A Search for Technicolor Production at DØ

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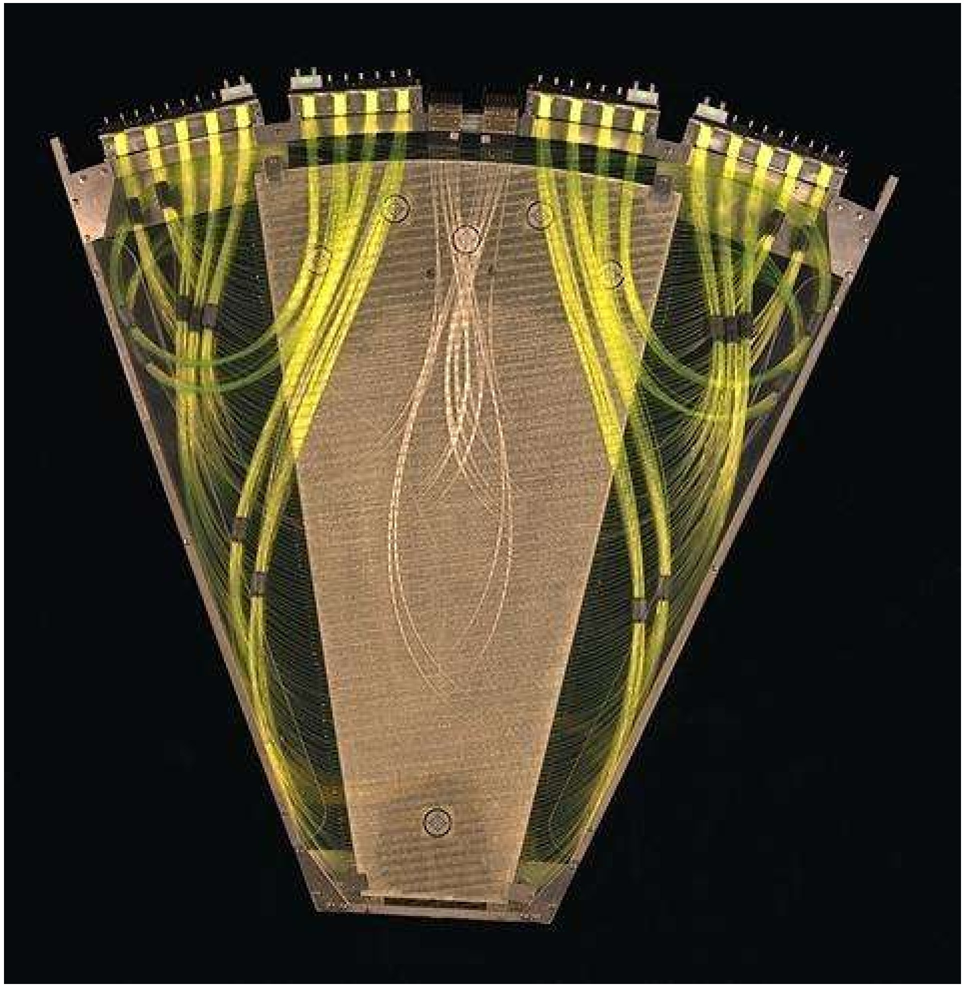


The Problem of Mass

- Standard Model is based on the principal of local gauge invariance
  - Assures renormalizability
  - Gives a technique for determining the Lagrangian
- Electroweak physics described by $SU(2)_L \otimes U(1)_Y$:

Left-handed Weak doublet: $\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$

$$f \rightarrow \exp\left(ig'\frac{Y}{2}\xi\right) f \qquad f_L \rightarrow \exp(ig\vec{\tau}\cdot\vec{\theta}) f_L$$

$$B_\mu \rightarrow B_\mu + \partial_\mu \xi \qquad W^i_\mu \rightarrow W^i_\mu + \partial_\mu \theta^i + g\epsilon^{ijk} W^j_\mu \theta^k$$

Mix to form γ, $W^\pm$, Z

- But fermions, W and Z are massive
- Mass terms violate Electroweak Symmetry

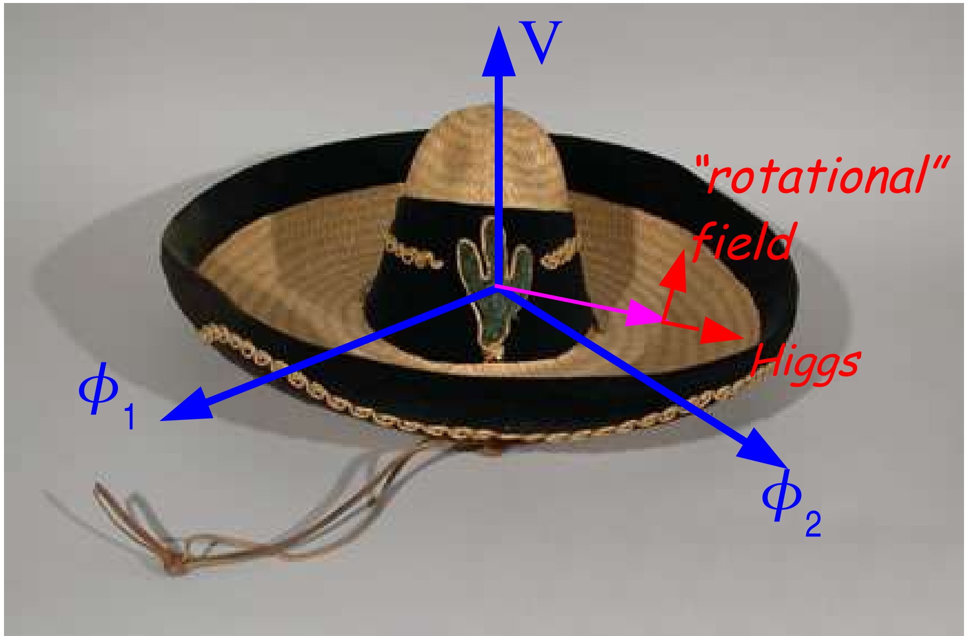
$$m(\overline{f_L} f_R + \overline{f_R} f_L)$$

$$M^2 B_\mu B^\mu$$

- Posit scalar electroweak doublet ϕ
- Quartic potential $(\mu^2<0)$

$$V=\mu^2|\phi|^2+\lambda|\phi|^4$$

- Ground states are degenerate
  - Individual ground state picks a direction (hides/breaks the symmetry)
  - Separated from others by a gauge transformation
  - Spontaneous symmetry breaking



Not just a potential Mexican hat

- With appropriate (arbitrary) choice of ground state:
  - "Radial" component becomes massive scalar particle: the Higgs
  - "Rotational" pieces become longitudinal states of $W^{\pm}$, Z
  - $W^{\pm}$, Z pick up masses

Flaws in the Standard Model

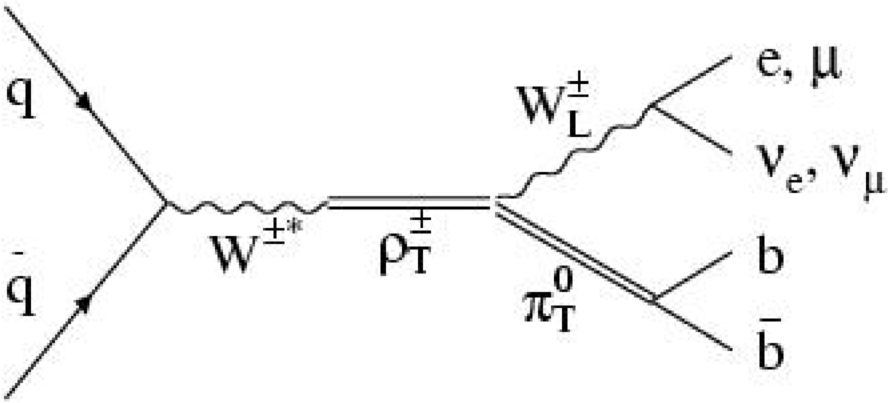
- This is all well and good, but there are some problems:
- All arise from the fact that the Higgs field is a fundamental scalar
  - Triviality – Higgs self coupling ($\lambda|\varphi|^4$) goes to zero when renormalized at scales ~ 1 TeV
  - Naturalness – Higgs propagator subject to quadratic divergences: M_H goes to renormalization cutoff squared
  - Hierarchy – If SM is part of some unified theory, the EW symmetry breaking scale wants to be the same as the GUT scale

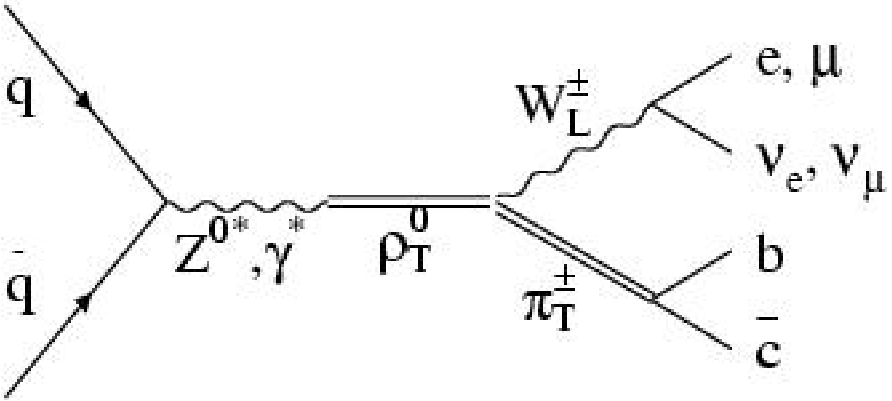
A Strong Inspiration

- Observe that QCD does the job qualitatively
- Respects an accidental symmetry between u and d quarks (chiral symmetry)
- Similar structure to weak isospin
- When QCD becomes strong, scalar bound states are formed (pions)
- Effective Higgs-like potential breaks electroweak symmetry
- $M_W \rightarrow \Lambda_{QCD} \approx$ 50 MeV/c^2
- Right idea, wrong scale
- Maybe something QCD-like can work instead

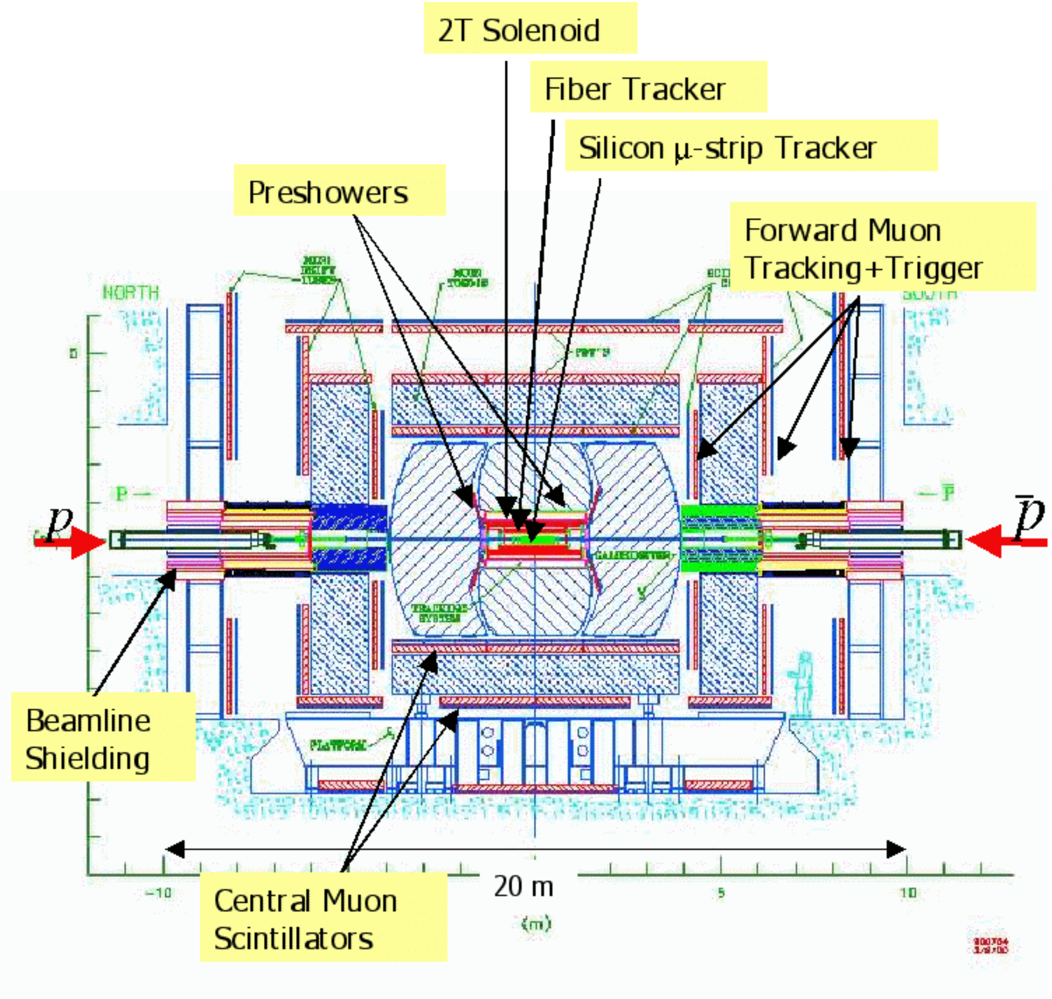
Technicolor in a Hurry

- Posit:
  - new fermions: *Techniquarks*
  - new interaction: *Technicolor*
- If $\Lambda_{TC} \approx$ 246 GeV, then you get the right masses
- No elementary scalars
- Broad spectrum of bound states, like QCD
- Larger cross-sections than Higgs
- Realistic models are more complicated

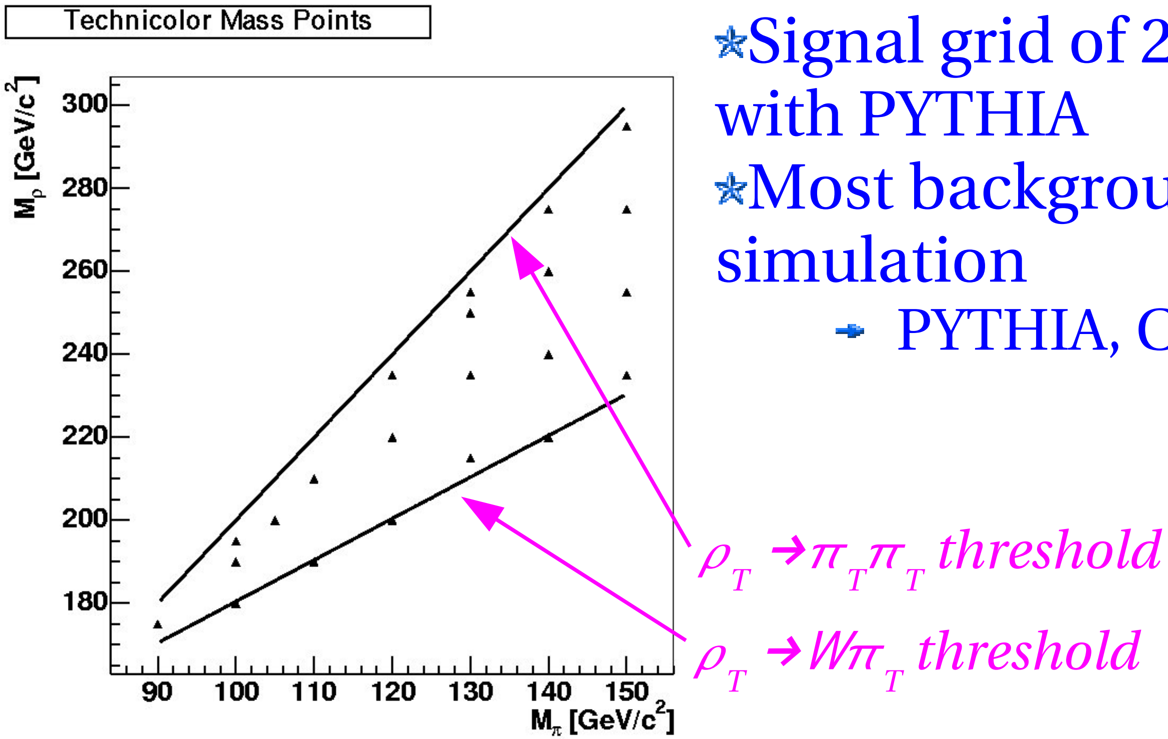




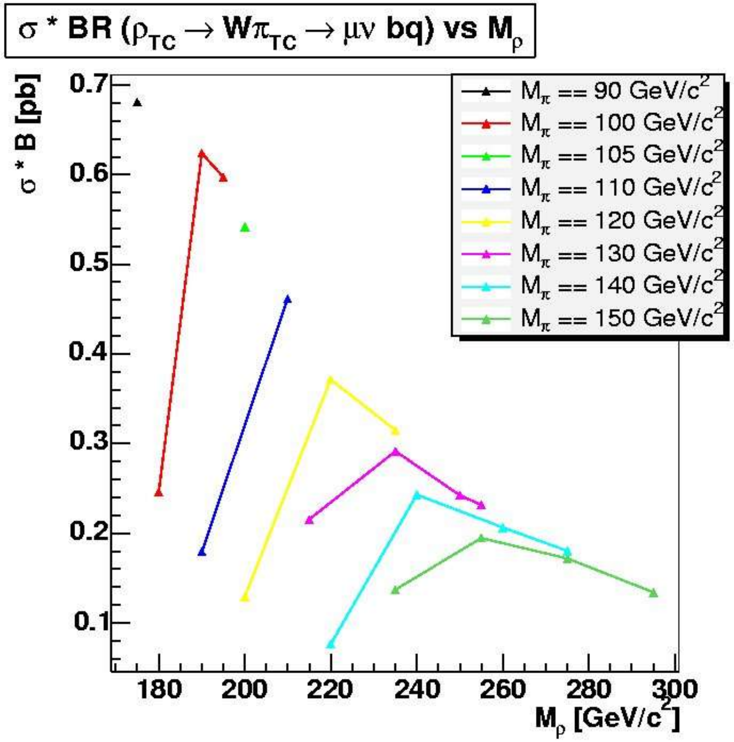
The DØ Detector



- Located at Fermilab
- Has recorded more than 1 fb^{-1}
- This analysis uses 300 pb^{-1}
- Makes use of almost all detector subsystems



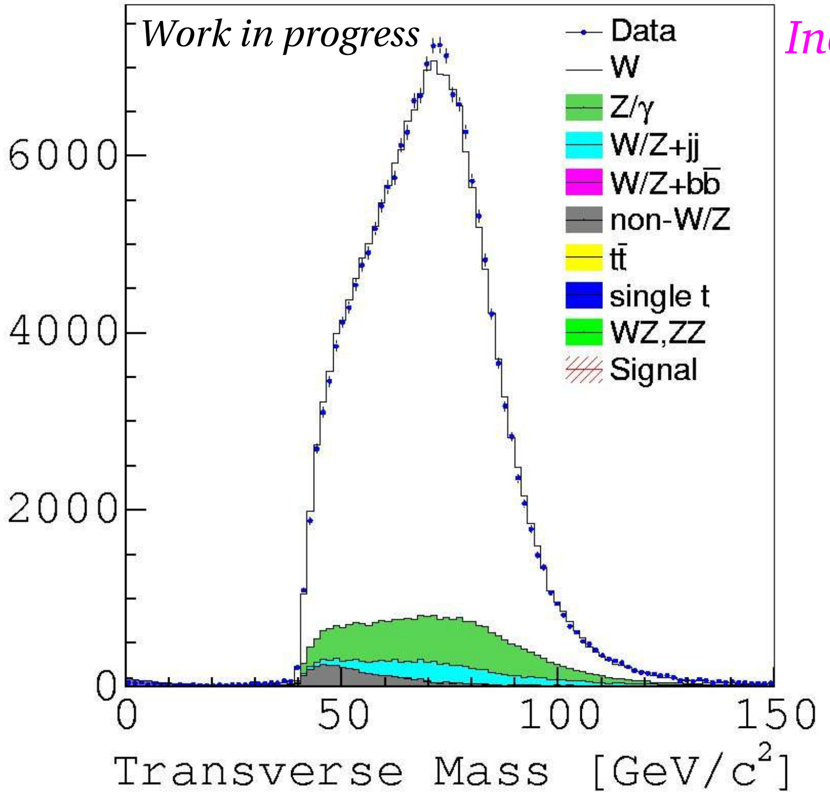
- Signal grid of 20 mass points, generated with PYTHIA
- Most backgrounds estimated by simulation
  - PYTHIA, COMPHEP, ALPGEN



M_V = 100 GeV

- Includes W/Z+jj/bb, WZ, ZZ, Top
- Instrumental backgrounds from data
- Collider data is 300 pb^{-1} collected with a single muon trigger

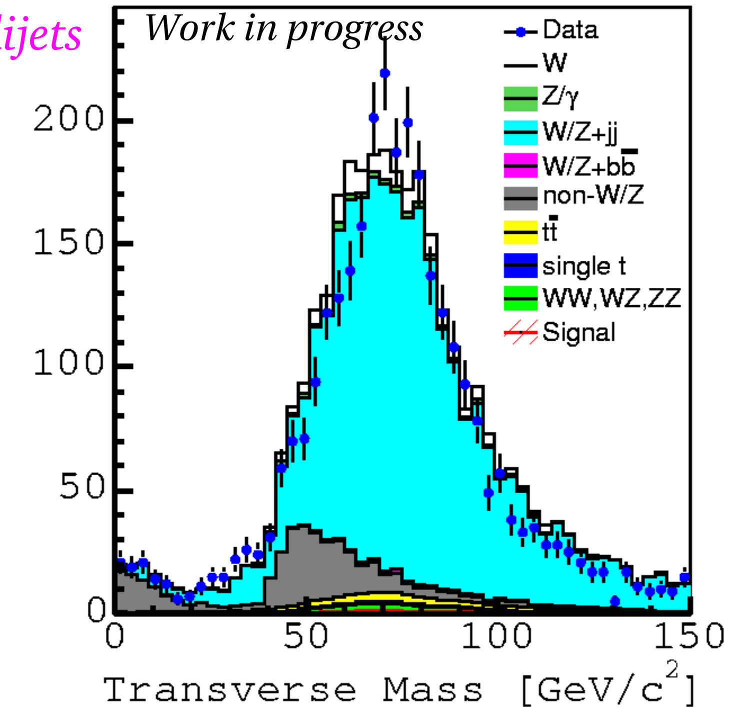
First Find the W



Inclusive W's

- Two jets with p_T > 20 GeV/c, $|\eta| < 2.5$

W plus dijets



- Primary vertex within silicon acceptance
- One isolated muon with p_T > 20 GeV/c, $|\eta| < 2.0$
- Missing transverse energy > 25 GeV
- Transverse mass$(\mu, \not{E}_T) > 30$ GeV/c^2 (not shown here)

Background Estimation (aside #1)

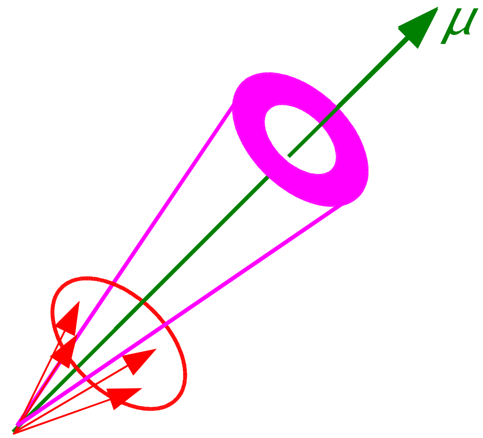
- QCD is a shorthand for a variety of background sources
  - Jets faking muons by punching through the calorimeter
  - Real muons from hadronic decays inside of jets
- The isolation requirement ideally removes these backgrounds
- In reality:

$$N_{pass} = \epsilon S + fB$$

$$N_{fail} = (1-\epsilon)S + (1-f)B$$

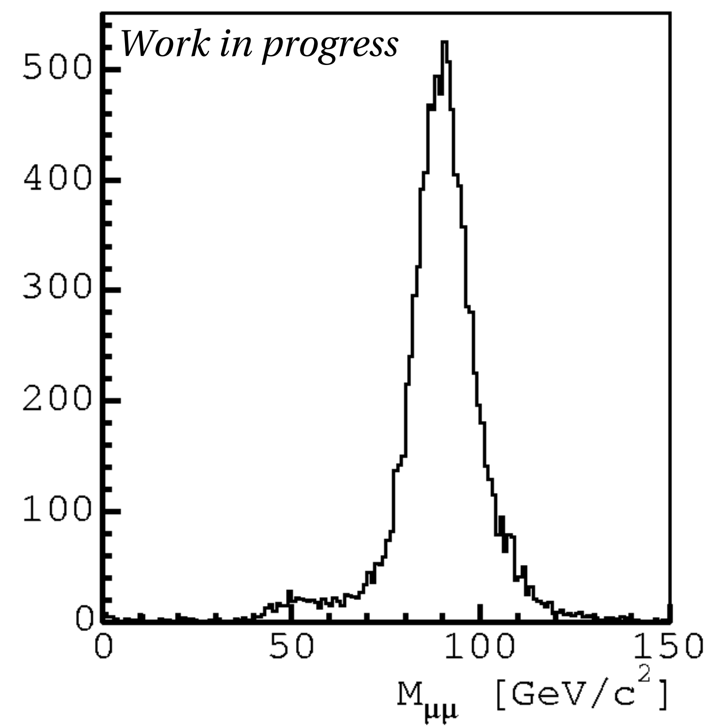
N_{pass} : # of events passing isolation requirement
N_{fail} : # of events failing isolation requirement
S : # of signal events
B : # of background events
ϵ : probability that a signal event passes isolation requirement
f : probability that a background event passes isolation requirement

- Solve for fB
- Already have N_{pass} and N_{fail}
- Measure ϵ from $Z\rightarrow\mu\mu$ events
- Measure f from muons in low missing E_T events



- ϵ and f are topology dependent
- 100% systematic assigned to background contribution

Topology	ϵ	f
W inclusive	0.957±0.002	0.179±0.002
W+j inclusive	0.89±0.01	0.141±0.002
W+jj inclusive	0.89±0.01	0.080±0.005
W+bj inclusive		0.06±0.01
W+bj exclusive		0.05±0.01



- Calorimeter Halo
  - 01. < ΔR < 0.4
  - Energy < 2.5 GeV
- Track Isolation:
  - ΔR < 0.5
  - Total p_T of nearby tracks < 2.5 GeV

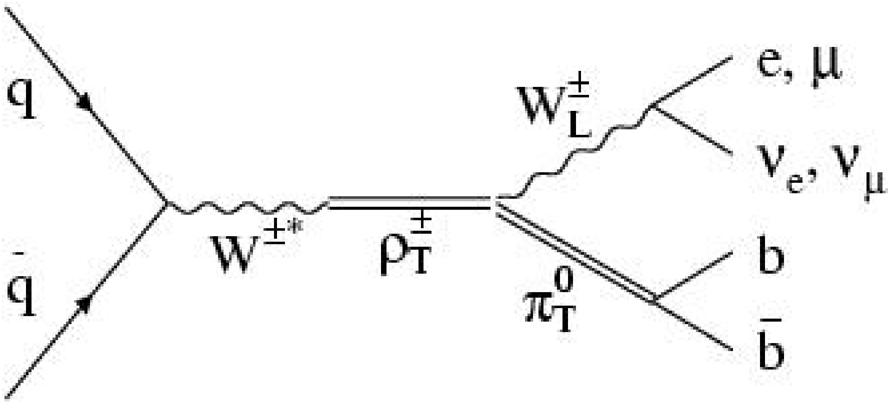
Normalization (aside #2)

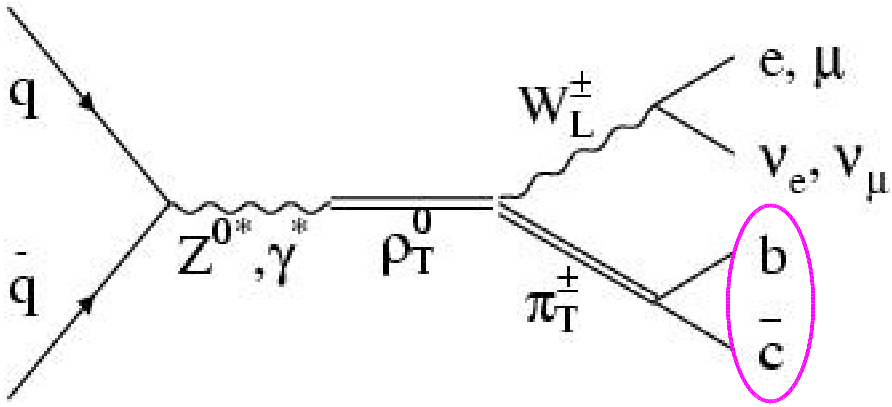
- Do not use recorded luminosity to normalize the simulation
- Instead determine cross section weighted sum of all backgrounds
- Force agreement at the inclusive W selection stage

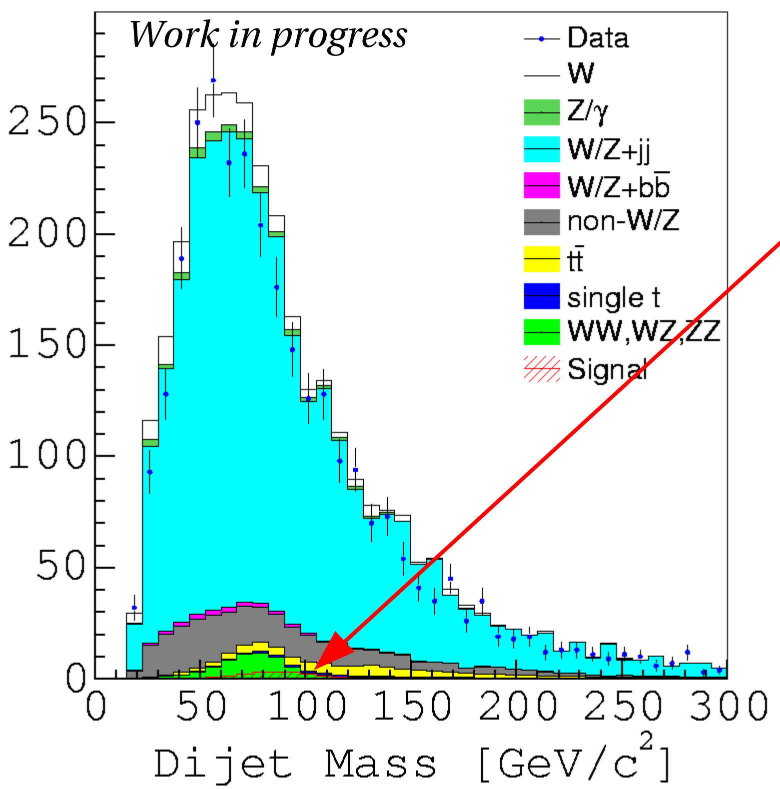
$$N_W^{data} = L' \sum_{i=channels} \epsilon_i^{W,mc} \sigma_i \Rightarrow L' = N_W^{data} \frac{\sum_{j=channels} \epsilon_j^{W,data} \sigma_j}{\sum_{i=channels} \epsilon_i^{W,mc} \sigma_i}$$

- Use effective luminosity (L') for everything else
  - Measure 200 pb^{-1}
- No systematic (6.5%) from recorded luminosity
- Other systematics cancel
  - Trigger efficiency
  - Muon selection scale factors
- Primary uncertainty is from W cross section (5%)

Back to Your Regularly Scheduled Search



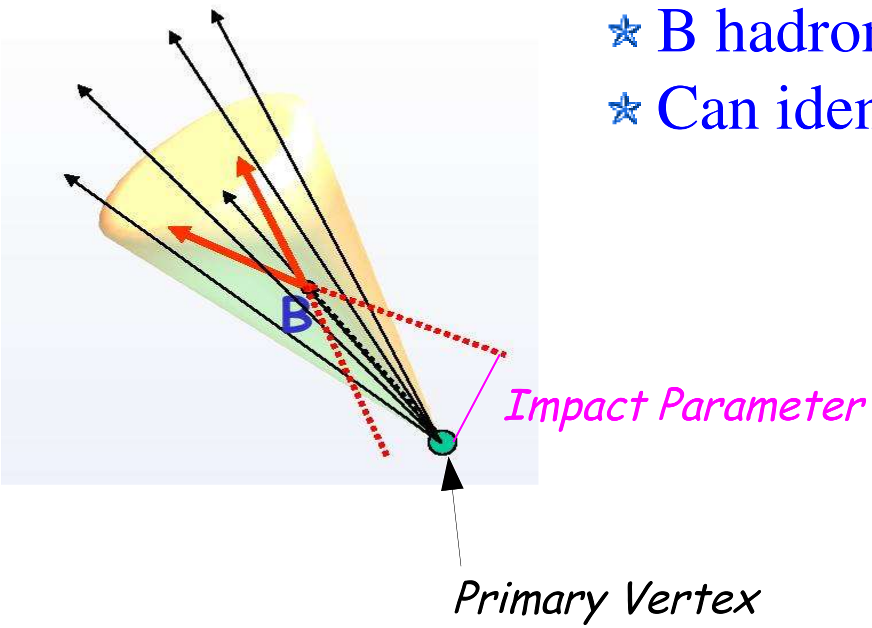


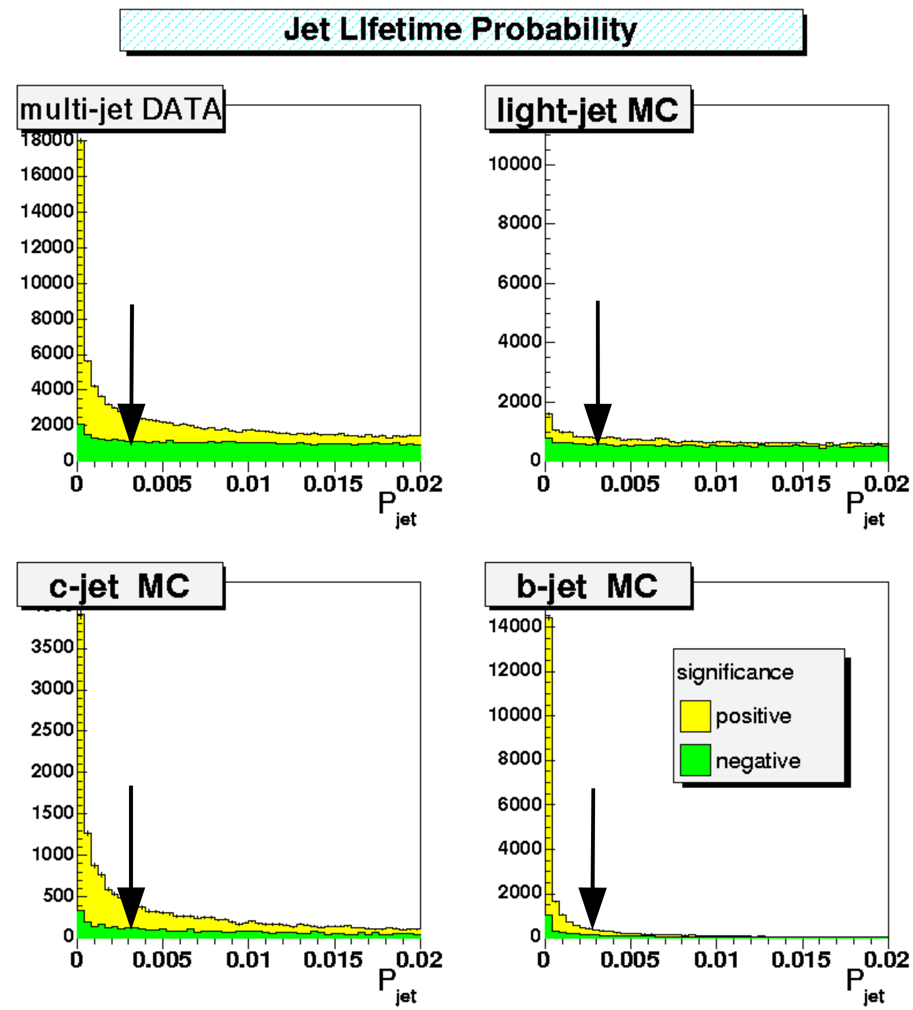


- Still hard to see the signal
- Try identifying b-jets
  - only ask for one
- Remove events with extra jets (tt) or leptons (tt, Z)
- Exploit resonances
- Heavy particles produced at rest

b-tagging

- B hadrons travel hundreds of microns before decaying
- Can identify them by reconstructing decay vertex

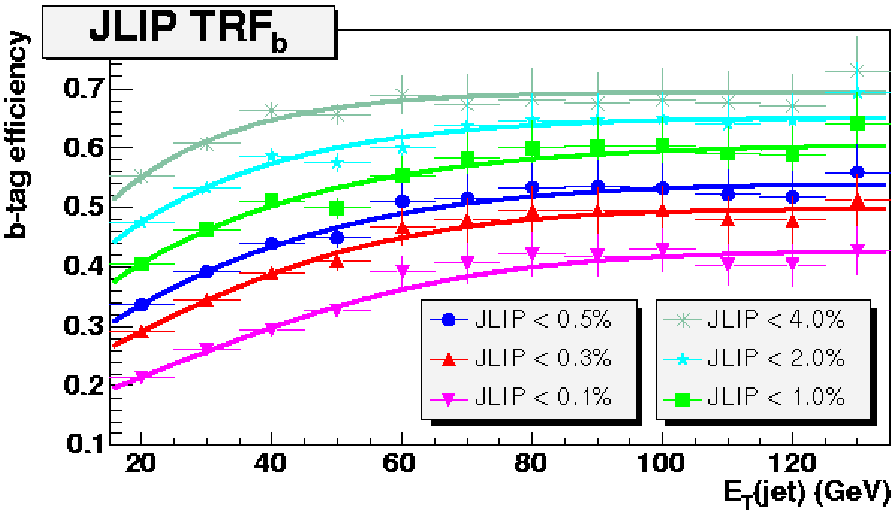


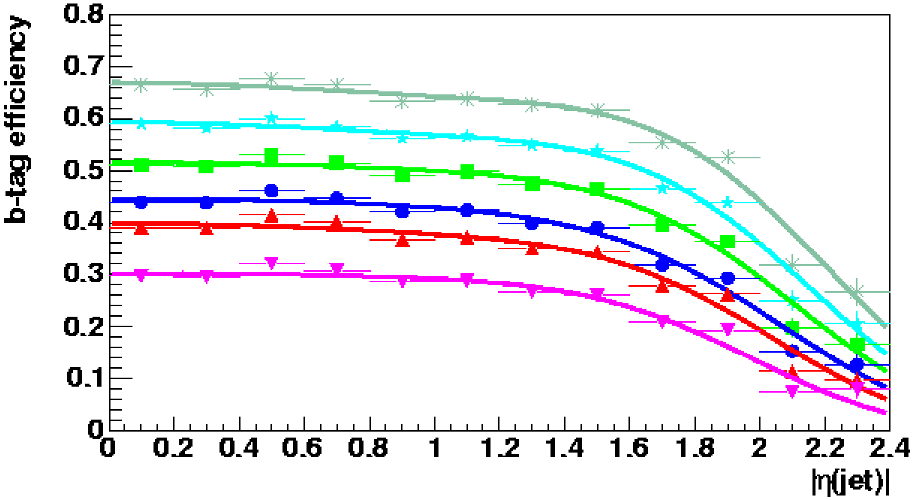


- Alternatively, look for tracks with large Impact Parameters
- Construct probability from IP significances that all tracks came from primary vertex
- Tag jets that have a probability less than 0.3%

b-tagging Rate

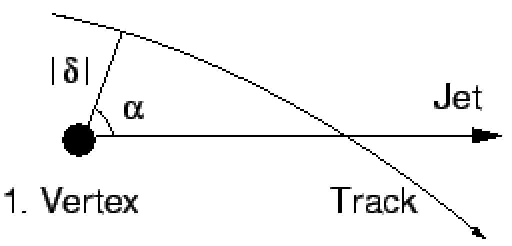
- Difficult to model tracks in jets correctly
- So don't try to tag in simulated events
- Instead, measure efficiency in data
- Use to compute event weights
- To get efficiencies use trick similar to QCD estimation
- Two samples with different b-quark composition
    - Muon-in-jet
    - Muon-in-jet with opposite jet tag
- Two uncorrelated taggers
    - The one we use
    - Muon momentum relative to jet
- Eight equations for event yields
- Invert for efficiencies, flavor composition



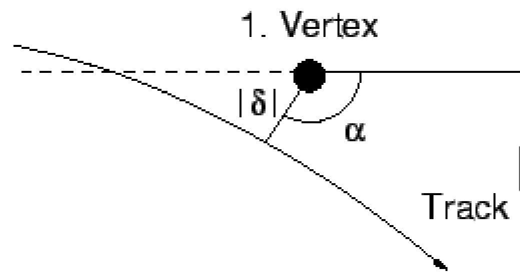


Mistagging

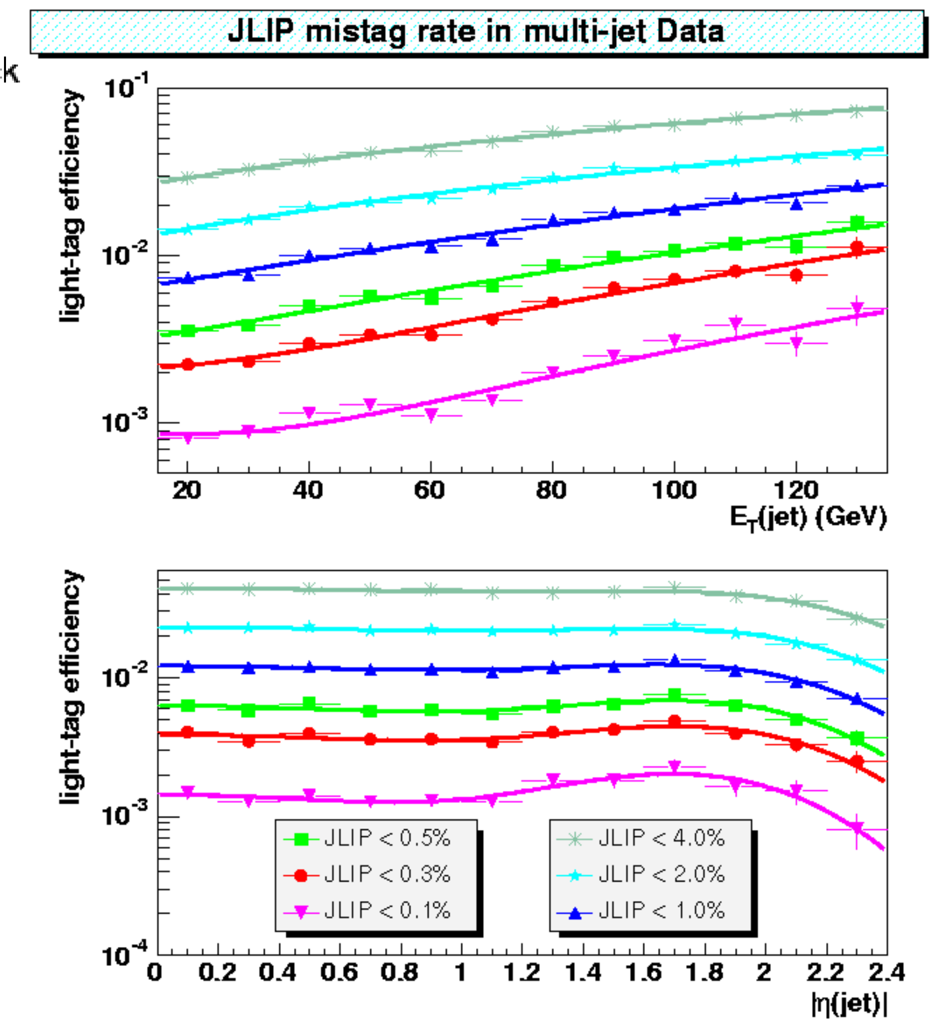
$\alpha < \pi/2 \rightarrow \delta = +|\delta|$



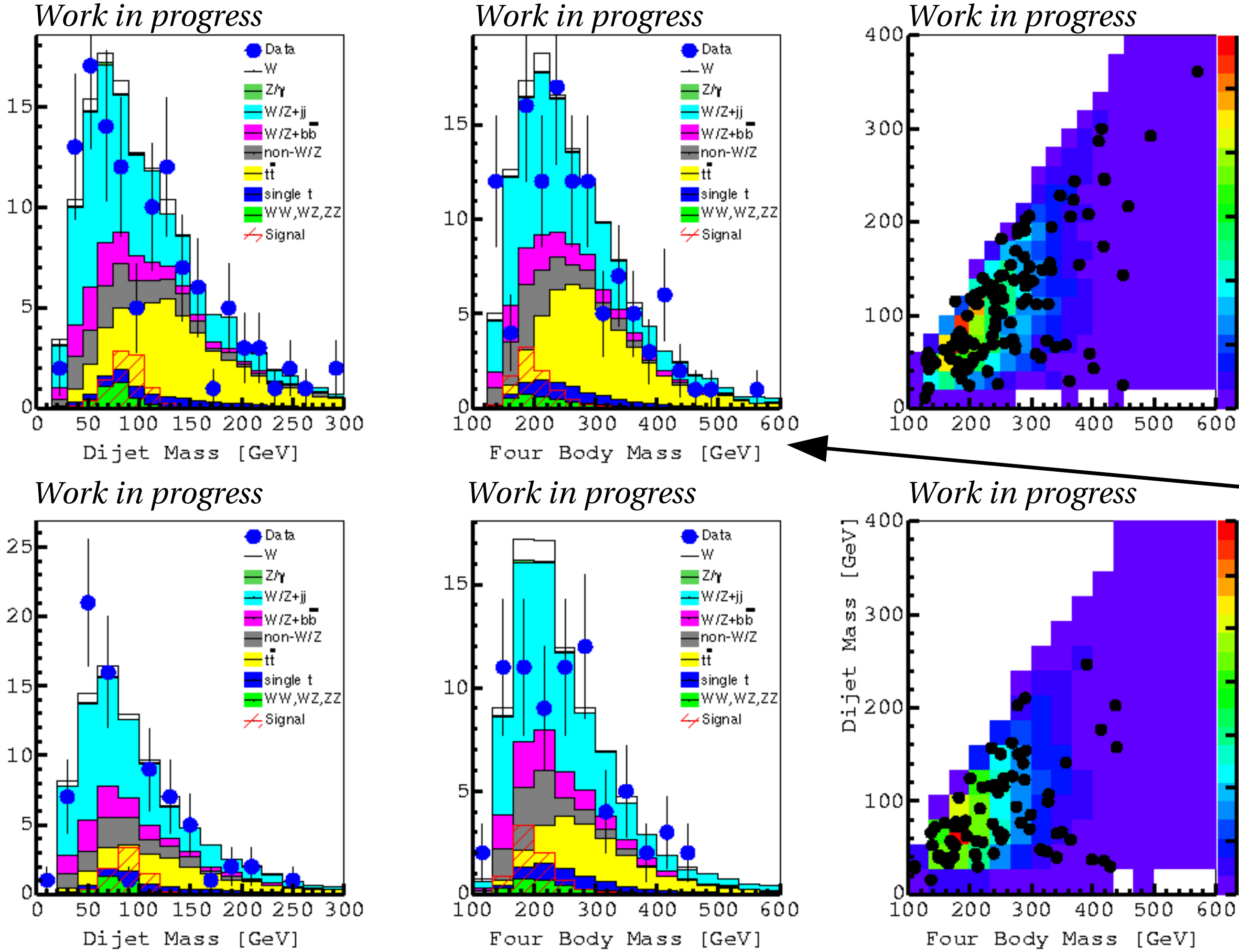
$\alpha > \pi/2 \rightarrow \delta = -|\delta|$



- Backgrounds to b-tags come from finite IP resolution
- Same resolution gives tracks with negative impact parameters (distribution symmetric about zero)
- Measure rate to tag jets with no b or c quarks from negative IP tracks in jets



Homing in on the Signal



Wbj inclusive selection

need to know p_z^{ν}!

Wbj exclusive selection

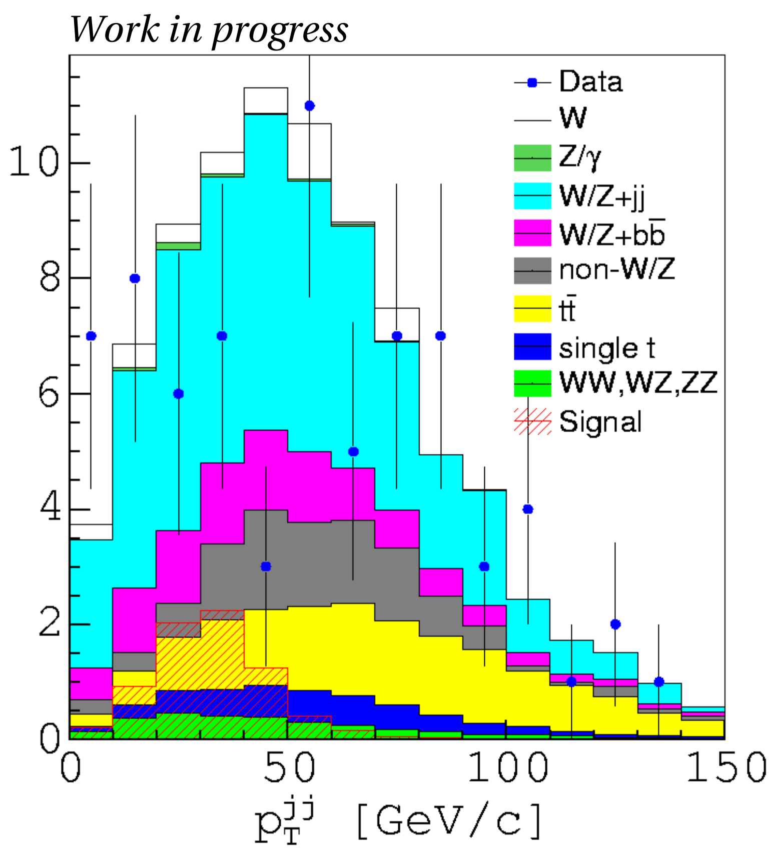
$M_\rho = 200\ GeV/c^2$, $M_\pi = 105\ GeV/c^2$

$M_V = 100\ GeV$

- Require at least one b-tag
- Veto on 3rd jet ($p_T > 15$ GeV/c)
- Veto on 2nd lepton ($p_T > 10$ GeV/c, loose isolation requirements)

First the QCD

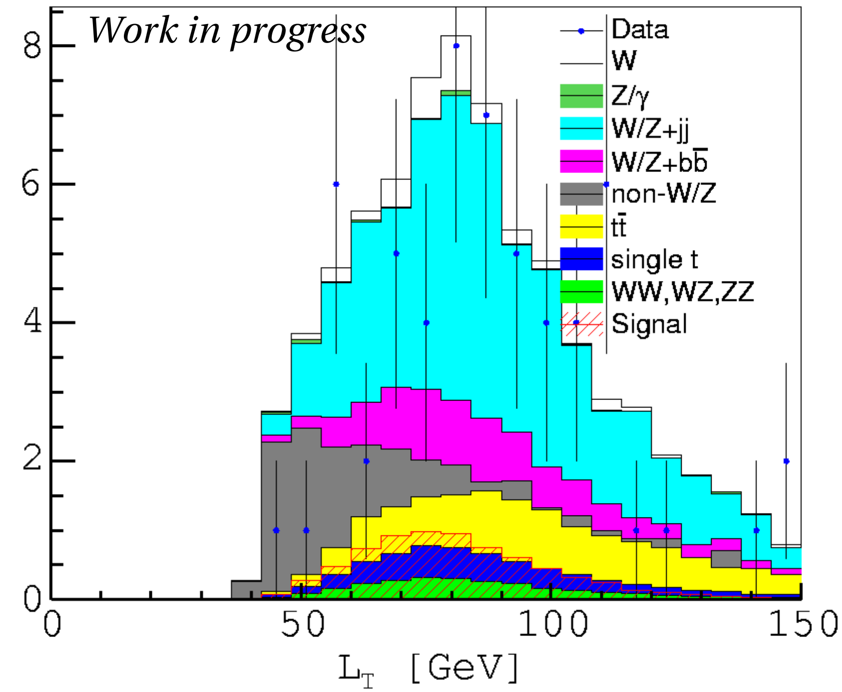
- Want to use a random grid search
- Loop over all samples several thousand times
- QCD estimated from data – takes too long!



M_ρ = 200 GeV/c^2

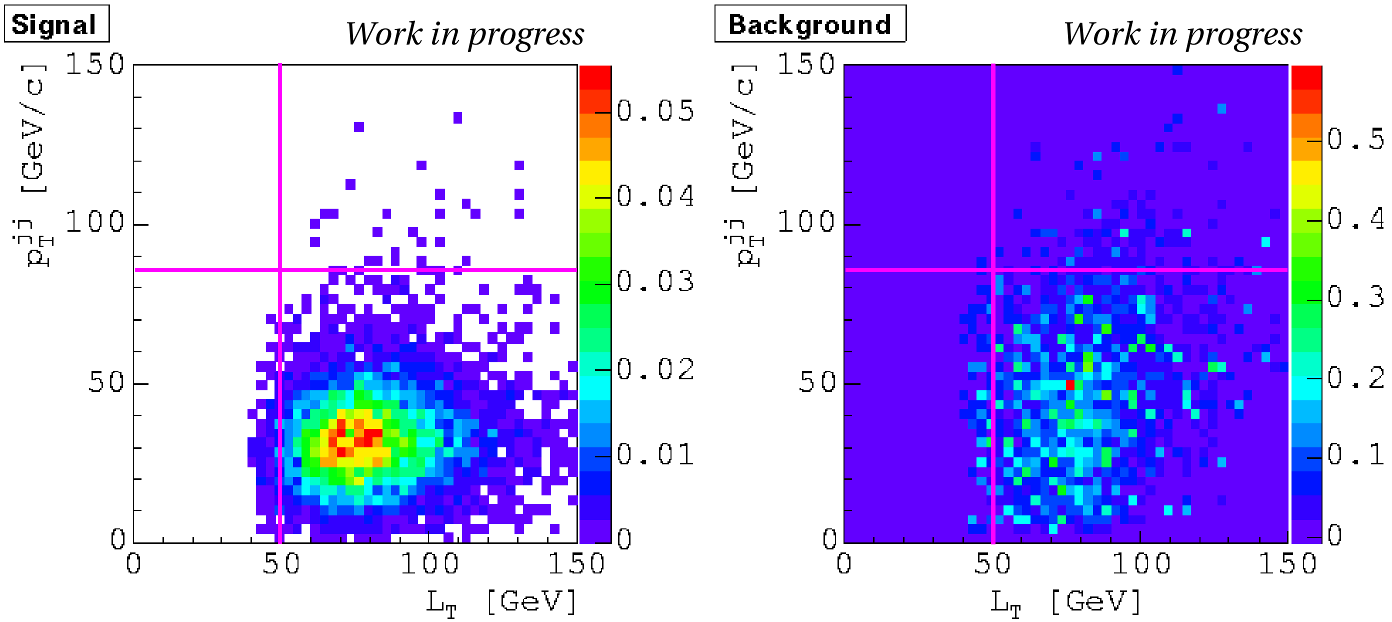
M_π = 105 GeV/c^2

M_V = 100 GeV



- Two more handles on QCD
  - p_T of dijet system (p_T^{jj})
  - Scalar some of p_T^{μ} and $\not{E}_T$ (L_T)

Histogram-based Optimization



$P_T^{jj} < 85$ GeV/c

$L_T > 50$ GeV

$M_\rho = 200$ GeV/c^2, $M_\pi = 105$ GeV/c^2

$M_V = 100$ GeV

- Instead, evaluate signal and background by integrating 2-d histograms
- Find cuts that maximize a modified significance

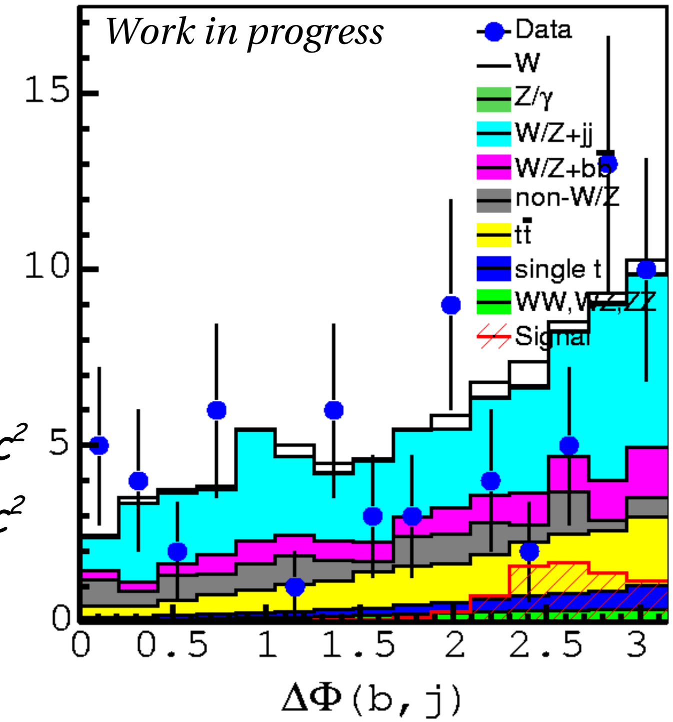
$$\frac{S}{\sqrt{(B + (0.3B))^2}}$$

- Allows for effect of systematic on backgrounds
- Choose loosest cut for each

Other Variables to Use

- Consider three more variables
  - M_{jj}: the dijet mass – window cut
  - M_{Wjj}: mass of the $\mu\nu$jj system – window cut
  - $\Delta\phi$(j,j): opening angle between the jets – minimum threshold
- Only measure E_T, not p_z^{ν}
  - How to get M_{Wjj}
  - Constrain to $\mu\nu$ system to M_W
  - Yields quadratic equation, two solutions
  - Pick one with smaller magnitude

M_ρ = 200 GeV/c^2
M_π = 105 GeV/c^2
M_V = 100 GeV

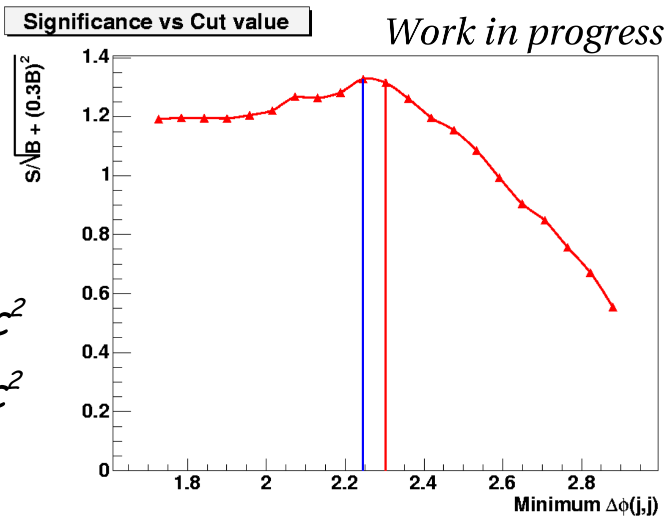


The Random Grid Search

- Consider all signal points that pass initial selection
  - each one defines a cut
  - $\Delta\phi(j,j) \rightarrow \Delta\phi^{min}(j,j)$
  - M_{jj}, M_{Wjj} $\rightarrow$ centers of fixed width windows ($\pm 1\sigma$)
- Pick the cut that maximizes

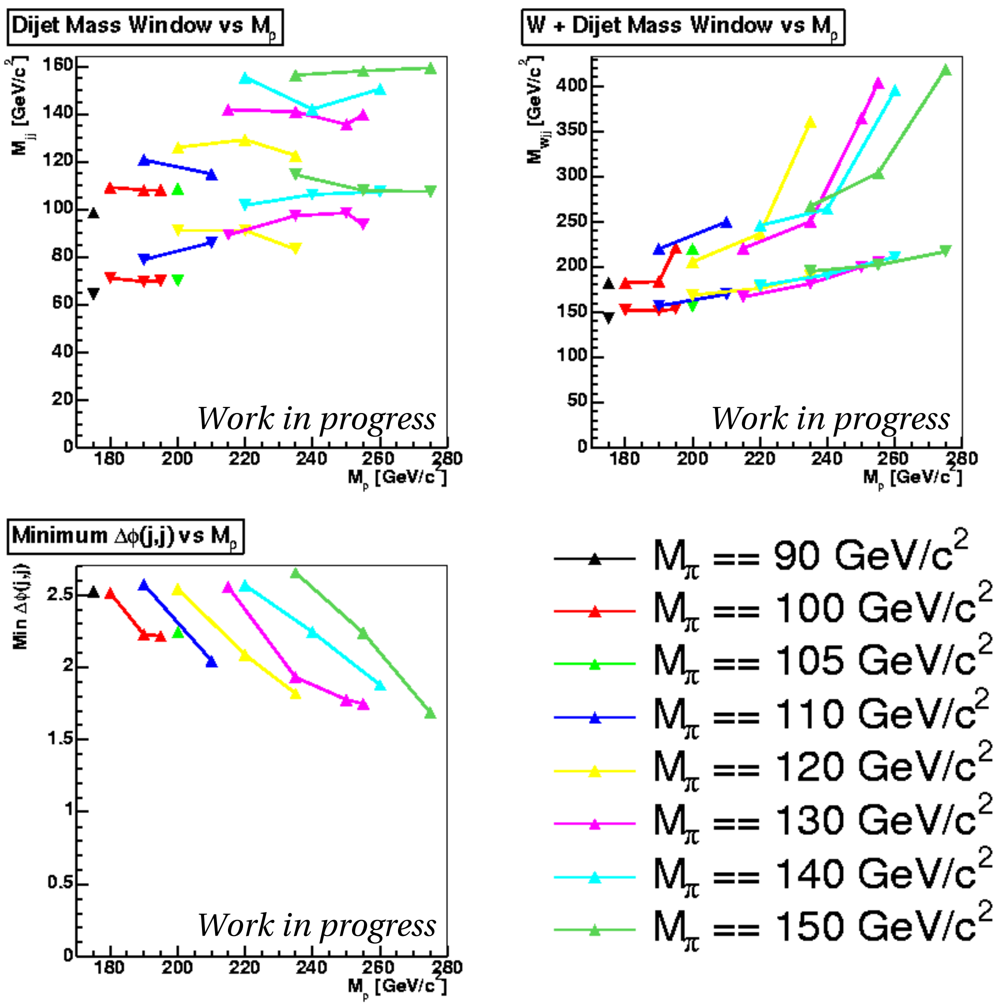
$$\frac{S}{\sqrt{(B + (0.3B))^2}}$$

- Refine varying each threshold by ±20% in 2% steps
- If new best is found, take it
- Repeat for each mass hypothesis



$M_\rho = 200\ GeV/c^2$
$M_\pi = 105\ GeV/c^2$
$M_V = 100\ GeV$

Optimized Selection

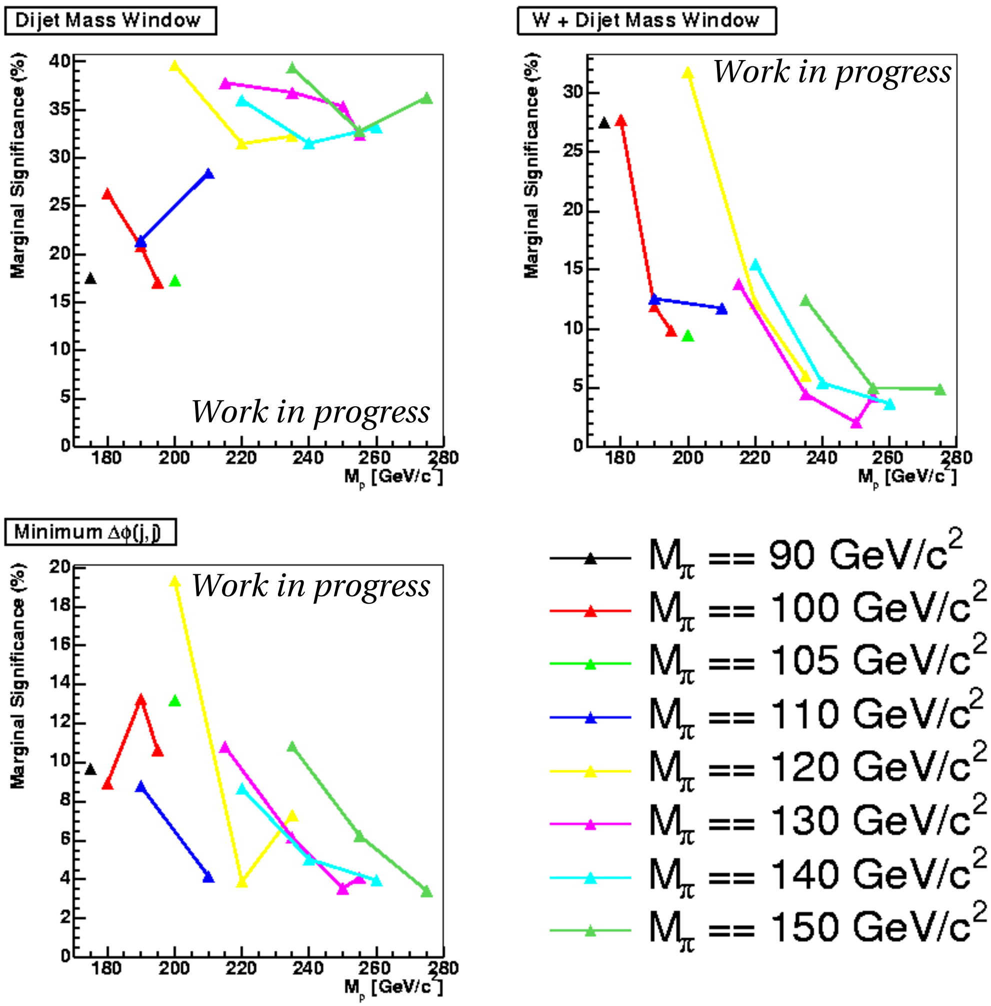


M_V = 100 GeV

- Optimal points mostly behave as expected
- M_{jj} depends only weakly on M_{π}, shifts with M_{ρ}
- M_{Wjj} shifts and widens with M_{ρ}
- $\Delta\phi(j,j)$ loosens as M_{ρ}-M_{π} difference increases (larger boosts)
- Note that cuts are looser at M_{ρ}

Marginal Significances

- Verify that these cuts are useful
- Compute relative change in significance when each is removed
- Dijet mass is clearly the best handle (in general)
- Four body mass is useful when M_ρ is small not so great when its big
- Opening angle is good, not great



M_V = 100 GeV

Systematics

Sources of Uncertainty:

- Jet energy calibration
- b-tagging efficiency
- Corrections for detector simulation
  - Efficiencies
  - Resolutions
- Statistical precision
- Background cross-sections
- Instrumental Backgrounds

Vary fit functions by their errors (Jet energy calibration, b-tagging efficiency)

Evaluate by turning off each correction and re-running the event selection (conservative approach) (Corrections for detector simulation)

Taken from scale variations, size of perturbative corrections (Background cross-sections)

Systematics (part 2)

Error Source	Signal	Background
Non W/Z BG Estimate		7.8%
Cross Sections		9.2%
Simulation Statistics	1.6%	3.0%
Jet Energy Calibration	1.3%	2.0%
b/c Tag Efficiencies	5.3%	4.4%
Mistag Efficiency		1.9%
Jet Energy Resolution	12%	7.0%
Track Momentum Resolution	3.2%	6.5%
Primary Vertex Efficiency	5.5%	8.9%
Jet Efficiency	4.2%	6.8%
Taggability Efficiency	2.9%	5.1%
Total	15%	21%

Evaluated for

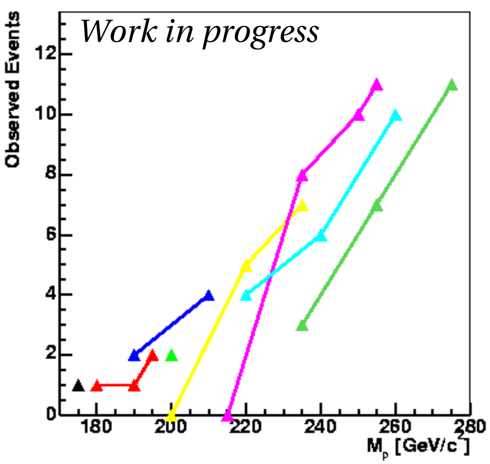
$M_\rho = 200\ GeV/c^2$, $M_\pi = 105\ GeV/c^2$

$M_V = 100\ GeV$

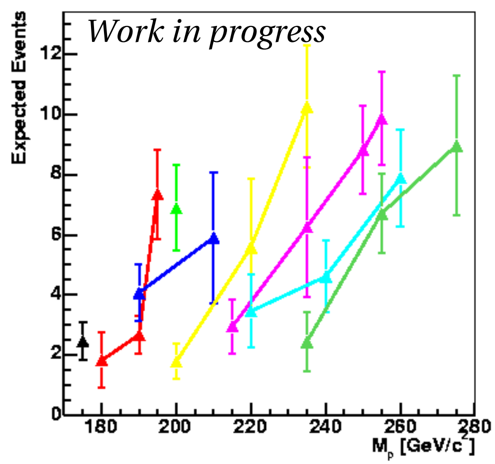
Not listed above: 5% uncertainty on effective luminosity

Results (part 1)

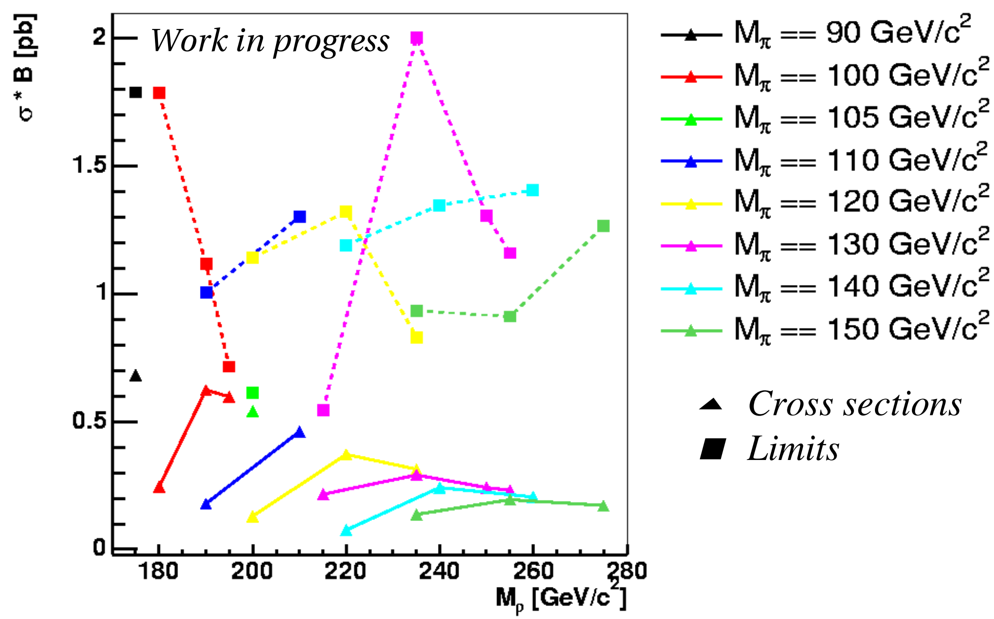
Events in Data



Background Expectations



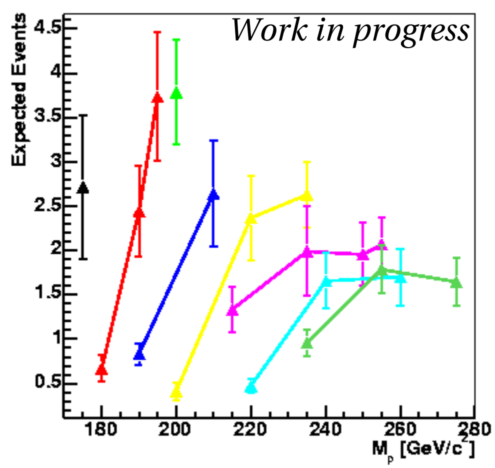
Technicolor Cross sections and Limits



M_V = 100 GeV

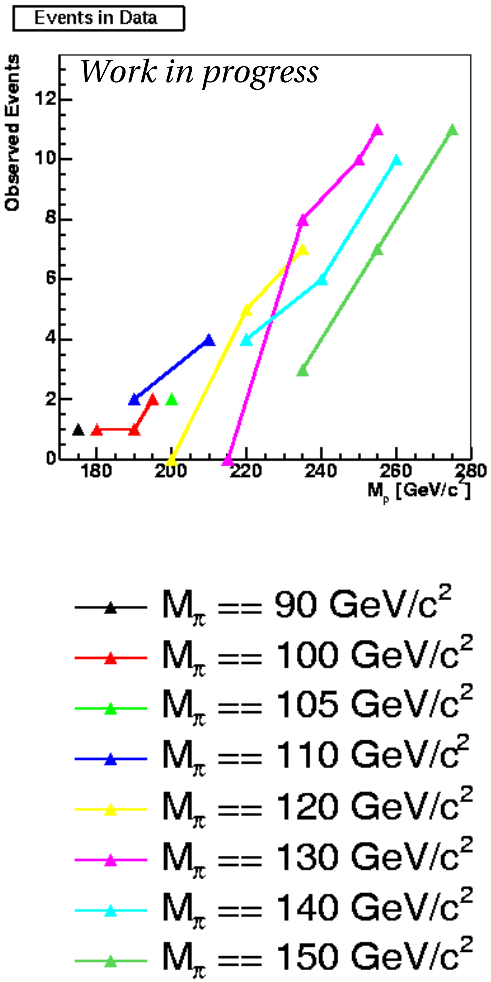
- M_π == 90 GeV/c^2
- M_π == 100 GeV/c^2
- M_π == 105 GeV/c^2
- M_π == 110 GeV/c^2
- M_π == 120 GeV/c^2
- M_π == 130 GeV/c^2
- M_π == 140 GeV/c^2
- M_π == 150 GeV/c^2

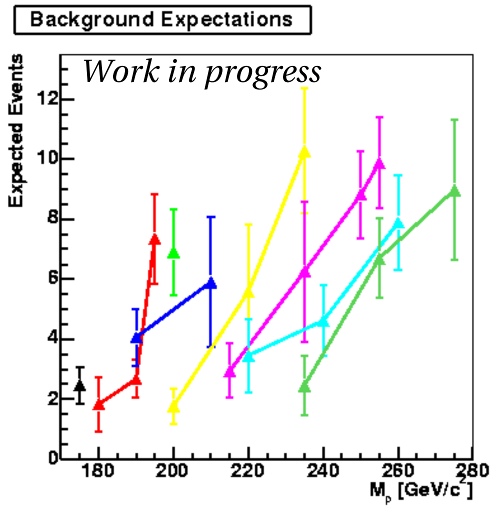
Signal Expectations

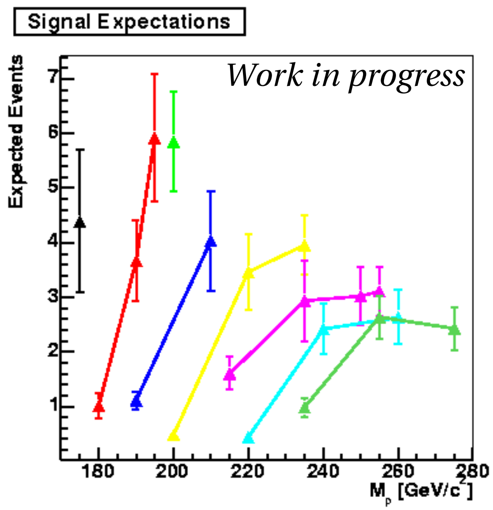


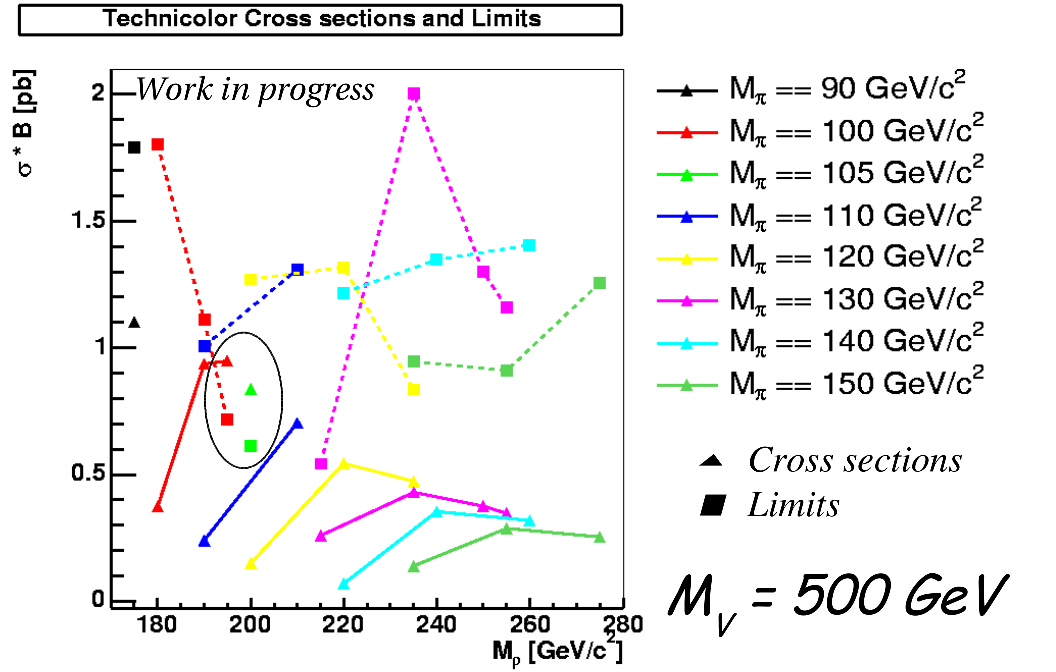
- Recall that optimized selection is looser for large M_ρ
- Can't say much here, but cross sections depend on M_V

Results (part 2)









M_V = 500 GeV

- Rule out two mass points:
  - $M_\rho = 195$ GeV/c², $M_\pi = 100$ GeV/c²
  - $M_\rho = 200$ GeV/c², $M_\pi = 105$ GeV/c²

Conclusions

- Have conducted a search for Technicolor production:
  - $\rho_T^{\pm} \rightarrow W^{\pm}\pi_T^{0} \rightarrow \mu\nu b\bar{b}$
  - $\rho_T^{0} \rightarrow W^{\pm}\pi_T^{\mp} \rightarrow \mu\nu b\bar{c}$
- No excess found in a 300 pb^{-1} dataset from DØ
- Ruled out (for M_V = 500 GeV)
  - M_ρ = 195 GeV/c^2, M_π = 100 GeV/c^2
  - M_ρ = 200 GeV/c^2, M_π = 105 GeV/c^2
- Results still in internal review
- A similar analysis in the electron channel (390 pb^{-1}) has excluded a larger region (neural nets promise even more)

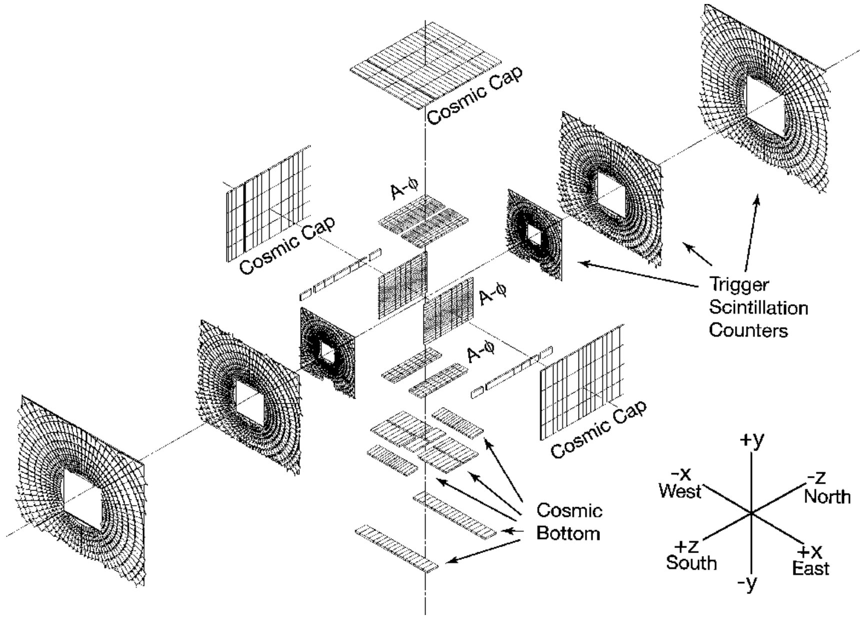
Outlook

- Even at unconstrained masses, not very far off
- Combination of channels
- Addition of more triggers
- More sophisticated analysis techniques are coming
  - Neural net b-tagging
  - Full NN analysis
  - Separate double b-tag analysis
  - Limit setting based on shapes, not event counts
- We have already recorded 1 fb^{-1}
- Will soon collect more with upgraded tracking and trigger
- Improved treatment of systematics will help (especially as statistics increase)
- Warm-up for a Standard Model Higgs search

Backup Slides

What's a Muon?

- Medium quality (really more complicated but other cuts limit special cases)
  - Two A-layer drift chamber hits
  - One A-layer scintillator hit
  - Same for BC layers
- Scintillator hits in the A (BC) layers within 10 ns (15 ns) of beam crossing
- p_T as measured by muon toroid > 8 GeV/c
- Central track match with
  - 14 CFT and 4 SMT hits
  - Reduced $\chi^2 < 4$
  - Pass near primary vertex
    - 1 cm along z-axis
    - 0.02 cm in x-y plane



JLIP Tagger Details

- Calculate impact parameter significance (S) for each track
- Evaluate consistency of track with primary vertex from integral over IP significance distribution (P_{trk})

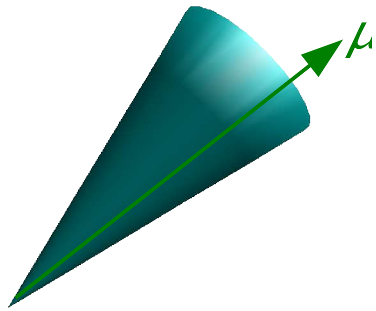
$$P_{trk} = \frac{\int_{-50}^{-|S|} R(s)\,ds}{\int_{-50}^{0} R(s)\,ds}$$

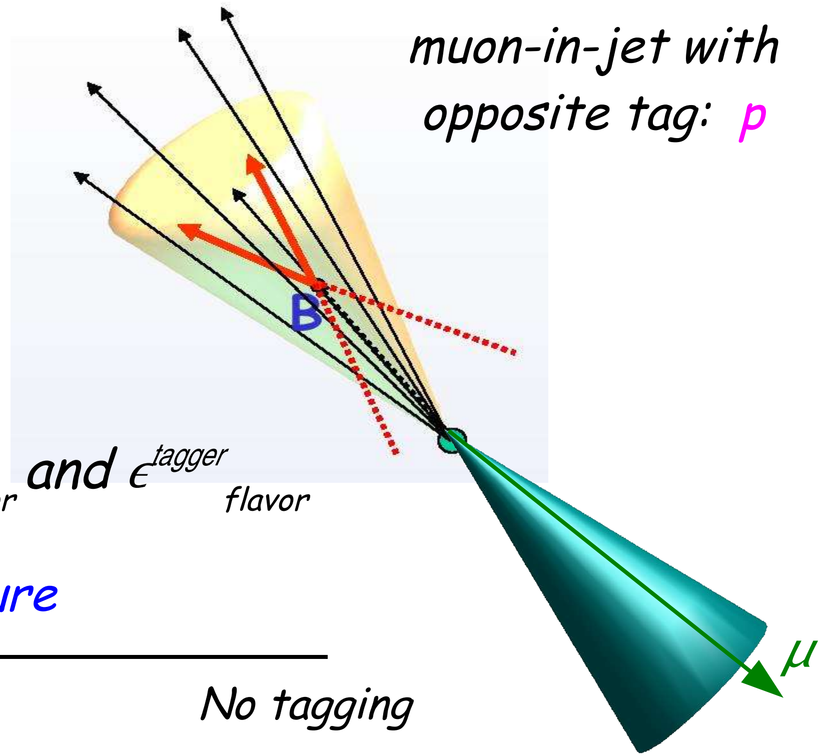
- Integrating over negative significances ➡ fold in only resolution effects (not real decays)
- Use tracks with positive IP to compute jet lifetime probability (P_{jet})

$$\Pi^{pos} = \prod_{pos\ trks} P_{trk}$$

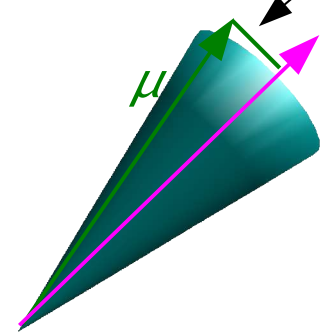
$$P_{jet} = \Pi^{pos} \times \sum_{i=0}^{N\ pos\ trks} \frac{(-\log \Pi^{pos})^i}{i!}$$

- Evaluation of mistag rate
  - using multi-jet data
  - repeat calculation with negative IP tracks
  - use MC to correct for heavy quark contamination, resolution asymmetries





muon-in-jet with opposite tag: p



muon-in-jet: n

Muon Tagging

solve for n_{flavor}, p_{flavor} and $\epsilon^{tagger}_{flavor}$

directly measure

$n = n_b + n_{cl}$ $p = p_b + p_{cl}$	No tagging
$n^{\mu} = \epsilon^{\mu}_b n_b + \epsilon^{\mu}_{cl} n_{cl}$ $p^{\mu} = \epsilon^{\mu}_b p_b + \epsilon^{\mu}_{cl} p_{cl}$	Muon Tagger
$n^{IP} = \epsilon^{IP}_b n_b + \epsilon^{IP}_{cl} n_{cl}$ $p^{IP} = \beta \epsilon^{IP}_b p_b + \alpha \epsilon^{IP}_{cl} p_{cl}$	JLIP Tagger
$n^{\mu,IP} = \kappa_b \epsilon^{\mu}_b \epsilon^{IP}_b n_b + \kappa_{cl} \epsilon^{\mu}_{cl} \epsilon^{IP}_{cl} n_{cl}$ $p^{\mu,IP} = \kappa_b \beta \epsilon^{\mu}_b \epsilon^{IP}_b p_b + \kappa_{cl} \alpha \epsilon^{\mu}_{cl} \epsilon^{IP}_{cl} p_{cl}$	Both Taggers

b: b-jets
cl: charm and light jets

- Assumptions validated in simulation:
  - Charm/light ratio same in both samples (α)
  - JLIP efficiencies same in both samples (β)
  - Uncorrelated efficiencies (κ_i)

Jet Energy Scale

- Just adding the cell energies doesn't due the trick
  - Calorimeter noise / Underlying event
  - Out of cone showering
  - Response to different particles

$$E_{true} = \frac{E_{raw} - E_{offset}}{R_{ooc} R_{jet}}$$

- All a function of energy, pseudorapidity
- Derive average corrections from data for data; simulation for simulation
  - Measure offset correction from energy density in min-bias events
  - Measure out of cone correction by looking at energy density around jets
  - Measure response from photon-jet events
- Dependence on instantaneous luminosity (# of PV's) assigned as a systematic