Minimum Bias and the Underlying Event at the LHC

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Outline:

I. Introduction:

- Historical perspective
  - Measuring hadronic inelastic collisions
  - ISR, SPS, Tevatron
  - “minimum bias” vs. the underlying event: aren’t they the same?

II. MC Models and LHC predictions:

- common ingredients & missing links (?)

III. Measuring minimum bias and the underlying event with “early” LHC data

IV. Summary

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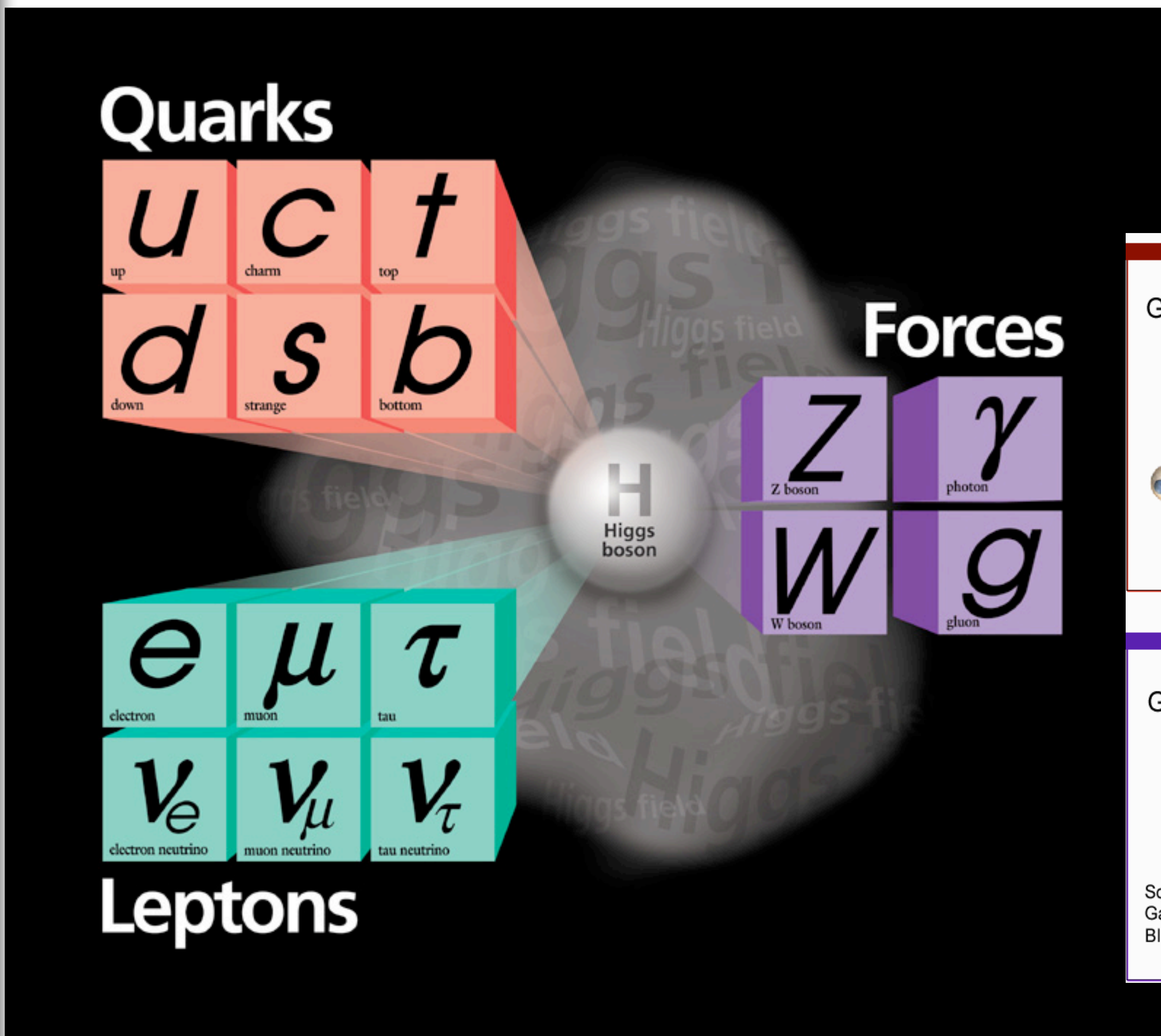
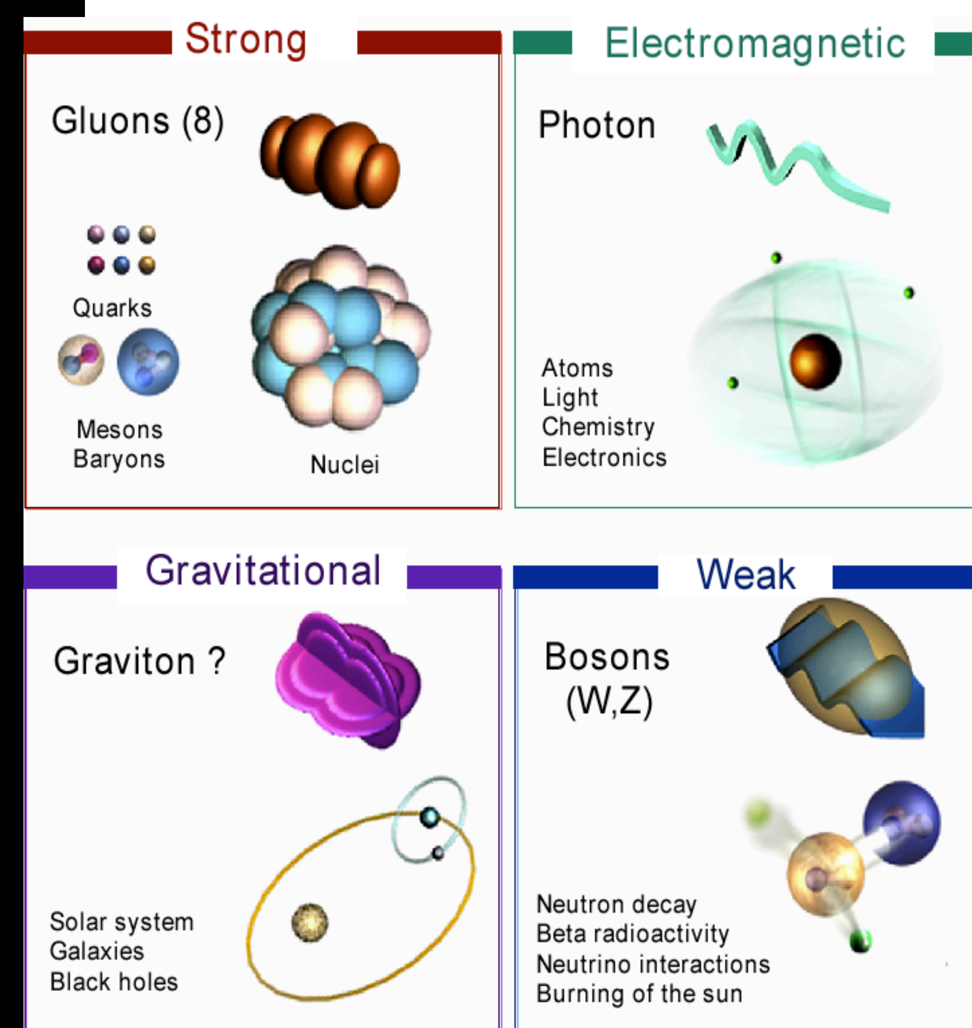
Why build a "Large Hadron Collider" ?

- The elementary particles and their interactions are described by the "Standard Model" (SM) which has been verified with extremely high precision over the last 35 years by experiments at CERN and at other laboratories all over the world.





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- However, several open questions and mysteries remain...
  - What is the origin of particle masses?
  - What is the nature of the Universe dark matter?
  - What is the origin of the Universe matter-antimatter asymmetry?
  - What are the constituents of the Universe primordial plasma?
  - What happened in the first moments of the Universe life after the Big-Bang?
  - ...

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  - ...

- The LHC will help elucidate these and other fascinating mysteries.

LHC Parton Kinematics

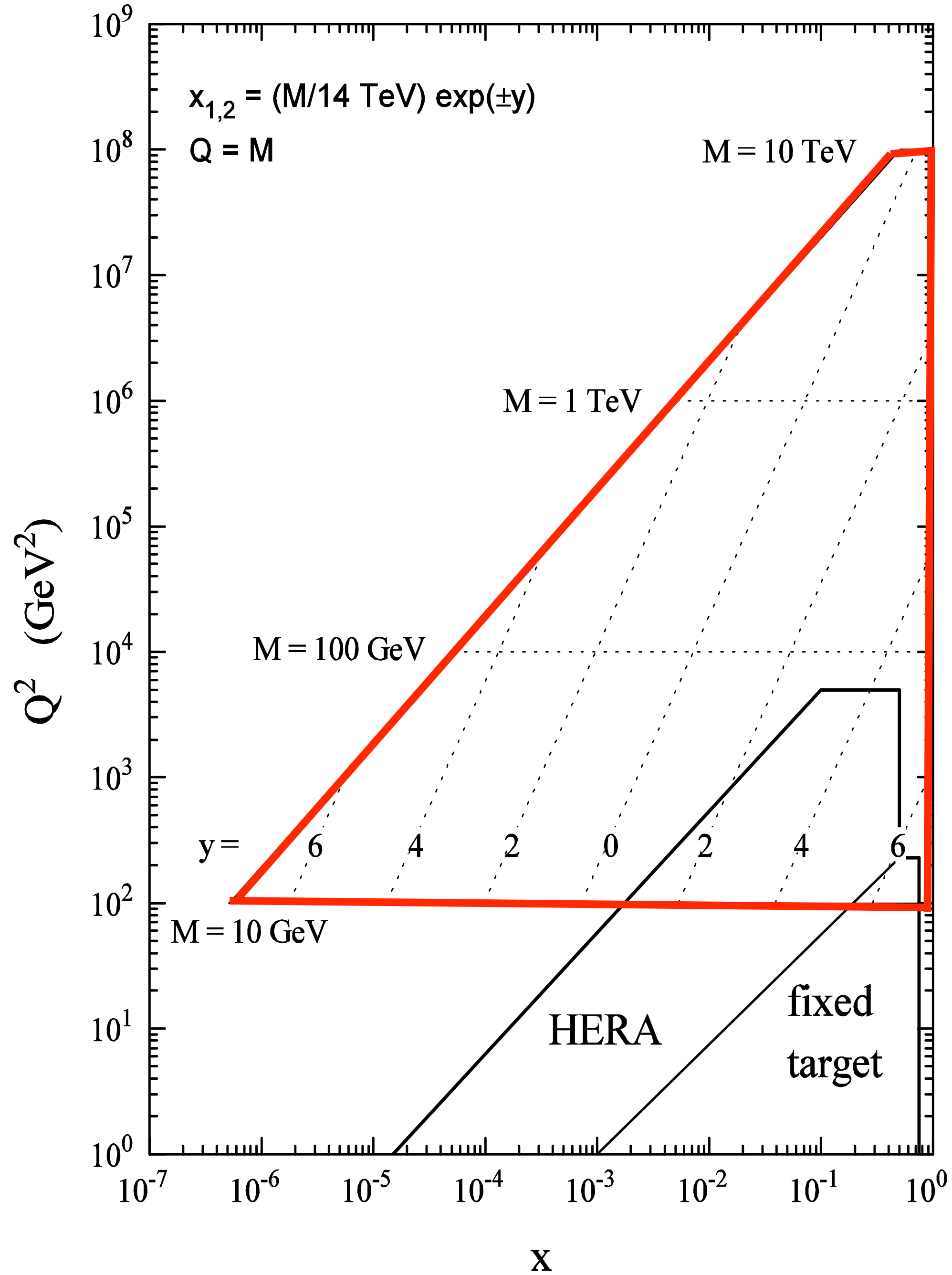
- Essentially all physics at LHC are connected to the interactions of quarks and gluons (small & large transferred momentum).

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron.

    - dominance of gluon on sea quark scattering;
    - large phase space for gluon emission and thus for the production of extra jets;
    - intensive QCD background!

- **This requires a solid understanding of QCD.**

- The kinematic acceptance of the LHC detectors allows a large range of **x** and **Q²** to be probed (ATLAS & CMS coverage: |η| < 5).



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Before we are able to claim discoveries, we will need to understand and explain the QCD environment at the LHC!

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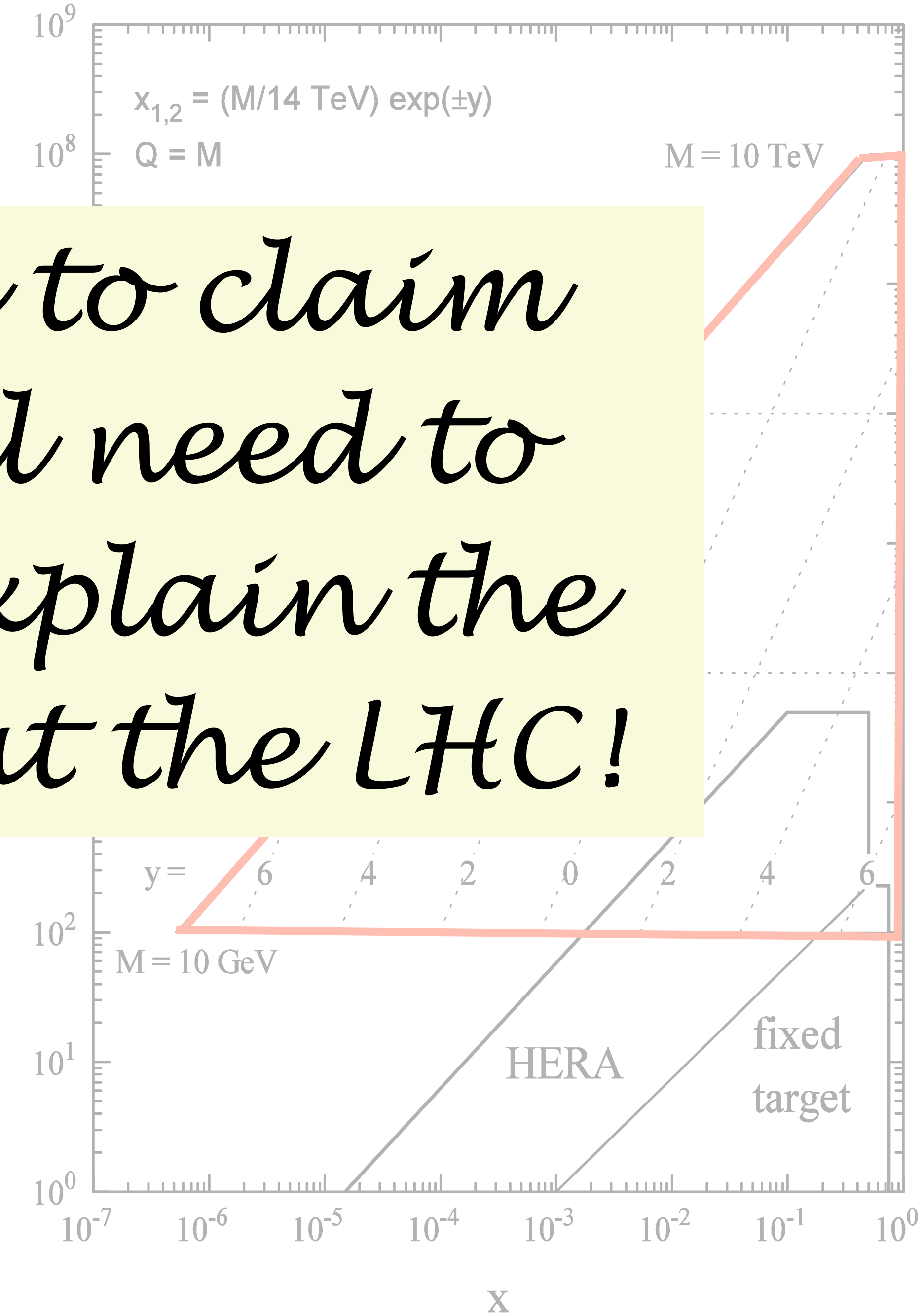
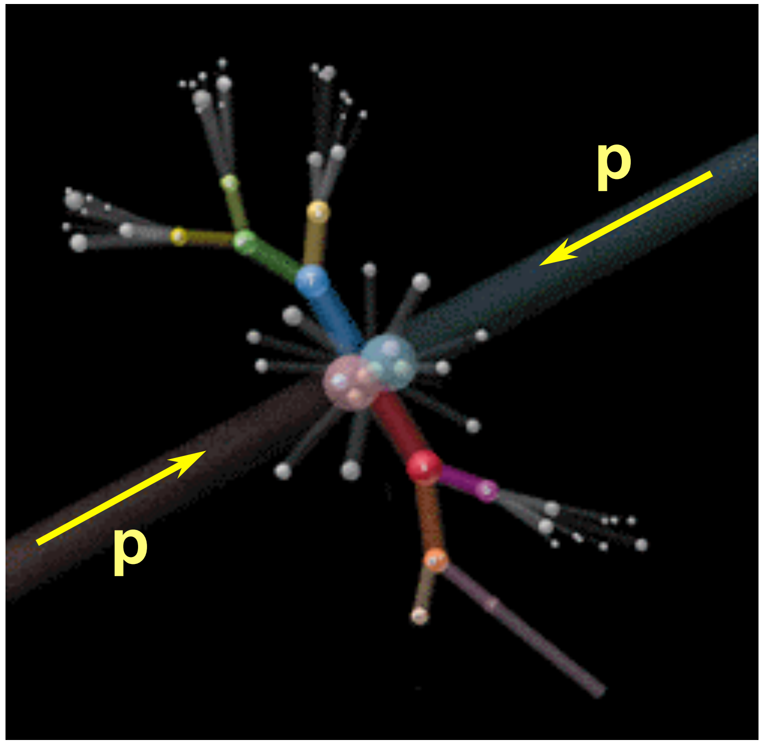


Hadron–hadron collisions

- Essentially all physics at high-energy hadron colliders are connected to the interactions of quarks and gluons (small & large transferred momentum).
  - Hard processes (high-p_T): well described by perturbative QCD
  - Soft interactions (low-p_T): require non-perturbative phenomenological models



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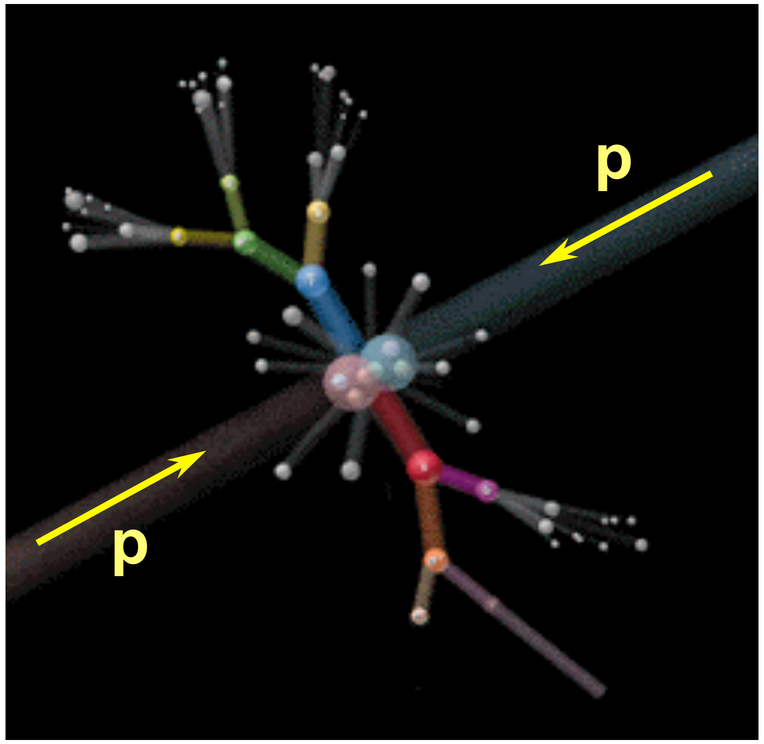

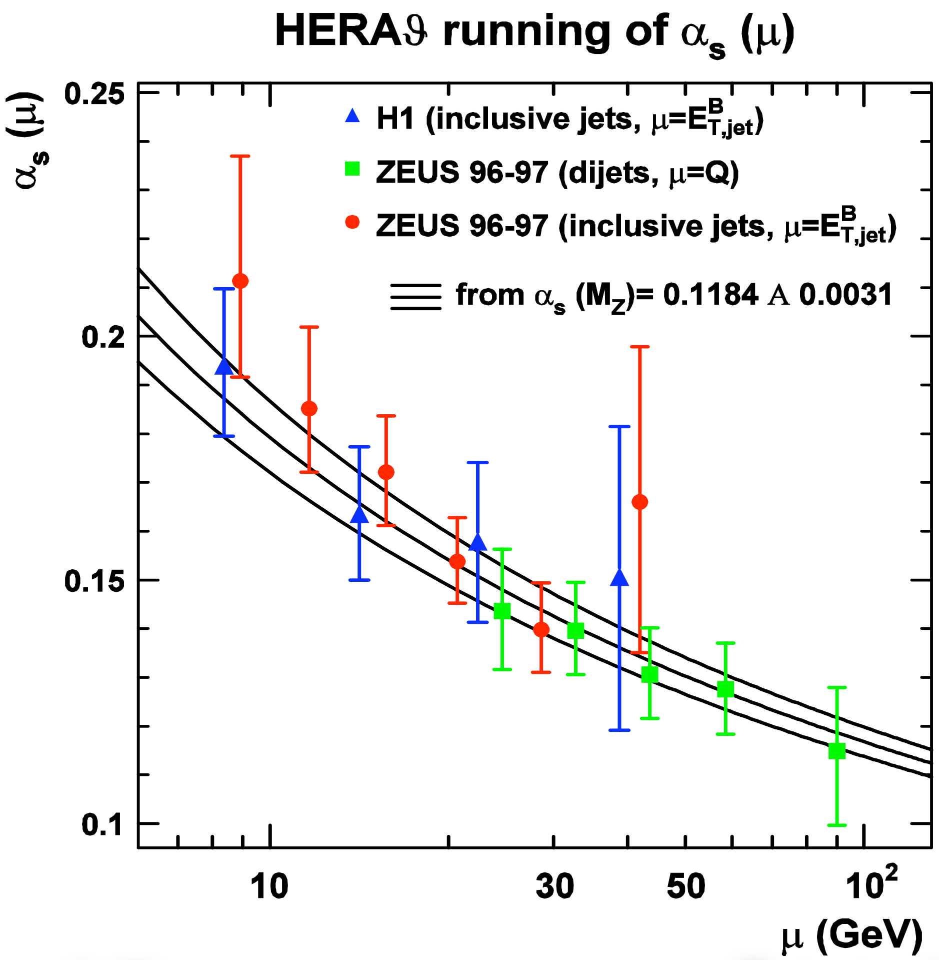

Soft Interactions: Problems with strong coupling constant, $\alpha_s(Q^2)$, saturation effects,…

- Inelastic hadronic events are dominated by **"soft"** partonic interactions.
- On average, inelastic hadron–hadron collisions have low transverse energy, low multiplicity.

The “dawn” of minimum bias measurements in hadron colliders

- What are the properties of high-energy hadron collisions?

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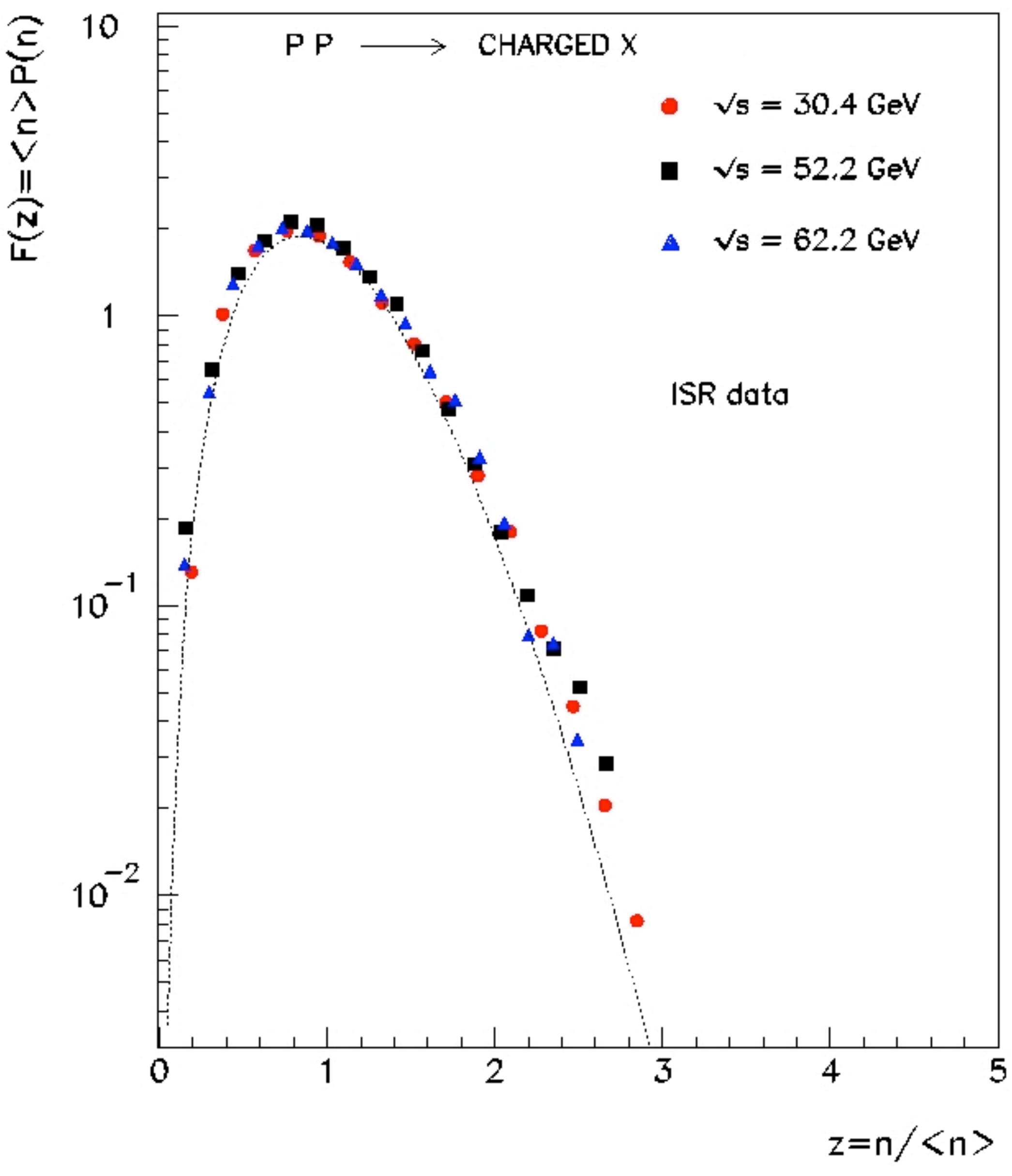
CERN ISR (√s up to ~62GeV): **study of inelastic properties in pp collisions**

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic}$$

- Inelastic particle production was expected to scale with the colliding energy (KNO scaling).
- ISR inelastic data seemed to confirm the KNO scaling.



Phys. Rev. D **30**(3), 528(1984)

The "dawn" of minimum bias measurements in hadron colliders

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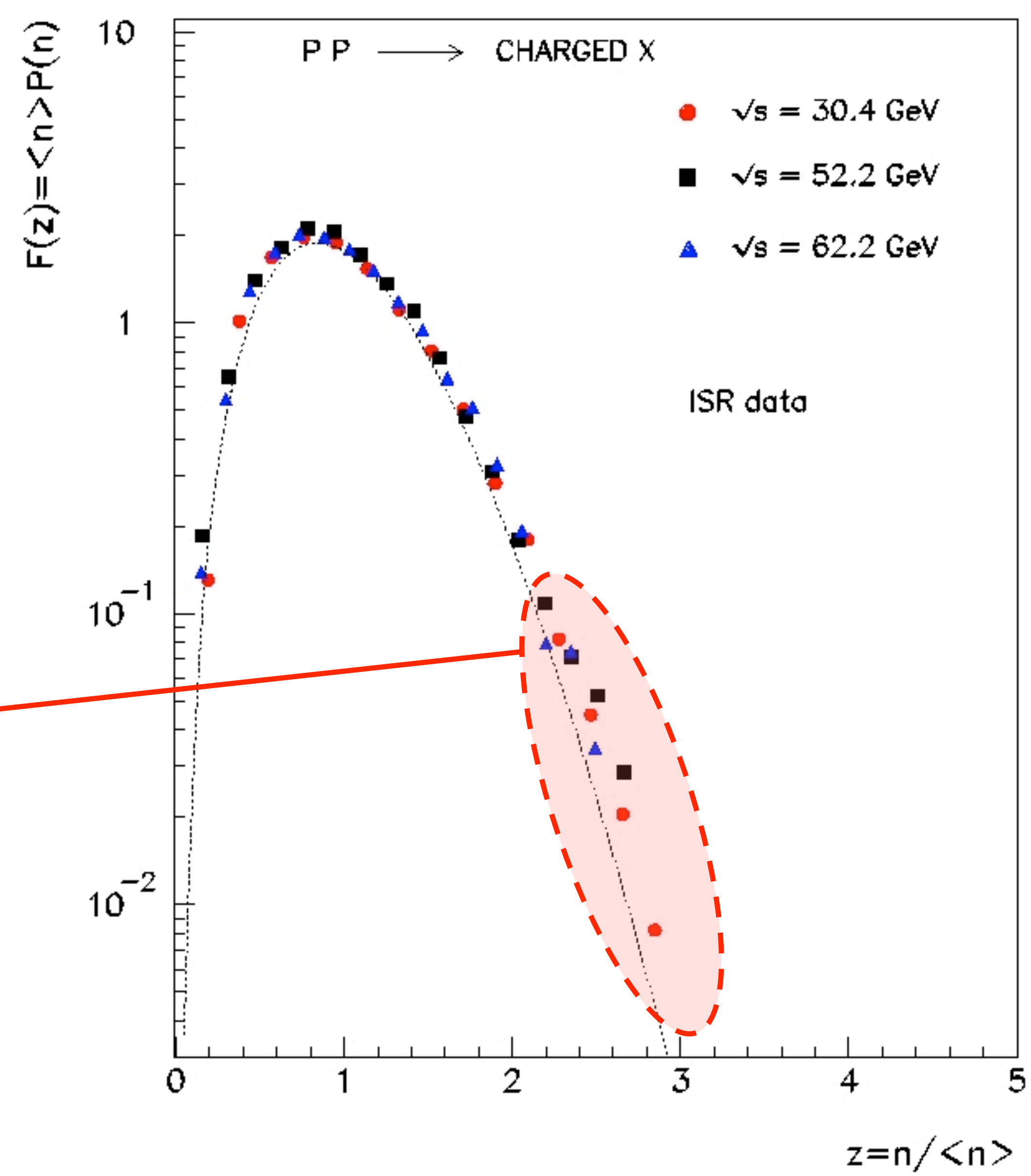

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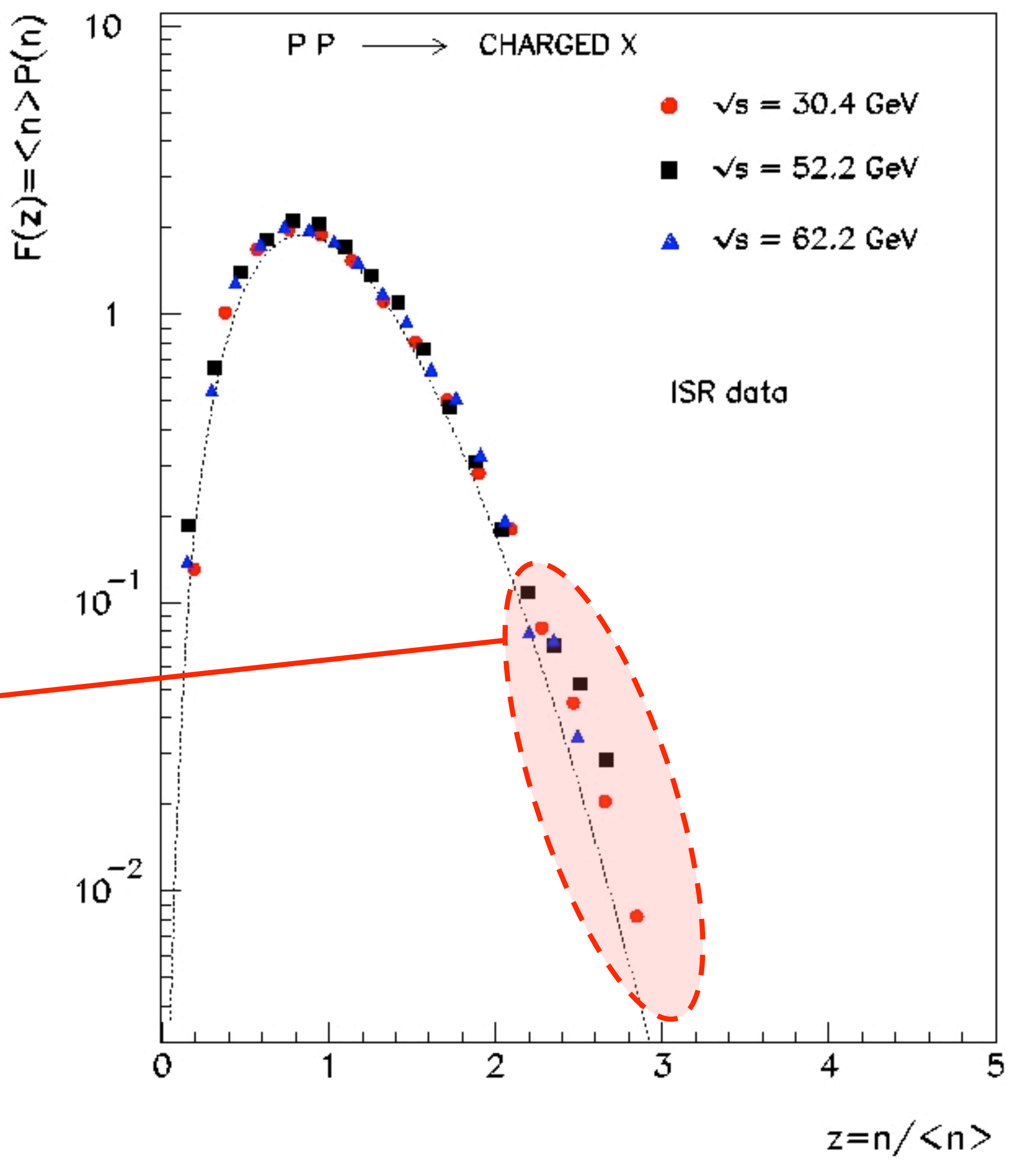
- However, statistical analysis indicated that as √s increased deviations from the KNO scaling were becoming more evident
- It was thought that by removing the diffractive component, the scaling would be restored.

$$\sigma_{tot} = \sigma_{elas} + \sigma_{inel} = \sigma_{elas} + \sigma_{nsd} + \sigma_{sd}$$



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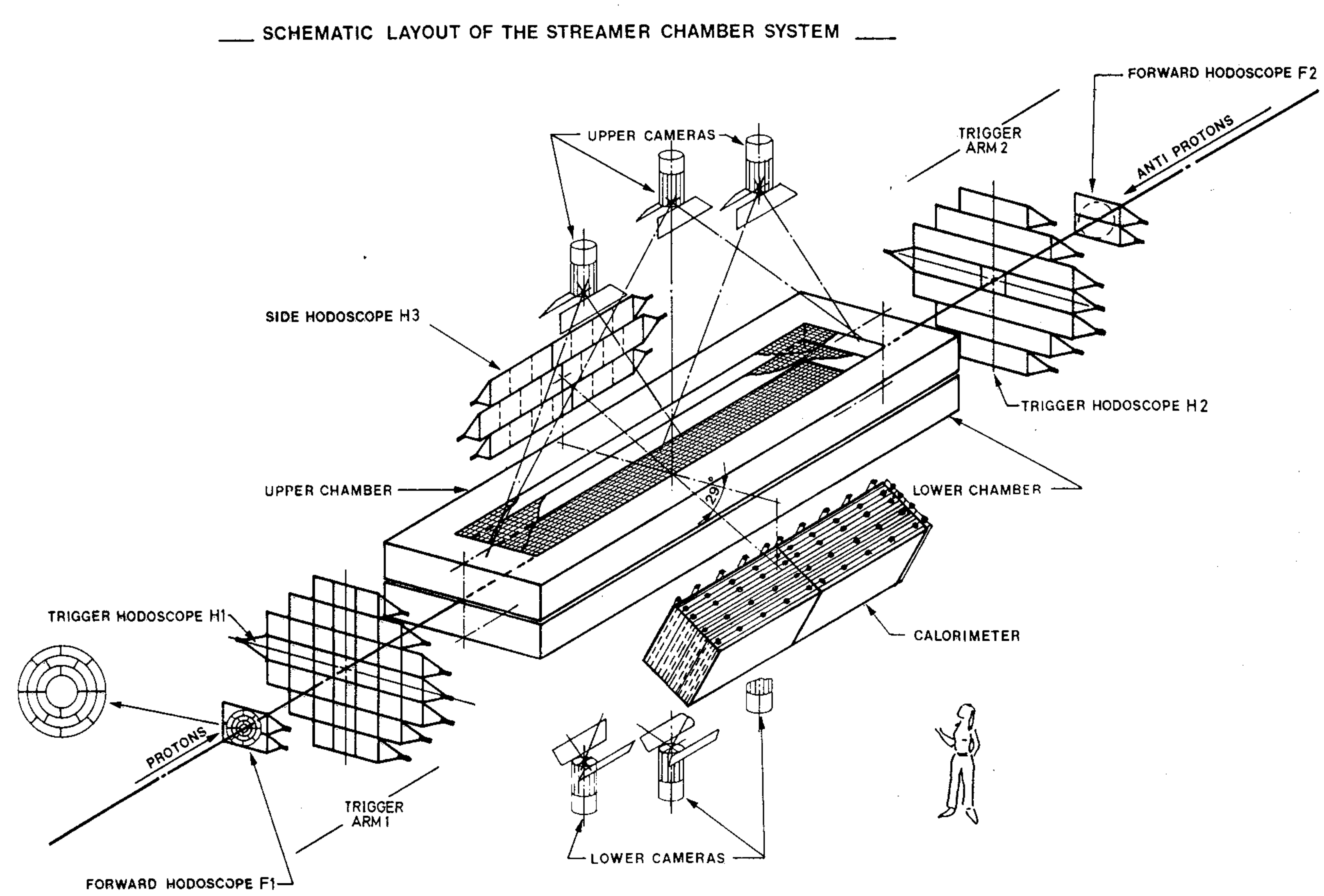
CERN SPS: UA5 streamer chambers
($\sqrt{s}$=200, 546 and 900GeV)

- UA5: experiment was optimized for the study of charged particle multiplicity for **non-single diffractive inelastic events** .



Phys. Rep. **154**, 247(1987)

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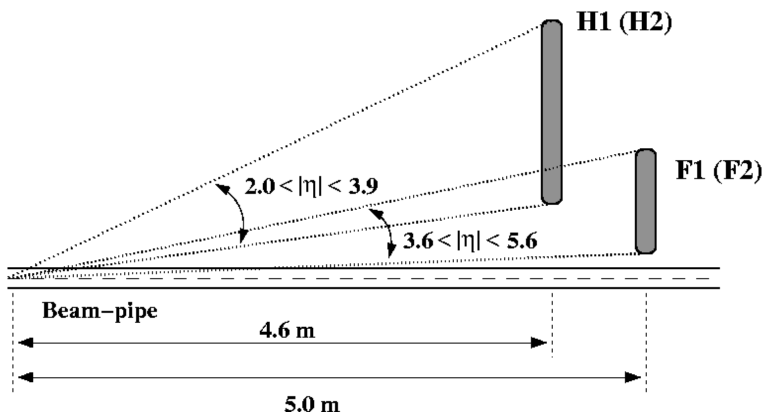
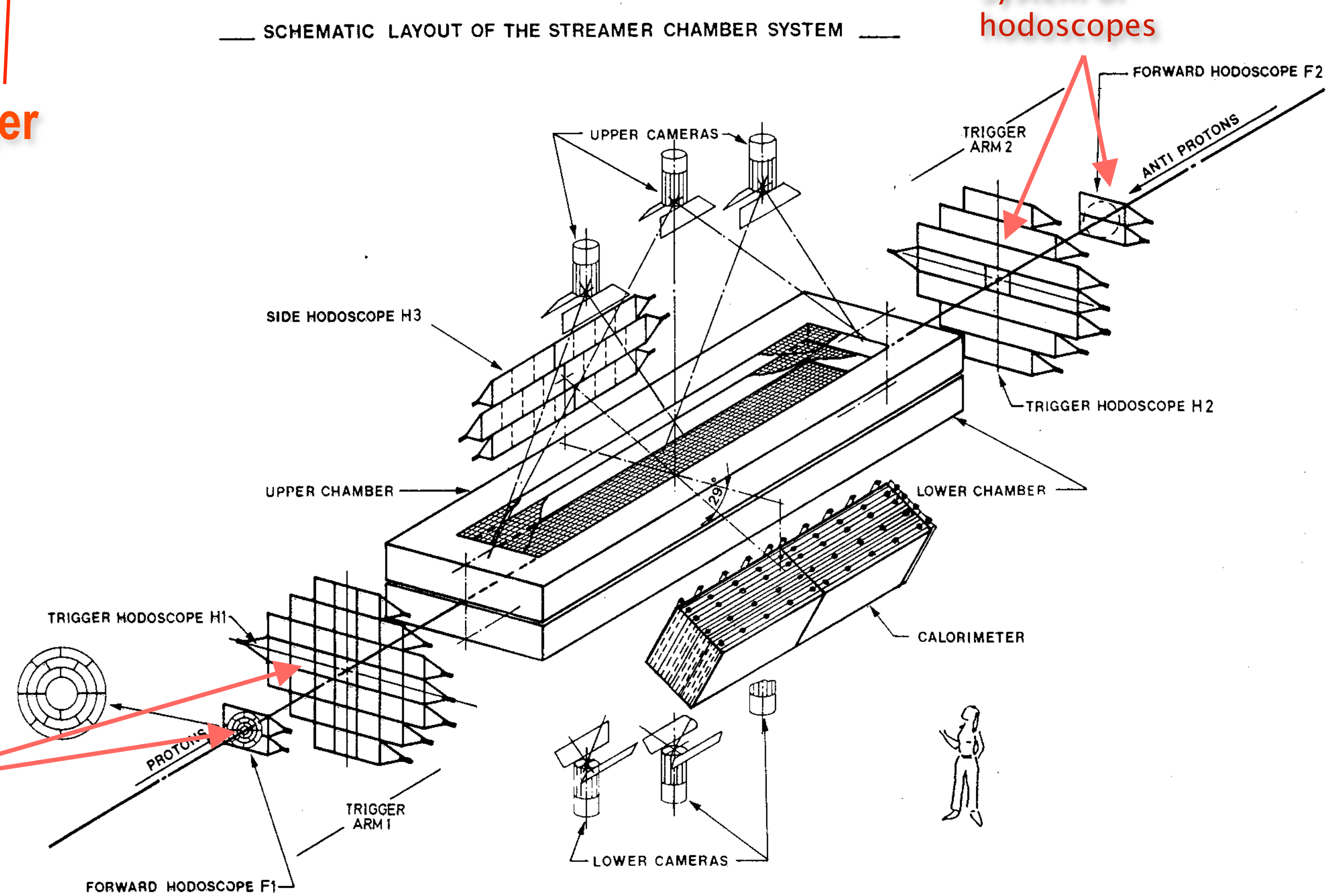
UA5: Min-bias trigger



Require coincidence between beam crossing and at least one hit in each side of the trigger system.

95% of non-single diffractive inelastic events.

System of hodoscopes



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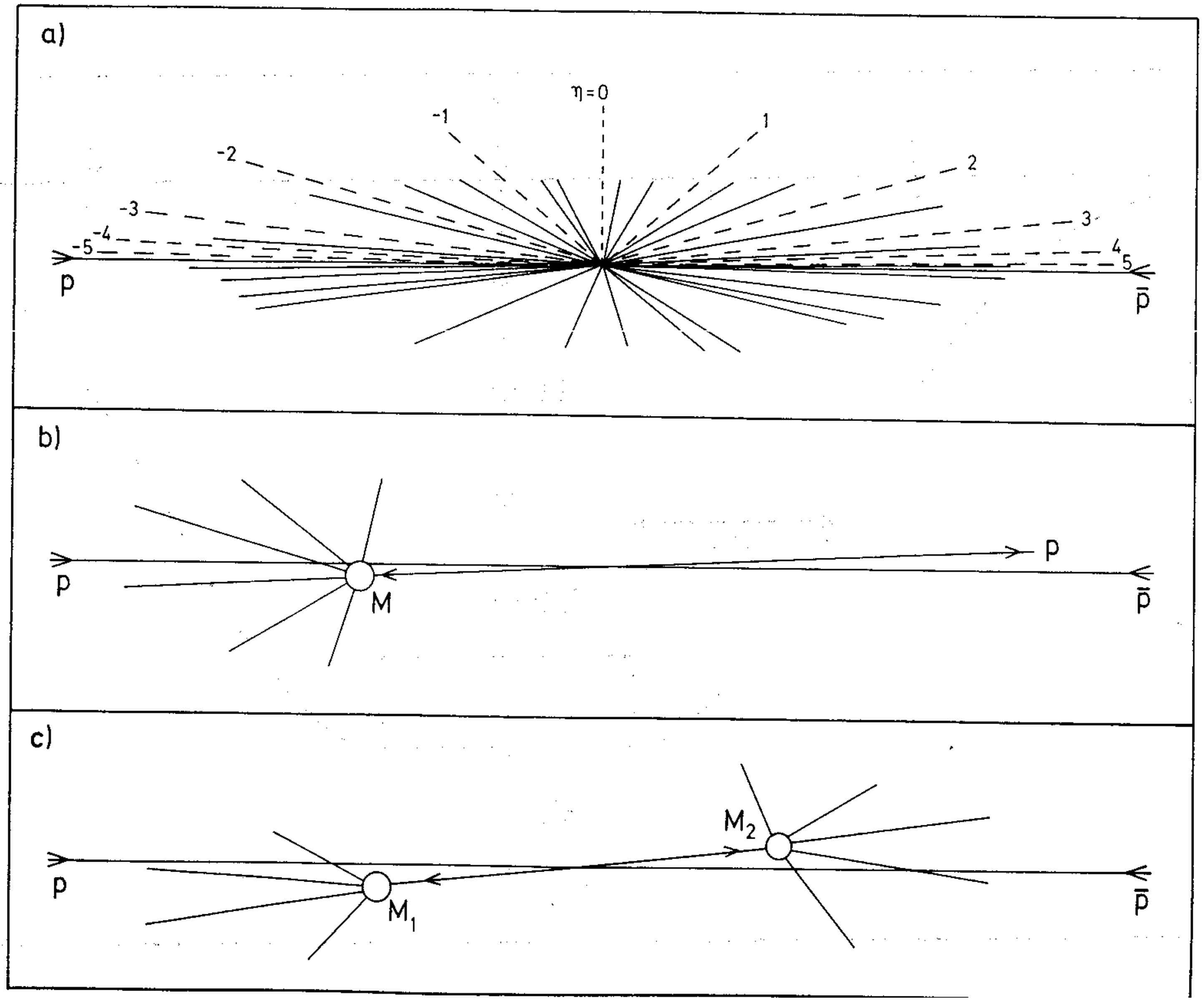
UA5: Minimum bias events



Non-diffractive inelastic

Single diffractive

Double diffractive

UA5: Minimum bias events

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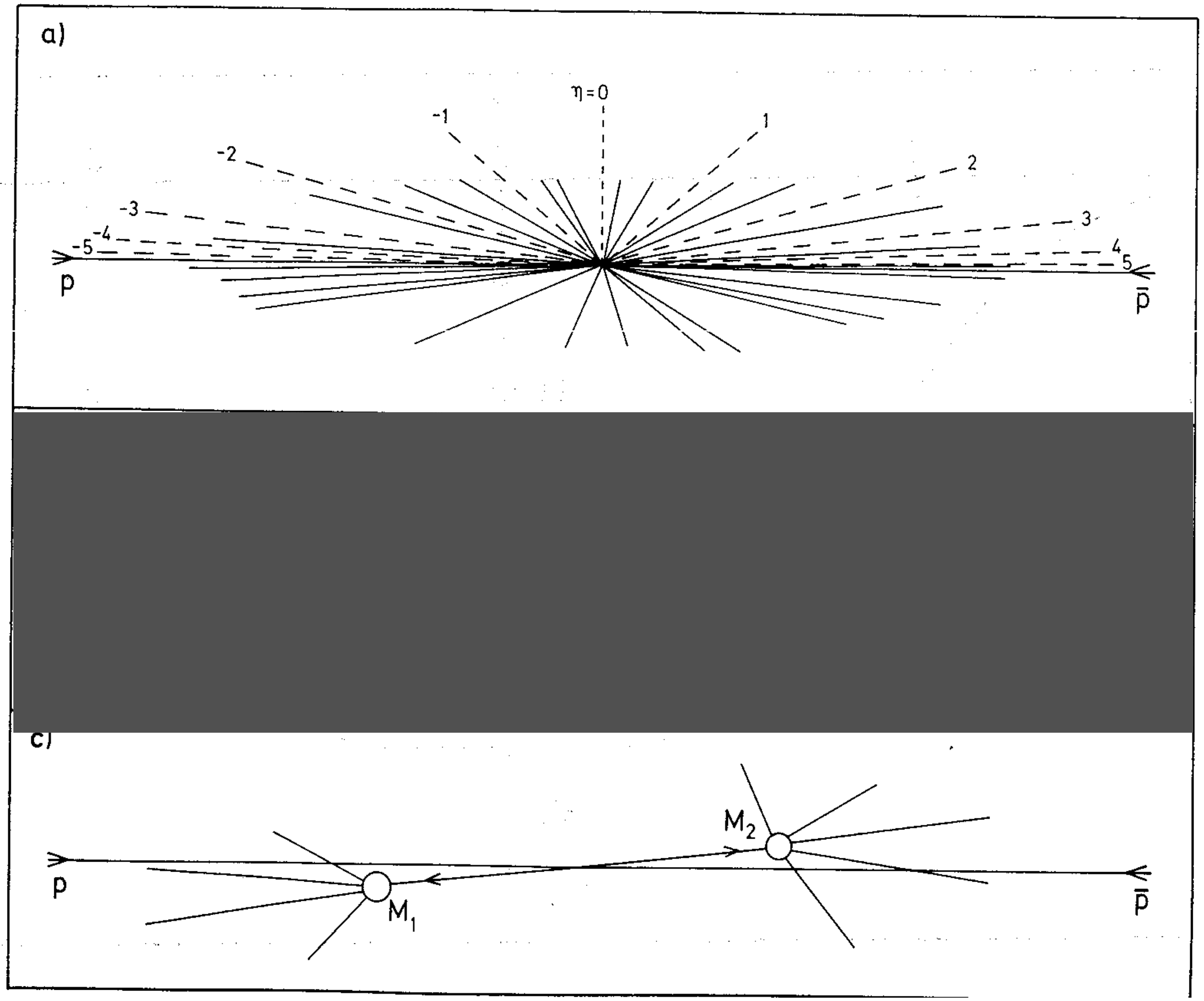

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Minimum bias

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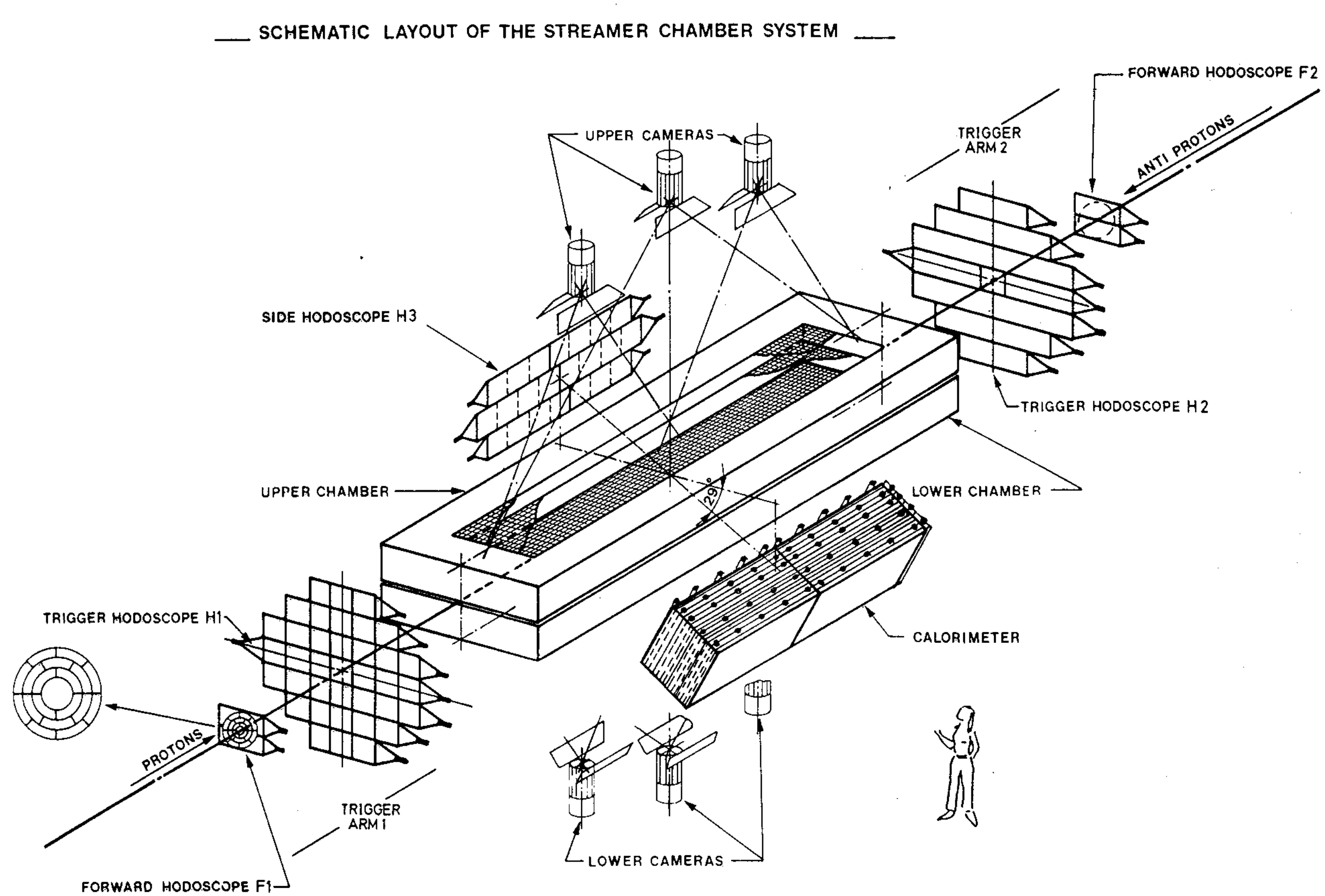

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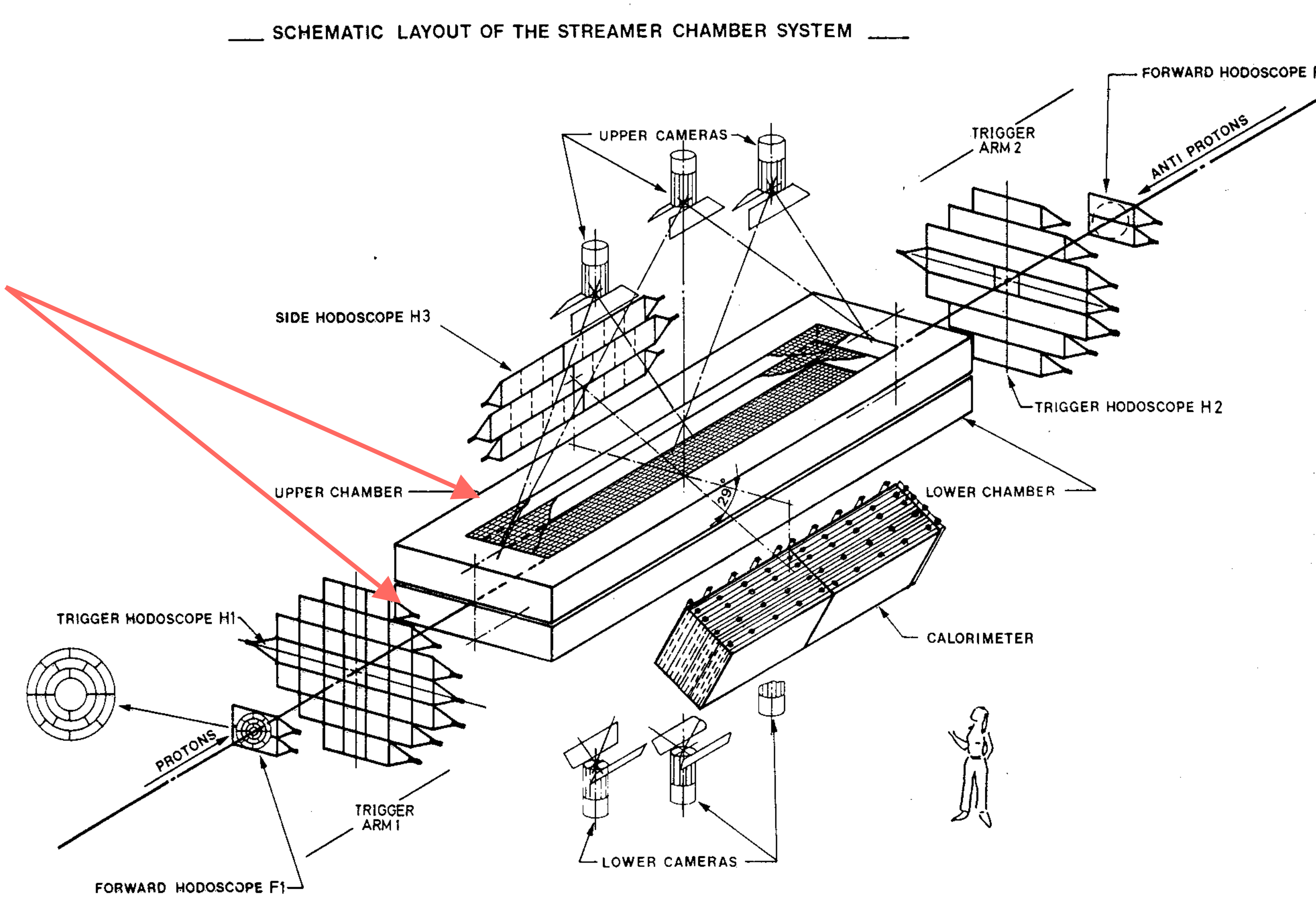
Streamer chambers: detect charged particles



No magnetic field.

Geometrical acceptance: ~95% for |η|<3 (falls to 0 as |η|→5) .

Tracks seen correspond to ~80% - 70% of the total estimated number of tracks going from 200GeV – 900GeV.

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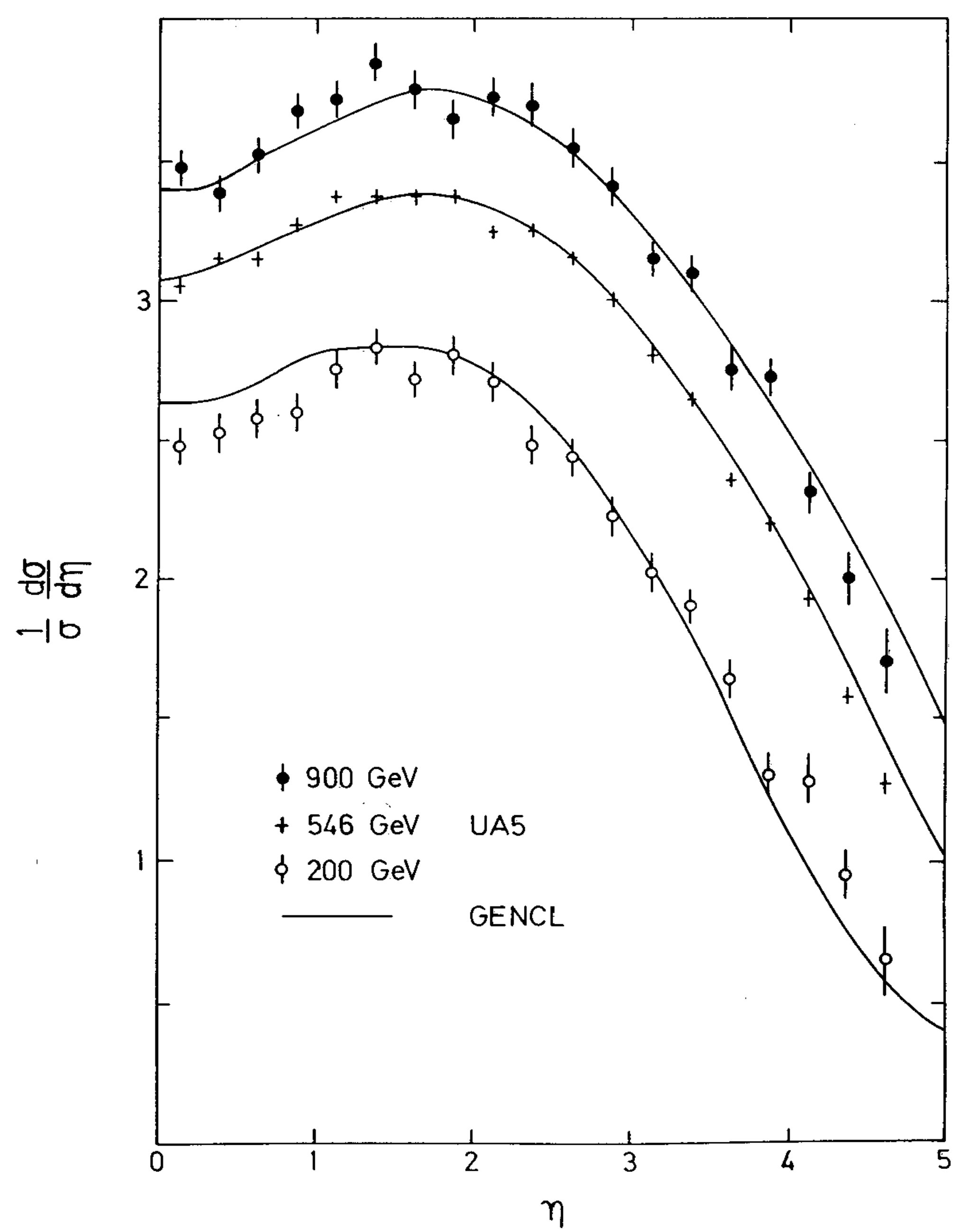
UA5: $dN_{ch}/d\eta$ and multiplicity distributions for minimum bias events

$dN_{ch}/d\eta$: pseudorapidity distributions for minimum bias events

$\sqrt{s}$	Number of selected events
200 GeV	4156
900 GeV	6839



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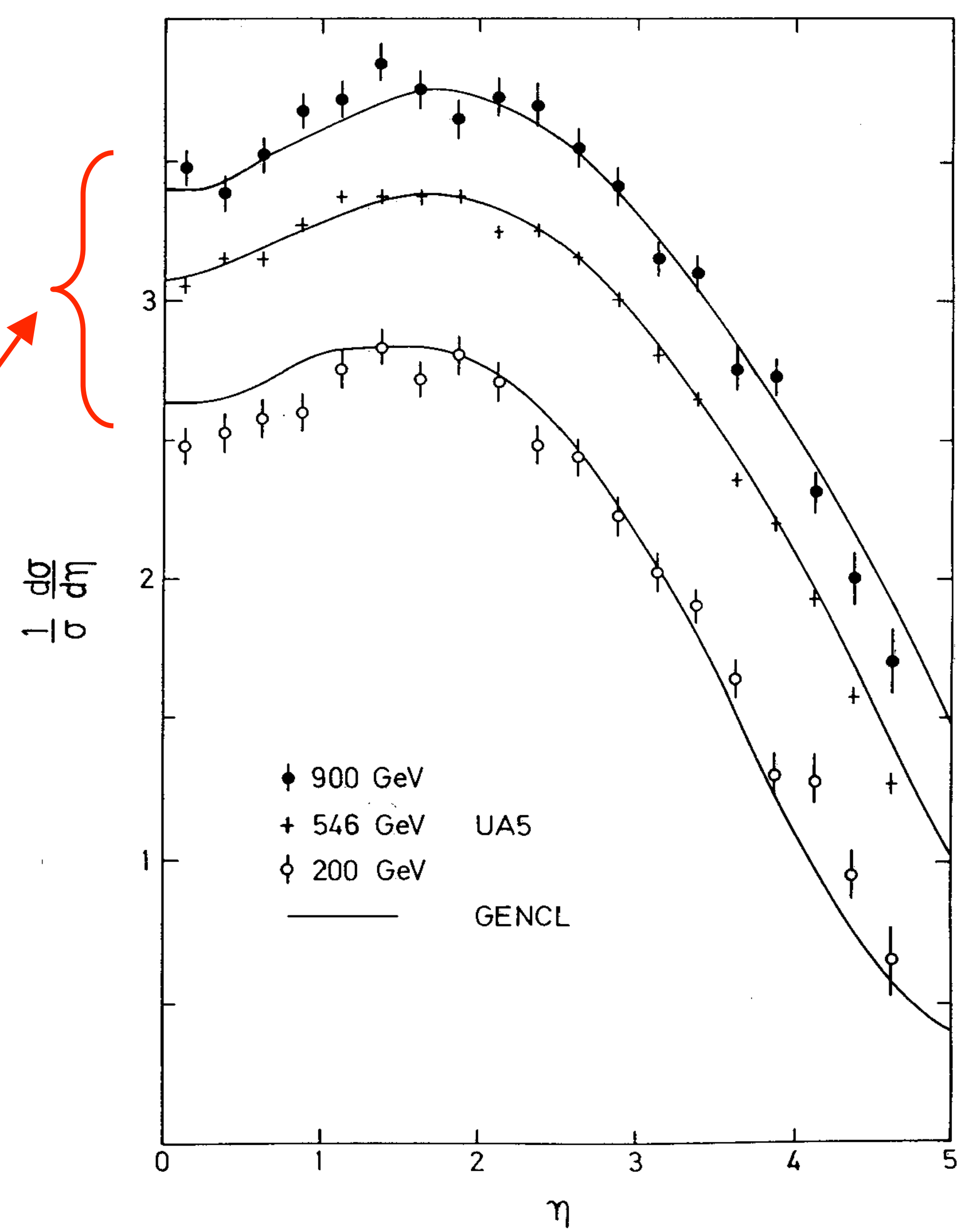
Rise of the central plateau: ~ln s



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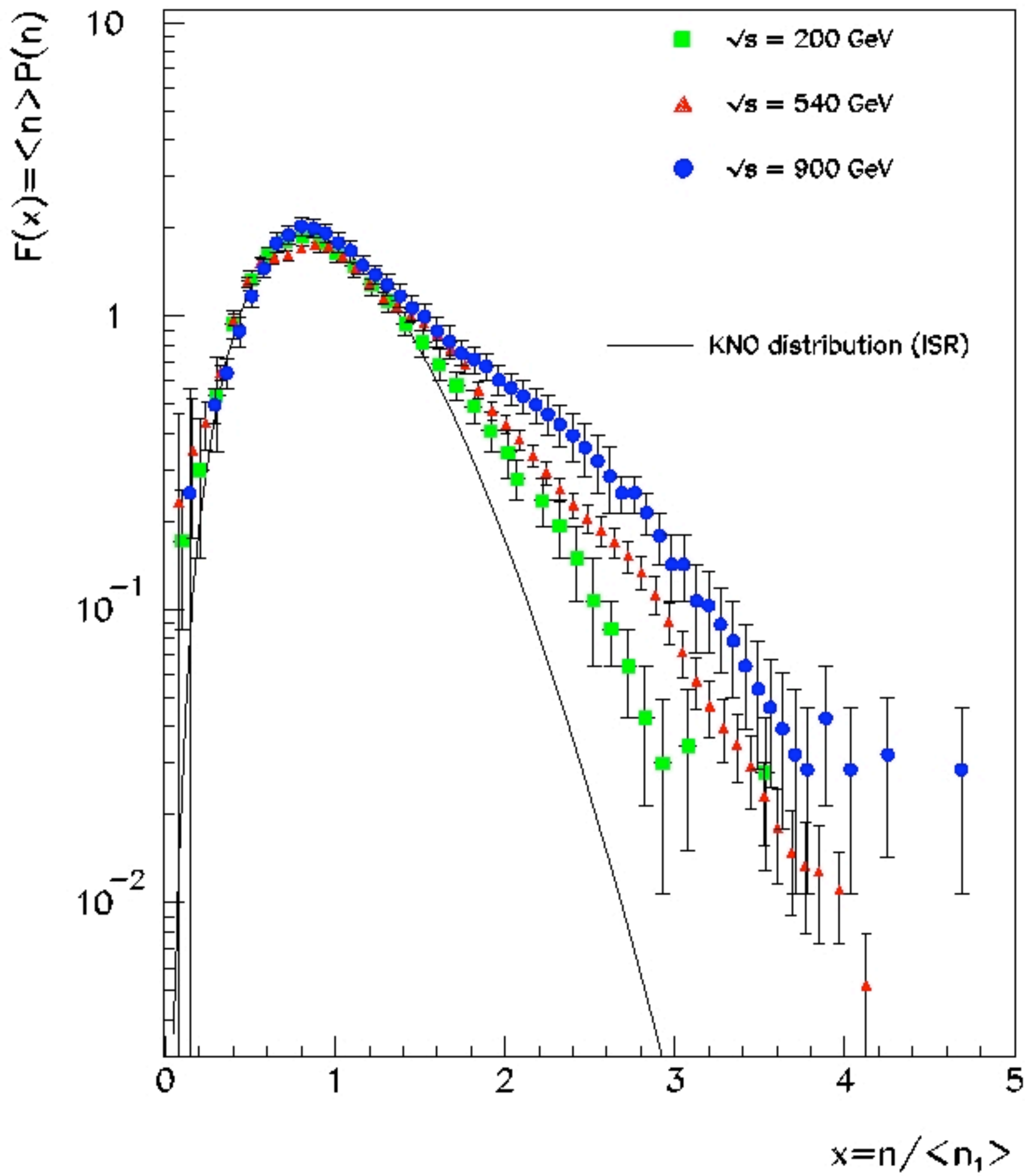


Multiplicity distributions for minimum bias events

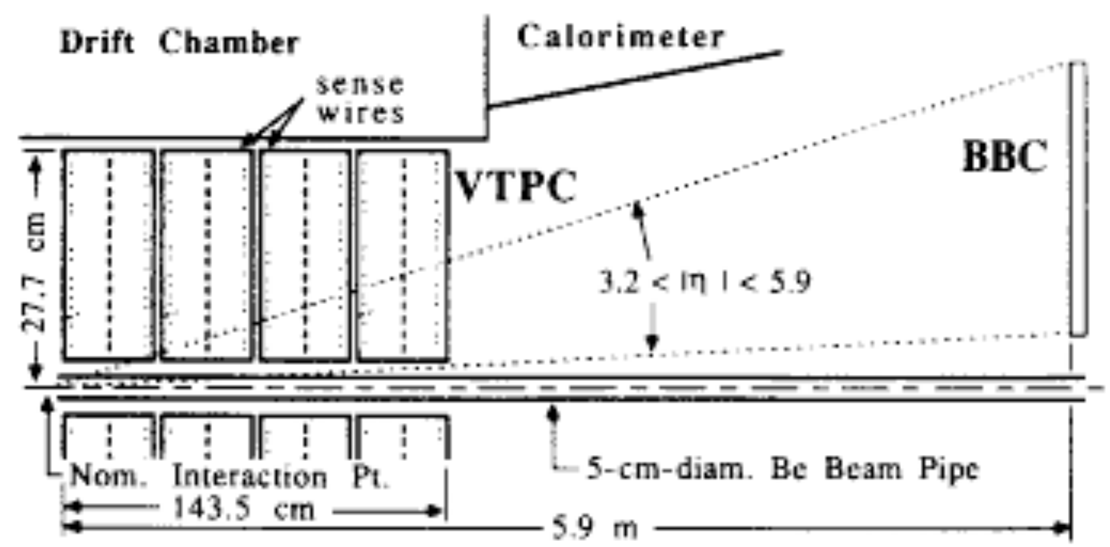
Clear violation of the KNO scaling: indication of multiple parton interactions!

QCD turned out to be more complex than first thought.

Tevatron: CDF experiment ($\sqrt{s}$=1.8TeV)

- **Detector subsystems used to measure minimum bias:**

Measurements of minimum bias done with Run I data (collected in 1987).



Phys. Rev. D **41**(7), 2330(1990)

Tevatron: CDF experiment ($\sqrt{s}$=1.8TeV)

- **Detector subsystems used to measure minimum bias:**

Beam-Beam Counter (BBC)

Trigger the detector

3.2<|η|<5.9

Requirement: one BBC hit in coincidence with the beam-crossing

Selected events must also have a minimum number of tracks in the VTPC

Vertices should be within ±12cm from the middle of the VTPC module.

Beam-gas: estimated from single p beam runs (~0.2% for 1.8TeV and <2% for 630GeV – no bias!)

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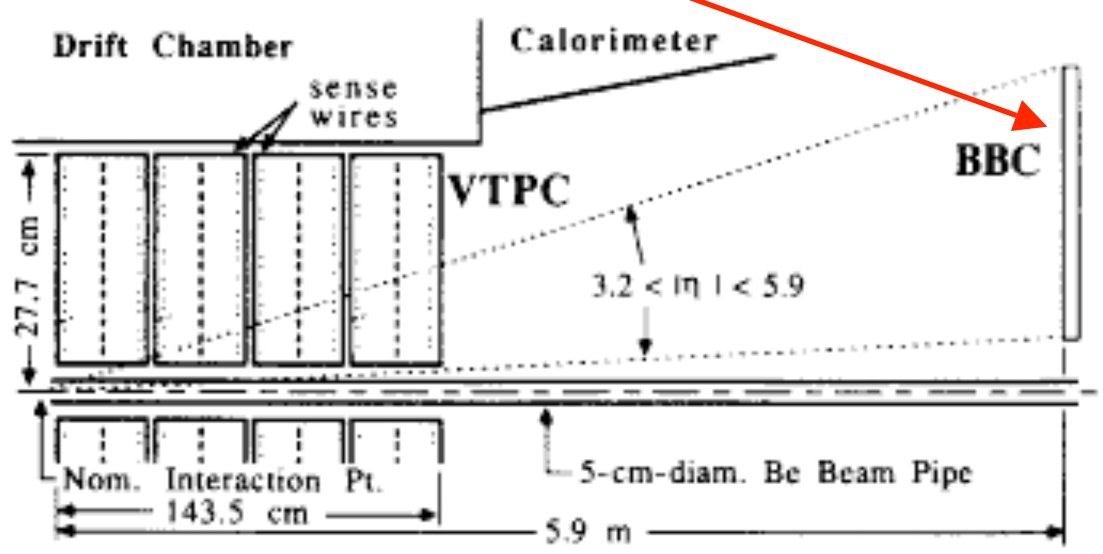

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Vertex Time Projection Chamber (VTPC)

Provides charged particle tracking

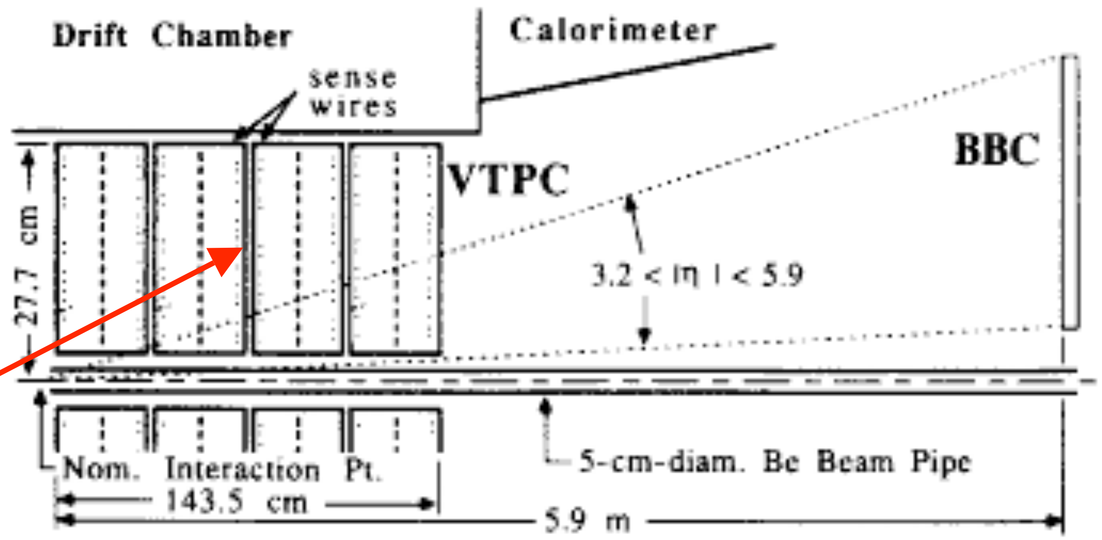
Coverage: 2π in azimuth, ±3 units in η .

Require minimum of 11 wire hits out of possible 24

Magnetic field: 1.5T

Low p_T cutoff: 50MeV (correcting back to p_T=0 → 3% effect for both 1.8TeV and 630 GeV)

Measurements of minimum bias done with Run I data (collected in 1987).



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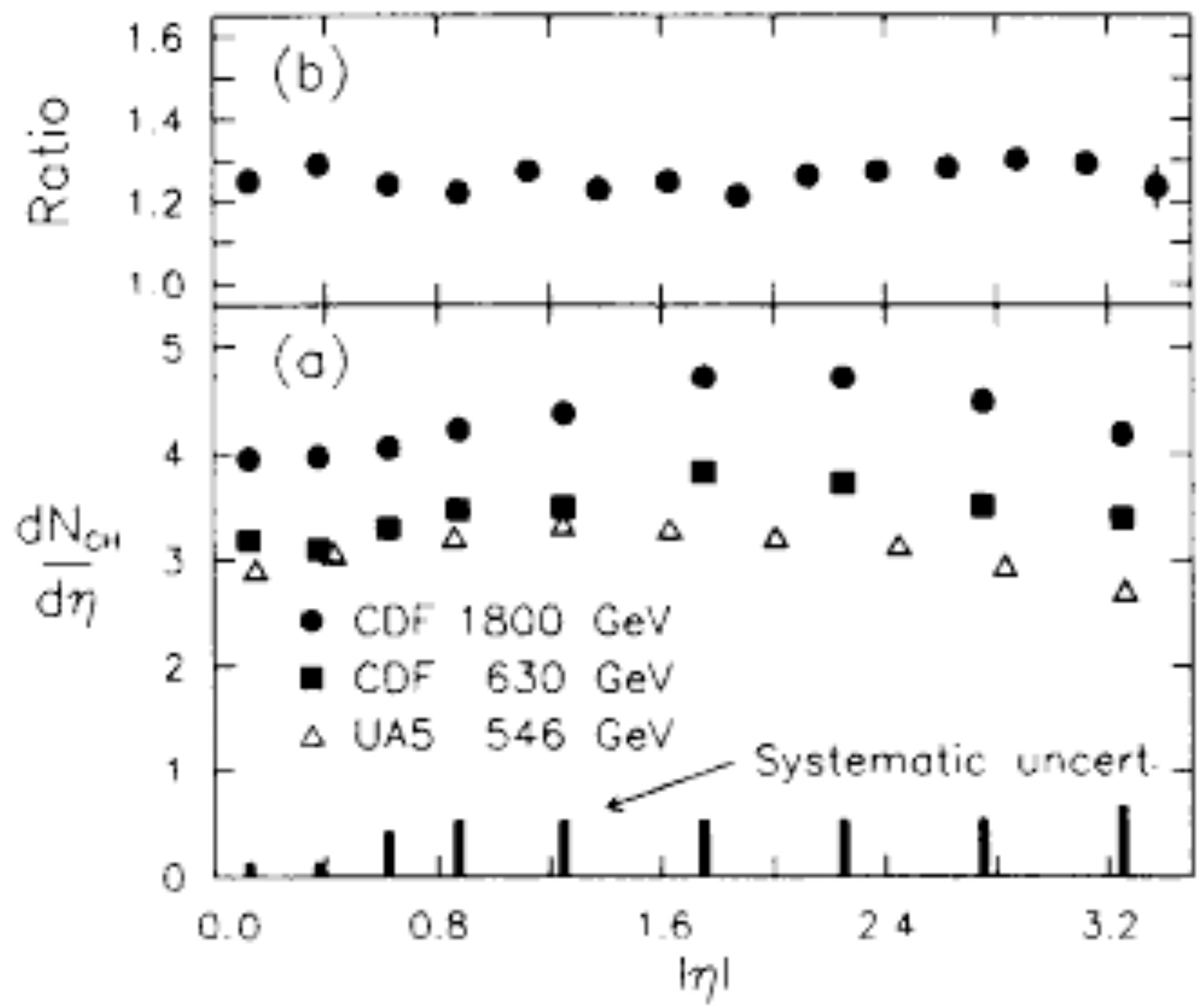
CDF: $dN_{ch}/d\eta$ for minimum bias events

$dN_{ch}/d\eta$: pseudorapidity distributions for minimum bias events

√s	Number of selected events
630 GeV	2800
1.8 TeV	21000



Tracking efficiency: measured from a visual scan of ~400 events at 1.8TeV (used to calibrate the reconstruction software)

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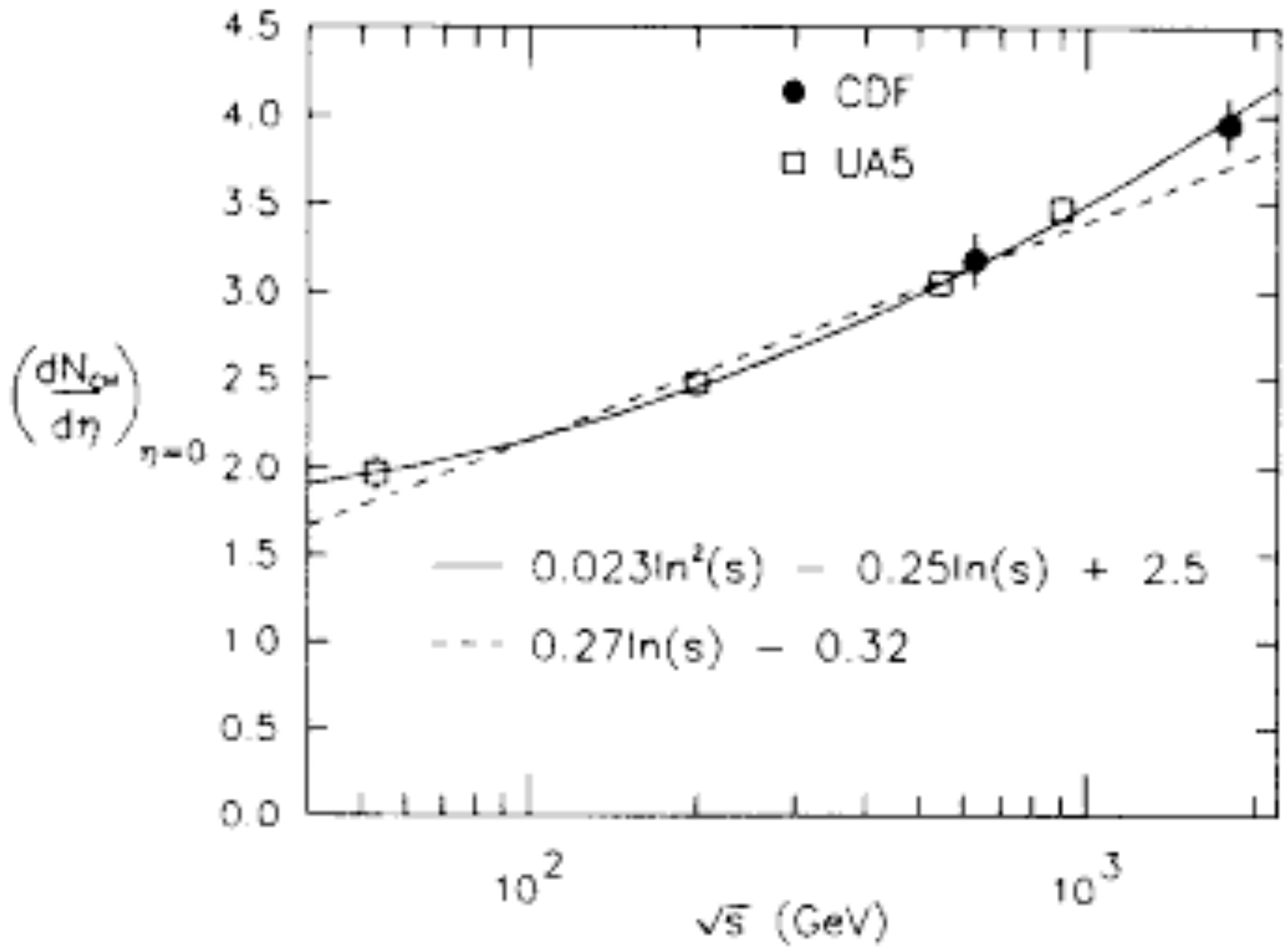
CDF: $dN_{ch}/d\eta$ for minimum bias events

Comparison: UA5 and CDF measurements of the central plateau



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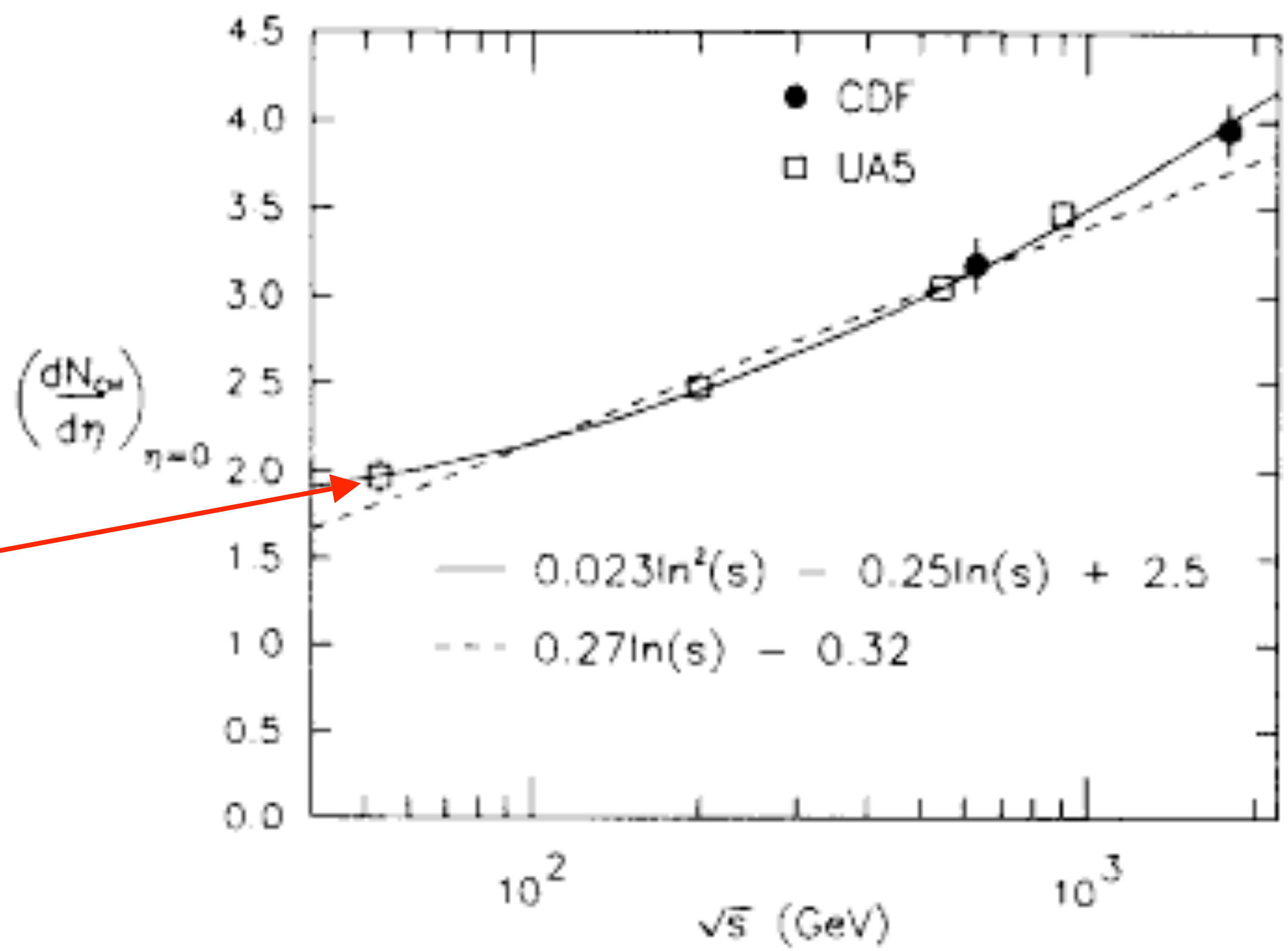
CDF: $dN_{ch}/d\eta$ for minimum bias events

Comparison: UA5 and CDF measurements of the central plateau

UA5: rise of the central plateau favors energy dependence ~ln s

CDF: rise of the central plateau favors energy dependence ~$\ln^2$ s

Further indication that multi-parton interactions become a visible effect in multiplicity distributions as $\sqrt{s}$ is increased.



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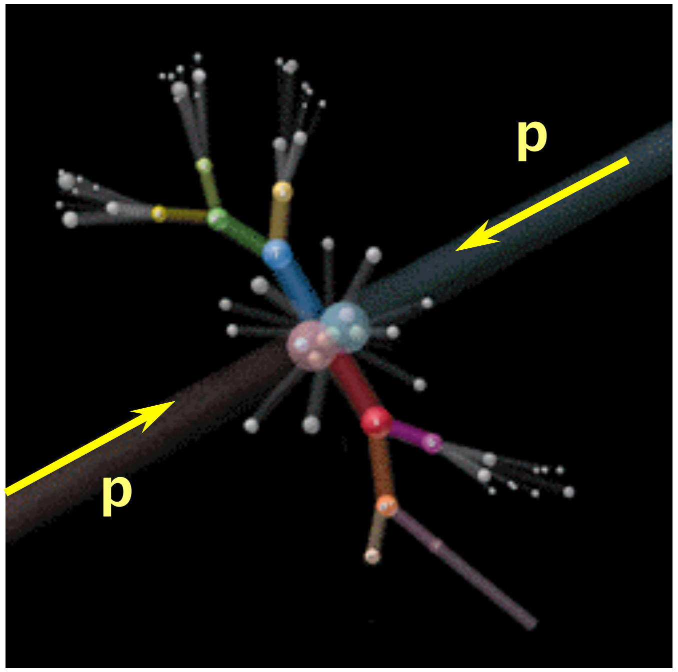
"Minimum bias" vs. the underlying event: aren't they the same?

- **The underlying event:** All particles from a single particle collision except the process of interest.

  - Sometimes, the underlying event can also be defined as everything in the collision except the hard process (high-Q^2).



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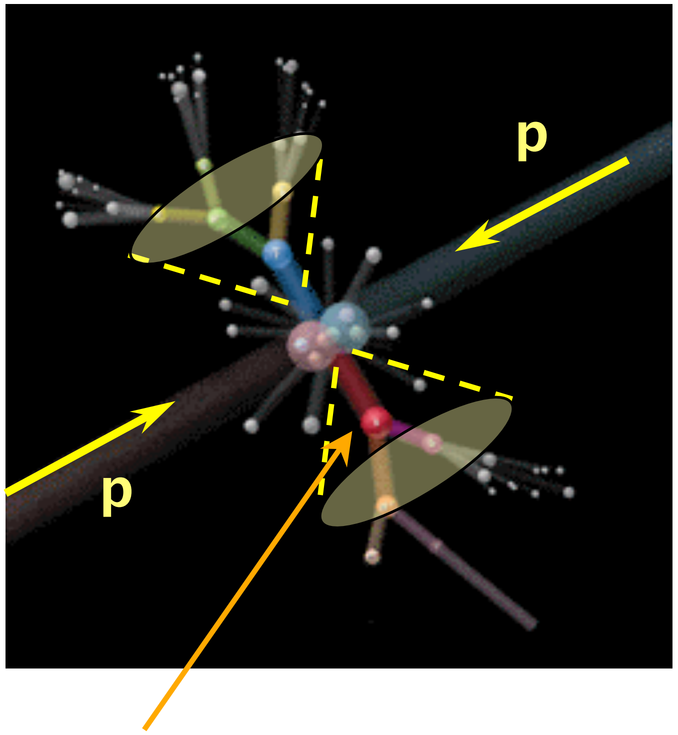

Process of interest (eg. high p_T jets, top-anti-top pair, Z boson)

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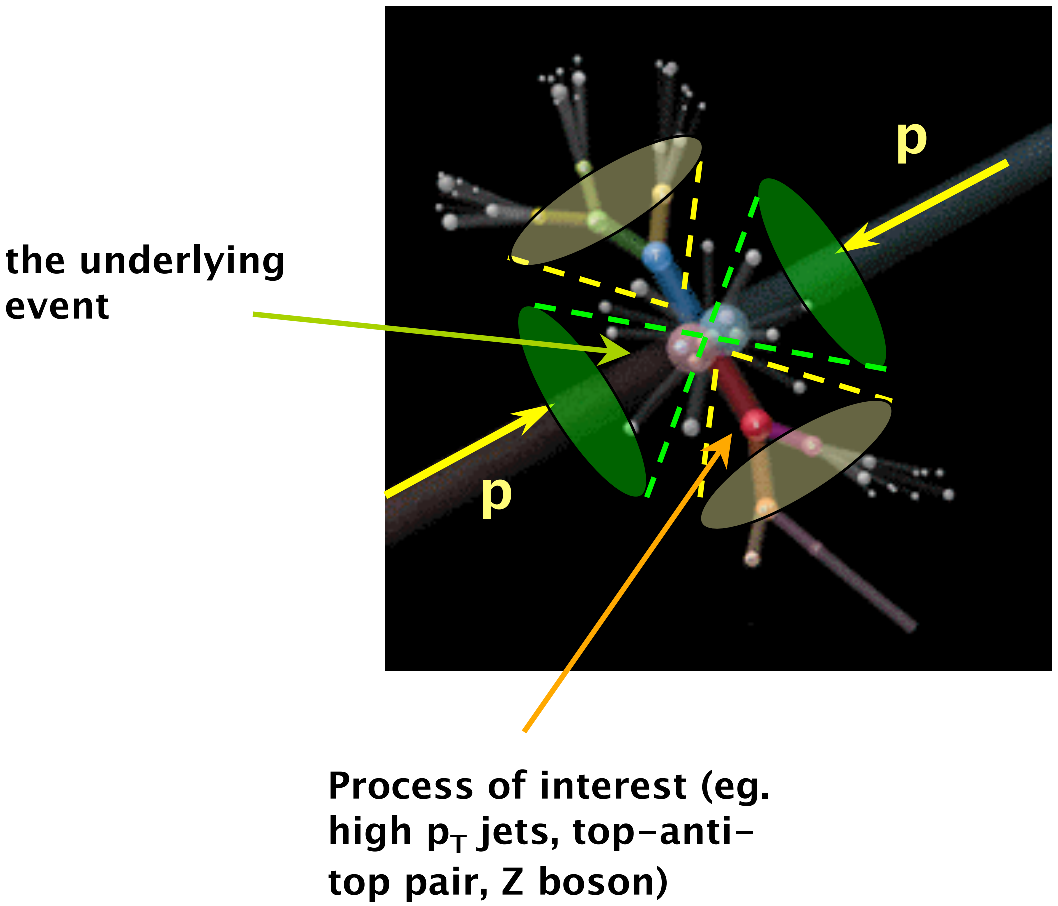

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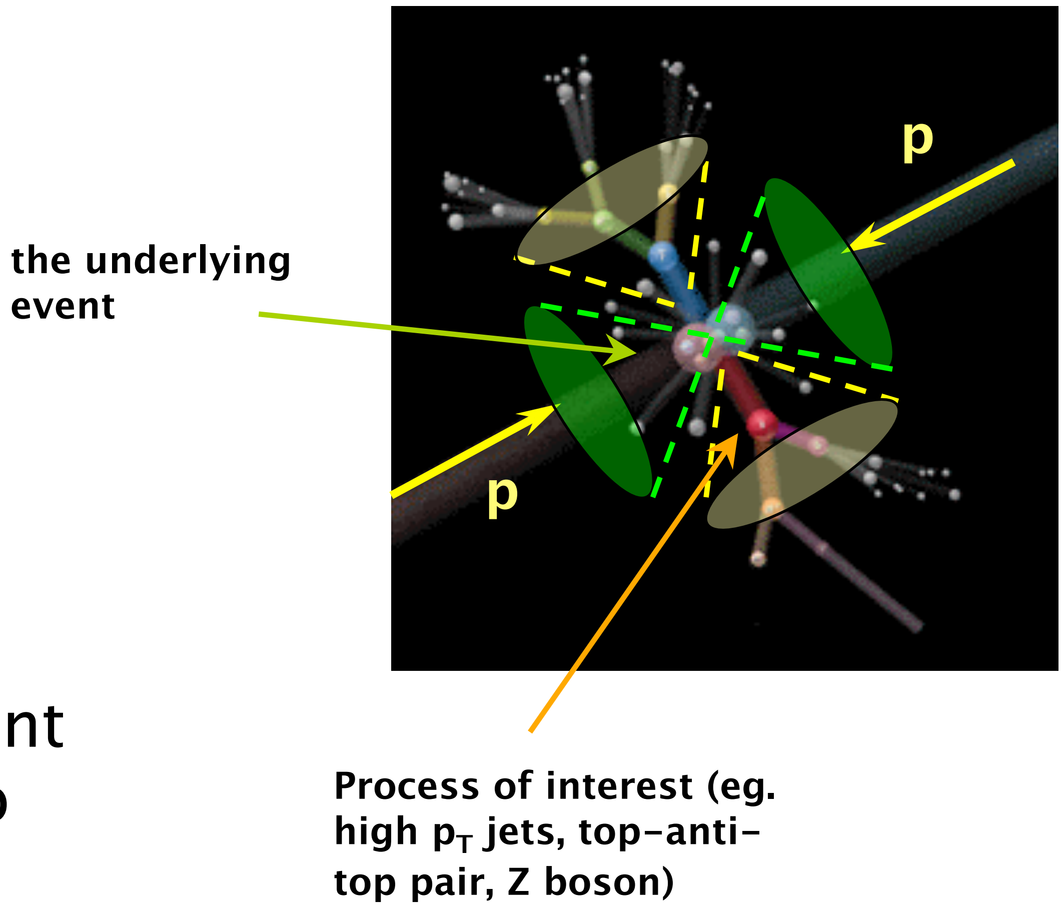
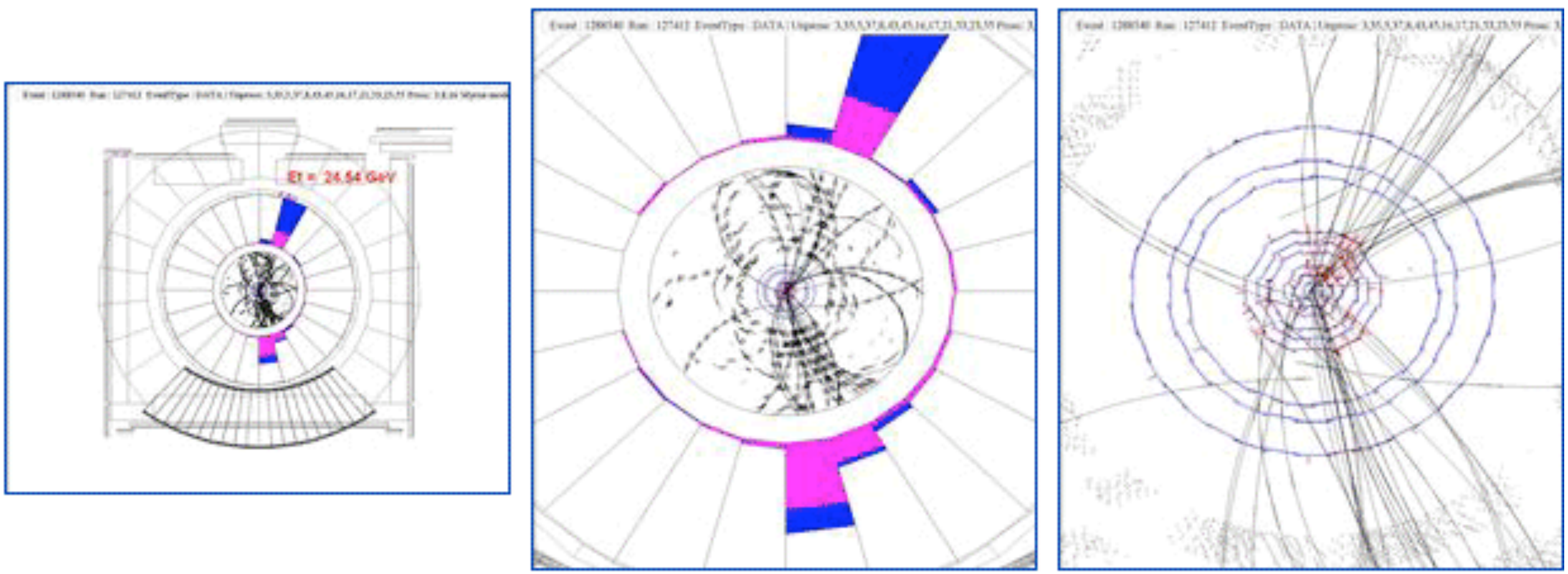


- **Common mis-conception**: in the pre-Tevatron era, the activity in the underlying event (particle multiplicity, p_T^{sum}, ...) was assumed to be **“approximately”** the activity measured in minimum bias events.

“Minimum bias” vs. the underlying event: aren’t they the same?

- During Run I, CDF investigated the underlying event associated to jets.

- The leading charged particle jet in the event was used as the “reference” signature.



T. Affolder et al., The CDF Collaboration, Phys. Rev. D65, 092002 (2002).

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CDF analysis:

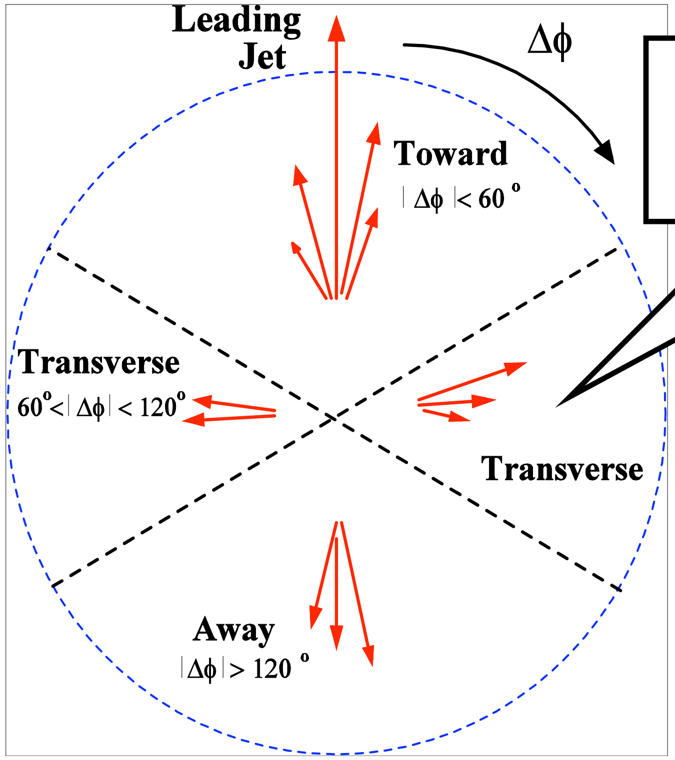
- charged particles:

p_t>0.5 GeV and |η|<1

- **cone jet finder:**

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$$

$$\Delta\phi = \phi - \phi_{\mathbf{ljet}}$$



UE is defined as the Transverse Region

T. Affolder et al., The CDF Collaboration, Phys. Rev. D65, 092002 (2002).

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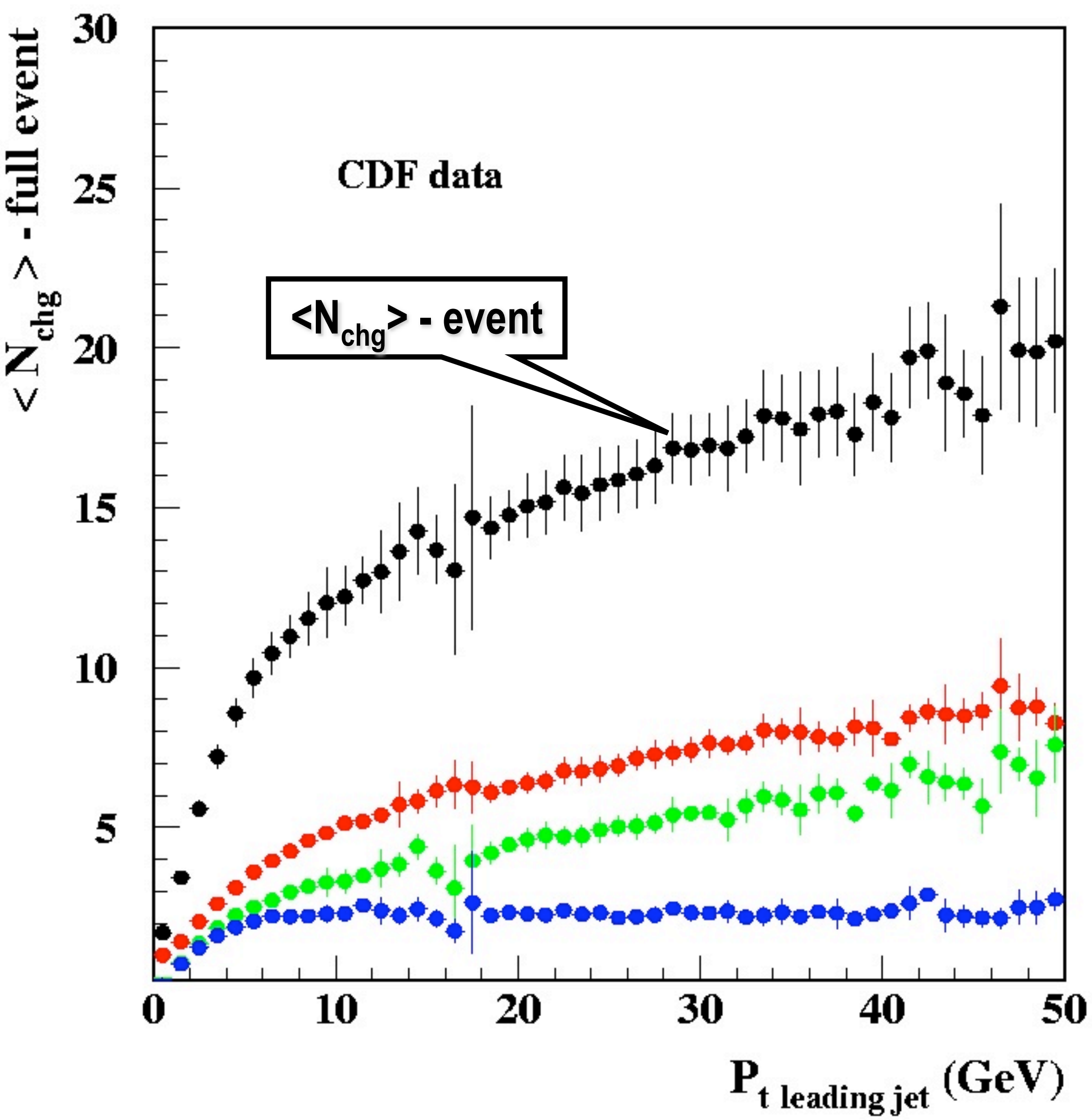
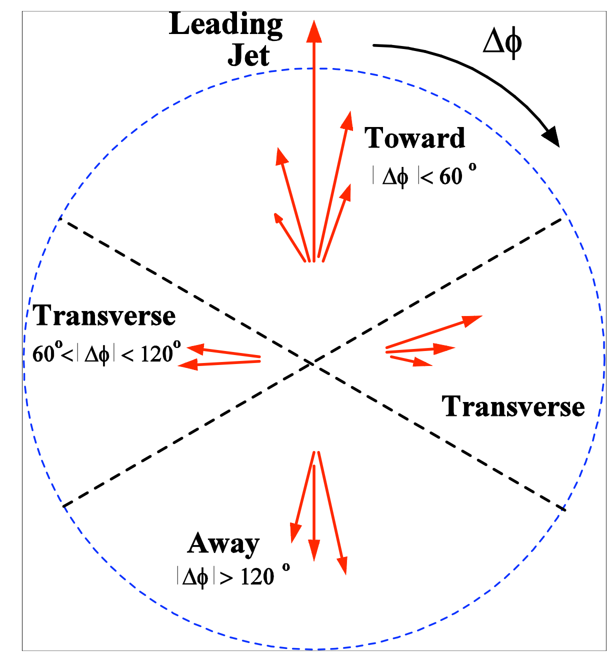
<N_{chg}> distributions (particles from different angular regions)





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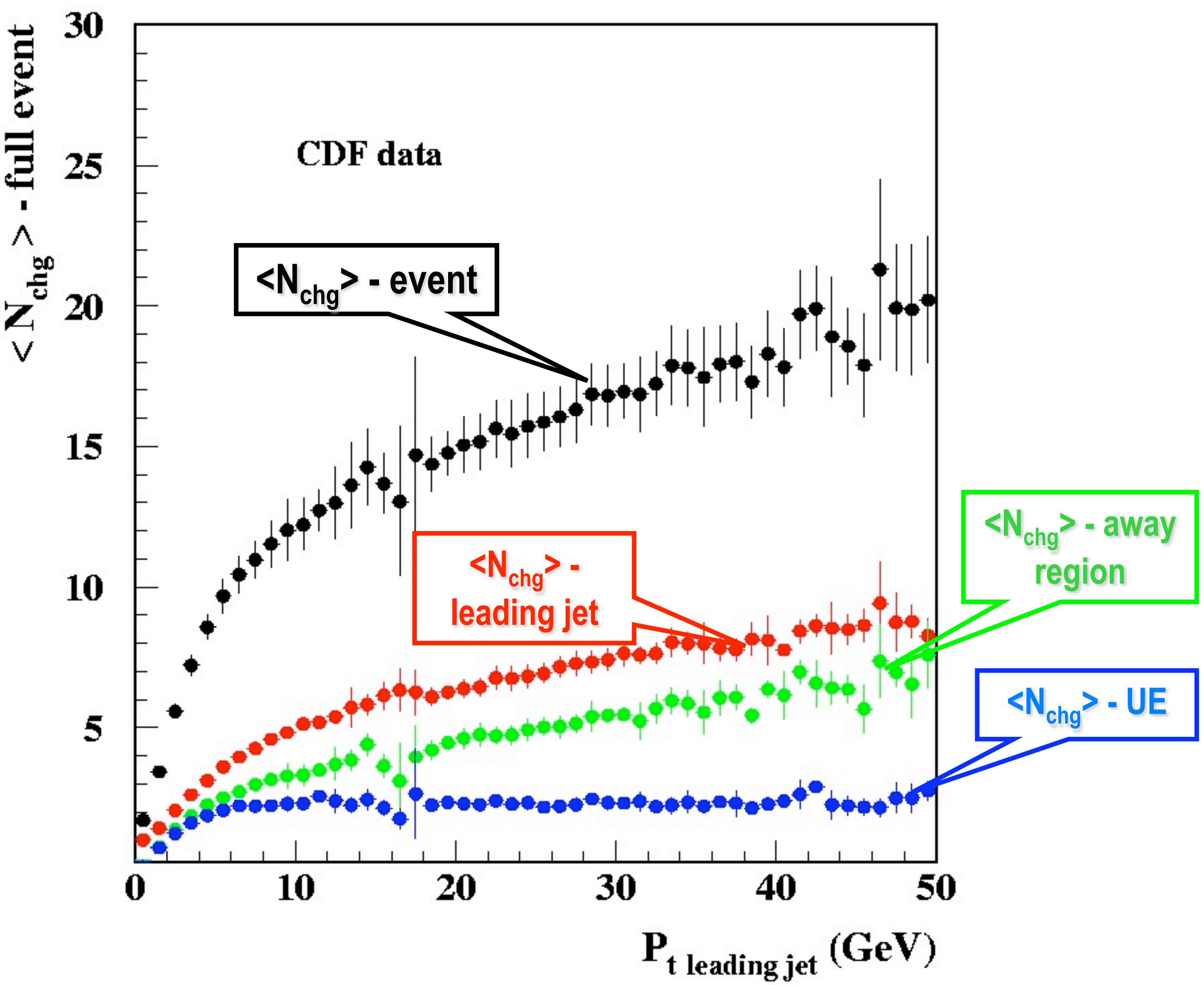

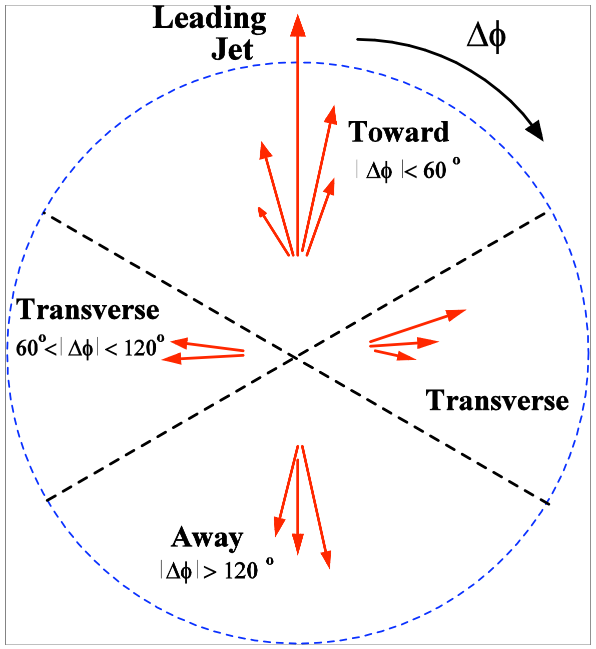

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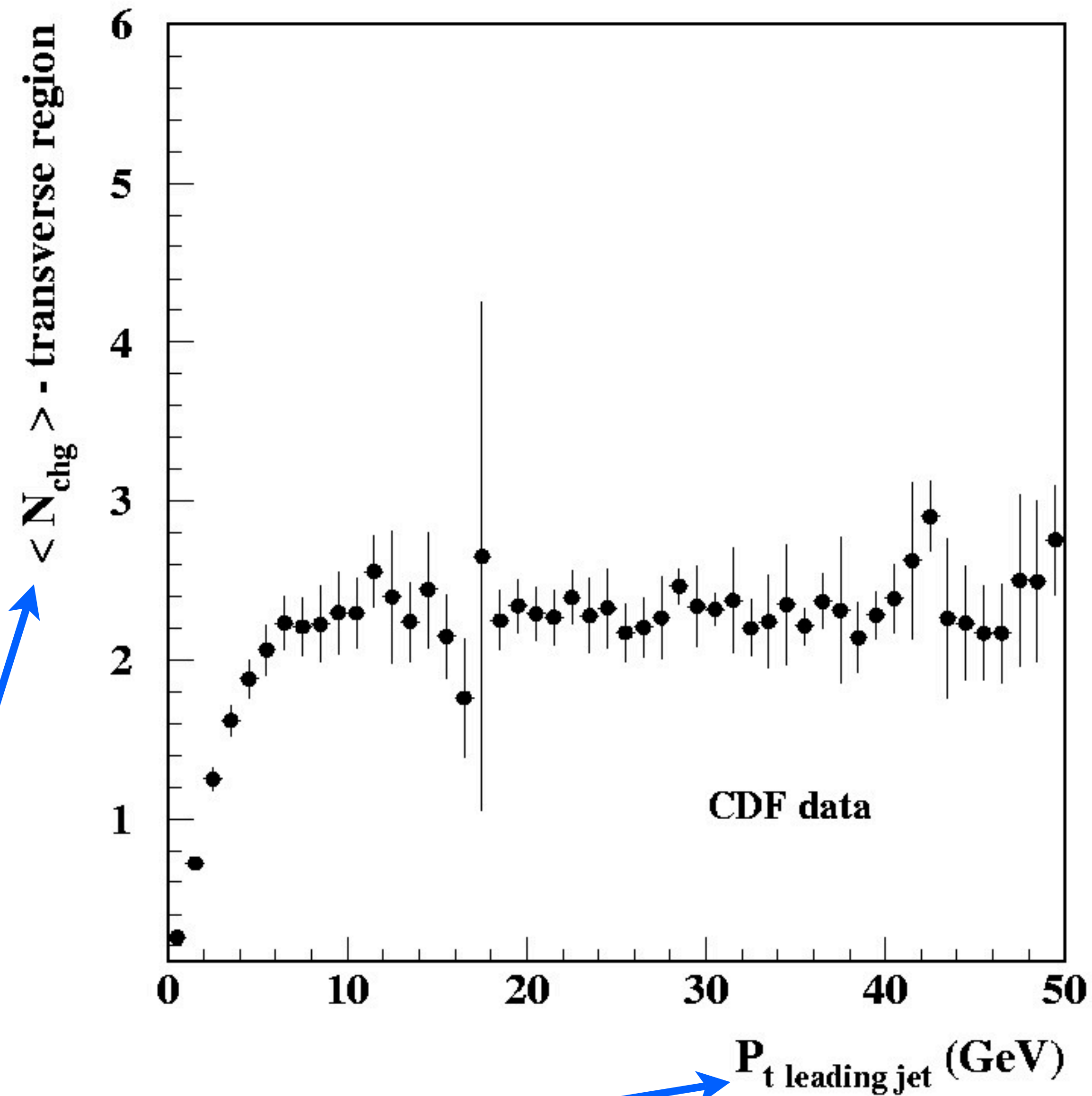
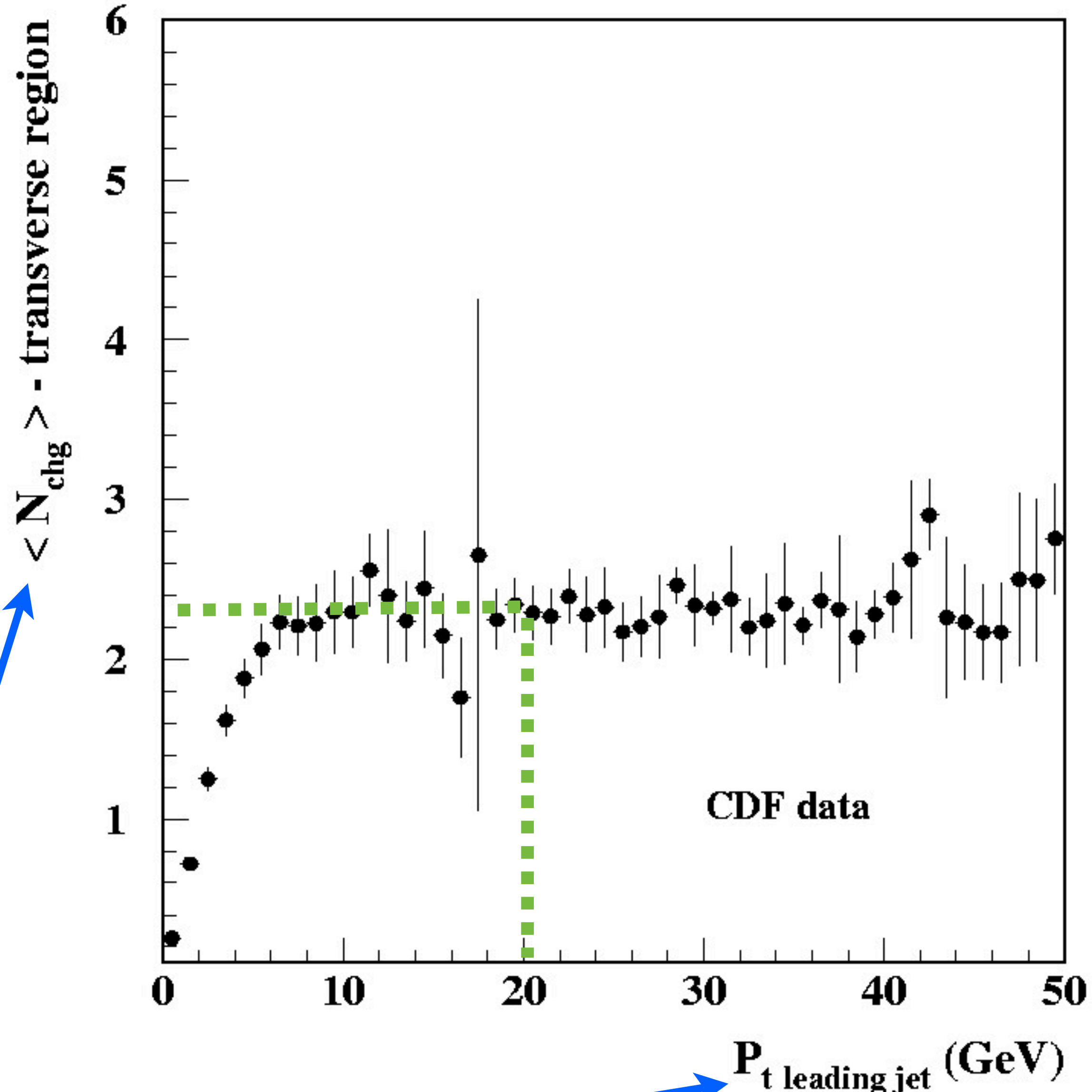


Average multiplicity of charged particles in the underlying event associated to a leading jet with $\mathbf{P_T}^{ljet}$ (GeV).



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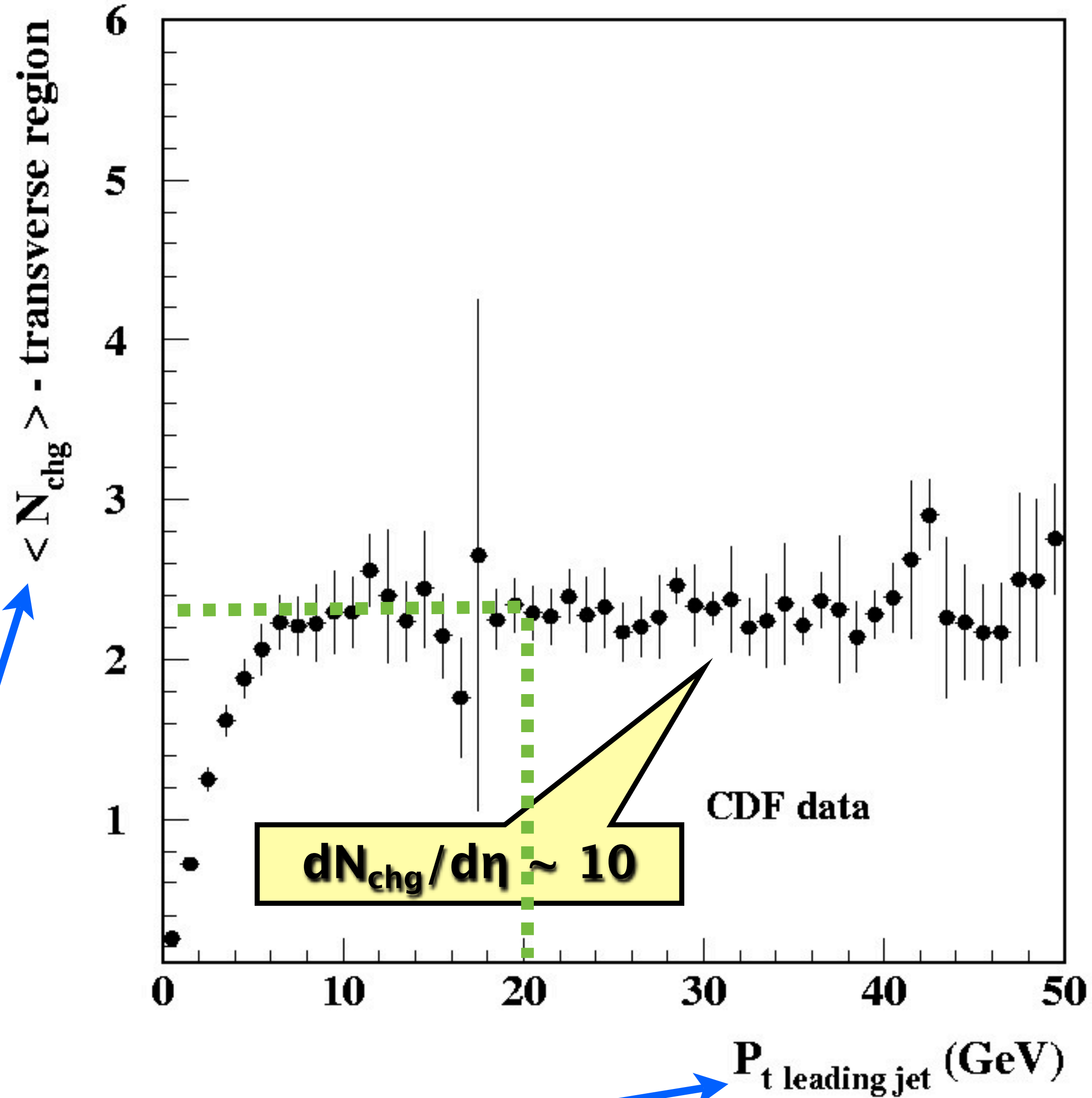


Average multiplicity of charged particles in the underlying event associated to a leading jet with P_T^{ljet} (GeV).

(a) ~**2.3** charged particles for event with leading jet p_T = 20GeV

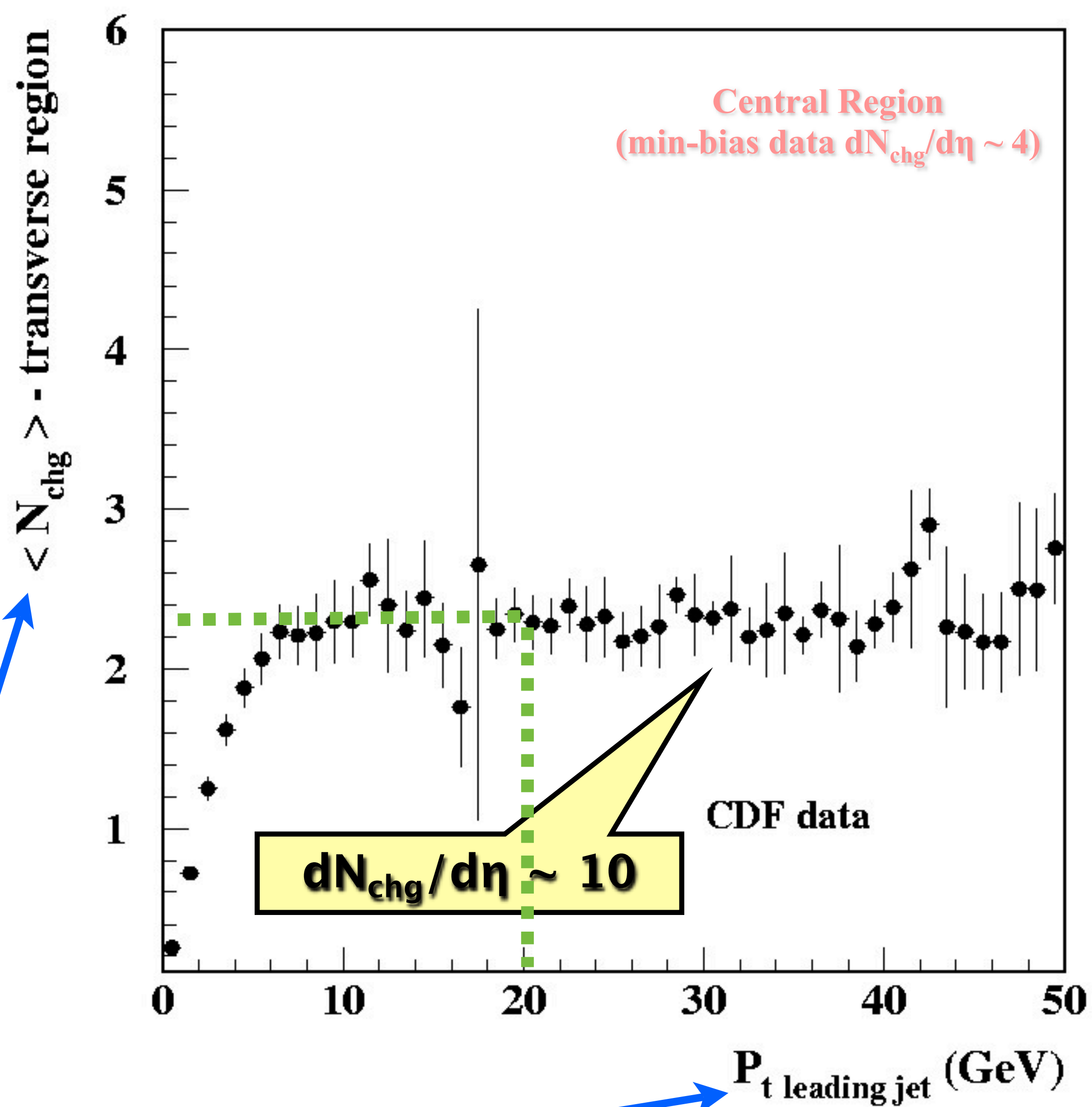
(b) **x 3** to get 360°

(c) ÷ **2** to for the units of η

(d) **x 1.09** to correct for track finding efficiency

(e) **x 2.7** to extrapolate track multiplicity from 0.5GeV back to 0.

~10 charged particles per unit of pseudorapidity in the UE



Average multiplicity of charged particles in the underlying event associated to a leading jet with $\mathbf{P_T}^{\mathbf{ljet}}$ (GeV).

(a) ~**2.3** charged particles for event with leading jet p_T = 20GeV

(b) **x 3** to get 360°

(c) ÷ **2** to for the units of η

(d) **x 1.09** to correct for track finding efficiency

(e) **x 2.7** to extrapolate track multiplicity from 0.5GeV back to 0.

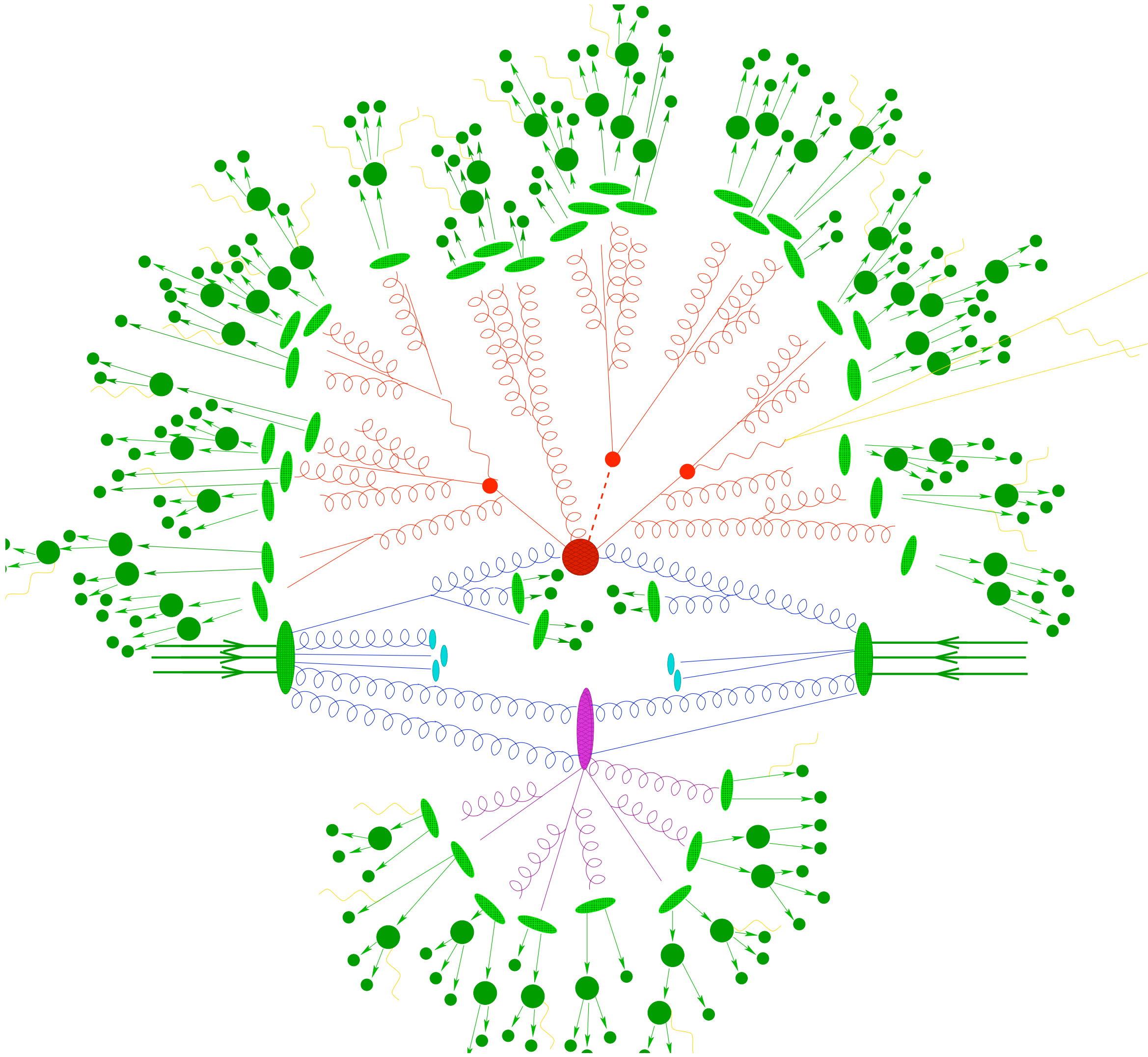
~10 charged particles per unit of pseudorapidity in the UE

- not ~4 charged particles as measured by CDF for minimum bias! (see dN/dη plot from Phys. Rev. D 41(7), 2330(1990))

- **The particle activity in the UE is twice as high as what is measured for minimum bias!**

More detailed look into the underlying event...

□ **Why is the underlying event "more active" than an average minimum bias interaction?**



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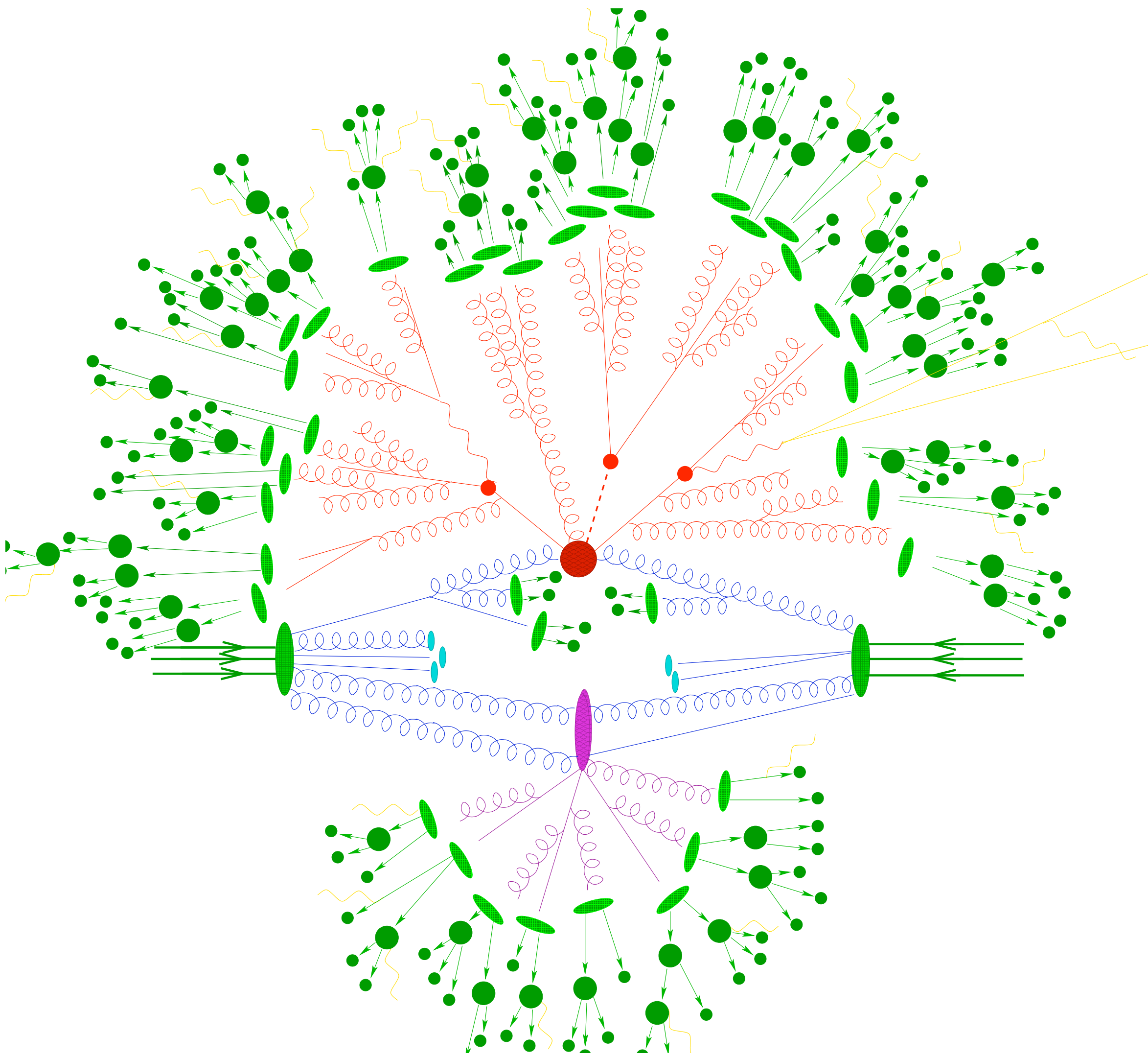

- Sub-set of minimum bias (inelastic) collisions
- More influenced by contributions from:
  - parton showers (ISR/FSR)
  - multiparton interactions

    (cross-section raises faster than originaly thought!)
  - colour field connecting hard-scatter to beam remnants

    (this appears to be essential to get correlation <p_T> - n_{chg} correctly described)

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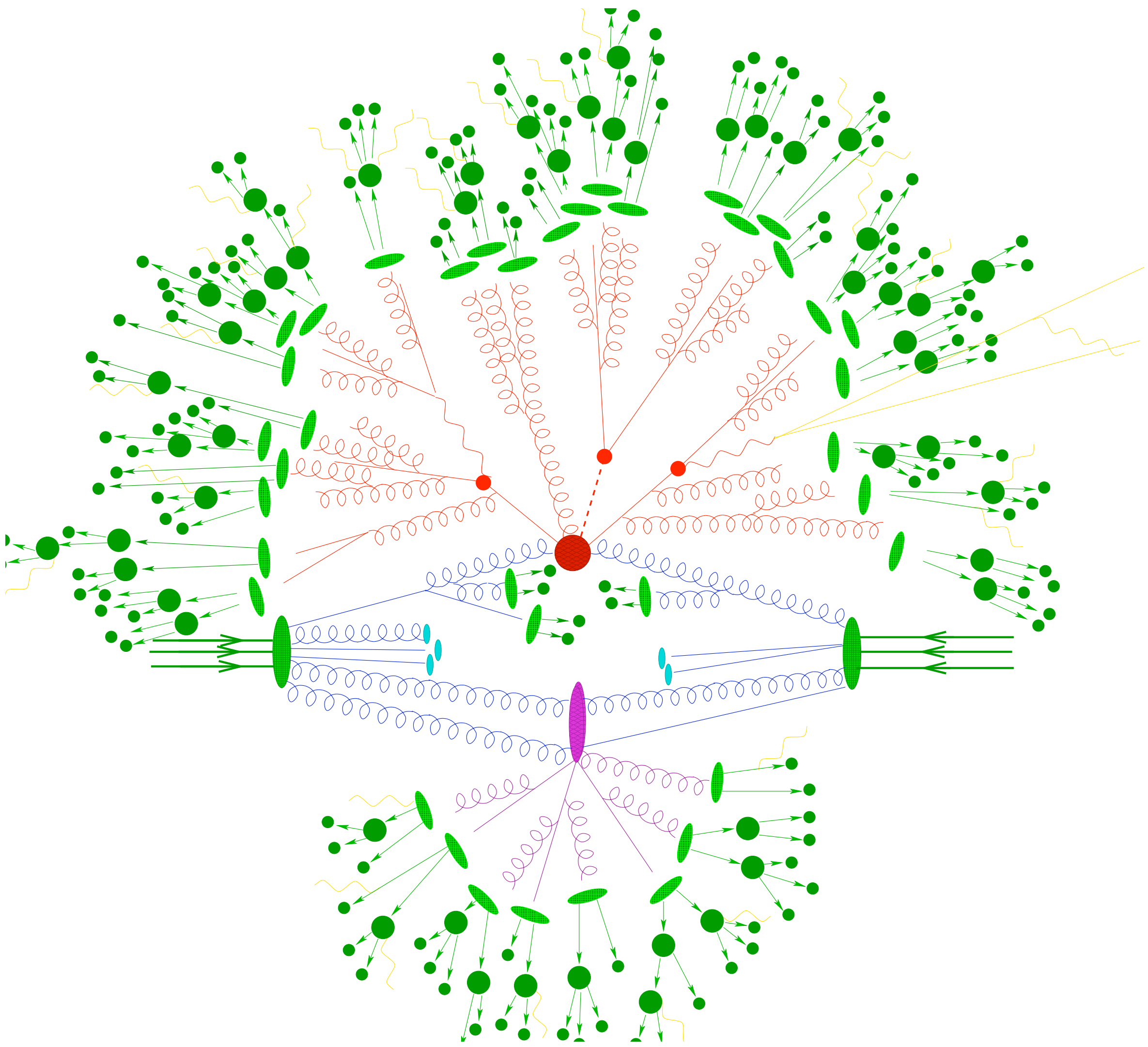

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Experimental challenge: define observables that allow us to "isolate" individual components of the underlying event!

More detailed look into the underlying event...

"MAX / MIN analysis" (CDF analysis – Run I data)

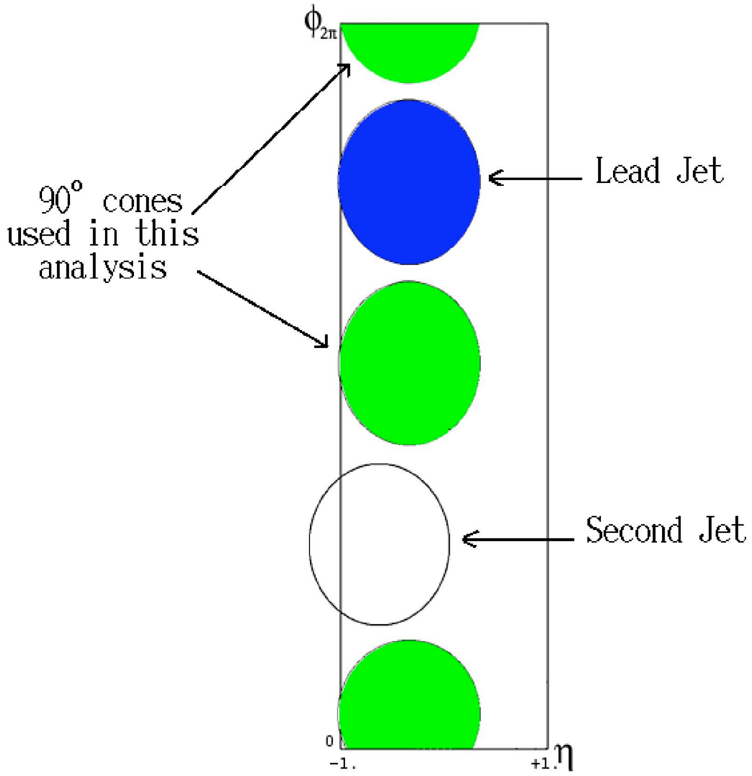
- **Two cones in $\eta-\phi$ space are defined:**

$\eta=\eta_{ljet}$ (same as the leading jet)

$\phi=\phi_{ljet} \pm 90°$

R=0.7

P_T^{90max} and P_T^{90min}



D. Acosta et al., The CDF Collaboration, Phys. Rev. D70, 072002 (2004).

More detailed look into the underlying event…

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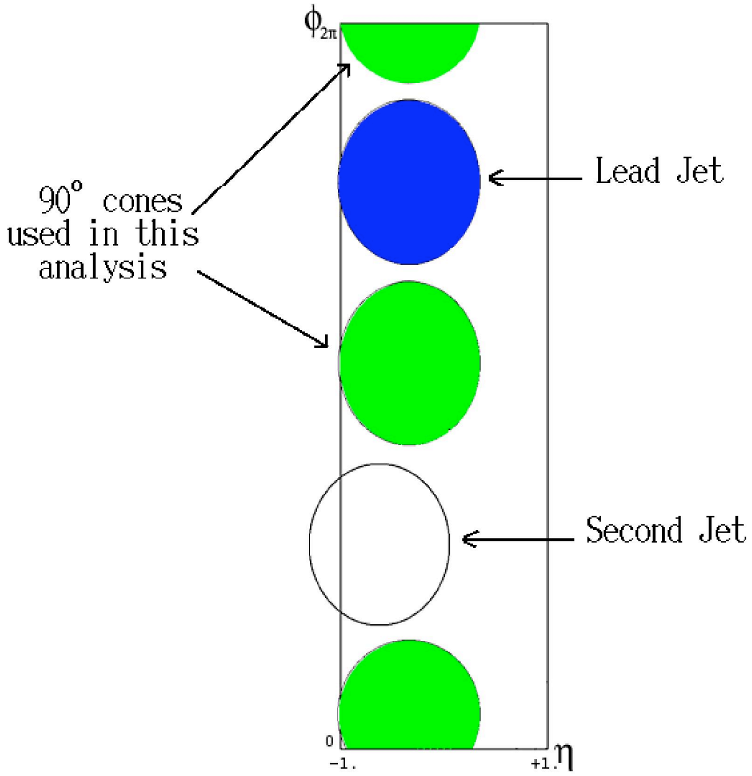

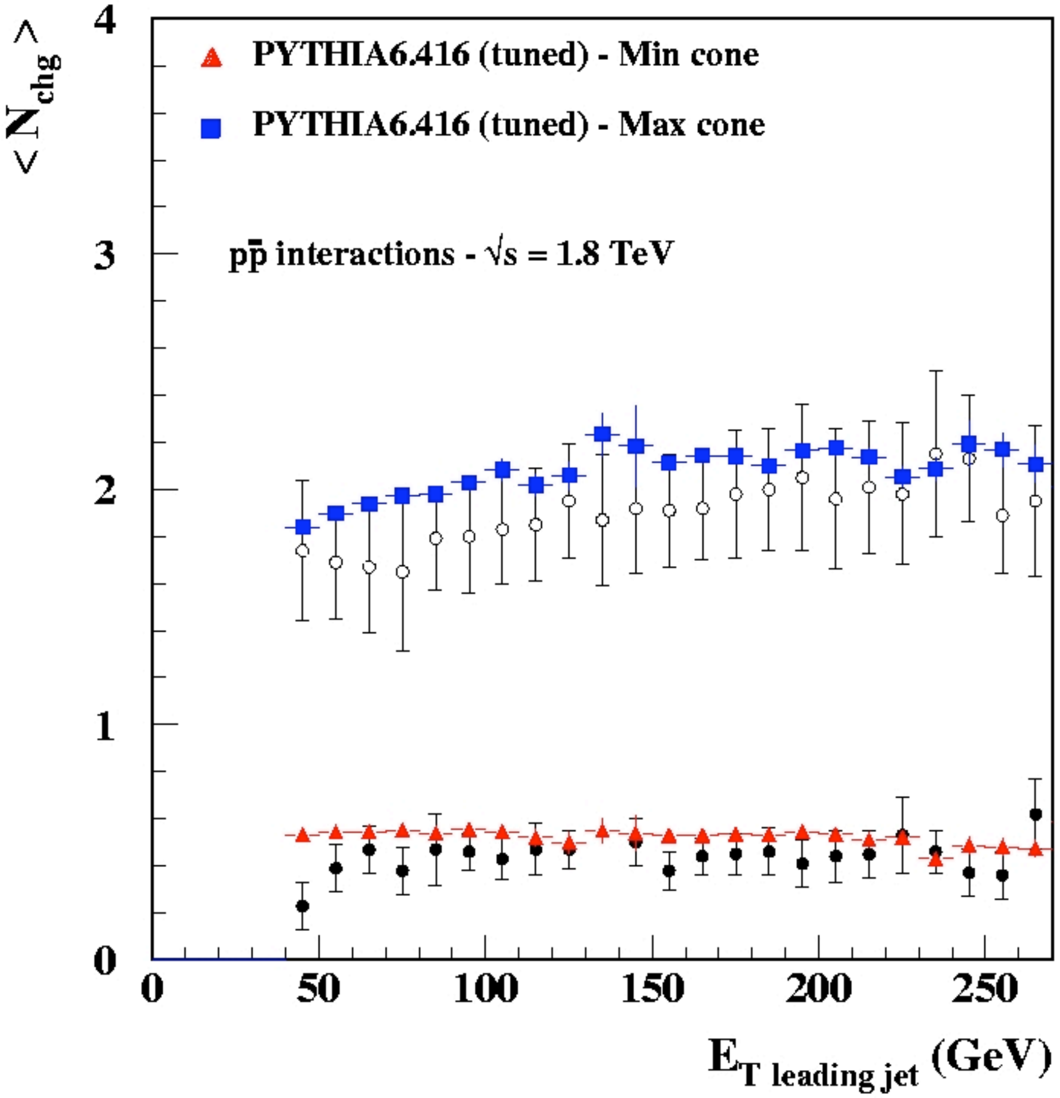

Average multiplicity of charged particles in the transverse MAX and MIN cones associated to a leading calorimeter jet.

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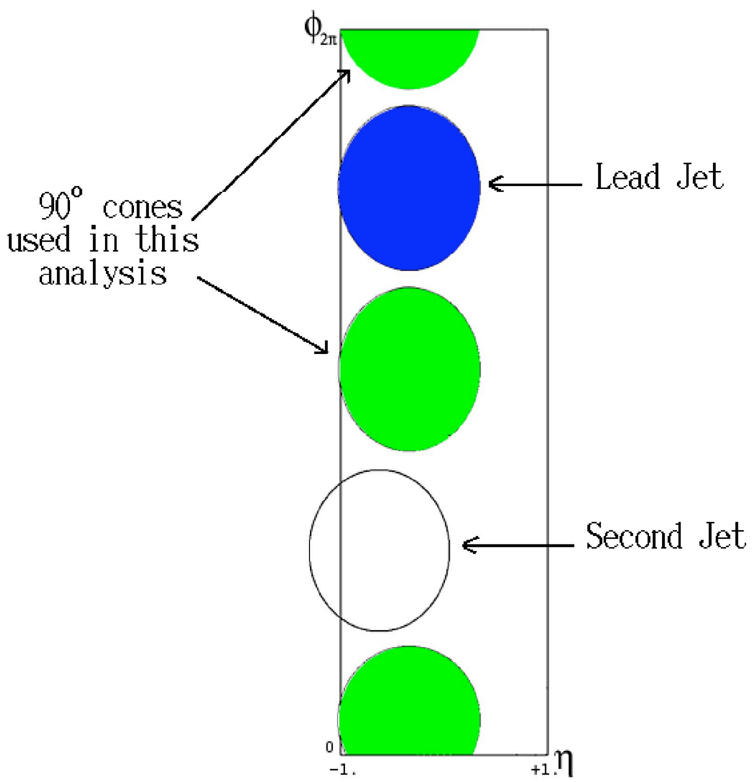

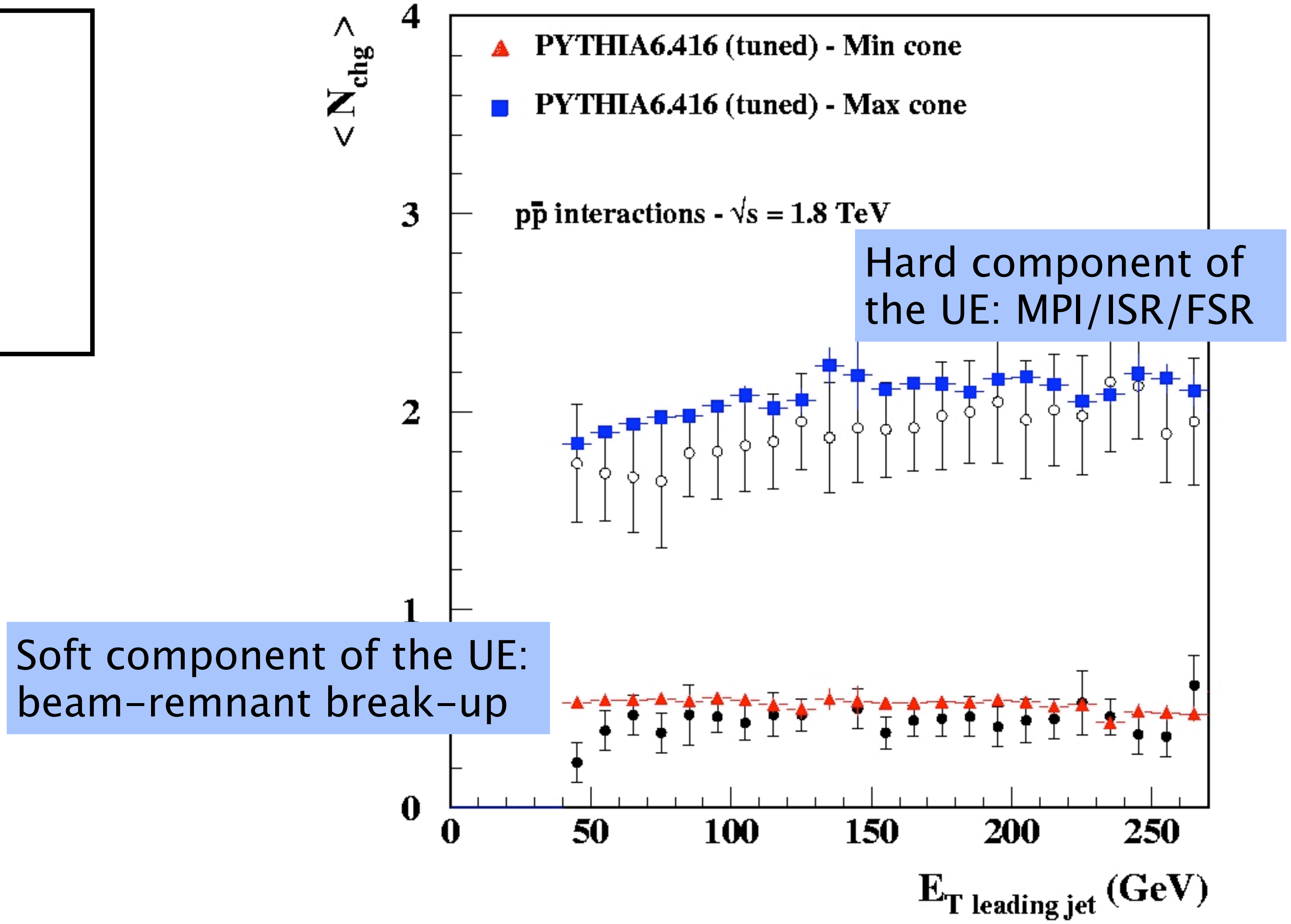

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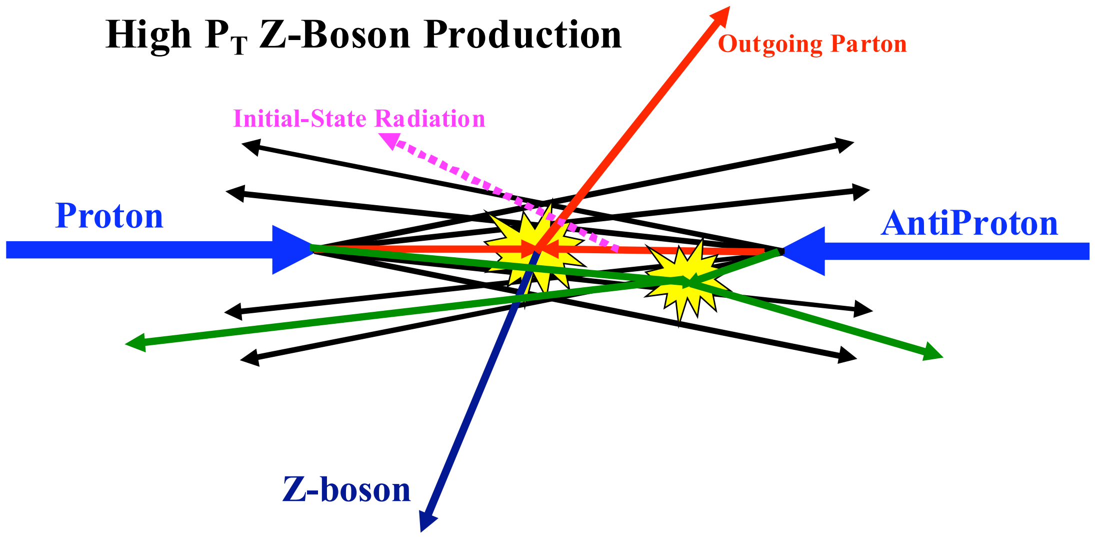
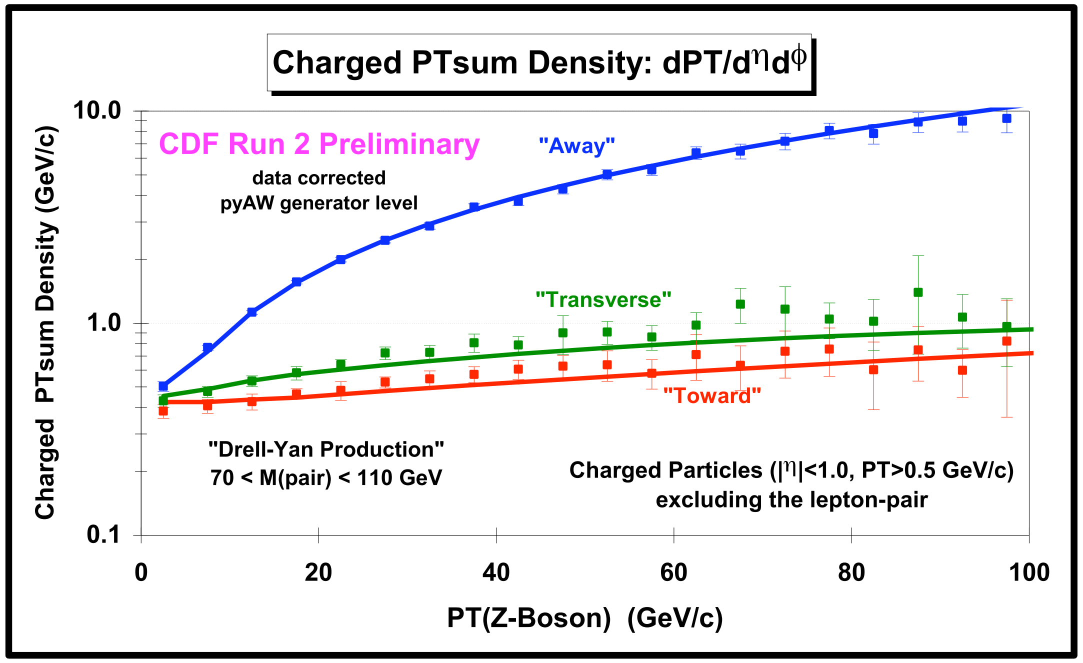
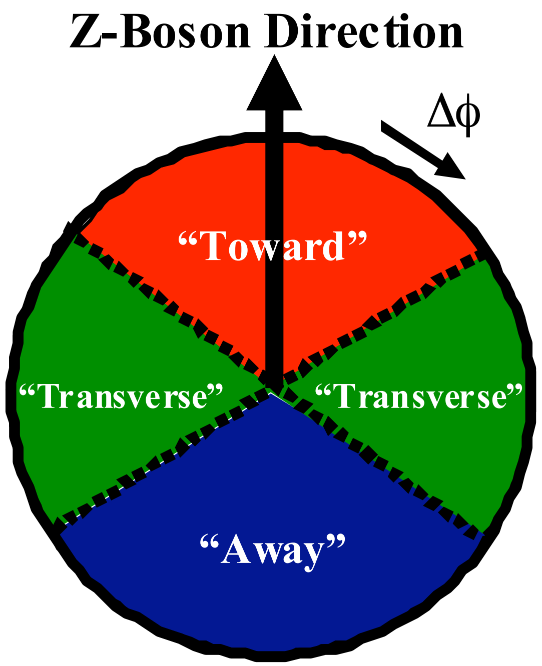
Underlying event in Drell-Yan processes (CDF - Run II)







CDF/PUB/CDF/PUBLIC/9351 (July 24, 2008)

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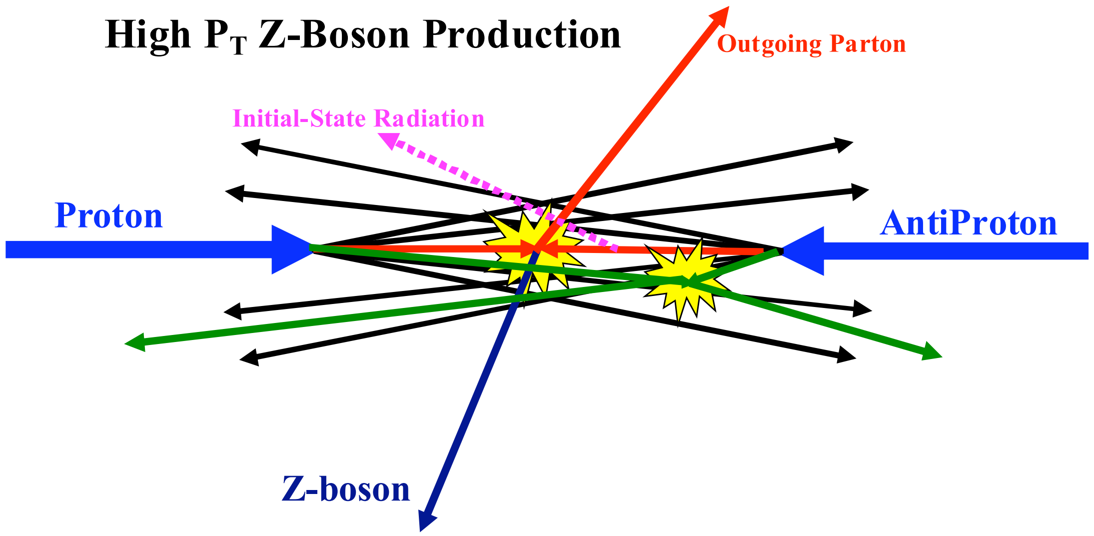
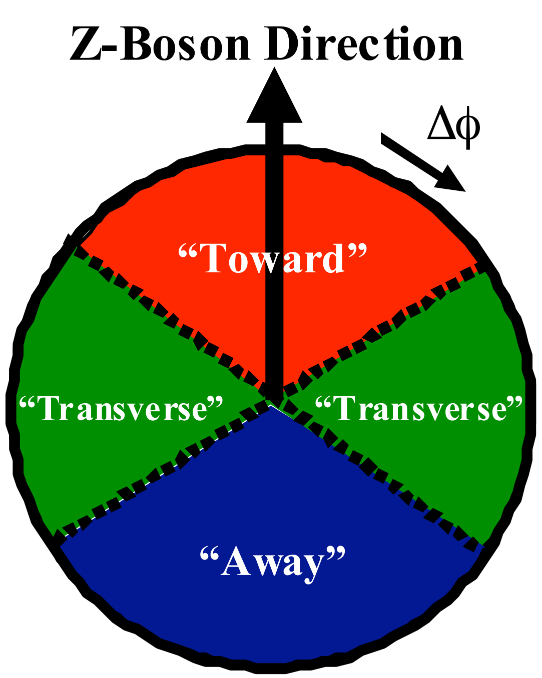
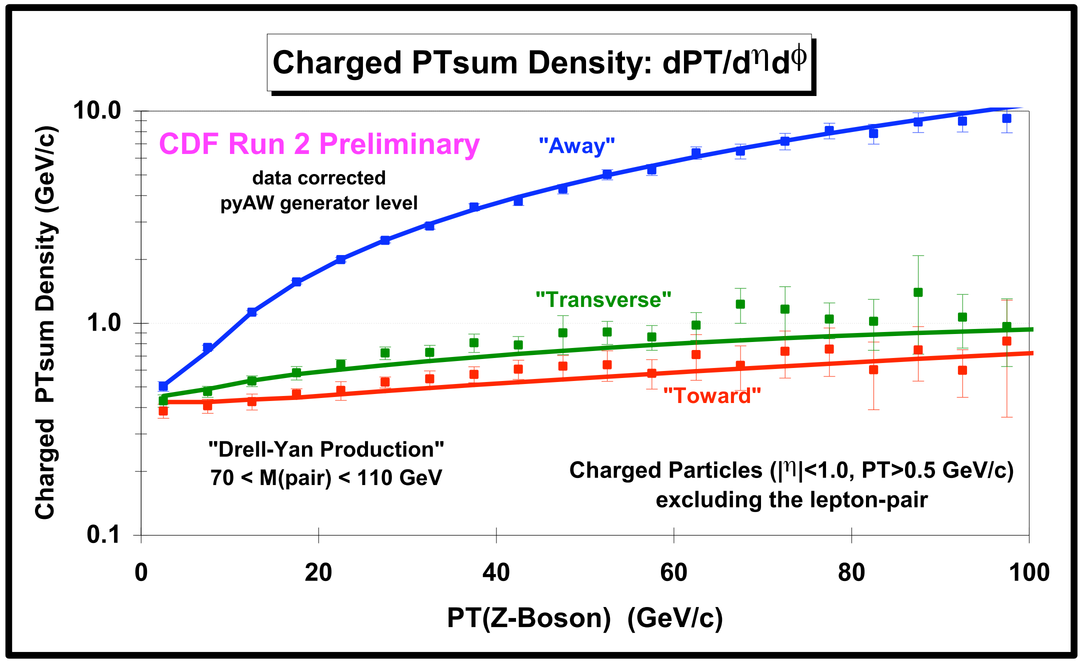
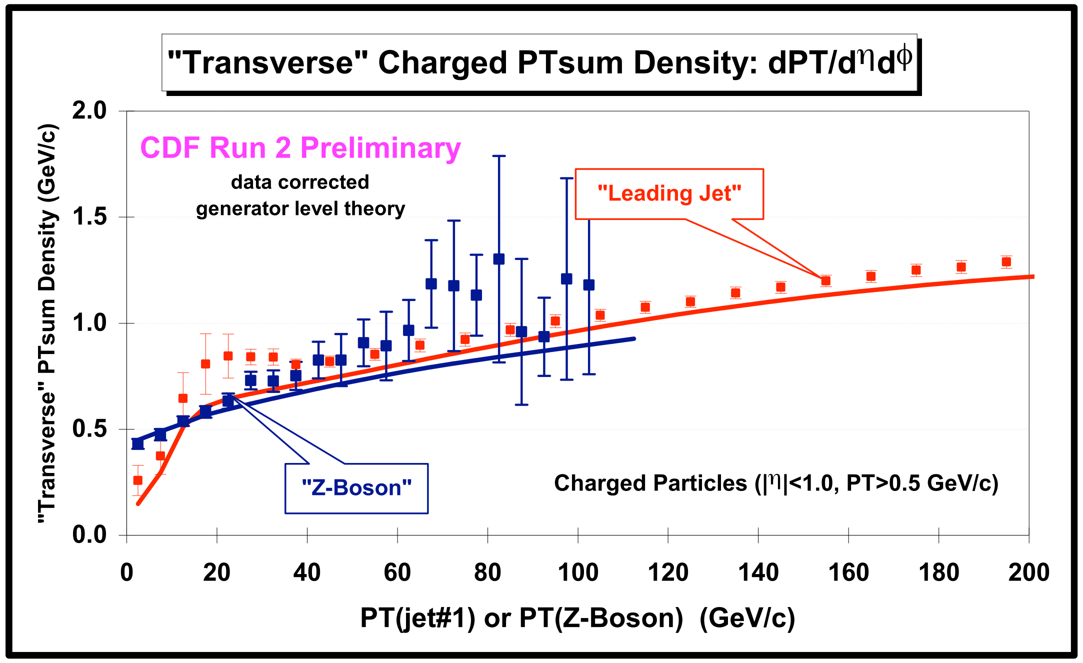








CDF/PUB/CDF/PUBLIC/9351 (July 24, 2008)

Outline:

I. Introduction:

- Historical perspective
  - Measuring hadronic inelastic collisions
  - ISR, SPS, Tevatron
  - “minimum bias” vs. the underlying event: aren’t they the same?

II. MC Models and LHC predictions:

- common ingredients & missing links (?)

III. Measuring minimum bias and the underlying event with “early” LHC data

IV. Summary

Models for minimum bias and the underlying event

- **Why do we need models for these processes?**

  - Observables cannot be calculated from perturbative QCD. Best option is to use phenomenological models!

  - Physics: improve our understanding of QCD (soft & hard), total cross-section, saturation, jet cross-sections, mass reconstructions,…

  - Experiments : occupancy, pile-up, backgrounds, radiation damage, radio-activation…

*** Modeling minimum bias and the underlying event is essential for virtually all high-p_T physics!**

Models for soft hadronic interaction (few examples)

- **Uncorrelated soft scatter – HERWIG/UA5 model (S.U.E.)** (http://hepwww.rl.ac.uk/theory/seymour/herwig/)

Questionable modeling for:
1. Energy dependence;
2. Minimum-bias and UE hard component;
3. Hard/soft correlation

- **Multiple interactions:**

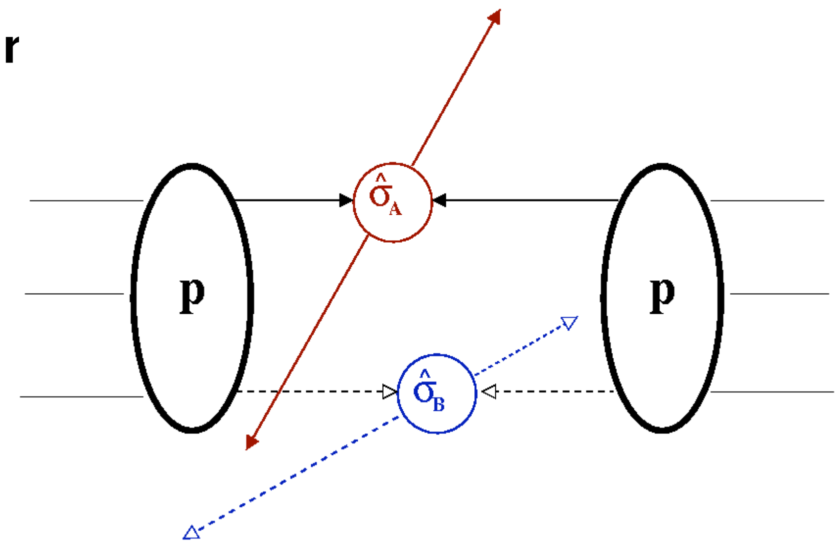
Soft partonic scatters matched to hard 2 → 2 scatter

• **PYTHIA (several options)** (http://www.thep.lu.se/~torbjorn/Pythia.html)

$$\sigma_{int} = \int_{p_{t0}}^{s/4} \frac{d\sigma}{dp_t^2} dp_t^2$$

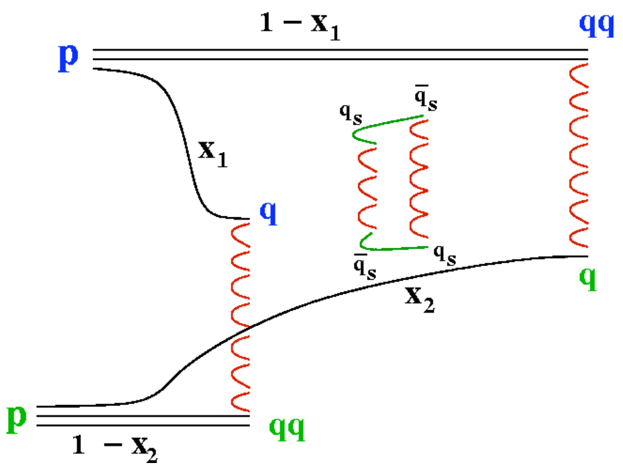
$n \sim \sigma_{int}$

↓pt_0 ↑n (and vice-versa)



- **PHOJET (based on DPM)** (http://www-ik.fzk.de/%7Eengel/phojet.html)

• Implements the DPM for low-pT processes;
• Multiple Pomeron exchanges are used to generate the event activity;
• Limited to strong interaction processes.



"Tuning" MC generators:

University of Glasgow

What is the strategy?

* Let experimental data guide you! (experimentalist's bias...)

  Gather as many measurements as possible about the physics you want to describe.

* Start by calibrating generators to describe average / global properties.

  for example: $<n_{chg}>$, $<p_T>$, $dN/d\eta$, ...

* Identify "specialized" distributions to tune particular model components.

  for example: dN/dp_T in the UE (sensitive to ISR), KNO plots in MB (sensitive to hadronic matter distribution), ...

* Use measurements taken at different c.m. energies

  a good model should be able to reproduce data from earlier colliders "BEFORE" it can be used to generate predictions for higher energies!

* Never lose sight of the physics!

  if parameter choices point to selections outside the physics reach of the generator, then the model needs to be changed!

ATLAS example can be found in: EPJ C 50, 435 (2007)

Tuning MC generators:

- LHC studies on the calibration of MC models have evolved considerably from the time of the Detector & Physics Performance TDRs (1999...).

- Minimum bias distributions (from the ATLAS TDR):

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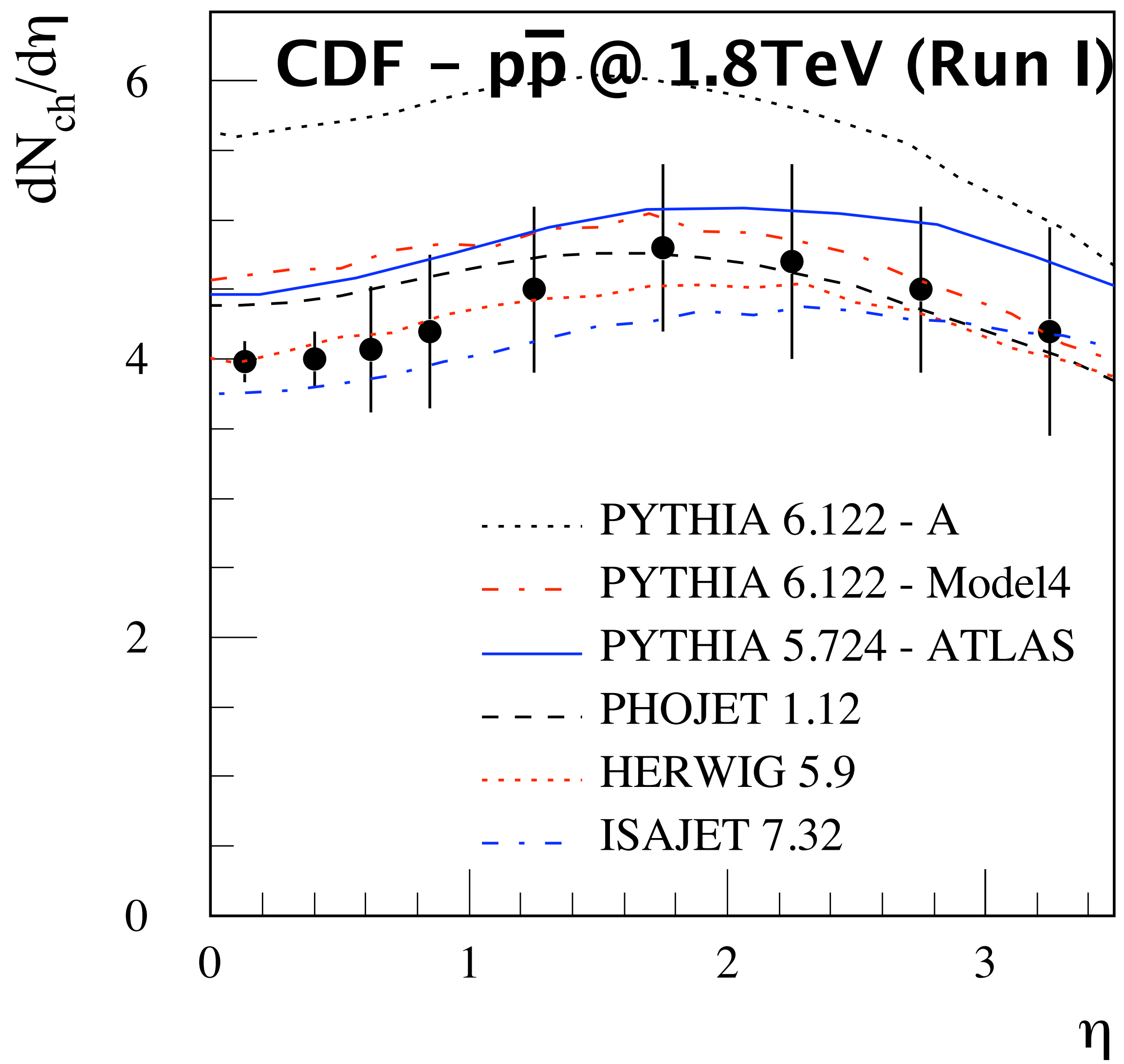

ATL-PHYS-99-019

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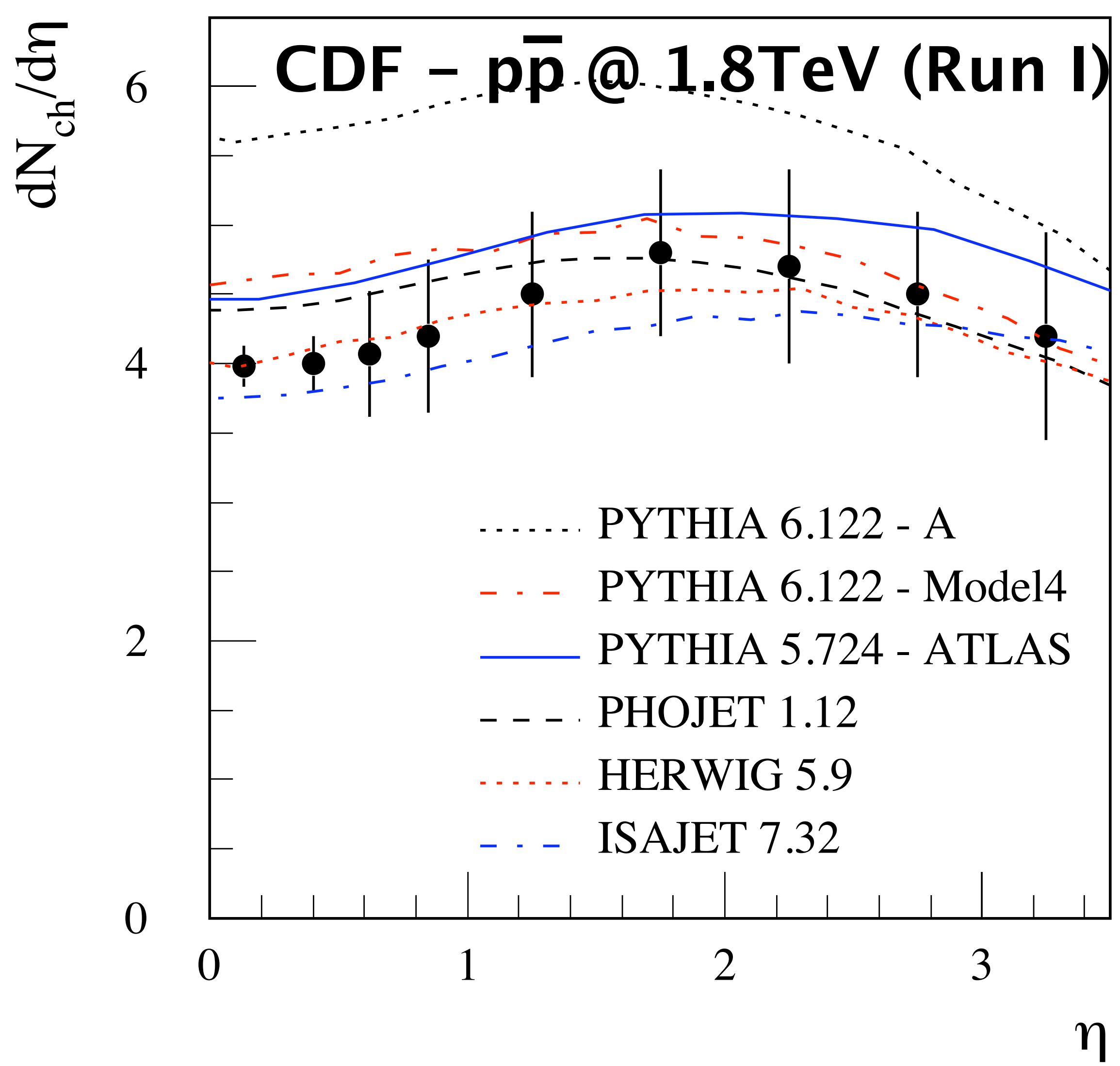
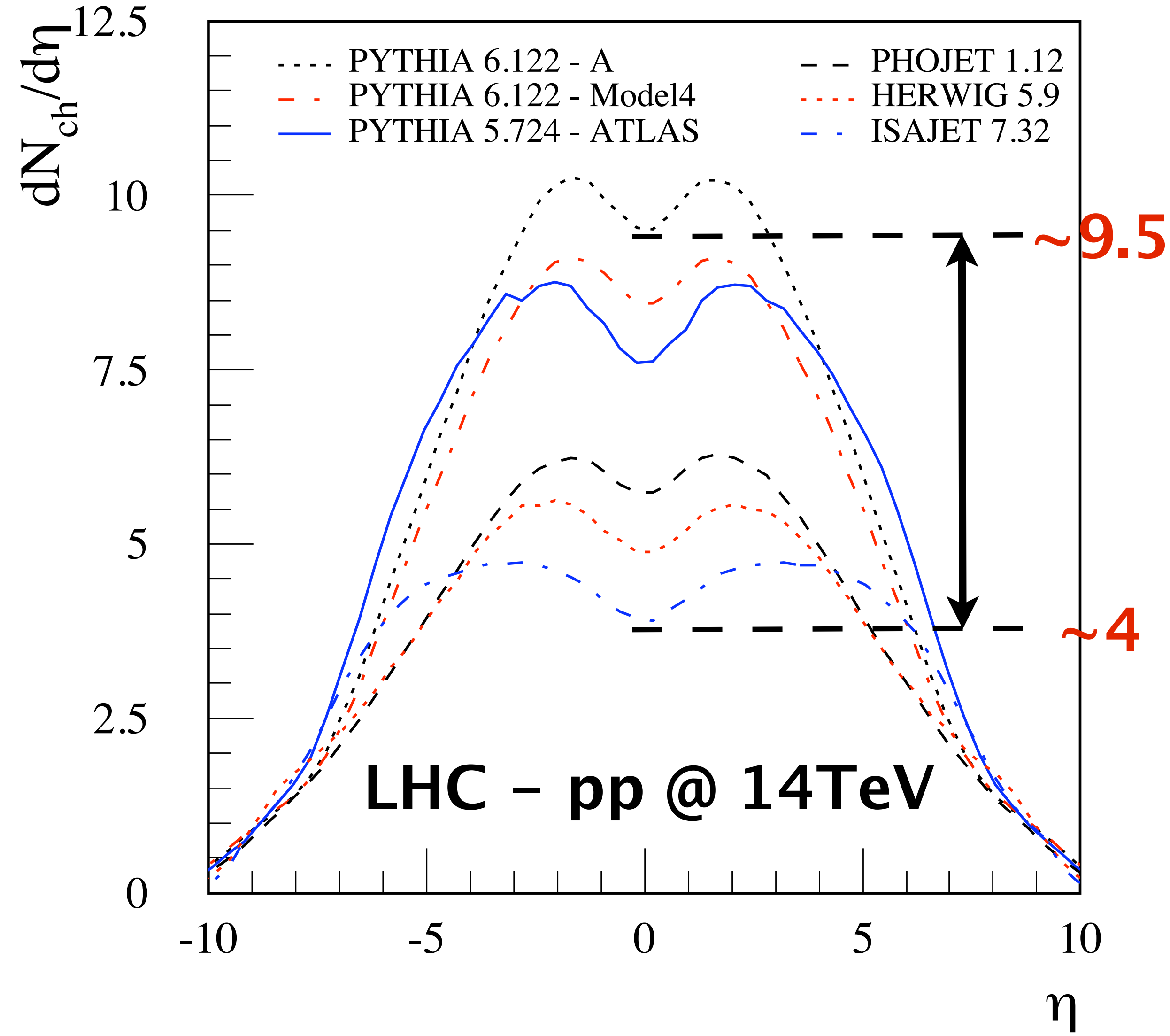
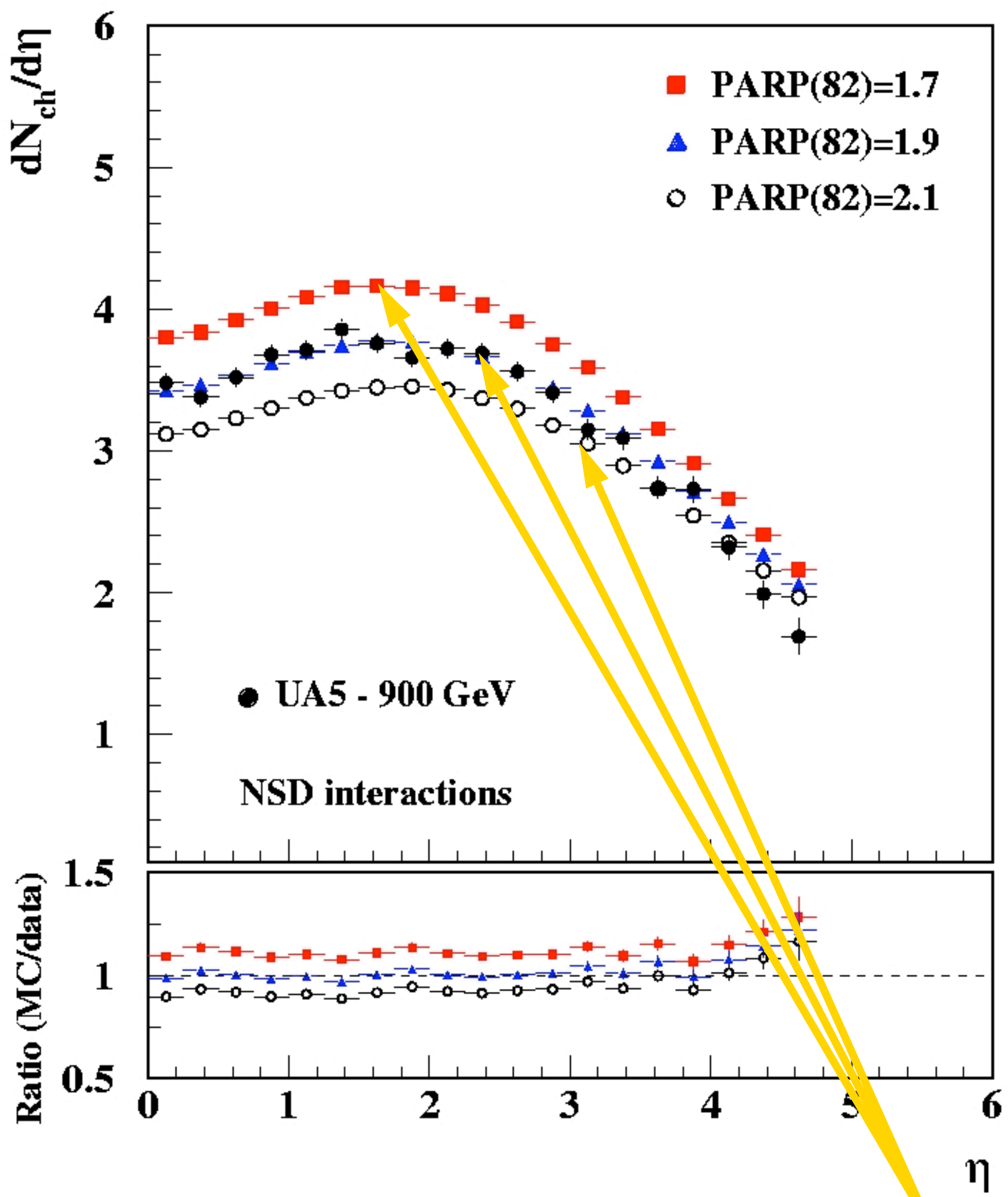




ATL-PHYS-99-019

Tuning models to minimum-bias data
(practical examples...)



Lower p_T cut-off determines the average particle density.

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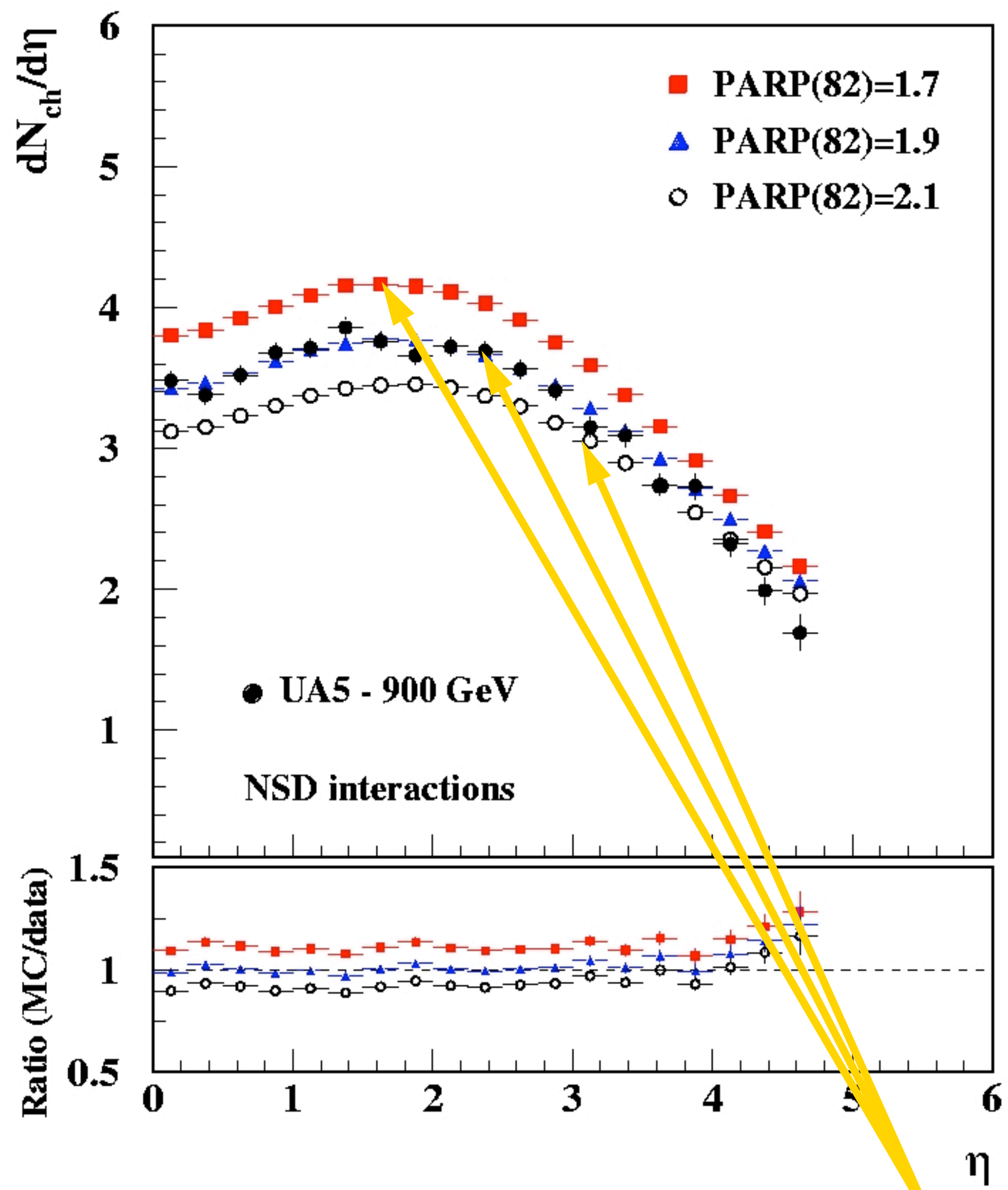
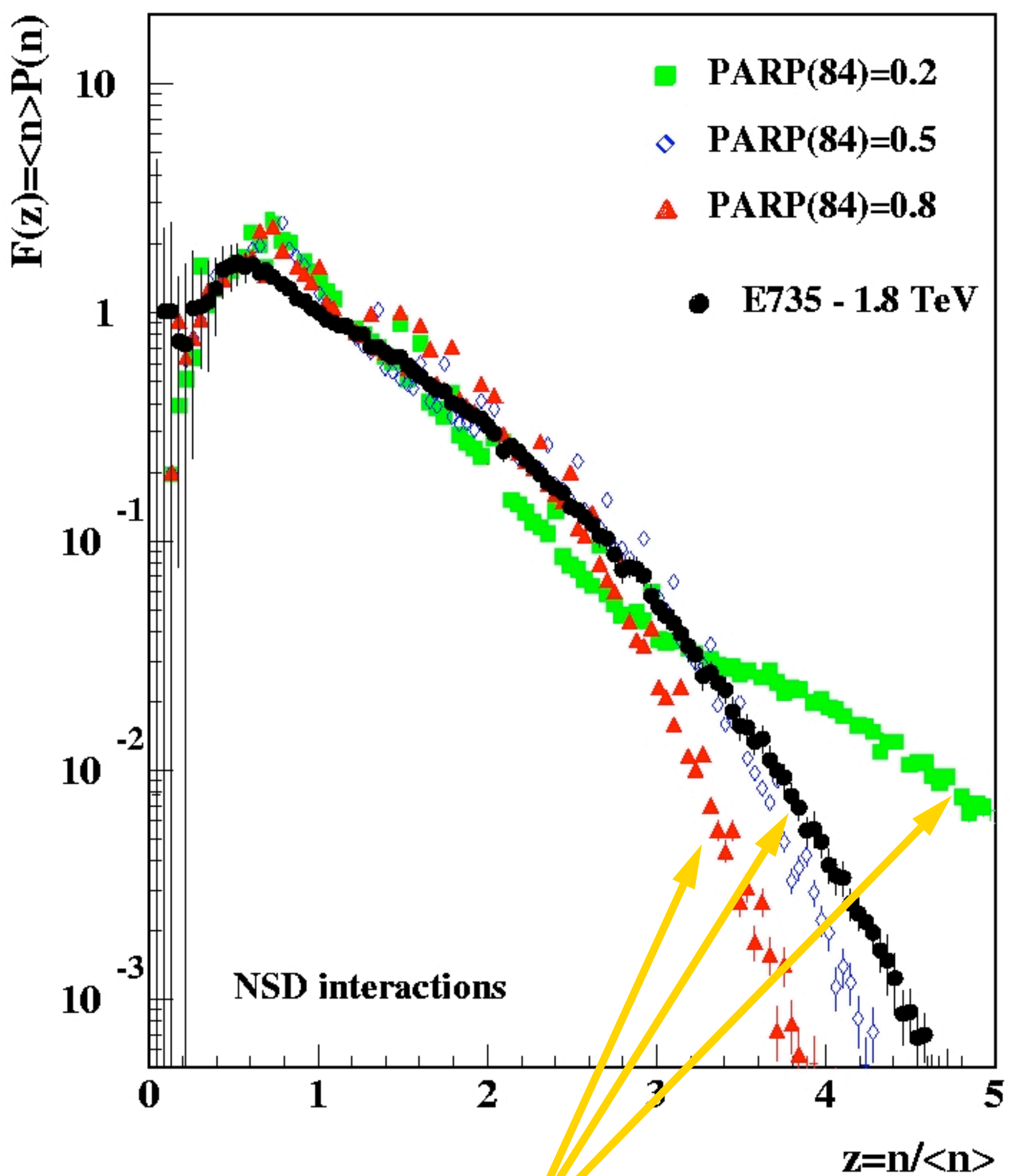
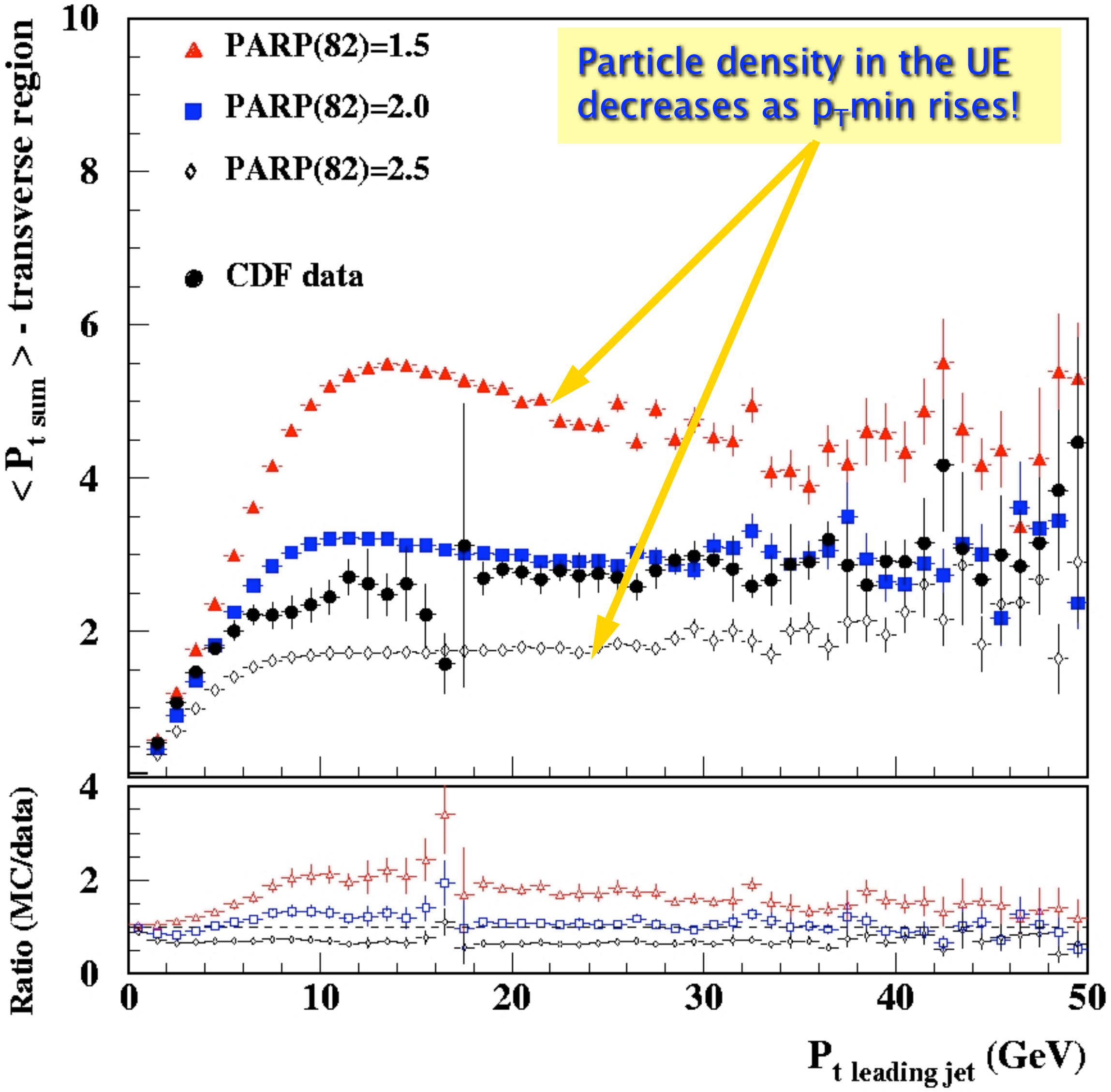




Lower p_T cut-off determines the average particle density.

High-multiplicity events are described differently by each tuning.

Tuning models to the underlying event
(few examples...)



Similarly to the observed for min-bias distributions, varying the lower p_T cut-off also changes the particle density (and p_T density) in the UE.

Tuning models to the underlying event
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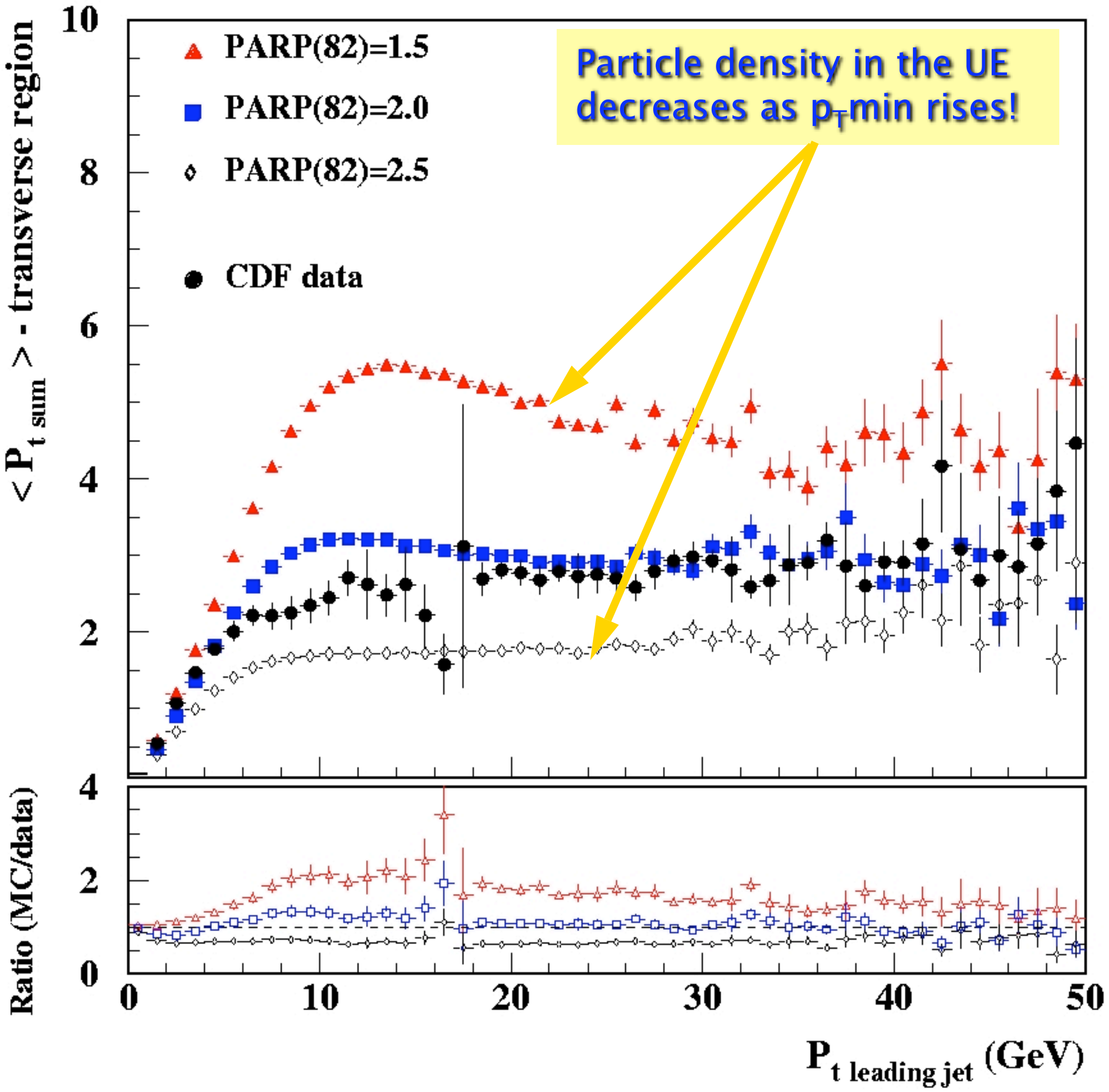
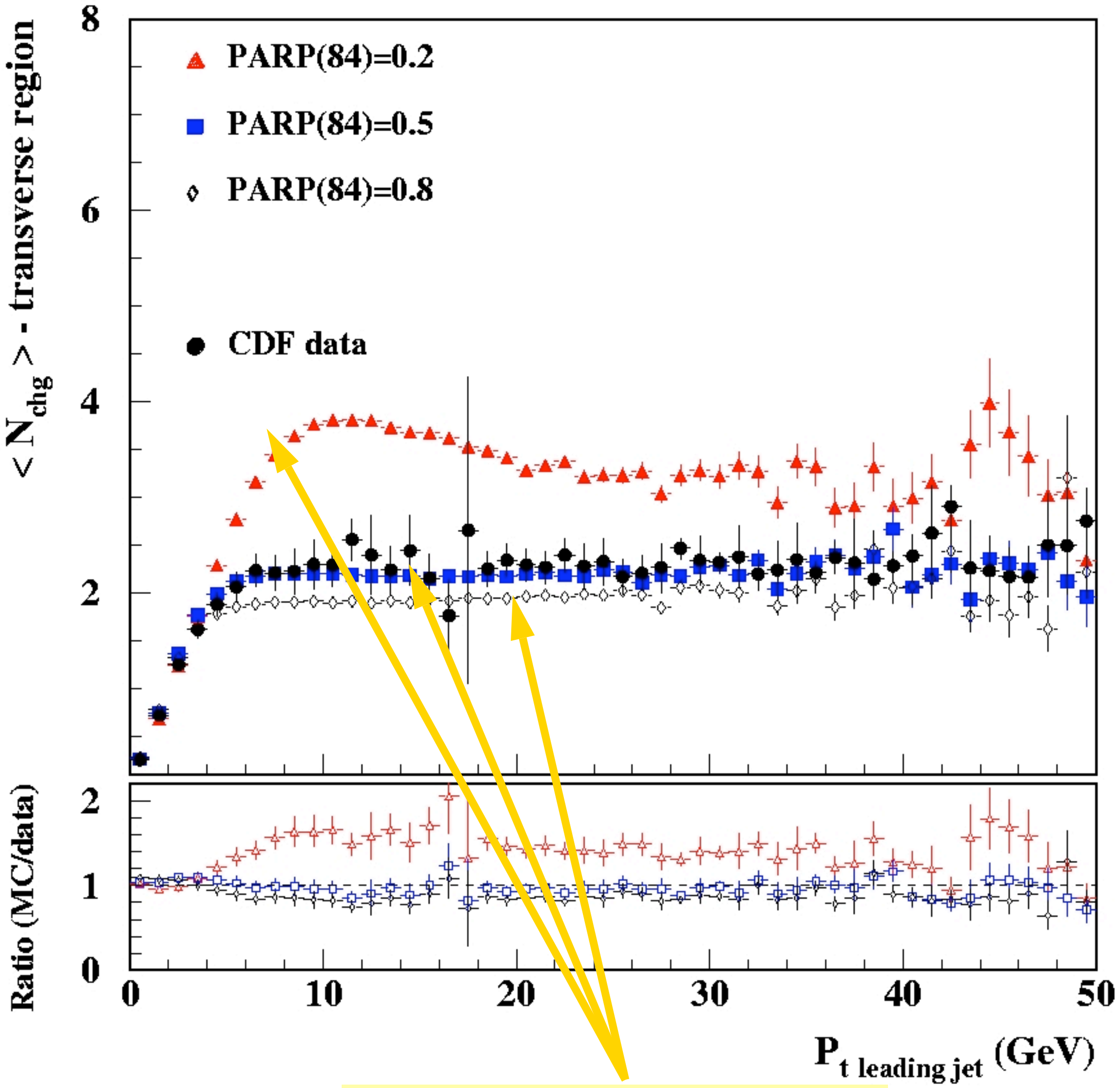


Particle density in the UE decreases as $p_T$min rises!

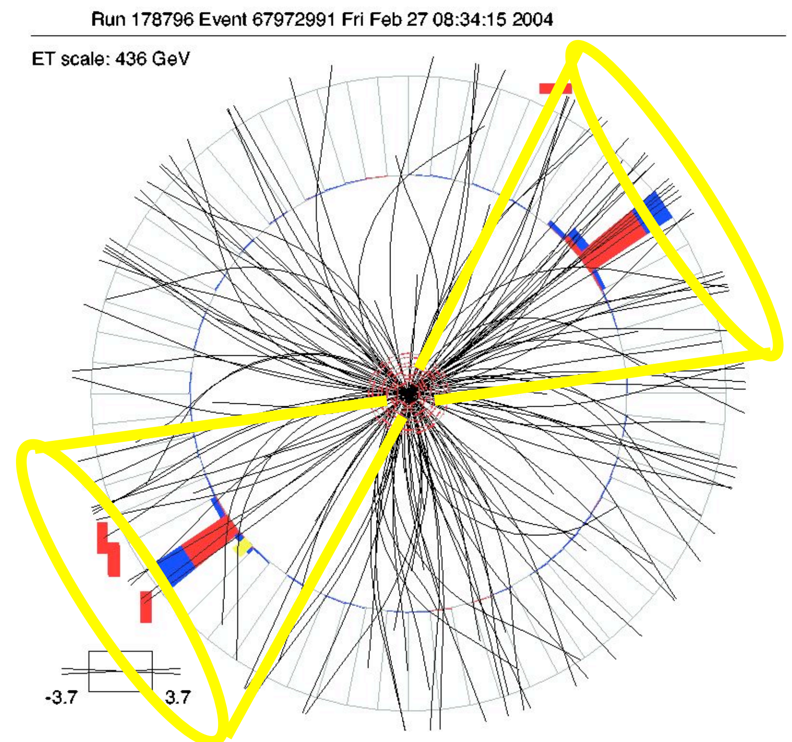


Small, dense core-size generates more multiplicity in the UE.

Similarly to the observed for min-bias distributions, varying the lower p_T cut-off also changes the particle density (and p_T density) in the UE.

Dijet azimuthal decorrelation

hep-ex/0409040 Sep. 2004
*PRL **94**, 221801 (2005)*



Jets are defined in the central region using seed-based cone algorithm (MidPoint - R=0.7)

- leading jet p_T^{max} > 75 GeV
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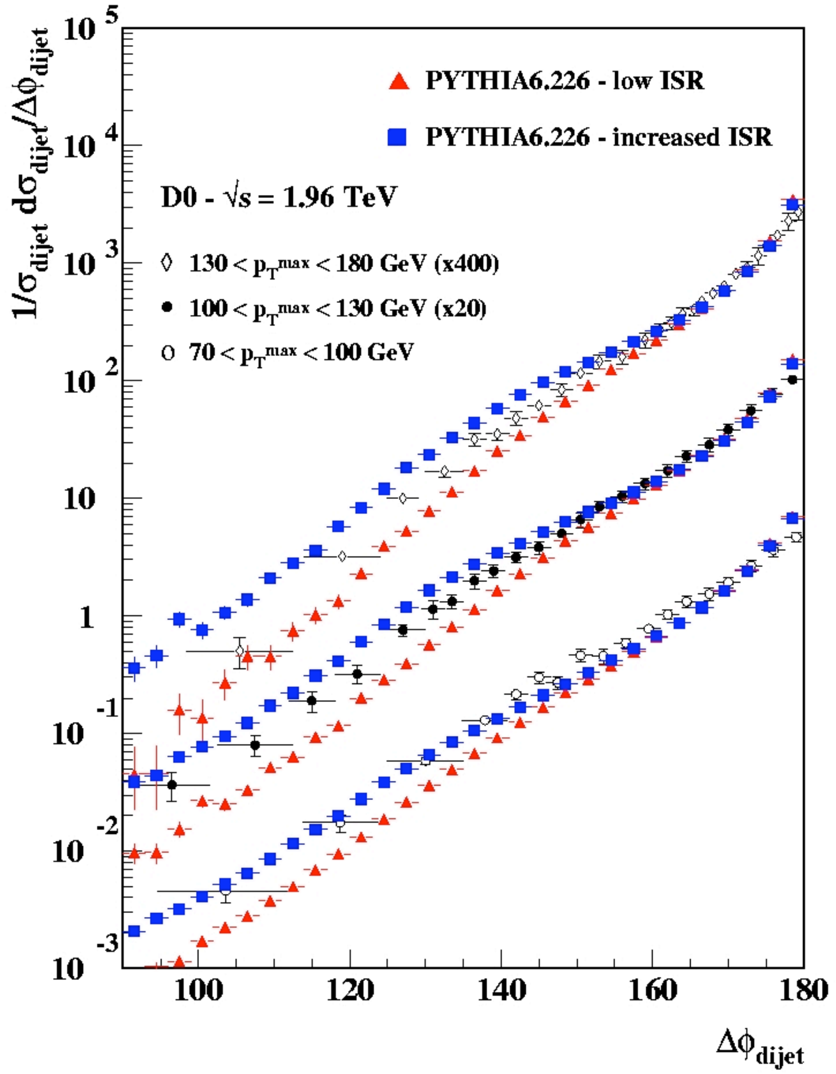
- both leading p_T jets: $|y_{jet}| < 0.5$



PYTHIA predictions for $\Delta\phi_{dijet}$ depend on the modelling of radiation associated to ISR.

PARP(67) defines the maximum parton virtuality allowed in ISR showers
(PARP(67) x hard scale Q^2)

(see also ATL-PHYS-PUB-2006-013).

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University of Glasgow

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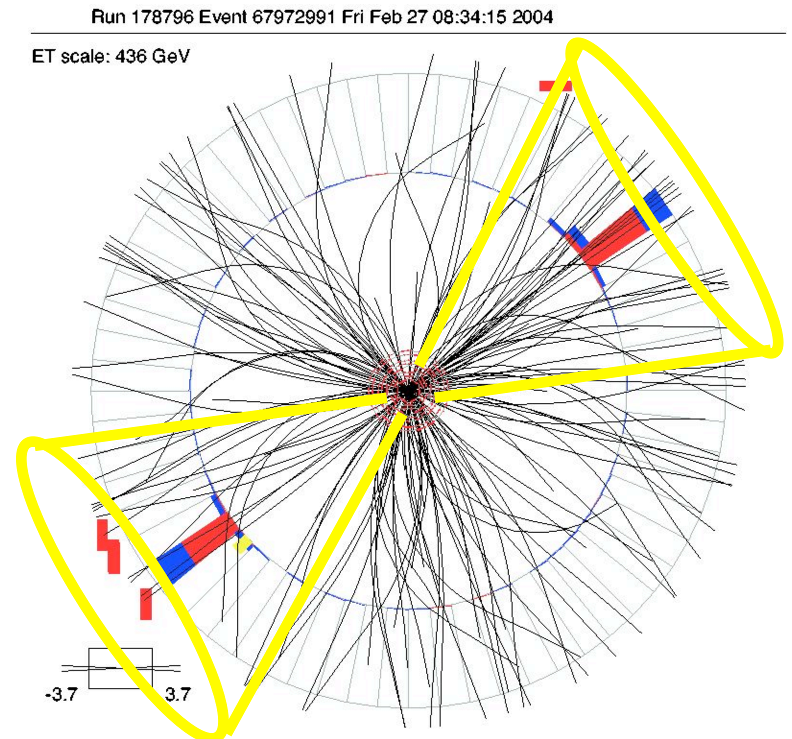

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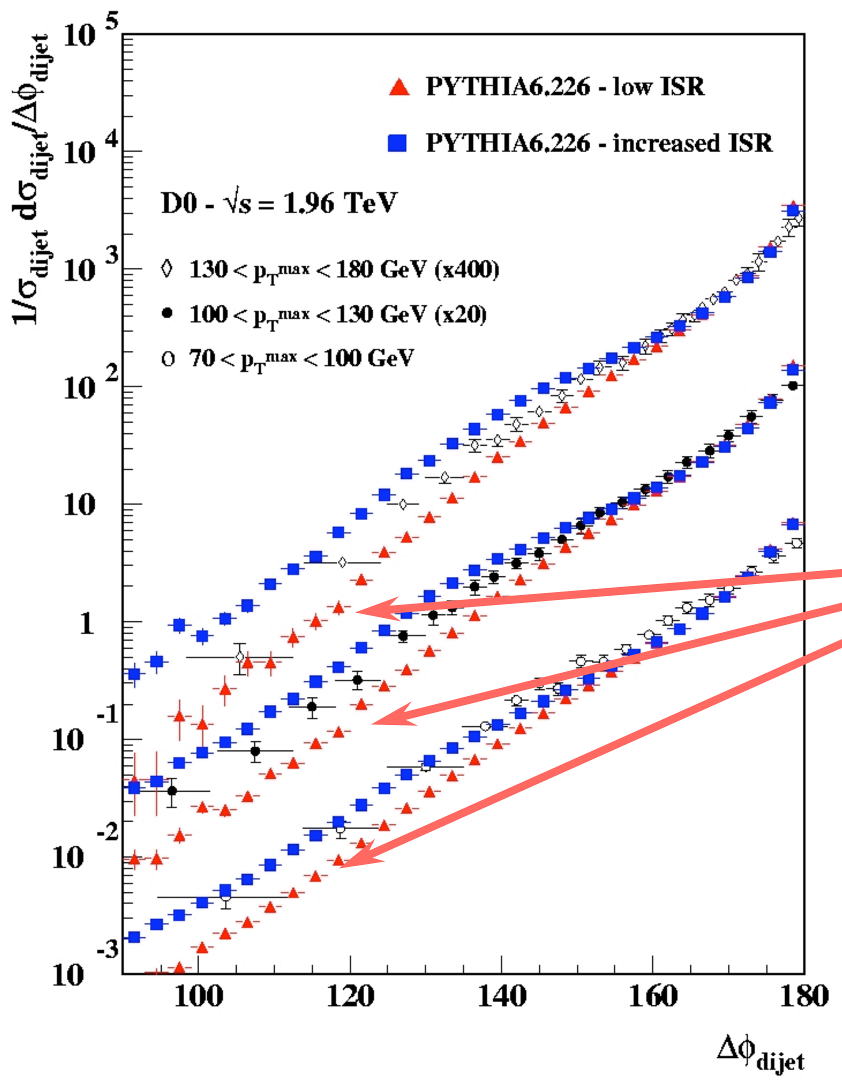

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distributions *underestimate* the data!
Need to increase the decorrelation effect, i.e. increase radiative and multiple interaction effects.

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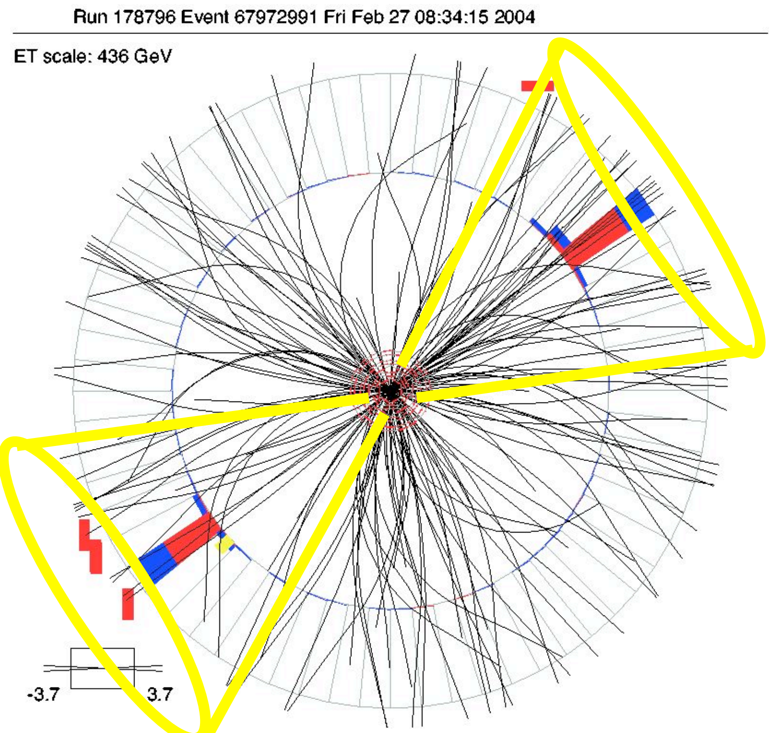

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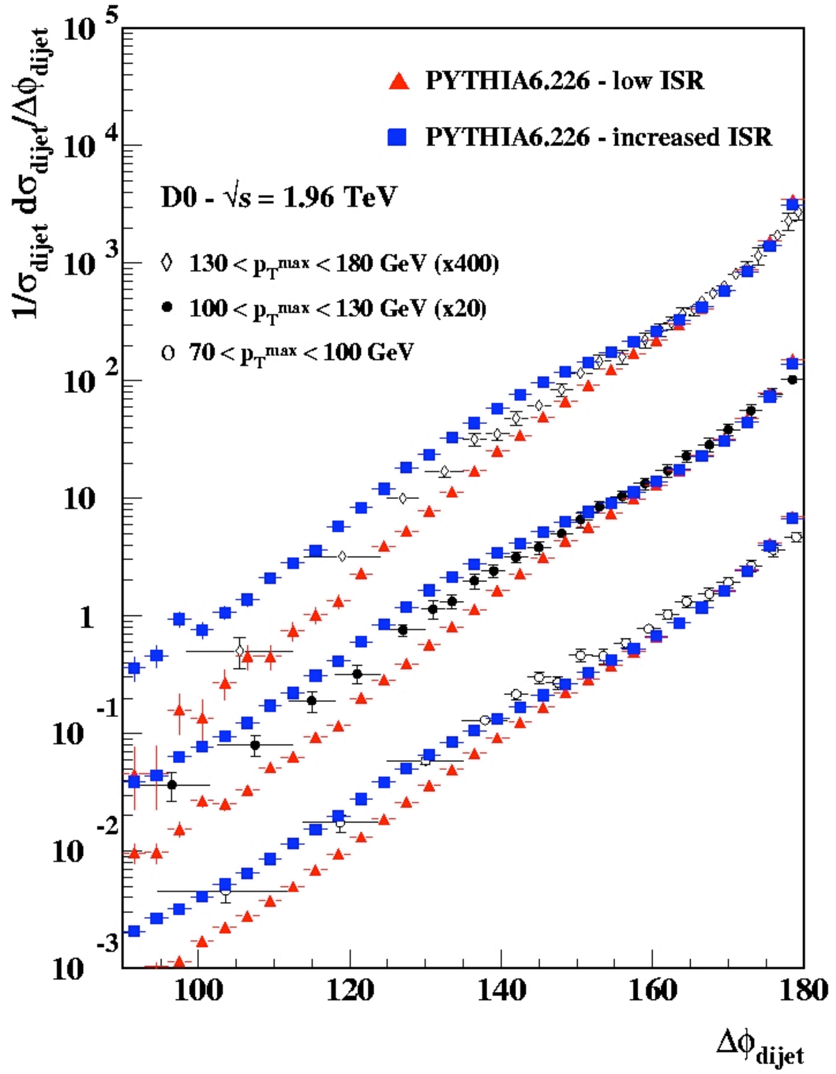

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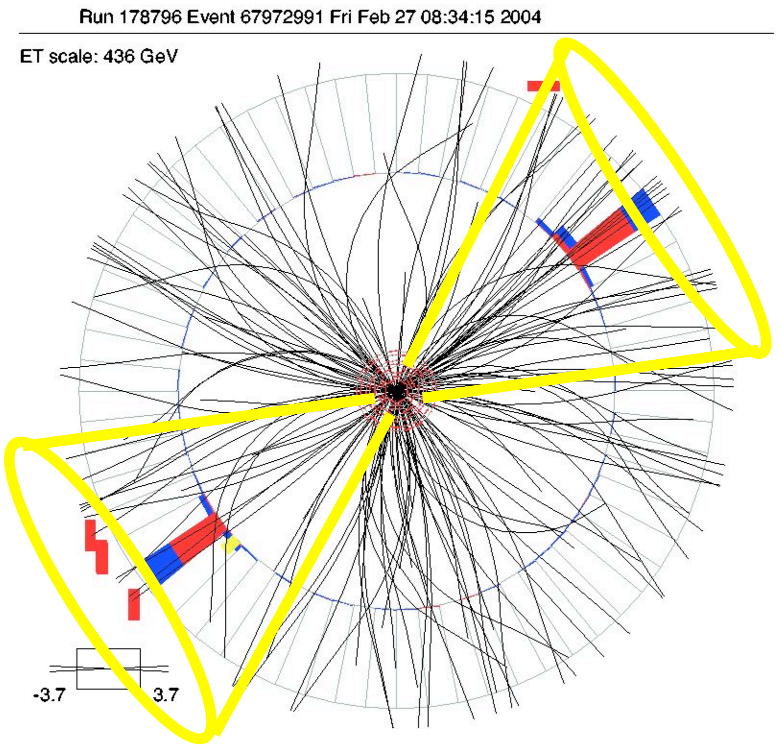

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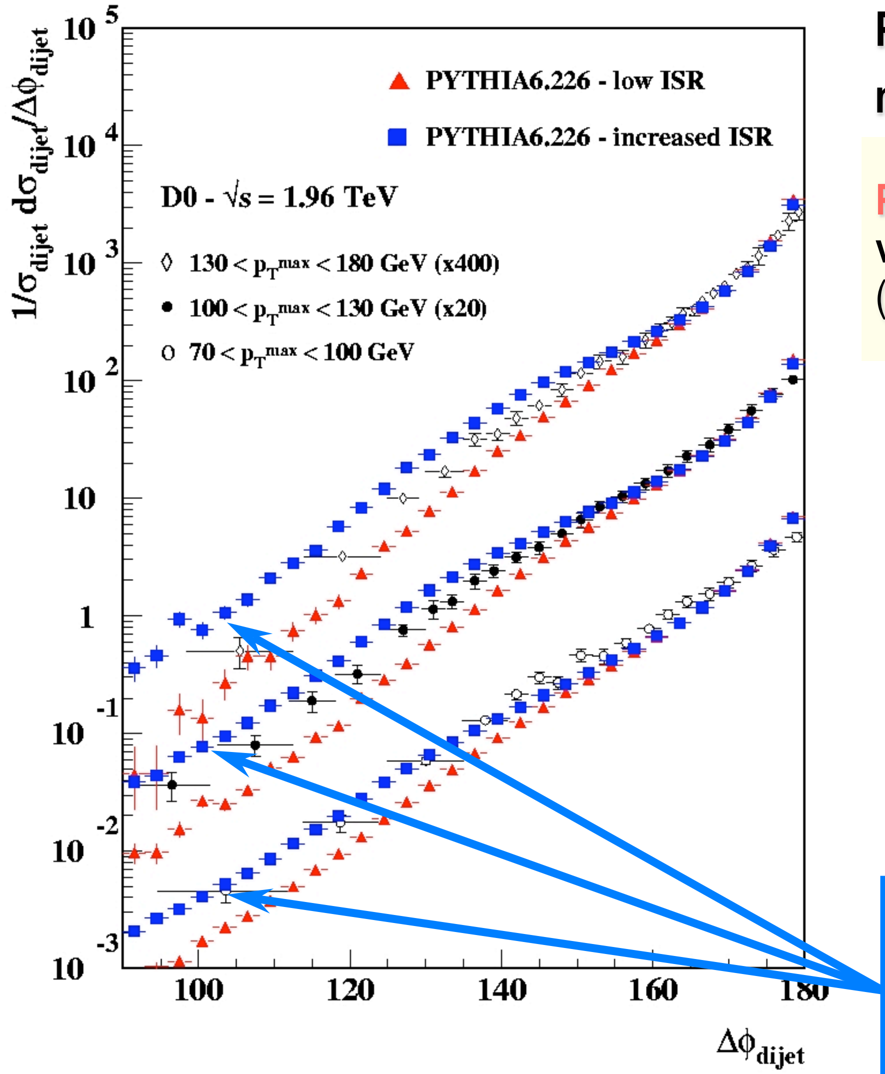

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Changing PARP(67) from 1 to 4, the azimuthal decorrelation is *increased*.

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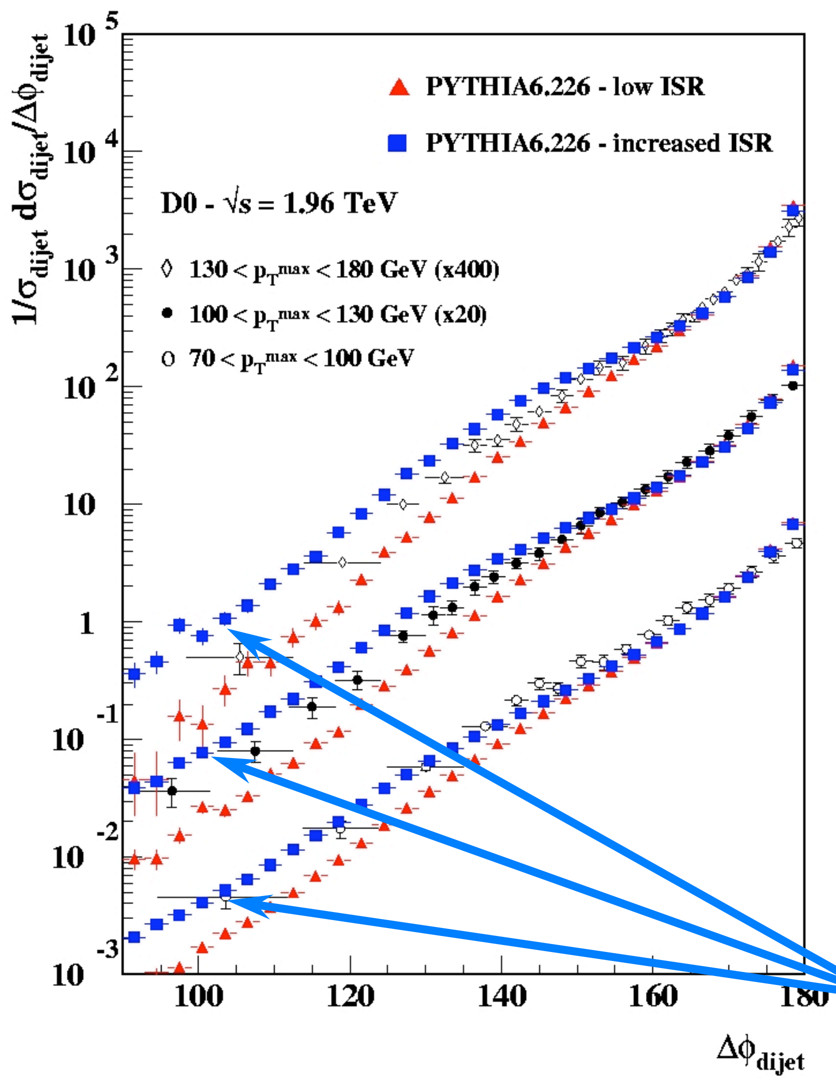

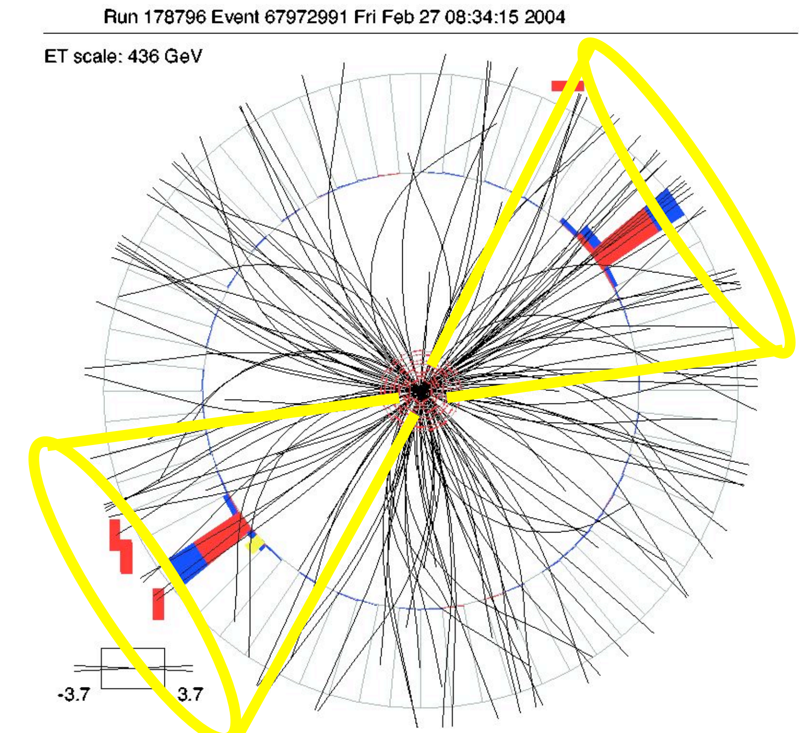

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Best value is somewhere between PARP(67)= 1 and 4!

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Generating predictions for the LHC

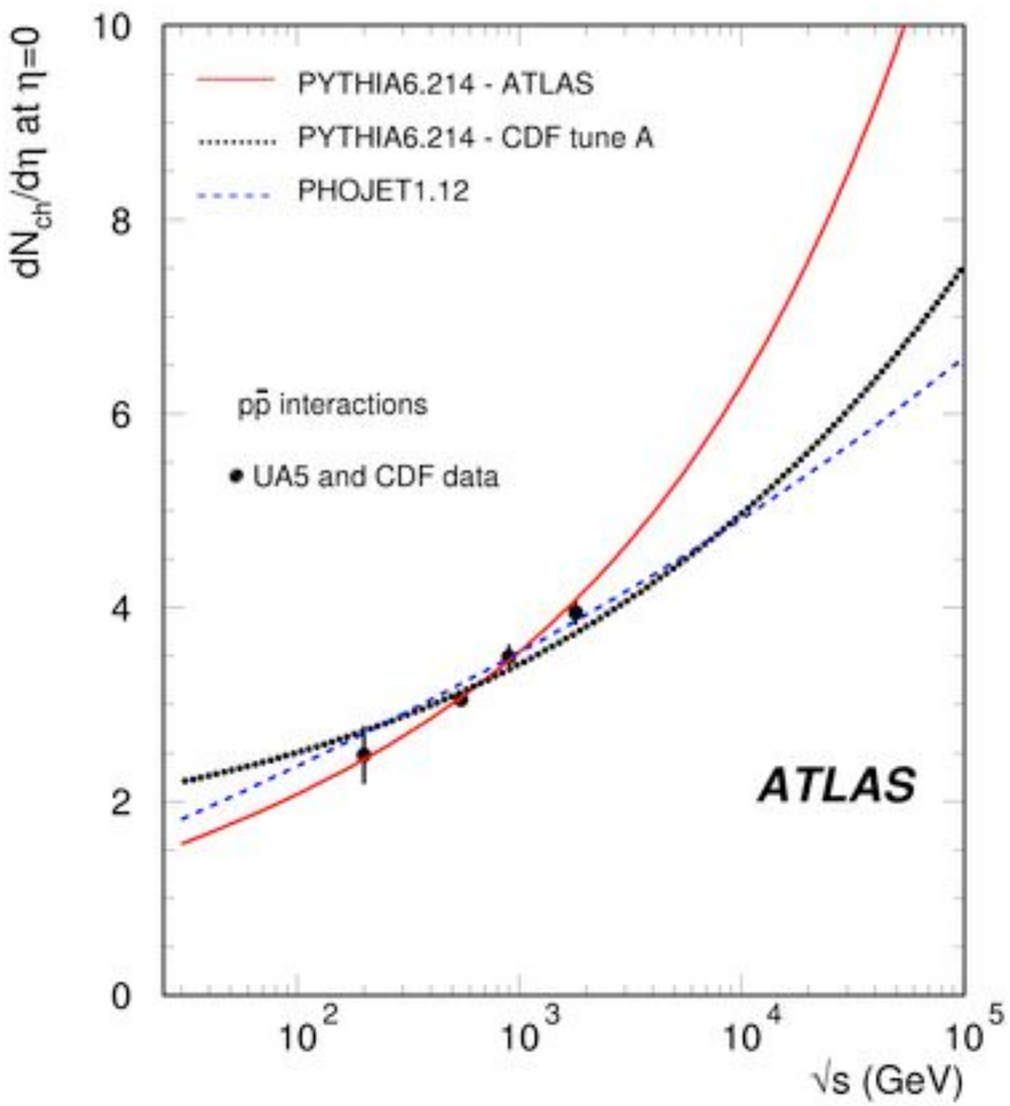
Generating predictions for the LHC

"Prediction is very difficult, especially if it is about the future."

Niels Bohr.

LHC Predictions: pp collisions at √s=14TeV

Charged particle density:
minimum bias



EPJ C 50, 435 (2007)

LHC Predictions: pp collisions at √s=14TeV

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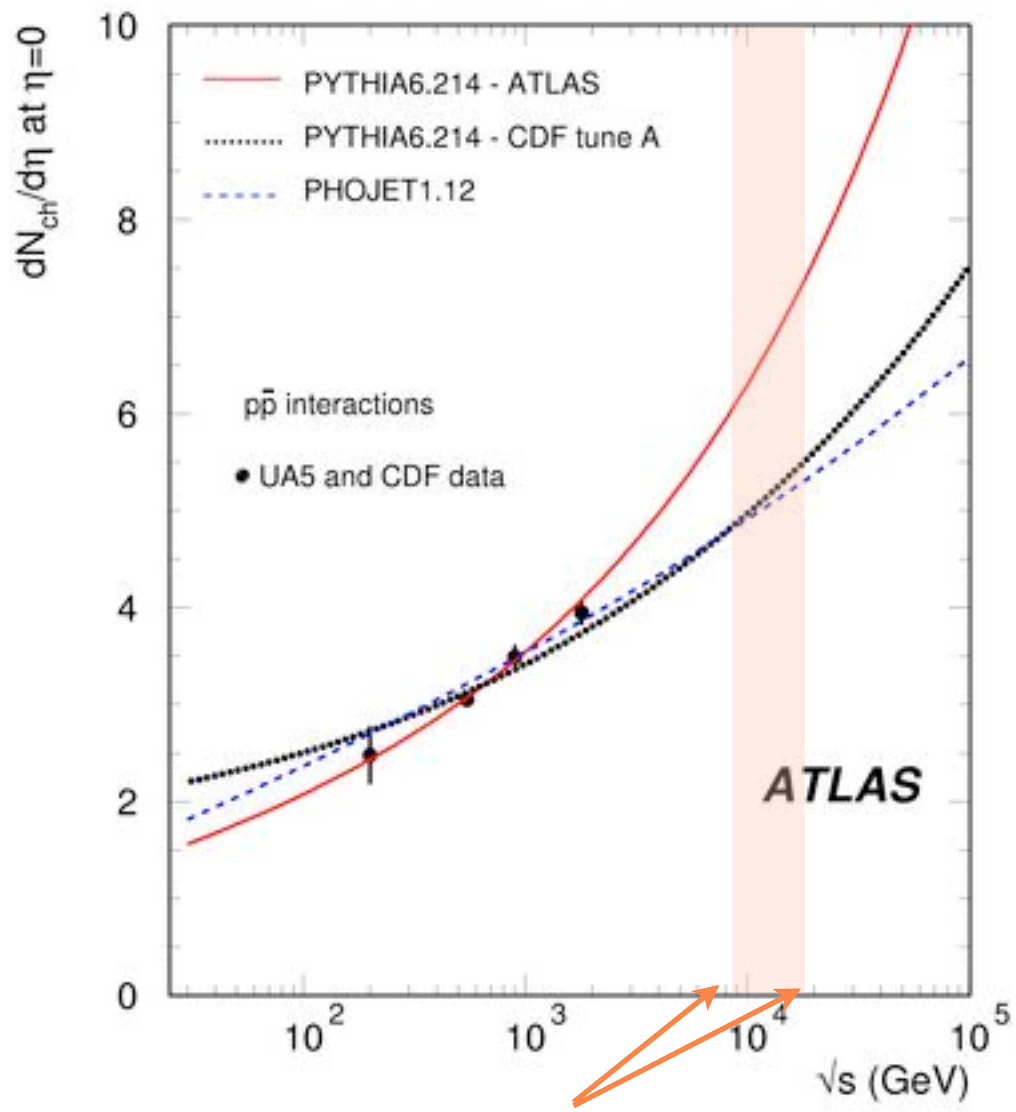

c.m. between 8 – 14TeV

EPJ C 50, 435 (2007)

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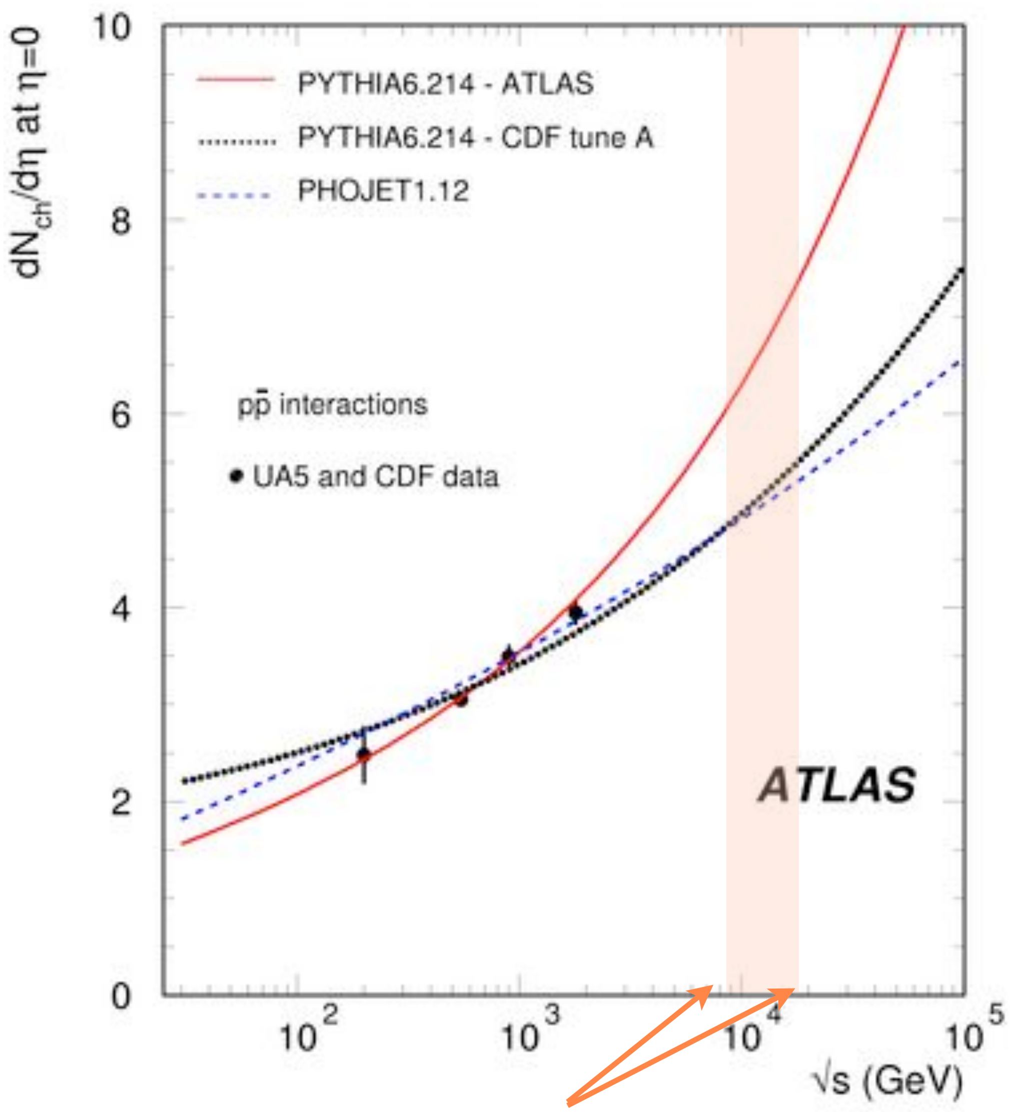
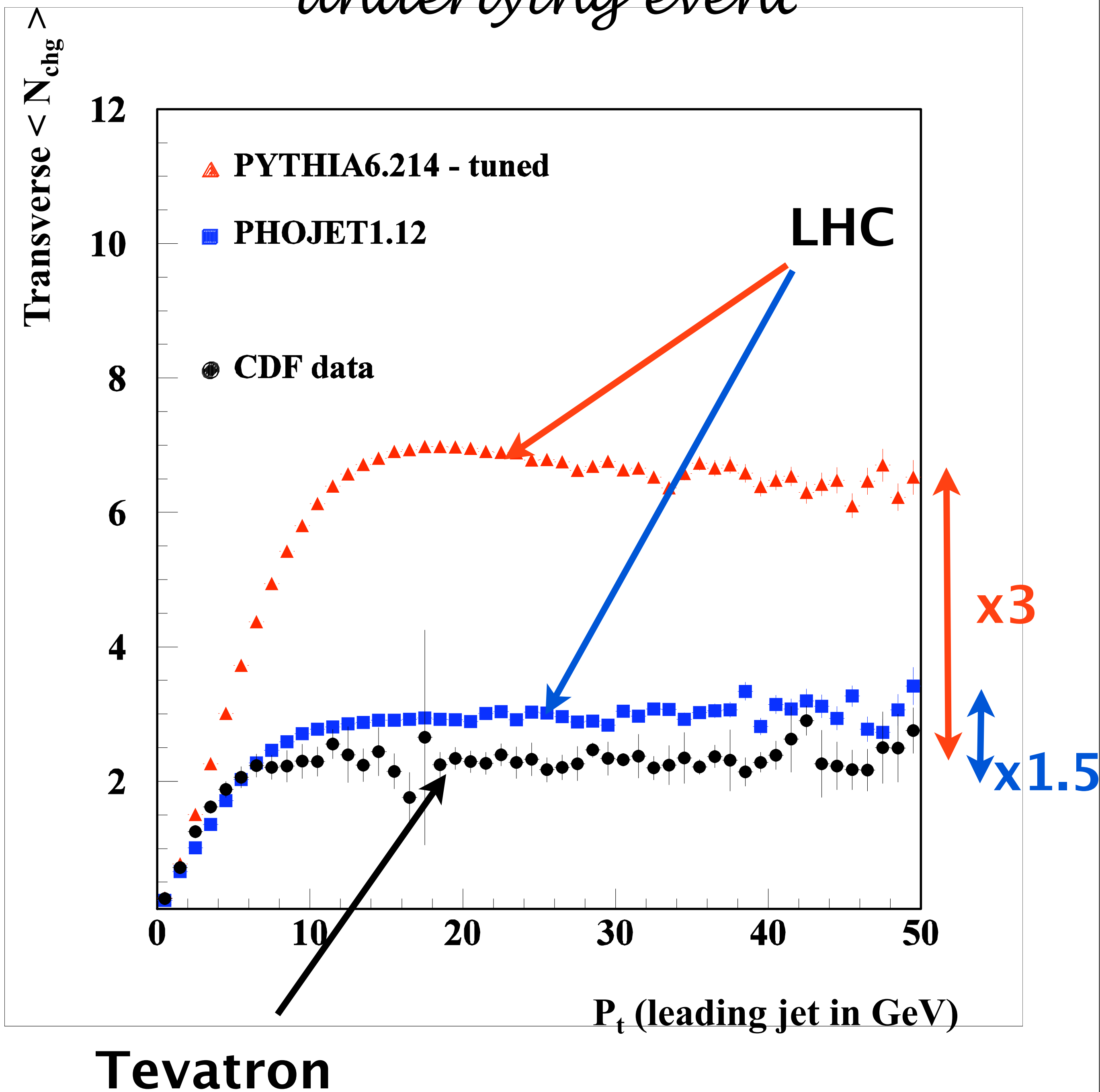


c.m. between 8 – 14TeV

Charged particle density: underlying event



EPJ C 50, 435 (2007)

LHC Predictions: pp collisions at $\sqrt{s}$=14TeV

Observable	PYTHIA6.214 – tuned	PHOJET1.12	Δ%
σ_{tot} (mb)	101.5	119.1	17.3
σ_{elas} (mb)	22.5	34.5	53.3
σ_{NSD} (mb)	65.7	73.8	12.3
Minimum bias Predictions			
$\langle n_{chg} \rangle$	91.0	69.6	30.7
$dN_{chg}/d\eta$ plaeau for $\lvert\eta\rvert<2.5$	~ 7.0	~ 5.5	27.3
$dN_{chg}/d\eta$ at $\eta = 0$	6.8	5.1	33.3
$\langle pT \rangle$ at $\eta = 0$ (GeV)	0.55	0.64	16.3
n_{tot} ($\lvert\eta\rvert<15$)	158.4	115.1	37.6
n_{tot} ($\lvert\eta\rvert<2.5$)	60.9	45.5	33.8
Underlying Event Predictions			
$\langle N_{chg} \rangle$ $pT_{ljet} > 10$ GeV	~ 6.5	~ 3.0	~ 115
$\langle pT_{sum} \rangle$ $pT_{ljet} > 10$ GeV	~ 7.5	~ 3.5	~ 115
$dN_{chg}/d\eta$ $pT_{ljet} > 10$ GeV	~ 29.0	~ 13.3	~ 125
UE/Min-bias $pT_{ljet} > 10$ GeV	~ 4	~ 2	~ 100

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LHC Predictions: pp collisions at $\sqrt{s}$=14TeV

Observable	PYTHIA6.214 – tuned	PHOJET1.12	Δ%
σ_{tot} (mb)	101.5	119.1	17.3
σ_{elas} (mb)	22.5	34.5	53.3
σ_{NSD} (mb)	65.7	73.8	12.3
	Minimum bias Predictions		
$\langle n_{chg} \rangle$	91.0	69.6	30.7
$dN_{chg}/d\eta$ plaeau for $\lvert\eta\rvert<2.5$	~ 7.0	~ 5.5	27.3
$dN_{chg}/d\eta$ at η = 0	6.8	5.1	33.3
$\langle pT \rangle$ at η = 0 (GeV)	0.55	0.64	16.3
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EPJ C 50, 435 (2007)

LHC Predictions: describing the region transverse to the leading jet

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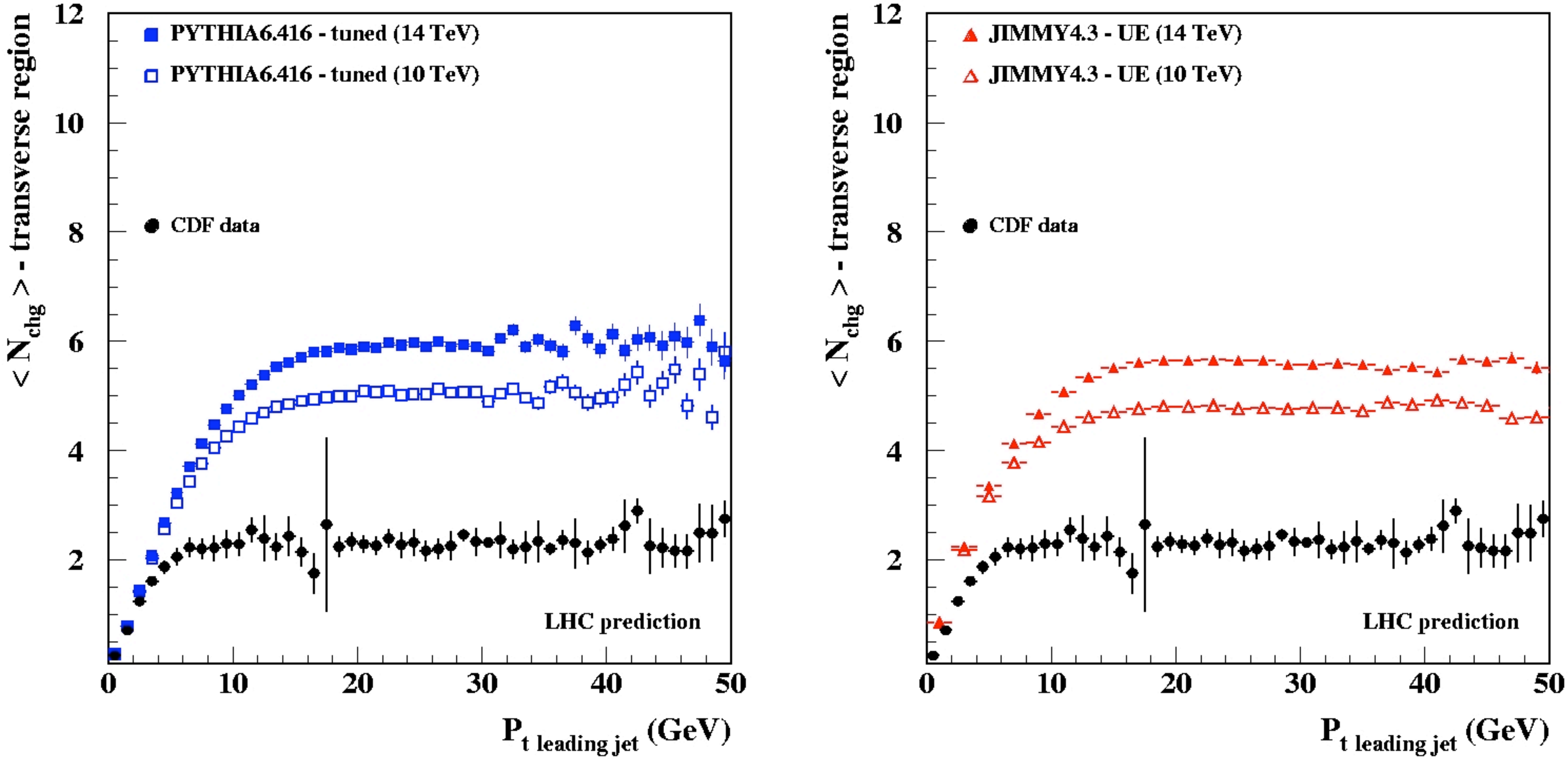
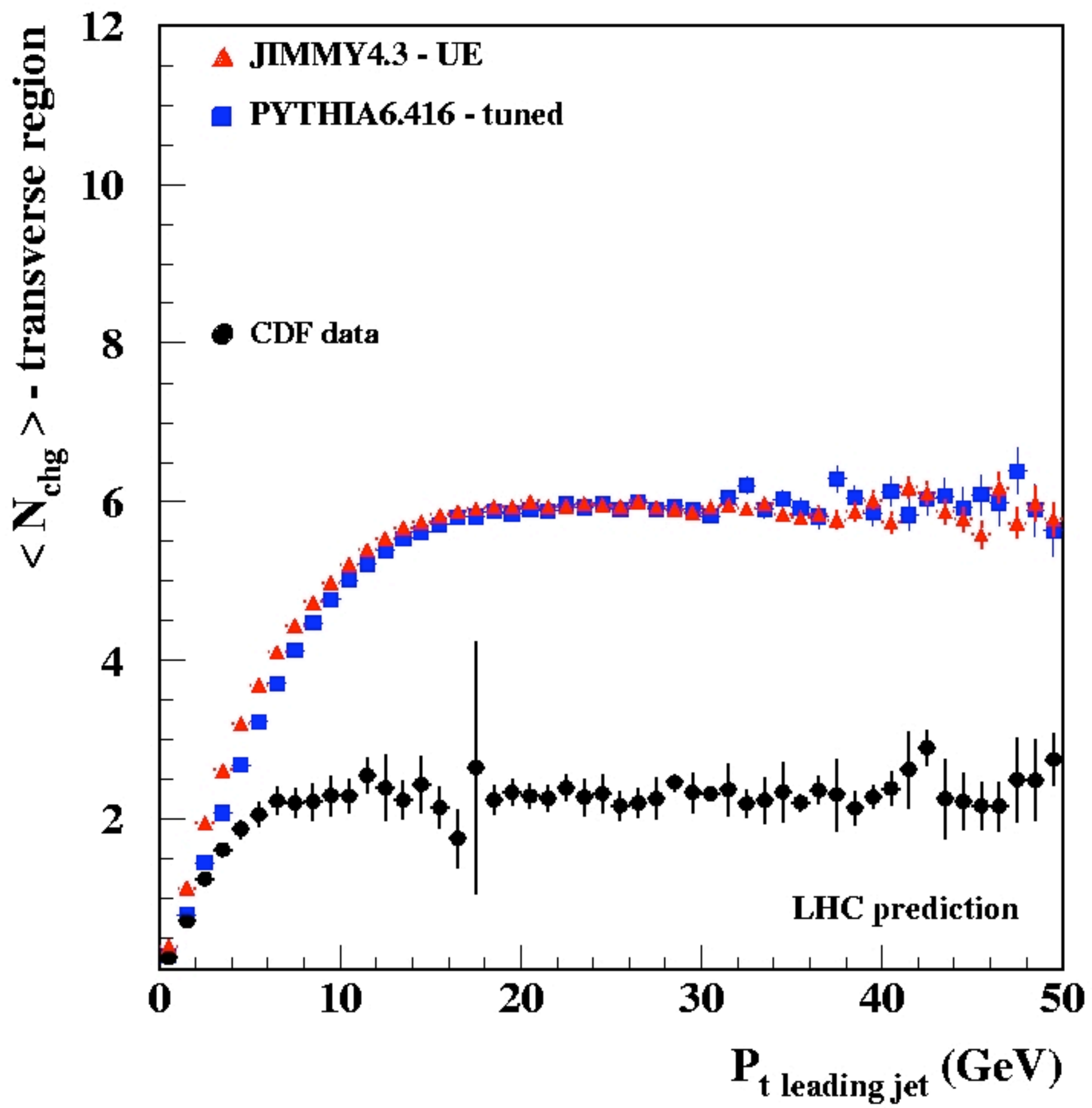
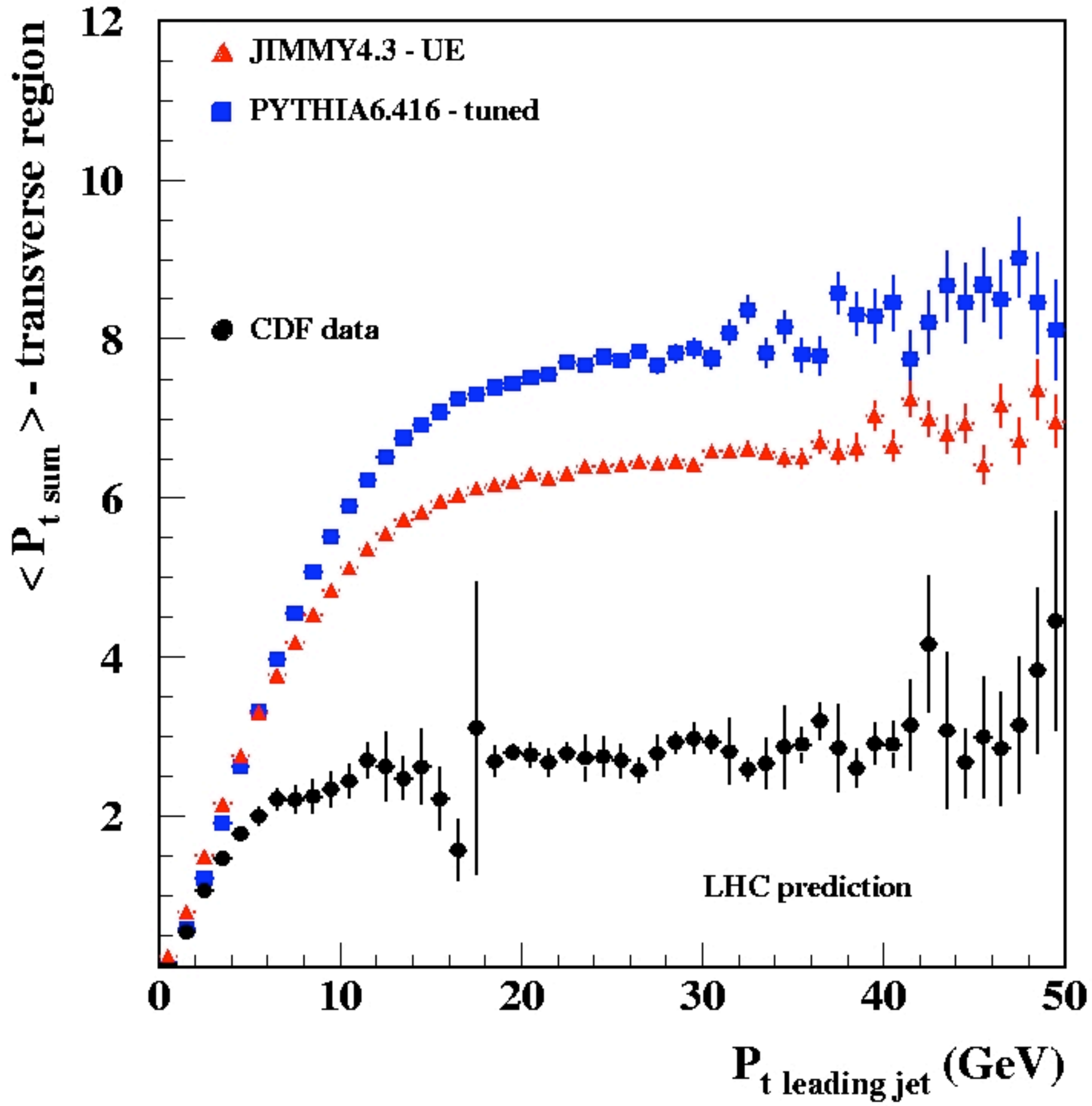


- Measurements of the particle density in the UE at $\sqrt{s}$=10TeV are predicted to reach a plateau ~2 times higher that what has been measured at the Tevatron.
- Measurements at different colliding energies will be very useful to tune energy dependence parameters in MC models. Big challenge to get models that will be able to describe data all the way from SppS to LHC!

LHC Predictions: describing the region transverse to the leading jet





- <N_{chg}> **distribution:** PYTHIA6.416 – tuned and JIMMY4.3 – UE predict same particle density at $\sqrt{s}$=14 TeV.
- <$P_{T\ SUM}$> **distribution:** PYTHIA6.416 – tuned generates harder particles!

Outline:

I. Introduction:

- Historical perspective
  - Measuring hadronic inelastic collisions
  - ISR, SPS, Tevatron
  - “minimum bias” vs. the underlying event: aren’t they the same?

II. MC Models and LHC predictions:

- common ingredients & missing links (?)

III. Measuring minimum bias and the underlying event with “early” LHC data

IV. Summary

Minimum bias and the underlying event with "early" LHC data

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- At the LHC, studies on minimum-bias and the underlying event **are planned to be done early on**.
  - Charged particle multiplicity $dN/d\eta$ and dN/dp_T : ~10K events (triggered)
  - Charged particle multiplicity distributions (KNO) : ~400K events
  - $\langle P_T \rangle$ vs n_{chg}: ~1M events
  - UE distributions (E_T up to 150GeV) : ~10M minimum bias events

Minimum bias and the underlying event with "early" LHC data

University of Glasgow

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  - Charged particle multiplicity distributions (KNO) : ~400K events
  - $<P_T>$ vs n_{chg}: ~1M events
  - UE distributions (E_T up to 150GeV) : ~10M minimum bias events
- Accumulating events for analysis is only constrained by the allocated trigger bandwidth!
  - $\mathbf{N_{events} = \sigma \times \mathcal{L}}$
    N_{MB} ➠ ~hundreds of billions of "minimum bias" events for $\mathcal{L}$ = 10pb^{-1}
- Low luminosity is ideal as the effect of overlapping proton-proton collisions is removed (or at least reduced)!

Minimum bias and the underlying event with "early" LHC data

- "All" LHC experiments will be measuring and analyzing minimum bias interactions with the early data.

- Common steps:
  - Triggering on minimum bias collisions
  - Reconstructing tracks / calorimeter clusters
  - Correcting back for detector effects (efficiencies & acceptances)

Triggering on minimum bias events

(strategy for low luminosity runs!)

What do we want in our final minimum bias sample?

- **most of the inelastic events** (with as little or "minimum" bias as possible).
- **later to be distilled into non-single diffractive inelastic events.**

Triggering on minimum bias events

(strategy for low luminosity runs!)

What do we want in our final minimum bias sample?

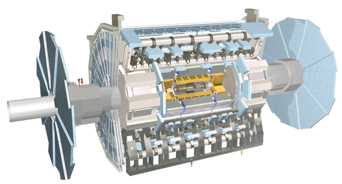
- **most of the inelastic events** (with as little or "minimum" bias as possible).
- **later to be distilled into non-single diffractive inelastic events.**

What do we need to separate?

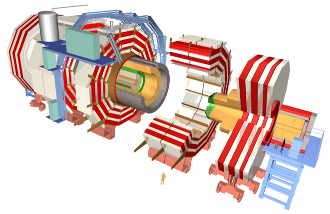
- **Empty events** (for initial runs with bunch spacing of 75ns, most bunch crossings are expected to be empty at $L=10^{31}cm^{-2}s^{-1}$)**;**
- **Beam-gas;**
- **Beam-halo;**
- **Pile-up** (not so much of a big issue early on, but important for $L\sim10^{33}cm^{-2}s^{-1}$ and greater).

Triggering on minimum bias events

(examples from ATLAS & CMS)



ATLAS



CMS

Random Trigger

- Trigger on crossing of filled bunches
- Zero bias, heavily pre-scaled
- Optimal for moderate intensity
- Not ideal for start-up: need to reject empty events

Track Trigger

- Trigger on clusters & tracks in tracker
- Optimal for low intensity running (e.g. @ 900 GeV)
- CMS (1 track): 99% ND, 69% DD, 59% SD
- ATLAS (2 tracks): 100% ND, 65% DD, 57% SD, 40% BG

MB Scintillator Trigger (ATLAS)

- Require energy deposit above threshold
- MB trigger scintillator counters ($2.1 < |\eta| < 3.8$)
- 1 hit on each side: 99% ND, 54% DD, 45% SD, 40% BG
- 2 hits on any side: 100% ND, 83% DD, 69% SD, 54% BG

Forward Triggers (ATLAS)

- Beam Conditions Monitor ($|\eta| = 4.2$)
- LUCID ($5.6 < |\eta| < 5.9$)
- Zero Degree Calorimeter ($|\eta| > 8.3$)

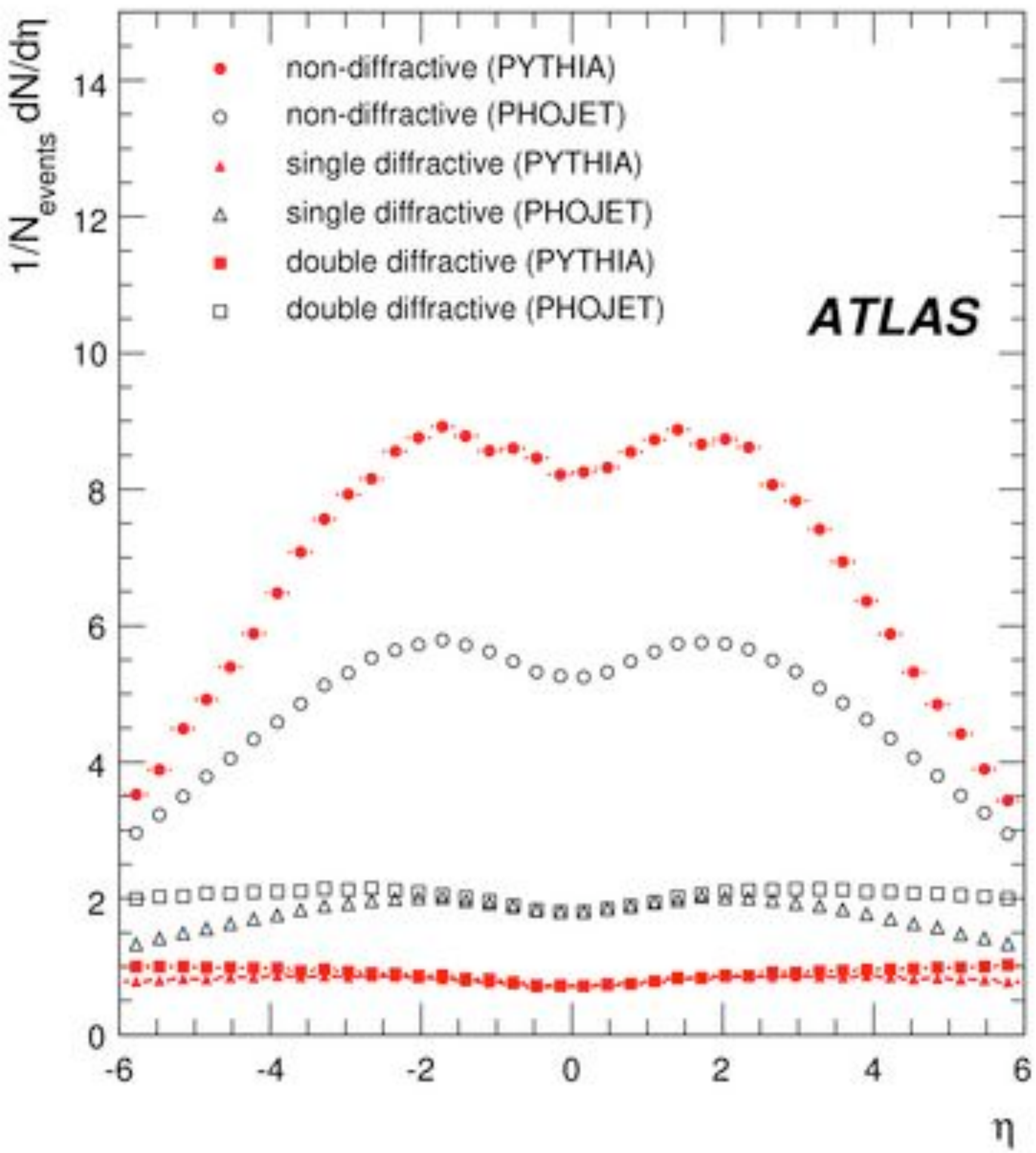
Forward Calorimeter Trigger (CMS)

- Count towers with $E_T > 1$ GeV
- Forward Hadronic Calorimeters ($3 < |\eta| < 5$)
- 1 tower on one side: 81% ND, 15% DD, 15% SD
- 1 tower on each side: 48% ND, 1% DD, 1% SD

Forward Triggers (CMS)

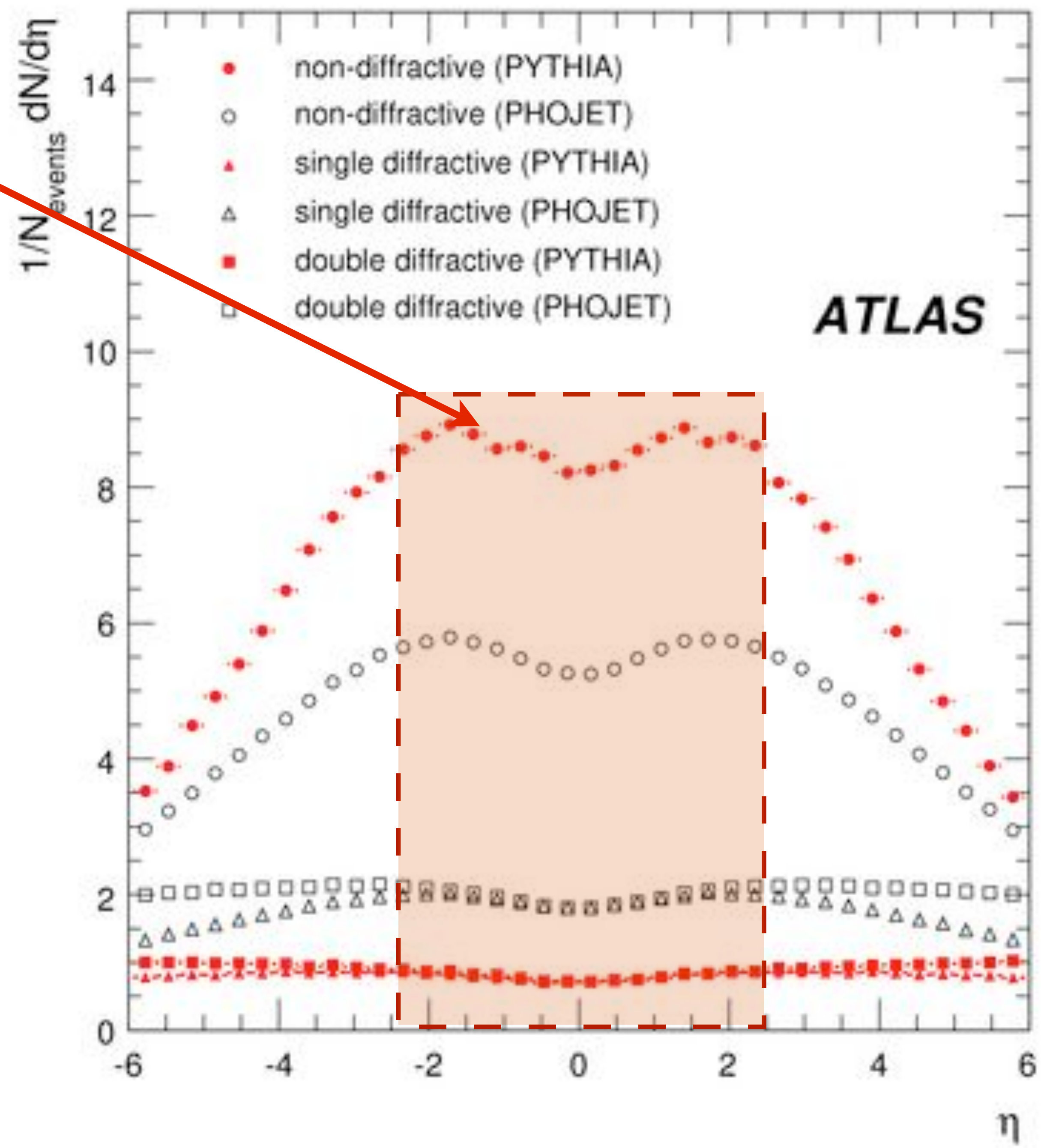
- CASTOR ($5.1 < |\eta| < 6.6$)
- TOTEM ($3.1 < |\eta| < 4.7$, $5.3 < |\eta| < 6.7$)
- Zero Degree Calorimeter ($|\eta| > 8$)

Triggering on minimum bias events



Triggering on minimum bias events

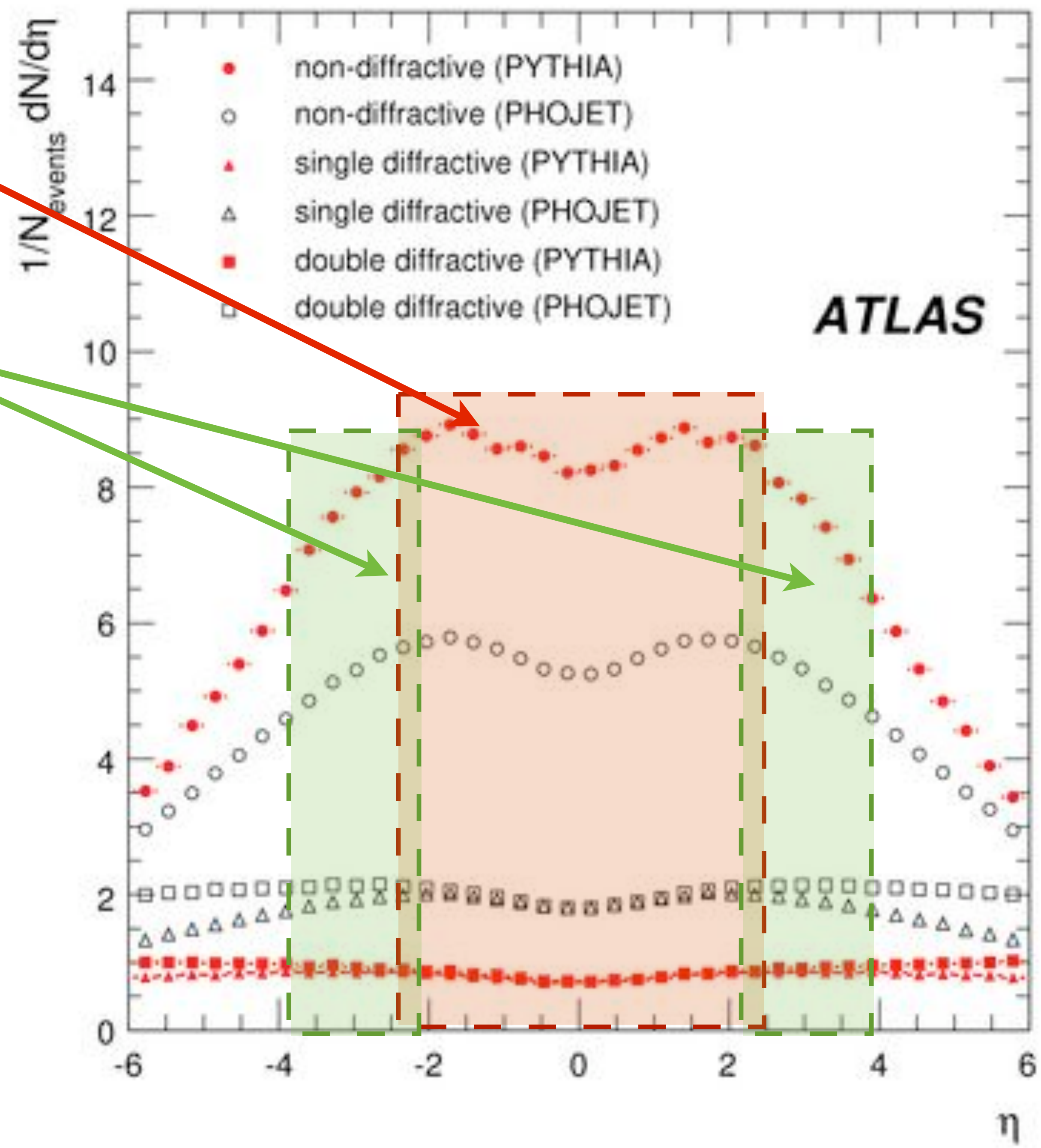
Inner detector space points



Triggering on minimum bias events

Inner detector space points

Minimum bias trigger scintillators



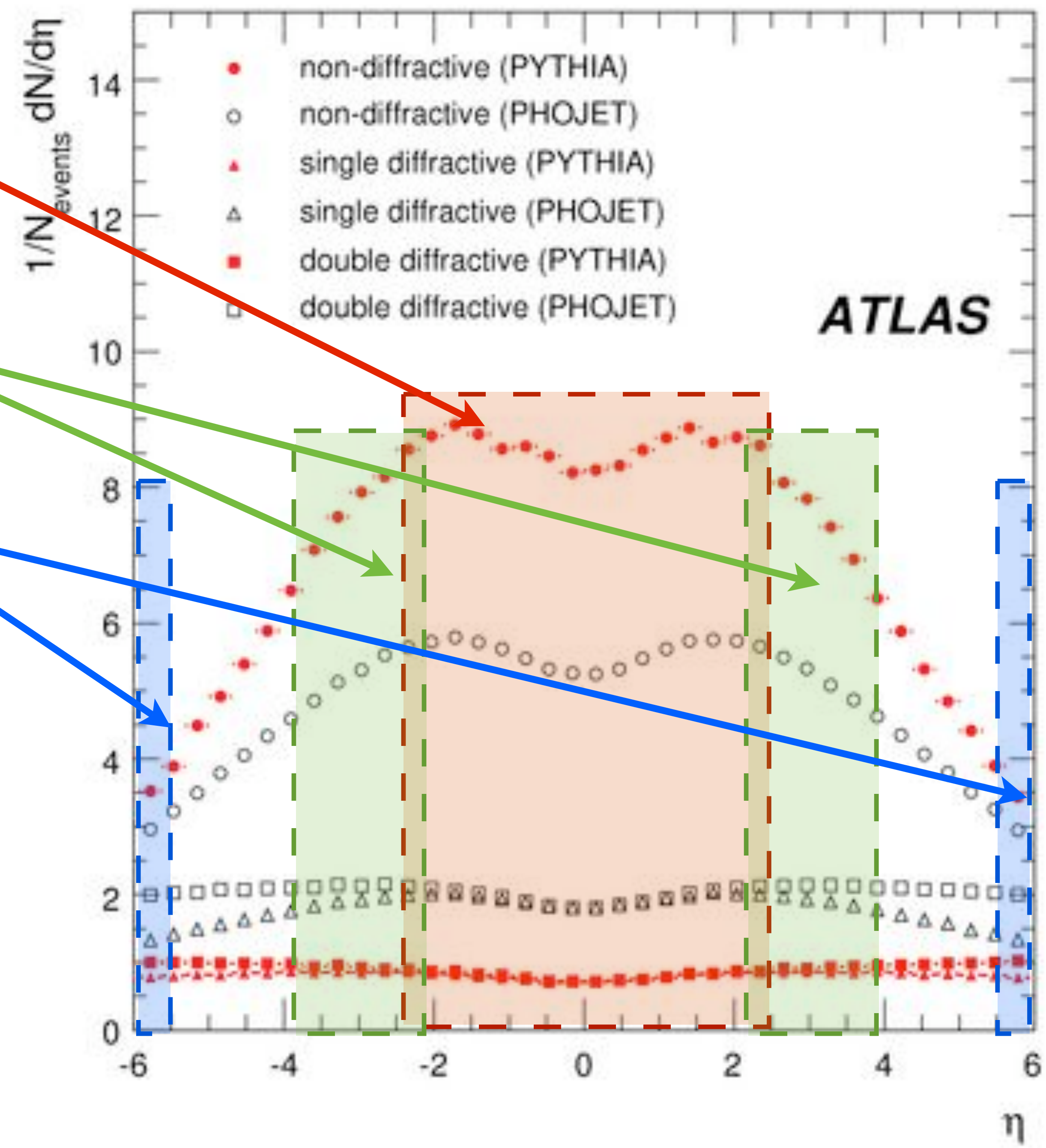
Triggering on minimum bias events

Inner detector space points

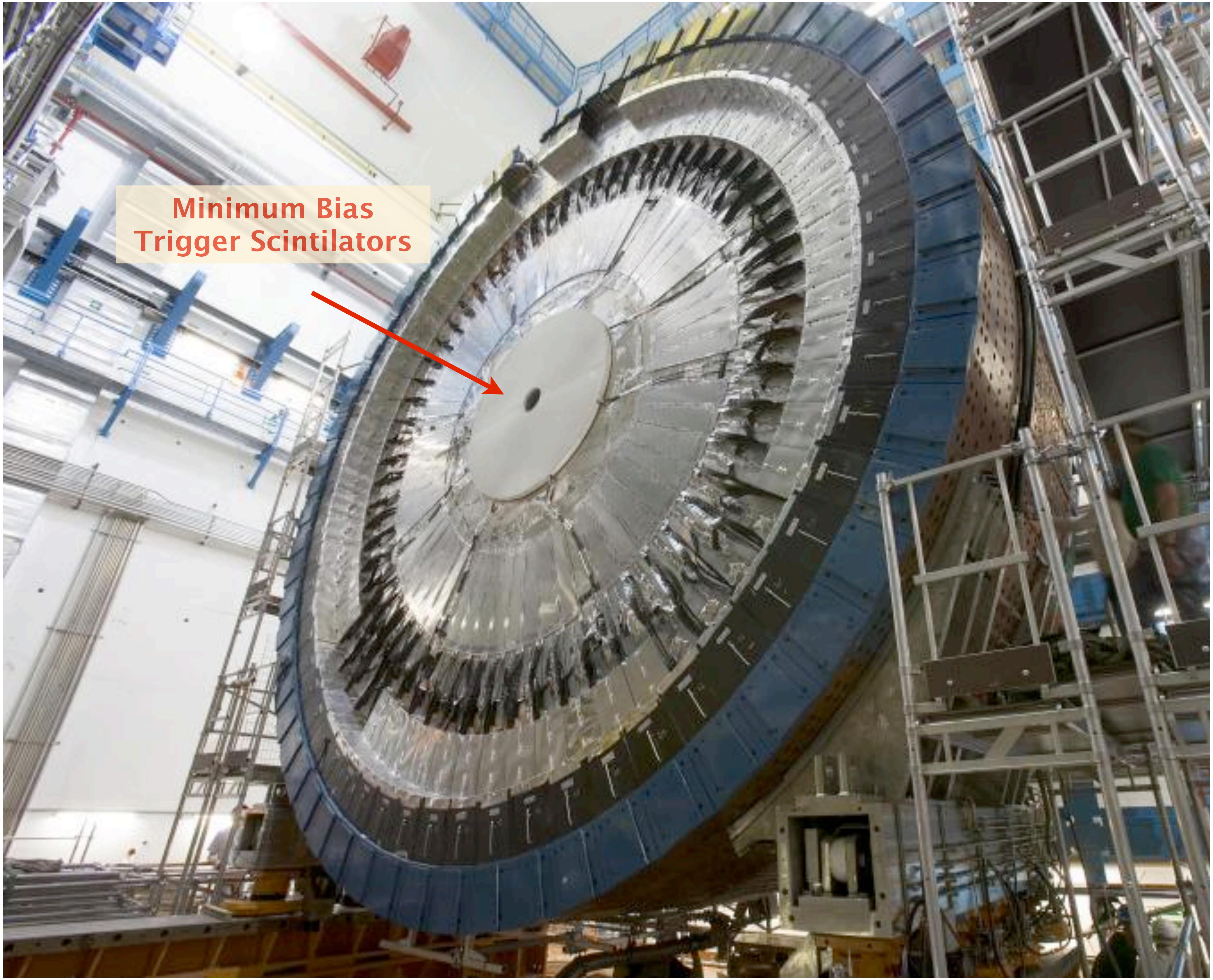
Minimum bias trigger scintillators

Cerenkov detector (LUCID)

Zero degree calorimeter (ZDC)
8.3 → ∞

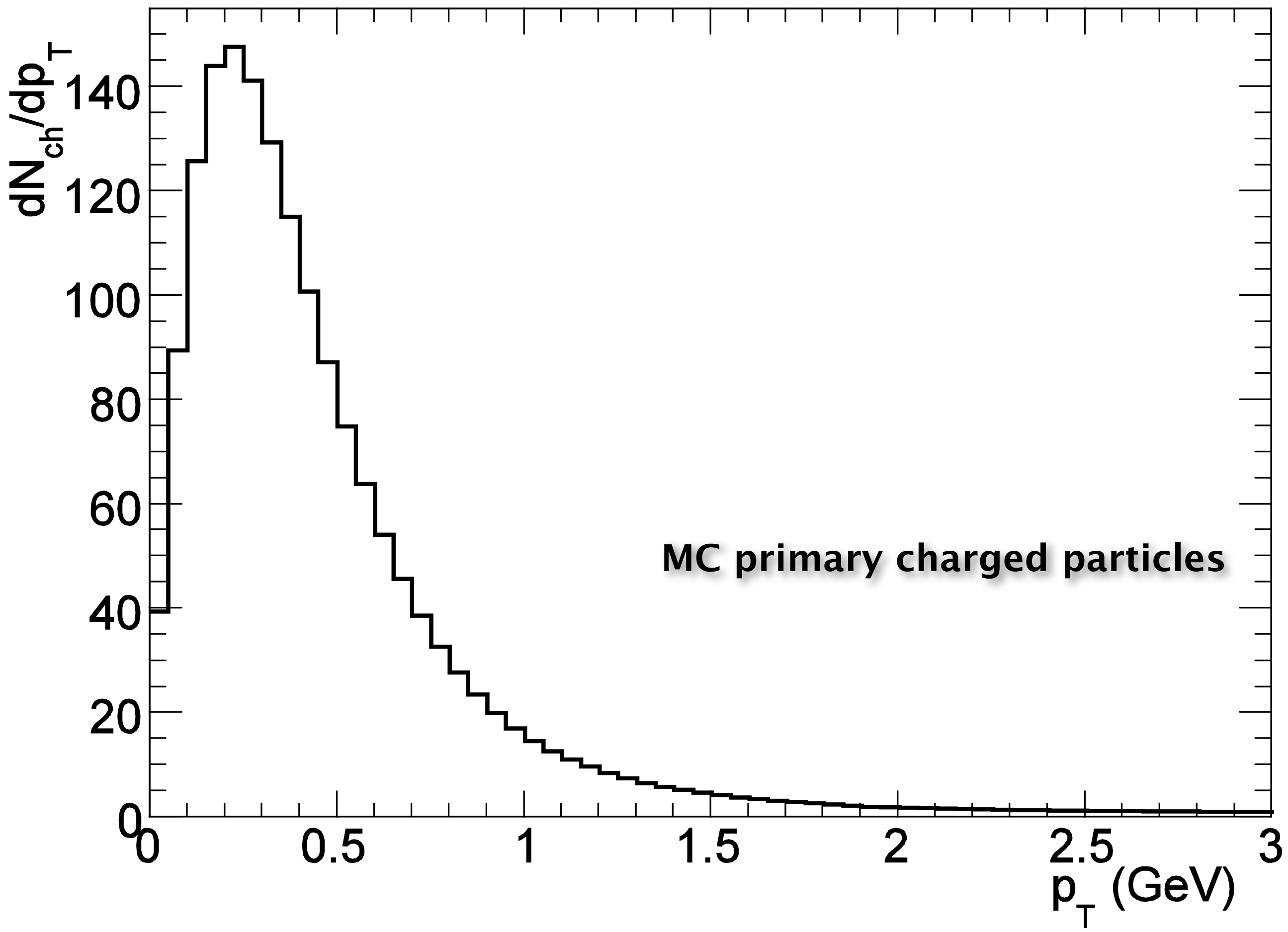


Triggering on minimum bias events



Reconstructing minimum bias events

- The goal is to reconstruct the event and recover all charged particles;
  - main limitation: soft track reconstruction!
  - standard reconstruction: low p_T cut set to 500MeV;



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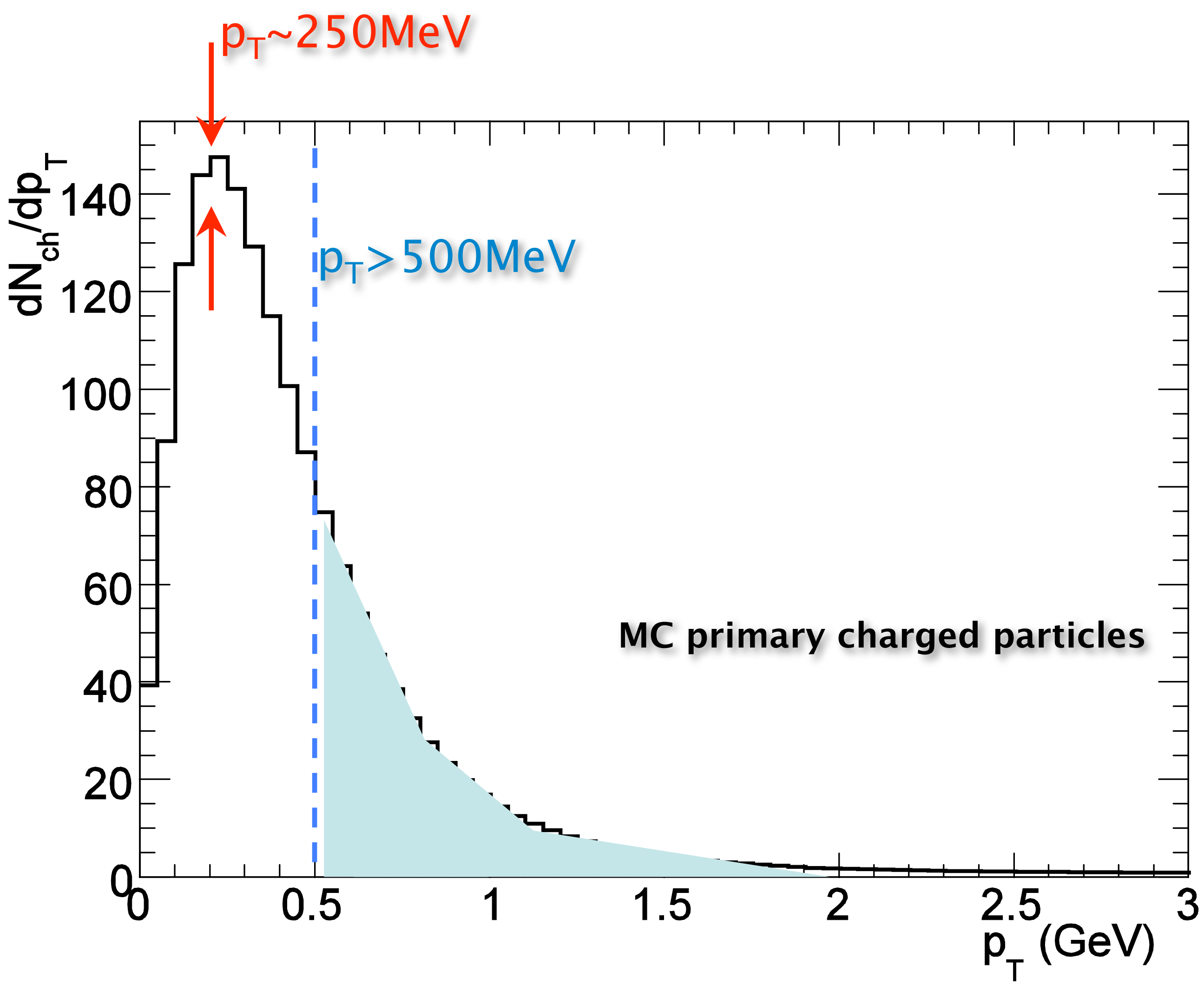
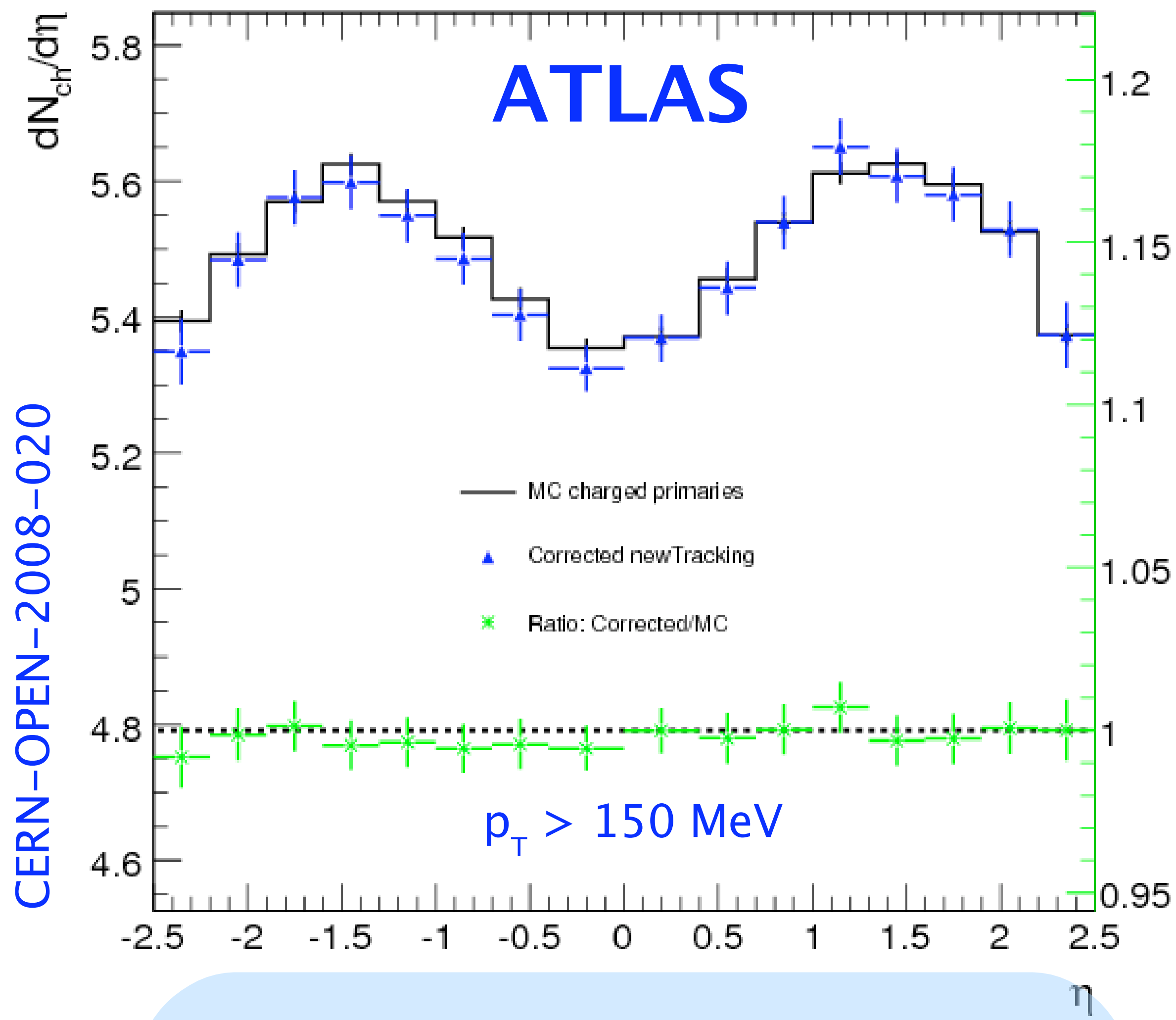
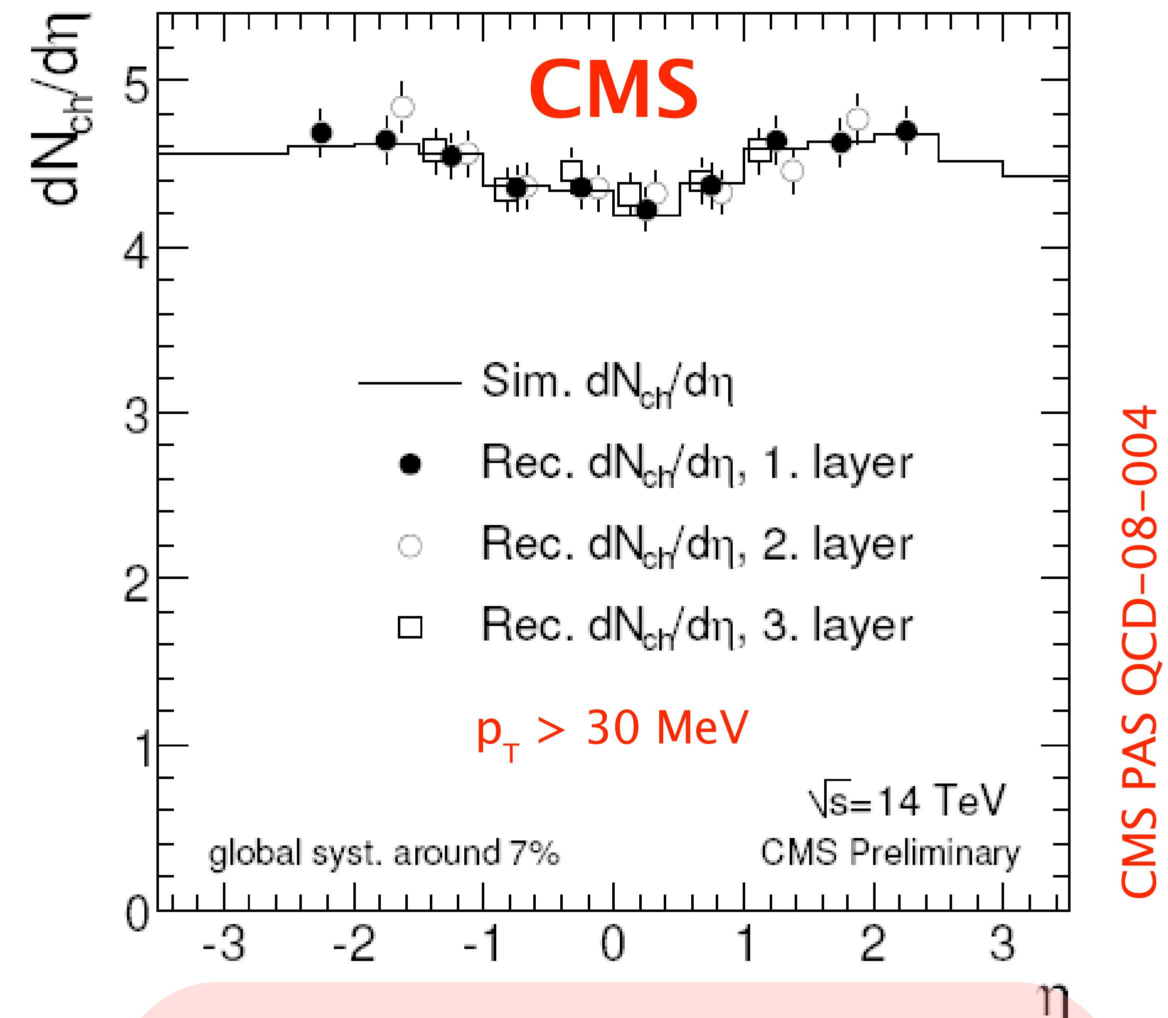


- Work is being done to push this limit to p_T ~ 100 – 200 MeV;
- Avoid large extrapolation factors for measurements such as $dN_{ch}/d\eta$.

Reconstructing minimum bias events





Track-based method

Corrections for track & vertex reconstruction inefficiency

Total systematic uncertainty: 7%

Uncertainty dominated by tracker misalignment

Hit-counting method

No tracking or alignment required!

Corrections for event selection & low-pT 'loopers'

Total systematic uncertainty: 7%

Uncertainty dominated by vertex bias and hit-to-track conversion

...going forward to higher luminosities

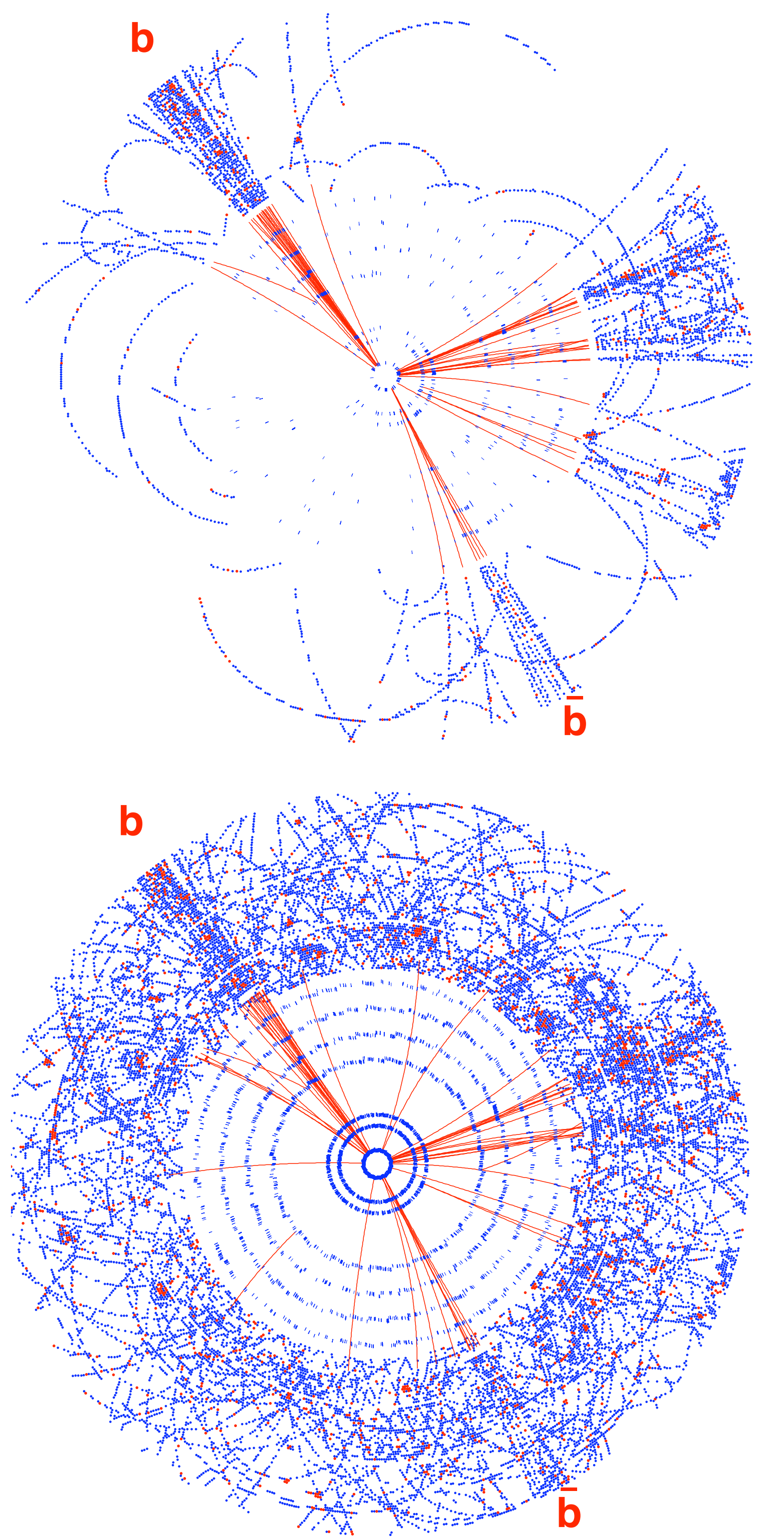
University of Glasgow

ATLAS Barrel Inner Detector

$H \rightarrow b\bar{b}$

Low-luminosity

$L = 10^{33}\ cm^{-2}s^{-1}$



$L = 10^{34}\ cm^{-2}s^{-1}$

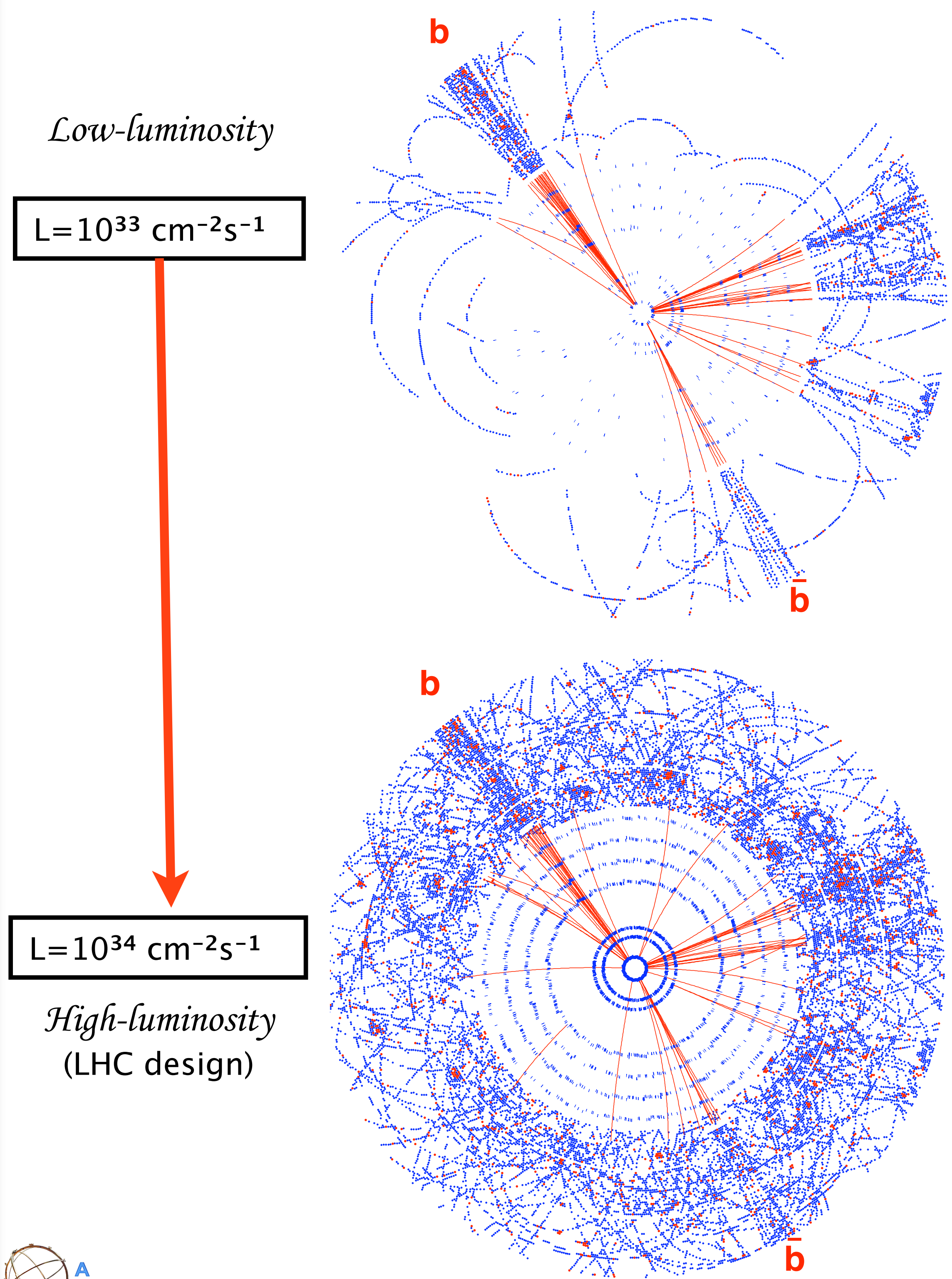
High-luminosity
(LHC design)

...going forward to higher luminosities

University of Glasgow

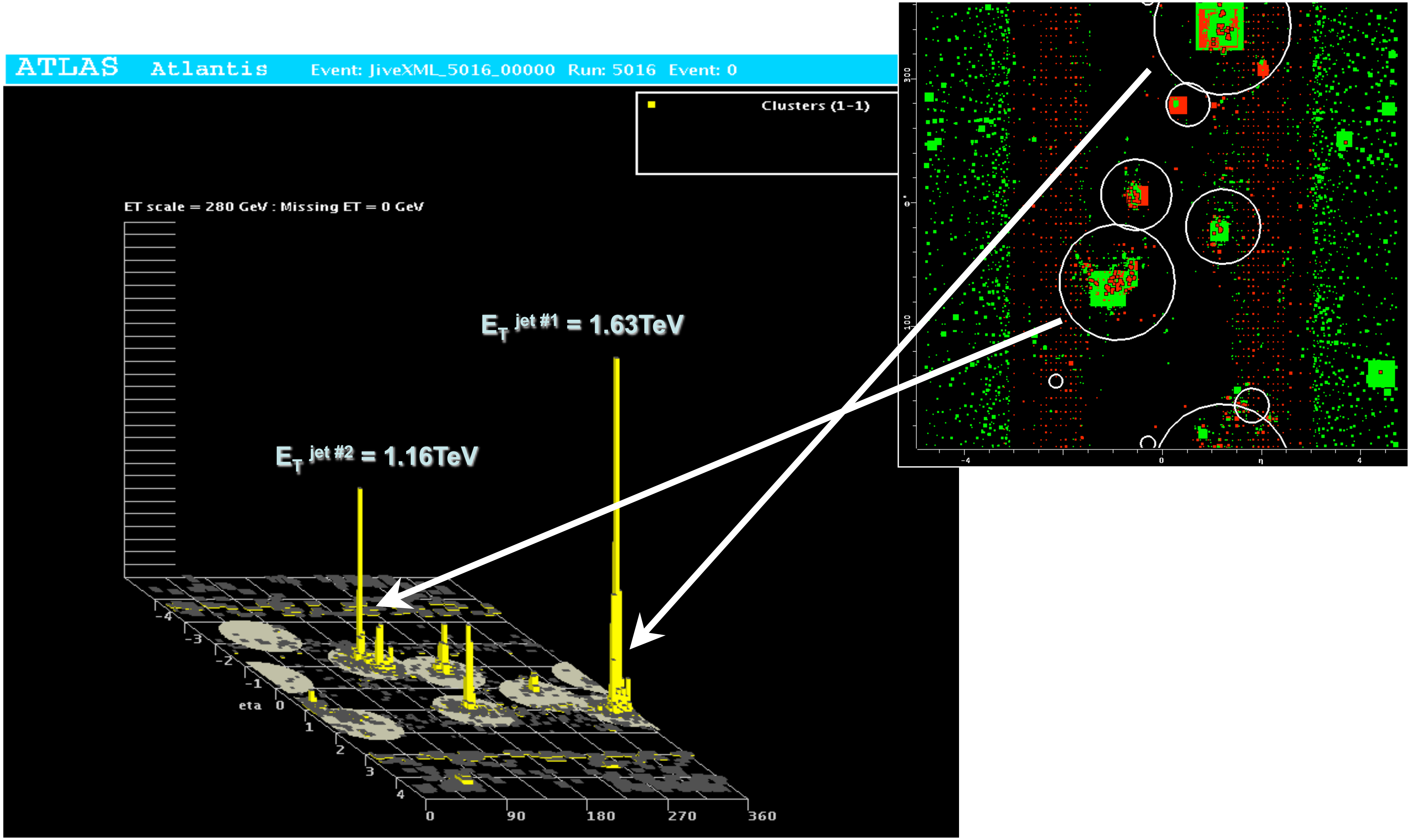
ATLAS Barrel Inner Detector

$H \rightarrow b\bar{b}$



- **Understanding of single inelastic collisions is essential.**
- **High-luminosity environment: can have up to 23 - 25 minimum bias pp collisions per bunch-crossing, ie ~1000 extra tracks!**
- **SLHC: from 2017(?), luminosity 10x greater than design value ($L_{SLHC} = 10^{35}$ cm^{-2} s^{-1})**
  - **higher event rates**
  - **better statistics & signal significance**
  - **sensitivity for smaller cross-sections**
- **Understanding multiple pp collisions will be essential for most of the discovery channel both in the Higgs and Supersymmetry sectors!**

Measuring the underlying event associated to jets



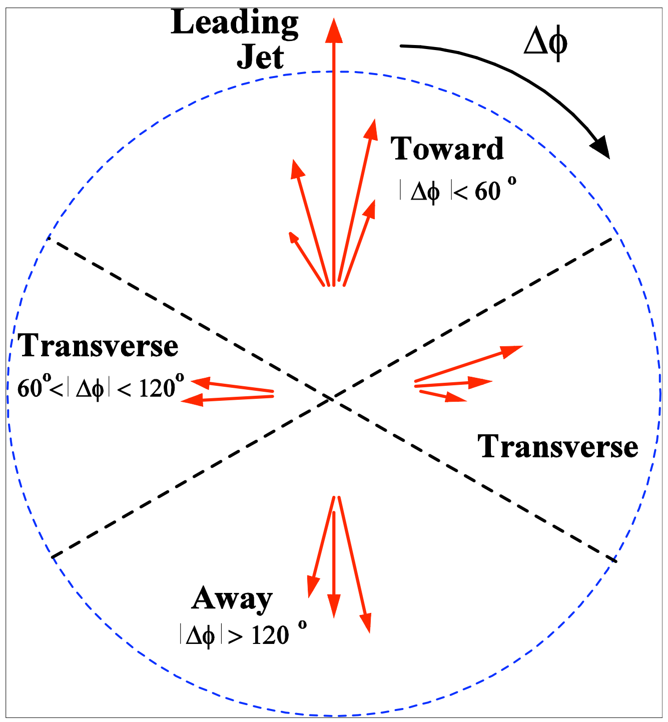
(Simulated event!)

1 pb^{-1} < $\mathcal{L}$ < 10 pb^{-1} – Underlying event associated to jets (depending on how far in Jet E_T one wants to explore)

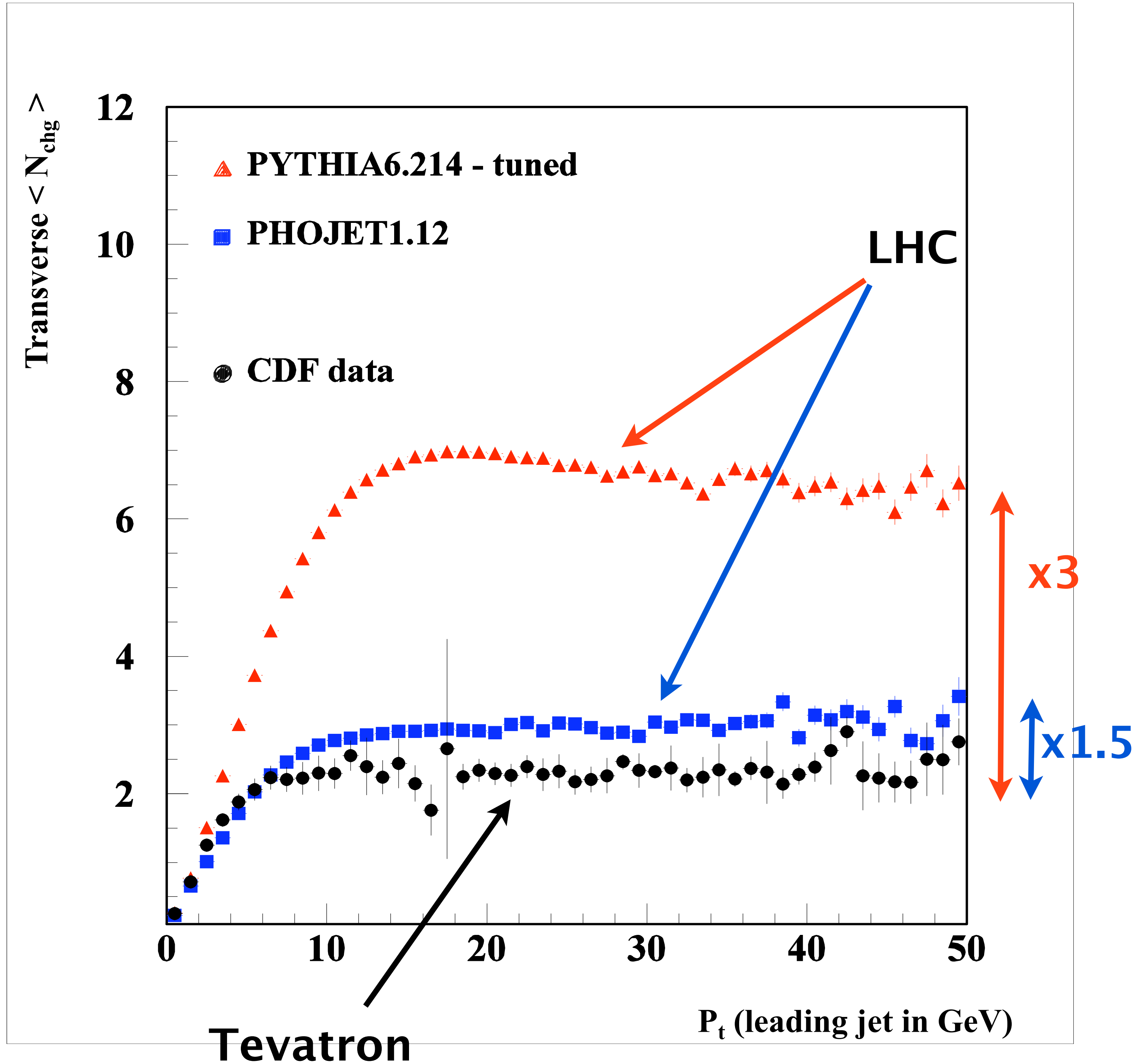
CDF - Run I "Style"

Charged particles:
p_t>0.5 GeV and |η|<1

Cone jet finder: R=0.7



UE particles come from region transverse to the leading jet.



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Estimating how well ATLAS can reconstruct the underlying event (see ATL-PHYS-PUB-2005-015).

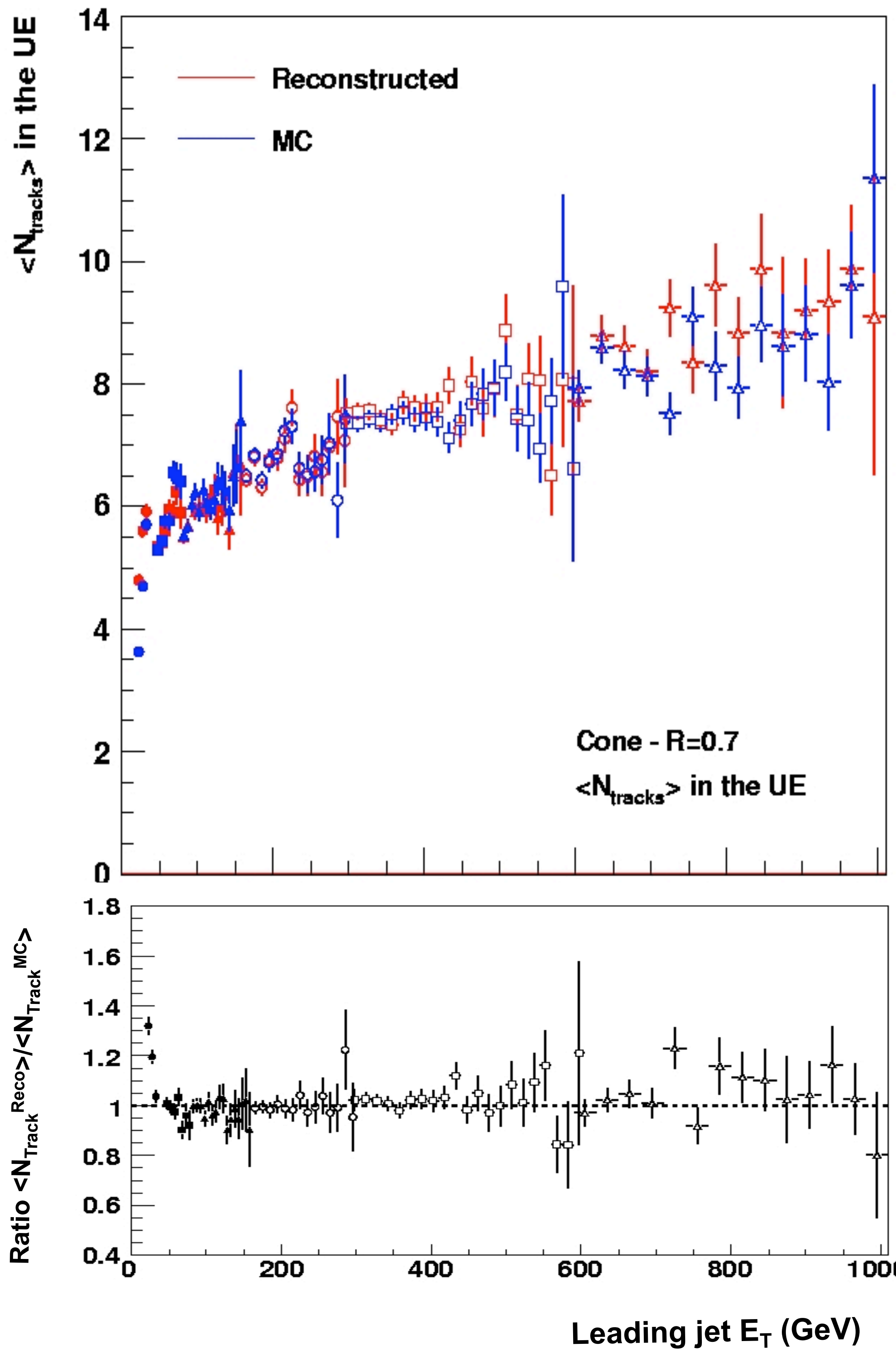
Selecting the underlying event:

i. Jet events:

$N_{jets} > 1$,
$|\eta_{jet}| < 2.5$,
$E_T^{jet} > 10$ GeV,

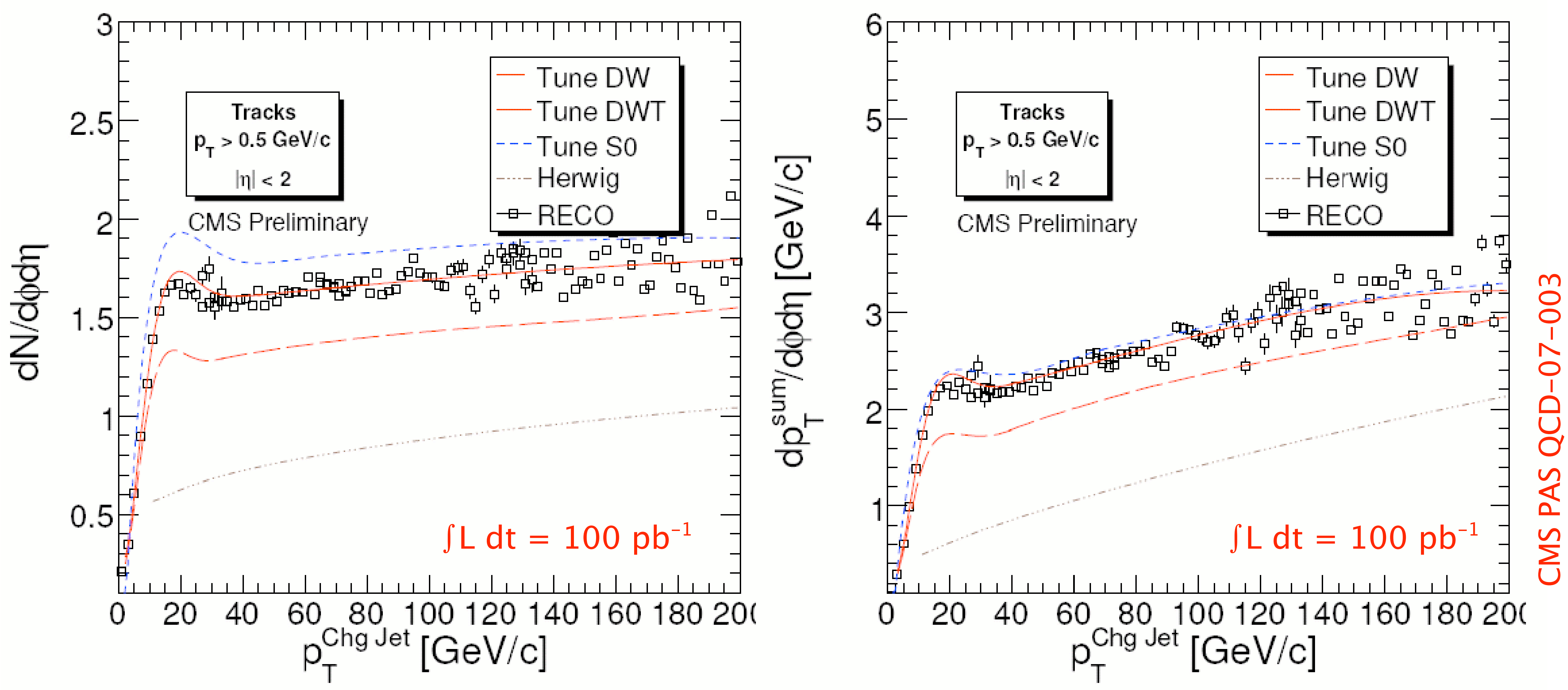
ii. Tracks:

$|\eta_{track}| < 2.5$,
$p_T^{track} > 1.0$ GeV/c



- Jet measurements with early data at ATLAS will extend considerably our knowledge of the underlying event!

- This study used ~ 60 pb^{-1} of integrated luminosity (few days at $L=10^{32}cm^{-2}s^{-1}$, $\varepsilon=50\%$)!



- Events selected with MB trigger and additional trigger on pT of leading calorimetric jet (p_T^{calo} > 20, 60, 120 GeV/c)
- Analysis uses charged jets, defined using only charged particles and no calorimeter information

...some other possible applications

- **Supersymmetry:** Estimation of QCD backgrounds to searches for supersymmetry (particularly relevant in multi-jet final states)

- **Higgs plus associated top production:** Attempt to improve signal selection using experience from UE studies in top-quark events.

- **UE in B+ events:** Better characterization/understanding of the UE can improve the signal selection in channels fighting the QCD background.

- **Re-calibration of MC models with early LHC data** (necessary for virtually all systematic corrections)

- **Underlying event measurements in events with forward jets separated by rapidity gaps:** Probe of Pomeron exchange models.

- **Collaboration with theory groups interested in soft QCD description.**

- **...**

Summary

- **The search for "New Physics" at the LHC will begin with the understanding the detector and the hadronic environment in LHC collisions.**

- **Early minimum bias and underlying event studies will take advantage of the data as it becomes available at the LHC** (potentially the first physics papers!)**.**
    - Minimum-bias and the underlying event: improved understanding of events dominated by soft processes.

- **CMS & ATLAS are not only exceptionally well designed to find new physics (ie. Higgs and SUSY) but will also deliver very precise and detailed measurements of the entire event through its tracker and calorimeter (including low-p_T tracks).**

- **"Early" measurements ≠ "Easy" measurements!** Remember: brand new physics environment & new technologies.

Backup

What can be done with early data?

- $\mathcal{L} < 1pb^{-1}$ – Minimum Bias measurements

- At the LHC, studies on minimum-bias **are planned to be done early on**. Low luminosity is ideal as the effect of overlapping proton-proton collisions is removed (or at least reduced)!

- Modeling of minimum bias pile-up and underlying event **necessary tool for high p_T physics!**

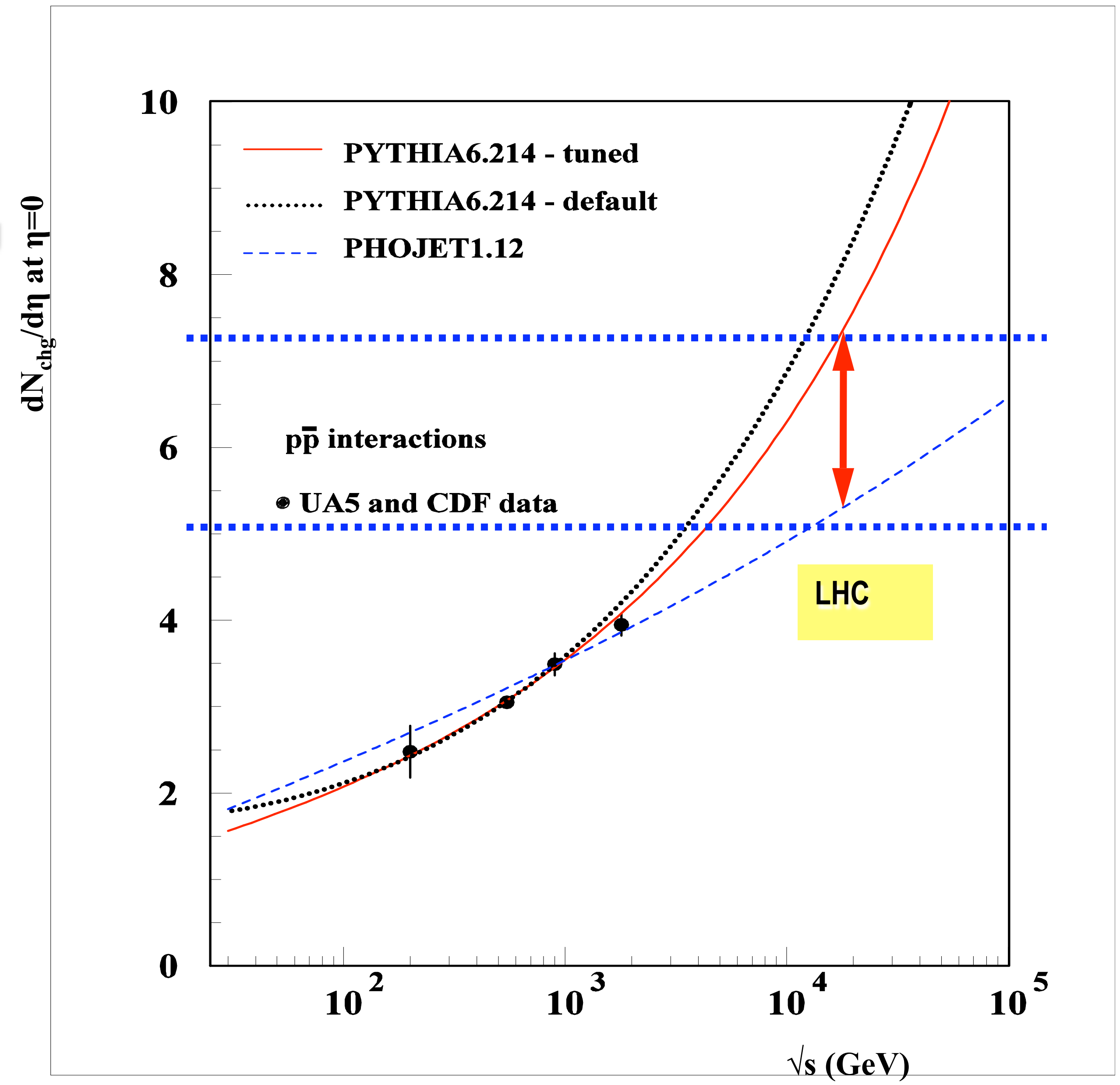
- “Minimum bias” is usually associated to non-single-diffractive events (NSD), e.g. ISR, UA5, E735, CDF,…

$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$

minimum bias event

$\sigma_{tot} \sim$ 102 - 118 mb (PYTHIA) (PHOJET)

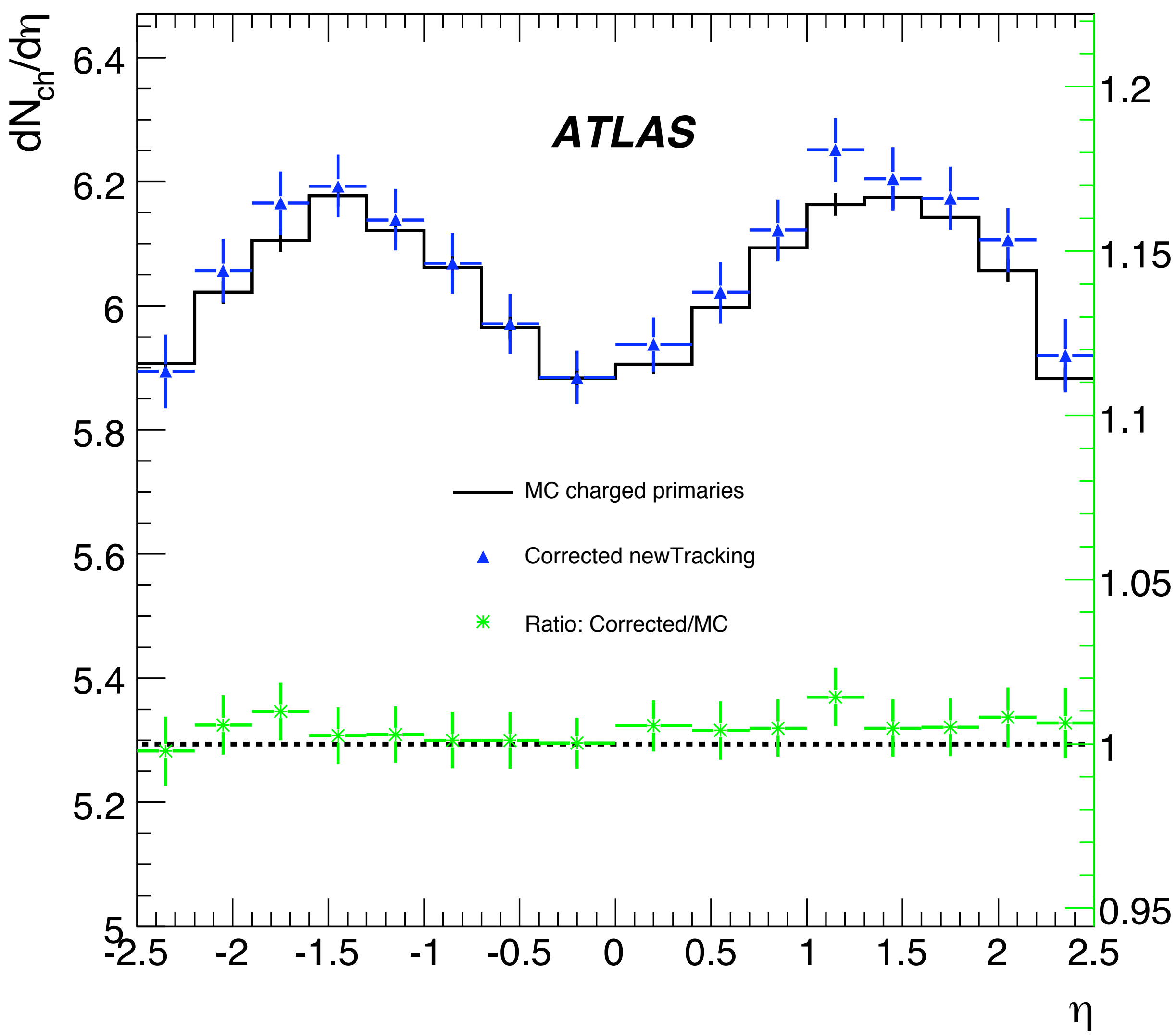
$\sigma_{NSD} \sim$ 65 - 73 mb (PYTHIA) (PHOJET)



- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a $\ln(s)$ dependence.

Estimating how well ATLAS minimum bias events can be reconstructed (see SM chapter on CSC book).

MC charged primaries & track p_T > 150MeV



- Reconstructed distribution for non-single diffractive inelastic events (for p_T > 150MeV)
- This can be directly compared to previous measurements from UA5 and CDF for example.

Summary of systematic uncertainties

Track selection cuts	2%
Mis-estimate of secondaries	1.5%
Vertex reconstruction	0.1%
Mis-alignment	6%
Beam-gas & pile-up	1%
Particle composition	2%
Diffractive cross-sections	4%
Total:	**8%**

ATLAS Collaboration, *Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics*, CERN-OPEN-2008-020, Geneva, 2008, to appear.