QCD and Jets Studies at the LHC

Dorian Kcira
University of Louvain
Center for Particle Physics and Phenomenology

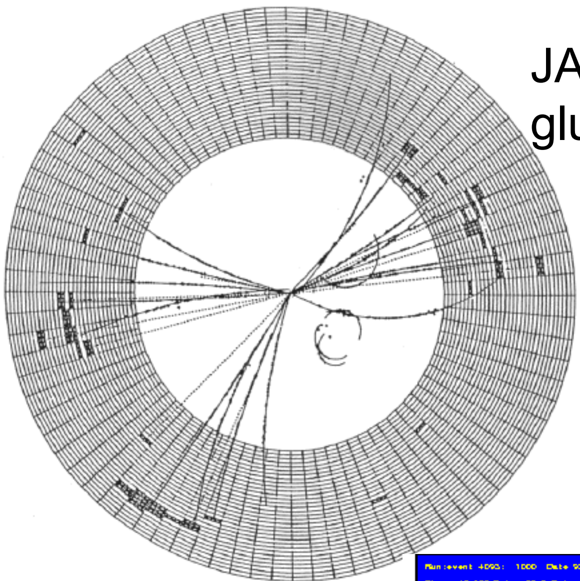
HLPW08
Strong Interactions & Astrophysics
6-8/3/2008 Sol Cress Spa, Belgium

Introduction

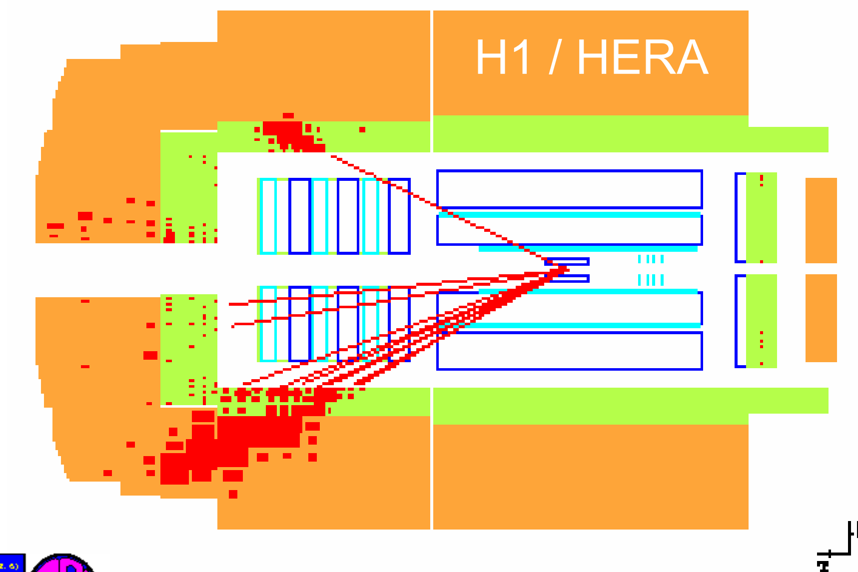
- Jets Algorithms
- QCD & Jets Measurements
- New Physics with Jets

Jets Algorithms

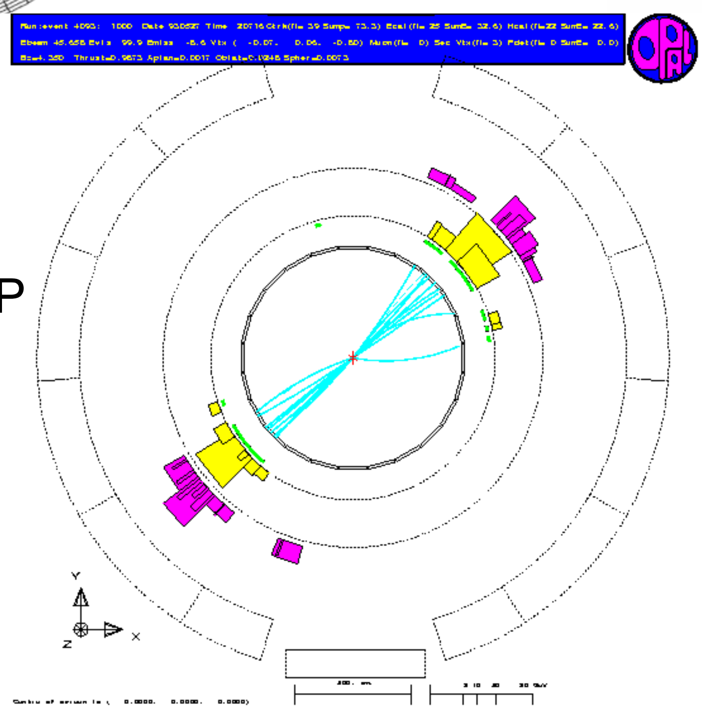
Jets: Footprints of Initial Partons



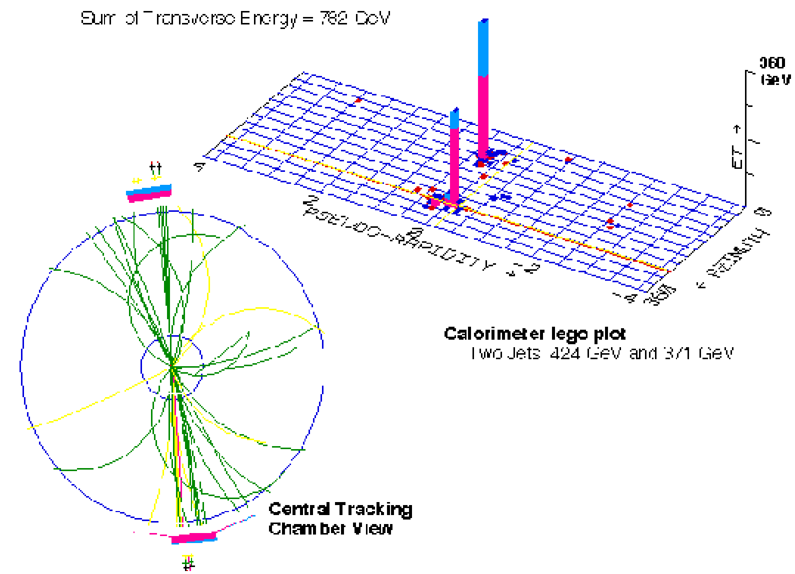
JADE / PETRA
gluon discovery



OPAL/LEP



CDF: Highest Transverse Energy Event
from the 1988-89 Collider Run

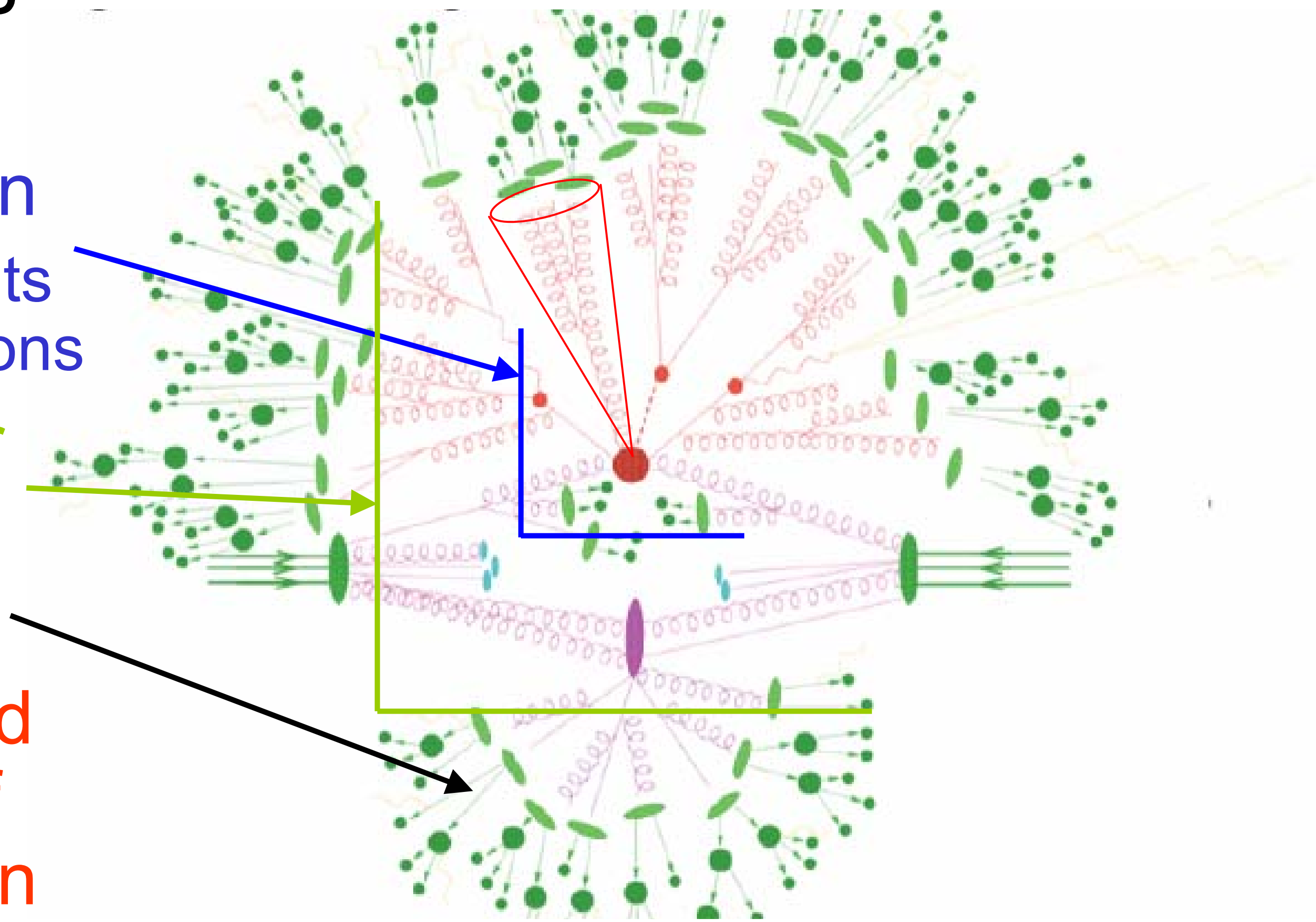


HEP Interactions and Jets

J.Alwall: http://cp3wks05.fynu.ucl.ac.be/Docs/Johan-KEK2006/

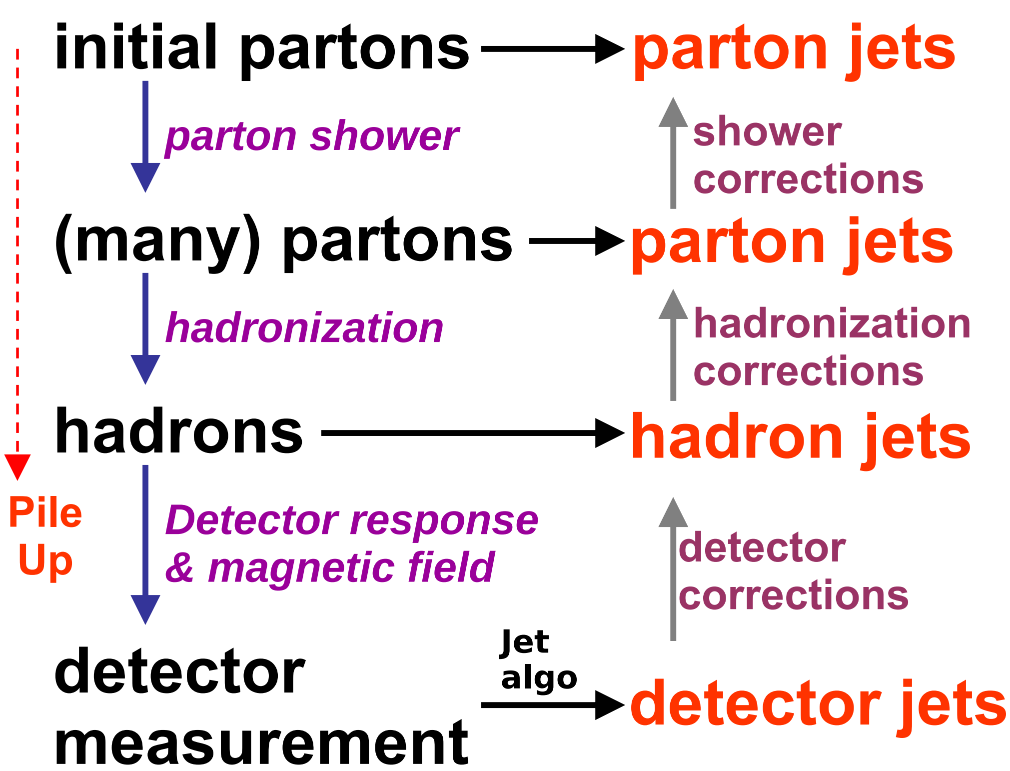
A schematic HEP interaction

- Hard interaction
  - Matrix Elements (ME) calculations
- Parton Shower
- Hadronization
- Jets: flow of hadrons around the direction of the initial parton
- Hadron / Parton / Detector Jets



From Partons to Jets (and back)

- Partons (quarks and gluons) produced in high energy collisions
- Only hadrons observed due to color confinement
- Collimated flow of particles around initial parton : Jet



Jet Algorithms

define a jet:

- associate final state particles in a jet
- allow calculation of jet quantities

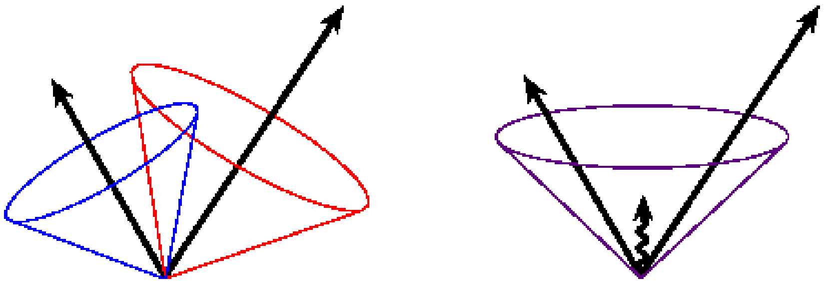
2 main classes of jet-algos

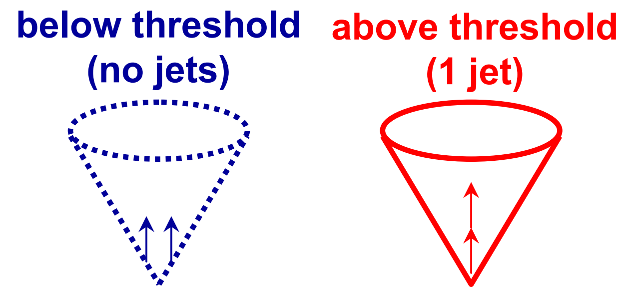
- Cone
- Clustering

based on hep-ph/9506421

Cone Algorithms

Maximize total transverse energy in a cone in rapidity-φ

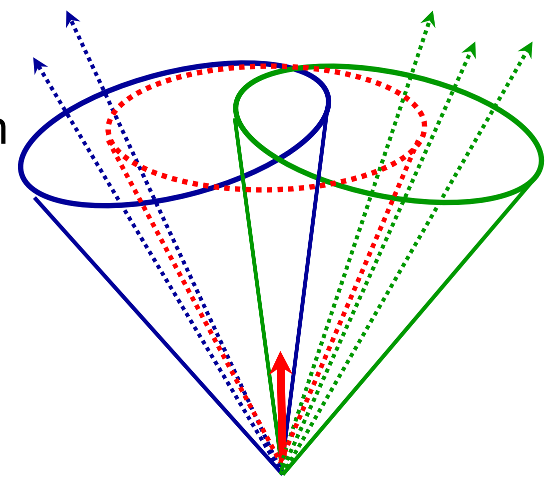




Cone-based algos not-infrare/collinear safe to all pQCD orders

Tevatron Run II ⇒ new cone-based algorithm: MidPoint

1. Draw a cone of radius R around each seed (CAL tower with E >1GeV) and form “proto-jet”
2. Draw new cones around “proto-jets” and iterate until stable cone
3. Put seed in Midpoint (eta-phi) for each pair of proto-jets separated by less than 2R and iterate for stable jet
4. Merging/Splitting

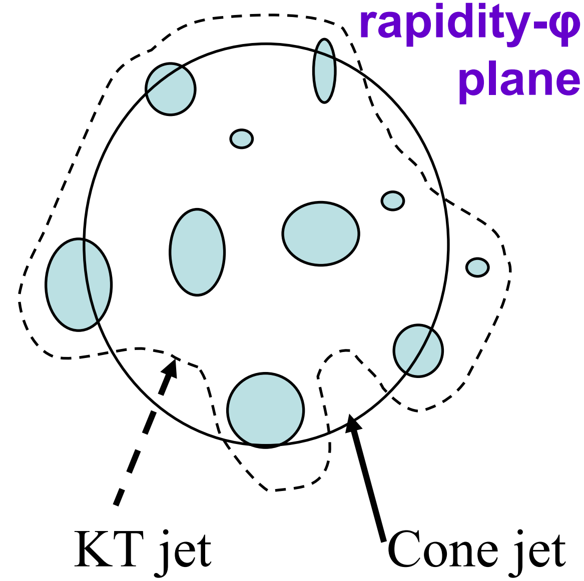


Cone-based jet algorithms include an “experimental” prescription to resolve situations with overlapping cones

merged if common E is more than 75 % of smallest jet ← This is emulated in pQCD theoretical calculations by an arbitrary increase of the cone size : R → R' = R * R_{sep}

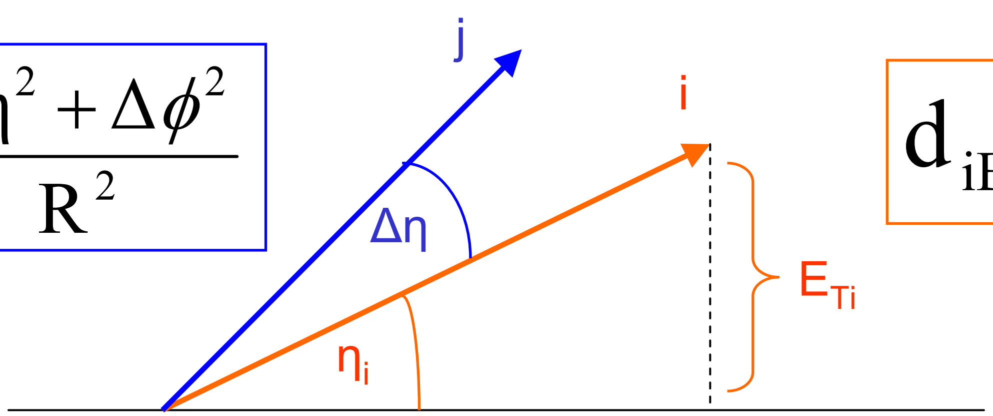
Clustering Algorithms : k_T

1. Calculate the distances
   - between the particles d_{ij}
   - beam distances d_{iB}
2. Combine particles with smallest d_{ij} .
   If d_{iB} smallest => i = jet
1. Repeat procedure until no particles left



- Only one parameter R,
  - default R=1, but this has to be studied
- Approximate inversion of branching process

$$d_{ij} = \min\left(E_{T_i}^2, E_{T_j}^2\right)\frac{\Delta\eta^2 + \Delta\phi^2}{R^2}$$



$$d_{iB} = E_{T_i}^2$$

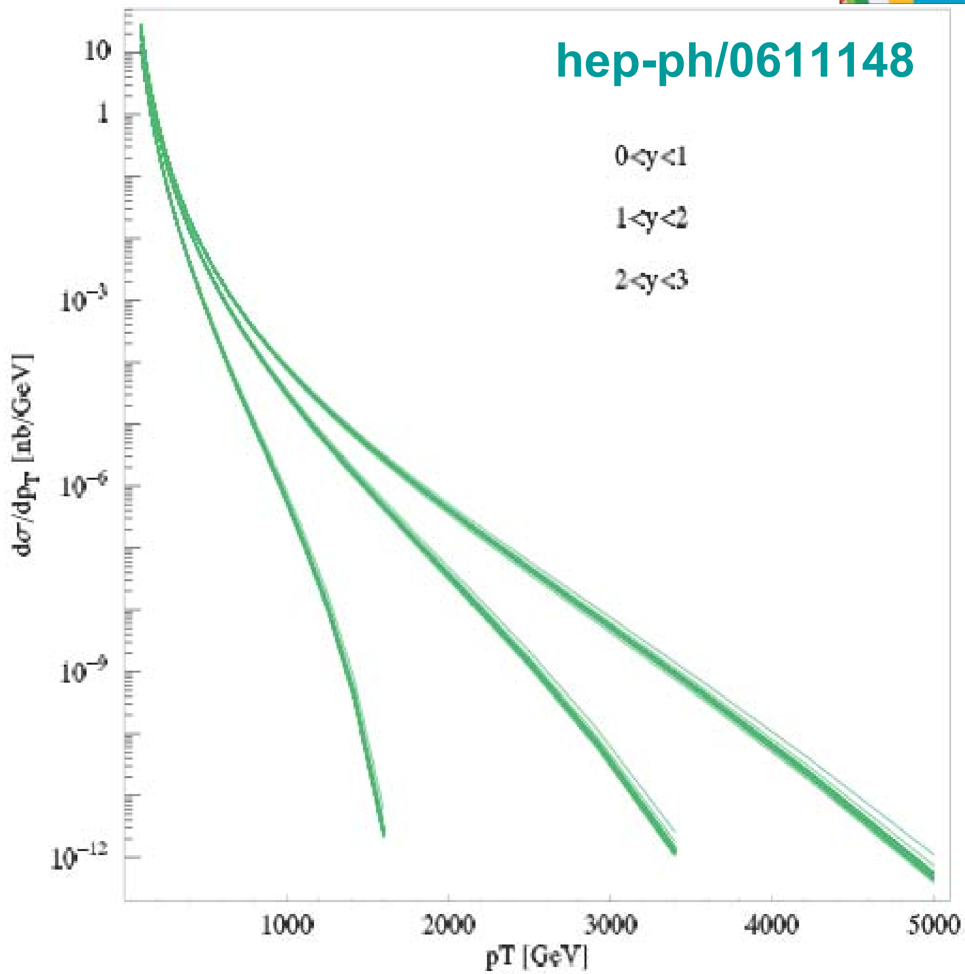
Jet Algorithm Requirements: Measurable, Calculable, Accurate, Robust

- Simple to use in experimental analyses
- Identical procedure at parton, hadron and detector
- Must be infrared and collinear (IRC) safe => it can be calculated order by order in perturbative QCD
  - kT safe at all orders by definition
  - Only seedless Cone safe at all orders
- Not very sensitive to hadronization
  - Close correspondence between partons and final state hadrons
- Not too sensitive to underlying event and pile up
- Not ignore large energy deposits

QCD & Jets Measurements @ LHC

Jets at LHC

- pp collision at 14 TeV cms. energy
- Large jet cross sections
- Inclusive jet cross sections at NLO
  - Calculated using EKS
- LHC jet production
  - Dominance of gluon and sea quark scattering
  - Larget phase space of gluon emission => extra jets



$10pb^{-1}$ in 2008

p_T^{min} (TeV/c)	σ (nb)	Events/year
0.2	100	$\approx$ 10^6
1.0	0.1	$\approx$ 10^3
2.0	1.0×10^{-4}	$\approx$ 1
3.0	1.3×10^{-6}	$\approx$ 0.01

Jets at LHC

- Jet multiplicities significantly higher at LHC as compared to Tevatron, especially for gg initiated processes
  - ➢Large initial state radiation

•Total cross sections for tT production saturated by tT + jet production for jet p_T values of order 10-20 GeV/c

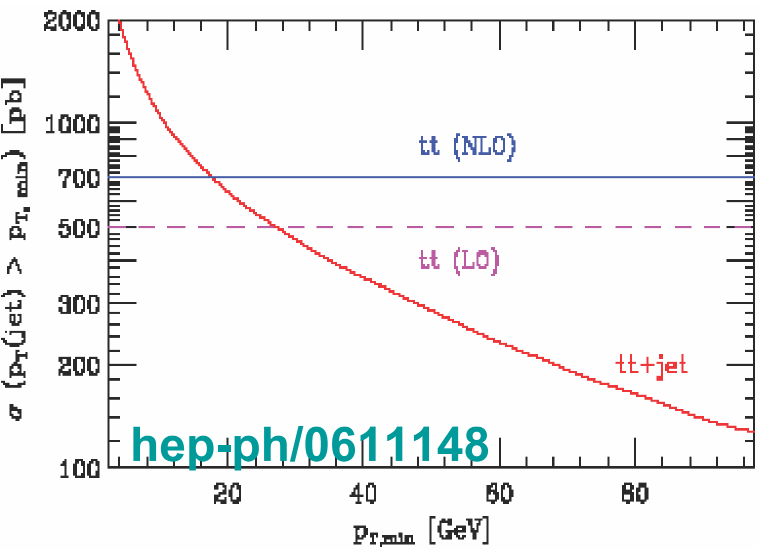


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

•σ(W+3 jets) > σ(W+2 jets) for $p_{T,\text{leading-jet}}$>100 GeV/c

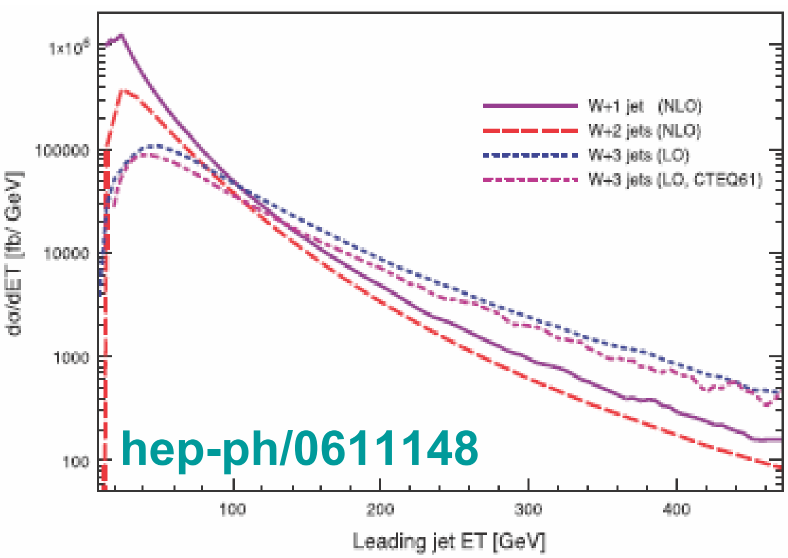
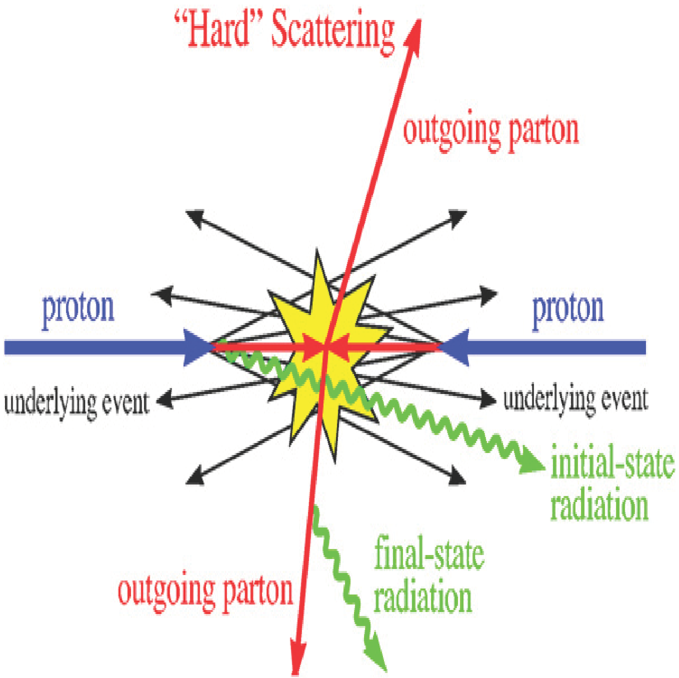


Figure 91. Predictions for the production of $W+ \geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

Jets at LHC: Underlying Event, Pile Up



Underlying Event (UE)

everything else in the event on top of the hard scattering

- softer interactions from the remaining partons in the colliding hadrons
- model description. e.g.: multiple-parton interactions

Pile Up (PU)

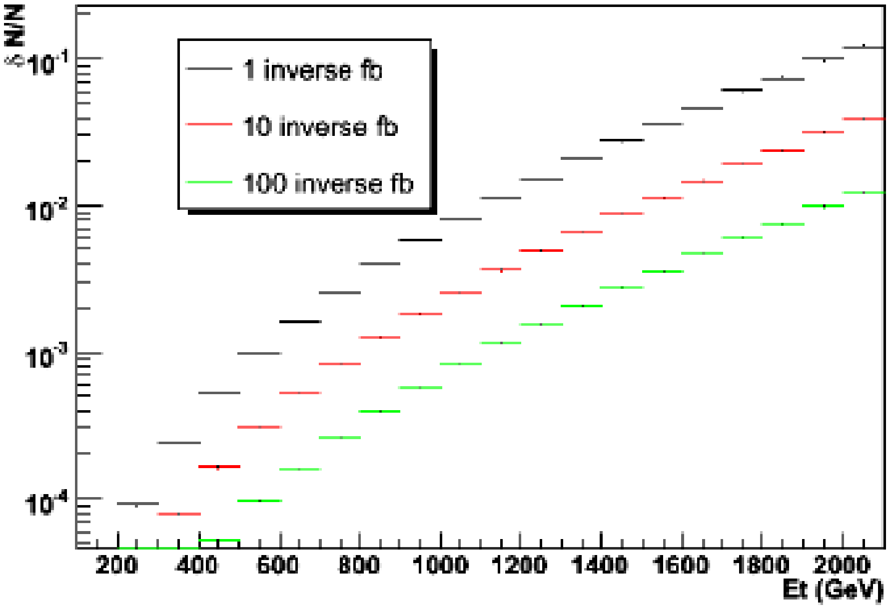
Additional minimum bias (MB) interactions overlayed to a physics collision in the same beam crossing

- statistical effect: Poisson distribution
- 5 PU interactions at low lumi ($10^{32}cm^{-2}s^{-1}$)
- 25 PU interactions at high lumi ($10^{33}cm^{-2}s^{-1}$)

Jet Cross Section Measurements

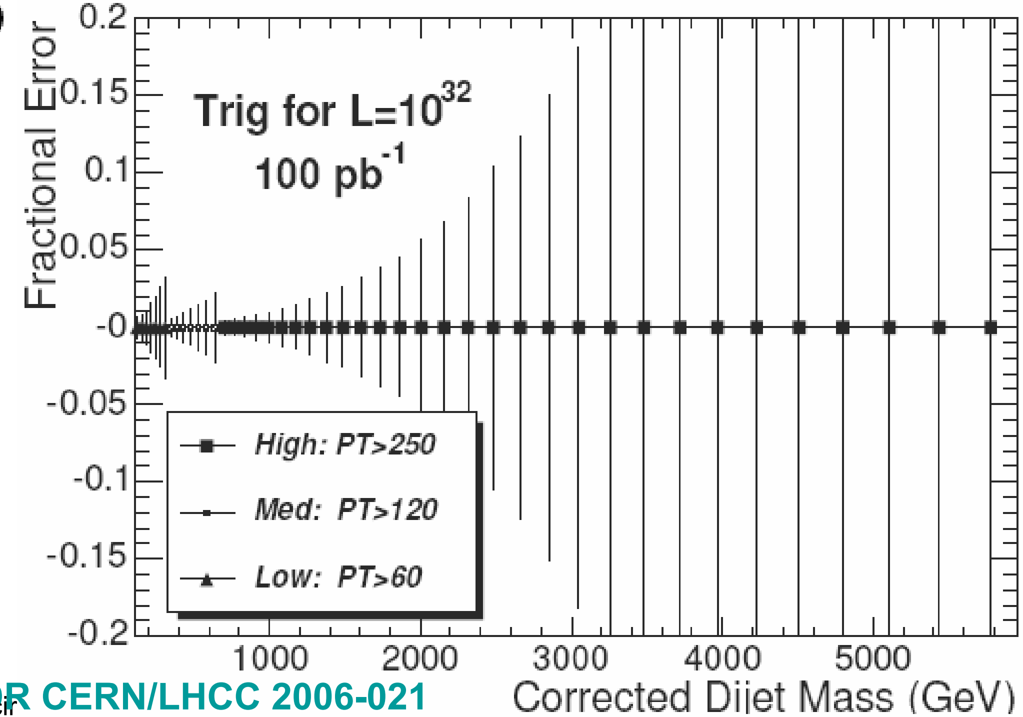
- Measurements of QCD cross sections and correct evaluation of their errors with LHC data is of great importance
  - QCD constitutes a background to almost all interesting physics processes
  - High p_T tails of inclusive cross sections are sensitive to potential new physics
  - Bad evaluation of the experimental errors of the measurement or theoretical errors of predictions can mask new physics or fake it (…)
- The main error sources are
  - Statistical
  - Experimental
  - Theoretical

Statistical Errors



- Estimation of stat. errors as a funtion of jet p_T for different integrated luminosities
  - simple Poissonian statistics
  - Jets considered with $|\eta|<3$
- At $1fb^{-1}$: 1% error for 1 TeV jets
- For more forward jets error is larger
  - (10% for $3.2<|\eta|<5$)

- $100pb^{-1}$: stat. errors for dijets
- 1 month of data taking at $10^{32}cm^{-2}s^{-1}$ with 40% efficiency
- structure comes due to mixing of different triggers



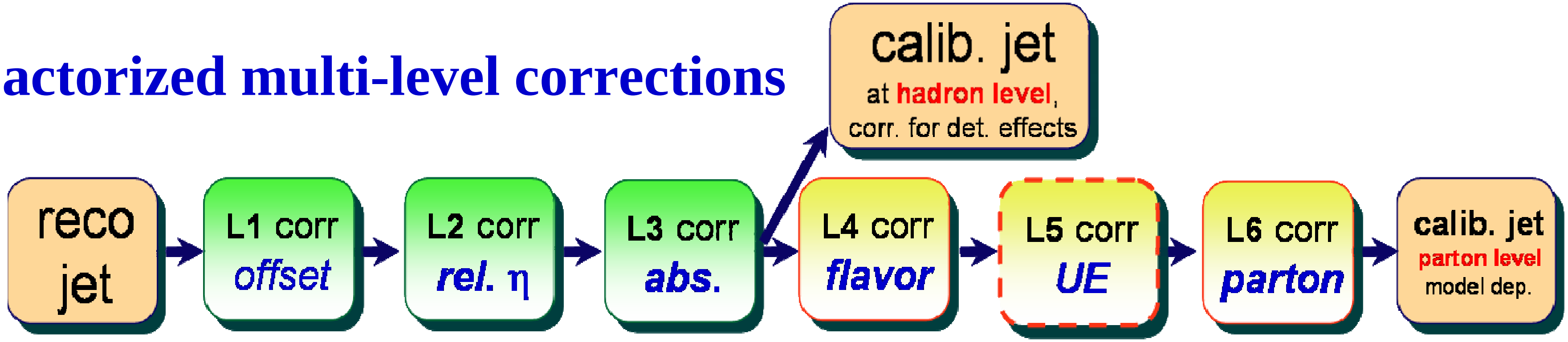
CMS TDR CERN/LHCC 2006-021

Experimental Errors

- In jet measurements experimental errors are determined from
  - Choice of jet algorithm
  - Choice of the parameters of the jet algorithm
  - Choice of input to jet algorithm
    - Jets of calorimeter objects
    - Jets of tracks
    - Particle flow jets
- The above choices translate into
  - Resolution of jet quantities
  - Jet energy scale (JES) uncertainty
- Other
  - Trigger efficiencies
  - Luminosity measurement (unrelated to jet finding)

Jet Energy Scale in CMS

Factorized multi-level corrections

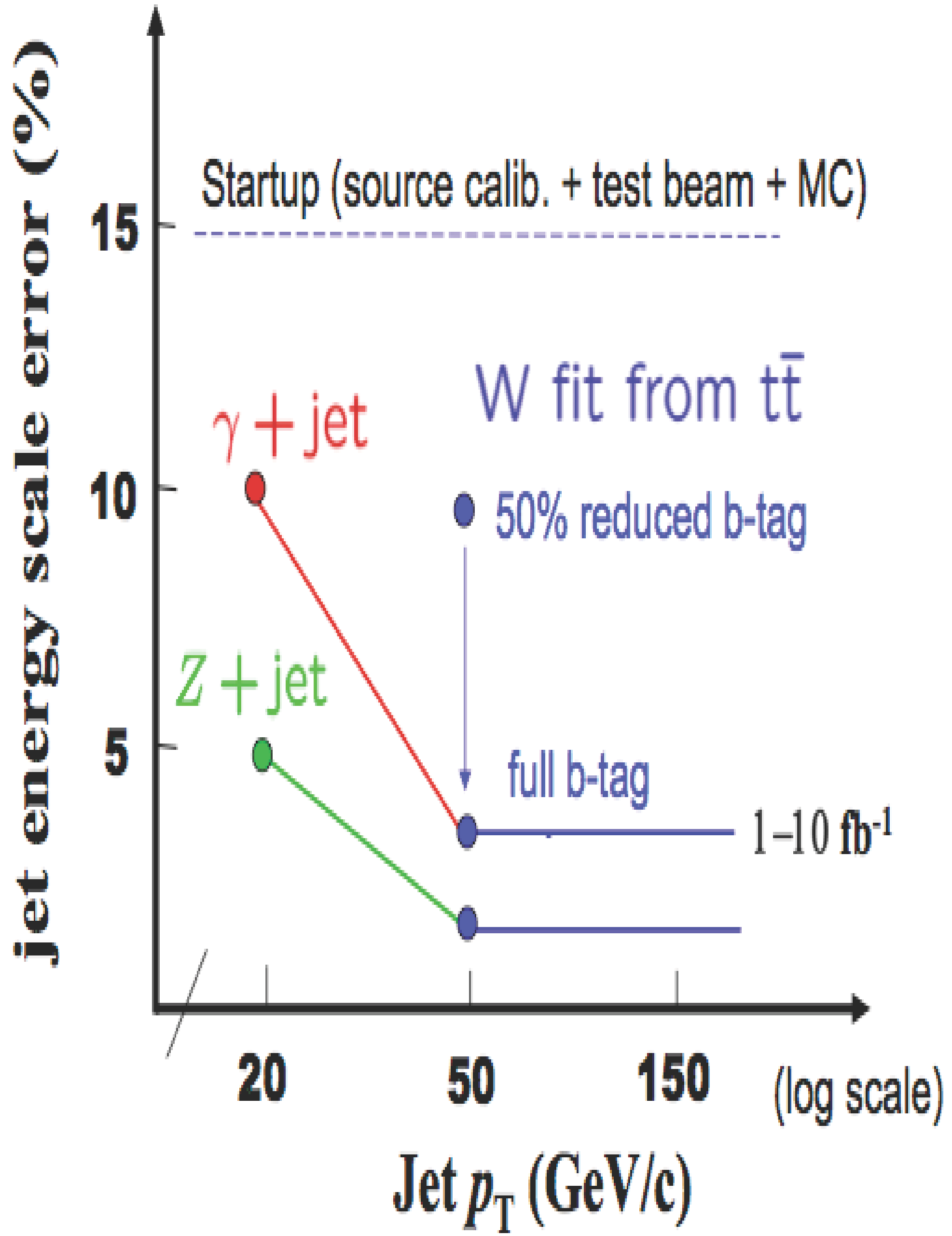


Offset: removal of pile-up and residual electronic noise
Relative (η): variations in jet response with η relative to control region
Absolute (p_T): correction to particle level versus jet p_T in control region
Flavor: correction to hadron level for different types of jet (b, tau, etc.)
Underlying Event: luminosity independent spectator energy in jet removed
Parton: correction to parton level

- **Default Corrections** are to the **hadron level**
- **Flavour, parton level and underlying event corrections are optional**

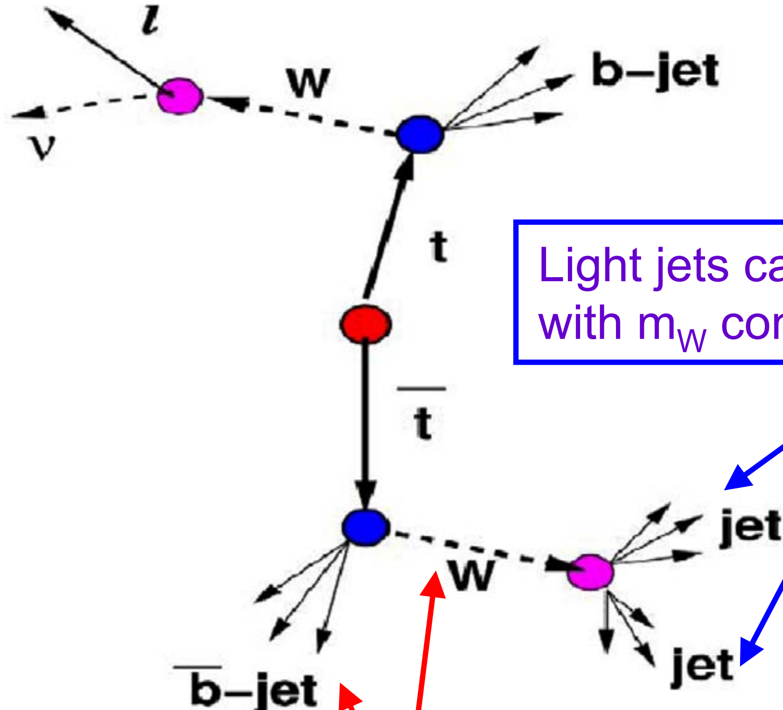
Jet Energy Scale (JES)

- JES uncertainty
  - 10% start-up
  - 5% ~ 1fb-1
  - 3% after some years
- Purely calorimeter jets used for most studies so far
- Addition of track jets
  - Improve resolution
  - Rejection of pile up
- Ultimate resolution achievable with particle flow jets



Jet Energy Scale with Top Quark Pairs

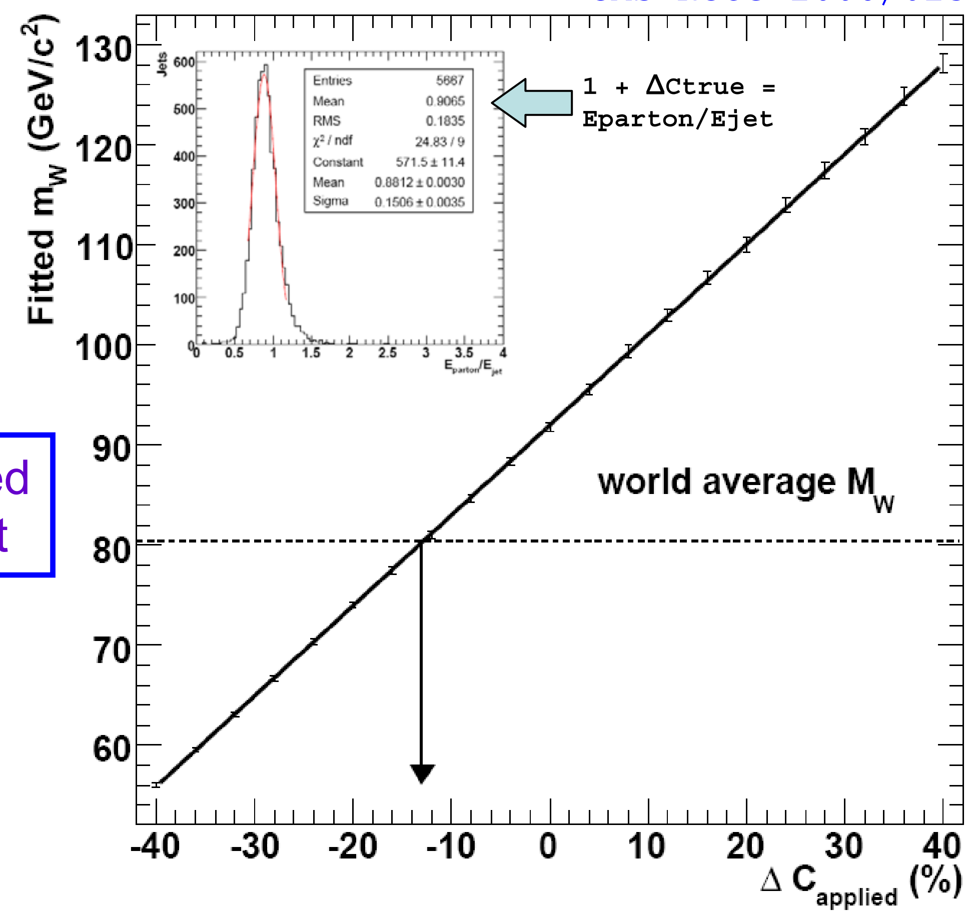
- Jet Energy Scale can be evaluated using top quark events.
- Use W mass constraint to calibrate JES for light quark jets



Light jets calibrated with m_W constraint

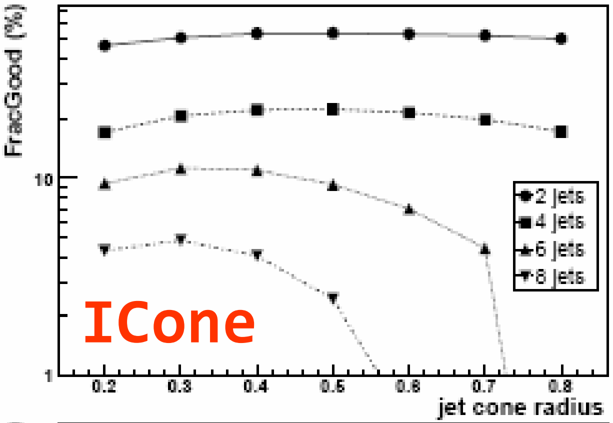
At start-up also calibrate b jets using top quark mass constraint

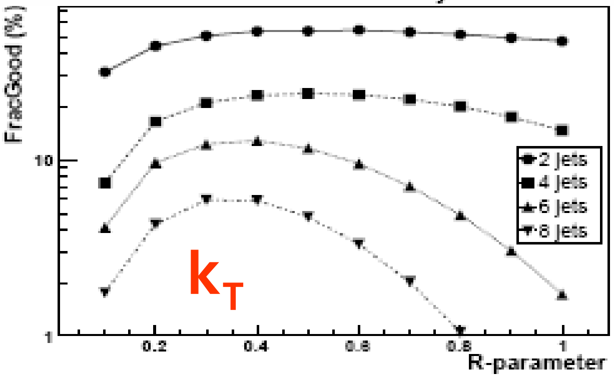
CMS Note 2006/025

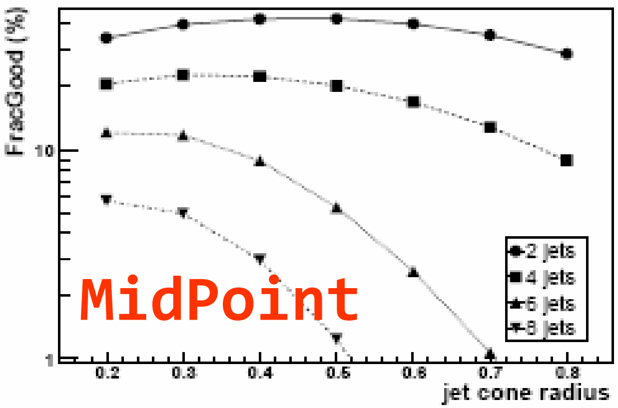


Optimization of Jet Algorithms

hep-ph/0604120







- Three different jet algos considered
  - Cone, MidPoint, k_T cluster
- Low lumi sample of events
  - ttbar (fully/semileptonic) and ttbarH (semil. & hadronic)
  - PU, UE, radiation (but no hard gluon radiation)
- Quality criteria defined
  - **ϵ_s**: event selection efficiency
  - Angular distance between jet and parton
  - Energy difference between jet and parton
  - **FracReco**: combined angular/energy variable, fraction of well reconstructed events
  - **FracGood**: fraction of selected and well reconstructed jets.
  - **FracGood = ϵ_s * FracReco**
- Studied performance of algorithms versus their parameters using the quality criteria
- Not studied: detector effects, magnetic field

Optimization of Jet Algorithms

• No apriori "natural" parameter values, optimizations specific to final state topology

• As expected higher multiplicities would require smaller radii of jets

• Present default CMS settings: Cone R_{jet}=0.5, k_T R=0.6 & 1.

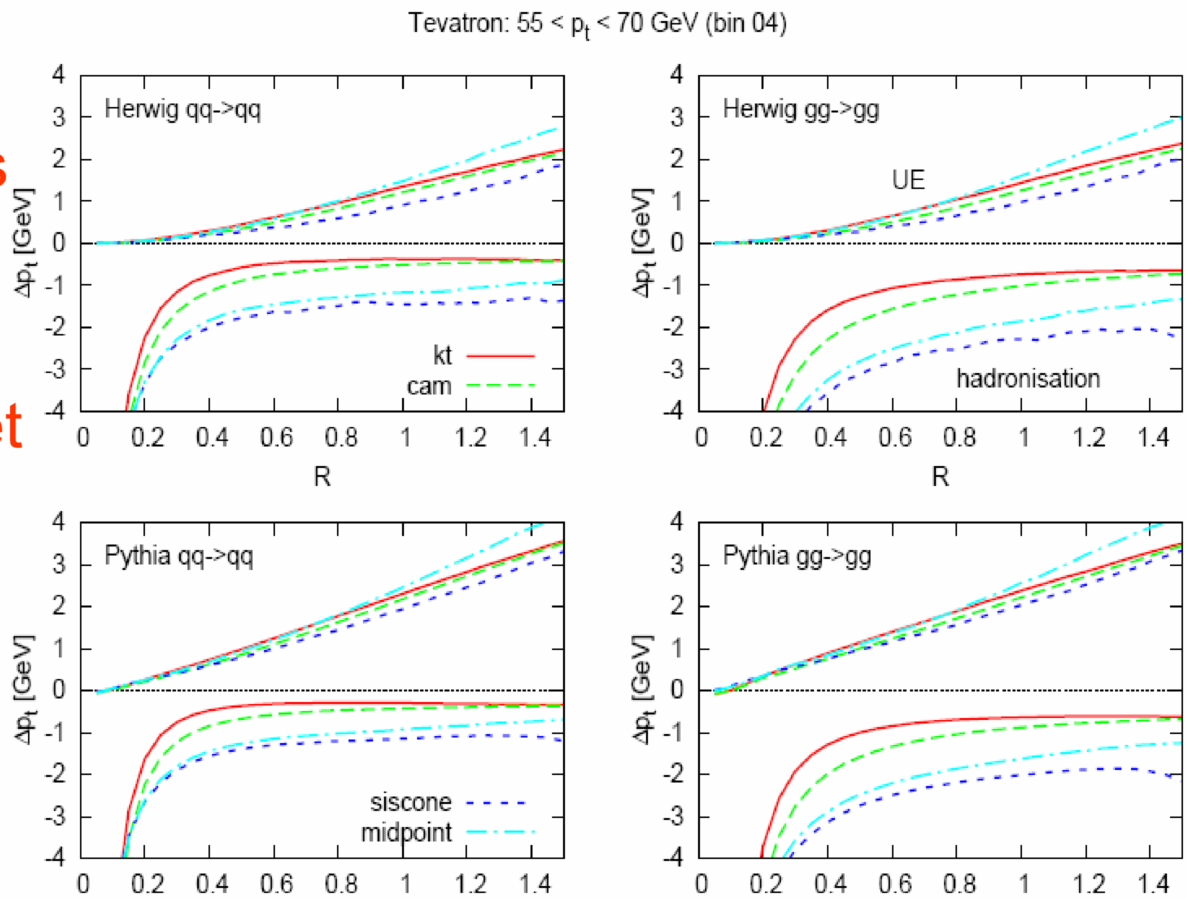
In general, CMS (LHC) studies favour smaller radii parameters

hep-ph/ 0604120	IC jet radius		k_T R-parameter		MC jet radius		MC Overlap Threshold	
	Value	*FracGood*	*Value*	*FracGood*	*Value*	*FracGood*	*Value*	*FracGood*
2 quarks	0.5	53.9	0.6	54.9	0.5	42.4	0.40	40.3
4 quarks	0.5	22.3	0.5	23.8	0.3	22.8	0.40-0.50	22.9
6 quarks	0.3	11.2	0.4	12.9	0.2	12.1	0.50-0.60	11.8
8 quarks	0.3	4.85	0.3	5.93	0.2	5.72	0.60	5.0

Flexibility

hep-ph arXiv:0712.3014

- There is no unique jet definition
- Performance depends on process and kinematics
- Must be able and should use different jet algorithms



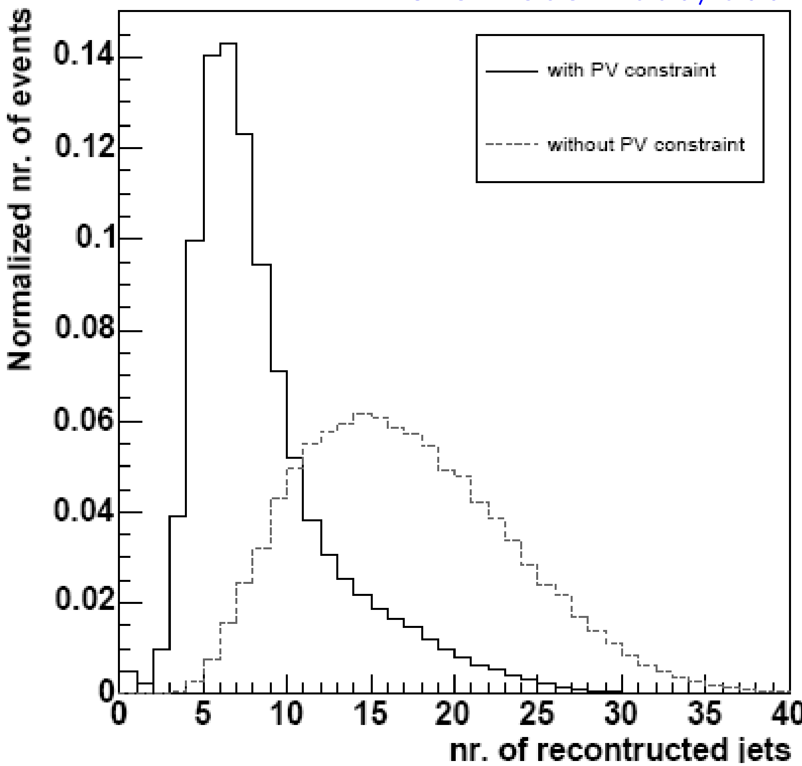
Example for physics effects: Hadronisation and UE

- Effect changes for algorithms, some have smaller UE, some smaller hadronisation
  - ➢ Large "R" → more UE,
  - ➢ small "R" → more hadronisation

Rejection of Fake Jets - Pile-Up

- Pile-Up (PU) affects jet and MET reconstruction
  - One of main causes of uncertainty in JES
- Adds randomness (Poisonnian distribution) to the event
  - Affects also event selection
- Can be reduced using primary vertex constraints
  - Jets at low momenta rejected by this method
  - Several methods used in PTDR analyses

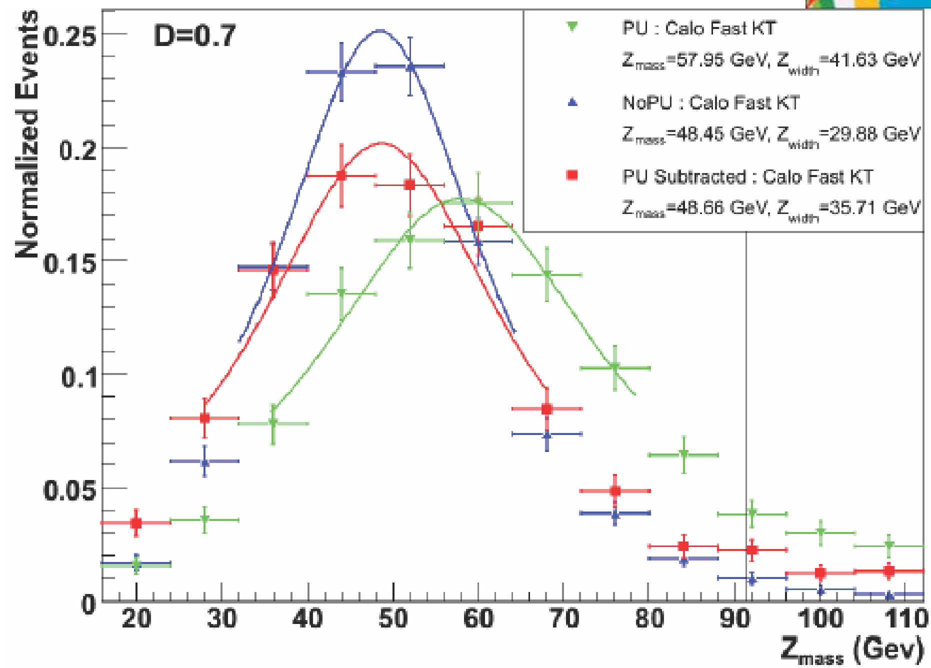
CMS Note 2006/066

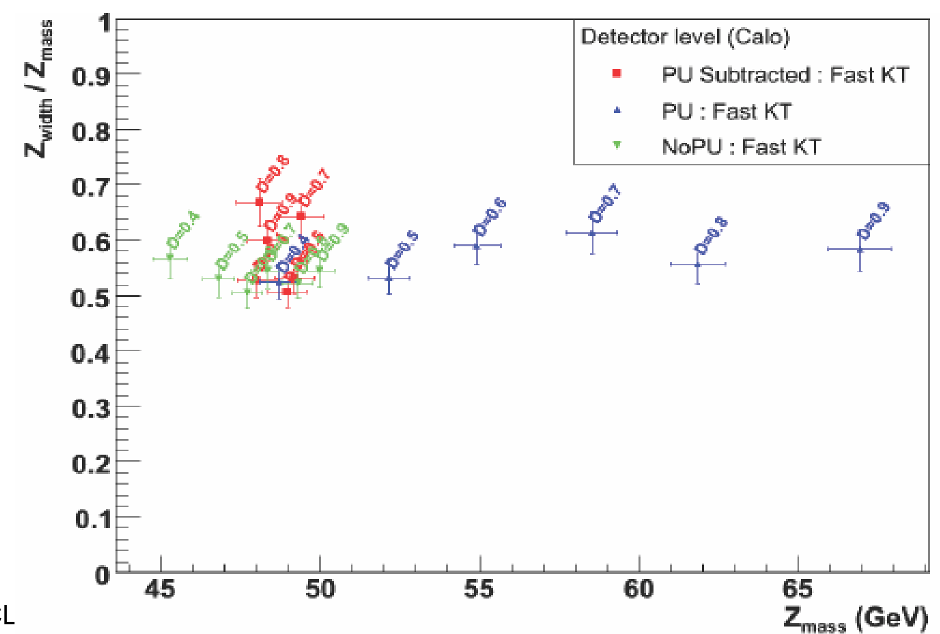


- Work ongoing to define uniform method for fake jet rejection
- Studies with different jet algorithms being performed
  - Can also use FastJet PU subtraction => see next slide

Pile Up Subtraction a la FastJet

- Subtract PU using minimum bias event-by-event subtraction procedure of the FastJet package
  - ➢ MC sample without and with addition of PU contribution
  - ➢ Low luminosity PU (10^32) 5 additional min. bias events per collision
- Z sample decaying into dijets
  - ➢ No JES corrections applied => Z mass shifted
  - ➢ With JES corrections goes to correct value, here just checking the subtraction
- Subtraction works. Peak shifts back to position before addition of PU
- The larger the radius the larger the PU effects
  - ➢ Subtraction works nicely subtracing more PU for larger radii



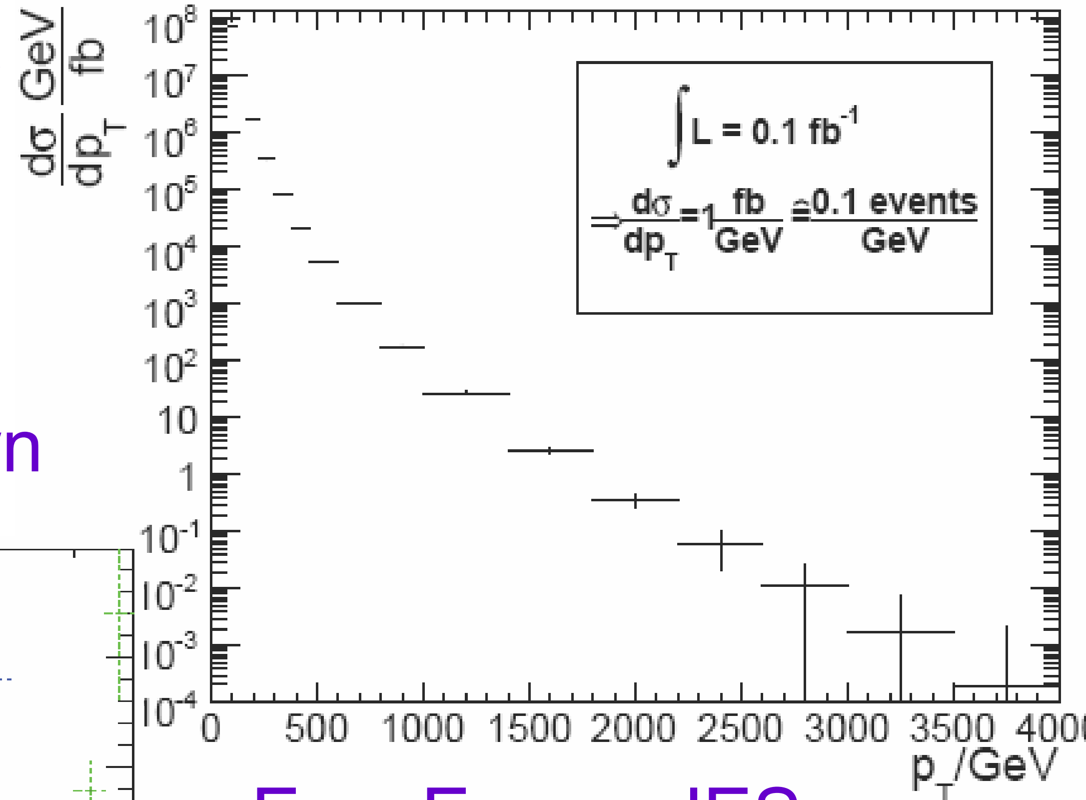


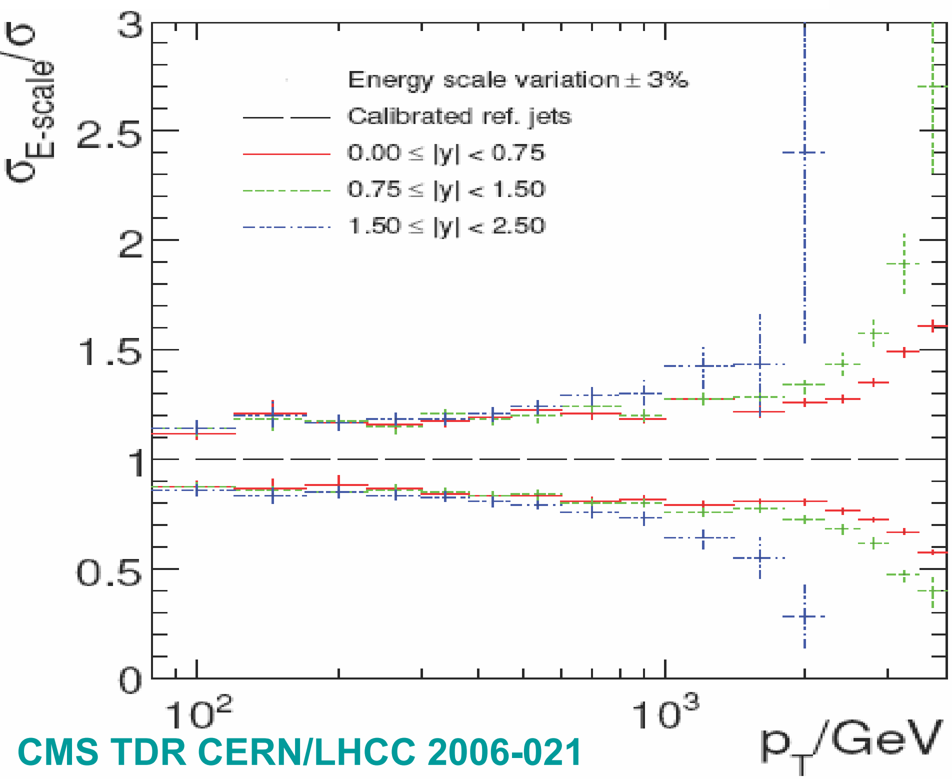
Choice of JetFinders at CMS

- Standard set of theoretically sound jet finders
  - kT with R=0.4, 0.6
  - SiSCone with R=0.5, 0.7
- Used in the trigger
  - IterativeCone with R=0.5
- Also available For Comparison
  - MidPointCone
  - Cambridge Aachen

Jet Measurements: Experimental Errors

- $100pb^{-1}$: reach ~2TeV
- $1fb^{-1}$: reach ~3TeV
  - ~10^4 events with pT>1TeV
- Only stat. errors shown





- Exp. Errors: JES uncertainty dominant source of uncert. to cross sections
  - 15% at low p_T
  - 50% at high p_T

CMS TDR CERN/LHCC 2006-021

Theoretical Errors: Scale Uncertainty

$$\sigma^{jet} = \sum_{a,b=q,\bar{q},g} \int dx_1\, f_a(x_1,\mu_F)\cdot dx_2\, f_b(x_2,\mu_F)\cdot \sigma_{a,b}(x_a,x_b,\mu_R)\cdot(1+\delta_{had})$$

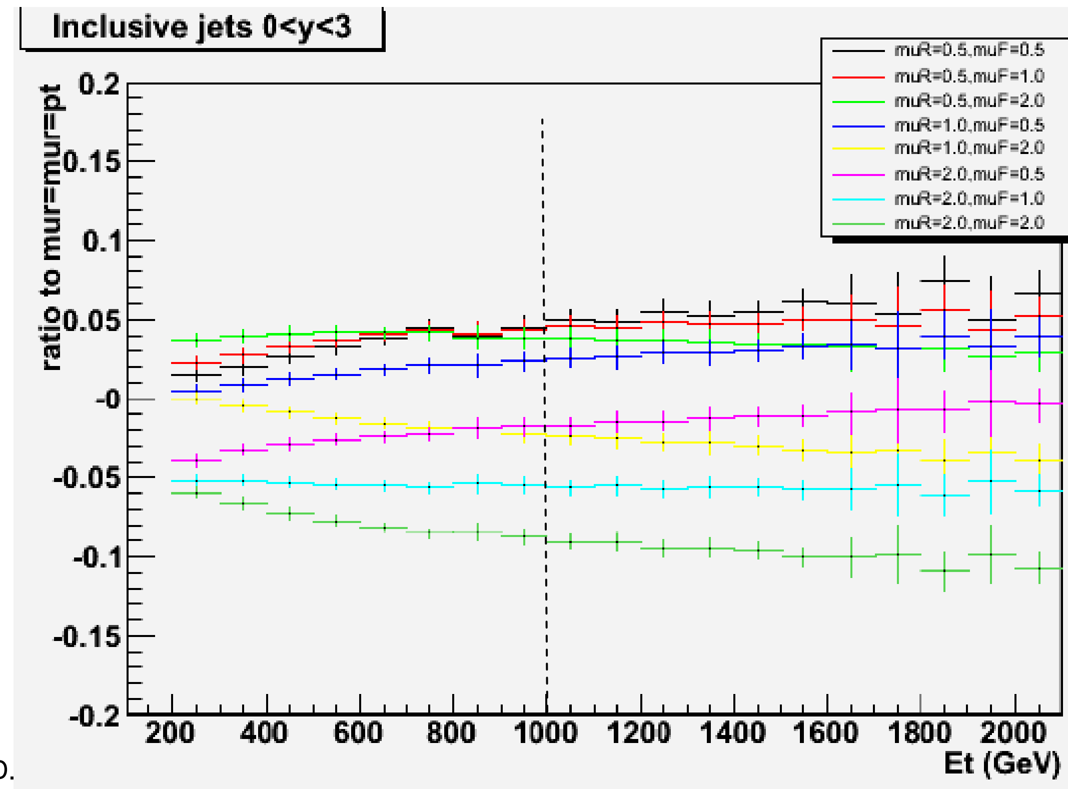
- **Factorization theorem: cross section as convolution of PDFs and parton hard scattering cross section**
- **Scale uncertainty: uncertainty in hard scatter cross section due to missing higher orders in the pQCD calculations.**

➢ **Evaluate scale uncertainty by varying both renormalization and factorization scales between half and twice their default value**

➢ **Here default value is**

$$\mu_R = \mu_F = p_T^{\text{hardest-jet}}$$

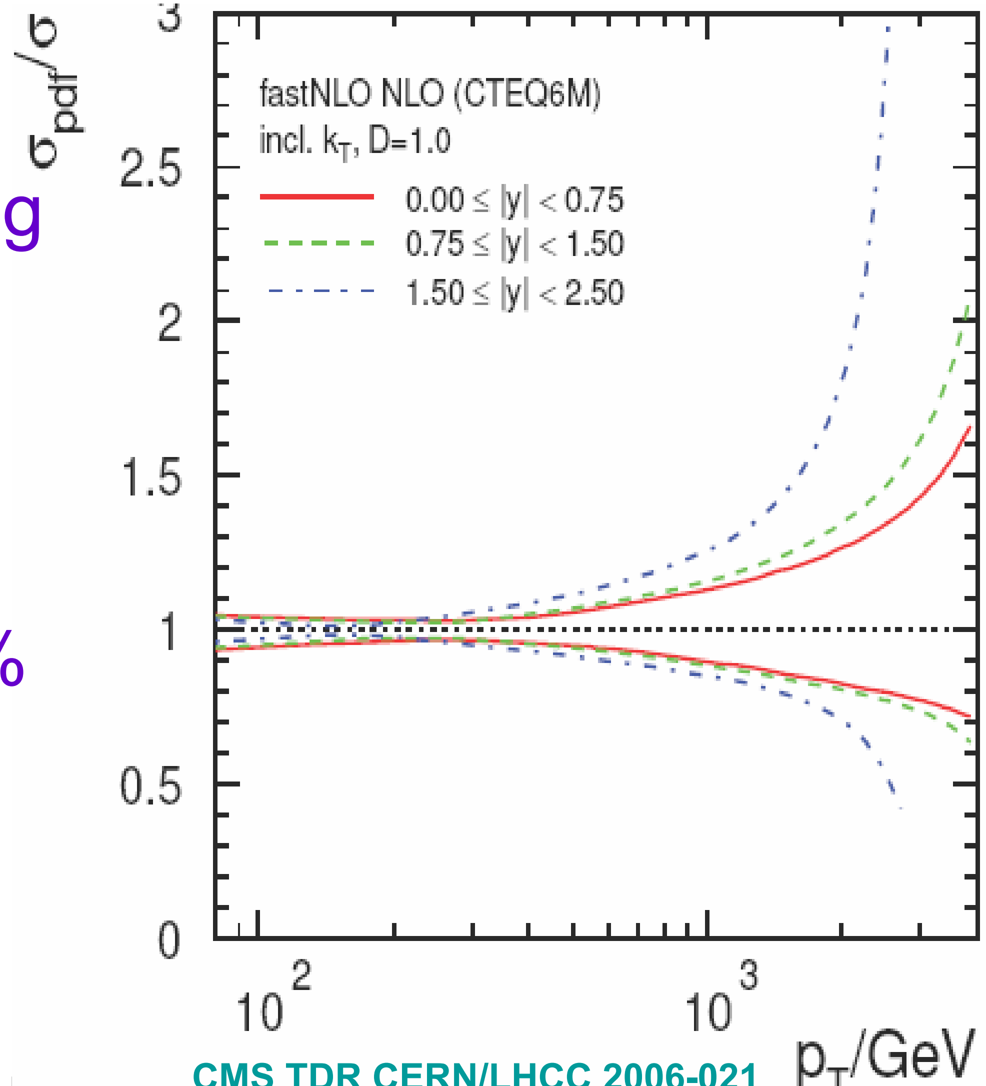
➢ **~10% uncertainty at 1TeV**



Theoretical Errors: PDF Uncertainties

- Uncertainty in the hadron level cross section due to the choice of the PDFs

- Evaluate uncertainty using CTEQ6M set of PDFs
- Plot ratio to central PDF used in the calculations
- Rises from ~5% at low momenta up to +65%,-30% at high momenta

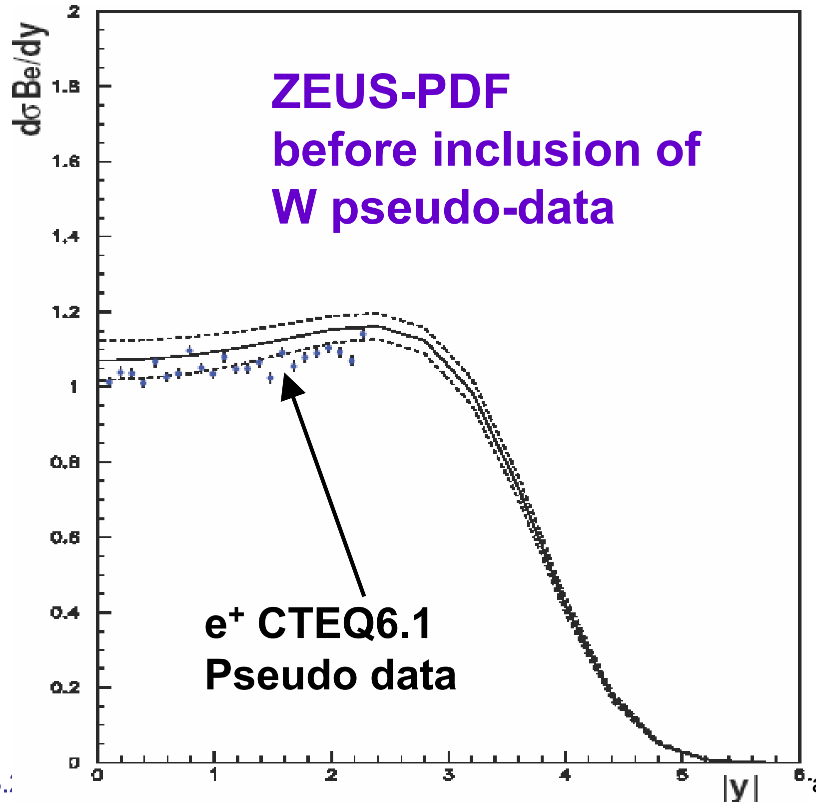


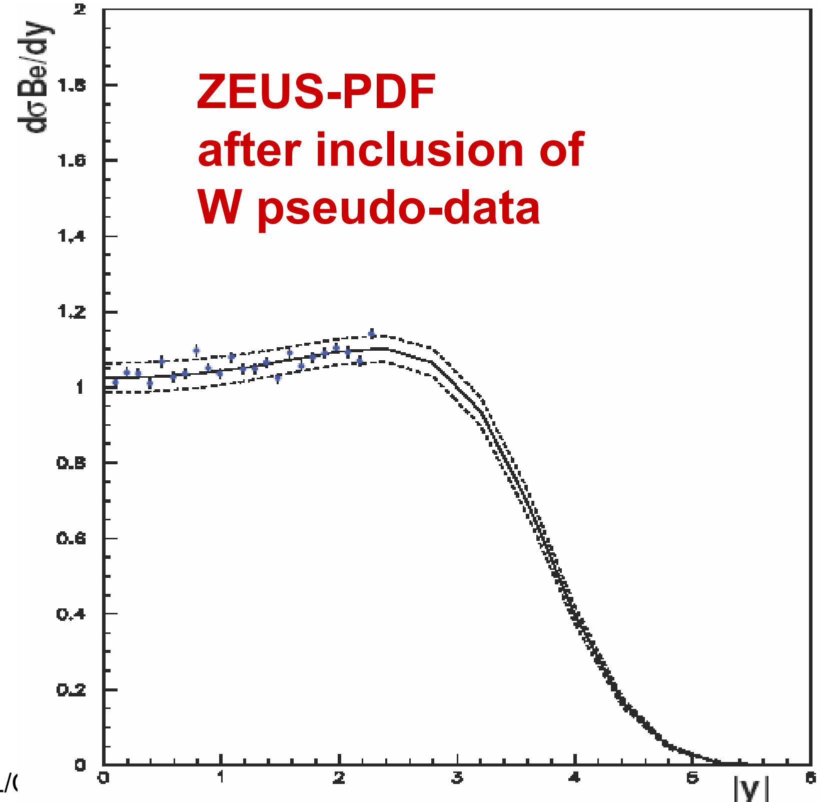
CMS TDR CERN/LHCC 2006-021

Constraining the PDFs with LHC Data

- W and Z cross sections predicted exactly for LHC
- Rapidity for lepton decays sensitive to PDFs
- Simulate events (HERWIG6.505+CTEQ6.1) with addition of a random 4% "systematic error" scatter on these pseudo-data. Redo the PDF fit including them.
- Error on parameter λ (xg(x)~x-λ) reduced by 35%

hep-ex/0509002v1





New Physics with Jets

Search for Contact Interactions at the LHC

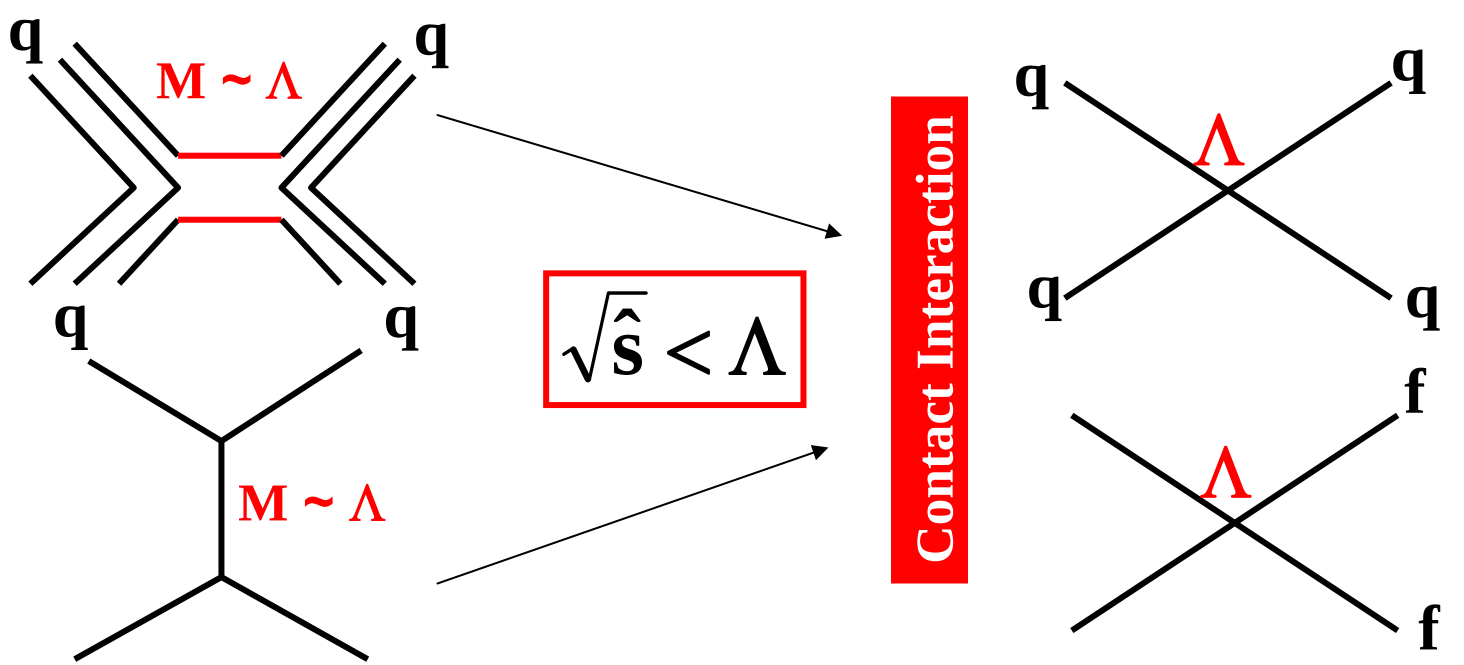
$$\frac{d\sigma}{d\Omega} = SM(s,t) + \varepsilon \cdot C_{Int}(s,t) + \varepsilon^2 \cdot C_{NewPh}(s,t)$$

$$\mathcal{L} = \frac{2\pi A}{\Lambda^2} \sum_{i,j=1}^{6} (\bar{q}_{iL}\gamma^{\mu} q_{iL})(\bar{q}_{jL}\gamma^{\mu} q_{jL})$$

$$A = \pm 1$$

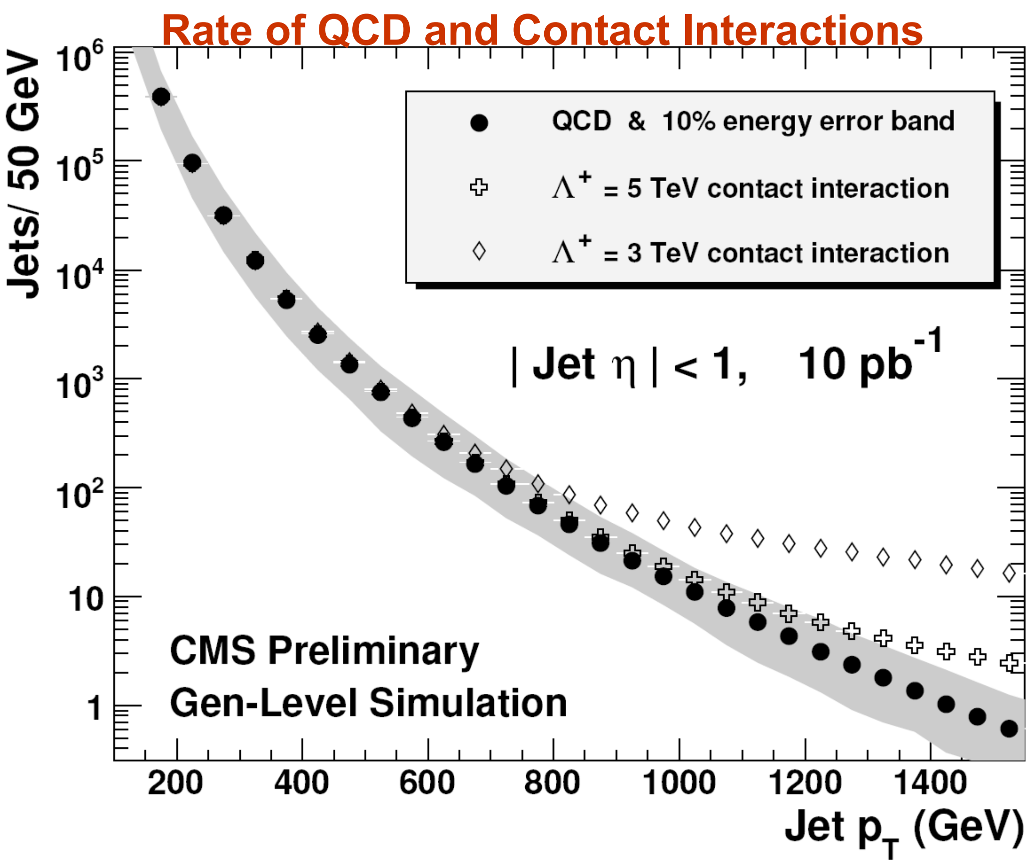
New physics at a scale Λ above the observed dijet (dilepton) mass is effectively modelled as a contact interaction.

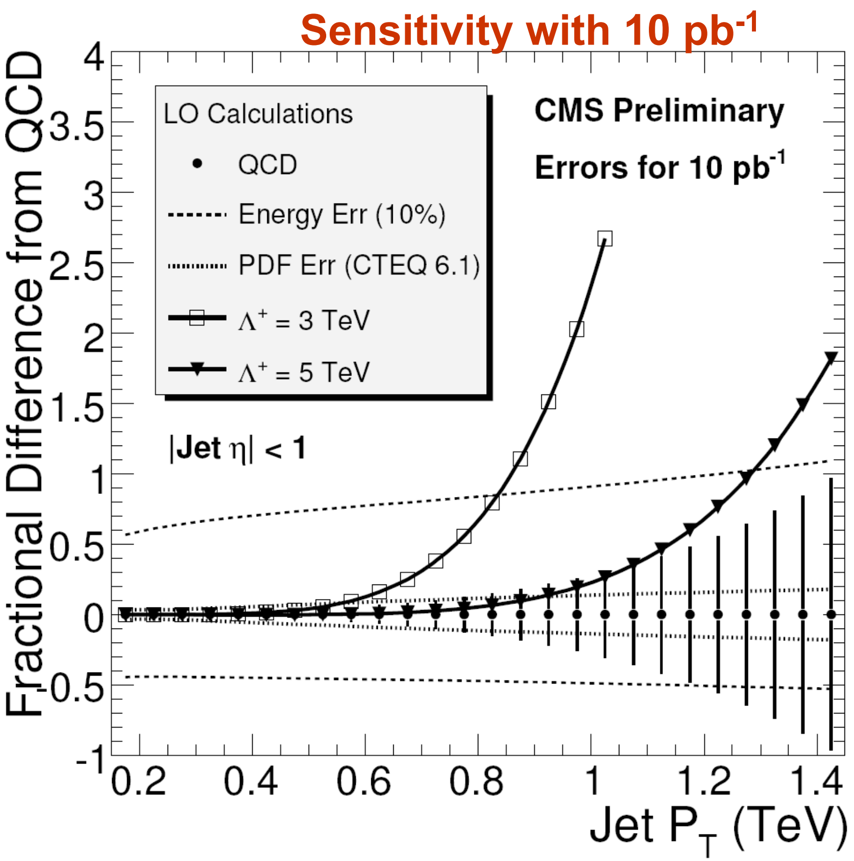
- **Quark compositeness**
- **New interactions from massive particles exchanged**



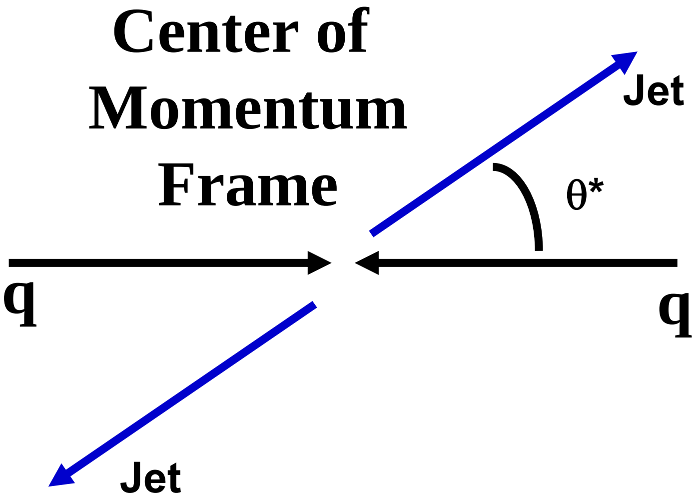
Contact Interactions in Jet Rates

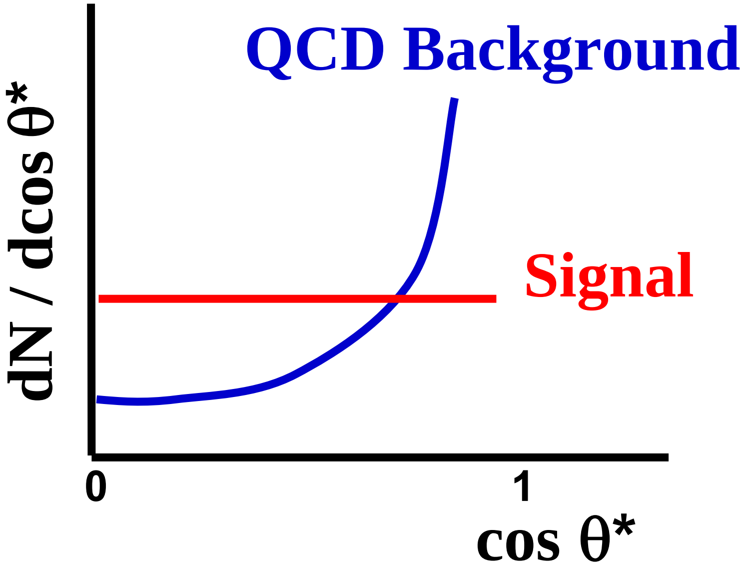
- Contact interactions: large rate at high p_T, immediate discovery possible
  - Error dominated by jet energy scale (~10%) in early running (10 pb^{-1})
    - $\Delta E \sim$ 10% not as big an effect as Λ^+= 3 TeV for p_T>1 TeV.
  - PDF uncertainty and statistical errors (10 pb^{-1}) smaller than E scale error
- With 10 pb^{-1} we can see new physics beyond Tevatron exclusion of Λ^+ < 2.7 TeV. But systematic errors are large





Contact Interactions in Angular Distributions



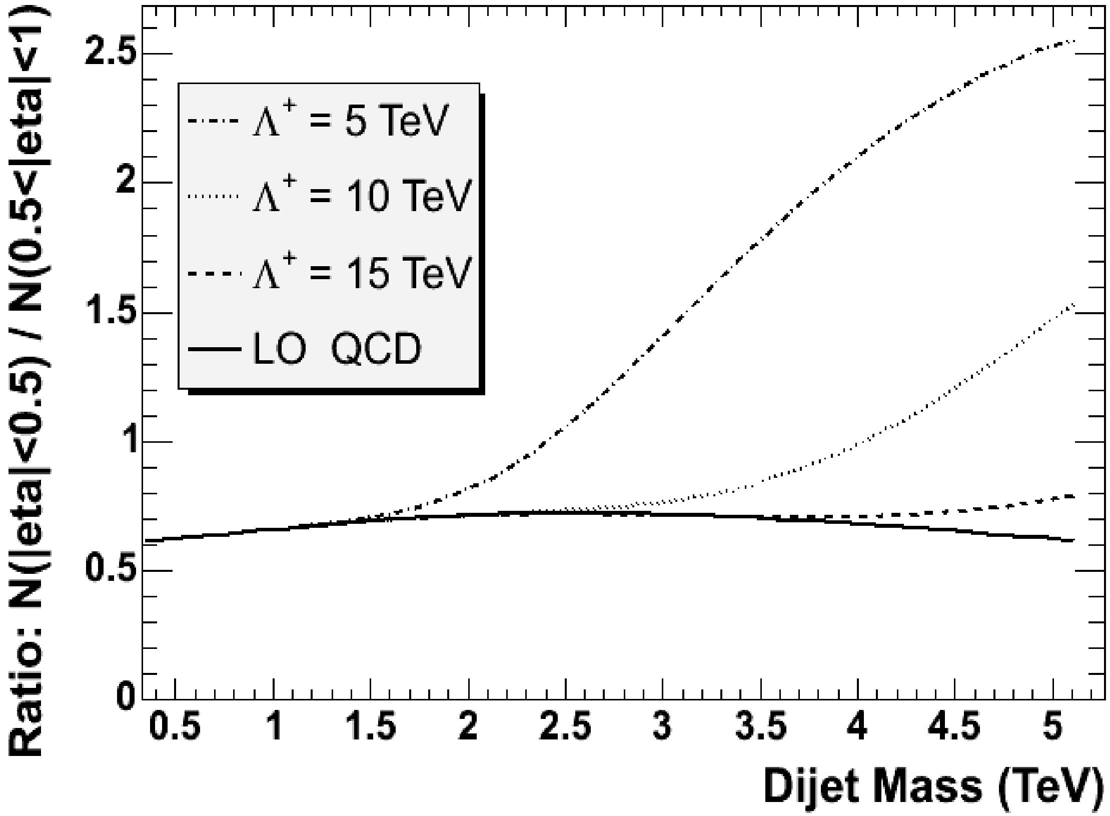


Contact interaction is often more isotropic than QCD

Angular distribution has much smaller systematic uncertainties than cross section vs. dijet mass

Effects emerge at high mass

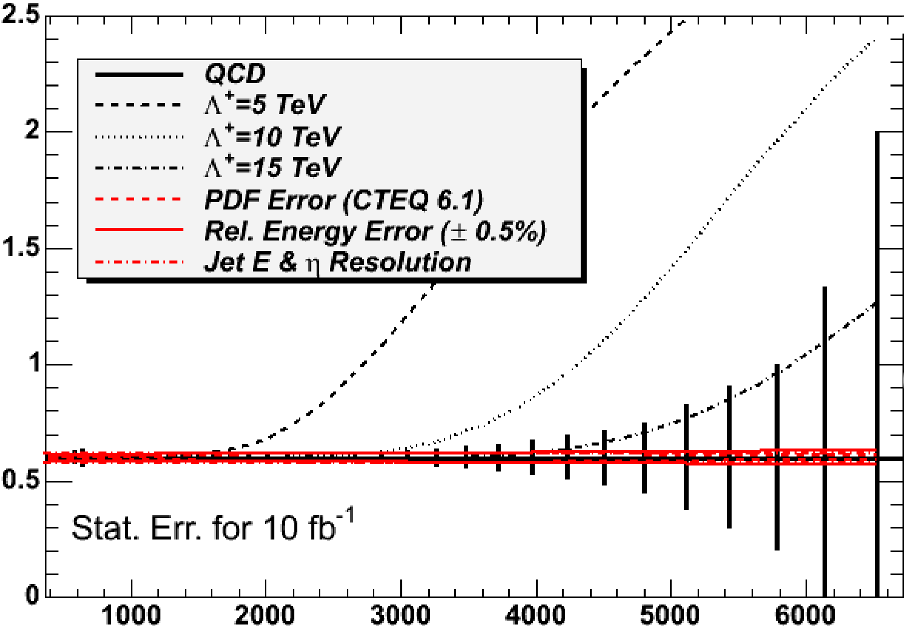
CIs: Dijet Angular Distributions

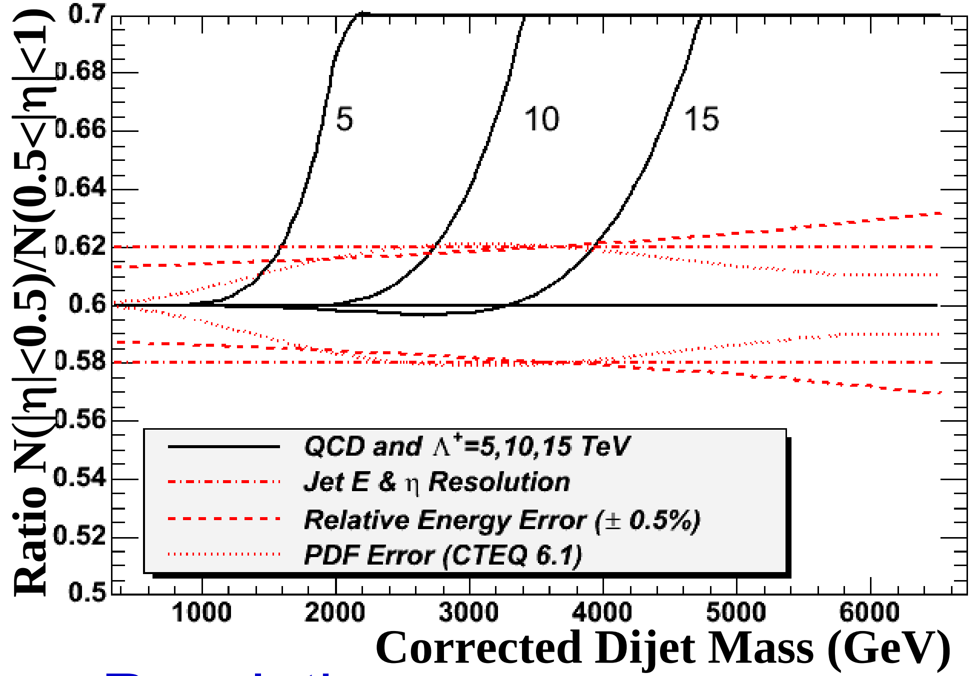


- Dijet Ratio = $N(|\eta|<0.5)/N(0.5<|\eta|<1)$

- Simple measure of the most sensitive part of the angular distribution
- Measure dijet ratio as a function of mass
- Systematics on the dijet ratio are small

Dijet Ratio Systematic Uncertainties



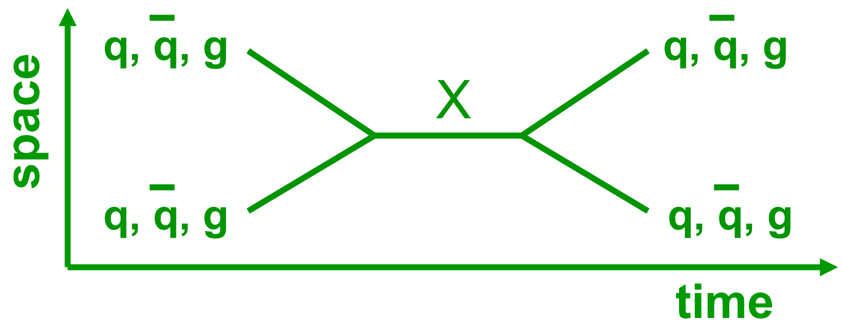


- Absolute Jet Energy Scale
  - No effect on QCD dijet ratio:
  - Flat vs dijet mass
  - Causes 5% uncertainty in Λ
- Relative Energy Scale
  - Energy scale in |η|<0.5 vs. 0.5 < |η| < 1

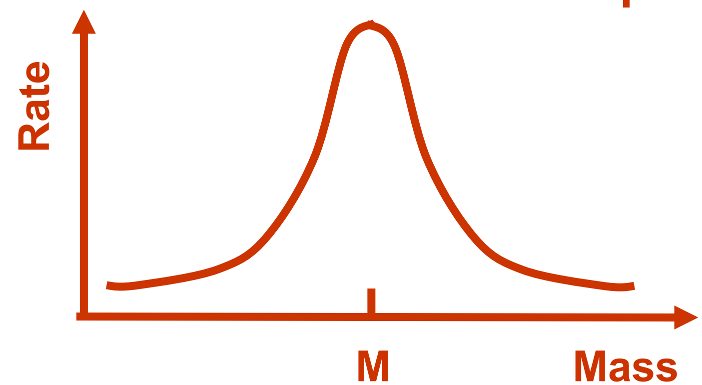
  ±0.5 % achievable in Barrel
  - Changes ratio between ±0.01-0.03
- Resolution
  - No change to the ratio when changing resolution
  - Systematics bounded by MC statistics: 0.02
- Parton Distributions
  - CTEQ6.1 uncertainties, Systematics on ratio <0.02
  - No testbeam data above 300 GeV. Discovery range in the regime where the calorimetric response is extrapolated

Dijet Resonances

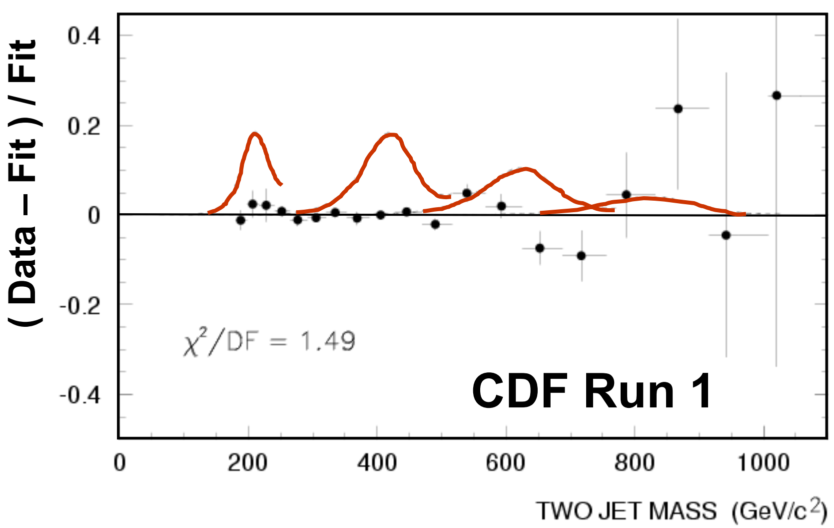
New particles, X, produced in parton-parton annihilation will decay to 2 partons (dijets).

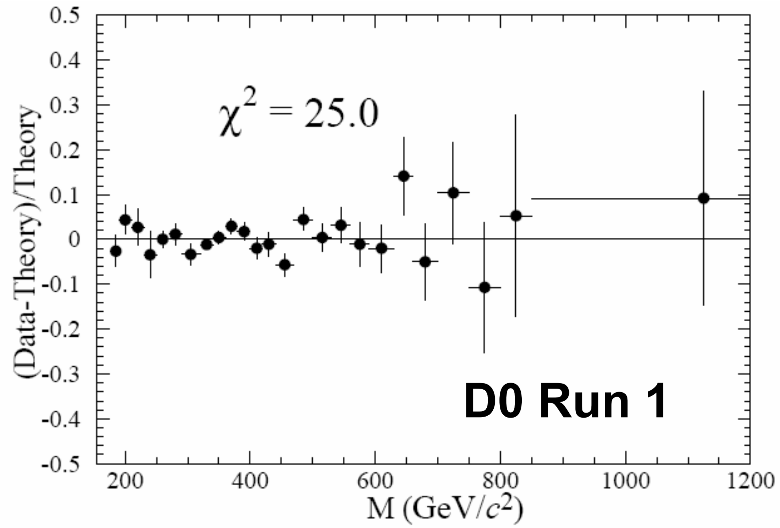


They are observed as dijet resonances: mass bumps.



Tevatron has searched but not found any dijet resonances so far:



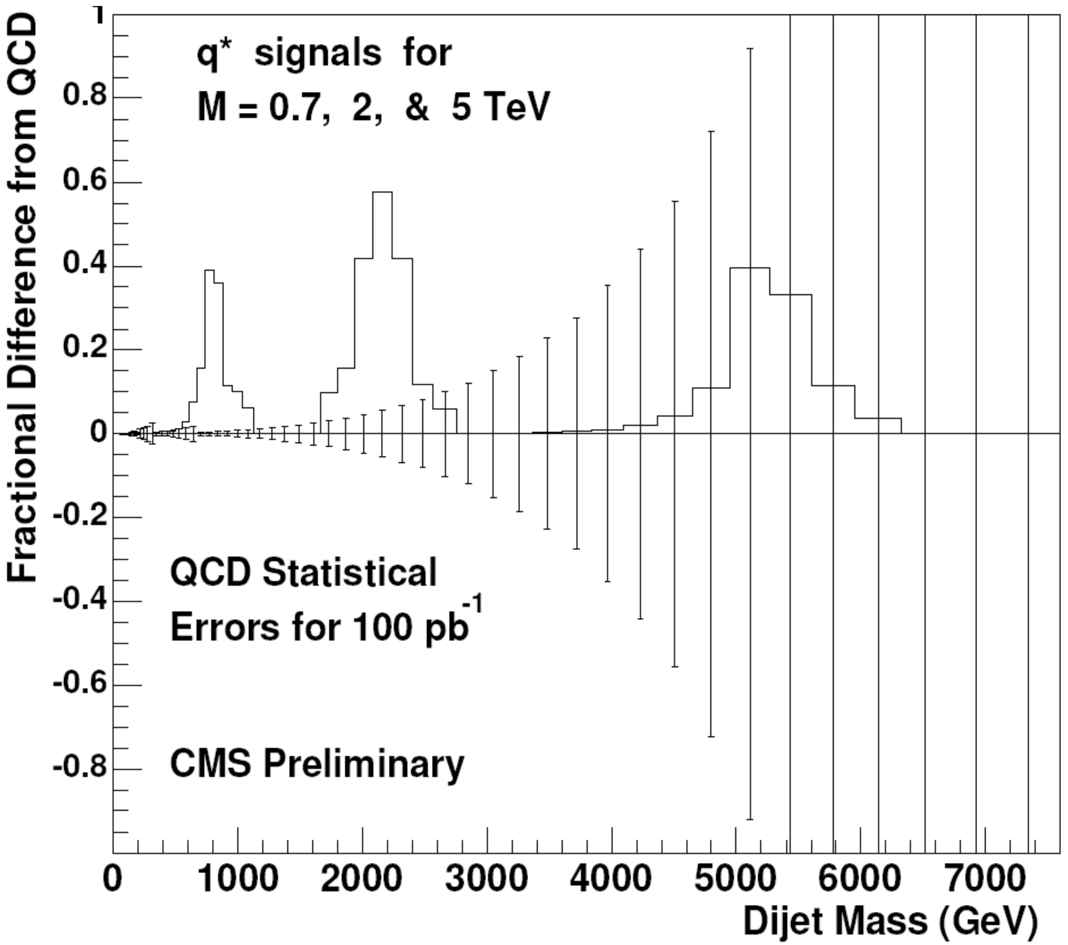


Resonances in Dijet Mass

- Measure jet rate vs. corrected dijet mass and look for resonances.
- Use a smooth parameterized fit or QCD prediction to model background

- Strongly produced resonances can be seen
- Convincing signal for a 2 TeV excited quark in 100 pb-1
- Tevatron excluded up to 0.86 TeV.

- Can also study resonances in Dijet Ratio (not discussed here)



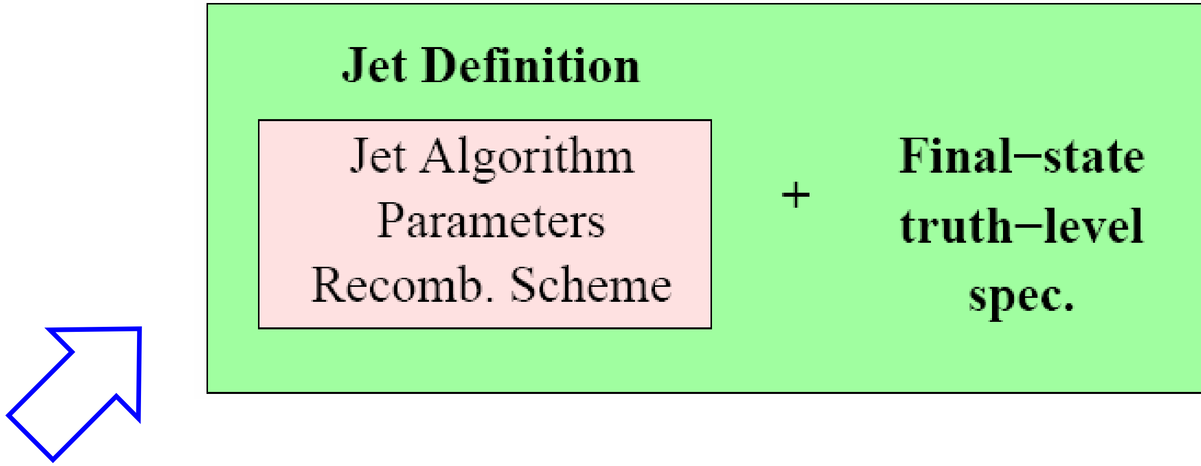
Conclusions

- Understanding of jets and QCD crucial for LHC
  - Background to many searches
  - Many processes have jets in final state
  - There are jet-only-based searches
- Measurements of jet cross sections suffer from theoretical and experimental uncertainties
  - dominant experimental error: Jet Energy scale uncertainty.
    - Can use W in top quark pair production to constrain this uncertainty down to 3% level
  - dominant theoretical error: uncertainty on PDFs, renormalization scale
    - Use Z and W production at LHC to reduce PDF uncertainties
- Searches using dijets can be performed:
  - Contact Interactions: jet rates, jet angle (dijet ratio)
  - Dijet Resonances: dijet mass, dijet ratio

Backup Slides

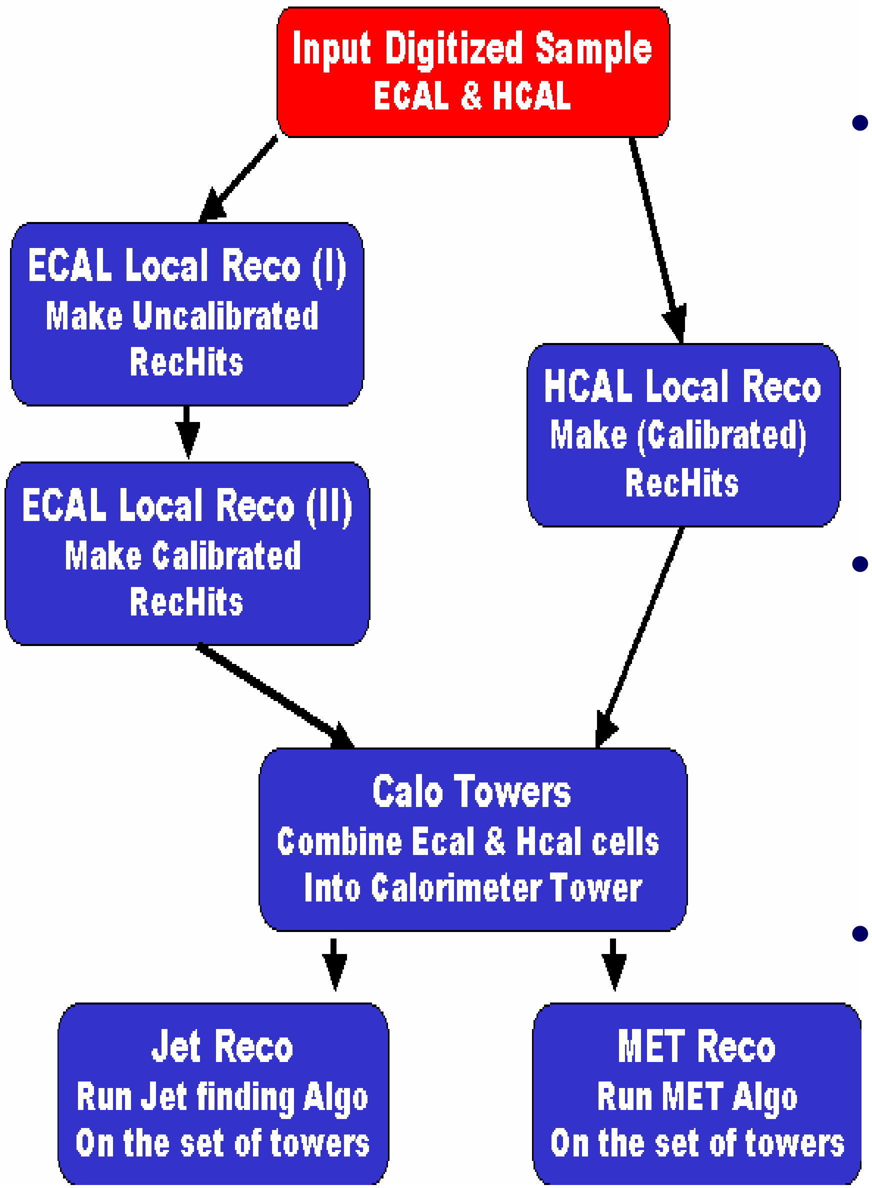
Reproducibility

http://www.lpthe.jussieu.fr/LesHouches07Wiki/index.php/Jets_nomenclature



- Algorithms should be described properly in talks and papers
- We should state clearly what we use
  - Before it was not always possible to know what code was used
  - CMS has made a lot of progress in this direction using external libraries instead of embedded code
- Without clear description impossible to reproduce results
  - In fact, even we ourselves will not be able to

Jets at CMS



- JetAlgorithms
  - Iterative Cone (IC)
  - Mid Point cone (MCone)
  - SiSCone (seedless)
  - k_T Cluster
  - Cambridge / Aachen

  (SiSCone, k_T Cluster, Cambridge / Aachen) } FastJet hep-ph/0512210

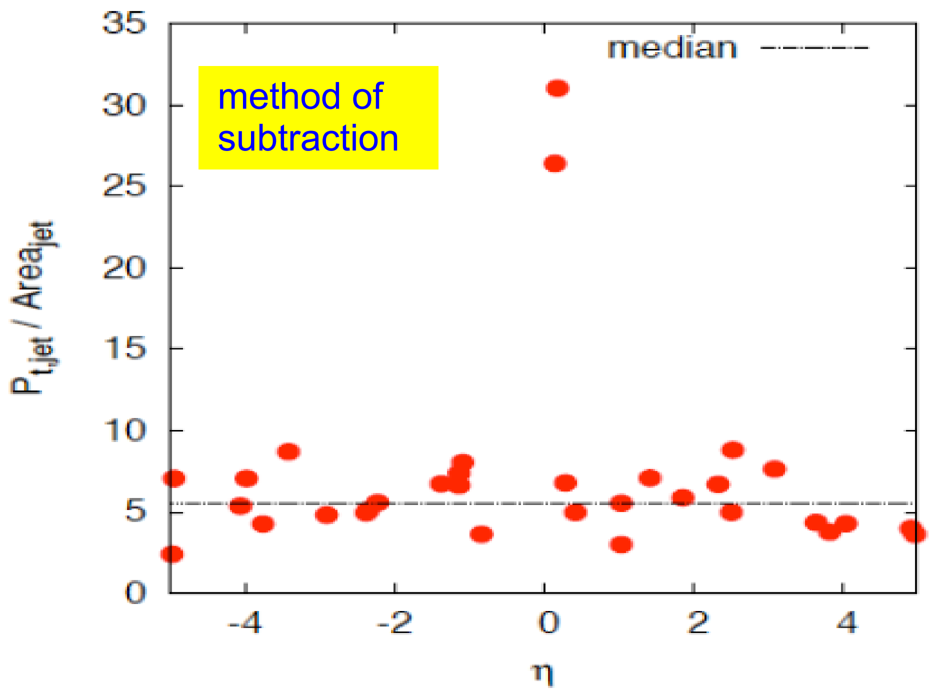
- Detector level Input
  - CaloTower, energy threshold of 0.5 GeV
  - Particle Flow Objects
  - Charged Tracks

- MC level(s)
  - 4 momenta of true level particles (HepMC:: GenParticles)

Subtraction of Min. Bias – Method
M. Cacciari, G. Salam hep-ph/0512210

<u>Estimation of Jet Area</u>

- Estimate area of each jet using "ghost" particles
- Fill event with very soft particles
- Recluster and count how many "ghost" particles fall in each jet
- <u>Possible since k_T infrared safe</u>



<u>Subtraction</u>

- pt/area is uniform for the non-hard jets
- Use median to estimate background
- Subtract from each jet depending on surface
- FastJet provides standard methods for doing the above

Dijet Resonances : Models
R. Harris

Dijet Resonances found in **many models** that address fundamental questions.

- Why Generations ? → Compositeness → Excited Quarks
- Why So Many Forces ? → Grand Unified Theory → W ' & Z '
- Can we include Gravity ? → Superstrings & GUT → E6 Diquarks
- Why is Gravity Weak ? → Extra Dimensions → RS Gravitons
- Why Symmetry Broken ? → Technicolor → Color Octet Technirho
- More Symmetries ? → Extra Color → Colorons & Axigluons

Model Name	X	Color	J^P	Γ / (2M)	Chan
E_6 Diquark	D	Triplet	0^+	0.004	ud
Excited Quark	q*	Triplet	$½^+$	0.02	qg
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
Octet Technirho	ρ_{T8}	Octet	1^-	0.01	$q\bar{q}$,gg
R S Graviton	G	Singlet	2^-	0.01	$q\bar{q}$,gg
Heavy W	W '	Singlet	1^-	0.01	$q_1\bar{q}_2$
Heavy Z	Z '	Singlet	1^-	0.01	$q\bar{q}$