
# Study of the rare decay $\Sigma^+ \to p\mu^+\mu^-$ at LHCb

XXXVI Cycle of the PhD in Physics

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Advisors: Dr. Monica Pepe
Dr. Mauro Piccini
Dr. Viacheslav Duk

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# My first year of PhD

- It has been exactly one year since I started my PhD in Physics

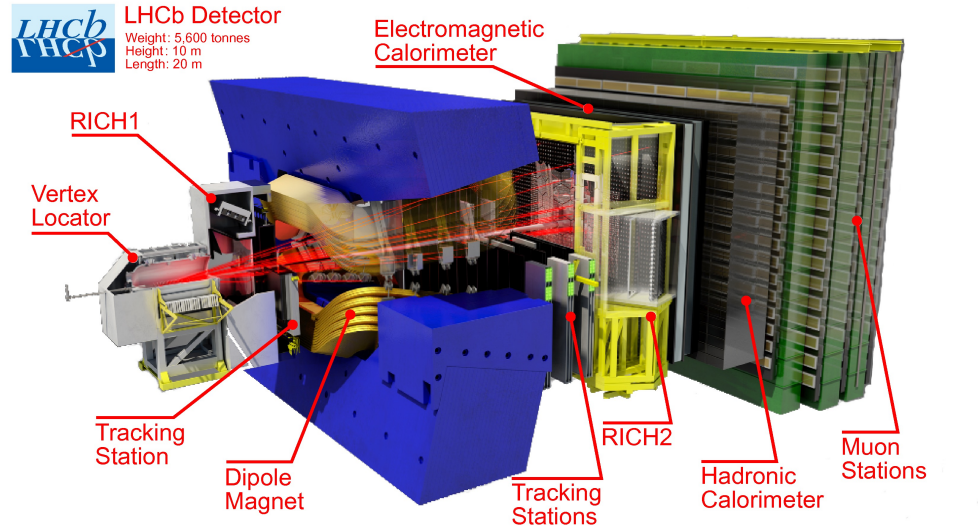
- Many things have happened (both academic and personal):
  - I moved from Rome to Perugia
  - I met new people, both among researchers and my fellow PhD students
  - I was able to participate in many courses and research activities with a high educational level

- Starting from November 2020, I joined the Perugia LHCb group under the supervision of Dr. Monica Pepe, Dr. Mauro Piccini and Dr. Viacheslav Duk

- **PhD thesis**: Study of the rare decay $\Sigma^+ \to p\mu^+\mu^-$ and work on the Light Leak Detector for RICH1 and RICH2 at LHCb

# The LHCb Experiment

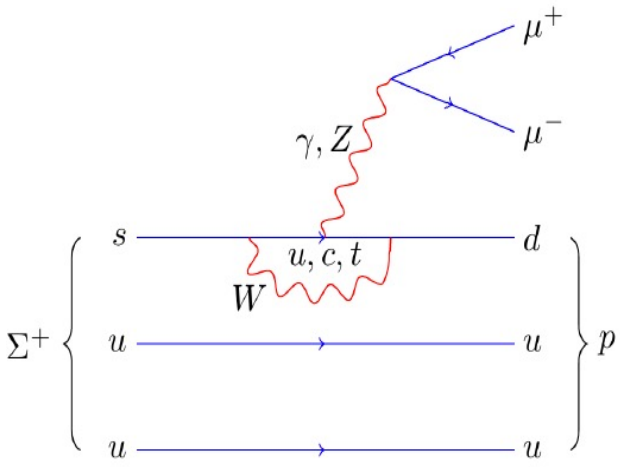
- Large Hadron Collider beauty (LHCb)
  - Experiment specialized in investigating differences between matter and antimatter
- Specialized in detecting mainly forward particles using a series of subdetectors
  - Unlike experiments such as ATLAS and CMS, detects those particles thrown forwards by the collision in one direction
- About 1400 scientists, engineers and technicians from 18 countries make up the LHCb collaboration

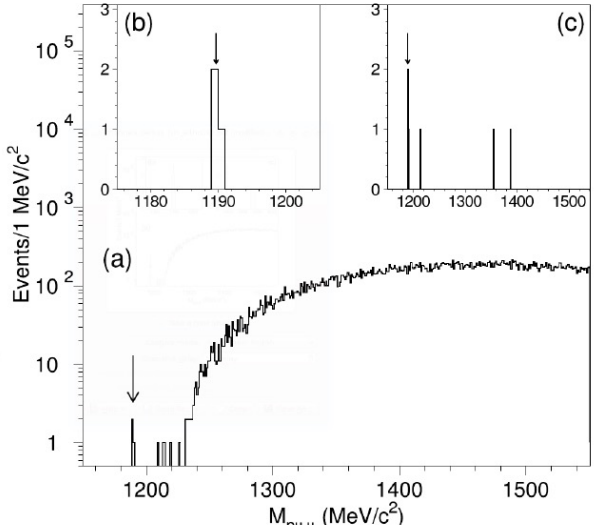


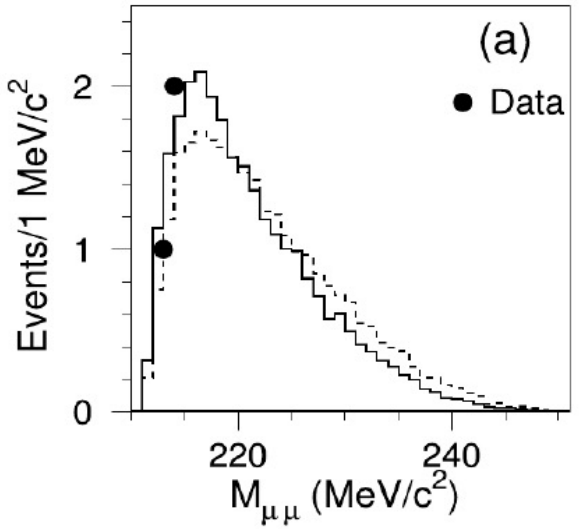

# $\Sigma^+ \to p\mu^+\mu^-$ in the Standard Model - HyperCP

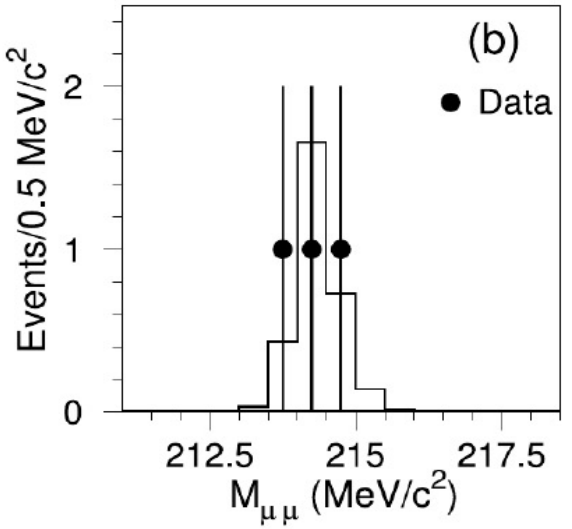
- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare Flavour Changing Neutral Current (FCNC) process
- Evidence for this decay was found by the HyperCP experiment with 3 events
  - Measured branching fraction:
    $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$
- All events have the same dimuon invariant mass pointing towards a $\Sigma^+ \to pX^0(\to \mu^+\mu^-)$ decay
  - Light pseudoscalar Higgs boson, sgoldstino in various supersymmetric models

*Phys. Rev. Lett. 94, 021801 (2005).*



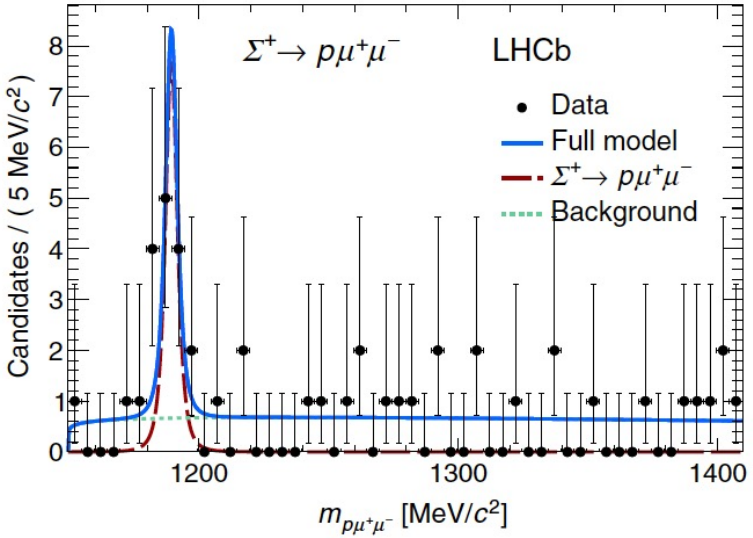



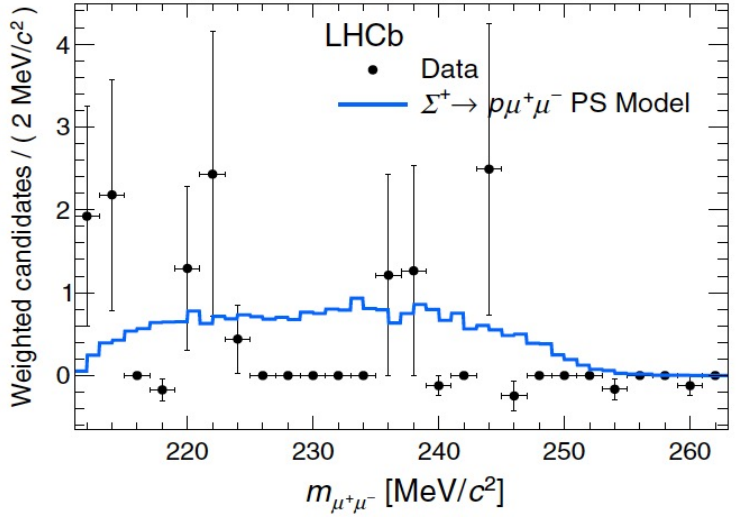



# $\Sigma^+ \to p\mu^+\mu^-$ in the Standard Model - LHCb

- A search for $\Sigma^+ \to p\mu^+\mu^-$ has been performed by LHCb using Run1 data
  - $\sqrt{s} = 7$ and $8\ TeV$, integrated luminosity of $3\ fb^{-1}$
- Evidence for this decay was found with a significance of $4.1\sigma$ including systematic uncertainties
- Measured branching fraction: $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \cdot 10^{-8}$
  - Consistent with the SM prediction
- No significant peak consistent with an intermediate particle is found in the dimuon invariant-mass distribution of the signal candidates



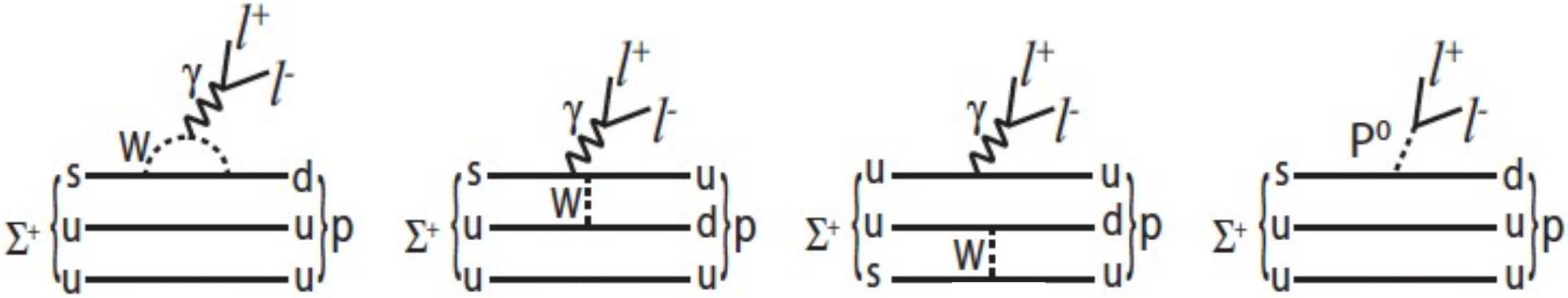




*Phys. Rev. Lett. 120 (2018) 221803.*

# Study of the Rare Decay $\Sigma^+ \to p\mu^+\mu^-$ at LHCb

- **Thesis goal**: Analysis of Run2 data collected by LHCb for the study of rare decay $\Sigma^+ \to p\mu^+\mu^-$ and for its normalization channel $\Sigma^+ \to p\pi^0$

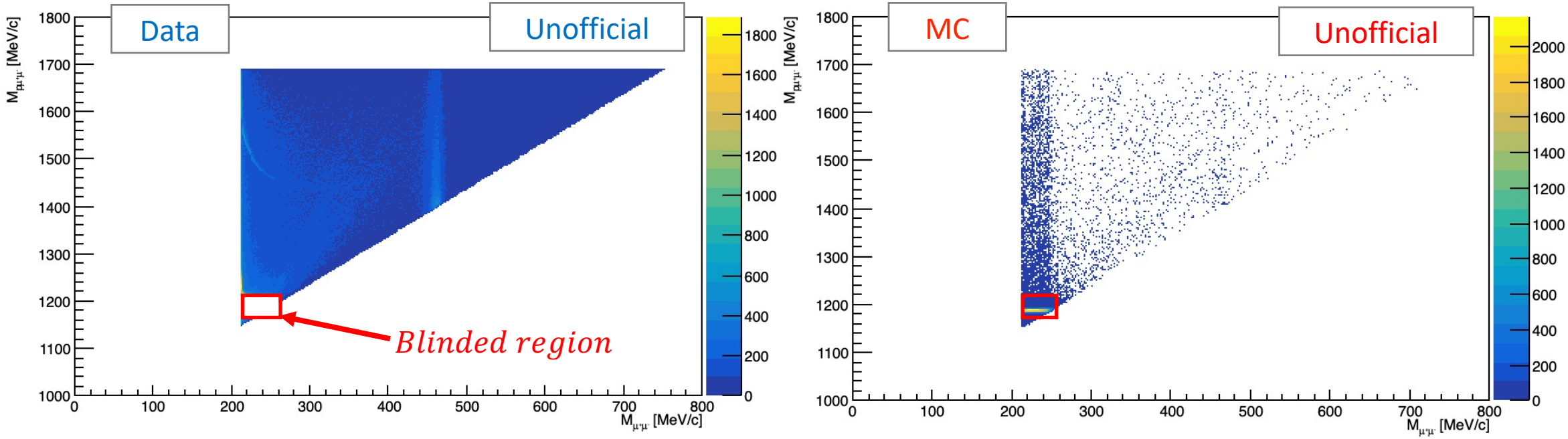
- **Additional activity**: Work on the Light Leak Detector for the RICH1 and RICH2 detectors of the LHCb experiment



# Signal channel: $\Sigma^+ \rightarrow p\mu^+\mu^-$

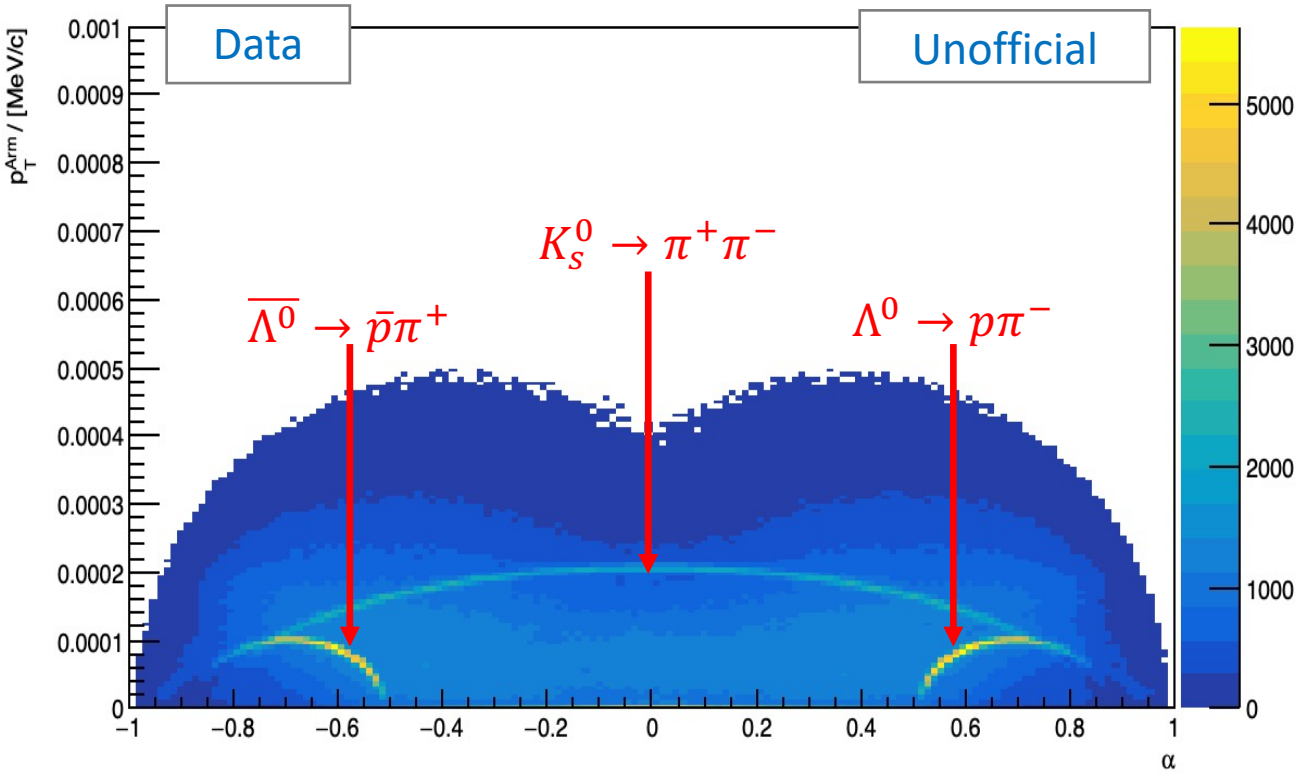
- Blind analysis tecnique has been implemented, the signal region is hidden
  - Box chosen to be larger than the signal region to avoid bias in the final cuts

$$1173.0 - 10 < M_{p\mu^+\mu^-} < 1205.0 + 10\ [MeV] \quad AND \quad 2m_\mu - 10 < M_{\mu^+\mu^-} < (m_{\Sigma^+} - m_p) + 10\ [MeV]$$



# Study of background events: Armenteros-Podolanski Plot

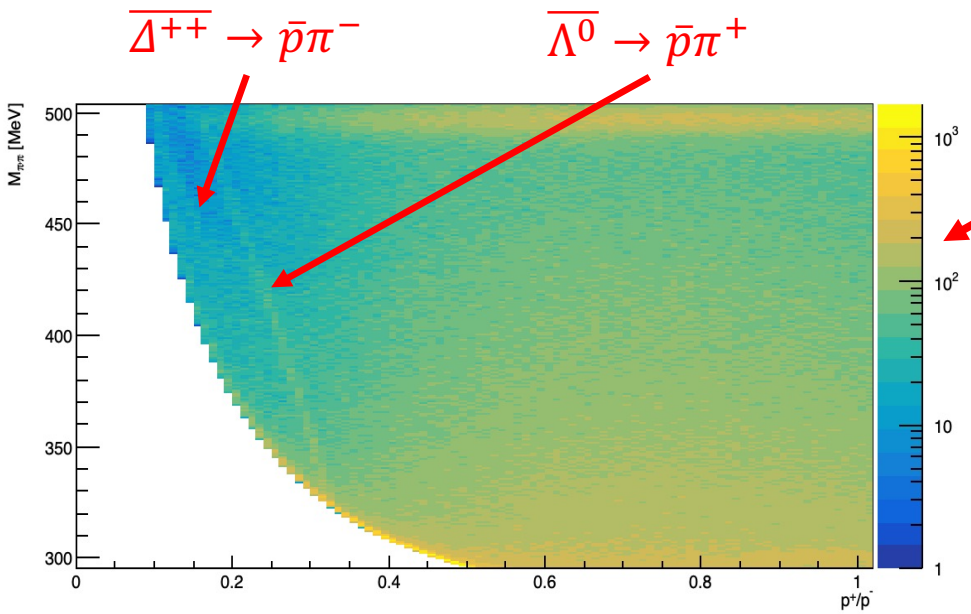
- Main background: Events with pions misidentified as muons + combinatorial
- Background of two-particle decays can be described from the observed momenta and angles of decays in flight: Armenteros-Podolanski Plot

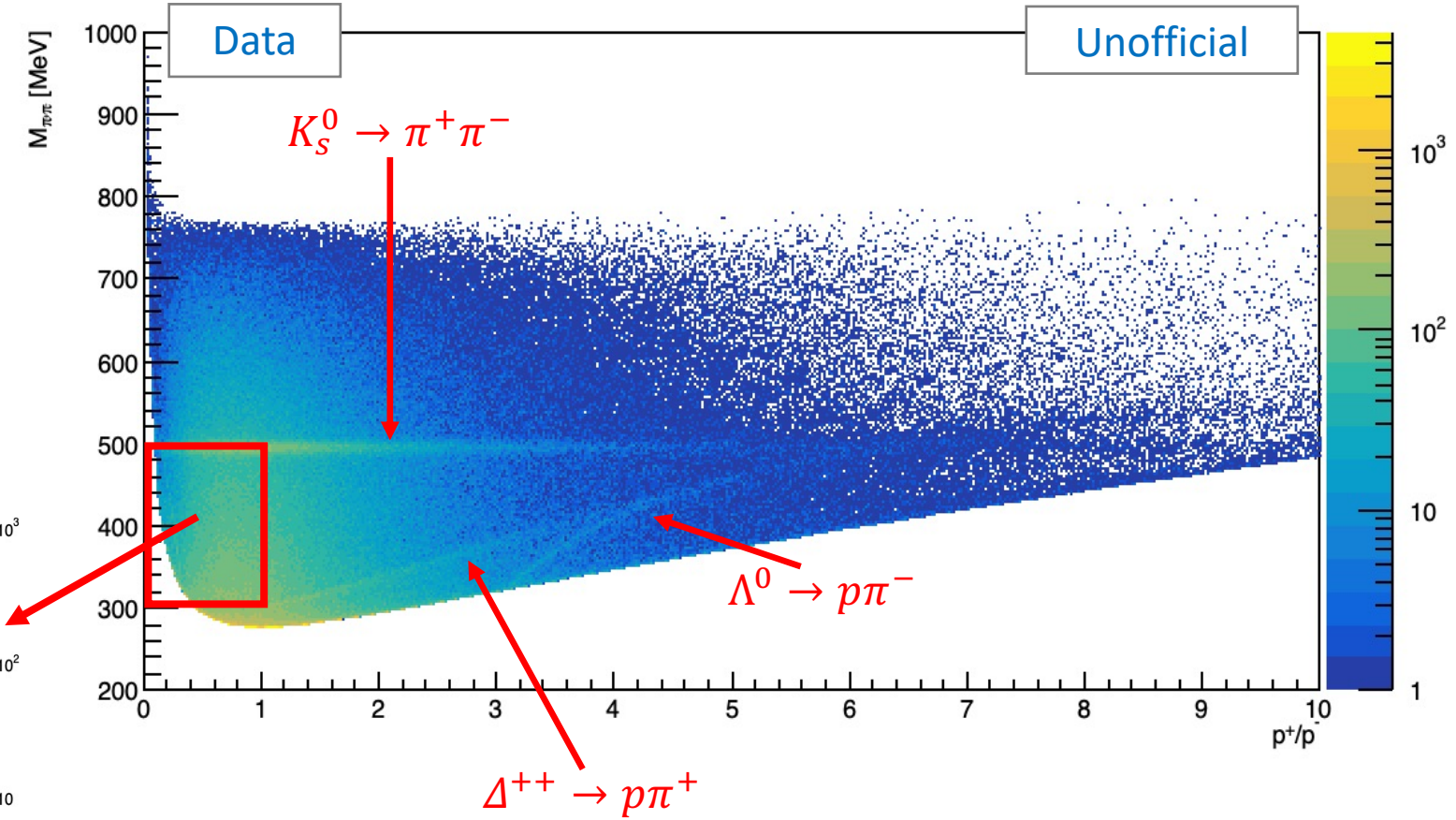



- $p_T^{Arm} = \sqrt{p^2 - p_L^2}$ - Transverse momentum
- $p_L$ - Longitudinal momentum
- $\alpha = \frac{p_L^1 - p_L^2}{p_L^1 + p_L^2}$ - Combination of the secondaries $p_L$
- Center of the ellipse: $(\alpha_0, 0) = \left(\pm\frac{m_1^2 - m_2^2}{M^2}, 0\right)$
- Radii of the ellipse: $\left(r_\alpha, r_{p_T^{Arm}}\right) = \left(\frac{2p_{cm}}{M}, p_{cm}\right)$

# Correlation between $\mu^{\pm}$ momenta and $M_{\pi^+\pi^-}$

- Background event map containing at least one charged pion
- All events identified with the Armenteros-Podolanski plots

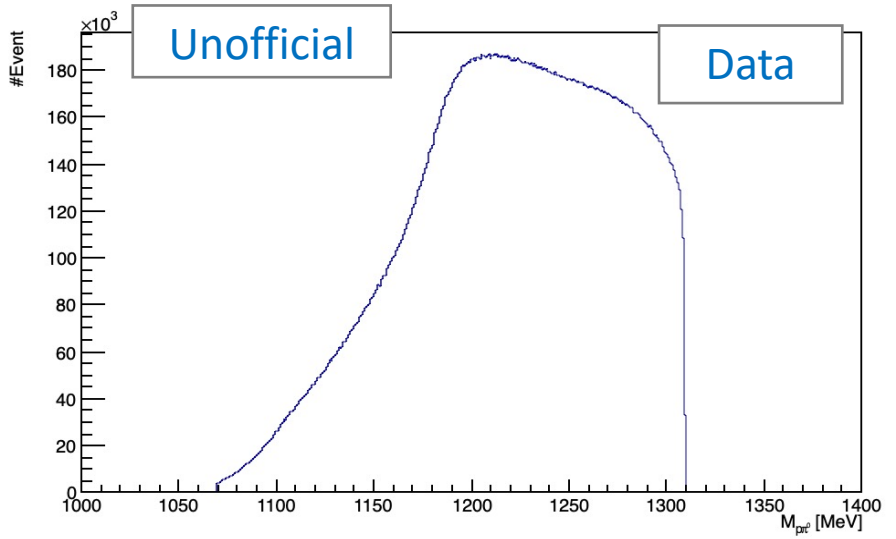


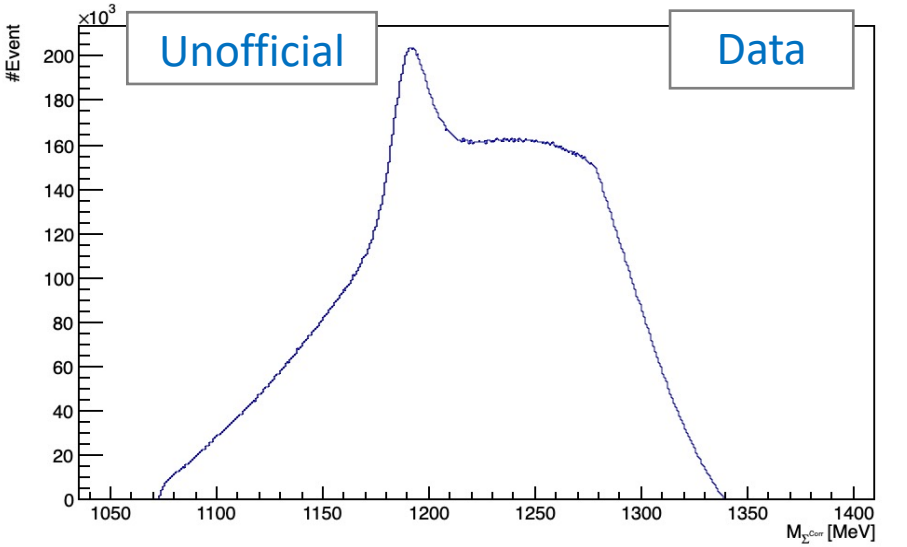



# Normalization Channel: $\Sigma^+ \to p\pi^0(\pi^0 \to \gamma\gamma)$

- The normalization channel $\Sigma^+ \to p\pi^0$ was also explored
  - $\Gamma_i/\Gamma = 51.77 \pm 0.30\ \%$
  - $\Sigma^+ \to p\pi^0(\pi^0 \to \gamma\gamma)$
  - No blind region

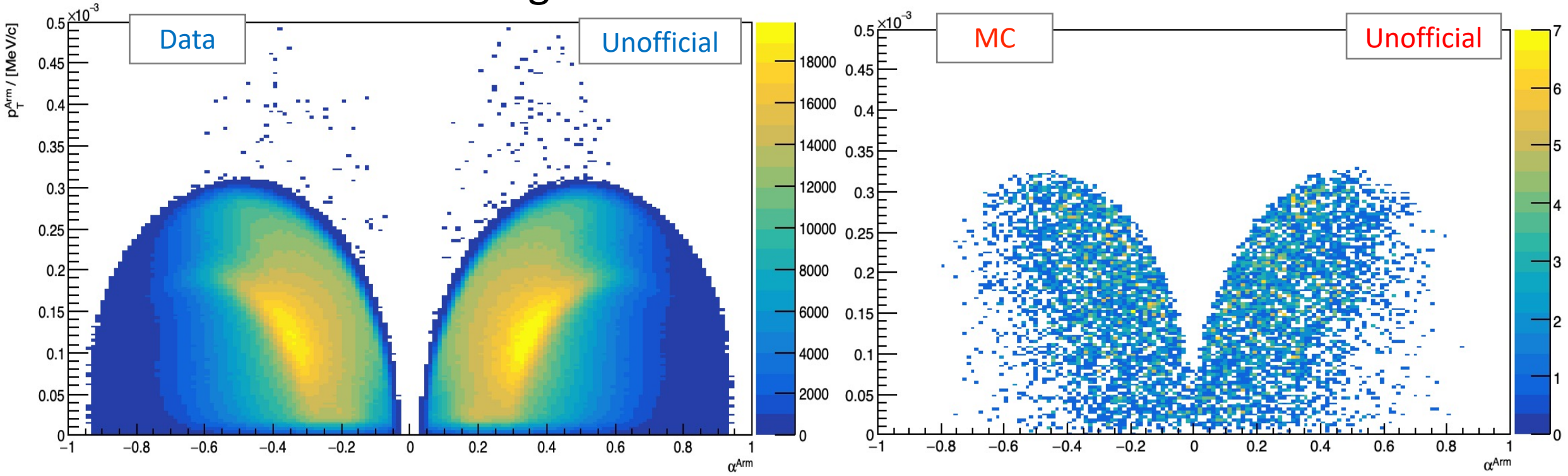
- $M_{p\pi^0}$ and $M_\Sigma$ corrected
  - $M_\Sigma^{corr} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}$
  - $m_{\pi^0}$ from PDG
  - Account for the limited precision in the reconstructed invariant mass of the two photons ($m_{\gamma\gamma}$)



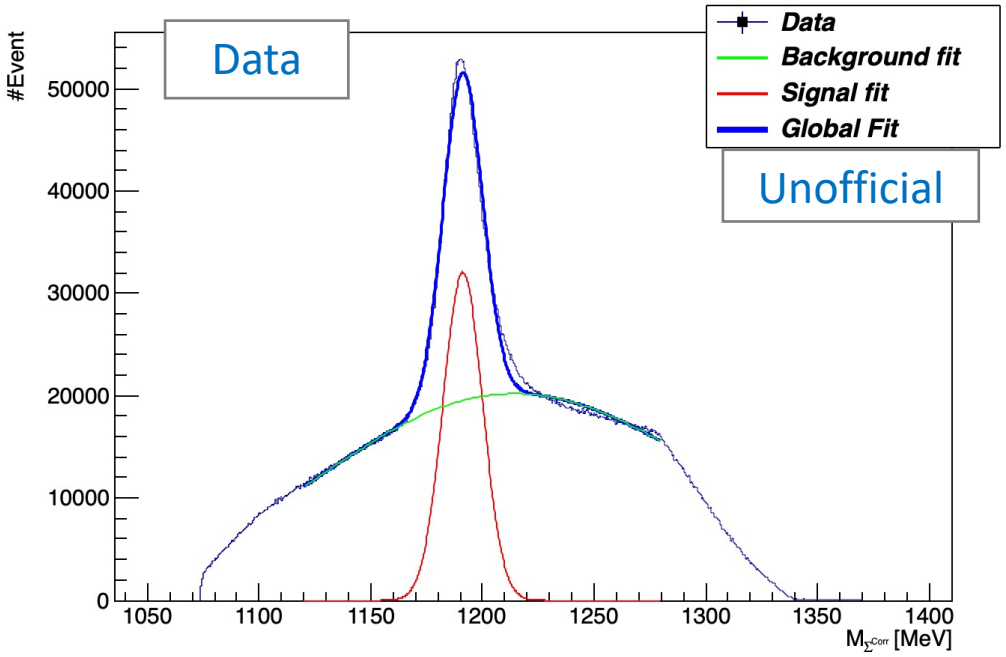
# Armenteros-Podolanski Plot: $p\pi^0(\pi^0 \rightarrow \gamma\gamma)$

- For the definition of cuts the Armenteros-Podolanski plot was once again exploited
  - Defined cuts also using variables such as PIDs



# Fit on $M_{\Sigma}^{corr}$ for $\Sigma^{+} \rightarrow p\pi^{0}(\pi^{0} \rightarrow \gamma\gamma)$

- Fit on the current final cut on $M_{\Sigma}^{corr}$ has been implemented
- Fit function implemented : Crystal-Ball + Argus function




$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

Crystal-Ball (Signal)

where

$$A = \left(\frac{n}{|\alpha|}\right)^{n} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$B = \frac{n}{|\alpha|} - |\alpha|,$$

$$N = \frac{1}{\sigma(C+D)},$$

$$C = \frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$D = \sqrt{\frac{\pi}{2}}\left(1 + \operatorname{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right).$$

$$f(x;\chi,c) = \frac{\chi^3}{\sqrt{2\pi}\,\Psi(\chi)} \cdot \frac{x}{c^2}\sqrt{1-\frac{x^2}{c^2}}\exp\left\{-\frac{1}{2}\chi^2\left(1-\frac{x^2}{c^2}\right)\right\},$$

Argus (Background)

for $0 \leq x < c$. Here $\chi$ and $c$ are parameters of the distribution and

$$\Psi(\chi) = \Phi(\chi) - \chi\phi(\chi) - \tfrac{1}{2},$$

# Analysis - Future Prospects

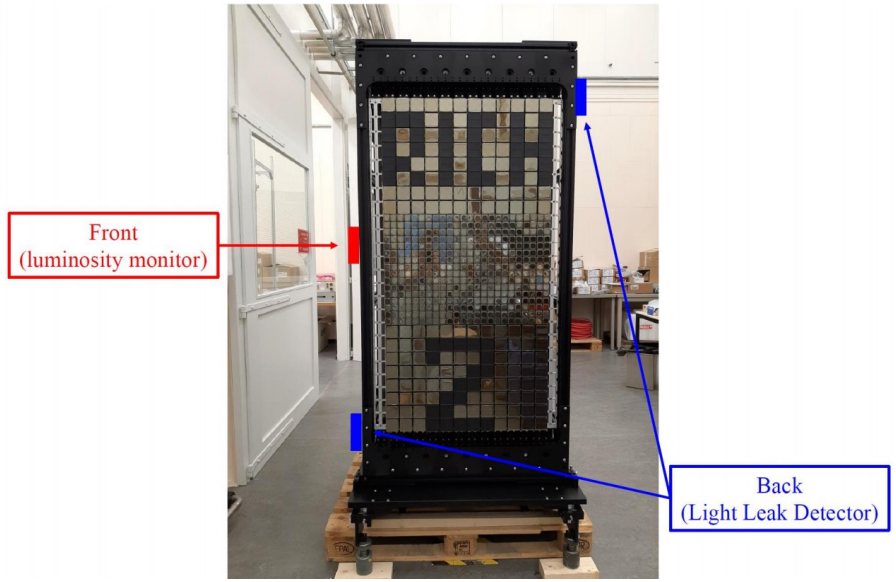
- The analysis on the $\Sigma^+ \to p\mu^+\mu^-$ decay has officially begun in the INFN section of Perugia

- What has been done:
  1) Implementation of a blind analysis technique (Hidden Box) for $\Sigma^+ \to p\mu^+\mu^-$
  2) Production of the Armenteros-Podolanski Plot for both $\Sigma^+ \to p\mu^+\mu^-$ and $\Sigma^+ \to p\pi^0(\pi^0 \to \gamma\gamma)$
  3) Implementation of the first cuts for both $\Sigma^+ \to p\mu^+\mu^-$ and $\Sigma^+ \to p\pi^0(\pi^0 \to \gamma\gamma)$
  4) First fit attempt on $M_\Sigma^{corr}$ with Crystal-Ball + Argus function

- What to do now:
  1) Identification of all background events for $\Sigma^+ \to p\mu^+\mu^-$
  2) Look at more variables to define cuts for both $\Sigma^+ \to p\mu^+\mu^-$ and $\Sigma^+ \to p\pi^0(\pi^0 \to \gamma\gamma)$
  3) Look at the Dalitz decay channel (also double Dalitz) for $\Sigma^+ \to p\pi^0$
  4) Improve the fit on $M_\Sigma^{corr}$

# Light Leak Detector

- Within the LHCb collaboration I am part of the group that deals with RICH1 and RICH2
- Currently I am working on the Light Leak Detector (LLD), a subsystem designed to detect photons from the environment outside a RICH detector
- LLD designed and built entirely by the LHCb group of Perugia




Left: R7400U Right: R7401/R7402

# Testing and assembly

- The LLD modules are tested and assembled in Perugia
  - K-meson laboratory (INFN), second floor
- Once assembled and tested, the LLD modules are packaged and shipped to CERN
- Once arrived, they are mounted in special columns for RICH1 and RICH2


# Direct contact with Cern

- From August 30th to September 13° I carried out my first journey at the LHCb experiment
- Next travel: from October 26th to November 4°
  - Test beam for RICH and hardware activity in the LHCB pit


# Educational Activities

**Courses (first semester):**

- *Introduction to Effective Field Theory (EFT)*
- *Probability and uncertainty in measurements*
- *Nanosystems and advanced materials*
- *Formazione trasversale ai dottorandi – EDIZIONE 2020*

**Courses (second semester):**

- *Multimessenger Astrophysics - from EM multifrequency to gravitational waves*
- *Physics at LHC*
- *Introduction to Atmospheric Physics, Climate and COPERNICUS DATA STORE (CDS)*
- *Teaching and Learning Physics at University*

[Updated to 25/10/2021]

**Schools:**

- *49th SLAC Summer Institute*

**Internal seminars:**

- *Perugia Advanced Physics (Cycle)*
- *Physics Highlights Perugia (Cycle)*
- *Soft X-ray Spectroscopies for liquids*

**External seminars:**

- *INFN Roma1 General Seminars (Cycle)*
- *Inferring vaccine efficacies and their uncertainties. A simple model implemented in JAGS/rjags*
- *Shedding light on X17 (3-day workshop)*

**Other activities**

- *LHCb@International Masterclass 2020*
- *LHCb Commissioning, Analysis, Technical meetings (Analysis/Technical meetings every 14 days)*

# List of Publications and Papers

**Corrisponding Author:**

- *Searching for dark sectors in multi lepton final state in $e^+e^-$ collisions*
  *April 2021, Journal of High Energy Physics*

- *Searching for New Physics with multilepton events at PADME*
  *August 2021, Il Nuovo Cimento C*

**Author:**

- Tests of lepton universality using $B^0 \to K_S^0 \ell^+ \ell^-$ and $B^+ \to K^{*+} \ell^+ \ell^-$ decays
- *Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13\ TeV$*
- *Observation of two new excited $\Xi_b^0$ states decaying to $\Lambda_b^0 K^- \pi^+$*
- *Simultaneous determination of CKM angle $\gamma$ and charm mixing parameters*
- *Observation of the suppressed $\Lambda_b^0 \to DpK^-$ decay with $D \to K^+\pi^-$ and measurement of its CP asymmetry*
- *Study of $Z$ bosons produced in association with charm in the forward region*
- *Measurement of $\chi_{cl}(3872)$ production in proton-proton collisions at $\sqrt{s} = 8$ and $13\ TeV$*
- *Study of the doubly charmed tetraquark $T_{cc}^+$*
- *Measurement of the $W$ boson mass*
- *Observation of an exotic narrow doubly charmed tetraquark*
- *Updated search for $B_c^+$ decays to two charm mesons*

[Updated to 25/10/2021]

# Thanks for your attention