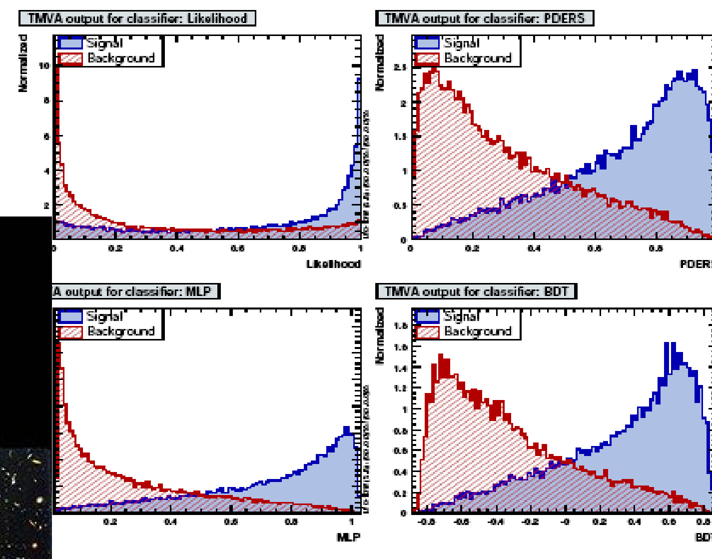
Heavy hadron spectroscopy

New eyes on the universe—400 years of telescopes
Marj Corcoran APS Meeting, Denver
May 2009



Heavy hadron spectroscopy

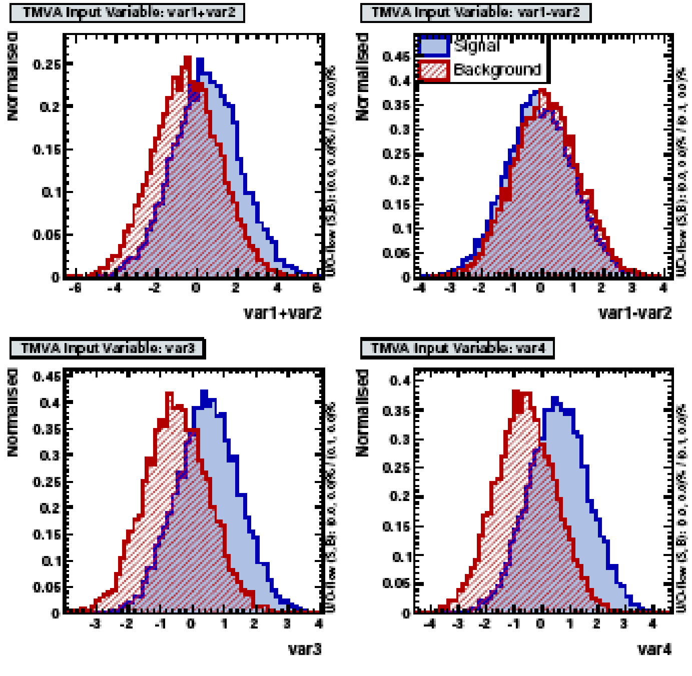
“new eyes”= new and powerful analysis techniques

Outline

I. Multivariate analysis techniques
II. B-baryons
III. Charmonium and bottomonium
IV. XYZ mesons

Multivariate techniques

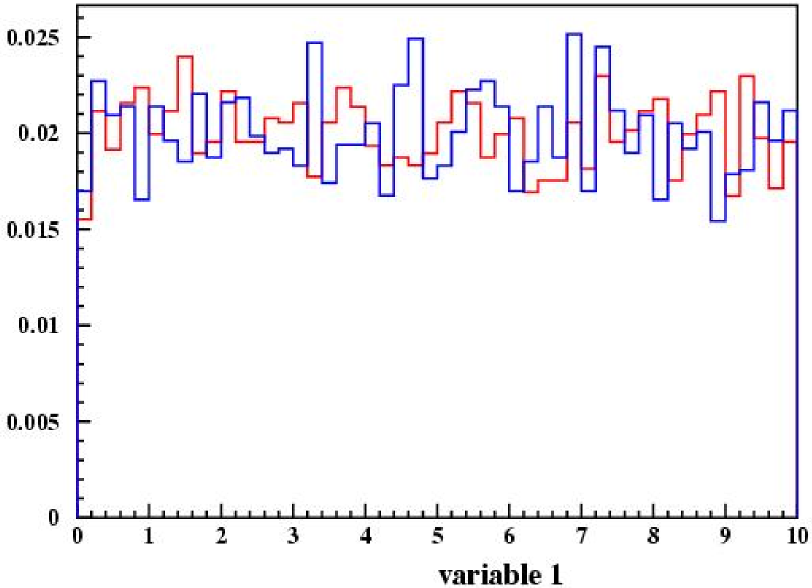
The "traditional cut-based " analysis methods make cuts on individual variables to separate signal and background.
But what if your variables look like this?



A clean separation between signal and background looks hard.

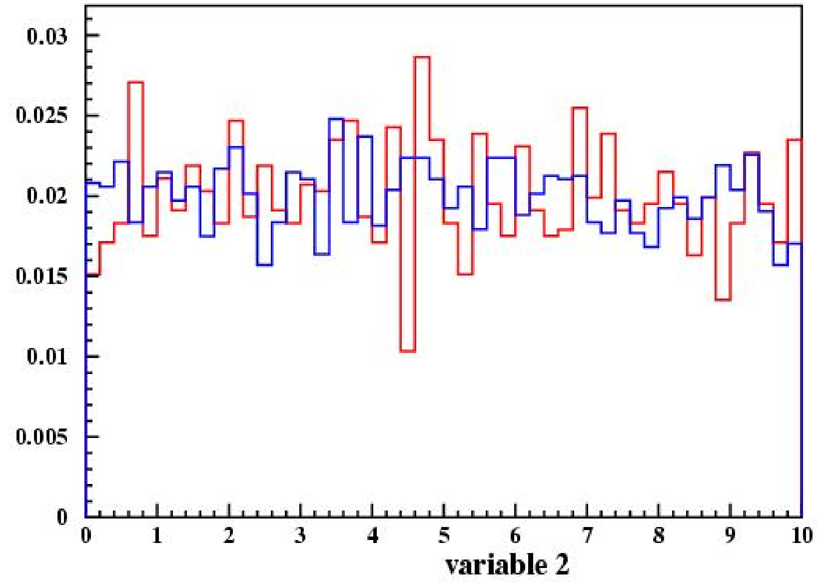
Over the past ~10 years, so-called multivariate techniques have gained acceptance.

A toy example

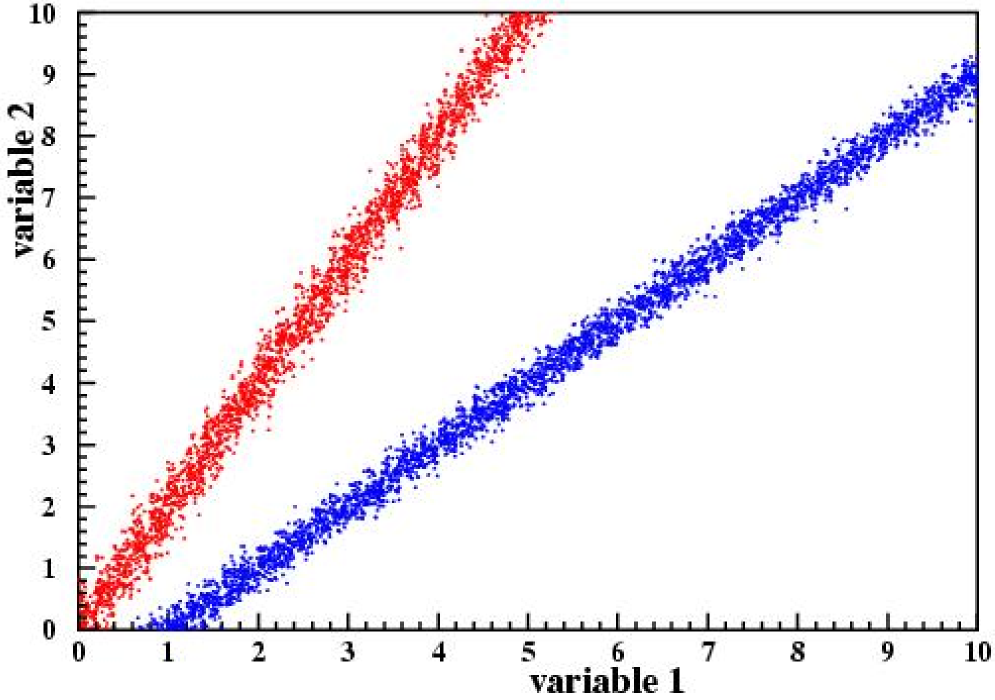


Here is a toy example—two variables blue for signal, red for background.

Cuts on these variables one at a time will not make much headway.

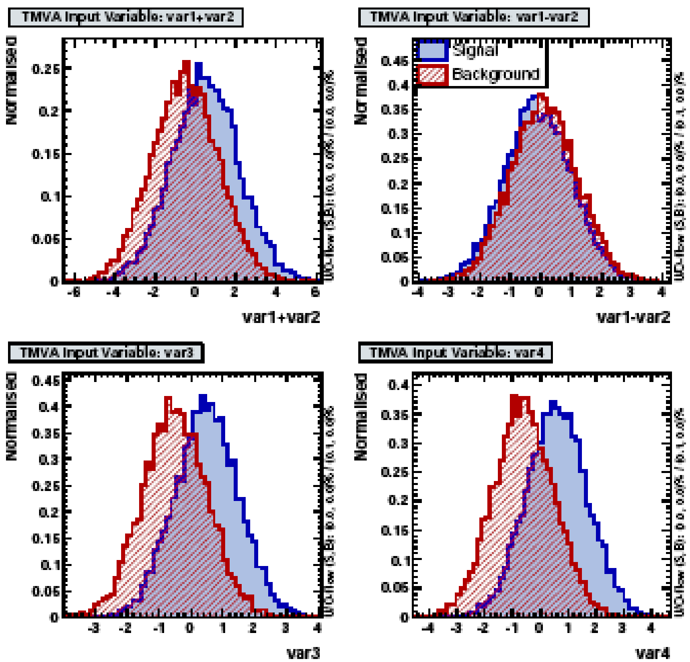


But a 2-D plot provides clear separation!

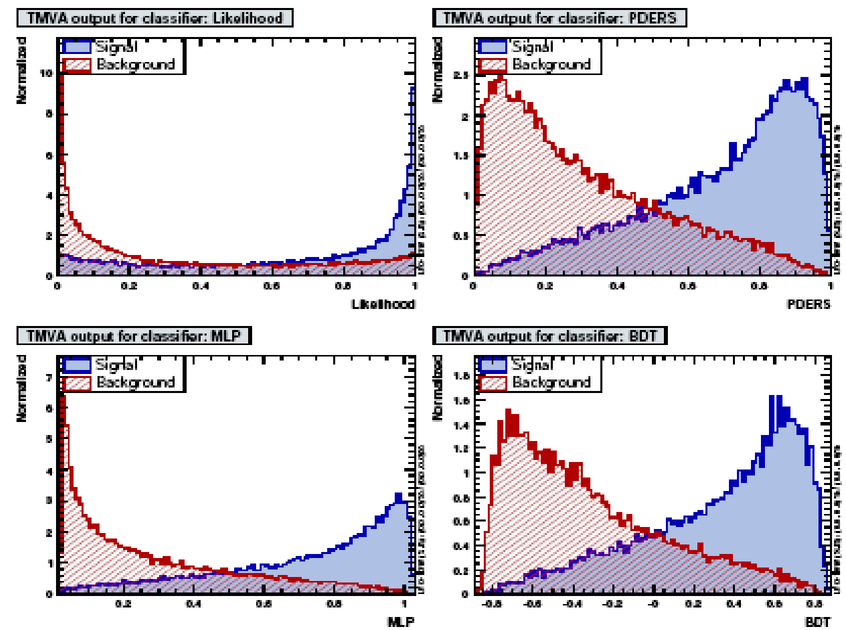


Generalize to 5 or 10 dimensions or more. Imagine making a generalized cut in a n- dimensional space. This is what multivariate techniques do.

A multivariate technique operates on several variables and produces a single output, the discriminate function.



input variables



The discriminant function classifies an event as “signal like” or “background like” with a single variable.

example plots from TMVA Users Guide arXiv physics/0703039

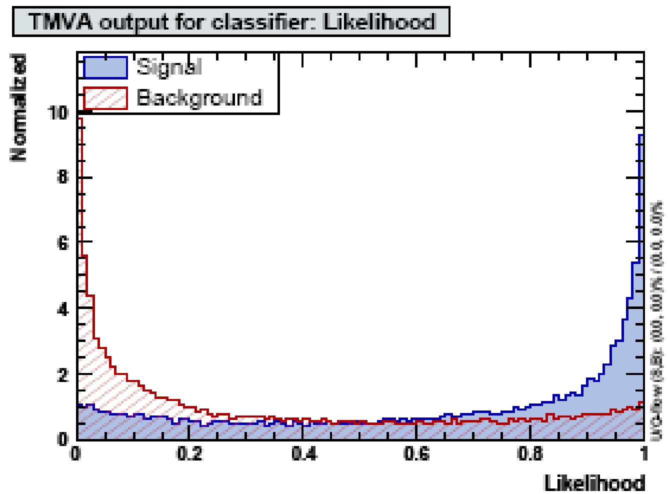
Excellent tools are now available

TMVA in ROOT (toolkit for multivariate analysis)
arXiv physics/070309   This is a great resource!

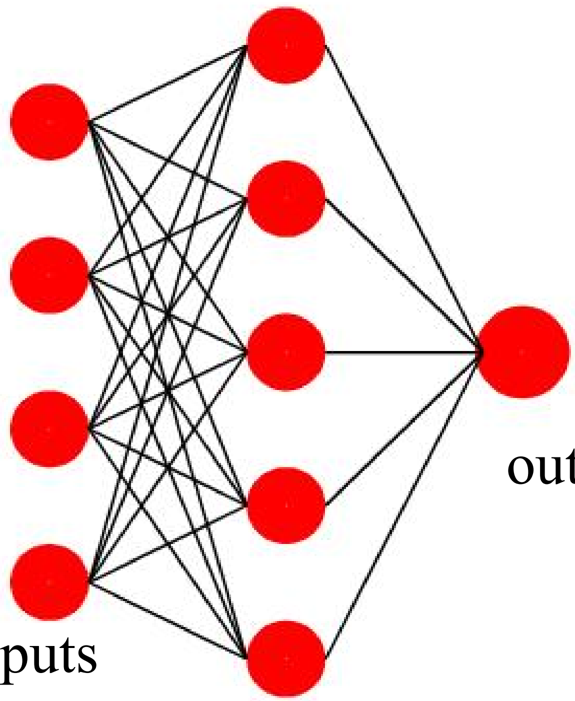
Most widely used (in my experience at D0):
Likelhood ratios, neural nets, decision trees

Likelihood ratio: Probability density functions (PDFs) for each variable are multiplied to form a joint PDF, separately for signal and background. A cut is made on the likelihood ratio:

$$y(i) = \mathcal{L}_s(i)/(\mathcal{L}_s(i)+\mathcal{L}_b(i))$$



Neural Networks

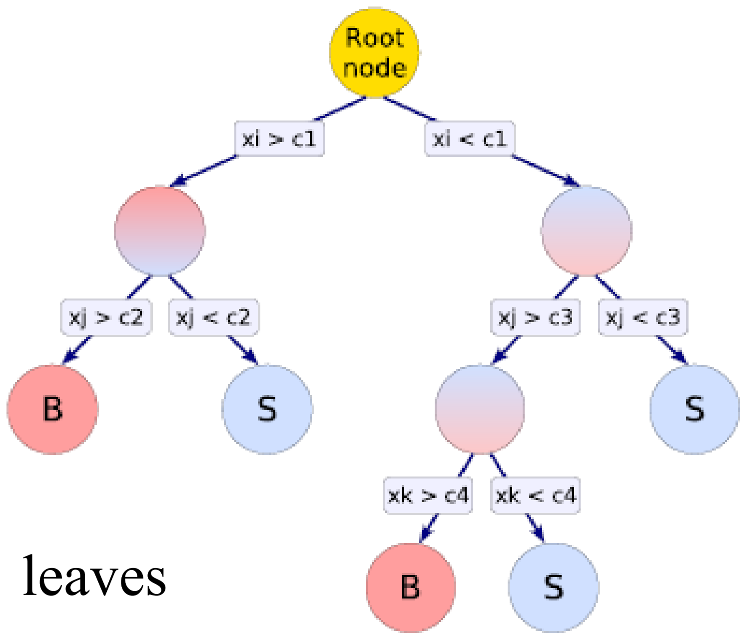


A neural net has several input nodes, all of which connect to one or more hidden layers of nodes with weights determined by the training process.

A NN must be trained with a known sample of signal and background events.

Criticism: it's a black box, you have no idea what its doing!
Pitfalls: The training samples must be general enough.

Decision trees



Decision trees branch on each variable depending on its value.

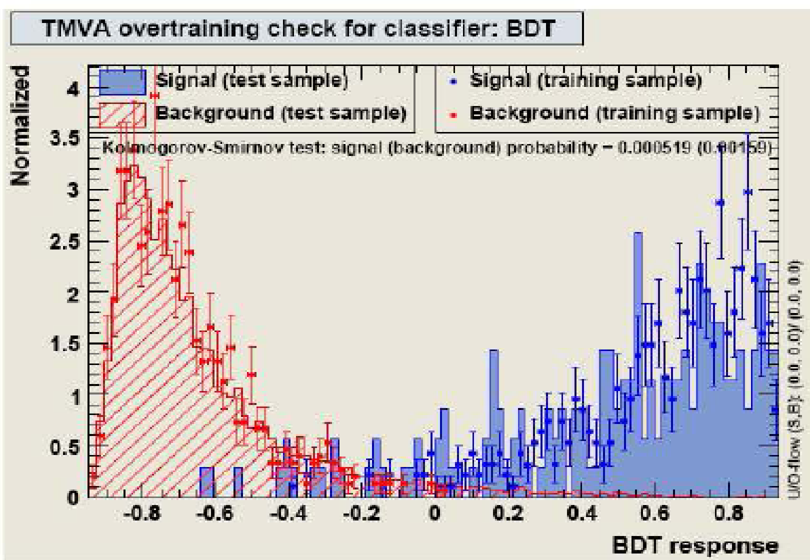
Like an NN, a decision tree must be trained on known signal and background samples.

The bottom nodes or leaves classify an event as S or B.

A single tree does a binary classification as S=+1 or B= -1

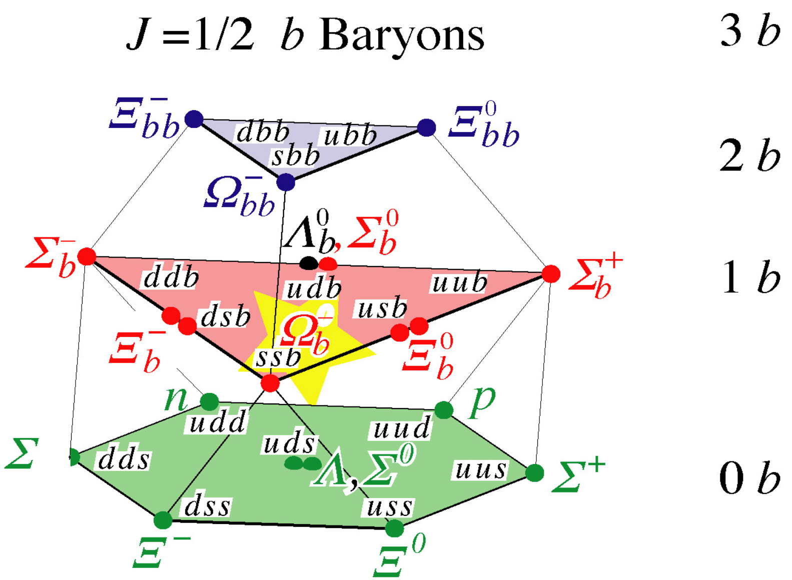
Boosted Decision Trees

A single decision tree can be unstable to statistical fluctuations in the training samples. A boosted decision tree creates may trees (a forest) by reweighting the training sample events.



The output discriminant function is a weighted average of the outputs from the forest.

B-baryons



Before RunII, only the Λ_b had been observed.

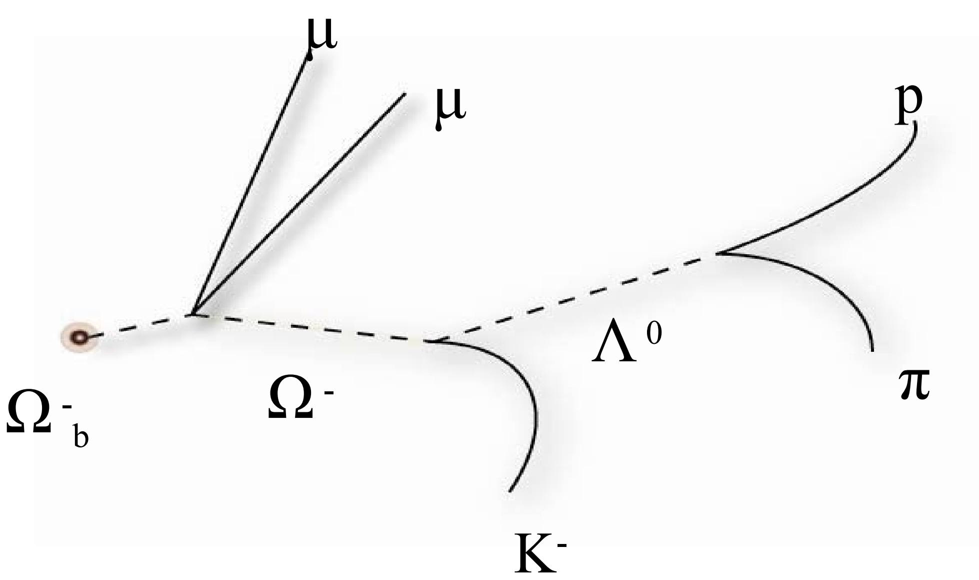
In 2006 CDF observed the charged Σ_b s and Σ_b^*

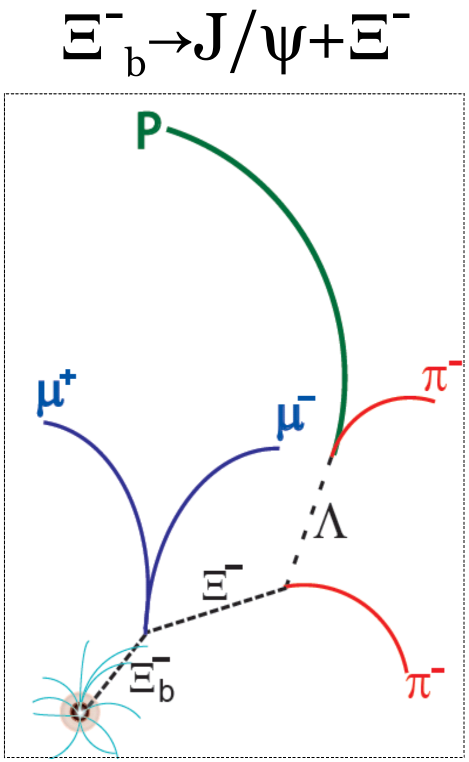
In 2007 both CDF and D0 observed the Ξ^-_b

In 2008 D0 observed the Ω^-_b

The lowest-lying states are expected to be the J=½ SU(4) 20-plet

Search for Ω_b

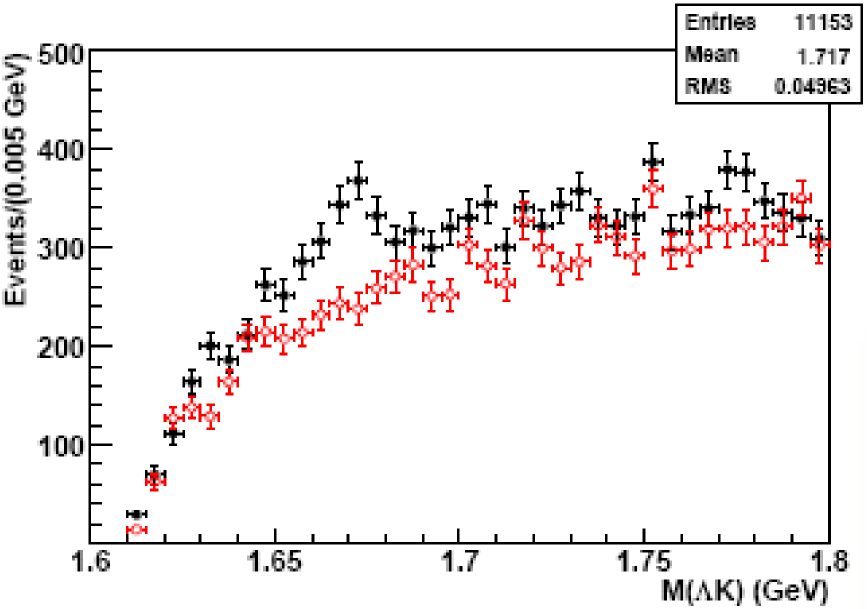




Decay of Ω^-_b,is very similar to the Ξ^-_b

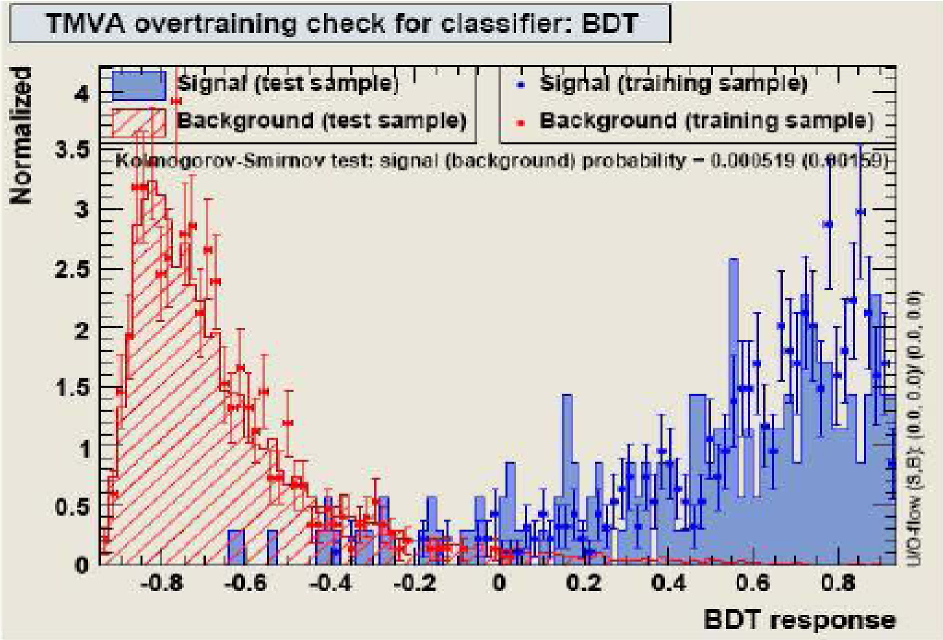
Reconstructing the intermediate Ω^- is crucial.

Initial Ω^- reconstruction



Red=wrong-sign background (Λ K^+)

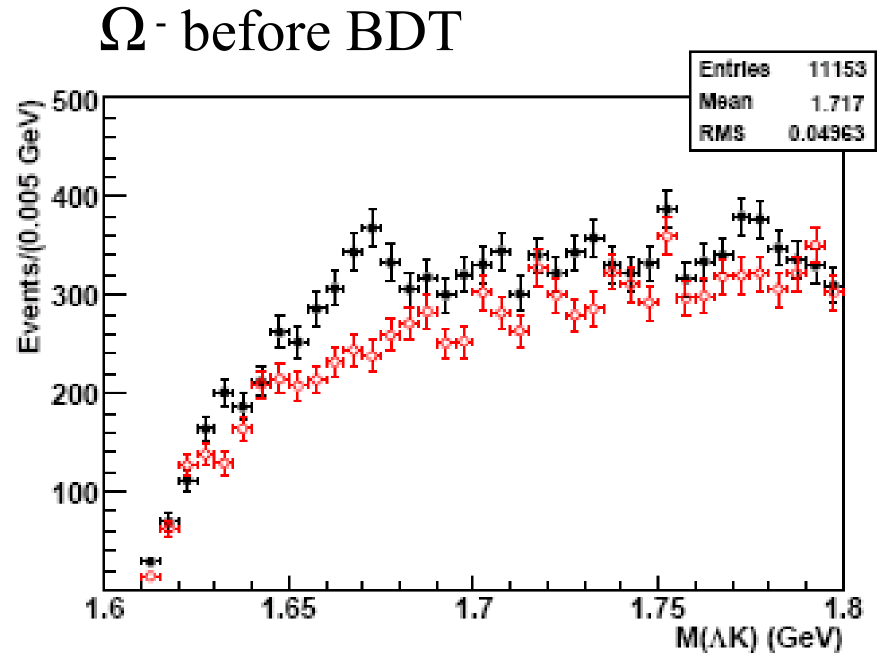
Applying a decision tree was key to pulling out the signal

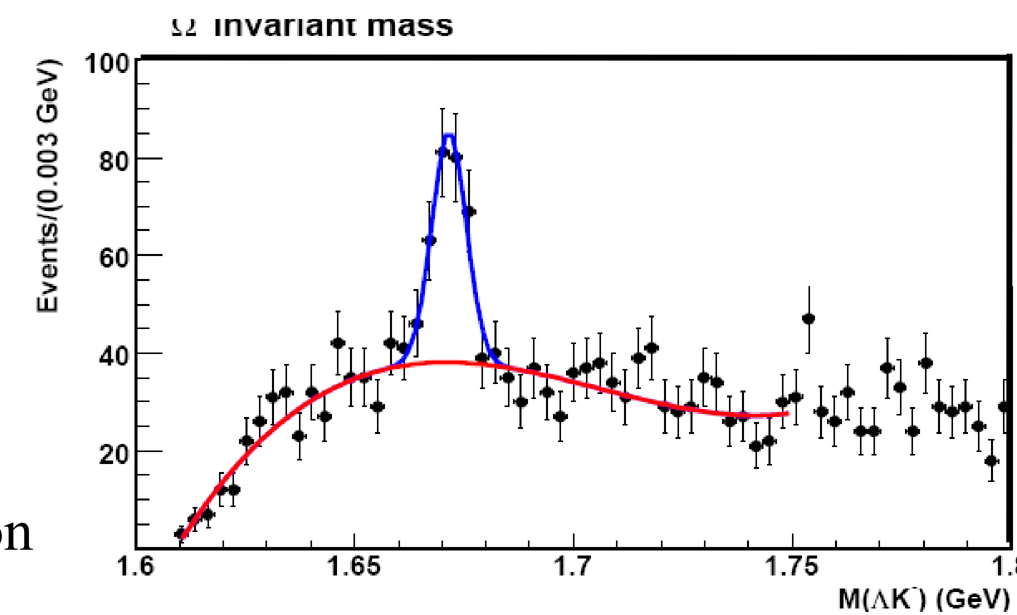


BDT discriminant function—cut at 0

20 variables in total, the most important were:
$p_t(K)$, $p_t(p)$ $p_t(\pi)$, Ω trasverse decay length

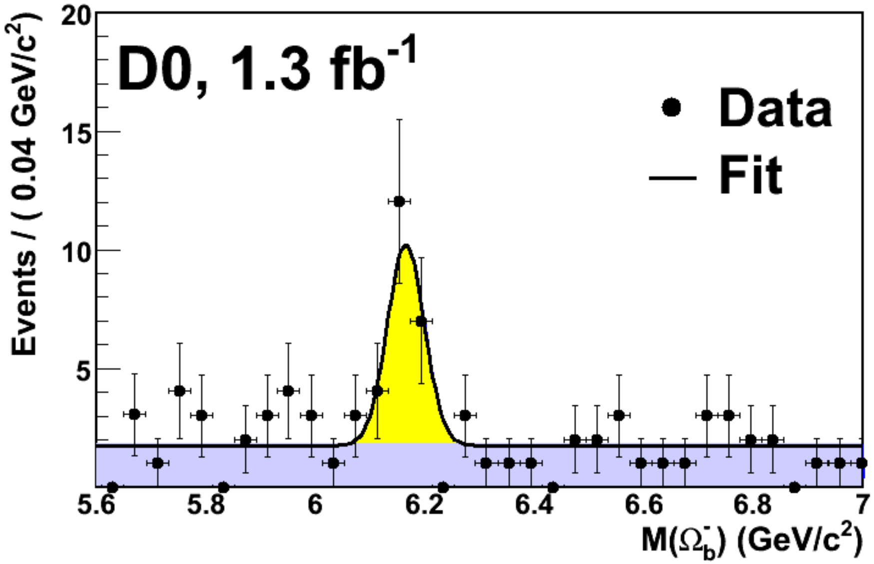
Decision trees handle correlated variables very well, and don't mind if you throw in extraneous variables.





after BDT selection

Final signal for Ω_b



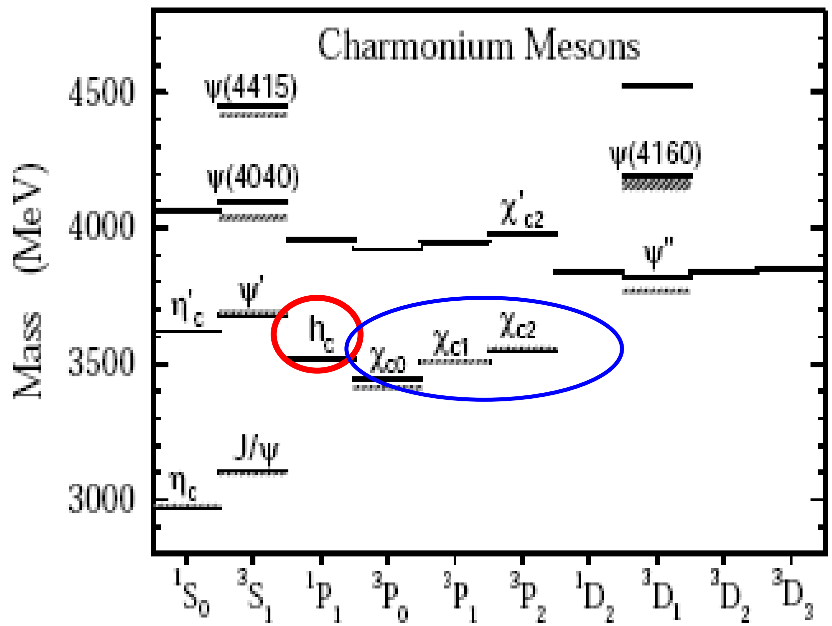
There are many more b-baryons, but finding them at the TeVatron will be hard.

Signal events 17.8 ± 4.9

Mass=6.165 ± 0.010(stat) ± 0.013 (sys)

significance=5.4 σ

Charmonium/ Bottomium states

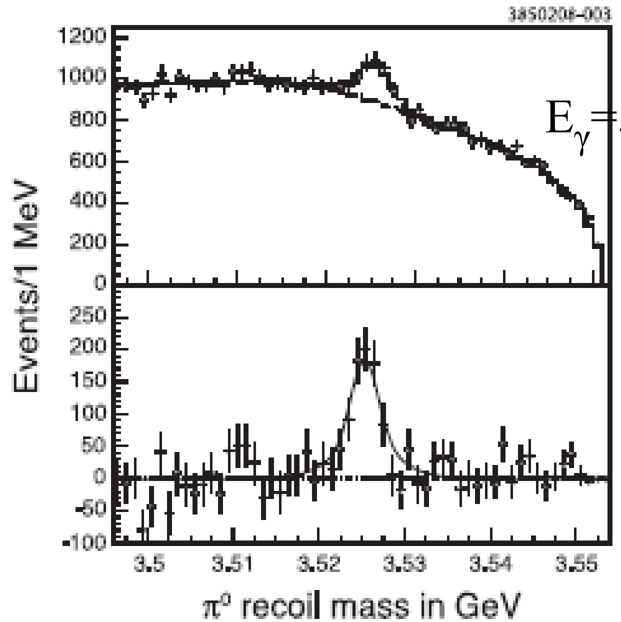


These states are well-understood as states in a potential that is Coulomb-like at short distances and linear at long distances.

CLEO has a recent precision mass measurement of the h_c

The mass splitting between the L=1 spin singlet and triplet states is expected to be zero for Coulomb-like potentials.

CLEO measurement of h_c mass



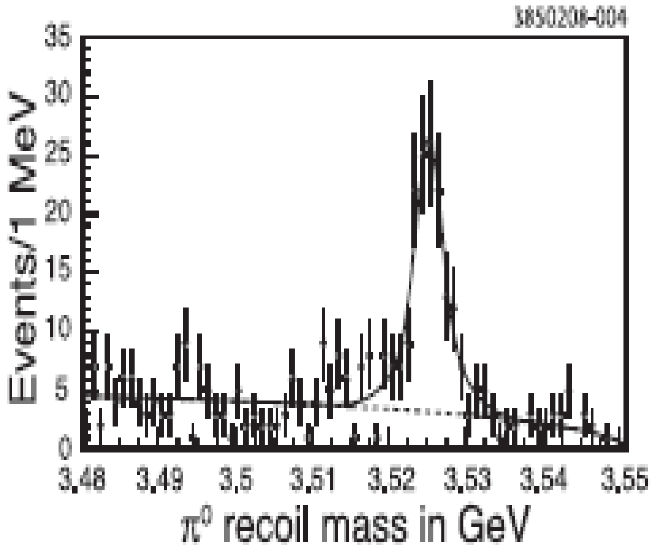
$E_\gamma = 503 \pm 35$ MeV

$\psi(2S) \rightarrow \pi^0 h_c$ with $\pi^0 \rightarrow \gamma\gamma$

and $h_c \rightarrow \gamma\, \eta_c$

One technique used inclusive events and measured the mass recoiling against the π .

CLEO measurement of the h_c mass



A second technique reconstructed the η_c in 15 different channels.

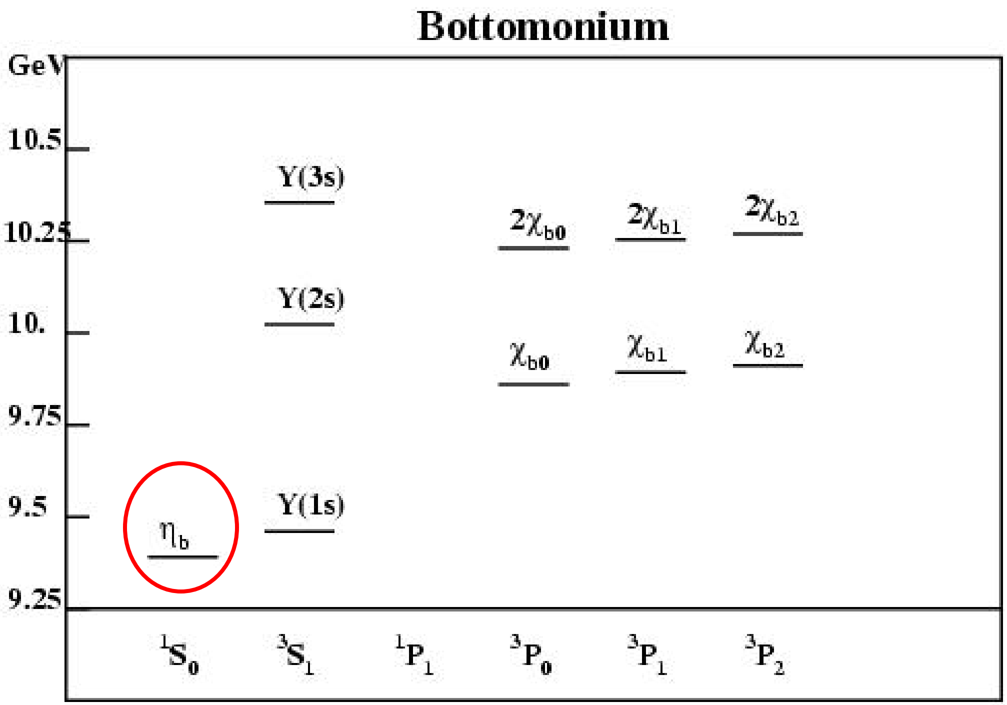
Results agree and can be averaged.

Mass of h_c =3525.28 ± 0.19(stat) ± 0.12(sys) MeV/c^2

Singlet/triplet splitting is 0.02 ± 0.19(stat) ± 0.13(sys)

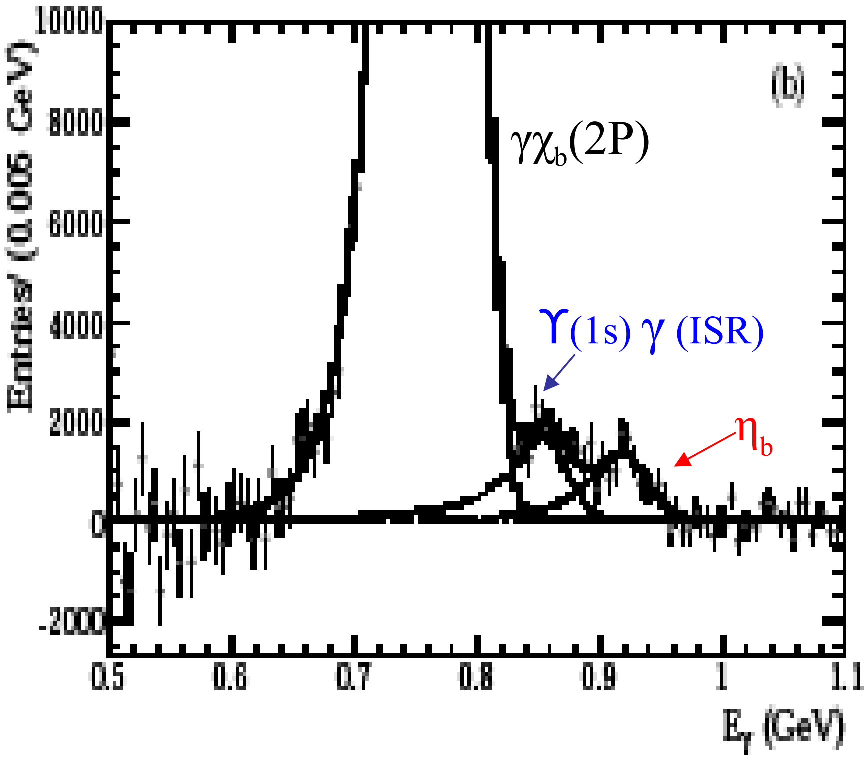
The triplet mass used is the spin-weighted averaged over the three J states of the χ

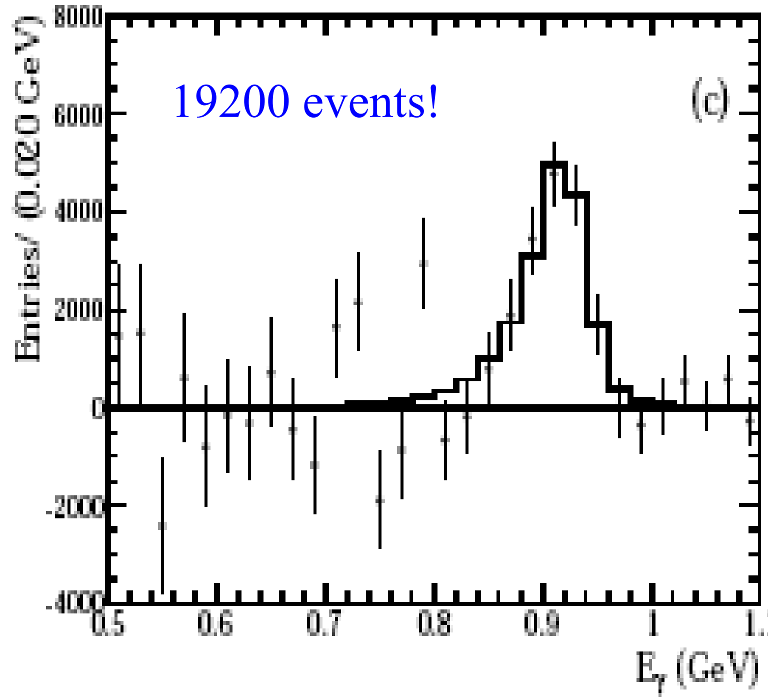
BaBar observation of η_b



After 30 years, the ground state of the $b\bar{b}$ system has finally been observed by BaBar. The η_b is found from $\Upsilon(3S) \rightarrow \gamma\, \eta_b$.

Observation of the η_b





η_b after background subtraction

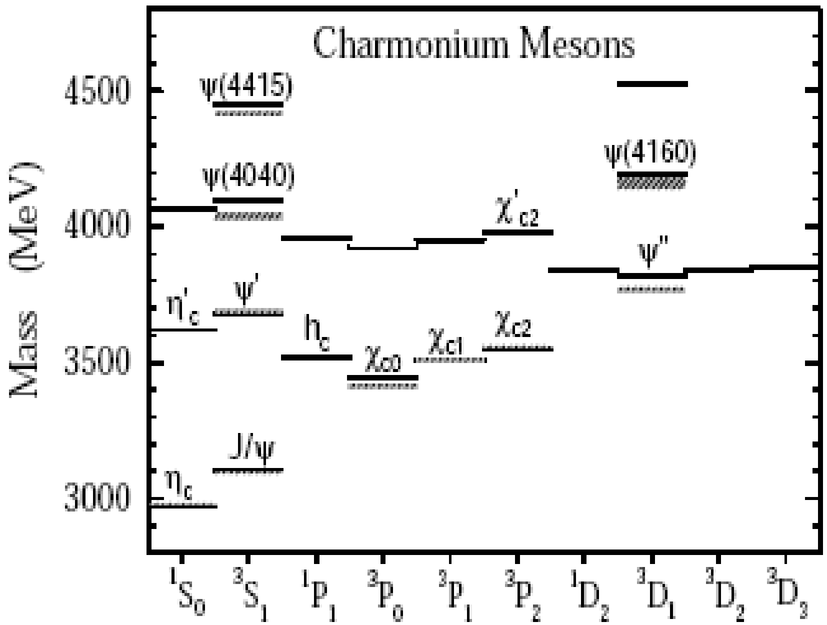
The photon is monoenergetic, but with substantial backgrounds from $\Upsilon(3S) \rightarrow \chi_b(2P)\,\gamma$ with $\chi_b(2P) \rightarrow \gamma\Upsilon(1S)$ and production via ISR of $\Upsilon(1S)\,\gamma$

Mass=9388.9 $^{+3.1}_{-2.3}$ (stat) ±2.7 (syst) MeV/c^2 a 10σ signal

PRL 100:071801 (2008)

η_b is also seen in $\Upsilon(2s)$ radiative decays at the $3.8\,\sigma$ level.

The "XYZ" Mesons



The charmonium states are well described by the $q\bar{q}$ potential.

So it was a surprise when a new state was found by Belle in 2003 that did not fit into the scheme. The X(3872) is now well-established. Several other states have been seen, the "XYZ" mesons.

The XYZ mesons

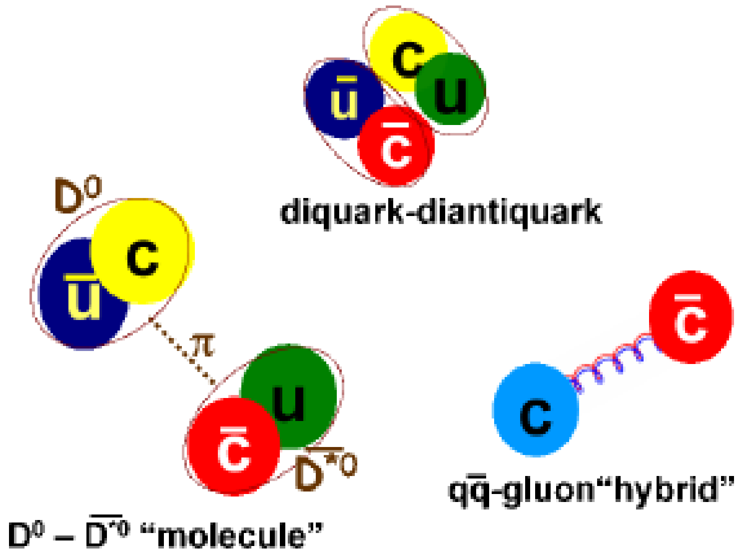
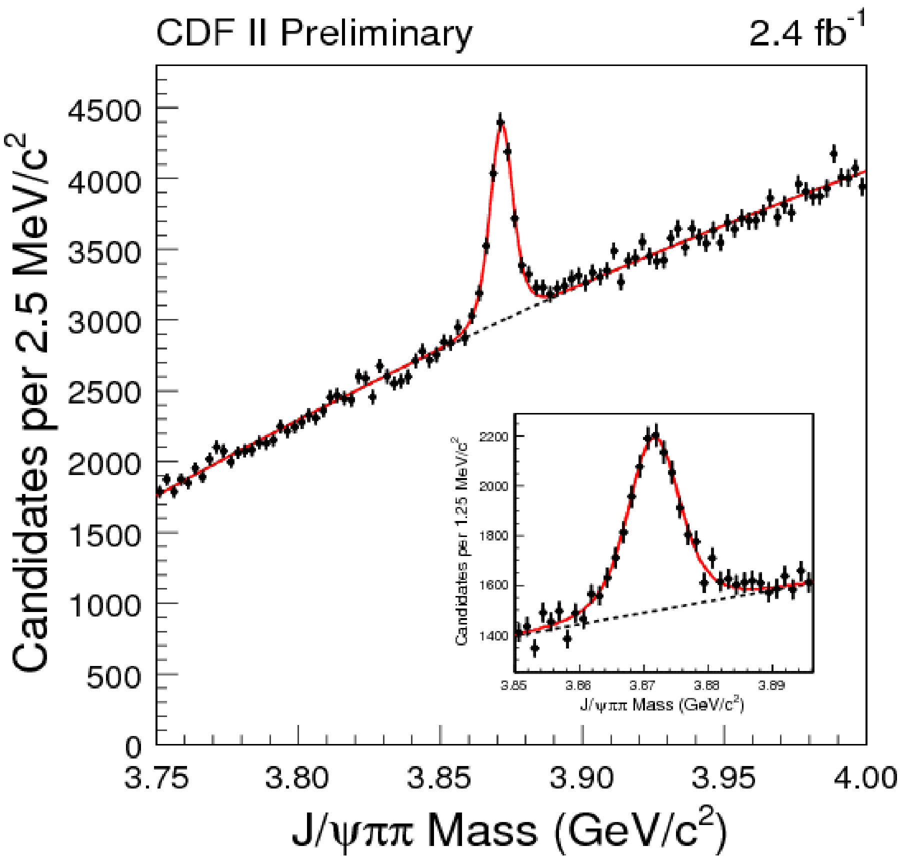


Figure is from an excellent review by Stephen Godfrey and Stephen Olson

arXiv:0801.3867

The exact nature of these states is under debate. It has been suggested they are molecular states, tetraquark states, or qqg hybrids.

X(3872) mass measurement by CDF



CDF has recently made a precision mass measurement of the X(3872)

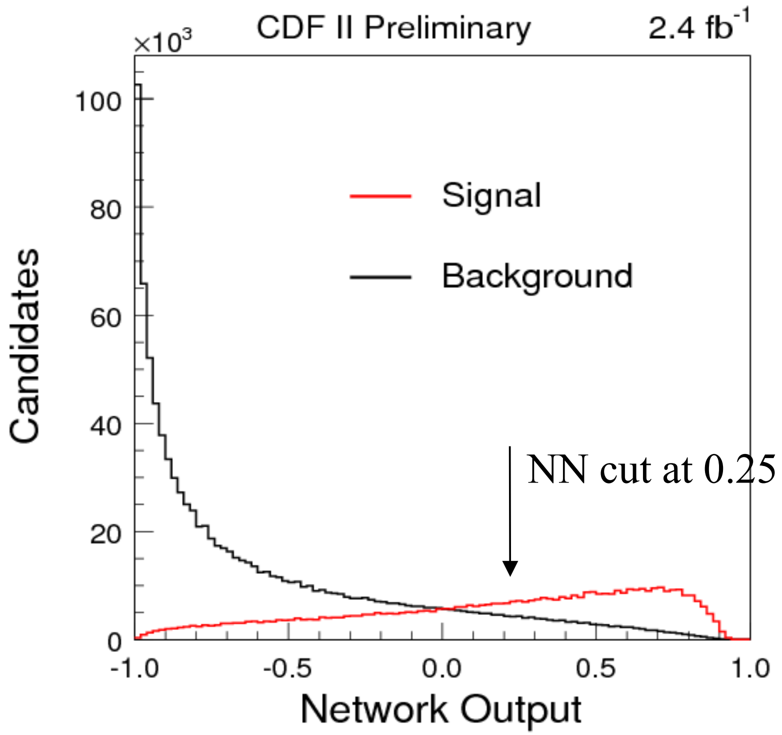
A tetraquark model predicts two states close together. A precise mass measurement can confirm or rule out two states.

X(3872)→J/ψ π π

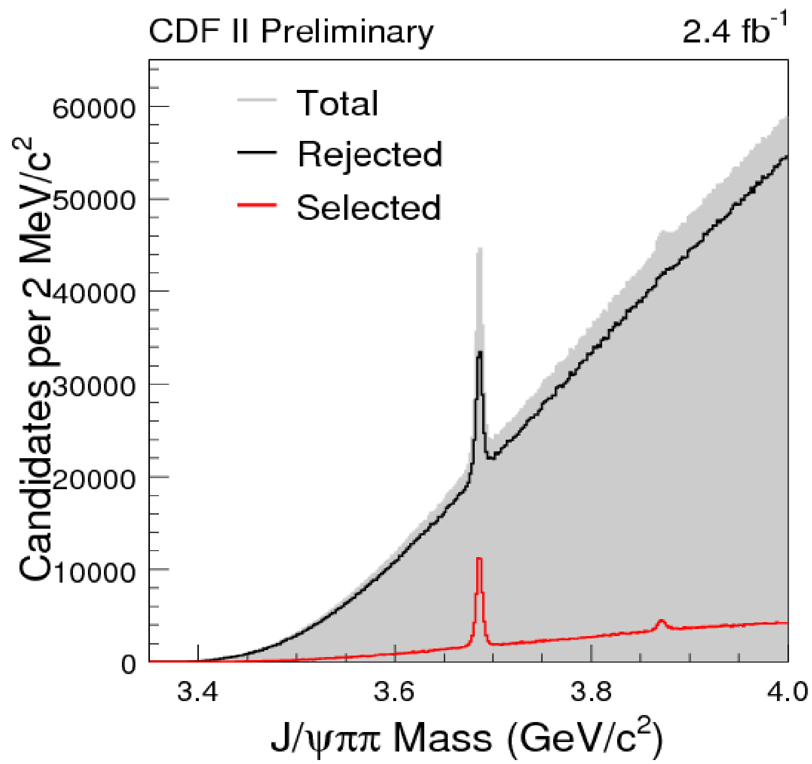
CDF Preliminary

X(3872)--CDF

CDF preliminary



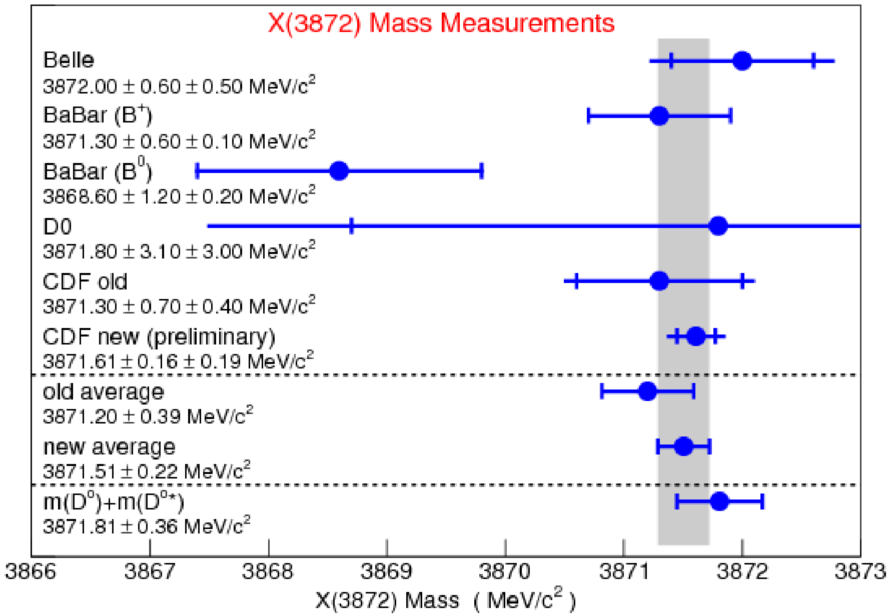
A neural net was used to help remove background



Effect of NN cut on mass

X(3872) mass

world data on X(3872) mass



There is no evidence for two states, $\Delta m < 3.6$ MeV/c^2 at 95% CL.

The X mass is below the $D + \overline{D}^*$ mass by 0.3 ± 0.4 MeV/c^2 so X could be a $D\overline{D}^*$ molecular state.

See the CDF conference note 9454, available from
http://www-cdf.fnal.gov/physics/new/bottom/bottom.html

More XYZ states

Z(3930) produced in $\gamma\gamma$ interactions, decays to $D\bar{D}$. Thought to be the radial excitation of the χ_{c2}

X(3940) produced in ee$\rightarrow$J/ψ X, decays to $D^*\bar{D}$, could be $\eta_c(3S)$

Y(3940) decays to J/ψ ω, first seen by Belle, recently observed by BaBar. Possibly radial excitation of χ_{c1}

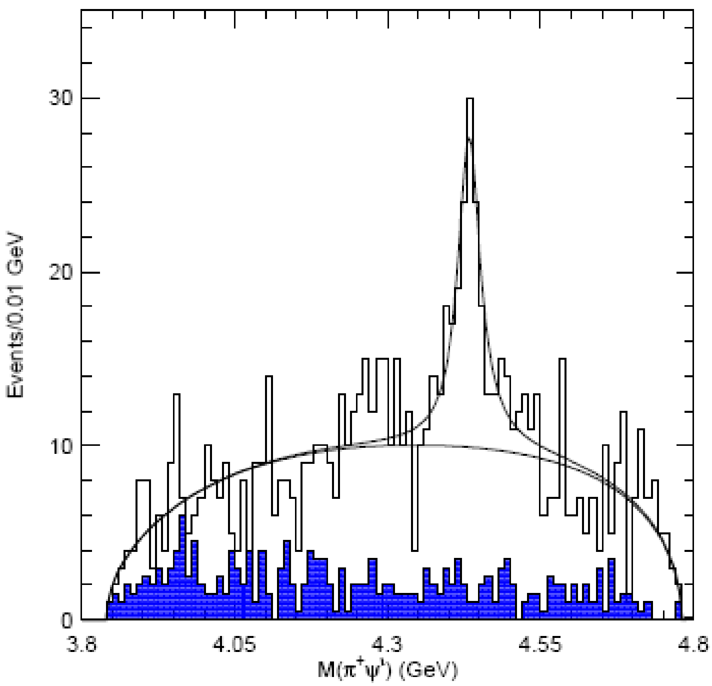
Y(4140) CDF recently reported evidence for this state, which decays to J/ψ Φ.

Y(4260) decays to J/ψ $\pi\pi$, produced in ISR

And charged states (next slide)

My head is spinning!

Charged XYZ States



Belle's Z(4430) mass peak

A charged state must have quark content $c\bar{c}d\bar{u}$, so such a state is a candidate for a tetraquark..

Belle has reported a charged state $Z(4430)^{\pm} \rightarrow \psi'\pi^{\pm}$ with significance 6.5σ
But this state is not seen by BaBar after a careful search.

Belle has recently reported two other charged states, Z(4051) and Z(4258) decaying into $\chi_{c1}\,\pi$

Belle: quoted $BR(B^0 \rightarrow K^+Z^-)*BR(Z^- \rightarrow \psi'\pi^-) = 4.1 \pm 1.0 \pm 1.4 \times 10^{-5}$

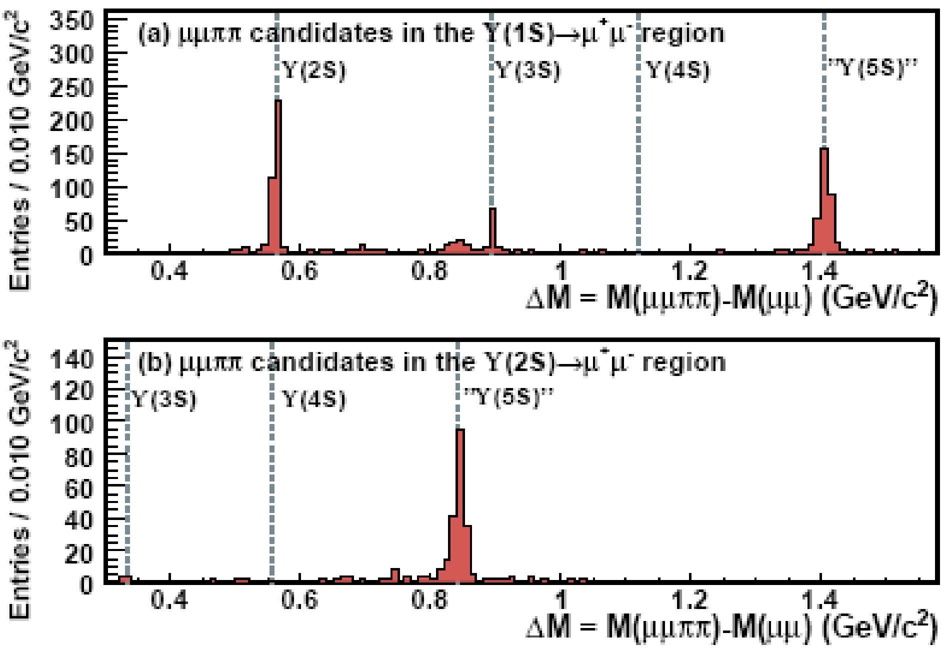
BaBar: $BR < 3.1 \times 10^{-5}$ at 95% CL

XYZ-type mesons in the $b\bar{b}$ system?

Belle has recently reported anomalous BR in $\Upsilon(5S)$ decays .

The decays $\Upsilon(5S) \rightarrow \Upsilon(1S)\,\pi\pi$ and $\Upsilon(5S) \rightarrow \Upsilon(2S)\,\pi\pi$ occur at rates100 expectations.

This could be evidence for a Y_b state close to and interfering with the $\Upsilon(5S)$



$M_{\mu\mu} = \Upsilon(1S)$

$M_{\mu\mu} = \Upsilon(2S)$

XYZ summary

•There are more states than I can keep track of, but not all are exotic. Some are most likely n=2,3 radial excitations of the η or χ states. But the situation remains confusing!

•The X(3872) is well-established, seems likely to be a loosely bound S-wave DD* state.

•The $Z(4430)^{\pm}$ could be a candidate for a tetraquark state but is not confirmed by BaBar.

•Two more charged states Z(4051) and Z(4258) are recently reported by Belle.

•Anomalous BRs of the $\Upsilon(5S)$ may be evidence for an "X-like" state in the bb system.

Summary

Powerful multivariate techniques such as neural nets and decision trees are gaining wide acceptance and are likely to become even more widely used in the future (at LHC for example).

b-baryons-- Ω_b has been observed by D0, not yet confirmed by CDF
Unclear if there will be more b-baryons from TeVatron.

charmonium—precision mass measurement of h_c confirms the small (possibly zero) of the singlet-triplet splitting for L=1.

bottomium—first observation of the η_b, the ground state of bb

Prospectives/thanks

Over the next few years, close collaboration between theorists and experimentalists will clarify the XYZ mesons and the excited charmonium/bottomonium states. We will hear a great deal more from Babar, CLEO, and Belle. The TeVatron can also help clarify the situation.

XYZ-type states should be seen in the $b\bar{b}$ system, and both the TeVatron and LHC experiments should look for them.

Many thanks to everyone who helped me with information for this talk:
Owen Long from BaBar
David Cassel from Cleo
Michal Kreps and Giovanni Punzi of CDF
Eduard de la Cruz Burelo and Brendan Casey of D0
Jon Rosner

Backup slides

Godfrey and Olsen's summary table

Table 1: A summary of the properties of the candidate XYZ mesons discussed in the text. For simplicity, the quoted errors are quadratic sums of statistical and systematic uncertainties.

state	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR), J/ψ decay
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi, \gamma J/\psi$	$B \to KX(3872)$, $p\bar{p}$
$X(3875)$	3875.5 ± 1.5	$3.0^{+2.1}_{-1.7}$		$D^0\bar{D}^0\pi^0$	$B \to KX(3875)$
$Z(3940)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma$
$X(3940)$	3942 ± 9	37 ± 17	J^{P+}	$D\bar{D}^*$	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	J^{P+}	$\omega J/\psi$	$B \to KY(3940)$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	J^{P+}	$D^*\bar{D}^*$	$e^+e^- \to J/\psi X(4160)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
Y_b	$\sim 10,870$	?	1^{--}	$\pi^+\pi^- \Upsilon(nS)$	e^+e^-

Similar states should exist in the bb system, and the TeVatron and LHC should search for them.