Physics with "2^{nd} Generation" Pixel Detectors

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1 Introduction

The first generation of pixel detectors for use in high-energy physics experiments was developed in the early 90's. They were characterized by a minimal circuitry in each pixel (pre-amplifier, discriminator, some trigger coincidence logic, a single flip-flop as part of a read-out shift register), and common thresholds. The full matrix was read out, resulting in relatively long read-out times. Their electronics was implemented in $\sim$1 μm technology. They were used by several CERN fixed-target heavy ion experiments (Omega3/LHC1 chip, with 50×500 $\mu\mathrm{m}^2$ pixels) and the Delphi experiment at LEP for forward tracking (330×330 $\mu\mathrm{m}^2$ pixels).

A second generation of detectors is being developed since the mid-90's: they contain a more complex circuitry in each pixel (pre-amplifiers with adjustable gain, individually adjustable discriminator thresholds, pulse height measurements, efficient read-out logic), and a sparse (therefore fast) read-out system. These new detectors are realized using the newly-developed (rad-hard) deep sub-micron technology, together with radiation-hard sensors and infrastructure. They are going to be used by the ATLAS [1] and CMS [2] collider experiments at LHC, the B-TeV [3] B-Physics experiment at FNAL and the ALICE [4] heavy-ion experiment at LHC.

Events at (near) future colliders are characterized by high rates ($\sim$20 p-p events per bunch crossing at LHC design luminosity) and high particle multiplicities (up to 8000 charged particles per unit of rapidity in heavy ion collisions at LHC). Pixel vertex detectors are needed because of their excellent 3-D position resolution ($\sim$10 μm) and 2-track resolution ($\sim$100 μm), their good timing resolution (better than one bunch crossing) and their very low occupancy ($\sim 10^{-4}$ for p-p high-luminosity interactions and $\sim 10^{-3}$ for heavy-ion interactions).

2 p-p experiments at LHC: ATLAS and CMS

The tracking systems of the two LHC general-purpose experiments are based on the same general principles, although several technological choices are somewhat different.

At the core of both experiments is a 3-layer pixel detector (perhaps only 2 layers initially), followed by four layers of silicon microstrip detectors. The outer part of the CMS tracker is constituted of six more layers of silicon microstrip detectors; ATLAS chose a straw tube detector, the Transition Radiation Tracker, which provides on average 35 one-dimensional measurements per track and gives transition radiation information for electron identification.

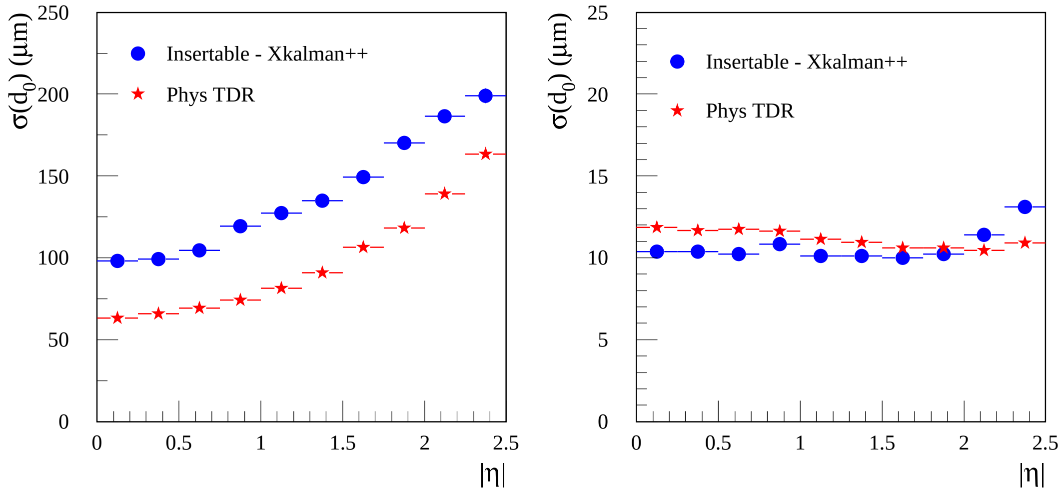

Figure 1: Transverse impact parameter resolution in ATLAS for a) 1-GeV and b) 200-GeV muons. The circles correspond to the current layout, the stars to the layout as described in the "Physics TDR" [1] in 1999.

ATLAS and CMS are both thick trackers: each pixel layer contributes more than 2% of a radiation length, plus the global support and cooling structures and the thermal and EMI screens. The impact parameter resolution depends strongly on the radius of innermost pixel layer, the thickness of pixel layers and the radius and thickness of beam pipe. For example the recent increase in the radius of the beam pipe envelope in ATLAS by 1 cm forced a corresponding increase in the radius of the innermost pixel layer, thereby increasing the coefficient of the multiple scattering term in the impact parameter resolution (see Fig.1); the impact parameter resolution can now be parameterized as:

$$\sigma(d_0) \approx 10 \oplus \frac{98}{p_T\sqrt{\sin\theta}}\ \mu\mathrm{m}.$$

At LHC design luminosity ~ 20 interactions occur in each beam crossing, spread along the beam axis with $\sigma(z_V) = 5.6$ cm. In order to identify the position of the primary vertex of the hard (triggered) interaction, associate correctly the reconstructed tracks to each interaction and reconstruct any secondary vertices in jets, the primary vertex resolution in the z direction is a very important design parameter. Pixel detectors allow primary vertex reconstruction with $\sigma(z) \approx 20$ μm for "easy" channels (such as $H \to \mu^+\mu^-\mu^+\mu^-$) and $\sigma(z) \approx 50$ μm for "difficult" channels (such as $A \to \tau^+\tau^-$, which contain several secondary particles).

Higgs bosons and supersymmetric particles couple preferentially to heavy leptons and quarks, therefore it is very important that the vertex detectors be able to identify b quarks (b jets) and τ leptons with high efficiency and low background. Several algorithms for b-jet identification have been tried by CMS and ATLAS, based on track impact parameter (track counting and jet probability), explicit secondary vertex reconstruction and decay length. Typical average performances for both experiments are $\varepsilon(u) \approx 1\%$ for $\varepsilon(b) = 60\%$ for the "interesting" jet p_T range ($50 < p_T < 130$ GeV) and all rapidities; best performance $\varepsilon(u) \approx 0.2$ for $\varepsilon(b) = 50\%$ for $p_T \sim 100$ GeV and central rapidity (see Fig.2a). If 3-prong τ events can be used in addition to 1-prong τ decays, a factor of 1.7 of signal events are gained for Higgs and supersymmetry studies. Three-prong decay vertices can be reconstructed with sufficient precision: the decay-length resolution of the order of a few mm is considerably smaller than the average flight path of a τ lepton from the decay of a Higgs or supersymmetric boson with a mass of a few hundred GeV.

3 p-p experiments at LHC: Higgs and Supersymmetry

Higgs bosons have many available decay channels, therefore it is important to be able to cover as many as possible with high efficiency. Let's take the channel $gg \to t\bar{t}H \to t\bar{t}b\bar{b}$ as a typical example: it is very sensitive to b-tag performance (there are four b-jets in the final state) and it needs the full reconstruction of both top decays to suppress the combinatorial background. The remaining backgrounds are due to direct $t\bar{t}b\bar{b}$ production (QCD and EW) (irreducible background) and $t\bar{t}jj$ and $t\bar{t}jb$ with misidentification of non-b jets (reducible background). If one takes the $\varepsilon(b) = 60\%$ point on the efficiency vs. rejection curve, one gets an average rejection $\sim$100 for light quarks and $\sim$7 for charm. Using also the appropriate p_T and η dependence, one can produce the $b\bar{b}$ mass spectrum in fig.2b. The background is dominated by irreducible QCD $t\bar{t}b\bar{b}$ events, as the b-tagging performance already good enough (see Table 1). The statistical significance is $S/\sqrt{B} \approx 3.5$ for an integrated luminosity of 60 fb^{-1} (3 years at initial LHC luminosity, 2×10^{33} cm^{-2}s^{-1}).

In the Minimal Supersymmetric Standard Model (MSSM), the $t\bar{t}h$ (with $h \to b\bar{b}$) channel can have a "reasonable" cross-section, depending on the MSSM parameters. The cross-section is in any case larger than for Standard Model $t\bar{t}H$ (with $H \to b\bar{b}$) production for most of the parameter space; the significance is larger than 5σ (the

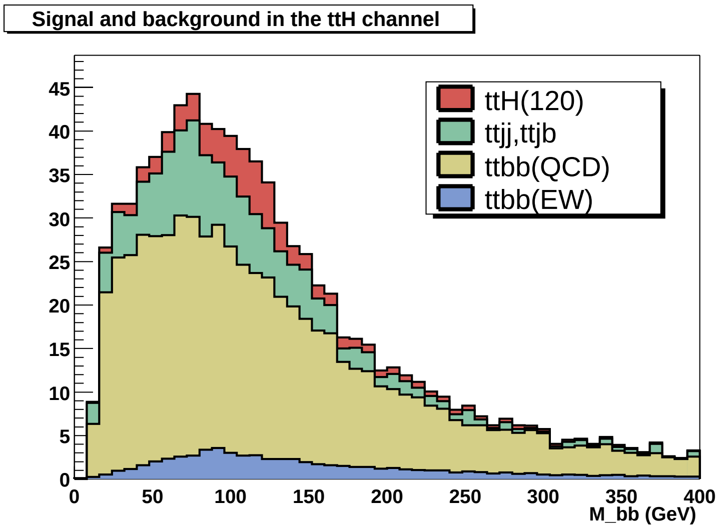

Figure 2: $b\bar{b}$ invariant mass spectrum from $t\bar{t}H(120)$ events and background, after all selection cuts.

"discovery threshold") over most of the parameter space for 100 fb^{-1} of integrated luminosity.

A large number of supersymmetric final states contain several b's and/or τ's. Good b and τ reconstruction allows the full or partial reconstruction of Supersymmetry events and the determination of some sparticle masses. Supersymmetry rates are dominated (depending on the details of the Supersymmetry model) by the production of $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ states. The lightest supersymmetric particle ($\tilde{\chi}_1^0$) is stable, neutral and weakly interacting (escapes the detector), therefore giving a "missing energy" signal. The classical signature for Supersymmetry production consists of an excess of final states with missing energy and several hard central jets arising from $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{q}$ and similar processes. The invariant masses and p_T distributions of multi-jet systems are sensitive to the masses of the sparticles and other parameters of the

Process	σ(pb)	$\sigma \times BR$(pb)
$t\bar{t}H(120)$	0.55	0.11
$t\bar{t}jj$, $t\bar{t}jb$	473	138
$t\bar{t}b\bar{b}$ (QCD)	8.6	2.5
$t\bar{t}b\bar{b}$ (EW)	0.90	0.26

Table 1: Signal and background contributions to the $H \to b\bar{b}$ spectrum in the $t\bar{t}H$ channel, for a Higgs mass of 120 GeV.

model. Supersymmetric cascade decays such as $\tilde{q}_L \to \tilde{\chi}_2^0 q$ (with $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ and $h \to b\bar{b}$) can be detected already after 30 fb^{-1} with more than 5σ significance over most of the model parameter space (see Fig.3).

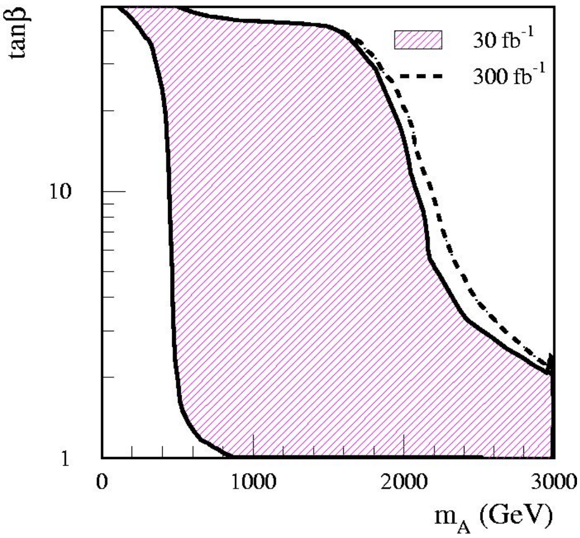

Figure 3: 5σ discovery contours of $h \to b\bar{b}$ from Susy cascade in the $(m_A, \tan\beta)$ plane.

4 B-Physics

Main goals of the B-Physics programme at future hadron accelerators are the measurements of CP violation in B decays, B_s mixing, rare B decay rates. In addition, it will be possible to search for "forbidden" decays, measure precisely Standard Model parameters and test for inconsistencies of the Standard Model, and finally search for Physics beyond the Standard Model.

The B-TeV experiment at FNAL plans to build 30 pixel detector stations and use them for their Level-1 pixel track trigger. The system will allow online track and primary vertex reconstruction, and displaced track selection. The experiment will take data at a centre-of-mass energy of 2 TeV and a luminosity of 2×10^{32} cm^{-2}s^{-1}, for an integrated luminosity of 2 fb^{-1}/year. The experimental programme foresees precision measurements of the CKM parameters: for example $\sin(2\beta)$ can be measured with a precision $\sigma(\sin(2\beta)) \approx 0.017$ after one year using the $B^0 \to J/\psi\ K_s^0$ channel, and similarly for the other angles. Penguin contributions to the asymmetry of $B^0 \to \pi^+\pi^-$ can be determined by the Dalitz plot analysis of $B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$, which is sensitive to both $\sin(2\alpha)$ and $\cos(2\alpha)$.

Consistency checks of the Standard Model are also important: for example, is it true that for the unitarity "triangle" $\alpha + \beta + \gamma = 180°$? The measurement of Δm_s can be compared with the value obtained by the Standard Model global fit (~ 17 ps^{-1}). New Physics can also produce high(er) rates of flavour-changing neutral current decays, such as $B \to K l^+ l^-$ and $B \to K^* l^+ l^-$, identifiable through the Dalitz plots and the $l^+ l^-$ mass spectra.

ATLAS and CMS are well equipped for broad B-Physics programmes. Beauty trigger strategies will be adapted according to luminosity conditions: di-lepton first level triggers at higher luminosities, single-leptons at lower luminosities, followed by track reconstruction. In CP violation the main emphasis will be on underlying mechanisms and evidence of new physics. ATLAS and CMS can measure (in 1 year at low luminosity) $\sin(2\beta)$ with precision similar to B-TeV. The sensitivity to Δm_s goes far beyond SM expectations. All parameters of the decay $B_s \to J/\psi\ \varphi$ can be measured with 1% precision (12% for $\Delta\Gamma_s$). Rare decays such as $B \to \mu\mu$ can be measured also at nominal LHC luminosity (10^{34} cm^{-2}s^{-1}). They will also measure the branching ratio of $B_s \to \mu\mu$ which is in the Standard Model of order 10^{-9}. Precision measurements will be done for $B \to K^* \mu\mu$.

Beauty production and correlations at central LHC collisions can be measured for QCD tests. For the measurement of the B production cross-section, ATLAS and CMS can complement and extend the range of phase space covered by CDF/D0 and by LHC-b and B-TeV, as shown in Fig.4. Overlapping regions will allow the cross-normalization of the results.

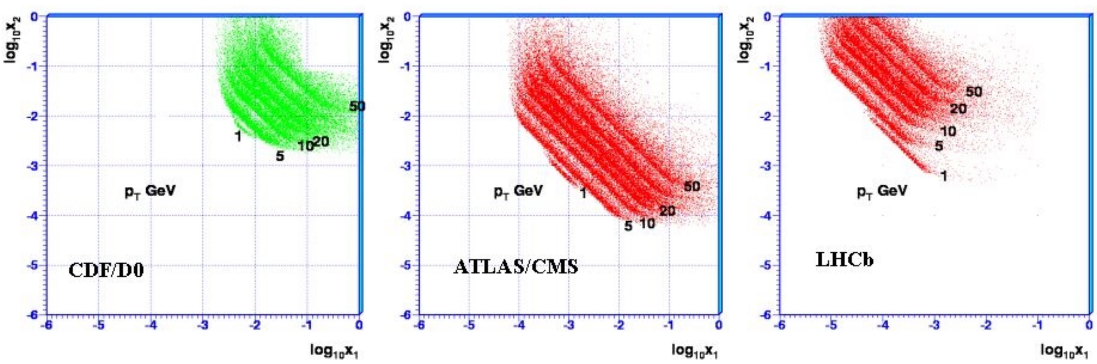

Figure 4: Coverage of the x_{Bj} space for B pair production by different hadronic production experiments.

5 Heavy-Ion Physics

The ALICE heavy-ion experiment has a tracking system consisting of two inner layers of silicon pixel detectors, two layers of silicon drift detectors and two layers of silicon microstrip detectors. A large TPC completes the tracker.

Physics topics of interest are open heavy-quark production, as natural normalization for quarkonia (J/ψ and Υ) production, and as B mesons are a source of non-prompt J/ψ. The cross-section is sensitive to the conditions of the initial reaction phase, to the structure functions and to the possible presence of "thermal" charm. On the other hand, the parton energy loss in deconfined matter alters the momentum spectrum; in any case this is an open window on hard processes.

Exclusive charm hadronic decays can be identified through the full reconstruction of the decay topology of "golden" decay channels: for example ALICE can reconstruct a D^0 signal with a significance of 35 after only 15 days of data taking. Such signals can be used to infer the total charm production cross-section.

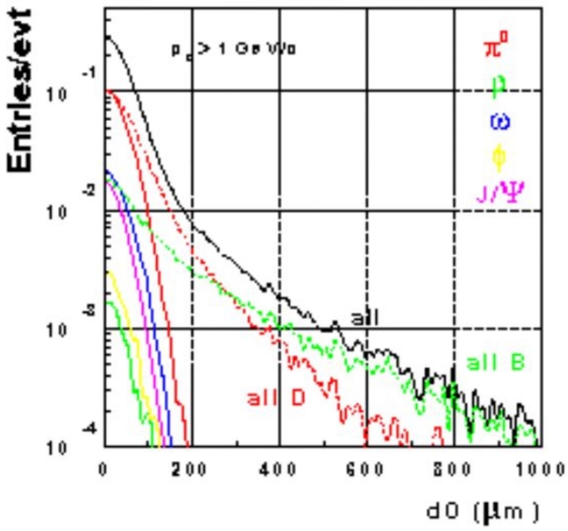

Figure 5: Impact parameter spectrum for electrons detected in heavy-ion interactions in the ALICE detector.

Charm and beauty semileptonic decays can be identified statistically through the analysis of the correlated transverse momentum and impact parameter electron spectra (see Fig.5). ATLAS and CMS can provide complementary information using muon spectra.

6 Conclusions

Pixel vertex detectors are essential for the forthcoming generation of experiments, for the reconstruction of primary interaction points (separation of multiple interactions), b and τ decay vertices (QCD, Higgs and SUSY Physics), tracks in high-density environments (high luminosity or heavy-ion interactions).

Their prospected performance is adequate for the time being, but some major limitations to the physics performance are due to material effects (hadronic interactions, photon conversions, multiple Coulomb scattering). Of some concern are the remaining limitations due to the data rate and dead time at high luminosity, which could cause some loss of data. Of course there are still some large unknowns, such as detector yields and efficiencies. The effects of radiation damage, although studied on large number of prototypes, will have to be properly evaluated on the actual detectors in realistic conditions.

The final conclusion is that, although not all technical challenges are met yet, there is the exciting prospect to have these new detectors available in the near future and be able to explore a new, vast domain of High Energy Physics.

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