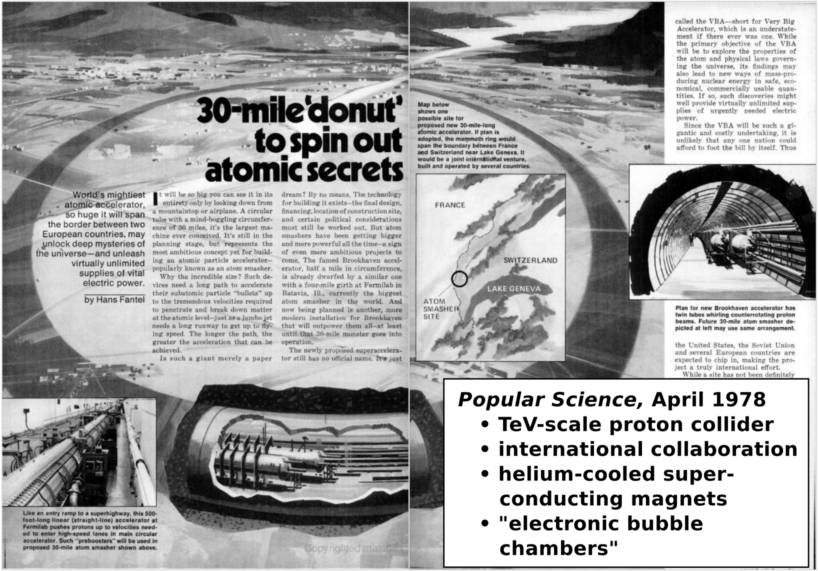
CMS Physics Overview

Jim Pivarski

on behalf of the CMS Collaboration

29 October, 2010

Introduction



30-mile 'donut' to spin out atomic secrets

World's mightiest atomic accelerator, so huge it will span the border between two European countries, may unlock deep mysteries of the universe—and unleash virtually unlimited supplies of vital electric power.

by Hans Fantel

It will be so big you can see it in its entirety only by looking down from a mountaintop or airplane. A circular tube with a mind-boggling circumference of 30 miles, it's the largest machine ever conceived. It's still in the planning stage, but represents the most ambitious concept yet for building an atomic particle accelerator—popularly known as an atom smasher.

Why the incredible size? Such devices need a long path to accelerate their subatomic particle "bullets" up to the tremendous velocities required to penetrate and break down matter at the atomic level—just as a jumbo jet needs a long runway to get up to flying speed. The longer the path, the greater the acceleration that can be achieved.

Is such a giant merely a paper dream? By no means. The technology for building it exists—the final design, financing, location of construction site, and certain political considerations must still be worked out. But atom smashers have been getting bigger and more powerful all the time—a sign of even more ambitious projects to come. The famed Brookhaven accelerator, half a mile in circumference, is already dwarfed by a similar one with a four-mile girth at Fermilab in Batavia, Ill., currently the biggest atom smasher in the world. And now being planned is another, more modern installation for Brookhaven that will outpower them all—at least until that 30-mile monster goes into operation.

The newly proposed superaccelerator still has no official name. It's just called the VBA—short for Very Big Accelerator, which is an understatement if there ever was one. While the primary objective of the VBA will be to explore the properties of the atom and physical laws governing the universe, its findings may also lead to new ways of mass-producing nuclear energy in safe, economical, commercially usable quantities. If so, such discoveries might well provide virtually unlimited supplies of urgently needed electric power.

Since the VBA will be such a gigantic and costly undertaking, it is unlikely that any one nation could afford to foot the bill by itself. Thus the United States, the Soviet Union and several European countries are expected to chip in, making the project a truly international effort.

While a site has not been definitely

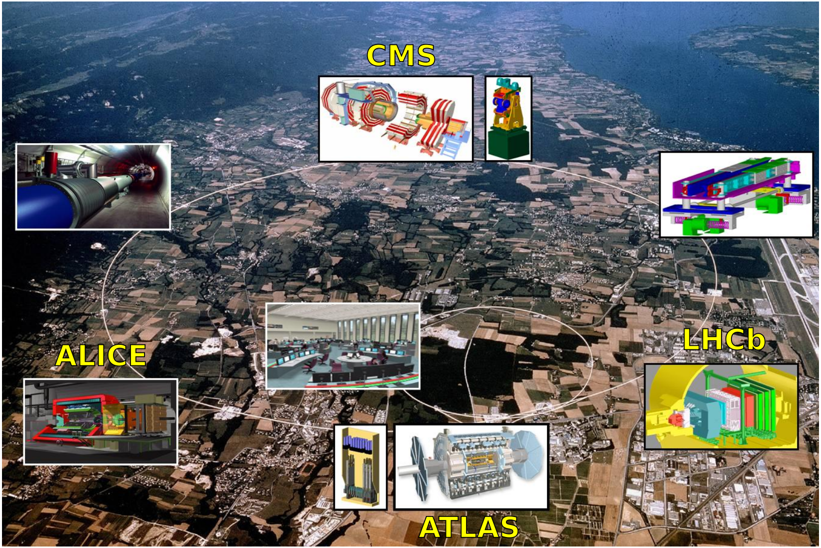
Map below shows one possible site for proposed new 30-mile-long atomic accelerator. If plan is adopted, the mammoth ring would span the boundary between France and Switzerland near Lake Geneva. It would be a joint international venture, built and operated by several countries.

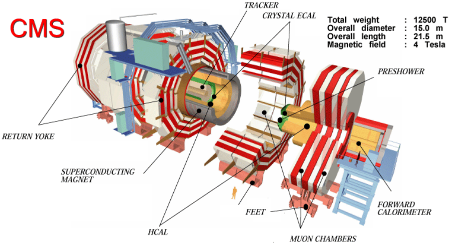
Plan for new Brookhaven accelerator has twin tubes whirling counterrotating proton beams. Future 30-mile atom smasher depicted at left may use same arrangement.

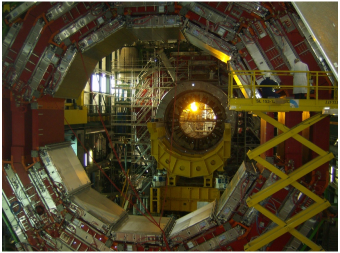
Like an entry ramp to a superhighway, this 500-foot-long linear (straight-line) accelerator at Fermilab pushes protons up to velocities needed to enter high-speed lanes in main circular accelerator. Such "preboosters" will be used in proposed 30-mile atom smasher shown above.

***Popular Science*, April 1978**

- **TeV-scale proton collider**
- **international collaboration**
- **helium-cooled super-conducting magnets**
- **"electronic bubble chambers"**

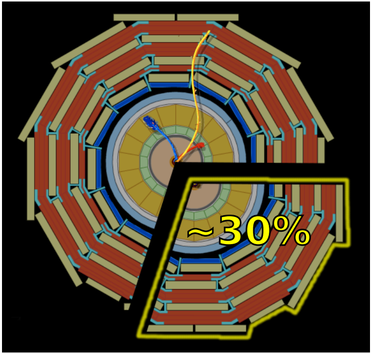

CMS
ALICE
LHCb
ATLAS

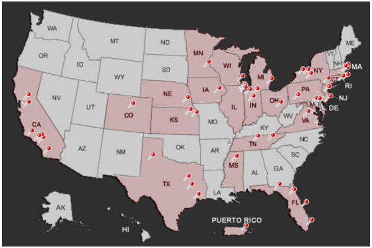




- CMS is an all-purpose detector, designed for discovery
- Modular for relatively easy access, strong $\vec{B}$-field, all-silicon tracker, all-software L2–L3 trigger
- Approximate scale of the project: 66M pixel channels, 10M silicon channels, 75k crystals, 150k silicon preshower channels, 15k HCAL channels, 250 DT chambers (170k wires), 470 CSC chambers (200k wires), 900 RPC chambers, 50 kHz DAQ system (10k CPU cores), GRID computing (50k cores), 2M lines of offline source code. . .

Introduction





- CMS: 190 institutions, 4700 participants, 1940 scientific authors, 800 students, 39 countries
- US-CMS: 49 institutions, 1400 participants, 640 scientific authors, 200 graduate students
- U.S.-led subsystems:
  - hadron calorimeter
  - endcap muons
  - forward pixels
  - trigger
- Strong U.S. participation:
  - data acquisition
  - silicon strip tracker
  - electromagnetic calorimeter
  - computing
  - physics analyses

Outline for this talk

By October 2009, the conventional wisdom of what to expect in the first year of LHC physics went something like the following:

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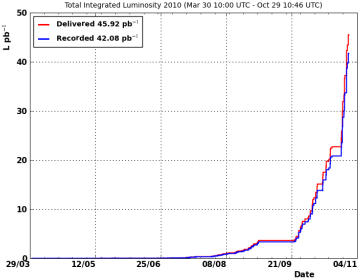
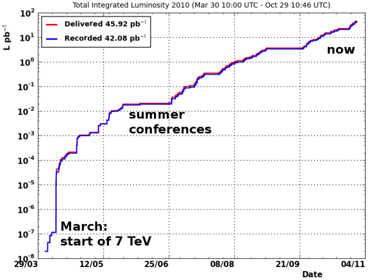
- "Expect the unexpected: we'll probably find things we weren't even looking for..."
- "Don't expect everything to work at first..."
  - here, we were surprised: even complex techniques like *b*-tagging, missing energy, particle flow, etc., *do* seem to be working as expected from simulations

Rapid rise in luminosity and data collection

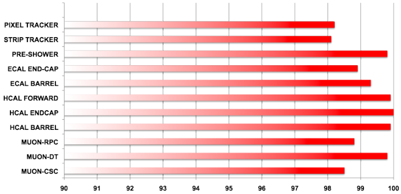
Integrated luminosity: linear scale



Integrated luminosity: log scale



- Steps in luminosity from $\mathcal{L} = 10^{27}$ to 10^{32} Hz/cm^2
- Not unusual for a weekend to double the entire dataset
- Maintaining ∼90% livetime (requiring all subsystems)

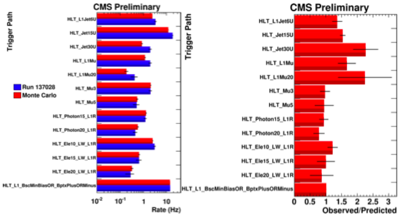


	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

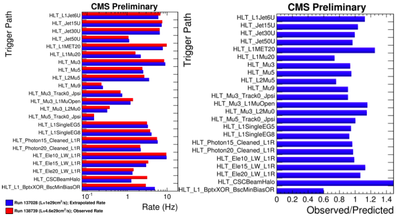
Luminosity and data collection

- We want wide-open triggers at first, narrowing as luminosity increases
- To minimize prescaling of good physics, we need accurate predictions of cross-sections, despite the fact that Monte Carlos have not been tuned to 7 TeV *pp* yet
- Bootstrap trigger estimates on previous datasets

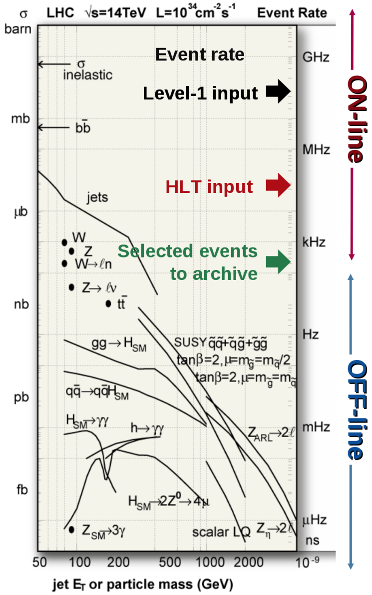
Predicting trigger rates from MC and verifying with early data:



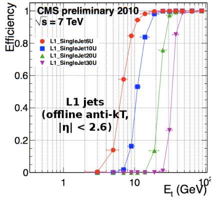
Predicting rates from early data extrapolated to higher luminosities:

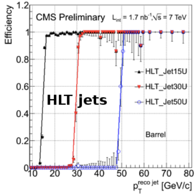


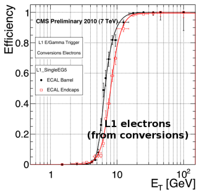
Luminosity and data collection

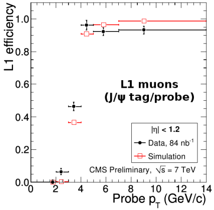


- L1 trigger: 45–70 kHz
- HLT (data-logging): 350–600 Hz
- Sample turn-on curves from data:



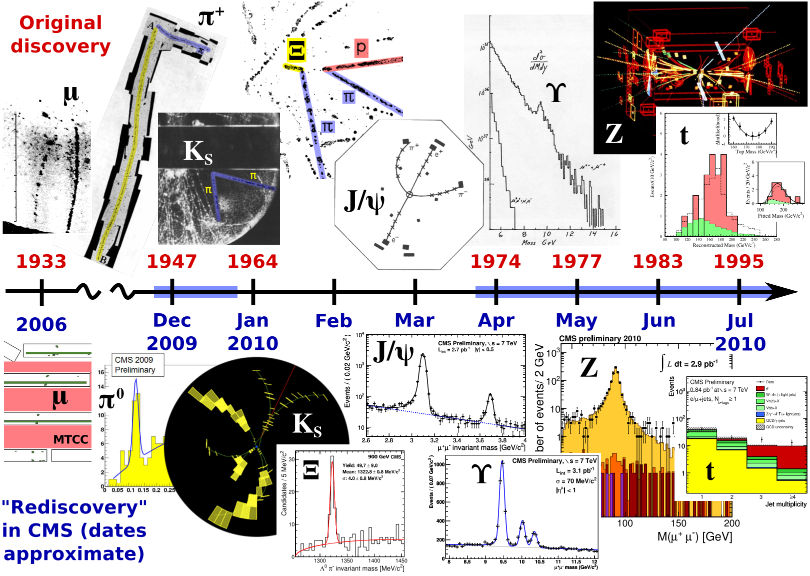






Rediscovering the Standard Model

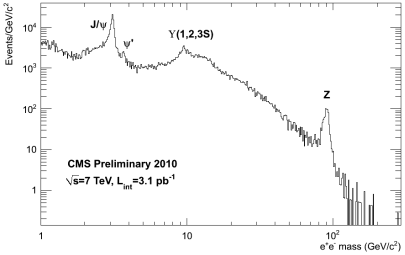
Rediscovering the Standard Model



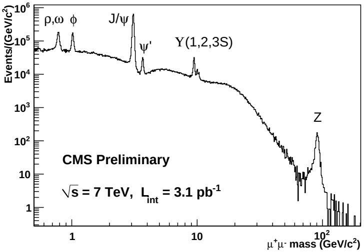
Sample plots

- The whole self-adjoint vector resonance spectrum:

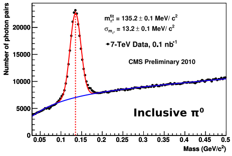
e^+e^- log mass

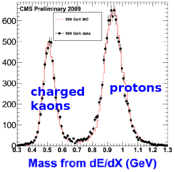


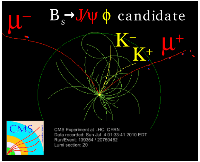
$\mu^+\mu^-$ log mass

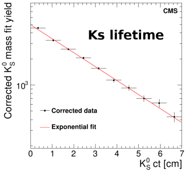


- And a few other nice examples:





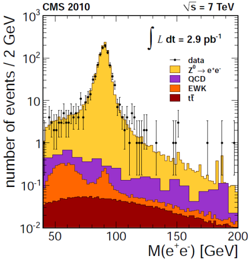


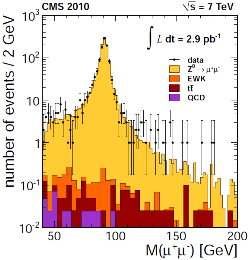


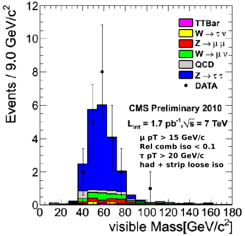
Electroweak bosons

electron(s) **muon(s)** **tau(s)**

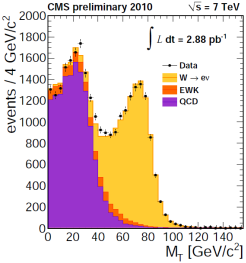
Z boson

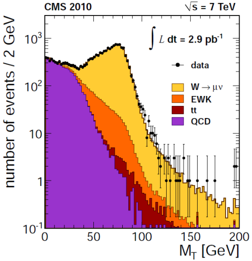


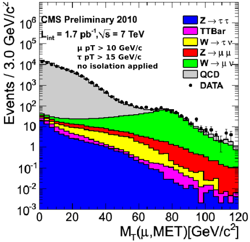


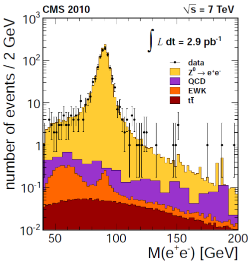
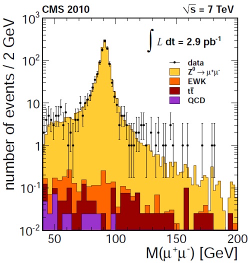
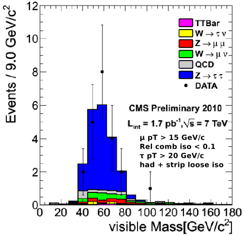
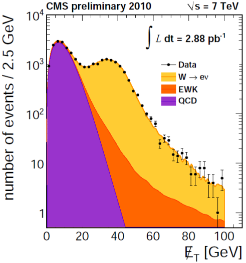
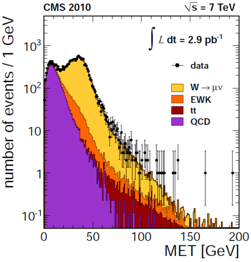
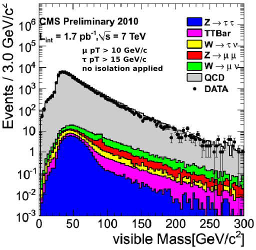


W boson

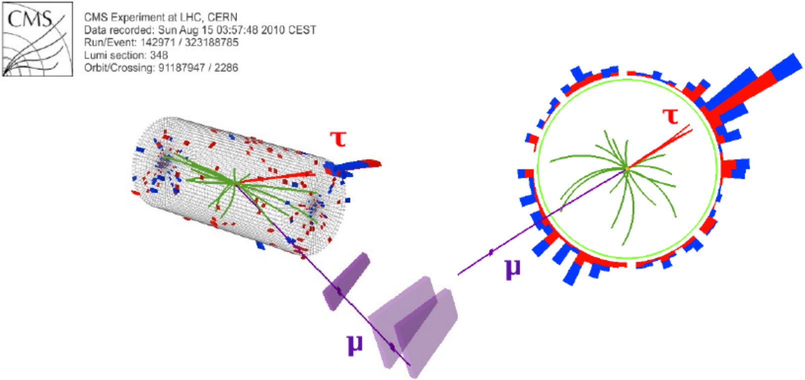






	electron(s)	muon(s)	tau(s)
Z boson			
W boson			

Z → tau tau → mu +tau$_{had}$ (three prong tau)

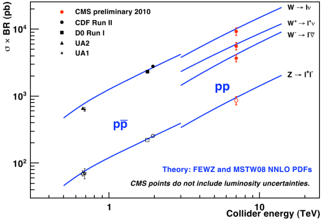


μ Pt = 32.4 GeV/c
η = 1.7

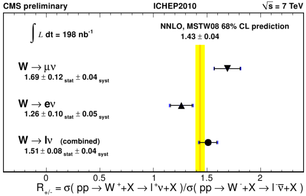
τ Pt = 37.4 GeV/c
η = 1.5
Mass = 1.2GeV/c²

Vis. Mass= 70 GeV/c²
M_T(μ,MET) =4.1 GeV

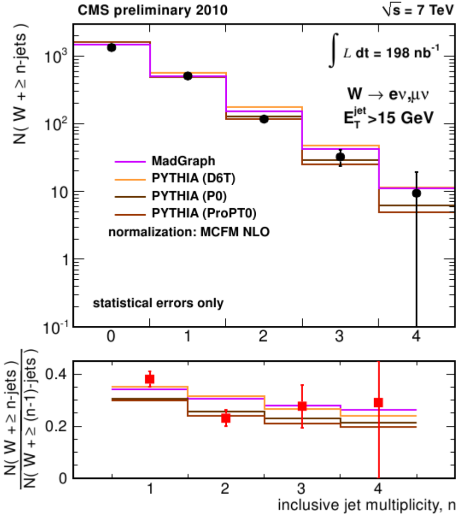
Production cross-sections
(see Andrew Kubik's talk)



$W^{\pm}$ charge asymmetry

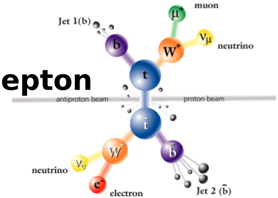


Number of jets produced with W

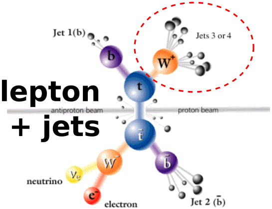


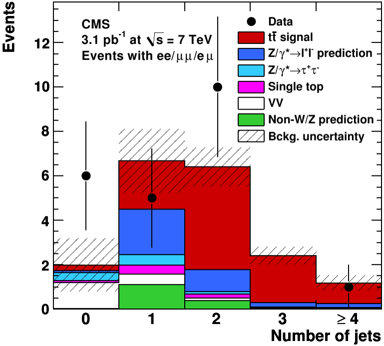
The top quark

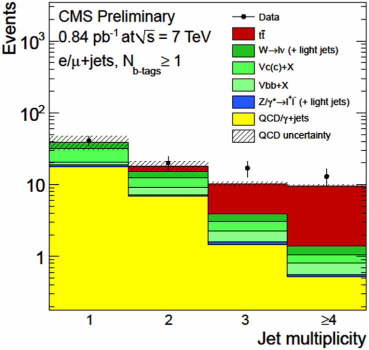
Top dilepton



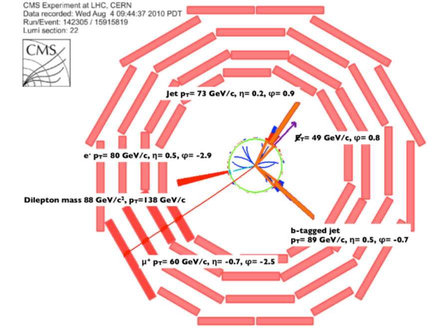
Top lepton + jets

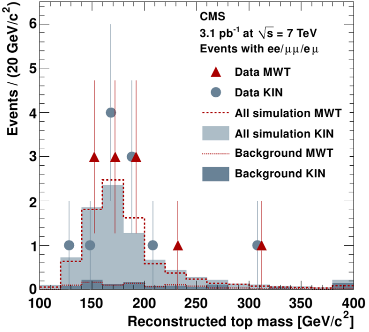






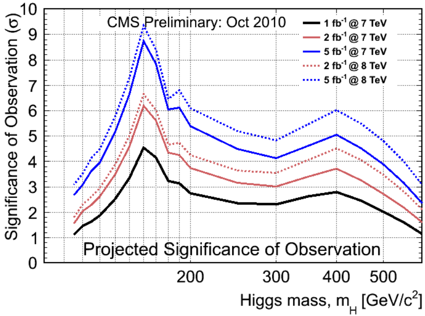
- Sample event display and mass in the dilepton channel
- Lepton $p_T > 20$ GeV$/c$, relative isolation $< 15\%$ $(\Delta R < 0.3)$, $\not\!\!E_T > 30$ GeV (20 GeV for $e\mu$), $|M_{\ell\ell} - M_Z| > 15$ GeV$/c^2$

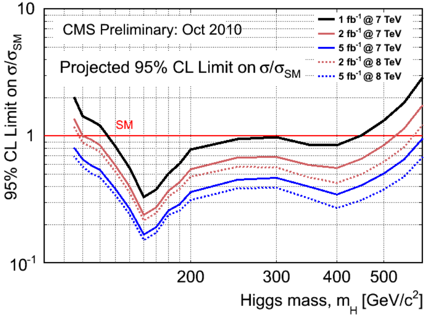




- $\sigma(7\text{ TeV } pp \to t\bar{t}) = 194 \pm 72$ (stat) $\pm$ 24 (syst) $\pm$ 21 (lumi) pb
- NLO prediction: $157.5^{+23.2}_{-24.4}$ pb (hep-ex/1010.5994)

- Higgs discovery/limit-setting begins at 1 fb^{-1}, but can cover from the LEP limit (114 GeV/c^2) up to 600 GeV/c^2 with 5 fb^{-1}, 8 TeV





- With 1 fb^{-1}, 7 TeV, "ATLAS + CMS" (2× CMS) projected 3σ sensitivity for $135 < m_H < 475$ GeV/c^2

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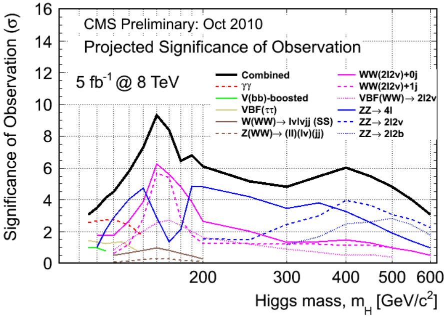

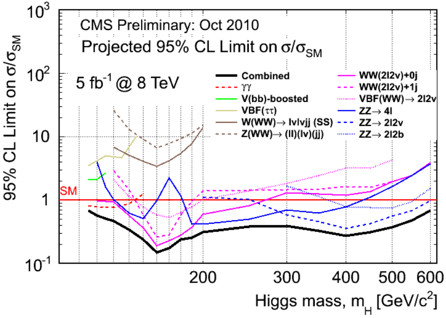

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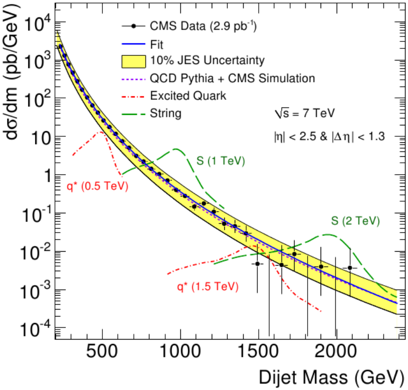
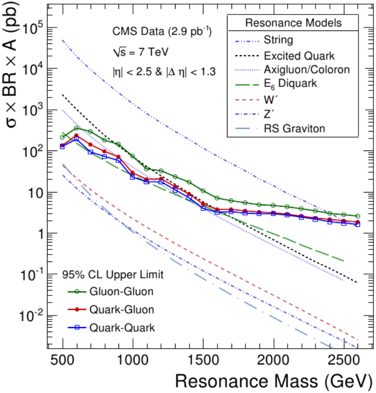
Beyond the Standard Model

Dijet spectrum

- Standard Model predicts a *smooth* distribution of dijet masses, new physics can produce narrow resonances: search for peaks
- Anti-k_T jets with $R = 0.7$, both within $|\eta| < 2.5$, $|\Delta\eta| < 1.3$

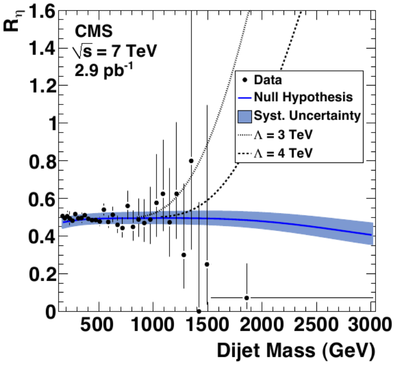


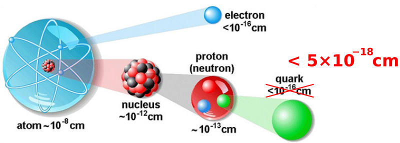


- Extends previous limits; accepted by PRL (hep-ex/1010.0203)

Beyond the Standard Model

Dijet angular distributions





- Standard Model jets are primarily at high $|\eta|$, new physics may be more central
- Define centrality ratio

$$R_\eta = \frac{N_{jj}(|\eta| < 0.7)}{N_{jj}(0.7 < |\eta| < 1.3)}$$

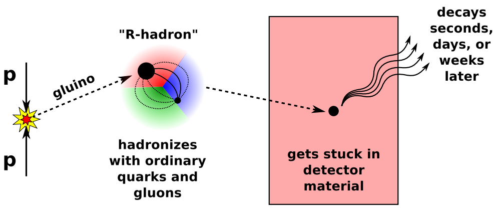
where $N_{jj}(\cdot)$ is the number of events with both leading jets in the specified range

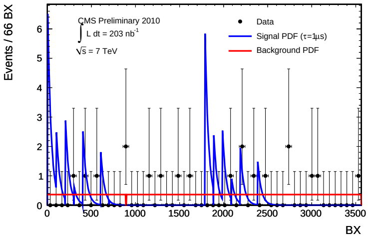
- Contact interaction $\Lambda < 4.0$ TeV at 95% C.L. where effective Lagrangian

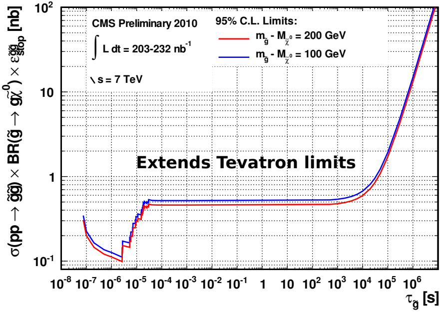
$$\mathcal{L}_{\text{eff}} = \frac{2\pi}{\Lambda^2}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma^\mu q_L)$$

- Extends limits; submitted to PRL (hep-ex/1010.4439)

Stopped *R*-hadrons





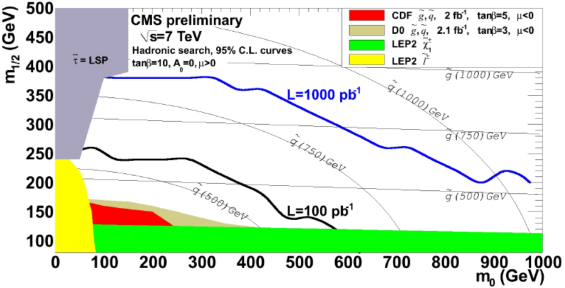


- 19 events observed in 115 hours of LHC operation (above) are consistent with expected backgrounds
- Model-independent limits over 14 orders of magnitude in gluino lifetime (left)
- $m_{\tilde{g}} < 229$ (225) GeV$/c^2$ with a lifetime of 200 ns (2.6 μs) excluded

Other exotica results

- Heavy, stable charged particles: identify tracks belonging to new, slow-moving ($\beta \lesssim 1$) particles by their energy loss (dE/dx)
  - observed 0 events with 0.1 expected background (0.198 pb^{-1})
- Leptoquarks: search for pairs of particles carrying both lepton number and baryon number: $\overline{\mathrm{LQ}}\,\mathrm{LQ} \to e\bar{q}\,eq$
  - see Dinko Ferencek's talk
- Extra dimensions from $G^* \to \gamma\gamma$: spin-2 graviton can decay into two spin-1 bosons; clean signature
  - see Duong Hai Nguyen's talk
- Many others in progress

- Many different signal topologies, all requiring 100 pb^{-1} or more

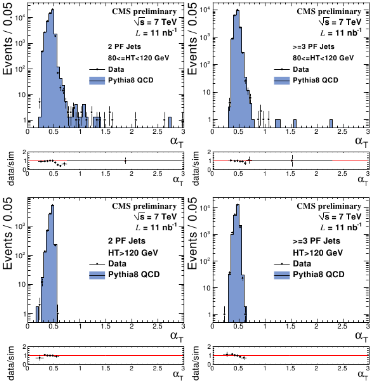


Watchmen, 1987

- Developing a toolbox of techniques and studying QCD backgrounds with existing data
  - high-$\not{E}_T$ tail, isolation, muons from decays in flight...
  - verifying discriminating power of kinematic variables

Beyond the Standard Model

Supersymmetry example



- Data/MC comparison of $\alpha_T = p_{T2}/M_T$ where p_{T2} is the second-highest jet momentum (with an extension to N-jets)
- Complementary to $H_T = \sum_i^{\text{jets}} p_{Tj}$
- Strong (4 orders of magnitude) supression of backgrounds in $\alpha_T > 0.55$ region

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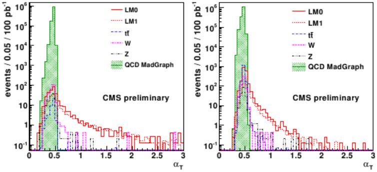


- MC study from a different paper, different cuts ($H_T > 350$ GeV$/c$; tighter)
- Typical SUSY signals dominate in $\alpha_T > 0.55$ region

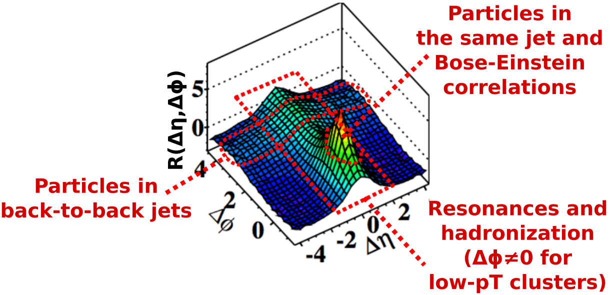
Expect the unexpected

- Unexpected *physical* effect observed in min-bias track correlations
- Definition of the correlation function:

$$R(\Delta\eta, \Delta\phi) = \left\langle (\langle N \rangle - 1) \left(\frac{S_N(\Delta\eta, \Delta\phi)}{B_N(\Delta\eta, \Delta\phi)} - 1 \right) \right\rangle_{\text{bins}}$$

$$S_N(\Delta\eta, \Delta\phi) = \frac{1}{N(N-1)} \frac{d^2 N^{\text{signal}}}{d\Delta\eta d\Delta\phi}, \; B_N(\Delta\eta, \Delta\phi) = \frac{1}{N^2} \frac{d^2 N^{\text{mixed}}}{d\Delta\eta d\Delta\phi}$$

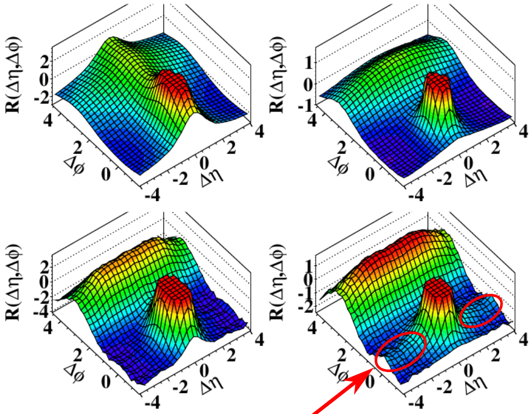
- Interpretation of the major features:



pT > 0.1 GeV/c **1 < pT < 3 GeV/c**

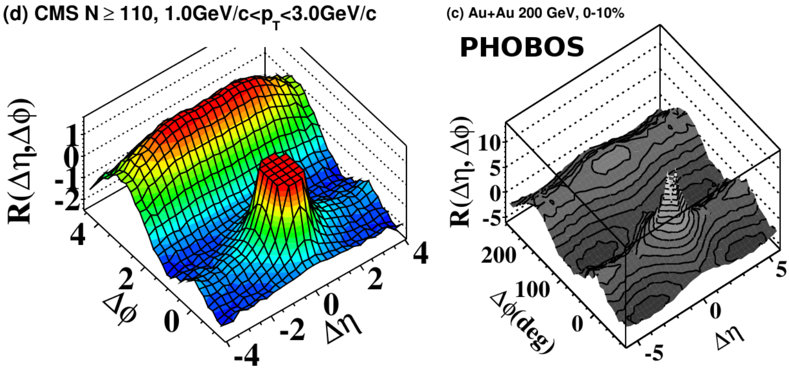
generic min-bias

high-multiplicity events (N ≥ 110)



unexpected qualitative feature

- This structure resembles features observed in heavy ion experiments
- *But the physical origin of our observation is not yet understood*



- hep-ex/1009.4122

“The triumph of optimism”

- Conventional wisdom: “be wary of techniques that rely on a detailed understanding of the detector until the experiment has become mature…” Things like
  - material budget
  - alignment
  - *b*-tagging
  - particle flow
  - missing energy
- But the start-up has been a lot smoother than anticipated, with many features well-described by simulation very early

The triumph of optimism

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  - material budget
  - alignment
  - *b*-tagging
  - particle flow
  - missing energy
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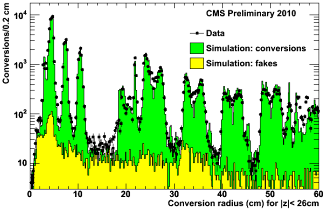
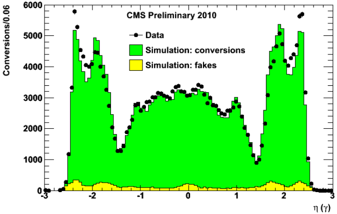
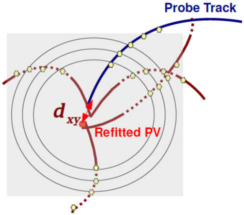
- For example, material budget (as seen by γ-conversions):

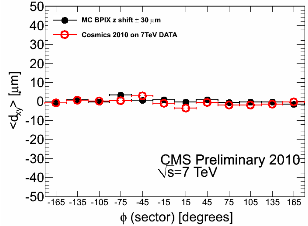




- Alignment had an extra year to improve with cosmics, so test the Cosmics Alignment with the primary vertex:



Fit the vertex with $N-1$ tracks, plot distance of closest approach of the probe track



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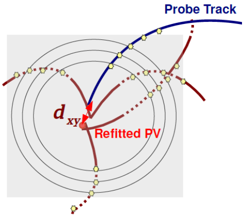

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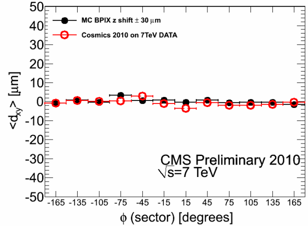
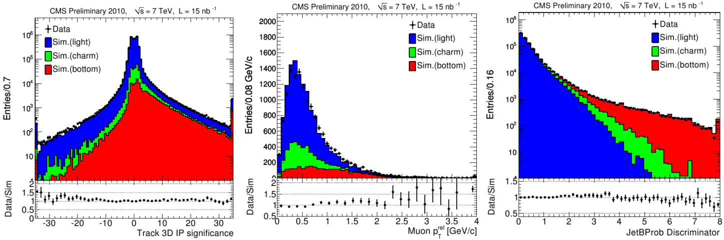
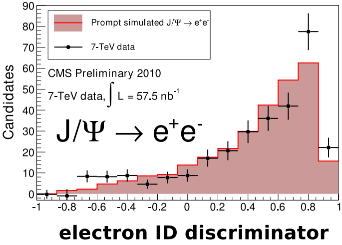


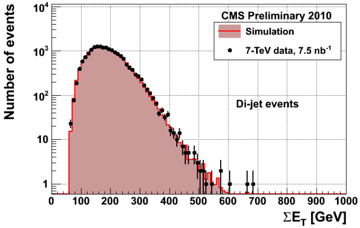
- ...which is useful for b-tagging:



The triumph of optimism

- Particle flow:





The triumph of optimism

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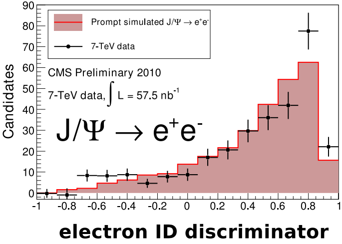
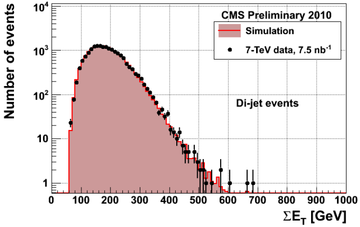
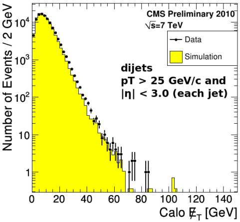
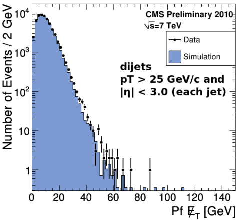
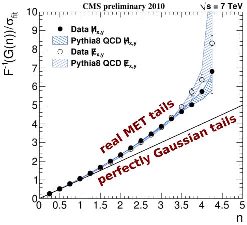




- ...which is useful for missing energy:







Conclusions

- Expectations for the first year of LHC physics were not set too high:
  - CMS followed the rapid rise in LHC luminosity, having collected over 40 pb^{-1} of quality data (and counting)
  - the Standard Model was rediscovered quickly; top quarks *do* exist in Europe
  - exotica searches that rely on high center-of-mass energy are already extending world limits
  - the feature in two-particle correlations was unexpected, perhaps the first taste of surprises yet to come
- In many ways, the 2010 results and maturity of the detector exceeded even the most optimistic expectations for the first physics run of the LHC
- Soon we will be entering the SUSY/Higgs-search era: looking forward to the resolution of 30 years of anticipation...