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Low-p_T proton–proton physics at low luminosity at LHC

JEAN-PIERRE REVOL for the ALICE Collaboration
EP Division, CERN, Ch-1211 Geneva 23, Switzerland

Abstract. This review of low-p_T proton–proton physics at low luminosity at the large hadron collider (LHC) should cover all LHC experiments, but in practice, is mainly related to ALICE, for reasons which will be explained. However, the relevance to other LHC experiments is clear, as low-p_T phenomena represent an important component of the background to their high-p_T phenomena which needs to be calibrated. The ALICE collaboration will study proton–proton collisions as part of their heavy-ion programme, where most signals are relative to the proton–proton system. In addition, the ALICE detector's unique acceptance at low p_T as well as its unique particle identification capability will make it possible to carry out a program of genuine proton–proton physics complementary to those of other LHC experiments.

Keyword. Large hadron collider.

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1. Introduction

Complete understanding of the physics of colliding protons requires the study of all phenomena, including those with large cross-section. Furthermore, we must exploit completely the scientific potential of an ambitious new instrument, LHC, which is the result of an unprecedented investment in resources, inventiveness and human effort.

These phenomena with large cross-sections ranging probably between 100 mb for the total cross-section, 60 mb for the inelastic, non-diffractive cross-section, 12 mb for the diffractive cross-section and of the order of 1 mb for the bottom quark production cross-section (cf. A Kaidalov) are generally characterized by low p_T and represent the bulk of proton–proton collisions. Obviously, they should not be neglected, as the detailed properties of events in a new energy domain must be measured.

It would indeed seem very strange to limit ourselves to the study of rare phenomena, those occurring at high p_T, with probabilities four to ten orders of magnitude smaller than the bulk of the events (figure 1), which we would ignore.

Low-p_T proton–proton studies are also required for some additional specific purposes:

– benchmark in understanding heavy-ion collisions;

– calibration of an important component of the background to high-p_T signals (Higgs and SUSY searches, etc.) where they contribute both as part of the underlying events and as event pileup (20 to 30 minimum bias events should occur on average in the same beam crossing at the LHC nominal luminosity) to a superimposed noise, limiting the performance of the detector. At the start-up of LHC, when the luminosity is still relatively low for ATLAS and CMS (10^{33} cm^{-2} s^{-1}), large cross-section phenomena will be investigated. ATLAS, CMS, LHCb and ALICE will study minimum bias events. TOTEM will use special running conditions to provide the absolute calibration for luminosity measurements.

I was asked to review low-p_{T} proton–proton physics at LHC. However, it turns out that this presentation mainly concerns ALICE because the other LHC experiments do not yet have a detailed study of their capabilities in this area. This is understandable given that their priority lies in very specific aspects connected with very high-p_{T} observables. However, as will be explained later on, many of the items discussed here are relevant to other LHC experiments. Little will be discussed about diffractive physics, because of lack of time. An update on the subject can be found for instance in the proceedings of a recent workshop held in Helsinki [1].

Understanding heavy-ion collisions requires the understanding of proton–proton collisions. As a consequence ALICE, from the start, included low-p_{T} proton–proton studies in their programme [2]. As predictions of absolute rates for heavy-ion collisions have large uncertainties, the idea is essentially to express all signals relative to the proton–proton case, as for instance in:

– particle multiplicity distributions;
– strangeness enhancement or suppression;
– J/Ψ and Ψ' suppression or enhancement;
– jet quenching;
– thermal photon production.

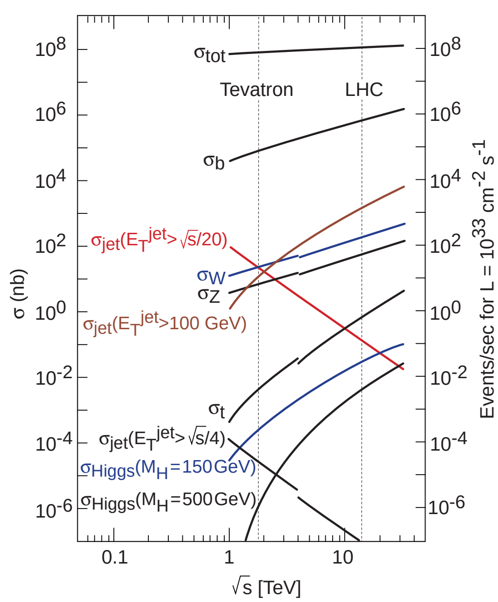

Figure 1. Proton–proton cross-sections (left-hand scale) and proton–proton collision rates for a luminosity of 10^{33} cm^{-2} s^{-1} (right-hand scale) as a function of the centre of mass energy.

The ALICE programme will, at the same time, include genuine proton–proton physics for all areas where ALICE is unique or at least competitive with respect to other LHC experiments.

Since LHC will start with proton–proton collisions, the ALICE detector commissioning will be carried out with proton–proton collisions, which will have the advantage of events much simpler than heavy-ion collisions. In other words, ALICE will be part of the LHC commissioning, and the first ALICE physics paper will be on proton–proton physics.

A discussion of proton–proton physics in ALICE can be found in ref. [3].

I found it useful to reflect on what could be meant by 'low-p_T' and by 'low luminosity' in the title of this presentation proposed by the organizers.

1.1 *What is low-p_T proton–proton physics?*

Low p_T is a notion which could be defined within the quantum chromodynamics (QCD) framework, where it relates to the perturbative expansion: it concerns a domain relevant to the connection between perturbative and non-perturbative regimes. It implies in practice p_T smaller than a few GeV/c. Note that this momentum scale depends only weakly on the beam momentum.

So why go to LHC to study it, while such study in principle could be performed at Tevatron? What LHC offers is access to much lower values of Bjorken x (down to 10^{-5}), which means that at LHC, higher orders in the QCD expansion containing typical terms in $\ln(1/x)$ will become more and more important. In practice, more higher order terms will have to be calculated within QCD. Certainly not a small task for theorists! In other words, as small x does not necessarily imply small p_T, low p_T at LHC implies exploring a new small x range where non-perturbative QCD is expected to become very important, if not dominant.

1.2 *What is low luminosity at LHC?*

For ATLAS and CMS low luminosity means 10^{33} cm^{-2} s^{-1}, the initial luminosity which the LHC division promises to deliver at the commissioning phase of the new machine. But ALICE could not run usefully much above 5×10^{30} cm^{-2} s^{-1} (limited by the event pile up in the 88 μs maximum drift time of the TPC – on average 16 events at 3×10^{30} cm^{-2} s^{-1}). Therefore, it is extremely important for ALICE to have the proton beams sufficiently defocused at the interaction point, implying the largest possible β^* value at Point 2. If this is not sufficient, as beam currents increase towards nominal LHC values, it is envisaged to separate the beams in the transverse direction. However, this beam displacement scheme to reduce the luminosity further may not provide ideal experimental conditions and so the use of low luminosity at the start of LHC operations may be precious for ALICE.

Assuming a non-elastic non-diffractive cross-section of 60 mb (A Kaidalov), one interaction per beam crossing occurs on average at a luminosity of 6.7×10^{32} cm^{-2} s^{-1}, two orders of magnitude above the ALICE maximum usable luminosity. Therefore, ALICE will always run under excellent conditions from the point of view of event pile up within the same bunch crossing, especially during the initial LHC period.

2. Low p_T proton–proton physics at LHC

The physics menu is essentially entirely based on the study of the strong interaction. I prefer not to say the 'study of QCD' as I have often seen written. The subject of the programme is an experimental study of strongly interacting matter. Of course this will imply testing the standard theory known as QCD. A non-exhaustive list of topics includes

- detailed measurement of minimum bias event properties (charged track multiplicity, p_T distributions, correlations, etc.);
- various important contributions to the total cross-section, such as minijets, but also relatively high p_T jets, multiple parton scattering, etc. (TOTEM will measure σ_{tot});
- photon production;
- baryon production;
- strange, charm and bottom particle production;
- quarkonia (decaying into e^+e^- or $\mu^+\mu^-$) production;
- diffractive physics in the central region (double pomeron exchange);
- cosmic ray related physics;
- search for exotic phenomena (centauro events, and other new phenomena, as usually done when exploring a new energy domain).

ALICE is in the process of preparing its physics performance report: at this time, the computing framework (simulation, reconstruction and analysis within the object oriented ROOT framework) is operational. Production of a large sample of fully simulated events just started both at CERN and at outside institutions (Bari, Catania, GSI, LBNL, Lyon, Torino, OSC-Ohio). A detailed analysis of ALICE's capability will be available by the end of 2003. Here we will only provide a global view of the ALICE proton–proton programme.

2.1 *Simulation of low-p_T phenomena*

So far high energy physics (HEP) is mainly using two general types of models:

- models starting from the simulation of high-p_T phenomena with low-p_T properties added using phenomenological parameters (such is the case for PYTHIA, HERWIG, ISAJET, etc.). These models, even after tuning, do not correctly describe all properties of the underlying event [4].
- models describing in principle everything, therefore, swamped by soft physics (DPMJET, FOURJETS, NEXUS) and not useful for high p_T (rare) physics.

The energy jump from Tevatron to LHC is larger than from the CERN proton–antiproton collider to Tevatron. Therefore, we can predict that tuning of minimum bias event and of underlying event properties in LHC simulations will be necessary. Even if significant progress is made in models, detailed comparison with data will still be necessary. This aspect is particularly important for ATLAS and CMS who need a precise understanding of all their backgrounds to high-p_T signals.

The present level of uncertainty in the charged track density predicted for proton–proton collisions at LHC is illustrated in figure 2a. The difference between the two sets of curves is due to the fact that PYTHIA includes a minijet contribution. The size of the difference underlines the importance of such contribution which, however, has large uncertainty.

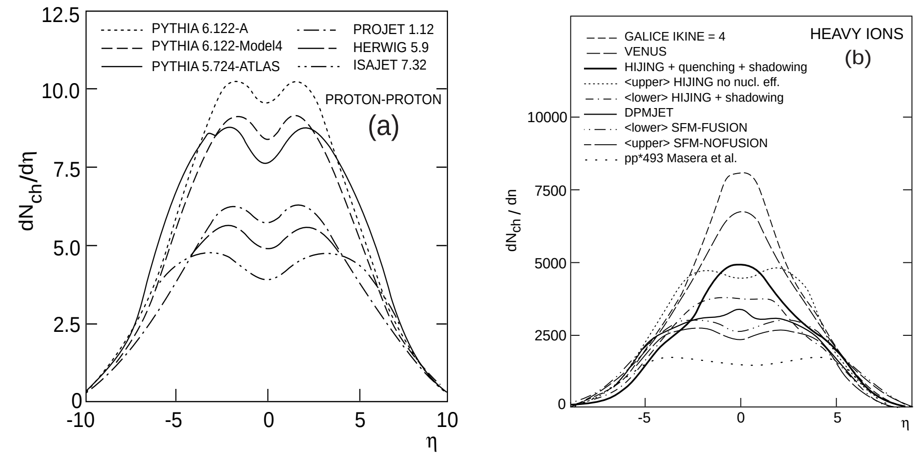

Figure 2. Comparison of current predictions for the density of charged track multiplicity in (**a**) proton–proton and (**b**) lead–lead collisions.

Going to predictions for heavy-ion collisions increases the uncertainty by a larger factor (figure 2b). RHIC data will narrow these predictions somewhat, but not very much, as we are dealing with highly non-linear phenomena, with a long lever arm in the extrapolation.

2.2 *Complementarity of LHC detectors*

ATLAS and CMS are optimized for high-p_{T} physics and high luminosity (up to 2×10^{34} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$). An illustration of the underlying event level and event pileup at a luminosity of 10^{34} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ is given by a 100 GeV/c^2 Higgs particle decaying into two photons as simulated in ATLAS and in CMS (figure 3).

LHCb is optimized for B physics in the forward region at moderate luminosity (up to 5×10^{32} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$). TOTEM is dedicated to measurements in the very forward region of total, elastic and diffractive cross-sections, thus providing an absolute calibration of the other experiments luminosity monitors. ALICE, because it is optimized for heavy-ion collisions is in practice ideally suited for low-p_{T} and high-multiplicity phenomena. It can, in certain cases (photons and jets), even reach high p_{T}. A comparison between the various experiments' acceptances is shown in figure 4, where the complementarity between experiments is clear.

ALICE has three main advantages:

(1) First of all, it is obvious that if ALICE is able to reconstruct 8000 charged tracks per unit of rapidity in heavy-ion collisions, it will have no problem in dealing with proton–proton collision multiplicities predicted on average of the order of 5 to 10 charged tracks per unit of pseudorapidity η (figure 2a). Figure 5 shows the simulation in ALICE of a typical proton–proton minimum bias event. Note that the outer diameter of the TPC is about 5 m.

(2) ALICE is sensitive to very low p_{T}, down to 0.1 GeV/c for pions, because of its low magnetic field and the small amount of material between the interaction region and the

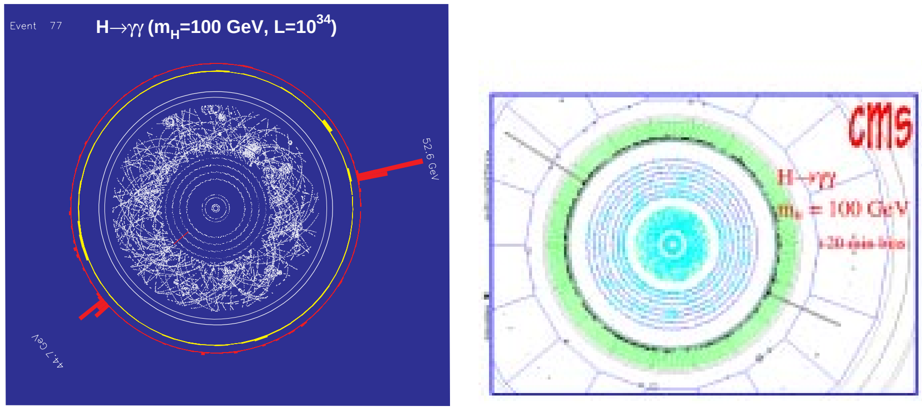

Figure 3. Left: ATLAS Higgs event, with 20 minimum bias events superimposed (courtesy of Fabiola Gianotti, ATLAS Collaboration). Right: CMS Higgs event, with 20 minimum bias events superimposed (courtesy of Lucas Taylor, CMS Collaboration).

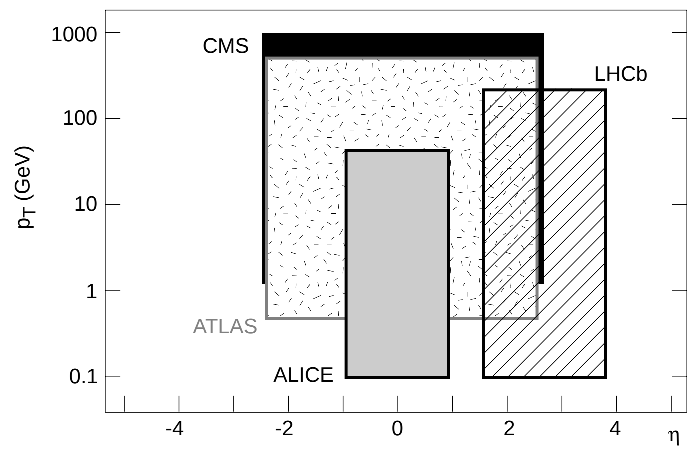

Figure 4. Comparison of p_T vs. pseudorapidity (η) reach of LHC experiments, for the trackers alone. Note that the high momentum limits are taken as the value at which $\Delta P/P = 30\%$.

detector (table 1). This is particularly important as the average p_T expected for minimum bias events is of the order of 0.6 GeV/c (figure 6), a momentum where CMS is essentially blind and ATLAS is reaching its limit.

(3) ALICE has unique particle identification capabilities, thanks to a combination of many different types of detectors: TPC and ITS for dE/dx and topology, TOF (time of flight), HMPID exploiting the RICH technique, TRD (transition radiation detector), a high precision electromagnetic heavy crystal calorimeter (PHOS) and a forward muon arm. The range of particle momenta covered by these various detectors is shown in figure 7.

Table 1. Parameters defining the minimum p_{T} for each of the LHC experiments. Note that for LHCb the minimum P is about 1 GeV, while for ALICE, $P \sim p_{\mathrm{T}}$.

Experiment	Magnetic field (T)	p_{T} cut-off (GeV/c)	Material thickness (X/X_0 in %)
ALICE	0.2–0.5	0.1–0.25	7
ATLAS	2.0	0.5	30
CMS	4.0	0.75	20
LHCb	4 Tm	0.1	3.2

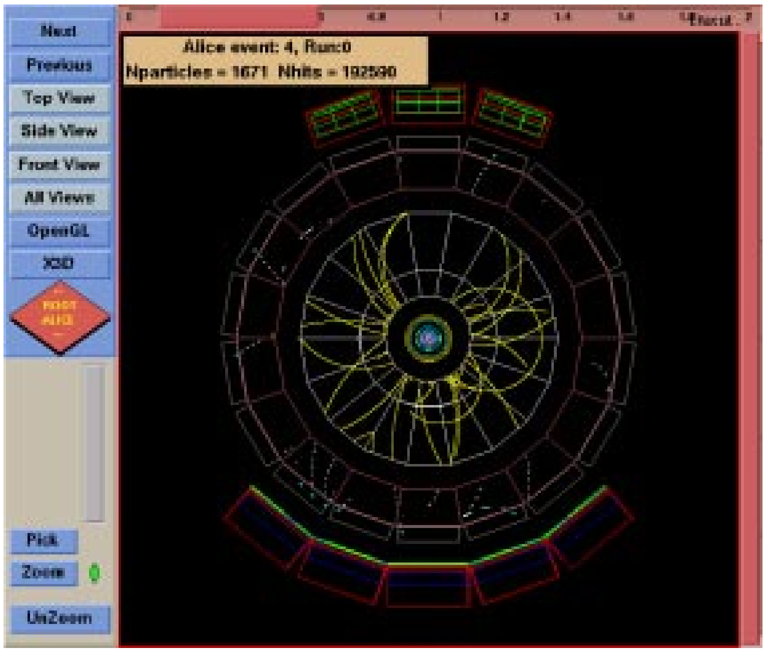

Figure 5. Simulation of one minimum bias proton–proton event in the ALICE central barrel.

The first data from an ALICE detector were collected at RHIC, in a prototype of the ALICE HMPID which is performing as expected (figure 8). It is clear that in a proton–proton environment the performance of this detector will be even better due to the much lower average occupancy.

3. Low p_{T} physics in ALICE experiment

3.1 *Proton–proton and heavy-ion collisions*

Proton–proton collisions at LHC might reach initial energy densities comparable to those expected in gold–gold collisions at RHIC (table 2). Therefore, they represent considerable

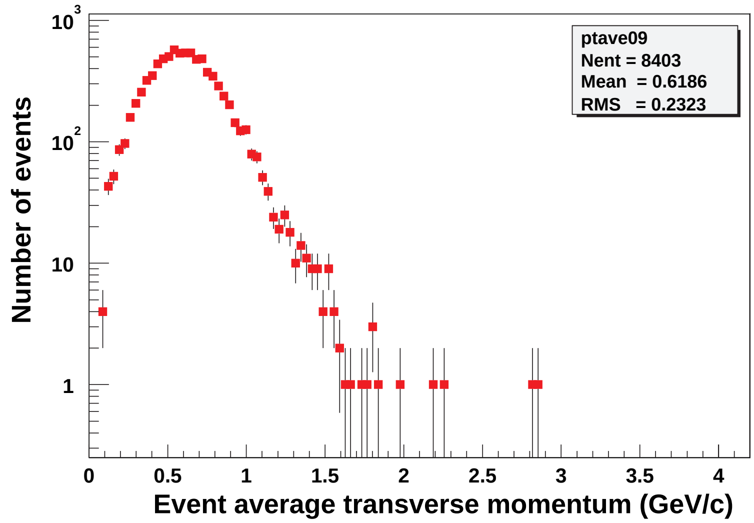

Figure 6. Average transverse momentum of charged tracks per event in minimum bias proton–proton events in ALICE ($\eta < 0.9$) (courtesy of Marco Monteno, INFN Torino).

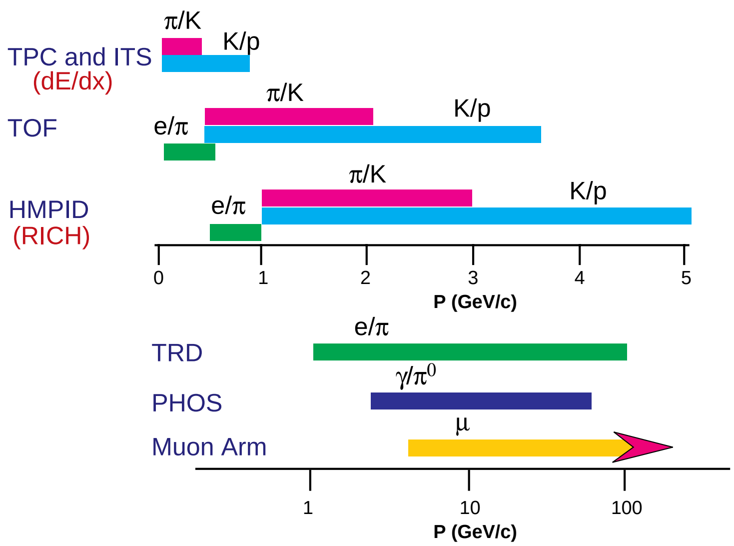

Figure 7. Momentum ranges for pion, electron, charged kaon, proton and photon separation in ALICE, with indication of the corresponding detector technique.

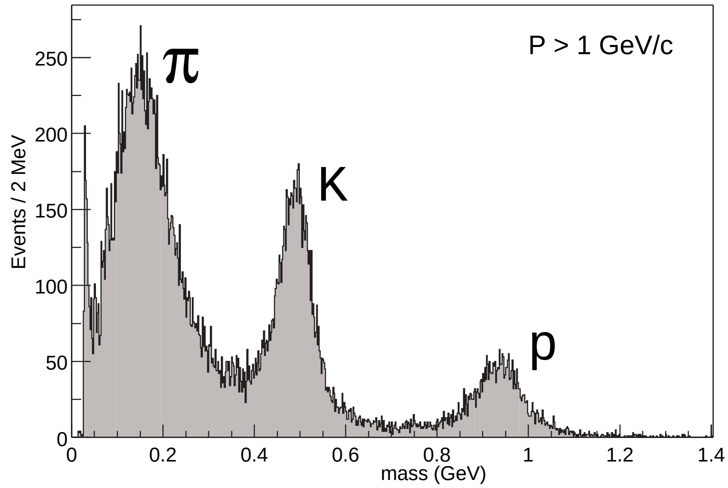

Figure 8. Separation between pions, kaons and protons with an ALICE HMPID prototype running as part of the STAR detector at RHIC (Au–Au collisions).

Table 2. Comparison of parameters of collisions for various beam systems leading to an estimate of the energy density scale (ε) based on the traditional Bjorken formula.

	$\langle E\rangle$ (MeV)	dn_{ch}/dy	V_i (fm^3)	ε_I (GeV/fm^3)
$\bar{p}p$ ($\sqrt{s} = 630$ GeV)	400	4	4.5	0.5
$\bar{p}p$ ($\sqrt{s} = 1800$ GeV)	400	5.3	4.5	0.7
pp ($\sqrt{s} = 14$ TeV)	500	7	4.5	1.2
Au–Au ($\sqrt{s} = 200$ GeV)	500	700	153	5
Pb–Pb ($\sqrt{s} = 5500$ GeV)	500	2000–8000	159	10–40

interest for the study of high energy densities going from small volumes with pp collisions to large volumes with heavy-ion collisions. It is particularly important to observe proton–proton and heavy-ion collisions in the same detector, in order to minimize systematic errors in the comparison. At RHIC all experiments used UA1 data for comparison with their initial heavy-ion data, which has large systematic errors, but are now collecting their own proton–proton data at $\sqrt{s} = 200$ GeV, to minimize systematic uncertainties by the use of the same detector in the comparison.

With a sample of 10^8 minimum bias events, one could reach particle multiplicities 8 times the average multiplicity, hence energy densities of 10 GeV/fm^3 which should overlap with energy densities in heavy-ion collisions at RHIC.

3.2 *Study of global event properties*

ALICE will collect a large sample of minimum bias events (10^9 events are needed as will be explained later). The trigger is provided by a coincidence between the V0 counters

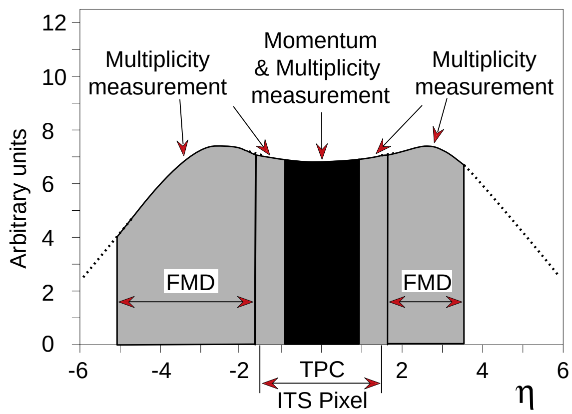

Figure 9. Charged particle density distribution as a function of pseudorapidity at LHC with indication of the ALICE measurement ranges for charged track multiplicity and momentum.

covering respectively a pseudorapidity range from -5 to -3.2 and from 1.6 to 4.8. This will select about 90% of the non-elastic non-diffractive events, corresponding to a cross-section of 60 mb. Charged particle multiplicity will be measured between -5.1 to $+3.4$ units of pseudorapidity while the momentum analysis will be possible in the central, 1.5 units with optimum momentum resolution in 0.9 units (figure 9).

While part of the heavy-ion studies requires running at low magnetic field (0.2 T), in proton–proton collisions, a higher magnetic field (up to 0.5 T) is needed to extend the momentum measurement reach to 30 GeV/c or above (figure 10). At the Z^0 mass the corresponding resolution should be 4%, which is quite respectable for an experiment which was not optimized for high p_T.

At a luminosity of 3×10^{30} cm^{-2} s^{-1}, the minimum bias event rate is 2×10^5 Hz. In ALICE the event size depends on the luminosity because of event pile up in the 88 μs drift time of the TPC, and is given in kilobytes by $60 + 3.2\times10^{-28}\times L$ (cm^{-2} s^{-1}). At a luminosity of 3 $\times10^{30}$ cm^{-2} s^{-1}, the average event size is about 1 Mb. However, if collected at 10^{28} cm^{-2} s^{-1} or lower, the event size drops to 60 Kb only. If ALICE is forced to run at high luminosity, the high level trigger (HLT) farm will be used online to remove the overlapping events so that the data volume will remain close to 60 Kb per event. In that case the total proton–proton data volume for 10^9 events would be smaller than 10% of the data volume needed for heavy ions. It will therefore have a small impact on computing resources. For essentially all luminosities envisaged for ALICE at Point 2, 10^9 events could be collected in one year (10^7 s) with a rate of 100 Hz, or at most 100 Mb/s, reaching a momentum of about 30 GeV/c (figure 11). Statistics are not likely to be limited by the collision rate, but rather by the capacity of ALICE to collect data at high rate!

ALICE will be able to achieve high precision measurements of minimum bias event properties. Already with a sample of 10^6 events, one should be able to test, for instance, some of Kaidalov's predictions on multipomeron exchange as a source of KNO scaling violation. The study of identified particle production will require the maximum sample size envisaged of 10^9 events, given the yield of the various particles of interest (table 3). Figure 12 shows the p_T distributions of pions, kaons and protons or antiprotons, from minimum

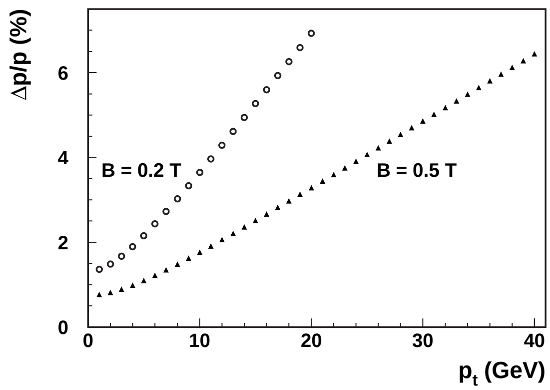

Figure 10. Momentum resolution expected in ALICE from the combined fitting of charged tracks in the TPC and the ITS.

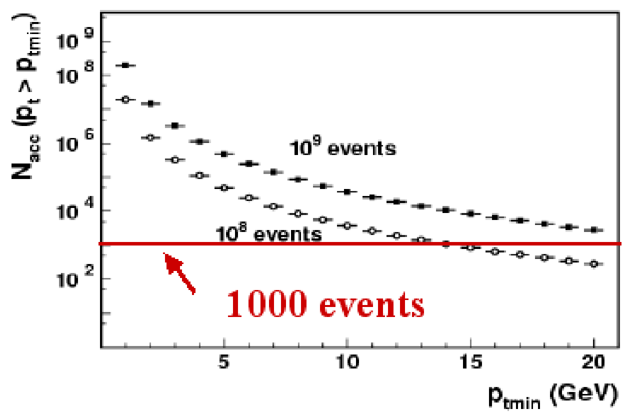

Figure 11. p_T distributions for two sample sizes (10^8 and 10^9 events) of minimum bias events, illustrating the statistics needed to reach a transverse momentum of 15 and 25 GeV/c respectively. The magnetic field value is 0.5 T.

Table 3. Yield in minimum bias events for the reconstruction of a few particles of interest, and the data sample size needed to ensure a statistics of the order 10^4 events.

	K_S^0	Λ	Ξ	Ω	p	$\bar{p}$
Yield	0.1	0.01	10^{-4}	10^{-5}	0.4	0.4
pp events	10^5	10^6	10^8	10^9	10^4	10^4

bias events generated with PYTHIA, and fully simulated in ALICE central region (±0.9 units of pseudorapidity). ALICE intends to produce a fully simulated sample of 10^5 events for its physics performance report.

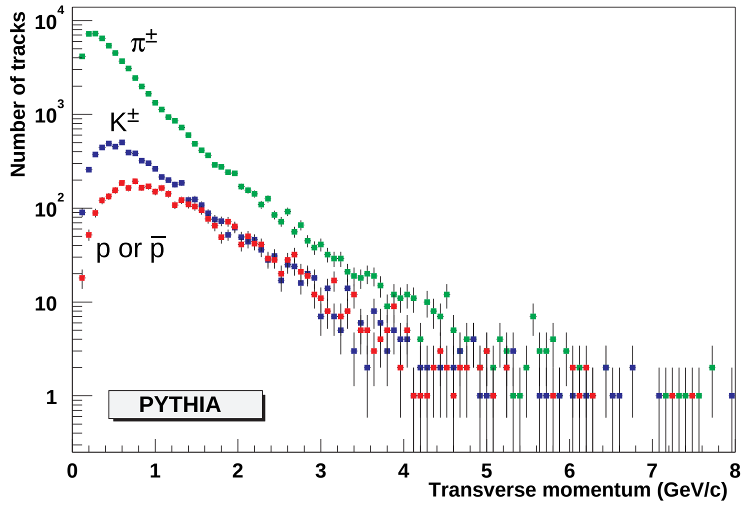

Figure 12. p_T distributions of pions, kaons and protons or antiprotons, from 10^4 minimum bias events generated with PYTHIA, and fully simulated in ALICE central region ($\pm$0.9 units of rapidity) (courtesy of Marco Monteno, INFN Torino).

3.3 *Photon physics in ALICE*

The photon physics in ALICE is driven by two main motivations:

(1) The need to calibrate photon production in nucleon–nucleon collisions to be able to substract this background source in heavy-ion collisions, in order to demonstrate the existence of a thermal component which is expected to approach the typical $\exp^{-P/T}$ spectrum characteristic of thermal equilibrium (see left panel of figure 13).

(2) Precise tests of QCD, by studying properties of jets recoiling from high p_T photons measured in the ALICE crystal calorimeter (PHOS). Two characteristic lowest order Feynman graphs are shown in the right panel of figure 13.

ALICE will be able to identify π^0s over an unprecedented momentum range (0.5–80 GeV) and with an excellent energy resolution of 2% above 3 GeV/c. This is made possible because the $PbWO_4$ crystals, which have the same transverse size (2.2×2.2 cm^2) as those of CMS, are installed three times farther away from the interaction region (at a radius of 4.6 m), allowing a better separation of the photon showers in π^0 decays.

Given the large cross-section, the limited solid angle of the PHOS ($\Delta\eta \sim 0.24$ and $\Delta\phi \sim 100°$) will be sufficient to collect significant statistics (figure 14). The ability to measure inclusive and direct photons at low p_T, down to a few GeV/c will allow ALICE to explore a new domain of QCD, well into the non-perturbative regime.

3.4 *Jet physics in ALICE*

The main strength of ALICE in this field is in the ability to study jet fragmentation by combining its excellent charged track momentum resolution with its unique double track

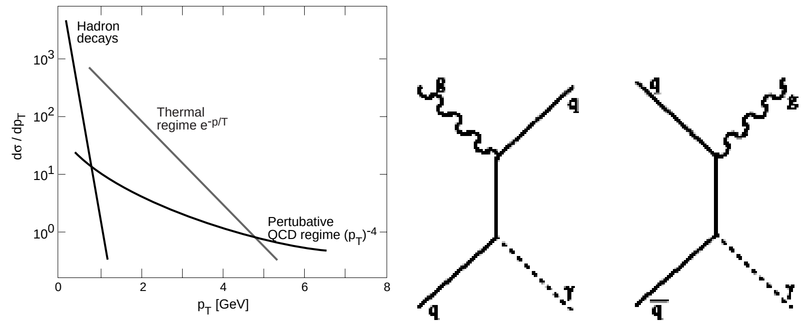

Figure 13. Left: Qualitative illustration of the various expected components of the photon spectrum in heavy-ion collisions. Right: Lowest order QCD Feynman graphs contributing to the production of isolated photons, in proton–proton collisions.

resolution and particle identification. This is expected to compensate for the mediocre jet energy resolution ($\Delta E_T / E_T \sim 30\%$), due to the absence of a proper calorimeter.

Jet rates are large, typically 10^7 events per year in the ALICE acceptance for $E_T > 100$ GeV, at $L = 10^{30}$ cm^{-2} s^{-1}. Jet reconstruction is limited to charged particles (figure 15), which carry about two-thirds of the energy. However, it will be possible to study correlations between leading particles, jet–jet correlations and, as already mentioned, jet fragmentation. One interesting issue linked to both jet physics and minimum bias event properties, is the correlation between charge track multiplicity and mean p_T. Such correlation discovered by UA1 (left part of figure 16) and also observed by CDF (right part of figure 16) for identified particles is not yet well-understood. For instance, while DPMJET fits the CDF pion data correctly, it does not fit the kaon data well and completely misses for antiprotons. These correlations are generally attributed to the production of minijets.

According to Capella and others, the minijet cross-section is expected to represent a dominant fraction of the total cross-section at LHC energy (figure 17), where it could contribute to the saturation of the Froissard bound. One could ask whether the increase of the total cross-section with centre of mass energy could have similarities with the increase of the non-unitarized minijet cross-section, which, as the number of minijets produced increases, is in fact nothing but the product of the average number of minijets by an effective cross-section. Discussions of these issues can be found in [5].

Kaidalov suggested that in pp collisions one could also have a phase transition, perhaps analogous to that of heavy-ion collisions, with parton saturation, and that this would produce dramatic modifications of the correlation shown in figure 17, especially at large multiplicities. This type of physics with ALICE will obviously be very exciting.

3.5 *Baryon production in the central rapidity region*

The question of baryon production in the central rapidity region has been an object of controversy where the standard view was that in proton–proton collisions at LHC baryon stopping would be negligible. However, Rossi and Veneziano proposed a new baryon model [6], based on string junctions, where baryon number can also be carried by gluons.

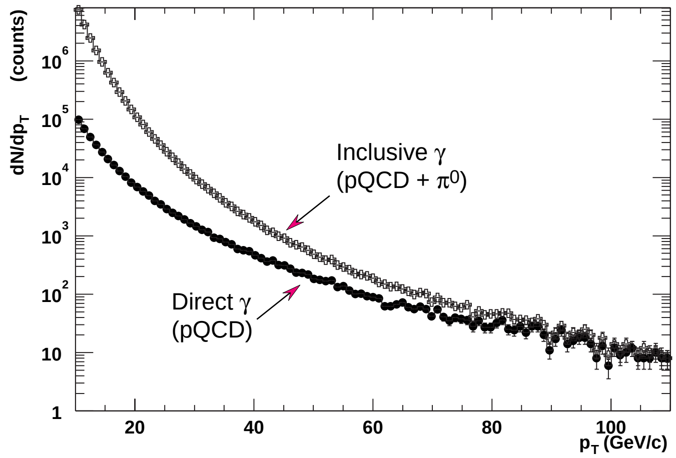

Figure 14. Photon transverse momentum distribution in the ALICE PHOS corresponding to one year of data taking at a luminosity of 10^{30} cm^{-2} s^{-1}. Both direct and inclusive photon rates are given.

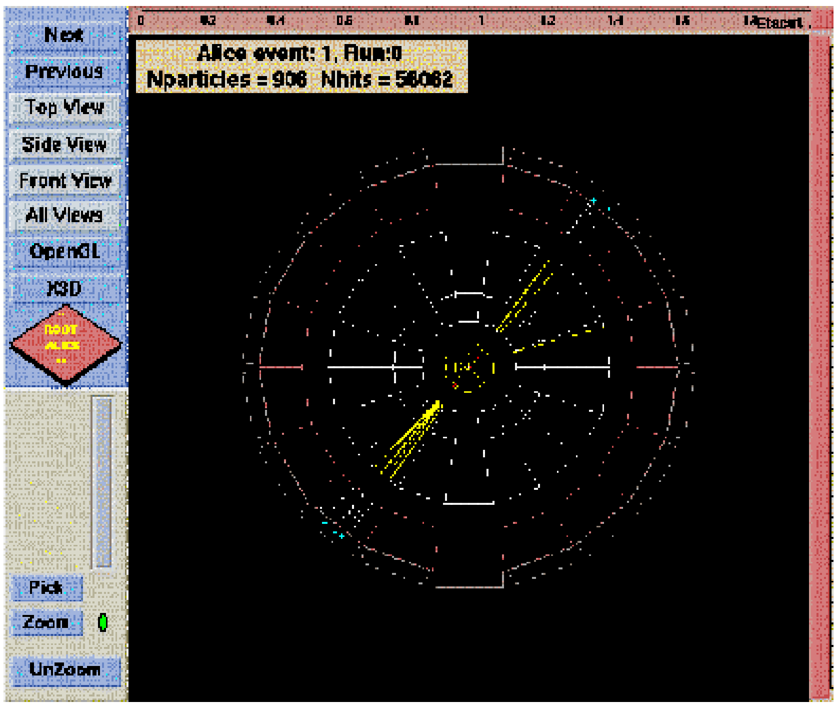

Figure 15. Typical two jet proton–proton event in the ALICE central region. All tracks with a momentum larger than 2 GeV/c are displayed.

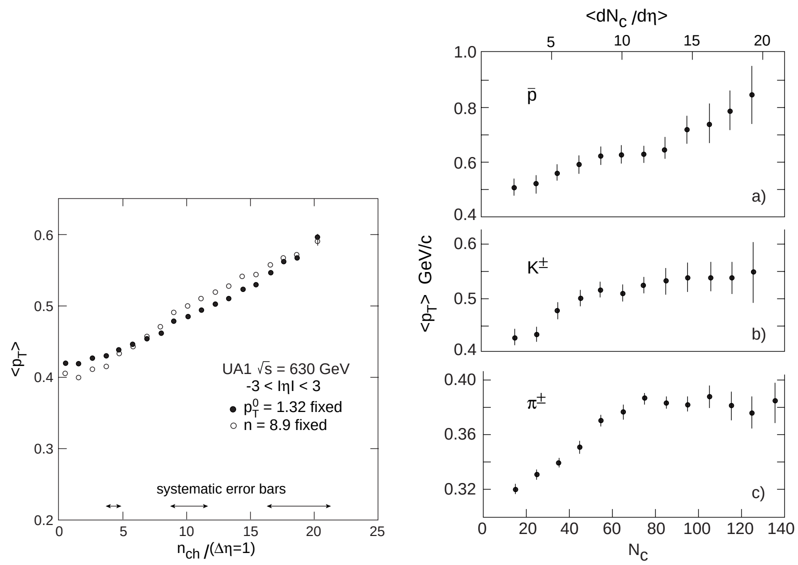

Figure 16. Left: UA1 measurement of the correlation between charged track multiplicity and average p_T in minimum bias events, at the CERN proton–antiproton collider. Right: Correlation between charged track multiplicity and average p_T of identified particles ((**a**) antiprotons; (**b**) $K^{\pm}$; and (**c**) $\pi^{\pm}$), measured by CDF at the Fermilab Tevatron.

In their model, the nucleon is no longer built out of direct colour strings exchange between valence quarks, but is essentially a string junction of colour field lines (left part of figure 18). If this is the case, then substantial baryon production could occur at LHC in the central rapidity region, as a result of the emission, by the incoming colour singlet of colour strings in a $\{10\}$ state, as shown in the right part of figure 18.

At LHC the incoming protons are at a rapidity of 9.6 units. In models where stopping is a ‘mechanical’ phenomenon (both energy and baryon number have to be stopped together) baryon production in the central rapidity region from incoming valence quarks is suppressed by a factor $e^{0.5\Delta y} \sim 120$. Therefore, the two cases should be easy to distinguish. Present attempts at HERA are not conclusive (figure 19), as the rapidity gap (in the centre of mass) is still too small compared to the large error bars in the data. In other words, the valence quark contribution is still relatively large.

The observable proposed by B Kopeliovitch is an asymmetry defined for each type of baryon:

$$A_{\mathrm{p}} = 2 \times (N_p - N_{\bar{p}})/(N_p + N_{\bar{p}}) \sim 5\% \text{ at LHC}$$

$$A_{\Lambda} = 2 \times (N_{\Lambda} - N_{\bar{\Lambda}})/(N_{\Lambda} + N_{\bar{\Lambda}}) \sim 30\% \text{ at LHC.}$$

Since baryon stopping implies more colour strings to exchange, it is also expected that baryon events will be characterized by higher multiplicities, hence a measurement of the asymmetry as a function of charge track multiplicity will be of interest.

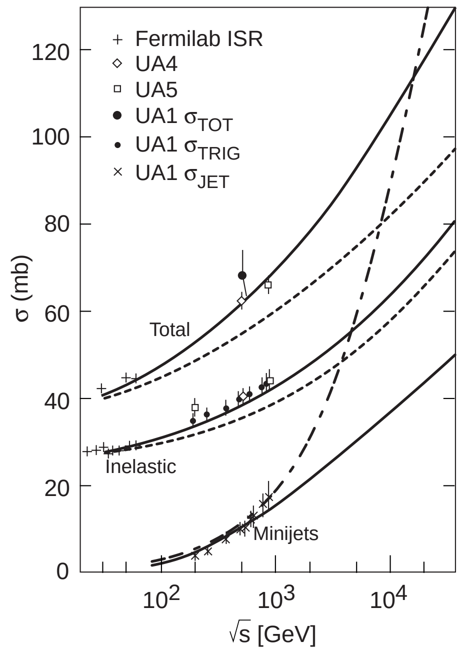

Figure 17. Total, inelastic non-diffractive and minijet cross-sections vs. centre of mass energy from ref. [7]. Dashed lines show behaviour without minijets.

We expect that 10^9 minimum bias events should contain 4×10^8 antiprotons and 10^7 Λs, more than enough to conclude on this type of study. In addition, such measurements should be relevant to heavy-ion collisions where baryon stopping should be dramatically enhanced due to the much increased probability of emitting a $\{10\}$ state.

As far as baryon physics is concerned, at the LHC it should be possible to study exotic baryon states such as Λ_b, Ξ_b, Ω_b, etc., which are all poorly known. For instance, with a $\Lambda_b \to J/\Psi$ branching ratio of $(4.7\pm2.8)\times10^{-4}$, a few thousand Λ_b baryons could be observed. There is even a chance to also observe Ξ_b and Ω_b.

3.6 *Bottom and charm quark production*

The *b* cross-section was not well-understood at the CERN collider, it is still not better understood at the Fermilab Tevatron, where in both cases the data are about a factor 2 above the predictions and it is not understood at HERA and in $\gamma\gamma$ collisions at LEP. This is clearly an area where a lot of work is still needed to resolve the current problems, and where the LHC data should help clarify the issues.

The cross-section corresponding to the ALICE rapidity acceptance was calculated by M Mangano (figure 20), from which we can deduce that at a luminosity of 3×10^{30} cm^{-2} s^{-1}, about 2×10^8 b's in the electron channel should be produced centrally, and that our 10^9 event minimum bias sample should contain 10^5 b$\to eX$, or perhaps many more, if the UA1/CDF trend continues. ALICE will cover the central pseudorapidity region (±0.9

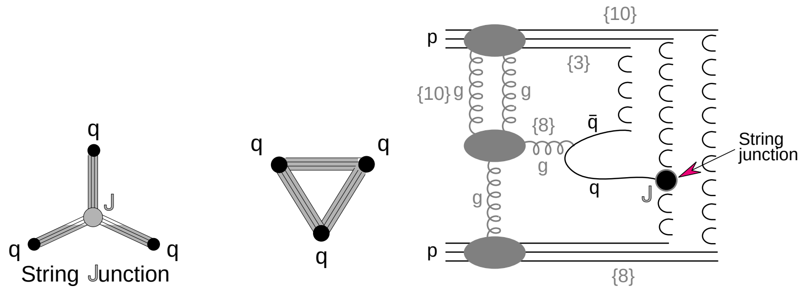

Figure 18. Left: Baryon representation as string junction (left-hand side) and as colour strings exchanged between valence quarks (right-hand side) (courtesy of B Kopeliovitch). Right: Typical diagram corresponding to the production of baryon through the emission of a $\{10\}$ colour state in the t-channel, creating a string junction (courtesy of B Kopeliovitch).

units) in the electron channel and the forward region (2.5 to 4 units) in the muon channel (figure 21).

It is likely that the b problem is in fact a problem for both charm and bottom quark production, and in this perspective, charm production studies will be mandatory. Equipped with a very precise vertex detector, ALICE can perform such studies in a unique way at LHC. In the $D^0 \to \pi K$ channel there is even hope to measure the total charm cross-section as present studies indicate that ALICE sensitivity extends essentially down to $p_{\rm T}$ (charm) $= 0$ (figure 22). We expect more than 10^4 D^0s in our sample of 10^9 minimum bias events. However, the transition radiation detector (TRD) may offer the possibility of a trigger on an electron signature and provide even larger samples.

3.7 *Quarkonia physics*

The interaction of heavy quark bound states with the quark gluon plasma is the object of much speculation, and may lead to unambiguous signatures of the production of this peculiar state of matter. ALICE was designed to be able to study quarkonia both in the muon channel, using the forward muon arm, and in the electron channel using the TRD.

In the muon channel (figure 23), $\Delta M = 90$ MeV at the Υ. In one year of data, large statistics will be available, $8\times10^5 J/\Psi$ and 6×10^3 Υ with an expected S/B ratio of 13 and 16.

In the electron channel statistics of $5\times10^5 J/\Psi$ in one year with a mass resolution $\Delta M = 50$ MeV, and $2\times10^3\Upsilon$ with $\Delta M = 100$ MeV, are expected. These J/Ψ measurements will explore a new kinematic domain of QCD (figure 24), going very deep into the non-perturbative region.

3.8 *Diffractive physics in the central rapidity region*

At LHC the cross-section for double diffraction is estimated to be 11–13 mb (A Kaidalov): $\sigma_{\rm SD} \sim \sigma_{\rm DD} \sim \ln(s/s_0)$.

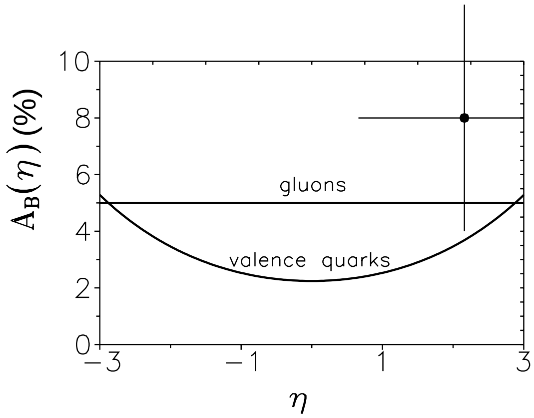

Figure 19. Baryon asymmetry as a function of pseudorapidity showing valence quarks and gluon contributions, and HERA data point plotted at a rapidity of $9.6 - 7.4 = 2.2$ (courtesy of B Kopeliovitch).

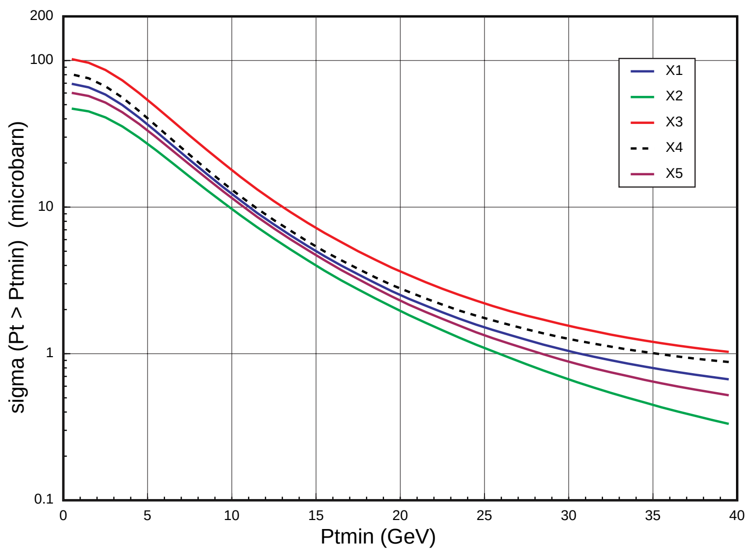

Figure 20. Bottom quark production effective cross-section above $p_T$min in ALICE, for five different choices of the QCD scale and structure functions, illustrating the typical spread of present predictions (courtesy of M Mangano).

ALICE is studying the possibility of implementing a trigger requiring two rapidity gaps on both sides of a central region of 1.5 units of rapidity. The ITS could be used to require some charged track activity in the central region. The selection can include electromagnetic energy deposition in the PHOS, or protons in the HMPID, or electrons identified with the TRD opening the possibility to study heavy flavour production in double diffractive events.

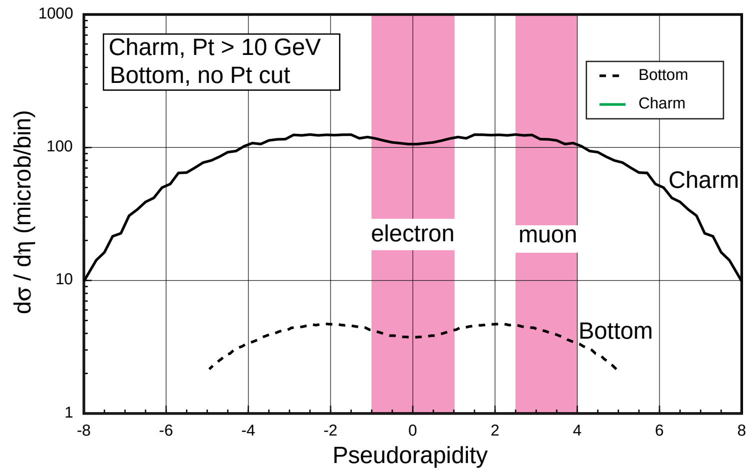

Figure 21. Pseudorapidity distribution of charm and bottom quarks produced at LHC, with indication of the regions covered by ALICE (courtesy of M Mangano).

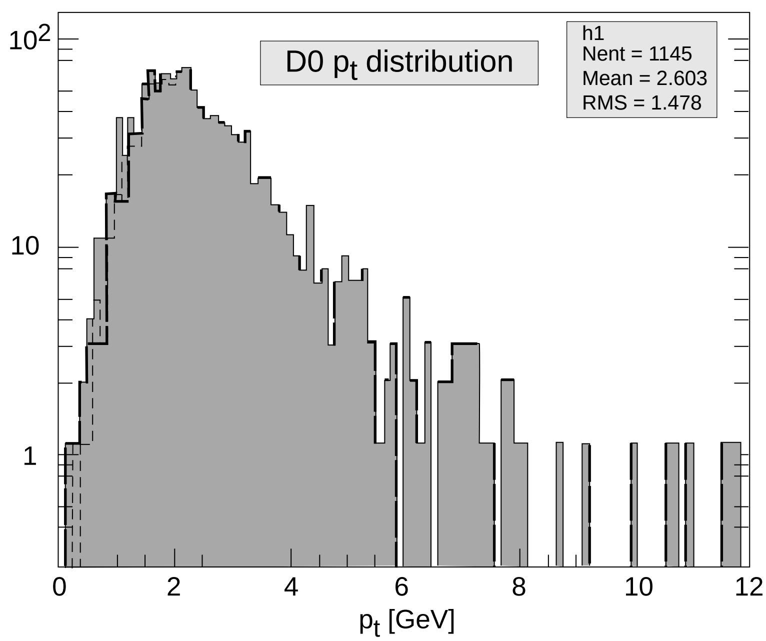

Figure 22. p_T distribution of charm quarks having produced a $D^0 \to \pi K$ reconstructed in the ALICE central region.

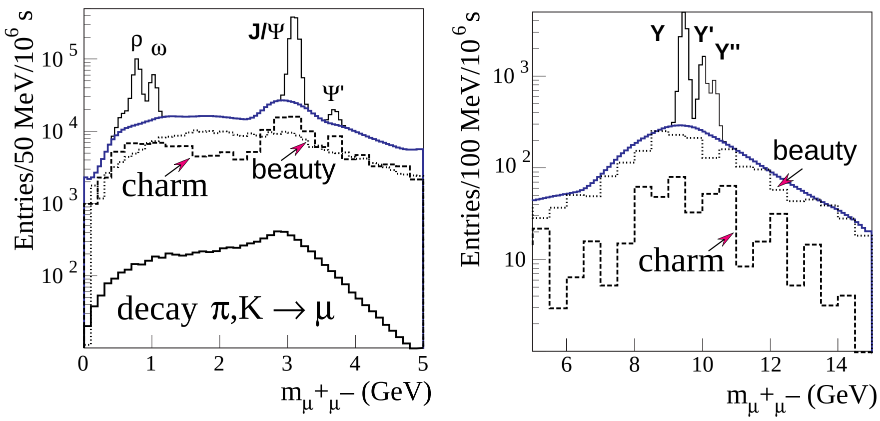

Figure 23. J/Ψ and Υ reconstructed in the ALICE forward muon arm (proton–proton).

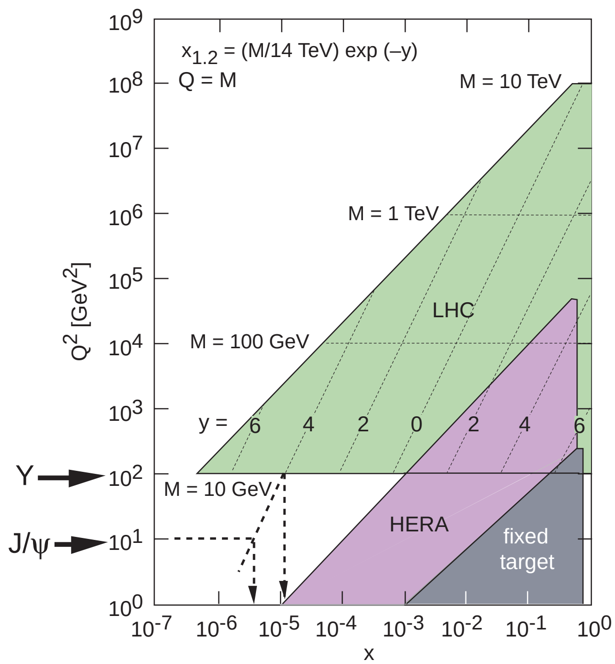

Figure 24. Parton kinematics domain (Q^2 vs. x) for LHC, HERA and fixed target experiments, showing the region reached by the ALICE Υ and J/Ψ measurements.

3.9 *Physics related to cosmic rays*

The famous 'knee' in the cosmic ray flux (figure 25) seems to occur between Tevatron and LHC energies. On average, a particle produced at central rapidity at LHC has a p_T of

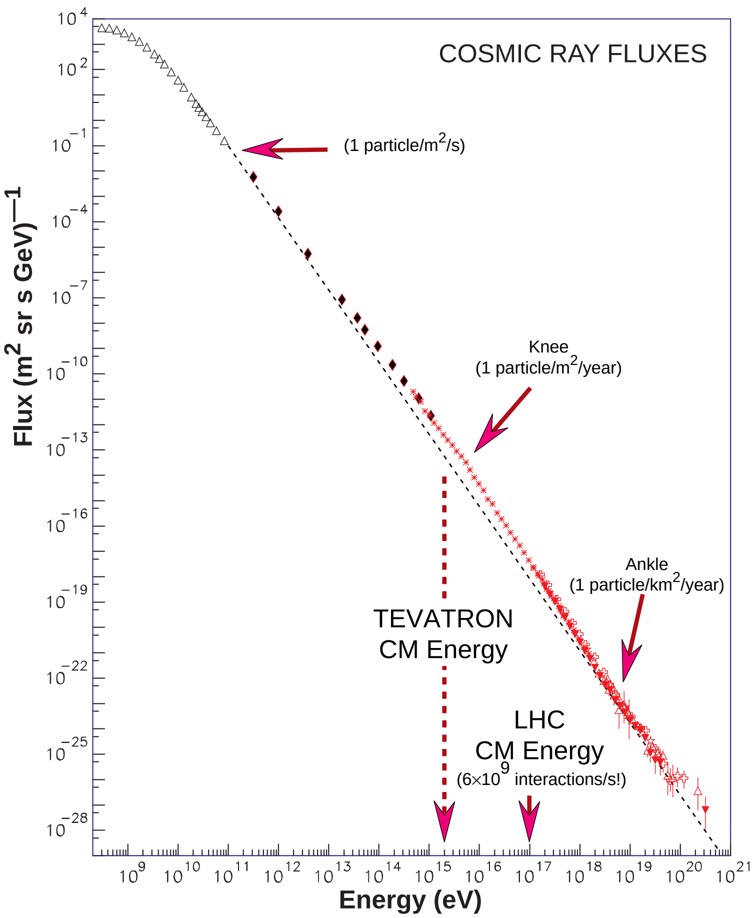

Figure 25. Cosmic ray flux as a function of energy, showing the famous knee structure appearing somewhere between Tevatron and LHC energies.

0.5–0.7 GeV/c corresponding to an opening angle of 10^{-4} radian in a cosmic ray shower of corresponding energy, allowing the exploration of a shower region down to a radius of 1 m for a primary interaction 10 km above ground. Therefore, the central rapidity region is relevant even though forward detectors will be needed to do a complete job.

4. Conclusion

Low-p_T phenomena constitute the bulk of the events at LHC. Their detailed study is mandatory, both because of the necessity to explore in detail a new domain of physics and because it should contribute greatly to our understanding of the strong interaction. The range of physics topics is extremely wide and should be a major component of the LHC programme. ATLAS, CMS and LHCb will need the best possible understanding of minimum bias and underlying event properties, both of which contribute to the background to their high p_T signals. ALICE is complementary to the other LHC detectors because it is optimized for heavy ions hence for low-p_T physics. ALICE should provide useful information to be combined with other LHC experiments. The detailed study of low-p_T physics with proton–proton collisions is needed for the understanding of heavy-ion collisions and has always been part of the ALICE programme. At the same time ALICE will study a range of proton–proton physics subjects where its detector properties (low-p_T acceptance, particle identification and ability to reconstruct high multiplicity events) make it unique or at least competitive with other LHC experiments.

This review is not exhaustive, by far. This is only a first look to illustrate the potential of ALICE. It is likely that other interesting ideas will come up between now and the start of LHC.

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References

[1] Forward Physics and Luminosity Determination at LHC, *Proc. Helsinki Workshop* (October 2000) published by World Scientific
[2] ALICE Collaboration, *Letter of Intent*, CERN/LHCC 93-16
[3] P Giubellino *et al*, ALICE 2000-28, Internal Note/PHY (24 November 2002)
[4] T Affolder *et al*, FERMILAB-PUB-01/211-E
V Tano, hep-ph/0111412
[5] R M Godbole *et al*, hep-ph/0104015
T Alexopoulos *et al*, *Phys. Lett.* **B435**, 453 (1998)
[6] G C Rossi and G Veneziano, *Nucl. Phys.* **B123**, 507 (1977); *Phys. Rep.* **63**, 149 (1980)
[7] A Capella *et al*, *Phys. Rev. Lett.* **58**, 2015 (1987)