

**Presentazione del dott. Fabio Ravera**  
**Dottorato di Ricerca in Fisica - XXIX Ciclo**  
**Università degli Studi di Torino**

Dottorando: *Dott. Fabio Ravera*

Tutor: *Prof.ssa Ada Maria Solano*

Titolo della tesi: *3D silicon pixel detectors for the CT-PPS tracking system and search for exclusive diphoton production with CMS*

Durante il triennio di dottorato il dott. Fabio Ravera ha seguito e sostenuto l'esame relativo ai seguenti corsi della Scuola:

- Calorimetry in particle physics experiments, docente prof.ssa Roberta Arcidiacono
- Fisica dei semiconduttori, docente prof. Paolo Olivero
- Quantum communication, docente prof. Ivo Degiovanni
- Elettronica digitale, docente prof.ssa Michela Greco

L'attività di ricerca del dott. Fabio Ravera nel triennio di Dottorato ha riguardato principalmente lo studio e lo sviluppo dei rivelatori al silicio a pixel detti 3D e la loro applicazione per il rivelatore di tracciamento del CMS-TOTEM Precision Proton Spectrometer (CT-PPS).

Il progetto congiunto CT-PPS delle due Collaborazioni CMS e TOTEM si prefigge di installare rivelatori di tracciamento e di tempo a circa 210 m dal punto di interazione di CMS, lungo le linee di fascio del Large Hadron Collider (LHC), allo scopo di misurare i protoni di alta energia che emergono intatti nelle interazioni di tipo  $pp \rightarrow pXp$ , diffusi a piccolissimo angolo all'interno del tubo a vuoto della linea di fascio. I rivelatori sono inseriti all'interno di strutture meccaniche mobili dette Roman pot così da poterli avvicinare ad una distanza di pochi mm dal fascio, distanza che attualmente corrisponde a  $15\sigma$ . In ragione della loro vicinanza al fascio, ai rivelatori sono richieste tre caratteristiche fondamentali: l'alta resistenza alle radiazioni, una regione non sensibile ridotta al minimo ed un'alta risoluzione spaziale, dell'ordine di  $10\mu\text{m}$ . Per queste ragioni la scelta dei sensori per il rivelatore di tracciamento si è indirizzata verso innovativi sensori di silicio a pixel, detti 3D per la struttura colonnare degli elettrodi, con pixel di  $150\mu\text{m} \times 100\mu\text{m}$ , compatibili con il chip di lettura (ROC) del tracciatore centrale a pixel di CMS. Il sensore è unito al ROC con la tecnica del bump-bonding.

In un primo tempo l'attività di ricerca si è focalizzata sugli studi di performance di questi sensori, di vari produttori e con varie possibili configurazioni degli elettrodi, al fine di validarne l'utilizzo in CT-PPS e sceglierne il disegno finale. Il dott. Ravera è stato responsabile della caratterizzazione dei rivelatori, sia prima sia dopo irraggiamento, con misure in laboratorio e su fasci di test. Ha proceduto all'allestimento del laboratorio, tra cui uno specifico setup laser, alla calibrazione e ottimizzazione del ROC, alla qualifica dei rivelatori, anche con misure a bassa temperatura per studiare i rivelatori irraggiati, misure con sorgenti  $\beta$  e con raggi X. Ha partecipato a numerose campagne di test su fascio, svolte al Fermilab di Chicago con fasci di protoni da 120 GeV/c, occupandosi oltre che delle misure anche dell'analisi completa dei dati raccolti. Ha presentato i risultati di questo lavoro a vari workshop e conferenze internazionali.

Per le competenze acquisite sulla strumentazione di laboratorio e sul setup al Fermilab, ha contribuito in questi anni anche allo studio di altre tipologie di rivelatori, in particolare rivelatori di tracciamento quali i planari a bordo sottile o epitassiali e rivelatori al diamante, che per la loro resistenza alle radiazioni sono considerati, insieme ai sensori 3D, validi candidati per l'upgrade del tracciatore di CMS in vista di High Luminosity LHC. Ha inoltre contribuito allo studio dei rivelatori al silicio detti Ultra-fast (UFSD), che una parte del gruppo di Torino impegnato in CT-PPS ha qualificato come ottimi rivelatori di tempo (con risoluzioni di  $\sim 30$  ps per piano) per CT-PPS.

Nell'ultimo anno l'attività di ricerca si è concentrata sulla costruzione del rivelatore di tracciamento di CT-PPS, che andrà installato nei primi mesi del 2017 durante lo shutdown invernale di LHC. Il dott. Ravera ha seguito personalmente tutta la qualifica dei rivelatori, a cominciare dai primi prototipi dei moduli, con misure in laboratorio e su fasci di test. Ha proposto e portato a termine uno studio volto alla mitigazione del danno da radiazione sul ROC. Ha testato la carta di front-end alla quale è collegato il rivelatore e ha stabilito e validato le procedure per i test finali dei moduli e i parametri di qualifica degli stessi. Ha recentemente terminato i test di tutti i moduli, attualmente in fase di assemblaggio per ottenere i pacchetti di rivelatori da installare nei Roman pot. L'impegno si sta ora spostando verso i test che devono precedere l'installazione, in particolare i test con il sistema finale di raffreddamento e di tenuta del vuoto e i test della catena completa di lettura, che si svolgeranno al CERN nelle prossime settimane. Per il suo contributo fondamentale nella costruzione del rivelatore di tracciamento di CT-PPS, al dott. Ravera è stato attribuito uno dei CMS Achievement Award 2016, riconoscimento che la Collaborazione CMS attribuisce a giovani dottorandi e postdoc che si sono distinti per il loro contributo nei vari sotto-rivelatori.

Infine, nell'ultimo anno, all'attività sul rivelatore si è affiancato lo studio

preliminare di un importante canale di fisica per il quale i rivelatori di CT-PPS svolgono un ruolo chiave. È questo il processo di produzione esclusiva di due fotoni,  $pp \rightarrow p\gamma\gamma p$ , che alla fine del 2015 aveva sollevato grande interesse per l'osservazione di un aumento di eventi a 750 GeV nel canale di decadimento in due fotoni. Benchè l'osservazione non sia stata confermata con la maggiore statistica acquisita nel 2016, questo processo riveste comunque grande interesse per lo studio dei limiti sugli *anomalous quartic gauge coupling parameters* e sull'eventuale osservazione di una deviazione dalle previsioni del Modello Standard. La misura dei due protoni finali in CT-PPS, unita a quella dei due fotoni nel rivelatore centrale di CMS, permette di eliminare la maggior parte degli eventi di fondo. Il dott. Ravera si è finora concentrato sulla simulazione degli eventi di segnale e di fondo, occupandosi in particolare della simulazione della propagazione del protone dal punto di interazione in CMS ai rivelatori di CT-PPS, dei quali ha implementato le corrette geometrie. Si sta ora occupando di includere le informazioni del protone nell'analisi dei dati del rivelatore centrale di CMS e di ottimizzare i tagli per questo canale di fisica.

Durante la sua attività di ricerca il dott. Fabio Ravera ha mostrato grande determinazione ed indipendenza nel perseguire gli obiettivi della ricerca, affrontando costruttivamente le difficoltà del progetto CT-PPS, e con il lavoro presentato in questa tesi ha contribuito in modo originale all'avanzamento delle conoscenze scientifiche nel campo della fisica delle particelle elementari e degli strumenti per la sua indagine. Egli ha raggiunto una vasta ed accurata competenza nel campo dello studio dei rivelatori, sia dal punto di vista hardware sia software. Allo stesso tempo, anche supportato da una solida preparazione accademica, ha affrontato con ottima maturità scientifica lo studio preliminare di un importante canale di fisica per il progetto.

Pertanto si esprime grande apprezzamento per l'eccellente lavoro svolto dal dott. Fabio Ravera durante il triennio del Dottorato di Ricerca.

Torino, 30/11/2016

Il tutor,  
Prof.sa Ada Maria Solano

Firma

## Presentazioni e partecipazione a scuole e conferenze

- QCD at LHC: forward physics and UPC collisions of heavy ions, 26-30 September 2016, Trento (Italy), **plenary talk:** The CT-PPS tracking detector
- 8th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging, 5-9 September 2016, Sestri Levante (Italy), **plenary talk:** The CT-PPS tracking system with 3D pixel detectors
- 3rd Elba Workshop on Forward Physics@LHC Energy, 31 May - 2 June 2016, La Biodola, Isola d'Elba (Italy), **invited talk:** CT-PPS pixel tracking detector
- 11th "Trento" Workshop on Advanced Silicon Radiation Detectors, 30 May - 1 June 2016, LPNHE, Paris (France), **plenary talk:** Beam test results of irradiated 3D pixel sensors for the CMS-TOTEM Precision Proton Spectrometer
- INFN Workshop on Future Detectors, 16-18 December 2015, Torino (Italy)
- CMS Italia 2015, 25-27 November 2015, Pavia (Italy), **plenary talk:** CMS-TOTEM Precision Proton Spectrometer
- Elba2015: 13th Pisa Meeting on Advanced Detectors, 24-30 May 2015, la Biodola, Isola d'Elba (Italy), **plenary talk:** CMS Tracker Upgrade for HL-LHC: R&D Plans, Present Status and Perspectives
- VI Scuola Nazionale "Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica, Applicazioni Spaziali e Fisica Medica, 23-27 March 2015, INFN National Laboratories of Legnaro (Italy), **plenary talk:** Results on FBK 3D pixel detectors for CMS
- 10th Anniversary "Trento" Workshop on Advanced Silicon Radiation Detectors, 17-19 February 2015, Trento (Italy), **plenary talk:** Results on FBK 3D pixel detectors for CMS
- CUPS - CMS Upgrade School, 17-21 November 2014, Hamburg (Germany)
- XXIV Giornate di Studio sui Rivelatori, 28-13 October 2014, Torino (Italy) **plenary talk:** Characterization and performance of 3D silicon pixel detectors for CMS

- 9th "Trento" Workshop on Advanced Silicon Radiation Detectors, 26-26 February 2014, Genova (Italy), **plenary talk:** Characterization and performance of 3D silicon pixel detectors for CMS

### **Attività all'estero e stage**

- Irradiation test of the ROC, CERN, 6-8 November 2016
- Pixel DOC shift, CERN, 8-23 August 2016
- Testbeam on radiation hard silicon detectors, Fermilab, Batavia, Illinois, USA, 23 March - 1 April 2016
- Testbeam on radiation hard silicon detectors, Fermilab, Batavia, Illinois, USA, 30 October - 9 November 2015
- Testbeam on CT-PPS timing detectors, CERN, 15-17 September 2015
- Pixel DOC shift, CERN, 31 August - 7 September 2015
- Pixel DOC shift, CERN, 13-20 July 2015
- Pixel DOC shift, CERN, 29 June - 6 July 2015
- Testbeam on radiation hard silicon detectors, Fermilab, Batavia, Illinois, USA, 7-19 June 2015
- Testbeam on radiation hard silicon detectors, Fermilab, Batavia, Illinois, USA, 19 August - 19 September 2014
- Testbeam on radiation hard silicon detectors, Fermilab, Batavia, Illinois, USA, 27 April - 7 May 2014
- Testbeam on radiation hard silicon detectors, Fermilab, Batavia, Illinois, USA, 26 January - 15 February 2014

### **Elenco delle pubblicazioni con diretto contributo**

- CMS Tracker upgrade for HL-LHC: R&D plans, present status and perspectives, F. Ravera, on behalf of the CMS Collaboration, Nucl.Instrum.Meth. A824 (2016) 455-458

- Laboratory and testbeam results for thin and epitaxial planar sensors for HL-LHC, M. Bubna et al., JINST 10 (2015) C08002
- Design optimization of ultra-fast silicon detectors, N. Cartiglia et al., Nucl.Instrum.Meth. A 796 (2015) 141-148
- Beam test results of a 15 ps timing system based on ultra-fast silicon detectors, N. Cartiglia et al., arXiv:1608.08681, submitted to Nucl.Instrum.Meth. A
- Tracking in 4 Dimensions, Nucl.Instrum.Meth. A (2016), N. Cartiglia et al. In press, available online 3 June 2016, <http://dx.doi.org/10.1016/j.nima.2016.05.078>
- The CT-PPS tracking system with 3D pixel detectors, F. Ravera, on behalf of the CMS and TOTEM Collaborations, To be published in JINST

### Elenco completo delle pubblicazioni

- Decomposing transverse momentum balance contributions for quenched jets in PbPb collisions at  $\sqrt{s[NN]} = 2.76$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1609.02466 [nucl-ex], 10.1007/JHEP11(2016)055, JHEP 1611 (2016) 055.
- Measurement of the ZZ production cross section and  $Z \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$  branching fraction in pp collisions at  $\sqrt{s}=13$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1607.08834 [hep-ex], 10.1016/j.physletb.2016.10.054, Phys.Lett. B763 (2016) 280-303.
- Measurement of the differential cross sections for top quark pair production as a function of kinematic event variables in pp collisions at  $\sqrt{s}=7$  and 8 TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1607.00837 [hep-ex], 10.1103/PhysRevD.94.052006, Phys.Rev. D94 (2016), 052006.
- Search for Resonant Production of High-Mass Photon Pairs in Proton-Proton Collisions at  $\sqrt{s} = 8$  and 13 TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1606.04093 [hep-ex], 10.1103/PhysRevLett.117.051802, Phys.Rev.Lett. 117 (2016), 051802.
- Phenomenological MSSM interpretation of CMS searches in pp collisions at  $\sqrt{s} = 7$  and 8 TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1606.03577 [hep-ex], 10.1007/JHEP10(2016)129, JHEP 1610 (2016) 129.

- Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at  $\sqrt{s} = 7$  and 8 TeV, ATLAS and CMS Collaborations (G. Aad et al.), arXiv:1606.02266 [hep-ex], 10.1007/JHEP08(2016)045, JHEP 1608 (2016) 045.
- Measurement of the W boson helicity fractions in the decays of top quark pairs to lepton + jets final states produced in pp collisions at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1605.09047 [hep-ex], 10.1016/j.physletb.2016.10.007, Phys.Lett. B762 (2016) 512-534.
- Search for supersymmetry in pp collisions at  $\sqrt{s} = 13$  TeV in the single-lepton final state using the sum of masses of large-radius jets, CMS Collaboration (V. Khachatryan et al.), arXiv:1605.04608 [hep-ex], 10.1007/JHEP08(2016)122, JHEP 1608 (2016) 122.
- Measurement of the double-differential inclusive jet cross section in proton–proton collisions at  $\sqrt{s} = 13$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1605.04436 [hep-ex], 10.1140/epjc/s10052-016-4286-3, Eur.Phys.J. C76 (2016), 451.
- Search for new physics in same-sign dilepton events in proton–proton collisions at  $\sqrt{s} = 13$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1605.03171 [hep-ex], 10.1140/epjc/s10052-016-4261-z, Eur.Phys.J. C76 (2016), 439.
- Search for Higgs boson off-shell production in proton-proton collisions at 7 and 8 TeV and derivation of constraints on its total decay width, CMS Collaboration (V. Khachatryan et al.), arXiv:1605.02329 [hep-ex], 10.1007/JHEP09(2016)051, JHEP 1609 (2016) 051.
- Measurement of the integrated and differential  $t\bar{t}$  production cross sections for high- $p_t$  top quarks in  $pp$  collisions at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1605.00116 [hep-ex], 10.1103/PhysRevD.94.072002, Phys.Rev. D94 (2016), 072002.
- Search for narrow resonances in dijet final states at  $\sqrt{s} = 8$  TeV with the novel CMS technique of data scouting, CMS Collaboration (V. Khachatryan et al.), arXiv:1604.08907 [hep-ex], 10.1103/PhysRevLett.117.031802, Phys.Rev.Lett. 117 (2016), 031802.
- Search for lepton flavour violating decays of heavy resonances and quantum black holes to an  $e\mu$  pair in proton-proton collisions at  $\sqrt{s} = 8$  TeV,

CMS Collaboration (V. Khachatryan et al.), arXiv:1604.05239 [hep-ex], 10.1140/epjc/s10052-016-4149-y, Eur.Phys.J. C76 (2016), 317.

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- Search for two Higgs bosons in final states containing two photons and two bottom quarks in proton-proton collisions at 8 TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1603.06896 [hep-ex], 10.1103/PhysRevD.94.052012, Phys.Rev. D94 (2016), 052012.
- Measurement of the top quark mass using charged particles in pp collisions at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1603.06536 [hep-ex], 10.1103/PhysRevD.93.092006, Phys.Rev. D93 (2016), 092006.
- Measurements of  $t\bar{t}$  charge asymmetry using dilepton final states in pp collisions at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1603.06221 [hep-ex], 10.1016/j.physletb.2016.07.006, Phys.Lett. B760 (2016) 365-386.
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- Search for neutral resonances decaying into a Z boson and a pair of b jets or tau leptons, CMS Collaboration (V. Khachatryan et al.), arXiv:1603.02991 [hep-ex], 10.1016/j.physletb.2016.05.087, Phys.Lett. B759 (2016) 369-394.
- $\Upsilon(nS)$  polarizations versus particle multiplicity in pp collisions at  $\sqrt{s} = 7$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1603.02913 [hep-ex], 10.1016/j.physletb.2016.07.065, Phys.Lett. B761 (2016) 31-52.
- Search for s channel single top quark production in pp collisions at  $\sqrt{s} = 7$  and 8 TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1603.02555 [hep-ex], 10.1007/JHEP09(2016)027, JHEP 1609 (2016) 027.



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- Measurement of the differential cross section and charge asymmetry for inclusive  $pp \rightarrow W^\pm + X$  production at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1603.01803 [hep-ex], 10.1140/epjc/s10052-016-4293-4, Eur.Phys.J. C76 (2016), 469.
- Search for direct pair production of supersymmetric top quarks decaying to all-hadronic final states in pp collisions at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1603.00765 [hep-ex], 10.1140/epjc/s10052-016-4292-5, Eur.Phys.J. C76 (2016), 460.
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- Measurement of dijet azimuthal decorrelation in pp collisions at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1602.04384 [hep-ex], 10.1140/epjc/s10052-016-4346-8, Eur.Phys.J. C76 (2016), 536.

- Search for R-parity violating decays of a top squark in proton-proton collisions at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1602.04334 [hep-ex], 10.1016/j.physletb.2016.06.039, Phys.Lett. B760 (2016) 178-201.
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- Search for massive WH resonances decaying into the  $\ell\nu b\bar{b}$  final state at  $\sqrt{s} = 8$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1601.06431 [hep-ex], 10.1140/epjc/s10052-016-4067-z, Eur.Phys.J. C76 (2016), 237.
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- Measurement of inclusive jet production and nuclear modifications in pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, CMS Collaboration (V. Khachatryan et al.), arXiv:1601.02001 [nucl-ex], 10.1140/epjc/s10052-016-4205-7, Eur.Phys.J. C76 (2016), 372.
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