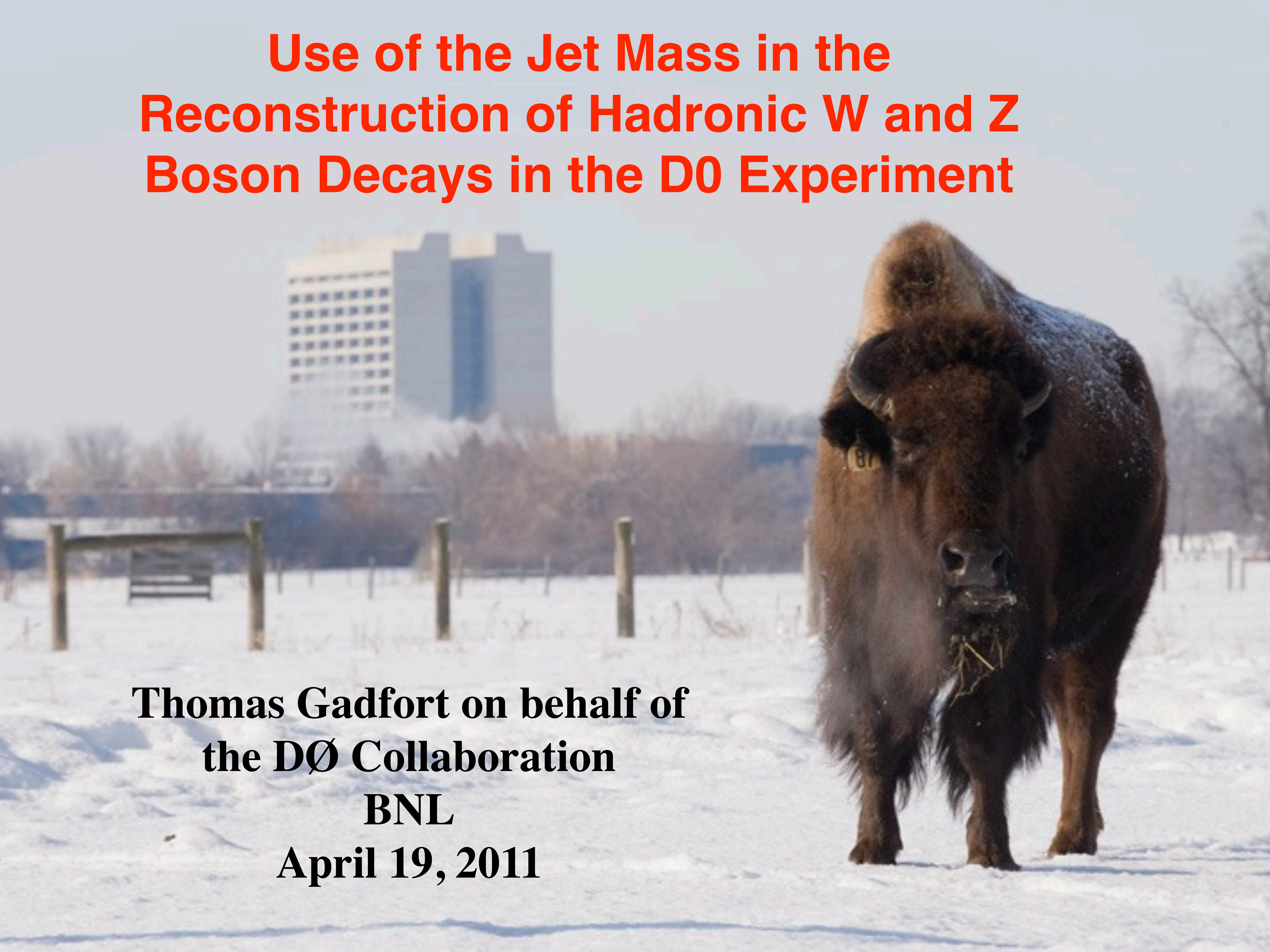
Use of the Jet Mass in the Reconstruction of Hadronic W and Z Boson Decays in the D0 Experiment



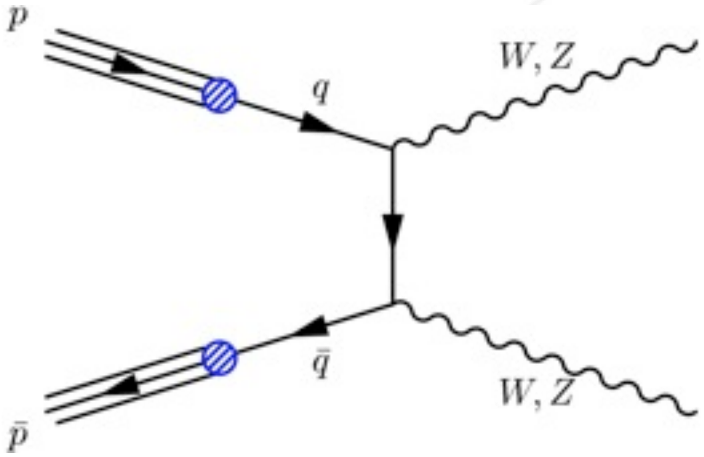
Thomas Gadfort on behalf of
the DØ Collaboration
BNL
April 19, 2011

Outline

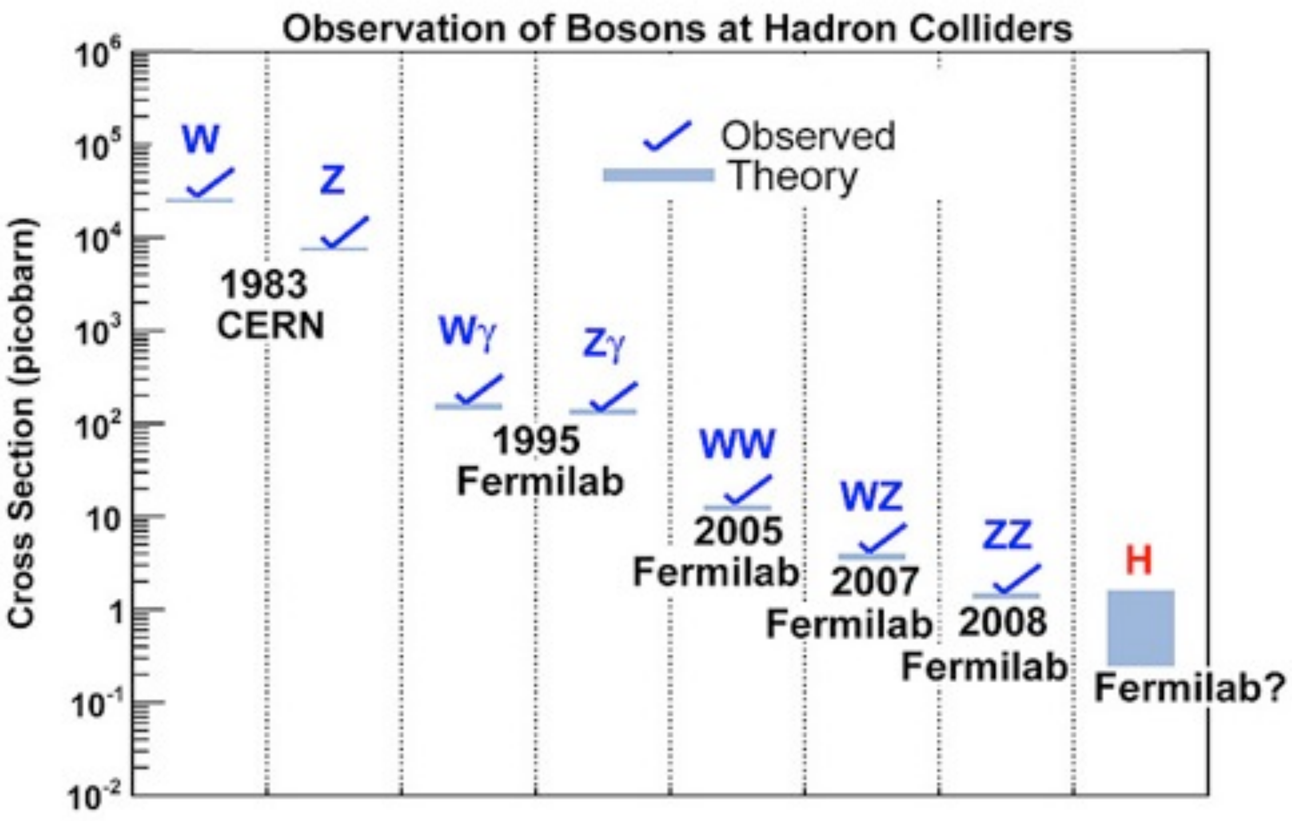
- Reconstructing high mass diboson resonances
  - Limitations and introduction of jet mass
- The Tevatron and the DØ experiment at FNAL
- Jet reconstruction and jet energy scale at DØ
- Diboson event selection and background estimation
  - Jet mass modeling in the Monte Carlo
- Results & Outlook

Diboson Production

- Standard Model diboson production occurs primarily through t-channel quark exchange.



- All diboson signals have been established by CDF and D0.
  - Remarkable agreement with SM!



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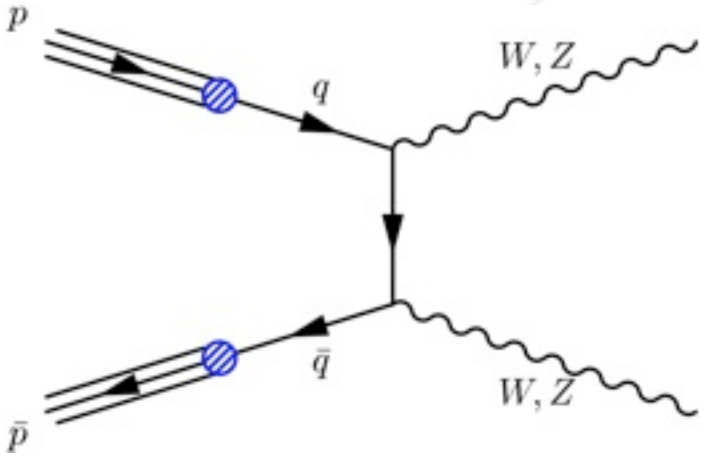
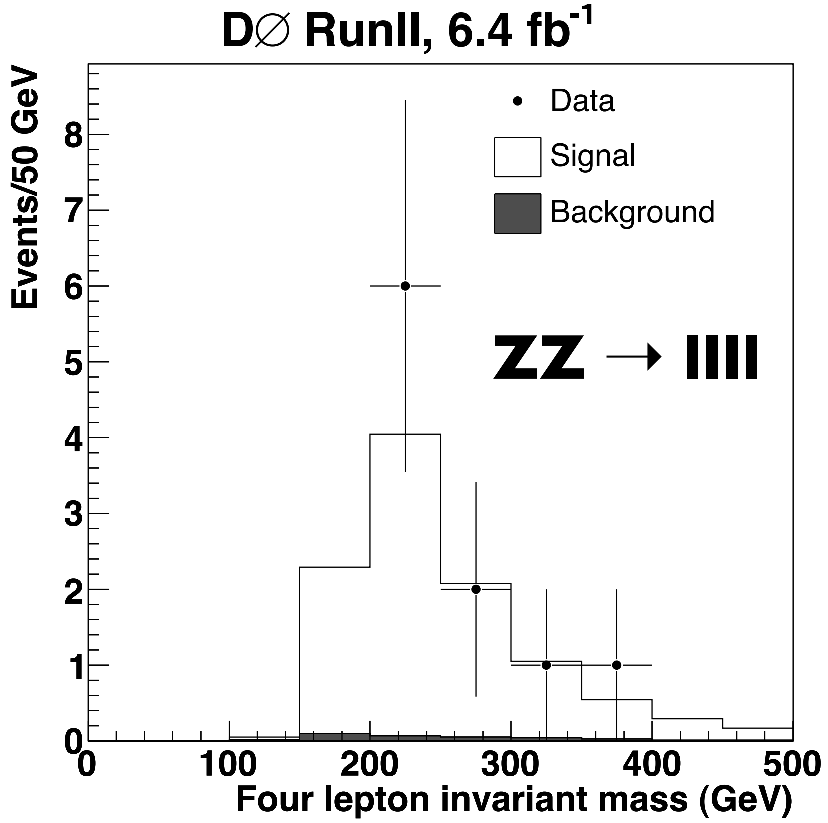


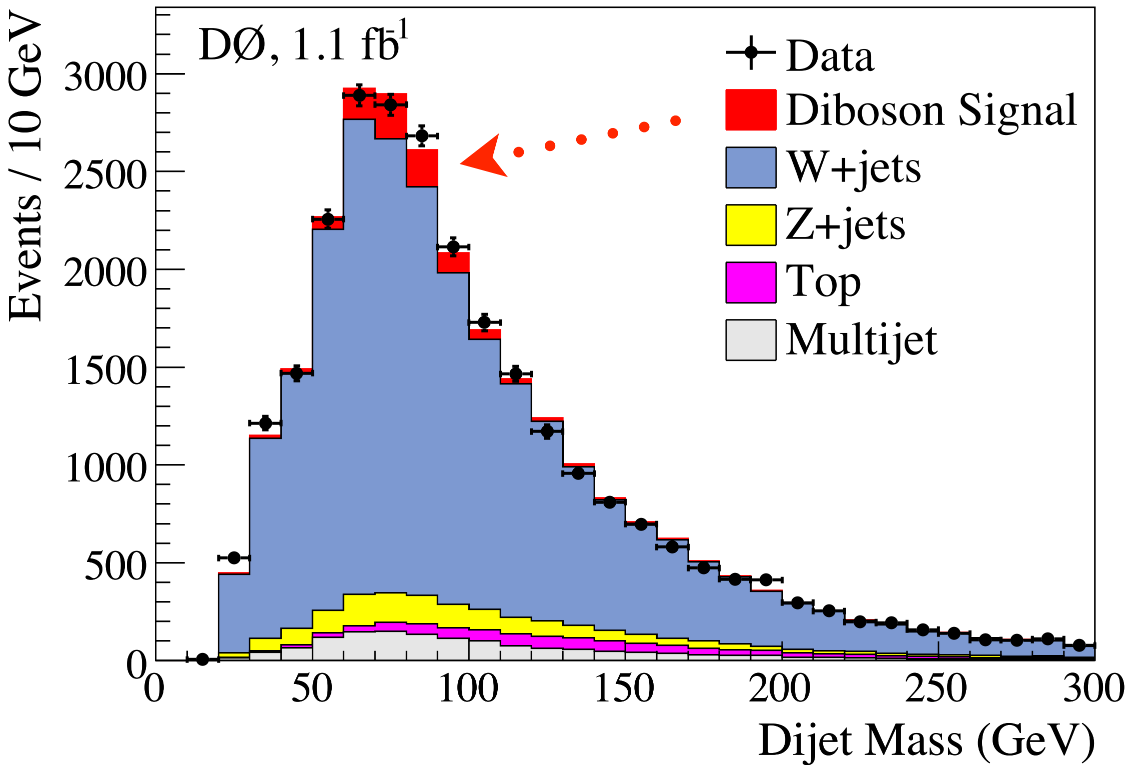
- All diboson signals have been established by CDF and D0.
  - Remarkable agreement with SM!

$$\sigma(p\bar{p} \to ZZ) = 1.19^{+0.44}_{-0.36}(\text{stat}) \pm 0.14(\text{syst})\ \text{pb}$$

$$\sigma_{SM}(p\bar{p} \to ZZ) = 1.4 \pm 0.1\ \text{pb}$$

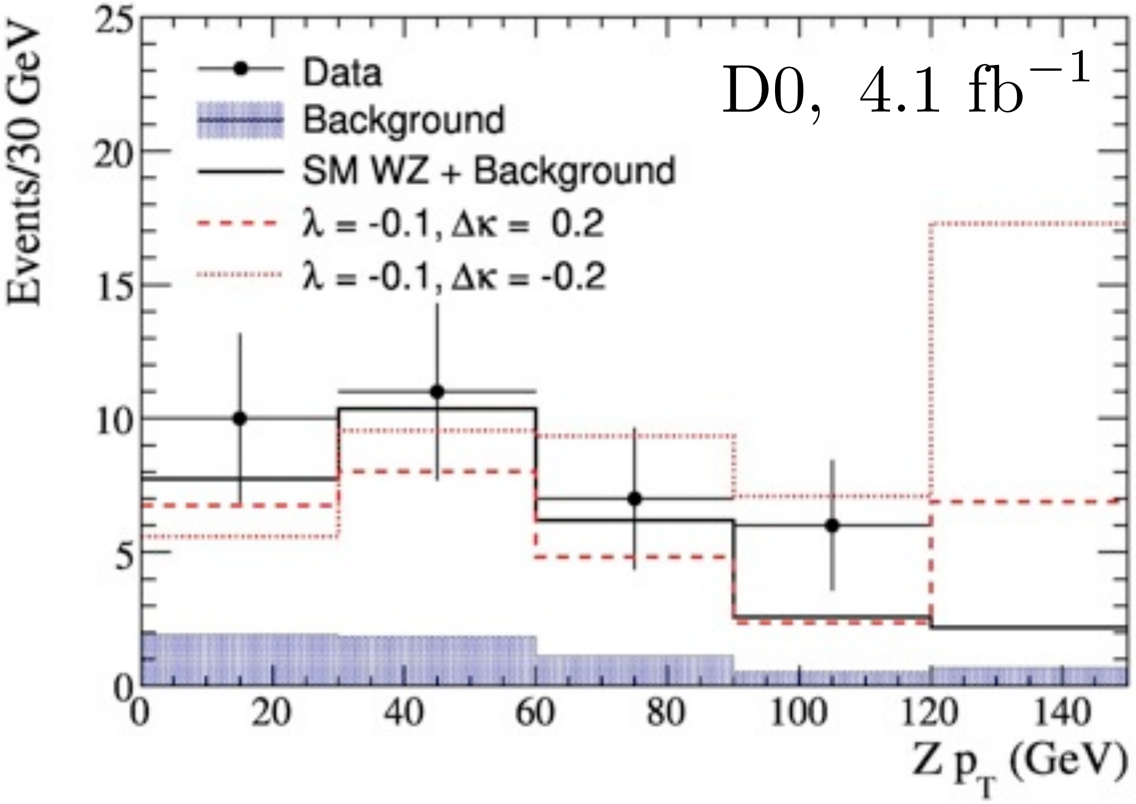


- All discoveries based on leptonic decays (Z → ll and/or W → lν), l = e, μ
- Recently, increased datasets allow W → jj or Z → jj decays as well.



BSM Physics in Diboson System

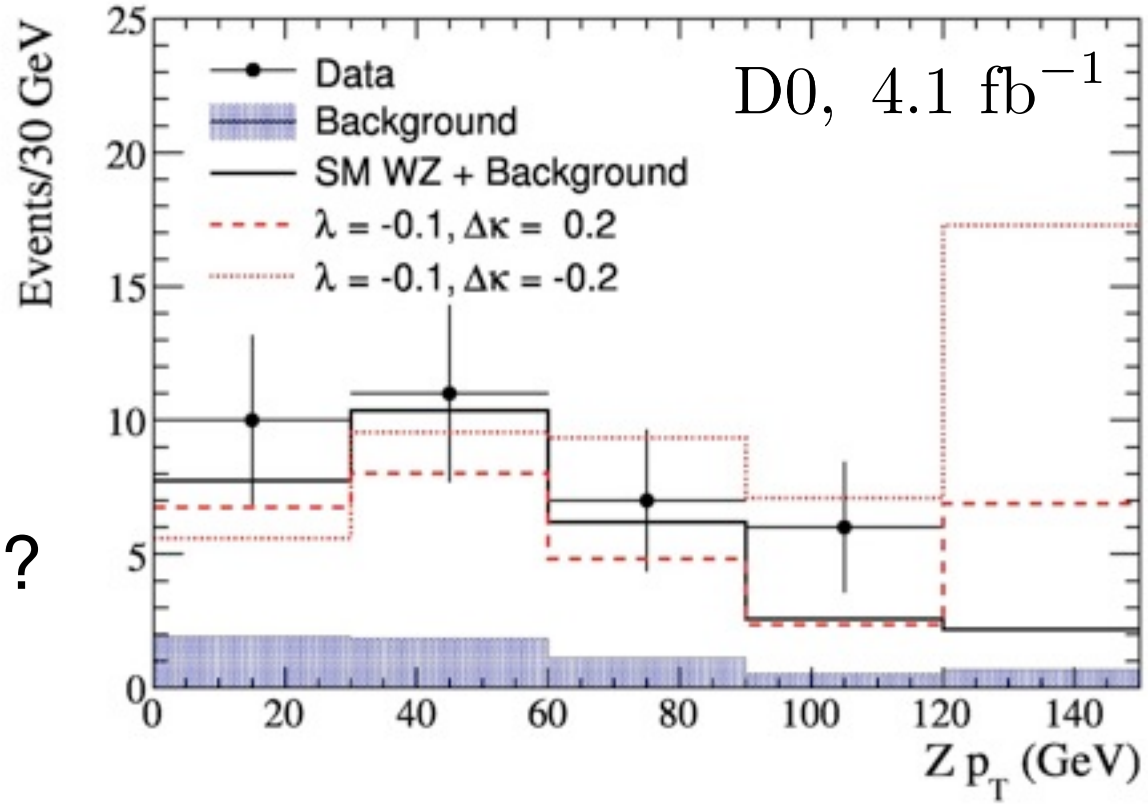
- Diboson cross sections agree very well with SM prediction.
  - Still room for new physics at high √ŝ.
- Traditional searches
  - WW → lνlν or WZ → lνll events and search for anomalous triple gauge couplings (TGCs).

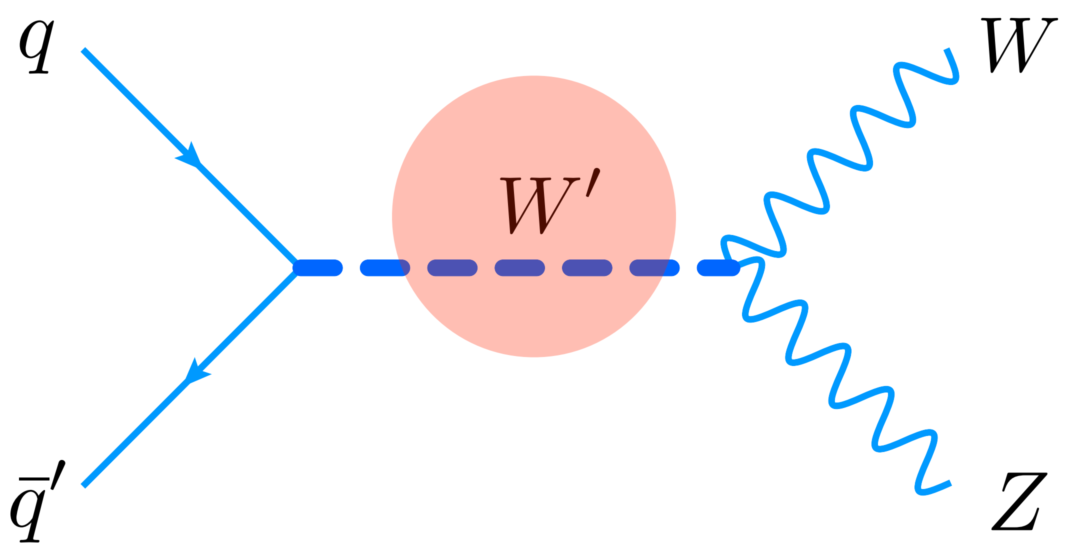


BSM Physics in Diboson System

BROOKHAVEN
NATIONAL LABORATORY

- Diboson cross sections agree very well with SM prediction.
  - Still room for new physics at high $\sqrt{\hat{s}}$.
- Traditional searches
  - $WW \to l\nu l\nu$ or $WZ \to l\nu ll$ events and search for anomalous triple gauge couplings (TGCs).
- What about direct resonance searches?
  - Plenty of BSM diboson resonances (e.g. H^+ , ρ_T , G^* , Z' , W')

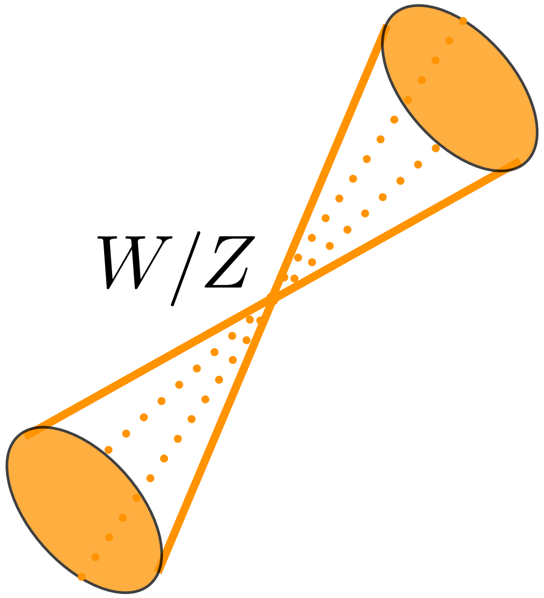




- Besides resonance, these events are quite special.
- If M(W′) >> M(W) + M(Z) then both W and Z bosons will be highly boosted.

Boosted W and Z Bosons

- W and Z boson decay products will become increasingly collimated as the boson p_T increases.
  - Eventually the spatial distance crosses the reconstruction size ($\Delta R(q, q) \approx R$)



$$\boxed{p_T(W/Z) \approx 0}$$

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$$p_T(W/Z) \approx 0$$

$$p_T(W/Z) \approx M(W/Z)$$

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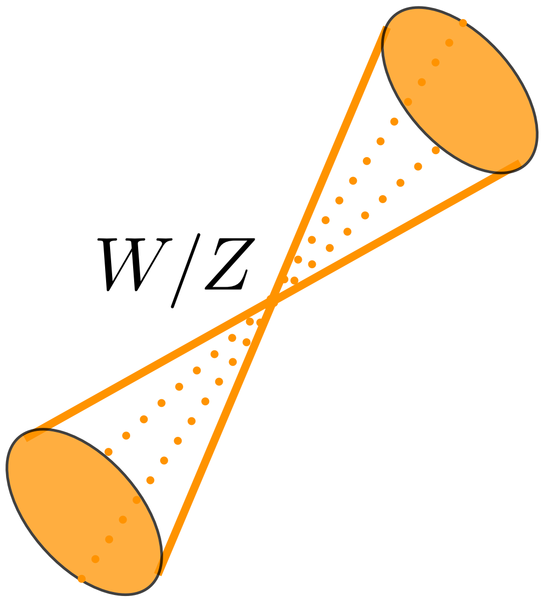

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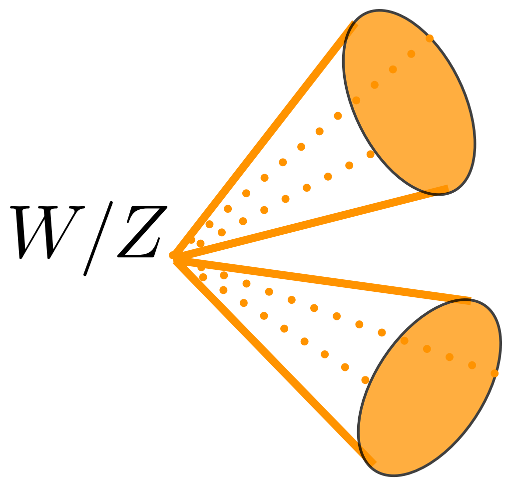

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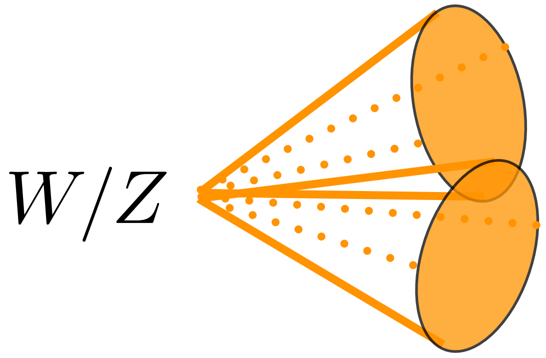

$p_T(W/Z) \gg M(W/Z)$

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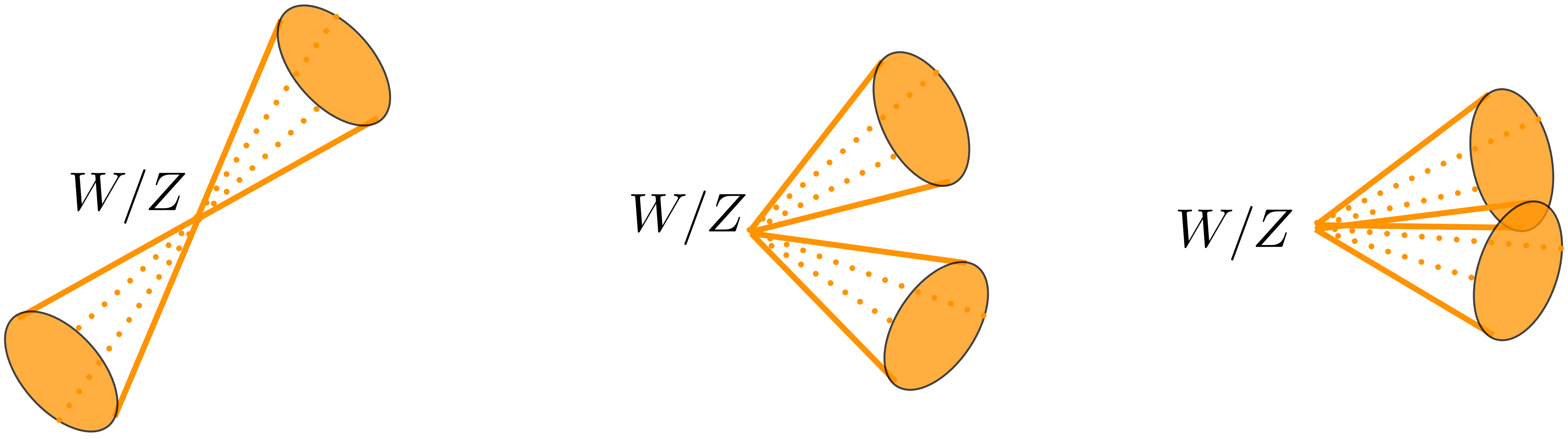


$p_T(W/Z) \approx 0$

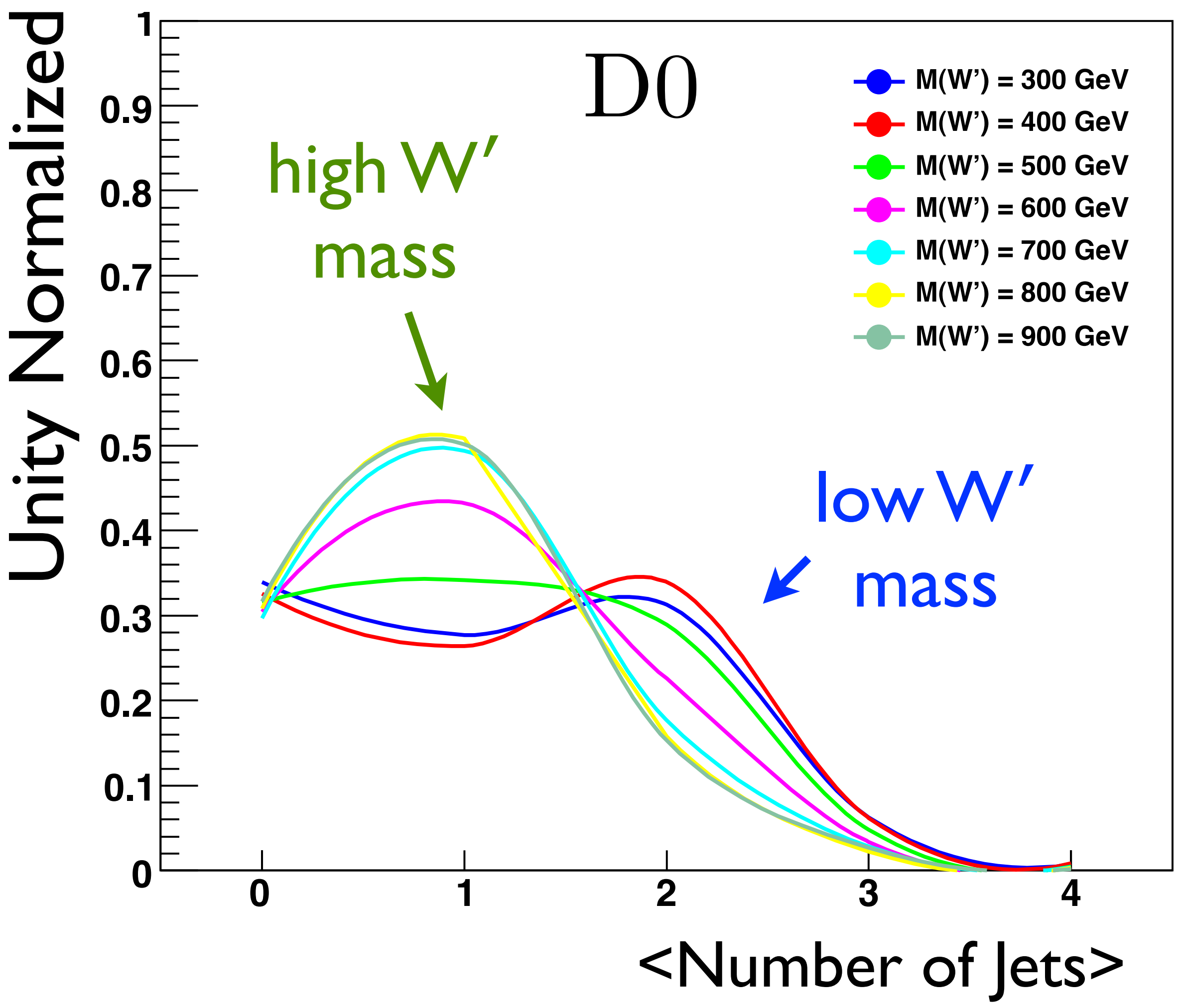
$p_T(W/Z) \approx M(W/Z)$

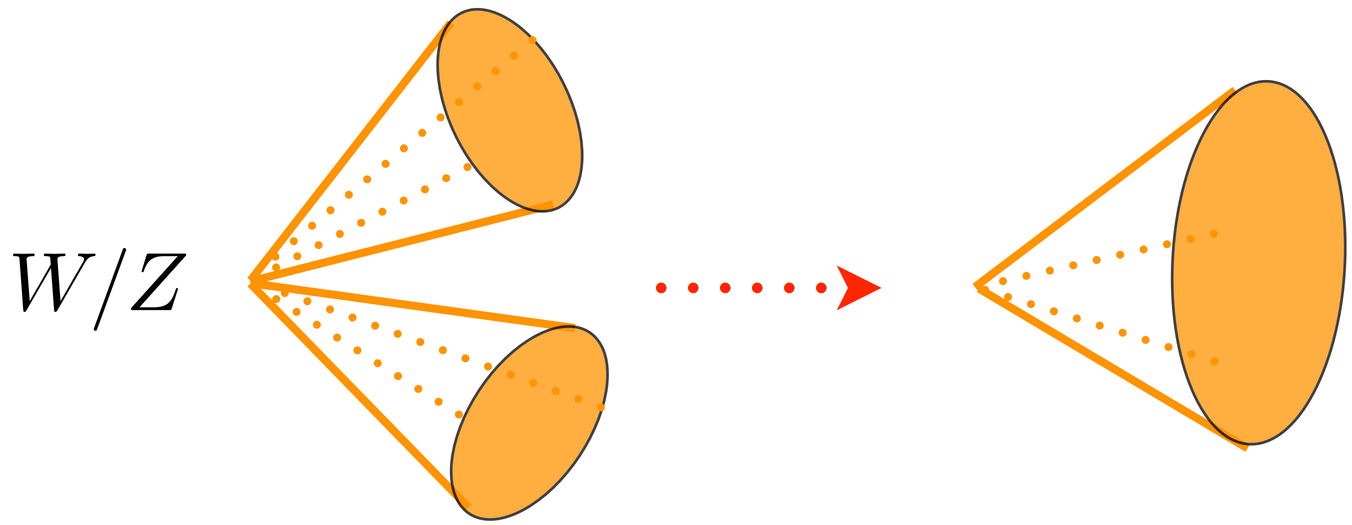
$p_T(W/Z) \gg M(W/Z)$

- Overlap will occur with jets before electrons or muons due to wider shower (thereby reconstruction) size ($R_{jet} >> R_{electron} > R_{muon}$)

Boosted Jet Reconstruction

- As W′ (WZ resonance) mass increases events will transition from two-jet events to one-jet events.



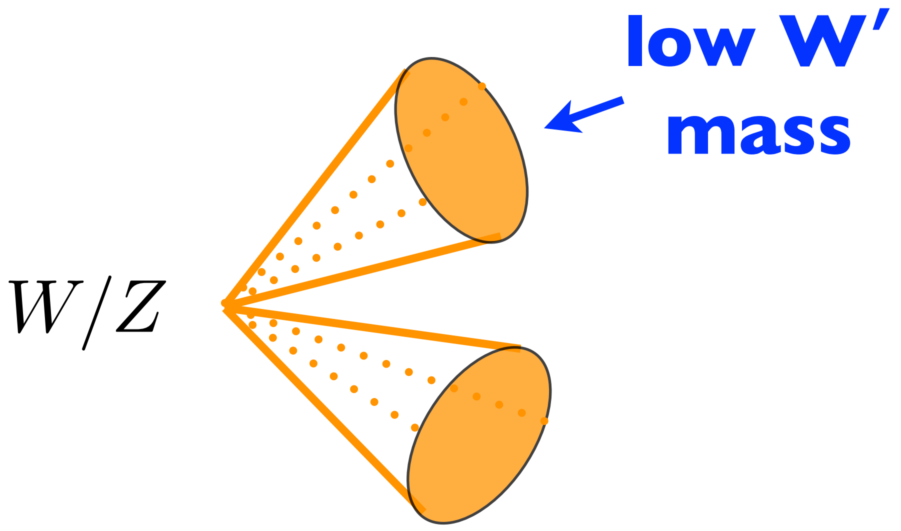


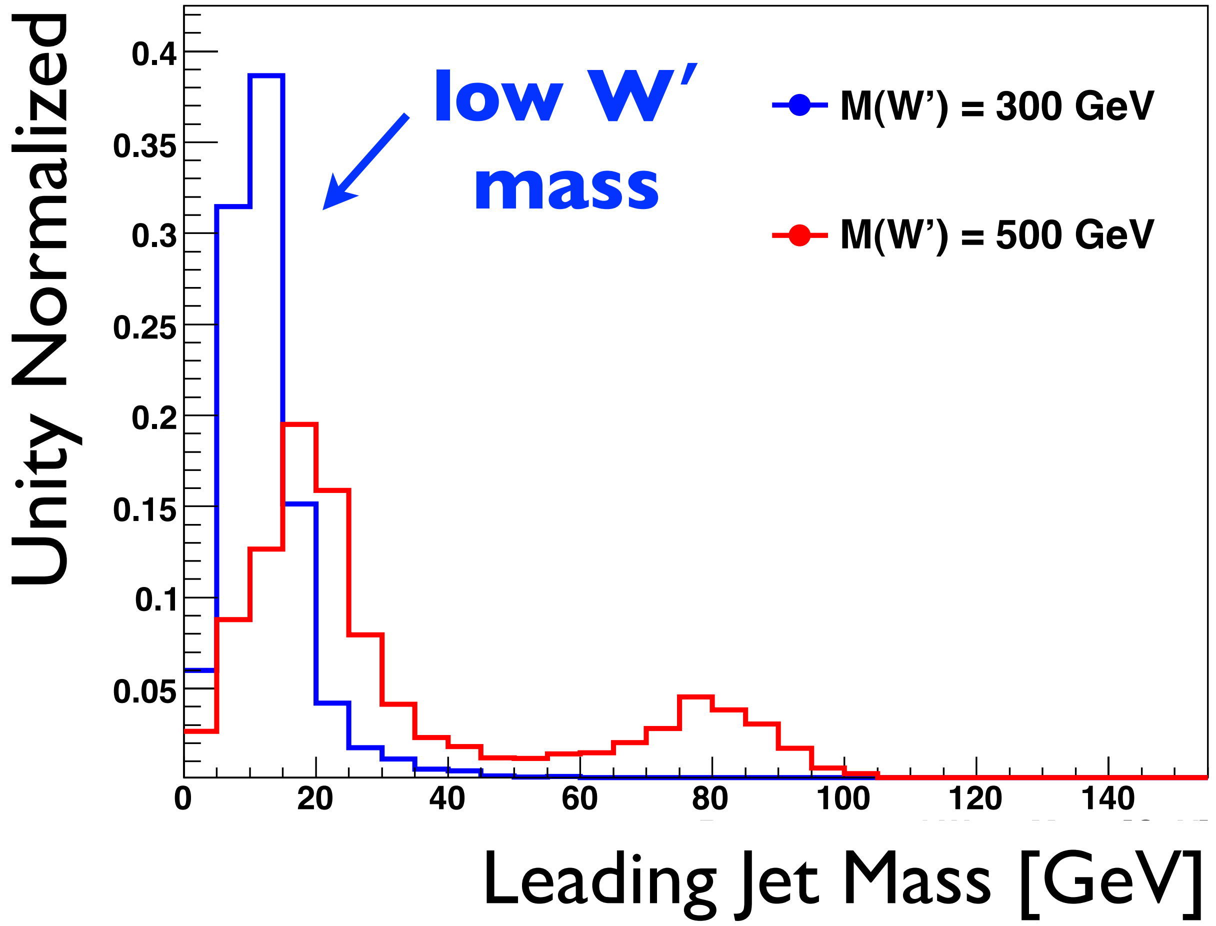
- Event topology depends on resonance mass (not terribly surprising).
- What do these merged jets look like?

Jet Mass

- Merged jet should show effect of W or Z boson origin.
- W and Z bosons are very heavy compared to QCD scale ⇒ look at mass of all jet constituents.

$$M_{\text{jet}} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_i^{x,y,z}\right)^2}$$





- Merged jets have a mass that peaks at W or Z boson mass!
- QCD-jets (quark or gluon initiated) have low mass (peak below 10-20 GeV).

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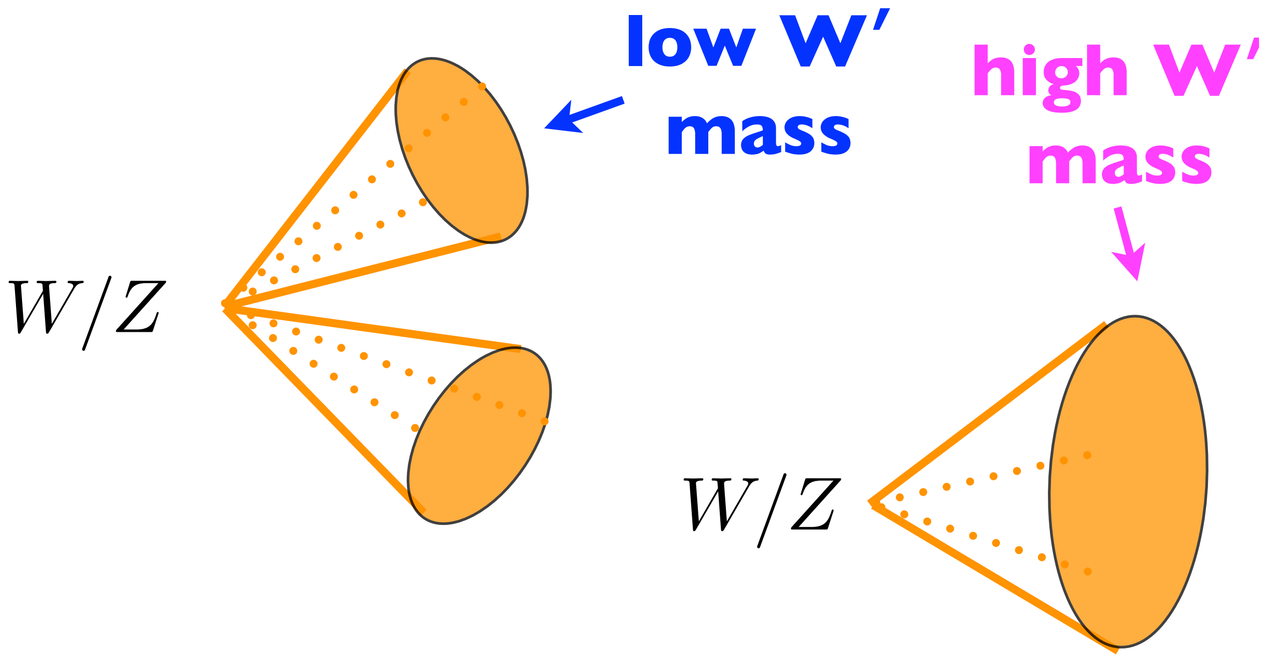

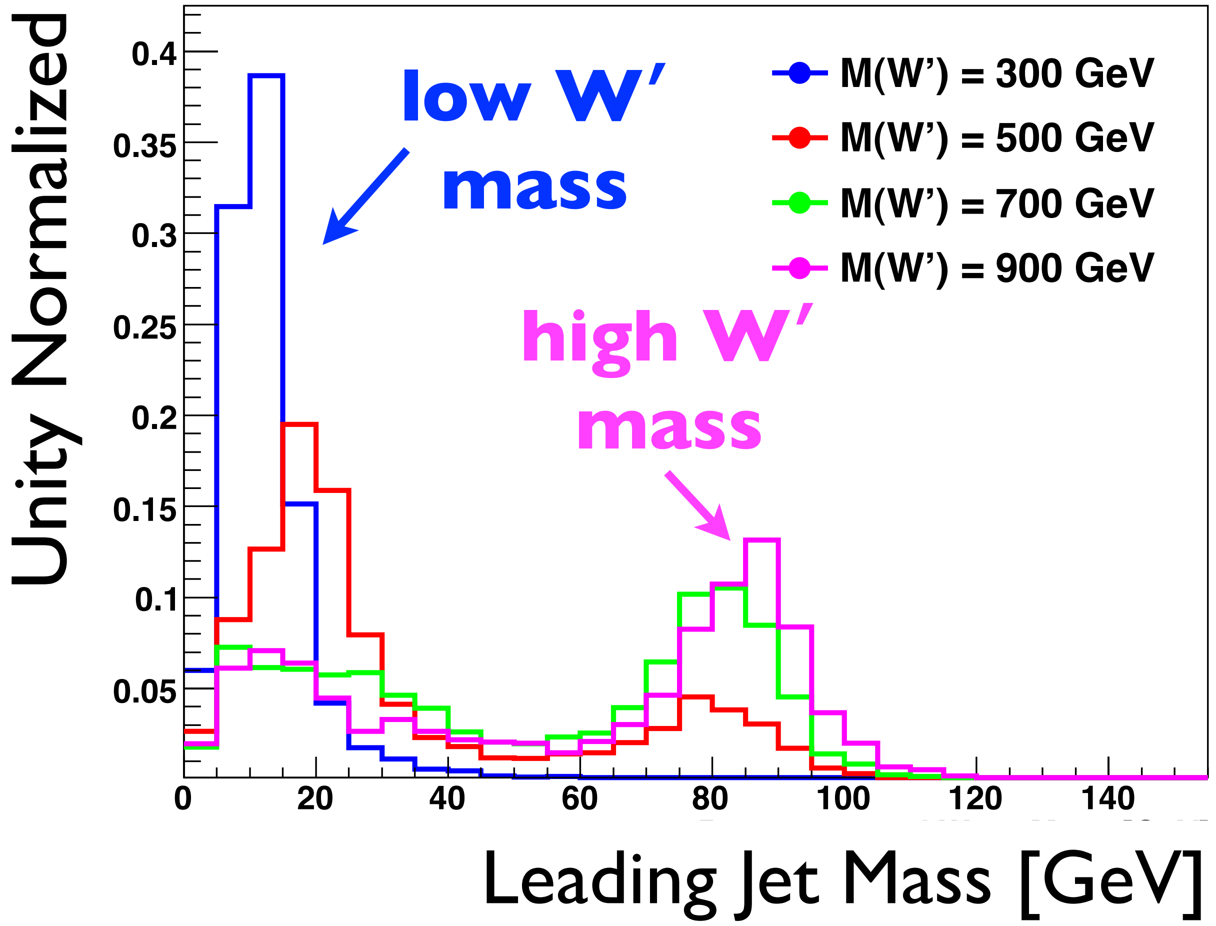

- Merged jets have a mass that peaks at W or Z boson mass!
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Event Reconstruction Strategy

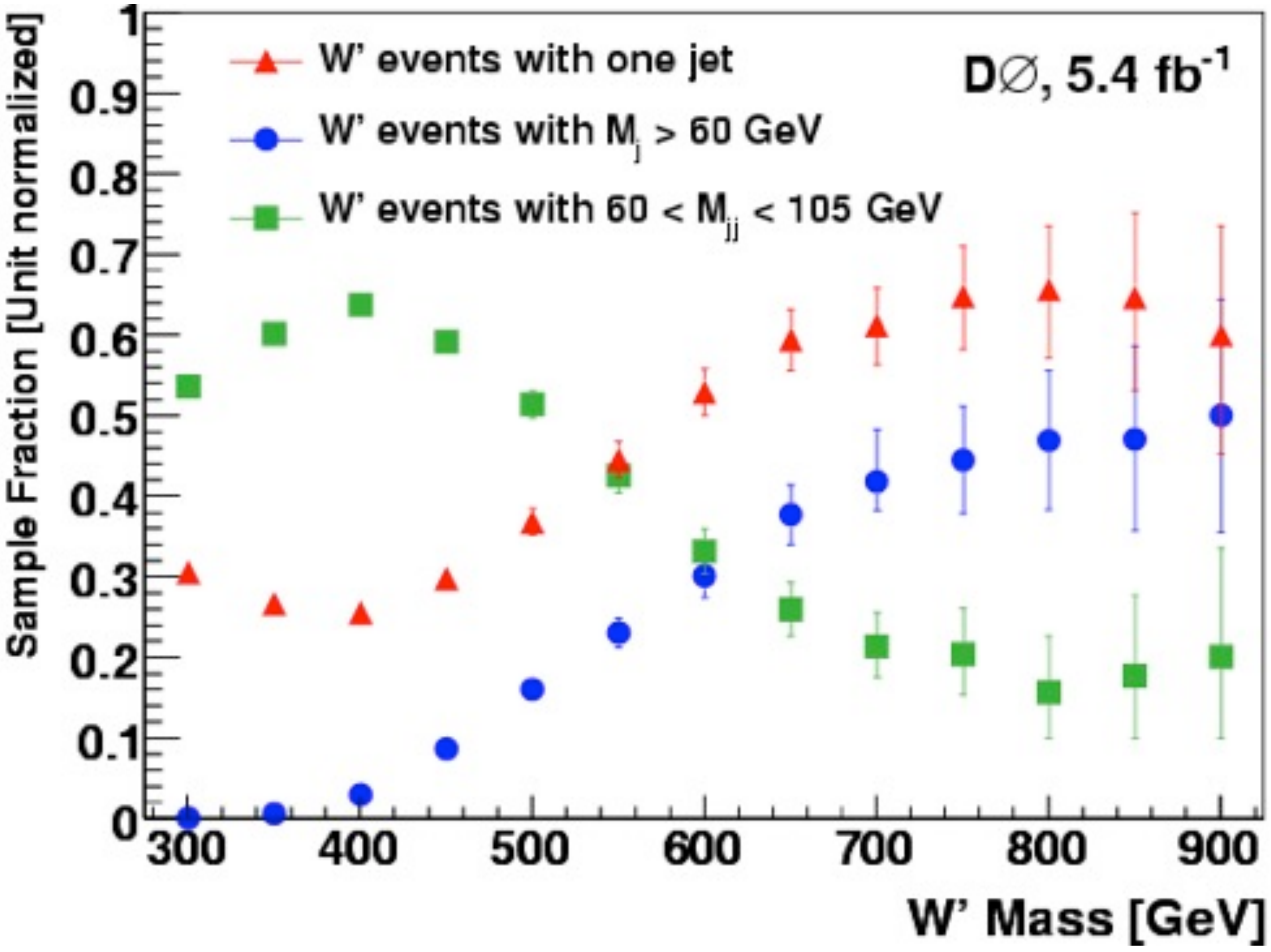
- Two distinct final states from WW or WZ resonance

$$(a)\quad WV \to \ell\nu + jj \qquad M_V - 2\sigma_{jj} < M_{jj} < M_V + 2\sigma_{jj}$$

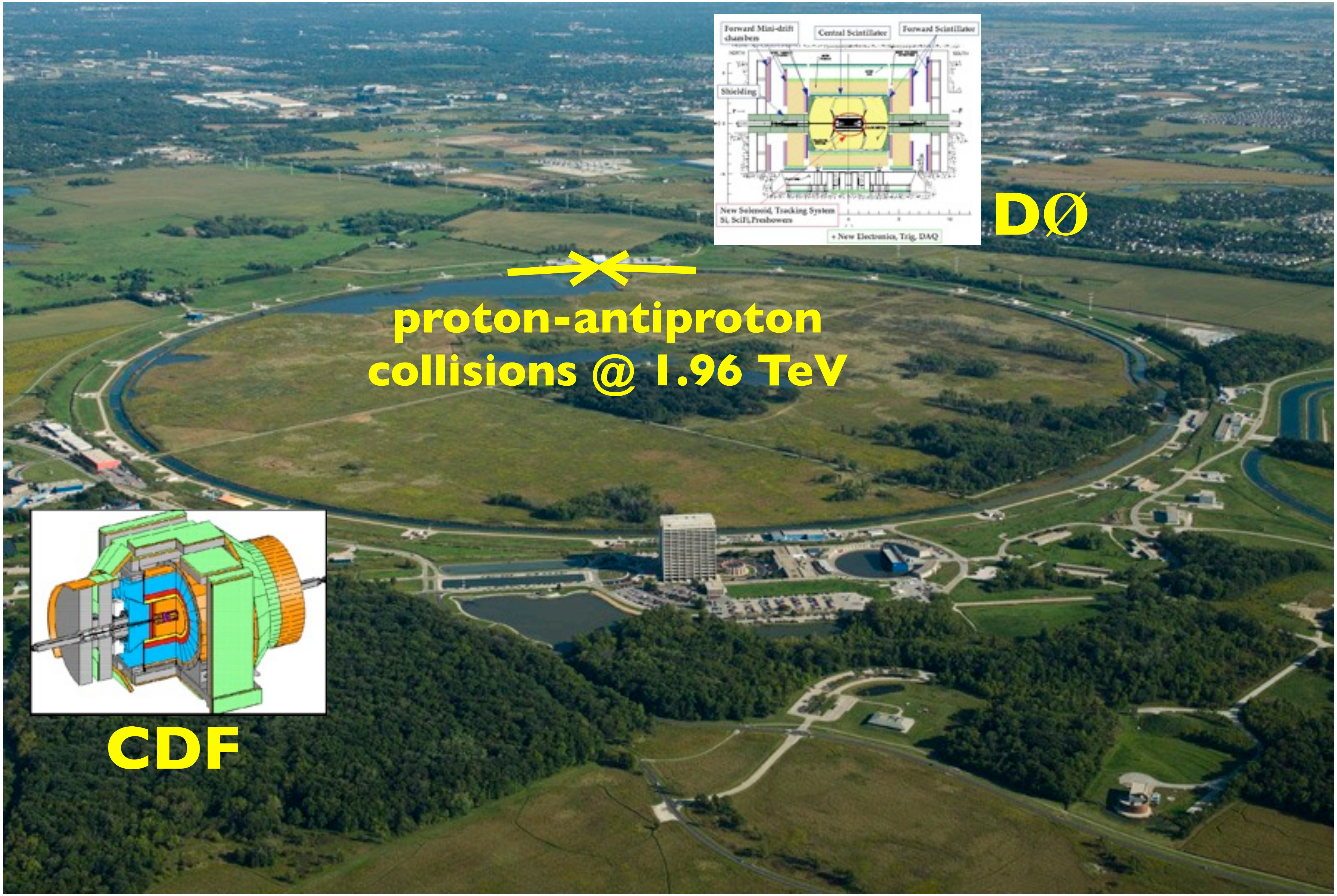
$$(b)\quad WV \to \ell\nu + j \qquad M_V - 2\sigma_j < M_j$$

- Without single jet events, mass reach is limited.

- First, a brief overview of the detector.



The Tevatron Collider @ FNAL

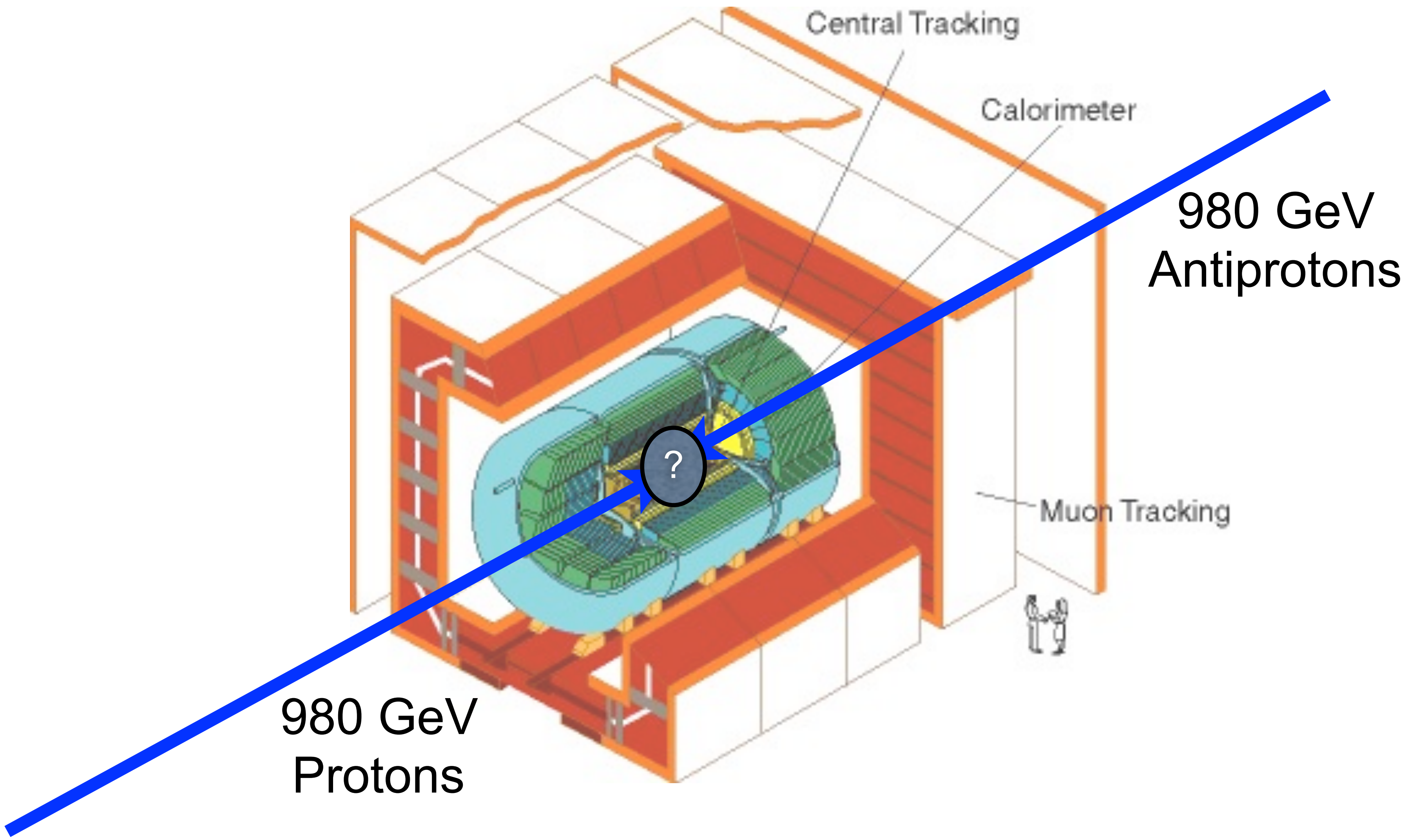


DØ

proton-antiproton collisions @ 1.96 TeV

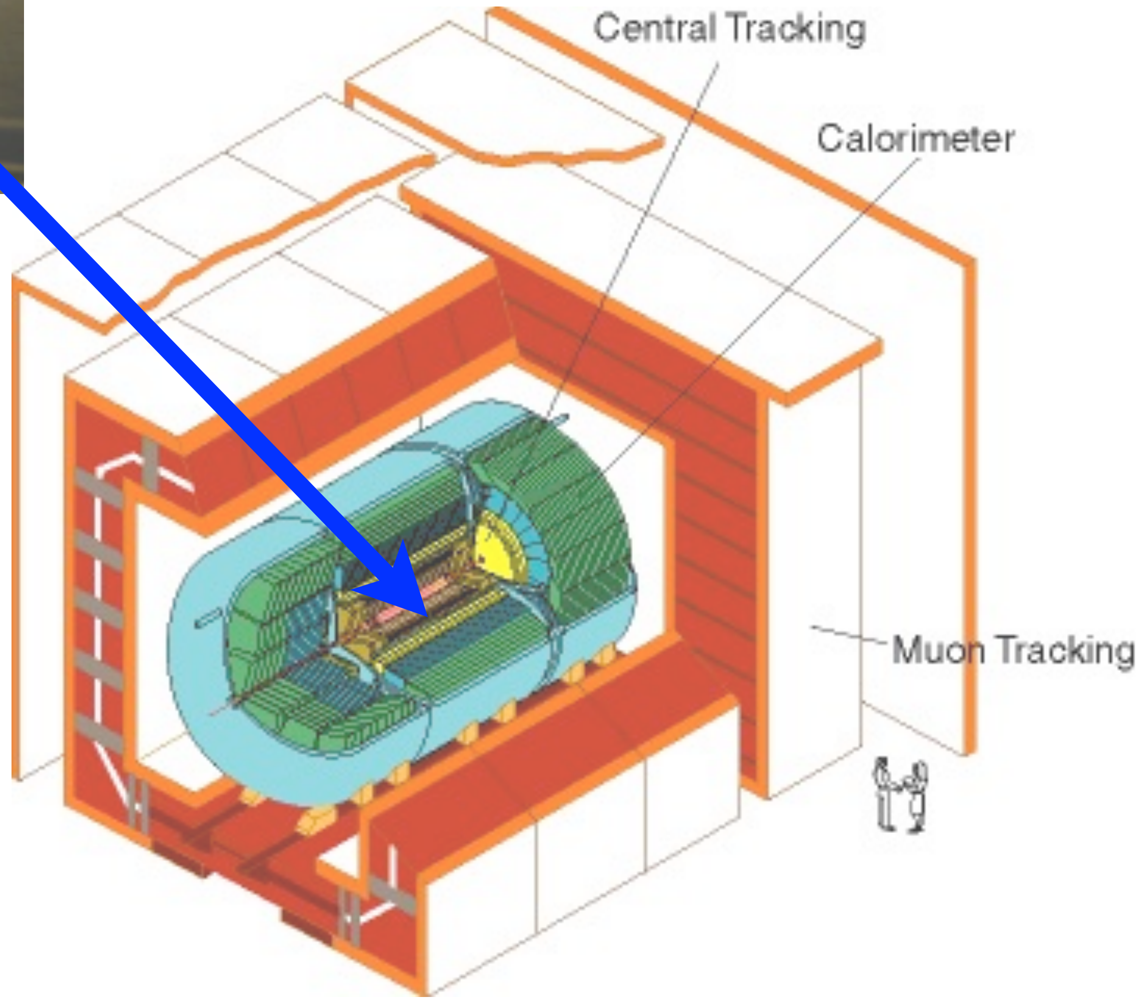
CDF

The DØ Detector



The DØ Detector

Silicon Detector
Vertex measurement
and tracking close to PV



The DØ Detector

<u>Silicon Detector</u>
Vertex measurement
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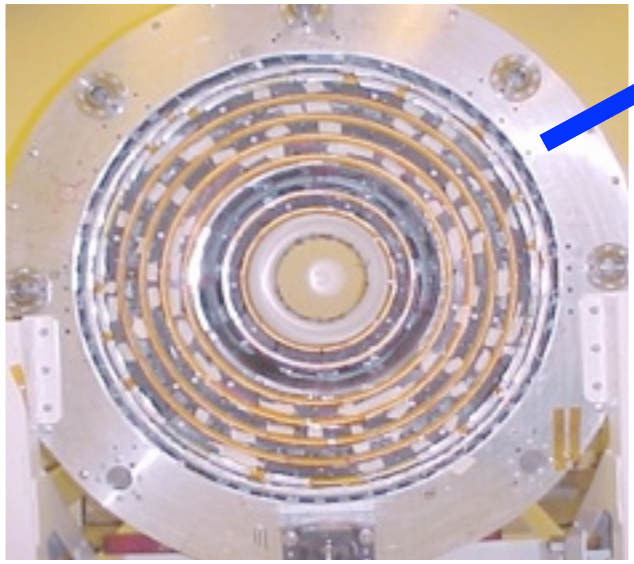
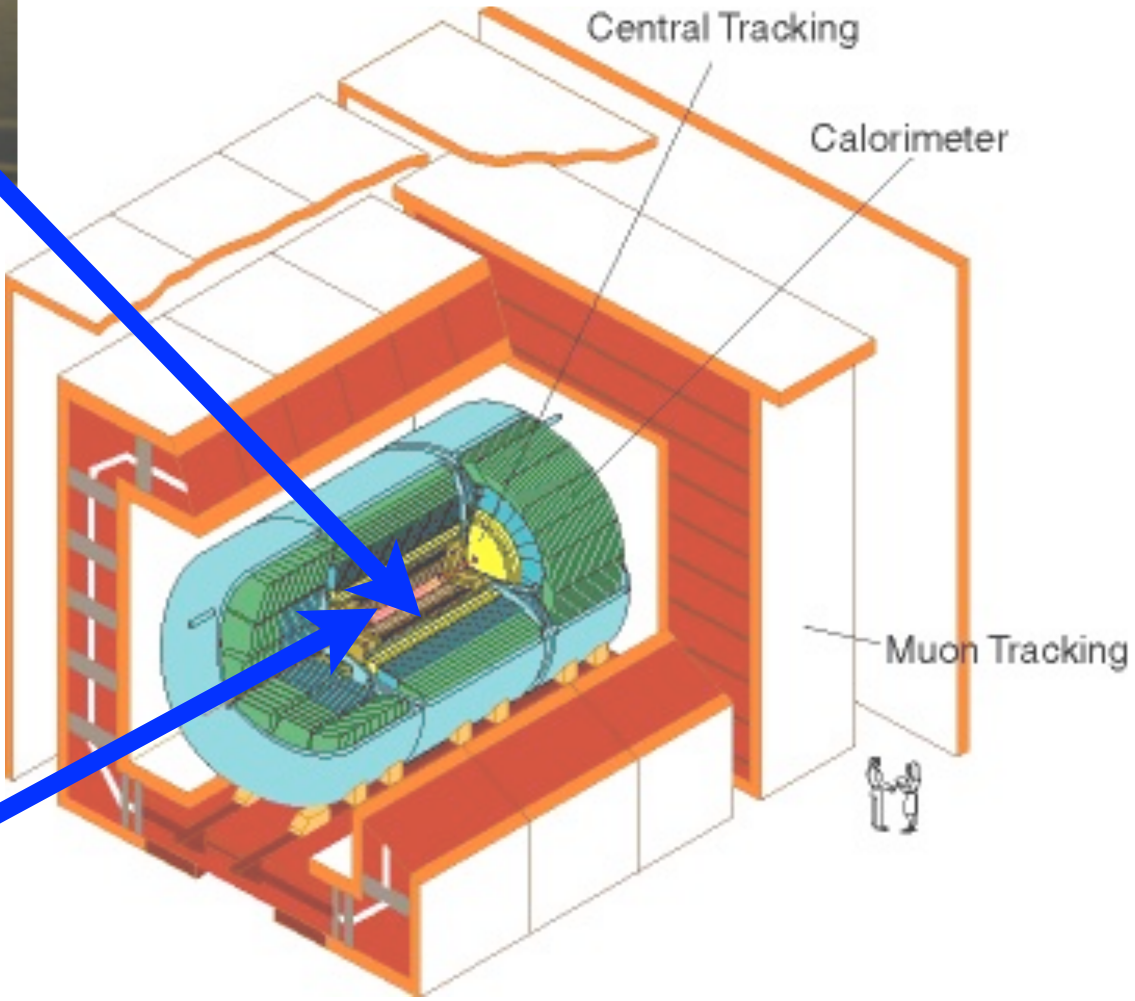
<u>Fiber Tracker</u>
Charged particle tracking
momentum + charge





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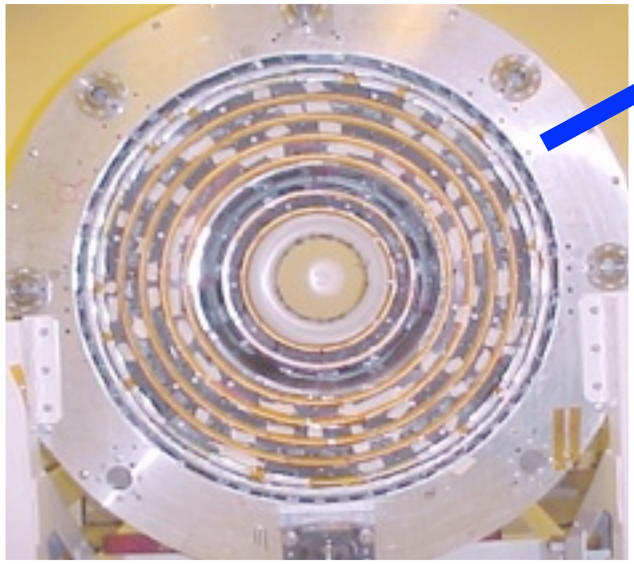
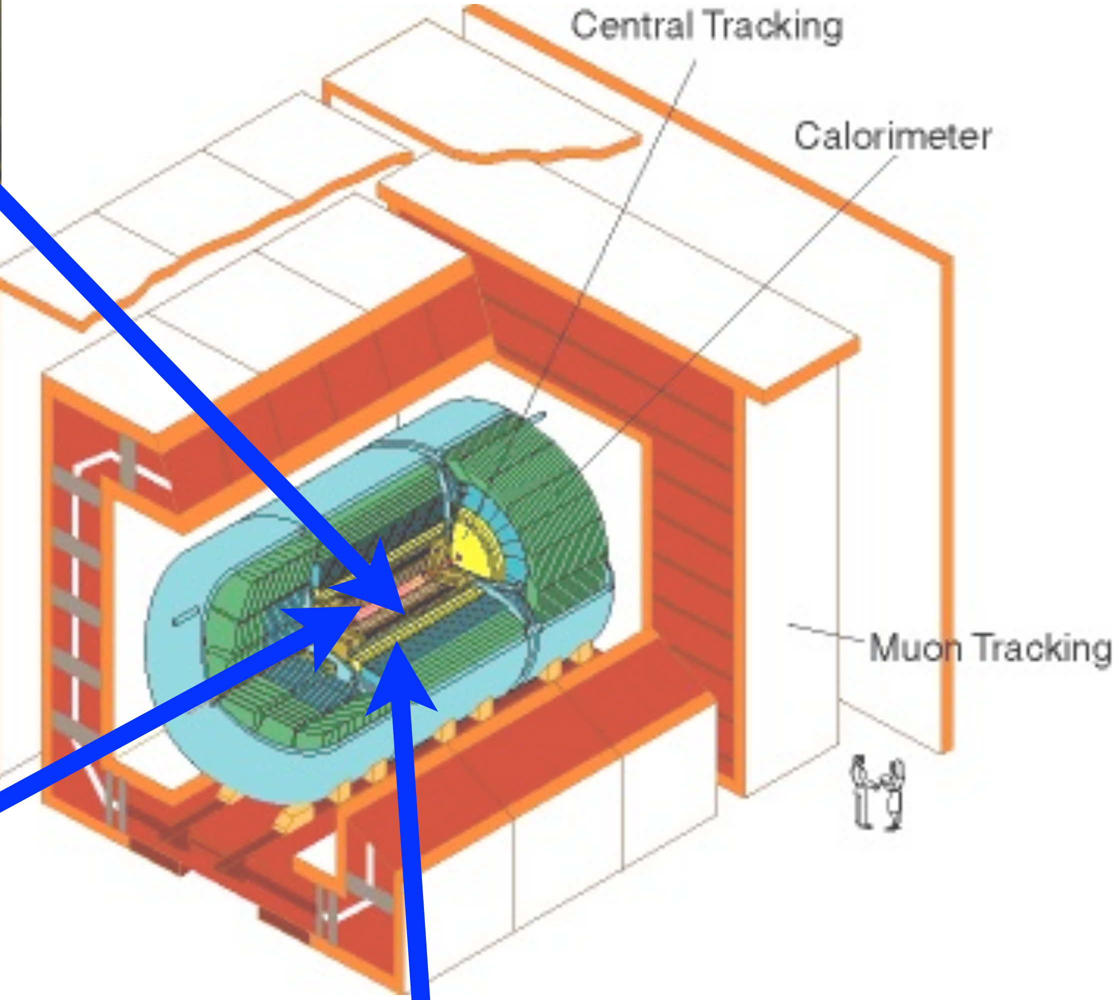
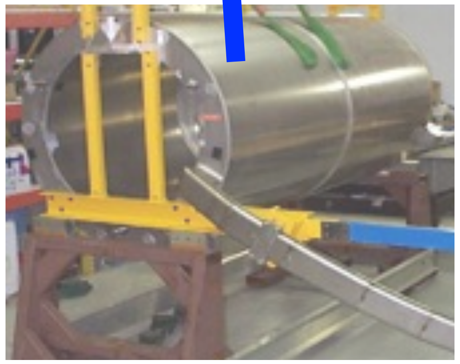




<u>Solenoid</u>
Trackers in
2 Telsa B
Field



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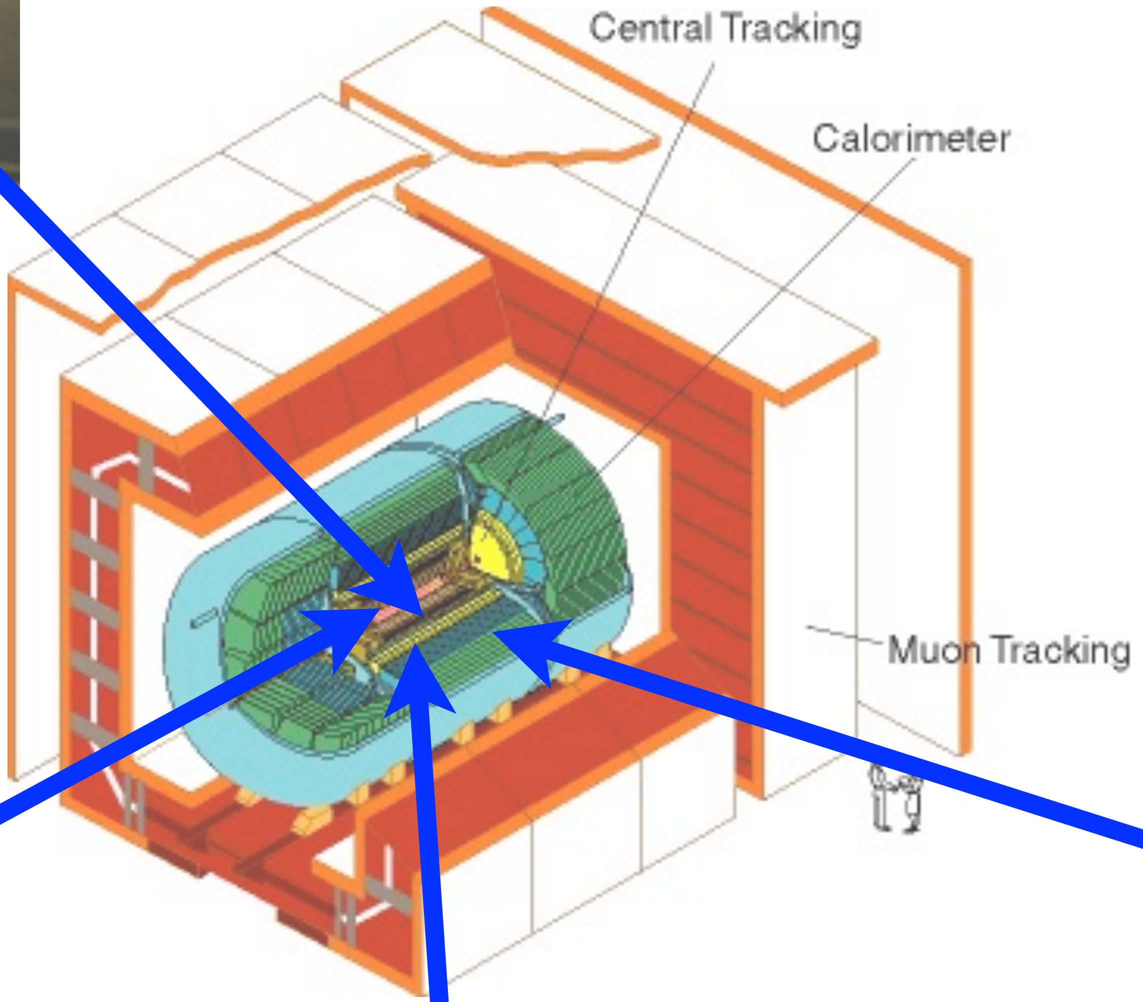

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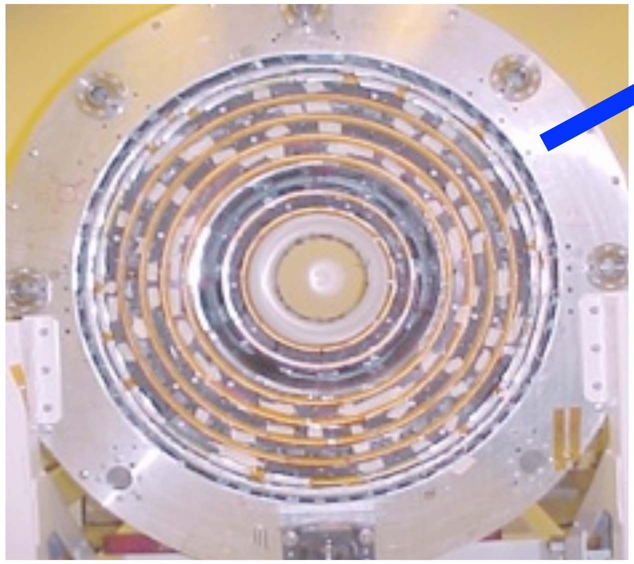

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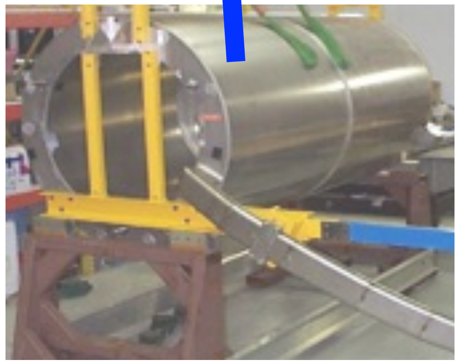
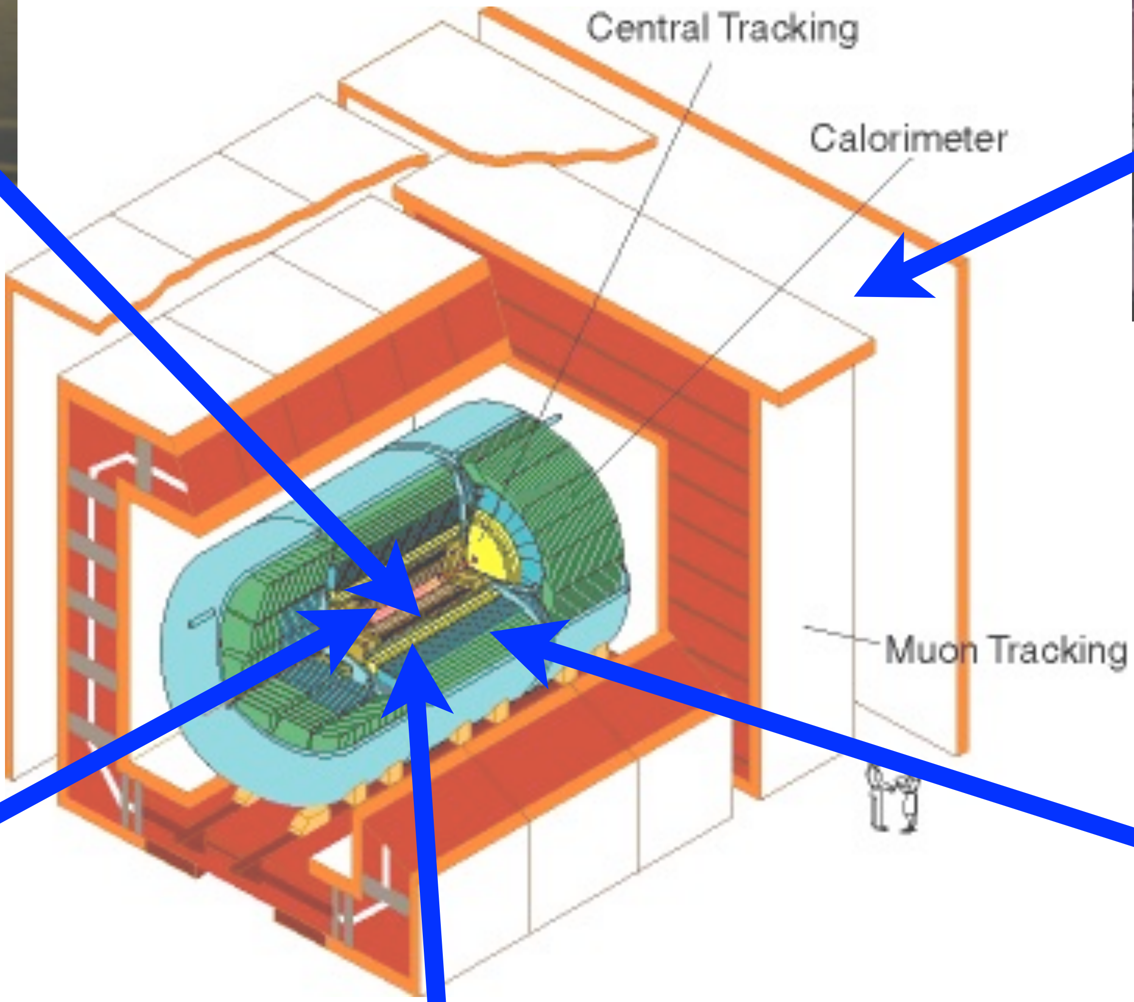


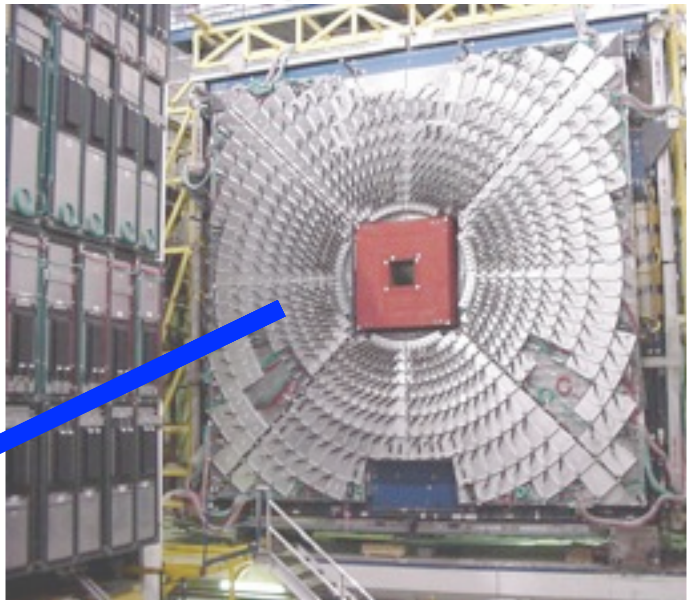
EM & Hadronic
Calorimeter
Energy
measurement

The DØ Detector

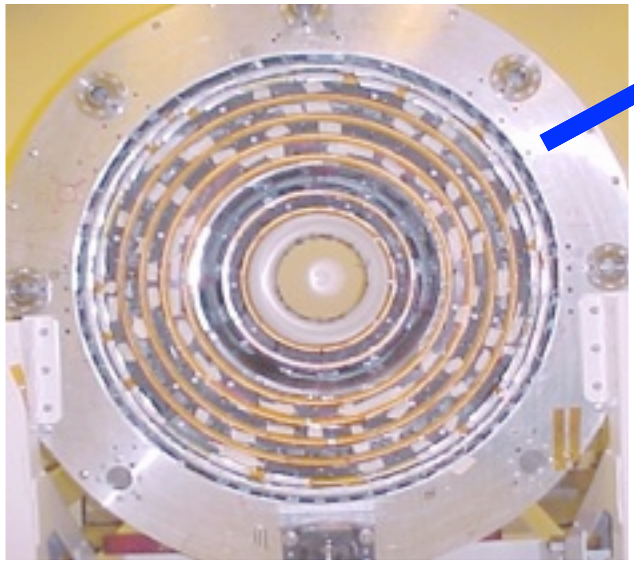
Silicon Detector
Vertex measurement
and tracking close to PV

Muon System
Drift chambers / scintillators
Muon position and tracking





Fiber Tracker
Charged particle tracking
momentum + charge



Solenoid
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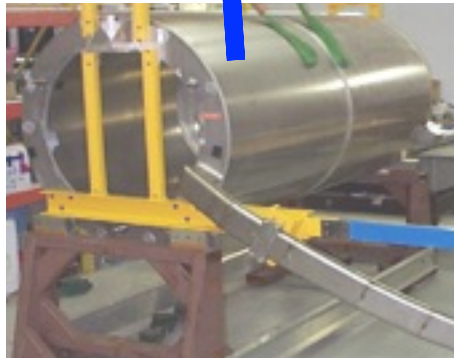
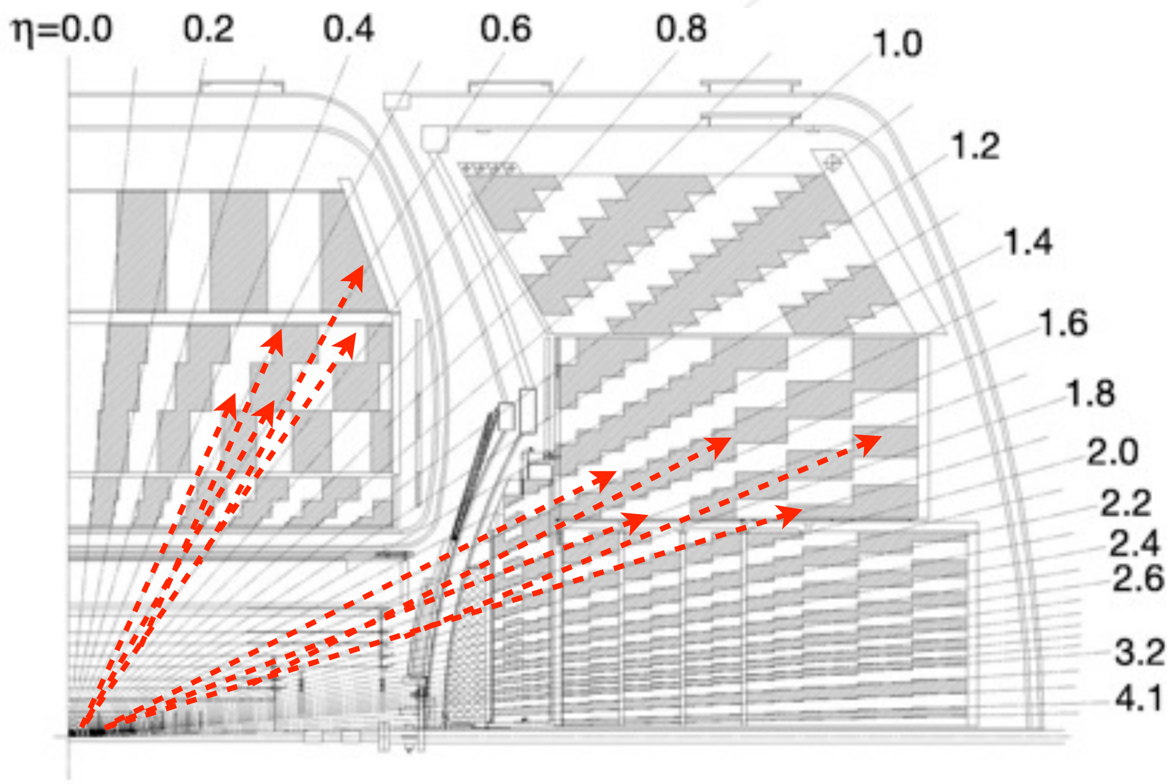
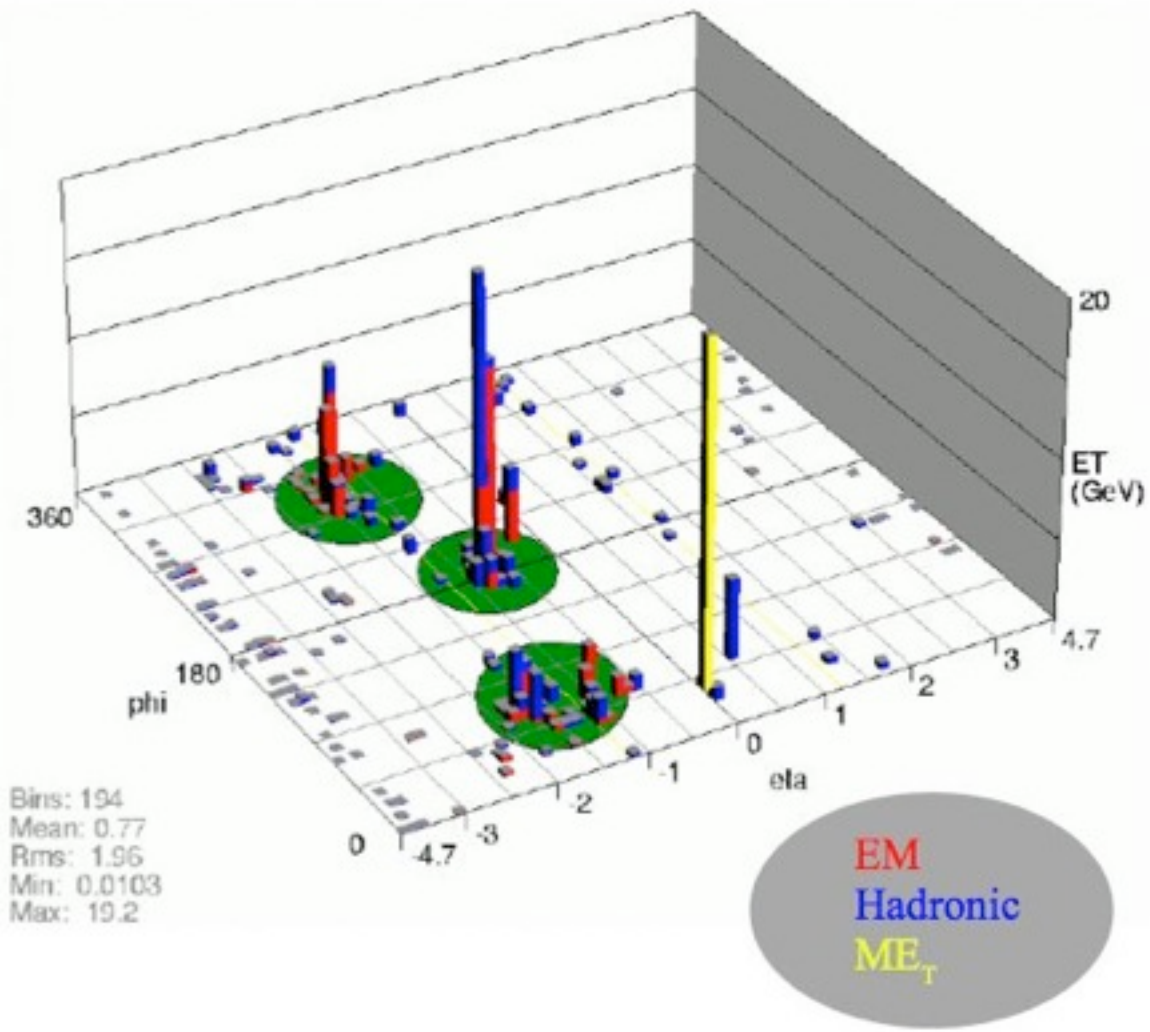


EM & Hadronic
Calorimeter
Energy
measurement

Jet Reconstruction @ DØ

- Quarks hadronize to form color singlet particles.
- We observe these particles as energy deposits in EM & HAD calorimeters.





- DØ Run II Jet Reconstruction:
  - 1) Sum energy within calorimeter towers and keep if E_T(tower) > 1 GeV. ($R_{tower} = \Delta\Phi \times \Delta\eta = 0.1$)
  - 2) Combine tower energies in cone of radius 0.5 and keep if $E_T > 6$ GeV.
  - 3) Split/merge overlapping jets.

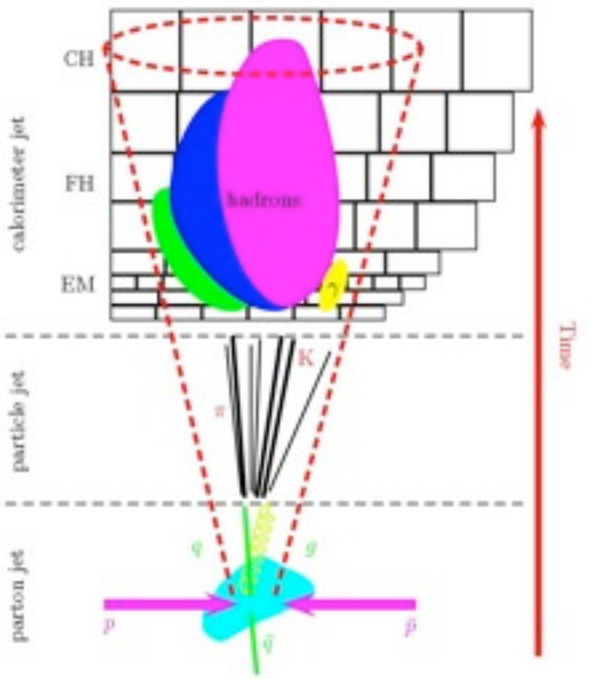
G.C. Blazey et al., "RunII Jet Physics", hep-ex/0005012

DØ Jet Energy Scale Correction

- Jet energy scale weight corrects the raw jet energy (calo) to the particle-level.

$$E_{jet}^{ptcl} = \frac{E_{jet}^{raw} - O}{F_{\eta} \cdot R \cdot S} \cdot k_{bias}$$

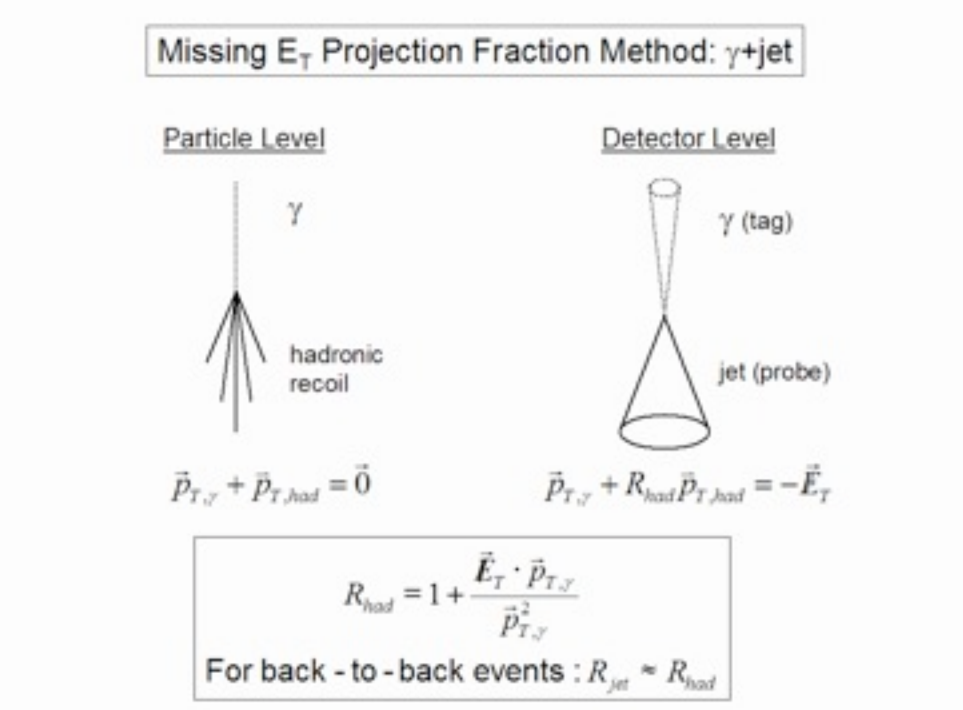
E_{jet}^{ptcl}: corrected jet energy
E_{jet}^{raw}: uncorrected jet energy
O: offset energy correction
F_{η}: relative response correction (η-intercalibration)
R: absolute response correction
S: showering correction
k_{bias}: correction for remaining biases



- Large source of photon+jet events available at the Tevatron.
  - Balance jet energy against well measured photon energy (EM-scale set by Z).

See Gianluca Petrillo’s Talk for more details.
https://indico.cern.ch/sessionDisplay.py?sessionId=7&confId=12162

  - Uncertainty less than 5% in high jet p_T events.


Missing E_T Projection Fraction Method: γ+jet

$$\vec{p}_{T,\gamma} + \vec{p}_{T,had} = \vec{0}$$

$$\vec{p}_{T,\gamma} + R_{had}\vec{p}_{T,had} = -\vec{E}_T$$

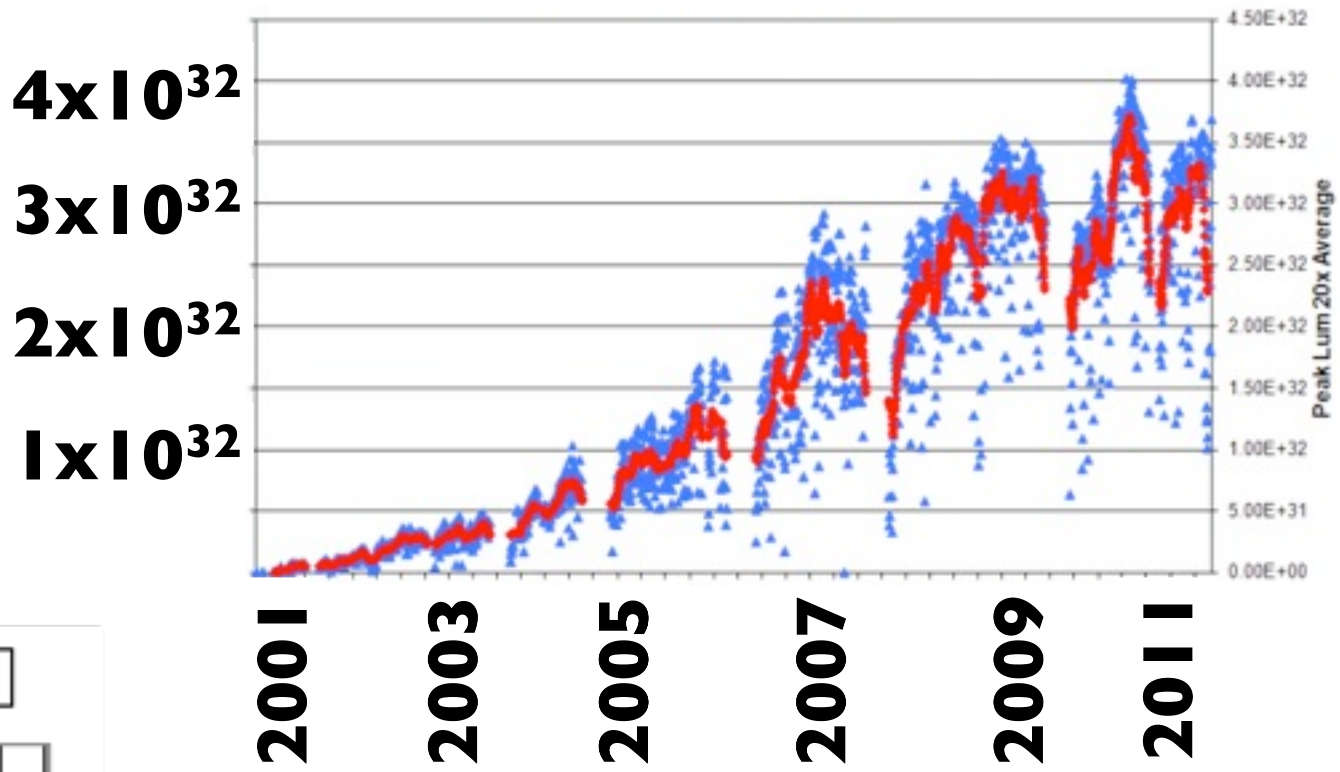
$$R_{had} = 1 + \frac{\vec{E}_T \cdot \vec{p}_{T,\gamma}}{\vec{p}_{T,\gamma}^{\,2}}$$

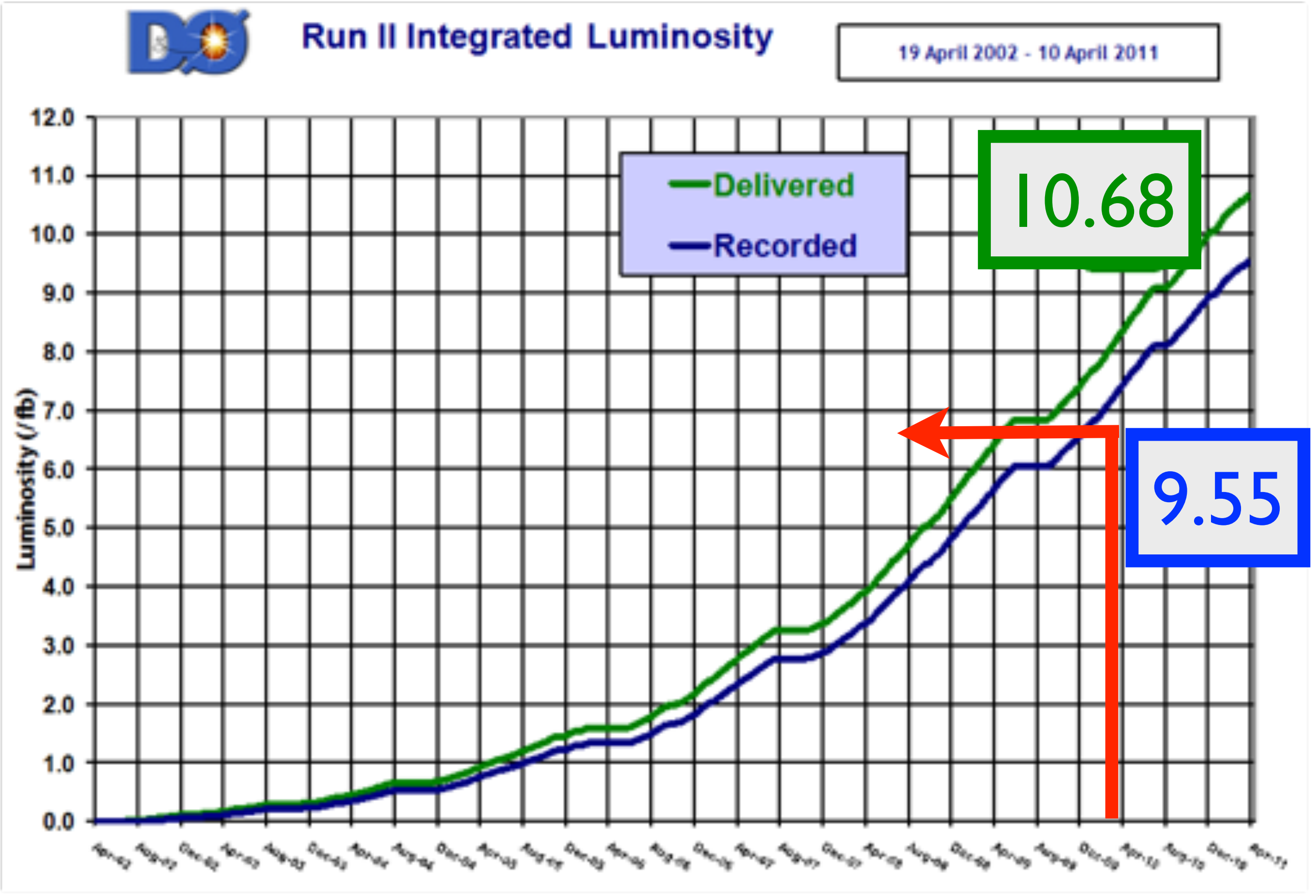
For back-to-back events: $R_{jet} \approx R_{had}$

Diboson Search with 5.4 fb^{-1}

- Tevatron performing very well.
- DØ has recorded over 9.5 fb^{-1} !

Run II Peak Luminosity

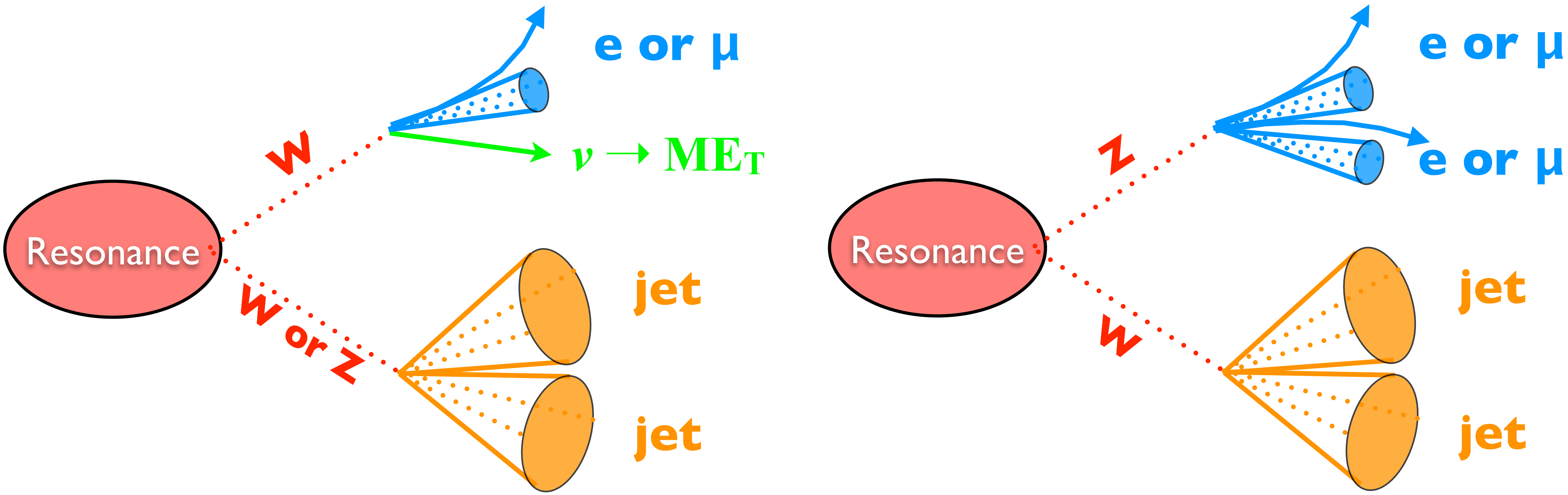




- *Analysis* presented uses half of current dataset (5.4 fb^{-1})

Diboson Event Selection

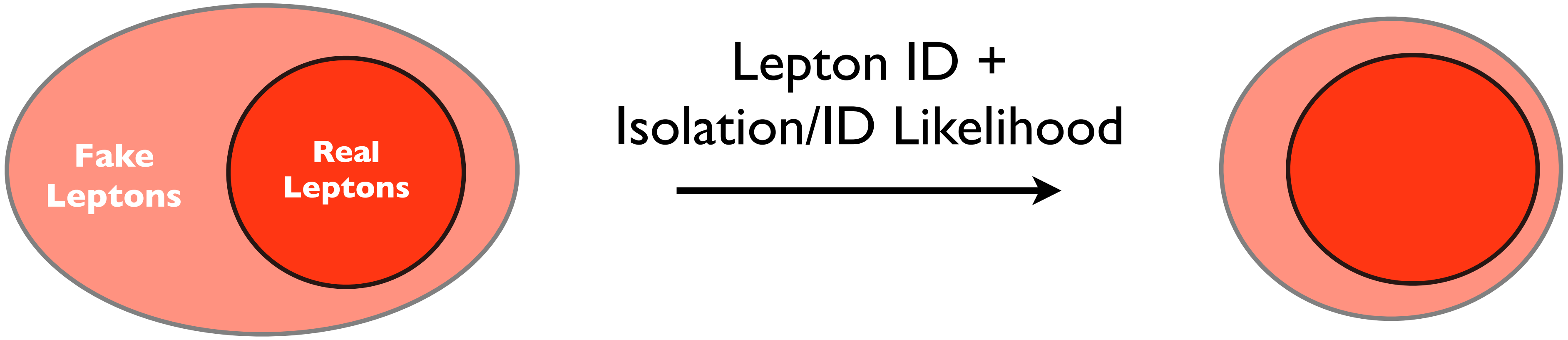
- We select WW or WZ events with 1 leptonic W/Z decay and 1 hadronic W/Z decay.



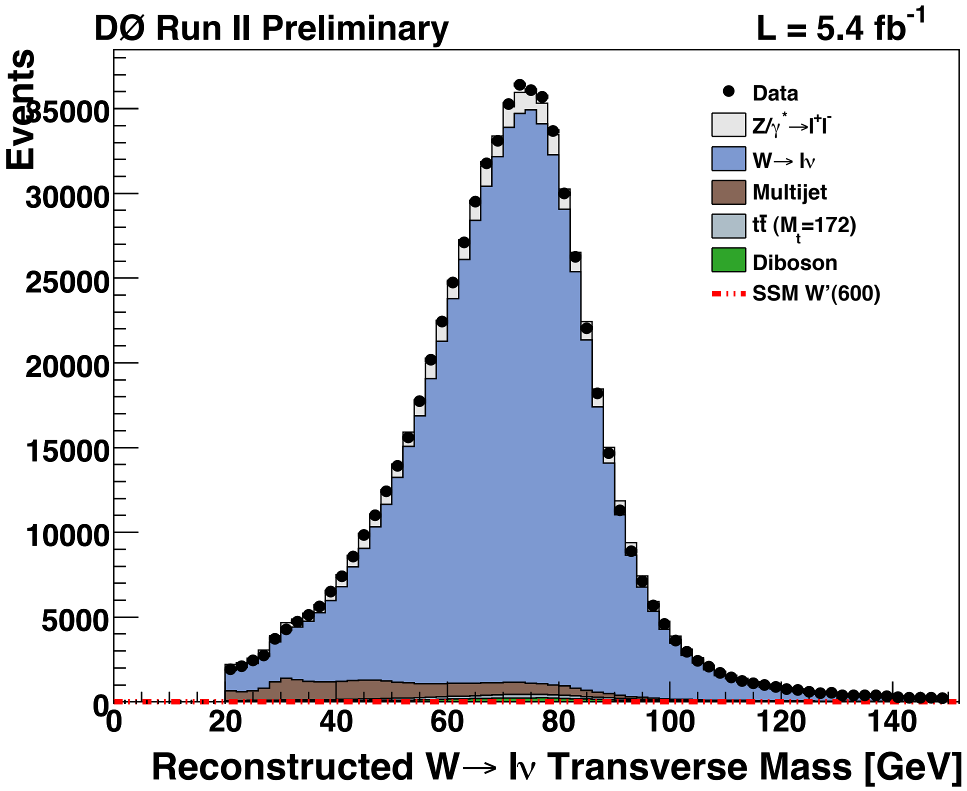
- **Electrons: EM cluster + track , $p_T > 20$ GeV and $|\eta| < 1.1$ or $1.5 < |\eta| < 1.5$.**
- **Muons: Muon scintillator + wire hits + track , $p_T > 20$ GeV and $|\eta| < 2.0$.**
- **Jets: $P_T > 20$ GeV and $|\eta| < 3.0$ (remove overlapping electrons).**
- **Missing E_T: Negative vector sum of calorimeter energy corrected for electrons, muons and jets.**

Background Estimation

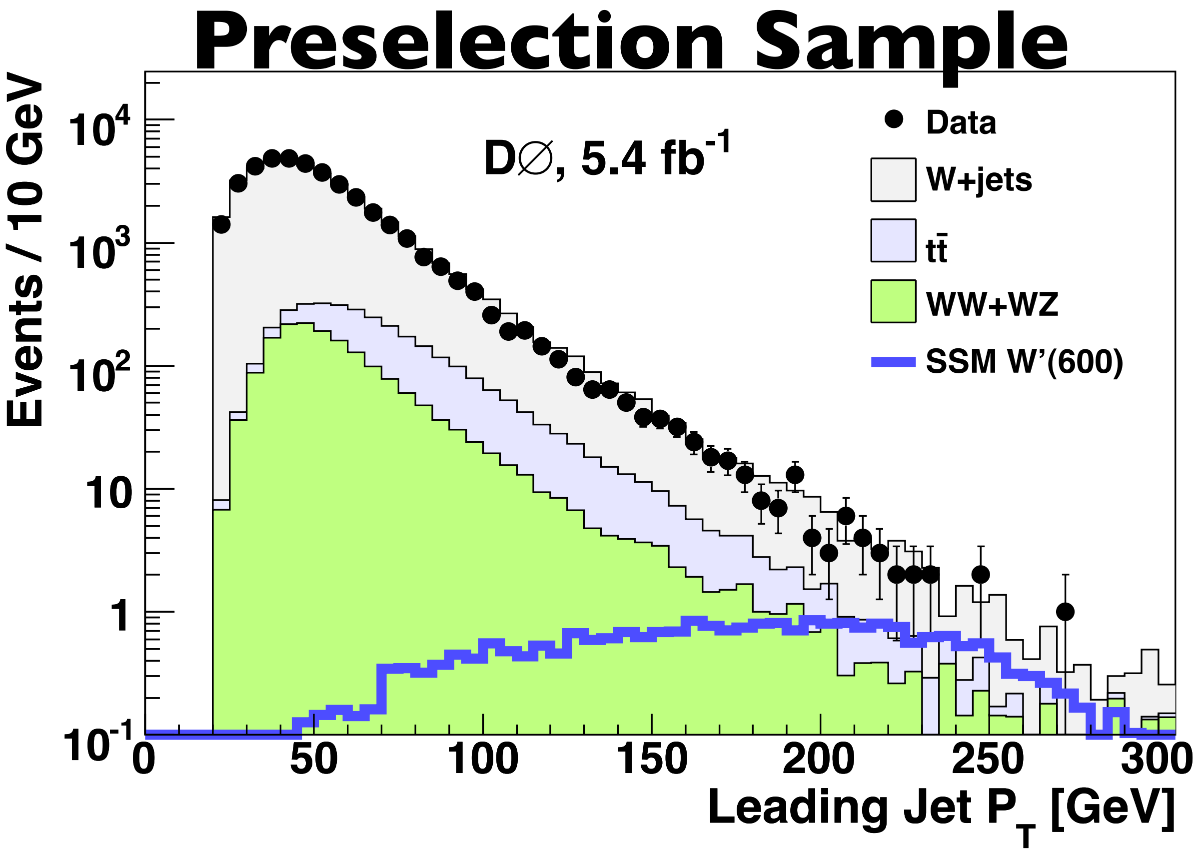
- Event selection yields high number of W and Z boson + jets events.
  - W/Z+jets modeled with ALPGEN + Pythia (MLM matching)
  - QCD multijet production modeled with data (reverse lepton ID).
    Normalized to data using matrix method (simultaneous QCD+W/Z+jets norm.)

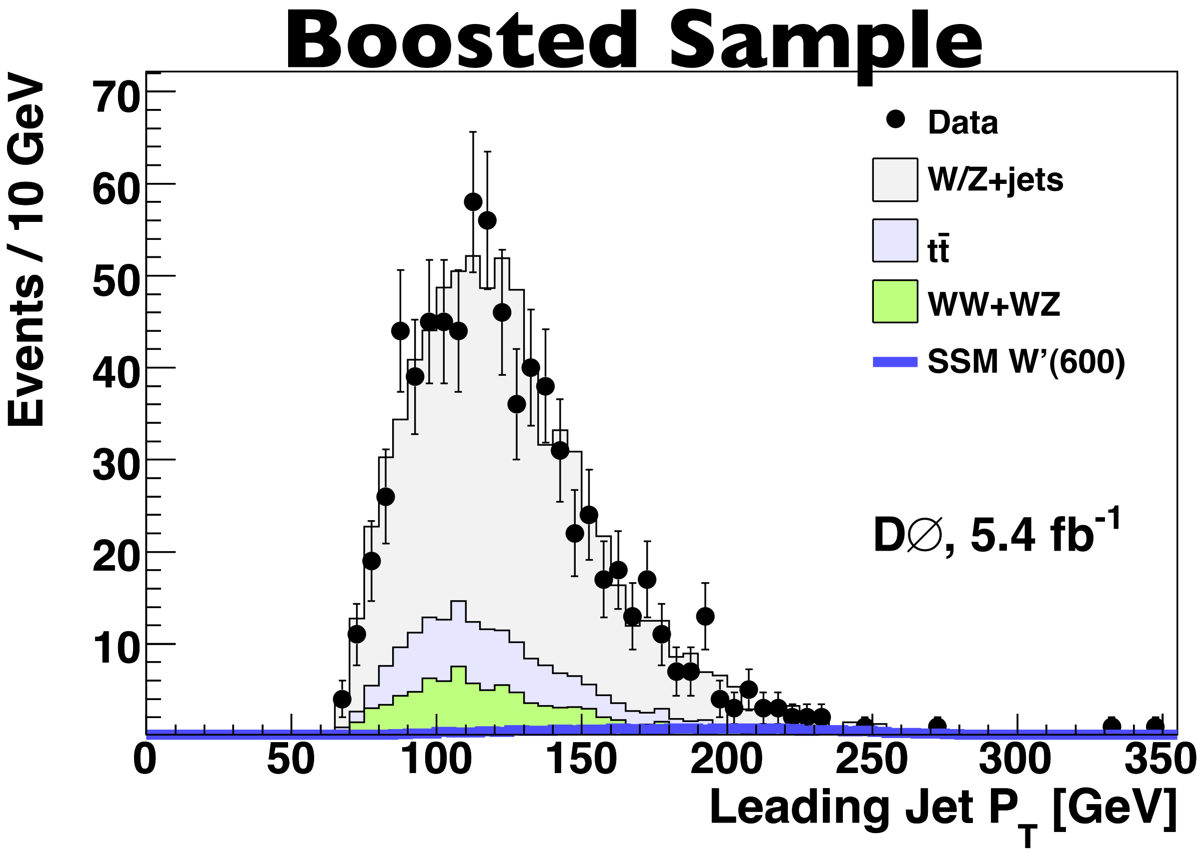


- MC used for all other backgrounds
  - ttbar modeled with ALPGEN + Pythia (MLM)
    scaled to ≈NNLO (http://arxiv.org/abs/0804.1476)
    assuming mtop = 172.5 GeV.
  - singletop (tb + tqb) modeled with CompHEP+Pythia
    scaled to ≈NLO (http://arxiv.org/abs/hep-ph/0609287)
    assuming mtop = 172.5 GeV.
  - WW/WZ/ZZ modeled with Pythia scaled to MCFM
    prediction.

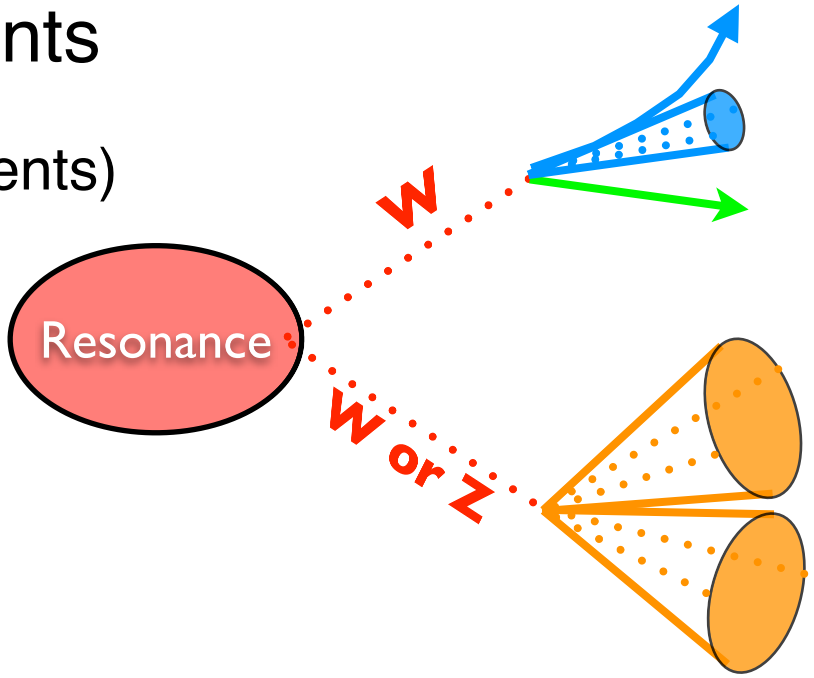


Signal Enhancement Cuts


Preselection Sample

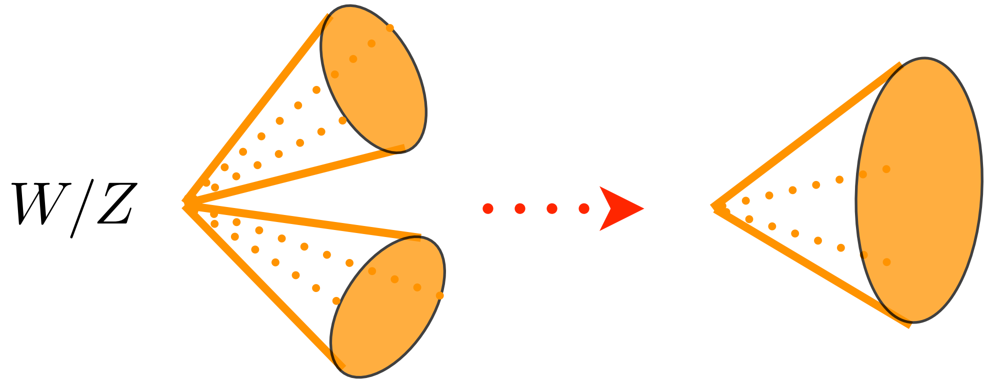

Boosted Sample

- Enhance signal content by selecting boosted events
  - Require 60(70) < M(jet1,jet2) < 105(115) GeV (if two jet events)
  - Require P_T(jet1,jet2) > 100 GeV or P_T(jet1) > 100 GeV (if single jet event).
  - Require $P_T(Z \rightarrow ll) > 100$ GeV or $P_T(W \rightarrow l\nu) > 100$ GeV.
  - ΔR(jet1, jet2) < 1.5 [Rad] (if two jets)
  - ΔR(lep1, lep2) < 1.5 [Rad] (if two leptons) or ΔΦ(lepton, ME_T) < 1.5 [Rad] (if one lepton)

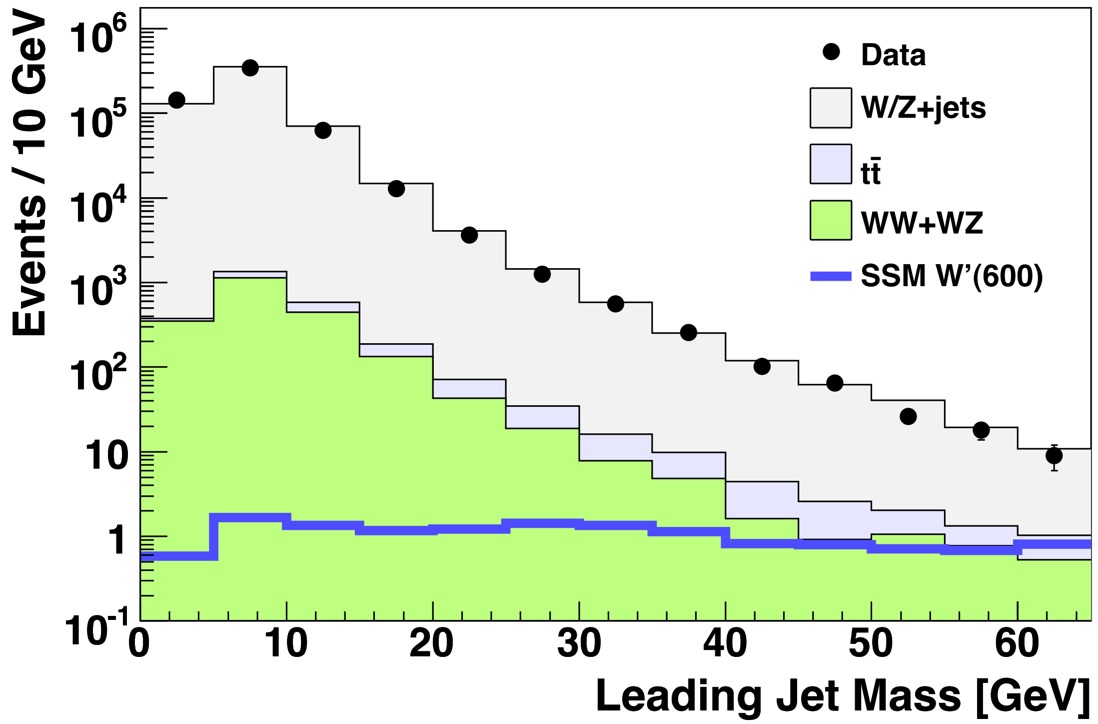


Boosted Jets

- So far, analysis follows previous search strategy (i.e. select isolated objects and form combined objects like W and Z bosons).
- Look for high mass jets in data
- Important to check background model.



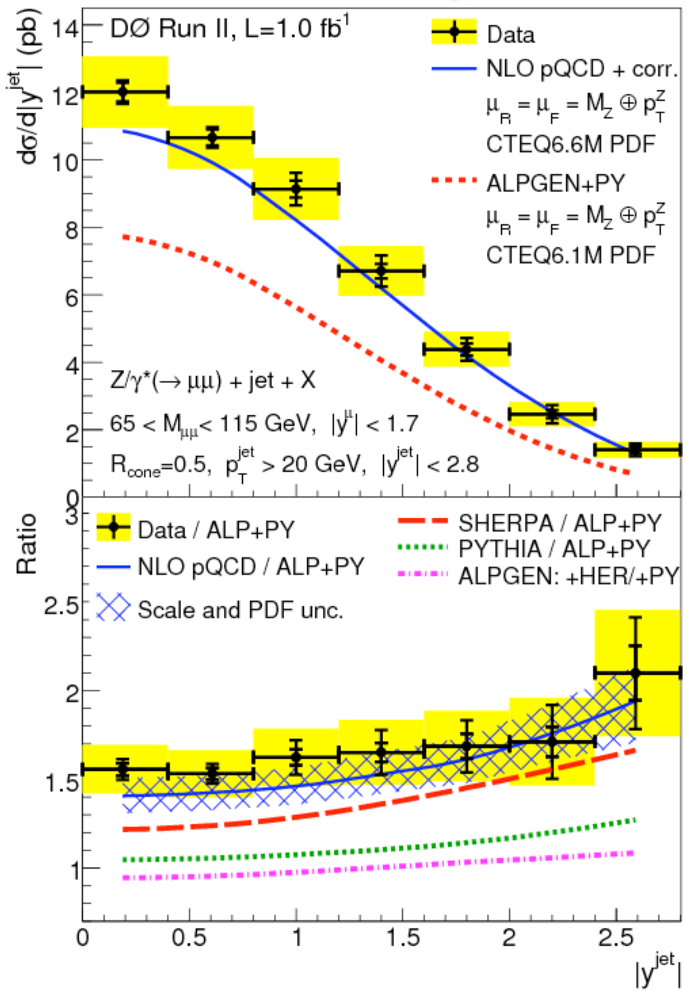
- Immediate difficulty: No easy control sample available due to very limited statistics even with 5.4 fb^{-1}.
    - Large jet mass events very rare in W/Z+jets events.
- Natural W/Z-jet sample from highly boosted diboson or ttbar events.
    - Low rate at Tevatron.
      Excellent calibration source for LHC.



- Mass is well modeled by ALPGEN.
  Uncertainty ranges from 10-25%
  based on data/MC agreement in signal free sample ($P_T(Z \rightarrow ll) < 100$ GeV)

More Monte Carlo Modeling

- Analysis requires reweighting V+jets MC
  - ALPGEN does not reproduce W and Z boson p_T. Jet pseudorapidity also not well modeled.
- Jet multiplicity well modeled with ALPGEN using MLM machine (not w/ Pythia alone)
  - Spectrum agrees for loose W and Z selection What about W/Z + highly boosted jets?



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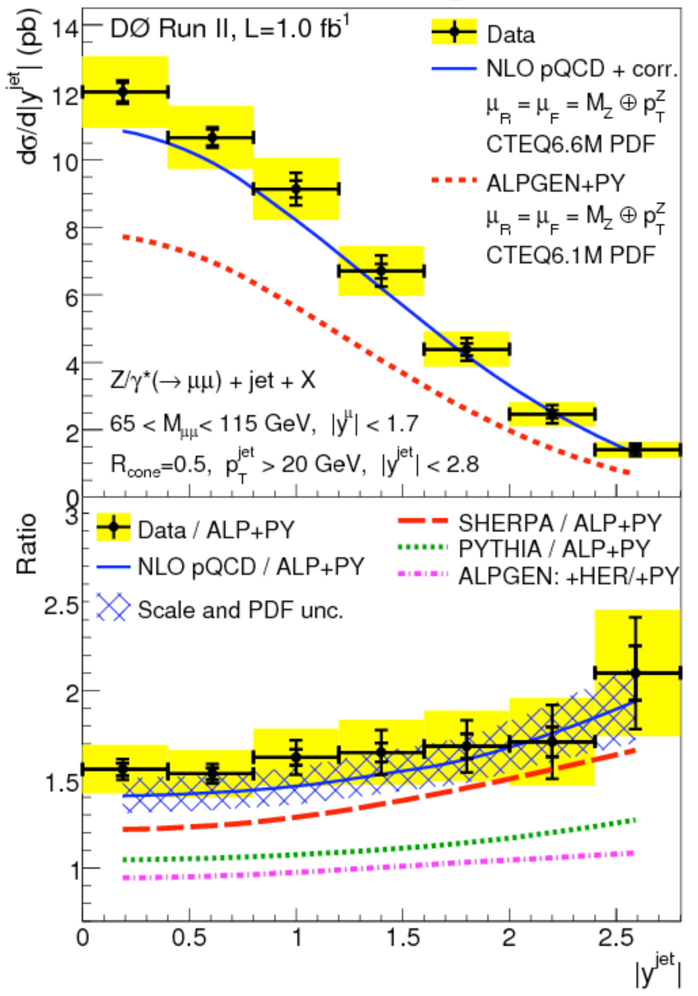
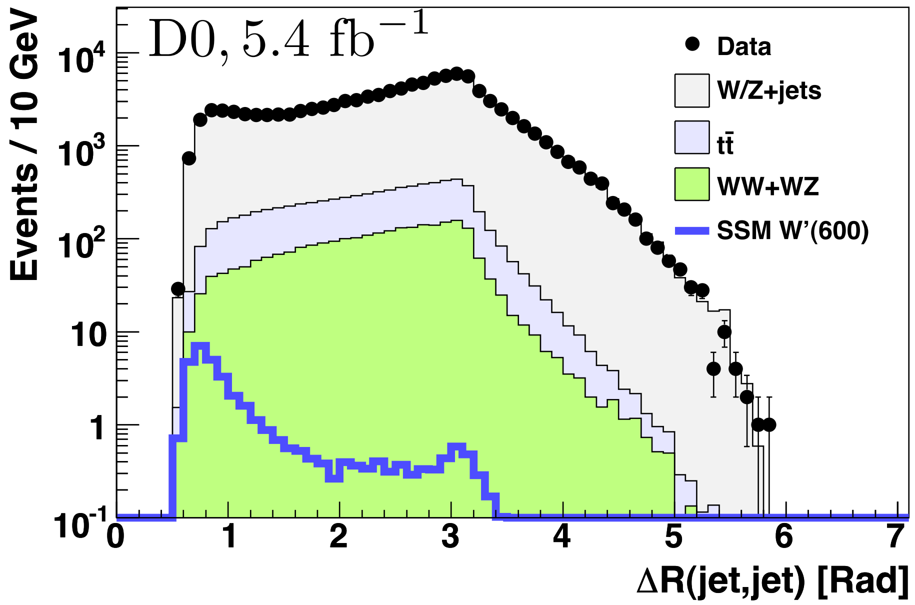
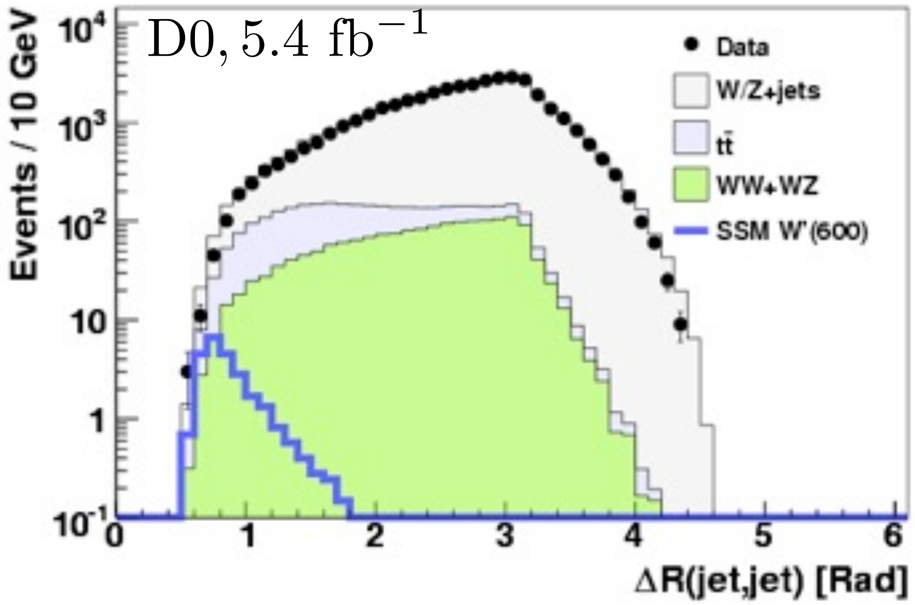
- ALPGEN has trouble with modeling ΔR(jet,jet).
  - Systematic taken as 100% of reweighting factor in control region (25% uncertainty on W/Z+jets).




Preselection Sample


M(jj) Selection Sample

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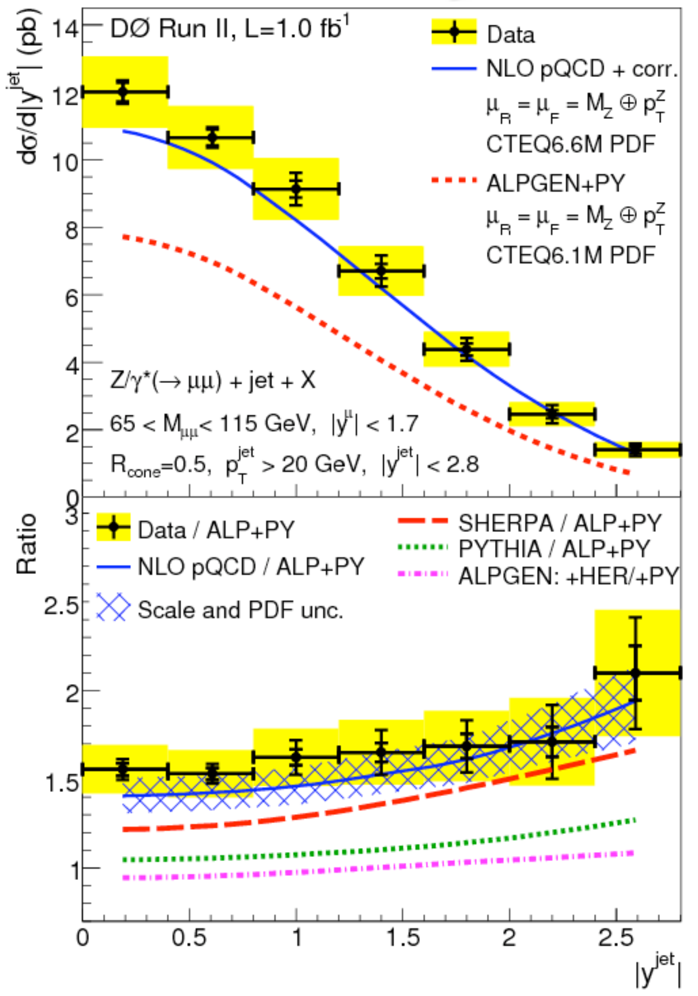

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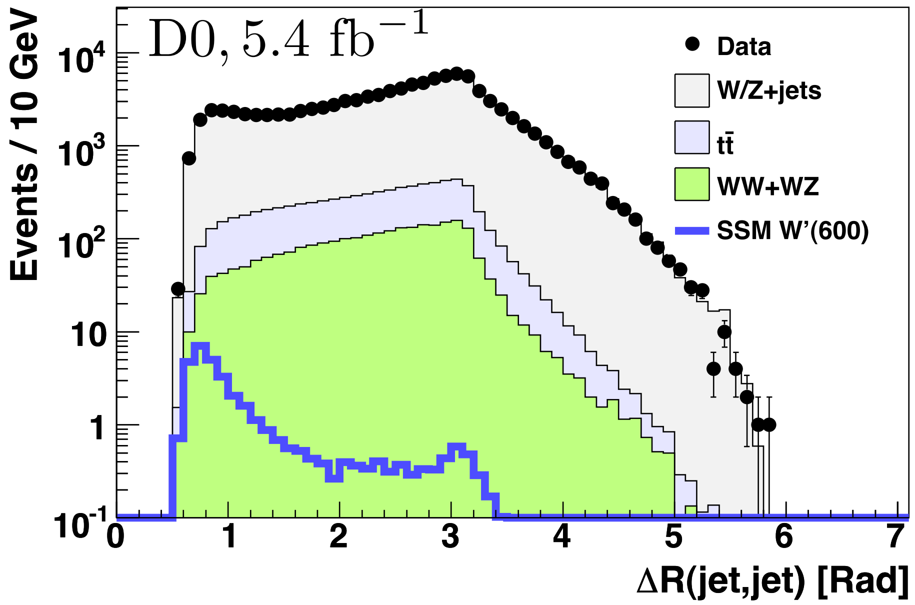

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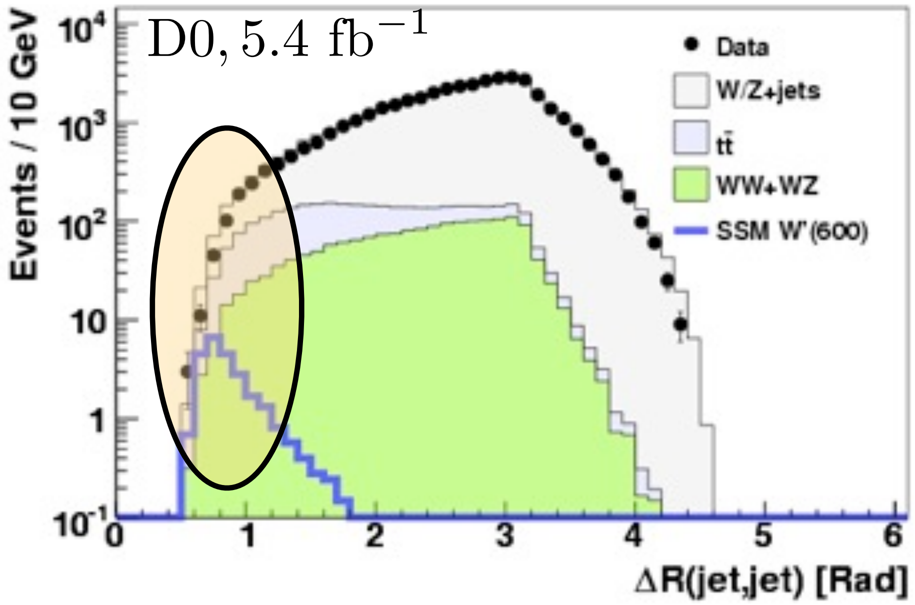
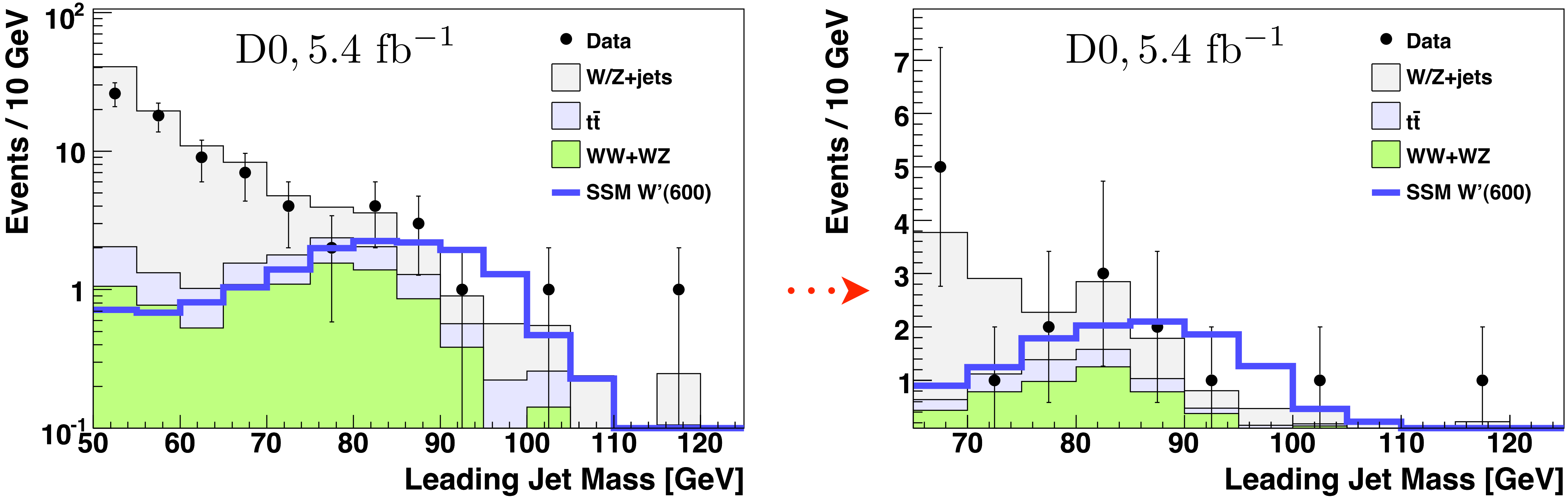


Large Jet Mass Results

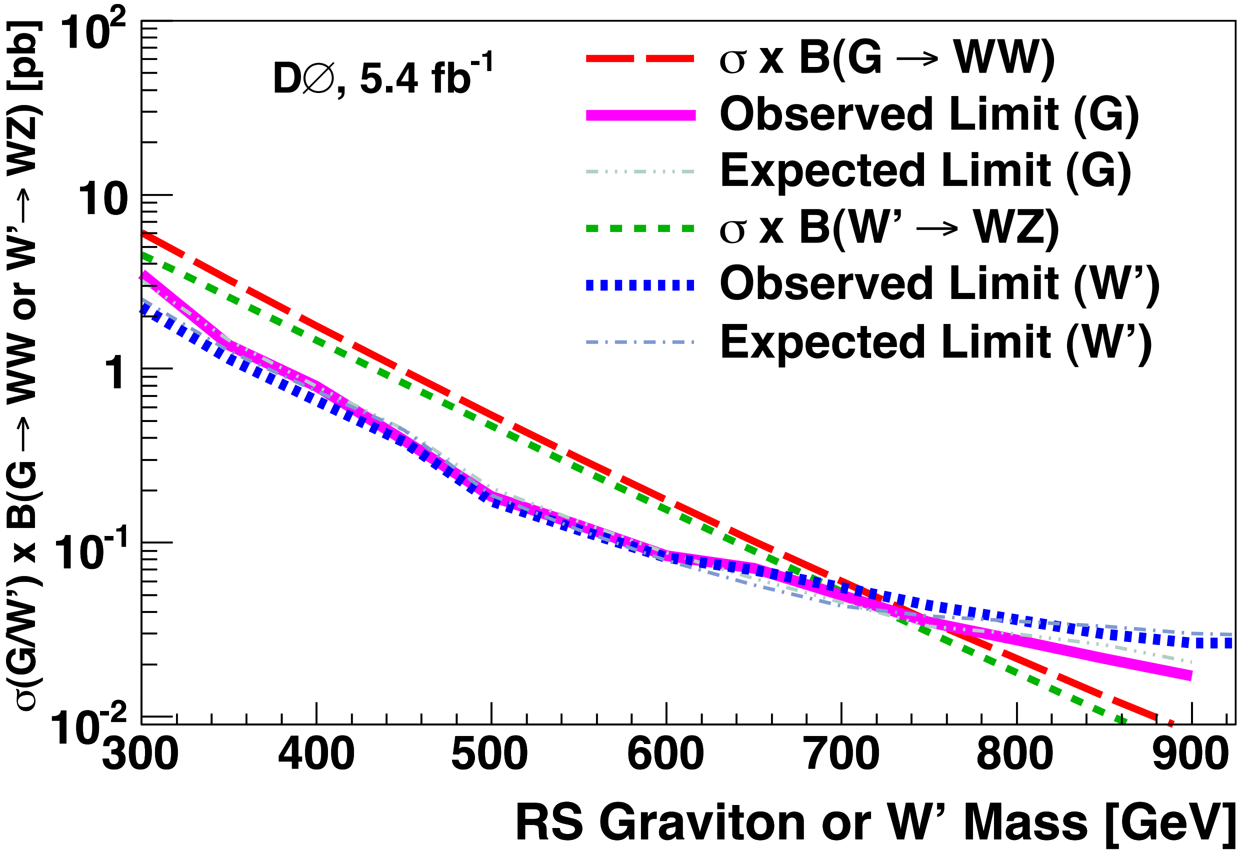
- No statistically significant excess of data in this search.
  - Very mild evidence for ttbar + WW + WZ in jet mass, but not significant.

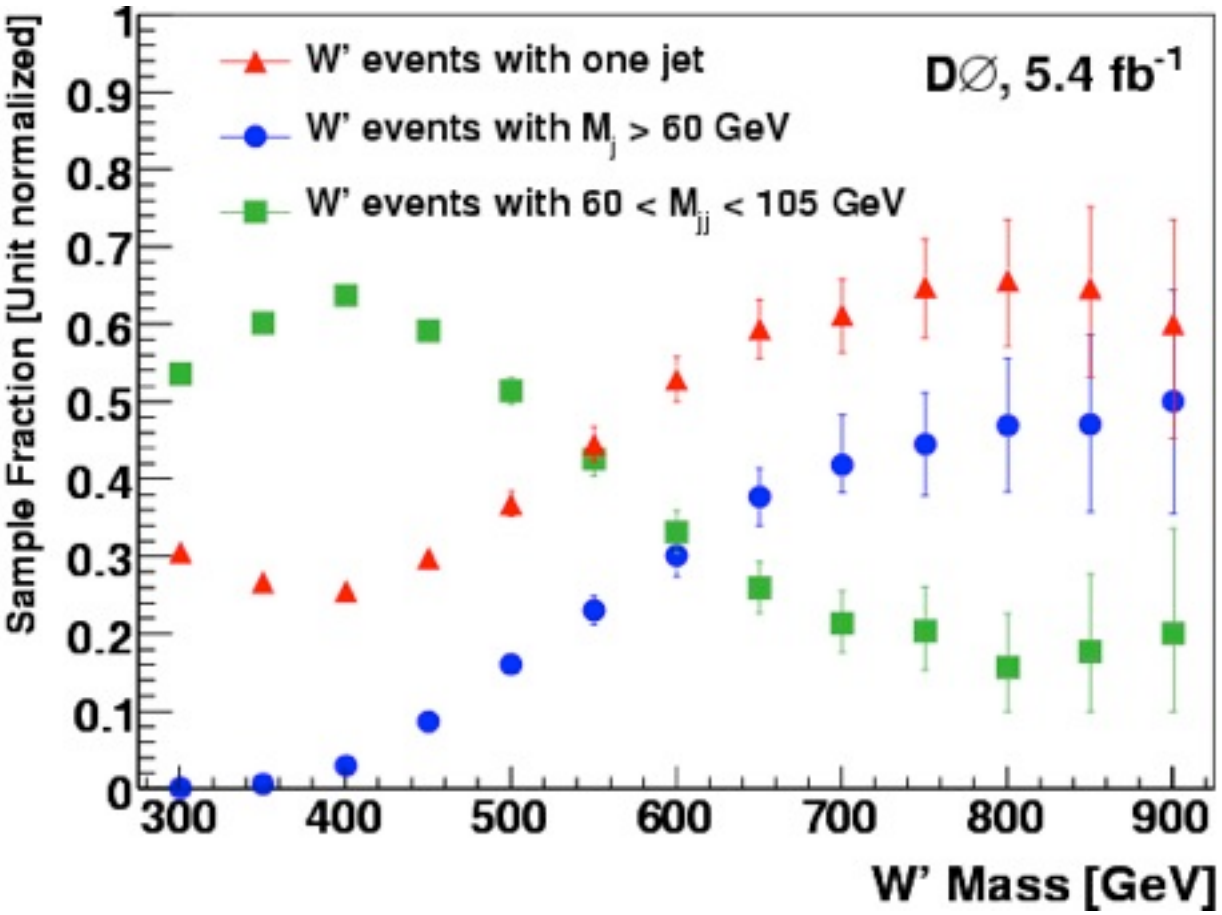


- Many improvements expected for LHC-era searches with much larger datasets and increased ttbar production.
  - Substructure using CA and k_T splitting scales,
  - Jet mass calibration similar to JES
  - Larger jet sizes combined with splitting scales.

Combined Search Results

- High mass resonance searches need hadronic final states to increase sensitivity.
  - Leptonic final states have low BR.
- Sensitive to WW/WZ resonance increased by 20% (same as 40% more $\int Ldt$).





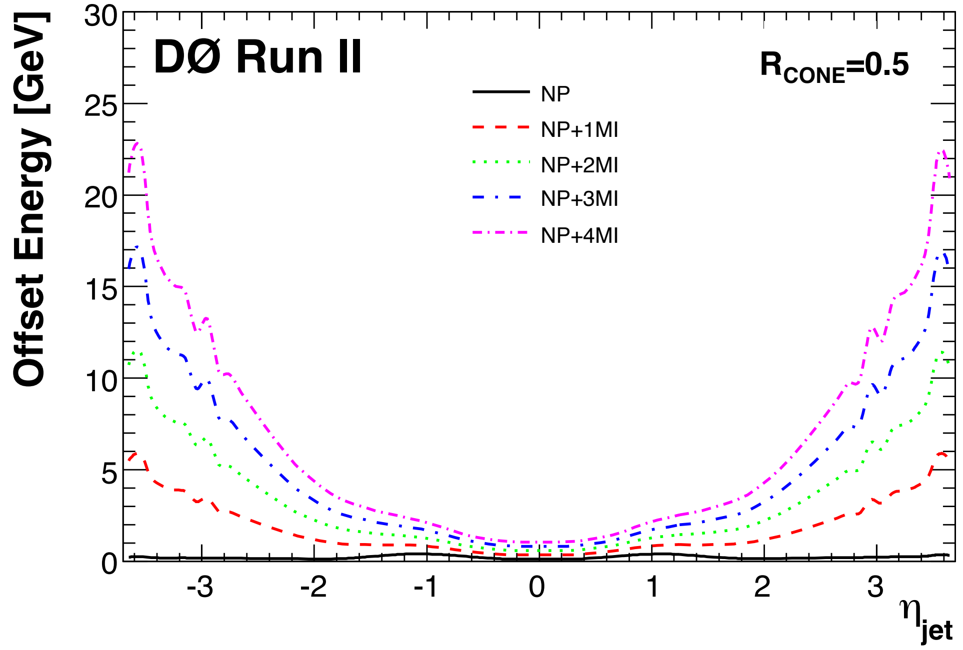
- Result recently accepted for publication in PRL.

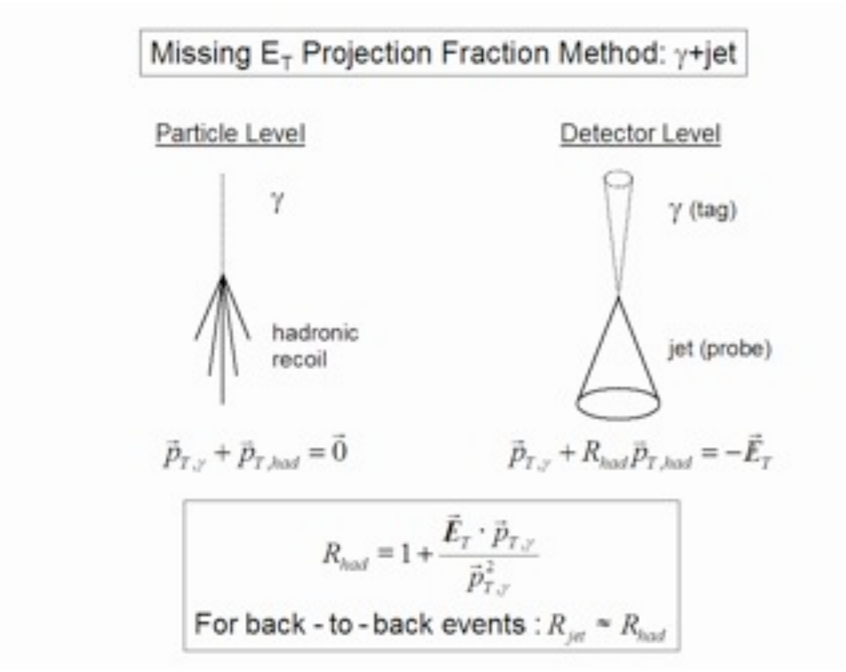
http://arxiv.org/abs/1011.6278

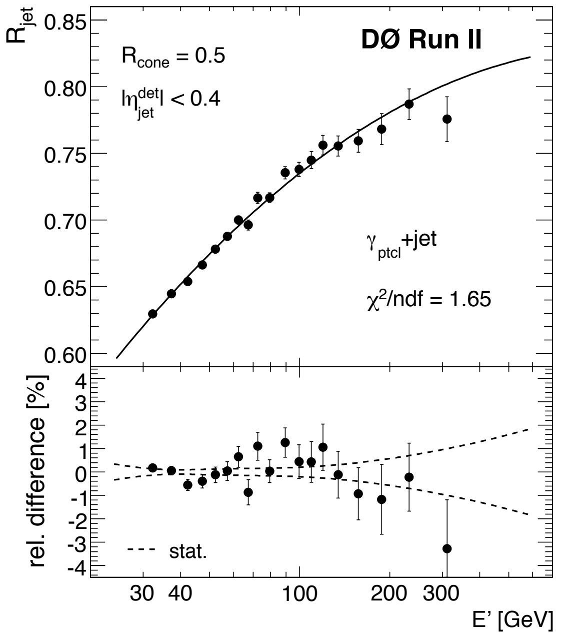
- Eager to test this and other jet reconstruction techniques with LHC data!

DØ Jet Energy Correction Inputs

- Offset Correction due to pileup (importance increases for forward jets)
  - Measured in minimum bias events (luminosity trigger) and zero bias events (Tevatron clock trigger).
- Response measured using γ+jet events.
  - Balance EM/γ scale (very well known) against hadron/jet scale (less well known).







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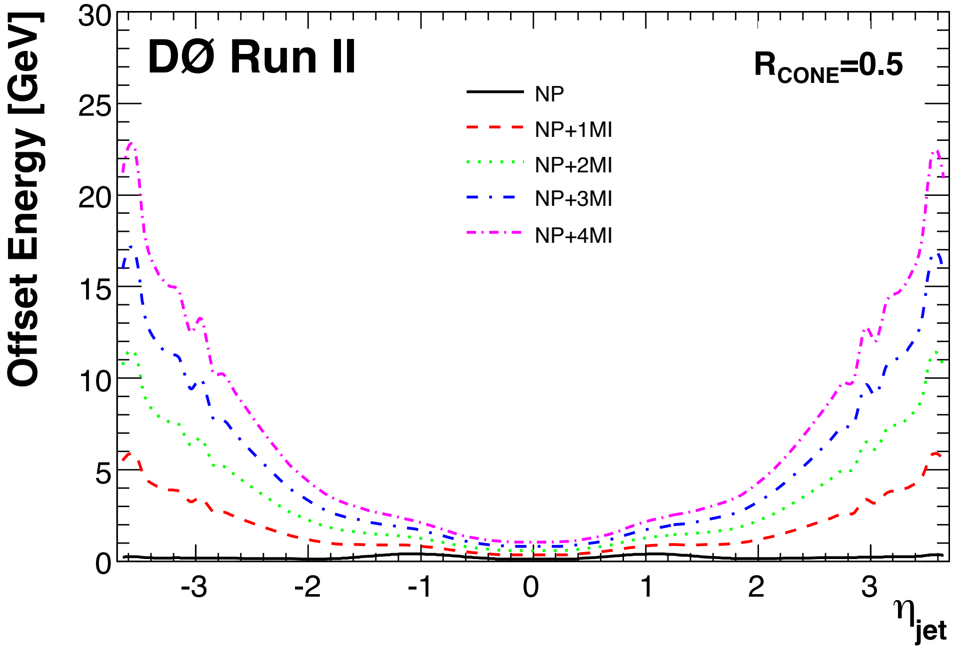

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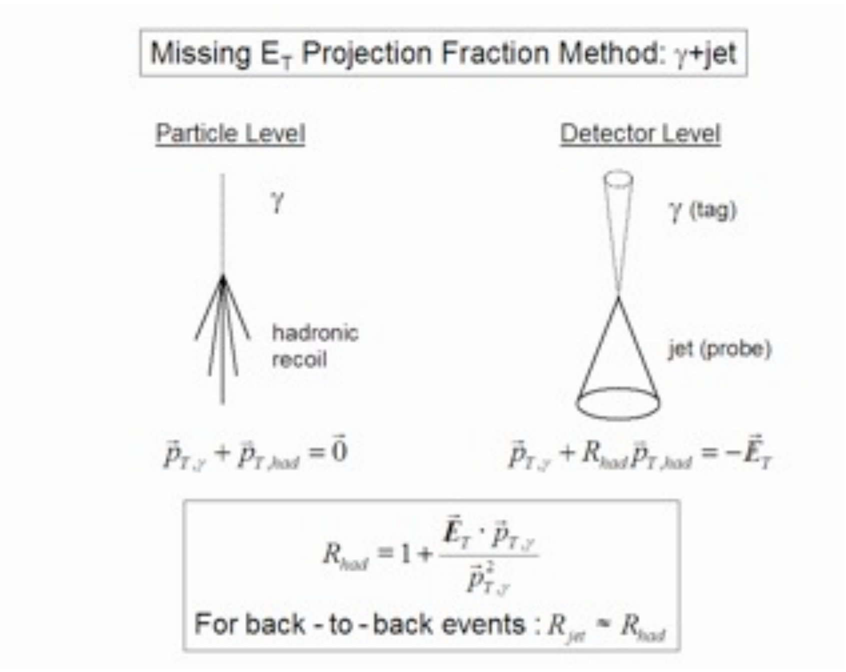
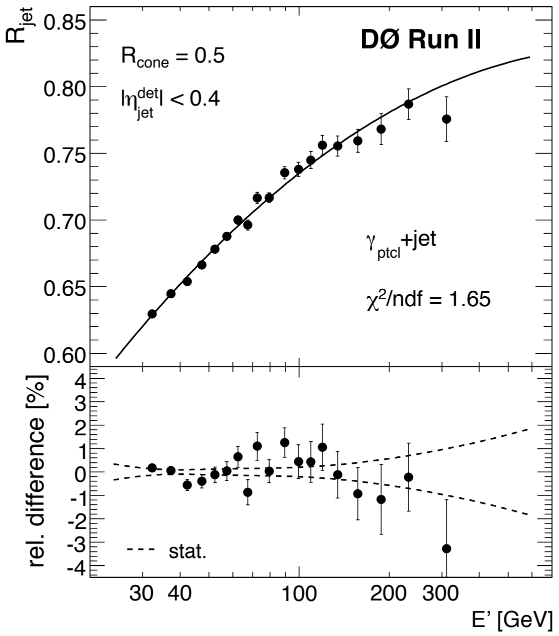
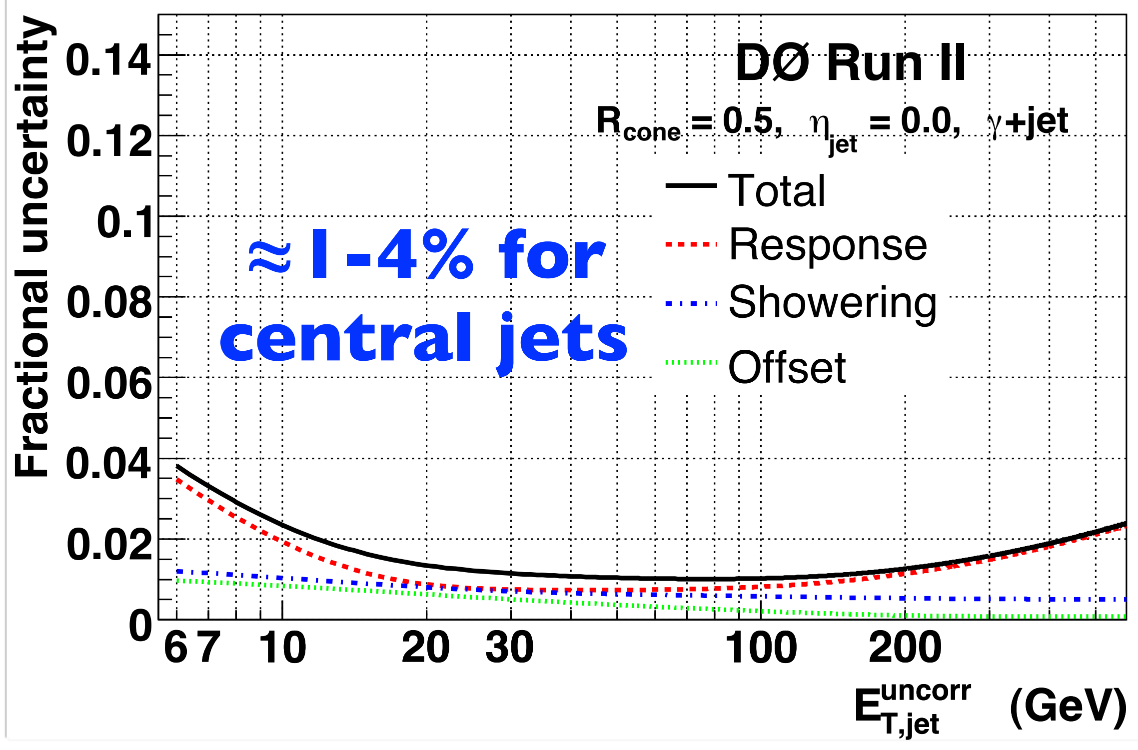




Combined Fractional Uncertainty



≈ 1-4% for central jets