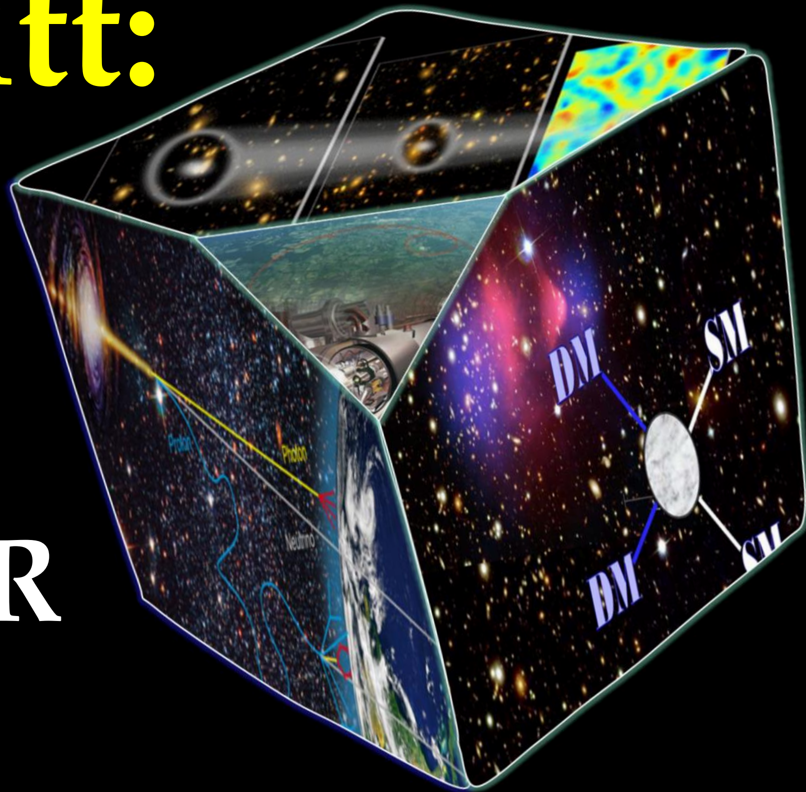
Arnowitt:

HUNT FOR DARK MATTER



[Credits]

- Images of Baryon Acoustic Bscillations with Cosmic Microwave Background by E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian (Lawrence Berkeley National Laboratory)
- Image of Neutrino Astrophysics, taken from https://astro.desy.de/
- Image of the LHC by CERN Photo
- Image of Bullet Cluster by NASA/ Chandra X-ray Center

Teruki Kamon[1),2)]

1) Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University

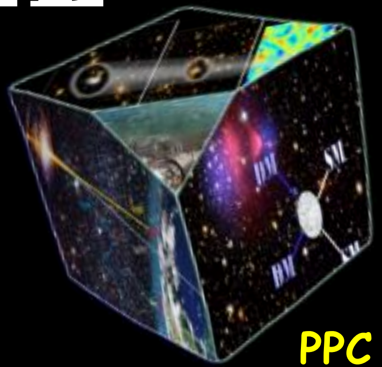
2) Kyungpook National University

Arnowitt Symposium

May 18, 2015

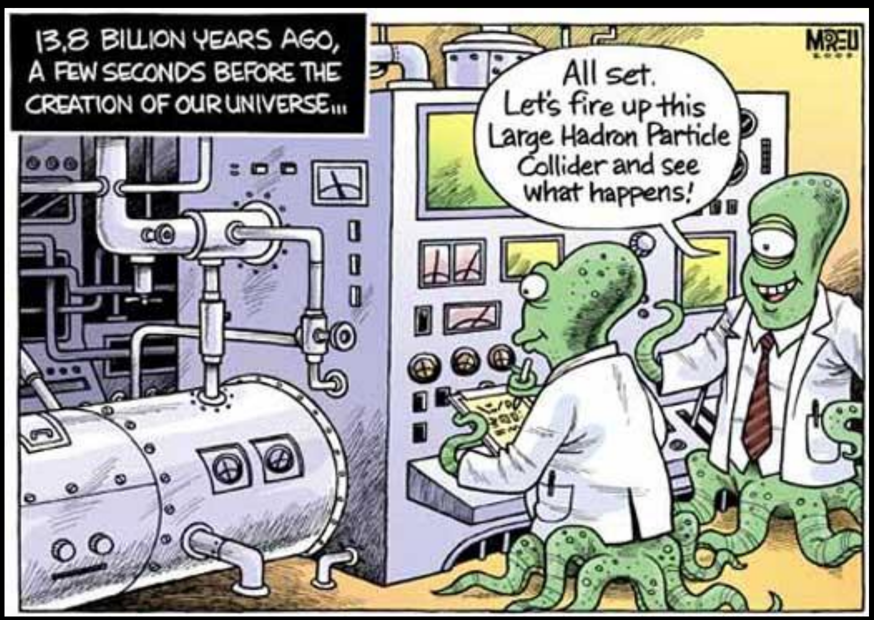
ARNOWITT-LINE^3

1) PHENO Projects
2) PPC
3) Chasing DM Signals



PPC Cube

Prologue



It has been 13.8 B years, since the LHC machine was set up. The LHC started taking data from proton-proton collisions at a center-of-mass energy of 7 TeV on March 30, 2010 and became the energy frontier machine to lead to discoveries such as 125-GeV Higgs boson in July 4, 2012).

The Standard Model is currently well tested up to ~100 GeV, but is expected to break down in the TeV domain where new physics should occur. This is precisely the domain that we will study at the LHC.

[1] PHENO Projects

Our PHENO projects have begun with his simple questions:

(a) how well mSUGRA models can be tested experimentally;

(b) how cosmologically-consistent collider signals can be determined.

This also helps us shaping up ideas of accelerator upgrades in the U.S.

The choice of PHENO project topics has been evolving as major scientific events occurred:

i) SSC was cancelled in 1993
ii) WMAP results were out in 2002.
iii) The Higgs boson was discovered in 2012.

Year	Publication
1993	**SSC, cancelled**
1994	(1) T. Kamon, J. Lopez, P. McIntyre, J. White, "Supersymmetry at a proposed $\sqrt{s}$ = 4 TeV upgrade of the Fermilab Tevatron", Phys. Rev. D50 (1994) 5676 (**R. Arnowitt** in acknowledgement)
1996	(2) **TeV2000 Study Group**, "Future Electroweak Physics at the Tevatron", FERMILAB-PUB-96-82 (unpublished)
1999	(3) P. McIntyre, E. Accomando, **R. Arnowitt**, B. Dutta, T. Kamon, and A. Sattarov, "The Tevatron Tripler: How to Upgrade the Fermilab Tevatron for the Higgs Boson and Supersymmetry," hep-ex/9908052 (unpublished)
2000	(4) **SUGRA Working Group** (S. Abel et al.), "Report of the SUGRA Working Group for Run II of the Tevatron", FERMILAB-PUB-00-386-T, hep-ph/0003154 (unpublished)
2001	(5) V. Krutelyov, **R. Arnowitt**, B. Dutta, T. Kamon, P. McIntyre, and Y. Santoso, "Prospect for Searches for Gluinos and Squarks at a Tevatron Tripler", Phys. Lett. B 505 (2001) 161.
2002	**WMAP**
2002	(6) **R. Arnowitt**, B. Dutta, T. Kamon, and M. Tanaka, "Detection of $B_s \to \mu^+\mu^-$ at the Tevatron Run II and Constraints on the SUSY Parameter Space," Phys. Lett. B 538 (2002) 121
2005	(7) V. Khotilovich, **R. Arnowitt**, B. Dutta, and T. Kamon, "The Stau Neutralino Co-annihilation Region at an International Linear Collider" Phys. Lett. B 618 (2005) 182
2006	(8) **R. Arnowitt**, B. Dutta, T. Kamon, N. Kolev, and D. Toback, "Detection of SUSY in the Stau-Neutralino Coannihilation Region at the LHC," Phys. Lett. B 639 (2006) 46
2007	(9) **R. Arnowitt**, A. Aurisano, B. Dutta, T. Kamon, N. Kolev, P. Simeon, D. Toback, and P. Wagner, "Indirect Measurements of the $\tilde{\tau}_1 - \tilde{\chi}_1^0$ Mass Difference and $M_{\tilde{g}}$ in the Co-annihilation Region of mSUGRA Models at the LHC," Phys, Lett. B. 649 (2007) 73
2008	(10) **R. Arnowitt**, B. Dutta, A. Gurrola, T. Kamon, A. Krislock, and D. Toback, "Determining the Dark Matter Relic Density in the Minimal Supergravity Stau-Neutralino Coannihilation Region at the Large Hadron Collider," Phys. Rev. Lett. 100 (2008) 231802

2009	(11) B. Dutta, A. Gurrola, T. Kamon, A. Krislock, D. Nanopoulos, A.B. Lahanas, and N.E. Mavromatos, "Supersymmetry Signals of Supercritical String Cosmology at the Large Hadron Collider," Phys. Rev. D 79 (2009) 055002
2010	(12) B. Dutta, T. Kamon, A. Krislock, N. Kolev, and Y. Oh, "Determination of Non-universal Supergravity Models at the Large Hadron Collider," Phys. Rev. D 82 (2010) 115009
2011	(13) B. Dutta, T. Kamon, A. Krislock, and N. Kolev, "Bi-Event Subtraction Technique at the Large Hadron Collider," Phys. Lett. B 703 (2011) 475
2012	**Higgs Boson**
2012	(14) B. Dutta, T. Kamon, A. Krislock, K. Sinha, and K. Wang, "Diagnosis of Supersymmetry Breaking Mediation Schemes by Mass Reconstruction at the LHC," Phys. Rev. D 85 (2012) 115007. (15) R. Allahverdi, B. Dutta, T. Kamon, A. Krislock, and K. Sinha, "Lepton Flavor Violation at the Large Hadron Collider," Phys. Rev. D 86 (2012) 015026 (16) B. Dutta, T. Kamon, N. Kolev, K. Sinha, and K. Wang, "Searching for Top Squarks at the LHC in Fully Hadronic Final State," Phys. Rev. D 86 (2012) 075004
2013	(17) B. Dutta, A. Gurrola, W. Johns, T. Kamon, P. Sheldon, and K. Sinha, "Vector Boson Fusion Processes as a Probe of Supersymmetric Electroweak Sectors at the LHC", Phys. Rev. D 87 (2013) 035029 (18) B. Dutta, T. Kamon, N. Kolev, K. Sinha, K. Wang, and S. Wu, "Top Squark Searches using Dilepton Invariant Mass Distributions and Bino-Higgsino Dark Matter at the LHC," Phys. Rev. D 87 (2013) 095007. (19) A.G. Delannoy, B. Dutta, A. Gurrola, W. Johns, T. Kamon, E. Luiggi, A. Melo, P. Sheldon, K. Sinha, K. Wang, and S. Wu, "Probing Dark Matter at the LHC using Vector Boson Fusion Processes," Phys. Rev. Lett. 111 (2013) 061801.
2014	(20) B. Dutta, Y. Gao, and T. Kamon, "Probing Light Nonthermal Dark Matter at the LHC", Phys. Rev. D 88 (2014) 096009 (21) B. Dutta, R. Eusebi, Y. Gao, T. Ghosh, and T. Kamon, "Exploring the Doubly Charged Higgs Boson of the Left-Right Symmetric Model using Vector Boson Fusionlike Events at the LHC", Phys. Rev. D 90 (2014) 055015. (22) B. Dutta, W. Flanagan, A. Gurrola, W. Johns, T. Kamon, P. Sheldon, K. Sinha, K. Wang, and S. Wu, "Probing Compressed Top Squarks at the LHC at 14 TeV", Phys. Rev. D 90 (2014) 095022.

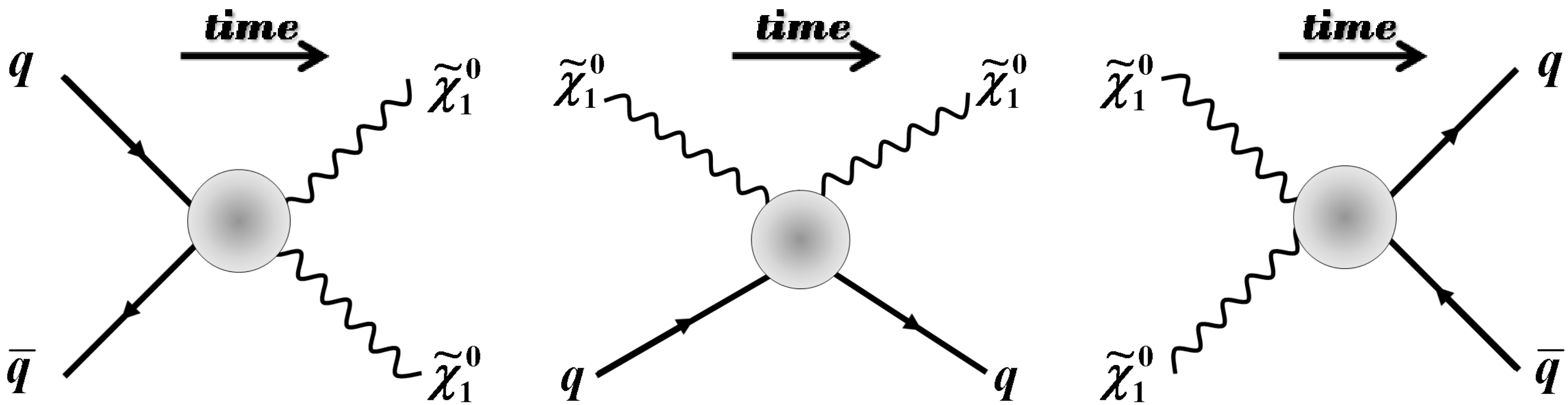
2015	(23) B. Dutta, T. Ghosh, A. Gurrola, W. Johns, T. Kamon, P. Sheldon, K. Sinha, K. Wang, and S. Wu, "Probing Compressed Sleptons at the LHC using Vector Boson Fusion Processes", Phys. Rev. D 91 (2015) 055025.

PHENO projects continue…

1.	SSC was cancelled in 1993	2 paper, 2 WG Reports, 1 Pre-print
2.	WMAP results were out in 2002	8 papers
3.	The Higgs boson was discovered in 2012	10 papers
4.	13-TeV LHC Run in 2015	Counting …

[2] Interconnection between …

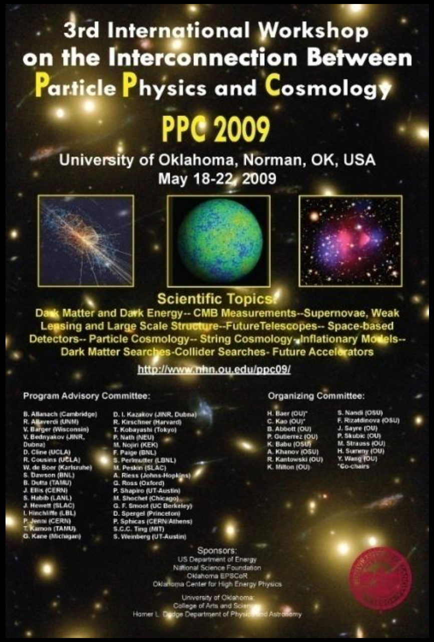
He wanted to listen to most recent results from both sides at the same conference. This is how we started International Workshop on the Interconnection between Particle Physics and Cosmology (PPC).



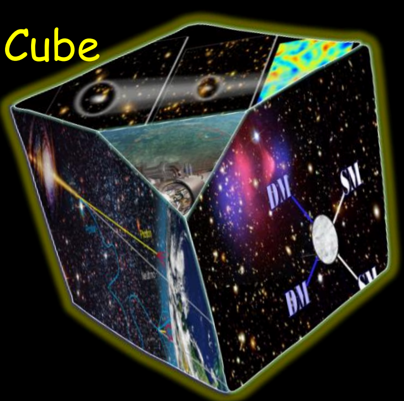
"Interconnection" between particles and dark matter

PPCs

Interconnection between Particle Physics and Cosmology

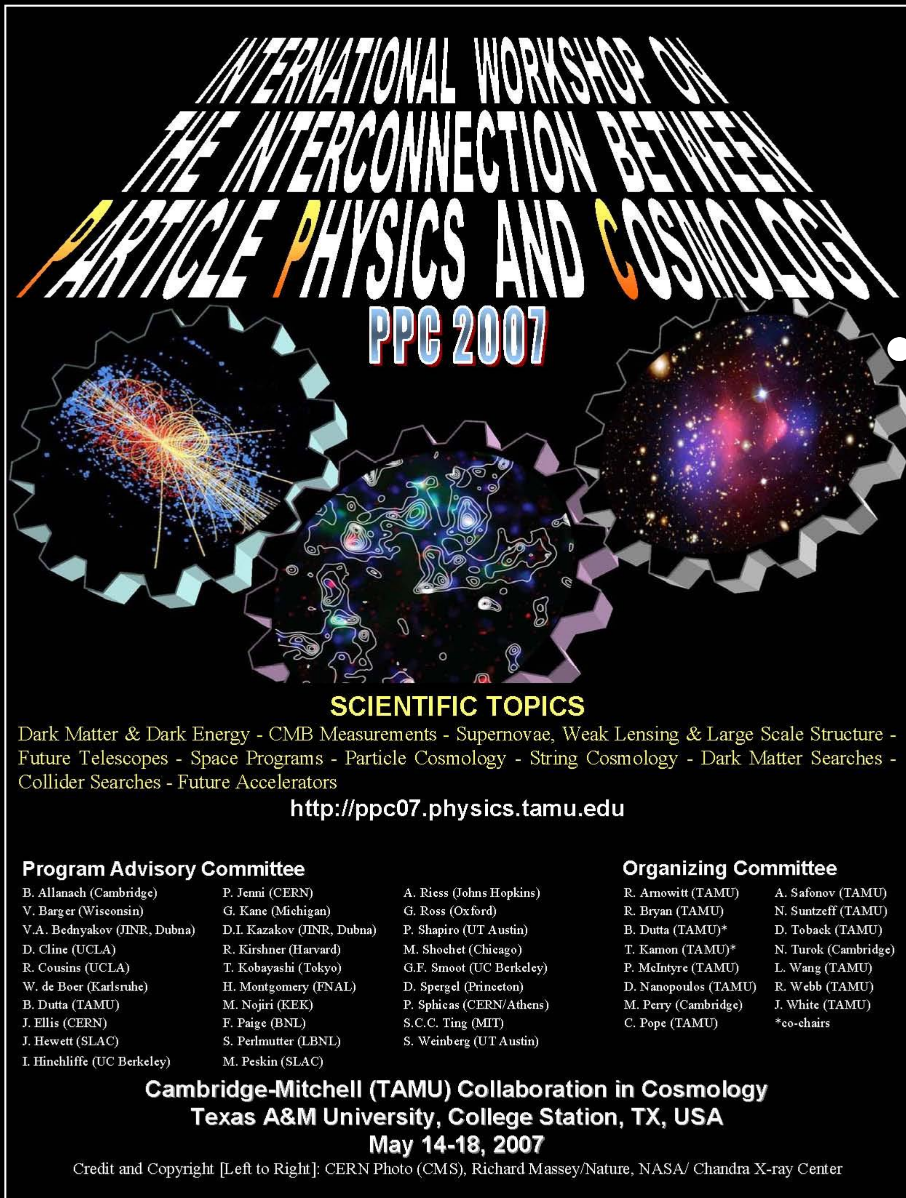


PPC Cube

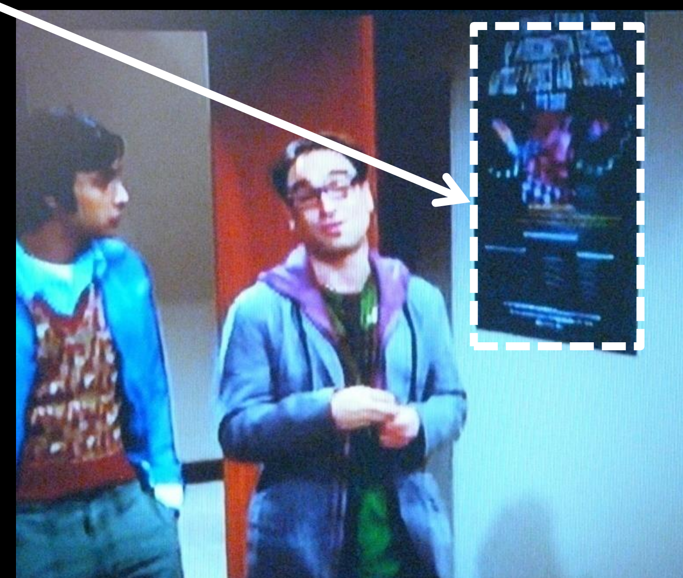


- PPC 2011 at CERN, June 14-18
- PPC 2012 at KIAS, Korea, Nov. 5-9
- PPC 2013 at CETUP*, SD, USA, July 8-13
- PPC 2014 at Univ. de Guanajuato, Mexico, June 23-27
- PPC 2015 at CETUP*, SD, USA, June 28 - July 3
- PPC 2016 at Brazil
- PPC 2017 at ???

Outreach: Big Bang Theory



CBS comedy "Big Bang Theory" (Season 1 Episode 15)

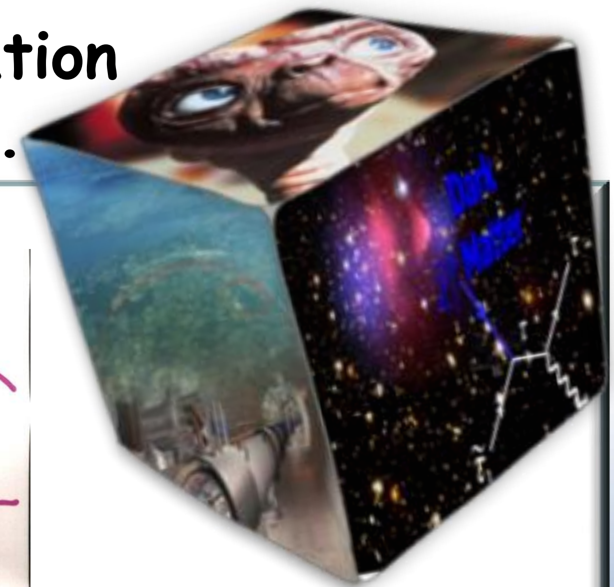


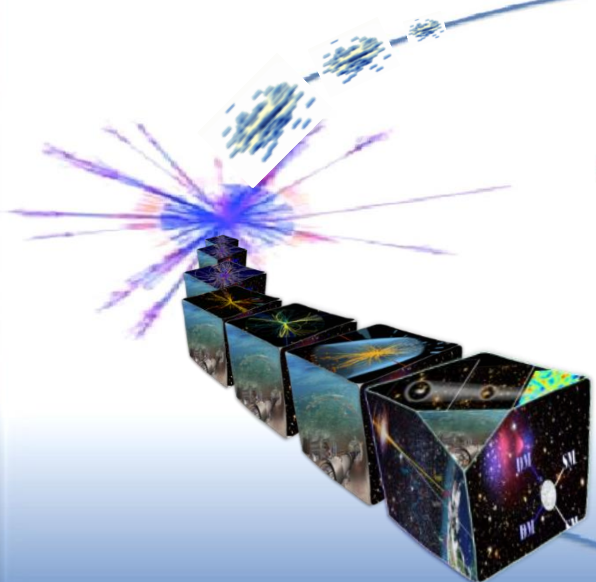
The poster was designed during lunch meetings with him…

[3] ET Collaboration & DM Signals

He was always chasing the signals of models. The story began with the Tevatron. However, the LHC changed a landscape of how to search new physics. It is a BIG thinking machine.

Experimentalist-Theorist (ET) collaboration helps to solve the "dark matter" puzzle.



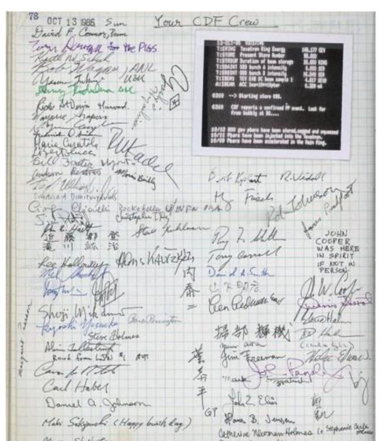


Even my daughter was influenced, and drawing "Texas-style SUSY hunting" in 2007.

1980's

My advisor, Kunitaka Kondo, was smiling and exciting, by saying "Kamon-kun, there is an interesting theory." It was "Supersymmetry". But I didn't pay attention much until 1990's.

- ❖ Supersymmtery at Snowmass workshop (1982)
- ❖ A.H. Chamseddine, R. Arnowitt, and P. Nath, PRL 49 (1982) 970; R. Arnowitt, A.H. Chamseddine, P. Nath, "The Development of Supergravity Grand Unification: Circa 1982-85", Int. J. Mod. Phys. A27 (2012) 1230028
- ❖ October 1986: First p-pbar collisions at 1.6 TeV



1990's

R. Arnowitt and D. Nanopoulos suggested to search for "tri-lepton" events as a SUSY signature at the Tevatron.

- Possible indication of grand unification with MSSM based on LEP data:
  - ✓ The LEP Collaborations, "Electroweak Parameters of the Z Resonance and the Standard Model, PLB 276 (1992) 247.
  - ✓ Ugo Amaldi, Wim de Boer, Hermann Furstenau, "Comparison of grand unified theories with electroweak and strong coupling constants measured at LEP," Phys. Lett. B 260 (1991) 447.
- My first SUSY analysis at CDF
- SSC was cancelled ('93) → DiTevatron (PRD 50 (1994) 5676) → Tripler ('01)
- March 1995: Discovery of top quark

1993	**SSC, cancelled**
1994	(1) T. Kamon, J. Lopez, P. McIntyre, J. White, "Supersymmetry at a proposed $\sqrt{s}$ = 4 TeV upgrade of the Fermilab Tevatron", Phys. Rev. D50 (1994) 5676 (**R. Arnowitt** in acknowledgement)
1996	(2) **TeV2000 Study Group**, "Future Electroweak Physics at the Tevatron", FERMILAB-PUB-96-82 (unpublished)

Phys. Rev. D50 (1994) 5676

ACKNOWLEDGMENTS

This work has been supported in part by DOE Grant No. DE-FG05-91-ER-40633. We would like to thank Dick Arnowitt for many suggestions and comments and for reading the manuscript. We thank Gerry Jackson, Jim Strait, and John Tompkins for discussions on magnet and accelerator issues. We also thank Howie Baer, Steve Mrenna, Xerxes Tata, and S. Willenbrock for useful discussions.

APPENDIX A: THE DITEVATRON

The Tevatron is the highest energy collider in the world today. The recently reported evidence for the top quark was only possible because of the energy reach of the Tevatron: its discovery at a lower collision energy would have been unthinkable, even with arbitrarily high luminosity. The Tevatron's single magnet ring produces collisions of protons and antiprotons at $\sqrt{s} = 1.8$ TeV. The superconducting magnets of the ring operate at a field strength of 4.1 T at the peak beam energy of 900 GeV. The Tevatron is itself an upgrade of the original Main Ring at Fermilab, which accelerated beams of protons to 400 GeV for fixed target experiments. The luminosity of the Tevatron is currently being upgraded to 10^{32} cm^{-2} s^{-1}.

The crowning success of the ill-fated Superconducting Super Collider was the development to production readiness of a 6.5 T superconducting dipole and corresponding quadrupole. A string of these magnets were operated successfully at this field at 4.2° K, validating the magnet technology required for SSC. The same magnets were also operated at 2° K, producing a field of 8.8 T. A ring of such magnets, placed in the existing Fermilab tunnel, could use the same source and the Tevatron as injector, and produce collisions at $\sqrt{s} = 4$ TeV—the DiTevatron. The beams adiabatically damp as they are accelerated, so that the DiTevatron luminosity would be

Luminosity vs. Energy

FERMILAB-Conf-94/249
hep-ex/9408005

TEVATRON ENERGY AND LUMINOSITY UPGRADES BEYOND THE MAIN INJECTOR

D. AMIDEI[c], A. BADEN[b], G. W. FOSTER[a], G.P. JACKSON[a], T. KAMON[d], J.L. LOPEZ[d], P. MCINTYRE[d], J. STRAIT[a], and J. WHITE[d]

[a] *Fermi National Accelerator Laboratory*
[b] *Department of Physics, University of Maryland*
[c] *Department of Physics, University of Michigan*
[d] *Department of Physics, Texas A&M University*

US Rep.(D-IL 11th District)

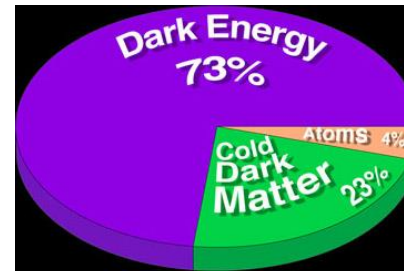
Abstract

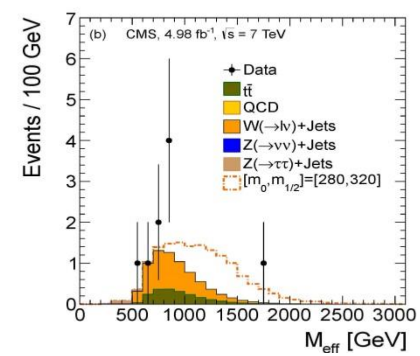
The Fermilab Tevatron will be the world's highest energy hadron collider until the LHC is commissioned, it has the world's highest energy fixed target beams, and Fermilab will be the leading high energy physics laboratory in the US for the foreseeable future. Following the demise of the SSC, a number of possible upgrades to the Tevatron complex, beyond construction of the Main Injector, are being discussed. Using existing technology, it appears possible to increase the luminosity of the $\bar{p}p$ Collider to at least 10^{33}cm^{-2}sec^{-1} (TevatronStar) and to increase the beam energy to 2 TeV (DiTevatron). Fixed target beam of energy about 1.5 TeV could also be delivered. Leaving the existing Tevatron in the tunnel and constructing bypasses around the collider halls would allow simultaneous 800 GeV fixed target and $\sqrt{s} = 4$ TeV collider operation. These upgrades would give Fermilab an exciting physics program which would be complementary to the LHC, and they would lay the groundwork for the construction of a possible post-LHC ultra-high energy hadron collider.

2000's

R. Arnowitt and B. Dutta suggested (i) $B_s \rightarrow \mu\mu$ search at the Tevatron (2002); (ii) stau-neutralino coannihilation search at the LHC (2004).

- ❖ WMAP results (2002) → Ω_{DM} = 23%
- ❖ Pheno papers (2002, 2006, …)
- ❖ My first B physics paper at CDF (2004)
- ❖ December 2005: Joined CMS
- ❖ June 2007: International Workshop on the Interconnection between Particle Physics and Cosmology.
- ❖ September 2008: First Beams in the LHC
- ❖ November 2009: LHC's First 900-GeV pp Collisions
- ❖ My first stau-neutralino paper at CMS (2013)





A Story of Rare B_s Meson Decay

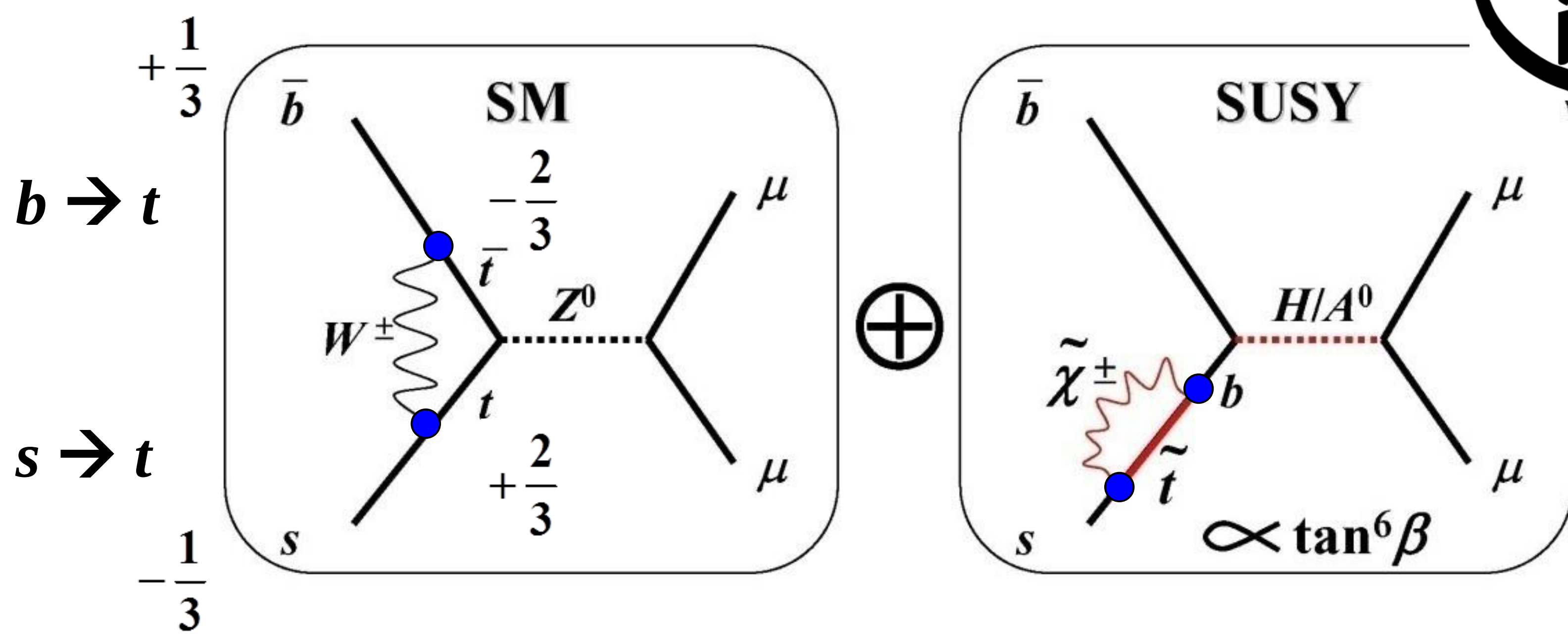
Detection of $B_s \to \mu^+\mu^-$ at the tevatron Run II and constraints on the SUSY parameter space

PLB 538 (2002) 121

R. Arnowitt [a], B. Dutta [a], T. Kamon [a], M. Tanaka [b]

[a] *Department of Physics, Texas A&M University, College Station, TX 77843-4242, USA*
[b] *Argonne National Laboratory, Argonne, IL 60439, USA*

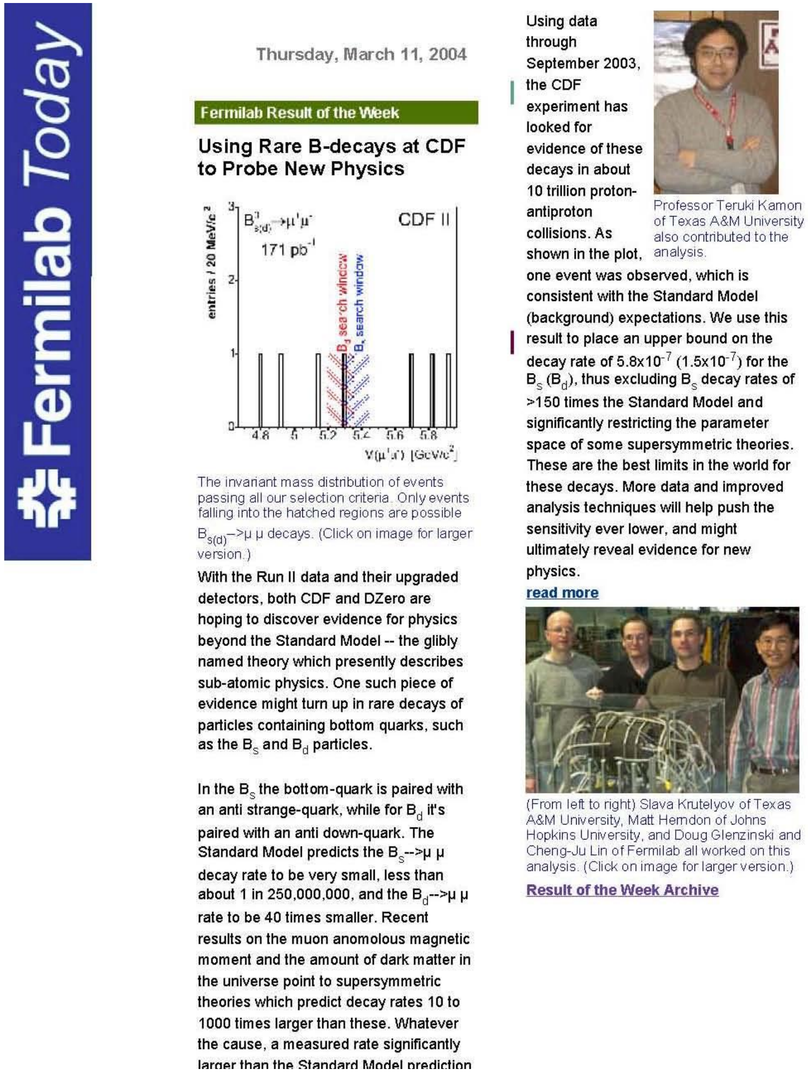
Received 18 March 2002; received in revised form 14 April 2002; accepted 15 April 2002



1st Round Analysis

2002 → 2013

PRL 93 (2004) 032001



Fermilab Today

Thursday, March 11, 2004

Fermilab Result of the Week

Using Rare B-decays at CDF to Probe New Physics

The invariant mass distribution of events passing all our selection criteria. Only events falling into the hatched regions are possible $B_{s(d)} \to \mu\mu$ decays. (Click on image for larger version.)

With the Run II data and their upgraded detectors, both CDF and DZero are hoping to discover evidence for physics beyond the Standard Model -- the glibly named theory which presently describes sub-atomic physics. One such piece of evidence might turn up in rare decays of particles containing bottom quarks, such as the B_s and B_d particles.

In the B_s the bottom-quark is paired with an anti strange-quark, while for B_d it's paired with an anti down-quark. The Standard Model predicts the $B_s \to \mu\mu$ decay rate to be very small, less than about 1 in 250,000,000, and the $B_d \to \mu\mu$ rate to be 40 times smaller. Recent results on the muon anomolous magnetic moment and the amount of dark matter in the universe point to supersymmetric theories which predict decay rates 10 to 1000 times larger than these. Whatever the cause, a measured rate significantly larger than the Standard Model prediction

Using data through September 2003, the CDF experiment has looked for evidence of these decays in about 10 trillion proton-antiproton collisions. As shown in the plot, one event was observed, which is consistent with the Standard Model (background) expectations. We use this result to place an upper bound on the decay rate of 5.8×10^{-7} (1.5×10^{-7}) for the B_s (B_d), thus excluding B_s decay rates of >150 times the Standard Model and significantly restricting the parameter space of some supersymmetric theories. These are the best limits in the world for these decays. More data and improved analysis techniques will help push the sensitivity ever lower, and might ultimately reveal evidence for new physics.

read more

Professor Teruki Kamon of Texas A&M University also contributed to the analysis.

(From left to right) Slava Krutelyov of Texas A&M University, Matt Herndon of Johns Hopkins University, and Doug Glenzinski and Cheng-Ju Lin of Fermilab all worked on this analysis. (Click on image for larger version.)

Result of the Week Archive

170 pb^{-1} ~ 8.5 x 10^{12} collisions

PLB 538 (2002) 121

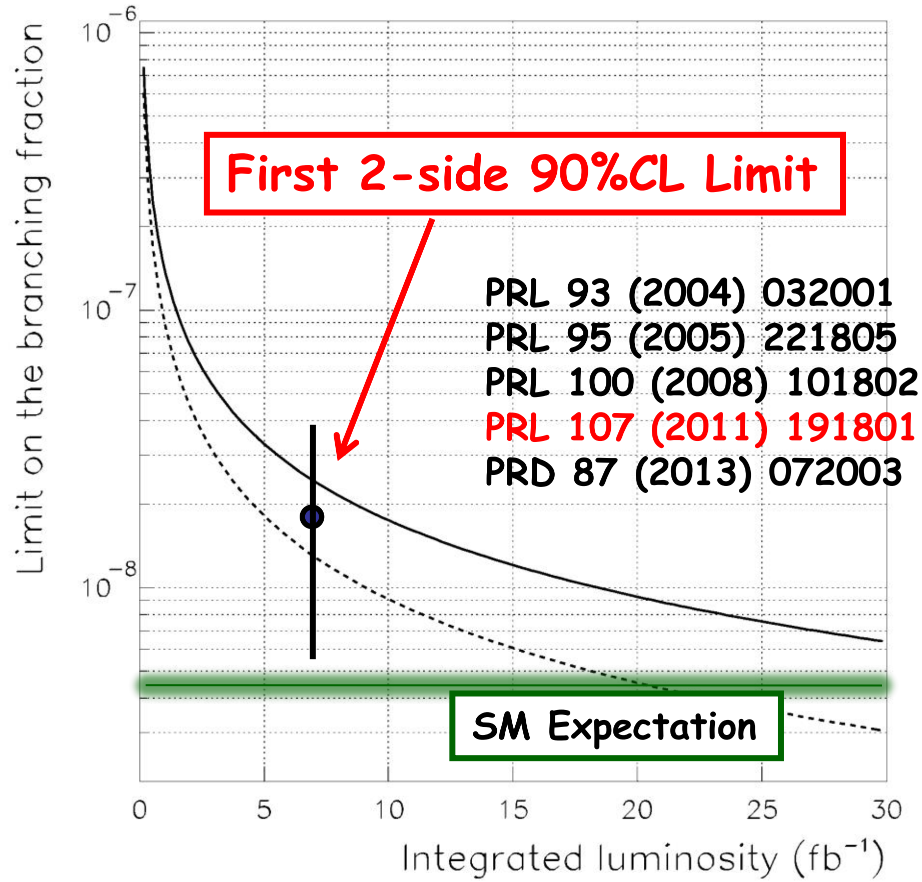


Fig. 2. Illustrated 95% C.L. limits on the branching ratio for $B_s \to \mu^+\mu^-$ at CDF in Run II as a function of integrated luminosity. Solid (Case A) and dashed (Case B) curves are based on different assumptions on the signal selection efficiency and the background rejection power. See the text for details.

2011.07.13

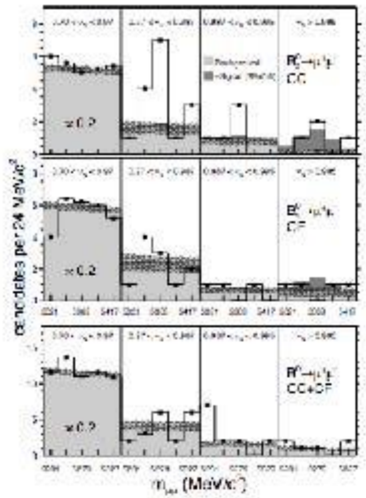
Additional news on $B_s \to \mu^+\mu^-$ (LHCb and CDF)

LHCb will unblind their analysis at the end of this week.

PRL 107 (2011) 191801

New paper from CDF *Search for B_s --> mu+mu- and B_d --> mu+mu- Decays.*
Submitted on 12 Jul 2011 arXiv:1107.230

A search has been performed for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays using 7 fb^{-1} of integrated luminosity collected by the CDF II detector at the Fermilab Tevatron collider. The observed number of B^0 candidates is consistent with background-only expectations and yields an upper limit on the branching fraction of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.0 \times 10^{-9}$ at 95% confidence level. We observe an excess of B_s^0 candidates. The probability that the background processes alone could produce such an excess or larger is 0.27%. The probability that the combination of background and the expected standard model rate of $B_s^0 \to \mu^+\mu^-$ could produce such an excess or larger is 1.9%. These data are used to determine $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ and provide an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% confidence level.



CDF

We expect that combining
sensitive enough to check
the combination to be sho
experiments will definitely

PRL 107 (2011) 191802

PRL 107, 191802 (2011) PHYSICAL REVIEW LETTERS week ending 4 NOVEMBER 2011

Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ Decays in pp Collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.*[*]
(CMS Collaboration)

CMS (7 TeV)

(Received 29 July 2011; published 1 November 2011)

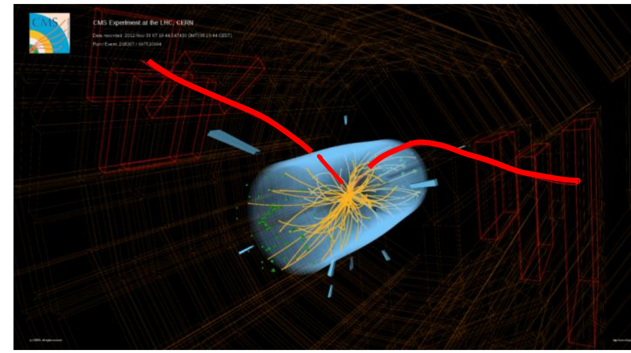
A search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ is performed in pp collisions at $\sqrt{s} =$ 7 TeV, with a data sample corresponding to an integrated luminosity of 1.14 fb^{-1}, collected by the CMS experiment at the LHC. In both cases, the number of events observed after all selection requirements is consistent with expectations from background and standard-model signal predictions. The resulting upper limits on the branching fractions are $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.9 \times 10^{-8}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$, at 95% confidence level.

2013.09.05

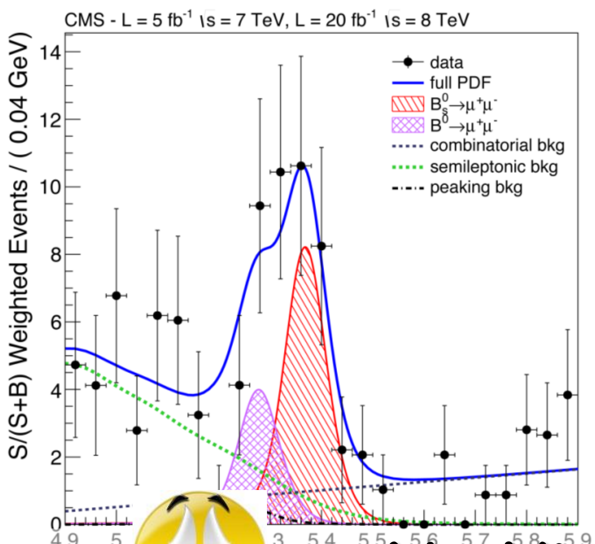
Measurement of the $B_s^0 \to \mu^+\mu^-$ Branching Fraction and Search for $B^0 \to \mu^+\mu^-$ with the CMS Experiment

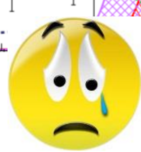
(Received 18 July 2013; published 5 September 2013)

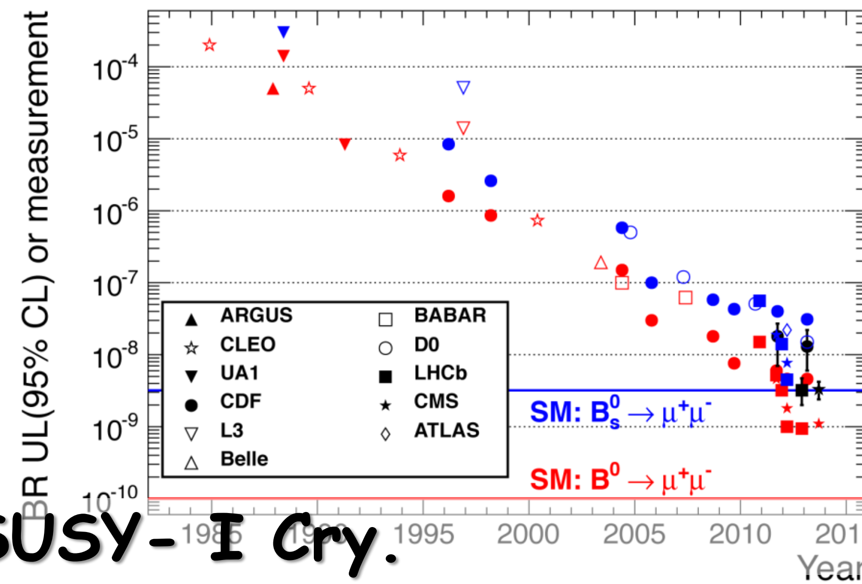
Results are presented from a search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV, with data samples corresponding to integrated luminosities of 5 and 20 fb^{-1}, respectively, collected by the CMS experiment at the LHC. An unbinned maximum-likelihood fit to the dimuon invariant mass distribution gives a branching fraction $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$, where the uncertainty includes both statistical and systematic contributions. An excess of $B_s^0 \to \mu^+\mu^-$ events with respect to background is observed with a significance of 4.3 standard deviations. For the decay $B^0 \to \mu^+\mu^-$ an upper limit of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ at the 95% confidence level is determined. Both results are in agreement with the expectations from the standard model.



PRL 111 (2013) 101804







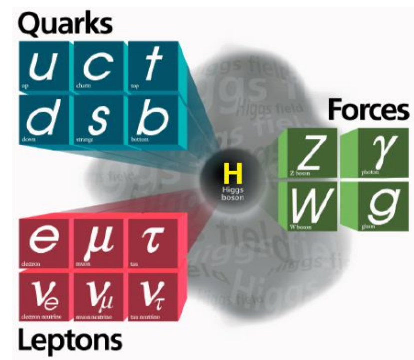
No Hint of SUSY- I Cry.

2010-2014

No hints of SUSY. SUSY (gluino and 1st/2nd gen. squarks) seems to be heavier than ~1.5 TeV.

- ❖ March 2010: First 7-TeV pp collisions

- ❖ December 2011: 3-sigma evidence for Higgs boson; no hint of SUSY
- ❖ July 2012: 5-sigma observation; still no hint of SUSY



- ❖ Sep. 2013: Strong evidence for Bs → μμ

- ❖ Lightest (?) scalar top quark (stop)
- ❖ Compressed chargino/neutralino mass spectra
- ❖ SUSY Higgs bosons

- ❖ Connection to the dark matter

Race to Discover SUSY at 7 TeV

He asked me one thing in 2006: "Teruki, how soon ATLAS and CMS can publish their first papers after the LHC turns on?".

I answered: "It will take 2 years". I was damn wrong.

LHC/ATLAS/CMS Timeline			
2008.09.10	First beam circulations		
2009.11.23	First pp collisions at 900 GeV		
2010.03.30	First pp collisions at 7 TeV		7-TeV pp program ended on Oct 29 (Fri)
2011.03.28	PRL 106 (2011) 131802	ATLAS	MSUGRA/CMSSM
2011.04.06	PLB 698 (2011) 196	CMS	CMSSM
2011.06.01	PLB 701 (2011) 186	ATLAS	MSUGRA/CMSSM
2011.08.31	JHEP 08 (2011) 155	CMS	CMSSM

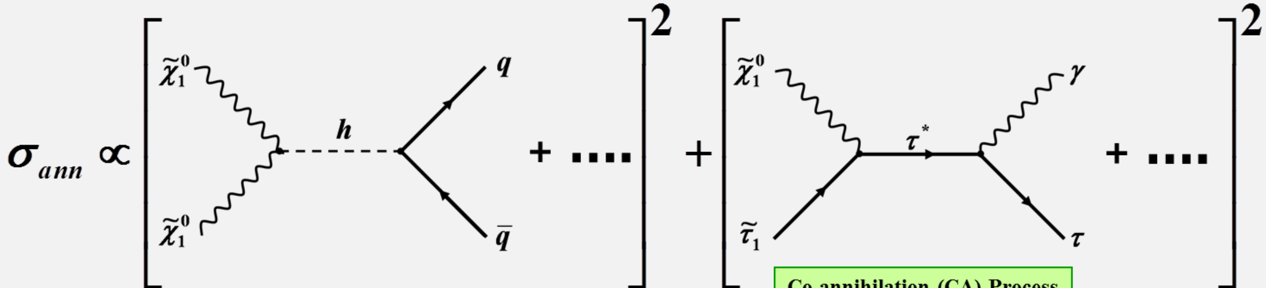
Cosmological Connection: $\Omega_{\chi_1^0} \overset{?}{=} \Omega_{DM}$

"Number" density (n_{DM}) → Ω_{DM}

$$\frac{dn}{dt} = -3Hn - \langle \sigma \cdot v \rangle \left(n^2 - n_{eq}^2\right)$$

$$\underbrace{\Omega_{\tilde{\chi}_1^0} h^2}_{0.27} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{ann} v \rangle} dx$$

Cross section (σ)

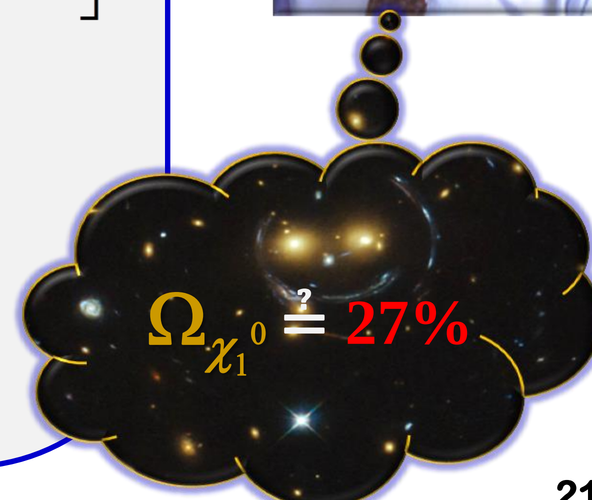


Co-annihilation (CA) Process
(Griest, Seckel '91)

SUSY Masses (at the LHC)

$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathcal{D}(\text{SUSY masses})$$

$$h \equiv H / [100 \ \text{km} \cdot \text{s}^{-1} \text{Mpc}^{-1}]$$



A Story of Coannihilation

March 2004: When the ILC coannihilation "**2tau**" analysis (last presented at ICHEP2004; published in PLB 618 (2005) 182) was near complete, we (R. Arnowitt, B. Dutta, T. Kamon) started thinking of a possibility of detecting the coannihilation signal in "**3tau**" at the LHC. The idea was to capture two χ_2^0's in the final state. → PLB 639 (2006) 46; PLB. 649 (2007) 73; PRL 100 (2008) 231802

MITCHELL SYMPOSIUM ON OBSERVATIONAL COSMOLOGY

Obs. Cosm
Texas A&M
4/16/04

DARK MATTER, PARTICLE PHYSICS AND COSMOLOGY

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B. DUTTA**
T. KAMON*
D. TOBACK*
P. WAGNER*

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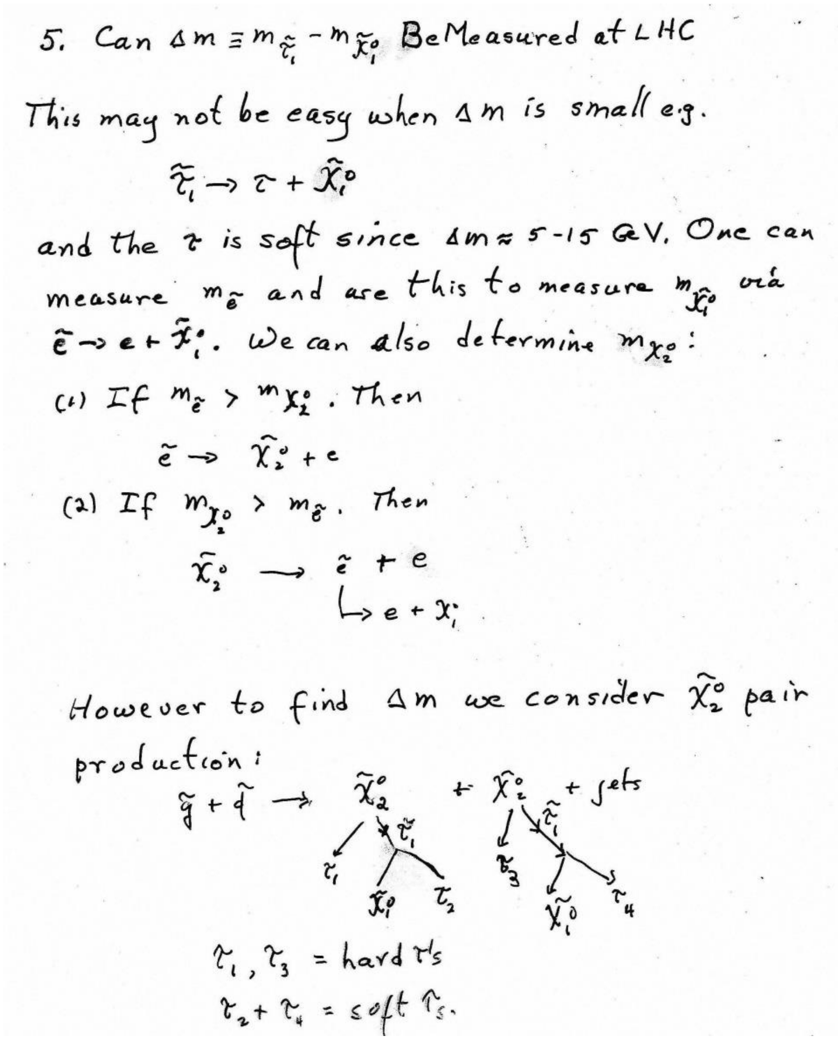
** University of Regina

1. Introduction

Over the past decade, particle physics and cosmology have become deeply interconnected. This has come about due to both theoretical and experimental developments. On the particle physics side, the Standard Model (of three generations of quarks and lepton with SU(3) ×SU(2)×U(1) gauge bosons) was given precision tests at LEP in the 1990's. In cosmology, the ΛCDM (or some quintessence variation) was developed and tested with remarkable accuracy most recently by WMAP.

2004 → 2013



5. Can $\Delta m \equiv m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ Be Measured at LHC

This may not be easy when Δm is small e.g.

$\tilde{\tau}_1 \to \tau + \tilde{\chi}_1^0$

and the τ is soft since $\Delta m \approx 5$-15 GeV. One can measure $m_{\tilde{e}}$ and use this to measure $m_{\tilde{\chi}_1^0}$ via $\tilde{e} \to e + \tilde{\chi}_1^0$. We can also determine $m_{\chi_2^0}$:

(1) If $m_{\tilde{e}} > m_{\chi_2^0}$. Then

$\tilde{e} \to \tilde{\chi}_2^0 + e$

(2) If $m_{\chi_2^0} > m_{\tilde{e}}$. Then

$\tilde{\chi}_2^0 \to \tilde{e} + e$, $\tilde{e} \to e + \chi_1$

However to find Δm we consider $\tilde{\chi}_2^0$ pair production:

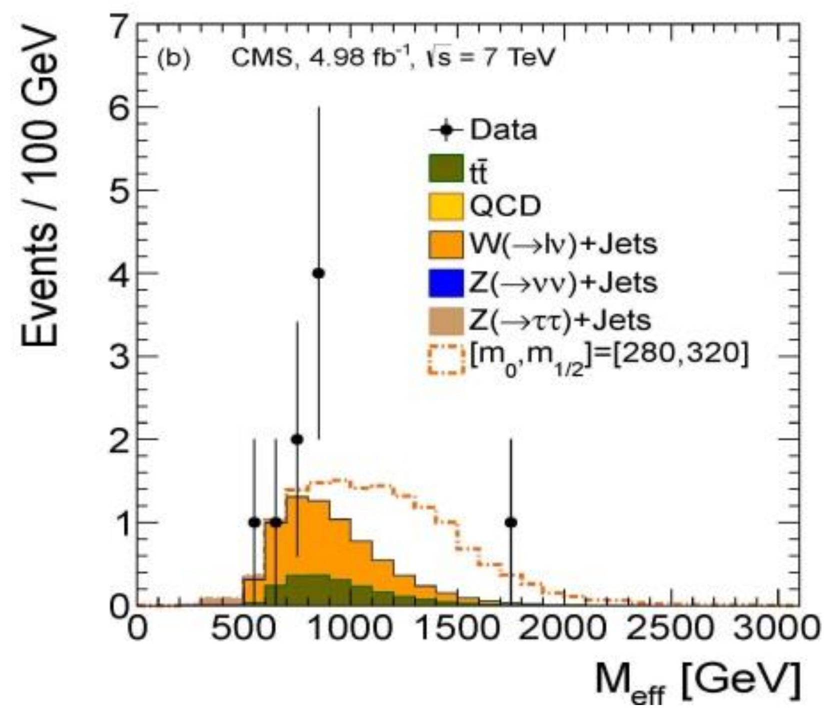
$\tilde{q} + \tilde{q} \to \tilde{\chi}_2^0 + \tilde{\chi}_2^0 + \text{jets}$

τ_1, τ_3 = hard τ's

$\tau_2 + \tau_4$ = soft τ's.

PHENO papers:
PLB 639 (2006) 46;
PLB. 649 (2007) 73;
PRL 100 (2008) 231802

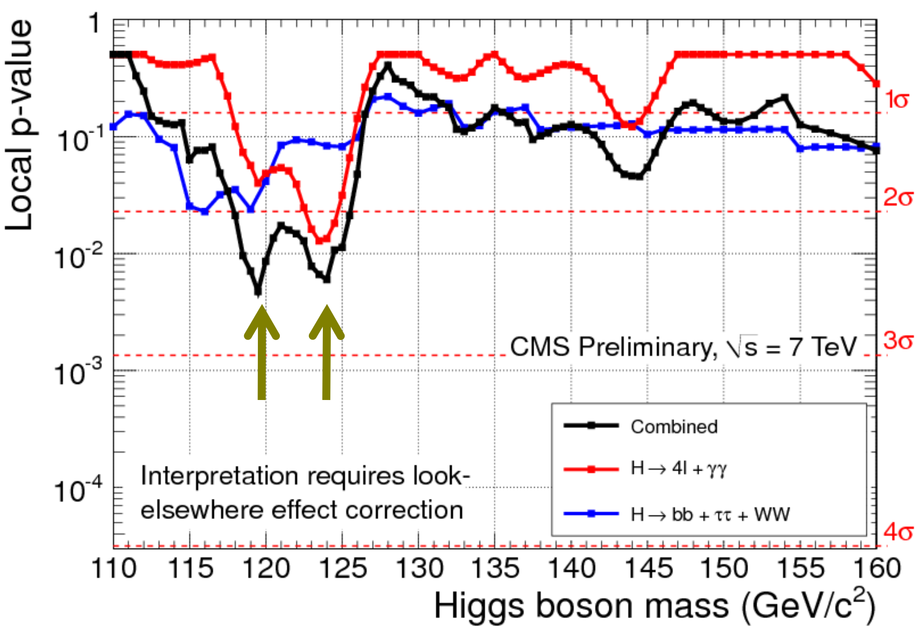
***CMS:* EPJC 73 (2013) 2283**



No Hint of SUSY- I Cry. But…

2011.12.13: Preliminary Results

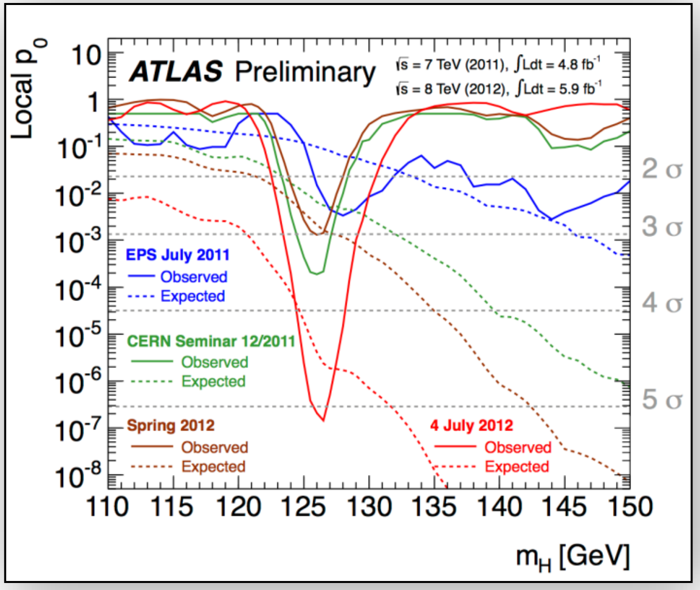
- Delivered by LHC : 5.72 fb^{-1}
- Recorded by CMS : 5.20 fb^{-1} (about 92%)
- High quality data : 4.7 fb^{-1} (~350 trillion collisions)

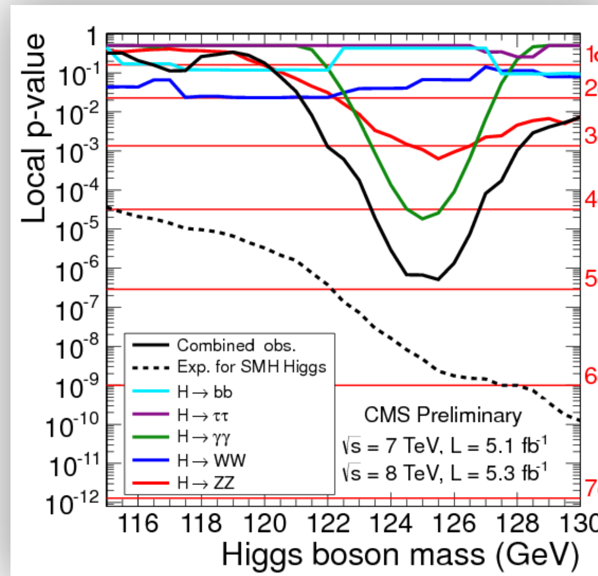


Keep in mind they are preliminary results;
Keep in mind they are small numbers;
Keep in mind we will run in the next year.

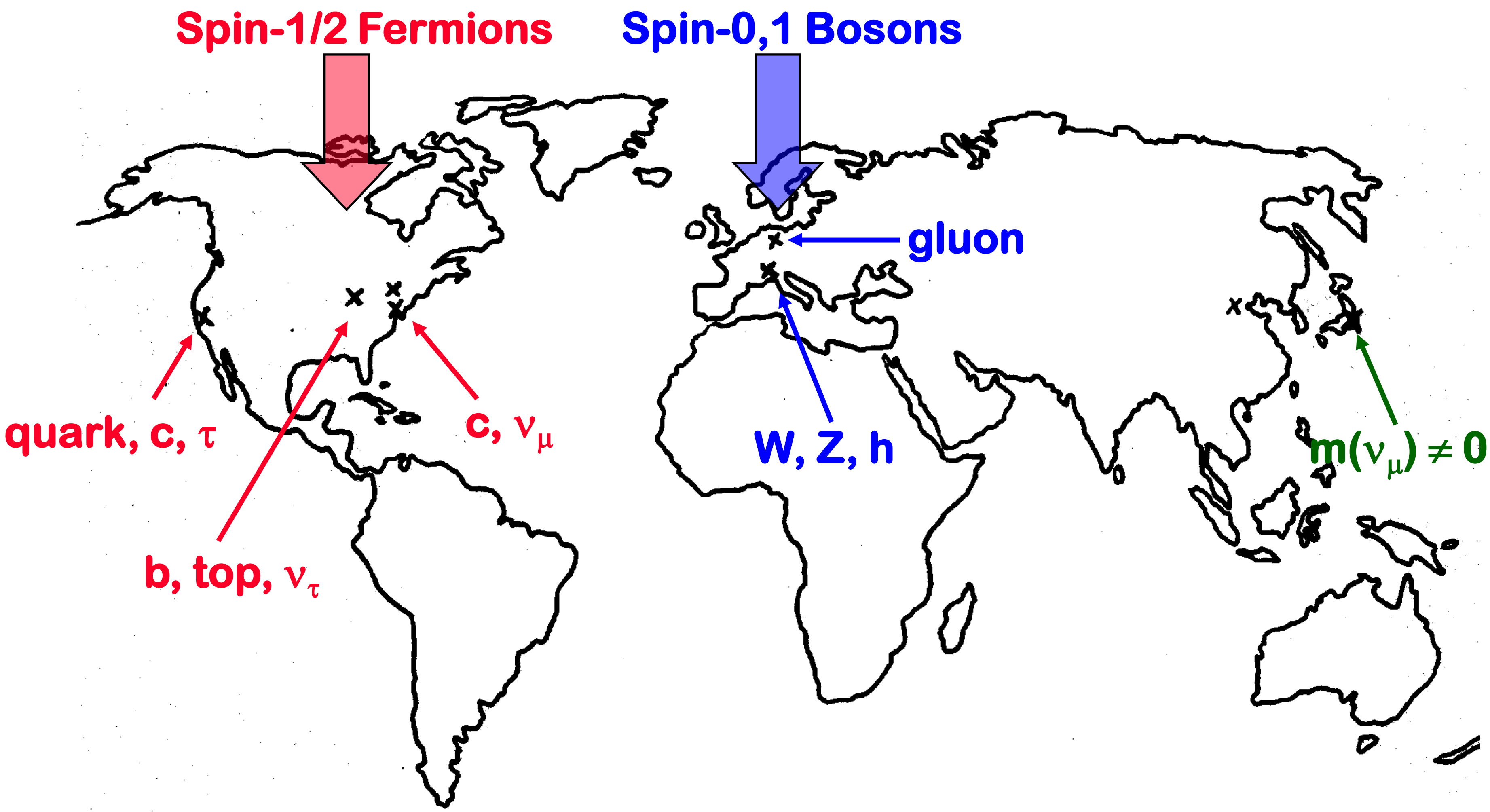
2012.07.04: After 48 Years of …

After 48 years of postulate, …





World "Discovery" Map

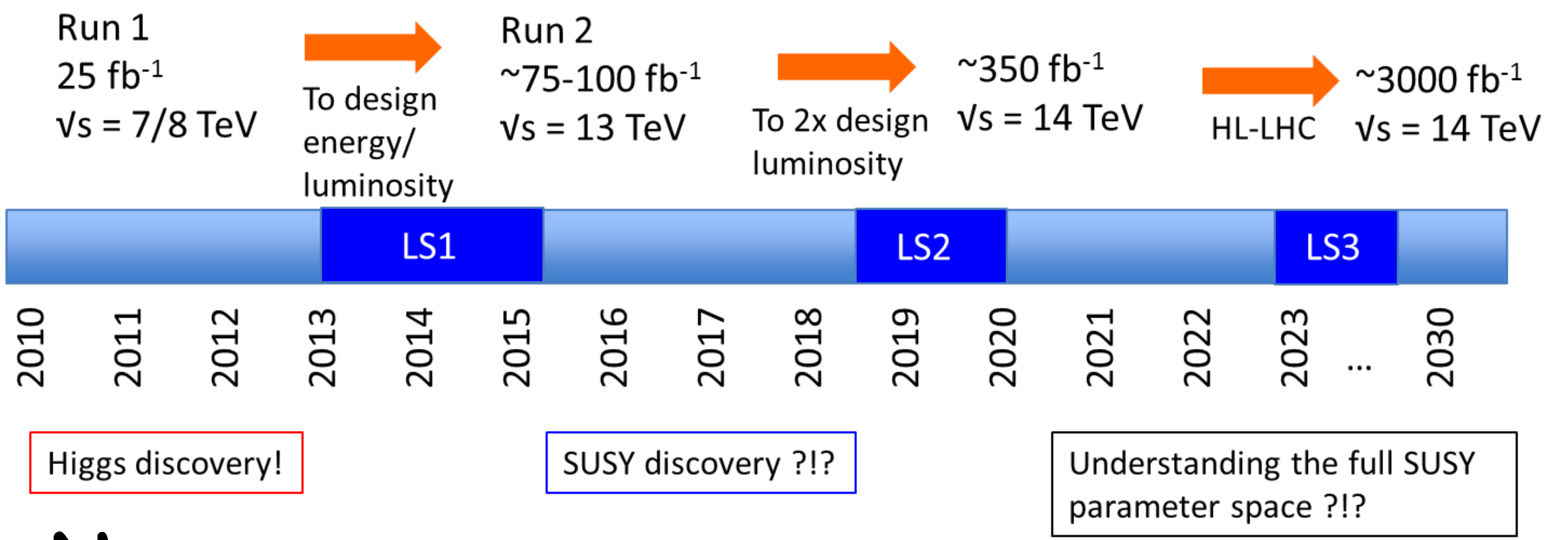


Where will more new particles be discovered ?
How about the dark matter particles ?

2015 and Beyond

I hope we see any sign of SUSY before my retirement…

- Long-term Planning



- Now
  - Vector Boson Fusion [PRD87 (2013) 035029]
  - MonoX in Nonthermal DM Model [PRD89 (2014) 096009]

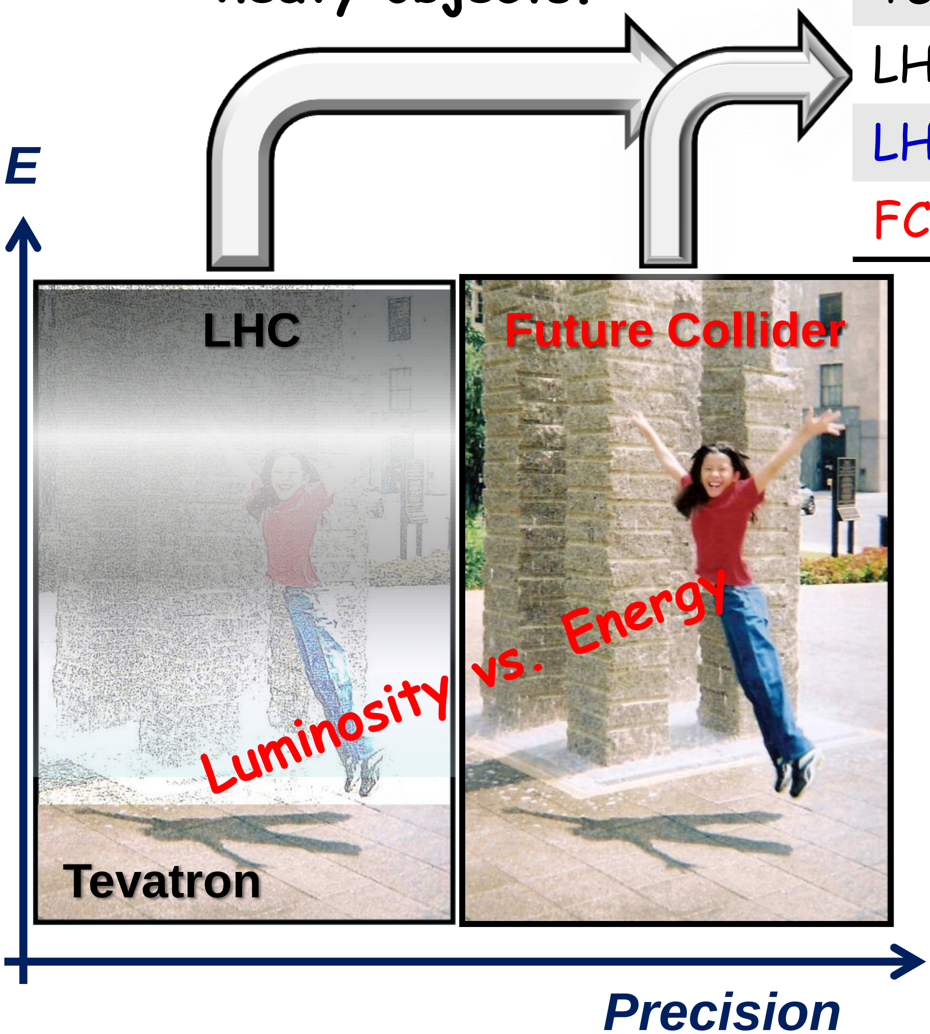
- Connection to the dark matter?

Energy Frontier Challenge

A 100-TeV collider is powerful in producing heavy objects.

Hadron Collider (√s)	Gluino/Squark Mass Reach (M)	M/√s
Tevatron (2 TeV)	~400 GeV	0.20
LHC (8 TeV)	~1.7 TeV	0.21
LHC (14 TeV)	~2.8 TeV*	0.20*
FCC (100 TeV)	~20 TeV*	0.20*

(*) just use a naïve scaling



Peter has been putting forward ideas of energy upgrade of the accelerator. Dick was always enjoying with physics discussion:

[1994] 4 TeV p-pbar Collider

[2001] 6 TeV p-pbar Collider

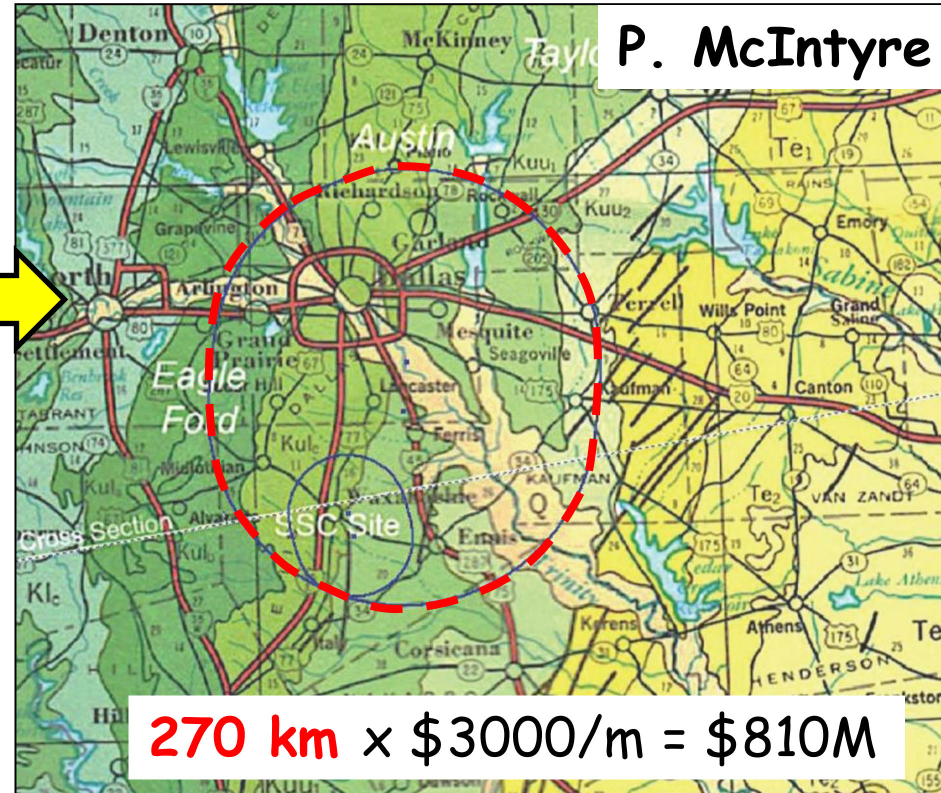
[2014] The history repeated. He is now proposing 100-300 TeV pp Collider.

❖ Understanding the limitations at the LHC14 will be an important step for FCC100pp

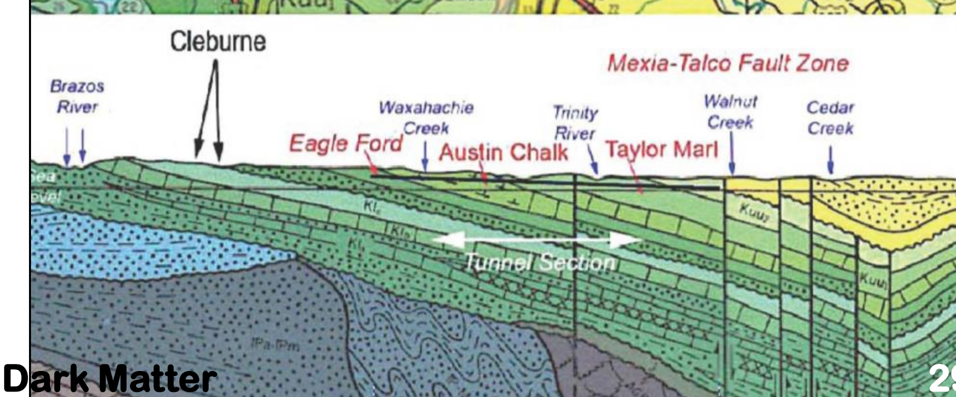
100-300 TeV pp Collider

http://arxiv.org/abs/1402.5973

P. McIntyre



270 km x $3000/m = $810M



Epilogue: Hunt for DM → Hint of DM

I am hungry. Can you make the DM sandwich with any Standard Model particle?

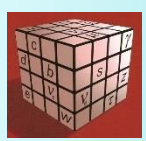
No, Sir. But with **neutralino**?

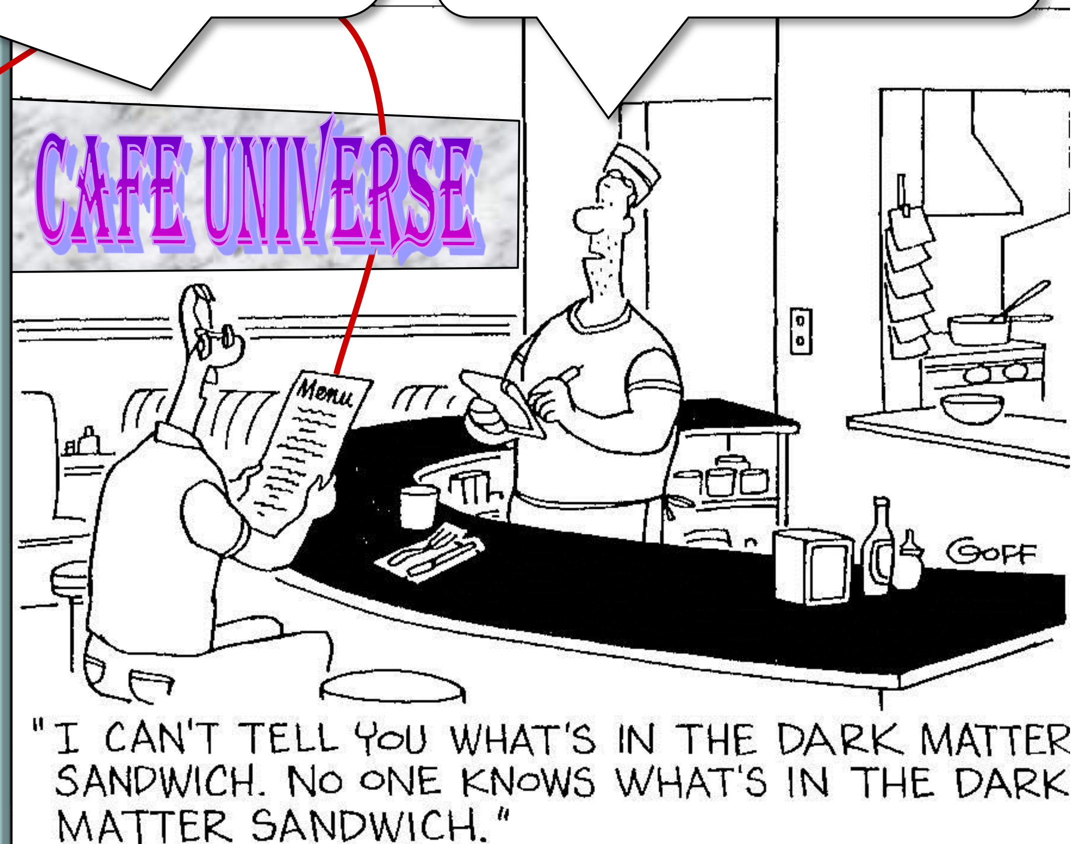
MENU
~SPECIALS~

*Dark Energy Power Drink .. $68
- Chef's choice
- (major puzzle)

*Dark Matter Sandwich …… $27
- Neutral, long-lived

*Atomic Soup ……………….. $5
- All elements in one





Discovery of Dark Matter in 20**?