# Lecture 3:
# Heavy flavor @ RHIC, jet reconstruction, jet measurements in p-p

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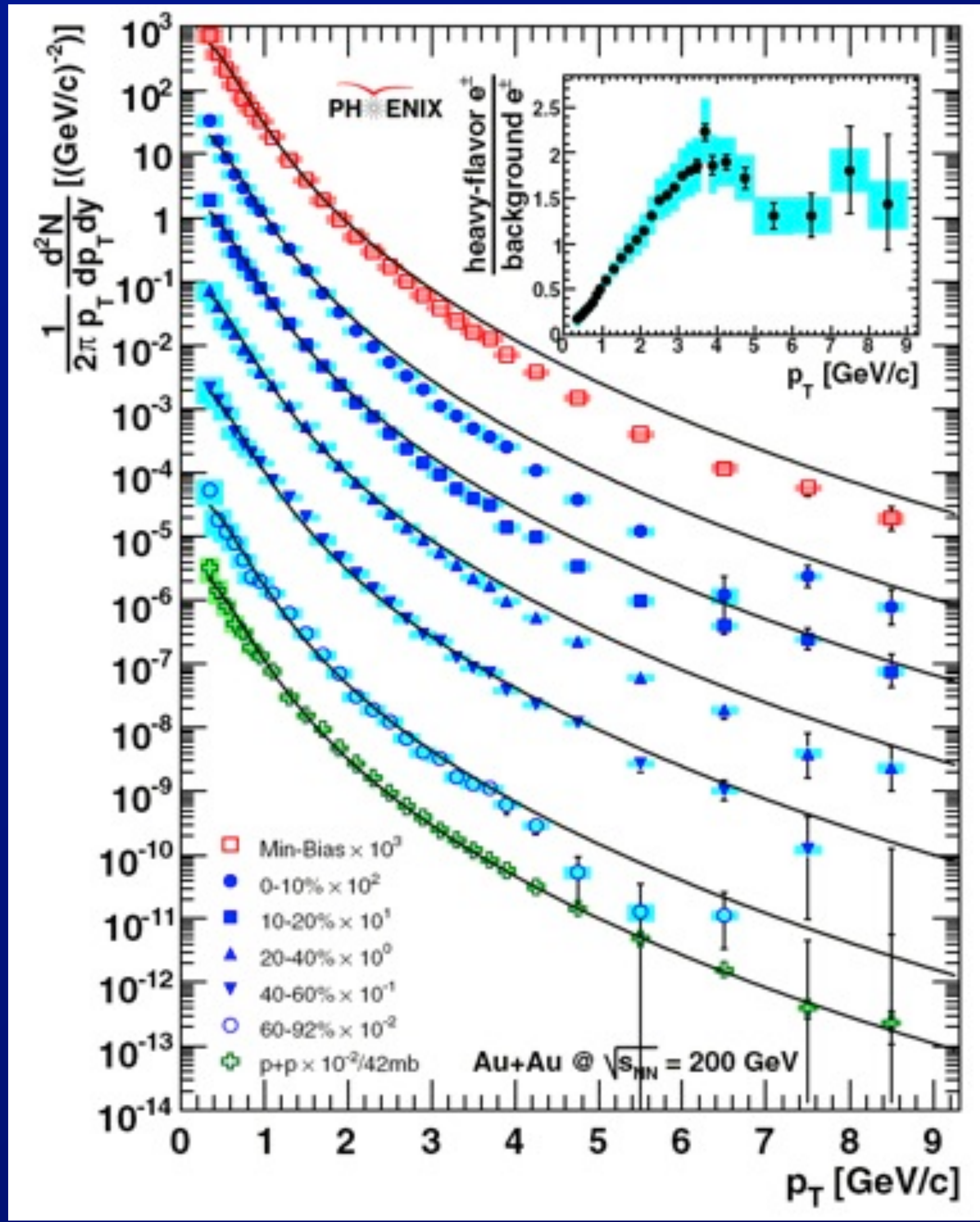
# PHENIX: Heavy Quark Quenching

- Measure via semi-leptonic decays
  - Single $e^+ + e^-$ spectrum
- 2 methods to estimate (large) backgrounds
  - Direct estimate of backgrounds (cocktail)
  - Data taken with extra converter material

    ⇒Directly measure



# Dead cone

## On specific QCD properties of heavy quark fragmentation ('dead cone')

Yu L Dokshitzer, V A Khoze and S I Troyan

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### 1. Introduction

It is the restriction on the phase space of emitting gluons connected with the kinematics of a heavy quark $Q = \mathrm{c, b}, \ldots$ which determines the difference of the QCD jet produced by $Q$ from that of ordinary light (practically massless) quarks $q = \mathrm{u,d,s}$ (see e.g. [1–3]). Hereafter we shall consider the $Q$-quark as relativistic ($E_Q \gg M_Q, \Theta_0 \equiv M_Q/E_Q \ll 1$) and taking care of logarithmic effects ignoring small (power) corrections of the order of $\Theta_0$.

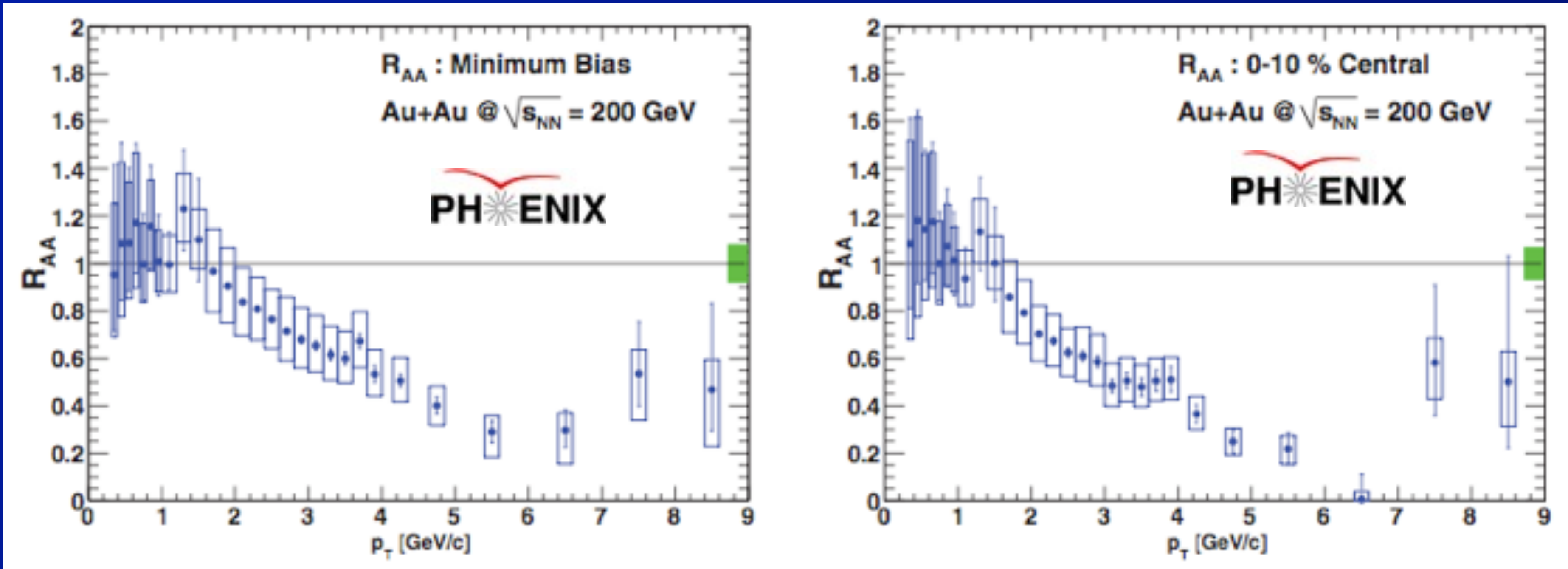
Considering the soft-gluon emission probability (disregarding effects of $\Gamma_Q$ for the moment)

$$d\sigma_{Q\to Q+g} = \frac{\alpha_S}{\pi} C_F \frac{(2\sin\Theta/2)^2 d(2\sin\Theta/2)^2}{[(2\sin\Theta/2)^2+\Theta_0^2]^2}\frac{d\omega}{\omega}[1+O(\Theta_0,\omega)] \quad (1)$$

one concludes that the large logarithmic contribution comes only from the region of relatively large radiation angles

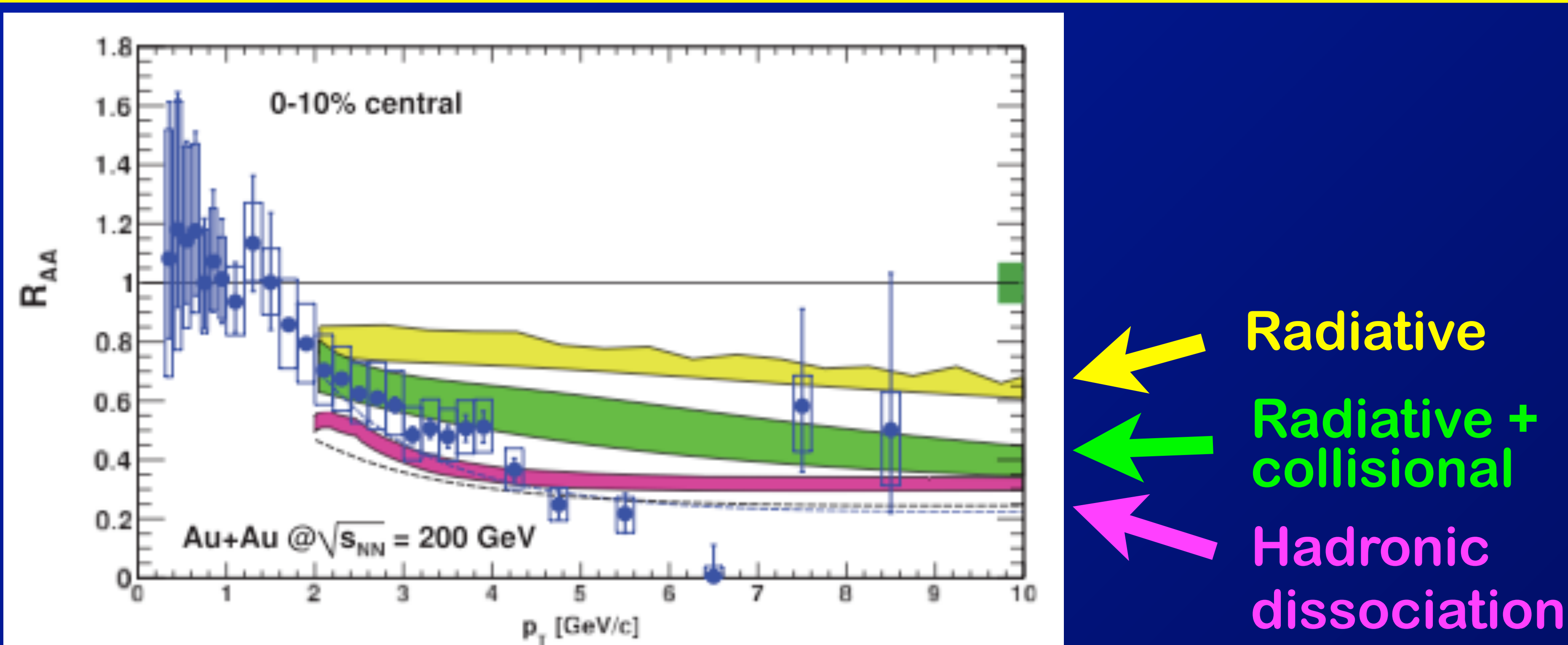
$$\Theta \gg \Theta_0. \quad (2)$$

# Heavy quark suppression



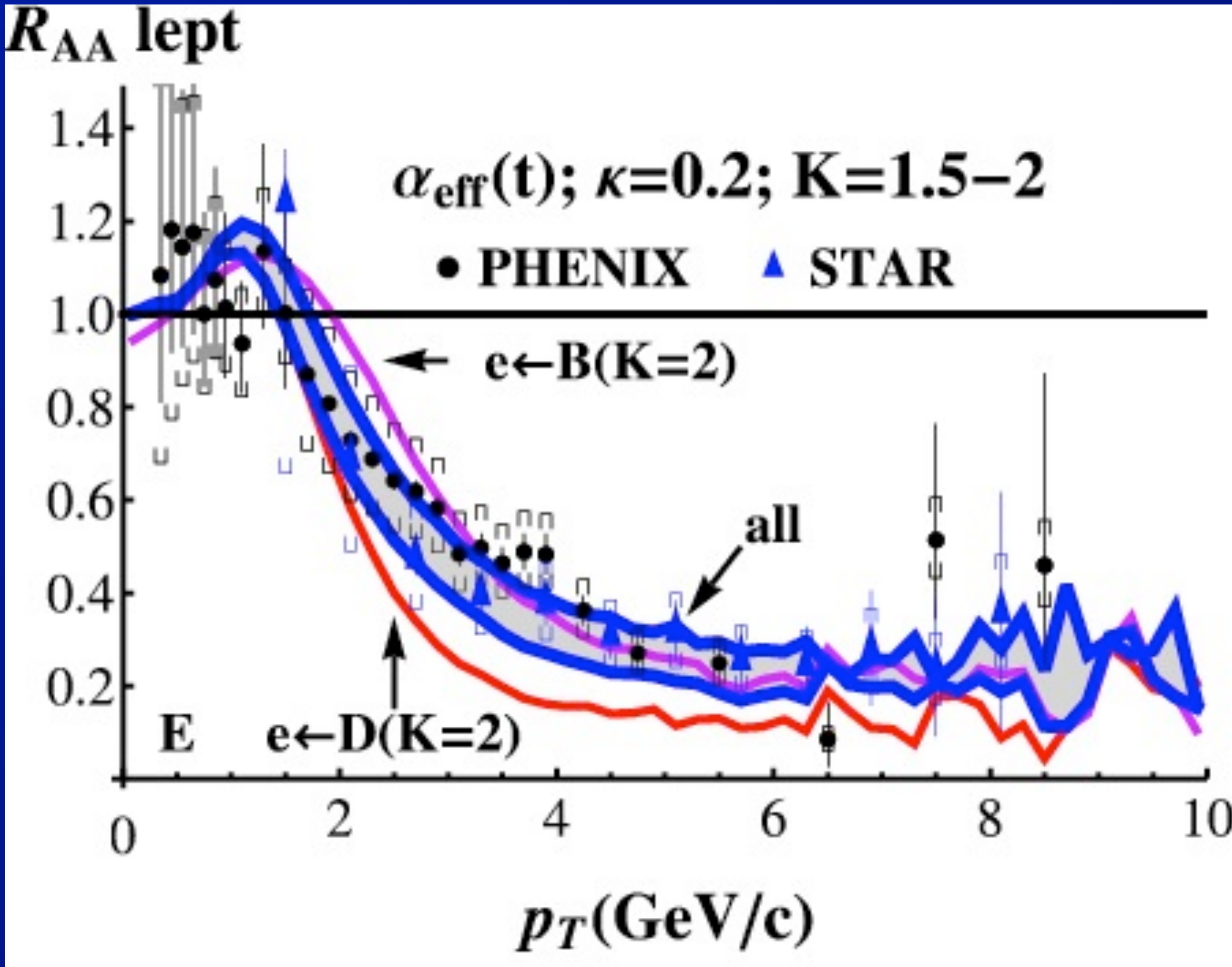

- Measure heavy quark production via semi-leptonic decays (B+D) to electrons
  - See suppression comparable to light mesons
    - ⇒Unexpected due to mass suppression of radiative contributions, especially for b quark.

# Heavy quark suppression



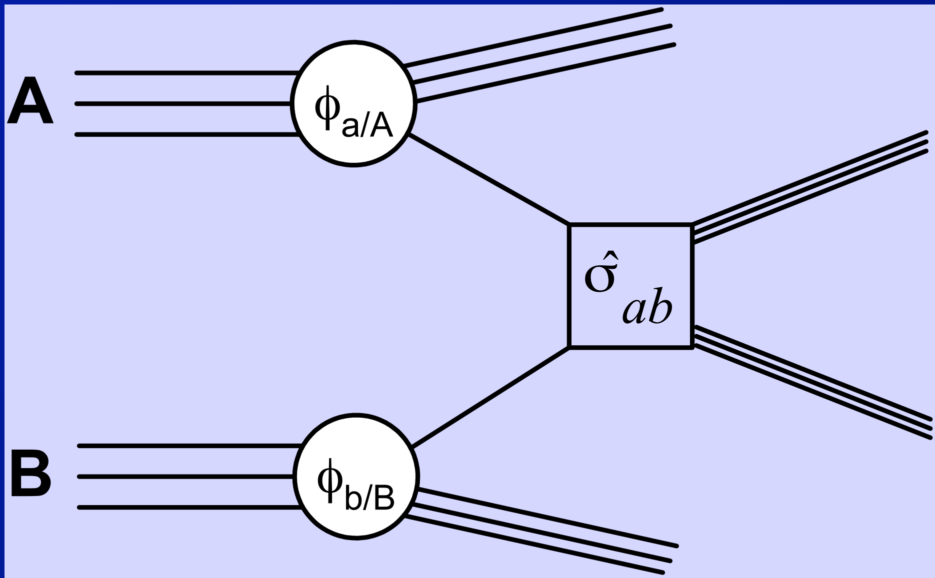

- Heavy quarks provide a valuable test of our understanding of energy loss
  - Large mass changes contribution of collisional and radiative energy loss
    - ⇒But RHIC semi-leptonic decay data proved challenging to describe theoretically.

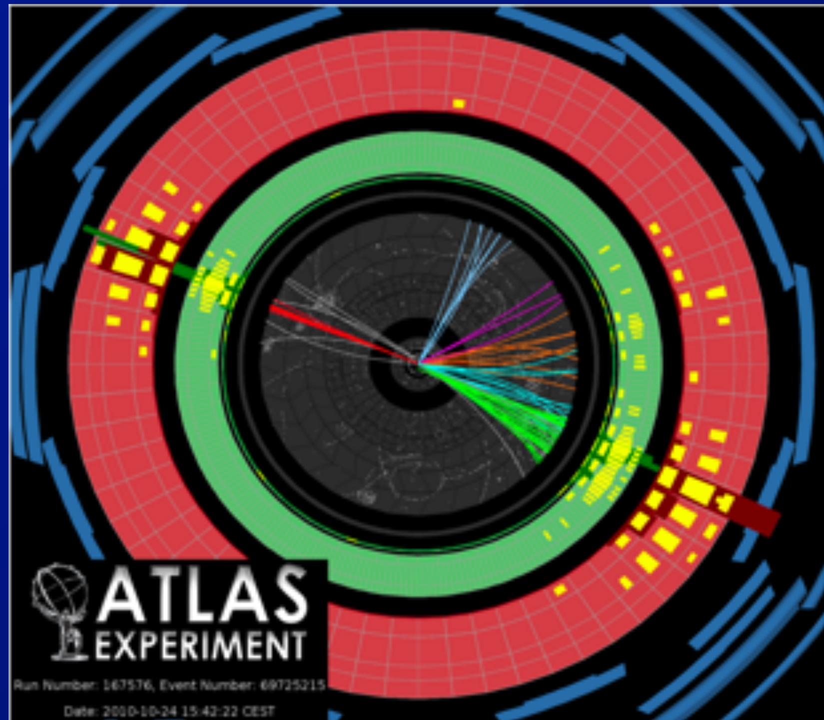
# Heavy quark suppression




- Recent calculations by Aichelin et al are able to describe RHIC results
  - But only by scaling up the collisional interaction rates by a factor of 1.5-2

# Hard Scattering in p-p Collisions



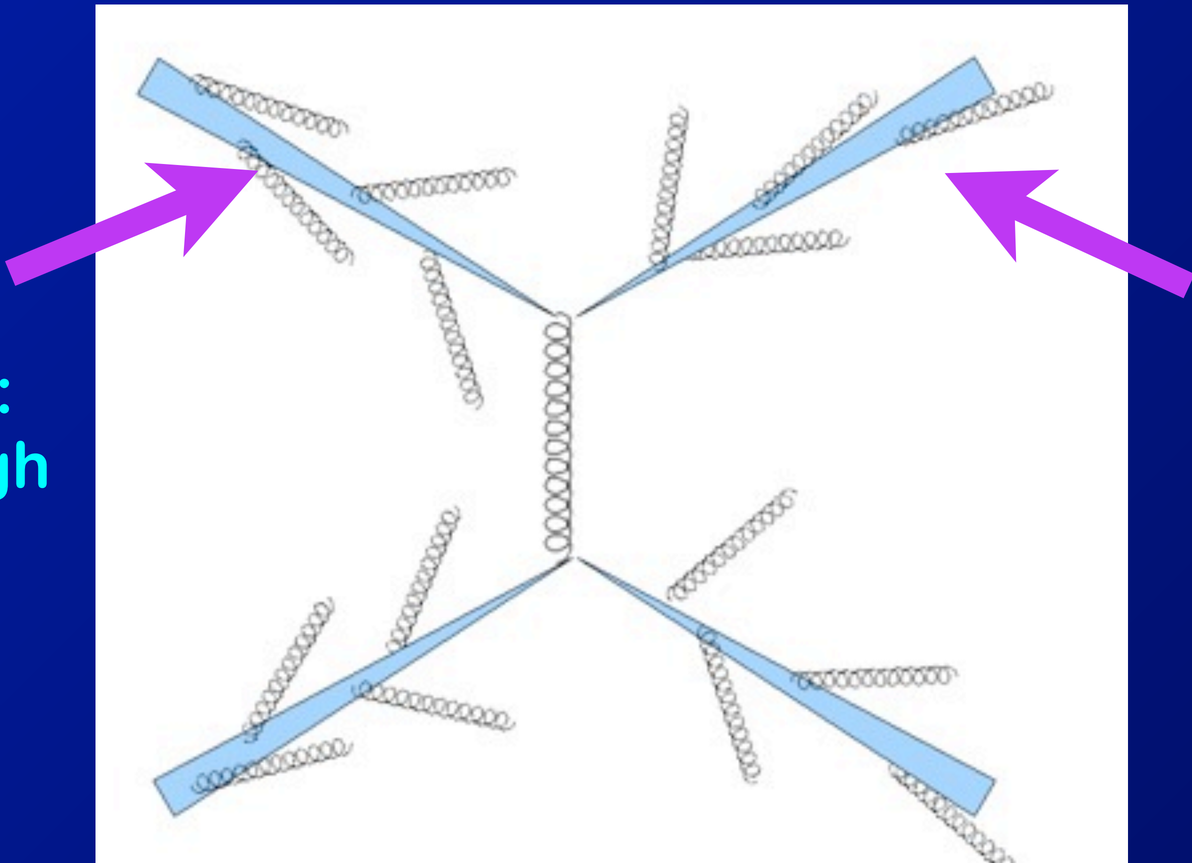




From **Collins, Soper, Sterman**
**Phys. Lett. B438:184-192, 1998**

$$\sigma_{AB} = \sum_{ab} \int dx_a dx_b \, \phi_{a/A}(x_a, \mu^2) \, \phi_{b/B}(x_b, \mu^2) \, \hat{\sigma}_{ab}\left(\frac{Q^2}{x_a x_b s}, \frac{Q}{\mu}, \alpha_s(\mu)\right) \left(1 + \mathcal{O}\left(\frac{1}{Q^P}\right)\right)$$

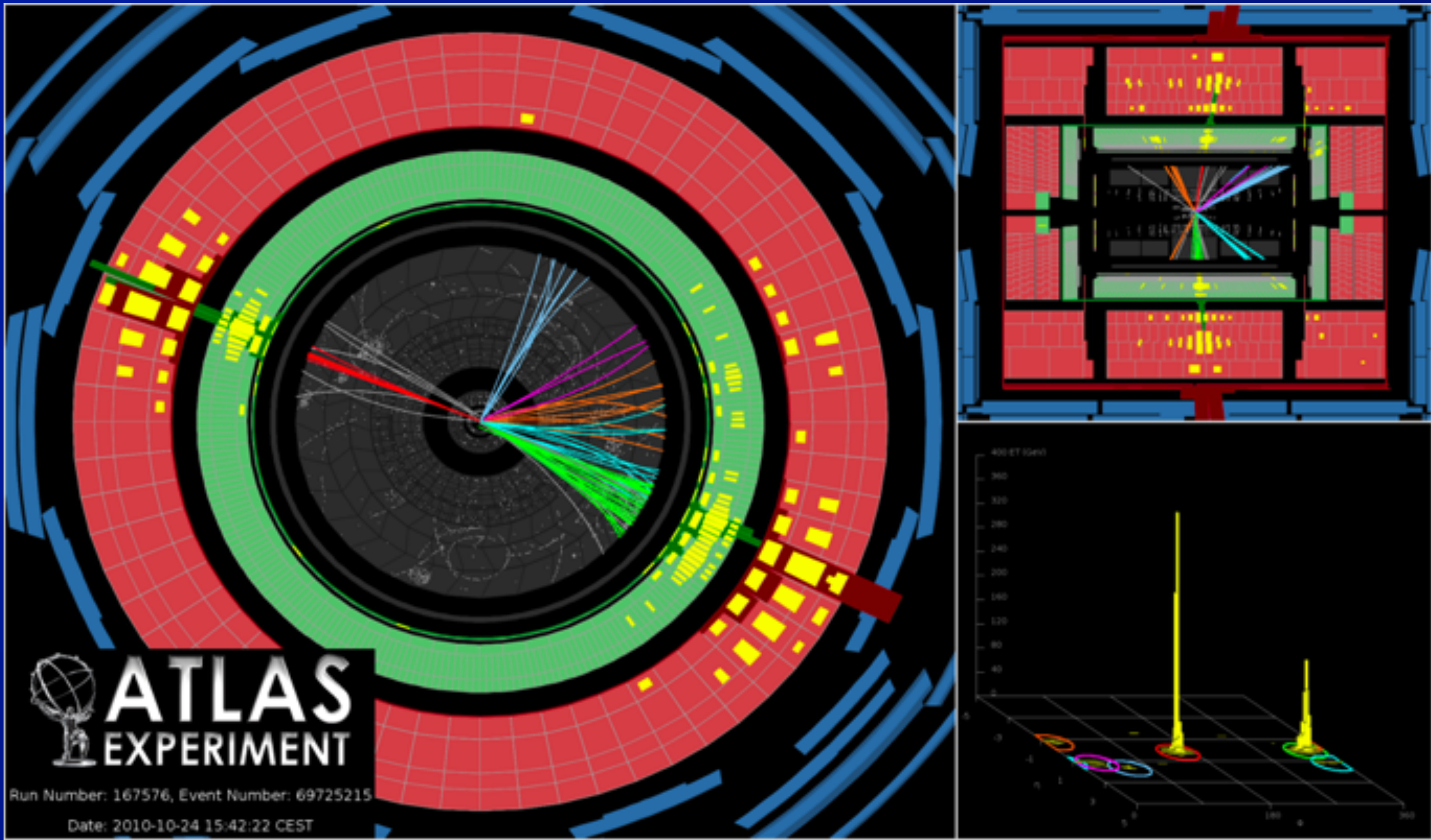
- **Factorization: separation of σ into**
  - Short-distance physics: $\sigma_{ab}$
  - Long-distance physics: φ's

# Hard Scattering & parton showers




- Initial and final state parton showers
  - Angular ordered (initial and) final state showers as by-product of virtuality evolution.

# An ATLAS p-p multijet event




- ➡ Leading jet : $p_T$= 670 GeV, η = 1.9, φ = -0.5
- ➡ Sub-leading jet: $p_T$ = 610 GeV, η = -1.6, φ = 2.8

# Jet finding algorithms

# Cone algorithms

- Start with a center position
  - Find all particles, towers, clusters, … *i* within a radius $\Delta R = \sqrt{(\eta_i - \eta_c)^2 + (\phi_i - \phi_c)^2}$ of $(\eta_c, \phi_c)$
- Calculate energy, new centroid position
  - Snowmass method:

$$\Rightarrow \quad E_{Tc} = \sum_{i \in c} E_{Ti}, \eta_c = \sum_{i \in c} \eta_i \frac{E_{Ti}}{E_{Tc}}, \phi_c = \sum_{i \in c} \phi_i \frac{E_{Ti}}{E_{Tc}}$$

- Iterate until cone is stable
  - But, cones can overlap, use same particles,…
  - Test if shared energy is larger than some fraction $f_{merge}$

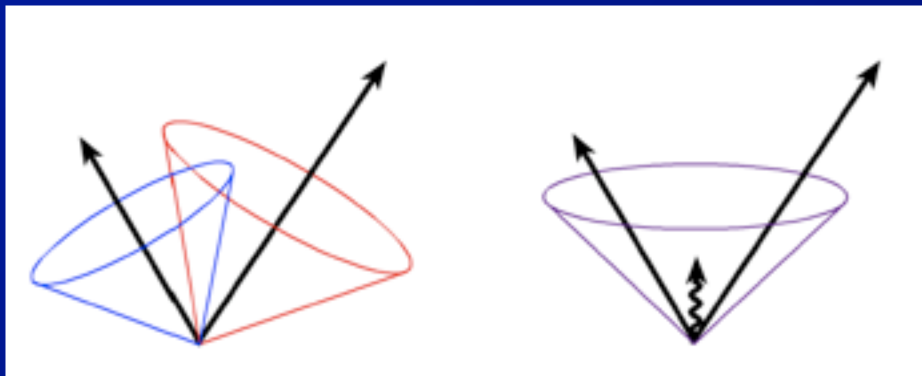
    ⇒ If so, merge jet, otherwise split.

# Cone algorithms

- How to come up with first set of initial cone positions?
  - Ideally seed detector with fine grid of centers
    - ⇒Iteration will cause most to converge to small set of stable jets
- Computationally challenging
  - So, usual solution is to start with ‘seed’ cones based on particles, towers, clusters, … above some threshold
    - ⇒Collinear unsafe
    - ⇒Sensitive to jet flavor
    - ⇒Typically detector/experiment specific

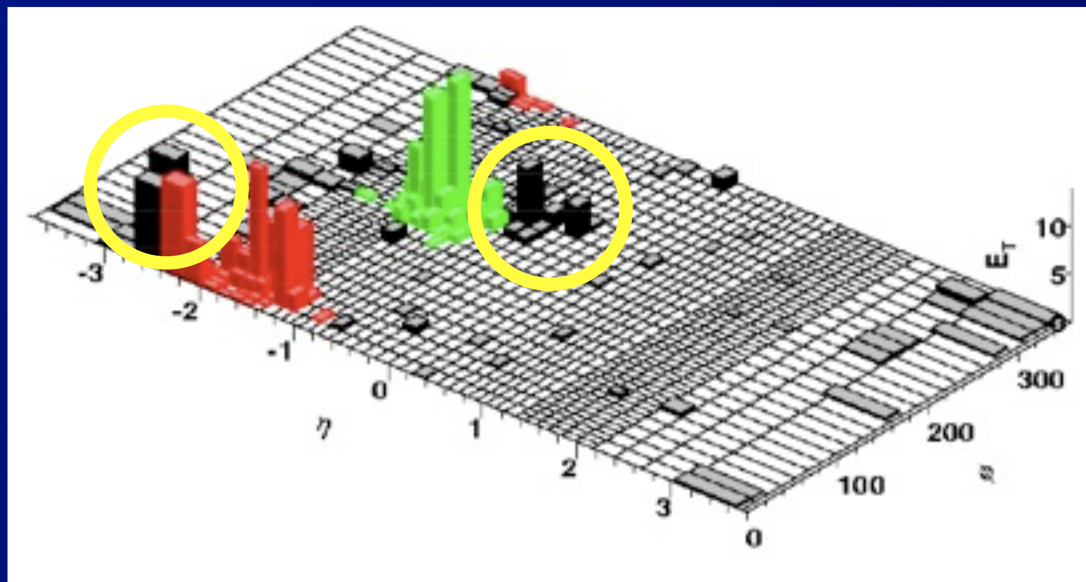
# IR (un)safety

- Cone algorithms are notoriously IR unsafe
  - addition of a very soft particle can change the topology of jets in a given event.

    ⇒ 

  - “Dark towers”

    ⇒ energy not put into any cone.



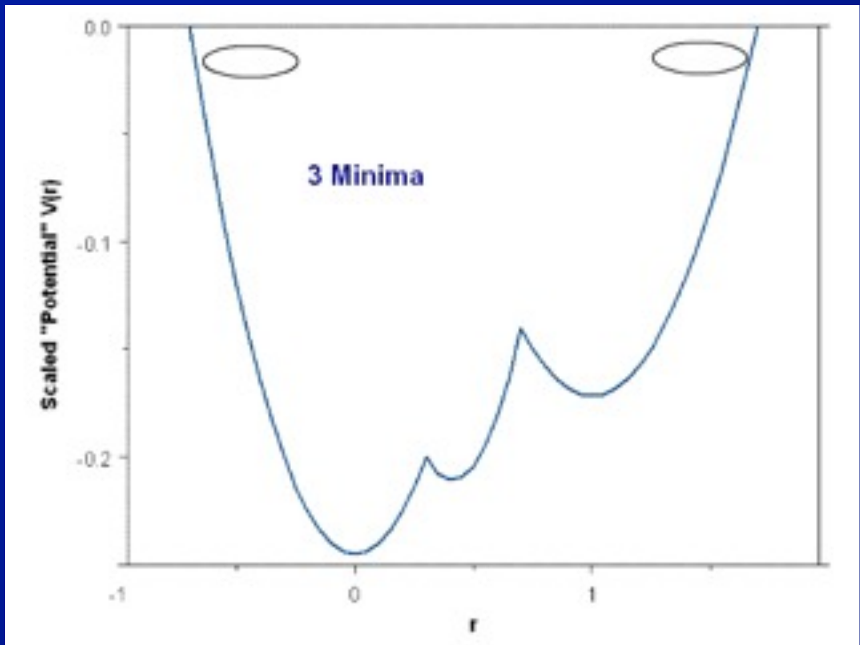
# Snowmass potential

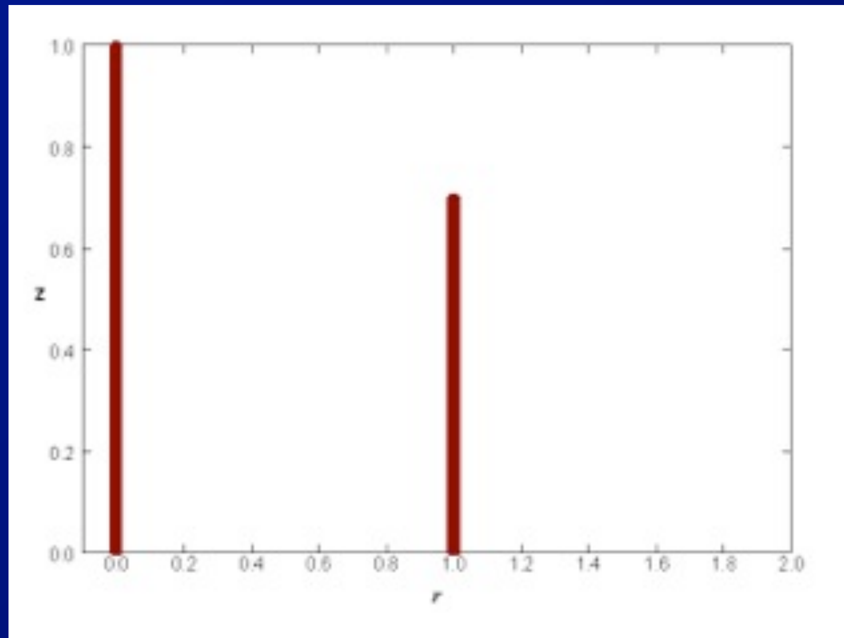
- Behavior of cone algorithm can be described by a "potential" in $\vec{r} = (\eta, \phi)$:
  - $V(\vec{r}) = -\frac{1}{2}\sum_i E_{Ti}\left(R^2 - (\vec{r}_i - \vec{r})^2\right)\Theta\left(R^2 - (\vec{r}_i - \vec{r})^2\right)$
- And a corresponding "force":
  - $\vec{F} = \sum_i E_{Ti}(\vec{r}_i - \vec{r})\,\Theta\left(R^2 - (\vec{r}_i - \vec{r})^2\right)$
- Minima of the potential are stable points
  - Force "pushes" trial cone to stable point.

    $\Rightarrow$ Describes flow of cones in $\vec{r}$

# Snowmass potential: split-merge

- Example (S. Ellis, Les Houches 2005 talk):

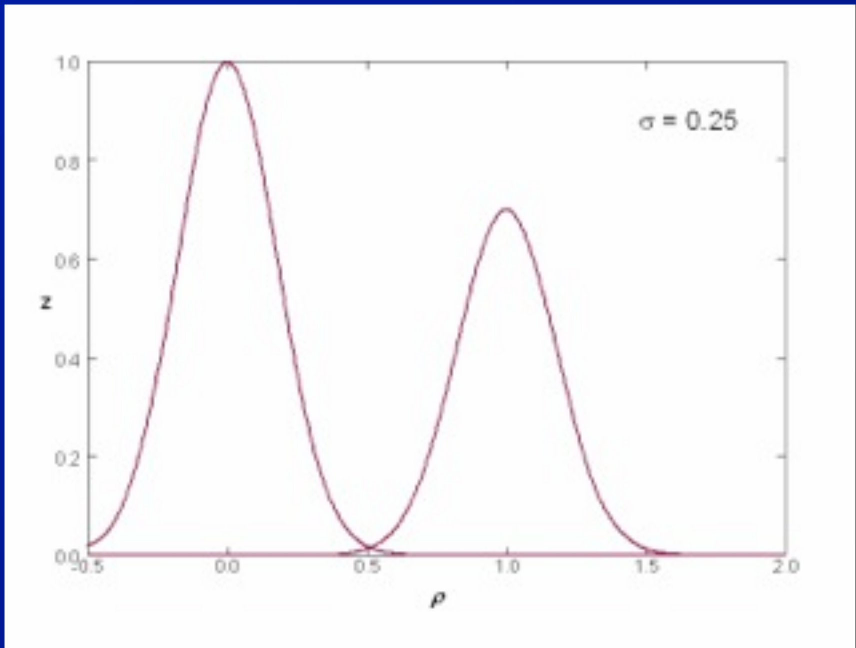


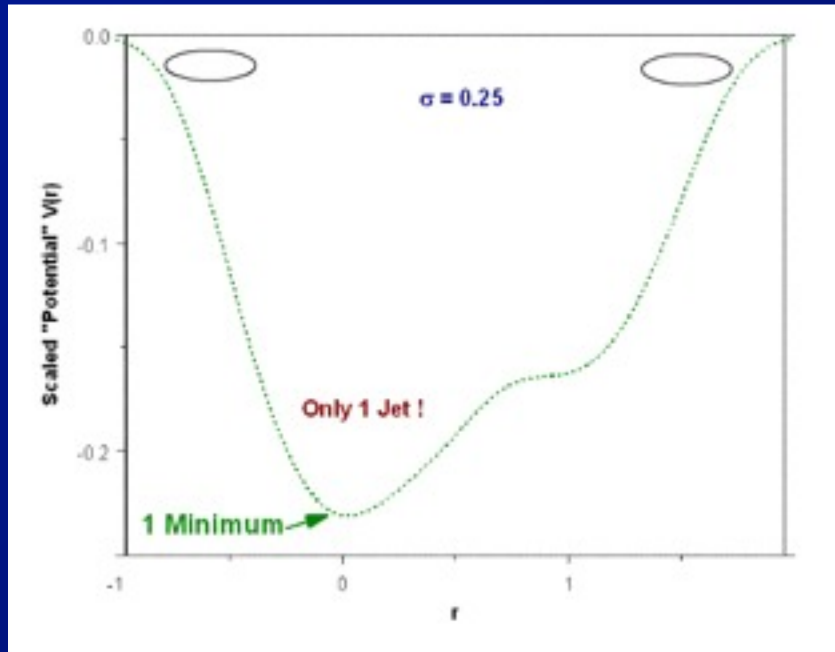




  - In principle, 3 minima (middle is combined jet)
    - ⇒But, seeding may only give separate jets
- Mid-point algorithm
  - Try seed midway between all pairs of jets
    - ⇒ad-hoc solution to fundamental problem

# Snowmass potential: split-merge

- Example (S. Ellis, Les Houches 2005 talk):




  - Consider effects of showering, hadronization, experimental resolution
    - ⇒ Can end up with a single minimum
    - ⇒ One example of why there are dark towers

# Successive recombination algorithms

- Start with "proto-jets"
  - Particles, towers, clusters, ...
- Define angular distance measure:
  - $D_{ij} = \min\left({p_T}_i^{2p}, {p_T}_j^{2p}\right) \frac{\Delta R_{ij}^2}{R^2}$ , p = -1, 0, 1.
  - $\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$
- Also, define single-jet "cutoff", $D_i = {p_T}_i^{2p}$
- From all pairs select minimum of $\{D_{ij}, D_i\}$
  - If $D_i$ is minimum, jet *i* is final
  - Otherwise combine *i* and *j* (below)
- Iterate until all jets are final

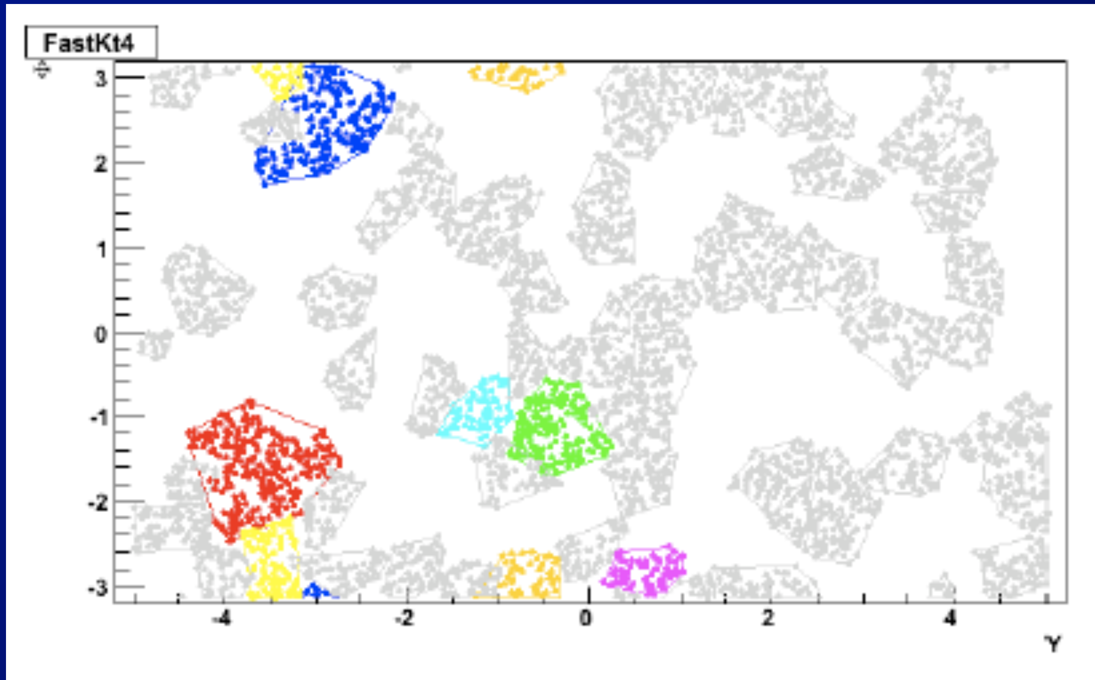
# $k_T$ algorithm

- $k_T$ algorithm, p = 1
  - $k_T$ of pair measured with respect to the higher energy parton

$$\Rightarrow D_{ij} = \min\left({p_T}_i^{2p}, {p_T}_j^{2p}\right)\frac{\Delta R_{ij}^2}{R^2} \rightarrow min(k_T^2)$$

$$\Rightarrow k_T \approx p_T \Delta R$$

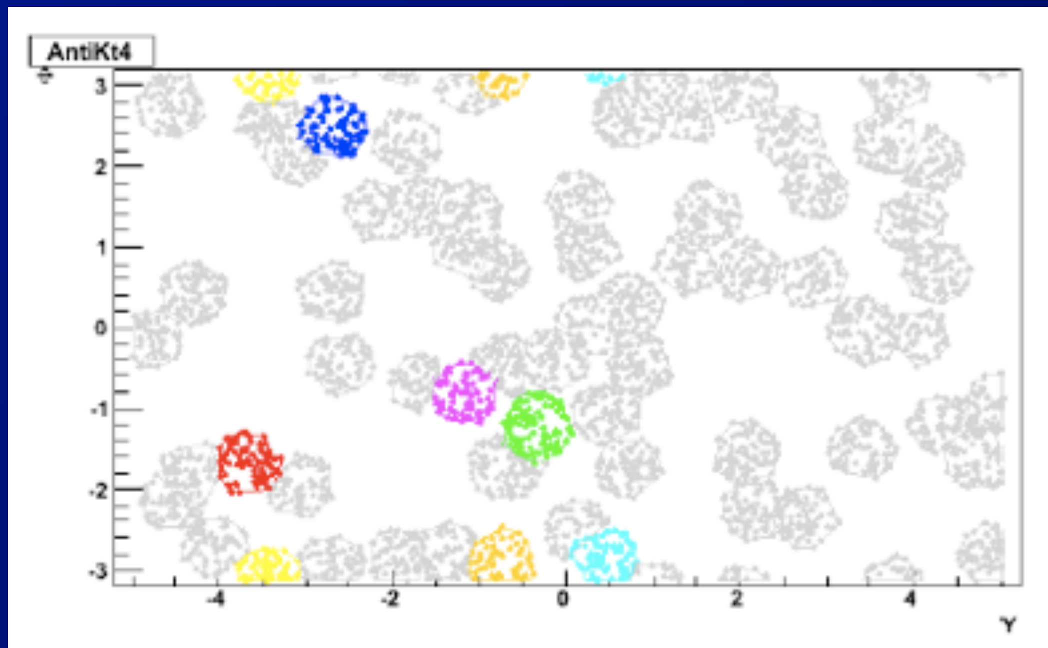
- designed to reverse pQCD splitting
  - tends to make large, lumpy jets




From 2009 talk by P.A. Delsart

# anti-$k_T$ algorithm

- $k_T$ algorithm, p = -1
  - High $p_T$ proto-jets provide minimum $1/p_T^2$
    - ⇒define stable points around which $D_{ij}$ is measured
    - ⇒Proto-jets get clustered to the local maximum proto-jet out to a radius R.
- anti-$k_T$ algorithm behaves like an IR and collinear safe cone algorithm.



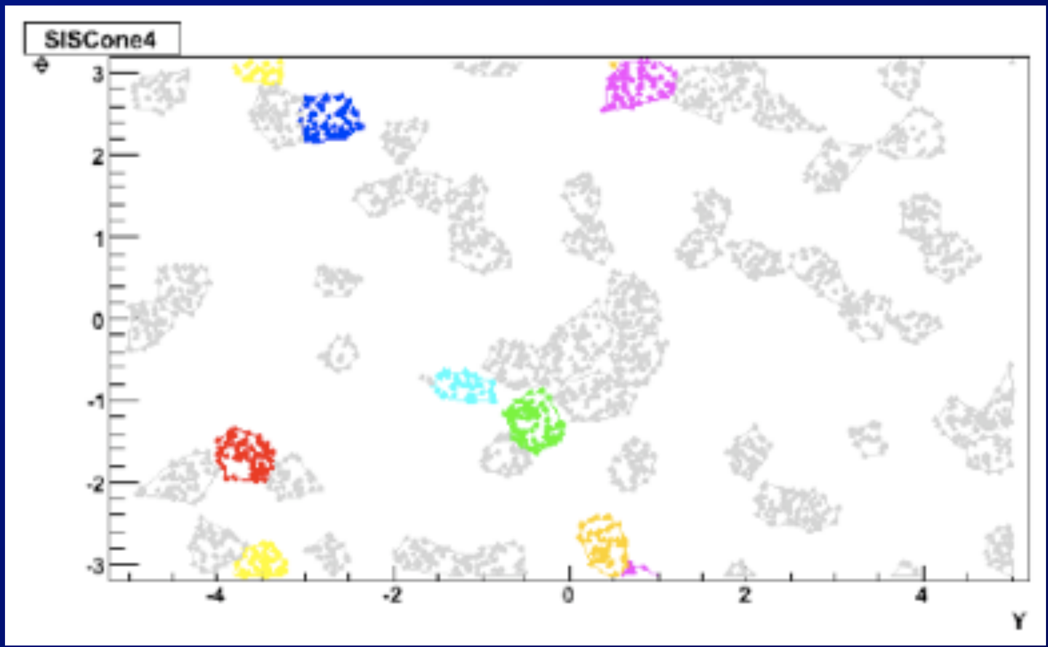

From 2009 talk by P.A. Delsart

# Cambridge-Aachen, SIScone

- Cambridge-Aachen algorithm, p = 0
  - Clusters proto-jets that are closest in angle

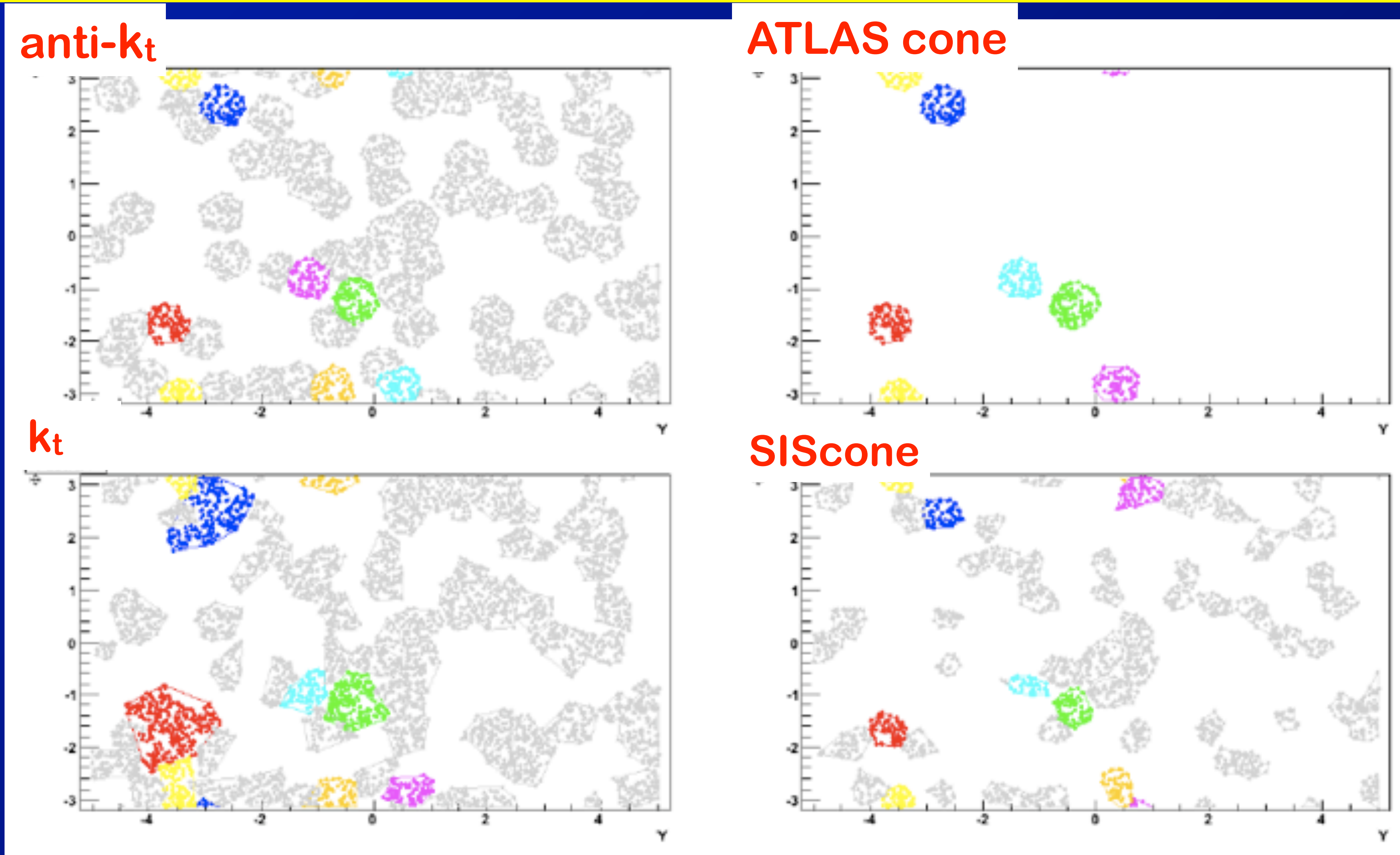
$$\Rightarrow \quad D_{ij} \rightarrow \frac{\Delta R_{ij}^2}{R^2}$$

  - Similar in behavior to $k_T$ algorithm
- SISCone
  - Seedless, infrared safe cone algorithm by Soyez



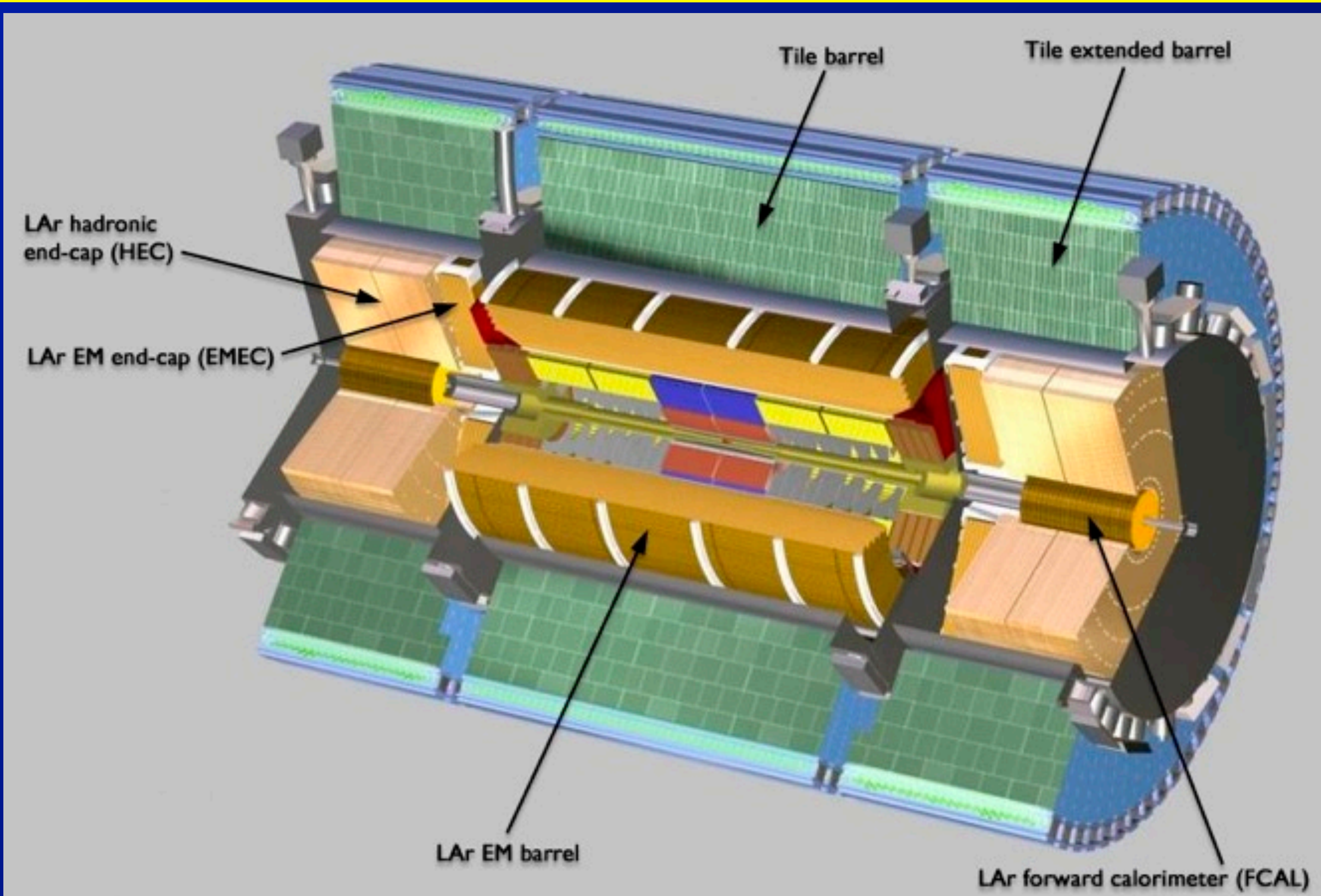

From 2009 talk
by P.A. Delsart

# Comparison of jet algorithms



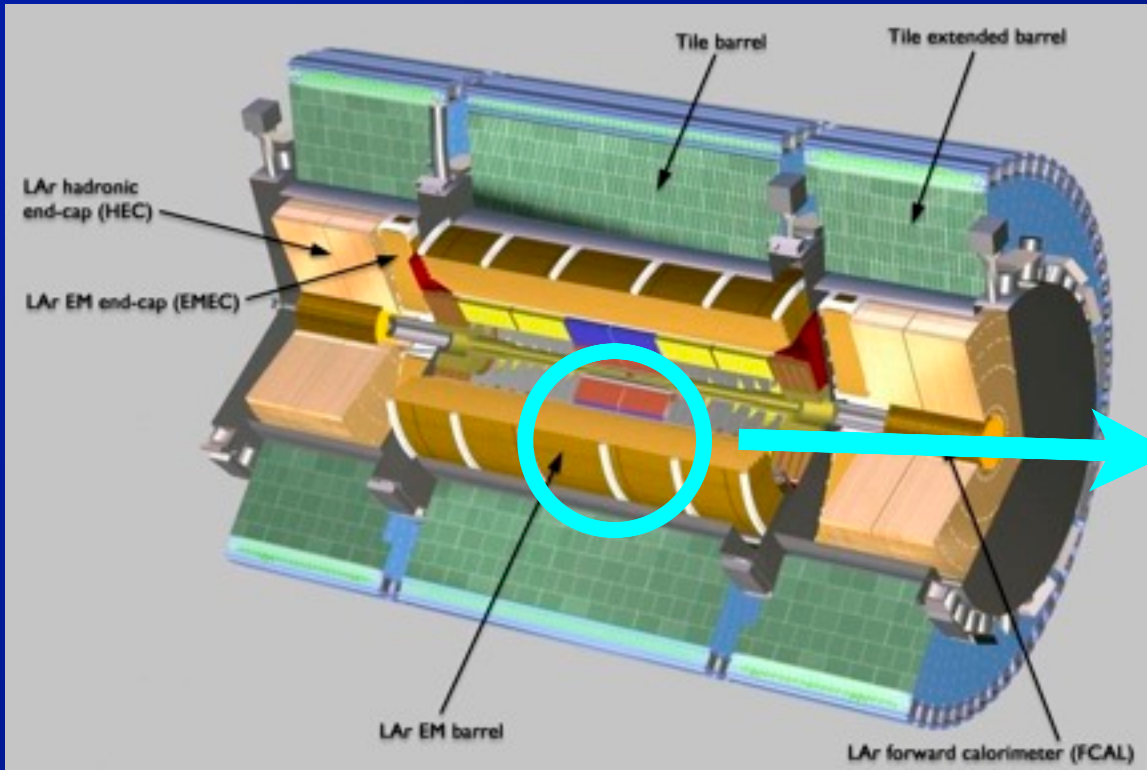

- Four algorithms, one event.
  - $k_t$, anti-$k_t$, and SIScone are collinear, IR safe

# Jet reconstruction: reality

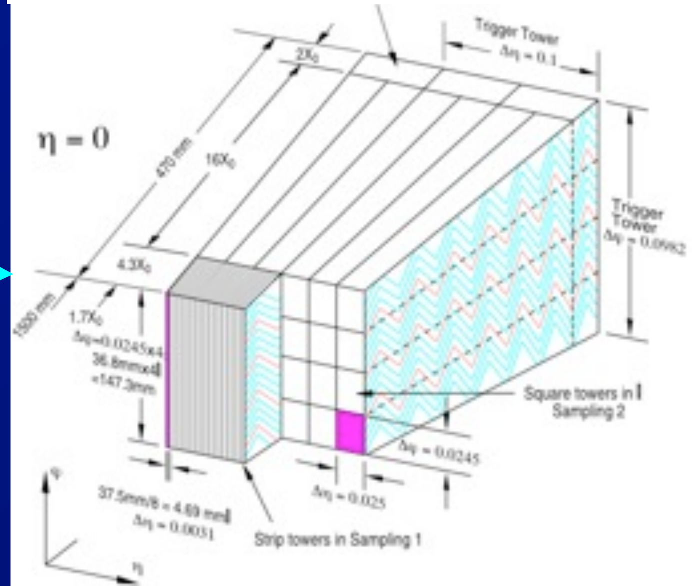



- ATLAS calorimeter system

# Jet reconstruction: reality



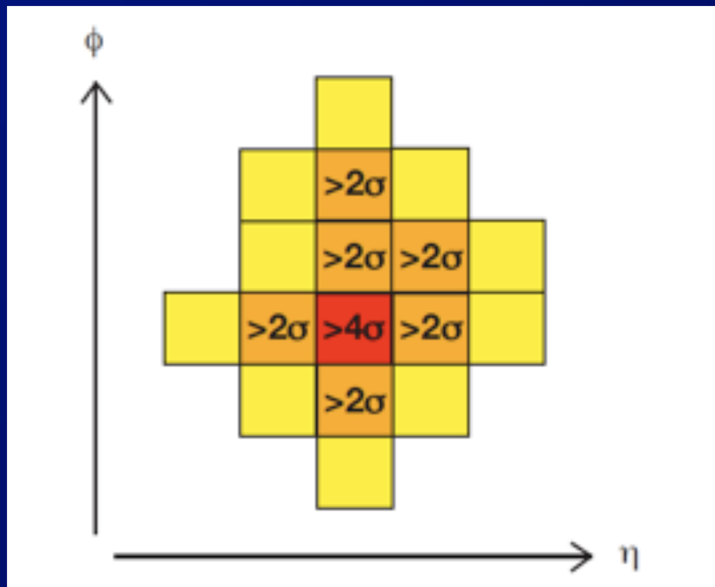

**EM Longitudinal Segmentation**



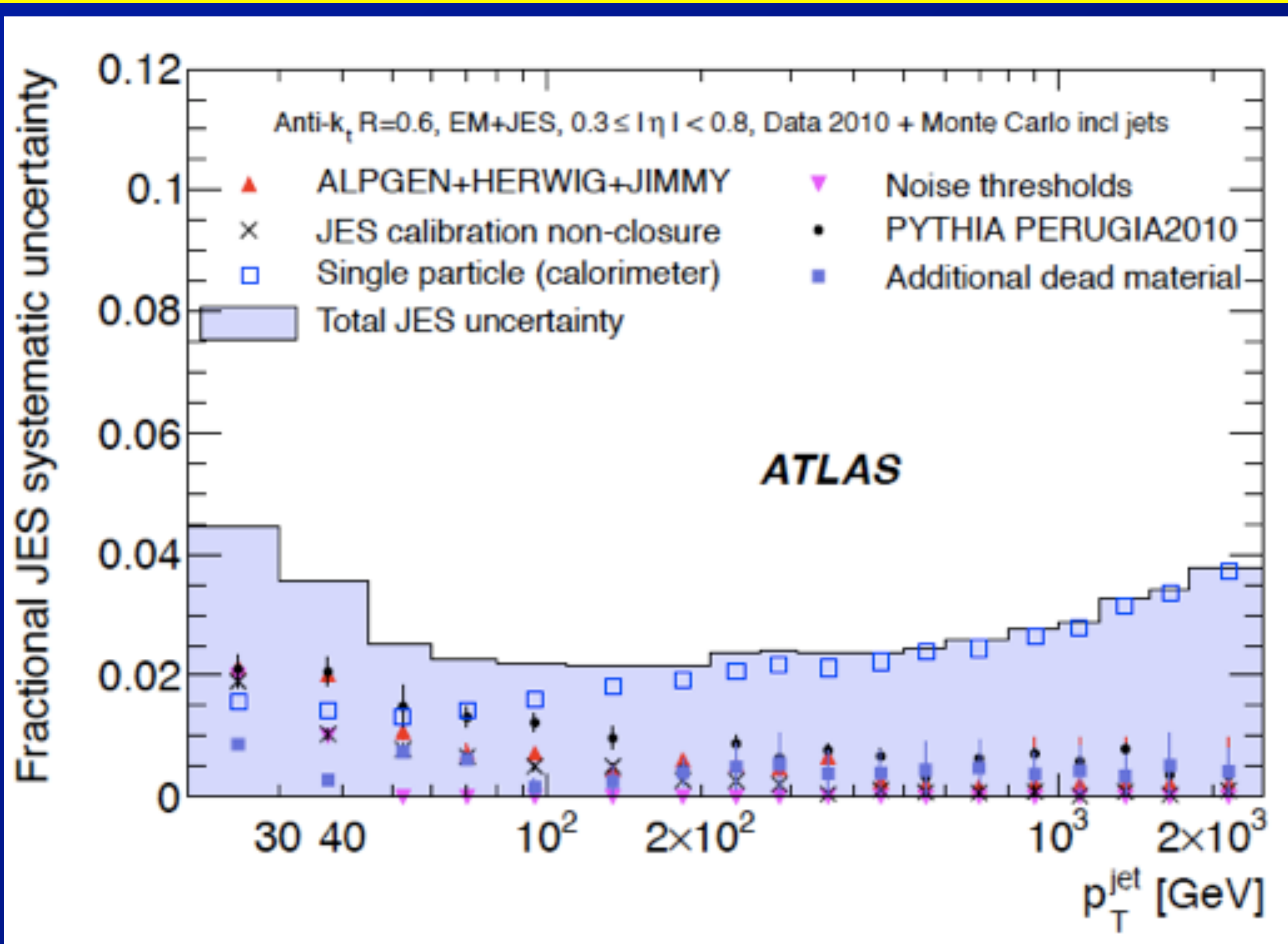

- **Details that matter for all calorimeters:**
  - Technology
  - Longitudinal, transverse segmentation
  - Hadronic vs electromagnetic response
  - Electronic noise
  - Dead material

# e.g. electronic noise (ATLAS)

- How to reduce contribution of electronic noise to jet measurement?
  - A single jet can include several 1000 cells with noise (σ) varying from 10-500 MeV
  - Can't simply apply a threshold to exclude noise
    - ⇒produces large upward bias on jet energies
- ATLAS topo-clustering (also D0)
  - Find "seed cell" with energy > 4σ noise
  - Collect surrounding cells (including longitudinally) with energy > 2σ noise
  - Add a "ring" of cells around edge with no threshold



# Jet energy scale

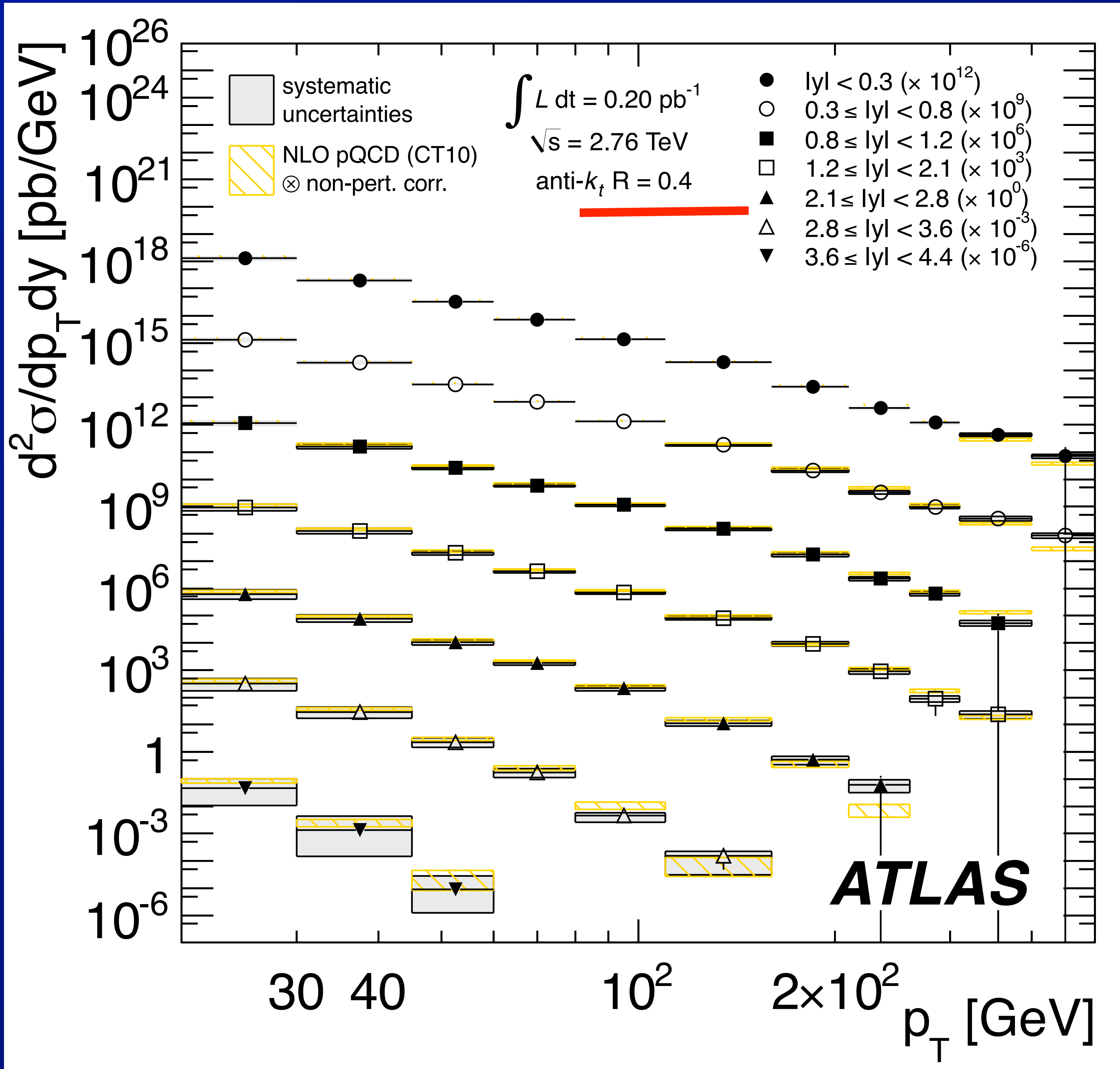



- Systematics on Jet energy scale are usually dominant systematic in any jet spectrum measurement.

# p-p jet cross-sections @ 2.76 TeV

**ATLAS**
**arXiv:**
**1304.4739**

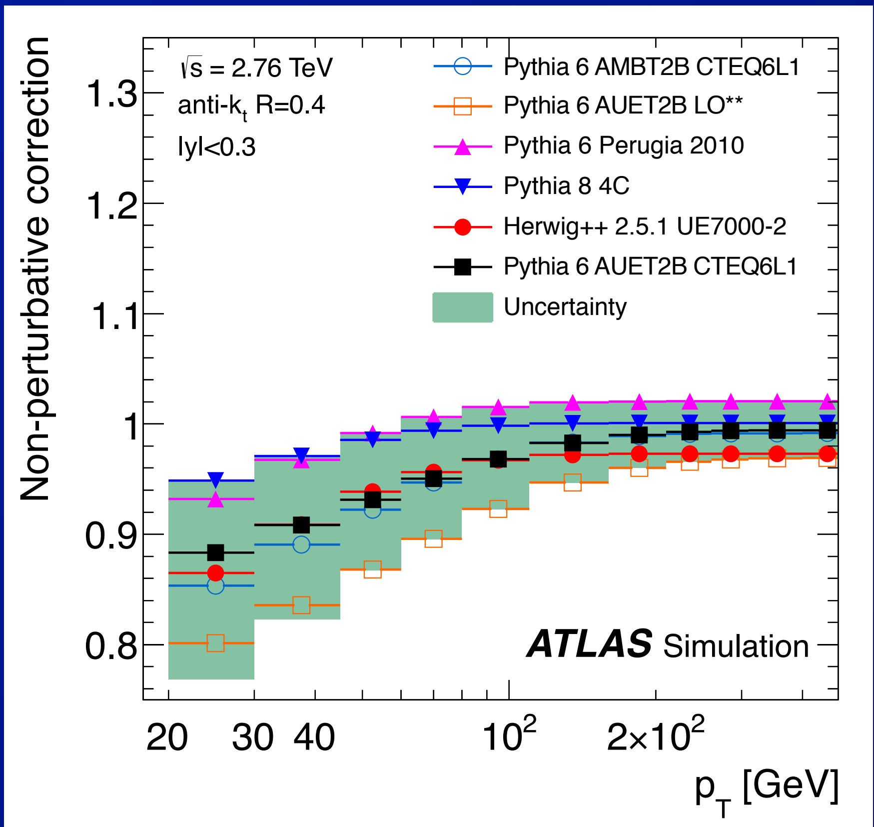
**submitted**
**to EPJC**



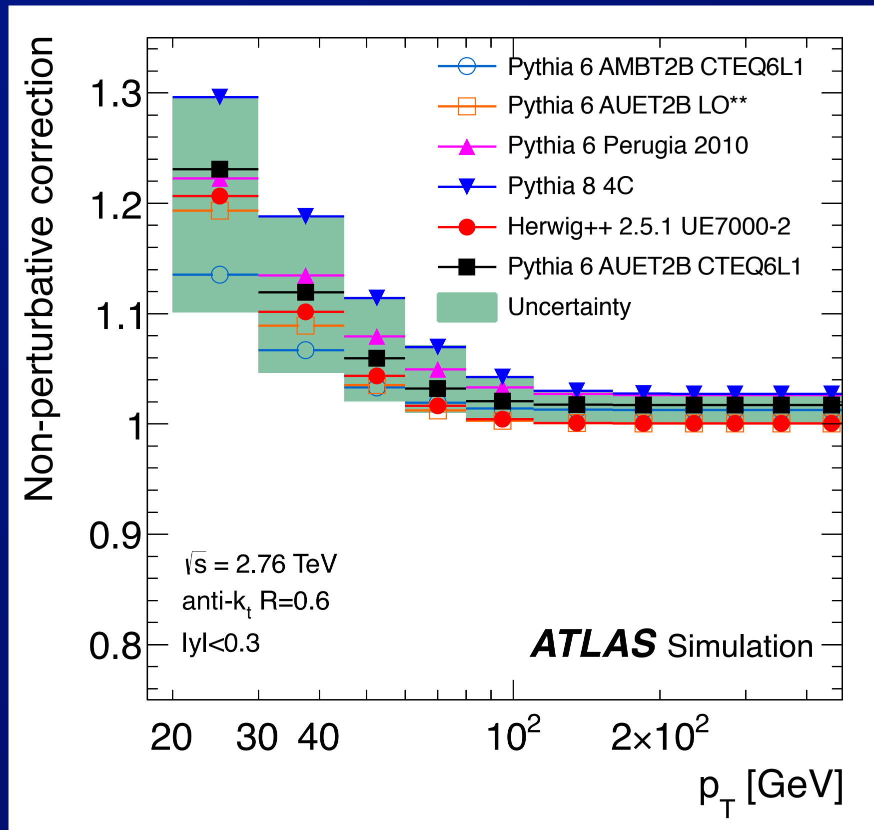
# NLOJet++, non-perturbative corrections

- NLOJet is parton-level NLO QCD weighted event generator.
  - "Non-perturbative" corrections due to parton shower, hadronizatio, UE calculated by PYTHIA

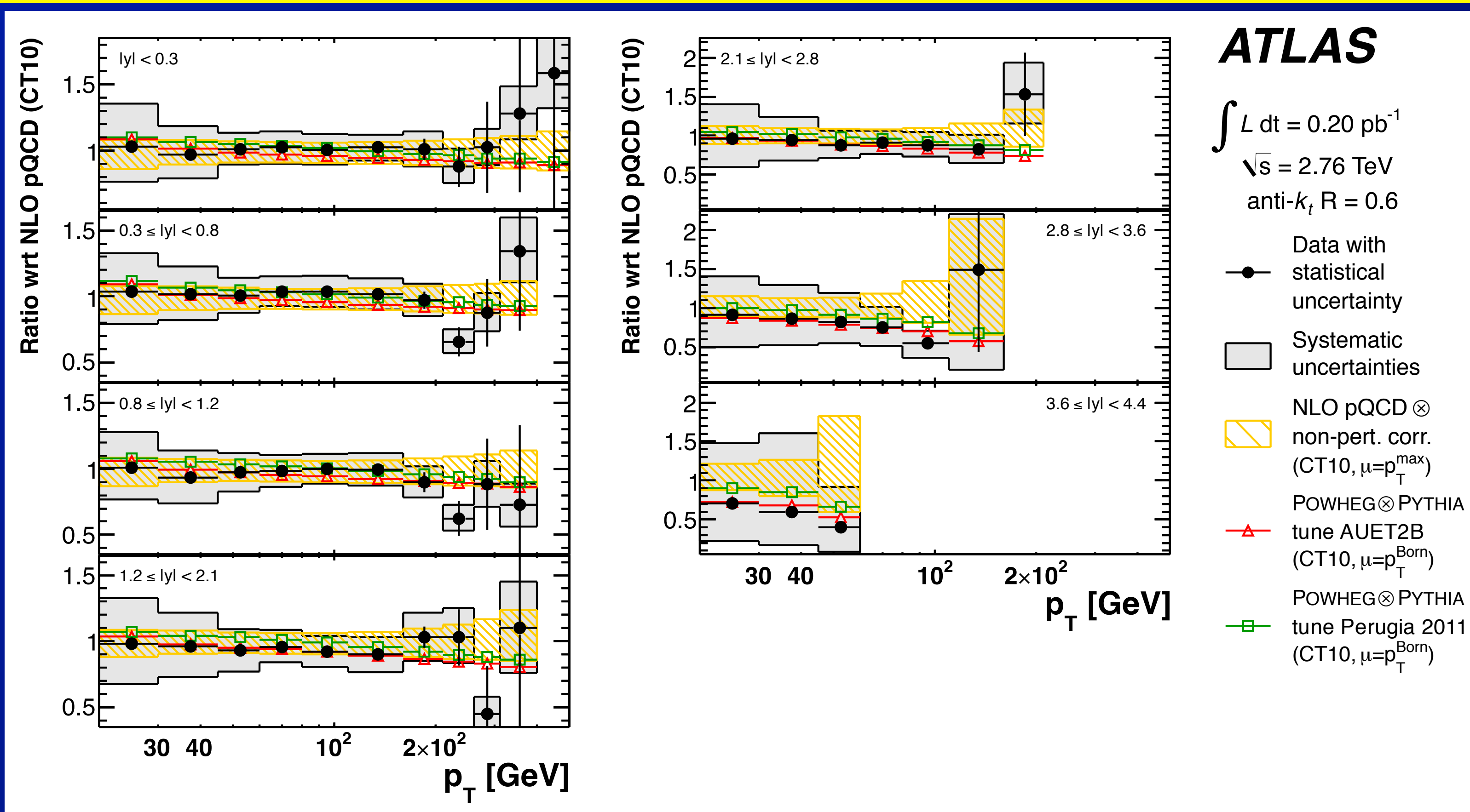
Dominated by out-of-cone loss

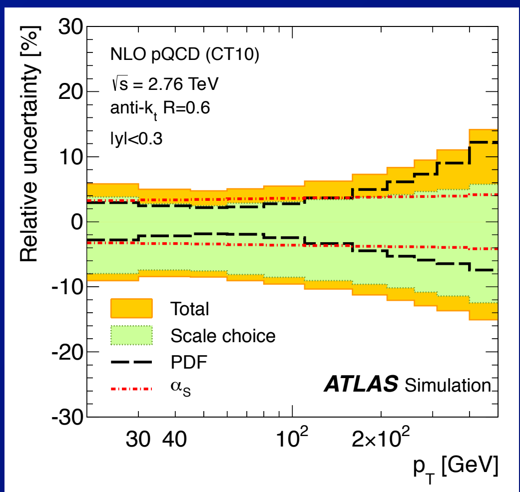



Dominated by additional PS jets

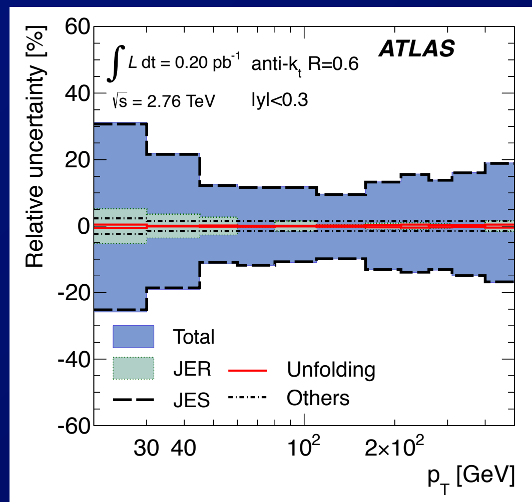


# NLOJet++ - data comparisons

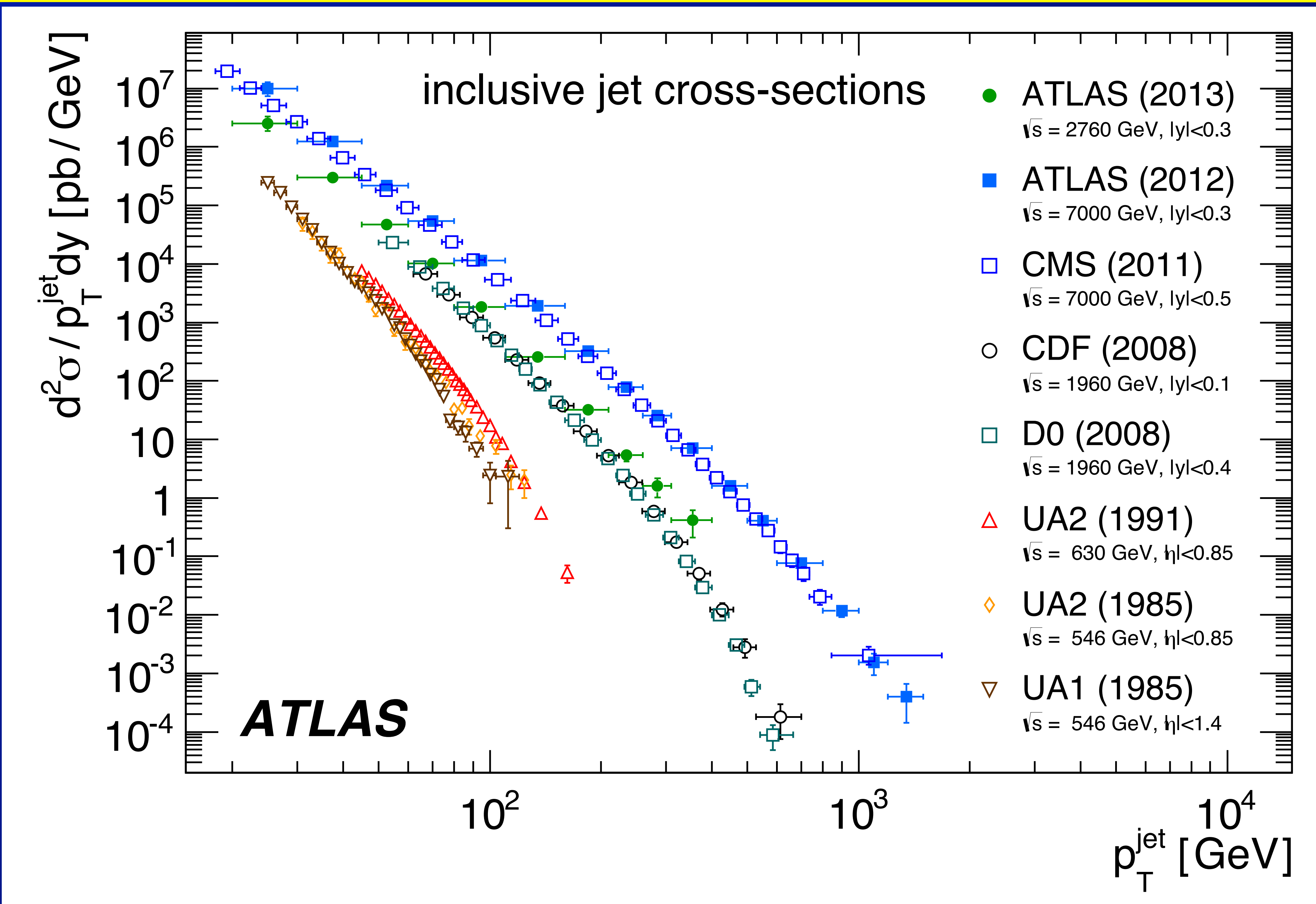



MC and data systematic uncertainties



# p-p jet cross-sections @ 2.76 TeV



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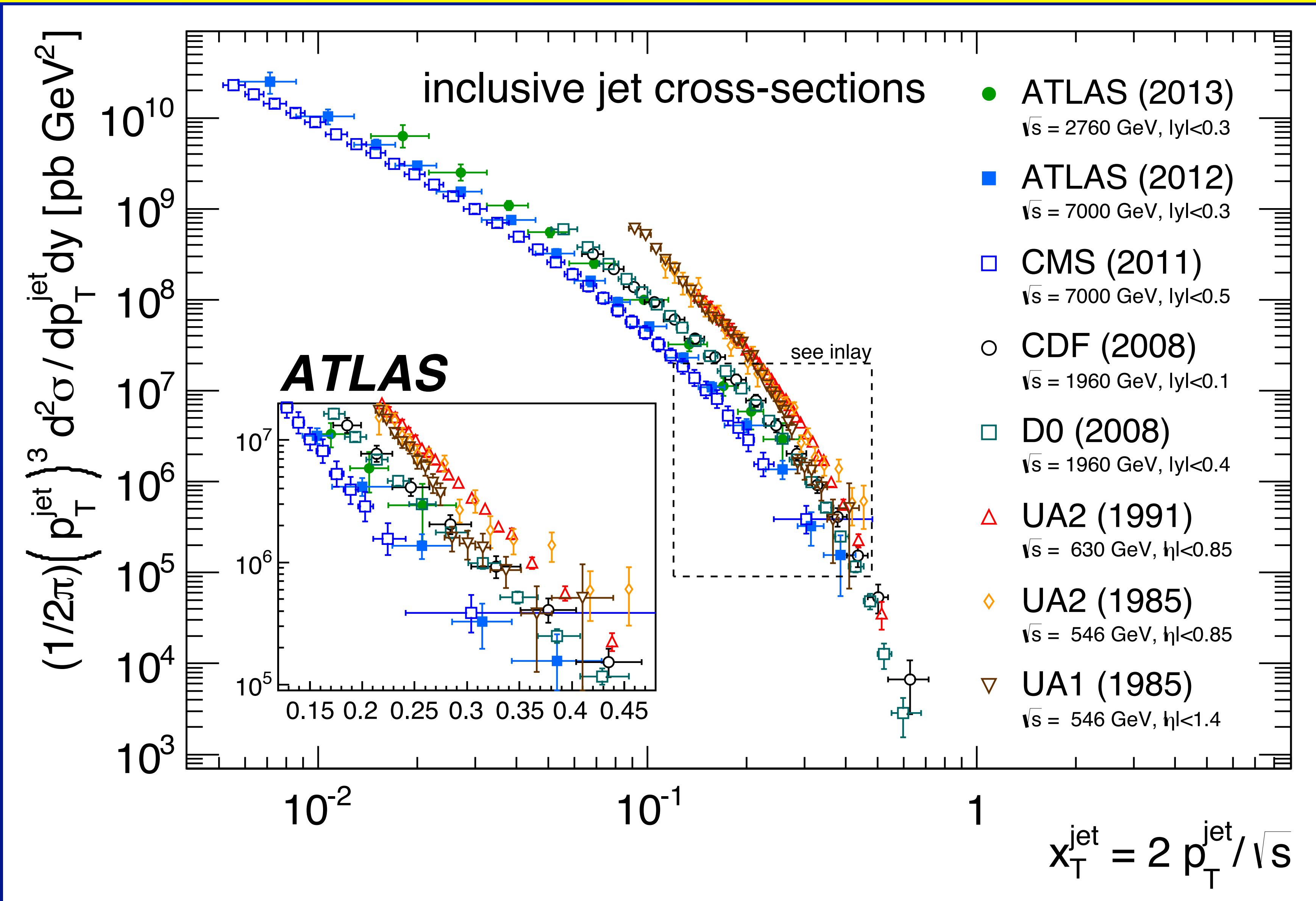
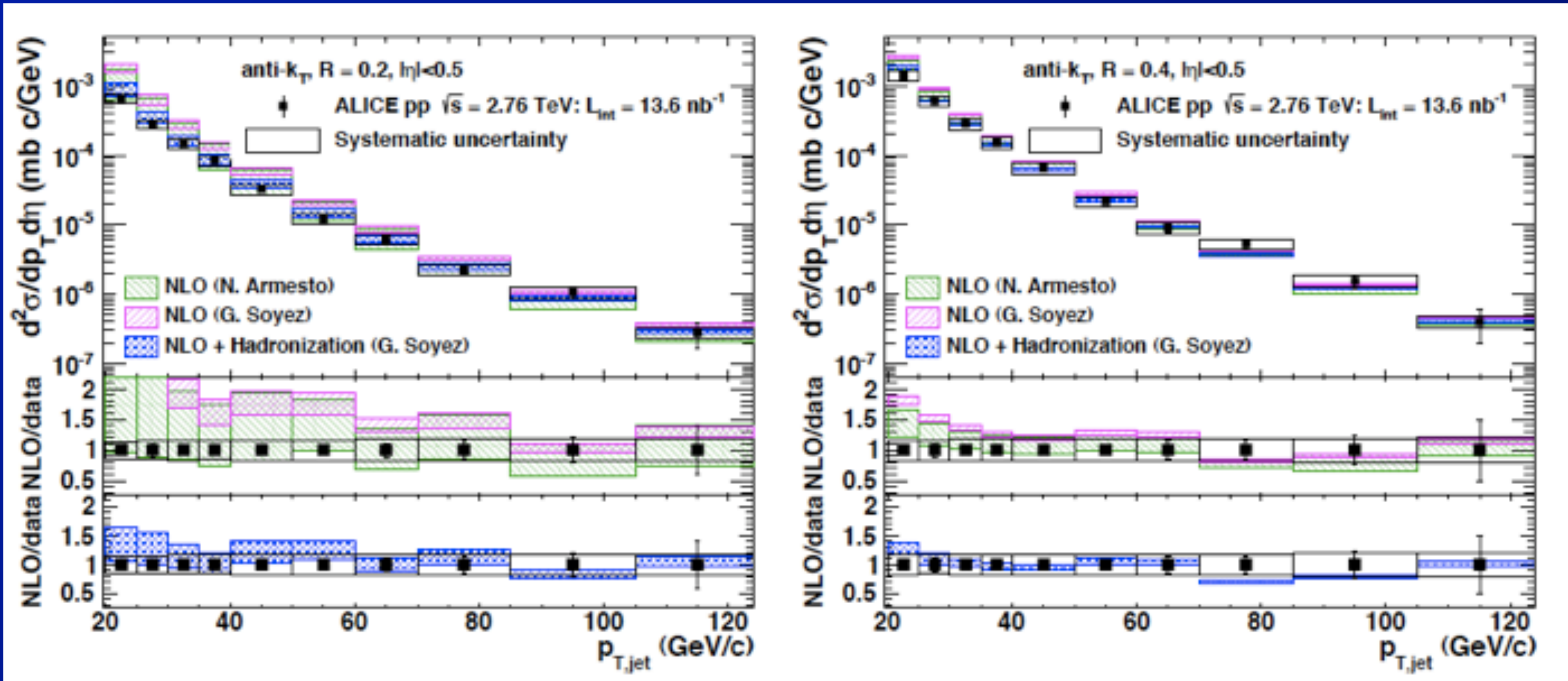


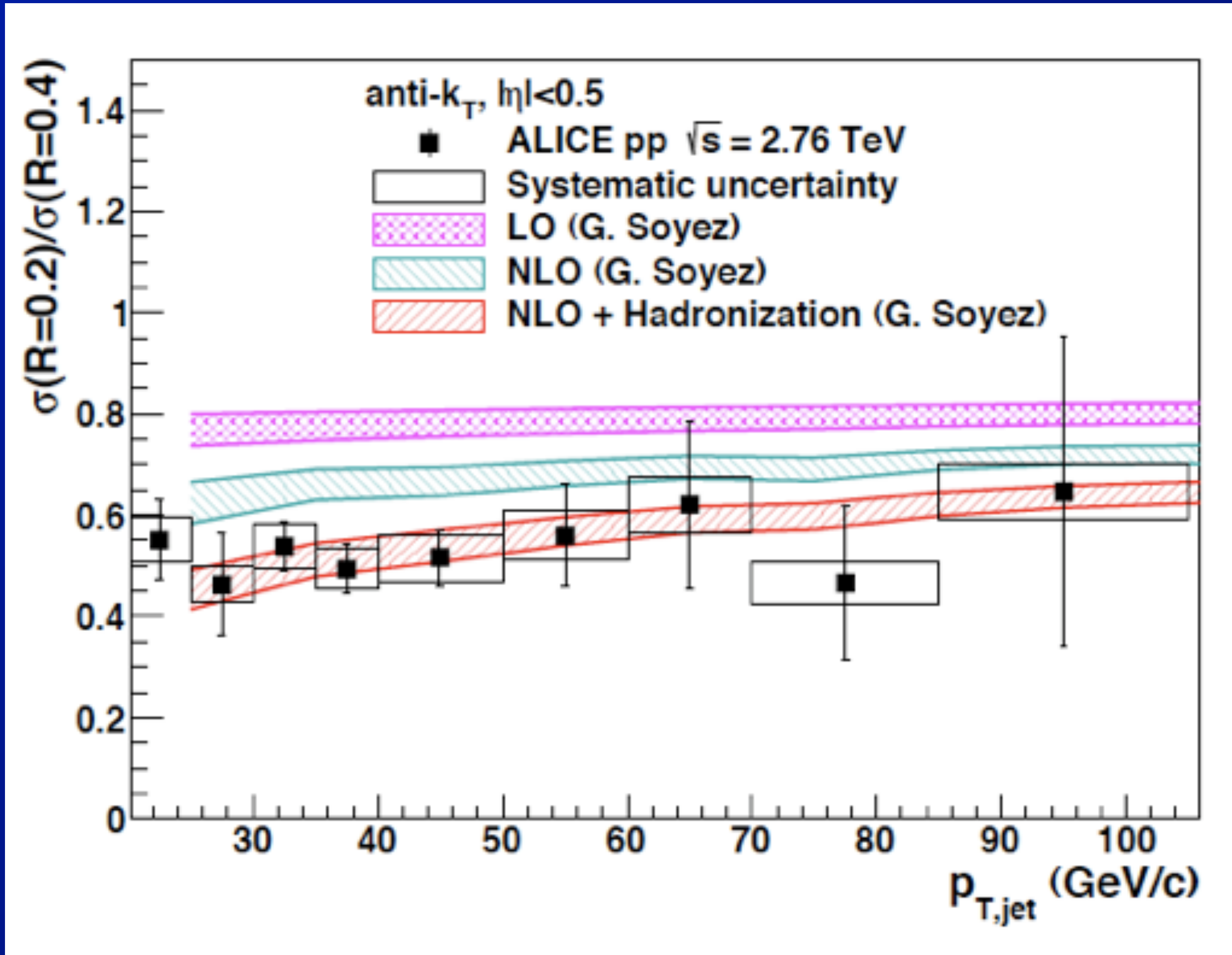

- Different η, y ranges, algorithms, sizes,…

# p-p jet cross-sections @ 2.76 TeV



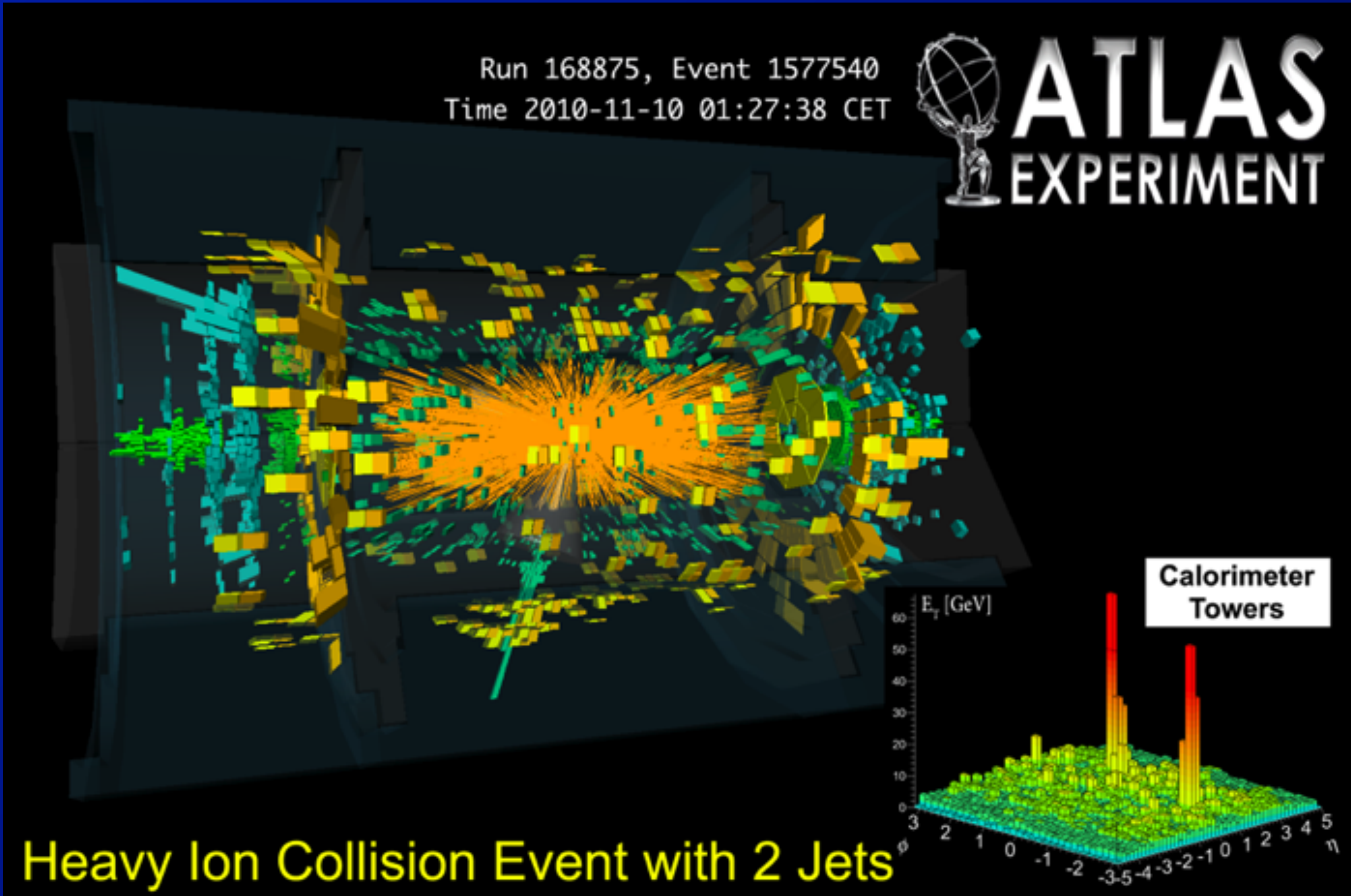

- Measured using TPC tracks + EMCal
  - anti-$k_T$, R = 0.2 (left), 0.4 (right)
- Compared to two different NLO calculations
  - one NLO + hadronization

# p-p jet cross-sections @ 2.76 TeV

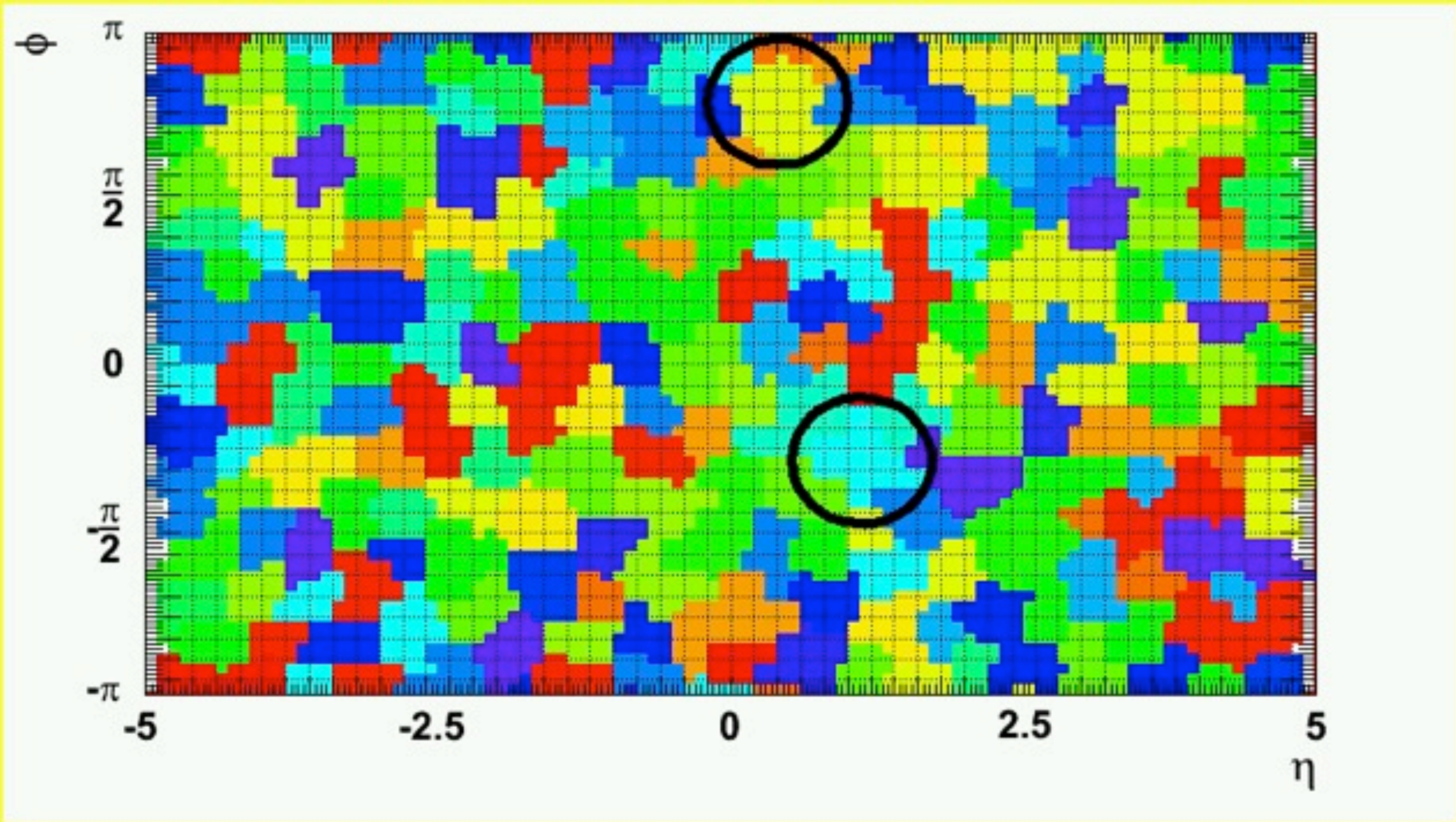



- (analytic) hadronization and (N)NLO make ~ equal contributions to (N)LO calculation.

# Heavy ion collisions



# The starting point




- Reconstruct (unsubtracted) Pb+Pb event
  - Here, for demonstration, with $k_t$ algorithm
    - ⇒But the kt algorithm is problematic because the background jets "eat" edges of real jets

# The underlying event

- ~ universal starting point for UE subtraction
  - $E_T^{\mathrm{subtr}} = E_T^{\mathrm{unsubtr}} - \rho A$

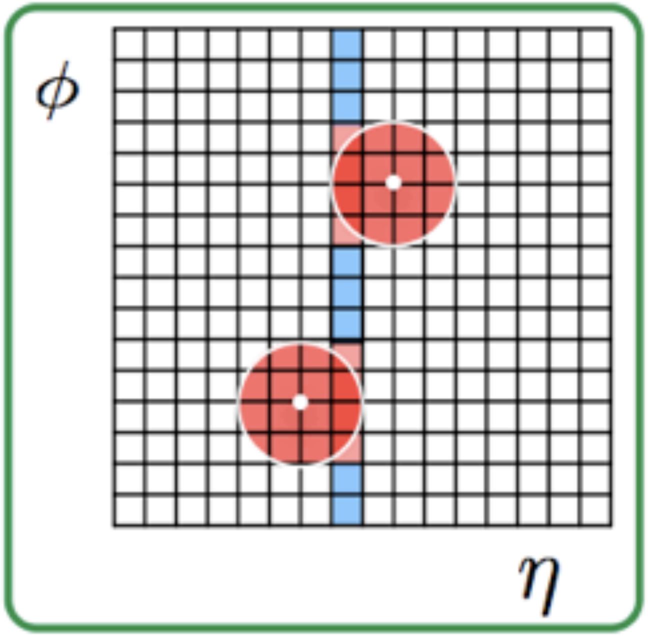
    ➡ But the details are critical
- Important considerations:
  - What kind of objects is subtraction applied to?

    ➡ Towers, topoclusters, cells, ...
  - How to estimate UE energy density, $\rho$ ?
  - With what granularity?
  - Event -by-event or event-averaged?

    ➡ But if averaged, need separate measure of $\mu$
  - How to exclude jets, photons, ... from $\rho$ ?

# The underlying event (ATLAS)

$$\rho(\eta) = \left\langle \frac{E_{\mathrm{T}}^{i}}{\Delta\eta^{i}\Delta\phi^{i}} \right\rangle_{i \notin \mathrm{jet},\, |\eta^{i}-\eta|<0.05}$$



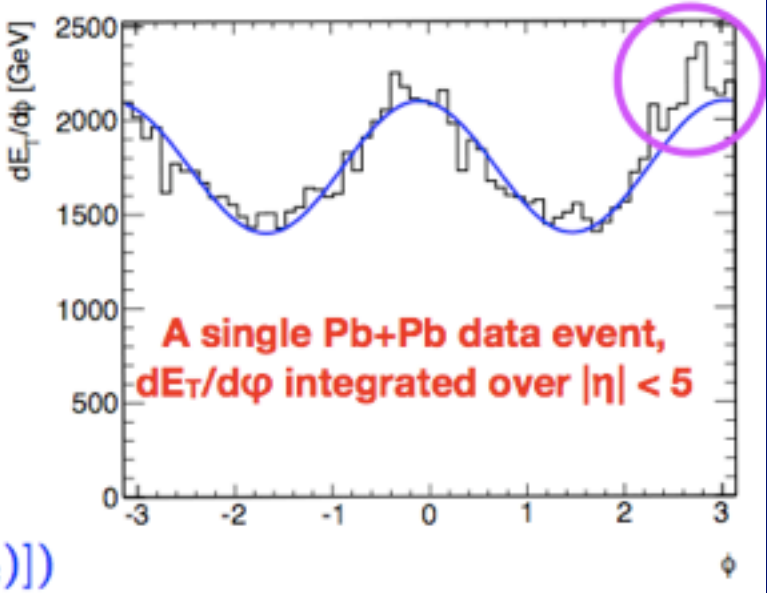

- For each Pb+Pb event:
  - For each calorimeter layer:
    - ➡ Calculate an AVERAGE (not median!) cell $E_T$ density in $\Delta\eta = 0.1$ intervals
    - ➡ Excluding cells that lie within $\Delta R = 0.4$ of seeds
- Then, apply $E_{\mathrm{T}}^{\mathrm{subtr}} = E_{\mathrm{T}}^{\mathrm{unsubtr}} - \rho A$ to each cell within tower constituents of reconstructed jets

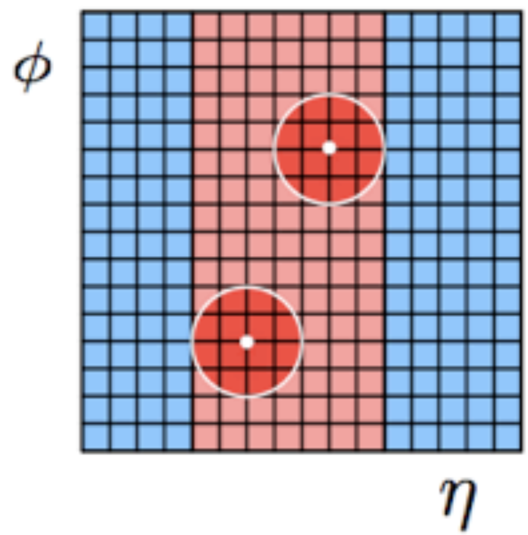
# The underlying event (ATLAS)

- Pb+Pb collisions present additional complications
  - collective flow in the UE
    - ➡ as large as ± 20%
    - ➡ fluctuates event to event
- Accounted for in subtraction
  - $\rho^{\mathrm{Pb+Pb}}(\eta, \phi) = \rho(\eta)(1 + 2v_2^{\mathrm{UE}} \cos[2(\phi - \Psi_2)])$
- With amplitude of modulation ($v_2$) determined event-by-event

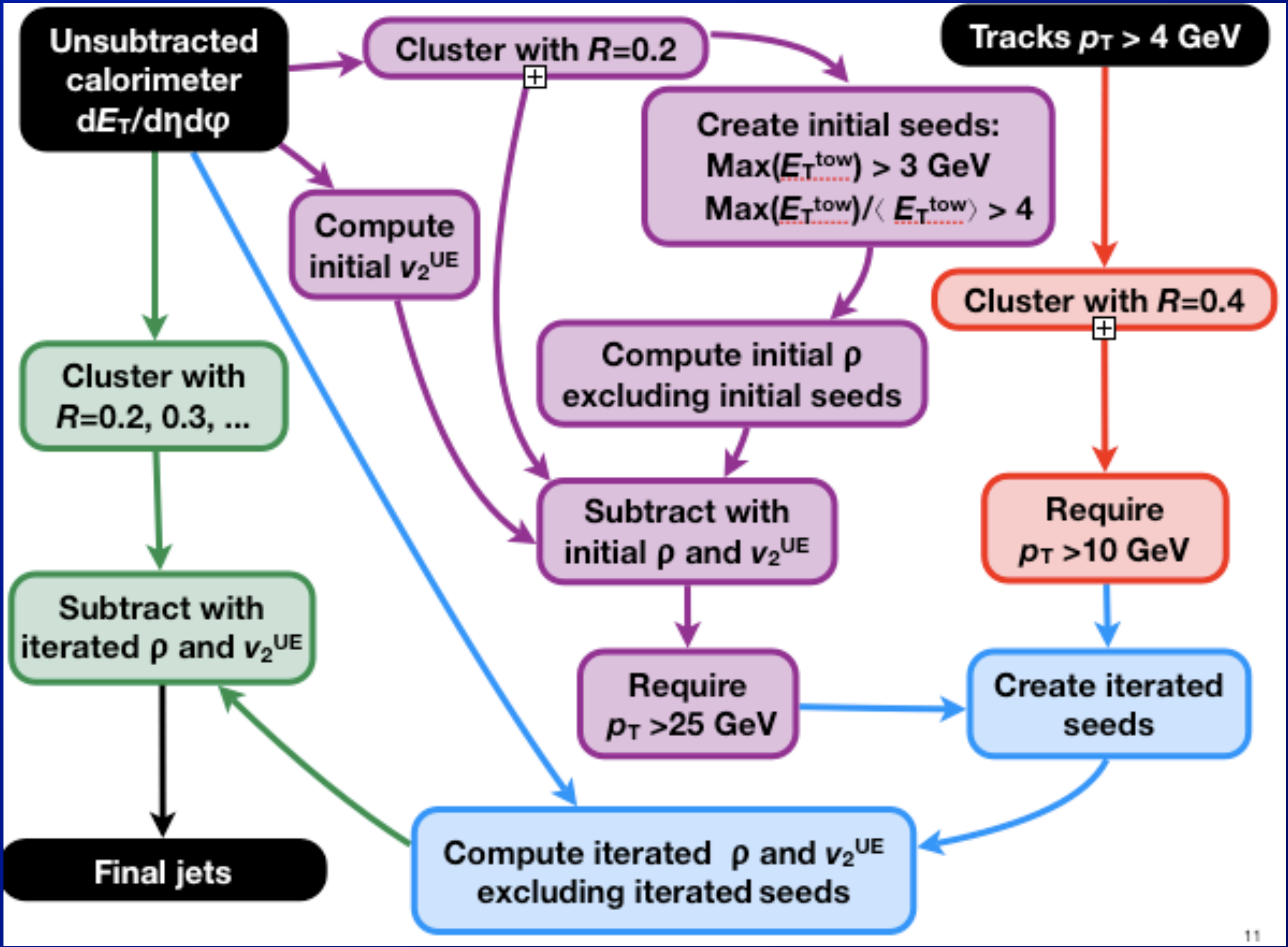
$$v_2^{\mathrm{UE}} = \langle E_{\mathrm{T}}^i \cos[2(\phi^i - \Psi_2)]\rangle_{i \notin \mathrm{jet}}$$

➡ excluding any η interval containing a seed



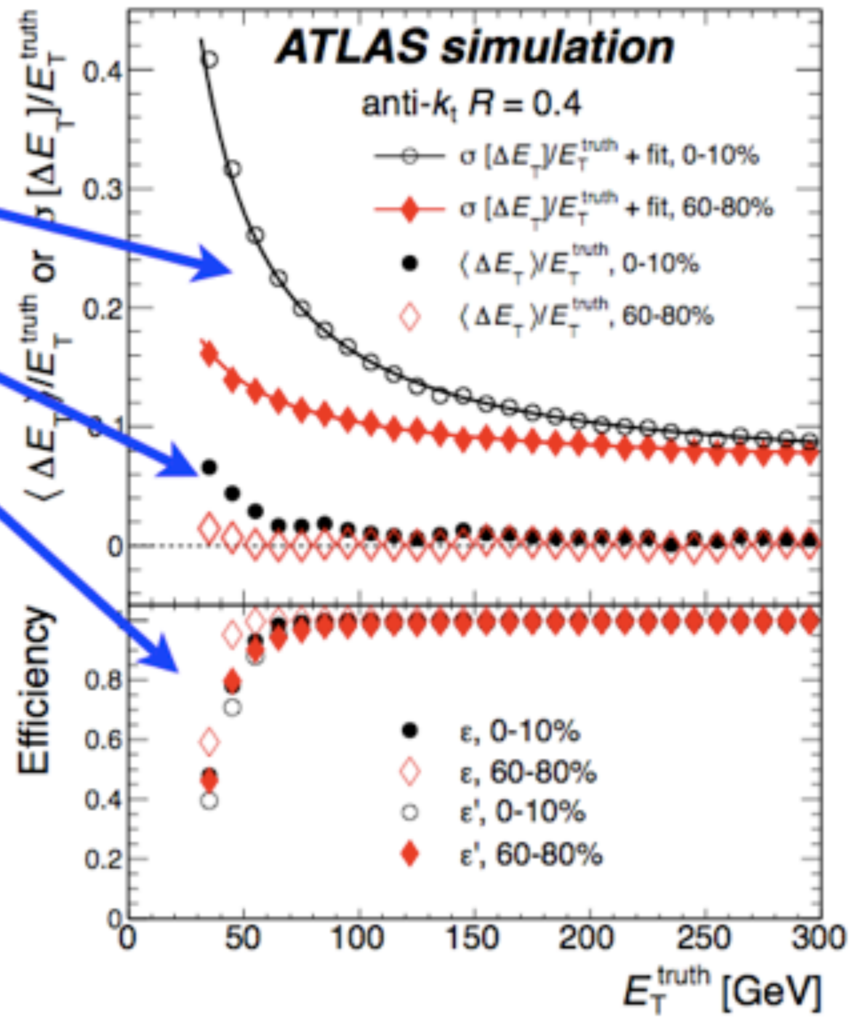



# The underlying event (ATLAS)



# ATLAS jet performance

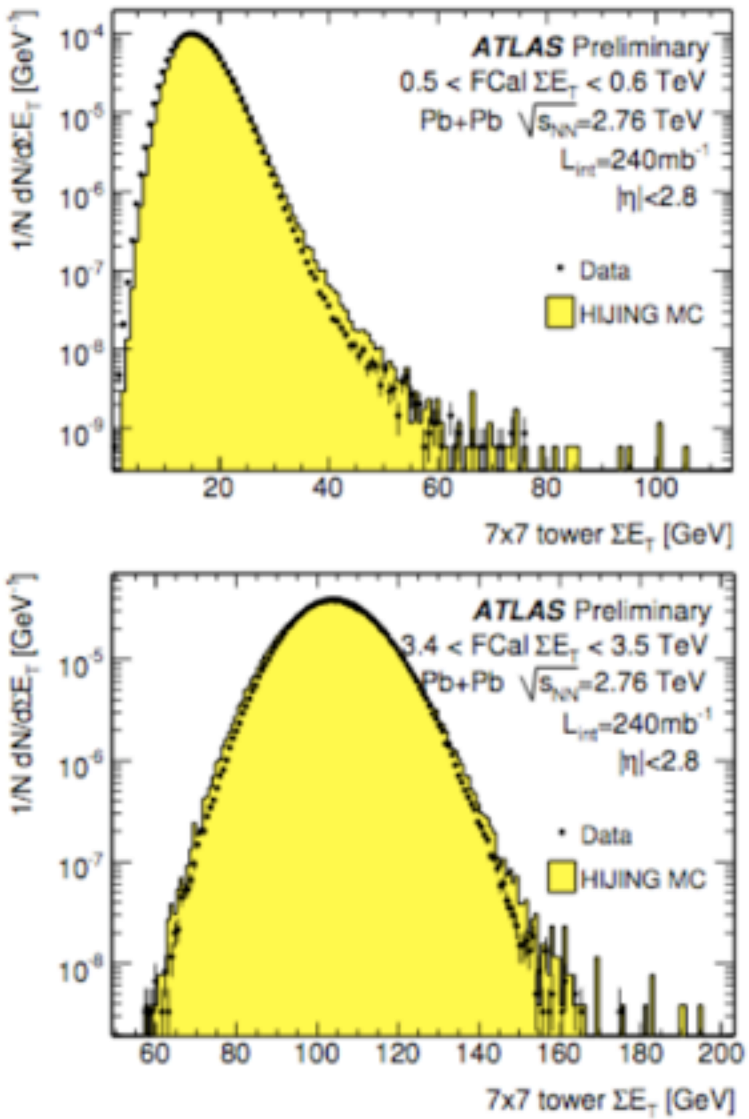
- Three metrics
  - Jet energy resolution
  - Jet energy scale
  - Jet reconstruction efficiency
    - ➡ with (ε') and without (ε) fake rejection
- Of these, we only have control over JES
  - ➡ Sensitive test of background subtraction




- Jet is considered not fake if within R = 0.2:
  - R = 0.4 track jet (rec. from tracks w/ $p_T > 4$ GeV), photon, or electron with $p_T > 7$ GeV

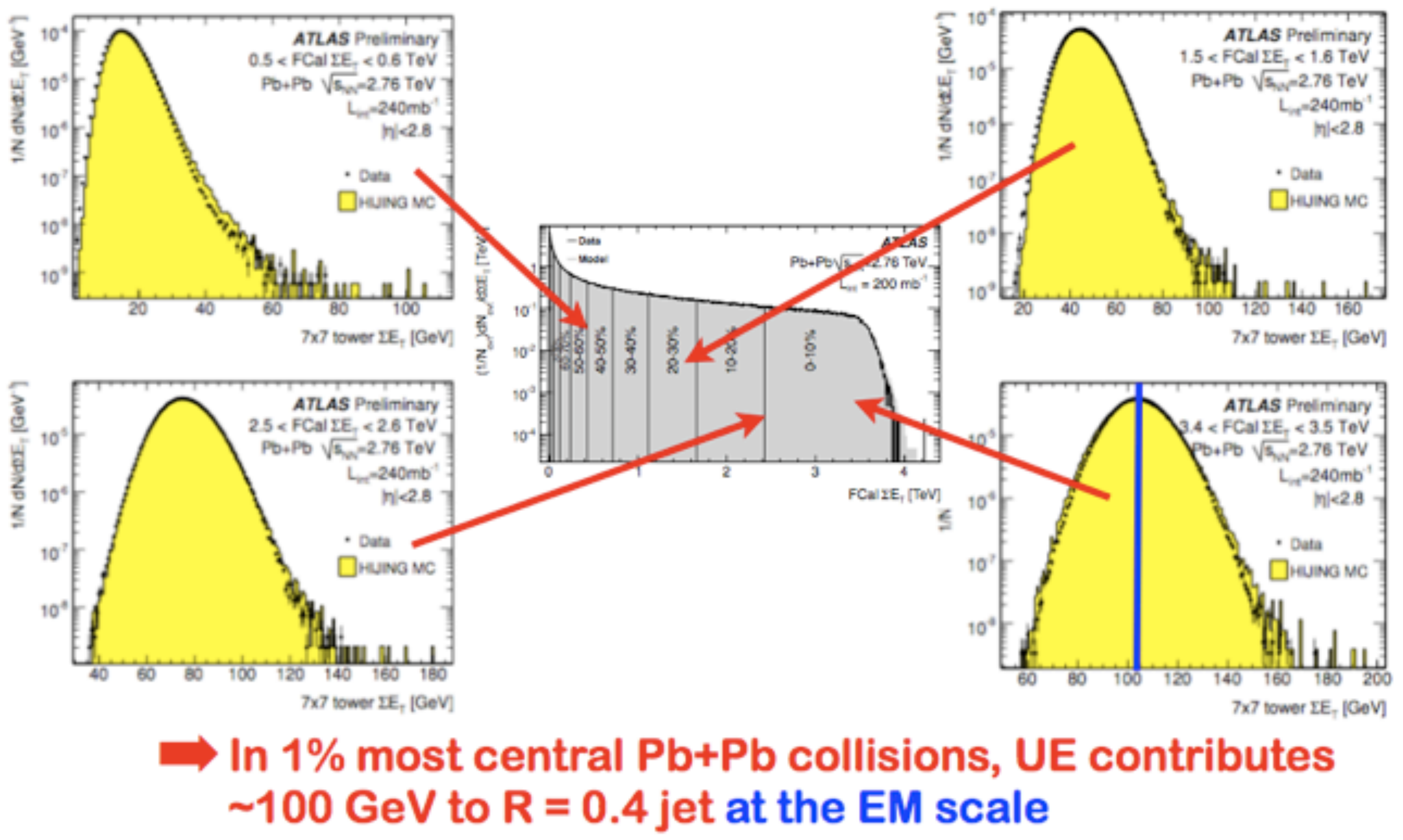
# The underlying event (ATLAS)

- In minimum-bias Pb+Pb events
  - Sum EM-scale tower $E_T$ over NxN groups of towers ($\Sigma E_T$)
  - N chosen to match jet sizes
    - ➡ R = 0.4 ↔ 7x7 ($\pi \times 0.4^2 = 0.50$)
- Distributions shown to right for two different centralities
  - ➡ top: peripheral
  - ➡ bottom: central
- Observe:
  - ➡ Distributions are NOT Gaussian (Gamma dist's)




- For the student: why gamma dist's?

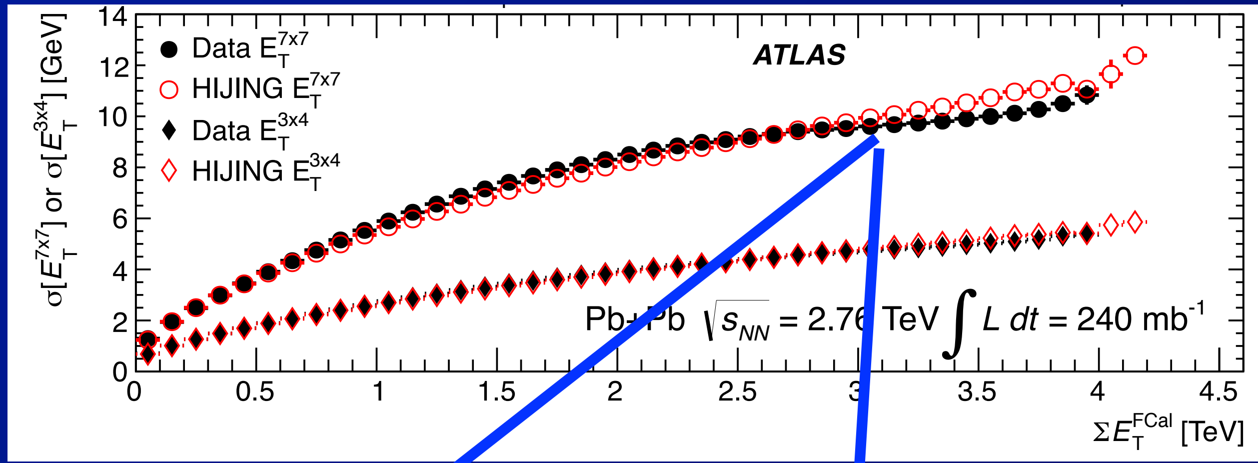
# The underlying event (ATLAS)




- Important: subtracting the correct average energy preserves jet energy scale.
  - Fluctuations on mean affect resolution.

# ATLAS jet performance (2010 data)

**Data-driven evaluation of underlying event fluctuations**




**HIJING MC evaluation of performance**