A Quantitative Measure of Experimental Scientific Merit

1. Motivation
2. Development
   a. Basic
   b. Advanced
3. Examples

Bruce Knuteson (MIT)

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arXiv.org > physics > arXiv:0712.3572

Physics > Data Analysis, Statistics and Probability

A Quantitative Measure of Experimental Scientific Merit

Bruce Knuteson

(Submitted on 20 Dec 2007)

Experimental program review in our field may benefit from a more quantitative framework within which to quantitatively discuss the scientific merit of a proposed program of research, and to assess the scientific merit of a particular experimental result. This article proposes explicitly such a quantitative framework. Examples of the use of this framework in assessing the scientific merit of particular avenues of research at the energy frontier in many cases provide results in stark contradiction to accepted wisdom. The experimental scientific figure of merit proposed here has the potential for informing future choices of research direction in our field, and in other subfields of the physical sciences.

Acknowledgments

The quantitative measure of experimental scientific merit proposed in this article grew through a thread of conversation held largely in the third week of September 2006. Notable participants in this discussion include Steve Mrenna, Georgios Choudalakis, and Conor Henderson. Bill Ashmanskas, Dan Marlow, Larry Rosenson, and Peter Fisher provided valuable feedback.

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experimental program review is not quantitative

Letters of recommendation

Dear Committee:

I am writing for Joe Smith, a postdoc I have been working with for the past ten years. During this time I have gained a deep understanding of his abilities.

A physicist like Joe is truly hard to find. His true talents were perhaps underutilized in the project he has recently been working on, which involved spending five years optimizing a neural network for a model that turned out to be wrong.

There is very little you can teach a person of Joe's caliber. He in an unbelievable worker, who could not care less about the number of hours he had to put in.

I will be grateful if he succeeds in working for you.

Regards,
Eddie

Bruce Knuteson

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POSITIONS

2003 Jul –	Assistant Professor of Physics, MIT
2002 Jan – 2003 Jun	Fermi/McCormick Fellow, University of Chicago
2001 Aug – 2001 Dec	NSF International Research Fellow, CERN
2001 Jan – 2001 Jul	Fermi/McCormick Fellow, University of Chicago
1998 Jul – 2000 Dec	DoD NDSEG Fellow, University of California, Berkeley

EDUCATION

University of California, Berkeley
Ph.D. Physics, December 2000
GPA: 4.00 / 4.00

Rice University, Houston, Texas
B.A. Physics and Mathematics, May 1997
GPA: 4.02 / 4.00
summa cum laude

HONORS

Charles Townes Young Scholars Competition Finalist
American Physical Society Tanaka Dissertation Award
National Science Foundation International Research Fellowship
Enrico Fermi Postdoctoral Fellowship (University of Chicago)
Pappalardo Fellowship (MIT)†
CERN Fellowship†
DoD National Defense Science and Engineering Graduate Fellowship
National Science Foundation Graduate Fellowship†
Department of Physics Fellowship (Berkeley)
Karl Taylor Compton Fellowship (MIT)†
First Year Merit Fellowship in Science and Mathematics (Princeton)†
Robert A. Millikan Fellowship (Caltech)†
Churchill Scholarship Finalist
Rhodes Scholarship Semifinalist
Rice University Outstanding Senior Award
Outstanding Senior in Physics (Rice University)
Phi Beta Kappa
Sigma Pi Sigma
Sigma Xi
Who's Who Among Students in American Universities and Colleges 1996, 1997
Associated Western Universities Undergraduate Research Fellowship
National Merit Scholarship

Application to the Ph.D. program in physics accepted by
Berkeley, Caltech, Cornell, Harvard, MIT, Princeton, Stanford

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SCIENTIFIC MERIT

Work	Reference	Merit	Cost (M$)	Merit/ M$
Global search Tevatron I	PRD, PRD, PRL	0.02	0.1	0.2
Global search LEP 2	Aleph, L3	0.02	0.1	0.2
Global search Tevatron IIa	PRD, PRL	0.2	0.4	0.5
Global search Tevatron IIb	CDF	0.02	0.2	0.1
Total		0.26	0.8	**0.3**

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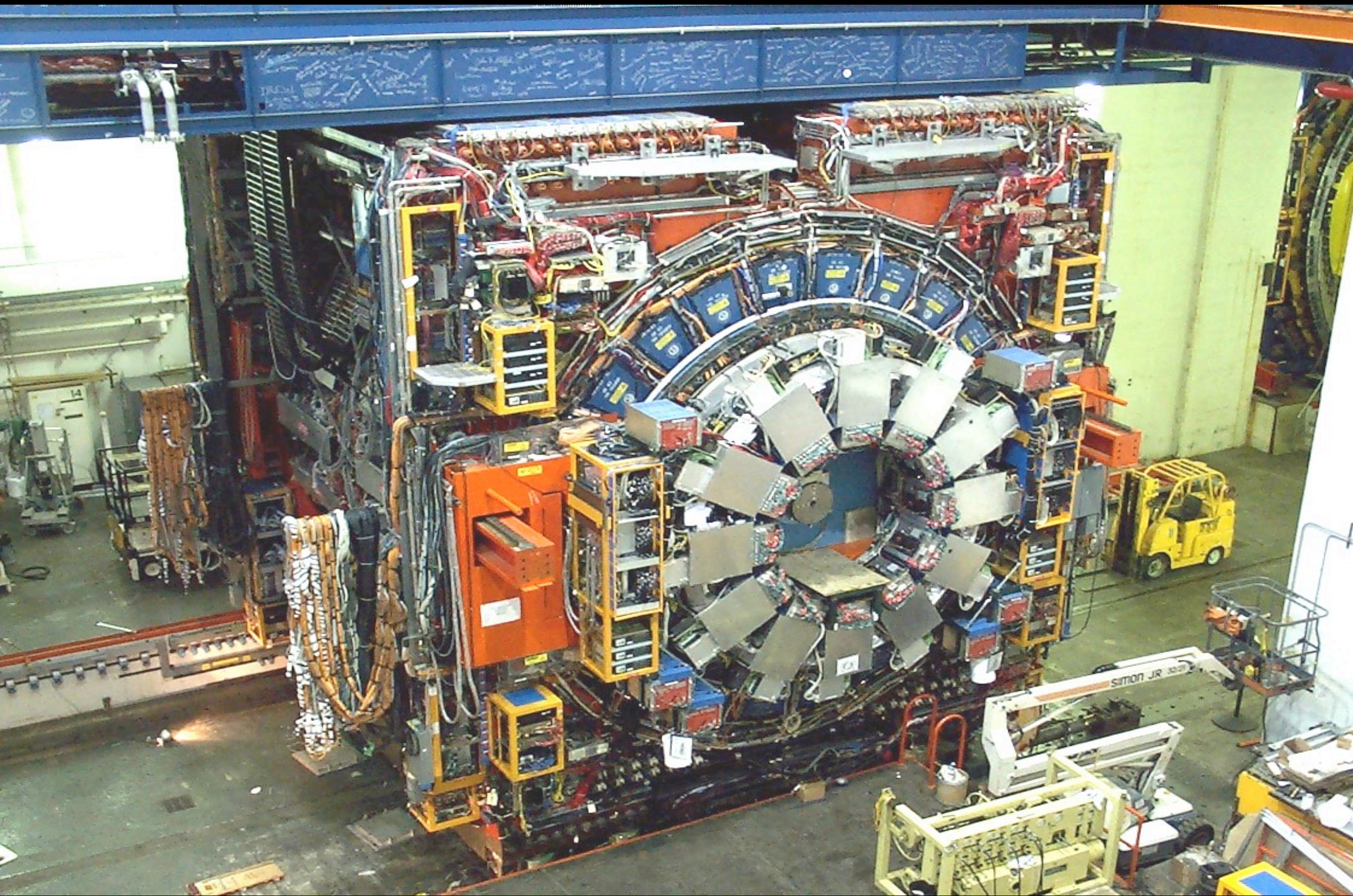
Minimize

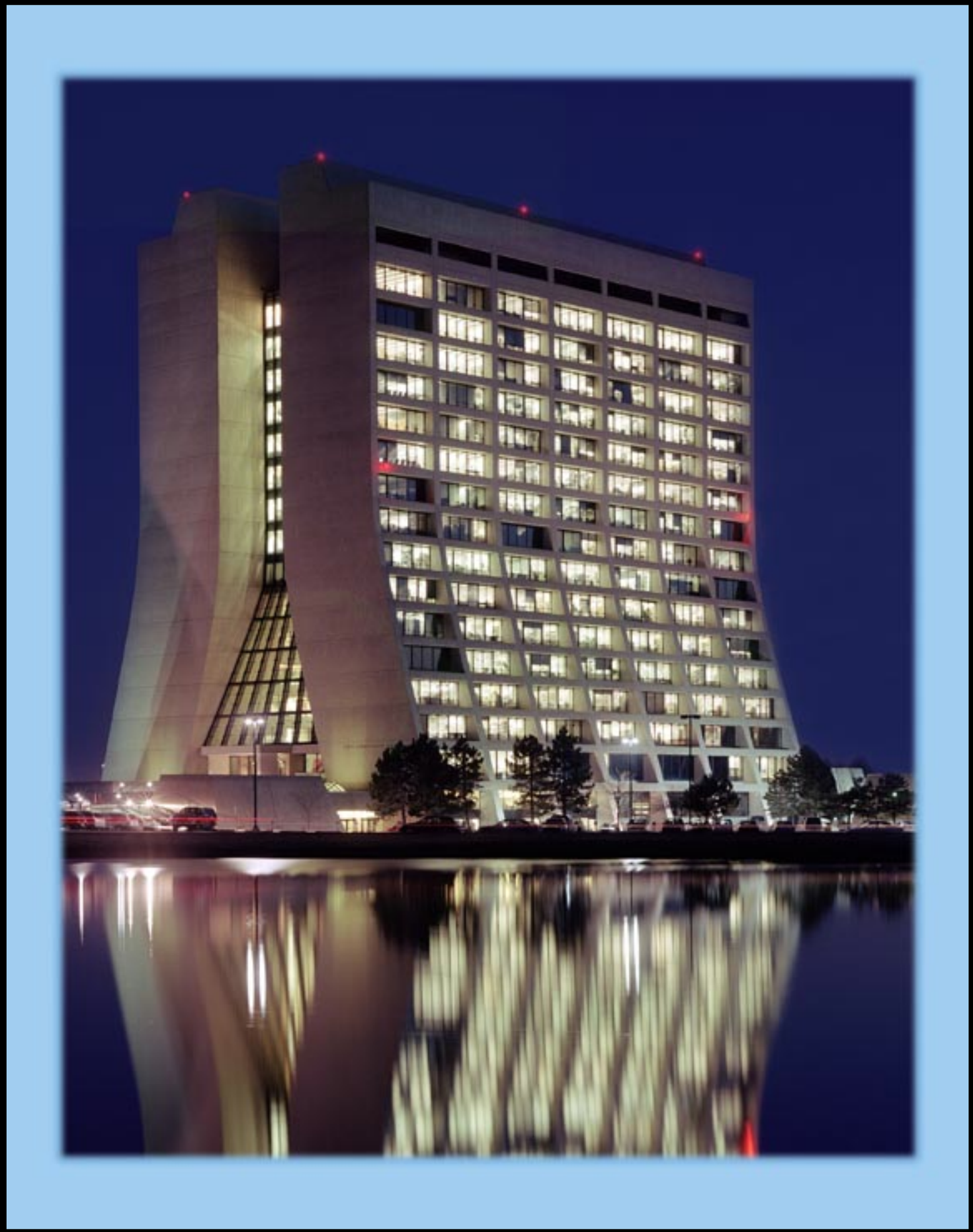
- discrimination
- good ol' boy network
- school elitism

Defines what people should be working toward

Defines what an experiment should be working toward



Defines what a lab should be working toward



Defines what the field should be working toward

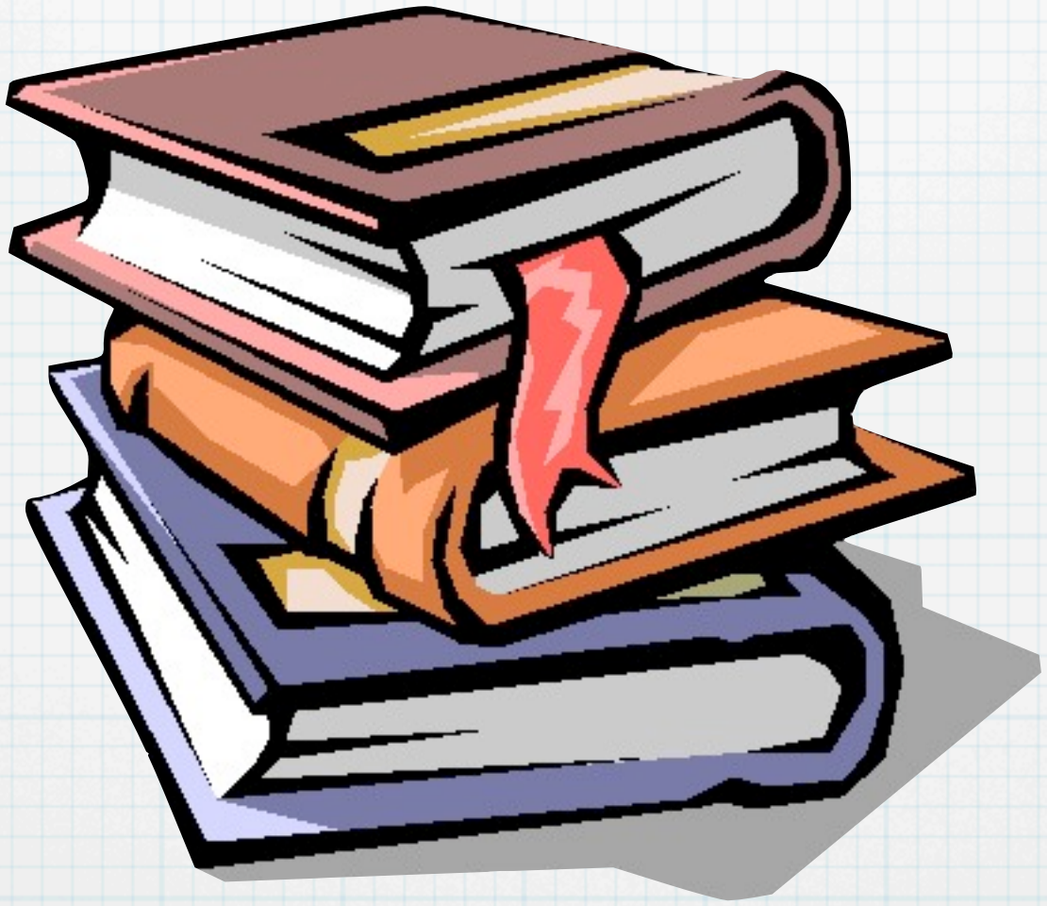
Industry has a well-defined figure of merit

Figure of merit criterion

Consider two often used measures:

- # publications
- # citations

publications: not invariant under stapling



citations: not invariant under stapling

Citation

From Wikipedia, the free encyclopedia

A **citation** or **bibliographic citation** is a reference to a book, article, web page, or other published item, with sufficient detail to allow a reader to locate it[*citation needed*].

In HEP, # citations also distorted by the Particle Data Group's Review of Particle Properties

REVIEW OF PARTICLE PHYSICS*

Particle Data Group

Abstract

This biennial *Review* summarizes much of particle physics. Using data from previous editions, plus 2633 new measurements from 689 papers, we list, evaluate, and average measured properties of gauge bosons, leptons, quarks, mesons, and baryons. We also summarize searches for hypothetical particles such as Higgs bosons, heavy neutrinos, and supersymmetric particles. All the particle properties and search limits are listed in Summary Tables. We also give numerous tables, figures, formulae, and reviews of topics such as the Standard Model, particle detectors, probability, and statistics. Among the 110 reviews are many that are new or heavily revised including those on CKM quark-mixing matrix, V_{ud} & V_{us}, V_{cb} & V_{ub}, top quark, muon anomalous magnetic moment, extra dimensions, particle detectors, cosmic background radiation, dark matter, cosmological parameters, and big bang cosmology.

A booklet is available containing the Summary Tables and abbreviated versions of some of the other sections of this full *Review*. All tables, listings, and reviews (and errata) are also available on the Particle Data Group website: `http://pdg.lbl.gov`.

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1. Motivation
2. Development
   a. Basic
   b. Advanced
3. Examples

Possible considerations in defining a figure of merit:

- contribution to Global Domestic Product
- lives saved
- reduction in carbon emissions

HEP is ≈ a purely academic field: all we provide is knowledge

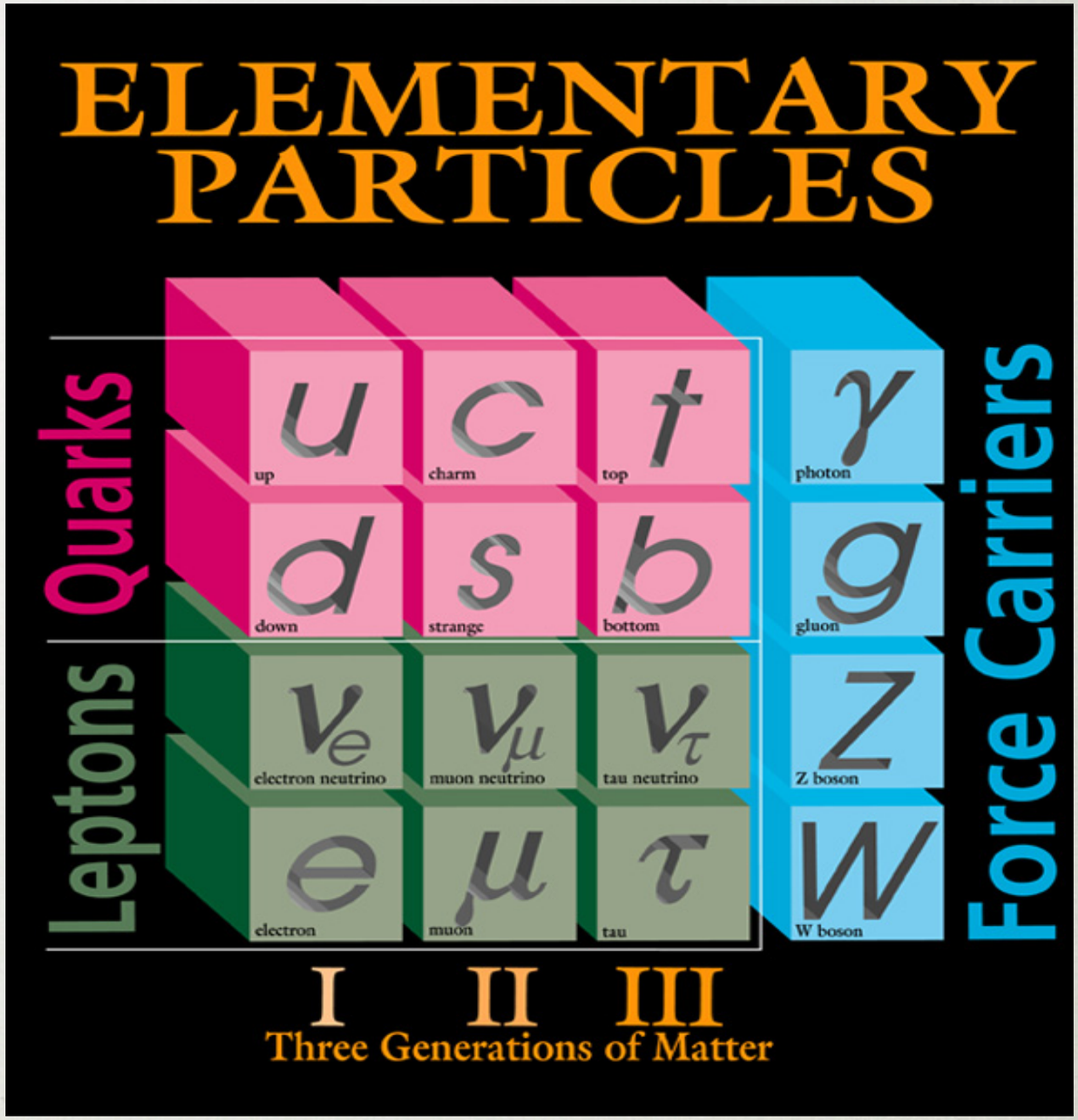

Figure of merit must therefore be a measure of how much is learned

Figure of merit must therefore be a function of how surprised you are at the result

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Experiment X

$X=\{x_1,x_2\}$

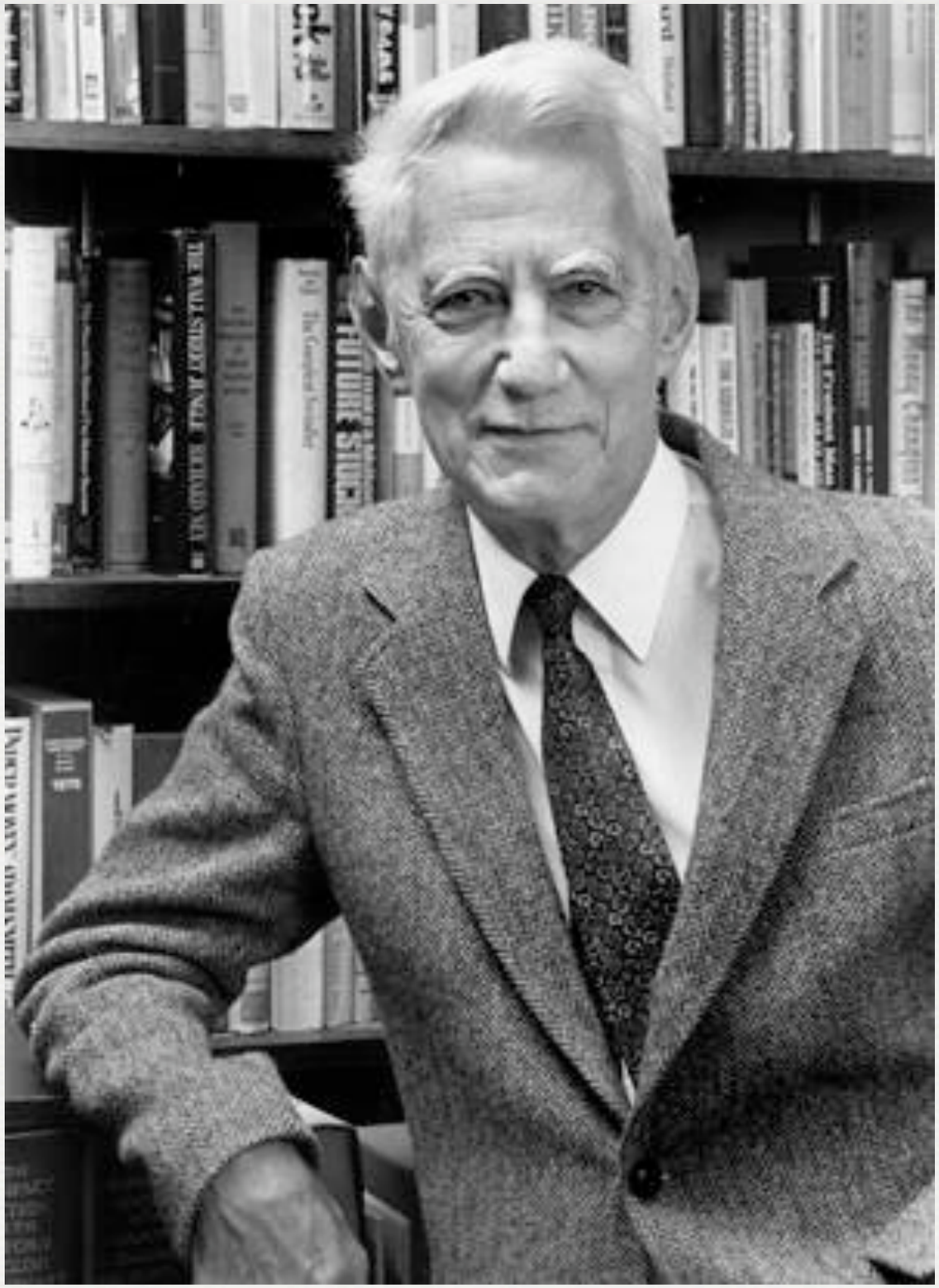
$p(x_1)+p(x_2)=1$

$p(x_1)=0.2,\ p(x_2)=0.8$

$$X = \{x_1, .., x_i, ..., x_n\}$$

$$x_i$$

$$p(x_i)$$



Claude Shannon
Information theory

criteria

- invariance under stapling
- monotonic function of $p(x_i)$ lead uniquely to

$$\text{surprisal}(x_i) = -\log_{10} p(x_i)$$

Completed experiment

merit =

$$\text{surprisal}(x_i) = -\log_{10} p(x_i)$$

Proposed experiment

Expected payoff

merit =

$$H(X) = \sum_i p(x_i)\,\text{surprisal}(x_i) = -\sum_i p(x_i)\log_{10} p(x_i)$$

Summary of basics

completed experiment

$$\text{surprisal}(x_i) = -\log_{10} p(x_i)$$

proposed experiment

$$H(X) = \sum_i p(x_i)\,\text{surprisal}(x_i)$$

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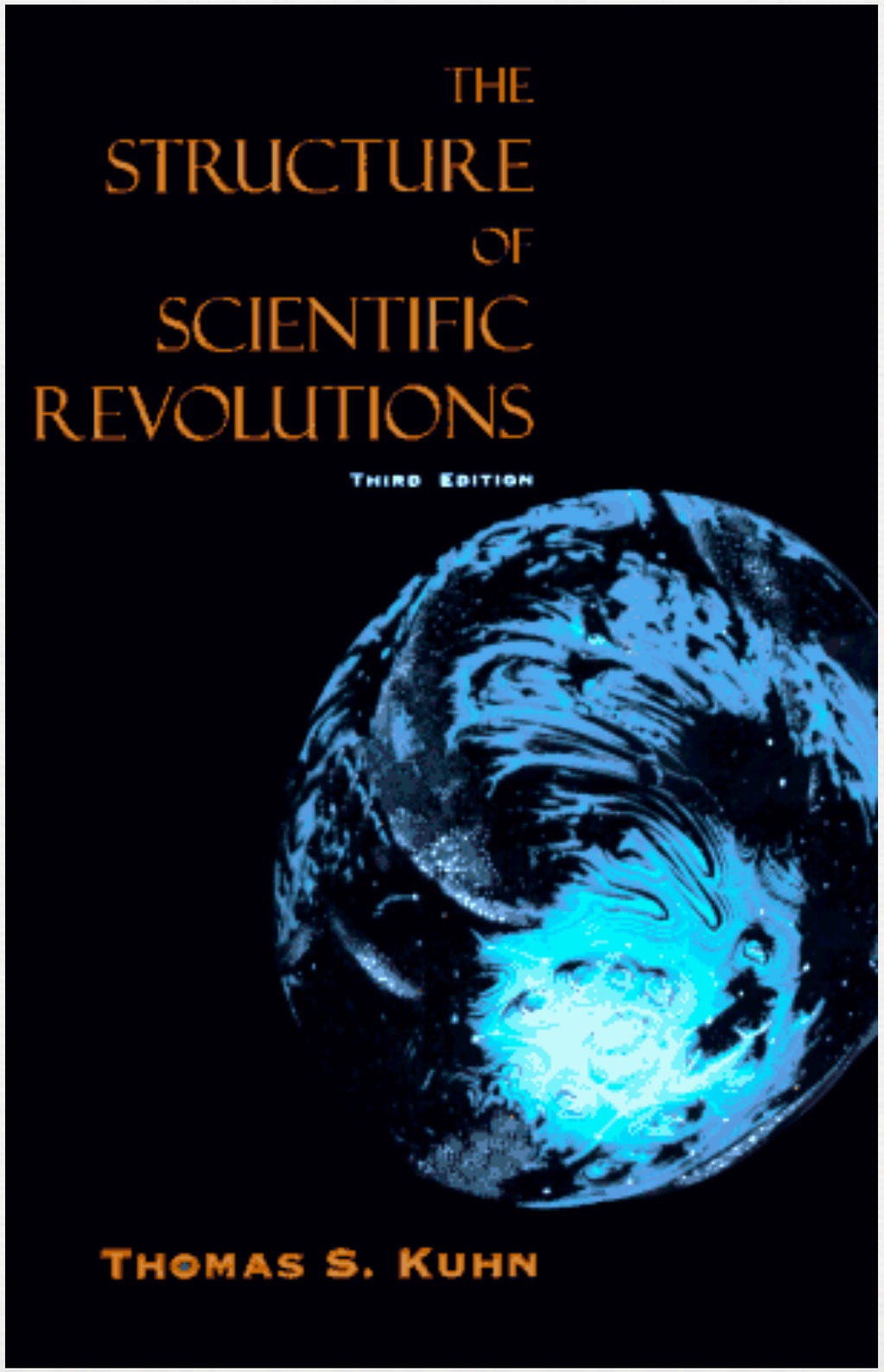
Qualitatively distinct states of knowledge

$$Y=\{ y_1 , \cdots , y_j , \cdots , y_m \}$$

$$\Sigma_j \; p(y_j)=1$$

Kuhn: normal science



Example: SM Higgs

$Y = \{ y_1 , y_2 \}$

y_1 = a Standard Model like Higgs boson exists

y_2 = no Standard Model like Higgs boson exists

$p(y_1) = 95\%$

$p(y_2) = 5\%$

Entropy

$$H(Y) = -\sum_j p(y_j) \log_{10} p(y_j)$$

disorder

confusion

Example: SM Higgs

$$H(Y) = -\sum_j p(y_j) \log_{10} p(y_j)$$

$H(Y) = - (0.95 \log_{10} 0.95 + 0.05 \log_{10} 0.05)$

$= 0.086$

If x_i is obtained,
the entropy will be

$$H(Y|x_i) = -\sum_j p(y_j|x_i) \log_{10} p(y_j|x_i)$$

Conditional entropy H(Y|X)

$$
\begin{aligned}
H(Y|X) &= \sum_i p(x_i)\, H(Y|x_i) \\
&= -\sum_i p(x_i) \sum_j p(y_j|x_i) \log_{10} p(y_j|x_i) \\
&= -\sum_{i,j} p(x_i, y_j) \log_{10} p(y_j|x_i).
\end{aligned}
$$

Proposed experiment

Expected information content

merit =

$$\Delta H = H(Y) - H(Y|X)$$

special case: H(Y|X)=0

Assume y_j is correct.
The evidence outcome x_i provides in favor of y_j is

$$\text{evidence}(y_j|x_i) = \log_{10} \frac{p(y_j|x_i)}{p(y_j)}$$

Completed experiment

information gain

merit =

$$\text{information gain } (x_i) = \sum_j p(y_j|x_i)\,\text{evidence}(y_j|x_i)$$

$$= \sum_j p(y_j|x_i)\ \log_{10}\frac{p(y_j|x_i)}{p(y_j)}$$

Note:

$$\Delta H = \sum_i p(x_i)\,\text{information gain } (x_i)$$

Summary of basics

(review)

X

completed experiment

$$\text{surprisal}(x_i) = -\log_{10} p(x_i)$$

proposed experiment

$$H(X) = \sum_i p(x_i)\,\text{surprisal}(x_i)$$

Summary of advanced

Y,X

Information entropy

$$H(Y) = -\sum_j p(y_j) \log_{10} p(y_j)$$

Proposed experiment

$$\Delta H = H(Y) - H(Y|X)$$

Completed experiment

$$\text{information gain } (x_i) = \sum_j p(y_j|x_i) \, \text{evidence}(y_j|x_i)$$

Expected payoff

$$\Delta H = \sum_i p(x_i) \, \text{information gain } (x_i)$$

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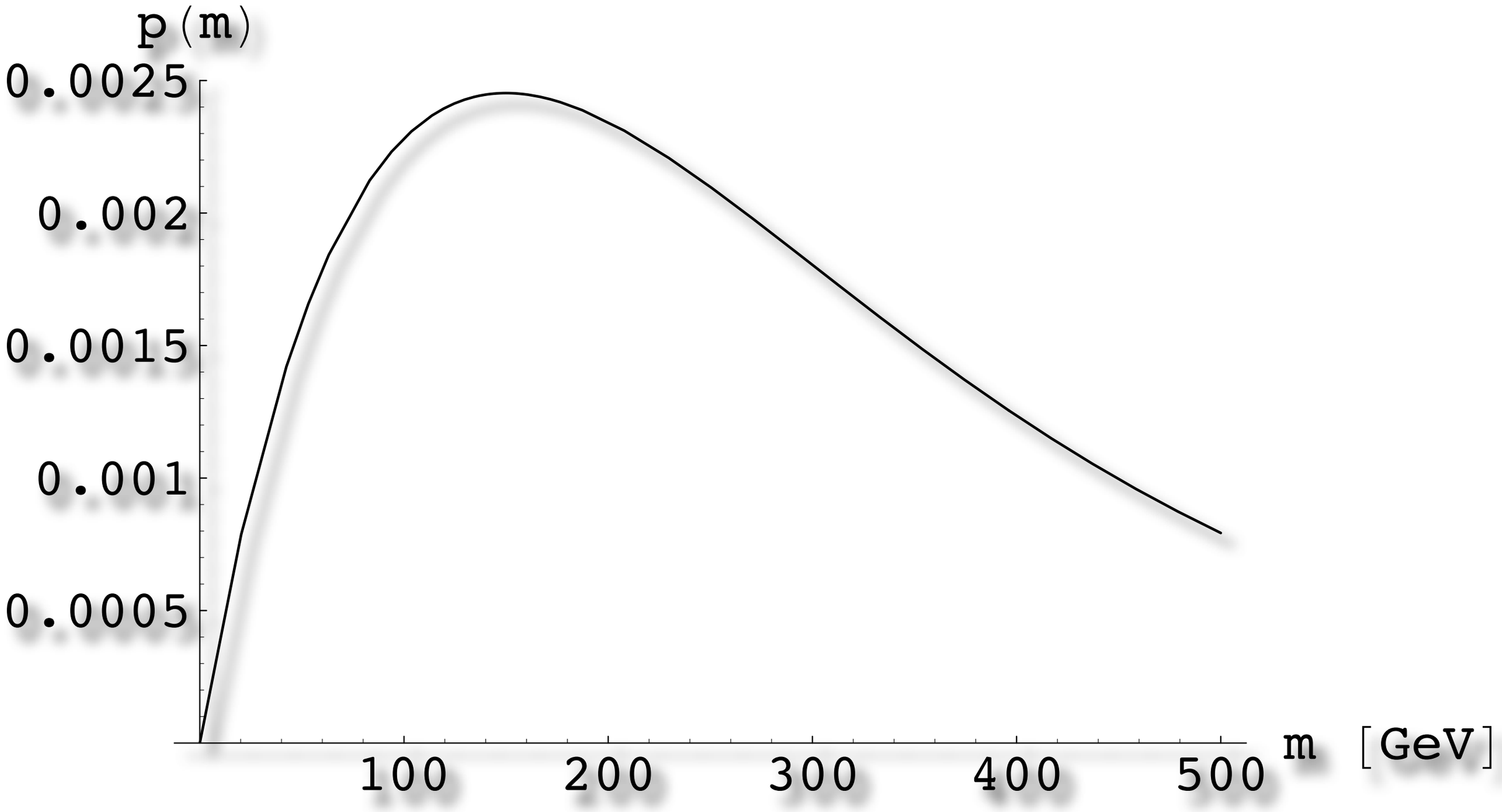
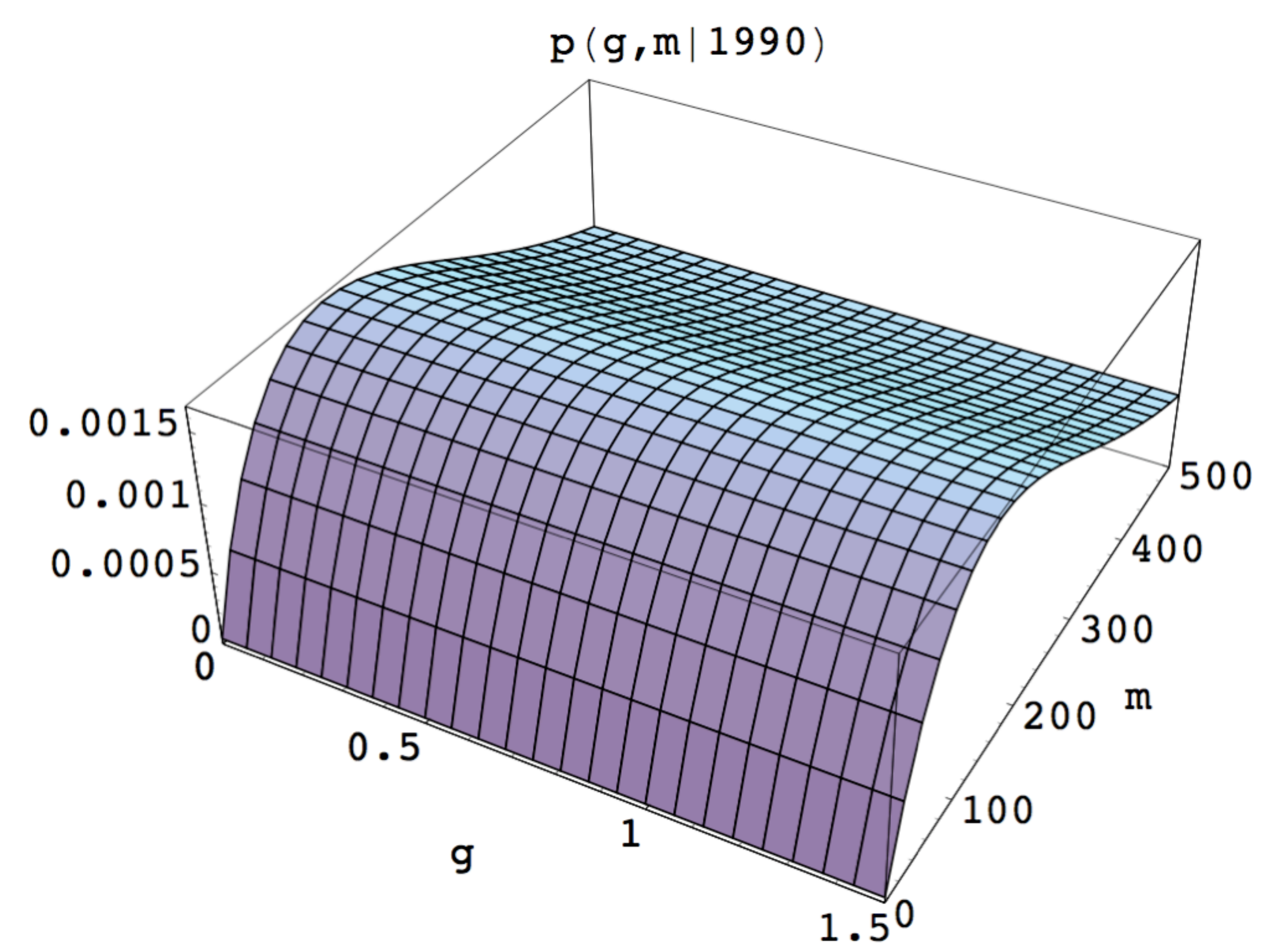
PRIOR PROBABILITIES

TEVATRON DISCOVERY

PROBABILITY


p(m)
0.0025
0.002
0.0015
0.001
0.0005
100
200
300
400
500
m [GeV]


p(g,m|1990)
0.0015
0.001
0.0005
0
0
0.5
1
1.5
g
0
100
200
300
400
500
m

p(g,m|1996)

0.0015
0.001
0.0005
0
0
0.5
1
1.5
g
0
100
200
300
400
500
m

p(g,m|2000)

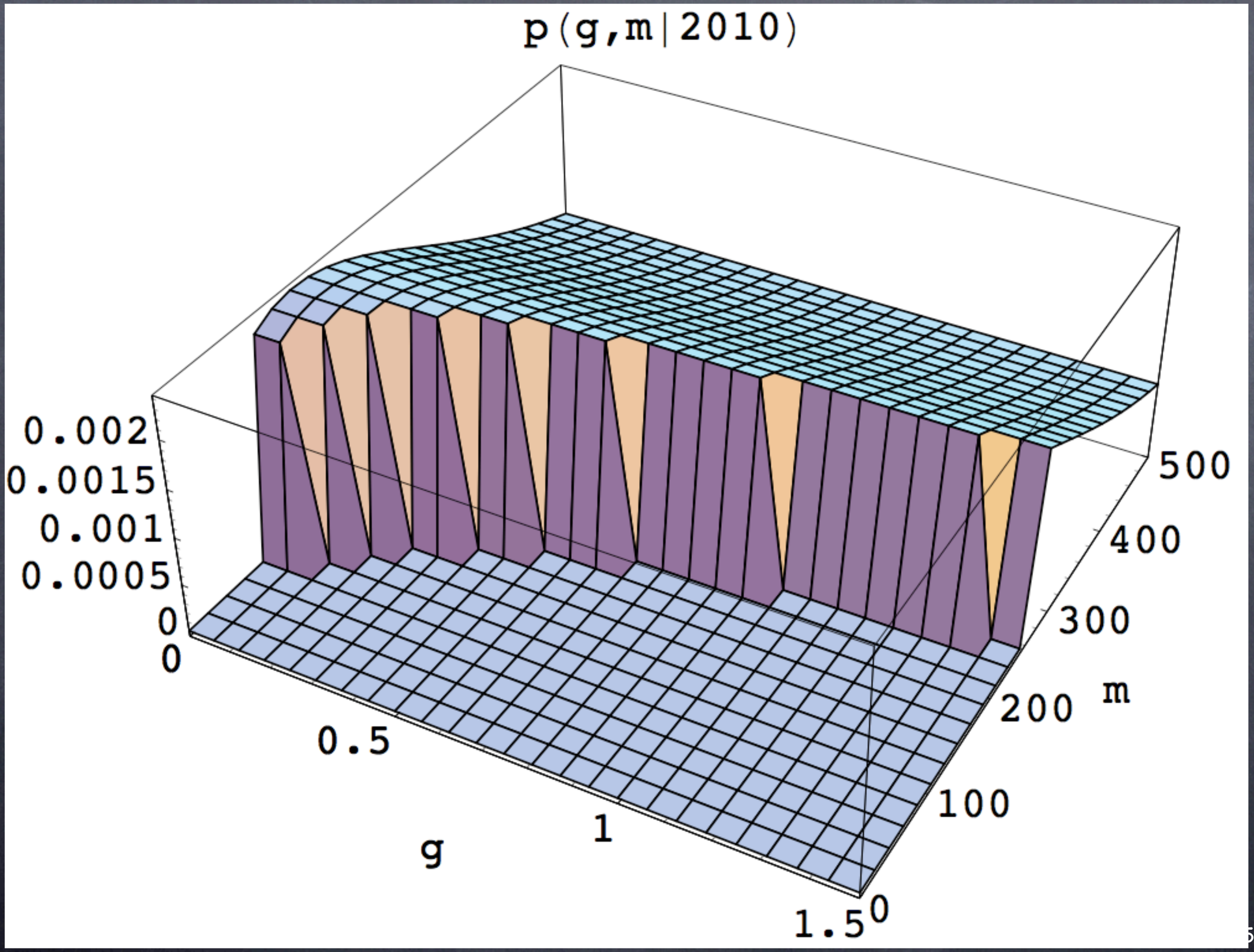
0.0015
0.001
0.0005
0
0
0.5
1
1.5
g
0
100
200
300
400
500
m

p(g,m|2006)

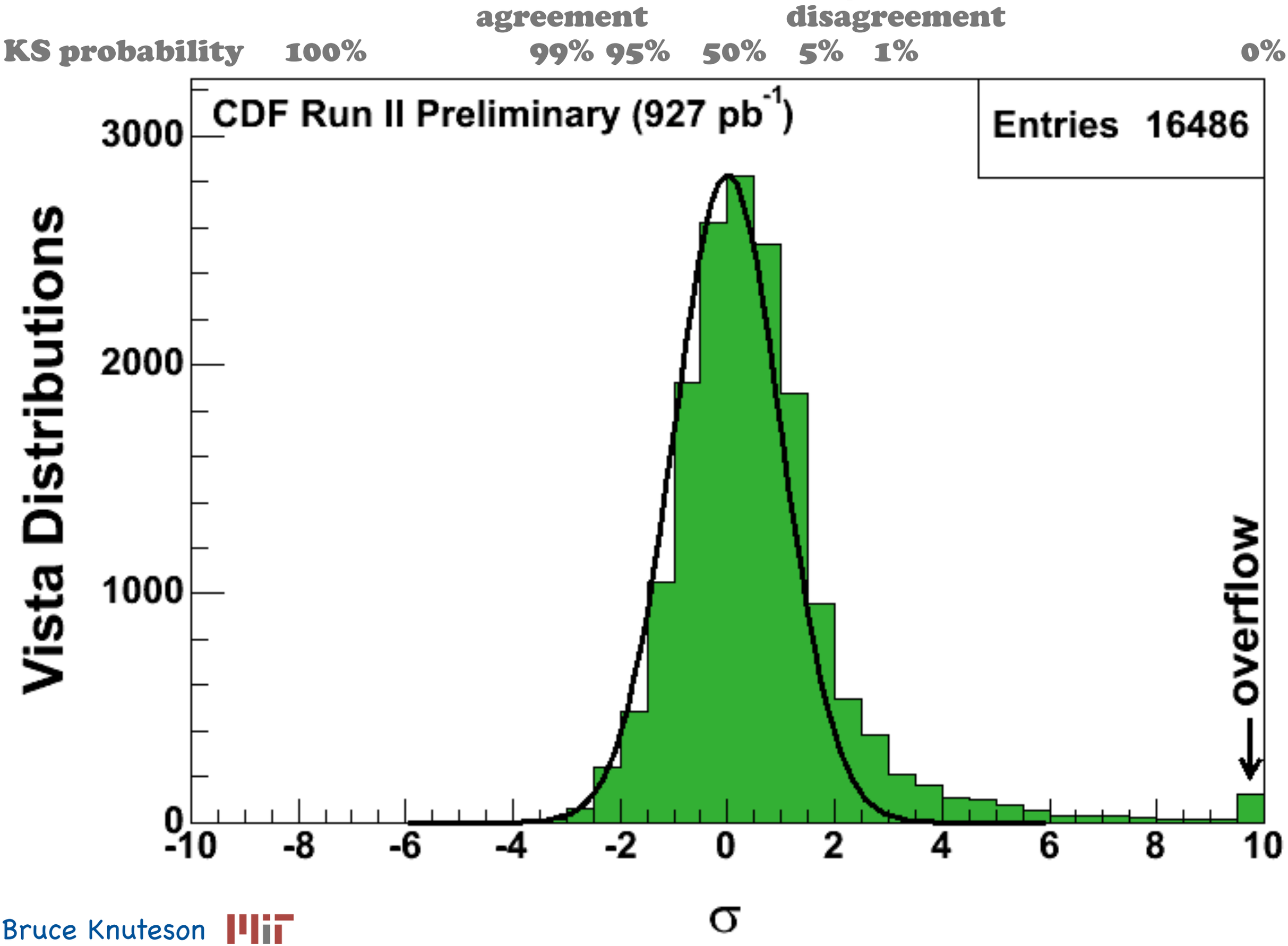
0.002
0.0015
0.001
0.0005
0

0
0.5
1
1.5
g

0
100
200
300
400
500
m


p(g,m|2010)
0.002
0.0015
0.001
0.0005
0
0
0.5
1
1.5
g
0
100
200
300
400
500
m

Vista kinematic shapes



Merit of proposed experiments

Analysis	Merit	Cost (M$)	Bang per buck (Merit per M$)
LHC, all searches	7	5e+03	1e-03
Tevatron II global search	1.4	3e-01	5
$\mu 2e$	2e-01	1e+02	2e-03
Tevatron Higgs search	2e-03	1e+01	2e-04
B_s mixing	1e-05	1e+01	1e-06
e^* search	7e-05	1e-01	7e-04
single top search	5e-05	5	1e-05
flipping a coin	0	1e-07	0

Merit of completed experiments

Result	Merit	Cost (M$)	Bang per buck (Merit per M$)
τ discovery	3	6e-01	5e+00
J/Ψ discovery	2	1e+01	2e-01
there is no Higgs†	1.3	5e+03	3e-04
Υ discovery	5e-01	1	5e-01
null Tevatron I + LEP 2	2e-01	3e+03	6e-05
global null Tevatron IIa	5e-02	3e-01	2e-01
global null Tevatron IIb†	5e-02	3e-01	2e-01
W and Z discoveries	2e-02	5e+02	4e-05
top quark discovery	2e-02	5e+01	4e-04
Higgs discovery†	2e-02	5e+03	4e-06
B_s mixing observation	4e-06	1e+01	4e-07
e^* search	4e-06	1e-01	4e-05
single top discovery†	4e-06	5	4e-06
coin comes up heads	0	1e-07	0

Summary

- A quantitative measure of scientific merit is desirable
- The appropriate figure of merit is based on information content
- The figure of merit proposed is unique
- Productively frames and focuses discussion