Fermilab
UIC University of Illinois at Chicago

"W/Z+Jets as a Laboratory for pQCD & New Physics at Hadron Colliders"

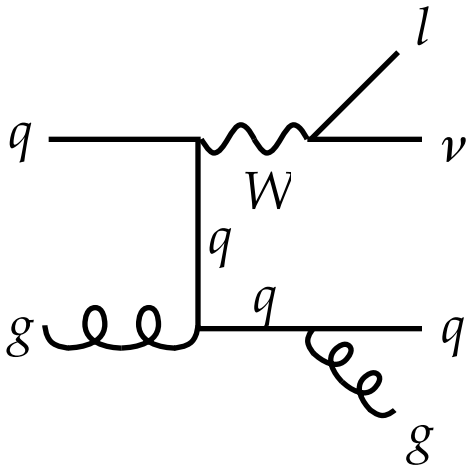
R. Cavanaugh
Fermi National Accelerator Laboratory
& University of Illinois at Chicago

IPMU, University of Tokyo, Japan
11 November, 2009

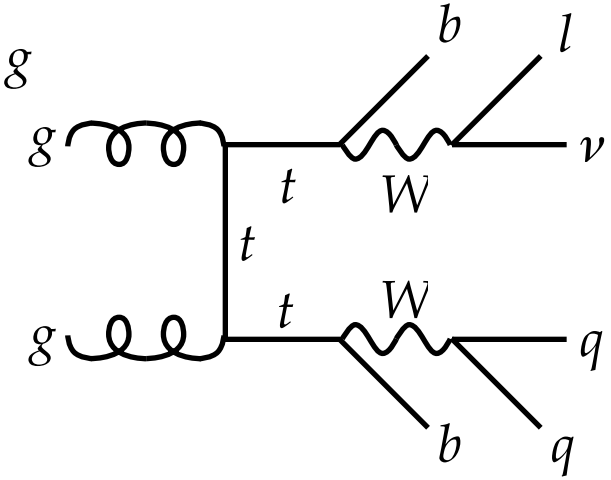
- **Motivation**
- **Tevatron Results**
- **LHC Expectations & Plans**

SM as a Lab for NP

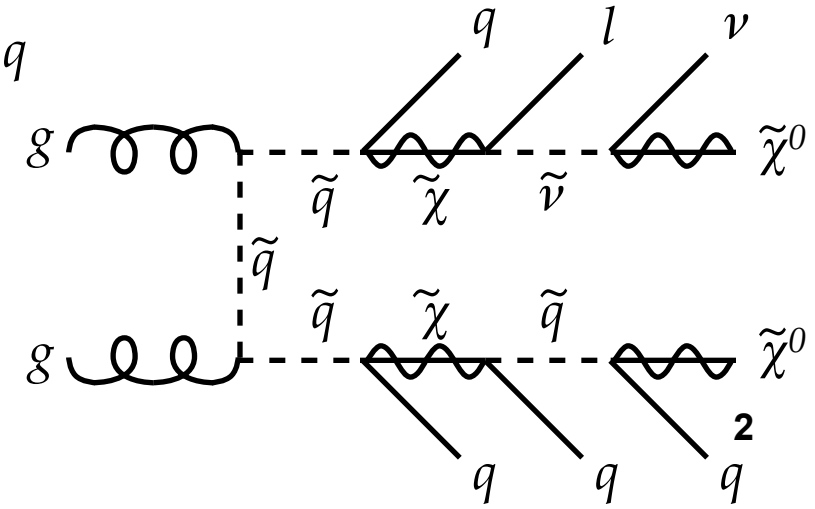
Fermilab
UIC University of Illinois at Chicago



Standard Model



New Physics



Primary Motivation

Fermilab
UIC University of Illinois at Chicago

- Searches for New Physics (NP) at LHC
  - SUSY signatures have large SM backgrounds
  - Several levels of SM pQCD processes must be crossed
- ATLAS showed sometime ago:
  - PYTHIA alone
    - optimistic est. of backgrounds
  - More realistic ME simulations
    - much less S/sqrt(B) discrimination!
- This led to earnest and well intentioned statements from CMS & ATLAS like:
  "We must
  - understand SM before discovery"
  - rely on accurate simulations"

  ...these are non-trivial statements!

σ_{tot}	100 mb
jets with $p_T > 100$	1 μb
W/Z	100 nb
$t^- t$	800 pb
SUSY ($M < 1$ TeV)	1-10 pb

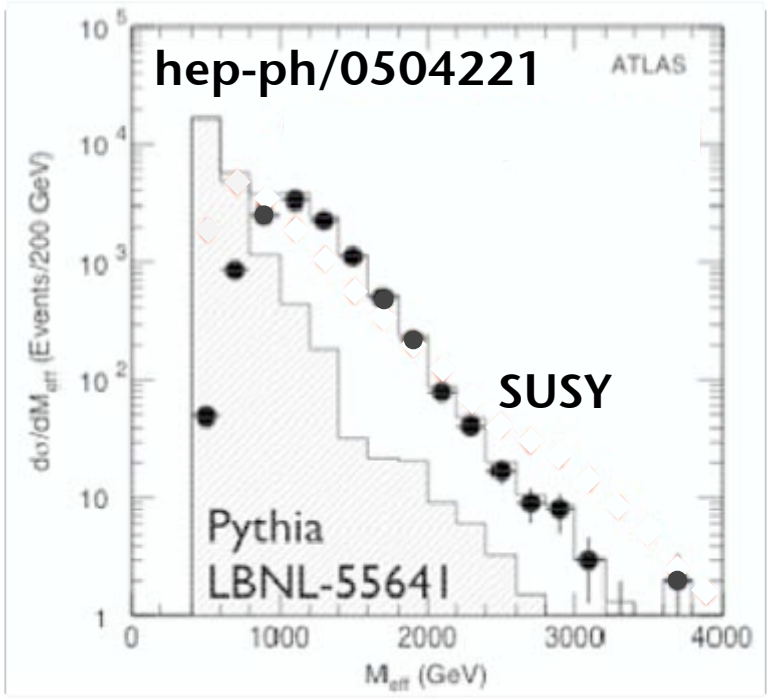
Primary Motivation

Fermilab
UIC University of Illinois at Chicago

- Searches for New Physics (NP) at LHC
  - SUSY signatures have large SM backgrounds
  - Several levels of SM pQCD processes must be crossed
- ATLAS showed sometime ago:
  - PYTHIA alone
    - optimistic est. of backgrounds
  - More realistic ME simulations
    - much less S/sqrt(B) discrimination!
- This led to earnest and well intentioned statements from CMS & ATLAS like: "We must
  - understand SM before discovery"
  - rely on accurate simulations"

...these are non-trivial statements!

σ_{tot}	100 mb
jets with $p_T > 100$	1 μb
W/Z	100 nb
t^-t	800 pb
SUSY ($M < 1$ TeV)	1-10 pb



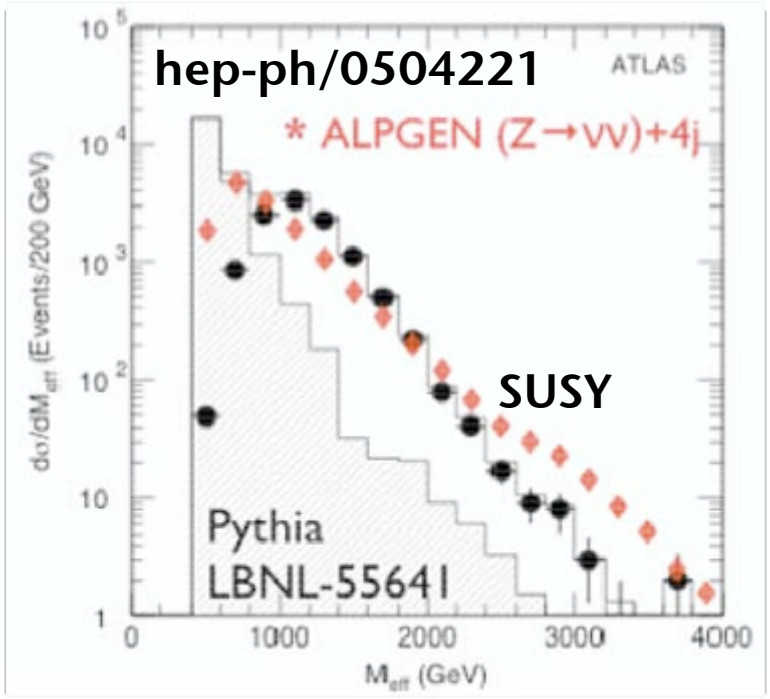
Primary Motivation

Fermilab
UIC University of Illinois at Chicago

- Searches for New Physics (NP) at LHC
  - SUSY signatures have large SM backgrounds
  - Several levels of SM pQCD processes must be crossed
- ATLAS showed sometime ago:
  - PYTHIA alone
    - optimistic est. of backgrounds
  - More realistic ME simulations
    - much less S/sqrt(B) discrimination!
- This led to earnest and well intentioned statements from CMS & ATLAS like: "We must
  - understand SM before discovery"
  - rely on accurate simulations"

...these are non-trivial statements!

σ_{tot}	100 mb
jets with $p_T > 100$	1 μb
W/Z	100 nb
t^-t	800 pb
SUSY ($M < 1$ TeV)	1-10 pb



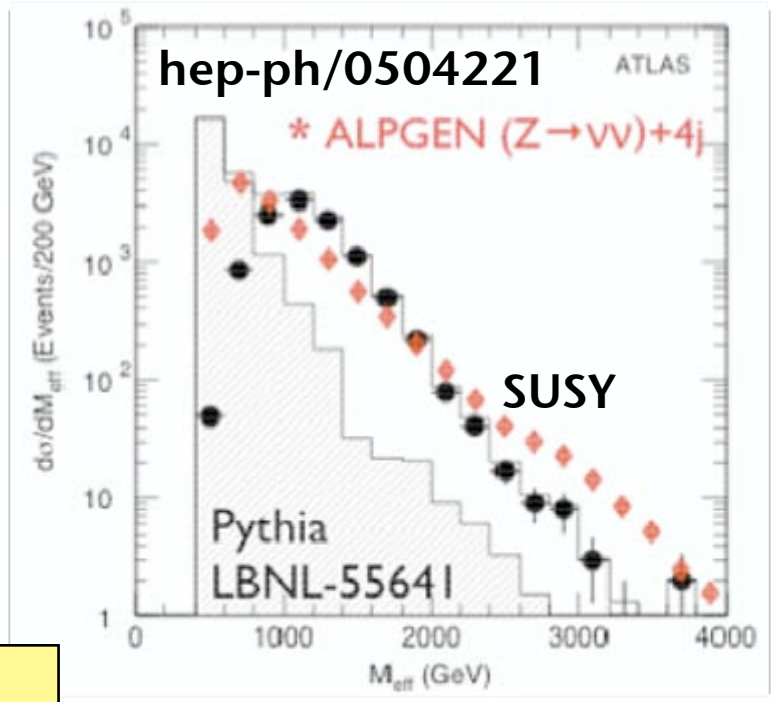
Primary Motivation

Fermilab
UIC University of Illinois at Chicago

- Searches for New Physics (NP) at LHC
  - SUSY signatures have large SM backgrounds
  - Several levels of SM pQCD processes must be crossed
- ATLAS showed sometime ago:
  - PYTHIA alone
    - optimistic est. of backgrounds
  - More realistic ME simulations
    - much less S/sqrt(B) discrimination!
- This led to earnest and well intentioned statements from CMS & ATLAS like: "We must
  - understand SM before discovery"
  - rely on accurate simulations"

...these are non-trivial statements!

σ_{tot}	100 mb
jets with $p_T > 100$	1 μb
W/Z	100 nb
t^-t	800 pb
SUSY ($M < 1$ TeV)	1-10 pb

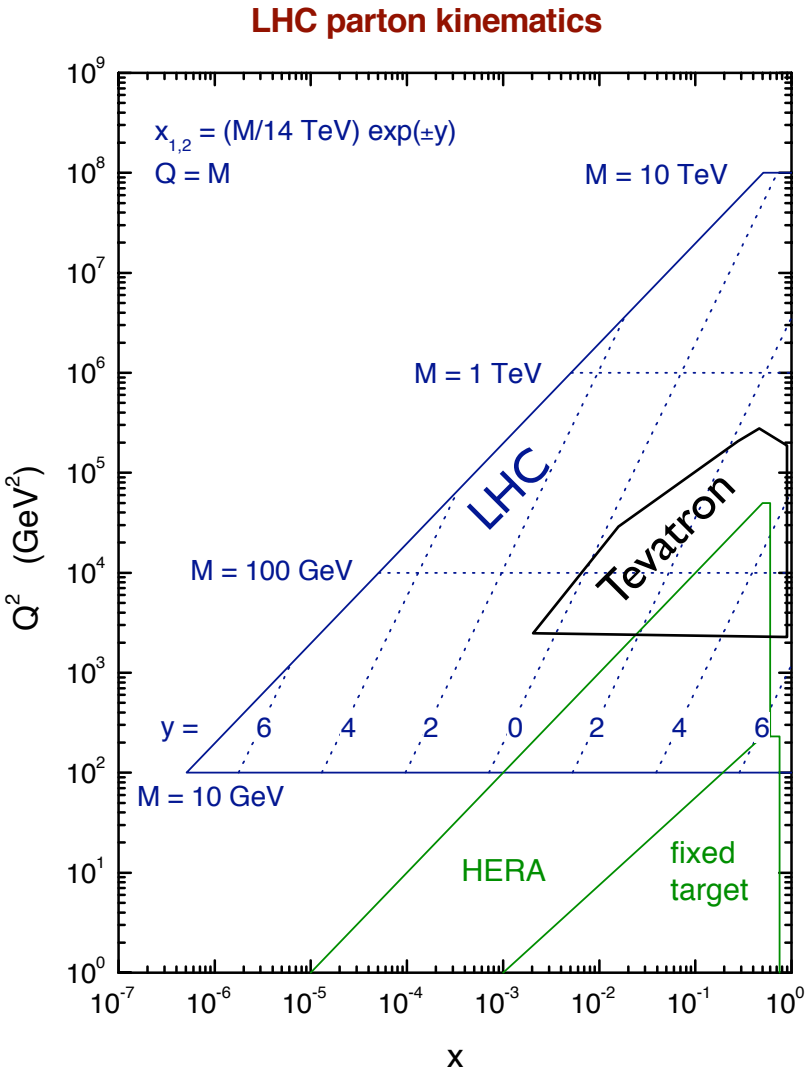


The Goal of this talk is to give a taste of what goes into precision V+Jets measurements

Tevatron paves way for LHC

Fermilab
UIC University of Illinois at Chicago

On the one hand…



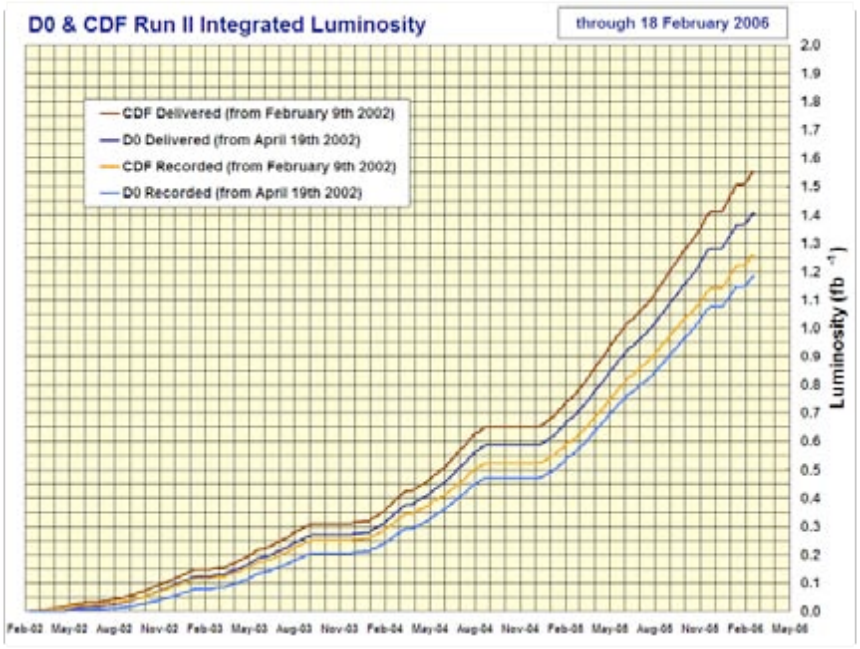
- Important for tuning MC models
  - kinematic overlap with LHC
- Monte Carlo Models
  - Pythia, HERWIG
  - Sherpa
  - ALPGEN
  - MADGRAPH
- Theoretical Calculations
  - MCFM
  - BlackHat

Tevatron excellent Lab for QCD

Fermilab
UIC University of Illinois at Chicago

On the other hand…

- Goal: measure W/Z+Jets cross sections (total and differential)
  - Large Tevatron datasets!
  - Well understood detectors!
  - Now able vet ME+PS models
  - Compare with LO/NLO predictions
- W/Z as precision probes of pQCD
  - leptonic decay modes:
    - colourless, low backgrounds
  - Complementary regime to
    - HERA, fixed target experiments
  - Parton Distributions
  - ISR/FSR - gluon radiation
  - pT spectra
- There's much more data waiting to be analyzed…
  - And there's more data coming!

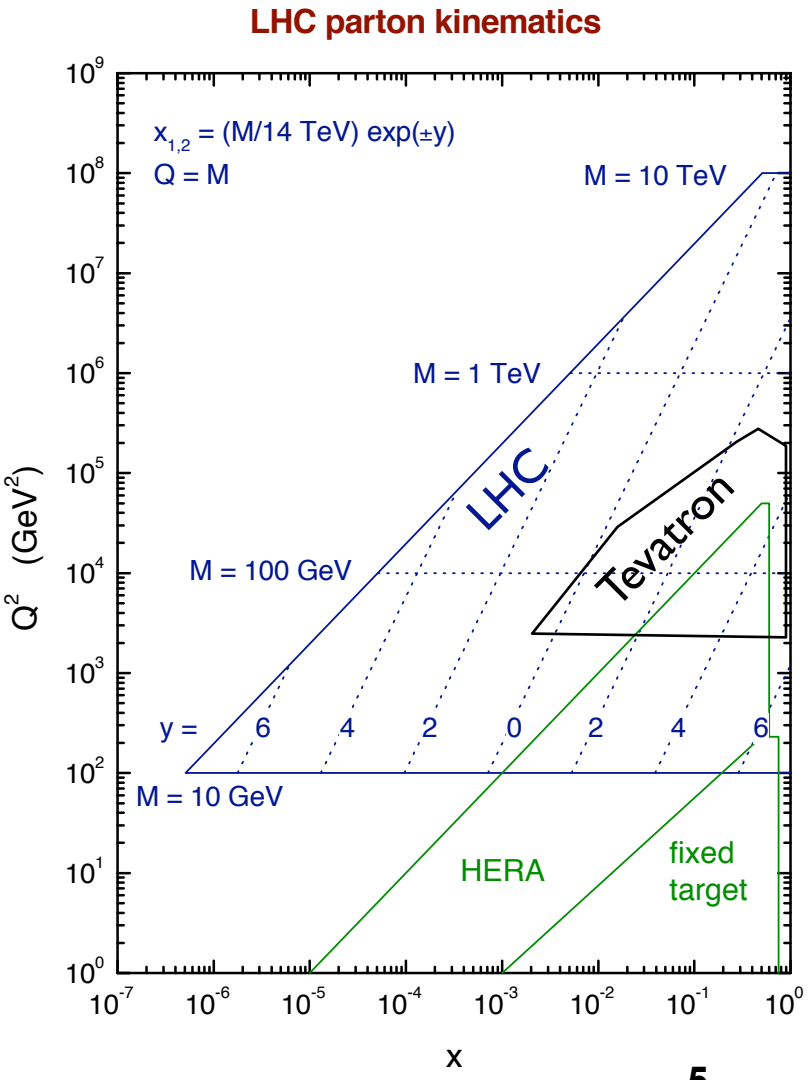


Tevatron excellent Lab for QCD

Fermilab
UIC University of Illinois at Chicago

On the other hand…

- **Goal: measure W/Z+Jets cross sections (total and differential)**
  - Large Tevatron datasets!
  - Well understood detectors!
  - Now able vet ME+PS models
  - Compare with LO/NLO predictions
- **W/Z as precision probes of pQCD**
  - leptonic decay modes:
    - colourless, low backgrounds
  - Complementary regime to
    - HERA, fixed target experiments
  - Parton Distributions
  - ISR/FSR - gluon radiation
  - pT spectra
- **There's much more data waiting to be analyzed…**
  - And there's more data coming!

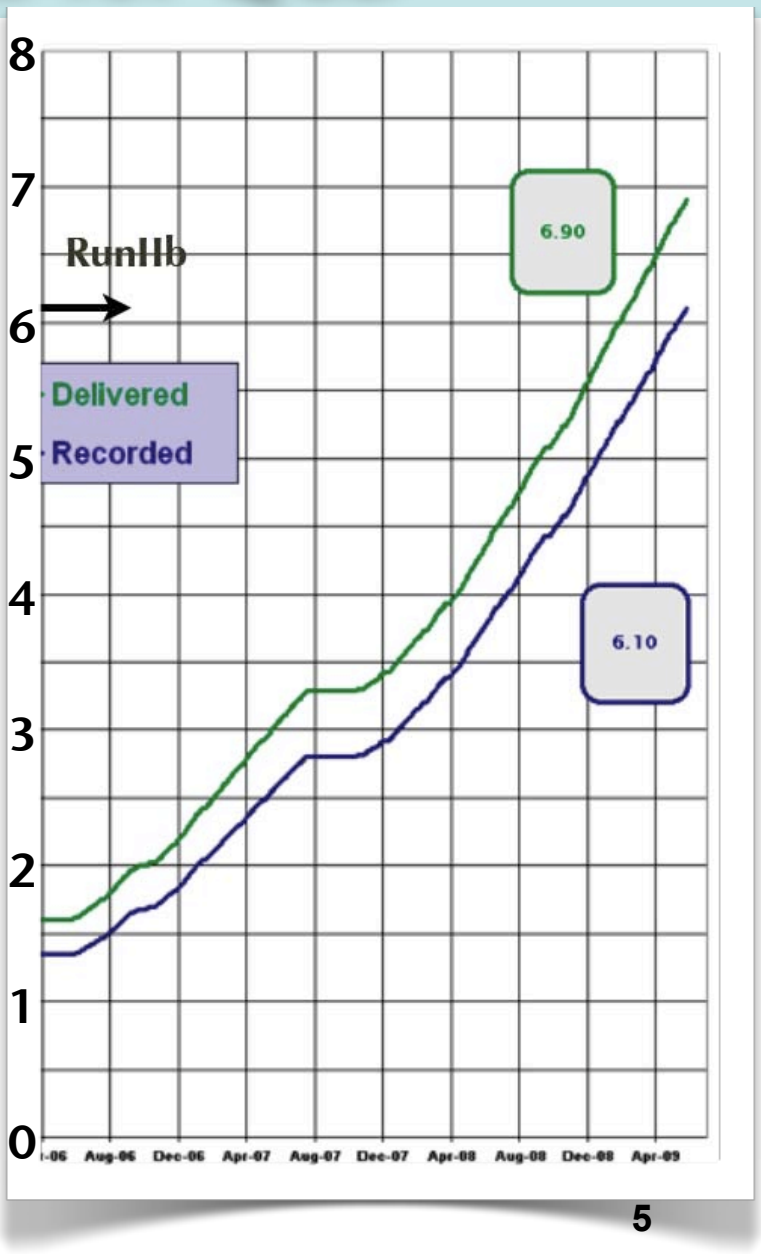


Tevatron excellent Lab for QCD

Fermilab
UIC University of Illinois at Chicago

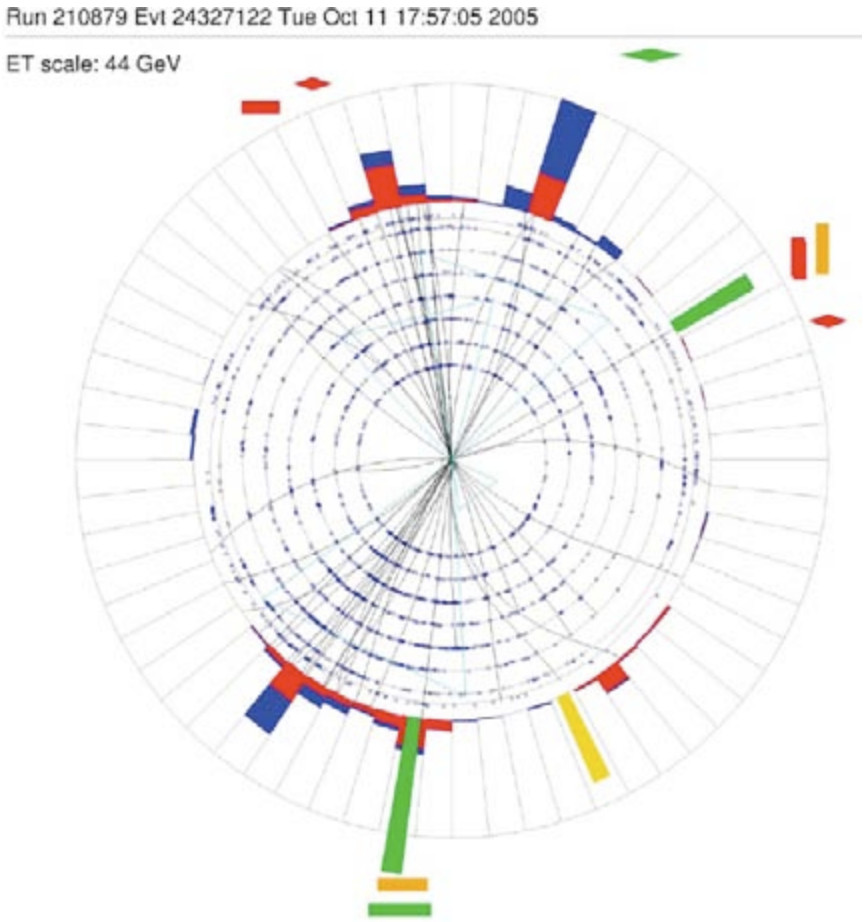
On the other hand…

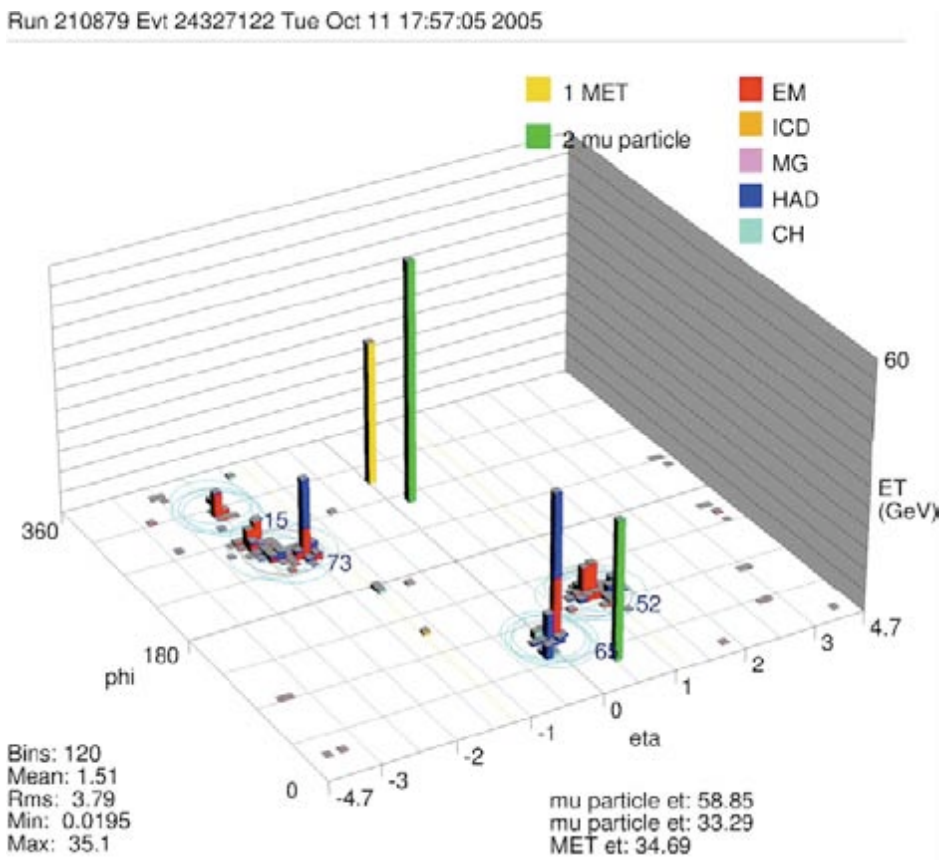
- Goal: measure W/Z+Jets cross sections (total and differential)
  - Large Tevatron datasets!
  - Well understood detectors!
  - Now able vet ME+PS models
  - Compare with LO/NLO predictions
- W/Z as precision probes of pQCD
  - leptonic decay modes:
    - colourless, low backgrounds
  - Complementary regime to
    - HERA, fixed target experiments
  - Parton Distributions
  - ISR/FSR - gluon radiation
  - pT spectra
- There's much more data waiting to be analyzed…
  - And there's more data coming!



Z+Jets Event Display at CDF

Fermilab
UIC University of Illinois at Chicago



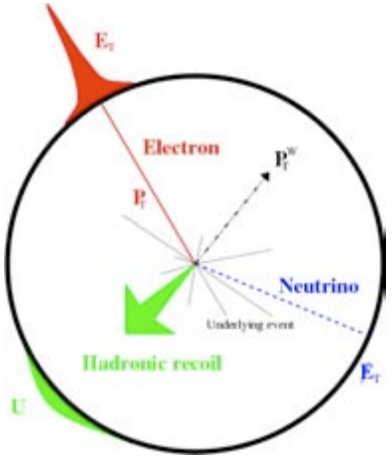


Leptons are THE Key Signatures

Fermilab
UIC University of Illinois at Chicago

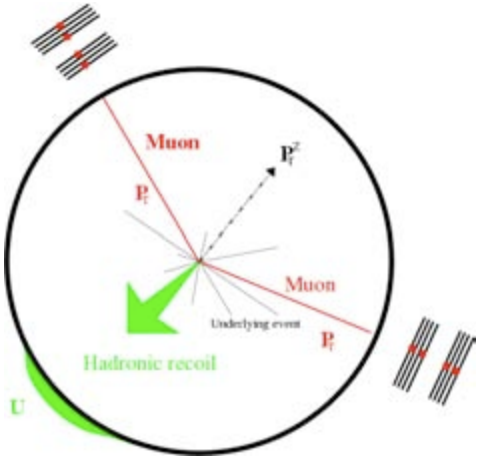
The Standard Model makes leptons through W's and Z's !

- Electrons
  - Identification
    - Calorimeter tower EM fraction > 0.9
    - Shower shape consistent with electron
    - EM deposit matched within 5 GeV of track momentum
    - likelihood
  - QCD background rejection
    - pT > 25 GeV
    - isolation within a cone



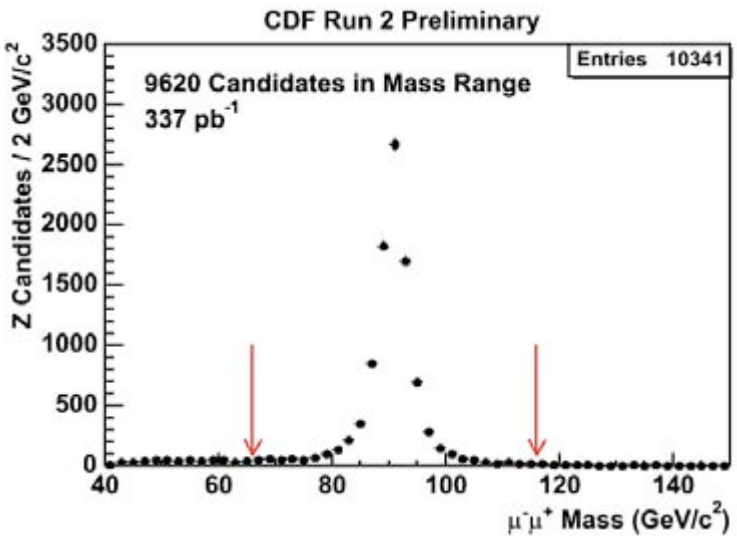
Example from D0 (CDF Similar)

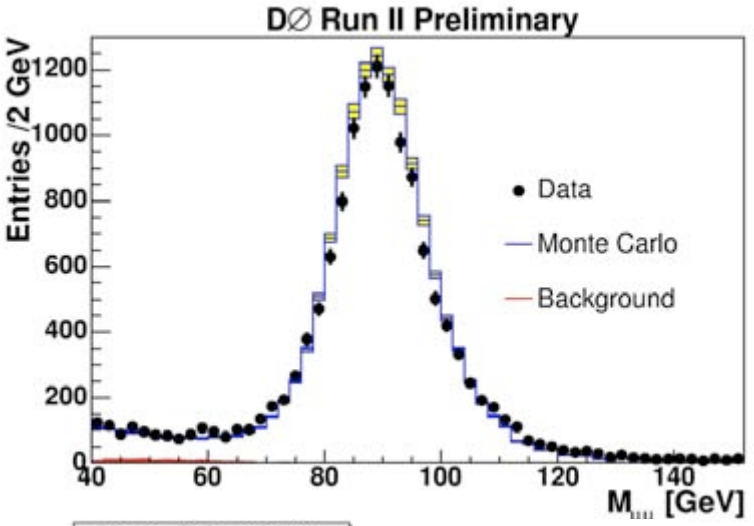
- Muons
  - Identification
    - hits in all layers of muon system
    - scintillator hits
    - track matching between central tracker and muon system
  - QCD background rejection
    - pT > 15 GeV
    - isolation

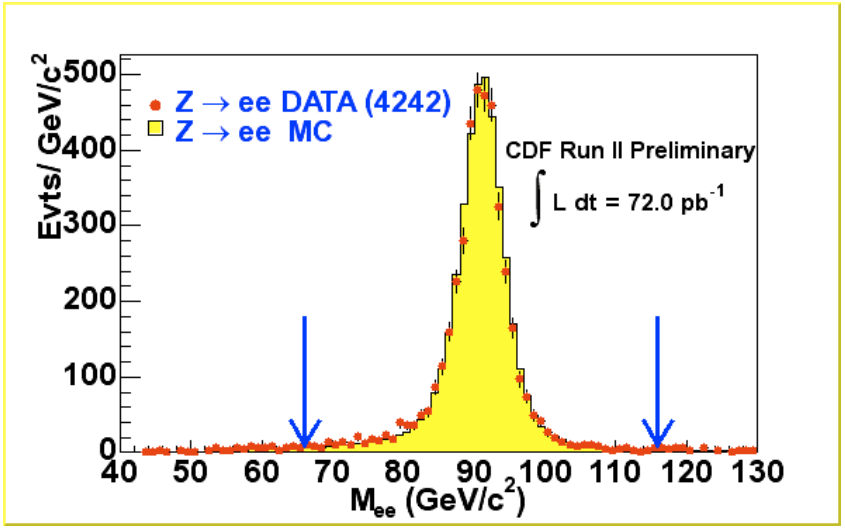


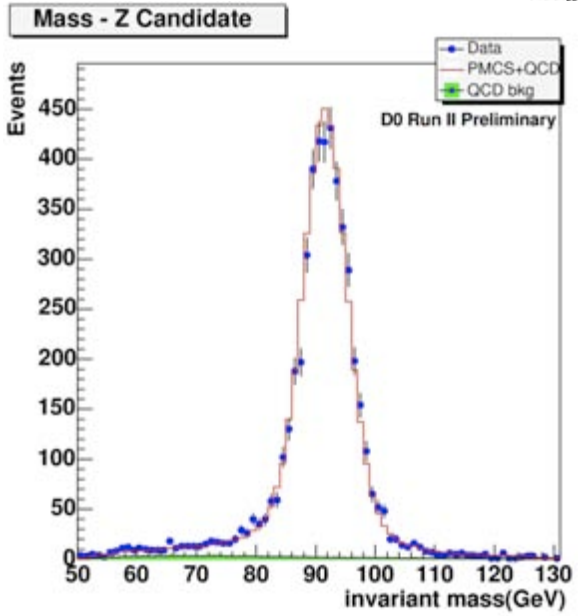
Z reconstruction

- Drell-Yan very clean! Almost background free!



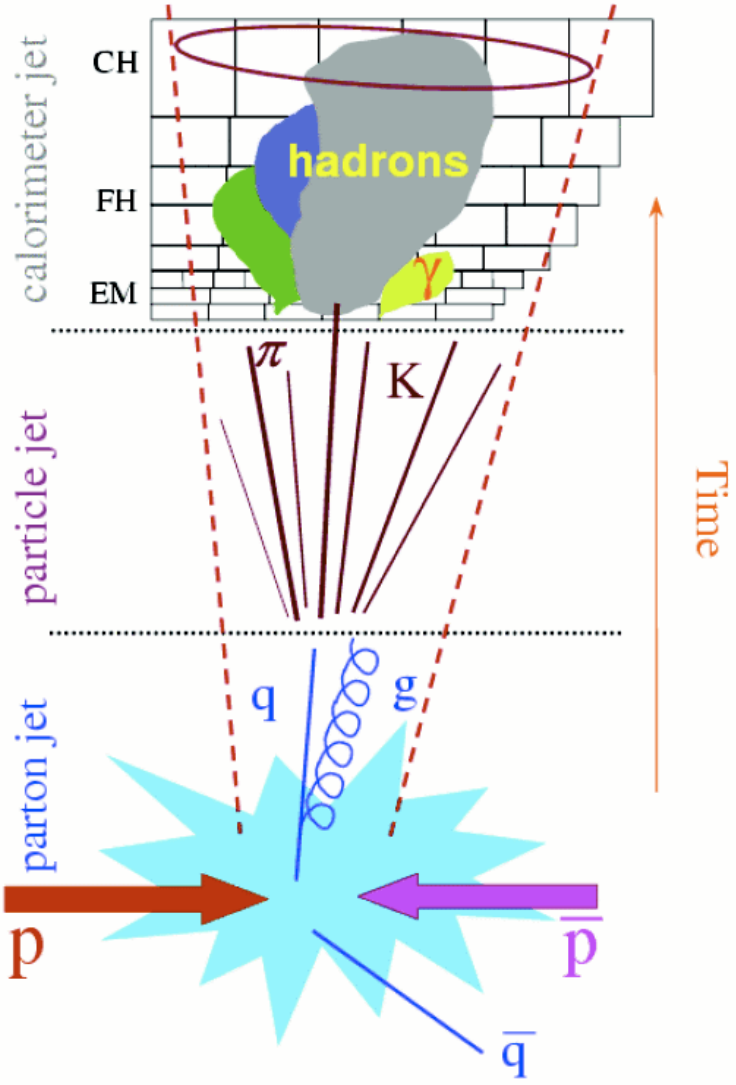






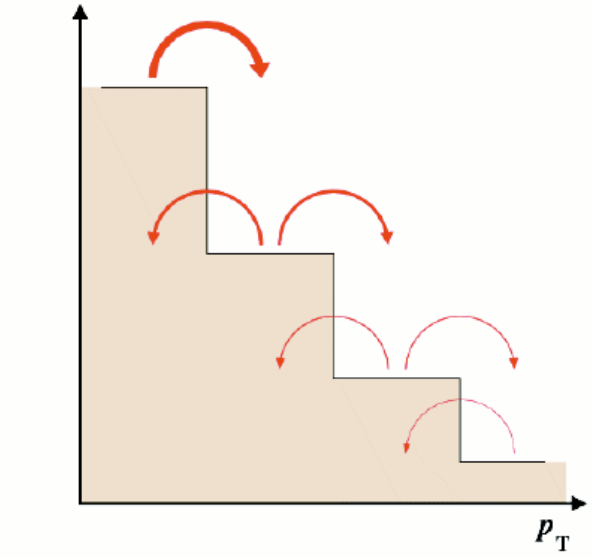
Jets at Tevatron

- D0
  - Iterative midpoint cone R = 0.5
- CDF
  - JETCLU with a cone R = 0.4
- Note:
  - ATLAS & CMS make different choices
- Jet Energy Corrections Applied
  - from photon + 1-jet events
    - forced pT balance
    - corrects to parton-level
  - from simulation
    - corrects to hadron particle-level
- Typical Jet quality requirements
  - pT > 15 GeV, |eta| < 2.0



Correcting for detector effects

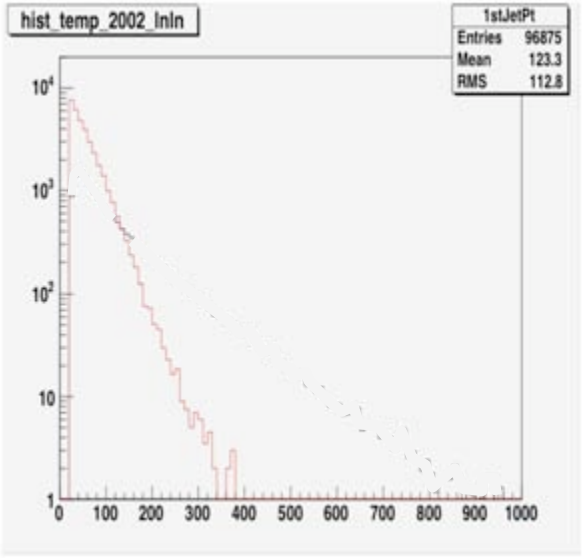
- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j



- Invert Probability Matrix and apply to measured pT distribution

Correcting for detector effects

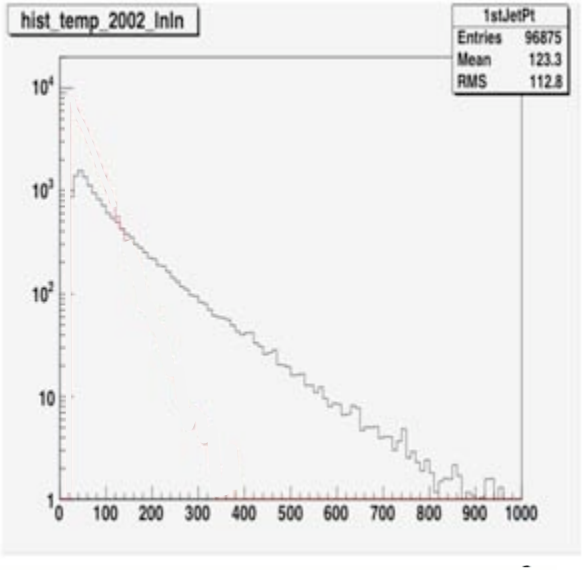
- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j



- Invert Probability Matrix and apply to measured pT distribution

Correcting for detector effects

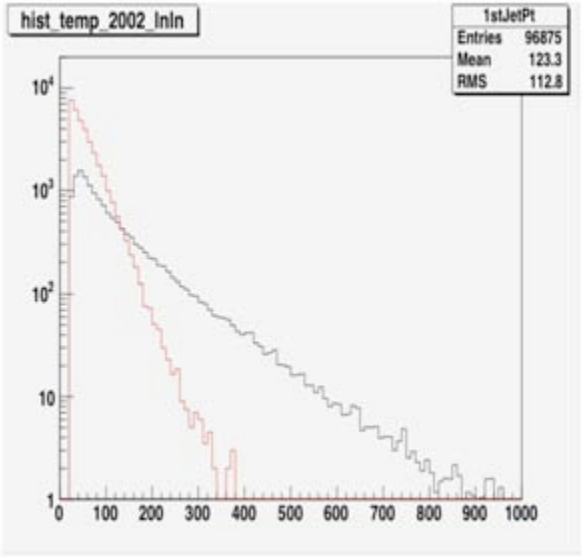
- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j



- Invert Probability Matrix and apply to measured pT distribution

Correcting for detector effects

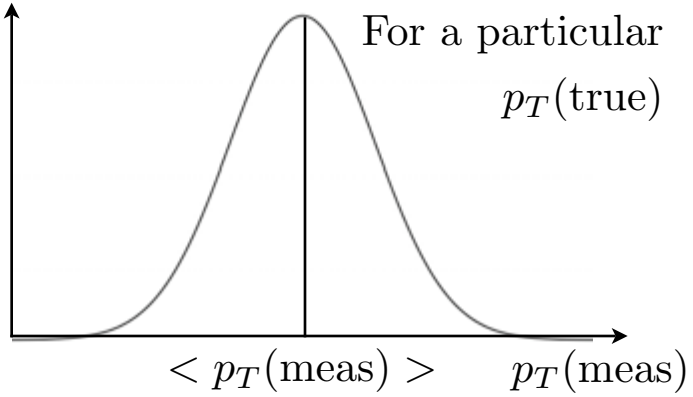
- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j

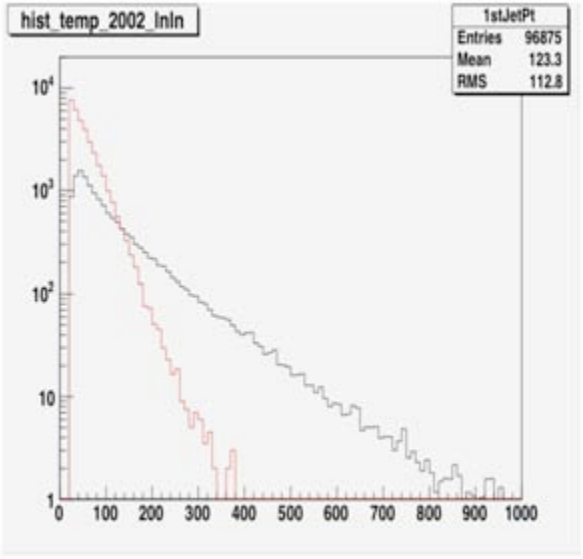


- Invert Probability Matrix and apply to measured pT distribution

Correcting for detector effects

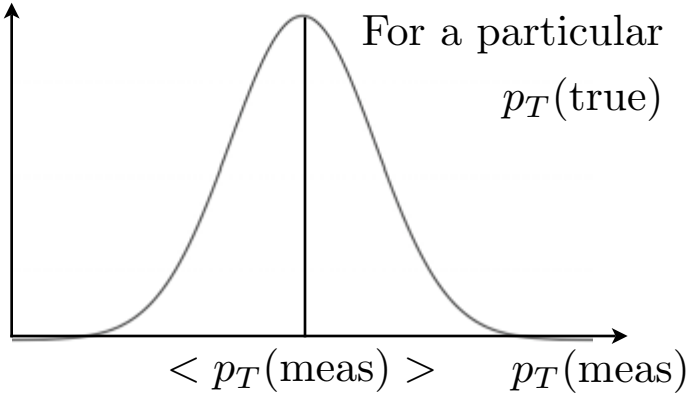
- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j

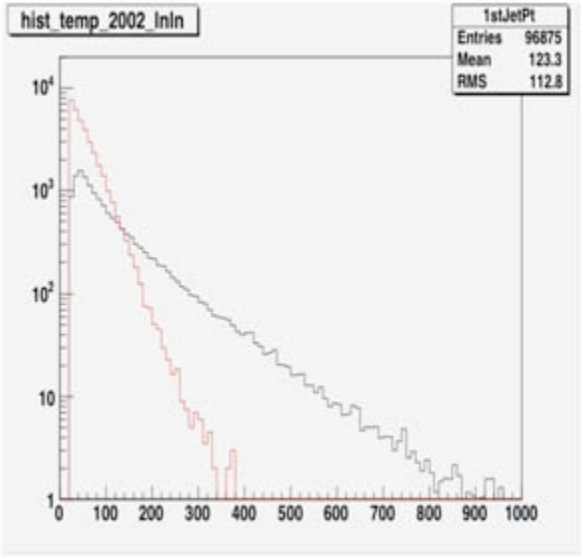


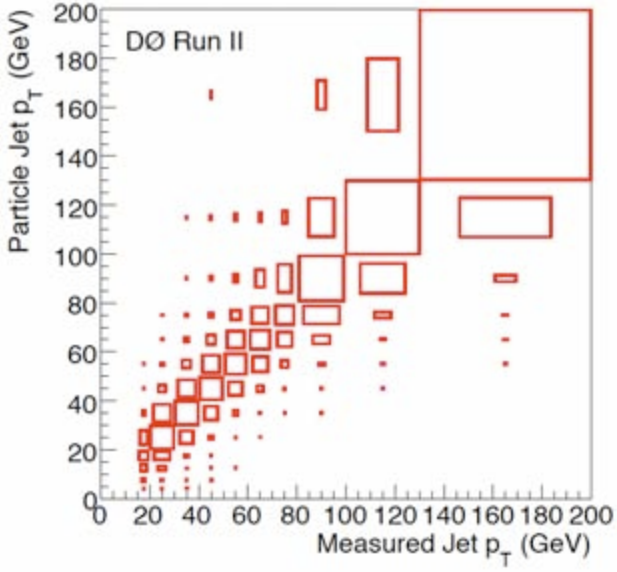


Correcting for detector effects

- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j

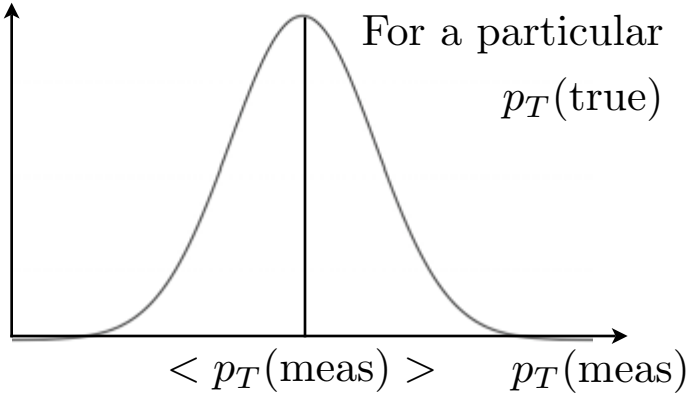


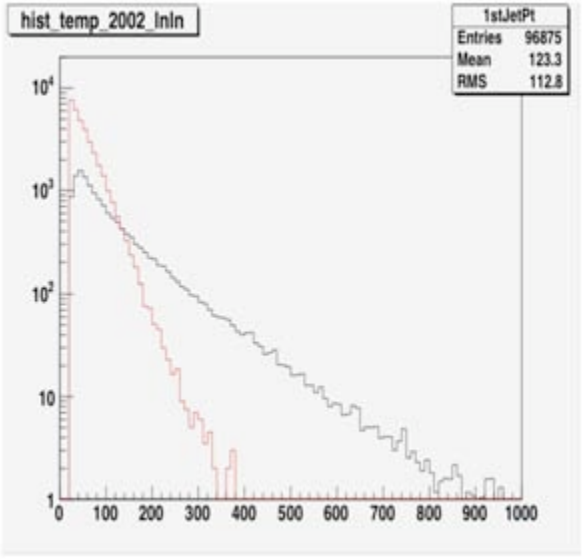


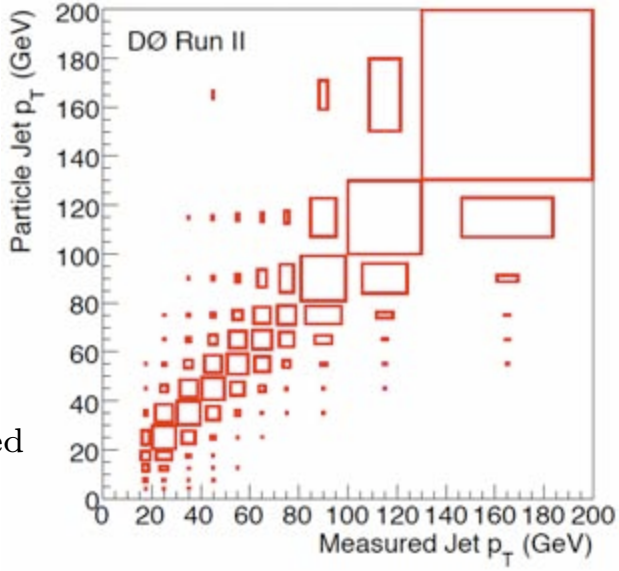


Correcting for detector effects

- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j





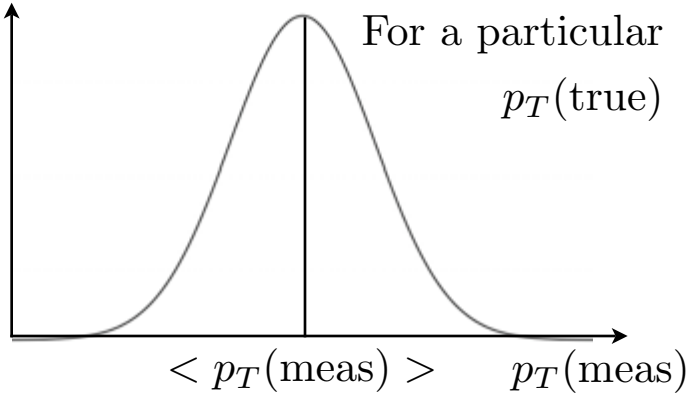


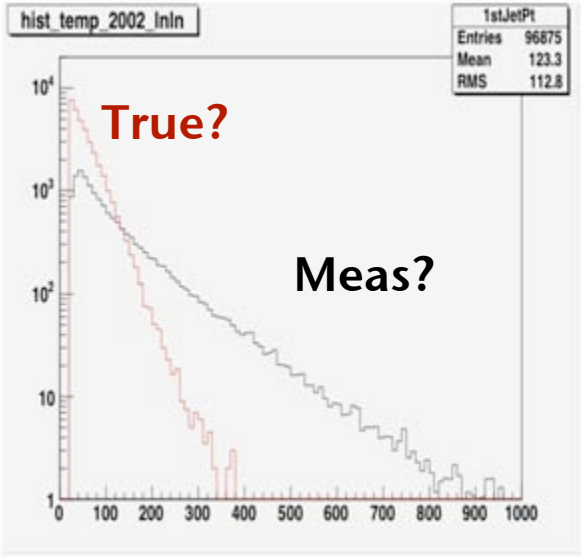
- Invert Probability Matrix and apply to measured pT distribution

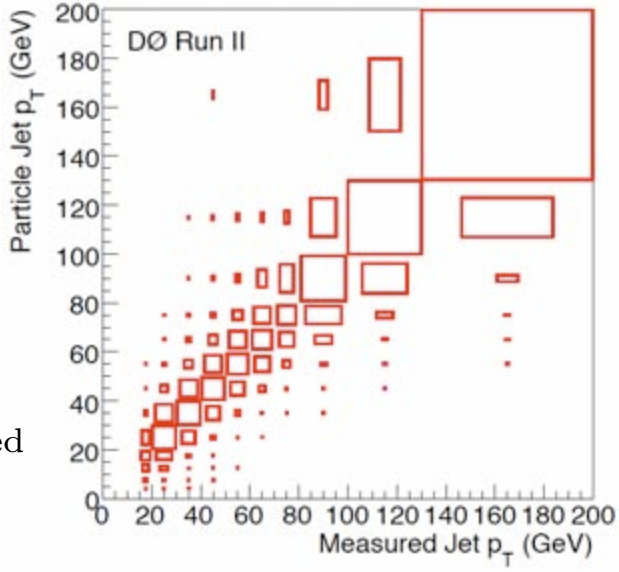
$$\left(\frac{d\sigma}{dp_T(\text{meas})}\right)_{\text{corrected}} = \mathbf{M}^{-1}\left(\frac{d\sigma}{dp_T(\text{meas})}\right)_{\text{uncorrected}}$$

Correcting for detector effects

- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j





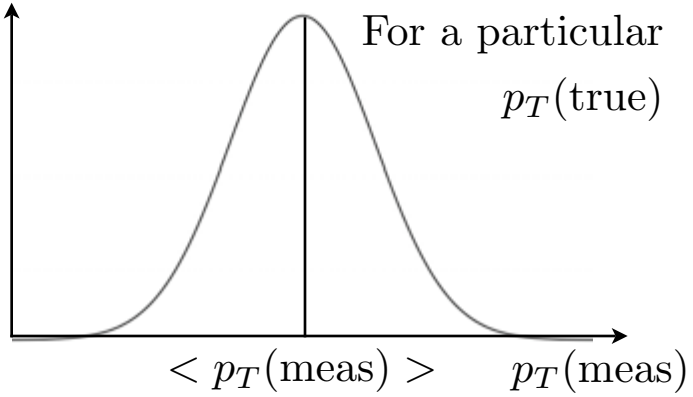


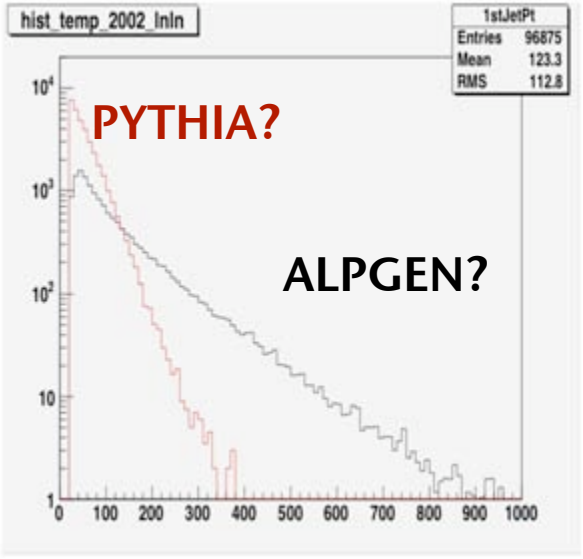
- Invert Probability Matrix and apply to measured pT distribution

$$\left(\frac{d\sigma}{dp_T(\text{meas})}\right)_{\text{corrected}} = \mathbf{M}^{-1}\left(\frac{d\sigma}{dp_T(\text{meas})}\right)_{\text{uncorrected}}$$

Correcting for detector effects

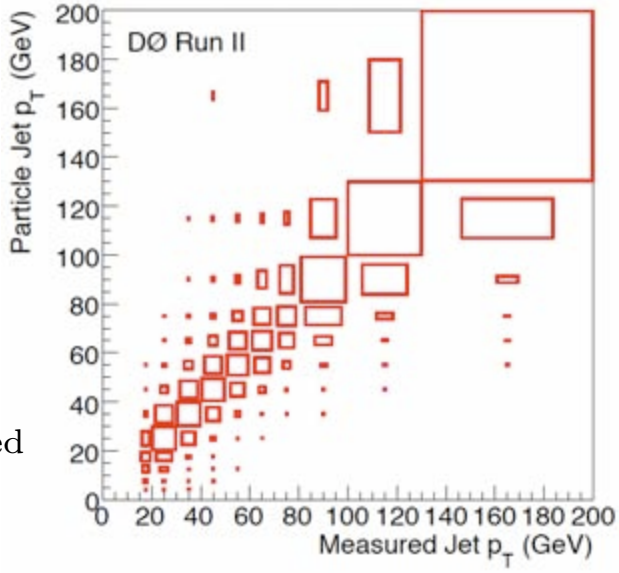
- Finite detector resolution on a steeply falling spectrum leads to longer tails
  - Must correct, to compare with Theory
- Form Probability Matrix, M_{ij}, that a jet
  - with true momentum in bin i,
  - is measured with momentum in bin j





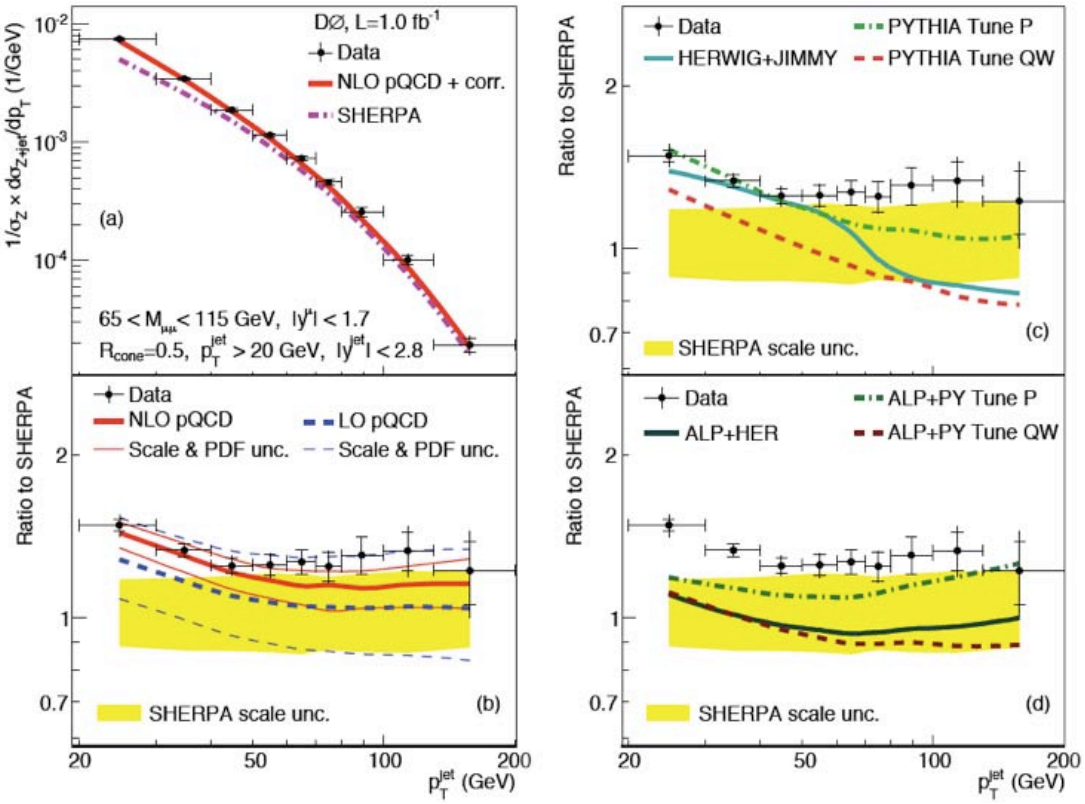
- Invert Probability Matrix and apply to measured pT distribution

$$\left(\frac{d\sigma}{dp_T(\text{meas})}\right)_{\text{corrected}} = \mathbf{M}^{-1}\left(\frac{d\sigma}{dp_T(\text{meas})}\right)_{\text{uncorrected}}$$



Z(μμ)+1 jet

- All cross sections normalized to inclusive (≥ 0 Jets) Z production
  - reduces systematic errors
- Theory predictions updated since PLB 669, 278 (2008), 0808.1296v2
  - Ratios relative to Sherpa v1.1.3
  - MCFM v5.4
    - PDF: MSTW2008
    - $\mu_r^2 = \mu_f^2 = p_T(Z)^2 + M(Z)^2$
  - Pythia v6.420
    - Tune P
    - Tune QW
  - HERWIG v6.510+JIMMY v4.31
  - ALPGEN v2.13+Pythia v6.420
  - ALPGEN v2.13+HERWIG v6.510
- Summary of results
  - NLO prediction with $p_T(Z) < 30$ GeV sensitive to UE
  - All LO predictions underestimate data normalization
  - Pythia can be tuned to reproduce data



Particle level phase space:

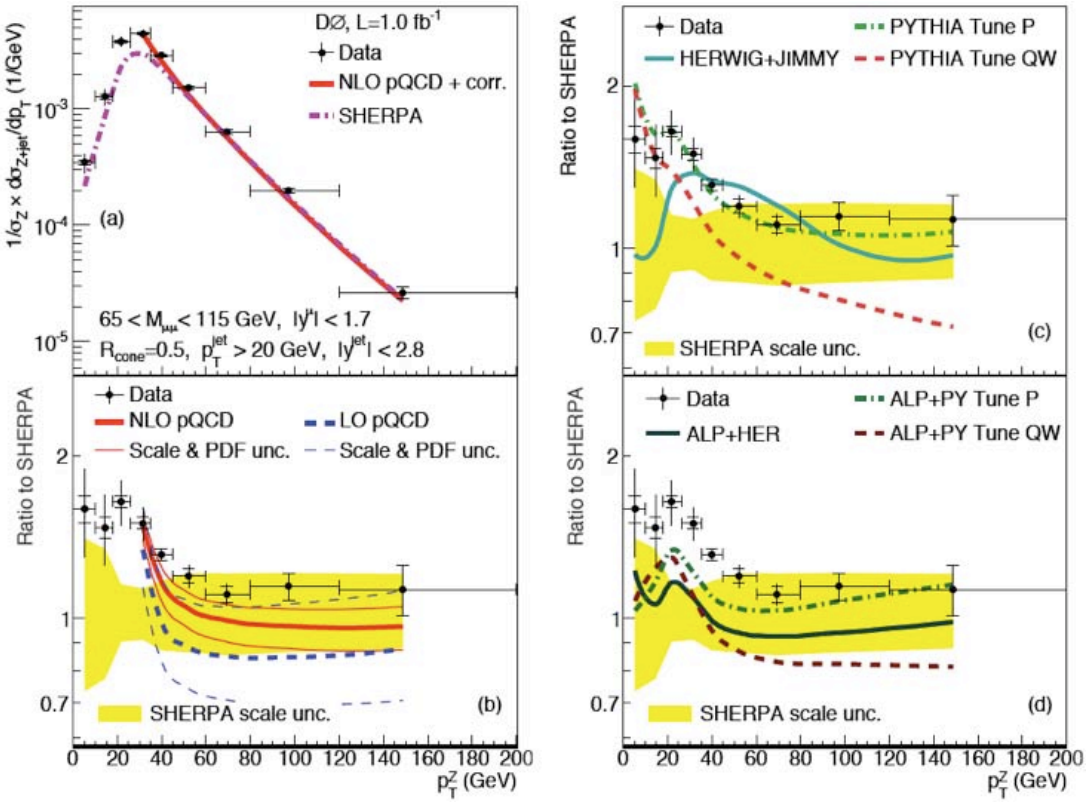
65 GeV< M(μμ) < 115 GeV,
D0 midpoint
R_{cone}=0.5,
p_T(jet) > 20 GeV
|y(jet)| < 2.8, |y(μ)| < 1.7

*Information courtesy Sabine Lammers

Z(μμ)+1 jet

Fermilab
UIC University of Illinois at Chicago

- All cross sections normalized to inclusive (≥ 0 Jets) Z production
  - reduces systematic errors
- Theory predictions updated since PLB 669, 278 (2008), 0808.1296v2
  - Ratios relative to Sherpa v1.1.3
  - MCFM v5.4
    - PDF: MSTW2008
    - $\mu_r^2 = \mu_f^2 = p_T(Z)^2 + M(Z)^2$
  - Pythia v6.420
    - Tune P
    - Tune QW
  - HERWIG v6.510+JIMMY v4.31
  - ALPGEN v2.13+Pythia v6.420
  - ALPGEN v2.13+HERWIG v6.510
- Summary of results
  - NLO prediction with $p_T(Z) < 30$ GeV sensitive to UE
  - All LO predictions underestimate data normalization
  - Pythia can be tuned to reproduce data



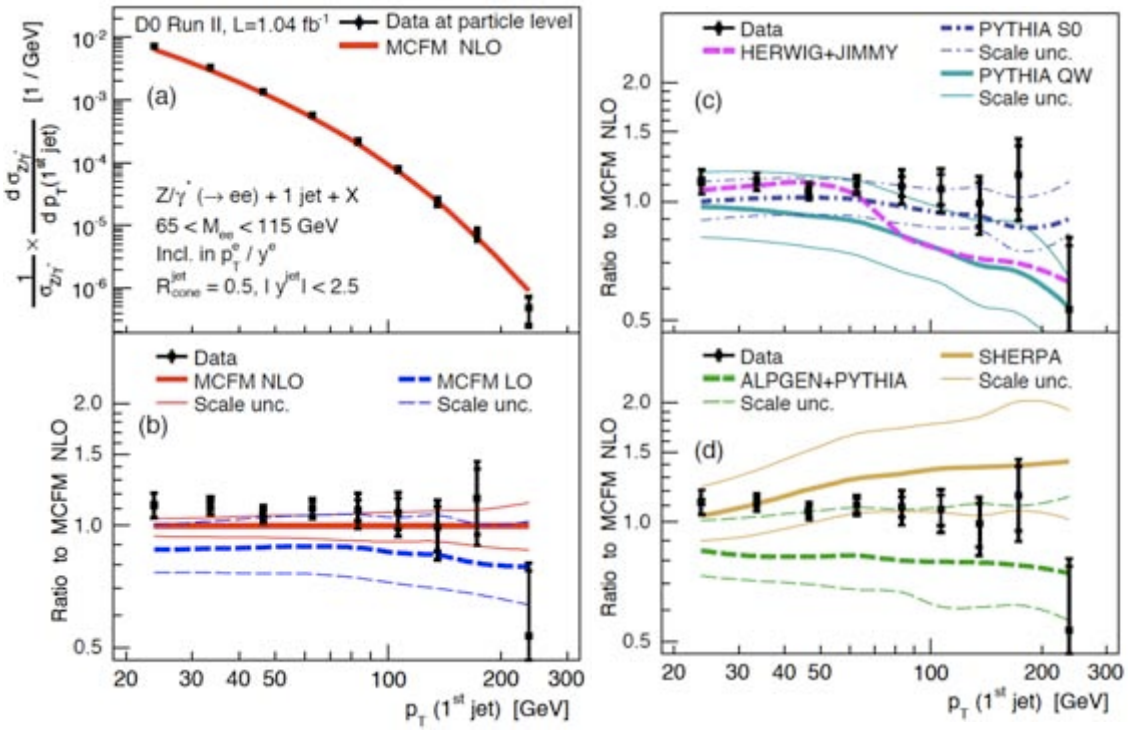
Particle level phase space:

65 GeV< M(μμ) < 115 GeV,
D0 midpoint
R_{cone}=0.5,
p_T(jet) > 20 GeV
|y(jet)| < 2.8, |y(μ)| < 1.7

*Information courtesy Sabine Lammers

Z(ee)+1 jet

- All cross sections normalized to inclusive (≥ 0 Jets) Z production
  - reduces systematic errors
- PLB 678, 45 (2009), 0903.1748v1
  - Ratios relative to MCFM v5.3
    - PDF: CTEQ6.6M
    - $\mu_r^2 = \mu_f^2 = p_T(Z)^2 + M(Z)^2$
  - Pythia v6.416
    - Tune P
    - Tune QW
  - HERWIG v6.510+JIMMY v4.31
  - ALPGEN v2.13+Pythia v6.325
  - Sherpa v1.1.1



- Summary of results
  - NLO predictions agree well with data
  - Large differences between models
  - Small experimental errors

Particle level phase space:

65 GeV< M(ee) < 115 GeV,

D0 midpoint

R_{cone}=0.5,

p_T(jet,e) > 20 GeV

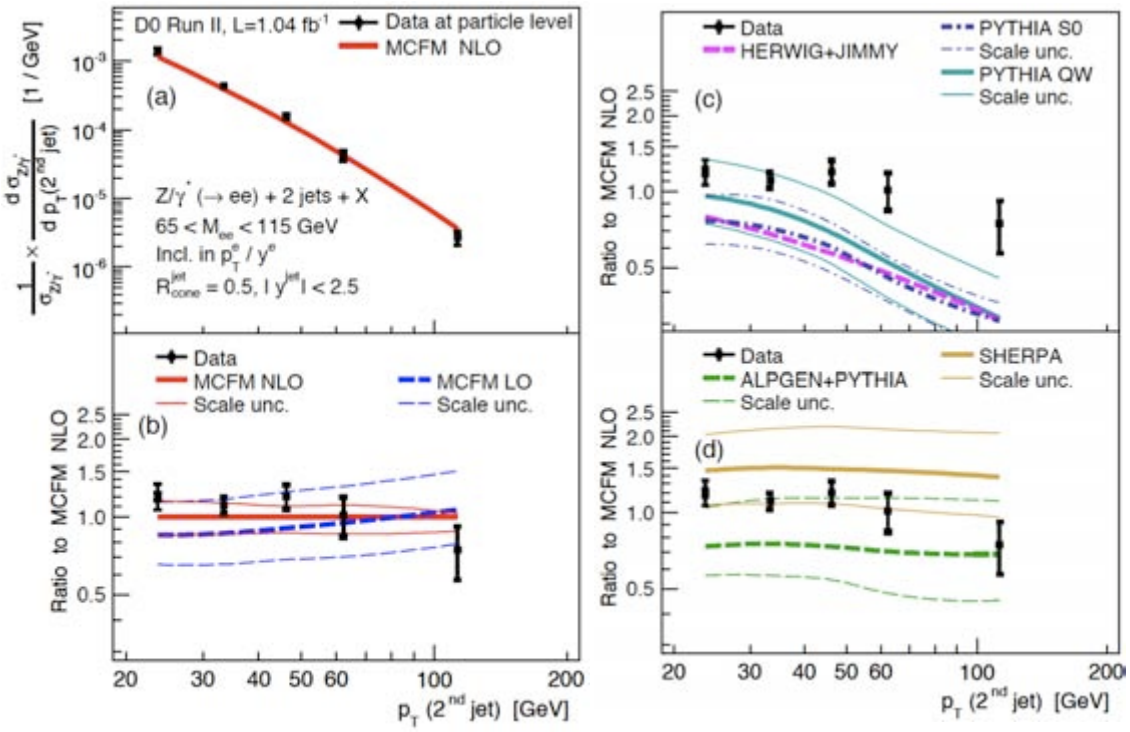
|y(jet,e)| < 2.5

*Information courtesy Sabine Lammers

Z(ee)+2 jets

Fermilab
UIC University of Illinois at Chicago

- All cross sections normalized to inclusive (≥ 0 Jets) Z production
  - reduces systematic errors
- PLB 678, 45 (2009), 0903.1748v1
  - Ratios relative to MCFM v5.3
    - PDF: CTEQ6.6M
    - $\mu_r^2 = \mu_f^2 = p_T(Z)^2 + M(Z)^2$
  - Pythia v6.416
    - Tune P
    - Tune QW
  - HERWIG v6.510+JIMMY v4.31
  - ALPGEN v2.13+Pythia v6.325
  - Sherpa v1.1.1



- Summary of results
  - NLO predictions agree well with data
  - Large differences between models
  - Small experimental errors

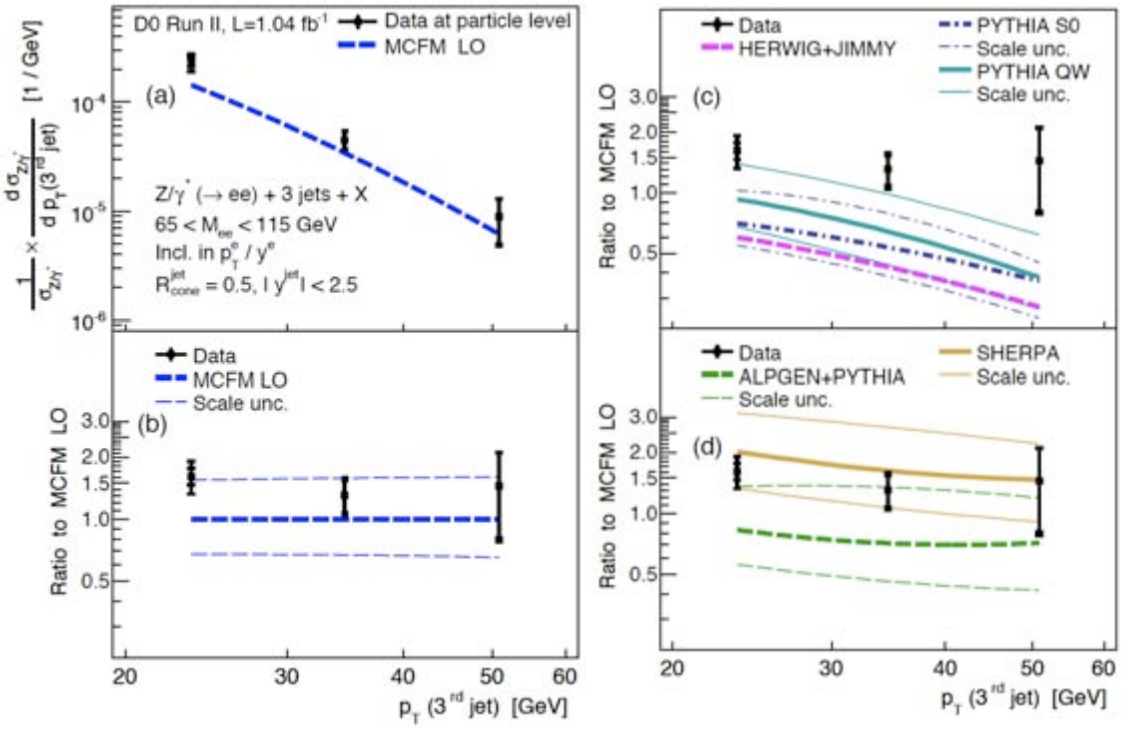
Particle level phase space:
65 GeV< M(ee) < 115 GeV,
D0 midpoint
R_{cone}=0.5,
p_T(jet,e) > 20 GeV
|y(jet,e)| < 2.5

*Information courtesy Sabine Lammers

Z(ee)+3 jets

Fermilab
UIC University of Illinois at Chicago

- All cross sections normalized to inclusive (≥ 0 Jets) Z production
  - reduces systematic errors
- PLB 678, 45 (2009), 0903.1748v1
  - Ratios relative to MCFM v5.3
    - PDF: CTEQ6.6M
    - $\mu_r^2 = \mu_f^2 = p_T(Z)^2 + M(Z)^2$
  - Pythia v6.416
    - Tune P
    - Tune QW
  - HERWIG v6.510+JIMMY v4.31
  - ALPGEN v2.13+Pythia v6.325
  - Sherpa v1.1.1



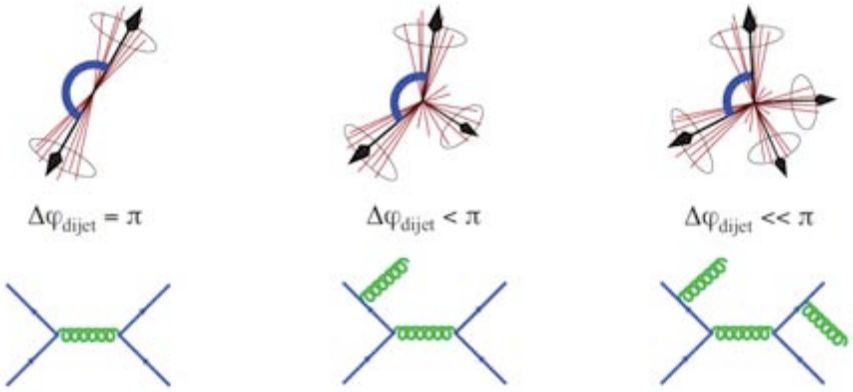
- Summary of results
  - Large differences between models
  - Small experimental errors

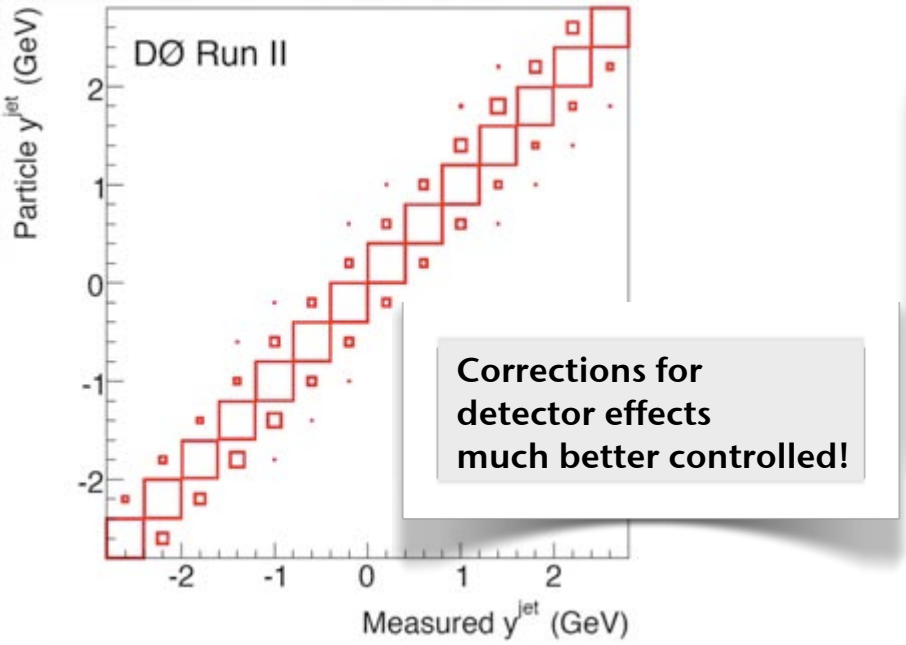
Particle level phase space:
65 GeV< M(ee) < 115 GeV,
D0 midpoint
R_{cone}=0.5,
p_T(jet,e) > 20 GeV
|y(jet,e)| < 2.5

*Information courtesy Sabine Lammers

Dijet φ decorrelation

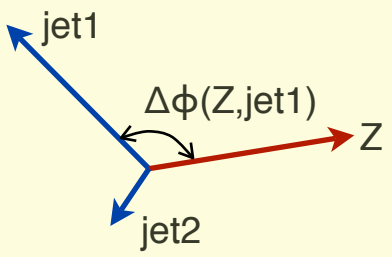
- leading jets Δφ distribution sensitive to higher order radiation
  - w/o explicitly measuring the radiated jets -- no jet counting!
- Particle level distributions
  - Corrections are dominated by JES and jet φ resolutions





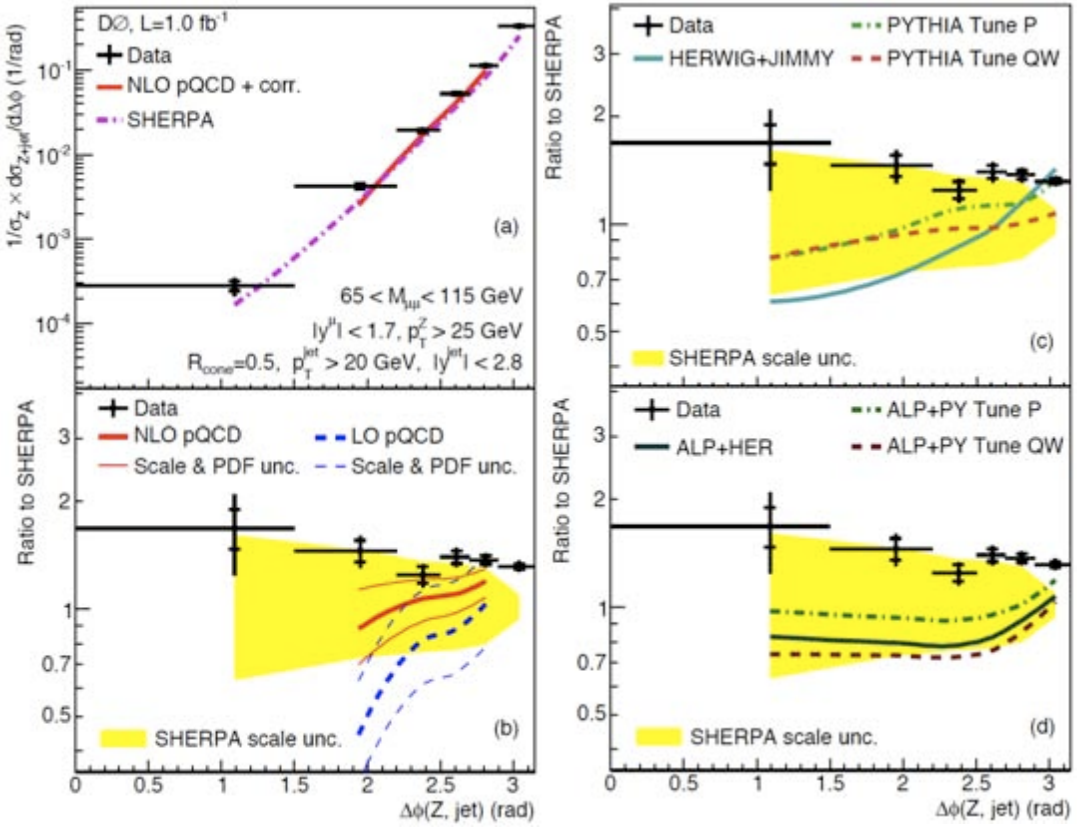
Corrections for detector effects much better controlled!

Apply same idea to Z+Jets



Z(μμ)+jets

- All cross sections normalized to inclusive (≥ 0 Jets) Z production
  - reduces systematic errors
- Theory predictions updated since Publication, 0907.4286v1
  - Ratios relative to Sherpa v1.1.3
  - MCFM v5.4
    - PDF: MSTW2008
    - $\mu_r^2 = \mu_f^2 = p_T(Z)^2 + M(Z)^2$
  - Pythia v6.420
    - Tune P (p_T ordered shower)
    - Tune QW (Q^2 ordered shower)
  - HERWIG v6.510+JIMMY v4.31
  - ALPGEN v2.13+Pythia v6.420
  - ALPGEN v2.13+HERWIG v6.510
  - CTEQ6.1 PDFs
- Summary of results
  - Within uncertainties, Sherpa describes angular decorrelation



Particle level phase space:

65 GeV< M(μμ) < 115 GeV,

D0 midpoint

R_{cone}=0.5,

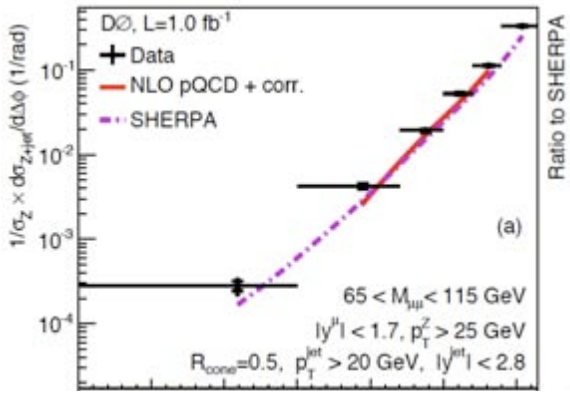
p_T(jet) > 20 GeV

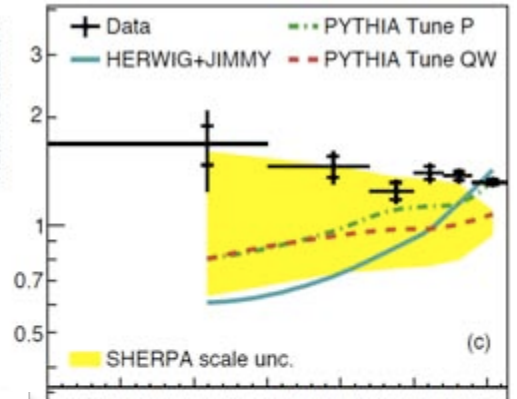
|y(jet)| < 2.5, |y(μ)| < 1.7

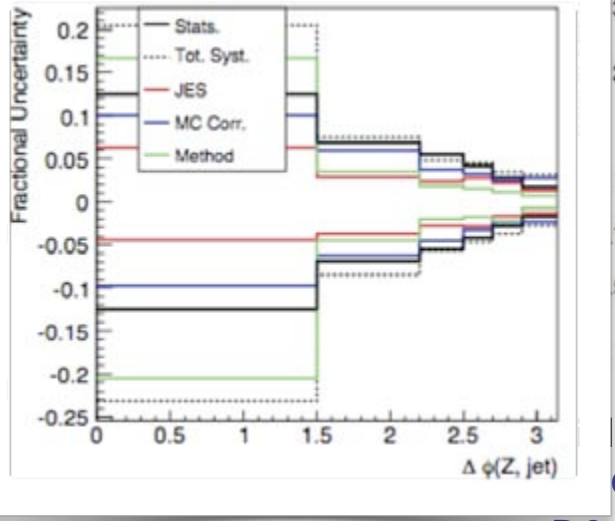
*Information courtesy Sabine Lammers

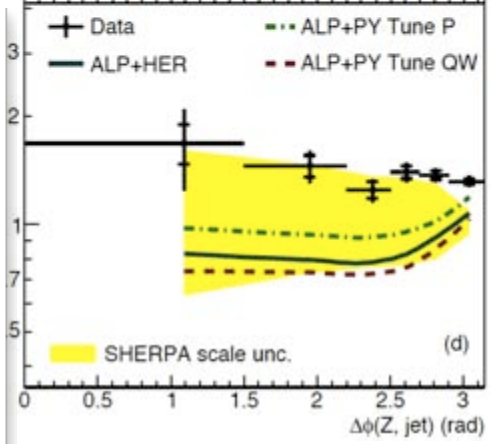
Z(μμ)+jets

- All cross sections normalized to inclusive (≥ 0 Jets) Z production
  - reduces systematic errors
- Theory predictions updated since Publication, 0907.4286v1
  - Ratios relative to Sherpa v1.1.3
  - MCFM v5.4
    - PDF: MSTW2008
    - $\mu_r^2 = \mu_f^2 = p_T(Z)^2 + M(Z)^2$
  - Pythia v6.420
    - Tune P (p_T ordered shower)
    - Tune QW (Q^2 ordered showe
  - HERWIG v6.510+JIMMY v4.31
  - ALPGEN v2.13+Pythia v6.420
  - ALPGEN v2.13+HERWIG v6.51
  - CTEQ6.1 PDFs
- Summary of results
  - Within uncertainties, Sherpa describes angular decorrelation









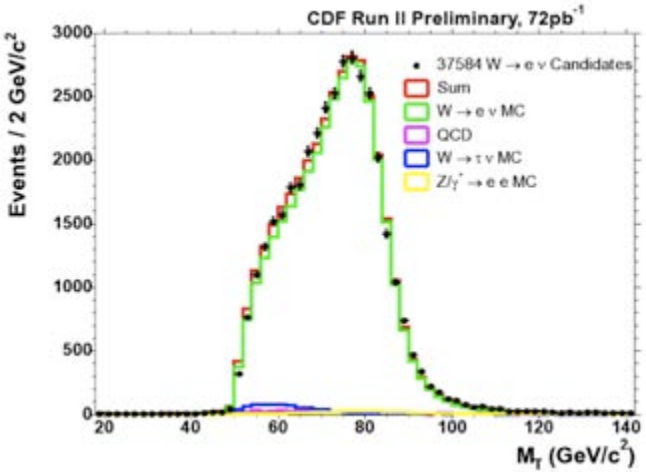
e level phase space:
GeV< M(μμ) < 115 GeV,
D0 midpoint
R_{cone}=0.5,
p_T(jet) > 20 GeV
|y(jet)| < 2.5, |y(μ)| < 1.7

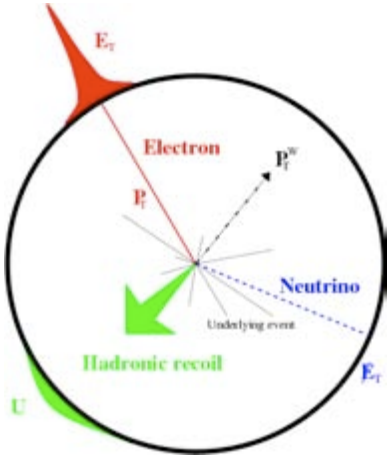
*Information courtesy Sabine Lammers

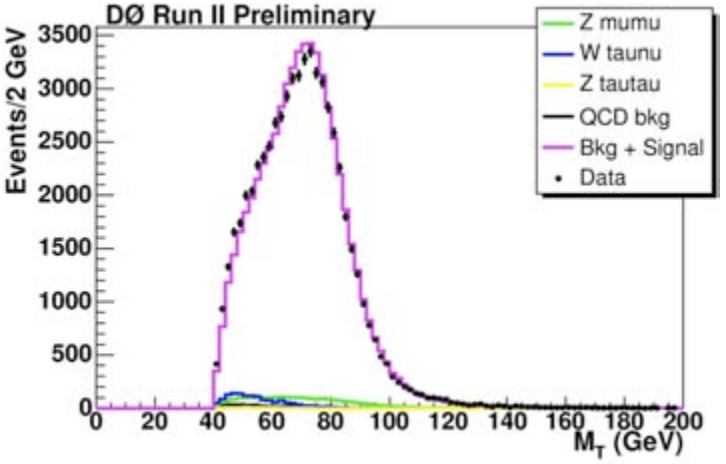
W Reconstruction

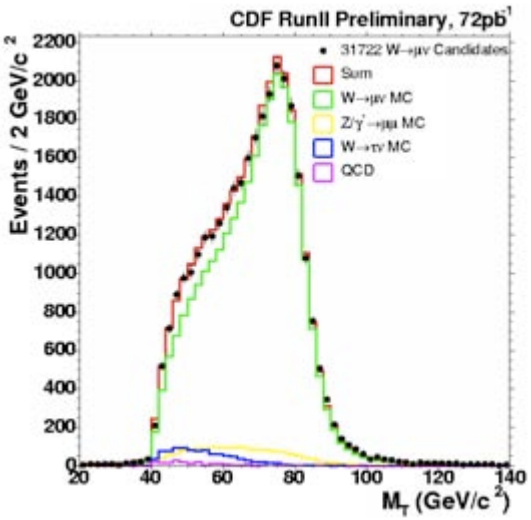
Fermilab
UIC University of Illinois at Chicago

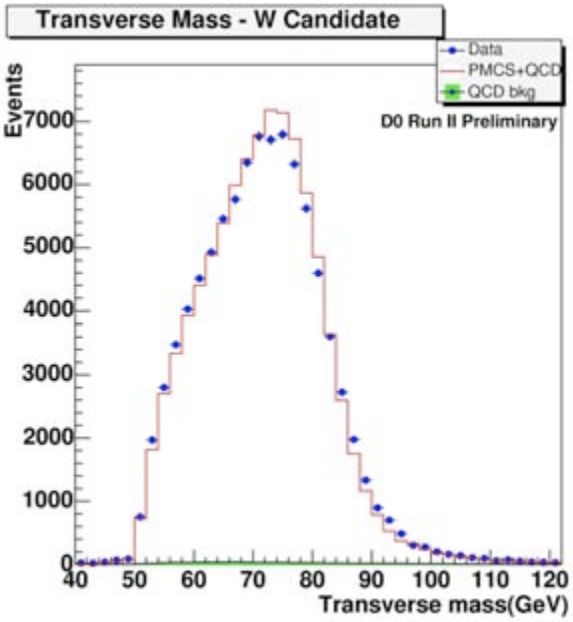
- Low backgrounds for ≥ 0 jets case







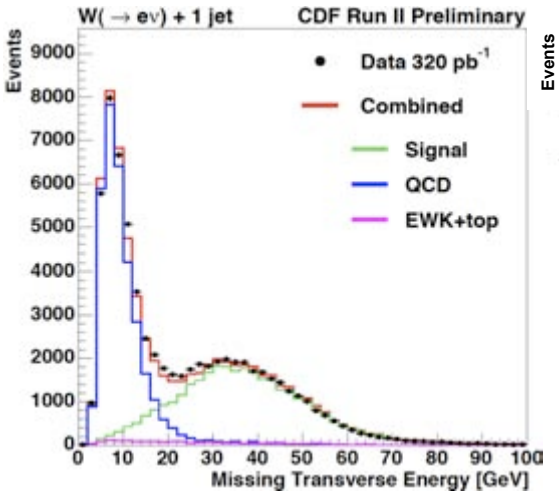


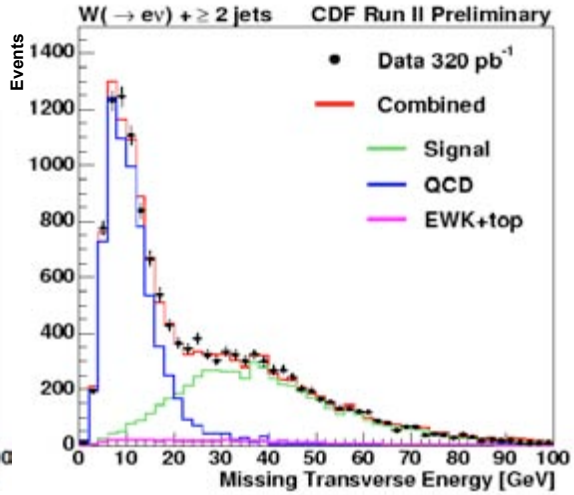


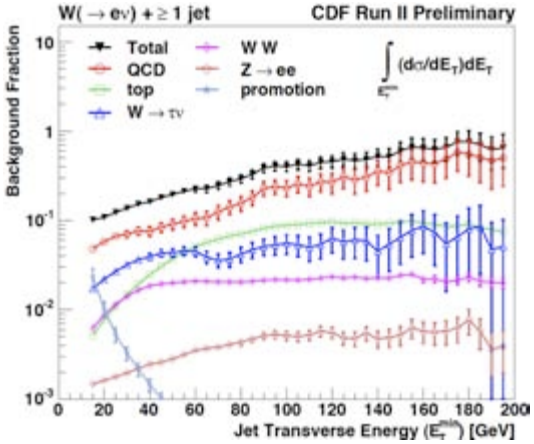
W Reconstruction

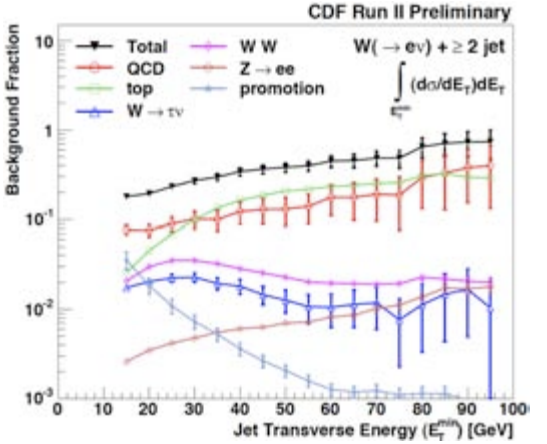
Fermilab
UIC University of Illinois at Chicago

- arXiv: 0708.1380v1 & 0711.4044v2
- But, significant backgrounds already with 1 & 2 jets
  - dominates at
    - high jet multiplicity
    - high pT







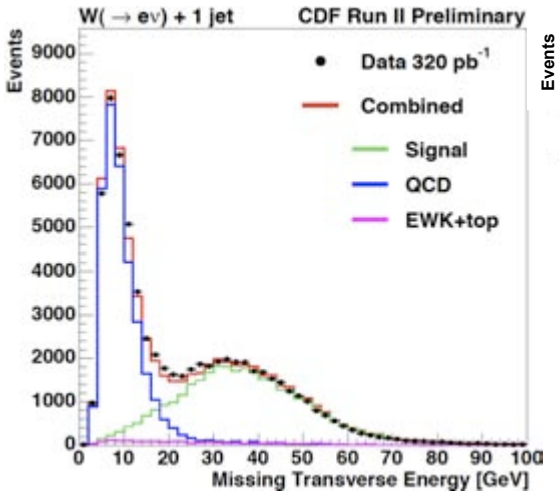


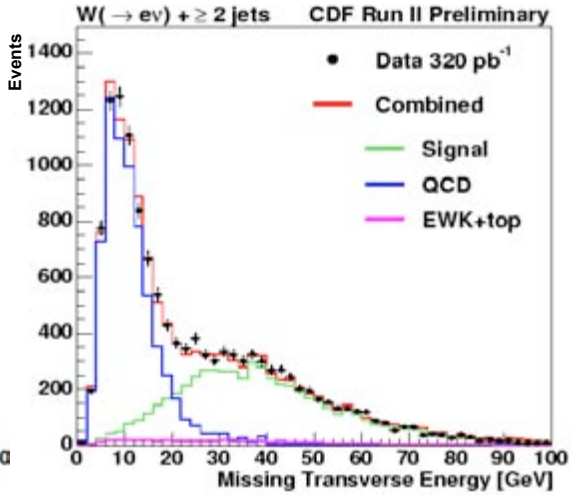
W Reconstruction

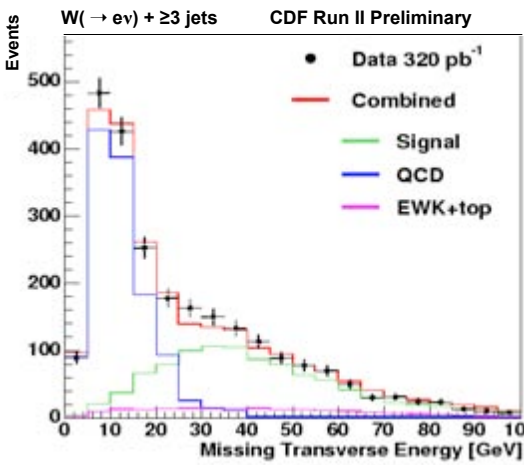
- arXiv: 0708.1380v1 & 0711.4044v2

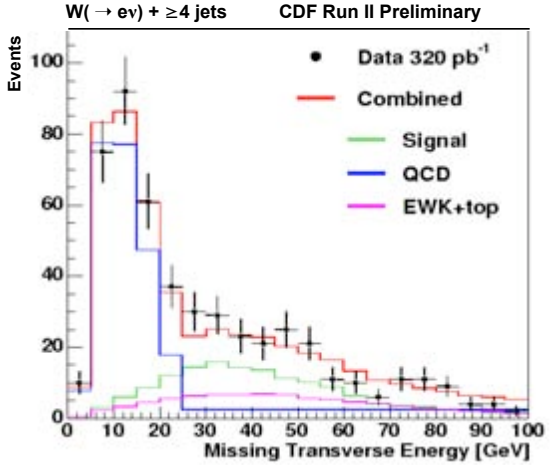
- But, significant backgrounds already with 1 & 2 jets
  - dominates at
    - high jet multiplicity
    - high pT
  - and especially with 3 & 4 jets

- Selection
  - e: ET > 20 GeV, |η| < 1.1
  - MET > 30 GeV;
    MT(W) > 20 GeV
  - Jet definition, R= 0.4:
    - Corrected ET > 20 GeV,
      |η| < 2.0



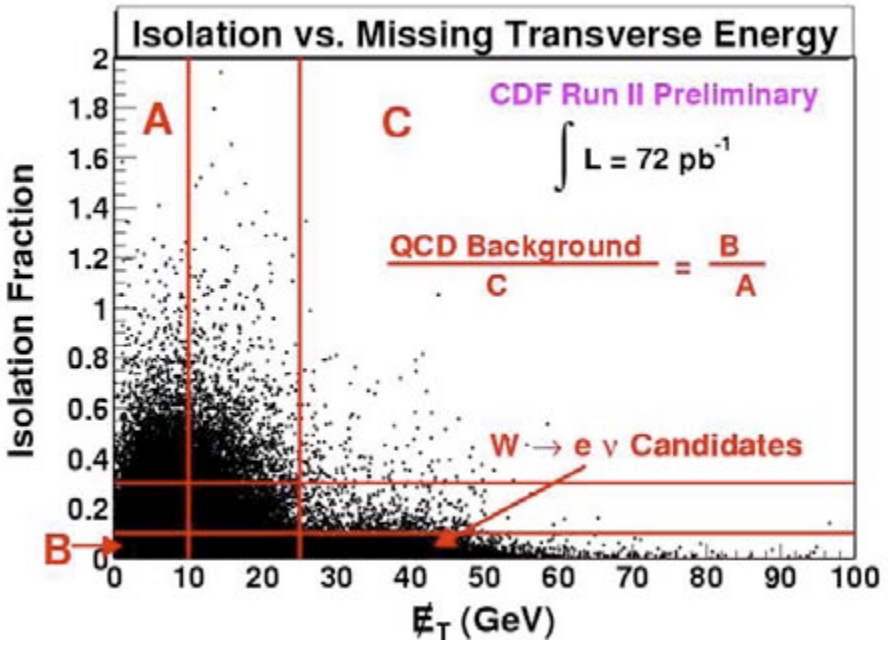




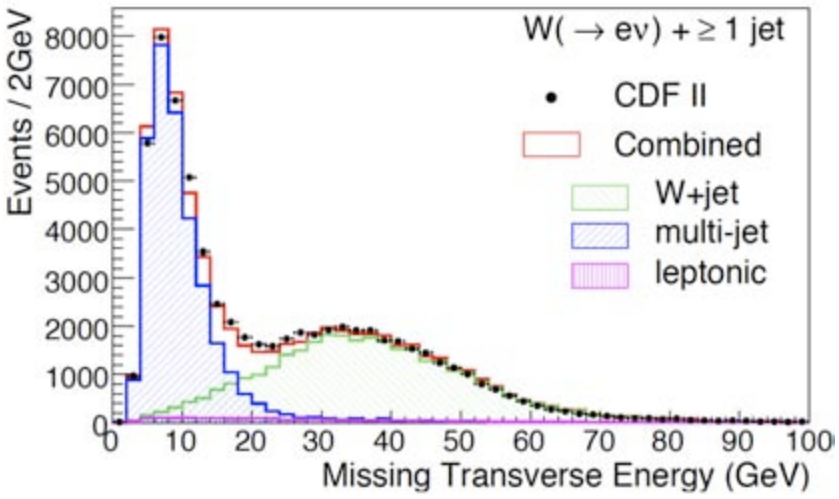


Background Estimation

- **Matrix Method**
  - requires at least two variables
    - discriminating
    - uncorrelated
  - assume ratio A/B same as ratio C/N
    - Background in signal region: N = B/A x C



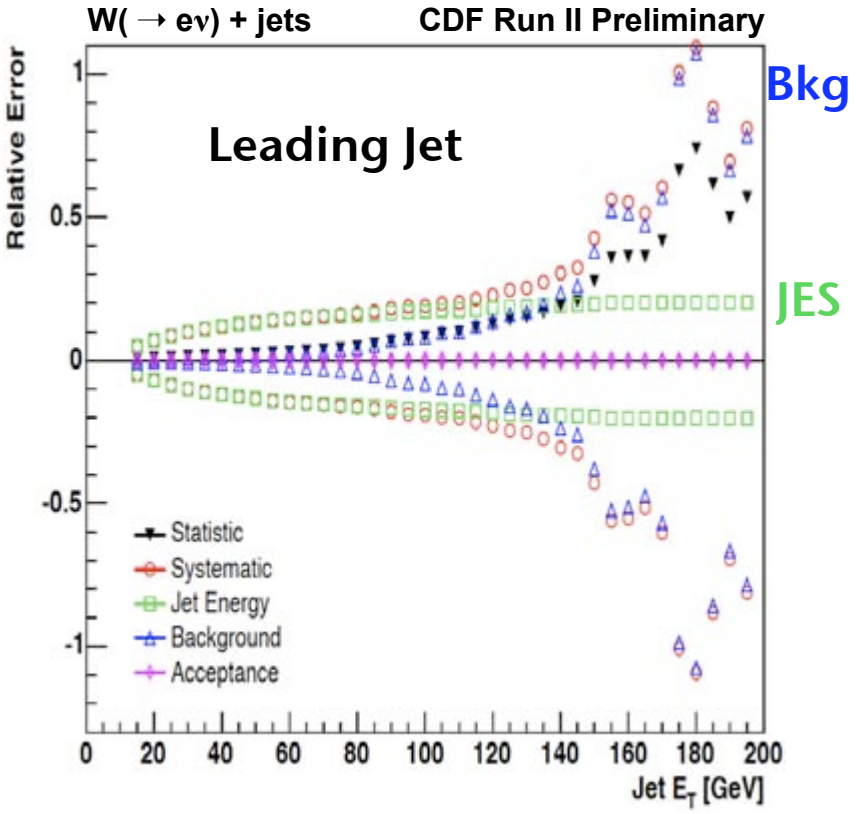
- **Template Fitting**
  - derive "dN/dMET" by inverting "Isolation Fraction" cut
  - Assumes that MET behavior in inverted region is same as in signal region
    - correlations! ➔ bad ansatz!
    - no correlations! ➔ good ansatz!

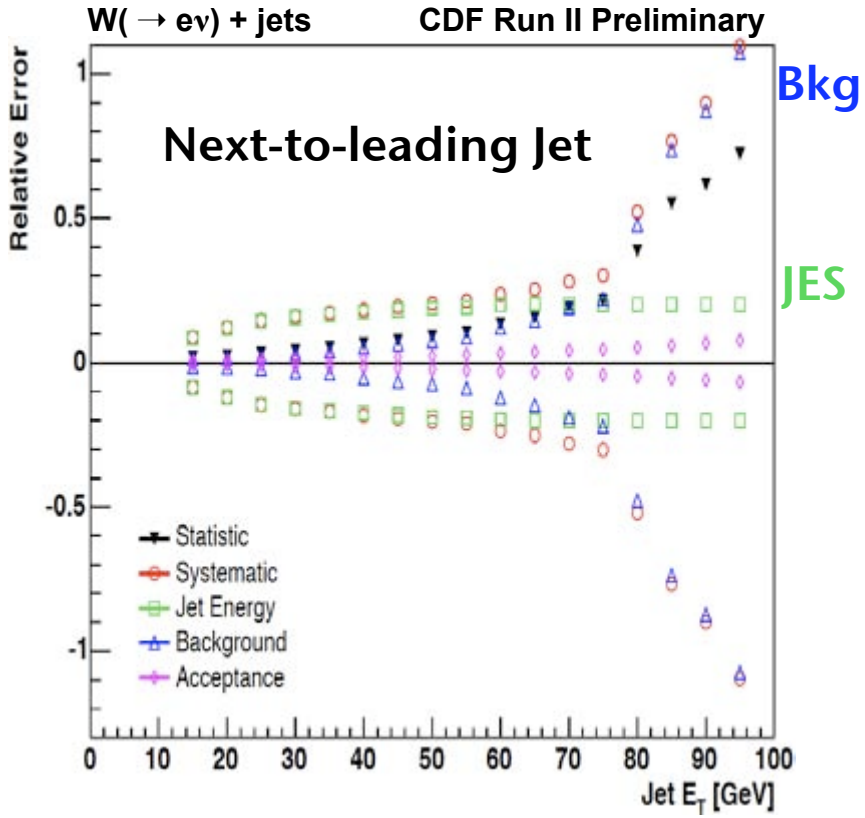


W + Jets Systematic Uncertainties

Fermilab
UIC University of Illinois at Chicago

- Jet Energy Scale dominates systematic uncertainty at low pT
- Background Estimation dominates at high pT
  - (the interesting region for searches!)



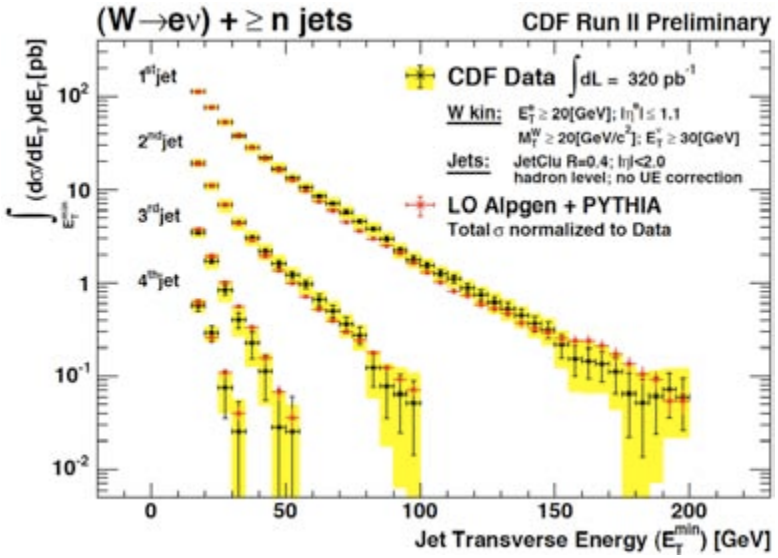


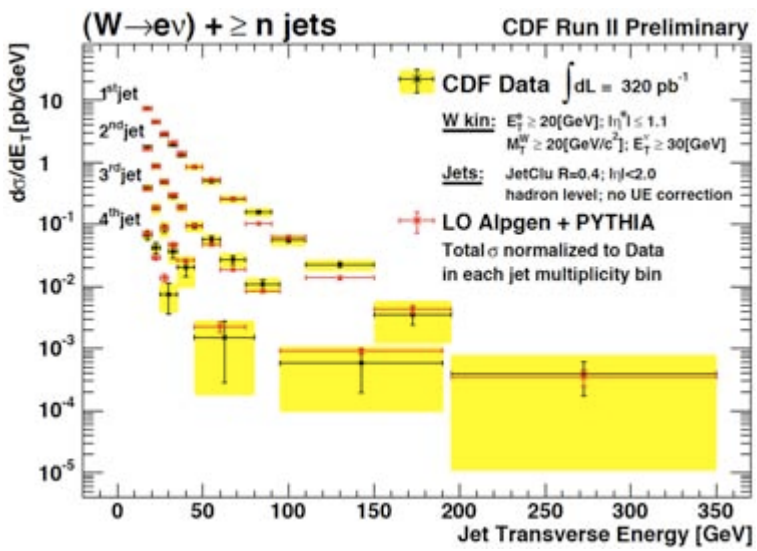
- arXiv: 0708.1380v1 & 0711.4044v2

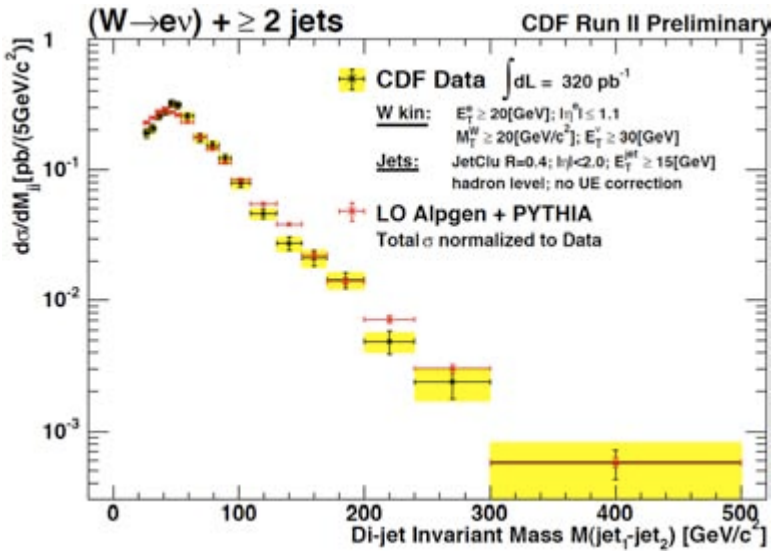
W(eν) + 4 jets

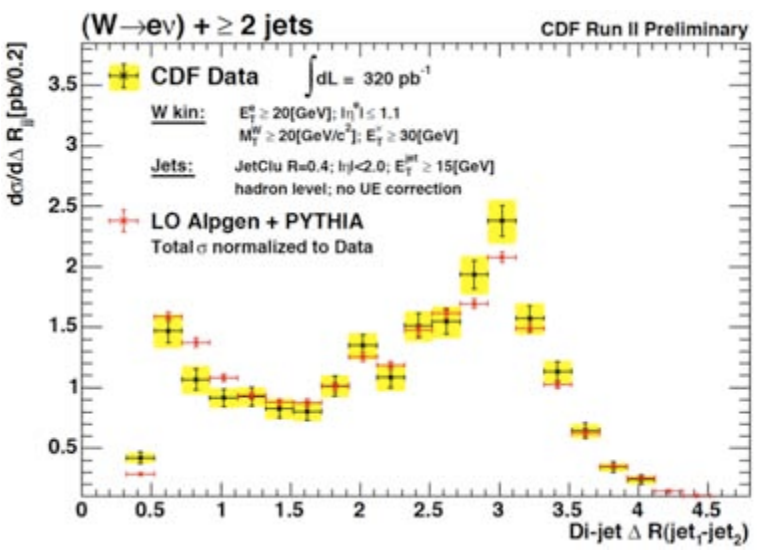
Fermilab
UIC University of Illinois at Chicago

- arXiv: 0708.1380v
- Study how well ME+PS describe **shape** of W+≥ n jets differential distributions





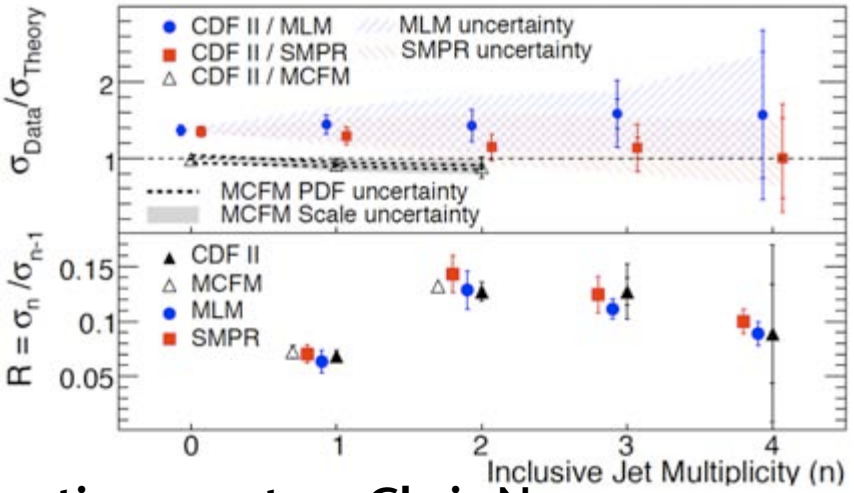


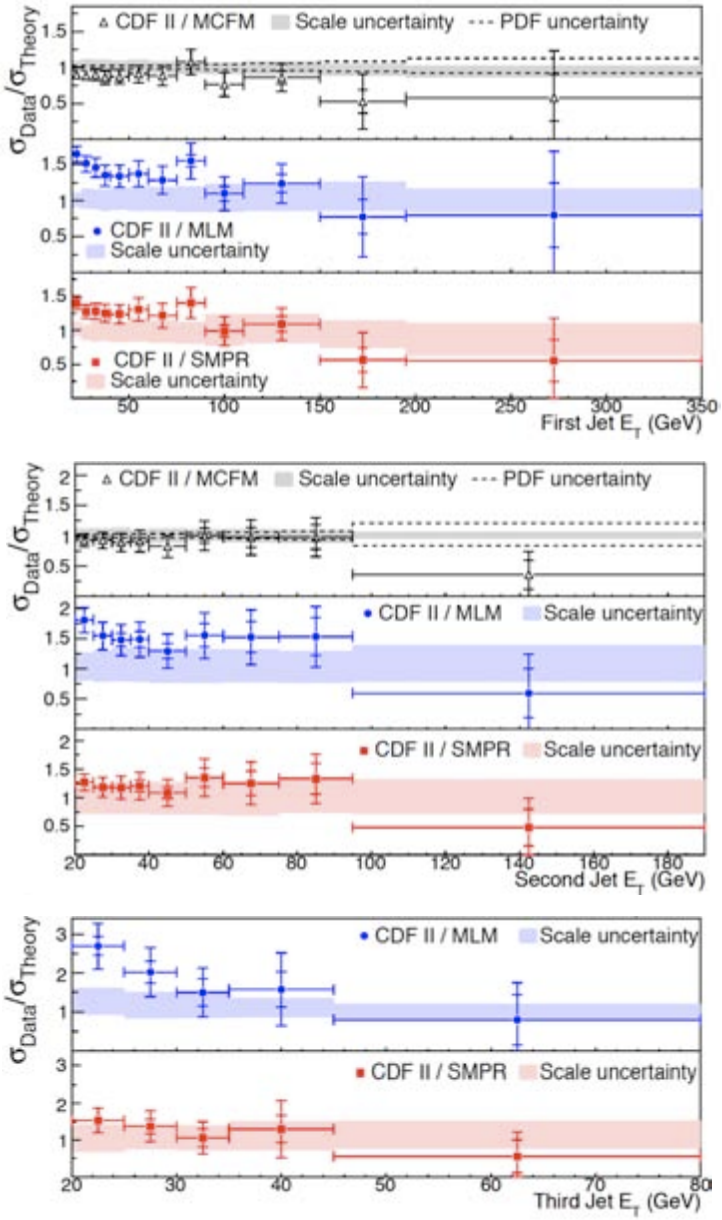


W(ev) + 4jets

- Full comparison
  - shape & normalization
- Theoretical Codes used:
  - MLM = ALPGEN v2.12 (LO) + Herwig v6.5 + MLM + CTEQ5L
  - SMPR = MadGraph v4 (LO) + Pythia v6.3 + CKKW + CTEQ6L1
  - MCFM = NLO, no had, no UE+ CTEQ6.1M (up to 2 jets only)
- Results:
  - Pythia+CKKW better than Herwig+MLM
  - NLO performs very well
    - even without had and UE corrections

- arXiv: 0711.4044v2



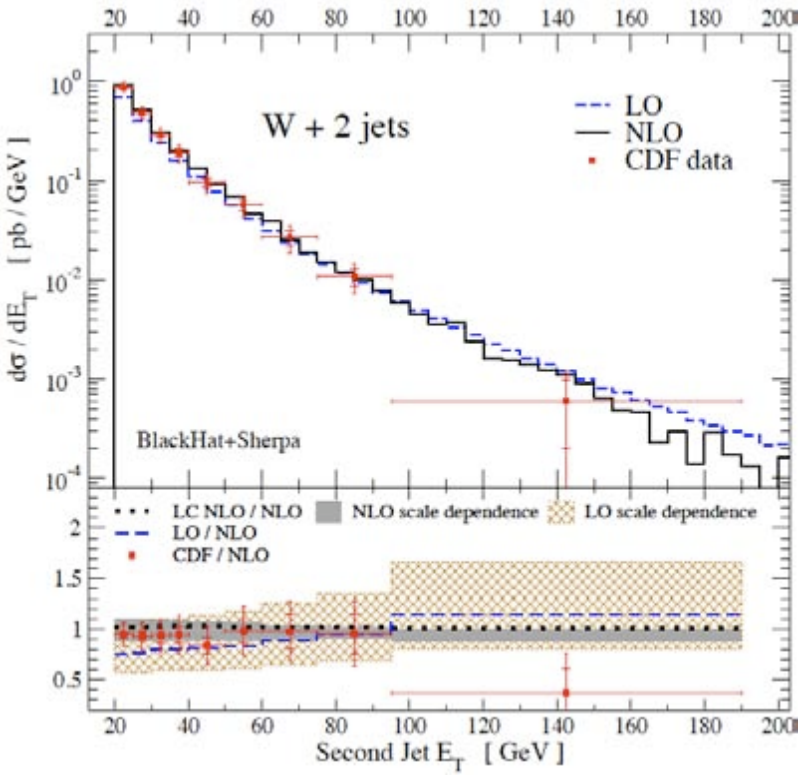


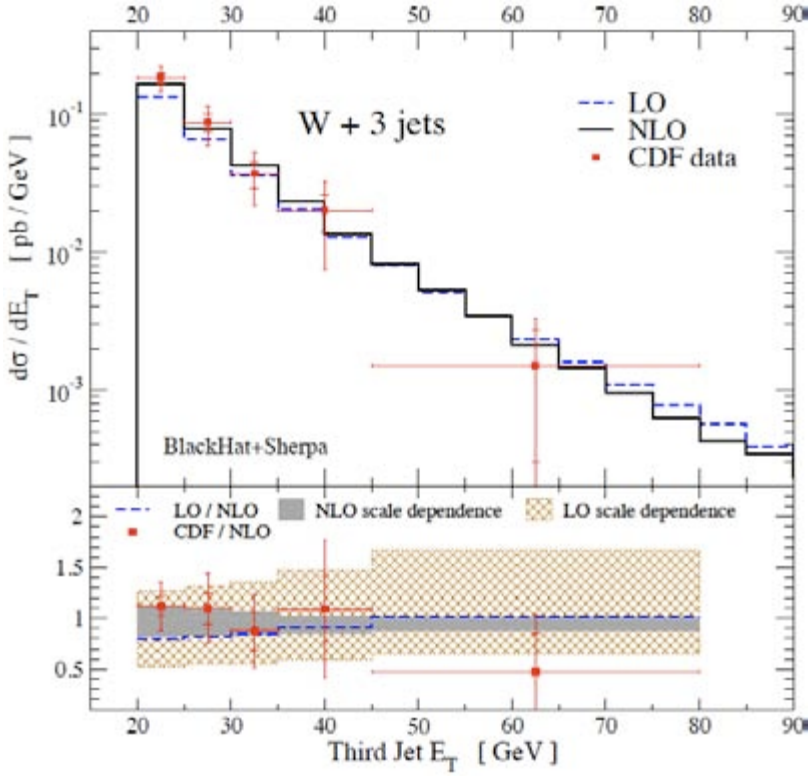
*Information courtesy Chris Neu

W + 3 Jets

Fermilab
UIC University of Illinois at Chicago

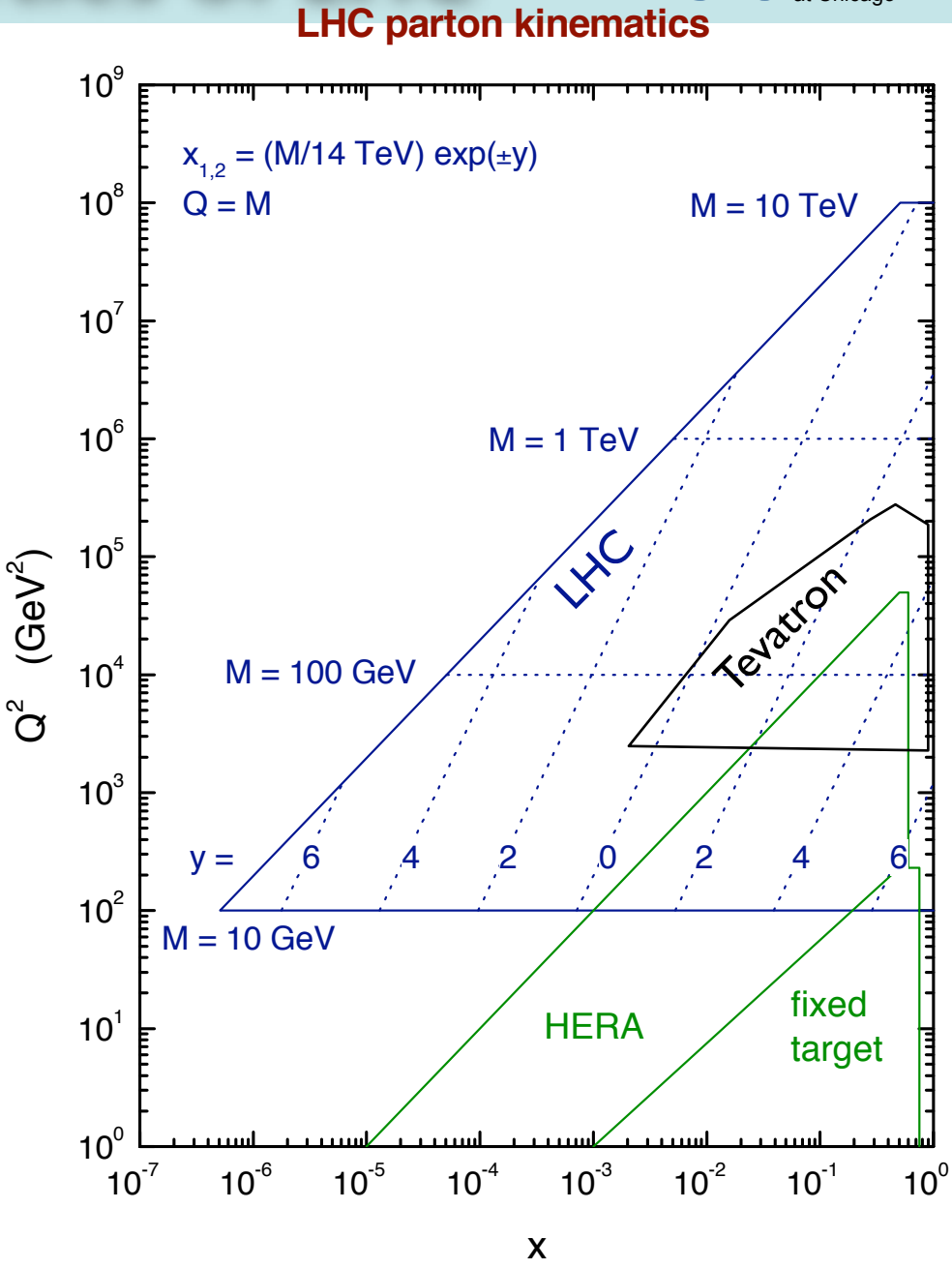
- Good agreement between CDF data and BlackHat NLO prediction for W + 2 and W + 3 jets





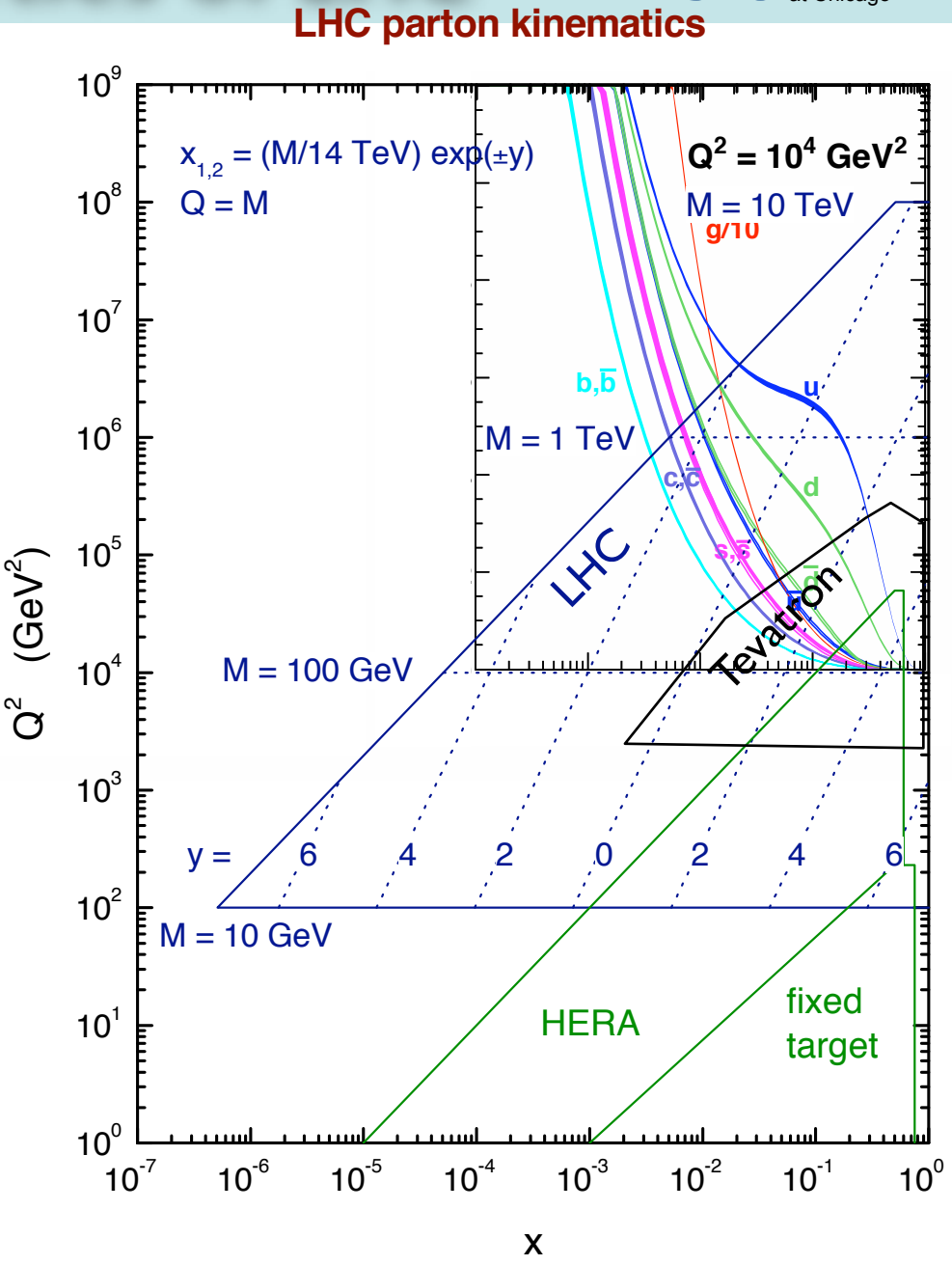
Unique Properties of LHC

- many more gluon interactions at LHC than at Tevatron
- Large phase space for production of extra jets
- Broad kinematic acceptance of LHC: can explore very high and very low x regions



Unique Properties of LHC

- many more gluon interactions at LHC than at Tevatron
- Large phase space for production of extra jets
- Broad kinematic acceptance of LHC: can explore very high and very low x regions



One of the very first LHC Physics Opportunities

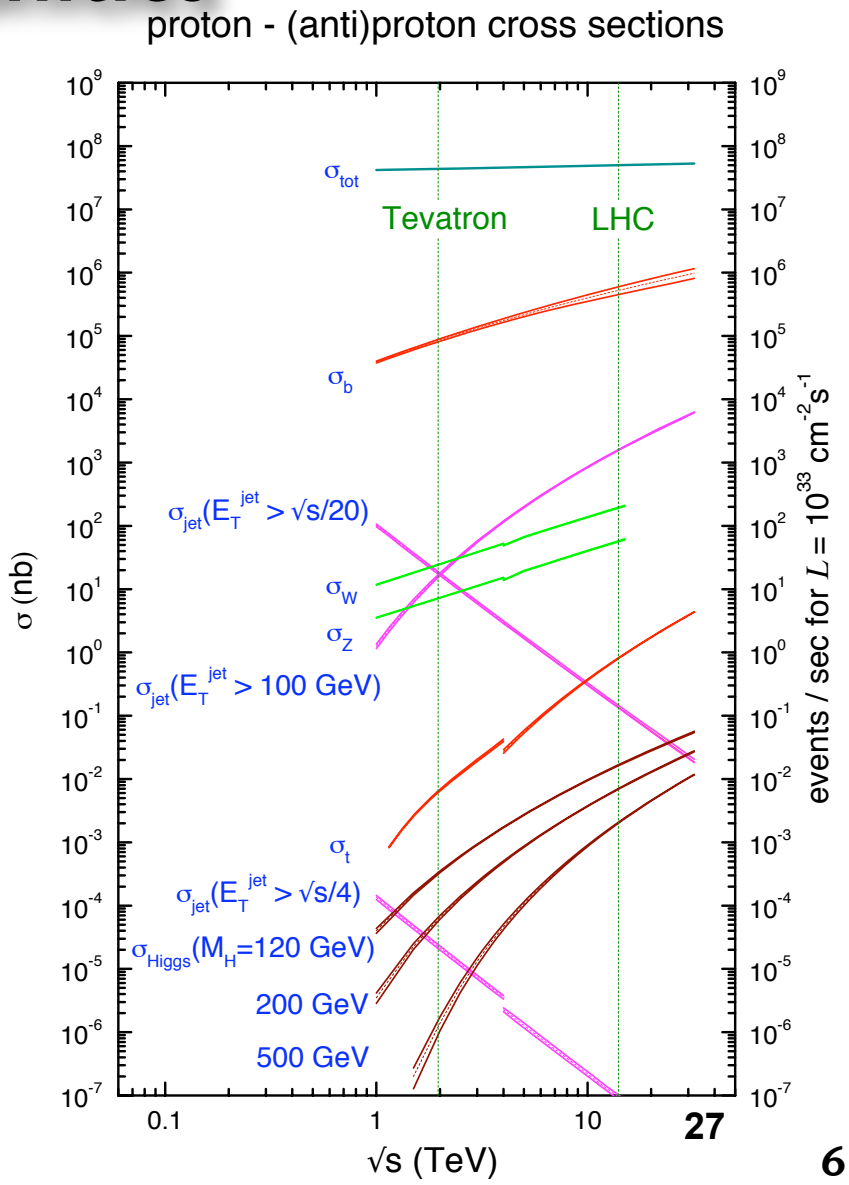
- W and Z bosons produced in large quantities at the LHC
  - At 14 TeV, W and Z production 10 times higher than at Tevatron

$\sigma \cdot BR$ (W→eν) [pb] (from M.Mangano)

N Jets →	1	2	3	4	5
Tevatron	230	37	5.7	0.75	0.08
LHC	3400	1130	340	100	28

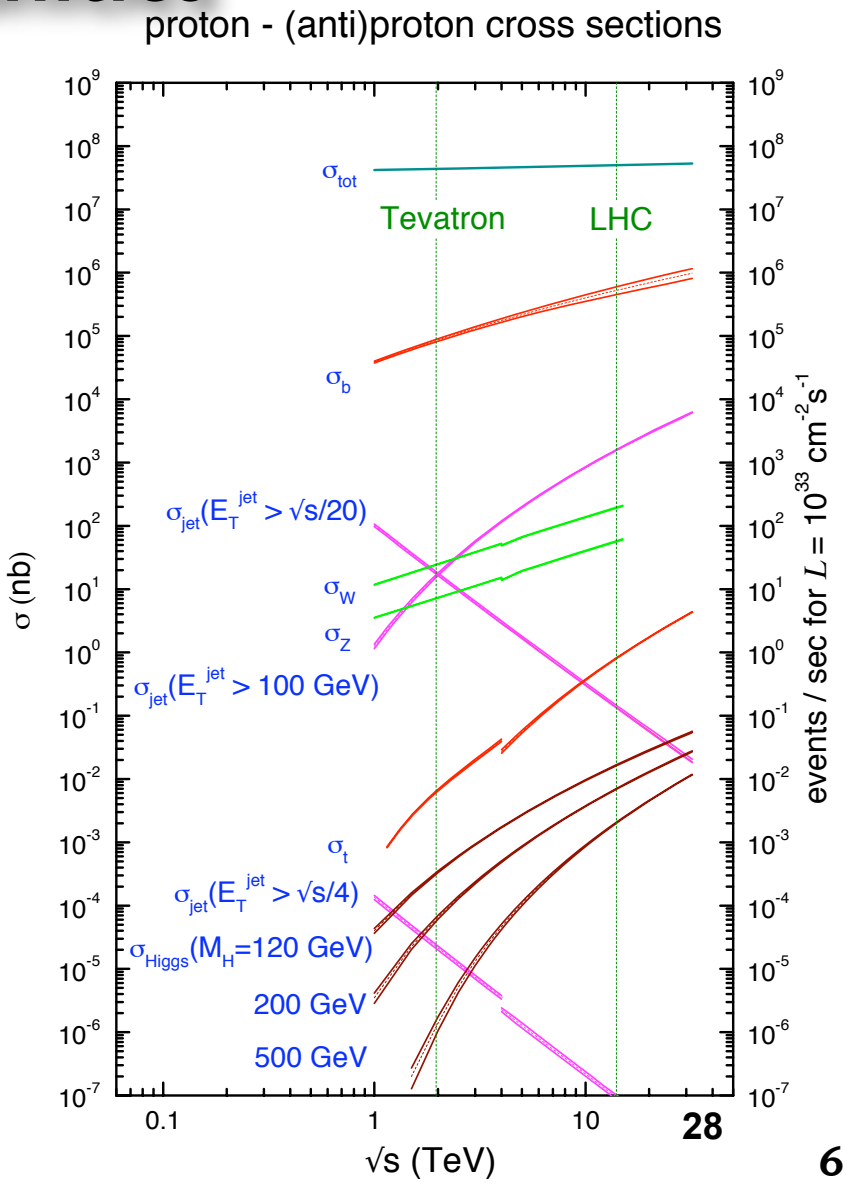
Et(jet)>20 GeV, $|\eta|$<2.5, ΔR=0.7

- Large hadronic background (!)
- not only a candle for QCD, also a test for detector performance studies
  - lepton efficiency determination
  - Jet energy corrections
  - Missing transverse energy corrections



One of the very first LHC Physics Opportunities

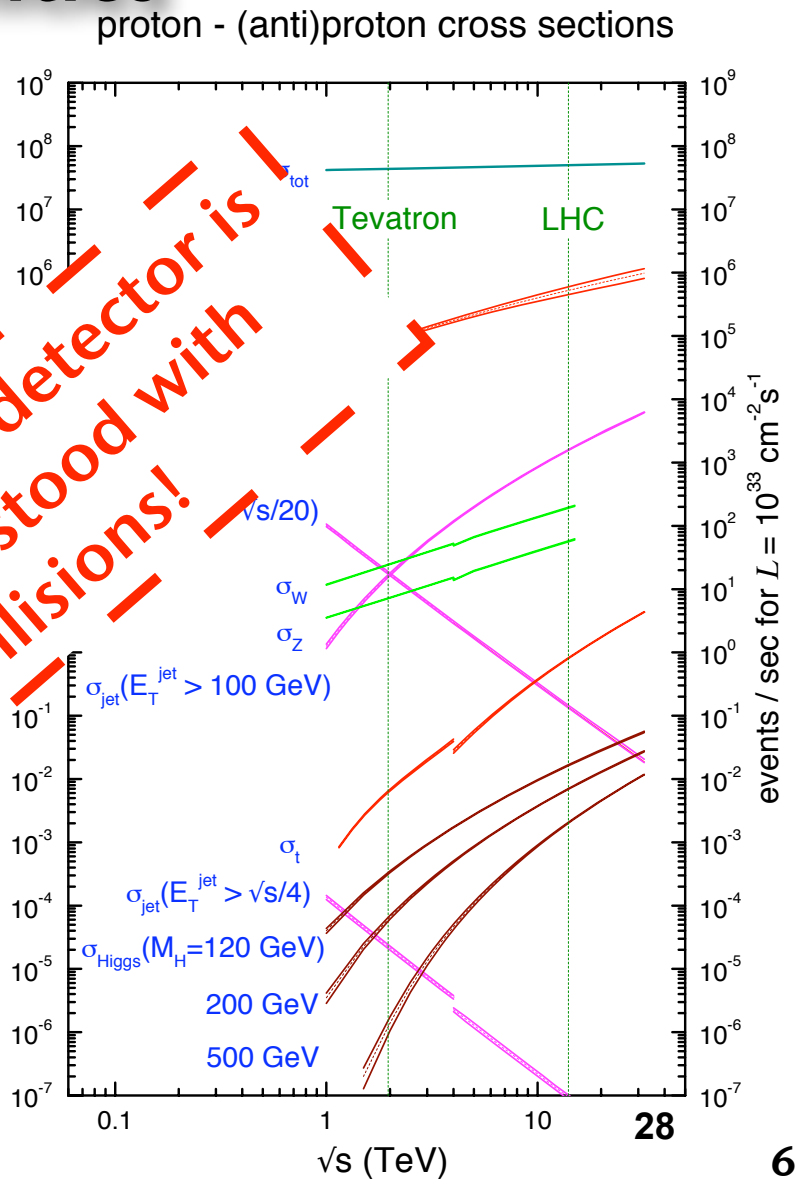
- **Centre-of-Mass profile (very rough est.)**
  - 1 pb^{-1} at 14 TeV:
    - ~200 000 W's (40 000 eν+μν)
    - ~60 000 Z's (4 000 ee+μμ)
  - 1 pb^{-1} at 6 TeV:
    - ~70 000 W's (15 000 eν+μν)
    - ~20 000 Z's (1 500 ee+μμ)
- **Luminosity profile (very rough est.)**
  - 1 pb^{-1} at 10 TeV:
    - ~100 000 W's (20 000 eν+μν)
    - ~40 000 Z's (2 000 ee+μμ)
  - 10 nb^{-1} at 10 TeV:
    - ~1 000 W's (200 eν+μν)
    - ~400 Z's (20 ee+μμ)



One of the very first LHC Physics Opportunities

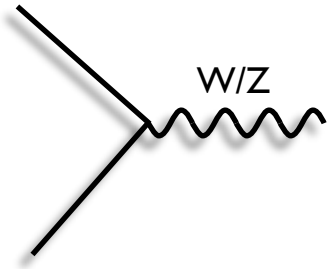
- **Centre-of-Mass profile (very rough est.)**
  - 1 pb^{-1} at 14 TeV:
    - ~200 000 W's (40 000 eν+μν)
    - ~60 000 Z's (4 000 ee+μμ)
  - 1 pb^{-1} at 6 TeV:
    - ~70 000 W's (15 000 eν+μ
    - ~20 000 Z's (1 500 e
- **Luminosity profile (very rough**
  - 1 pb^{-1} at 10 TeV:
    - ~100 000 W's (20
    - ~40 000 Z's (2 000
  - 10 nb^{-1} at 10 TeV:
    - ~1 000 W's (200 eν+μν)
    - ~400 Z's (20 ee+μμ)

…all while the detector is being understood with 1st LHC Collisions!

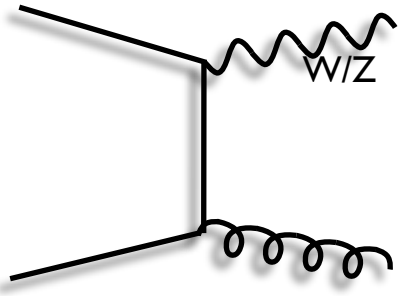


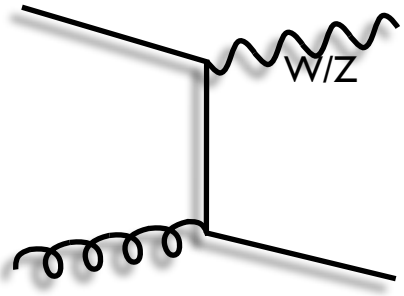
Unique Properties of LHC

- Production in association with multijets enhanced at LHC (hence pure QCD reason to study V+Jets at LHC)
  - W/Z+0 partons (LO)-> need q, $\bar{q}$
    - valence-valence process at Tevatron
    - valence-sea, sea-sea process at LHC



  - W/Z+1 parton:
    - q $\bar{q}$ -> W/Z + gluon (Tevatron) q g -> W/Z q (LHC)



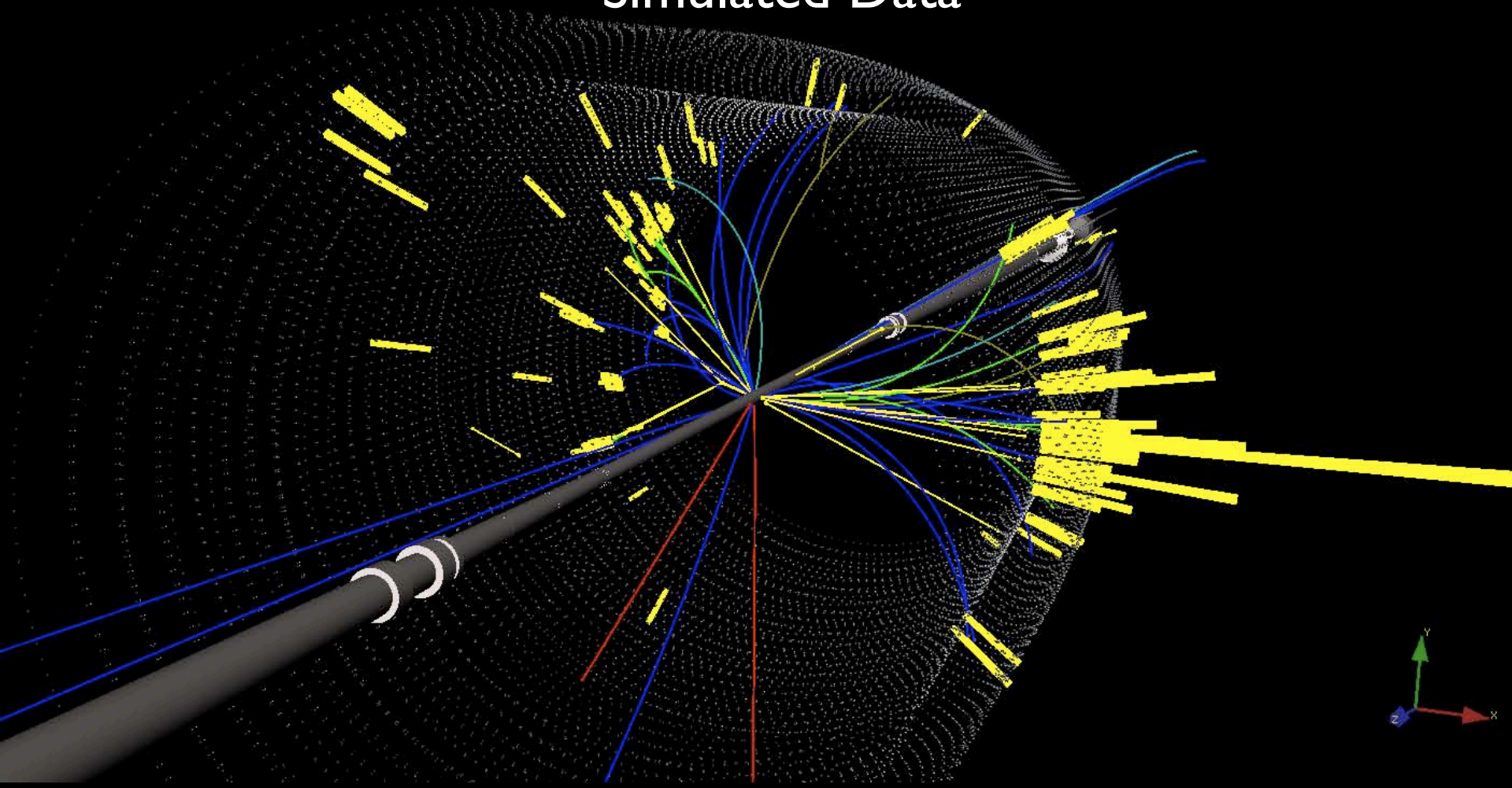


  - W/Z + Jets is enhanced at LHC
    - large gluon contribution, large phase space for additional jets

*slide modified from Maria Fiascaris

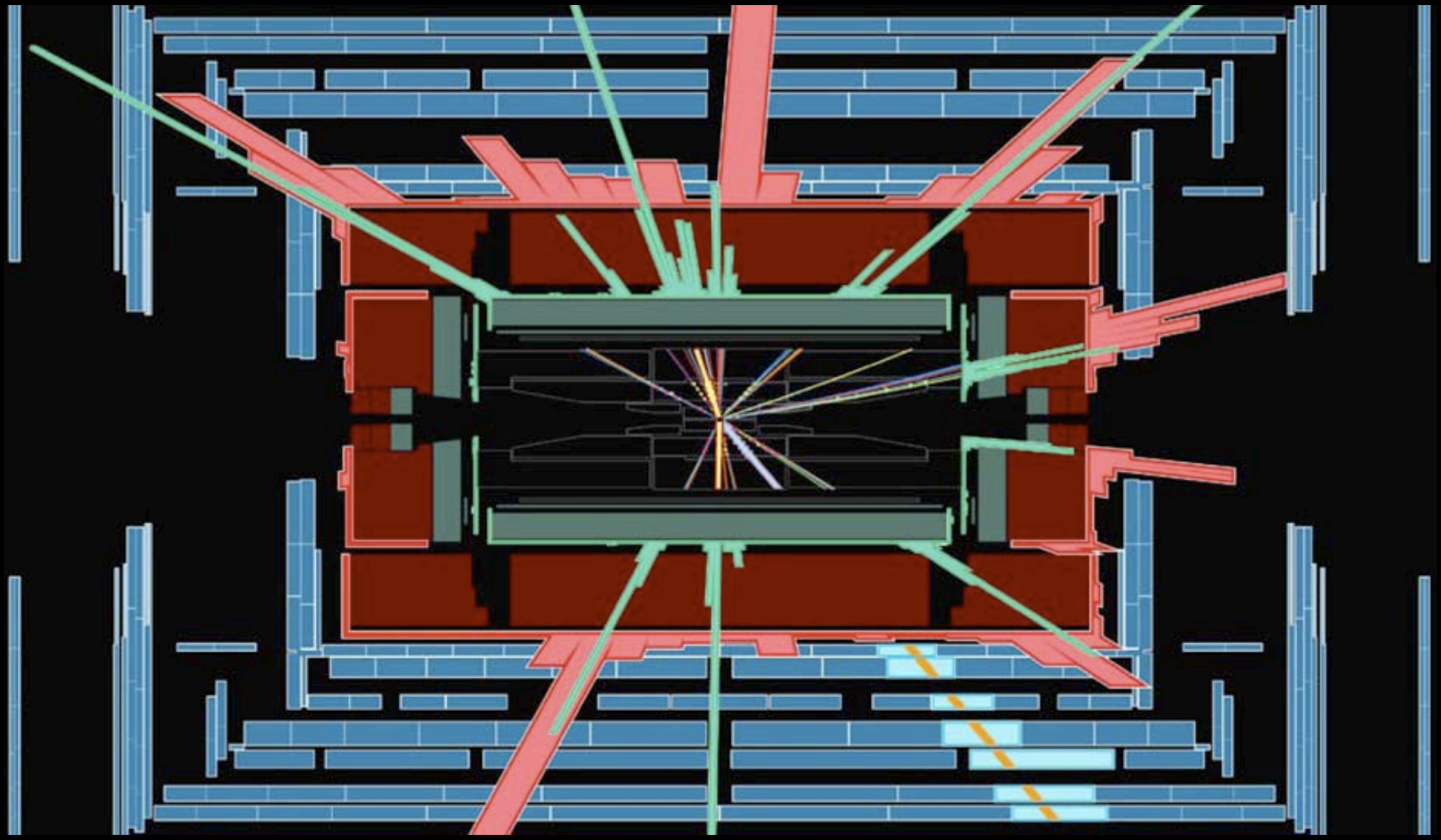
Z(μμ) + Jets Event Display

Simulated Data



W(μν) + Jets Event Display

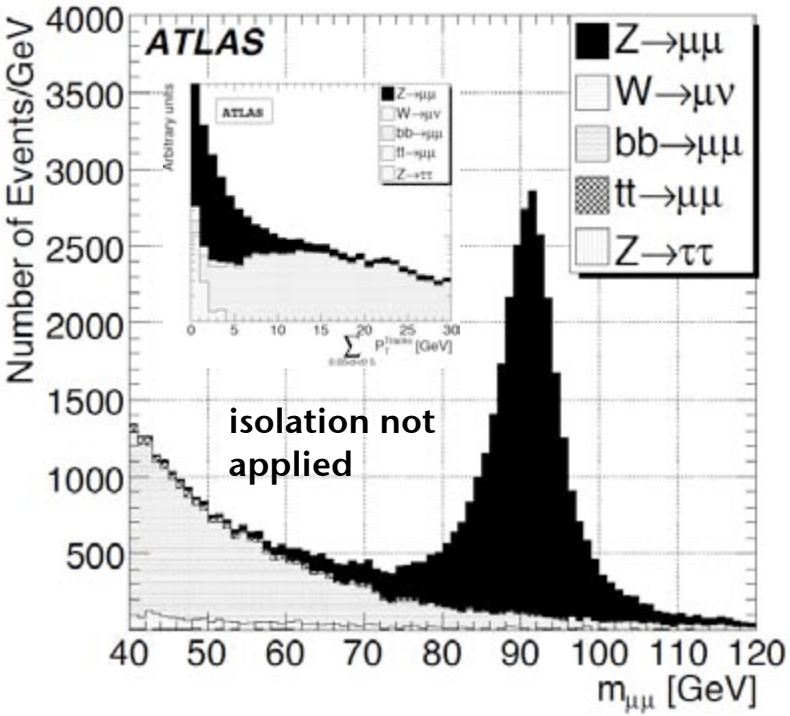
Simulated Data

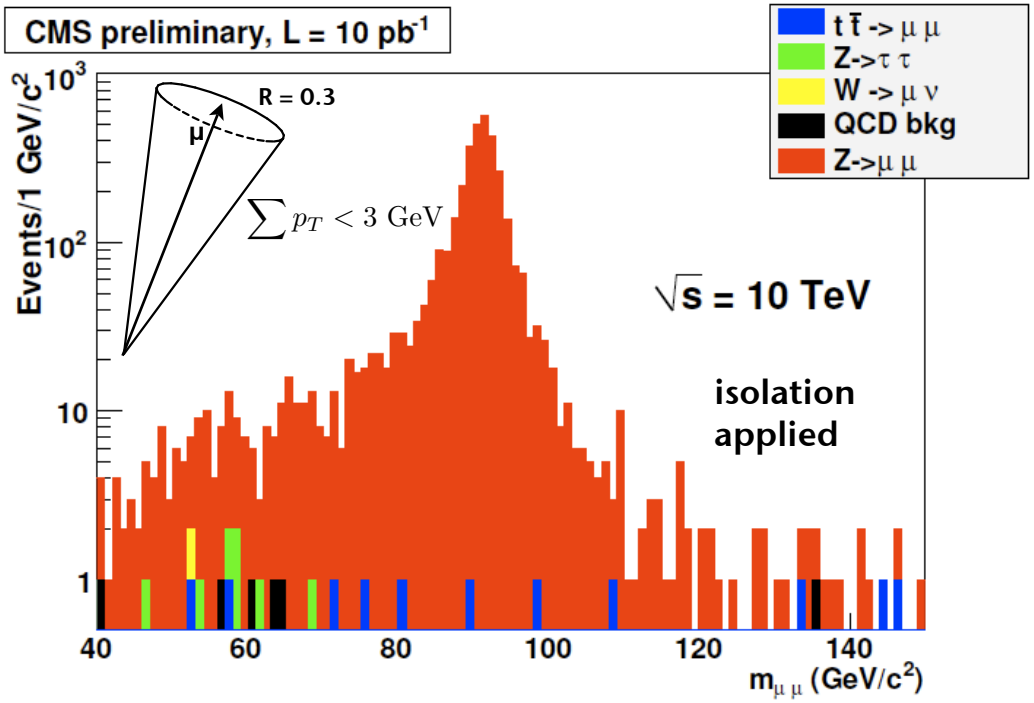


Inclusive Z production

Fermilab
UIC University of Illinois at Chicago

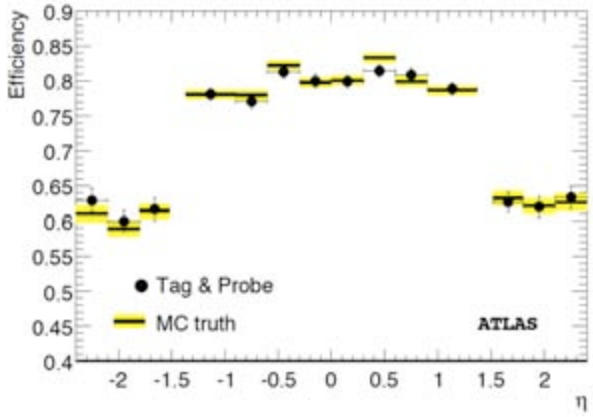
- DY at LHC is also very clean!

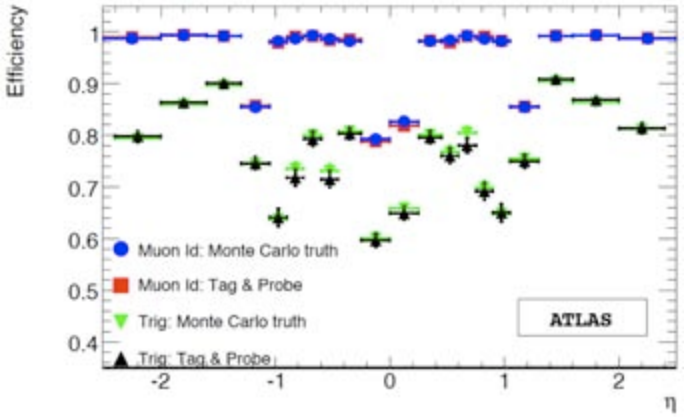




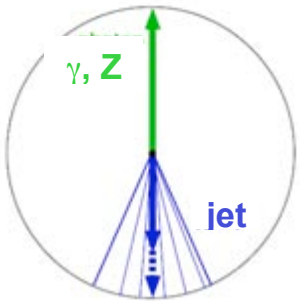
CMS: Z candle

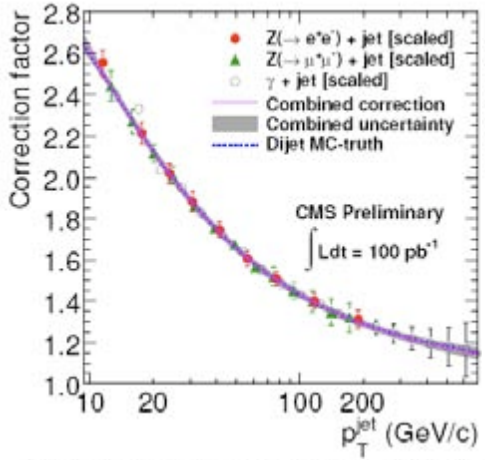
- Tag & Probe: lepton efficiencies

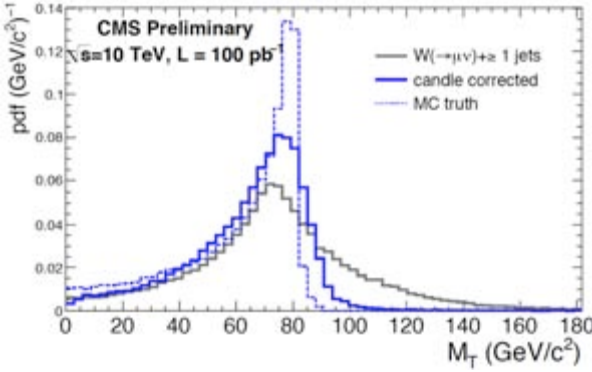




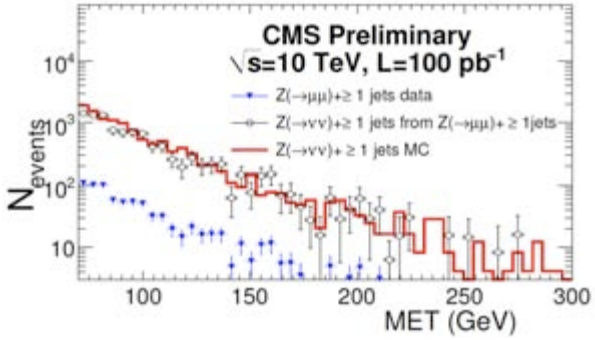
- Jet & MET Energy Corrections







- Zvv background estimation



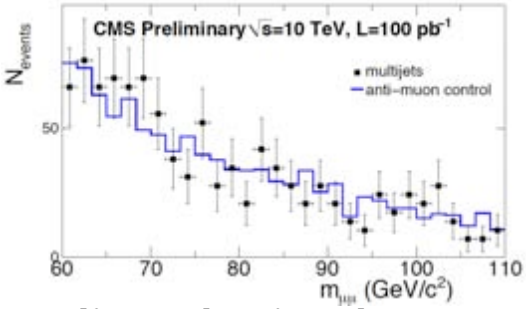
Jet Algorithms at LHC

- Past: Iterative Cone, Midpoint
- Present: SISCone, kT, anti-kT
  - Iterative Cone still used at trigger level
- Future: kT, anti-kT
  - Iterative Cone still used at trigger level
- Different types of input
  - traditional calorimeter cells
    - treats everything as if neutral hadron (to 1st order)
  - reconstructed tracks
    - only considers charged particles
  - reconstructed particles (new in CMS!)
    - links tracks to calorimeter clusters → complete list of { $e^{\pm}, \mu^{\pm}, h^{\pm}, h^{0}, \gamma$ }
    - dramatically improved performance!

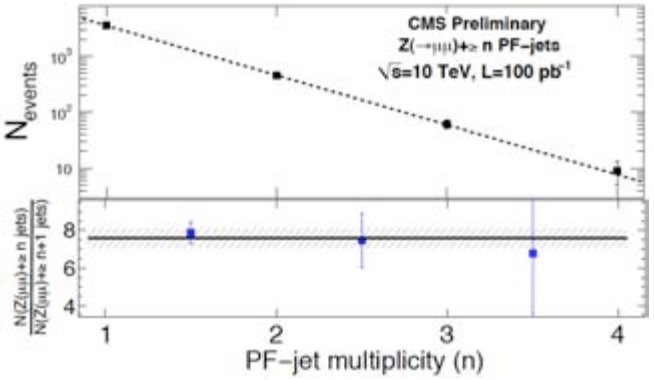
Z + 4 Jets

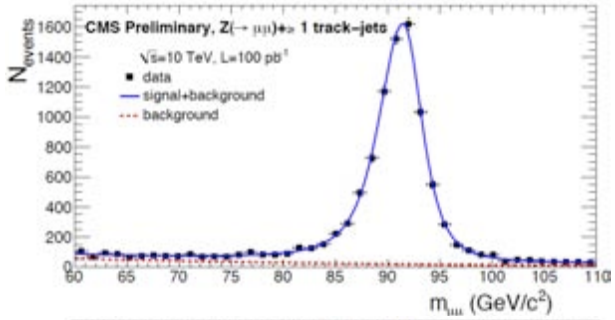
Fermilab
UIC University of Illinois at Chicago

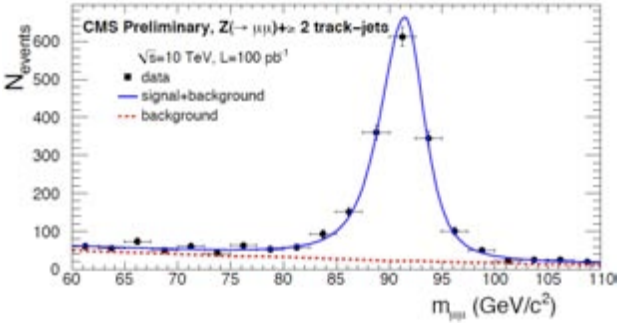
- CMS EWK-08-006
- Goal: investigate n/(n+1) ratio
  - probe new physics with multijets and Z's in final state
- Generators:
  - MADGRAPH+PYTHIA; PDFs from CTEQ6L1
- High Jet Multiplicities require small background subtraction
  - derive by inverting lepton isolation

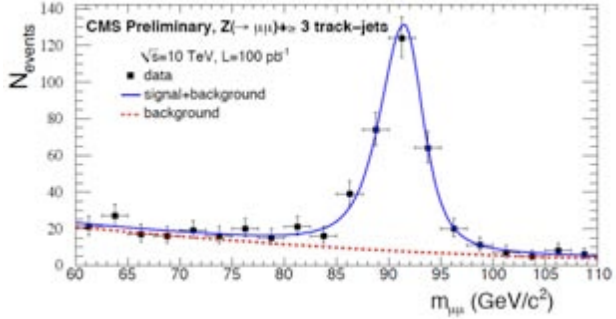


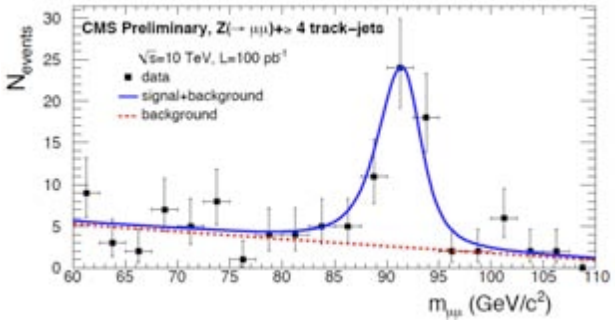
- Expected Berends-Giele scaling obtained







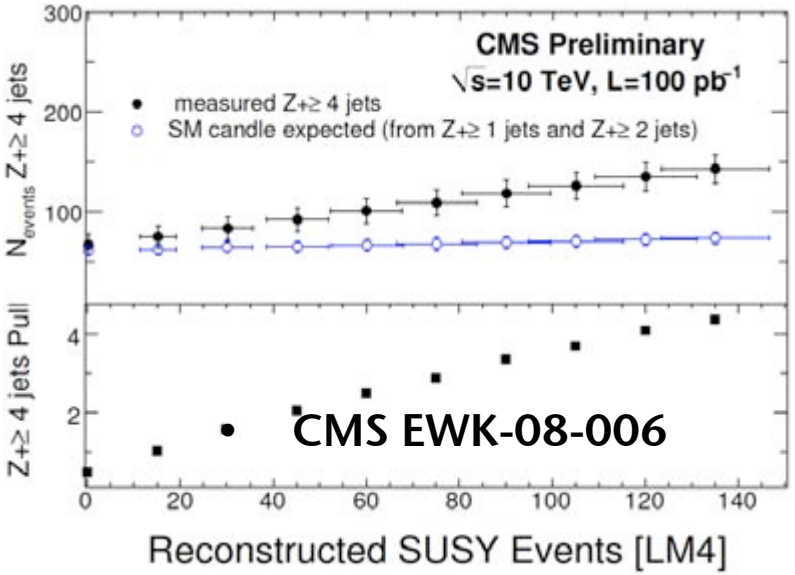




Probe Possible New Physics

Fermilab
UIC University of Illinois at Chicago

- Demonstrate sensitivity to breaking of Berends scaling
  - Consider LM SUSY benchmark with neutralino decays to Z's
    - Form sample with SM background and some admixture of SUSY signal
  - Predict N ≥ 4 jets using the ≥ 1 and ≥ 2 jet yields

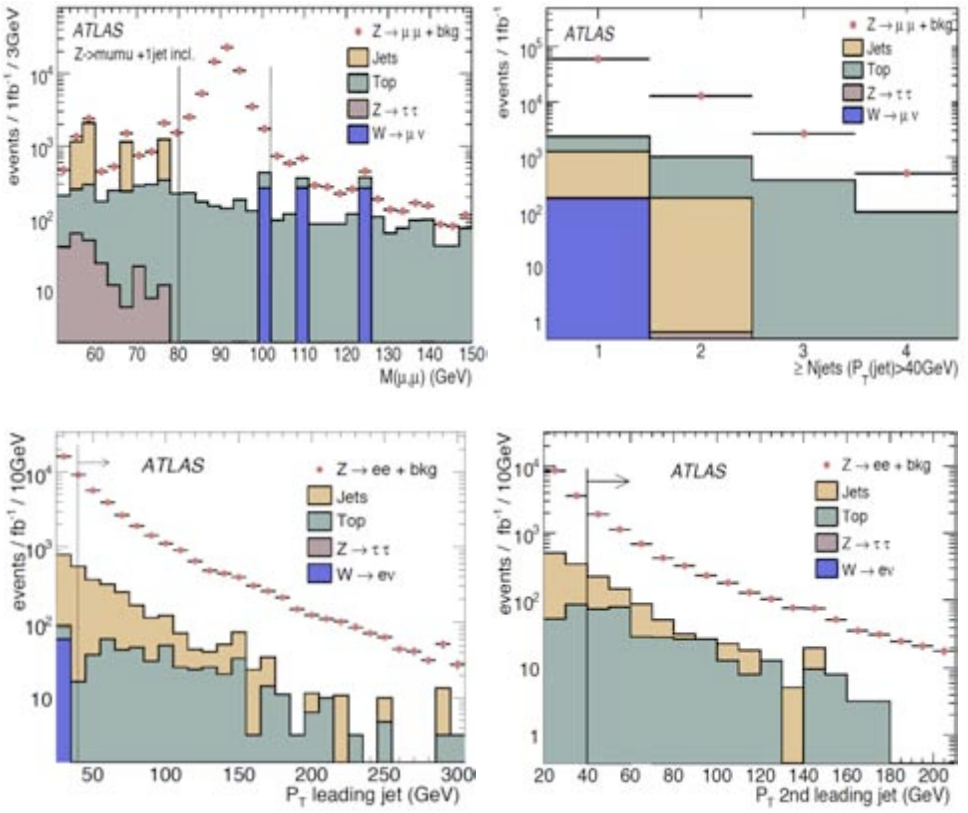


- With 100 pb-1, convincing Discrepancy could be seen between measured vs predicted for high multiplicities
  - Simultaneous discrepancy from calorimeter jets and track jets very unlikely

Z+Jets differential x-sections

Fermilab
UIC University of Illinois at Chicago

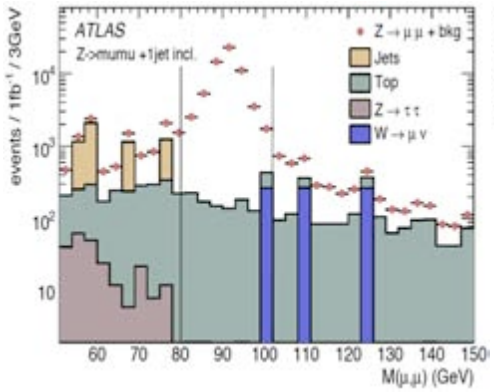
- What can be expected with 1 fb-1?
  - at 14 TeV
- Theoretical Codes:
  - MCFM v5.1 + LHAPDF 5.2.3
    - corrected for had, UE
  - ALPGEN v2.05 + HERWIG
    - $\mu_r = \mu_f = M(Z)^2 + p_T(Z)^2$
    - CTEQ6LL
  - PYTHIA v6.323 (V+Jets)
    v6.403 (tt, QCD)
- pT(Jet) > 40 GeV; R = 0.4
- pT(e,mu) > 25 GeV, 15 GeV

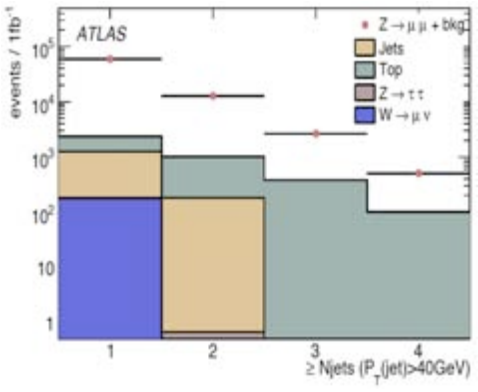


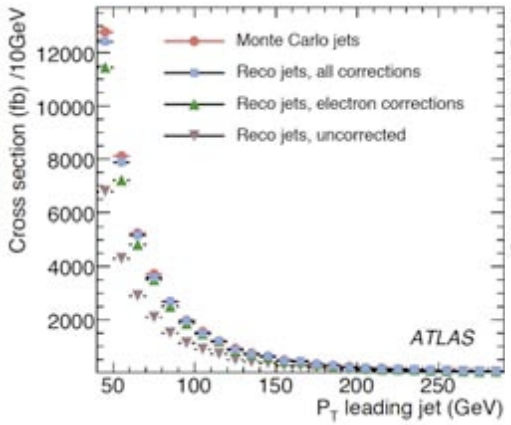
Z+Jets differential x-sections

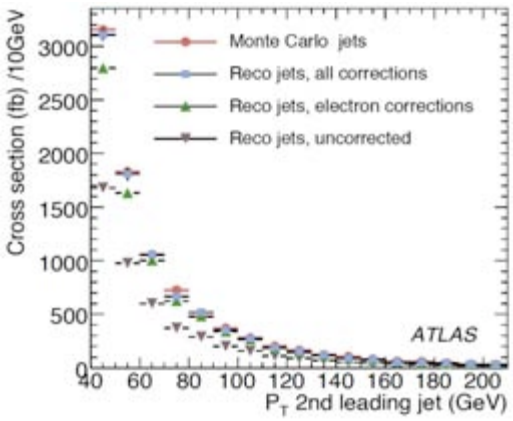
Fermilab
UIC University of Illinois at Chicago

- What can be expected with 1 fb-1?
  - at 14 TeV
- Theoretical Codes:
  - MCFM v5.1 + LHAPDF 5.2.3
    - corrected for had, UE
  - ALPGEN v2.05 + HERWIG
    - $\mu_r = \mu_f = M(Z)^2 + p_T(Z)^2$
    - CTEQ6LL
  - PYTHIA v6.323 (V+Jets)
    v6.403 (tt, QCD)
- pT(Jet) > 40 GeV; R = 0.4
- pT(e,mu) > 25 GeV, 15 GeV
- Subtract Backgrounds
- Correct for lepton ID and trigger efficiency (largest effect)
- Correct for non-linear Jet energy scale, Jet energy resolution, jet reconstruction efficiency





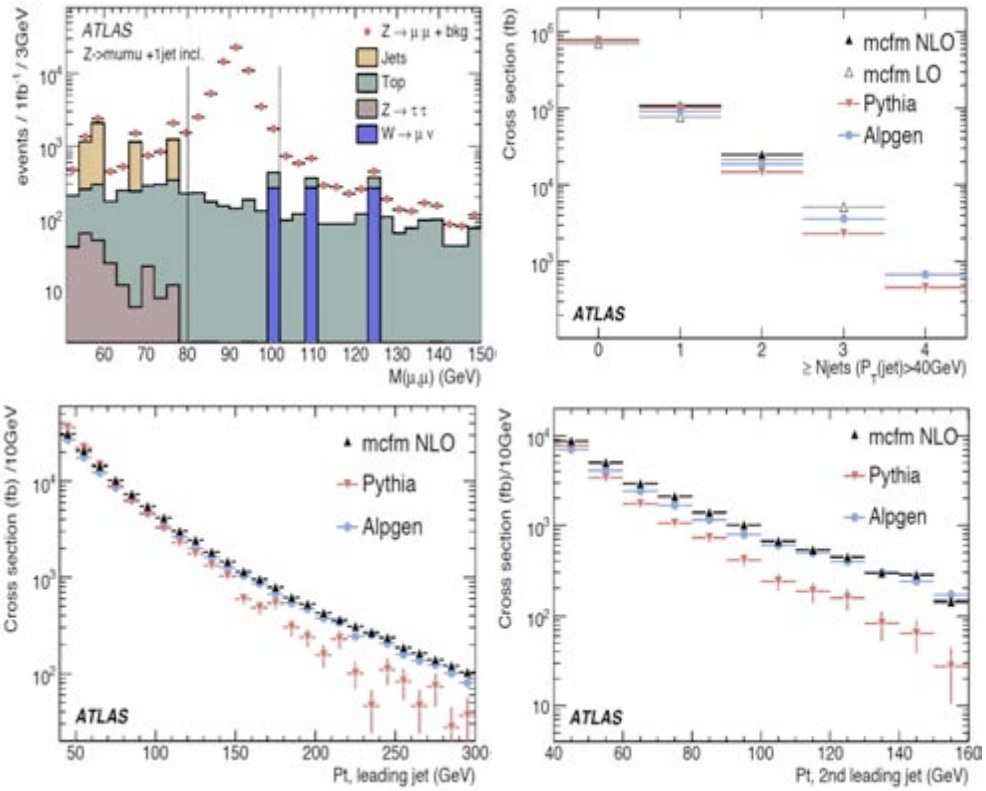




Z+Jets differential x-sections

Fermilab
UIC University of Illinois at Chicago

- What can be expected with 1 fb-1?
  - at 14 TeV
- Theoretical Codes:
  - MCFM v5.1 + LHAPDF 5.2.3
    - corrected for had, UE
  - ALPGEN v2.05 + HERWIG
    - $\mu_r = \mu_f = M(Z)^2 + p_T(Z)^2$
    - CTEQ6LL
  - PYTHIA v6.323 (V+Jets)
    v6.403 (tt, QCD)
- Compare with pseudo data:
  - Jet Multiplicity
  - Leading Jet pT
  - Prediction: MCMF with hadronization & underlying event corrections
  - Pseudo-data: ALPGEN with unfolding corrections
- Good agreement: Successful "closure" test!



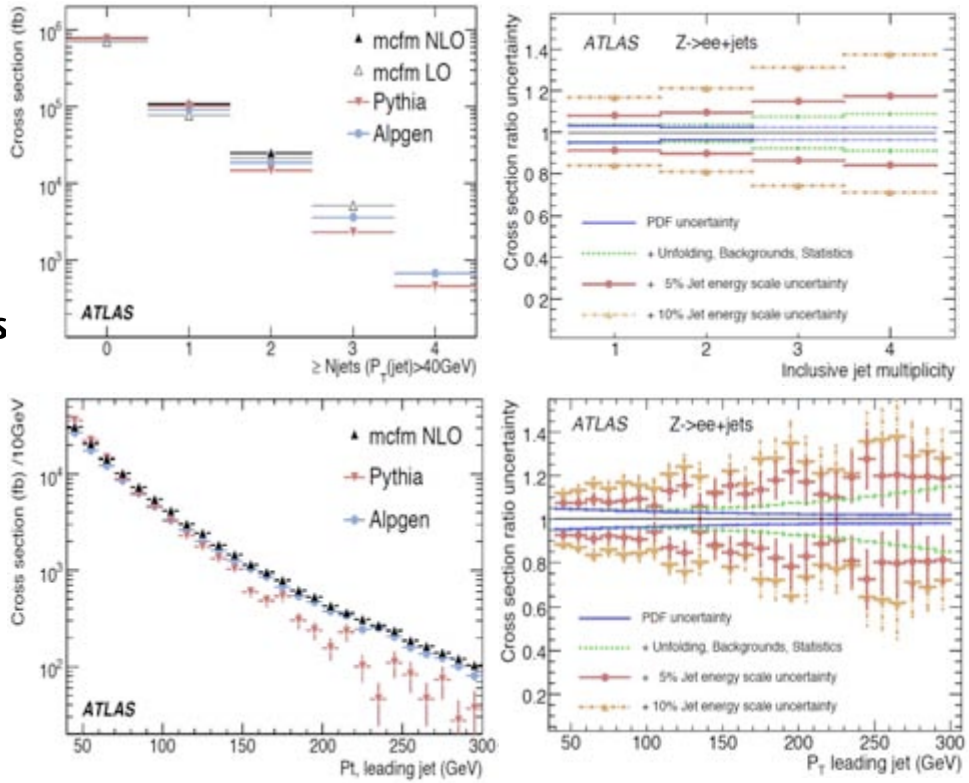
Z+Jets differential x-sections

Fermilab
UIC University of Illinois at Chicago

- What can be expected with 1 fb-1?
  - at 14 TeV
- Compare PseudoData/Theory and effect of systematic uncertainties
  - If ratio PseudoData/Theory = 1 what are the uncertainties?
- Jet Energy Scale uncertainty of 5% > sum of all other uncertainties
- PDF uncertainties small,
- Statistical errors increase with Njets, Ptjet

- Recall:
  - LO/NLO difference ~20-30%, Alpgen-Pythia-MCFM~10-60%
- But:
  - σ(JES) = 5% → Total Exp. Unc. = 10-20%
    σ(JES) = 10% → Total Exp. Unc. = 20-30%

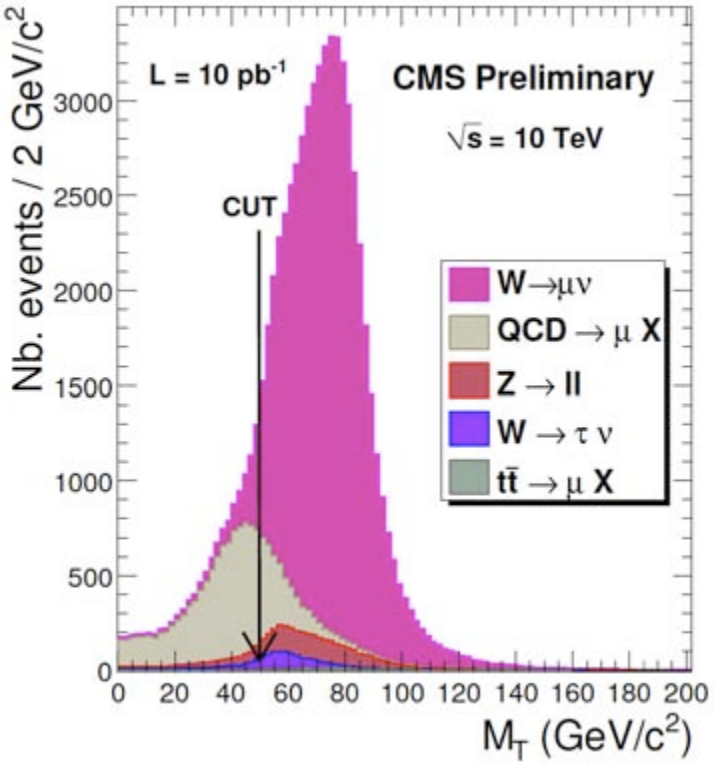
Systematic Uncertainties

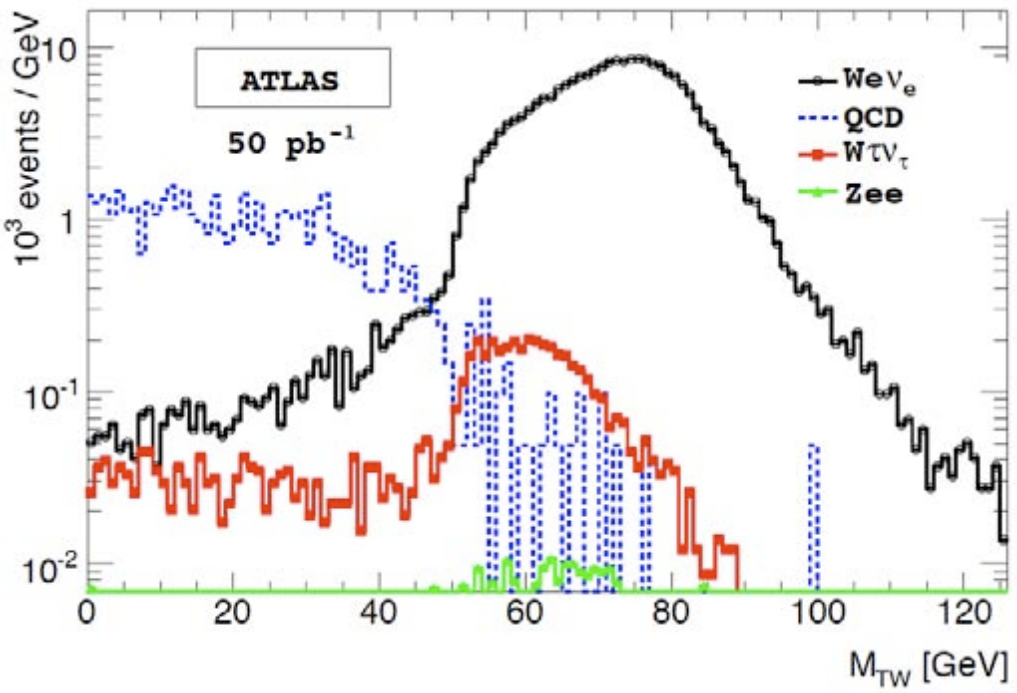


Would not distinguish LO/NLO predictions or between predictions of different generators!

Inclusive W production

- As at Tevatron, low backgrounds for ≥ 0 jets case
  - Background estimation still needed, though

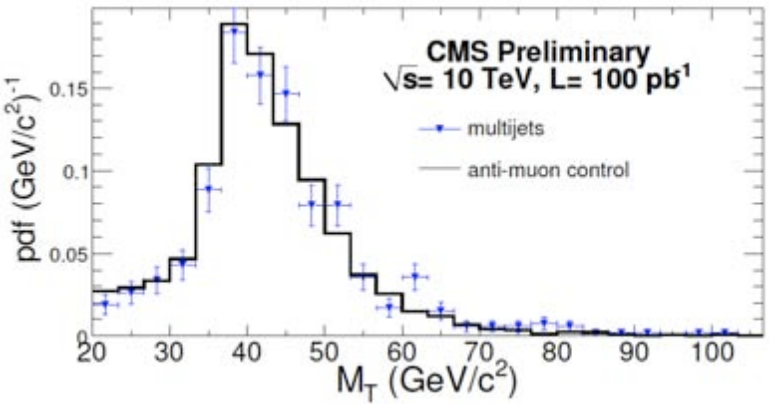


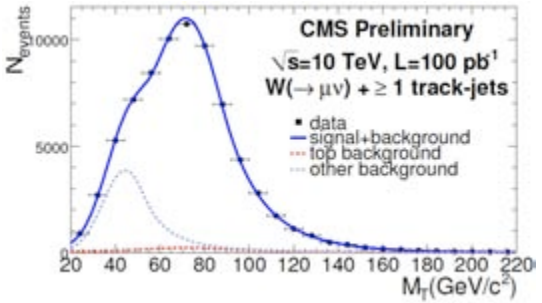


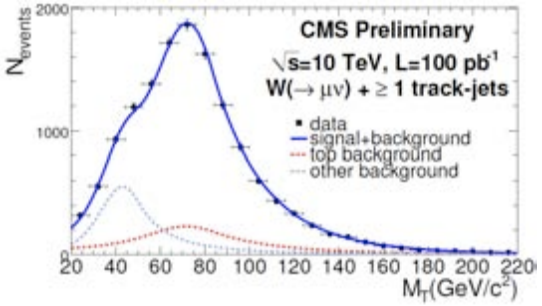
W + 4 jets

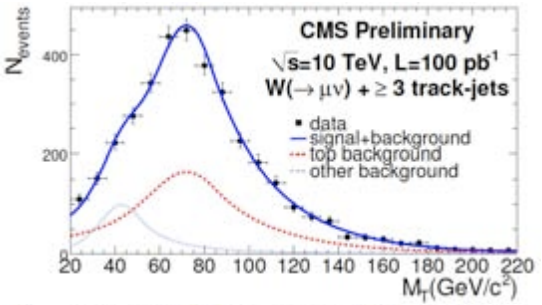
Fermilab
UIC University of Illinois at Chicago

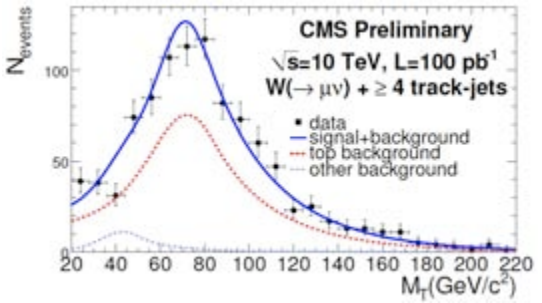
- CMS EWK-09-006
- At Low jet multiplicity
  - QCD backgrounds dominate
  - apply “anti lepton-isolation”
    - derive QCD background control sample







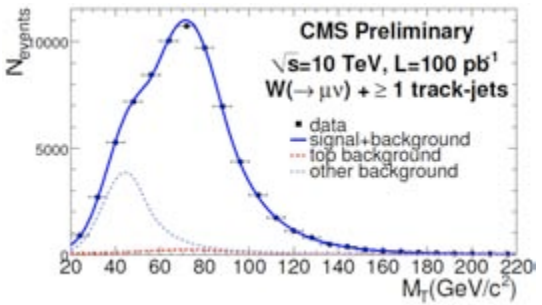


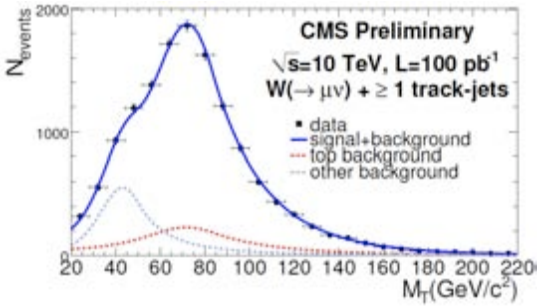


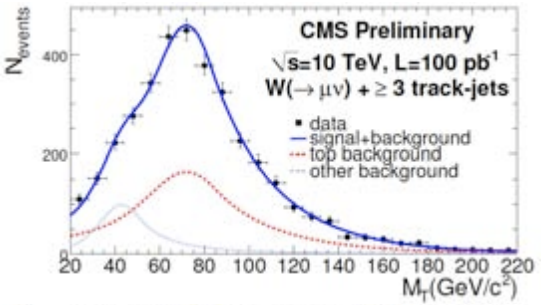
W + 4 jets

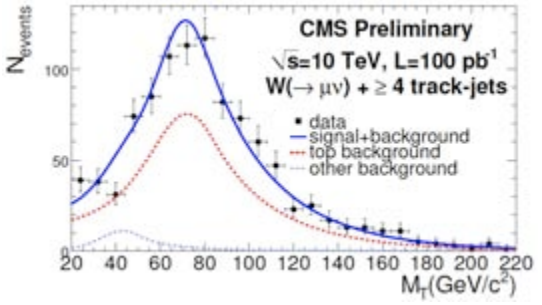
Fermilab
UIC University of Illinois at Chicago

- CMS EWK-09-006
- At High jet multiplicity
  - top backgrounds dominate
  - apply “anti b-tag”
    - derive top background control sample





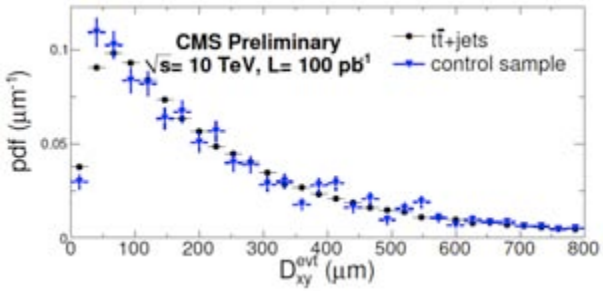


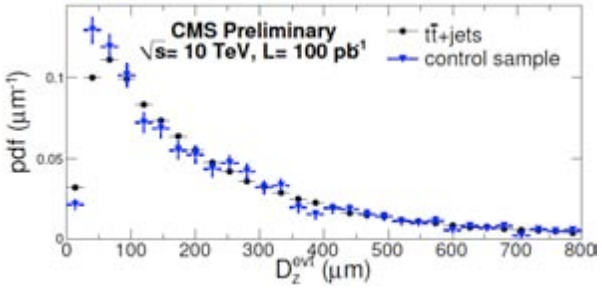


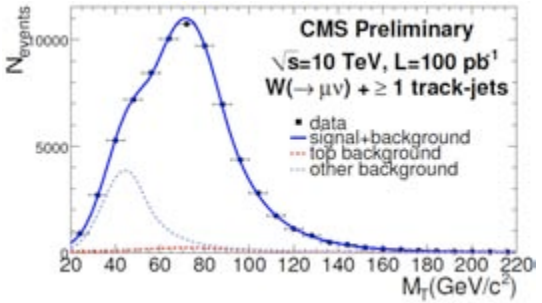
W + 4 jets

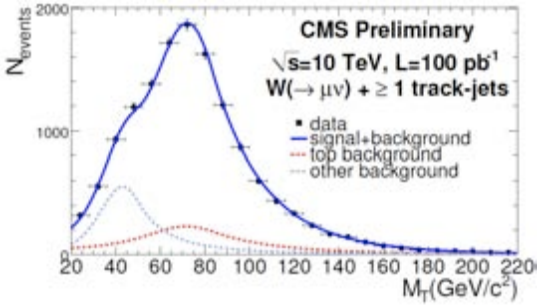
Fermilab
UIC University of Illinois at Chicago

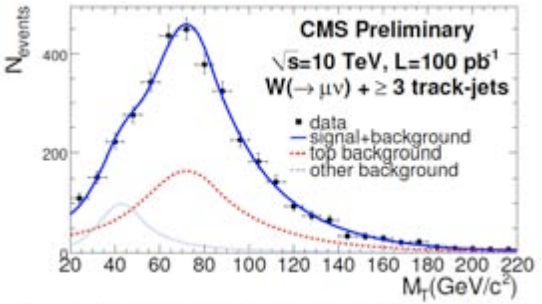
- CMS EWK-09-006
- At High jet multiplicity
  - top backgrounds dominate
  - apply “anti b-tag”
    - derive top background control sample

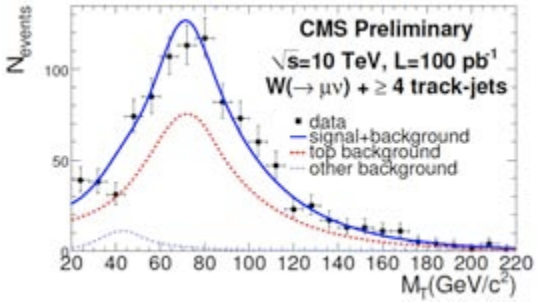








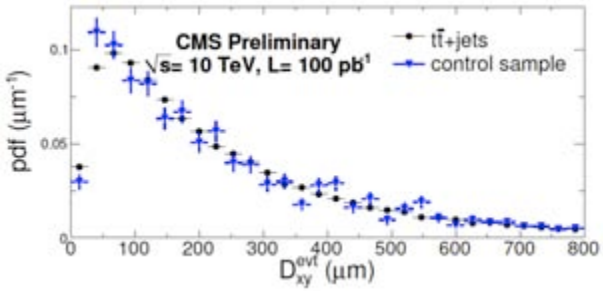


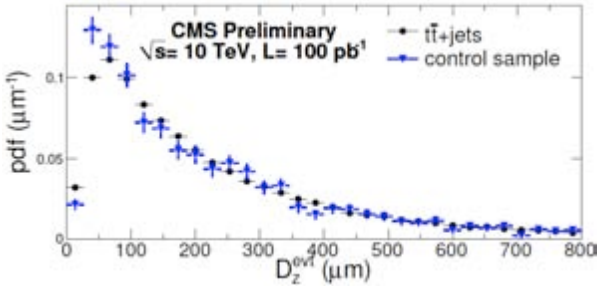


W + 4 jets

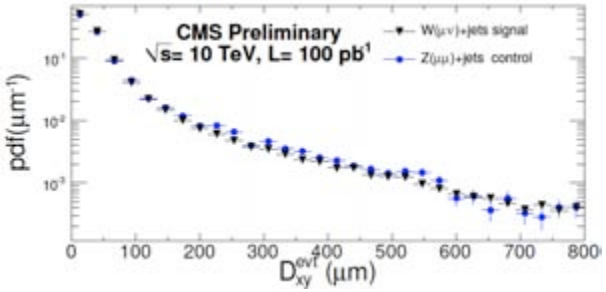
Fermilab
UIC University of Illinois at Chicago

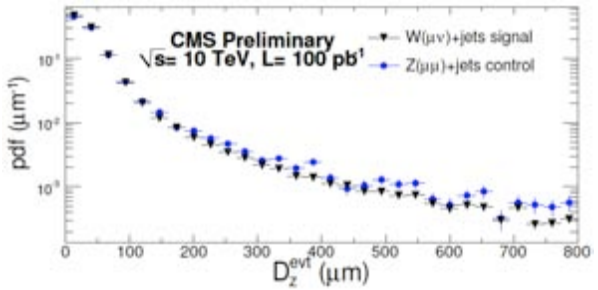
- CMS EWK-09-006
- At High jet multiplicity
  - top backgrounds dominate
  - apply “anti b-tag”
    - derive top background control sample

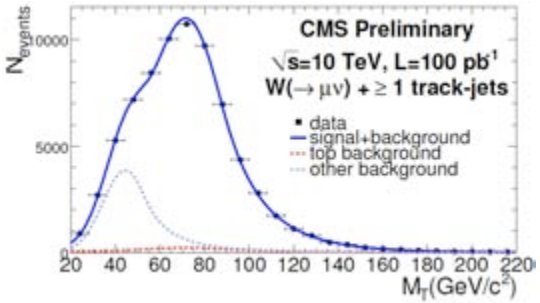


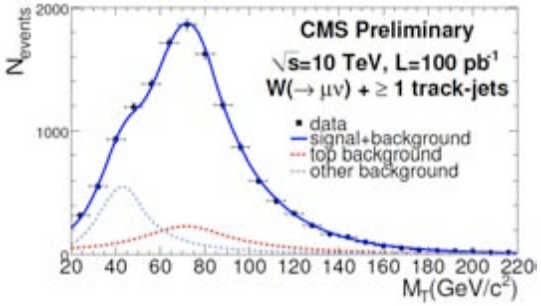


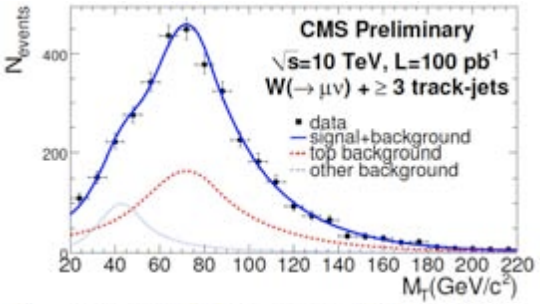
- use Z+Jets sample: throw away one lepton
  - provides W signal control sample

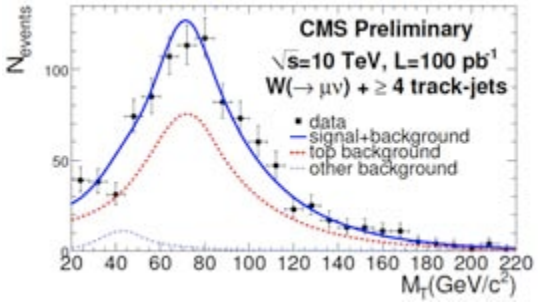








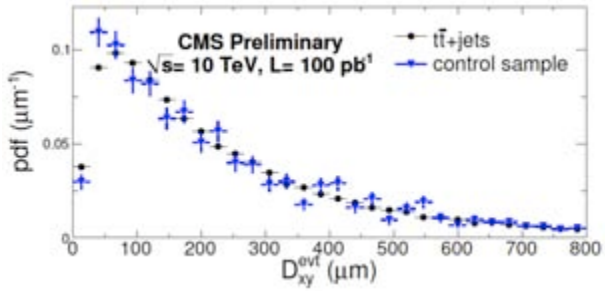


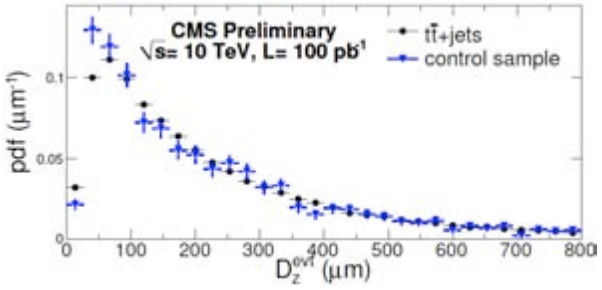


W + 4 jets

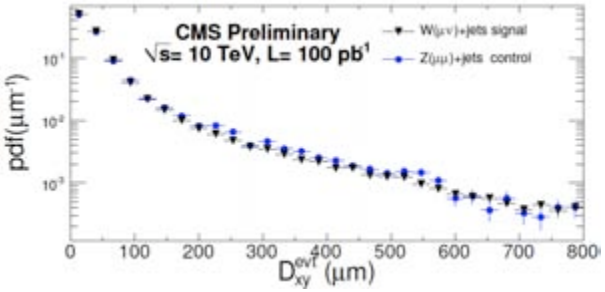
Fermilab
UIC University of Illinois at Chicago

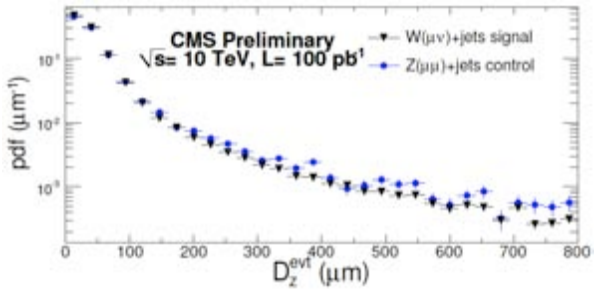
- CMS EWK-09-006
- At High jet multiplicity
  - top backgrounds dominate
  - apply “anti b-tag”
    - derive top background control sample



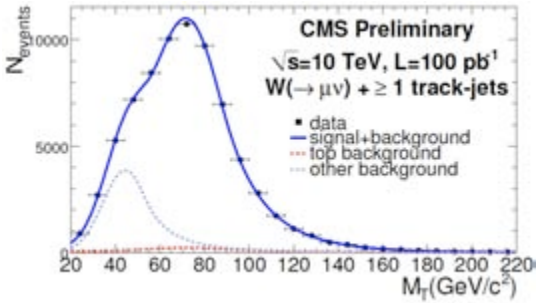


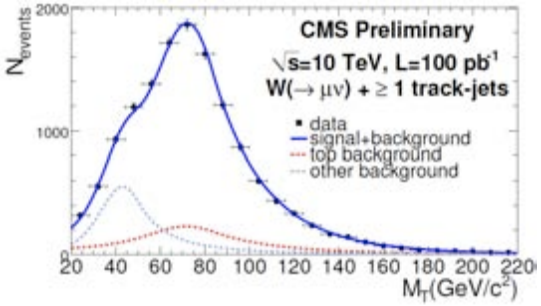
- use Z+Jets sample: throw away one lepton
  - provides W signal control sample

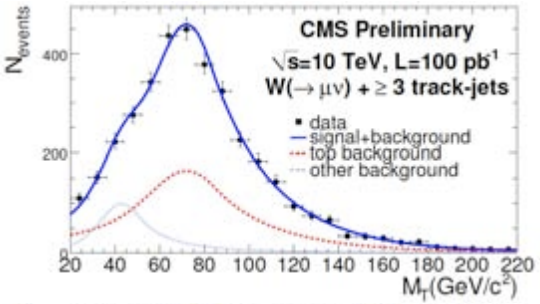


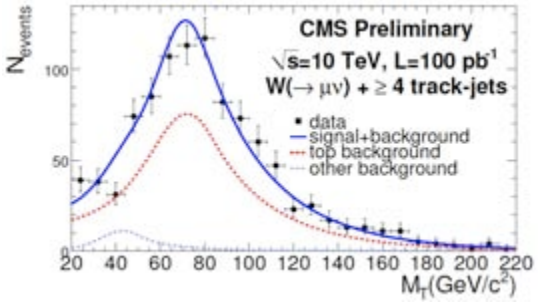


- important to help convince we understand Dxy
- cross check for signal yield (assumes Z x-sect)









Summary

Fermilab
UIC University of Illinois at Chicago

- Study of multijets in W and Z production at Hadron Colliders
  - important handle for commissioning detector performance,
  - provides precision tests of perturbative QCD predictions.
- Most difficult backgrounds (estimated with data)
  - at Tevatron: QCD multijets
  - at LHC: QCD multijets & ttbar
- Precision of
  - inclusive W/Z cross-section is 2% (both Tevatron & LHC), dominated by systematic uncertainties
  - W/Z+jets differential cross-sections decreases with increasing the jet multiplicity (5-30%).
    - dominated by jet energy scale uncertainty at low pT: < 3% needed for a reliable data-theory comparison
    - dominated by background estimation at high pT
- Personal guess for LHC 100 pb^{-1}: jet counting papers
  1 fb^{-1}: differential x-sect. papers