Higgs, Electroweak Physics and QCD-I

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1st CERN-Bangladesh School on Particle Physics
University of Dhaka
15-18th December, 2014

How knowing electroweak physics and QCD helped us in discovering the Higgs...

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OUR ROUTE...

Newer techniques

Searching for new particles

Testing the models by measurements

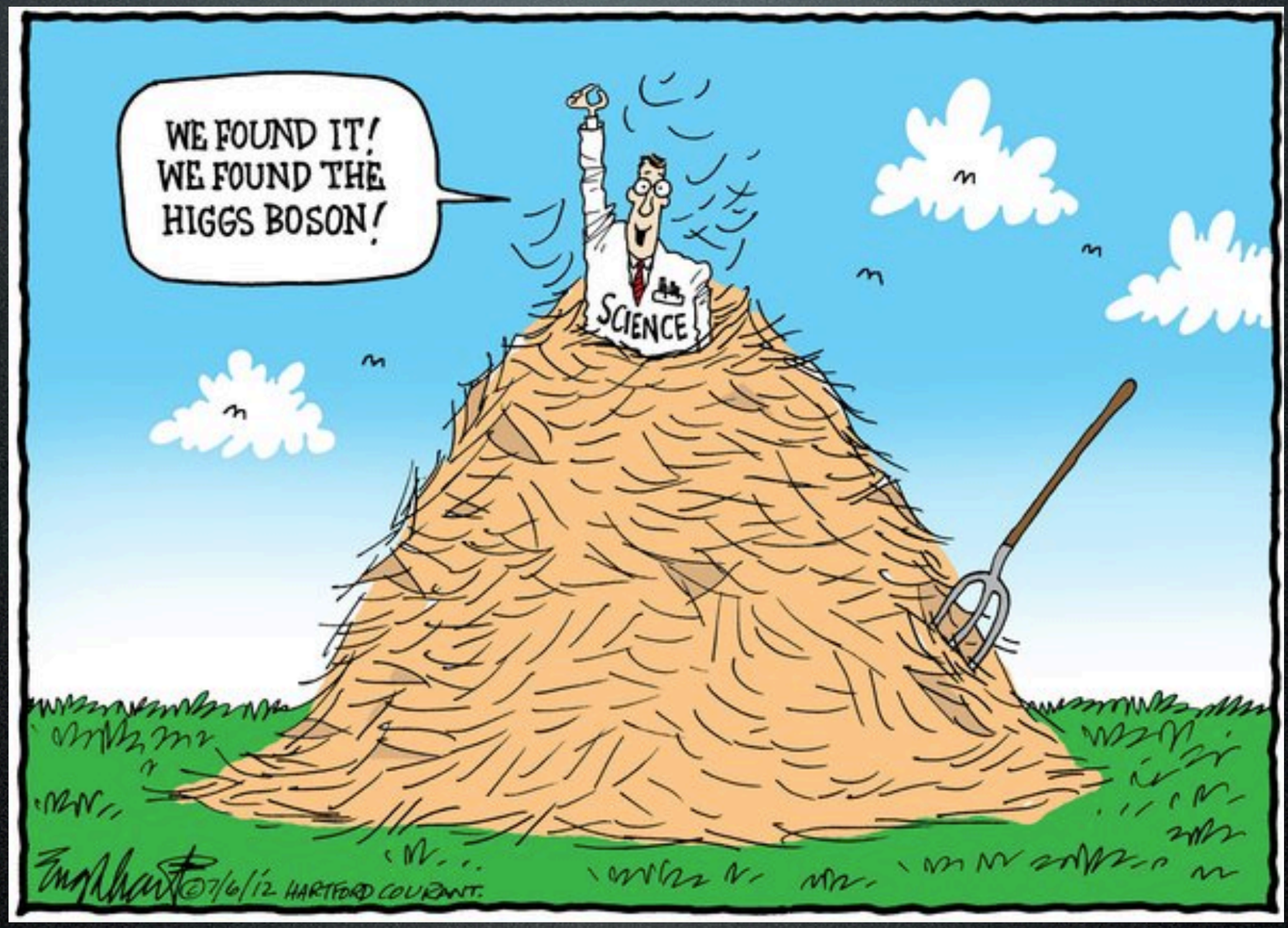
What happens in a collision?

Modelling the collisions

Discovery

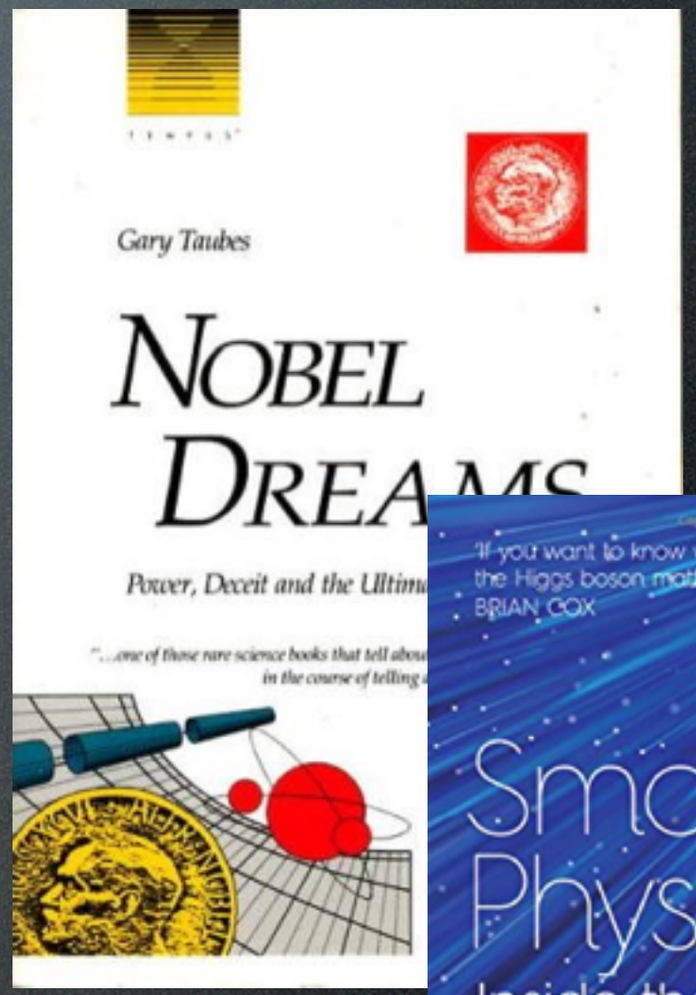
What is a discovery?

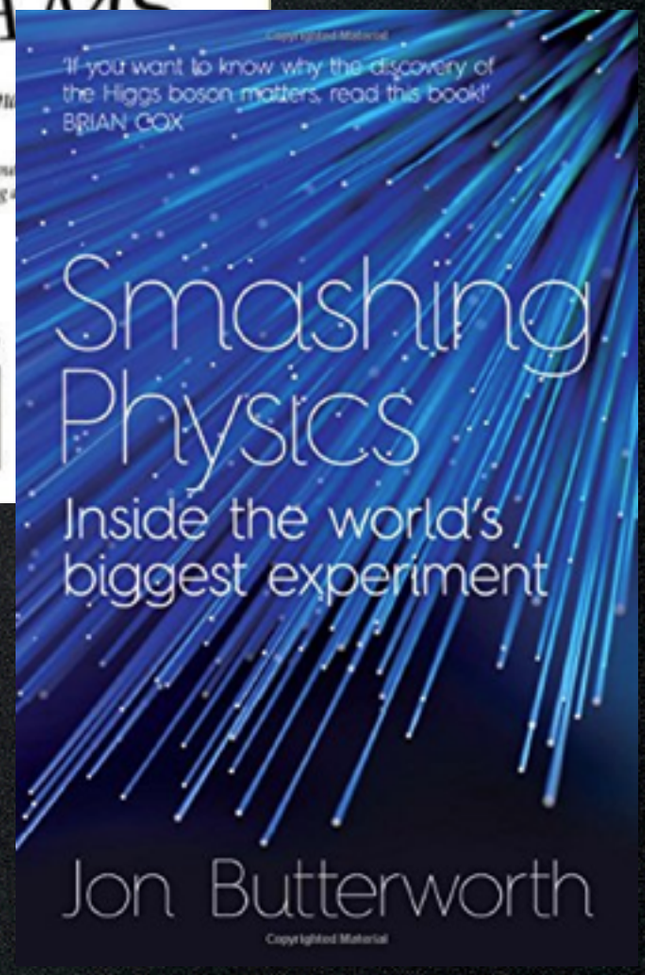
How to make a discovery in particle physics?



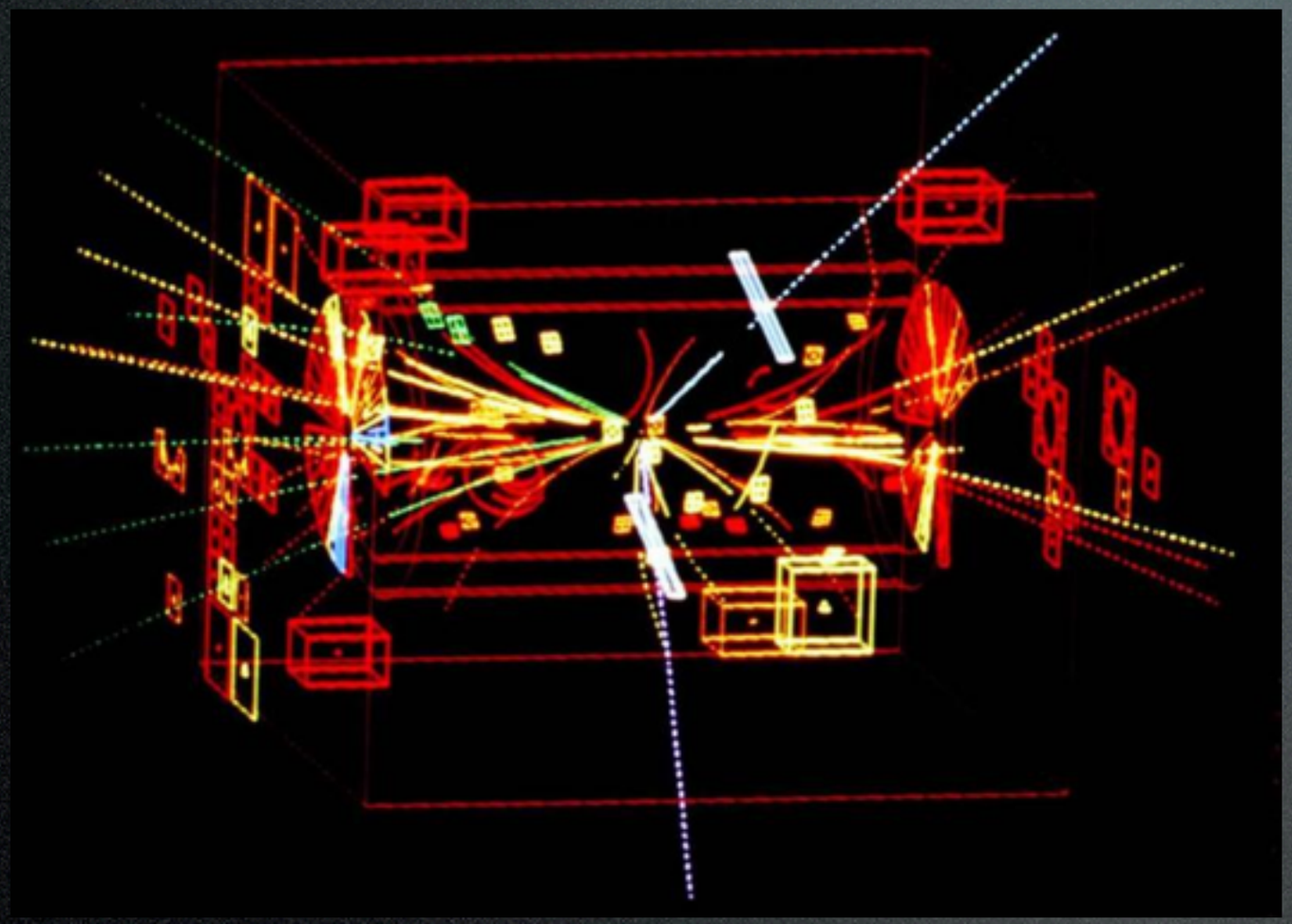
How to make a discovery in particle physics?

- W/Z boson in UA1/UA2
- Top quark in CDF/DØ
- Higgs boson in ATLAS/CMS
- What next?





Z-boson discovery

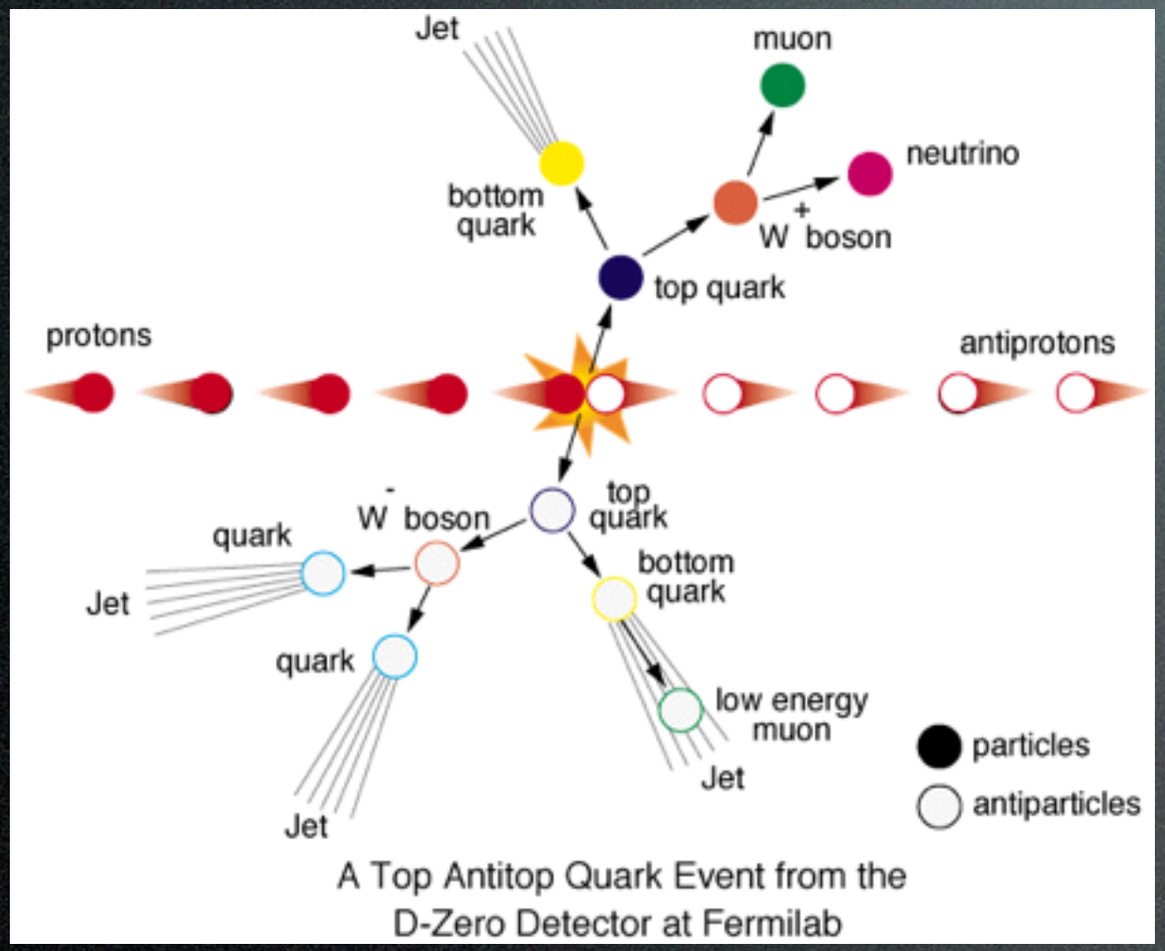


UA1, CERN, 30th April 1983

Can't see the Z directly!

High energy electron and positron flying off in opposite directions

Top discovery

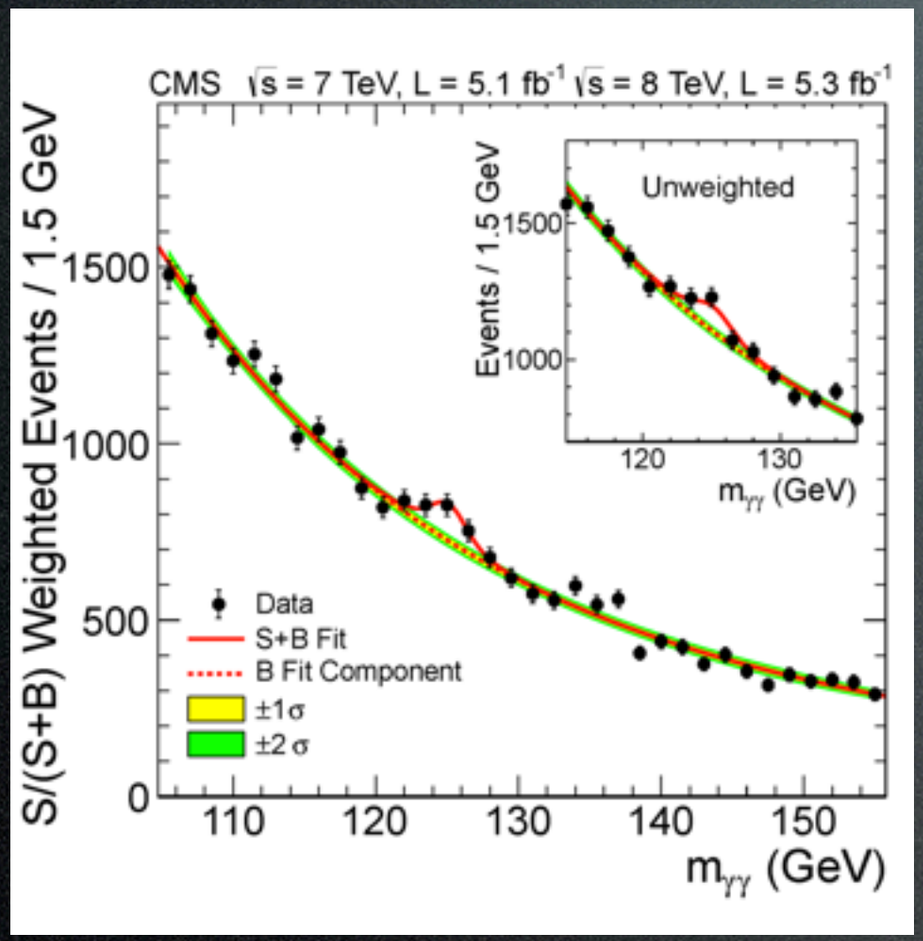


A Top Antitop Quark Event from the D-Zero Detector at Fermilab

Statistical significance used to claim discovery.

Number of observed events at CDF and DØ corresponded to odds of 1 or 2 in million that these events are caused by background processes.

Higgs discovery

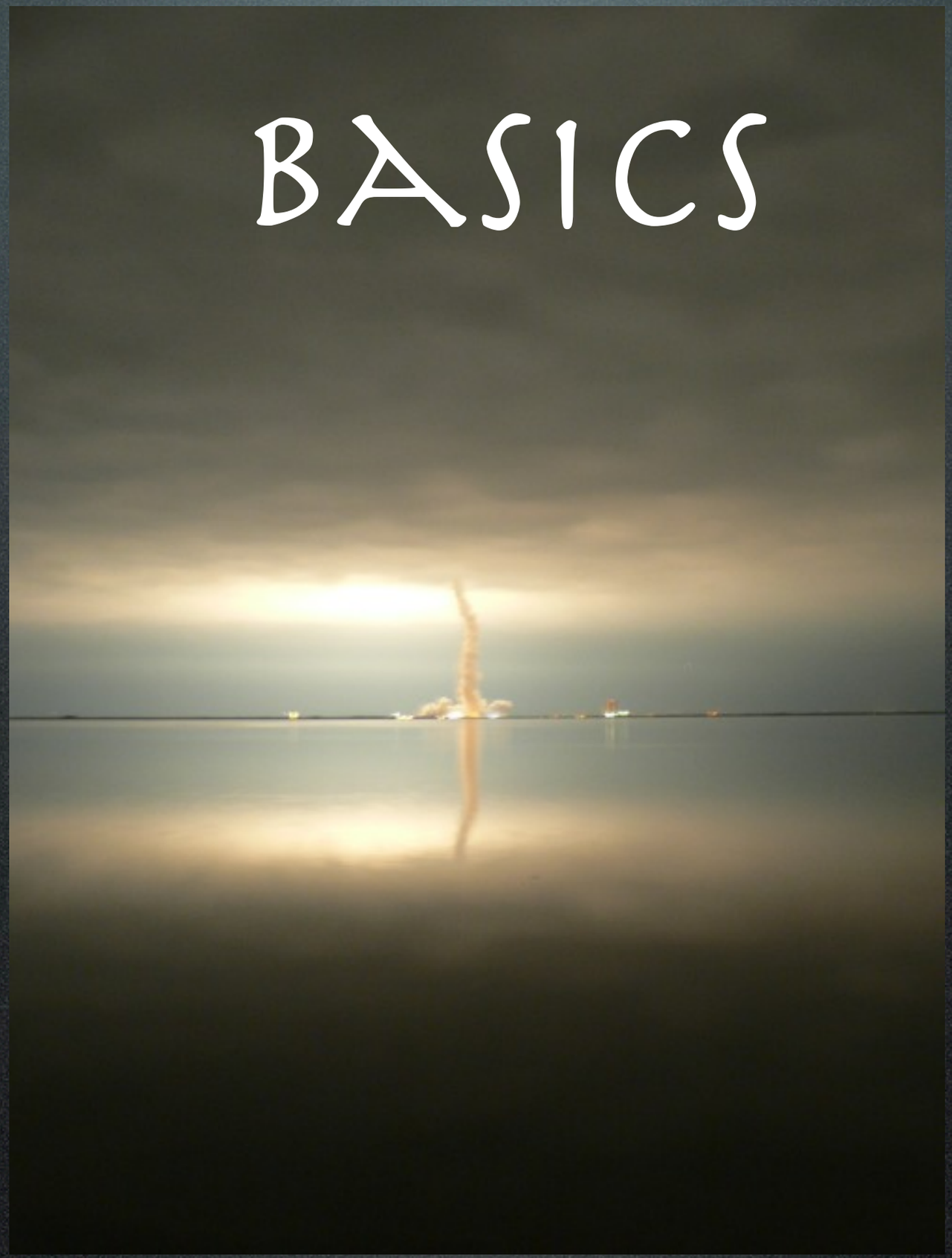


5 sigma: if the experiment was done 3.5 million times, only once the background fluctuation will result in the signal.

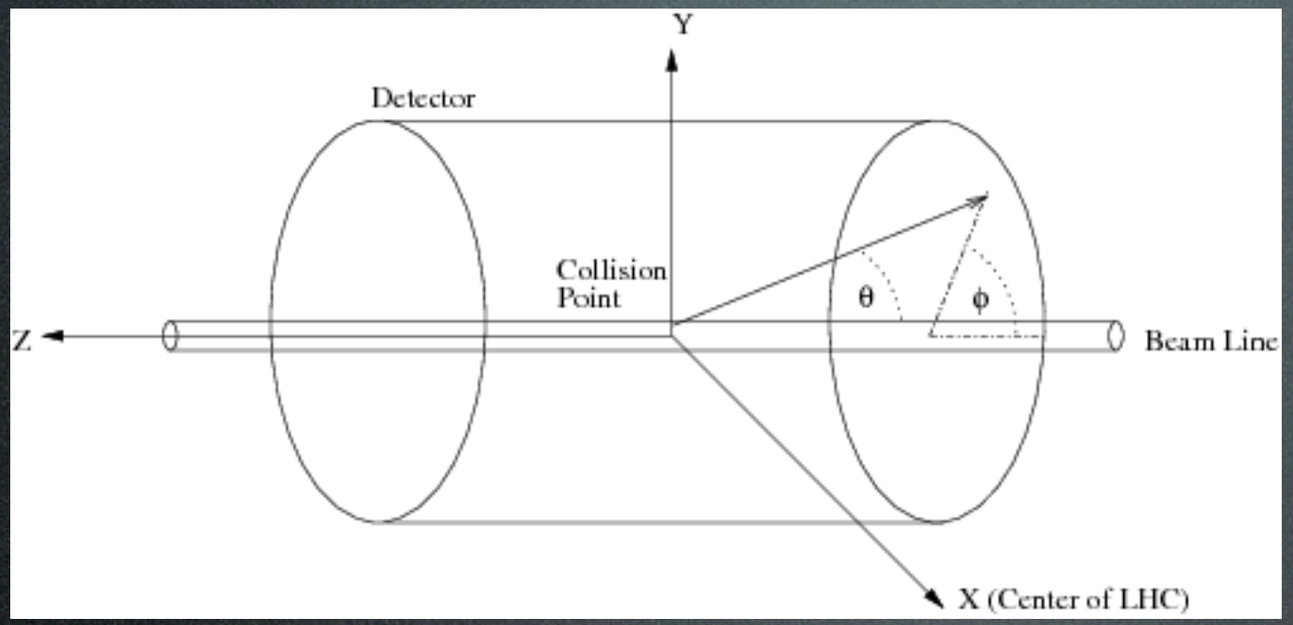
More on Higgs (discovery) tomorrow!

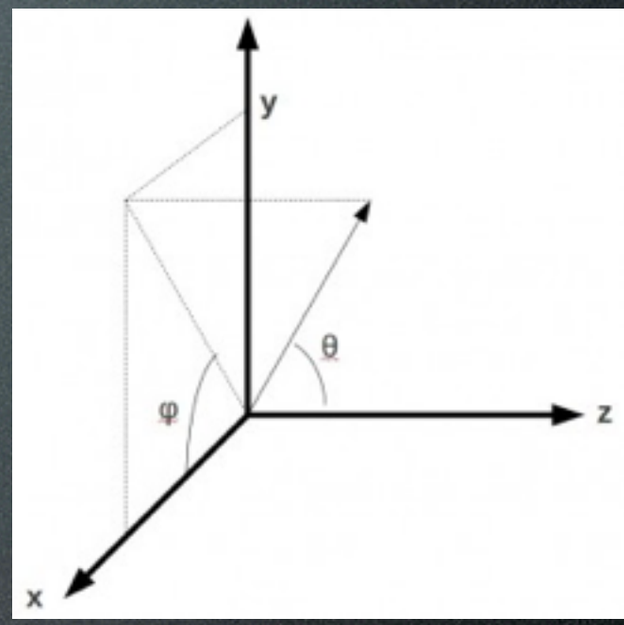
Phys.Lett. B716 (2012) 1-29
Phys.Lett. B716 (2012) 30-61

BASICS



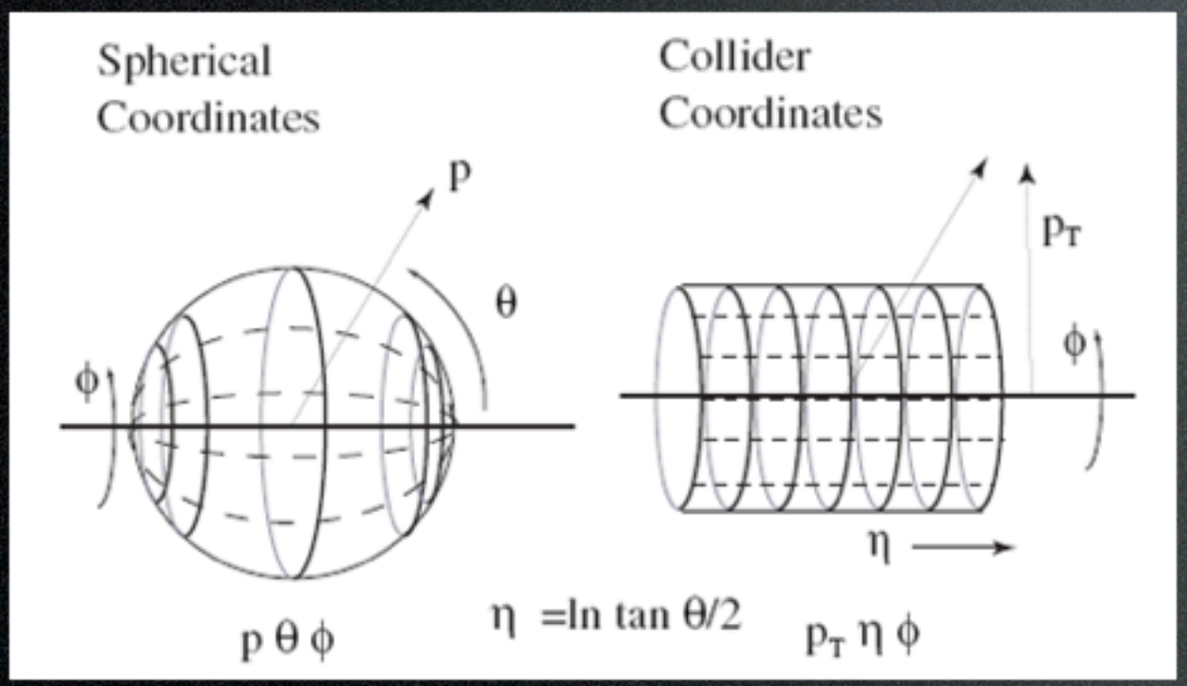
Detector Coordinates

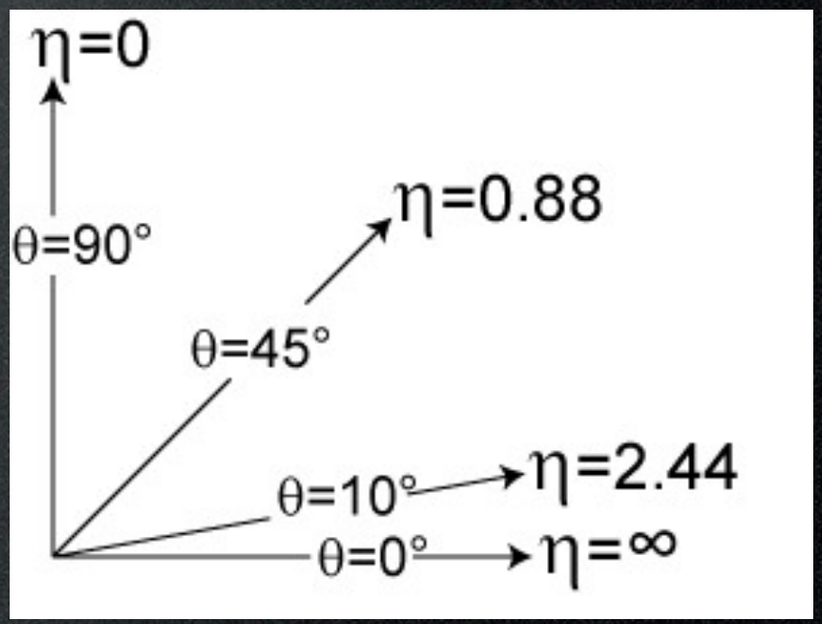




Define pseudorapidity:

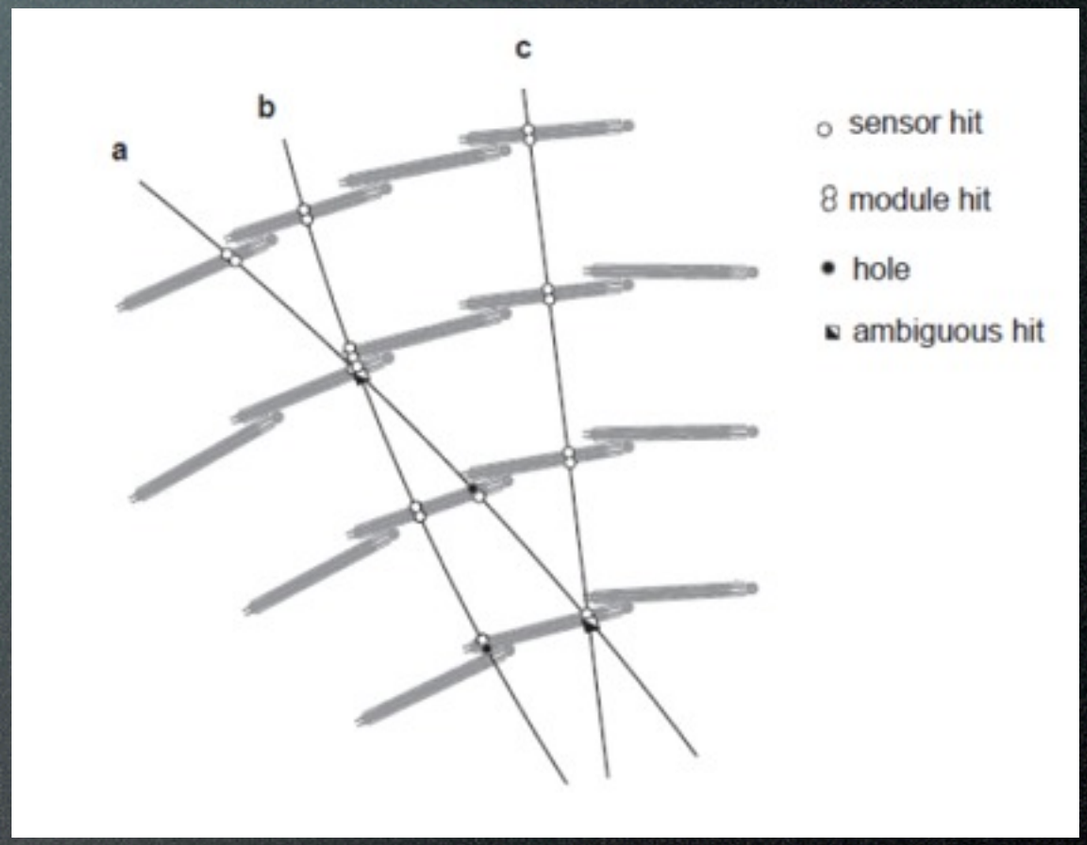
$$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$$

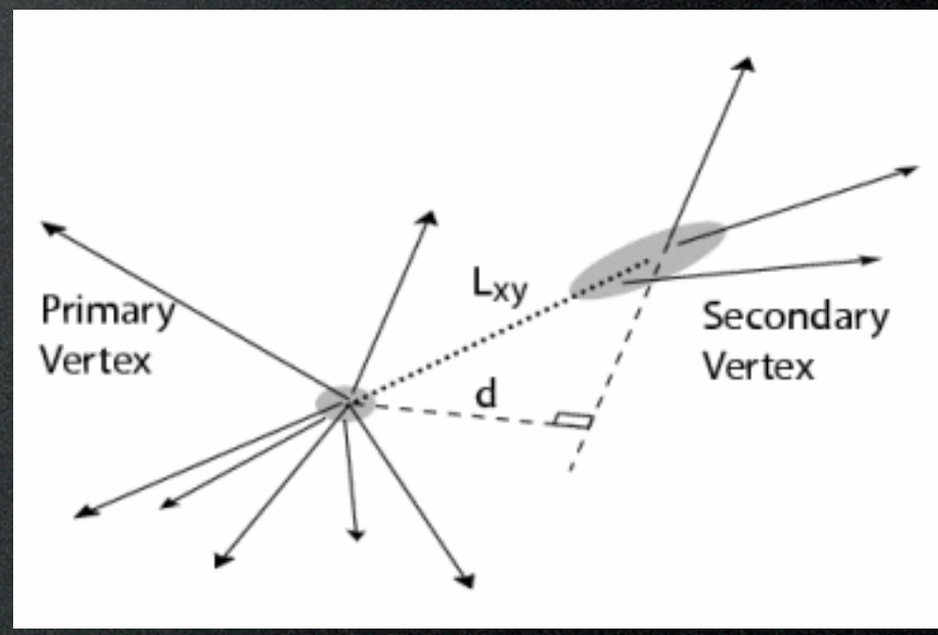




Object Reconstruction

- Detectors measure energy deposit, particle hits and trajectory, charge etc.
- Reconstruct “final” objects/particles and their four-vectors from that.





Jets

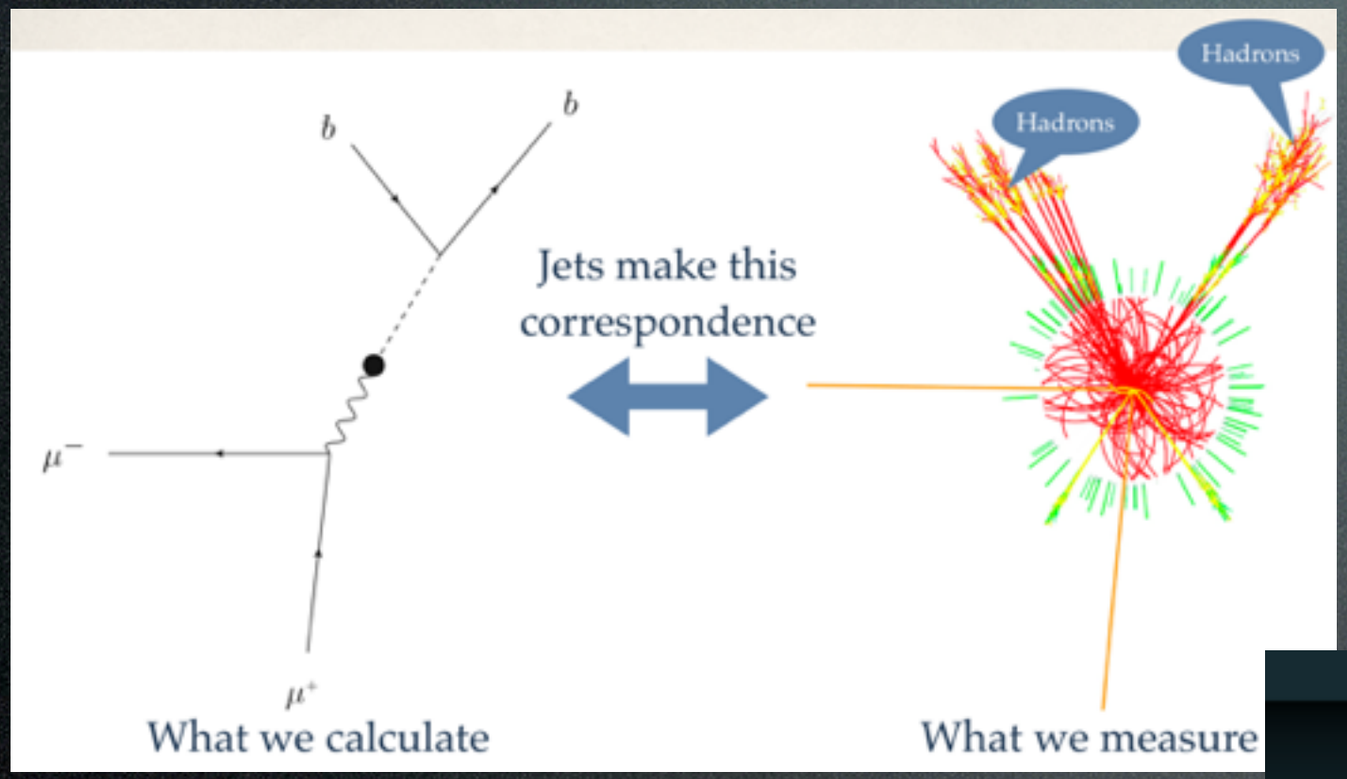
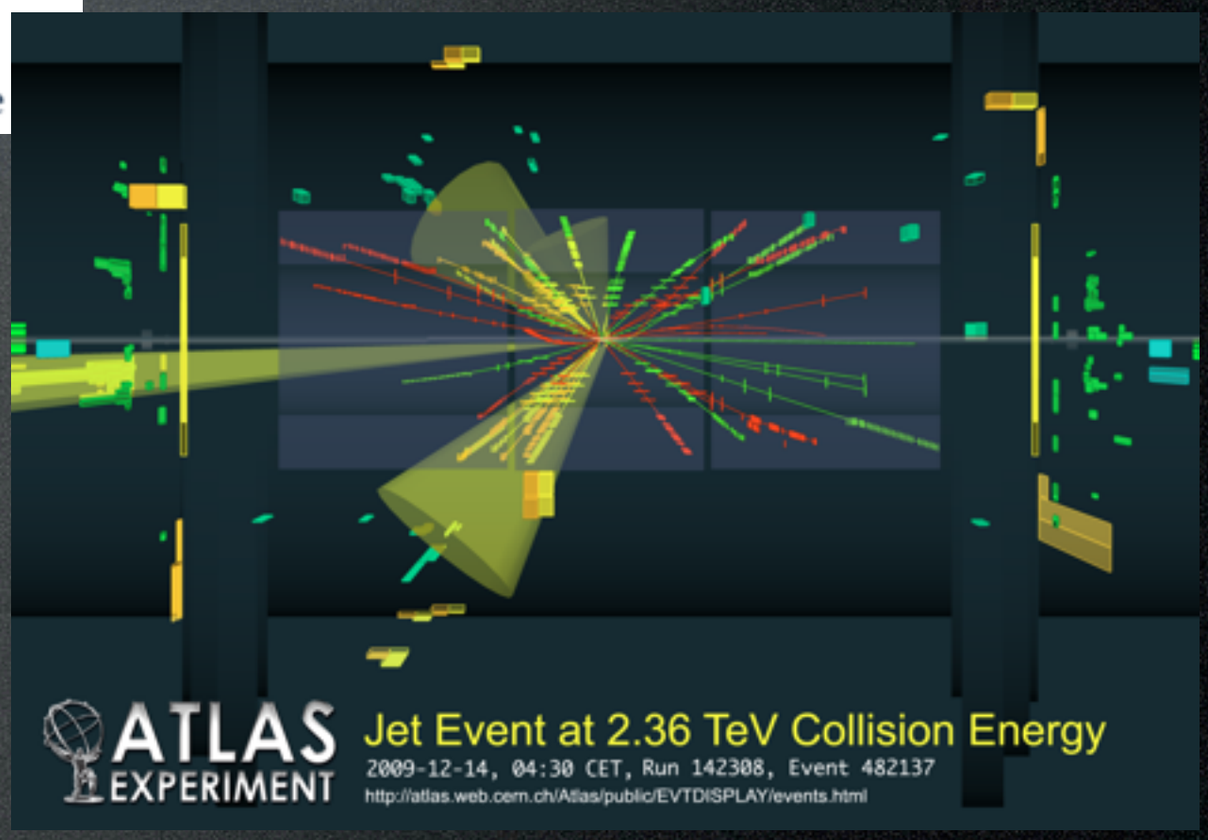


Image from quantum diaries blog

We measure energy deposit in our calorimeters

Jets are **defined** by how it is formed (algorithm), and the (cone) size/radius.



Jet Forming

Inputs can be particles, tracks, calorimeter objects...

- Sequential recombination algorithms (momentum space): iteratively pairwise **combination** of the inputs till a minimum inter-jet distance is reached.

- Cone algorithms (coordinate space): Collect all inputs within a cone such that the cone axis is the vector sum of momenta in it.

Made by James Ferrando

Stephen D. Ellis, Davision E. Soper; arXiv:hep-ph/9305266

Matteo Cacciari, Gavin P. Salam, Gregory Soyez; arXiv:0802.1189

Jet Clustering

Distance between two input objects

Distance between each input object and beam

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2}; \quad d_{iB} = k_{ti}^{2p}; \quad p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

Intrinsic transverse momentum

Fixed “radius” parameter

- Find the smallest of all $\{d_{ij}, d_{iB}\}$
- If this is one of the d_{ij} values, inputs i and j are merged.
- If it is one of the d_{iB} values, i^{th} input is considered a jet.
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Stephen D. Ellis, Davision E. Soper; arXiv:hep-ph/9305266
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How to Combine?

Distance between two input objects

Distance between each input object and beam

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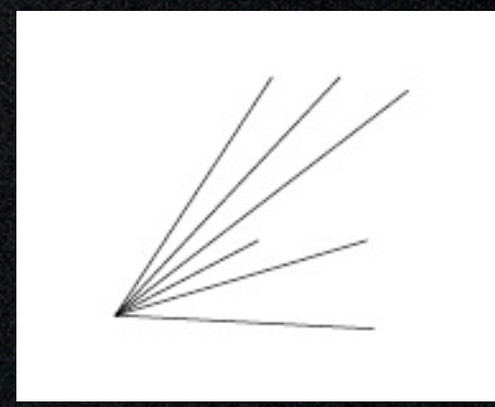

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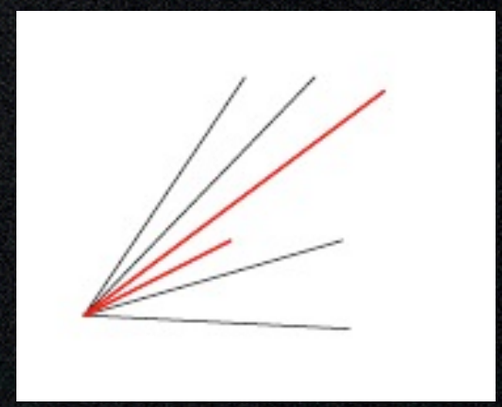

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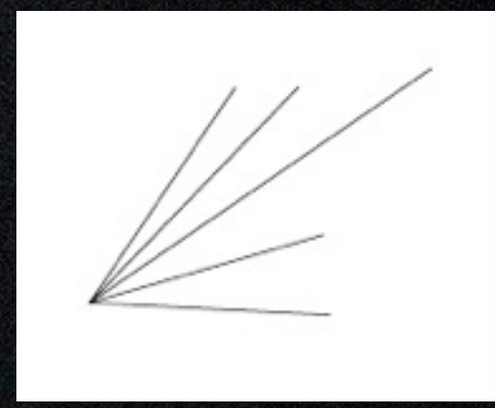

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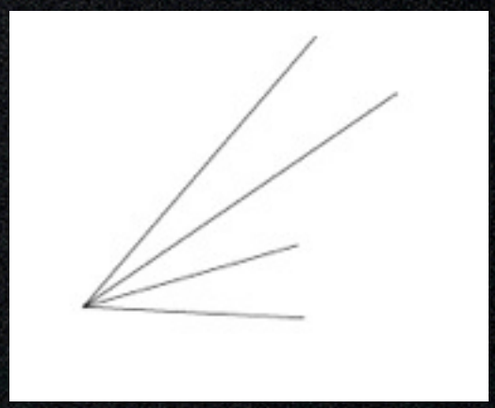

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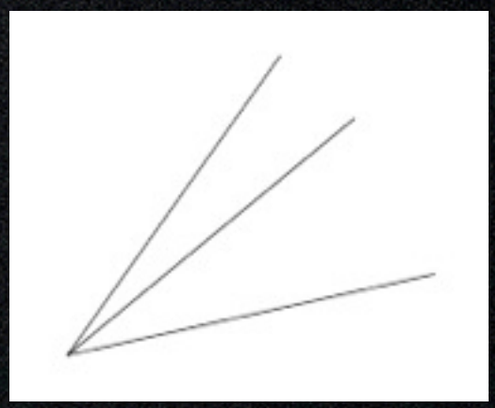

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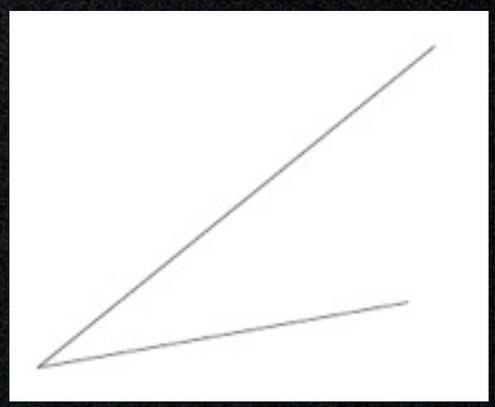

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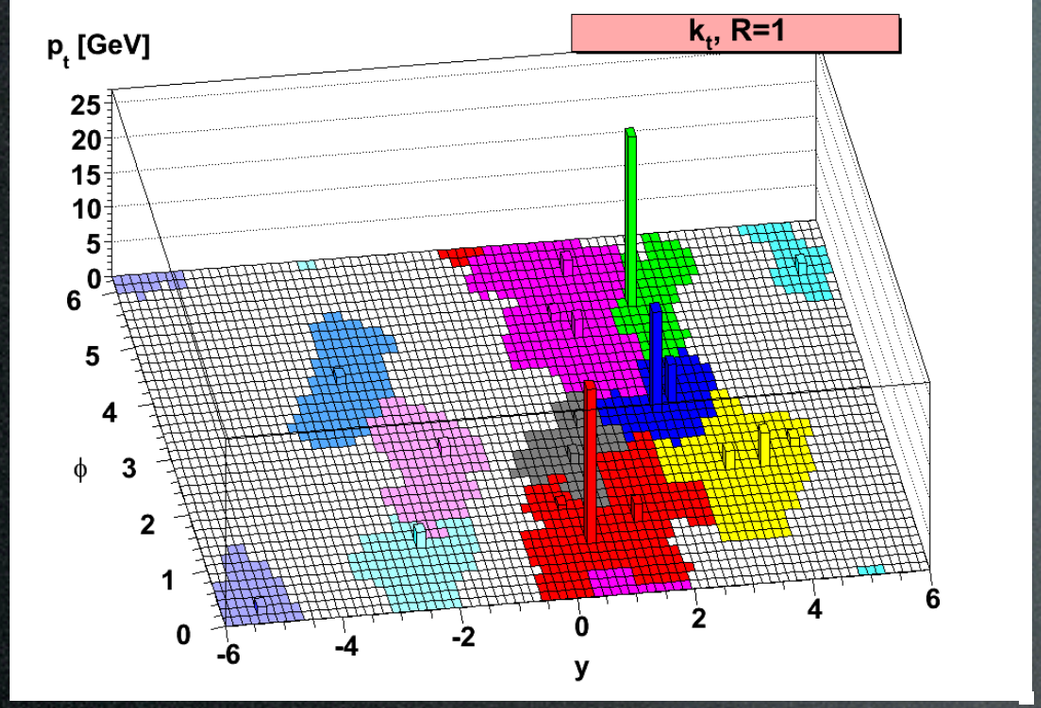
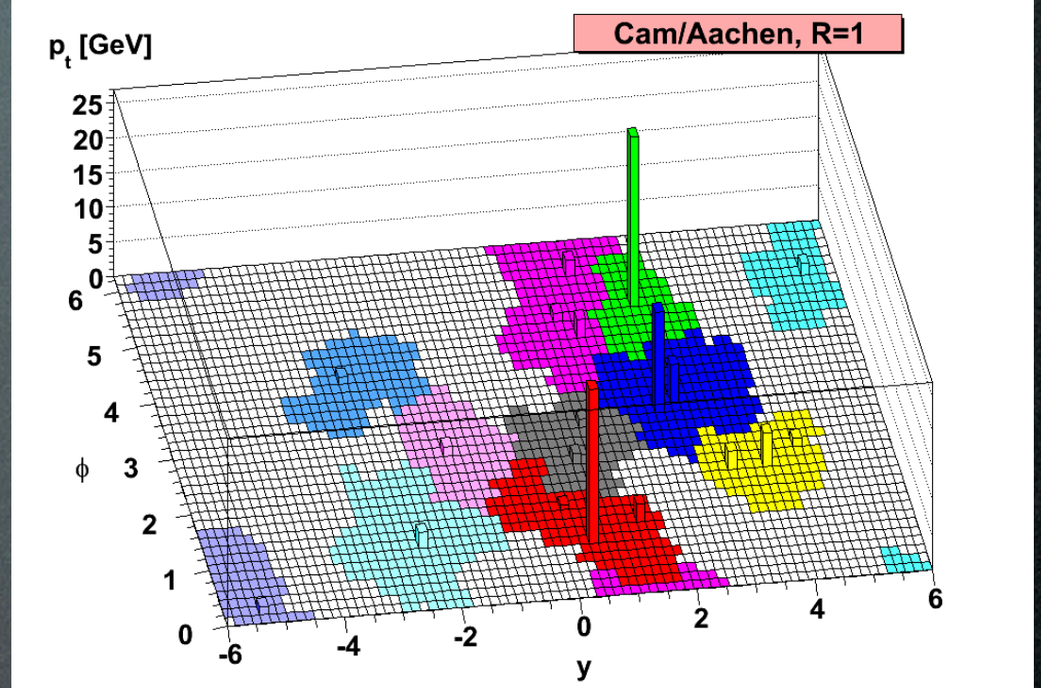
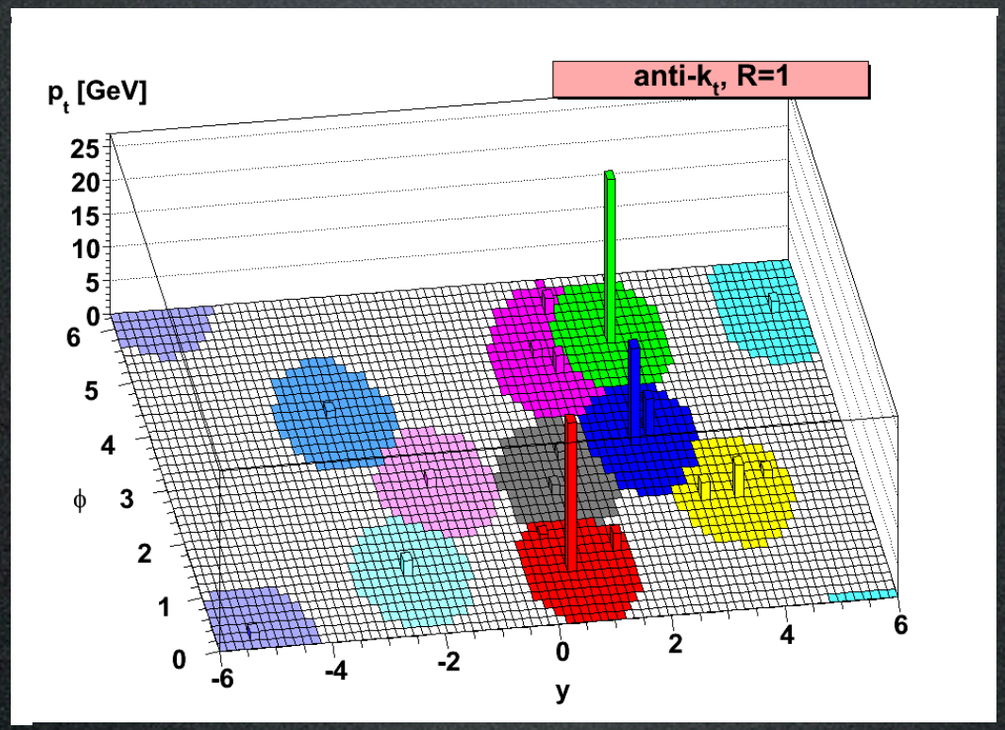


Irregularly shaped jets



Shape follow angular distribution of components



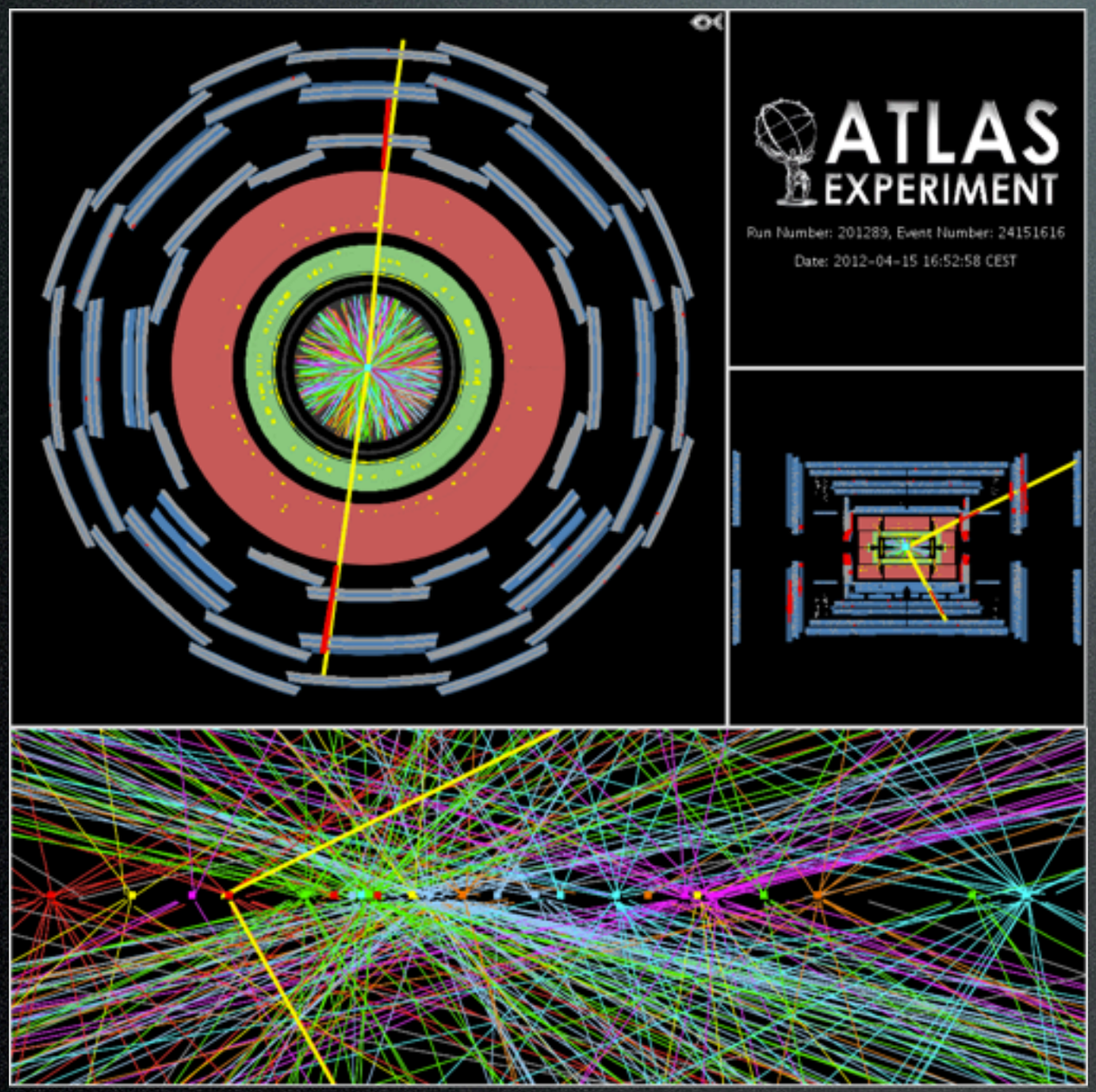
Almost circularly shaped jets

Diagrams from Gavin Salam

Experimental Limitations

- We dont get what is coming out of the collisions.
- Finite lifetime of particles, decays before reaching the detector.
- Detectors have finite resolution, less than perfect response and efficiency.
- There may be “dead” components.

Pile-up



We collide proton bunches, so overlap between different collisions is inevitable!

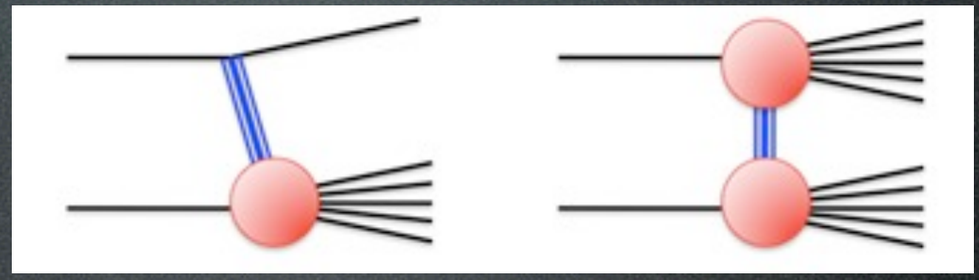
Increases with higher luminosity

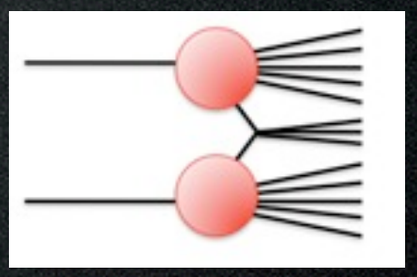
Anatomy of Collisions

$$\sigma_{total} = \sigma_{el} + \sigma_{inel}$$

Anatomy of Collisions

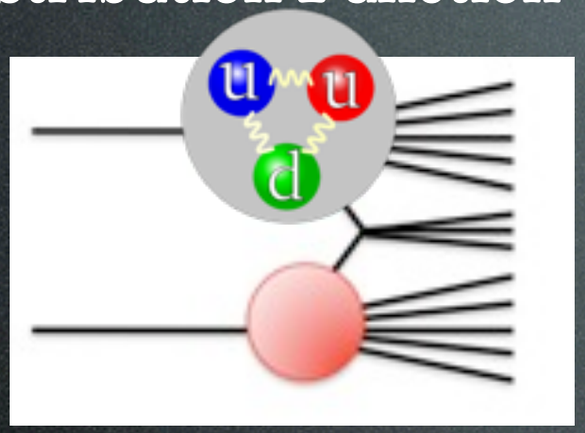
$$\sigma_{total} = \sigma_{el} + \sigma_{sd} + \sigma_{dd} + \sigma_{nd}$$

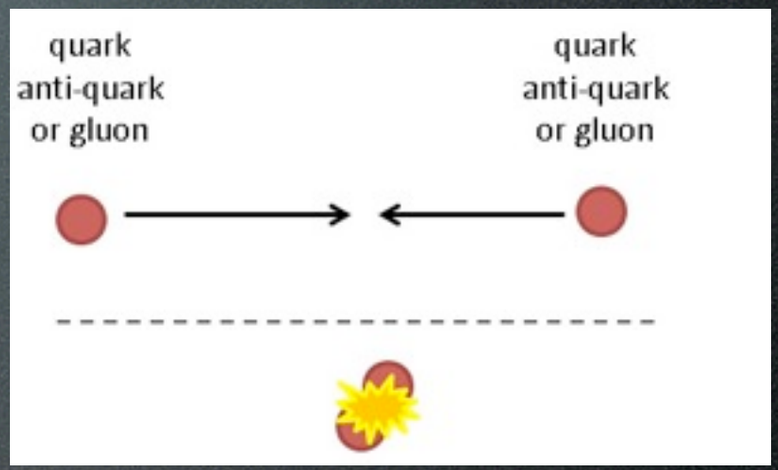




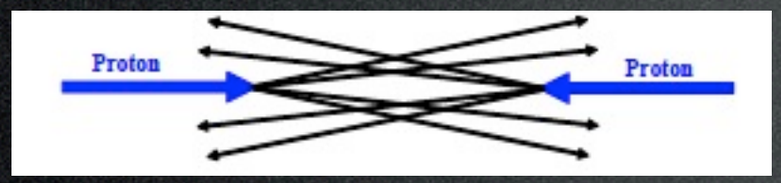
Anatomy of Collisions

Parton **D**istribution **F**unction



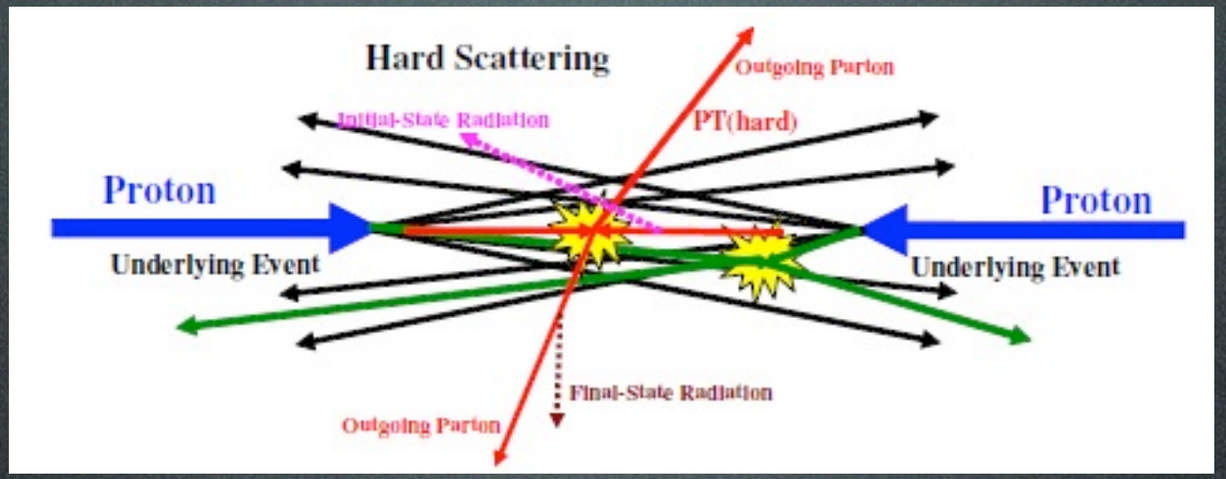


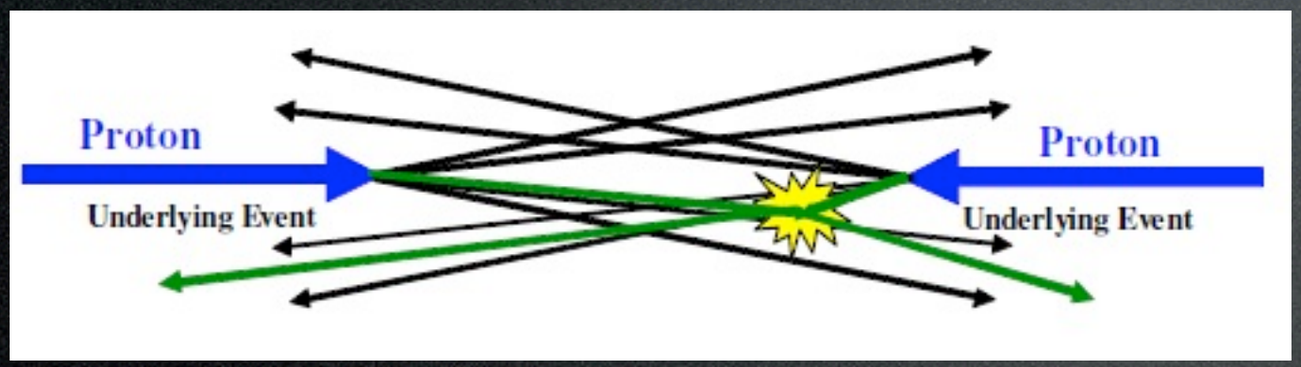
Interesting part!

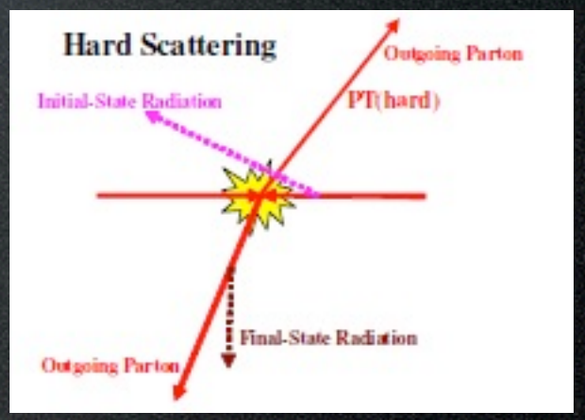


No hard scatter

Anatomy of Collisions







Underlying event = BBR+ MPI+ (ISR+FSR)

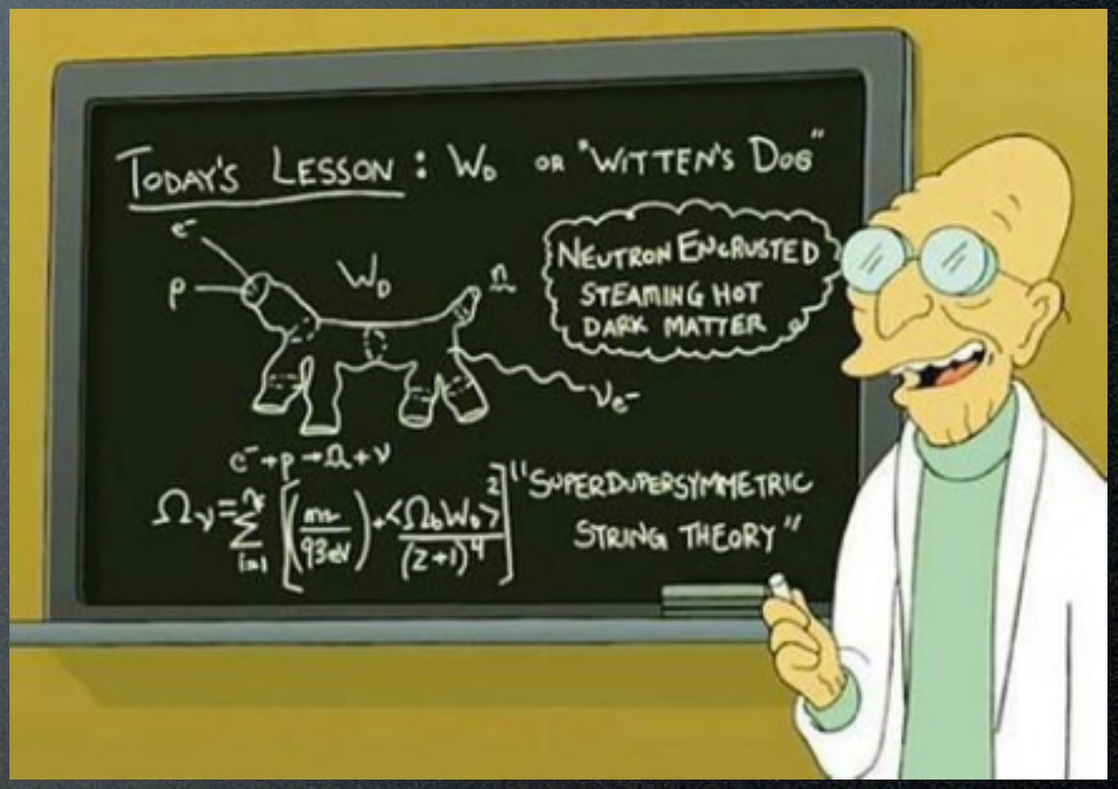
BBR: Beam-beam remnants
MPI: Multiple Parton interactions
ISR/FSR: Initial/Final state radiation

Event Generators

- We want realistic simulation of the collision events. Why? Devise analysis strategy, background model, study/ remove detector effect, etc.

- The hard scattering part can be calculated theoretically (in some order) .

- The soft part is not calculable, so we use phenomenological models implemented in Monte Carlo event generators.

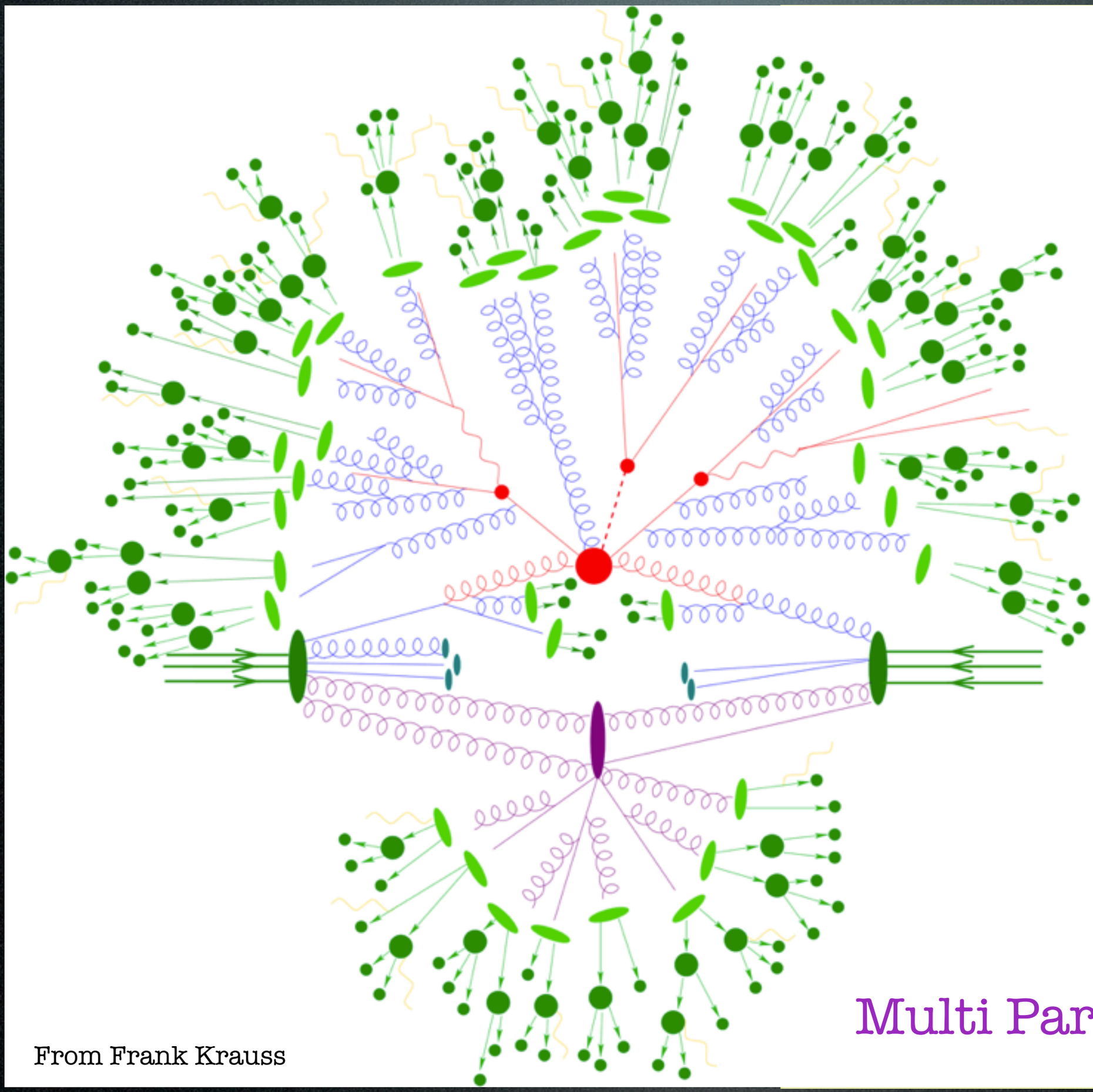


Actually two step process, but not going to discuss detector simulation!

Monte Carlo Models

"The predictions of the model are reasonable enough physically that we expect it may be close enough to reality to be useful in designing future experiments and to serve as a reasonable approximation to compare to data. We do not think of the model as a sound physical theory . . . "

– Richard Feynman and Rick Field, 1978



Hard Process

Parton Shower

Hadronization

Decays

Multi Parton Interaction

From Frank Krauss

Tuning

- Ultimate goal: models need to describe real data.
- “Free” parameters control all these aspects of the models, which cannot be derived analytically.
- A bunch of correlated (or anti-correlated) parameters describe one aspect, so have to change them simultaneously.

Tune: A particular optimized parameter setting in a particular MC generator to match the simulation with available data. Differ according to which datasets are included.

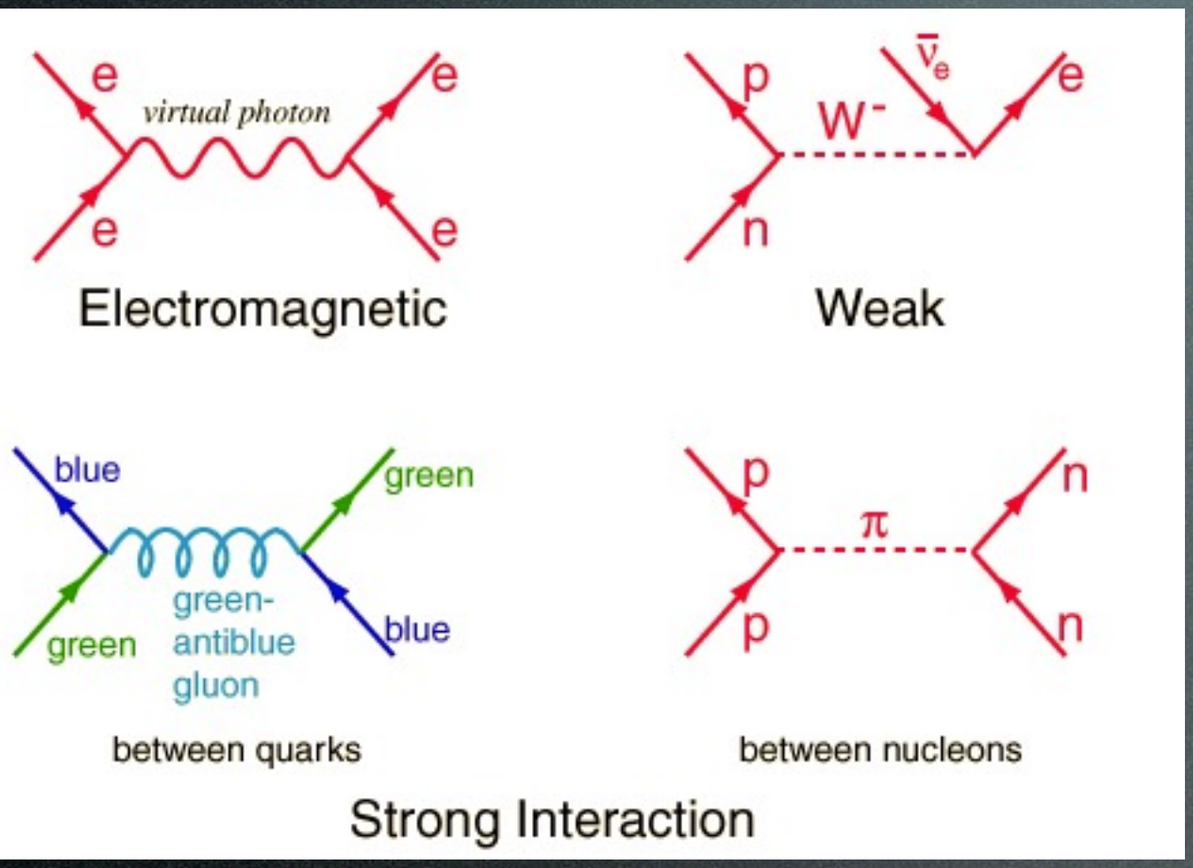
MEASUREMENTS

Measurements

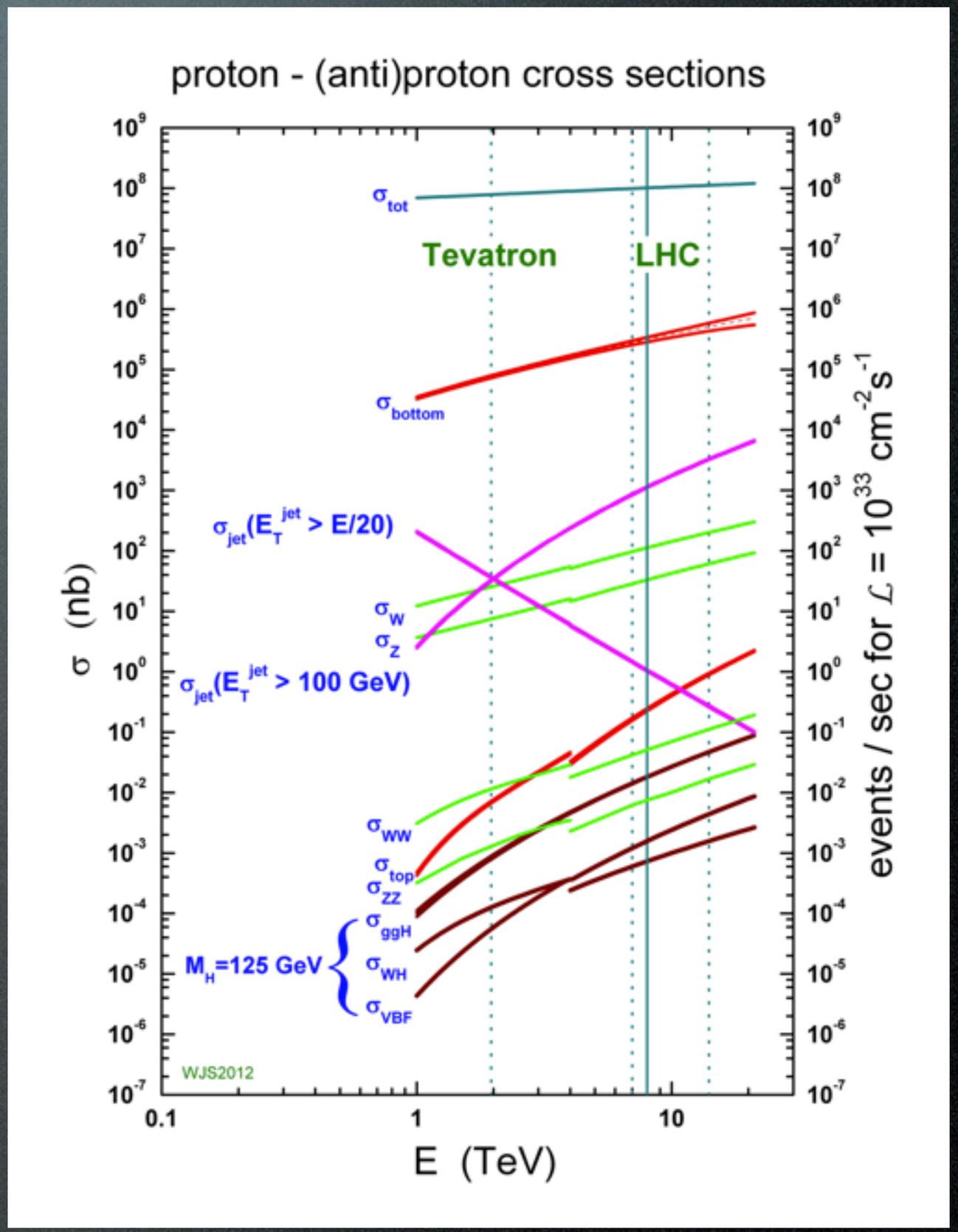
- To validate Standard Model (in a new energy regime)
- Measure the free parameters of SM (often indirectly)
- To test the predictions of MC generators
- Background for searches

Detour: Unfolding

- We measure at detector level.
- But each detector is different!
- Unfold the detector effect to arrive at generator level.
- Mathematically: $m_i = \sum_j \alpha_{ij} t_j$, which is an ill-posed problem!
- Bin-by-bin or (iterative) Bayesian method.

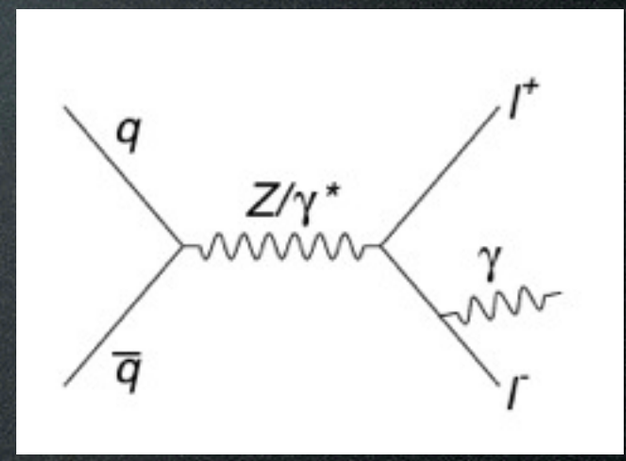


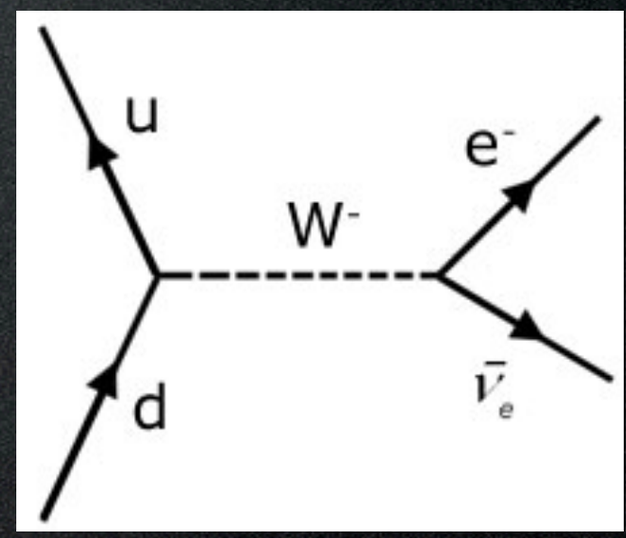
At LHC, very few pure Electroweak (EW) measurements, many more using EW bosons as probes

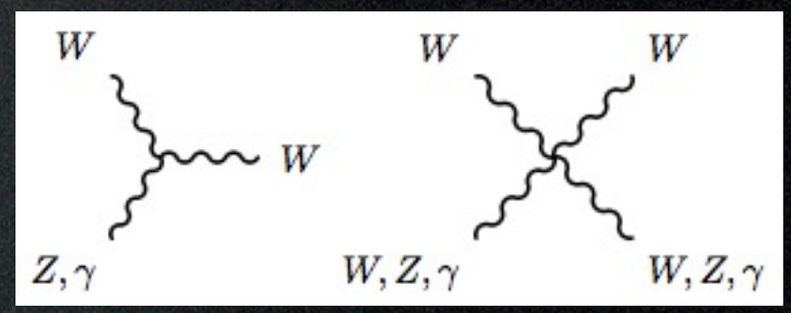


EW Measurements

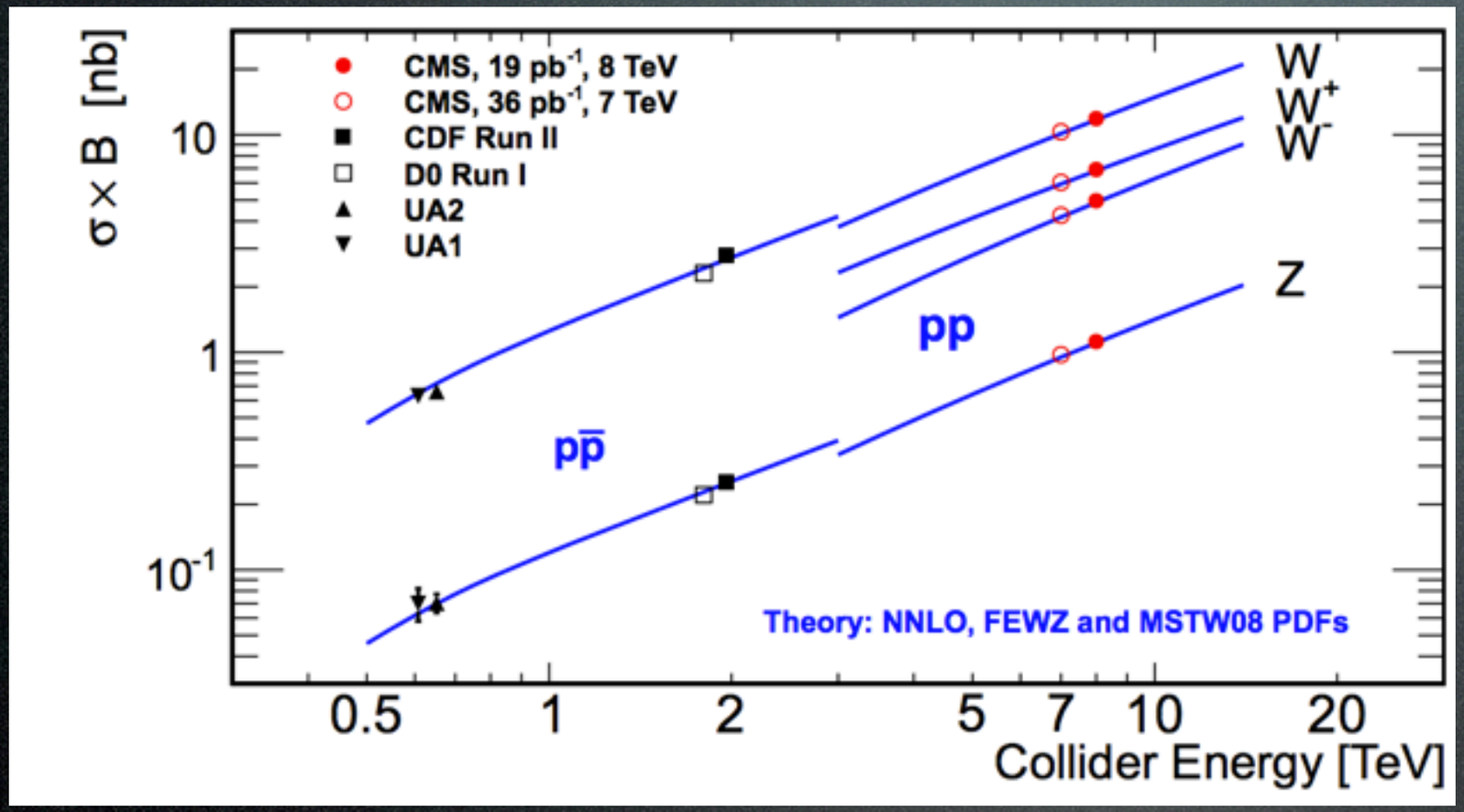
- Involves single or combination of W, Z and isolated γ, cross sections or kinematic observables.
- Reconstructed using leptons, missing energy (and jets).
- Probe triple or quartic self interactions (and set limits)





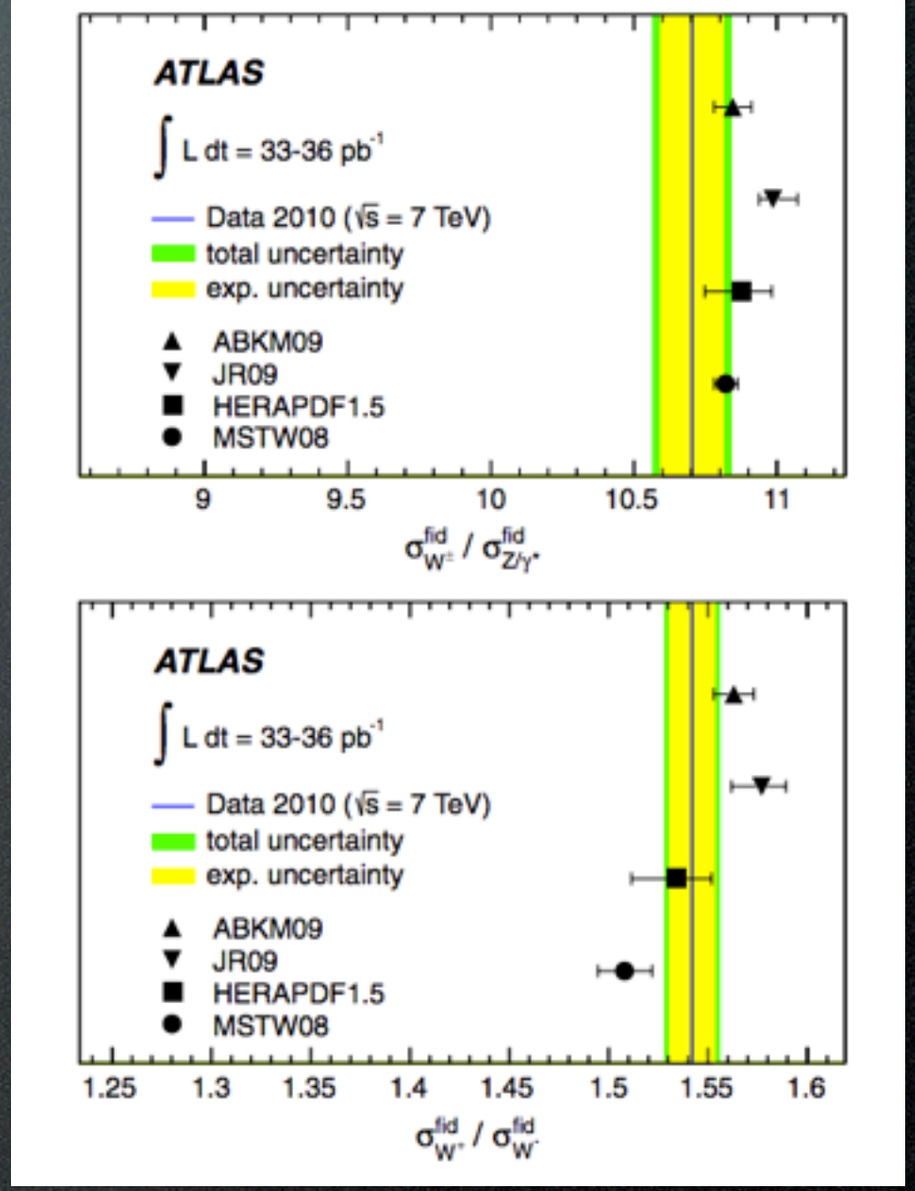


Inclusive W/Z Production



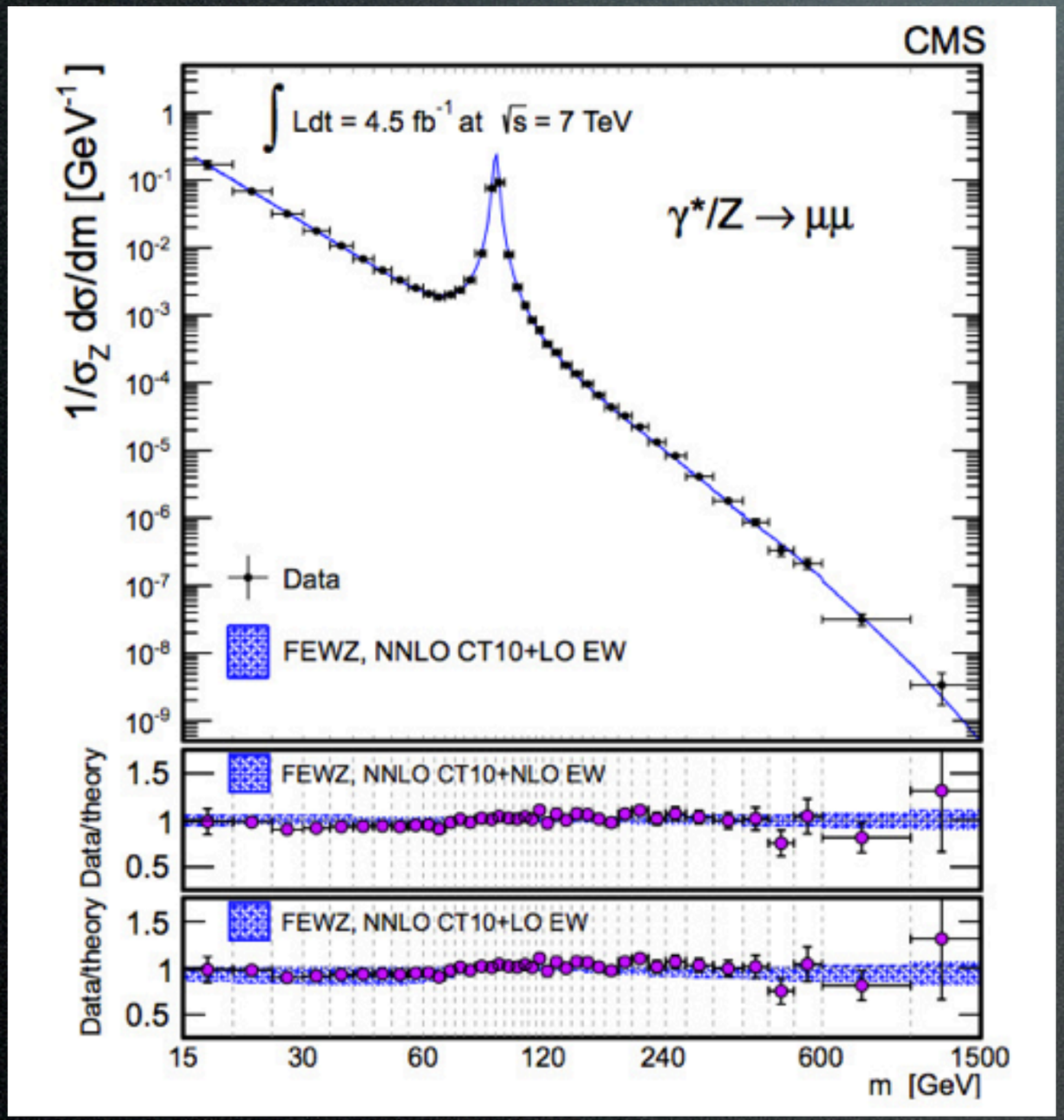
Very precise measurements,
Also probes the difference
between ppbar and pp

Good agreement with predictions

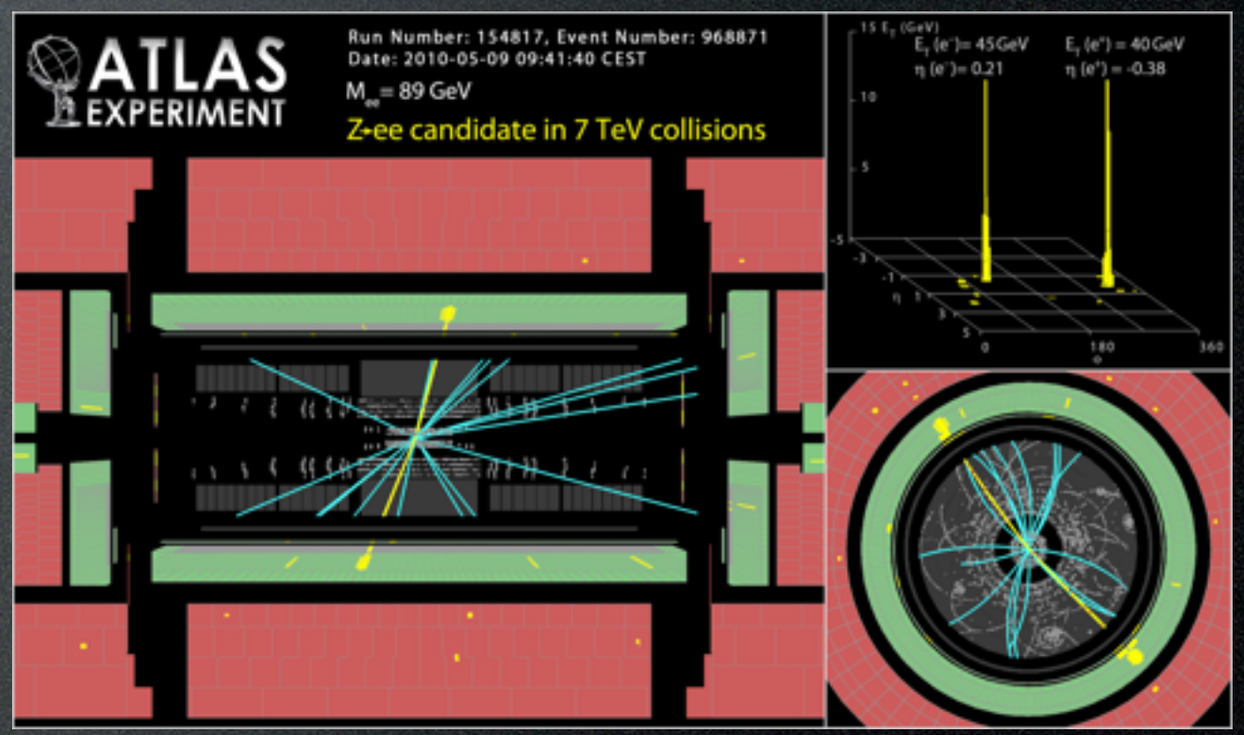


Ratio cancels
uncertainties

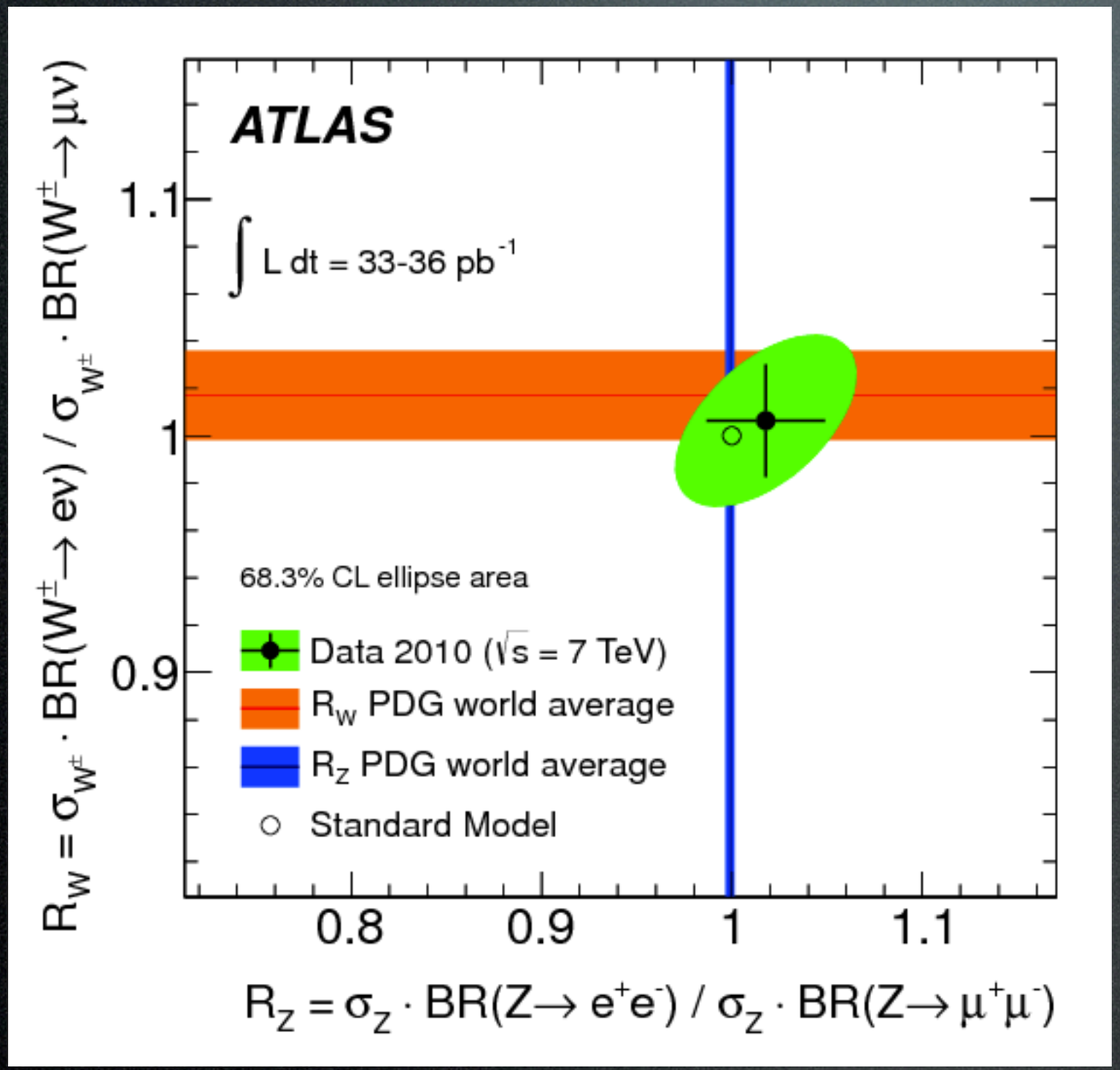
Z differential cross section



Again very good agreement with theory/generator predictions



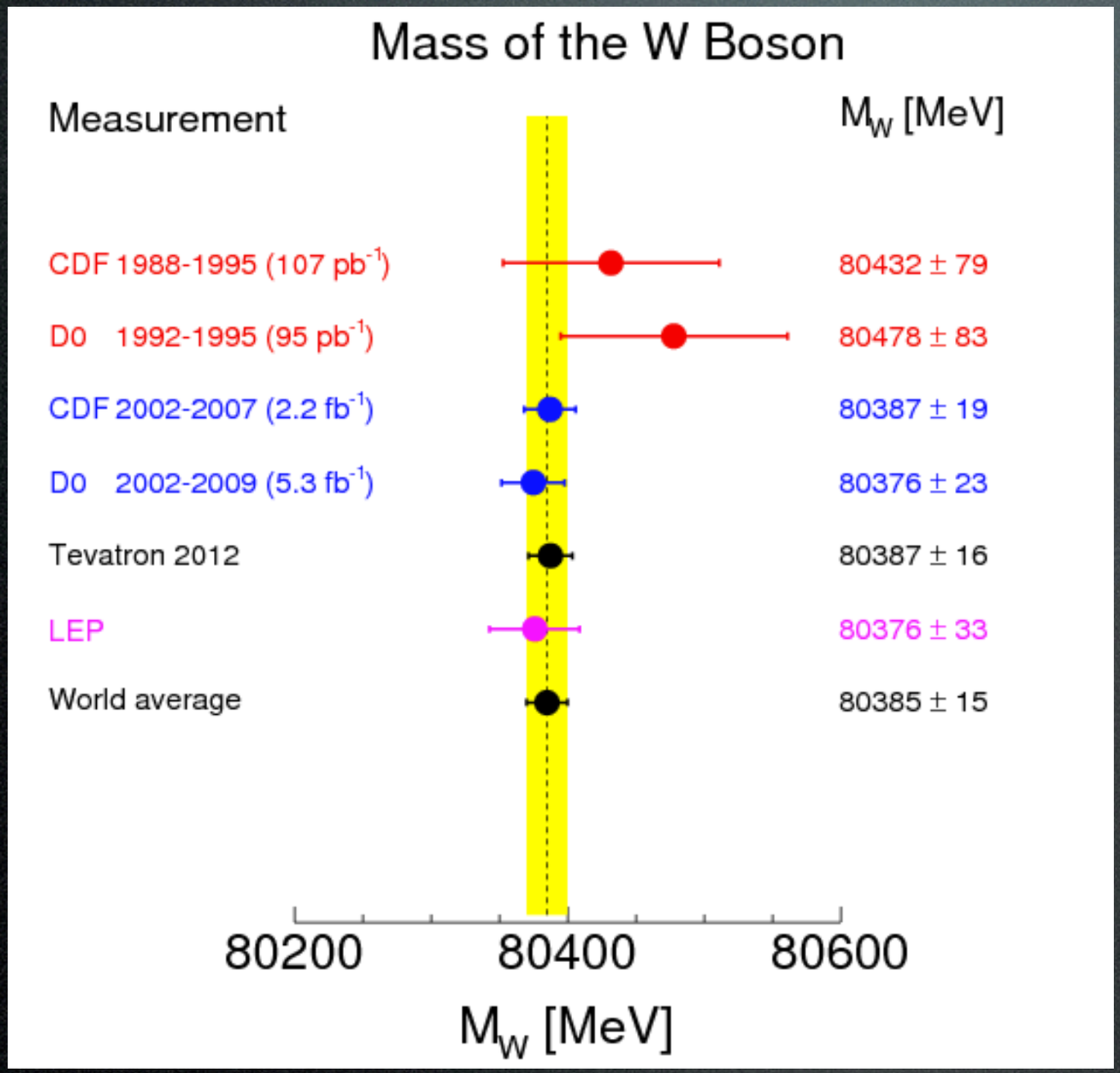
Lepton Universality



Coupling of leptons to W and Z bosons should be independent

Cross sections measured in electron and muon channel compared

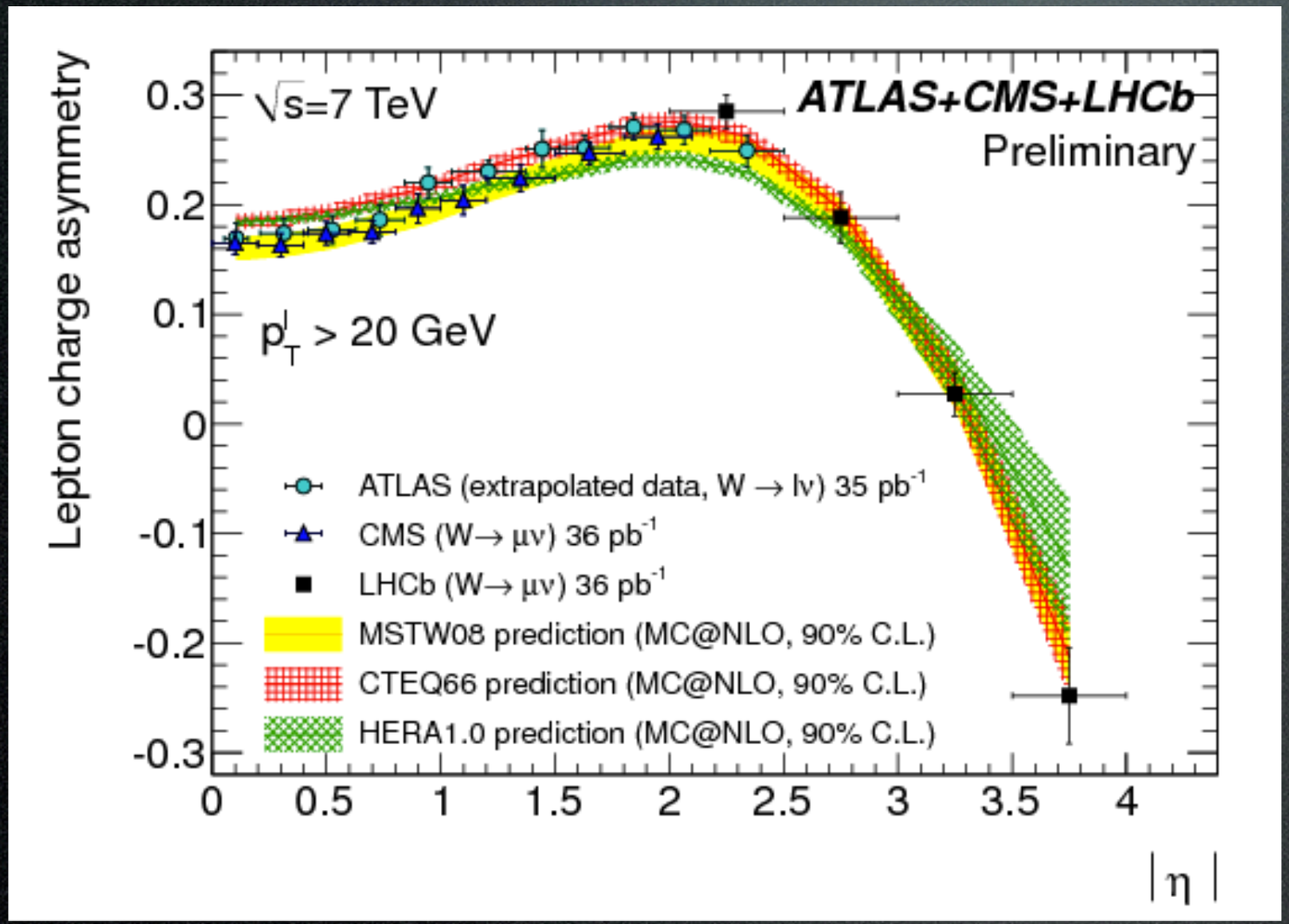
W Mass



No result from LHC yet

Necessary for precision measurement for other EW processes

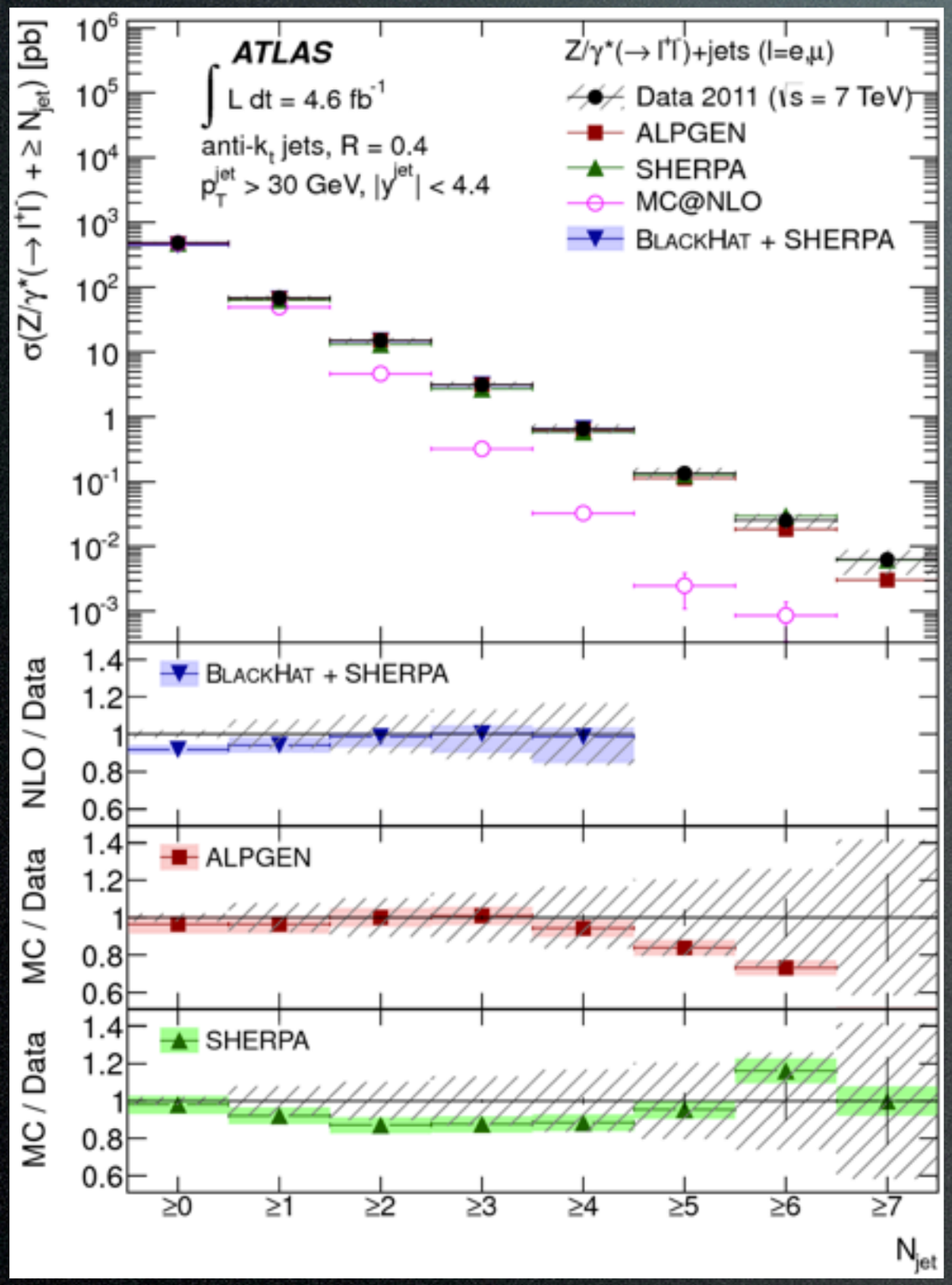
W Lepton Charge Asymmetry



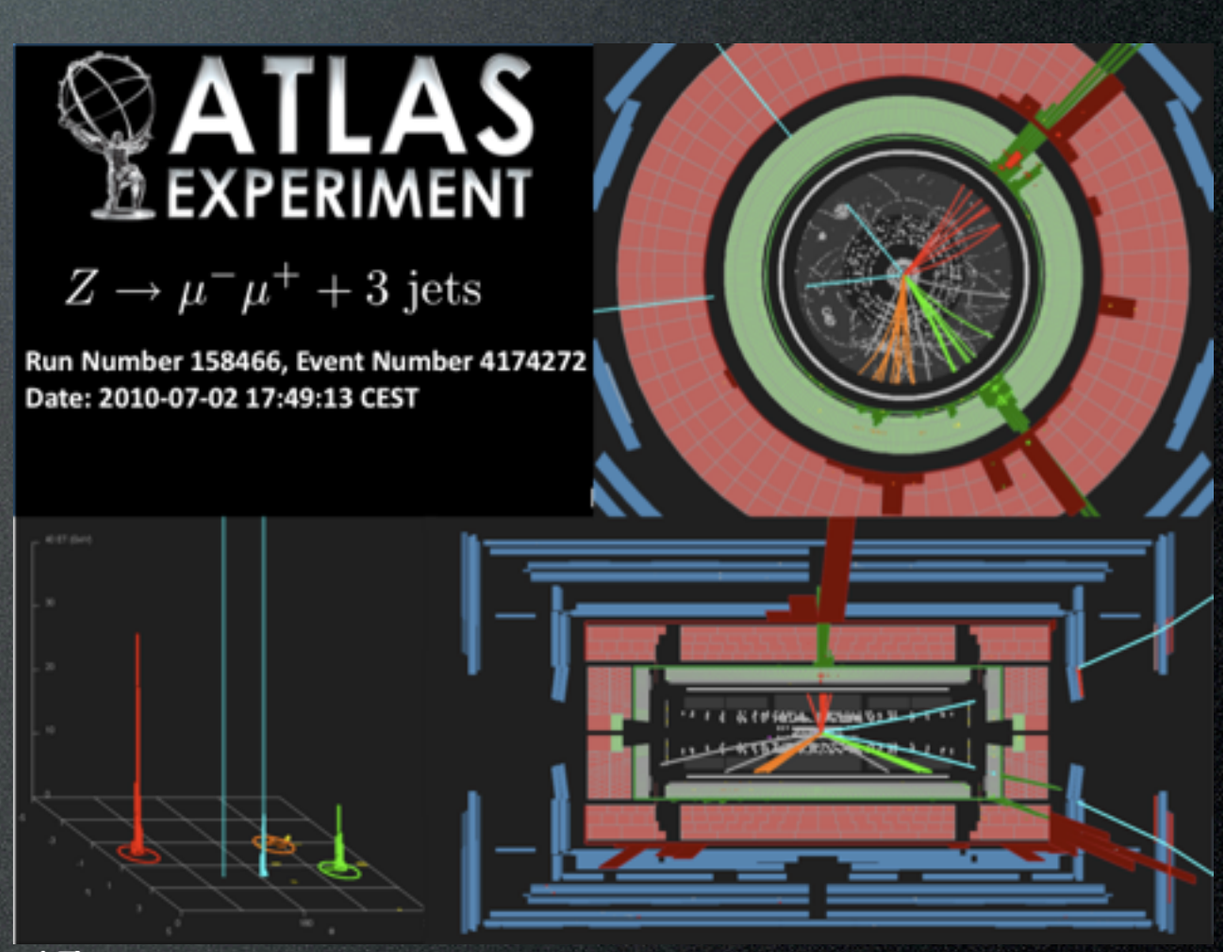
$$A_W = \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}$$

Sensitive to quark distributions inside the proton

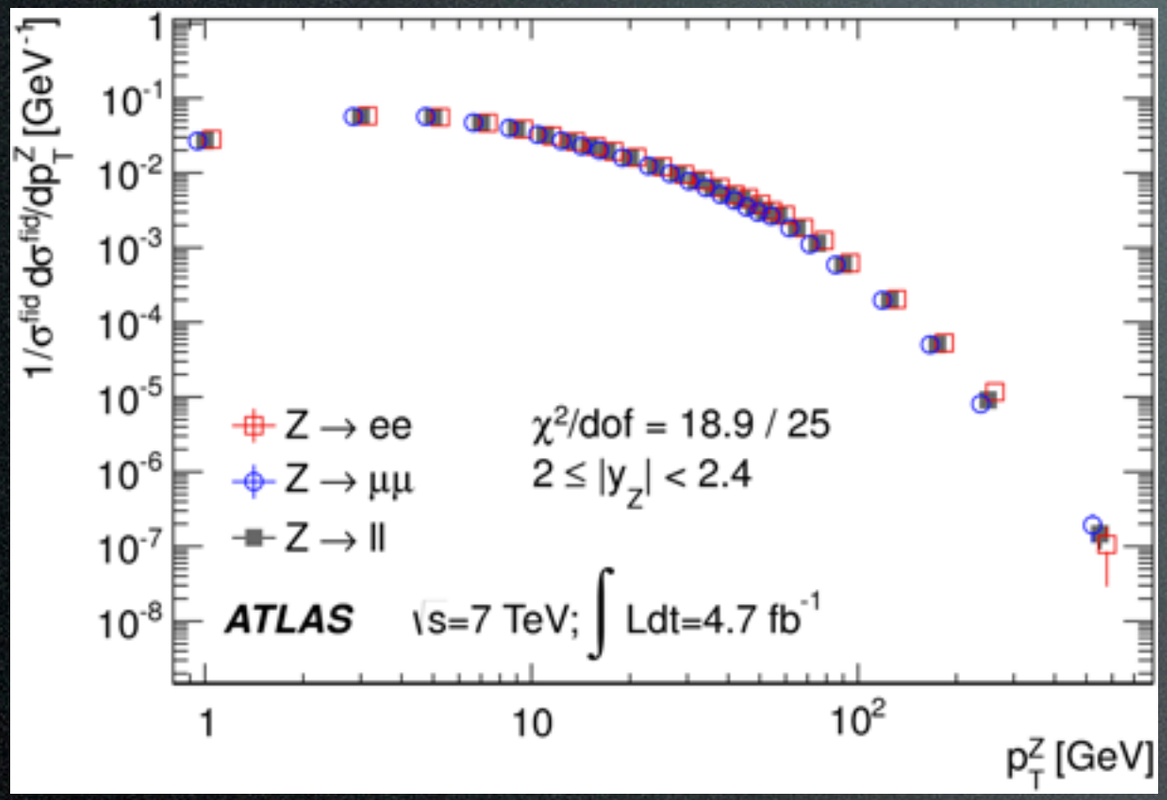
W/Z+jets Productions

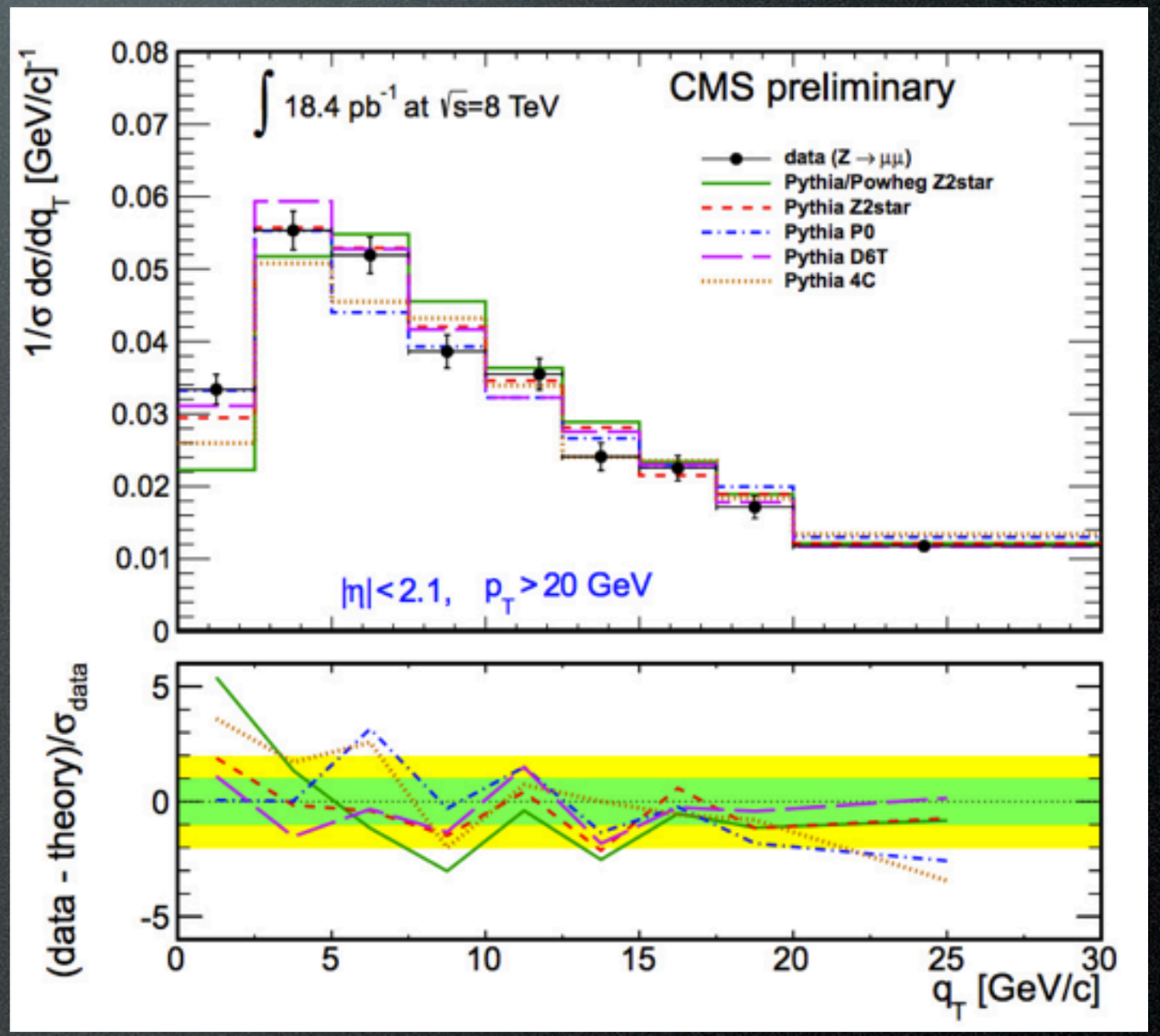


Recoil against hard jet, additional jets from radiation



Z Transverse Momentum





Stringent test of (perturbative) QCD calculations

THATS IT FOR TODAY