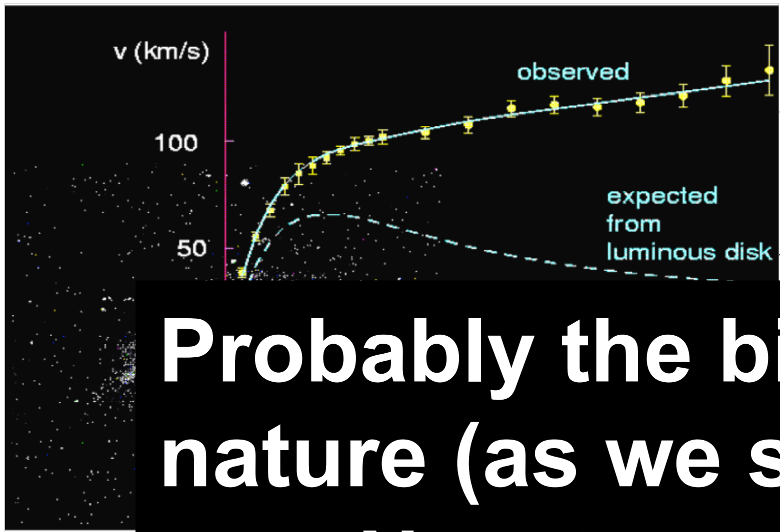
The search for new physics (at the LHC)

Paris Sphicas
CERN & University of Athens
CERN Summer Student program
July 29 - 31, 2013

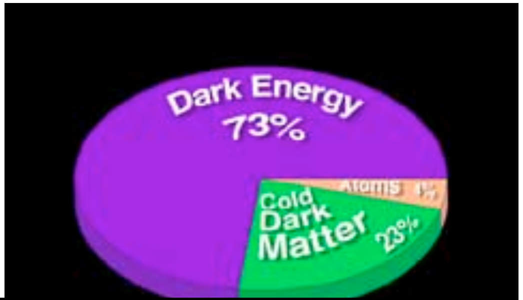
- **Prelude – reminder of the prerequisites**
  - **Why we believe there should be new physics BSM**
  - **Proving that there is "new physics"; main prerequisites: understanding the detector, understanding (measuring) Standard Model physics at 7 and 8 TeV**
  - **What happens when we do not find a new signal [limits]**
- **Searching for New Physics**
  - **Searching for substructure, new interactions**
  - **Supersymmetry [SUSY]**
  - **Searches for Exotica**
- **Summary**

Prelude:
Why we believe that there should be new physics (physics beyond the SM)

Real reason(s): dark matter



Dark (invisible) matter!

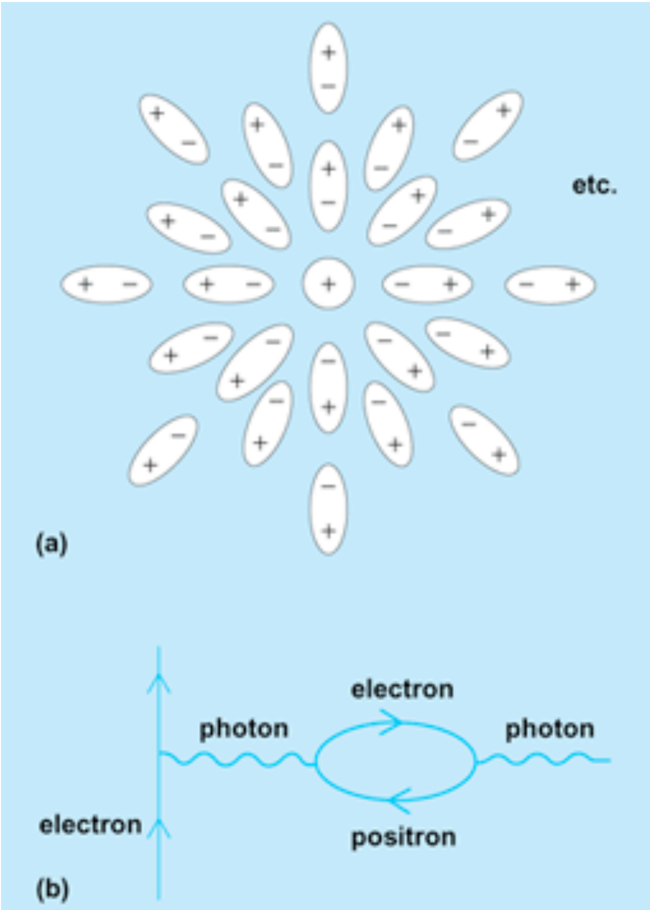


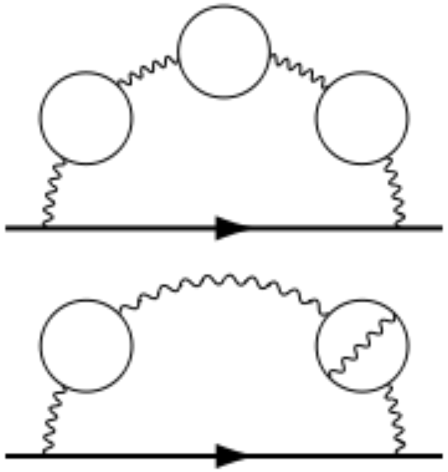
Probably the biggest mystery in nature (as we speak)

- **New type of matter?**
- **New forces?**
- **New dimensions?**

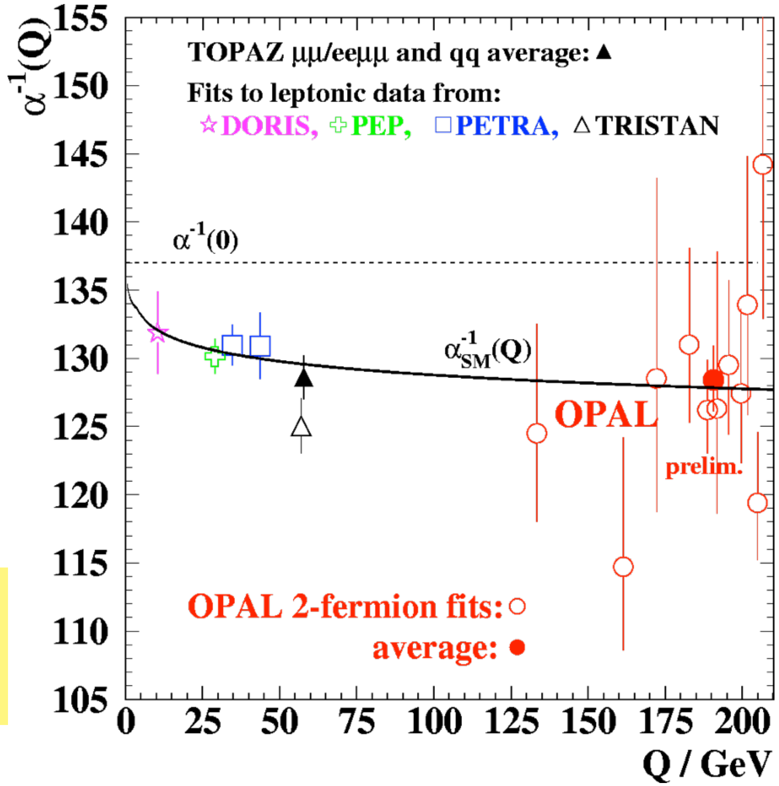
Virtual reasons (I)

- **Quantum mechanics + relativity: strength of force varies with distance (energy scale)**
  - **Antimatter (positron) regularizes infinity in self-energy (e^2/r)**



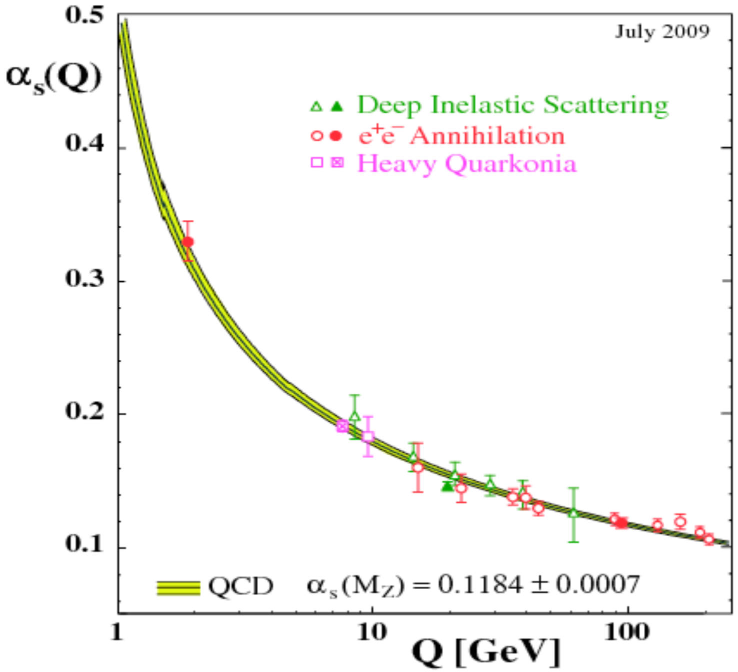


$$\beta(\alpha_s^{\mathrm{ren}}) \equiv \mu^2 \frac{d\alpha_s(\mu^2)}{d\mu^2}$$



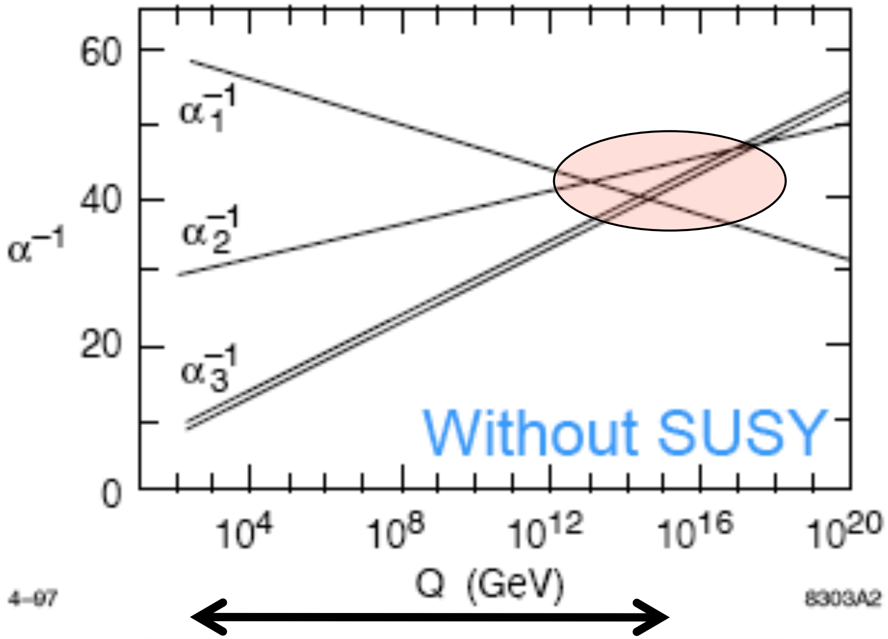
So, things run

- **Strong interaction: gets weaker with energy**



  - **Electromagnetism gets stronger…**

- **Extrapolating all three forces:**

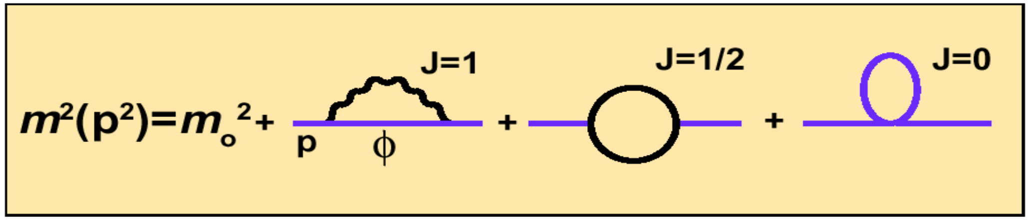


Extravagant! though possible!?

But the Higgs self-energy does not like this

Standard Model (problems or blind spots)

- **Foremost: how can the mass of the Higgs boson be anything "small"?**
  - It should "resist" itself (since it couples to mass, it should couple to itself as well)
  - Its mass should be almost infinite!
- **Quadratic divergence in the Higgs mass**



$$m^2(p^2) = m^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2$$

  - Why is the Higgs mass so low? What is the mechanism?
  - Strong dependence of Physics(Λ_{EWK}) on Physics(Λ_{PL})
    - It's like saying that to describe the Hydrogen atom one needs to know about the quarks inside the proton (not true!)
    - Implies extreme fine-tuning (ETF) of parameters

Some additional questions

- If cut off at Λ_{PL}, why $m_W \ll M_{Pl}$? Or, why is gravity ($G \sim 1/M_{Pl}$) so weak?
  - And by the way, the mighty SM ignores gravity (too weak)
- Interestingly, beyond the Higgs, the biggest problems come from gravity-related measurements:
  - Dark matter, Dark Energy, and a non-matter-dominated universe
- Where is all this vacuum energy?
  - We would expect a tremendous energy density, >Googol (10^{100}) times larger than observed! ("Cosmological constant too small")
  - Size of the universe if the Higgs, as we expect it was there (ALONE): a football (soccer) ball)

The way beyond

- **The most tractable of all these questions is that of the weak/Higgs mass scale – and “naturalness”**

- **Four “solutions” (with numerous variants):**
  - **New physics appears near EWK scale (SUSY? fix divergences)**
  - **New physics modifies couplings: GUT at the EW scale**
  - **Extra dimensions: gravity is strong in ND, weak in 4D; e.g. $M_{Pl}(5D)$ ~ TeV ?**
  - **Anthropic principle: accept ETF! statistical explanation of $m_W \ll M_{Pl}$: due to huge number of “input ensembles”**

Mission of the LHC: probe the TeV scale

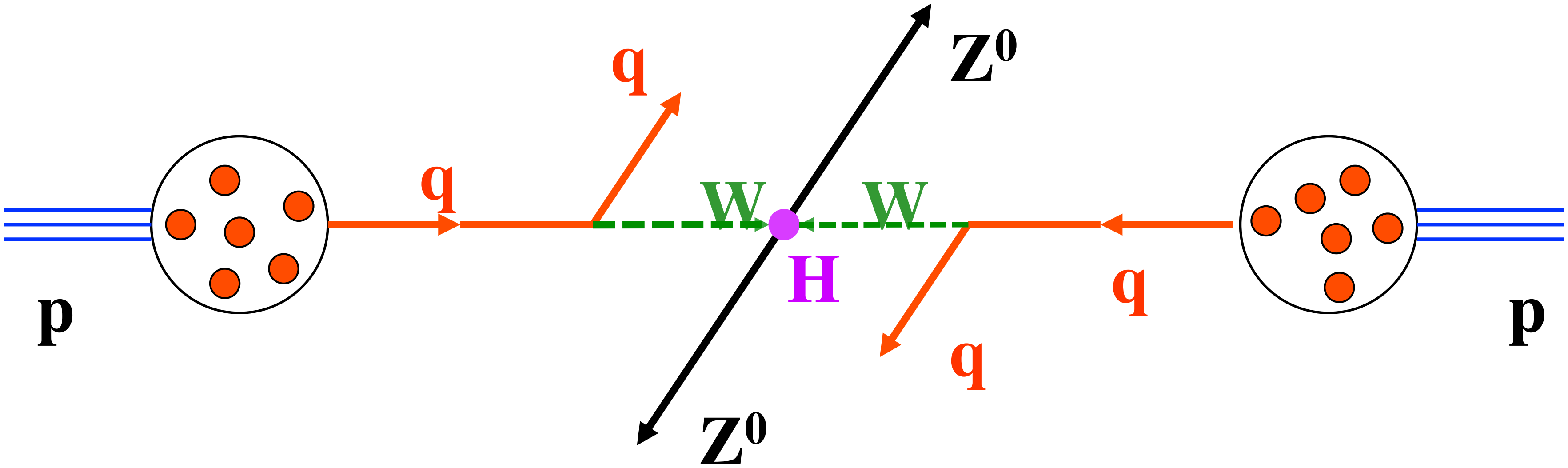
- **A (long-sought) Higgs boson has been found!**
  - Still quite a bit to do to establish properties etc.

- **Even if the new boson is *the SM Higgs*, all is not 100% well with the Standard Model alone**
  - The same mechanism that gives all masses would drive the Higgs mass to the Planck scale.
  - If SUSY (see later) is the answer, it must show up at O (TeV)
  - TeV-scale gravity? Again, something should happen in the O(1-10) TeV scale if the above issues are to be addressed

- **Conclusion: we need to study the TeV region**
  - Corollary: need to understand SM physics at 1TeV first!

Probing the TeV region pp collisions

Higgs Production in pp Collisions



$M_H \sim 1000$ GeV

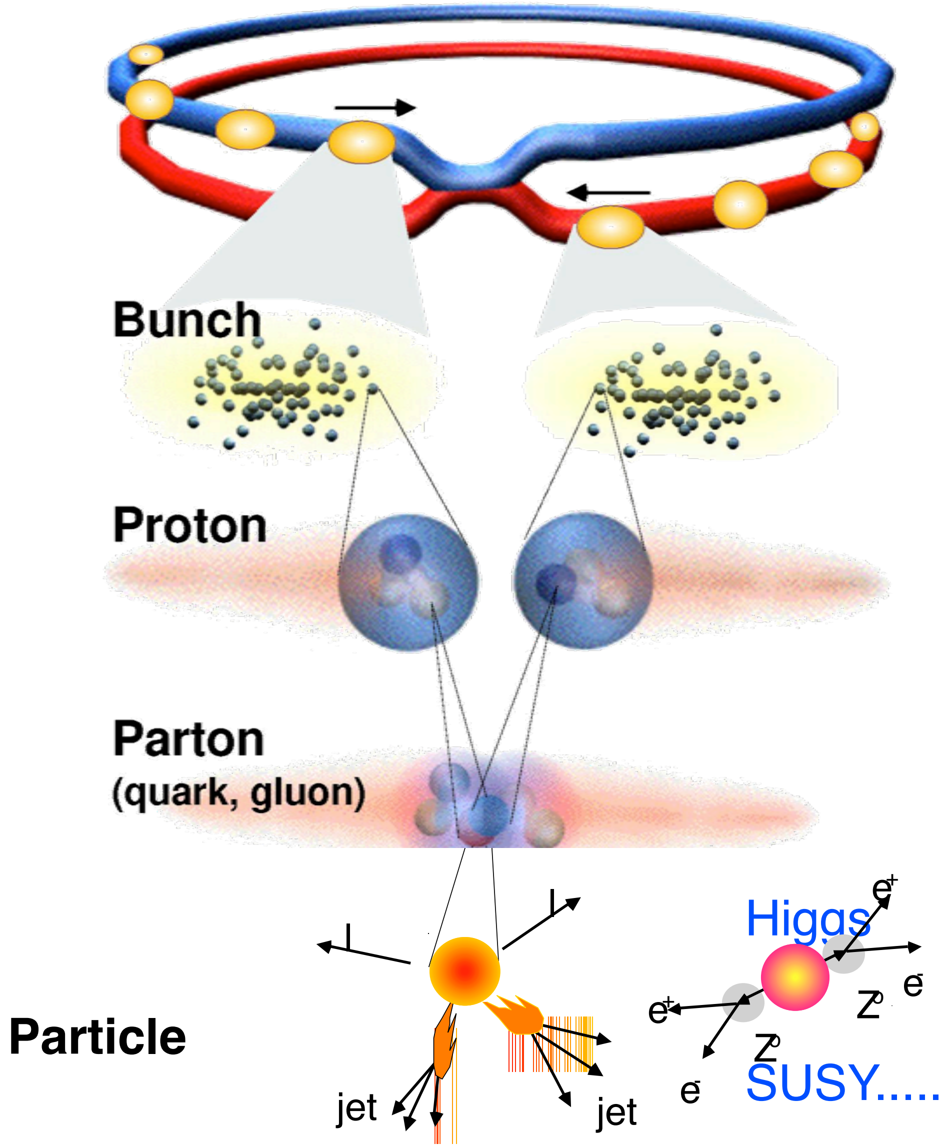
$E_W \geq 500$ GeV

$E_q \geq 1000$ GeV (1 TeV)

$E_p \geq 6000$ GeV (6 TeV)

→ Proton Proton Collider with $E_p \geq$ 6-7 TeV

Collisions at the LHC: summary

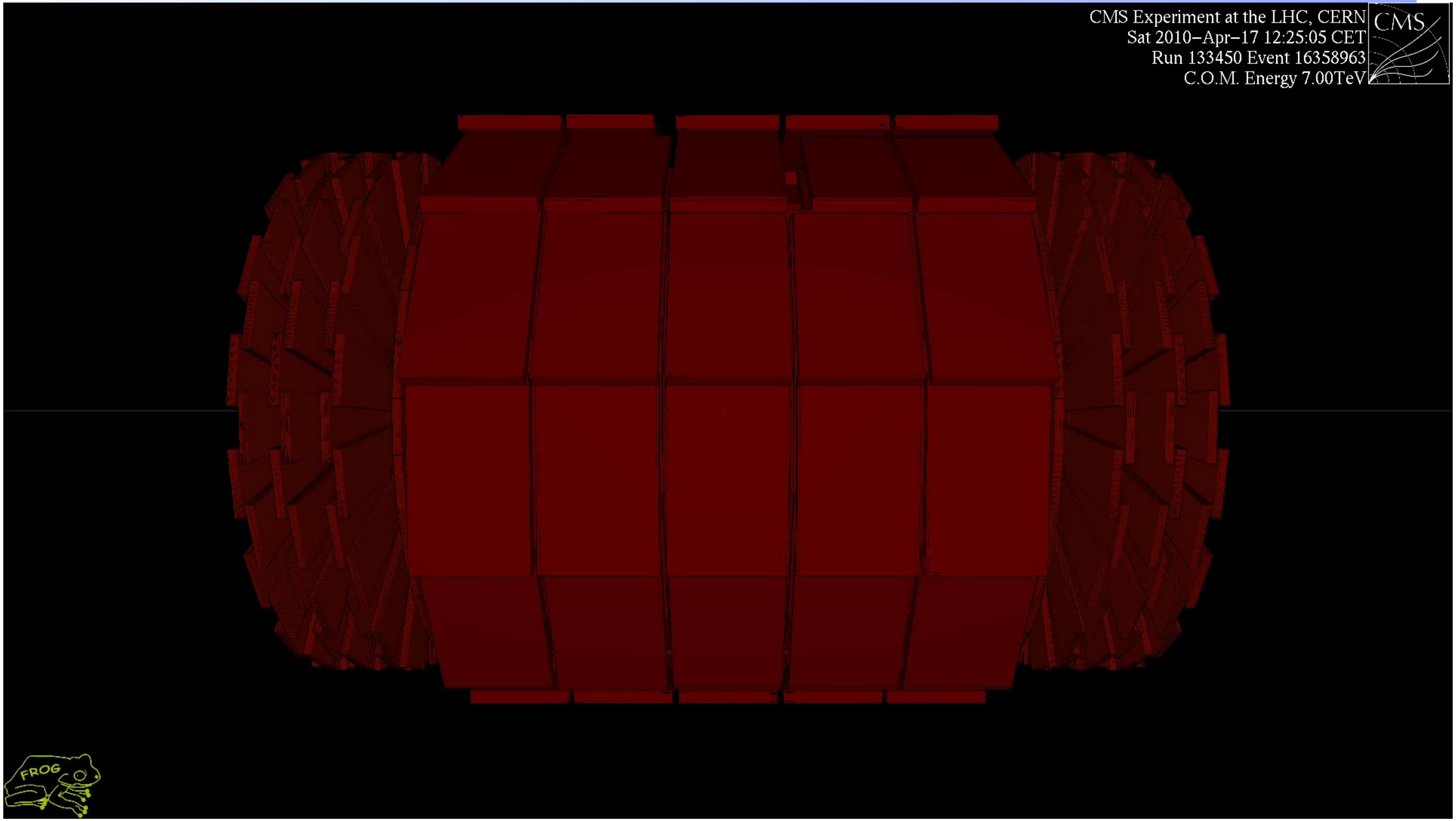


Proton - Proton	2808 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	$10^{34}cm^{-2}s^{-1}$
Crossing rate	40 MHz
Collision rate ≈	10^{7}-10^{9}

New physics rate ≈ .00001 Hz

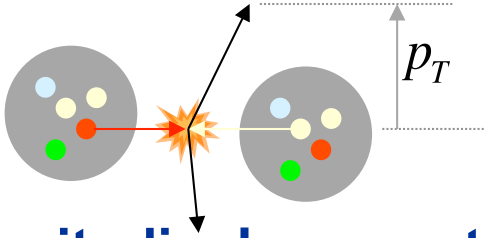
Event selection:
1 in 10,000,000,000,000

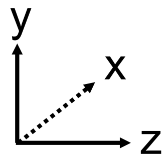
A real event from a pp collision at the LHC

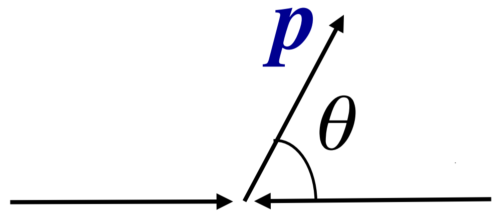


pp collisions: kinematics (I)

- "Natural" variables would be p, θ, ϕ





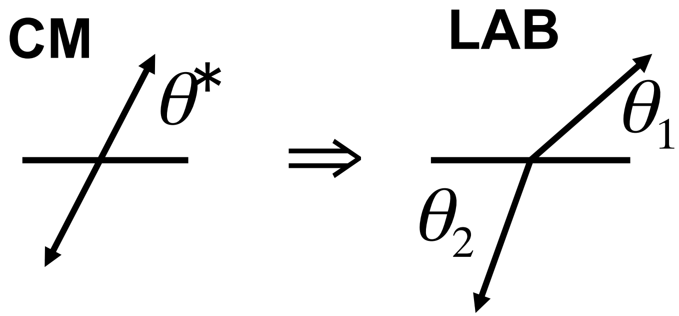


  - Longitudinal momentum & energy, p_z & E: not useful
    - Particles escaping detection have large p_z; visible p_z not conserved: $\sum_i p_{z,i} \neq 0$
  - More useful: transverse momentum, p_T
    - Particles escaping detector (low θ) have pT≈0; visible p_T conserved: $\sum_i p_{T,i} \approx 0$

- LAB ≠ parton-parton CM system

Parton CM (energy)^2 $\rightarrow \hat{s} = x_1 x_2 s$

Worse: p, θ not invariant under Lorentz boosts along z (not good, especially in two-particle correlations)



pp collisions: kinematics (II)

- **Using rapidity and pseudorapidity instead**

Rapidity (y)

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

$$\beta \to 1 \ (m << p_T):$$

Pseudo-rapidity (η)

$$\eta \equiv -\ln\tan\frac{\theta}{2}$$

$\Delta y, \Delta\phi$: invariant under Lorentz boosts along z

Distance between two particles:

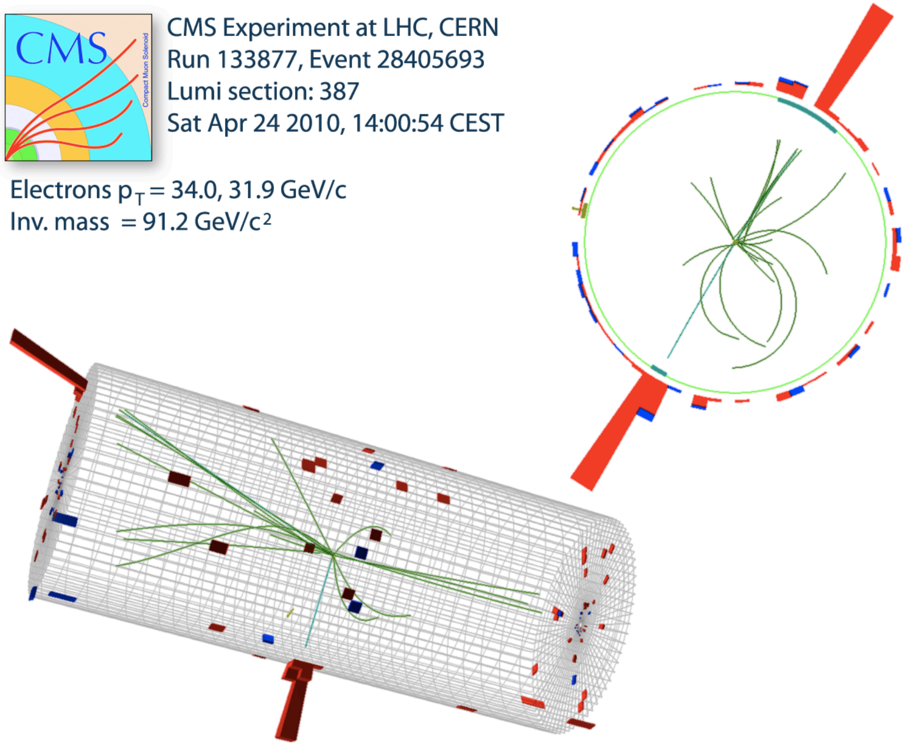
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

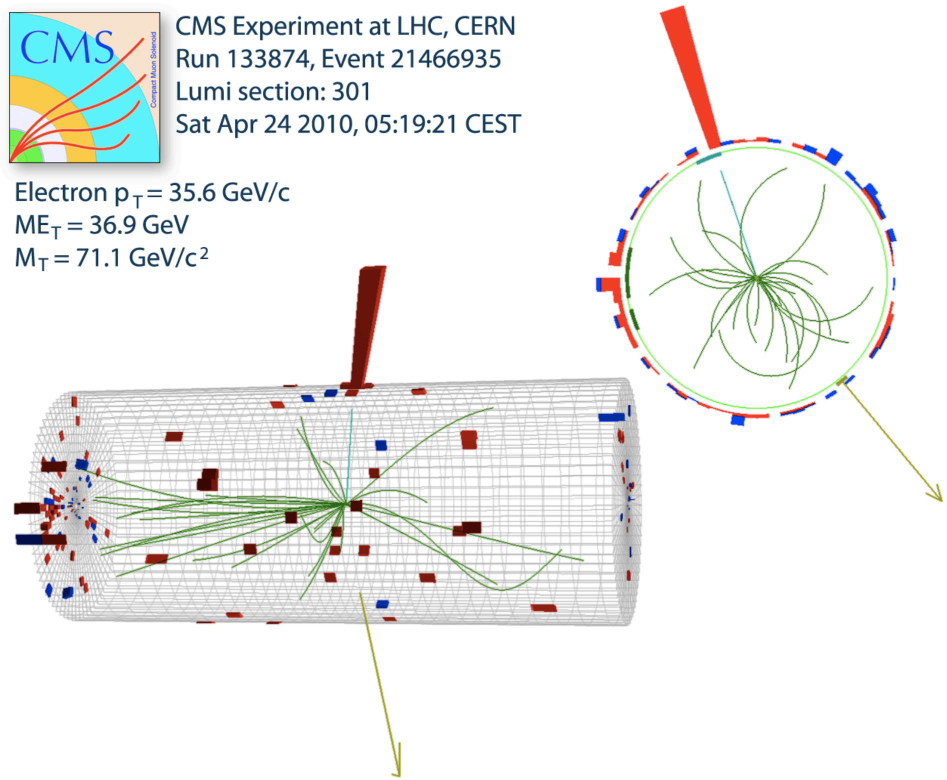
- **Bottom lime: particles described by p_T, y, ϕ**

Mass, MET & transverse mass

Z → electron + positron

W → electron + neutrino



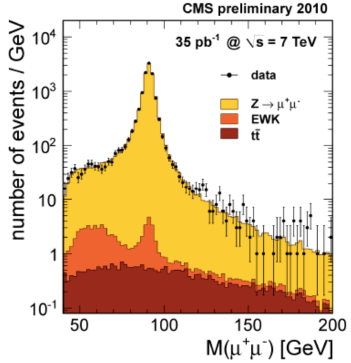


Transverse Mass,

$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1-\cos\Delta\phi_{e,miss}}$$

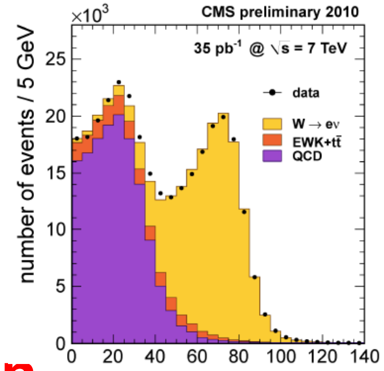
Summary of high-P_T & high-mass probes

- **High-P_T di-objects: jets, leptons and photons**
  - Mass(jet-jet), Mass(ℓℓ), Mass(γγ)

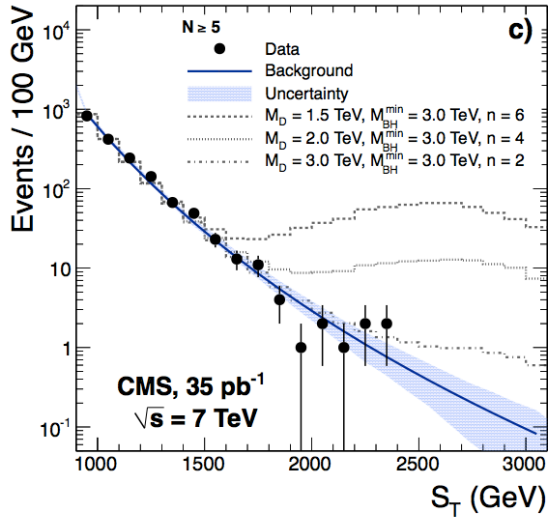


- **High-P_T lepton + ME_T (e.g. from neutrino)**
  - Transverse mass

$$M_T = \sqrt{2E_T^{\mu} E_T^{miss}\left(1-\cos\Delta\phi^{*}\right)}$$

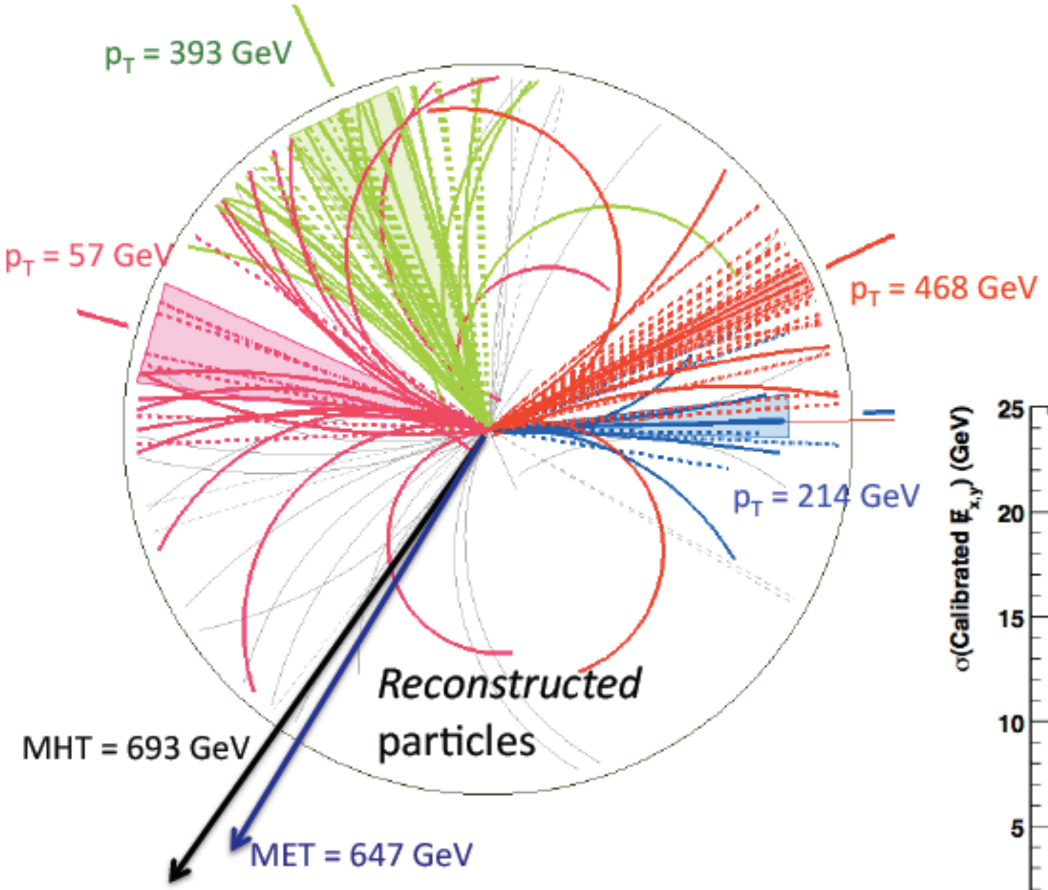


- **Combination of objects, e.g. as in SUSY and BH searches**
  - Various sums of transverse energies in the event
  - H_T: sum of all hadronic jets
  - S_T: sum of E_T of all objects (add leptons, photons, ME_T)
    - Also called "effective mass" (M_{eff}) in past LHC publications



Hadronic variables: definition

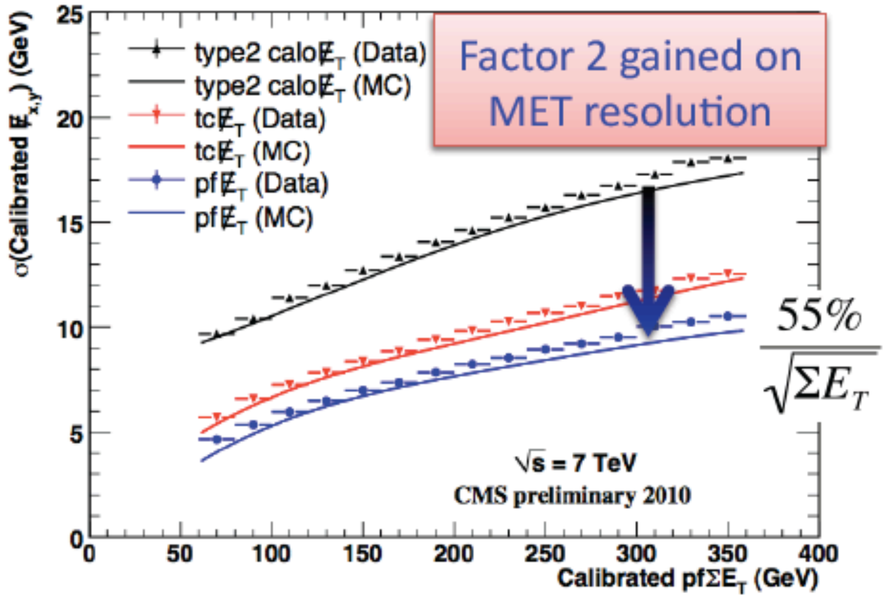
Highest MET multi-jet event recorded in 2010



$$\vec{E}_T^{miss} = \overrightarrow{MET} = -\sum_{\text{All particles}} \vec{p}_T$$

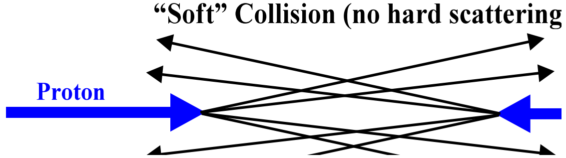
$$\overrightarrow{MHT} = -\sum_{\text{Jets}} \vec{p}_T$$

$$HT = \sum_{\text{Jets}} p_T$$



The “underlying event"

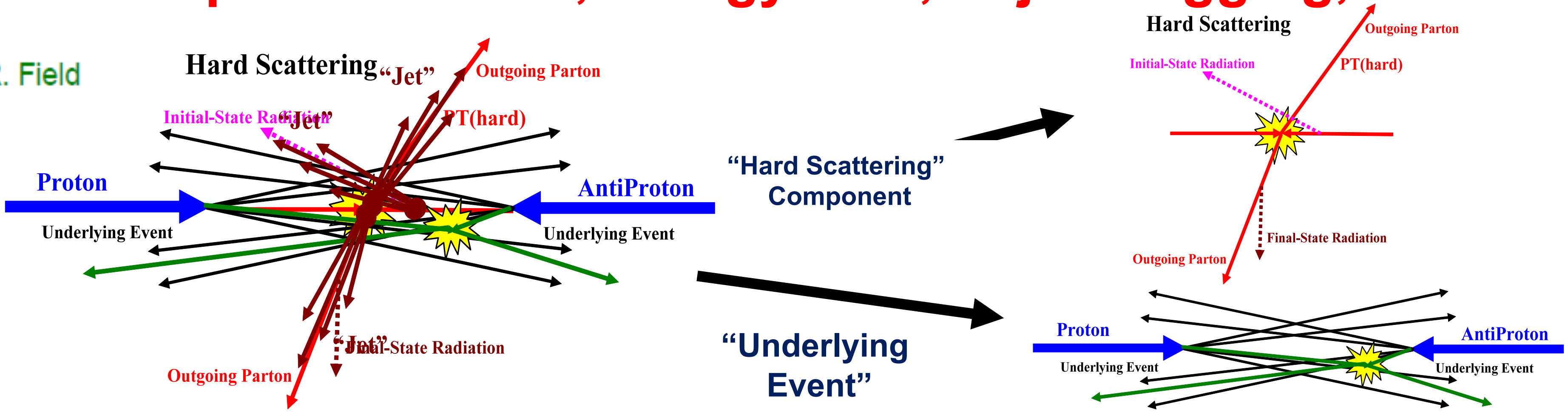
- **The UE consists of the “beam remnants” and from particles arising from soft or semi-soft multiple parton interactions (MPI)**
  - **The underlying event is not the same as a minimum bias event**



No hard scattering
“Min-Bias” event

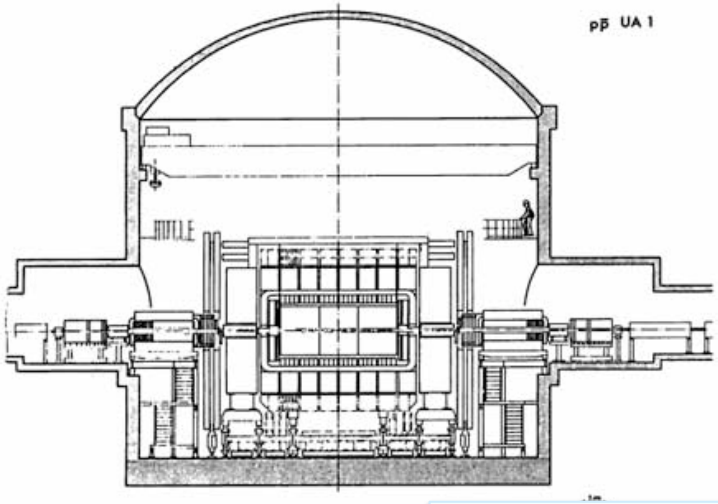
- **Modeling of UE: important ingredient for jet physics and lepton isolation, energy flow, object tagging, etc**

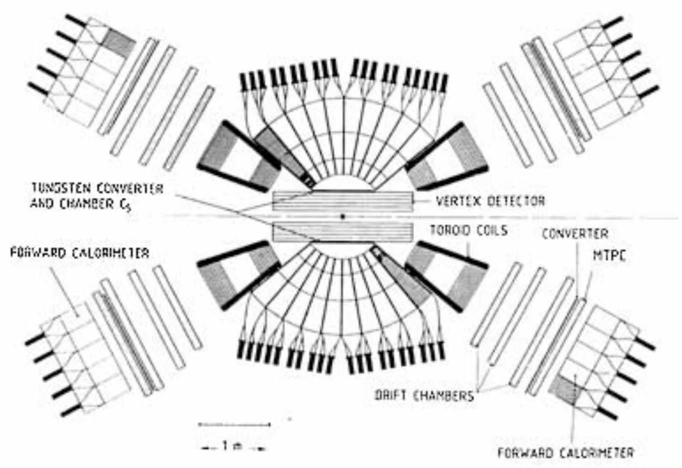
à la R. Field

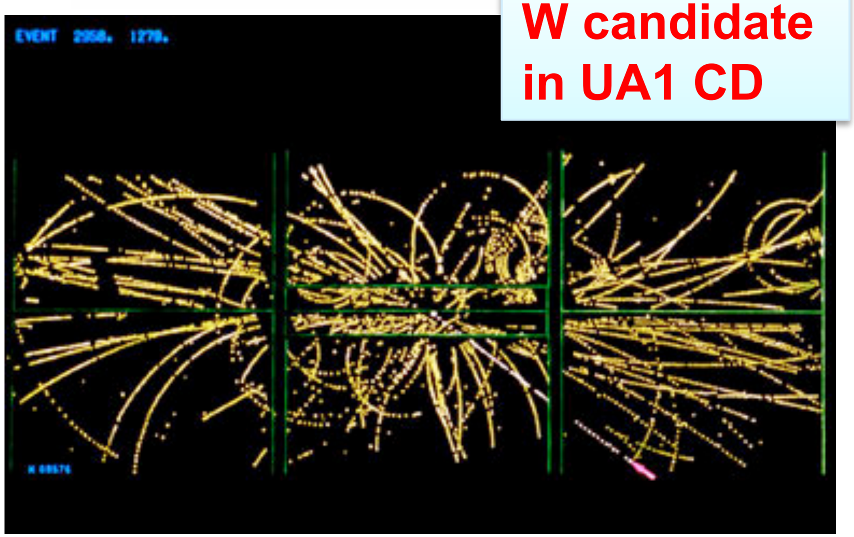


Defeating the underlying event (the 80's)

- **Short parentheses** (history of "dirtiness" in hadron collisions)

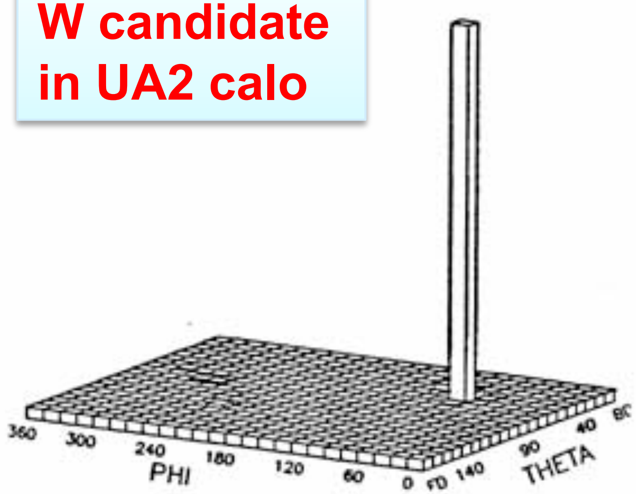






W candidate in UA1 CD

W candidate in UA2 calo



How to discover new physics

FAQ: HTDNP

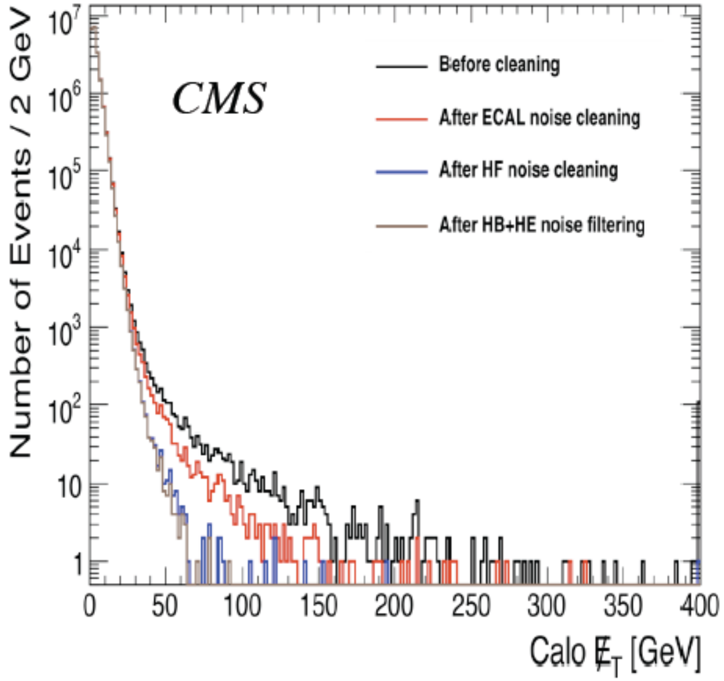
- 100 (+2) years after Rutherford: is there [yet] another layer in matter? Are quarks and gluons composite [just like the proton/neutron in the 1960's; and the atom 100 years ago?]
- Recipe:
  - Scatter probes off of object-of-interest (LHC machine, experiments)
  - Ensure one calibrates experiments, basic outgoing objects
  - Ensure expectations from all that is known up to that point are well understood; if there are uncertainties: make *&^#! sure they are correctly estimated
  - Compare data with "theory": any departure from the expectations?
- The two big issues: convince the world we understand the "expectation"; and convince the world we know what we have found.

Understanding the detector (I)

- **Example 1: understand reconstruction of physics objects [e.g. for electrons or muons]**
  - Suppose Grand Theory X342 implies that we should be looking for a signature of one muon, plus 3 jets
    - Naturally: use a combination of Monte Carlo simulation of all known processes [e.g. W+3 jets; $W \to \mu\nu$] that give this signature plus data events with 1μ+3jets
    - But what about another background: Z+3 jets, for which we lose one lepton from the $Z \to \mu\mu$ decay?!
  - Worse: we can only get a *feeling* for the size of the effect from Monte Carlo and detector simulation
    - *But this [MC+simu] will never get the answer quite right*
    - One needs to find a way of calculating this efficiency from the only source that speaks the absolute truth: the data!
- **Thus, we refer to "data-driven" methods / techniques**

Understanding the detector (II)

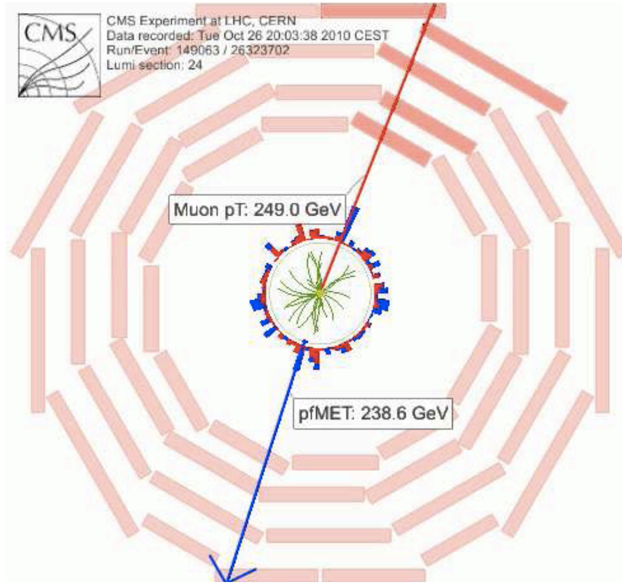
- **Example 2: understand missing transverse energy**
  - There are many instrumental sources of MET!
  - Calorimeter Noise
    - Need "noise filter"
  - Beam halo [particles from the beams]
    - Need "halo filter"
  - Cosmic muons traversing detector!
    - Can shower in the calorimeter!
    - Use tracks, topological cuts

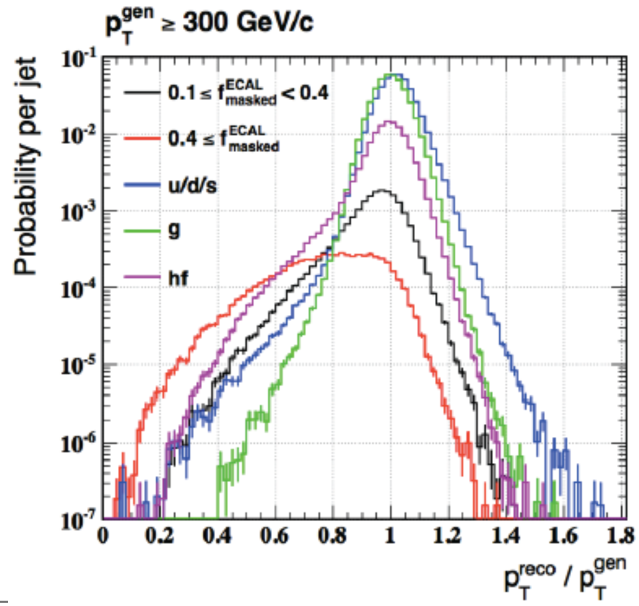


  - Here, for certain, simulation is of little help!
- **Again, one needs to rely on data**

Understanding the detector – ME_T (III)

- **Even worse: "honest mistakes"**
  - A misreconstructed muon can do damage: since muons leave only MIP energy in the calorimeter, in correcting the MET from the calos, one has to add the muon momentum! But if the muon is fake, one is correcting in error!
- **Tails of jet response!**
  - Effects of 1:10,000?
  - Detector cracks!
    - A jet that's heading straight into a detector crack will lose quite a bit of energy – and thus there will be a fake ME_T reconstructed [because the E_T will not be reconstructed!]

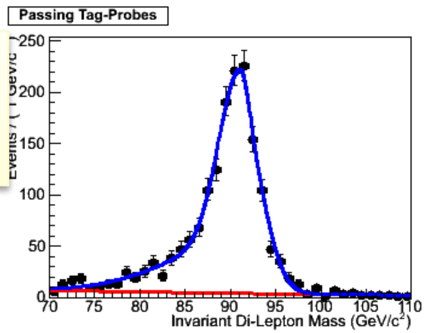


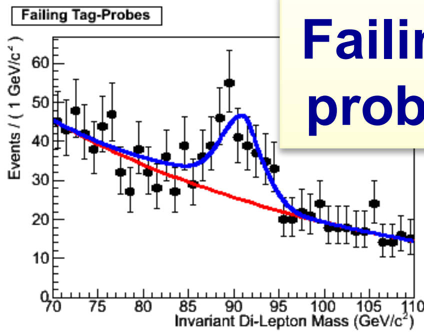


Obtaining (in)efficiencies from data

- **What is the efficiency of the tight muon identification cuts? Or of the trigger? Use "tag and probe" method in, e.g. $Z \rightarrow \mu\mu$ decays:**
  - **Make a selection based on one muon that "tags" the type of event (e.g. passes tight cuts; or passes the trigger)**
  - **Then demand that second muon does the same**

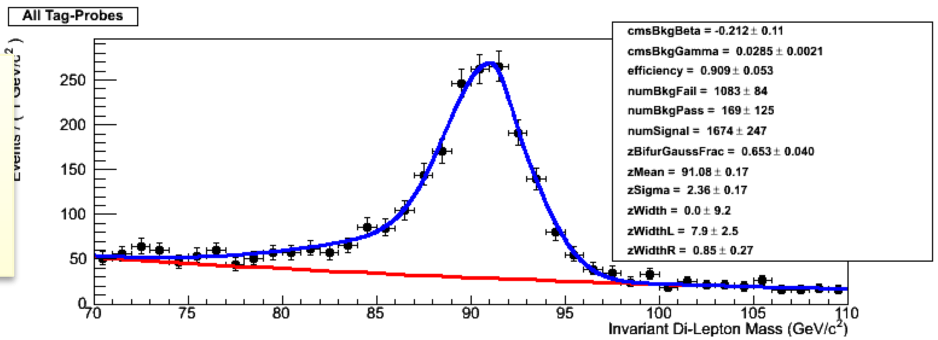
Passing probes

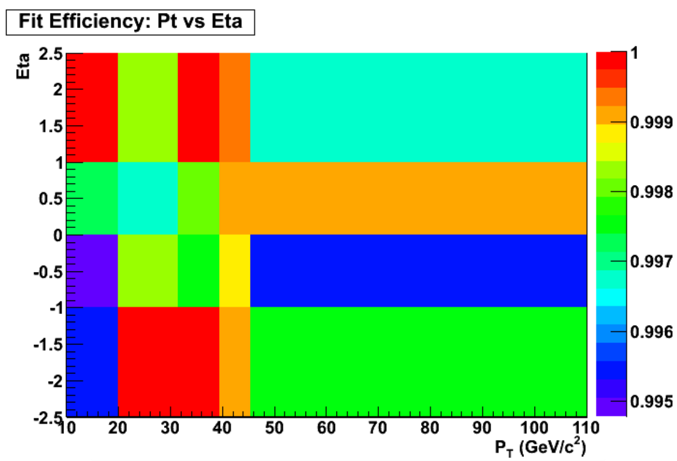




Failing probes

All combi-nations





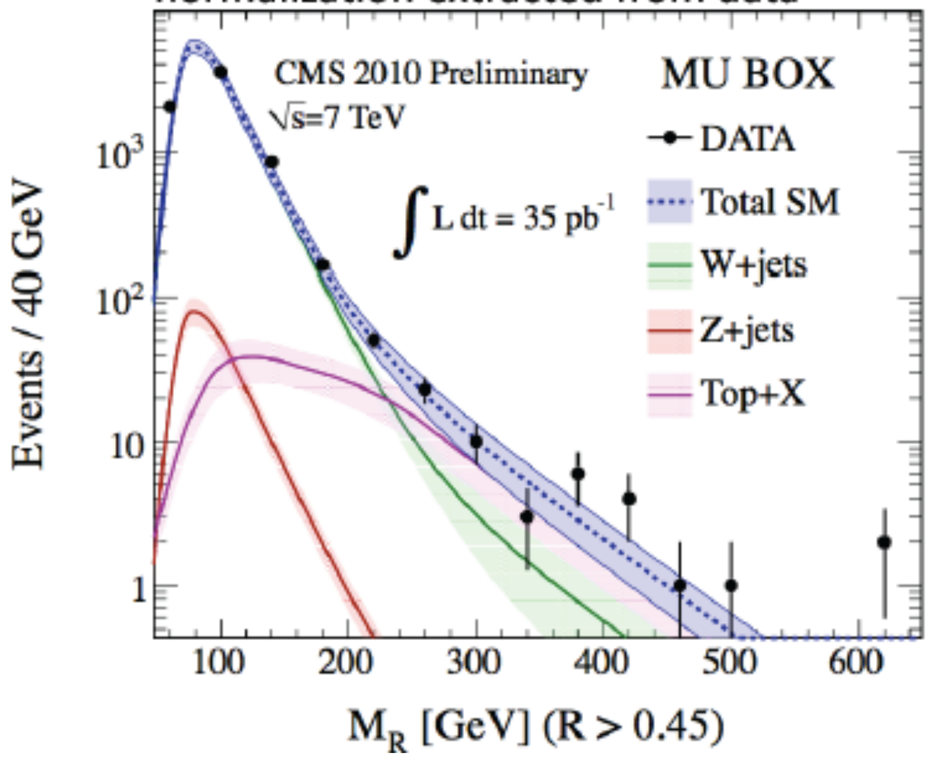
Obtain efficiency map

Understanding the physics background!

- **Suppose one is searching in the "jets + MET" signature**
  - We will encounter this later in the SUSY searches
  - Even after understanding the "reducible backgrounds" – i.e. detector response, the filters, etc, -- there are "irreducible backgrounds" from physics processes which give the same signature

Prime example 1: Z+jets
And the Z decays to neutrinos
So the MET is genuine!
Prime example 2: t-tbar
And one of the two W's decays to a tau and a neutrino

Background Shapes and normalization extracted from data



- **Cannot rely (only) on MC+simu!**

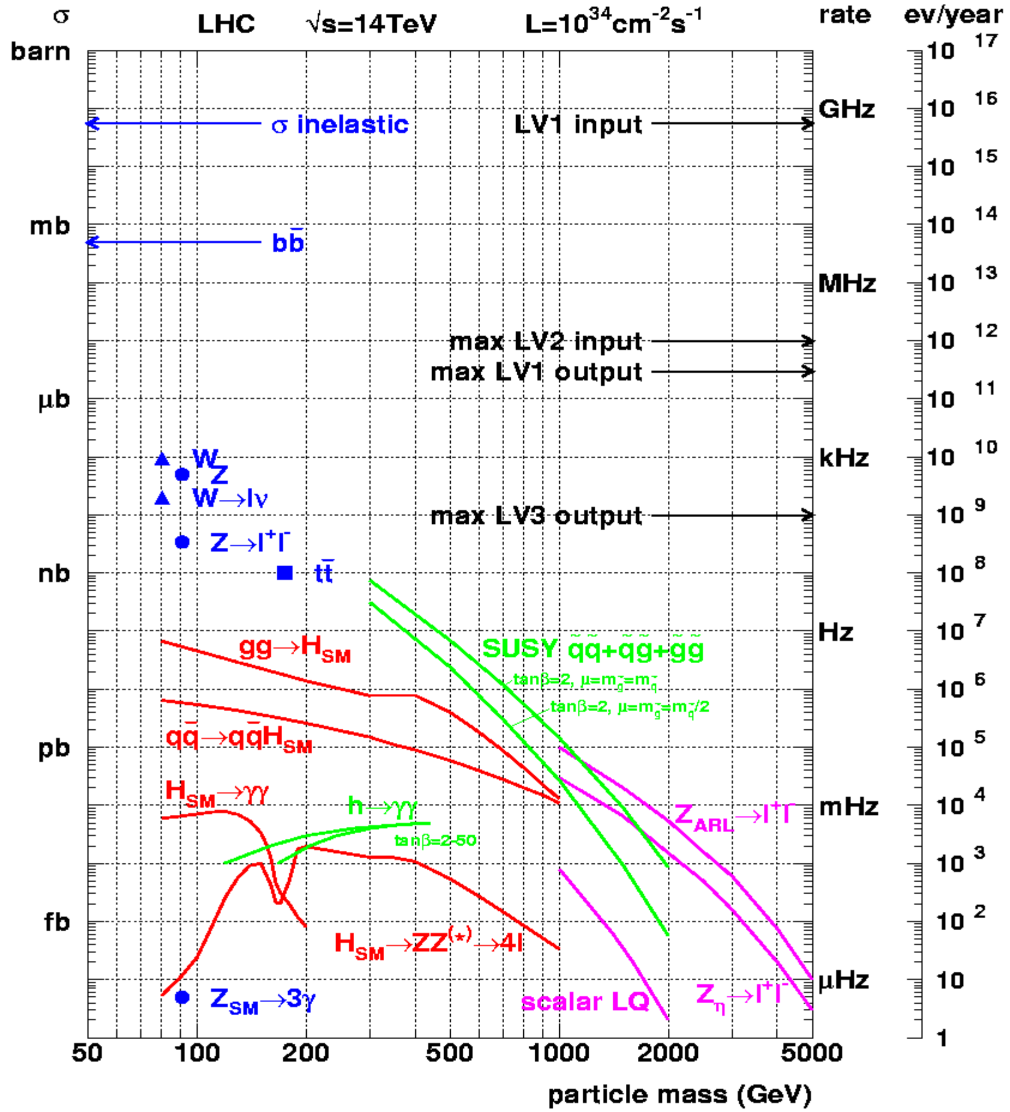
The problem: the background

Huge background: implications

- Very difficult to select the “right” event(s); what are the criteria? Cannot interview every single person
  - Need an automated procedure; by necessity, it will rely on a set of successive approximations
  - One has to design these selection steps; and one has to ensure that they are unbiased!
    - Very difficult to avoid biases in the selection process!
    - Particularly important in the online trigger system!
- Number of “input” events is so large that one expects all abnormalities to show up
  - Even with a probability of occurrence of 1:10,000, in a crowd of 1,000,000 people, there will be 100 “cases”!
  - In practice, implies a new level of understanding – cannot rely on Monte Carlo to simulate things at this level of detail

The problem: signal much smaller than bkg

- **General event properties**
- **Heavy flavor physics**
- **Standard Model physics**
  - **QCD jets**
  - **EWK physics**
  - **Top quark**
- **Higgs physics**
- **Searches for SUSY**
- **Searches for 'exotica'**



How do we discover something “new”?

Significance and implications (I)

- **An experiment that expects 49 events [from SM processes] observes a total of 56 events.**
  - **Clearly, it has NOT "discovered a new physics process that creates this type of event"**
    - **The observation is within "1σ" of the expectation. One in three experiments would do this. Not an observation**

- **The standard for discovery has been set – in a fairly ad hoc manner – at "5σ". It is $p = 2.9 \times 10^{-7}$.**

Significance and implications (II)

- **Reversing the argument: what does the observation of 56 events, when 49 are expected, imply for all new physics processes?**
  - An upper limit on the number of events from these processes
  - Thus, an upper limit on their cross section
  - Assuming we know the cross section as a function of some unknown parameter, e.g. the mass, a lower limit on the mass!
- **Suppose an experiment finds 0 candidate events.**
  - The "95% CL upper limit on the average number of events expected", μ, assuming a Poisson pdf is found by solving

$$0.95 = \mathrm{CL} = \sum_{n=1}^{\infty} \frac{e^{-\mu}\mu^n}{n!} \Rightarrow 1 - \mathrm{CL} = 1 - \sum_{n=1}^{\infty} \frac{e^{-\mu}\mu^n}{n!} = e^{-\mu}$$

$$\Rightarrow \mu = -\ln(1 - \mathrm{CL});\ \ \mathrm{CL} = 0.95\ \ (0.90) \rightarrow \mu = 3.0\ \ (2.3)$$

Significance and implications (II) contd

- **If there is background, with mean expectation b, and s is the mean expected signal, then μ=s+b**
  - **Repeat exercise, using number of events observer in data, N_D**

$$0.95 = \mathrm{CL} = \sum_{n=N_D+1}^{\infty} \frac{e^{-\mu}\mu^n}{n!} \Rightarrow 1 - \mathrm{CL} = \sum_{n=0}^{N_D} \frac{e^{-\mu}\mu^n}{n!}$$

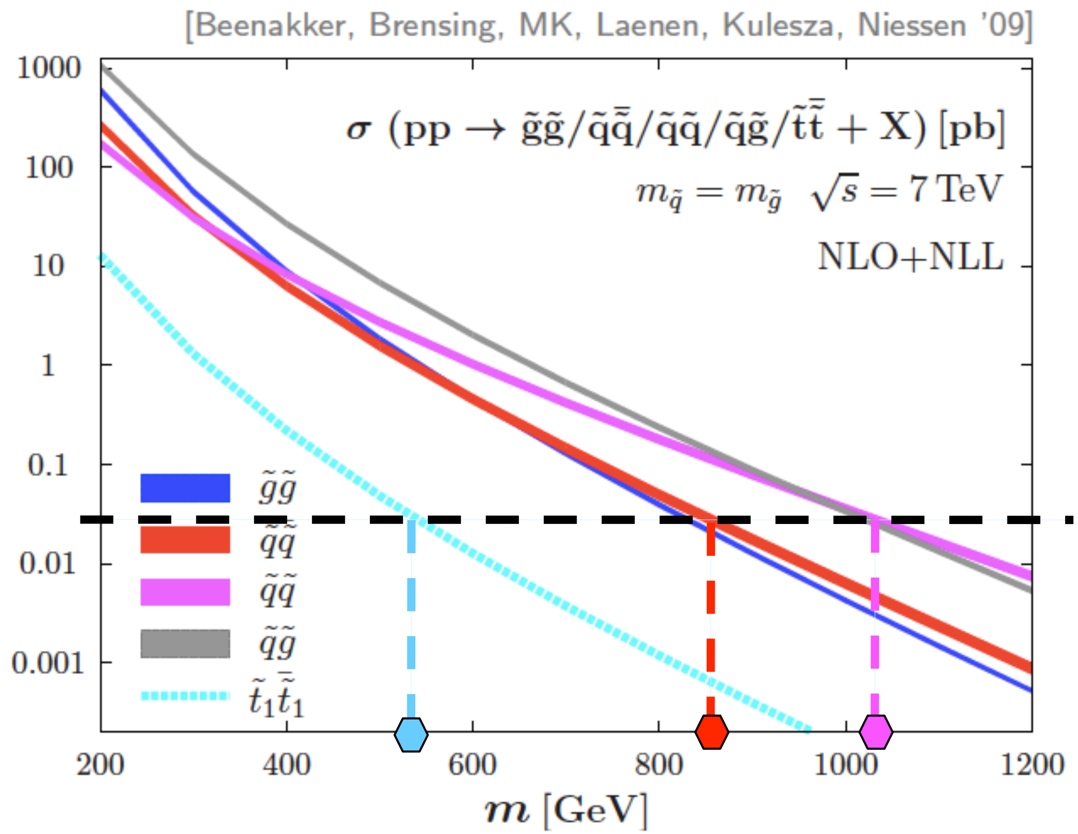
Significance and implications (III)

- **Armed with the upper limit on the number of events:**
  - Use Monte Carlo (simulation) to estimate fraction of events passing the selection requirements, e.g. they have one muon with p_T>20 GeV, |η|<2.1, 2 jets with P_T>50 GeV and ME_T>100?). This is the signal "acceptance", α.
  - Use data (as much as possible; some simulation as well) to estimate fraction of events within the acceptance that actually get reconstructed.
    - Not all muons with p_T>20 GeV, |η|<2.1 get reconstructed!
    - Use data to measure this "efficiency", ε.
  - Use measured integrated luminosity, L
- **We obtain an upper limit on the cross section for the production of this new particle X:**

$$\sigma^{\text{upper limit}}\left(pp \rightarrow X\right) = \frac{N^{\text{upper limit}}}{\alpha \;\; \varepsilon \;\; L}$$

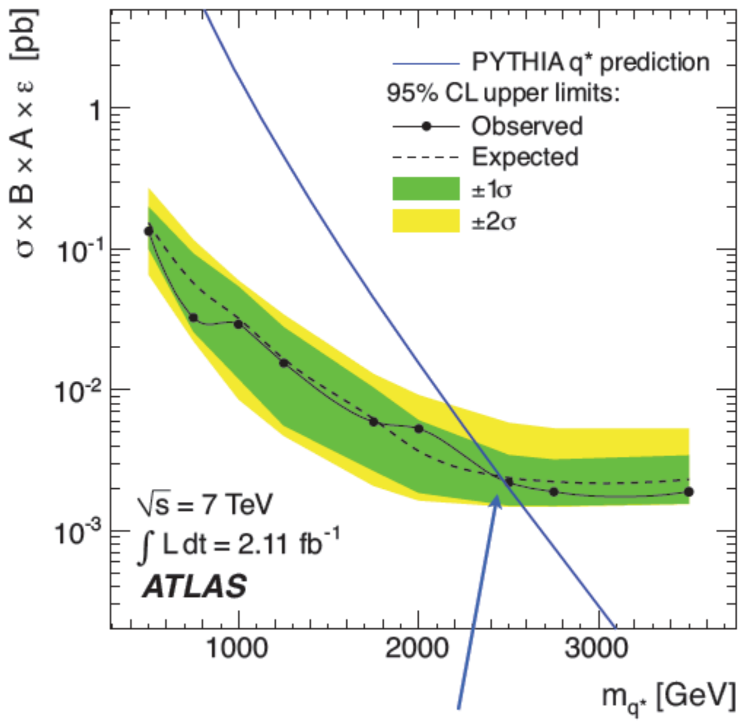
Significance and implications (IV)

- **Finally, we use theory to compute the cross section of the hypothesized particle X, as function of some key parameter – e.g. the mass of the particle**



A real-life example

- **The acceptance and efficiency may well depend on the parameter of interest (e.g. the mass of the X)**
  - **In these cases the upper limit on the cross section is itself a function of the mass of the X:**



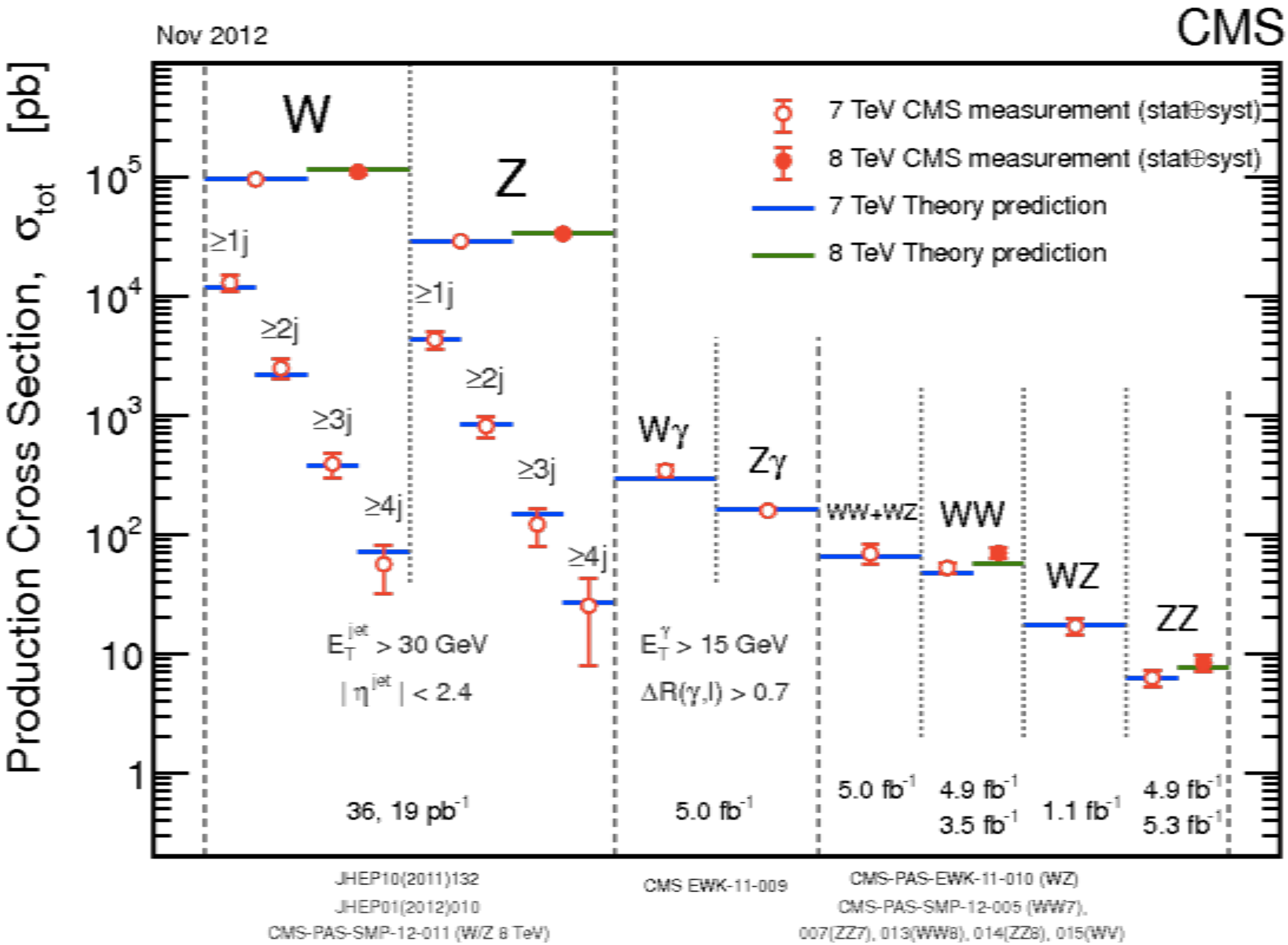
Excited quark cross section limit: 2.46 TeV @ 95% CL

The “SM” in “BSM”

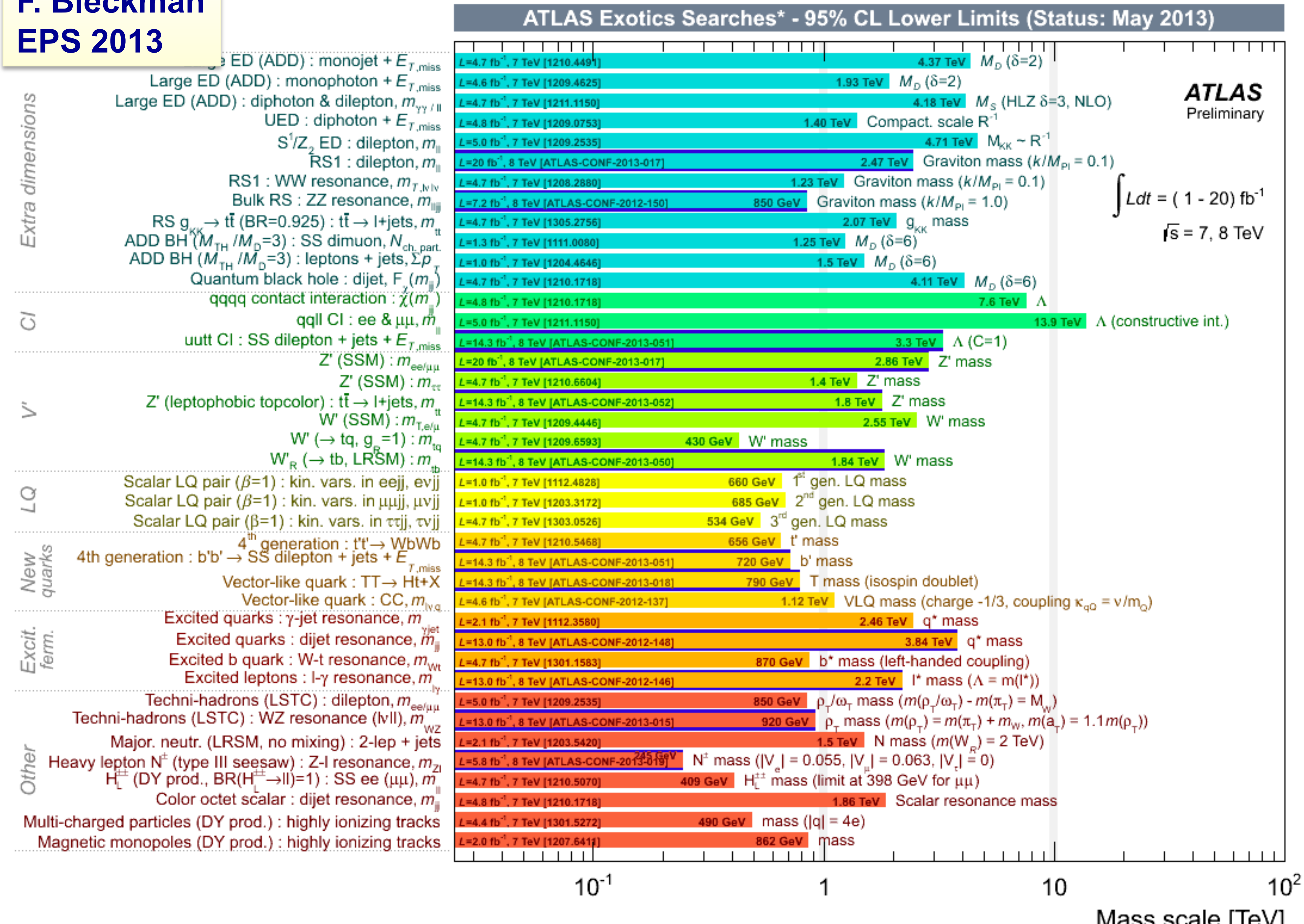
Understanding the Standard Model

- **The last piece of the puzzle before embarking on a search for Physics Beyond the Standard Model is to understand the Physics Of the Standard Model**
- **Our searches have signatures that involve a combination of leptons and jets; but also MET & b-jets**
  - **Strong (QCD) processes**
  - **Electroweak (EWK) processes**
  - **Combination of the two: processes that are relevant at high transverse momenta/energies**
    - **W+jets; Z+jets; t-tbar; very high-p_T jets**
    - **WW, WZ, ZZ; also with jets**
    - **Rare processes, e.g. tW**
- **Thankfully, these have been studied in detail [subject of lectures on SM]**

A cool set of SM measurements



F. Bleckman
EPS 2013



*Only a selection of the available mass limits on new states or phenomena shown

Summary [1/3]

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- **Plenty of reasons to look for physics beyond the standard model**
  - Experimental evidence: dark matter!
  - Theoretical evidence: weaknesses in Higgs "story"
- **Proving there is a phenomenon beyond all that we have discovered so far is not easy**
  - Need detailed understanding of detectors as well as the "standard physics"
  - The backgrounds are huge; only a "data-driven" analysis (with a healthy dose of Monte-Carlo-based extrapolation) can really "prove" there is something genuinely new