Underlying Event I

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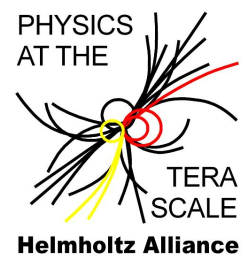


Outline

- Lecture I — Underlying Event: Introduction.
  - Triggers, harder triggers, experimental facts.
- Lecture II — Underlying Event: Modelling.
  - Mostly Herwig++

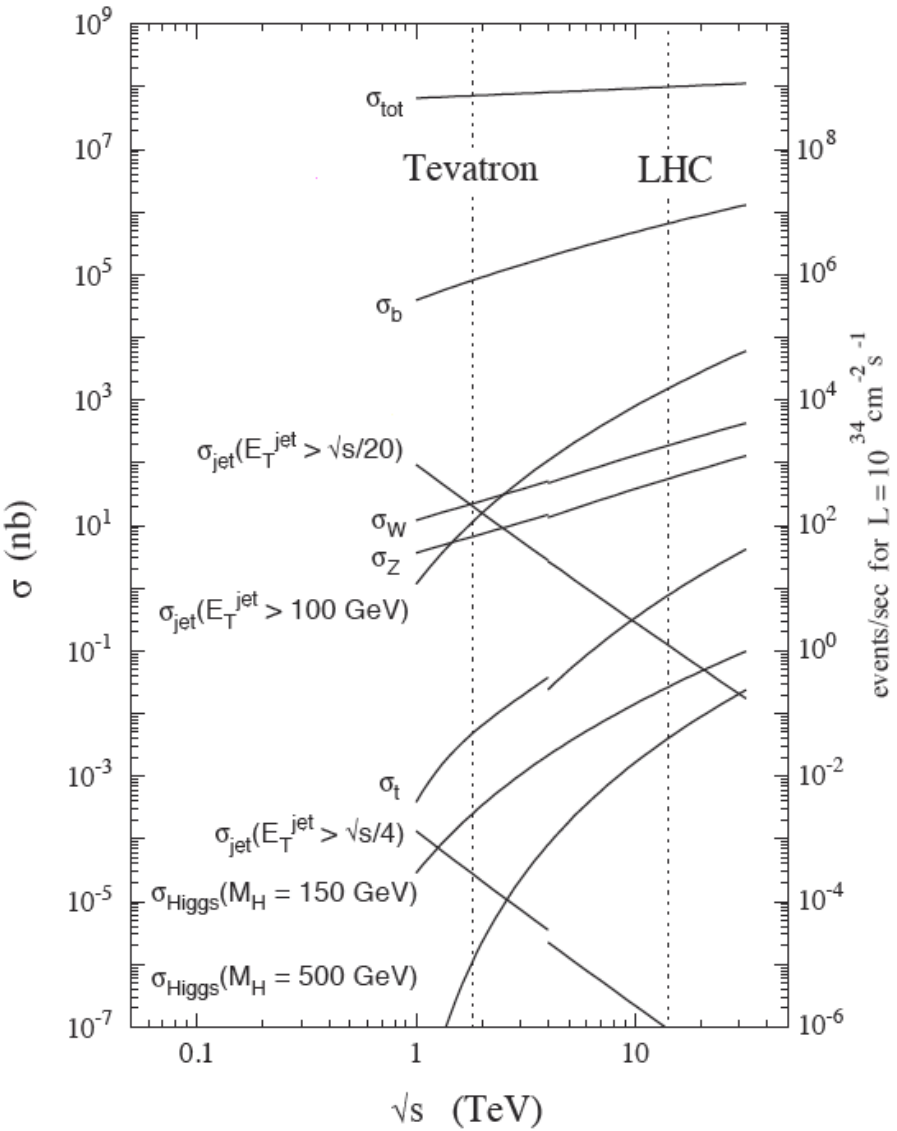
Outline Lecture I

- Collider cross sections
- Zero bias, Min bias, Underlying event
- Inclusive $\rightarrow$ exclusive. The structure of underlying events.
- Multiple interactions.

Collider cross sections

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{SD}} + \overbrace{\sigma_{\text{DD}} + \underbrace{\sigma_{\text{soft}} + \sigma_{\text{hard}}}_{\sigma_{\text{ND}}}}^{\sigma_{\text{NSD}}}$$

Collider cross sections



What is the Underlying event?

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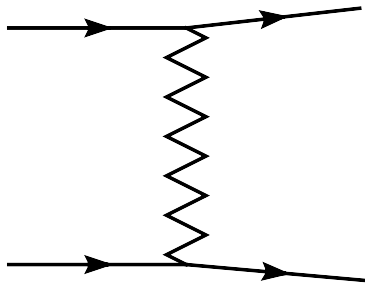

elastic

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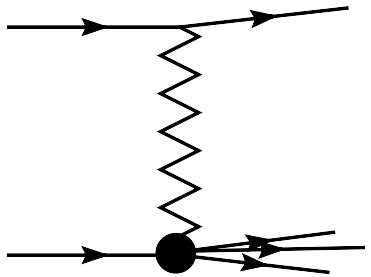

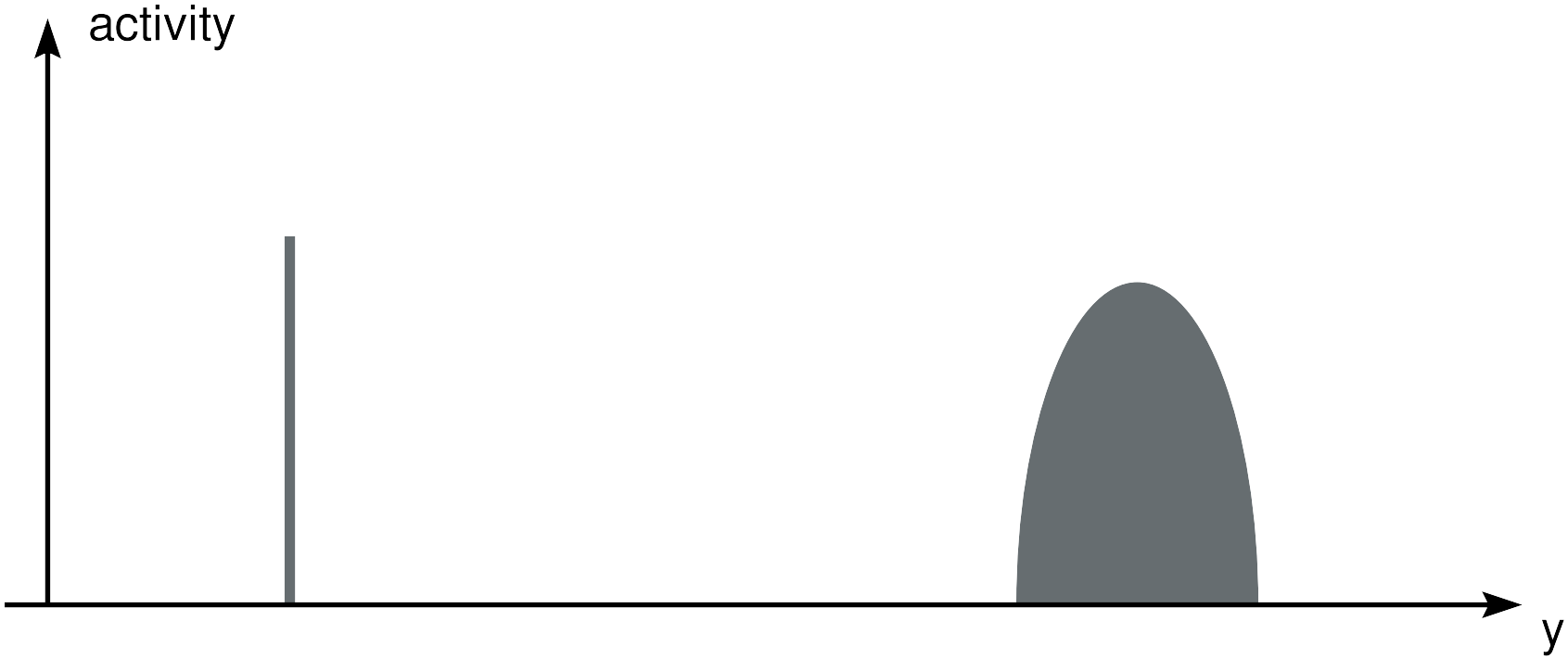

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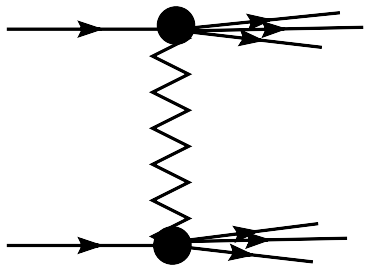

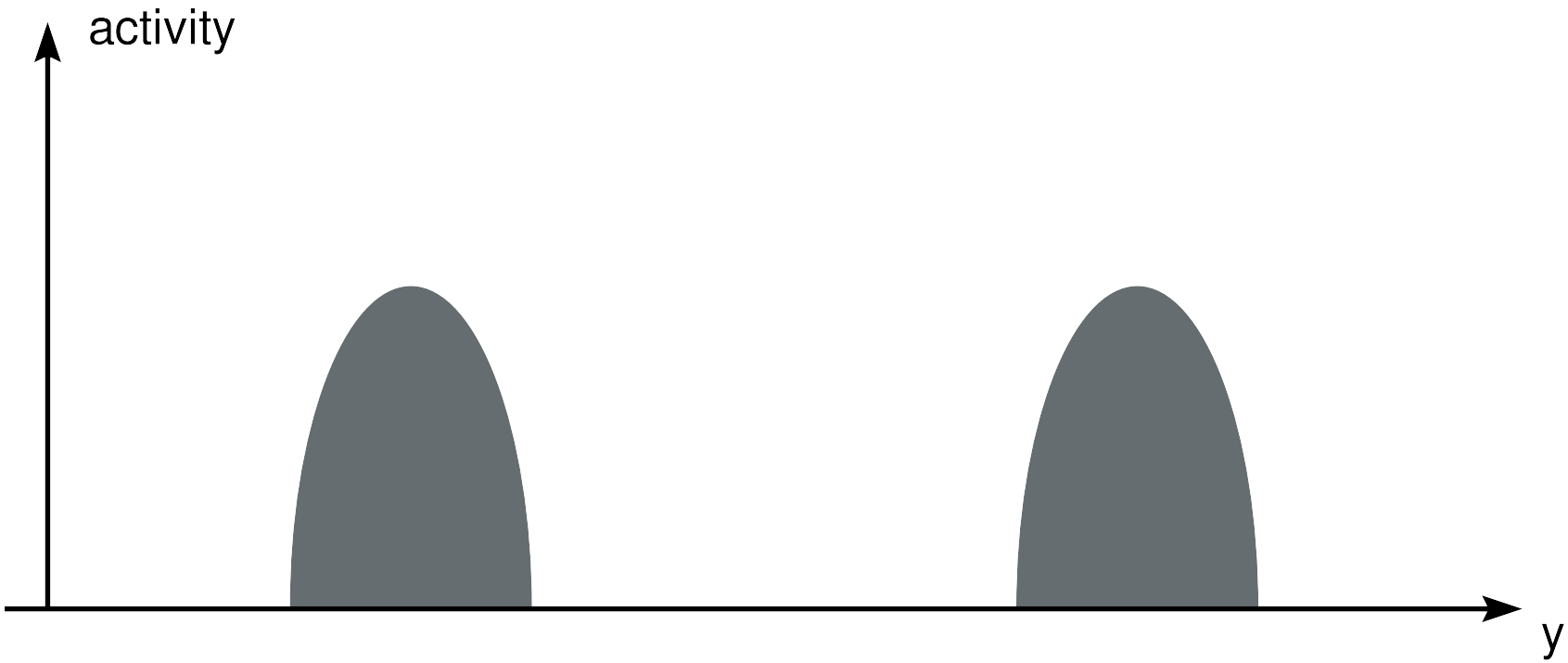

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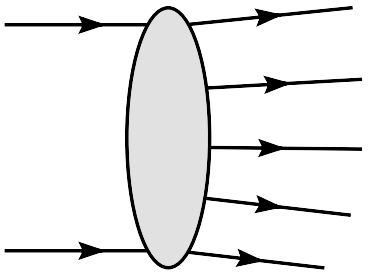

(multiple/soft) interactions

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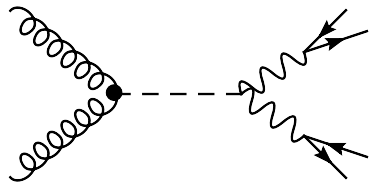

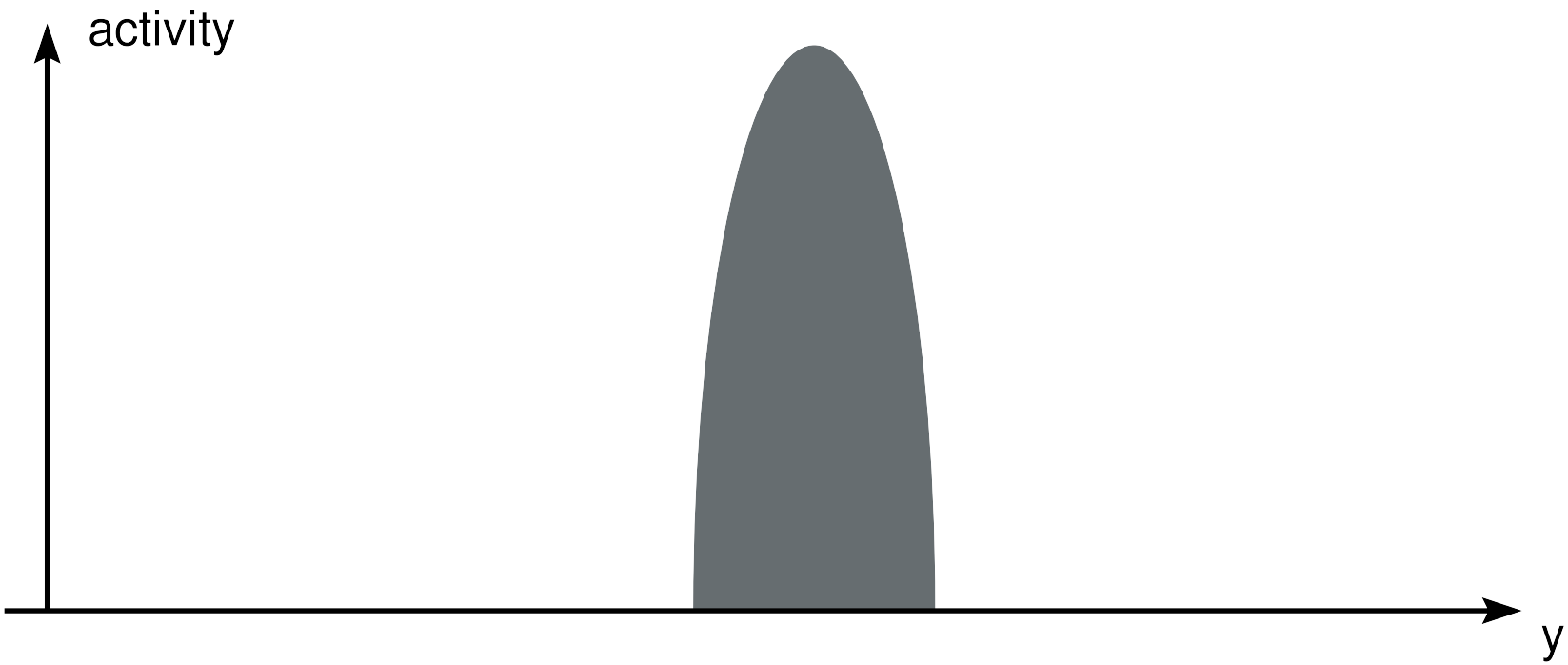

hard scattering

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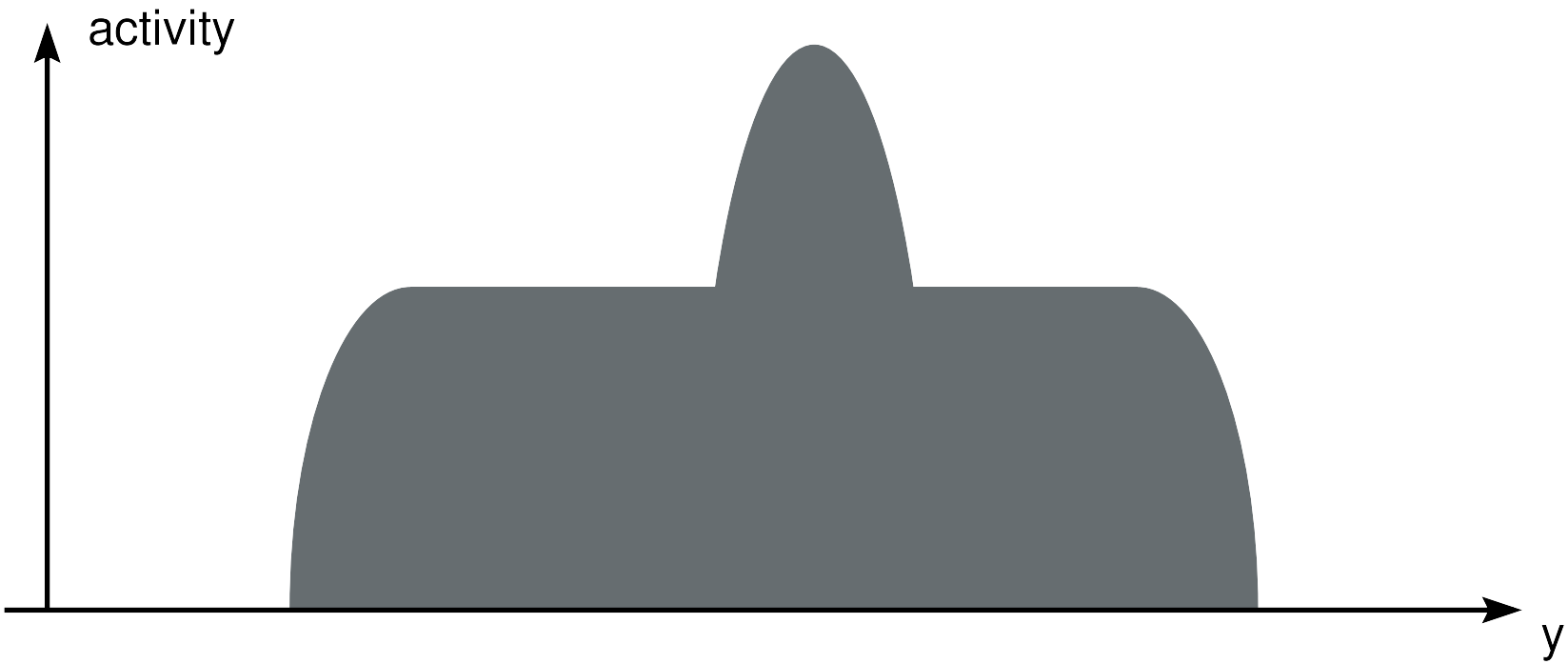

hard scattering + underlying event

What is the Underlying event?

"Everything except the process of interest."

- Experimentalist: "includes parton showers etc."
- MC author: "everything on top of primary hard process."

The Underlying event (UE) is everywhere in the detector.

- Cannot select UE
- May spoil measurements.
- What characteristics?
- Hard?
- Soft?

Why should I learn about it?

- UE comes with every event.
- Can't trigger/select it away.
- Gives additional tracks and calorimeter hits, in the same cells as your signal.
- Jet energy scale determination.
- Important systematic error.
- Jets where your signal shouldn't give any (VBF).

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  - *Every* event in a perfect 4π detector.

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  - At least have to distinguish from noise/cosmics.
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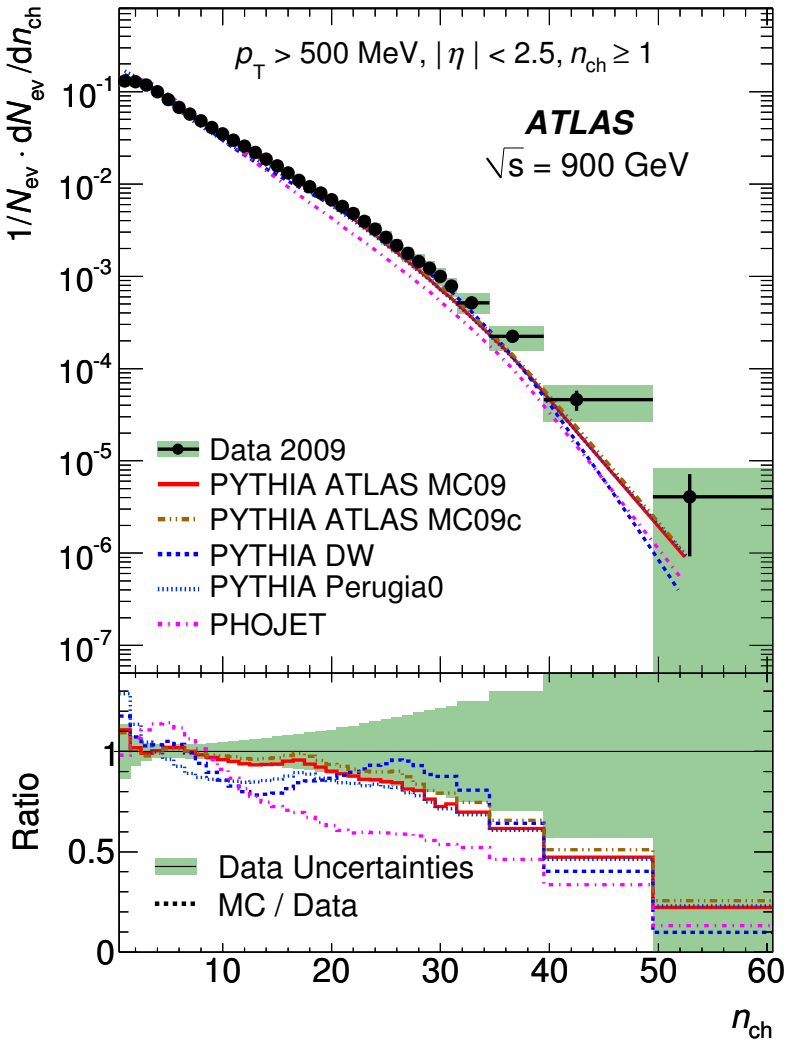
Physics in MB and UE very similar.

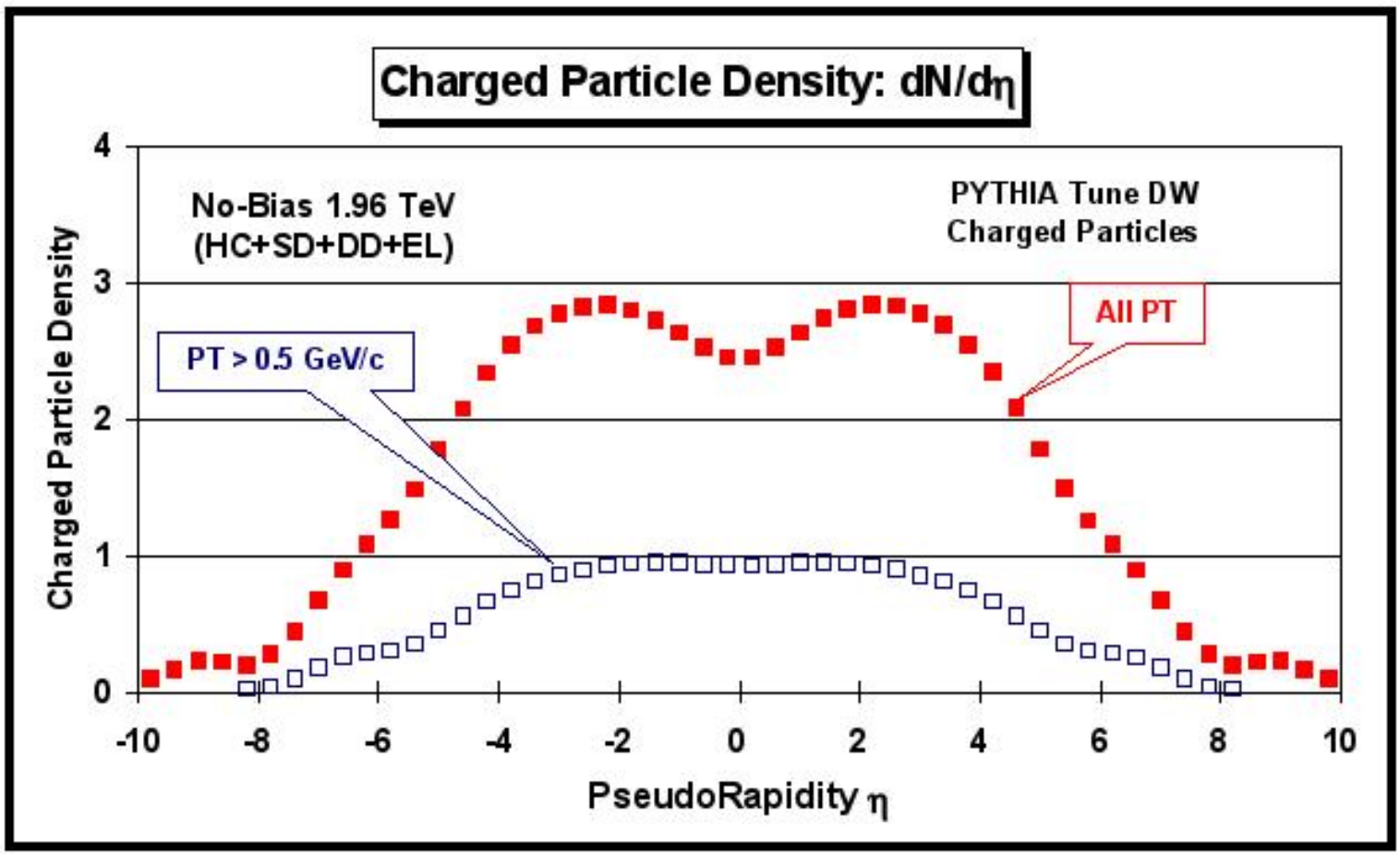
Charakteristics of MB events

N_{ch}



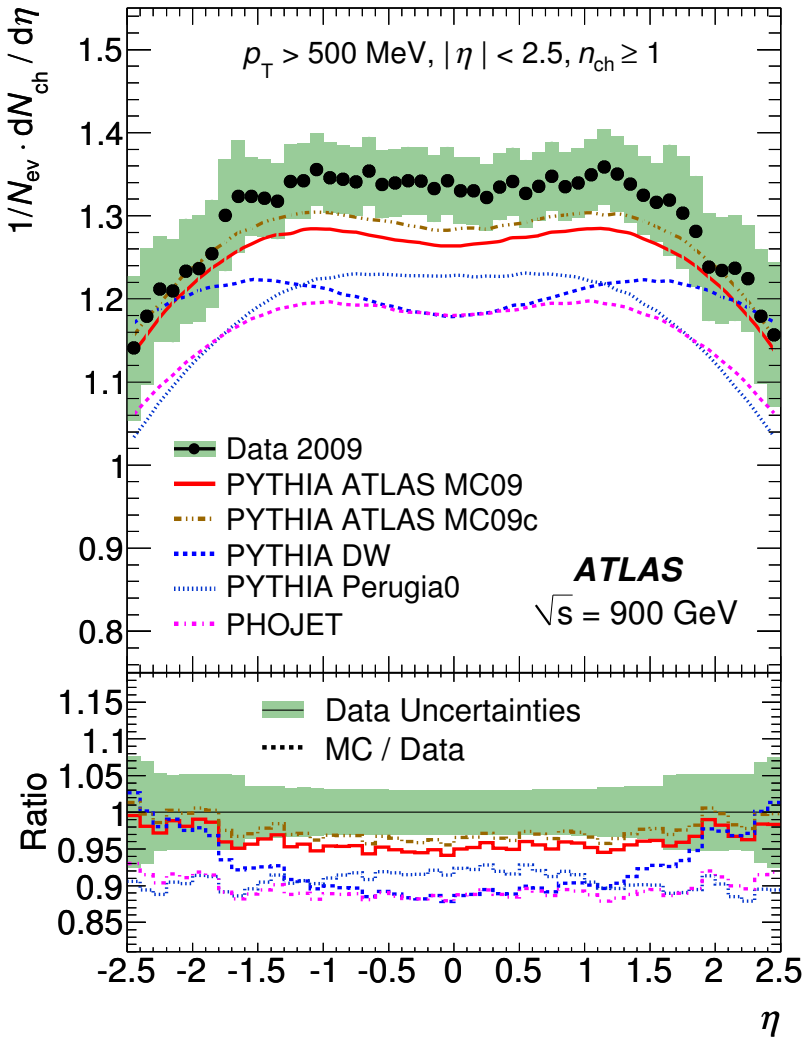
Charakteristics of MB events

$dN/d\eta$ Zero bias vs min bias (Tevatron)



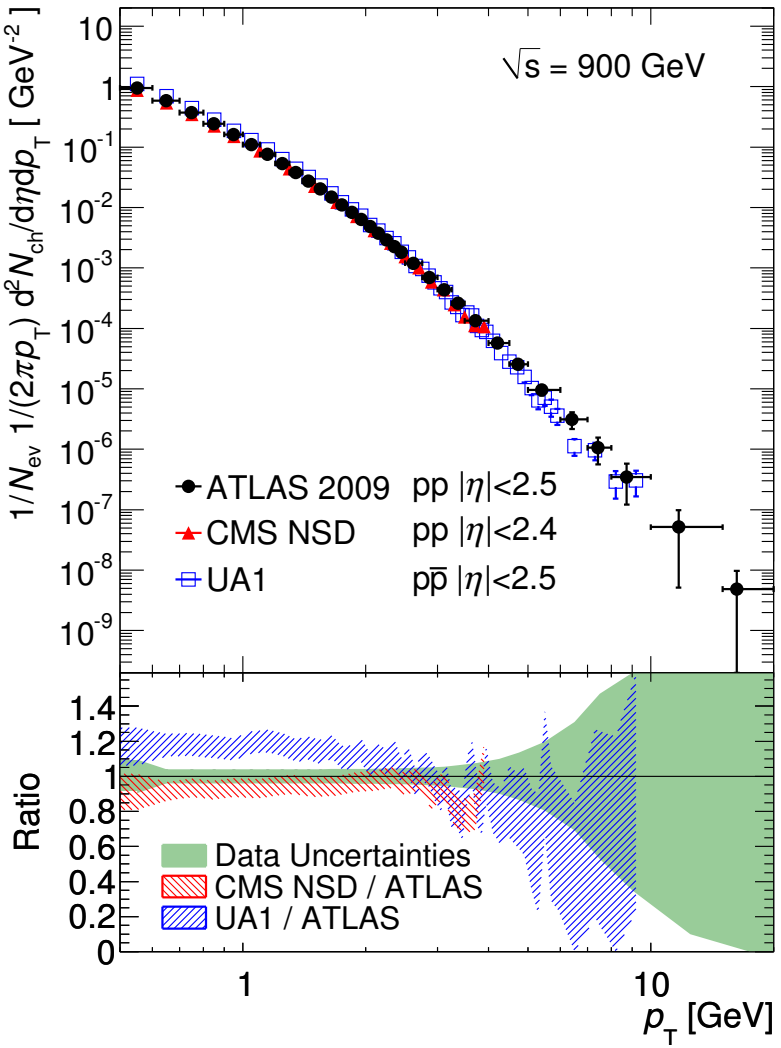
Charakteristics of MB events

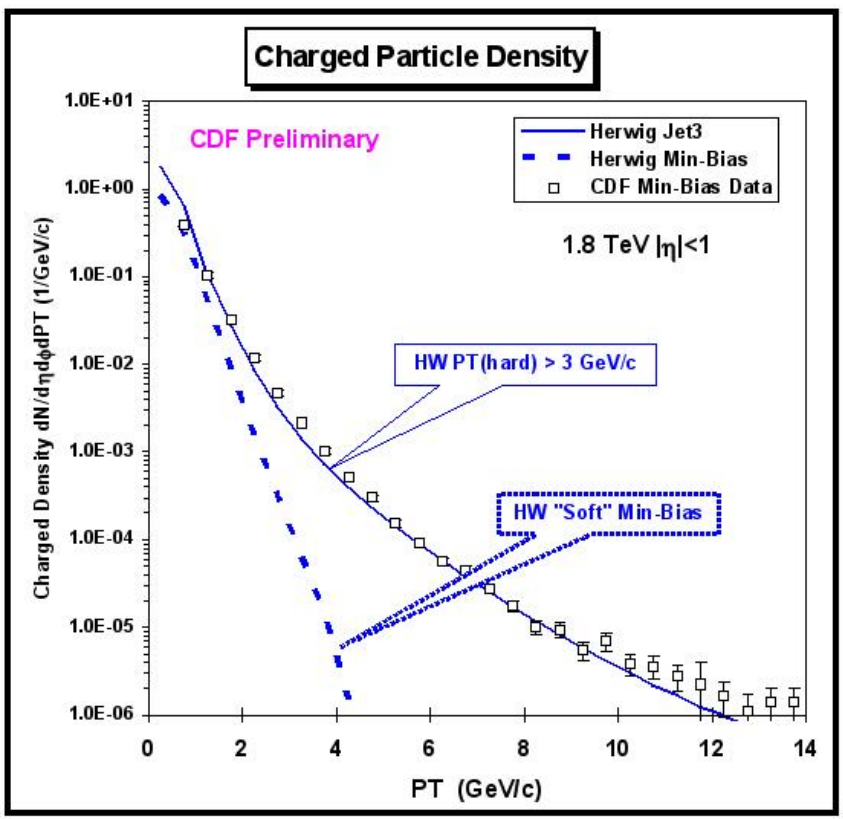
$dN/d\eta$ ATLAS



Charakteristics of MB events

$p_\perp$ spectra of all particles





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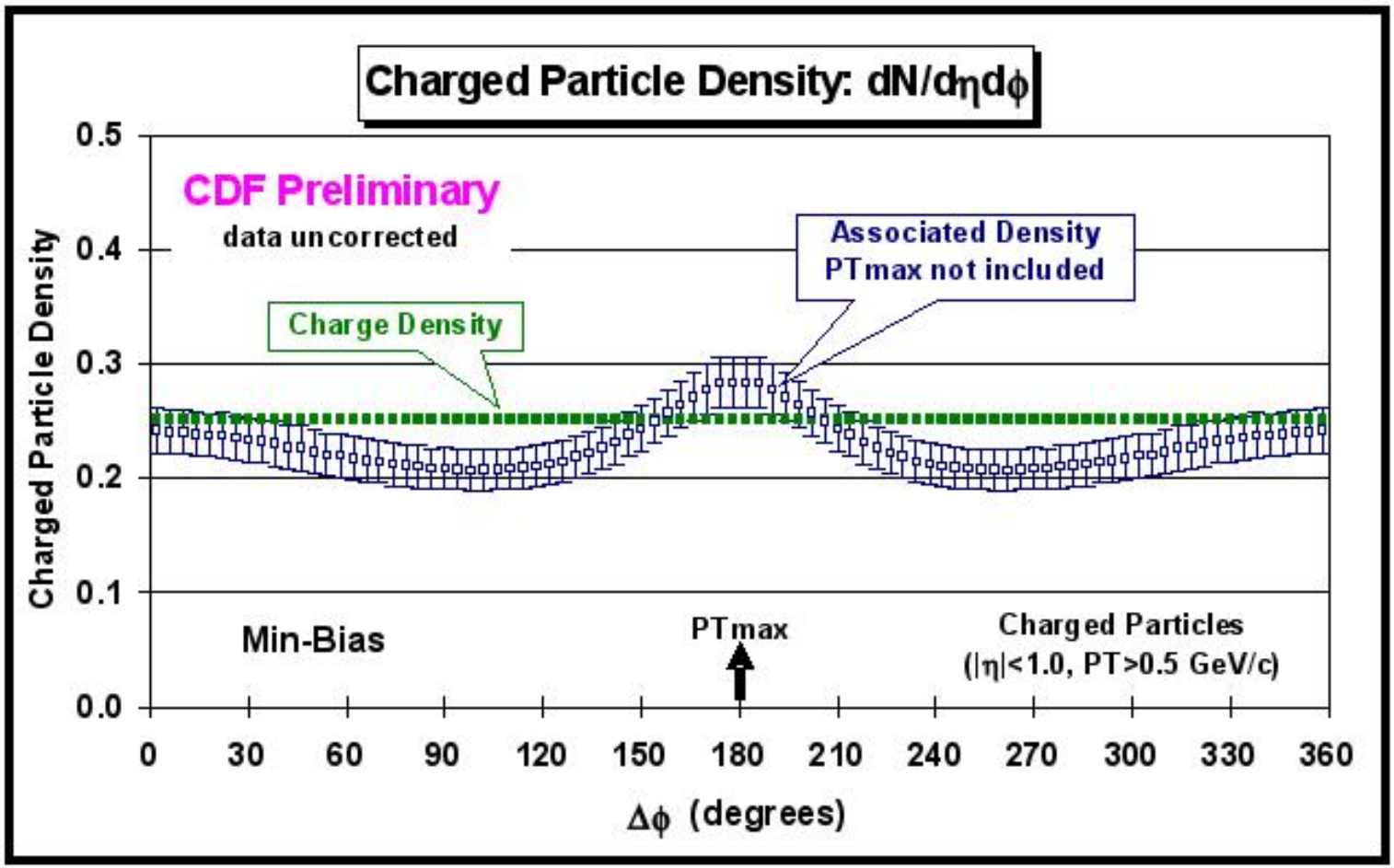
Charakteristics of MB events

- Inclusive quantities have to be correct, of course.
- Already show, that soft component is important in modelling.
- Don't tell much about morphology of event.
- $\rightarrow$ look at distributions inside detector.
- $\rightarrow$ leading particles.

Azimuthal distributions

Measure $\Delta\phi$ relative to leading particle/jet/track.



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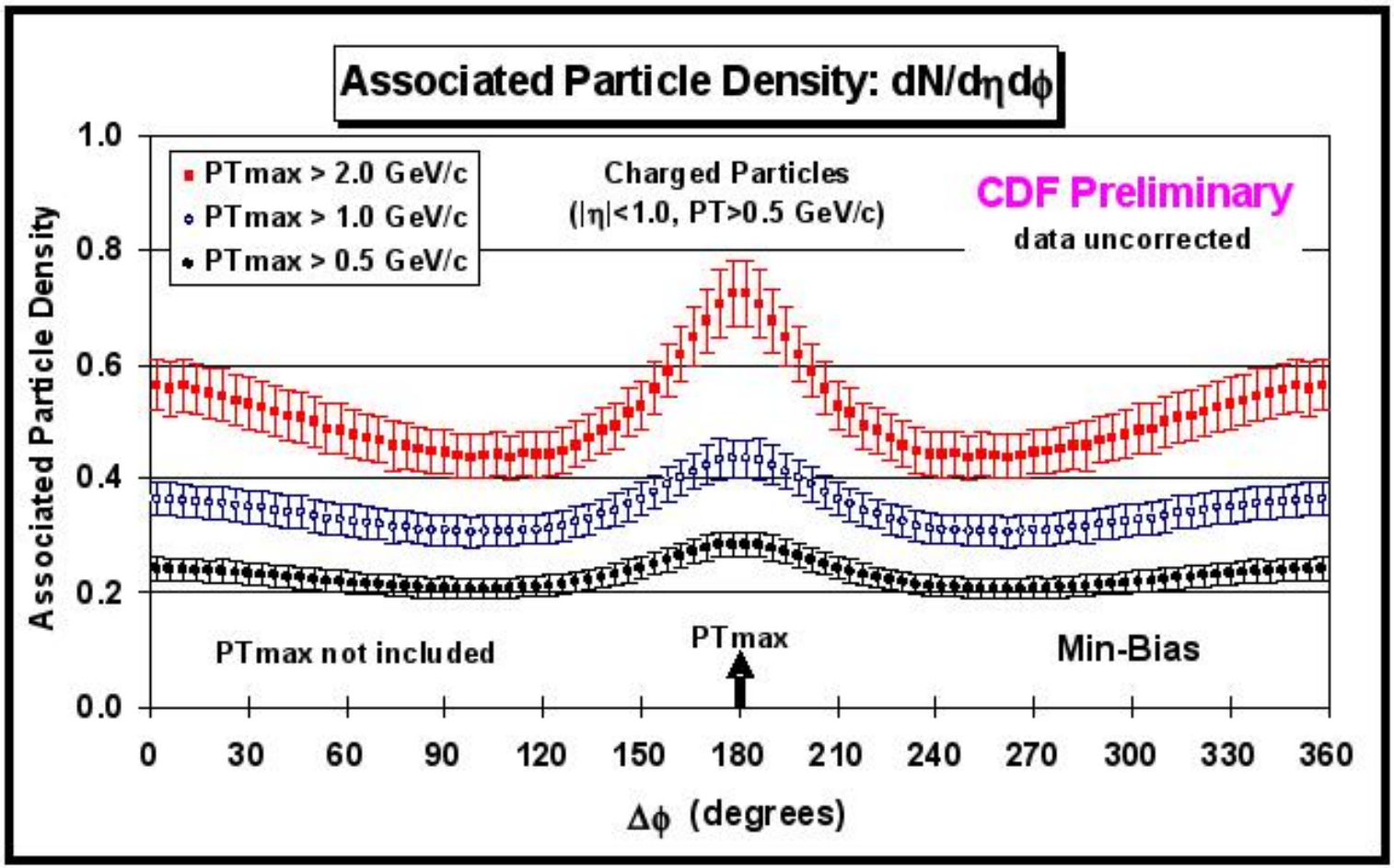


Azimuthal distributions

Observation:

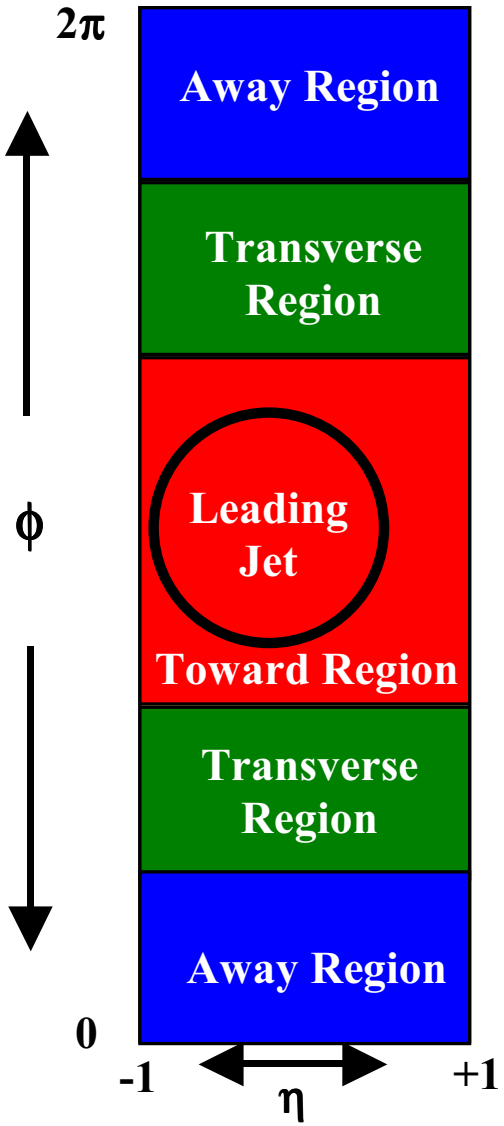
- Events not flat. Have 'leading object'.
- Harder leading object:
  - $\rightarrow$ harder recoil.
  - $\rightarrow$ more activity everywhere, also transverse.

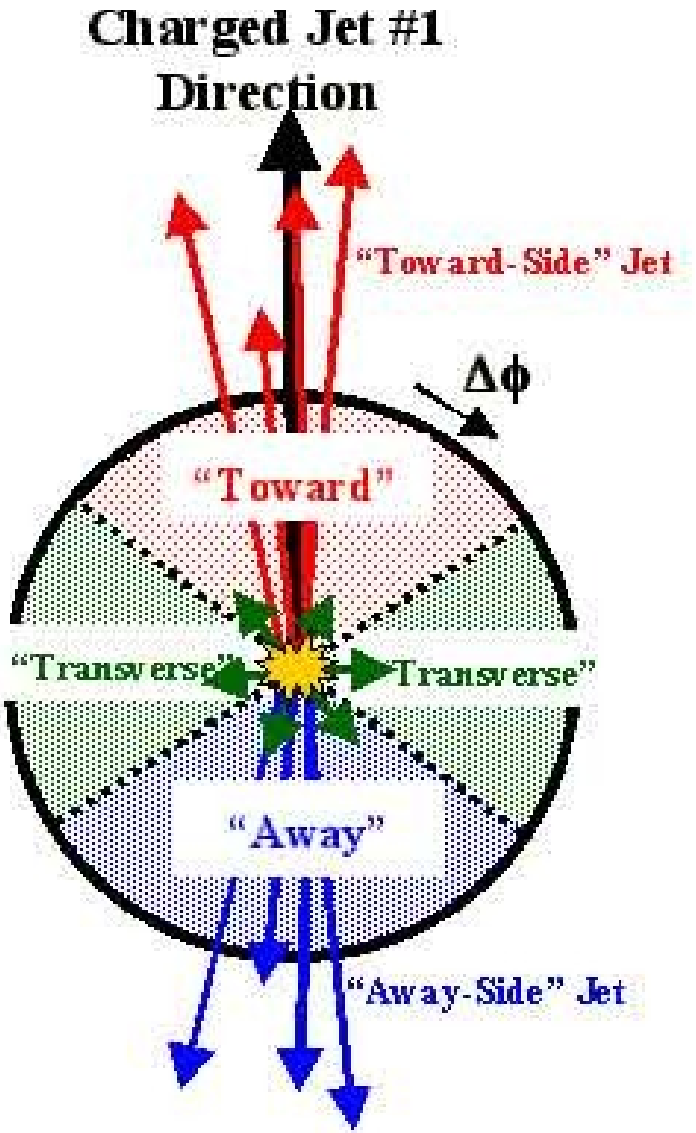
Trigger: The harder leading object, the more jets are inclusively just below this threshold (pedestal effect).

Closer look at transverse region!

"Rick Field analysis".

Towards, away, transverse

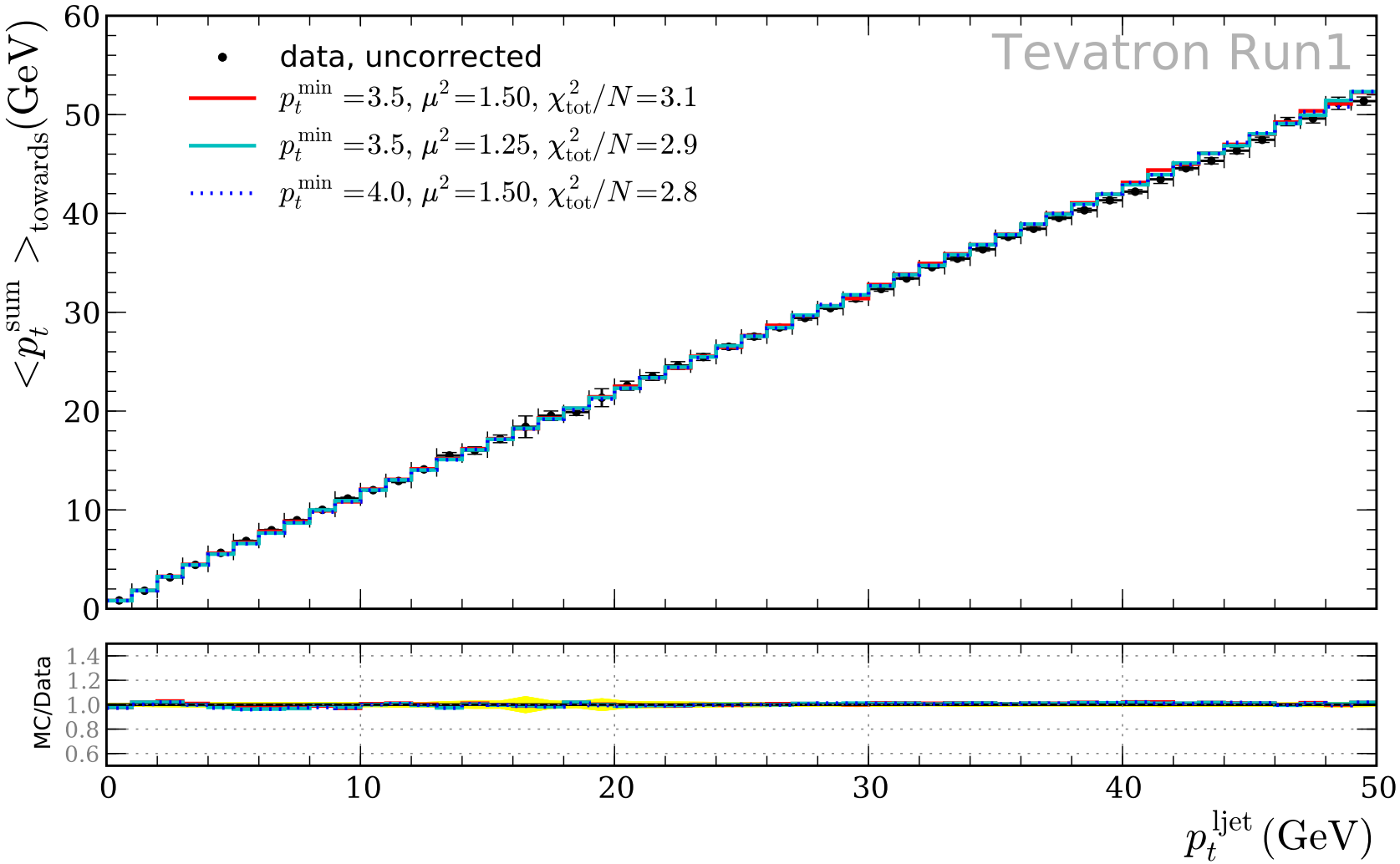




Measurements of the UE: separate from hard bit of event.

- How big is the 'activity' in the different regions?
- How does it depend on the leading object?
- If UE is really *underlying*,
  should decouple from leading event.

Detailed look at observables: Towards Region



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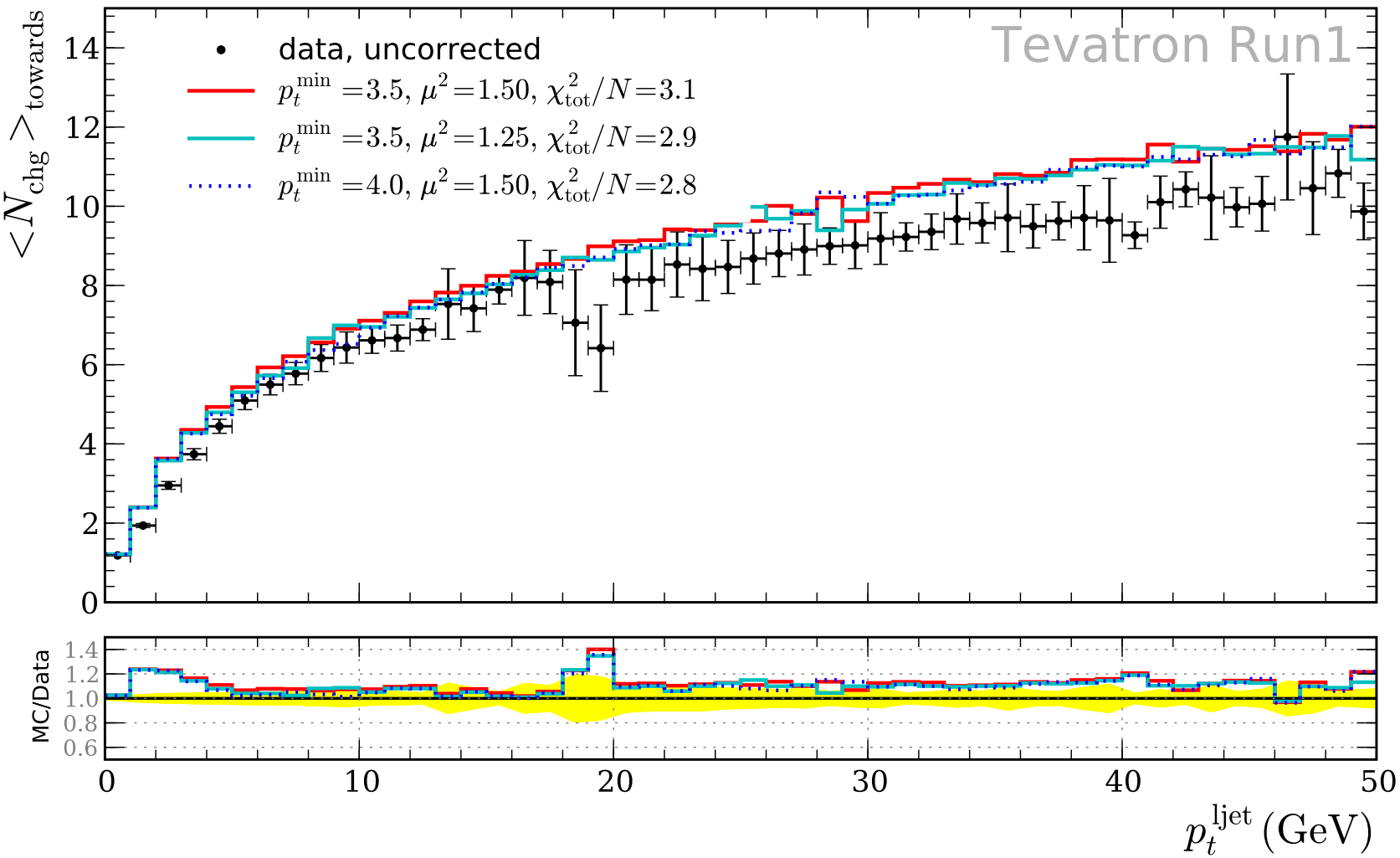
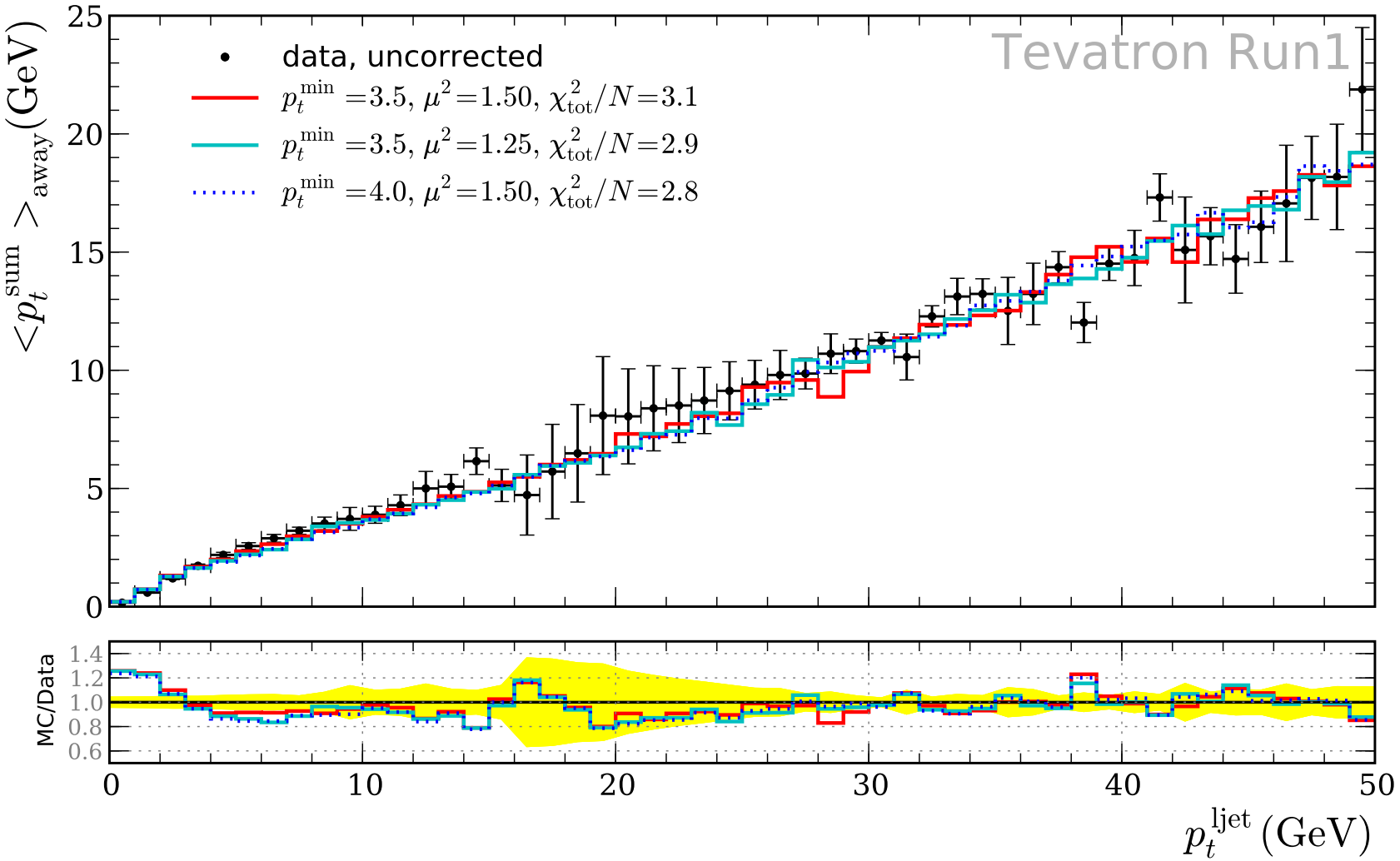


Detailed look at observables: Away Region



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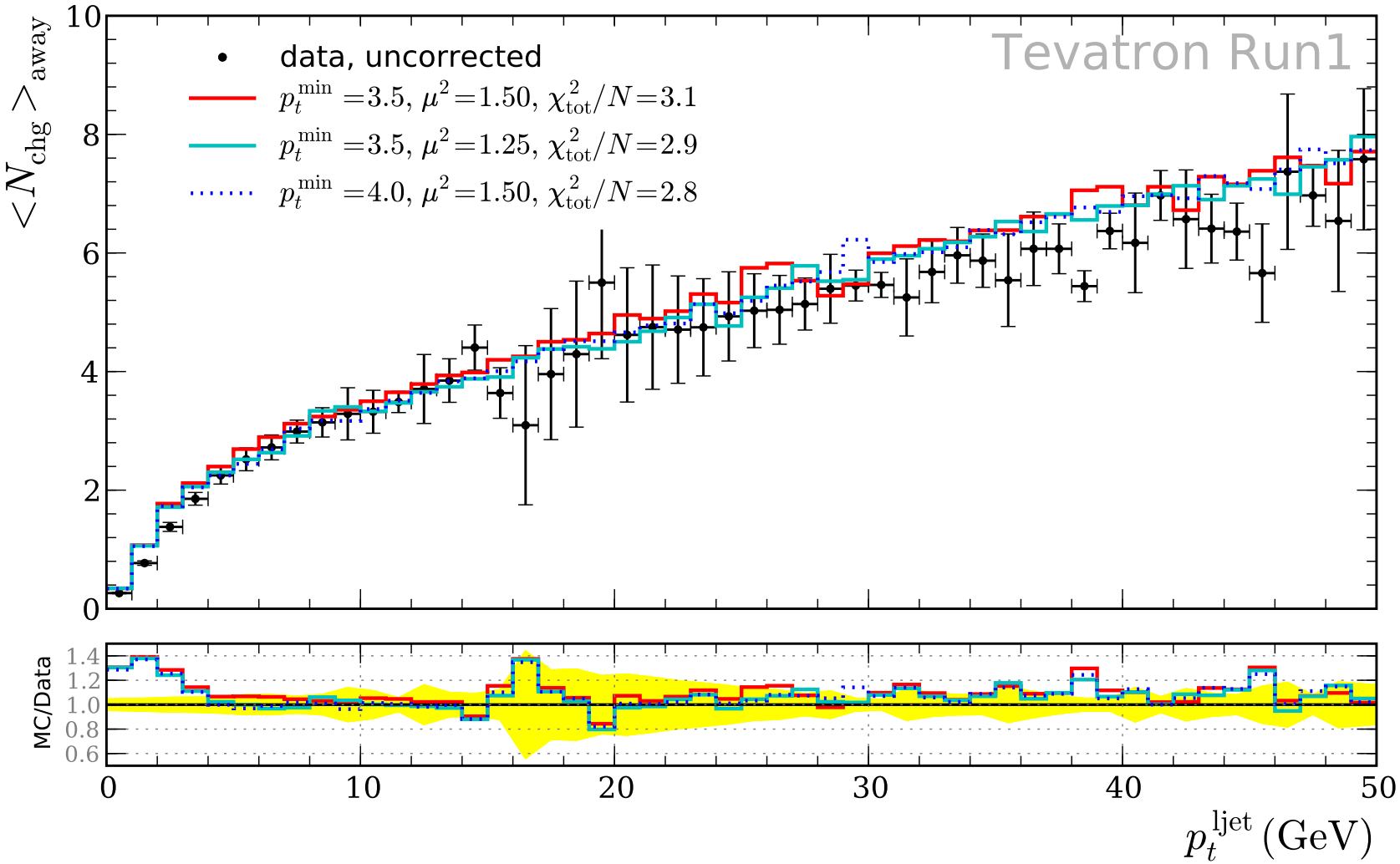
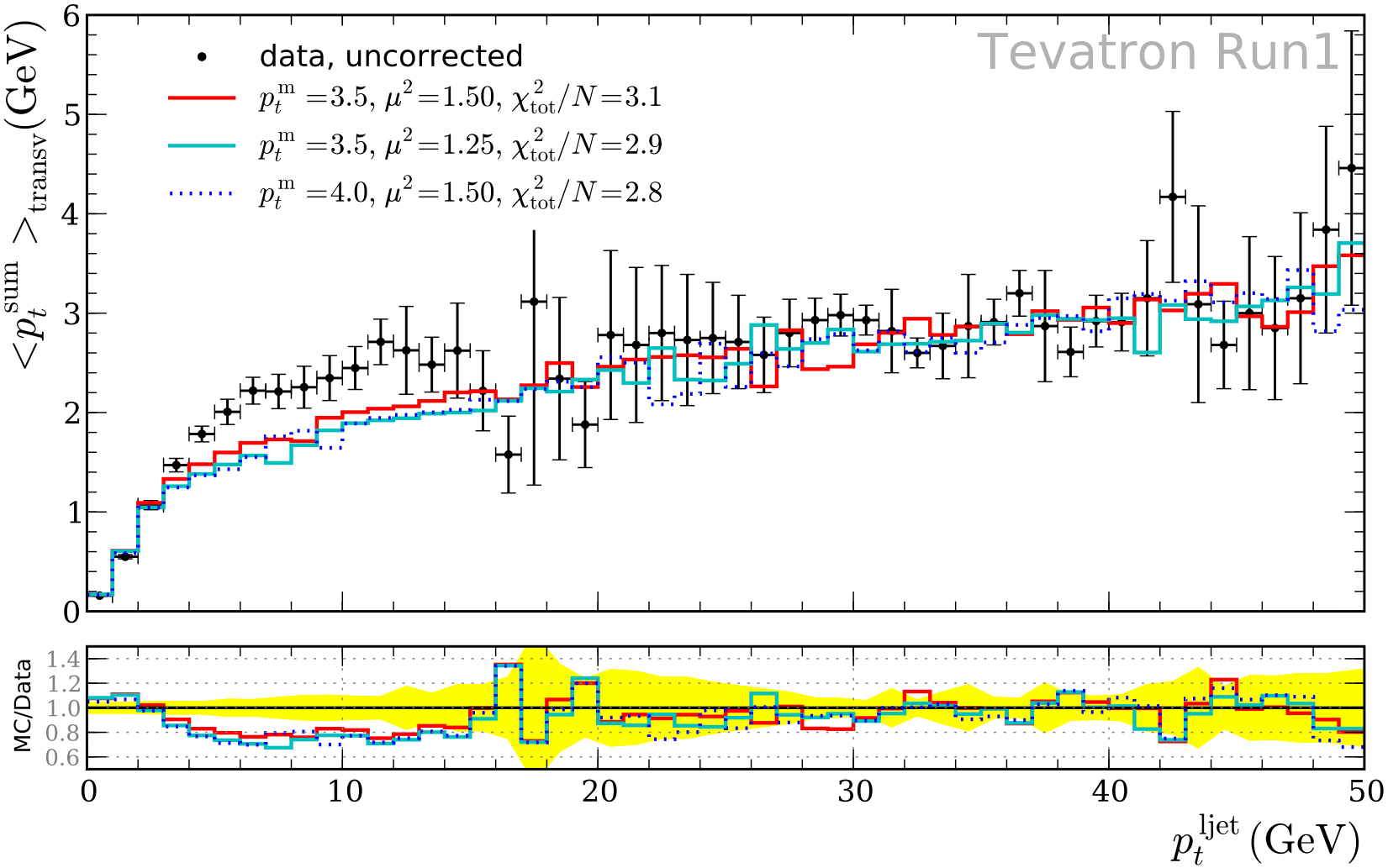
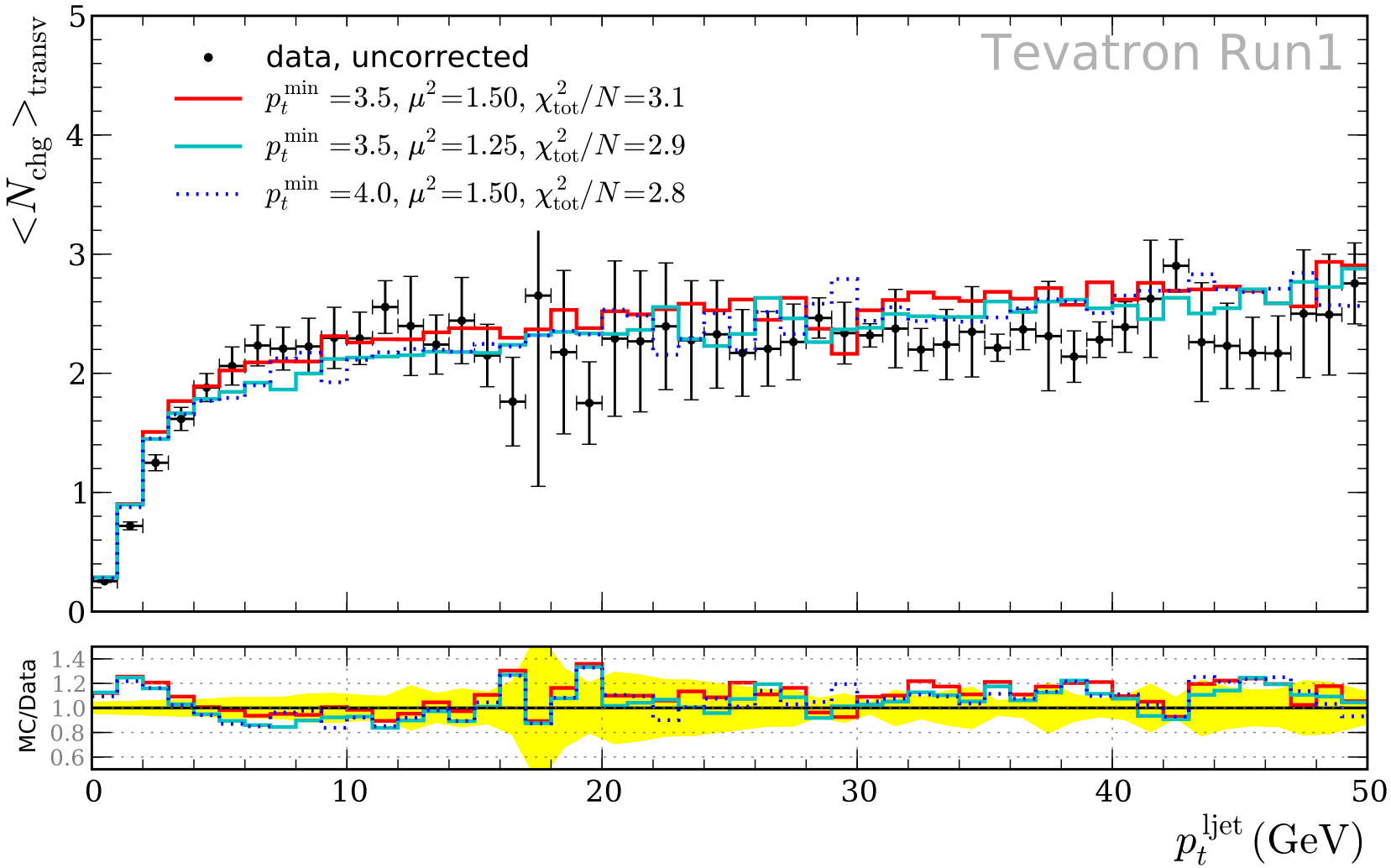


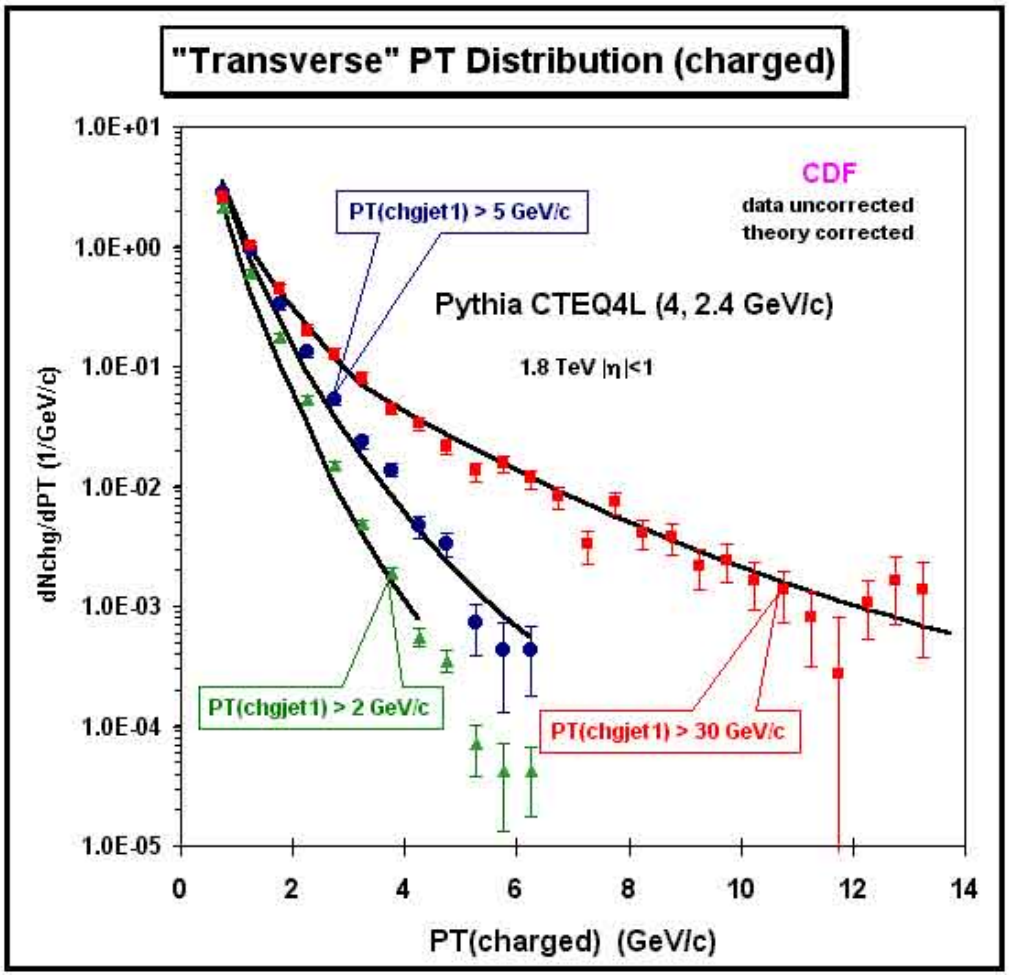
Detailed look at observables: Transverse Region



Detailed look at observables: Transverse Region



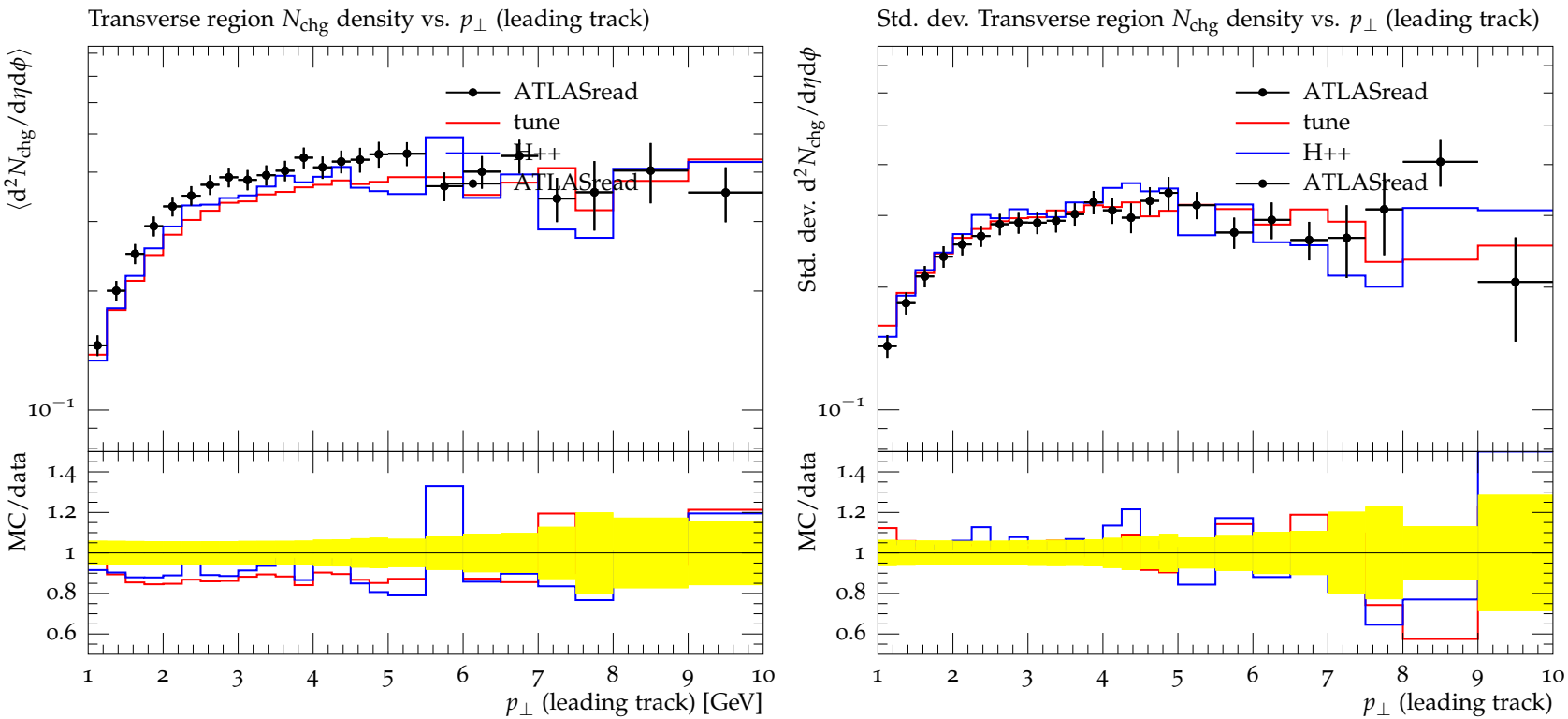
Spectrum in transverse region



Not only average important. The UE has a jetty substructure!

Underlying Event (ATLAS 900 GeV)

Also include Std deviation!



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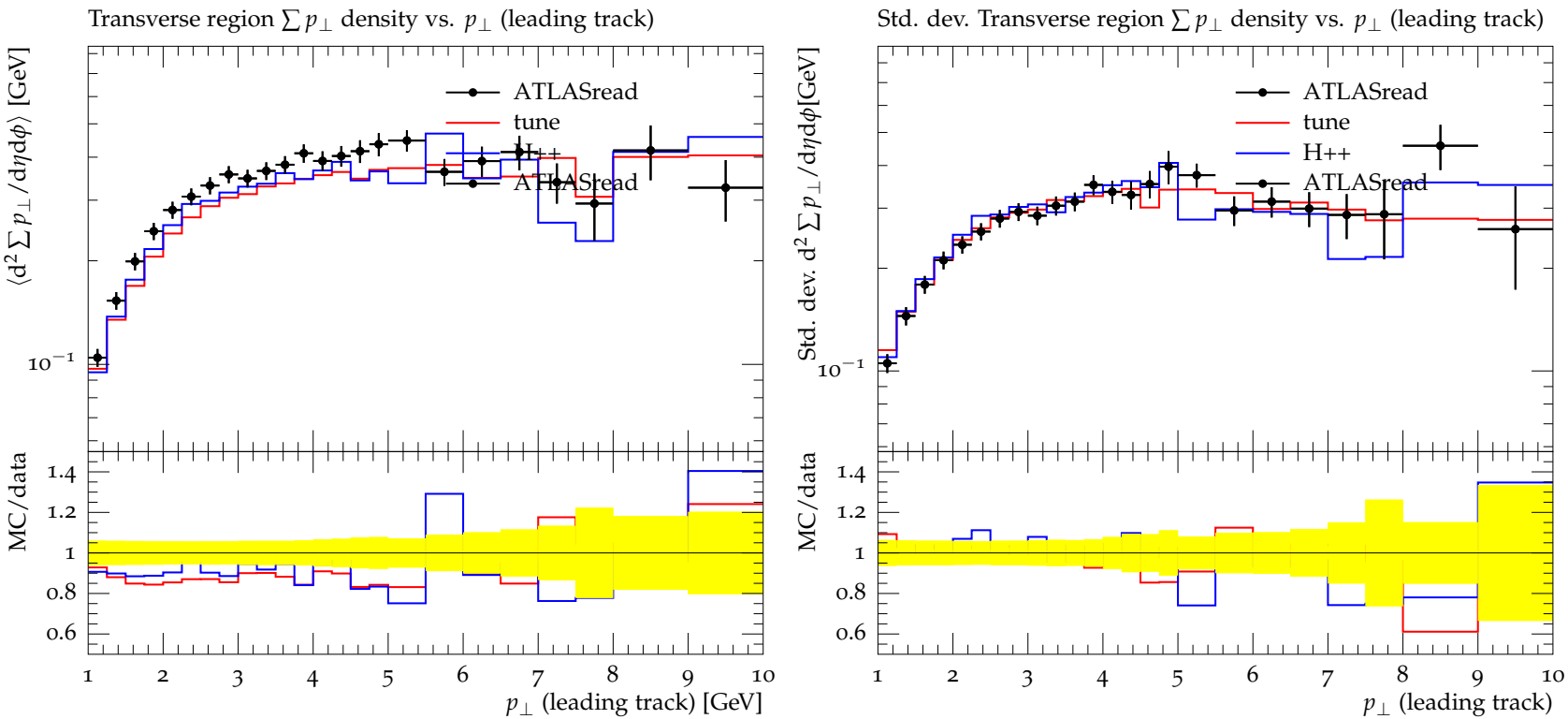
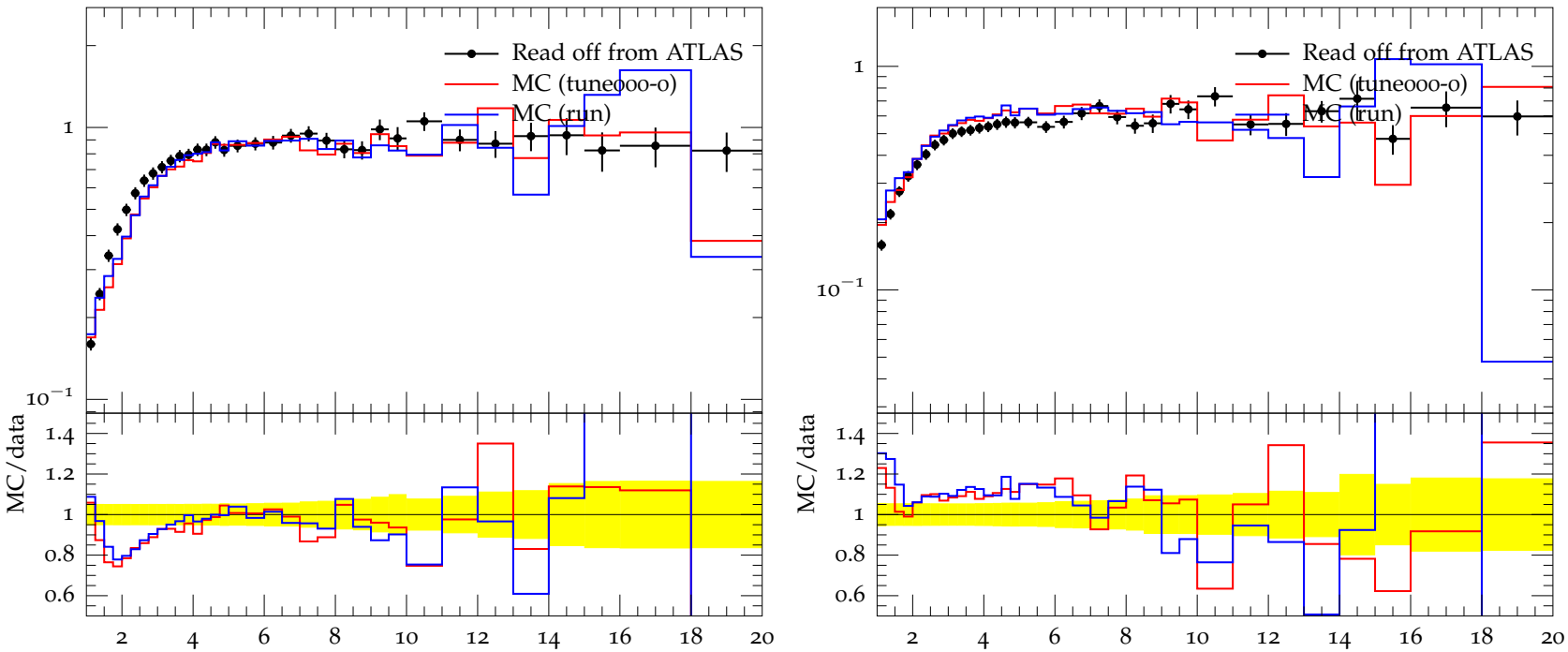


Underlying Event (ATLAS 7 TeV)

N_{ch}/StdDev transverse vs p_t^{lead}/GeV.

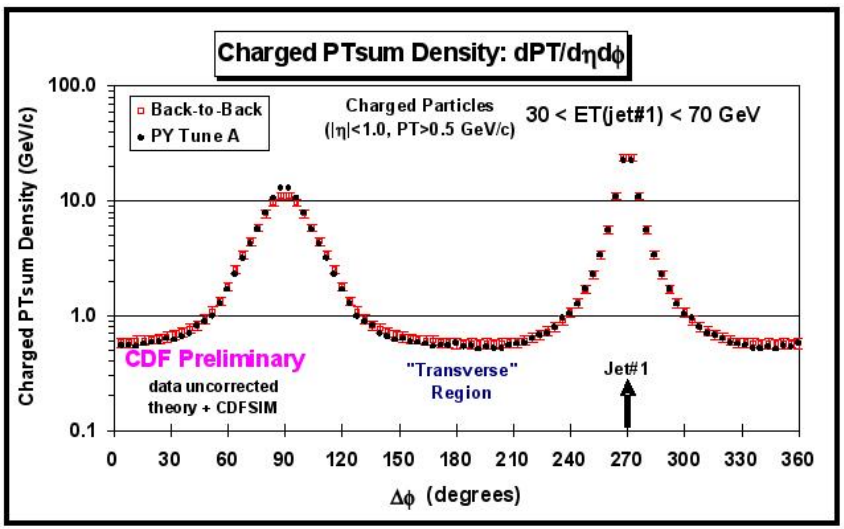


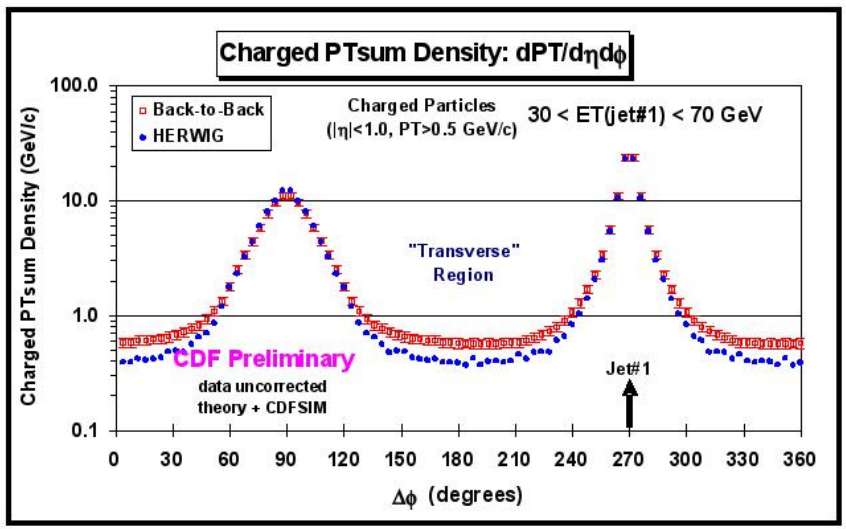
So far

- Idea of decoupling UE from hard event seems to hold.
- UE has jetty structure.
- Must contain hard physics as well.

More azimuthal distributions

Require at least two nearly b2b jets.
Dominated by hard physics.





Old Herwig soft model not sufficient.

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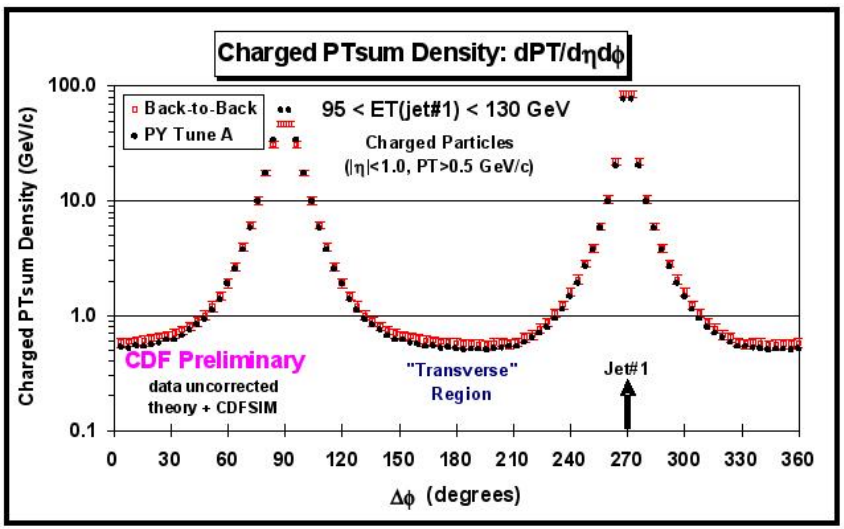
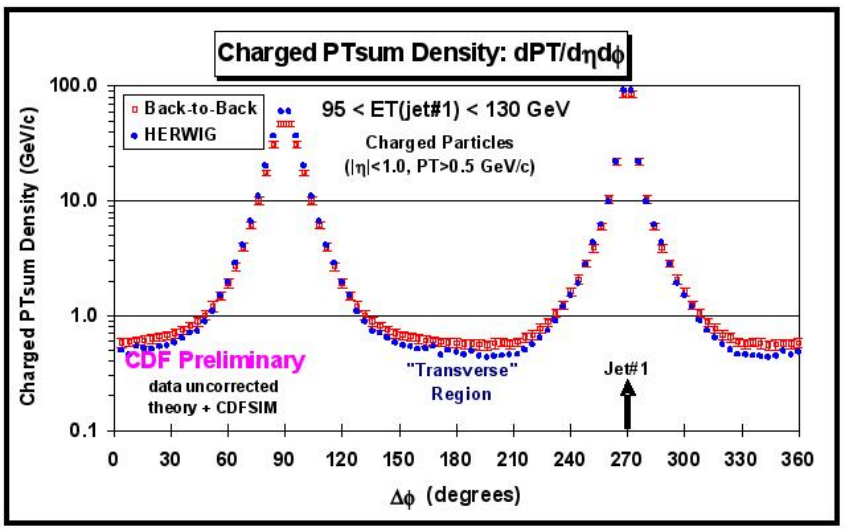
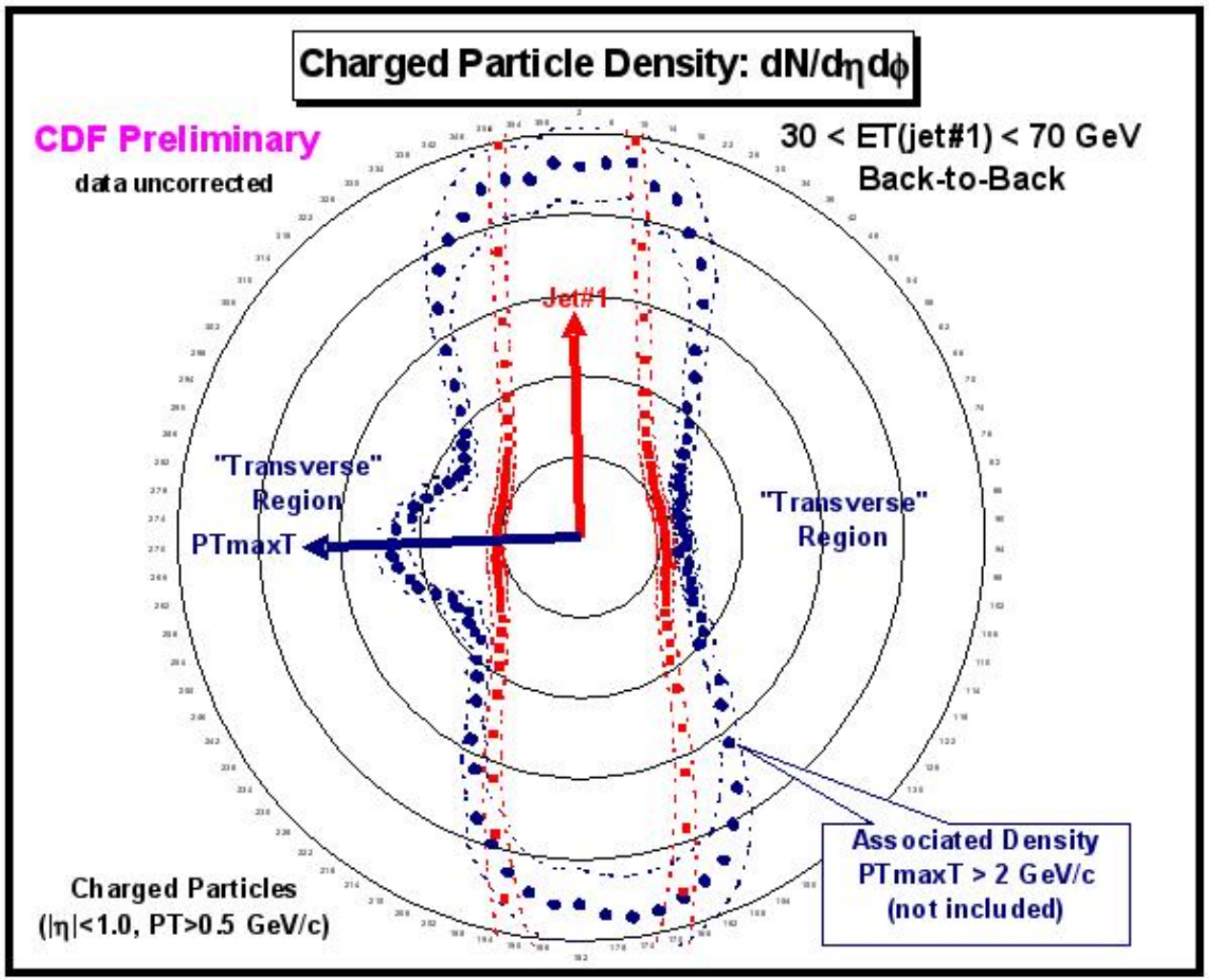




Better with harder jets.

More azimuthal distributions

Now select the hardest of the two transverse regions only (TransMAX): associated distribution:



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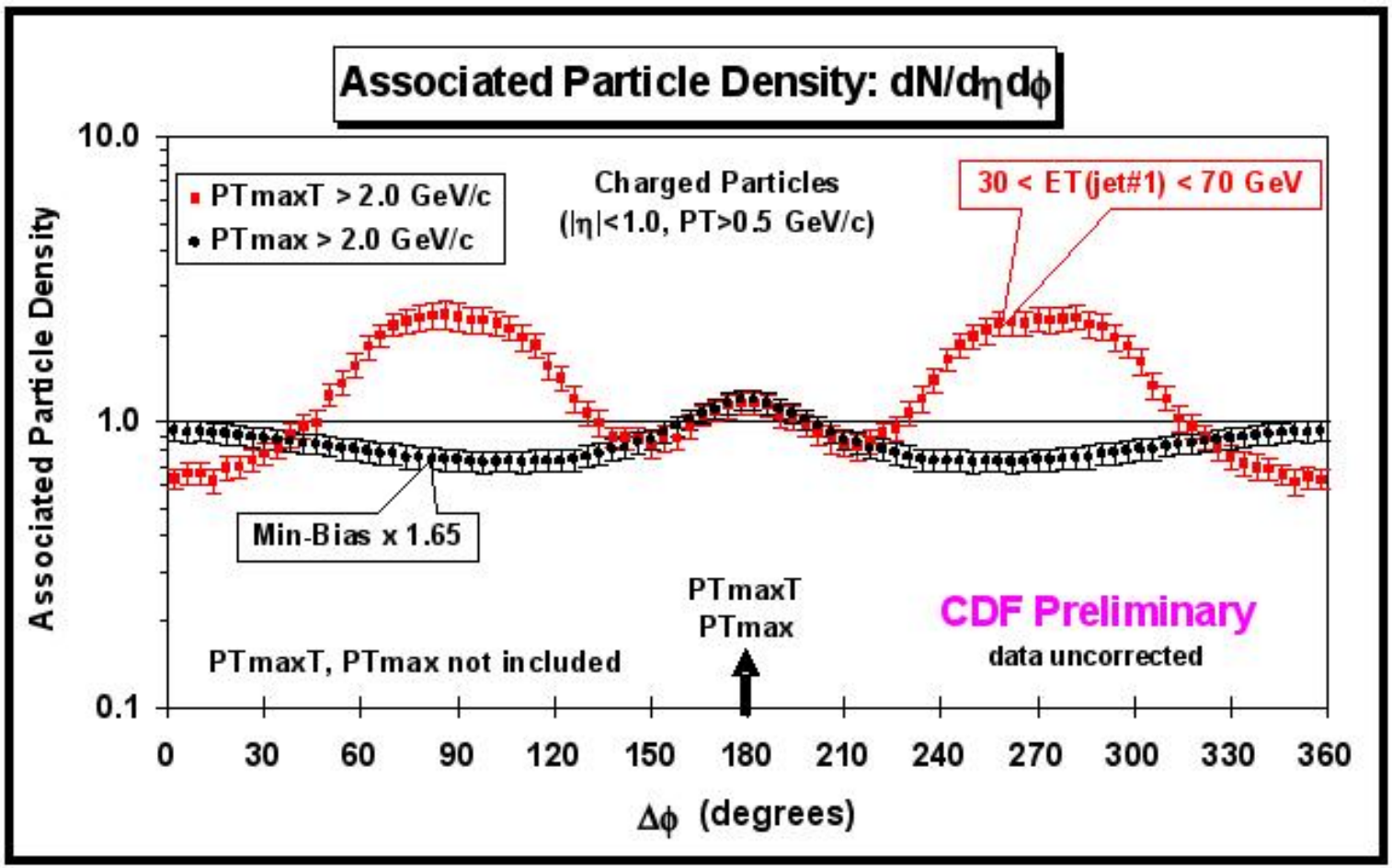
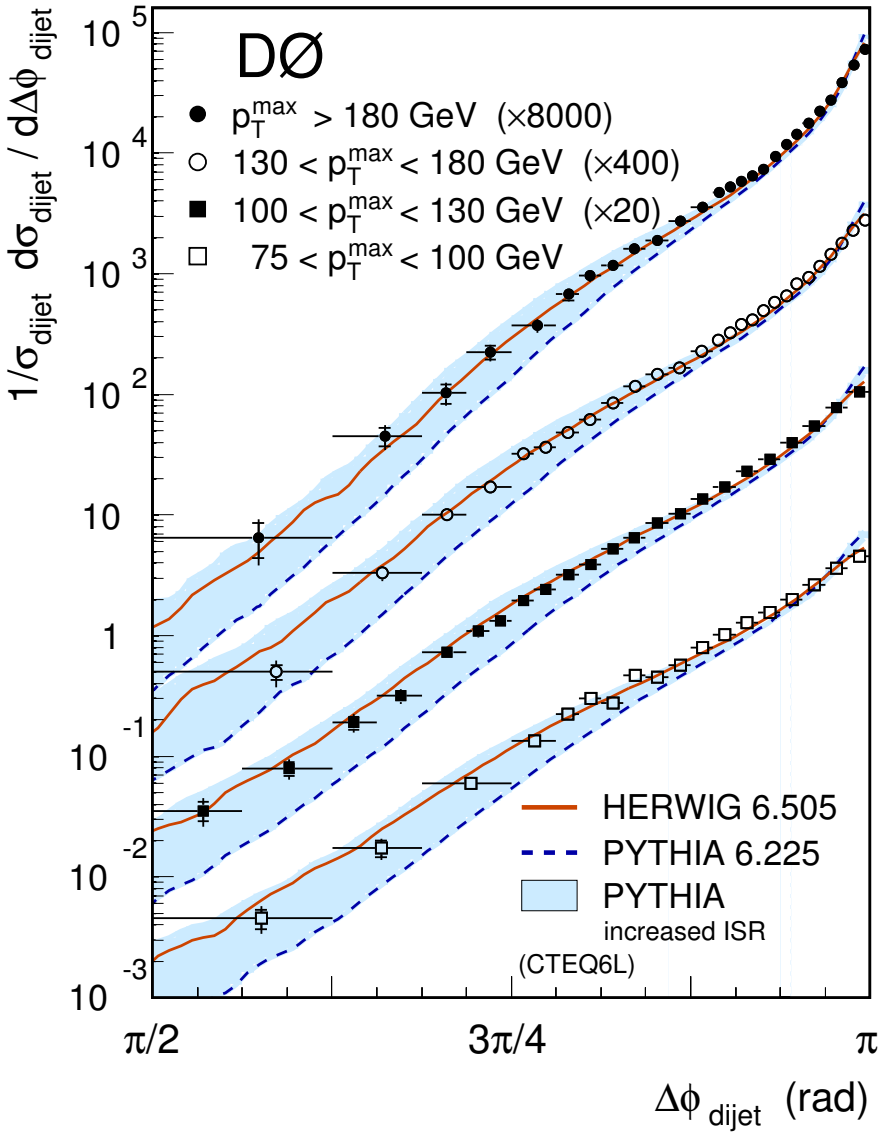


Birth of 3rd jet ~ leading jet in MinBias

Hard dijets



Angles between hard jets modeled by parton showers.

Towards modelling

- Leading jet in Minimum bias $\sim$ 3rd jet in back–to–back sample.
- UE and MB really seem to reflect the same physics.
- Hard component important.
- Hard jets not sufficient
  (but well described $\rightarrow$ D0 dijet angular decorrelation).

Hard jets in the UE via multiple interactions?

- Additional Partonic $2 \rightarrow 2$ interactions (MPI).
- No correlation with hard event.

Indirect evidence for MPI

N_{ch} distribution (vs UA5; Sjöstrand, van Zijl (1987))

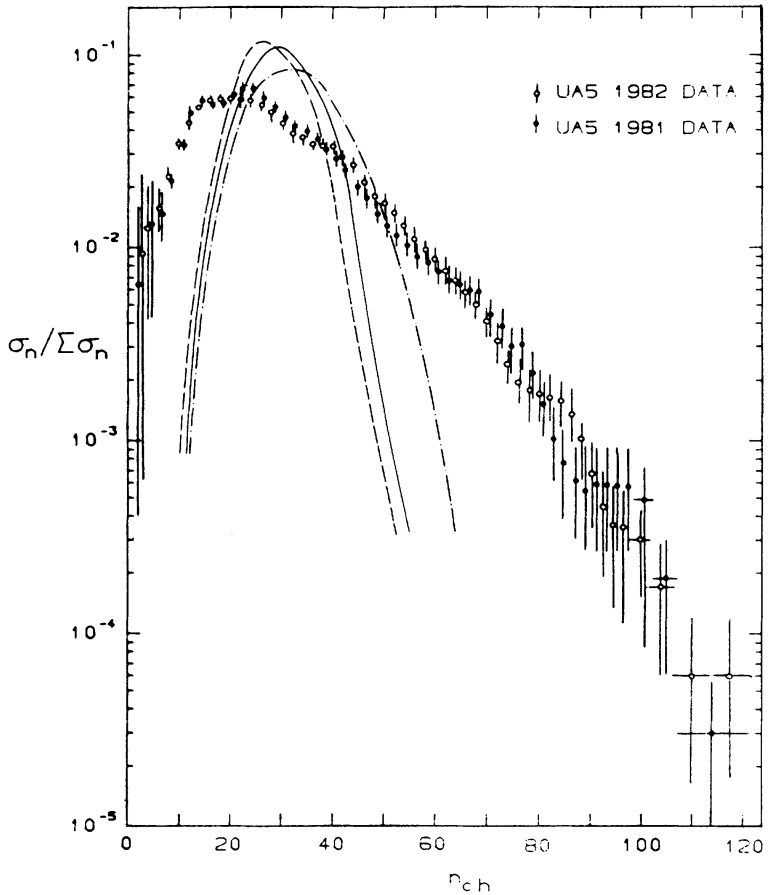


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

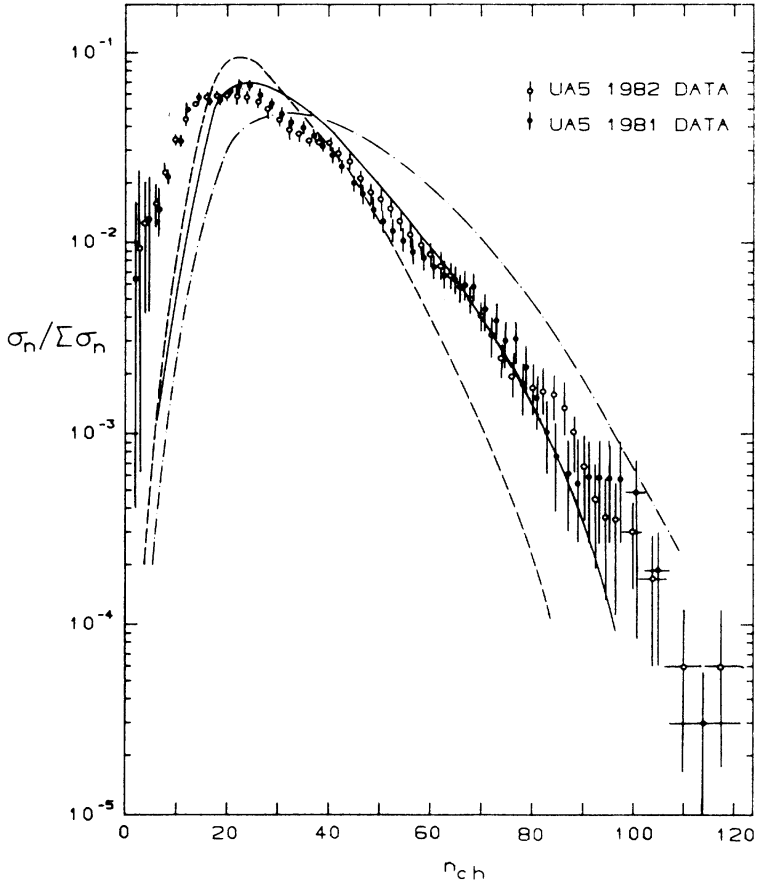


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

no MPI (left)/MPI (right).

Indirect evidence for MPI

FB correlation in η bins (vs UA5; Sjöstrand, van Zijl (1987))

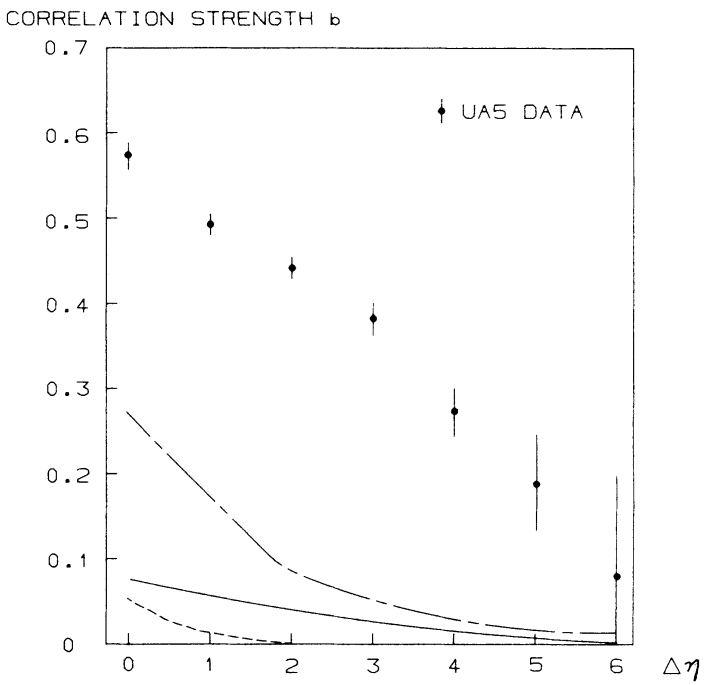


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

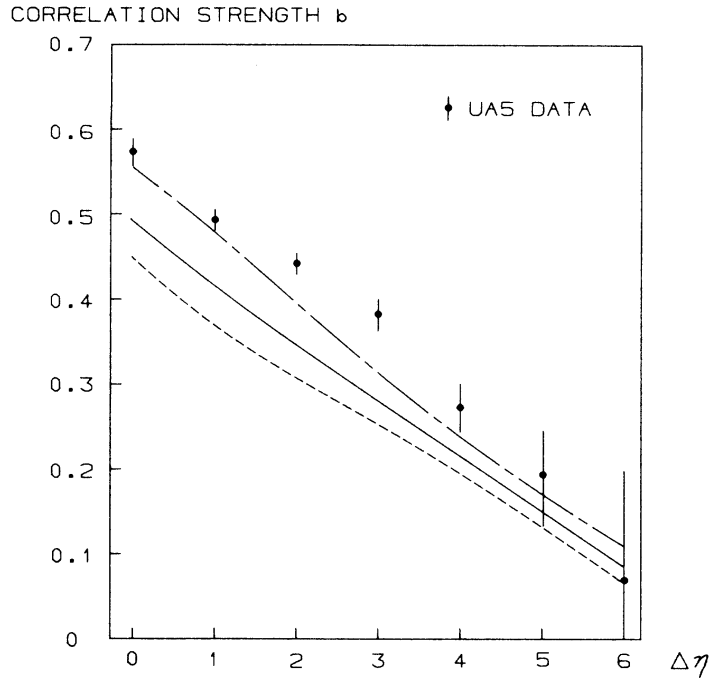


FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

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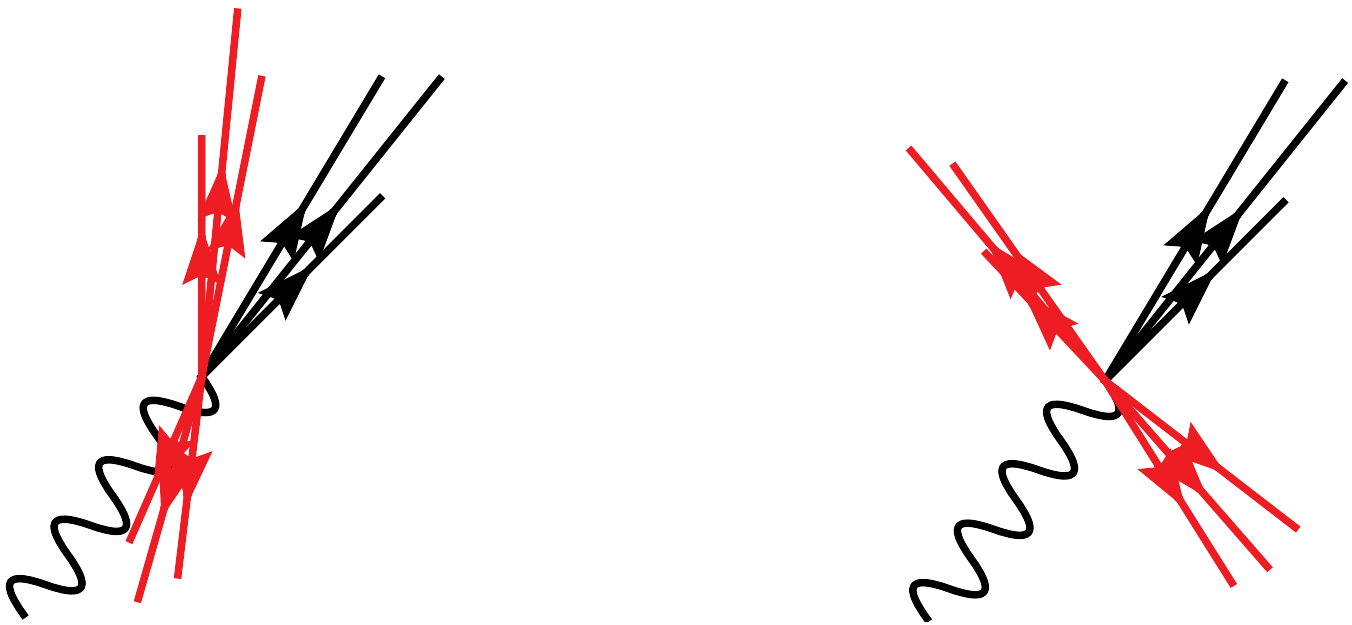
Evidence for MPI

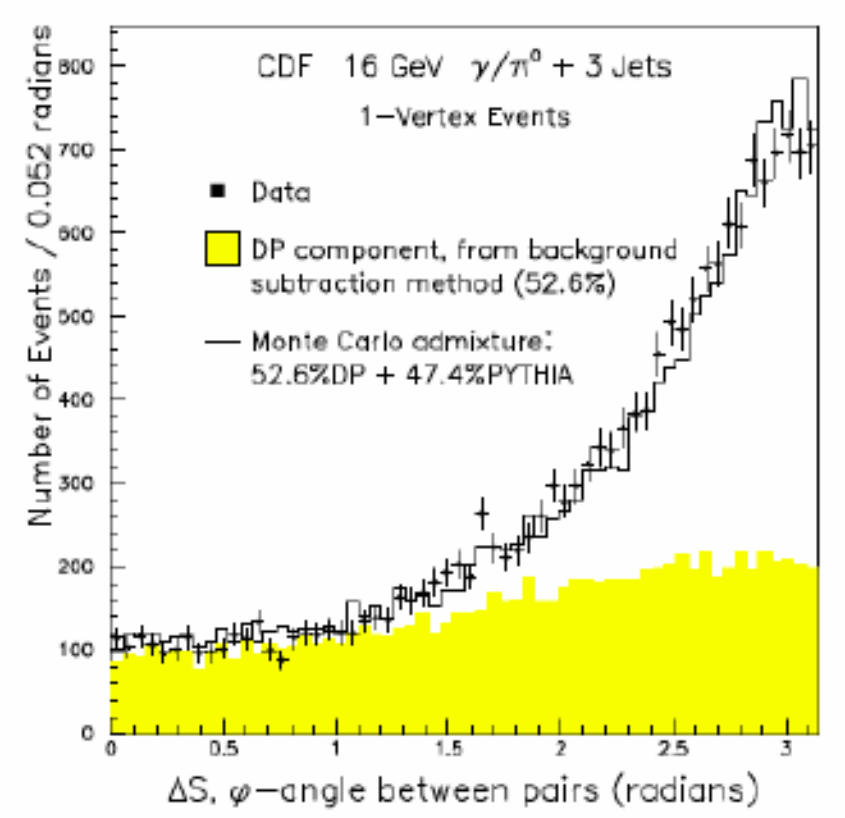
Angle ϕ from 4 final state objects (jets, γ).



Evidence for MPI

Angle ϕ from 4 final state objects (jets, γ). Latest: CDF ('97).

$$\phi = \angle(\vec{p}_1 \pm \vec{p}_2, \vec{p}_3 \pm p_4)$$



53% double parton scattering needed!

Take home

At hadron colliders:

- Underlying event is everywhere.
- Min bias is everywhere (pile–up).
- Both contain similar physics.
- The underlying event is “lumpy”.
  It contains soft AND hard physics.
  Important to get fluctuations as well as averages.
- Important effects based on Multiple Partonic Interactions.