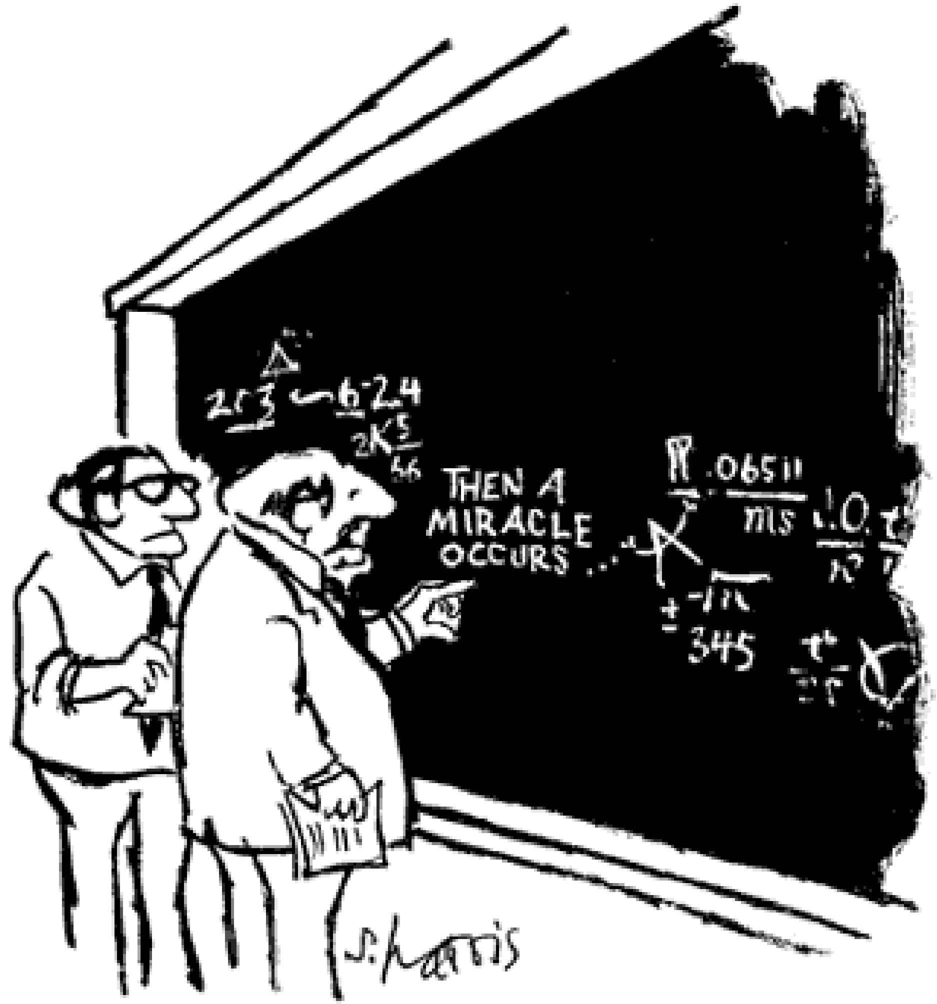
Introduction to the Scientific Method

Ralph J. Steinhagen, CERN



"I think you should be more explicit here in step two."

Science vs. science

- … (how-to) gain knowledge of the universe

- Why science?
  - We care about certainty
  - The inaccuracy of intuition
  - The limitations of dogma

- What is science?
  - How does it work?
  - Why does it work?
  - Why not do things differently?

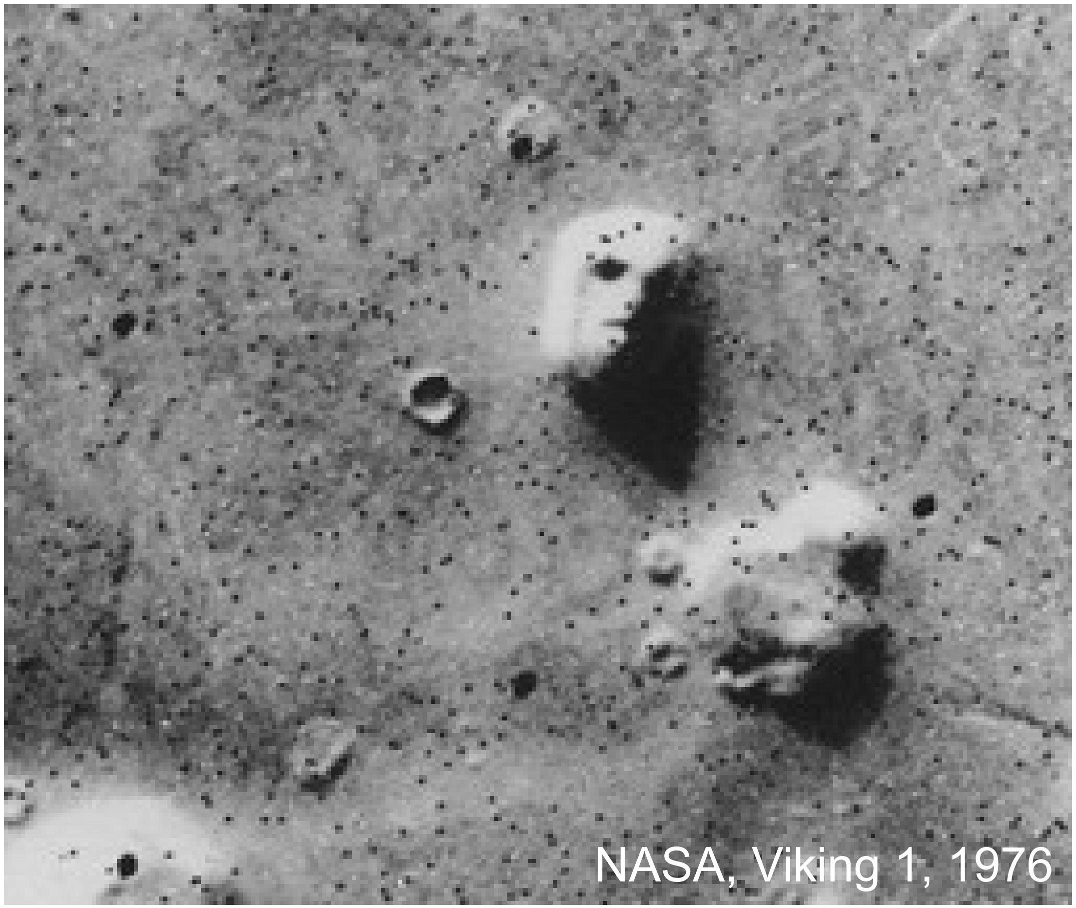

Science is not about finding 'truths' ...
...but about discovering how nature works.

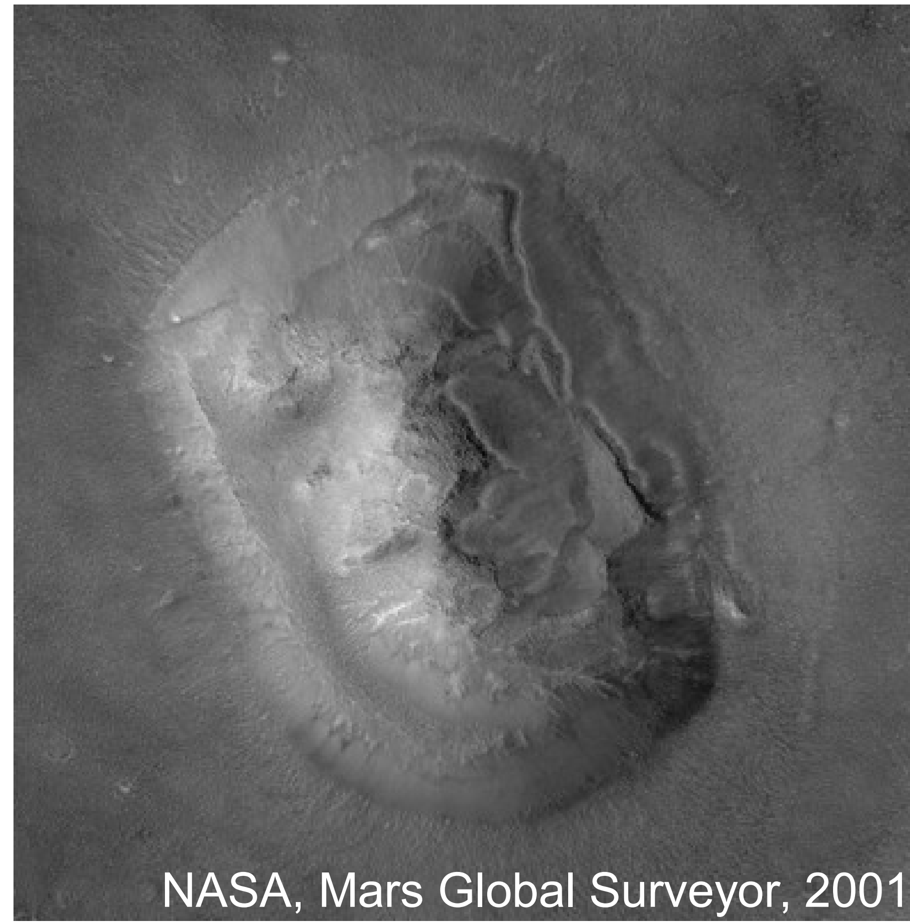
Science

- How do we gain knowledge?
  - Intuition?
  - Guesswork?
  - Dogma?
  - Word-of-mouth?
  - Heuristics?

- What are the drawbacks of these?
- How can we improve on them?
- Need science with its self-correcting mechanisms of replication and peer review

Patternicity – *Seeing things when there aren't*





Patternicity – *Seeing things when there aren't*

- *Michael Shermer[1]:*
  “Our brains are belief engines: evolved pattern-recognition machines that connect the dots and create meaning [..] in nature.”

- Foster & Kokko[2] – two recognition error types:
  - Type-I 'false-positive': finding non-existent pattern
  - Type-II 'false-negative': not recognizing real pattern
- Inner-demon fighting against science:
  natural selection favours patternicity, if cost of 'false-positive' is less than the cost of 'false-negative'.
- Predator example
  - 'false-positive' → detected non-existent predator → evasion → limited cost/calories
  - 'false-negative' → missed the predator → no-evasion → fatal cost

[1]*Scientific American, Nov., 2008,* [2]Proc. R. Soc. B, 2009, 276

Fundamental assumption of Science

A) The Universe operates according to stable underlying laws
   - Physics seems to be constant on 'human' to up to 'galactic' scales

B) Our senses give us an accurate information about the world
   - i.e. we do not live in 'The Matrix' → Empiricism & Goethe

C) Preference for Simplicity → Ockham's Razor

Ockham's Razor

- *… There are always infinitely many potential explanations for any observation*

→ *Assume explanation with the least number of extra of unproven assumption*

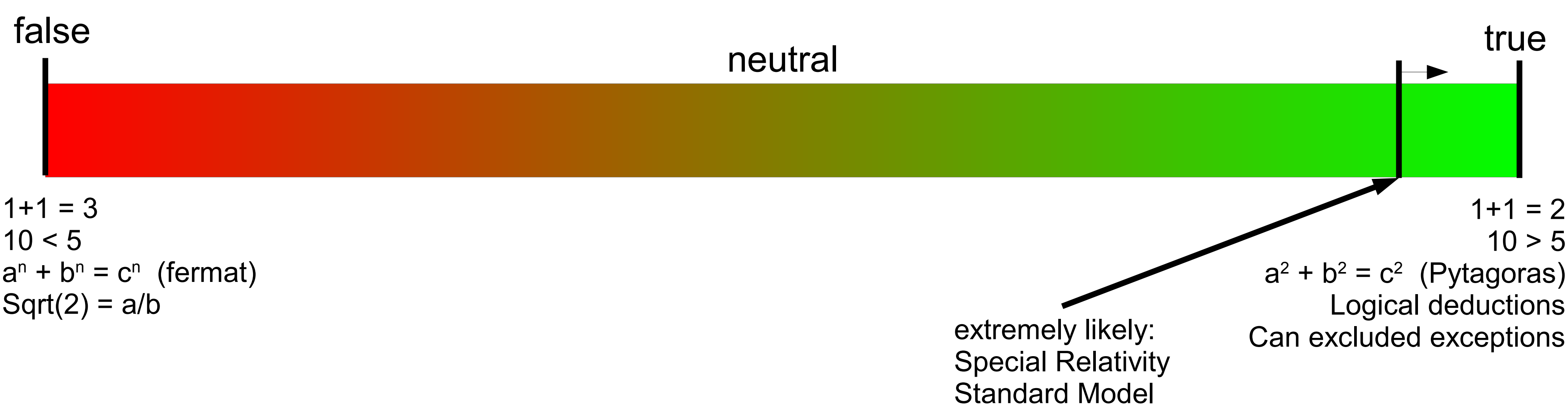
William of Ockham
1288-1348

- More “modern” version:
  - “Rule I. We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.” (Isaac Newton, Principia mathematica, 1687)
  - “Whenever possible, substitute constructions out of known entities for inferences to unknown entities.” (Bertrand Russell, 1924)

- Without, no useful knowledge can be gained about anything, ever!

Spectrum of Certainty

- An inconvenient truth:
  Science aims at finding truth but cannot establish them
- In natural science, spectrum between [false, true[
  - we can exclude theories or proof them wrong
  - Notable exception: mathematics, provided there is **no logically possible exception**

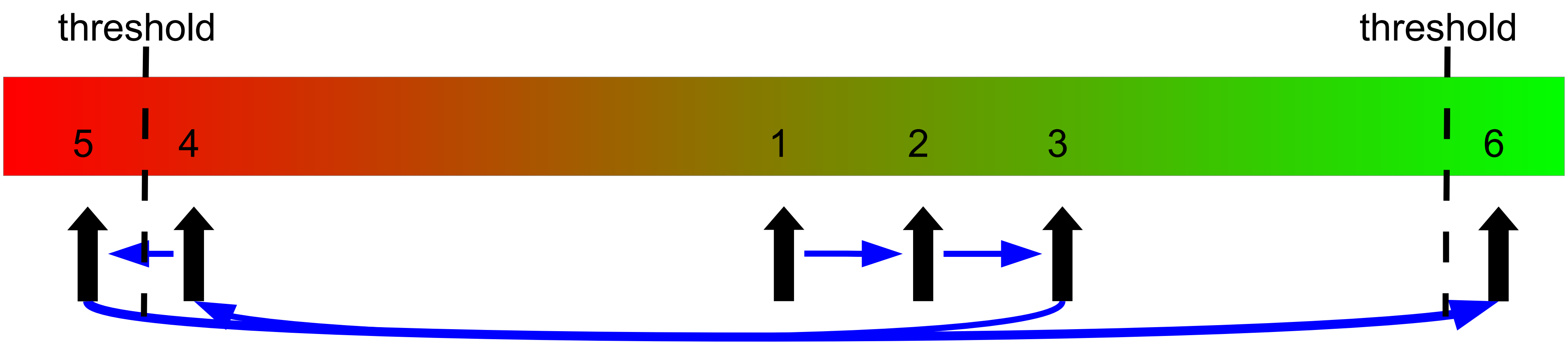


We observe part of universe –
cannot remove ourself from the equation

Scientific Process

- Start with no knowledge
- Gradually add information and adjust assigned probabilities
- Continue until (sufficiently) certain
- Always be willing to move to arrow!

- Chess grandmaster example:



Bayes' Theorem

- Defines level of confidence P(H|E) in any Hypothesis, depending the level of support by the Evidence:

Thomas Bayes
1701-1761

$$P(H|E) = \frac{P(E|H)}{P(E)} \cdot P(H)$$

Posterior

Support

Prior

- shows us what effect new evidence should have on our perception

"Extraordinary claims require extraordinary evidence."

Carl Sagan (paraphrasing Hume & Laplace)

N.B. alternate writing: $P_E(H) = P(H|E)$

Bayes' Theorem – Example

Organic gravity

”Gravity only acts on organic things”

vs

Newtonian gravity

“Gravity acts identically on every type of object”

- Test 1 – drop an apple
  - Both theories are equal
- Test 2 – drop a stone
  - Newtonian gravity wins

Bayes' Theorem – Example cont'd

Let’s investigate in bit more detail of what we just did...

- Test 1 didn’t really help
  - It didn’t differentiate
  - It provided equal support to each
- Test 2 solved the issue
  - distinguished between the proposals
  - provided support to Newtonian theory

Organic Gravity Revisited

- Dropping an apple gave no preference
  - P(H) = 0.5 for both

$$P(\text{Newtonian} \mid \text{Stone Falls}) = \frac{P(\text{Stone Falls} \mid \text{Newtonian}) * P(\text{Newtonian})}{P(\text{Stone Falls})}$$

$$= \frac{1 * 0.5}{0.5} = 1$$

$$P(\text{Organic} \mid \text{Stone Falls}) = \frac{P(\text{Stone Falls} \mid \text{Organic}) * P(\text{Organic})}{P(\text{Stone Falls})}$$

$$= \frac{0 * 0.5}{0.5} = 0$$

Assumptions

- Assumption of completeness
  - Don’t have to make this assumption
  - Though we do need some way to calculate P(E)
- Assumption that the evidence was accurate
  - Can factor this into P(E|H)
    → uncertainty of measurement apparatus & detectors (this school)
- Assumption that you understand your models
  - Do you really know P(E|H)?
    → gives rise to sub-field of e.g. 'Theoretic Physics'

Scientific Method – Motivation

Scientific Method – Outline

1. Define a Question
2. Form Hypotheses
3. Perform Experiments
4. Analyse the Data
5. Interpret the Data
6. Peer Review
7. Repeat the Experiment
8. Continual Review

1. Define a Question

- Question must be…
  - Specific
  - Measurable
  - Objective
  - Meaningful
  - Open
- But not necessarily…
  - Naturalistic
- Science is methodologically naturalistic

2. Form Hypothesis

- Possible models to answer our question
  - e.g. origin of 'dark matter'
    - Massive objects – dead stars, wandering planets?
    - Super massive objects – black holes?
    - Weakly interacting massive particles – Elementary particles?
- Background Research/Compare to existing theories
  - see where your theory differs or can falsify the alternate hypothesis
- Models to guide your investigation
  - What are your measurable observables?
  - What are the uncertainties on your observables
    - both theoretic and experimental
- Make measurable predictions <u>before</u> next step!

3. Perform Experiment

- Is it plausible?
  - Back-of-the-envelope calculations, simulations
  - Rough estimates for what we expect to see
- Set the parameters
  - We need our result to be
    - Statistically significant
    - Unbiased → i.e. avoid patternicity, detector systematics/errors
    - Unambiguous
- For large/costly experiments: confirm small-scale/proof-of-concept → large scale
  - improves confidence w.r.t. limit of upper-cost limits, technological hurdles (your sponsors will ask for it)

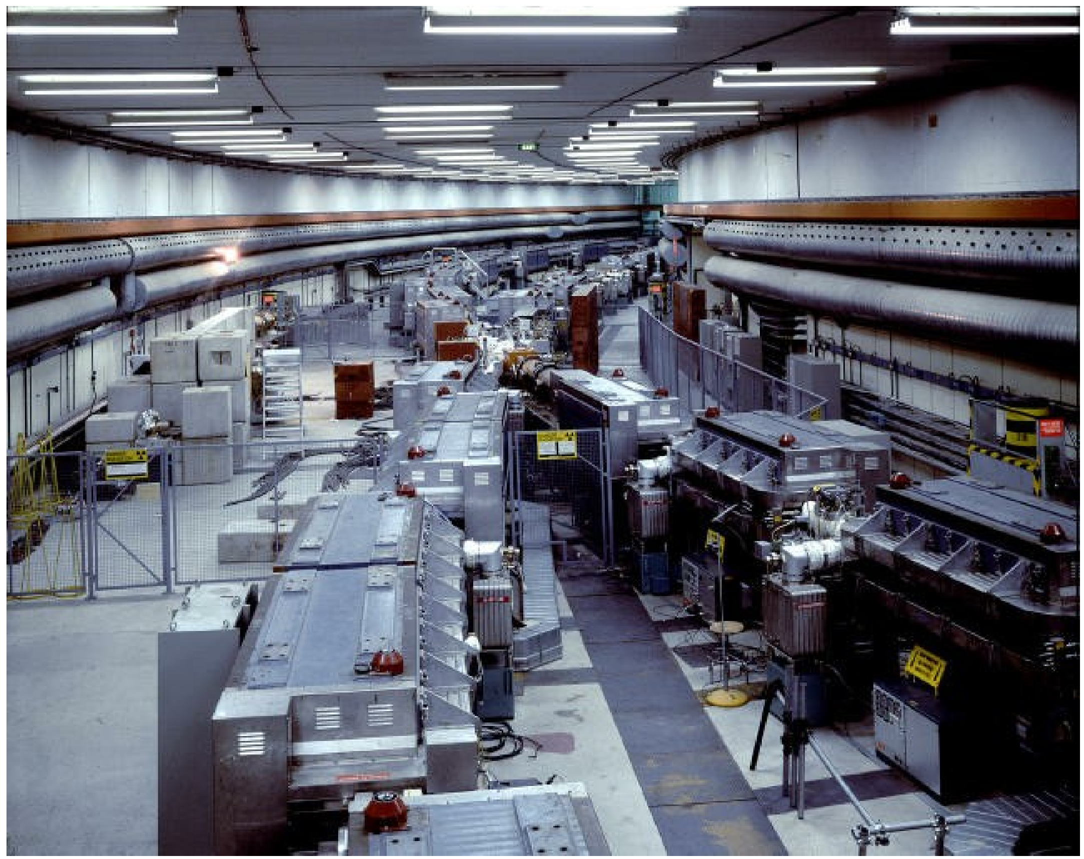
Johann Wolfgang von Goethe

Johann von Goethe
1749 - 1832

- Goethe's disaster of modern physics:
  "man [..] is the greatest and most accurate physical apparatus that there can be, and that is precisely what is of the greatest harm to modern physics, that [..] separated experiments from man;
  one wants to know nature merely through what manmade instruments show, yes, wants to limit and prove thereby what nature can do. [..]
  But man stands at such a high level precisely through the fact that what otherwise could not manifest itself does manifest itself in him."
- Contradictory to building scientific instruments?
- Humans are naturally biased
  - subjective space, time and patternicity perception
  - cannot perceive many (sub-) microscopic effect impacting our life (i.e. germs & elementary particles)
- Instruments more precise, quantitative and reproducible
  - However, instrument measure only what they are designed for (builder's bias)

Intersecting Storage Ring & J/ψ

- Proton-Proton Hadron Collider at CERN (1971-1984)
  - centre-of-mass up to 62 GeV, but missed the J/ψ@3.1 GeV



  - J/ψ later discovered by Burton Richter at SLAC (SPEAR) and Samuel Ting at BNL (AGS) in 1974
  - N.B. however, ISR accelerator forged many modern accelerator concept
    (e.g. Schottky monitor→ stochastic cooling for anti-protons → W/Z Boson at $Sp\bar{p}S$ in '83 → Nobel prize in '84)

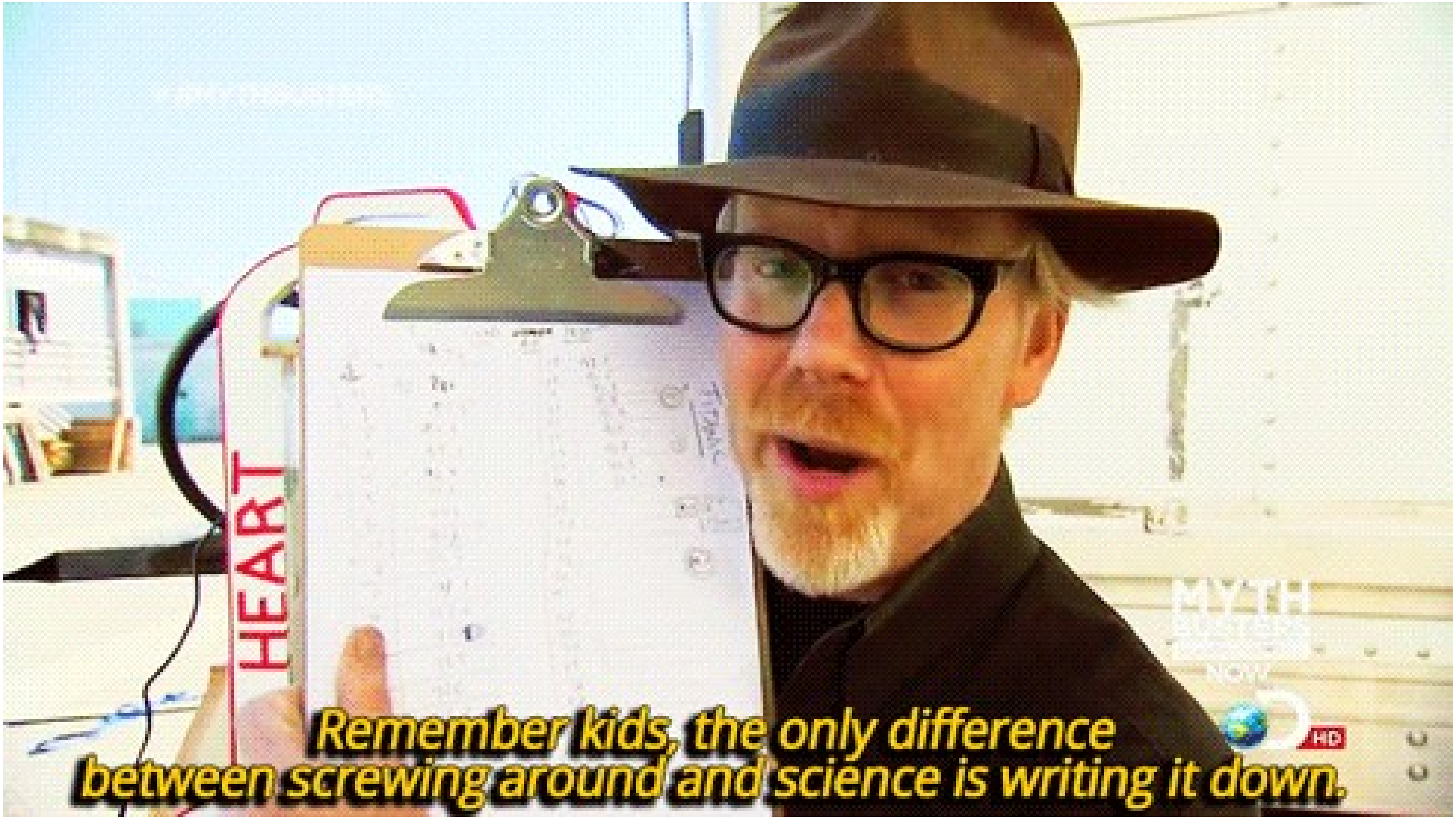
4. Analyse the Data

- This is a very tricky area
  - Scientists often get this wrong
- Statistical significance
  - Agreeing with our hypothesis vs. confirming our hypothesis
- Randomised, placebo-controlled trials
  - The gold-standard for medicine
  - Avoiding accidental or deliberate bias

5. Interpret the Data

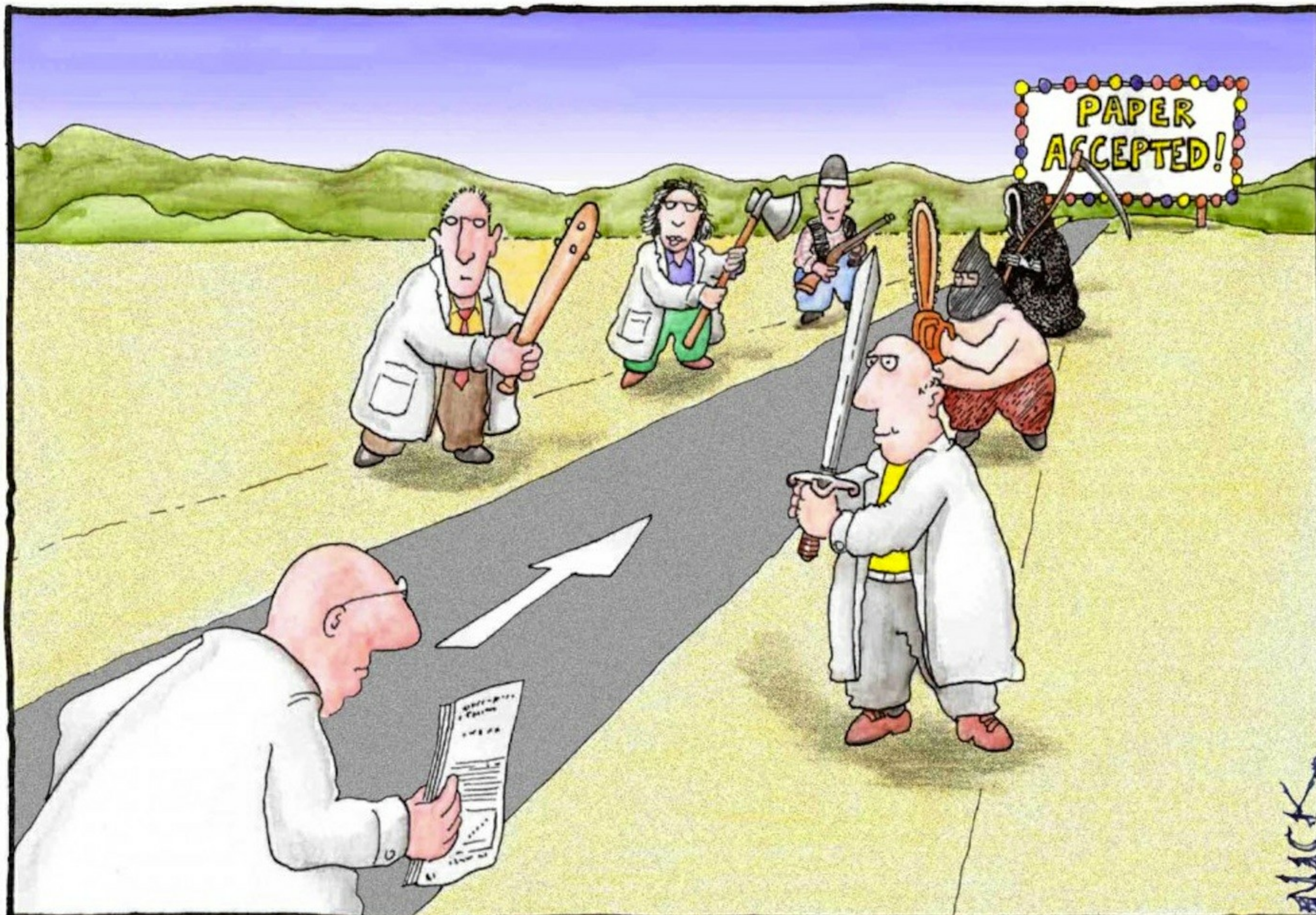
- Bayes' Theorem
  - Do our results support our hypothesis?
  - Remember to include previous results!
- Publication bias
  - Half the story is worse than none
- "Texas sharpshooter" fallacy
  - Outcomes should be clear before the study is performed

Documentation



Courtesy Adam Savage

6. Peer Review



Most scientists regarded the new streamlined peer-review process
as "quite an improvement."

5. Peer Review

- Humans commit errors
  - Confirmation bias
  - Measurement errors
  - Methodological errors
  - Omissions
  - Ignorance

- Peer review reduces errors
  - Humans think differently
  - Incentivises accuracy

7. Repeat the Experiment

- Unknown unknowns
  - E.g. germ theory
- Anomalies sometimes occur
  - Repeat to confirm
- We’re looking for underlying laws
  - Laws should be consistent
  - Tests should be repeatable
- Different assumptions
  - Different mistakes
  - Different equipment
  - Different analysis
  - Pons & Fleischmann

8. Continual Review

- Science does not dictate truths
  - …it assigns probabilities
- Theories are always open to review
  - By anyone
  - Though there is a burden of proof
- Experiments should be repeated
  - Better equipment
  - New methods
  - Different background assumptions

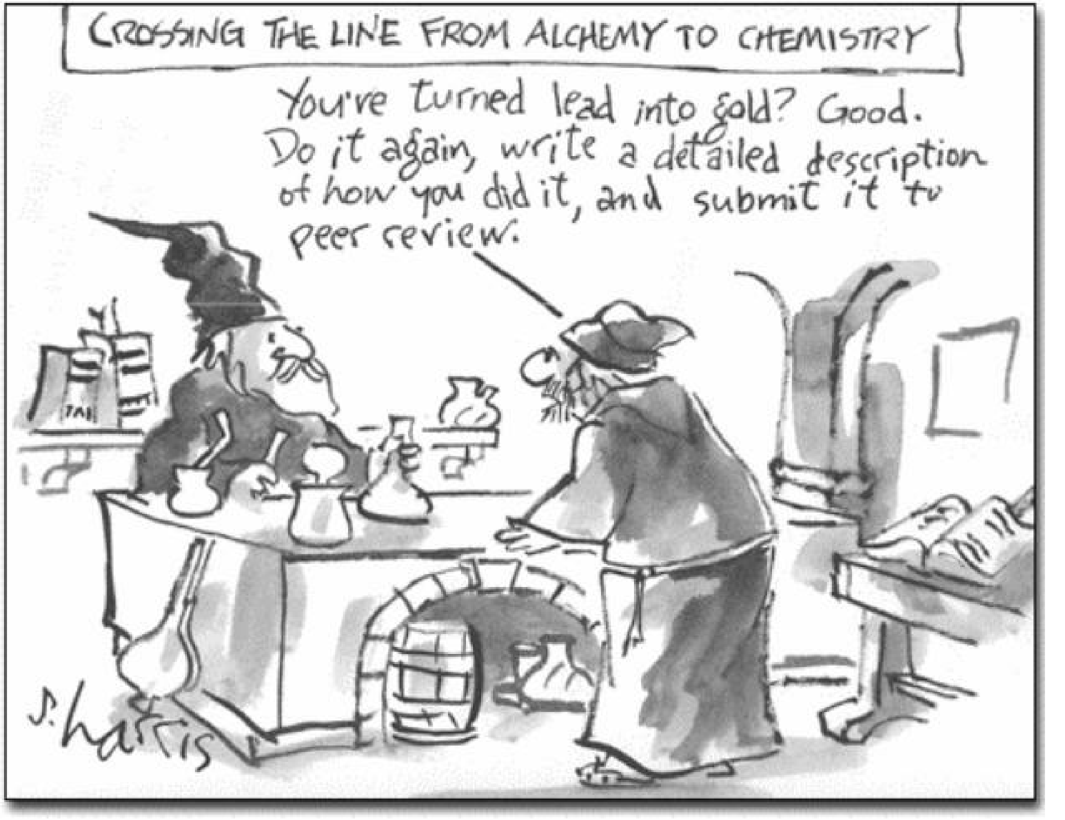
Publication and Impact

Welcome to the Team. Remember, if you follow the University Motto, you'll do fine...

Pseudo-Science

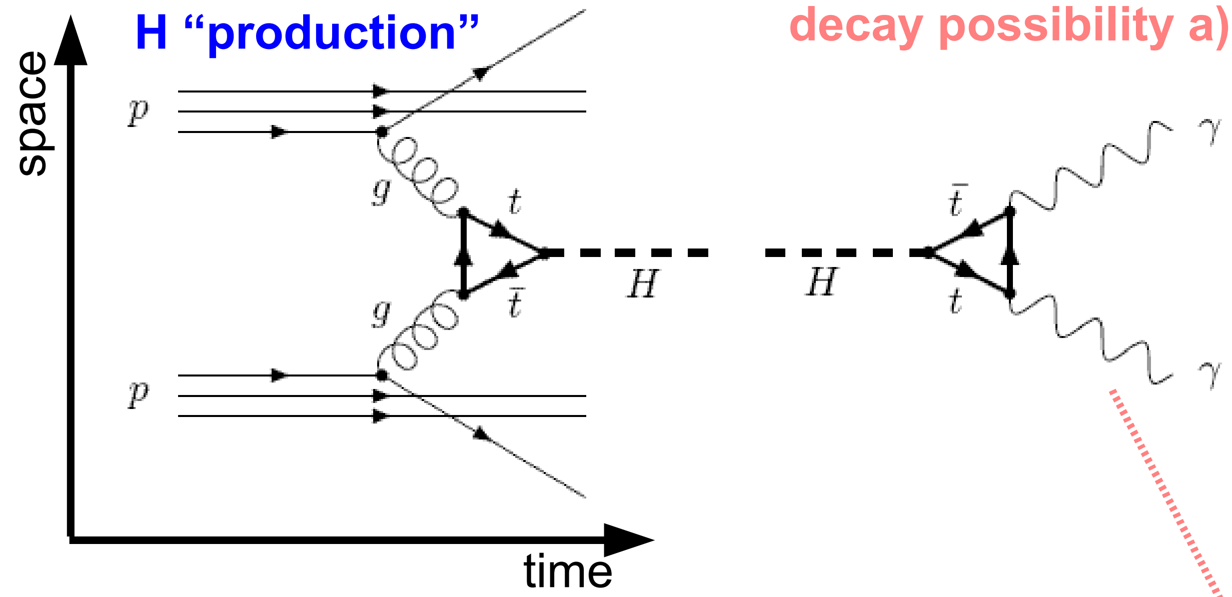
- … looks like science and pretends to be science … but isn't
  - … often guided by motivations other than improving knowledge

- Pseudoscience relies on …
  - Scientific language
  - Appeal to authority
  - Forceful arguments
  - Appeal to intuition
  - Popular media

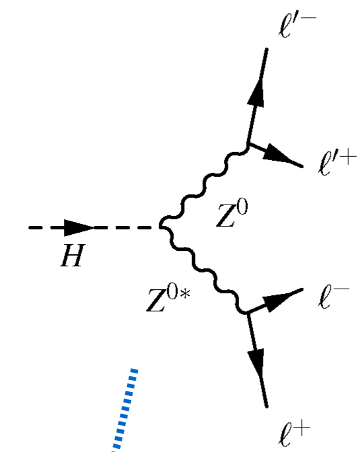


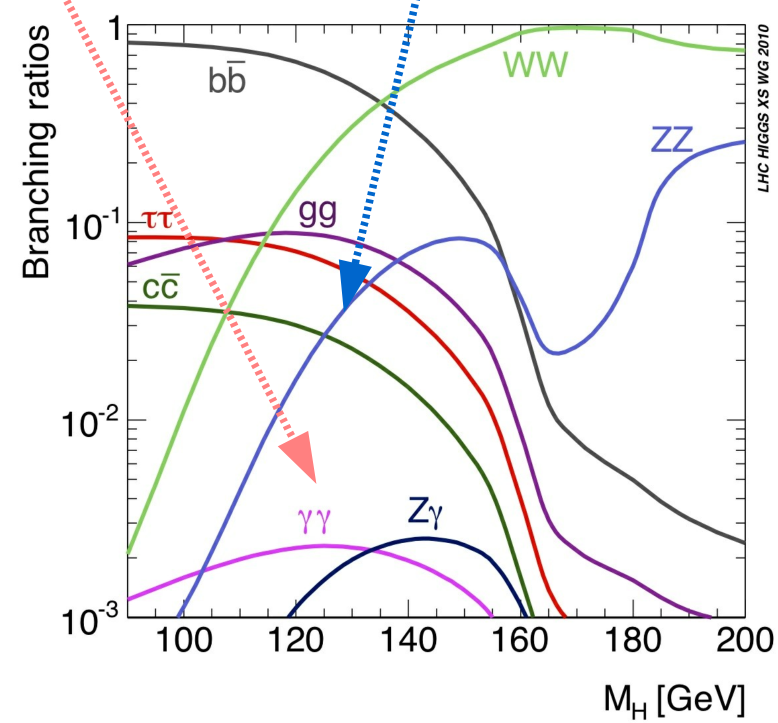
- Michael Shermer: "Baloney Detection": http://www.michaelshermer.com/2001/12/more-baloney-detection/
- List of common logic fallacies: http://www.nizkor.org/features/fallacies/

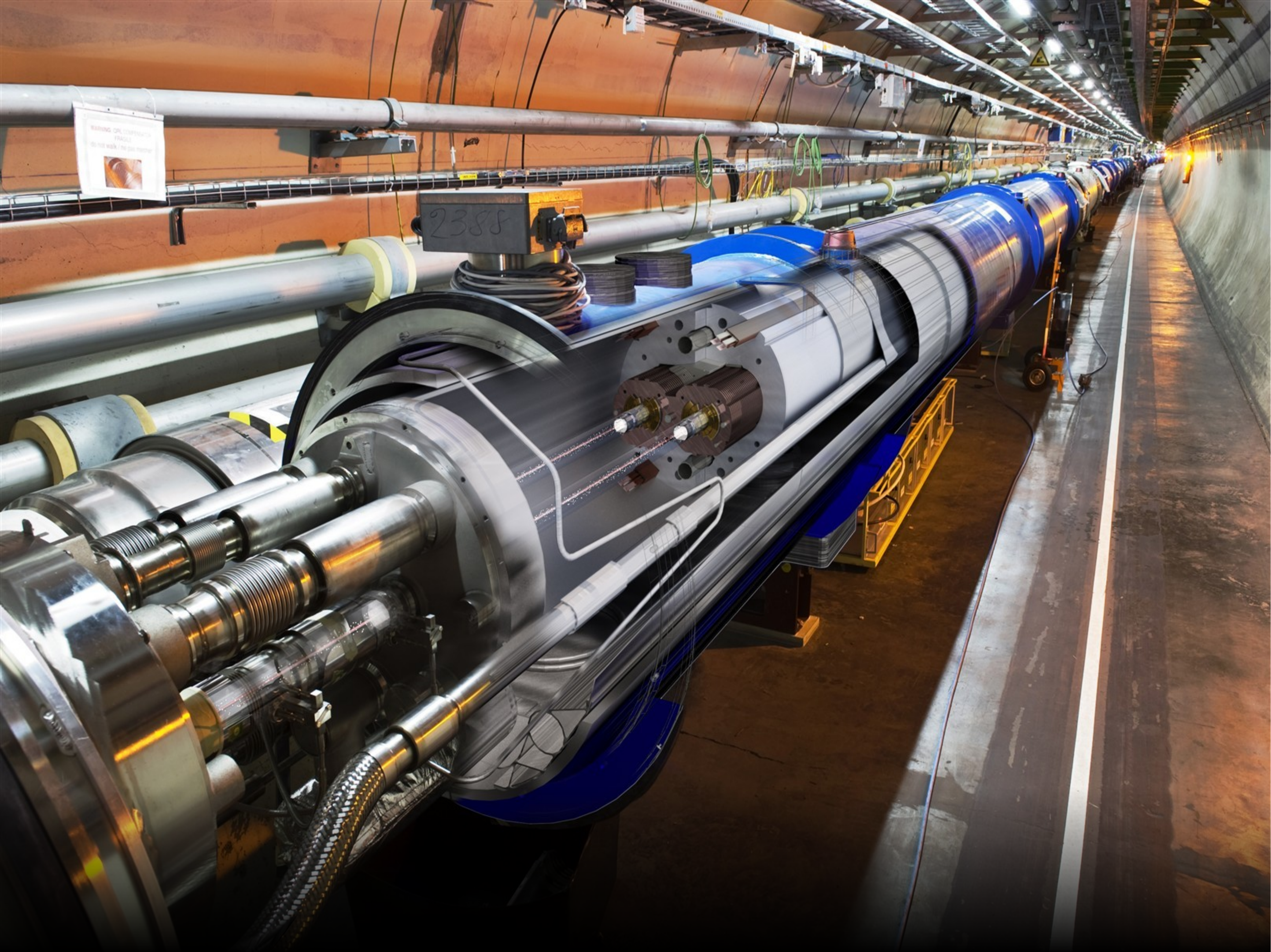
Standard-Model & Feynman Diagrams

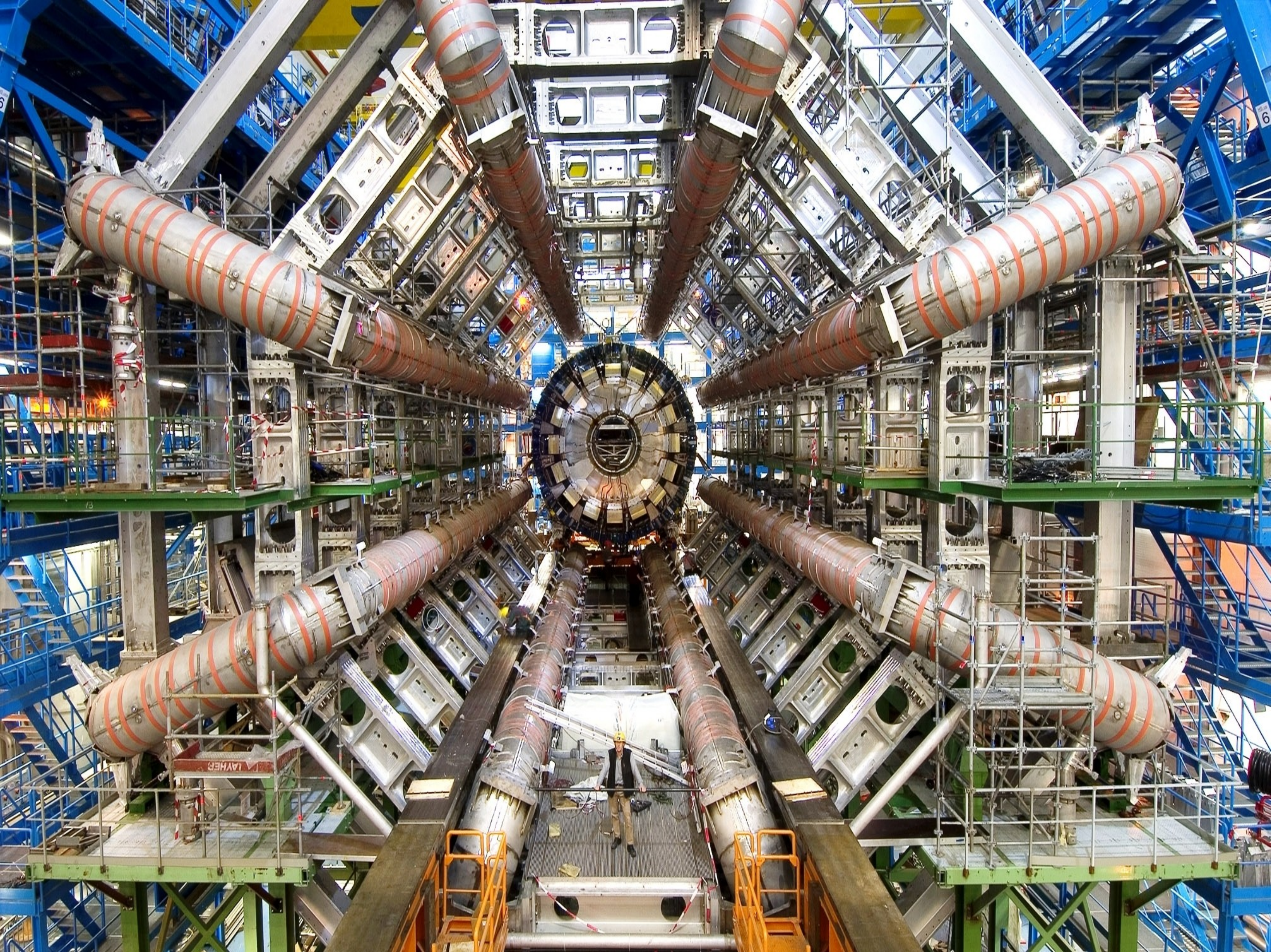


decay possibility b)

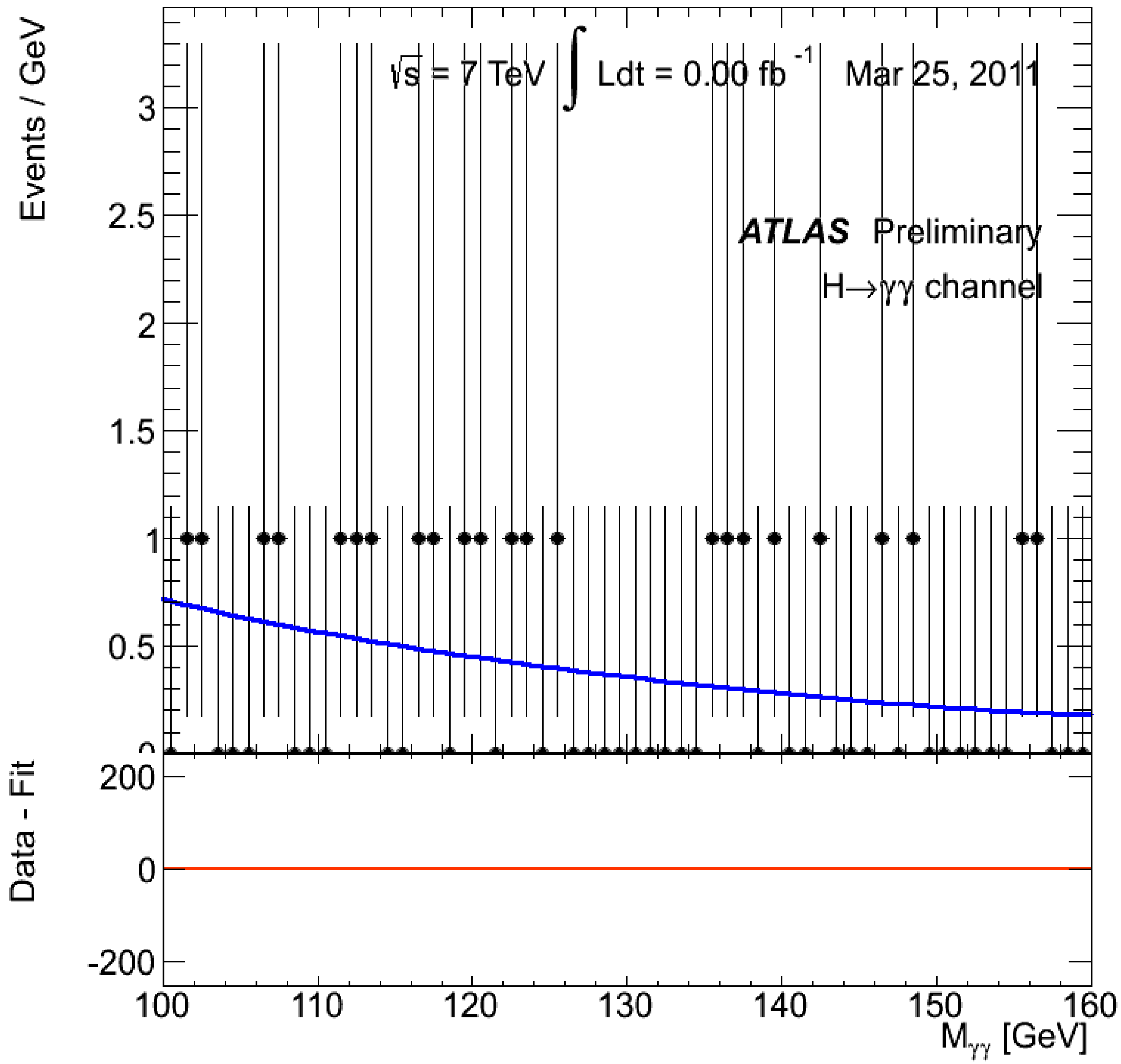




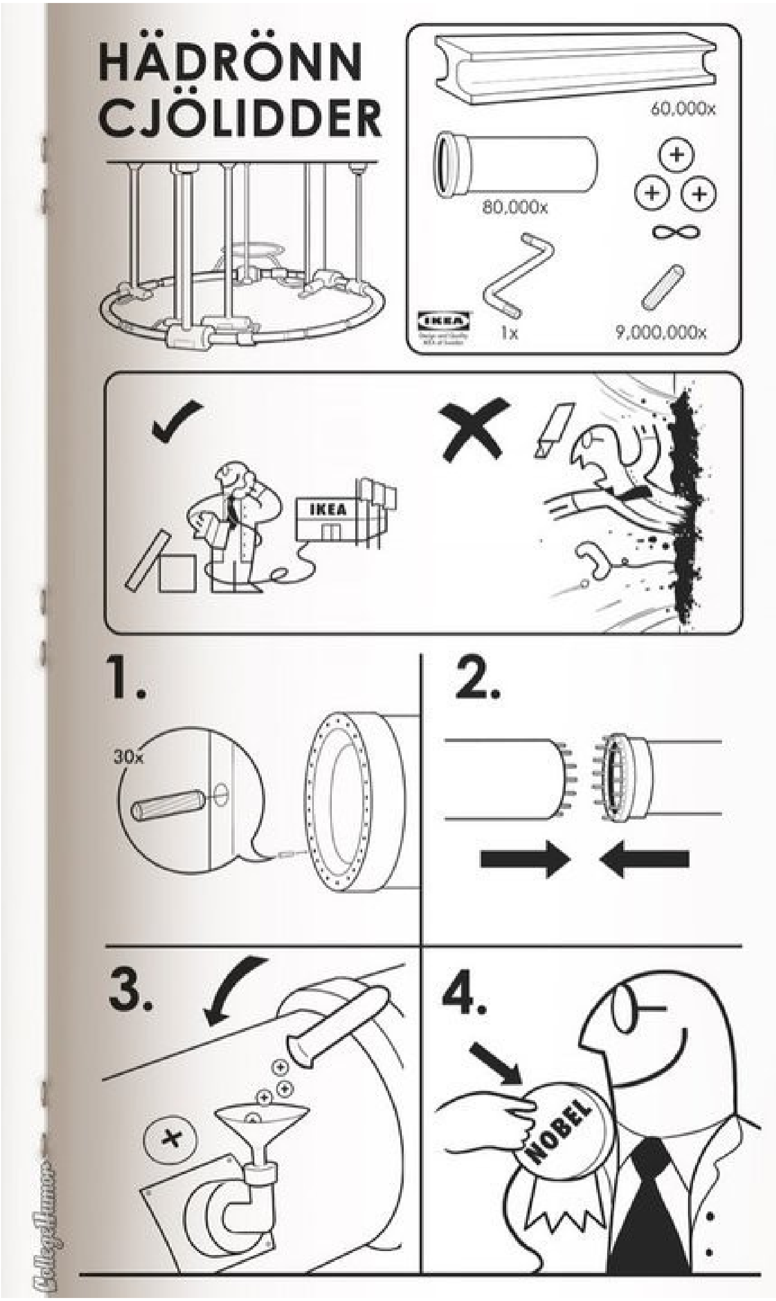

2388


LAYHER

2011 → 2012 The Higgs Hunt: H → γγ



It all looks so easy...



Practise makes perfect

- Scientific method needs to honed...
  … like any other skill (e.g. musical instrument, sports, …)

- First tutorial: 'Electronic Dice'
  Learn to construct simple electronic circuit, apply what you just learned:
  1. Given Questions:
     “Did your tutor temper with your dice kit – is it a fair dice?”
  2. Form Hypotheses
  3. Perform Experiments
  4. Analyse the Data
  5. Interpret the Data
  6. Peer Review → student session on Wednesday
  7. Repeat the Experiment
  8. Continual Review

- Prizes await you for best 'analysis', 'original idea' and 'presentation'!

Summary

- Scientific Method …
  - process for acquiring new, correcting and integrating previous knowledge.
  - designed (over centuries) to…
    - minimise error & maximise discovery of true information
    - build coherent theories & understand weaknesses in our models
    - iteratively improve on our knowledge

- Theories can rarely claim absolute certainty (aka. 'truths')
  - are always tentative
  - assign probabilities to hypothesis

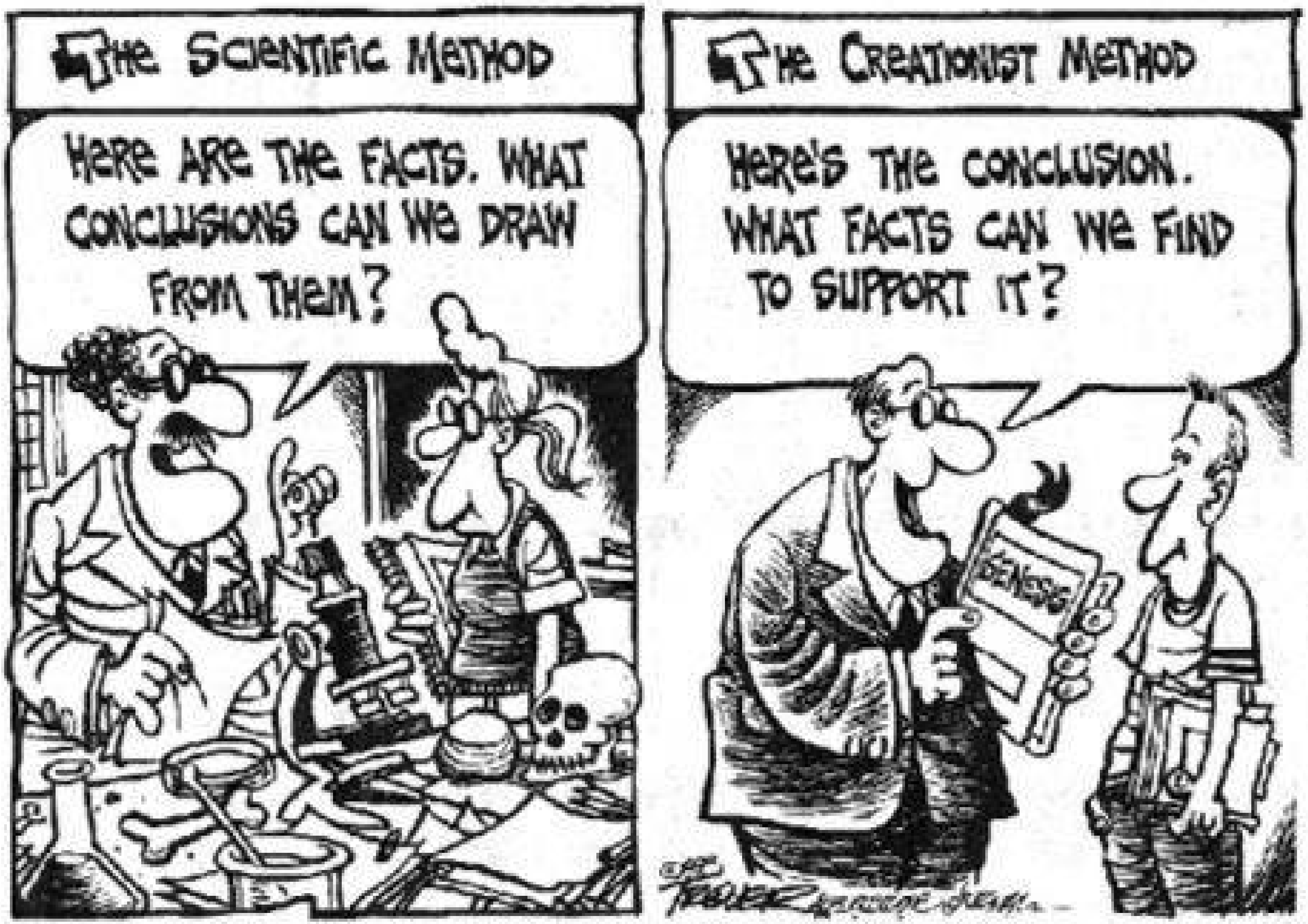
- Bayes theorem allows us to:
  - update hypotheses in response to evidence
  - evaluates the support that evidence gives for a hypothesis

- Needs to be practised to gain perfection

Acknowledgements & Resources

- Very good resource this lecture is based upon:
  - Richard Feynman, “Lecture on Scientific Method”, 1964: http://www.youtube.com/watch?feature=player_embedded&v=EYPapE-3FRw
  - 'Understanding Science' lecture series by Colin Frayn: http://frayn.net/blog/?page_id=354
  - Foster & Kokko: “The evolution of superstitious and superstition-like behaviour”, Proc. R. Soc. B, 2009, 276
  - Michael Shermer: “Patternicity: Finding Meaningful Patterns in Meaningless Noise”, Scientific American, Nov'2008 http://www.scientificamerican.com/article.cfm?id=patternicity-finding-meaningful-patterns
  - Michael Shermer: “Baloney Detection”: http://www.michaelshermer.com/2001/12/more-baloney-detection/
  - The Skeptics Society: http://www.skeptic.com/
  - List of common logic fallacies: http://www.nizkor.org/features/fallacies/

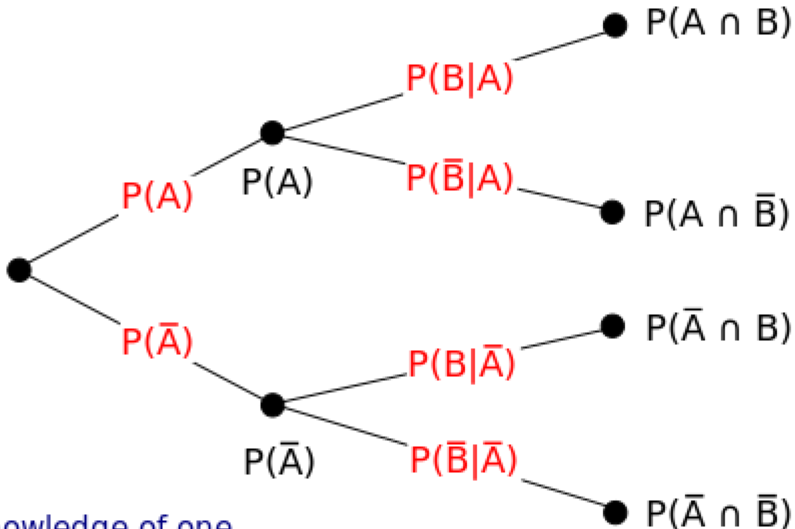
'Scientific Method' – Corner Stone of Science

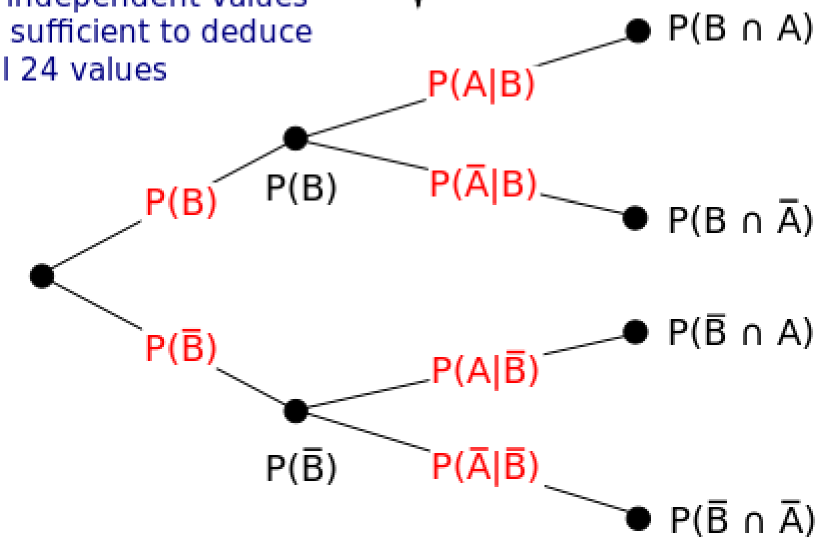


The facts are coming! The facts are coming!

Bayes' Theorem – The Math View

Knowledge of any
3 independent values
is sufficient to deduce
all 24 values





Knowledge of one
diagram is sufficient
to deduce the other

$$P(H|E)\cdot P(E) \;=\; P(H\cap E) \;=\; P(E|H)\cdot P(H)$$

N.B. alternate writing: $P_E(H) = P(H|E)$

Isaac Newton Additional

- “Rule I. We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.” (Isaac Newton, Principia mathematica, 1687)
- Rule II. Therefore to the same natural effects we must, as far as possible, assign the same causes.
- Rule III. The qualities of bodies, which admit neither [intensification] nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.
- Rule IV. In experimental philosophy we are to look upon propositions collected by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, 'till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions,

Publication and Nobel Prizes