Jet shape and event topology in Z + jets production

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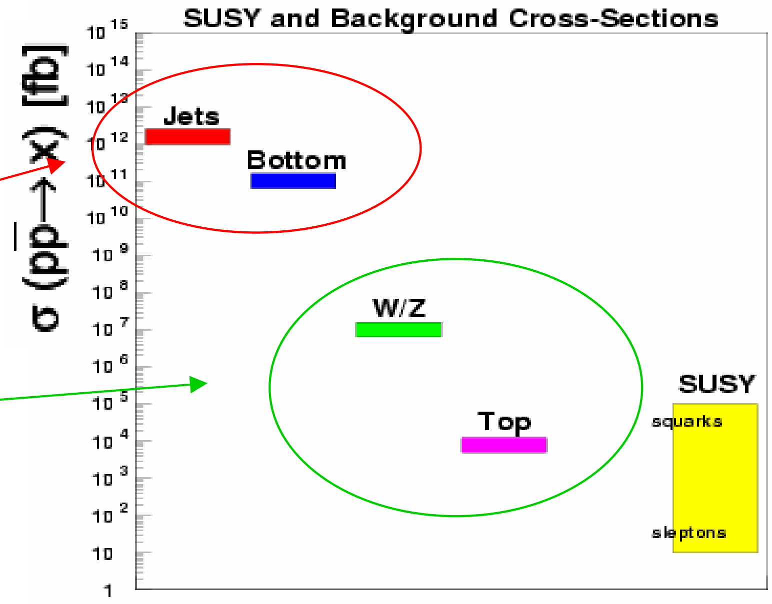
Motivations

- Use Tevatron Data on Boson + jets production:
  - Important by itself as QCD measurement
  - Z and photon + jet used to define jet energy correction
  - Test ground of Monte Carlo generators
- Last Workshop: progress in W+jets studies (A. Messina)
- Here: measurements on the Z(ee) + jets production
  - Cleaner sample
  - Important to estimate the Z($\nu\nu$) + jets irreducible background on many searches.

Key factors

- Good understanding of Jet reconstruction and Energy calibration tools

- Careful study of Monte Carlo generators (usually at LO), to be tested on data in a regime not sensitive to the signal.



Outline

- The Tevatron and CDF/D0 detectors
- Comprehensive study of hadronic final states in Z boson production:
  - Energy flow
    - P_T profile of the event
    - P_T^{in} and P_T^{out}
  - Jet shapes
  - Event topology:
    - Inclusive jet transverse momentum distributions
    - Jet Multiplicity
    - DR(Z, leading jet)
    - Invariant Mass Z-jet
- Comparison with simulations: Pythia *vs* Herwig as Parton Shower associated to Matrix Element MC
- Summary and future plans

The Tevatron

Highest-energy accelerator currently operational

Peak luminosity

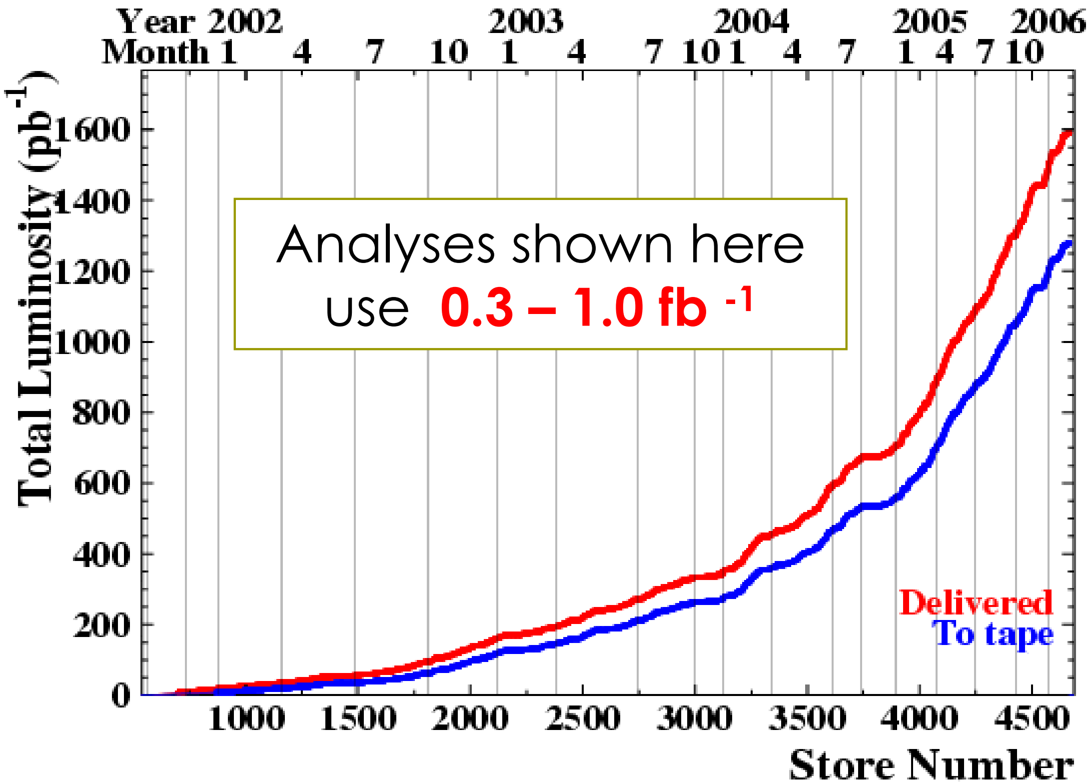
→ **1.8×10^{32} cm^{-2} s^{-1}**

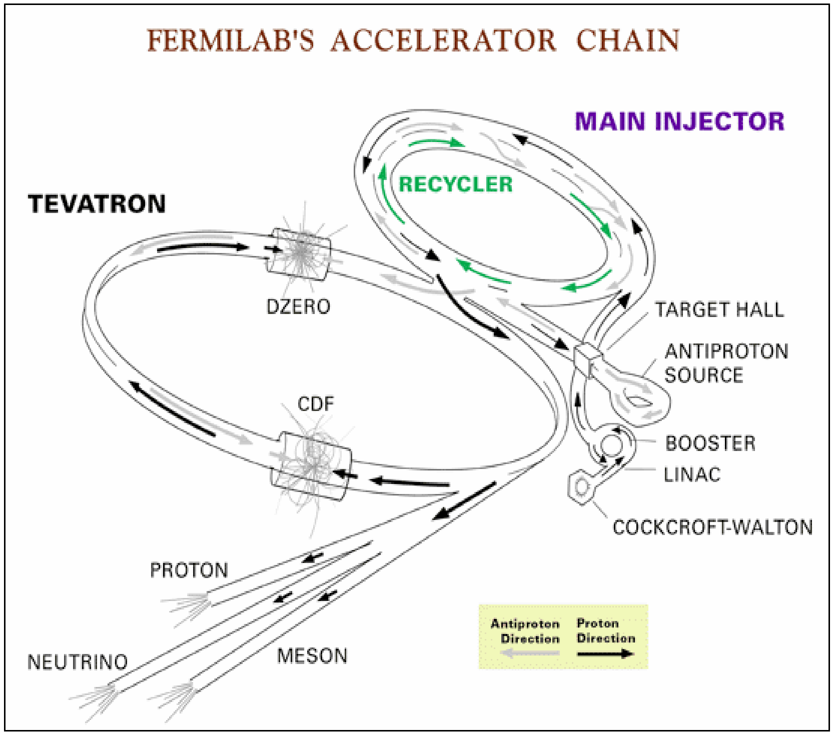
Integrated luminosity/week

→ **about 25 pb^{-1}**

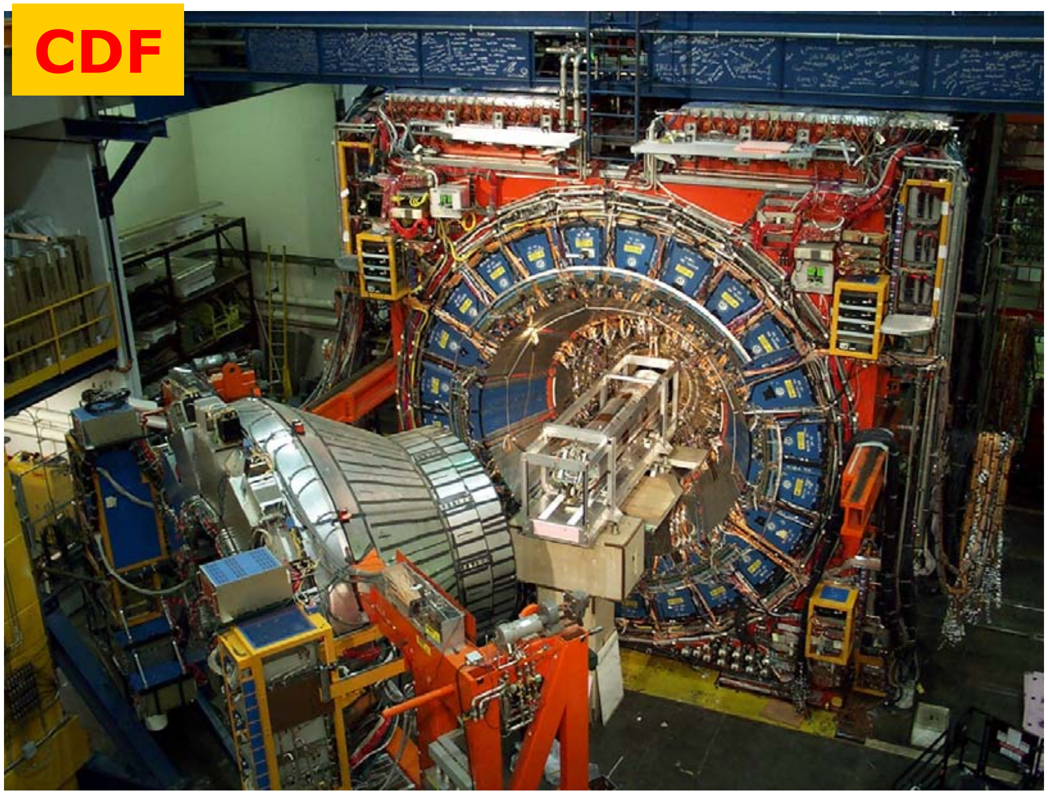
CDF and D0:

→**~1.2 fb^{-1}** on tape





CDF and D0 in RunII

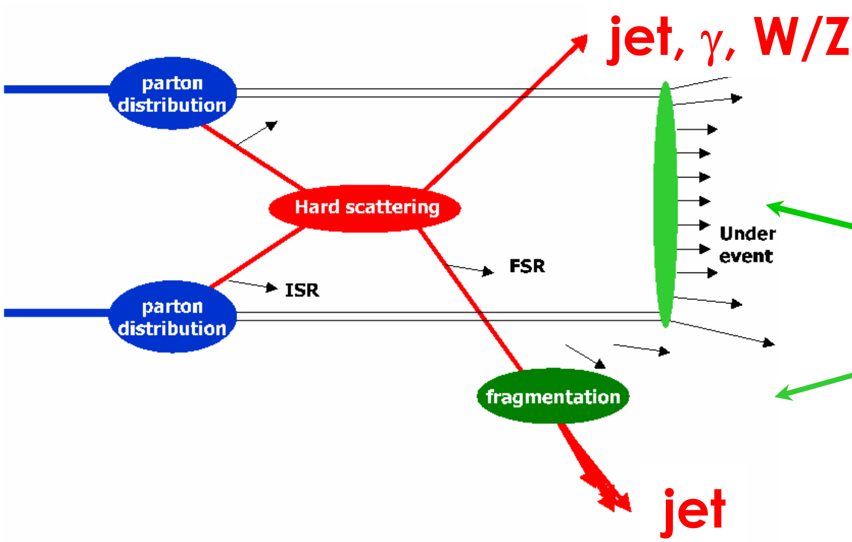


Both detectors
- Silicon microvertex tracker
- Solenoid
- High rate trigger/DAQ
- Calorimeters and muons

L2 trigger on displaced vertices
Excellent tracking resolution

Excellent muon ID and acceptance
Excellent tracking acceptance $|\eta| < 2\text{-}3$

Jet Physics @ Tevatron



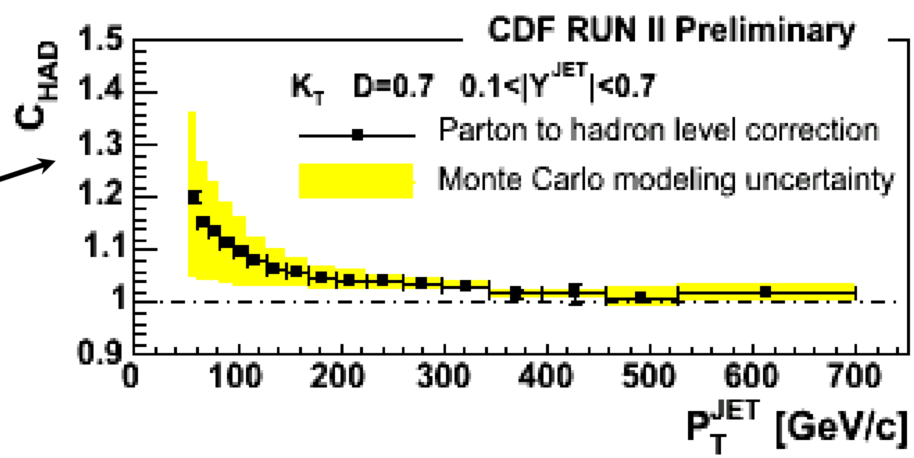
A typical Tevatron event consists of :

- hard interaction
- initial soft gluon radiation
- interaction between remnants

All production processes → QCD related

- Fundamental parameter (highest Q^2 probed → precise test of pQCD at NLO)
- Background for many physics channels
- Phenomenology of non-perturbative regime

Precise measurements at low P_T require good modeling of the non-pQCD terms



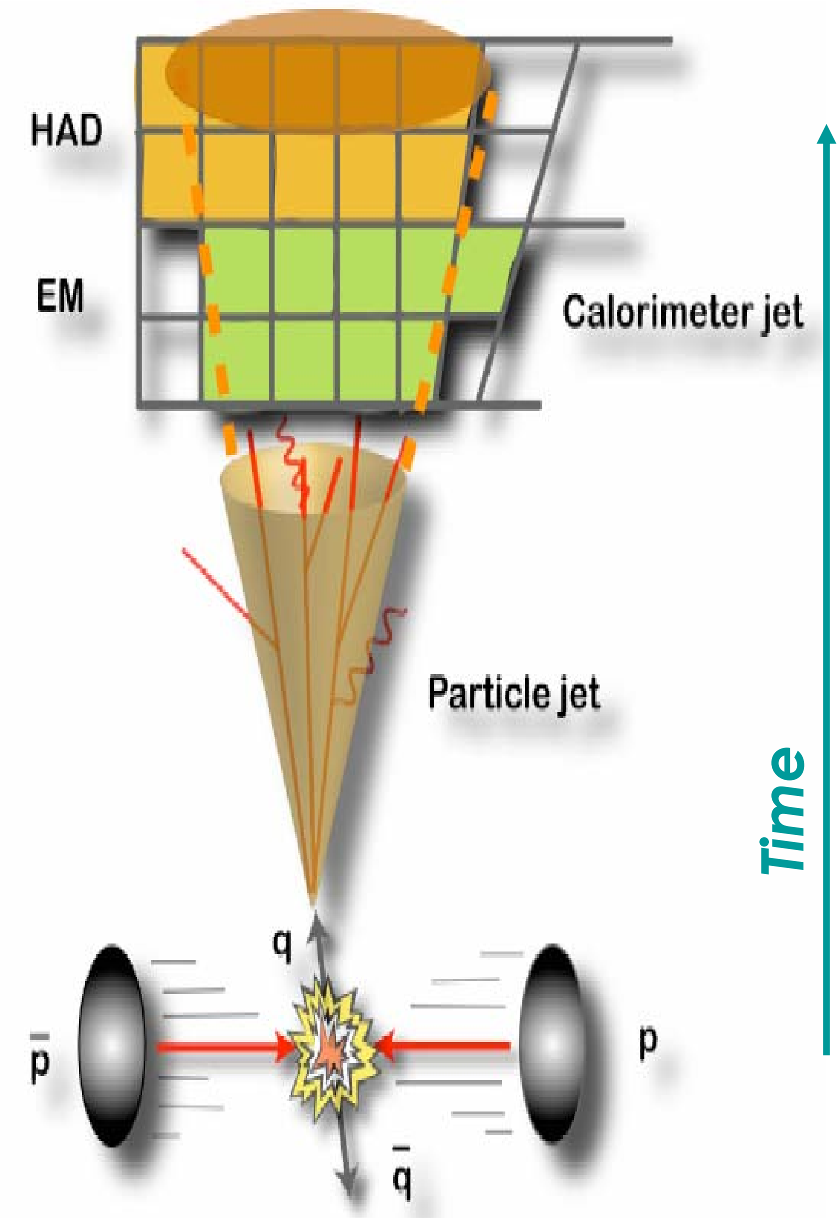
Jet Reconstruction

A jet is a composite object:
- complex underlying physics
- depends on detector properties

Corrections for different effects:
- ➢ calorimeter response to hadrons (non-linear and non-compensating calorimeter)
- ➢ Multiple parton interactions
- ➢ Underlying event

For Calibrations: use $Z \rightarrow e^+e^-$ and Minimum Ionizing Particles (as J/ψ)

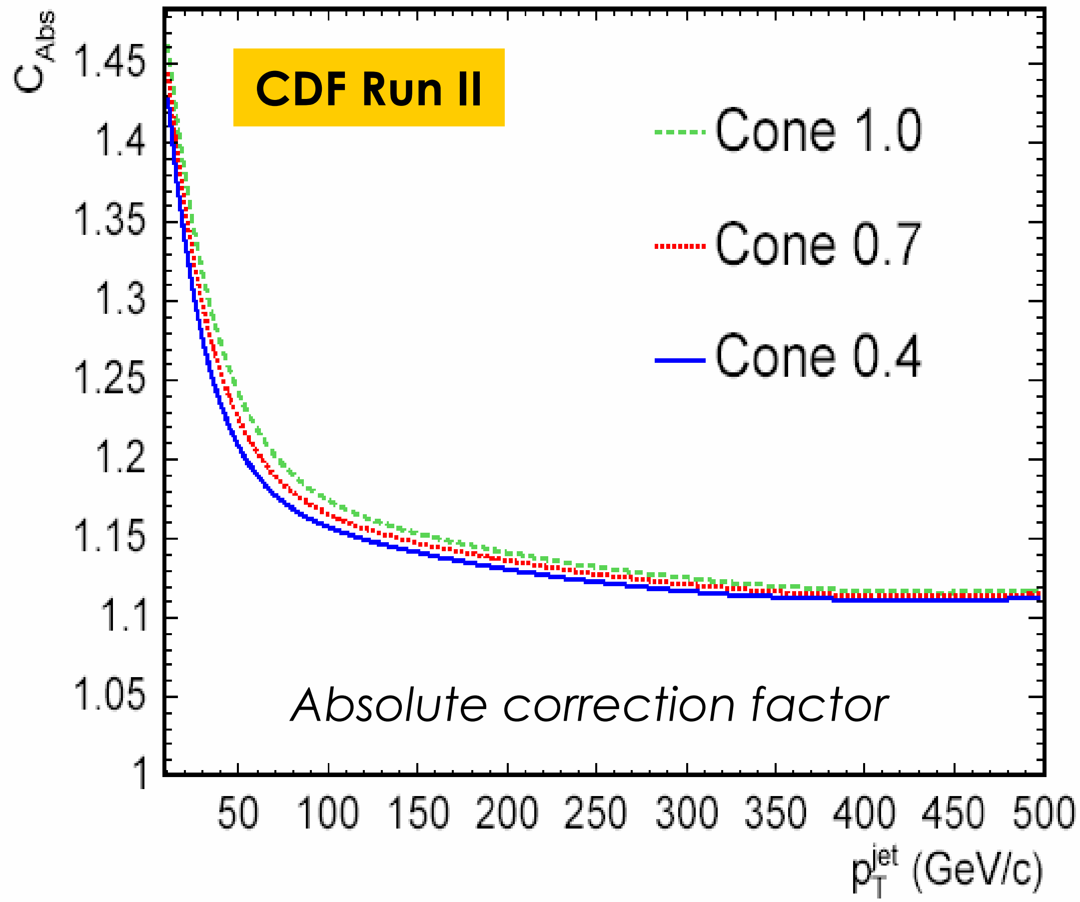
For Corrections: use MC simulations tuned using tracking detector
→ model single particle response (E/p)



CDF Jet Energy Scale Method

Different correction factors:

- (f_{rel}) Relative Corrections
  - → Make response uniform in η
- (MPI) Multiple Particle Interactions
  - → Energy from different ppbar interaction
- (f_{abs}) Absolute Corrections
  - → Calorimeter non-linear and non-compensating
- (UE) Underlying Event
  - → Energy associated with spectator partons in a hard collision

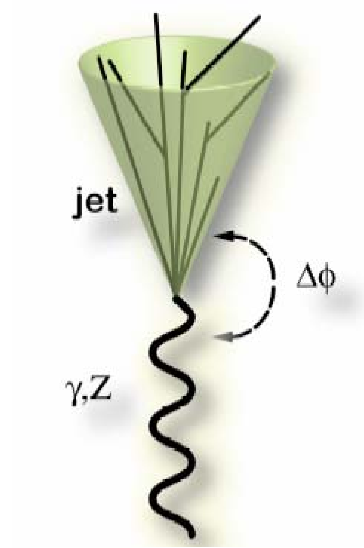


$$P_{T\,jet}(R) = [\, P_{T\,jet}^{raw}(R) \times f_{rel}(R) - MPI(R)] \times f_{abs}(R) - UE(R)$$

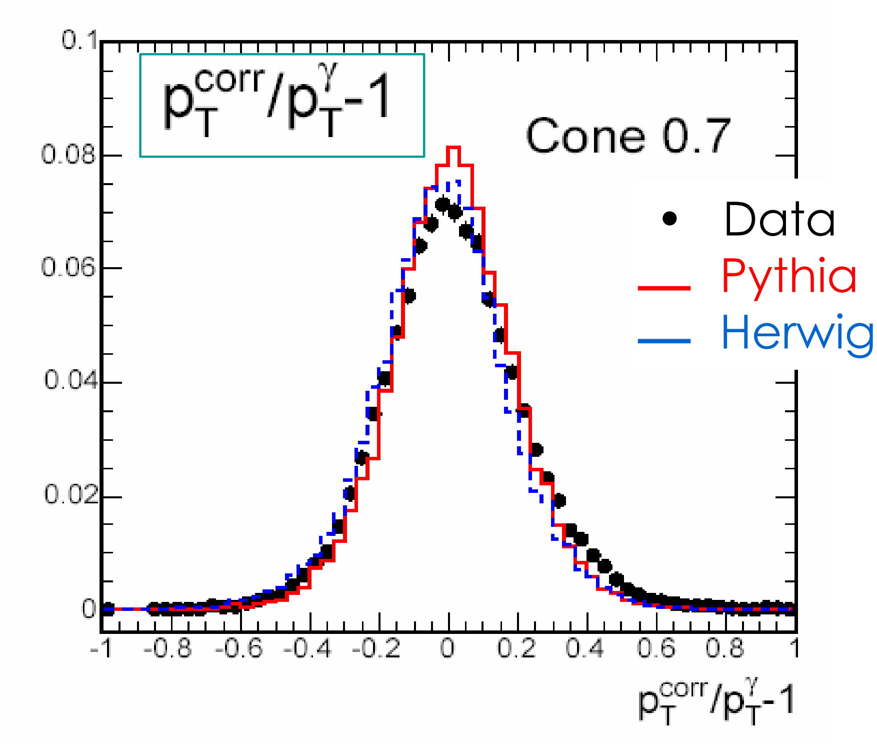
Total systematic uncertainties for JES → between 2% and 3%

γ (Z) + jet p_T balance

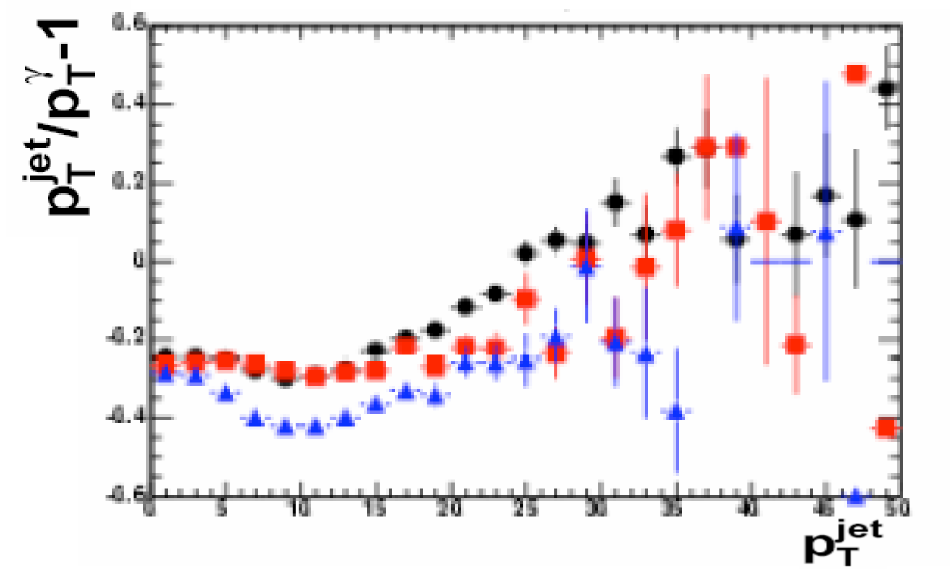
- γ/Z + jet used for many cross checks
- Also: to define JES uncertainties
  → difference between data and MC
    - E_T leading jet > 25 GeV
    - E_T (second jet) < 3 GeV
    - $\Delta\phi$ (Jet-γ) > 3



$$p_T\text{Balance} = \frac{p_T^{jet}}{p_T^{\gamma}} - 1$$



Sensitive to radiation effects when allow second jet:
Herwig farther away from jet cone

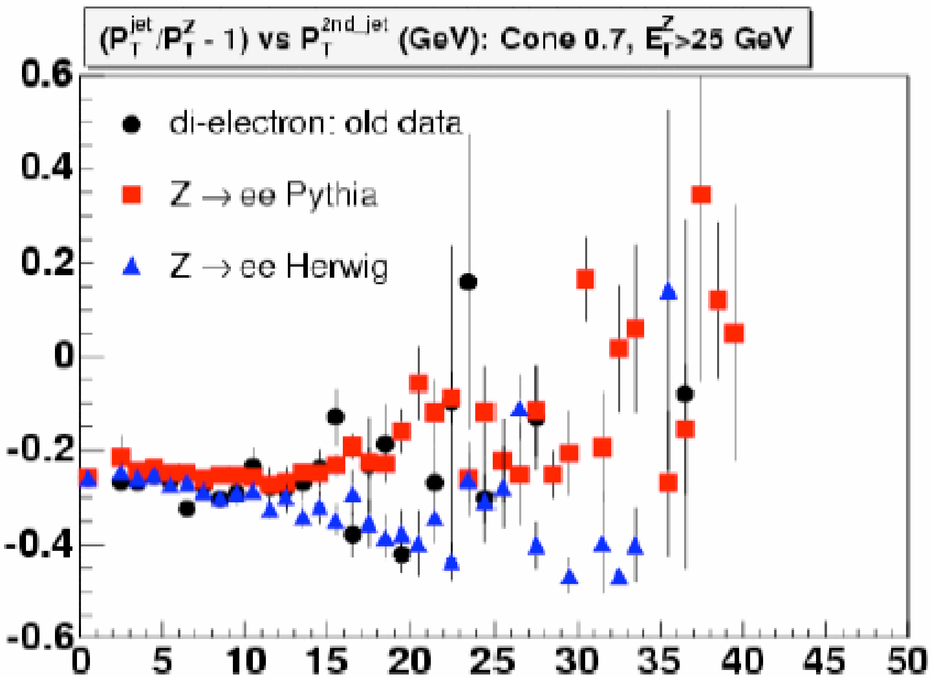


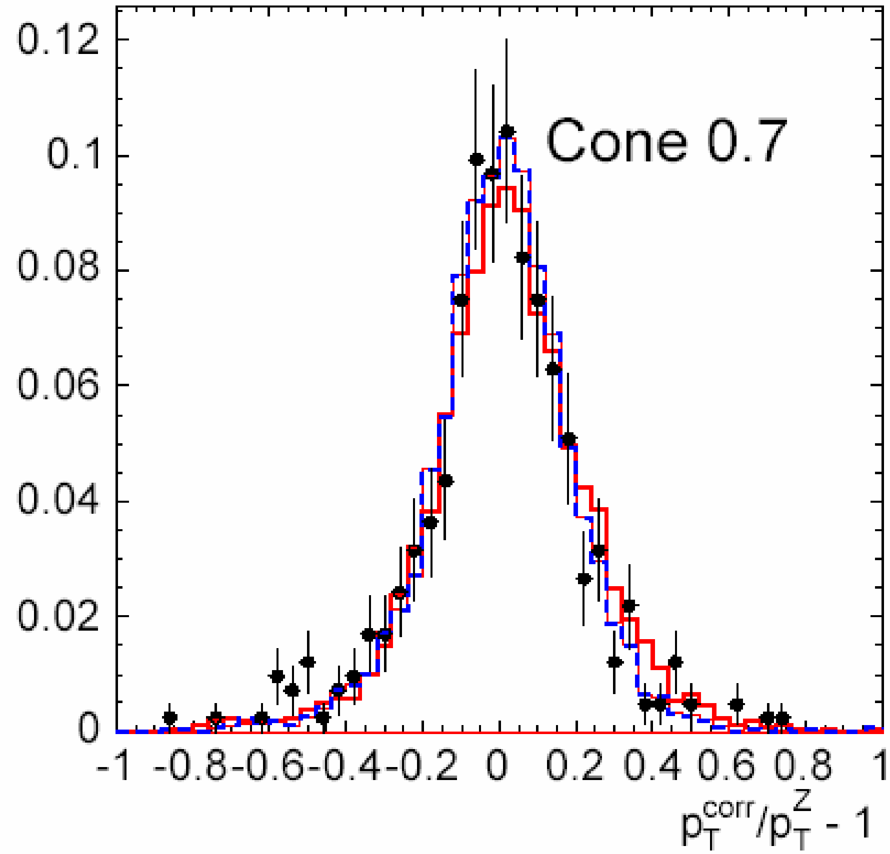
p_T balance:
Agreement Data/MC within 3%

Z-jet p_T balance

Selection

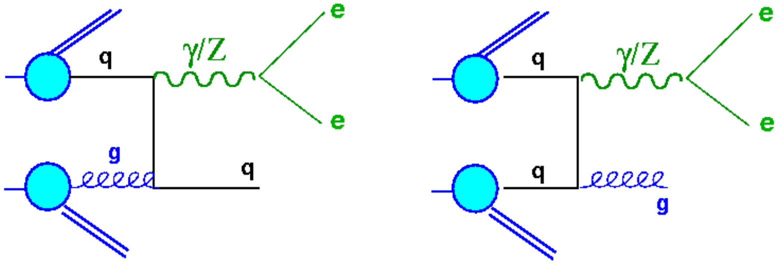
- two e(μ) with E_T>18 GeV (p_T>20 GeV)
- 76 < $M_{ee(\mu\mu)}$ < 106 GeV
- E_T leading jet > 25 GeV
- E_T (second jet) < 3 GeV
- $\Delta\phi$ (Jet-Z) > 3





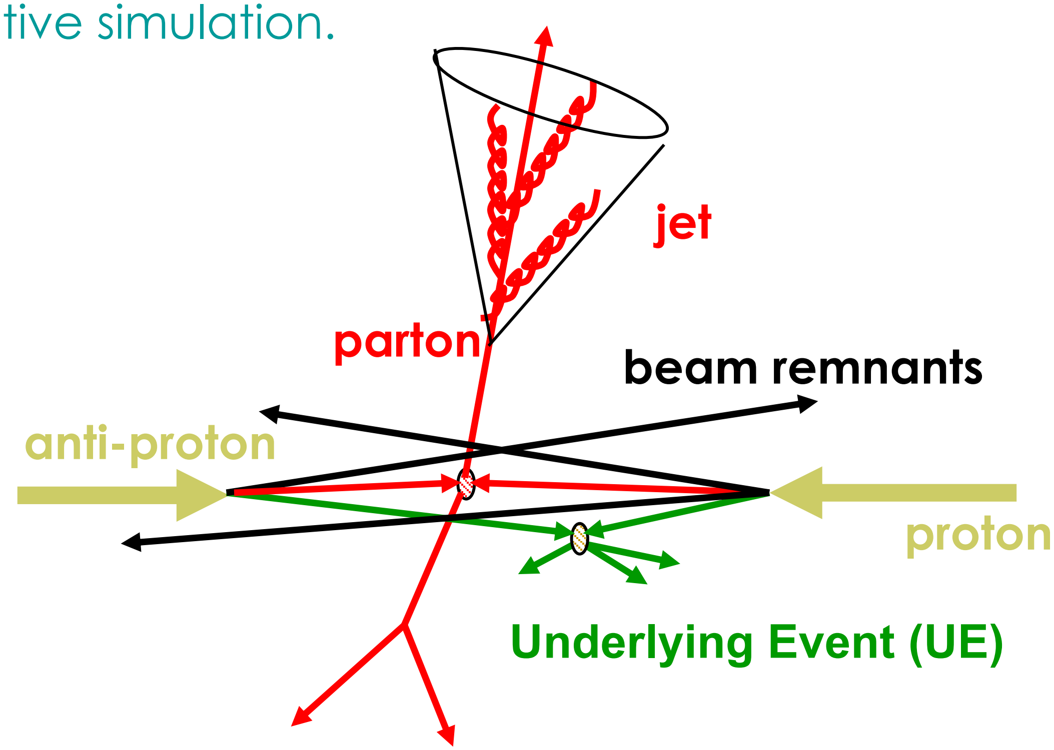
Similar Herwig behaviour
for Z+jet w.r.t. γ+jet but less visible

Z + jets production



- Same good features of W+jets:
  - Presence of a boson ensures high Q^2
  - Large BR into leptons
- No New Physics expected in Z+jets
- $\sigma(Z) \sim \sigma(W) / 10$, but $Z \rightarrow e^+e^-$ cleaner

→ to study all aspects of hadronic collisions and relative simulation.



LO and **NLO** calculations

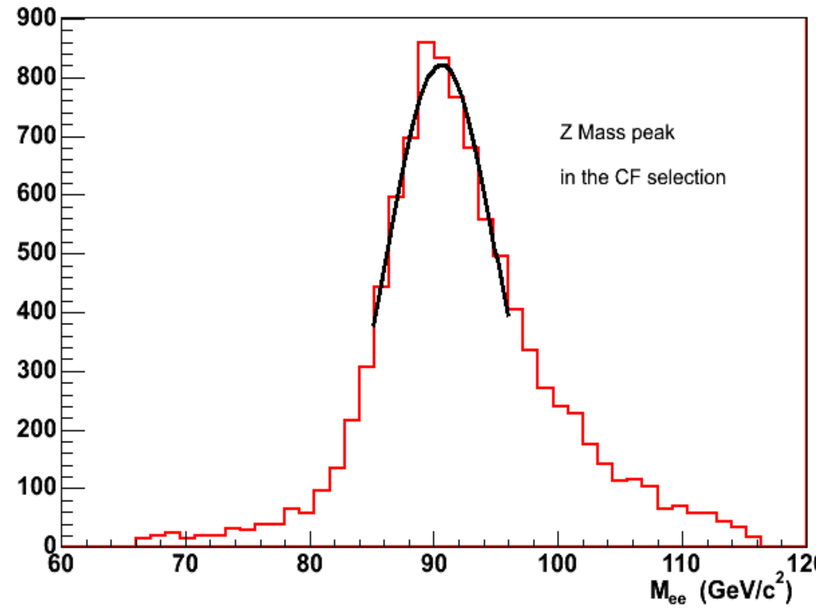
- Pythia, Herwig:
→ shower, ME (Z+1 parton)
- Alpgen, Sherpa, Madgraph:
→ME with shower (Z + multi-parton)
- MCFM: NLO ME (Z +1, 2 or 3 partons)

Z event selection

- $Z \rightarrow e^+e^-$
  - Two electrons, $|\eta_e| < 2.8$, $E_T > 25$ GeV
  - $66 < M_{ee} < 116$ GeV/c^2
- $P_T^{jet} > 25$ GeV/c, $|Y^{jet}| < 2.1$

Jets reconstructed with the **MidPoint** cone algorithm (R = 0.7)

$$Peak\ Value = 90.58 \pm 0.09(fit)\ \frac{GeV}{c^2}$$



Data

- obtained with the CDF II detector
- Trigger: Two Electromagnetic objects with $E_T > 18$ GeV

MC samples: **$Z \rightarrow e^+e^-$ + 1p**

- Pythia Tune A
- Alpgen+Herwig

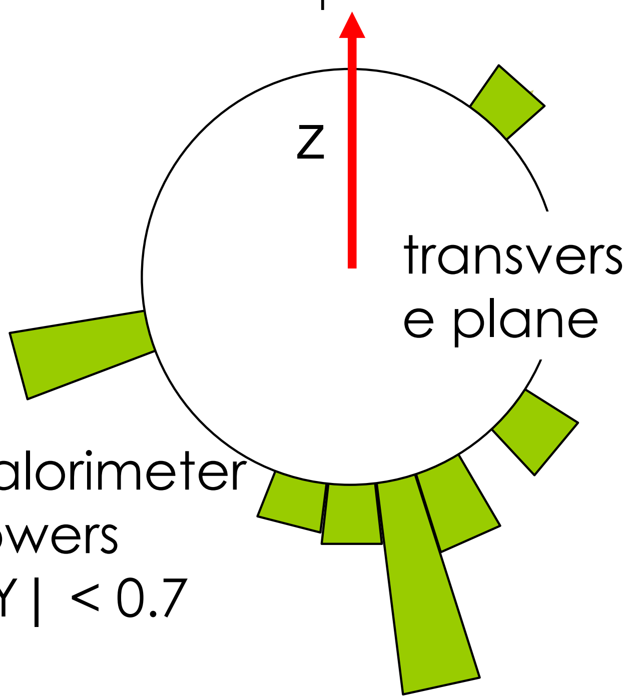
$$\sigma = \frac{N_{obs} - N_{bckg}^{QCD}}{\varepsilon_{trig} \cdot \varepsilon_Z \cdot \varepsilon_{vtx} \cdot A \cdot \int L\, dt}$$

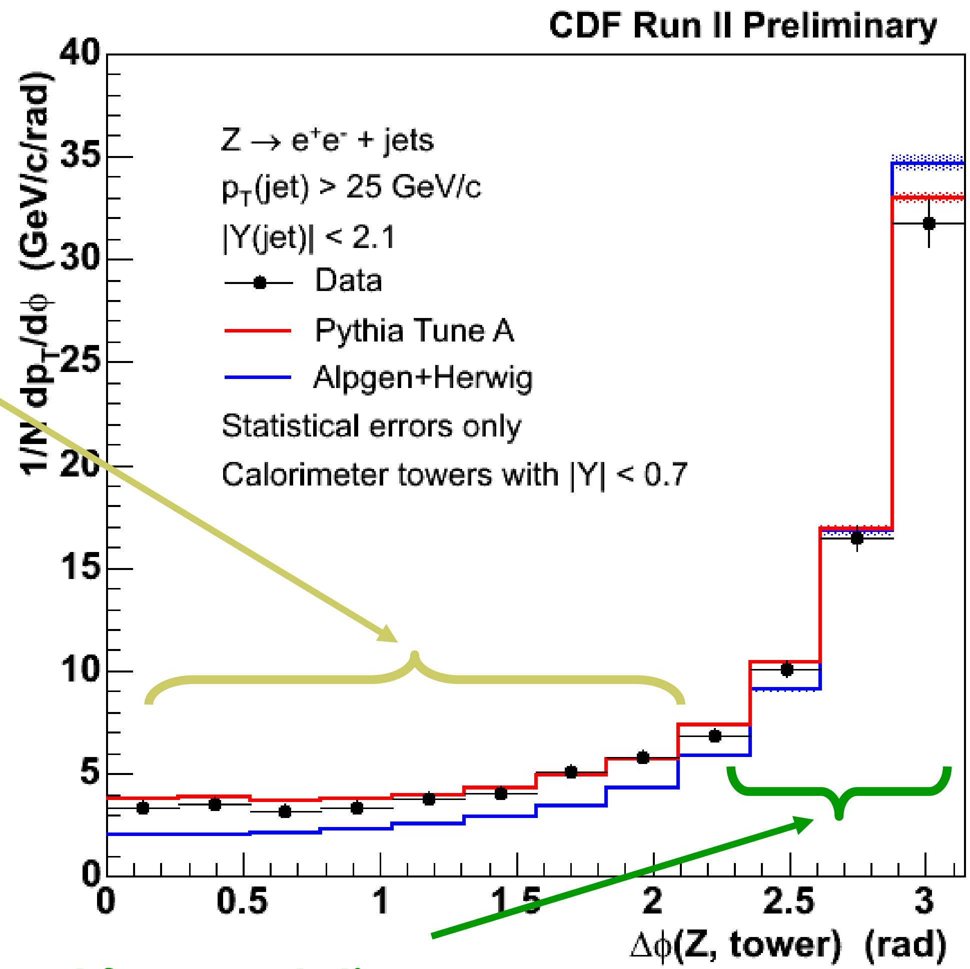
Reproduce the mass and the inclusive Z cross-section values at the expected level

Z+jets energy flow: P_T profile

Energy between the jet and the Z.

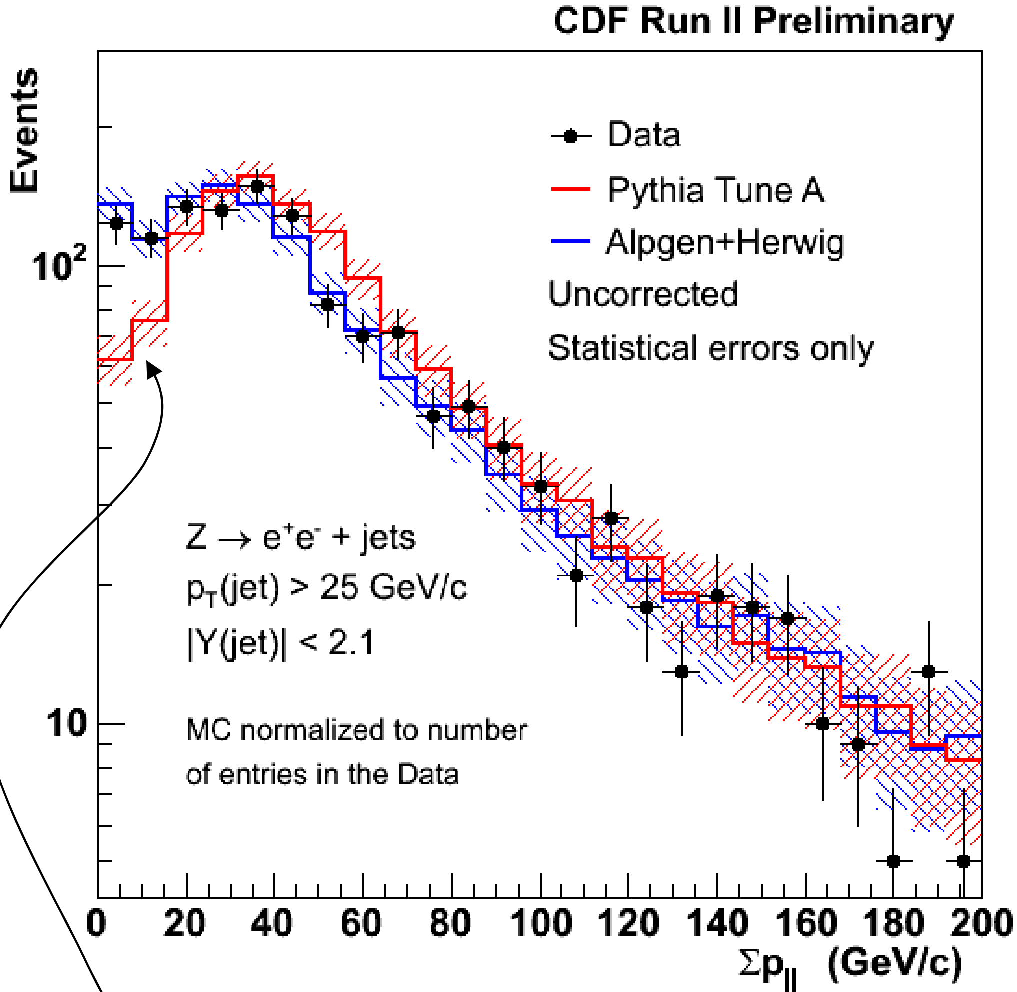
- Dominated by the **UE**.
- Independent of the p_T of the jet.





Pythia with the Tune A is the simulation that better reproduces the **jet fragmentation** and the **Underlying Event level**

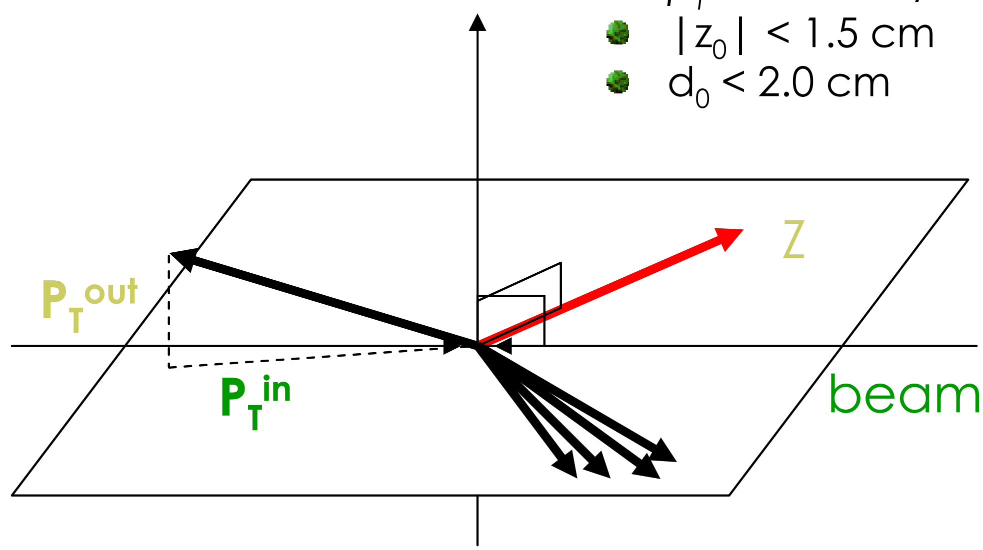
P_T^{in}



Sum of the components of the momentum of the track parallel to the plane defined by the Z particle direction and the beam axis.

Using tracks with:

- $p_T > 0.5$ GeV/c
- $|z_0| < 1.5$ cm
- $d_0 < 2.0$ cm

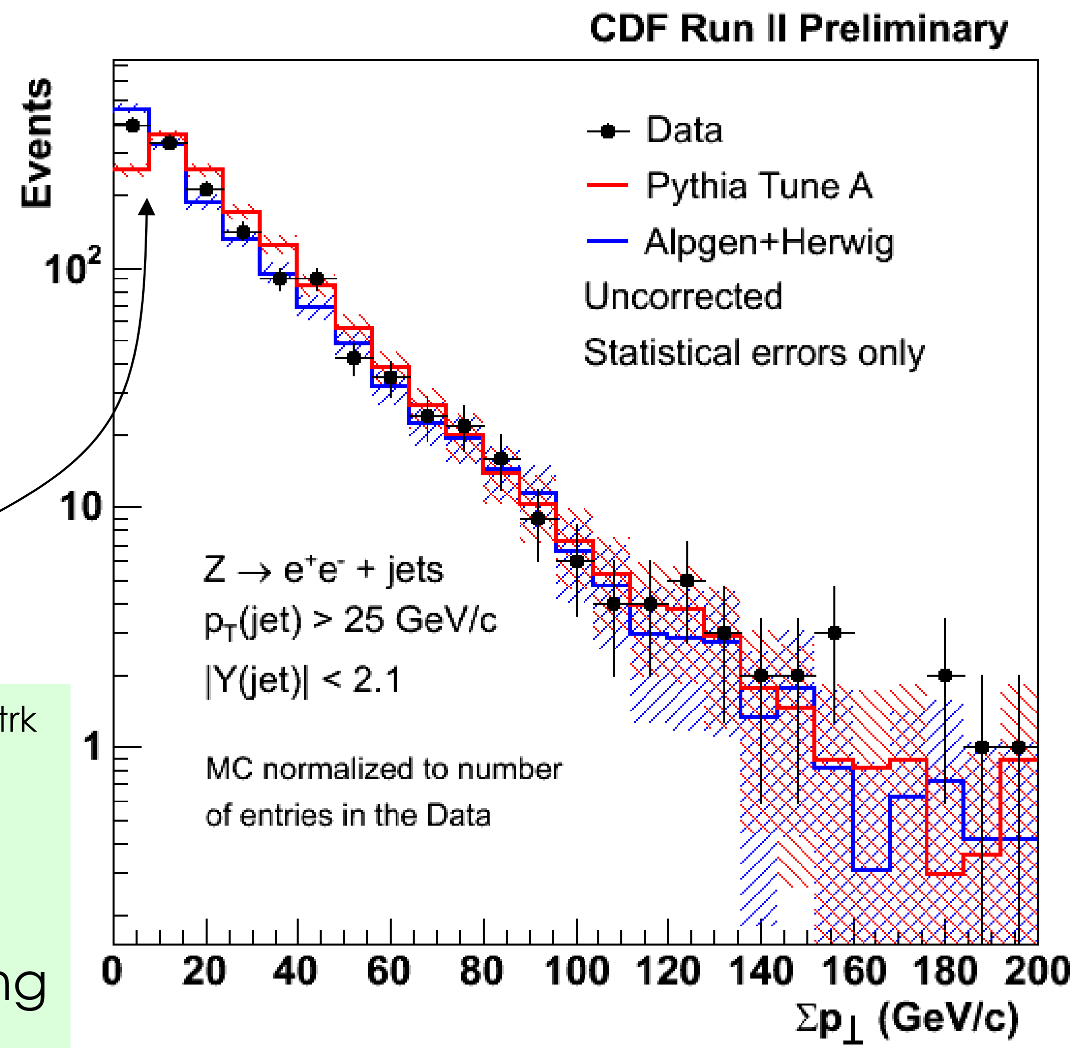


G.Marchesini et al., JHEP 0108(2001) 047 hep-ph/0106278

Pythia is always generating some amount of activity (tracks) in the plane

P_T^{out}

Sum of the transverse component to the Z-beam plane, of the momentum of the tracks

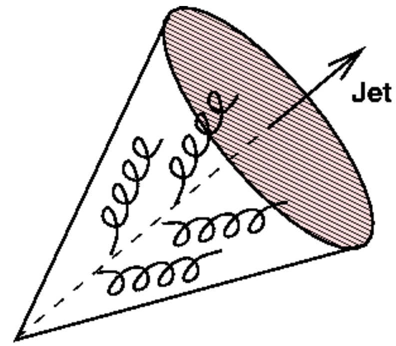


Out of the plane (transverse component to the plane) the effect is no so visible.

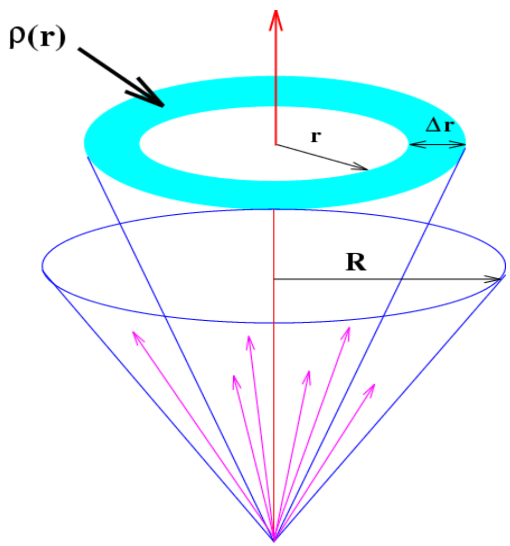
Some "clean" events (very low p_T^{trk} in the event) in the data.
Well simulated by **Herwig**.
Pythia puts always a certain amount of extra activity (Underlyng Event tuning)

Jet Shapes

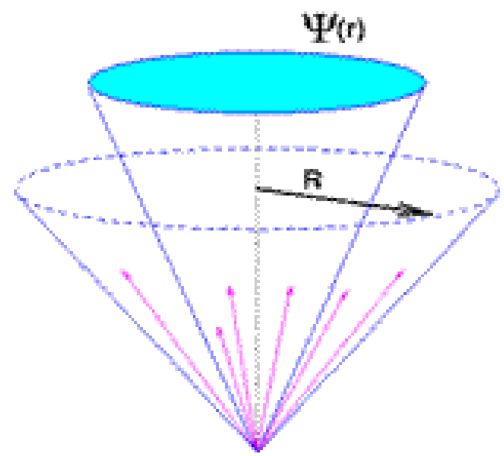
- Jet shape dictated by multi-gluon emission form primary parton
- Test of parton shower models and their implementations
- Sensitive to underlying event structure in the final state



$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{p_T(0,r)}{p_T(0,R)}$$



Differential shape
(steps of $\Delta R = 0.1$)



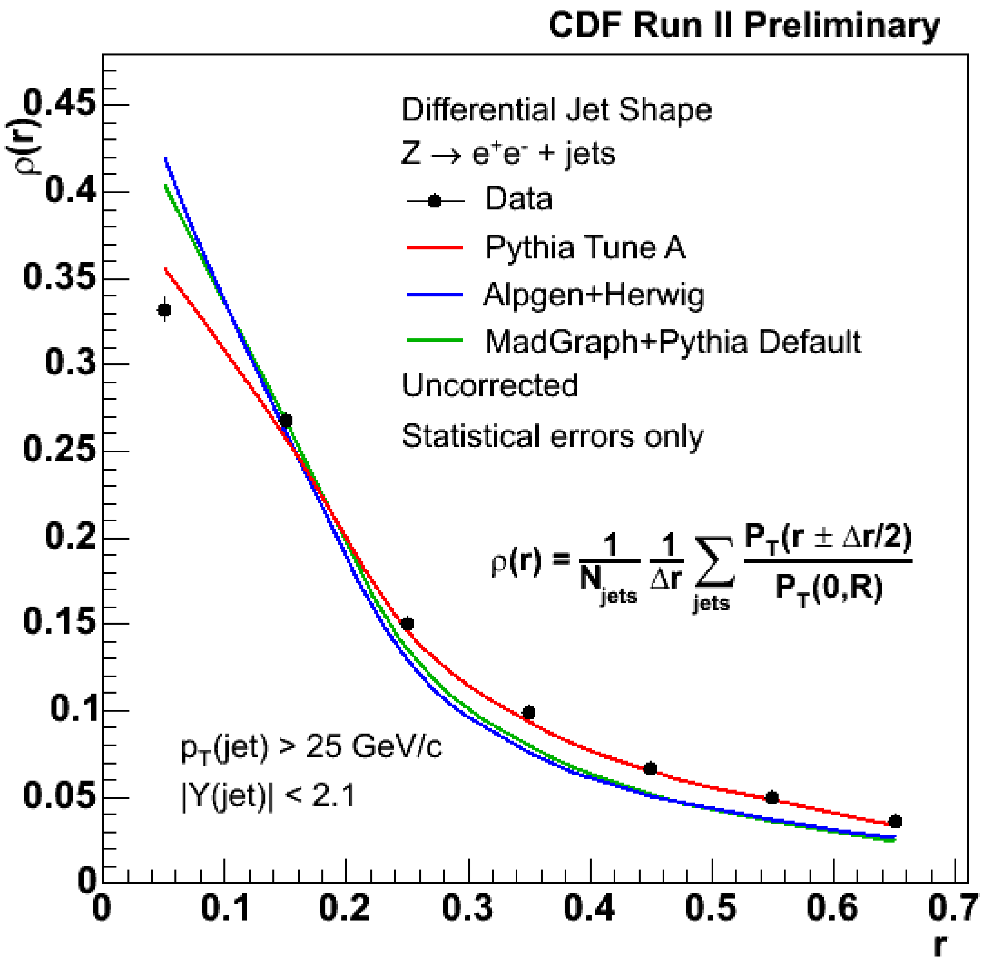
$$\rho(r) = \frac{1}{N_{jets}} \frac{1}{\Delta r} \sum_{jets} \frac{p_T(r \pm \Delta r)}{p_T(0,R)}$$

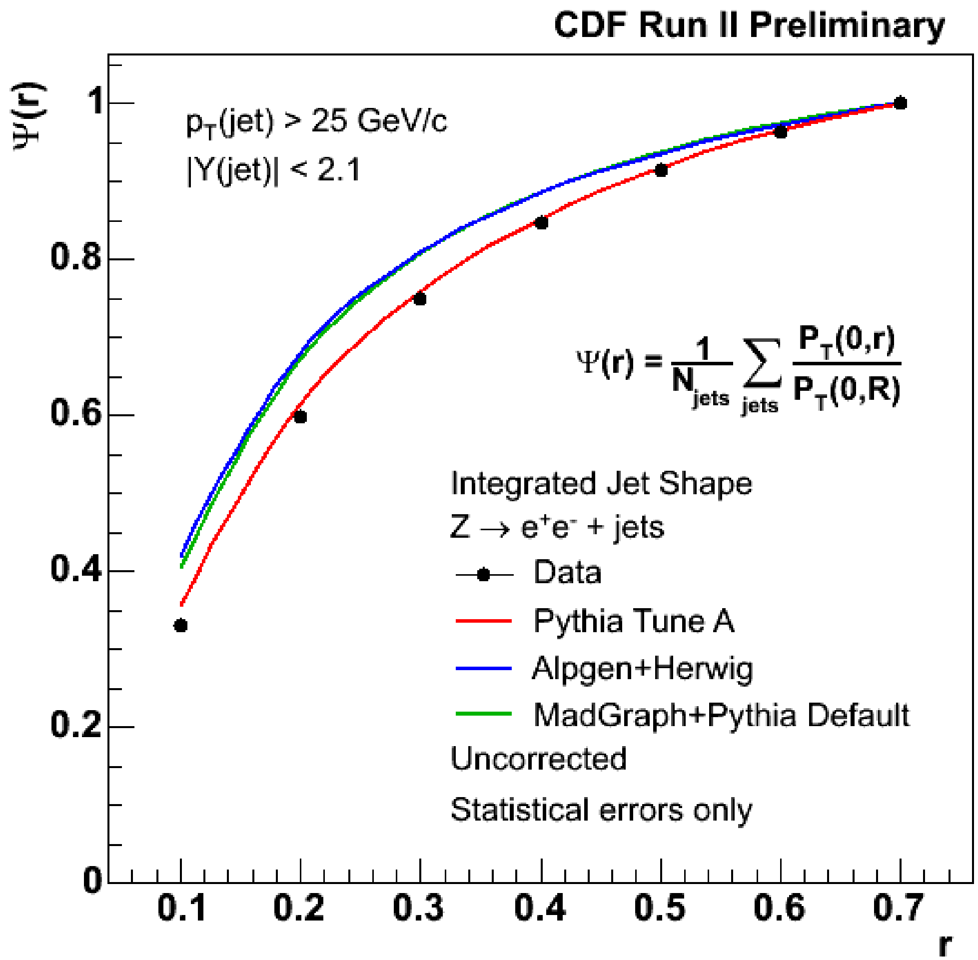
Integrated shape

Jet Shapes

Calorimeter shape

Using the E_T of the calorimeter towers in jets with pT>25GeV/c and |Y|<2.1





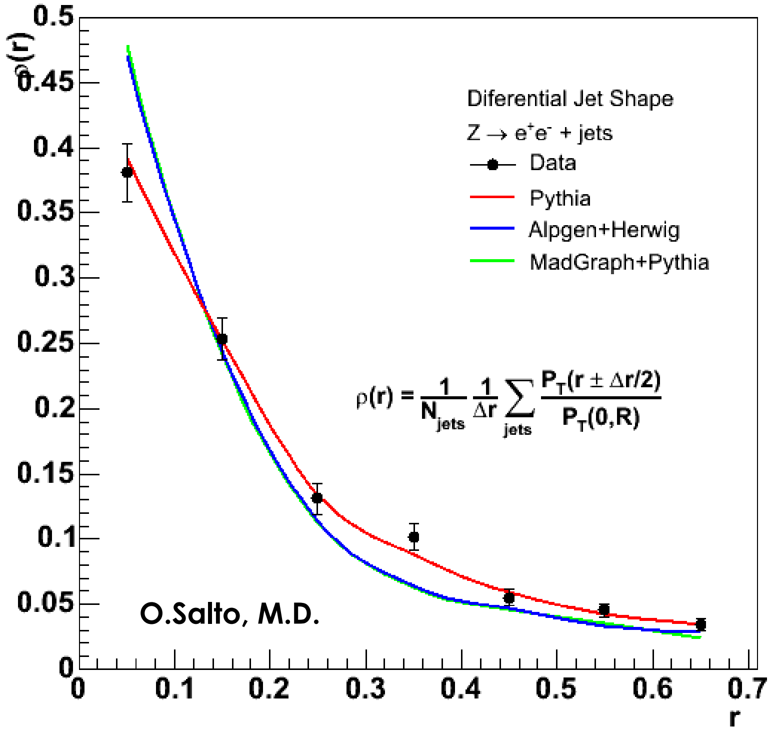
- PYTHIA Tune A describes the data (enhanced ISR + MPI tuning)

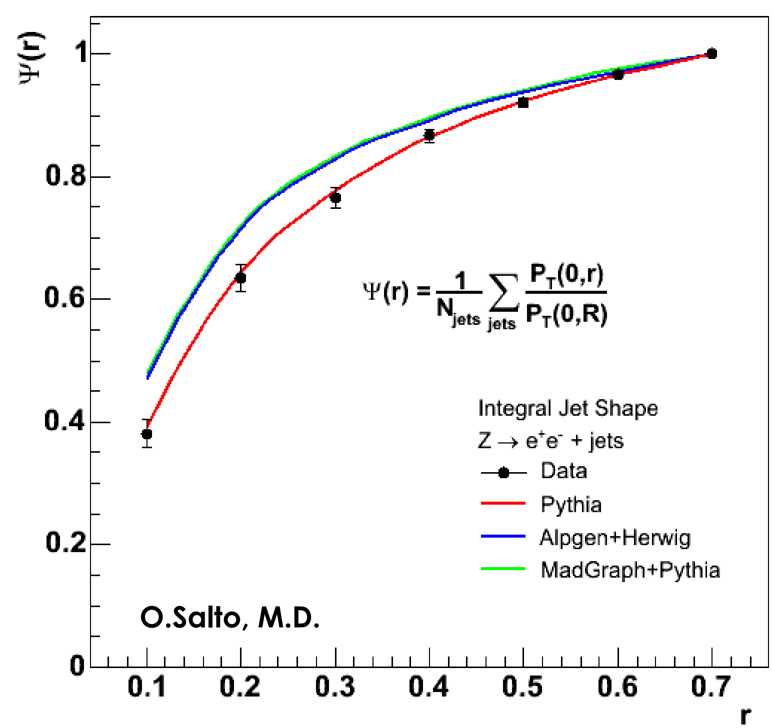
- PYTHIA default too narrow
- HERWIG too narrow

Jet Shapes

Tracks shape
Using the p_T of the tracks.
Jets until |Y(jet)| < 0.7 with p_T > 25 GeV/c

Using tracks with:
- p_T > 0.5 GeV/c
- nHits > 20
- |z0| < 1.5   d0 < 2.0





- The jet shapes in the calorimeter and in the COT are accurately described by the Pythia simulation
- Herwig do not reproduce properly the fragmentation of the jet.

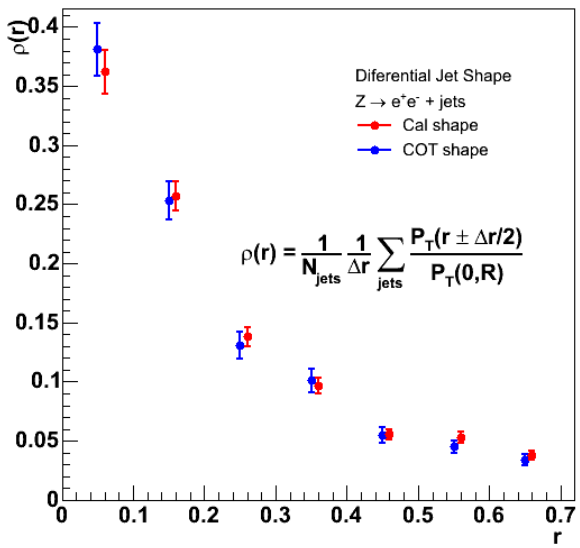
Jet Shapes

Calorimeter vs. COT shape for the data

Jets until

| Y(jet) | < 0.7

O.Salto, M.D.



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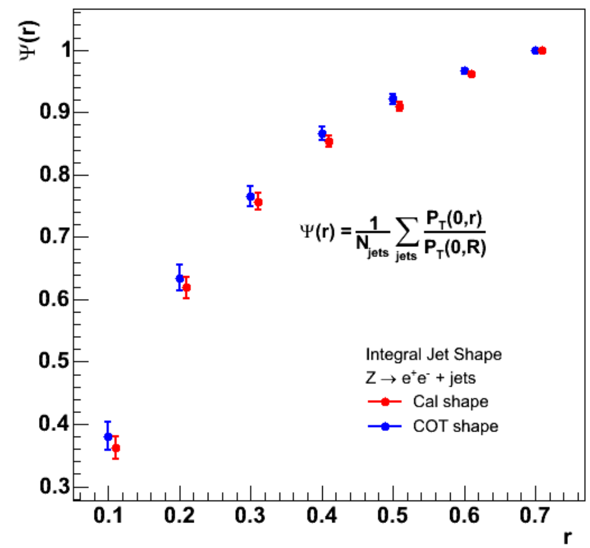
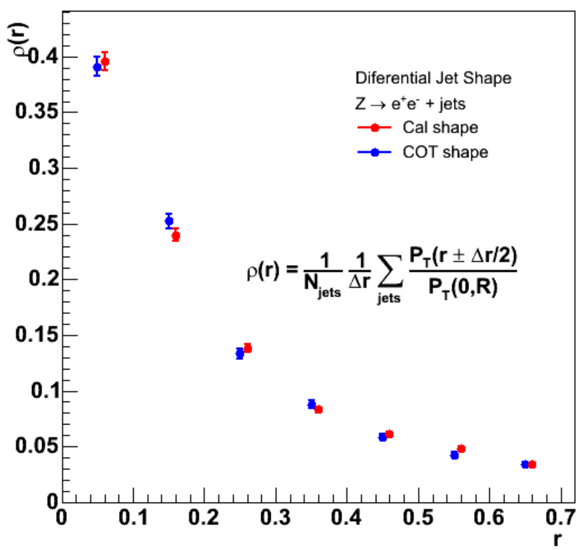
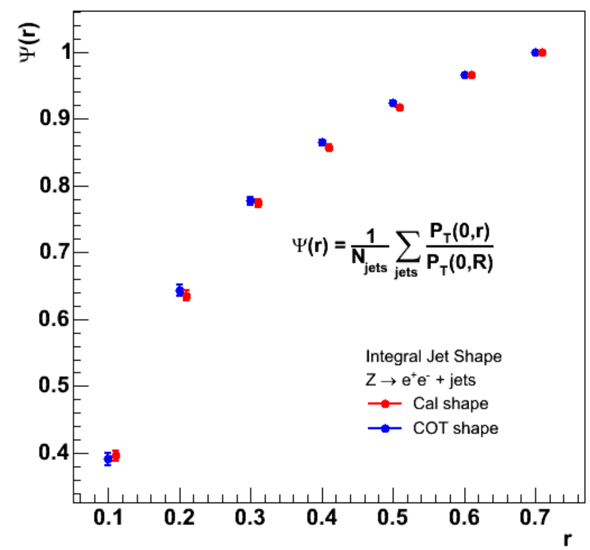


Calorimeter vs. COT shape for Pythia

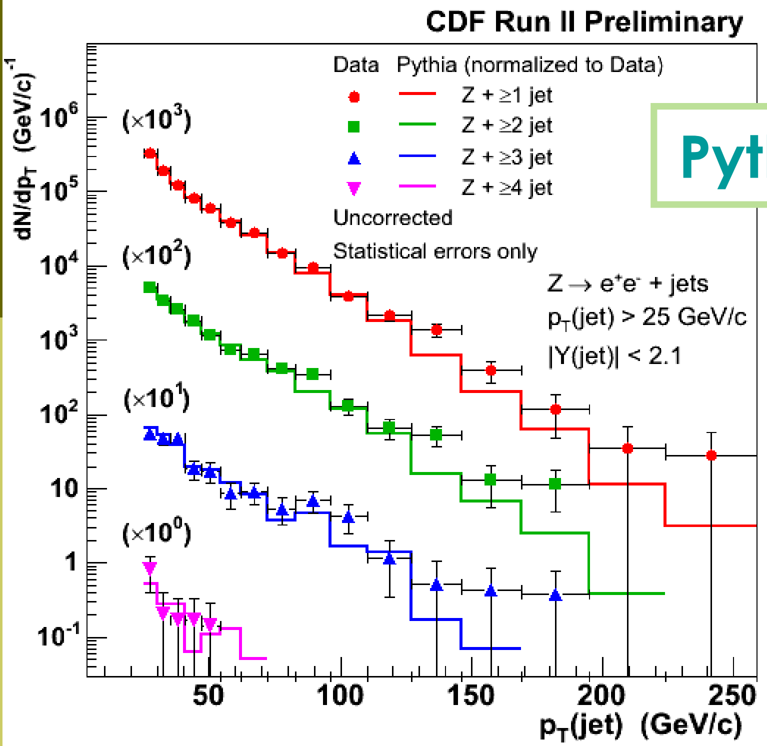
Jets until

| Y(jet) | < 0.7





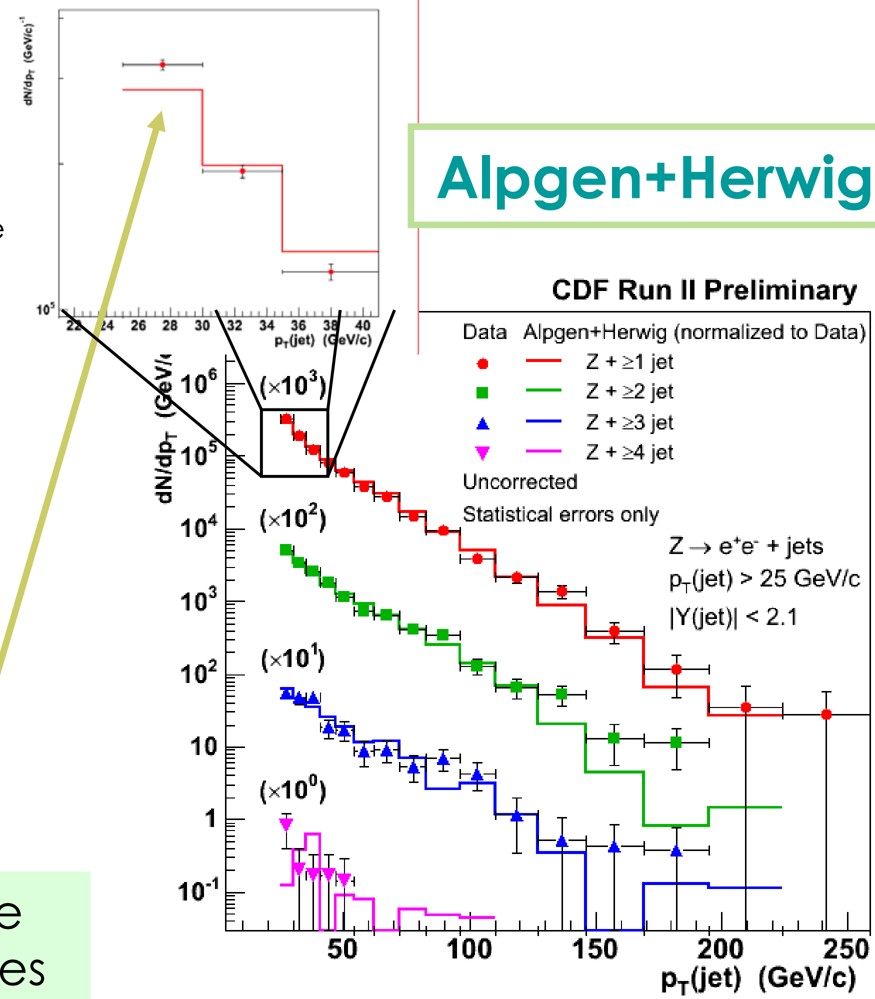
Inclusive p_T^{jet} distribution



Pythia

P_T distribution of the jets in events with Z + ≥n jets

Every MC distribution is normalized to the number of entries in the data



Alpgen+Herwig

Note: Same process in Pythia and Alpgen+Herwig (Z+1p) at tree level

While Pythia reproduces well the shape of the p_T distributions, **Alpgen+Herwig** underestimates jets with low p_T due to the lack of UE

Alpgen+Pythia

→ Check impact of interfaced shower
→ Use **Alpgen + Pythia** Tune A

Interfacing Alpgen ME with Pythia gives slightly better agreement in shape

→ further tuning could be necessary (still 10% difference)

Issue: Alpgen + PS not have the correct absolute normalization

Data/MC ~ 1.X

Until now: shape comparison
And renormalization to inclusive W/Z production
→ Could be useful to understand how to improve it

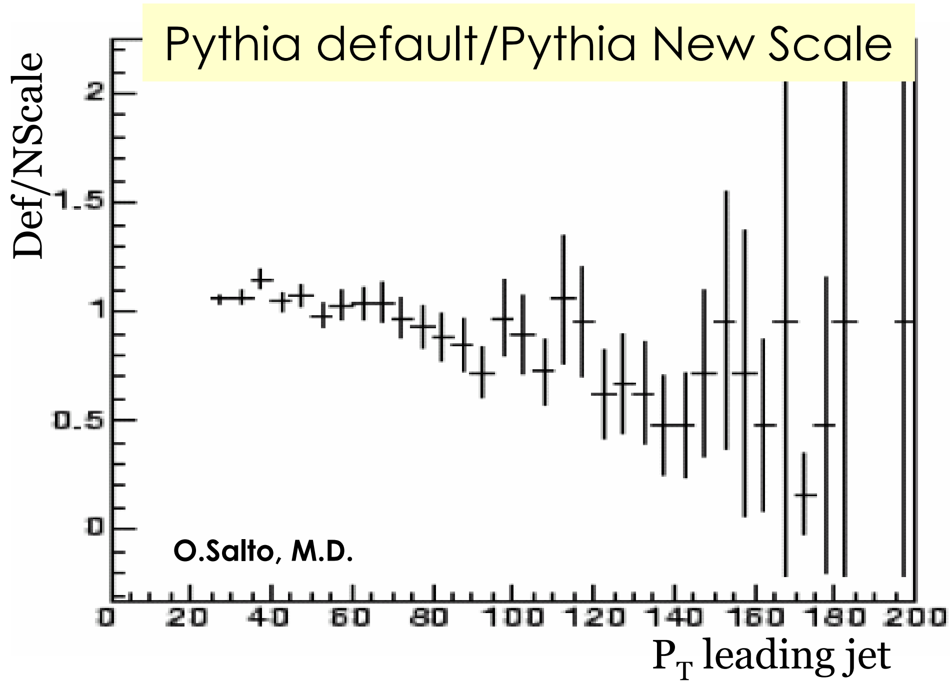
- Parton-level checks:

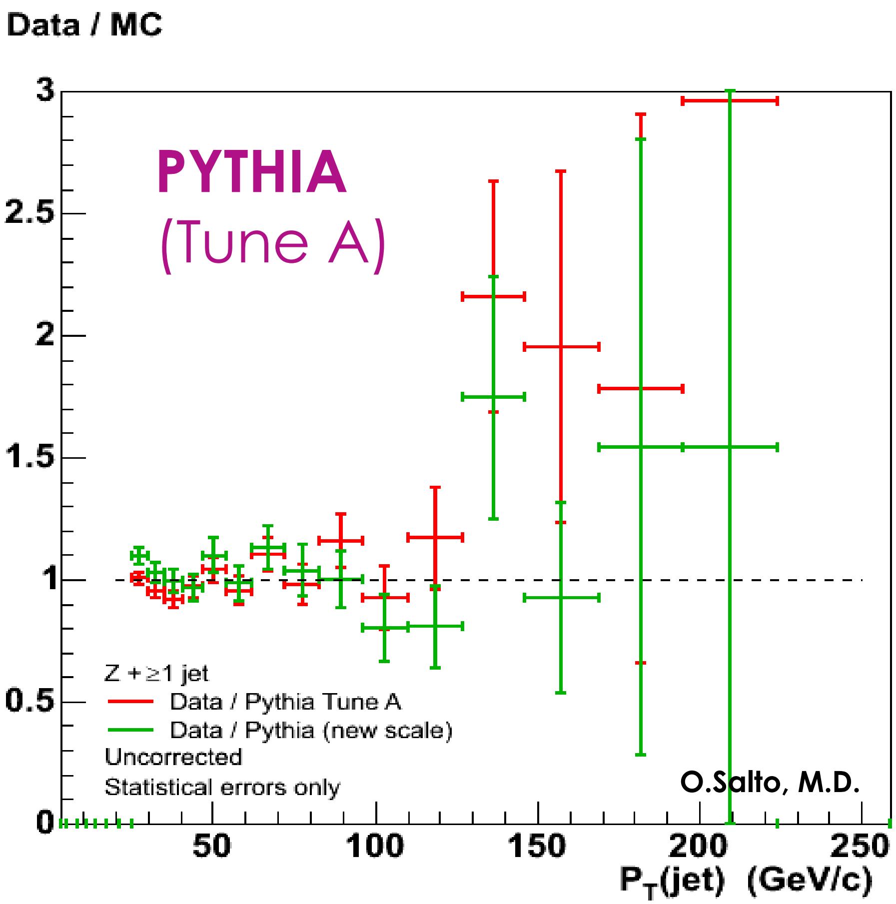
→ same cross sections for Pythia and Alpgen+Pythia (Z+1p)

Z+parton(s) processes simulated with Alpgen depends on many parameter:
- Shower evolution
- parton-jet matching
- **Q^2 scale → effects?**

Q^2 scale effects

- For Alpgen ME use:
  - $Q^2 = m_Z^2 + \Sigma\, p_T^2$(partons)
- Use 2 different scales for Pythia:
  - Default: ~ $Q^2 = (m_Z^2 + \Sigma\, p_T^2)/2$
  - New Scale: ~ $Q^2 = m_Z^2 + \Sigma\, p_T^2$



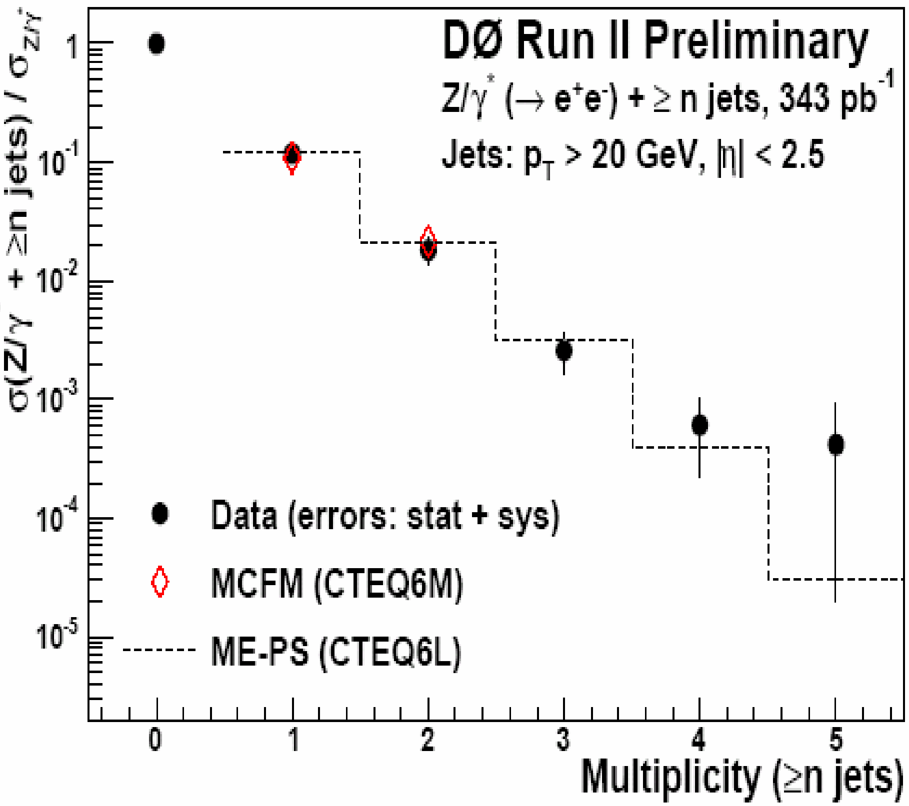


- No negligible effects (~10%), important to evaluate NLO/LO k-factors → Use **MCFM**:
  - same LO scale required at NLO
- Does not explain the 1.X factor
- Data suggest Pythia default Q^2
- Tests on-going: Z+jets events can help to constrain Q^2 scale

Jet multiplicity

$$R_n = \frac{\sigma_n}{\sigma_0} = \frac{\sigma[Z/\gamma^*(\rightarrow e^+e^-) + \geq njets]}{\sigma[Z/\gamma^*(\rightarrow e^+e^-)]}$$

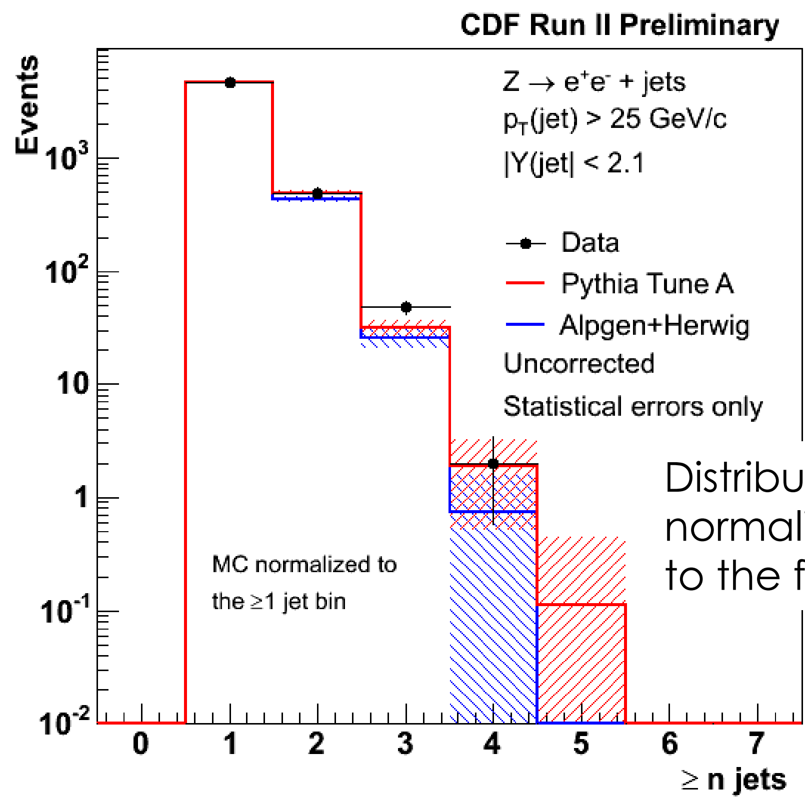
LO calculations → expected less events with high jet multiplicity.



Pythia: simulation of the parton shower leads to an accurate number of jets.

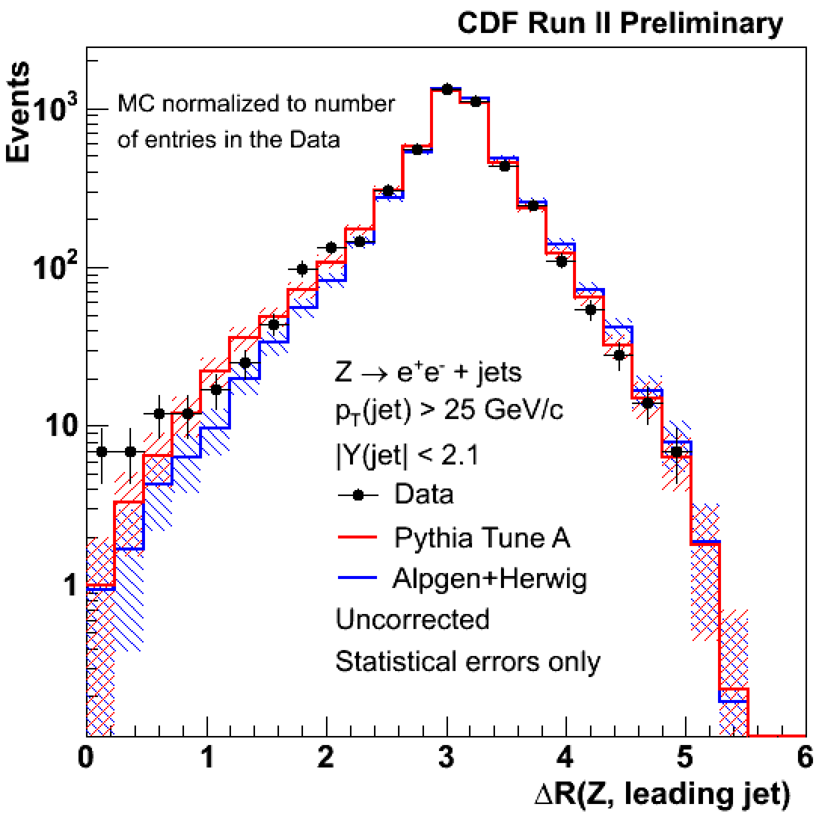
ME + PS: MADGRAPH + Pythia tree level process up to 3 partons → reproduce shape of N_{jet}

MCFM → good description of the measured cross sections



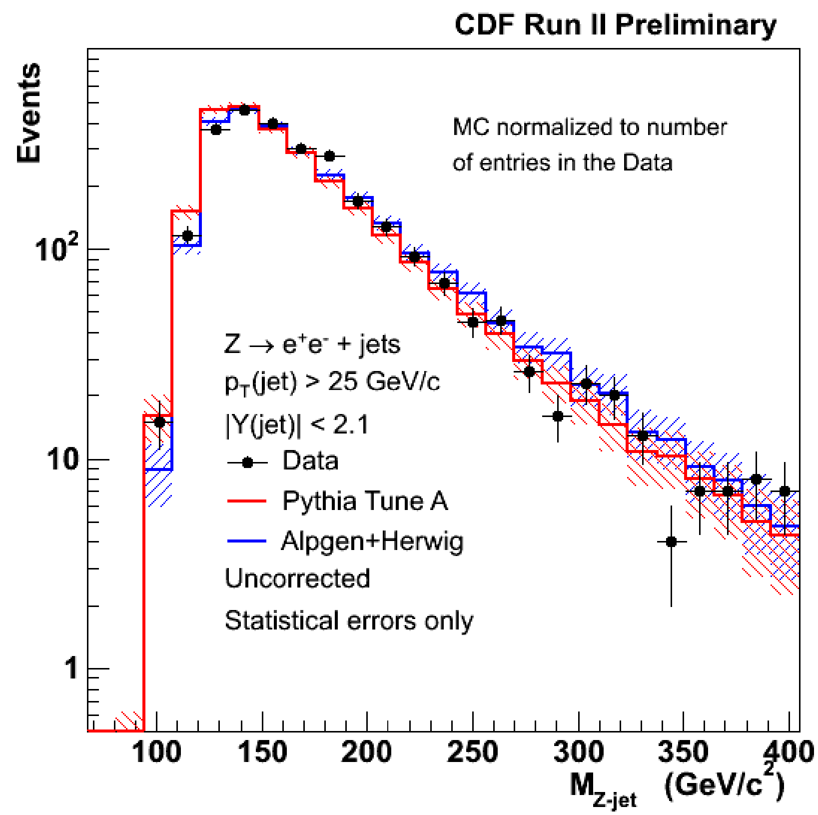
Distributions normalized to the first bin

Z-leading jet correlations



ΔR ($\phi - \eta$ space) distance between Z and the leading jet

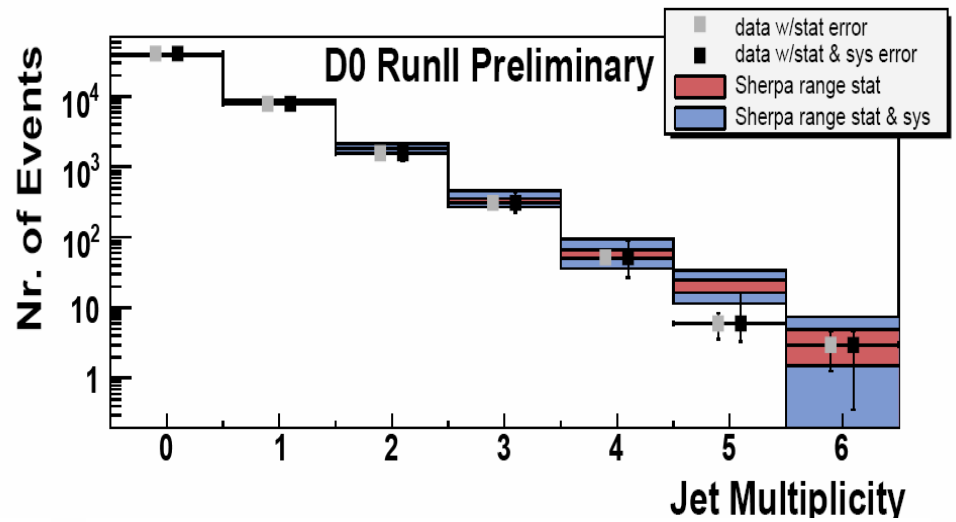
Invariant mass of the Z and the jet

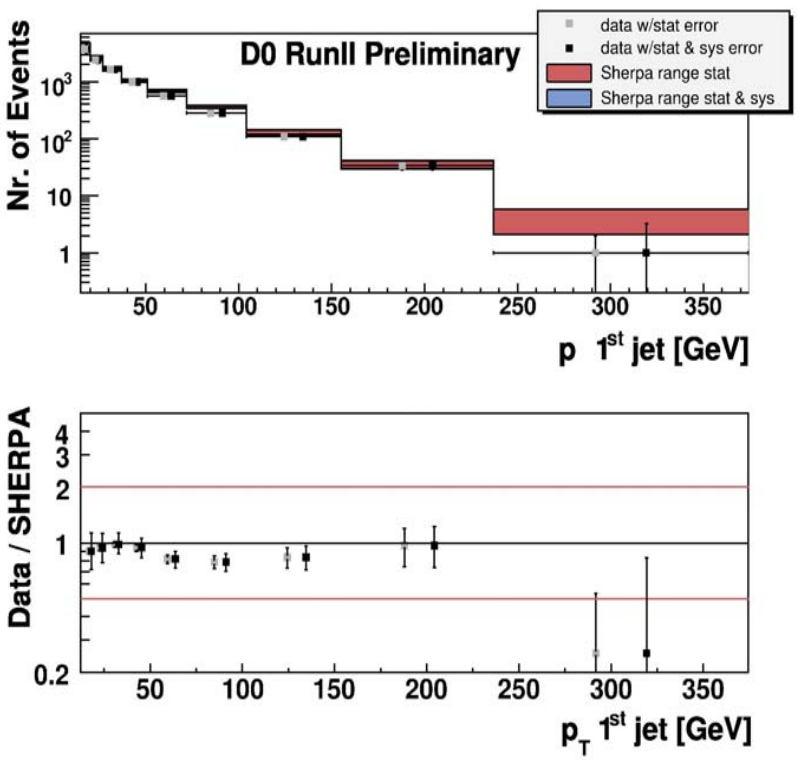


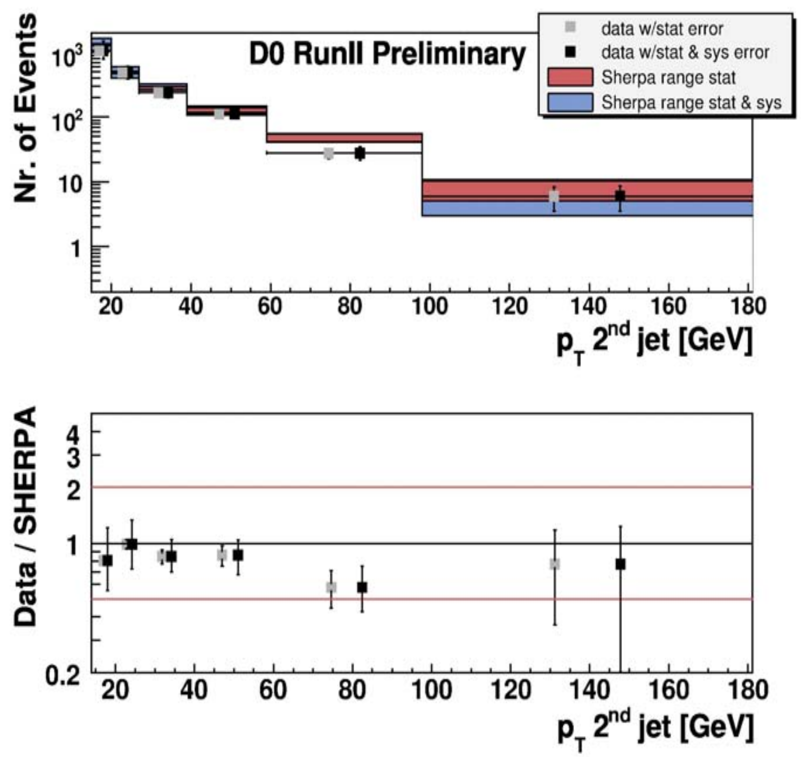
The kinematic distributions between the Z and the leading jet are well reproduced by both Pythia and **Alpgen+Herwig**.

D0: Z+jets with Sherpa

- Interesting to cross check other showering generators
- **Sherpa** LO MC seems to give good description in term of Jet Multiplicity although a bit high.







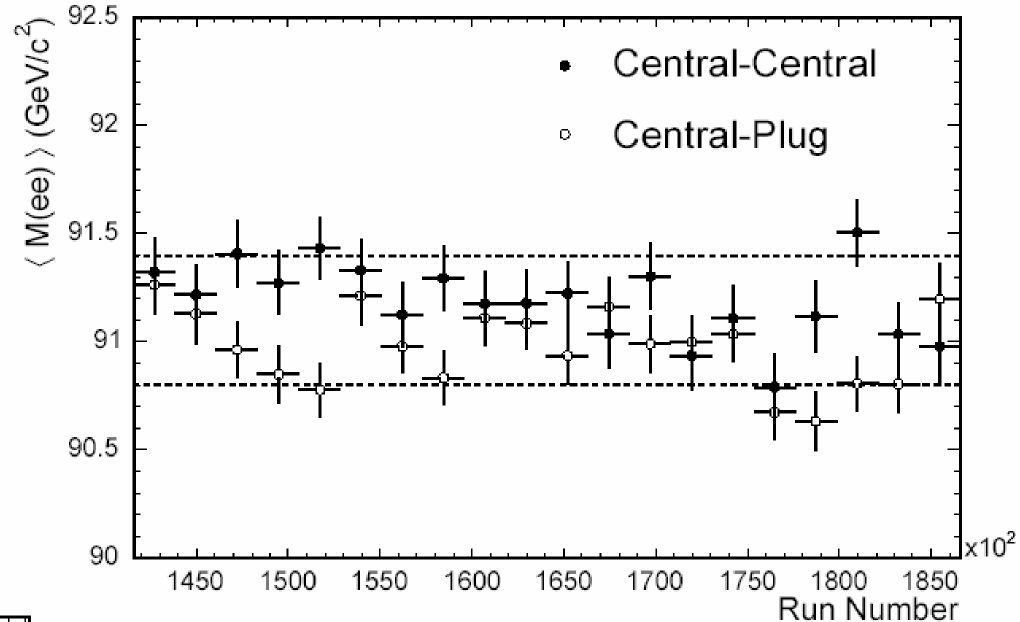
Summary and conclusions

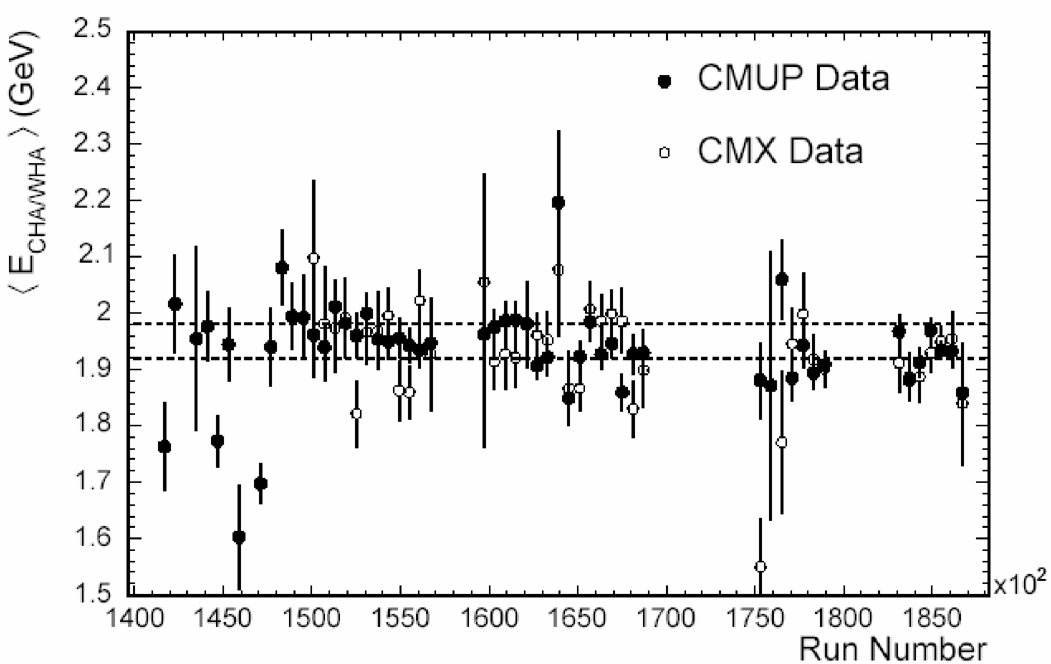
- In 2005, Tevatron achieved the 1 fb^{-1} goal
  - → 1.2 fb^{-1} on tape ready for data analyses!
- Very rich physics program ongoing at CDF
  - Tevatron is currently one of the best places to search for new physics and test MC tools → Very important for the LHC
- Boson + jets events (in particular Z + jets) are used to test LO ME with parton shower Monte Carlo
- We have a set of observables very sensitive to the Underlying Event that allow a very accurate study of the phenomena
  - Final results on Z+jets cross section (CDF) expected for Summer 2006

Back up

Calorimeter calibration

Use Z→e⁺e⁻ mass peak stability



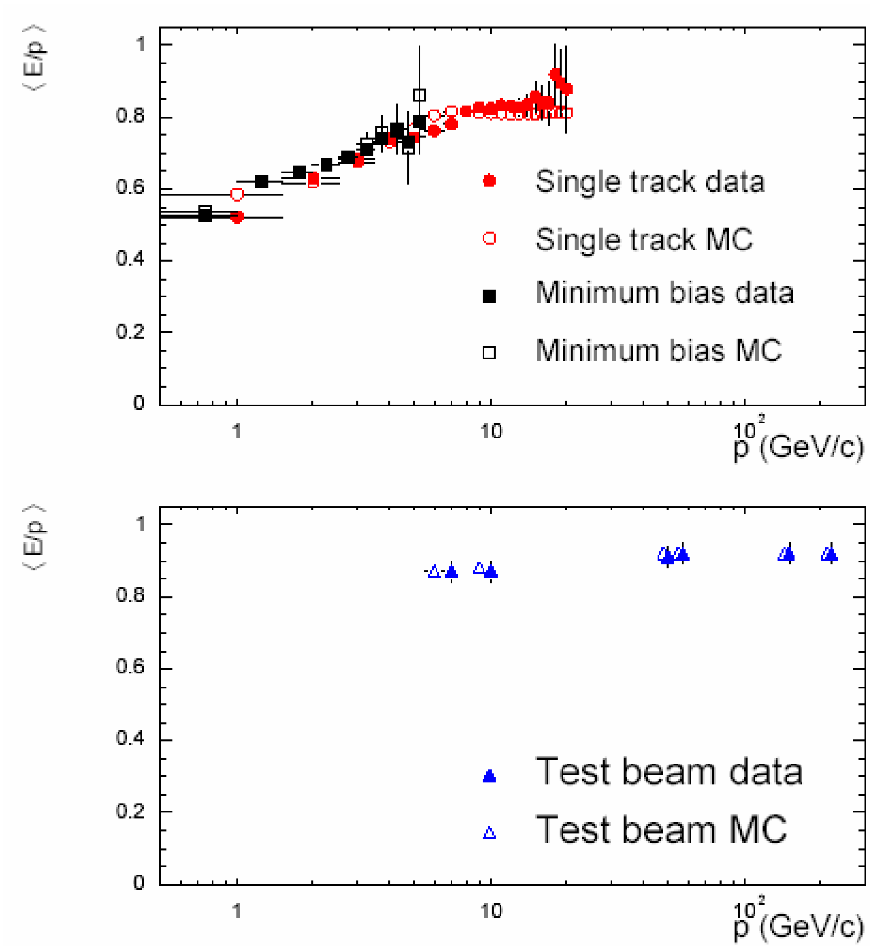


Use Minimum Ionizing Particles:

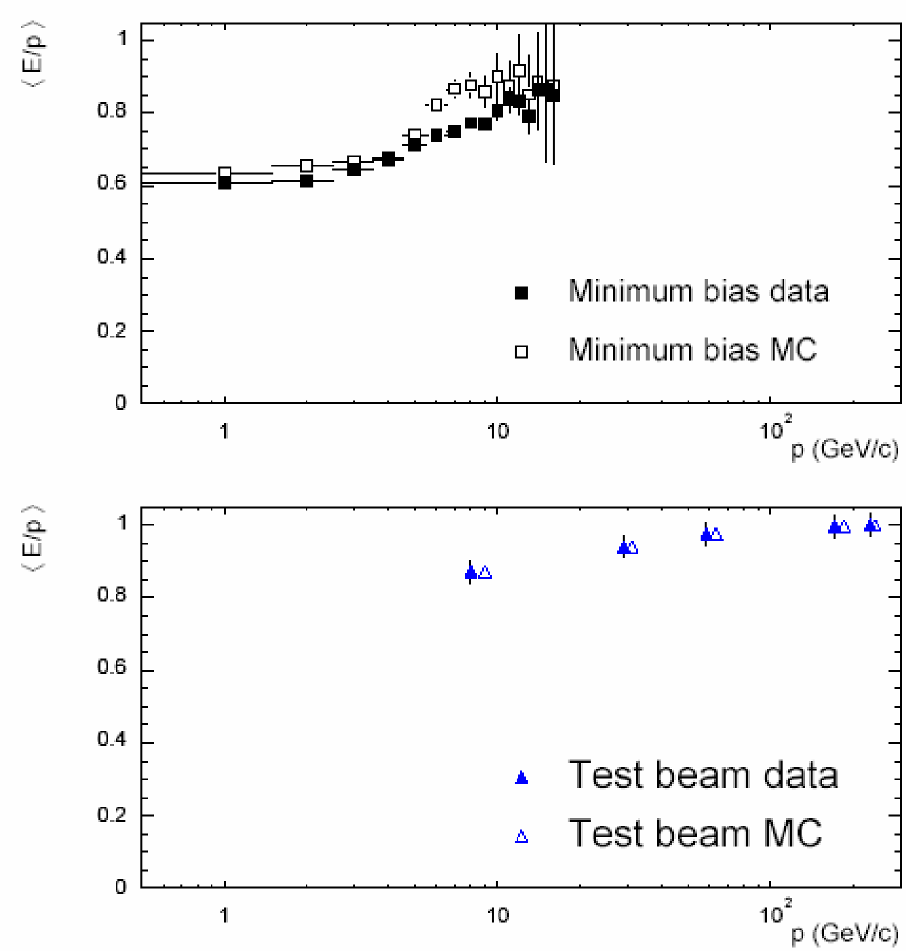
- J/ψ and W
- Peak HAD and EM calorimeter
- Time dependence

Tuning of CDF simulation

Measure p of particles using tracking, E from HAD and EM calorimeter
→ Use isolated tracks from Minimum Bias data
→ E/p used to tune simulation (GFLASH parametrization)



Central calorimeter

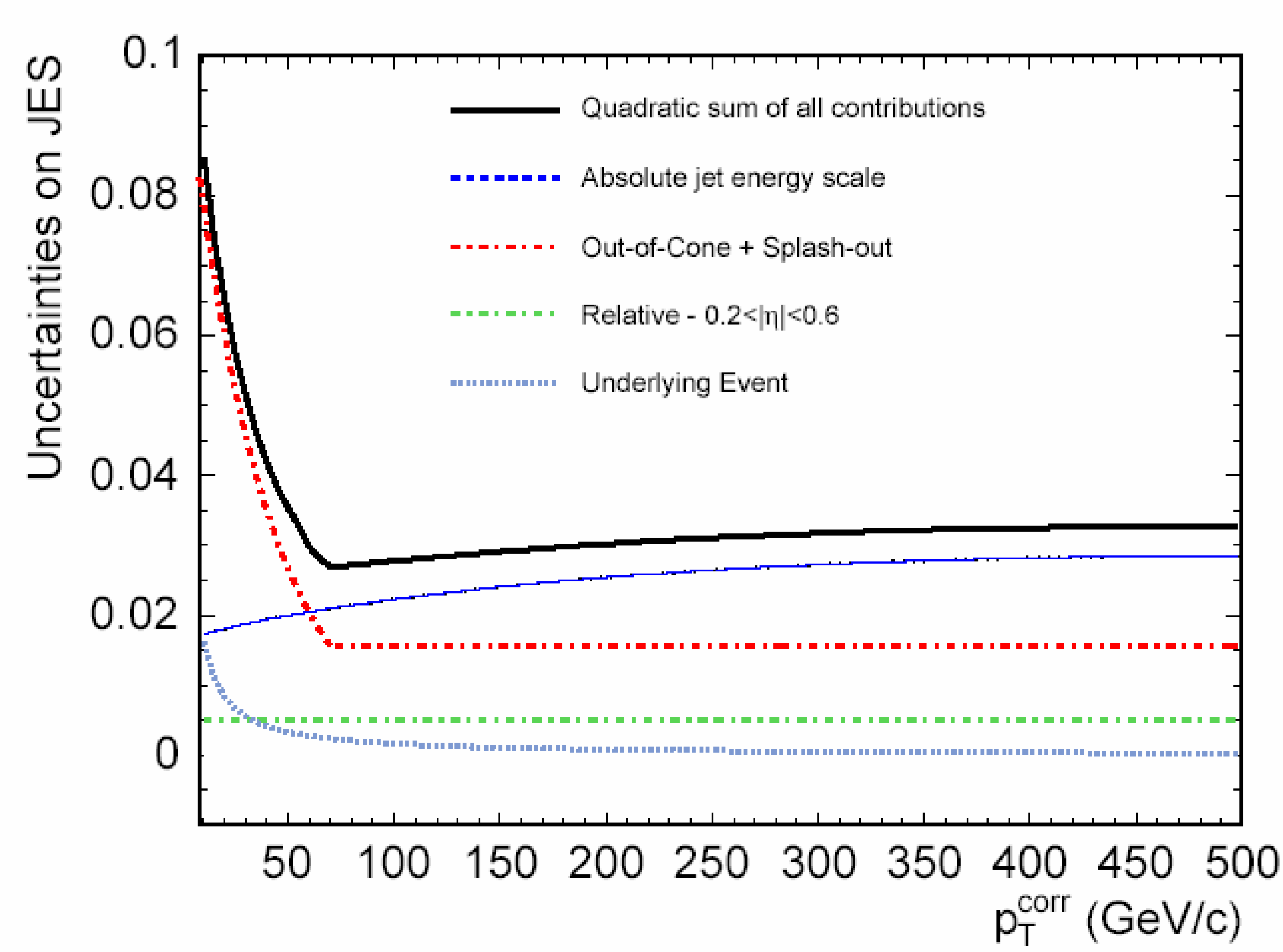


Plug calorimeter

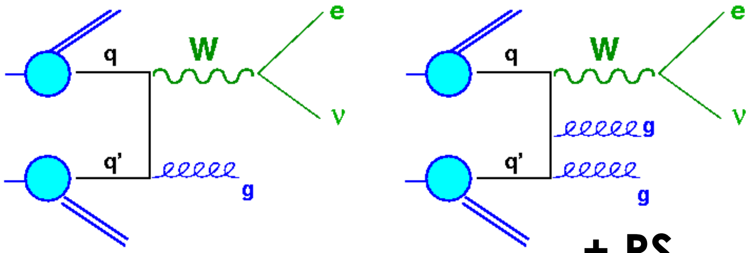
JES Systematic uncertainties

Total systematic uncertainties for JES

→ between 2 and 3% as a function of corrected transverse jet momentum



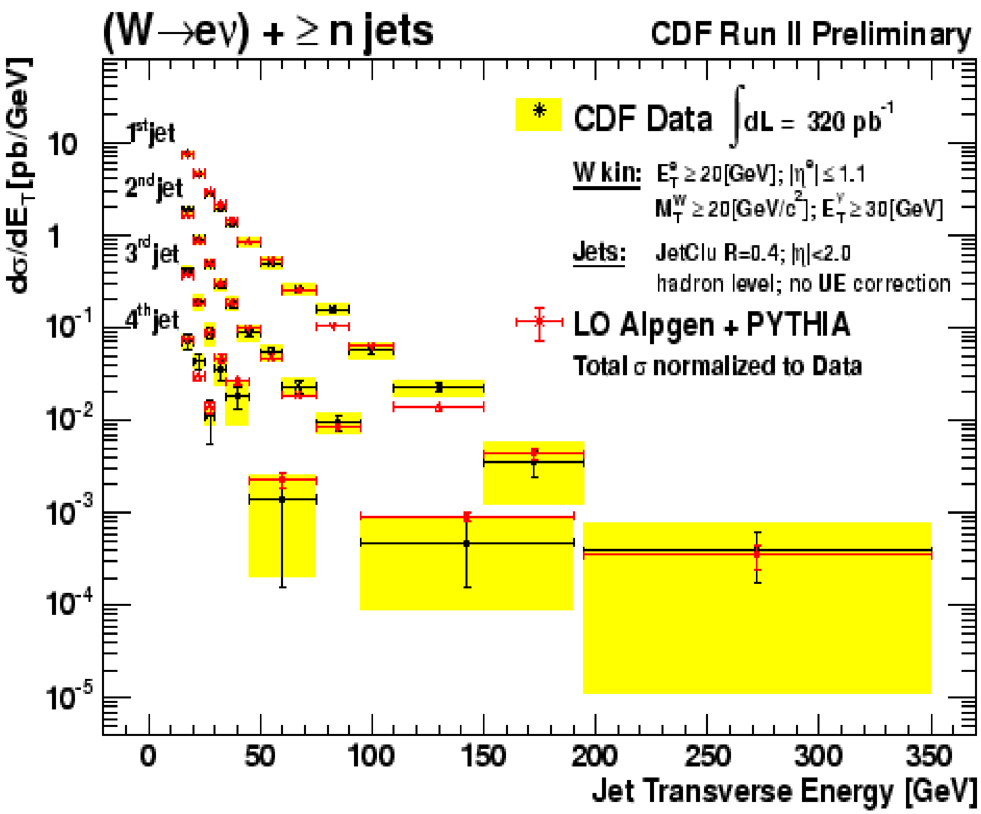
W+jets production

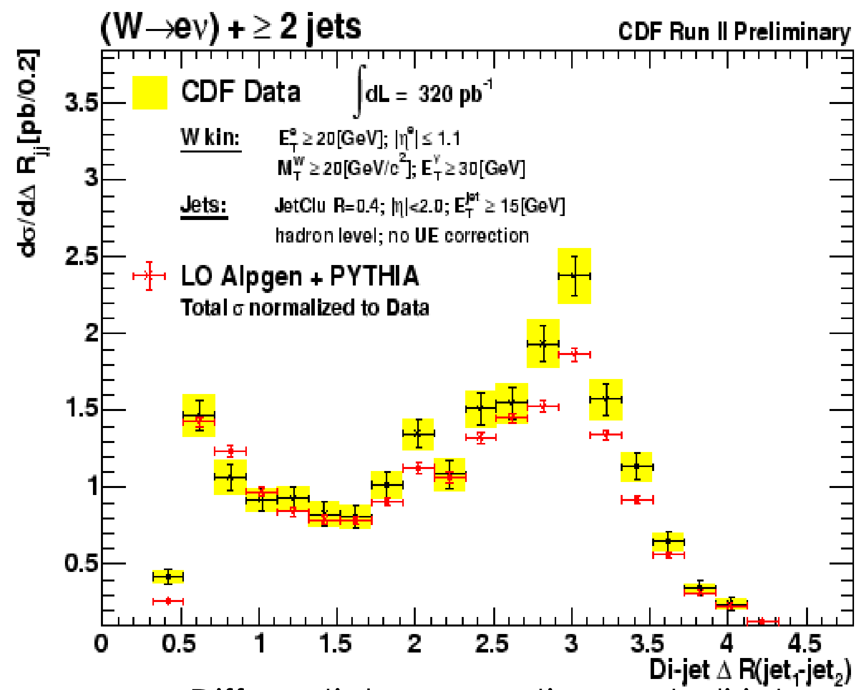


- Background also to top and Higgs Physics
- Testing ground for pQCD in multijet environment
  - Sample to test LO and NLO ME+PS predictions

LO predictions: **ALPGEN+Pythia** normalized to data integrated cross sections

Differential cross section w.r.t. E_T jet spectrum in W+n jets inclusive sample





Differential cross section w.r.t. di-jet ΔR in the W+2 jet inclusive sample

Electron Selections

- Tight Central Electron
  - $|\eta| < 1.0$
  - $|z_0| < 60$ cm
  - $p_T > 10$ GeV/c
  - $E_T > 25$ GeV
  - Track quality cuts
    - > 3 Stereo SL w/ hits >= 7
    - > 3 Axial SL w/ hits >= 7
  - Iso4 – Leak $< 0.1 \cdot E_T$
  - HadEm $< 0.055 + 0.00045 \cdot E_T$
  - E/p < 2.0 OR $p_T < 50$ GeV/c
  - Lshr < 0.2
  - $\chi^2_{CES} < 10.0$
  - -3.0 cm $< Q \cdot \Delta x <$ 1.5 cm
  - $|\Delta z| < 3.0$ cm
  - Fiduciality == 1

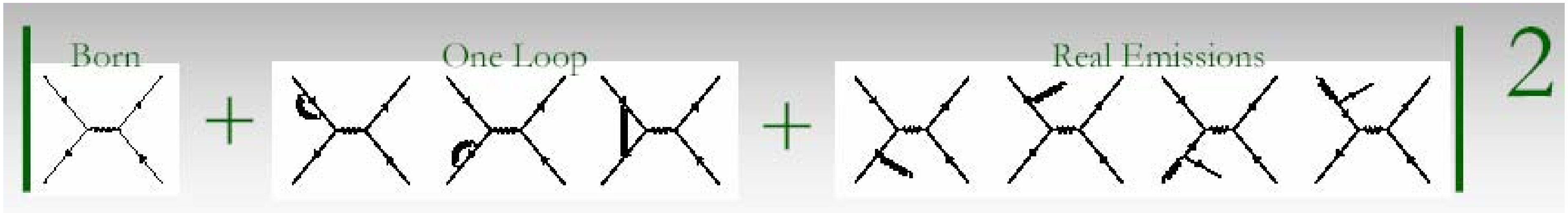
- Loose Central Electron
  - $|\eta| < 1.0$
  - $|z_0| < 60$ cm
  - $p_T > 10$ GeV/c
  - $E_T > 25$ GeV
  - Track quality cuts
    - > 3 Stereo SL w/ hits >= 7
    - > 3 Axial SL w/ hits >= 7
  - Iso4 – Leak $< 0.1 \cdot E_T$
  - HadEm $< 0.055 + 0.00045 \cdot E_T$
  - Fiduciality == 1

- Plug Electron
  - $1.2 < |\eta| < 2.8$
  - $E_T > 20$ GeV (30 GeV for the FF)
  - Iso4 < 4
  - HadEm < 0.05
  - $\chi^2_{PEM} <= 10.0$

MCFM

Parton-Level Monte Carlo:

- NLO event integrator
- In the Matrix Element Calculation $|M|^2$:



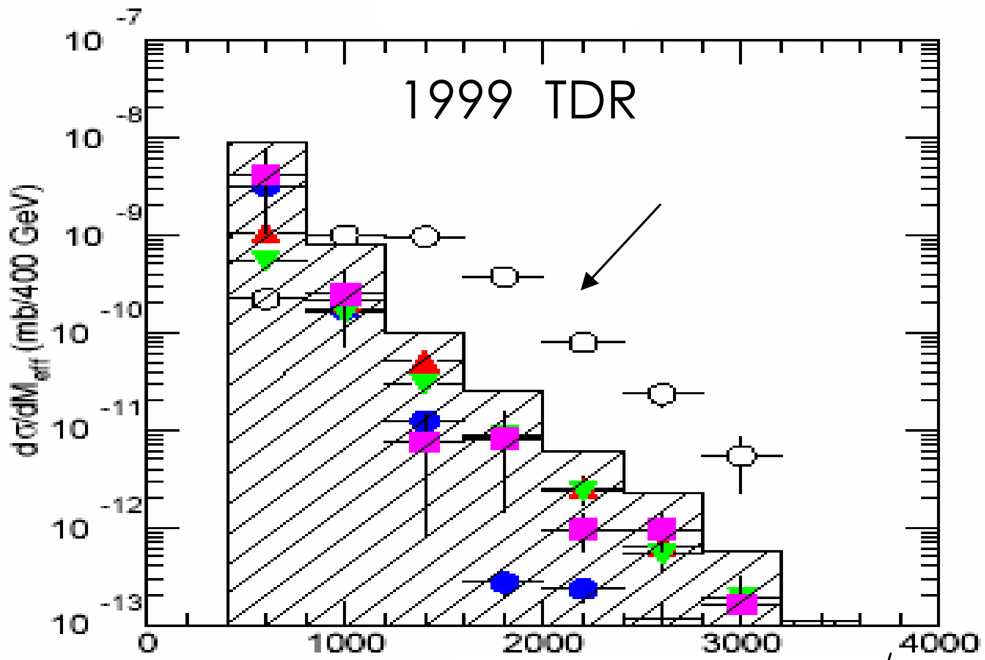
$$\sigma_{\mathrm{NLO}} \propto \underbrace{\underbrace{\mathcal{M}^2_{\mathrm{Born}}}_{\mathrm{LO}} + \mathcal{M}_{\mathrm{Born}} \otimes \mathcal{M}_{\mathrm{OneLoop}}}_{\mathrm{n-body}} \tilde{+} \underbrace{\mathcal{M}^2_{\mathrm{RealEmission}}}_{\mathrm{(n+1)-body}}$$

$$\underbrace{\mathcal{M}_{\mathrm{Born}} \otimes \mathcal{M}_{\mathrm{OneLoop}} \tilde{+} \mathcal{M}^2_{\mathrm{RealEmission}}}_{\mathrm{NLO}(\alpha_S)\ \equiv \mathcal{O}(\alpha_S{}^1)}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dP_T^2} \cong \frac{1}{P_T^2} A_1 \alpha_s \ln\frac{M^2}{P_T^2} + A_2 \alpha_s{}^2 \ln^3 \frac{M^2}{P_T^2} + A_3 \alpha_s{}^3 \ln^{2n-1} \frac{M^2}{P_T^2} + \ldots$$

→ Complementary approach to LO showering event generators
→ Give a prediction of **total cross section** and distribution at parton level but is not a fully implemented event generator

Possible effects of low ISR …



$$M_{eff} = H_T + \not{E}_T$$

Preliminary MC studies (1999) at the LHC suggested that SUSY could be discovered via the jet+MET channel within weeks after LHC started

Signal uses now Pythia (IsaSUGRA for ME)

Additional changes in tools Used on the background

→ Very dependent from MC!!