W Bosons and *b* Quarks at the Tevatron:
Understanding the Haystack to Help Find the Needle

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Outline

- **Particle Physics – What, Why and How**
- **The Pursuit of the Higgs**
- ***W*'s and *b*'s at the Tevatron**
- **Implications and Future**

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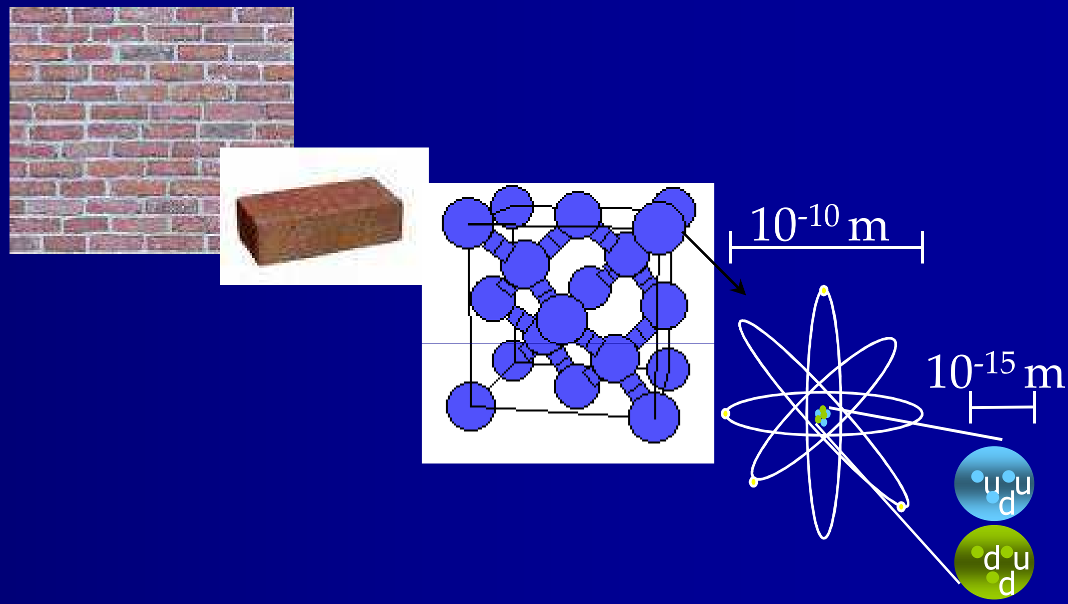
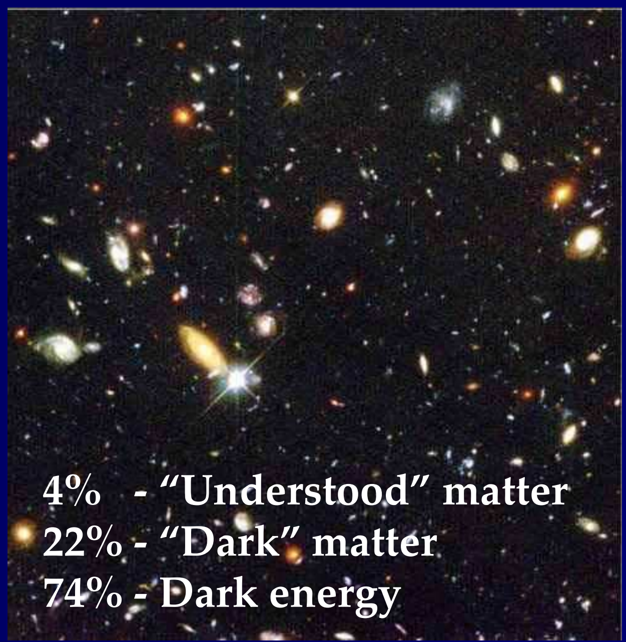
What is Particle Physics?

Particle physics is the study of the fundamental building blocks of the universe and how those building blocks interact.

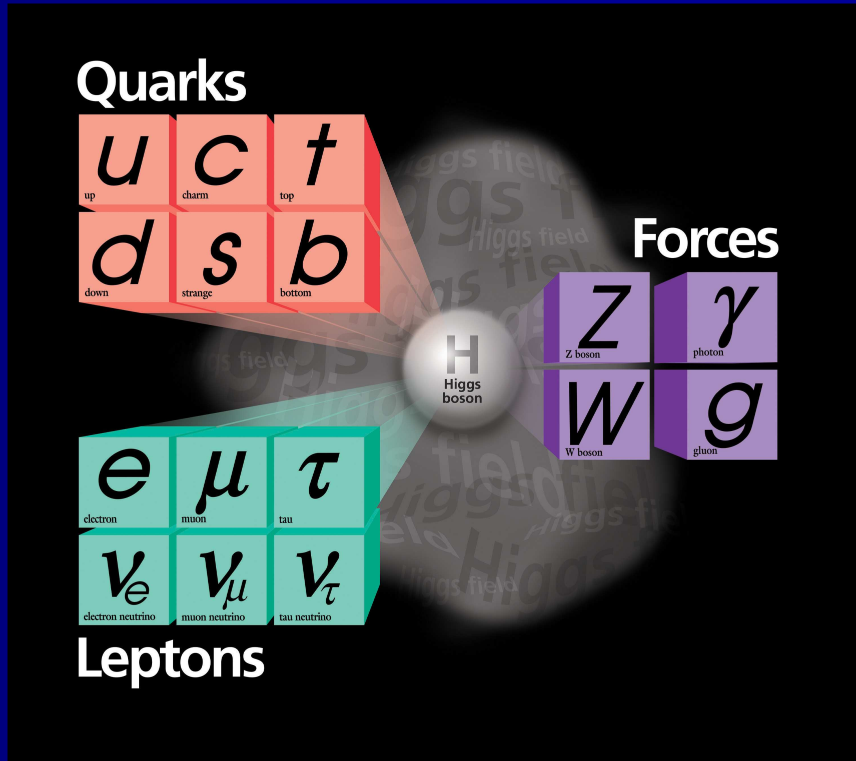
What is the world made of?





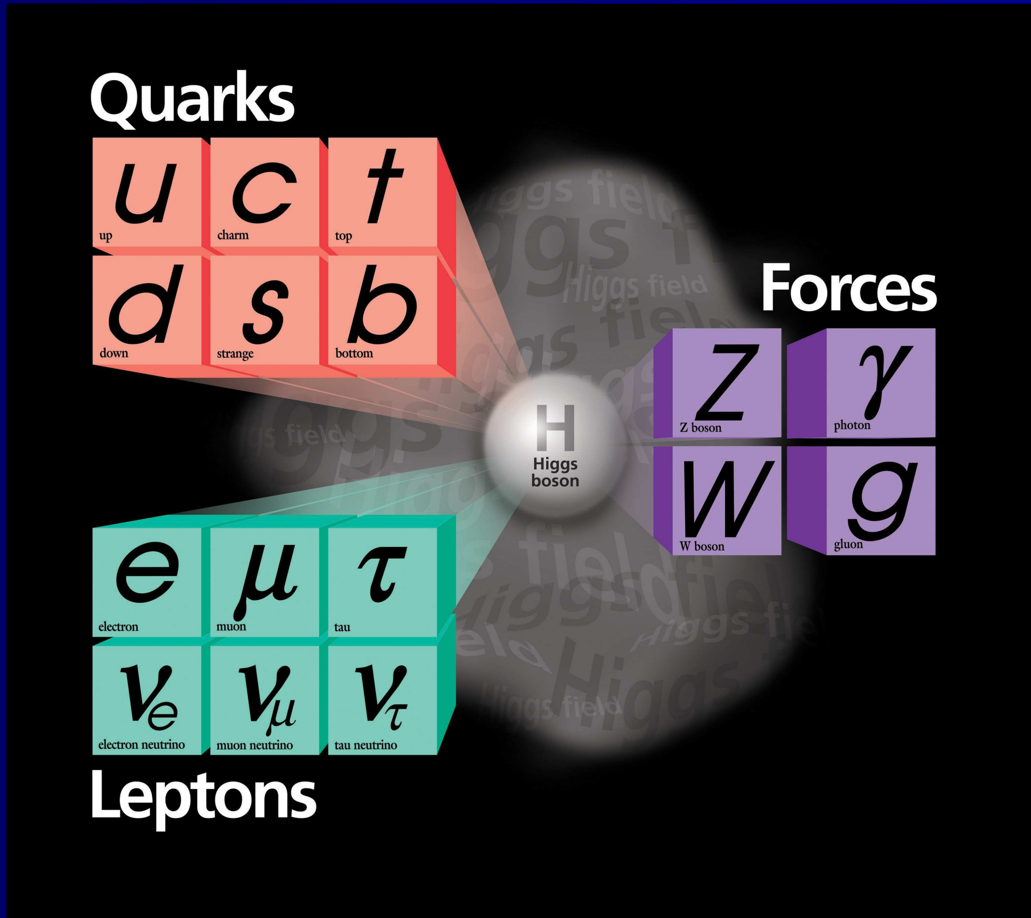
Relevant at the smallest and largest scales.

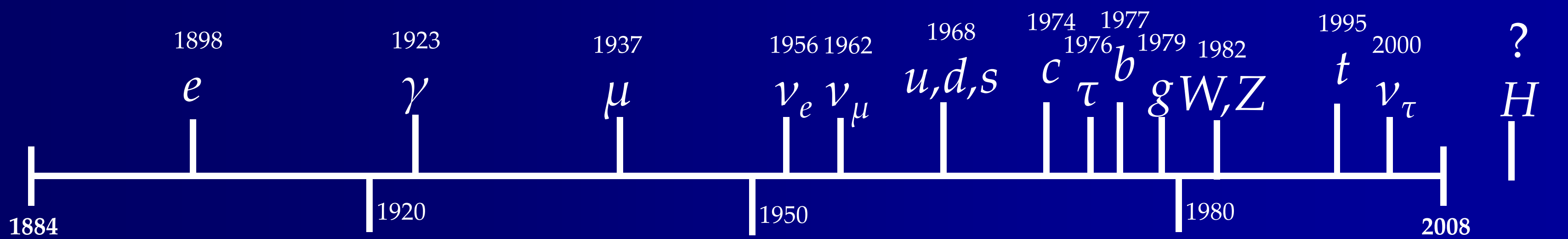
We've Come Quite A Long Way



- **First particle physicist:**
  - Empedocles ~450 BC
- **Picture today:**
  - Matter particles and force carriers
  - Highly successful "standard model"

Timeline of Discoveries





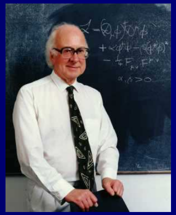
The Electromagnetic and Weak Forces

Feature:

- Electromagnetic and Weak forces are unified

Force carriers:

- Photon massless
- *W, Z* very massive
- **Why?**

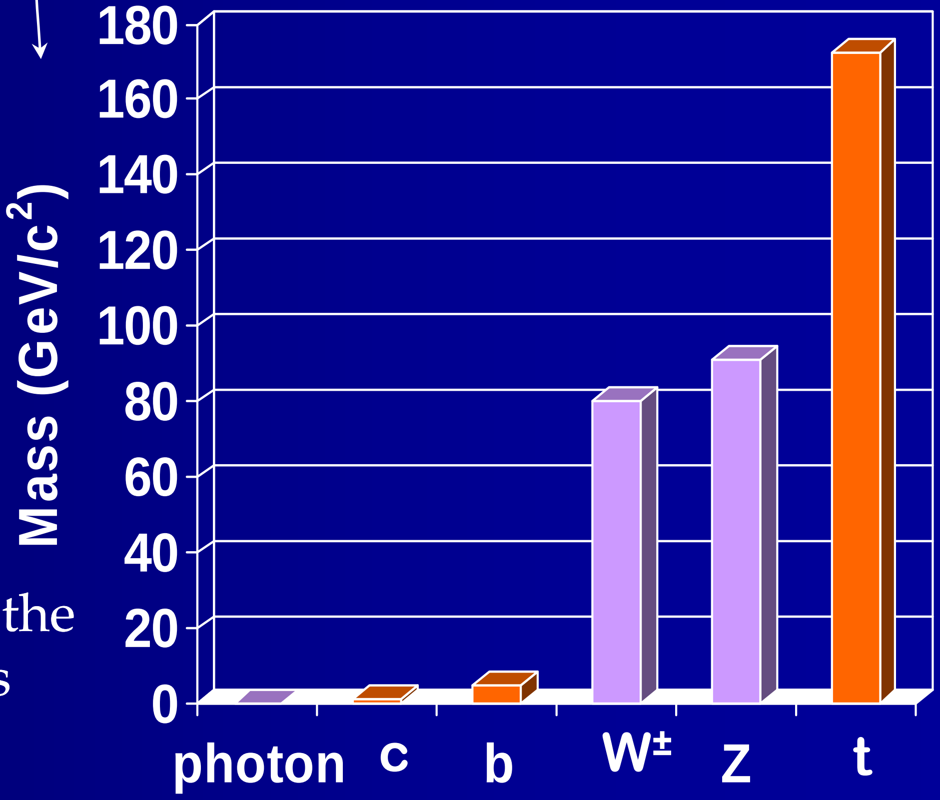


Higgs Mechanism:

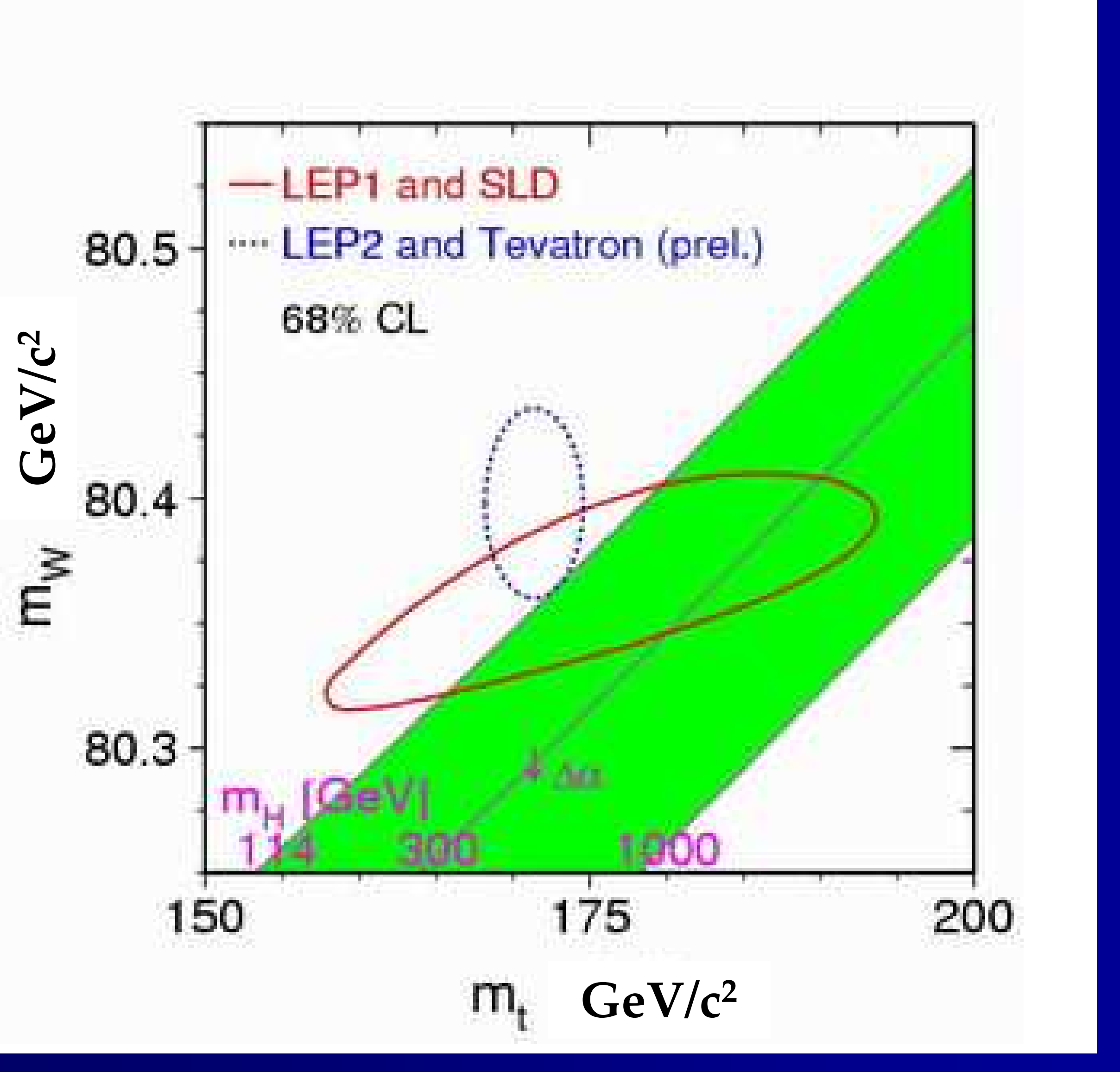
- Explains masses of *W, Z*
- Other particles interact with the Higgs field and acquire mass
- Additional consequence: new particle, the Higgs boson - ***not yet discovered!***

GeV/c² is a unit of mass:
1Gev/c² = 1.8E-27 kg = mass of 1 proton

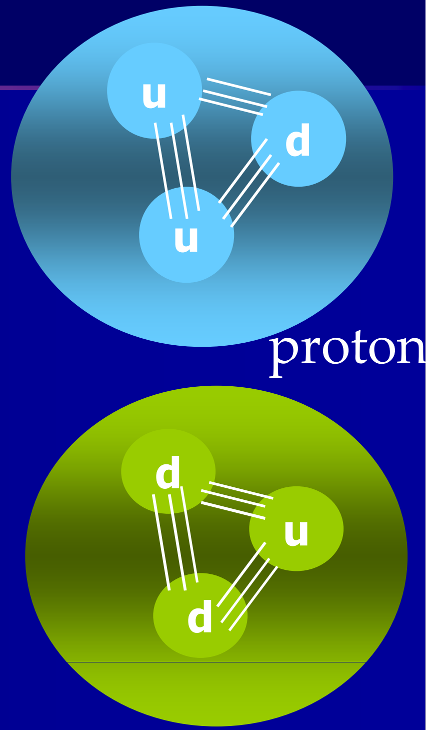
Aside: Given E=mc², energy units we frequently use are GeV.



The Higgs: What Do We Know?



Mass – What's the Big Deal?



- Higgs boson credited with the **"origin of mass"**
- **This is not the complete story**
  - **Most of the visible universe** is protons and neutrons
  - Protons (*p*) and neutrons (*n*) are a bound state of *u, d* quarks (~3-8 MeV apiece)
  - The *p, n* masses (938 and 940 MeV) come mostly from the **strong force** holding the quarks together
  - Strong force proceeds with or without the Higgs
- **However,** what if there were however no Higgs?
  - If $m_u = m_d = 0$, then $M_{proton} > M_{neutron}$ – this would be bad

$$p \rightarrow n e^+ \nu_e$$ – proton decay….which means no hydrogen

  - If $m_e = 0$, the Bohr radius of atoms would be large
    - Chemistry as we know it would not exist! This too would be bad

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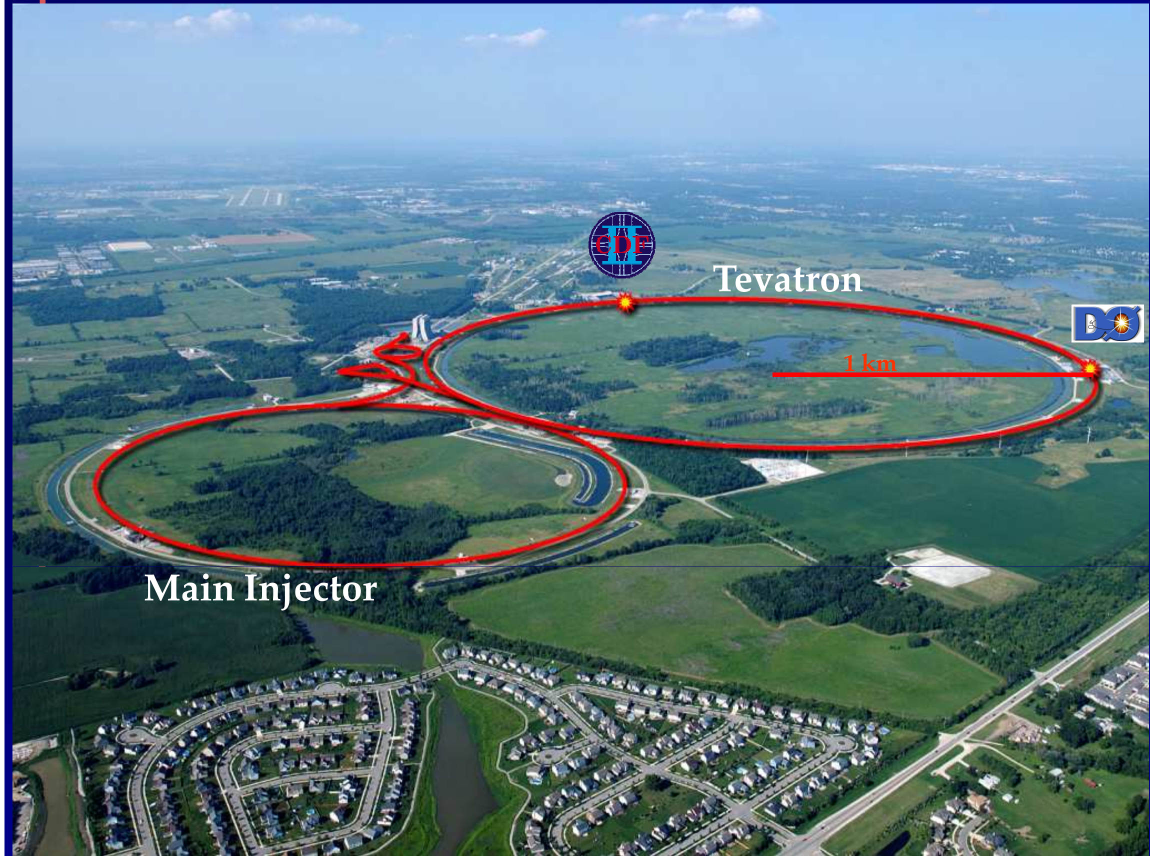
In Pursuit of the Higgs at the Tevatron



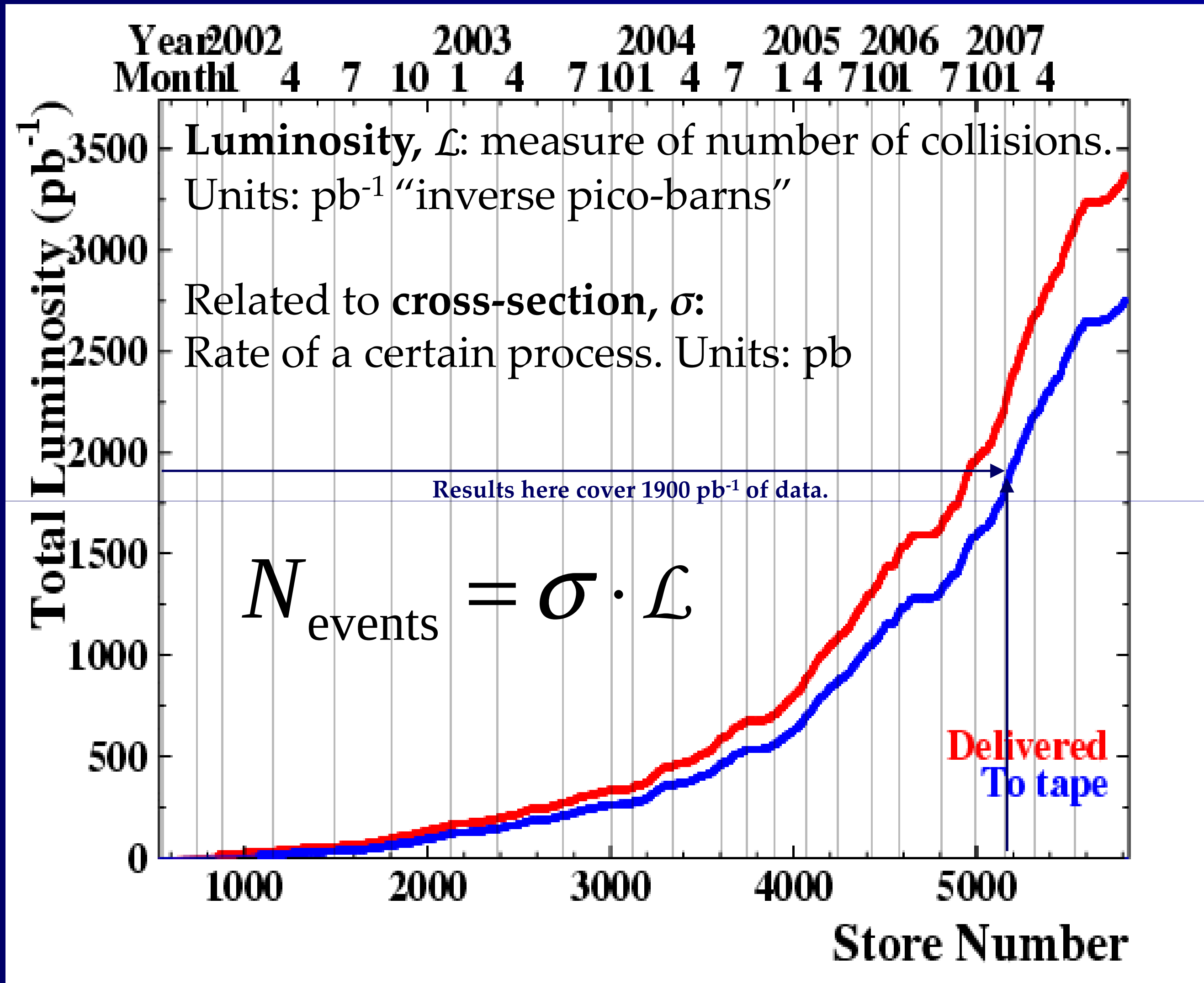
Current hunting grounds:

Tevatron accelerator
Located at
Fermi National Accelerator Laboratory
in Batavia, IL
~35 miles outside Chicago

	Tevatron
Radius (km)	1
Beams	$\bar{p}$-p
C.M. Energy (TeV)	1.96
N-per-bunch (1E9)	60 x 240
N-bunches	36 x 36
Bunch Spacing (ns)	396
Collision Rate (MHz)	1.7

The only game in town
for the time being

What the Tevatron Provides



Luminosity, $\mathcal{L}$: measure of number of collisions.
Units: pb^{-1} "inverse pico-barns"

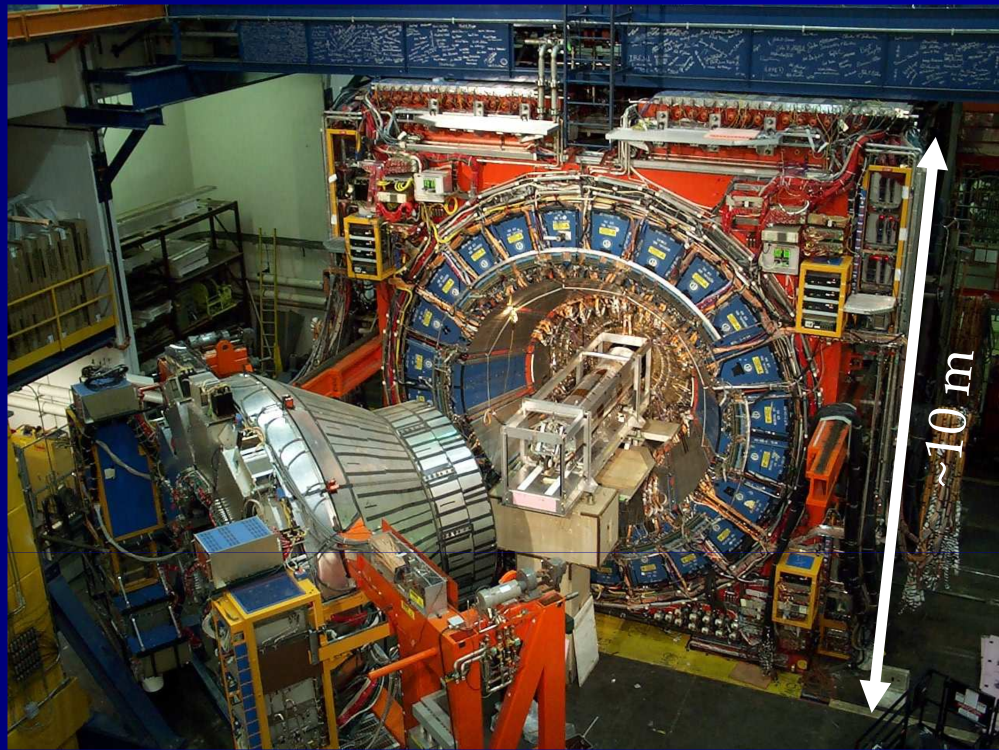
Related to **cross-section, σ:**
Rate of a certain process. Units: pb

$$N_{events} = \sigma \cdot \mathcal{L}$$

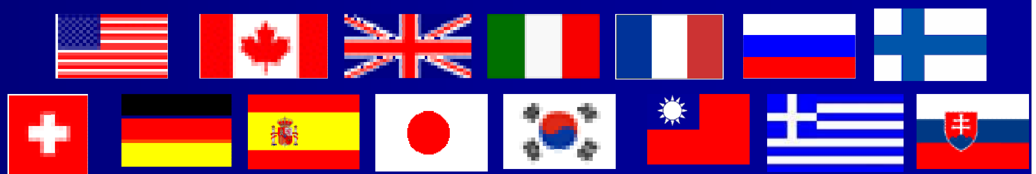
Luminosity is important!

The CDF Experiment

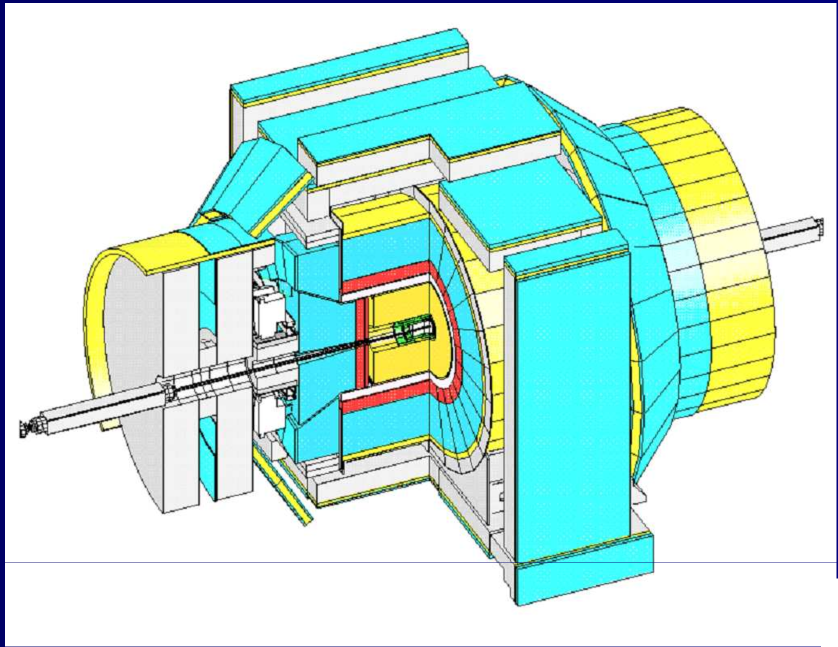
- **Collider Detector at Fermilab** Experiment
  - A collaborative effort
  - One of two collider physics experiments at the Tevatron
- **CDF detector:**
  - General-purpose
    - Can detect various decay products
    - Allows us to look for all sorts of phenomena
  - Unique design
    - Cannot buy these things at Radio Shack!



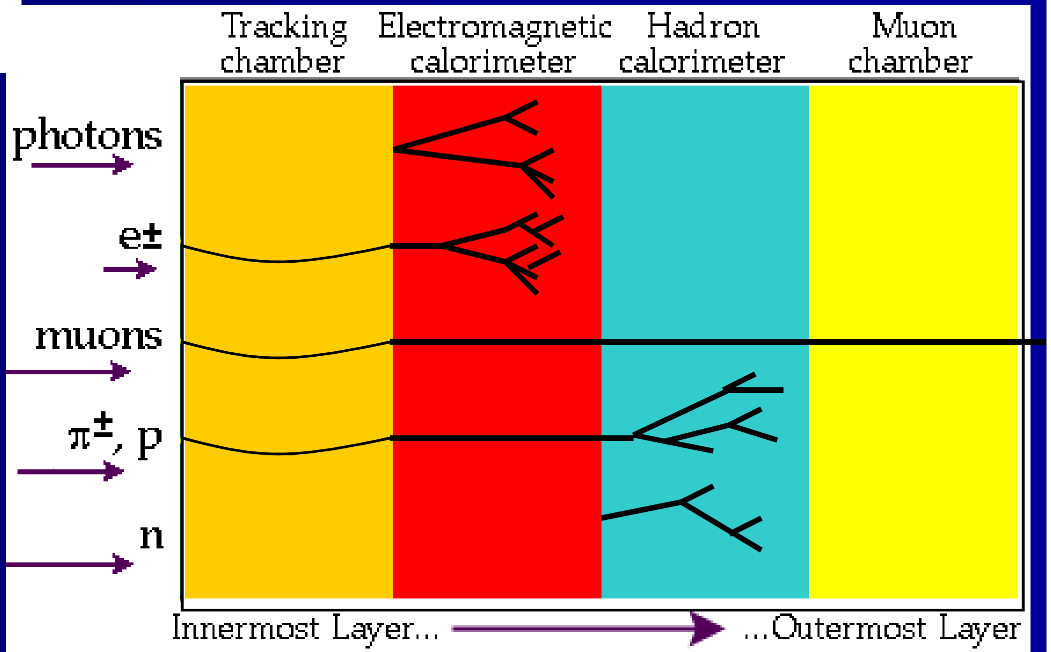
CDF Collaboration:
Over 600 physicists
63 institutions
15 countries



Particle Detector

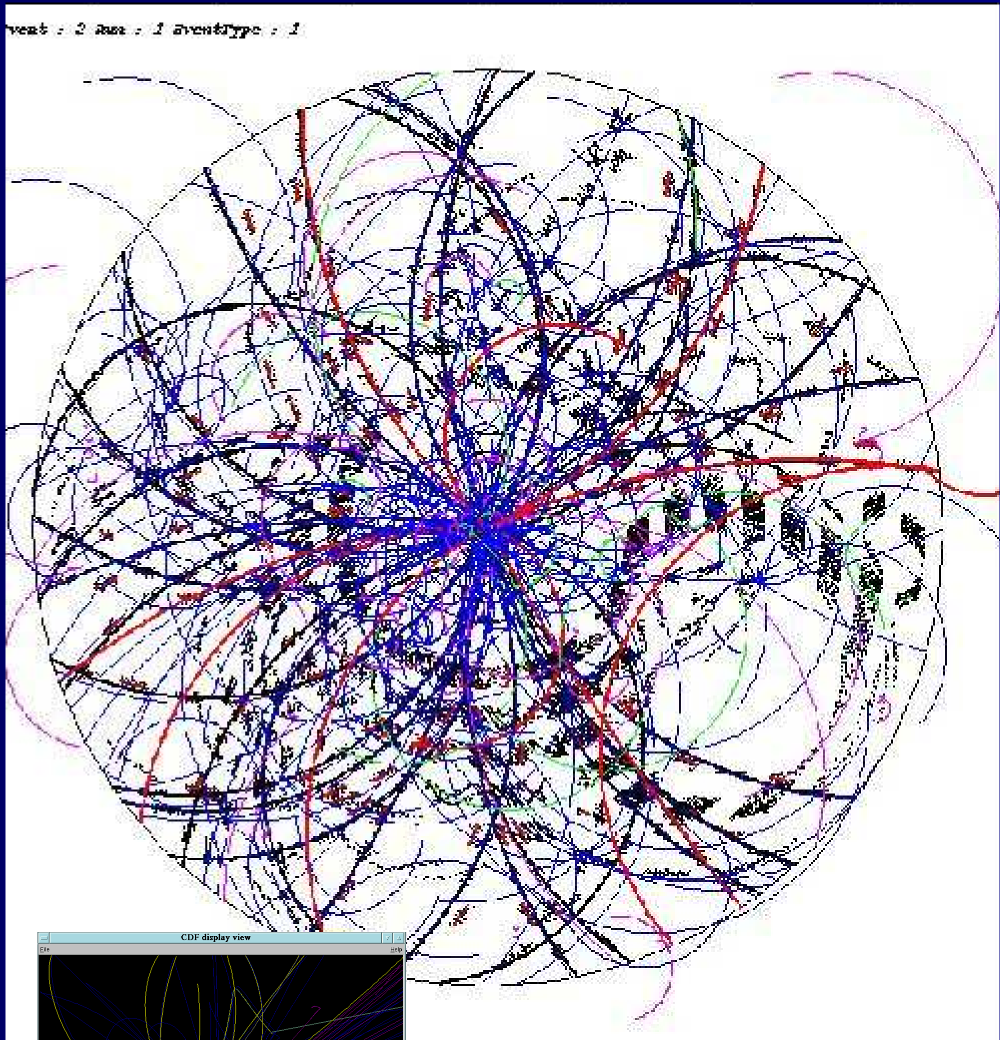


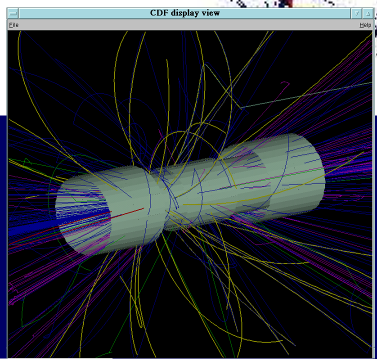
- Need to be able to observe the stable end-product particles created in the collisions



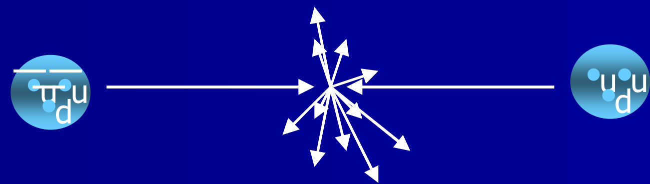
- **Electron, muon, photon** detected directly
- **Quarks** form bound states of **hadrons** (eg., π, p, n) due to strong force
  - But not just one hadron…many
  - "Jets" of hadrons

Collider Physics Experimental Challenge



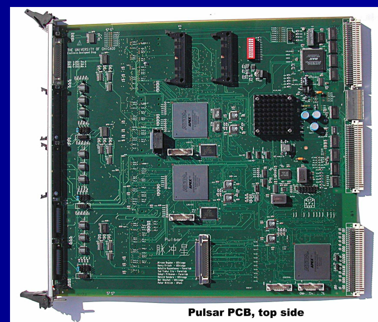


This is just the tracking!

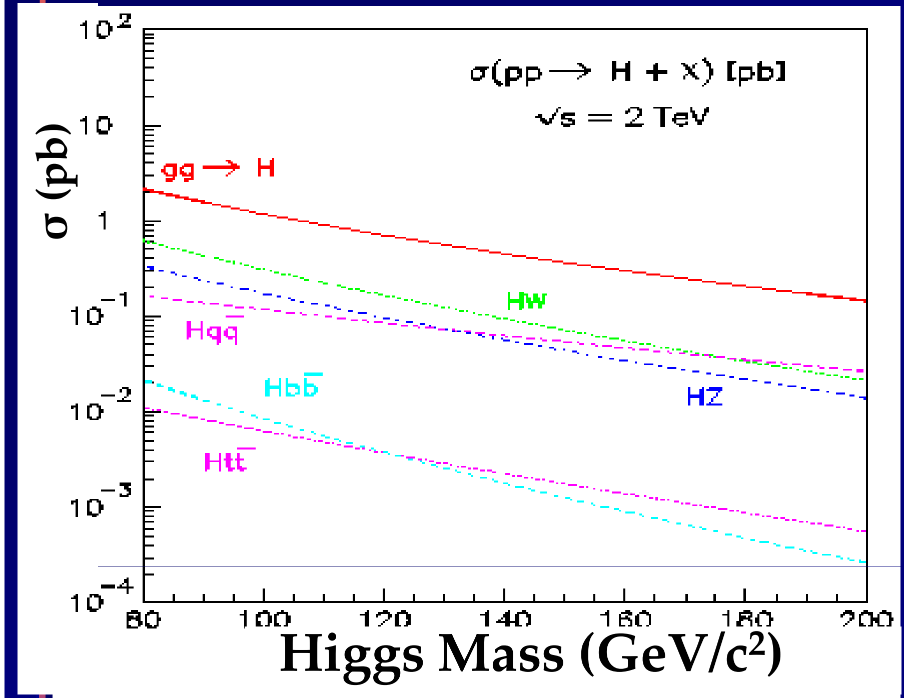


at 1.7 MHz

	Rate (Hz)
p-pbar Collision	1700000
L1 Accept	30000
L2 Accept	1000
L3 Accept	~100



Higgs: Production and Signature



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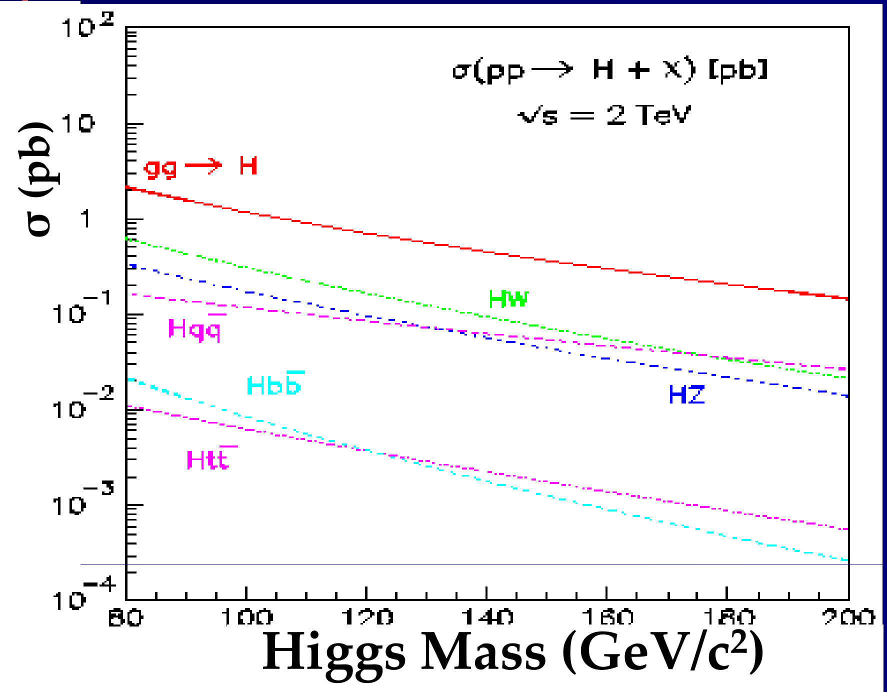

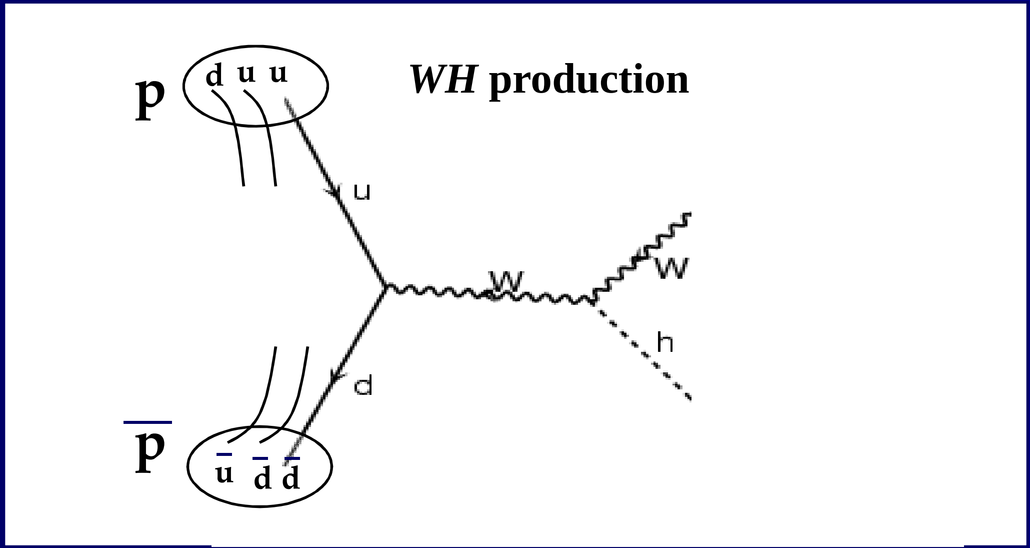

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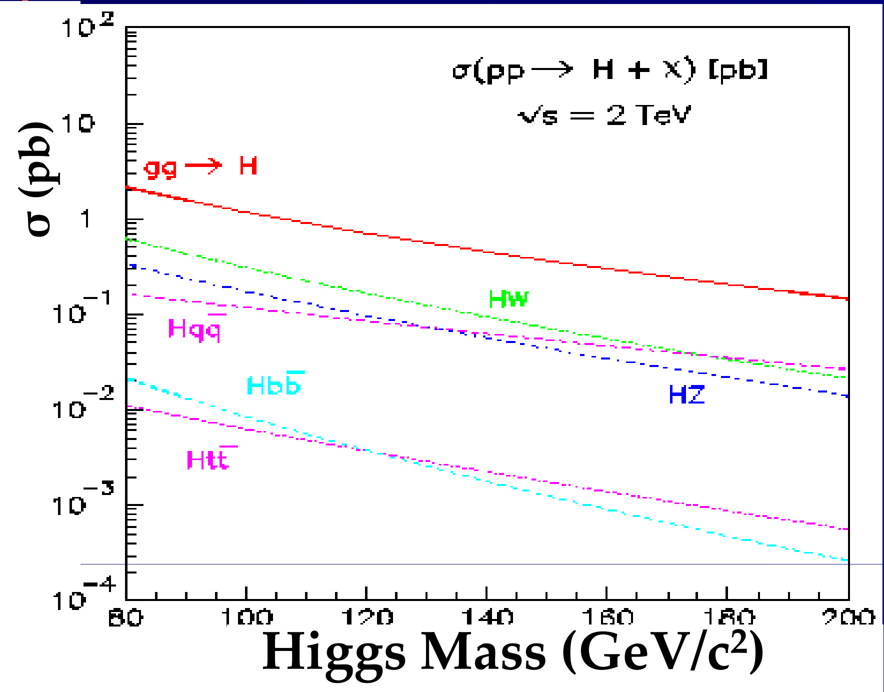

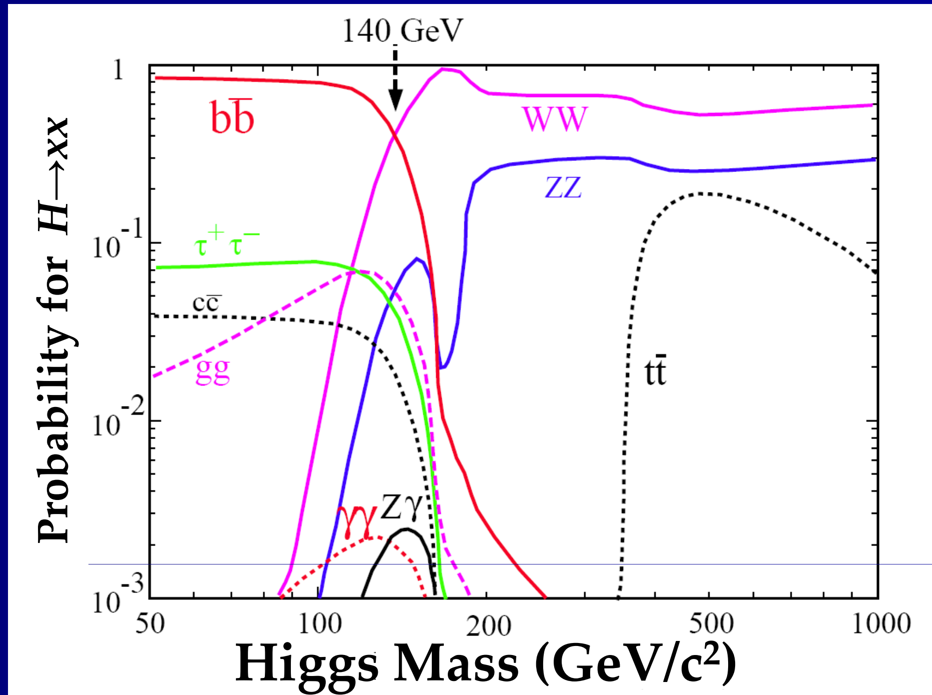

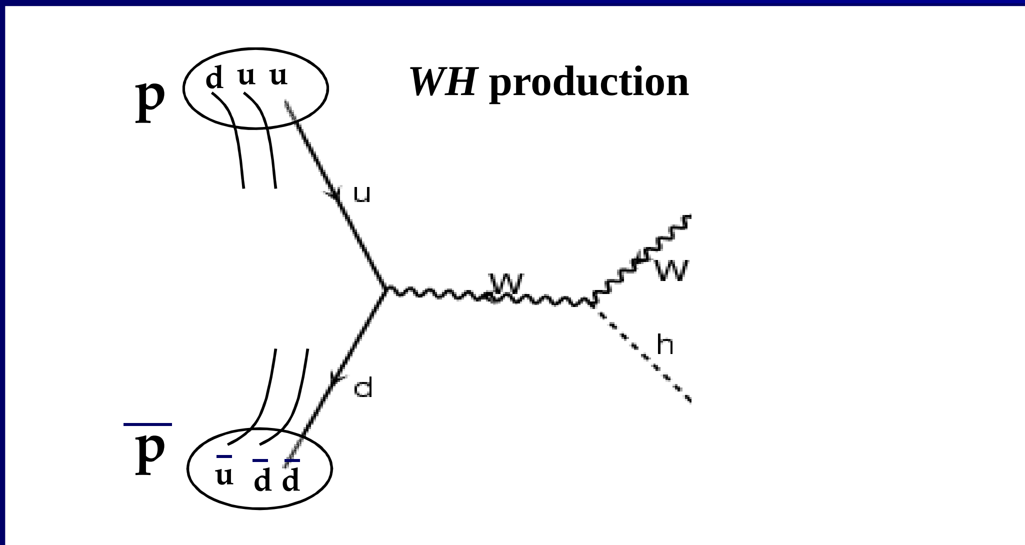

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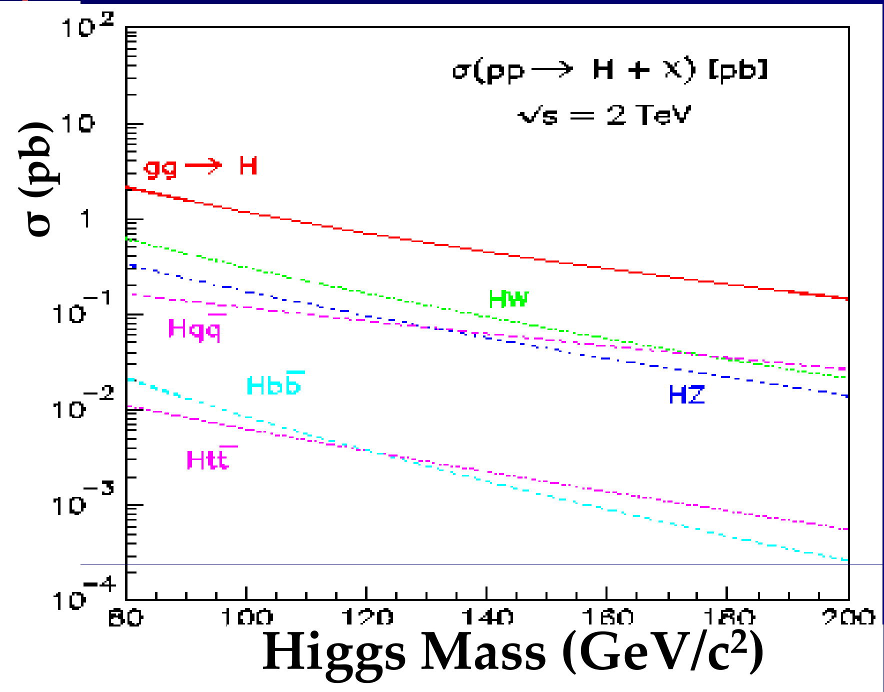
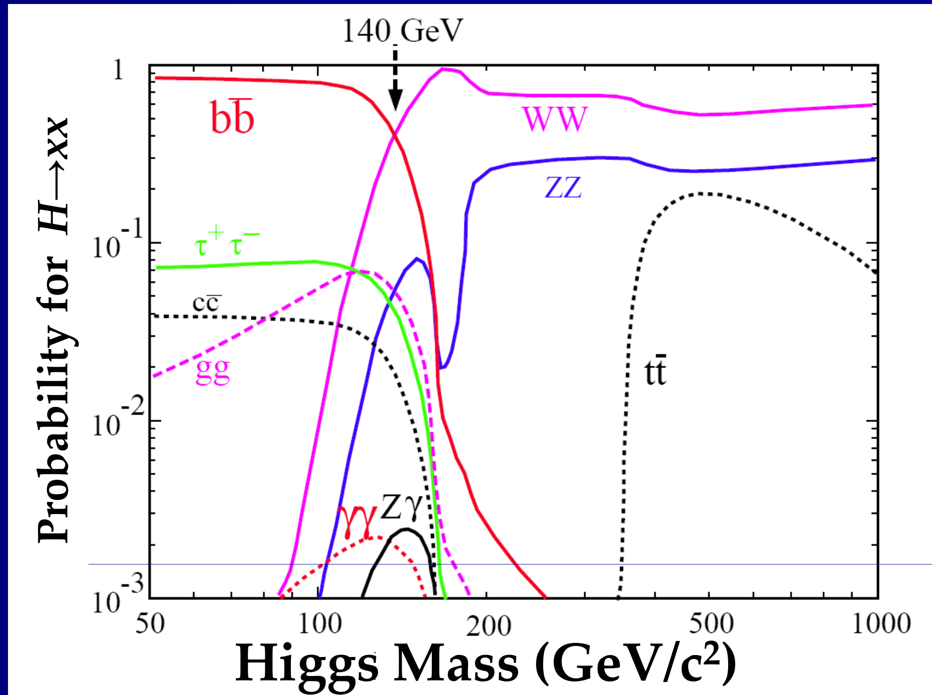
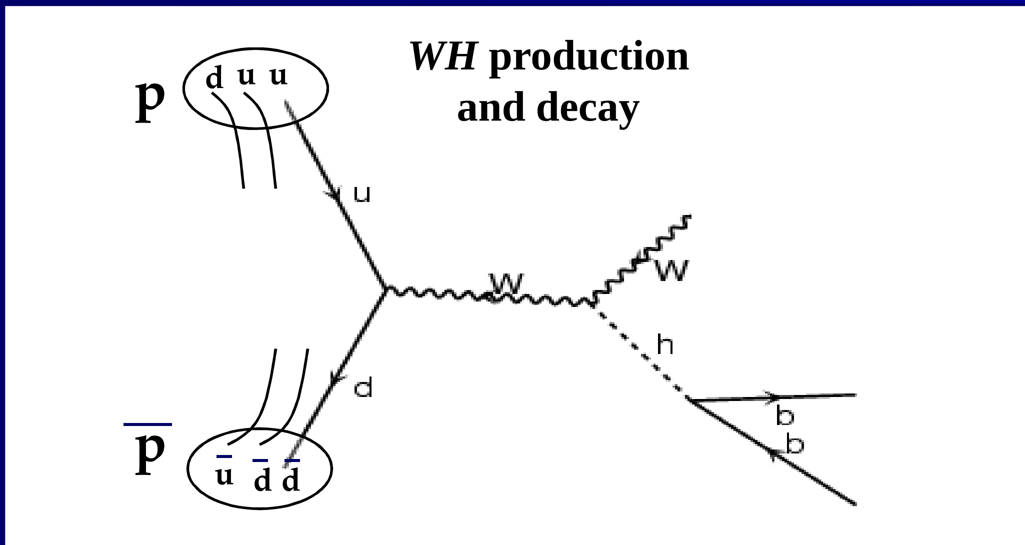
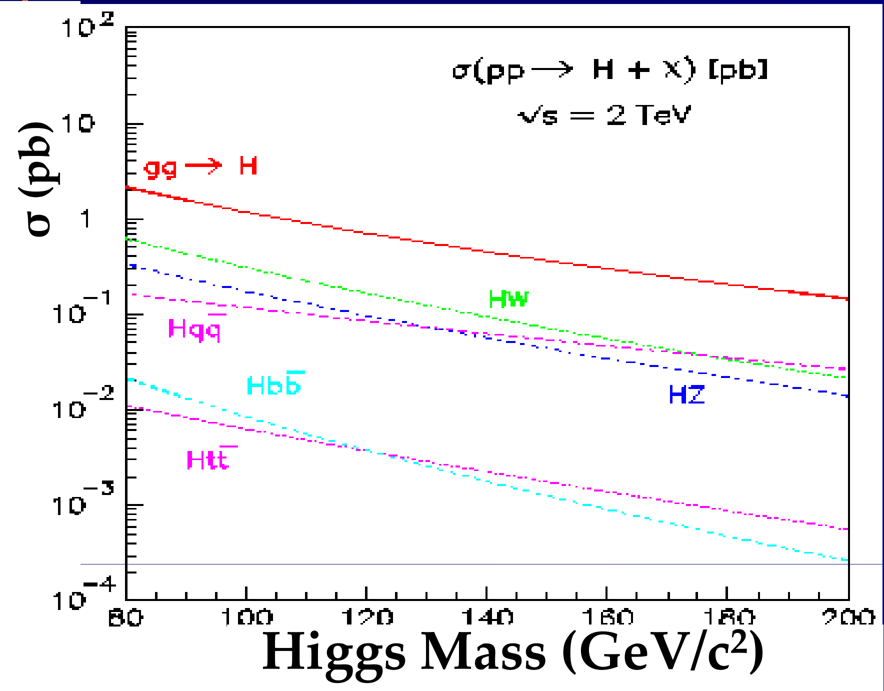


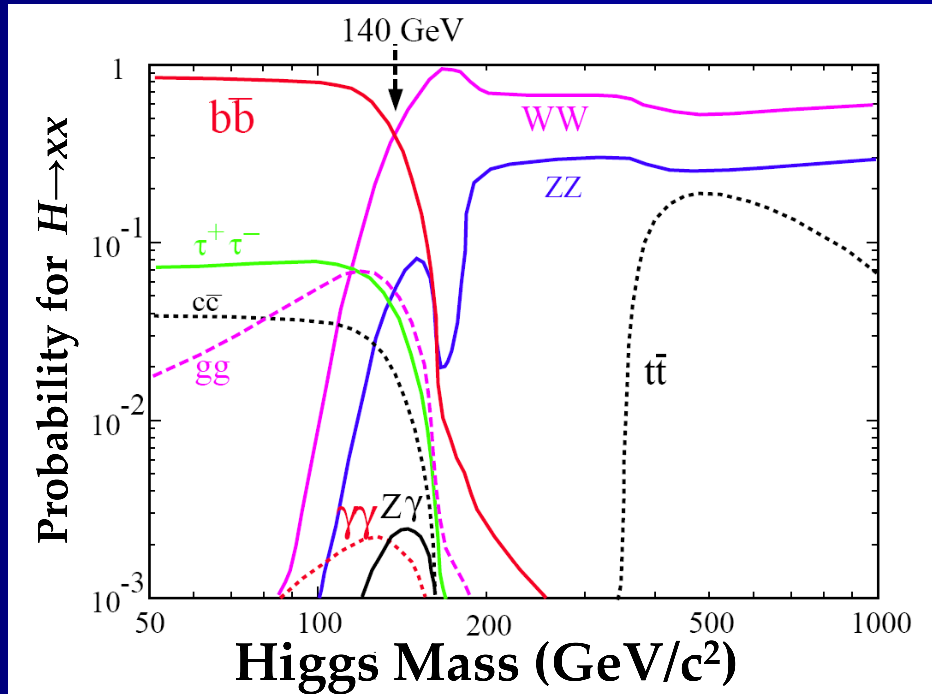


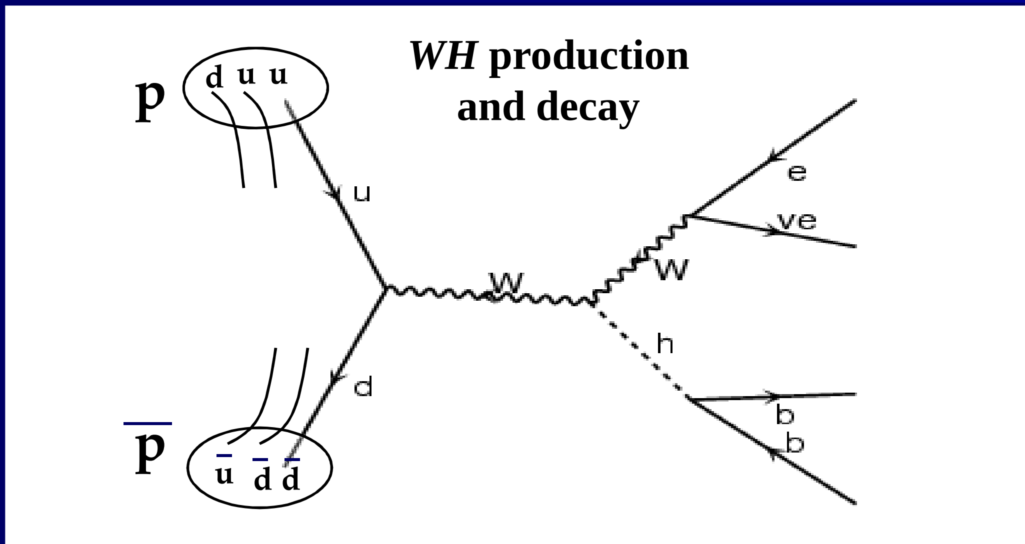


Focus here on search for the Higgs with $M_H < \sim 140$ GeV/c²

Higgs: Production and Signature

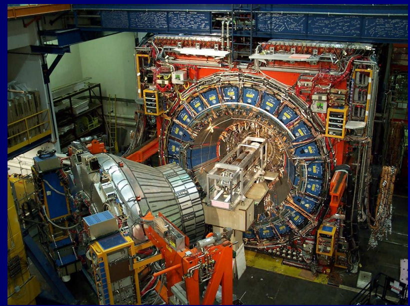


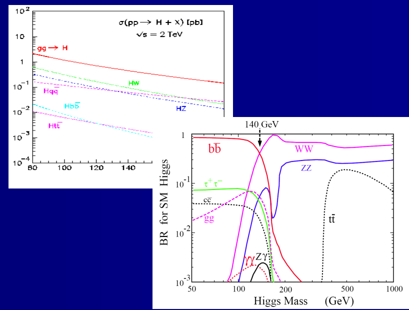


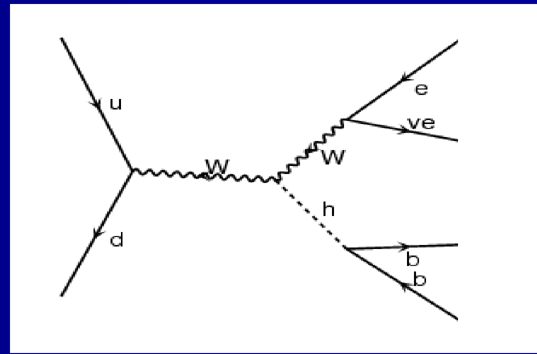


Focus here on search for the Higgs with $M_H <$ ~140 GeV/c^2

The Difficulty in the Search for the Higgs







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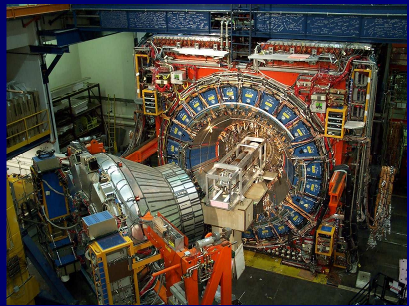
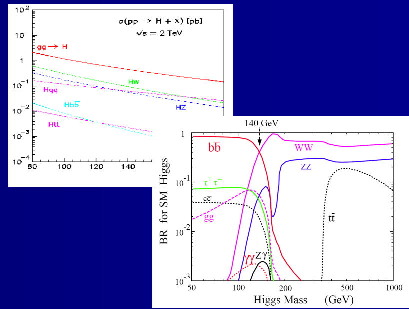
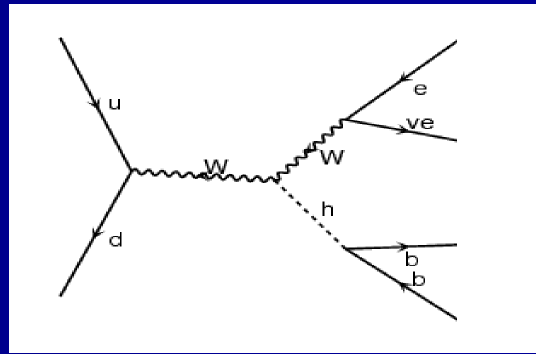
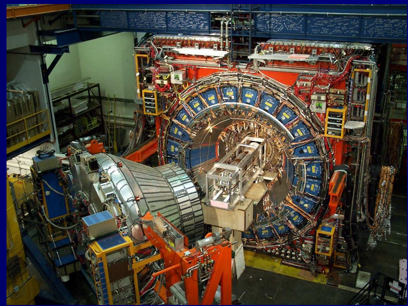


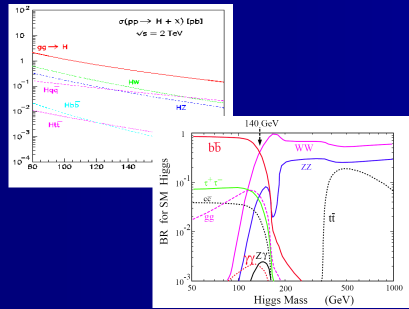


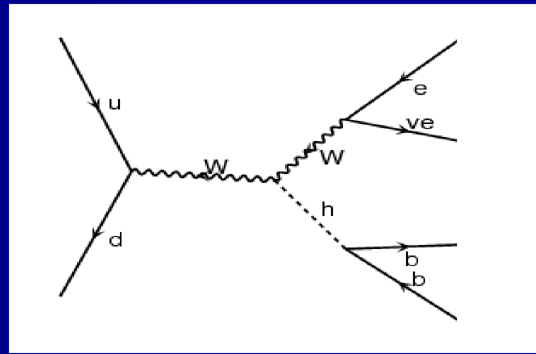


So what's the problem?

The Difficulty in the Search for the Higgs







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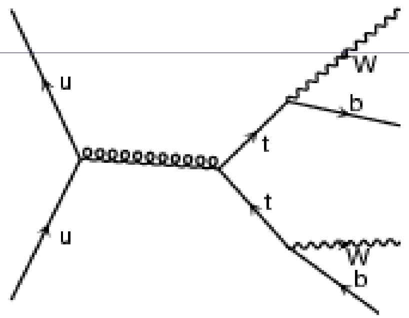
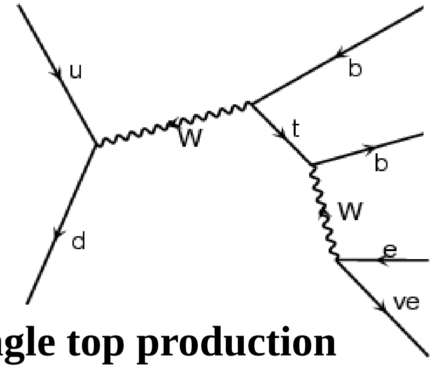
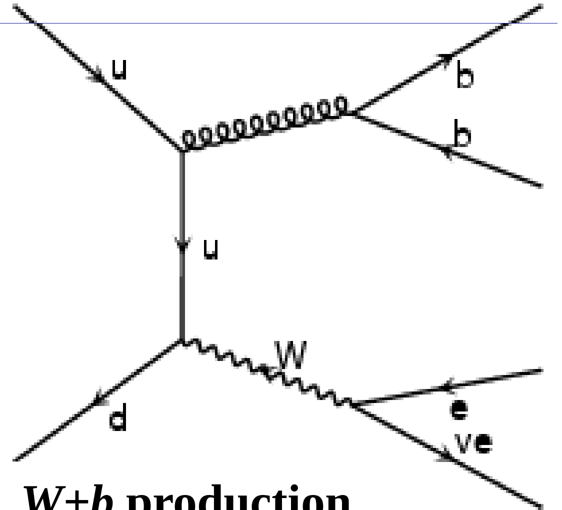


top pair production



single top production



***W+b* production**

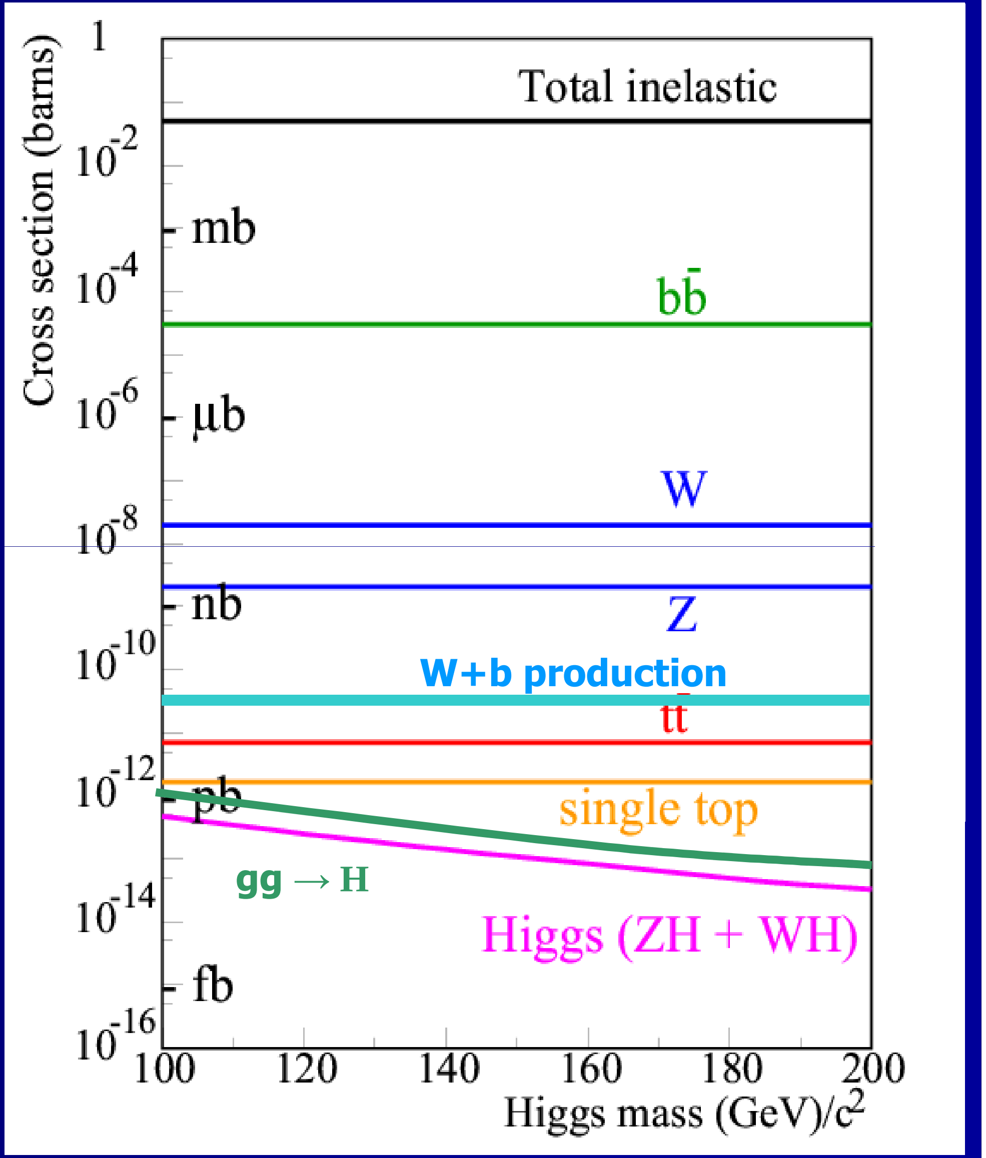
Importance of *W+b* Production

- *W+b* production casts a long shadow over the Higgs search:
  - Same signature as *WH*
  - Rate for *W+b* production exceeds *WH* significantly:

    Theory prediction is **40-60x** larger than expected *WH* rate

- Good understanding of the *W+b* production process is essential for success in the Higgs search

- Experimental insight on the process has so far been imprecise



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Measurement of *W+b* Production Rate

Typical particle physics measurement:

Recall $N_{sig}^{tot} = \sigma_{sig} \cdot \mathcal{L}$ for some signal. We seek here σ_{W+b}.

We do not have complete efficiency or acceptance for observing *W+b*. We can express it this way:

$$N_{W+b}^{obs} = \sigma_{W+b} \cdot \mathcal{L} \cdot \mathcal{E} \cdot \mathcal{A}$$

In the data we observe:

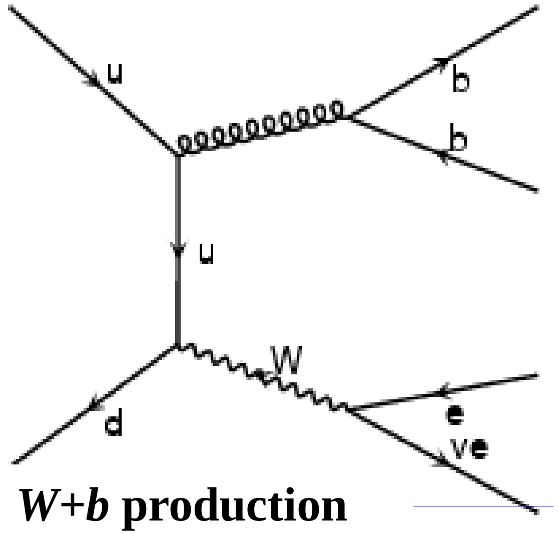
$$N_{tot}^{obs} = N_{W+b}^{obs} + N_{other}^{obs}$$

So it follows that

$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{other}^{obs}}{\mathcal{L} \cdot \mathcal{E} \cdot \mathcal{A}}$$

Measurement of *W+b* Production Rate

$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{other}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$

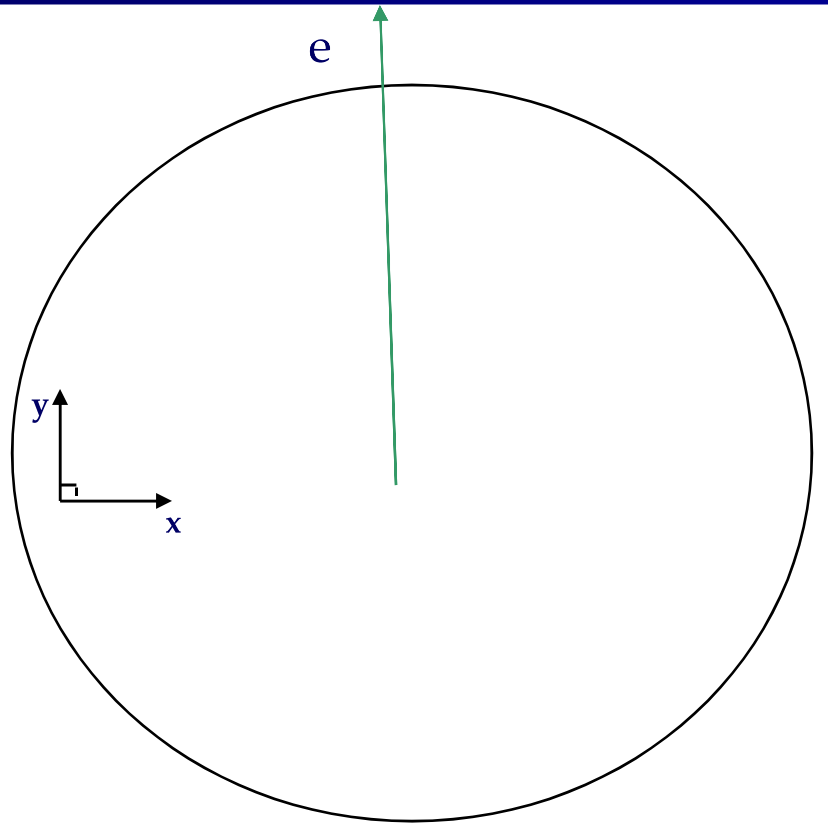


***W+b* production**

- Cannot go into every detail but I will tell you about the following:
  - ***Selecting events*** from *W+b* production
  - Understanding the ***purity*** of the events that are selected
  - Surmising the ***backgrounds*** – the "other" in the above expression
  - Understanding the ***efficiency*** ε for identifying *W+b* production

Selecting *W+b* Events

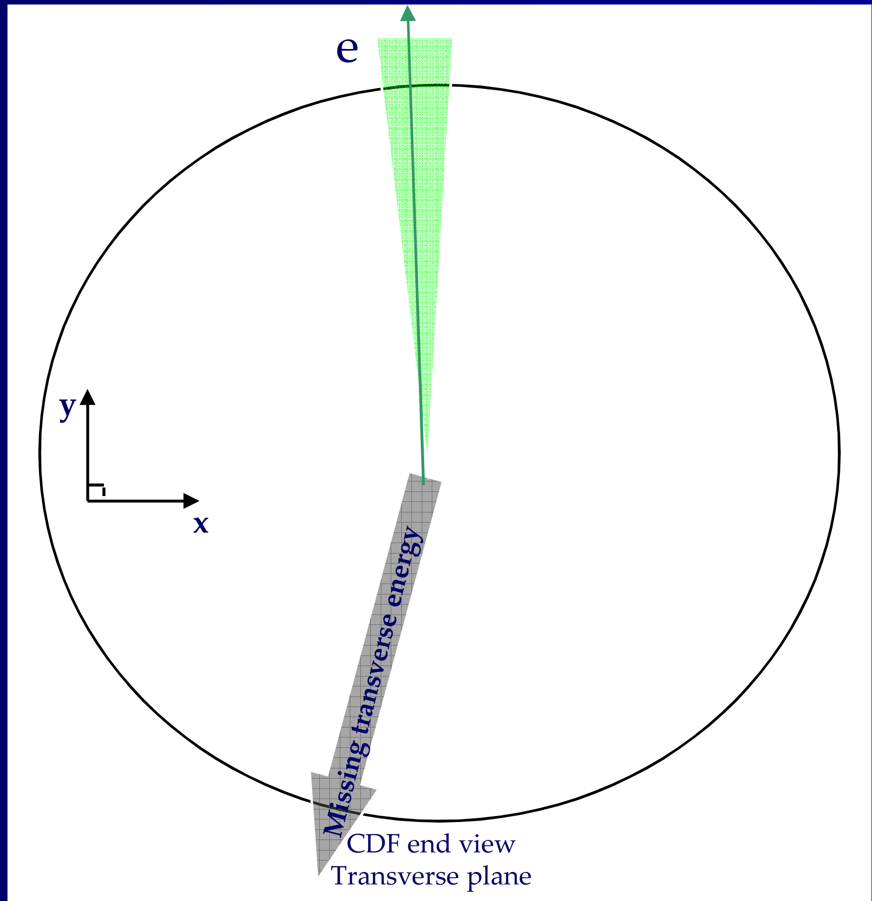
$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$



CDF end view
Transverse plane

Selecting *W+b* Events

$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$



Selecting *W+b* Events

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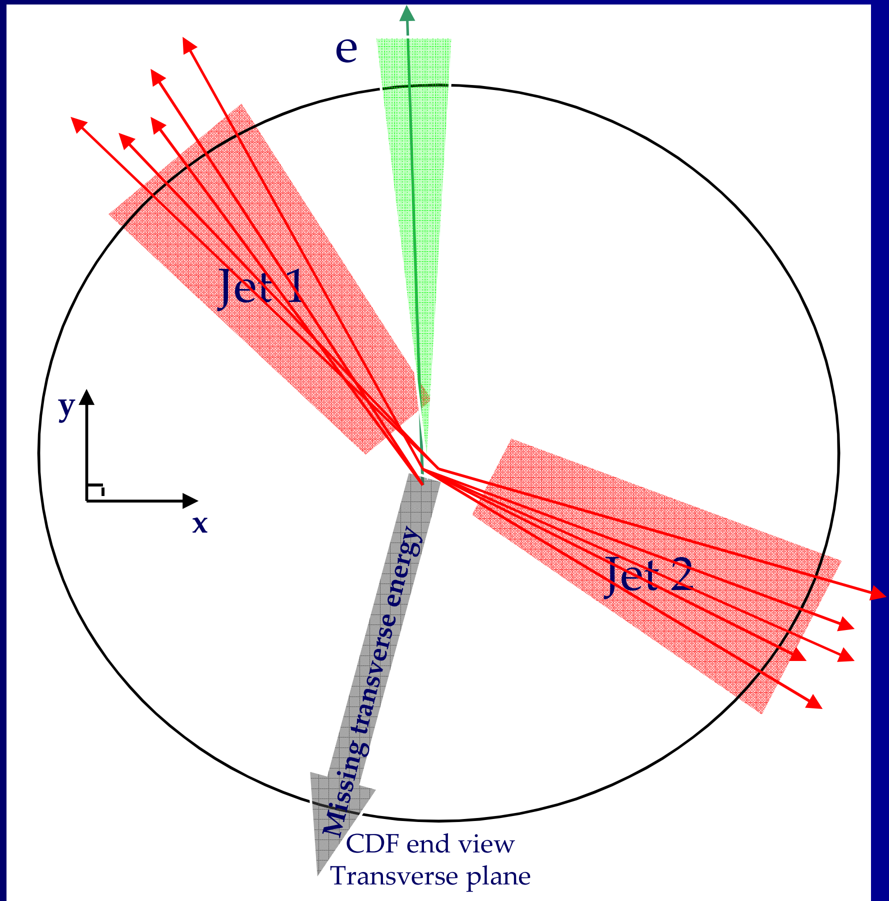
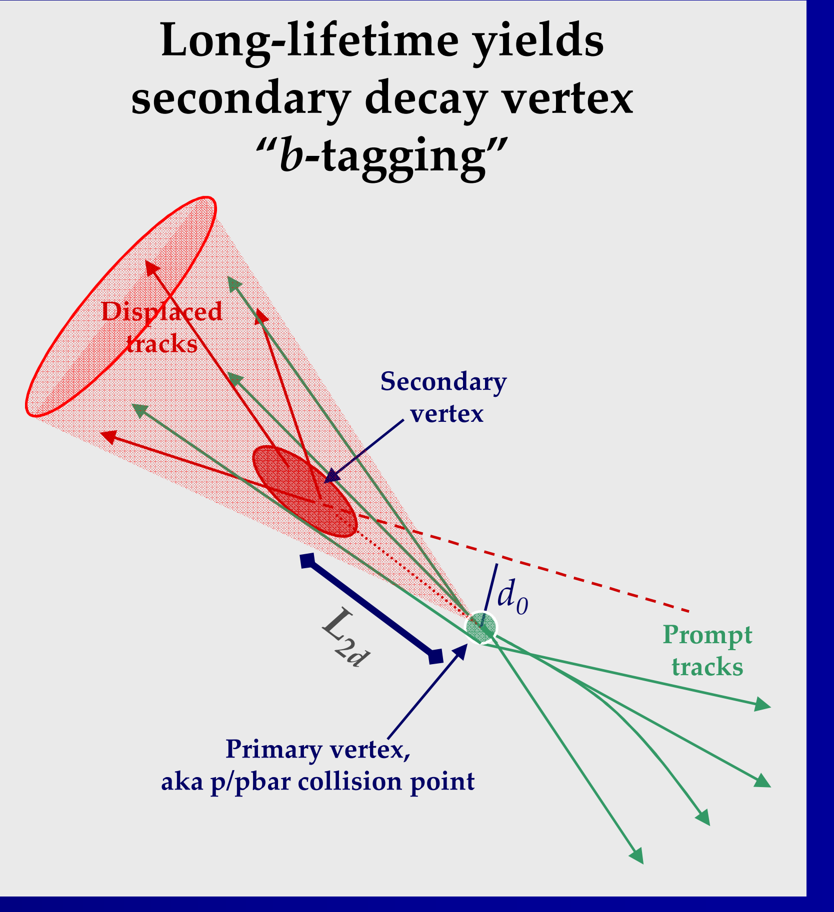


Selecting *W+b* Events: Identifying *b* Jets

$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$

- ***B* hadon lifetime**: ~1.5 ps
  - Decays into several particles (charged and neutral)
  - Seems like a short time…
  - Large boost (v ~ 0.95*c*) means the *B* lifetime is really long in the lab frame

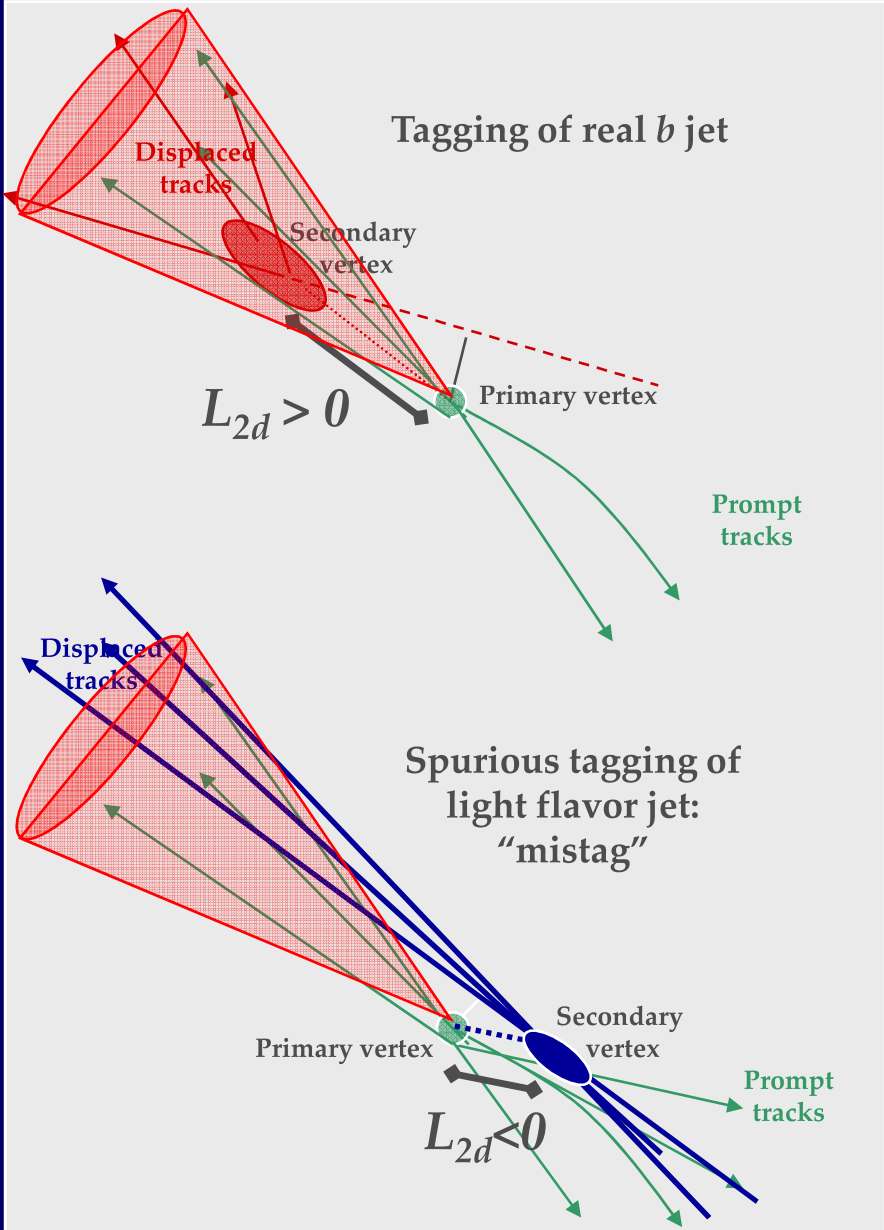


- **Exploit the long lifetime!**
  - Reconstruct charged particle tracks
  - See if they intersect at a common point
  - Require the common point be significantly displaced from the primary $\bar{p}$-p collision point

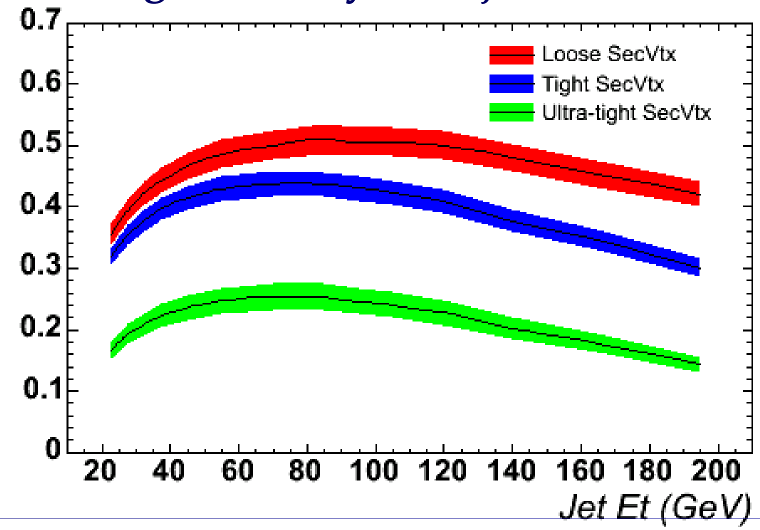
	Meaning	Typical	Resolution
d_0	Track impact parameter	150um	40um
L_{2d}	Vertex displacement	2-3mm	100um

Tagging: *b*'s and Non-*b*'s

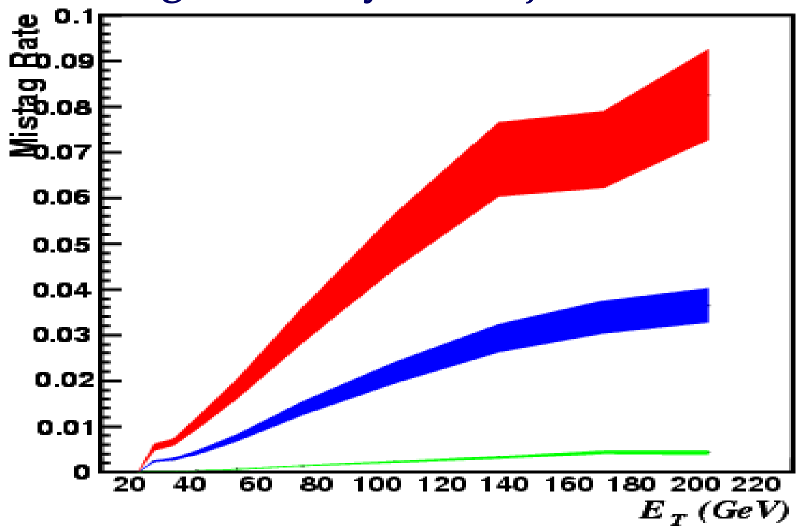
$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \mathcal{E} \cdot \mathcal{A}}$$



Tag efficiency for *b* jets



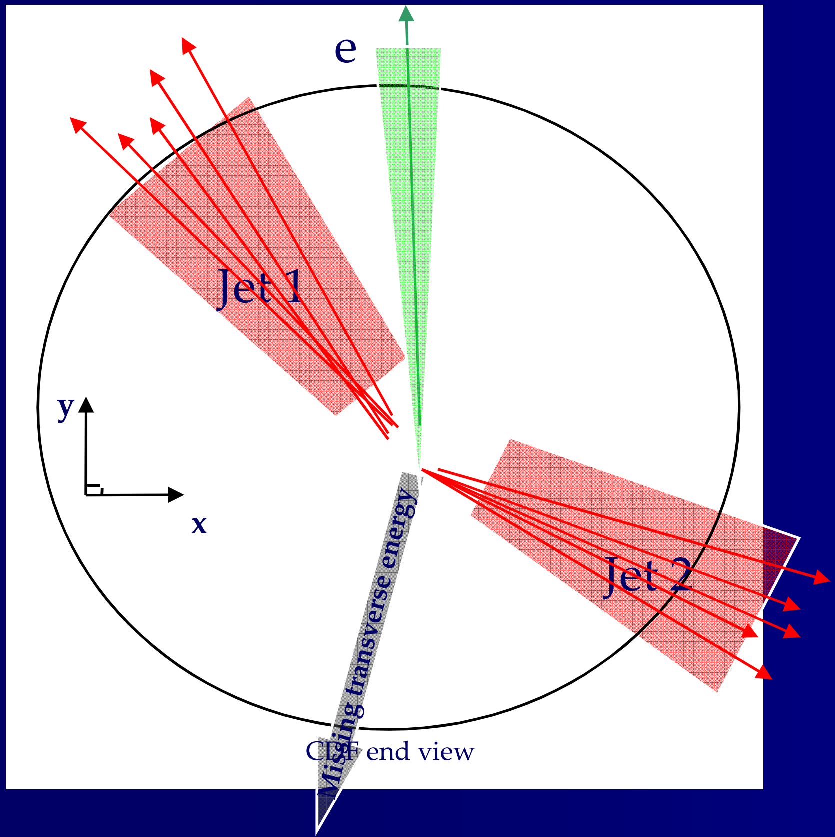
Tag efficiency for LF jets



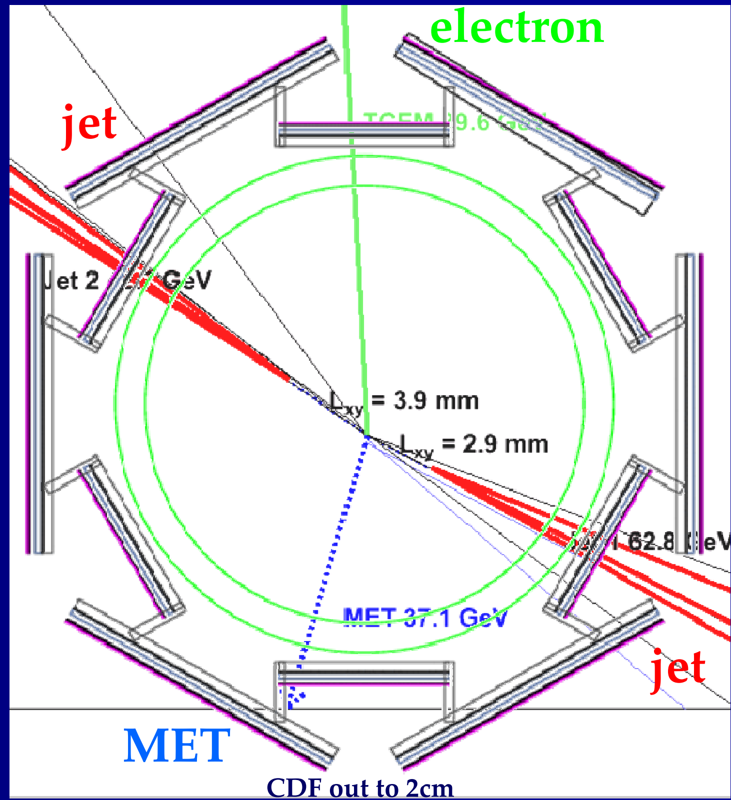
Yield of Tagged Jets

$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$

Schematic:



The real thing: an event recorded 10/2005



Event has 2 tagged jets!

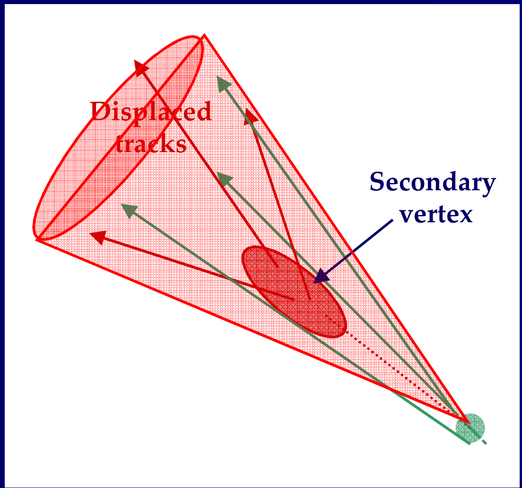
Yield in 1900/pb of CDF data:

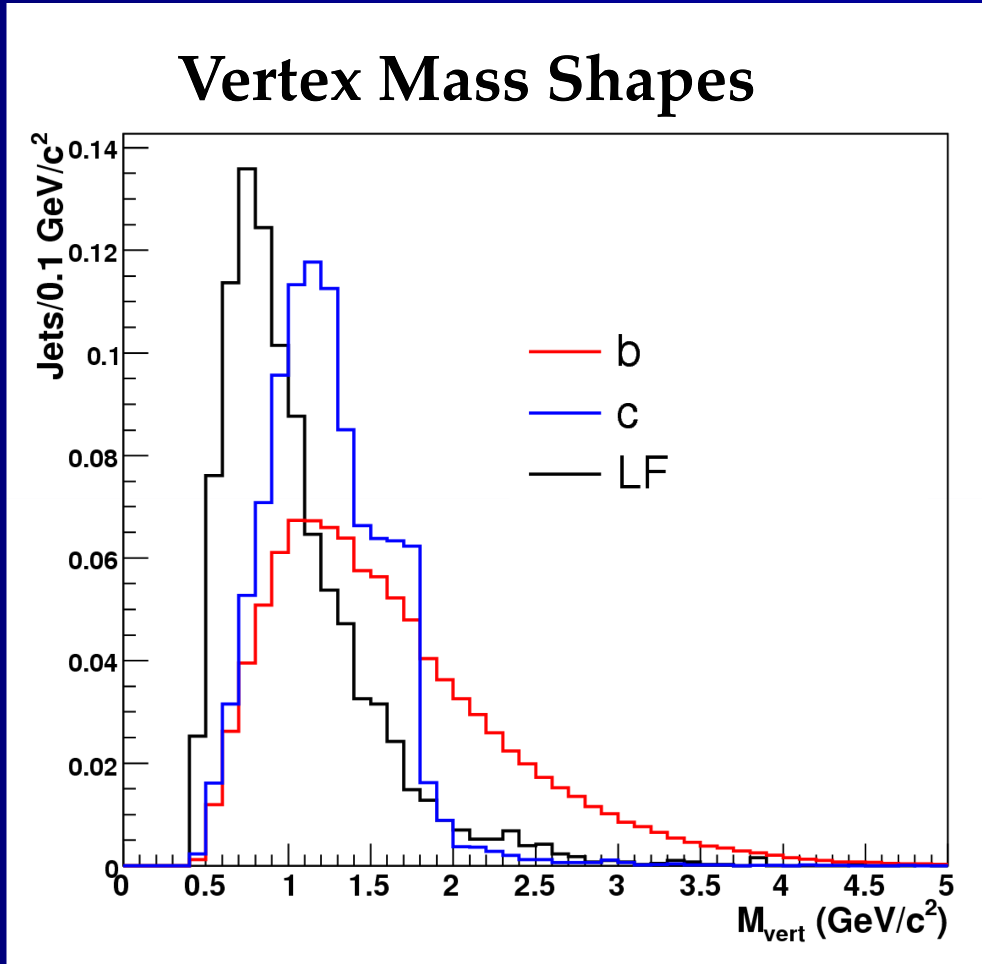
Selected Events (before tagging)	175712
Total Jets	199670
Tagged Jets	943

Purity: A *b* or not a *b*?

$$\sigma_{W+b} = \frac{N^{obs}_{tot} - N^{obs}_{bkg}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$

- Discriminate the species of tagged jets via **vertex mass, M_{vert}**:





  - Mass of charged particle tracks in vertex
  - Correlated to mass of decaying hadron:

    $M_B > M_C > M_{LF}$

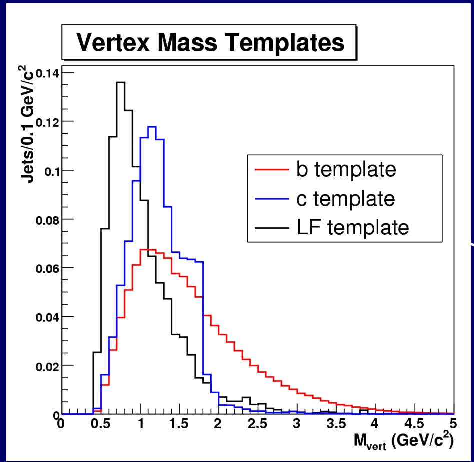
    so

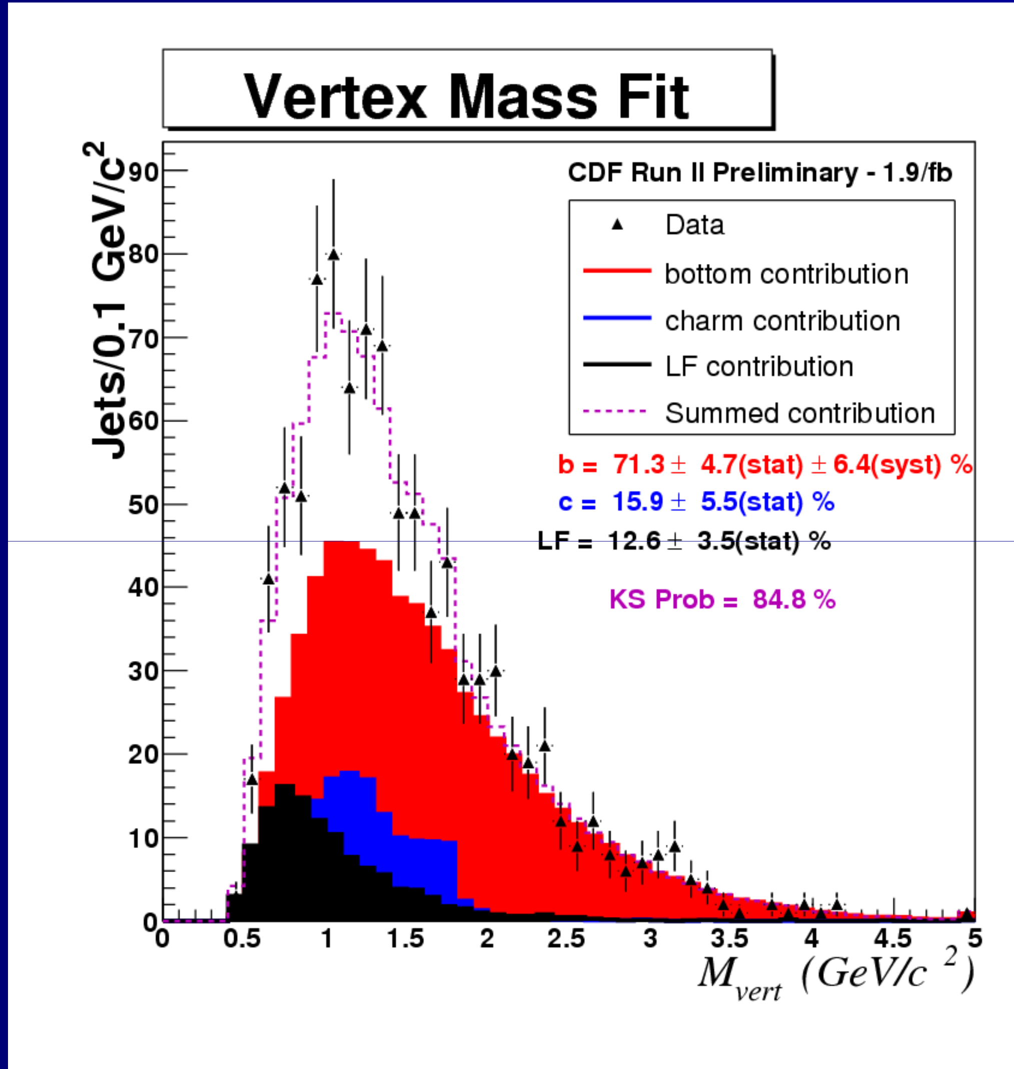
    $M^b{}_{vert} > M^c{}_{vert} > M^{LF}{}_{vert}$

b, c, LF ("light flavor" = u/d/s) shapes from simulations of $\bar{p}$-p collisions

Purity: Results

$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$





- **Fit results in the CDF data!**
- Fit prefers ~71% of tagged jets are from *b*.
- Given the yield of 943 tagged jets that corresponds to

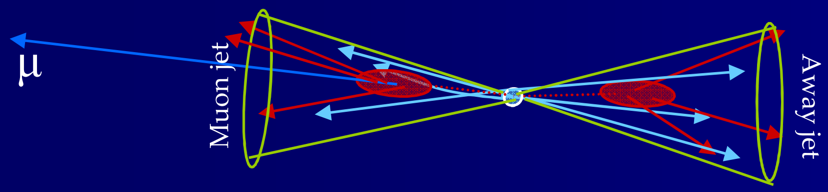
$$N_{tot}^{obs} = 672.3 \pm 44.3(\text{stat}) \pm 60.4(\text{syst})$$

Where does this systematic error come from?

Is The Shape for *b* Correct?

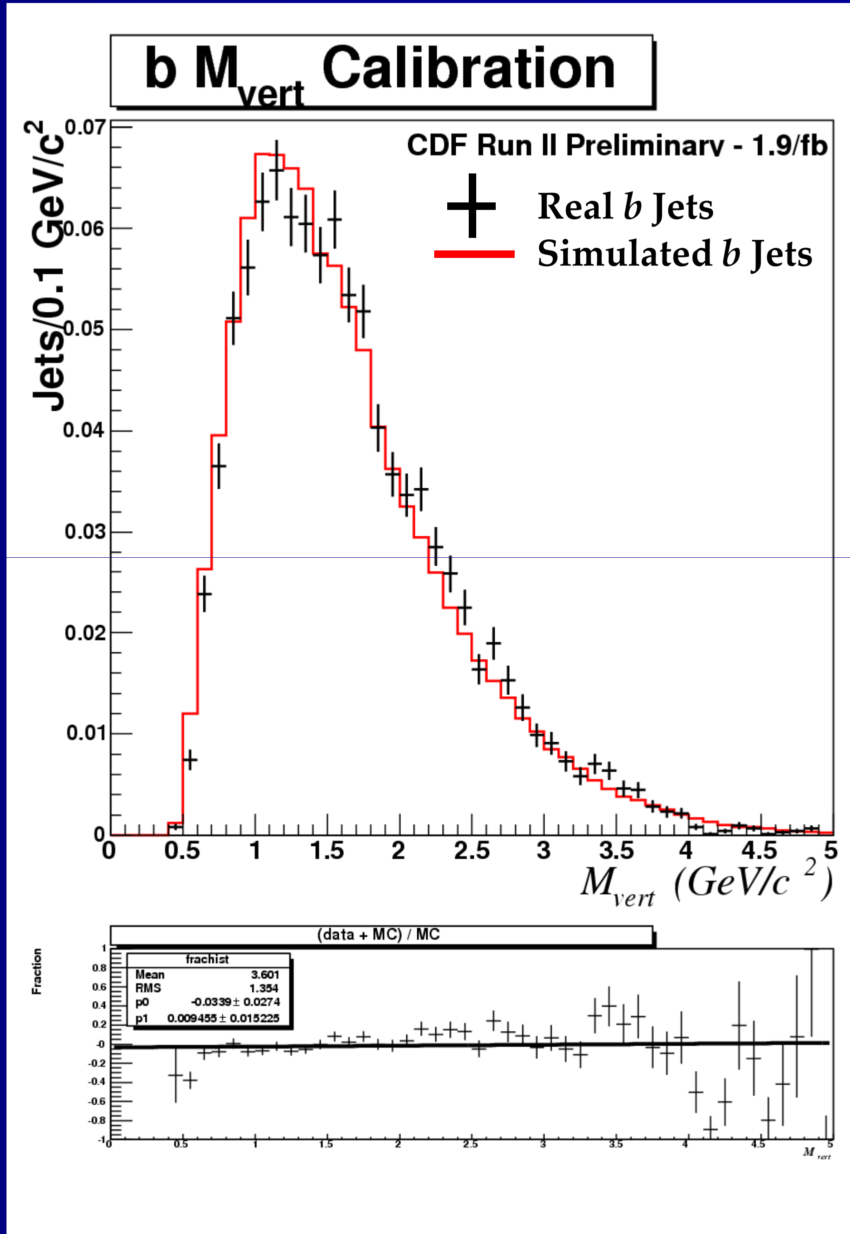
$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$

- Can construct a **pure sample of tagged *b* jets in data:**



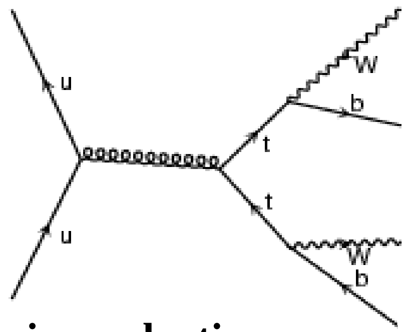
  - Require both jets be tagged
  - *b* purity > 99%

- **Shape difference:** a $\delta f_b/f_b$ = 8% effect

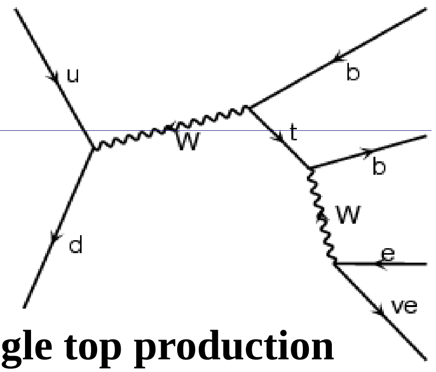


Background Sources of *b* Jets

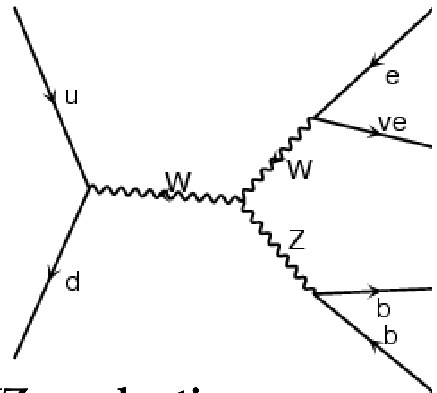
$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$



top pair production



single top production



***WZ* production**

We are trying to measure *W+b* production.

Other processes share this signature:

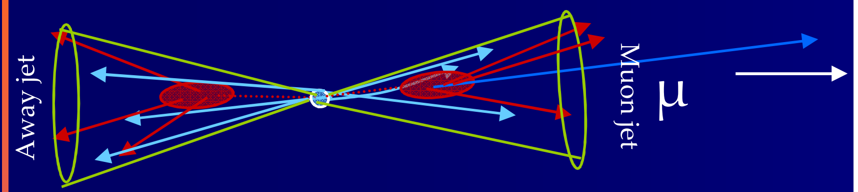
Process	Contribution
top pairs	73.1 ± 10.1
single top	55.6 ± 17.8
WZ	9.1 ± 1.0
Fake W	24.5 ± 8.4
Others	14.5 ± 3.0
Total = N_{bkgd}^{obs}	**176.8 ± 22.3**

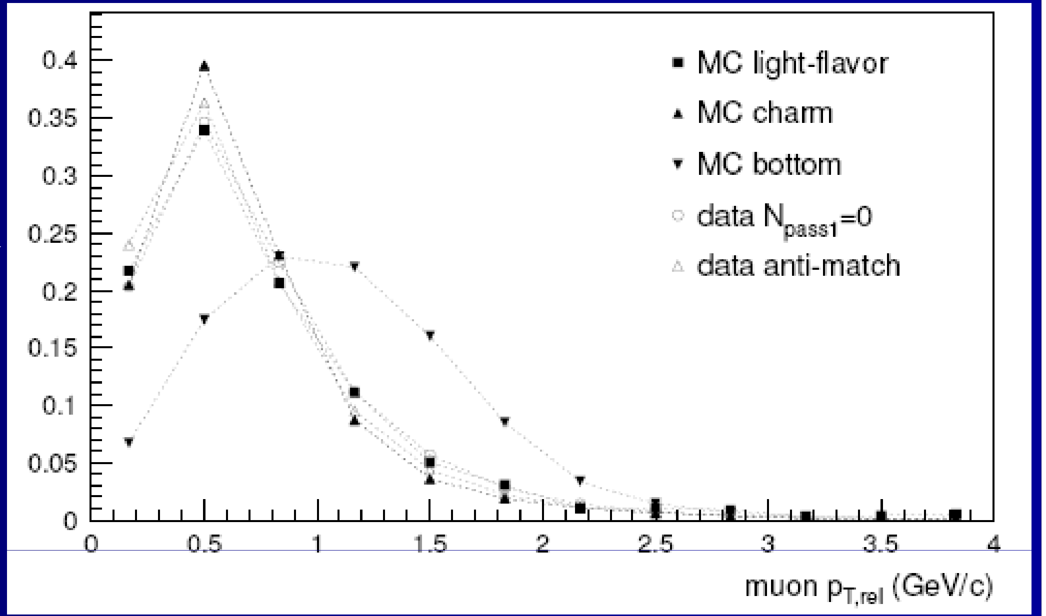
Why no *WH* here?
Assumed to be small…

Tag Efficiency

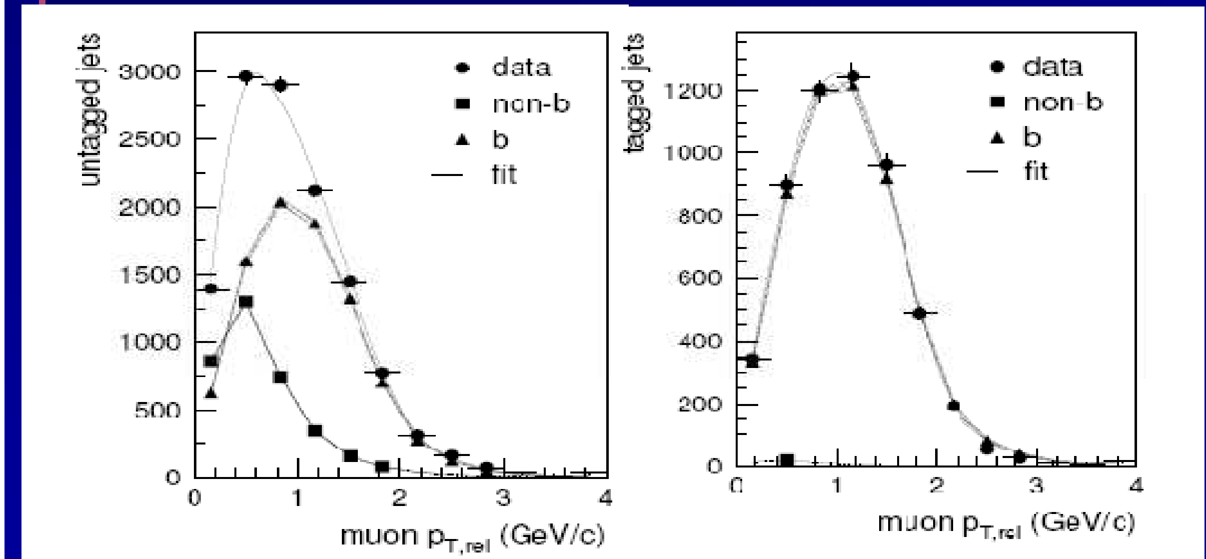
$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$

Identification efficiency for *b* jets





Use a similar sample as in the calibration of the vertex mass shape



For *b* jets in *W*+*b* production:

$$\varepsilon = 0.16 \pm 0.01\ (\text{syst})$$

W+b Cross Section Result

Pieces:

$$N_{tot}^{obs} = 672.3 \pm 44.3(\text{stat}) \pm 60.4(\text{syst})$$

$$N_{bkg}^{obs} = 176.8 \pm 22.3(\text{syst})$$

$$\mathcal{A} = 0.593 \pm 0.017(\text{syst})$$

← Didn't talk about this one…

$$\varepsilon = 0.16 \pm 0.01(\text{syst})$$

What about the luminosity?

$$\mathcal{L} = 1905 pb^{-1}$$

Insert pieces here:

$$\sigma_{W+b} = \frac{N_{tot}^{obs} - N_{bkg}^{obs}}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{A}}$$

And finally:

$$\sigma_{W+b} = 2.74 \pm 0.25(\text{stat}) \pm 0.44(\text{syst})\ \text{pb}$$

CDF RunII Preliminary – 1.9/fb

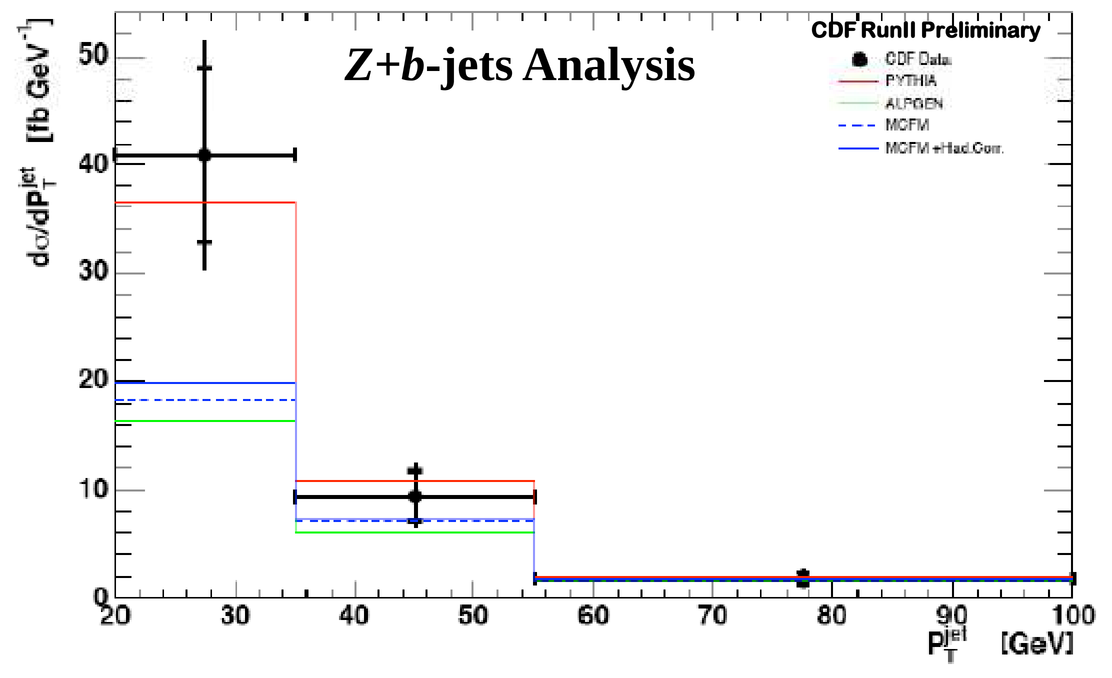
This cross section is for *b* jets from *W*+*b* production in events with a high p_T central lepton, high p_T neutrino and 1 or 2 total jets.

Discussion

- **Measured *b*-jet cross section in *W*+*b*-jets: <u>2.74 ± 0.25(stat) ± 0.44(syst) pb</u>**
  Theory *b*-jet cross section in *W*+*b*-jets: <u>0.78 pb</u> **(ALPGEN)**
  - Mismatch not unexpected – not an easy process to calculate
  - Important: First quantification of mismatch
  - NB: more complete theory prediction is available – comparison coming

- CDF sees a similar mismatch in *Z*+*b* production
  - Very similar process

- Need to get to the bottom of this!



Outline

- Particle Physics – What, Why and How
- The Pursuit of the Higgs
- *W*'s and *b*'s at the Tevatron
- Implications and Future

Example: *W+b* Prediction in *WH* Search

- WH→ℓνbb analysis needs prediction for *W+b* yield
- Predicted rates from theory **distrusted** for *W+b* production
- Ultimate prediction is frought with systematic error
- **Small *WH* signal** obscured by error on the background
- We must be able to do better!

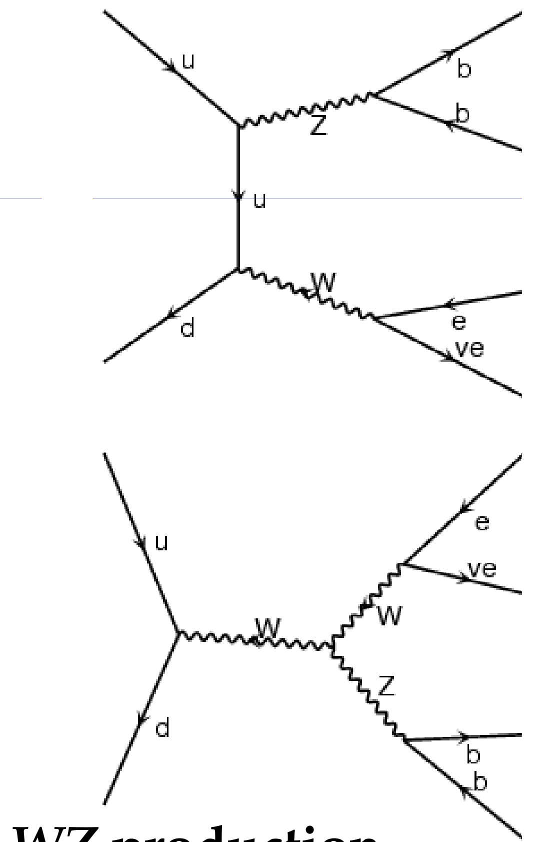
Predicted Event Yields

Jet Multiplicity	1 jet	2 jets	3 jets	≥ 4 jets
WLF	139.7 ± 27.3	53.9 ± 10.7	15.7 ± 3.1	4.2 ± 0.8
$Wb\bar{b}$	306.9 ± 106.9	144.7 ± 49.4	29.9 ± 9.7	6.4 ± 2.5
$Wc\bar{c}$	63.1 ± 22.0	43.0 ± 14.7	8.7 ± 2.8	1.9 ± 0.8
Wc	185.7 ± 47.2	34.4 ± 9.0	3.4 ± 0.9	0.6 ± 0.2
$t\bar{t}$(6.7pb)	6.9 ± 1.2	42.0 ± 6.6	84.9 ± 12.8	98.6 ± 14.3
Single Top	16.7 ± 1.8	23.5 ± 2.4	4.8 ± 0.5	0.8 ± 0.1
Diboson/$Z^0 \rightarrow \tau\tau$	11.7 ± 2.2	14.2 ± 2.3	3.9 ± 0.9	1.0 ± 0.3
non-W QCD	84.2 ± 14.1	38.9 ± 6.7	12.1 ± 2.3	5.5 ± 1.2
Total Background	814.9 ± 140.7	394.4 ± 66.6	163.4 ± 18.7	118.9 ± 14.9
Observed Events	856	421	177	139
Expected Signal Events Higgs Mass 120		1.26 ± 0.12		

Question:
Can we ***measure*** *W+b production and* ***improve these predictions?*** *Ultimately* ***improve the models****?*

Implications and Future

- 16% relative error on the cross section
  - x2 improvement over prediction for *W+b* production as background in Higgs search
  - Need to incorporate this result into the background prediction!
- Story is not yet completed
- First usage: Search for WZ production
  - same final state as WH
  - x3-4 larger production rate than WH
  - Good testbed for all new ideas and techniques



***WZ* production**

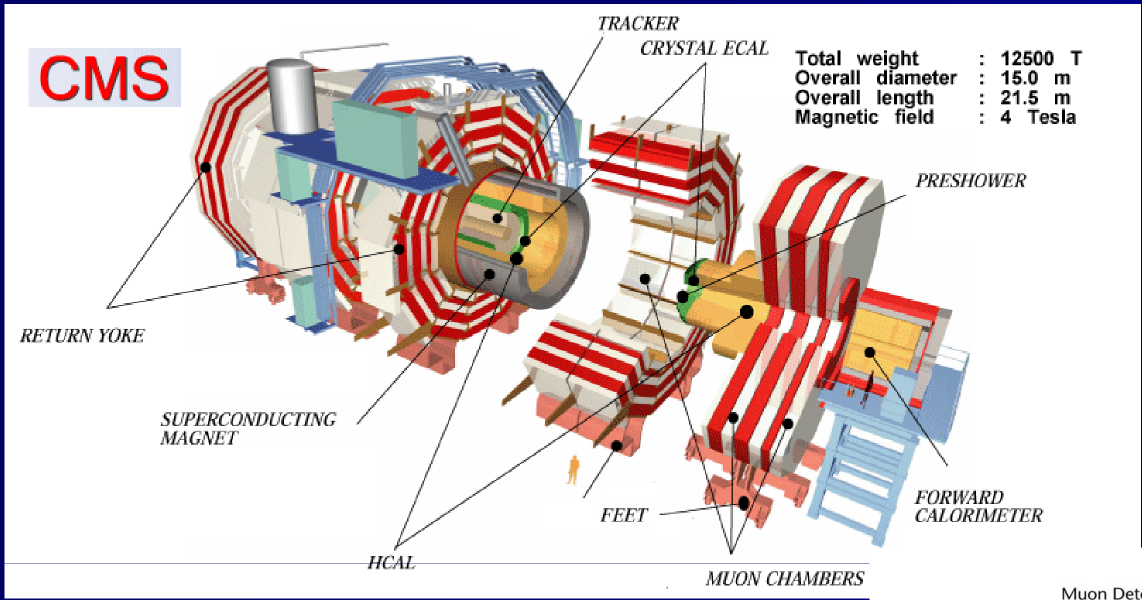
The Dawn of a New Era

	Tevatron	LHC
Radius (km)	1	4.3
Beams	$\bar{p}$-p	p-p
C.M. Energy (TeV)	1.96	14
N-per-bunch (1E9)	60 x 240	110 x 110
N-bunches	36 x 36	2808 x 2808
Bunch Spacing (ns)	396	25
Collision Rate (MHz)	1.7	40

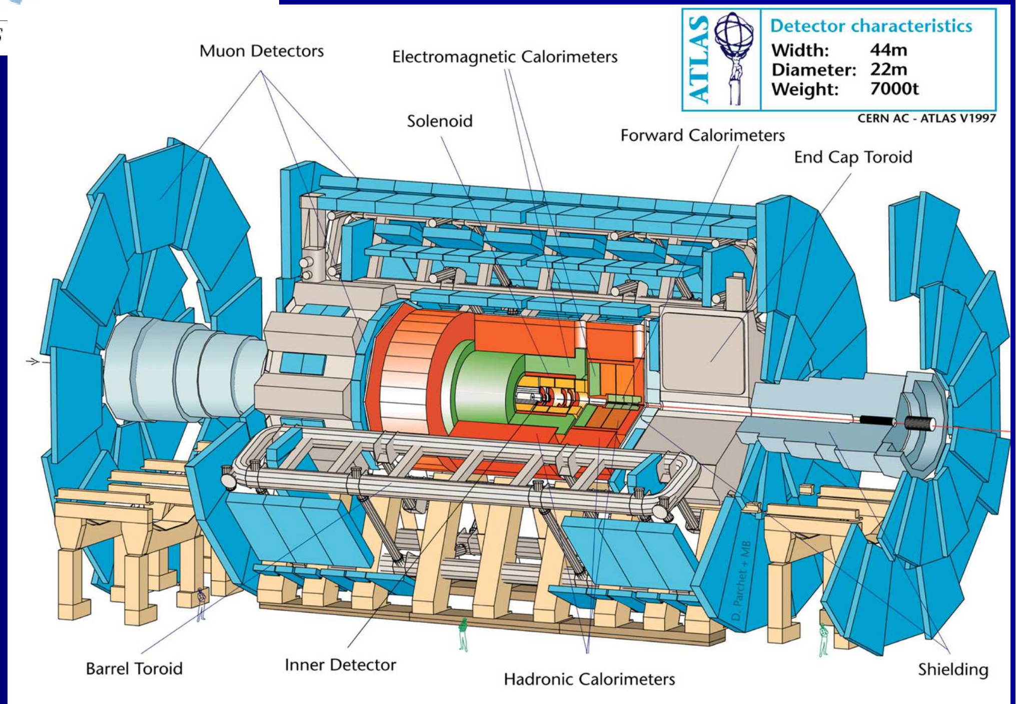
The Large Hadron Collider

Geneva, Switzerland

The Experiments of the LHC



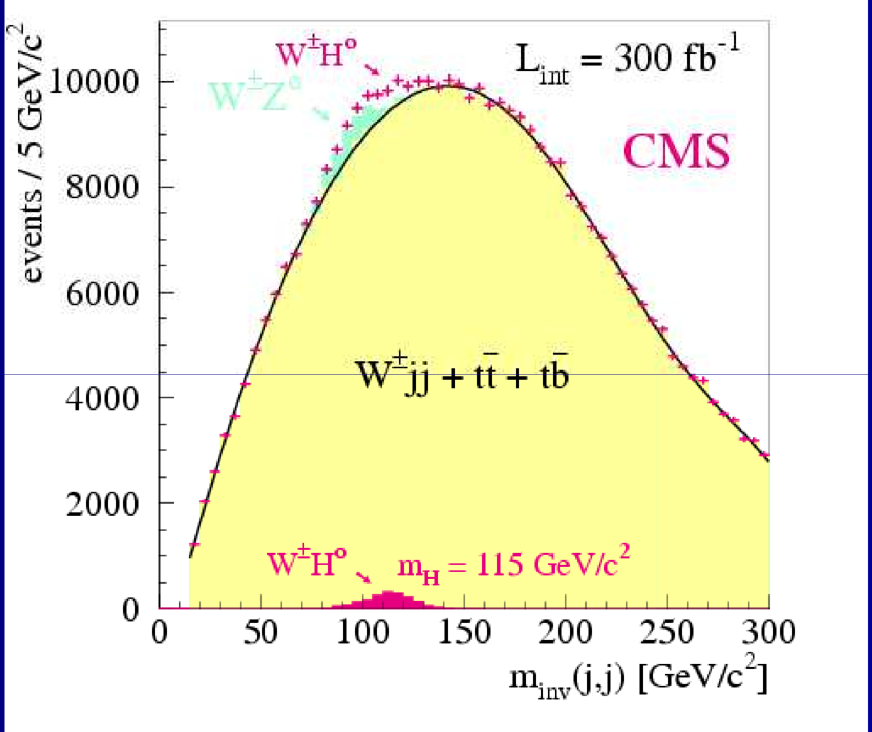
- **Mission:**
  - *Confirm* what we think we know
  - *Probe* what we know we are missing
  - *Search* for things yet only imagined



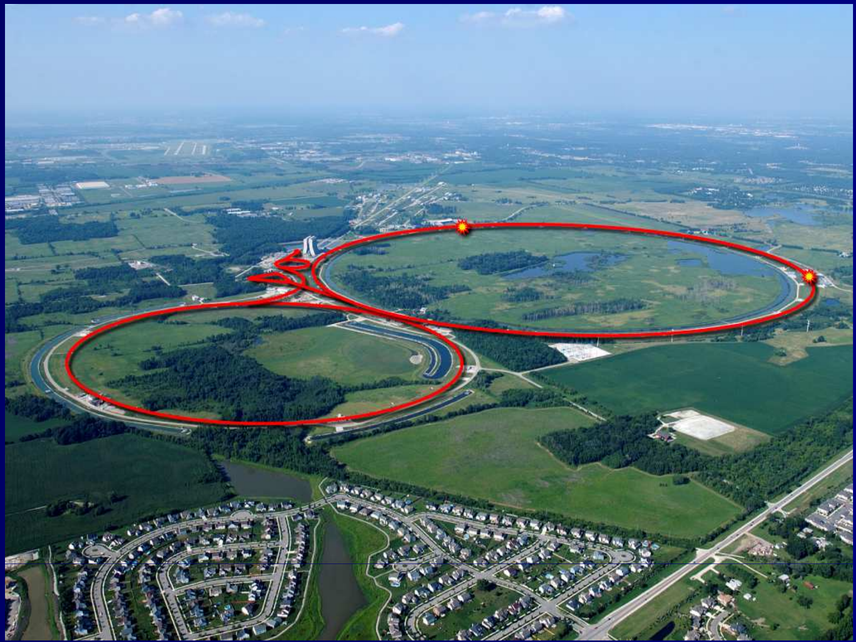
W+b Production: Relevance at the LHC

- Understanding *W+b*-jets at the Tevatron is important also for LHC
  - *WH* observation will be sought at CMS - not a discovery mode but still important
  - This channel plays a vital role in understanding a Higgs discovered through other avenues
  - Lessons learned at the Tevatron can help build better models for ATLAS and CMS

CMS 2002/006



Conclusions



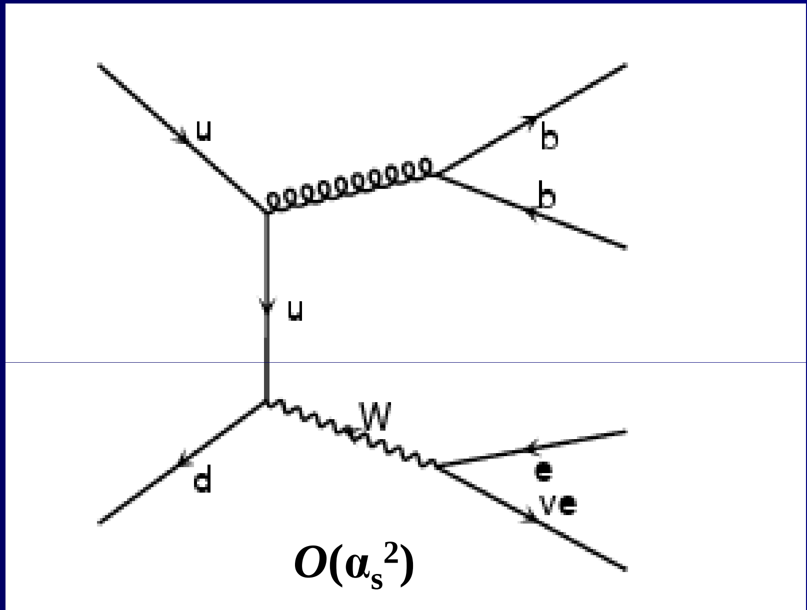
- This is an exciting time for particle physics!
- The search for the Higgs is at the heart of some crucial questions about the fundamental world
- There are many opportunities to contribute – success will hinge on understanding every facet of the search

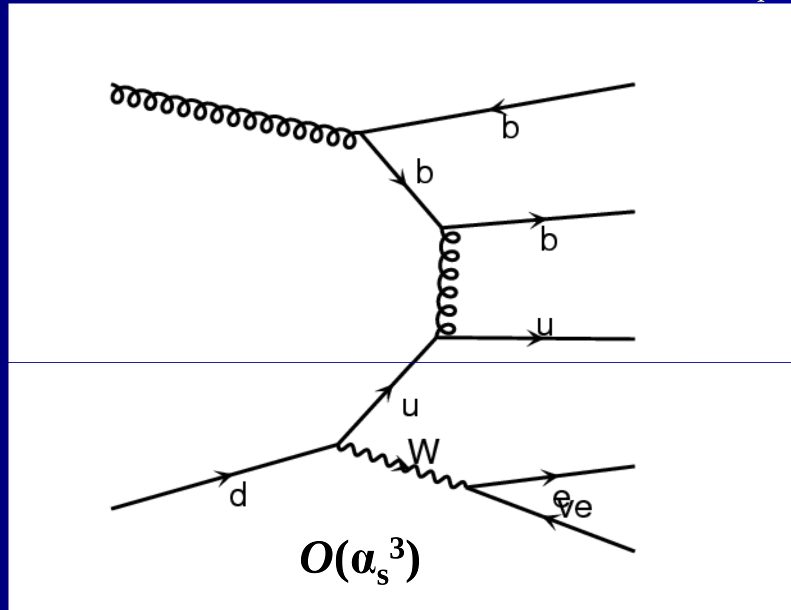
Backup Slides

Why Study *W*+*b*-jet Production?

- **First, a definition:**
  - ***W*+*b*-jets** refers to QCD production of *b*-jets in events with a *W* boson

Made with MadGraph





Examples of *W*+*b*-jets production at tree level

- **Why is *W*+*b*-jets interesting?**
  - Consider some primary Run II targets…