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PRAGUE

Faculty of Nuclear Sciences and Physical
Engineering

Department of Physics



Research task

**Measurement of underlying event properties using
charged particles in 13 TeV proton-proton collisions
with the ATLAS experiment**

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1. Seznámení se s korekční metodou HBOM a její implementace
2. Opravit rozdělení citlivá na underlying event o efekty detektoru
3. Výpočet systematických a statistických chyb pro měřená rozdělení

Součástí zadání výzkumného úkolu je jeho uložení na webové stránky katedry fyziky.

Literatura:

[1] ATLAS Collaboration, Phys. Rev. D 83 (2011) 112001, arXiv:1012.0791 [hep-ex].

[2] J. W. Monk and C. Oropeza-Barrera, The HBOM Method for Unfolding Detector Effects, Nucl. Instrum. Meth. A701 (2013) 17, arXiv: 1111.4896 [hep-ex].

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Title:

Measurement of underlying event properties using charged particles in 13 TeV proton-proton collisions with the ATLAS experiment

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Abstract: In order to push the high energy frontier of particle physics, the Large Hadron Collider has recently undergone a challenging upgrade to collide protons with two times higher energy than before. New analyses are being carried out by physicists all over the world to measure particles of interests representing building blocks of Standard Model such as W or Higgs bosons, using data at the new collision energy. The environment in which these particles are created tends to be rather busy thanks to all sorts of underlying phenomena. How is this environment, arising from fascinating behavior of proton inner structure, behaving at 13TeV is a tempting and important study to be performed.

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Chapter 1

Introduction

Protons are interesting particles to collide mainly for their inner structure. Constituents of protons are quarks and gluons which are in general termed partons because each one of these partons carry part of proton momentum. Therefore, collision of protons at the LHC, where the energy is high enough, can be viewed as interactions between partons inside protons rather than interaction of protons as the whole.

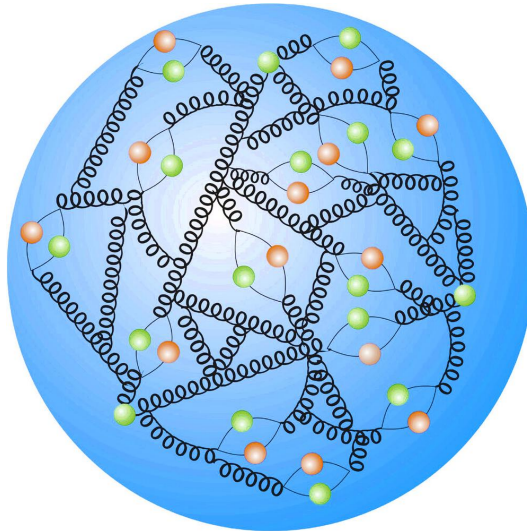


Fig. 1.1: Idea of inner structure of proton. Red balls, green balls and strings representing quarks, antiquarks and gluons respectively [1].

Interaction between partons can be classified as either hard or soft depending on how much momentum was transferred¹. To create heavy particles such as W or Higgs bosons a lot of momentum has to be transferred. Except for this hard process between pair of partons it is also possible for multiple pairs to interact (multi-parton interaction MPI) with each other giving rise to new particles. As partons carry color charge they can radiate another color charged particles which can further radiate particles and so on to eventually form a cascade. Whether the radiation takes place before or after the collision it is termed initial or final state radiation (ISR/FSR). Together with leftover partons from collided proton (beam and beam remnants - BBR) MPI, ISR and FSR represent additional activity, collectively

¹When one particle "scatters" off other particle it changes its momentum. The difference between the initial momentum of impacting particle and its momentum after scattering is the momentum transfer.

named underlying event (UE), in the collision environment which can negatively contaminate physics measurement.

Unfortunately the UE can not be subtracted from each event. However, it is possible to study its contribution by introducing space regions and several observables sensitive to UE in this regions. Aim of this thesis is to study these observables constructed from primary charged particles. These particles are coming either from collision and have mean life time $\tau_{prim} \geq 0.3 \cdot 10^{-10}$ s or from decays of particles with $\tau \leq \tau_{prim}$. Strange baryons are excluded from measurement due to their dependence on generator model.

UE contribution to events can not be calculated as it consists of both hard and soft interaction, where perturbation theory can be applied only for the hard part. Different approach is used in a form of phenomenological models implemented in Monte Carlo generators. These models have several parameters which needs to be tuned to experimental data.

The text is structured as follows. Firstly plane regions are defined followed by list of all observables and brief mention about detector, trigger and used MC generators in the rest of the Chapter 1. Chapter 2 is focused on analysis selection requirement. Chapter 3 describes reconstruction efficiencies together with the amount of contributions from non-primary particles and also strange baryons which are removed from analysis due to their high dependence on MC modelling. Chapter 4 introduces correction procedure, namely weighting and hit backspace once more method, used to obtain all observables on particle level. Systematic uncertainties are summerized in Chapter 5 followed by results in Chapter 6. Conclusion is provided in final Chapter 7.

1.1 Plane regions

This analysis use the same approach to study UE as in ATLAS studies at center of mass energies 900GeV and 7 TeV [2] by defining $\eta - \phi$ space regions². In each event particle with the highest transverse momentum (leading particle) divide the plane perpendicular to the beampipe by difference in azimuthal angle $|\Delta\phi|$ of particle from leading particle into 3 main regions.

- Toward region $|\Delta\phi| < \pi/3$
- Transverse region $\pi/3 < |\Delta\phi| < 2\pi/3$
- Away region $2\pi/3 < |\Delta\phi|$

As can be seen from the Fig 1.2 by definition the toward and away regions are contributed from the hardest scattering event leaving the transverse region occupied mainly by UE. Both transverse regions can be also studied separately. As suggested in [11] one of the transverse region could be more active (transverse max) in the case of three jet situation and contain MPI with FSR whereas the other (transverse min) mainly MPI. Subtraction of these two transverse region (transverse diff) could provide information about activity solely from radiation.

1.2 Observables

All measured observables on particle and detector levels are in Tab. 1.1. On detector level these observables are constructed from selected tracks³(more about selection in section 2). Charged particle density is defined as number of charged particles in a given region divided by $\eta\phi$ area. The same applies for sum of p_T of all particles in the region. These two observables are plotted with respect to the transverse momentum of the leading particle p_T^{lead} and also with respect to the difference in azimuthal angles $|\Delta\phi|$. Last observable is mean particle transverse momentum which is constructed on event-by-event basis and plotted against number of particles n_{ch} and also p_T^{lead} .

²Another UE studies were performed for example by CMS at 7 TeV [3], CMS at 13 TeV [4] and CDF at 1.8 TeV [5] and 1.96 TeV [6].

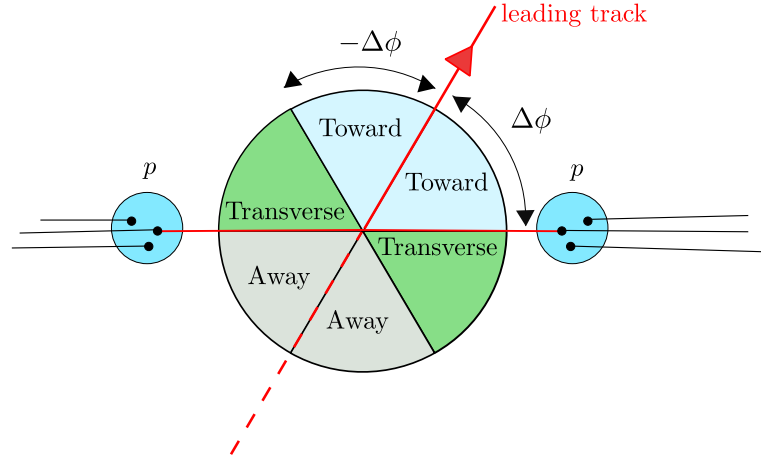


Fig. 1.2: Introduction of toward, transverse and away regions defined using leading track and its difference in azimuthal angle compared to other tracks $\Delta\phi$.

	$\langle d^2 N_{ch} / d\eta d\phi \rangle$	$\langle d^2 \Sigma p_T / d\eta d\phi \rangle$	$\langle mean p_T \rangle$
Particle level	Mean number of stable charged particles per unit $\eta\phi$	Mean scalar p_T sum of stable charged particles per unit $\eta\phi$	average p_T of stable charges particles
Detector level	Mean number of selected tracks per unit $\eta\phi$	Mean scalar p_T sum of selected tracks per unit $\eta\phi$	average p_T of selected tracks

Tab. 1.1: Observables on detector and particle level.

1.3 ID and Trigger

The analysis is performed with ATLAS which is one of the main four detectors at the LHC. The most important part of ATLAS for this measurement is inner detector (ID) which consists of newly installed insertable beam layer (IBL), pixel detectors, semiconductor tracker (SCT) and transition radiation tracker (TRT) situated respectively from the beampipe [7]. As particles propagate from collision, they leave signals in these layers of the ID. Paths of particles are then reconstructed from these signals. The ID is placed inside large solenoid magnet. If the particle has an electric charge, magnetic field will curve its trajectory from which p_T could be calculated.

Trigger used for this particular analysis is minimum bias trigger scintillator (MBTS). Minimum bias (MB) measurement is in close relation with UE measurement due to soft events (coming mainly from non diffractive collisions) which contribute to both of them. MBTS acceptance in Run II is for the inner ring $2.76 < |\eta| < 3.86$ and for the outer ring $2.08 < |\eta| < 2.76$.

1.4 MC generators

ATLAS is fully simulated by generators Pythia8 [8], Herwig++ [9] Epos [10]. These are used in reconstruction study (deriving efficiencies, correction procedure). Comparison of generators and data is in Chapter 6.

³As particle flies through detector, it leaves its track - signals in layers of detector- the path of the particle is reconstructed from these signals . Therefore, particle on detector level is referred as track.

Chapter 2

Selection

The experimental data used for this analysis are from the LHC at 13 TeV. In particular run 267358, 267359, 267360, 267366, 267367, 267385 and 267599 with total integrated luminosity $1618.4 \mu b^{-1}$. More informations about individual pile up, luminosity or cut flow in each run are presented in Tab. 2.1

Requirement on passing event and track selection was necessary to reduce contribution from pile up, cosmic radiation and other background effects. Effects of following selections on MC and data are in Tab 2.2 and 2.3.

1. Event selection

- Good run list applied (pass of events with good luminosity).
- Hit on either side of Minimum bias trigger scintillator MBTS (called , technically L1_MBTS_1) to fire L1 trigger, this trigger is passed through the HLT and the event is always recorded.
- Presence of a primary vertex.
- Not contain a second vertex with four or more tracks (in order to remove events with more than one interaction per beam crossing).
- at least one good track in the event with a $p_T > 1 \text{ GeV}$ (To take events with sufficient hard scattering).

2. Track selection

- $p_T > 500 \text{ MeV}$ and $|\eta| < 2.5$.
- At least 1 pixel hit.
- If a hit is expected in IBL, then one is required. The active area coverage of the IBL layer is more than 99%. If a track passes through an inactive IBL module, then a hit is required in the next layer if one is expected.
- At least 6 SCT hits for tracks with a transverse momentum above 500 MeV and $|\eta| < 2.5$. If a track passes through an inactive layer, it is counted as a hit. This makes the selection less sensitive to differences in the number of dead module in data and simulation.
- The transverse impact parameter d_0 calculated with respect to the LHC beam line is required to be less than 1.5mm ($|d_0| < 1.5 \text{ mm}$).
- The longitudinal impact parameter z_0 is calculated with respect to the primary vertex. It is required that the distance between the primary vertex and the track at the point where d_0 is measured multiplied by $\sin(\theta)$ is $|z_0| \sin(\theta) < 1.5 \text{ mm}$.
- If the track p_T exceeds 10 GeV, then the probability of track χ^2 must be > 0.01 in order to suppress mismeasured tracks.

Run	All	GRL	Trigger	Vtx	No PU	$p_T^{lead} > 1\text{GeV}$	L [μb^{-1}]	μ
267358	8665704	7272839	4545977	3775181	3769062	2725118	62.0	0.3%
267359	12292491	10504126	6309244	5387438	5368881	3880743	89.1	0.7%
267360	12558421	8309283	5178427	4487985	4441881	3211685	74.1	3%
267367	17111228	16469031	8438677	7237217	7153981	5172711	120.8	3%
267385	71217242	71095463	48021030	41001542	40596031	29358370	690.4	3%
267599	105611891	105610048	41221102	34963098	34668626	25063706	582.3	1%-3%
Total	227456977	219260790	113714457	96852461	95998462	69412333	1618.4	-

Tab. 2.1: Number of events in used runs after selection. Each column has also applied selections from all previous left columns. "All" represents number of events before any selection. Numbers in third column are after requirement on good run list. Trigger selection uses HLT_noalg_L1_MBTS.1. Number of events after requirement on primary vertex, no pile up and cut on transverse momentum of leading track are presented as well. Last two columns represent integrated luminosity and fraction of events with pile up in individual runs.

	Simulation Events	% passing	Data Events	% passing
Before cuts	10000000		10855221	
After primary vertex and pile up suppression	9946359	99.46%	9137943	84.18%
After requiring 1 track above $p_T > 500$ MeV	9543913	95.44%	8863268	81.64%
After requiring 1 track above $p_T > 1$ GeV	7024167	70.24%	6605861	60.85 %
After requiring 1 track above $p_T > 3$ GeV	1632390	16.32%	1272417	11.72%
After requiring 1 track above $p_T > 5$ GeV	350672	3.51%	243966	2.24%
After requiring 1 track above $p_T > 10$ GeV	28311	0.28%	17913	0.16%

Tab. 2.2: Number of events in data (only runs 267358-9 to show only % effect of cuts) and simulation (Pythia8 A2 ND) before and after applying all the event selection criteria. For data the first row displays the data after GRL and trigger requirement which is not applicable to MC which has first row without any cuts.

	Simulation Tracks	% passing	Data Tracks	% passing
All Tracks	383347948		348184417	
$p_T > 500$ MeV	176287238	45.98%	156564908	44.96%
$ \eta < 2.5$	172502488	44.99%	153371861	44.04%
Innermost hit requirement	160072434	41.75%	142237089	40.85%
Pixel Hit > 1	138319599	36.08%	121358755	34.85%
SCT Hits > 6	127912396	33.36%	112042699	32.17%
$ d_0 < 1.5$ mm	123473650	32.20%	107548913	30.88%
$z \sin \theta < 1.5$ mm	122392824	31.92%	106342692	30.54%
χ^2 probability	122391969	31.92%	106342115	30.54%

Tab. 2.3: Number of tracks in data (only runs 267358-9 to show only % effect of cuts) and simulation (Pythia8 A2 ND) after event selection (without 1 GeV cut) before and after applying all the track selection criteria.

Chapter 3

Reconstruction efficiencies

The fact that the detector and other used tools are not 100% efficient has to be accounted for. Knowledge of these efficiencies is then used to estimate correction of observables to particle level. Trigger, vertex and tracking efficiency were studied by minimum bias group [13] in order to correct distributions to particle level.

For this particular analysis Minimum bias trigger scintillator MBTS were used. This trigger is situated on both sides of ATLAS detector and for event to be accounted for the trigger has to fire at least on either sides of MBTS. The trigger efficiency ϵ_{trk} is taken as the ratio of MBTS (full name:EF_noalg_L1_MBTS_1) triggered events to events in control sample (triggered by HLT_mb_sptrk_1). Events selected at L1 are filtered by requirement to have at least two pixel hits with a time over threshold of at least 20 bunch crossings and at least three SCT hits. Additional condition is to reconstruct at least one track with $p_T > 200$ MeV and its longitudinal impact parameter with respect to the center of the ATLAS coordinate system less than 40 mm.

The trigger efficiency parameterized as a function of selected tracks n_{sel}^{BL} is depicted in Fig. 3.1. These selected tracks are different from selected tracks in 2 due to loosen requirement on $z_0^{BL} < 1000$ mm which is applied in order to avoid biasing the vertex position along the beam line¹. The trigger efficiency is above 98 % and even reaches 100 % for selected tracks $n_{sel}^{BL} > 6$.

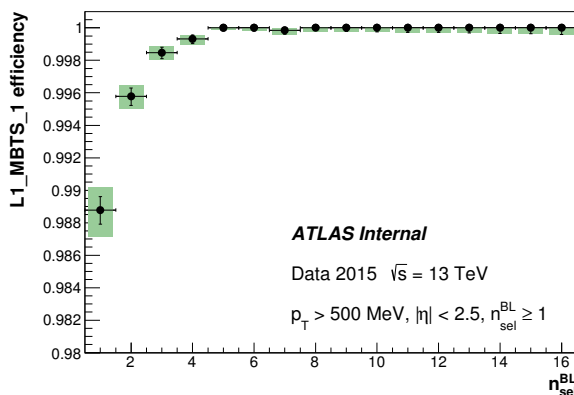


Fig. 3.1: Trigger efficiency plotted as a function of the number of selected tracks n_{sel}^{BL} . A reconstructed vertex is not required. The statistical errors are shown as black lines, the total errors as green shaded areas [13].

¹Beam line also referred as beam spot is a mean value of primary vertex (vertex with the highest sum of tracks p_T in an event) coordinates x,y,z in run.

3.1 Vertex efficiency

Tracks which reconstruct vertex need to pass following criteria

- $p_T > 100$ MeV
- At least 1 Pixel hit
- At least 4 SCT hits
- At least 6 Silicon hits
- Transverse and longitudinal impact parameters as well as their uncertainties calculated with respect to the beam line (BL): $|d_0^{BL}| < 4$ mm, $|z_0^{BL}| < 1000$ mm, $\sigma_{d_0^{BL}} < 5$ mm, and $\sigma_{z_0^{BL}} < 10$ mm

Vertex efficiency ϵ_{vtx} is taken as a ratio of MBTS triggered events with reconstructed vertex to all MBTS triggered events after subtraction of non-collision background. Dependence of ϵ_{vtx} on η and n_{sel}^{BL} (with the same definition as for ϵ_{trig}) is depicted in Fig. 3.2 where for η case it is only for events with $n_{sel}^{BL} = 1$. If the number of selected track $n_{sel}^{BL} > 2$ then the efficiency of vertex reconstruction ϵ_{vtx} is 100 %. The $p_T^{lead} > 1$ GeV requirement in this analysis shift the n_{sel}^{BL} into higher values Fig. 3.3. Therefore, for most of the events ϵ_{trig} and ϵ_{vtx} are equals to 1 and only for small portion of events (≈ 2 %) are the values different from 1.

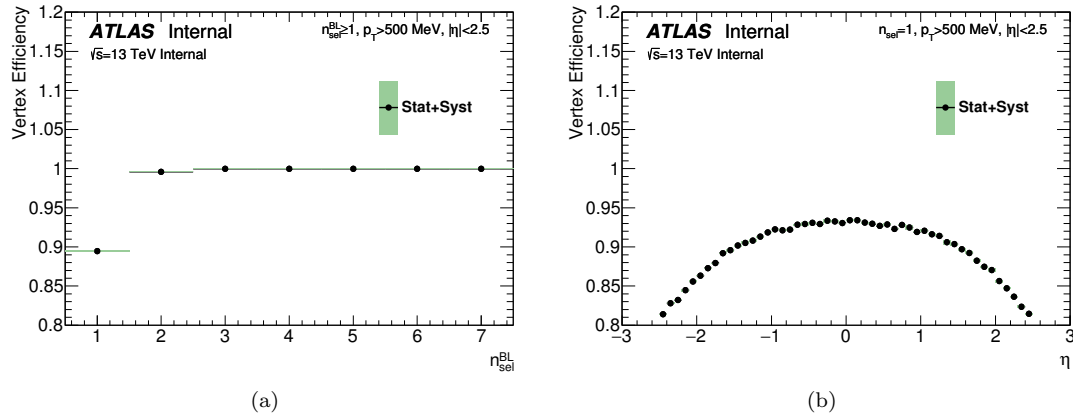


Fig. 3.2: Data driven vertex efficiency plotted as a function of selected tracks n_{sel}^{BL} (a) and as a function of η (b) where the ϵ_{vtx} is only for $n_{sel}^{BL} = 1$. The statistical errors are shown as black lines, the total errors as green shaded areas. The systematic errors are from the subtraction of the non-collision beam background [13].

3.2 Tracking efficiency

The efficiency to reconstruct a track ϵ_{trk} is taken from a simulation where truth primary particles are matched to tracks. ϵ_{trk} is parameterized by p_T and η Fig. 3.4. As can be seen from figures tracks are reconstructed with 85 % probability in central rapidity regions. This efficiency decreases towards forward region reaching $\approx 67\%$ for $\eta = 2.5$. Dependence of ϵ_{trk} is rising from ≈ 87.5 % at 500 MeV to $\approx 92\%$ at 100 GeV.

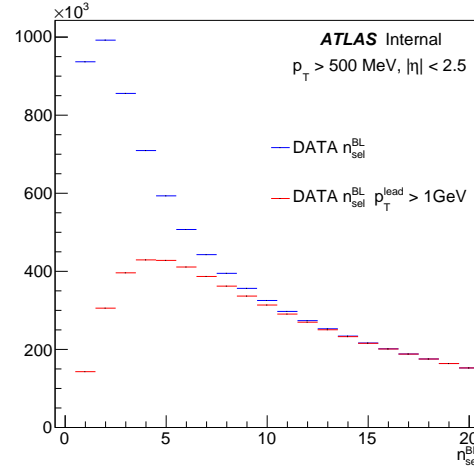


Fig. 3.3: The multiplicity distribution of selected tracks n_{sel}^{BL} , with requirement on leading track above $p_T^{lead} > 1$ GeV (**red**) and without (**blue**).

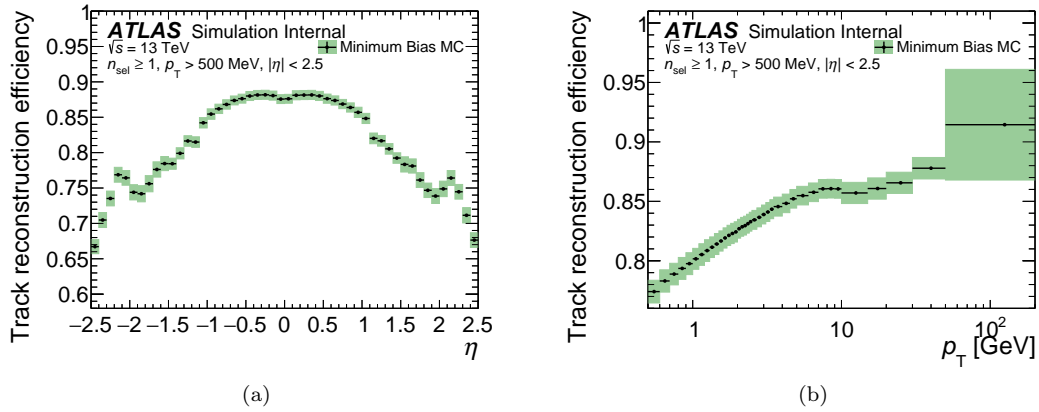


Fig. 3.4: Tracking efficiency plotted as a function of η which is integrated over p_T (**a**) and p_T which is on the other side integrated over η (**b**). The total errors as green shaded areas [13].

3.2.1 Fraction of non-primary tracks

The rate of particles which are non-primary is used in determining the final corrections. These particles come from hadronic interaction of particles with material, decay of particles with non-zero strangeness and also from photon conversion. The rate of non-primary particles was obtained by using side-band fits of the MC d_0 and z_0 distributions to the data. The resulting fraction of non-primaries in data is 0.0228 ± 0.005 . More information about the procedure in [13].

3.2.2 Fraction of strange baryons

Contribution of strange baryons is taken as a background due to their bad reconstruction efficiency and thus is removed. Their modeling is significantly MC generator dependent. Epos was chosen to estimate this background for its best description of strange baryons in ALICE experiment measurements. Measured fraction of strange baryons are presented in Fig 3.5

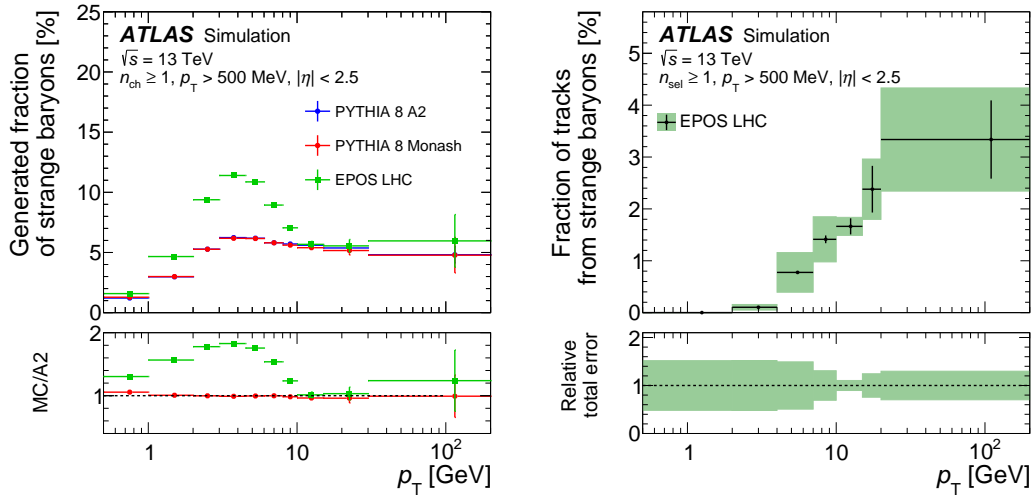


Fig. 3.5: **Left:** Comparison of generated fractions of strange baryons in MC Epos, Pythia8 A2 and Pythia8 Monash. **Right:** Predicted fraction of tracks due to strange baryons in Epos generator [13].

Chapter 4

Correction

To obtain observables on particle level, they have to be corrected. In this particular analysis two step correction is used. First step is the correction due detector effects. These effects were discussed in previous chapter 3 and include inefficiencies of trigger, vertex and track reconstruction. The observables are multiplied by event and track weights which are constructed from efficiencies in question. The requirement of second correction is due to introduction of regions more or less sensitive to UE. If the leading track is not reconstructed the next track with the highest momentum (subleading) takes its place. However as the subleading track might have different ϕ the topology of event is changed and some activity for example in transverse region will contribute to other regions or vice versa. The hit backspace once more (HBOM) method was used to account for this reorientation effect. Application of weights will be discussed at first followed by description of HBOM method.

4.1 Event and track weights

Event weight is constructed as one over efficiencies of trigger and vertex reconstruction and is applied on event-by-event basis.

$$w_{ev} = \frac{1}{\epsilon_{trig}(n_{sel}^{BL})} \frac{1}{\epsilon_{vtx}(n_{sel}^{BL}, \eta)} \quad (4.1)$$

The multiplicity of selected tracks with no impact parameter cuts n_{sel}^{BL} is for $p_T^{lead} > 1\text{GeV}$ high enough (Fig. 3.3) making the event weight close to 1 for most of the events. The η dependence is taken into consider only for the case with $n_{sel}^{BL} = 1$ hence η corresponds to pseudorapidity of leading track.

Track weight as name suggest includes tracking efficiency and also subtraction of fractions with significant contribution.

$$w_{trk} = \frac{1}{\epsilon_{trk}(p_T, \eta)} \cdot (1 - f_{okr}(p_T, \eta) - f_{nonpr}(p_T, \eta) - f_{sb}(p_T)) \quad (4.2)$$

Due to resolution of detector tracks outside the kinematic region (p_T, η) might migrate inside the region. Fraction of these tracks f_{okr} was estimated using Monte carlo method (effect of a few %). f_{nonpr} and f_{sb} corresponds to fraction of non-primary particles and fraction of strange baryons respectively which were discussed in 3.2.1 and 3.2.2.

Track weight is applied to discussed observables as follows

- $\Sigma p_T \rightarrow \Sigma_i p_T^i w_{ev} w_{trk}^i$
- $N_{ch} \rightarrow \Sigma_i w_{ev} w_{trk}^i$
- $\text{mean } p_T = \Sigma_i p_T^i w_{ev} w_{trk}^i / \Sigma_i w_{ev} w_{trk}^i$

4.2 HBOM

Unfortunately applying only track-event weight corrections is not sufficient. To account for other effects such as mentioned reorientation the HBOM method [12] was performed. This method is based on randomly losing tracks from events according to their track reconstruction efficiency in several iterations. The result is then extrapolation to one step before the 0-th iteration¹. This method is then performed in each bin for all observables. By default the number of HBOM iteration is 6 + 0-th (see left Fig. 4.1). Each iteration starts with a different seed to avoid correlation between the iterations. In order to avoid tracking efficiency effects between iteration (meaning to keep focus only on correcting reorientation and other effects) additional reweighting of track weight by one over its tracking efficiency is performed in each iteration if the track survives.

The uncertainty of the method is taken as 68 % confidence interval around mean value of generated toy experimental results in -1 (see right Fig. 4.1). For each toy, each iteration is smeared according to gaussian distribution with mean as the initial value of observable for given iteration and statistic uncertainty as σ .

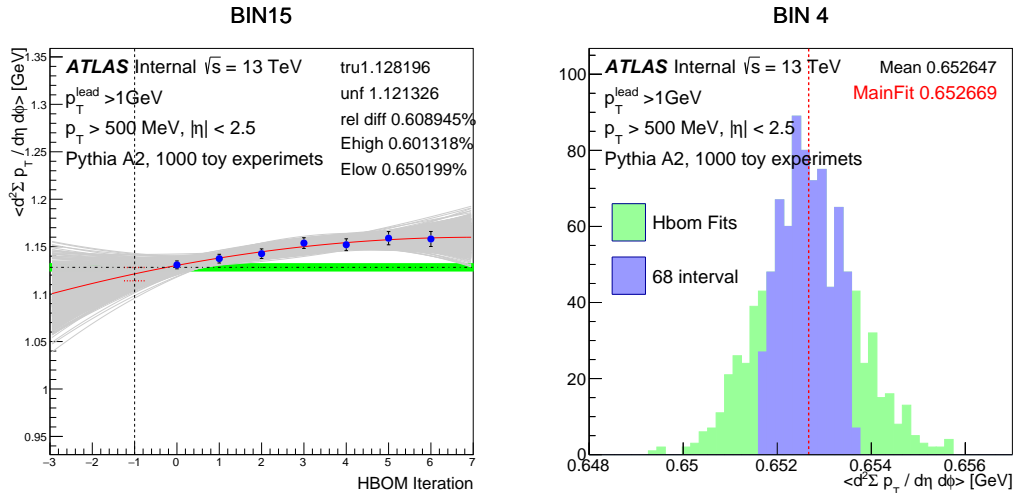


Fig. 4.1: **Left:** Result of extrapolation to -1 using 6 iteration and parameterization by polynomial of second degree in one particular bin for Σp_T wrt p_T^{lead} distribution. Red line represents the main fit, gray lines are 1000 toy experiments fits. For comparison tru distribution is added as dotted horizontal line with green band as statistical uncertainty. **Right:** Distribution of toy experiments values in -1. Red dotted vertical line represents main fit from initial values which is almost the mean of toys in -1.

4.2.1 Effect of HBOM correction

To test whether the observables better match particle level with or without HBOM correction, all of them were studied with MC generator Pythia8 A2 ND. In all following figures for this section there is a comparison between truth level (black line), track-event corrected level (green line) and hbom atop track-event correction (red line). Each figure is also appended by the ratio plot below which is done with respect to the truth level. The following figures is not complete collection of all observables rather just a few examples to demonstrate the effect of HBOM correction. For more see upcoming note [15]. All corrections on Σp_T and N_{ch} distributions with respect to p_T^{lead} show similar trend Fig. 4.2. The HBOM is not sufficient in first 2-3 bins which is the region with the highest probability to loose tracks.

¹The 0-th iteration is in this case defined as only track-event weight corrected observables

Non-closure between hbom and truth spectrum in these bins is within 1 % which is still better than closure between track-event corrected and truth spectrum. The rest of the bins are corrected to particle level within the statistic uncertainty except for last bins for some regions where low statistics resulted in a low quality fit.

The difference between truth track-event corrected spectrum for mean p_T distributions plotted as a

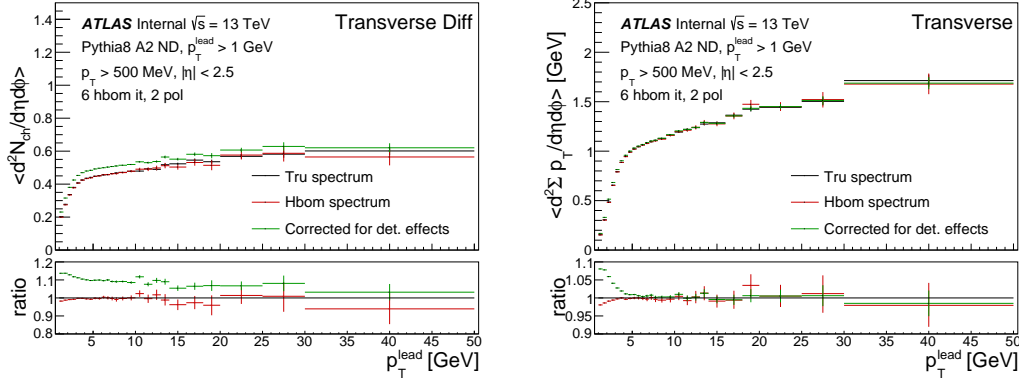


Fig. 4.2: Comparison of truth (black), track-event corrected (green) and hbom (red) spectrums for charged particle density in transverse diff region on the left and sum of p_T in the transverse region on the right both with respect to p_T^{lead} .

function of p_T is only within a 2% however the HBOM helps to reduce even this little non-closure 4.3. HBOM also appears to be significant help for mean p_T distribution with respect to n_{ch} where its application brings very good agreement with the truth level except last bins with low statistics.

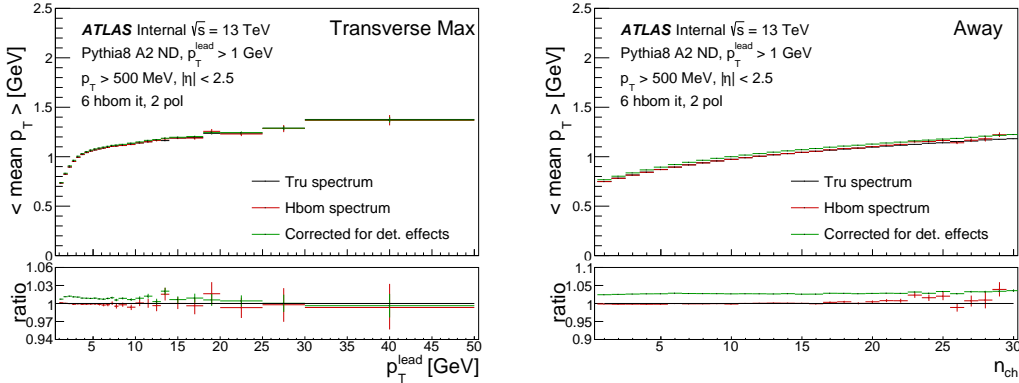


Fig. 4.3: Comparison of truth (black), track-event corrected (green) and hbom (red) spectrums for mean p_T with respect to p_T^{lead} in transverse max region on the left and mean p_T with respect to N_{ch} in the away region on the right.

For distributions Σp_T and N_{ch} plotted as a function of $|\Delta\phi|$ is non-closure between HBOM and truth within 1%. As these two distributions are normalized to number of events taken from distribution of p_T^{lead} , HBOM was performed on unnormalized spectrum and also on p_T^{lead} distribution separately and only then were both normalized.

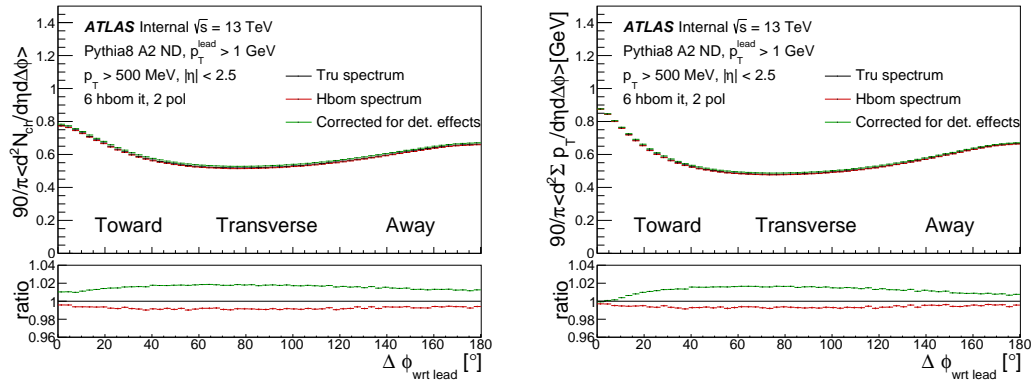


Fig. 4.4: Comparison of truth (black), track-event corrected (green) and hbom (red) spectrums for charged particle density on the left and sum of p_T on the right both with respect to $|\Delta\phi|$.

Chapter 5

Systematic uncertainties

The total systematic uncertainty consists of material modelling, non-primary contribution, HBOM non-closure and difference in number of HBOM iteration.

Uncertainties from bad material modeling and contribution of non-primary particles are propagated by modification of track weights.

As non-closure still persists for some distributions, this difference between truth and hbom level from Pythia8 A2 ND is taken as a correction and also as a systematic uncertainty. The choice to use one certain MC is justified by the fact that HBOM method is MC independent. The non-closure correction and uncertainty is applied for distributions plotted as function of p_T^{lead} only in first bins Fig. 4.2 where it reaches maximum of 2% for most of the distributions except in transverse diff region where is the non-closure highest around 20 %. For distributions plotted as a function of $|\Delta\phi|$ Fig. 4.4 is the difference below 0.5 % for all bins. Taken uncertainties for these azimuthal distributions were smoothed. Distributions with respect to n_{ch} have manually setup non-closure band due to existence of few bins without nc correction embodied inside the multiplicity range. Except for transverse diff region where the threshold of mentioned non-closure band was setup on 1 % have all regions default 0.5% as non-closure.

The number of HBOM iteration is by default 6 with parameterization by second polynomial degree. Behavior of all observables with different default setup was studied and is also provided in the support note [15]. Some examples are in Fig. 5.1. The difference is significant in the first bins for all p_T^{lead} distributions. The same method as in previous case is applied for distributions plotted as a function of $|\Delta\phi|$. Contribution of iteration systematic uncertainty to n_{ch} distribution is included in non-closure bands mentioned above.

Examples of combinations of all used systematic uncertainties are presented in Fig. 5.2 and 5.3.

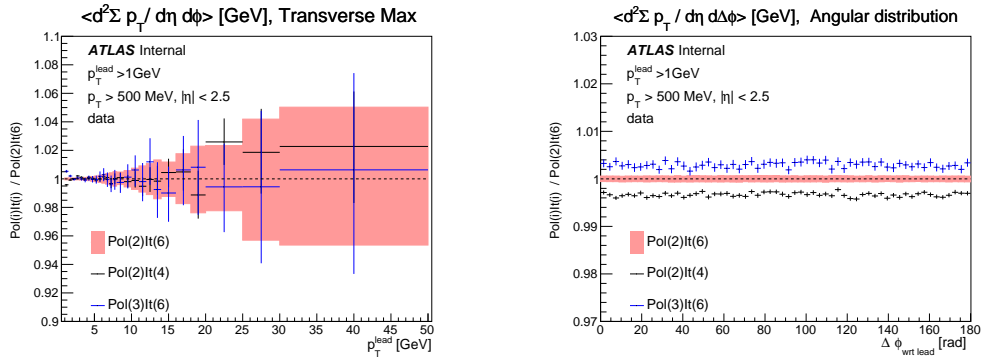


Fig. 5.1: 4 HBOM iteration with 2nd polynomial parametrization and 6 iteration with 3rd polynomial parametrization compared to default 6 iteration and 2nd polynomial parametrization. Σp_T with respect to p_T^{lead} in transverse max on the left and with respect to $|\Delta\phi|$ on the right.

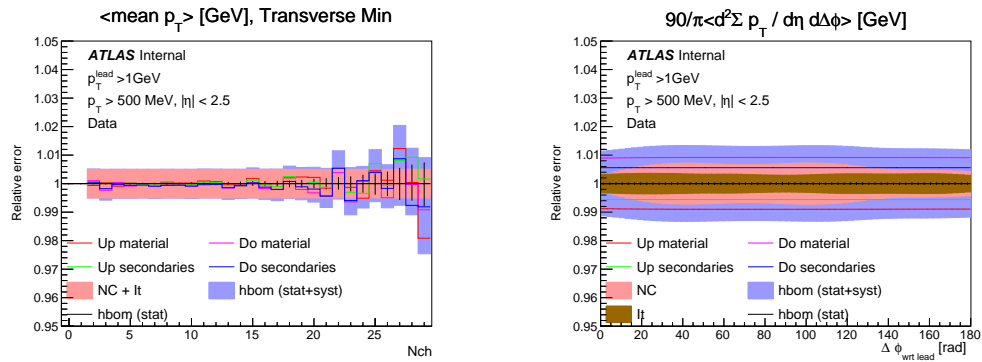


Fig. 5.2: Combination of all used systematic uncertainties for mean p_T plotted as a function of N_{ch} in transverse min region on the left, where the iteration systematic is included in the non-closure band, and Σp_T as a function of $|\Delta\phi|$ on the right.

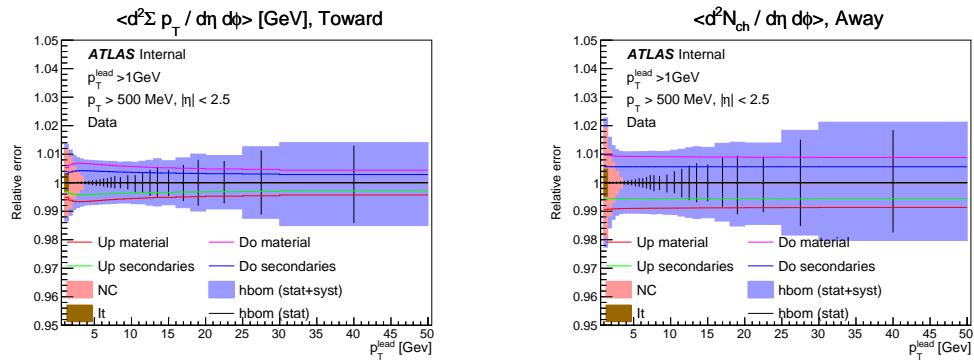


Fig. 5.3: Combination of all used systematic uncertainties for Σp_T in the toward region on the left and N_{ch} in the away region on the right both plotted as functions of p_T^{lead} .

Chapter 6

Results

The final plots are comparison of several MC generators to HBOM unfolded data. Chosen MCs are Herwig++, Herwig 7, Epos and from Pythia8 family A2, Monash and A14. All distributions are normalized to number of events and to $\eta\phi$ space region which means especially for $|\Delta\phi|$ distributions division by a conversion factor $180/2\pi$ to be able compare previous results measured in radians [14].

6.1 Σp_T and N_{ch} distributions wrt $|\Delta\phi|$

In Fig. 6.1 there are Σp_T and N_{ch} distributions plotted as a function of $|\Delta\phi|$ for $p_T^{lead} > 1, 5, 10$ GeV respectively. The toward region, which is defined up to 60° has the highest activity for both observables. However the away region is just slightly lower than toward for $p_T^{lead} > 1$ GeV which gives a hint about the topology of events. It seems that events have a pencil like structure. On the other side the transverse region seems to have constant contribution through its whole region.

None of the MCs are describing well the whole toward region neither away for $p_T^{lead} > 1$ GeV. The transverse region is better described with 5% non-closure for A2, Epos and also A14 for Σp_T . As A2 is Minimum bias tune its description for rising p_T^{lead} is worse. However this is not the case for the rest of MCs tuned to describe UE except Epos.

6.2 N_{ch} distribution wrt p_T^{lead}

Similar rising trend for charged particle density in all regions for $p_T^{lead} < 5$ GeV can be seen in Fig. 6.2. The rest of the range is however slightly different. Contributions in both toward and away regions are slowly rising with p_T^{lead} . Interesting point is that charged particle density is in the away region even higher than in the toward. An explanation was provided in 7 TeV ATLAS analysis [2]. There is less energy to redistribute among other particles in the toward regions as most of it is taken by the leading track. There is a visible plateau called underlying event pedestal in the transverse region from $p_T^{lead} > 5$ GeV meaning that the density of charged particles remains constant even with the harder scattering events. Therefore, the density of underlying event is a constant background with rising p_T^{lead} . As mentioned in the introduction the transverse min region contains contribution solely from MPI and this effect is mainly responsible for the UE pedestal which is also visible for charged particle density in this region. On the other hand transverse max is except MPI contributed also from ISR/FSR giving the density distribution slight rise in the region in question.

MCs seems to have failed to describe the data in first bins which is a "soft" region. But as p_T^{lead} rises the UE tuned MCs start to decrease the non-closure and describe the data reasonably well.

6.3 Σp_T distribution wrt p_T^{lead}

Σp_T distribution is dominant in the toward from all regions due to presence of the leading track followed by the away region Fig. 6.3. Also the transverse region exhibits slow rise in Σp_T whereas the density seemed almost constant.

Non-closure between the data and MCs is similar to the previous case with charged particle density.

6.4 Mean p_T distribution wrt p_T^{lead}

In Fig. 6.4 there are distributions of mean p_T plotted as a function of p_T^{lead} in all regions. Mean p_T is rising in all regions except the transverse min which has a visible pedestal for Σp_T and also for N_{ch} . In most of the cases are the data undershooting by MCs but the non-closure is kept within 10 % except for Epos.

6.5 Mean p_T distribution wrt N_{ch}

Steady rise in mean p_T distribution wrt N_{ch} in all regions can be seen in Fig. 6.5, the only exception is first bins of the toward region due to presence of the leading track.

MCs describe the data within 5% non-closure.

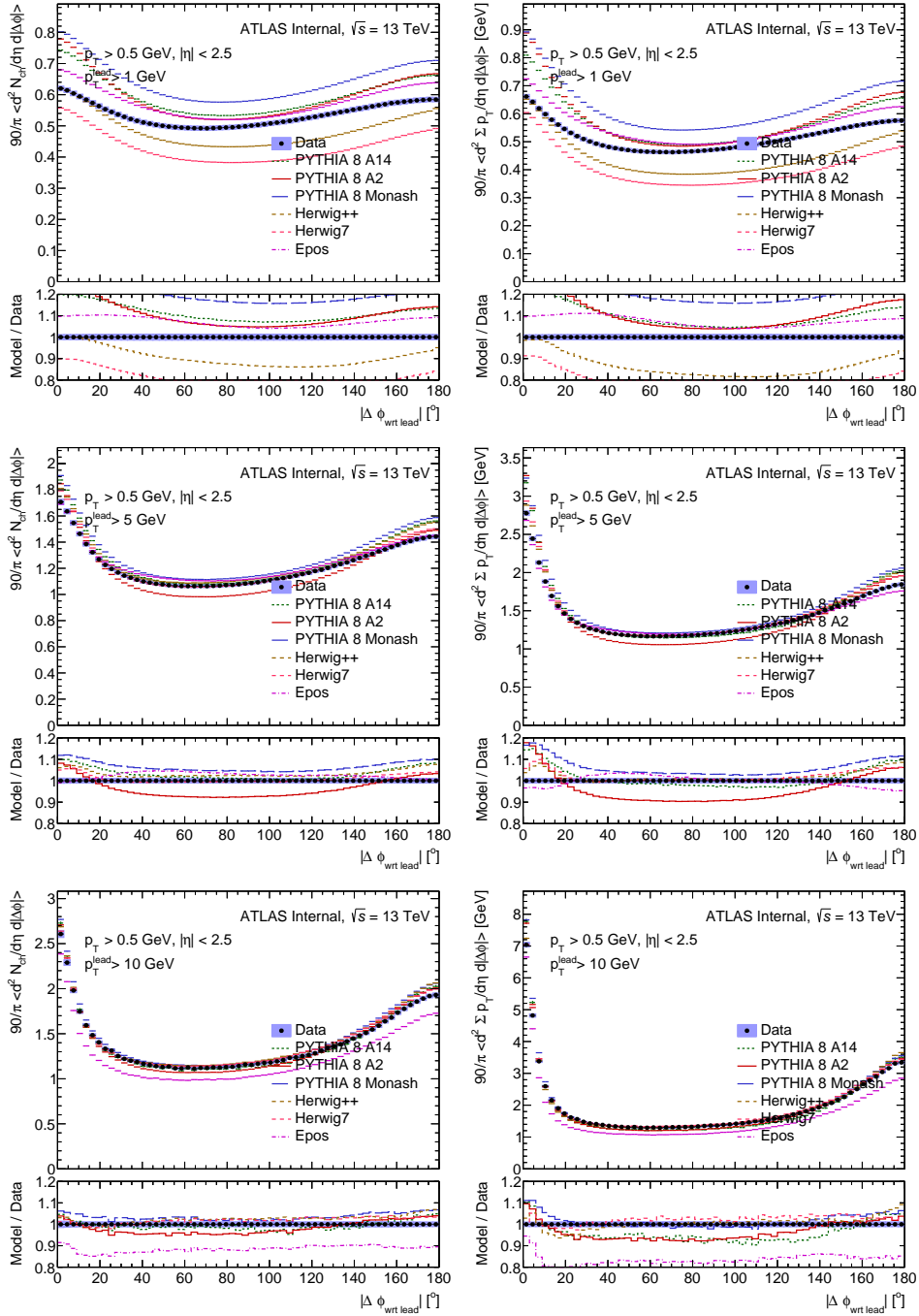


Fig. 6.1: Mean charged particle multiplicity N_{ch} on the left and Σp_T on the right with respect to $|\Delta\phi|$ measured in degrees. Rows of figures are for $p_T^{\text{lead}} > 1, 5, 10 \text{ GeV}$ respectively. Blue shaded bands represent combination of statistic and systematic uncertainties given in previous chapters.

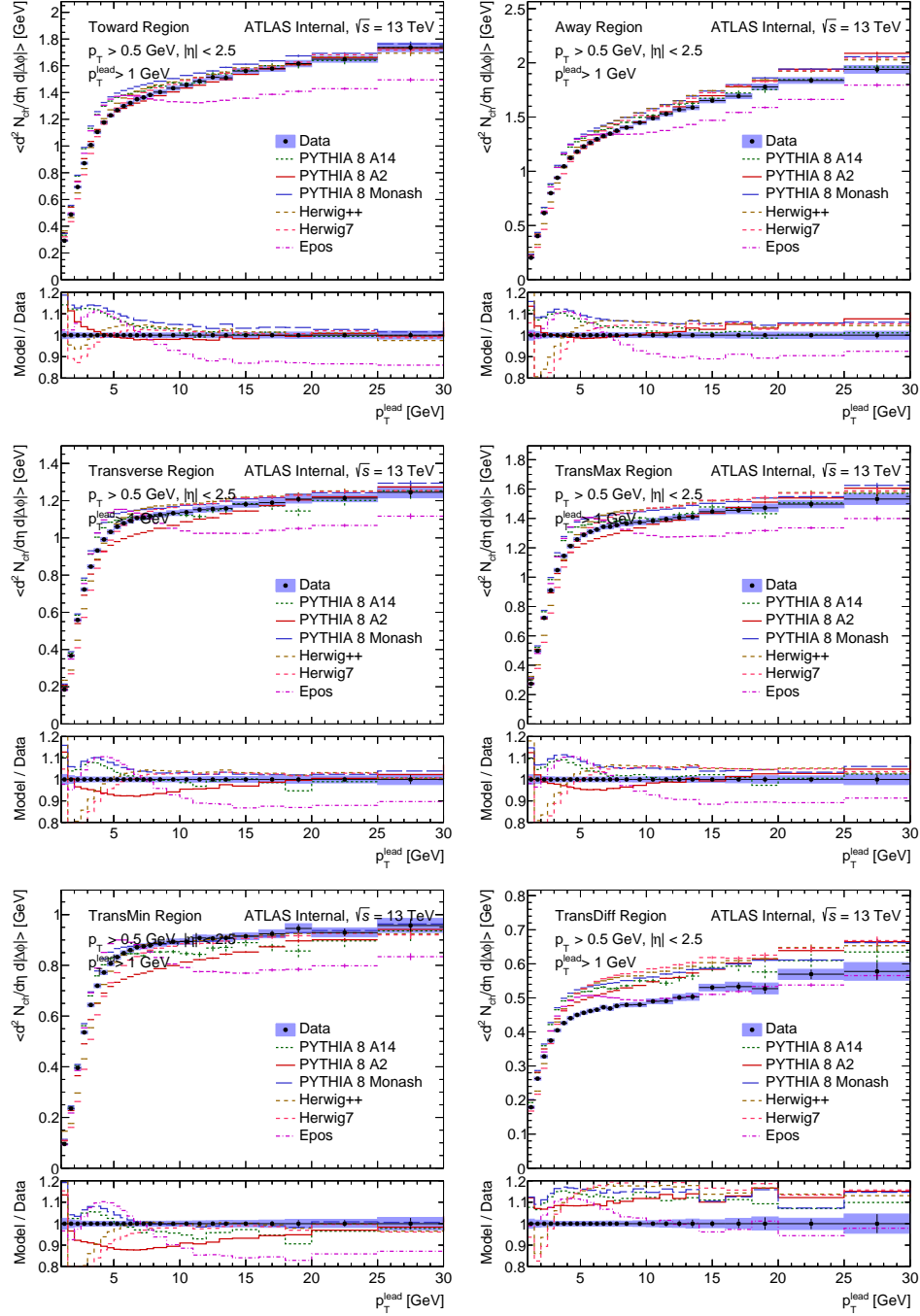


Fig. 6.2: Mean charged particle multiplicity N_{ch} plotted as a function of p_T^{lead} in all studied regions. Blue shaded bands represent combination of statistic and systematic uncertainties given in previous chapters.

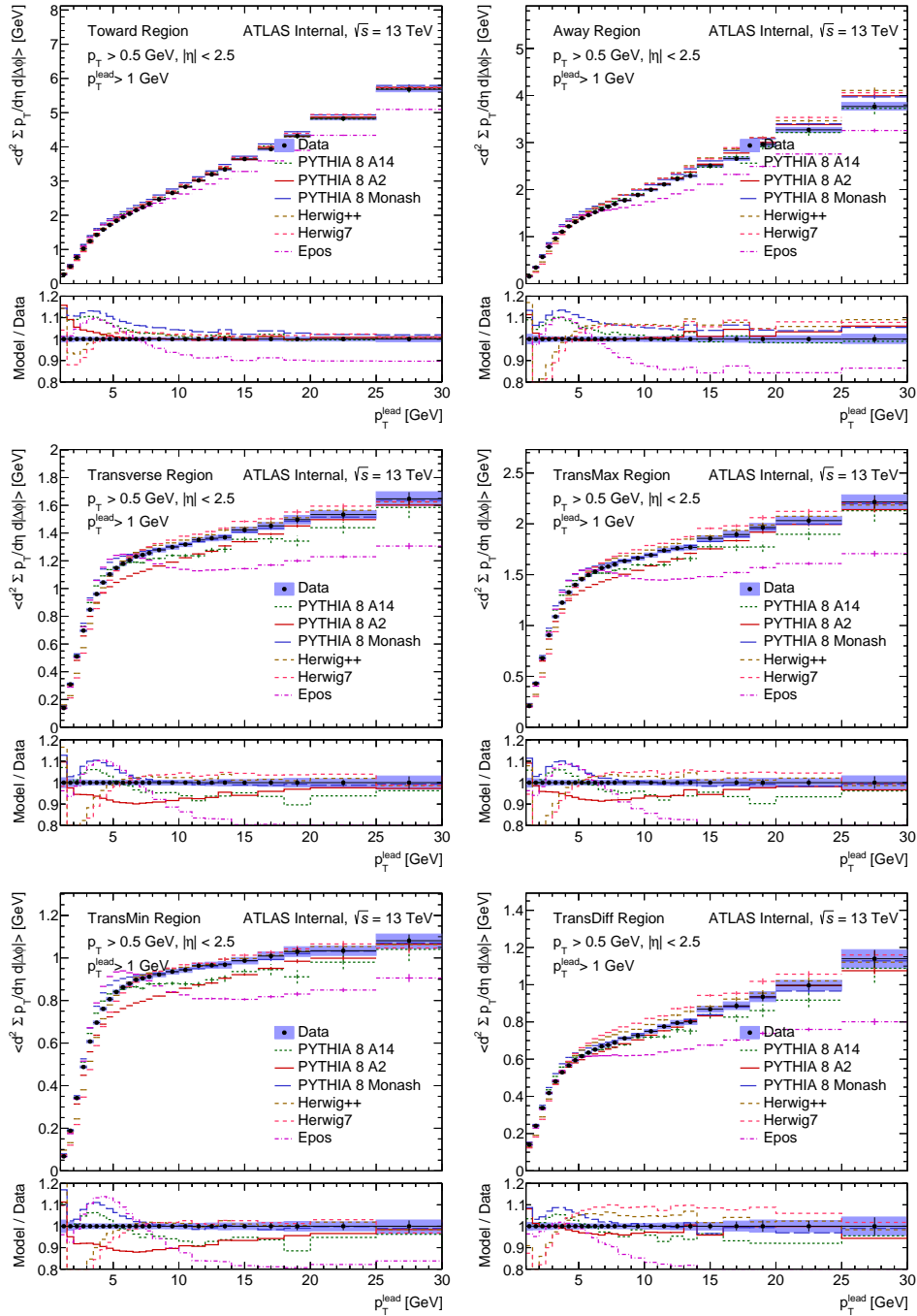


Fig. 6.3: Mean sum of transverse momentum Σp_T plotted as a function of p_T^{lead} in all studied regions. Blue shaded bands represent combination of statistic and systematic uncertainties given in previous chapters.

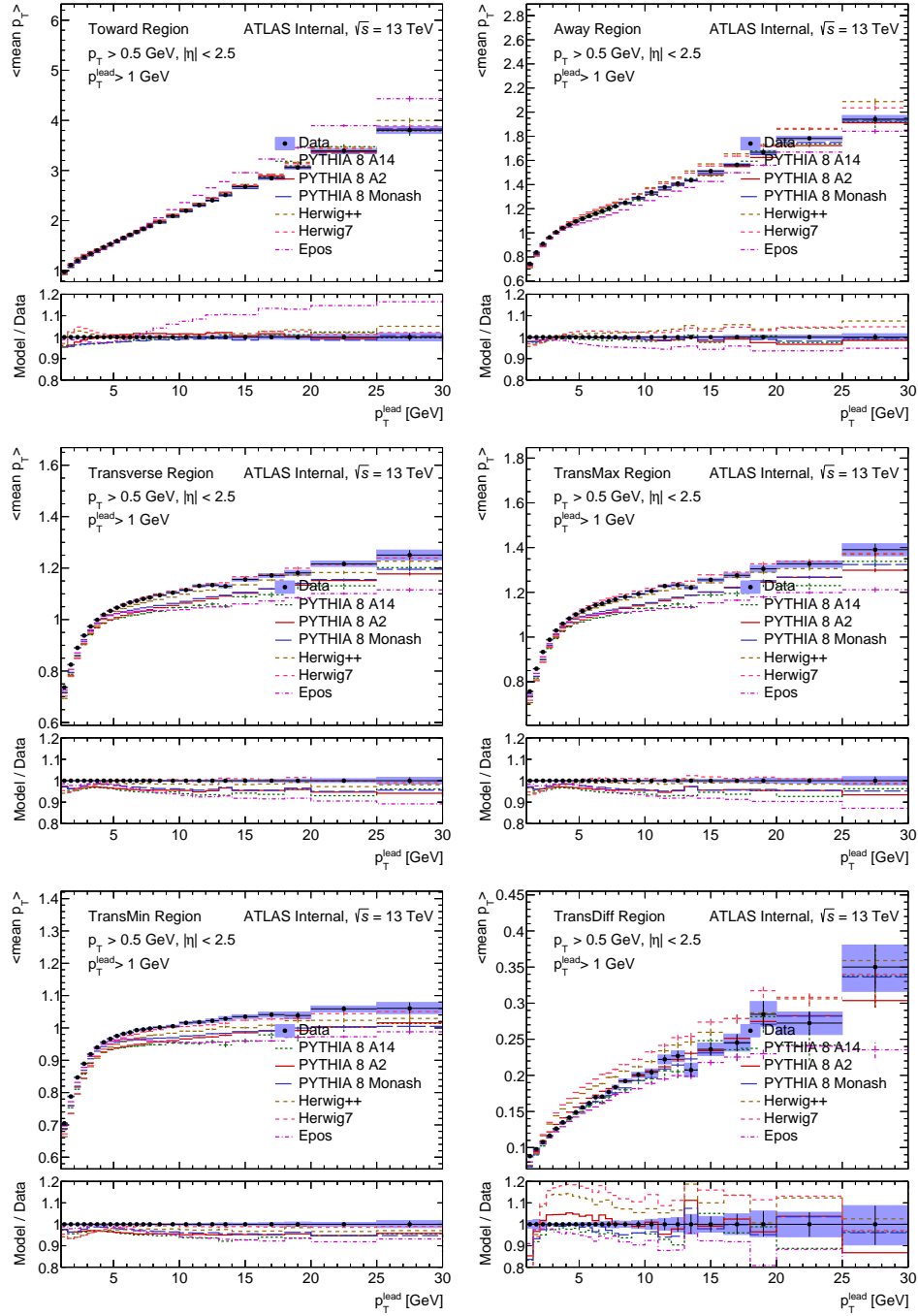


Fig. 6.4: Mean values (normalized for events) of mean of transverse momentum p_T plotted as a function of p_T^{lead} in all studied regions. Blue shaded bands represent combination of statistic and systematic uncertainties given in previous chapters.

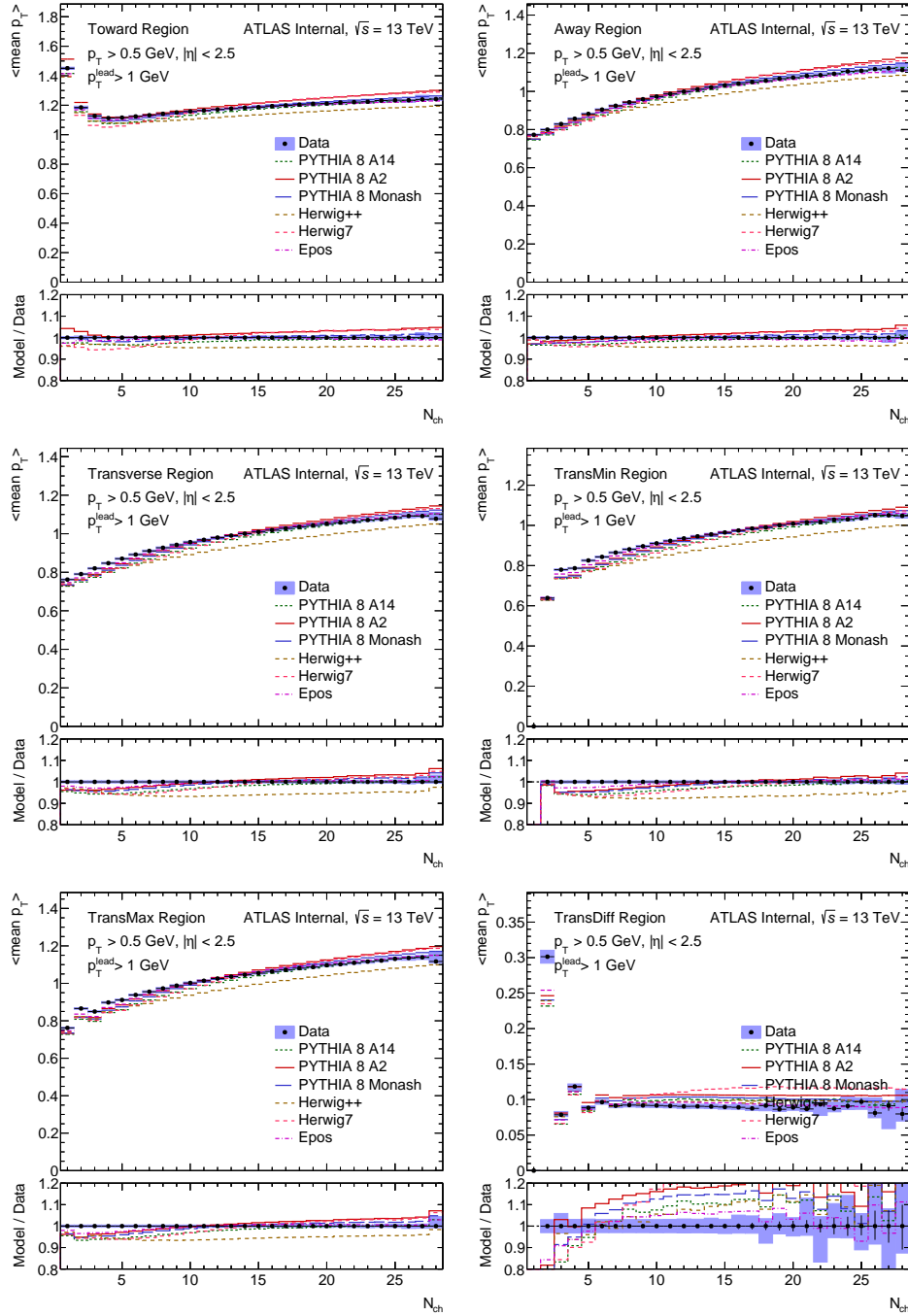


Fig. 6.5: Mean values (normalized for events) of mean of transverse momentum p_T plotted as a function of N_{ch} in all studied regions. Blue shaded bands represent combination of statistic and systematic uncertainties given in previous chapters.

Chapter 7

Summary

The behavior of underlying event was studied in 30 distributions sensitive to these effects and constructed from primary charged particles. The approach was similar as in previous analysis by defining few regions in an azimuthal plane perpendicular to the beam pipe using a track with the highest transverse momentum in an event with p_T above 1 GeV.

To obtain particle level information, observables were corrected by weights to account for trigger, vertex and track reconstruction efficiency. Additional correction called HBOM were performed as well. This correction helped to achieve more precise corrections to particle level. The data were corrected for this non-closure. Systematic uncertainties are constructed from material modeling, contribution of non primary particles, non-closure and difference between the number of HBOM iteration.

The constant behavior (UE plateau) in transverse region with rising p_T^{lead} is observed. It is even more visible in distributions calculated in transverse min region inhibited mostly by MPI than in transverse max with combination of MPI, ISR and FSR.

The observables were constructed from the low pile up early data taken by the LHC at 13 TeV and measured with ATLAS. The data were compared with several MC generators namely Herwig++, Herwig7, Epos, and from Pythia8 family A2, A14, Monash. The MCs describe the data reasonably well except for low p_T^{lead} .

The UE ATLAS measurement at 13 TeV shows rise in activity about 20% in comparison to 7 TeV ATLAS study [2].

ATLAS paper of the analysis is currently being prepared [16] with its support note [15].

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