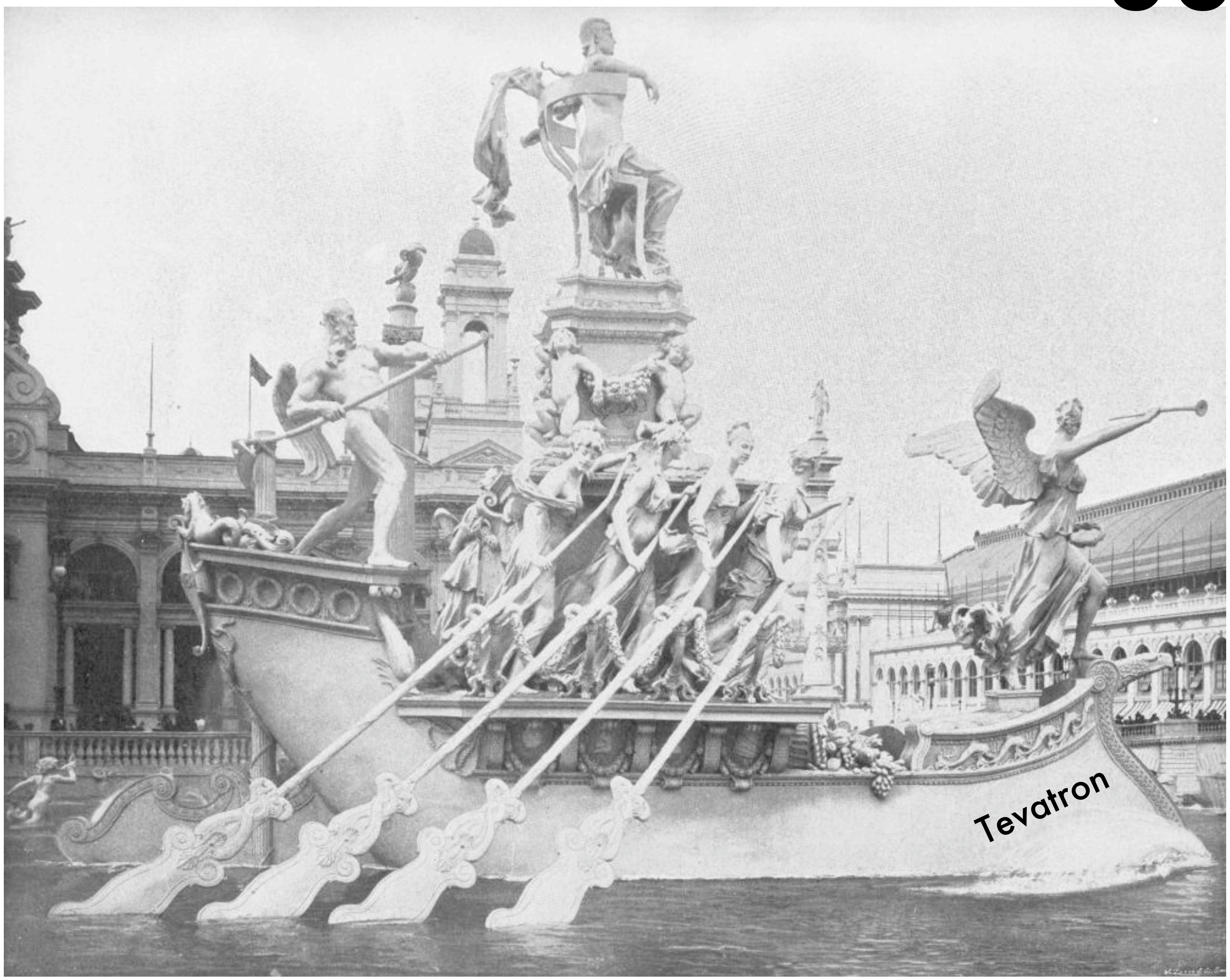
Missing E_T+b-jets: from single top observation to limits on Higgs at



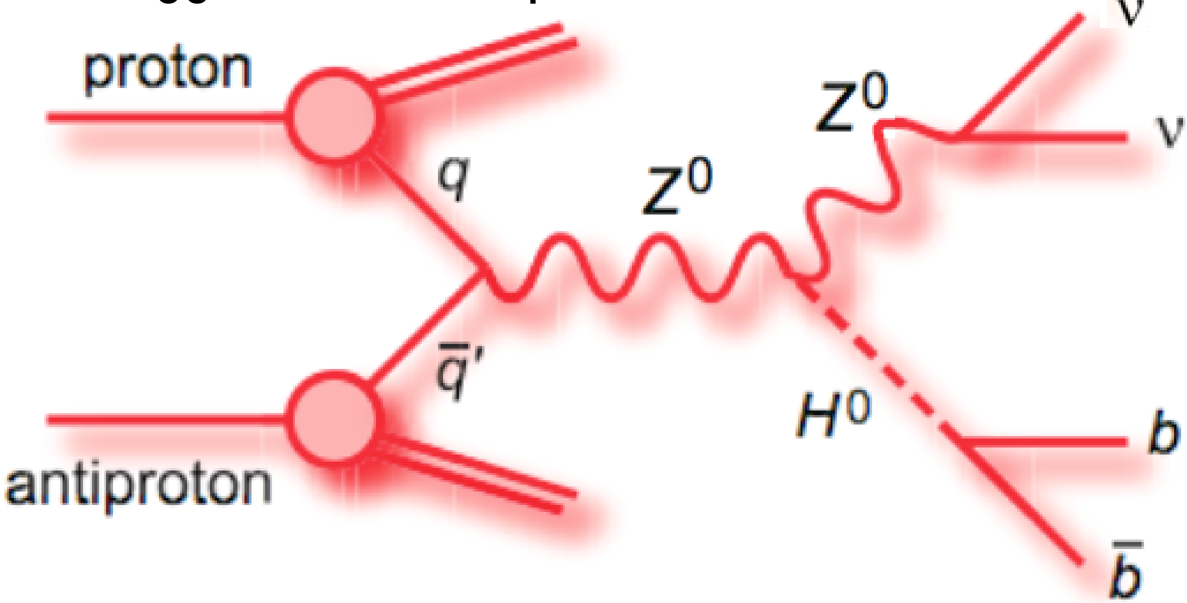
Photograph of the Columbian Fountain at the World's Columbian Exposition in Chicago

Fabrizio Margaroli
Purdue University
On behalf of CDF

The missing E_T+b-jets signature

Searches in MET+b-jets signature are very interesting:

- In SM, with this signature you can catch one of the most striking production modes for the Higgs boson
- Associated production of Higgs boson together with a vector boson
- Search for SM Higgs boson in the process $ZH \rightarrow \nu\nu\, bb$

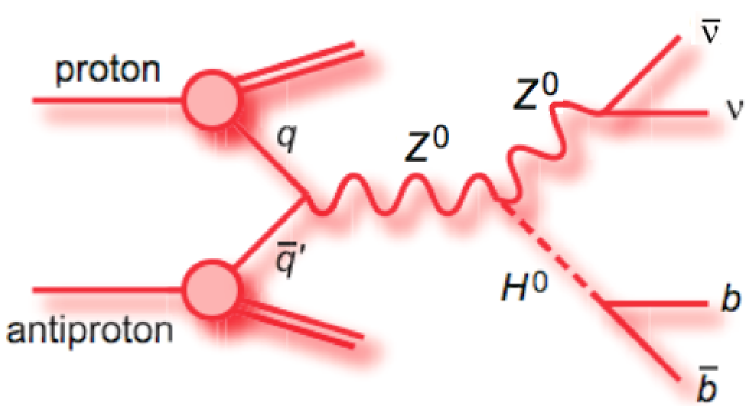


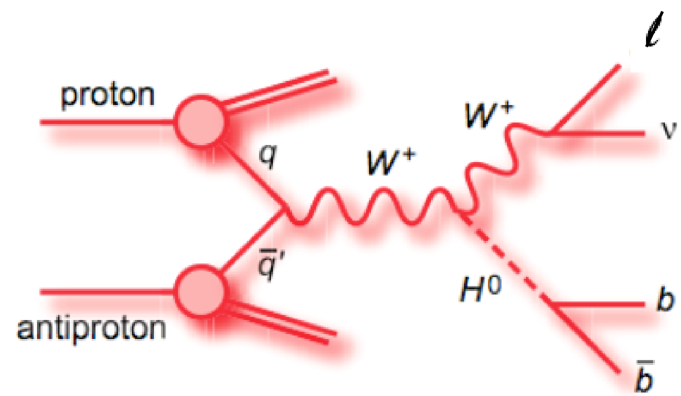
- Several SUSY processes (squarks/gluinos) would show up in the MET+(b)jets signature

The missing E_T+b-jets signature

That would be the end of the story for an *ideal detector*. We are going to cover here much more though. Infact, due to limitations in the lepton coverage, this signature is actually ***way more interesting*** than that

- Whenever you miss the lepton, you accept in the same sample another key production mode for the Higgs boson, WH → lν bb





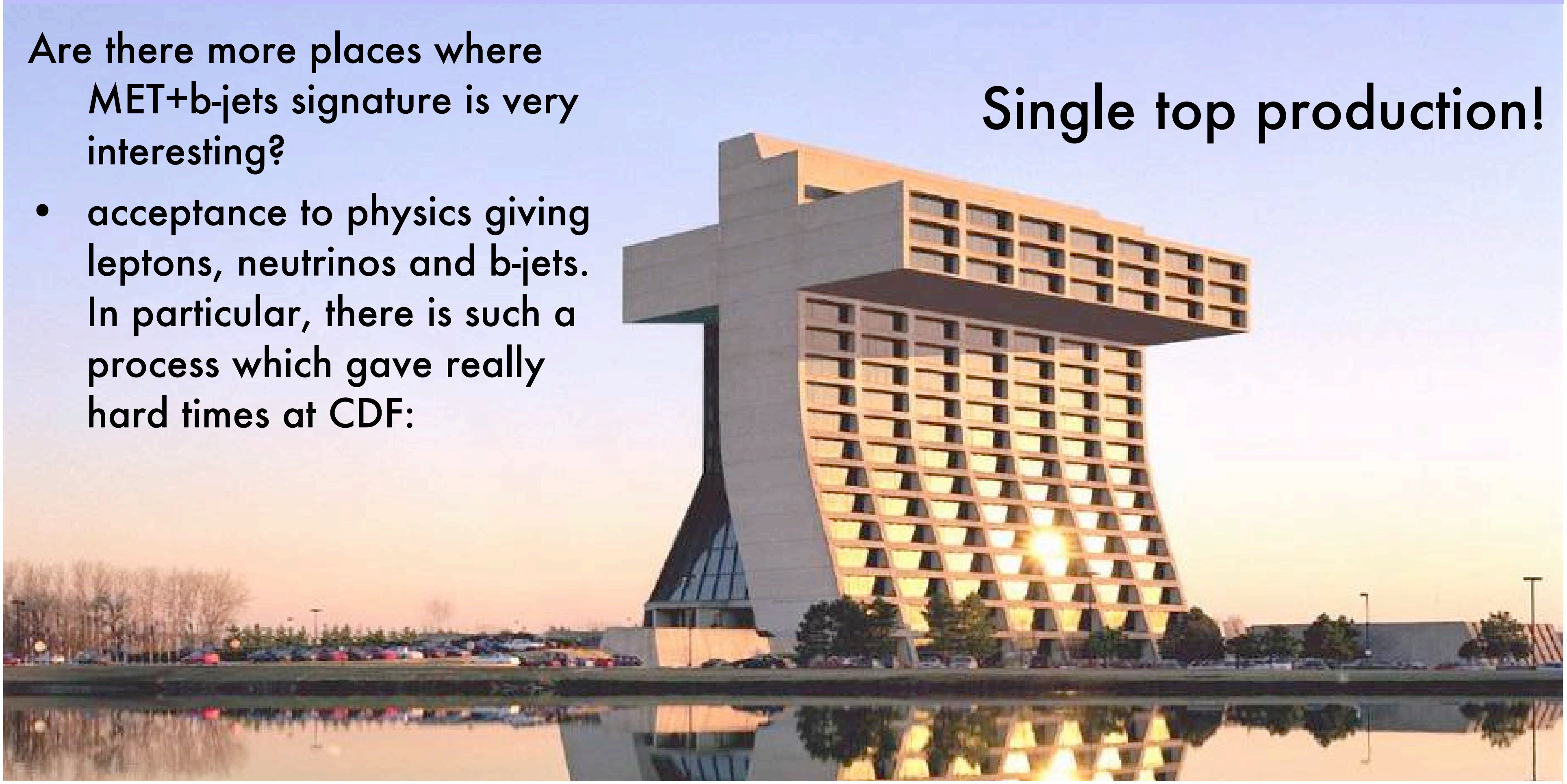
- Search for ZH → νν bb and WH → lν bb in the MET+b-jets signature

Extra goodies!

Are there more places where MET+b-jets signature is very interesting?

- acceptance to physics giving leptons, neutrinos and b-jets. In particular, there is such a process which gave really hard times at CDF:

Single top production!

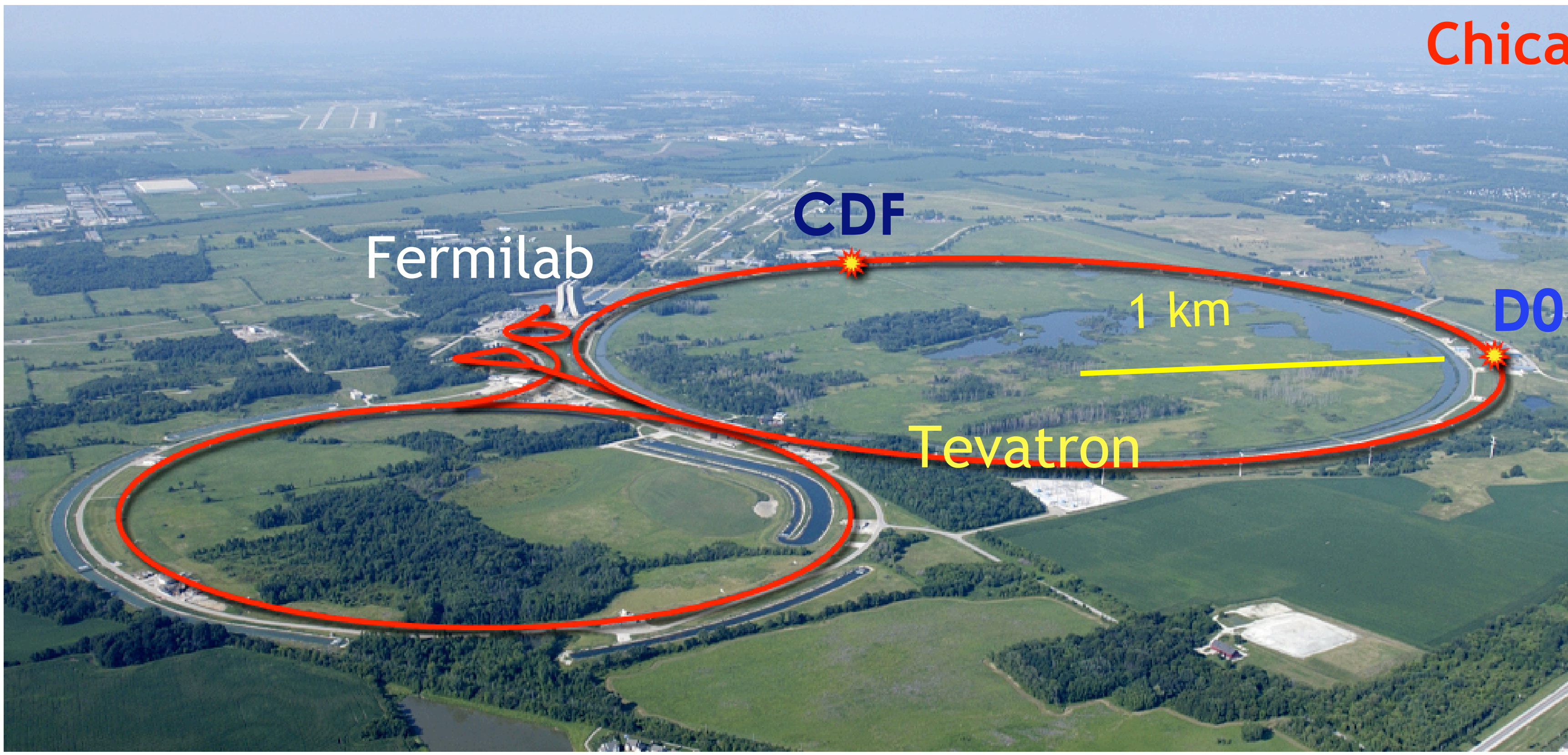


I am going to present today:

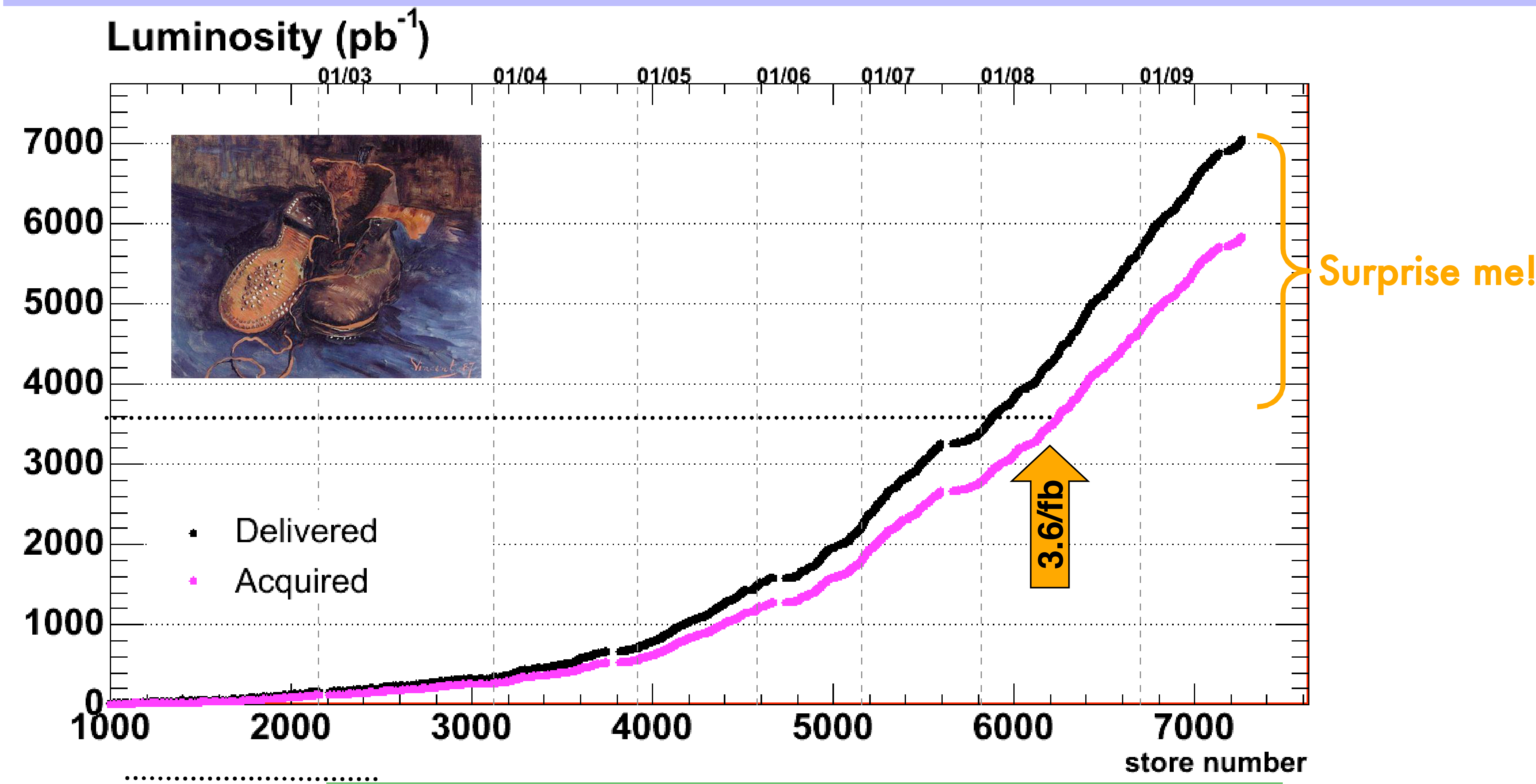
- first single top search in the MET+b-jets signature
- Tevatron most stringent limits to Higgs production in MET+b-jets signature

The Tevatron collider

- Fermilab's Tevatron Run II $p\bar{p}$ collider at 1.96 TeV, running since 2001. Currently performing very well:
  - $3.7 \cdot 10^{32}$ cm^{-2} s^{-1} new record in instantaneous luminosity!
  - Almost $2 fb^{-1}$ collected per year
  - Two multi-purpose, well-understood detectors CDF and D0



A long way ...



Delivered > 7.0 fb^{-1}

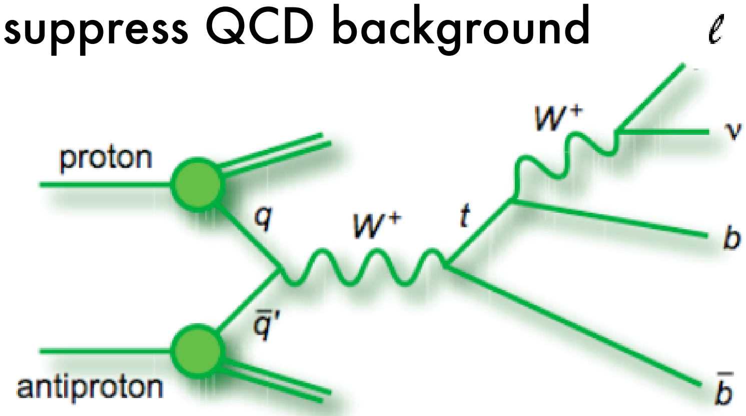
Acquired almost 6 fb^{-1} (slightly less w/ silicon)

Up to 3.6fb^{-1} used in following searches

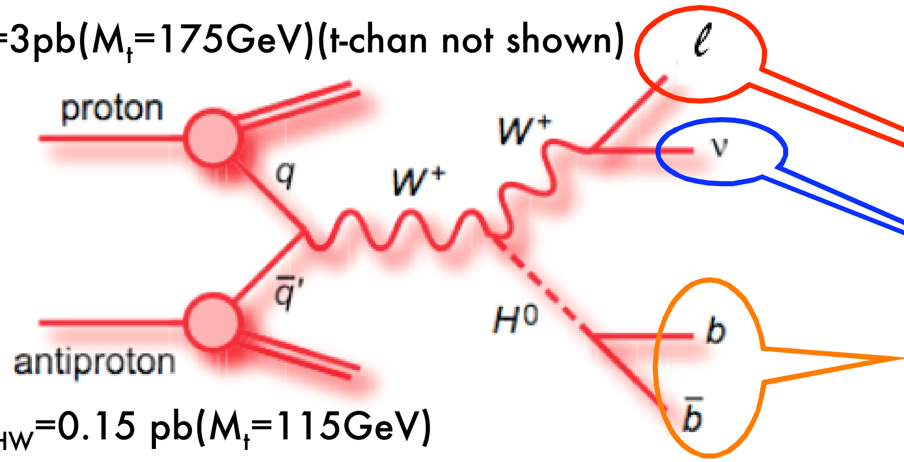
The rarest SM processes

The l+$\not\!E_T$+b-jets search challenges

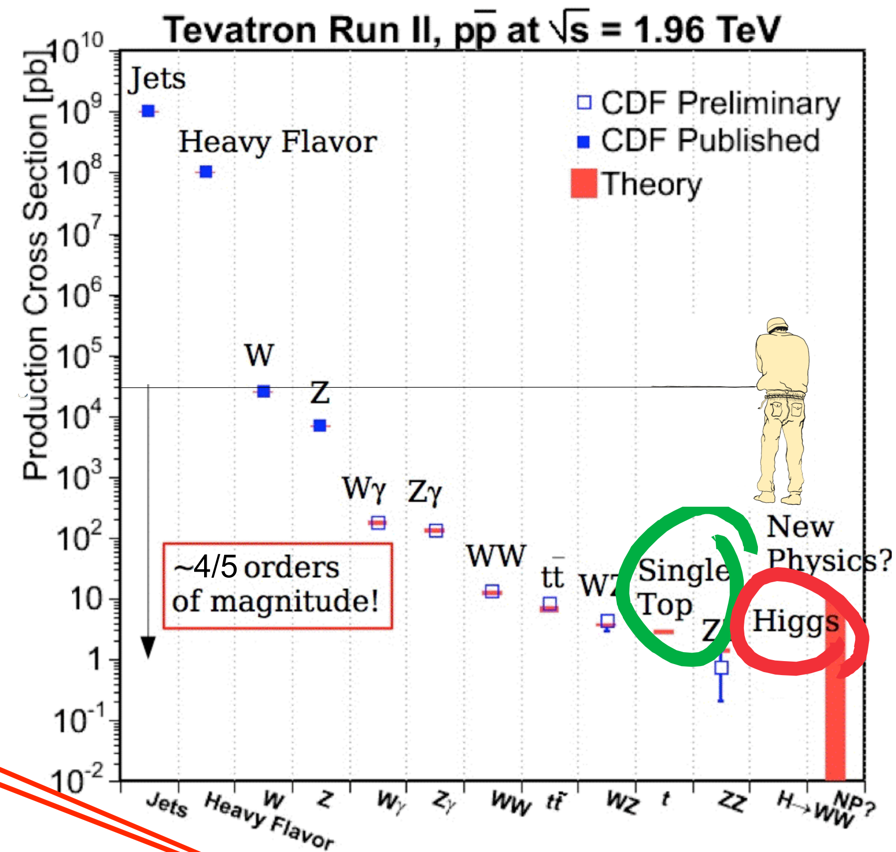
With so much data, it is time to shed light on the rarest SM processes. Lepton signature very popular at hadron colliders to suppress QCD background



σ_t=3pb(M_t=175GeV)(t-chan not shown)



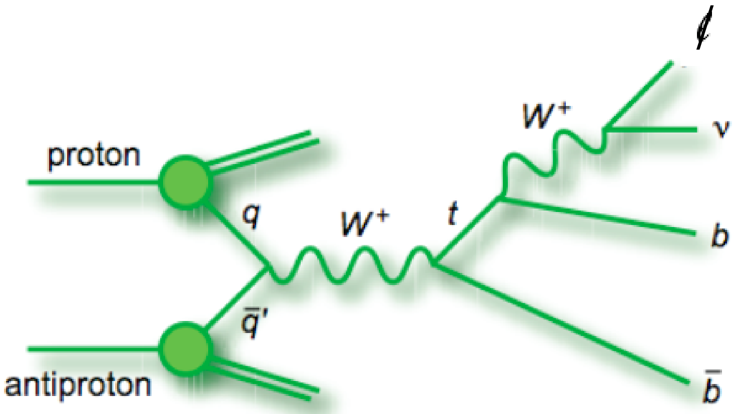
σ_{HW}=0.15 pb(M_t=115GeV)



- b-jets or MET and leptons reduces bck by many orders of magnitude
- But W/Z+2 jets still high!

The $\not{E}_T$+b-jets search challenges

Need to improve precision/sensitivity. Use orthogonal signature of MET+b-jets.
Much more challenging than with leptons!!



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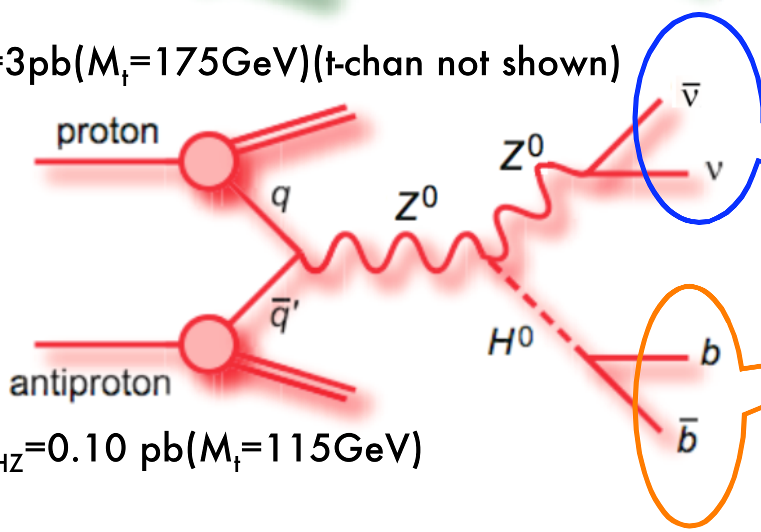
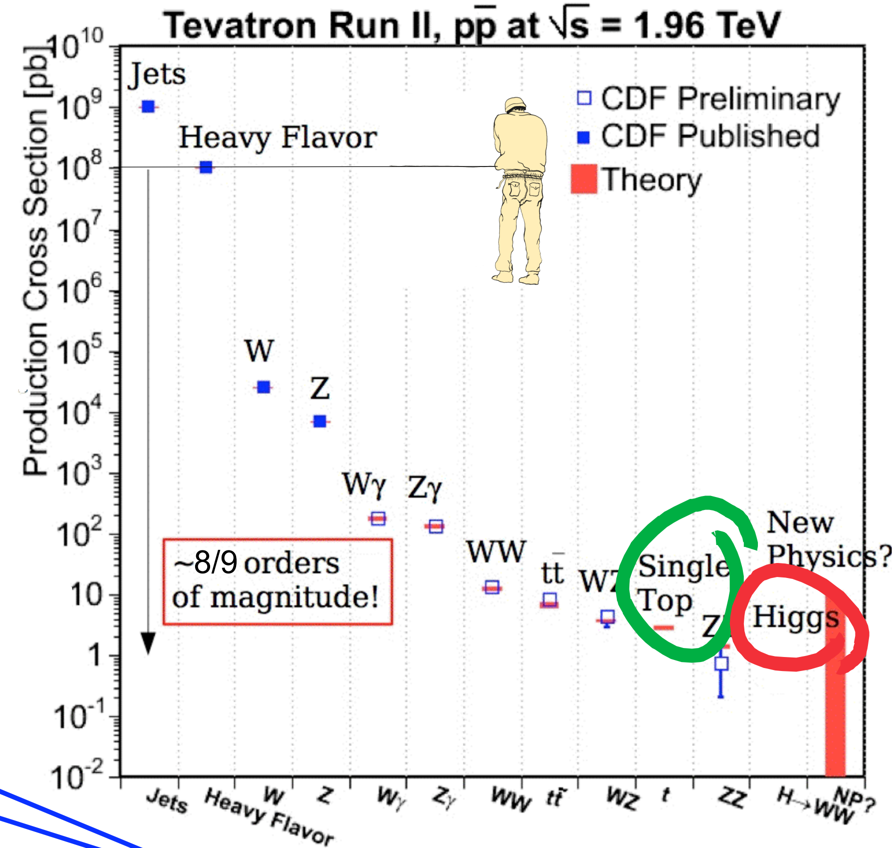


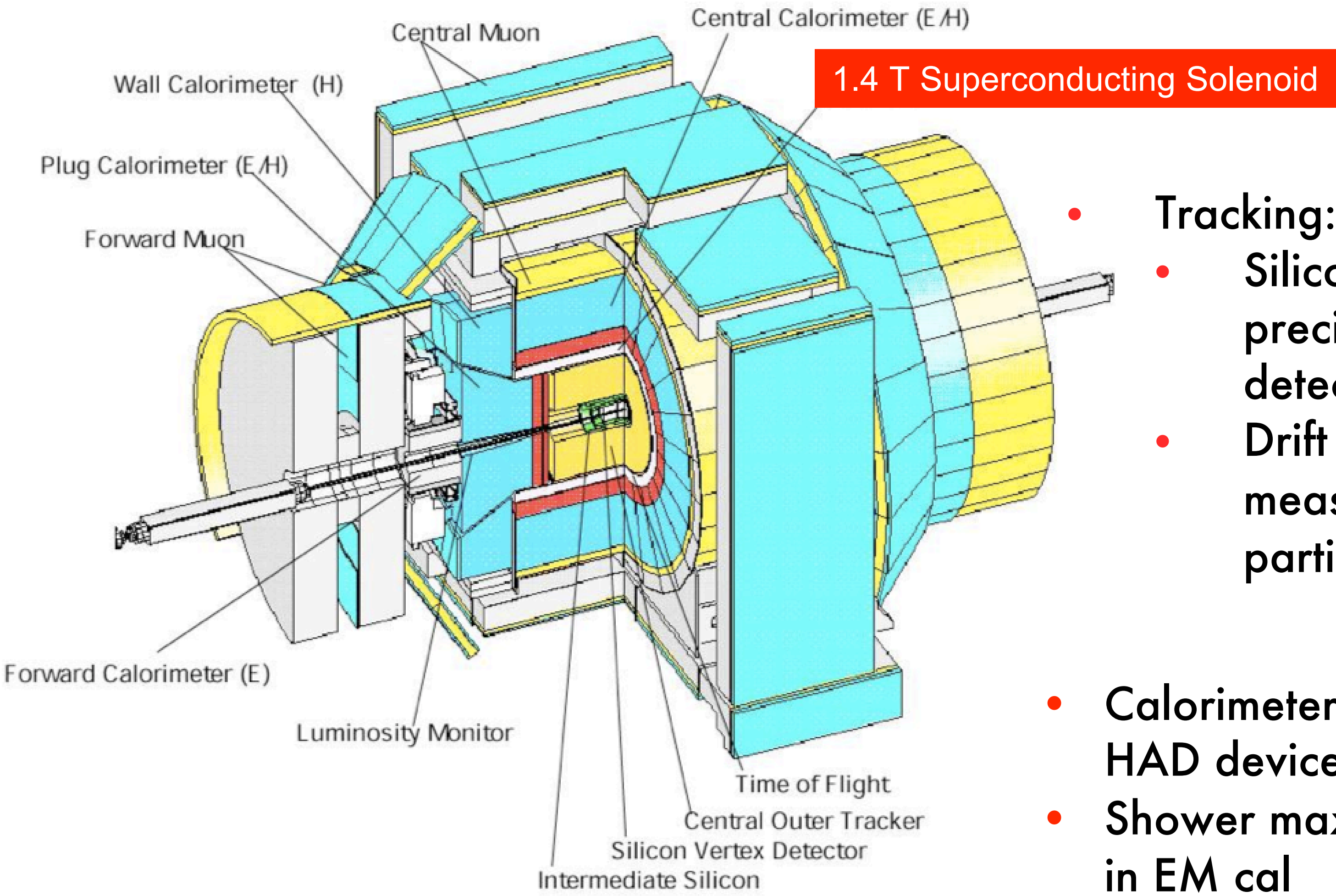
σ_{HZ}=0.10 pb(M_t=115GeV)



- b-jets and MET reduces physics background by a lot, but instrumental QCD background still huge!

The tools of the trade

The CDF II detector

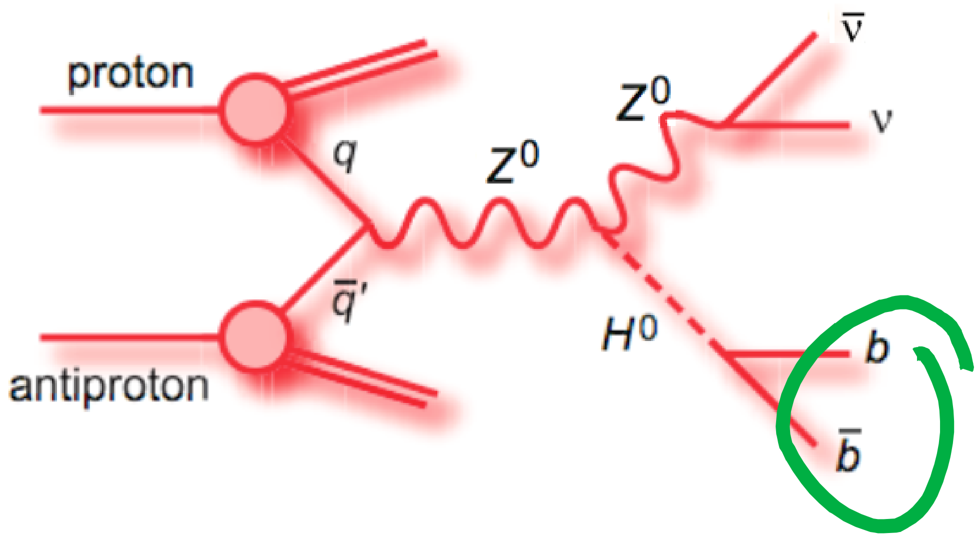


- Tracking:
  - Silicon tracker allows precision vertex detection $|\eta|<2$
  - Drift chamber $|\eta|<1$ measures charged particle P_T

- Calorimeter split in EM and HAD devices $|\eta|<3.6$
- Shower maximum detector in EM cal

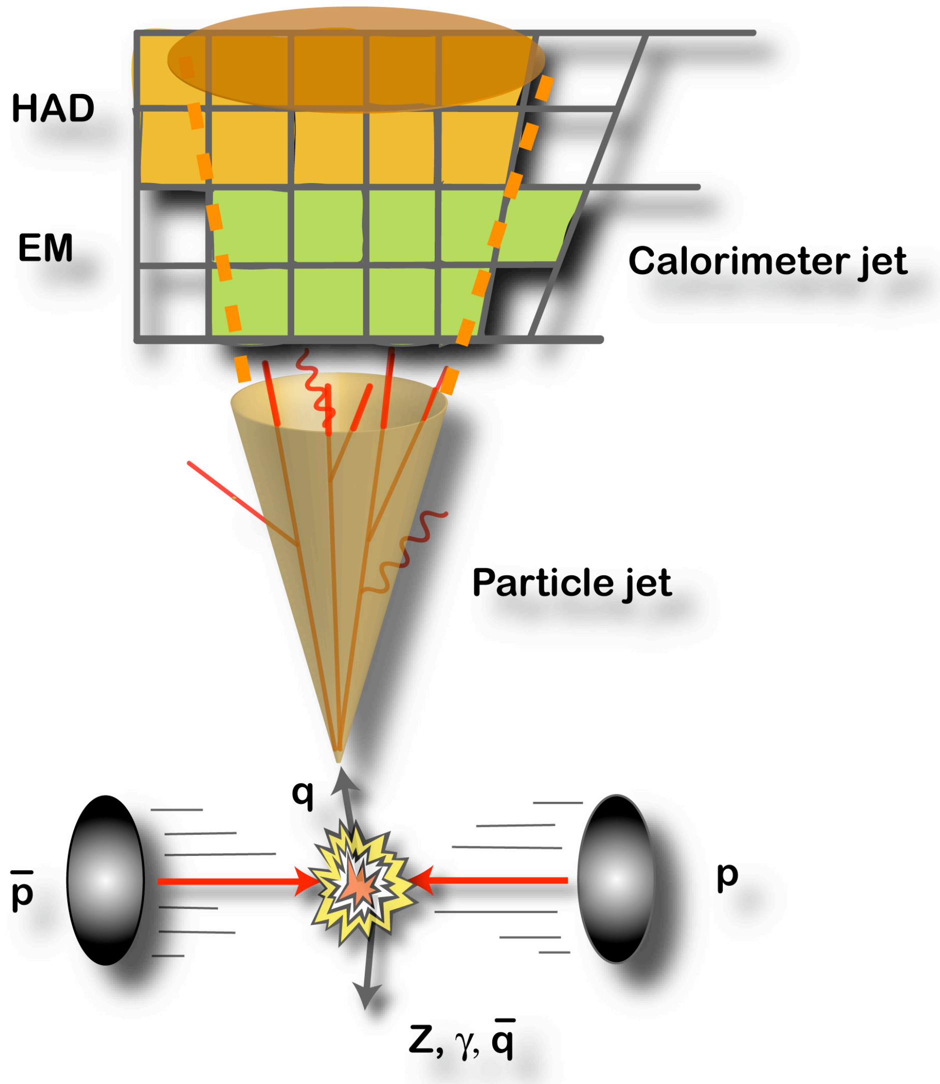
- Muon chamber outside calorimeter coverage $|\eta|<1.5$

The jets signature

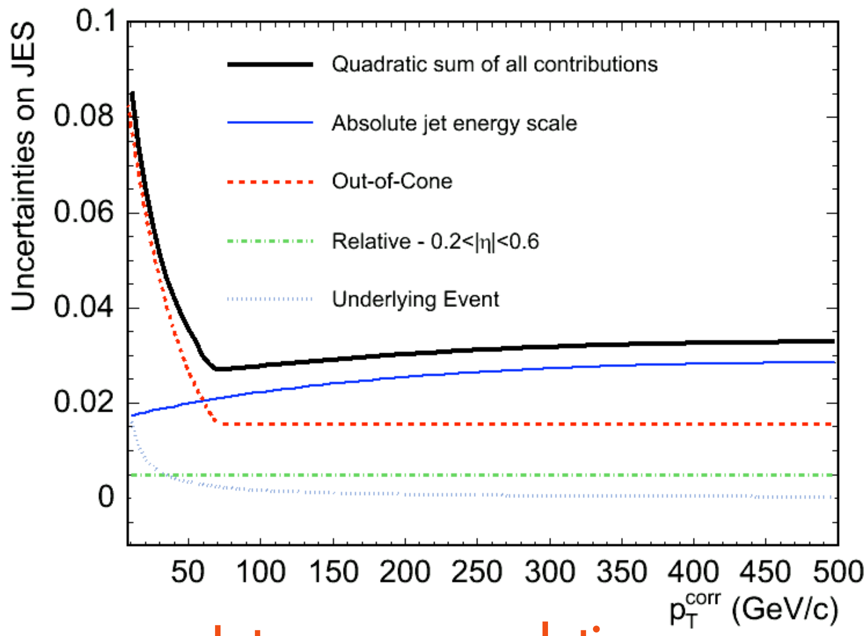


Generic jets

- Quark/gluons hadronize and produce particle jets
- CDF uses cone based jet reconstruction algorithm. Loops over calorimetric towers
- Jets are easy to find
  - Jets are macroscopic objects: reconstruction efficiency is nearly 100%
  - CDF calorimeter covers almost all solid angle ($|\eta|<2.8$ here)
- But carry a lot of complications
  - Jet energy resolution driven by had cal resolution $80\%/\sqrt{E_T}$ *source of missing E_T*
  - Non-instrumented regions in calorimetry lead to underestimation of jet E_T → *source of missing E_T*



Jets at CDF

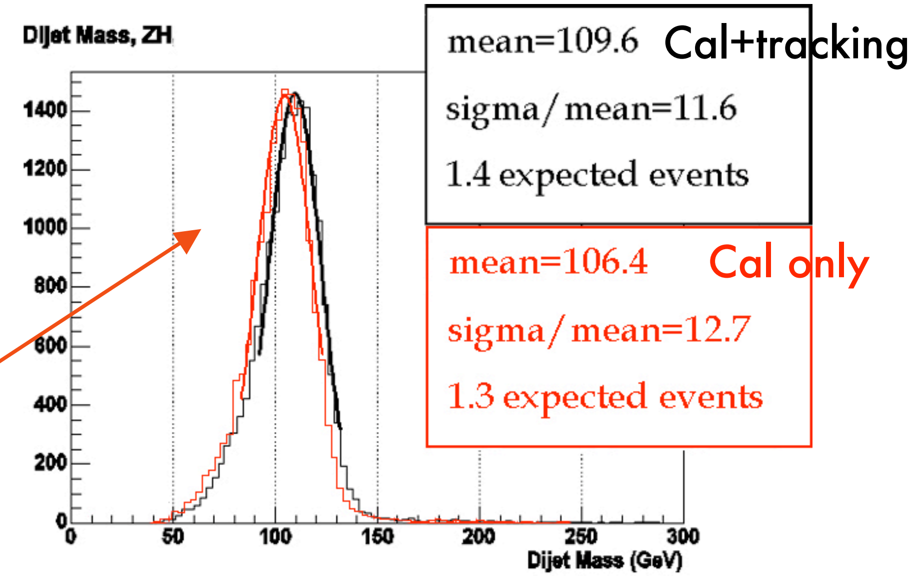


Jet energy scale uncertainty

- Systematic difference from data and Monte Carlo, convolution of many effects
  - 5% to 3% of the jet energy

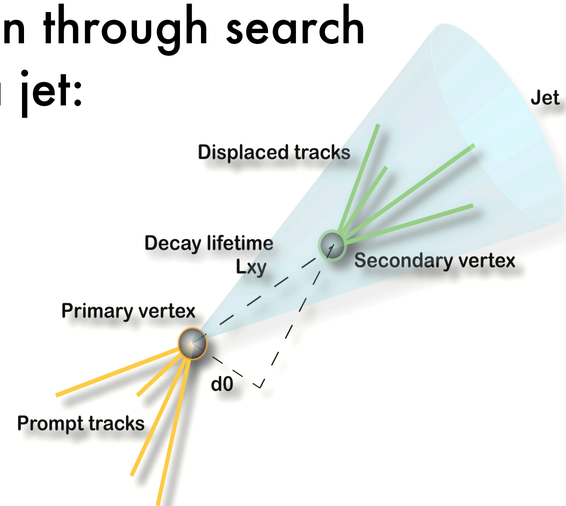
Jet energy resolution

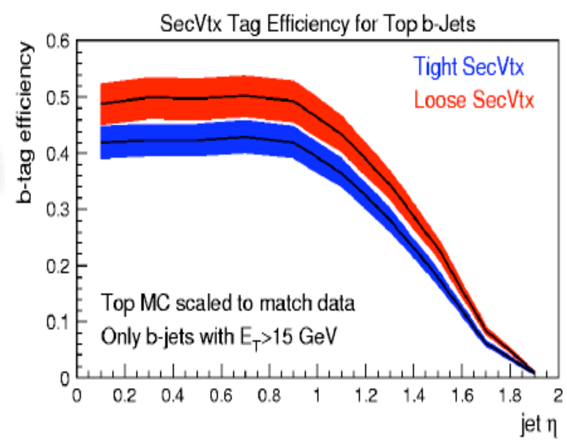
- Tracks resolution is far better than calorimeter resolution for particles with P_T<50 GeV
- New jet reconstruction algorithm substitute track P_T with cal E_T whenever possible to improve jet energy resolution (10% improvement)



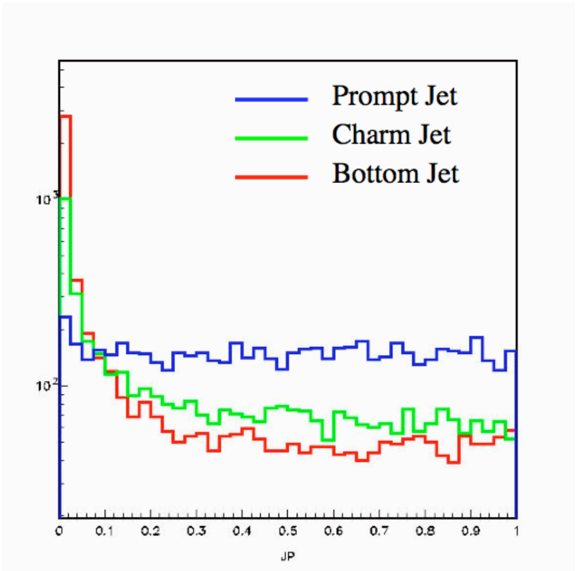
b-jets

- ✓ SecVTX: b-quark id'ed w long lifetime of the B mesons they form: identification through search of a secondary vertex within a jet:
  - b-tag eff: ~ 40%
  - fake rate ~ 0.5%

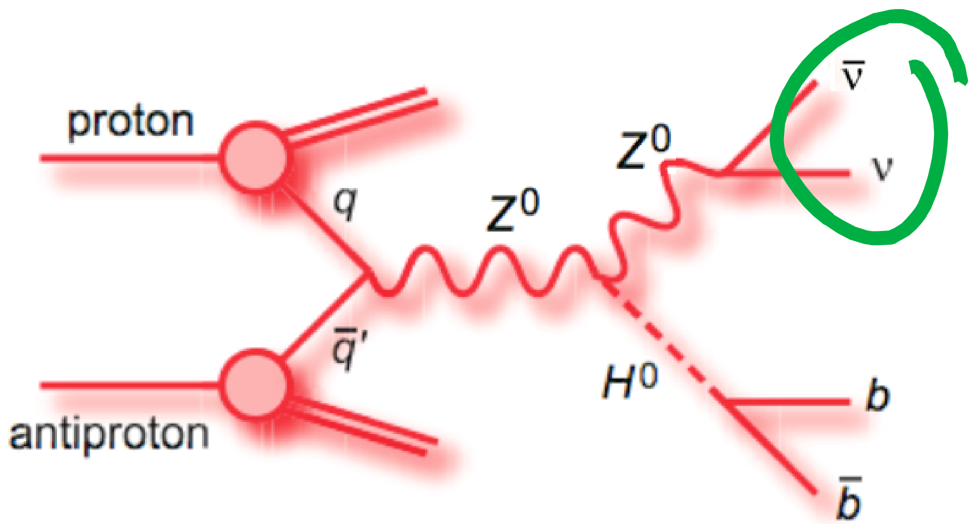




- ✓ JetProb: Jet probability algorithm: determines prob that the tracks within a jet are consistent with coming from the primary vertex
  - b-tag eff ~50%
  - fake rate~5%



The missing E_T signature



Missing E_T, and more

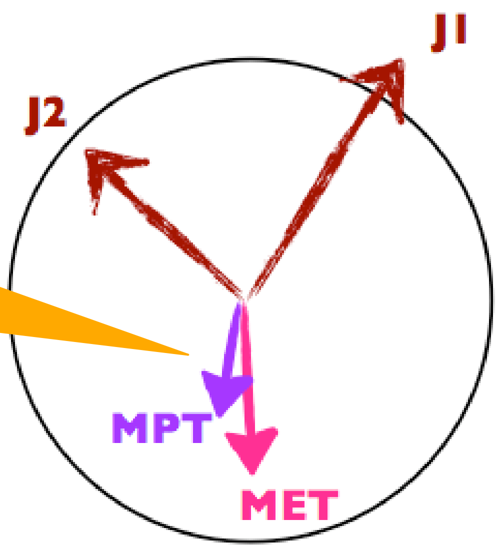
Neutrinos:

- measured using the missing transverse energy (MET) from calorimeter.
- Now using also the ***momentum flow imbalance in the transverse plane*** as measured from the *spectrometer*: the missing transverse momentum (MPT) *New!*
  - MPT largely correlated to true neutrino energy/direction
  - For QCD events, MPT very different!

Example: events selected with large MET, 2 high P_T b-jets

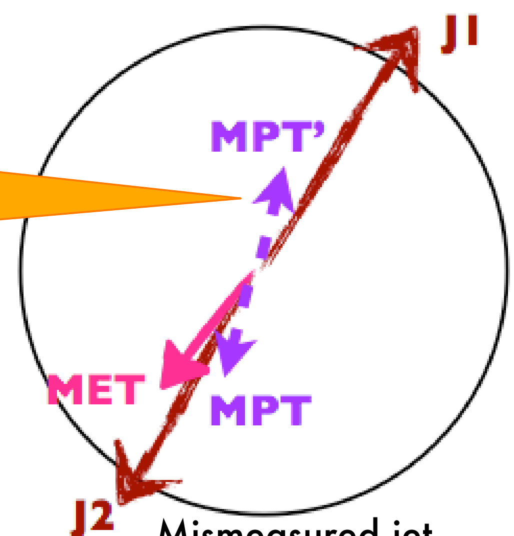
A ZH → νν bb event

MPT in events with neutrinos is aligned to MET



A QCD bb event

MPT in QCD events is aligned to one jet or the other



Mismeasured jet

Missing E_T, and more

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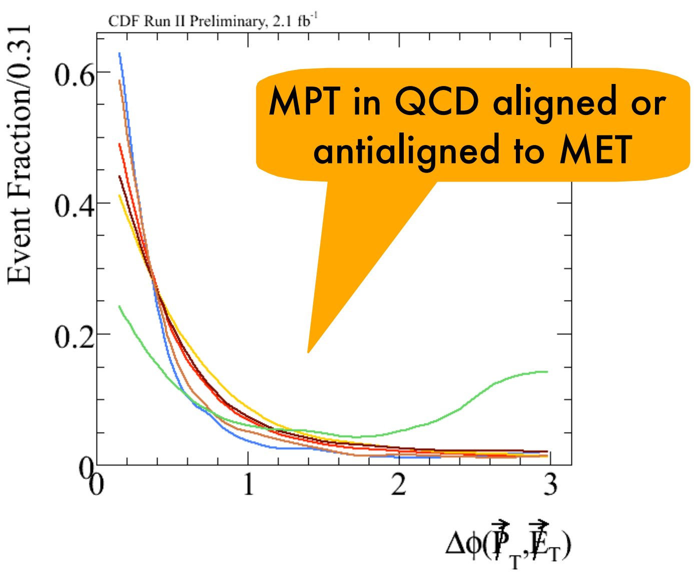
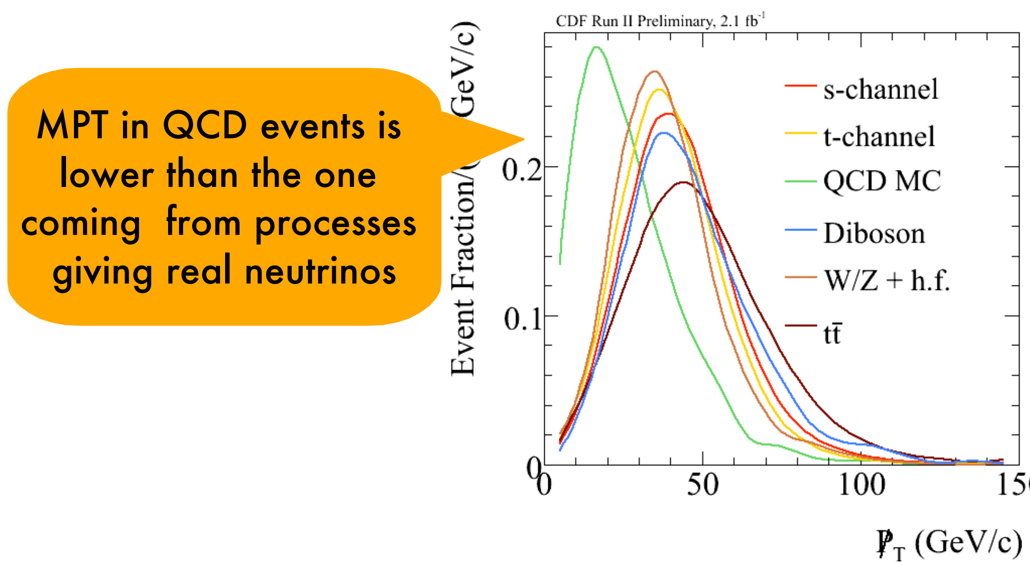
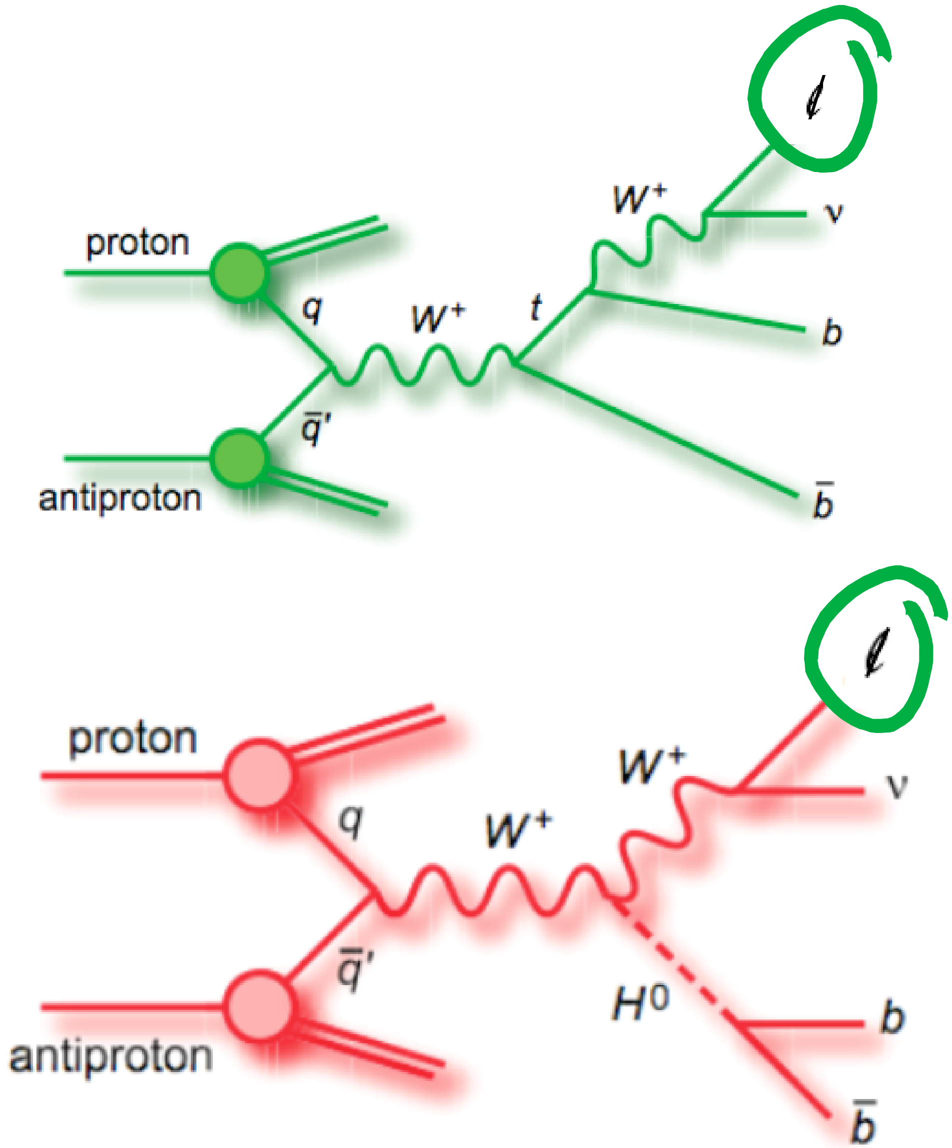




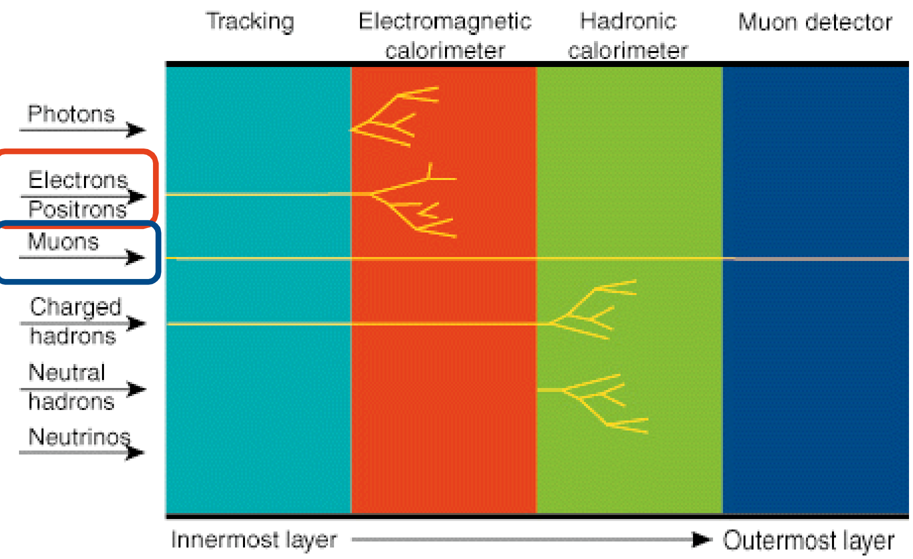
The lepton (absence) signature



Charged leptons

Electrons:

- Track in central tracker *MATCHING* to em calo deposit *AND* shower max (reject π^0s) *AND* isolation (reject showers from quark)



Muons:

- track in central tracker *MATCHING* to stubs in muon chambers (if $|\eta|<1.3$)

Taus:

- No explicit τ ID here.
  Accept $\tau \rightarrow$*leptons* through μ,e
  and $\tau \rightarrow$ *hadrons* through jets

Strict requirement to ID a lepton.
Moral: often you don't identify them!
Missing leptons can appear as **Jets**(e,τ) or **MET**(e,μ,τ)!

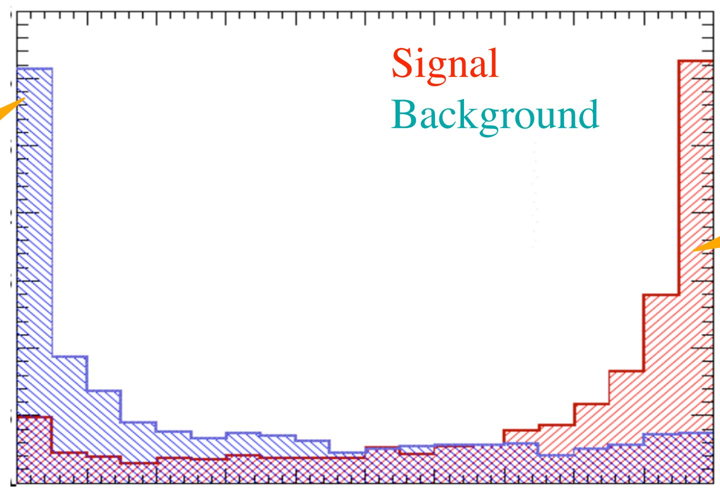
Multivariate techniques

Small S and large B with large uncertainties σ_B: need to maximize statistical power

CDF uses different classes of multivariate techniques:

- Physics oriented exploit knowledge of the *matrix element* (ME) of the process
- Likelihood ratio(LR) Probability density estimators for each variable combined in1
- Machine-learning techniques such as and neural networks (NN)
  - Better than LR because exploit correlations among different observables.
  - ME not used here because too little information on signal final state *and* hard to trust QCD Monte Carlo

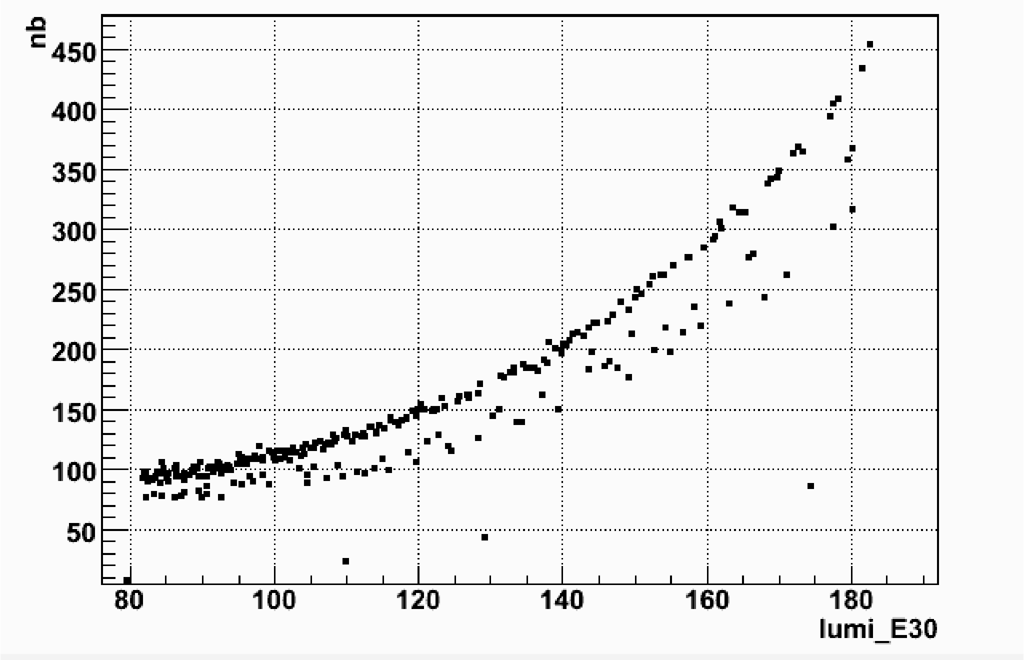
Data in left-hand side effectively constrains bck rate systematics



In the right-hand side Increase S/B, thus increasing sensitivity

The MET+jets trigger

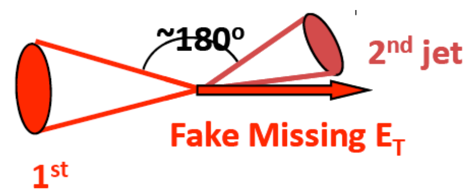
- Trigger on events with large MET, and 2 jets
- Jet E_T and MET resolution low at trigger level → huge rates at level 1 and 2



- After trigger cuts at level 3, the trigger cross section is O(10nb)
  - 4 or 5 orders of magnitude larger than our signal!
- Require MET>50GeV to ensure trigger efficiency on MC
- Large separation between jets, to avoid jet merging
  - Both requirements can be loosened after trigger upgrade

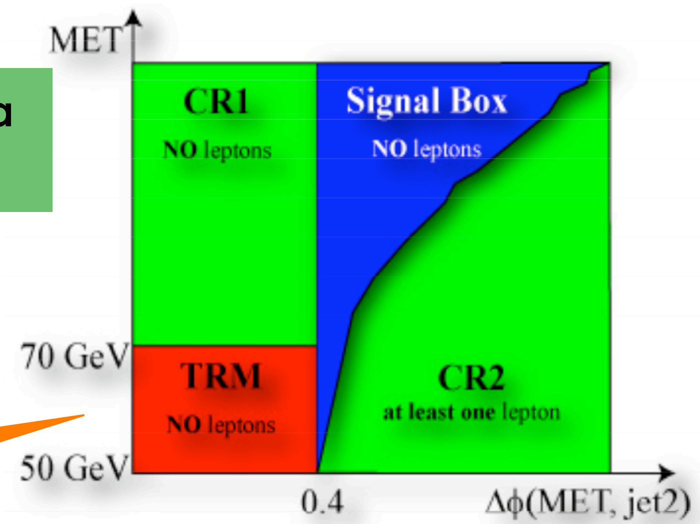
QCD background modeling

MC modeling suffers from
- poorly known cross-sections
- need generation of huge samples (>billion events)



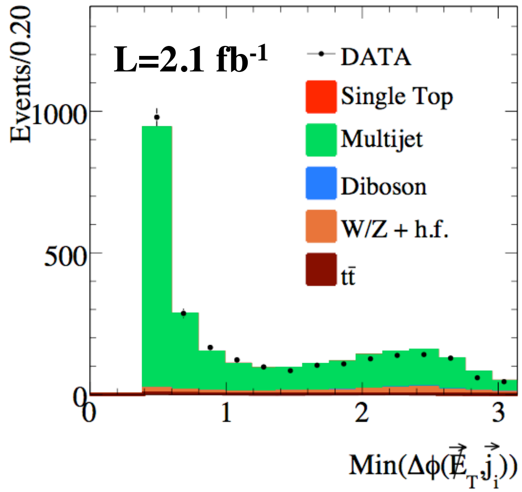
Sample is QCD dominated → use data itself as a model, but have to account for b-tagging bias

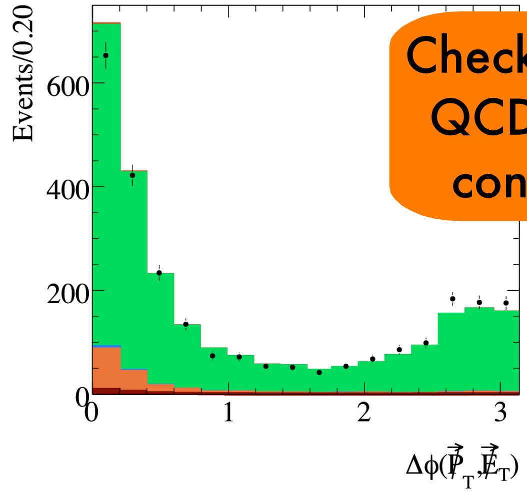
Derive per-jet tag probability



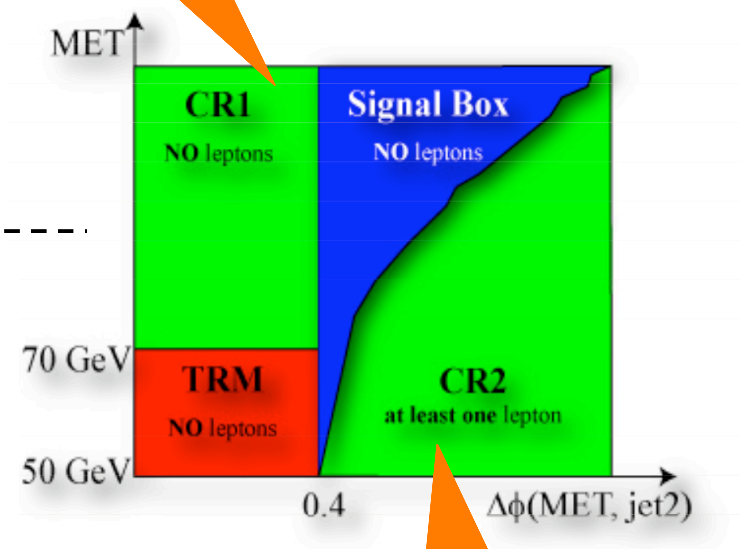
Data-driven modeling contains W+light flavor jet production
We use Monte Carlo for all other processes

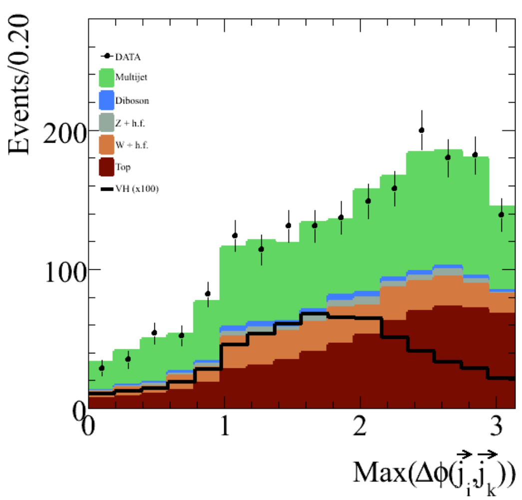
QCD background modeling

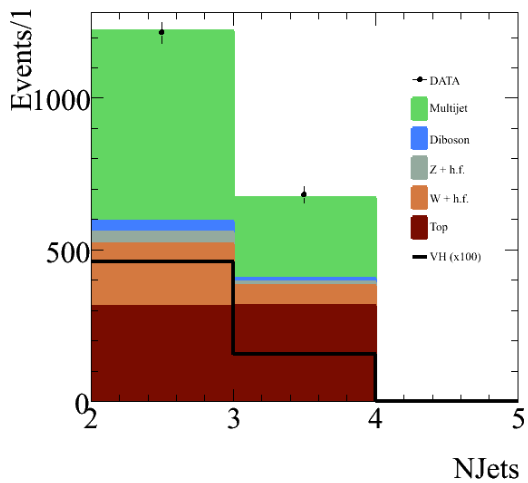




Check modeling in QCD-dominated control regions





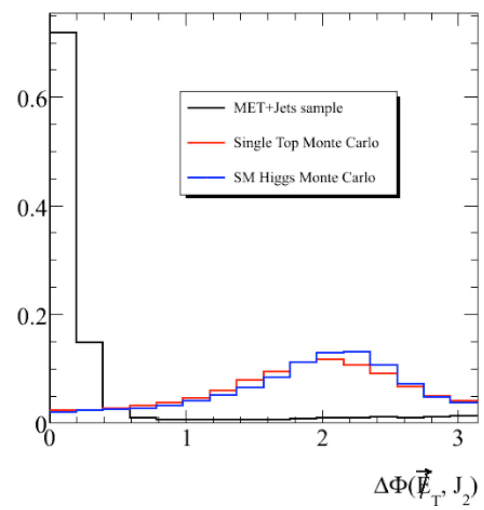


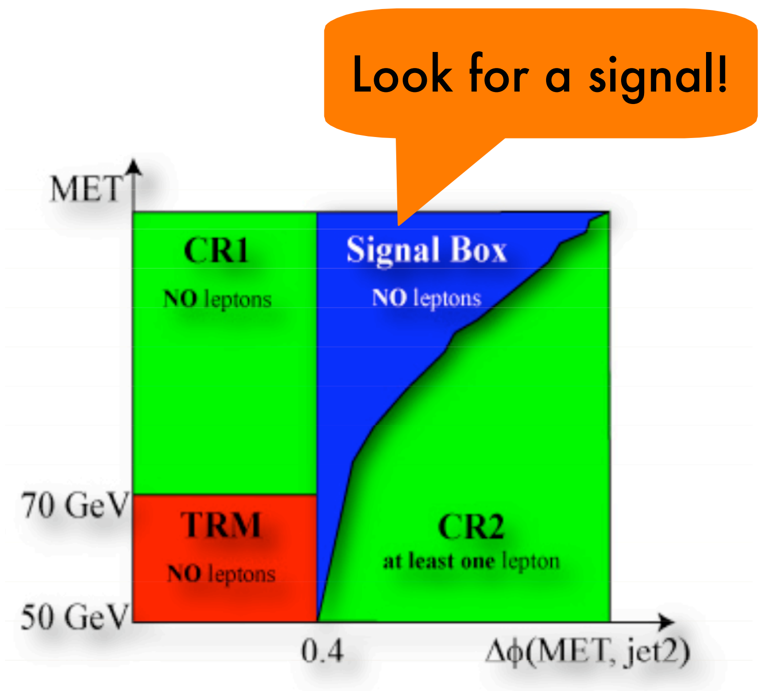
"Multijet" modeling contains W+light flavor jet production

Check modeling in EWK-dominated control regions

Basic MET+b-jets selection

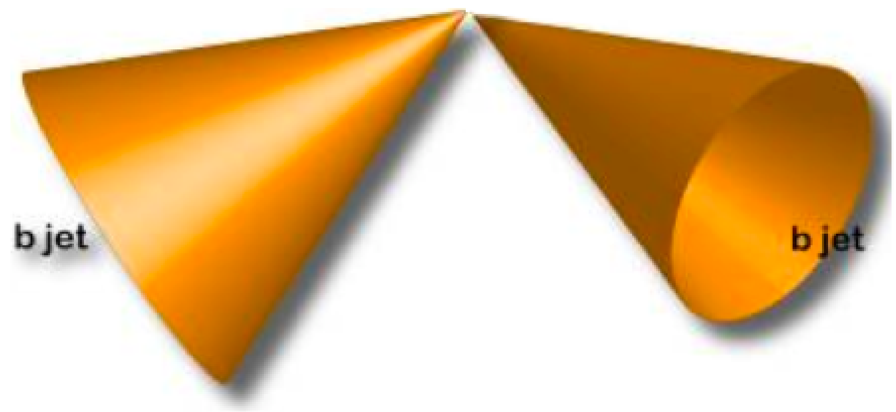
- Veto presence of identified leptons to be orthogonal to lepton+MET+jets search
- Large MET>50GeV and 2 or 3 jets, where 3rd jet can come from
  - Initial/final state radiation
  - e or τ leptons reconstructed as jets
- Require MET misaligned with jets: rejects 1 order of magnitude of backgrounds, with loss of only about few % of signal





- Require b-tagging to reject QCD production of light flavor jets (improves S/B by 1-2 orders of magnitude)

A typical candidate event

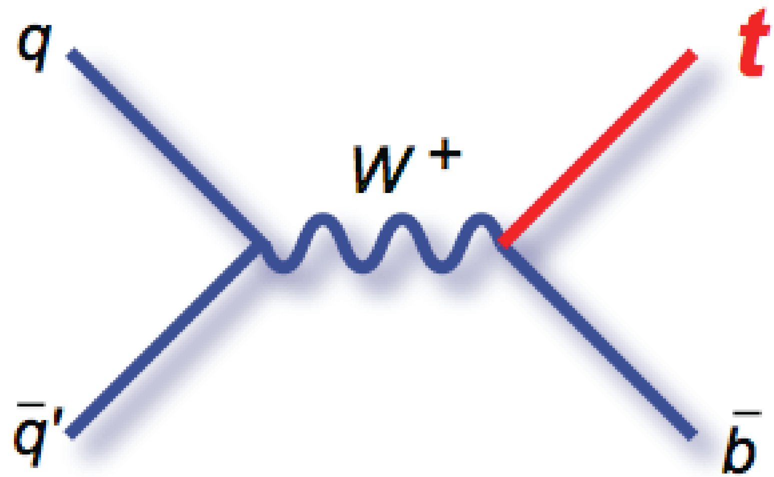


It looks a lot like QCD indeed…clearly a conservative approach won't work.
But how can you pretend to find the Higgs here,
if you don't measure something first?

The single top search in MET + b-jets

Why measure σ(single top)?

- Allows measurement of CKM matrix element $|V_{tb}|$:
  - Is this Matrix 3x3 ? Is there a 4[th] generation ?
  - Does unitarity hold ?
    $$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 \stackrel{?}{=} 1$$
  - "simple" 4[th] generation ruled out by EW fits but see e.g.
    J. Alwall et. al., "Is $|V_{tb}|$~1?" Eur. Phys. J. C49 791-801 (2007).
  - Probe new physics W'/FCNC



Direct measurements

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Ratio from Bs oscillations

Not precisely measured
Inferred using unitarity

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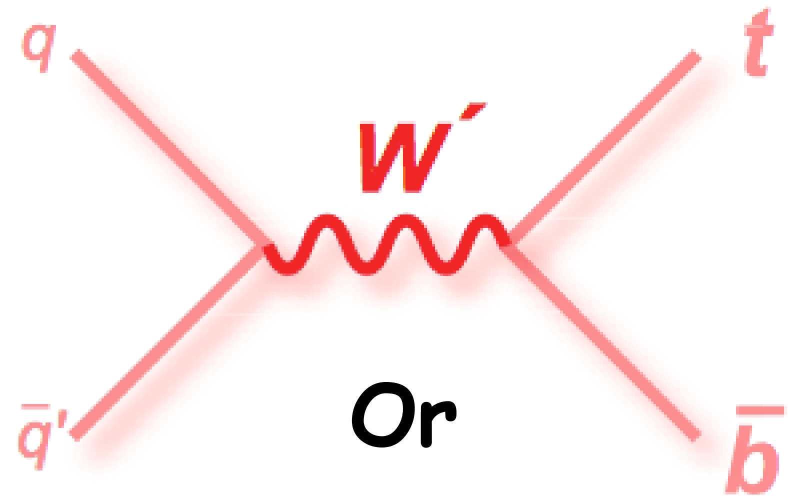


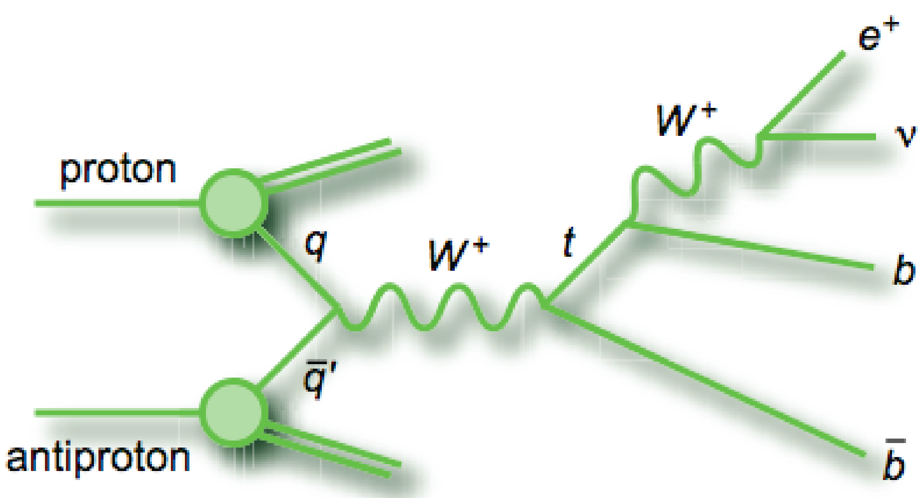
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yt}? & V_{YX}? \end{pmatrix}$$

Single top decays

Hard times to get the single top evidence and observation in leptonic mode.

Were we unlucky?

Or something else was hiding?

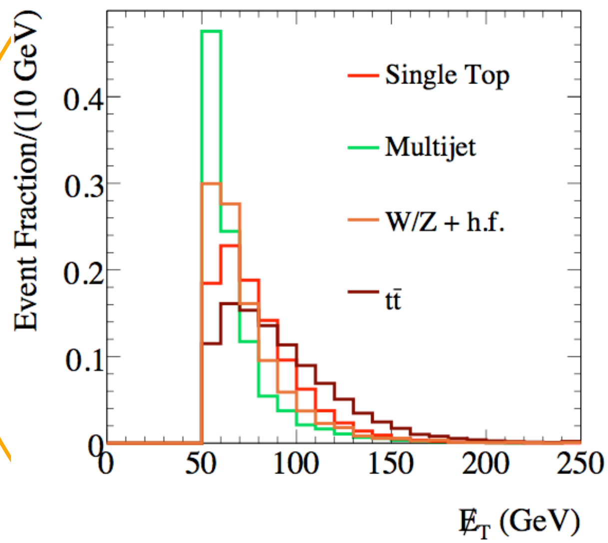


- Ele/mu+neutrino+b-jets — The good
  - "decent" branching ratio
  - S/B ratio not awful
  - 4.8 sigma excess with 3.2 fb-1
- All jets — The bad
  - large BR, but:
  - huge QCD *physics* backgrounds.
  - No efficient trigger at CDF
  - Never attempted
- MET+b-jets *signature* — The ugly
  - Recover lost leptons, but
  - large QCD *instrumental* background (see next slide)
  - no chance to identify top
  - Newly attempted!

Know your enemy

(Enemy=QCD=green histo)

Start with the basics



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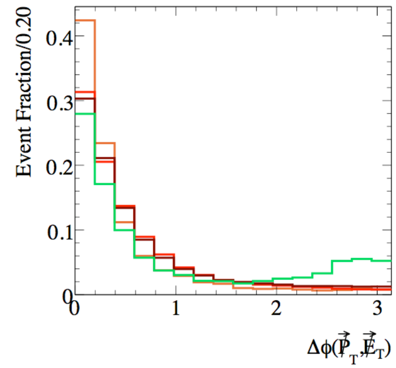

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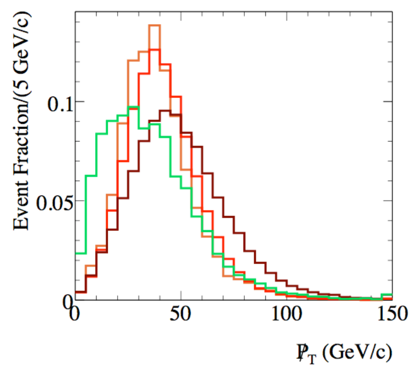

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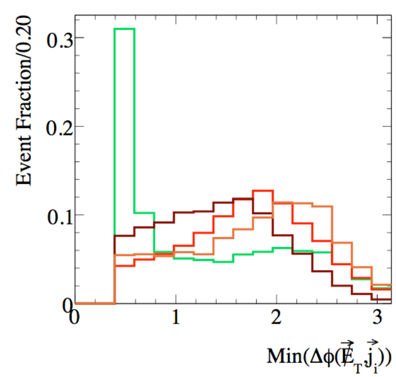

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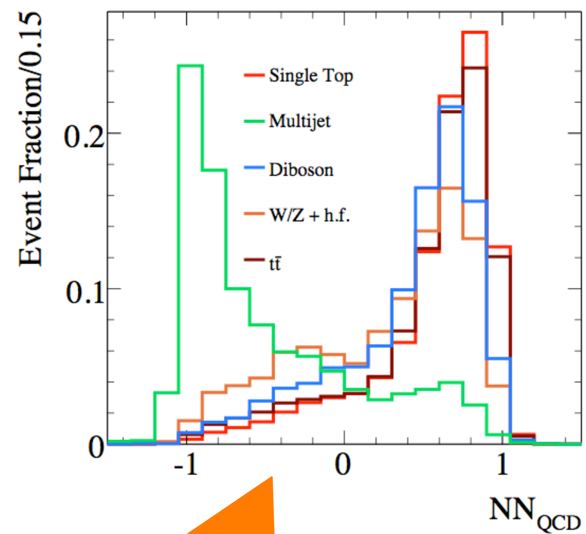


Finally, enjoy the ride

Then, going into the (far) less obvious

Very general approach to QCD-suppression in MET+jets (no heavy flavor required)

QCD-suppressing event selection

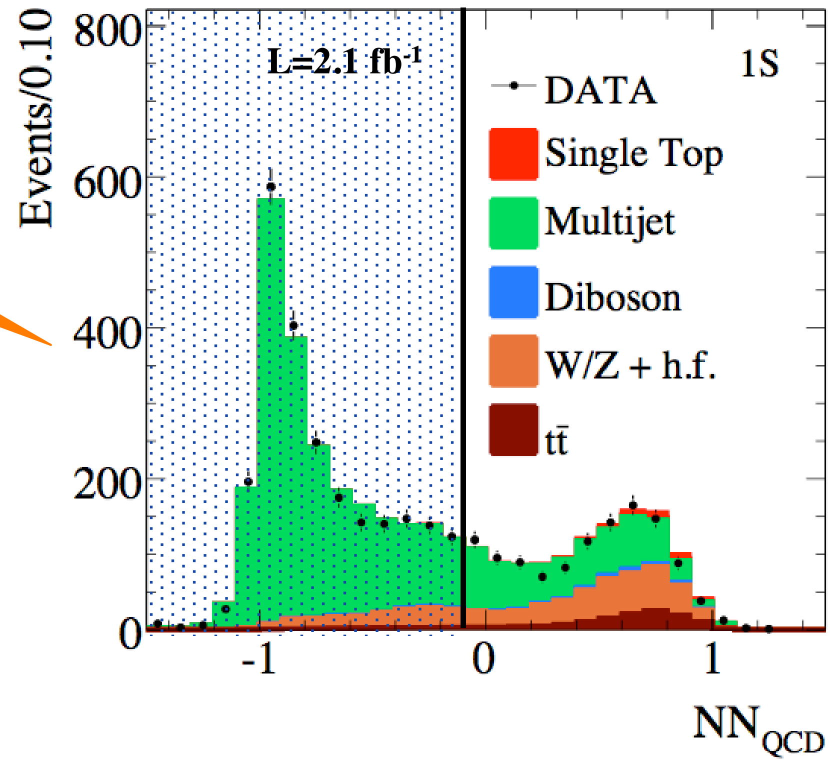
Choose a cut to isolate the signal

- Compromise between maximizing background rejection and keeping high signal acceptance (remember, it's a blind analysis)

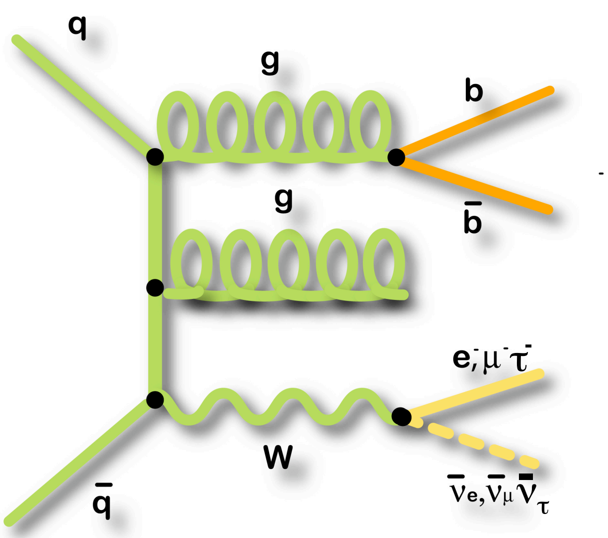
Showing NN output on events with 1 identified b-jet (b-tag)

Average over the three b-tagged subsamples

Qt.y	Preselection	After QCD cut	Difference
S	70	64	- 9%
B	4000	1400	- 65%
S/B	1/57	1/22	times 2.5!
$S/\sqrt{S+B}$	1.1	1.7	+ 50%



SM backgrounds producing ν's

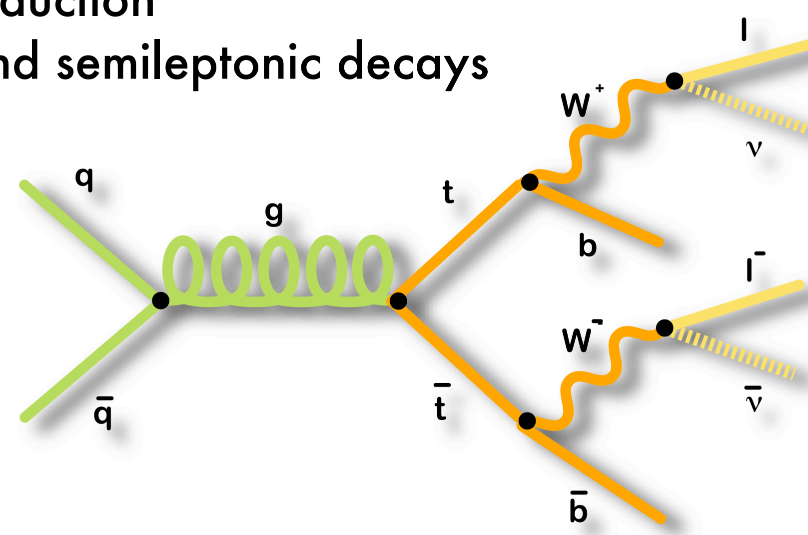


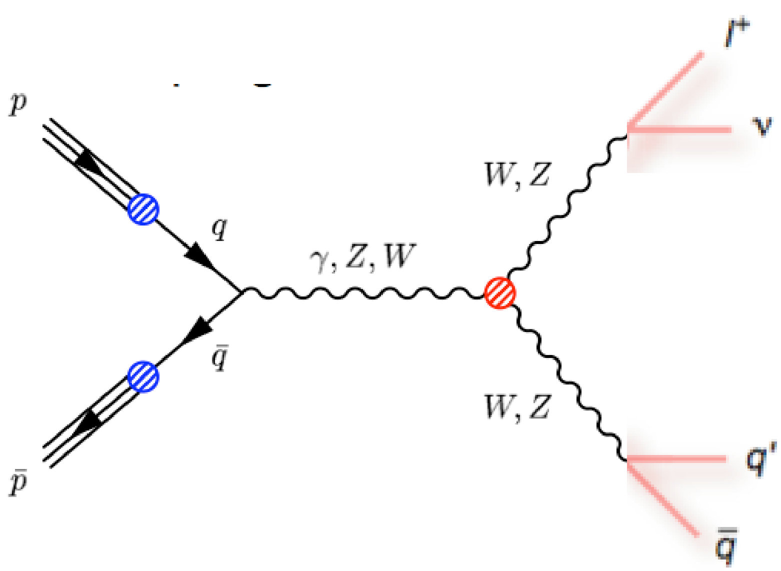
W/Z production in association with jets

Is the largest background after QCD

Top pair production

Dileptonic and semileptonic decays





Dibosons production with semileptonic decays WW/WZ/ZZ

b quarks from Z decay or light quarks misidentified as b-quarks

Single top acceptance table

CDF only!

Process	$\ell + \not{E}_T$ + jets	$\not{E}_T$ + jets
s-channel signal	77.3 ± 11.2	29.6 ± 3.7
t-channel signal	113.8 ± 16.9	34.5 ± 6.1
$W + HF$	1551.0 ± 472.3	304.4 ± 115.5
$t\bar{t}$	686.1 ± 99.4	184.5 ± 30.2
Z+jets	52.1 ± 8.0	128.6 ± 53.7
Diboson	118.4 ± 12.2	42.1 ± 6.7
QCD+mistags	777.9 ± 103.7	679.4 ± 27.9
Total prediction	3376.5 ± 504.9	1404 ± 172
Observed	3315	1411

- +50% acceptance per fb^{-1} mostly coming from taus
- With same S/B ratio as in l+MET+jet

Table from Phys. Rev. Lett. 103, 092002 (2009)

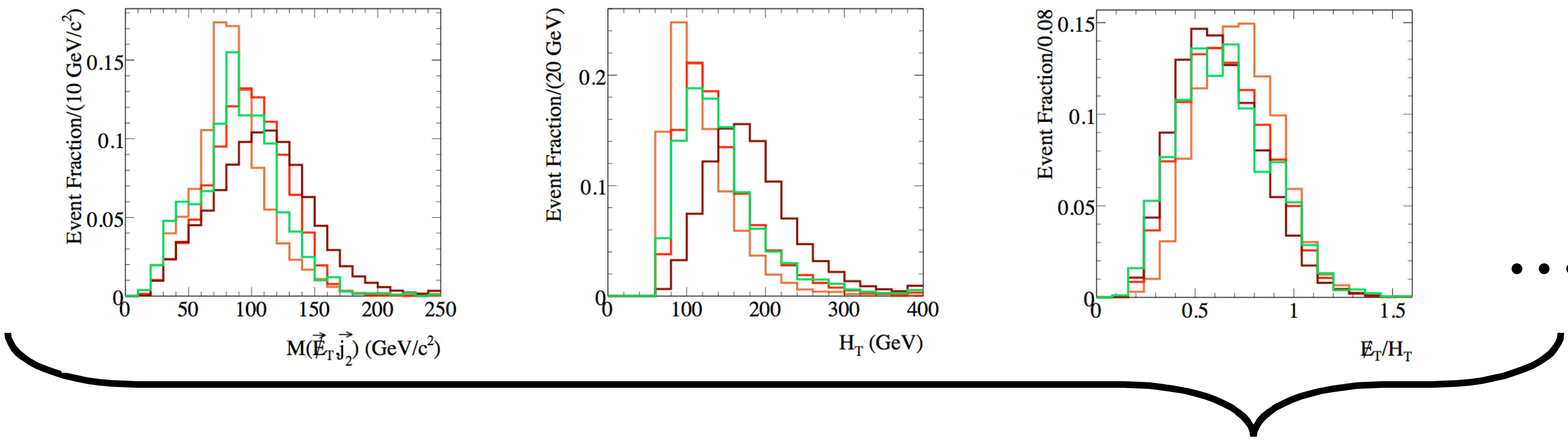
MET + b-jets systematics

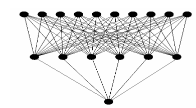
Uncertainty on backgrounds 3 times larger than signal!

Systematic source	Rate	Shape	Comment
Top quark pair cross section	$\pm$ 12%	-	
W/Z + h.f. cross section	$\pm$ 40%	-	
Diboson cross section	$\pm$ 11%	-	
Luminosity	6%	-	Not for QCD multijet
Trigger efficiency	$<$ 2.6%	X	
B tagging scale factors	4.3% to 12%	-	
Lepton Veto	2%	-	
ISR/FSR	-4.5% ... +16%	X	Only for top quark processes
JES	-14% ... +23%	X	
PDF	$\pm$1% ... $\pm$ 2%	X	Shape for signal only
QCD multijet model	4.5% ... 13%	X	
Background scaling	2%	-	
Signal cross section	$\pm$ 12%	-	Only for p-value and V_{tb} computation
Top quark mass dependence	-16% ... +7.5%	X	

Let's see whether we have some residual handles

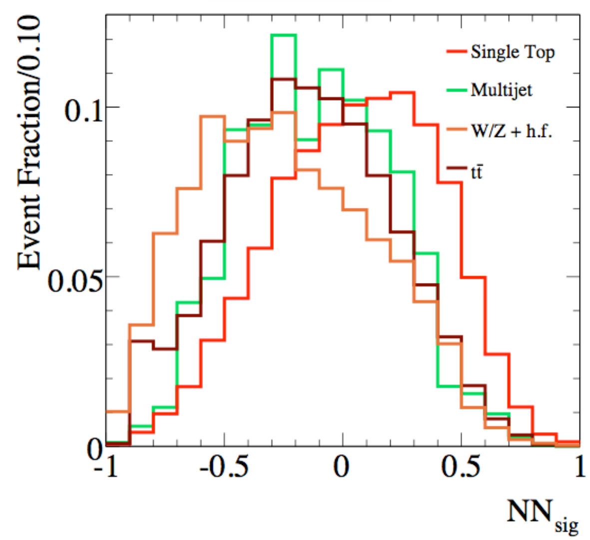
Toward the signal



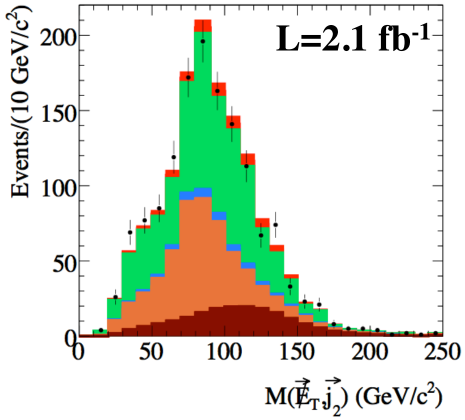


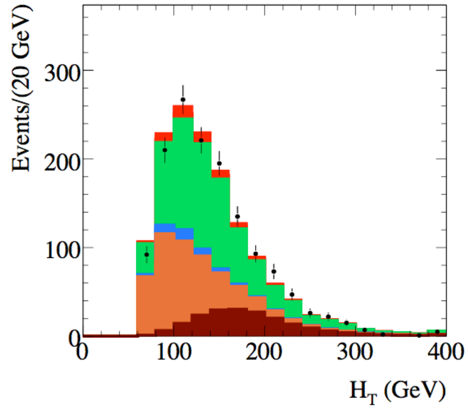
Missing ET plus jets NN (MJ)

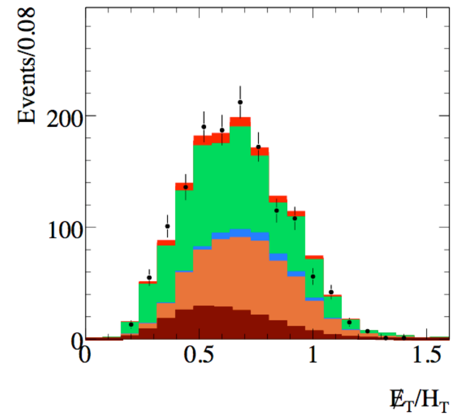
- Each variable has little power *per se*
  - 3σ excess, *statistics only*
  - down to 2σ once *including systematics*
- But still orthogonal to other channels, adds sensitivity and serves as consistency check
  - first search in the channel!



Toward the signal







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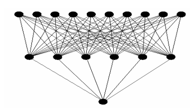
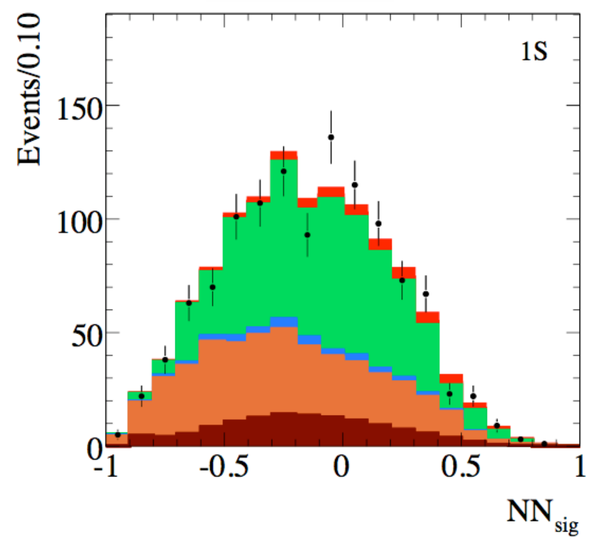
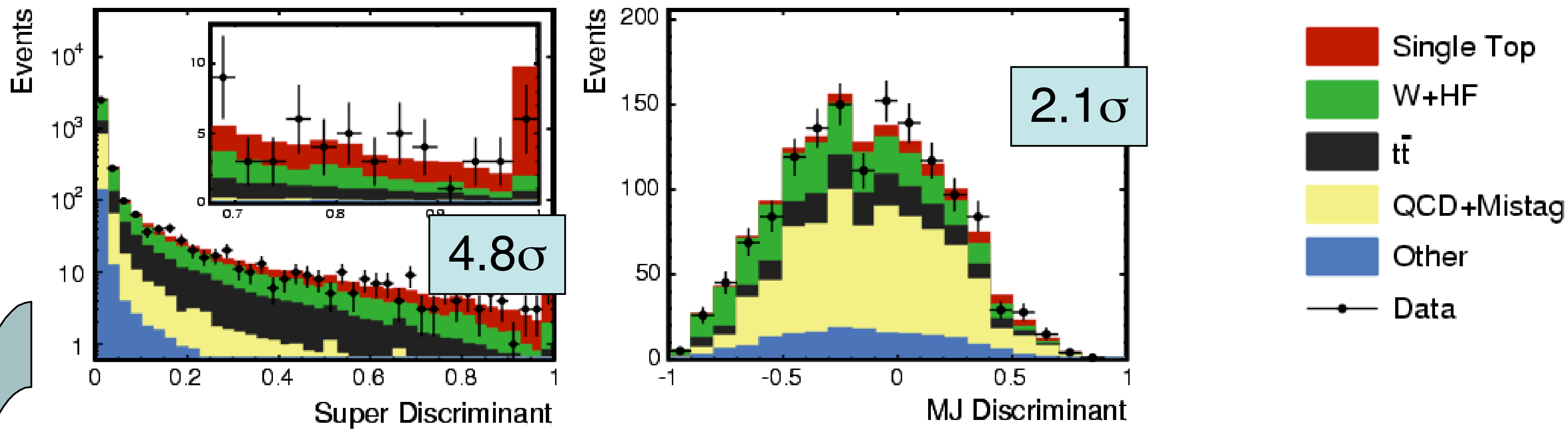


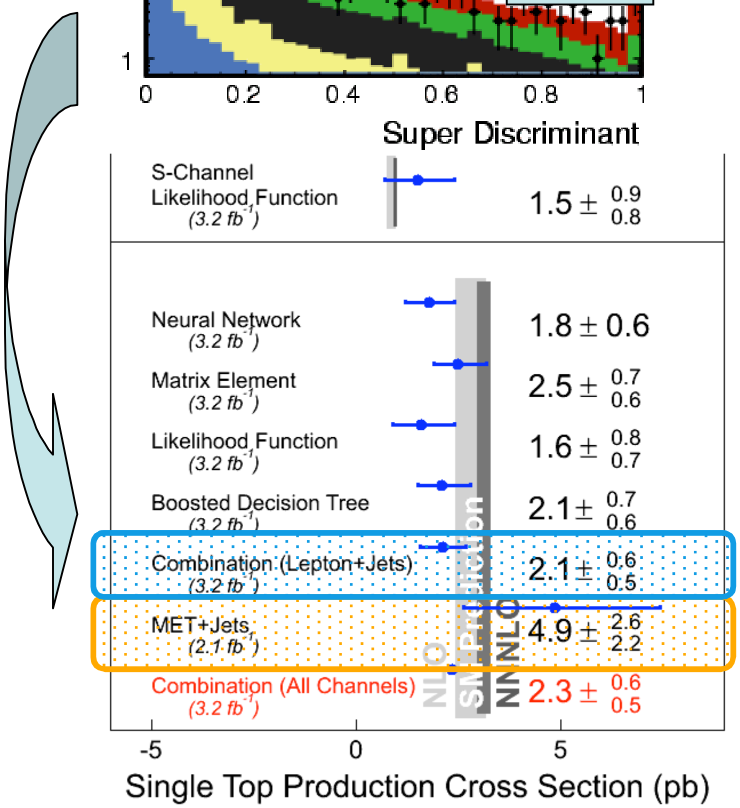
Missing ET plus jets NN (MJ)

- Each variable has little power *per se*
  - 3σ excess, *statistics only*
  - down to 2σ once *including systematics*
  - *-Measure sigma$_t$=4.9+2.6-2.2*
- But still orthogonal to other channels, adds sensitivity and serves as consistency check
  - first search in the channel!
  - arxiv1001.4577, submitted to PRD



CDF results and combination





Highly correlated analyses (identical dataset)
historically observed deficit of signal

+

Completely independent analysis

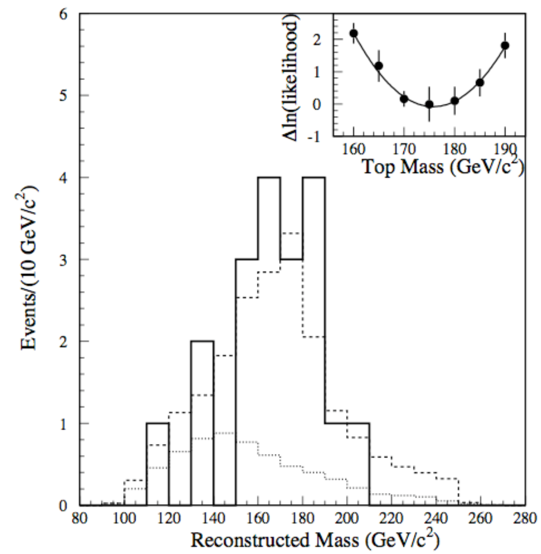
=

5σ Observation!

Phys. Rev. Lett. 103, 092002 (2009)

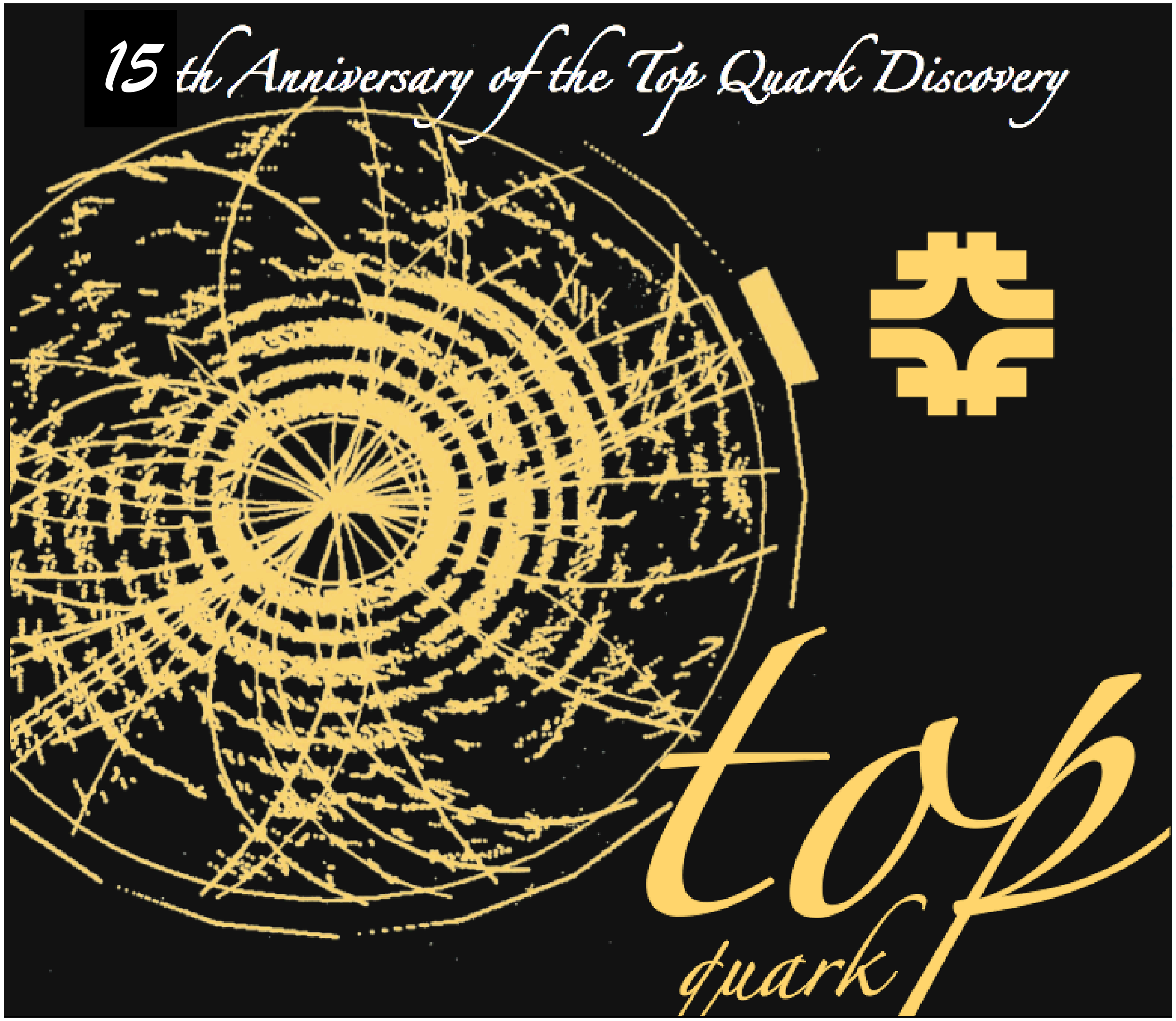
Top in 1995

Top quark discovered in pair production at CDF



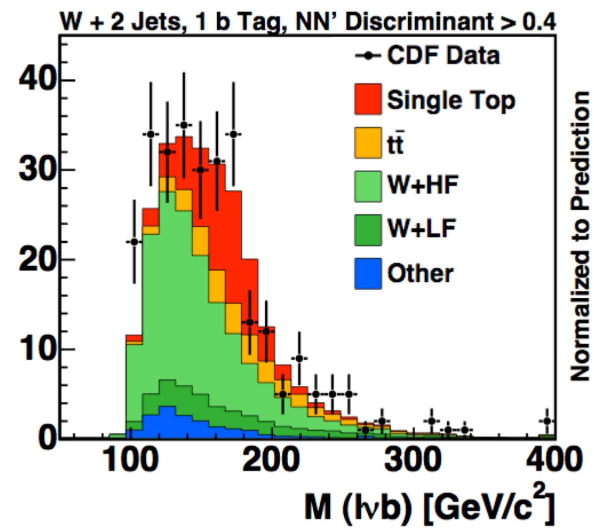
For many years, the only place where to study the top quark

Top in 2010



Why so long?

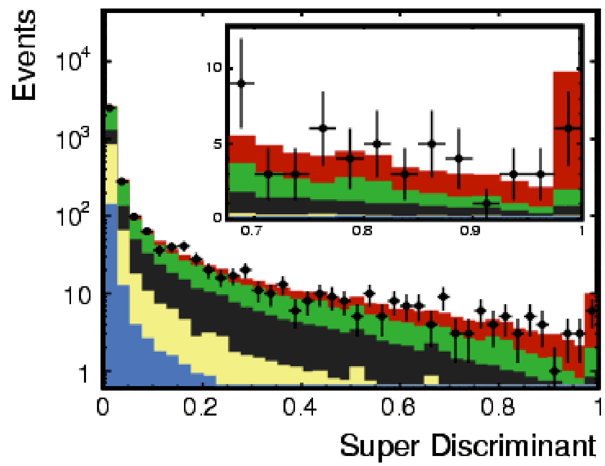
- half the cross section as ttbar production
- about 100 times worse S/B ratio



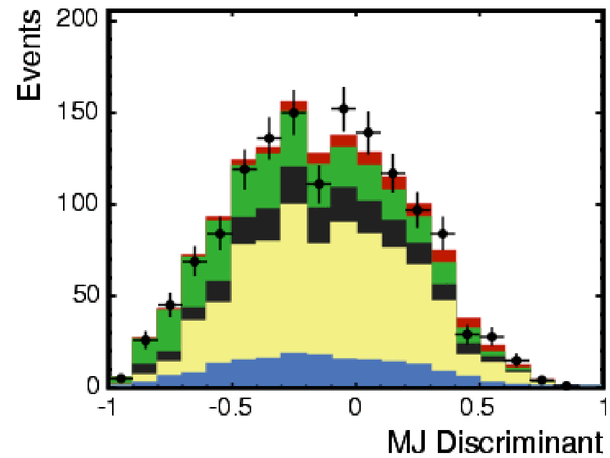
Now exploring a new window to top quark physics

A 5.5fb^{-1} result

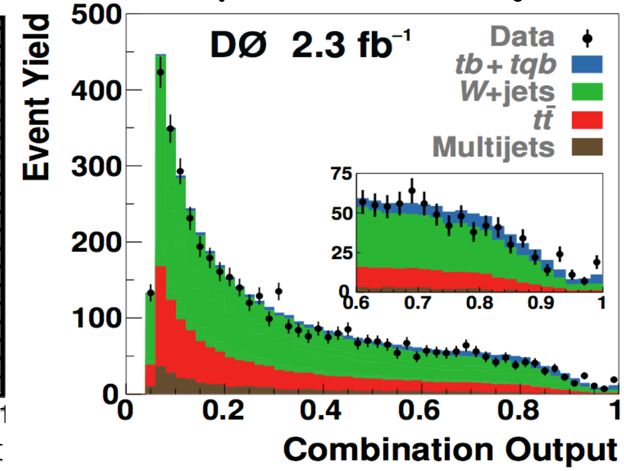
lepton + MET + jets

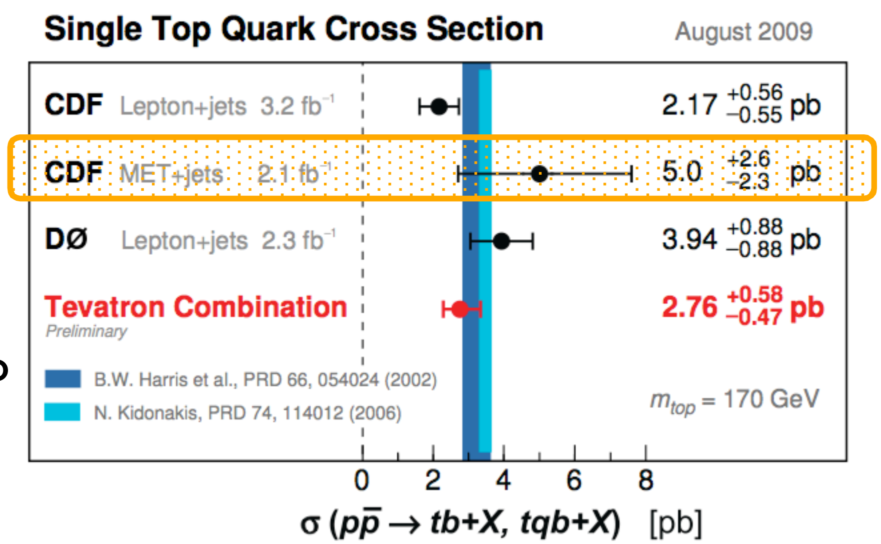


MET + jets



lepton + MET + jets





Important to have a result in a different signature (and in both experiments) to increase confidence

Crucial to combine them to increase precision

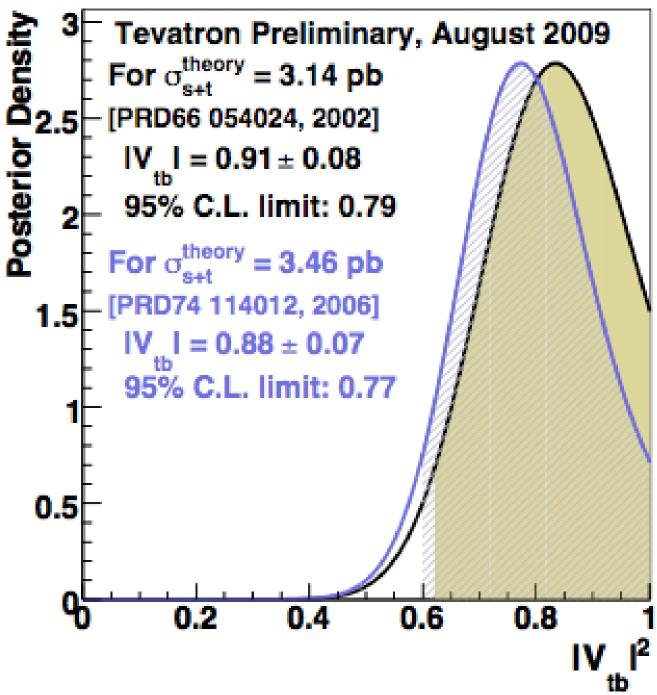
arXiv:0908.2171

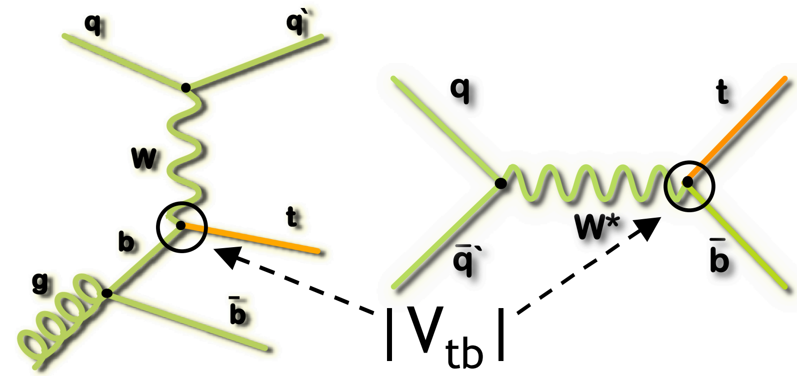
20% better than single experiment determination

Direct $|V_{tb}|$ Measurement

- Using cross section result measure $|V_{tb}|$
- Assume Standard Model (V-A) coupling and $|V_{tb}| >> |V_{ts}|, |V_{td}|$ (from BR($t \rightarrow Wb$) measurements)

$$\left|V_{tb,meas}\right|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot \left|V_{tb,SM}\right|^2$$





Tevatron combined fit:

$|V_{tb}|$>0.79 at 95% C.L.

$|V_{tb}|$= 0.91 ± 0.08 (exp+theor)

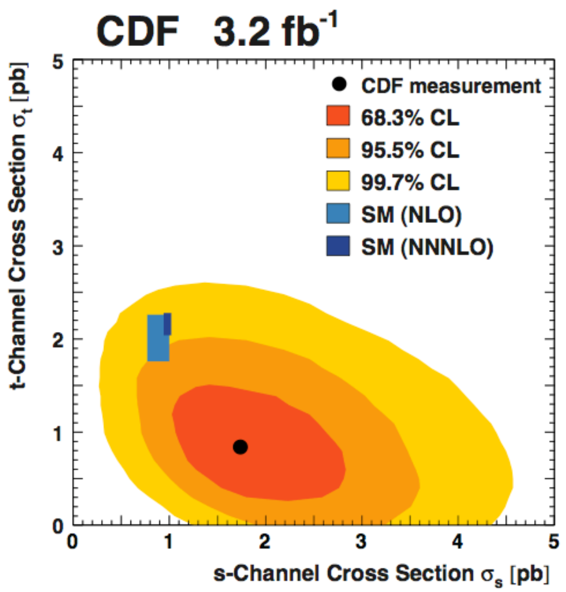
Combination increases precision from 13% to 9% on V_{tb}

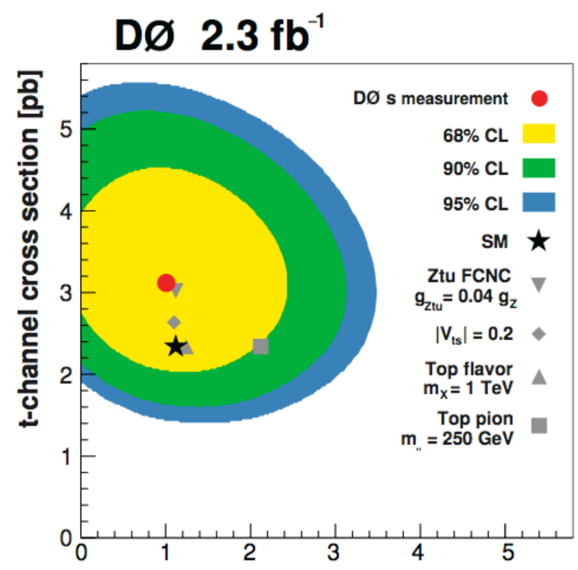
Experimental uncertainty comparable to theoretical uncertainty

arXiv:0908.2171

s- vs t-channel

- The two observation analyses measured combined single top quark cross section, assuming SM ratio between s and t
- This ratio is modifid in several new physics scenarios
  - for example in models with additional quark generations,
  - new heavy bosons
  - flavor-changing neutral currents
  - anomalous top quark couplings

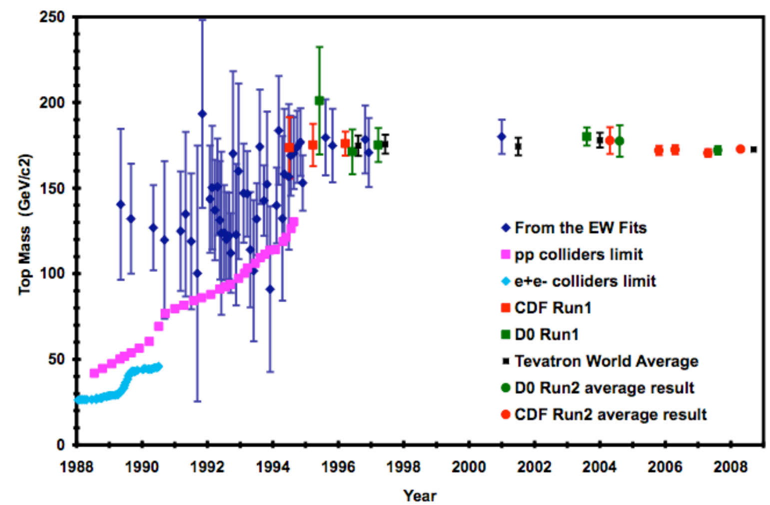




The Higgs search in MET+b-jets

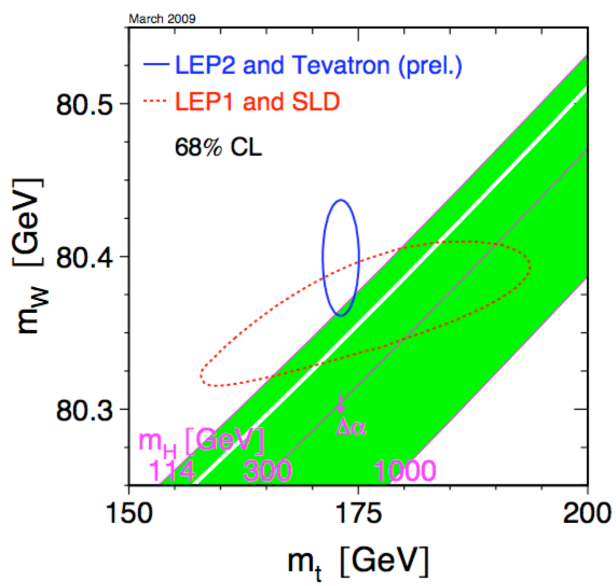
Now the Higgs: where to look?

Top quark mass was found in agreement with prediciton from fits to EWK parameters
Now use m_{top} and more to point us to the Higgs!



Tevatron's results:
m_{top} = **173.1 ± 1.3 GeV** (arXiv:hep-ex/0903.2503v1)
m_W = **80.399 ± 0.025 GeV**
which in the EWK fit give the following predictions

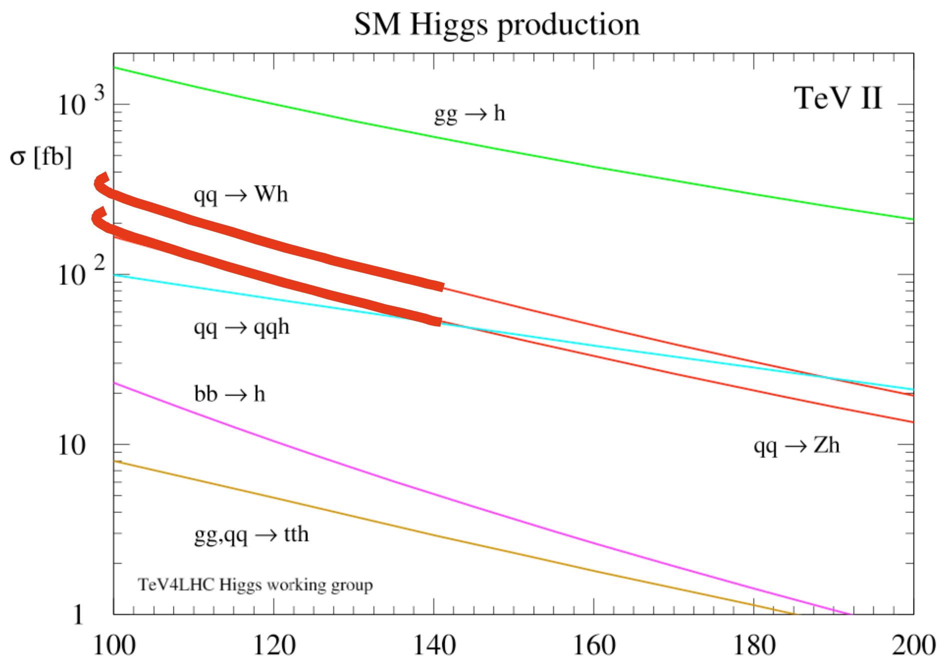
- $m_H = 90^{+36}_{-27}$ GeV @ 68 % CL
- m_H < 163 GeV @ 95 % CL



LEP directly searched the existence of the Higgs boson and found: m_H > **114.4 GeV** @ 95% CL

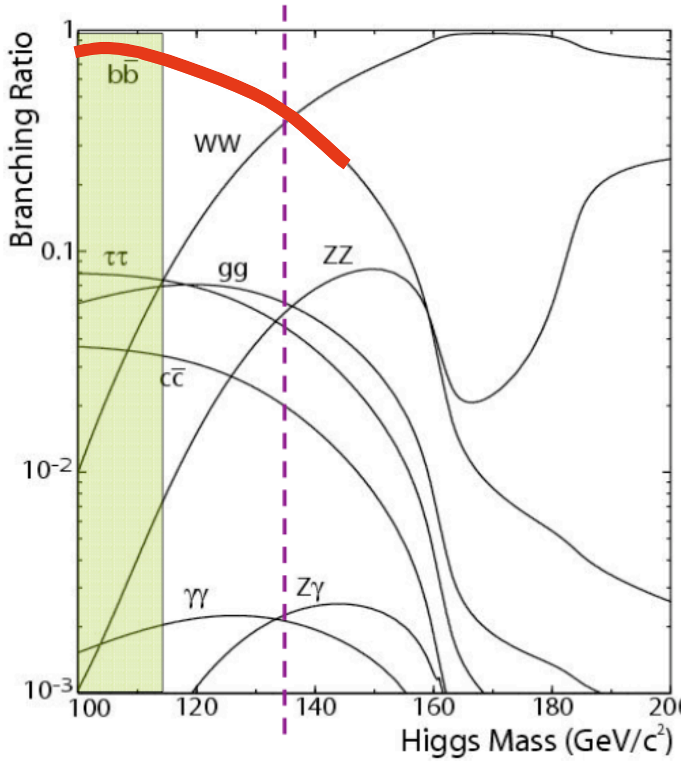
Low mass is SM favored region…
…*and where the MET+b-jets signature matters!*

Higgs strategy at the Tevatron



Higgs production cross section at the Tevatron:

- gg→H highest production x-sec
- W/Z+H about a order of magnitude smaller



Low mass m_H < 135GeV:
BR(H→bb) dominates:
gg → H → bb too challenging! QCD irreducible
Look at HV evts, use W/Z signatures to increase S/B

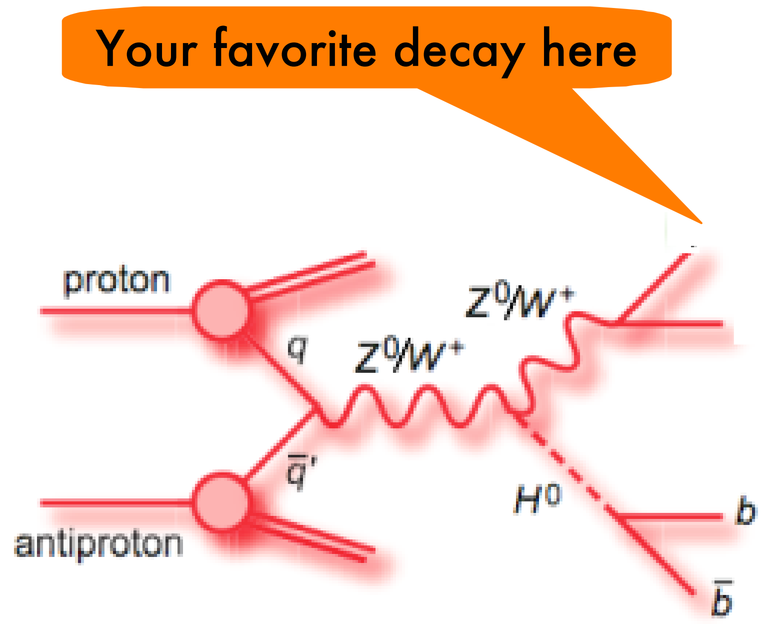
WH/ZH decays

- Dileptonic(e,mu) ZH → ll $b\bar{b}$
  cleanest channel and fully reconstructed final state - *BUT* lowest σXBR

- Ele/mu+Jets WH → lν $b\bar{b}$
  good S/B ratio, limited lepton coverage

- All hadronic WH/ZH → qq $b\bar{b}$
  challenging channel: highest BR *BUT* huge QCD *physics* backgrounds (hard to reduce)

- Missing Energy plus jets ZH → $\nu\bar{\nu}$ $b\bar{b}$
  here not just a "recovery" signature (see next slide), huge QCD *instrumental* background

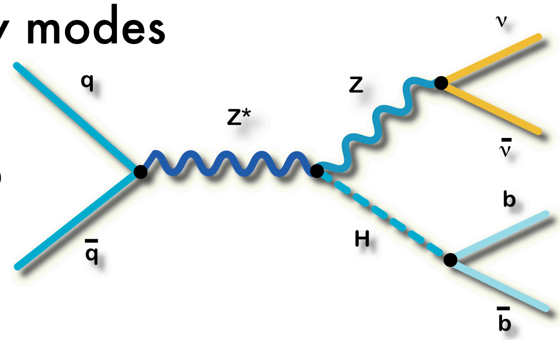


Single channels not sensitive to Higgs: exclusion can be achieved by combination of DEDICATED analysis for EACH channels from BOTH experiments!

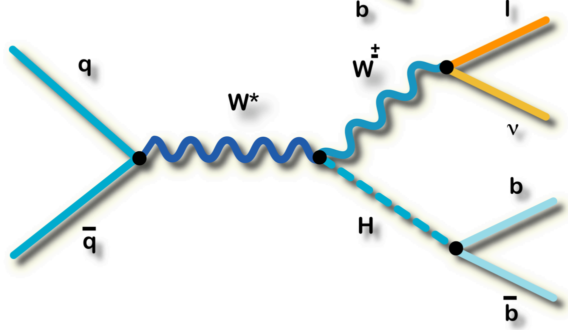
ZH/WH→ missing E_T +b-jets

Same preselection same as single top search in MET+b-jets.
Acceptance to HV production through H → $b\bar{b}$ decay and many different vector boson decay modes

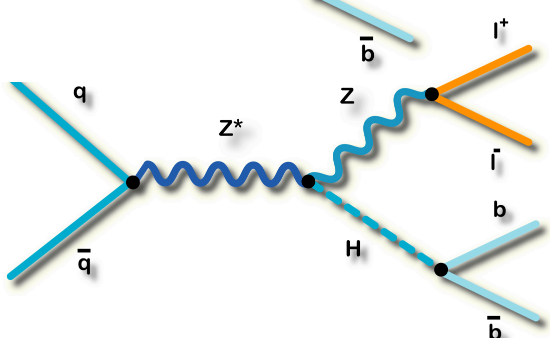
ZH→ $\nu\bar{\nu}$ $b\bar{b}$

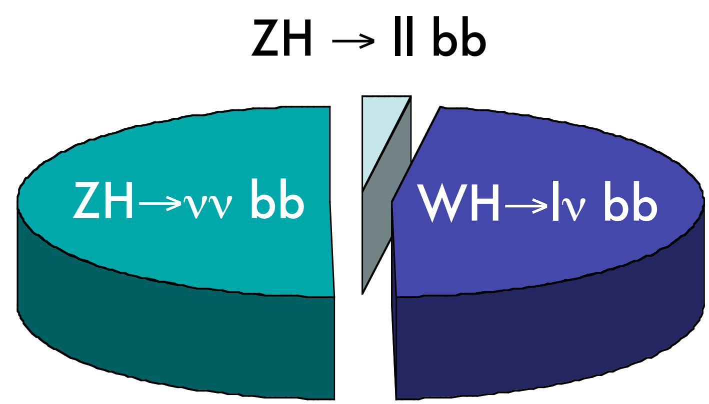


WH→l$\nu b\bar{b}$



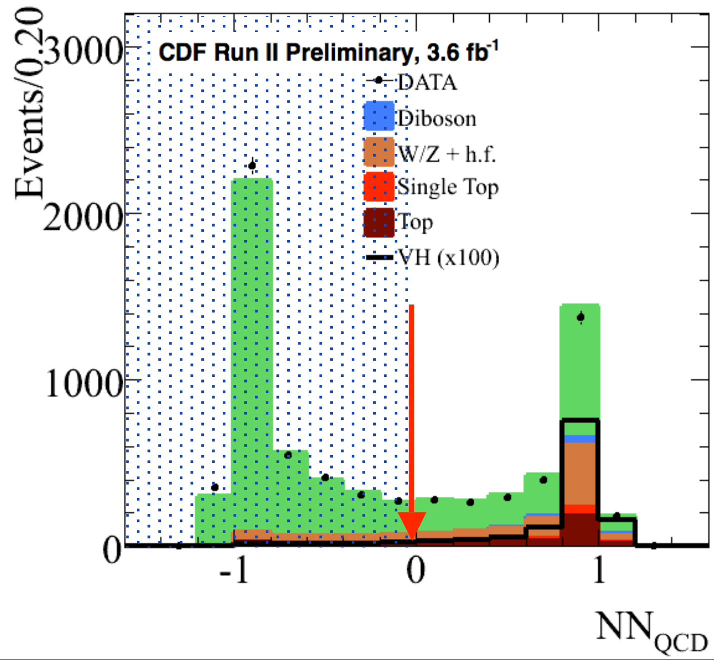
ZH→ ll $b\bar{b}$





- no identified leptons→QCD <u>instrumental</u> contribution huge!(mismeasured jets=MET)
- generic signature →large number of signal events!

Final Higgs event selection



- Use 3.6fb^{-1} of recorded data here
- slightly different QCD killer NN
  - maximize acceptance
  - almost 4 evts/fb-1

DIVIDE ET IMPERA

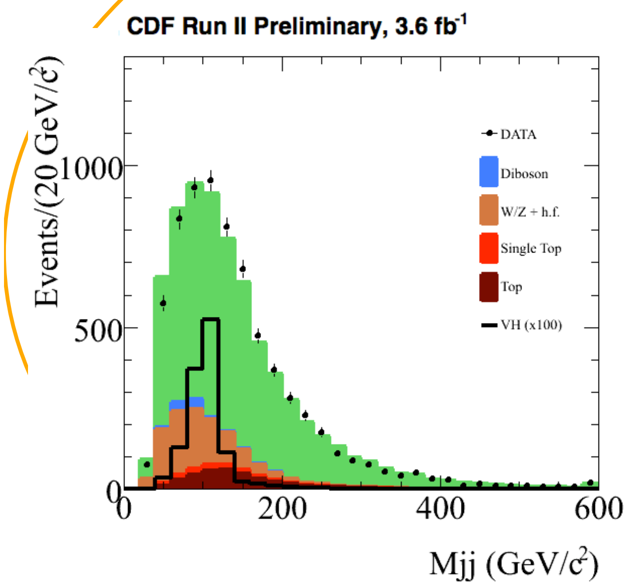
Split in high and low significance S/√B

- 40% improvement by splitting in high and low S/√B regions
- 10% improvement by including the worst S/√B region (1 b-tagged jet)

b-tags	N Higgs evts (@115GeV)	N bck evts	S/√B
All	12.4	2930	0.23
1 SecVTX	6.7	2500	0.13
1 SecVTX +1 JetProb	2.6	260	0.16
2 SecVTX	3.1	170	0.24
Quadrature sum of three categories			0.32

Multivariate discriminant

Similar challenges to single top search: but here we do reconstruct the signal resonance, so a lot more to gain!



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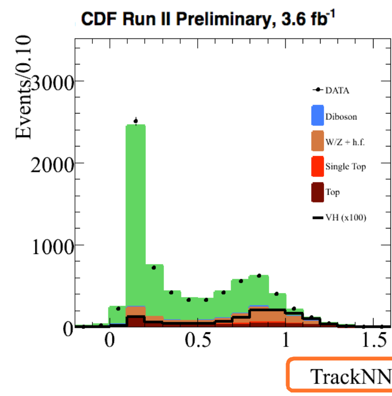

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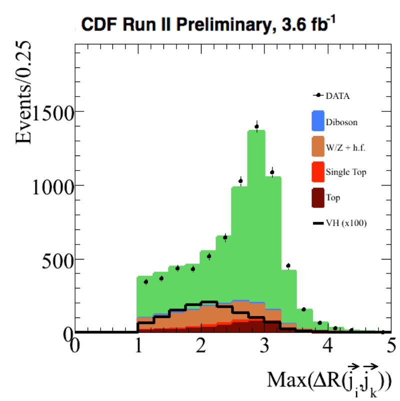

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more

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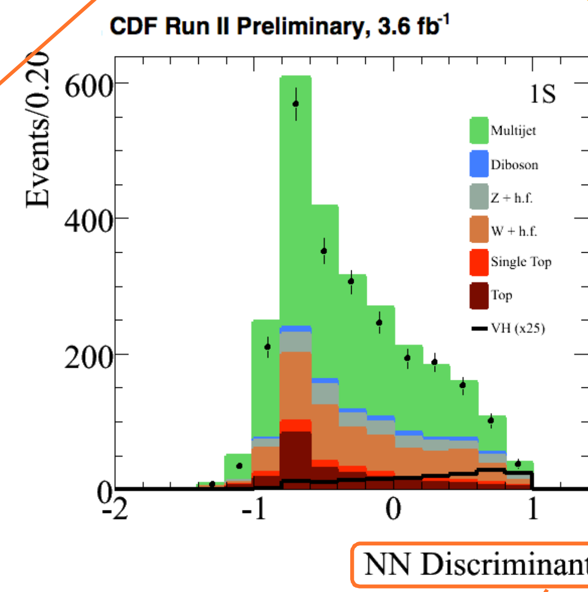
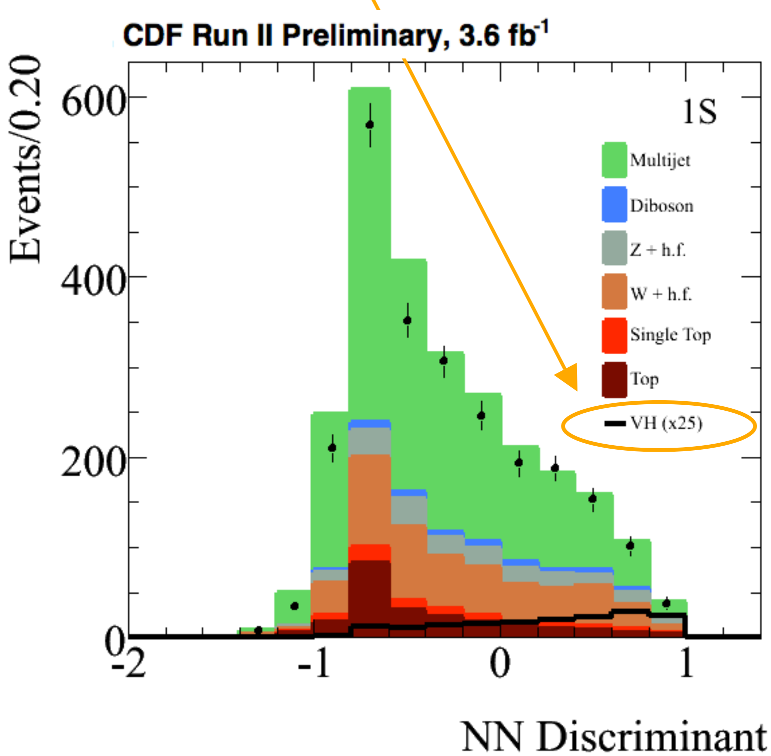


Convolution of many track-related observables, discriminate residual instrumental QCD

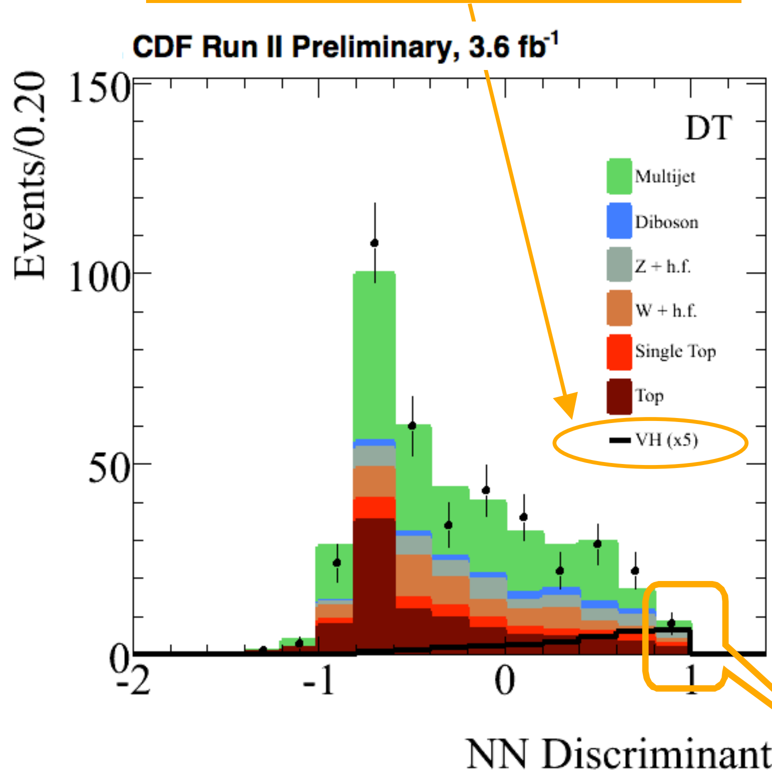
Look for signal!

A close look at the discriminant

Higgs magnified X 25



Higgs magnified X 5

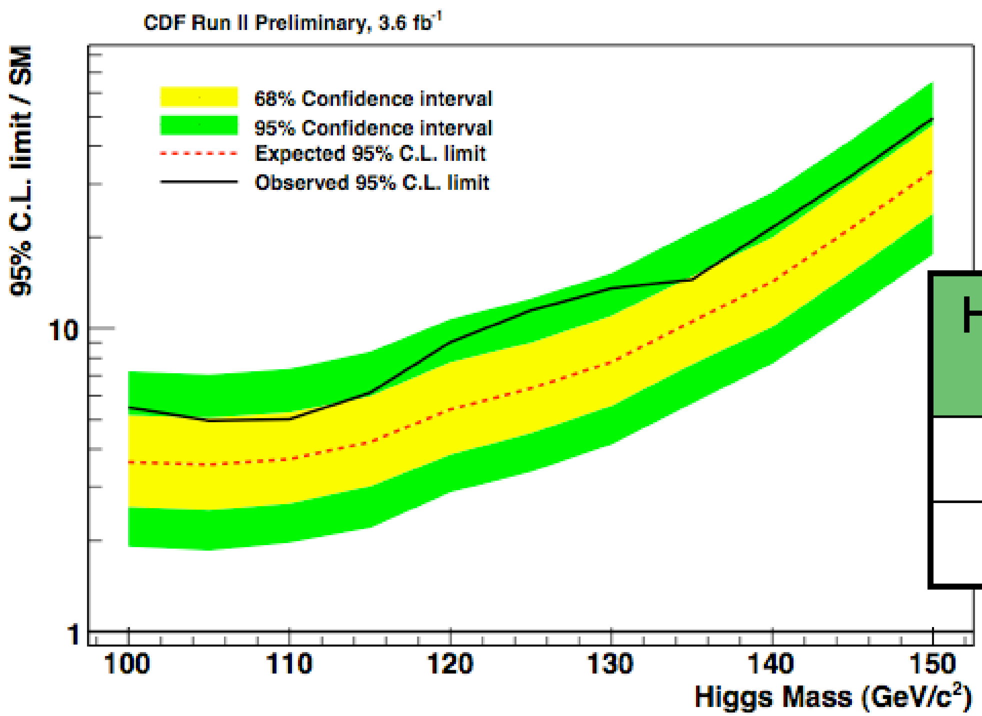


Analysis	ll+jets	l+MET+jet	MET+jets
S (ev/fb^{-1})	.7	3.8	3.5
S/B	1/50 - 1/250	1/70 - 1/400	1/50 - 1/350

S/B ratio 1/6 in most sensitive bin
We expect 1.4 Higgs events here
(assuming M_H=115)

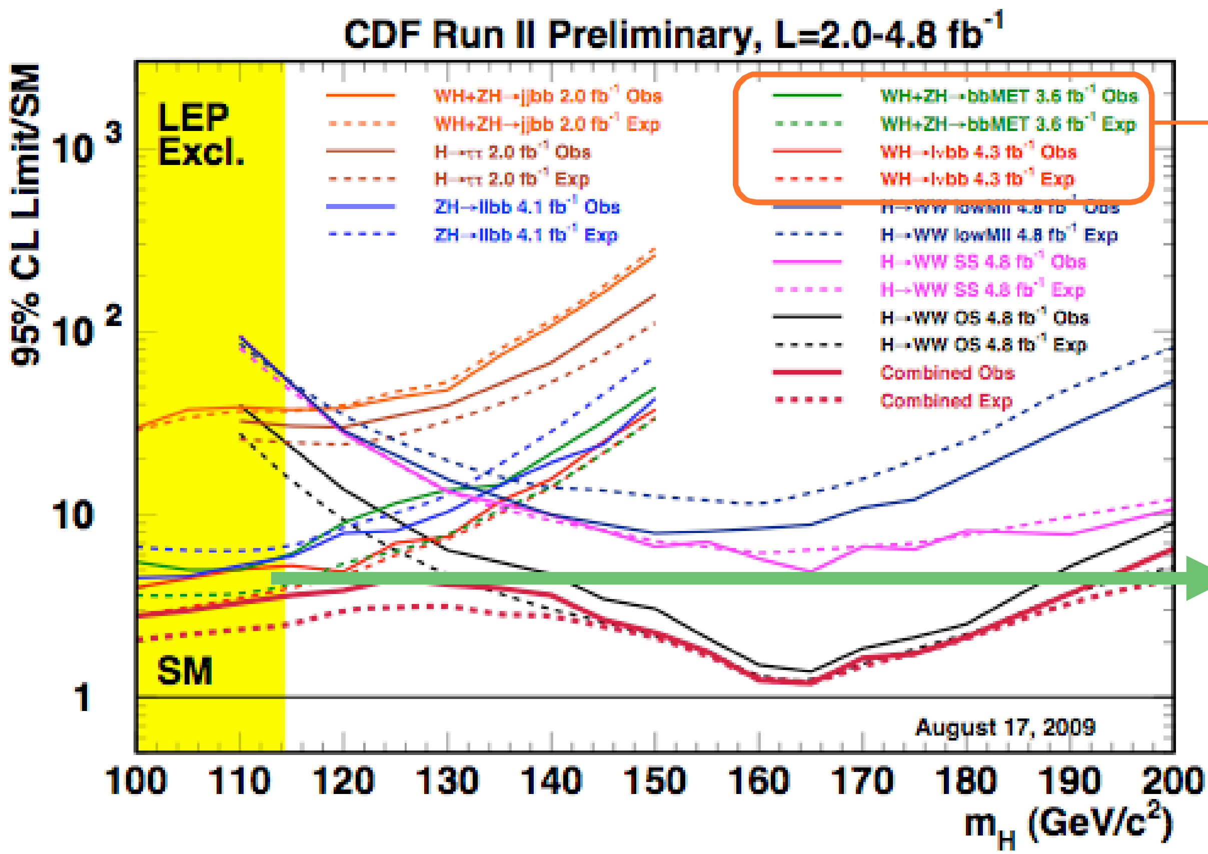
The MET+jets results

- Do a binned likelihood scan of the 3 NN discriminant distributions
  - In absence of an excess, report the 95% CL limit on the cross section
  - For simplicity, quote number as X times the SM Higgs cross section
  - With an expected limit of 4.2 the SM xsec for 3.6fb^{-1} analyzed, this search is the *most sensitive low mass Higgs search* per fb^{-1} at the Tevatron, comparable to the CDF WH to lνbb search
  - Search *twice more sensitive* per fb^{-1} than the previosly published one



Higgs mass (GeV)	105	115	125	135
Exp	3.6	4.2	6.3	11
Obs	5.0	6.1	11.5	15

How it fits in the CDF combination



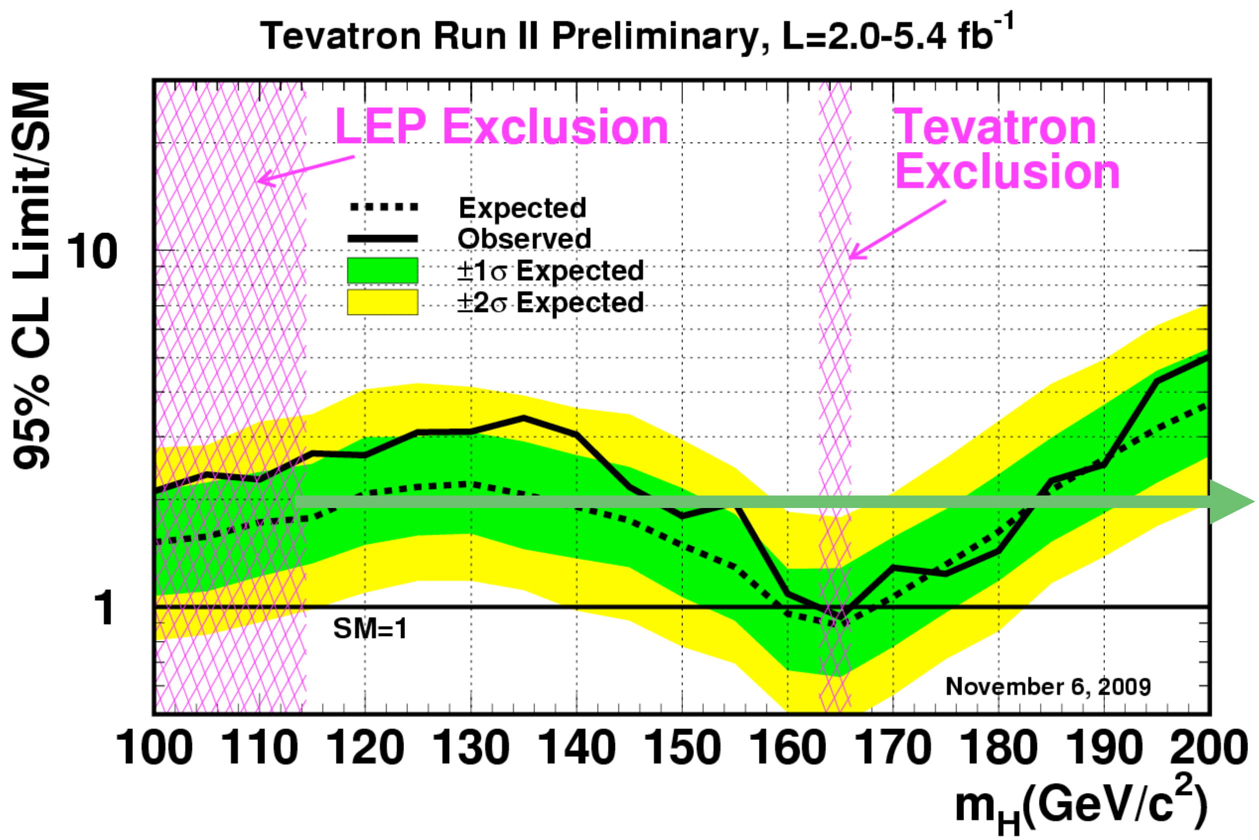
Same samples/ analyses techniques used for single top observation

Below 3 times the SM expectation everywhere

As mentioned earlier..

- No single analysis at low mass sensitive to Higgs
- BUT! Combination provides a x2 improvement with respect to to single best analysis

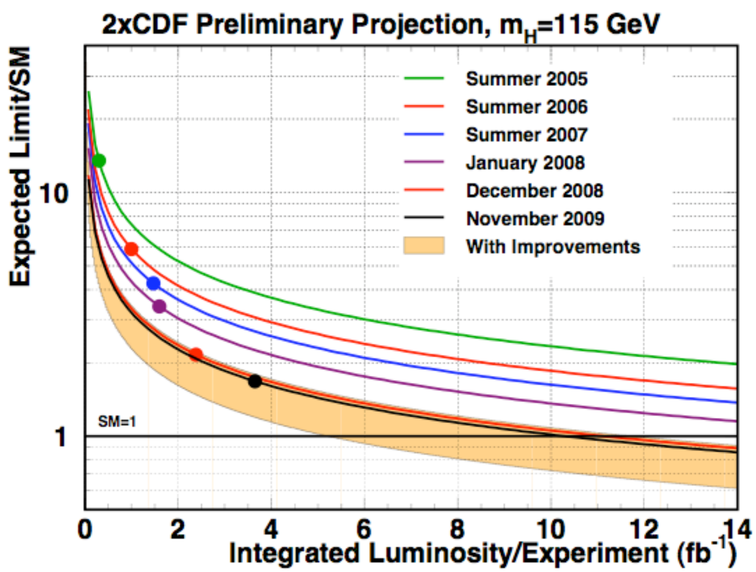
And in the Tevatron combination

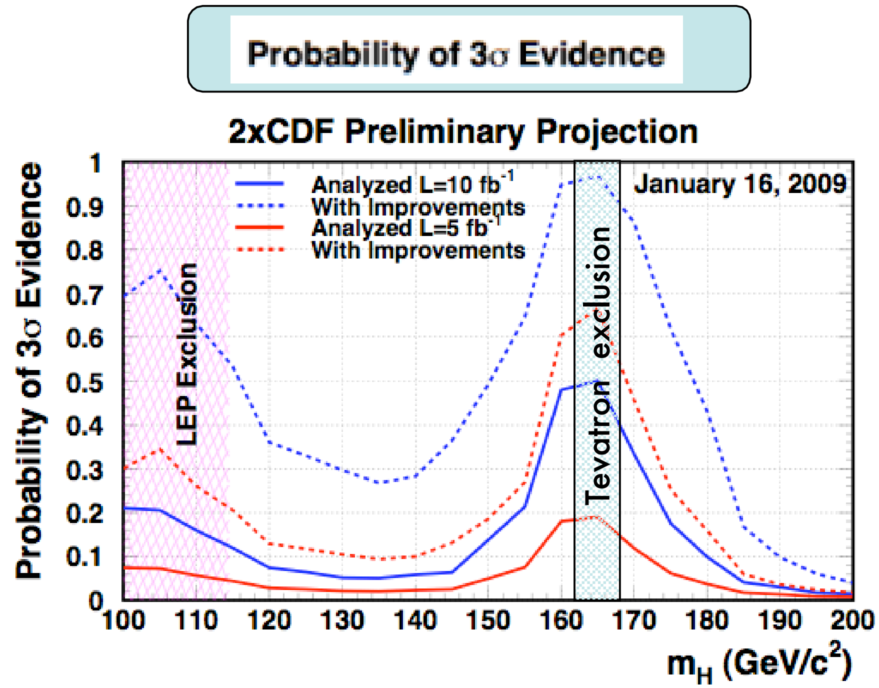


Expect below 2 times the SM expectation everywhere

- At 115Gev, we are 1.8 times the Standard Model cross section (average lumi used 4.5fb^{-1})

Tevatron future at low mass





- Experiments are continuously improving analysis technique:
  - Summer 07 projection expect a improvements between 1.5 to 2.25 to existing sensitivity
  - increased indeed by a factor of >1.5 last year: equivalent of using more than double luminosity
  - More/new ideas currently being tested to increase further sensitivity

Conclusions

MET+b-jets is a very hard signature at hadron colliders.

Infact, you need to:

- contantly control - and especially evolve! - understanding of MET, jets, and the way you trigger data acquisition on them
- model QCD accurately, fight it relentlessly

- Now several others SM and SM-searches benefiting from the above understanding

But there is a lot of satisfaction to all this:

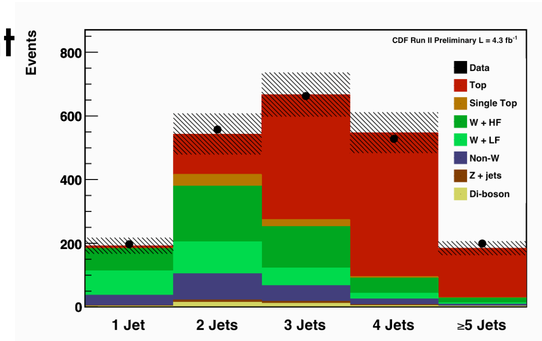
- MET+b-jets contributed to single top observation at CDF
- **MET+b-jets golden mode** to search for low mass Higgs at the Tevatron

Are multivariate techniques safe?

Look at top pair production x-sec measurements in different *samples*, with different *techniques*

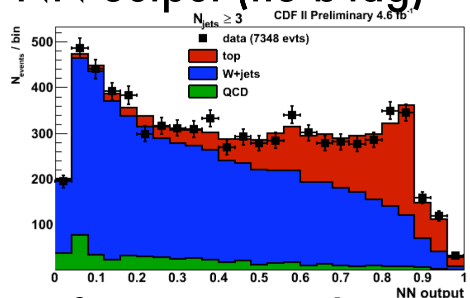
Semileptonic, Counting experiment

- S/B~3/1
- Conf. Note 9462



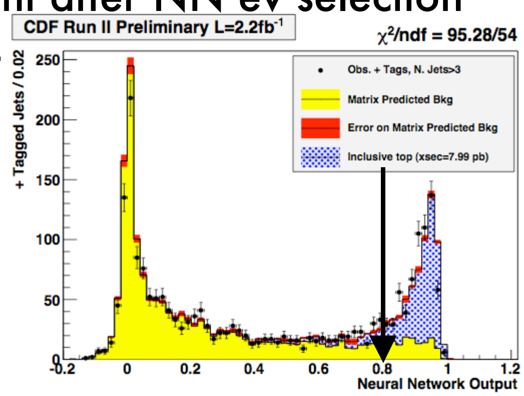
Semileptonic, Likelihood fit to NN output (no b-tag)

- S/B~1/5
- Conf. Note 9474



MET+jets, counting experiment after NN ev selection

- S/B ~1/3 before NN cut
- S/B ~4/1 after NN cut

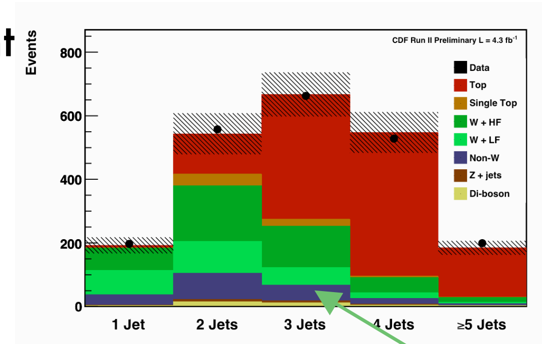


Are multivariate techniques safe?

Look at top pair production x-sec measurements in different *samples*, with different *techniques*

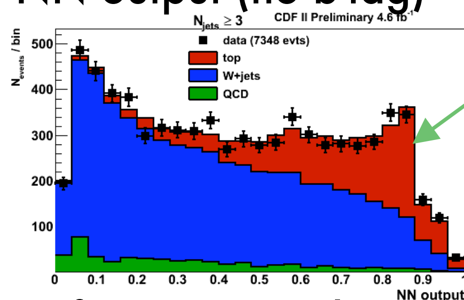
Semileptonic, Counting experiment

- S/B~3/1
- Conf. Note 9462



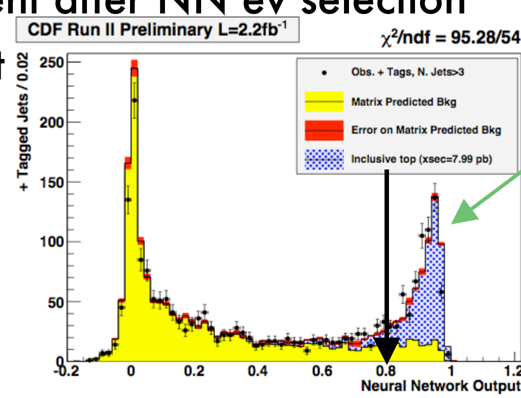
Semileptonic, Likelihood fit to NN output (no b-tag)

- S/B~1/5
- Conf. Note 9474

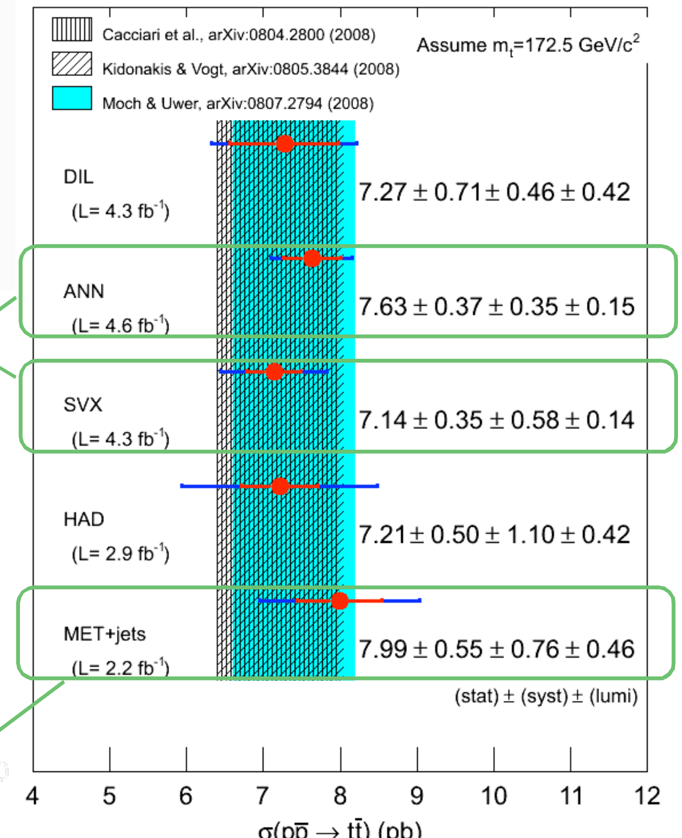


MET+jets, counting experiment after NN ev selection

- S/B ~1/3 before NN cut
- S/B ~4/1 after NN cut



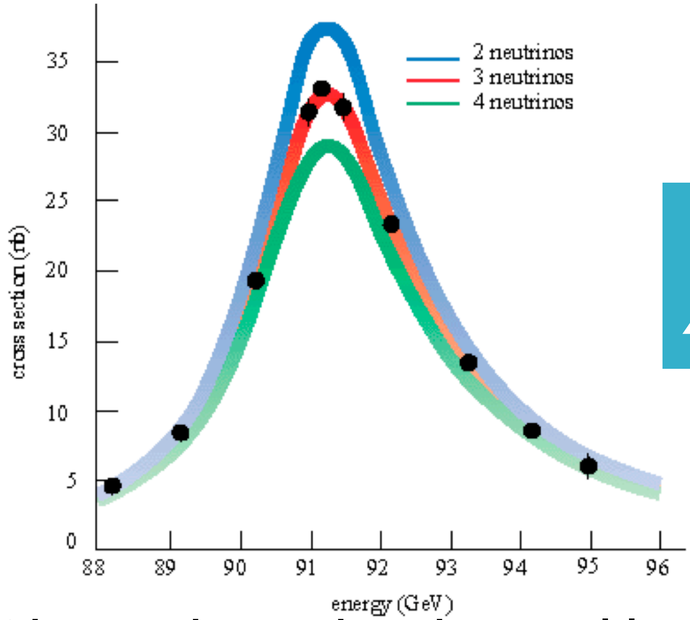
YES!



They all agree with each other and SM prediction: bad S/B ratio can be handled

Fourth generation

- LEP set indirect limit on number of light neutrinos to be 3; $M(\nu_4)$>45GeV

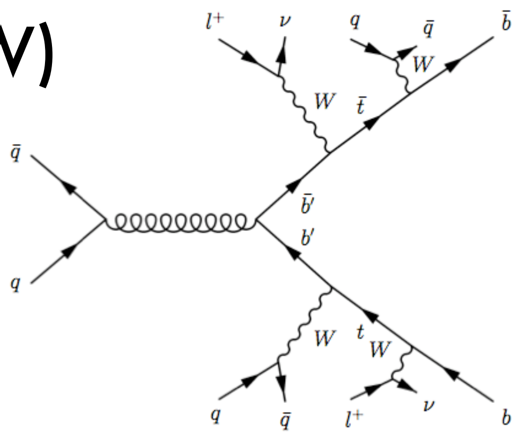


Z width from the 4 LEP experiments

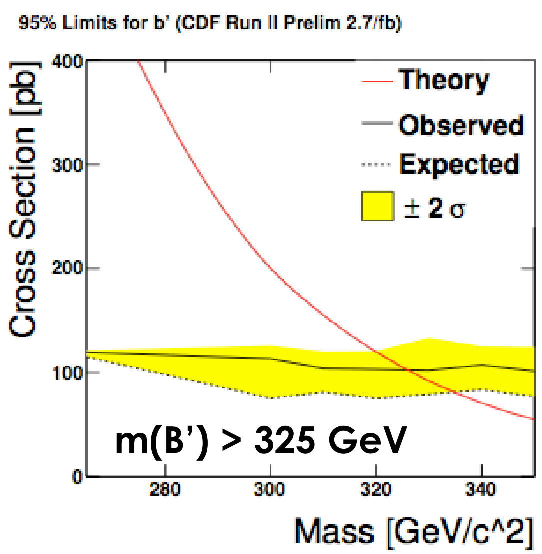
- LEP set direct limits on 4th gen charged and neutral leptons to be M(l,ν,t′,b′)>100GeV
- Tevatron has sensitivity to higher mass range, up to the 0.5 TeV range
- Search for `*fourth generation*' or `*4th generation*' on Spires gives >250 results, mostly phenomenology papers
  - Many possible scenarios still compatible with direct and indirect constraints!
  - Simple model, also relaxes the constraint on Higgs mass to be low mass

Fourth generation of quarks

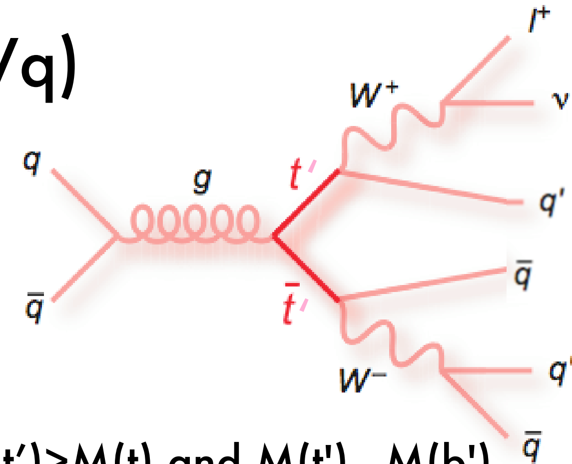
b′ (to tW)



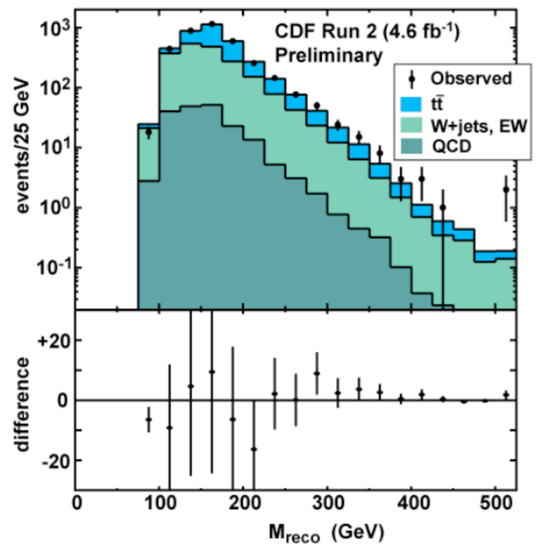
Assumes M(b′)>M(t)+M(W)
Look at same-sign dilepton, MET, b-jets
Scan for an excess in Njets distribution



t′ (to Wq)



Assume M(t′)>M(t) and M(t') - M(b') < M(W) then decay t′t′→qqWW. Same as ttbar but different reconstucted mass



m(t′) > 335 GeV