Final results of the OPERA experiment on $\nu_\tau$ appearance in the CNGS beam

Giuliana Galati, Ph.D
Università Federico II & INFN, Napoli

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Outline

❖ The OPERA experiment
❖ 2015: discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance
❖ New strategy for $\nu_\tau$ selection
❖ Final results about $\nu_\mu \rightarrow \nu_\tau$ appearance:
  ‣ $\nu_\tau$ appearance significance improvement
  ‣ measurement of $\Delta m^2_{23}$ and $\nu_\tau$ CC cross section on lead
  ‣ $\nu_\tau$ lepton number observation
❖ Final results about $\nu_\mu \rightarrow \nu_e$ appearance
❖ On-going analysis
Neutrino Oscillations

- **Neutrinos in the Standard Model:**
  - *massless*, electrically neutral, weakly interacting particles, spin 1/2
  - 3 flavours: $\nu_e$, $\nu_\mu$, $\nu_\tau$ and their antiparticles
  - lepton numbers are conserved
  - neutrino flavours do not change

- 1957, Pontecorvo: neutrinos could be a state superimposition of two different massive neutrinos

- 1962, Maki, Nakagawa and Sakata: **mixing between neutrinos of different flavours**

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23} \\
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13} \\
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1 \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

- **Amospheric ν:** SuperK, K2K, MINOS, T2K …
- **Chooz, Daya Bay, RENO, T2K, MINOS, NOvA …**
- **Solar ν:** Borex, SuperK, SNO, KamLAND …
The atmospheric neutrino anomaly

- T. Kajita, Neutrino’98: Super-Kamiokande discovery of oscillations with atmospheric neutrinos

Results confirmed by other experiments (SNO, MACRO, Soudan-2)

- The missing $\nu_\mu$ must have oscillated into $\nu_\tau$ or into a new non-interacting “sterile” neutrino $\nu_x$

Ref: Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. Phys. Rev. Lett., 81:1562–1567, 1998
The OPERA experiment

❖ The OPERA experiment (Oscillation Project with Emulsion tRacking Apparatus) was designed to directly observe, for the first time in **APPEARANCE MODE**, the $\nu_\mu \rightarrow \nu_\tau$ oscillation in a pure $\nu_\mu$ beam.

❖ The search for direct appearance was based on revealing the short-lived $\tau$ lepton produced in $\nu_\tau$ charged-current interactions.

❖ Requirements:

• High energy beam for $\tau$ production
• Long baseline for oscillation at the atmospheric scale
• High density and large target mass for statistics
• Micrometric accuracy and resolution to identify $\tau$ decays and neutrino interaction kinematics

| Channel | BR  |
|---------|-----|
| $\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$ | 17.8% |
| $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$ | 17.7% |
| $\tau^- \rightarrow h^- \nu_\tau (n\pi^0)$ | 49.5% |
| $\tau^- \rightarrow 3h\nu_\tau (n\pi^0)$ | 15.0% |
CERN Neutrinos to Gran Sasso

- Long baseline (730 km from CERN to LNGS)
- $\langle E_\nu \rangle$ on target $\sim 17$ GeV
- $L/E \sim 43$ km/GeV
- $\bar{\nu}_\mu$ contamination = 2.1%
- $\nu_e$ and $\bar{\nu}_e$ contam. <1%
- $\nu_\tau$ contamination negligible
- Data taking from 2008 to 2012
- #p.o.t. = $17.97 \cdot 10^{19}$
The OPERA detector

Underground location: **Gran Sasso Laboratory** (10^6 reduction of cosmic ray flux)
The OPERA detector

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Underground location: Gran Sasso Laboratory (10^6 reduction of cosmic ray flux)
57 films of nuclear emulsion (300 μm thick)
56 lead plates (1mm thick)
8.3 kg
10 $X^0$
Fast fully automated optical microscopes
3D track reconstruction with **micrometric** resolution
Changeable Sheets Doublet

Two emulsion films, packed in an envelope placed inside a plastic cover, to be removed without opening the brick

- Interface between the brick and the closest downstream TT plane
- Go from Target Trackers resolution (~cm) to the μm spatial resolution of nuclear emulsions
- Predictions about the area to be scanned

✓ confirm the brick
✓ reduce scanning load
✓ save detector target mass
Main background sources

Signal topology:

Possible backgrounds:

Charmed hadron decays where muon at 1ry vtx is not identified

Reduced by Track Follow-down procedure

Hadronic re-interactions

Reduced by track scanning and nuclear fragment search

Large angle muon scattering

Eur. Phys.J. C74 (2014) 2986

PTEP9 (2014) 093C01

IEEE Transactions on Nuclear Science Vol. 62, 5, 2015
Track Follow Down

To separate muons from hadrons, momentum-range correlations are characterized by the discriminating variable $D_{TFD}$:

$$D_{TFD} = \frac{L}{R_{lead}(p)} \frac{<\rho>}{\rho_{lead}}$$

Is Muon if $D_{TFD} > 0.8$

Is Hadron if $D_{TFD} < 0.6$
\( \nu_\tau \) Appearance kinematical selection

| Variable      | \( \tau \rightarrow 1h \) | \( \tau \rightarrow 3h \) | \( \tau \rightarrow \mu \) | \( \tau \rightarrow e \) |
|---------------|----------------|----------------|----------------|----------------|
| \( z_{dec} \) (\( \mu m \)) | [44, 2600] | <2600 | [44, 2600] | <2600 |
| \( p_{miss}^T \) (GeV/c) | <1* | <1* | / | / |
| \( \phi_{IH} \) (rad) | >\( \pi/2* \) | >\( \pi/2* \) | / | / |
| \( p_{2\text{ry}} \) (GeV/c) | >0.6 (0.3)* | / | >0.25 | >0.1 |
| \( p_{2\text{ry}} \) (GeV/c) | >2 | >3 | [1, 15] | [1, 15] |
| \( \theta_{kink} \) (rad) | >0.02 | <0.5 | >0.02 | >0.02 |
| \( m, m_{min} \) (GeV/c\(^2\)) | / | [0.5, 2] | / | / |

Cuts marked with * are not applied for Quasi-Elastic event

* \( p_{2\text{ry}}^T \) cut is 0.3 in the presence of \( \gamma \) particles associated to the decay vertex

**p\(^T\)\(_{2\text{ry}}\) for \( \tau \rightarrow \mu \)**

**\( \phi_{IH} \) for \( \tau \rightarrow 3h \)**
2010: the 1\textsuperscript{st} $\nu_\tau$ candidate
2010: the 1$^{\text{st}}$ $\nu_\tau$ candidate
The first 5 $\nu_\tau$ candidates

- $\tau \rightarrow h$
- $\tau \rightarrow 3h$
- $\tau \rightarrow \mu$

Physics Letters B691 (2010) 138

JHEP 1311 (2013) 036

Phys. Rev. D89 (2014) 5, 051102

PTEP 10 (2014) 101C01

Phys. Rev. Lett. 115 (2015) no.12, 121802
Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance in the CNGS neutrino beam

| Channel | Expected Background | Expected Signal | Observed |
|---------|---------------------|-----------------|----------|
| $\tau \rightarrow 1h$ | $0.04 \pm 0.01$ | $0.52 \pm 0.10$ | 3        |
| $\tau \rightarrow 3h$ | $0.17 \pm 0.03$ | $0.73 \pm 0.14$ | 1        |
| $\tau \rightarrow \mu$ | $0.004 \pm 0.001$ | $0.61 \pm 0.12$ | 1        |
| $\tau \rightarrow e$ | $0.03 \pm 0.01$ | $0.78 \pm 0.16$ | 0        |
| **Total** | **0.25 \pm 0.05** | **2.64 \pm 0.53** | **5**    |

Probability of background fluctuation = $1.1 \cdot 10^{-7}$

$\rightarrow$ absence of signal excluded with a significance of $5.1\sigma$

Ref: Discovery of tau neutrino appearance in the CNGS neutrino beam with the OPERA experiment

PRL 115 (2015) 121802
New Strategy for the $\nu_\tau$ candidate selection

**Goal**: estimate the oscillation parameters in appearance mode and $\nu_\tau$ properties with reduced statistical error

- Looser kinematical selection to increase the number of $\nu_\tau$ candidate
- Multivariate analysis: Boosted Decision Tree

New Strategy applied to the final sample:

| Category                        | Total |
|---------------------------------|-------|
| p.o.t. ($10^{19}$)              | 17.97 |
| 0$\mu$ events                   | 1197  |
| 1$\mu$ events ($p_\mu < 15$ GeV/c)| 4406  |
| Total events                    | 5603  |
# New Kinematical Selection

| Variable       | \( \tau \rightarrow 1h \) | \( \tau \rightarrow 3h \) | \( \tau \rightarrow \mu \) | \( \tau \rightarrow e \) |
|----------------|----------------------------|----------------------------|-----------------------------|-----------------------------|
|                | OLD            | NEW            | OLD            | NEW            | OLD            | NEW            | OLD            | NEW            |
| \( z_{\text{dec}} (\mu m) \) | [44, 2600] | <2600          | <2600          | <2600          | [44, 2600] | <2600          | <2600          | <2600          |
| \( \theta_{\text{kink}} (\text{rad}) \) | >0.02         |                | <0.5           | >0.02          | >0.02         |                | >0.02          |                |
| \( p_{2\text{ry}} (\text{GeV/c}) \) | >2            | >1             | >3             | >1             | [1, 15]      | >1             | >0.25          | >0.1           |
| \( p_{2\text{ry}}^T (\text{GeV/c}) \) | >0.6 (0.3)    | >0.15          | /              | /              | >0.25         | >0.1           | /              | /              |
| \( p_{\text{miss}}^T (\text{GeV/c}) \) | < 1           | /              | < 1            | /              | /             | /              | /              | /              |
| \( \phi_{\text{IH}} (\text{rad}) \) | >\(\pi/2\)   | /              | >\(\pi/2\)    | /              | /             | /              | /              | /              |
| \( m, m_{\text{min}} (\text{GeV/c}^2) \) | /             | /              | [0.5, 2]       | /              | /             | /              | /              | /              |

*Decay vertex definition*
## New Kinematical Selection

A table showing kinematical selection parameters for different decay modes:

| Variable         | $\tau \rightarrow 1h$ | $\tau \rightarrow 3h$ | $\tau \rightarrow \mu$ | $\tau \rightarrow e$ |
|------------------|------------------------|------------------------|-------------------------|-----------------------|
|                  | OLD        | NEW       | OLD        | NEW       | OLD        | NEW       | OLD        | NEW       | OLD        | NEW       |
| $z_{\text{dec}}$ (µm) | [44, 2600] | $<2600$   | $<2600$    | $<2600$   | [44, 2600] | $<2600$   | $<2600$    | $<2600$ |
|                  | $>0.2$     |           | $<0.5$    | $>0.02$   |           | $>0.02$   |           | $>0.02$ |
|                  | $>2$       | $>1$      | $>3$      | $>1$      |           | $>1$      |           | $>1$     |
| $p_{2\text{ry}}$ (GeV/c) | $>0.6 (0.3)$ | $>0.15$  |           |           |           |           |           |          |
| $p_{2\text{ry}}^T$ (GeV/c) | $<1$       | /         | $<1$      | /         |           | /         |           | /        |
| $\phi_{\text{IH}}$ (rad) | $>\pi/2$  | /         | $>\pi/2$ | /         |           | /         |           | /        |
| $m, m_{\text{min}}$ (GeV/c²) | /         |           | [0.5, 2] | /         |           | /         |           | /        |

Short decays now included!
p^{T}_{2\text{ry}} \text{ cut in } \tau \rightarrow h \text{ decay channel}

- Removing the cut on p^{T}_{2\text{ry}} would lead to an unaffordable increase of hadronic re-interaction background
- Blind study to optimise this cut
- Aim: minimize the uncertainty on the product of the Range of $\Delta m^2_{23} \cdot \sigma_{\nu\tau}$

| $p^{T}_{2\text{ry}}$ cut (GeV/c) | Increase Factor |
|-------------------------------|-----------------|
| 0.10                          | 71              |
| 0.15                          | 54              |
| 0.20                          | 45              |
| 0.25                          | 38              |
| 0.30                          | 31              |

Increase factor = $\frac{N_{\text{bkg \ NEW \ CUT}}}{N_{\text{bkg \ STANDARD}}}$

Best cut: 0.15 GeV/c
Number of expected events

| Channel | Expected Background | $\nu_\tau$ Exp. | Observed |
|---------|---------------------|-----------------|----------|
| $\tau \rightarrow 1h$ | | 2.96 ± 0.59 | 6 |
| $\tau \rightarrow 3h$ | | 1.83 ± 0.37 | 3 |
| $\tau \rightarrow \mu$ | | 1.15 ± 0.23 | 1 |
| $\tau \rightarrow e$ | | 0.84 ± 0.17 | 0 |
| Total | | 6.8 ± 0.75 | 10 |

10 observed events: 5 “golden” + 5 “silver”

Monte Carlo simulation normalized to the expected number of events
5 additional $\nu_T$ candidates

Event 11143018505

Event 11172035775

Event 11213015702

Event 9190097972

Event 10123059807
Event 11143018505: a peculiar topology

Muon-less event with 2 decay vertices

- *Ad hoc* simulations and multivariate analysis to distinguish between possible interpretations

| Sample                | μ mis-identified | Exp Events ($10^{-3}$) |
|-----------------------|------------------|------------------------|
| $\nu_\tau \text{ CC + charm}$ |                  | 45                     |
| $\nu_\mu \text{ CC + charm + } h_{\text{int}}$ | yes              | 21                     |
| $\nu_\mu \text{ NC + cc_bar}$ |                  | 13                     |
| $\nu_\tau \text{ CC + } h_{\text{int}}$ |                  | 9                      |
| $\nu_\mu \text{ CC + 2}h_{\text{int}}$ | yes              | 4                      |
| $\nu_\mu \text{ NC + 2}h_{\text{int}}$ |                  | 4                      |
| **TOTAL**             |                  | **100**                |

Probability of not being $\nu_\tau \text{ CC + charm} \sim 10^{-4}$

$\rightarrow$ Significance $= 3.5 \sigma$
Examples of signal and background distributions

$\tau\rightarrow 1h$ : 6 $\nu_\tau$ candidates

Signal: $\tau\rightarrow 1h$ (DIS + QE)
Background: - charm$\rightarrow 1h$ (10.5%)
- had re-int (89.5%)

$\tau\rightarrow 3h$ : 3 $\nu_\tau$ candidates

Signal: $\tau\rightarrow 3h$ (DIS + QE)
Background: - charm$\rightarrow 3h$ (84.6%)
- had re-int (17.3%)

$\tau\rightarrow \mu$ : 1 $\nu_\tau$ candidate

Signal: $\tau\rightarrow \mu$ (DIS + QE)
Background:
- charm$\rightarrow \mu$ (33.3%)
- Large angle scattering (66.7%)
Monte Carlo simulation has been validated comparing its results with the measured $\nu_\mu$ CC interactions when producing:

- **hadron reinteractions**
  (H. Ishida et al., PTEP 2014, 093C01 (2014))

- **charmed hadron decays**
  (N. Agafonova et al., Eur. Phys. J. C (2014) 74: 2986)

- **LAS muons**
  (A. Longhin et al., IEEE Trans. Nucl. Sci. 62, 2216 (2015))
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The Boost Decision Trees method (BDT)

- Multivariate machine learning method to classify observations
- It is based on a “forest” of trees of binary choices
- Sequential series of rectangular cuts split the data into nodes and leaves
- The BDT response is a value between 1 (signal-like events) and -1 (background-like events)

Ref: Hoecker et al. TMVA: Toolkit for Multivariate Data Analysis. PoS, ACAT:040, 2007
Boosted Decision Tree analysis

- Multivariate methods can help rejecting background
- Use also events features to evaluate $\nu_\tau$ appearance significance

- Different multivariate techniques have been considered and their performances for signal to background discrimination compared
- Best discrimination power is given by BDT
Example: $\tau \rightarrow h$: Kinematical variables

- Input = events surviving the looser selection
- Signal and Bkg normalized to unity
$\tau \rightarrow h$: Correlation between variables

Correlation Matrix (signal)

Correlation Matrix (background)
τ → h: DBT response

- Signal and Bkg normalized to the number of expected events
BDT response for all decay channels
Extended Likelihood

\[ \mathcal{L}(\mu, \beta_c) = \prod_{c=1}^{4} \left( \text{Pois}(n_c|\mu s_c + \beta_c) \prod_{i=1}^{n_c} f_c(x_{ci}) \right) \cdot \prod_{c=1}^{4} \text{Gauss}(b_c|\beta_c, \sigma_{b_c}) \]

Channels

Signal strength

True bkg (floating param.)

Expected signal

Expected bkg

Observed events in the \( c \)th channel

BDT response

\[ f_c(x_{ci}) = \frac{\mu s_c}{\mu s_c + \beta_c} \text{PDF}_c^{\text{sig}} + \frac{\beta_c}{\mu s_c + \beta_c} \text{PDF}_c^{\text{bkg}} \]
\( \nu_\tau \) appearance significance

- Likelihood ratio: \( \lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\beta}_c(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\beta}_c)} \)

- Results:
  - \( \mu = 1.1^{+0.5}_{-0.4} \)
  - \( P_{\text{value}} = 4.8 \cdot 10^{-10} \)
  - Significance = 6.1\sigma

-profiled values of the nuisance parameter \( \beta_c \), maximizing \( \mathcal{L} \) for the given \( \mu \)
-value of the likelihood at its maximum
$\Delta m^2_{23}$ measurement

$$N_{\nu_\tau} = f(\Delta m^2) = \int \Phi(E)\sigma_{\nu_\tau}(E)\epsilon(E)\mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}(E)dE \simeq (\Delta m^2_{23})^2 L^2 \int \Phi(E)\frac{\sigma_{\nu_\tau}(E)}{E^2}\epsilon(E)dE$$

$$\mu \propto \sigma^C_{\nu_\tau} \cdot \mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}$$

Assumptions: maximal mixing, $\nu_\tau$ CC interaction cross section as in Genie v2.6 default

- Result: $\Delta m^2_{23 \text{ meas}} = 2.7^{+0.7}_{-0.6} \cdot 10^{-3} \text{ eV}^2$
  
  (68% C.L)

First measurement in appearance mode

Agreement with PDG value within $1\sigma$
ντ CC cross section on lead

Until now, ντ+anti-ντ cross section measured only by:

- DONuT (9 ντ+anti-ντ) (Ref: Phys.Rev. D78 (2008) 052002)
- Super-Kamiokande (Ref: arXiv 1711.09436 (2017))

➤ OPERA: First measurement with negligible contamination from anti-ντ

\[
\langle \sigma \rangle = \frac{\int \Phi_{\nu_\mu}(E) \mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}(E) \sigma_{\nu_\tau}(E) dE}{\int \Phi_{\nu_\mu}(E) \mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}(E) dE}
\]

\[
\langle \sigma \rangle_{\text{meas}} = \frac{(N_{\text{obs}} - N_{\text{exp}B})/(\epsilon N_T)}{\int \Phi_{\nu_\mu}(E) \mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}(E) dE}
\]

overall efficiency
number of lead nuclei in the fiducial volume
ντ CC cross section on lead

- Δm²²³ fixed to PDG value

- Result: 
  \[ \langle \sigma \rangle_{meas} = (5.1^{+2.4}_{-2.0}) \cdot 10^{-36}\text{cm}^2 \]

- Default configuration of Genie v. 2.6: 
  \[ \langle \sigma \rangle_G = (4.29 \pm 0.04) \cdot 10^{-36}\text{cm}^2 \]

\[ \langle \sigma \rangle_{meas} = (1.2^{+0.6}_{-0.5}) \langle \sigma \rangle_G \]
νₜ lepton number

- Lepton number of νₜ has never been observed
- Muon decay channel: ν can be distinguished from ν̅?
- CNGS beam: 2% contamination of ν̅μ which could oscillate into ν̅ₜ
- Expected ν̅ₜ with τ⁺ → μ⁺ with misidentified or not measured charge = 0.0024 ± 0.0005
ντ lepton number observation

- Extended likelihood function
- Significance of having observed a τ⁻ → μ⁻: 3.7 σ
- Assumption: lepton number is conserved in the neutrino interaction

First observation of ντ lepton number
Summary of OPERA final results on \( \nu_\tau \) appearance

- **New strategy for the \( \nu_\tau \) selection**
- 5603 fully analysed \( \nu \) events: 10 \( \nu_\tau \) candidates satisfying the looser criteria
- Multivariate analysis to fully exploit event features
- \( \nu_\tau \) appearance significance improved: 6.1\( \sigma \)
- The number of observed \( \nu_\tau \) candidates after bkg subtraction is a function of \( \Delta m^2_{23} \cdot \sigma_{\nu_\tau} \)
  - \( \Delta m^2_{23} = 2.7^{+0.7}_{-0.6} \cdot 10^{-3} \text{eV}^2 \) at 68\% C.L.  ➔ first measurement in appearance mode
  - \( <\sigma_{\nu_\tau}> \text{ CC} = 5.1^{+2.4}_{-2.0} \cdot 10^{-36} \text{cm}^2/\text{GeV} \)  ➔ first measurement ever
- First observation of the \( \nu_\tau \) lepton number with a significance of 3.7\( \sigma \)
OPERAs Final Stamp on Neutrino Oscillations
May 22, 2018

The final analysis of data collected by the OPERA experiment improves the precision of measurements of neutrinos oscillating between muon and tau flavors.

Synopsis on:
N. Agafonova et al. (OPERA Collaboration)
Phys. Rev. Lett. 120, 211801 (2018)
OPERA final results for $\nu_\mu \rightarrow \nu_e$ oscillations search
Reconstructed energy distributions of the observed $\nu_e$ candidates

No oscillation hypothesis

$N_{\text{exp}} = 31.9 \pm 0.5 \text{ (stat.)} \pm 3.1 \text{ (syst.)}$

3 neutrino flavour mixing

$N_{\text{exp}} = 34.3 \pm 0.5 \text{ (stat.)} \pm 3.4 \text{ (syst.)}$

$N_{\text{obs}} = 35$

Ref: arXiv:1803.11400
Final results for $\nu_\mu \rightarrow \nu_e$ oscillations search

- Results compatible with the no-oscillation hypothesis as well as with the 3 neutrino flavour one

  Upper limit: $\sin^2(2\theta_{13}) < 0.43$ at 90\% C.L.

- 3+1 model hypothesis:
  $\sin^2(2\theta_{\mu e}) = 0.021$ for $\Delta m_{41}^2 \geq 0.1$ eV$^2$ at 90\% C.L.

- OPERA is the only appearance experiment excluding neutrino mass difference down to $4 \times 10^{-3}$ eV$^2$

Ref: arXiv:1803.11400
Is it all?
On-going

- Annual modulation of cosmic-muon rate
- Exploit unique feature of identifying all three flavours: use tau appearance, electron appearance and muon disappearance at the same time
- Open Data at CERN
Thank you for your attention