Physics at the LHC
Lecture 2: The Standard Model at the LHC (I)

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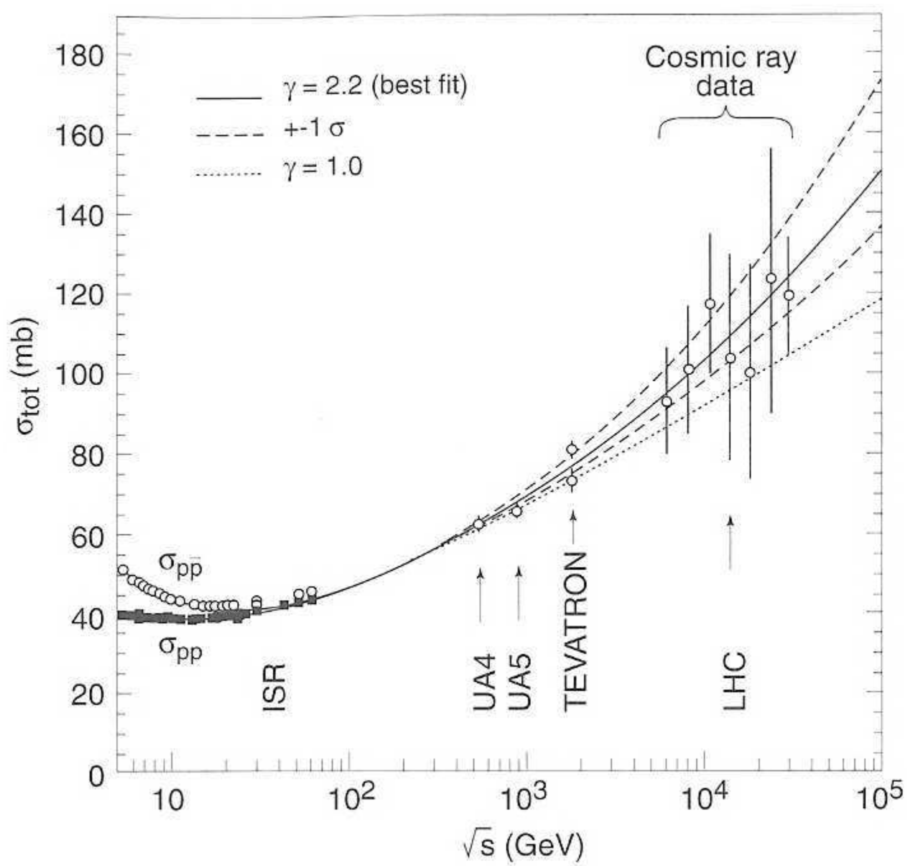
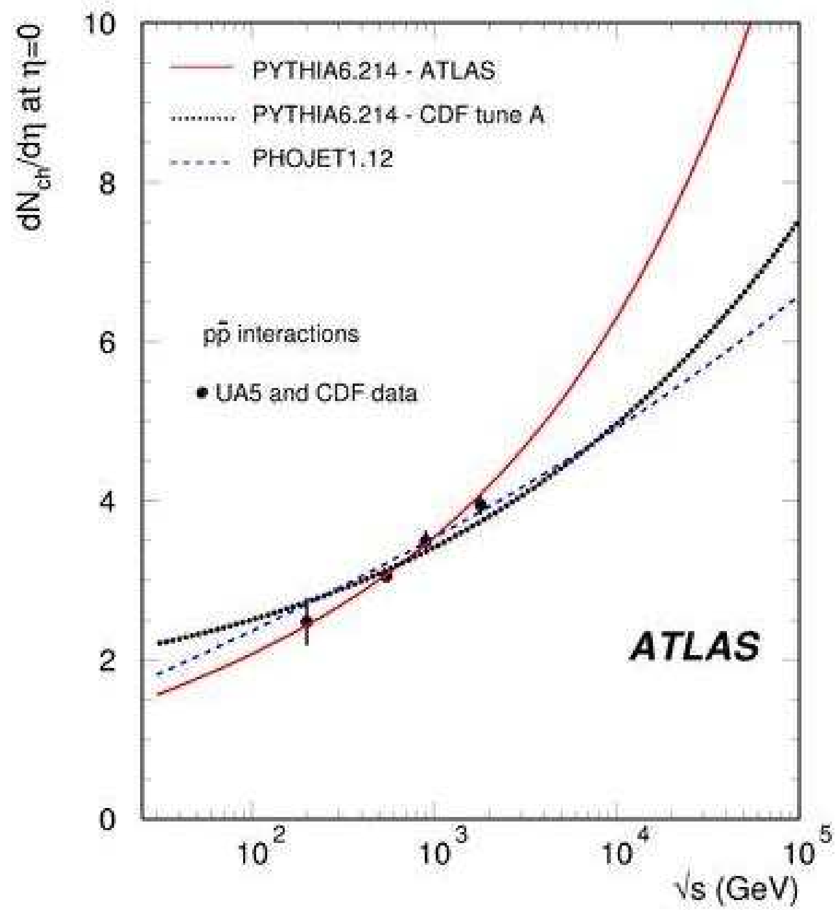
Minimum bias events

Proton-proton cross section at high energies $\mathcal{O}(100\text{mb})$
⇒ several soft events per bunch crossing at LHC ("minimum bias")

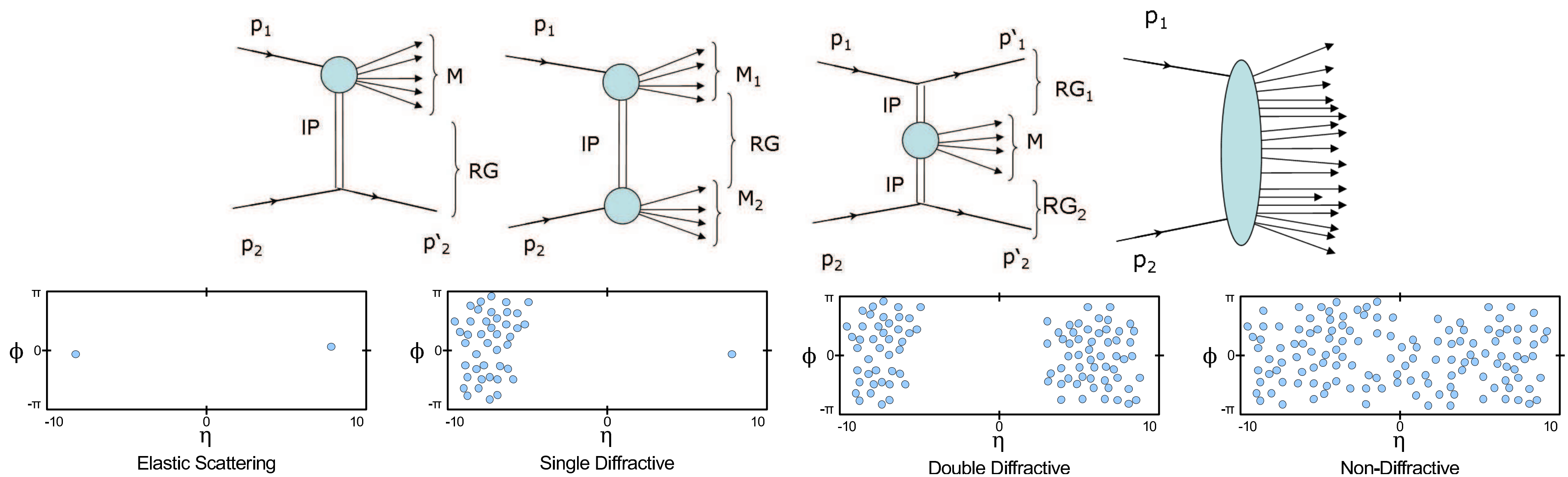
Also predictions for quantities like multiplicities rather uncertain
⇒ must measure these events at LHC with low luminosity





The total cross section can be written as

$$\sigma = \sigma_{el} + \sigma_{sd} + \sigma_{dd} + \sigma_{cd} + \sigma_{nd}$$



Approximate values at 14 TeV [mb]

σ_{tot}	σ_{el}	σ_{sd}	σ_{dd}	σ_{cd}	σ_{nd}
100	20	15	10	1	60

Largest part is non-diffractive collisions with particles distributed over the full η range.

Calculation of nd-cross section

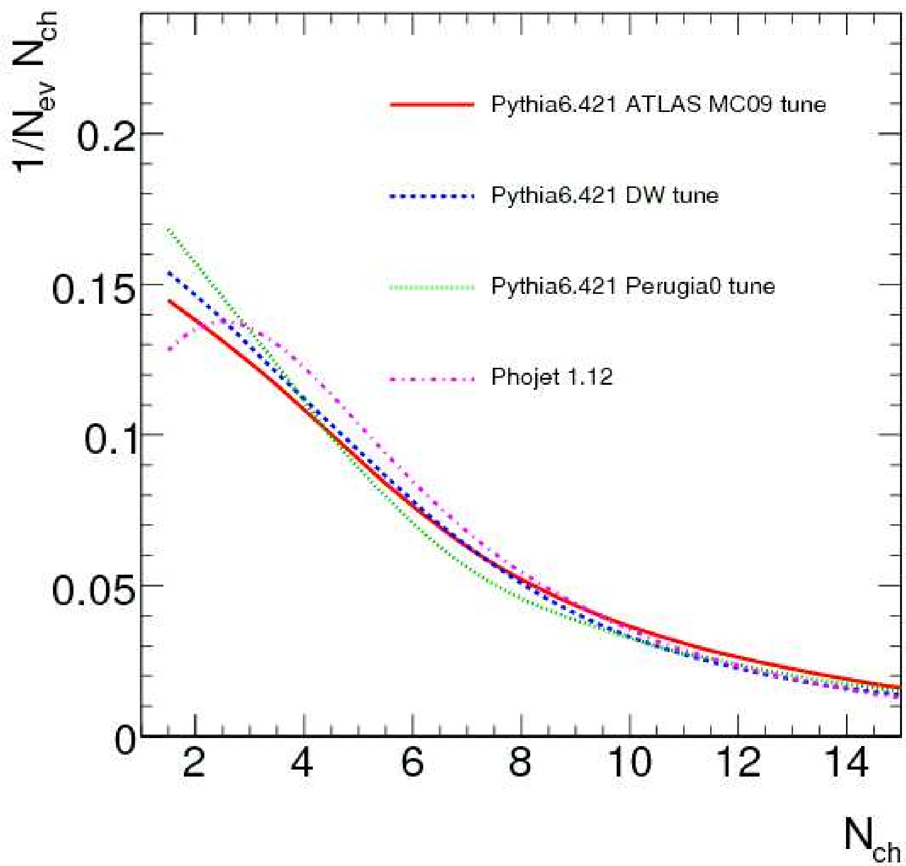
$$\sigma_{pp}(s) = \int_{x_1}\int_{x_2} dx_1 dx_2\, p_g(x_1) p_g(x_2)\, \sigma_{gg}(x_1 x_2 s)$$

- gg cross section above a cutoff $p_{t,cut}$ can be calculated in perturbative QCD
- The calculated cross section is larger than then measured pp cross section
- Standard explanation, multiple interactions: In one pp interaction several parton-parton interactions take place
- This makes the events dependent on the transverse parton distributions

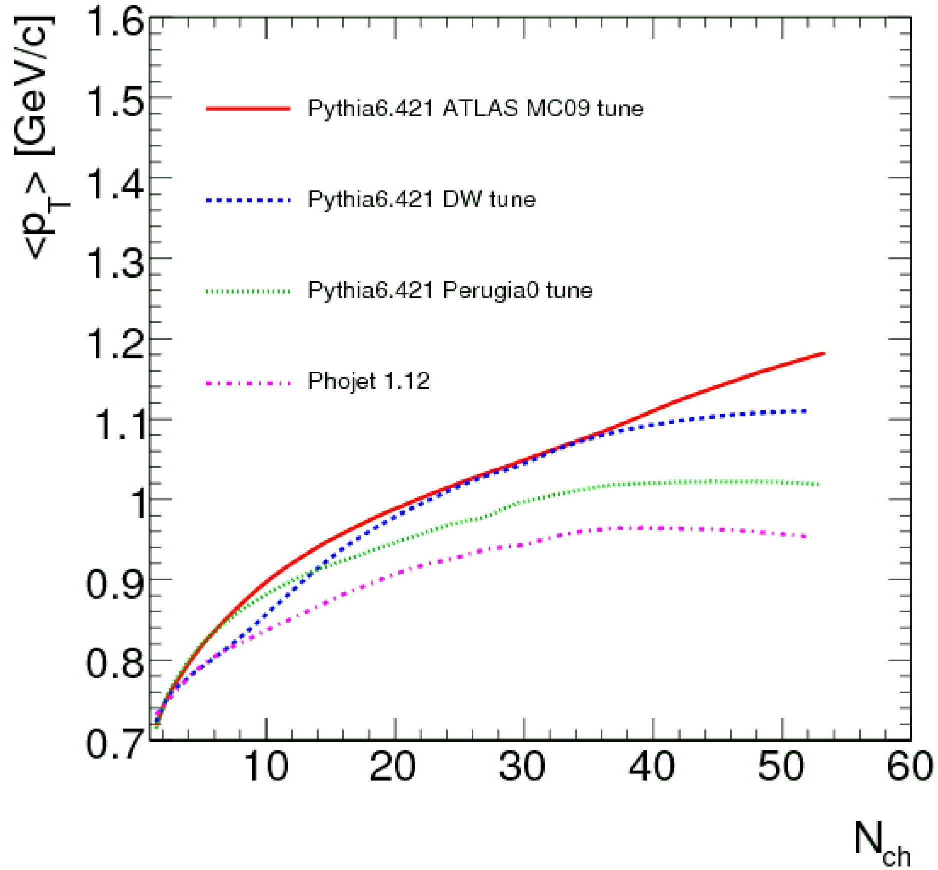
➡ Events even more difficult to predict

Typical signals of multiple interactions:

Tails in multiplicity distributions



Rise of $\langle p_t \rangle$ vs N_{ch}



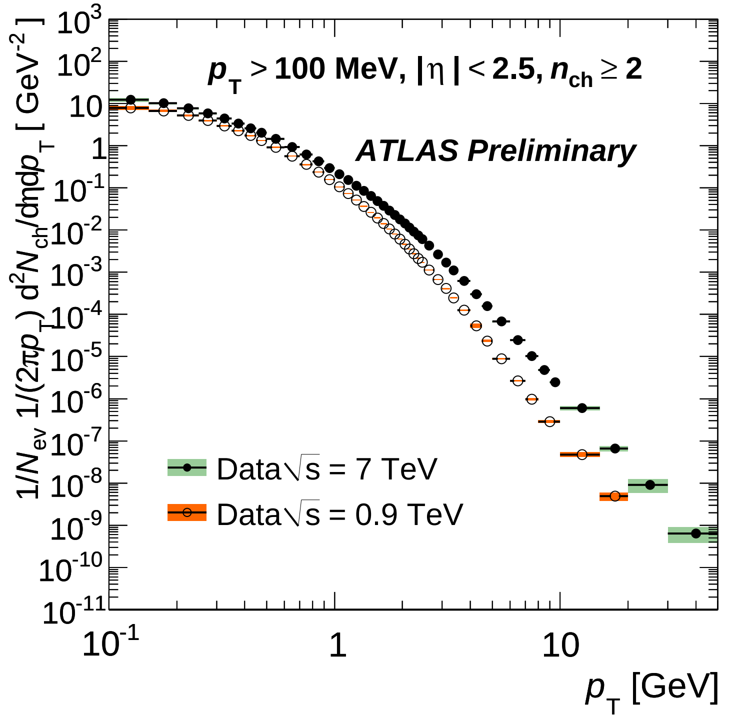
Other observables are sensitive to fragmentation parameters

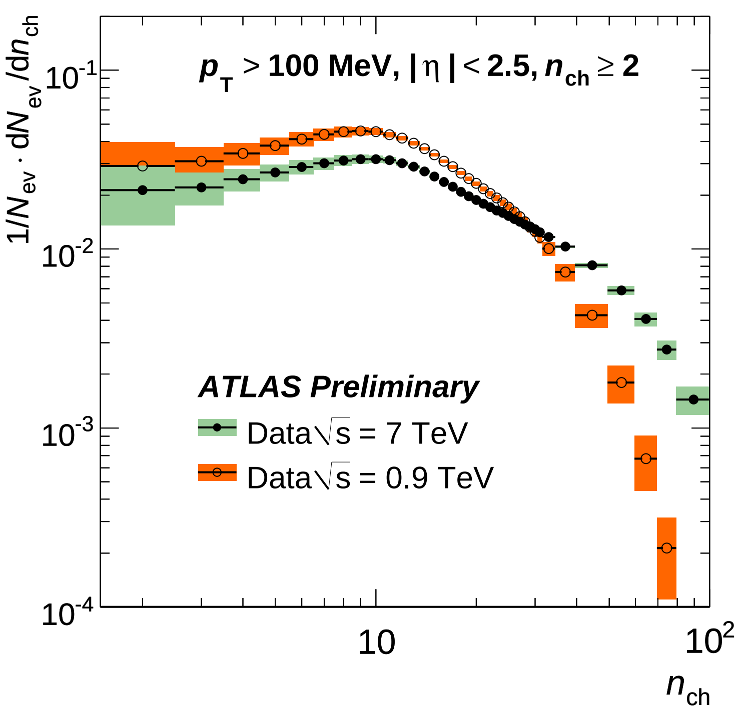
Analysis of minimum bias events

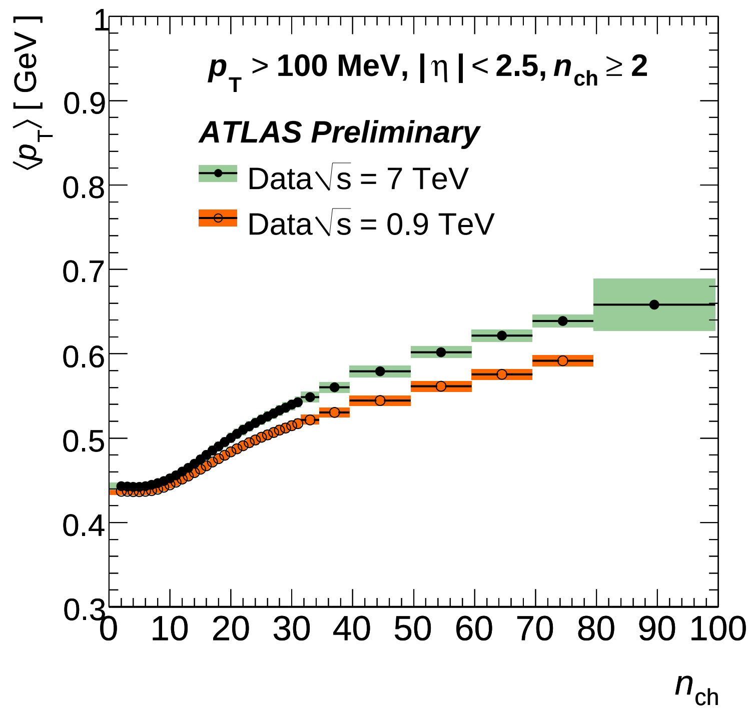
- The experiments have a large dataset at 7 TeV, a reasonable one at 0.9 TeV and a small dataset at 2.36 TeV
- At 2.36 TeV no stable beam was declared so that data are not always taken under nominal conditions
- The experiments have analysed the data with different phase space cuts
- Especially ATLAS does not try to correct for full phase space and specific subprocesses to avoid model dependent corrections

Results:

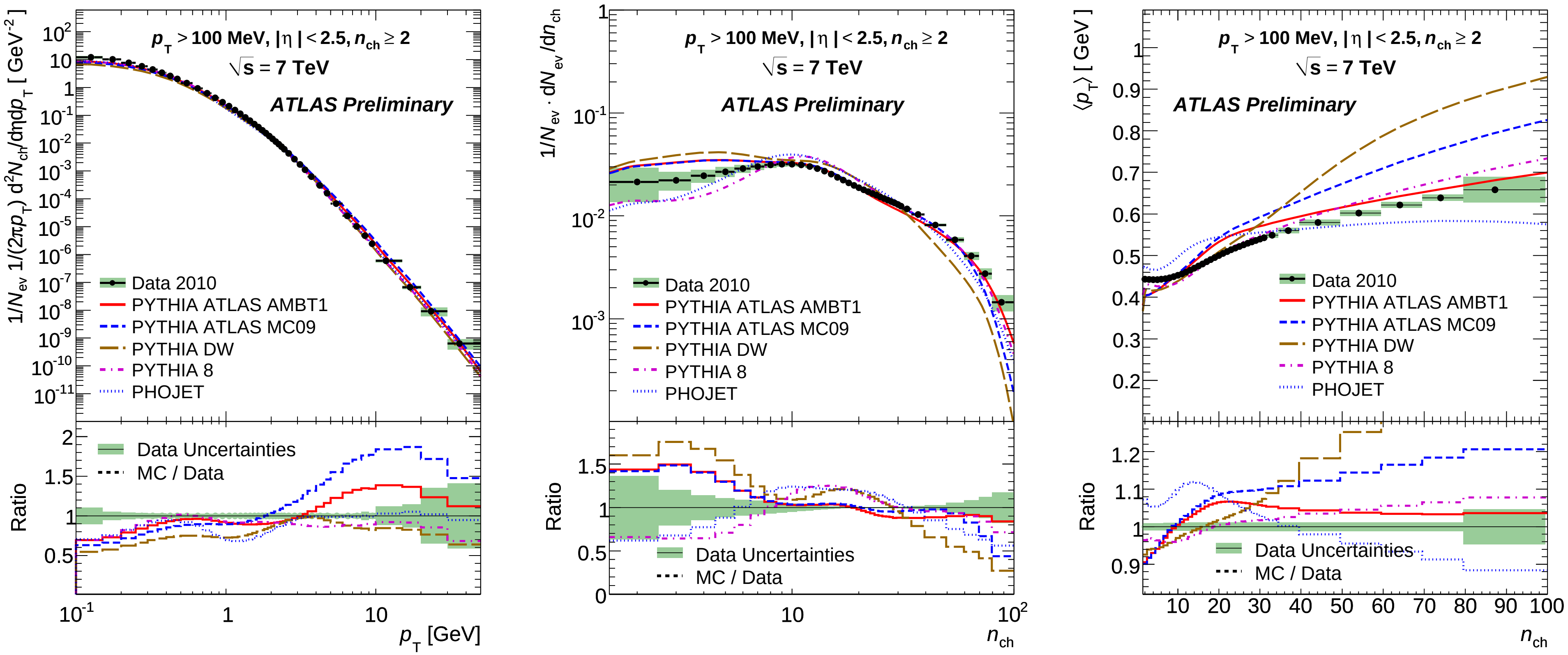
- Multiplicity rises significantly with energy
- Also average transverse momentum rises



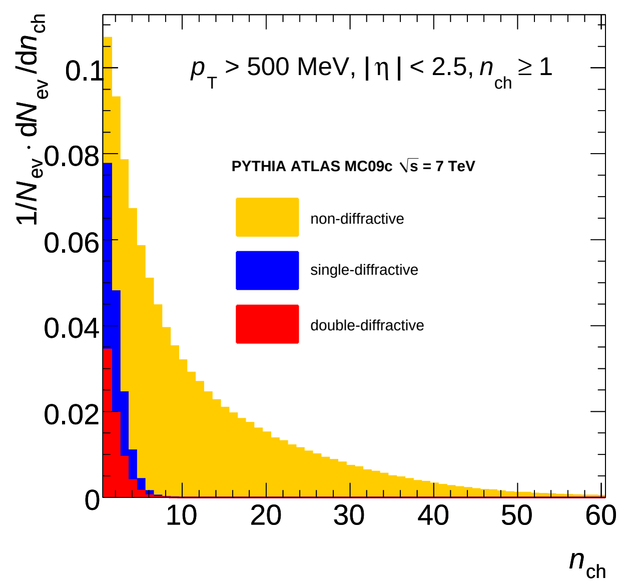


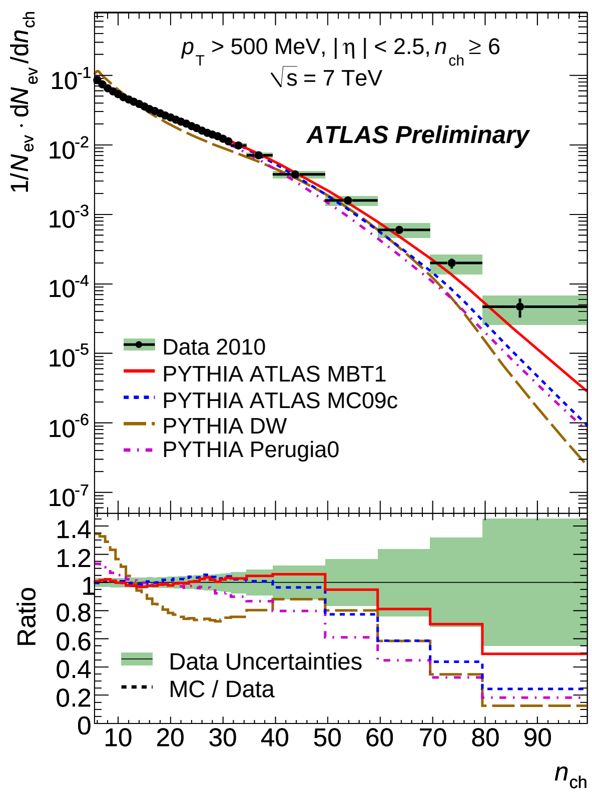


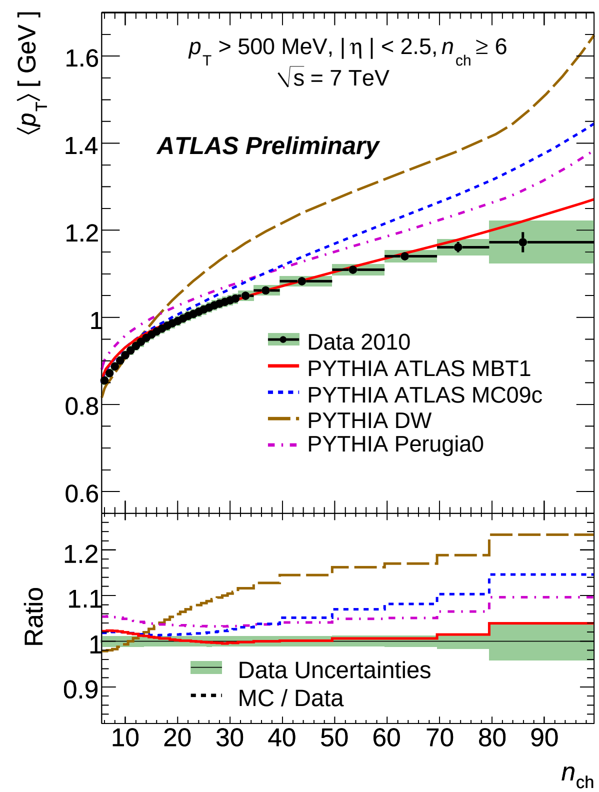
Description by Monte Carlo generators is marginal



- With harder phase space cuts the diffractive components can be suppressed
- In the diffraction depleted selection a satisfactory Monte Carlo tuning is possible

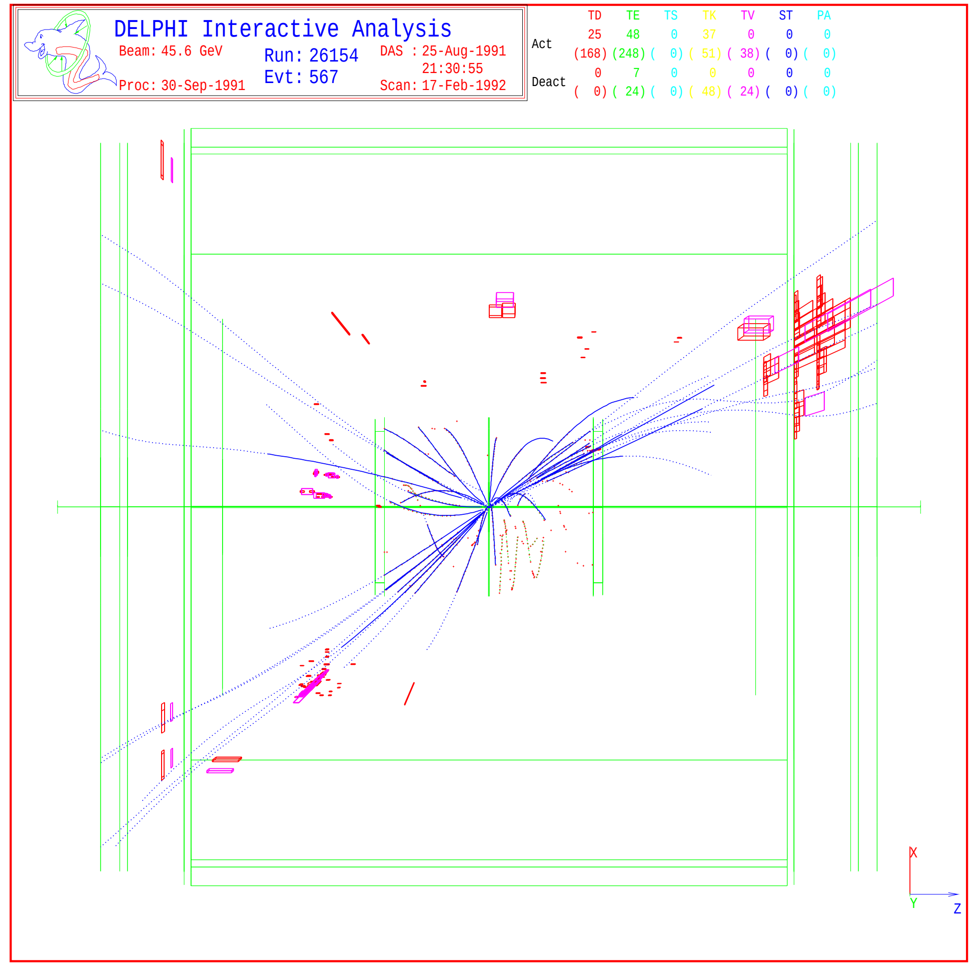




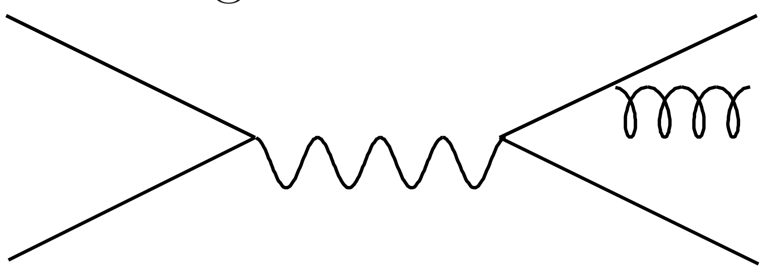


Jets in e^+e^-

Experiment: Measures hadrons



Theory: calculates final states with quarks and gluons



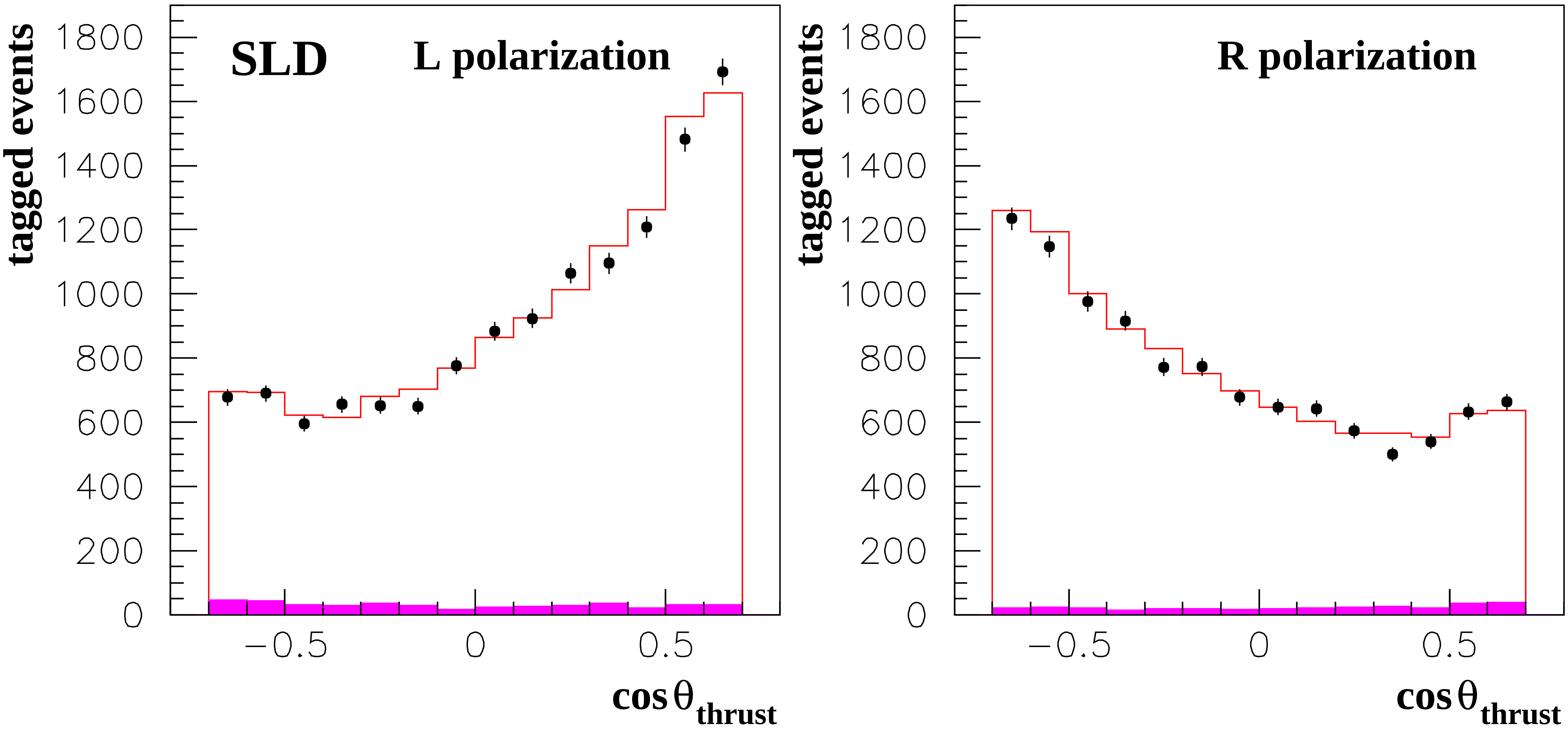
Must try to understand transition partons → hadrons

Must try to reconstruct partons from hadrons

Experimental observation:

- Hadrons come in bundles (jets)
- Jets remember parton momentum

Signed $\cos\theta$ distribution of jets in polarised e^+e^- scattering

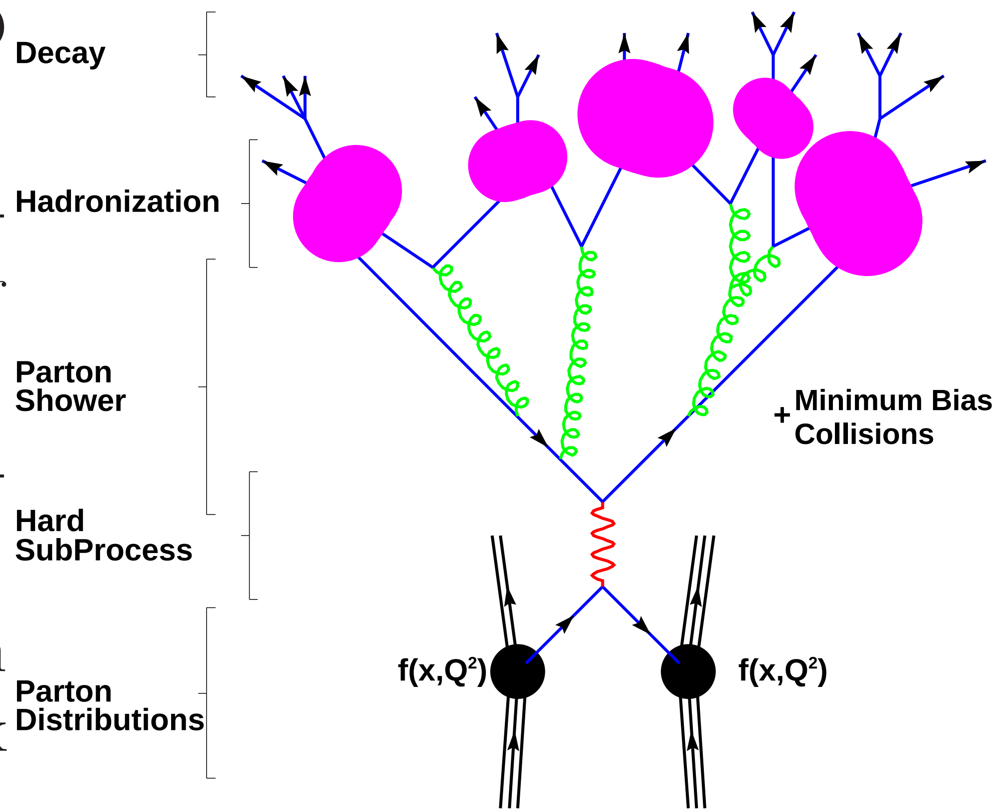


Model of fragmentation

- Quarks and gluons radiate gluons
- Gluons split into $q\bar{q}$ pairs
- "final state" partons rearrange into hadrons

MC description of gluon emission/splitting (parton shower)

- Radiation according to QCD splitting functions
- Interference dealt with by ordering principle (e.g. angular ordering)
- Shower stops at a scale of typically 1 GeV
- First one or two radiations can be according to exact matrix element



Fragmentation models

String fragmentation (Pythia, Lund model)

- Quarks span a string between them
- When the quarks move apart string tension increases
- When the tension reaches a critical value string breaks creating a new $q\bar{q}$ pair at the new ends
- When the energy is small enough hadrons are formed

Cluster fragmentation (HERWIG)

- Remaining gluons split into $q\bar{q}$ pairs
- $q\bar{q}$ pairs rearrange into colour singlet clusters
- Clusters decay isotropically

Jet algorithms

Try to "undo" fragmentation

Warning: Hadrons are colour singlets, quarks and gluons are colour triplets/octets $\Rightarrow$ quark/gluon "reconstruction" can never be exact

General jet algorithm:

- Define distance measure d_{ij} for pair of particles
- Define combination algorithm

Jet algorithm

- Calculate d_{ij} for all pairs and find $d_{ij,min}$
- If $d_{ij,min} > d_{cut}$ STOP
- Combine particles corresponding to $d_{ij,min}$
- Restart

Distance measure:

- Most obvious choice: invariant mass (JADE algorithm)
  In practice massless approximation $d_{ij} = \frac{E_i E_j}{s}(1 - \cos\theta)$
  - was successfully used for QCD studies
  - algorithm tends to cluster all low energy particles first ➡ not so good for parton reconstruction
- To solve this problem replace mass by relative transverse momentum (k_T, Durham algorithm)
  $d_{ij} = \frac{\min(E_i^2 E_j^2)}{s}(1 - \cos\theta)$
  - equally well behaved for QCD studies
  - prefers to combine low angles ➡ closer to physics of parton showers

Combination procedure

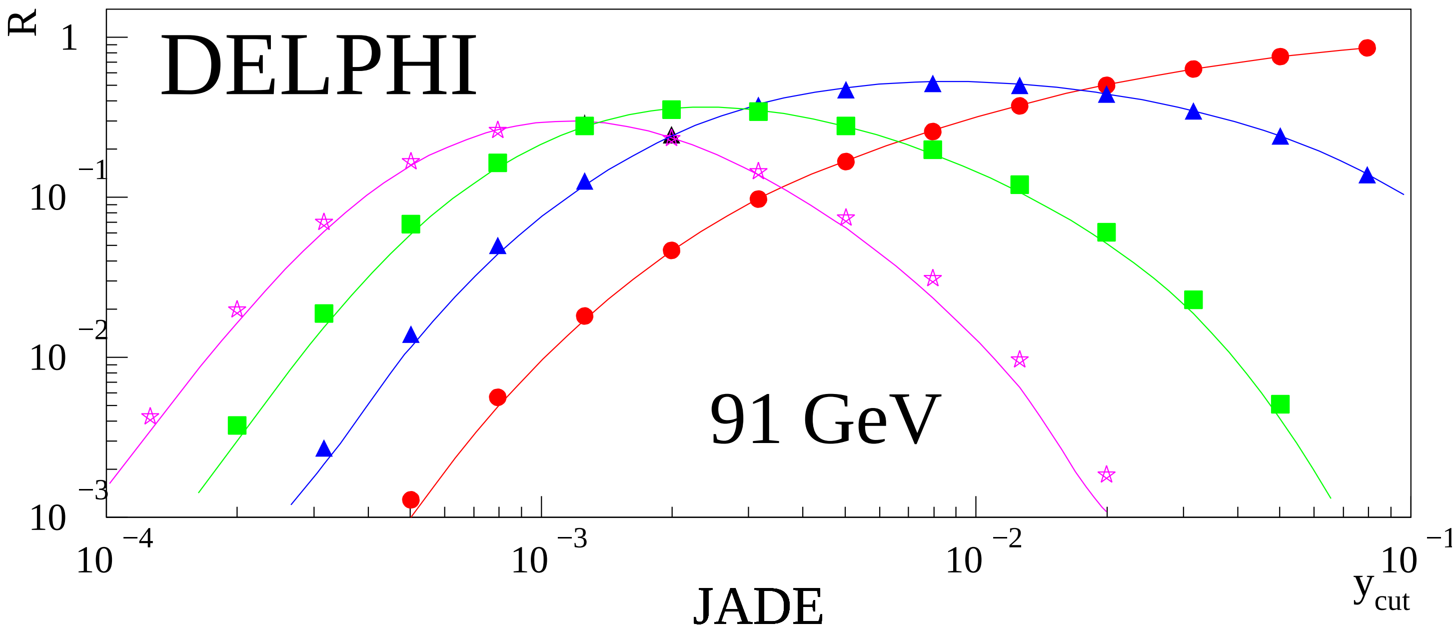
- Most obvious: add 4-momenta $p_n = p_i + p_j$
- Quarks and gluons are massless, two alternatives in use:
  - add 3-momenta and calculate energy assuming $m = 0$
  - add 4-momenta and rescale 3-momentum so that $m = 0$

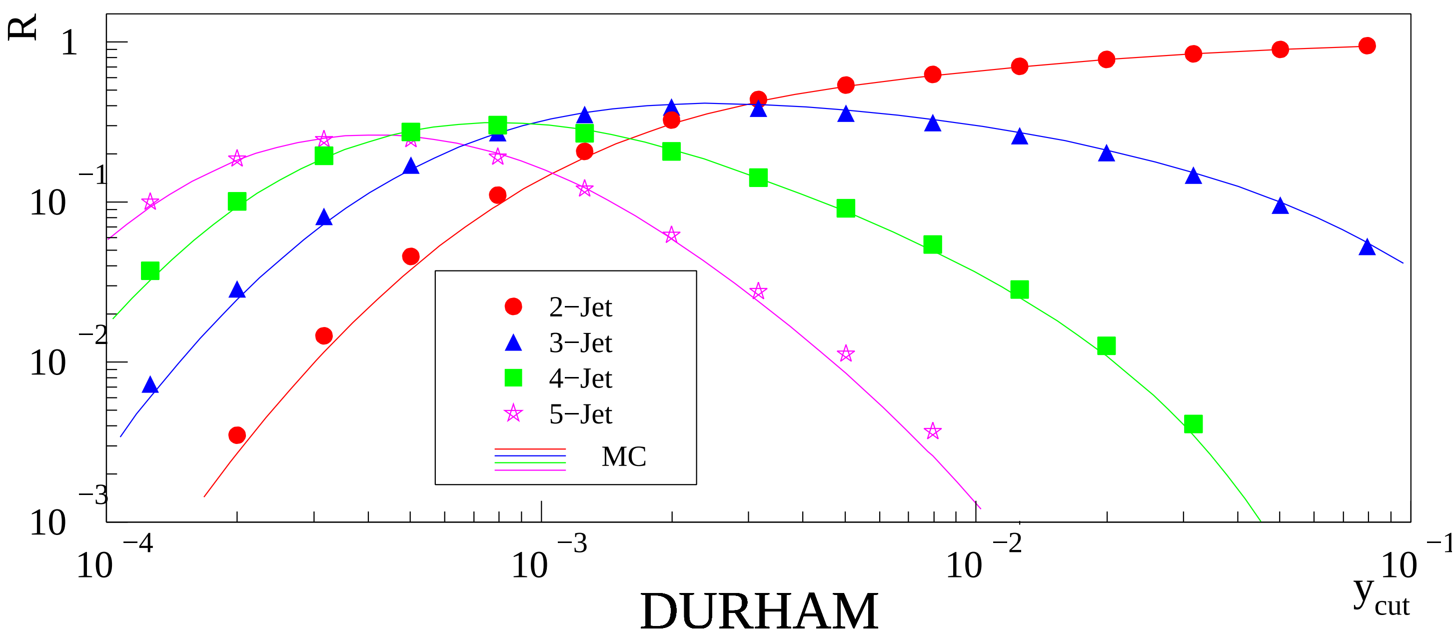
Infrared and collinear safety:

- QCD Feynman graph diverges for $p_g \longrightarrow 0$
  ➠ algorithm must be stable when particle with $p \approx 0$ is added
- QCD Feynman graph diverges for splitting with $\theta \longrightarrow 0$
  ➠ algorithm must be stable when particle is split into two with $\theta \approx 0$

ok for JADE and k_T

Jet rates in e^+e^-





Jets in pp

Differences to e^+e^-

- Protons disappear as colour non-singlets in the beampipe
- Final state is boosted and algorithms not Lorenz invariant
- The underlying event adds activity in the detector
- At high luminosity there are additional minimum bias events that cannot be separated

Must adapt k_T algorithm

New algorithms in pp ($p\bar{p}$): cone algorithms

Adaptation of k_T algorithm

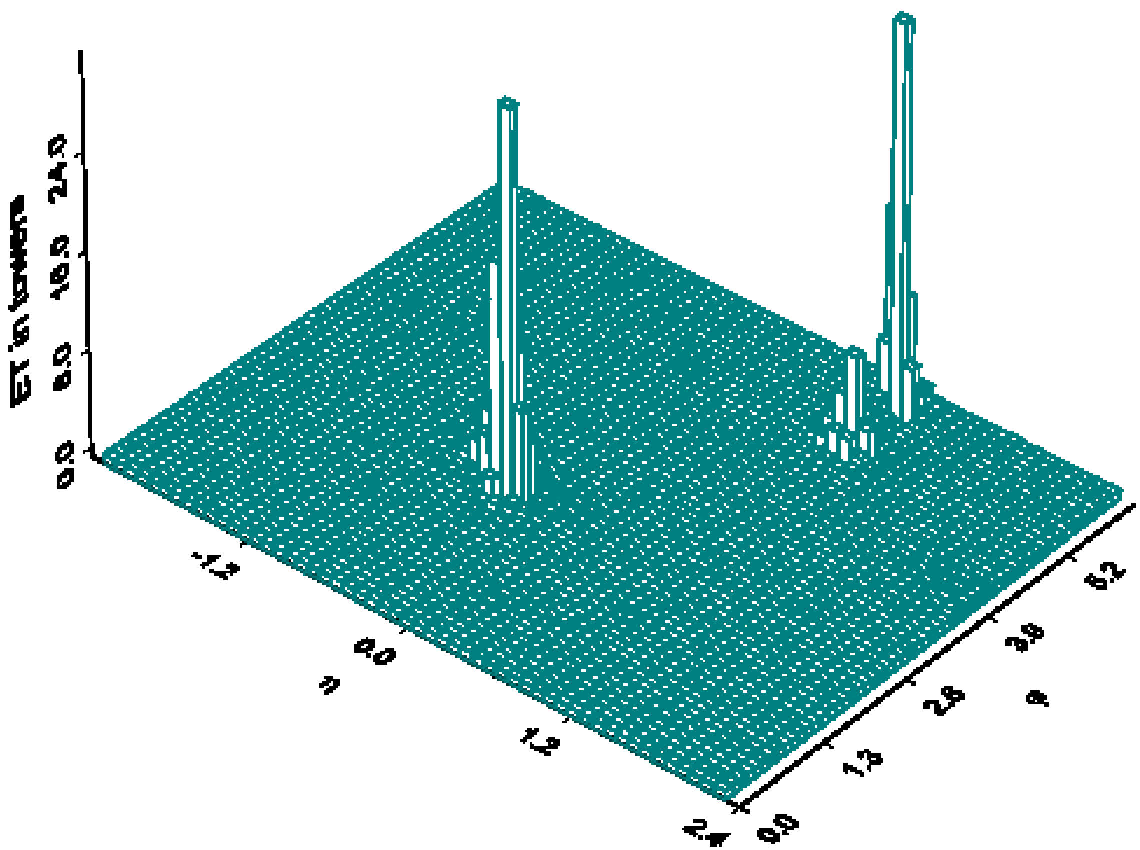
- Replace $1 - \cos\theta_{ij}$ by $\Delta R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$
- Distance $d_{ij} = \min(p_{t,i}^2, p_{t,j}^2)\frac{\Delta R_{ij}}{D^2}$ (D adjustable parameter)
- Add to pairs also single particles $d_i = p_{t,i}^2$
- If minimum is a particle: Define as jet and remove from list
- If minimum is a pair combine and start again
- Stop if nothing left

Features of the k_T algorithm

- Every hadron is uniquely assigned to a jet
- Every hadron is assigned to a jet
  - few hadrons that belong to a given parton are missing
  - significant noise from underlying event and minimum bias
- Jets have complicated shapes

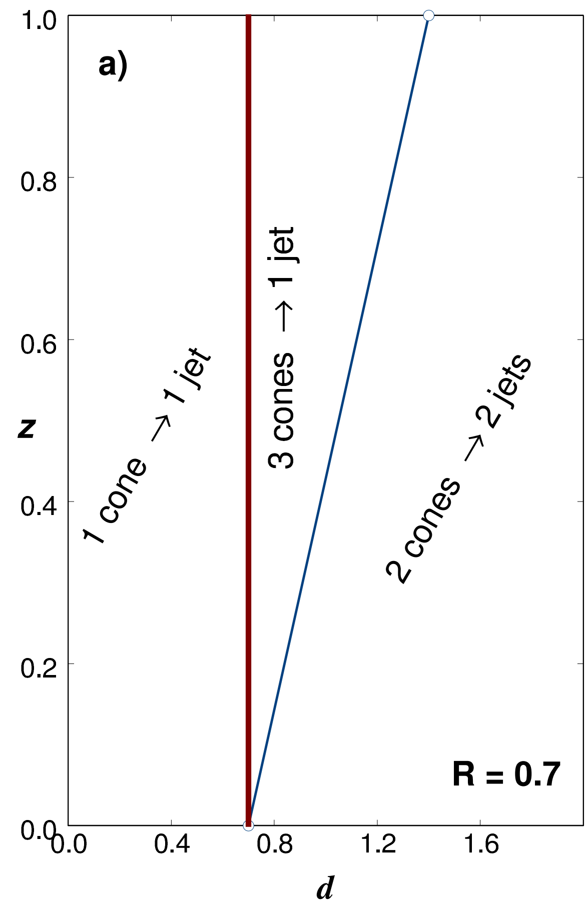
Cone algorithms

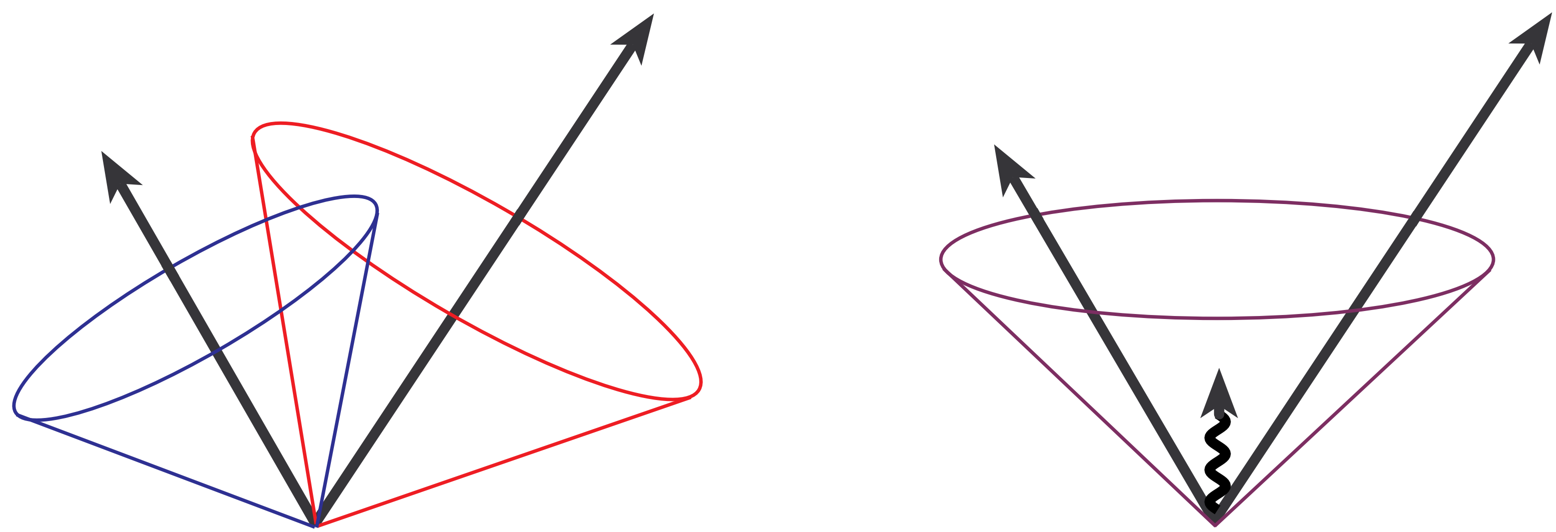
- Naively imagine a jet as a energy flow within a cone in (y, ϕ) space
- Consequently 1st $p\bar{p}$ jet algorithms add energy within a cone
- Iterative procedure
  - Start with a cone containing some energy and opening angle R
  - Calculate the cone centre e.g. by adding 4-momenta
  - Recalculate energy in cone
  - Iterate until a stable cone is reached.



Stability problems

- Solution is not unique
- Usually seeds are used in experiment ➡ infrared unsafe (partially solved by artificial seed between two real ones (midpoint algorithm))
- Large fragmentation corrections in cases where two jets are merged into one
- Jets may overlap and splitting procedure is needed





- A new cone algorithm exists that is equivalent to a seedless one solving the theoretical problems (SISCone)
- Anyway it turns out that the theoretical uncertainties are only on the 10% level

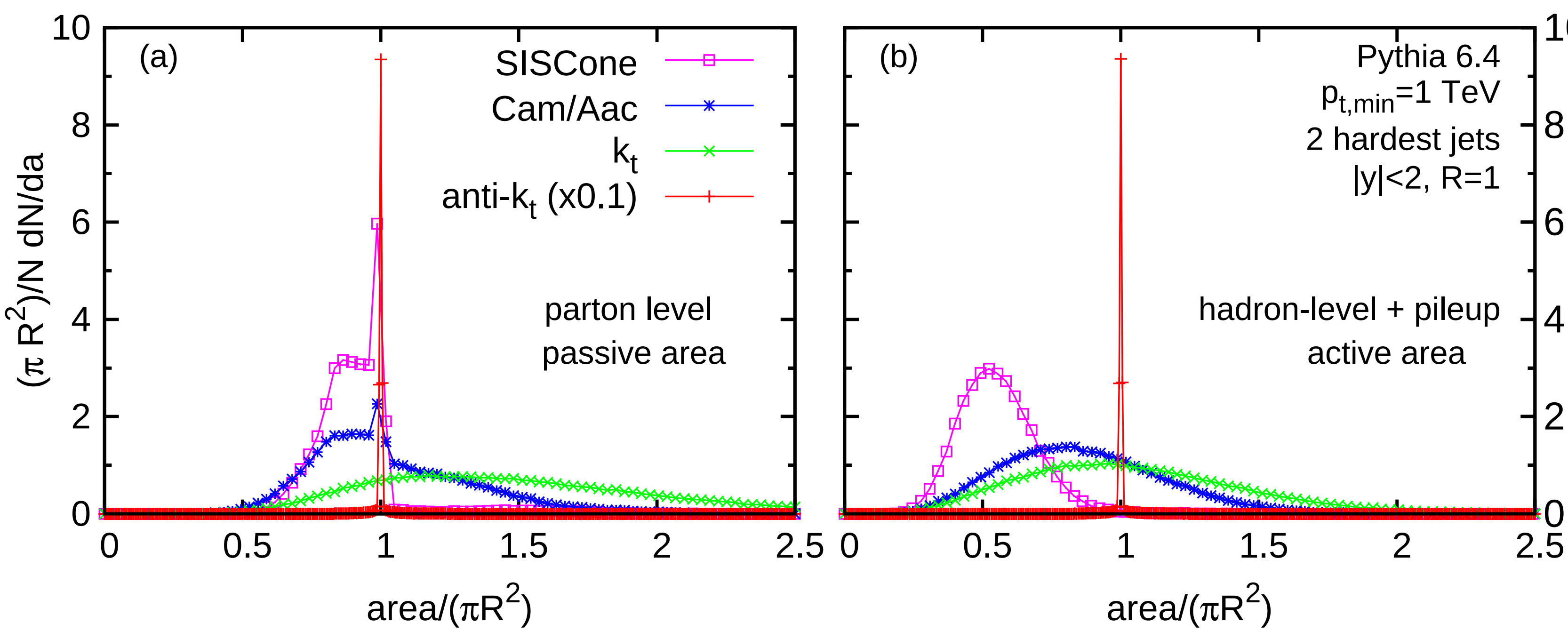
Features of cone algorithms

- Low energy hadrons are not all included in jets
  - energy missing for event reconstruction
  - lot of underlying event/pileup rejected
- Jet shapes are usually round ➡ makes underlying event, pileup, noise corrections easier

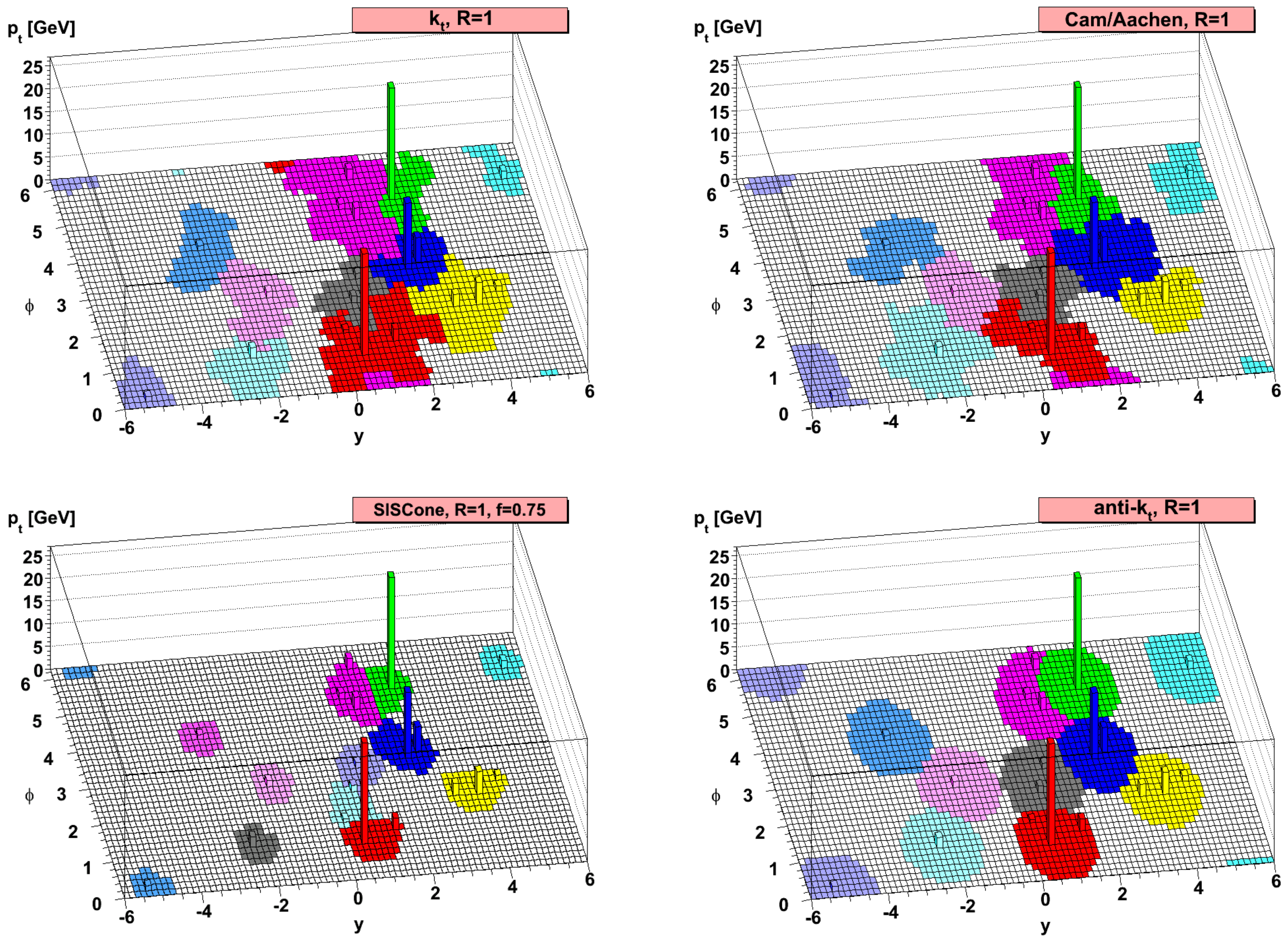
New idea: anti k_T algorithm

Define new distance measure: $d_{ij} = \min(p_{t,i}^{-2}, p_{t,j}^{-2}) \frac{\Delta R_{ij}}{D^2}$

- First cluster high energy with high energy and high energy with low energy particles
- This keeps jets round, with well defines area
- Algorithm still infrared and collinear safe!

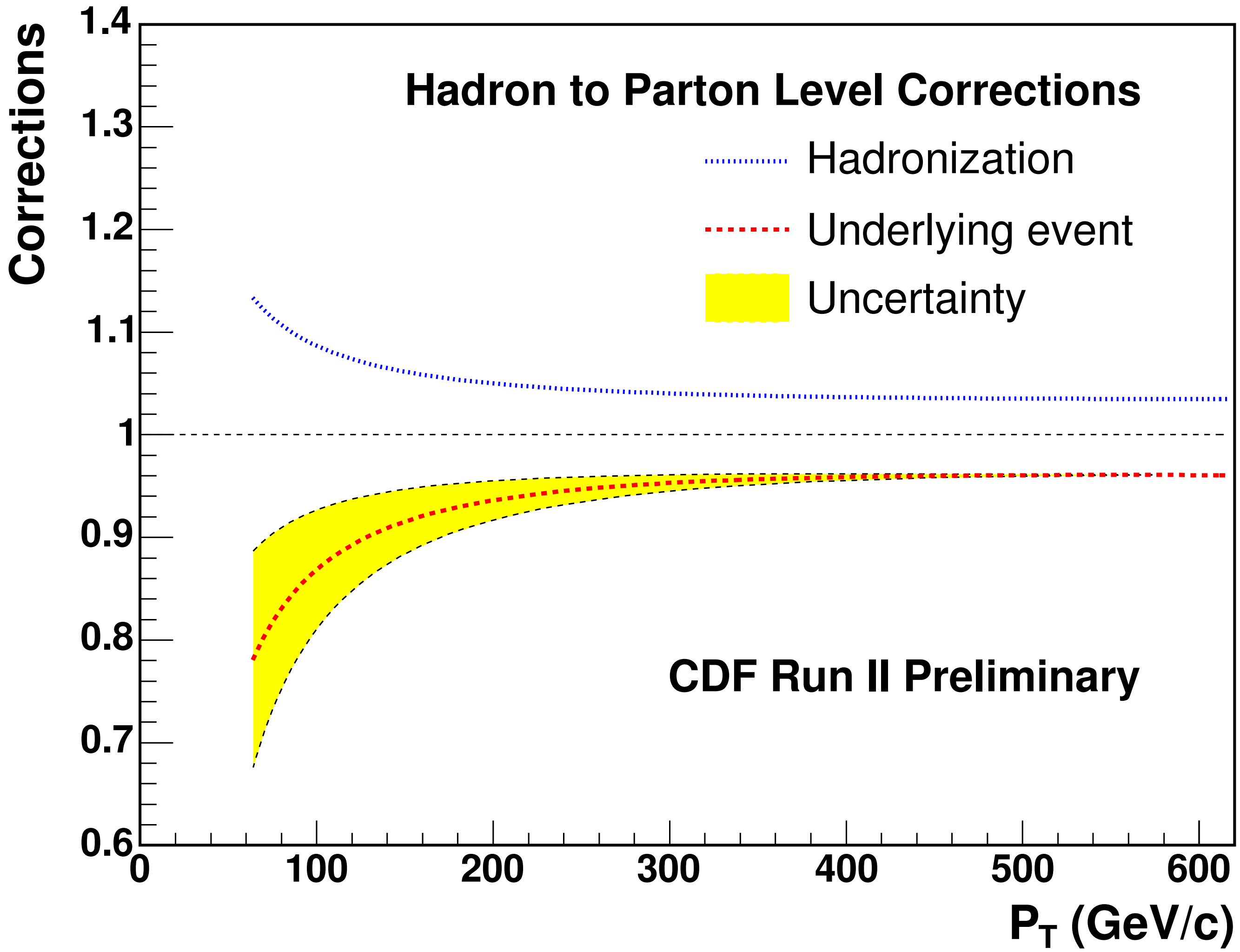


Typical shapes for IR and collinear safe algorithms

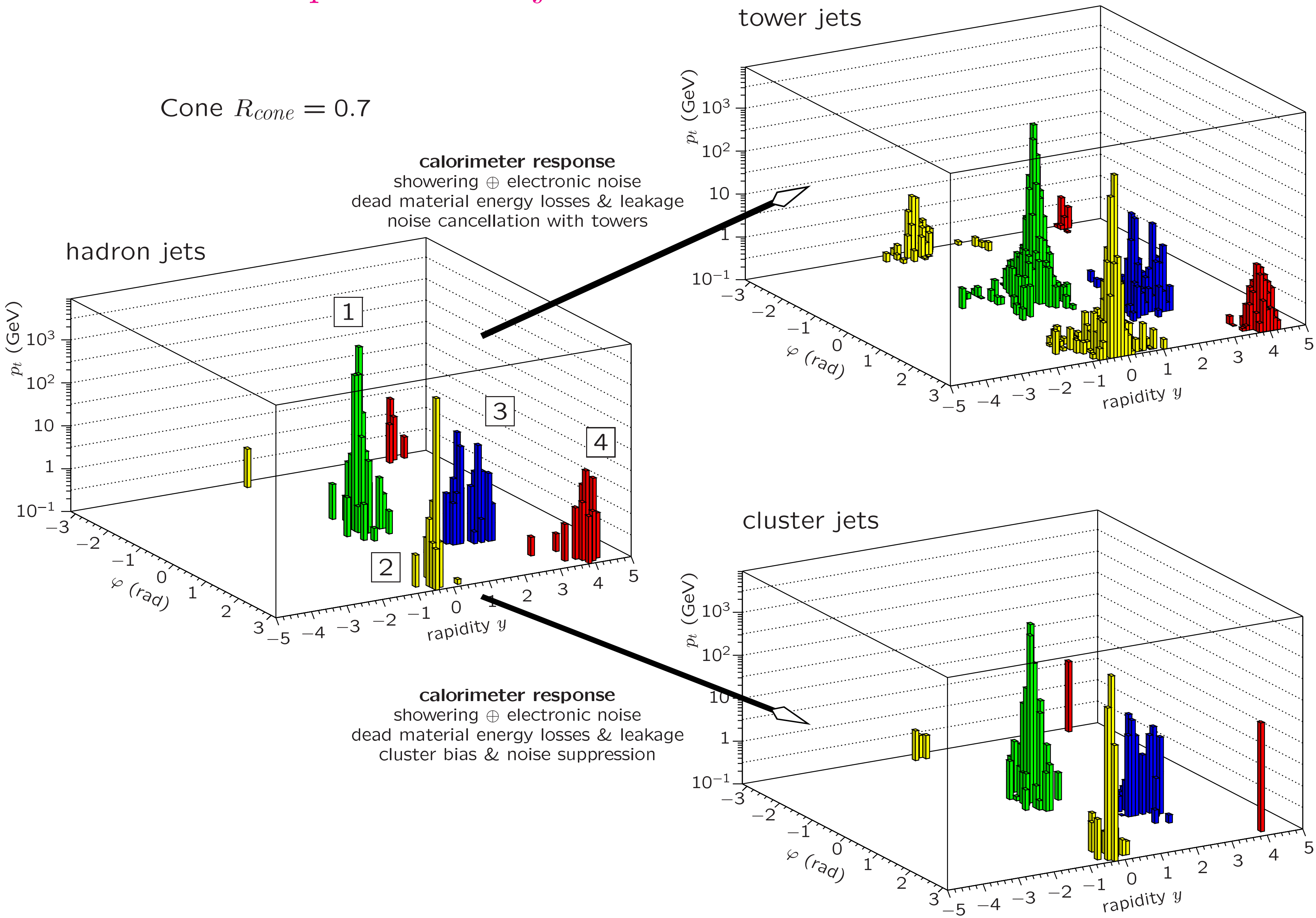


Experimental issues

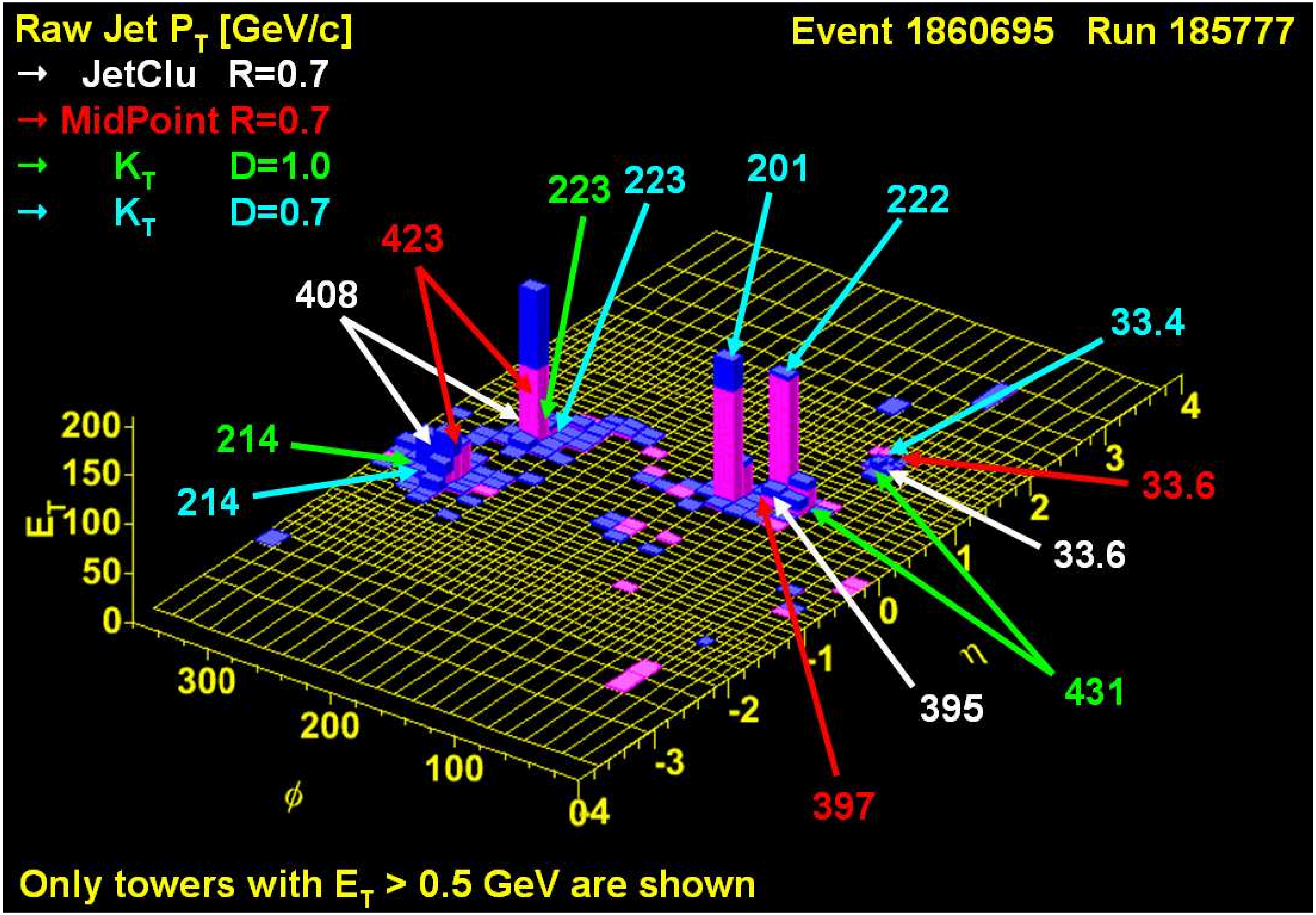
- Some part of the jet is outside the cone ➟ needs corrections
- Energy from the underlying event or pileup gets into the cone
- Treatment of noise in the calorimeter cells affects reconstructed jets



Dependence of jets on calorimeter treatment



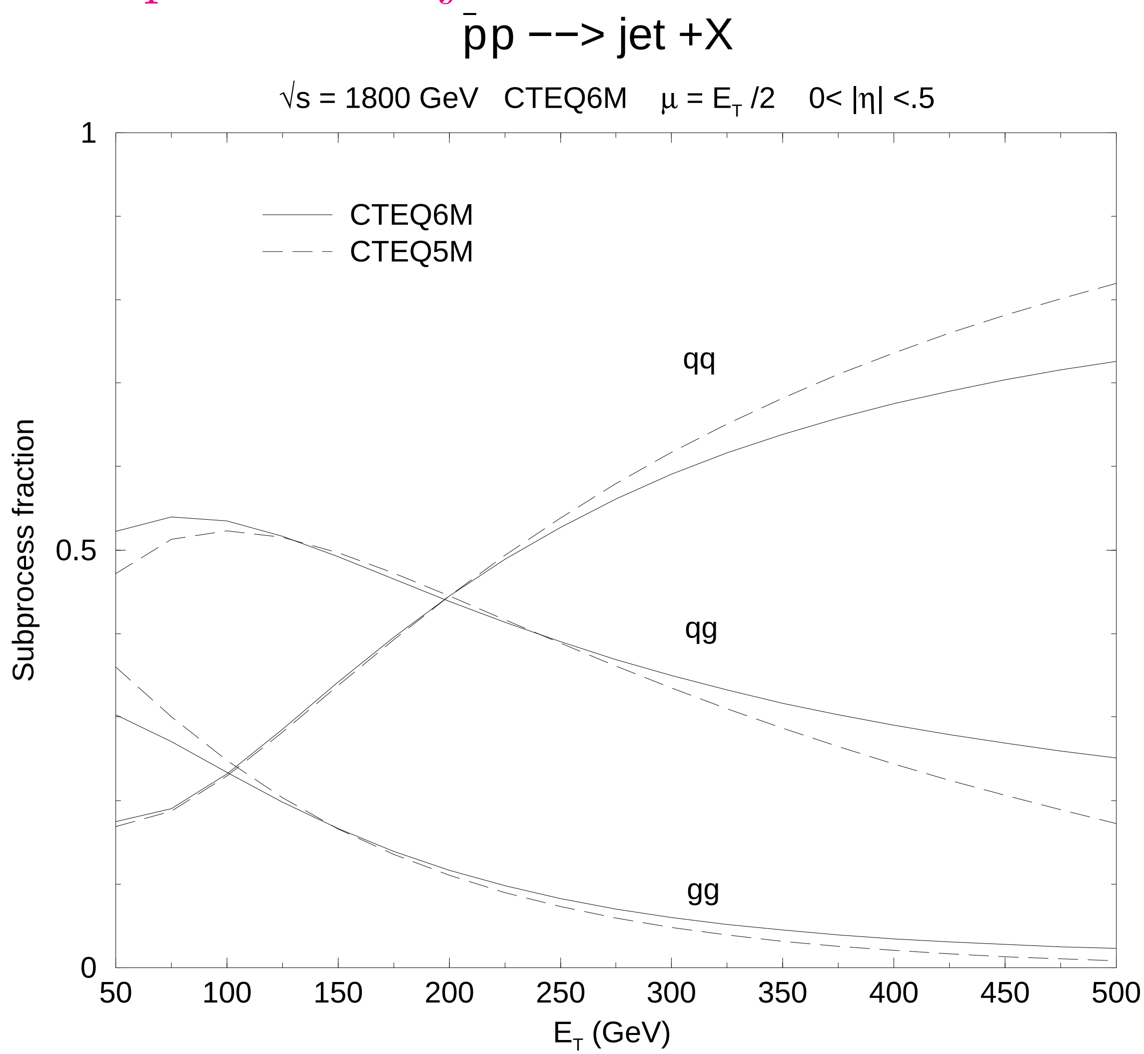
Results of different jet algorithms for one CDF event



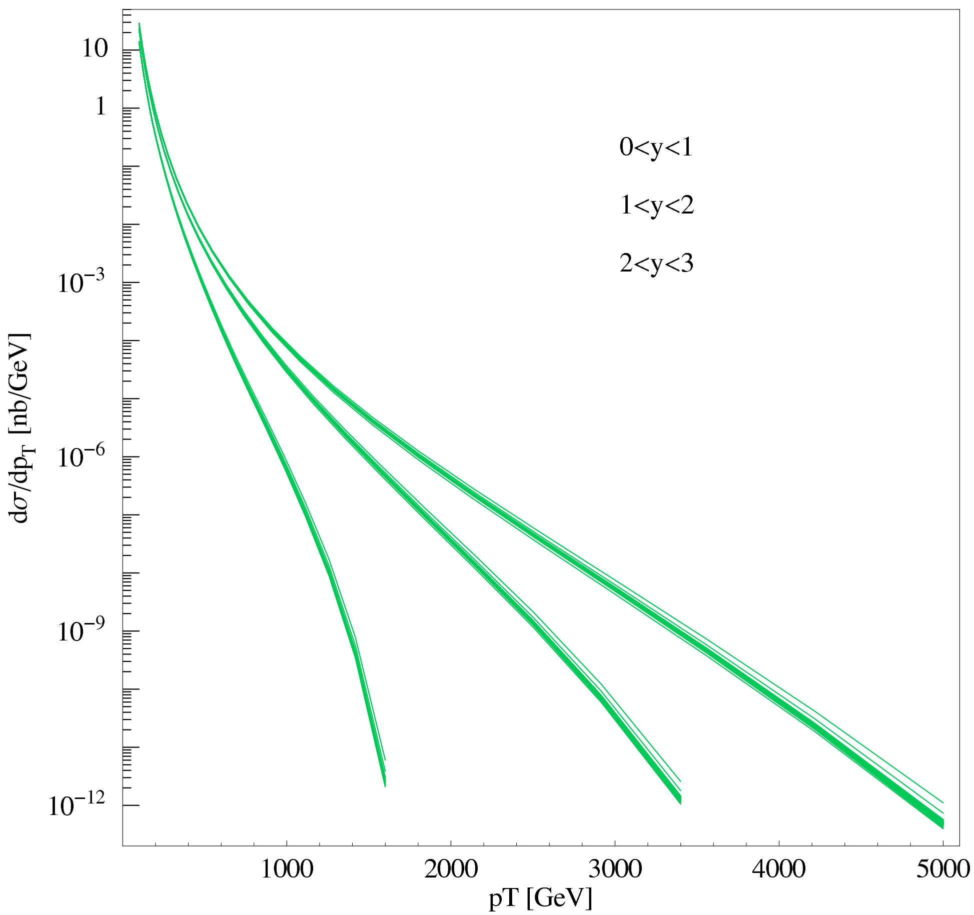
QCD predictions for jet-rates

- Jet-events originate from gg, qg, qq scattering
- They can be calculated in QCD integrating over the PDFs
- At medium energies qg dominates, at high energies qq is dominant

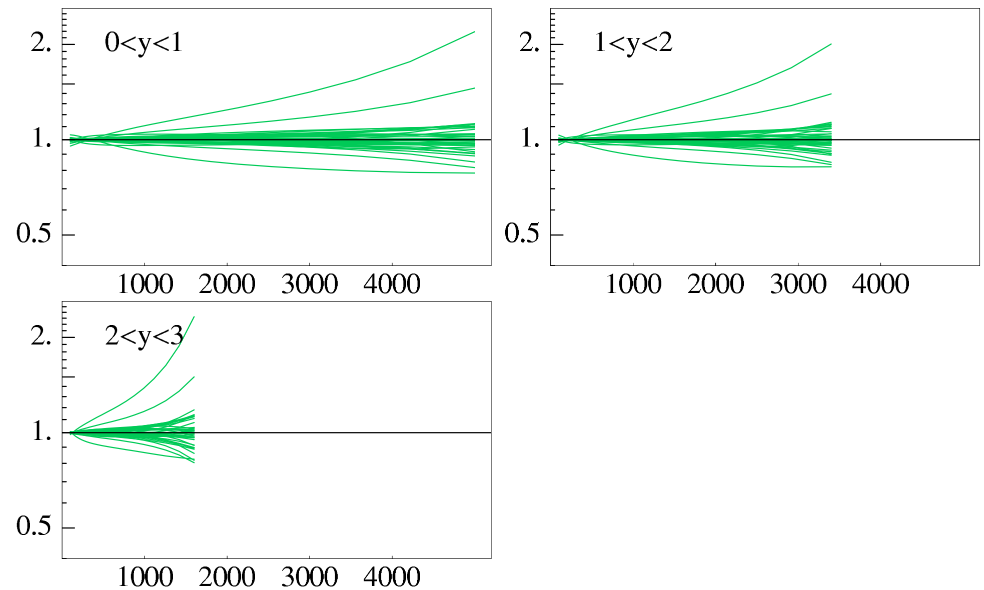
Composition of jet events at the Tevatron



Jet cross sections at the LHC



Uncertainties due to PDFs are of the order 20-30%

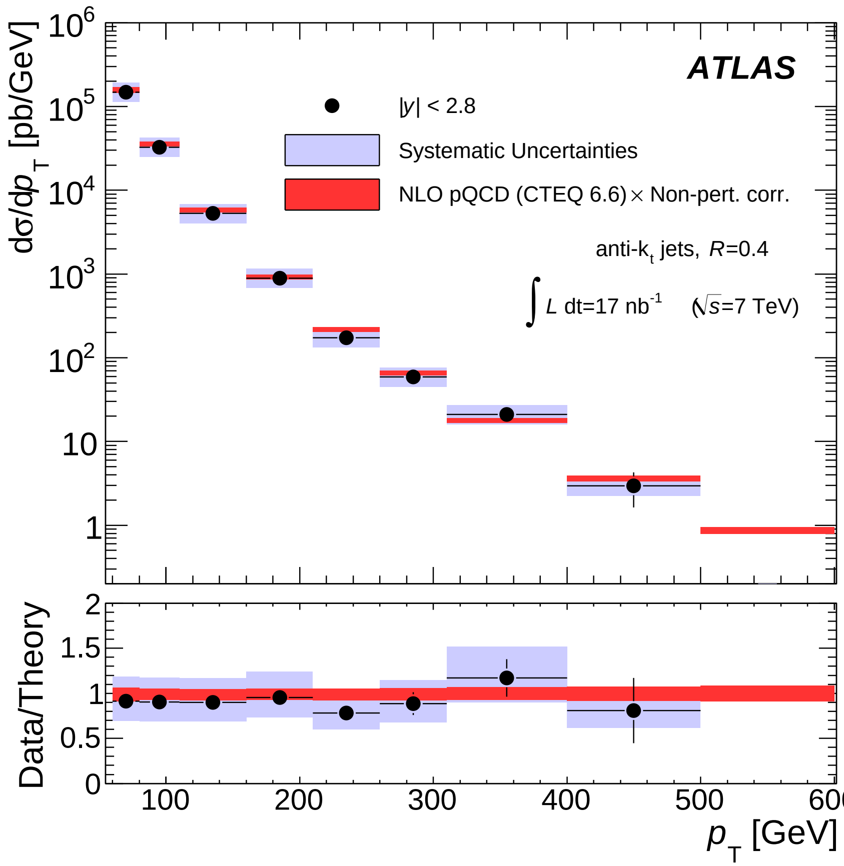


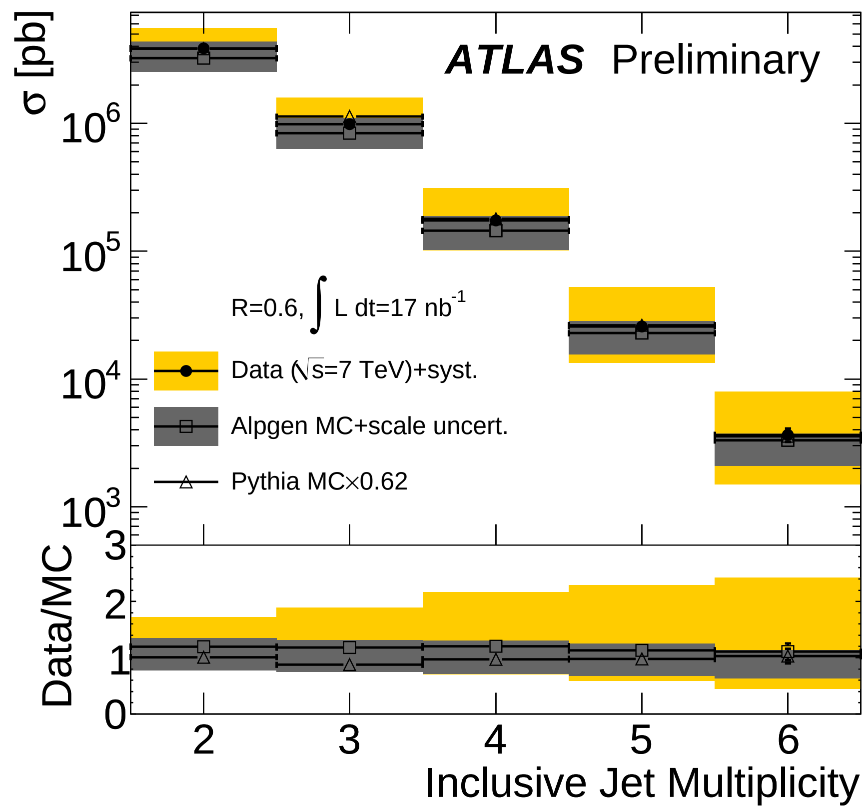
Rates at $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- 1000 ev./s for $p_T > 100\,\mathrm{GeV}$
- 1 ev./s for $p_T > 1\,\mathrm{TeV}$

Measurements from the LHC

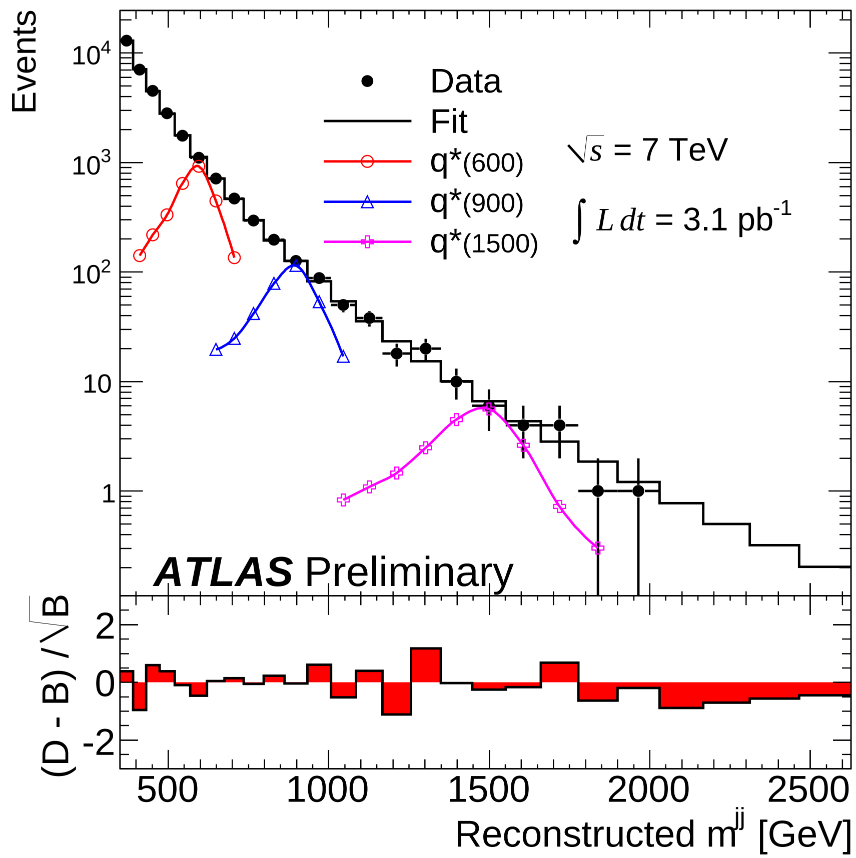
The inclusive jet rate for $p_T < 500\,\text{GeV}$ and the jet-multiplicity with relatively soft cuts have been measured with 0.1% of the present multiplicity

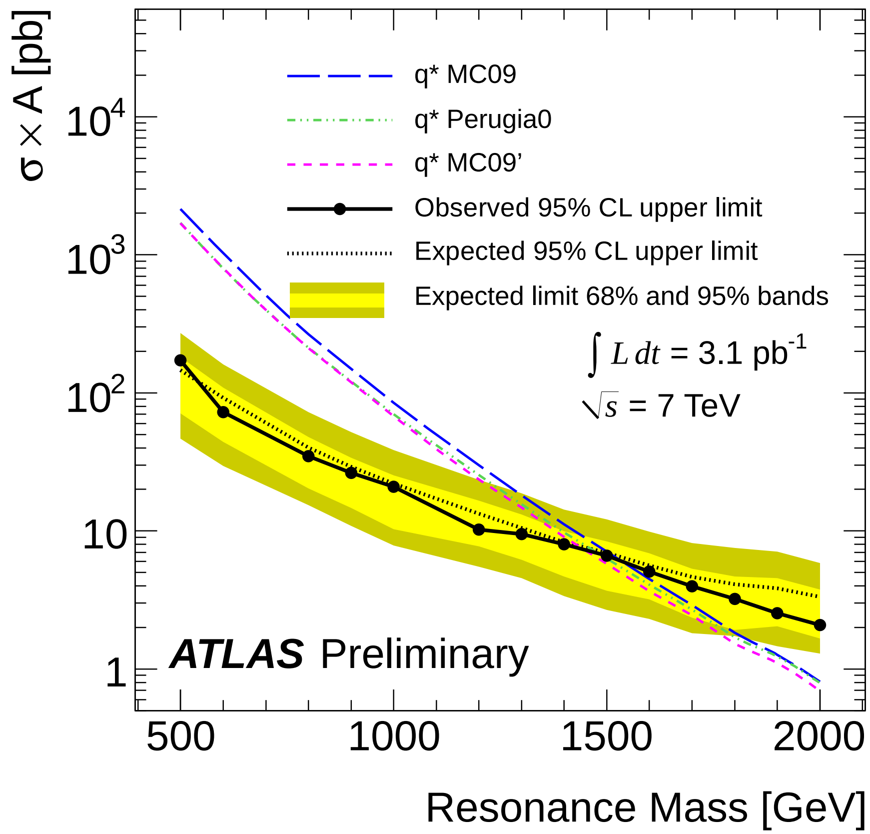




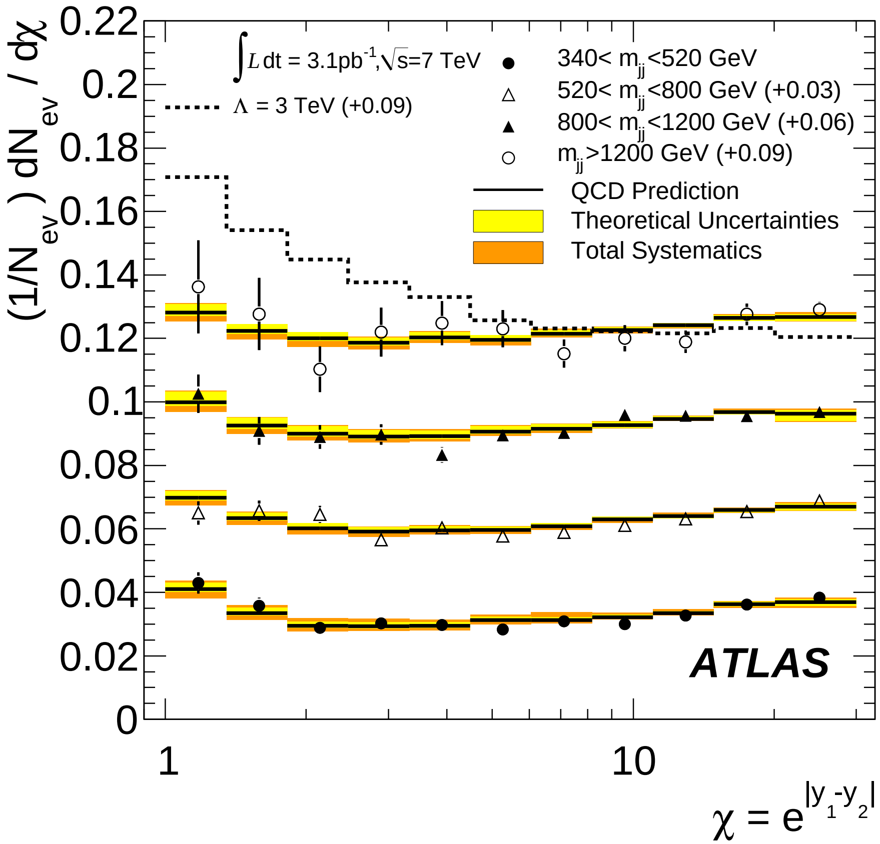
The jet-observables allow already to set limits beyond the Tevatron!

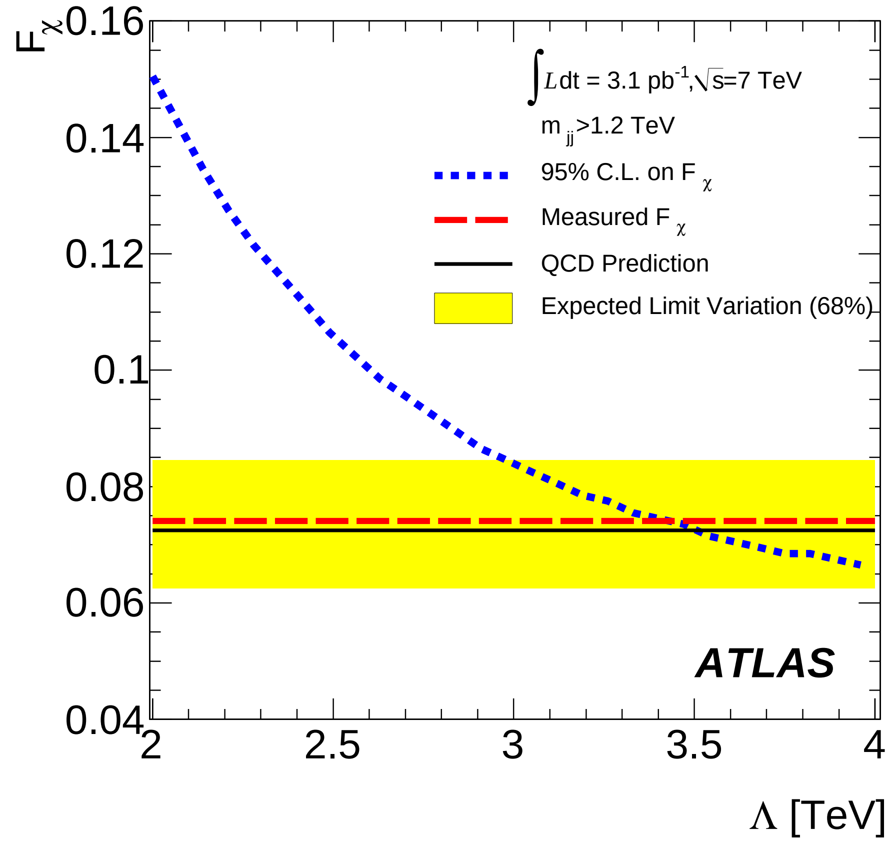
E.g. Mass of excited quarks $> 1.5\,$TeV from the jet-jet mass





and a contact interaction limit of 3.5 TeV from the angular distribution at high jet mass





Conclusions of 2nd lecture

- Minimum bias events have been studied and the non-diffractive part seems understood
- Quarks and gluons always end up in jets
- Most interesting physics at the LHC involves final state quarks (and gluons) ➠ jets
- There is always an arbitrariness in the definition of jets
- With jet-observables the LHC already surpasses the Tevatron