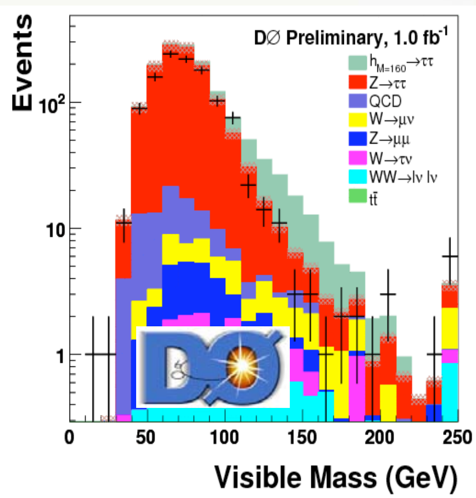
Dijets at the LHC



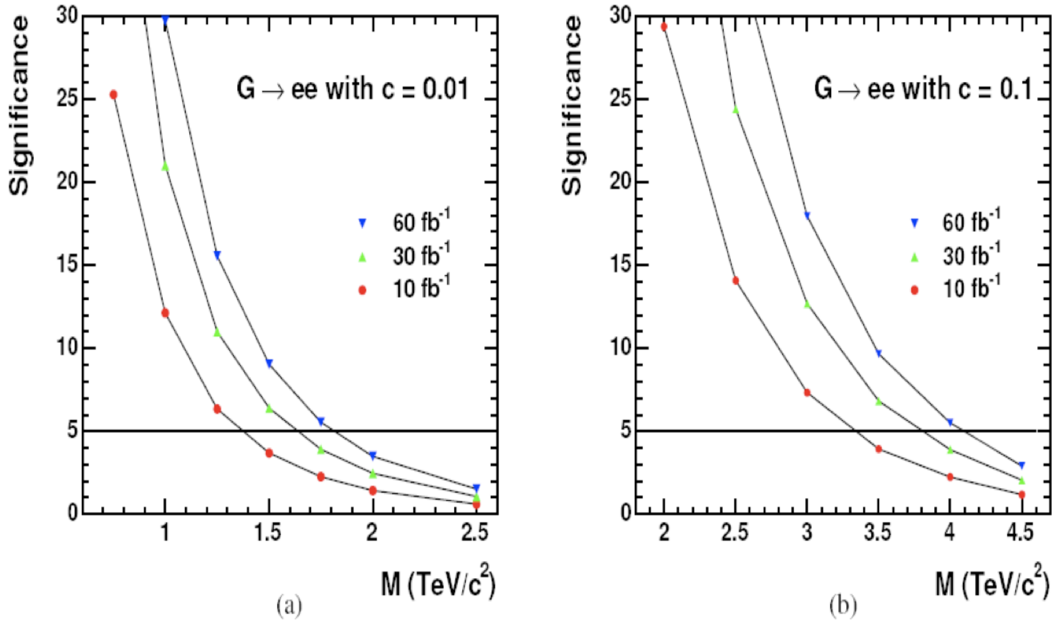
- Ditau channel is less studied for BSM discovery reach by the LHC collaborations, but still can be accessible for early physics
  - N.B. The first Tevatron Run II precision measurement paper was DØ Z(ττ) cross section determination
- Very interesting reach for MSSM Higgs and other resonances; could also be tricky?

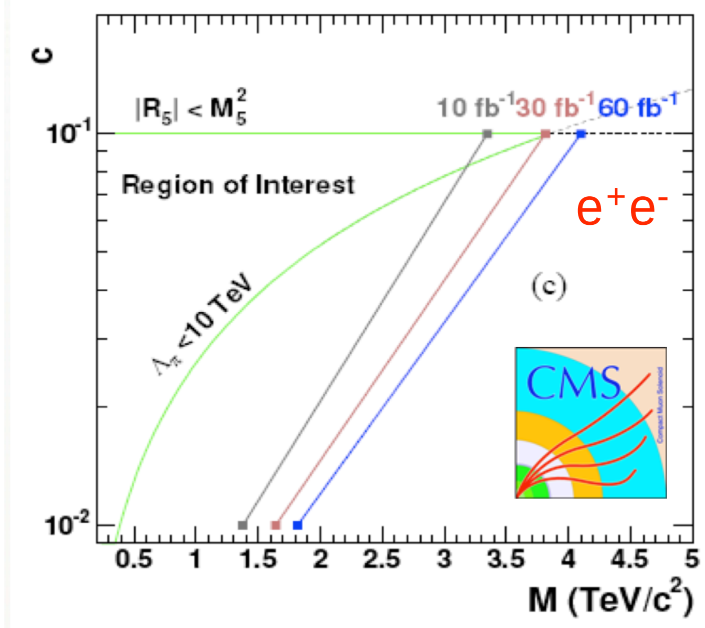
1 fb^{-1} ditau surprise at the Tevatron

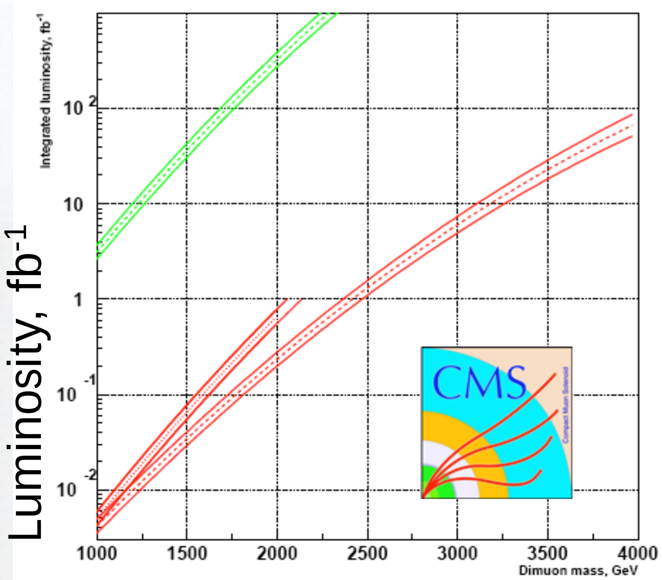




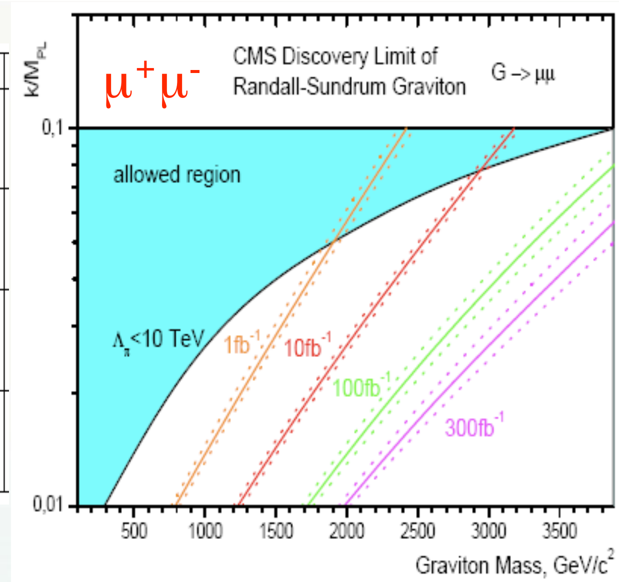
Randall-Sundrum Graviton Reach





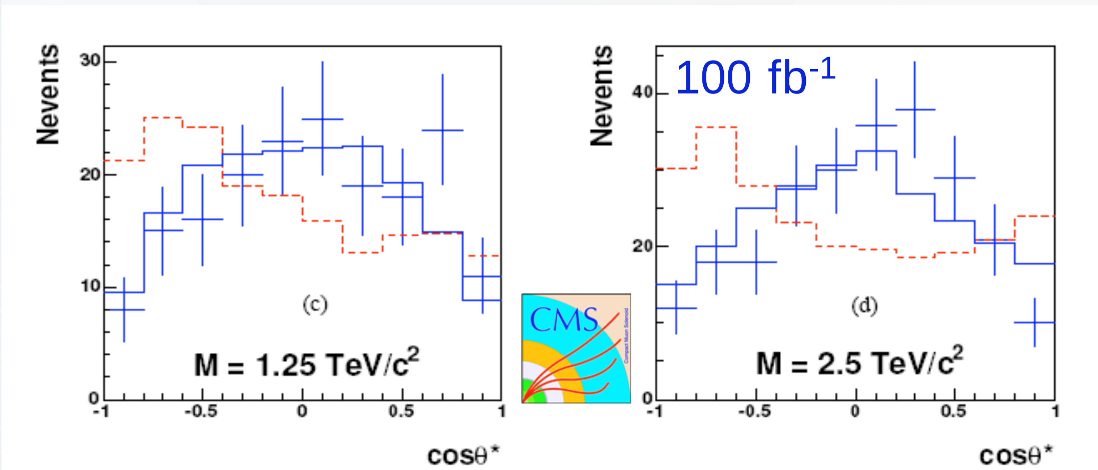


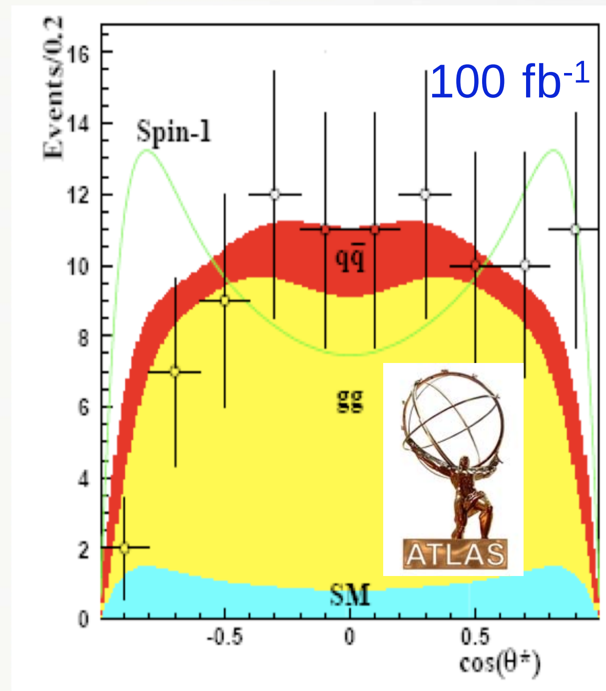
Coupling constant c	Estimator	1 fb^{-1}	10 fb^{-1}
0.01	S_{cP}	0.75	1.20
	S_{cL}	0.77	1.21
	S_L	0.78	1.23
0.02	S_{cP}	1.21	1.72
	S_{cL}	1.22	1.72
	S_L	1.22	1.74
0.05	S_{cP}	1.83	2.48
	S_{cL}	1.85	2.49
	S_L	1.85	2.51
0.1	S_{cP}	2.34	3.11
	S_{cL}	2.36	3.13
	S_L	2.36	3.16

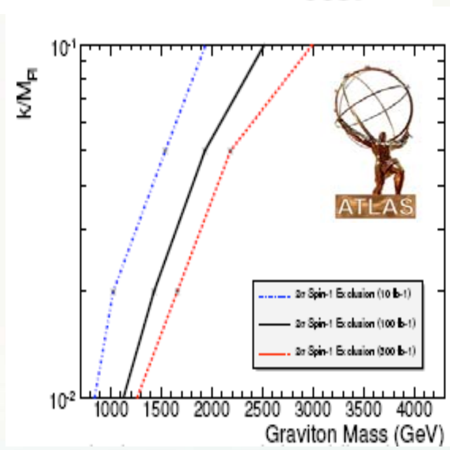


Angular Distributions?

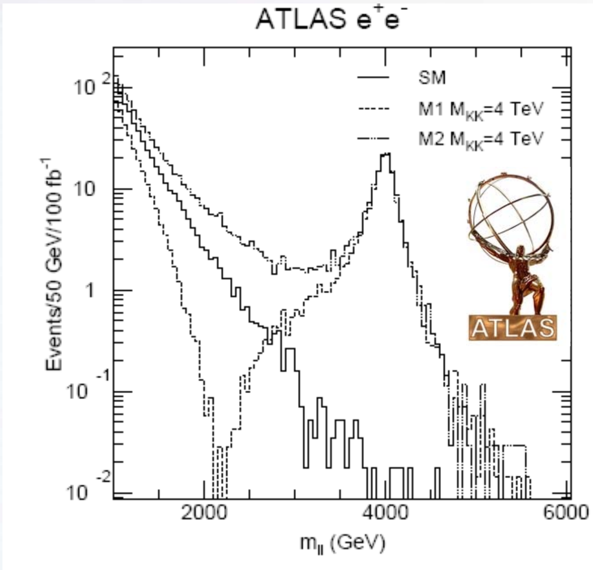
- Not in the early running!
  - "One event – discovery; two events – cross section measurement; three events – angular distributions"
  - Nevertheless observation in the diphoton channel excludes spin 1!

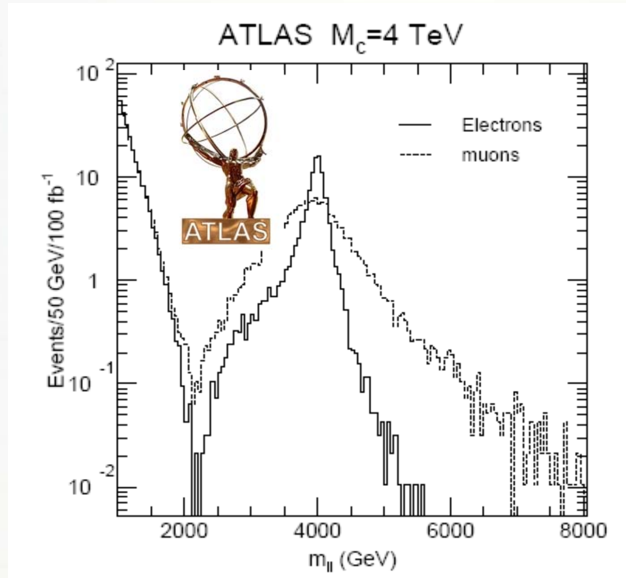


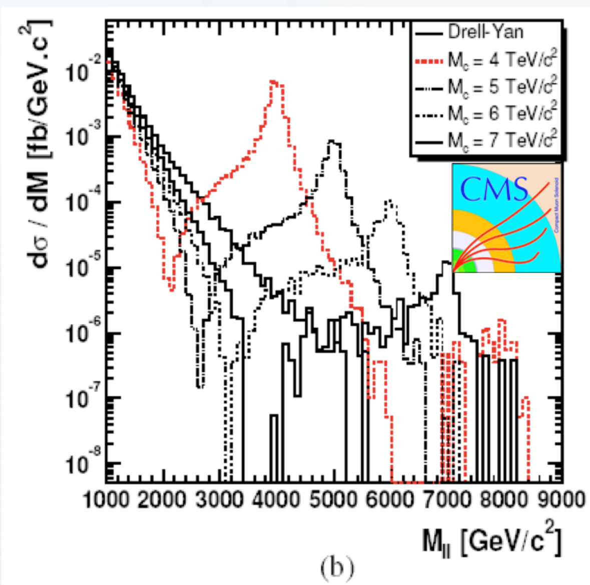


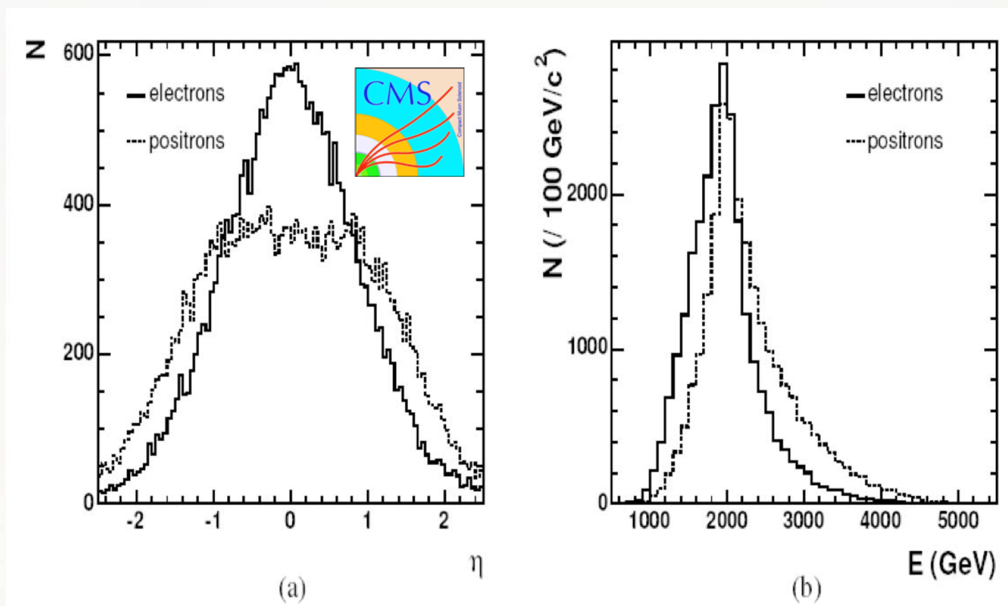


KK Excitations of the Z Boson



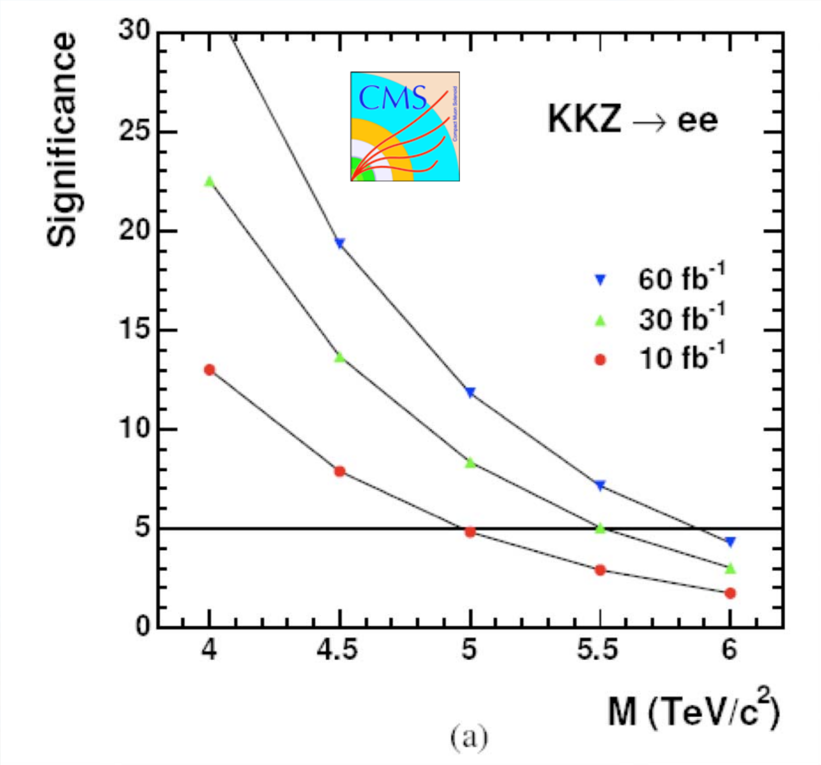


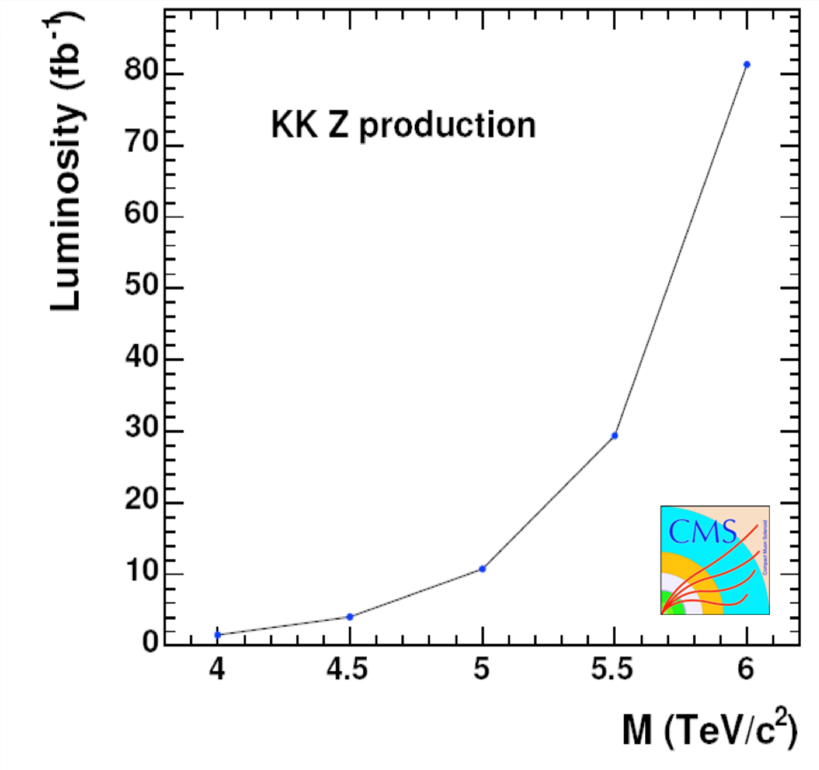




KK Reach

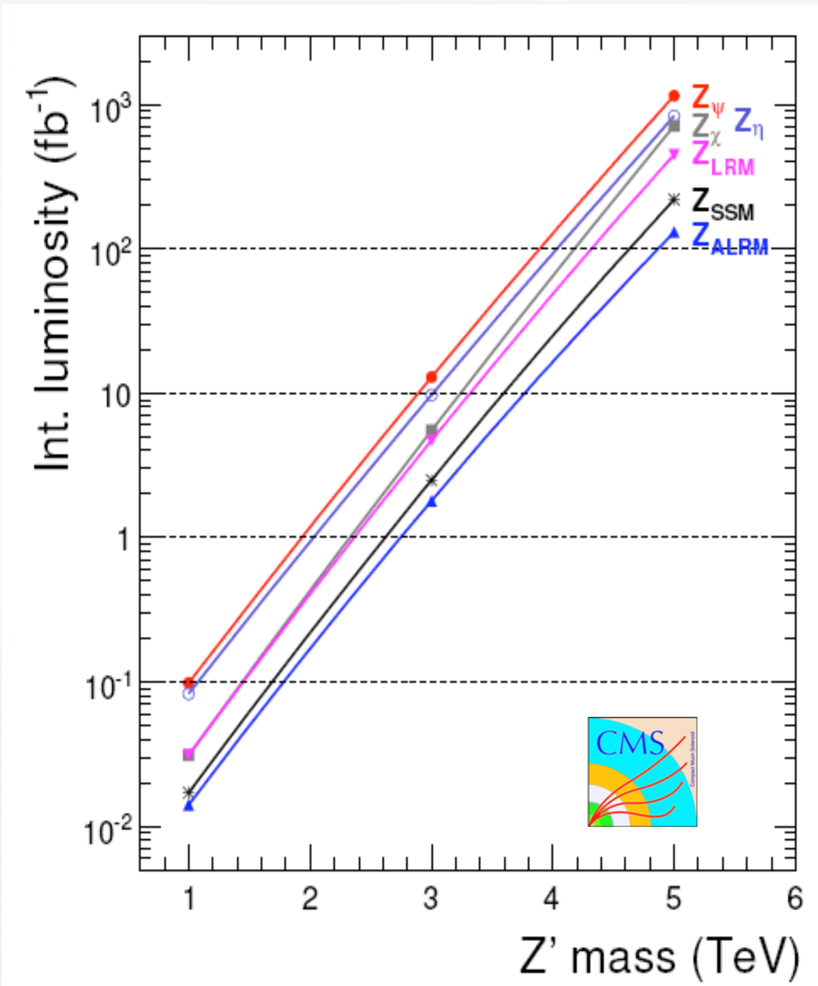
- Dramatic reach even with ~1 fb^{-1}



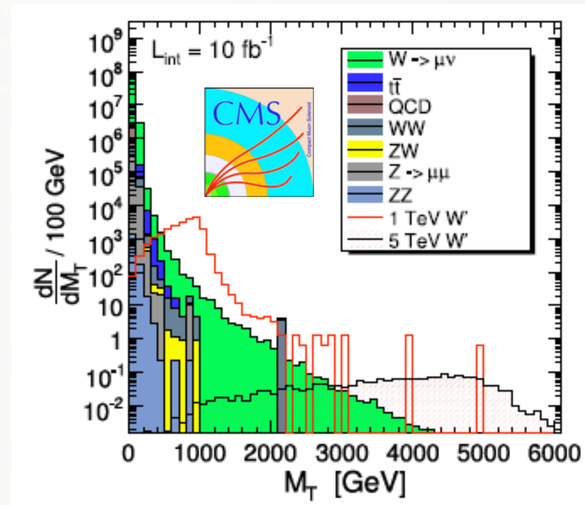


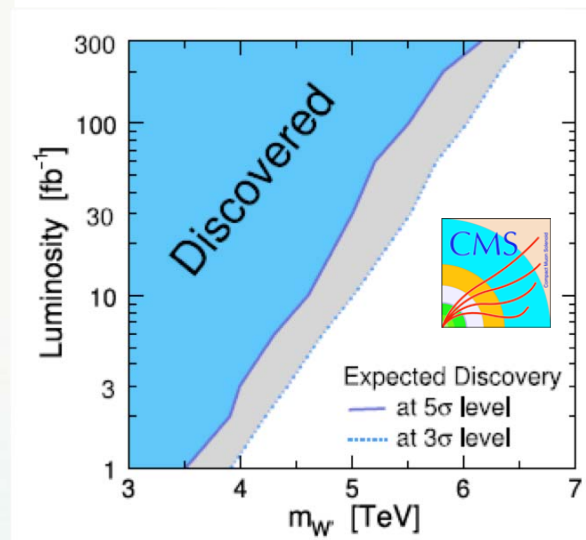
Z' and W' Reach

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



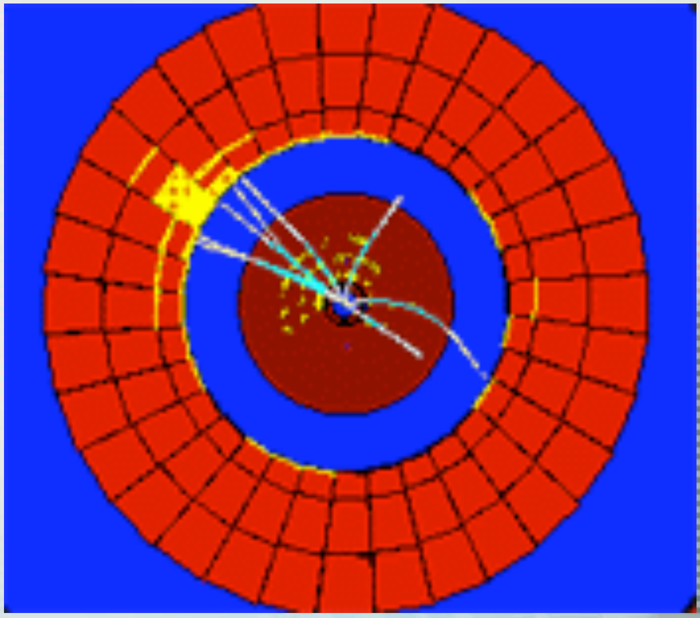
CMS reach in the dimuon channel





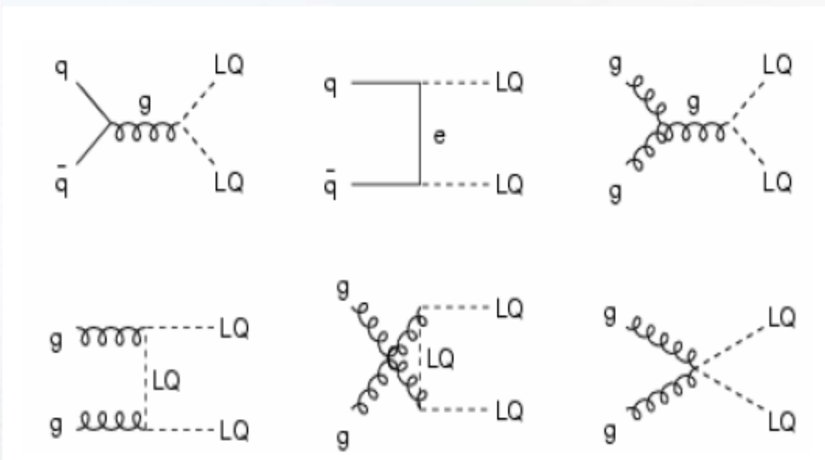
Example 4: Leptoquarks and Such

Exotic particles having properties of both quarks and leptons

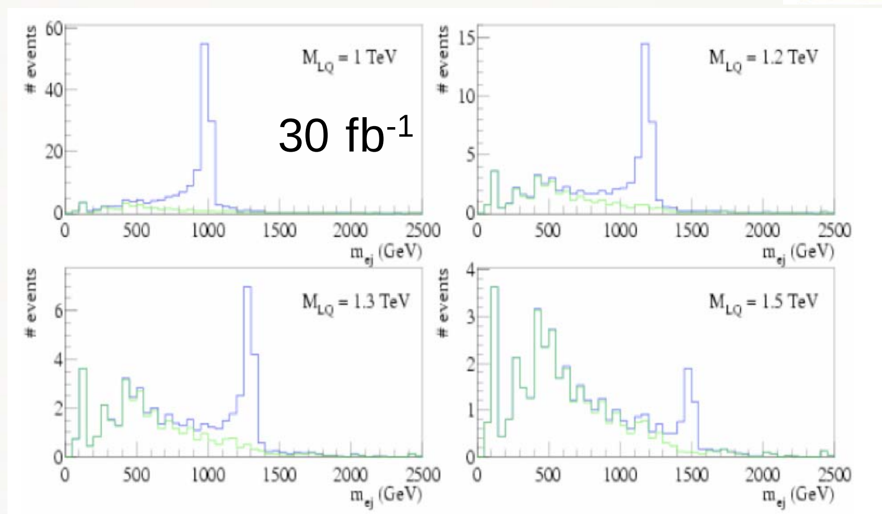


Leptoquarks

- Once ll channel is understood, adding extra objects is easy, even if they are as messy as jets!
- Focus on the lljj channel
  - eνjj is a possibility, but no existing studies
  - ννjj will take long time

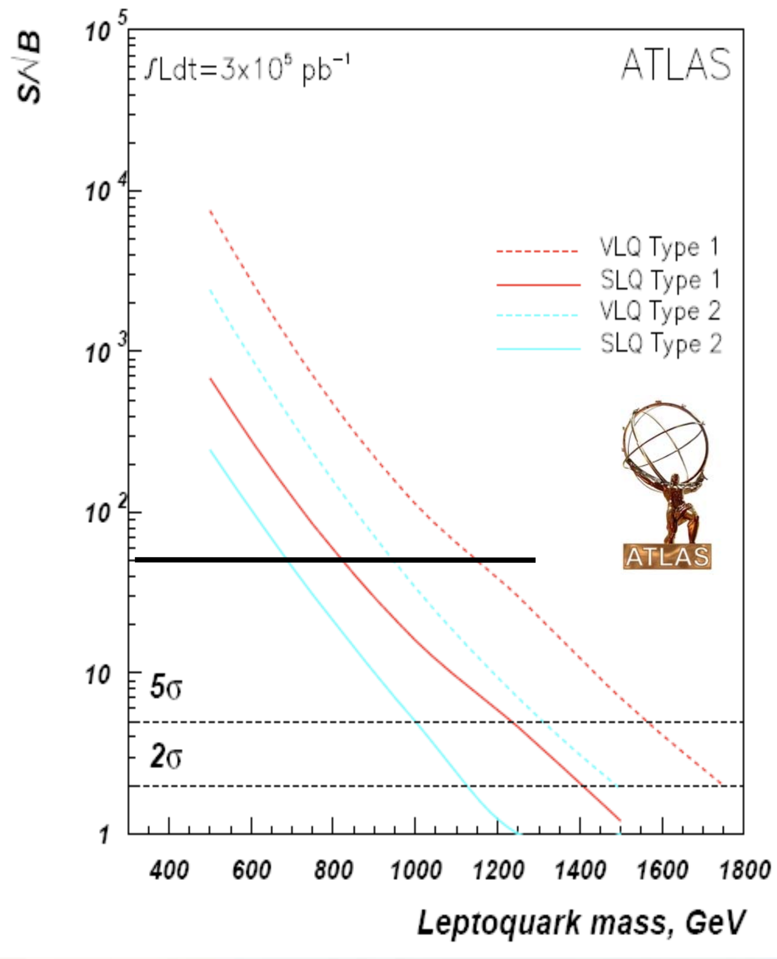


M_{LQ} (TeV)	σ (fb)	Signal	Background	$S/\sqrt{B}$
1.0	4.96	98.5	2.84	58
1.2	1.33	22.0	2.43	14
1.3	0.713	12.8	1.44	11
1.5	0.223	3.62	0.376	5.9



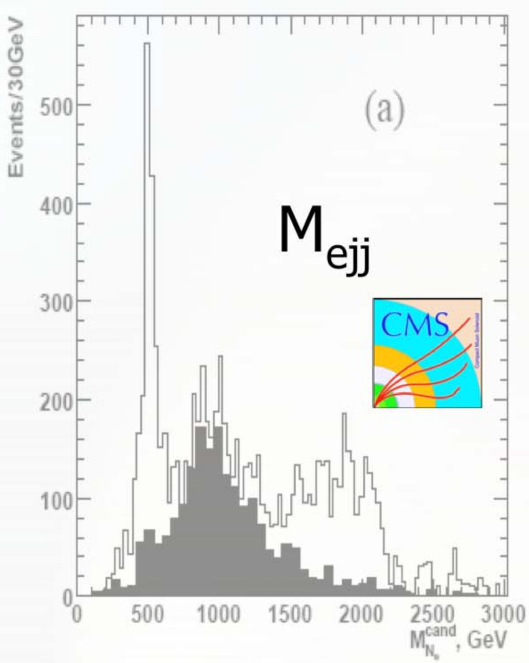
Leptoquarks: Reach

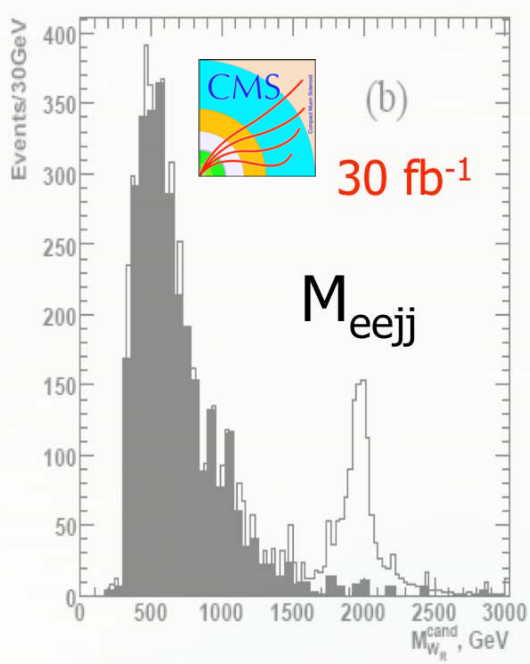
- Reach plot available for 300 fb^{-1}
  - Scale significance as sqrt(L)
  - S/sqrt(B) of 50 correspond to 5 sigma at 3 fb^{-1}

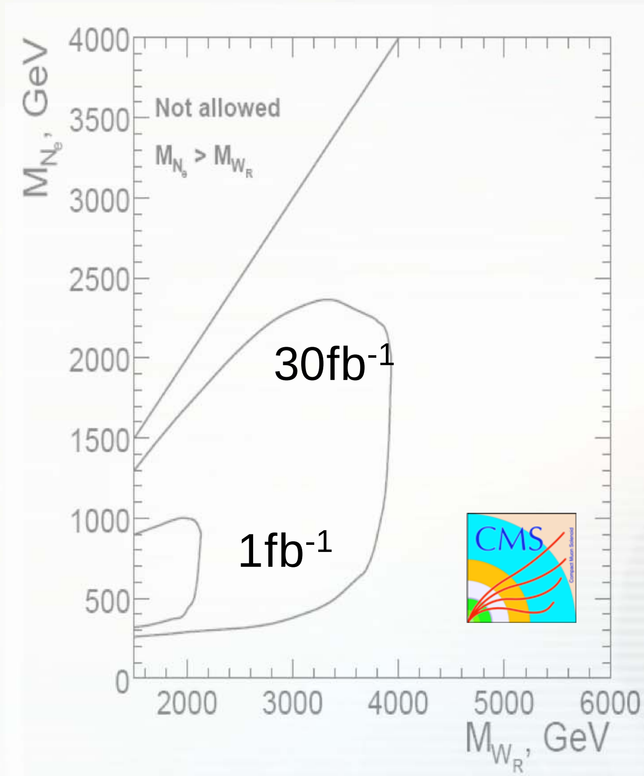


Can Also Probe Right-Handed W

- Pair produced; typical final state: 2 leptons + 2 jets
- No dedicated CMS analysis yet
- However, other processes can be looked at in the same final state:
  - W_R production, with $W_R \rightarrow l + N \rightarrow l + ljj$
  - Interesting reach even with ~1 fb^{-1}





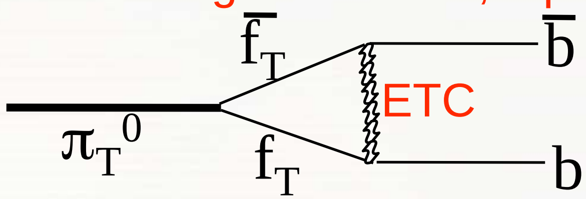


Example 5: Strong Dynamics

QCD is realized in Nature, why not another similar force?

Strong Dynamics

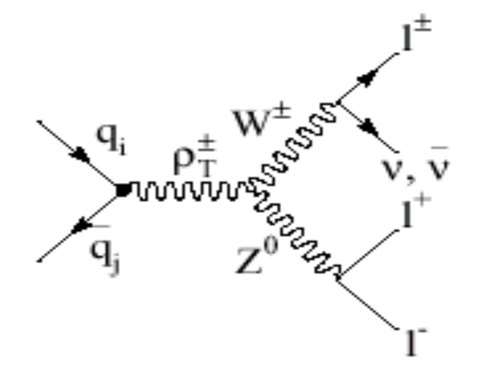
- New, QCD like force with “pions” at ~ 100 GeV and a number of QCD meson-like bound state
- No fundamental Higgs particle; global EW symmetry is broken dynamically, which results in nearly massless Goldstone bosons, analogous to pions in QCD
  - Three degrees of freedom are consumed by the longitudinal W/Z modes; the rest become physical meson-like particles
  - This is the way chiral symmetry is broken in QCD
  - To explain observed W/Z masses, need new techniparticles to be ~10^3 times heavier than the QCD particles
  - The role of Higgs boson in SM is played by a condensate of fermion-antifermion pair (e.g., new pion), resembling superconductivity
- Several realizations, e.g. technicolor
  - Excluded by LEP precision measurements in its simplest form
  - Cures: walking technicolor, topcolor assisted TC, extended TC



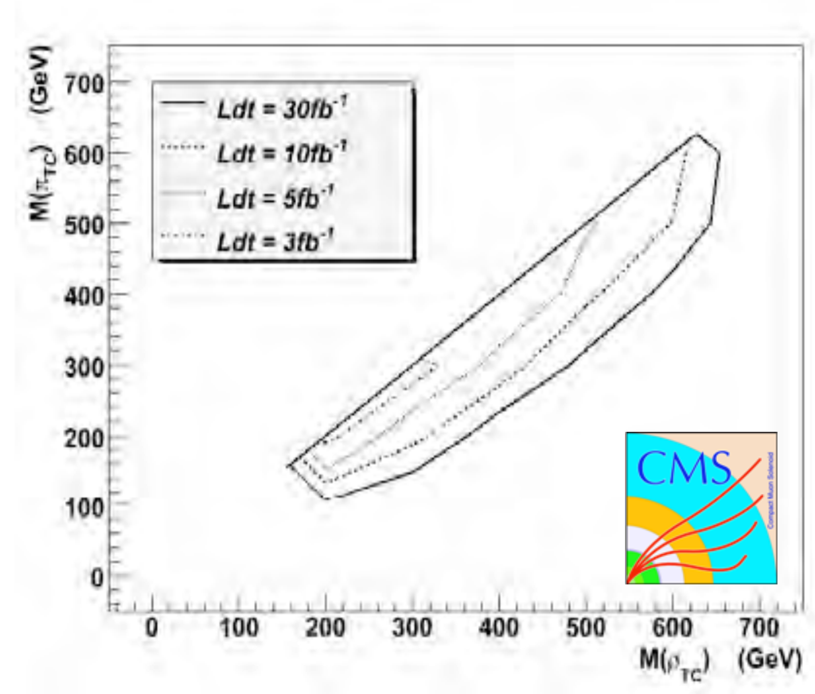
Analogous to the Higgs decay

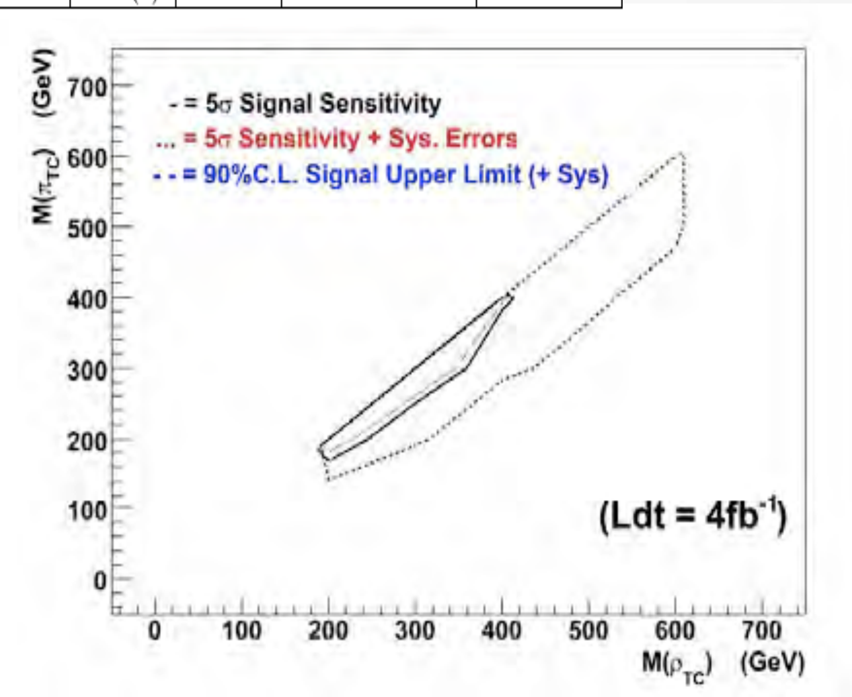
Technicolor Reach

- $\rho_T \rightarrow WZ \rightarrow 3l + ME_T$



m_{ρ_T} GeV/c^2	m_{π_T} GeV/c^2	Γ_{ρ_T} GeV/c^2	BR ($\rho_T \rightarrow WZ$)	$\sigma \times BR$ (pb)
220	110 (a)	0.93	0.13	0.16
500	110 (e)	67.1	0.014	1.04×10^{-3}
	300 (b)	4.47	0.21	1.3×10^{-2}
	500 (f)	1.07	0.87	5.4×10^{-2}
800	110 (g)	130.2	0.013	1.5×10^{-4}
	300 (h)	52.4	0.032	3.6×10^{-4}
	500 (c)	7.6	0.22	2.5×10^{-3}





Challenges

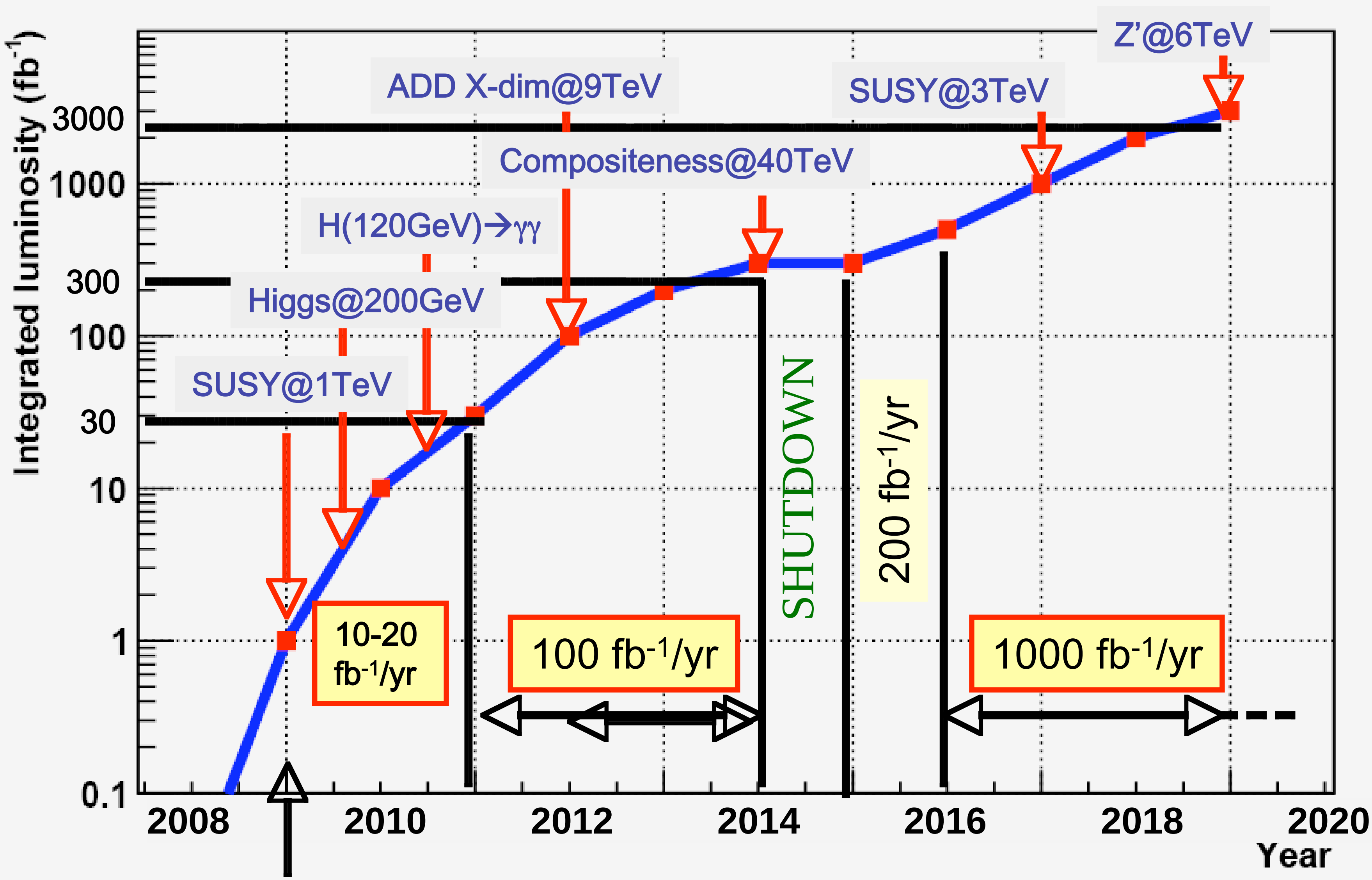
There will be surprises on the way!

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'			Alignment
ALRM	M ~ 1 TeV	0.01	
SSM	M ~ 1 TeV	0.02	
LRM	M ~ 1 TeV	0.03	
E6, SO(10)	M ~ 1 TeV	0.03 – 0.1	
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	0.1	Alignment
	M_D~ 5 - 4 TeV, n = 3-6	1	
ADD Direct G_{KK}	M_D~ 1.5-1.0 TeV, n = 3-6	0.1	MET, Jet/photon Scale
SUSY	M ~1.5 – 1.8 TeV	1	MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backgrounds
Jet+MET+0 lepton	M ~0.5 TeV	0.01	
Jet+MET+1 lepton	M ~0.5 TeV	0.1	
Jet+MET+2 leptons	M ~0.5 TeV	0.1	
mUED	M ~0.3 TeV	0.01	ibid
	M ~ 0.6 TeV	1	
TeV^{-1} ($Z_{KK}^{(1)}$)	M_{z1} < 5 TeV	1	
RS1			
di-jets	M_{G1}~0.7- 0.8 TeV, c=0.1	0.1	Jet Energy Scale
di-muons	M_{G1}~0.8- 2.3 TeV, c=0.01-0.1	1	Alignment

LHC Discovery Roadmap



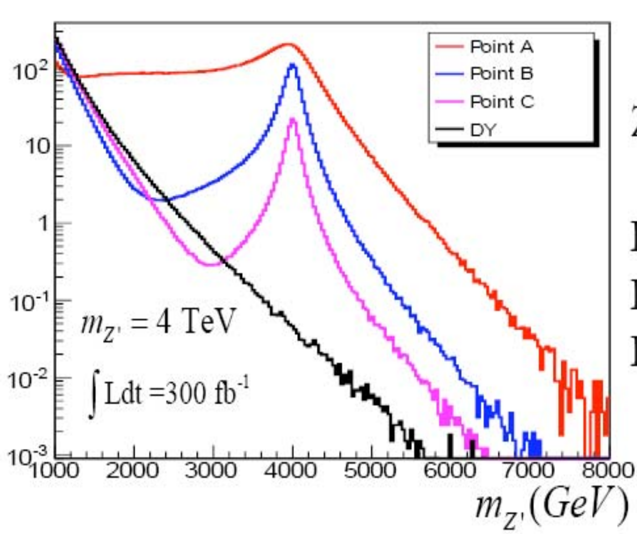
Before One Can Succeed in Searches

- 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!

Challenges: General

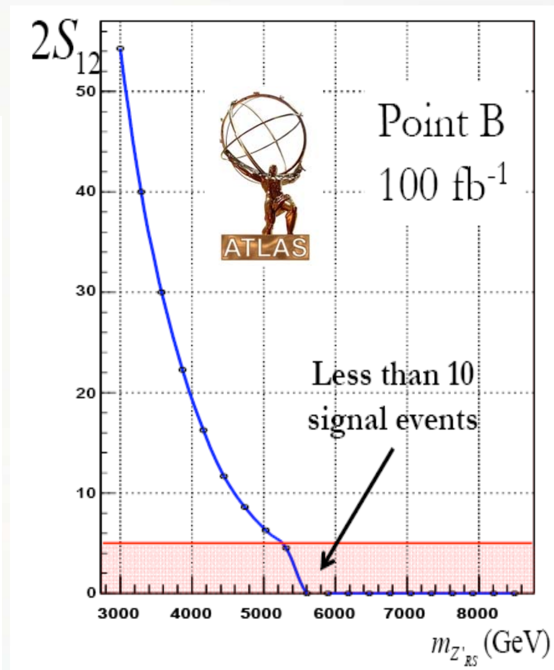
- Broad resonance are possible at high masses; signal start looking compositeness (or instrumental effect!) like
- Reduces the reach; requires different optimization of the search

Example: bulk Z_{KK} in RS model



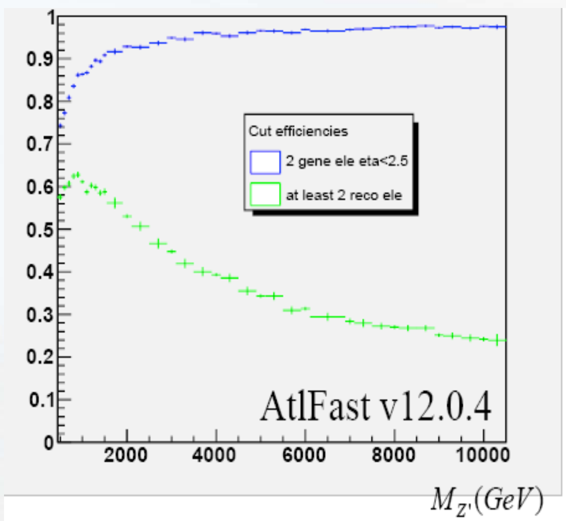
Z' Width @ $M_{Z'}$=4 TeV

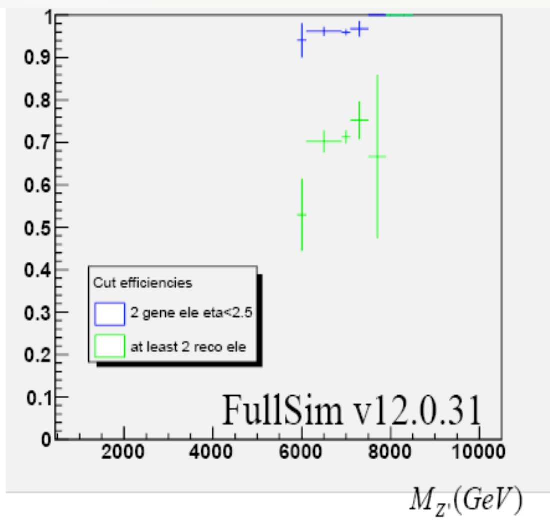
Γ = 800 GeV for point A (0.2 $M_{Z'}$)
Γ = 200 GeV for point B (0.05 $M_{Z'}$)
Γ = 170 GeV for point C (0.04 $M_{Z'}$)

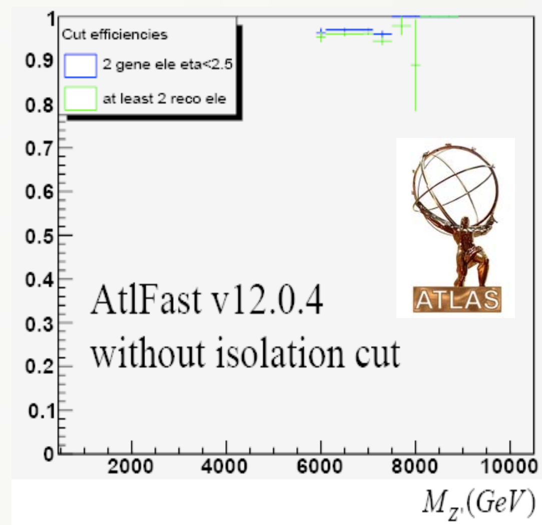


Example form ATLAS

- Electron efficiency drops fast with mass when “standard” isolation cut is used
  - Loosely confirmed by full simulation
- New set of isolation cuts is being developed to recover efficiency at high masses

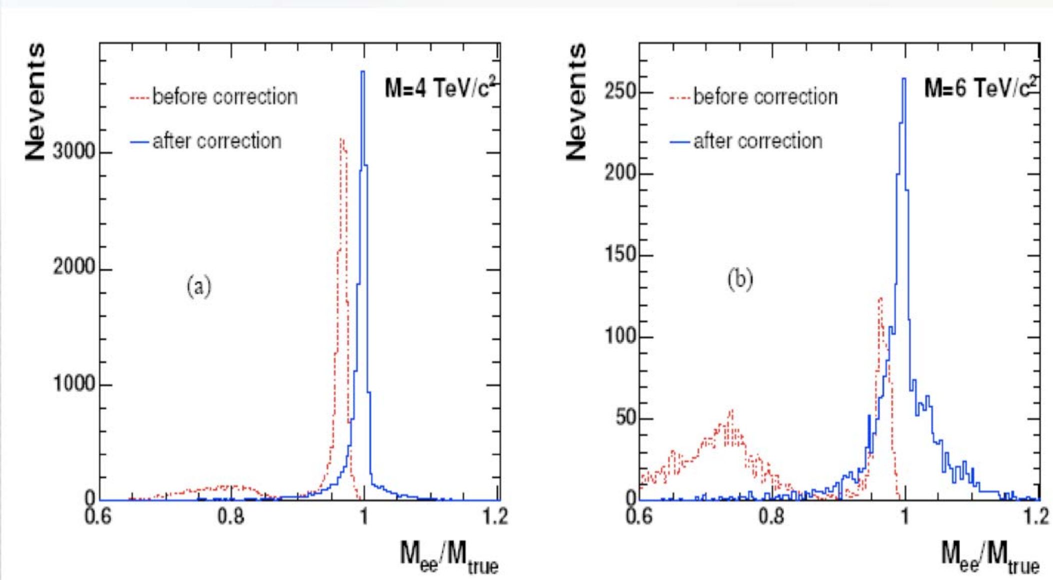


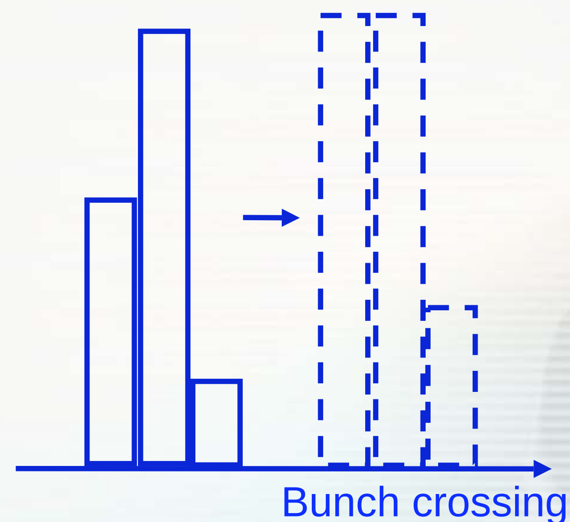




Example from CMS

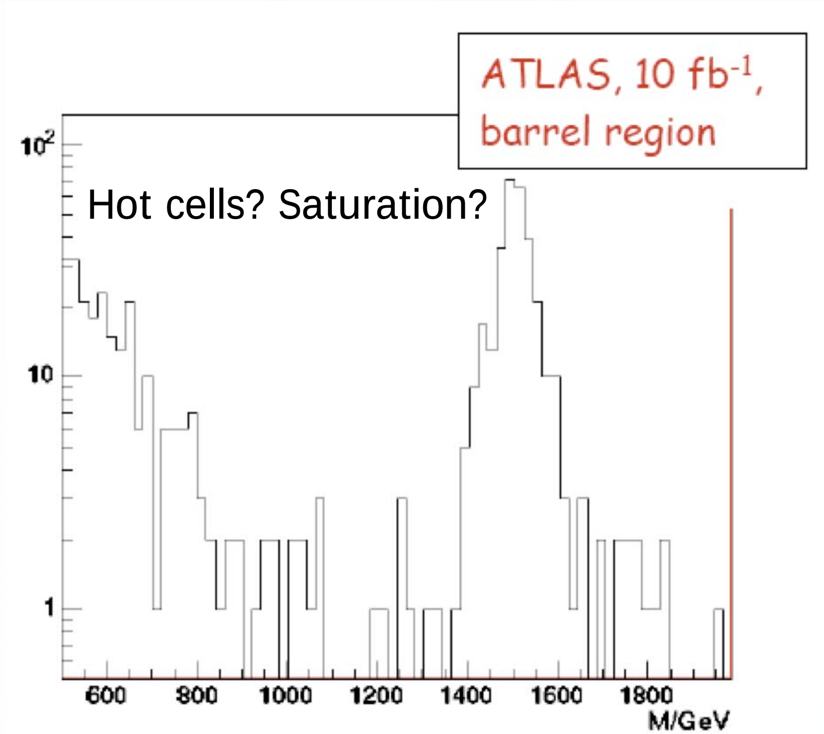
- ECAL saturation: a single crystal saturates at ~1.7 TeV; start seeing effect for >4 TeV Z'
- Correct energy at a slight resolution loss using "charge-sharing" technique
- Triggering with saturation could present another challenge!
- Ramon Barros Luco: "Ninety-nine percent of all problems will find a solution by themselves, the remaining one percent have no solution."





Last-Bin Effect

- Note the last-bin effects: saturation can easily cause a peak
  - Unlikely that confirmation could come from the dimuon (resolution) or ditau (ID, trigger, Z($\tau\tau$) first!) channel at the time of discovery
  - Thus many cross checks will be required



Last-Bin Effect

- Note the last-bin effects: saturation can easily cause a peak
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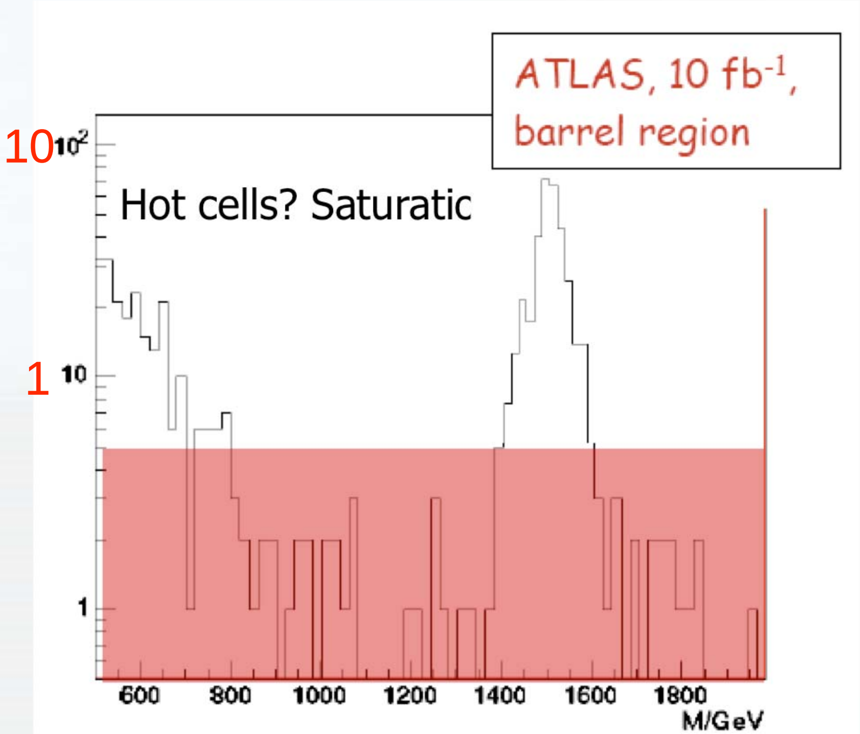

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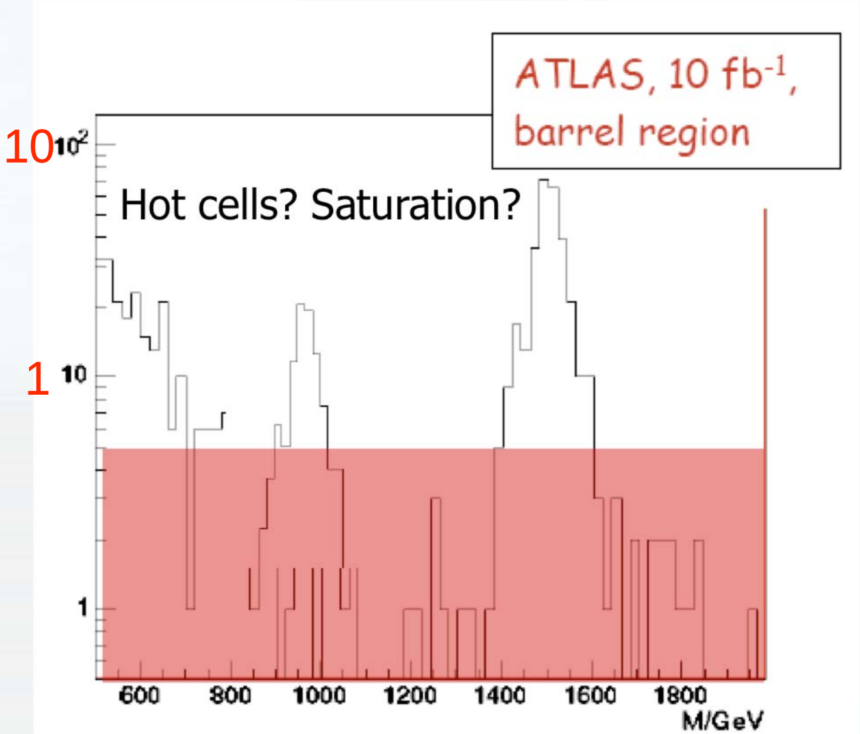

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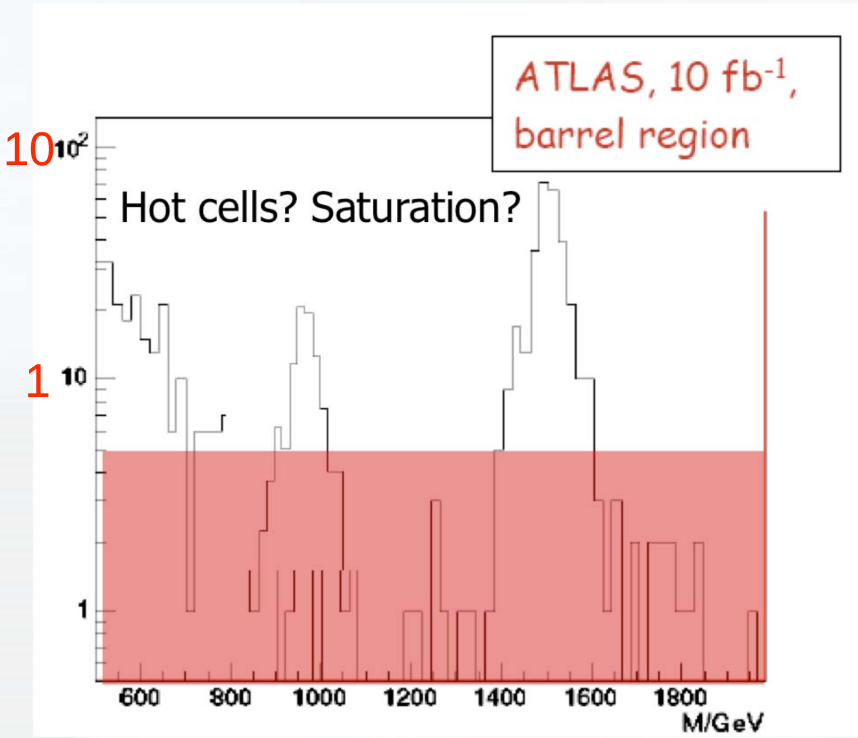

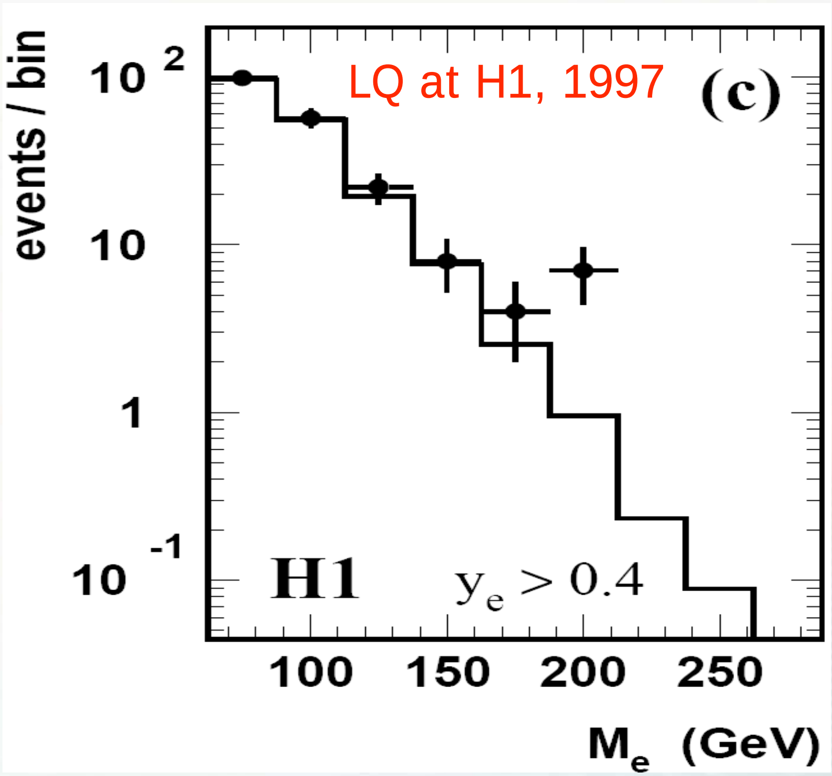

Memento Pentaquarks…

- Involved about a dozen (!) of groups all over the globe!
- Generated about 400 references in the literature
- Net result: every single claim of 2003 has been disputed by at least one other group
- IMHO: quite a shame for the field, which is over 100 years old and so proud of the widely-accepted 5σ discovery standard
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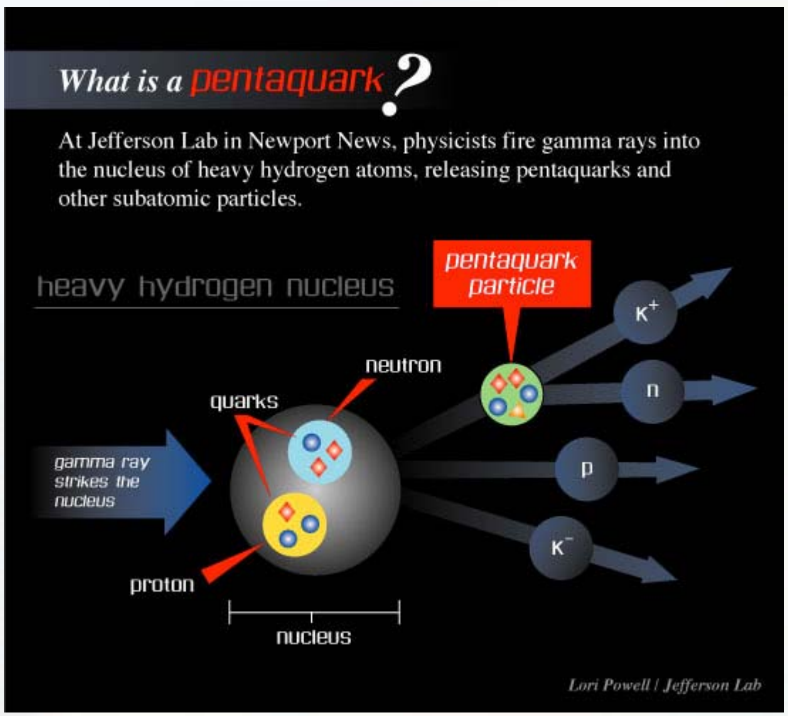

Experiment	Reaction	State	Mode
LEPS(1)	$\gamma C_{12} \to K^+K^-X$	θ^+	K^+n
LEPS(2)	$\gamma d \to K^+K^-X$	θ^+	K^+n
CLAS(d)	$\gamma d \to K^+K^-(n)p$	θ^+	K^+n
CLAS(p)	$\gamma p \to K^+K^-\pi^+(n)$	θ^+	K^+n
SAPHIR	$\gamma p \to K^0_S K^+(n)$	θ^+	K^+n
COSY	$pp \to \Sigma^+ K^0_S p$	θ^+	$K^0_S p$
JINR	$p(C_3H_8) \to K^0_S pX$	θ^+	$K^0_S p$
SVD	$pA \to K^0_S pX$	θ^+	$K^0_S p$
DIANA	$K^+Xe \to K^0_S p(Xe)'$	θ^+	$K^0_S p$
νBC	$\nu A \to K^0_S pX$	θ^+	$K^0_S p$
NOMAD	$\nu A \to K^0_S pX$	θ^+	$K^0_S p$
HERMES	quasi-real photoproduction	θ^+	$K^0_S p$
ZEUS	$ep \to K^0_S pX$	θ^+	$K^0_S p$
NA49	$pp \to \Xi\pi X$	Ξ_5	$\Xi\pi$
H1	$ep \to (D^*p)X$	θ_c	D^*p

[Dzierba et al, hep-ex/0412077]

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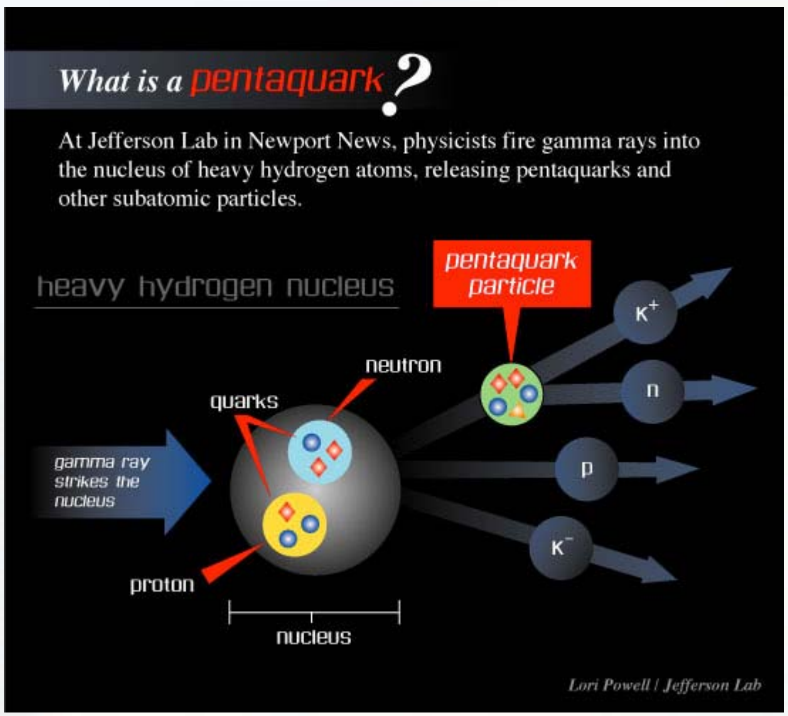

Experiment	Search Reaction	θ^+	Ξ_5	θ_c
ALEPH	Hadronic Z decays	$\Downarrow$	$\Downarrow$	$\Downarrow$
BaBar	$e^+e^- \to \Upsilon(4S)$	$\Downarrow$	$\Downarrow$	–
BELLE	$KN \to PX$	$\Downarrow$	–	$\Downarrow$
BES	$e^+e^- \to J/\psi(\psi(2S) \to \theta\bar{\theta}$	$\Downarrow$	–	$\Downarrow$
CDF	$p\bar{p} \to PX$	$\Downarrow$	$\Downarrow$	$\Downarrow$
COMPASS	$\mu^+(^6LiD) \to PX$	$\Downarrow$	$\Downarrow$	–
DELPHI	Hadronic Z decays	$\Downarrow$	–	–
E690	$pp \to PX$	$\Downarrow$	$\Downarrow$	–
FOCUS	$\gamma p \to PX$	$\Downarrow$	$\Downarrow$	$\Downarrow$
HERA-B	$pA \to PX$	$\Downarrow$	$\Downarrow$	–
HyperCP	$(\pi^+, K^+, p)Cu \to PX$	$\Downarrow$	–	–
LASS	$K^+p \to K^+n\pi^+$	$\Downarrow$	–	–
L3	$\gamma\gamma \to \theta\bar{\theta}$	$\Downarrow$	–	–
PHENIX	$AuAu \to PX$	$\Downarrow$	–	–
SELEX	$(\pi, p, \Sigma)p \to PX$	$\Downarrow$	–	–
SPHINX	$pC(N) \to \theta^+C(N)$	$\Downarrow$	–	–
WA89	$\Sigma^-N \to PX$	–	$\Downarrow$	–
ZEUS	$ep \to PX$	$\Uparrow$	$\Downarrow$	$\Downarrow$

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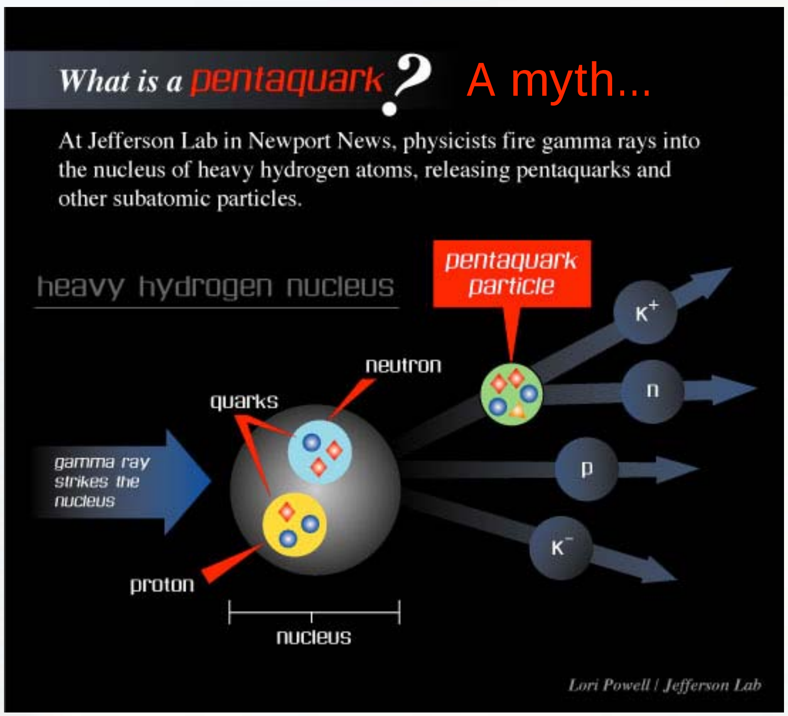

Experiment	Search Reaction	θ^+	Ξ_5	θ_c
ALEPH	Hadronic Z decays	⇓	⇓	⇓
BaBar	$e^+e^- \to \Upsilon(4S)$	⇓	⇓	–
BELLE	$KN \to PX$	⇓	–	⇓
BES	$e^+e^- \to J/\psi(\psi(2S) \to \theta\bar{\theta}$	⇓	–	⇓
CDF	$p\bar{p} \to PX$	⇓	⇓	⇓
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[Dzierba et al, hep-ex/0412077]

Peaks Are Not Easy to Fake?

Lee Ann Womack – "Now You See Me, Now You Don't"

Better take a good look before I disappear
Because I'm just about to be your used-to-be
You might catch a glimpse of my taillights in the dust
And if you notice something missin', well it's me
'Cause I tried and you lied
…
Now you see me, now you don't
First you do but then you won't
Watch me vanish right before your eyes
You might think you see me there
In a cafe on a street somewhere
Yeah, that might be me but I'll be gone
Now you see me, now you don't
…

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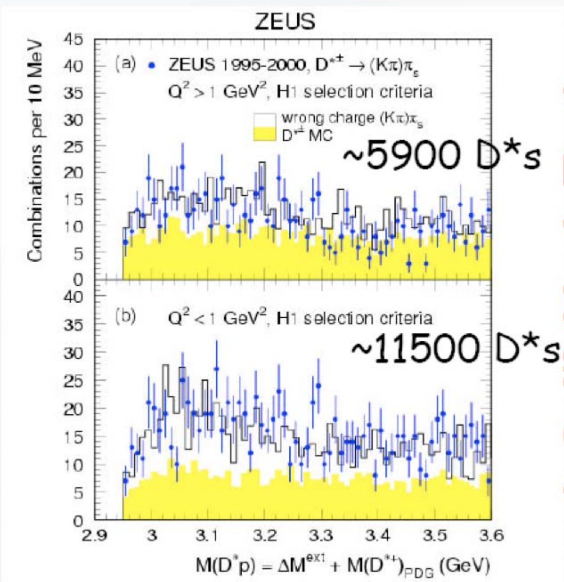

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Conclusions

It's Fun to be a Theorist Today

- Enormous landscape of models
  - Peaks, deserts, valleys, some of which may be hidden!
- Emerging connection of physics at the smallest and largest distances
- Wild West of models; some are pretty imaginative
  - New particles
  - New dimensions
  - New geometries and topologies
- State of the art high-precision calculations at NLO and NNLO
- Improved QCD calculation precision:
  - Important insights from string theory methods (twistor space, AdS/CFT)
  - Greatly improved lattice QCD
- Very powerful MC generators
- Good understanding of PDF and uncertainties
- Interesting attempts to reverse-engineer experimental data

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- The future is bright; no bumps on the road would stop us
- We are destined to find unknown, perhaps of a much more puzzling type than any of us could now imagine!

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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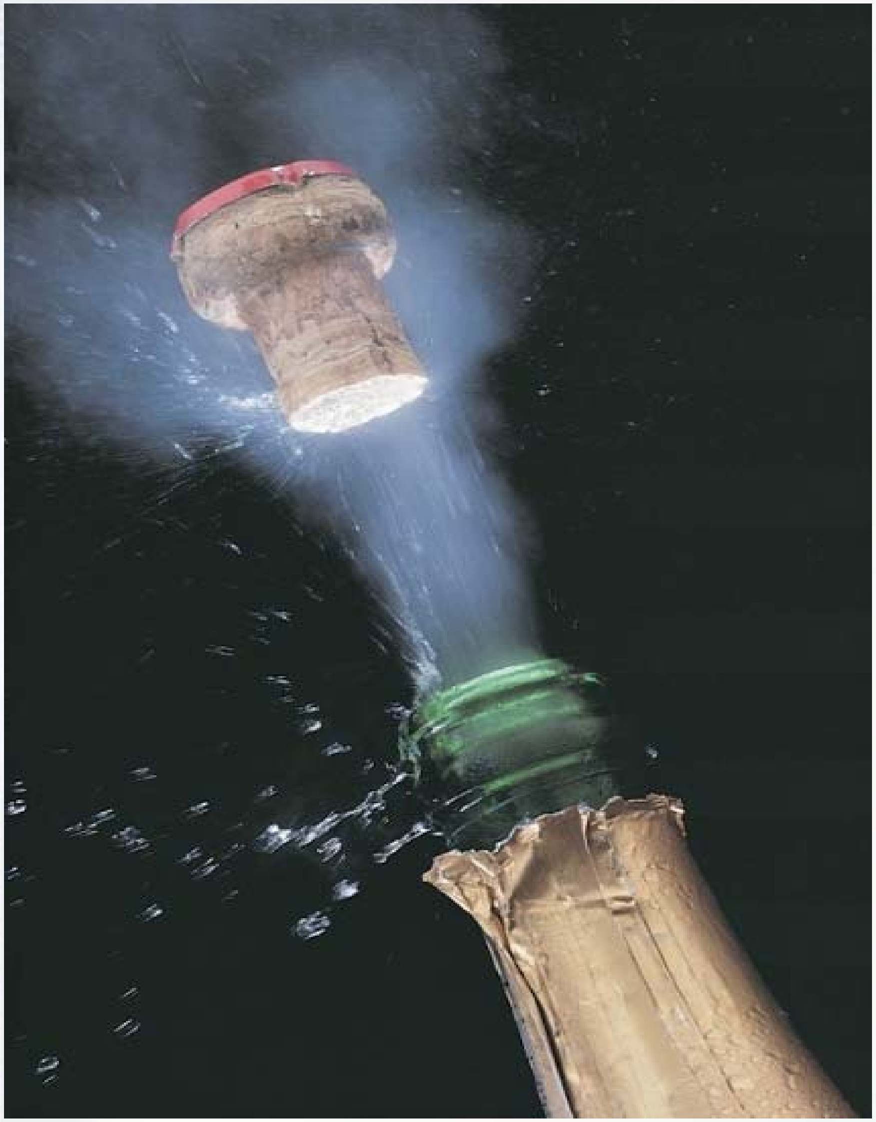

¡Prospero Año Nuevo 2008: el año de LHC!