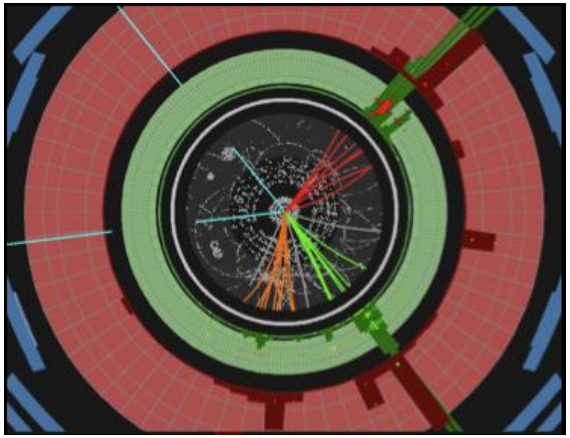
QCD at Colliders

Lecture 2
Jets and parton showers



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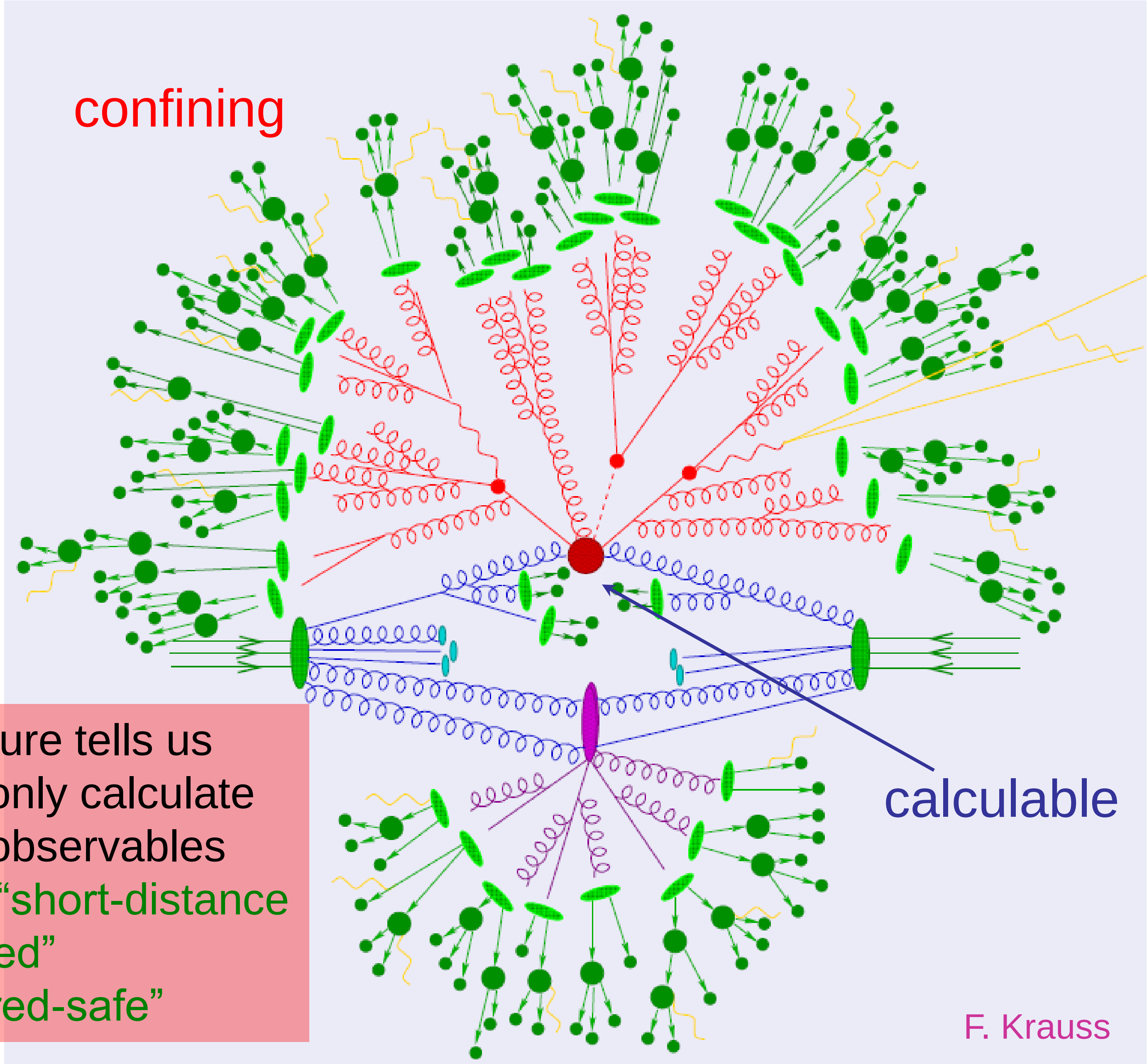
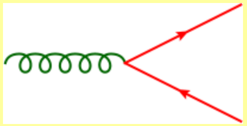


This picture tells us we can only calculate reliably observables that are "short-distance dominated" or "infrared-safe"

Two ways to be IR unsafe

1) Ask a question which is sensitive to collinear splitting, such as "how many quarks are there in the event?"



2) Ask a question which is sensitive to soft gluon radiation, such as "what is the probability of no hadrons in this region of the detector?"

- Of course we could just look at the leptonic decay products of W's, Z's and Higgs bosons, but that would be rather restrictive
- Jets are a way to study hadronic energy flow, in a way that correlates pretty well with "the underlying partons", and yet is infrared safe (for modern jet algorithms).

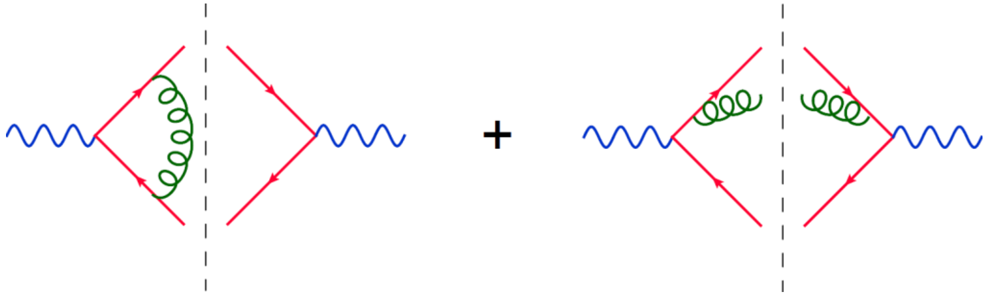
Technical definition of infrared safety

Infrared-safe observables *O* are defined for an arbitrary number of partons (or hadrons) *n*, and satisfy:

$$O_{n+1}(\ldots, k_s, \ldots) \rightarrow O_n(\ldots, \not{k_s}, \ldots) \qquad k_s \rightarrow 0$$

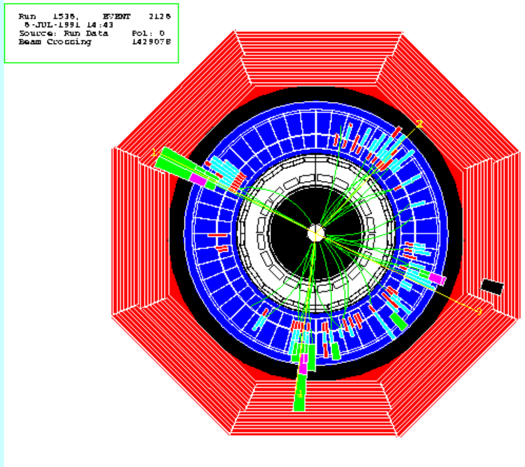
$$O_{n+1}(\ldots, k_a, k_b, \ldots) \rightarrow O_n(\ldots, k_P, \ldots) \qquad k_a \,||\, k_b$$

- Physically, insensitive to soft gluon emission and general collinear splitting.
- In perturbative QCD, virtual corrections with n partons cancel singularities from real emission with n+1 partons.



Jets in e^+e^- annihilation

Given a set of n particles $\{i\}$ (or clusters of energy in a calorimeter) define a "distance" measure d_{ij}, which vanishes when $i \,||\, j$ or i or j becomes soft.

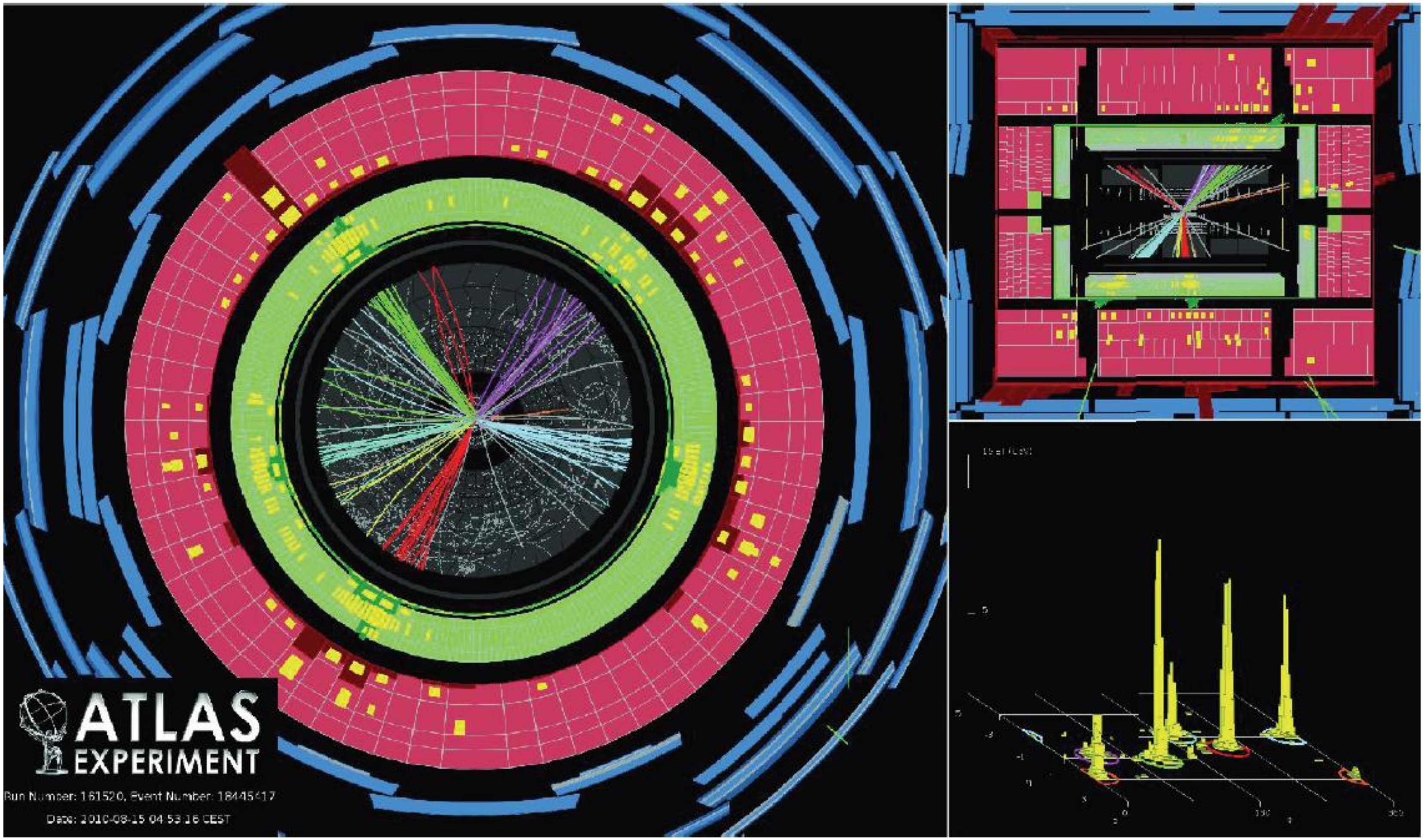


- For example (Durham/k_t algorithm)

$$d_{ij} \equiv y_{ij}^D = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}$$

- Cluster the two "closest" partons into a single proto-jet, assigning momentum by (say) $p_{ij} = p_i + p_j$
- Repeat procedure on the remaining n-1 proto-jets.
- Iterate until all $y_{ij} >> y_{cut}$ (= jet resolution parameter)
- Remaining objects are jets.
- Properties depend on d_{ij}
- Automatically IR safe because starts with most soft/collinear

Jets at hadron colliders



A word about kinematics

- At a hadron collider, we have no idea where the "rest of the proton" went (mostly down the beampipe)
- Since we have no idea about longitudinal momentum conservation, we would like variables that transform simply under

  longitudinal Lorentz boosts:

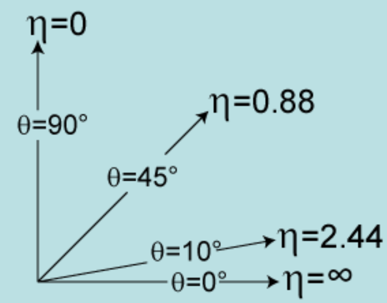
$$\begin{pmatrix} E \\ p_z \end{pmatrix} \to \begin{pmatrix} \gamma & \beta\gamma \\ \beta\gamma & \gamma \end{pmatrix} \begin{pmatrix} E \\ p_z \end{pmatrix} \qquad \Rightarrow \qquad E \pm p_z \to \gamma(1 \pm \beta)(E \pm p_z)$$

- Rapidity $y \equiv \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \qquad y \to y + \frac{1}{2} \ln \left(\frac{1+\beta}{1-\beta} \right)$
- For massless particles, rapidity is equal to

  pseudorapidity:

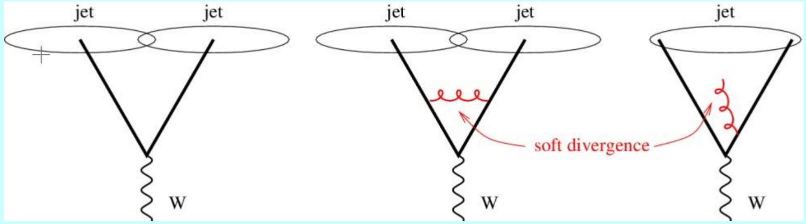
$$\eta \equiv -\ln \tan \left(\frac{\theta}{2} \right) = \frac{1}{2} \ln \left(\frac{1 + \cos\theta}{1 - \cos\theta} \right) = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z} \right)$$

- Detector "coordinates": $(p_{\mathrm{T}}, \eta, \phi)$



Jets at hadron colliders

- Historically, "cone algorithms" were used, rather than e^+e^- style "cluster algorithms".
- However, definitions of "seed" for early cone algorithms (where you start looking for a jet) were not IR safe.



Salam 1011.5131

- First cluster algorithm at hadron colliders was k_t algorithm

(Catani et al., 1992; Ellis, Soper, 1993)

- "distance" measure d_{ij} modified to be invariant under longitudinal boosts:

$$d_{ij} = \min(p_{t,i}^2, p_{t,j}^2) \frac{\Delta R_{ij}^2}{R^2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- Also need to define distance to beam: $d_{iB} = p_{t,i}^2$
- If d_{iB} is smallest, proto-jet is removed and called a jet.
- IR safe, but irregular shaped jets were inconvenient for estimating effects of "underlying event"

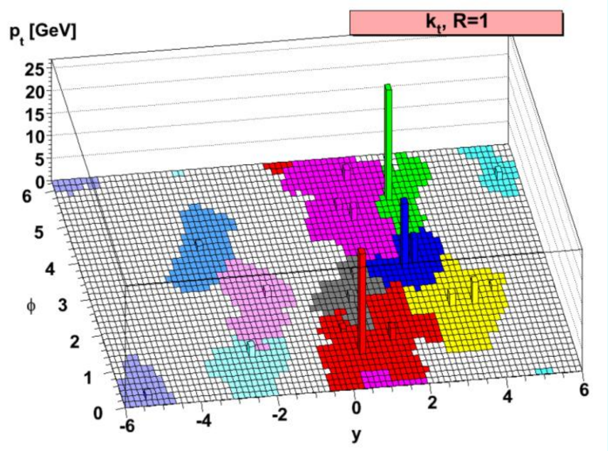
Anti-k_t jet algorithm

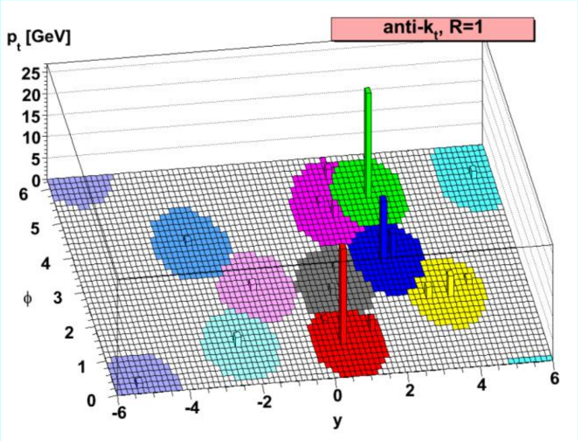
Cacciari, Salam, Soyez, 0802.1189

- Simply invert the p_t factors in k_t algorithm:

$$d_{ij} = \min(p_{t,i}^{-2}, p_{t,j}^{-2}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{t,i}^{-2}$$

- Now the hardest (largest p_t) particles tend to cluster first, soft wide angle ones last. (Still IR safe to add soft last) Now boundary of jet (catchment area for an additional soft particle) is very circular.



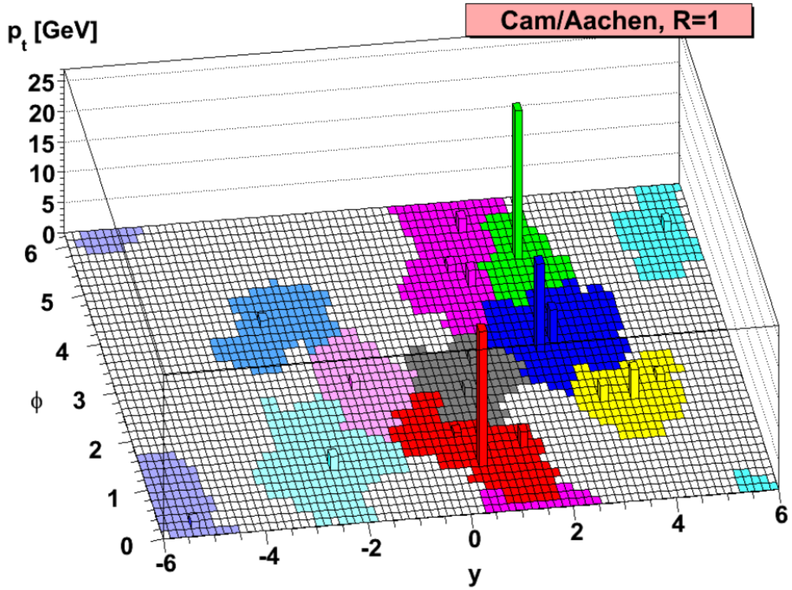


Cacciari, Salam, Soyez, 0802.1188; Salam, 0906.1833

- Anti-k_t is default for both ATLAS ($R = 0.4,0.6$) and CMS ($R = 0.5,0.7$)

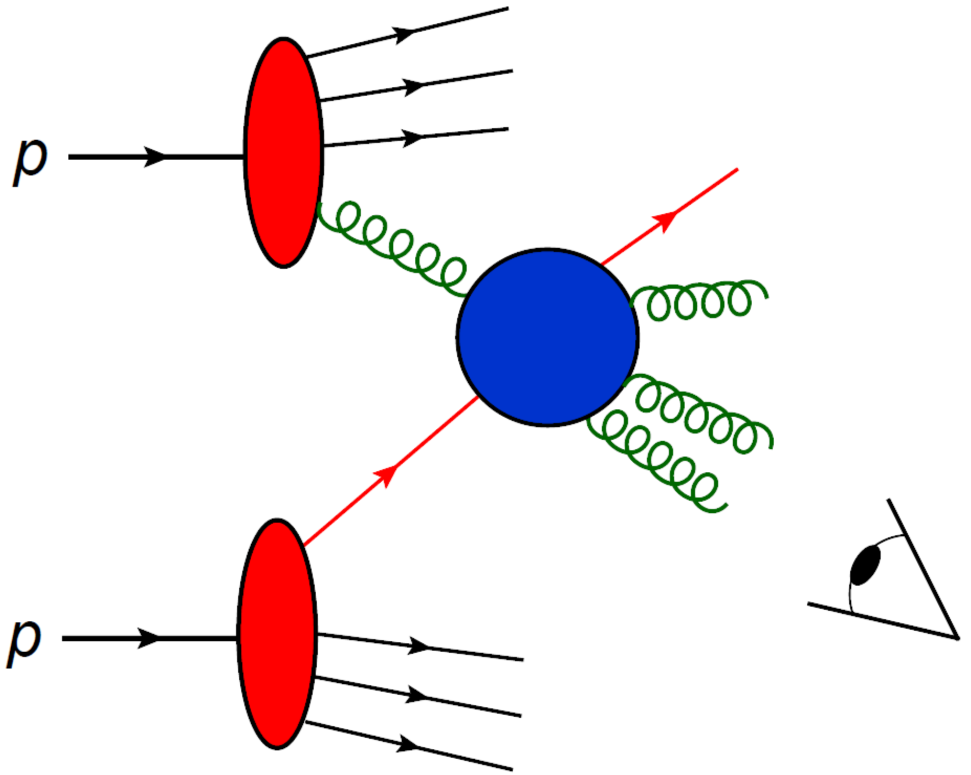
Cambridge/Aachen (C/A) jet algorithm

- Intermediate between k_t and anti-k_t algorithms, clustering depends only on angles: $d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$ $d_{iB} = 1$
- Typically used with a large R, say $R = 1.2$, as the first step in jet substructure studies. (Anti-k_t jets don't work well for this.)



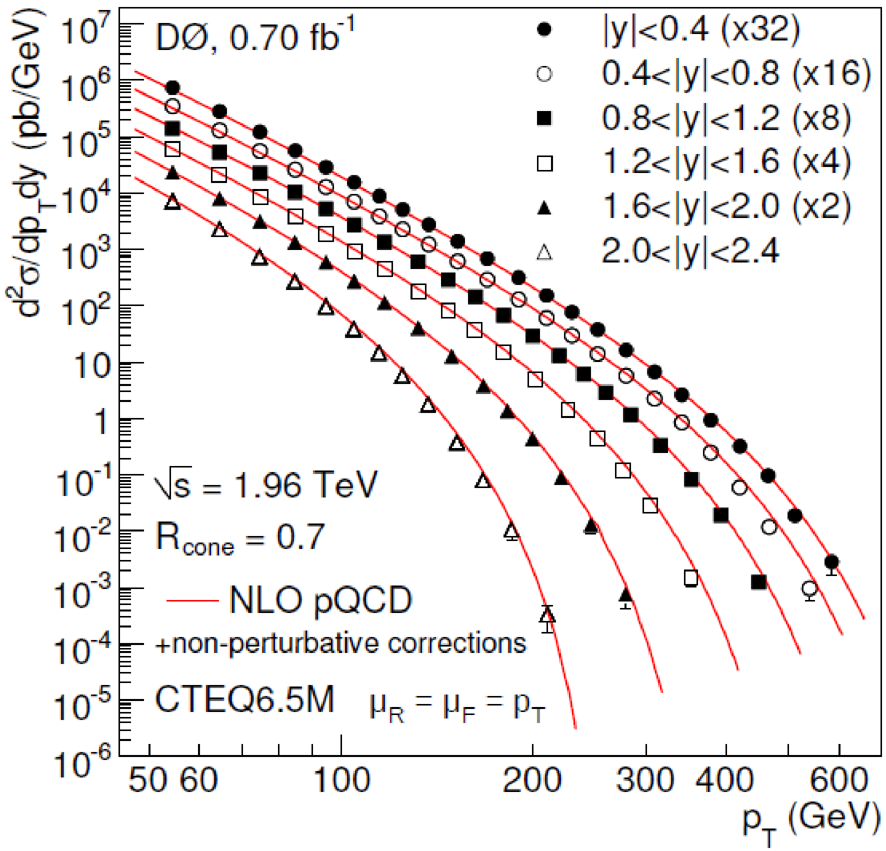
Inclusive Jets

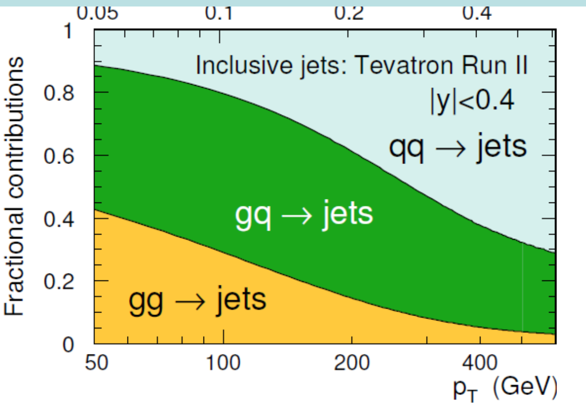
- Just ask for a single jet, in a given range of p_T and η

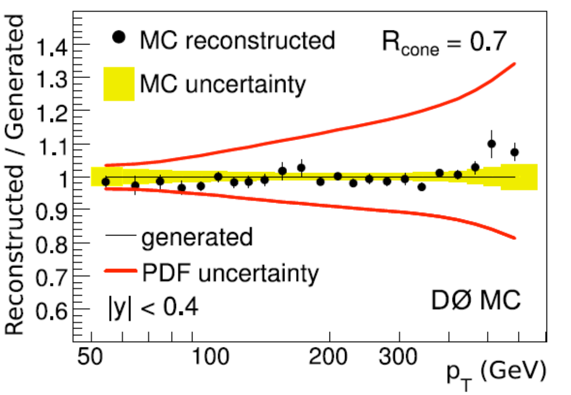


Inclusive jets at Tevatron

- "Midpoint" cone algorithm not IR safe in general but OK here (through NLO).
- Note sensitivity to pdfs, especially large *x* gluon, which is poorly constrained.



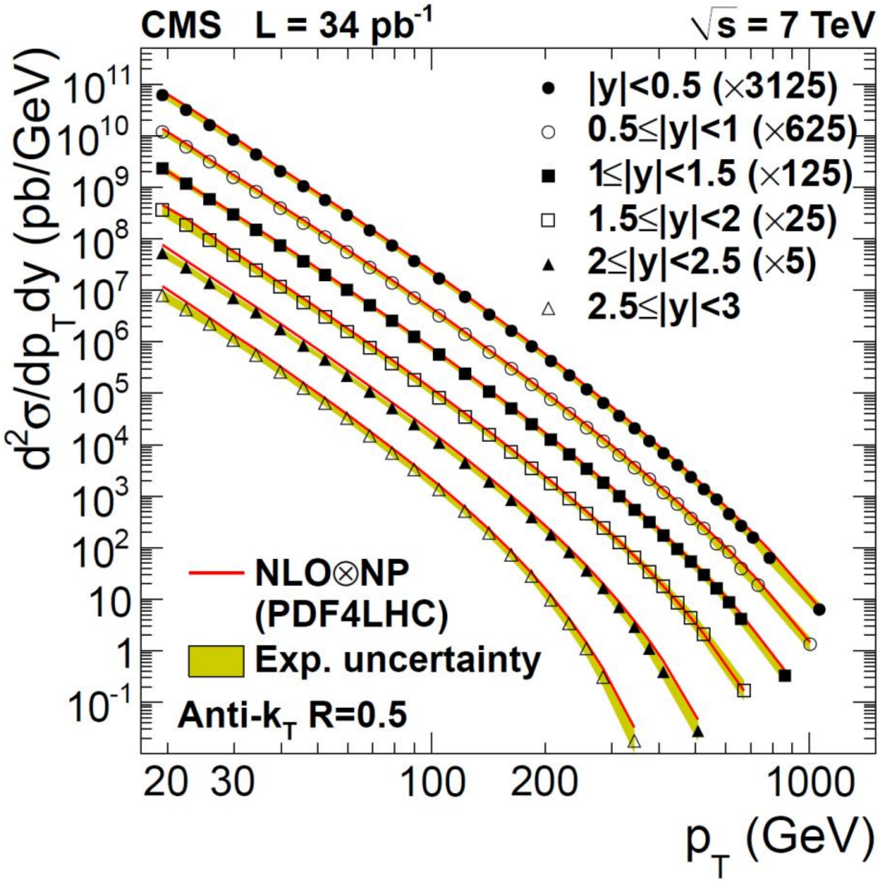


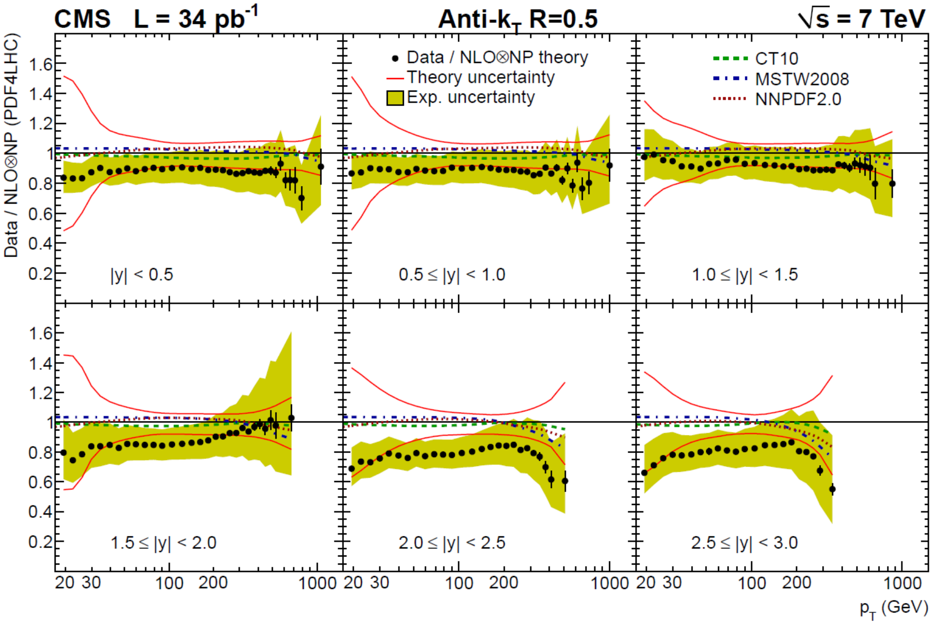


D0, 1110.3771

Inclusive jets at LHC

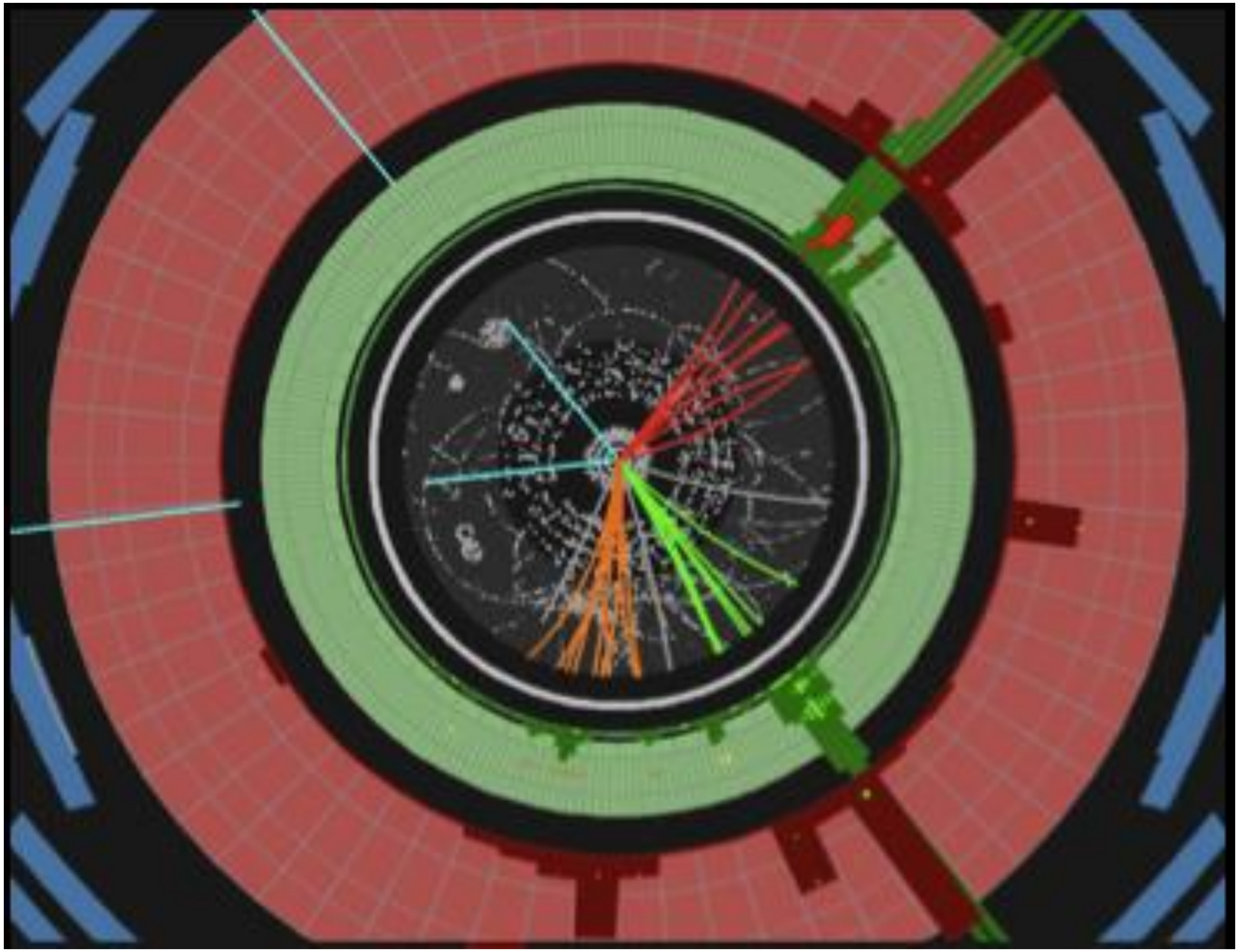
- IR safe anti-k_t jet algorithm, better coverage at forward rapidities (where NLO theory is not working quite as well)





CMS, 1106.0208

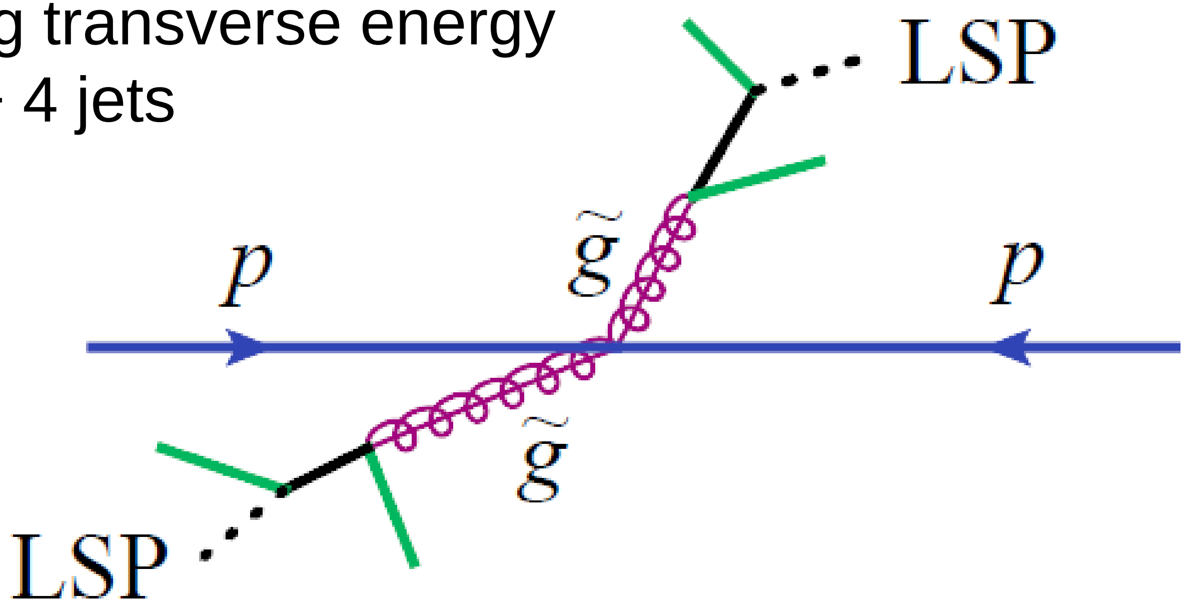
More complicated final states



Classic SUSY dark matter signature
→ Multiple jets + missing energy (+ lepton(s)?)

In models such as supersymmetry, heavy produced particles (colored) decay rapidly to stable Weakly Interacting Massive Particle (WIMP) plus jets

→ Missing transverse energy
MET + 4 jets



Happens in Standard Model too

- **MET + 4 jets from**

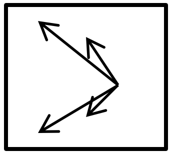
pp → *Z* + 4 jets,

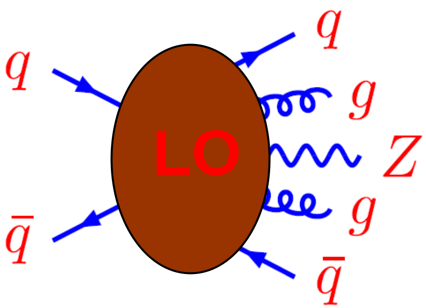
Z → $\nu\nu$

Neutrinos also weakly interacting, escape detector.
Irreducible background.
Also a large background from
pp → *W* + 4 jets,

W → $l\nu$

(~ 10x *Z* → $\nu\nu$ rate)
if you lose the charged lepton
(or if you want a lepton)

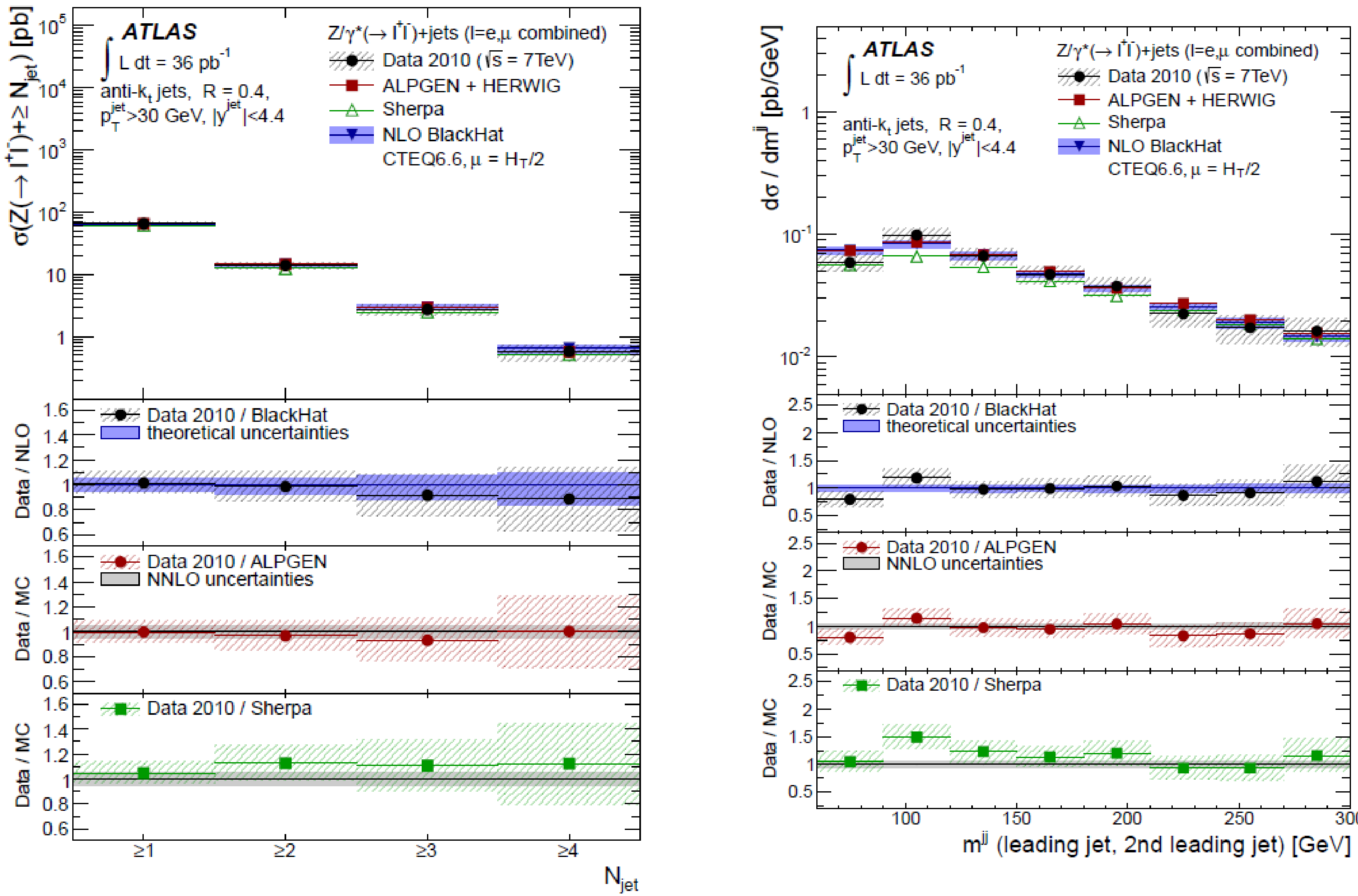




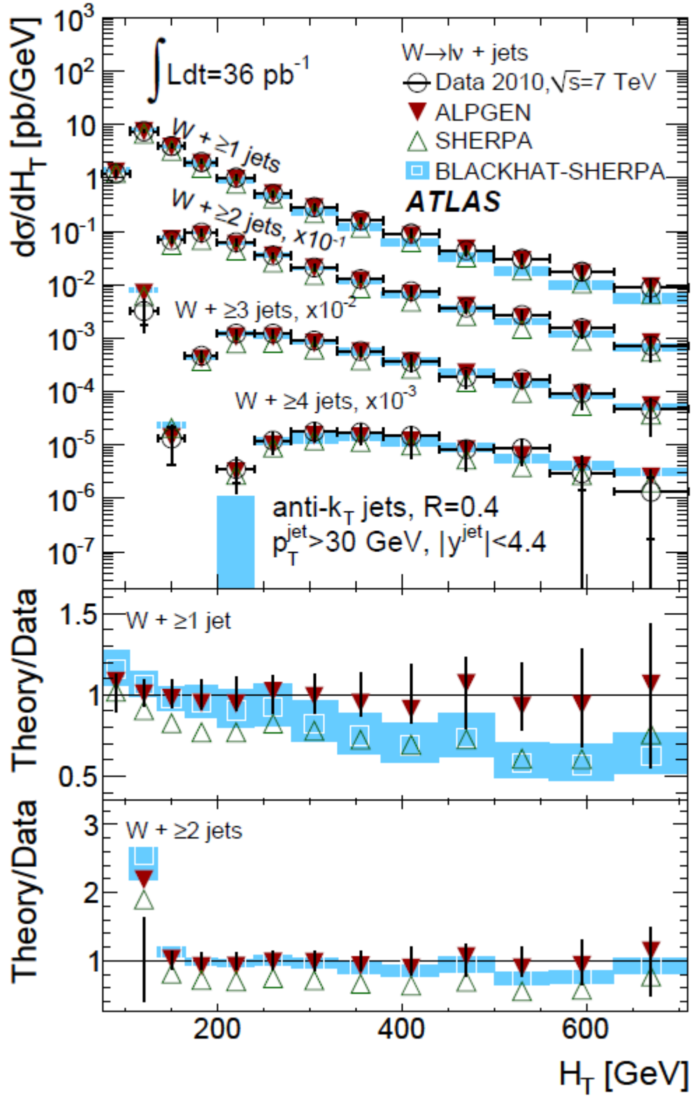
→ ν ν

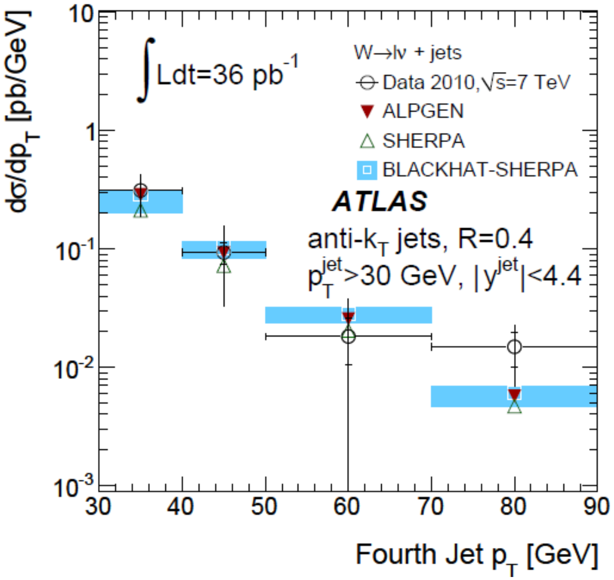
Motivates study of *V* + n jets at Tevatron and LHC

NLO $pp \rightarrow Z + 1,2,3,4$ jets vs. ATLAS 2010 data



NLO $pp \rightarrow W + 1,2,3,4$ jets vs. ATLAS 2010 data



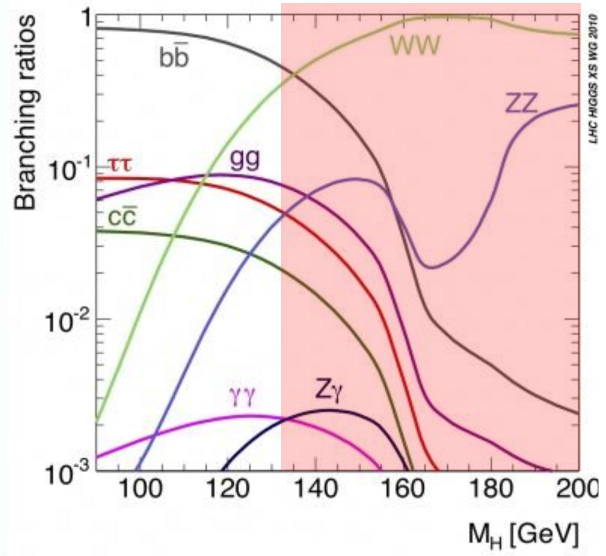


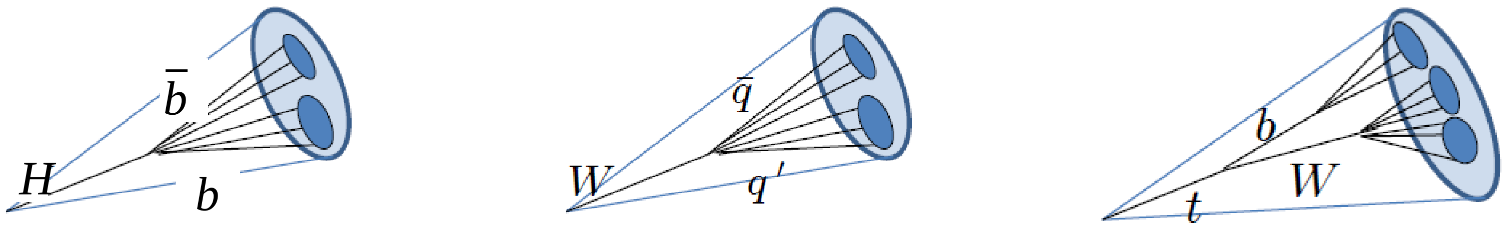
NLO undershoots badly for W + 1 jet – production dominated by W + 2 parton configurations. Theory can be improved here: Rubin, Salam, Sapeta 1006.2144

$$H_T = p_T^l + p_T^\nu + \sum_j p_T^j$$

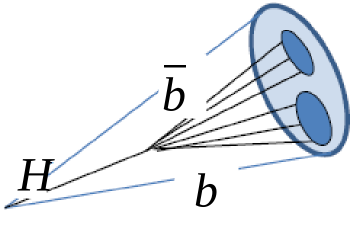
Boosted jets & jet substructure

- Decays of heavy particles can produce multiple jets:
- A light SM Higgs boson → *bb* *most of the time*
- Top quark → *Wb* → $q\bar{q}b$ *most of the time*
- How to find if parent particle is boosted, so jets merge?
- How to distinguish from jets from direct QCD production?





pp → WH → $l\nu b\bar{b}$

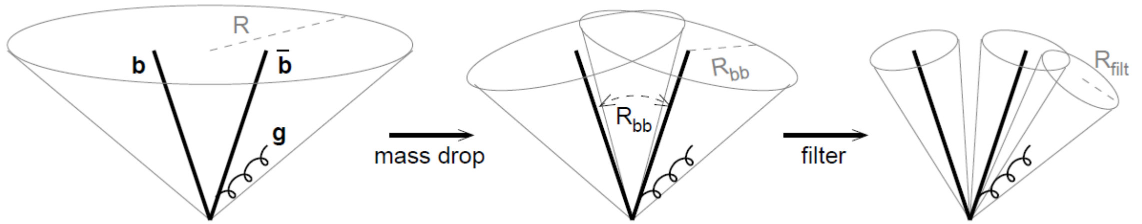


Butterworth, Davison, Rubin, Salam, 0802.2470

- For WH near production threshold, backgrounds from top ($t\,\bar{t}$ → $l\nu b\bar{b}jj$) made search for H → $b\bar{b}$ at LHC look very difficult.
- Background suppressed well above threshold, p_T^H ~ 200-300 GeV, because the b quarks are boosted, moving in same direction.
- Start with C/A $R = 1.2$ "fat jet". Break jet j into 2 subjets, j_1 and j_2 , by undoing last C/A clustering. Look for a large "mass drop",

$$\mu m_j > m_{j1} > m_{j2}$$

  and a splitting that is "not too asymmetric" (to suppress QCD soft radiation)
- Another "filtering" stage looks for 3 hardest subjets on a finer angular scale, to keep perturbative QCD radiation while suppressing the underlying event.



pp → WH → $l \nu b\bar{b}$, and more

Butterworth, Davison, Rubin, Salam, 0802.2470

- Result is a greatly boosted S/√B
- Also heavy H → WW → $l \nu jj$

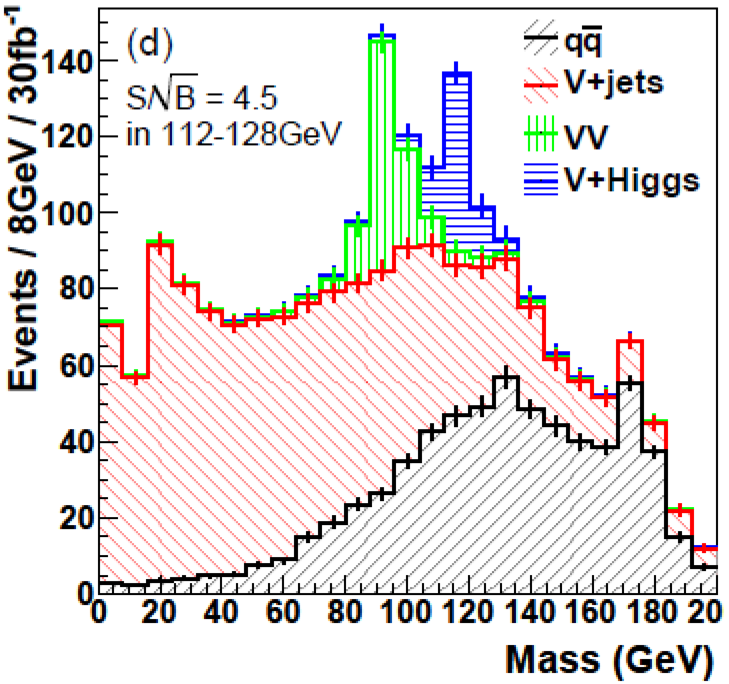
Seymour (1994)

- Many subsequent variations

on boosted jets and jet substructure techniques: trimming, pruning, angular correlation functions, …

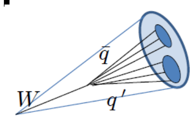
- Also applied to beyond-SM

scenarios such as ~ TeV scale resonances decaying to top quark pairs.

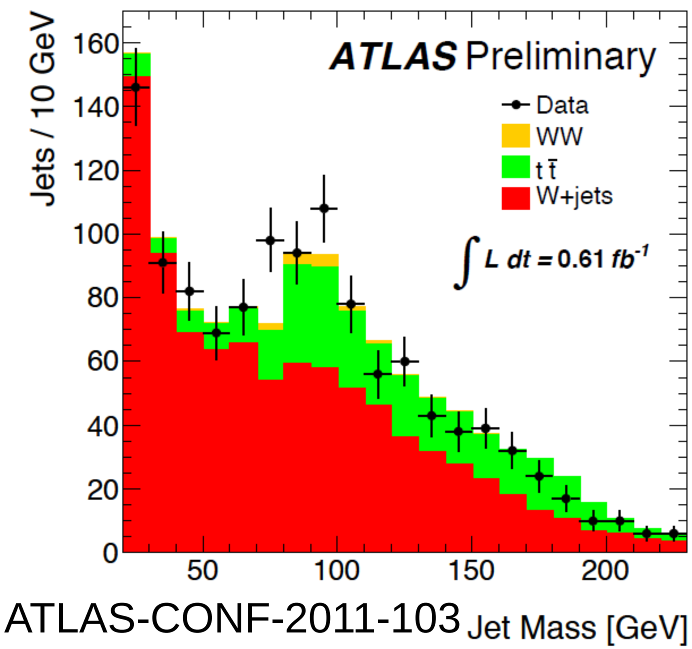


pp → $t\bar{t}$ → $l\nu b\bar{b}jj$

- Large cross section makes it ideal place to test these techniques experimentally



$p_T^{W\to l\nu} > 200\ \text{GeV},\quad p_T^{\text{C/A jet}} > 180\ \text{GeV}$



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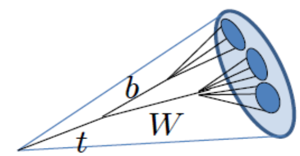
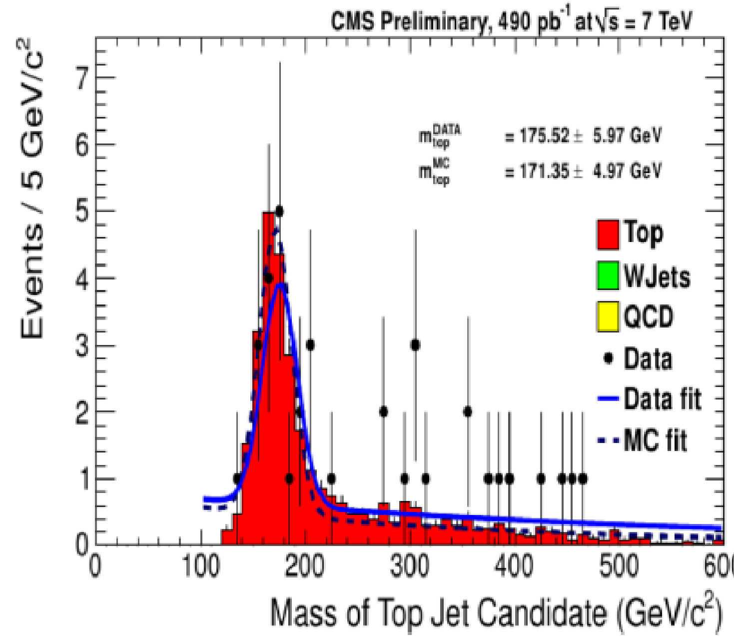




Levels of Approximation

- Monte Carlos (PYTHIA, HERWIG,…)
- LO, fixed-order matrix elements (ALPGEN, SHERPA, MADGRAPH)
- LO MEs matched to parton showers (DITTO)
- NLO MEs (parton level; multiple programs)
- NLO MEs + shower (MC@NLO, POWHEG)
- NNLO MEs (FEHiP, FEWZ; HNNLO, DYNNLO)
- MC@NNLO?

Parton Shower Monte Carlos

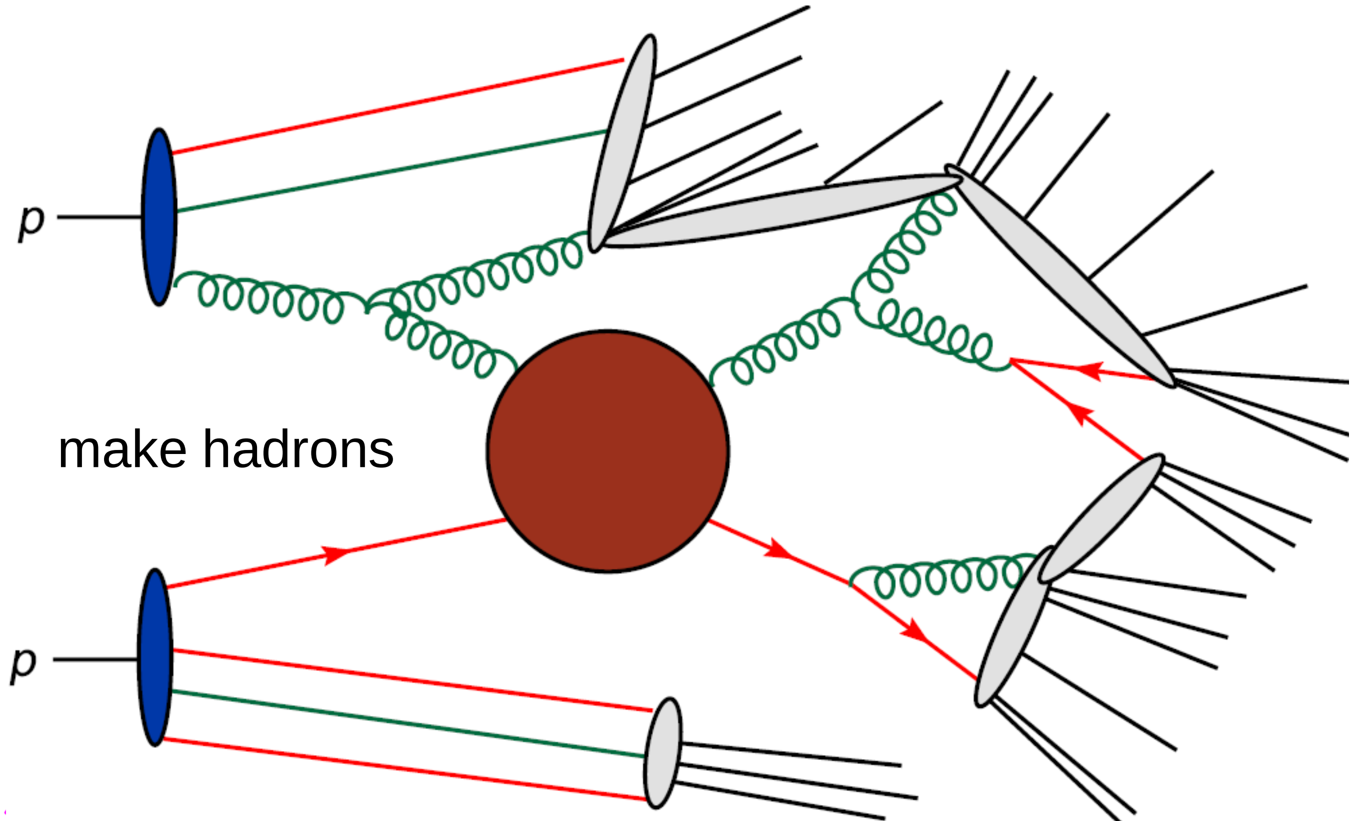
- Allow exclusive description of individual events at hadron level
- Can apply models for hadronization, the underlying event
- Indispensable to experimental analyses
- Overall normalization accuracy sacrificed a bit – but this is improving rapidly as NLO+MC programs expand their reach

Monte Carlos

- Based on properties of soft and collinear radiation in QCD
- Partons surrounded by "cloud" of soft and collinear partons
- Leading double logs of Q_{hard}/Q_{soft} exponentiate, can be generated probabilistically
- Shower starts with basic 2 → 2 parton scattering
  -- or basic production process for *W, Z, tt*, etc.
- Further radiation approximate, based on LO Altarelli-Parisi kernel + soft behavior.
- Requires infrared cutoff
- Shower can be evolved down to very low Q_{soft} , where models for hadronization and spectator interactions (underlying event) can be applied
- Complete hadron-level event description attained
- Normalization of event rates unreliable
- Event "shapes" sometimes unreliable

Monte Carlos in pictures

Splitting probability: $\mathsf{P}_g(q^2) = \int_0^1 dz \frac{\alpha_s(q^2)}{2\pi} \hat{P}_{gg}(z) \Theta(q^2 - q_0^2)$



Sudakov

$\Delta_g(Q^2, q^2) = \exp\left[- \int_{q^2} \frac{}{\tilde{q}^2} \mathsf{P}_g(q^2) \right]$

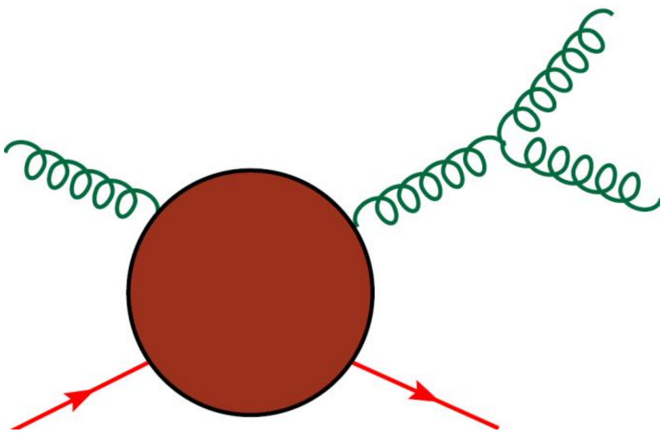
Matching MEs to showers

- Would like to have both:
  - accurate hard radiation pattern of MEs
  - hadron-level event description of parton-shower MCs
- Why not just use 2 → 3,4,… parton processes as starting point for the shower?
- Problem of double-counting:

  When does radiation "belong"

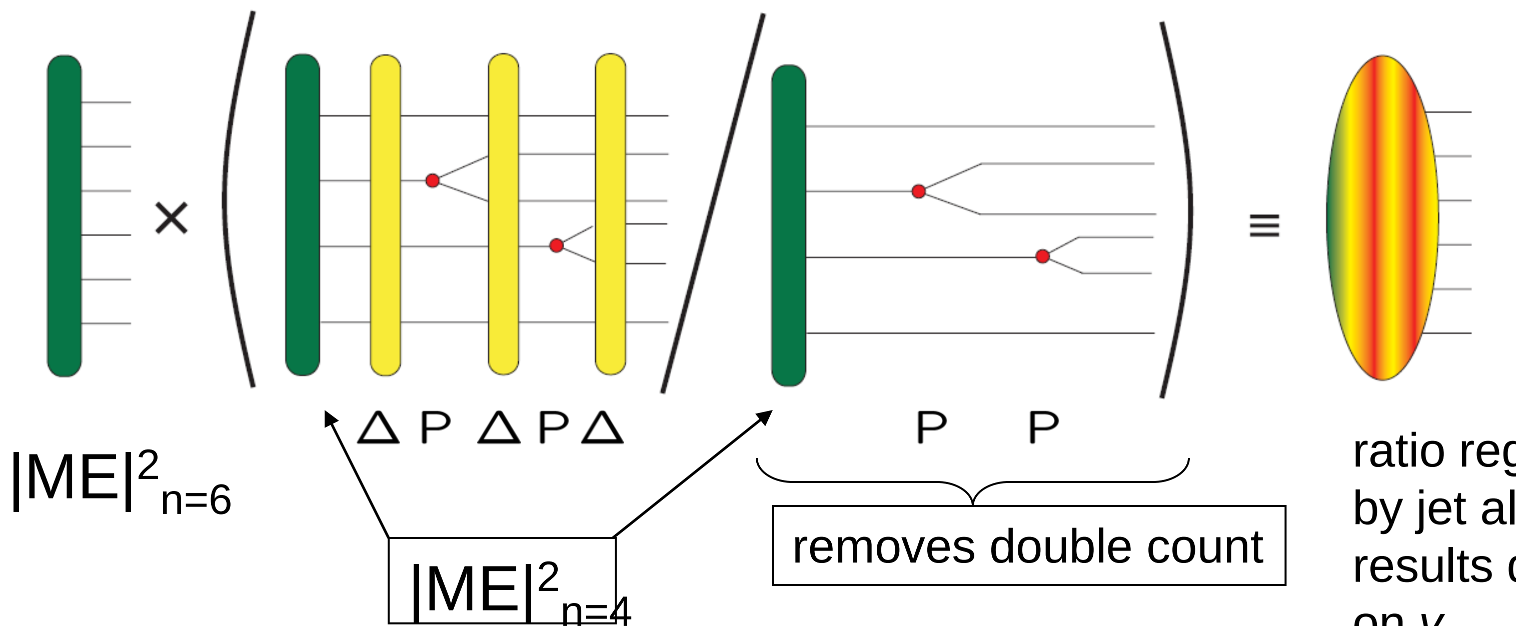
  to the shower, and

  when to the hard matrix element?



ME/shower matching

- CKKW matching: Catani, Kuhn, Krauss, Webber, hep-ph/0109231
  - separate ME and shower domains using a common jet cluster algorithm variable (k_T algorithm with $y = y_{ini}$)
- an example in pictures: Nagy, Soper, hep-ph/0607046



ratio regulated by jet algorithm; results depend on y_{ini}

ME/shower matching (cont.)

Several other general matching schemes available or in the works, e.g,:

MLM scheme (ALPGEN)

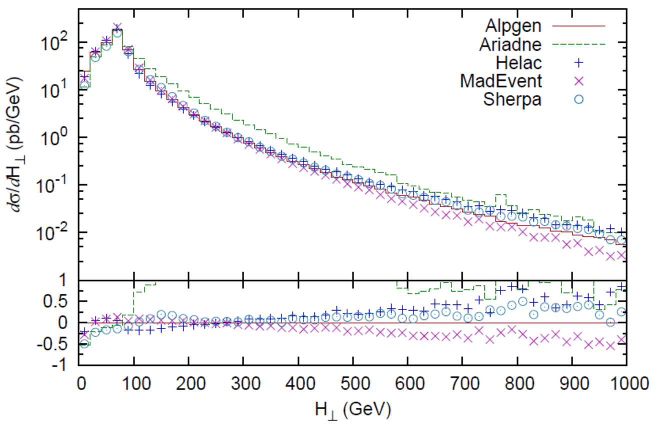
Lonnblad, hep-ph/0112284 (Ariadne)

CKKW (Sherpa)

Mrenna, Richardson, hep-ph/0312274

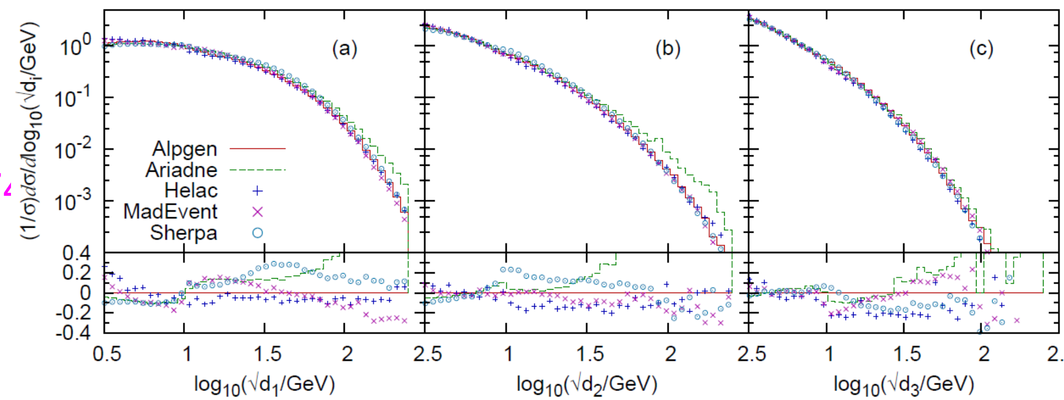
Nagy, Soper, hep-ph/0601021

VINCIA (Skands, Giele, Kosower)



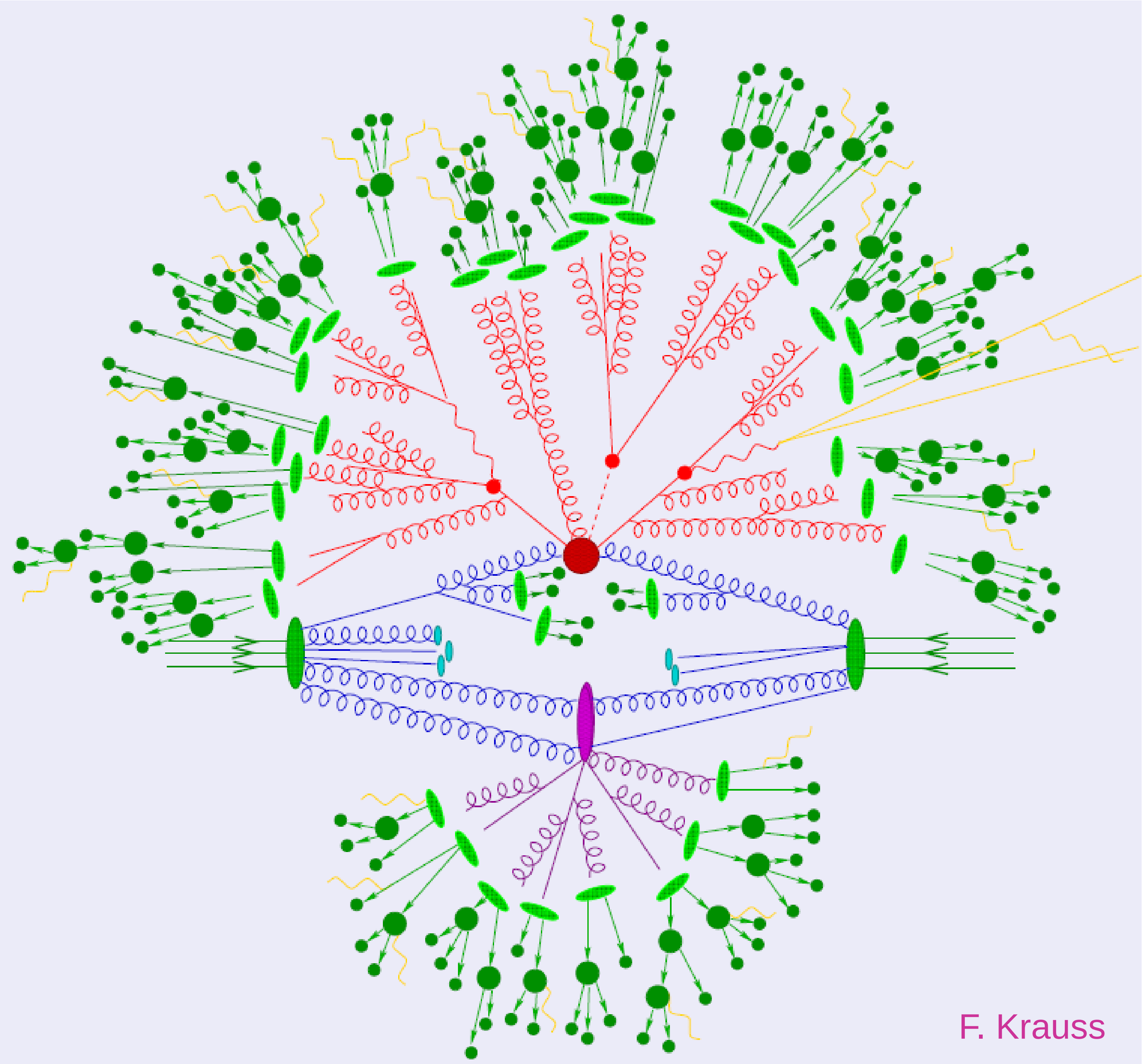
reasonable agreement between different schemes [0706.2569]

$p\bar{p} \to W + n$ jets at Tevatron



d_i indicates transition between i and i-1 jets in k_T algorithm

$$H_T = p_T^l + p_T^\nu + \sum_j p_T^j$$


F. Krauss