(Re)Discovering the Standard Model and the Road to the Higgs

- A brief overview of the Tevatron and LHC accelerators
- Detectors and observables
- Examples of standard model measurements
- Higgs hunting 101
- The road ahead

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Times are changing fast

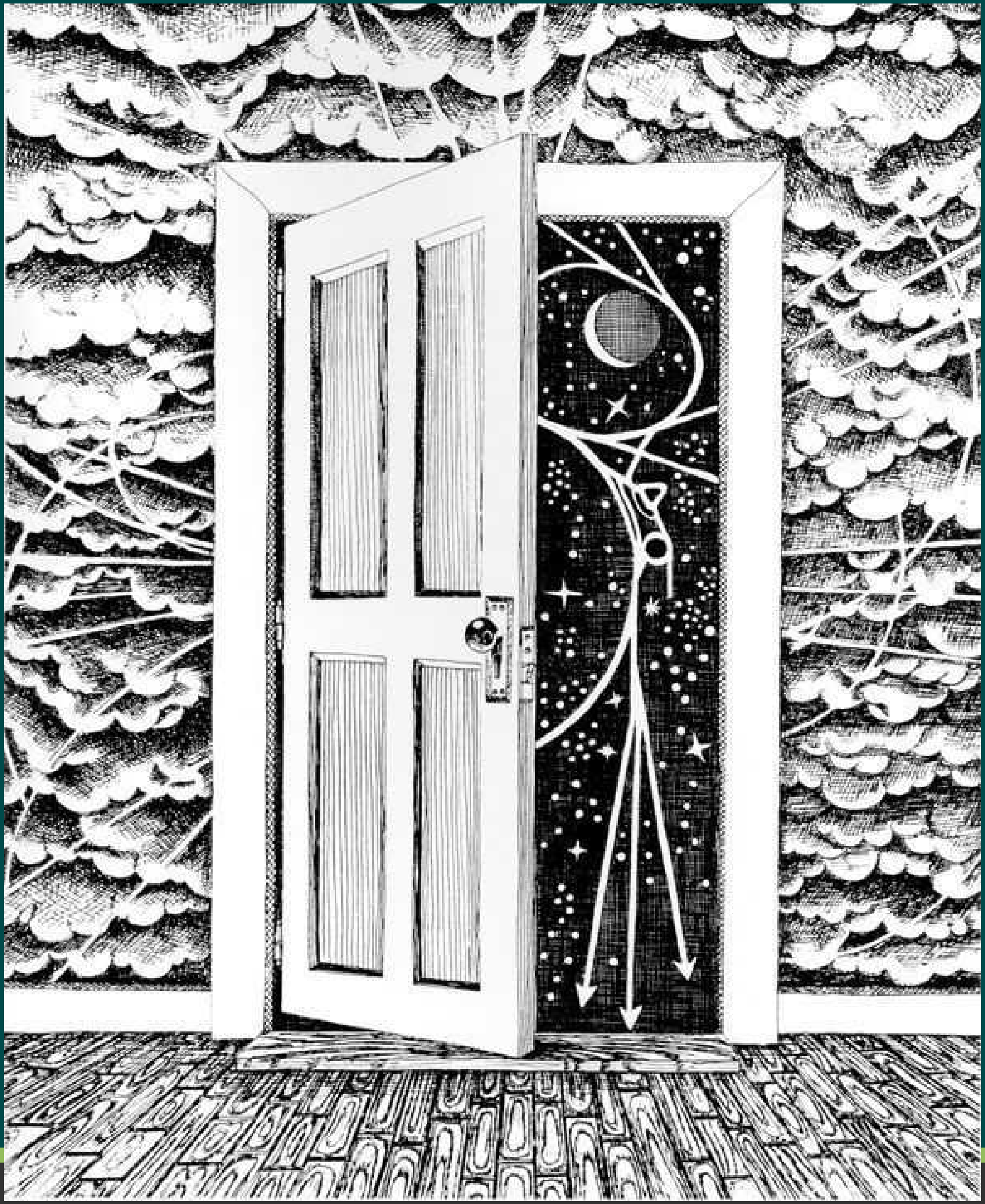
Most results shown here are being refined now for the major summer conferences

The large collaborations frequently update current results on their home pages:

- ATLAS : http://atlas.ch/
- CDF : http://www-cdf.fnal.gov/
- CMS : http://cms.web.cern.ch/cms/index.html
- D-Zero : http://www-d0.fnal.gov/

Very latest results are being presented this week at the European Physical Society conference: http://eps-hep2011.eu/

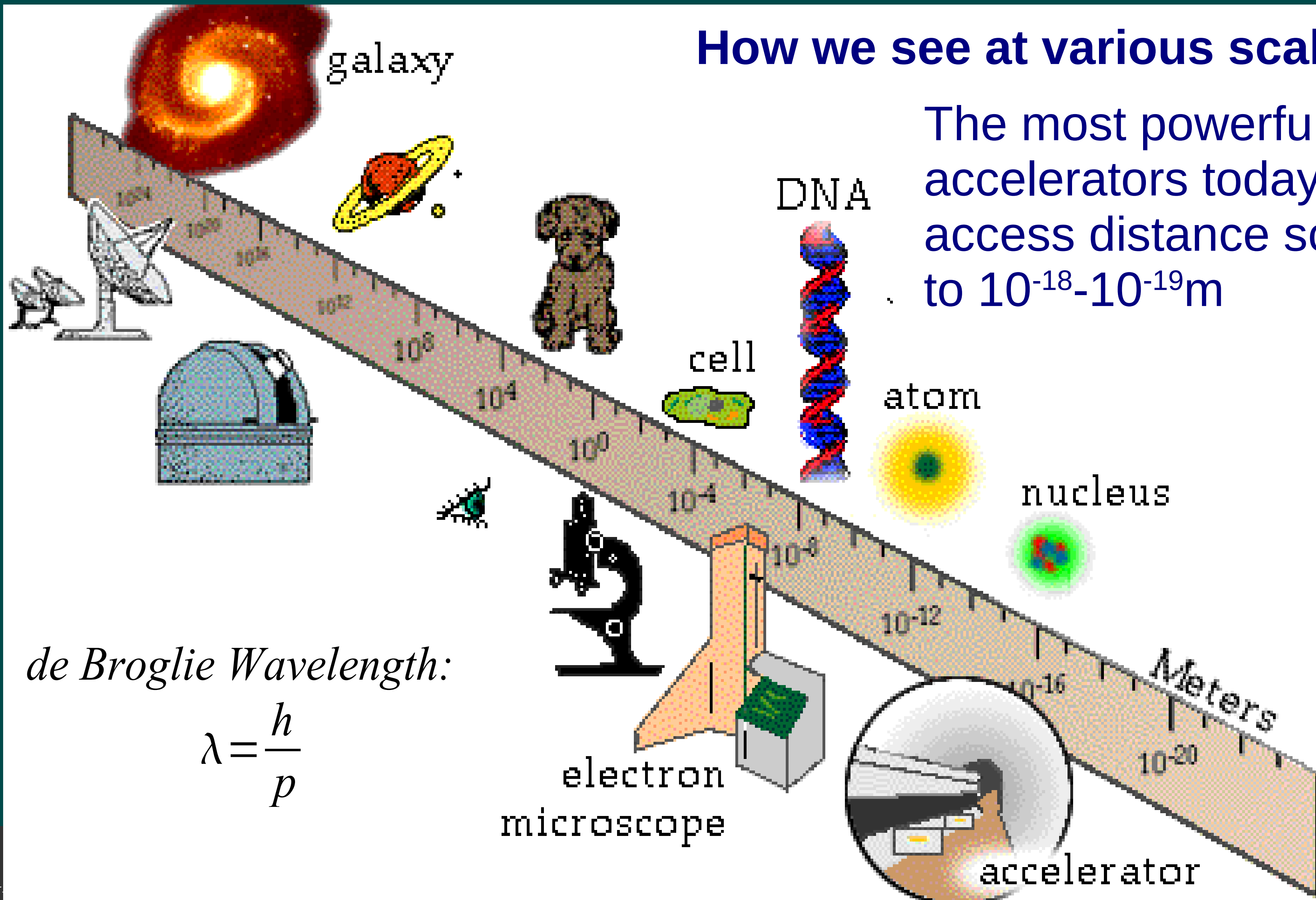
Let's get small



Imaging

How do we see really small things?

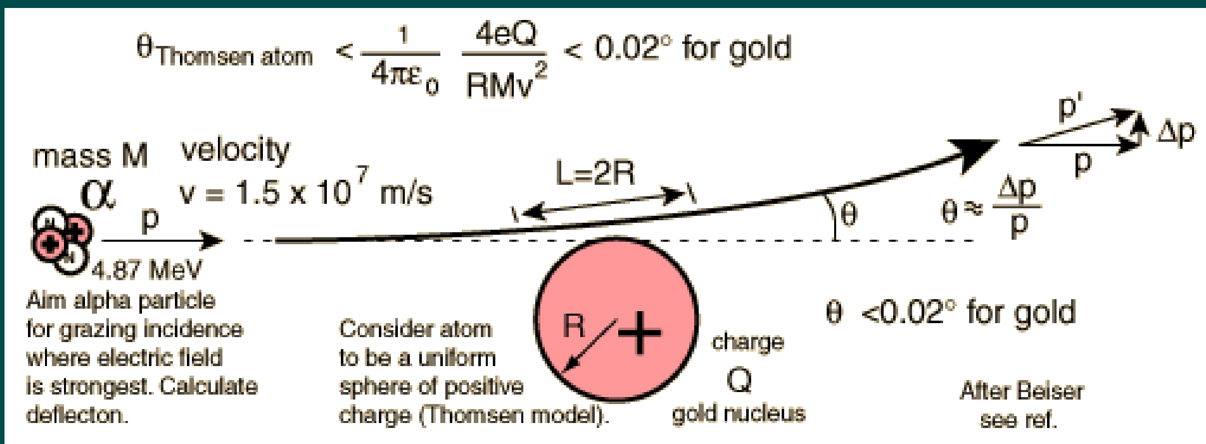
Accelerators used to study basic constituents and forces (powerful microscope...)



The most powerful accelerators today can access distance scales to 10^{-18}-10^{-19}m

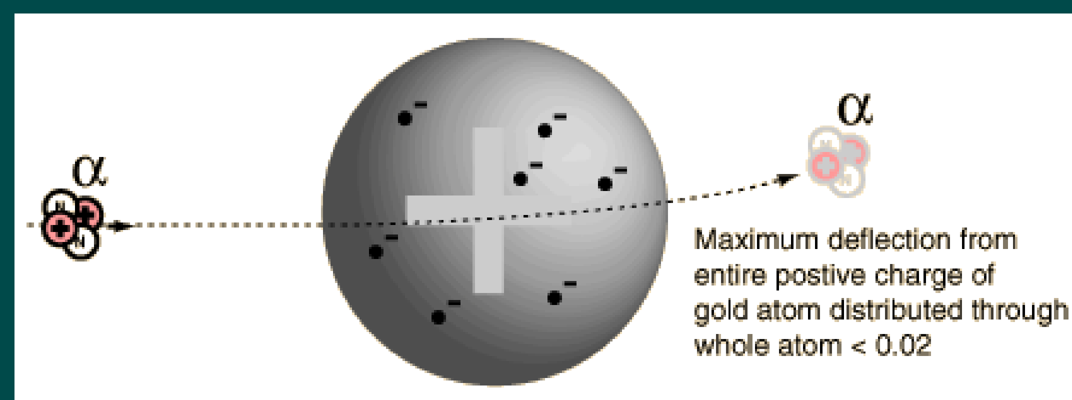
This is the classic physics of Rutherford

1909: The classic scattering experiment (Geiger, Marsden, Rutherford)



$$\theta_{max} < \frac{1}{4\pi\varepsilon_0}\frac{4eQ}{RMv^2} < 0.02^{\circ}$$

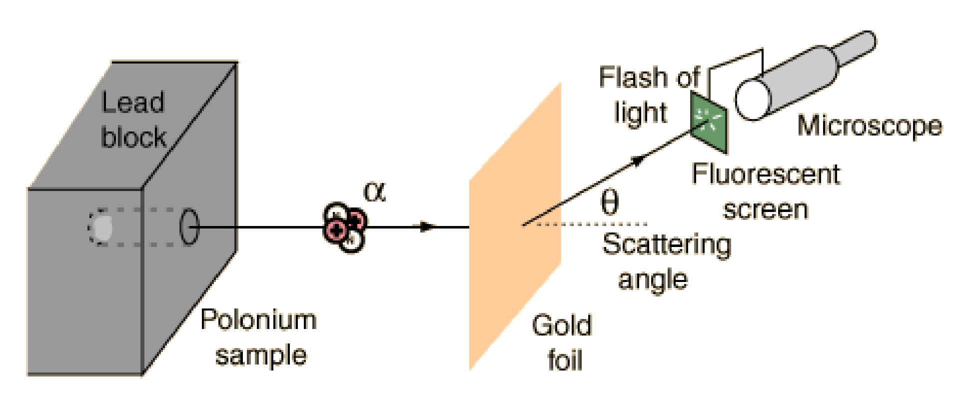
Scattering angle based on Coulomb force. Initial theory of atom, electrons distributed over sponge-like atom (Thompson model).

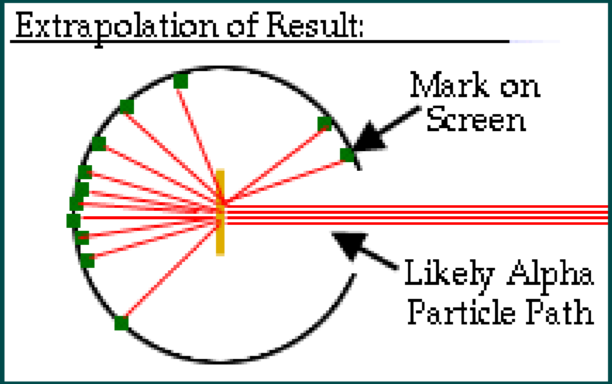


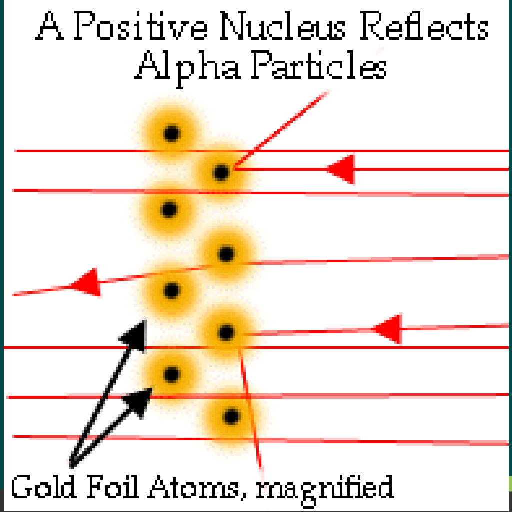
What happened?

Geiger and Marsden showed that 1 in 8000 alpha particles scattered with angle >90 degrees.

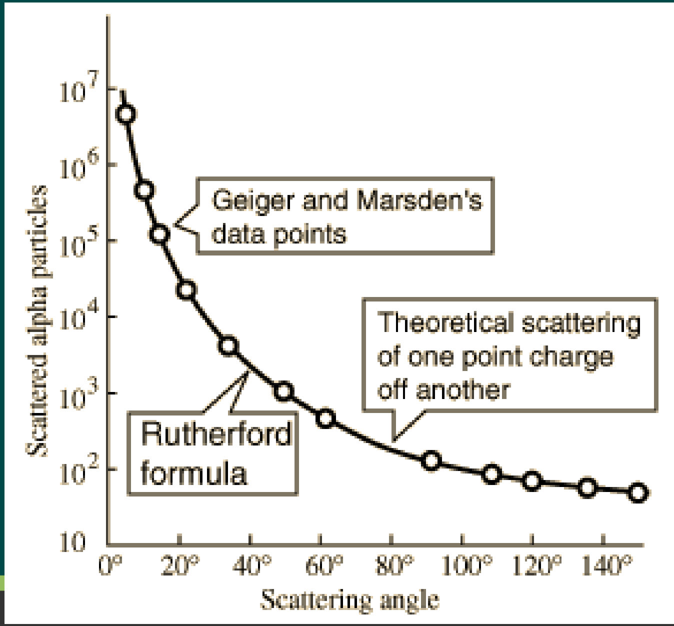
Evidence for massive, positive nucleus in atom. A big surprise to everyone!







This experiment nicely illustrates the work of particle physics. **Particle collisions serve as our eyes in the sub-atomic world...**

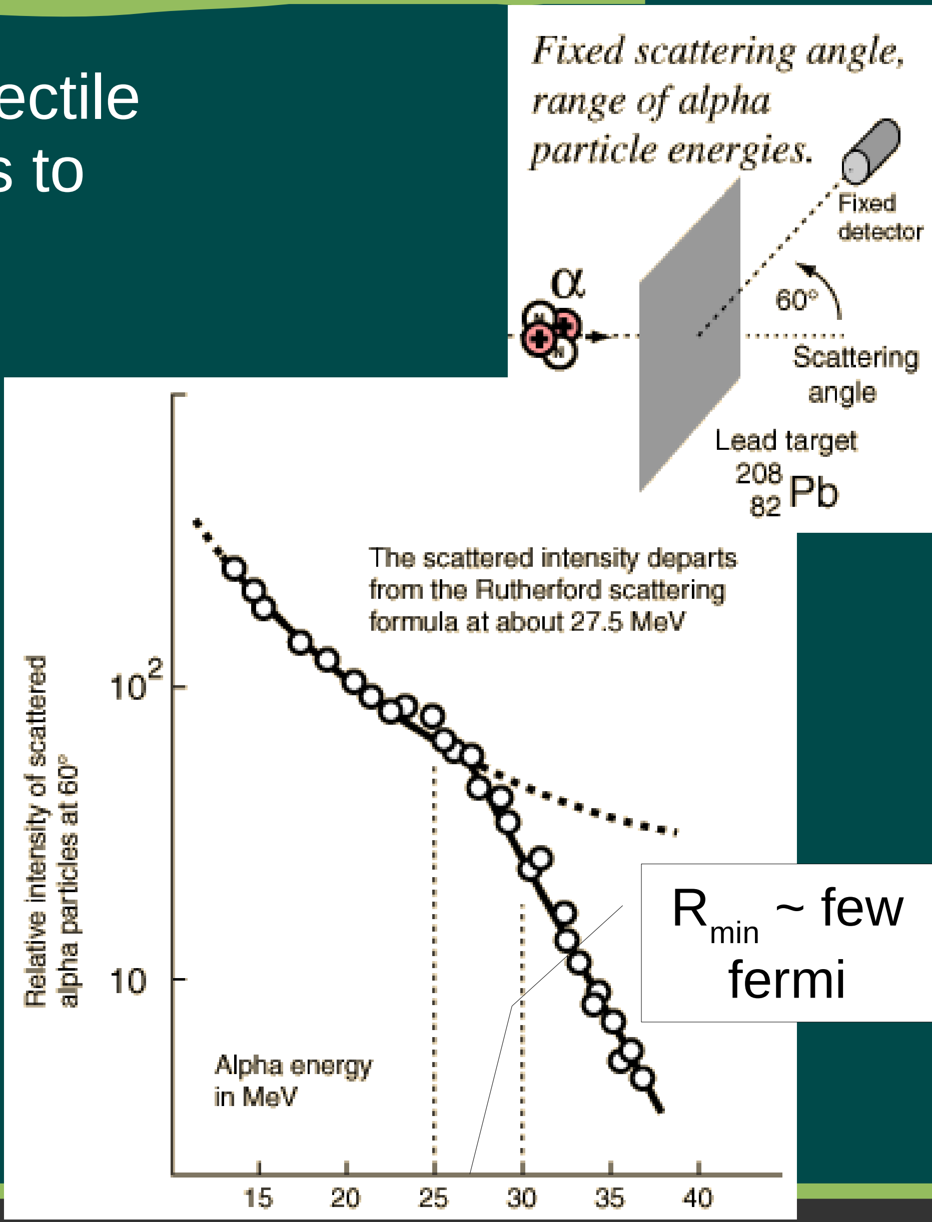


A few years later, now with larger KE

With higher α-particle energies the projectile punches in close enough to the nucleus to feel the nuclear strong force and the distribution of scattered alphas departs sharply from the Rutherford formula.

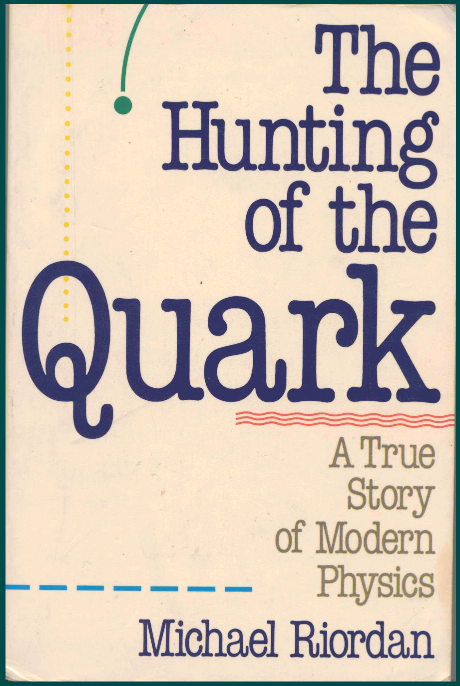
Departure point from the Rutherford scattering gives estimate of the nuclear radius, onset of new physics....

Allows study of new physics of the nucleus. **New energy scale, opens up new distance scales, and in this case entirely new physics.**

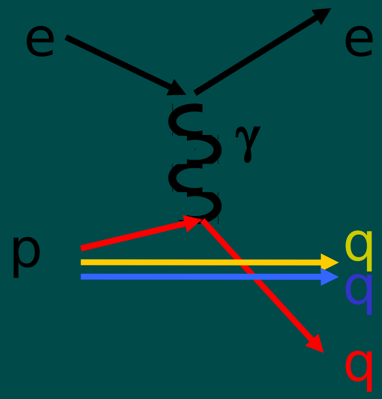


R_{min} ~ few fermi

One more step to the elementary particles



1967: evidence for quarks in electron-proton scattering at SLAC. Proton/Neutron internal structure becomes evident.



Proton behaves as if made of point-like constituent particles.

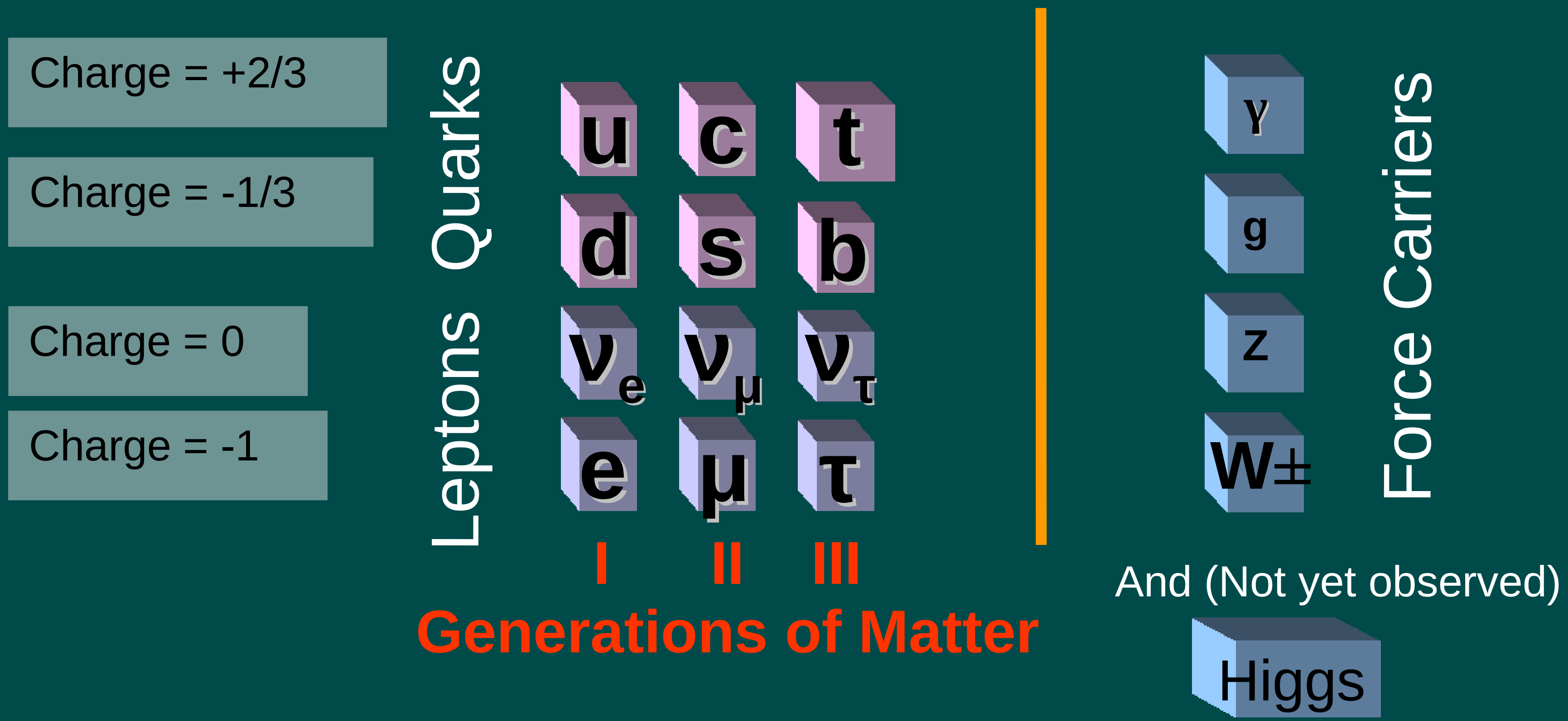
Results similar to Rutherford scattering! Initially....

Building blocks of ‘Standard Model’ of Elementary particle physics

The Elementary Particles

“periodic table of fermions.”

Bosons



Seems simple enough, but....

The Standard Model Lagrangian* supports an enormous range of phenomena

*shown post EW-symmetry breaking with Higgs model.

(...imagine addition of broken SUSY, ouch!)

$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \bar{d}_j^\lambda(\gamma\partial + \\
m_d^\lambda)d_j^\lambda + igs_w A_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \tfrac{2}{3}(\bar{u}_j^\lambda\gamma u_j^\lambda) - \tfrac{1}{3}(\bar{d}_j^\lambda\gamma d_j^\lambda)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \\
\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u_j^\lambda) + \\
(\bar{d}_j^\lambda\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d_j^\lambda)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(1 + \\
\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \gamma^5)u_j^\lambda)] + \\
\tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1 - \gamma^5)d_j^\kappa) + m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1 + \\
\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1 + \gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1 - \gamma^5)u_j^\kappa] - \\
\tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5 d_j^\lambda) + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + \\
igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + \\
igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + \\
igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \\
\tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \\
\bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \\
\bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$

Now let's start to explore the physics of the standard model

Step 1: In the direct approach*, we need to accelerate probes to high energies and collide them to initiate the interactions we want to study.

But QM processes are random, so all we can do is to create necessary conditions and take what we get. But repeating this many, many times will eventually map out the range of possible phenomena.

* see talks by Craig Dukes for some indirect approaches

Now let's start to explore the physics of the standard model

Step 2: choose a probe. For this talk I'll only consider protons/(anti)protons.

Why not electrons/positrons?

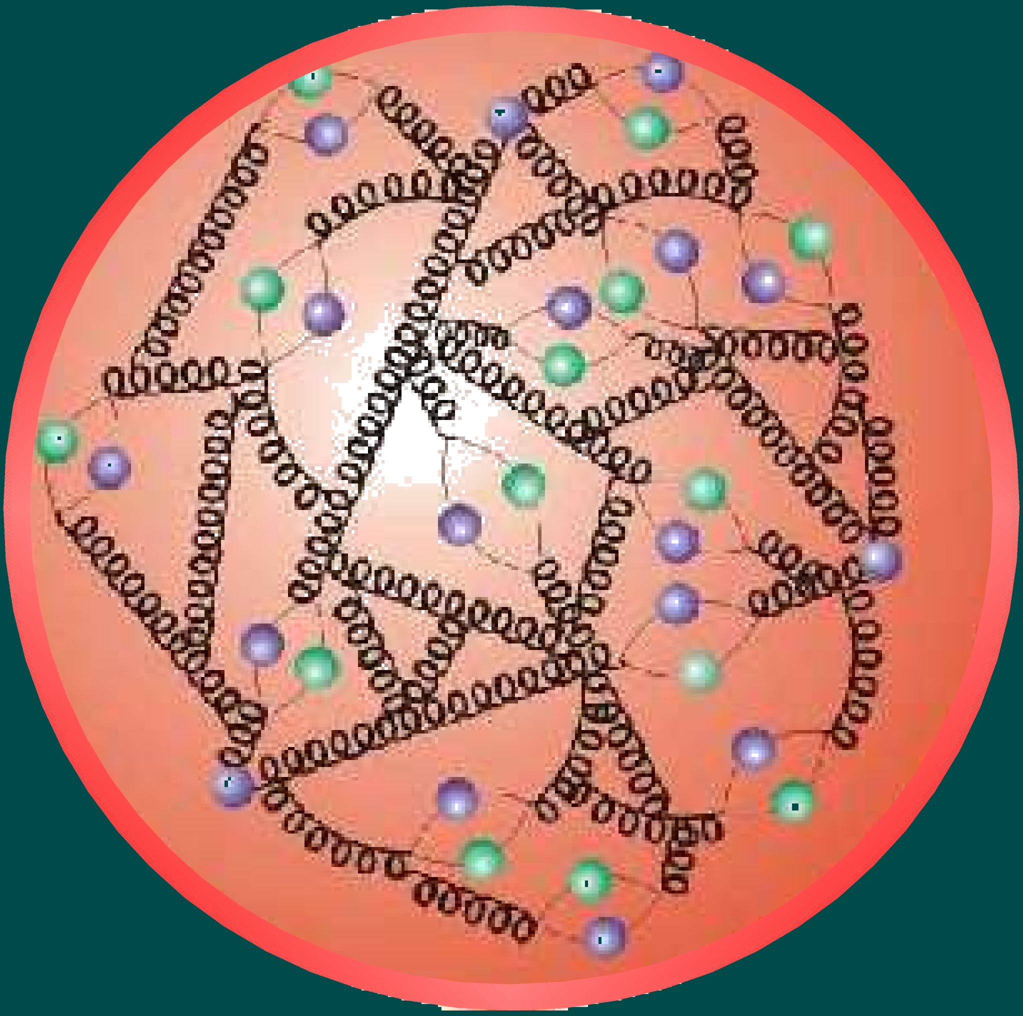
The big advantage of protons is that b/c of their high mass, their velocity is smaller for a given beam energy/momentum. This means they radiate less when curving in a magnetic field.

So it's possible to go to MUCH higher energies in a circular collider of “REA$ONAB£€” size, w/o losing too much of that energy in synchrotron radiation.

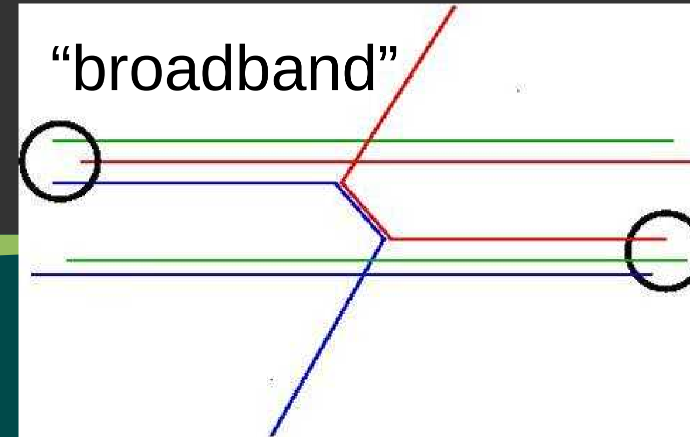
One more thing to consider

At very high energies, are we really colliding protons?

Bowl of soup



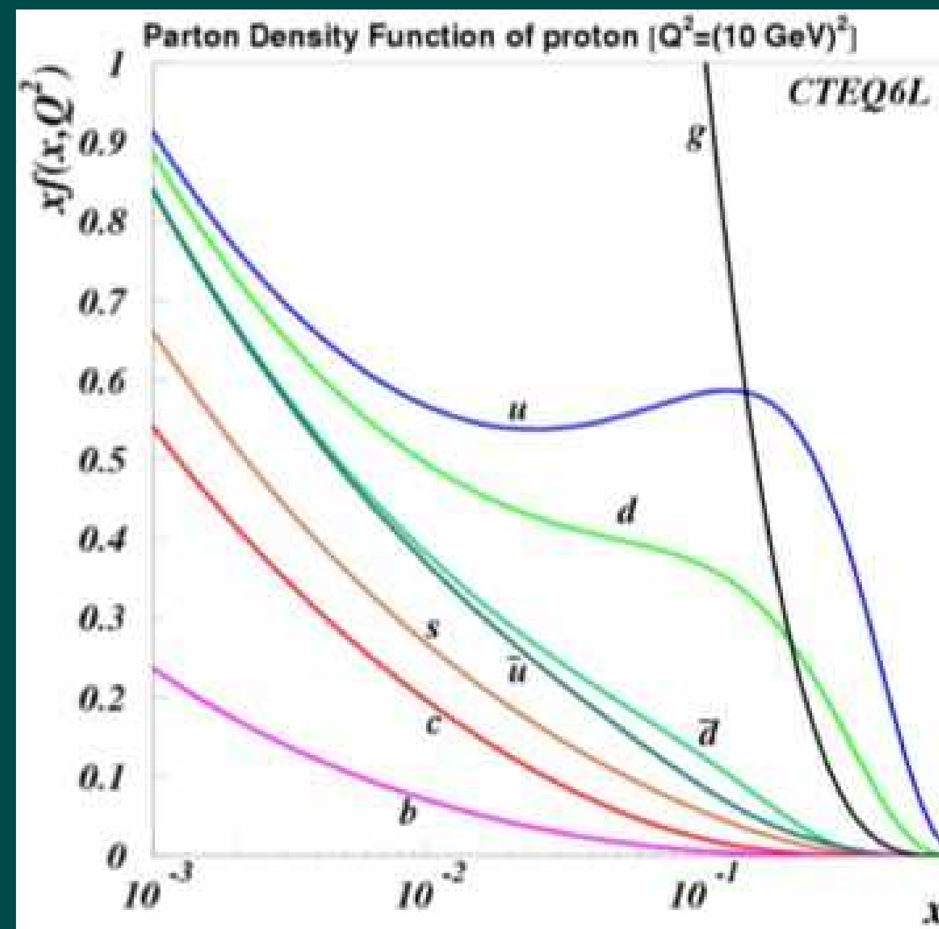
Parton colliders...

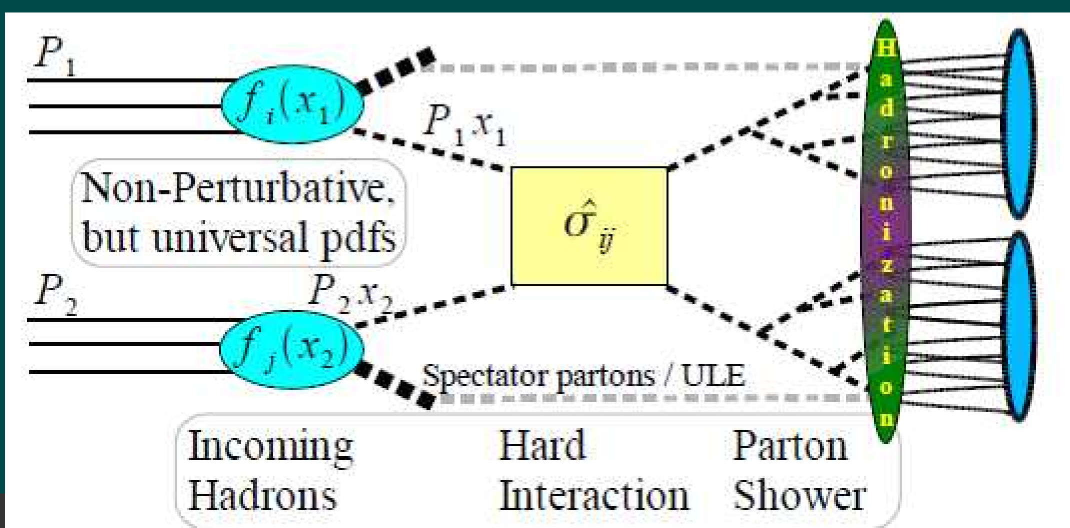


Proton collisions are messy

In general only a small fraction of the proton's momentum, participates in a hard scatter

Also, what a proton is made of depends on how hard you look...



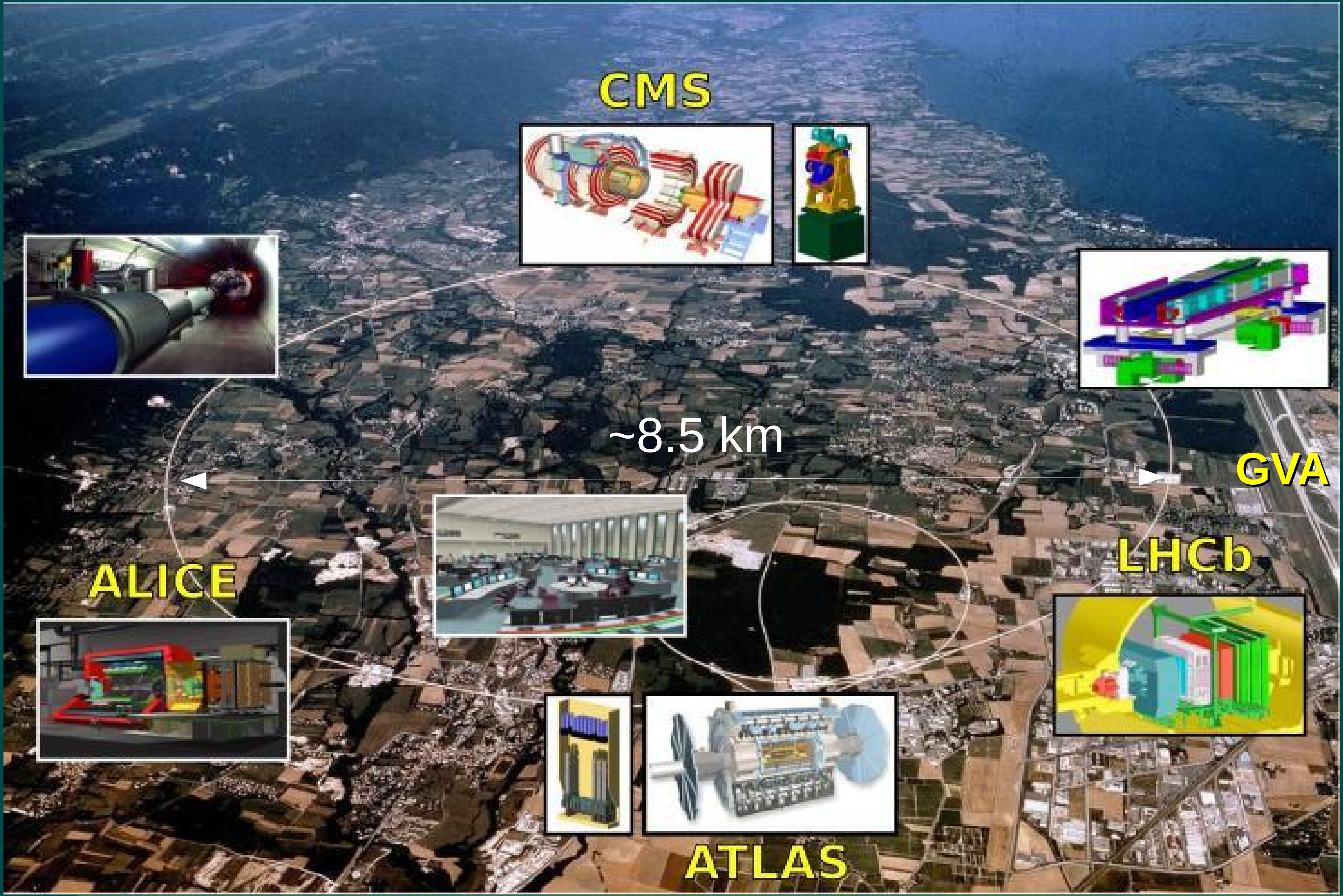


Partons<<P_{proton} Partons~P_{proton}

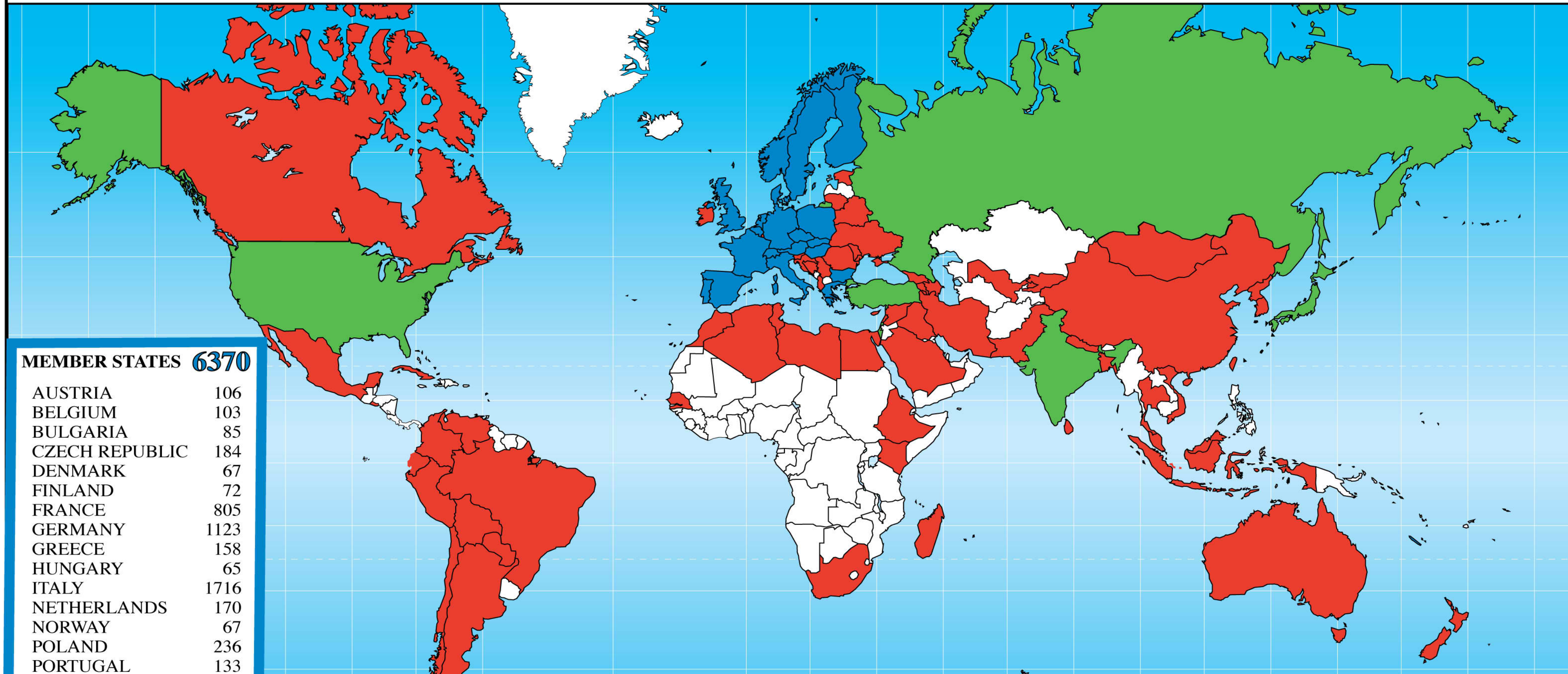
A look at the machines

The Fermilab Tevatron

The Large Hadron Collider



Distribution of All CERN Users by Nationality on 20 January 2010



MEMBER STATES 6370

AUSTRIA	106
BELGIUM	103
BULGARIA	85
CZECH REPUBLIC	184
DENMARK	67
FINLAND	72
FRANCE	805
GERMANY	1123
GREECE	158
HUNGARY	65
ITALY	1716
NETHERLANDS	170
NORWAY	67
POLAND	236
PORTUGAL	133
SLOVAKIA	78
SPAIN	330
SWEDEN	67
SWITZERLAND	200
UNITED KINGDOM	605

OBSERVER STATES 2444

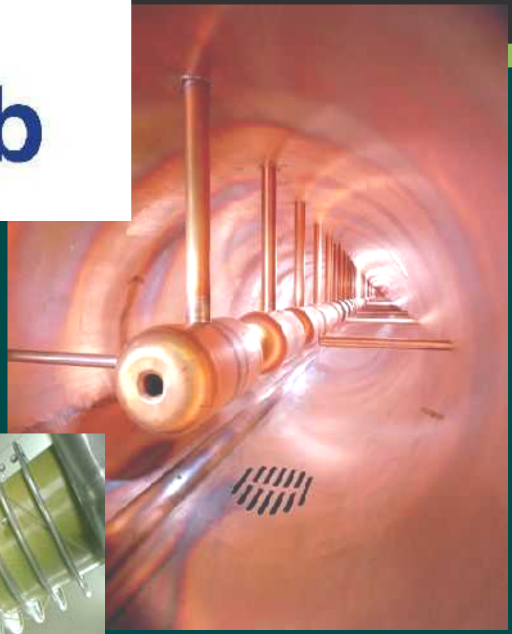
INDIA	158
ISRAEL	51
JAPAN	229
RUSSIA	1027
TURKEY	87
USA	892

OTHERS 1205

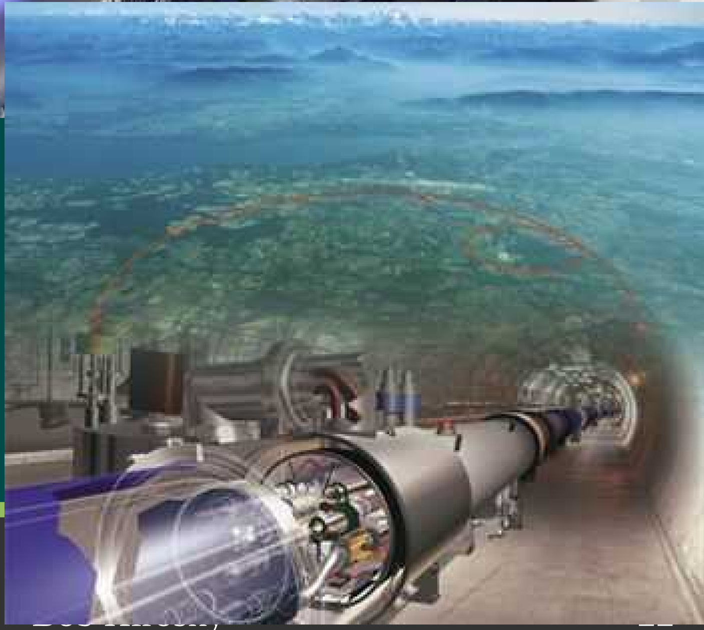
ALBANIA	2
ALGERIA	8
ARGENTINA	11
ARMENIA	24
AUSTRALIA	20
AZERBAIJAN	5
BANGLADESH	3
BELARUS	36
BOLIVIA	2
BOSNIA AND HERZEGOVINA	1
BRAZIL	79
CANADA	136
CHILE	3
CHINA	202
CHINA (TAIPEI)	41
COLOMBIA	19
CROATIA	24
CUBA	4
CYPRUS	12
ECUADOR	2
EGYPT	6
EL SALVADOR	1
ESTONIA	9
ETHIOPIA	1
GEORGIA	31
GIBRALTAR	1
HONG KONG	2
INDONESIA	1
IRAN	20
IRAQ	1
IRELAND	20
KENYA	2
KOREA, D.P.R.	3
KOREA REP.	85
KYRGYZSTAN	1
LEBANON	8
LITHUANIA	9
LUXEMBOURG	5
LIBYA	1
MADAGASCAR	3
MALAYSIA	7
MALTA	3
MAURITIUS	1
MEXICO	46
MOLDOVA	1
MONGOLIA	1
MOROCCO	16
NEPAL	3
NEW ZEALAND	10
PAKISTAN	33
PALESTINE (O.T.).	1
PARAGUAY	1
PERU	2
ROMANIA	101
SAN MARINO	1
SAUDI ARABIA	2
SENEGAL	1
SERBIA	34
SINGAPORE	1
SLOVENIA	20
SOUTH AFRICA	9
SRI LANKA	6
SYRIA	2
THAILAND	1
TUNISIA	5
UKRAINE	40
UZBEKISTAN	2
VENEZUELA	5
VIET NAM	6

Fermilab

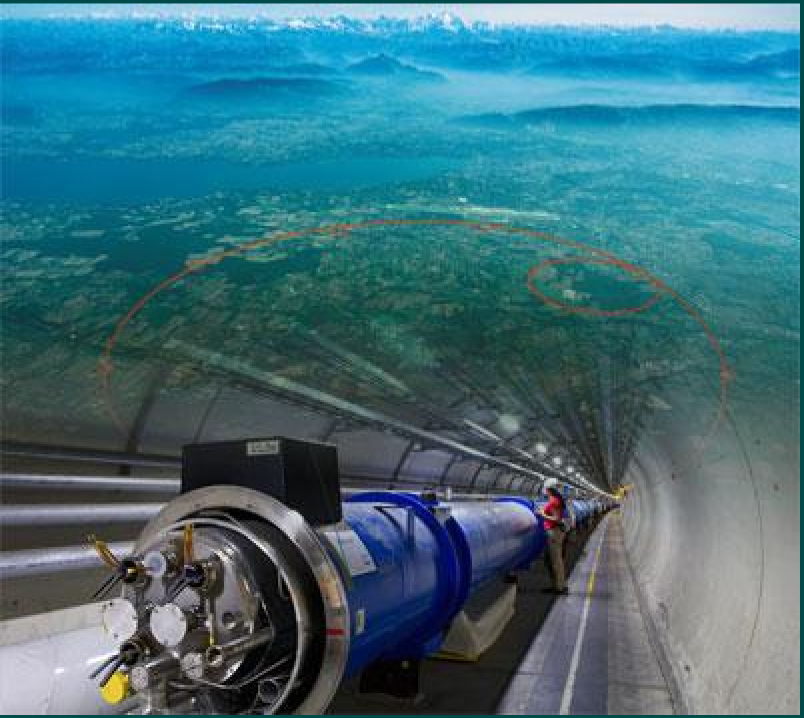
CERN



Tevatron



The Large Hadron Collider



Circumference: 26 659 m, total of 9300 magnets

World's Largest refrigerator!
60 tons of liquid He cool magnets to 1.9 K

v_protons = c - 6mph (for 7TeV)
Beam E: 362 MJ (Design) ~ 77.4kg TNT

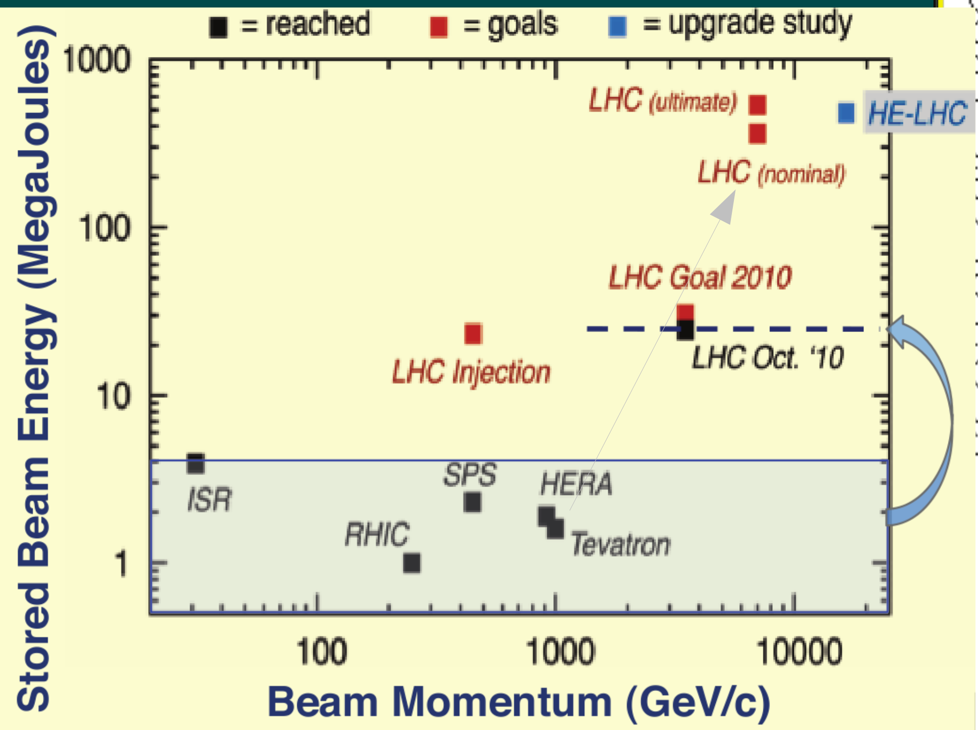
pp Collision E: 

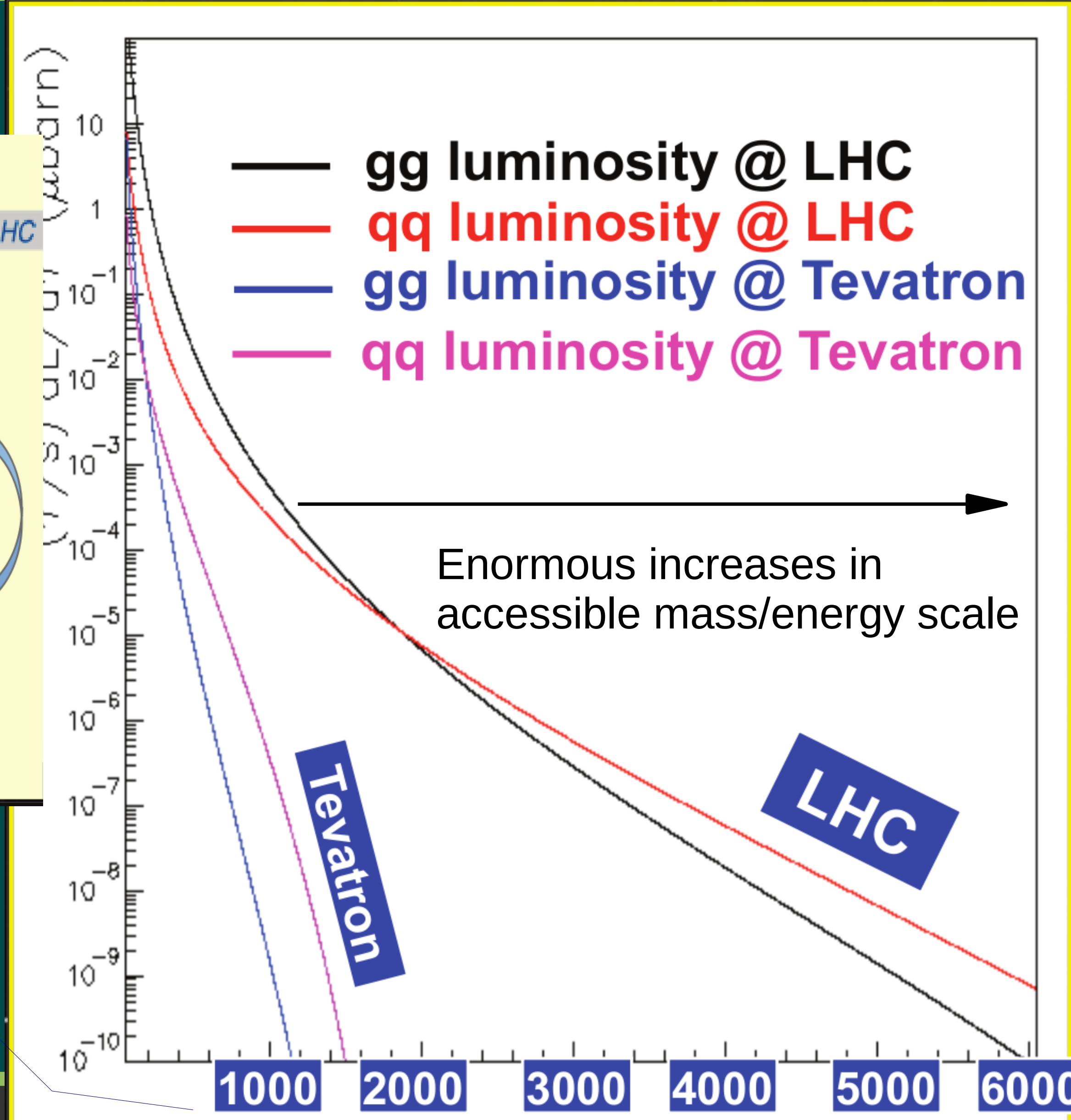
about the same as the kinetic energy of a slow flying mosquito
BUT confined to a space ~a billion times smaller!

Collision point >100,000 times hotter than center of Sun

Data equiv: 100,000 DVD's/year (after >100,000x on-line data reduction)

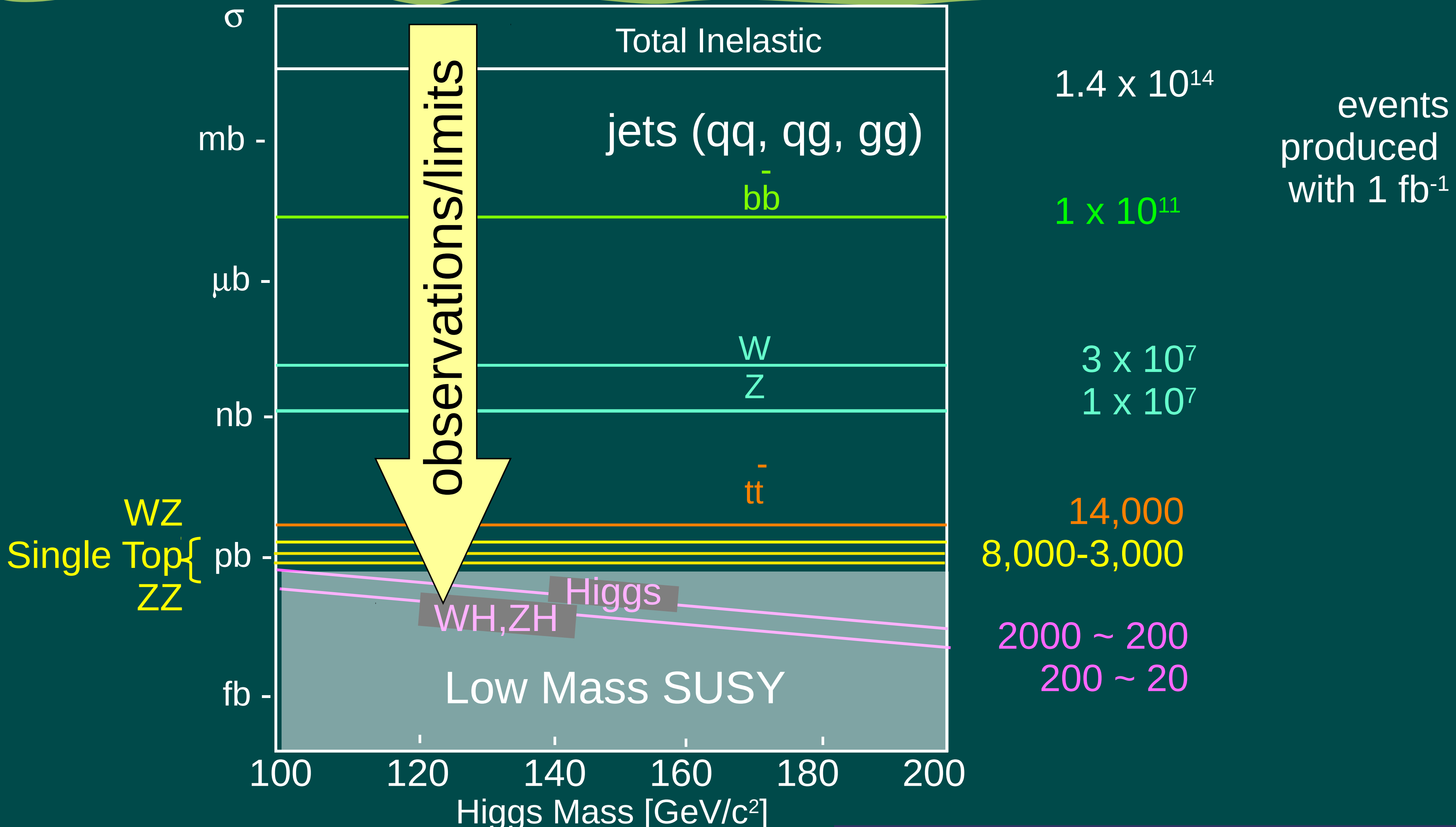
Evolution of the machines





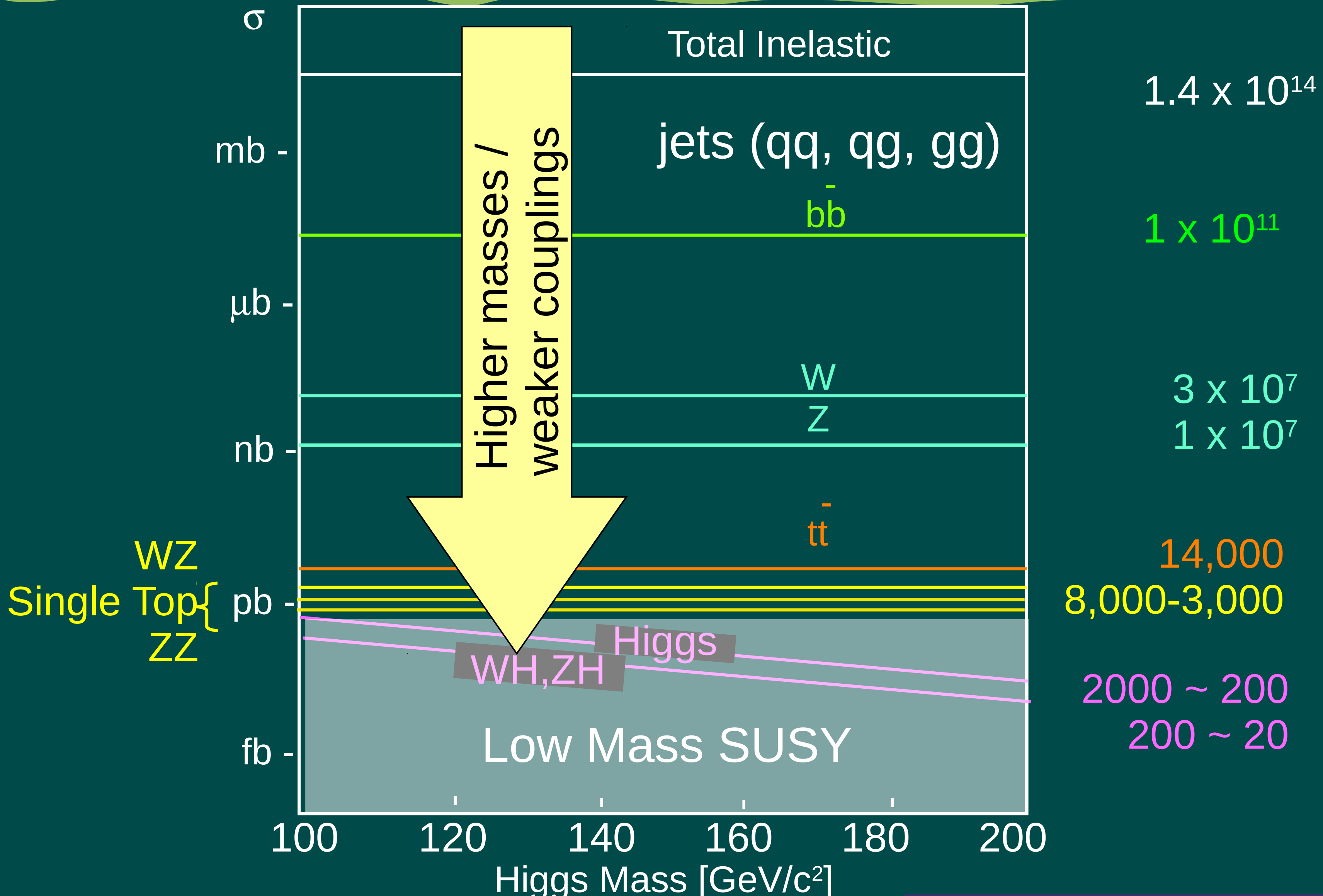
Parton CM Energy (GeV)

Typical rates for standard model processes at the Tevatron, larger numbers for LHC



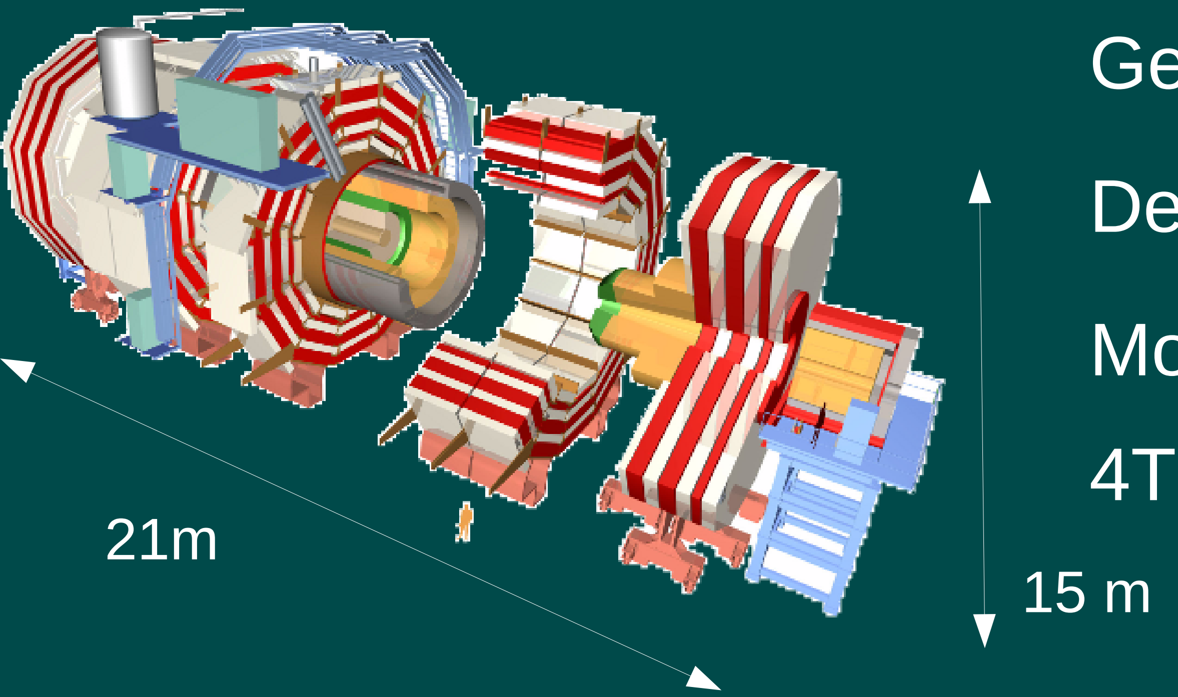
Compensate for small yields w/ high rates

Typical rates for standard model processes at the Tevatron, larger numbers for LHC



Compensate for small yields w/ high rates

Example collider detector: Introduction to CMS



General Purpose Detector

Designed for discovery

Modular: ~ easy access

4T B field, all silicon tracking

Approx Stats: 66/10 million Si pixels/strips, 76K $PBWO_4$ ECAL crystals, 150K Si preshower channels, 15K HCAL channels, muon channels: DT (170K wires), CSC (200K wires), 900 RPC chambers

The Environment

Detectors and observables

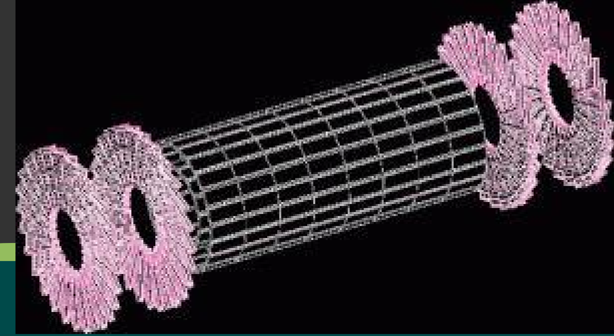
Detectors measure the following long-lived observables

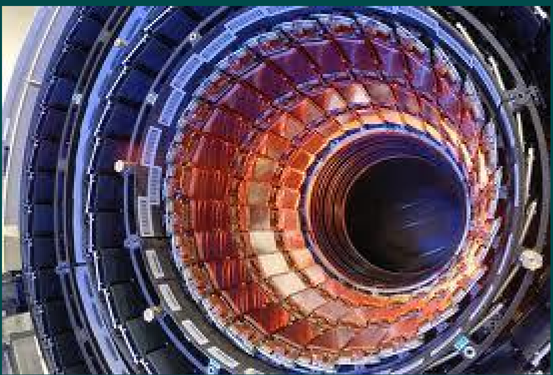
- Charged particle tracks
- Electrons
- Photons
- Jets (and tau)
- Muons
- Neutrinos (inferred)

Essentially all of the physics we study produces varying amounts of these basic objects. Combine these observables to reconstruct the kinematics of the scattering and and short-lived particle states produced in the collisions.

Next: a quick look at the performance of CMS for observables and SM benchmarks. A bit out of date results, but the ideas are not.

Tracking

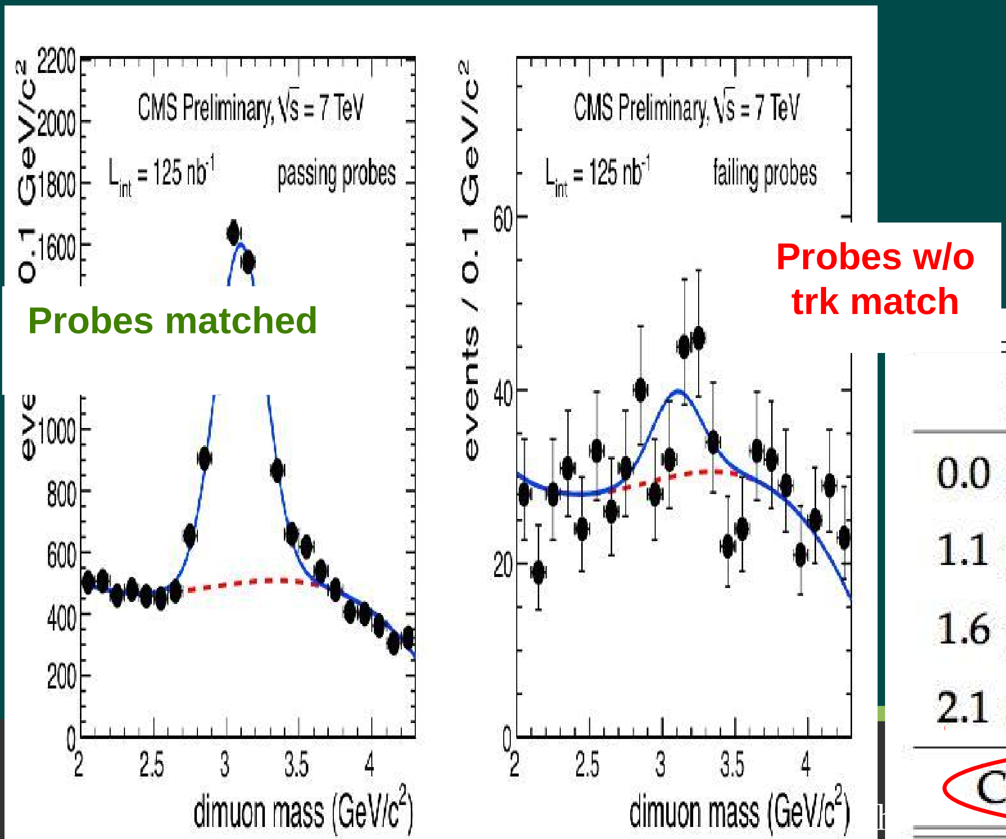




High performance tracker, central to CMS design. (Charged particle detection)

Enough silicon to cover a tennis court!

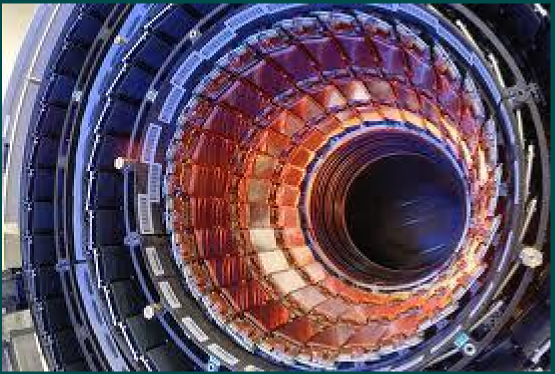
Excellent efficiency and resolution

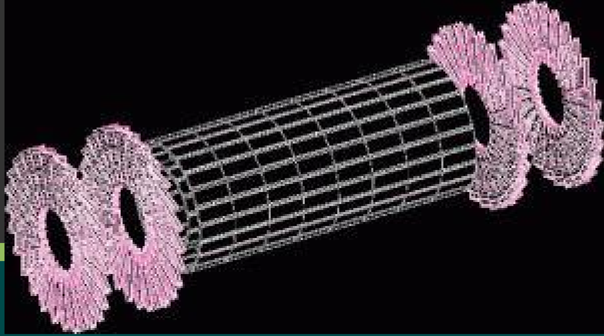


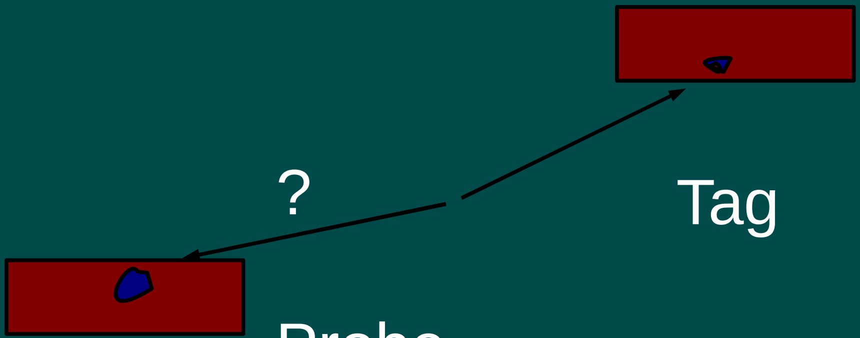
J/Psi Tag and probe

Region	Data Eff. (%)	Sim Eff. (%)	Data/Sim
$0.0 \leq \|\eta\| < 1.1$	$100.0^{+0.0}_{-0.3}$	$100.0^{+0.0}_{-0.1}$	$1.000^{+0.001}_{-0.003}$
$1.1 \leq \|\eta\| < 1.6$	$99.2^{+0.8}_{-1.0}$	$99.8^{+0.1}_{-0.1}$	$0.994^{+0.009}_{-0.010}$
$1.6 \leq \|\eta\| < 2.1$	$97.6^{+0.9}_{-1.0}$	$99.3^{+0.1}_{-0.1}$	$0.983^{+0.009}_{-0.010}$
$2.1 \leq \|\eta\| < 2.4$	$98.5^{+1.5}_{-1.6}$	$97.6^{+0.2}_{-0.2}$	$1.010^{+0.015}_{-0.016}$
Combined	$98.8^{+0.5}_{-0.5}$	$99.2^{+0.1}_{-0.1}$	$0.996^{+0.005}_{-0.005}$

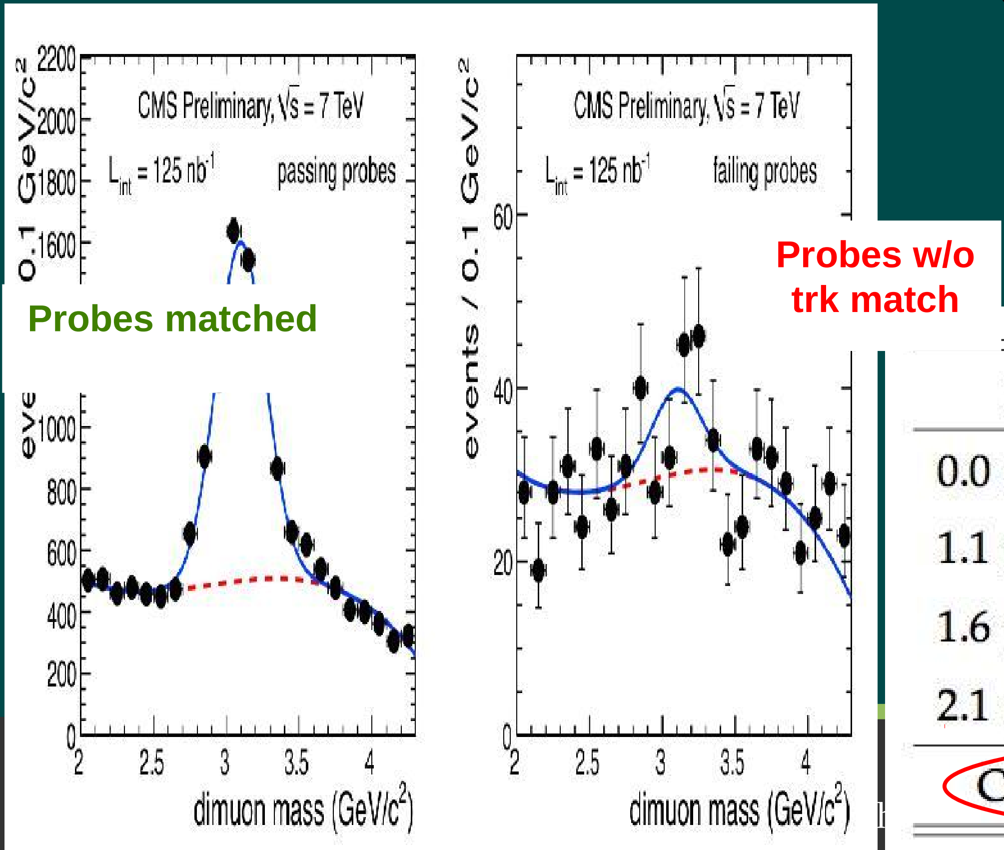
Tracking







J/Psi Tag and probe



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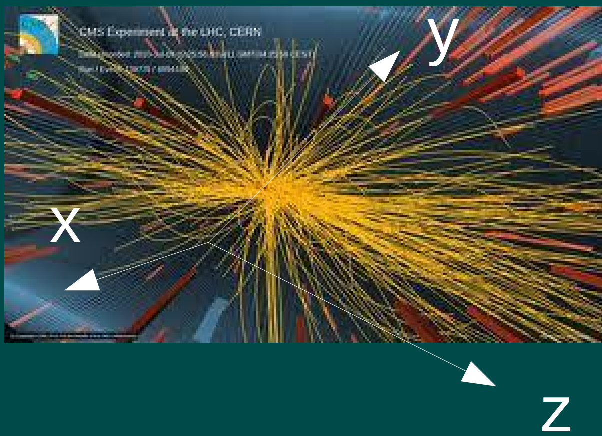
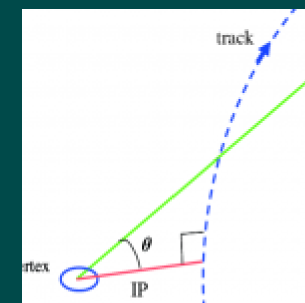
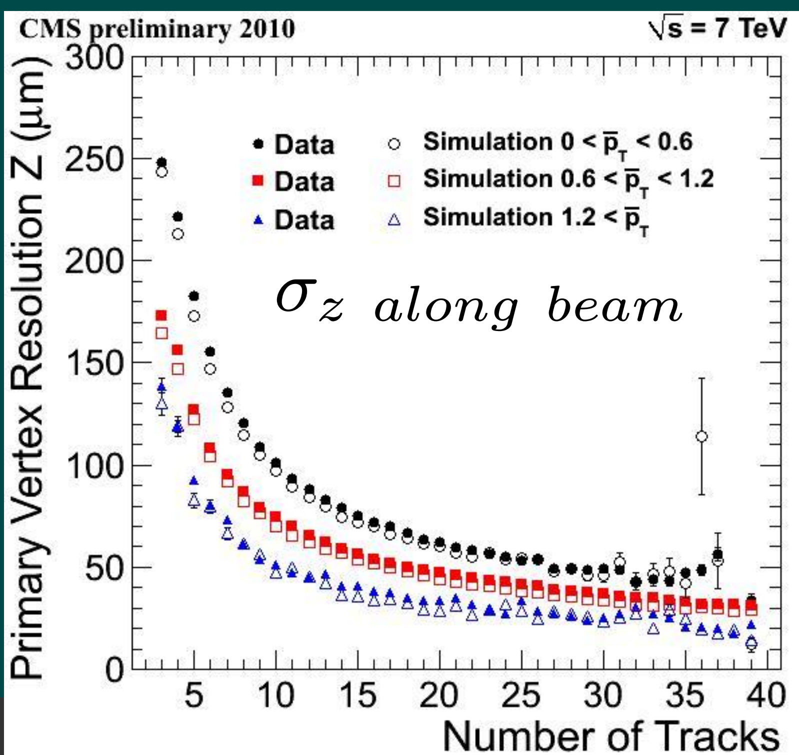
Vertex and IP Measurements

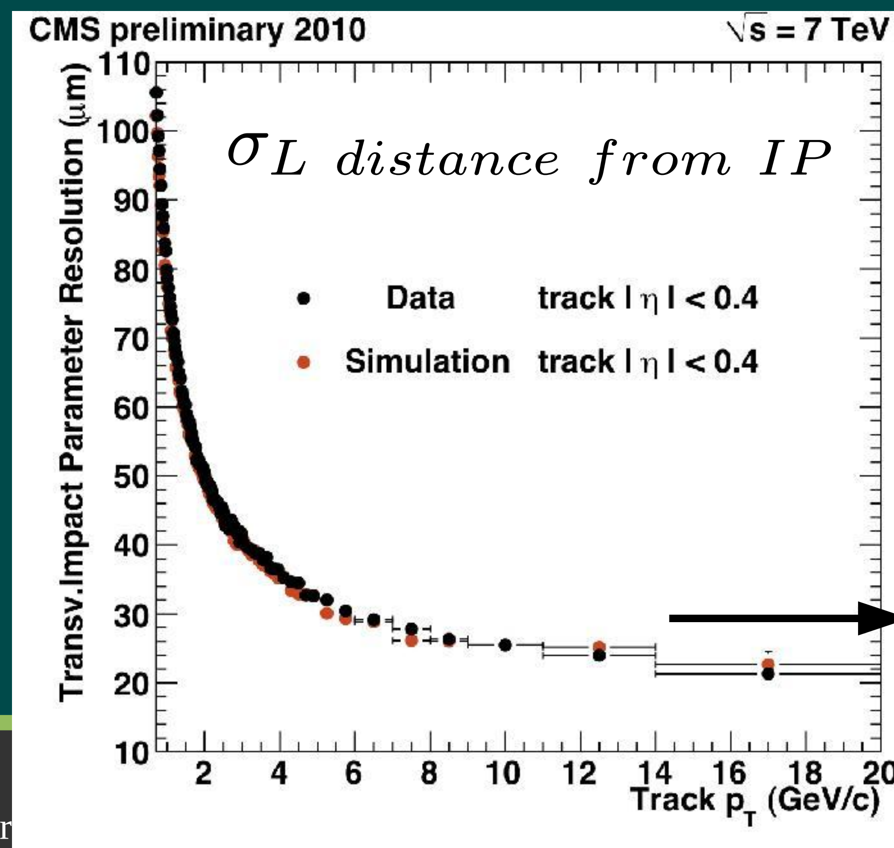


Q: Where did this collision occur?

Q: Did a track come from from the primary interaction, or a subsequent decay?



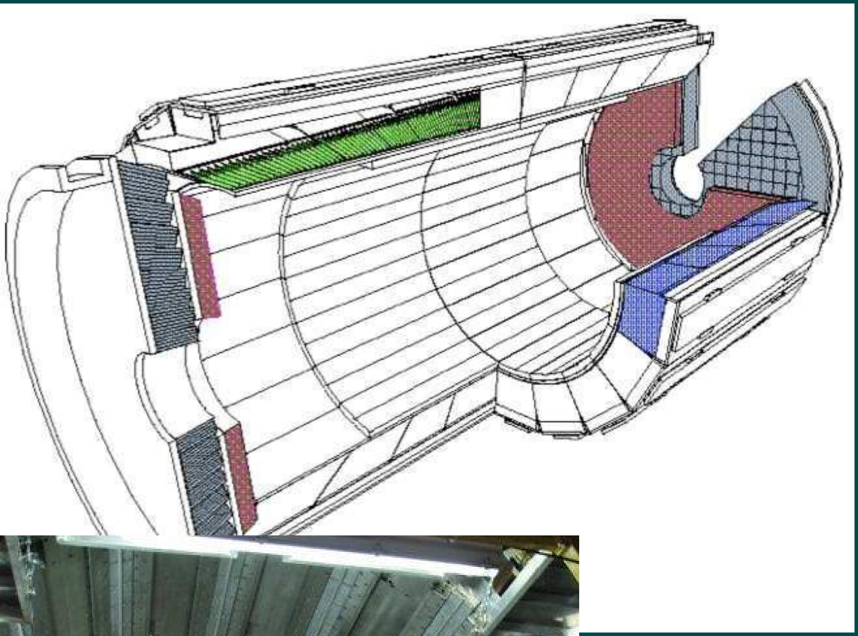


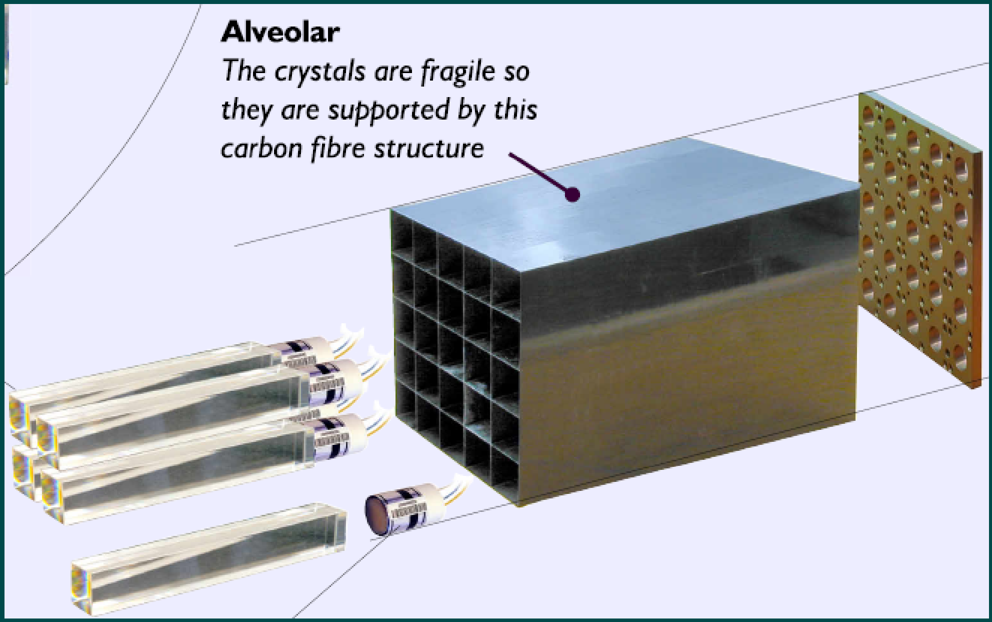


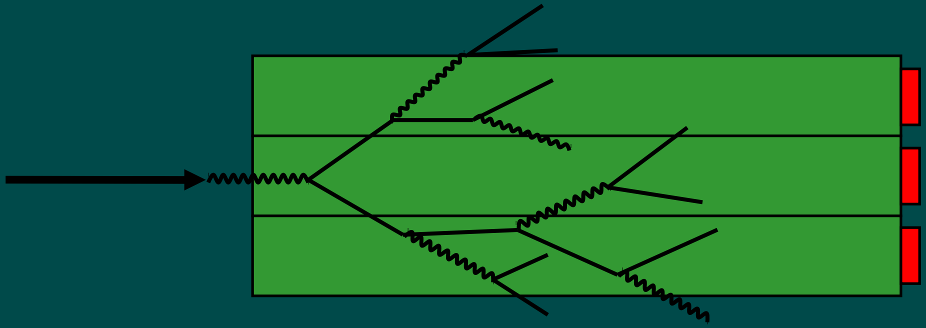
Equiv. to roughly 10 fempto-seconds for v~c !

Detect/measure E for electrons/photons

ECAL



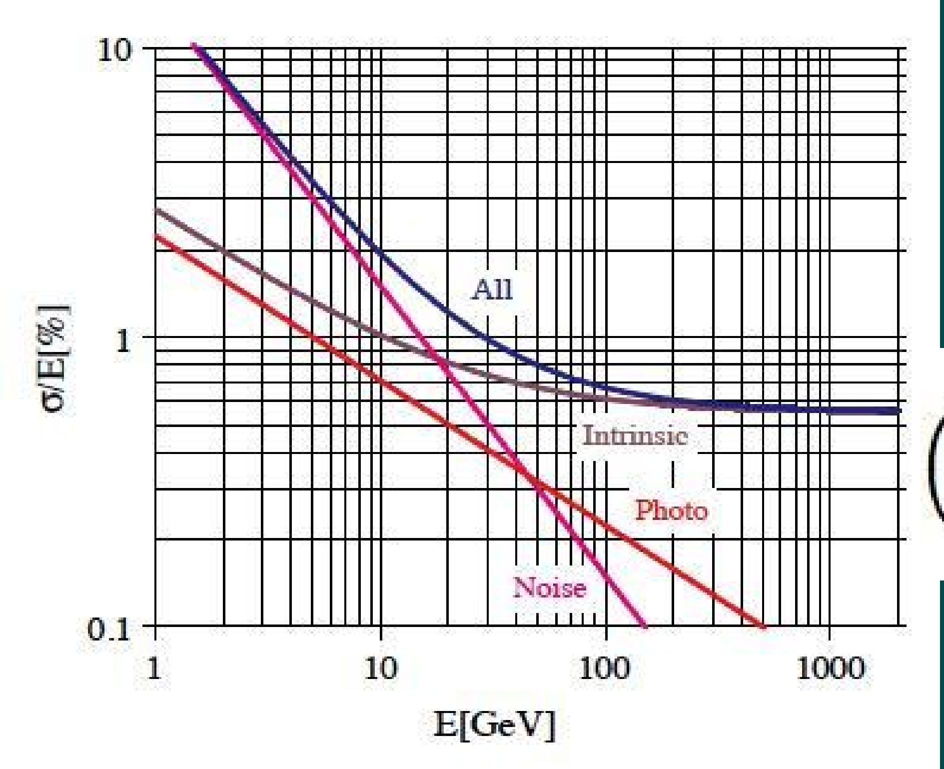




Light detector
APD/VPT

Homogeneous calorimeter:
crystal serves as both absorber and detector

ECAL Performance

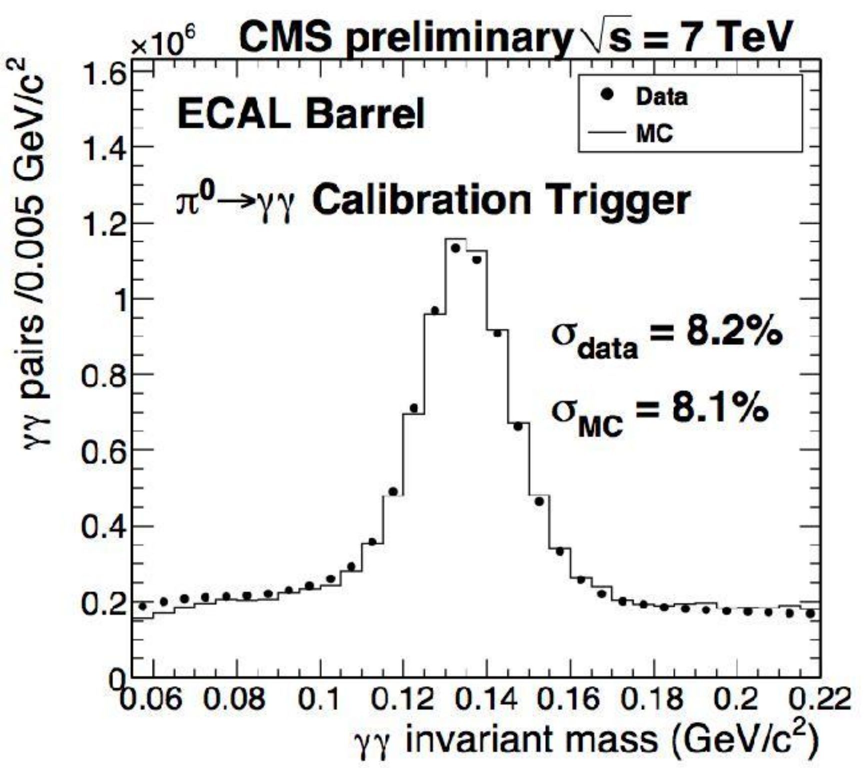


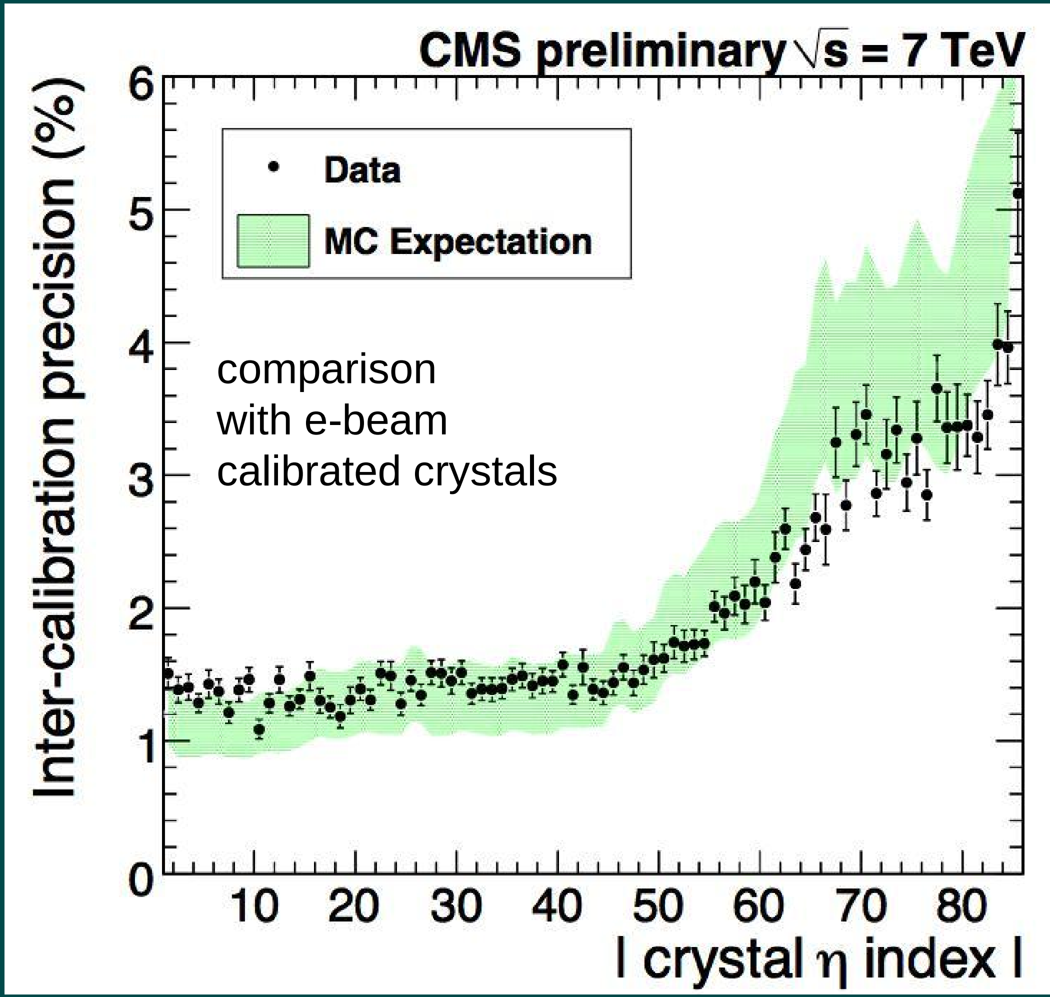
small constant term needed to detect narrow $\gamma\gamma$ resonances

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2$$

Test beam exposure (25% of detector) confirmed the potential of the $PbWO_4$ crystals, key point is accurate inter-calibration

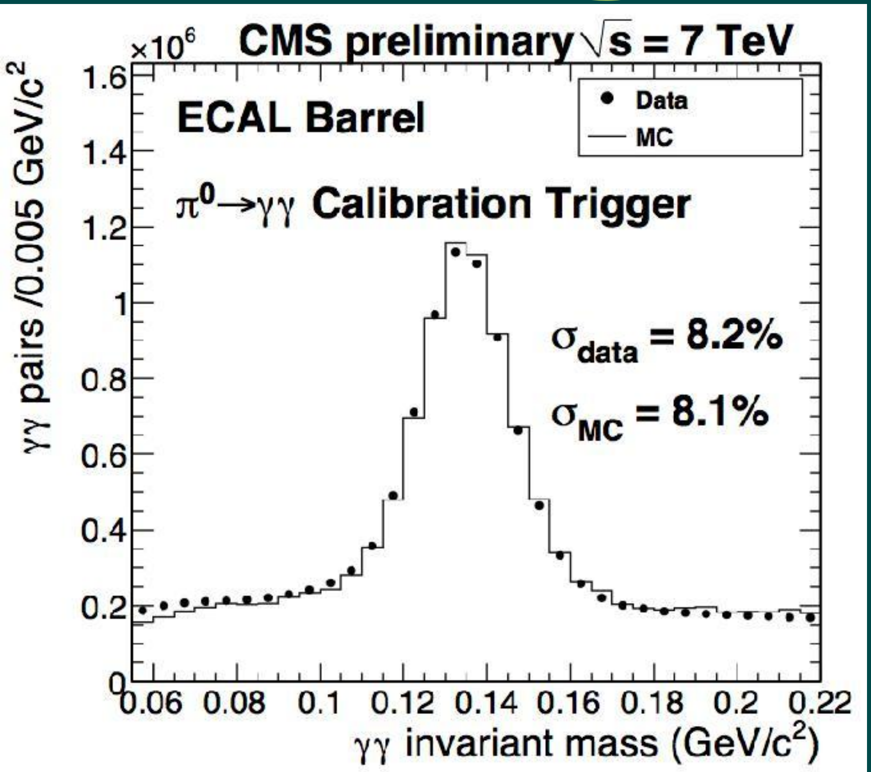
ECAL π^0 calibration

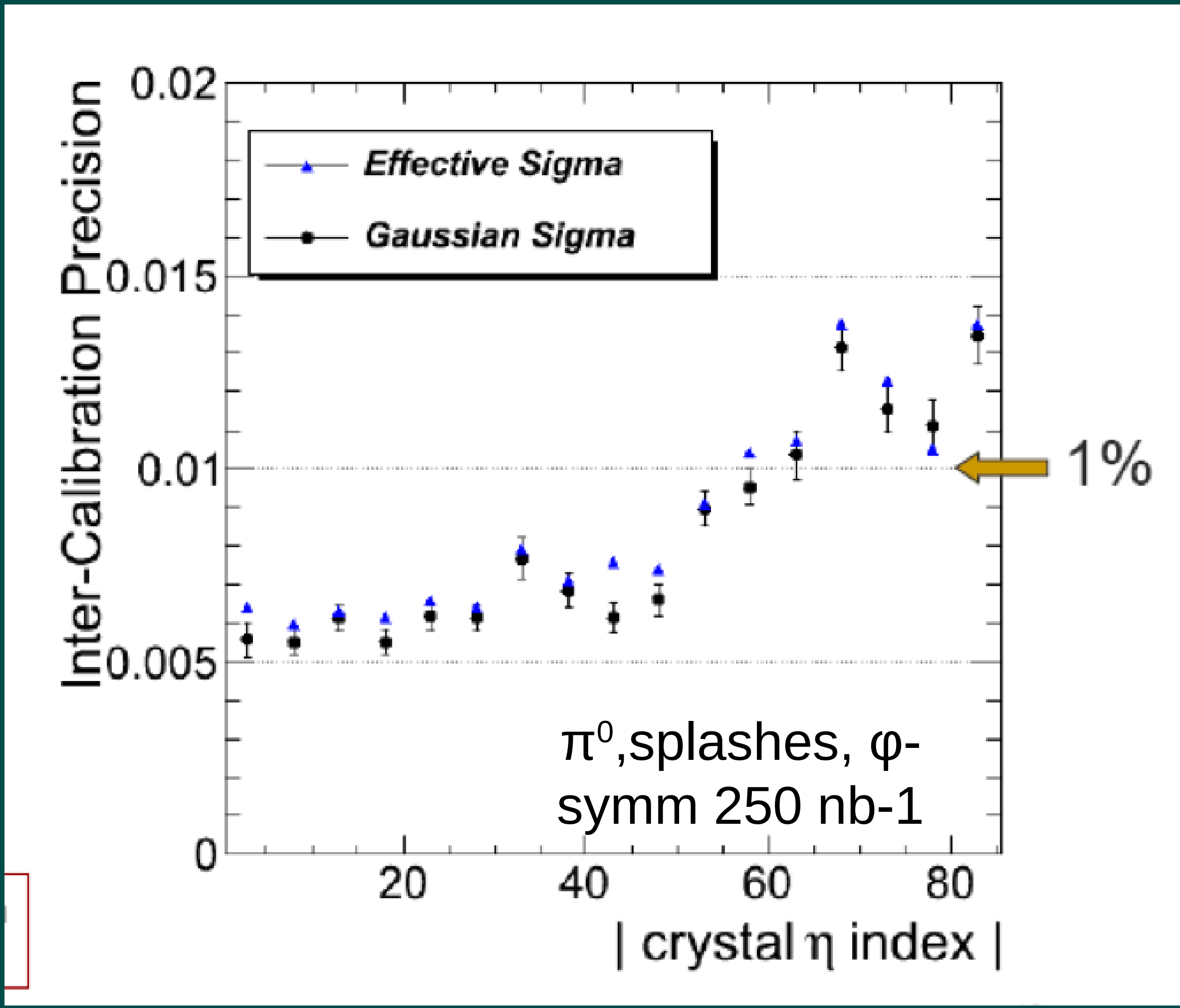




π^0 data combined with φ symmetry to calibrate

ECAL π^0 calibration

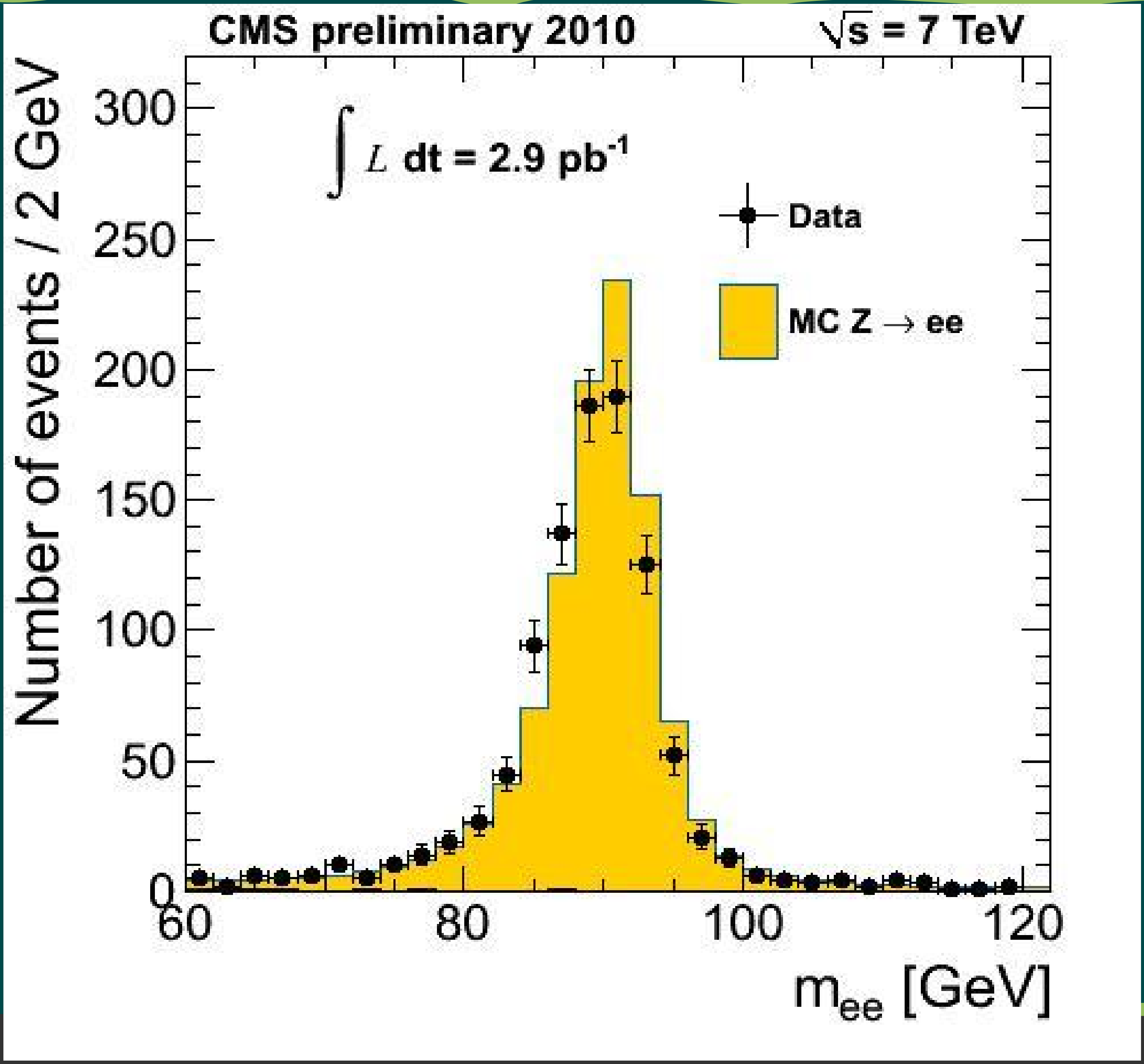




π^0 data combined with φ symmetry to calibrate

Reaches 0.5 to 1.2%

ECAL energy calibration

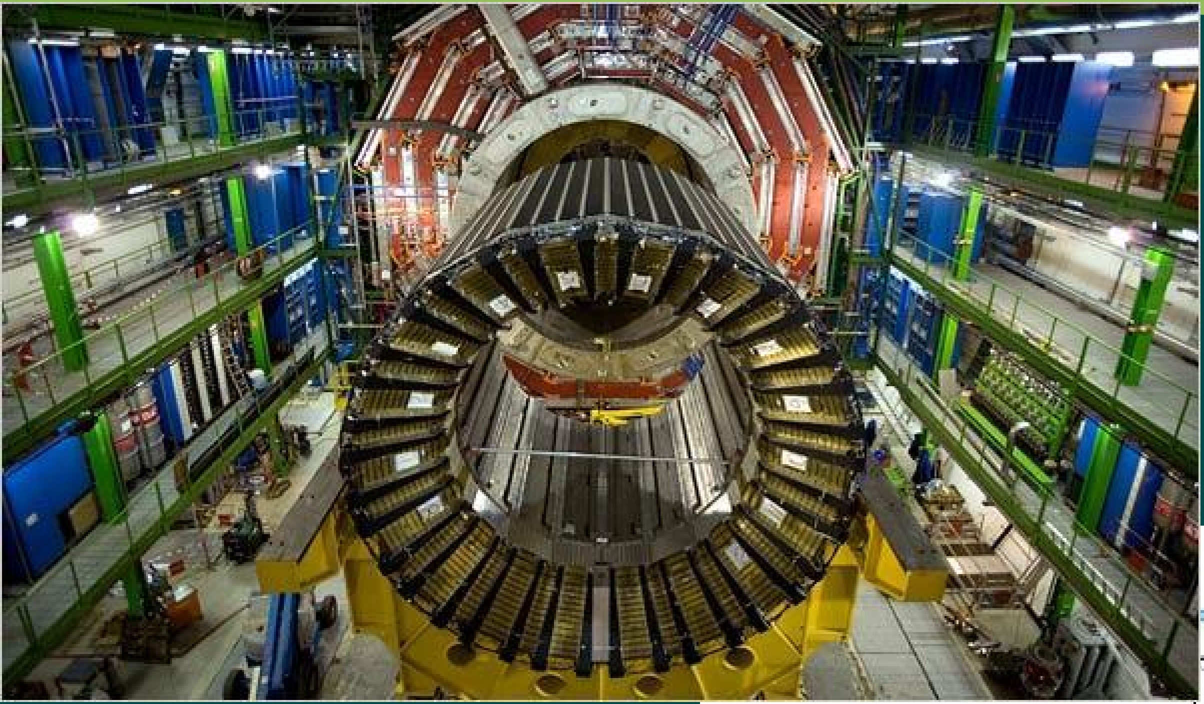


scale has been set by the π^0 calibration

Barrel ~1%
Endcap ~ 3%

Can continually refine using Z boson

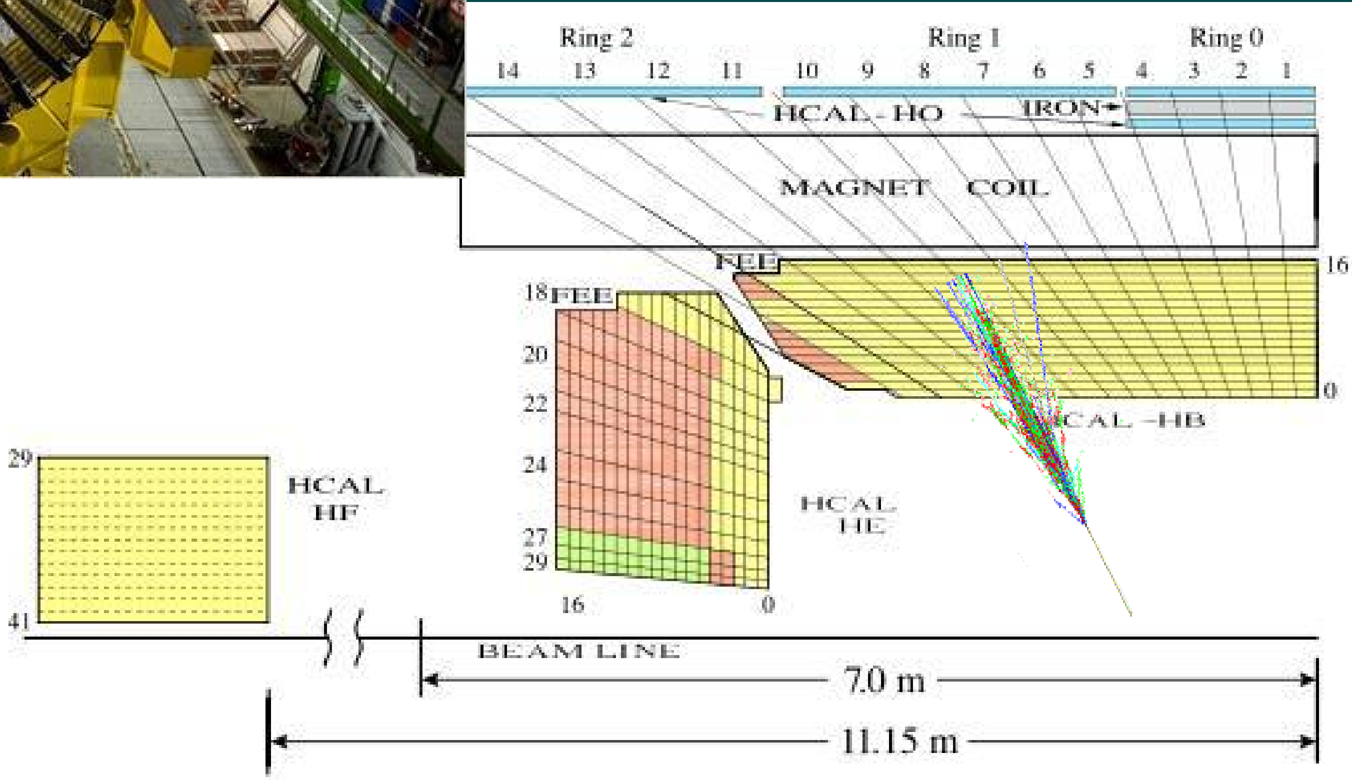
HCAL



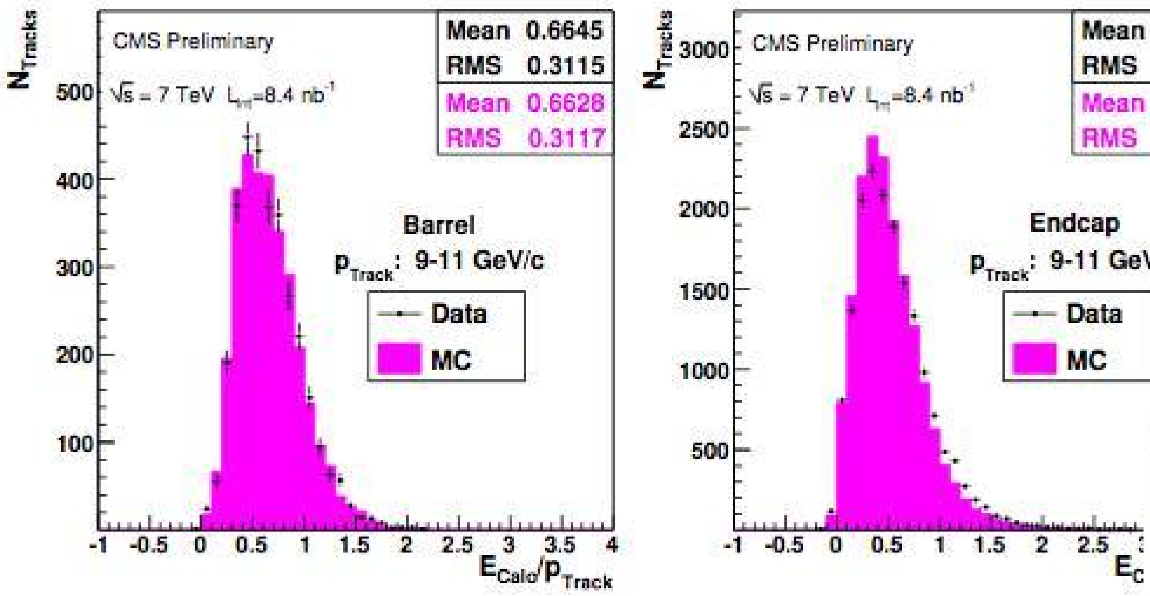
Brass/Scintillator calorimeter

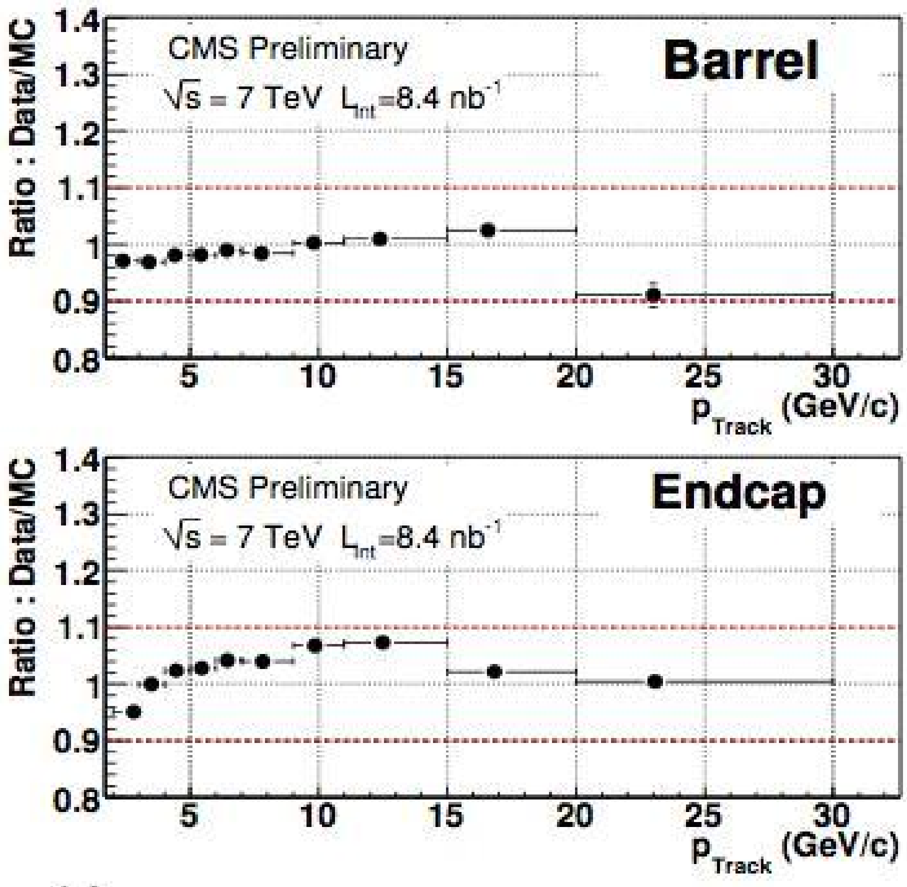
Former artillery shells!

Detect energies of jets/hadron showers



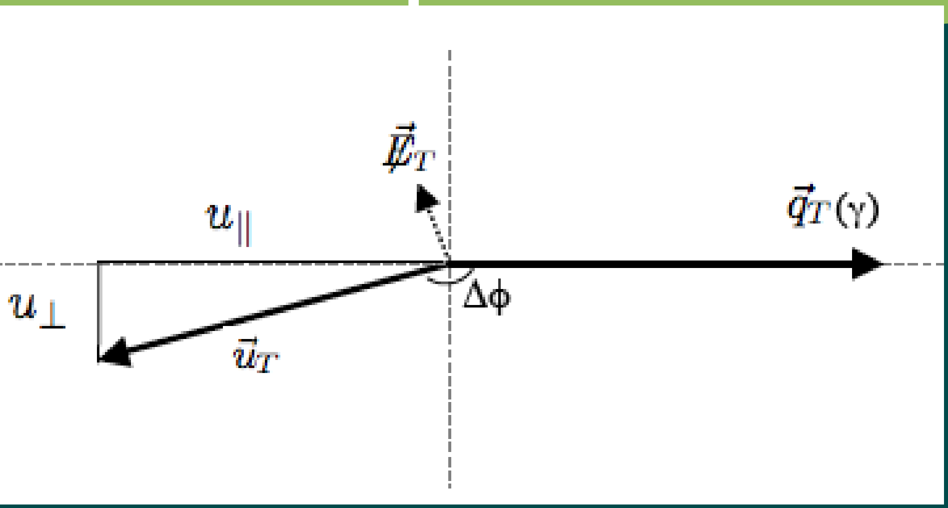
HCAL performance, single particles



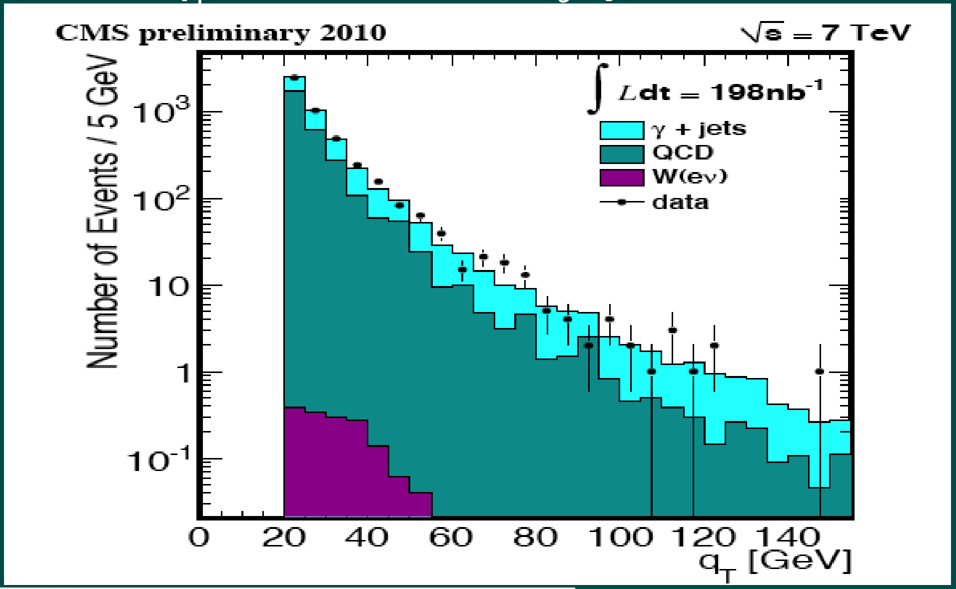


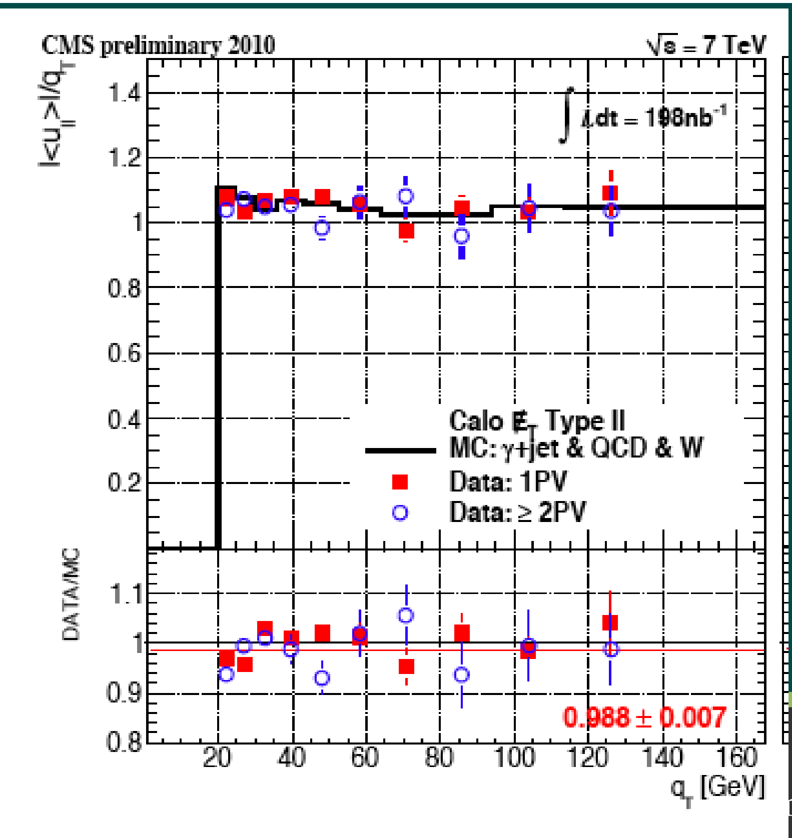
HCAL response to single particles reasonably well modeled in detector simulations. Important for modeling quantities, such as: jet energy corrections, resolutions, missing energy.

HCAL performance, photon+jet events



q_T distribution of γ-jet candidates





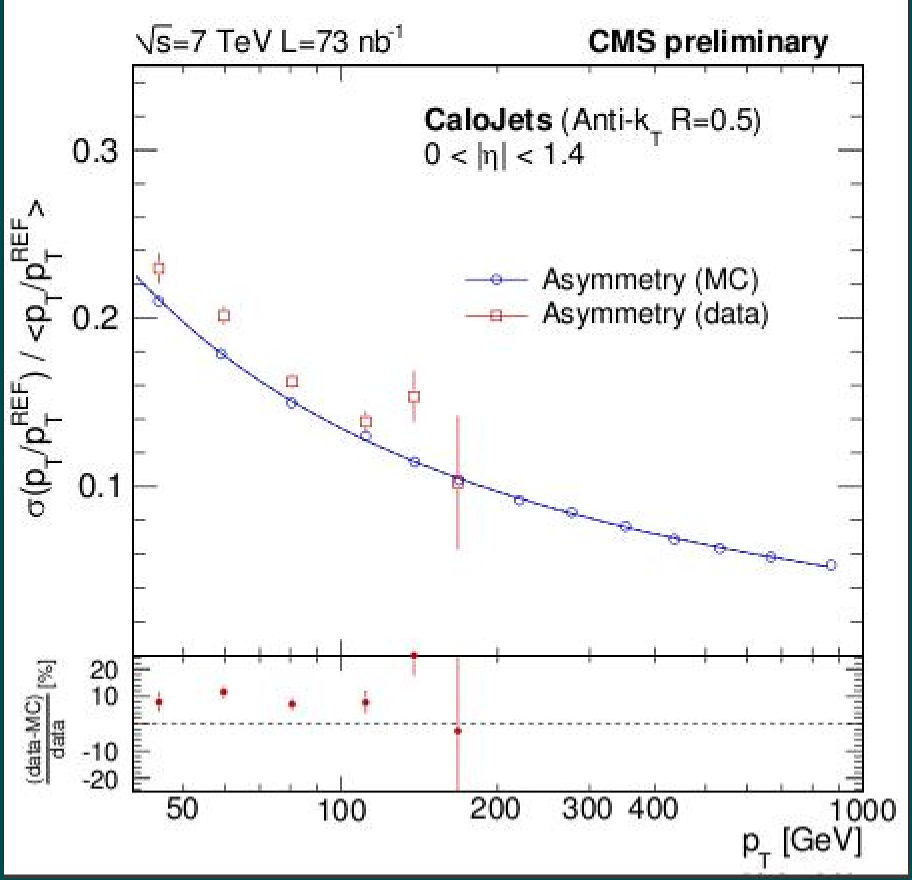
$$u_{||} = \vec{u}_T \cdot \vec{q}_T$$

$$\frac{|\langle u_{||} \rangle|}{q_T} = C_{MET}(Q_{flavor}, JES)$$

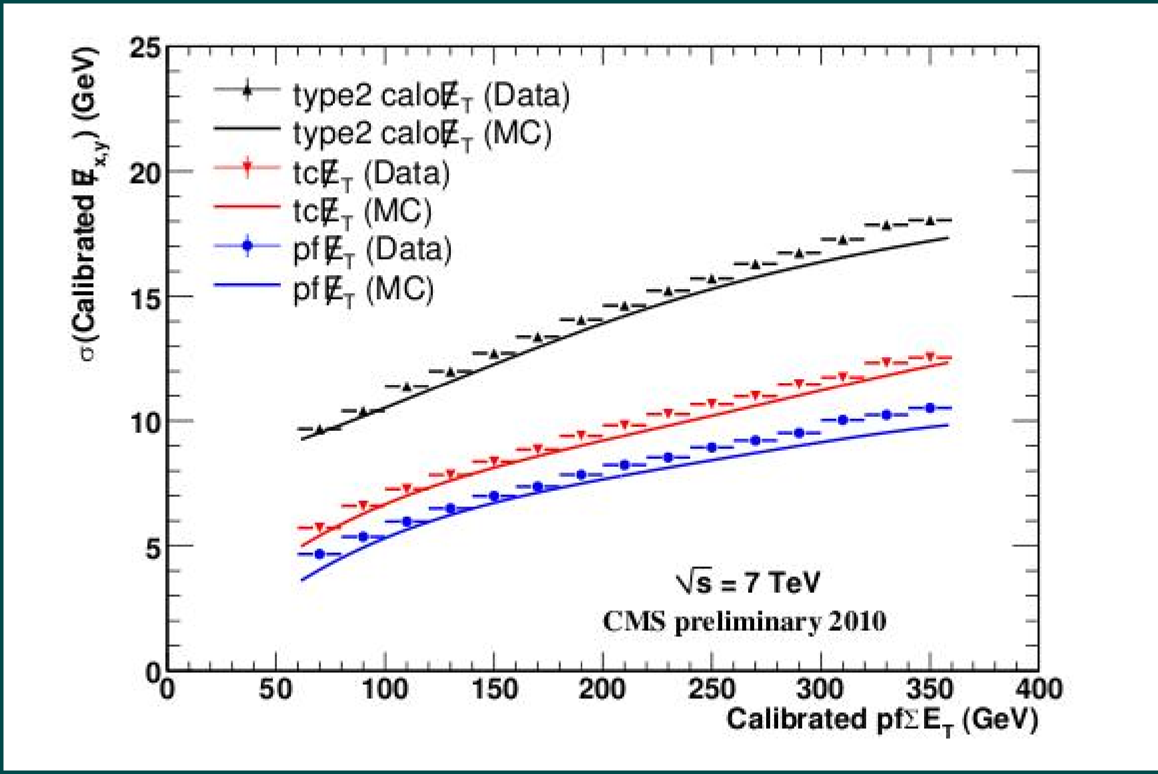
Missing recoil energy = Missing Et correction factor (depends on quark flavor and JES)

HCAL performance, Jet/$\not{E}_T$ resolutions

Jet PT resolution



Missing ET resolution



Magnet

Installation at Point 5 of the dump resistors for the CMS magnet surface tests.

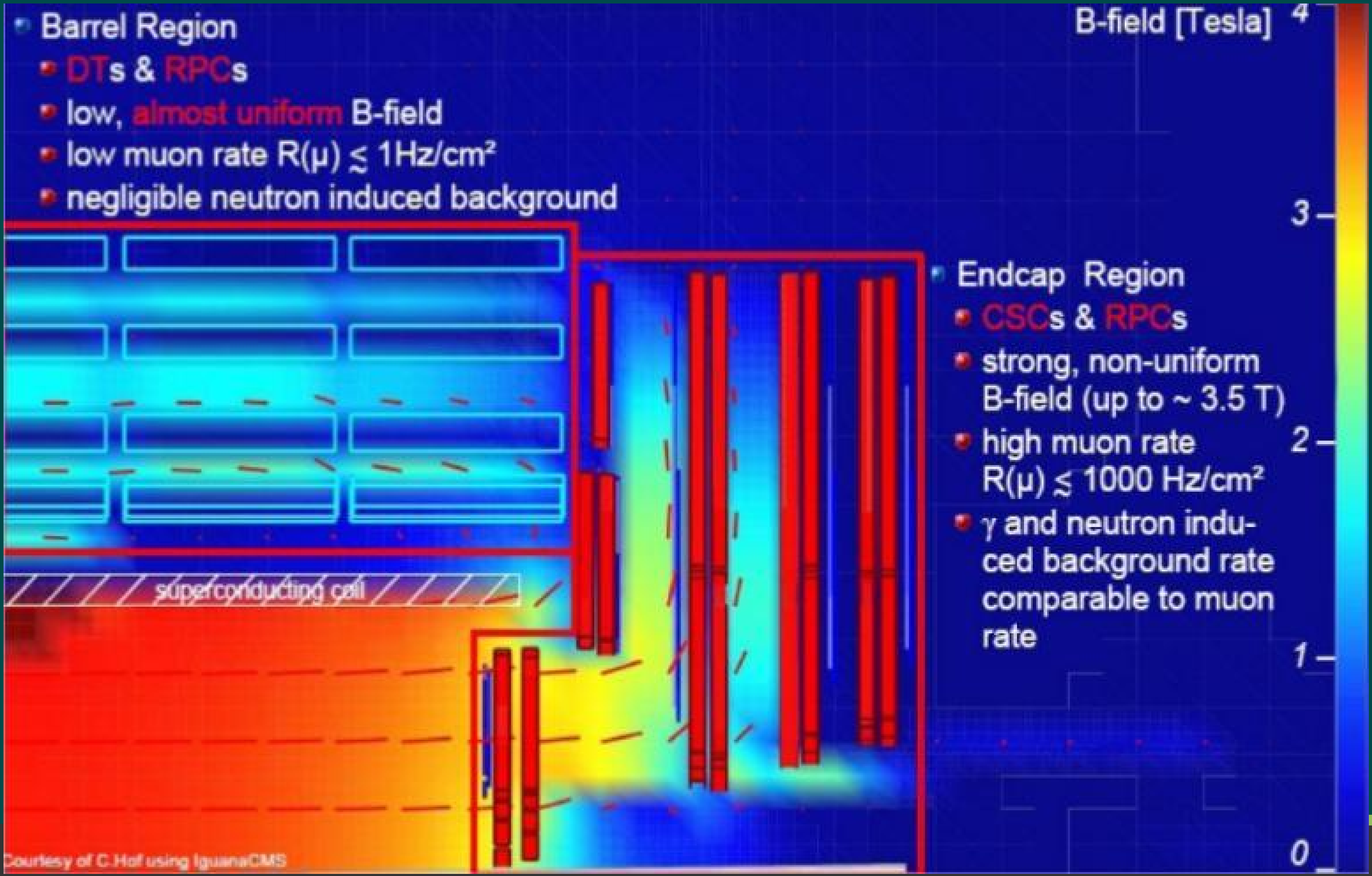
World's largest superconducting solenoid

6m diameter, 18m long

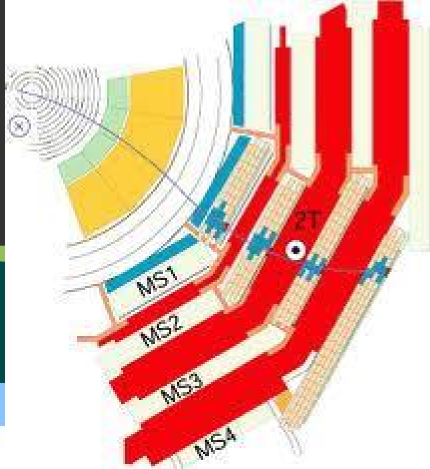
1GJ of stored energy!

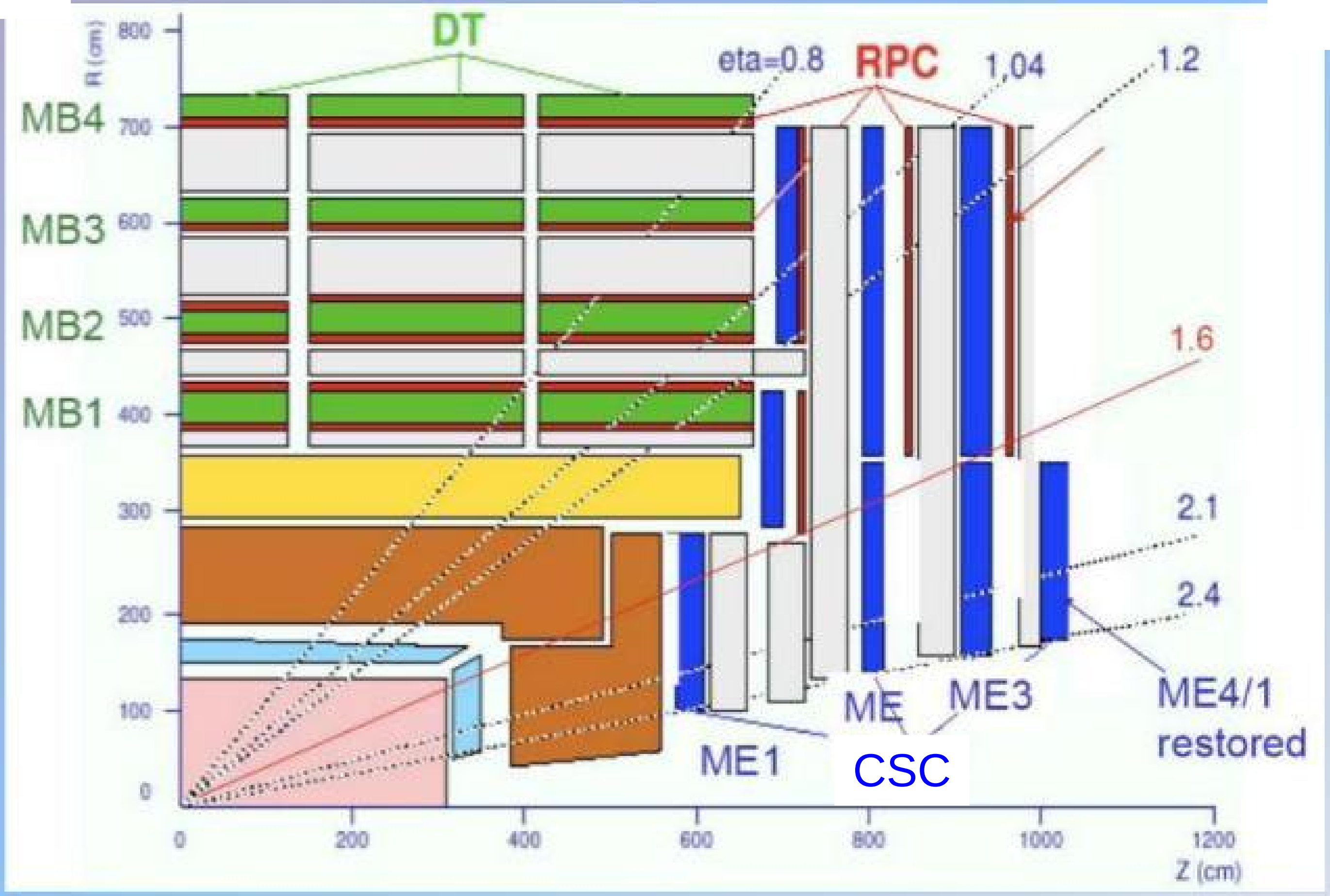
Enough energy to melt ~4 tons of copper.

B Field and rates in Muon Detectors



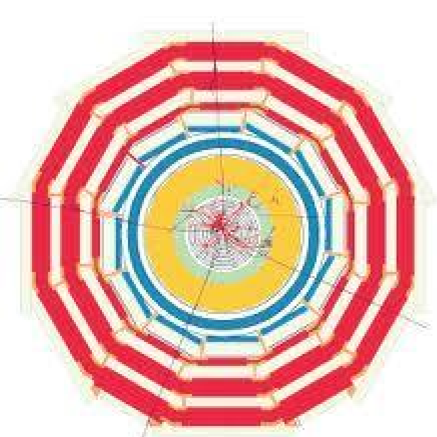
Muon



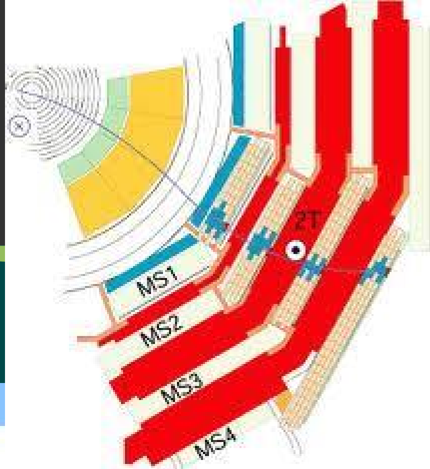


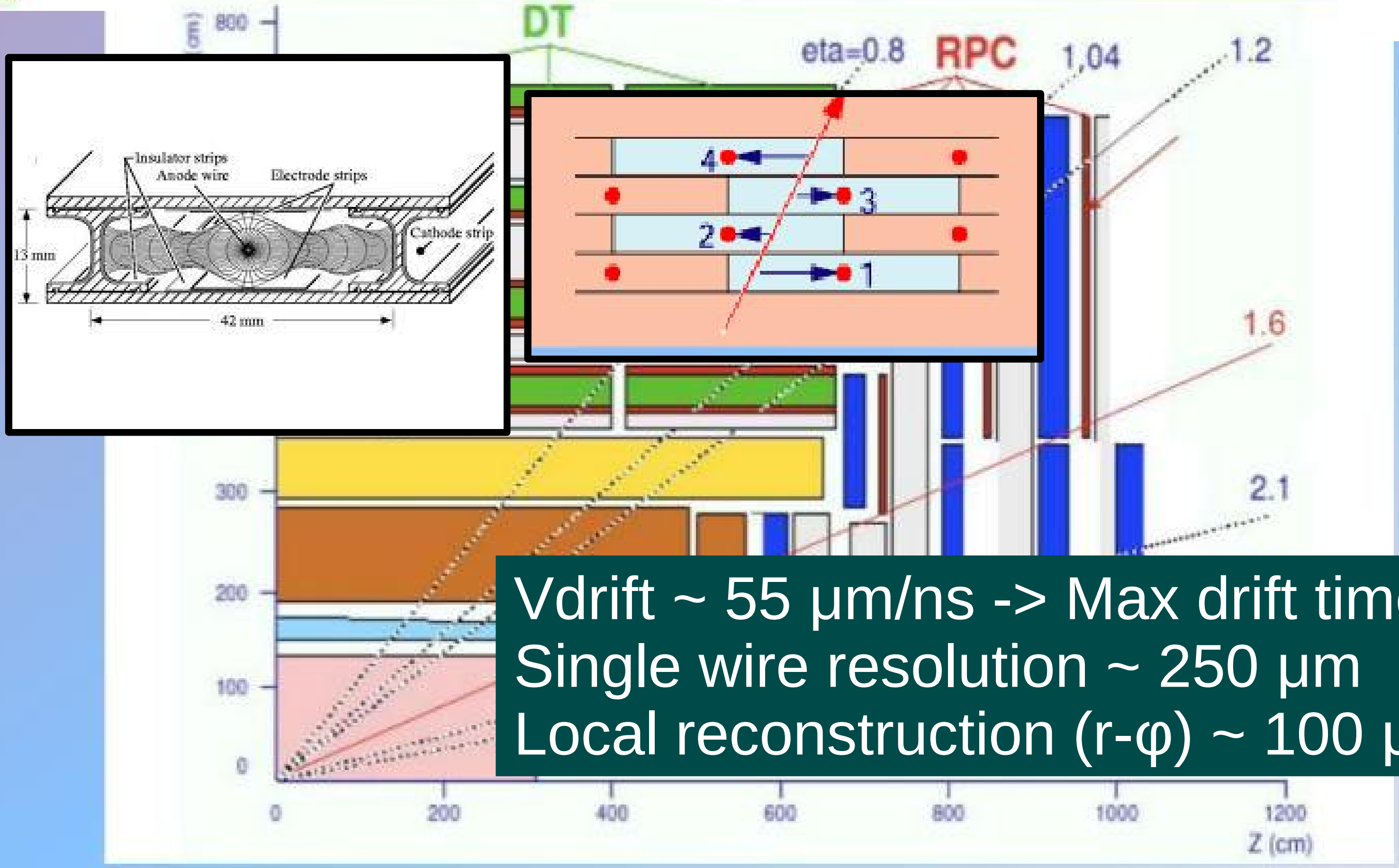
Barrel: Drift-Tubes (DT), Resistive-Plate-Chambers (RPC)

End-Caps: Cathode-Strip-Chambers (CSC), Resistive-Plate-Chambers (RPC)



Muon Drift Tubes



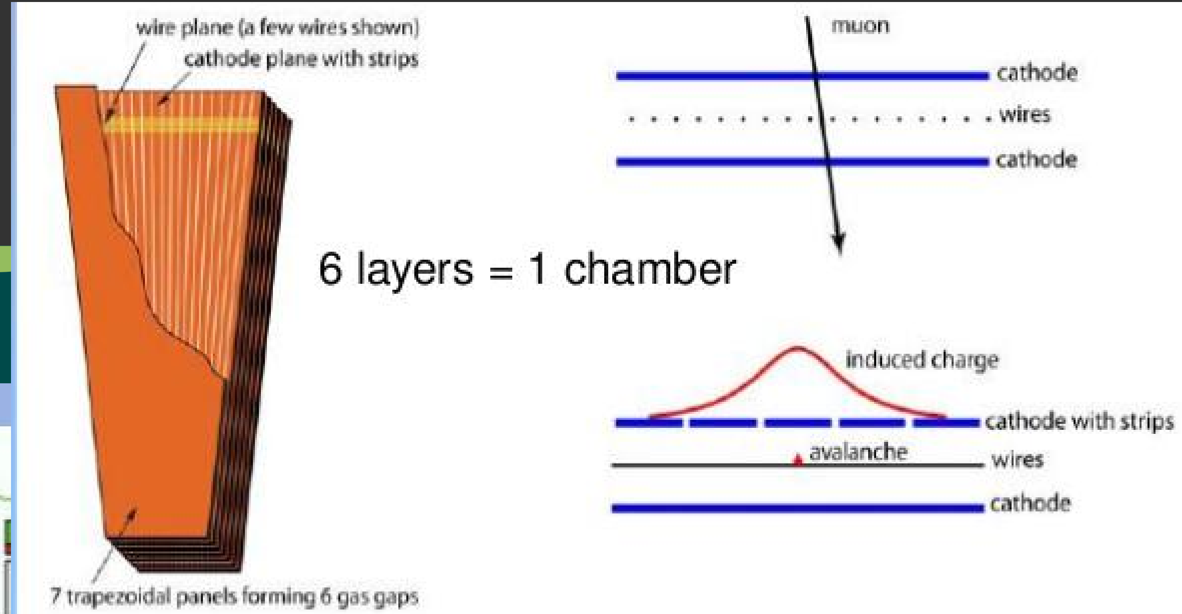


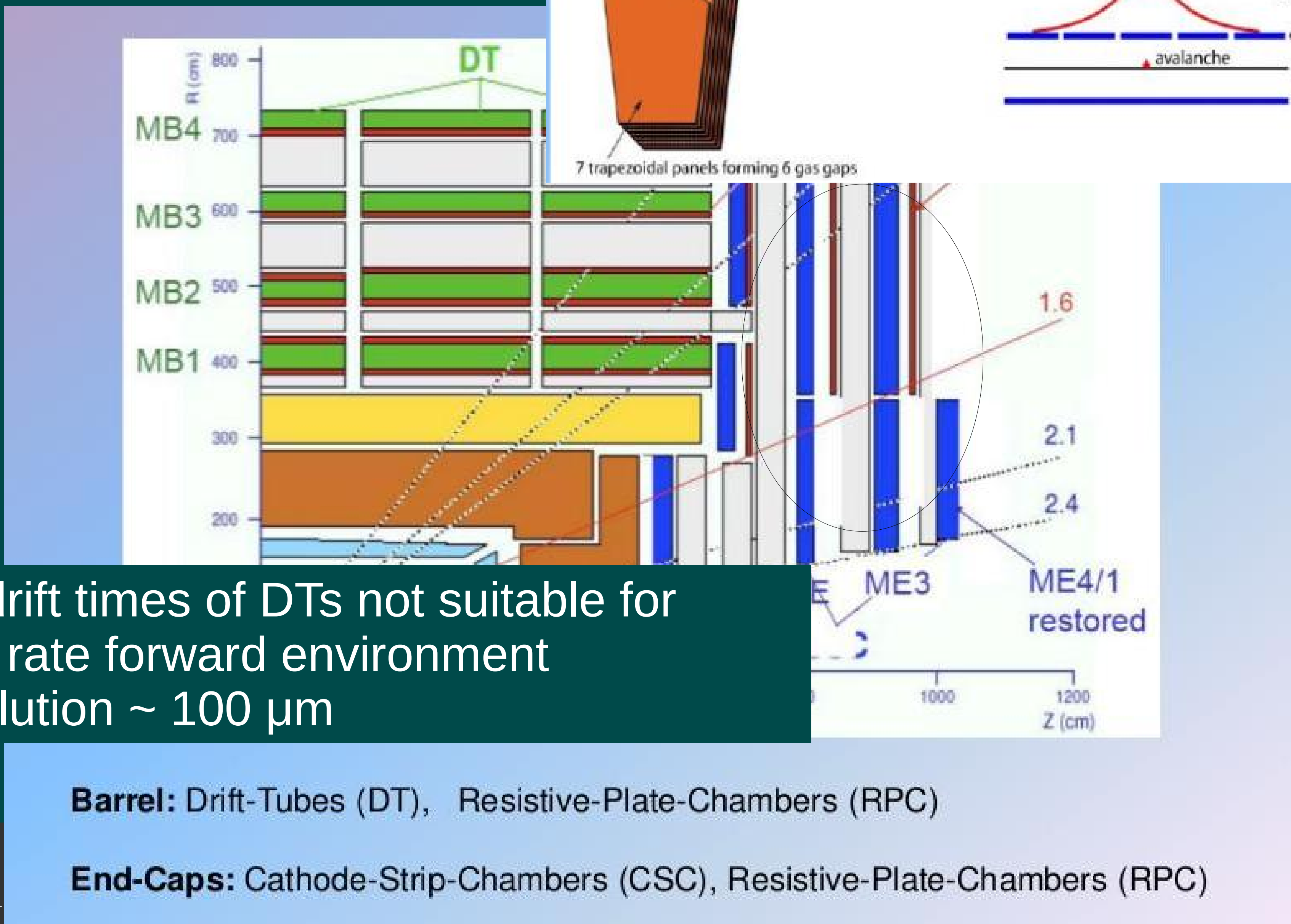
Vdrift ~ 55 μm/ns -> Max drift time ~380 ns
Single wire resolution ~ 250 μm
Local reconstruction (r-φ) ~ 100 μm

Barrel: Drift-Tubes (DT), Resistive-Plate-Chambers (RPC)

End-Caps: Cathode-Strip-Chambers (CSC), Resistive-Plate-Chambers (RPC)

Muon
cathode strip chambers



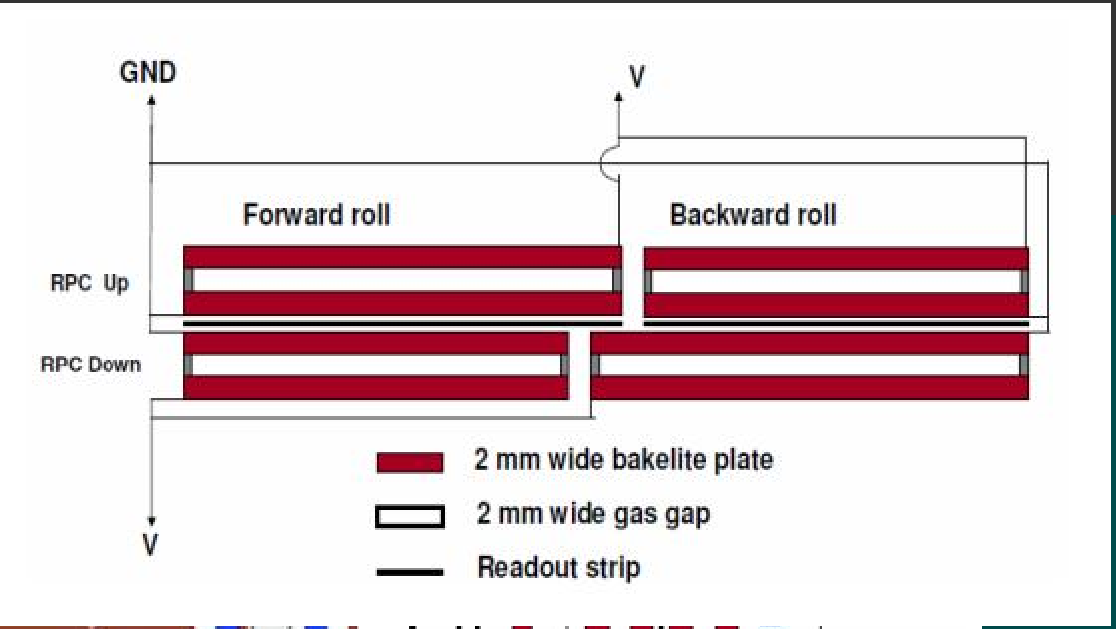


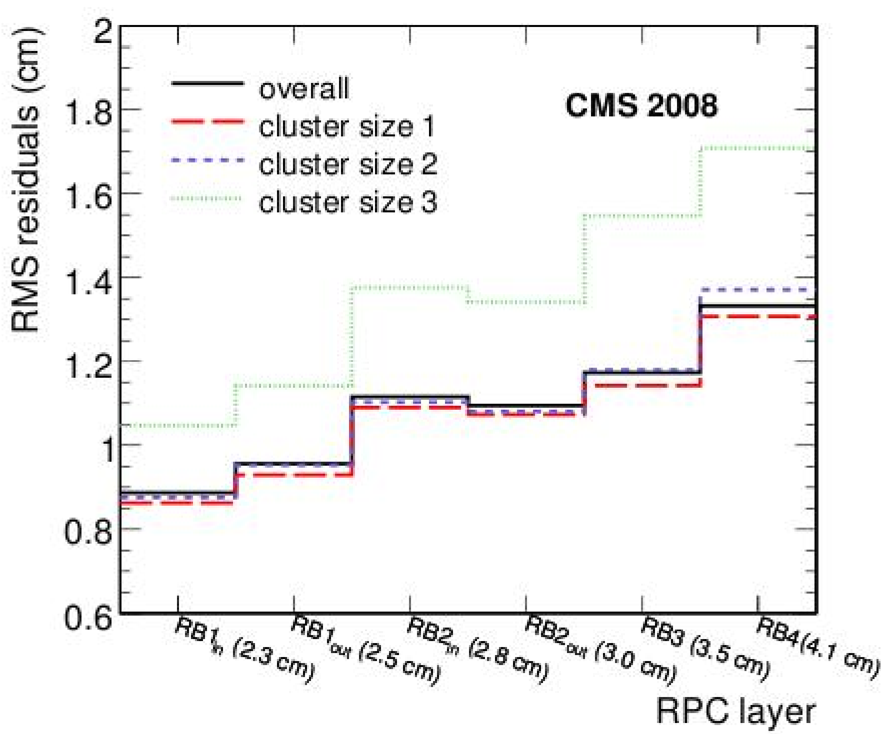
Long drift times of DTs not suitable for higher rate forward environment

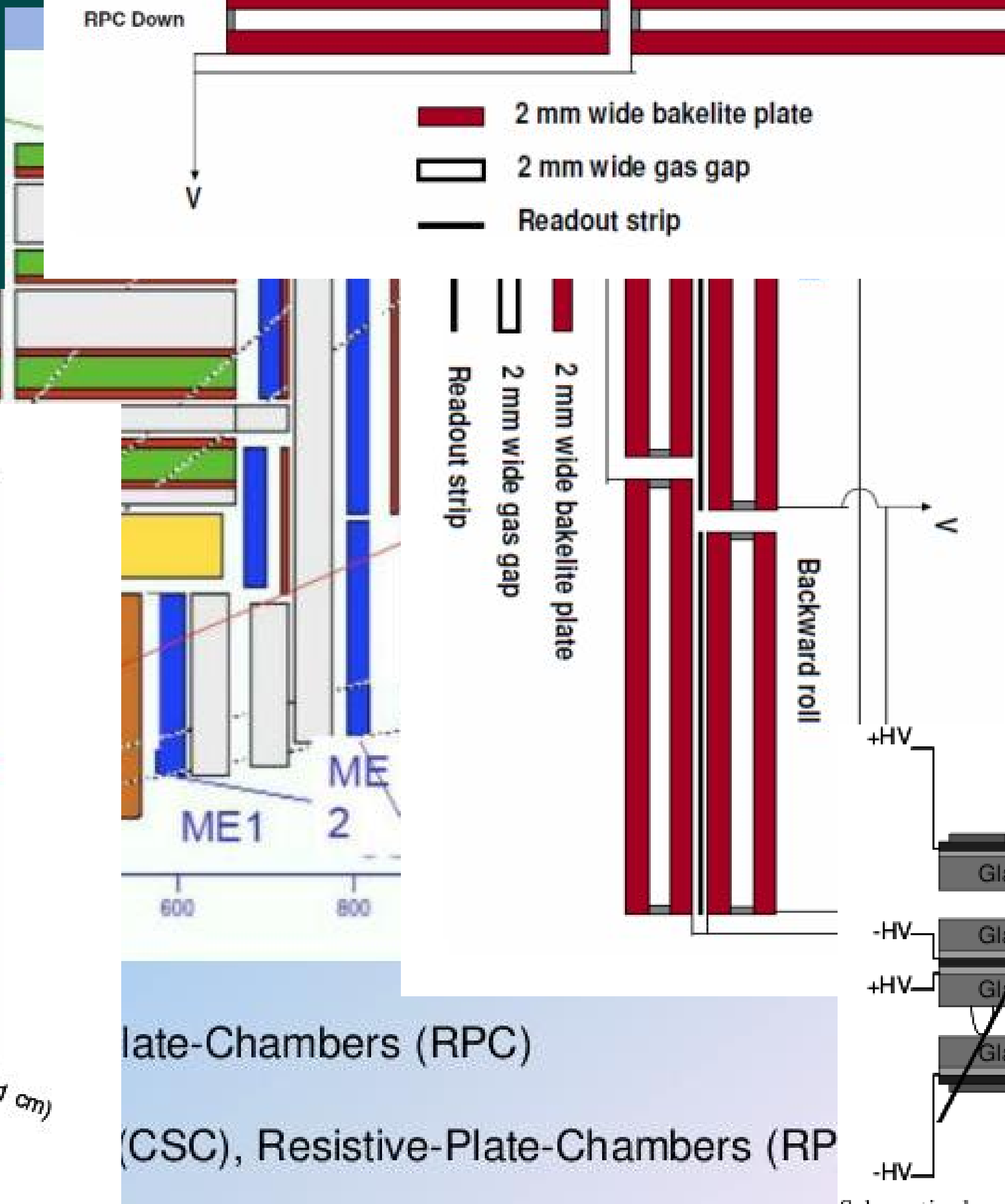
φ resolution ~ 100 μm

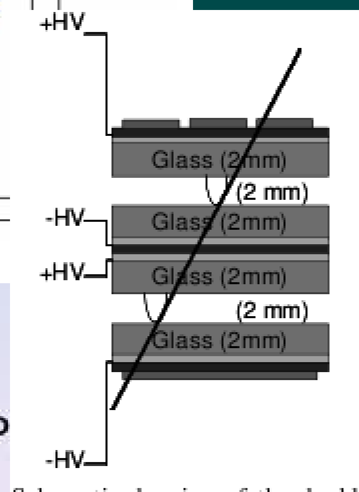
Muon
resistive plate chambers

Fast detectors for 1st level triggering
Reasonable position resolution





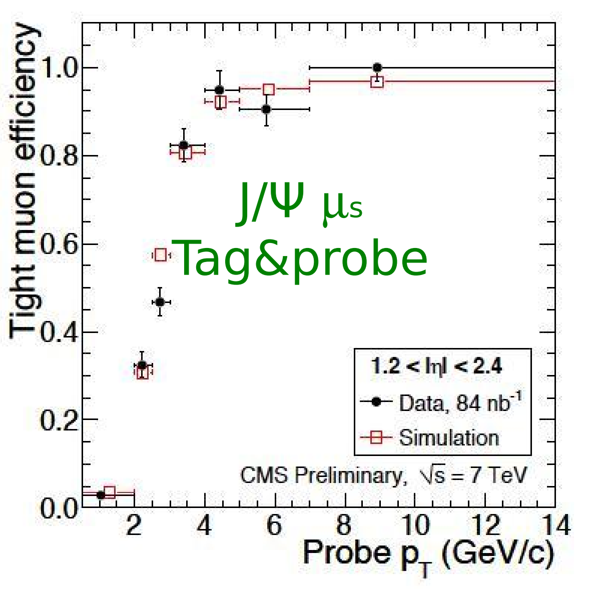


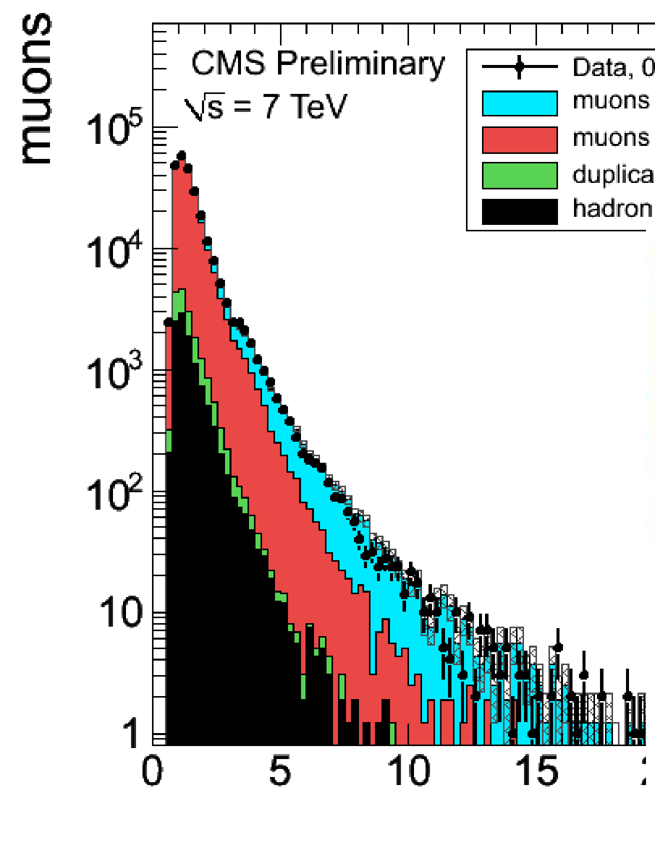


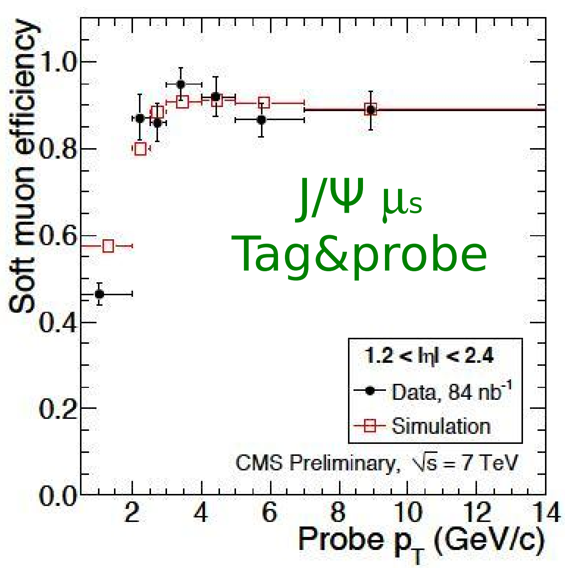
Muon ID

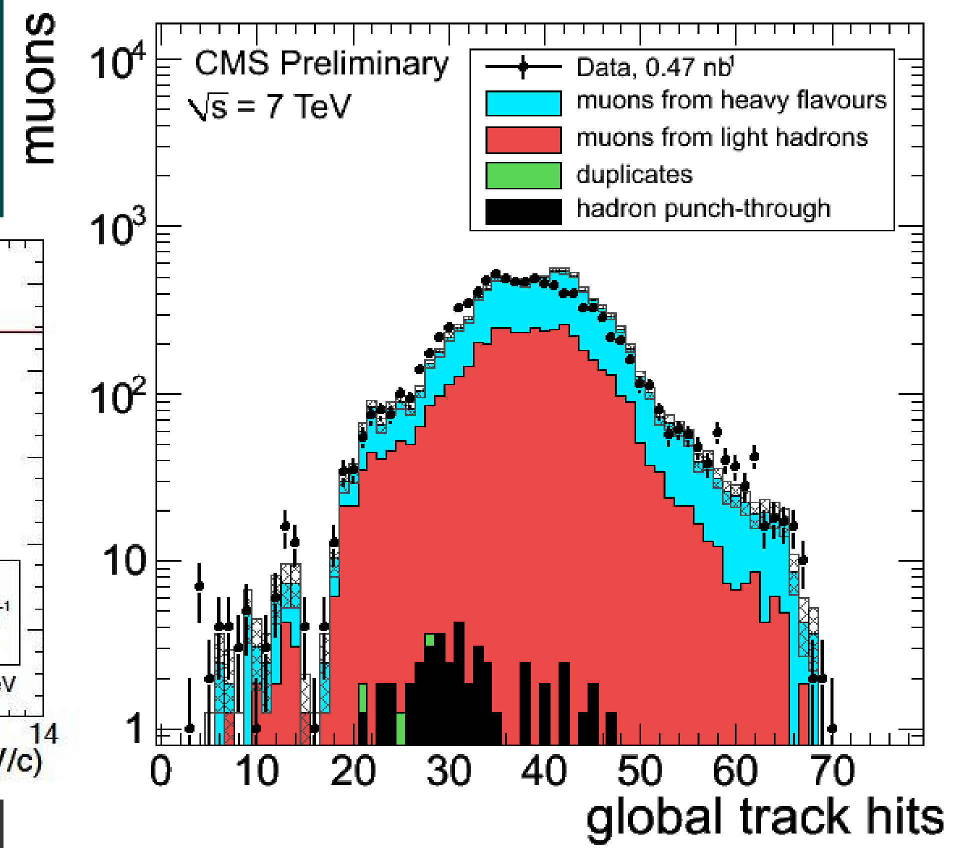
Soft muon: a tracker track matched >=1 CSC or DT stub, collect muons down to pT ~500 MeV in endcaps

Tight muon: a good quality track from combined fit of hits in the tracker and muon system.







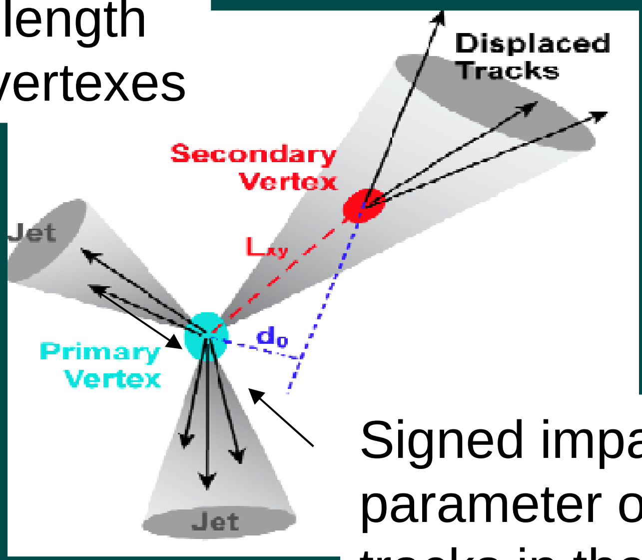


B tagging

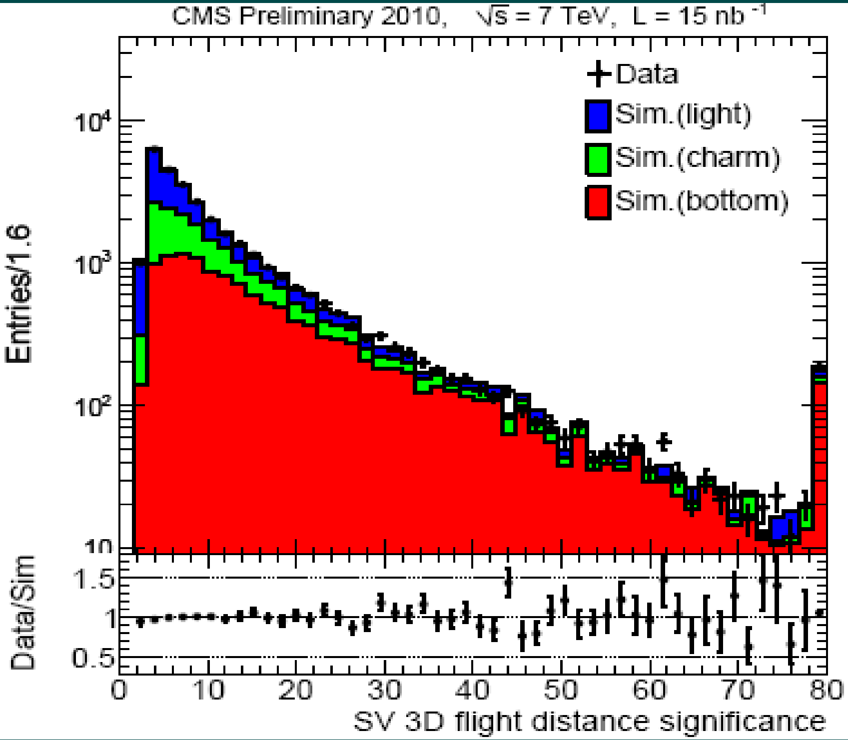
Reconstruct PF jets in 18<p_T<300 GeV with anti-kT in R=0.5, with |y|<2.0
b-jets identified with secondary vertex tagger

Secondary vertices (SV) from b- and c/light-quark decays can be distinguished by their relative distance from the primary vertex using a 3D decay length significance

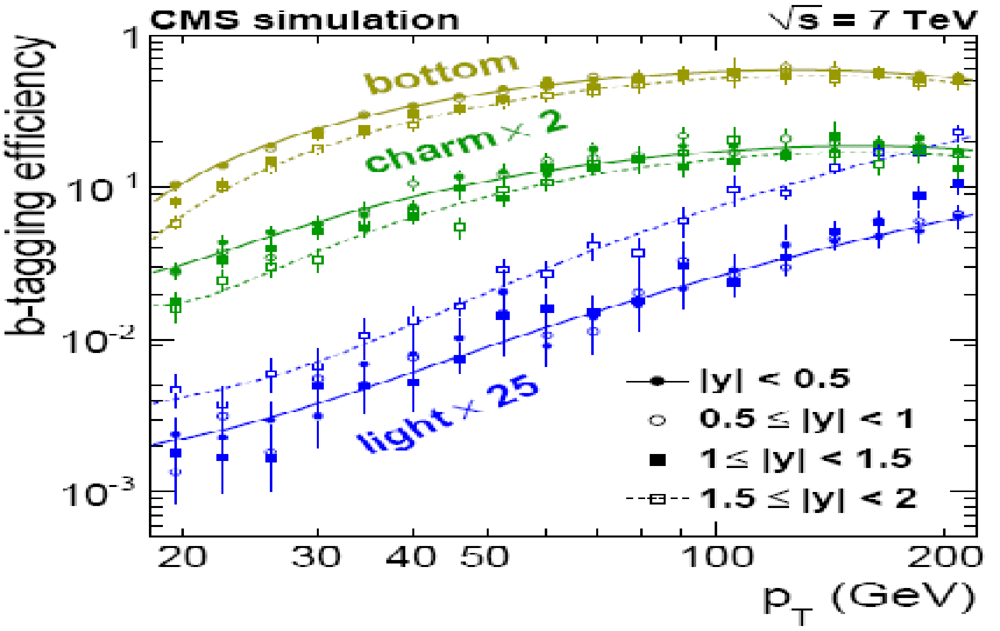
Signed decay length of secondary vertexes



Signed impact parameter of tracks in the jet

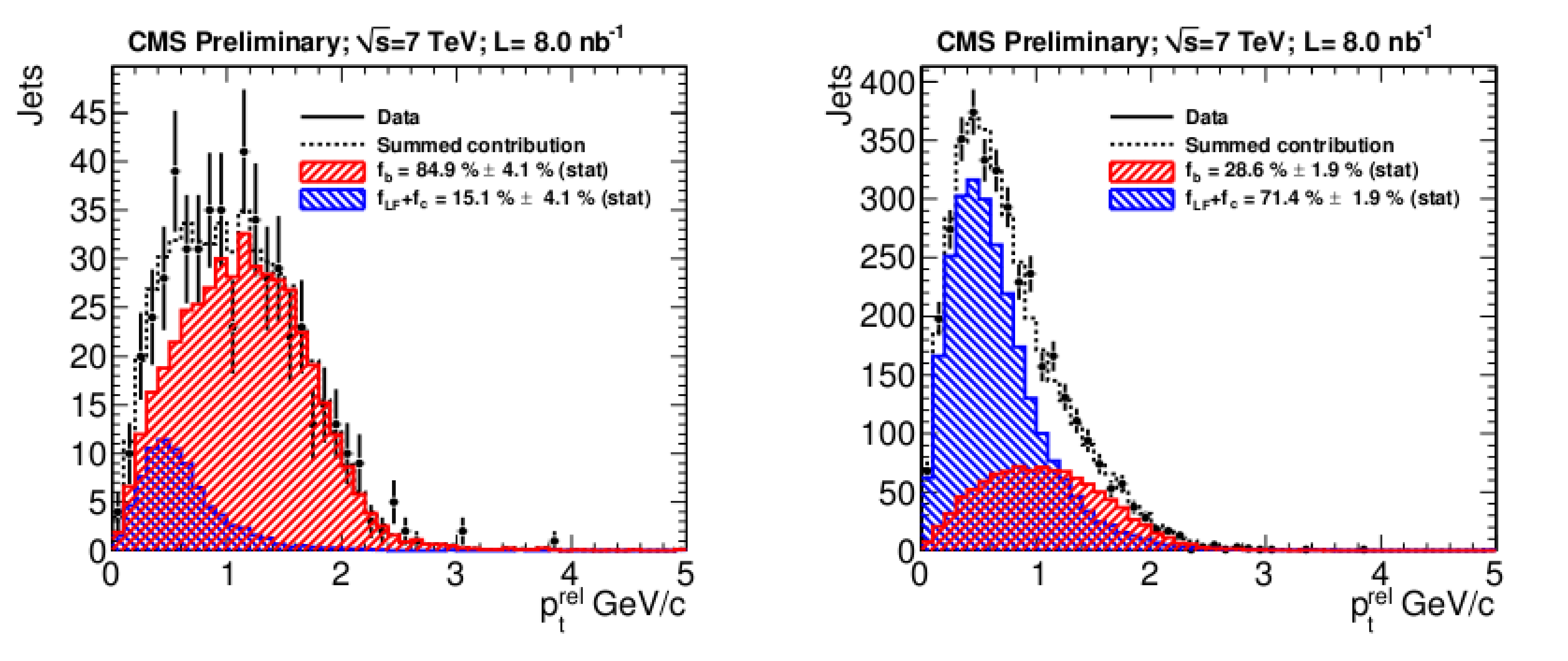


B tagging



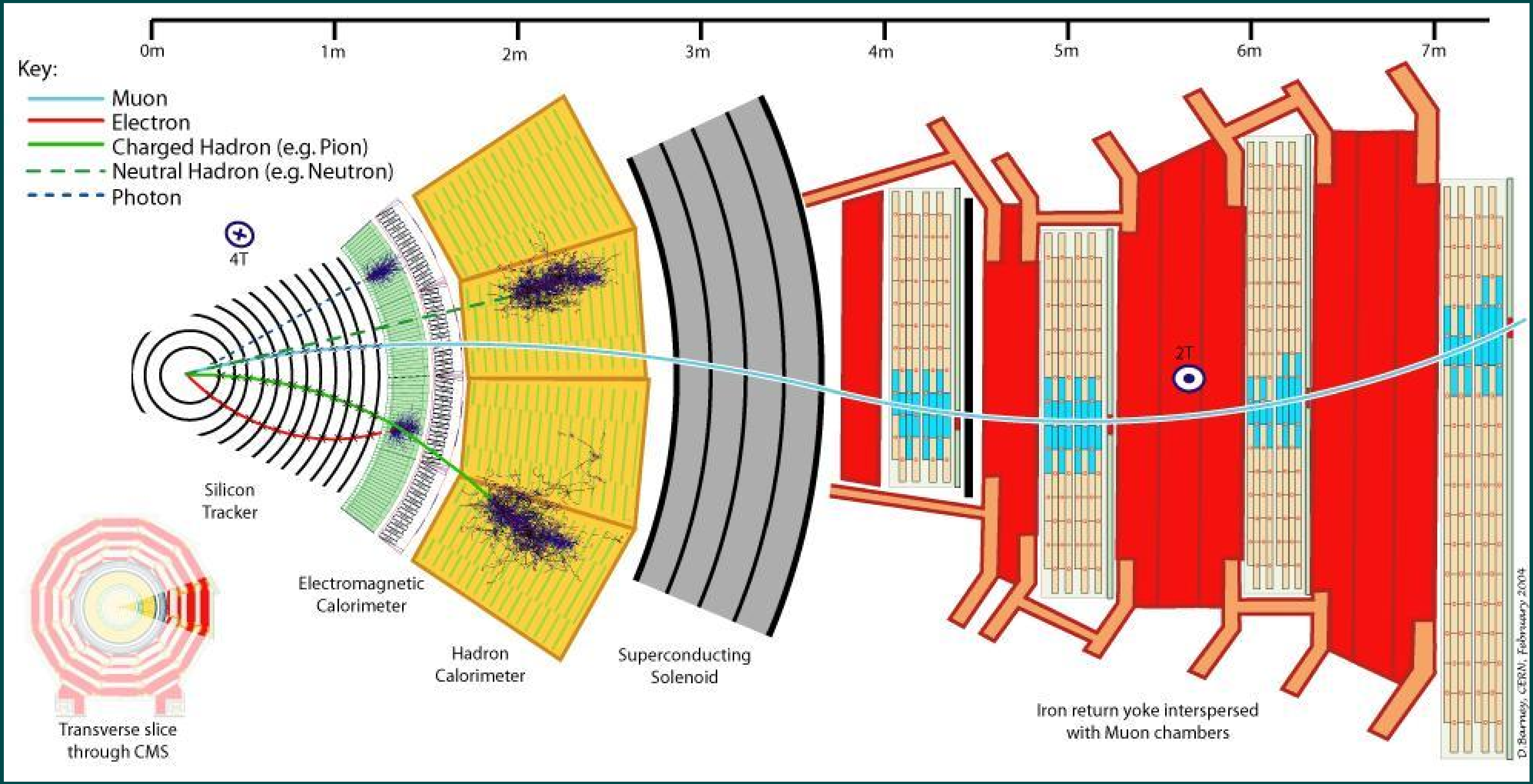
Efficiency of tagging b-jets from simulation.

Measured in the data using semileptonic decays of b-> μ+jets. Fit p_T^{rel} both in b-tagged and in non b-tagged sample. Efficiency given by ratio of corresponding Nb



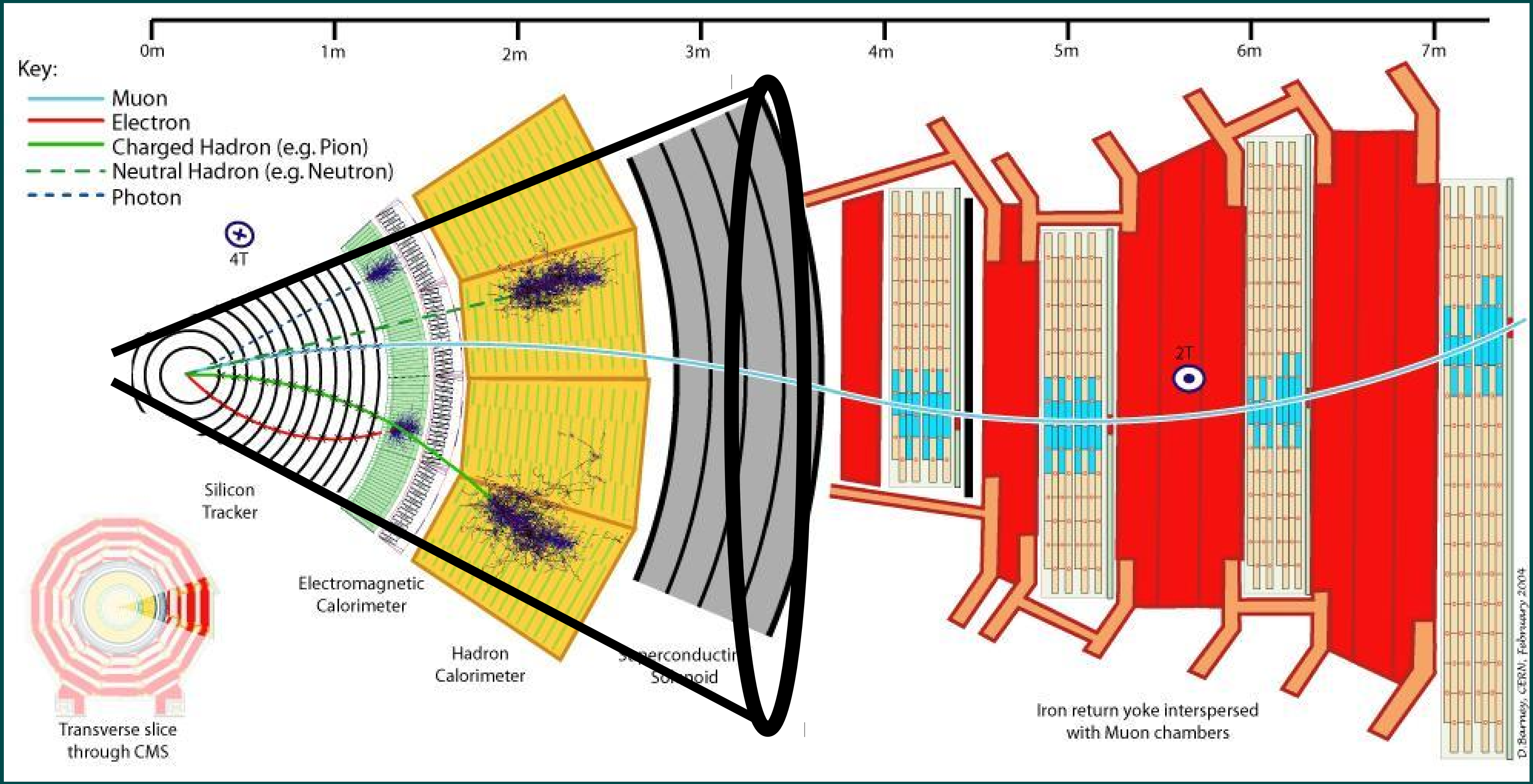
Data/MC ratio: 1 within 20% statistical uncertainty.

Summary of detectors/objects



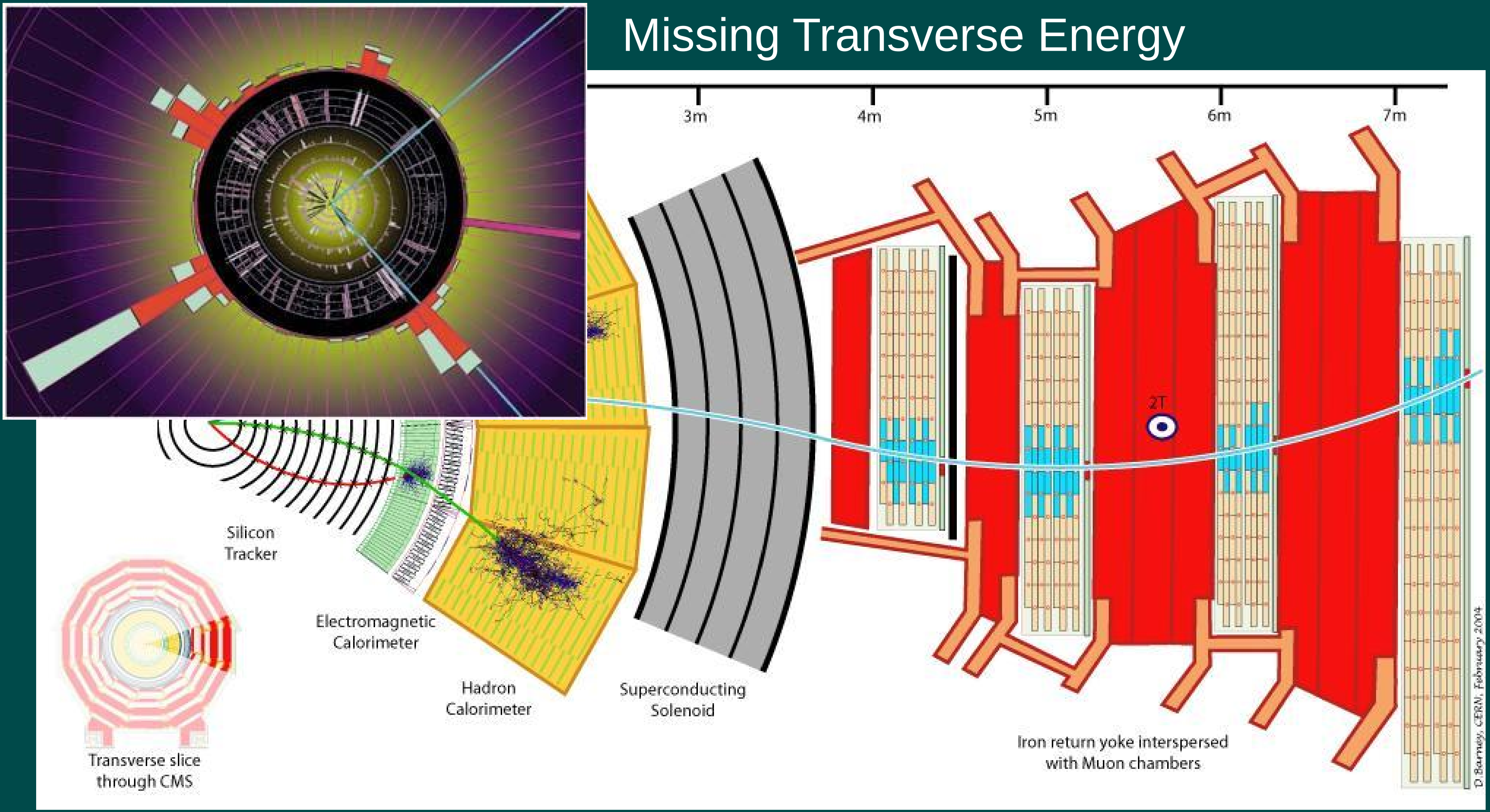
Summary of detectors/objects

Jets



Summary of detectors/objects

Missing Transverse Energy



Summary of detectors/objects

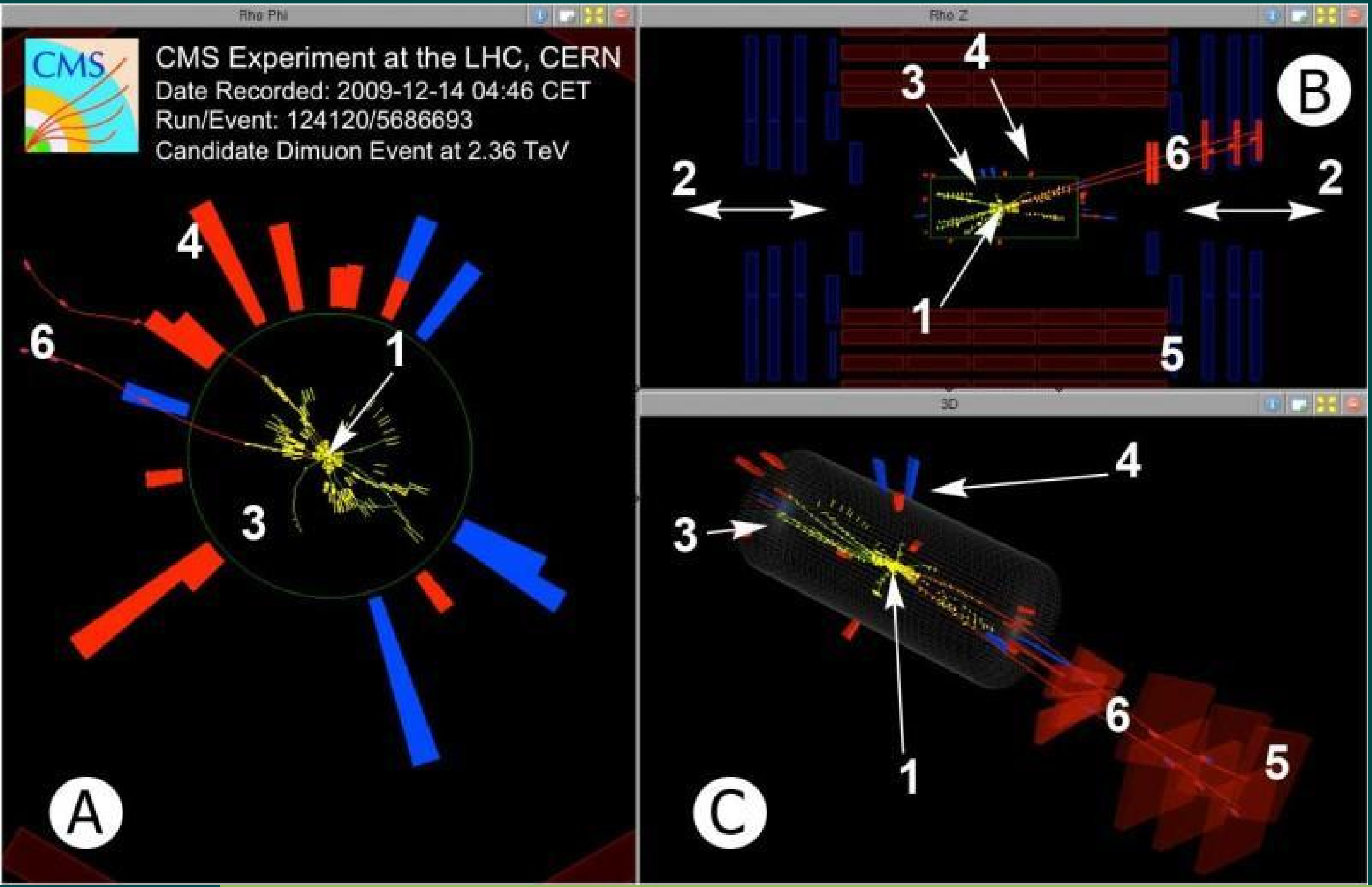
These are the basic tools of the trade for studying the physics in high energy collisions:

- Electrons
- Photon
- Muons
- Jets
- Charged particle tracks

From these final products, we identify short lived states:

- Various resonant states
- W's, Z's
- b-quarks, top-quarks
- And eventually: Higgs, SUSY(?), new bosons(?), black holes(?), ...

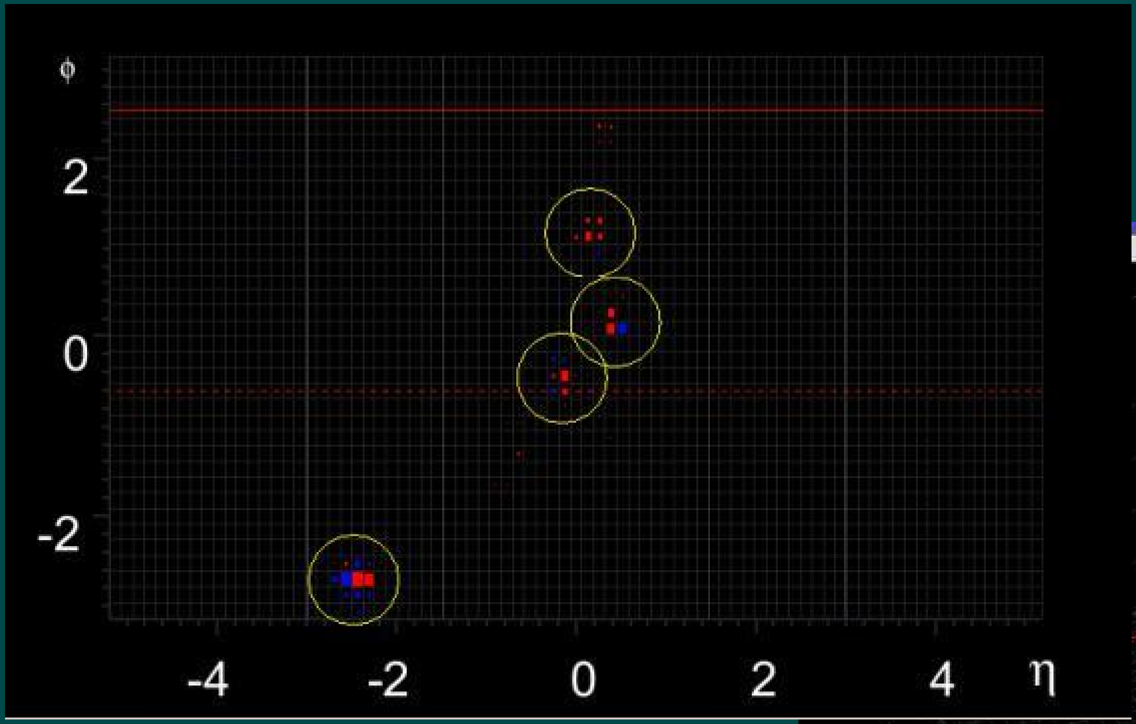
Visualizing the events

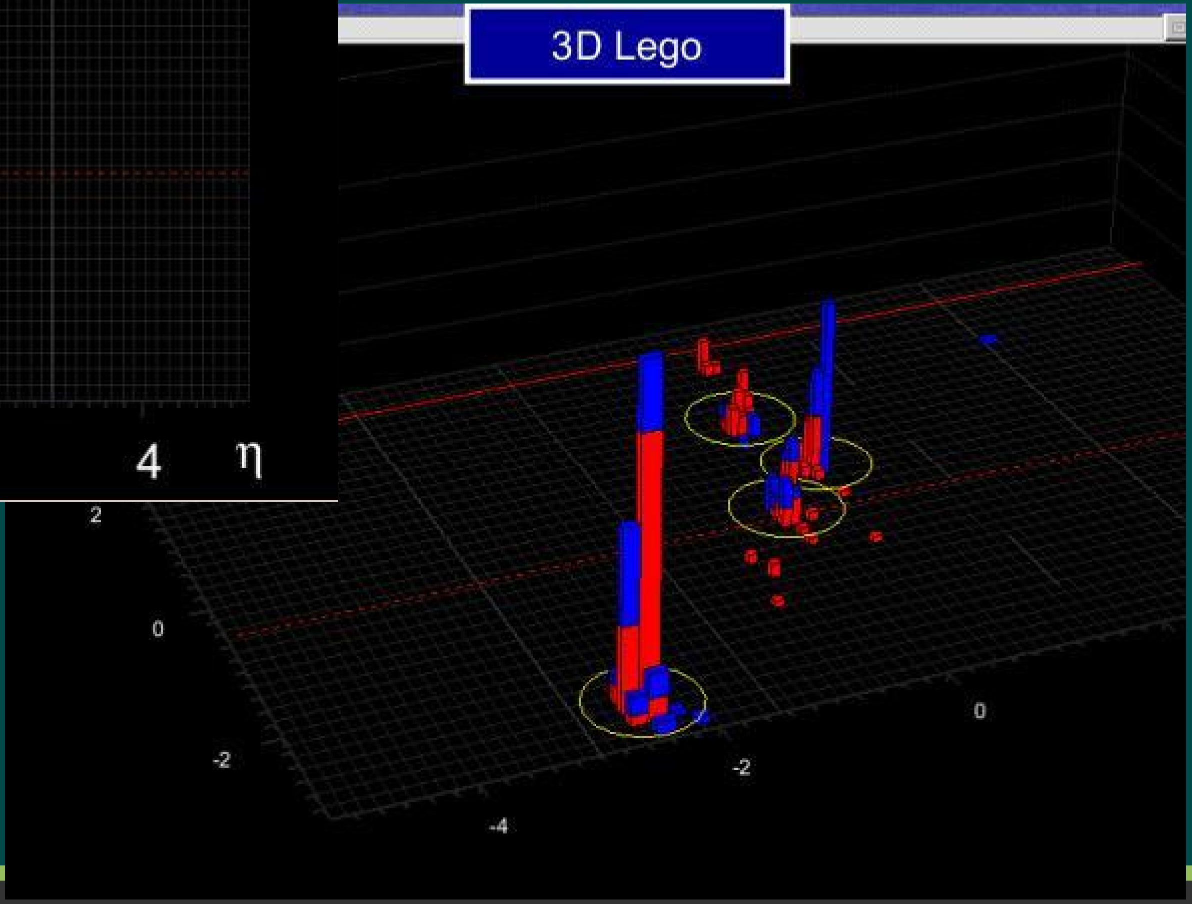


1) IP
2) Beam
3) Tracker
4) Calors.
5,6) Muon

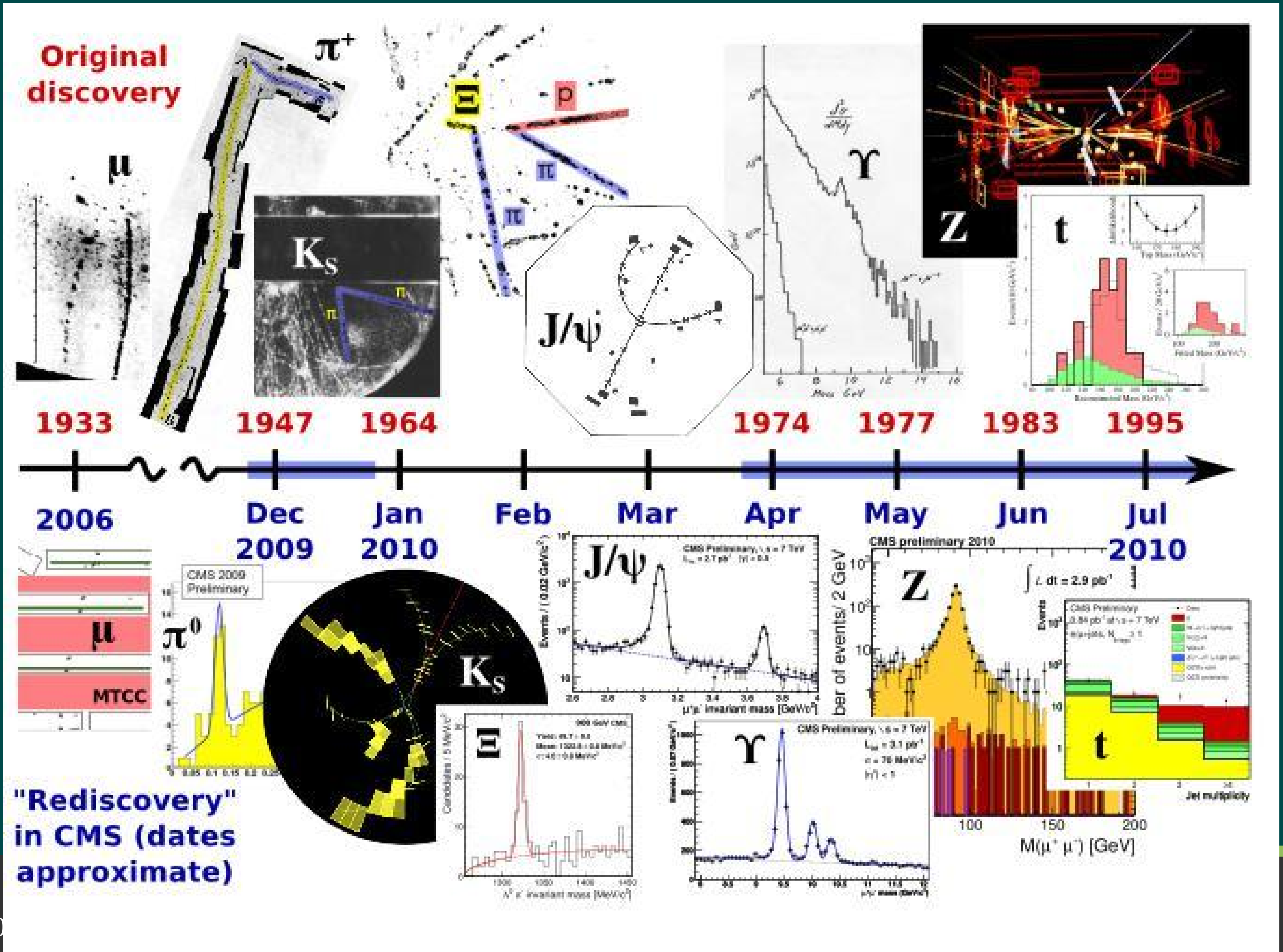
Visualizing the events

Box /Lego plots
Typically used for calorimeter data

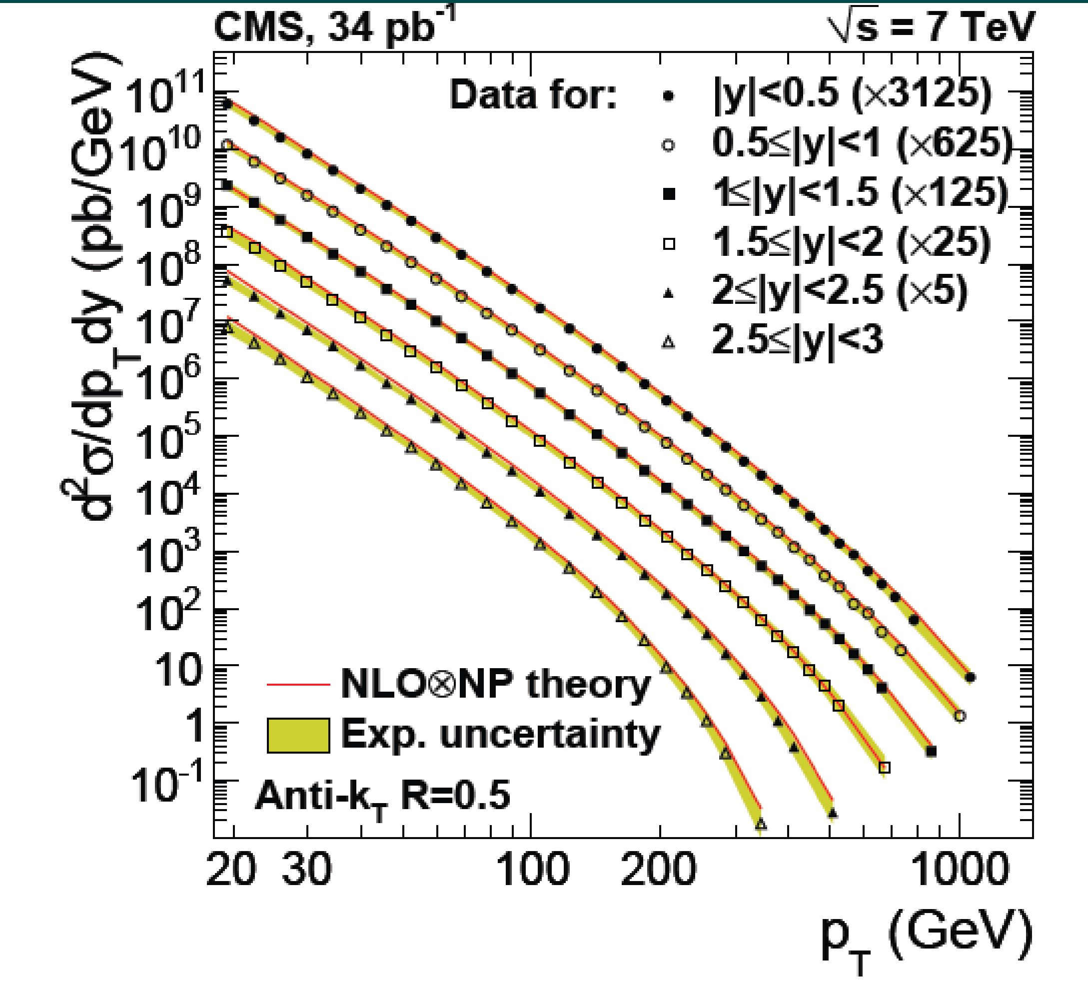




A brief history of particle/CMS physics



Rediscovering the standard model



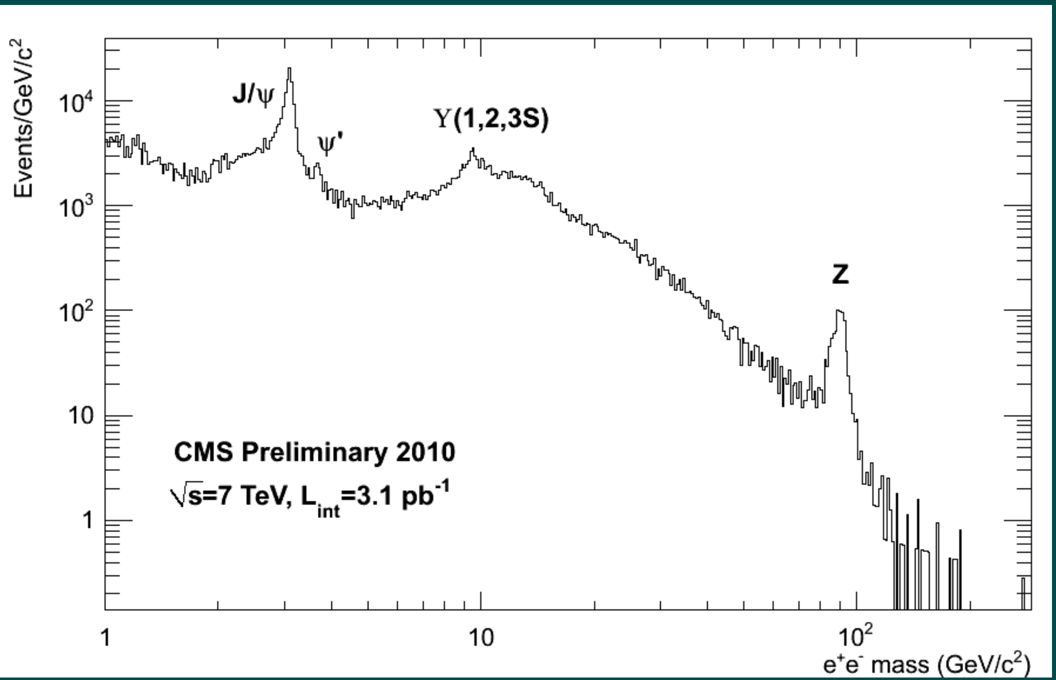
Cross section measurement covers from 18 GeV to 1.1 TeV in jet pT

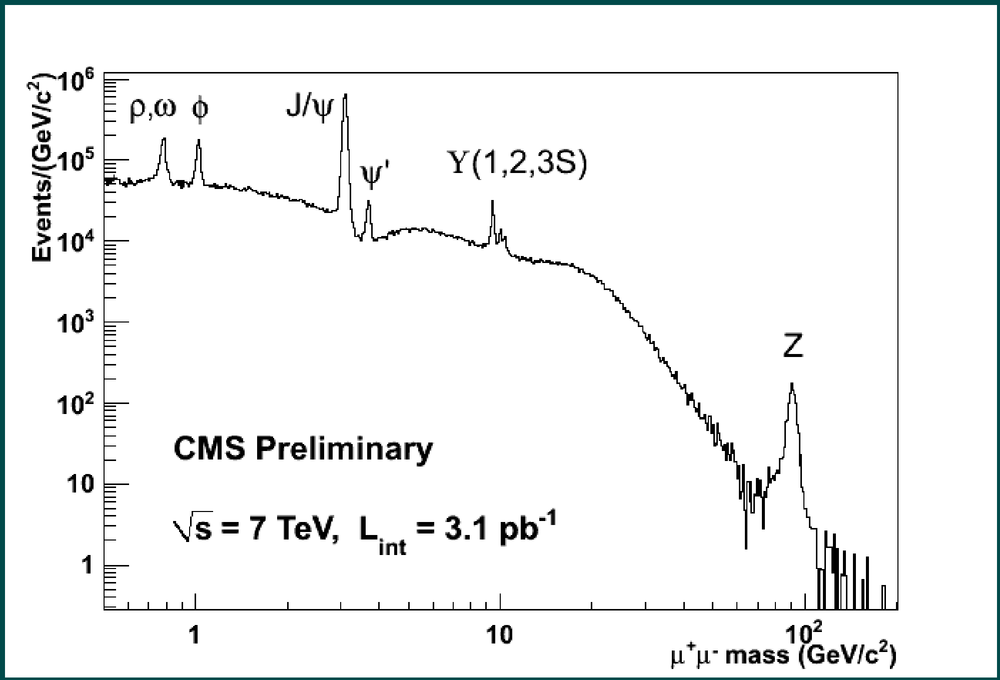
Good agreement with NLO theory predictions over 10 orders of magnitude in 6 rapidity bins

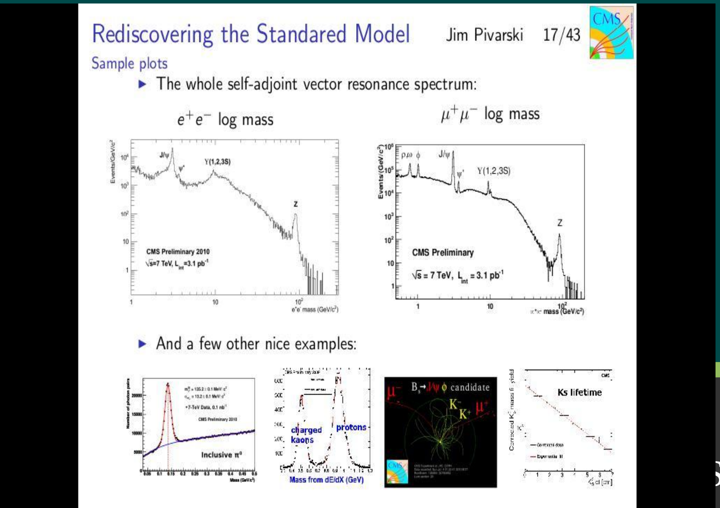
Rediscovering the standard model

e+e- mass

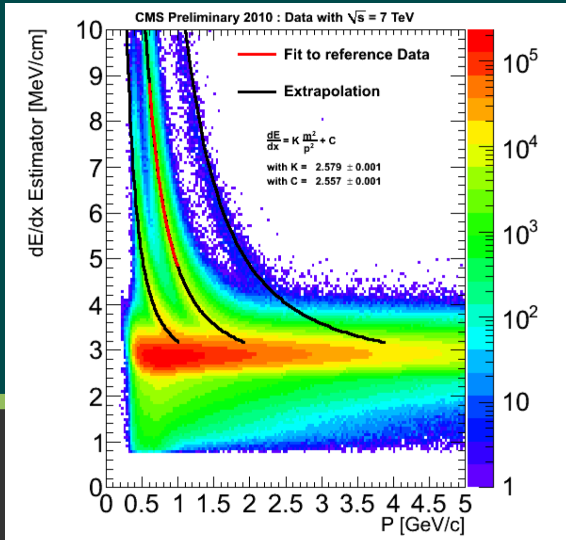
mu+mu- mass







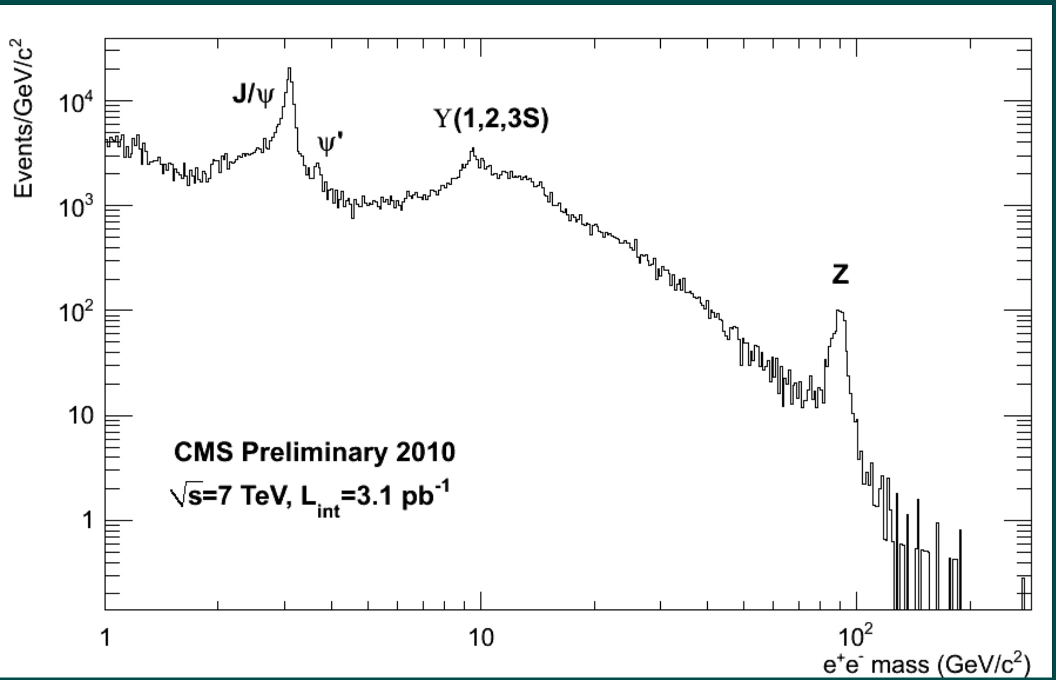
Pi0 signal



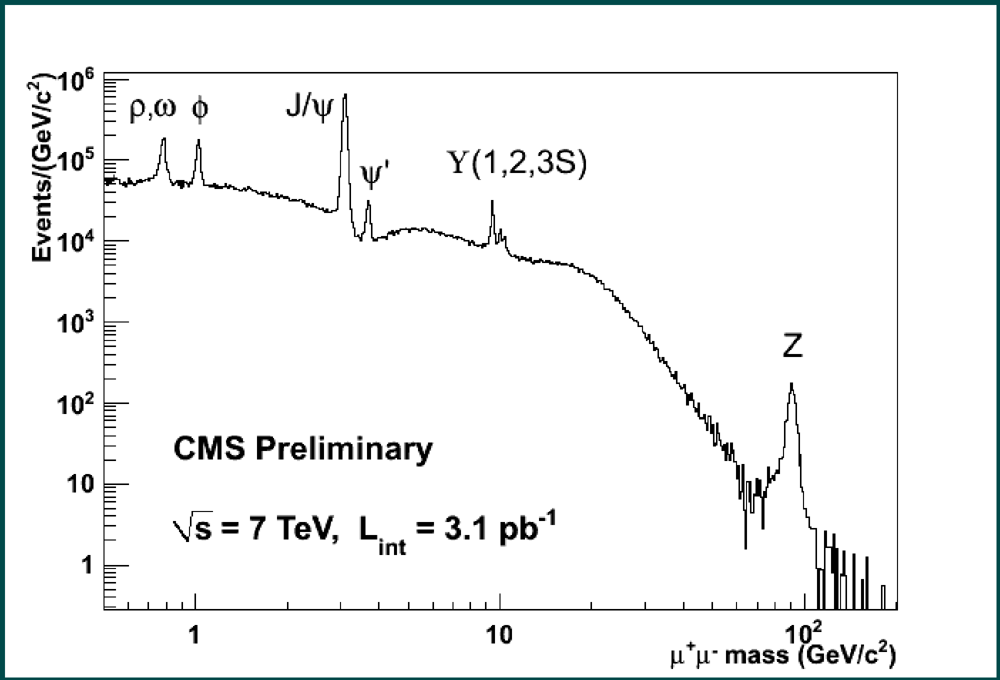
dE/dx in tracker K,p, & deuteron

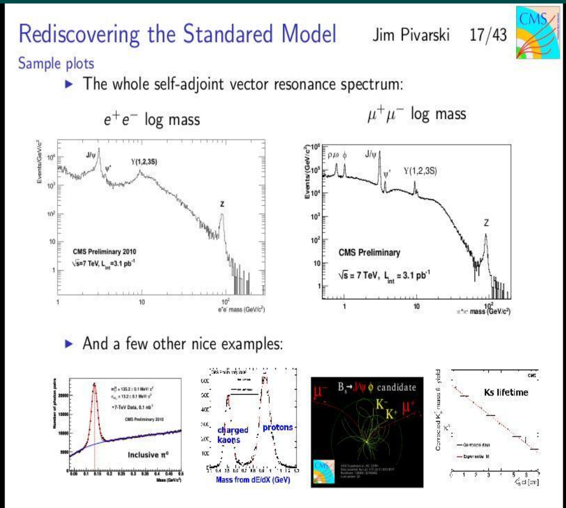
Rediscovering the standard model

e+e- mass

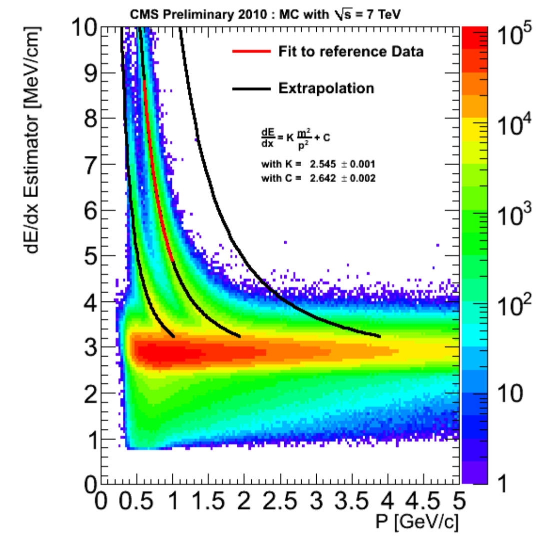


mu+mu- mass



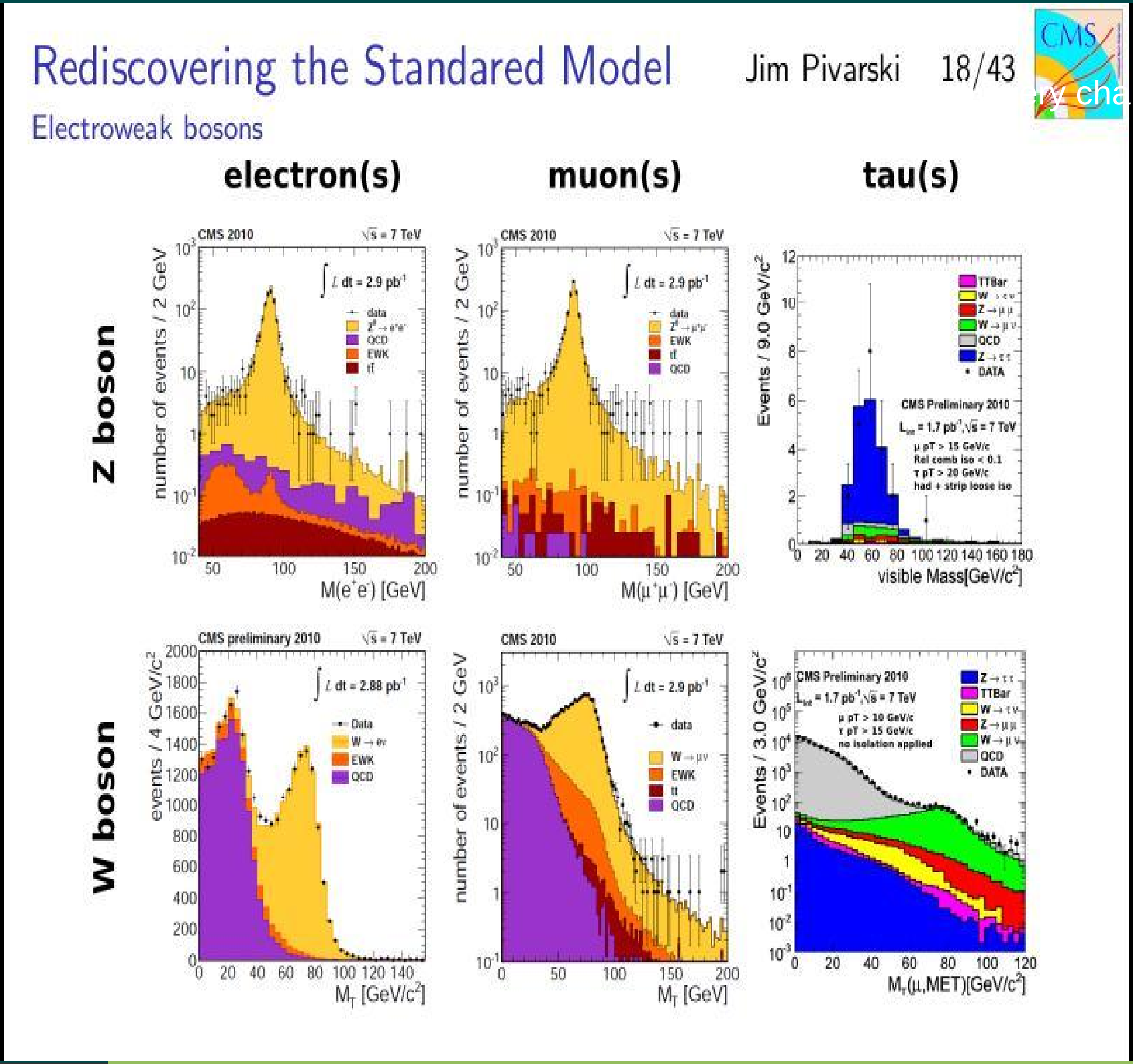


Pi0 signal



dE/dx in tracker K,p, & ~~deuteron~~ in MC!

Rediscovering the standard model



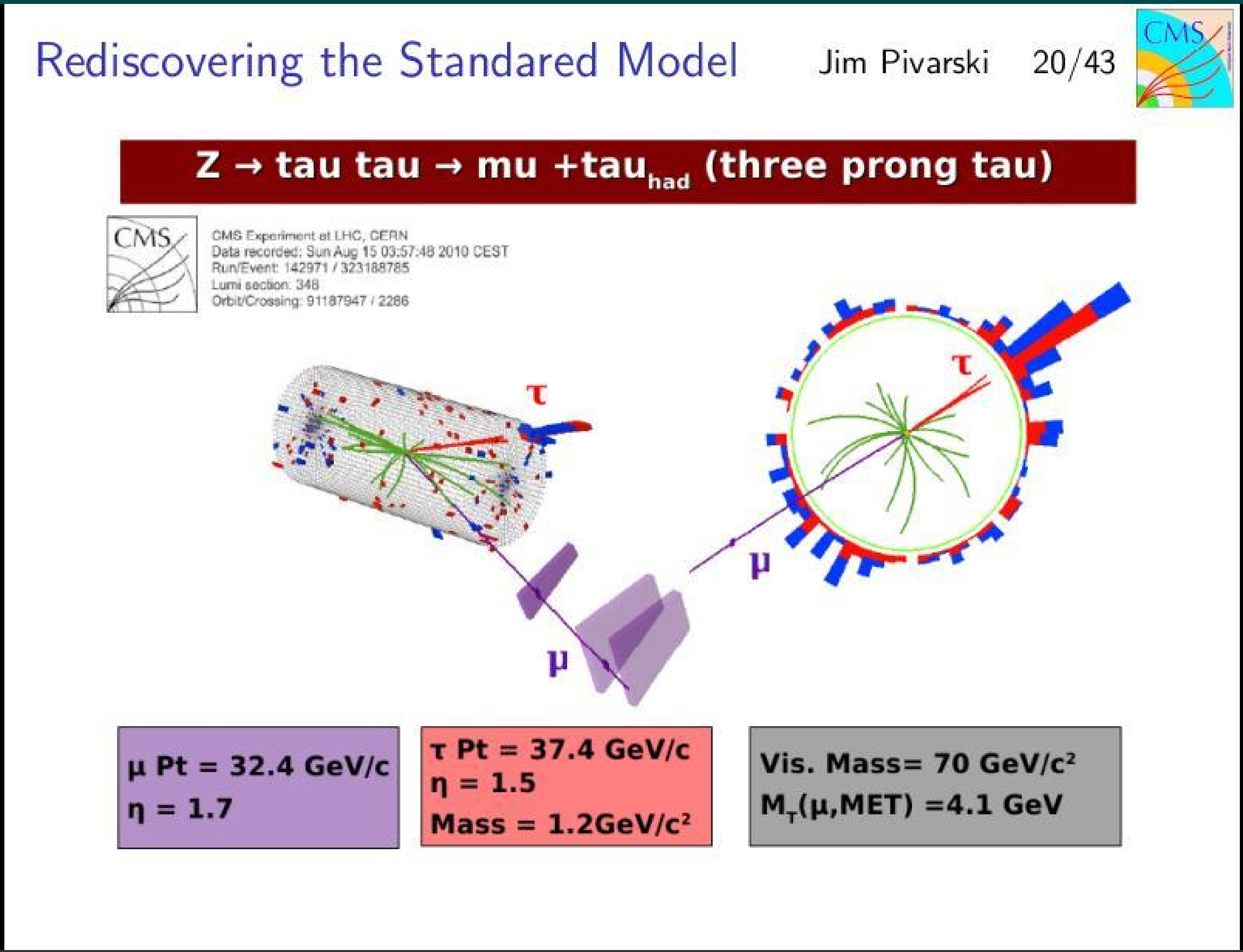
ry challenging!

Data and background modeling for W/Z bosons

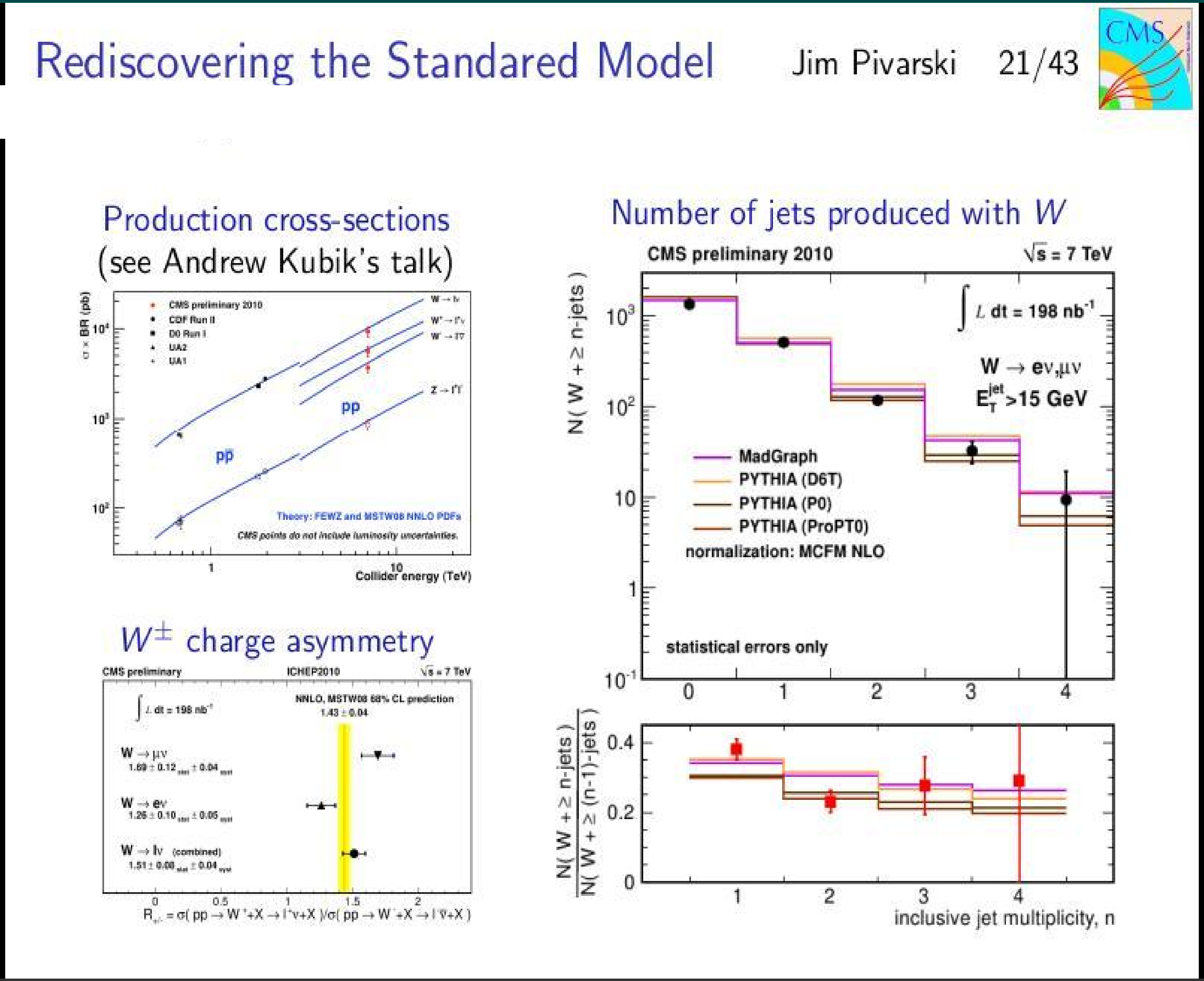
- excellent agreement in early days

- important objects to study SM interactions and for new physics searches

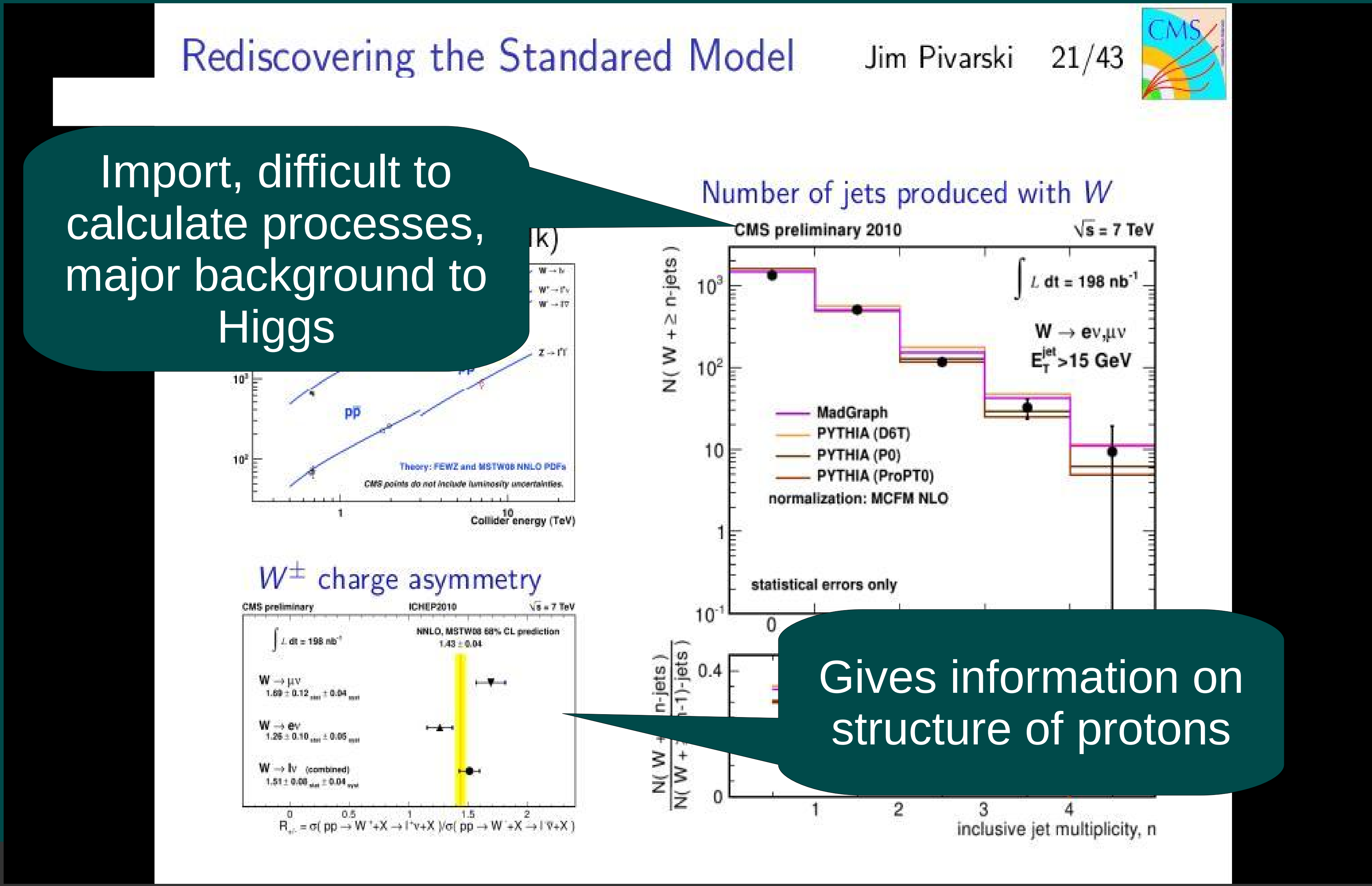
Z → tau tau → mu + tau_{had} (3 prong tau)



More W measurements



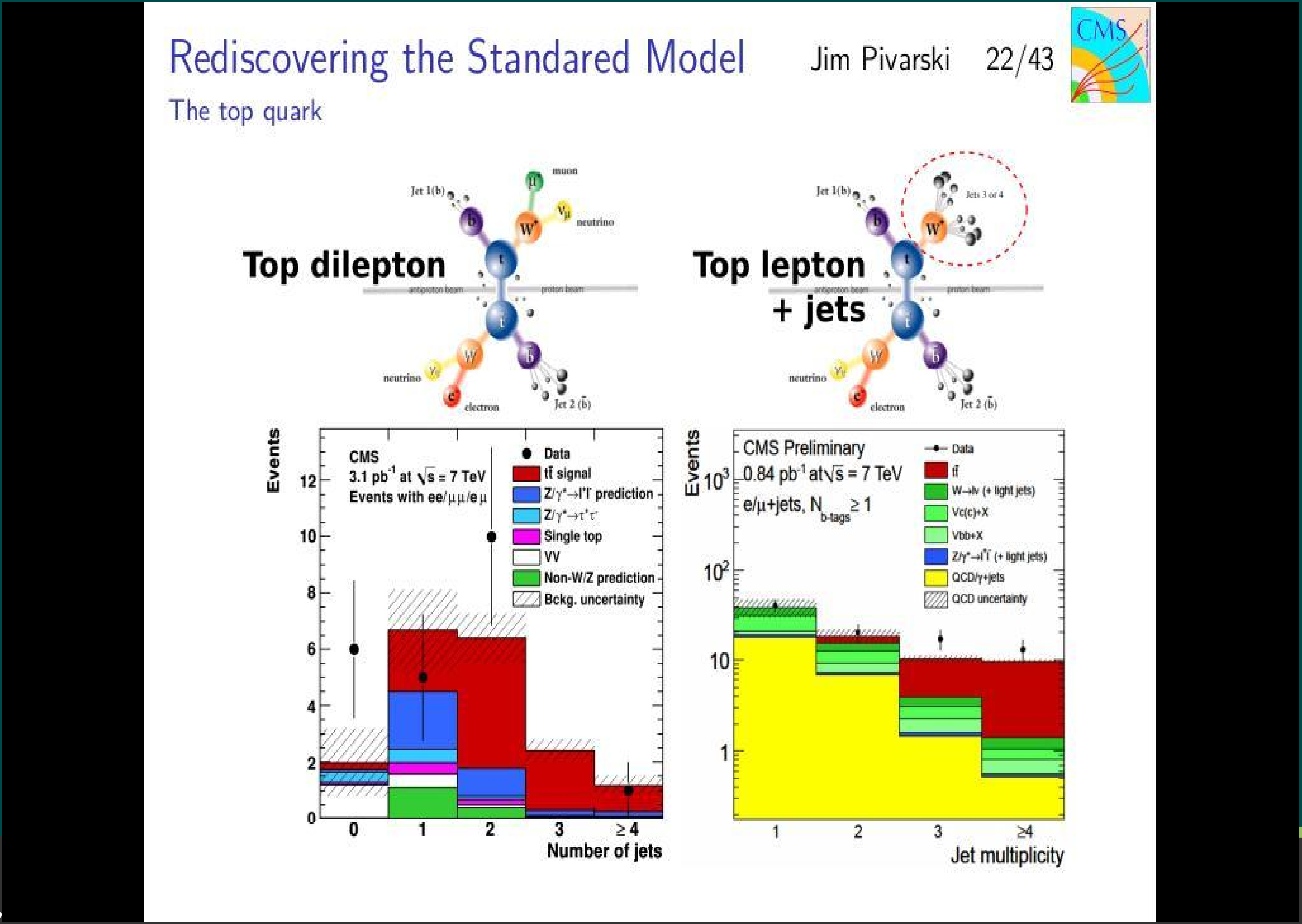
More W measurements



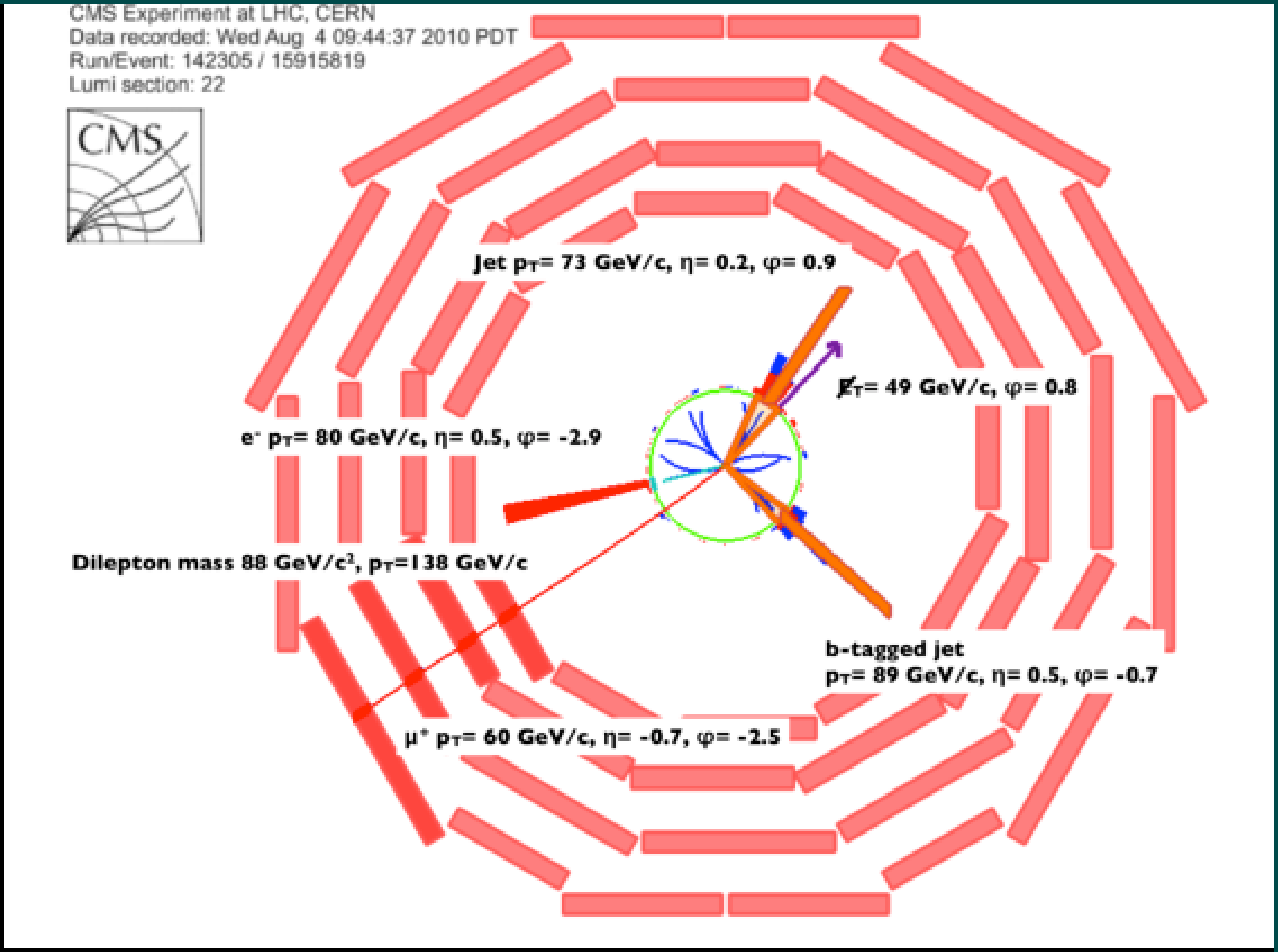
Import, difficult to calculate processes, major background to Higgs

Gives information on structure of protons

The top quark: 1st sighting at LHC



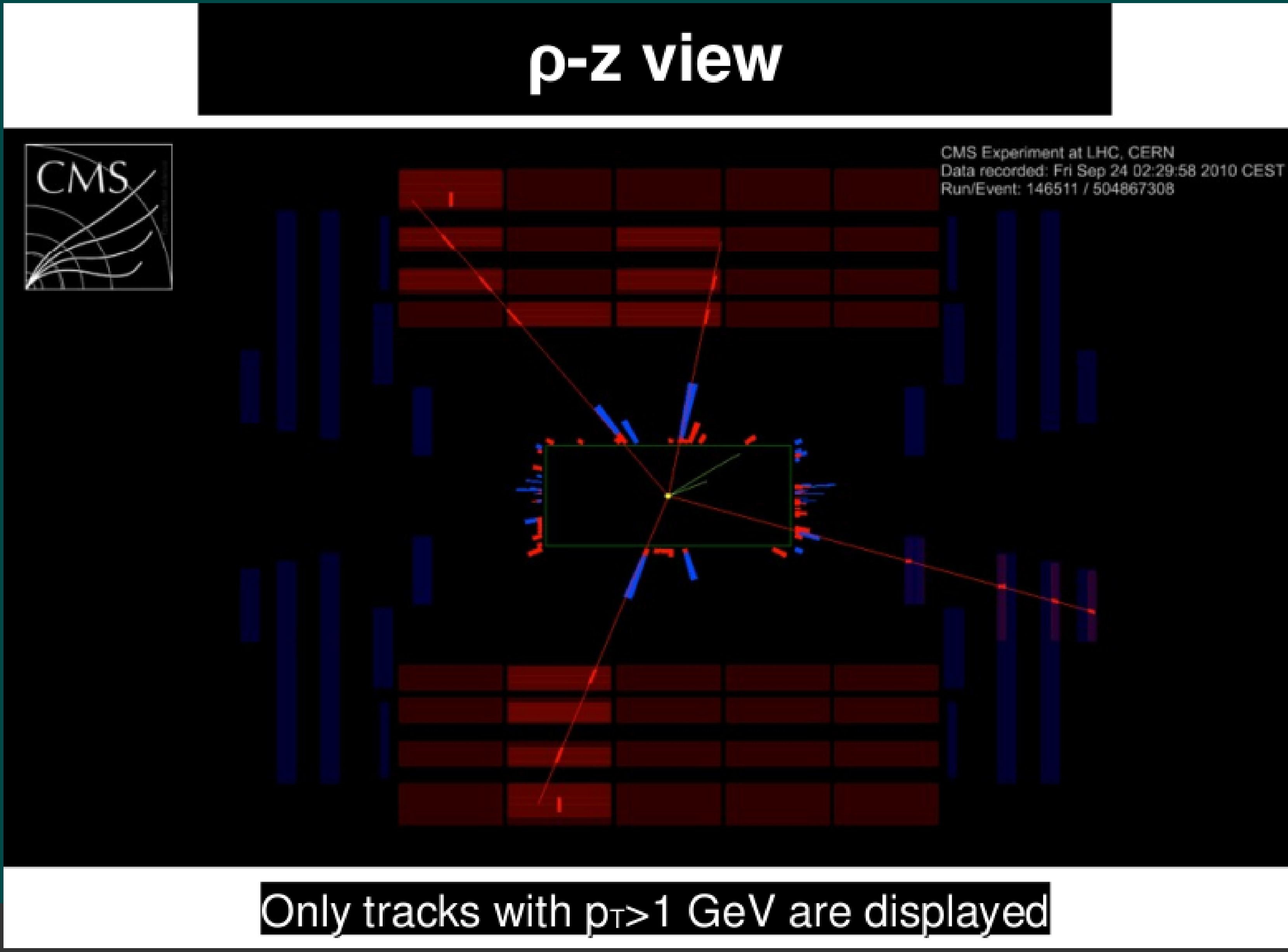
$t\bar{t} \rightarrow e\mu$+jets



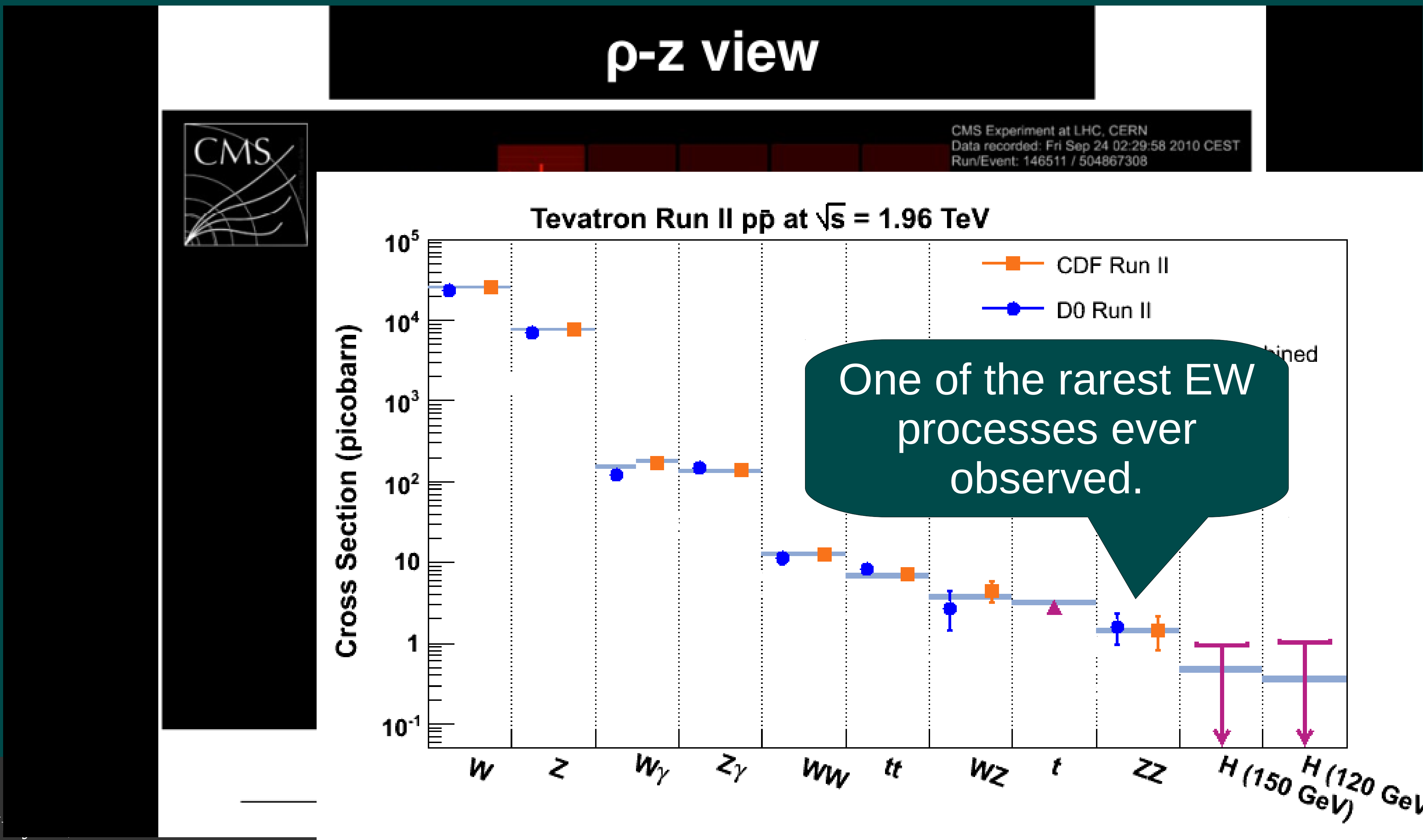
"golden candidate"

$t\bar{t} \rightarrow WWb\bar{b} \rightarrow e\mu\nu\nu jj$

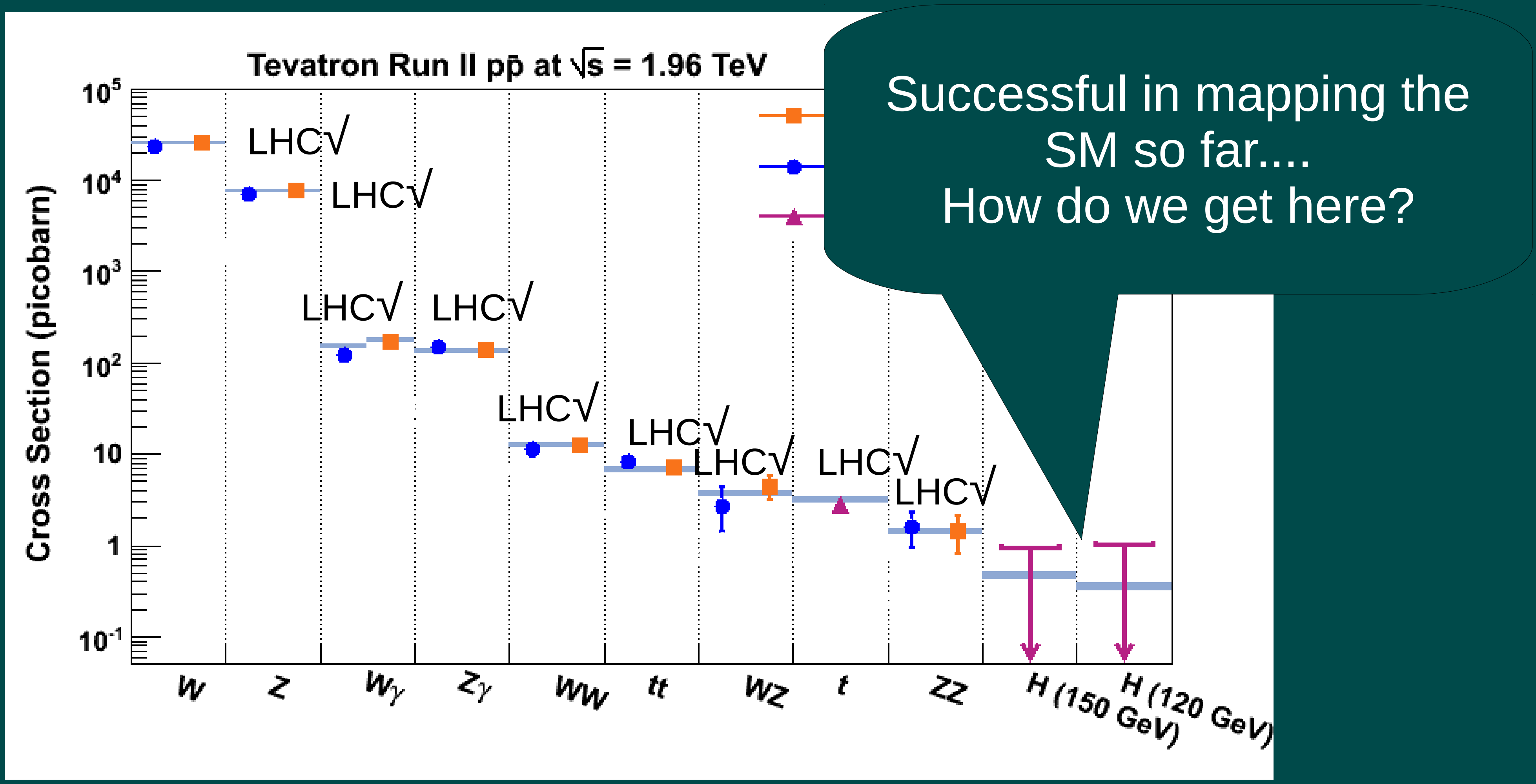
ZZ → 4 muon event



ZZ → 4 muon event

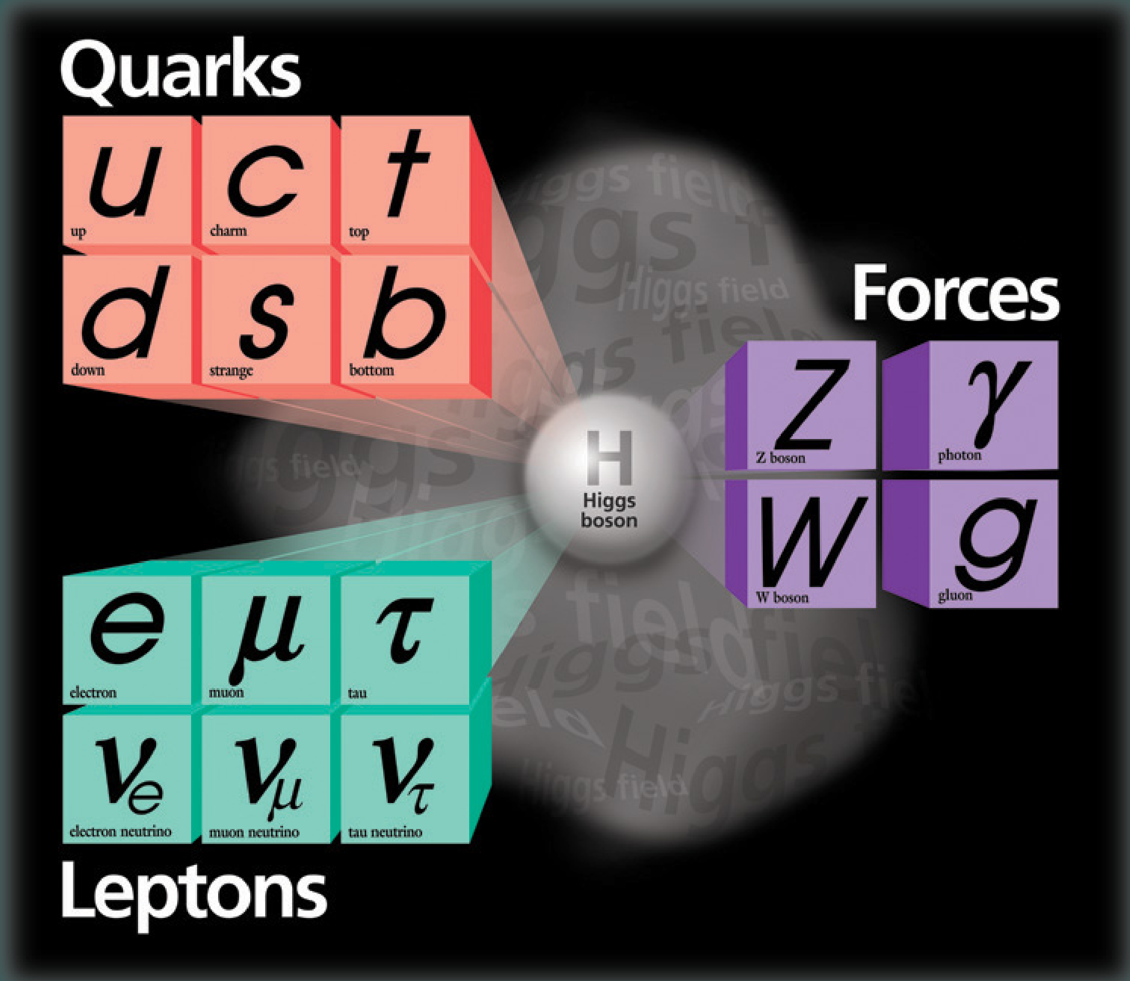


Completing the SM picture



Just about one year at LHC to demonstrate discoveries from last few decades!

Searches for the Higgs Boson at the Tevatron



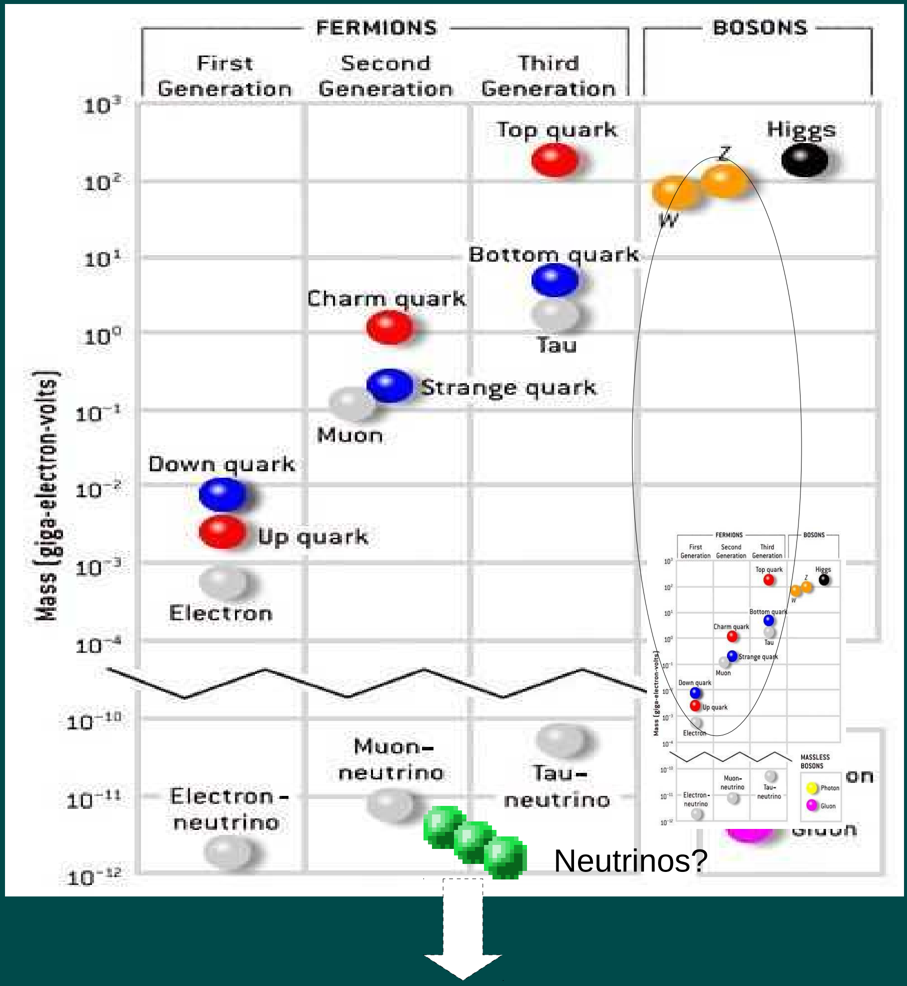
How Does Mass Enter the Picture?

Explicit addition of massive particle fields breaks fundamental gauge-invariance (symmetry) in the standard model.

Electroweak symmetry famously broken by presence of massive W,Z bosons.

Nonphysical behavior (eg. unitarily violation for W/Z interactions)

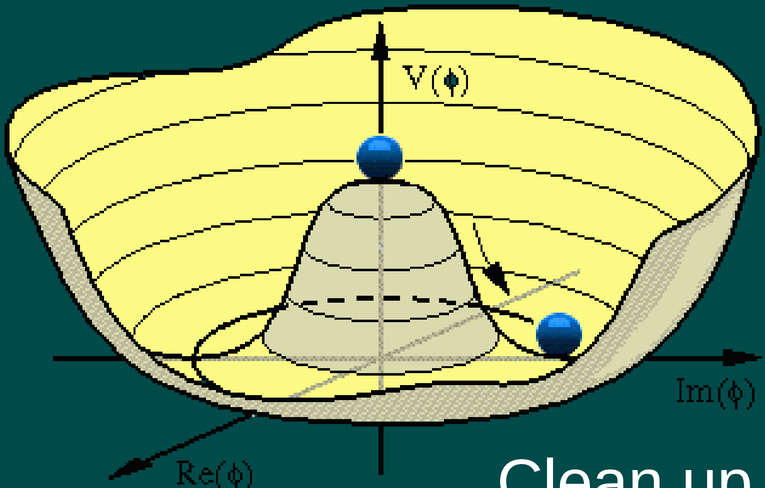
The fundamental building blocks of the standard model span a wide range of masses, yet to be understood.



How Does Mass Enter the Picture

The Higgs Mechanism provides an economical way to generate mass and break electroweak symmetry

Spontaneous symmetry breaking
Non-zero ground state -> field permeating vacuum, framework for adding mass



Clean up

* W and Z bosons acquire mass from degrees of freedom of Higgs field

* Fermions acquire mass from interactions with the Higgs field

* A new fundamental (scalar) particle, the Higgs boson is predicted

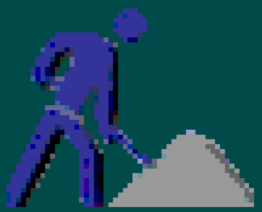
* Fixes unitary problem

From Theory to Experiment

This is a theory that has captured the imagination and interests of physicists and the general public.

Confirming the origin of mass. An exciting prospect for physics!

2010 Sakurai Prize awarded to developers of the essential components to elucidate this mechanism for EW symmetry breaking (Guralnik, Hagen, Kibble, Brout, Englert, and Higgs)



Very testable theory

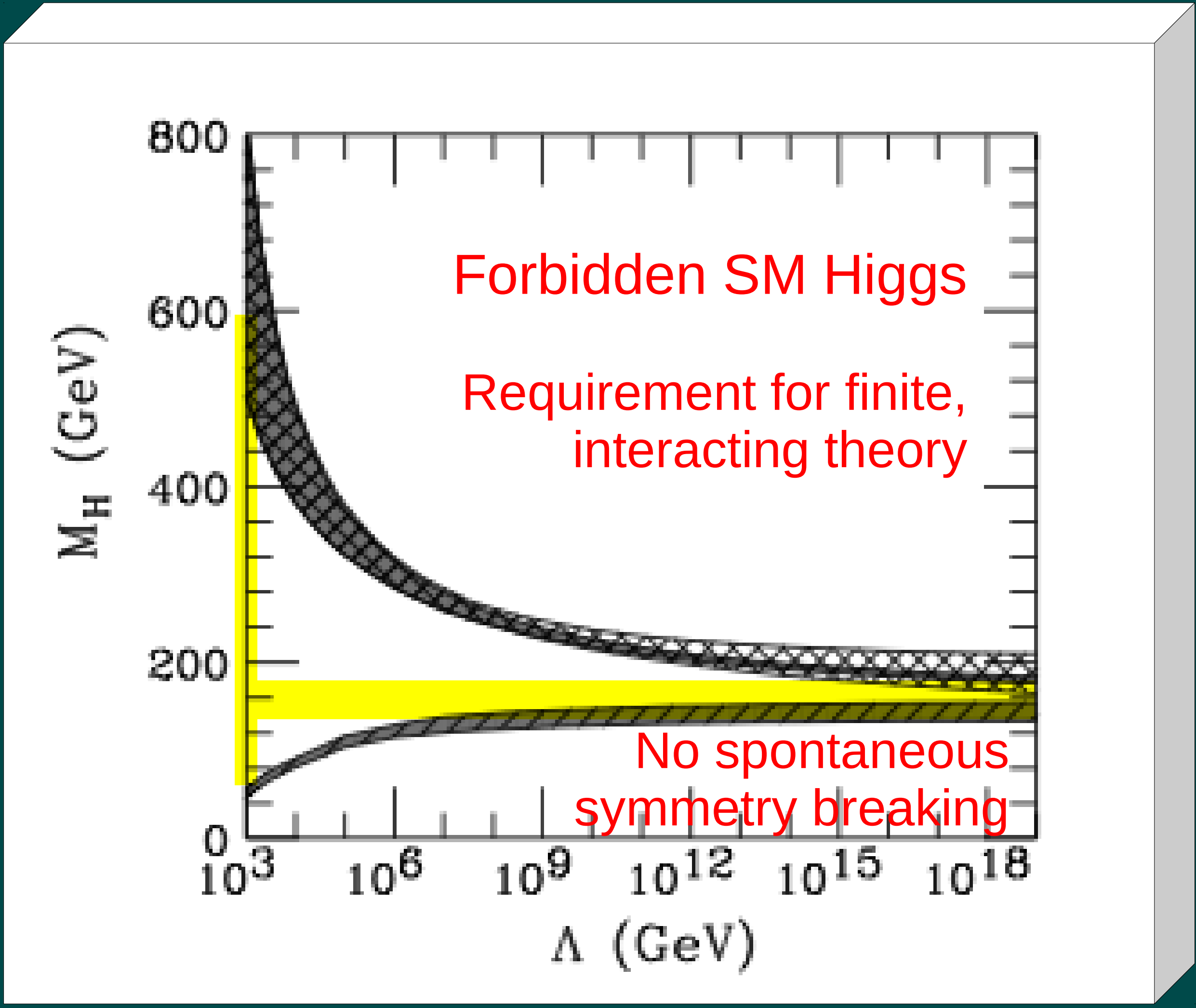
Requires addition of scalar particle, H, with unknown mass (slight wrinkle), but observables precisely calculable WRT M_H

Theoretical Limits on M_H

Standard model Higgs yields consistent theory to high energy scales, only for limited mass range.

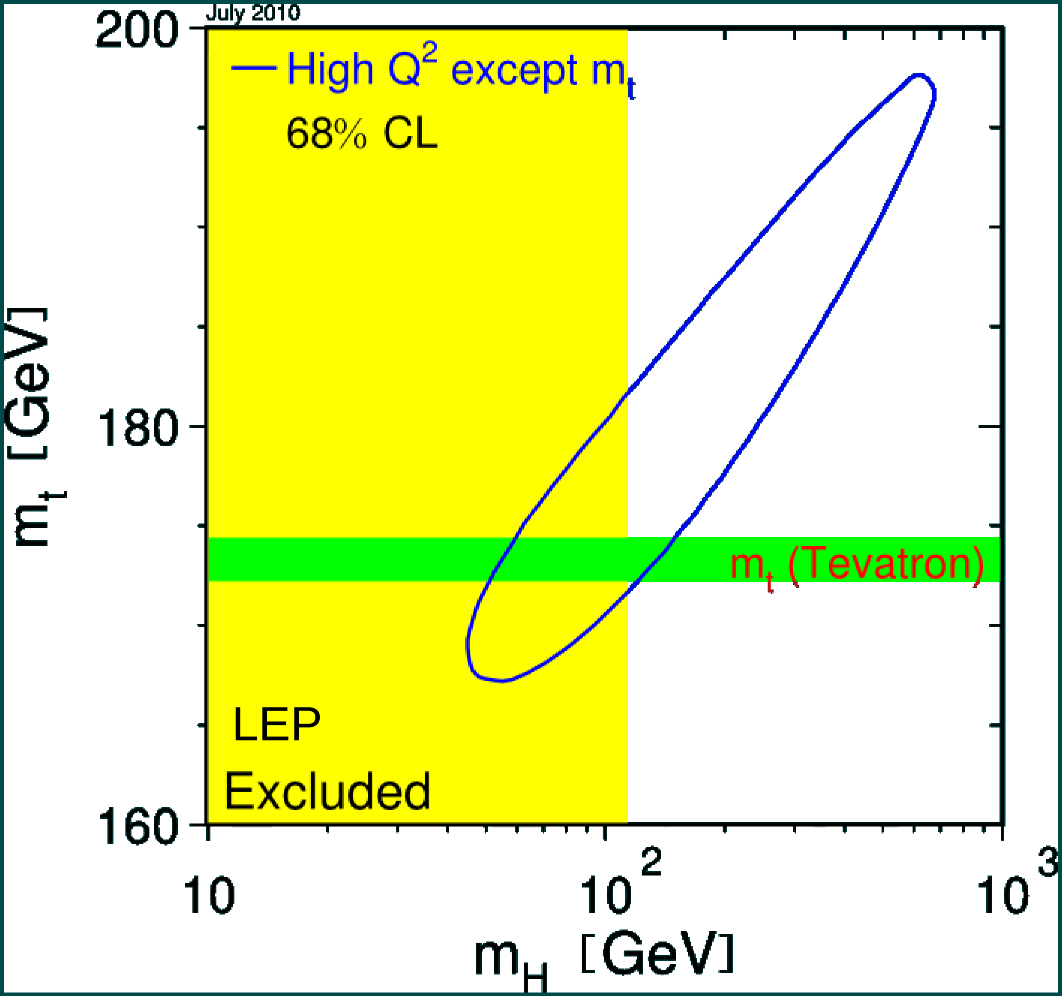
(But M_H unnaturally low in this scenario.)

In particular observation of a heavy Higgs suggests new physics at low energy scale.



Scale for new physics

Indirect limits from Electroweak data



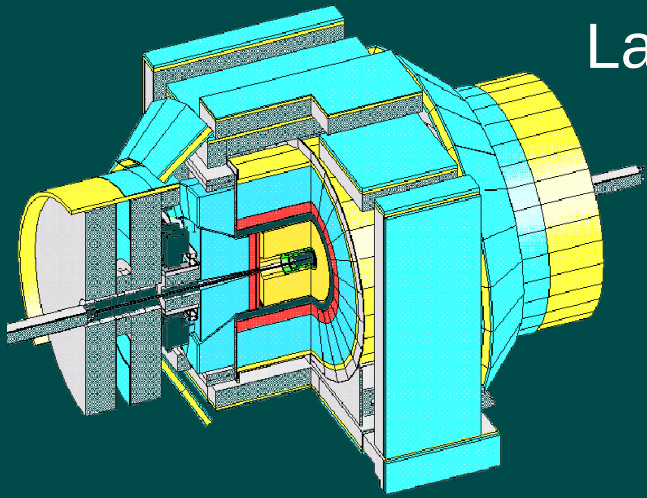
Precision measurements in EW data provide strong limits on mass of SM Higgs boson

$$M_W = \left(\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}\right)\frac{1}{sin\theta_W\sqrt{1-\Delta r}}$$

$$lnM_W \propto \Delta M_W \propto M_t^2$$

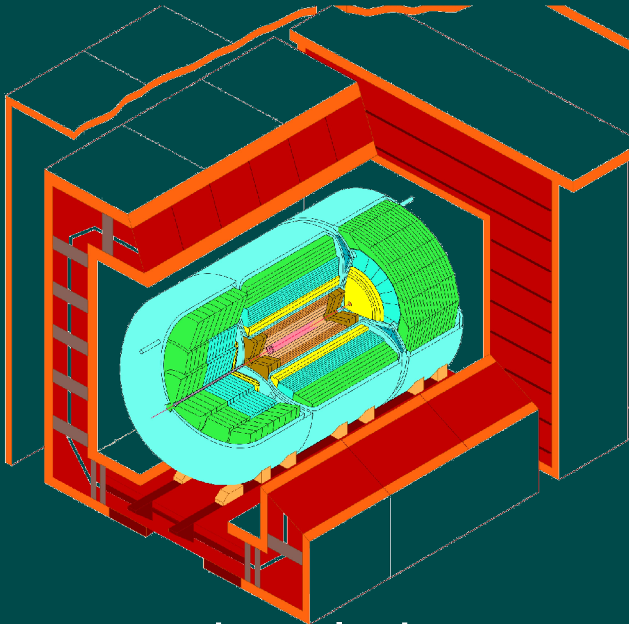
connection via radiative corrections

CDF and DØ Detectors



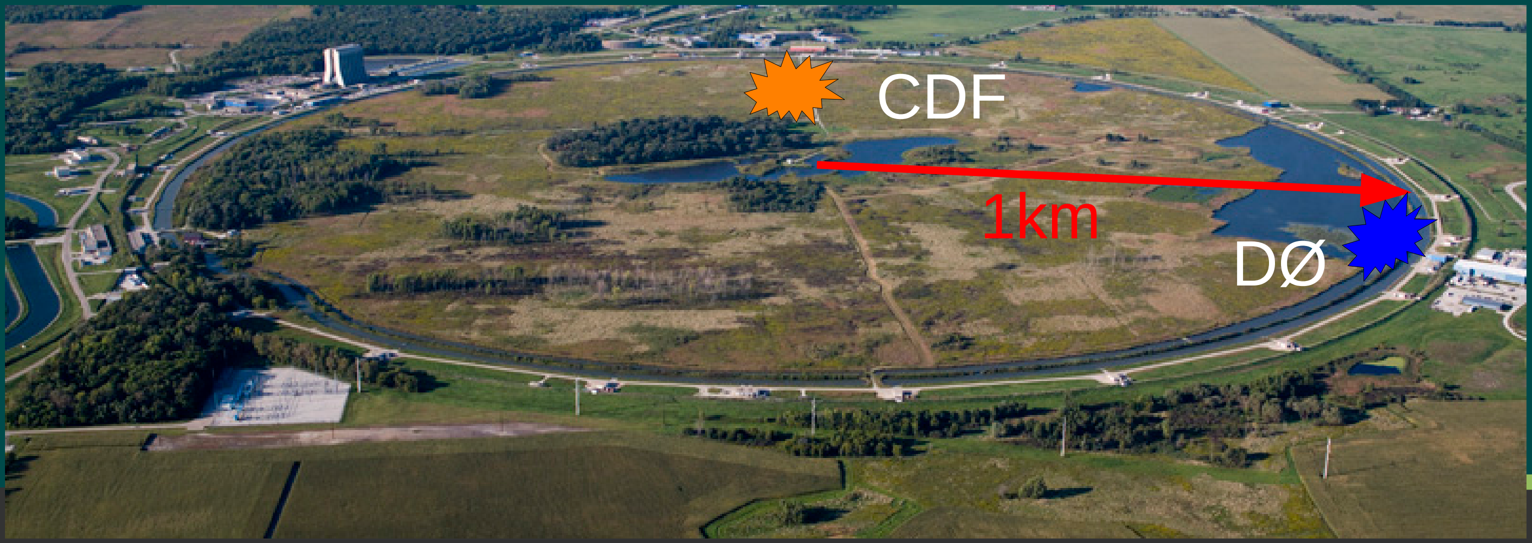
Large, multipurpose detectors

~4π coverage
* Tracking
* Calorimetry
* Muon detection
* Missing ET → infer ν's

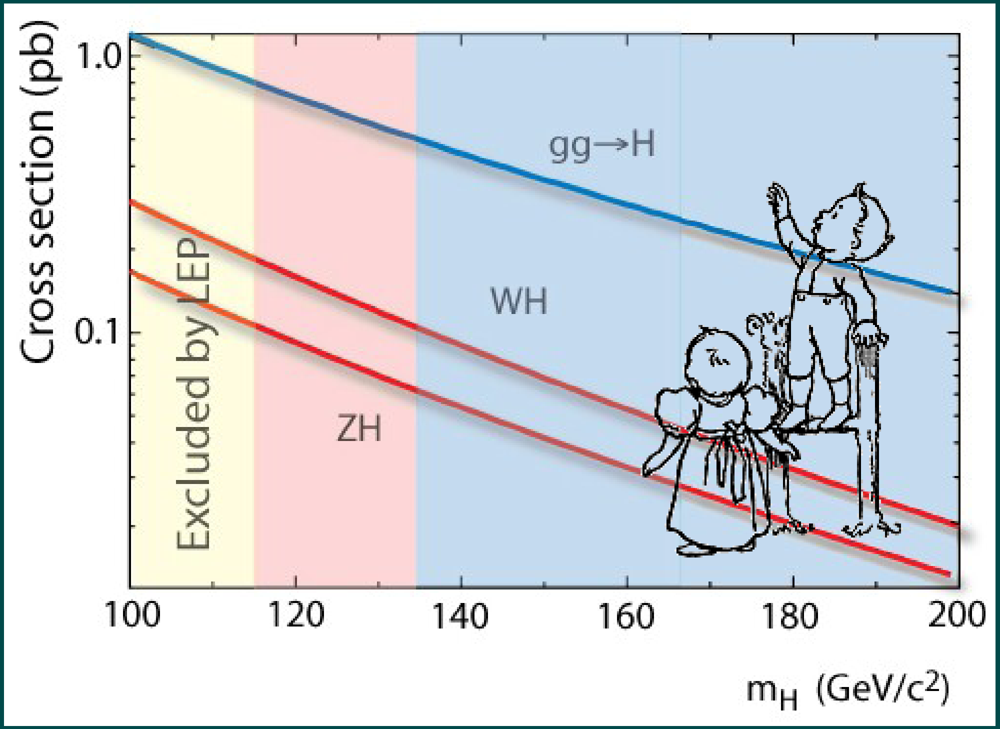


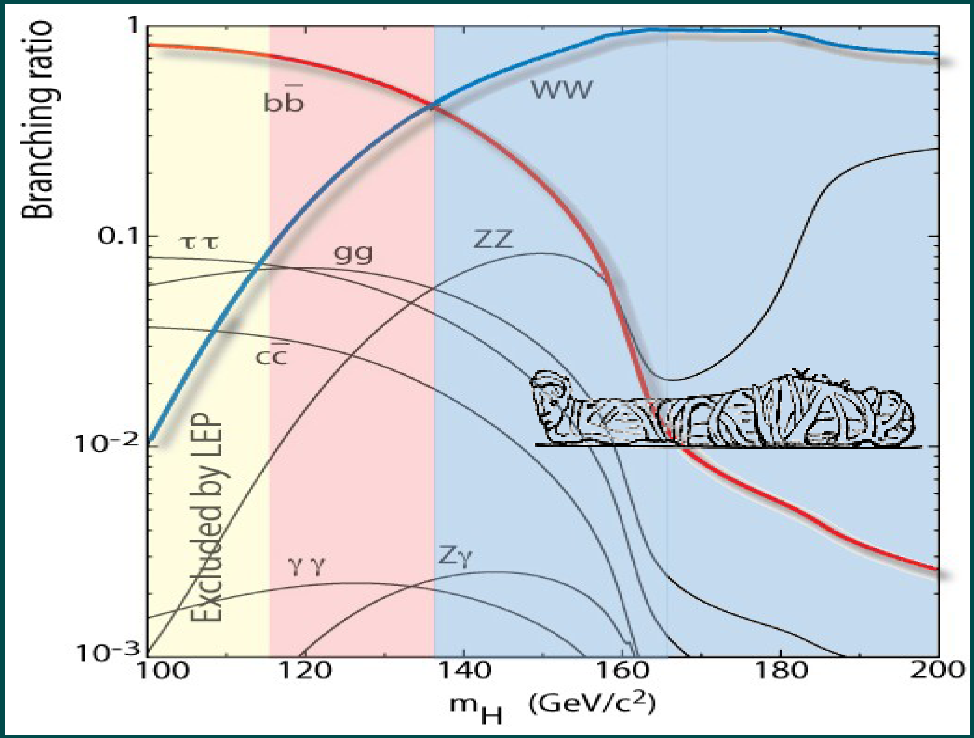
Large tracking volume

Hermetic calorimetry,
μ coverage



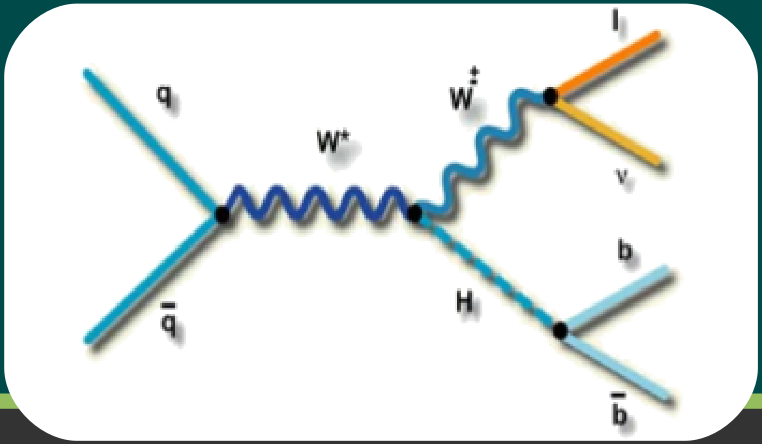
Primary Production/Decay Mechanisms



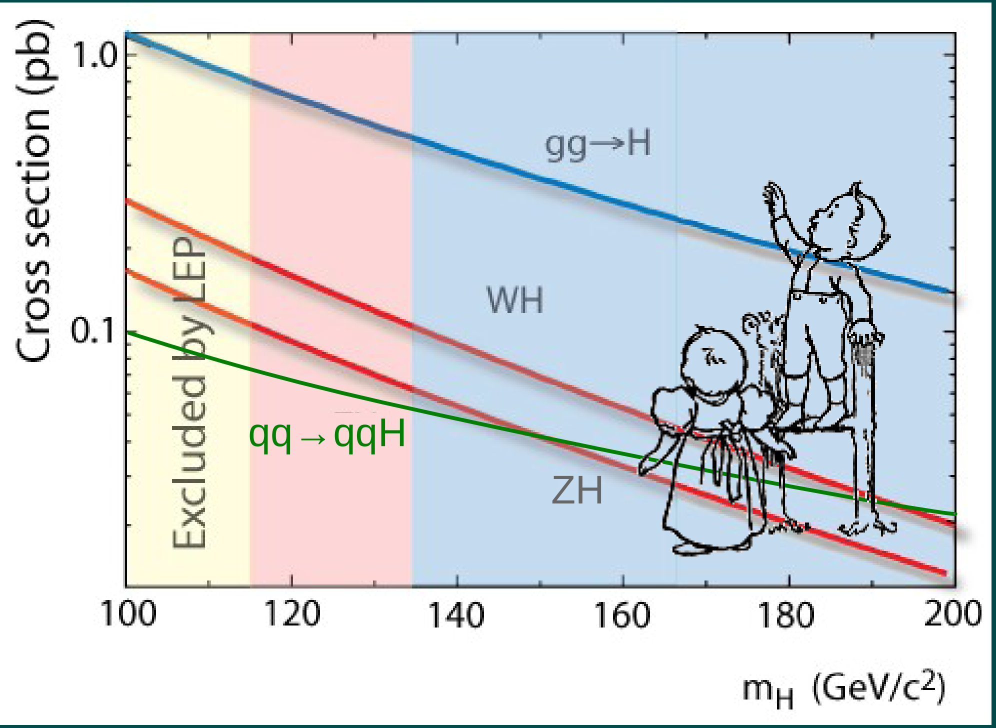


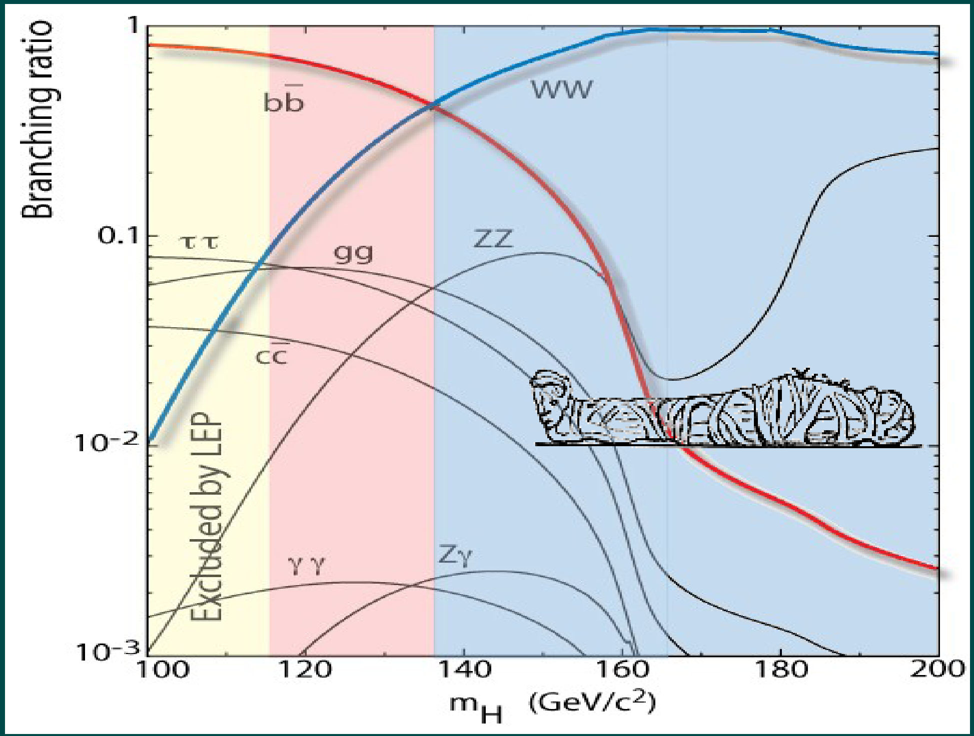
Best chance: Require W/Z bosons in final state to avoid QCD-produced $b\bar{b}$ background

At low masses (M_H<135 GeV) $b\bar{b}$ channel produced by Higgs-Strahlung (0.5-0.03 pb)



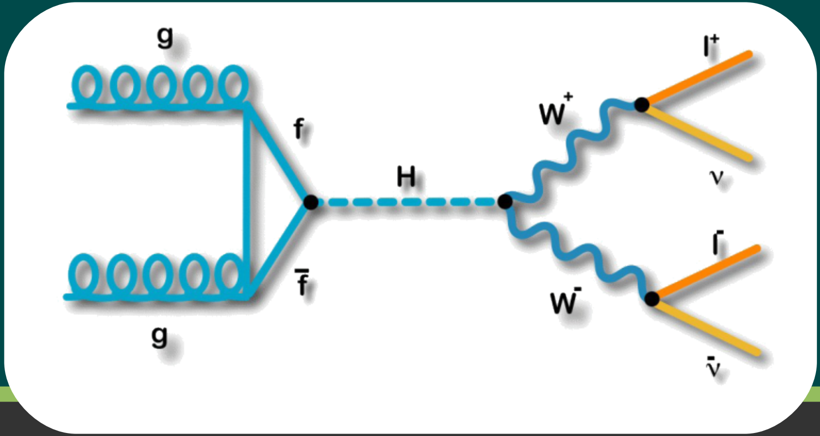
Primary Production/Decay Mechanisms





Best chance: Require W/Z bosons in final state to avoid QCD-produced $b\bar{b}$ background

At high masses (MH>135 GeV) W W channel produced by gg fusion (1.8 – 0.2 pb)



$\frac{\text{background}}{\text{Higgs}}$ ~10^9

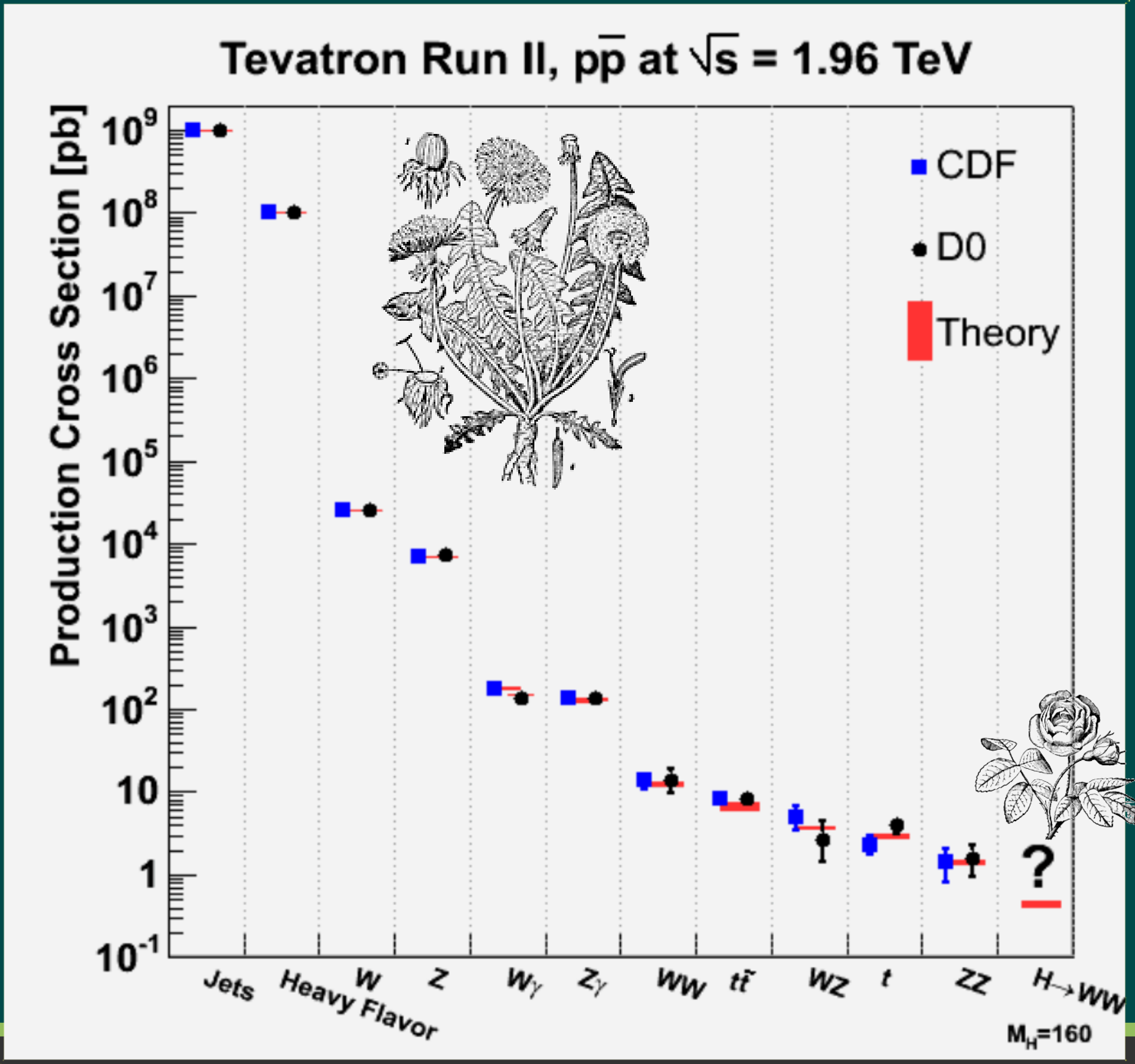
Background Rates

Typical Higgs σ x BR < 1pb

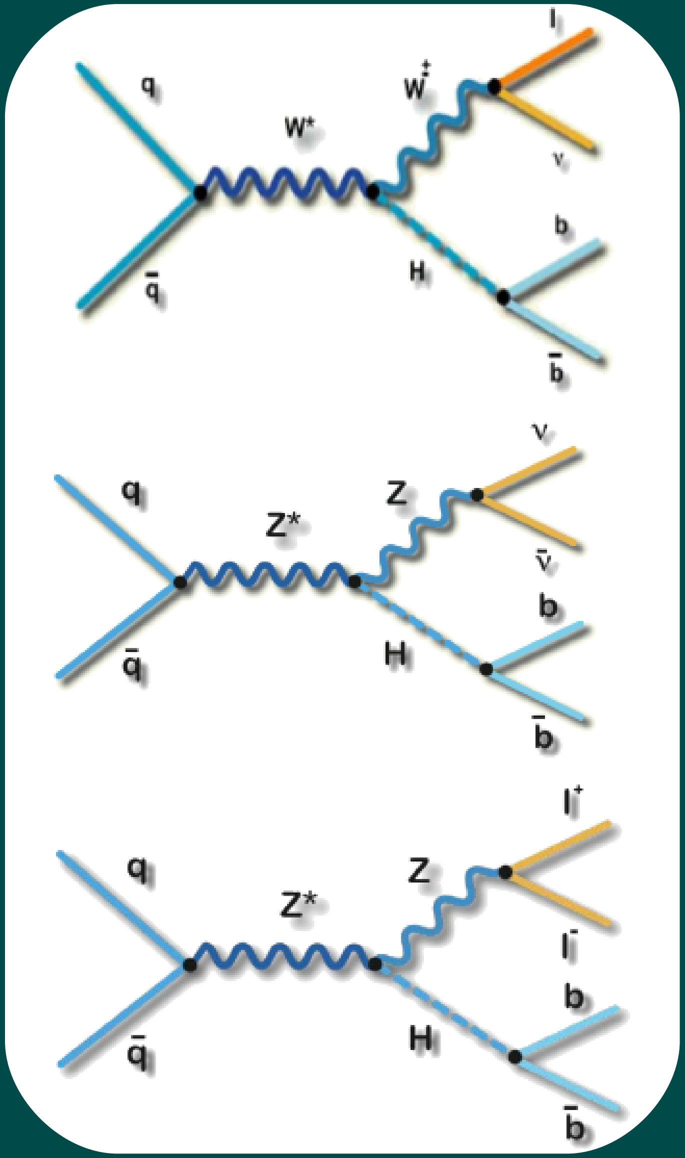
All important SM background processes measured:

- W/Z+jets (including HF),
- single and double top,
- dibosons (WW,WZ,ZZ)

Final benchmark process before reaching Higgs:
WZ/ZZ→W/Z(Z→$b\bar{b}$)
hopefully coming soon...



Favored Channels for Low-Mass Searches



Observables

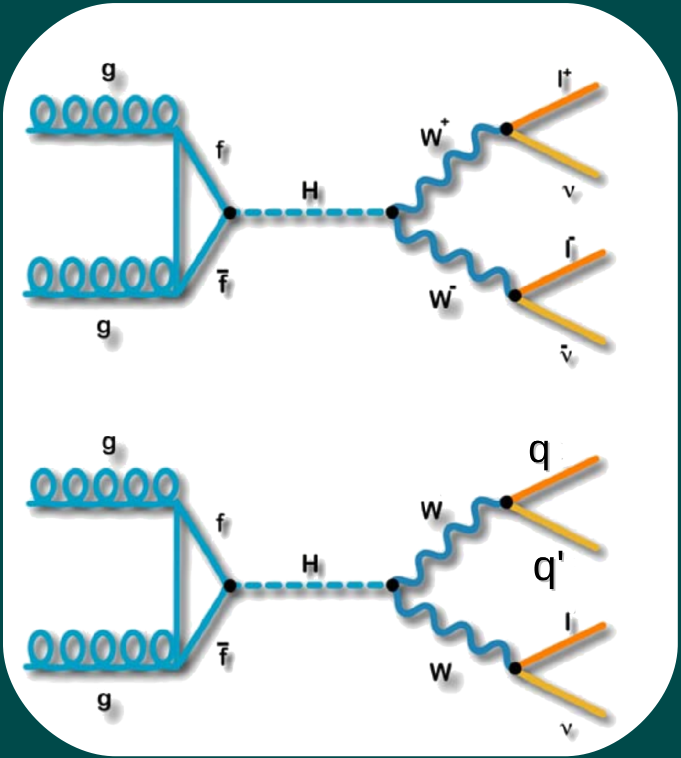
Charged leptons: $e^{\pm}$ $\mu^{\pm}$ ($\tau^{\pm}$ or jets)

Neutrinos: Missing Transverse Energy (MET) and always b-quarks

n.b. These signatures overlap if a lepton fails detection

M_H>135 GeV

Favored Channels for High-Mass Searches



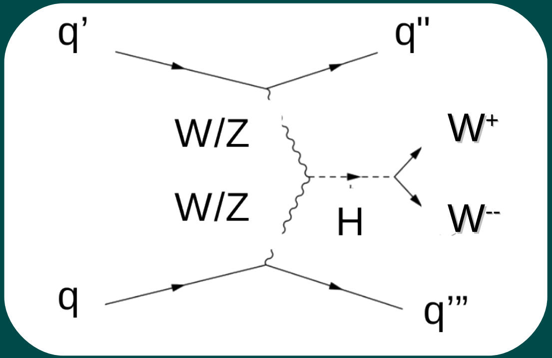
Observables

Opposite sign (OS) charged leptons and MET

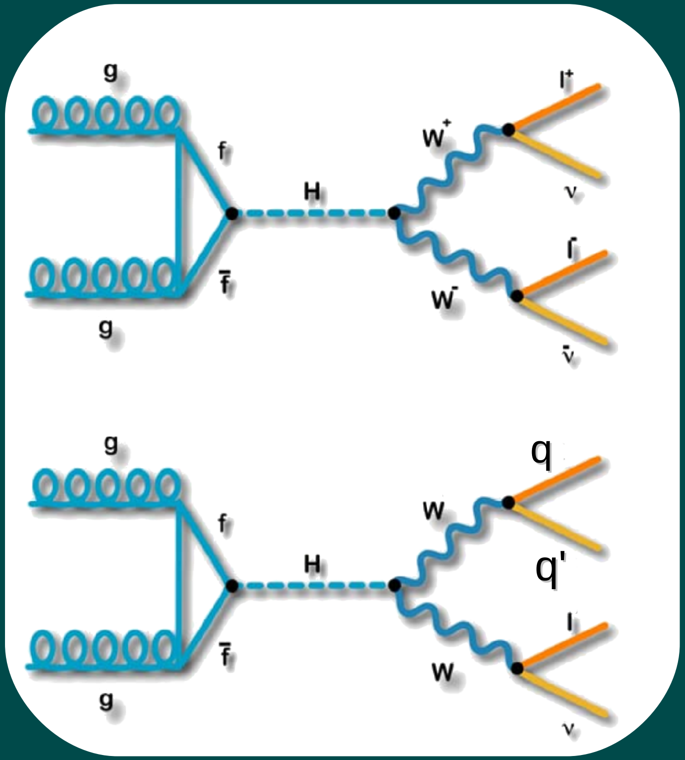
charged lepton + MET + jet-pair

g-g fusion enhanced for > 3 generations of fermions

Typically also consider vector-boson fusion (VBF) process. ~10% additional contribution in Tevatron high-mass searches



Favored Channels for High-Mass Searches



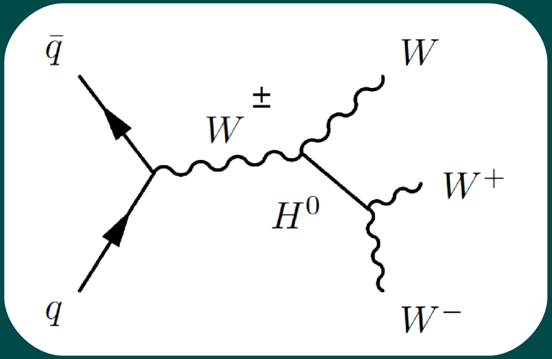
<u>Observables</u>

Opposite sign (OS) charged leptons and MET

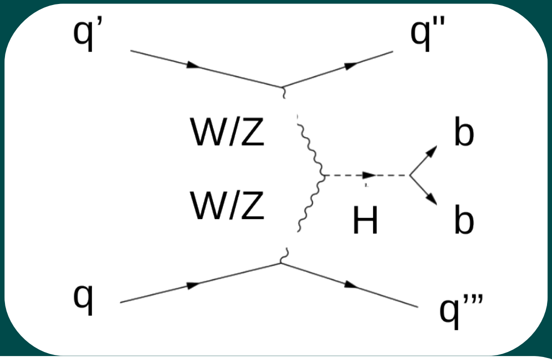
charged lepton + MET + jet-pair

g-g fusion enhanced for > 3 generations of fermions

For intermediate masses:
Higgs-Strahlung w/ $H \rightarrow W^+W^-$
$\rightarrow W^\pm(W^+W^-) \rightarrow l^\pm(l^+l^-$ or $l^\pm jj)$
consider like-sign lepton-pair + jets or trileptons

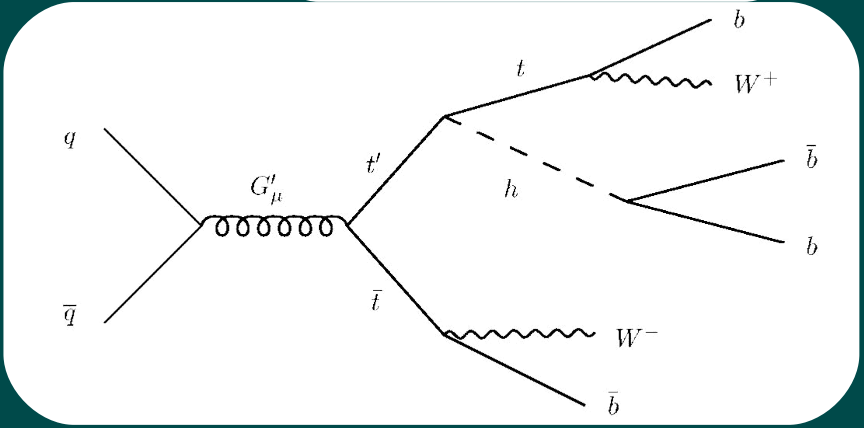


Additional Channels Considered



VBF $q_1q_2 \to W(V^*V^*)q_3q_4 \to Hq_3q_4$ (tagged by 2 jets)
~ 2 x smaller than Higgs-Strahlung – still non negligible

Smaller cross section – but contributing to the limits



Associated production with a top-quark-pair
$g \to t^*t \to Ht\bar{t} \to b\bar{b}t\bar{t}$
Enhanced if g is replaced by massive $G' \to t't \to Ht\bar{t}$

H→γγ
Small BR in SM (~10^{-3})
Smaller QCD background and better mass resolution then H→bb
Enhanced (~30x, M_H~110GeV) if H doesn't decay to fermions (fermiophobic Higgs)

H→τ τ
Enhanced in MSSM by ~$\tan^2\beta$

Higgs is a testbench for various NP models.

Collecting the data

<u>Trigger</u>

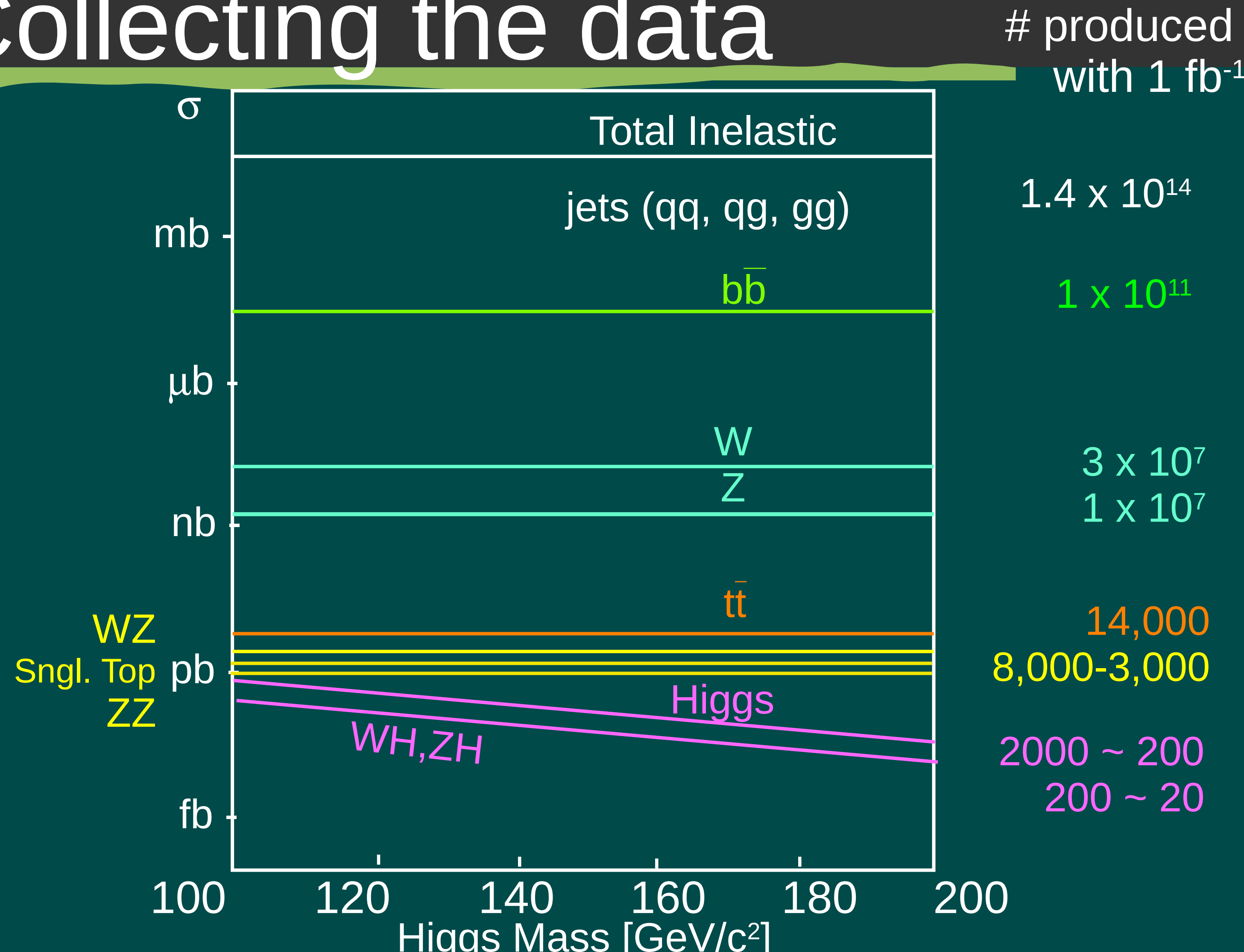
Typical Rates (DØ)

5-10 MHz interaction rate
→~2kHz (L1)
→~1kHz (L2)
→~200Hz (L3)

Primary trigger:
on high p_T e and μ
(applies to most channels)

Jet+MET triggers: modes with no charged leptons
(ex.: ZH→ννbb search)

Dedicated τ triggers



Higgs production rate
(M_H=115 GeV) ~ 55/fb-1 = 3.5×10^{-6} Hz

Search Strategies

Most advantageous production/decay mechanisms depend on M_H

Maximize acceptance by using:
* relaxed kinematic selections
* looser, more clever, ID requirements
* multiple trigger suites

Verify background models with selection criteria

Address backgrounds using multivariate techniques
* don't cut phase space w/ low signal purity => constrain background
* to enhance sensitivity in high signal purity regions

* Combine results from all modes examined, accounting for correlations between uncertainties => maximize overall sensitivity

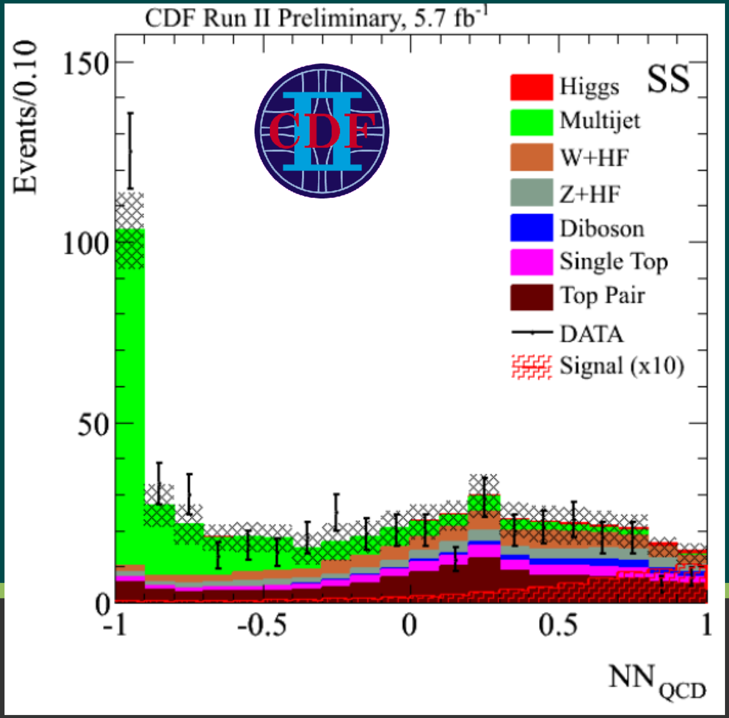
Selecting Events

Want to select region with enhanced signal, but best acceptance usually requires looser cuts

Need to demonstrate good understanding of detector/background models
EW background simulated in MC w/ NLO(NNLO) cross sections
(W/Z+jets, WZ+HF, ttbar, single-top, di-boson, ...)
Compare with data in signal depleted regions
Multijet (instrumental) background determined from data
(mis-measured energy, jets faking leptons, ...)

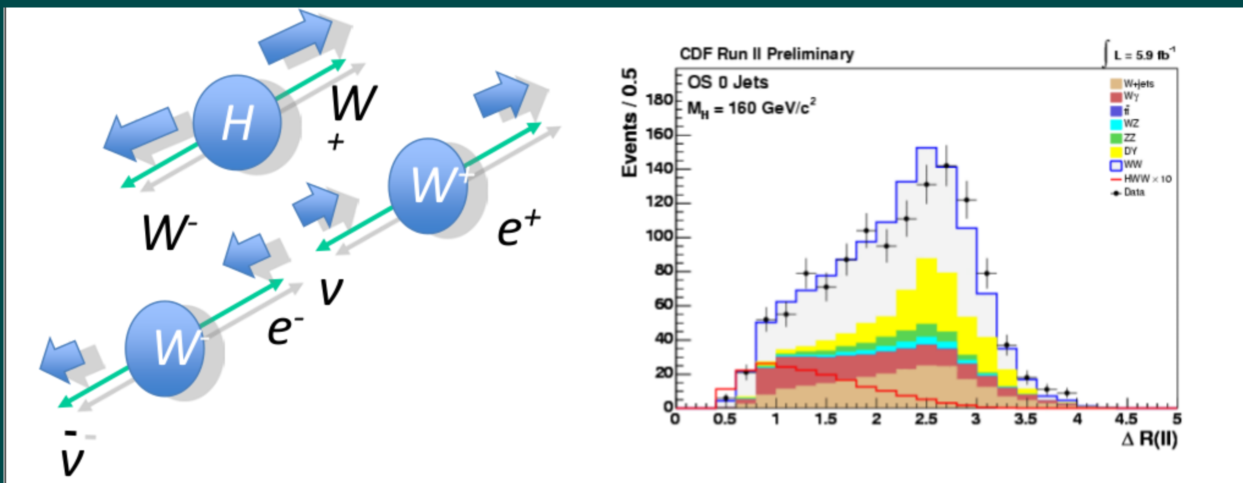
Multivariate techniques can also applicable to individual backgrounds

NN output used to separate multijet background from signal in $ZH \rightarrow llbb$ analysis



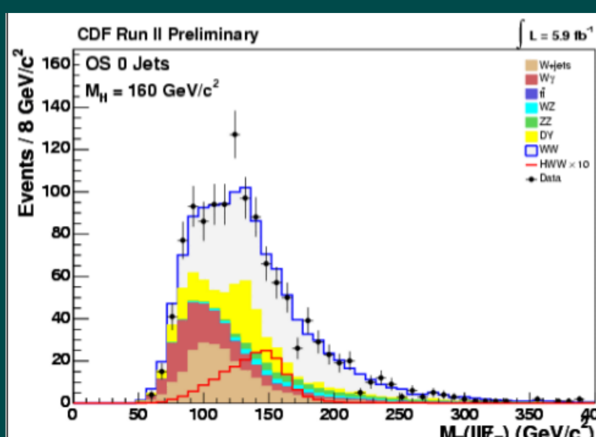
Choosing Distributions to Build Final S/B Discriminant

After event selections, choose variables sensitive to S, B differences, typically numerous (weak) classifiers exist

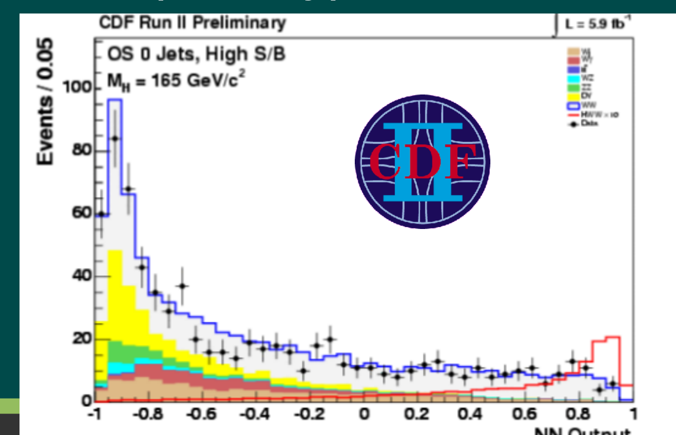


Good physics example: Charged leptons tend to align in H → WW decay due to spin 0 Higgs

Combine in multivariate analysis (MVA), reduce to (usually) 1-D classifier



Examples of inputs and outputs of NN used in gg → H → WW → eeνν

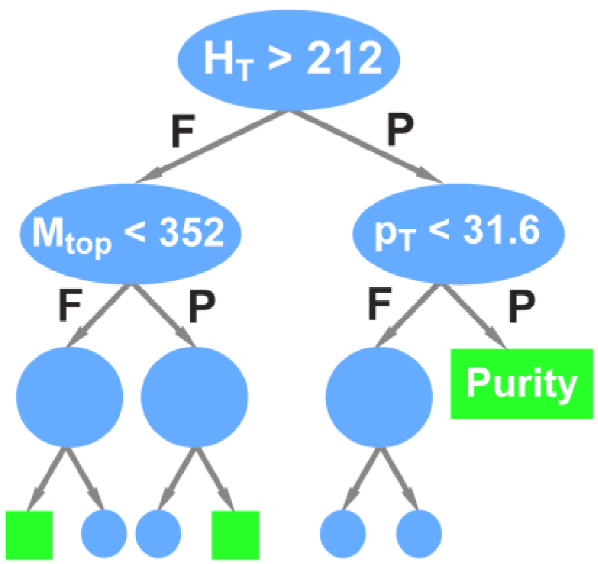


Common Multivariate Techniques

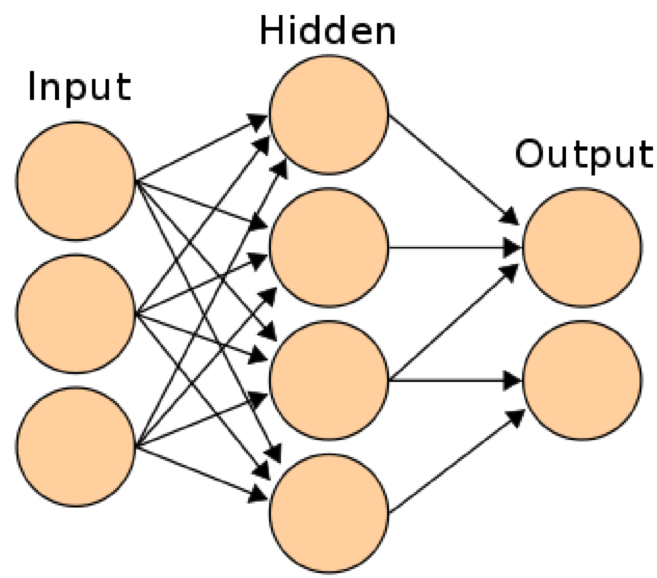
Matrix Element Method

$$P(\ell, p_{jet}) = \frac{1}{\sigma}\int d\rho_{jet}\, dp_{\nu} \sum \phi_4 |M(p_\ell)^2| \frac{f(q_1)f(q_2)}{|q_1||q_2|} W_{jet}(E_{parton}, E_{jet})$$

(Boosted) Decision Trees

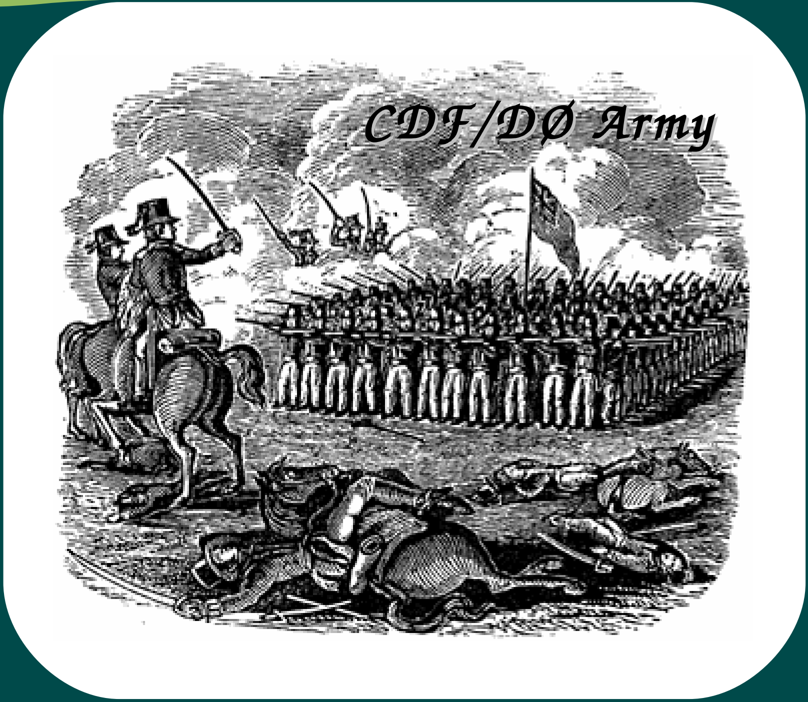


Neural Networks



Divide and Conquer

Create sub-channels as is feasible
Each will have different makeup of S/B
Tune multivariate discriminants on different mixes of signal and background contributions



Examples

CDF $H \rightarrow WW$:

- 2x(0,1 jets)
- 2+ jets
- low m_{ll}
- $e + \tau_{had}$
- $\mu + \tau_{had}$

DØ $\tau\tau$+2j:

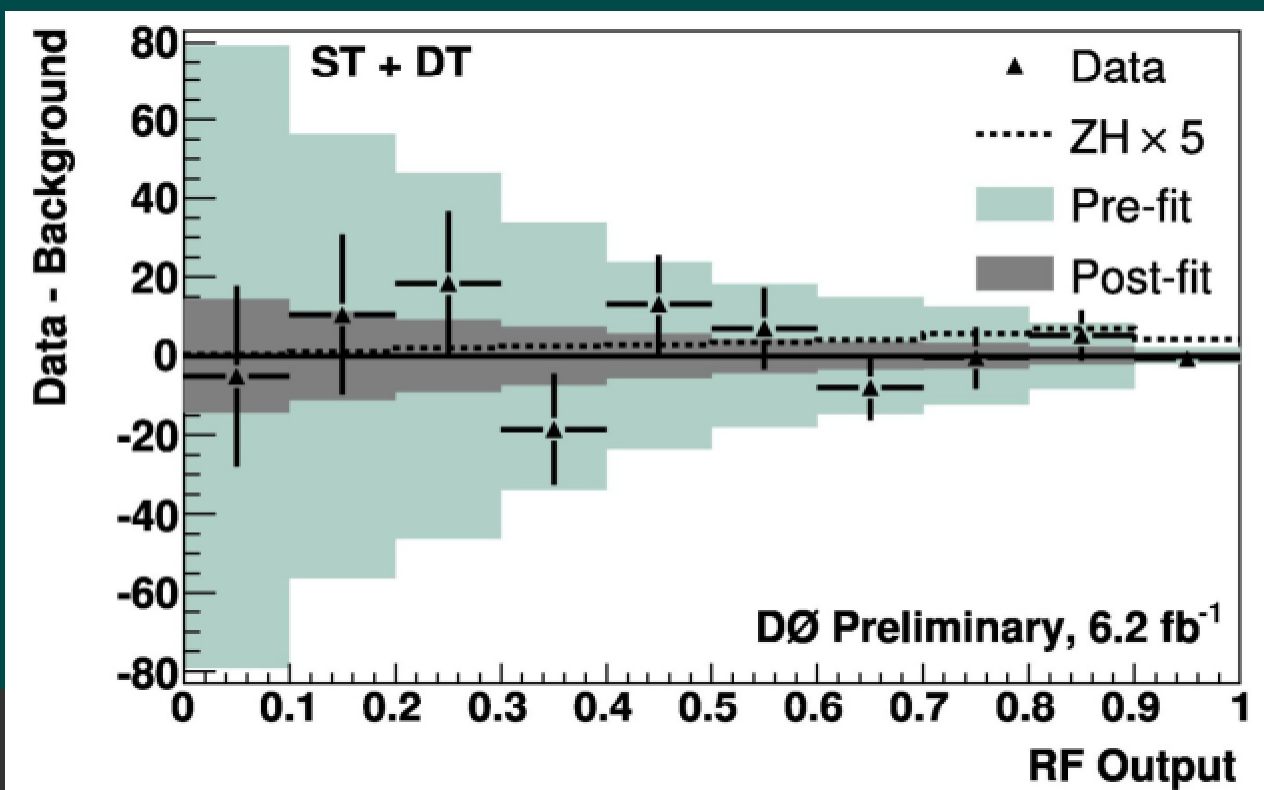
Mass region	Signals
low	GGFH$\tau\tau$, VH$\tau\tau$, VBFH$\tau\tau$
Intermediate	GGFH$\tau\tau$, GGFH$_{WW}$, VH$\tau\tau$, VH$_{WW}$
High	GGFH$_{WW}$, VH$_{WW}$, VBFH$_{WW}$

Systematic Uncertainties in Final Discriminant

can be larger than signals, but can constrained using backgd-dominated data

* p-pbar cross section used in luminosity calculation 3.8%
* Luminosity mis-measurement 4.5%
* Signal and background cross sections including (HF) k-factors, PDF's 6-30%
* Object reconstruction and ID efficiencies (leptons, jets, b-tagging) 1-10%
* Energy scale correction, resolutions 1-7%
* …

Correlations between experiments/channels/bins affect shapes/normalizations



Bkgd subtracted data of final discriminant, ZH→llbb analysis.

Systematic uncertainties shown before after constraints from fitting to data

Setting Limits in the Absence of ^observed Signal

In the absence of a signal-like excess above expected background, set upper limits on the SM Higgs production CS @95% CL

Based on binned Poisson-likelihoods of final MVA distributions

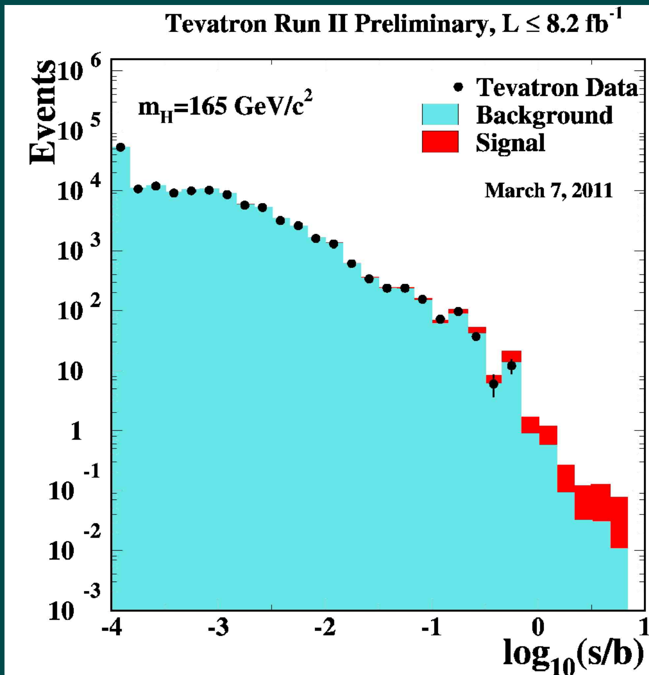
CDF: Bayesian posterior probability (w/ integration over nuisance params.)

DØ: CLs method, ratio of confidence levels s+b and b-only LLR distributions (w/ fitting of nuisance parameters to data)

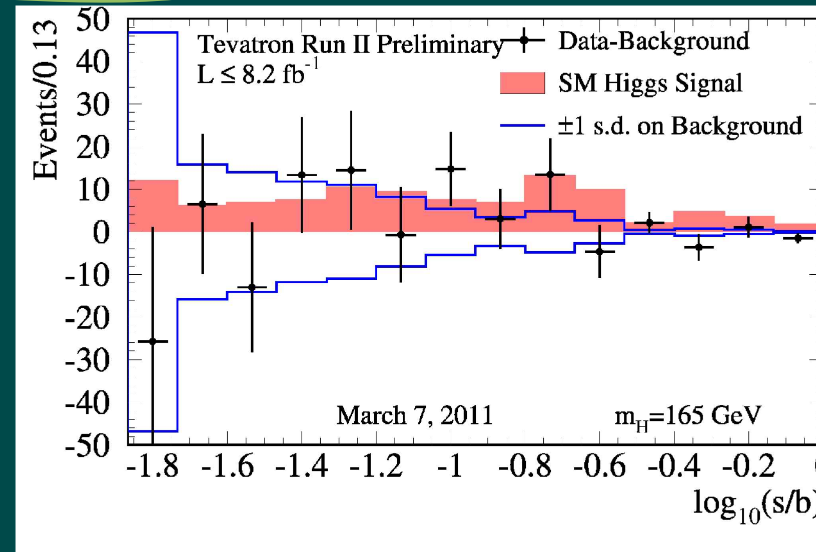
Expected limits are calculated using background-only pseudo-experiments. The methods give numerically similar results.

Express upper limits in units of SM =ross section: R, R=1 is 95% exclusion
- Calculated at NNLO in QCD w/ NNLL soft gluon resummation
- Includes 2-loop EW effects
- Running b-quark mass

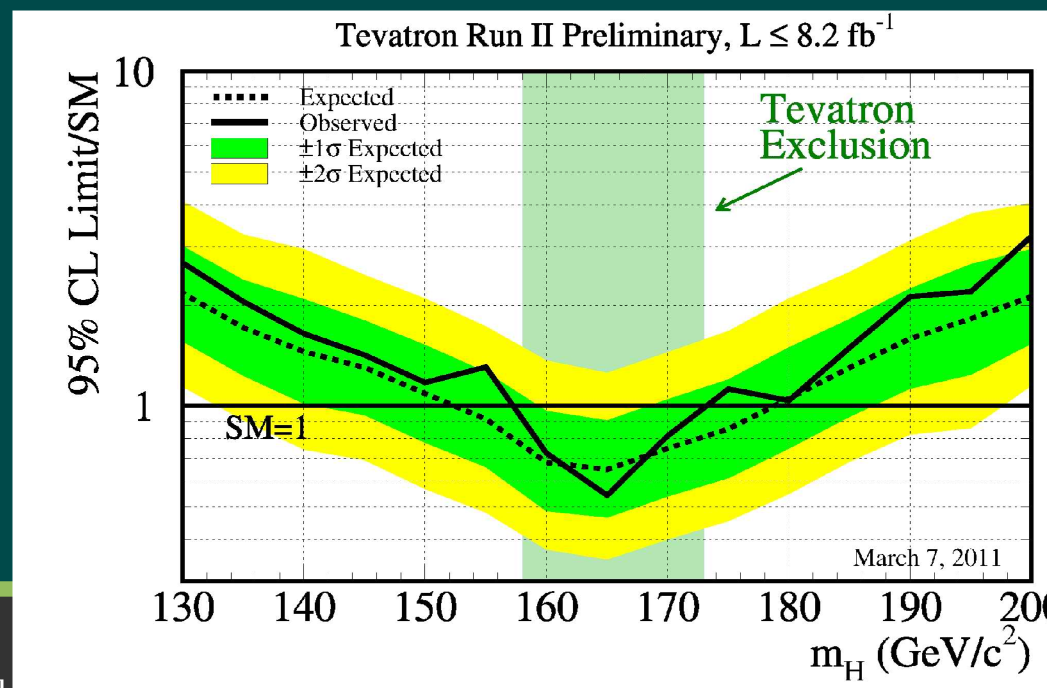
Combined Limits Reported for Spring 2011



Inputs

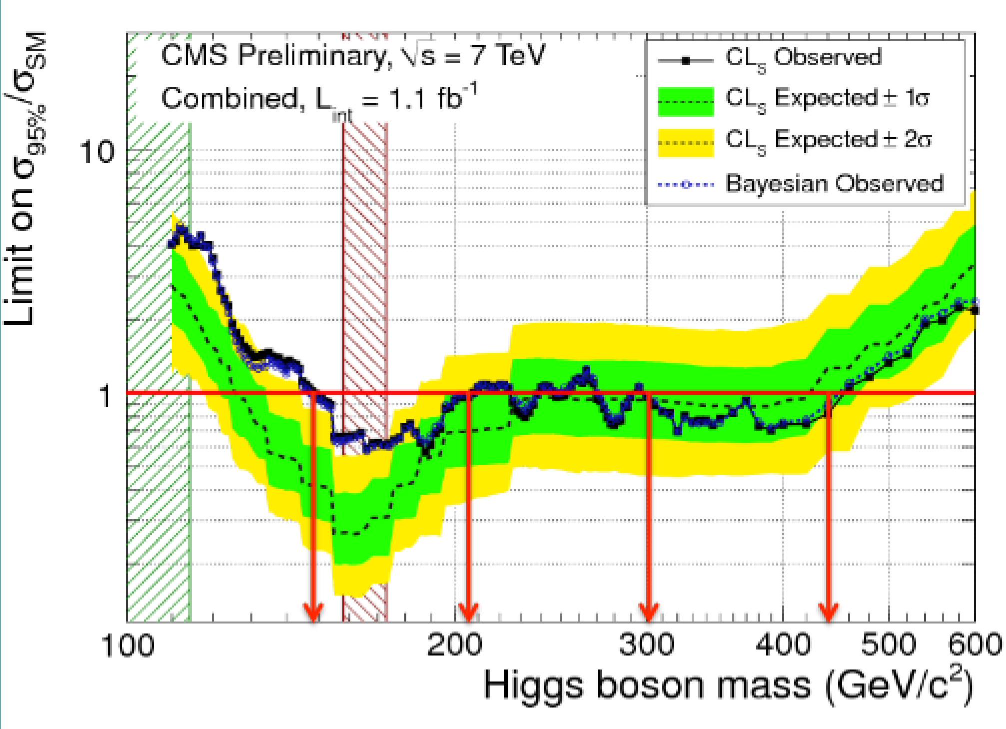


Exclusion
Exp. 153 – 179 GeV
Obs. 158 – 173 GeV



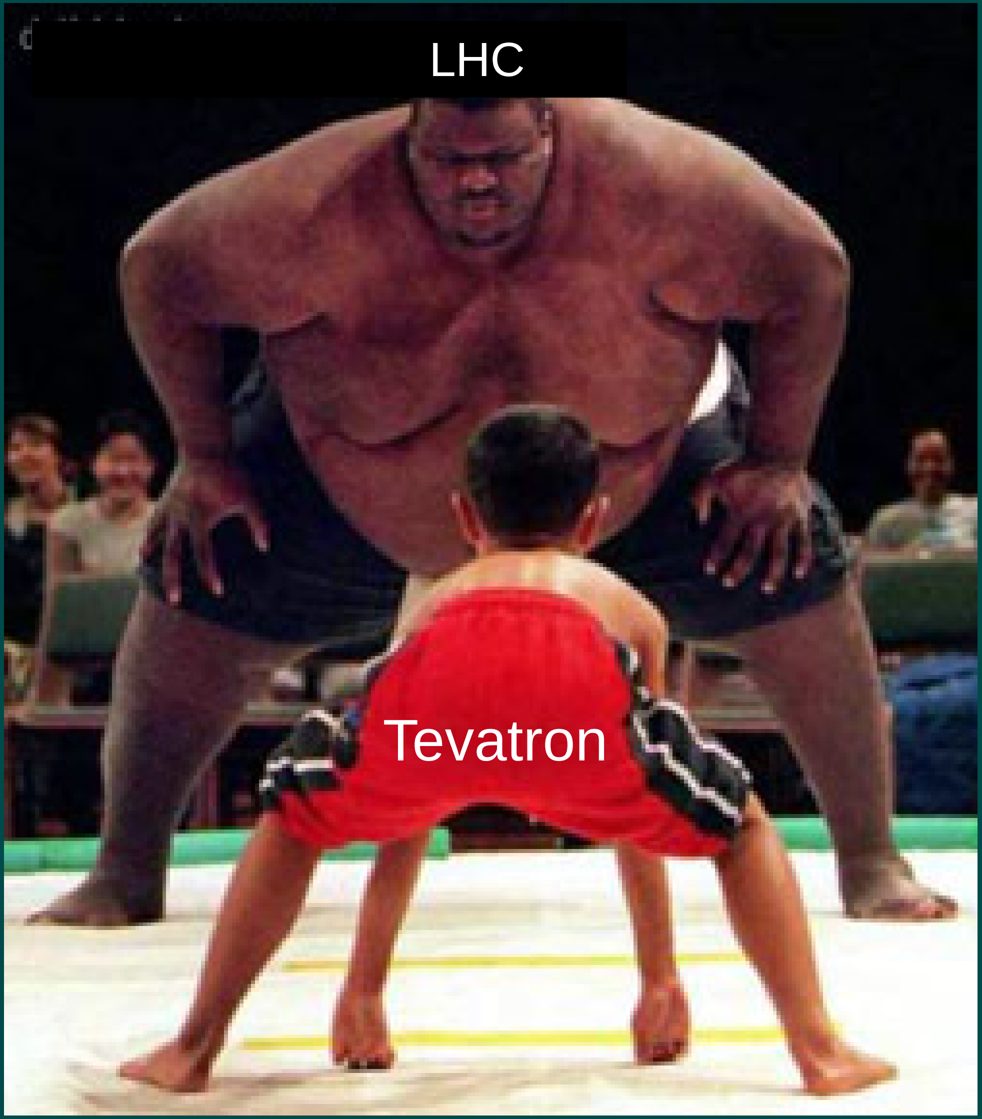
New CMS Result (this week)

channel	mass range (GeV/c^2)	luminosity (fb^{-1})
$H \to \gamma\gamma$	110-140	1.1
$H \to \tau\tau$	110-140	1.1
$H \to WW \to 2\ell 2\nu$	110-600	1.1
$H \to ZZ \to 4\ell$	110-600	1.1
$H \to ZZ \to 2\ell 2\nu$	250-600	1.1
$H \to ZZ \to 2\ell 2q$	226-600	1.0
TOTAL (6)	**110-600**	**1.0-1.1**

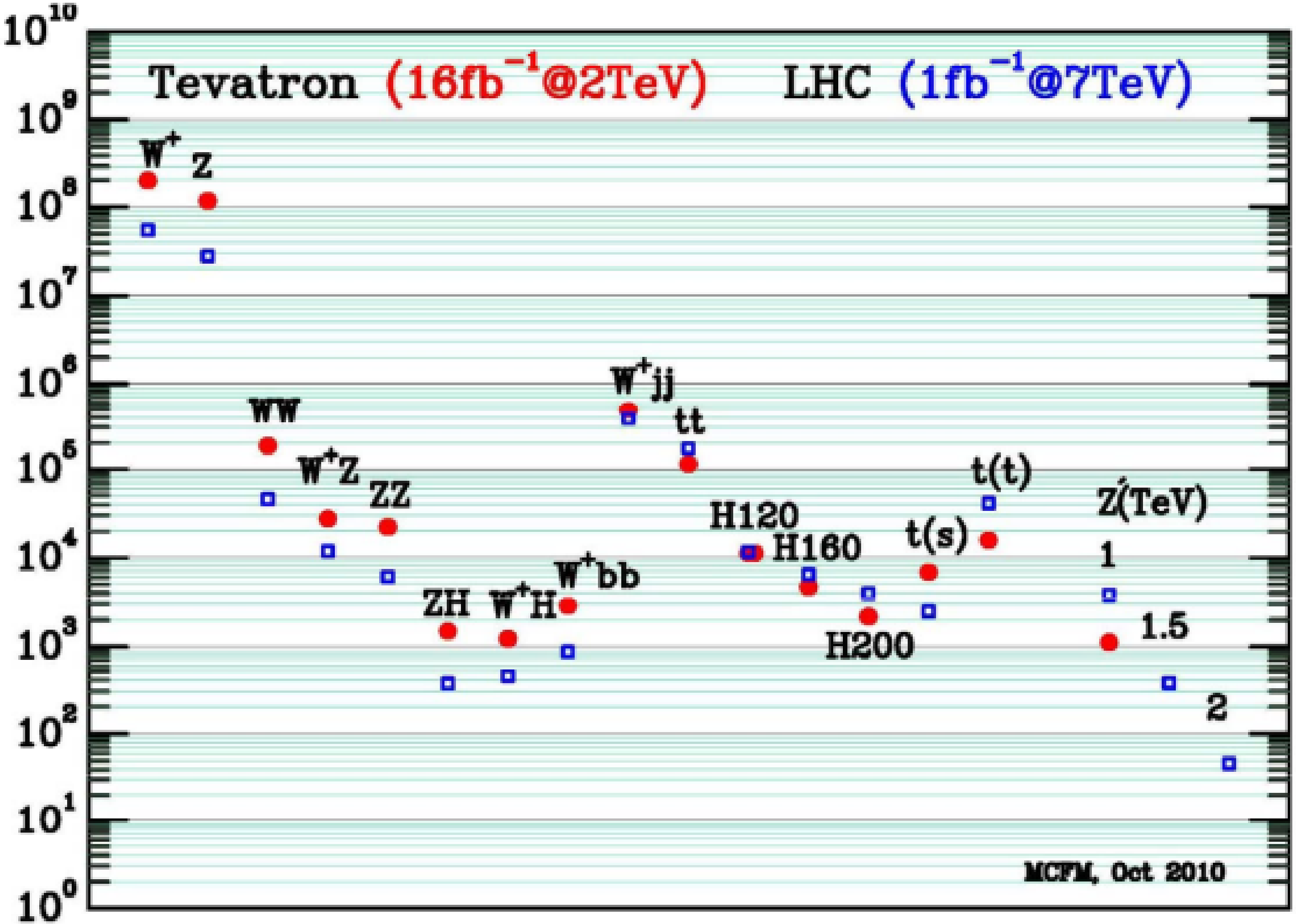


Excluded (GeV)
[149---206] ...[300---440]
and
3 short segments in between

LHC has definitively taken the lead at high mass...

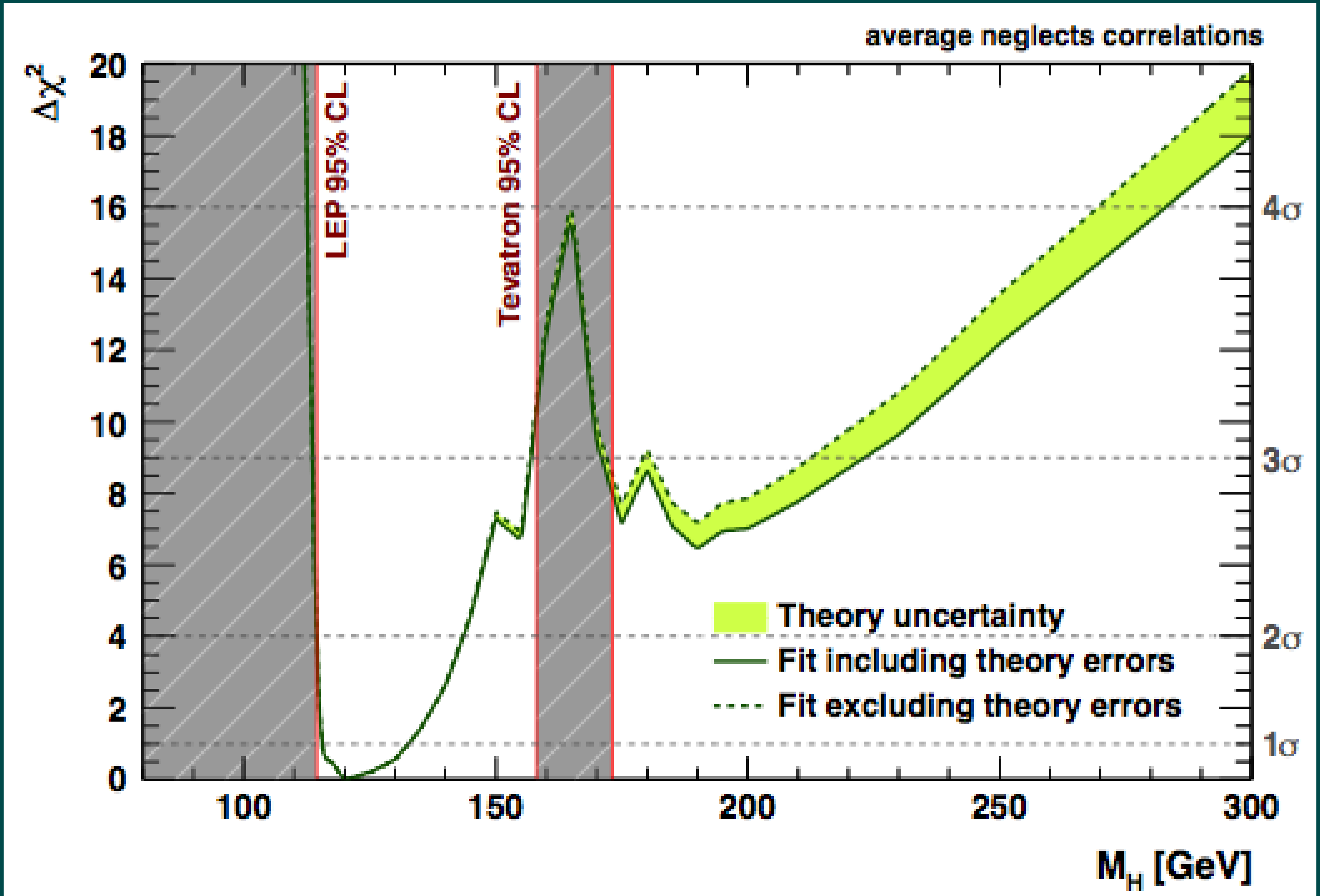

LHC
Tevatron

Tevatron and LHC - Complementarity



High yields of low mass states, including Higgs, at the Tevatron complement large cross sections of heavy objects at the LHC

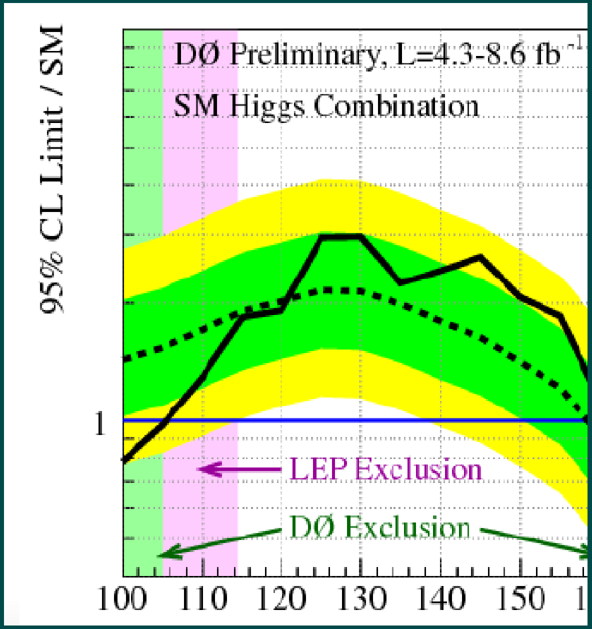
Gfitter results



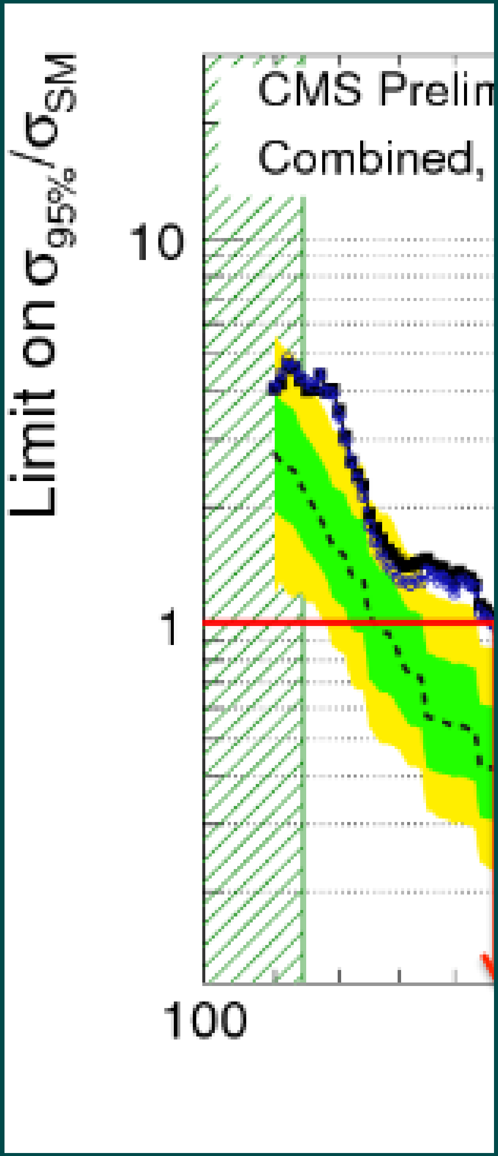
Compare sensitivities near LEP limit

Both from this week at EPS

D-Zero



CMS



Comparable for now. Lowest mass window will probably require at least a few fb-1 to close at the LHC.

Bottom line?

We expect to see the (SM) Higgs boson or exclude it entirely in the next couple years.

The next phase..

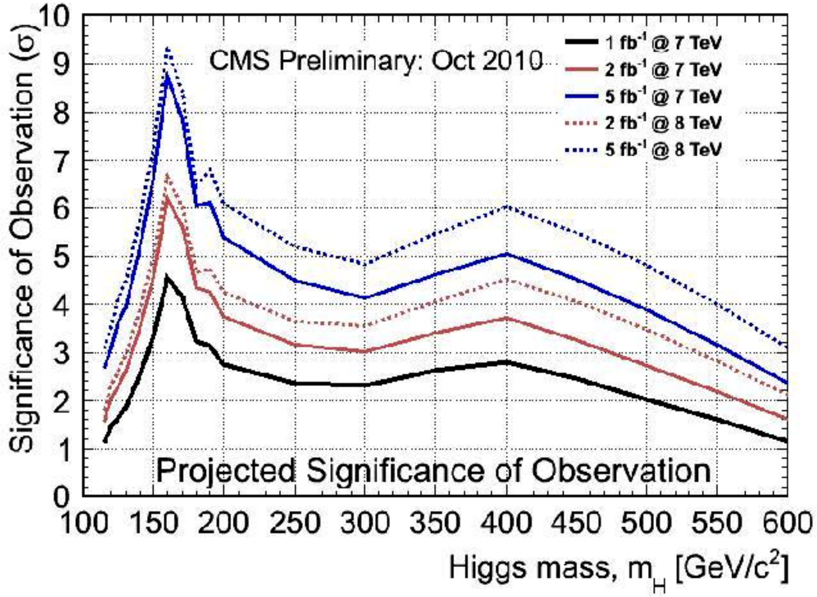
If found: Verify this is the SM Higgs or something else

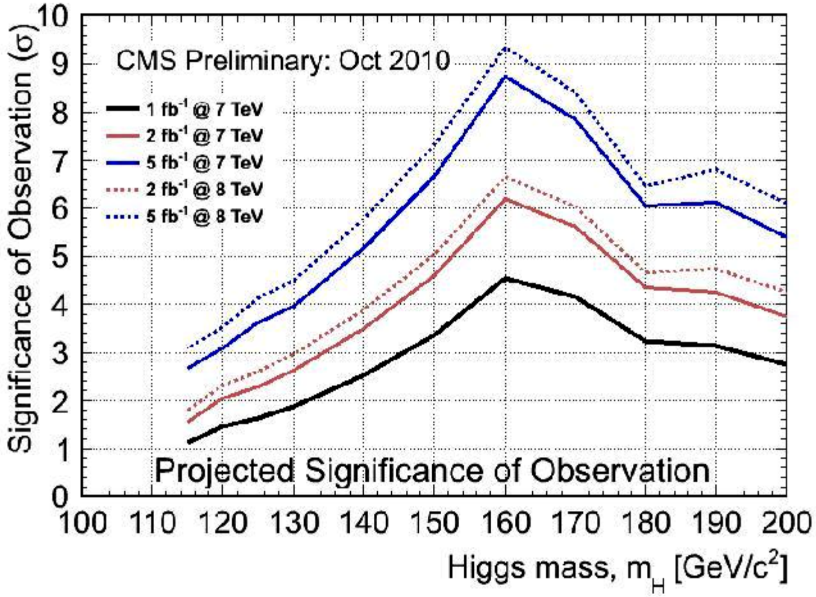
If not found: It's back to the drawing board!

Next up: H. Ngyuen will talk about some methods used to improve experimental sensitivities in Higgs (or other searches).

Backup

SM Higgs Observation Sensitivity





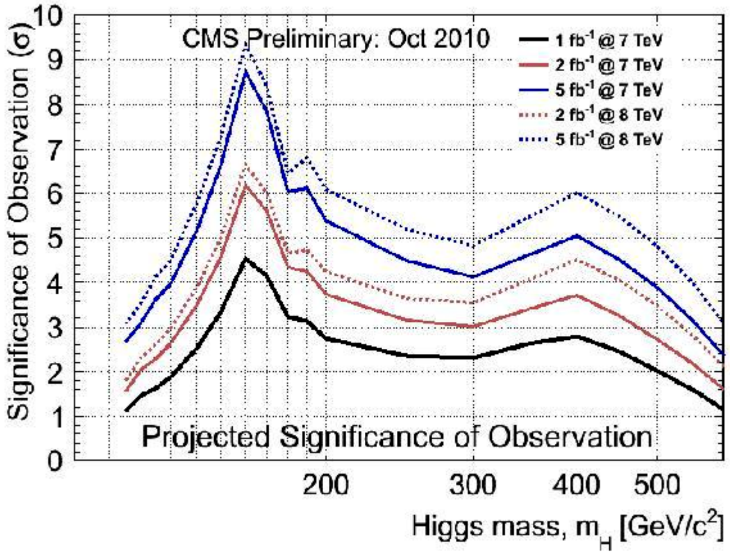
<u>7 TeV, 1 fb-1</u>

"LHC" (2 x CMS) projected 3σ sensitivity: MH = 135-475 GeV

<u>8 TeV, 5 fb-1</u>

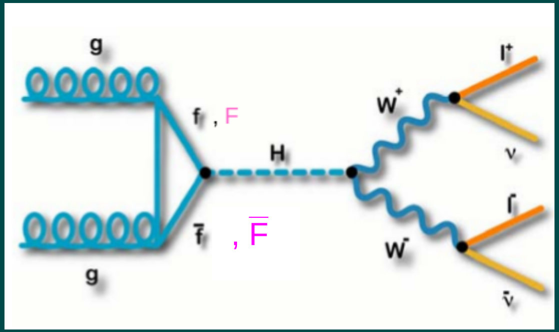
CMS projected 3σ sensitivity:

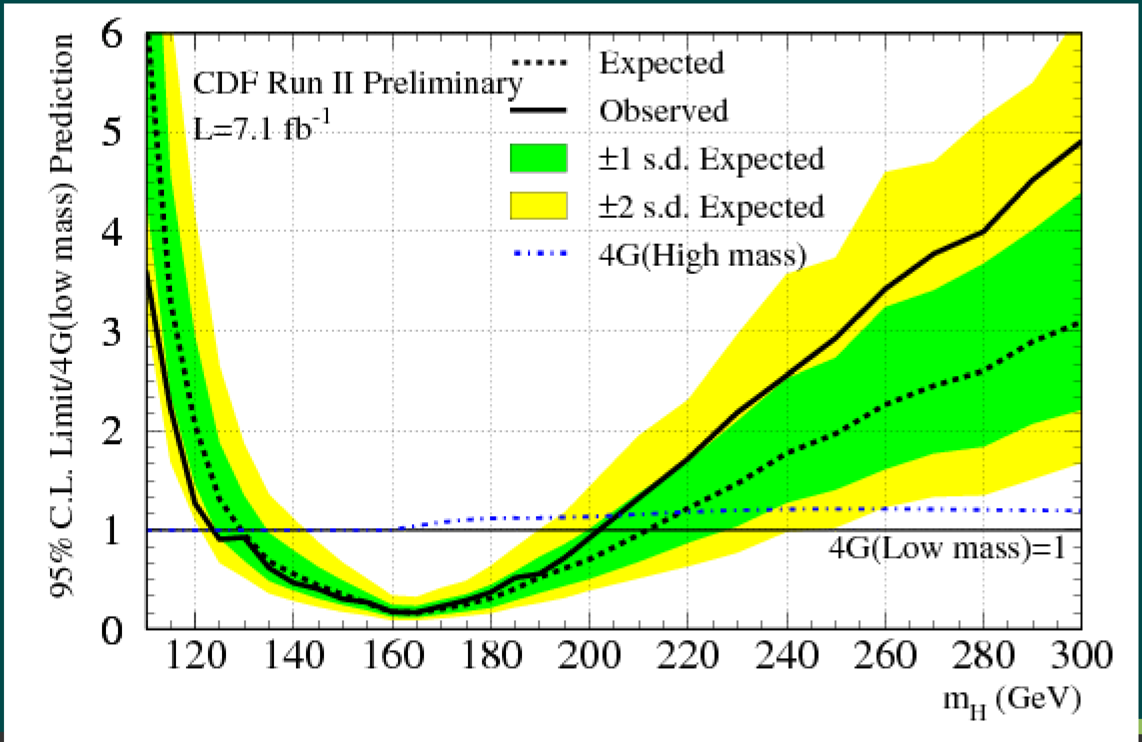
from LEP limit (114) up to 600 GeV



4^{th} generation scenario

H→WW* is sensitive to > 3 SM generations
- add'l heavy fermion (F) loops in the dominant gg-fusion process enhances Higgs production cross section ~9 times
- the WW* decay is best suited to study the gg-fusion production (bb and gg final states are swamped by the QCD background)





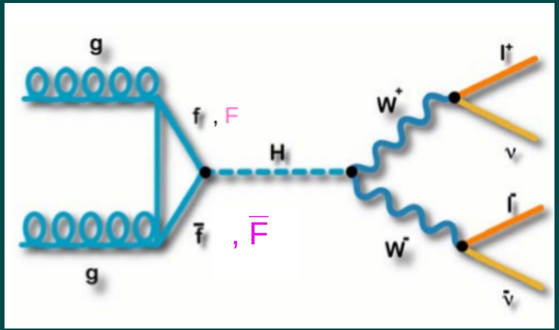
New CDF result with combined WW channel

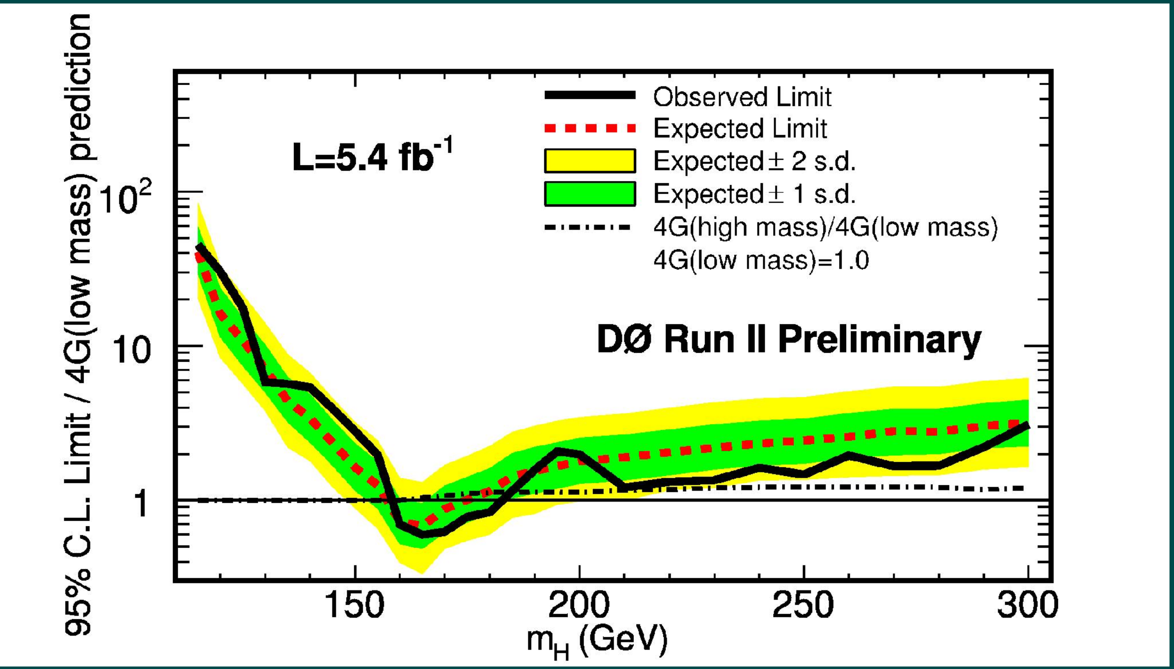
excludes at the 95% C.L. a SM-like Higgs boson with a mass in the range 124 − 202 GeV

Comparible with previous Tevatron combination

4^{th} generation scenario

H→WW* is sensitive to > 3 SM generations
- add'l heavy fermion (F) loops in the dominant gg-fusion process enhances Higgs production cross section ~9 times
- the WW* decay is best suited to study the gg-fusion production (bb and gg final states are swamped by the QCD background)





New D0 result with combined WW→lnujj channel

excludes at the 95% C.L. a SM-like Higgs boson with a mass in the range 159 − 183 GeV

Comparible with WW → lnulnu for MH>~250 GeV at fixed integrated lumi.