Discovering New Physics with Early LHC Data

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IN DEO SPERAMUS

OleMiss Physics Colloquium

April 8, 2008

Outline

- Astro-Particle Physics
- The Standard Model
- Beyond the Standard Model
- The Machine, the Detectors
- Searches for New Physics with early LHC Data*
- Conclusions

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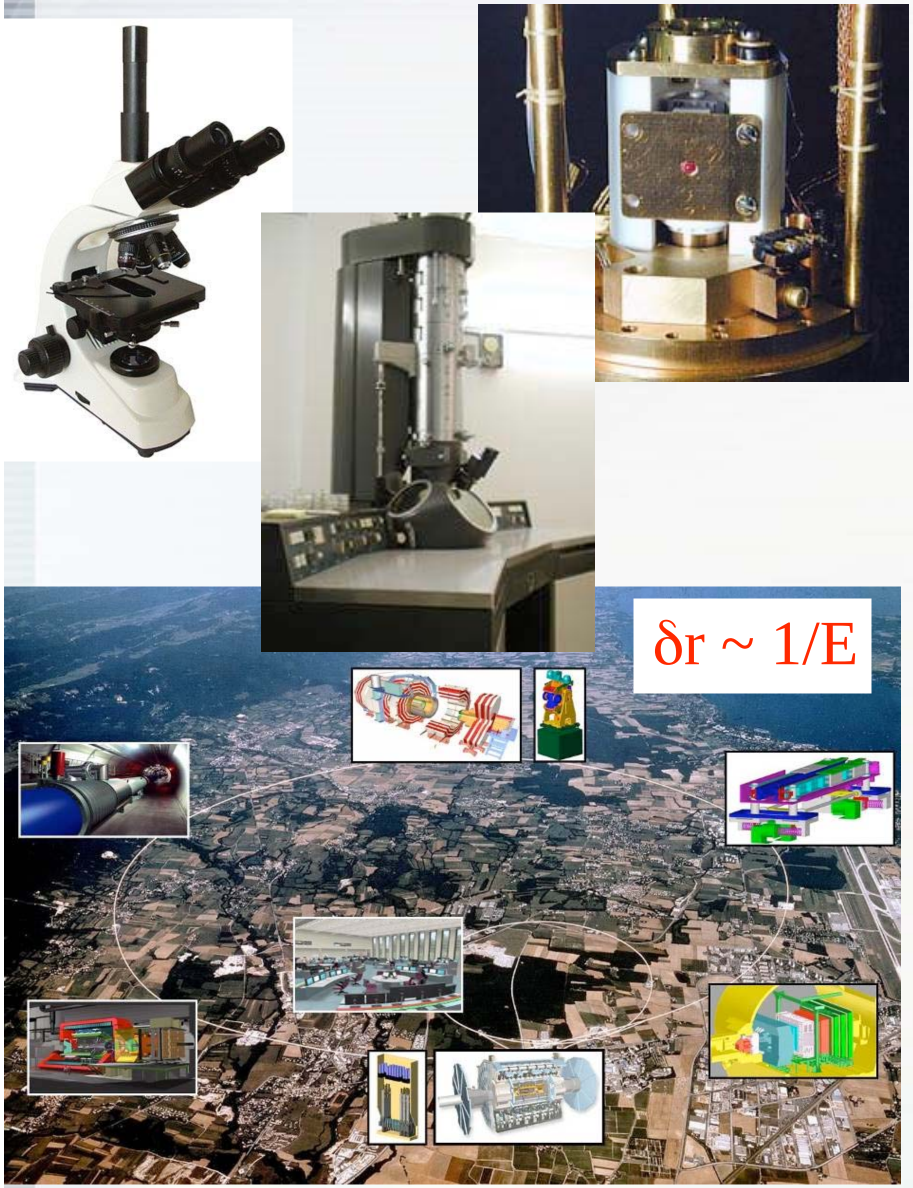
*) Chose to focus on a few characteristic examples, rather than being too inclusive

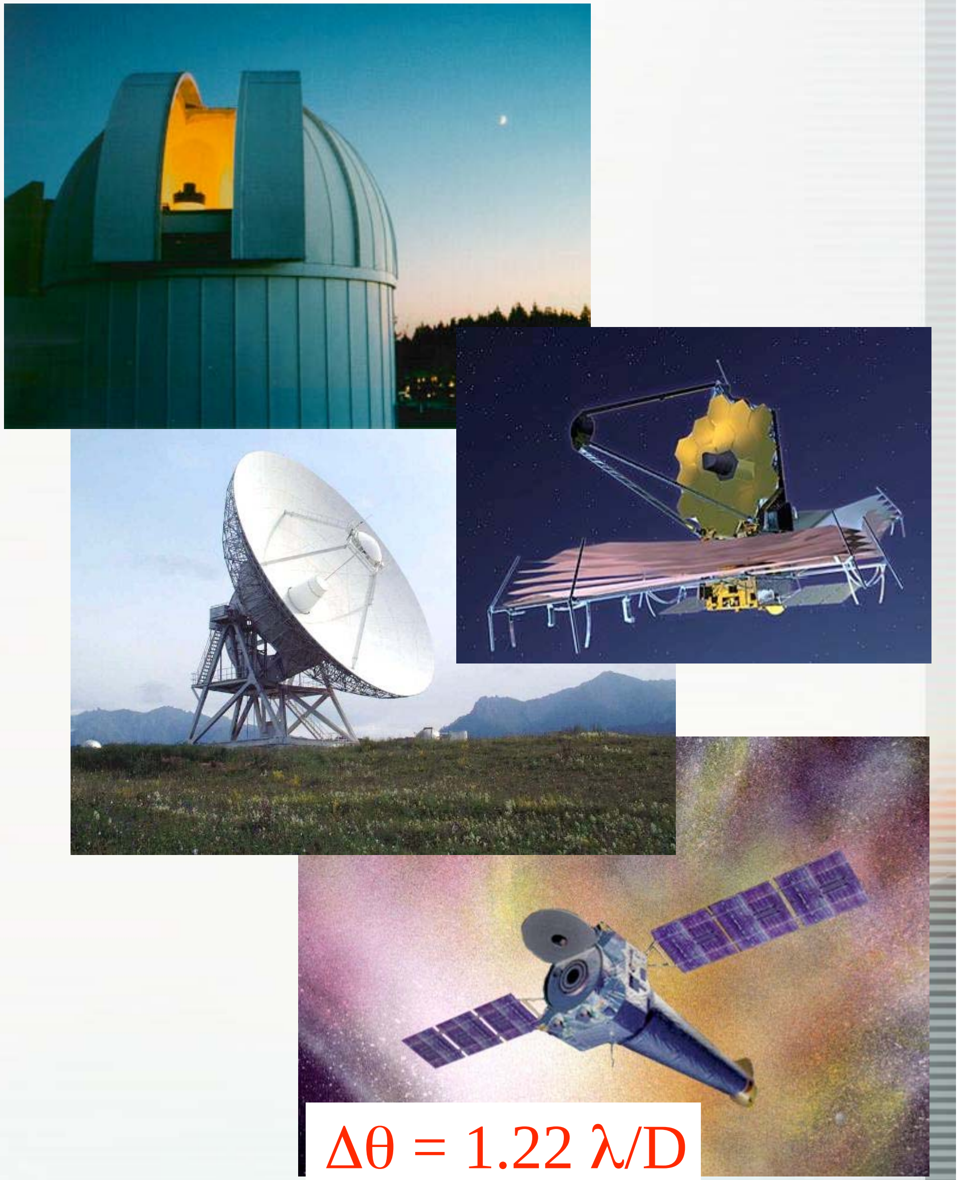
Astro-Particle Physics

- Last decade emphasized remarkable connection between the astrophysics and particle physics:
  - Searches for dark matter
  - QFT connections to early universe and inflation
  - Black hole thermodynamics
  - The “landscape” of string theory
- The more we study these seemingly different subjects, the more connections we discover
  - Physics at the very large distances may be inherently connected to the physics at the shortest ones
- More similarities:
  - Microscopes vs. telescopes
  - Large international collaborations
  - Complicated detectors
- We are (hopefully!) doing the things via two complementary

Microscopes vs. Telescopes

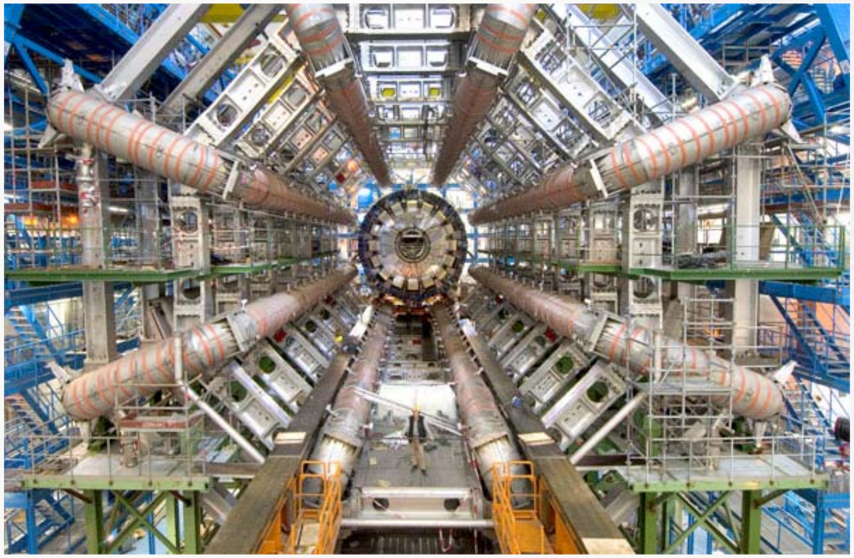


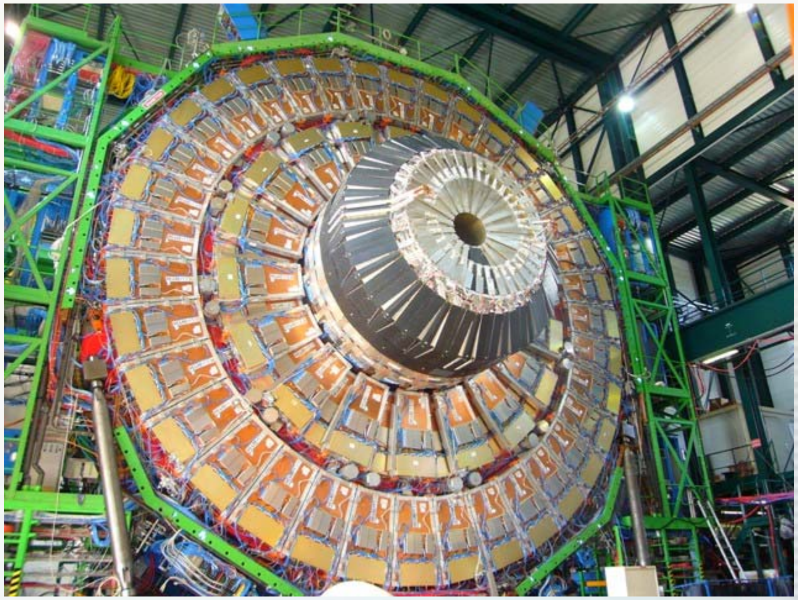
$\delta r \sim 1/E$



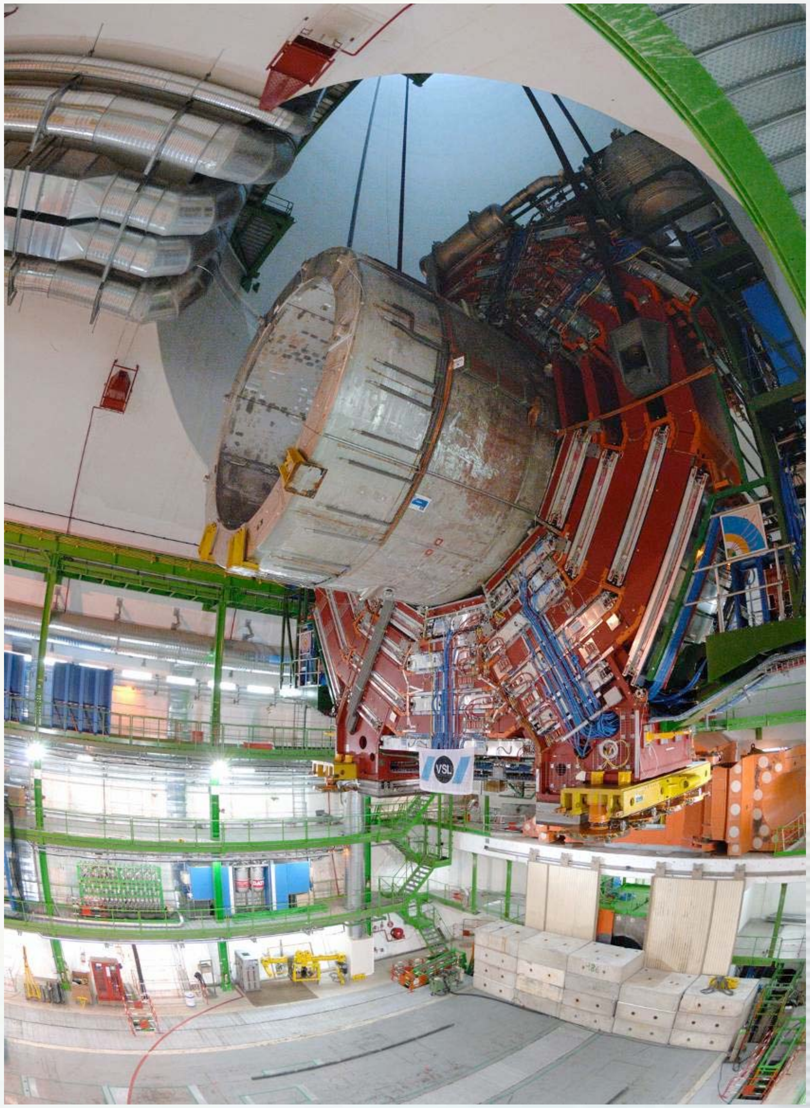
$\Delta\theta = 1.22\,\lambda/D$

Beautiful Instruments

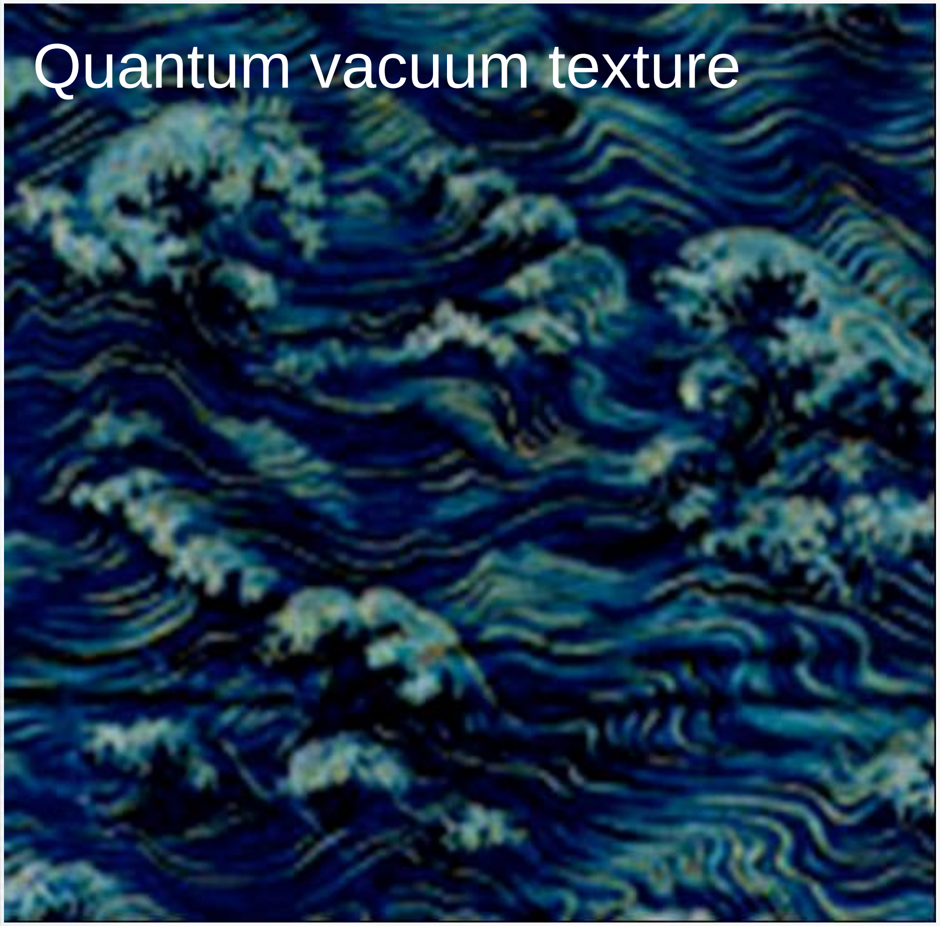




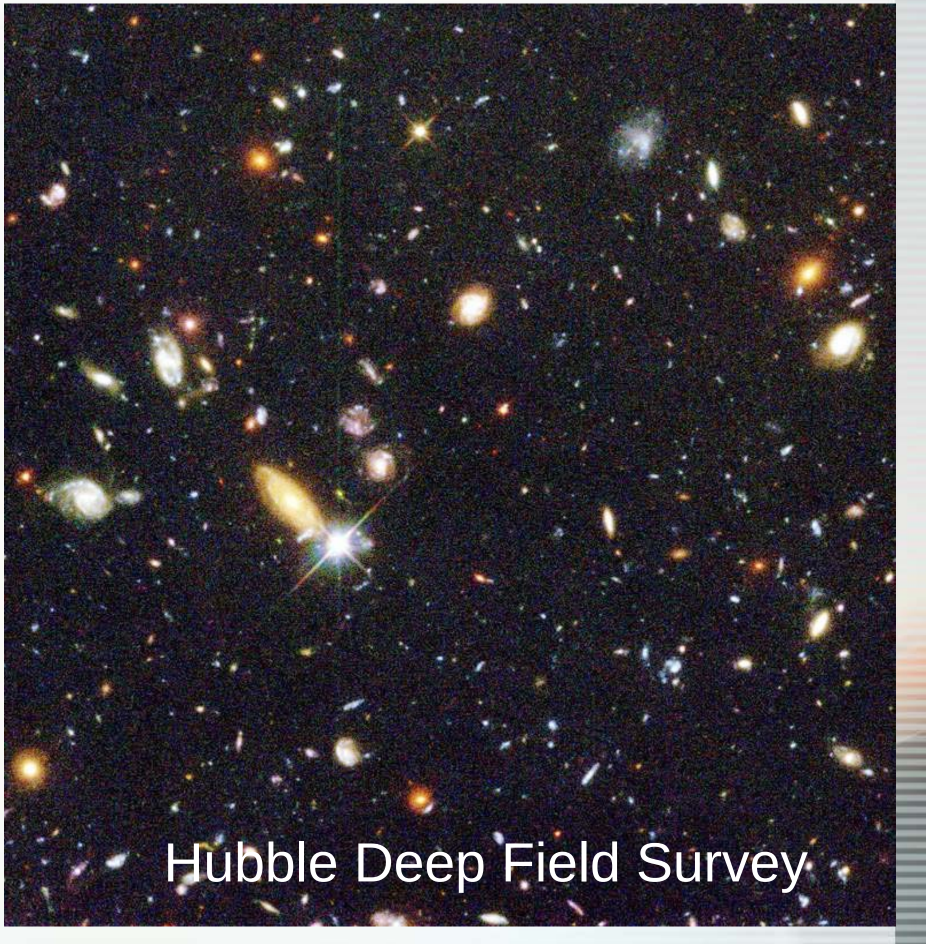
Spectacular Launches



Deep Fields



Quantum vacuum texture



Hubble Deep Field Survey

Unification

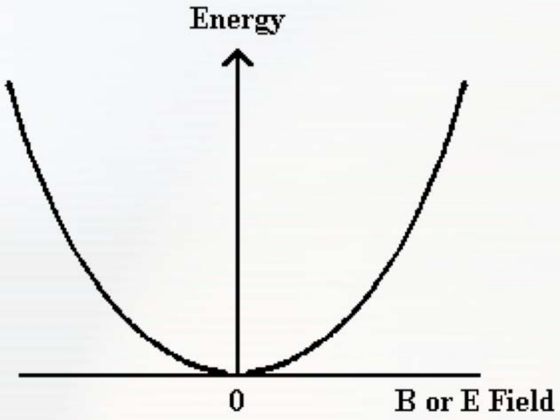
- Physics is about *unification* of seemingly different phenomena:
  - XVIIth century – Newton: Force that makes an apple to fall from the tree is the same force that keeps the Moon orbiting around the Earth
  - XIXth century – Faraday & Maxwell: Electricity and Magnetism are two manifestations of the common electromagnetic (EM) force
  - XXth century – Glashow, Salam, Weinberg: EM and weak force are two manifestations of the common electroweak force
  - XXIth century – Grand Unification of all Forces?
- Unification is the key to the scientific method – *reductionism*

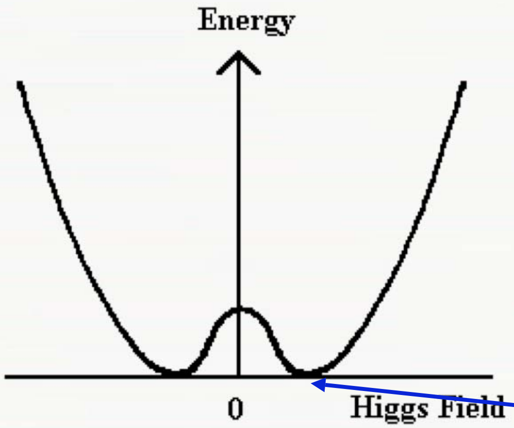
The Standard Model

- 1960-ies: Glashow, Salam, Weinberg, t'Hooft, …
  - EM interactions (Faraday, Maxwell, Feynman, …)
  - Weak interactions (Fermi, Cabibbo, …)

  ⬇

  - Unified electroweak interaction: $SU(2)_L \times U(1)_{EM}$
  - Symmetry is spontaneously broken to give mass to W/Z and leave photons massless
  - Particles acquire masses by interacting with the Higgs field





Electroweak Symmetry Breaking

$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow{\text{LSB}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix};$$

$v \equiv vev = 246$ GeV

4 degrees of freedom → $W^{\pm}$, Z^0, h^0

The Higgs Mechanism

A particle acquiring mass:

[After D. Miller]

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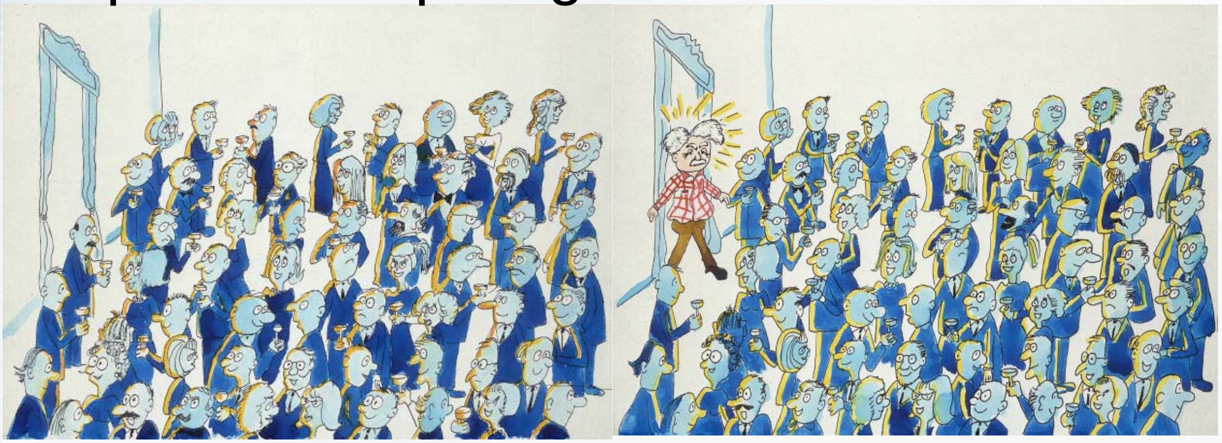

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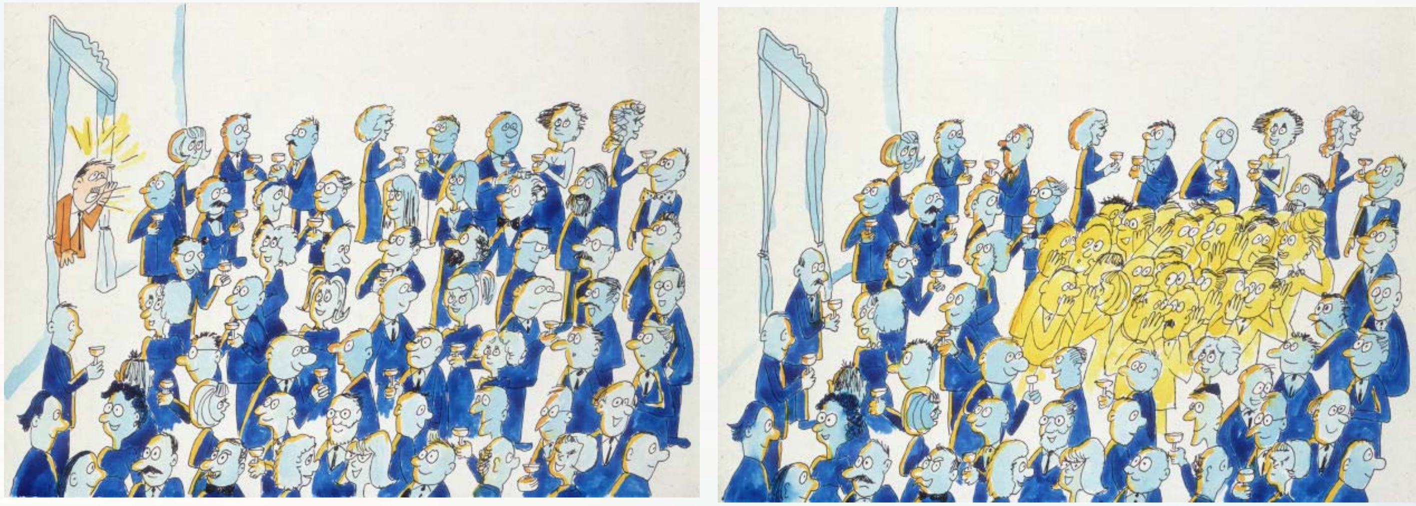


[After D. Miller]

Standard Model Components

Fermions:

$$\begin{pmatrix} \nu_i \\ l_i^- \end{pmatrix}_L \quad \begin{pmatrix} u_i \\ d_i' \end{pmatrix}_L \quad \begin{matrix} (\nu_i)_R & (u_i)_R \\ (l_i)_R & (d_i)_R \end{matrix}$$

Left-handed fields are SU(2) doublets; right-handed fields are SU(2) singlets. Hence: C, P violation

Bosons:

$$\vec{A} = \begin{pmatrix} A_1 \\ A_2 \\ A_3 \end{pmatrix}, \qquad B,$$

$$Z = -B\sin\theta_W + A_3\cos\theta_W$$

$$\gamma = B\cos\theta_W + A_3\sin\theta_W$$

$$W^\pm = \frac{1}{\sqrt{2}}\left(A_1 \pm iA_2\right)$$

$$M_W = \frac{1}{2}\frac{ev}{\sin\theta_W}$$

Weinberg angle

$$M_Z = M_W / \cos\theta_W$$

Standard Model Parameters:

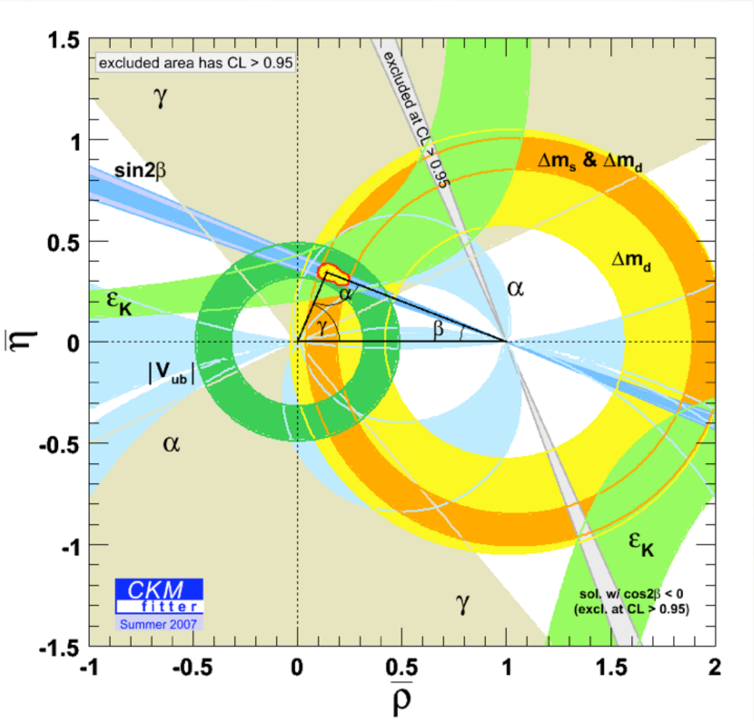
Fine structure constant α = $e^2/4\pi$ = 1/137.03599911(46) [QHE]
(at Z-pole α ≈ 1/128 and depends on the renormalization scheme)

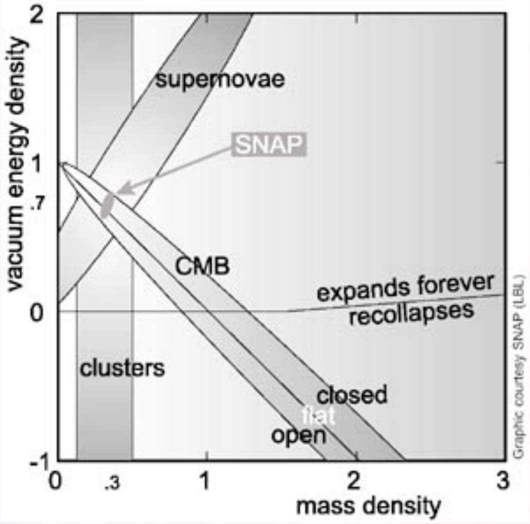
Fermi constant $G_F = 1.16637(1)\times10^{-5}$ GeV^{-2} [muon lifetime]

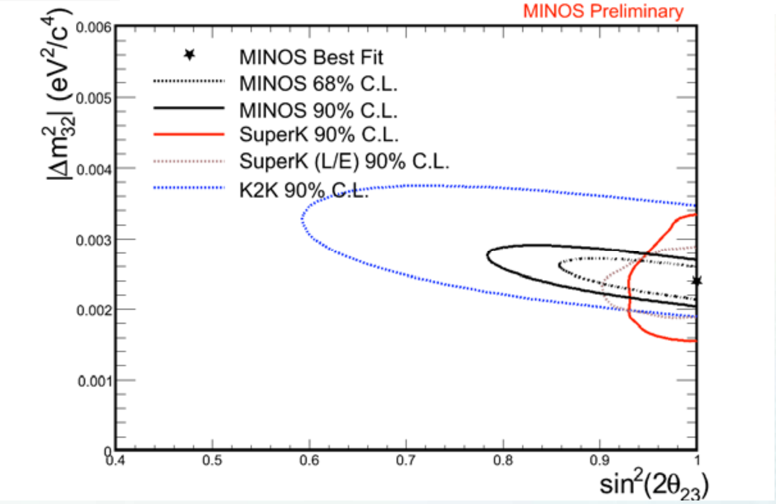
M_Z = 91.1876(21) GeV [LEP 1 Z line-shape measurements]

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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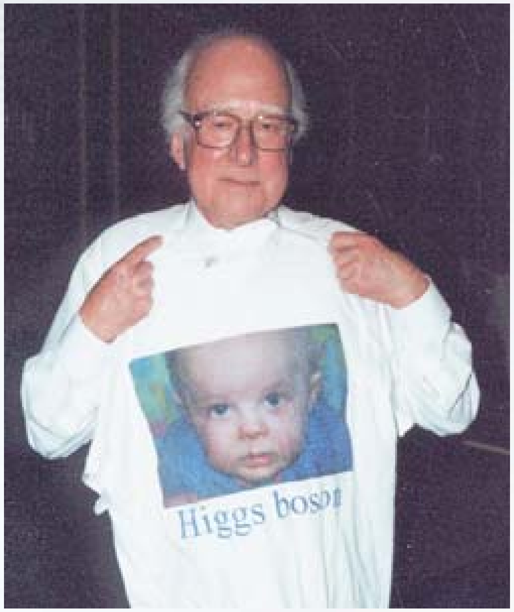

The only Higgs observed in Nature

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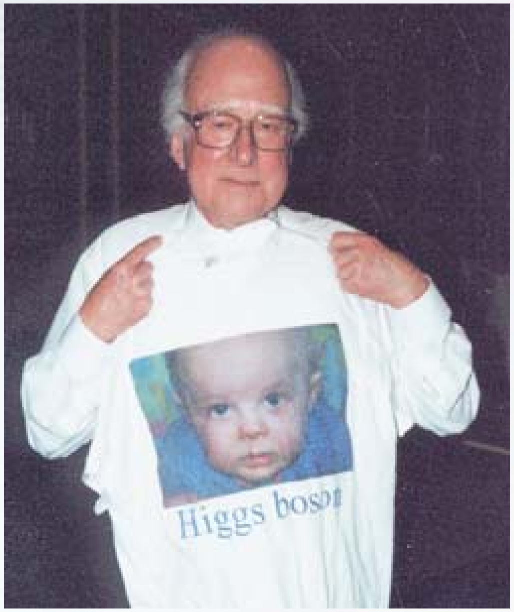

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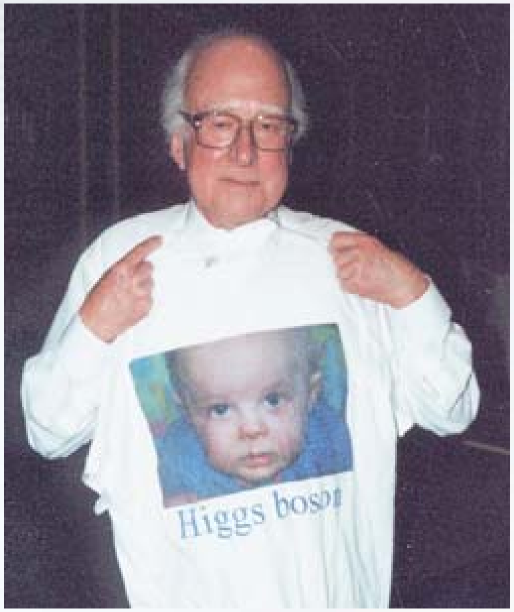

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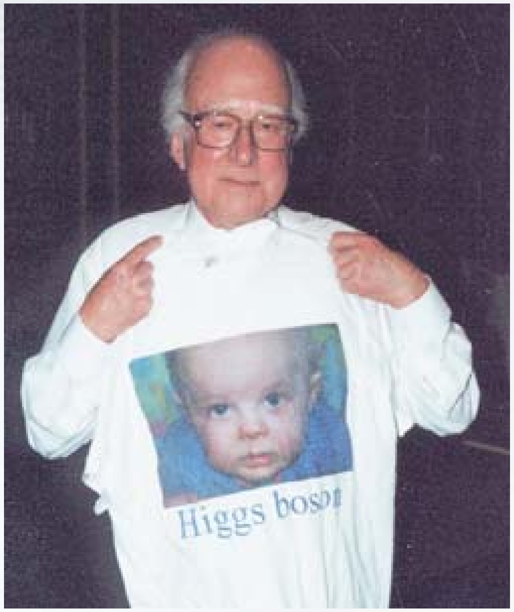

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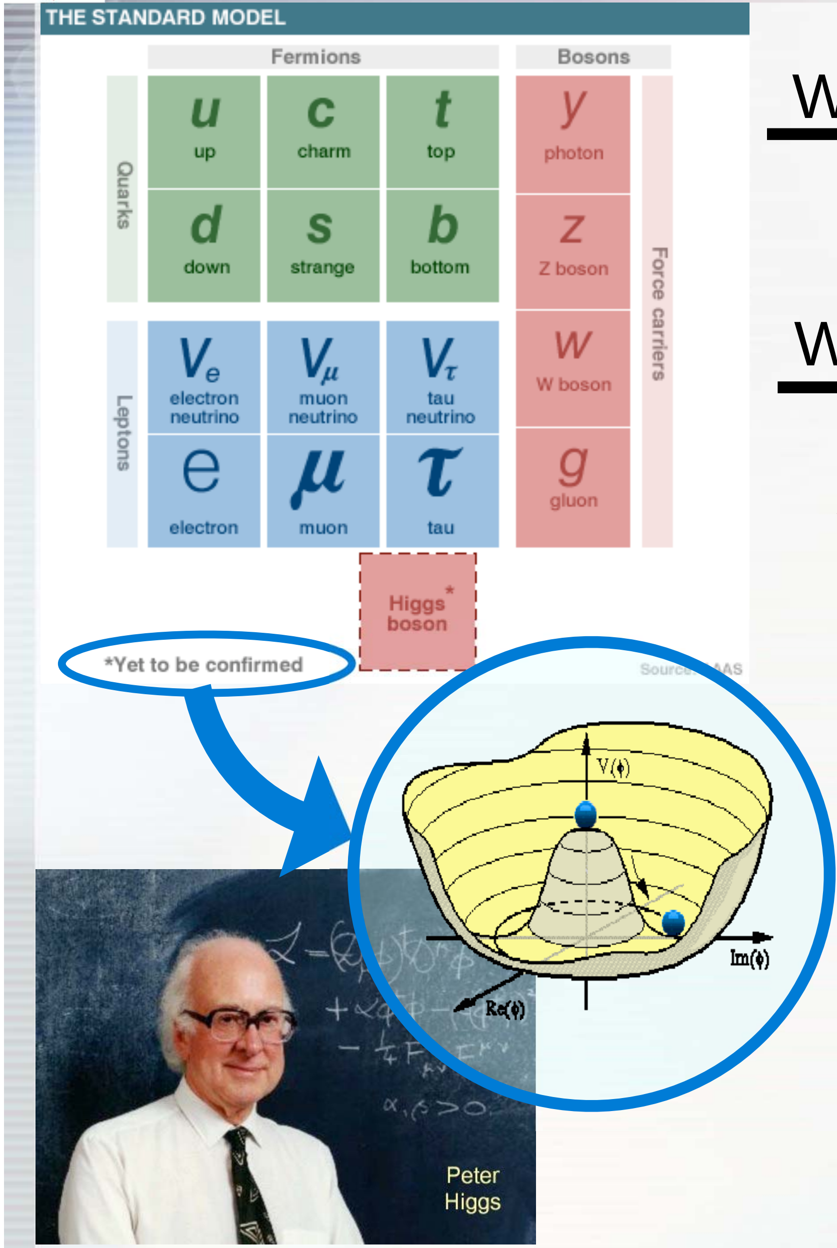
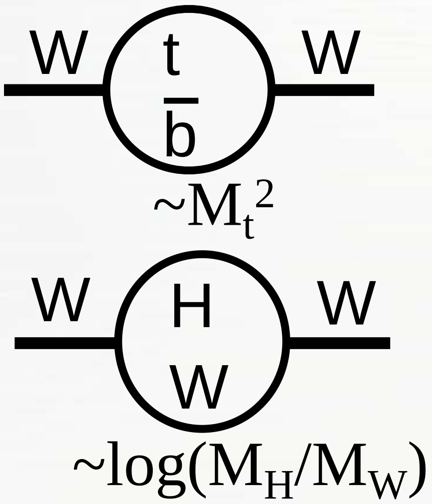
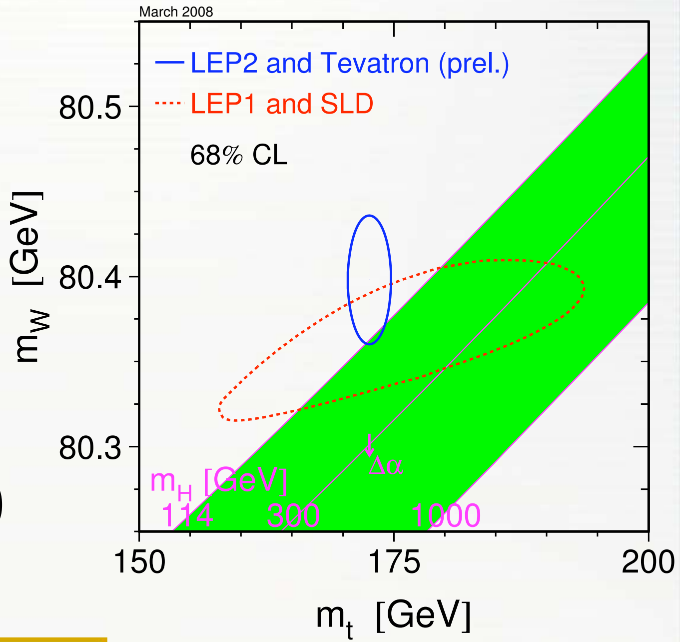
A lot of dark energy...

Puzzle: Where is the Higgs?





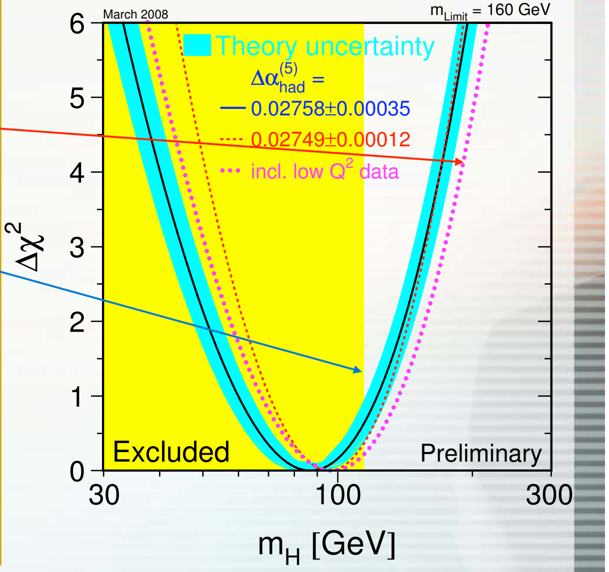


At the 95% CL:

M_H < 160 GeV (EW fit)

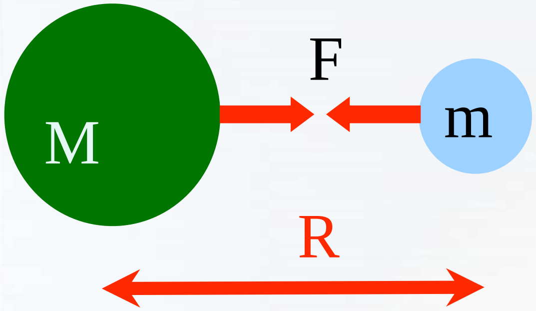
M_H > 114.4 GeV (direct searches)

Most likely mass is just above the direct exclusion!

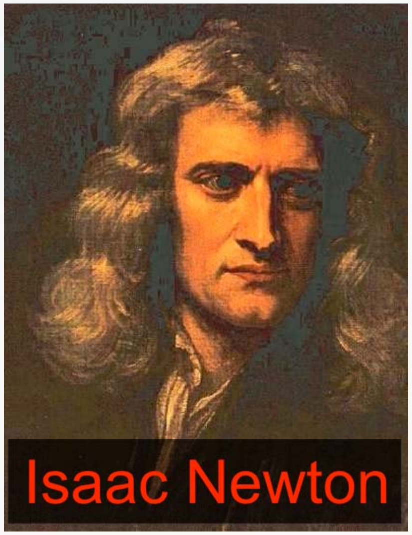


Puzzle: Mass and Gravity

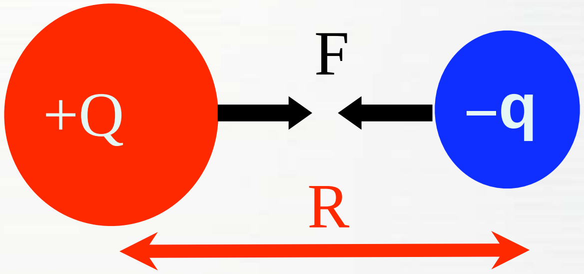
- Isaac Newton: the force that makes the apple fall is the same force that keeps the moon going around the Earth!



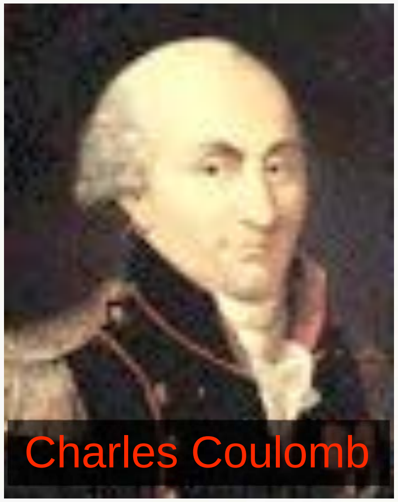
$$F = G_N \frac{Mm}{R^2}$$


Isaac Newton

- Charles Coulomb: opposite electric charges attract!



$$F = G_C \frac{Qq}{R^2}$$


Charles Coulomb

- Mass is analogous to electric charge?!
- But gravity is 10^{38}=100,000,000,000,000,000,000,000,000,000,000,000,000 (hundred trillion trillion trillions!) times WEAKER than electricity! The hierarchy/ naturallness problem: $M_{Pl} = G_N^{-½} = 10^{16}$ TeV » M_{EW} ~ 1 TeV ~ 1000 M_p

Standard Model: Beauty & the Beast

Beauty…

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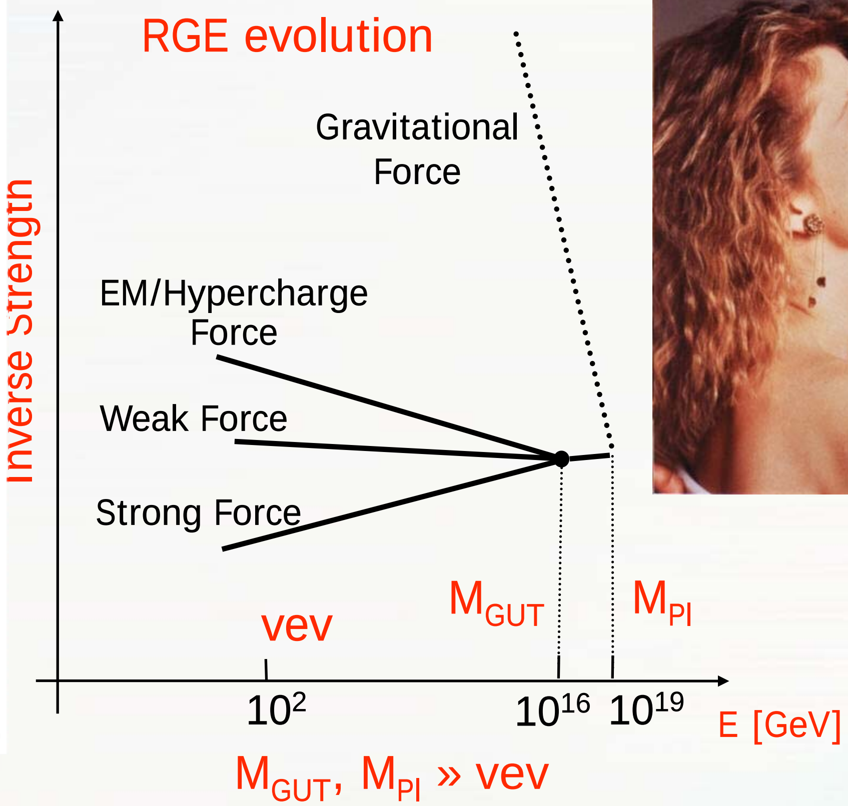

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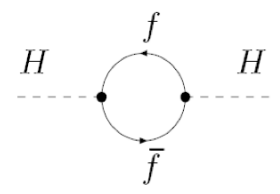
Physics beyond the SM may get rid of the beast while preserving SM's natural beauty!

Naturalness and Triviality

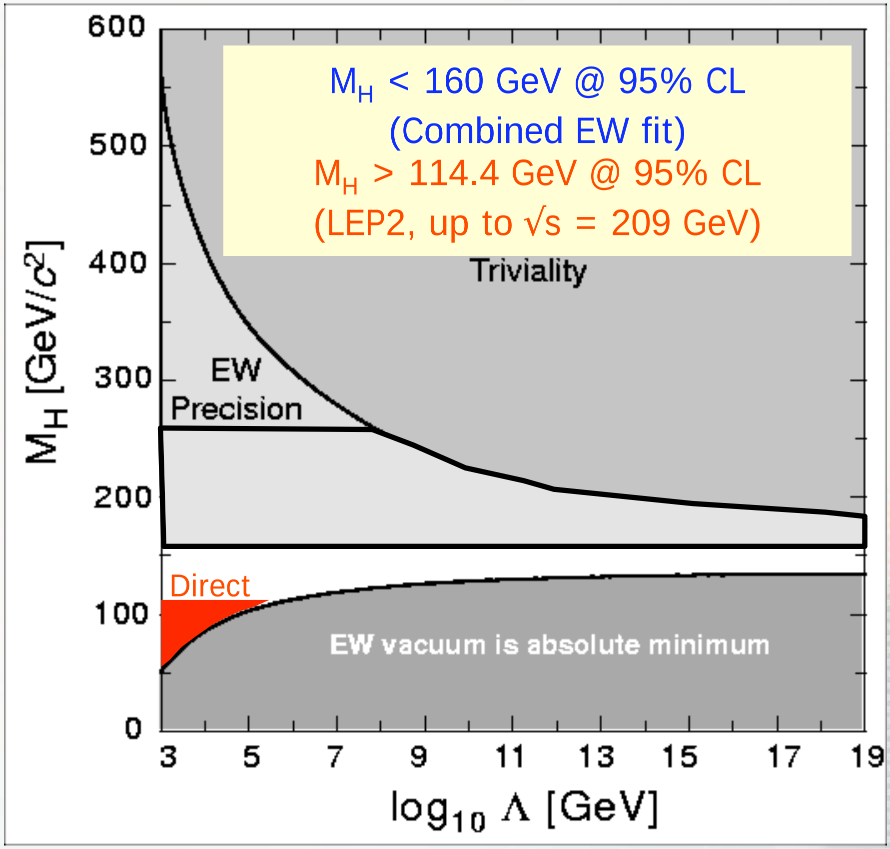
- Higgs mass receives corrections from fermion loops:



- The size of corrections is ~ to the UV cutoff (Λ) squared:

$$\Delta M_H^2 = \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + M_H^2) + \ldots$$

- In order for the Higgs mass to be finite, a fine tuning (cancellation) of various loops is required to a precision $\sim(M_H/\Lambda)^2 \sim 10^{-34}$ for $\Lambda \sim M_{Pl}$
- Higgs mass can't be too light or the potential won't have a Mexican hat shape and will turn negative at large values
- For the SM to be valid up to Planck scale, $M_H > 135$ GeV
- Triviality: if the Higgs mass is too large, the Higgs self-coupling drives the mass to infinity above certain scale
- If one wants the SM to be correct all the way up to Planck scale, $135 < M_H < 175$ GeV is required



Large Hierarchies Tend to Collapse...

More Large Hierarchies

Collapse of the Soviet Union

The nineties…

Gravitational Hierarchy Collapse

With thanks to Chris Quigg and the B44 restaurant in San Francisco

- Human Castles in Catalonia

Note: Some Hierarchies are Surprisingly Stable...

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- Alternative: the *anthropic principle*
  - Properties of the universe are so special because we happen to exist and be able to ask these very questions
  - Is it time to give up science for philosophy? – So far reductionist method worked very well!

Beyond the Standard Model

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- Apart from the hierarchy problem:
  - Standard Model accommodates, but does not explain:
    - EWSB
    - CP-violation
    - Fermion masses
  - It doesn't provide natural explanation of the:
    - Neutrino masses
    - Cold Dark Matter

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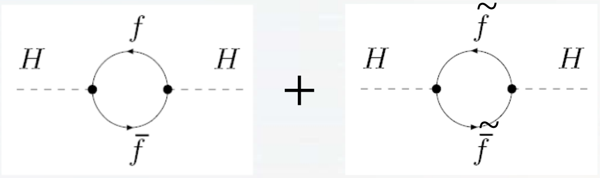
  - –Standard Model accommodates, but does not explain:
    - EWSB
    - CP-violation
    - Fermion masses
  - –It doesn’t provide natural explanation of the:
    - Neutrino masses
    - Cold Dark Matter
- Logical conclusion:
  - –Standard model is an effective theory – a low-energy approximation of a more complete theory, which ultimately explains the above phenomena
  - –This new theory must take off at a scale of ~1 TeV to avoid significant amount of fine tuning
  - –Three classes of solutions:
    - Ensure automatic cancellation of divergencies (SUSY/Little Higgs)
    - Eliminate fundamental scalar and/or introduce intermediate scale $\Lambda \sim 1$ TeV (Technicolor/Higgsless models)
    - Reduce the highest physics scale to ~1 TeV (Extra Dimensions)

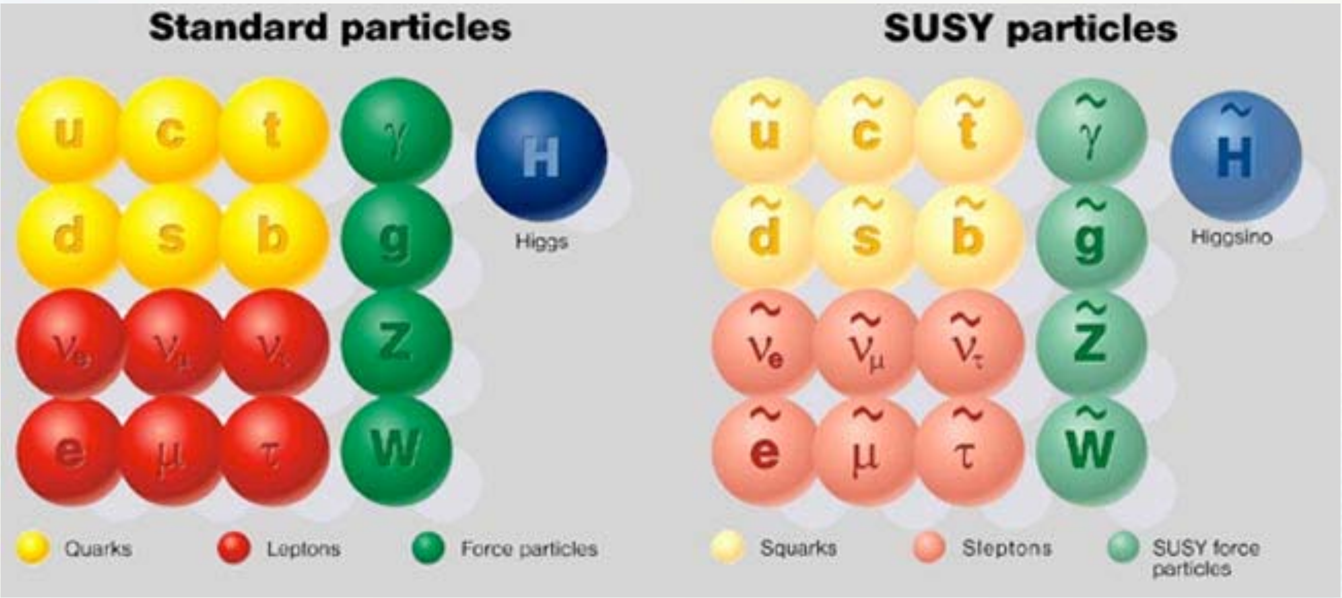
SuperSymmetry (SUSY)

- Observation: loop corrections change sign when a fermion is replaced with a boson
  - Solution to the hierarchy problem: for each fermion, introduce a boson with the same Yukawa coupling to the Higgs field and vice versa!
  - Loops cancel and thus quadratic divergencies are (nearly) cured:



$$\rightarrow \Delta M_H^2 = \sum_f \frac{\lambda_f^2}{4\pi^2}\left(M_f^2 - M_{\tilde f}^2\right) + \ldots$$

  - High price to pay: double the number of known particles
  - SUSY is clearly broken; masses of superpartners can't be more than ~ 1 TeV
  - Also need more than one Higgs doublet to cancel anomalies



SUSY: Gauge Sector

- Higgses: two complex doublets (8 d.o.f.)
  - One gives masses to down-type, and another one – to up-type quarks
  - Ratio of vacuum expectation values is conventionally called tanβ
  - 3 d.o.f. are “eaten” by massive Z, $W^\pm$
  - 5 remaining d.o.f. become physical states: h^0, H^0, $H^\pm$, A^0
  - $M_H > M_h$ by definition; $M_h < 135$ GeV
  - A is a CP-odd Higgs
  - Supersymmetric partners of the two Higgs doublets mix with the partners of SM EWK gauge bosons to give four neutral (neutralinos) and two pairs of charged (charginos) gauginos
  - Gluino remains unmixed

$\tilde{Z}^0, \tilde{\gamma}, \tilde{h}_1^0, \tilde{h}_2^0$

$\tilde{W}^\pm, \tilde{h}^\pm$

$\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$

$\chi_1^\pm, \chi_2^\pm$

SUSY: Even More Complex

- To describe SUSY breaking, explicit ("soft") terms are added to the Lagrangian: >100 parameters!
- Typically, reduce number of parameters by introducing phenomenological constraints (e.g., no FCNC) and often requiring R-parity conservation

$$R_p = (-1)^{3B+L+2S}$$

*Originated in footnote$^{\pm 7}$ of classical Farrar-Fayet paper [PL **76B** (1978) 575]*

- B, L – baryon and lepton numbers; S – spin

"Ordinary" particles +1 ← R_p → -1 **SUSY particles**

P-parity? - Was taken!; Q-parity? - Pardon my French!; hence - R-parity

- R_p-conservation implies that SUSY particles are produced in pairs
- Consequently, the LSP is stable and serves as an excellent dark matter candidate (and also escapes at colliders)
- Cosmology: LSP is neutral and weakly interacting

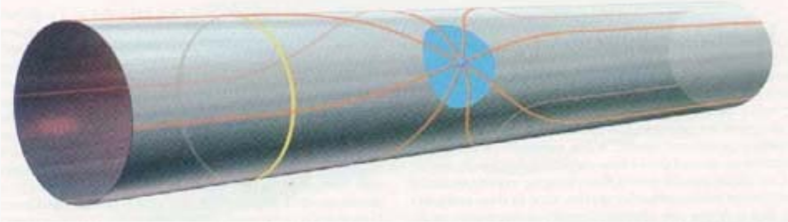
Large Extra Dimensions

- But: what if there is no other scale, and SM model is correct up to M_{Pl}?
  - Give up naturalness: inevitably leads to anthropic reasoning
  - Radically new approach – Arkani-Hamed, Dimopoulos, Dvali (ADD, 1998): maybe the fundamental Planck scale is only ~ 1 TeV?!!
- Gravity is made strong at a TeV scale due to existence of *large* (r ~ 1mm – 1fm) extra spatial dimensions:
  - SM particles are confined to a 3D “brane”
  - Gravity is the only force that permeates “bulk” space
- What about Newton’s law?

$$V(\rho) = \frac{1}{M_{\mathrm{Pl}}^2}\frac{m_1 m_2}{\rho^{n+1}} \to \frac{1}{\left(M_{\mathrm{Pl}}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{\rho^{n+1}}$$

- Ruled out for infinite ED, but does not apply for compact ones:

$$V(\rho) \approx \frac{1}{\left(M_{\mathrm{Pl}}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^n \rho}, \mathrm{for}\,\rho \gg r$$



- Gravity is fundamentally strong force, but we do not feel that as it is diluted by the large volume of the bulk space $G'_N = 1/(M_{\mathrm{Pl}}^{[3+n]})^2$ = $1/M_D^2$; M_D ~ 1 TeV

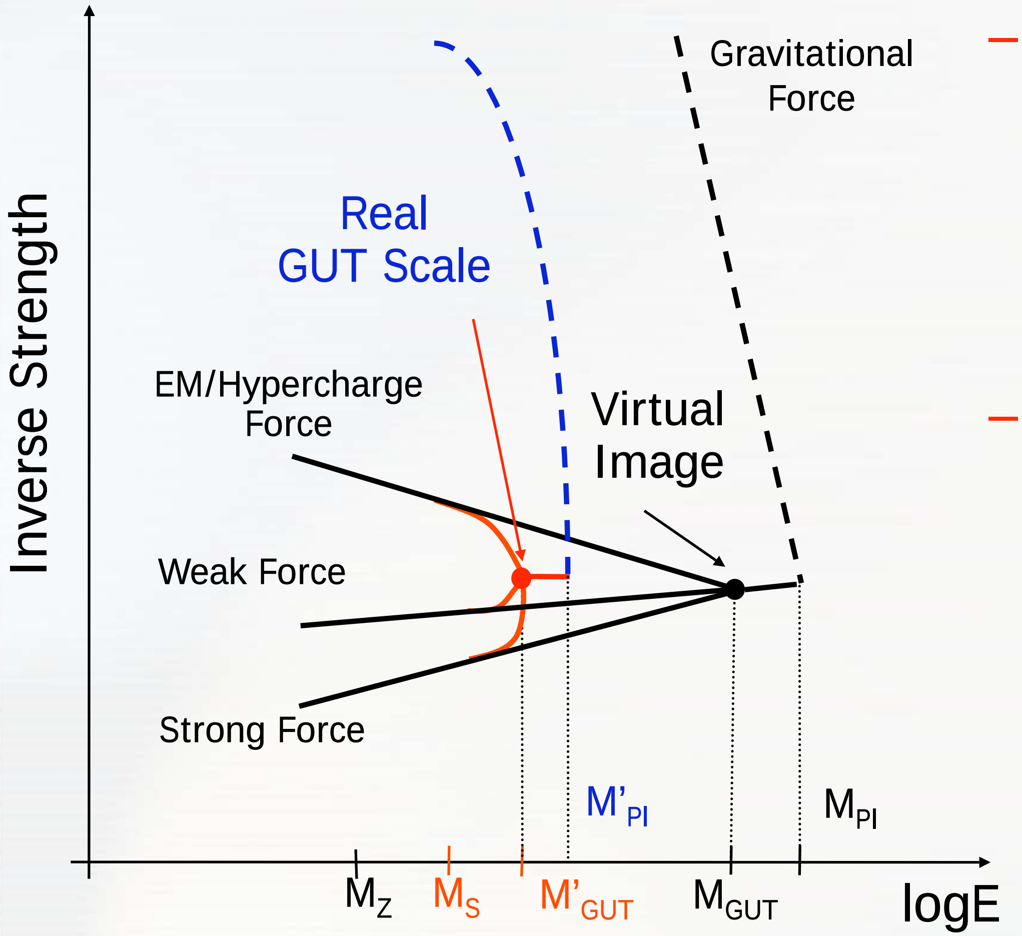
$$M_D^{n+2} \sim M_{\mathrm{Pl}}^2/r^n$$

- More precisely, from Gauss’s law:

$$r = \frac{1}{\sqrt{4\pi}M_D}\left(\frac{M_{\mathrm{Pl}}}{M_D}\right)^{2/n} \sim \begin{cases} 8\times 10^{12}m, & n=1 \\ 0.7mm, & n=2 \\ 3nm, & n=3 \\ 6\times 10^{-12}m, & n=4 \end{cases}$$

- Amazing as it is, but as of 1998 no one has tested Newton’s law to distances less than ~ 1mm!
- Thus, the fundamental Planck scale could be as low as 1 TeV for n > 1

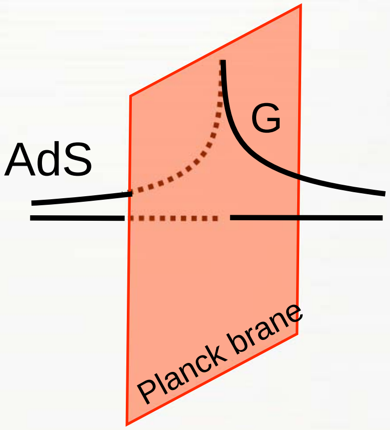
TeV^{-1} Extra Dimensions



- Simultaneously, another idea has appeared:
  - Explore modification of force behavior in (3+n)-dimensions to achieve low-energy grand unification: Dienes, Dudas, Gherghetta [PL **B436**, 55 (1998)]
  - To achieve that, allow other force carriers (g, γ, W, and Z) to propagate in an extra dimension, which is "longitudinal" to the SM brane and compactified on a "natural" EW scale:
    - r ~ 1 TeV^{-1} ~ 10^{-19} m

Randall-Sundrum Model

- Randall-Sundrum (RS) model [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - –One + brane – no low energy effects
  - –Two + and – branes – TeV Kaluza-Klein modes of graviton
  - –Low energy effects on SM brane are given by Λ_π; for kr ~ 10, Λ_π ~ 1 TeV and the hierarchy problem is solved naturally



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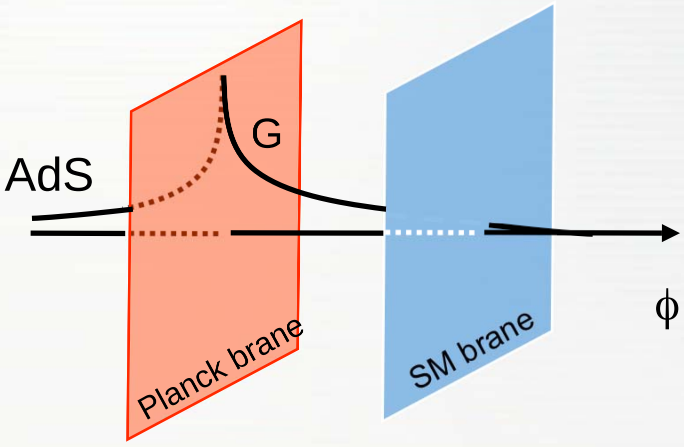

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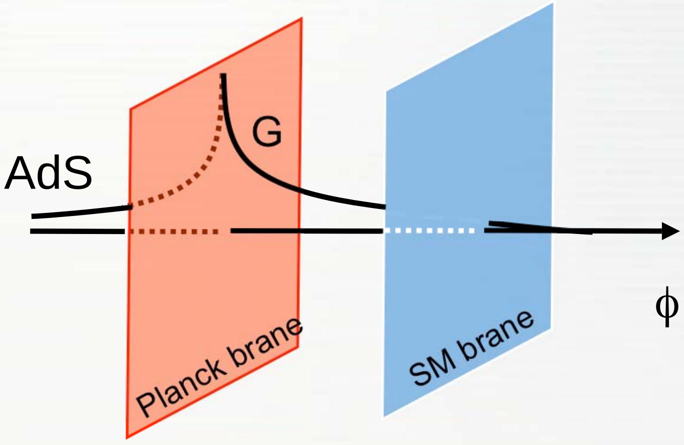
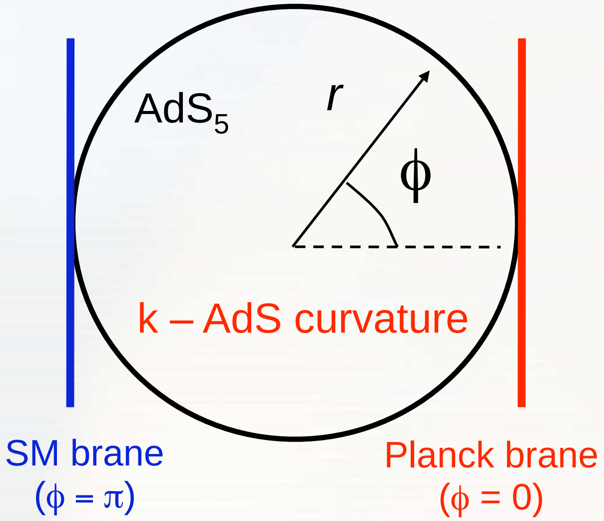




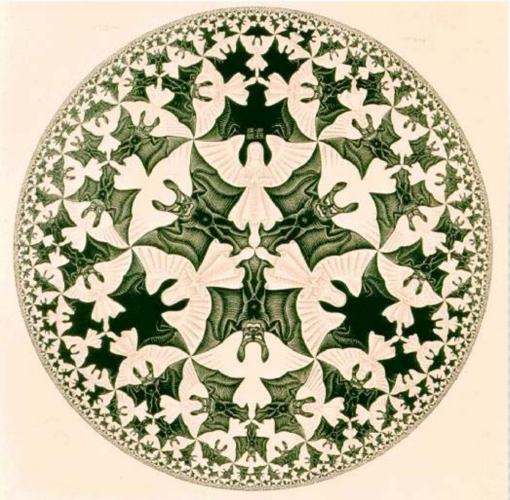
Anti-deSitter space-time metric:

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$

$$\Lambda_\pi = \overline{M}_{\rm Pl} e^{-kr\pi}$$

Reduced Planck mass:

$$\boxed{\overline{M}_{\rm Pl} \equiv M_{\rm Pl}/\sqrt{8\pi}}$$

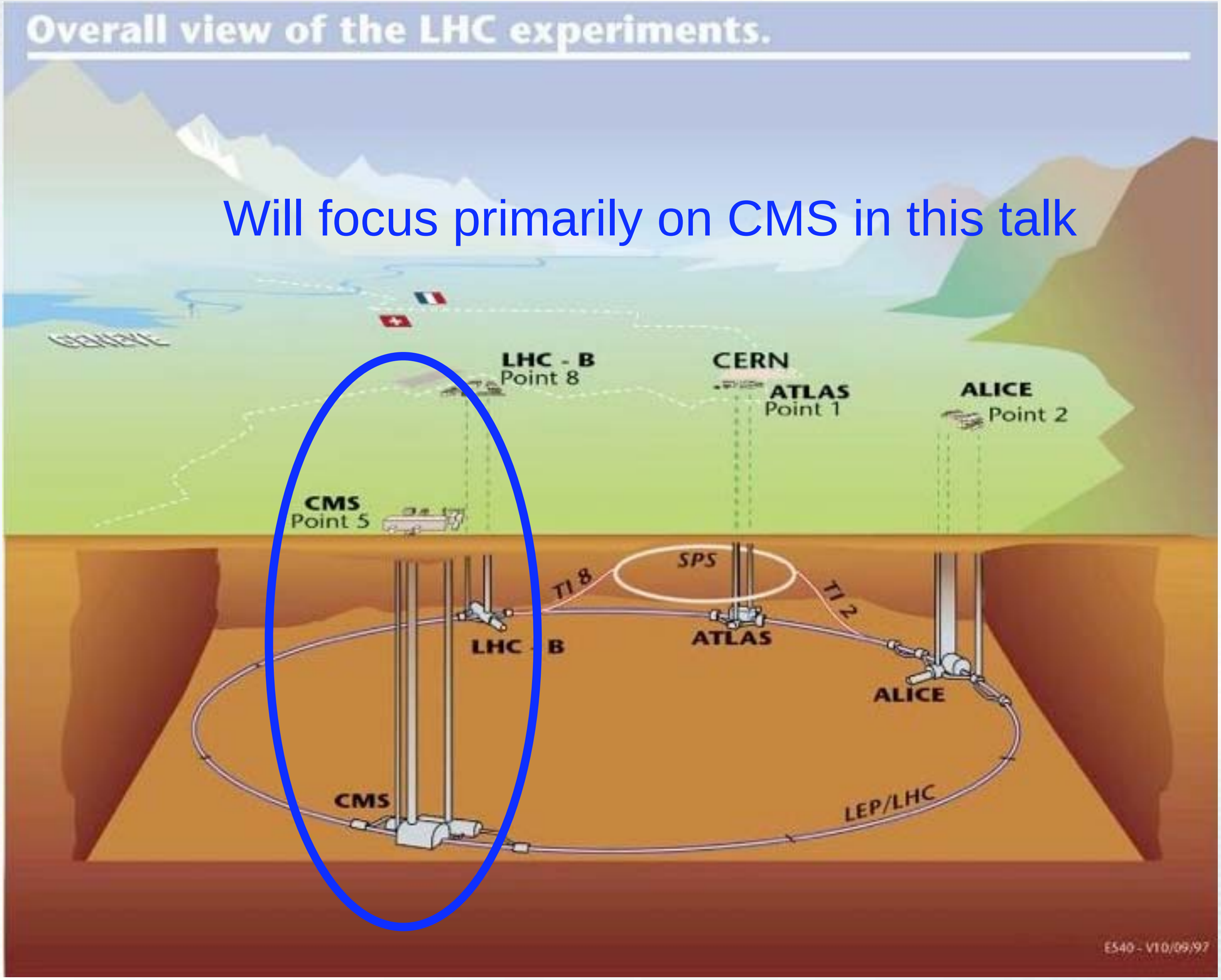


The Machine

The LHC

The LHC - Aerial View

The LHC



Will focus primarily on CMS in this talk

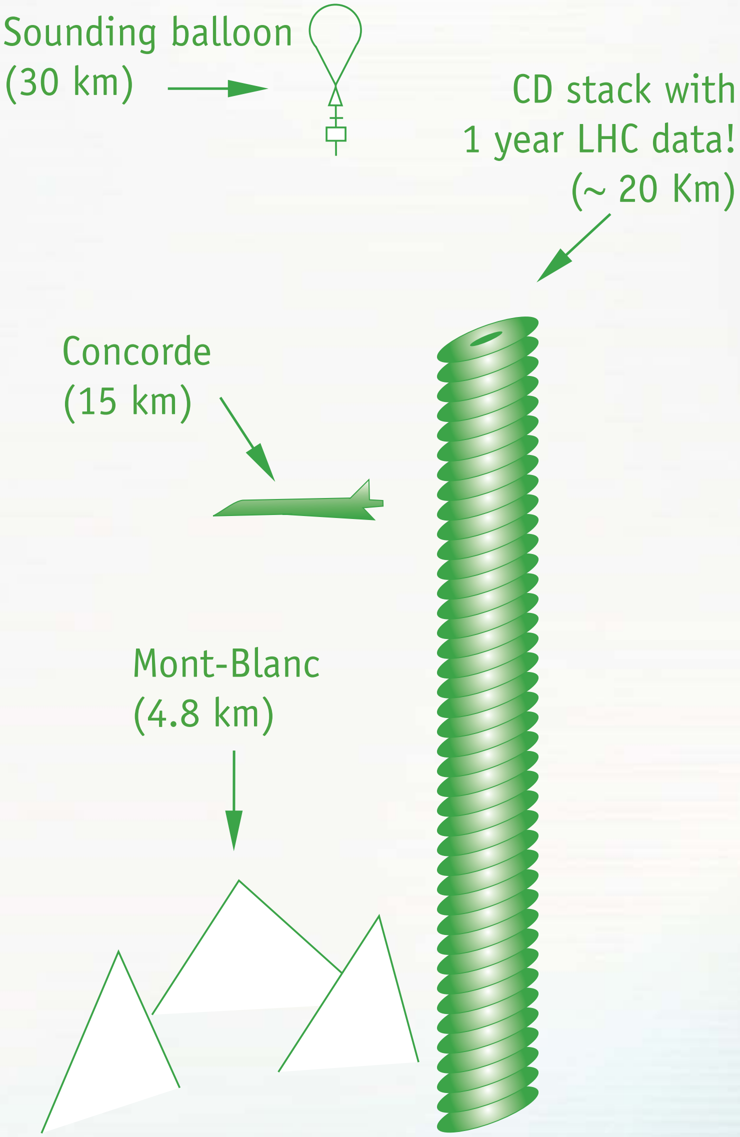
LHC: facts

- Energy: 7 x 7 TeV (will start at 5 x 5 TeV), i.e. 7 times more powerful than the existing machines
- Circumference: 26.7 km
- Number of proton bunches: 2808 x 2808
- Number of protons per bunch: 1.15 x 10^{11}
- Magnetic field: 8.3 T
- Luminosity: 10^{34} $cm^{-2}s^{-1}$ = 10^{-2} $pb^{-1}s^{-1}$ = 7 top pairs/s = 100 W(eν)/s
- Energy stored in magnets: 10 GJ = A380 at a cruise speed of 700 km/s. Can heat and melt 12 tons of copper!

- Energy stored in a single beam: 360MJ = 90 kg of TNT = 8 liters of gas = 15 kg of chocolate

LHC: Niagara worth of Data!

- *ATLAS will produce 320 MB/s*
- *CMS will produce 220 MB/s*
- *LHCb will produce 50 MB/s*
- *ALICE will produce 100 MB/s*



Sounding balloon
(30 km)

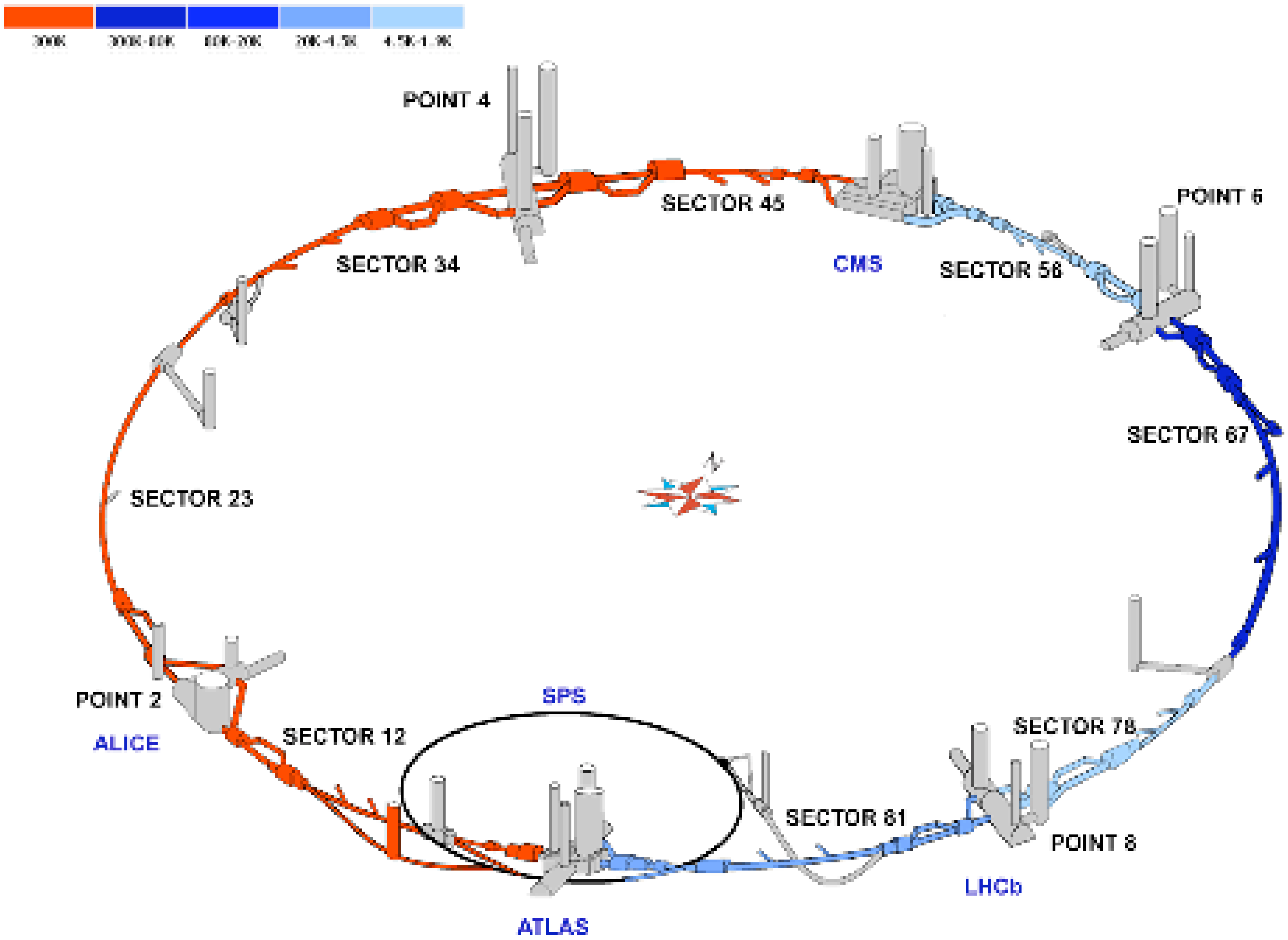
CD stack with
1 year LHC data!
(~ 20 Km)

Concorde
(15 km)

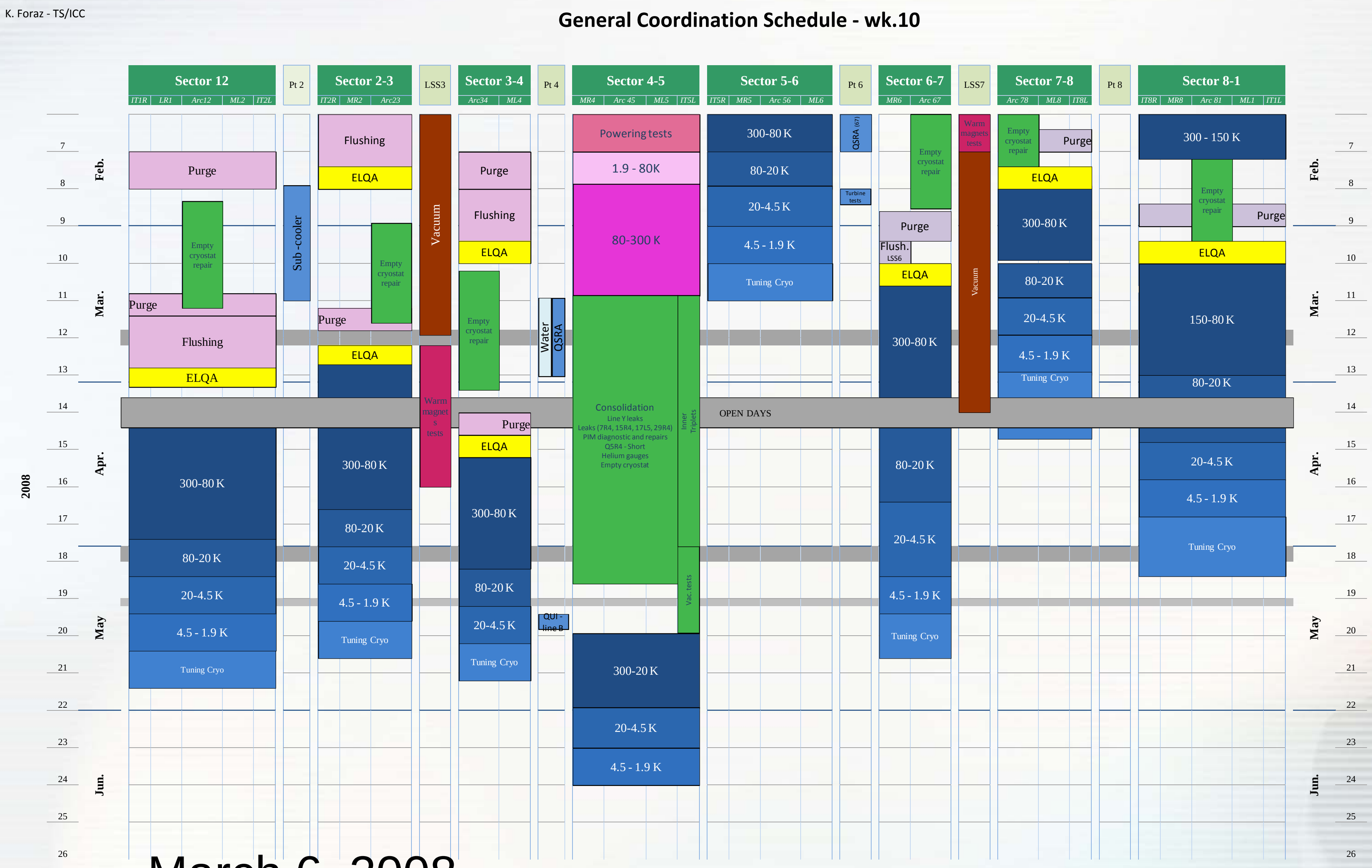
Mont-Blanc
(4.8 km)

Cooldown Status

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



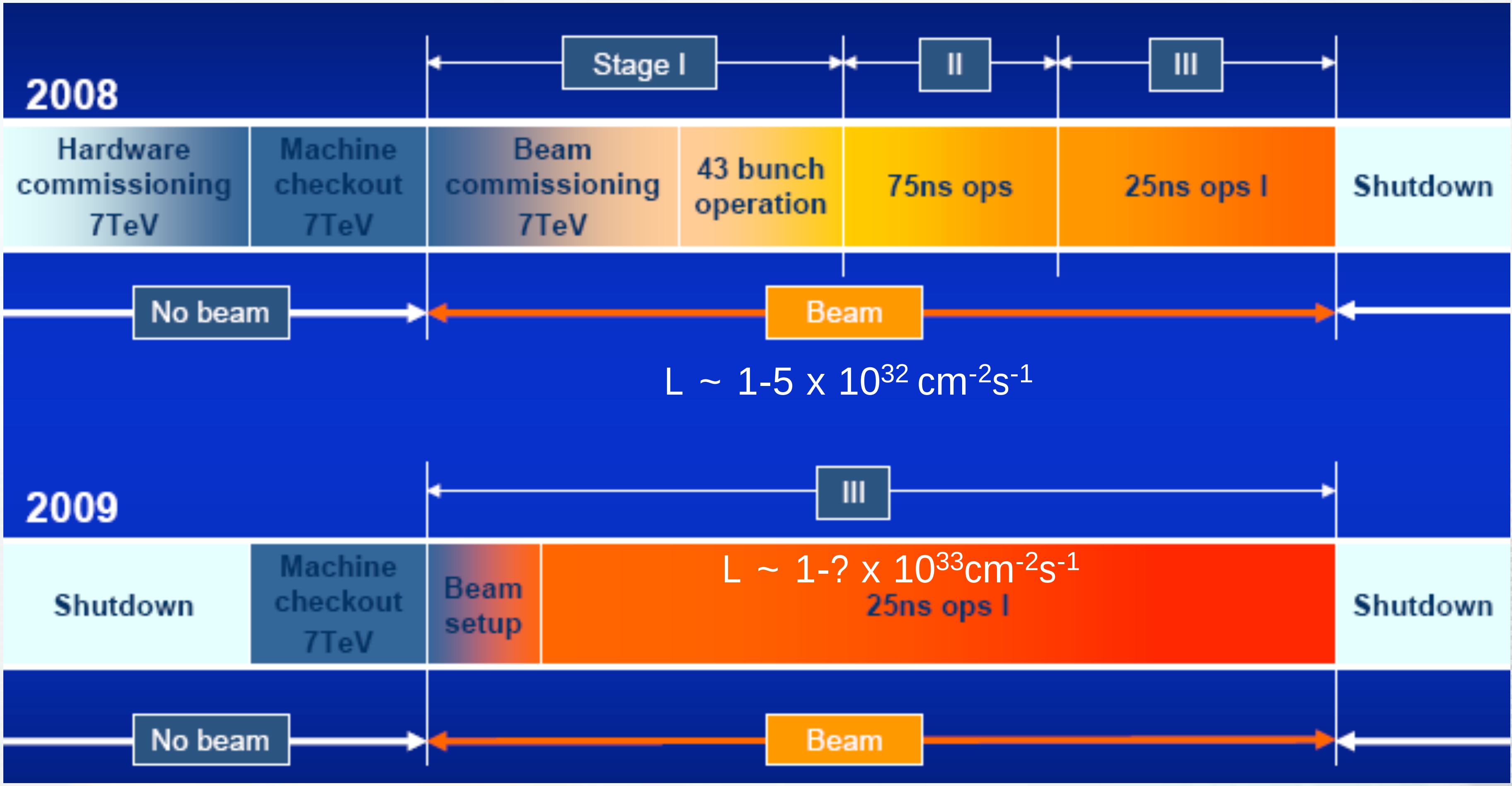
Cooldown Schedule



March 6, 2008

The LHC Operation Stages

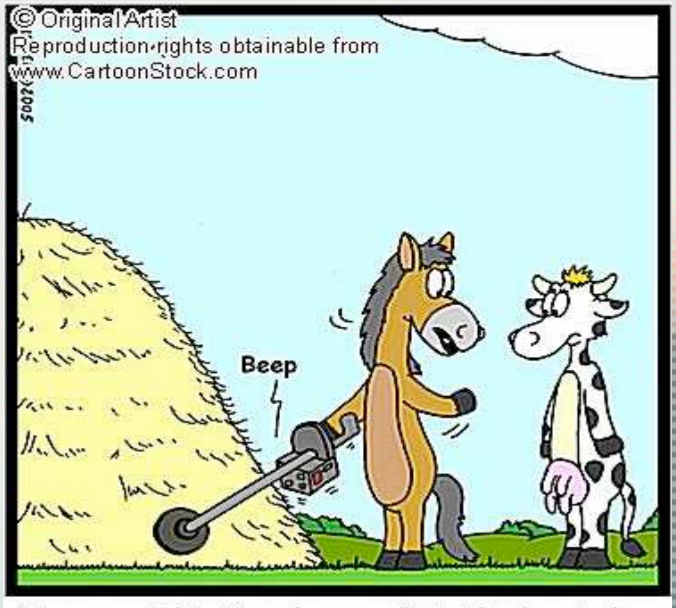
- First 14 TeV Collisions: ~Summer/Fall 2008
- Effective ATLAS/CMS running time/year: ~1000 hours ~ 4 x 10^6 s ~ 4 x 10^{39} cm^{-2} = 4 x 10^{15} b^{-1} = 4 fb^{-1} @ 10^{33} $cm^{-2}s^{-1}$
- Expected luminosity: ~10-100 pb^{-1} in 2008 (@10 TeV); a few fb^{-1} in 2009



L ~ 1-5 x 10^{32} $cm^{-2}s^{-1}$

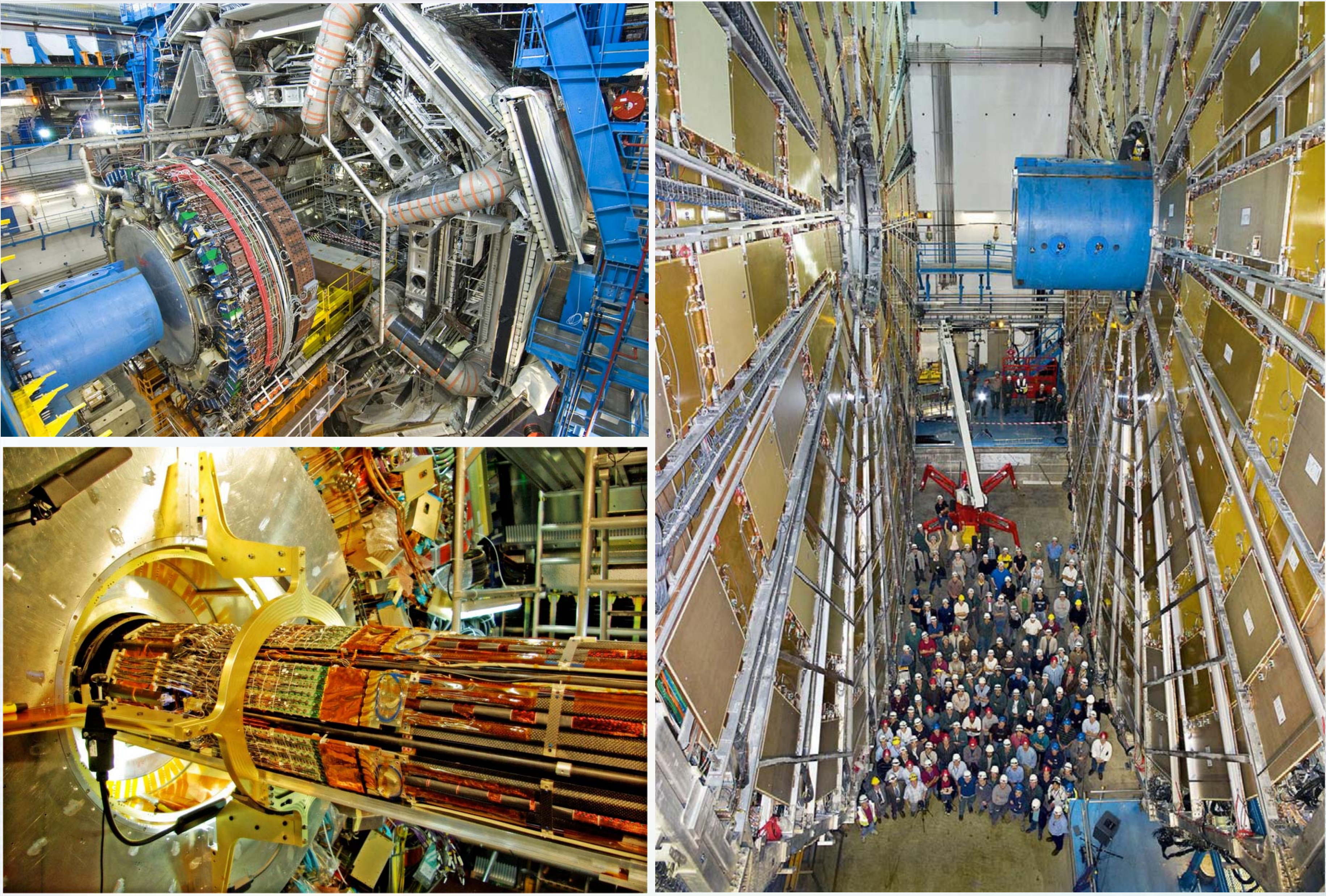
L ~ 1-? x $10^{33}$$cm^{-2}s^{-1}$

The Detectors

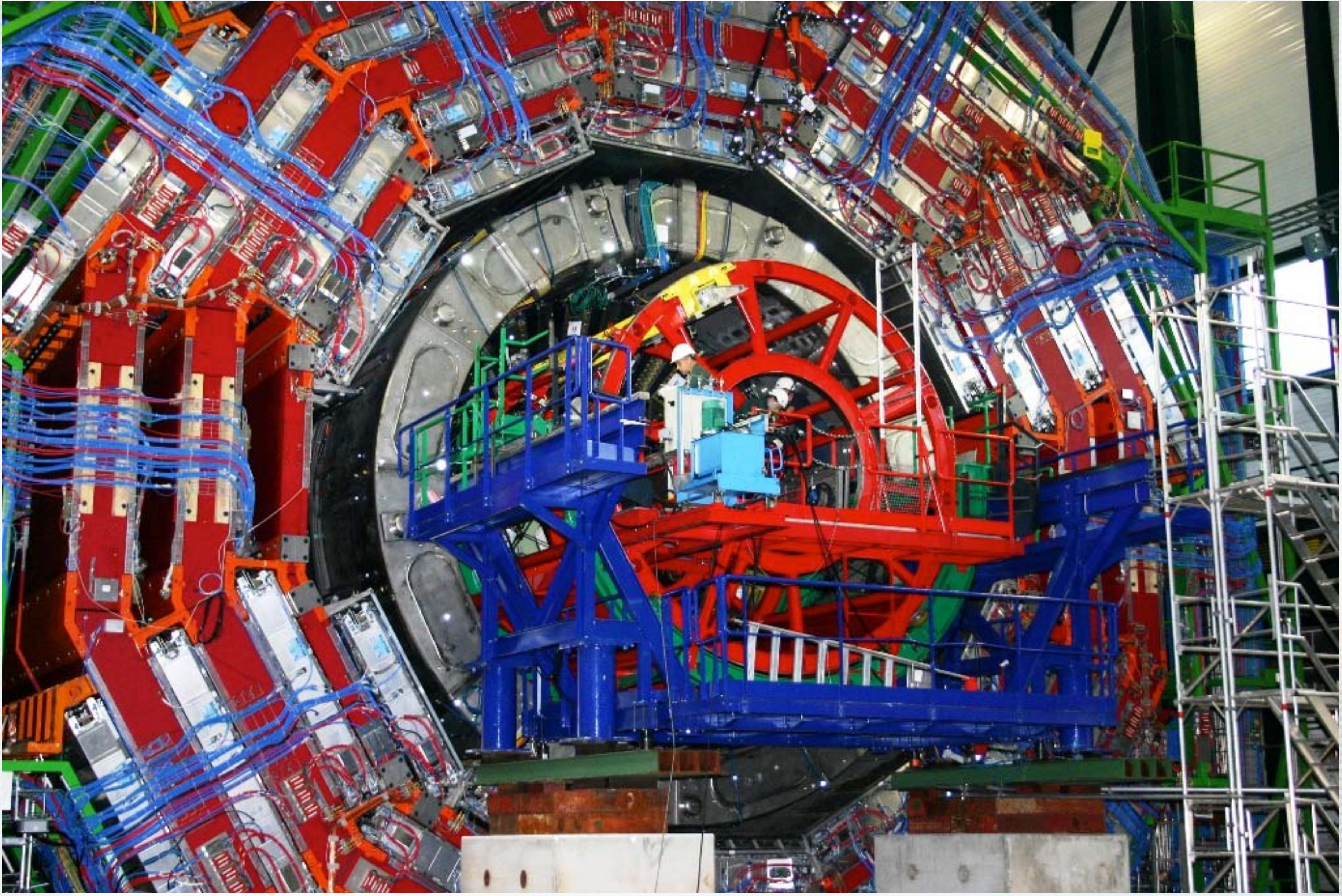


You were right: There's a needle in this haystack...

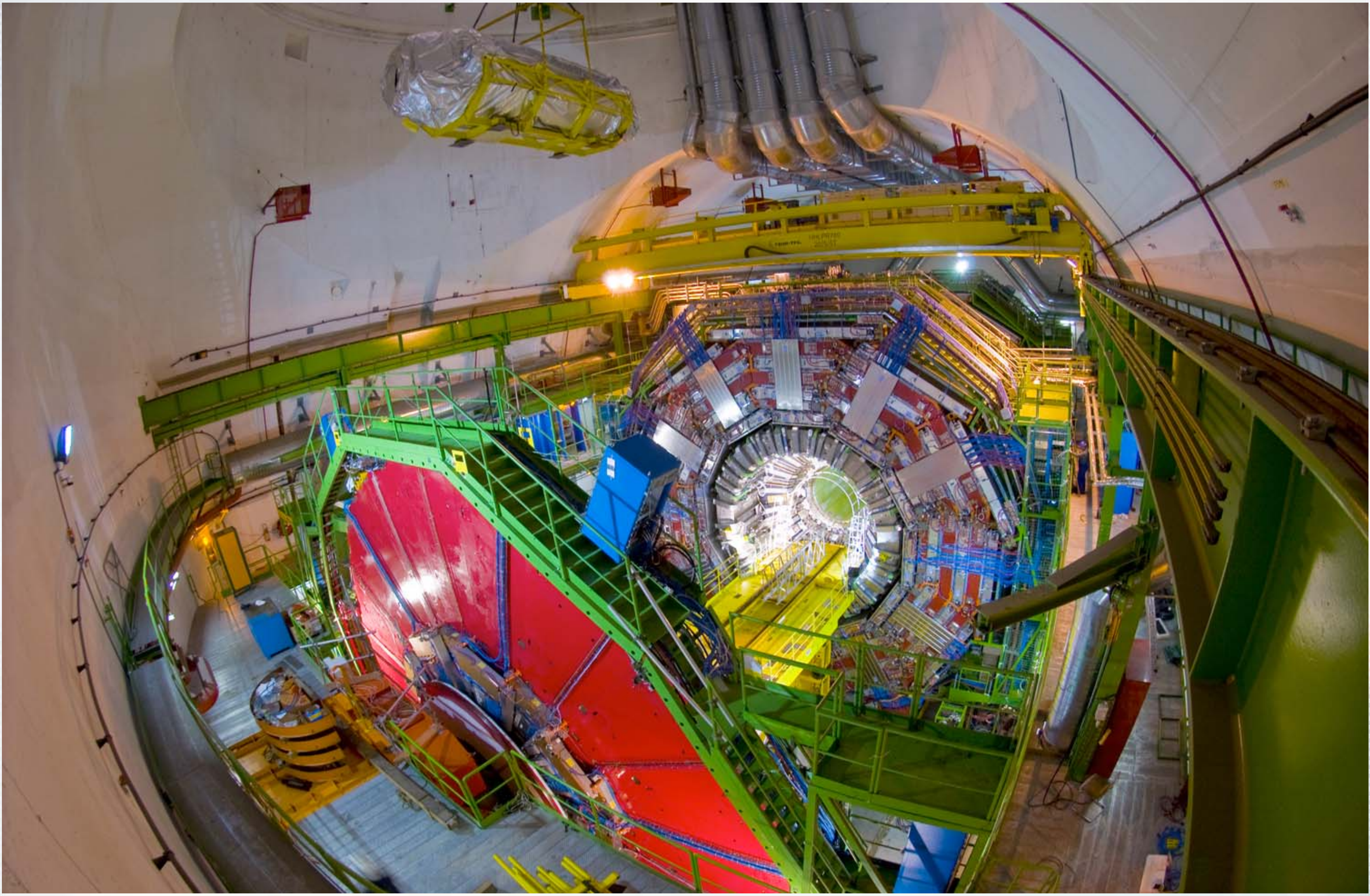
ATLAS Now



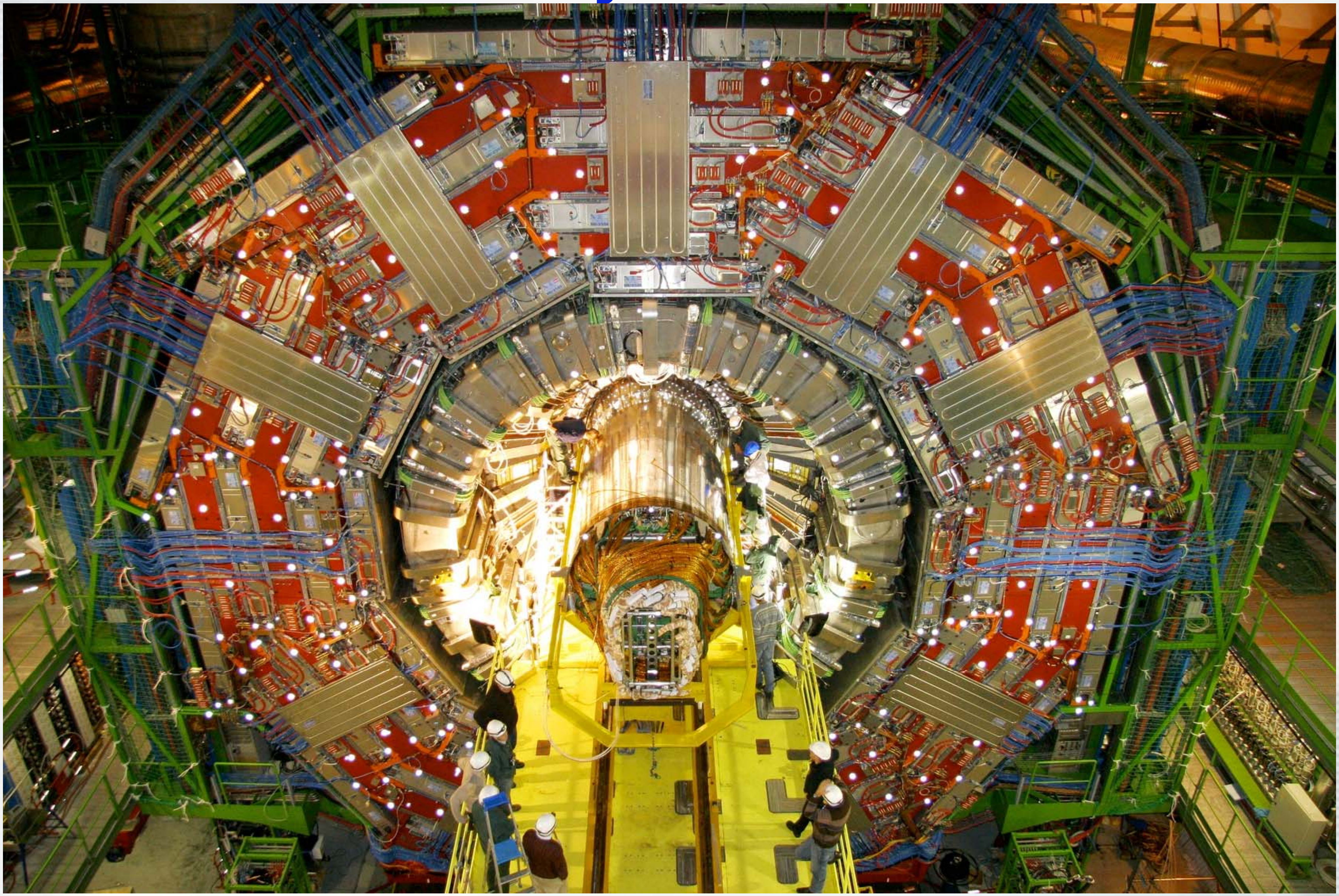
CMS - 2006



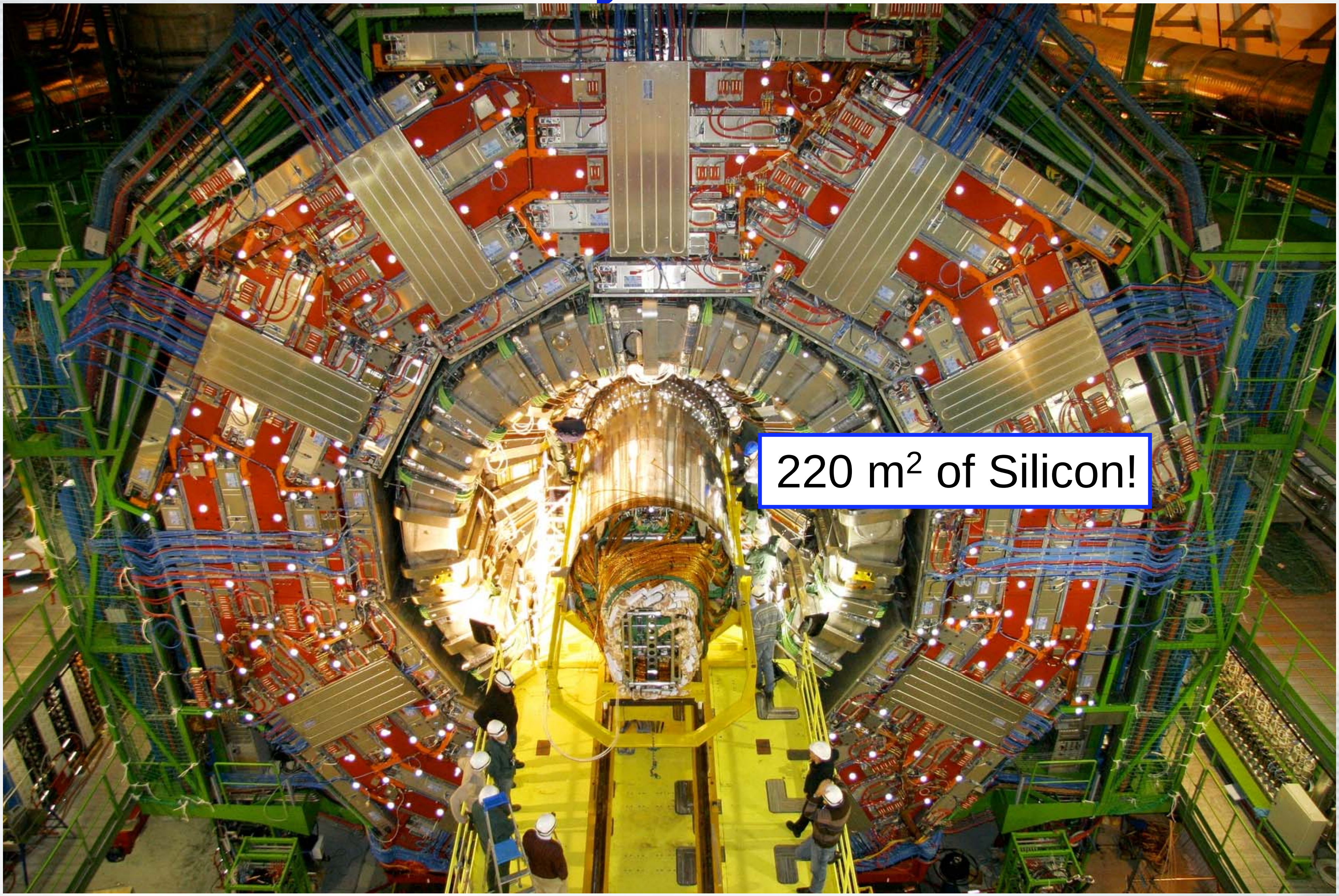
CMS in December, 2007



CMS in January



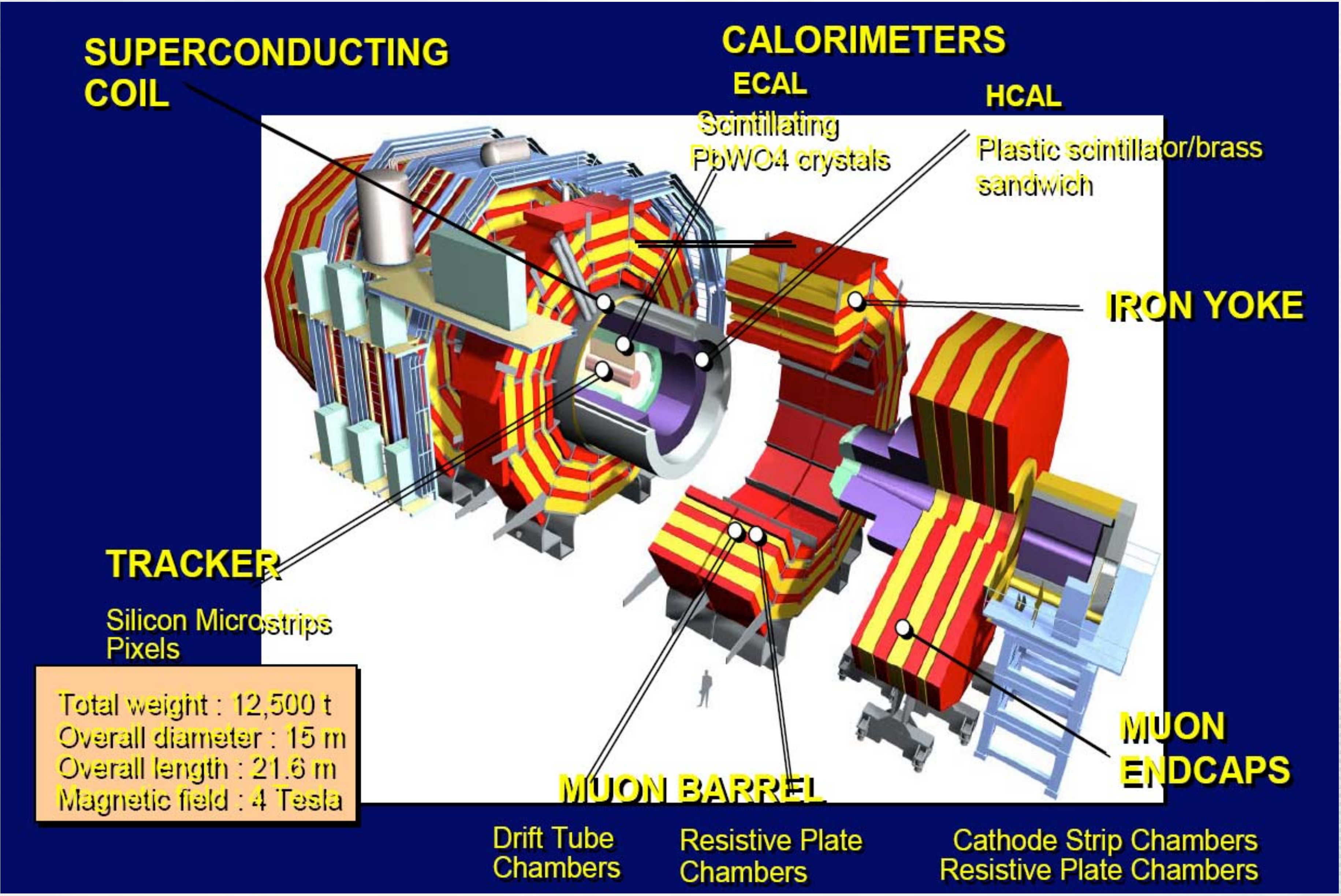
CMS in January



220 m^2 of Silicon!

CMS Explained

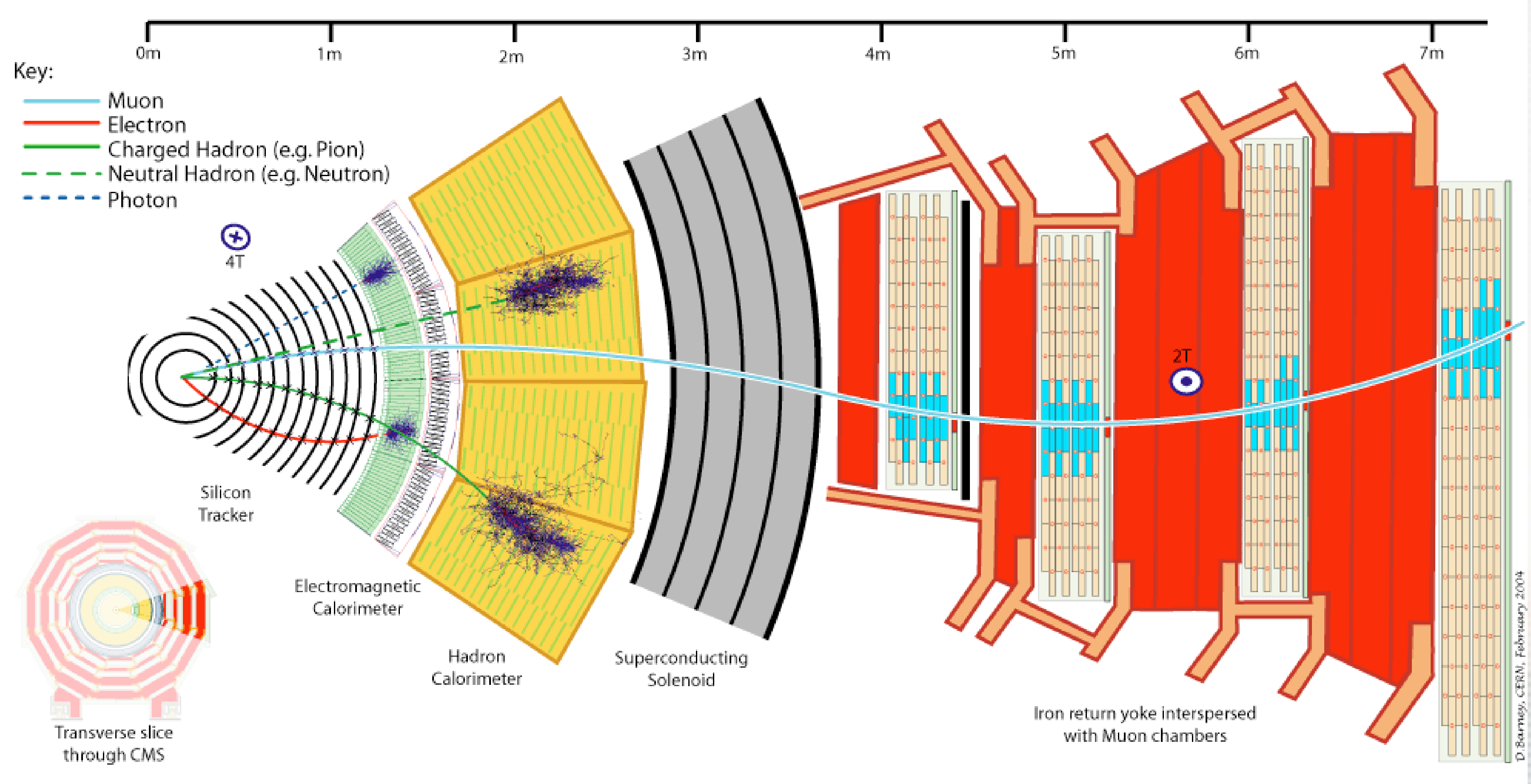
A 100 MP digital camera,
which takes 40 million frames/sec!



Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Detector Concept

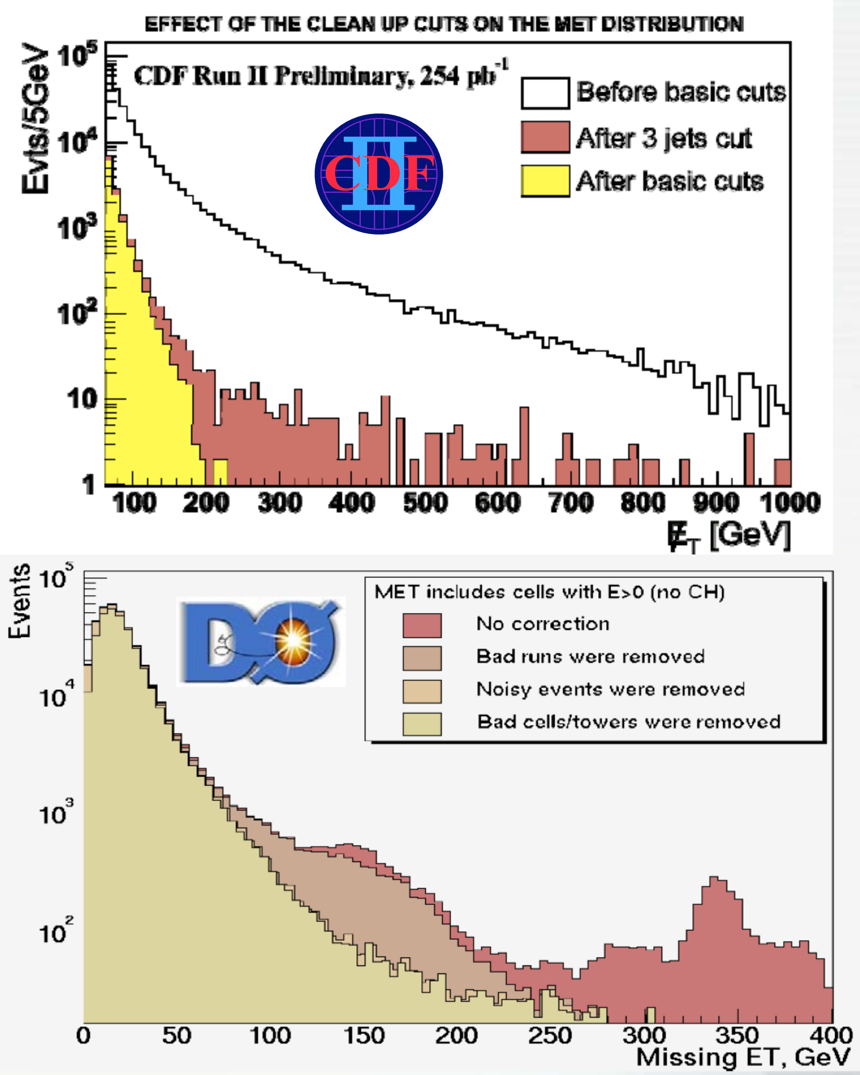
- Nearly 4π, hermetic, redundant, Russian-doll design



And Missing Transverse Energy (ME_T) for anything, which does not interact or interacts weakly

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

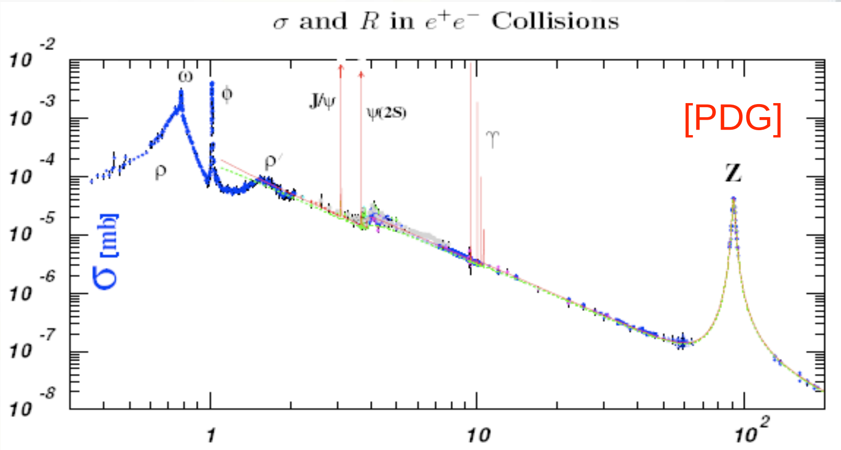


- Raw ME_T spectrum at the Tevatron and that after thorough clean-up

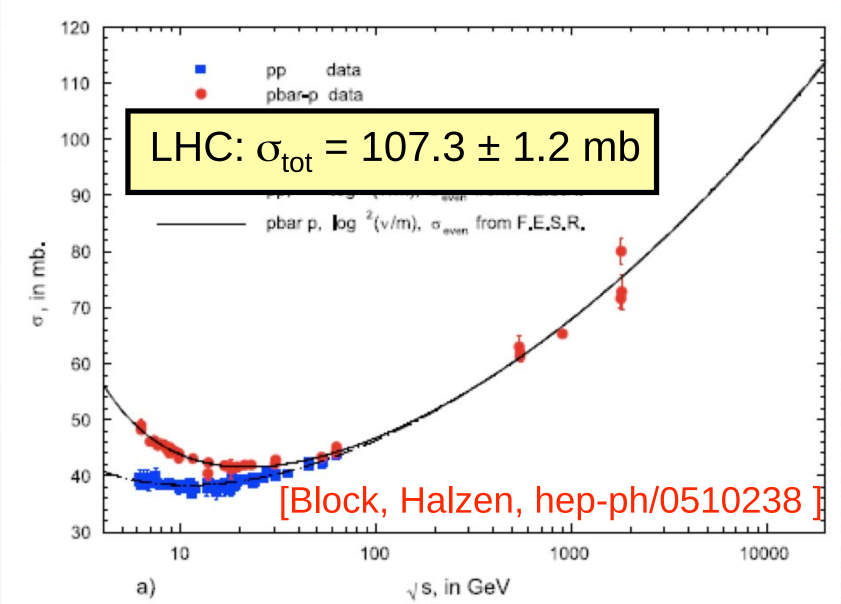
Trigger

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



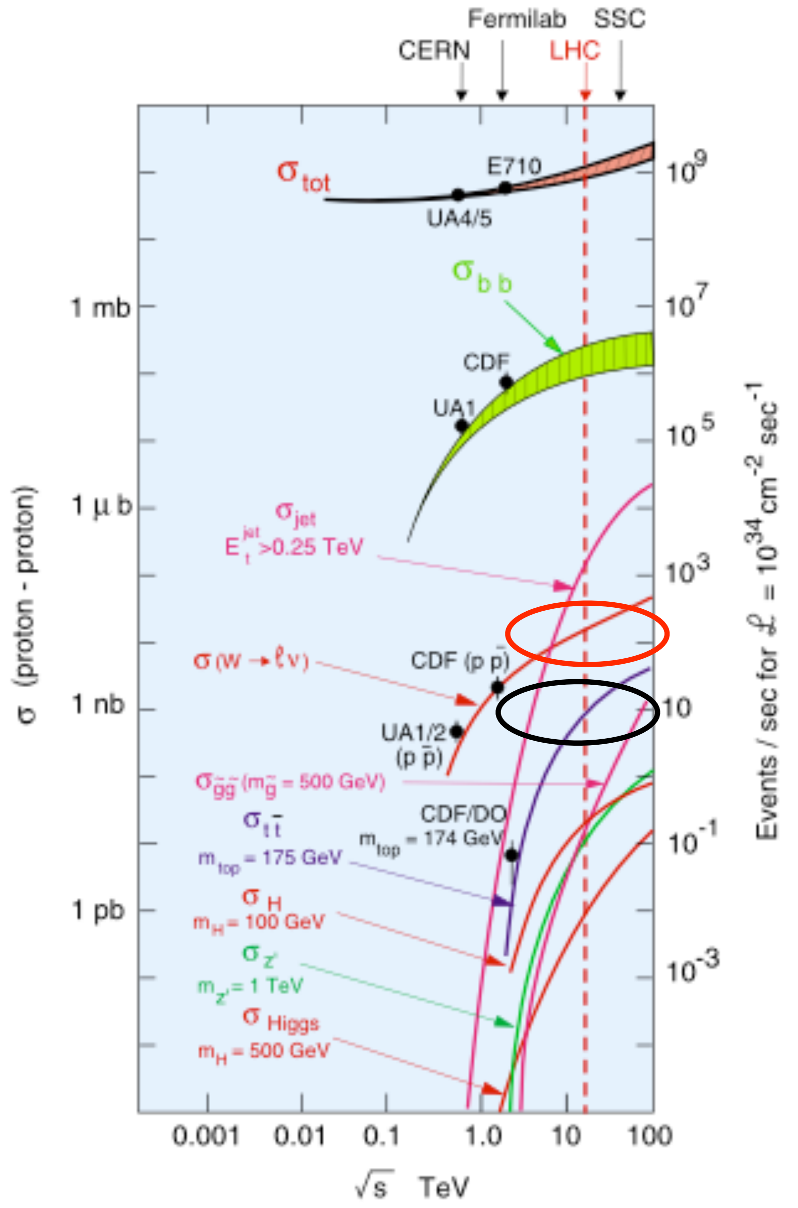
[PDG]



LHC: σ_{tot} = 107.3 ± 1.2 mb

[Block, Halzen, hep-ph/0510238]

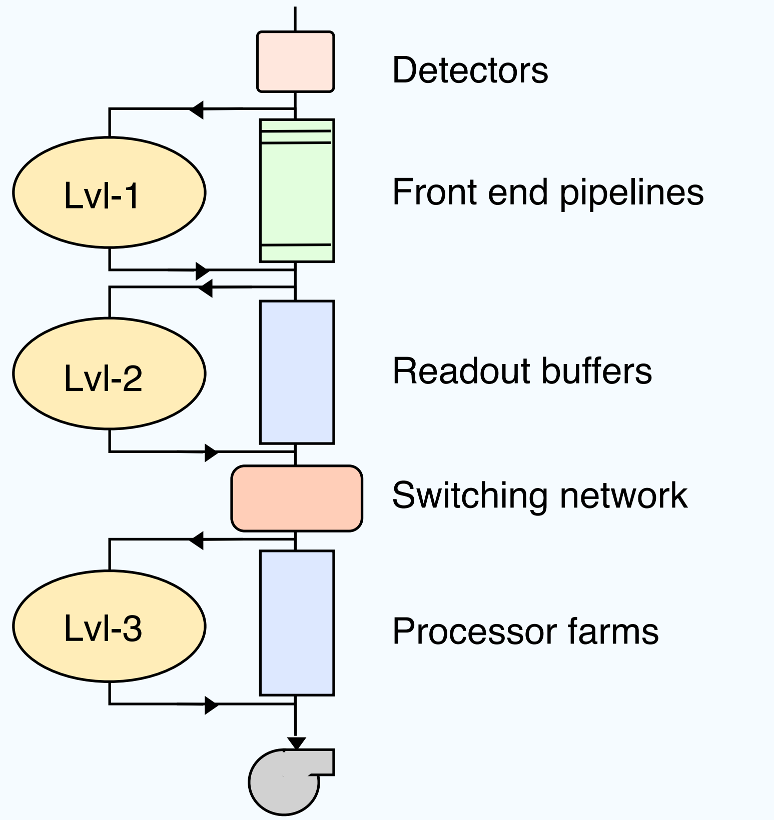
More Trigger Challenges



- LHC Physics Demands
  - –EWSB in SM (Higgs, W, Z)
    - Lepton/photons $E_T \sim 50$ GeV
    - High rate (10 Hz of top events and 200 Hz of $W(l\nu)$ events!)
  - –TeV scale supersymmetry, UED
    - Multiple leptons, jets and LSPs (missing E_T), $E_T < 100$ GeV
- QCD Background
  - –Jet $E_T \sim 250$ 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 ⇒ $\leq 10^2$ Higgs events
- Benchmark: $\sigma = 100$ pb $\rightarrow$ 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”



Lvl-1

Lvl-2

Lvl-3

Detectors

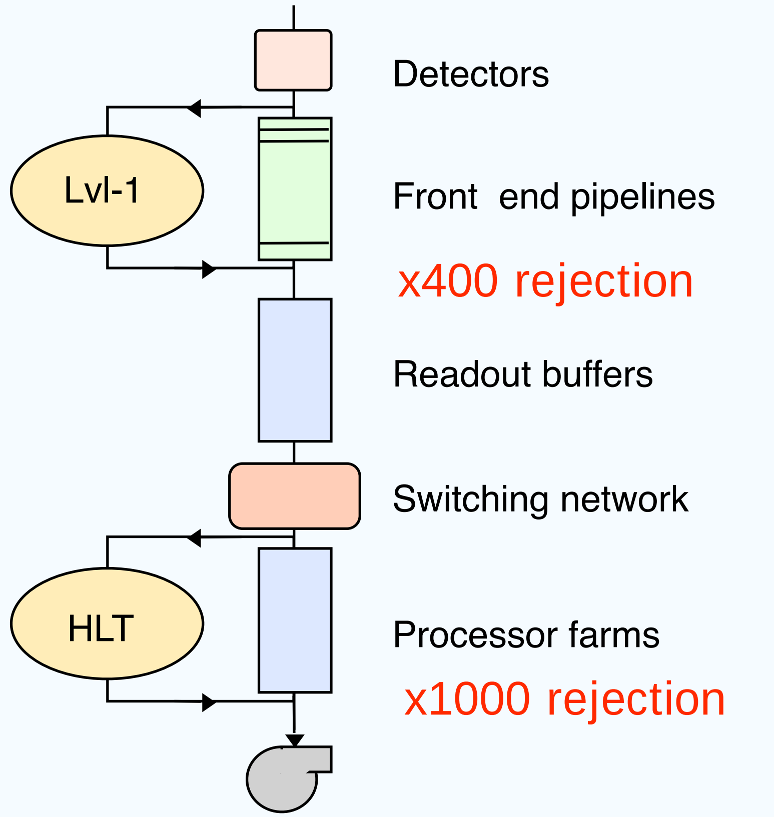
Front end pipelines

Readout buffers

Switching network

Processor farms

“Traditional”: 3 physical levels, ATLAS



Lvl-1

HLT

Detectors

Front end pipelines

x400 rejection

Readout buffers

Switching network

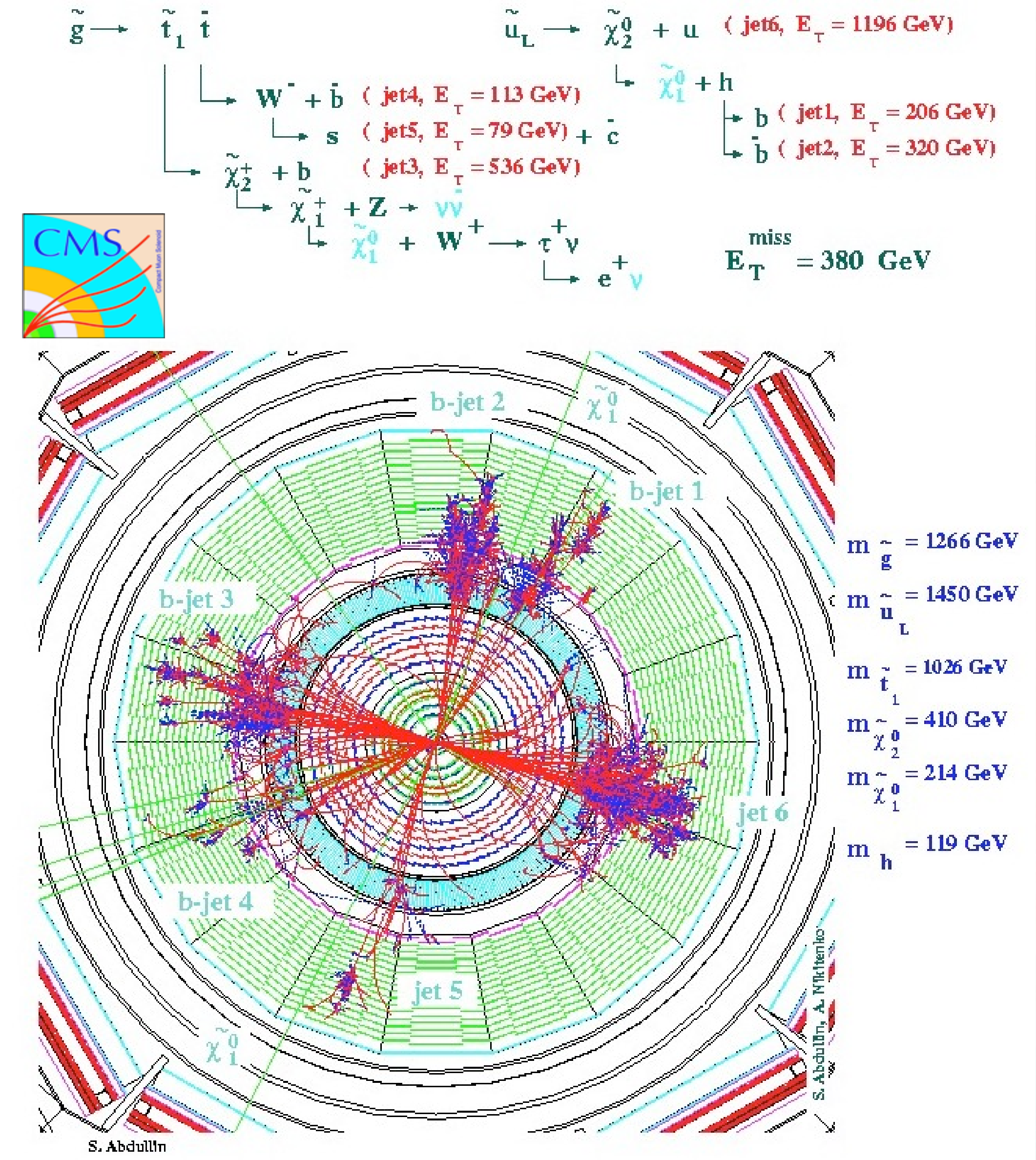
Processor farms

x1000 rejection

CMS: 2 physical levels

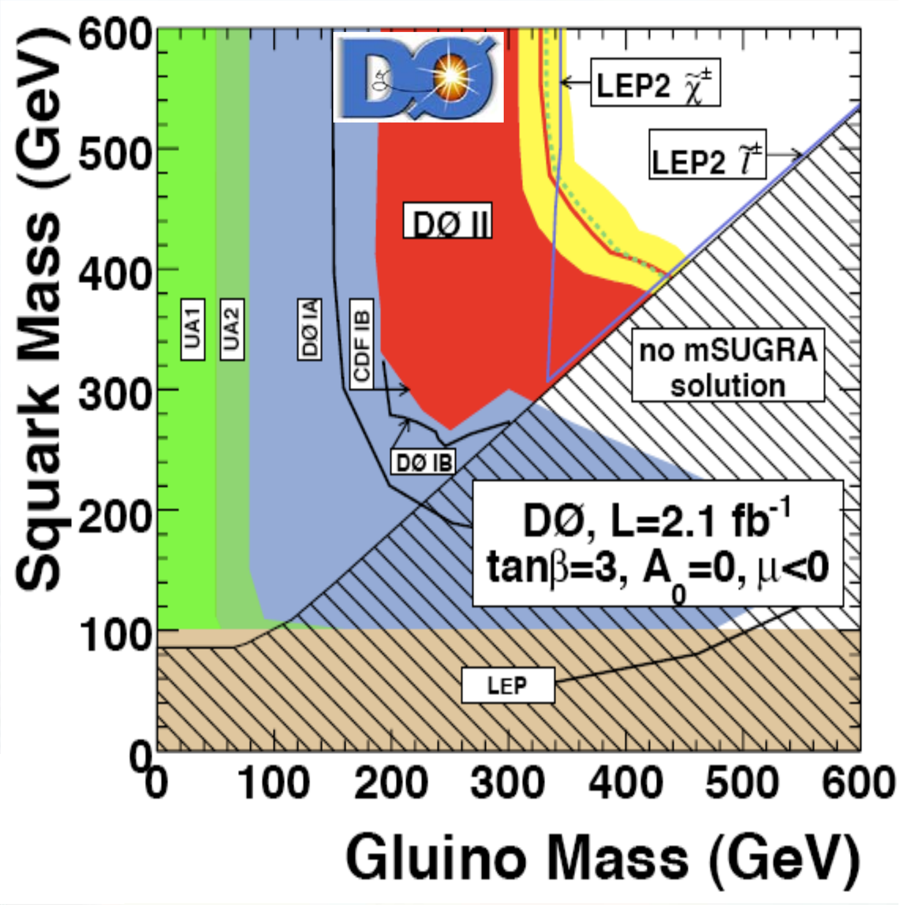
Example 1: SUSY in Jets + ME$_T$

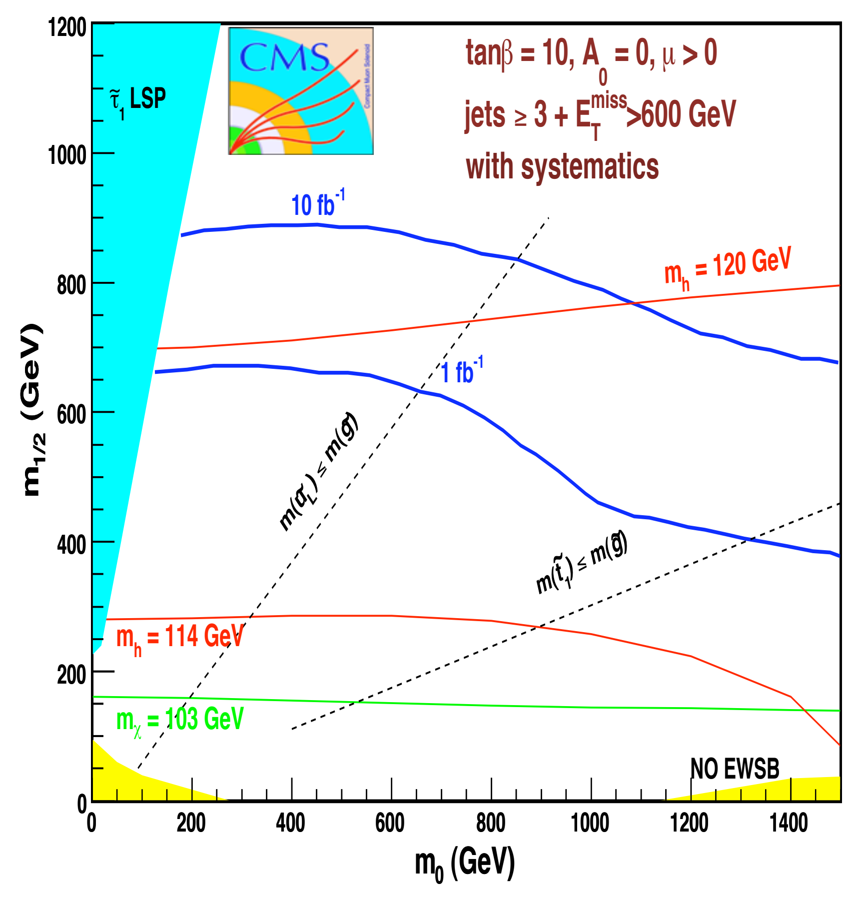
Strong Production, Complicated Events



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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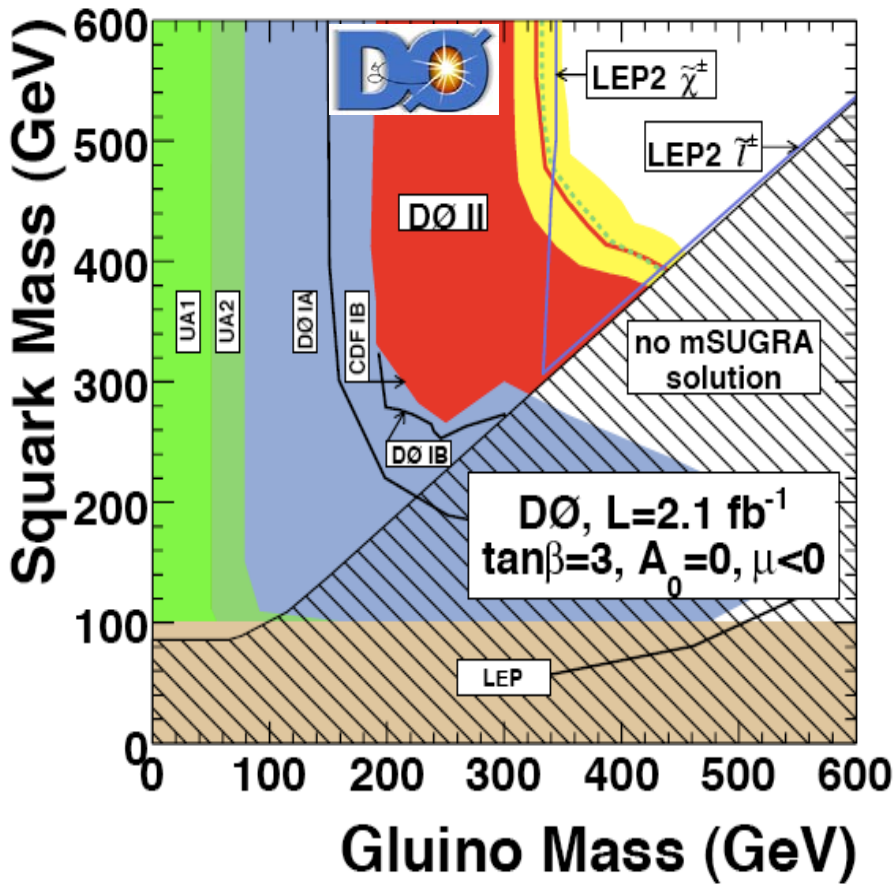
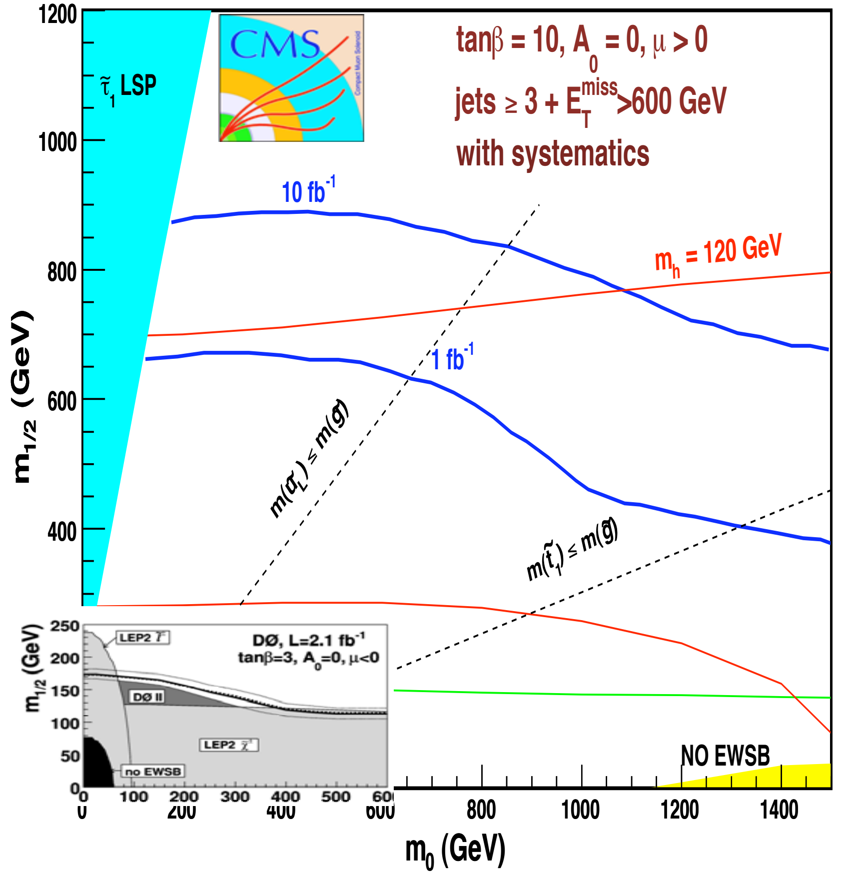
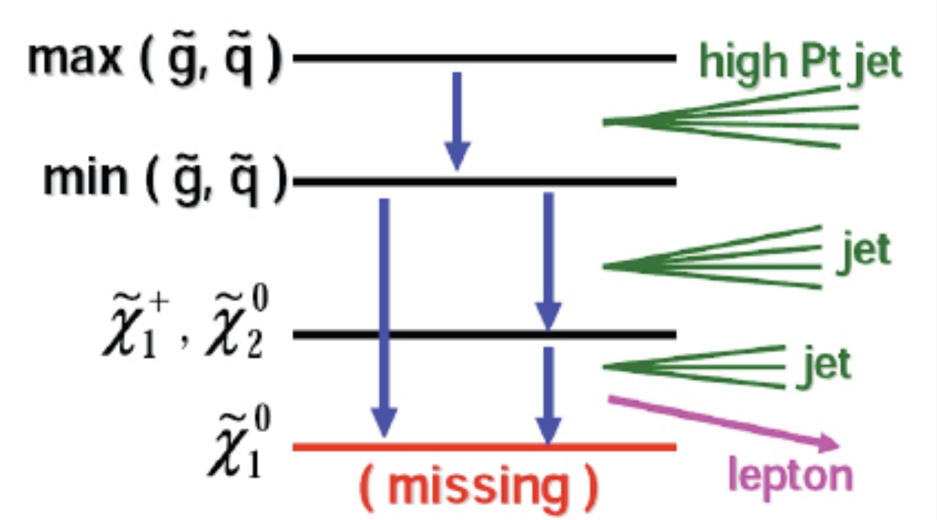


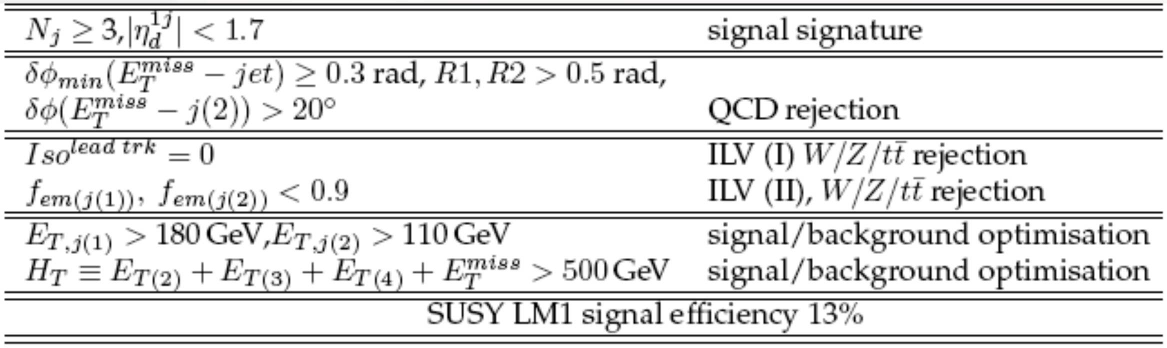


SUSY Event Selection

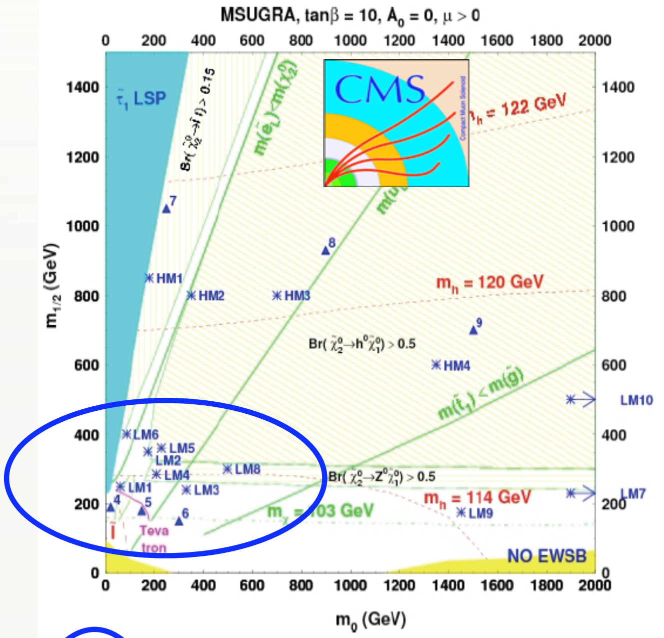
- Focus on low-mass SUSY points
- Jets and ME$_T$ always present; no hit for leptonic branching fraction

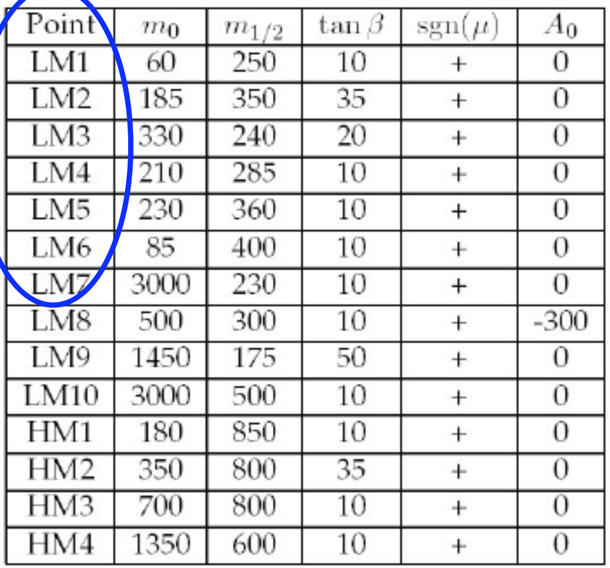


ME$_T$ > 200 GeV



$N_j \geq 3, \lvert\eta_d^{1j}\rvert < 1.7$	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
$E_{T,j(1)} > 180\,\text{GeV}, E_{T,j(2)} > 110\,\text{GeV}$	signal/background optimisation
$H_T \equiv E_{T(2)} + E_{T(3)} + E_{T(4)} + E_T^{miss} > 500\,\text{GeV}$	signal/background optimisation
SUSY LM1 signal efficiency 13%	

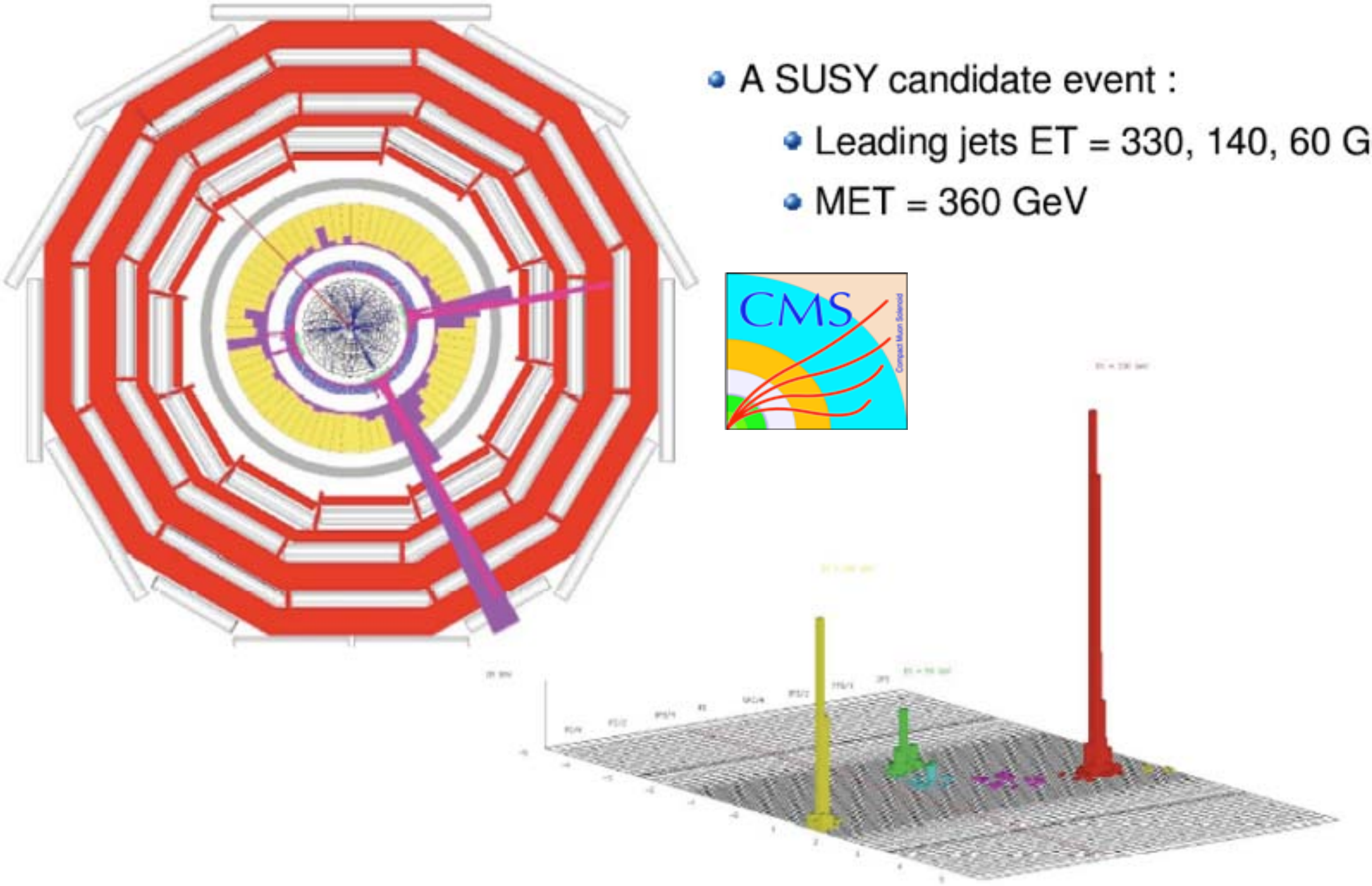




Point	m_0	$m_{1/2}$	$\tan\beta$	sgn(μ)	A_0
LM1	60	250	10	+	0
LM2	185	350	35	+	0
LM3	330	240	20	+	0
LM4	210	285	10	+	0
LM5	230	360	10	+	0
LM6	85	400	10	+	0
LM7	3000	230	10	+	0
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0
LM10	3000	500	10	+	0
HM1	180	850	10	+	0
HM2	350	800	35	+	0
HM3	700	800	10	+	0
HM4	1350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

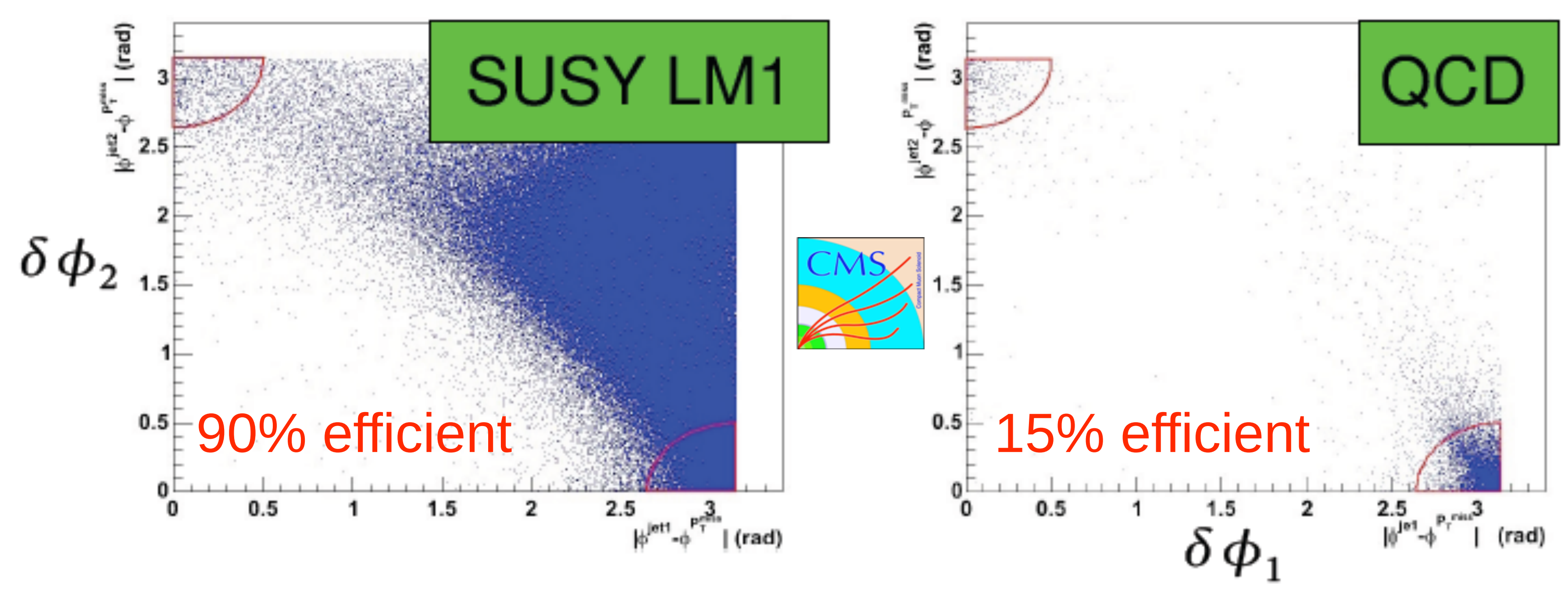
A Typical SUSY Event

- 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)

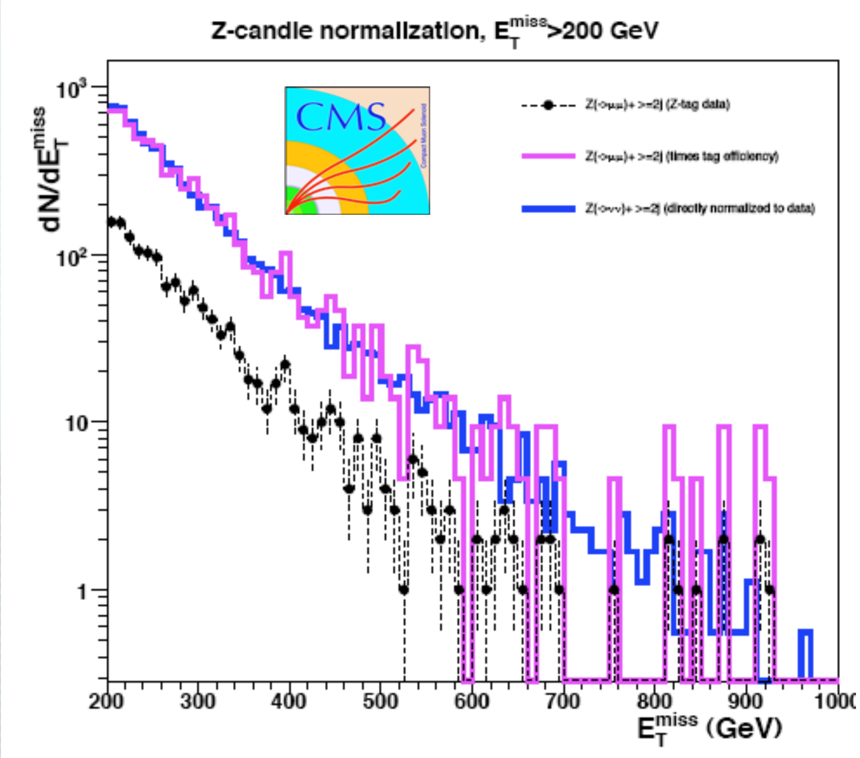


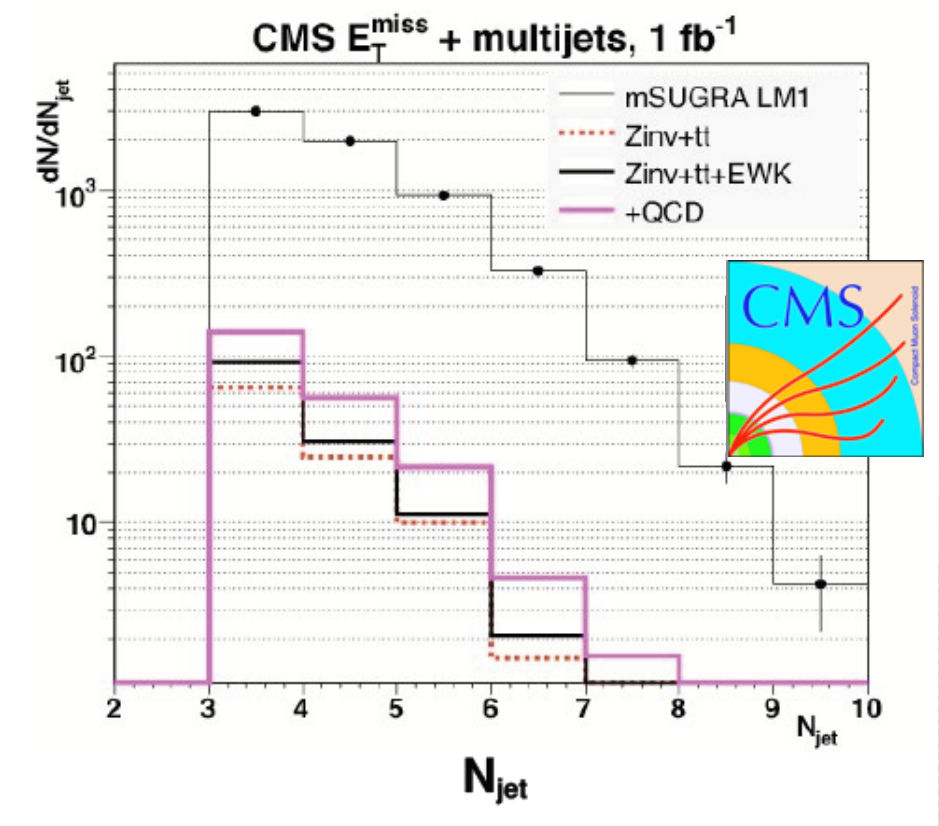
90% efficient

15% efficient

Z($\nu\nu$) + Jets: Estimate from Data

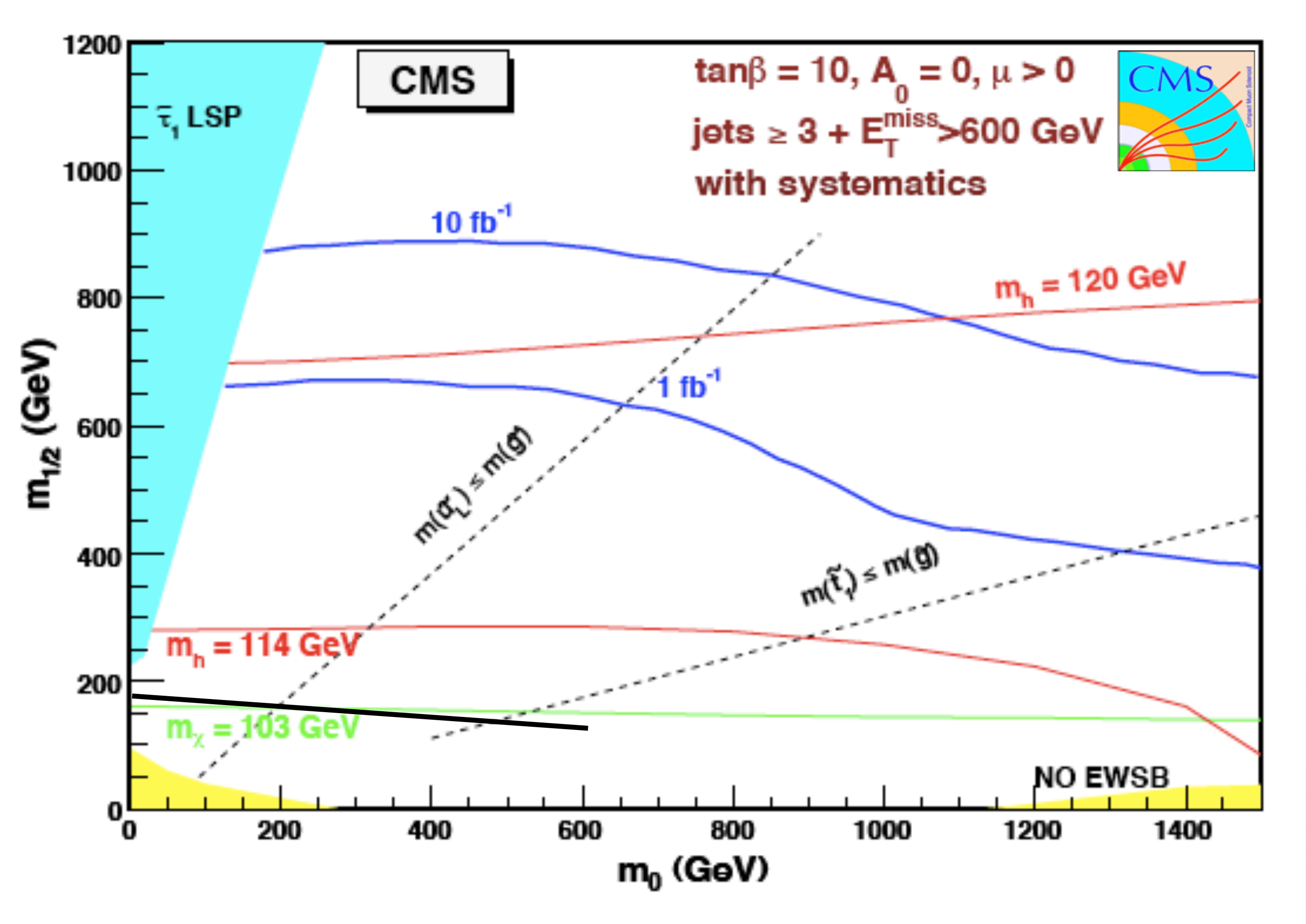
- Use Z(ee) and Z($\mu\mu$) + jets for normalization; acceptance corrections via MC
- Necessary since the signal and background shapes are similar


Z-candle normalization, E_T^{miss}>200 GeV


CMS E_T^{miss} + multijets, 1 fb^{-1}

Reach

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



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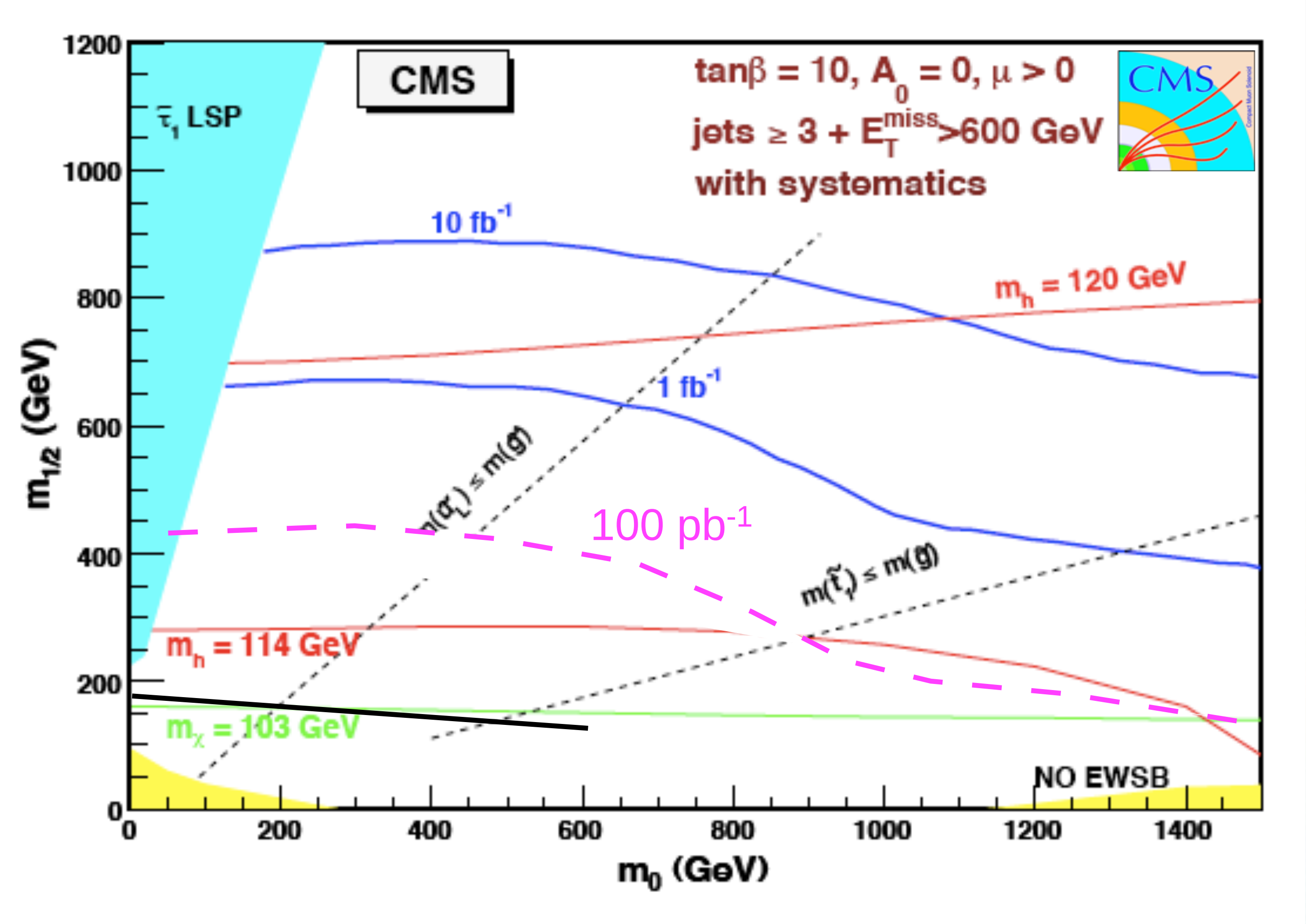
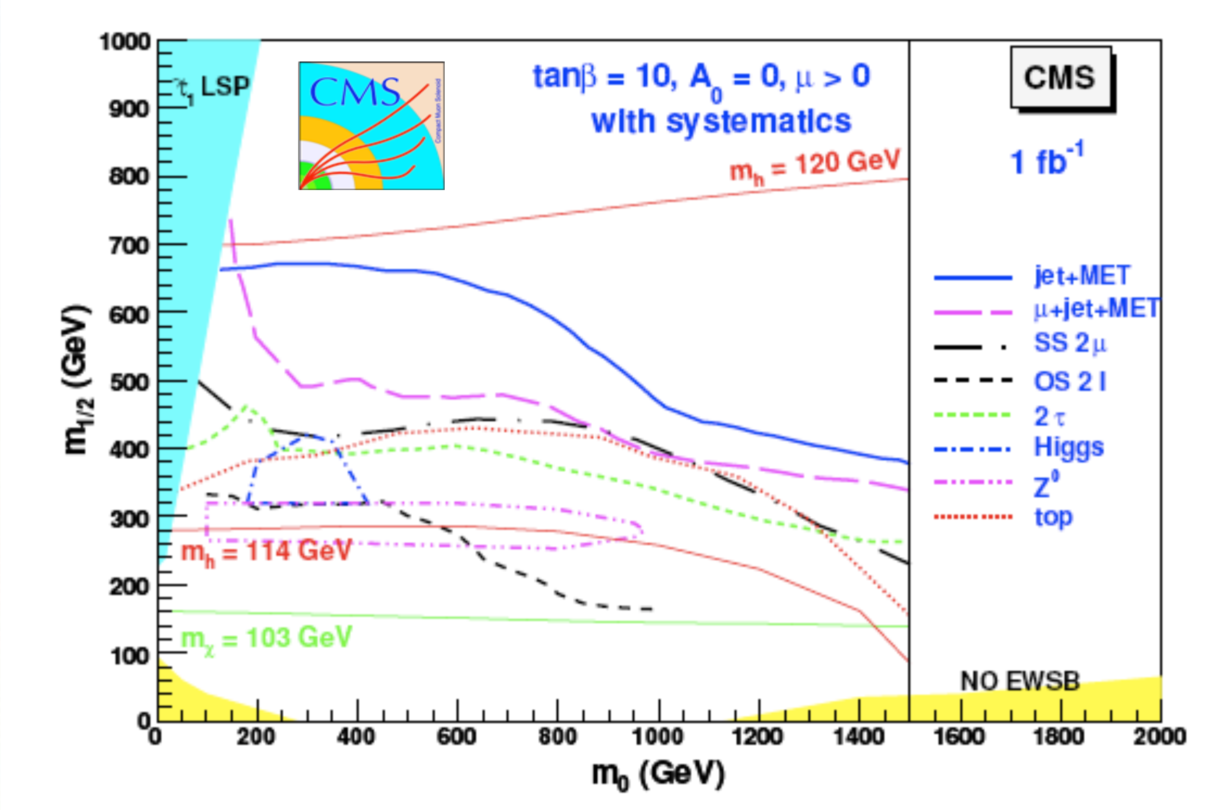


Other SUSY Channels

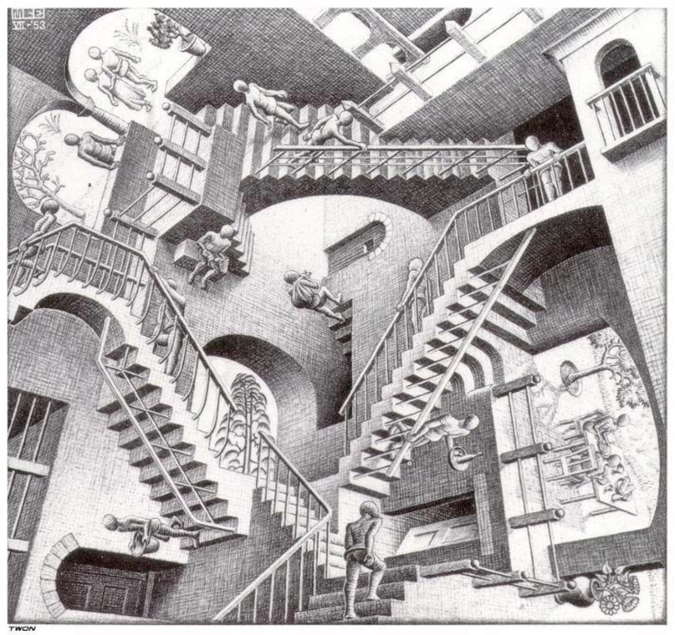
- Clearly, a number of channels will be investigated in parallel, including lepton+jets, like- and opposite-sign dileptons, channels with tau's, and MSSM Higgs searches
- Sensitivity in all these channels is being reevaluated using most realistic simulation available
- Previous studies suggest that the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



(More) Exotic Models

"Particles, particles, particles."

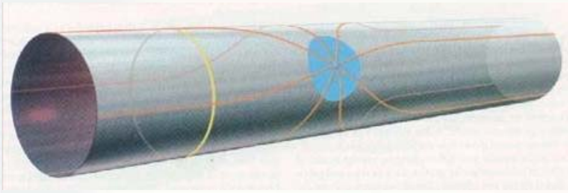
Example 2:
Extra Dimensions in Space



Extra Dimensions: a Brief Summary

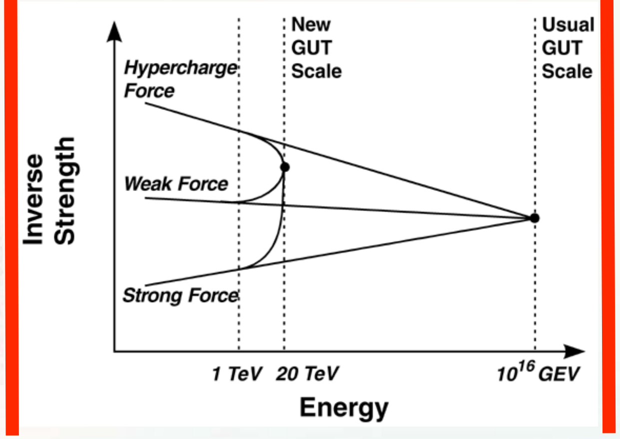
ADD Paradigm:

- 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



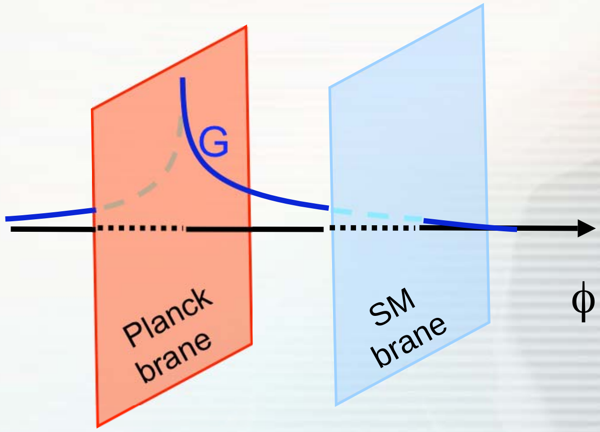
TeV^{-1} Scenario:

- 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:

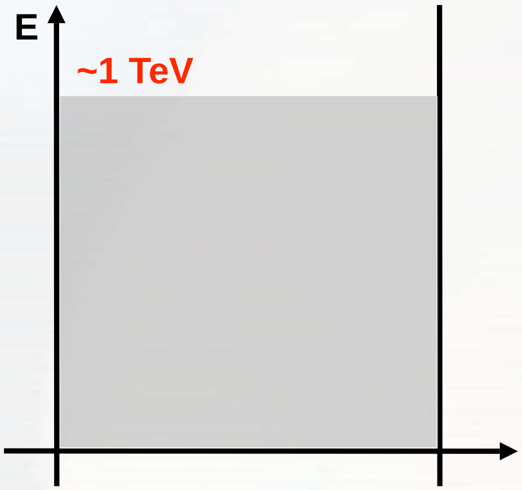
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

ADD Paradigm:

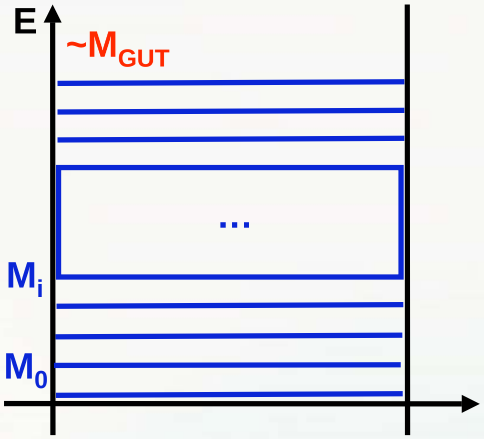
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



TeV^{-1} Scenario:

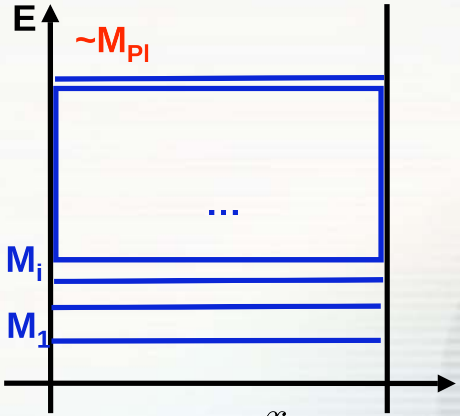
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~ 1 TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_W per mode

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



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



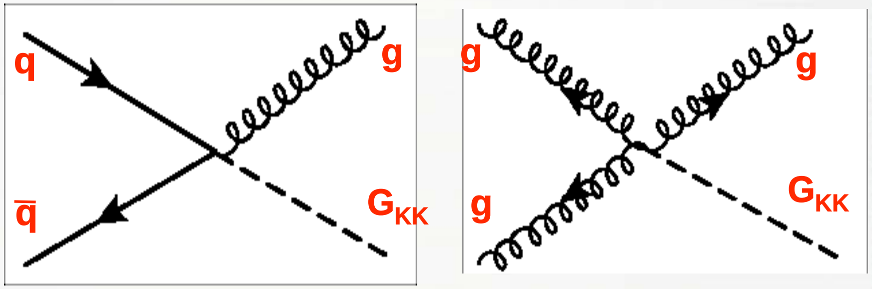
$$M_0 = 0;\ M_i = M_1\frac{x_i}{x_1} \approx M_1,\ 1.83M_1,\ 2.66M_1,\ 3.48M_1,\ \ldots$$

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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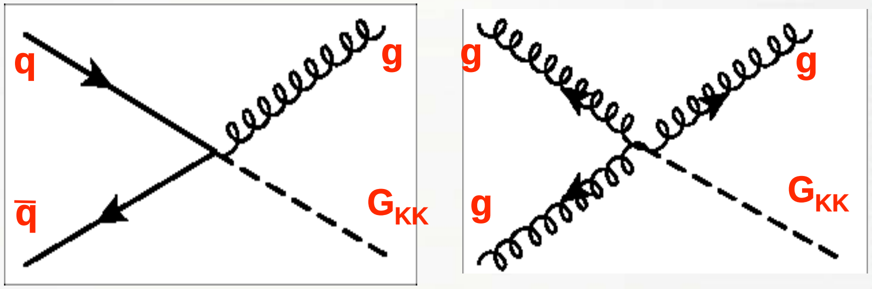
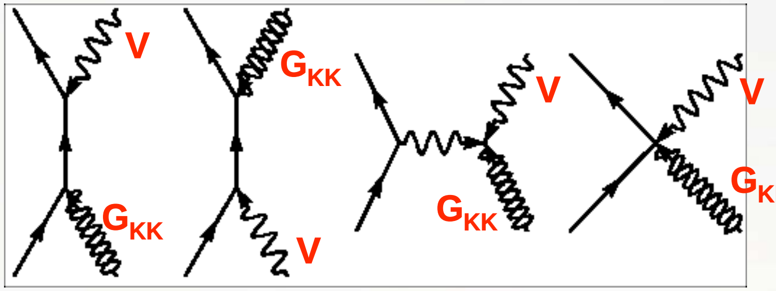


Single VB at hadron or e^+e^- colliders



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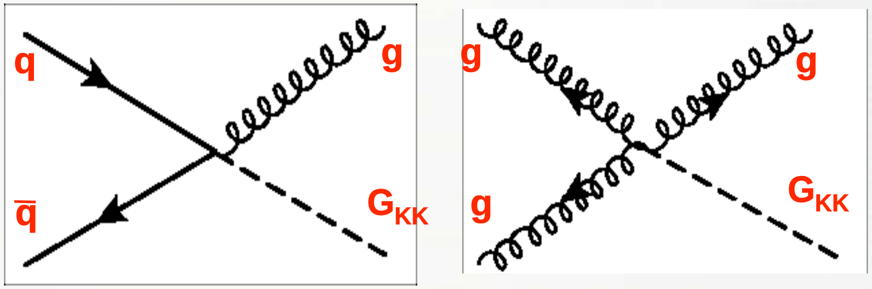

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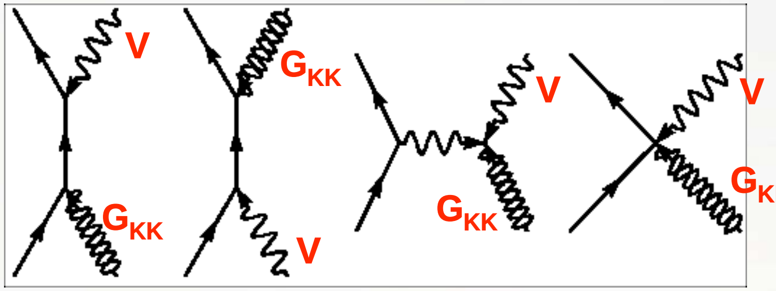
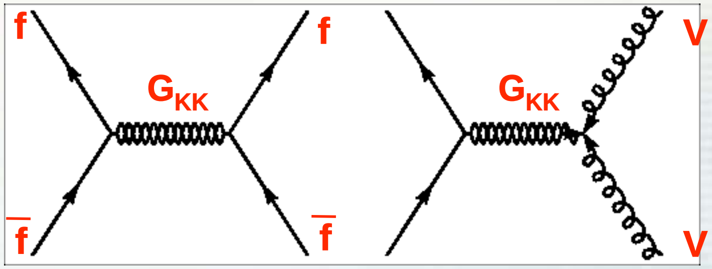
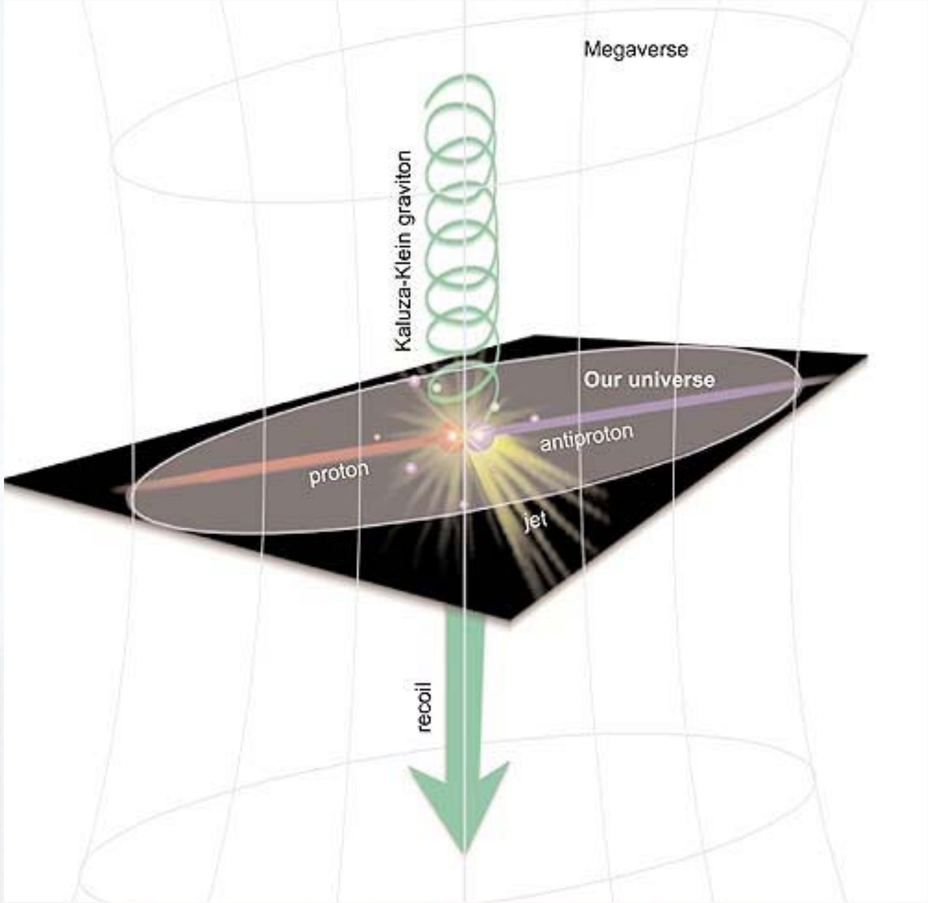


Virtual Graviton Effects

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

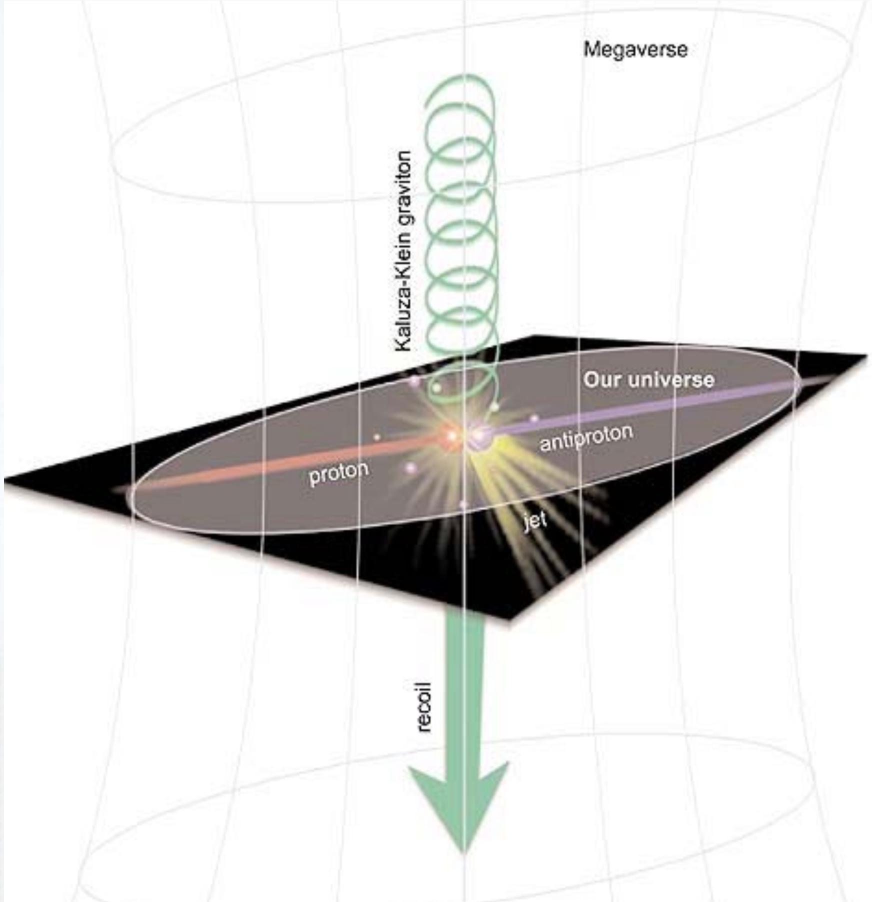


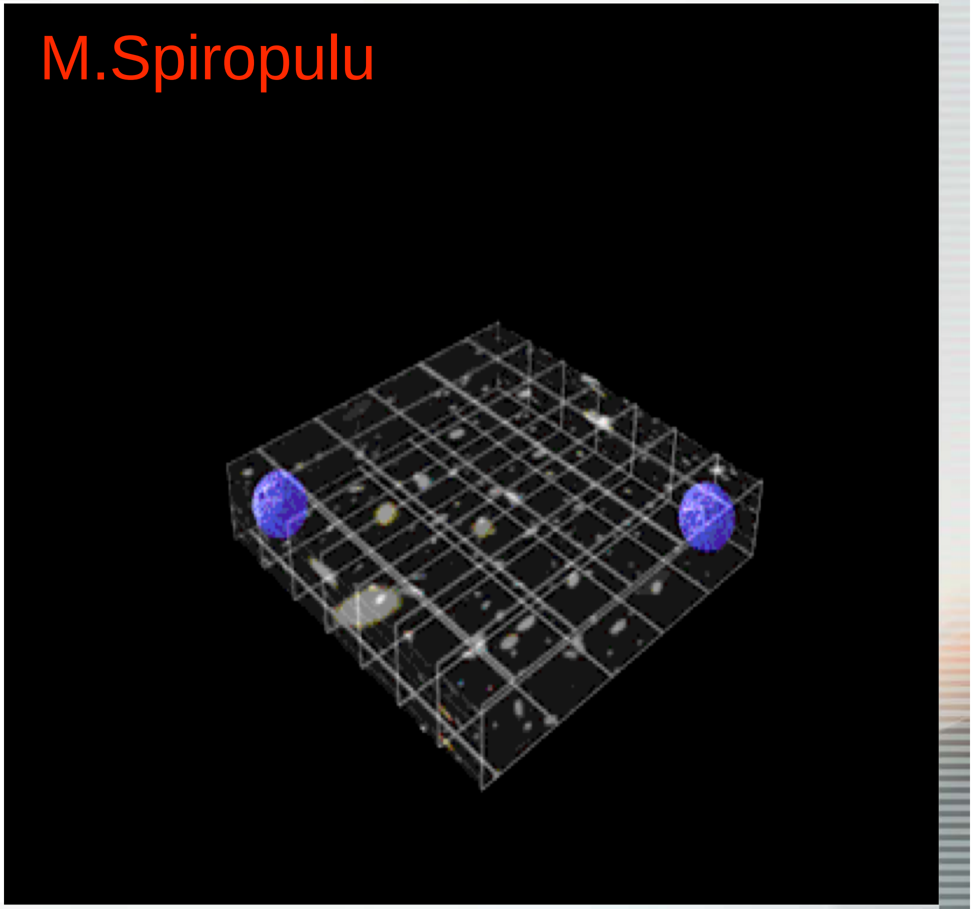
Looking for ED at Colliders



[© 2000, Ferminews]

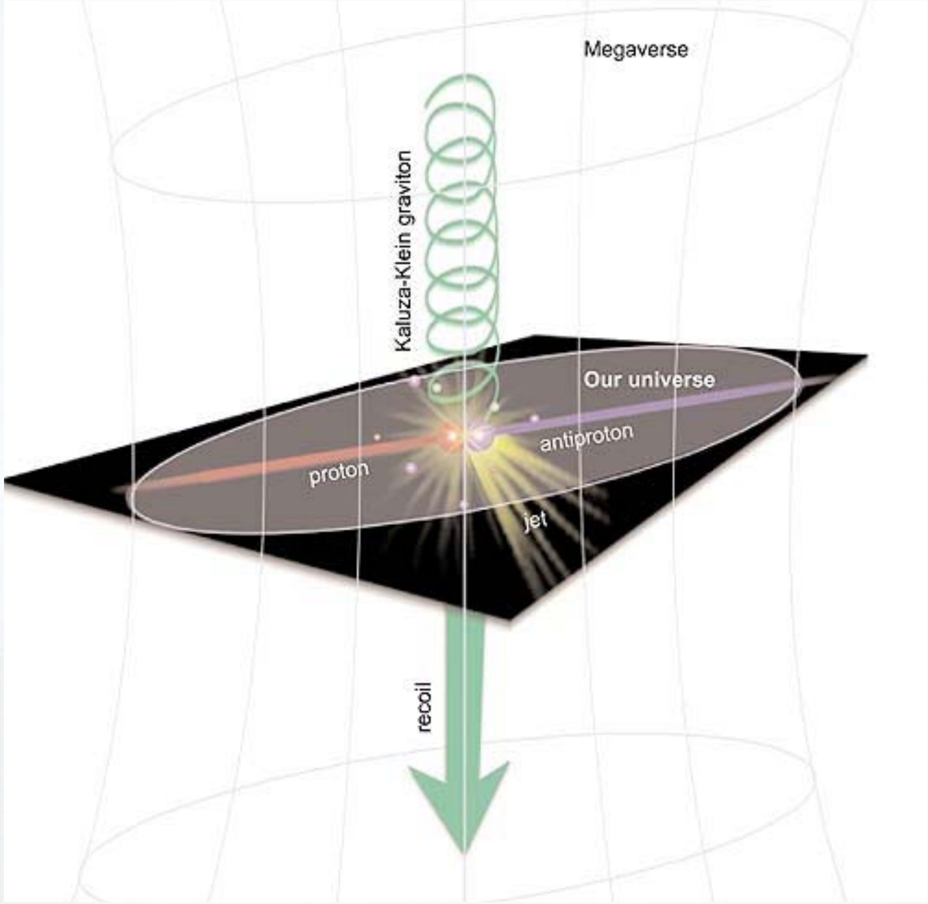
Looking for ED at Colliders

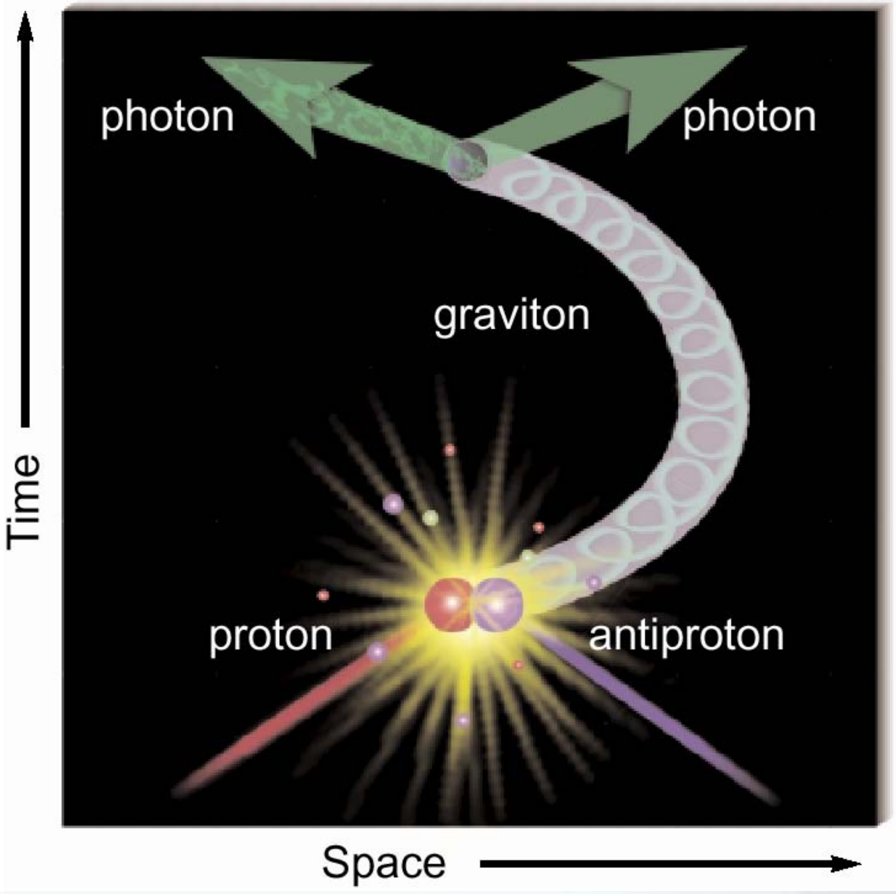




[© 2000, Ferminews]

Looking for ED at Colliders





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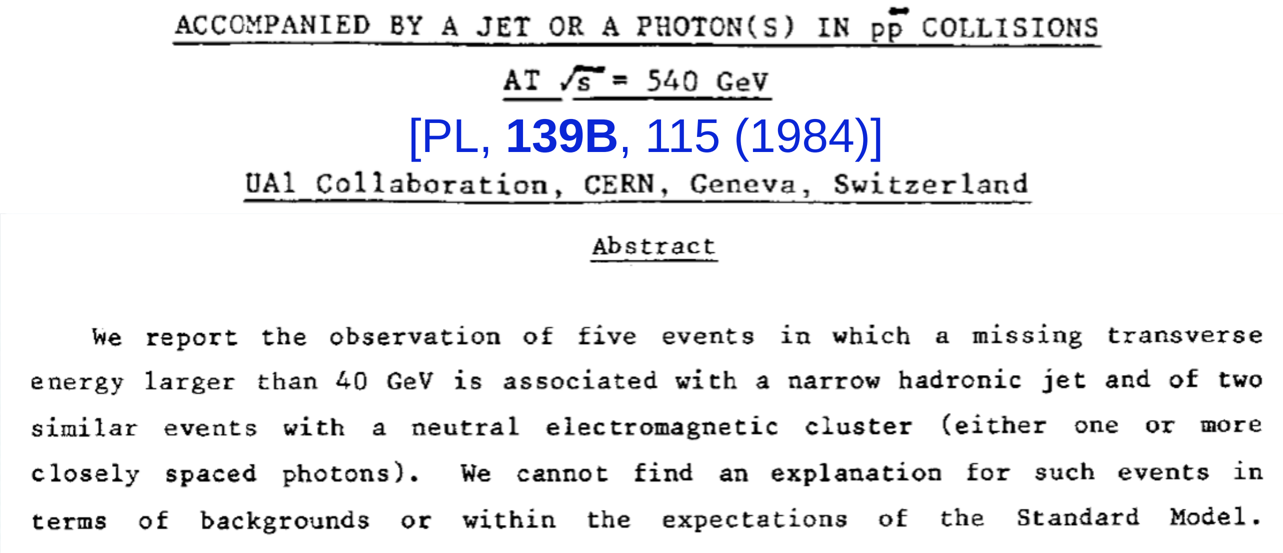
Monojets: Tainted History



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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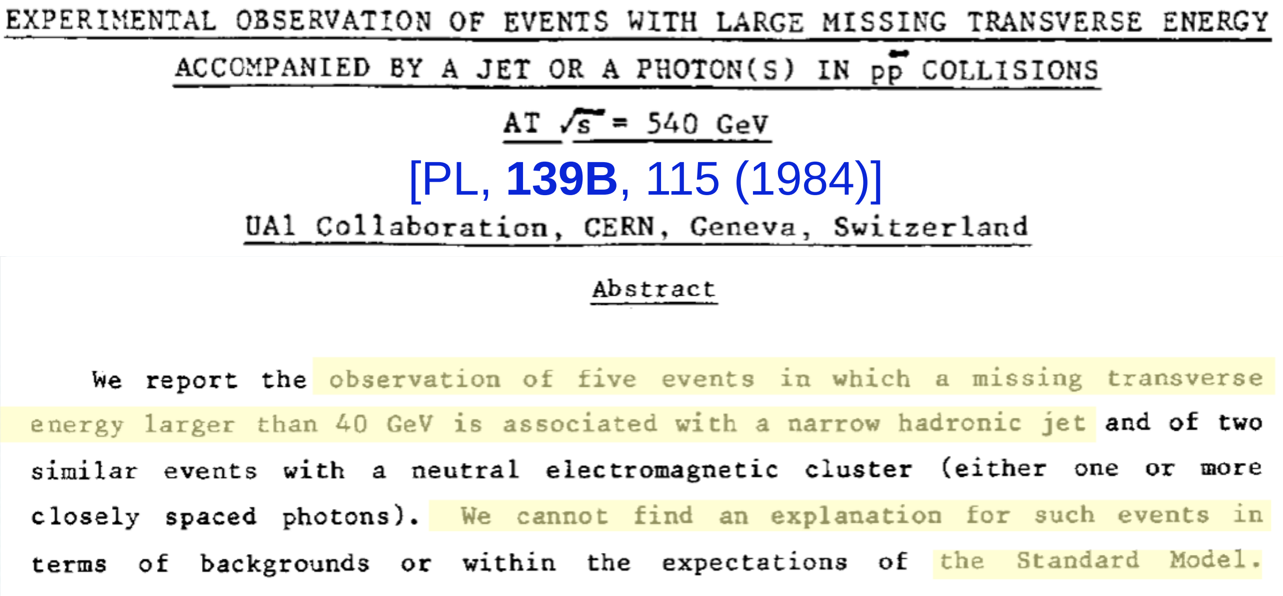

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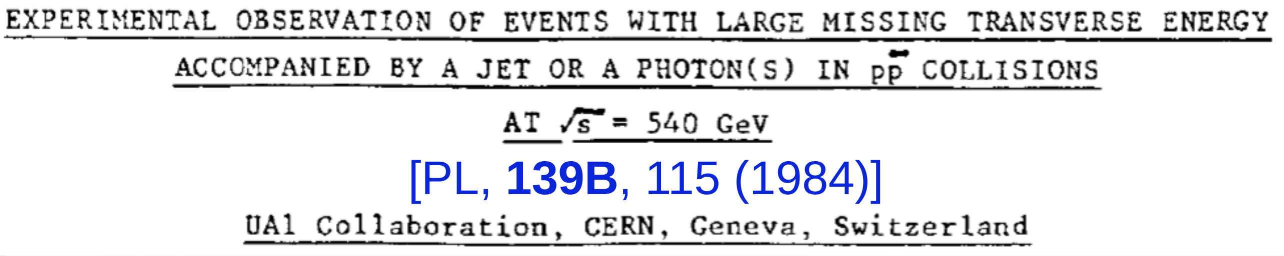

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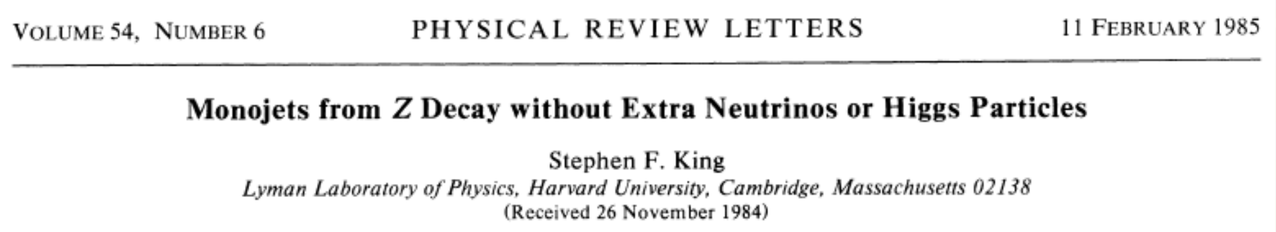


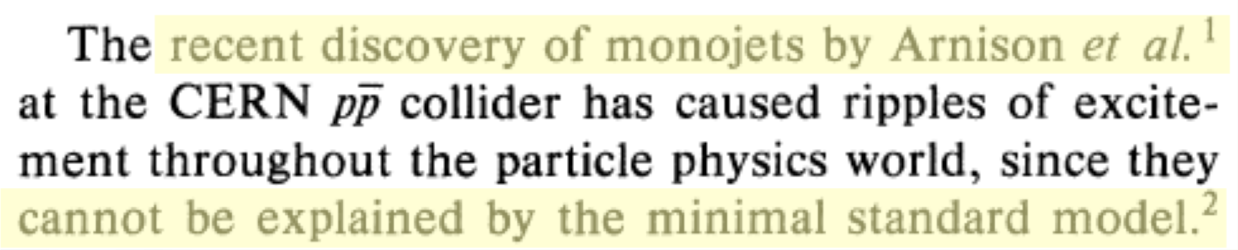
VOLUME 54, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1985

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

Stephen F. King

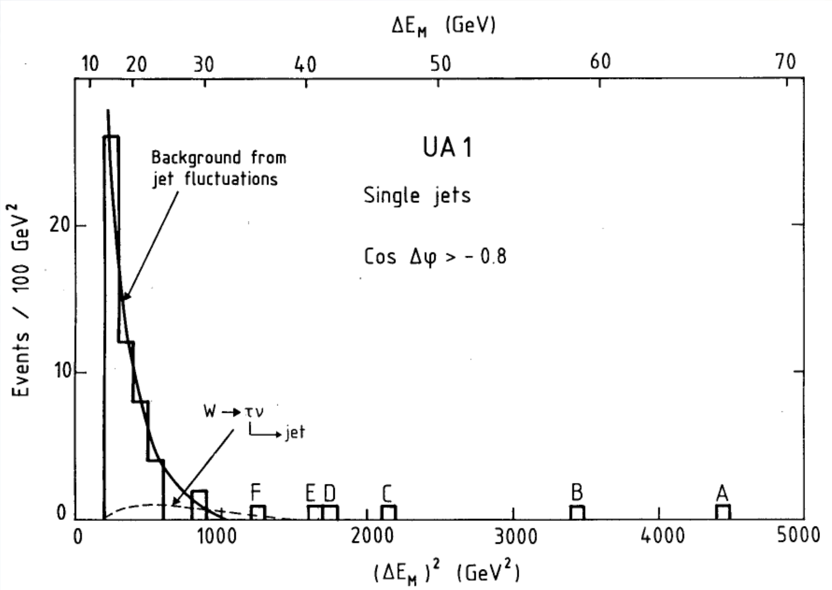
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

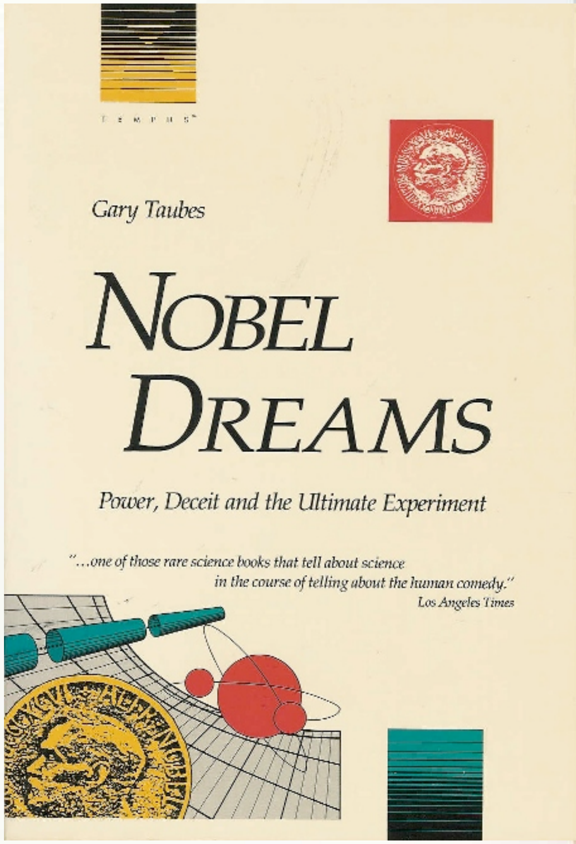
(Received 26 November 1984)



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





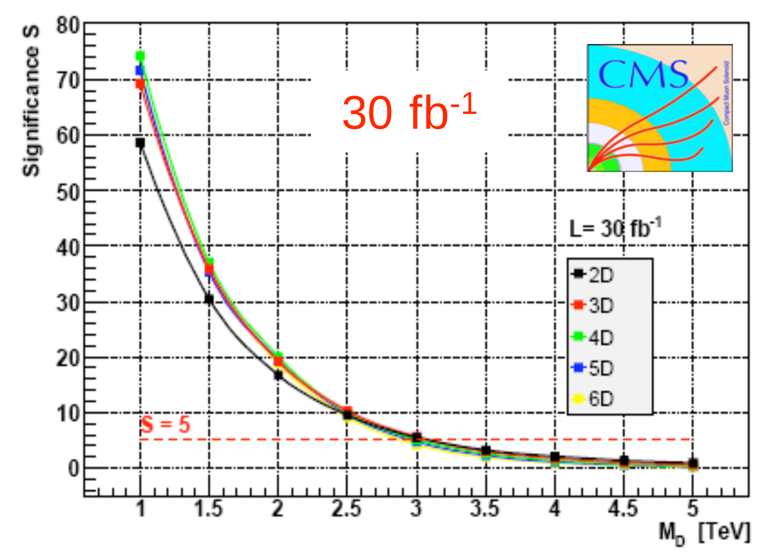
- These monojets turned out to be due to unaccounted background

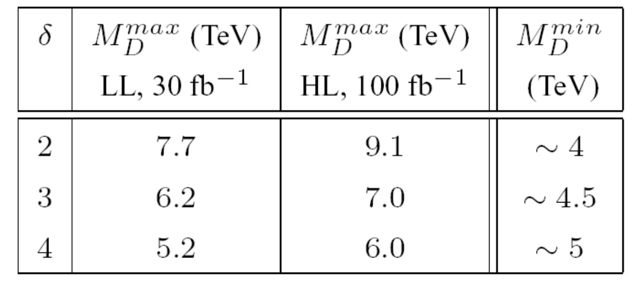
- The signature was deemed doomed and nearly forgotten

- It took many years for successful monojet analyses at a hadron collider to be completed (CDF/DØ)

Expectations at the LHC

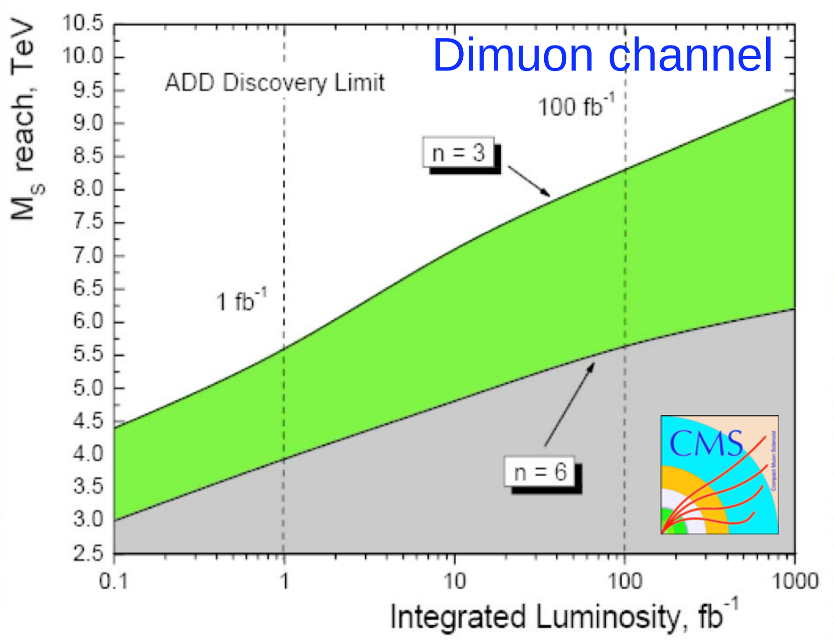
- Monojets are tough; what about monophotons?
  - CMS simulations only done for 30 fb^{-1} so far, but the luminosity dependence is weak ($\sim L^{1/4}$)





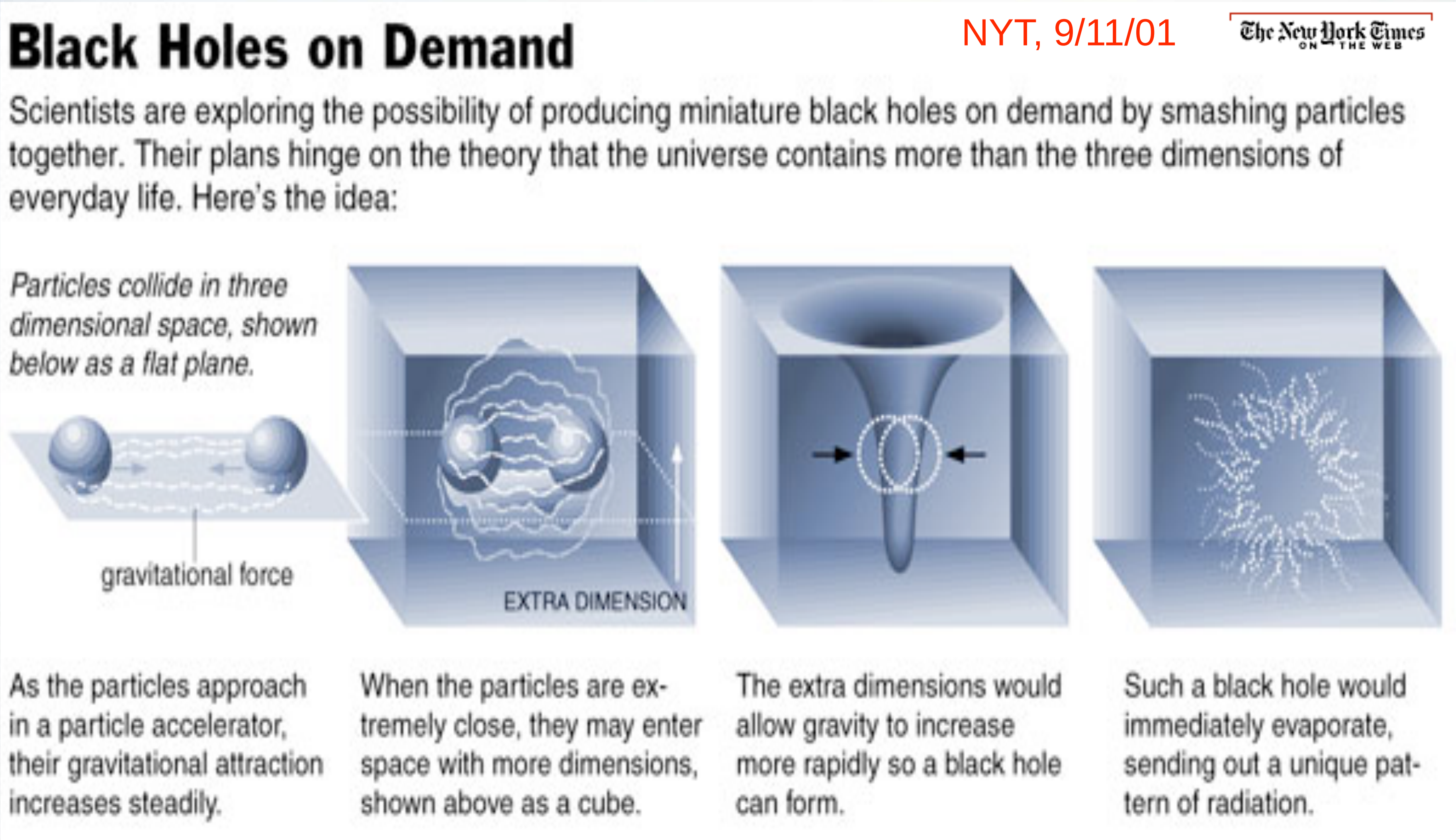
δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

- 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



Black Holes at the LHC?

Black Holes on Demand



NYT, 9/11/01

Black Holes on Demand

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.

As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

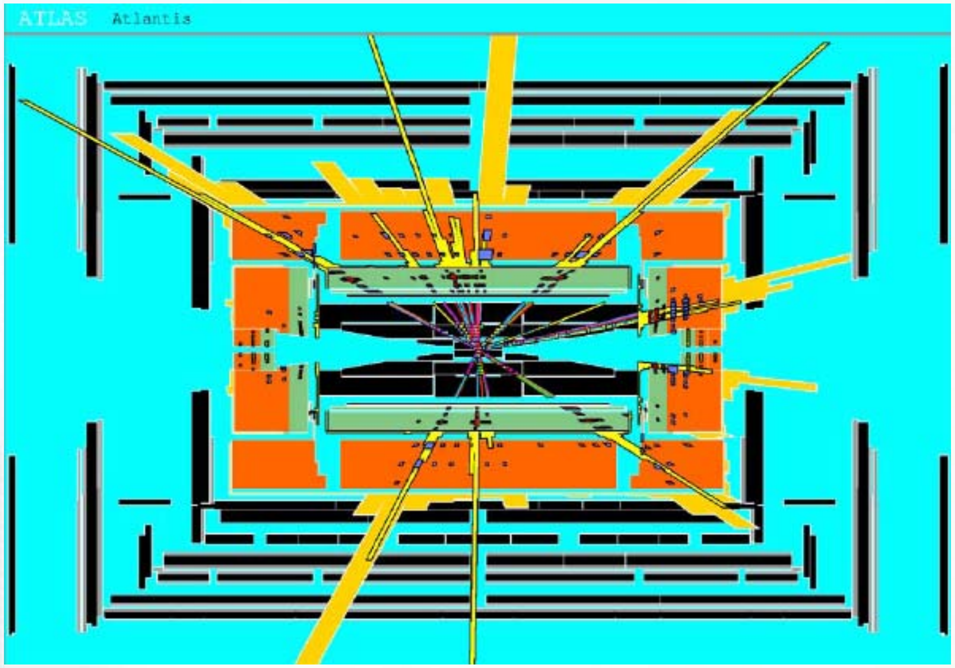
When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

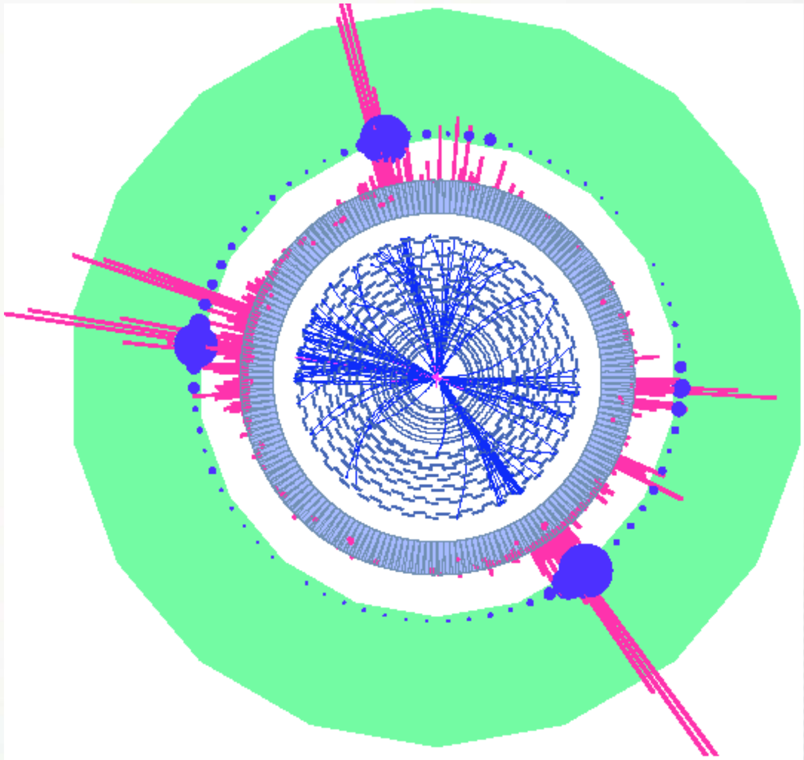
Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Black Hole Events

- Detailed studies already started in ATLAS and CMS
  - ATLAS –CHARYBDIS (HERWIG-based generator with an elaborated decay model by Harris/Richardson/Webber)
  - CMS – TRUENOIR, GL/CHARYBDIS/CATFISH (OleMiss)
- The hunt is going on!



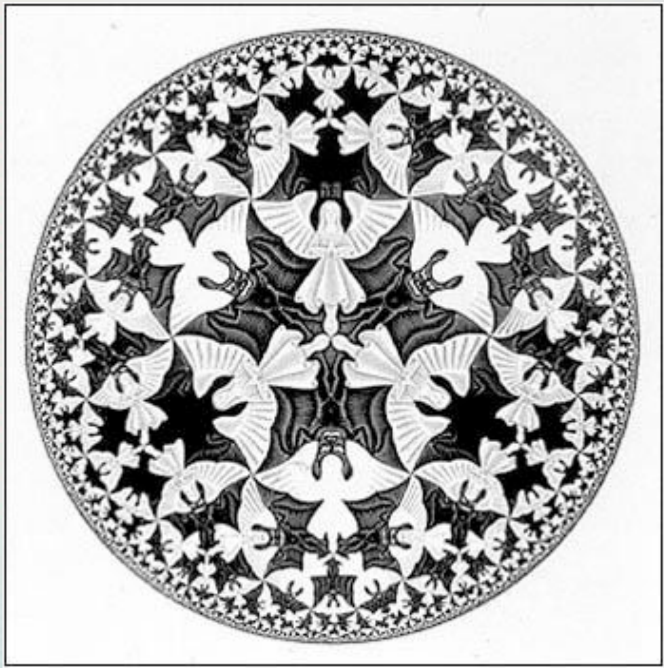
Simulated black hole event in the ATLAS detector, from ATLAS-Japan Group



Simulated black hole event in the CMS detector, A. de Roeck & S. Wynhoff

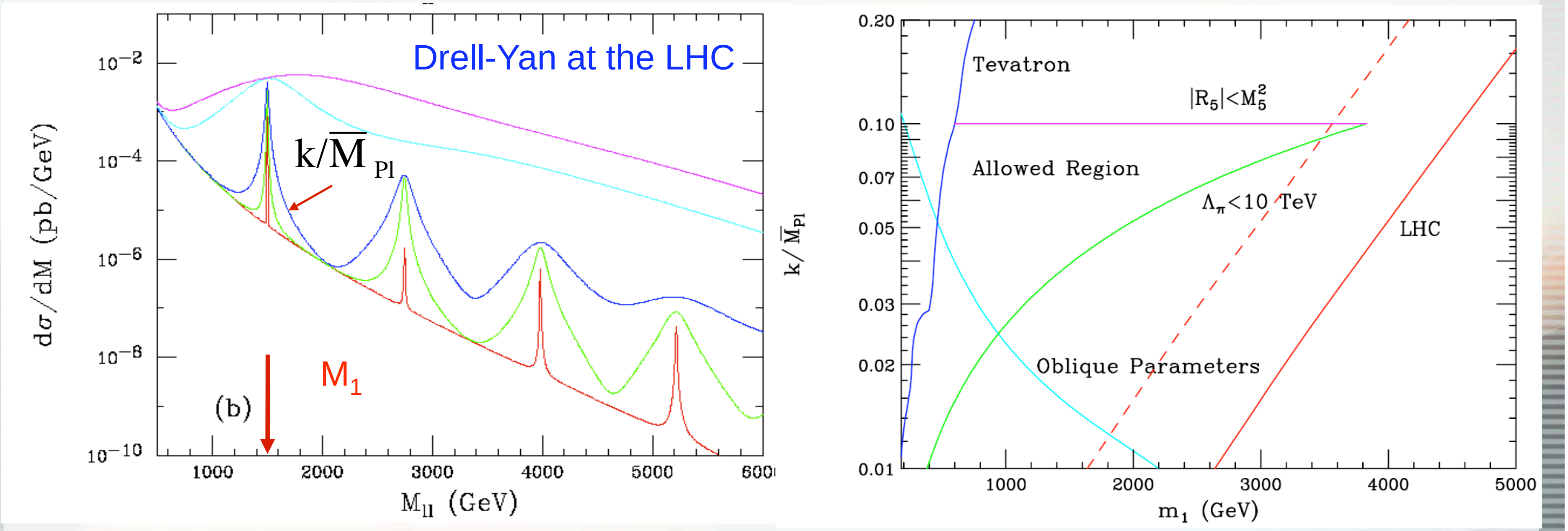
Example 3: Kaluza-Klein Resonances/Z′

Found in RS, TeV^{-1} models and in various Z$^{\prime}$ models



Randall-Sundrum Model Observables

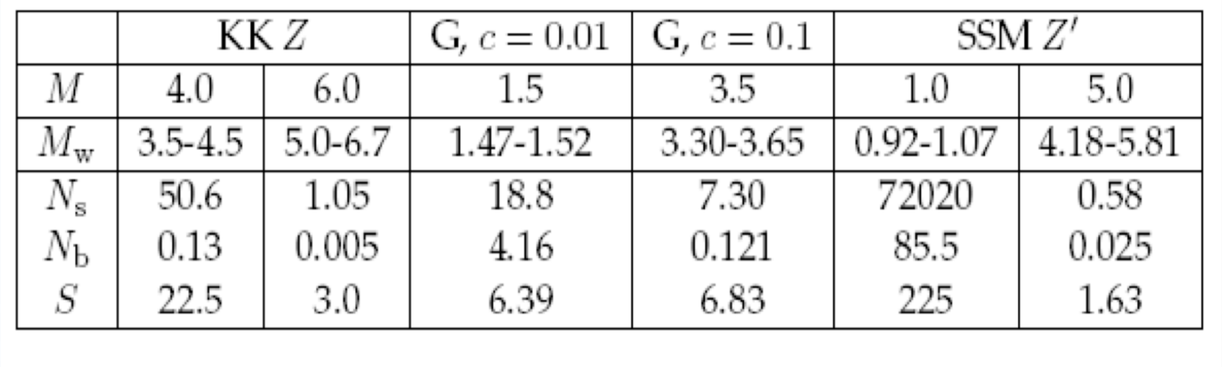
- Need only two parameters to define the model: k and r
- Equivalent set of parameters:
  - The mass of the first KK mode, M_1
  - Dimensionless coupling $k/\overline{M}_{\rm Pl}$, which determines the graviton width
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \leq k/\overline{M}_{\rm Pl} \leq 0.10$ 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

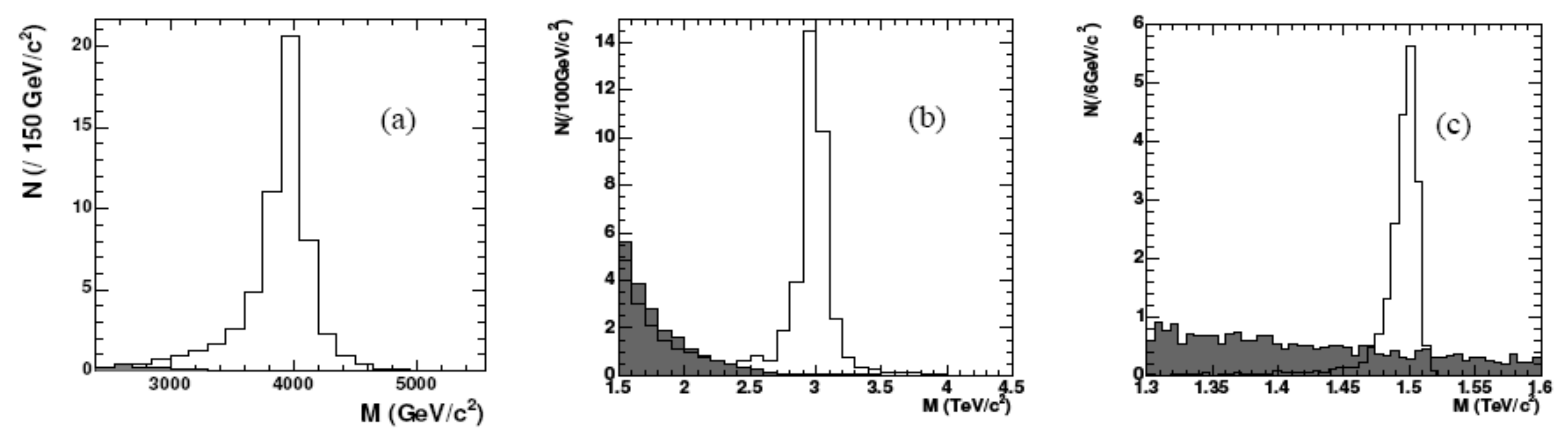
- Excellent resolution 5-10%/sqrt(E, GeV) (calorimeter based) and detection efficiency
- Low background above ~1 TeV



	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

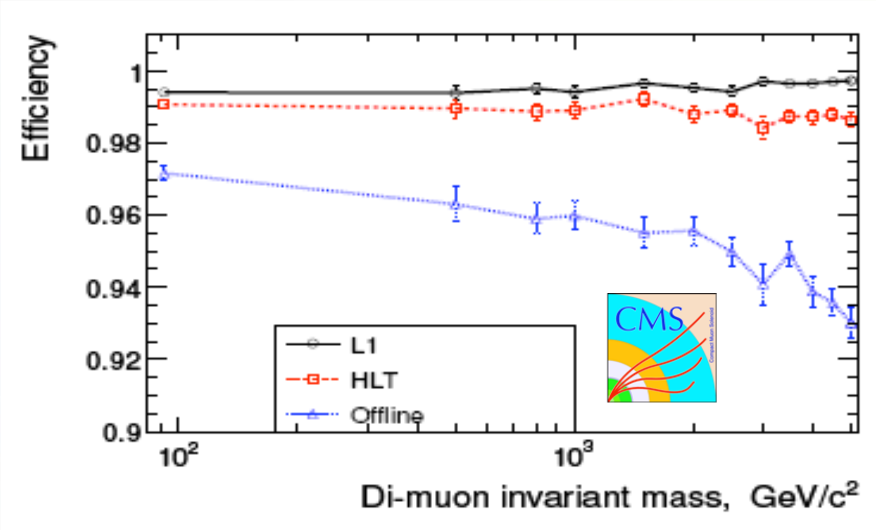
CMS, 30 fb^{-1}

Z_{KK} production

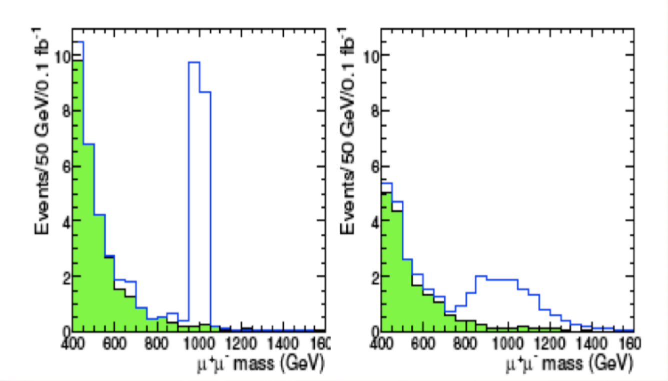


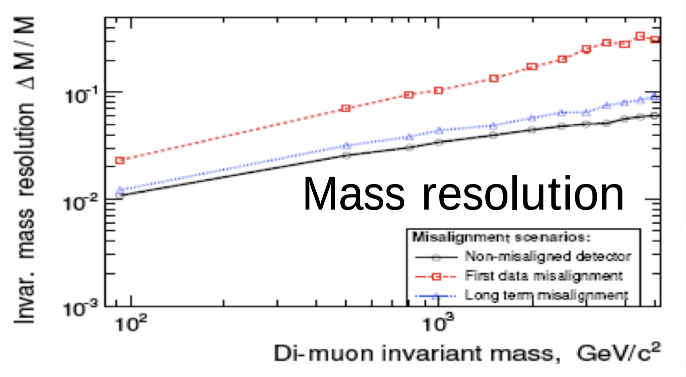
Dimuons: Confirmation Channel?

- Generally worse rapidity coverage, detection efficiency



- Significantly worse momentum resolution than for electrons

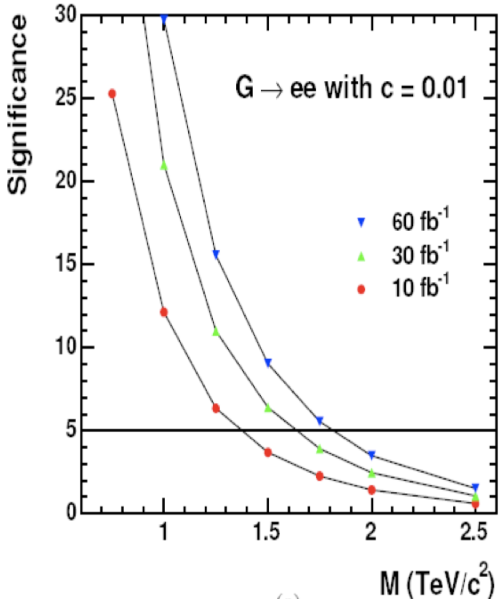




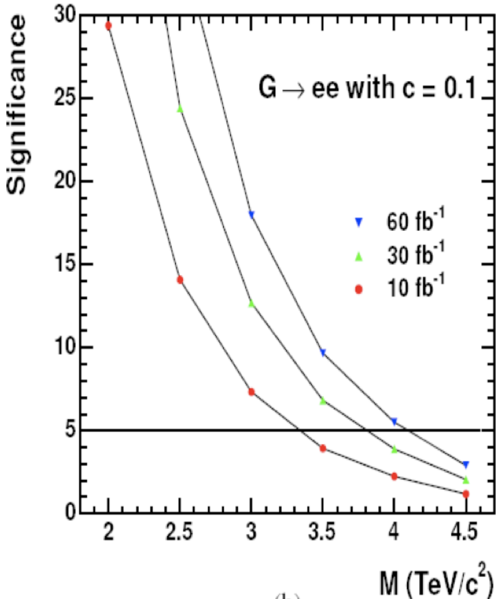
Mass resolution

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

Randall-Sundrum Graviton Reach



(a)



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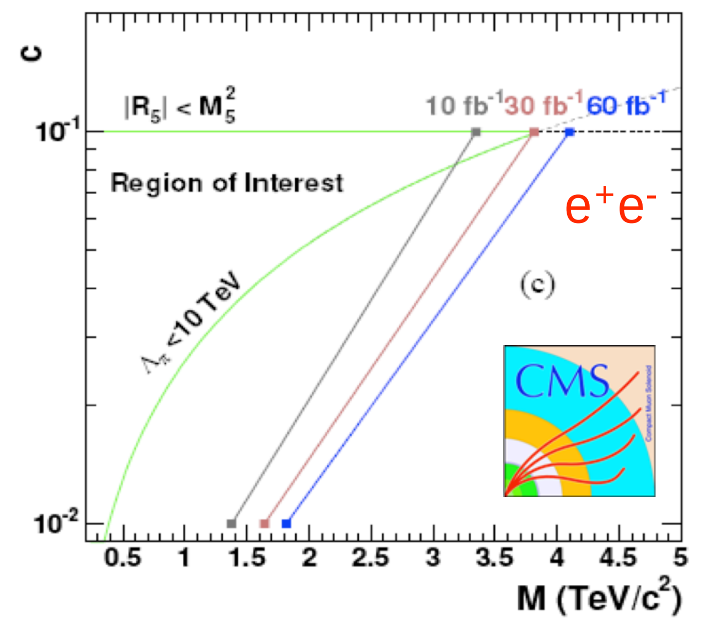
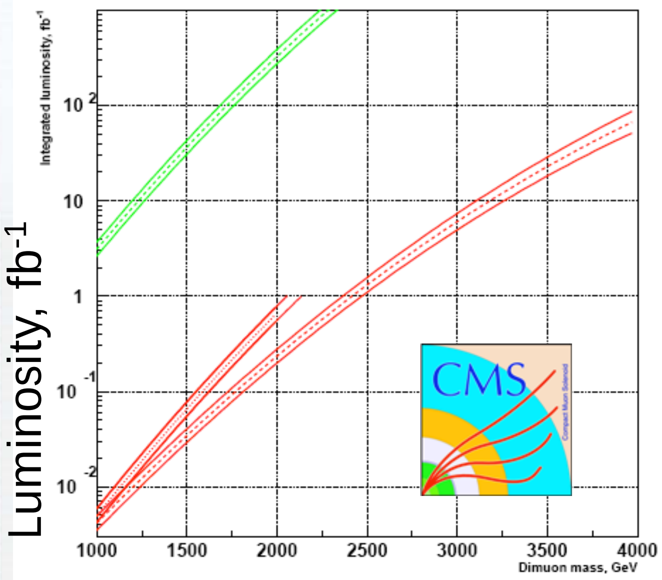
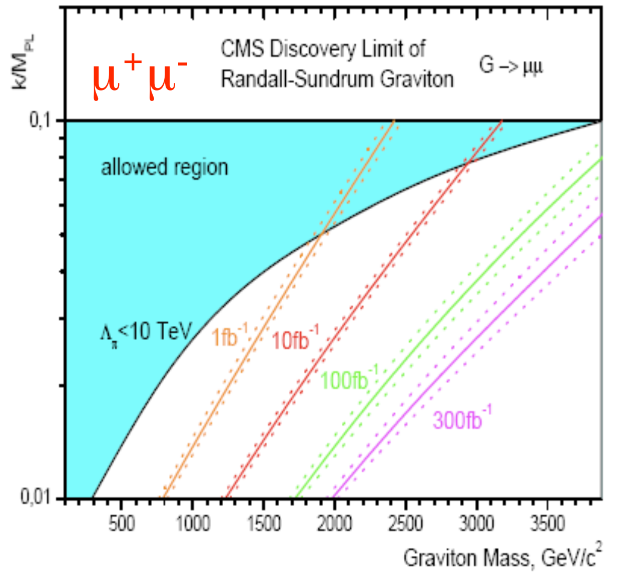


e^+e^-

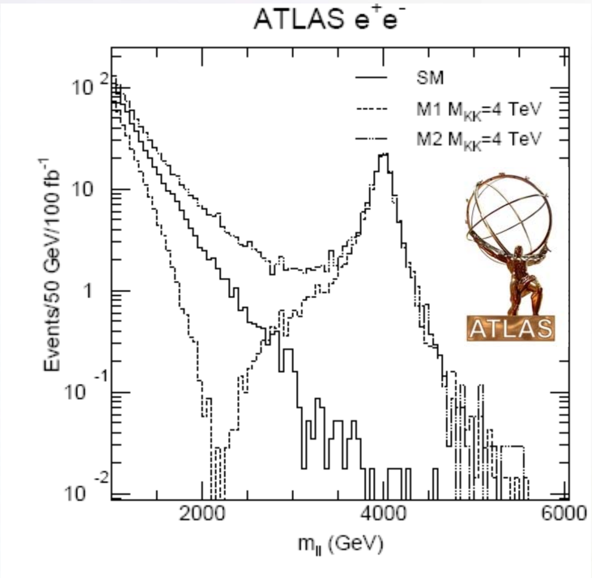


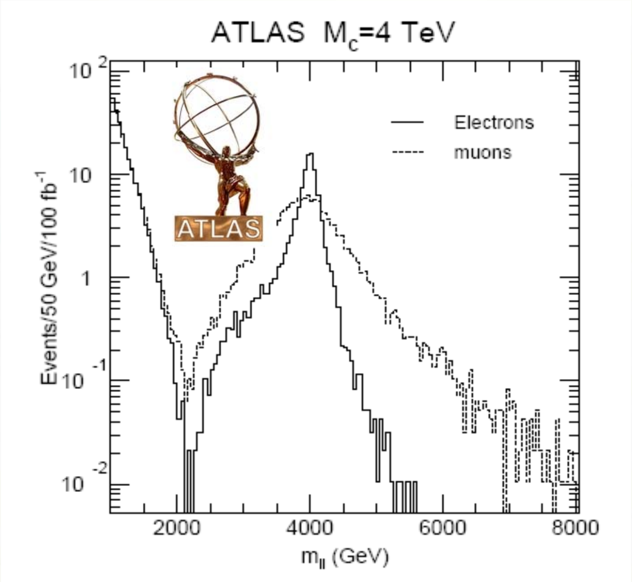
Coupling constant c	Estimator	1 fb^{-1}	10 fb^{-1}
0.01	S_{cP}	0.75	1.20
	S_{cL}	0.77	1.21
	S_L	0.78	1.23
0.02	S_{cP}	1.21	1.72
	S_{cL}	1.22	1.72
	S_L	1.22	1.74
0.05	S_{cP}	1.83	2.48
	S_{cL}	1.85	2.49
	S_L	1.85	2.51
0.1	S_{cP}	2.34	3.11
	S_{cL}	2.36	3.13
	S_L	2.36	3.16

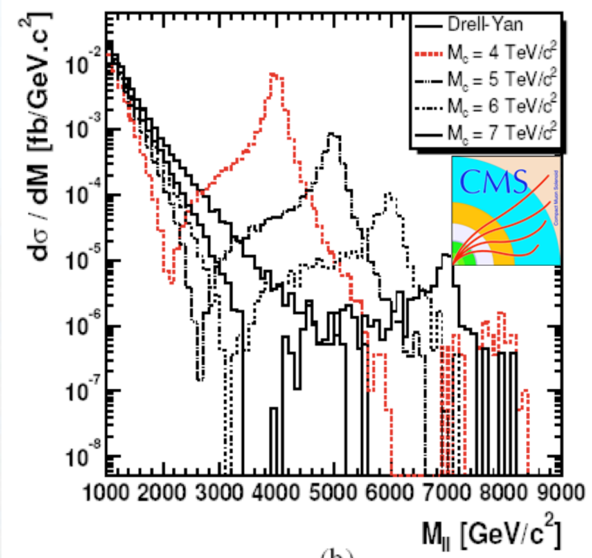
$\mu^+\mu^-$



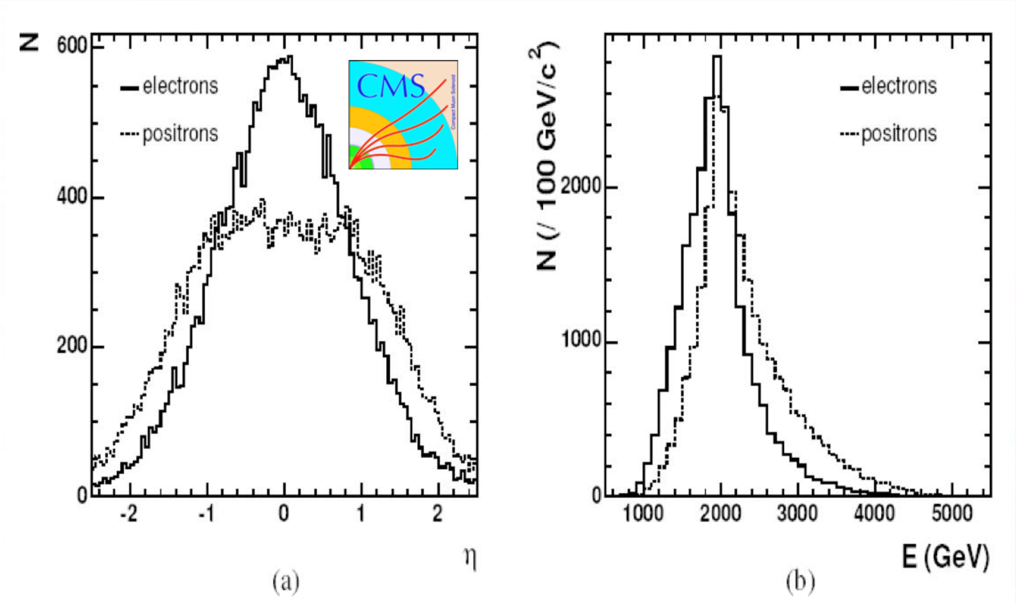
KK Excitations of the Z Boson







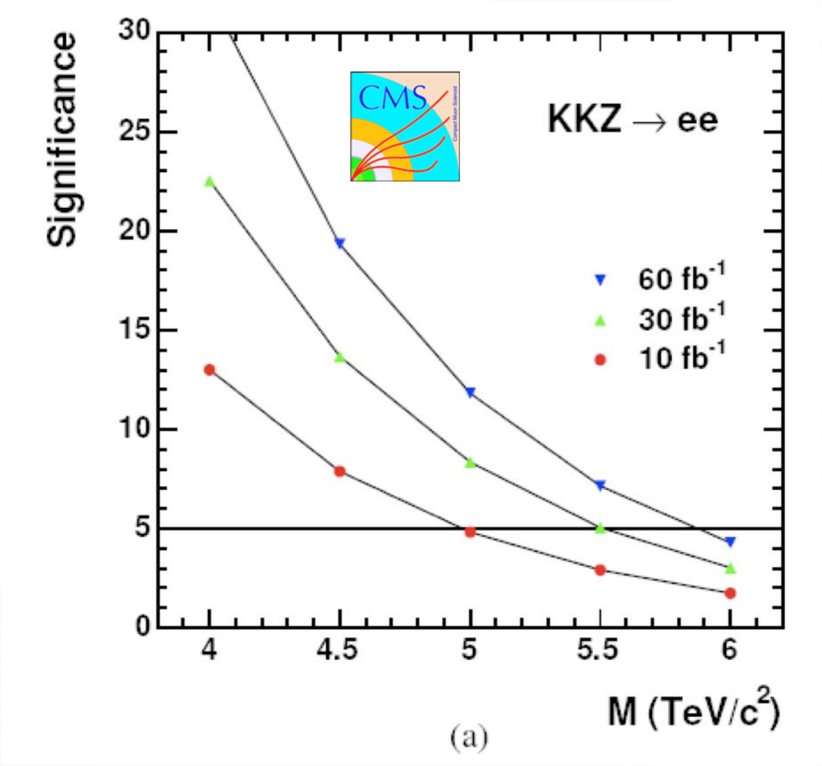
(b)



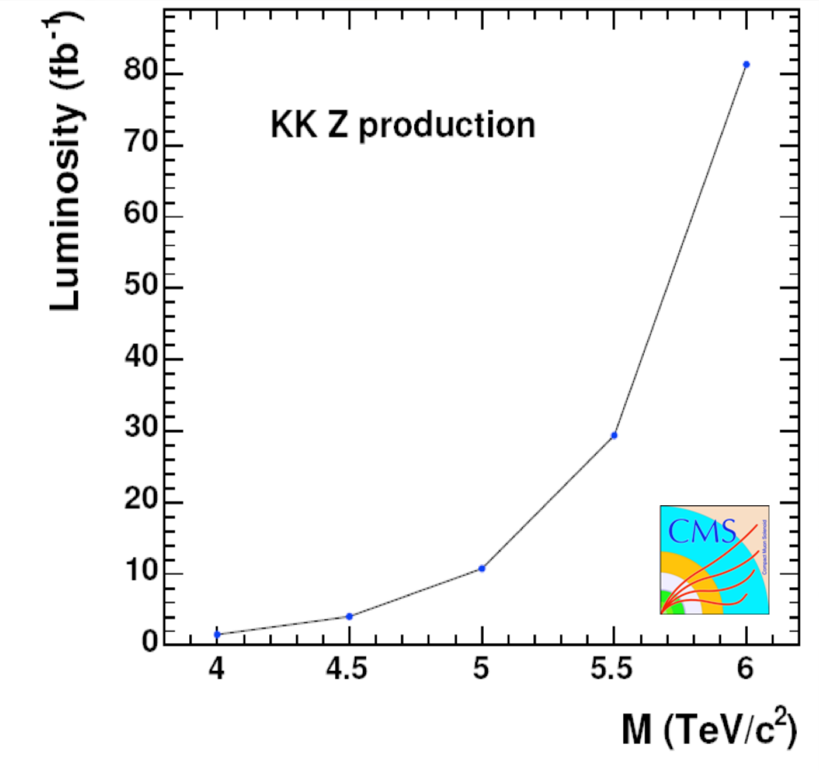
(a) (b)

KK Reach

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

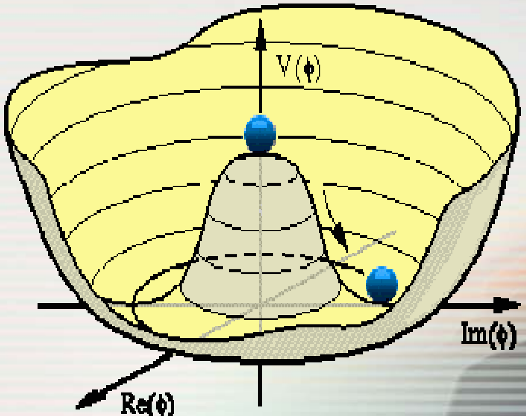


(a)



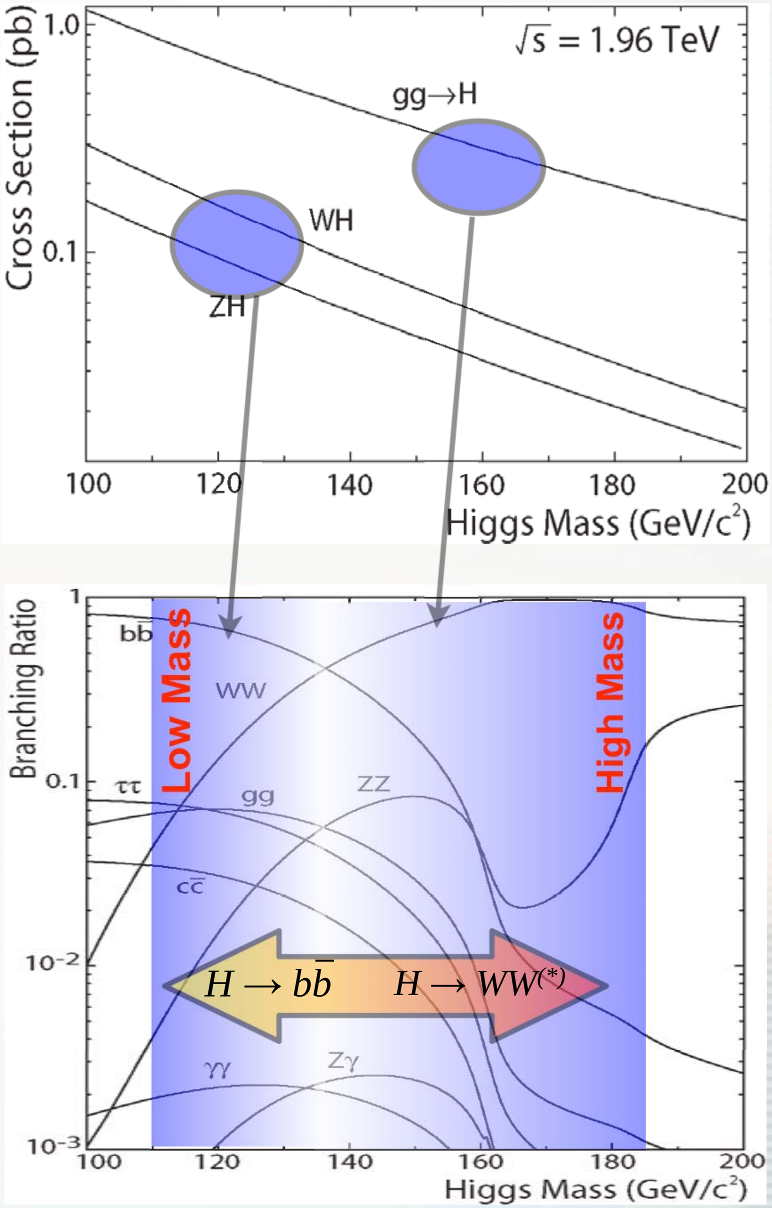
Example 4: The Higgs

The race of two machines



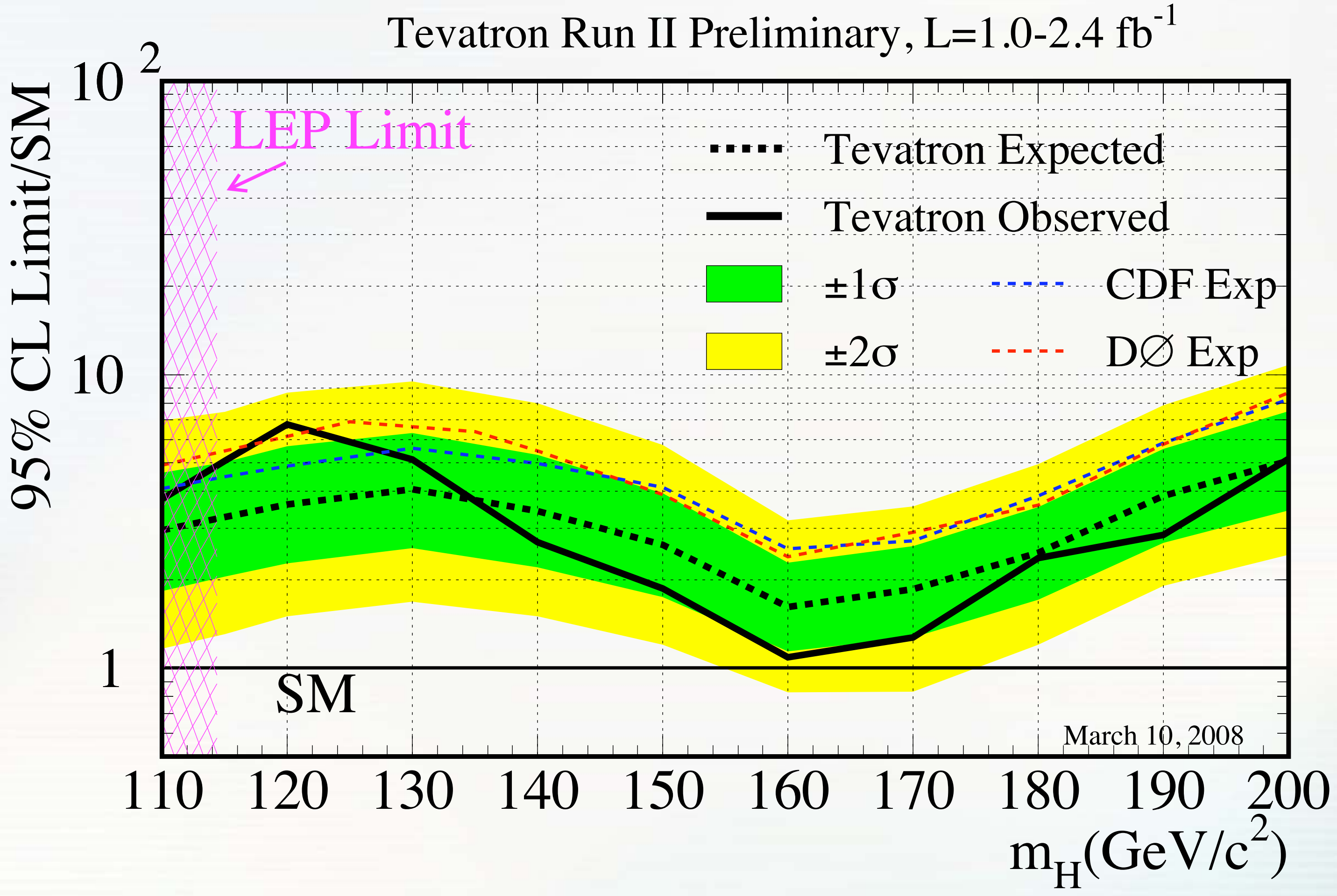
Tevatron Search Strategy

- Low mass Higgs (M_H < 135 GeV):
  - bb decay channel
  - Associated WH/ZH production to keep backgrounds under control
  - Final states: ℓνbb, ℓℓbb, ννbb or ℓνbb
- High mass Higgs (M_H > 135 GeV):
  - $WW^{(*)}$ decay channel
  - Production via gluon fusion to maximize cross section
  - Final states: ℓℓ'νν'
- Backgrounds:
  - W/Z + (heavy quark) jets, dibosons
  - Single and pair top production
  - QCD multijets
- Analyses:
  - ℓνbb: 1.9 fb^{-1} CDF + 1.7 fb^{-1} DØ
  - ℓℓbb: 1.0 fb^{-1} CDF + 1.1 fb^{-1} DØ
  - ννbb: 1.7 fb^{-1} CDF + 0.9 fb^{-1} DØ



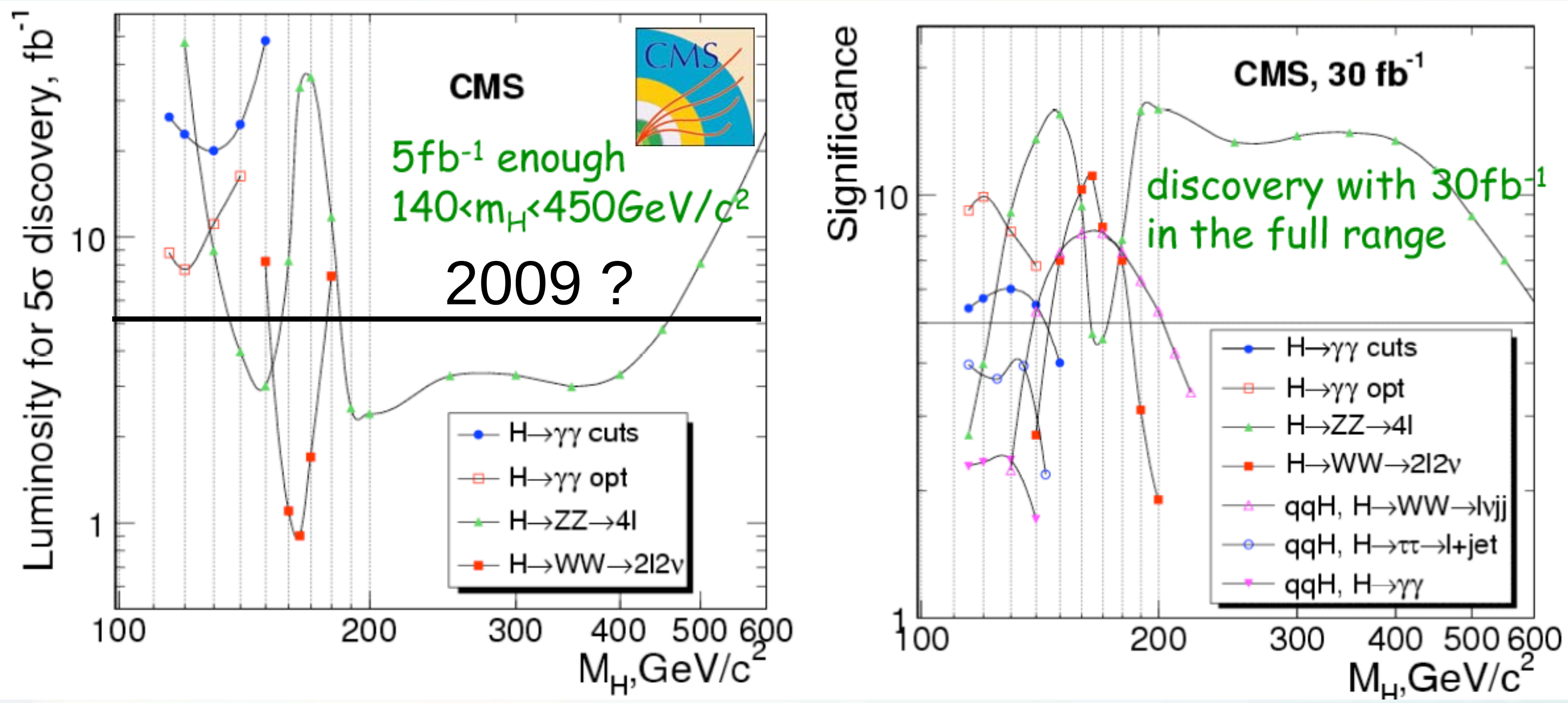
Tevatron Results

- For M_H = 115 GeV, σ^{95}/σ_{SM} = 5.1 (3.3) observed (expected)



The Race is On!

- Challenge: commissioning detectors simultaneously with search for Higgs
- Early running: gluon fusion production; $\gamma\gamma$, $WW^{(*)} \rightarrow ll'\nu\nu'$, $ZZ \rightarrow lll'l'$
- Discovery possible with ~ 5fb^{-1} of *well understood* data: 2009?



5fb^{-1} enough $140 < m_H < 450$GeV/c^2

2009 ?

discovery with 30fb^{-1} in the full range

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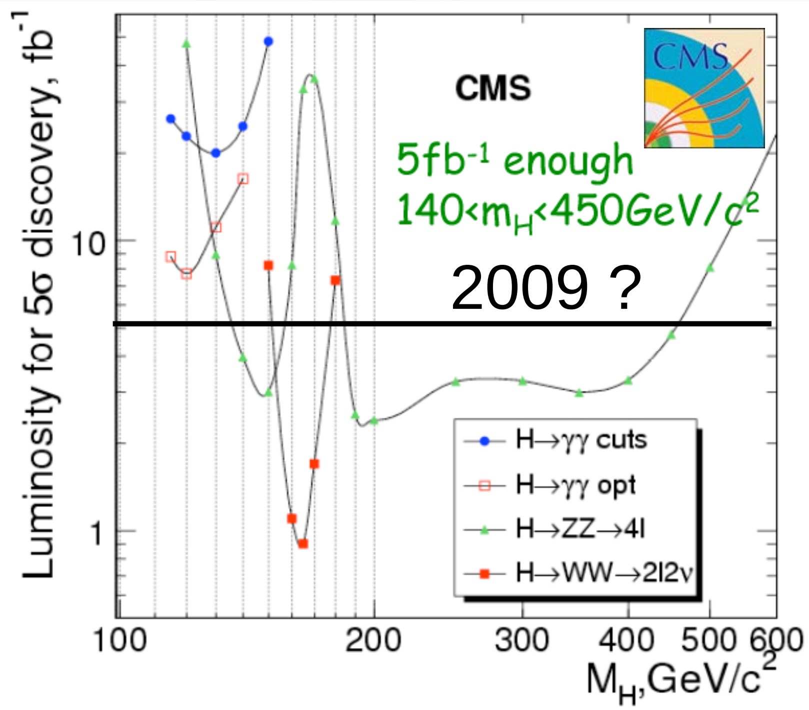
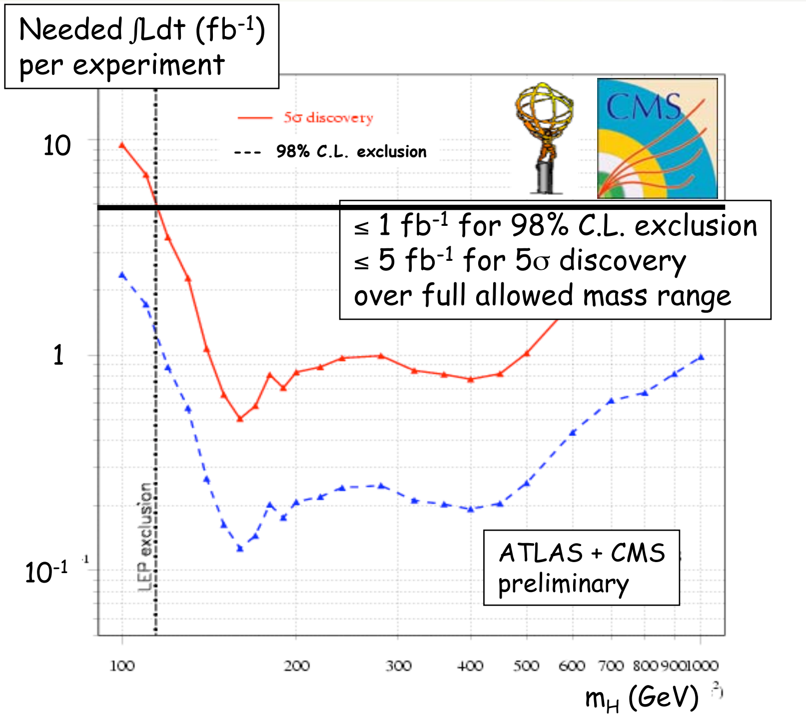


5fb^{-1} enough
$140 < m_H < 450\text{GeV}/c^2$

2009 ?

Needed ∫Ldt (fb^{-1})
per experiment



≤ 1 fb^{-1} for 98% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range

ATLAS + CMS
preliminary

The Race is On!

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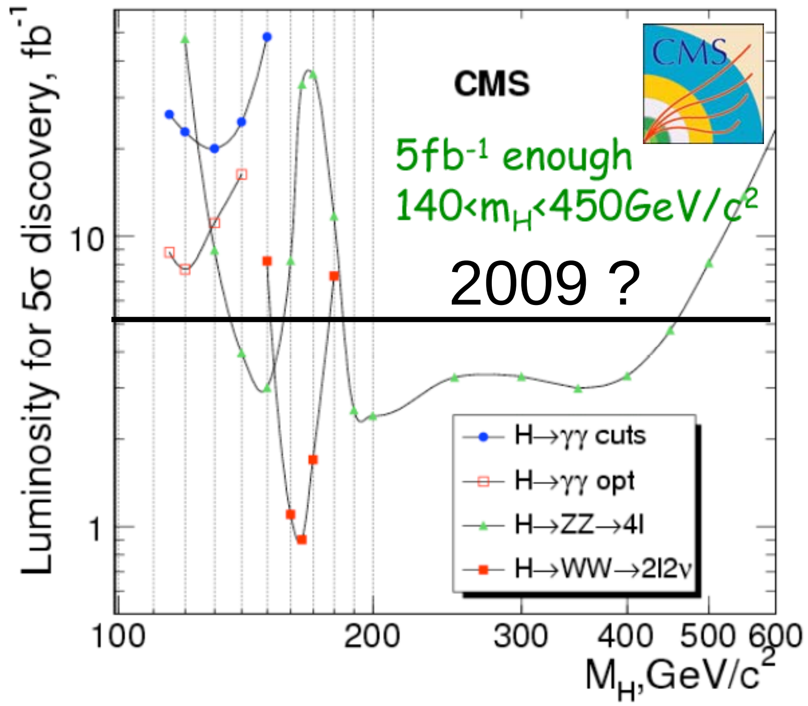
- Discovery possible with ~ $5 fb^{-1}$ of *__well understood__* data: 2009?

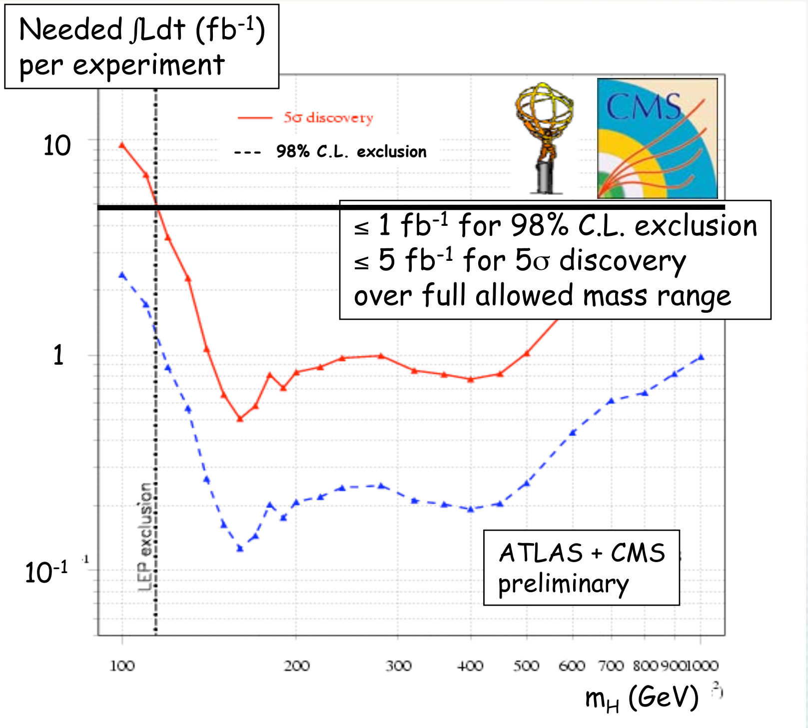

Tevatron


LHC



$5fb^{-1}$ enough $140 < m_H < 450 GeV/c^2$

2009 ?


Needed ∫Ldt (fb^{-1}) per experiment

≤ 1 fb^{-1} for 98% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery over full allowed mass range

ATLAS + CMS preliminary

Challenges

There will be surprises on the way!

Before One Can Succeed in Searches

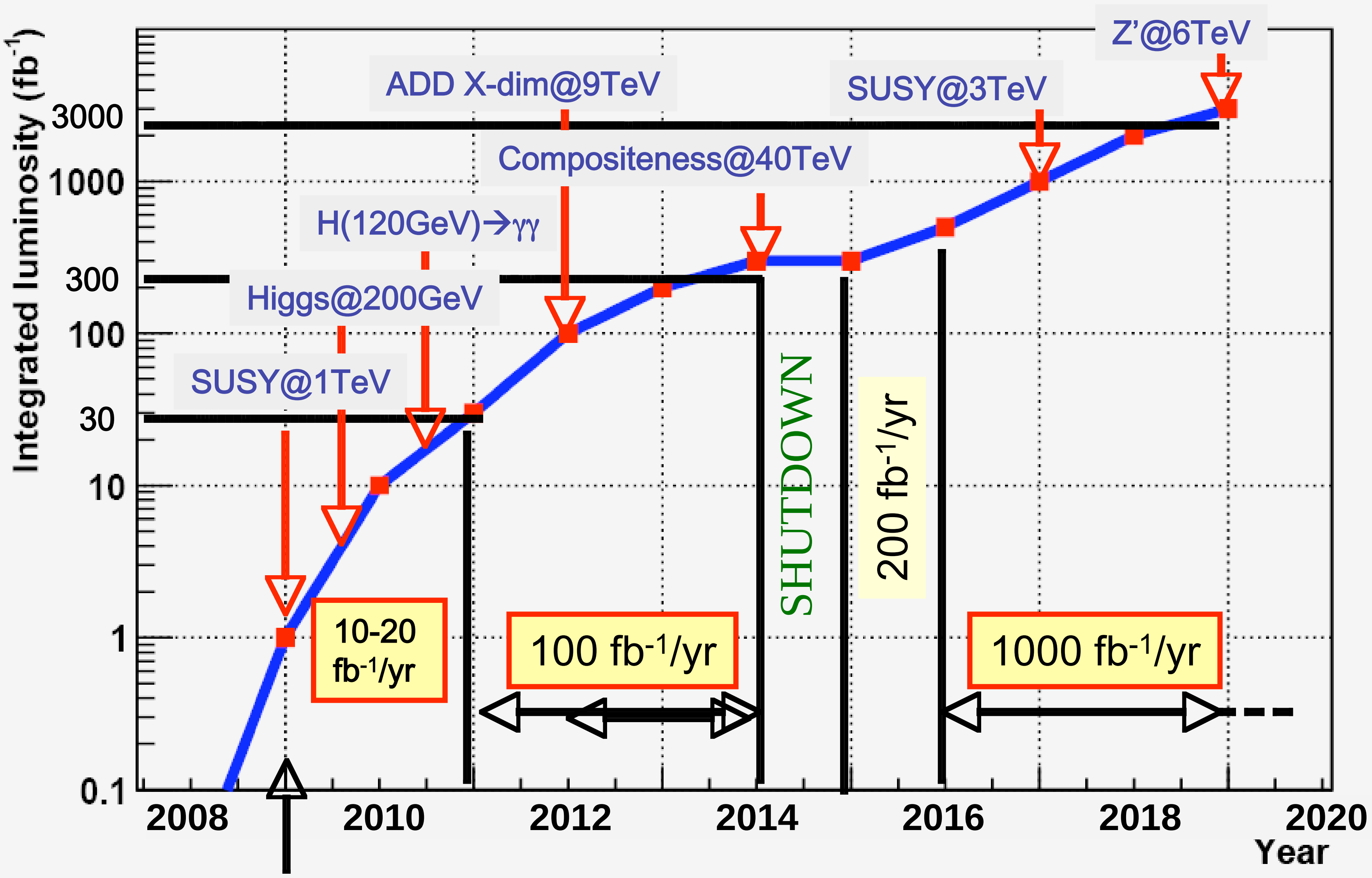
- Proper detector calibration, alignment, and detailed simulation is required
- Taunting task, which easily takes several years
- Searches typically look for one event in a million; that means that the detector often has to be understood to the 10^{-6} level!
- Use calibration samples of well understood 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’			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



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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- We have detailed maps - theoretical guidance - but let's not forget that we may be in the uncharted waters
- 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!
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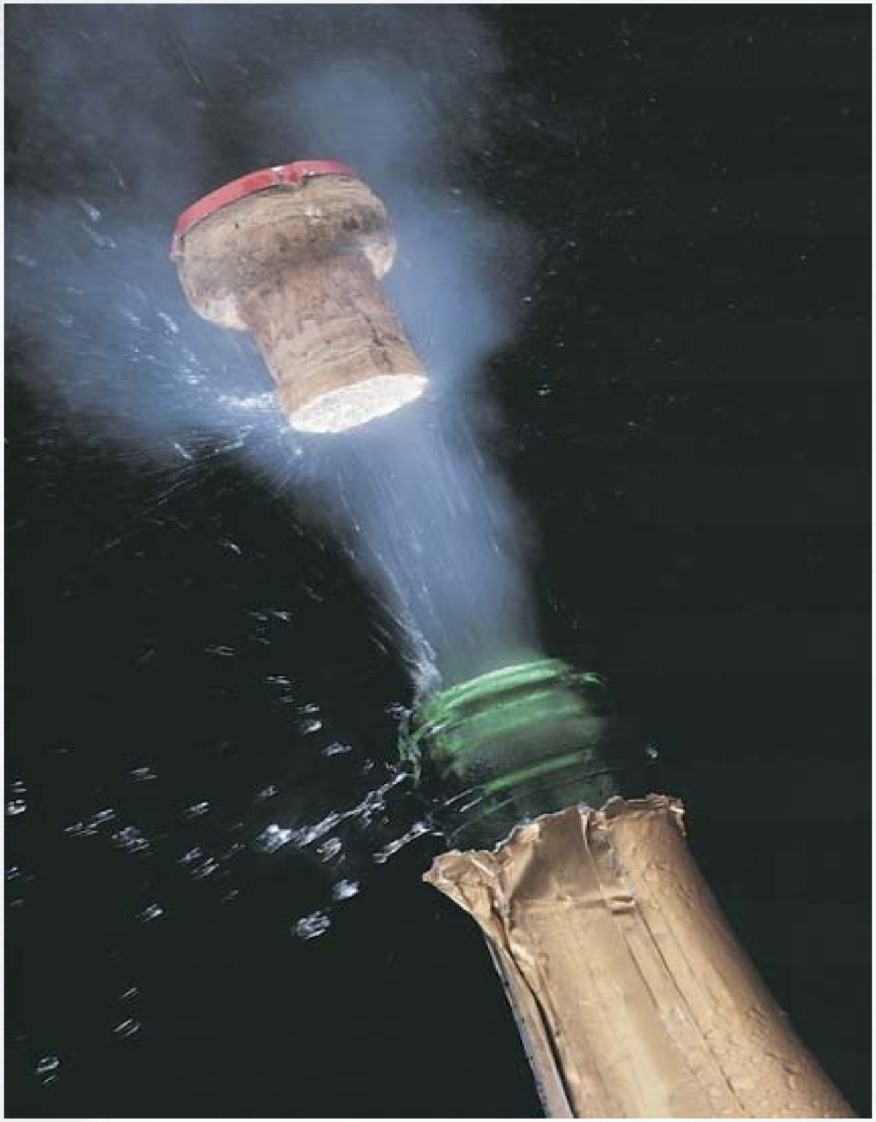

¡Prospero Año Nuevo 2008: el año de LHC!