Measurement of Z/γ^* + jets differential cross sections with the CDF detector

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PhD defense

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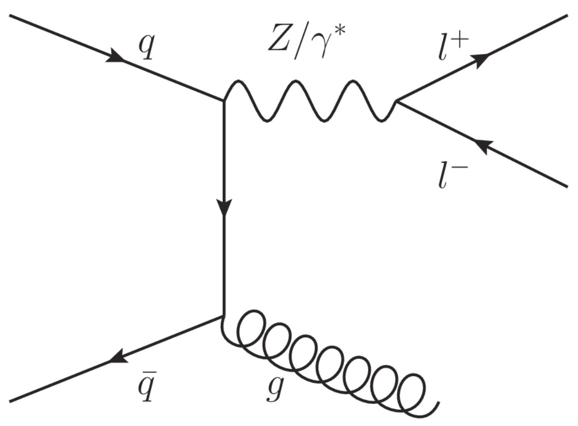
Z/γ^* + jets differential cross sections

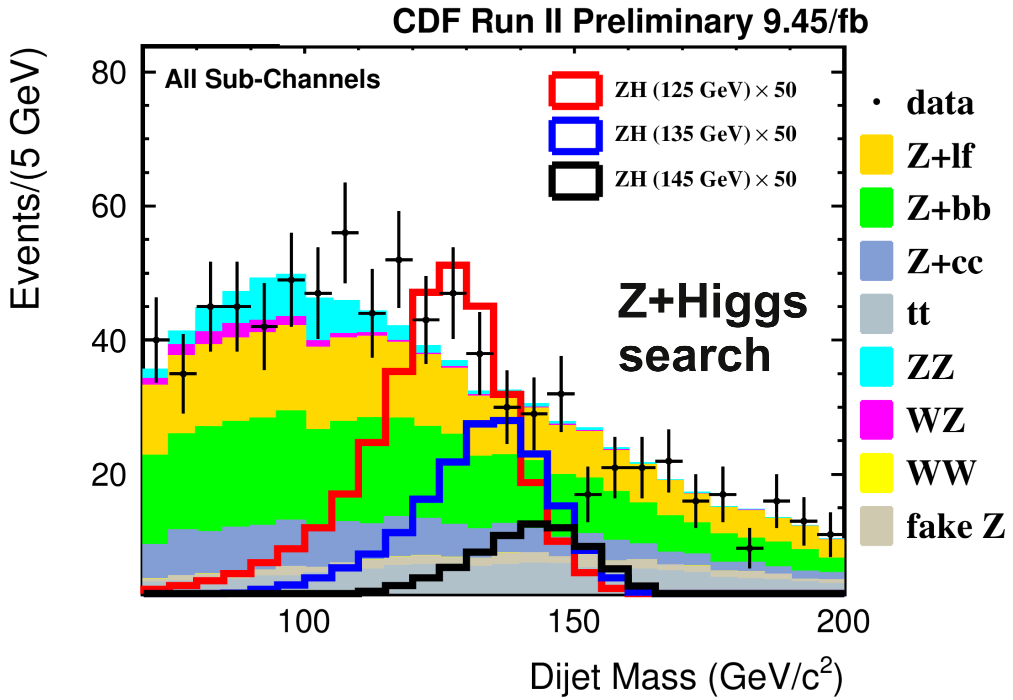
- Motivation
- QCD and predictions at hadron colliders
- Tevatron and CDF
- Measurement of $Z/\gamma^* \rightarrow l^+l^-$ + jets
- Results

Motivation

Measure $Z/\gamma^* \rightarrow l^+l^-$ + jets with l = e, μ

- Clear signature





- Test perturbative QCD at high Q^2
- Background for rare SM processes (top, diboson, Higgs) and new Physics searches

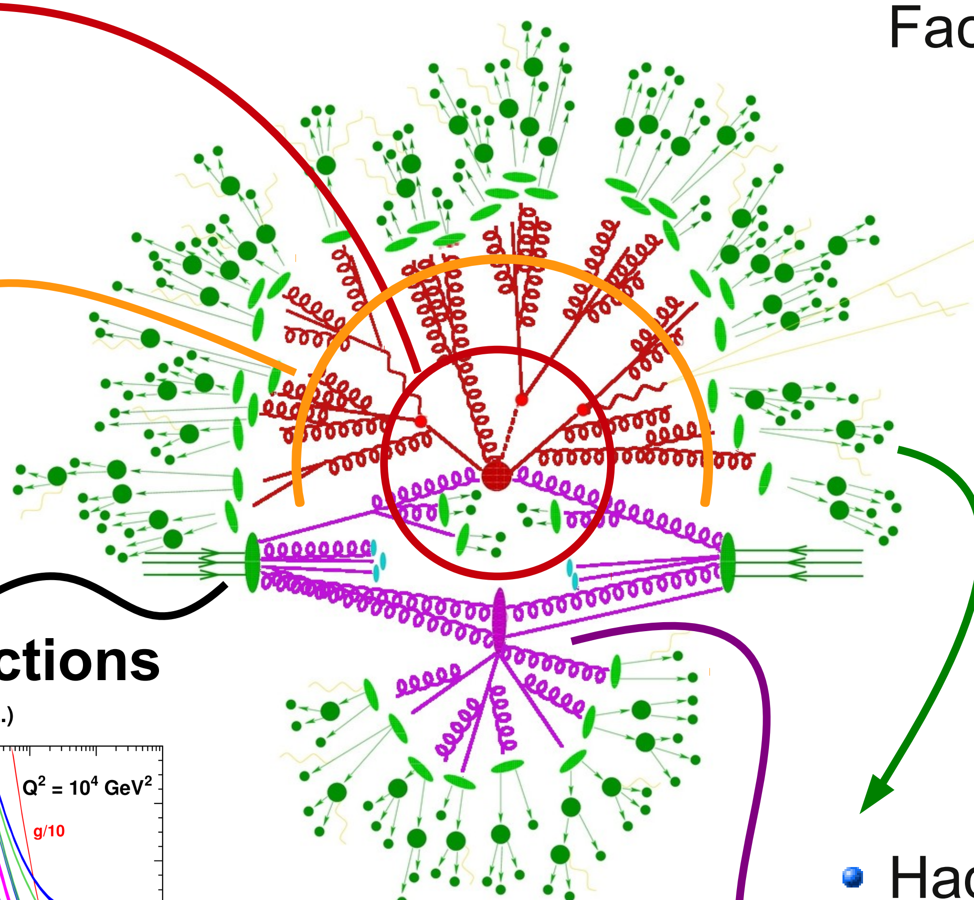
QCD predictions

Perturbative QCD

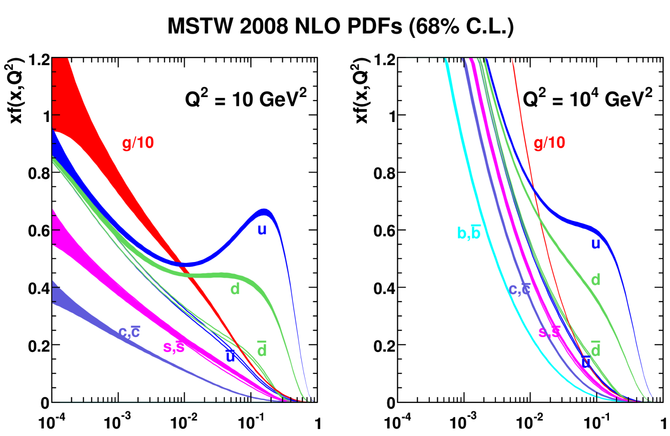
$$\sigma_{p\bar{p}\to X} = \Sigma_{i,j} \int dx_1 dx_2 f_i^p(x_1,\mu) f_j^p(x_2,\mu) \times \sigma_{i,j}$$

- **Hard scattering**
  - Fixed Order
  - Resummation
- Fragmentation
  - Parton Shower

Factorization



Parton Distribution Functions (PDF)



non-pQCD

- Hadronization
- Underlying Event

QCD predictions

Perturbative QCD

Hard scattering

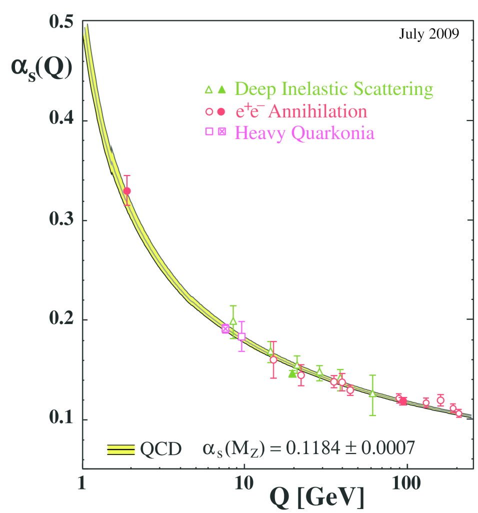
Fragmentation

Fixed order	LO - NLO
MLM-CKKW matching	Z+1, 2,...N jets ME-LO + PS
POWHEG merging	NLO + PS
LOOPSIM	Z+1, 2 jets NLO → approximate nNLO
Resummation	Resum log enhanced terms at all orders

PDF → Parametrization, analysis, input data...

non-perturbative QCD → Tune of phenomenological parameters

Absorb divergences → Renormalization scale, Factorization scale



Unphysical dependence of cross section on μ_R μ_F

↓

Handle to estimate theoretical uncertainty

Use the data to test the accuracy of the different models

Jet algorithms

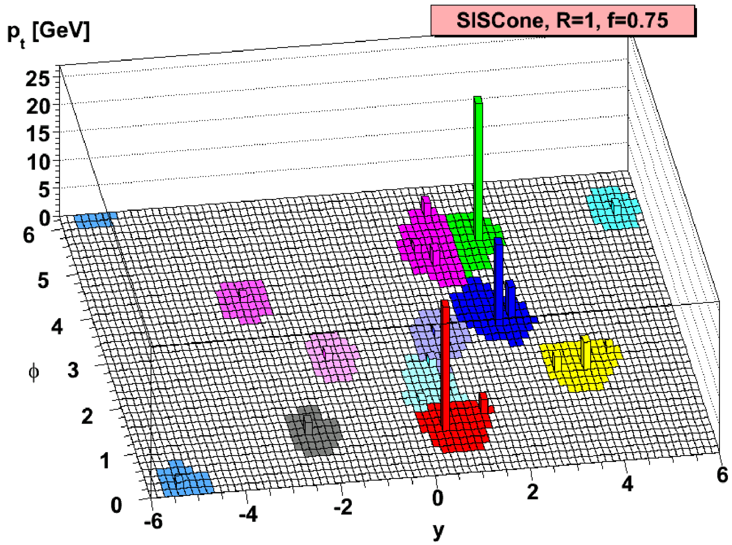
→ Cluster jets of collimated particles

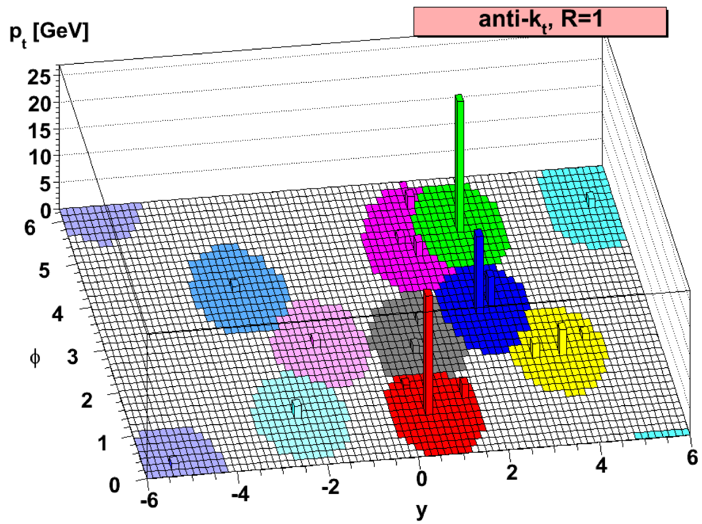
Iterative cone algorithms

- Cluster particles around a cone of radius R
- Split-merge or split-drop procedure to assign common particles
- IRC-unsafe when seeds are used
- Jetclu, midpoint, SIScone

Sequential recombination algorithms

- Define a distance DR between particles
- Cluster particles in order of increasing distance
- IRC-safe at all order
- kt, Cambridge/Aachen, anti-kt

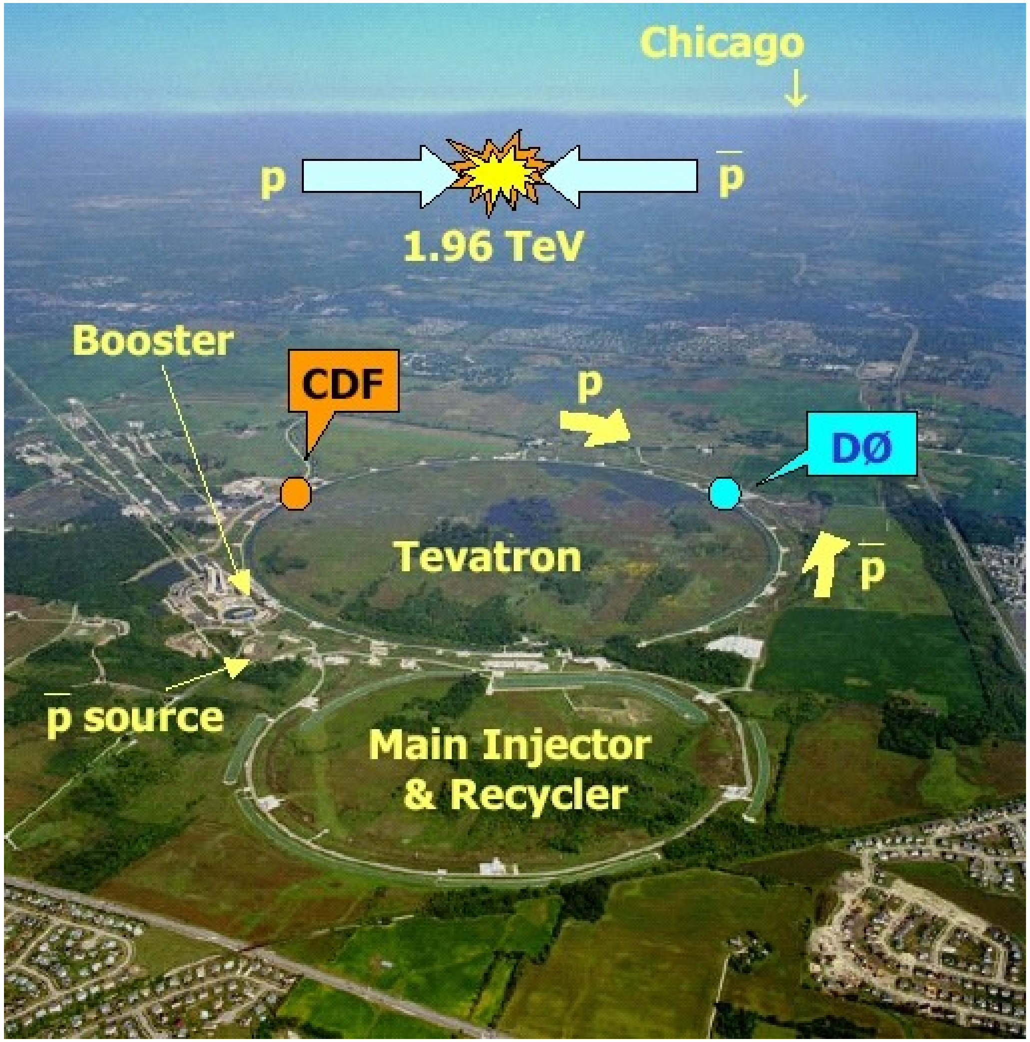




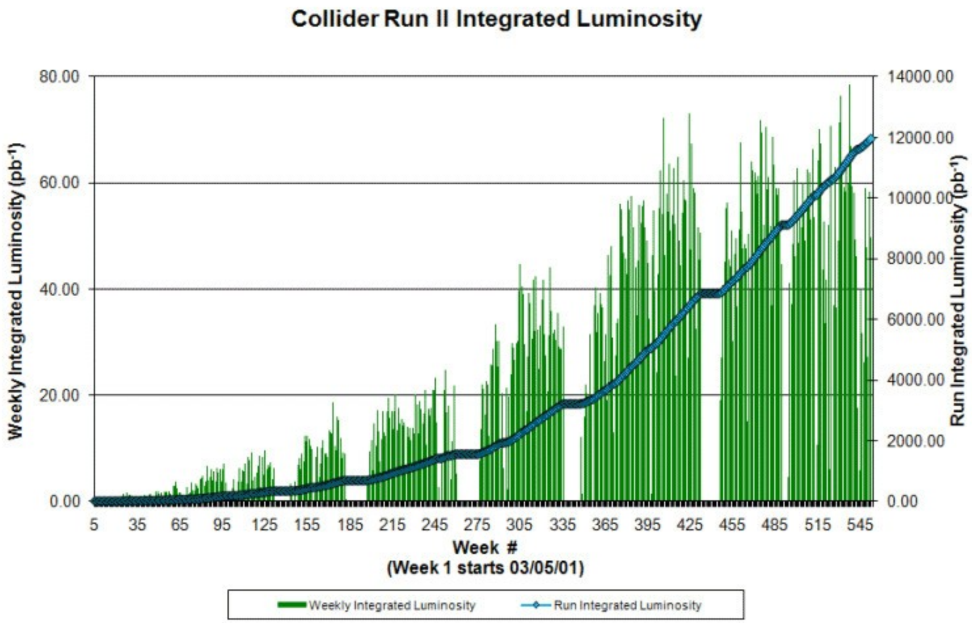
- There is not a “best choice” of algorithm and parameters
- Experimental calibration effort need to focus on few algorithms

Tevatron Run II

Full Tevatron Run II dataset
$\mathcal{L} = 10\ fb^{-1}$



- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Peak instantaneous luminosity ~ 4 x 10^{32} cm^{-2} s^{-1}
- 10 years of data acquisition: February 2002 – September 2011

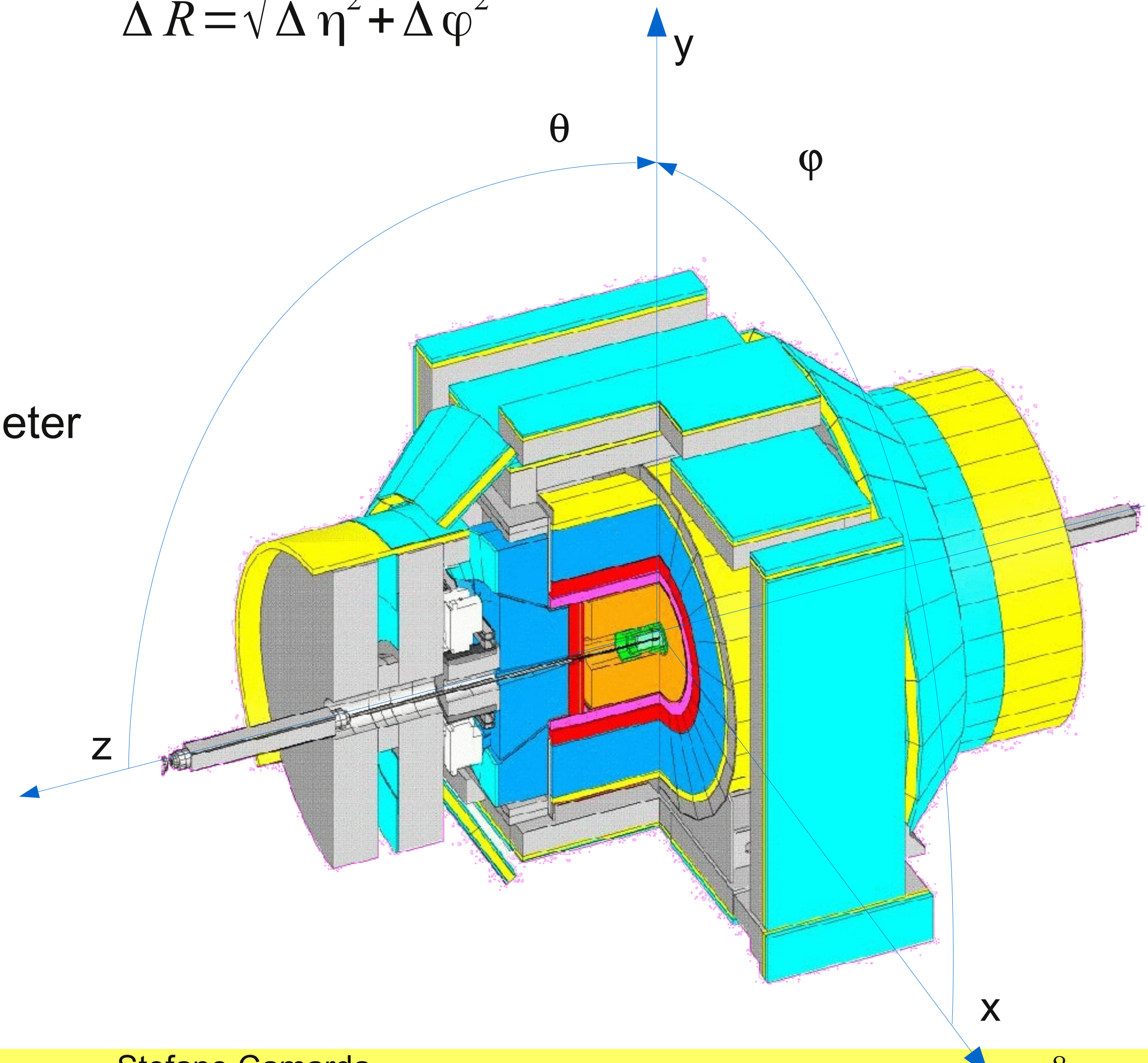


CDF Detector

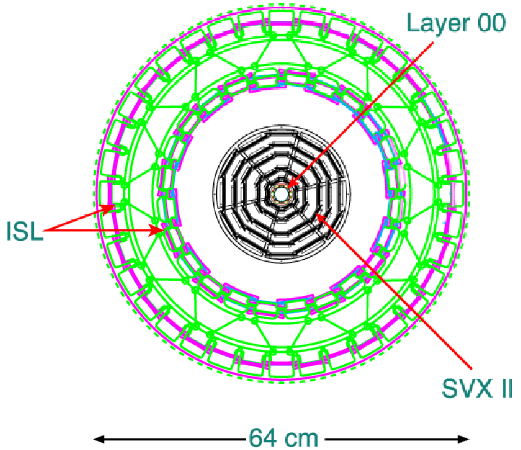
$$\eta = -\ln\left[\tan\left(\theta/2\right)\right]$$

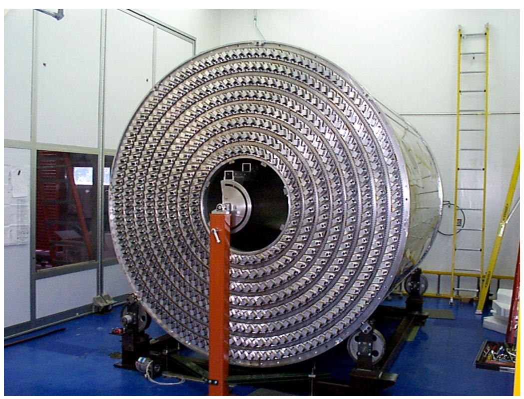
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

- Tracking system
  - Silicon detectors
  - Drift chambers COT
- 1.4 T Magnetic field
- Calorimeter
  - Electromagnetic calorimeter
  - Hadronic calorimeter
- Muon detectors
  - Wire chambers
  - Scintillators
- 3 Level Trigger System
  - 1.75 MHz → ~ 100 Hz

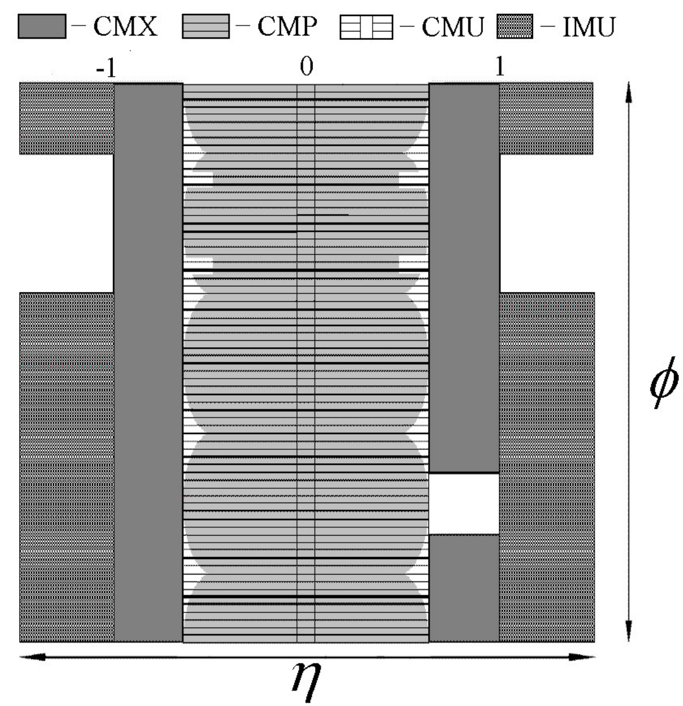


CDF Detector

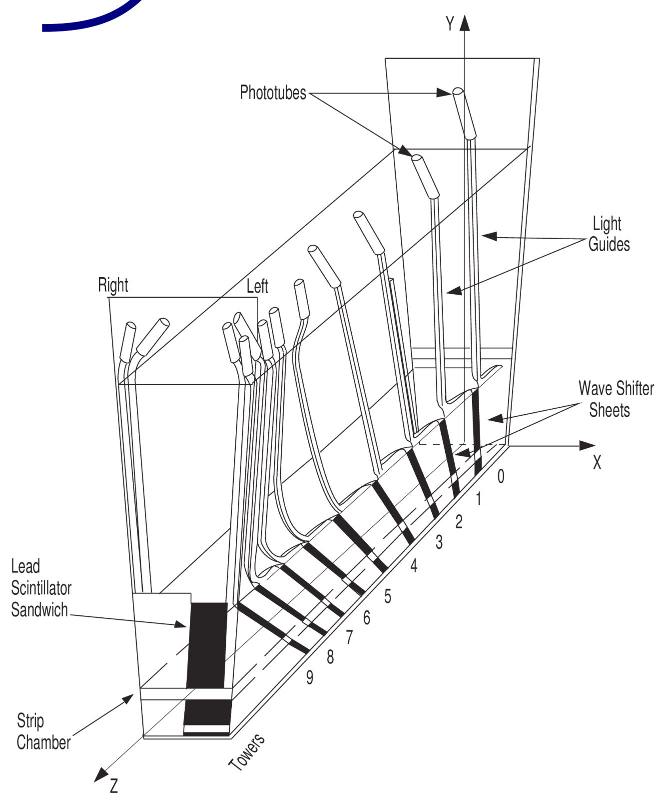




Tracking
- Muon 4-momentum
- Electron angular coordinates



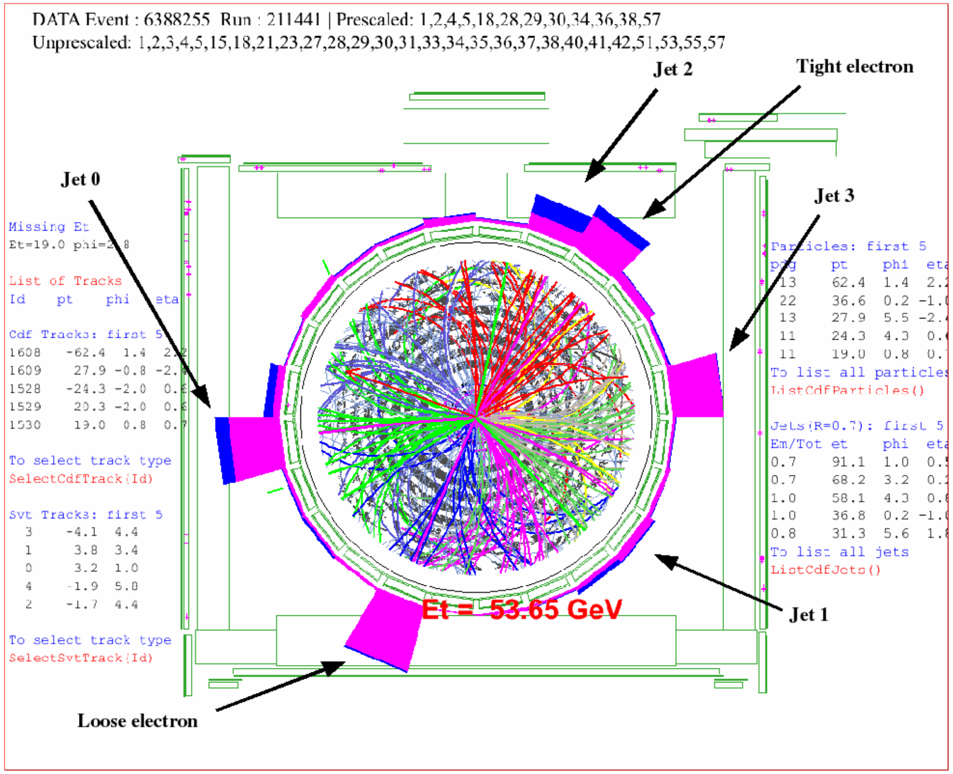
Muon chambers
- Muon trigger
- Muon ID



Calorimeter
- Electron Energy
- Hadronic jets reconstruction
- Muon ID

Z/γ* → l^+l^-+ jets measurement

- Muons, Electrons, Z → l^+l^- and Jets reconstruction
- Background estimation
- Z → l^+l^- inclusive cross section
- Unfolding
- Systematic uncertainties
- Z/γ* → e^+e^- and Z/γ* → $\mu^+\mu^-$ Combination



Event selection and Monte Carlo samples

High p_T leptons are used to trigger Z/γ^* + jets events

Leptons
- $E_T^e \geq 25$ GeV, $p_T^\mu \geq 25$ GeV/c
- $|\eta^l| \leq 1$

Z/γ^*
- Two electrons or muons
- $66 \leq M_{Z \to ll} \leq 116$ GeV/c^2
- Opposite charged muons

Jets
- $p_T > 30$ GeV/c
- $|y| < 2.1$

Monte Carlo Samples

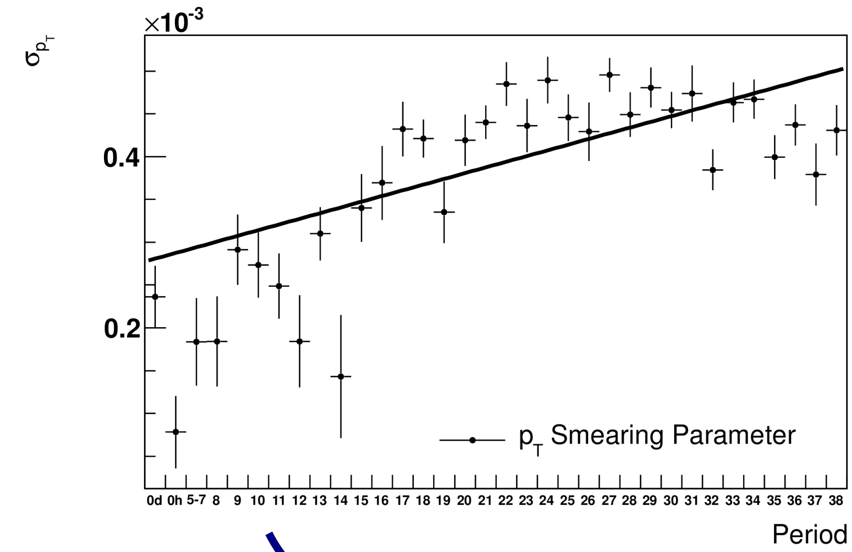
Process	Generator
Z/γ^* + jets	ALPGEN+PYTHIA
$Z/\gamma^* \to l^+l^-$	PYTHIA
EW and QCD backgrounds	PYTHIA

Lepton reconstruction

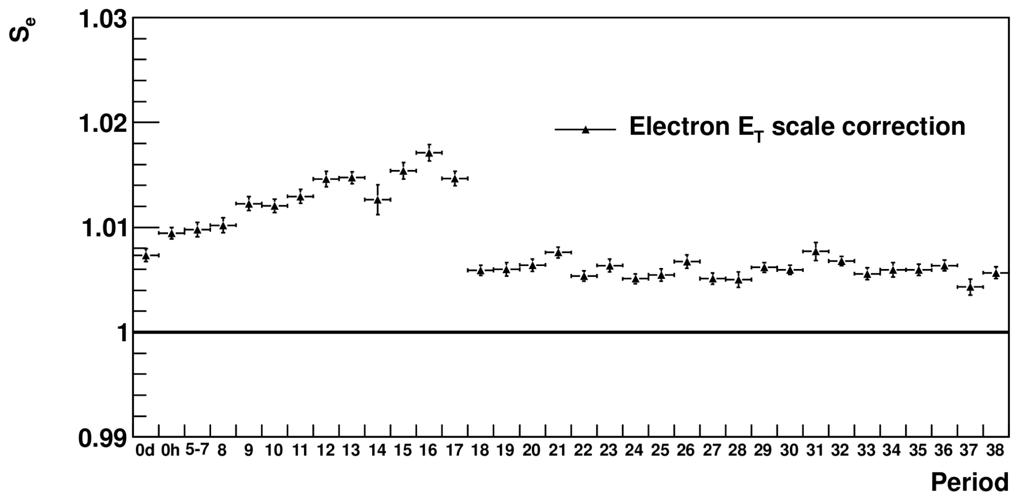
Leptons reconstructed from tracks associated to energy deposit in the calorimeters

Ad-hoc lepton reconstruction and identification

- No isolation requirements
  → multijet environment
- Beam constrained tracks
  → prompt leptons from Z decay
- Muons fake rejection cuts



Correct muon p_T resolution in Monte Carlo



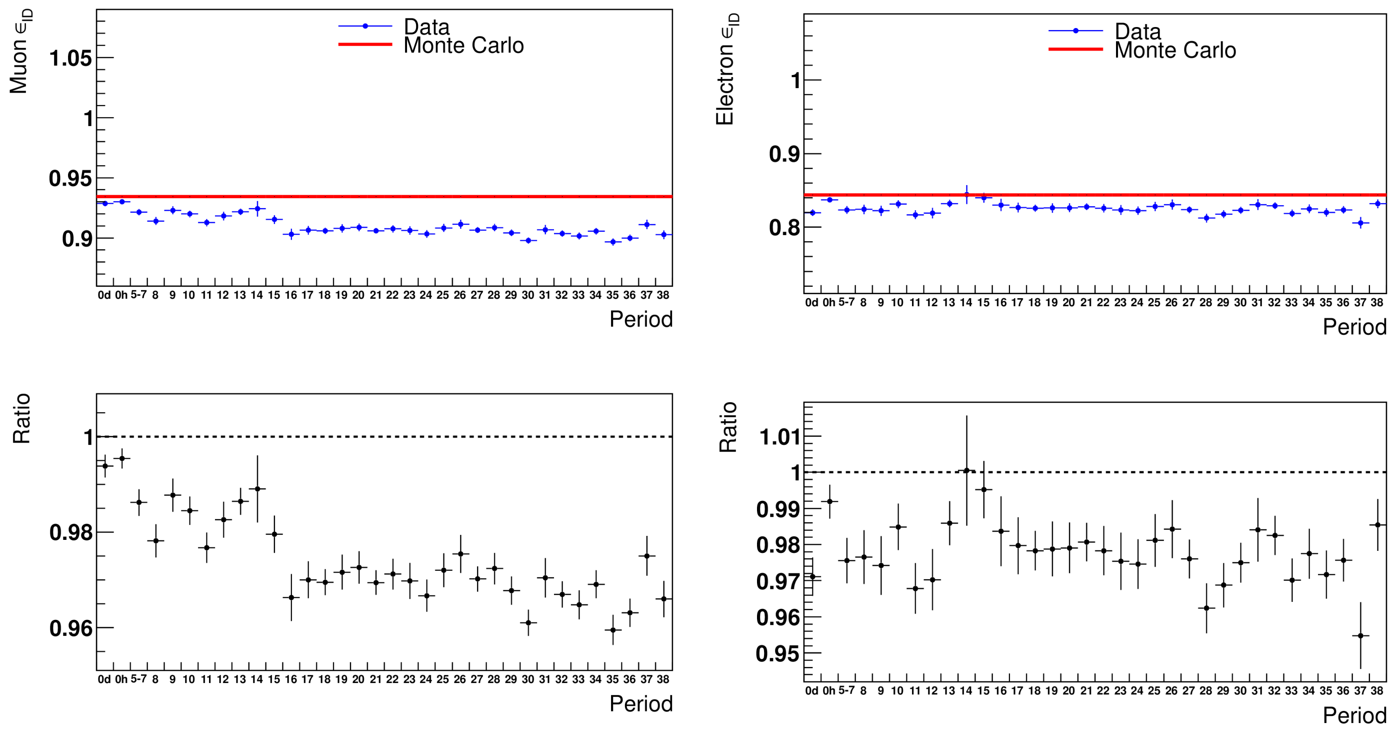
Correct muon p_T and electron E_T scale in data

→ **Improved reconstruction**

Trigger and lepton ID efficiencies

Exploit Z → ll leptons to evaluate efficiencies

- tag–probe legs method



Trigger efficiencies evaluated accounting for correlation with the lepton selection

All efficiencies evaluated as a function of data taking time
→ account for variations in detector conditions

→ Improved measurement accuracy

Jet reconstruction

Cluster calorimeters towers

CDF Run II midpoint algorithm

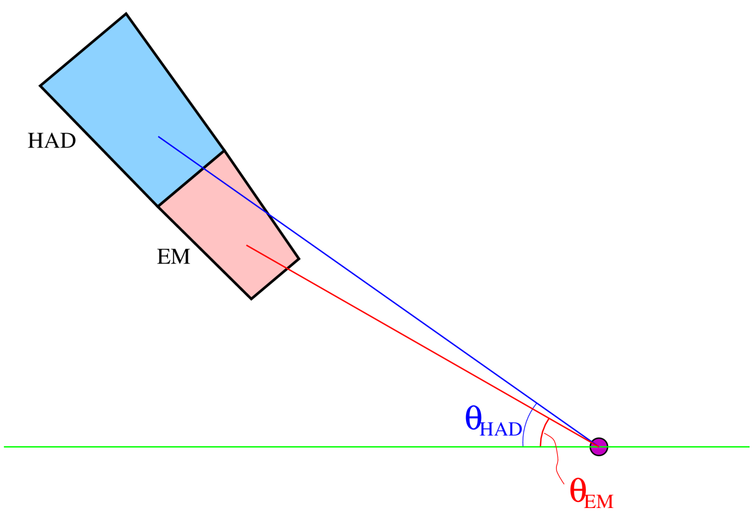
- Iterative Cone jet algorithm
- Split-Merge procedure
- E-scheme recombination

Jet parameters:

- R = 0.7
- Overlap threshold f = 0.75
- Seed p_T = 1 GeV/c

Ad-hoc reconstruction

Calorimeter cluster associated to electrons and muons are removed before jet clustering



z-coordinate of primary vertex taken as reference point for clustering

Jet energy corrections

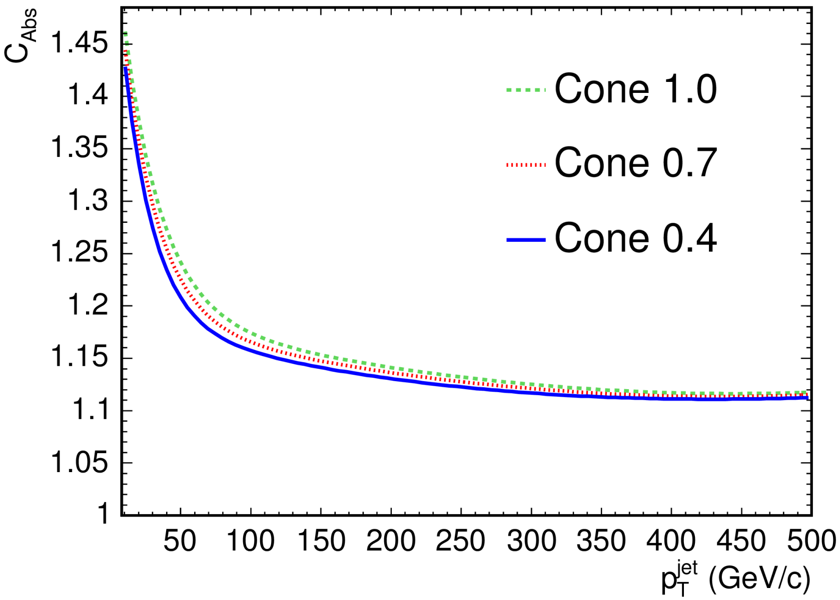
Jet energy is corrected to remove detector effects combining several correction factors

$$p_T = [p_T^{raw} \times f_\eta - f_{p\bar{p}I}] \times f_{jes}$$

- Single track E/p energy calibration
- f_η |η| dependent correction to correct for gaps and different response
- f_{ppI} Pile-up of multiple pp interaction, parametrized as a function of the number of additional interaction vertexes
- f_{jes} Absolute jet energy scale

Jet energy corrections validated with γ + jet to check stability as a function of data taking time

Nucl.Instrum.Meth. **A566 (2006) 375-412**

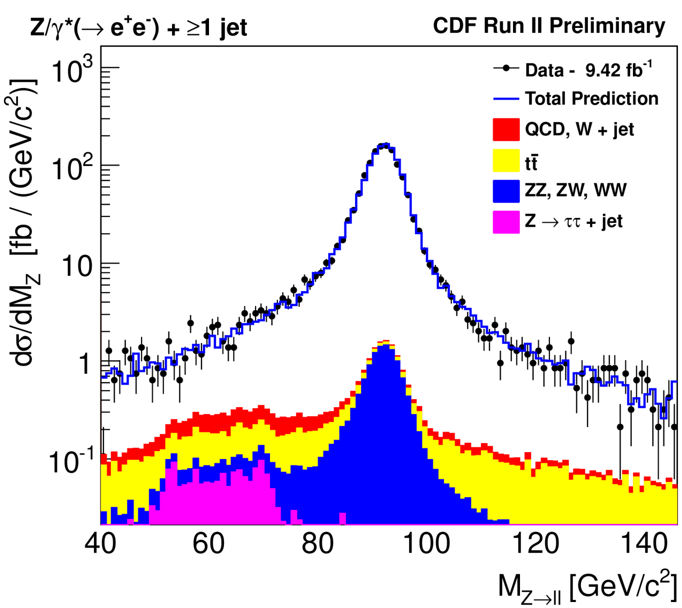


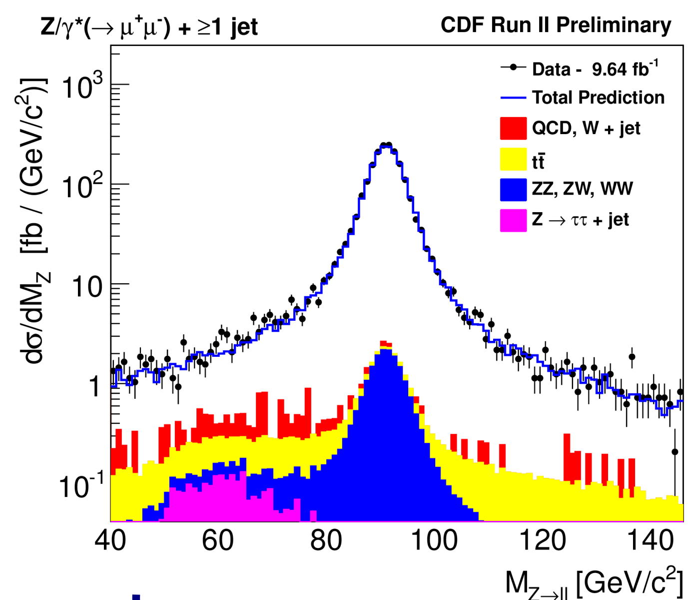
Background estimation

MC backgrounds
- Top
- Diboson WW, WZ, ZZ
- $Z \rightarrow \tau\tau$ + jets

Data driven backgrounds
- multi-jet
- W + jets

Muons → Same charge
Electrons → Jet fake rate

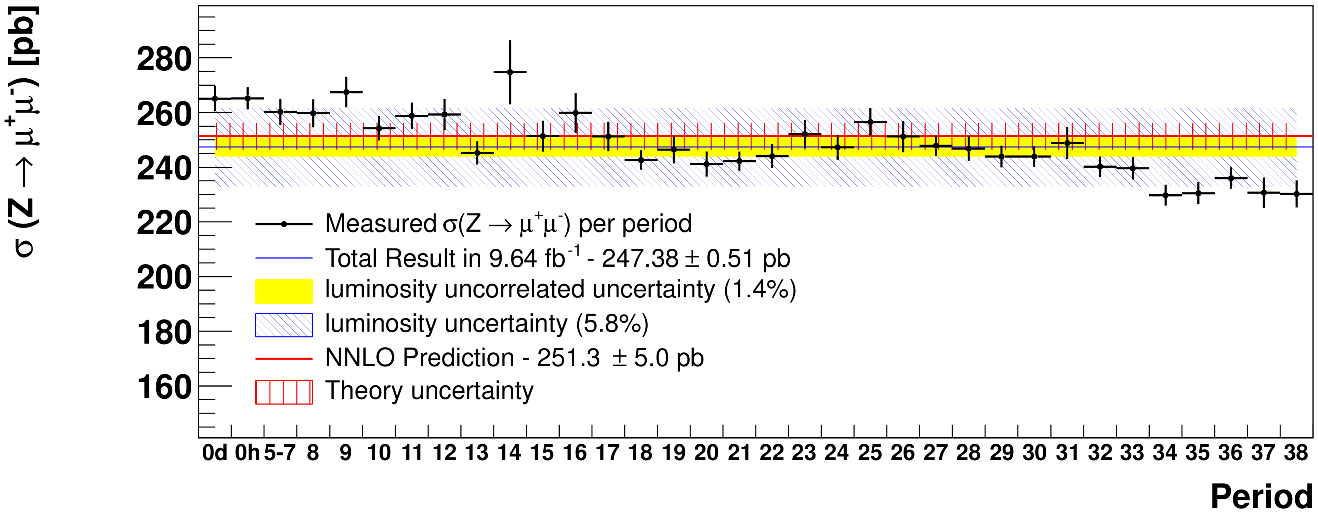




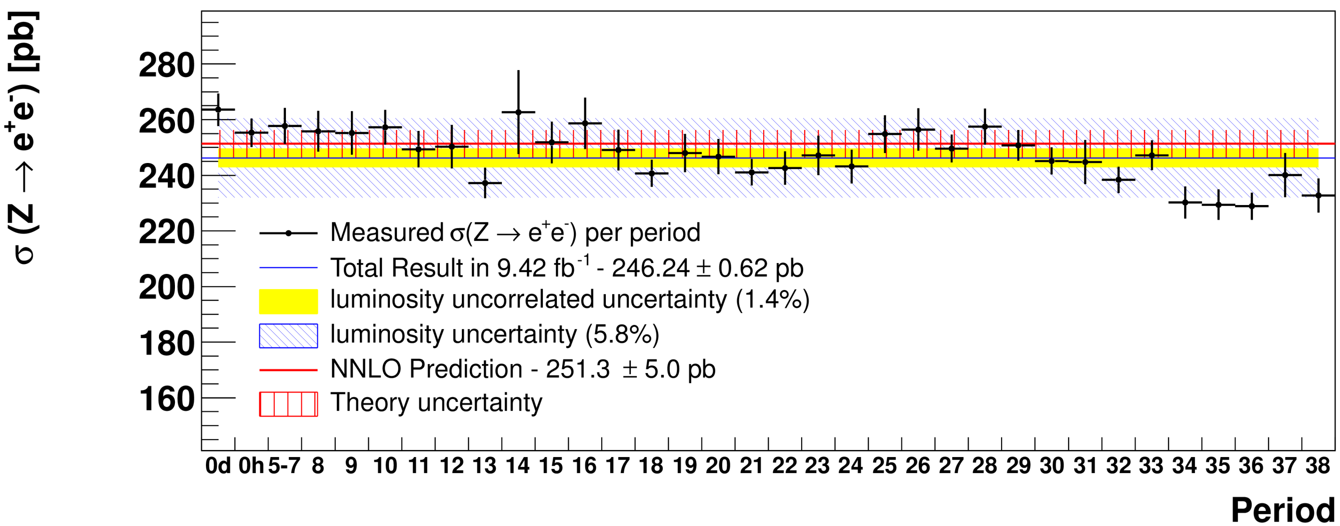
- Side bands provide check of background estimation
- Good modeling of Z invariant mass peak

Low background contamination between 2% - 10%

Z/γ* → l^+l^- Cross section



Inclusive $\sigma(pp \rightarrow Z \rightarrow l^+l^-)$ provides a stringent test of lepton reconstruction and efficiencies



Check stability of measured cross section as a function of data taking time

$Z/\gamma^* \to l^+l^-$ Cross section

	Measured Cross Section ± stat ± lumi [pb]
$Z/\gamma^* \to \mu^+\mu^-$	246.24 ± 0.62 ± 14.3
$Z/\gamma^* \to e^+e^-$	247.38 ± 0.51 ± 14.3
NNLO prediction	251.3 ± 5.0

Excellent agreement between $Z/\gamma^* \to \mu^+\mu^-$ and $Z/\gamma^* \to e^+e^-$ channels within 0.2% statistical uncertainty

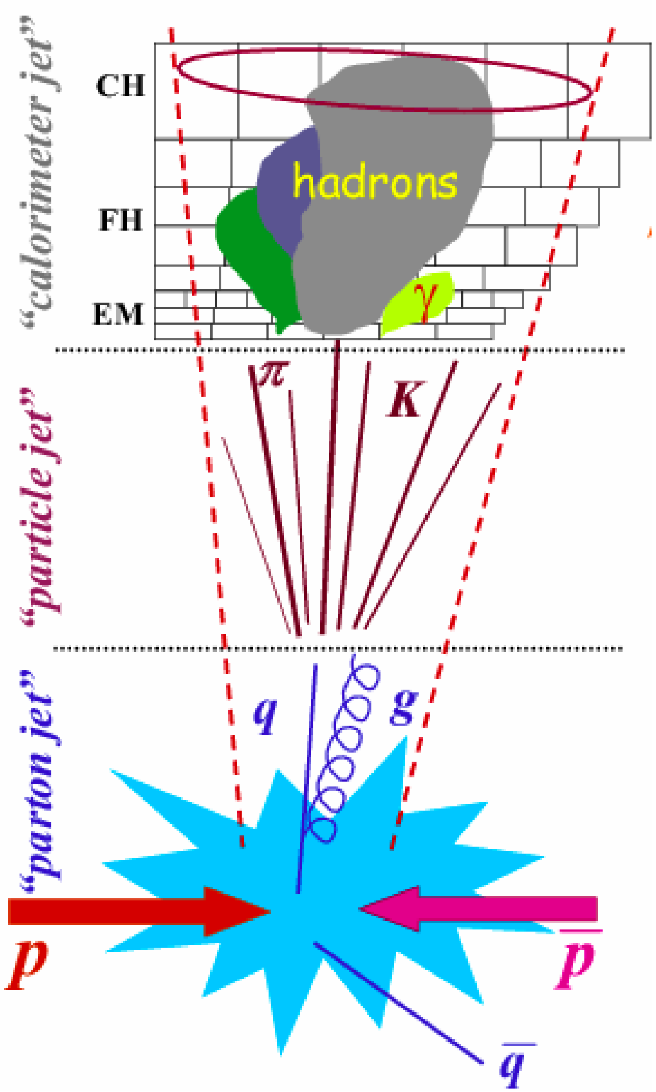
→ Good control over lepton ID and trigger efficiencies

Z/γ* + jets measurement definition

$$\frac{\Delta\sigma}{\Delta\alpha} = \frac{N^{data} - N^{bkg}}{L} \cdot U$$

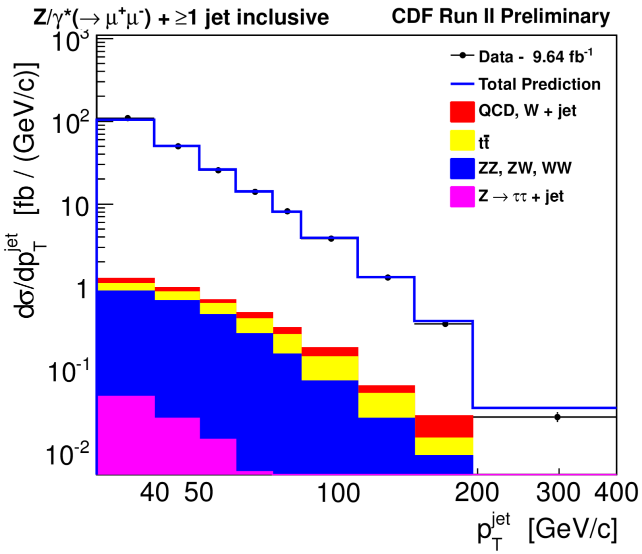
Detector level cross sections unfolded back to particle (hadron) level

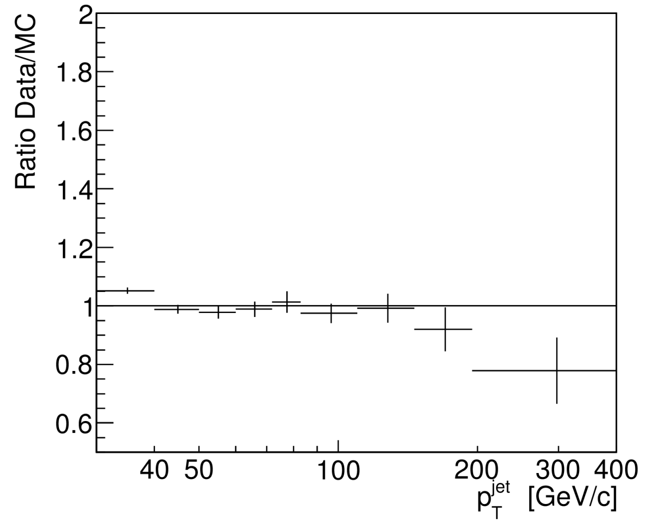
- Measurement defined at particle level in the same kinematic region of detector objects
  → avoid extrapolation uncertainty
- Applied photon lepton recombination in $\Delta R_{l\text{-}\gamma} < 0.1$
  → allows inclusion of NLO EW corrections
- Z + γ process included in the definition of Z + jets



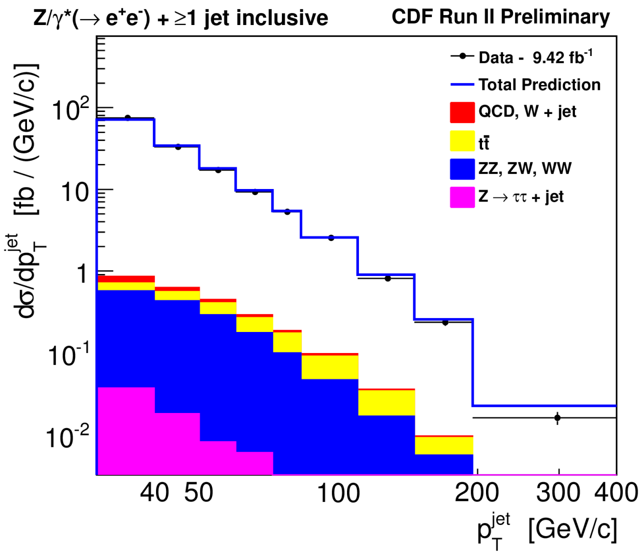
Detector level

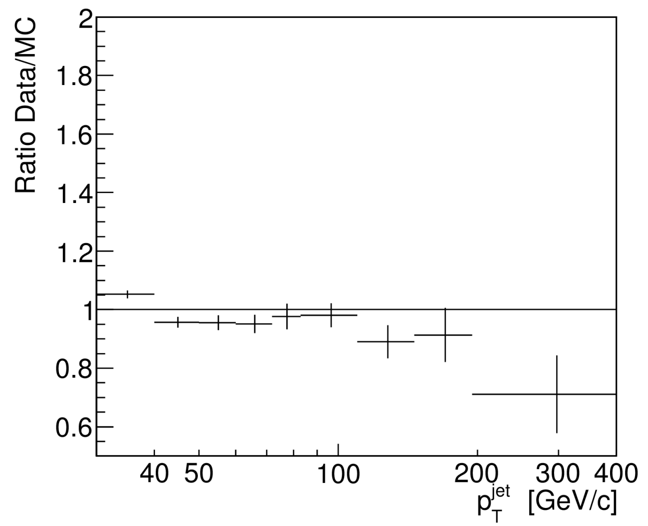
Detector level cross sections compared to
ALPGEN+PYTHIA Monte Carlo prediction plus background





Muons





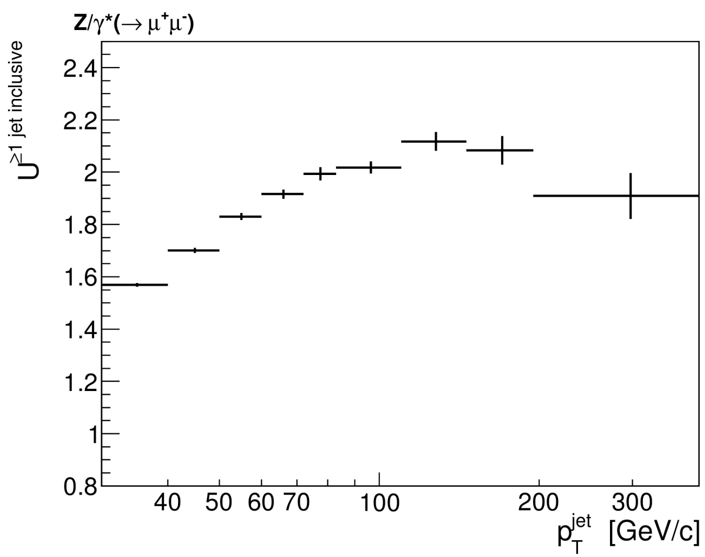
Electrons

Particle level unfolding

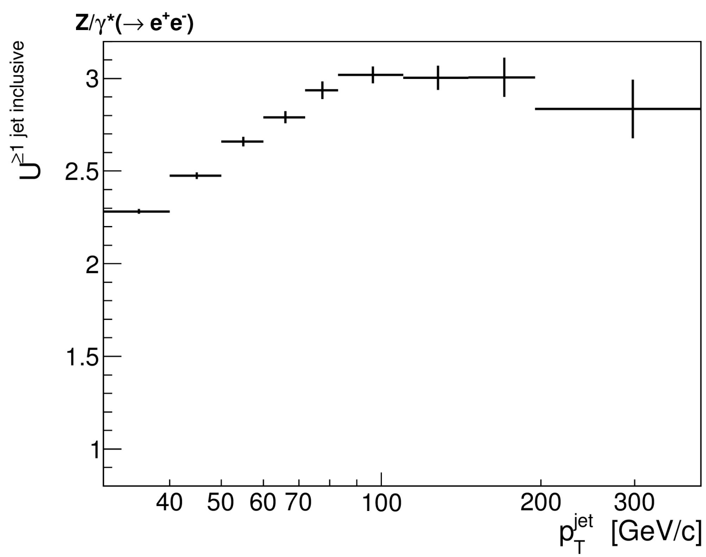
$$U(\alpha)=\frac{\frac{\Delta\sigma}{\Delta\alpha}(particle\ level)}{\frac{\Delta\sigma}{\Delta\alpha}(detector\ level)}$$

- Bin-by-bin unfolding
- Evaluated with ALPGEN+PYTHIA Z/γ^* + jets Monte Carlo sample

Muons



Electrons

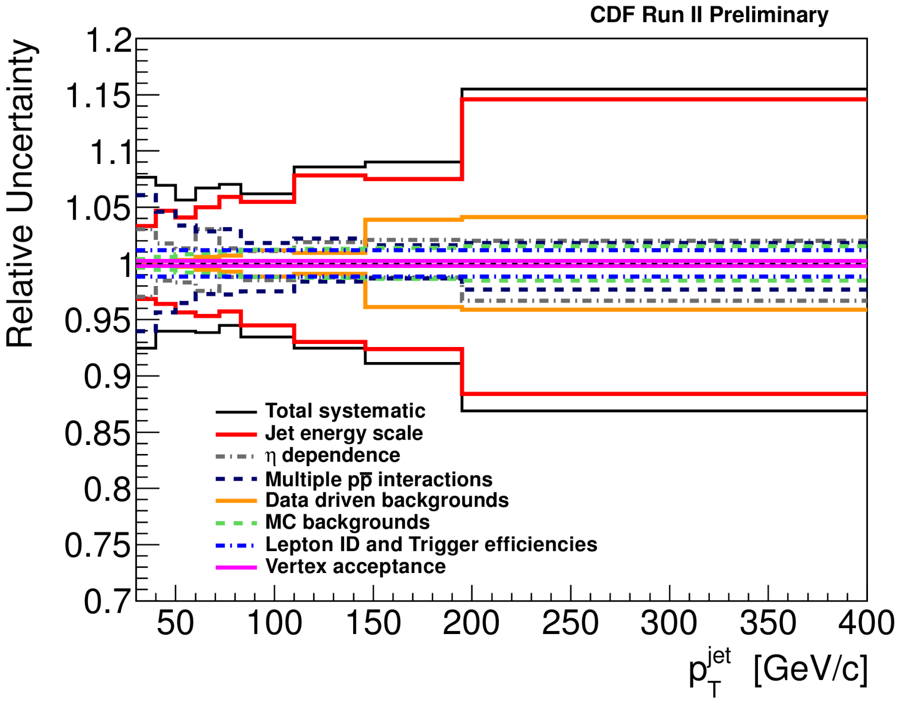


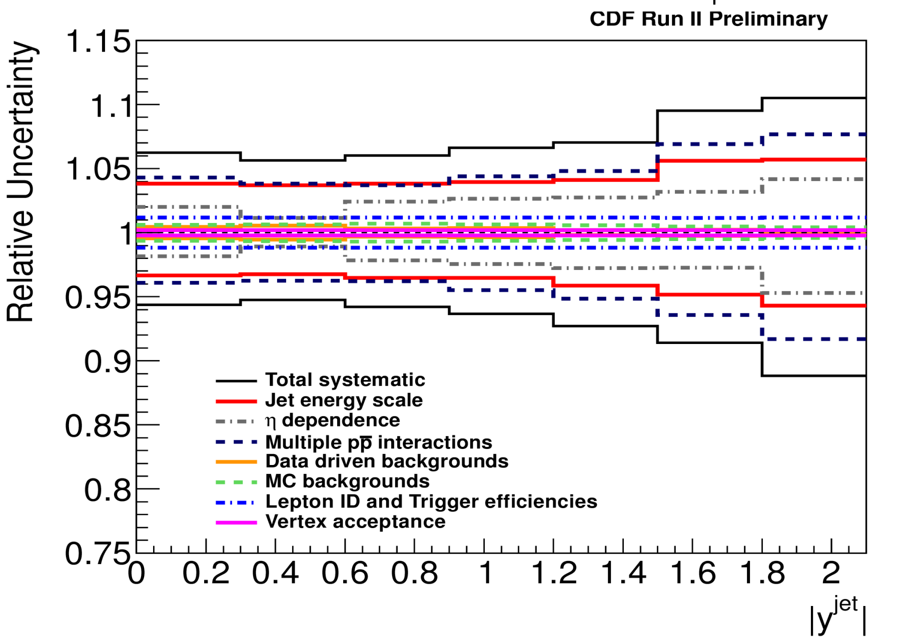
Simultaneously account for:

- $Z/\gamma^* \rightarrow l^+l^-$ acceptance
- Jets reconstruction
- Residual pile-up of multiple pp interactions

Systematic uncertainties

- Jet Energy Scale 5%-15%
- Calorimeter uniform response in η 2%-5%
- Multiple pp interactions 2%-10%
- Monte Carlo backgrounds 2%-3%
- Data Driven backgrounds 1%-4%
- Trigger and Lepton ID efficiencies 1%
- Primary Vertex acceptance <1%

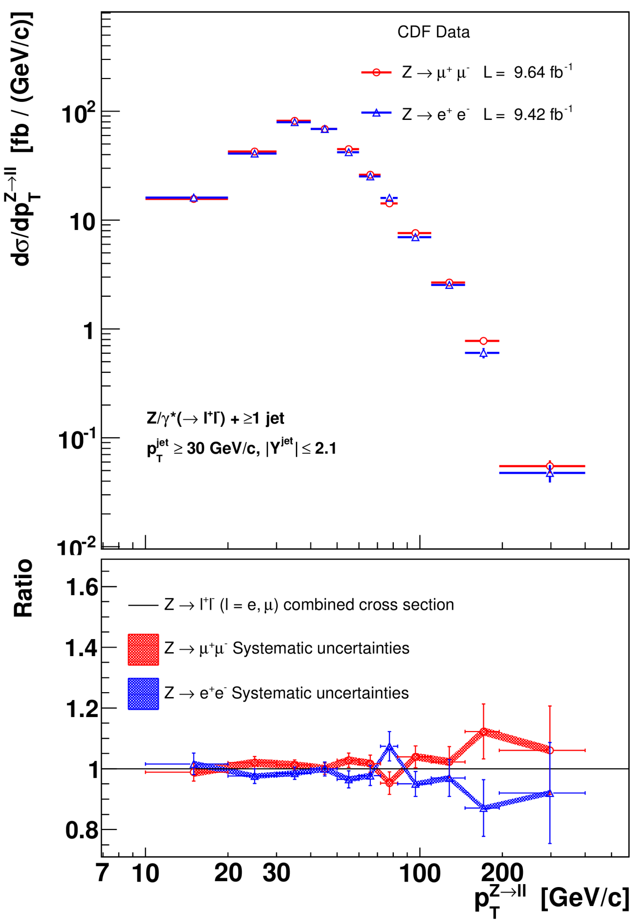


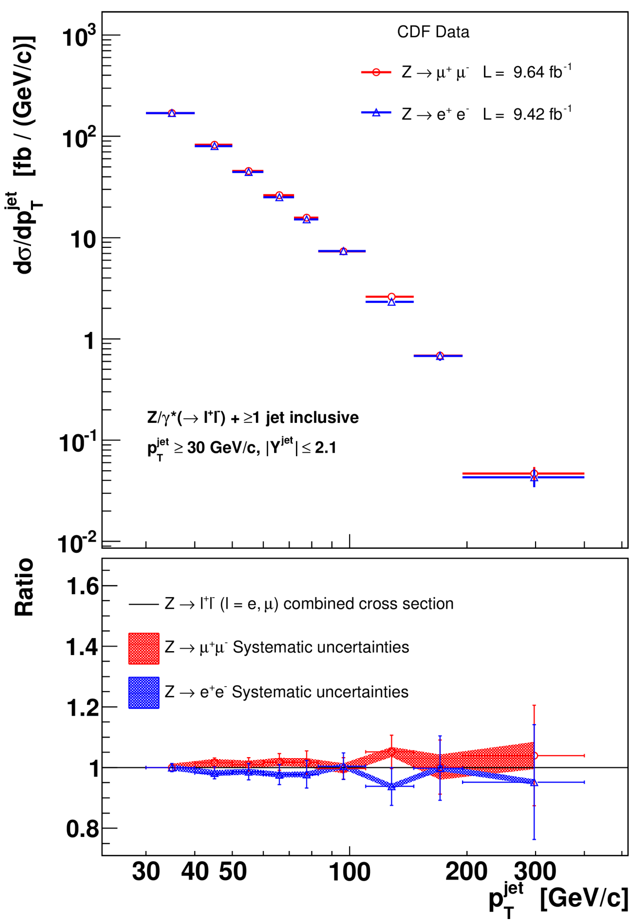


$Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ combination

BLUE (Best Linear Unbiased Estimator) method

- Weighted average
- Account for uncertainties correlation
- Iterative: re-evaluate proportional uncertainties with respect to combined value
- Account for asymmetric errors





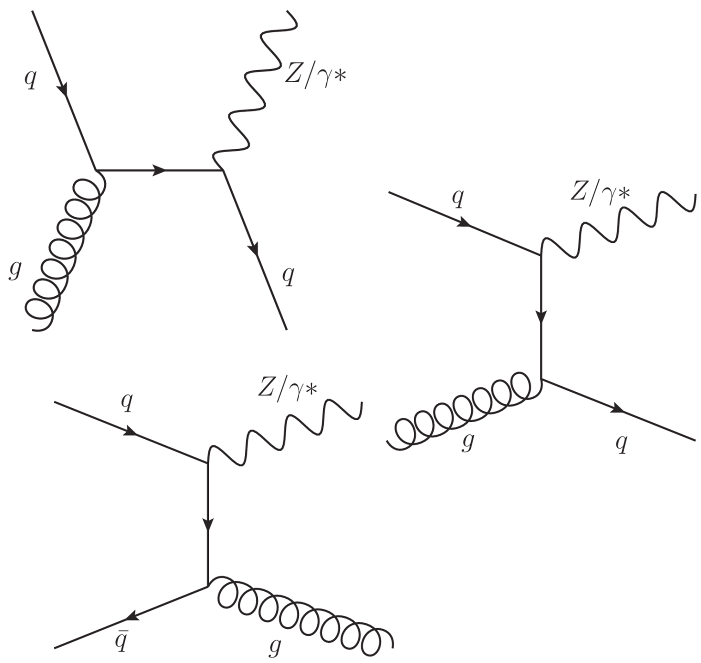
Z/γ^* + jets measurement

- Analyzed full Tevatron Run II dataset ~10 fb^{-1}
- Ad-hoc lepton and jets reconstruction, accounting for the specific $Z/\gamma^* \rightarrow l^+l^-$ + jets final state
- Accurate check of $Z/\gamma^* \rightarrow l^+l^-$ cross section
- Measurement defined at particle level
- $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ combined accounting for uncertainties correlation
- Measured several differential cross sections in Z/γ^* + ≥1, 2, 3 jets

Results

- Theoretical predictions
- non-perturbative QCD corrections
- Midpoint jet IR unsafety
- Setting and parameters
- Data-Theory comparison
  - Z + ≥ 1 jet
  - Z + ≥ 2 jets
  - Z + ≥ 3,4 jets
  - ALPGEN
  - POWHEG

Z/γ* + jets Theory Predictions



MCFM and BLACKHAT+SHERPA
NLO fixed order perturbative QCD
→ reduced scale uncertainty wrt LO

ALPGEN+PYTHIA
Matched LO-ME+PS
→ fundamental tool for Z+jets simulation

POWHEG+PYTHIA
Merged NLO+PS
→ good modeling of high p_T and low p_T physics

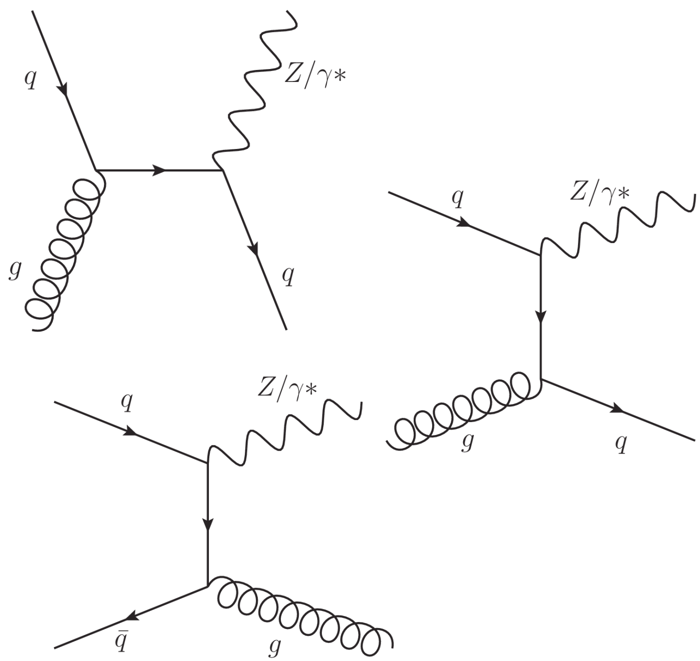
LOOPSIM+MCFM
Approximate nNLO
→ best pertubative QCD accuracy

NLO QCD x NLO EW
Factorized NLO QCD and EW (ArXiv:1103.0914)
→ Important corrections at high p_T

Comparison with many available theoretical predictions

- Largest theory uncertainty: μ_0 scale variation
- PDF uncertainties: 2%-4%

Z/γ* + jets Theory Predictions



Comparison with many available theoretical predictions

- Largest theory uncertainty: μ_0 scale variation
- PDF uncertainties: 2%-4%

L. Dixon, F. Febres, Z. Bern

MCFM and BLACKHAT+SHERPA

NLO fixed order perturbative QCD

→ reduced scale uncertainty wrt LO

M. Mangano, A. Messina, B. Cooper

ALPGEN+PYTHIA

Matched LO-ME+PS

→ fundamental tool for Z+jets simulation

C. Oleari, E. Re, S. Alioli

POWHEG+PYTHIA

Merged NLO+PS

→ good modeling of high p_T and low p_T physics

S. Sapeta, G. Salam

LOOPSIM+MCFM

Approximate nNLO

→ best pertubative QCD accuracy

A. Mueck

NLO QCD x NLO EW

Factorized NLO QCD and EW (ArXiv:1103.0914)

→ Important corrections at high p_T

non-pQCD and QED radiation corrections

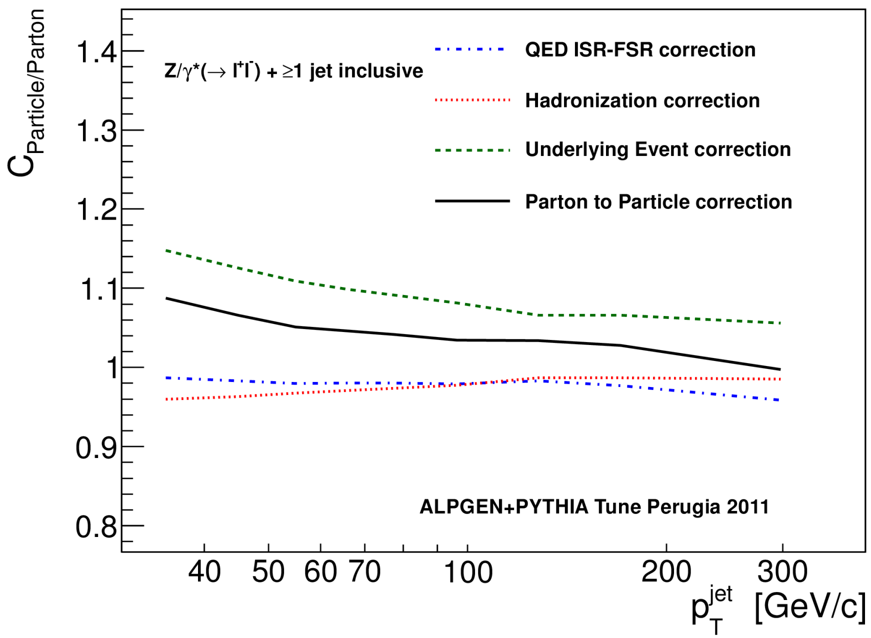
Fixed order perturbative QCD predictions need to be corrected for non-perturbative and EW effects

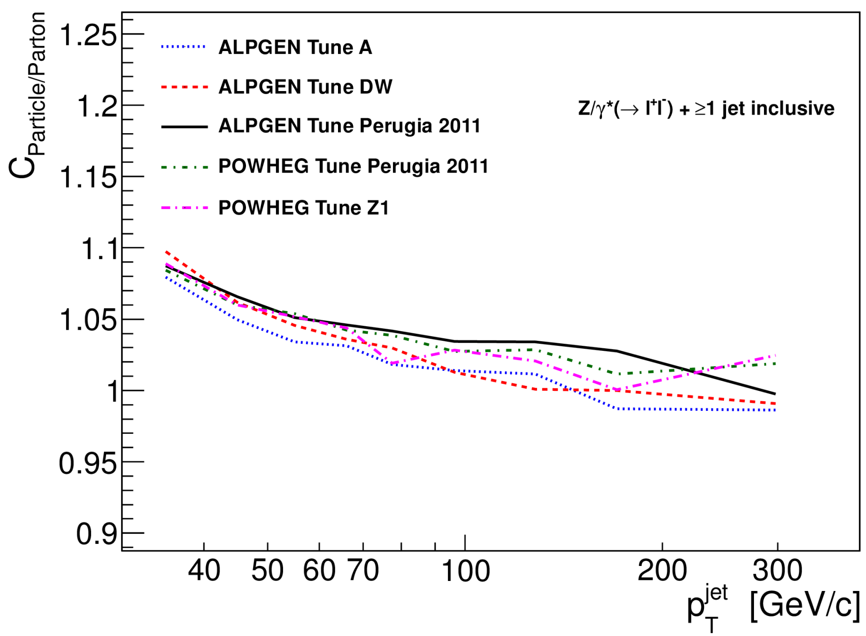
- Hadronization
- Underlying event
- QED photon radiation

Evaluated with
ALPGEN+PYTHIA Monte Carlo

Switch on/off
hadronization,UE,QED

Studied the effect of
PYTHIA tune variations



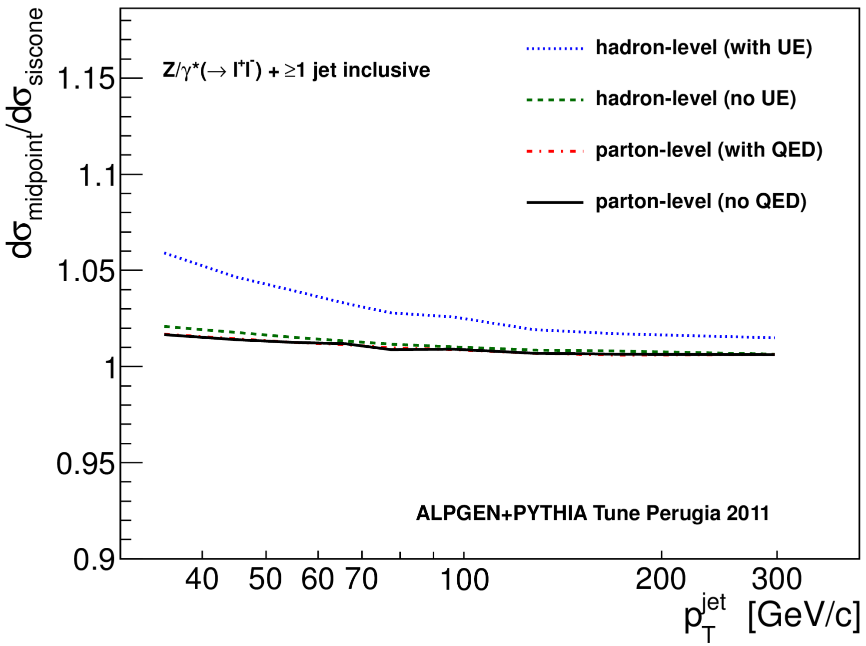


IRC safe jet algorithms

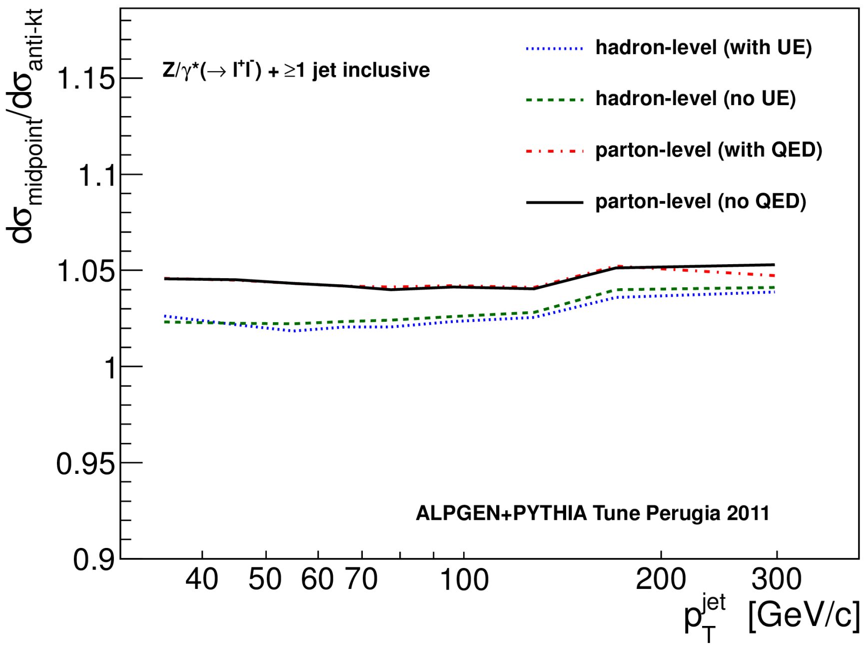
Perturbative QCD predictions need to be evaluated with a IRC safe jet algorithm

→ Study difference at parton showered level between SISCone or anti-kt and midpoint

SISCone



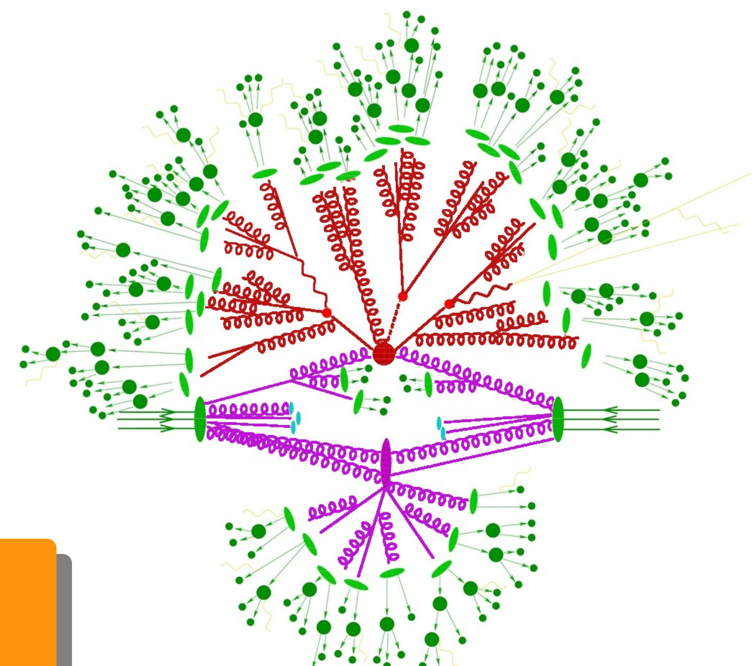
anti-kt



- SISCone is the best choice
- Residual differences of 2%-3% and flat with respect to jet multiplicities

Setting and parameters of the predictions

Setting	Variations	Uncertainty
Renormalization and factorization scale	$\mu_0 = H_T$ $\mu_0 = E_T^Z$ $\mu_0 = p_T^{jet}$	$\mu_0 = 2\mu_0; \mu_0/2$
PDF	MSTW2008 CTEQ6.6 NNPDF2.1 CT10	68% CL variations → Hessian method
TUNE (Parton shower, hadronization, Underlying event)	TUNE A TUNE DW TUNE Perugia 2011	



$\alpha_s(M_Z)$, Λ_{QCD} variations, and additional Monte Carlo specific parameters and variations

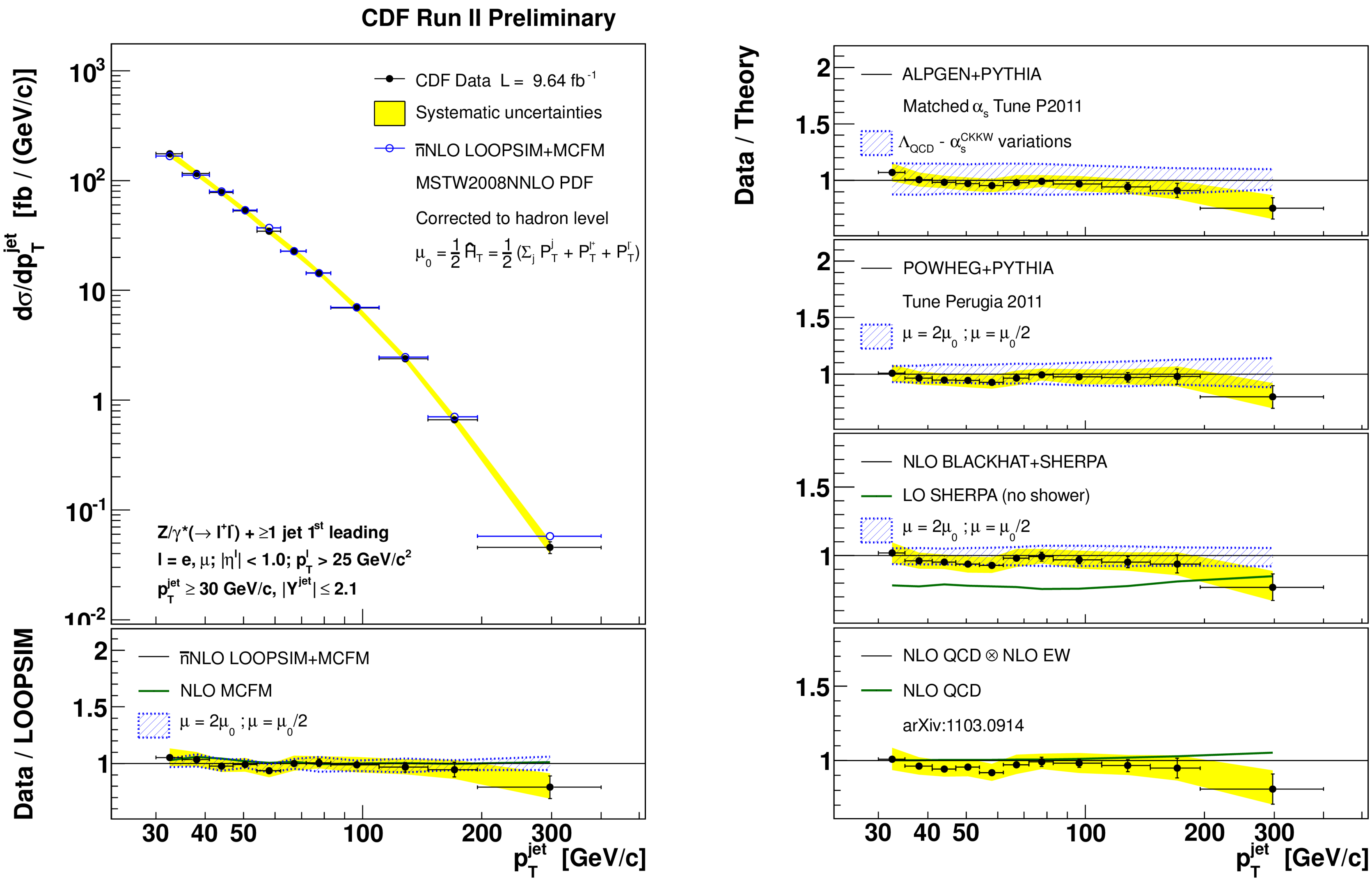
Extensive study of variations and uncertainties of setting and parameters

$Z/\gamma^* + \geq 1$ jet

- Leading jet p_T
- $H_T^{jet} = \Sigma\, p_T^{jet}$
- Z/γ^* p_T

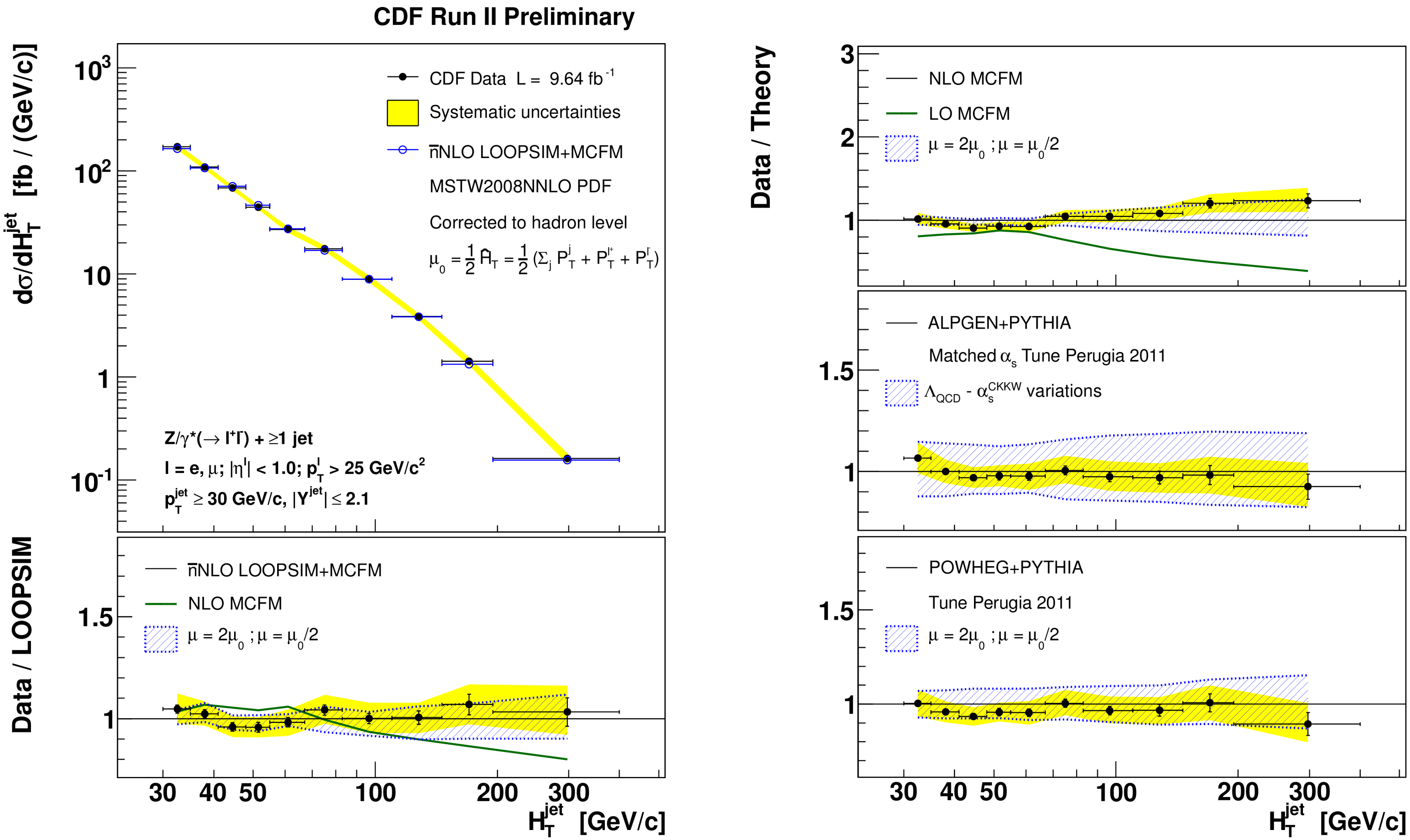
Available predictions:
MCFM, BLACKHAT, ALPGEN, POWHEG, LOOPSIM, NLO QCD x NLO EW

$Z/\gamma^* + \geq 1$ jet leading p_T^{jet}



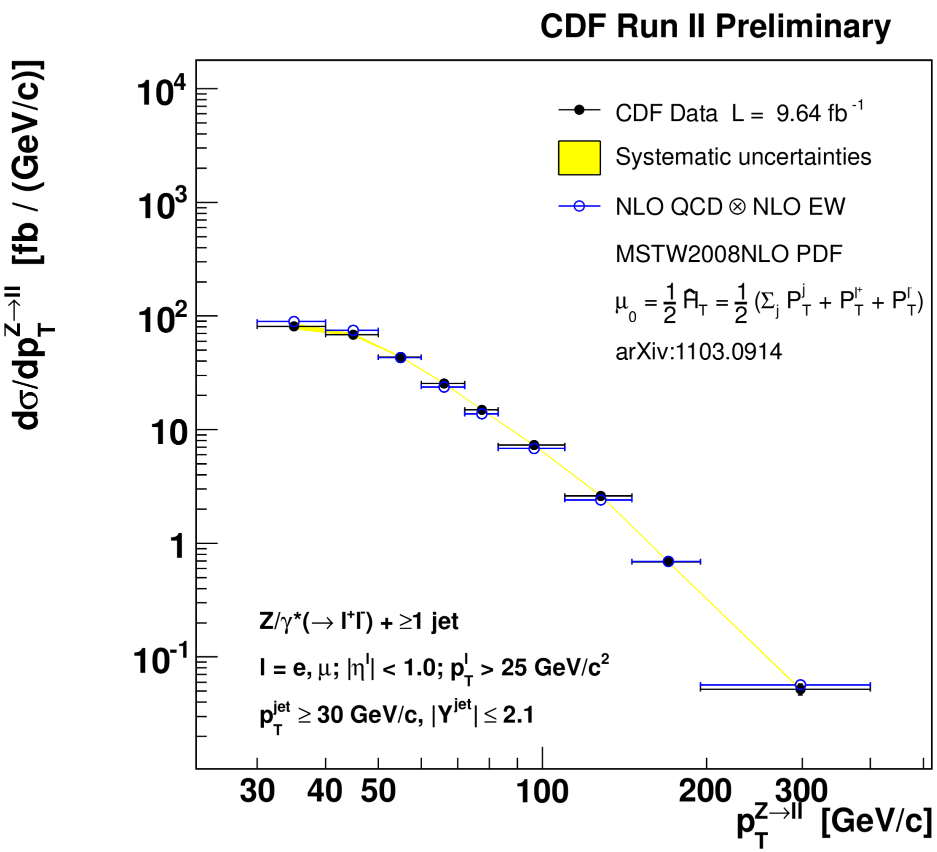
- LOOPSIM+MCFM only 4%-6% scale uncertainty
- NLO EW correction ~5% at high pt → large virtual Sudakov logarithms

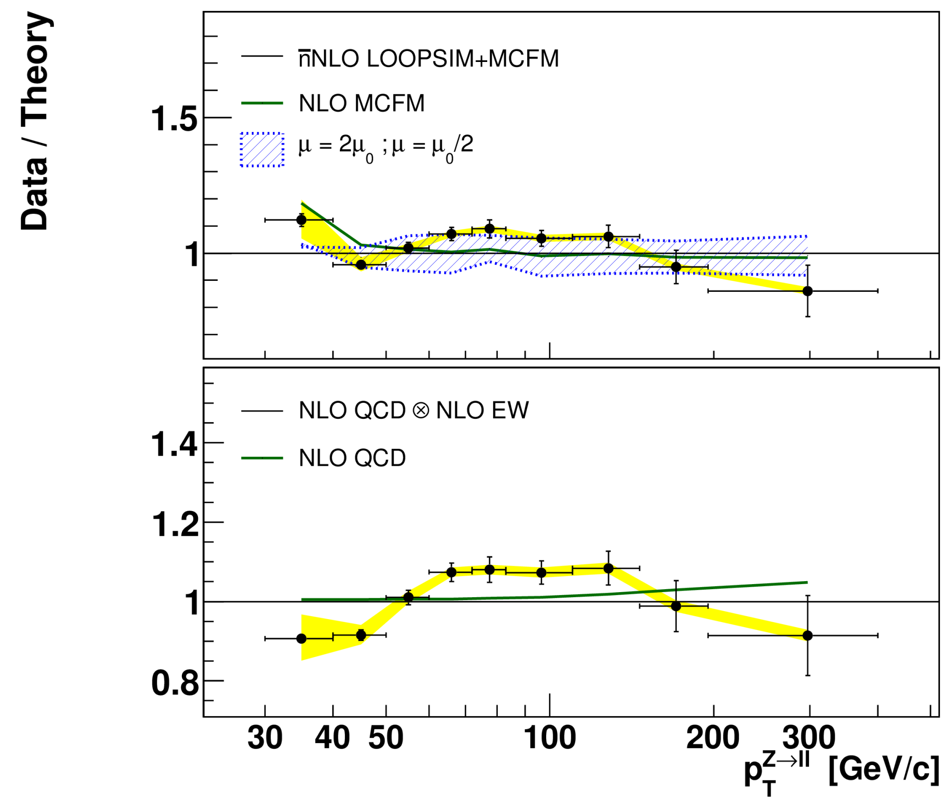
$Z/\gamma^* + \geq 1$ jet H_T^{jet}



- Large NLO/LO K factor ≥2 at high H_t^{jet}=Σ p_T^{jet} → Significant beyond NLO corrections
- LO-ME+PS (ALPGEN) and NLO+PS (POWHEG) properly model data with large scale uncertainty
- Good modeling of approximate nNLO LOOPSIM with reduced scale uncertainty

$Z/\gamma^* + \geq 1$ jet p_T^Z





NLO EW and NLO QCD corrections applied with a *factorized* ansatz

- NLO EW correction ~5% at high p_T → large virtual Sudakov logarithms
- NLO EW corrections of the same order of approximate nNLO scale uncertainty

$Z/\gamma^* + \geq 2$ jets

Important final state for Higgs measurement

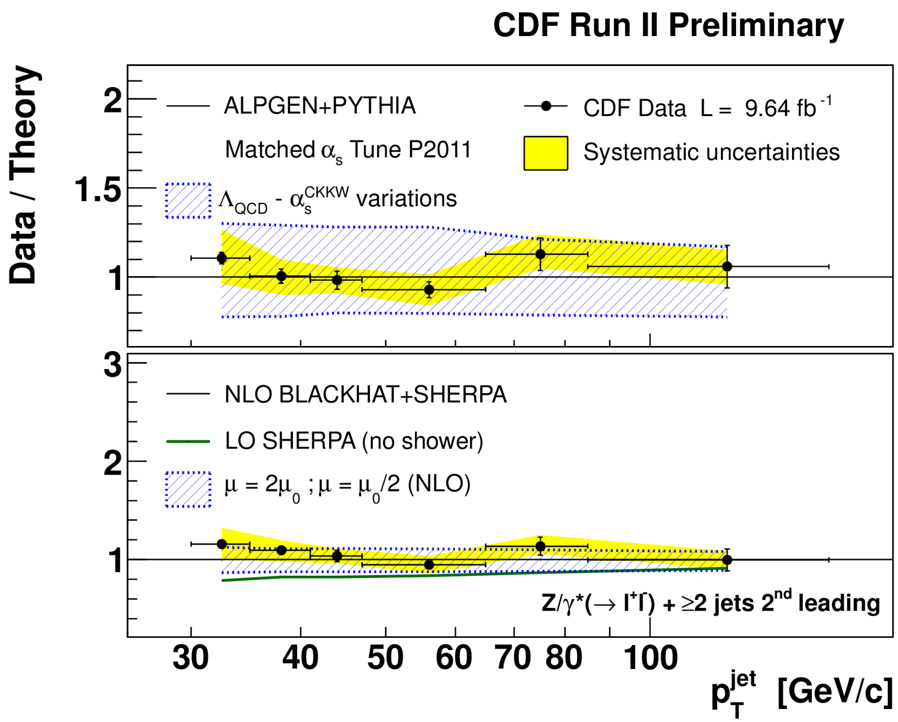
and beyond SM searches

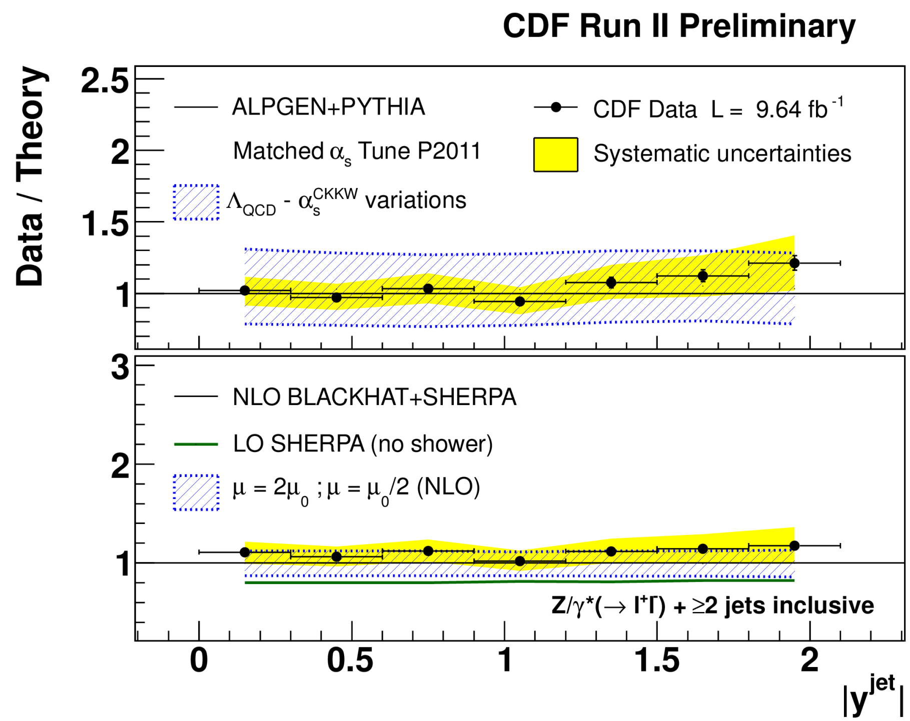
→ sensitive to new resonances

- 2^{nd} leading jet p_T
- Inclusive jet $|y|$
- Di-jet mass, Z-jj mass
- Dihedral angle $\theta_{Z\text{-}jj}$
- Di-jet Δy, ΔR

Available predictions:
MCFM, BLACKHAT, ALPGEN

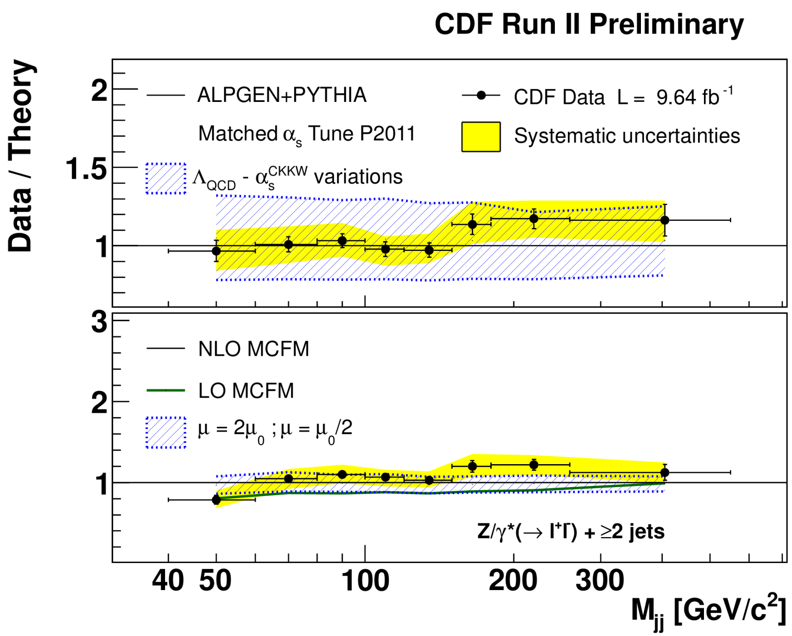
$Z/\gamma^* + \geq 2$ jets

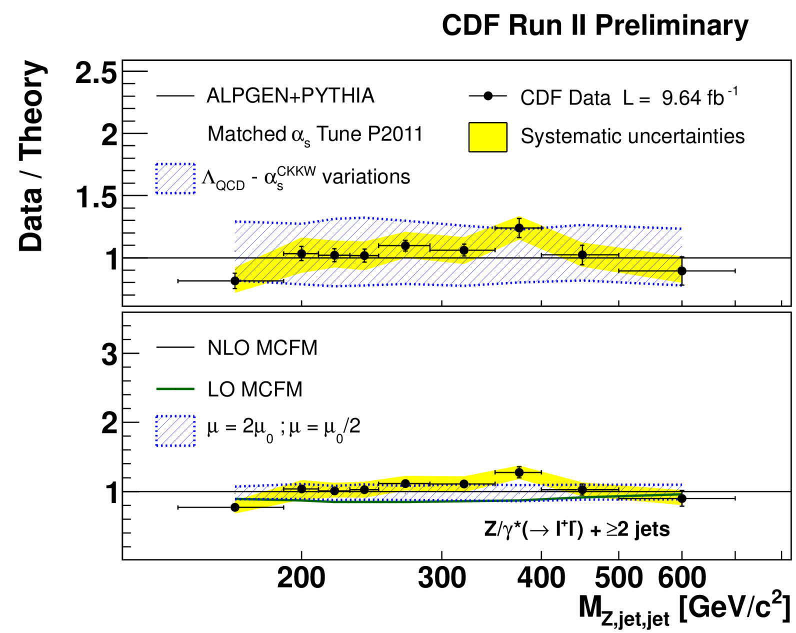


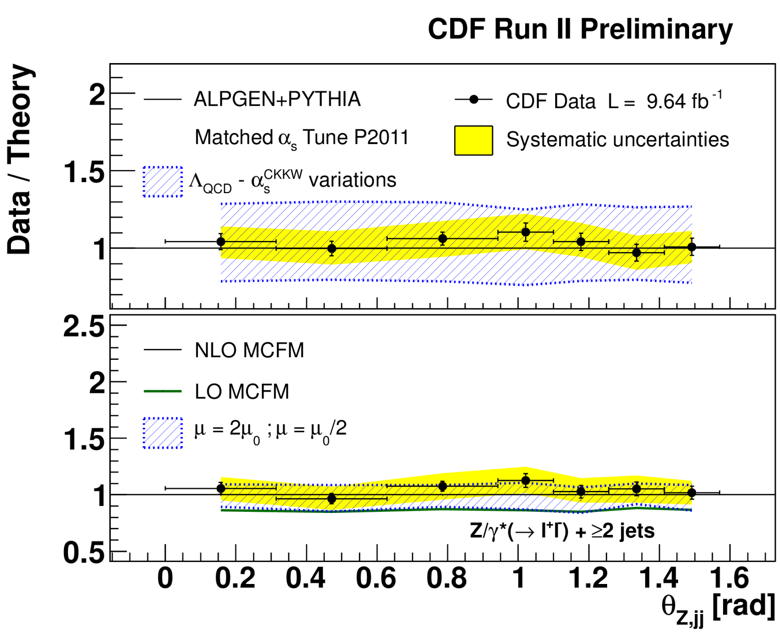


Good agreement
→ validation of Z/γ^* + jets modeling

Z/γ* + ≥ 2 jets



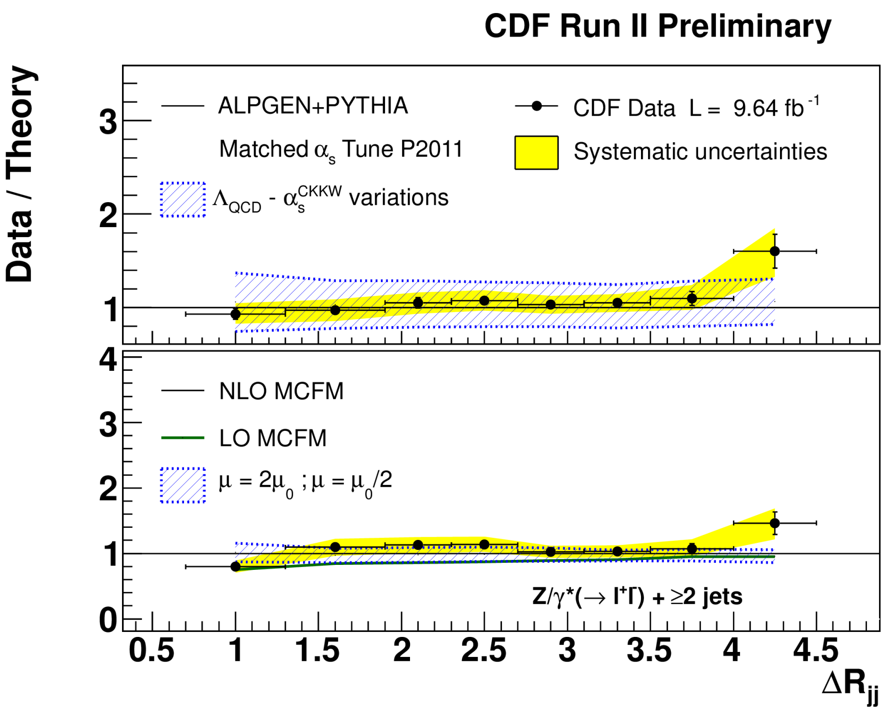


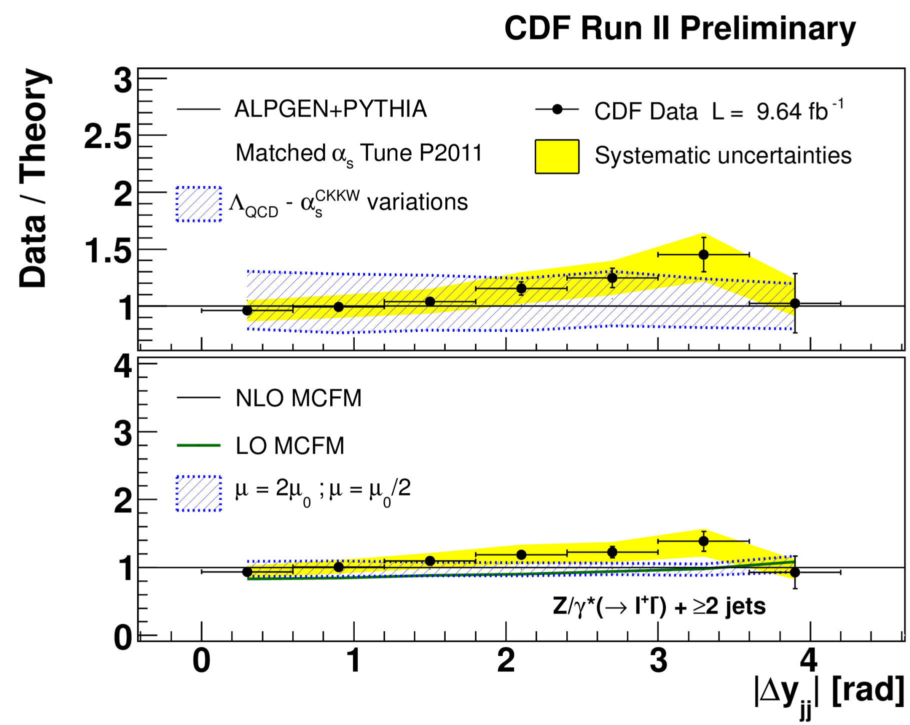


Agreement within large experimental and theoretical uncertainties

Angle between the Z/γ* decay plane and the di-jet plane
→ useful to study spin properties of new resonances

Z/γ* + ≥ 2 jets





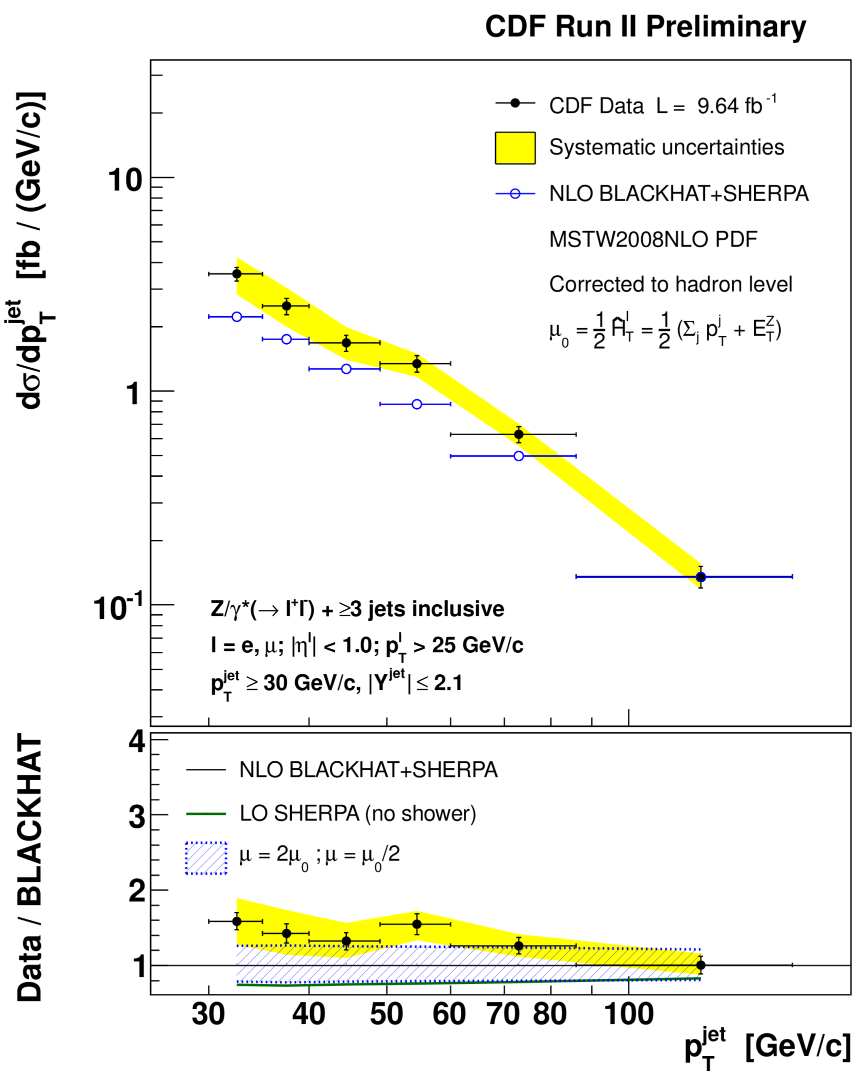
Di-jet angular separation

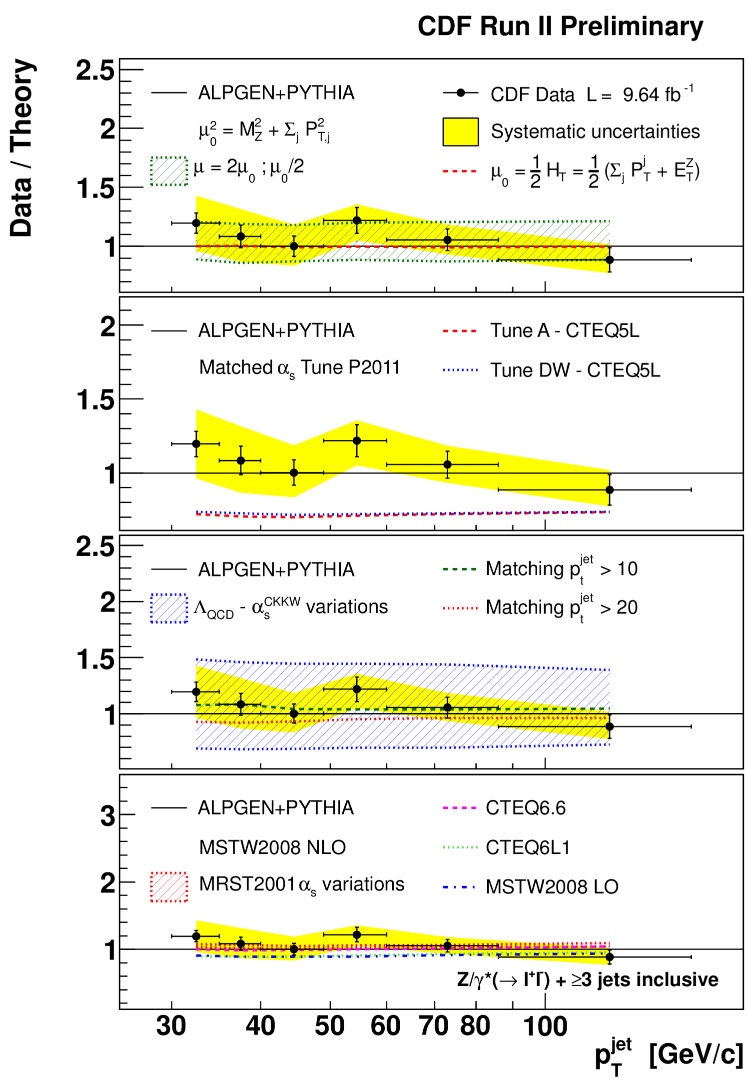
$Z/\gamma^* + \geq 3$ jets

- Inclusive jet p_T
- Inclusive jet $|y|$

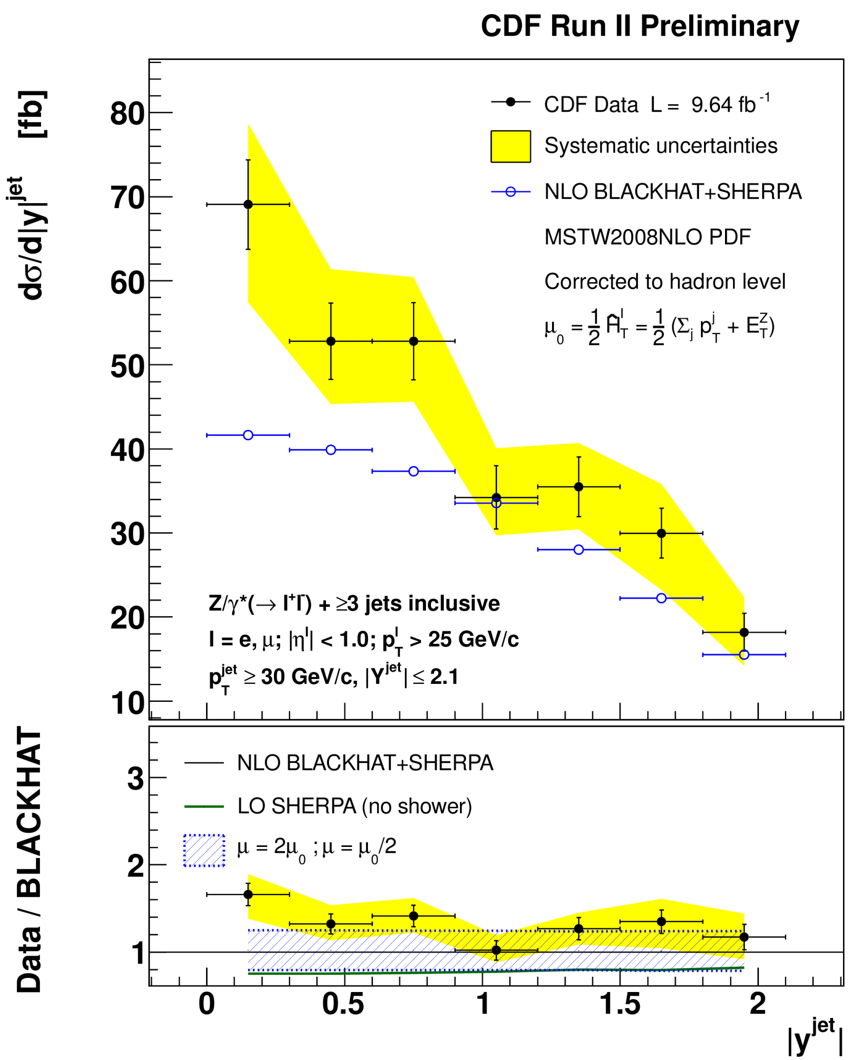
Available predictions:
BLACKHAT, ALPGEN

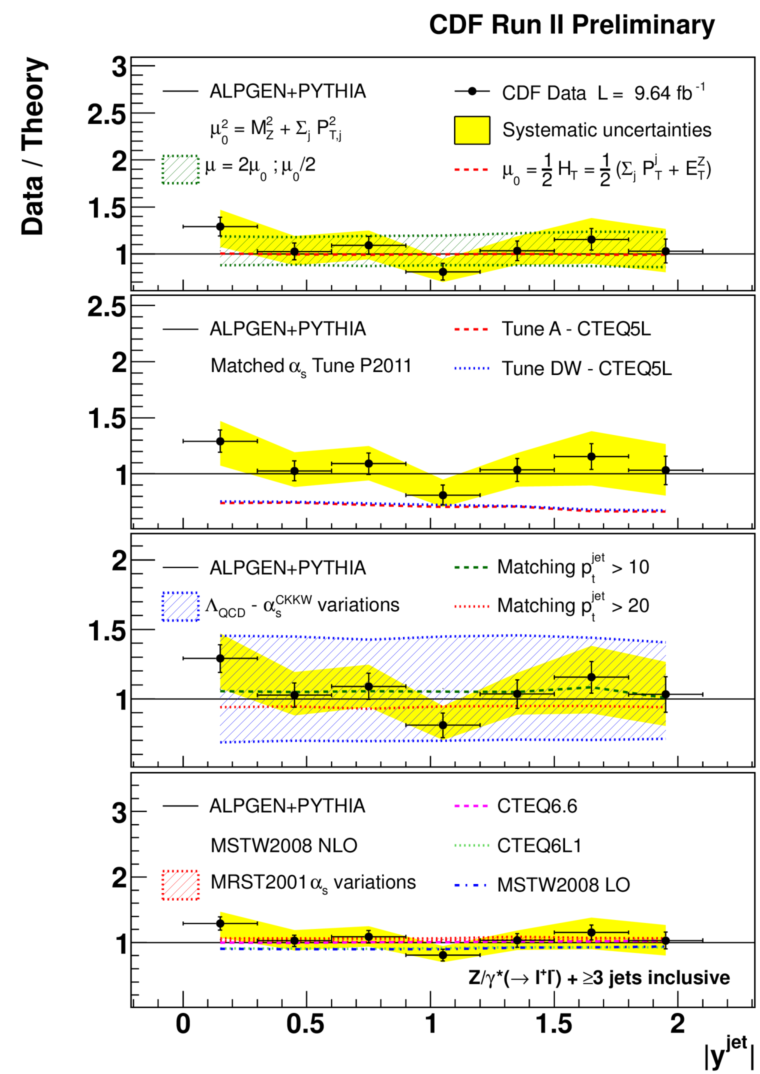
$Z/\gamma^* + \geq 3$ jets inclusive jet p_T



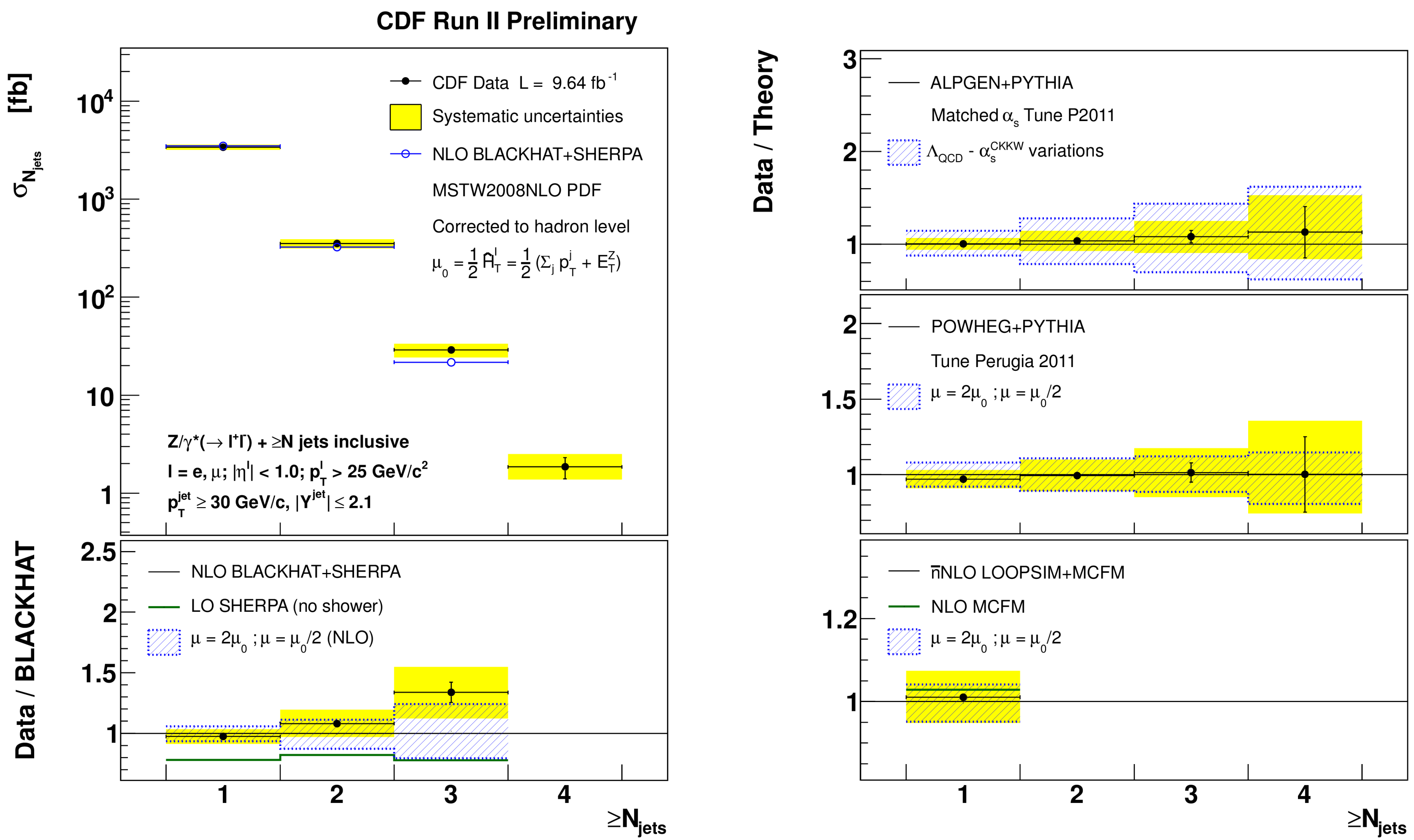


Z/γ* + ≥ 3 jets inclusive jet |y|





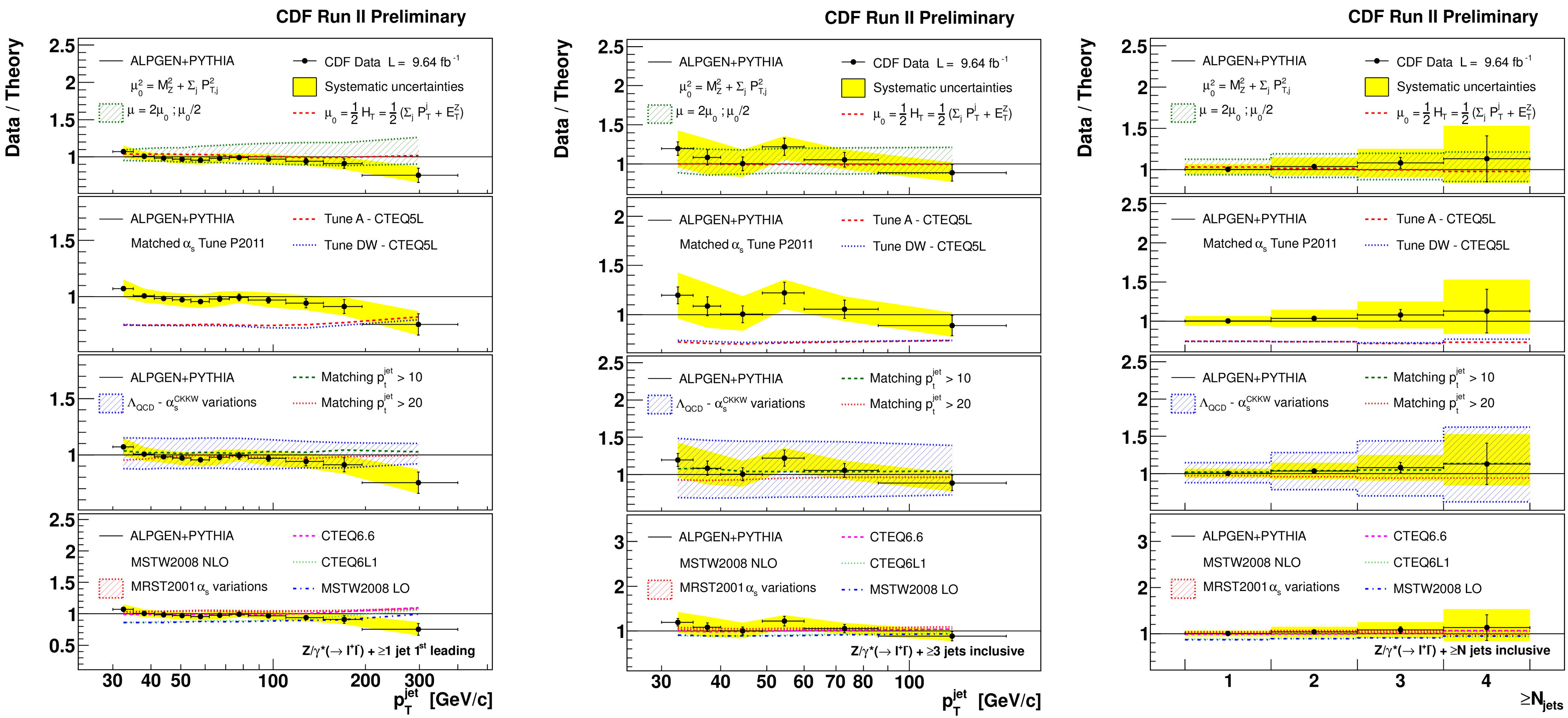
$Z/\gamma^* + \geq N$ jets



Measurement extended up $Z/\gamma^* + \geq 4$ jets

- LOOPSIM+MCFM scale variation lower than experimental uncertainty

Z/γ* + jets ALPGEN+PYTHIA

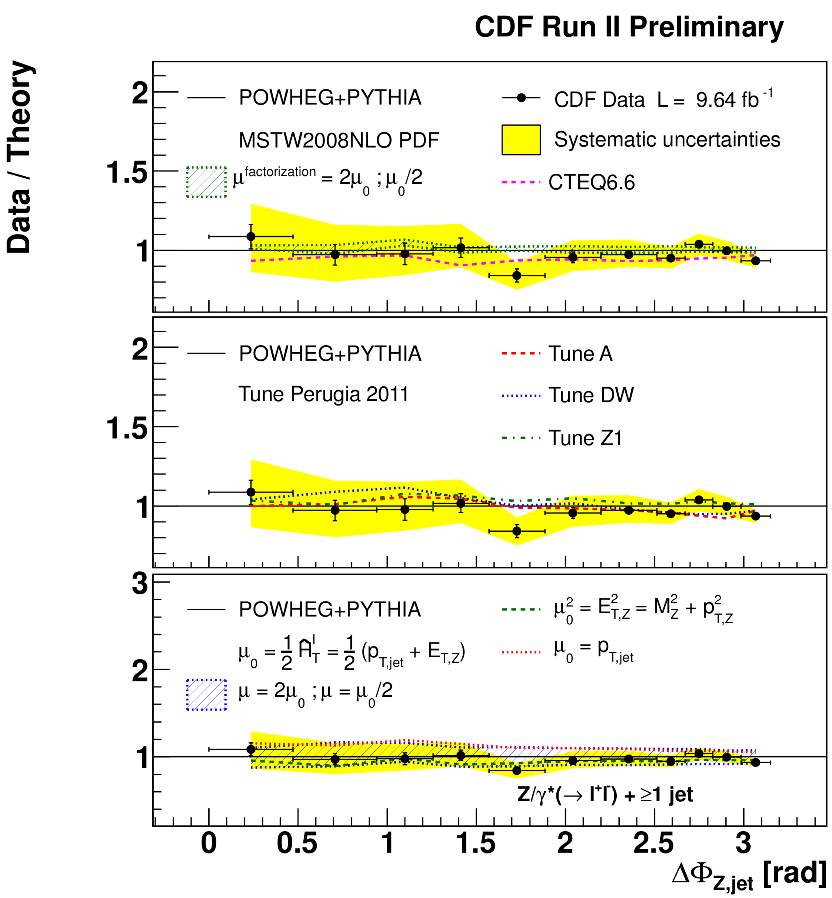


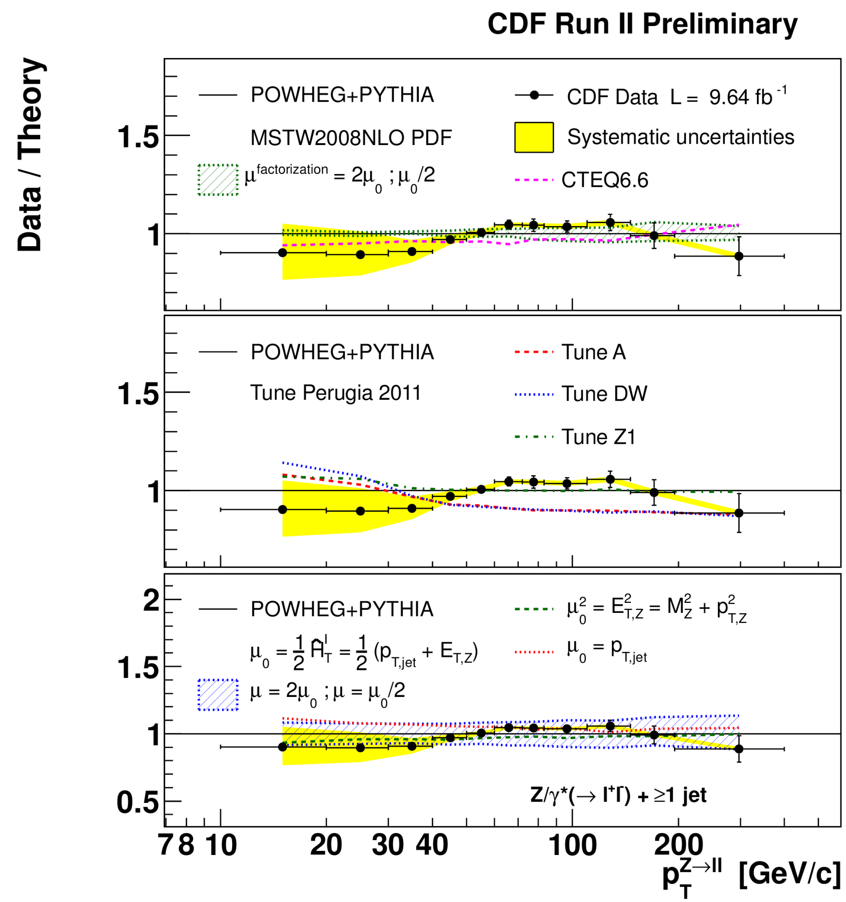
α_s "matched" ALPGEN+PYTHIA setting and Tune Perugia 2011

- coherence between CKKW α_s in ALPGEN and λ_{QCD} in PYTHIA
- Can use NLO (2-loop) PDF

No normalization factor needed

Z/γ* + jets POWHEG+PYTHIA

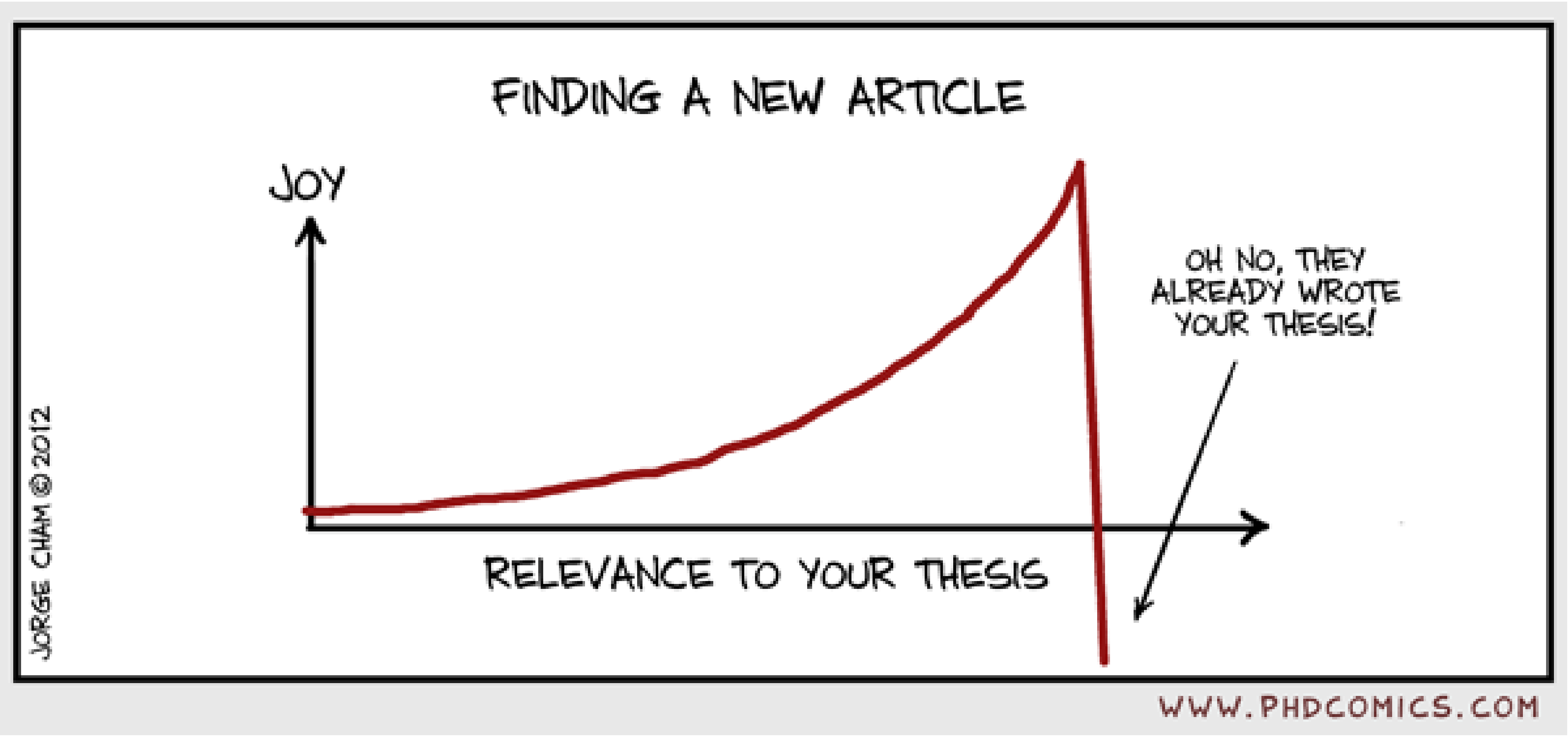




- Good modeling of perturbative high p_T (NLO accuracy) and non-perturbative low p_T (PS+hadronization+UE) regions
- POWHEG cross section independent of parton shower modeling
  → lower dependence from PYTHIA Tune

Summary

- Z/γ^* + jets Tevatron Legacy measurement
- High accuracy achieved through $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ combination
- Measured a large set of differential cross sections in Z/γ^* + 1, 2, 3 jets
- Data compared to state of the art theoretical predictions thanks to a tight exchange with several theoretical groups



Thanks for your attention

BACKUP

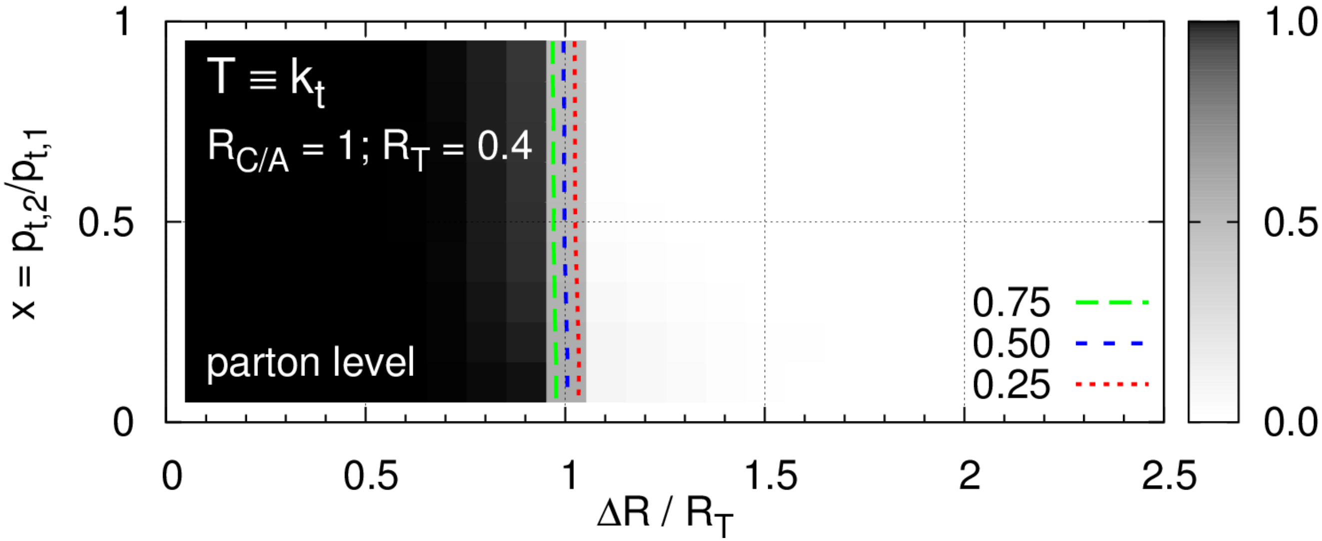
Z + ≥N jets - BLACKHAT

NLO/LO K-factor			
	$Z/\gamma^* + \geqslant 1$ jet	$Z/\gamma^* + \geqslant 2$ jets	$Z/\gamma^* + \geqslant 3$ jets
SISCone	1.28	1.22	1.28
anti-kt	1.22	1.10	1.03
LO-ME+PS/NLO ratio			
	$Z/\gamma^* + \geqslant 1$ jet	$Z/\gamma^* + \geqslant 2$ jets	$Z/\gamma^* + \geqslant 3$ jets
SISCone	0.96	1.02	1.19
anti-kt	0.97	1.01	1.03

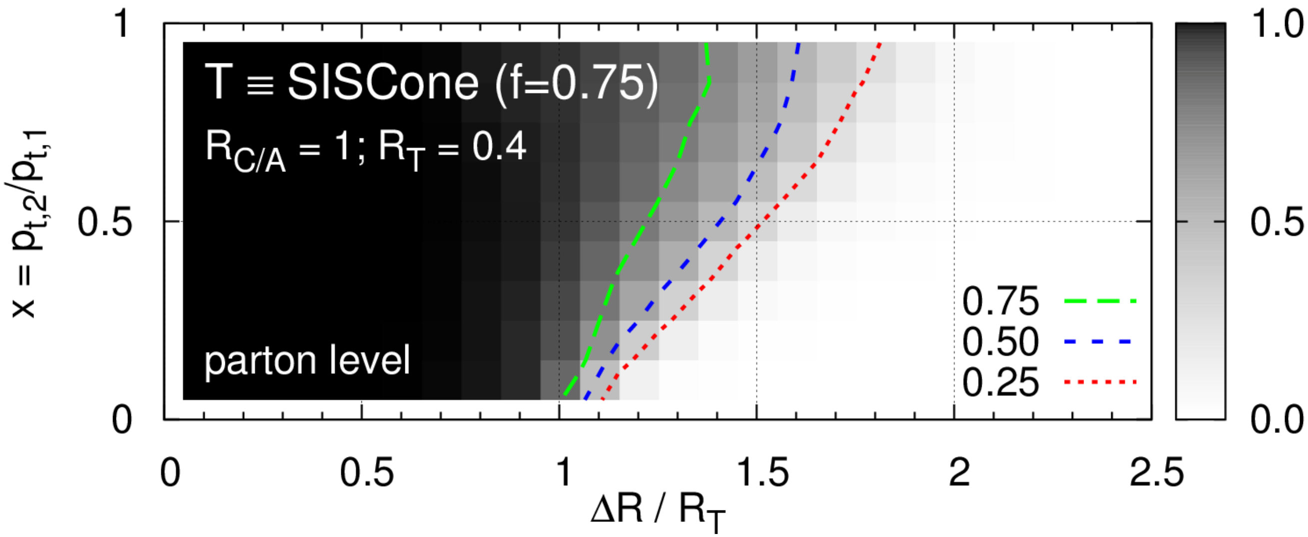
Anti-kt has a flat LO-ME+PS / NLO ratio

SISCone has an increasing LO-ME+PS / NLO ratio

Z + ≥N jets - BLACKHAT



$\Delta R < R$



$\Delta R < (1 + x) R$

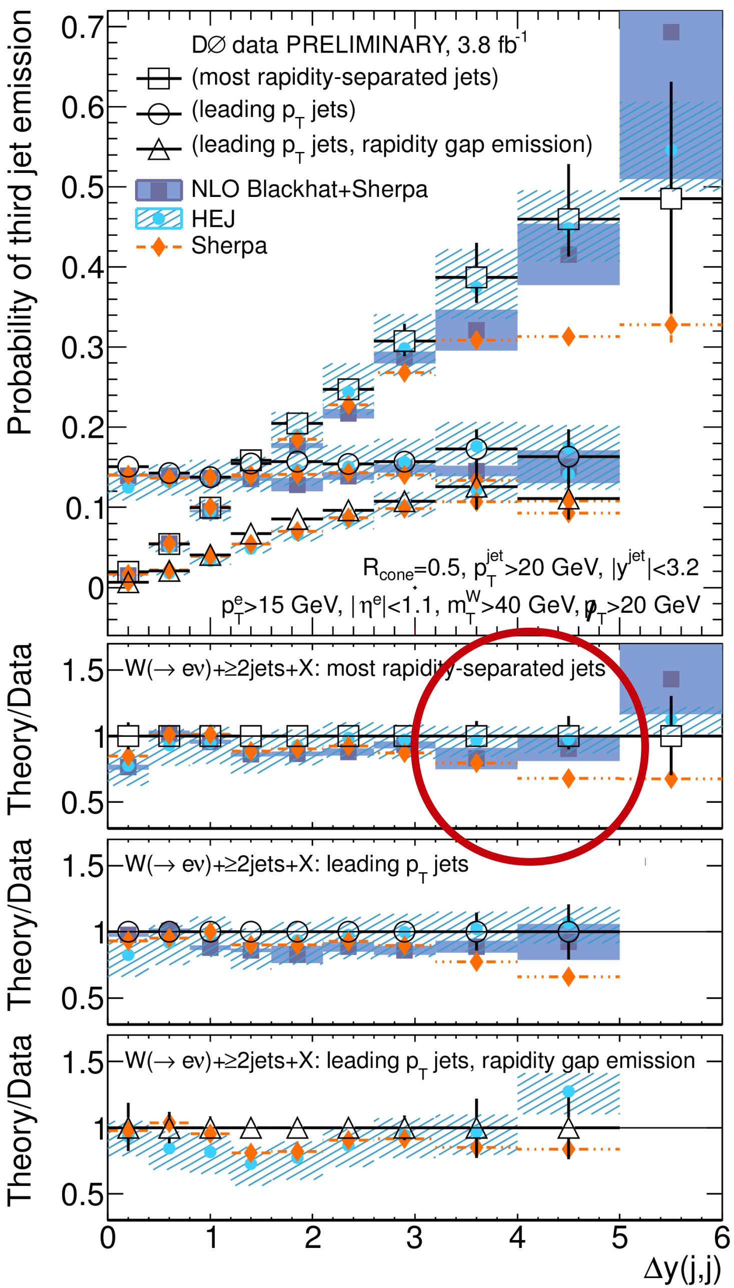
Rsep ~ 1.6

Z + ≥N jets - BLACKHAT

LO perturbative QCD		
	BLACKHAT+SHERPA SISCone	MCFM $R_{sep} = 1.3$
$Z/\gamma^* + \geqslant 1$ jet	2553	2589
$Z/\gamma^* + \geqslant 2$ jets	244.9	266.3
$Z/\gamma^* + \geqslant 3$ jets	15.0	19.6
$Z/\gamma^* + \geqslant 4$ jets	0.63	/
NLO perturbative QCD		
	BLACKHAT+SHERPA SISCone	MCFM $R_{sep} = 1.3$
$Z/\gamma^* + \geqslant 1$ jet	3276	3244
$Z/\gamma^* + \geqslant 2$ jets	298.3	307.5
$Z/\gamma^* + \geqslant 3$ jets	19.3	/

Z + 3 jets cross section sensitive to Rsep

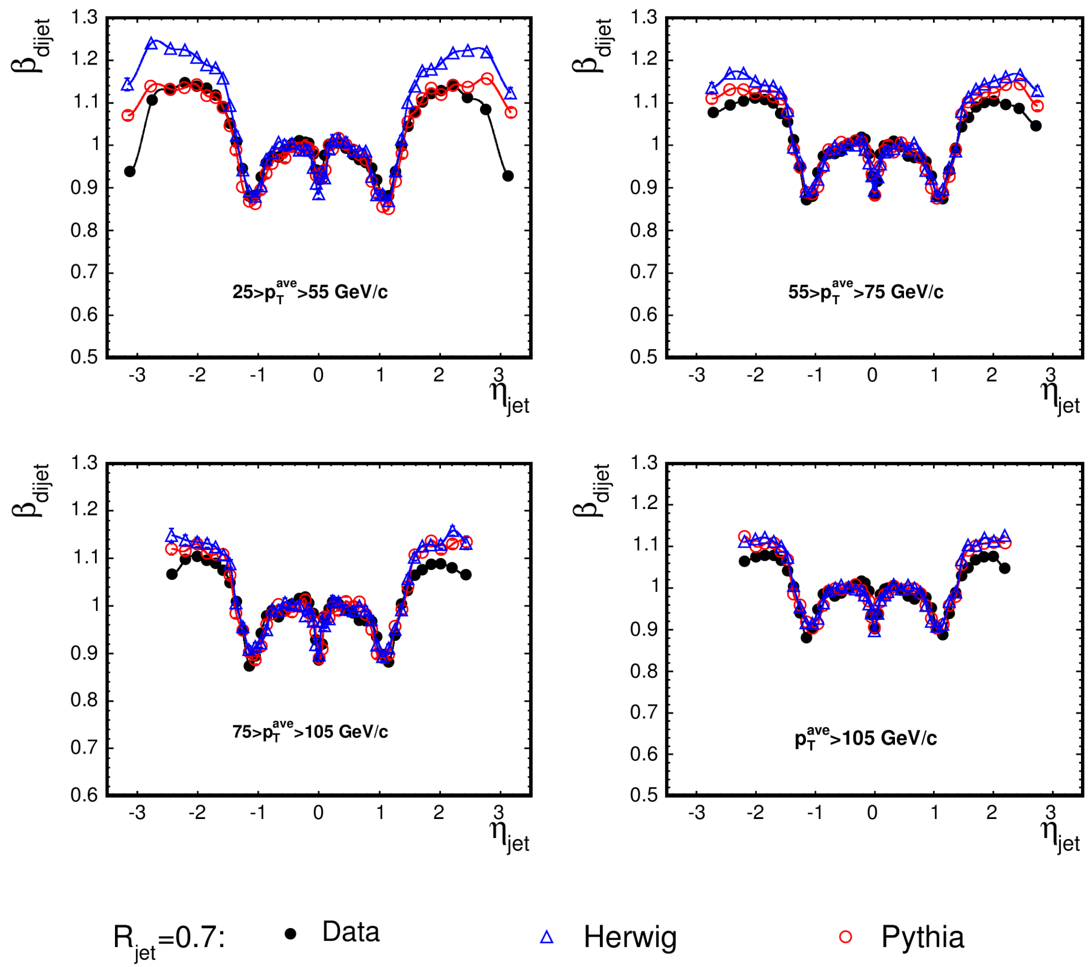
W + ≥ 2 jets - di-jet |Δy|



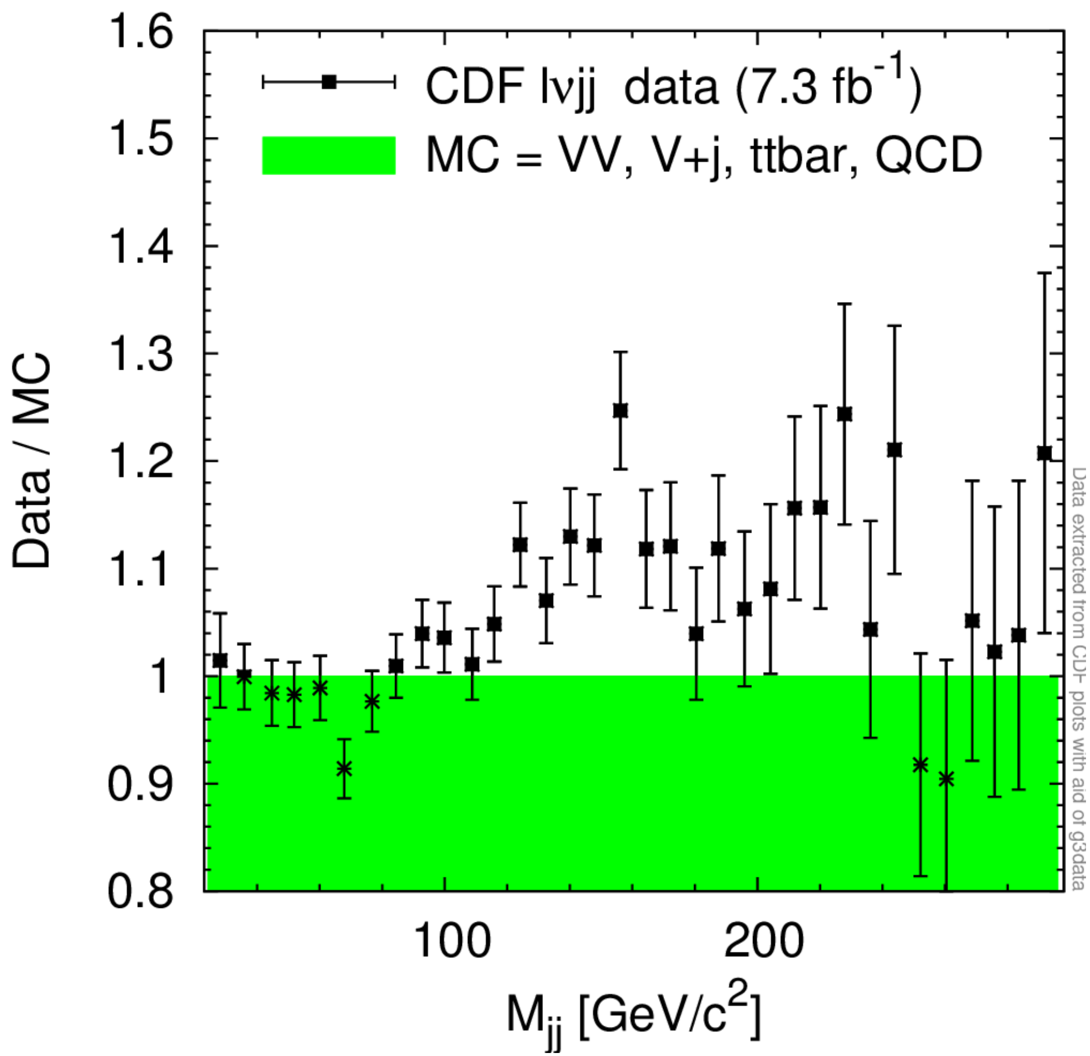
D0 W+jets measurement

HEJ (large angle resummation) approach shows some differences wrt to sherpa at high Δy

η-dependent jet energy correction

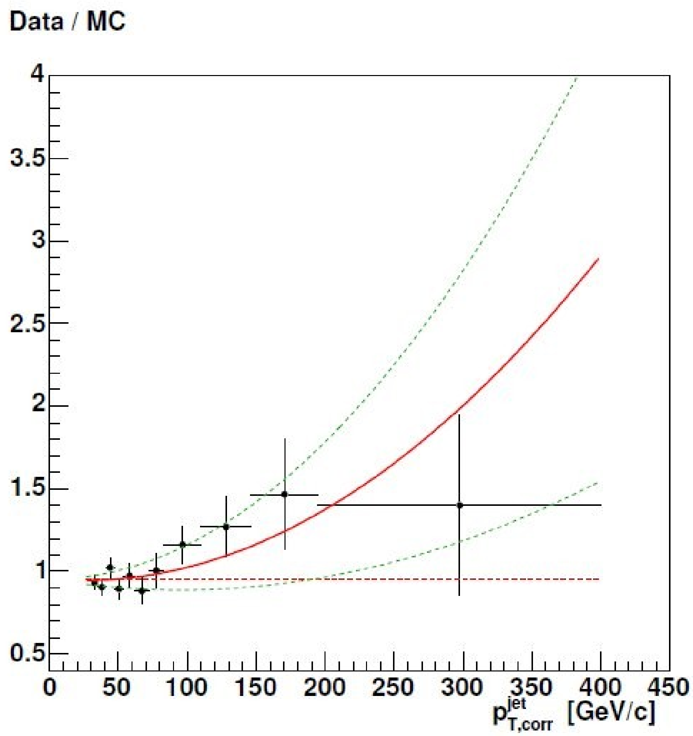


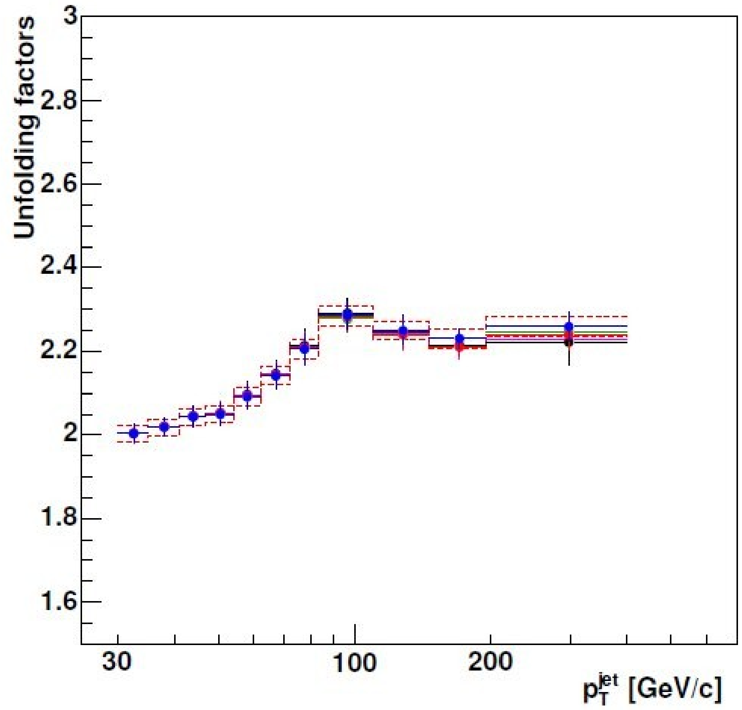
W + jj mass



From arxiv:1207.0462

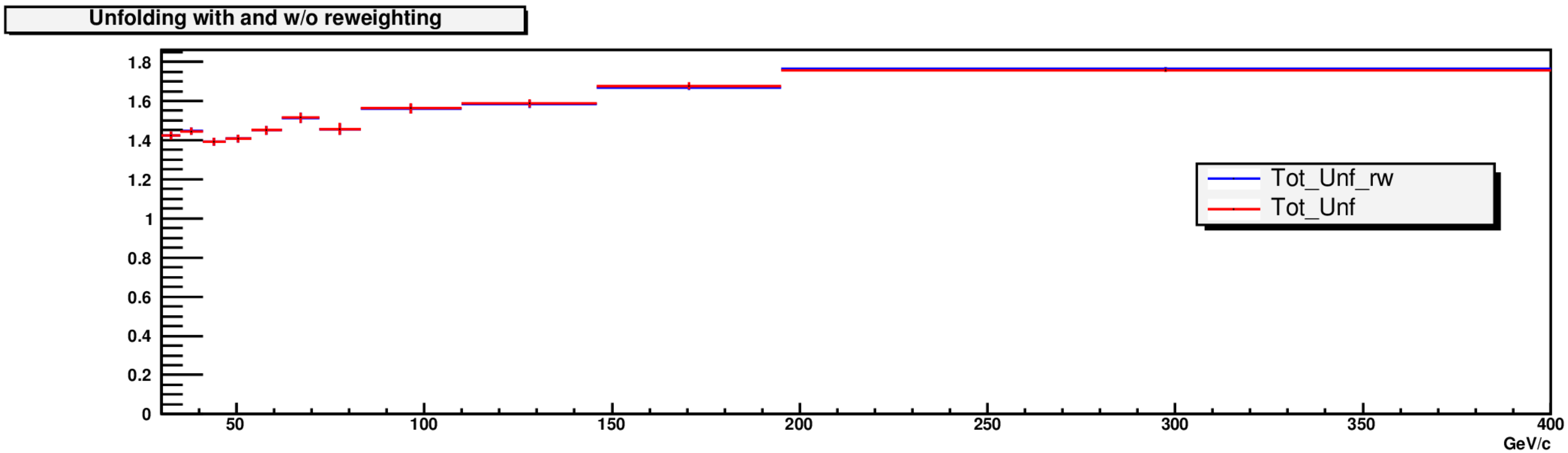
Unfolding

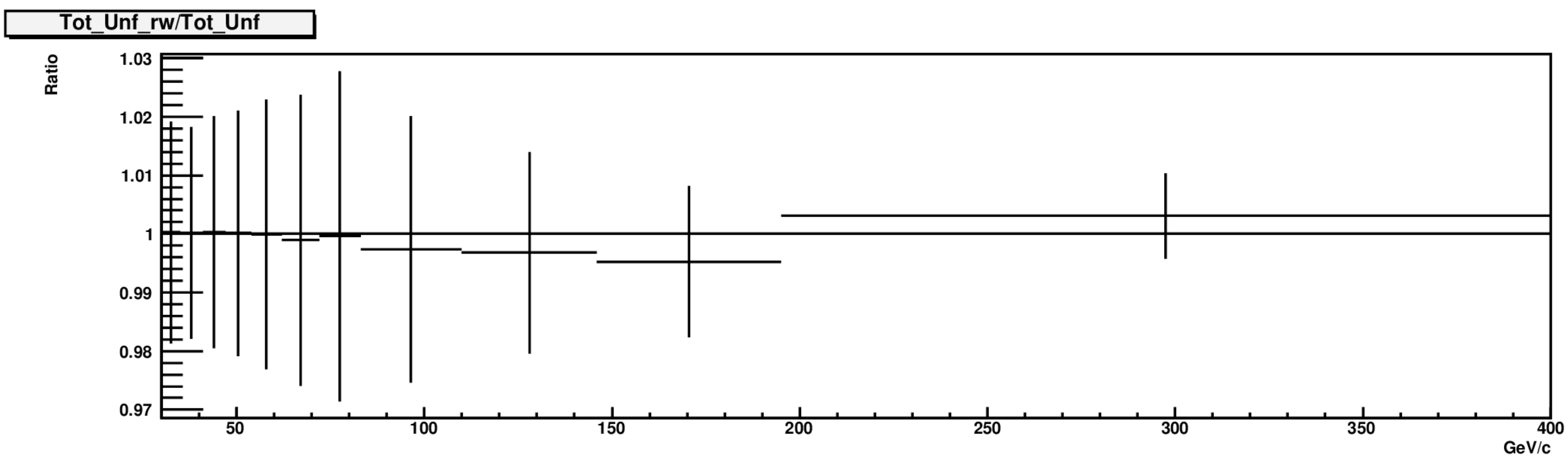




Effect of reweighting pt hat MC in previous Z → ee + jets analyis is within 1%

Unfolding





Same reweighting function applied in current analysis, unfolding factors within 1%