Final results of the OPERA experiment on ν_τ appearance in the CNGS beam

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Outline

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

Neutrino Oscillations

- **Neutrinos in the Standard Model**:
  - massless, electrically neutral, weakly interacting particles, spin 1/2
  - 3 flavours: ν_e, ν_μ, ν_τ and their antiparticles
  - lepton numbers are conserved
  - neutrino flavours do not change
- 1957, Pontecorvo: neutrinos could be a state superimposion of two different massive neutrinos
- 1962, Maki, Nakagawa and Sakata: **mixing between neutrinos of different flavours**

$$\nu_l = \sum_{i=1}^{3} U^*_{l_i} \nu_i$$

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

Amospheric ν
SuperK, K2K, MINOS, T2K …

Chooz, Daya Bay, RENO, T2K, MINOS, NOvA …

Solar ν, Borex, SuperK, SNO, KamLAND ...

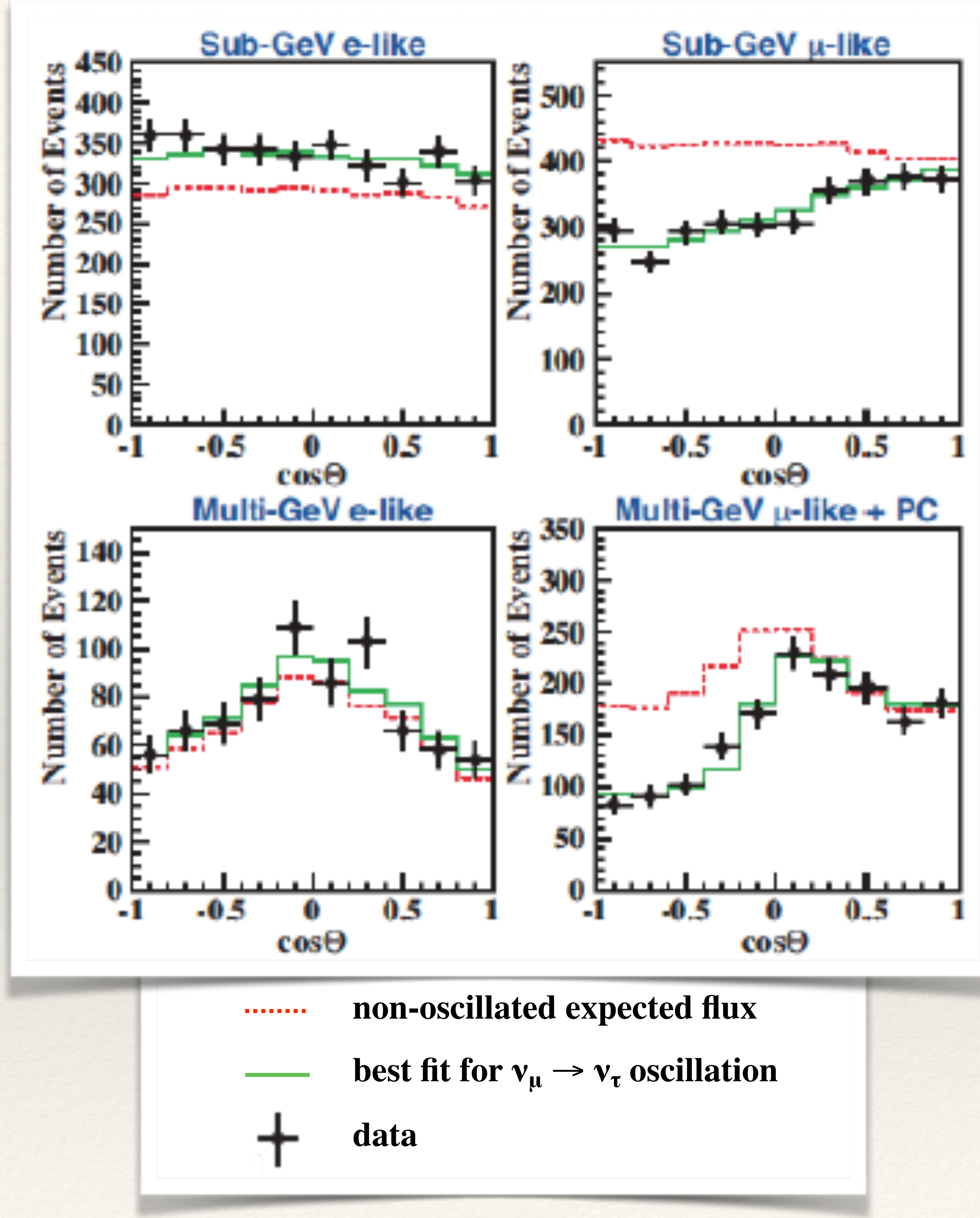
The atmospheric neutrino anomaly

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

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

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

- The missing ν_μ must have oscillated into ν_τ or into a new non-interacting "sterile" neutrino ν_x



The OPERA experiment

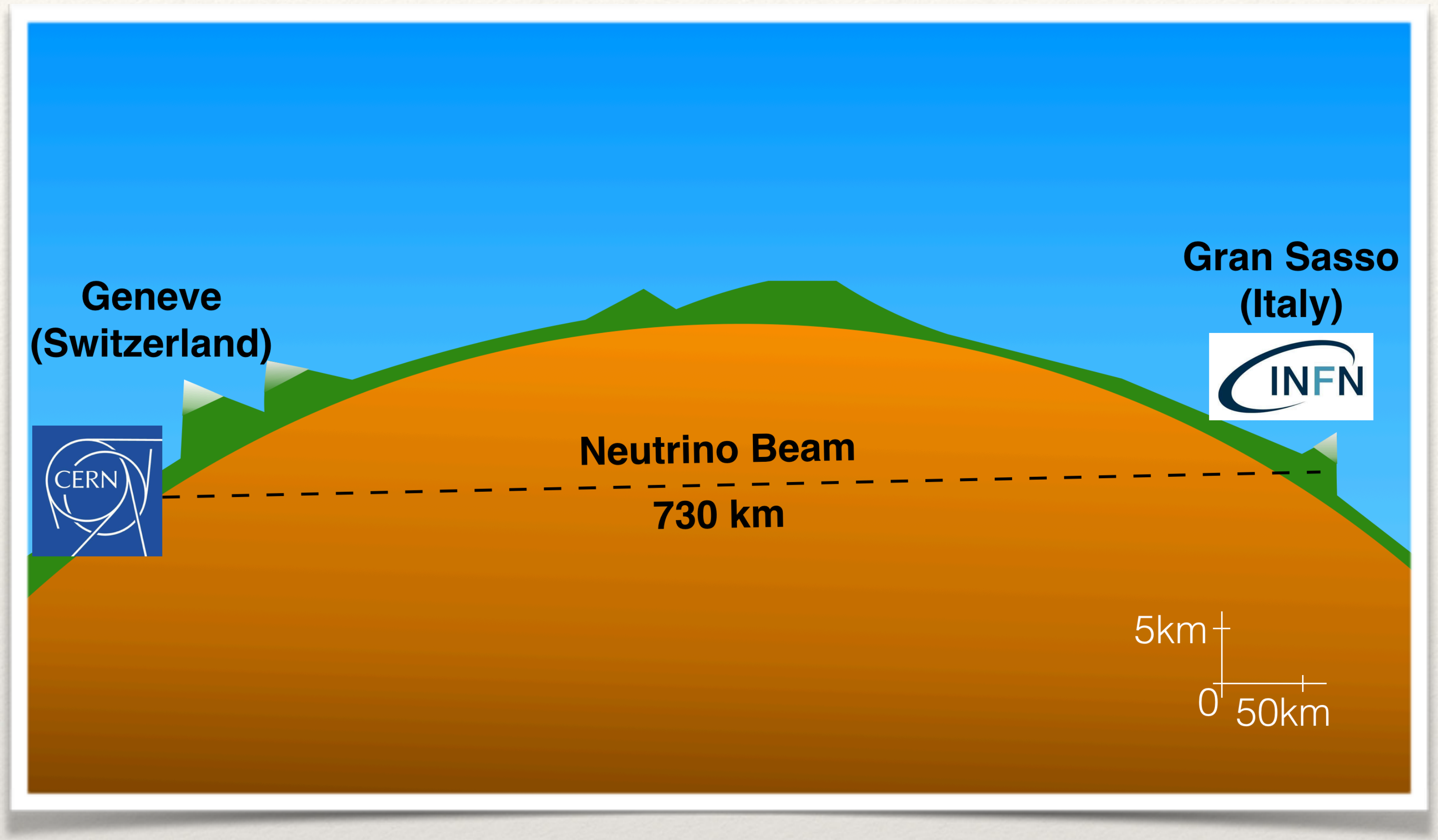
- **The OPERA experiment (Oscillation Project with Emulsion tRacking Apparatus) was designed to directly observe, for the first time in <u>APPEARANCE MODE</u>, the $\nu_\mu \rightarrow \nu_\tau$ oscillation in a pure ν_μ beam.**

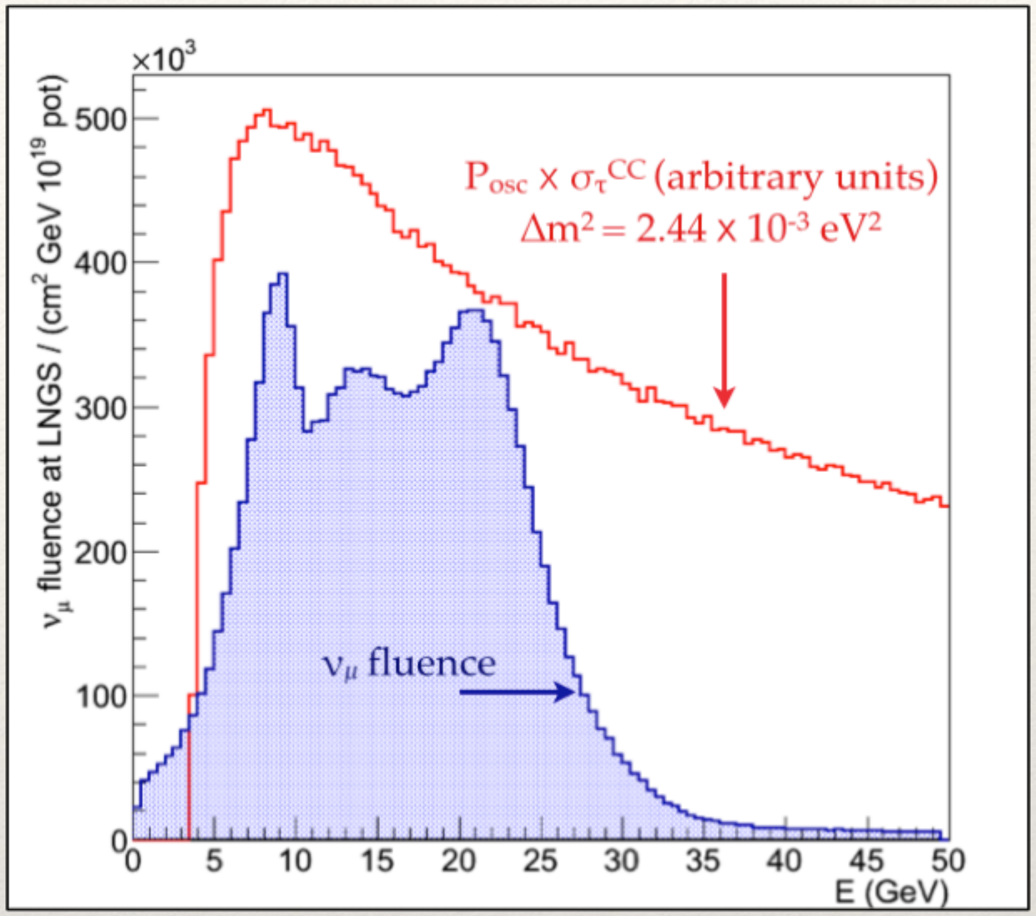
- The search for direct appearance was based on revealing the short-lived τ lepton produced in ν_τ charged-current interactions

Channel	BR
$\tau^- \rightarrow e^- \nu_\tau \overline{\nu_e}$	17.8%
$\tau^- \rightarrow \mu^- \nu_\tau \overline{\nu_\mu}$	17.7%
$\tau^- \rightarrow h^- \nu_\tau (n\pi^0)$	49.5%
$\tau^- \rightarrow 3h\nu_\tau (n\pi^0)$	15.0%

- Requirements:
  - High energy beam for τ production
  - Long baseline for oscillation at the atmospheric scale
  - High density and large target mass for statistics
  - Micrometric accuracy and resolution to identify τ decays and neutrino interaction kinematics

CERN Neutrinos to Gran Sasso





- Long baseline (**730 km** from CERN to LNGS)
- <E_ν> on target **~17 GeV**
- L/E ~ 43 km/GeV

- $\bar{\nu}_\mu$ contamination = 2.1%
- ν_e and $\bar{\nu}_e$ contam. <1%
- ν_τ contamination negligible

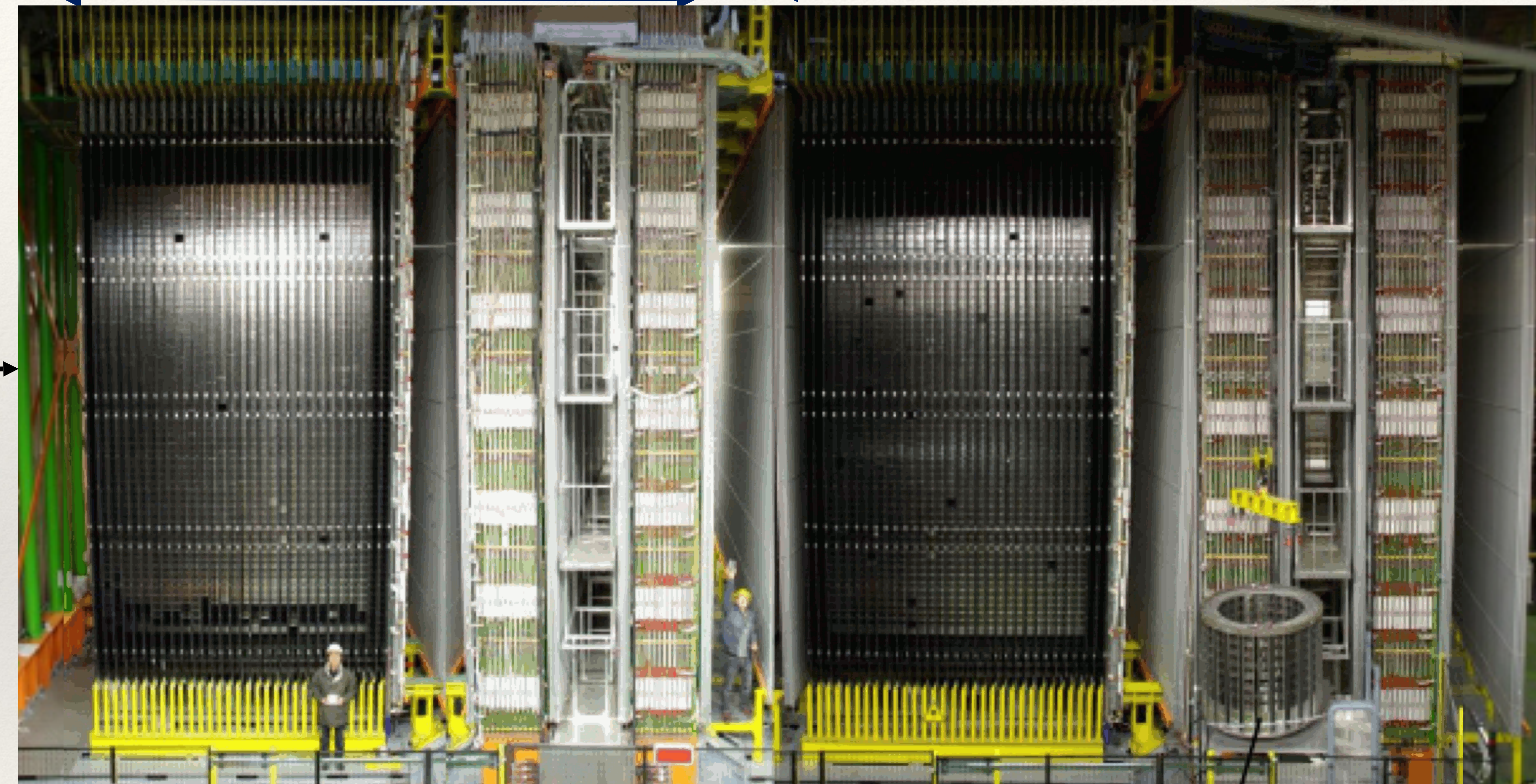
- Data taking from 2008 to 2012
- **#p.o.t. = 17.97 ·10^{19}**

The OPERA detector

SM1

SM2

ν



Target Area

Brick walls+Target Tracker

Scintillator strip planes

Spectrometer

RPC+Drift Tubes

Brick Manipulating System

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

The OPERA detector

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SM2

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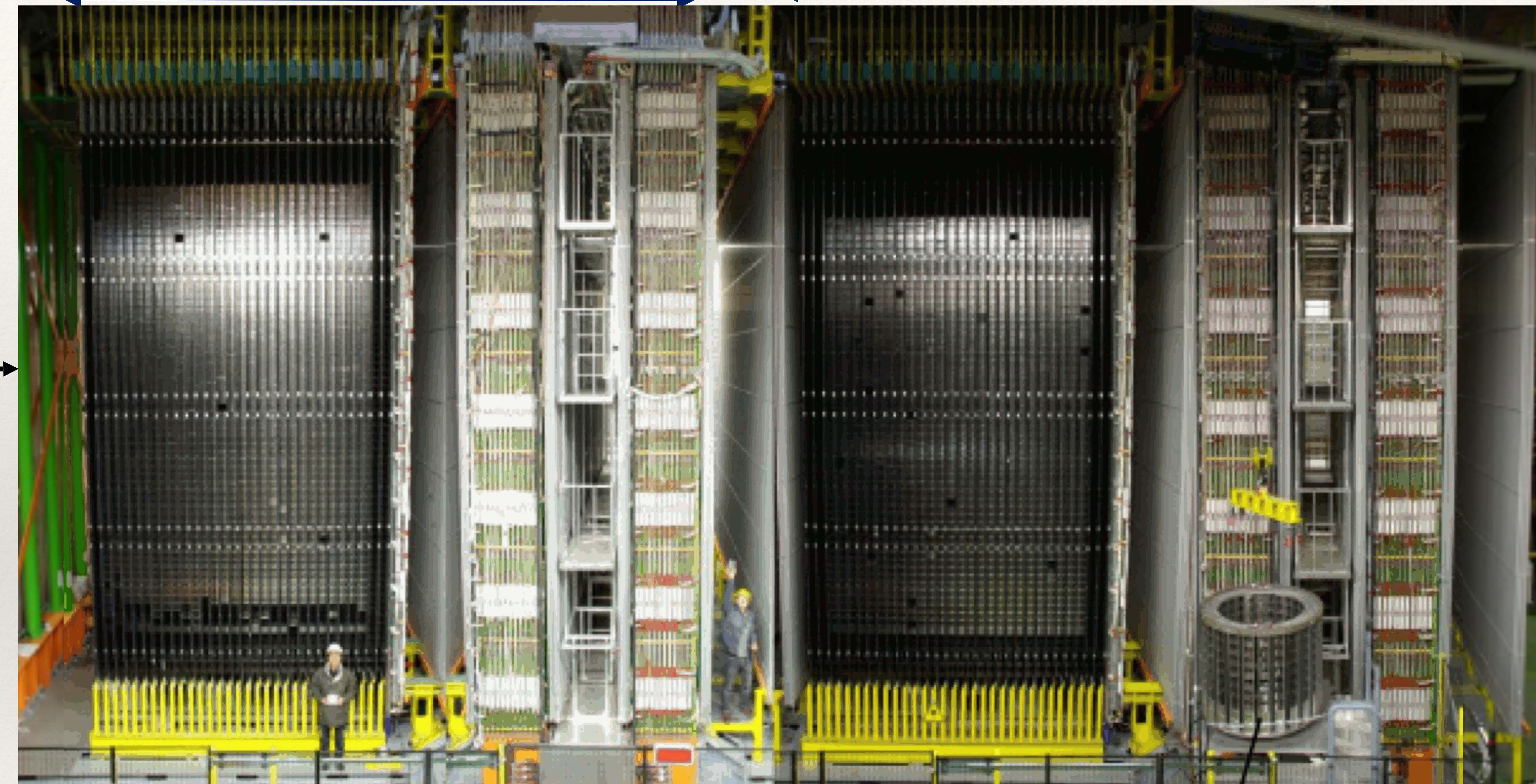

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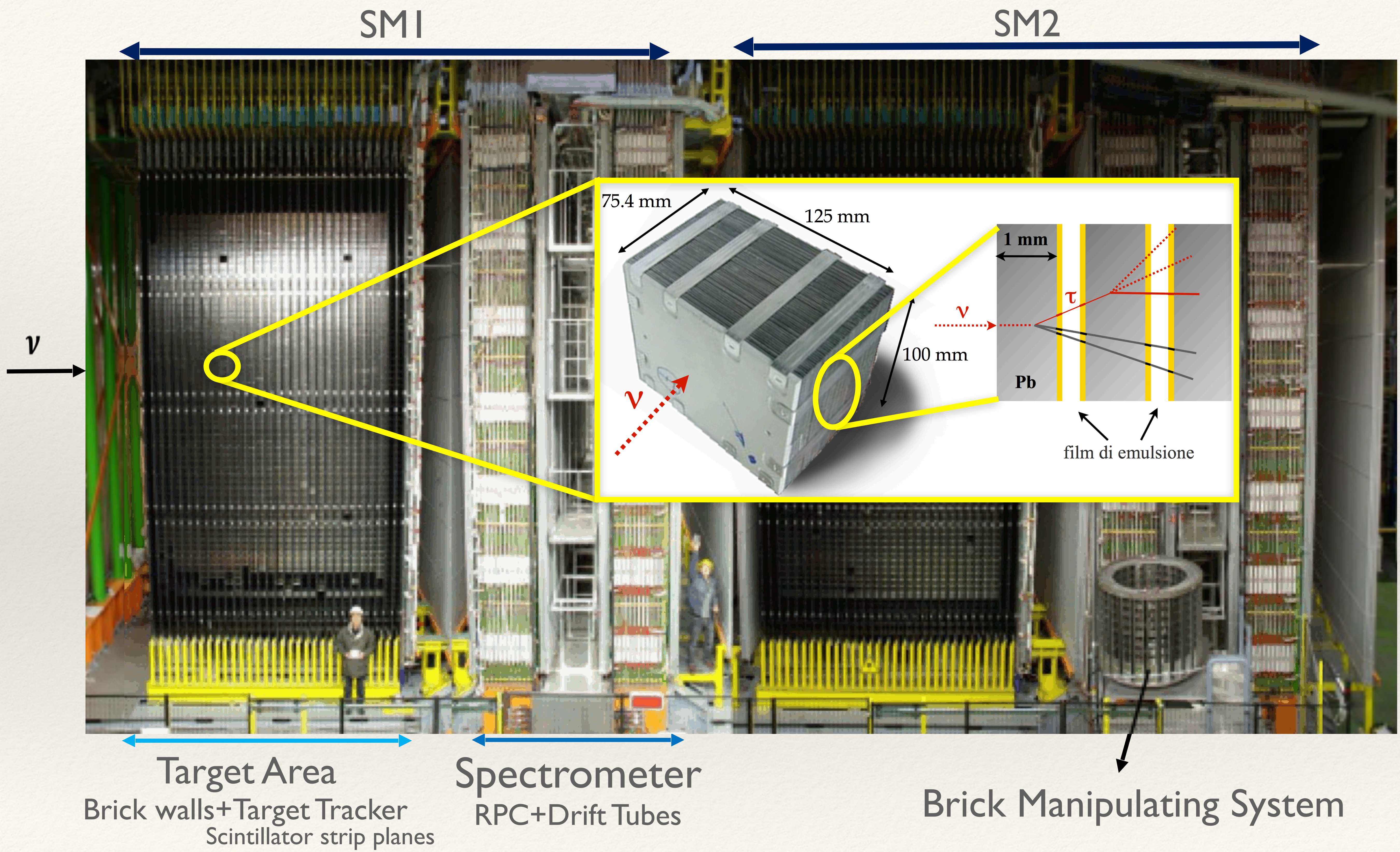
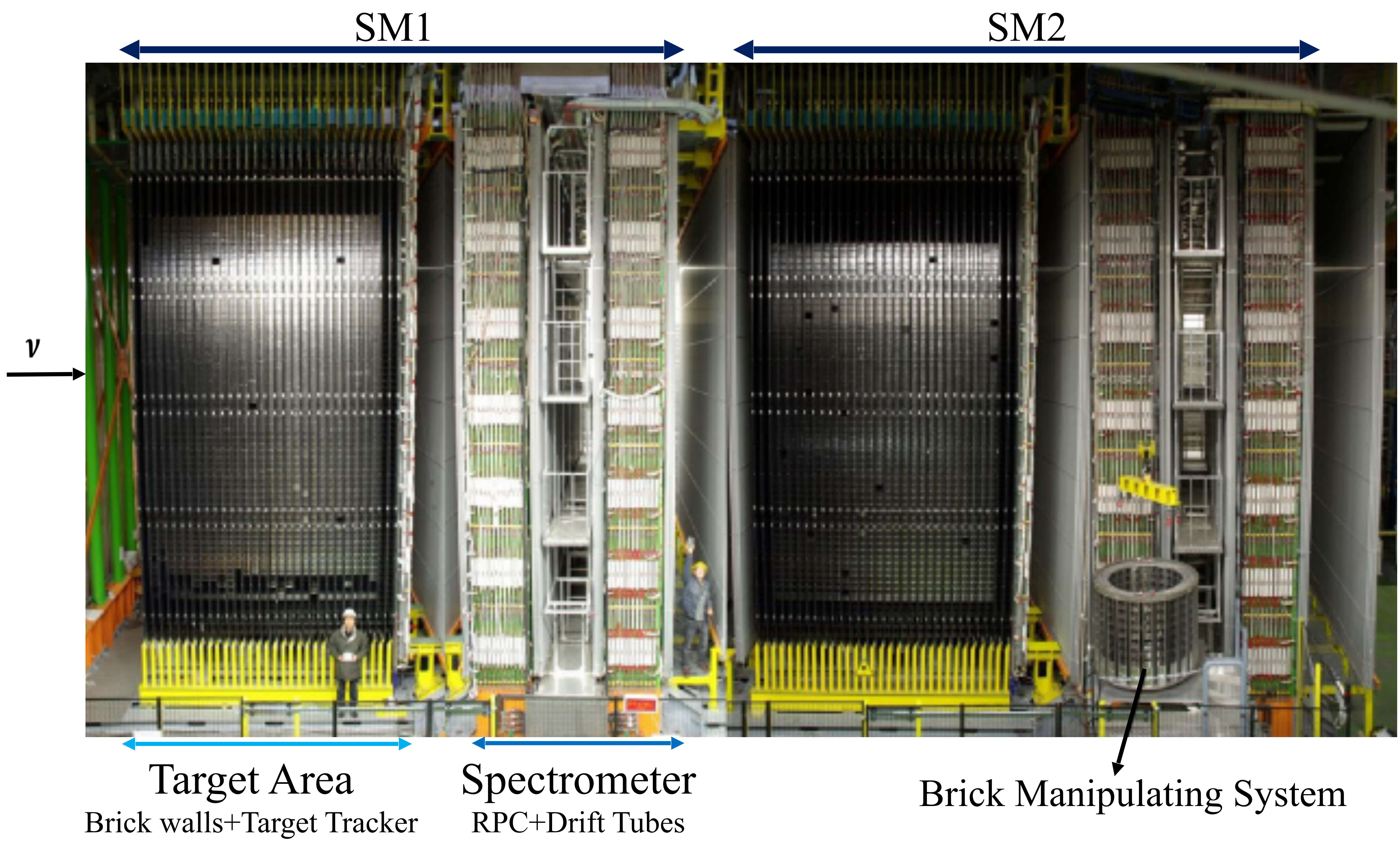
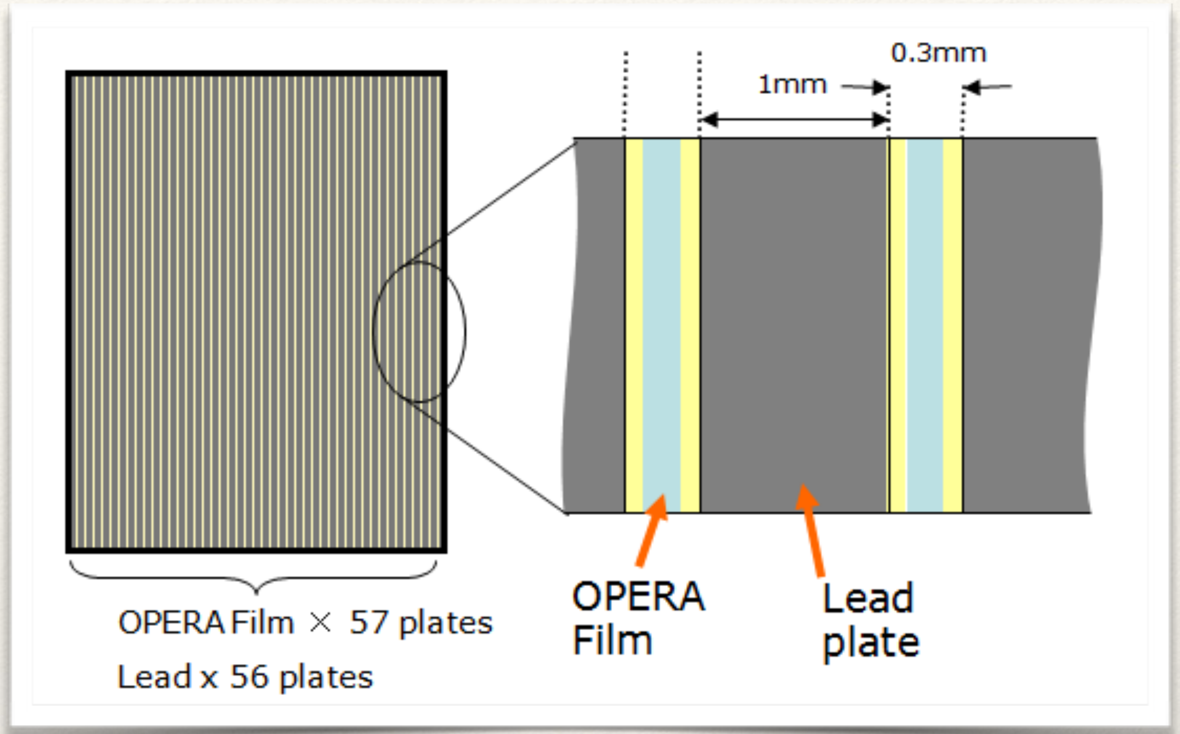
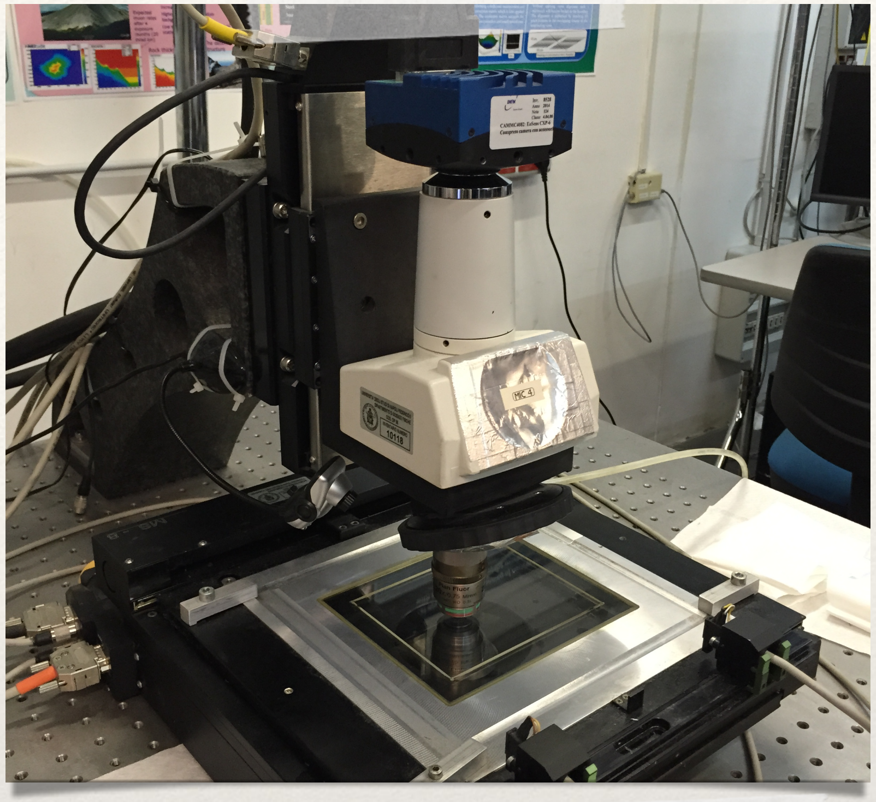


Underground location: **Gran Sasso Laboratory** (10^6 reduction of cosmic ray flux)

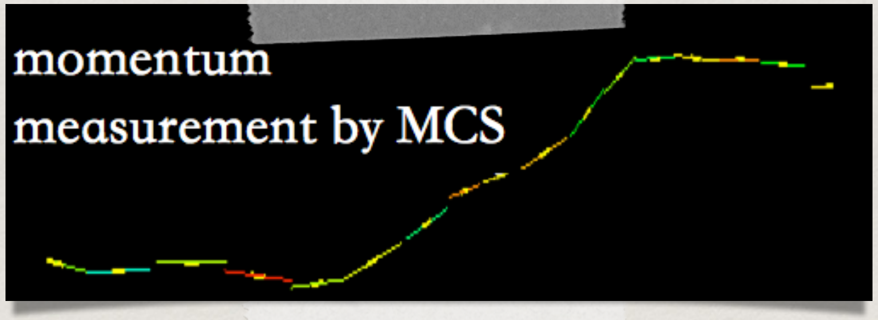

SM1
SM2
ν
Target Area
Brick walls+Target Tracker
Spectrometer
RPC+Drift Tubes
Brick Manipulating System

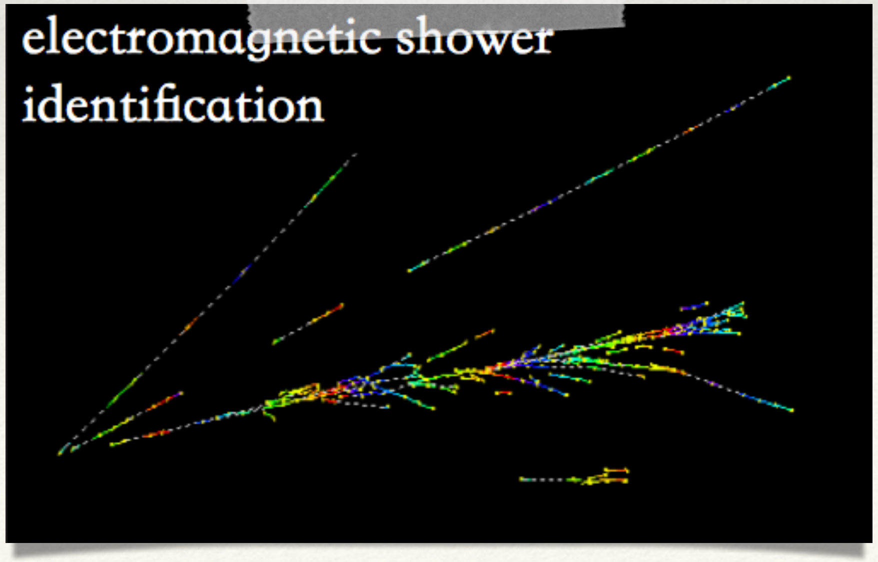
Emulsion Cloud Chamber





- 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

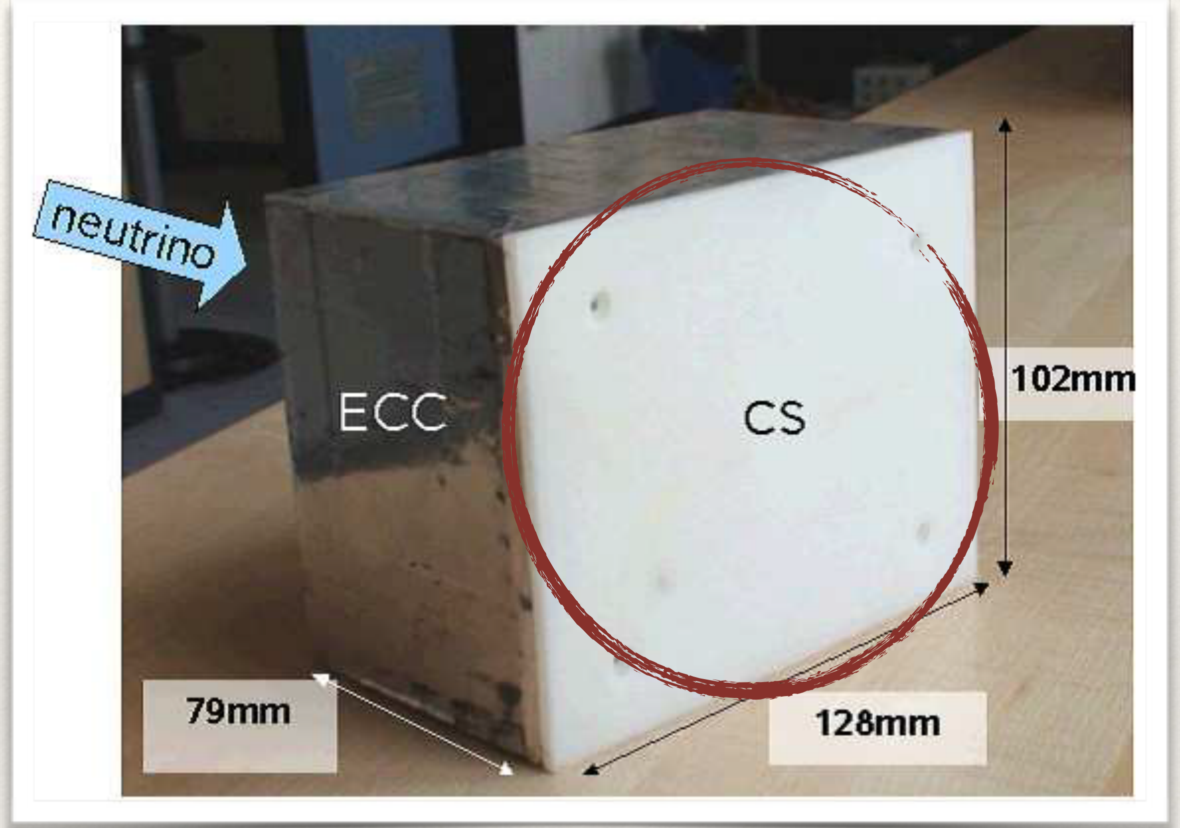




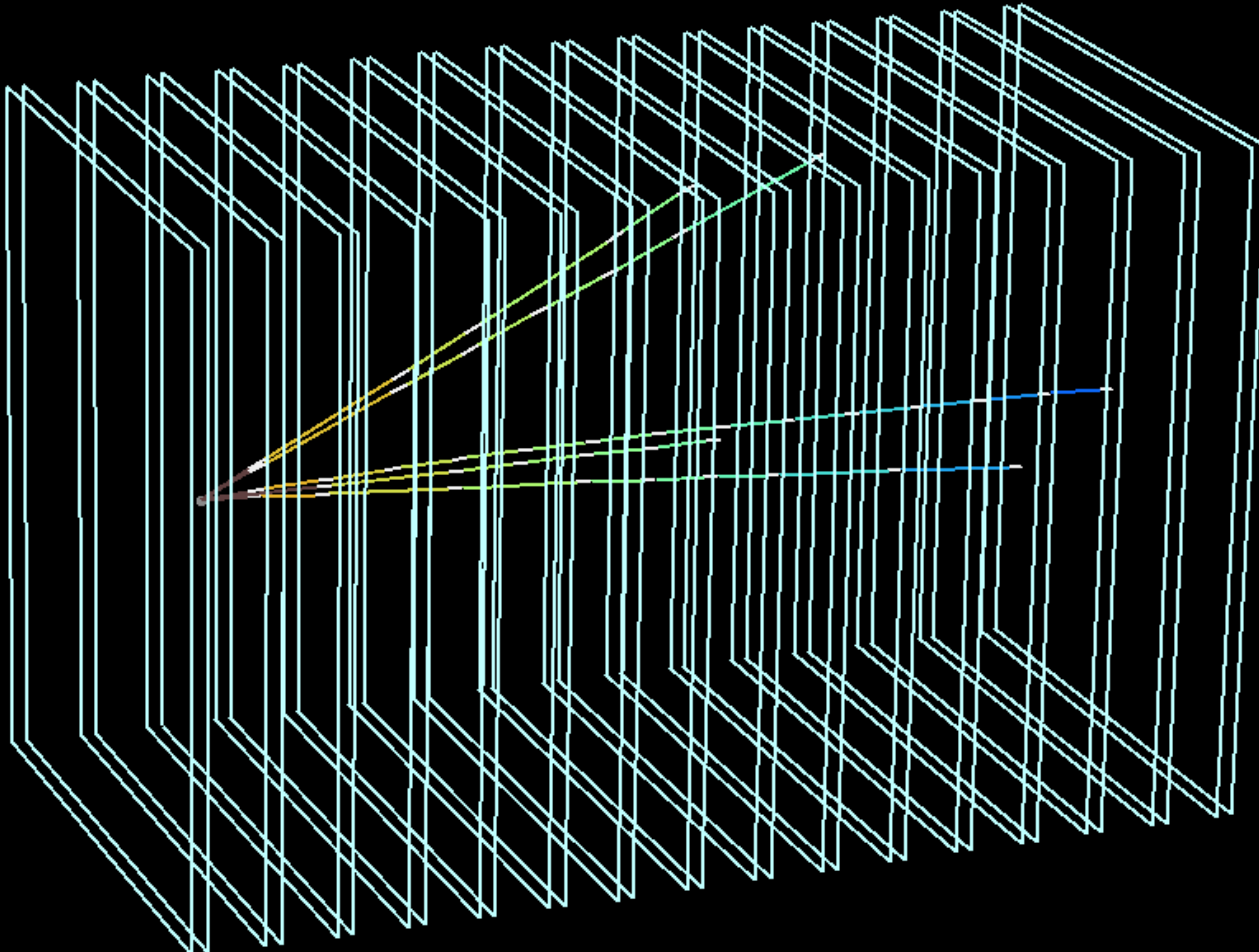
Changeable Sheets Doublet

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

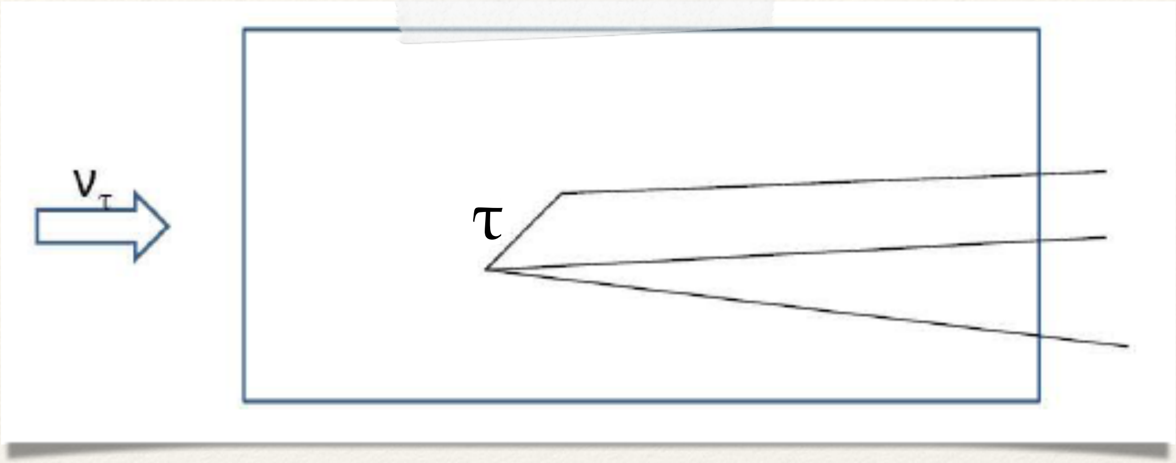


- ✓ confirm the brick
- ✓ reduce scanning load
- ✓ save detector target mass



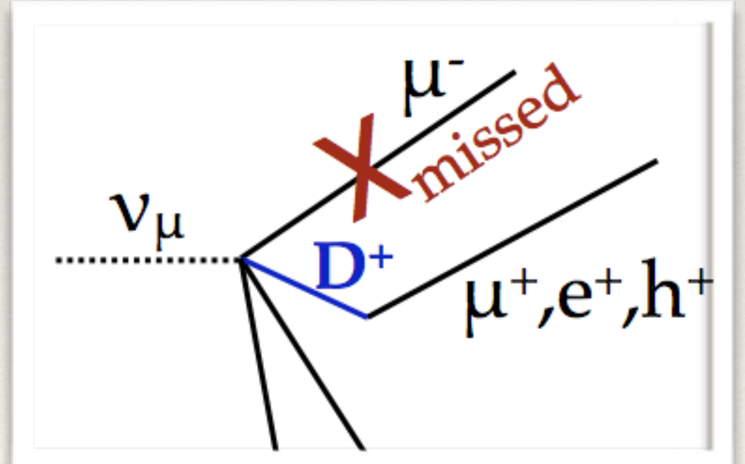
Main background sources

Signal topology:



Possible backgrounds:

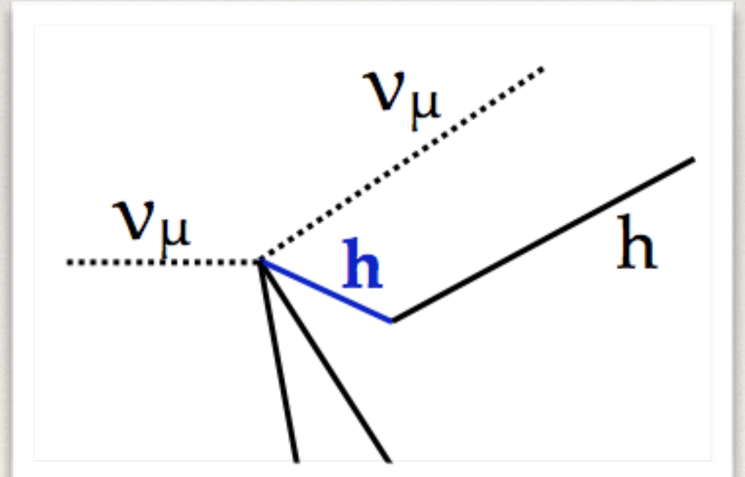
Charmed hadron decays where muon at 1ry vtx is not identified



Eur. Phys.J. C74 (2014) 2986

Reduced by Track Follow-down procedure

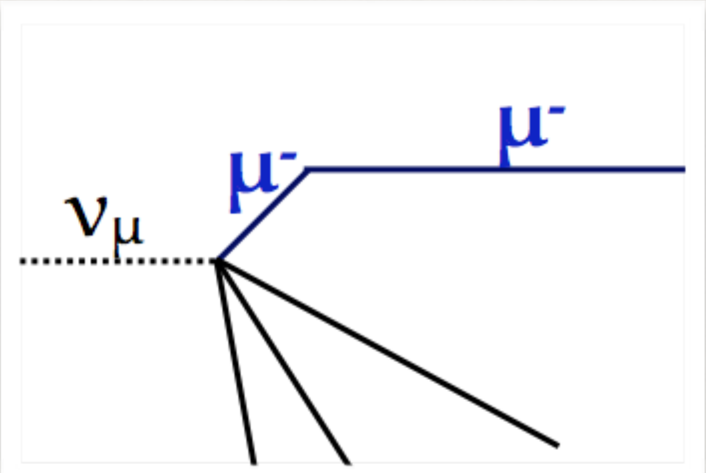
Hadronic re-interactions



PTEP9 (2014) 093C01

Reduced by large angle scanning and nuclear fragment search

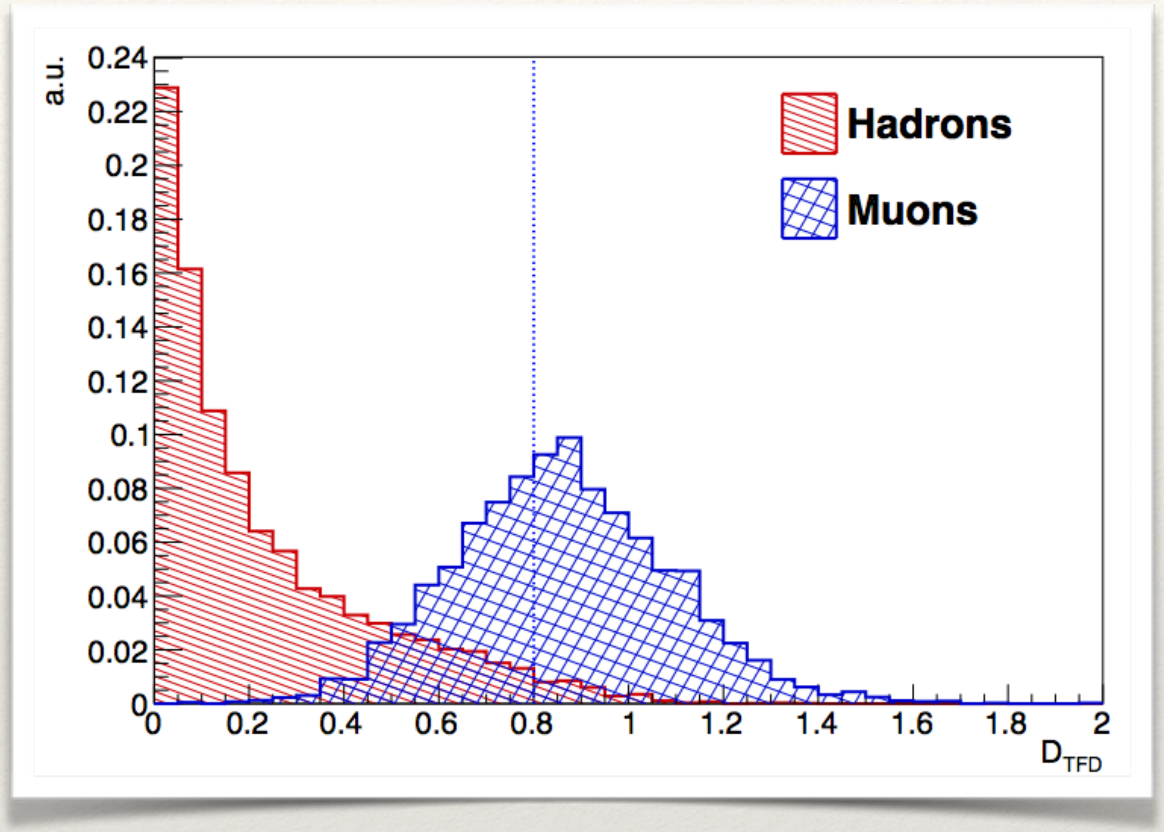
Large angle muon scattering



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 $D_{TFD}>0.8$

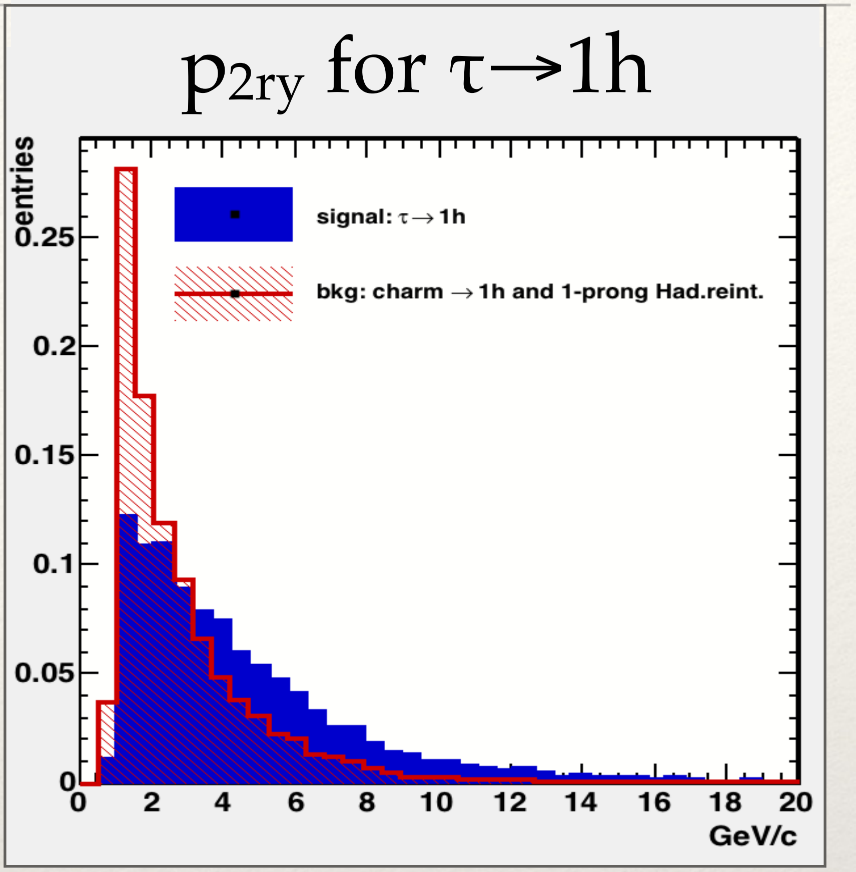
Is Hadron if $D_{TFD}<0.6$

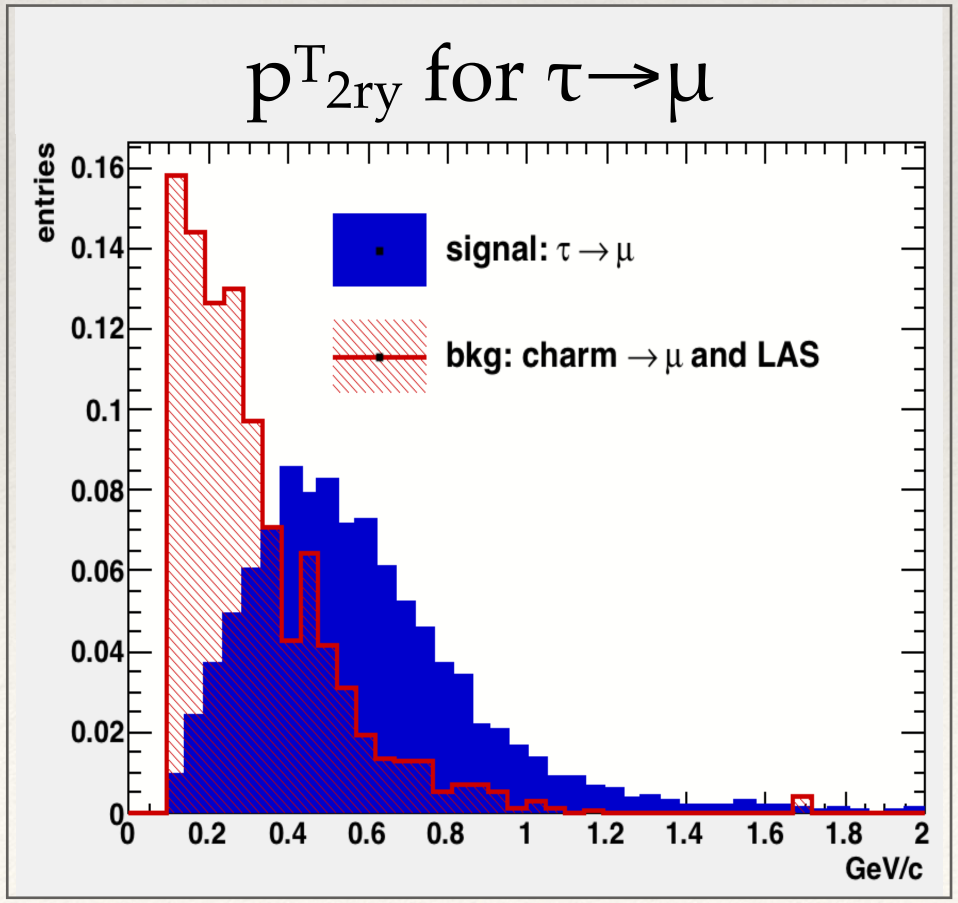
ν_τ Appearance kinematical selection

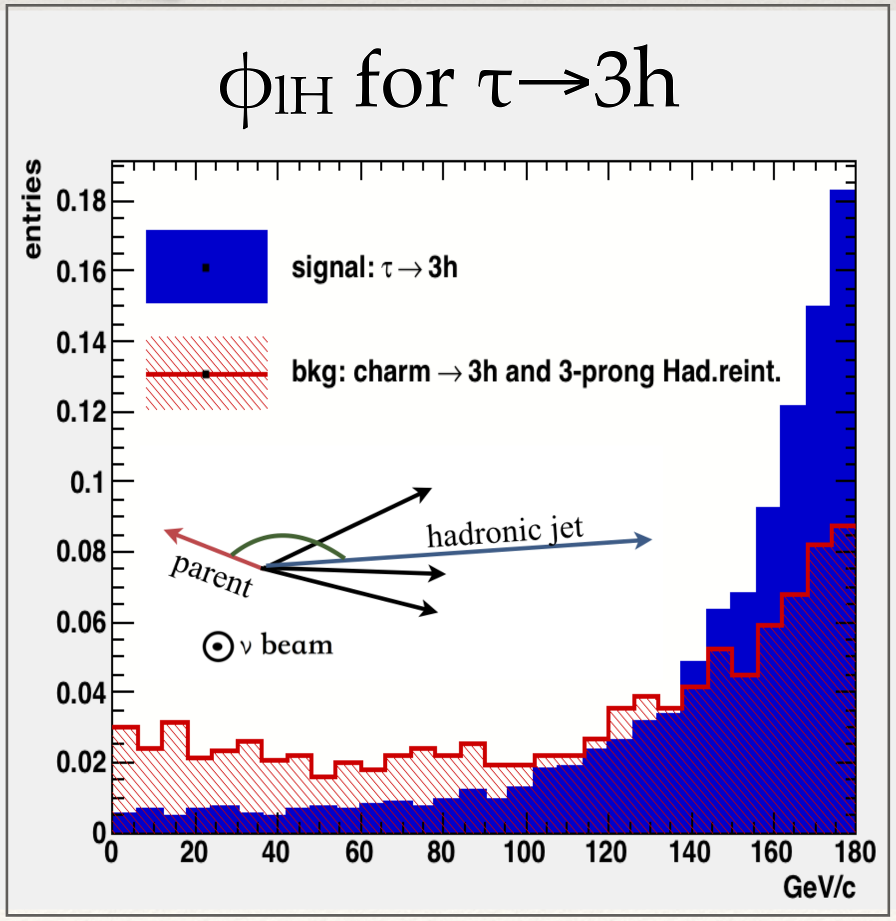
Variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
z_{dec} (μm)	[44, 2600]	<2600	[44, 2600]	<2600
p^T_{miss} (GeV/c)	$< 1\star$	$< 1\star$	/	/
ϕ_{lH} (rad)	$>\pi/2\star$	$>\pi/2\star$	/	/
p^T_{2ry} (GeV/c)	>0.6 (0.3)*	/	>0.25	>0.1
p_{2ry} (GeV/c)	>2	>3	[1, 15]	[1, 15]
θ_{kink} (rad)	>0.02	<0.5	>0.02	>0.02
m, m_{min} (GeV/c^2)	/	[0.5, 2]	/	/

Cuts marked with $\star$ are not applied for Quasi-Elastic event

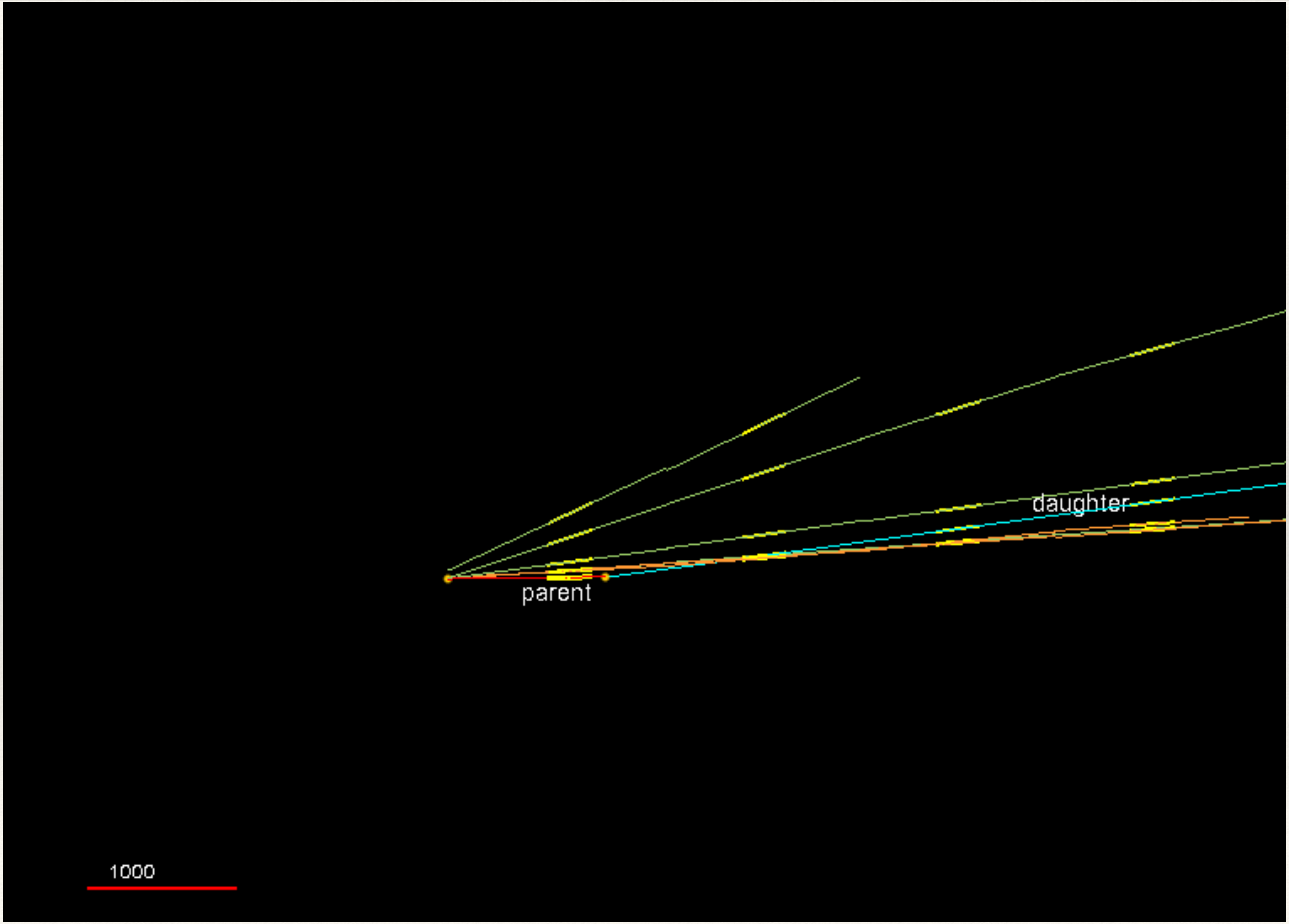
* p^T_{2ry} cut is 0.3 in the presence of γ particles associated to the decay vertex



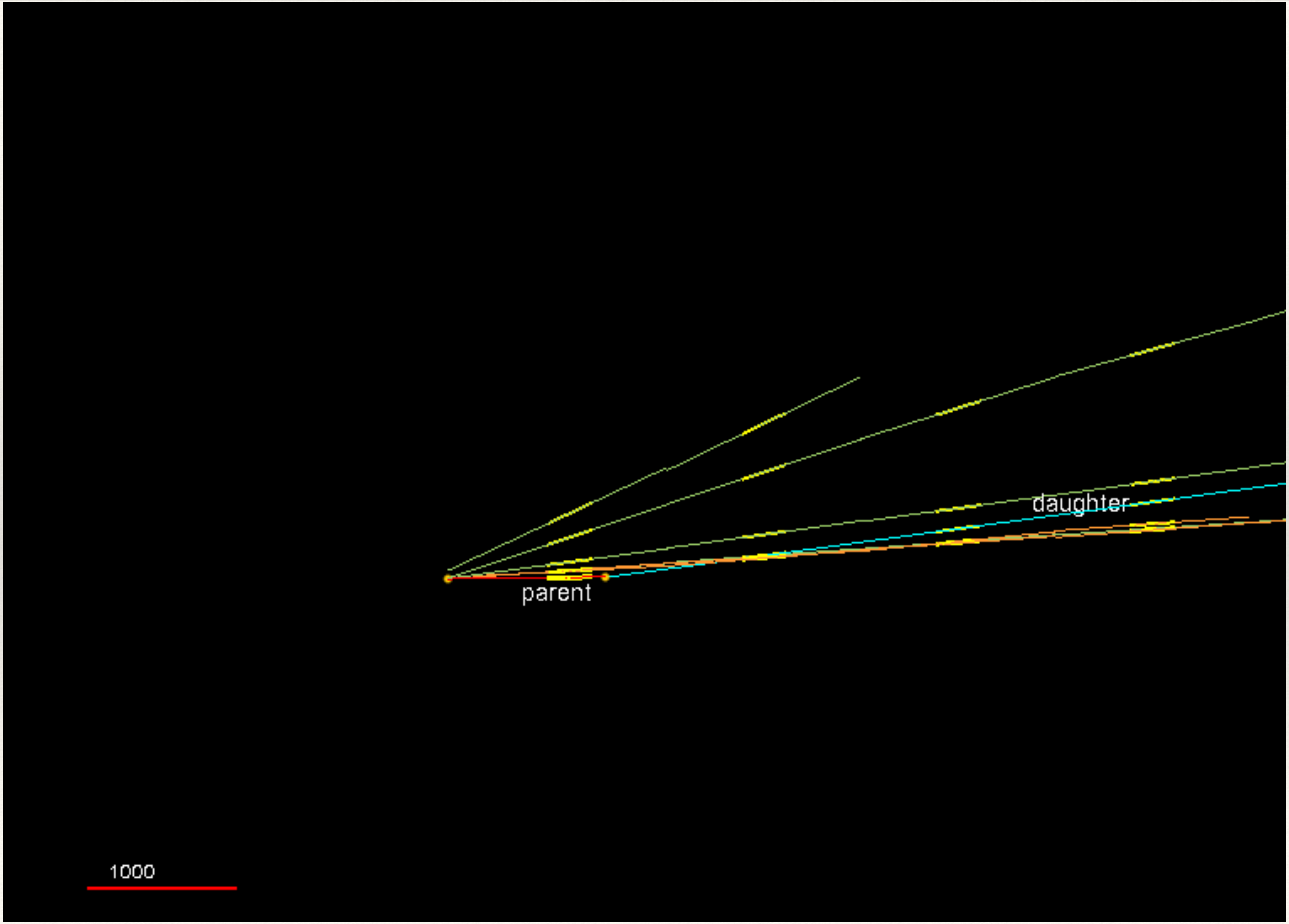




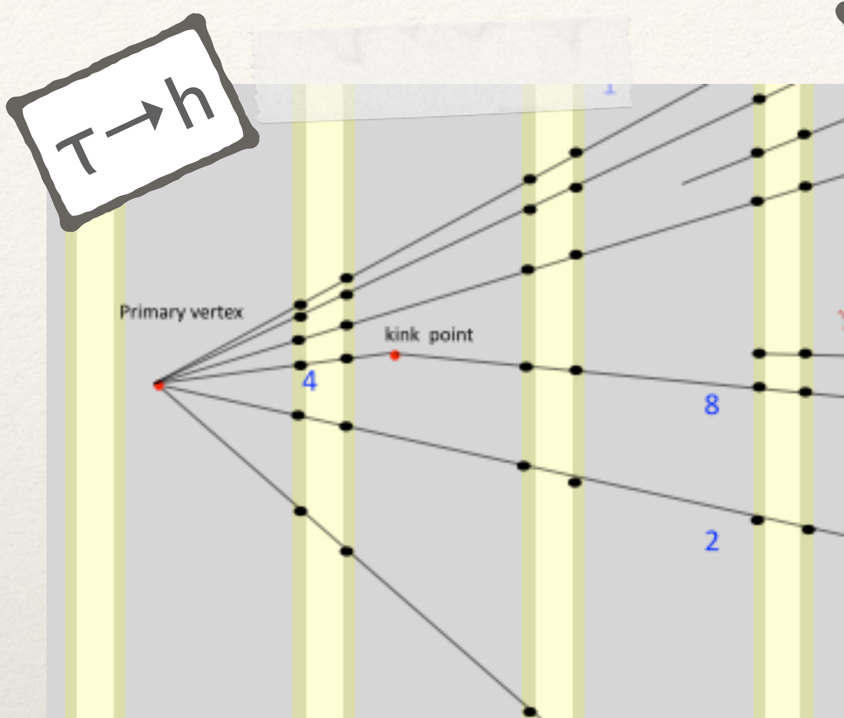
2010: the 1st ν_τ candidate



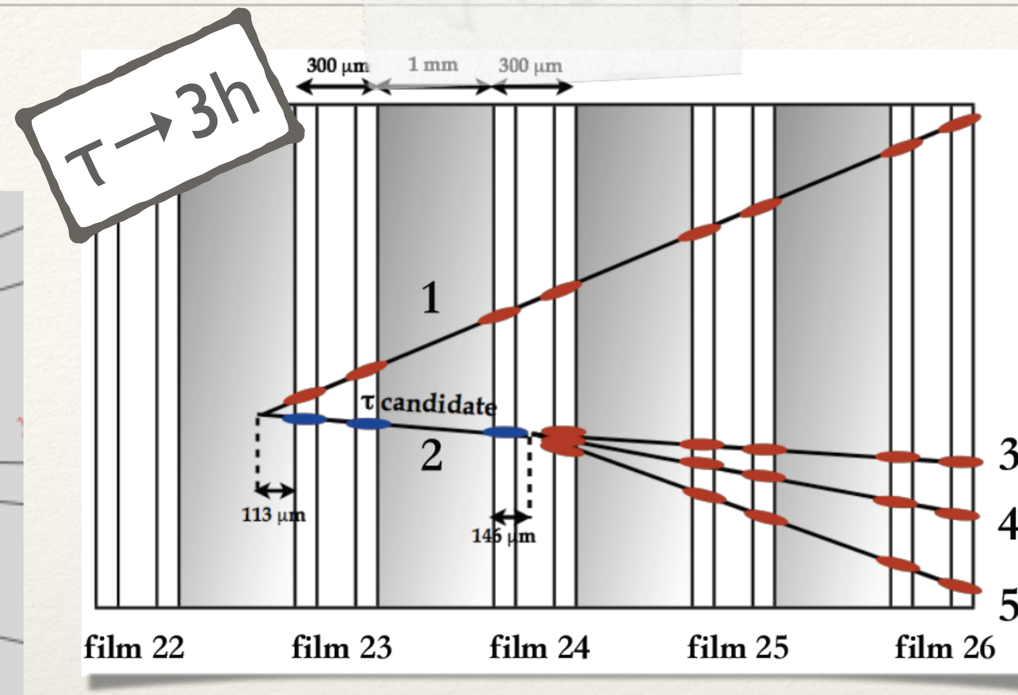
2010: the 1st ν_τ candidate



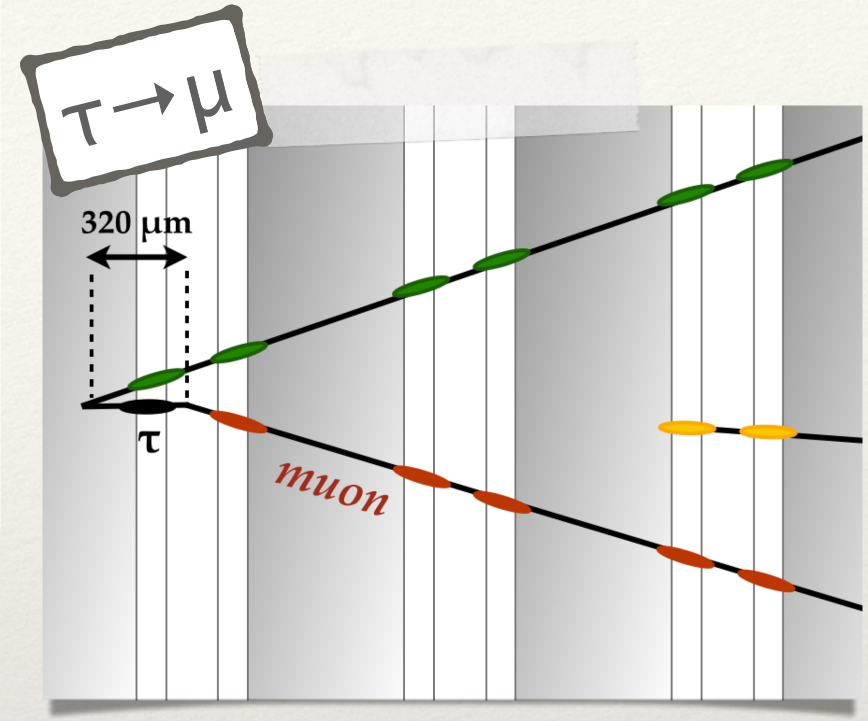
The first 5 ν_τ candidates



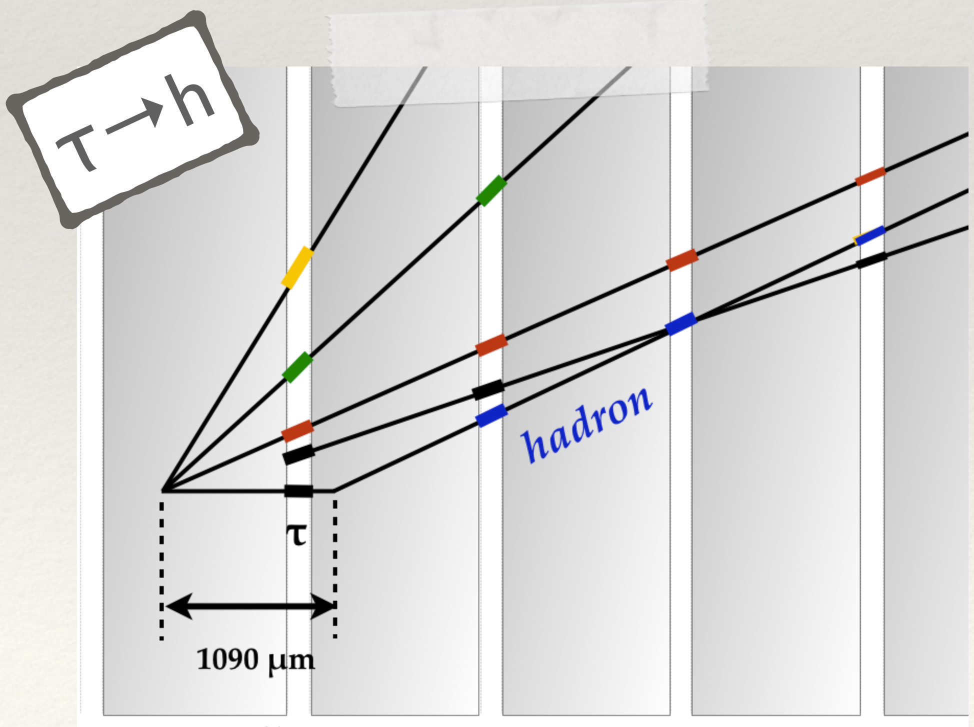
Physics Letters B691 (2010) 138



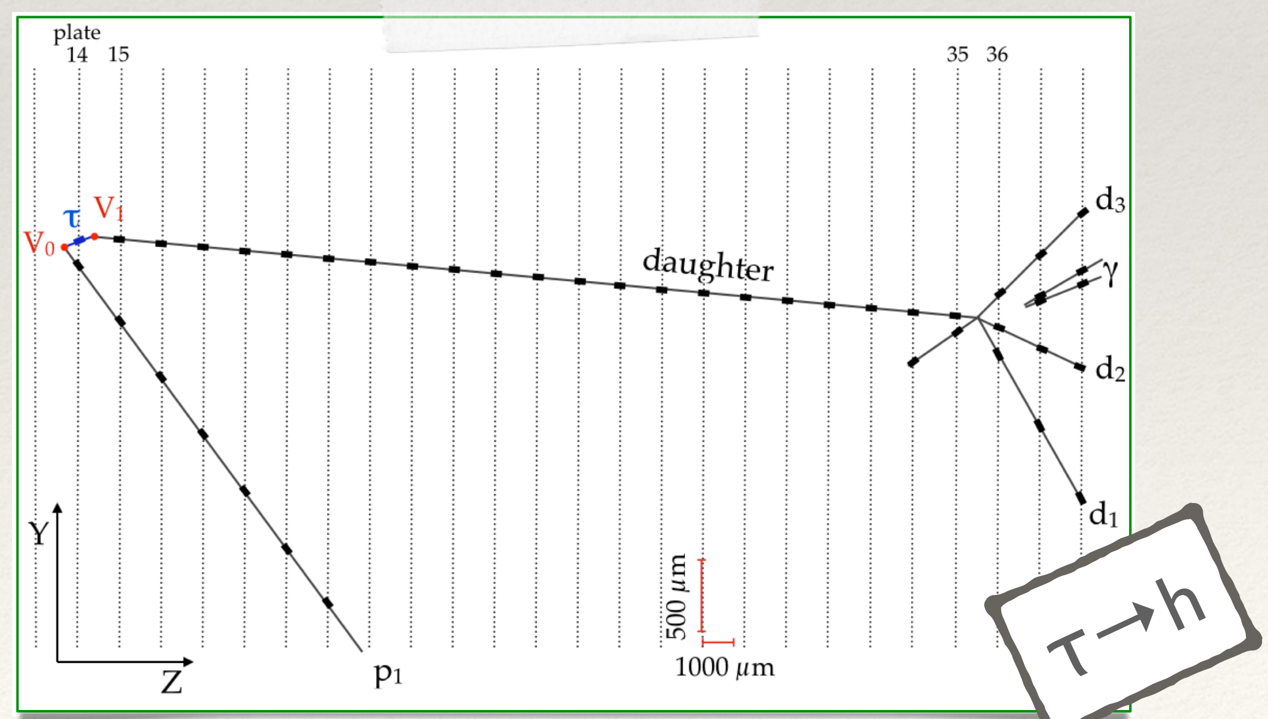
JHEP 1311 (2013) 036



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 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.25 ± 0.05	2.64 ± 0.53	5

Probability of background fluctuation = $1.1 \cdot 10^{-7}$
→ absence of signal excluded with a significance of **5.1σ**

Ref: Discovery of tau neutrino appearance in the CNGS neutrino beam with the OPERA experiment PRL 115 (2015) 121802

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6 OCTOBER 2015

Scientific Background on the Nobel Prize in Physics 2015

NEUTRINO OSCILLATIONS

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

Super-Kamiokande's oscillation results were confirmed by the detectors MACRO [55] and Soudan [56], by the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a muon-neutrino beam has been demonstrated on an event-by-event basis by the OPERA experiment in Gran Sasso, with a neutrino beam from CERN [62].

New Strategy for the ν_τ candidate selection

Goal: estimate the oscillation parameters in appearance mode and ν_τ properties with reduced statistical error

- Looser kinematical selection to increase the number of ν_τ candidate
- Multivariate analysis: Boosted Decision Tree

New Strategy applied to the final sample:

	Total
p.o.t. (10^{19})	17.97
0μ events	1197
1μ events ($p_\mu < 15$ GeV/c)	4406
Total events	5603

New Kinematical Selection

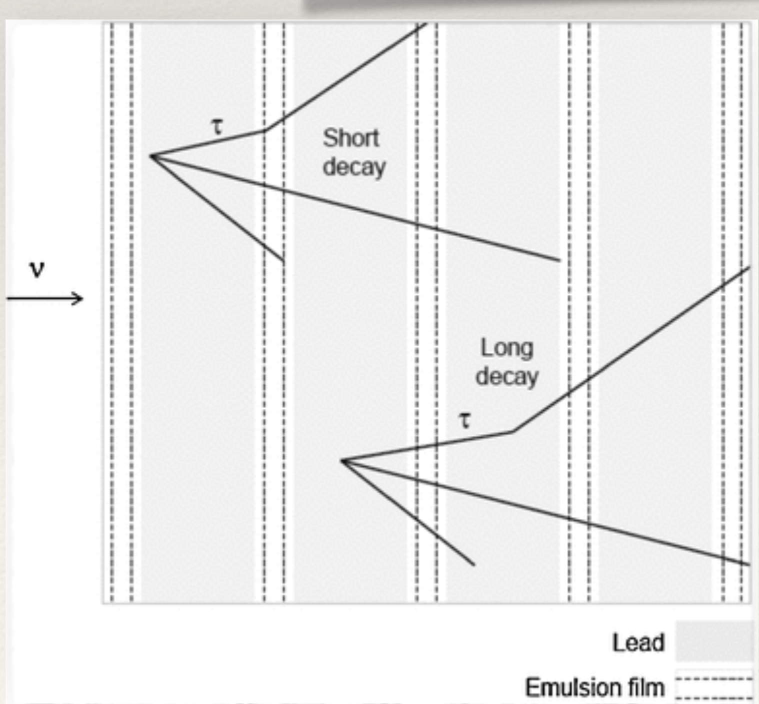
Decay vertex definition

Variable	$\tau \to 1h$		$\tau \to 3h$		$\tau \to \mu$		$\tau \to e$	
	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW
z_{dec} (μm)	$[44, 2600]$	<2600	<2600		$[44, 2600]$	<2600	<2600	
θ_{kink} (rad)	>0.02		<0.5	>0.02	>0.02		>0.02	
p_{2ry} (GeV/c)	>2	>1	>3	>1	$[1, 15]$		$[1, 15]$	>1
p_{2ry}^{T} (GeV/c)	$>0.6\,(0.3)$	>0.15	/		>0.25	>0.1	>0.1	
p_{miss}^{T} (GeV/c)	<1	/	<1	/	/		/	
ϕ_{lH} (rad)	$>\pi/2$	/	$>\pi/2$	/	/		/	
m, m_{min} (GeV/c^2)	/		$[0.5, 2]$	/	/		/	

New Kinematical Selection

Decay vertex definition

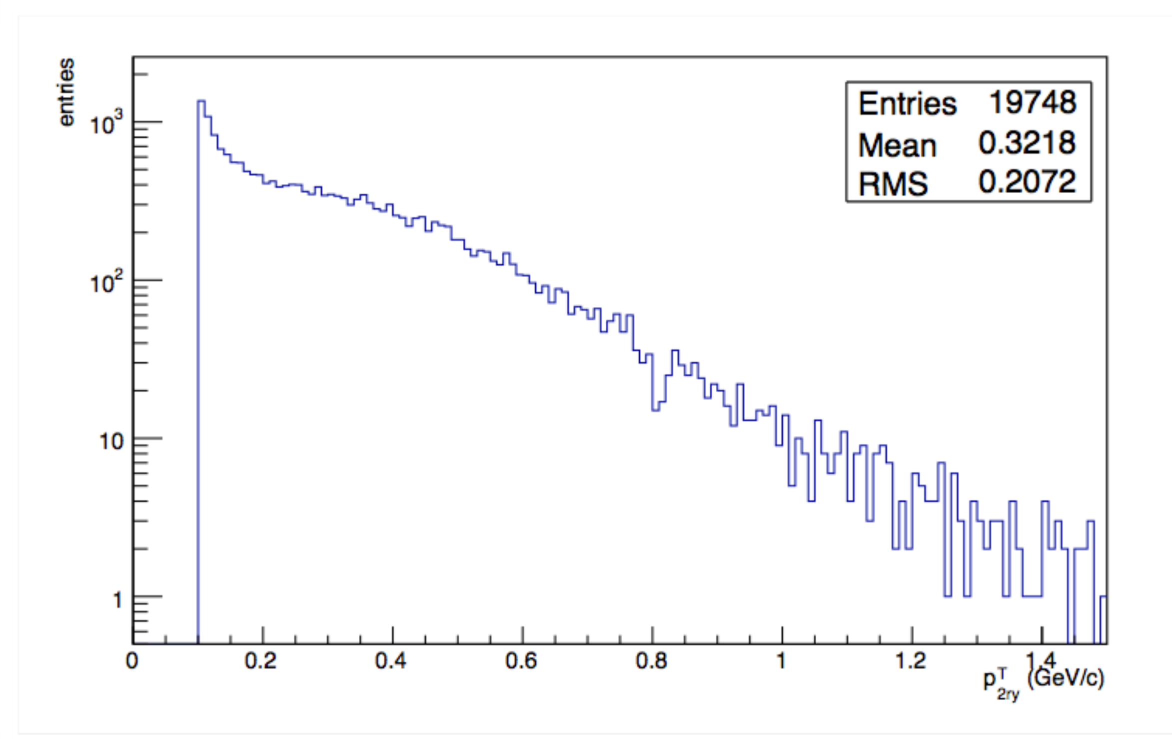
Variable	$\tau \to 1h$ OLD	$\tau \to 1h$ NEW	$\tau \to 3h$ OLD	$\tau \to 3h$ NEW	$\tau \to \mu$ OLD	$\tau \to \mu$ NEW	$\tau \to e$ OLD	$\tau \to e$ NEW
z_{dec} (μm)	[44, 2600]	<2600	<2600		[44, 2600]	<2600	<2600	
θ_{kink} (rad)	>0.02		<0.5	>0.02	>0.02		>0.02	
p_{2ry} (GeV/c)	>2	>1	>3	>1	[1, 15]		[1, 15]	>1
p_{2ry}^{T} (GeV/c)	>0.6 (0.3)	>0.15	/		>0.25	>0.1	>0.1	
p_{miss}^{T} (GeV/c)	< 1	/	< 1	/	/		/	
ϕ_{lH} (rad)	>π/2	/	>π/2	/	/		/	
m, m_{min} (GeV/c^2)	/		[0.5, 2]	/	/		/	



Short decays now included!

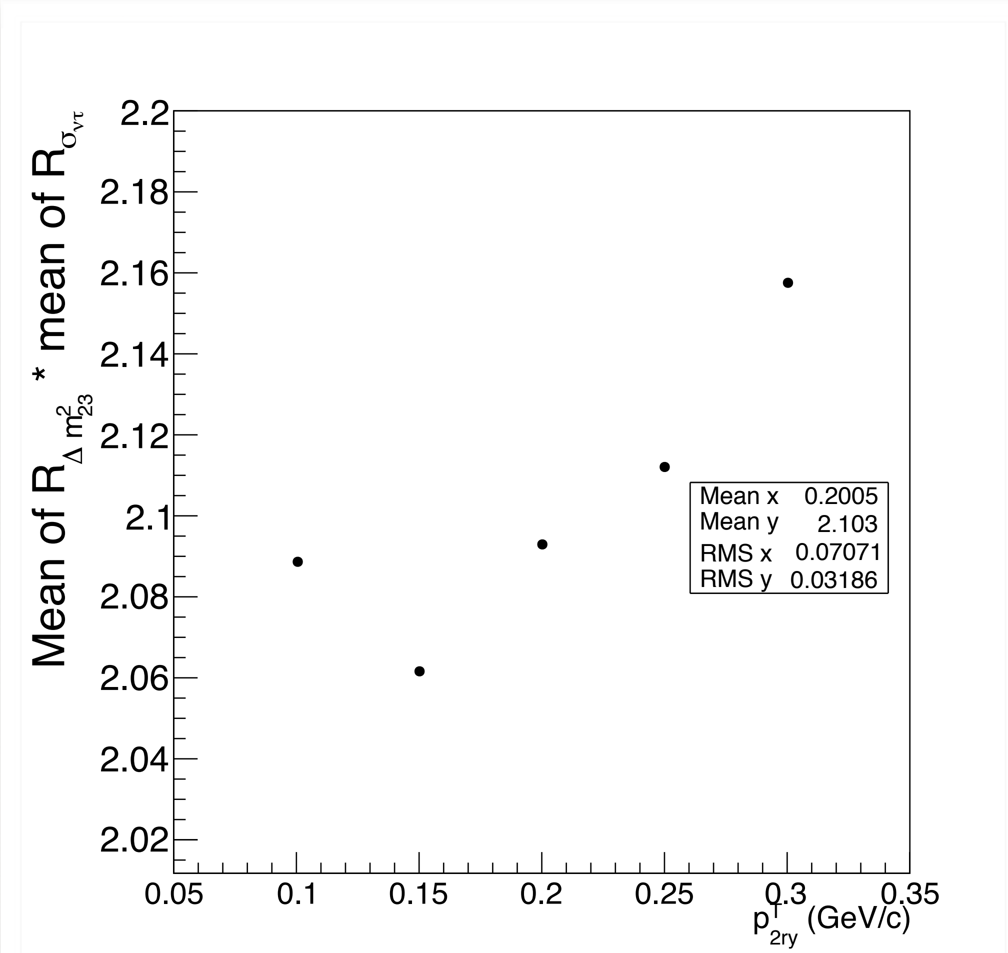
p^T_{2ry} cut in $\tau \rightarrow h$ decay channel

- Removing the cut on p^T_{2ry} 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_{2ry} cut (GeV/c)	**Increase Factor**
0.10	71
0.15	54
0.20	45
0.25	38
0.30	31

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

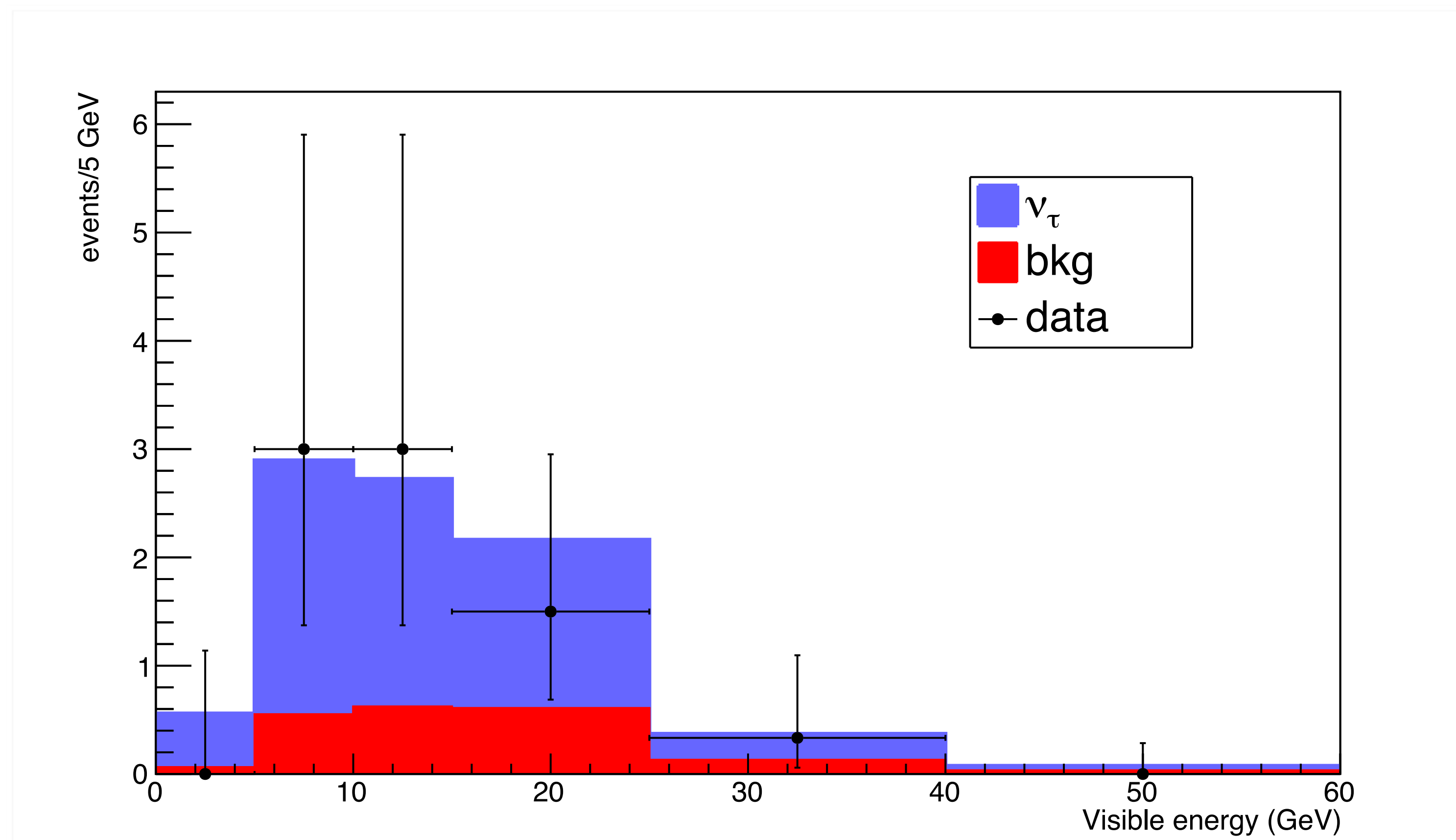


Best cut: 0.15 GeV/c

Number of expected events

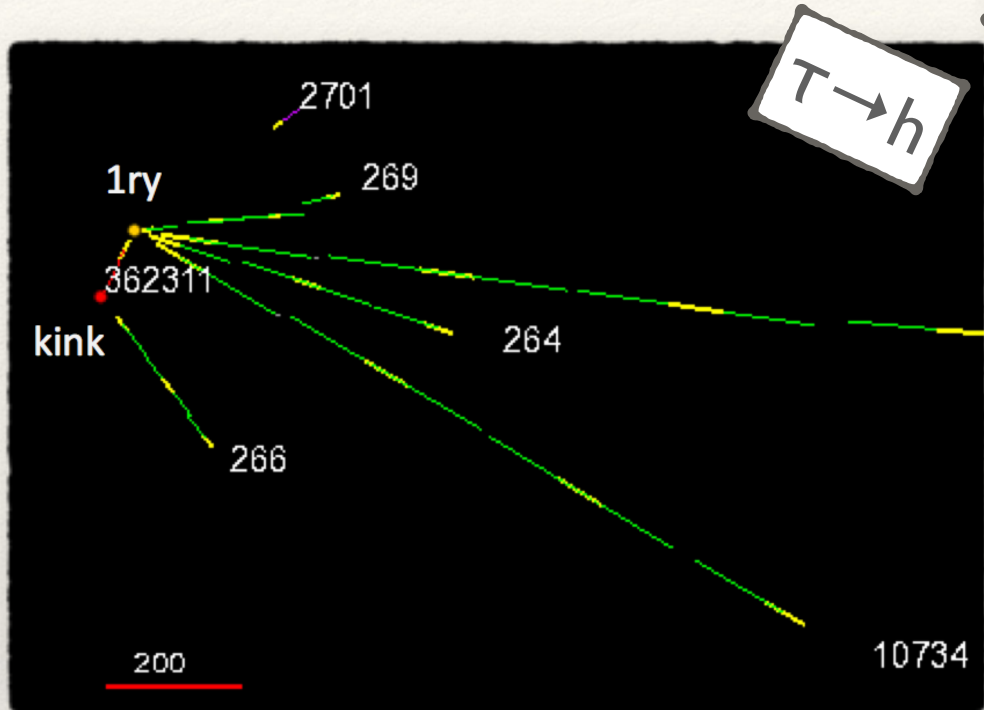
Channel	Expected Background				ν_τ Exp.	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.15 ± 0.03	1.28 ± 0.38	–	1.43 ± 0.39	2.96 ± 0.59	6
$\tau \to 3h$	0.44 ± 0.09	0.09 ± 0.03	–	0.52 ± 0.09	1.83 ± 0.37	3
$\tau \to \mu$	0.008 ± 0.002	–	0.016 ± 0.008	0.024 ± 0.008	1.15 ± 0.23	1
$\tau \to e$	0.035 ± 0.007	–	–	0.035 ± 0.007	0.84 ± 0.17	0
Total	0.63 ± 0.10	1.37 ± 0.38	0.016 ± 0.008	2.0 ± 0.4	6.8 ± 0.75	10

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

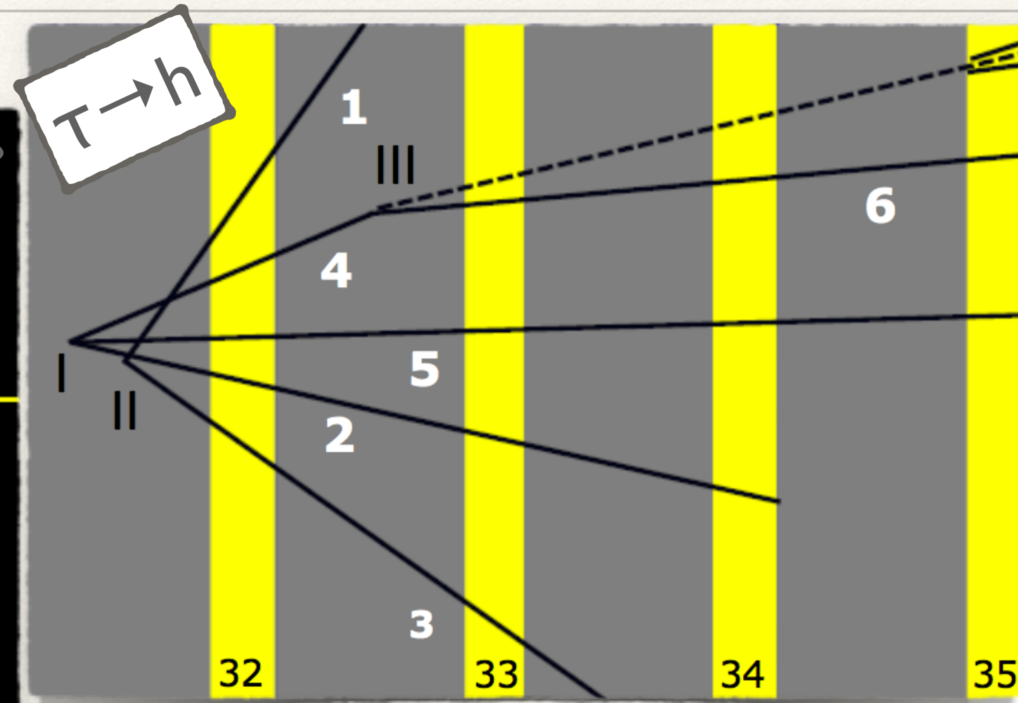


Monte Carlo simulation normalized to the expected number of events

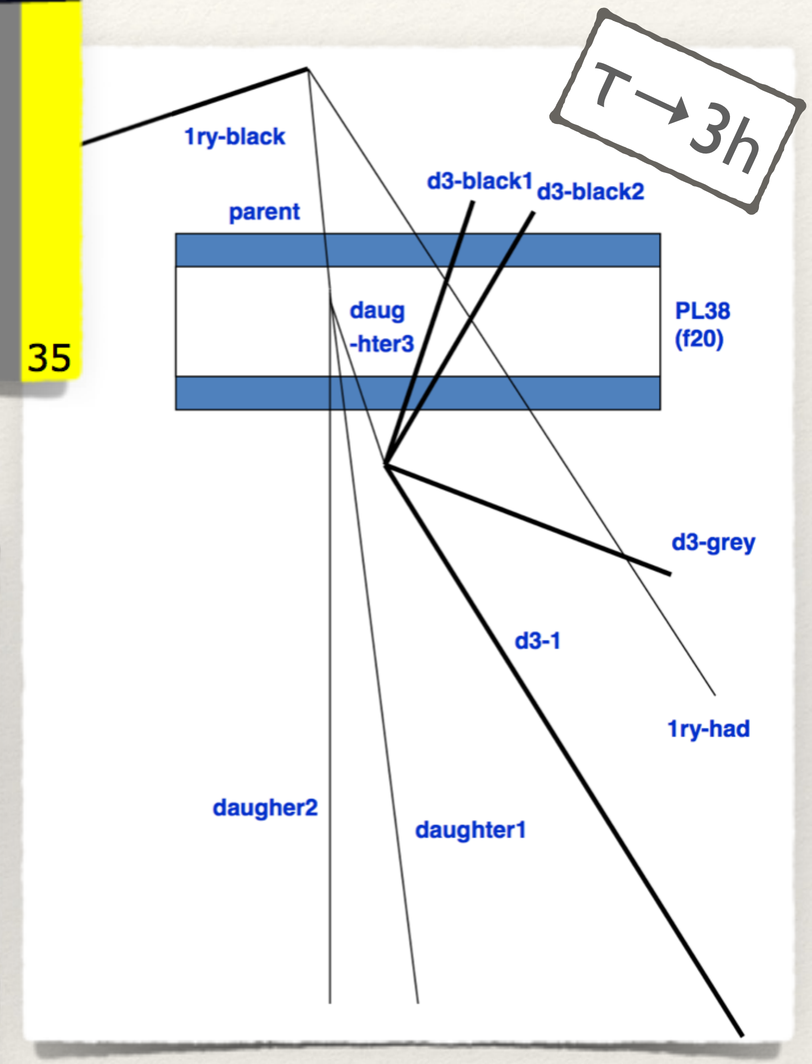
5 additional ν_τ candidates



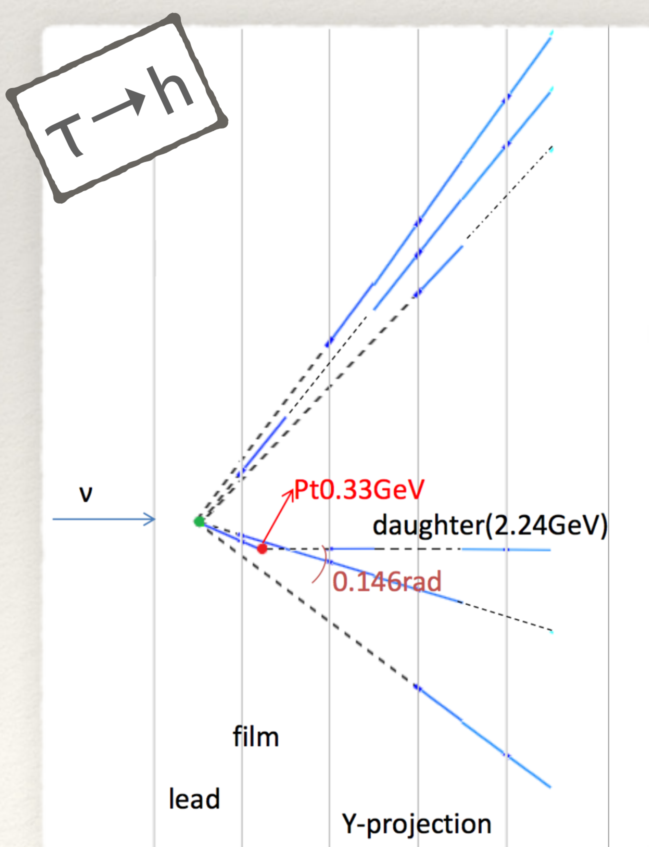
Event 11172035775



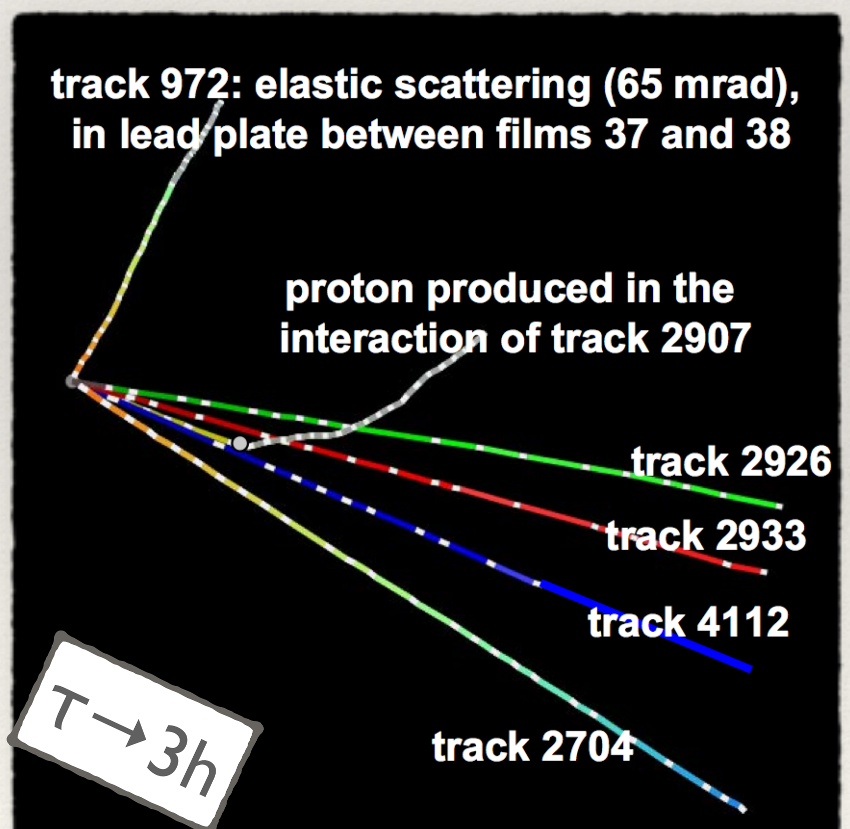
Event 11143018505



Event 11213015702



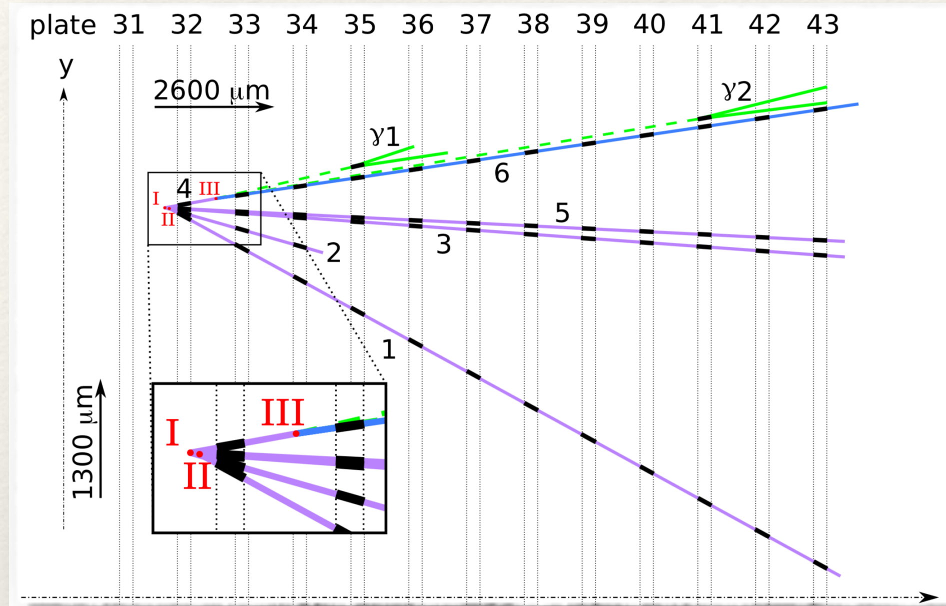
Event 9190097972

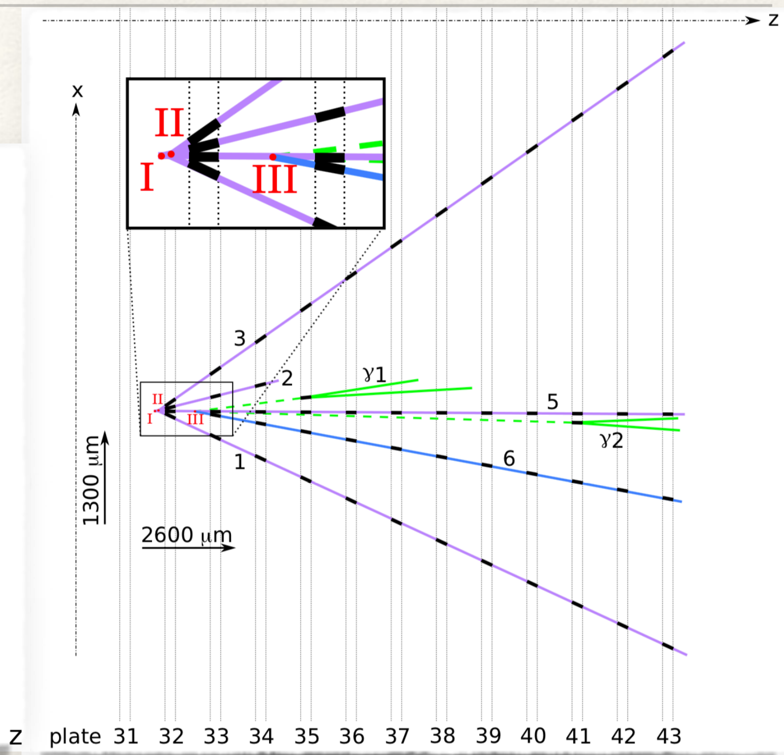


Event 10123059807

Event 11143018505: a peculiar topology

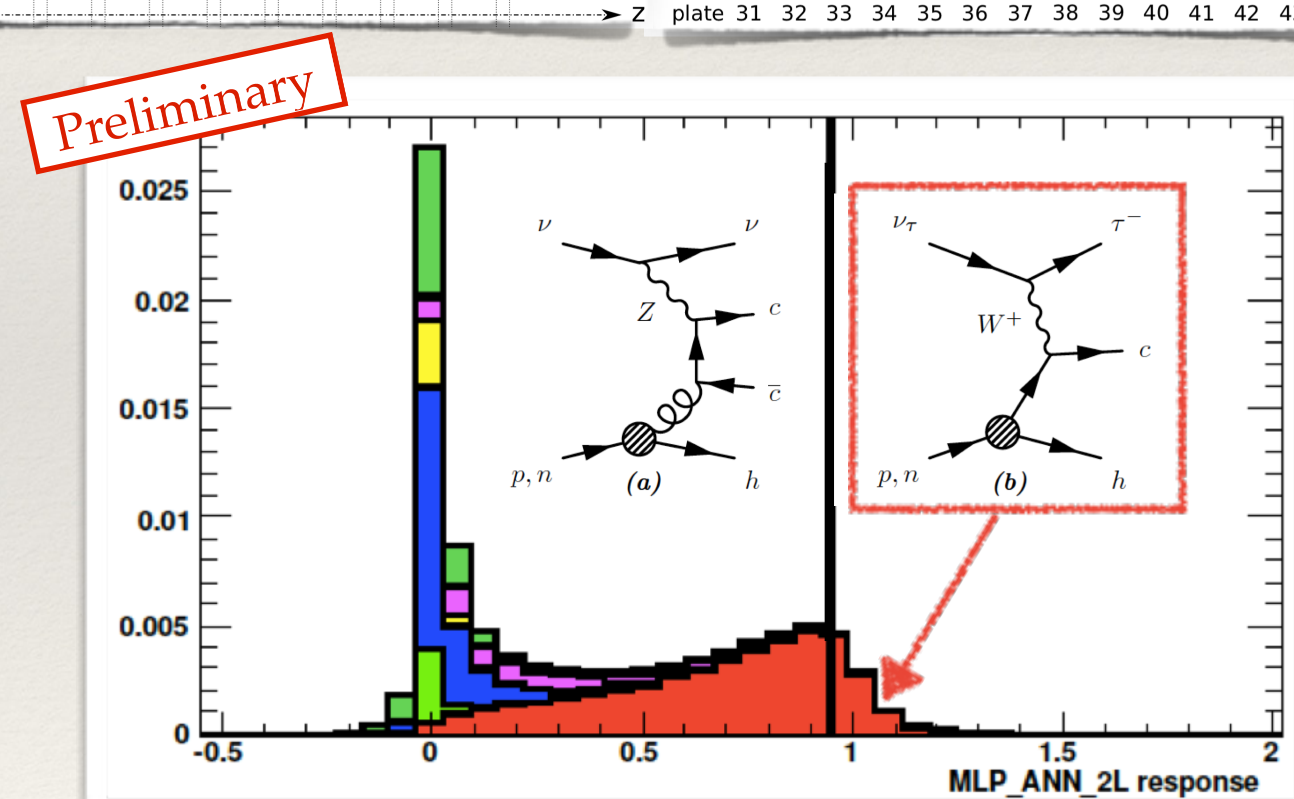
Muon-less event with 2 decay vertices





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

Sample	μ mis-identified	Exp Events (10^{-3})
ν_τ CC + charm		45
ν_μ CC + charm + h_{int}	yes	21
ν_μ NC + cc_bar		13
ν_τ CC + h_{int}		9
ν_μ CC + 2h_{int}	yes	4
ν_μ NC + 2h_{int}		4
TOTAL		100



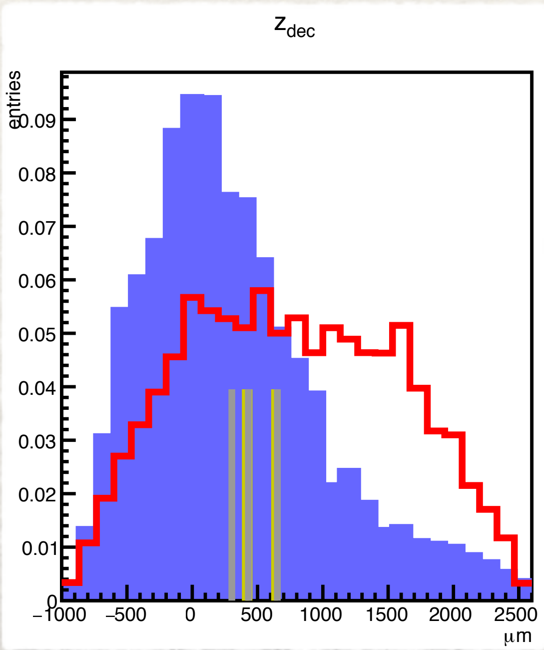
Probability of not being ν_τCC + charm ~ 10^{-4}
→ Significance = 3.5 σ

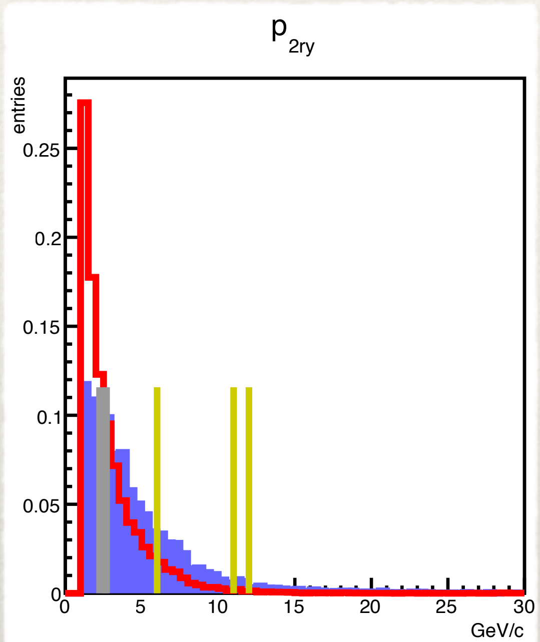
Examples of signal and background distributions

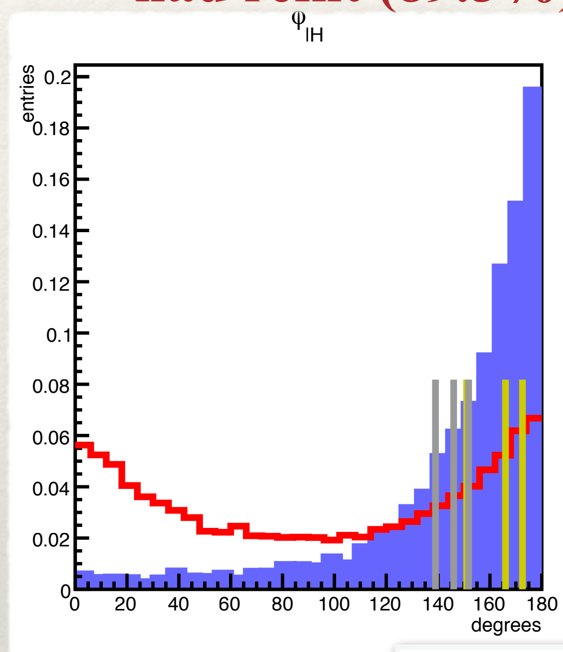
τ→1h : 6 ν_τ candidates

Signal: τ→1h (DIS + QE)

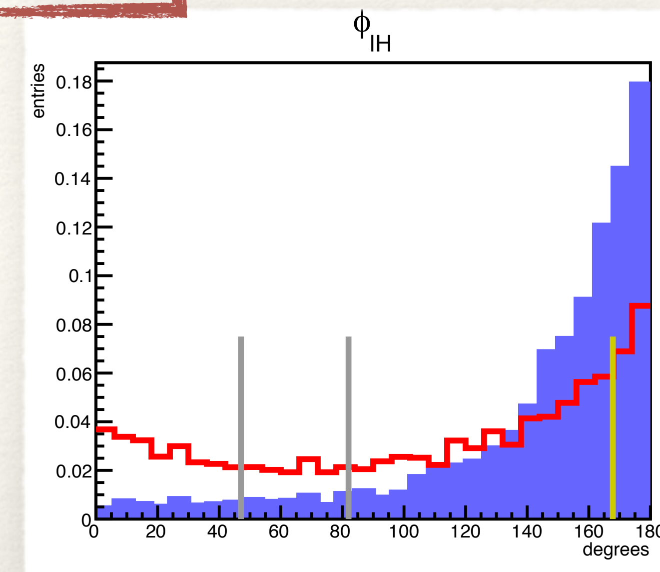
Background: - charm→1h (10.5%)
- had reint (89.5%)





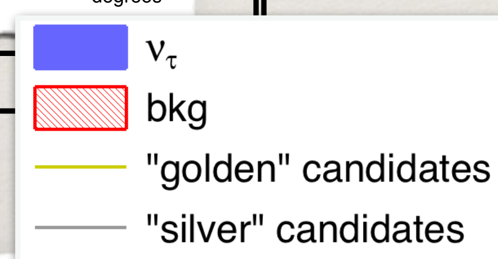


τ→3h : 3 ν_τ candidates

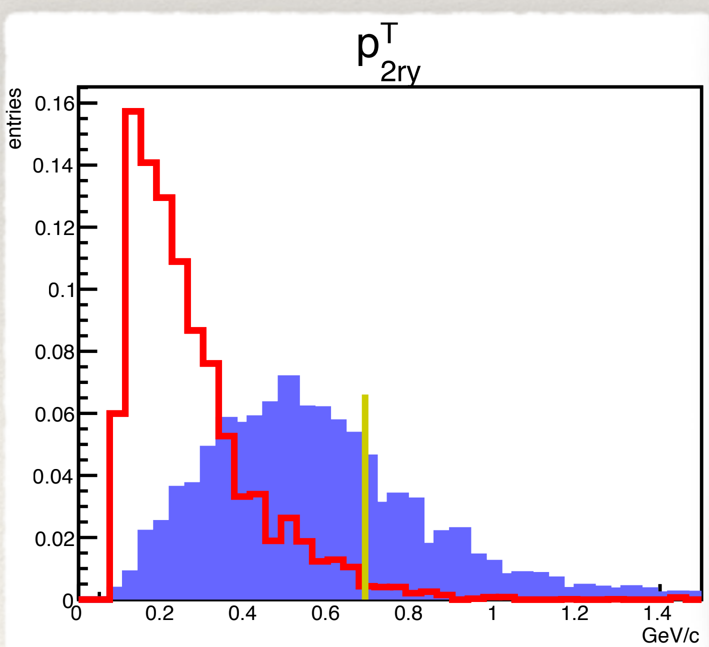


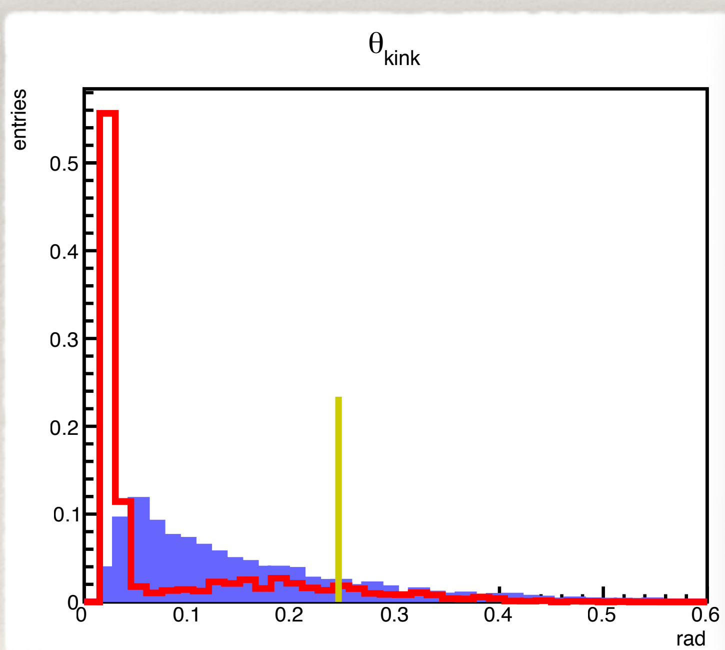
Signal: τ→3h (DIS + QE)

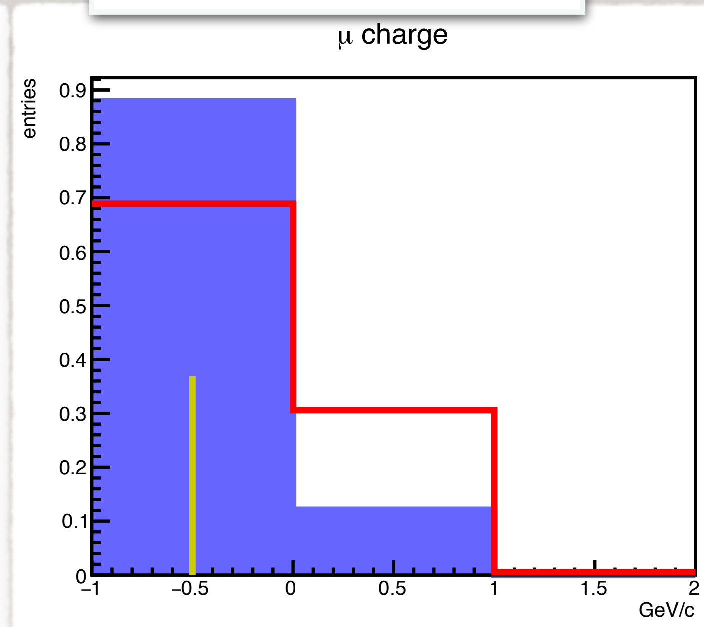
Background: - charm→3h (84.6%)
- had reint (17.3%)



τ→µ: 1 ν_τ candidate







Signal: τ→µ (DIS + QE)

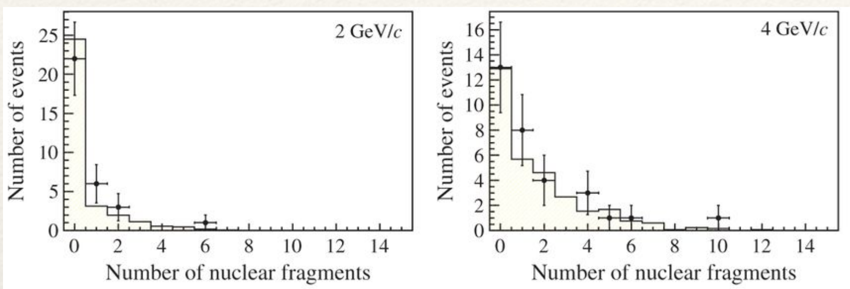
Background:
- charm→µ (33.3%)
- Large angle scattering (66.7%)

Background validation

Monte Carlo simulation has been validated comparing its results with the measured ν_μ CC interactions when producing:

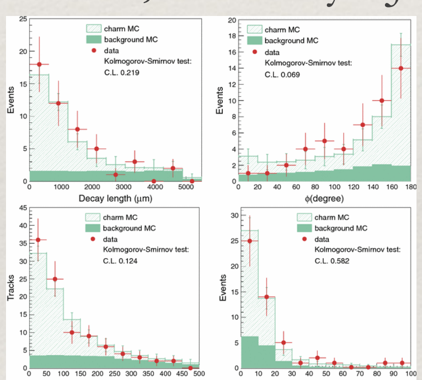
- hadron reinteractions

  ([H. Ishida et al., PTEP 2014, 093C01 (2014)](#))



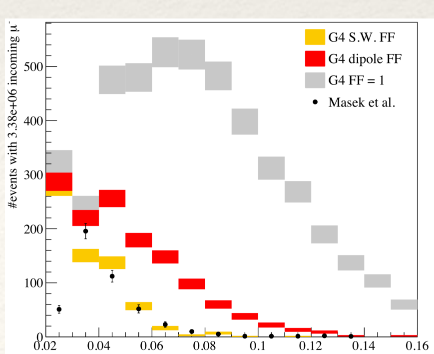
- charmed hadron decays

  ([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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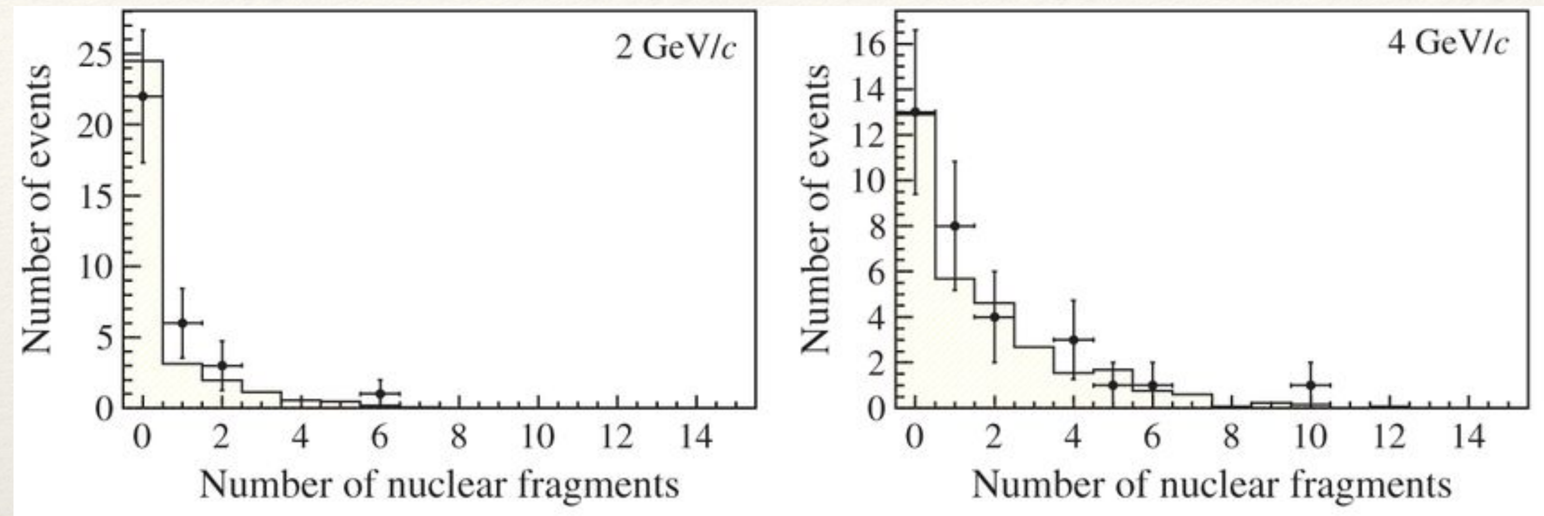

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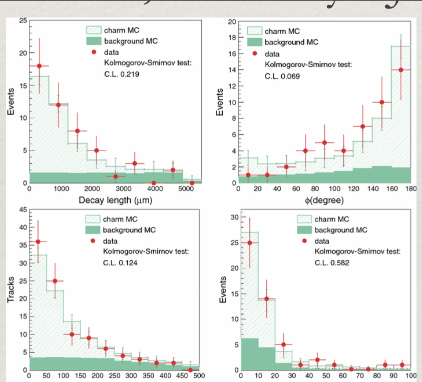

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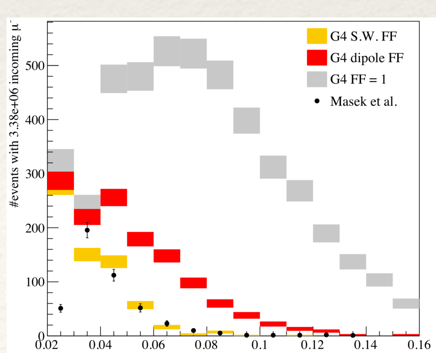

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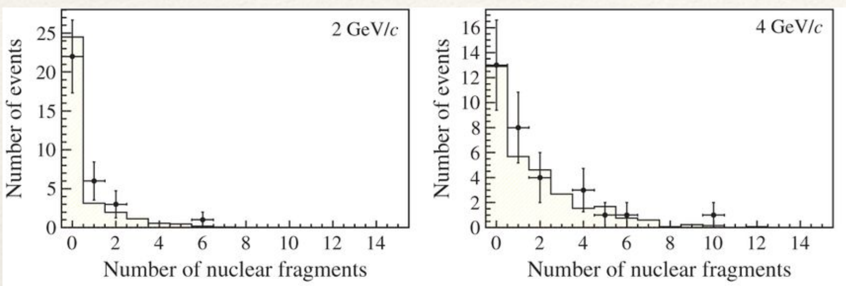

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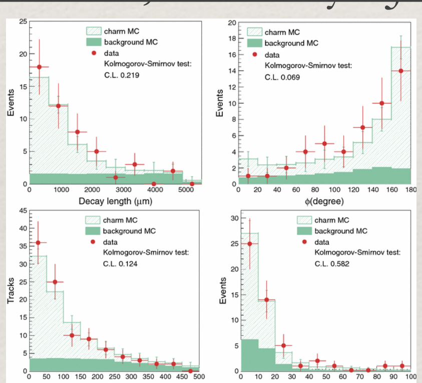

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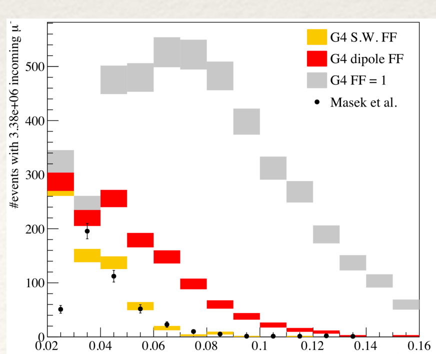

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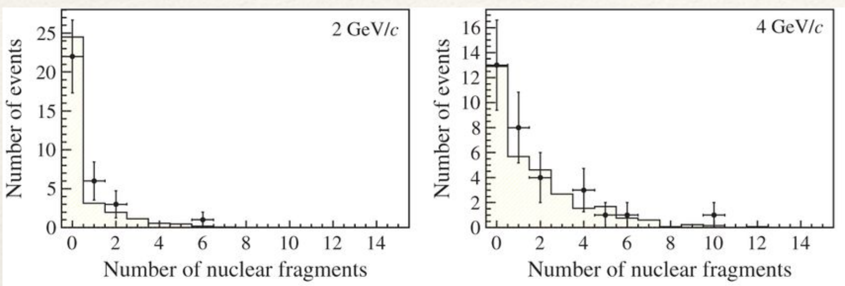

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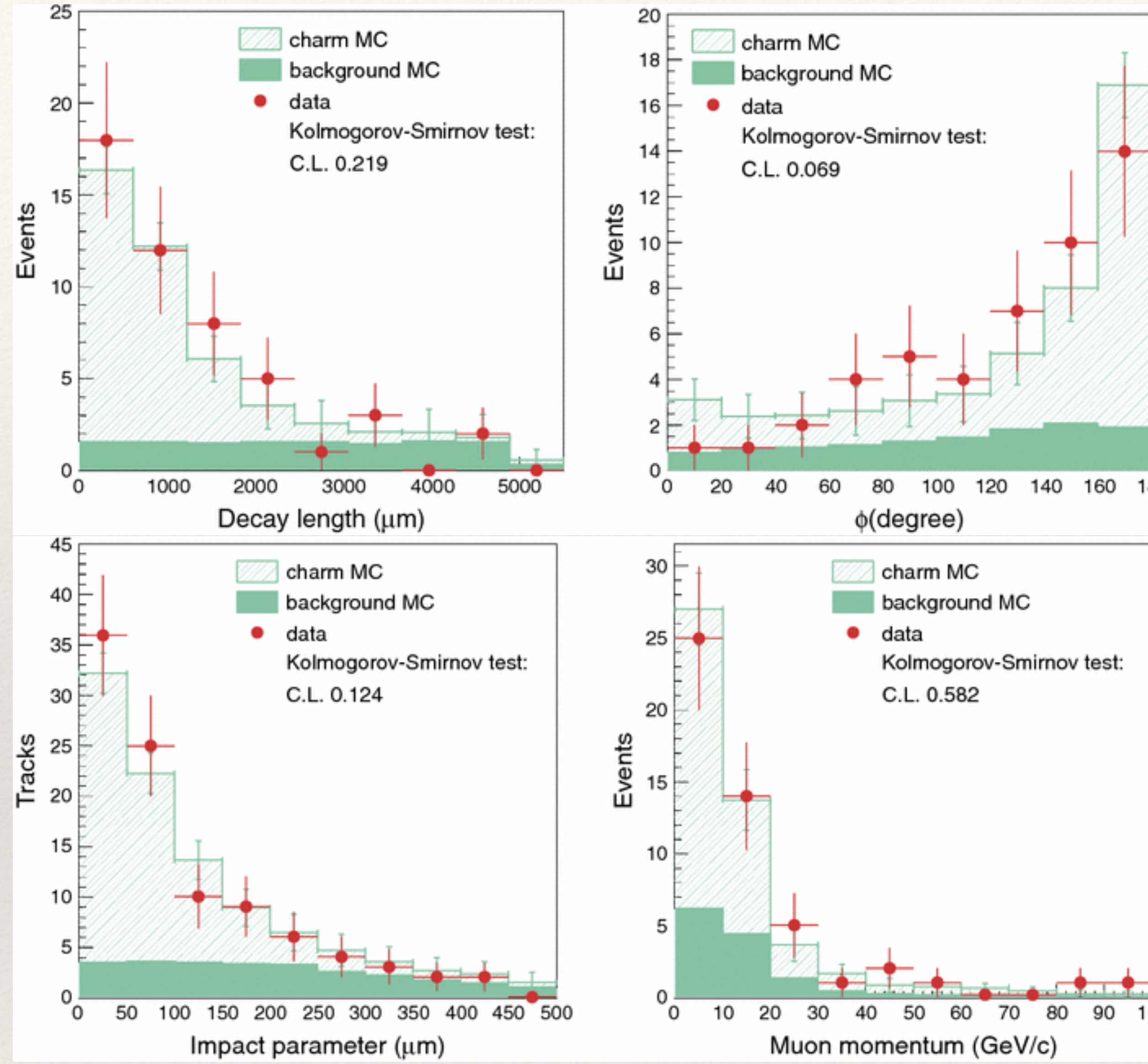

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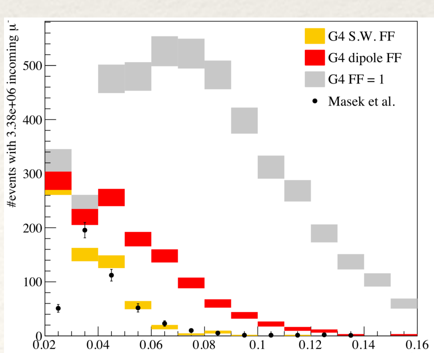

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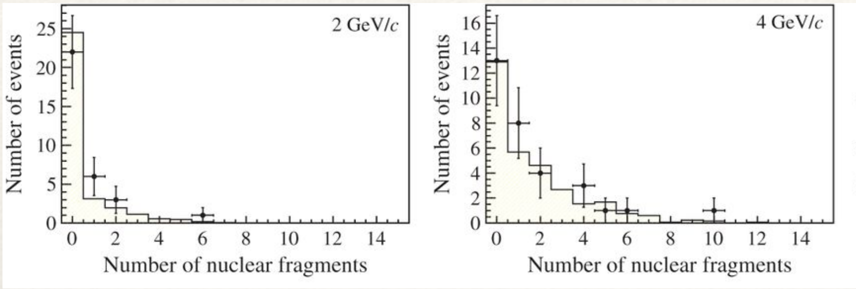

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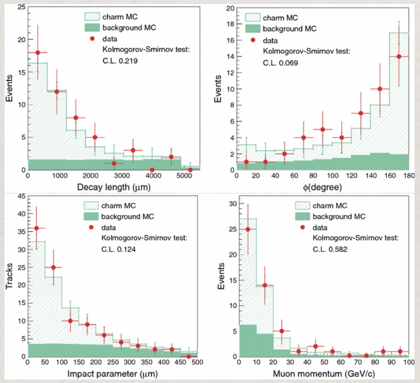

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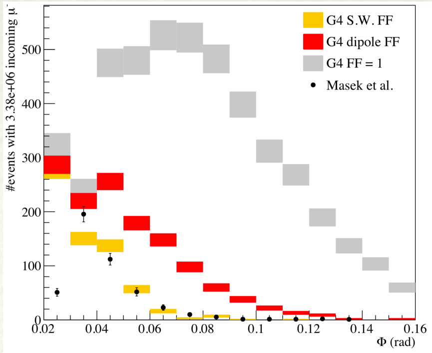

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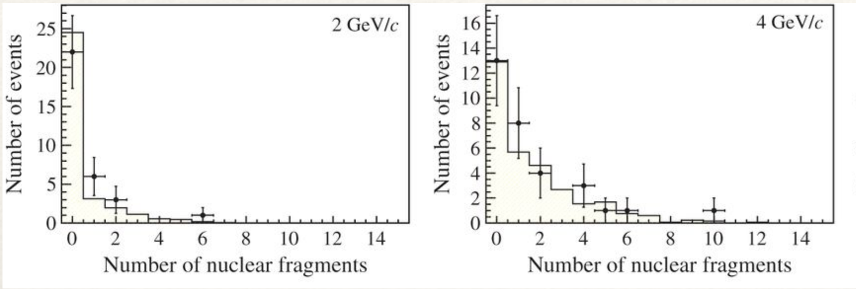

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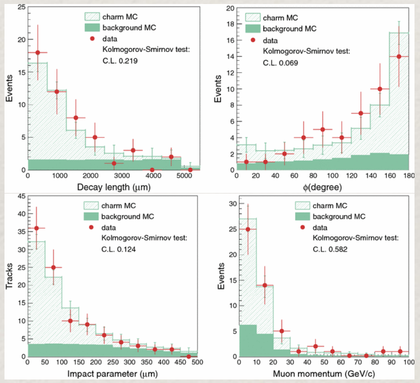

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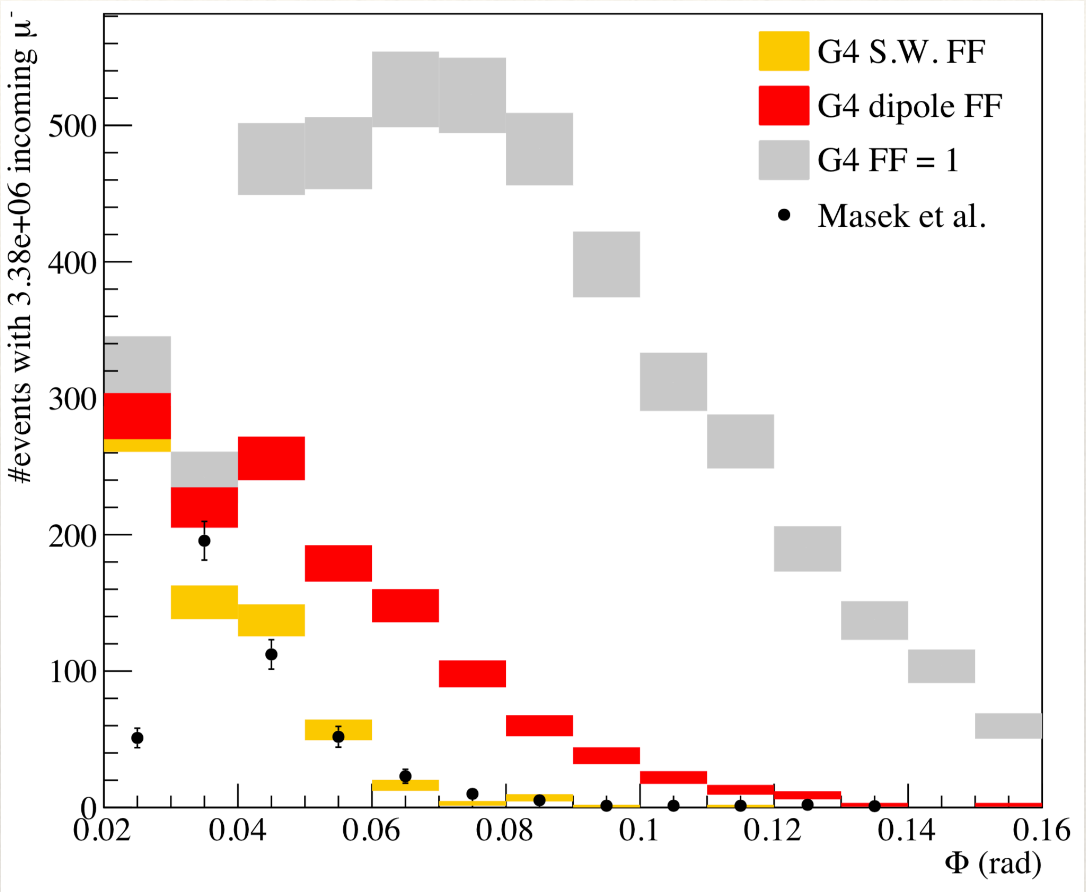

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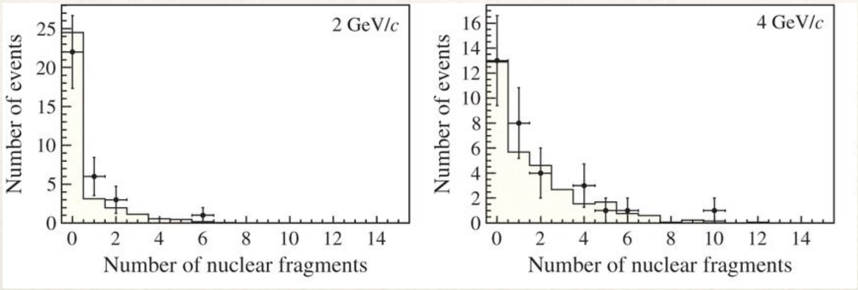

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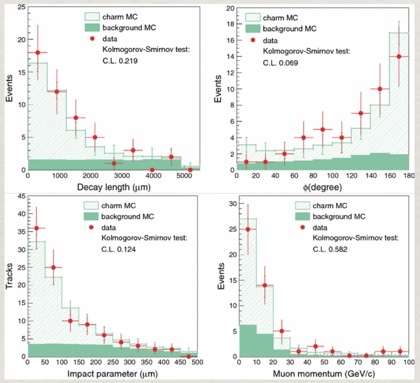

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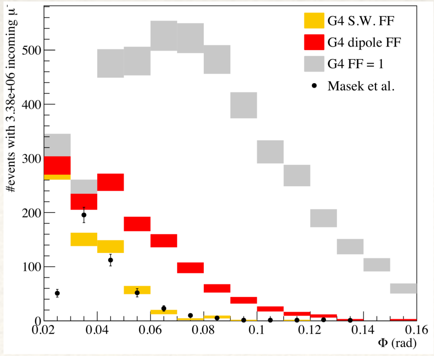
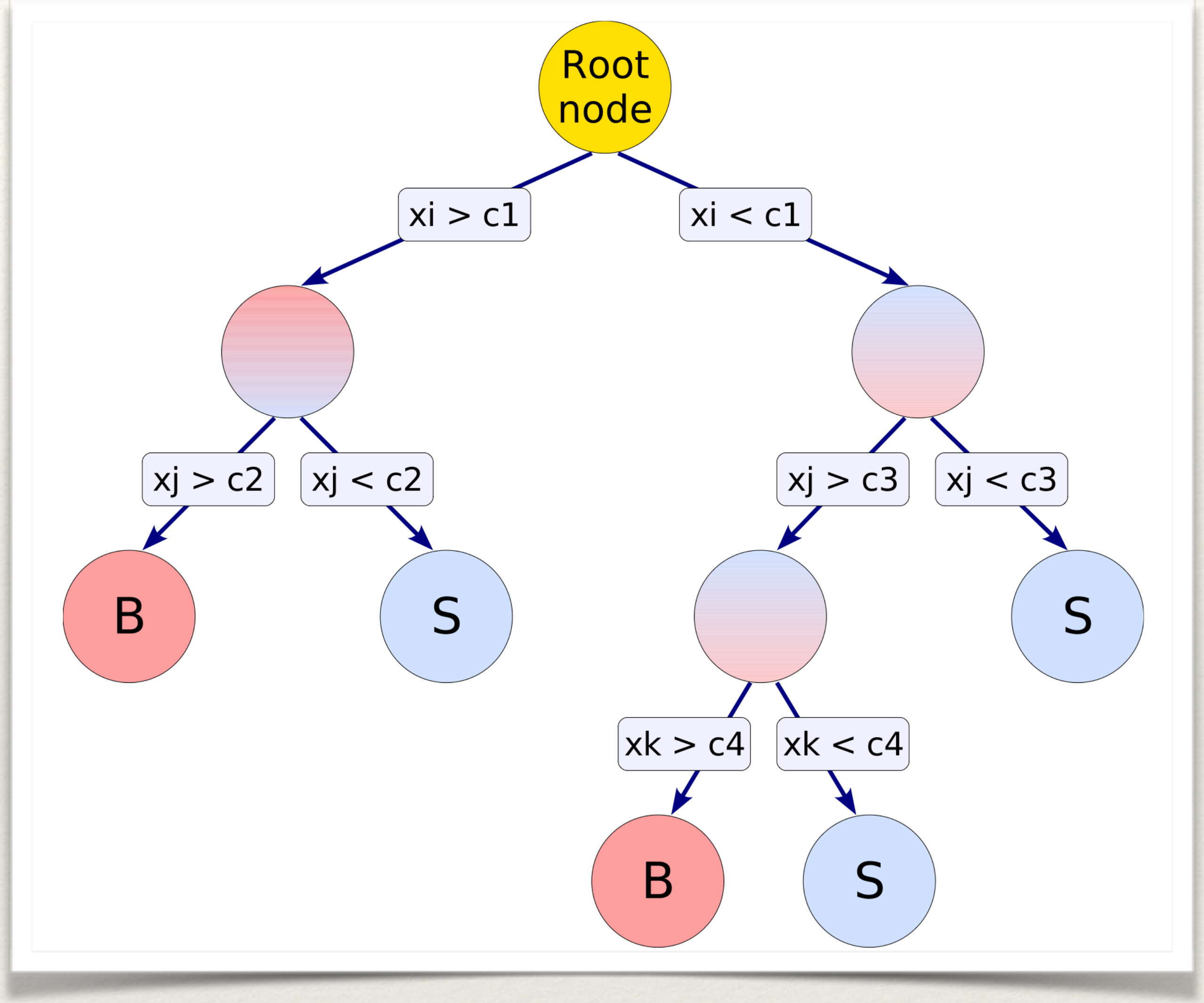


The Boost Decision Trees method (BDT)

- 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)

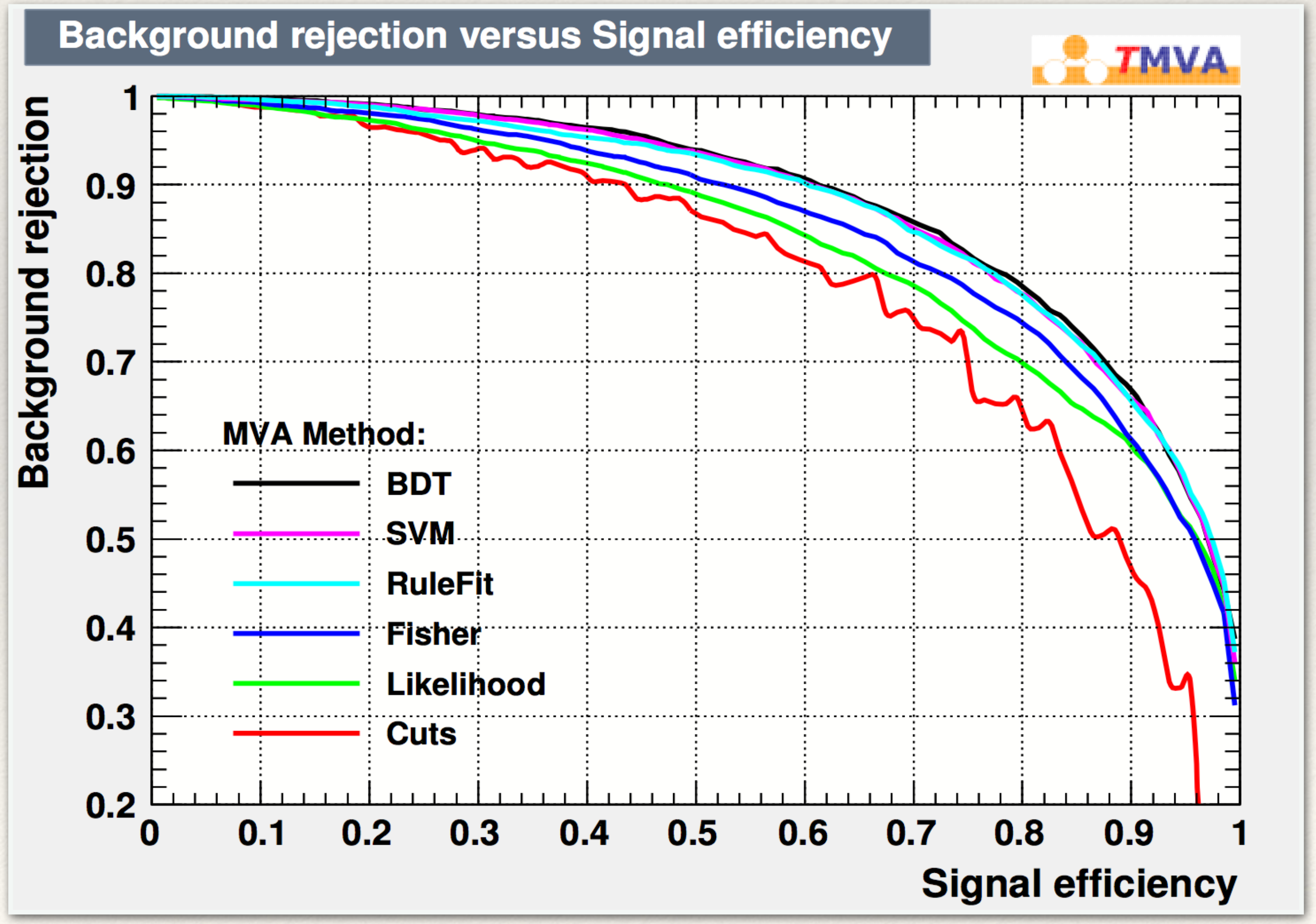


Ref: Hoecker et al. TMVA: Toolkit for Multivariate Data Analysis. PoS, ACAT:040, 2007

Boosted Decision Tree analysis

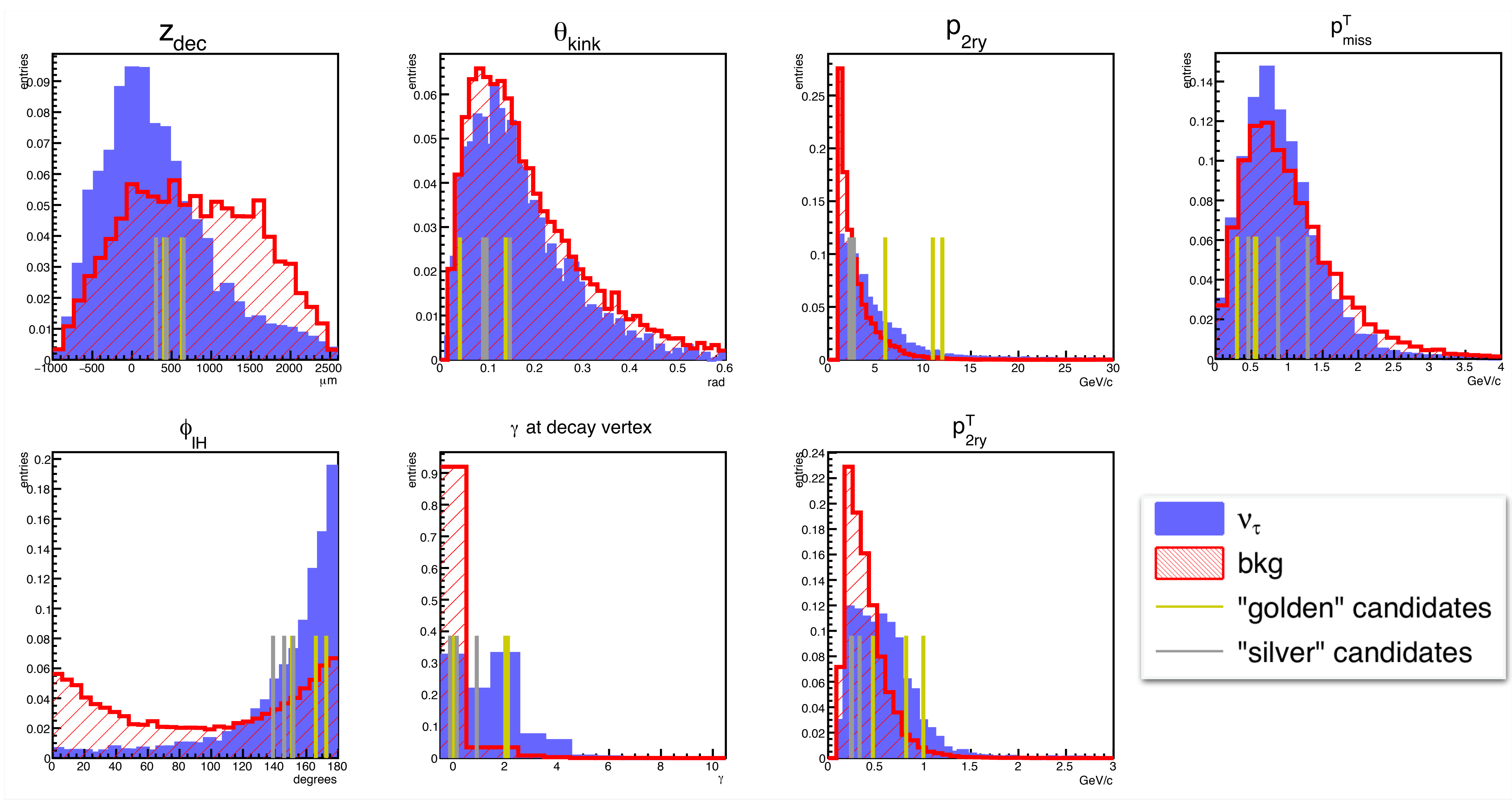
- Multivariate methods can help rejecting background
- Use also events features to evaluate ν_τ appearance significance

- Different multivariate techniques have been considered and their performances for signal to background discrimination compared
- Best discrimination power is given by BDT

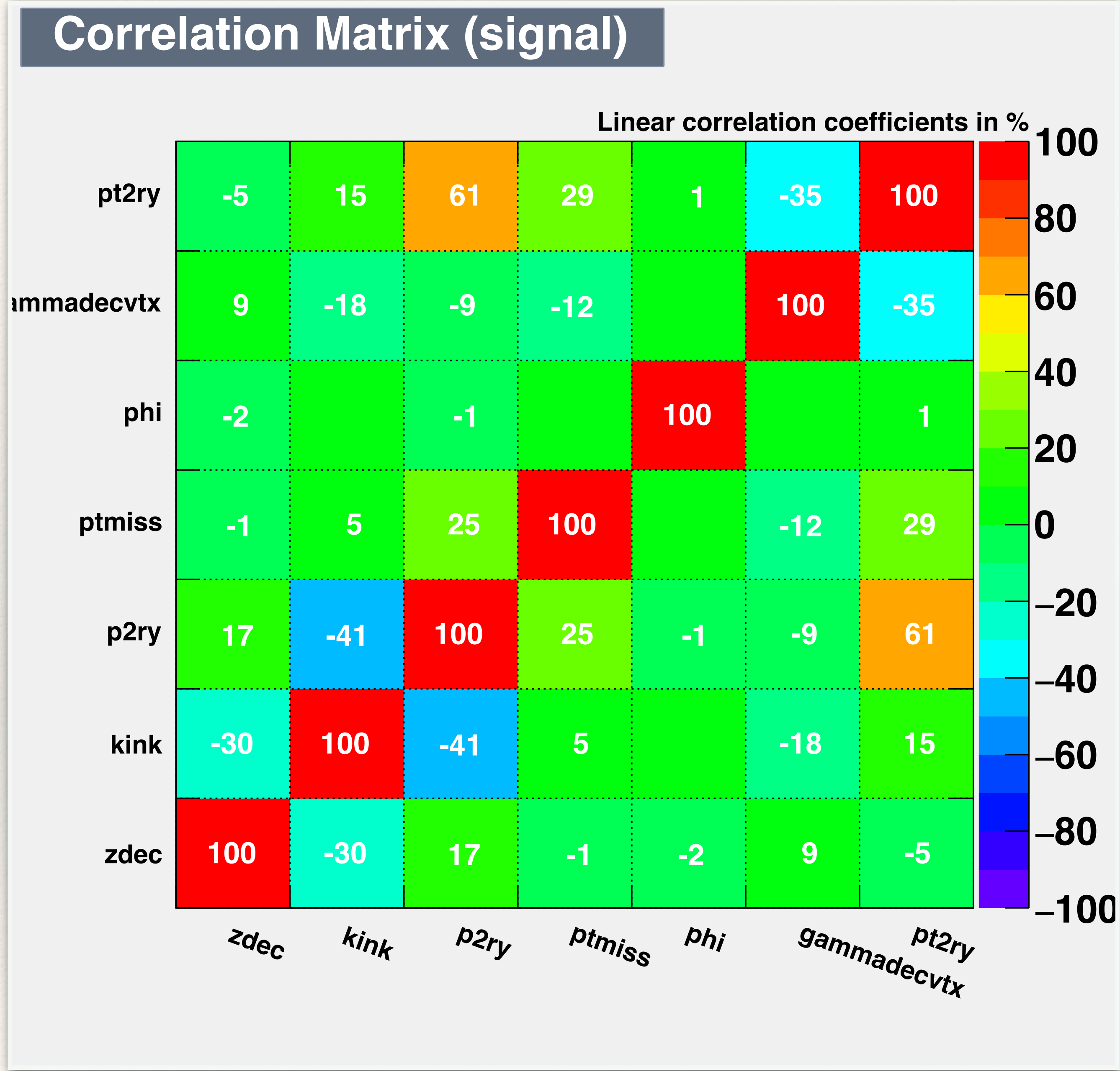


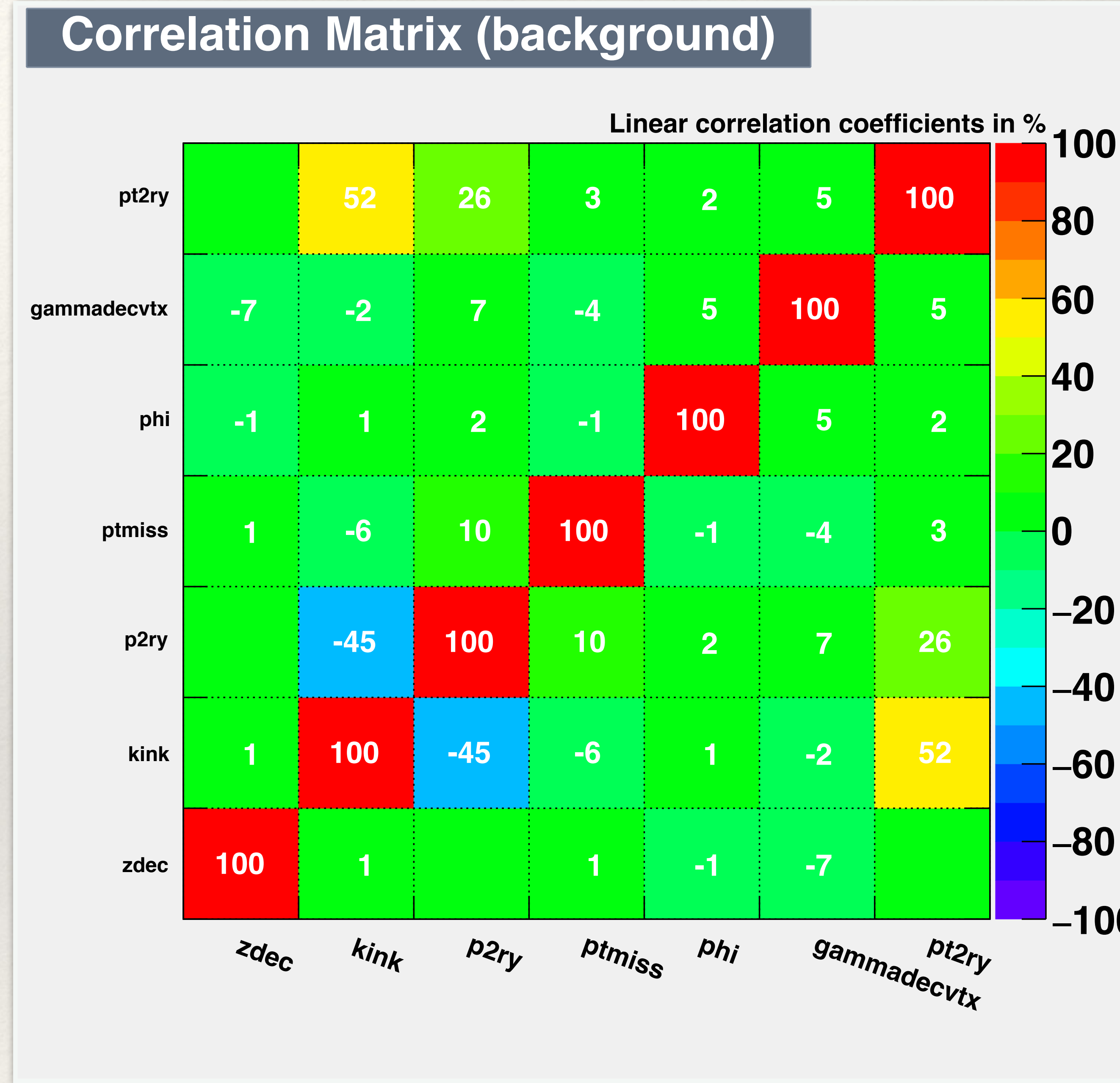
Example: τ→h: Kinematical variables

- Input = events surviving the looser selection
- Signal and Bkg normalized to unity



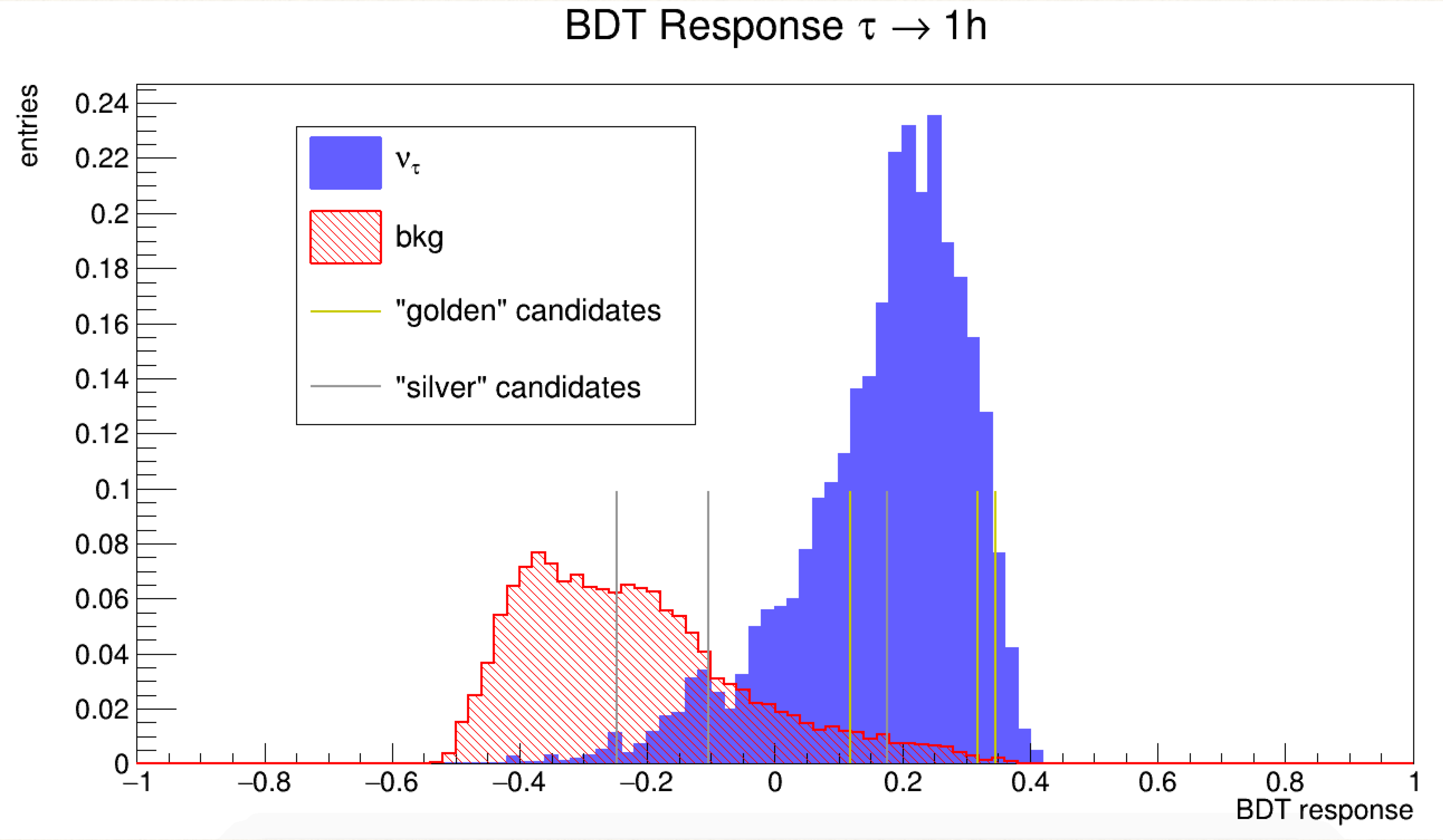
τ→h: Correlation between variables



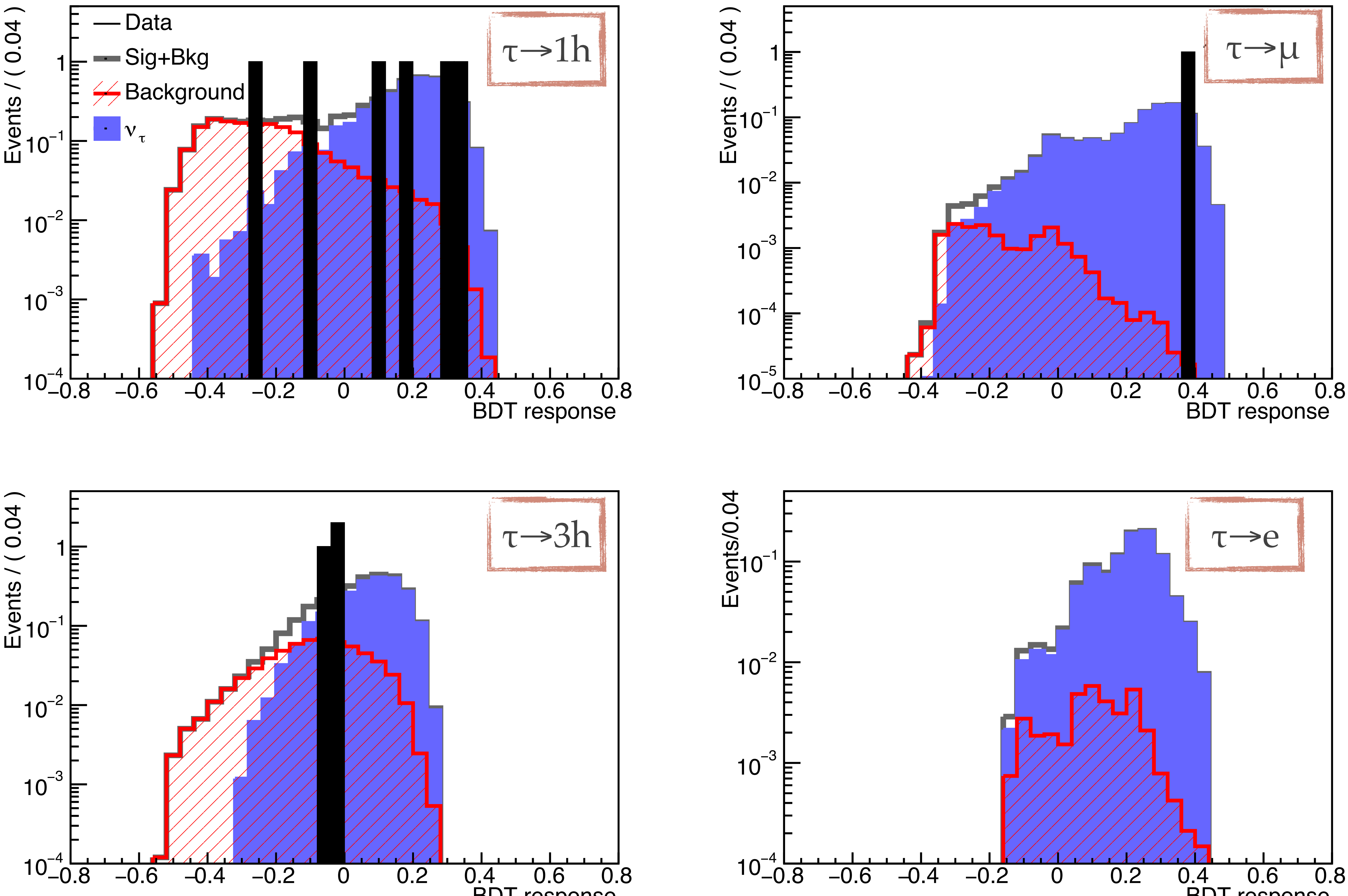


τ→h: DBT response

- Signal and Bkg normalized to the number of expected events



BDT response for all decay channels



Extended Likelihood

signal strength

true bkg (floating param.)

uncertainty on exp bkg

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

channels

obs events in the cth channel

expected signal

BDT response

expected bkg

$$f_c(x_{ci}) = \frac{\mu s_c}{\mu s_c + \beta_c} \text{PDF}_c^{\text{sig}} + \frac{\beta_c}{\mu s_c + \beta_c} \text{PDF}_c^{\text{bkg}}$$

ν_τ appearance significance

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

  profiled values of the nuisance parameter β_c, maximizing $\mathcal{L}$ for the given μ

  value of the likelihood at its maximum

- Results:

  $\mu = 1.1^{+0.5}_{-0.4}$

  $P_{value} = 4.8 \cdot 10^{-10}$

  Significance = 6.1σ

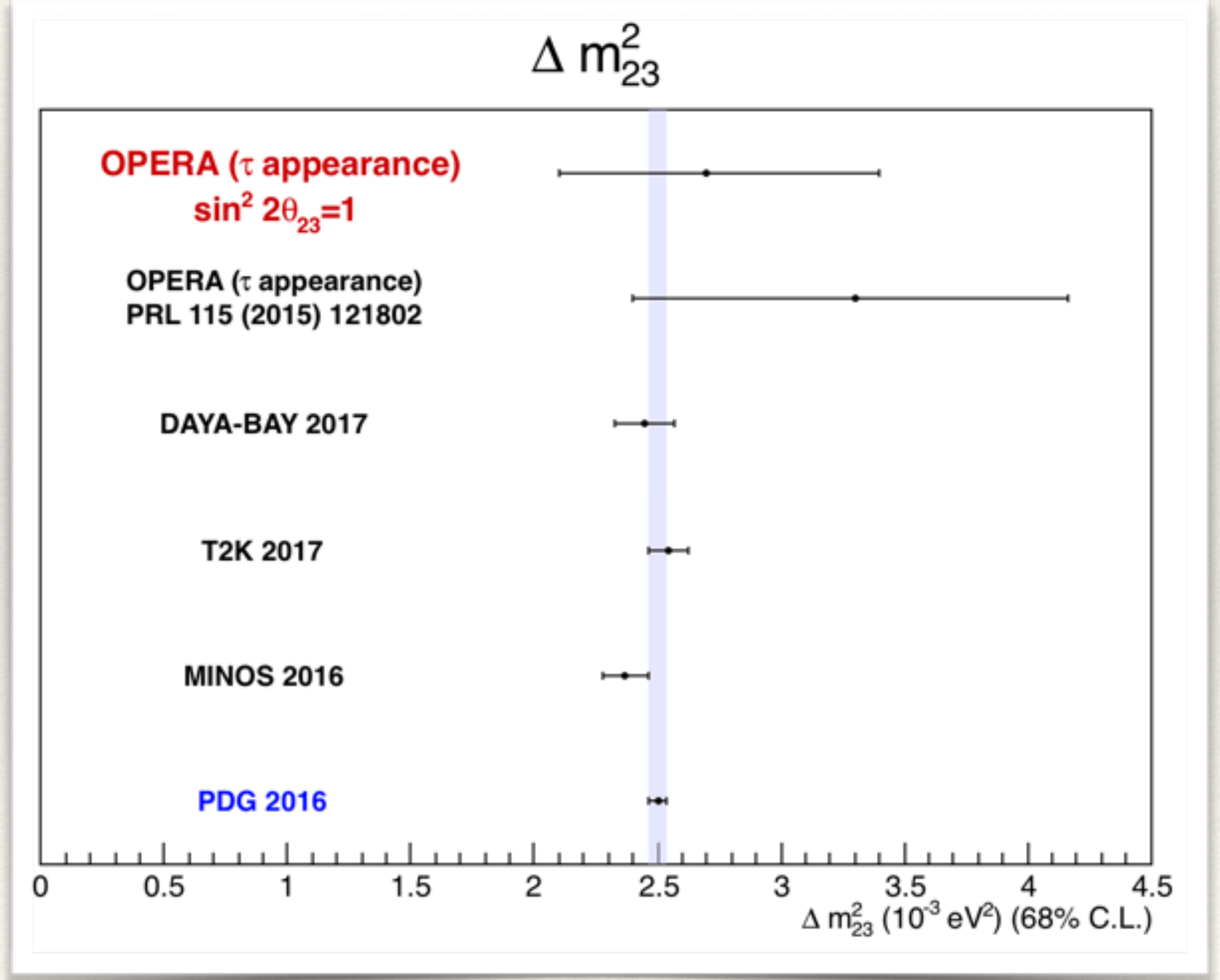
Δm^2_{23} measurement

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

$$\mu \propto \sigma^{CC}_{\nu_\tau} \cdot \mathcal{P}_{\nu_\mu\to\nu_\tau}$$

Assumptions: maximal mixing, ν_τ CC interaction cross section as in Genie v2.6 default

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



First measurement in appearance mode

Agreement with *PDG* value within 1σ

ν_τ CC cross section on lead

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

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

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

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

$$\langle\sigma\rangle_{meas} = \frac{(N^{obs} - N^{expB})/(\epsilon N_T)}{\int \Phi_{\nu_\mu}(E)\mathcal{P}_{\nu_\mu\to\nu_\tau}(E)dE}$$

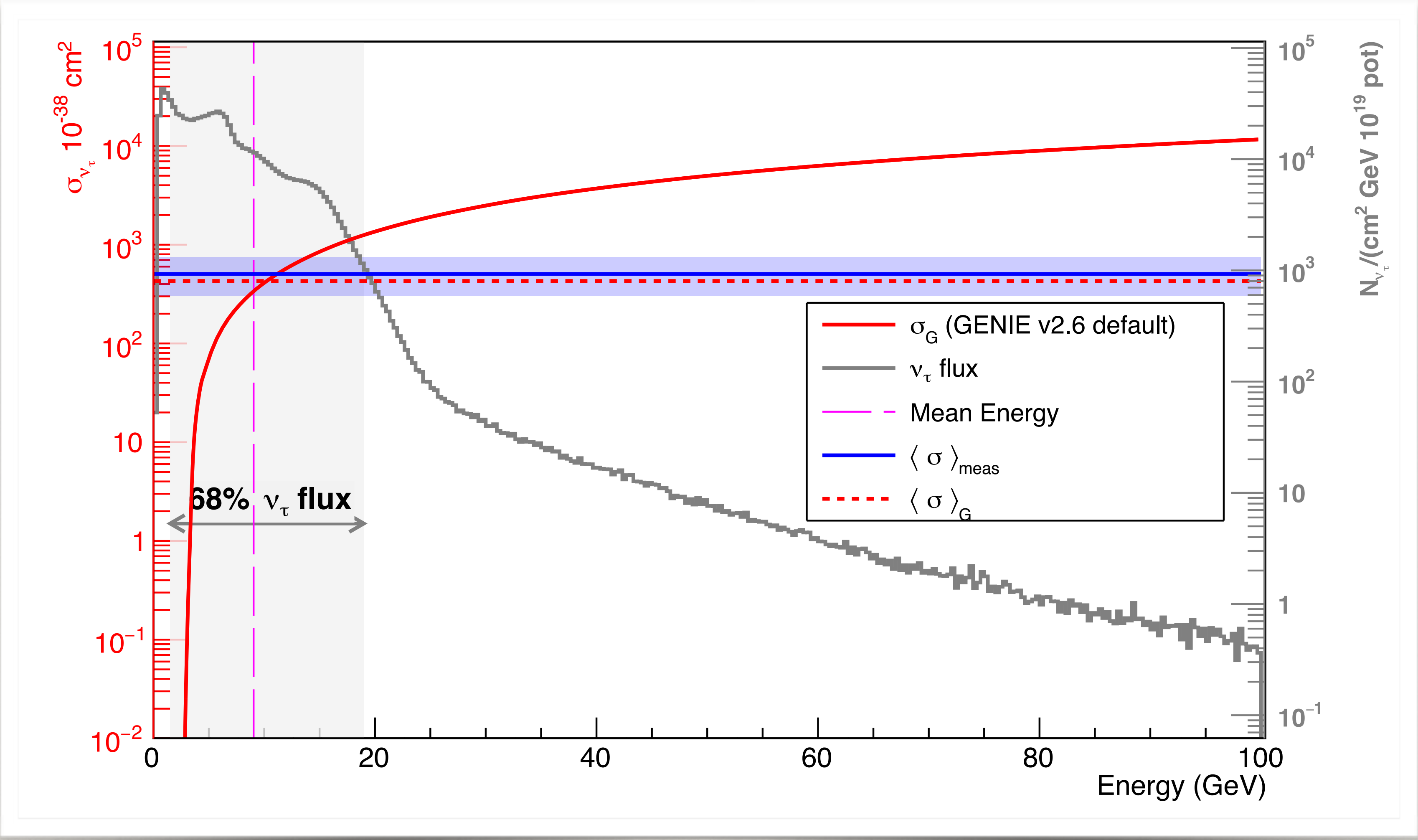
ϵ: overall efficiency

N_T: number of lead nuclei in the fiducial volume

ν_τ CC cross section on lead

- Δm^2_{23} 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: $\langle\sigma\rangle_G = (4.29 \pm 0.04) \cdot 10^{-36}\text{cm}^2$

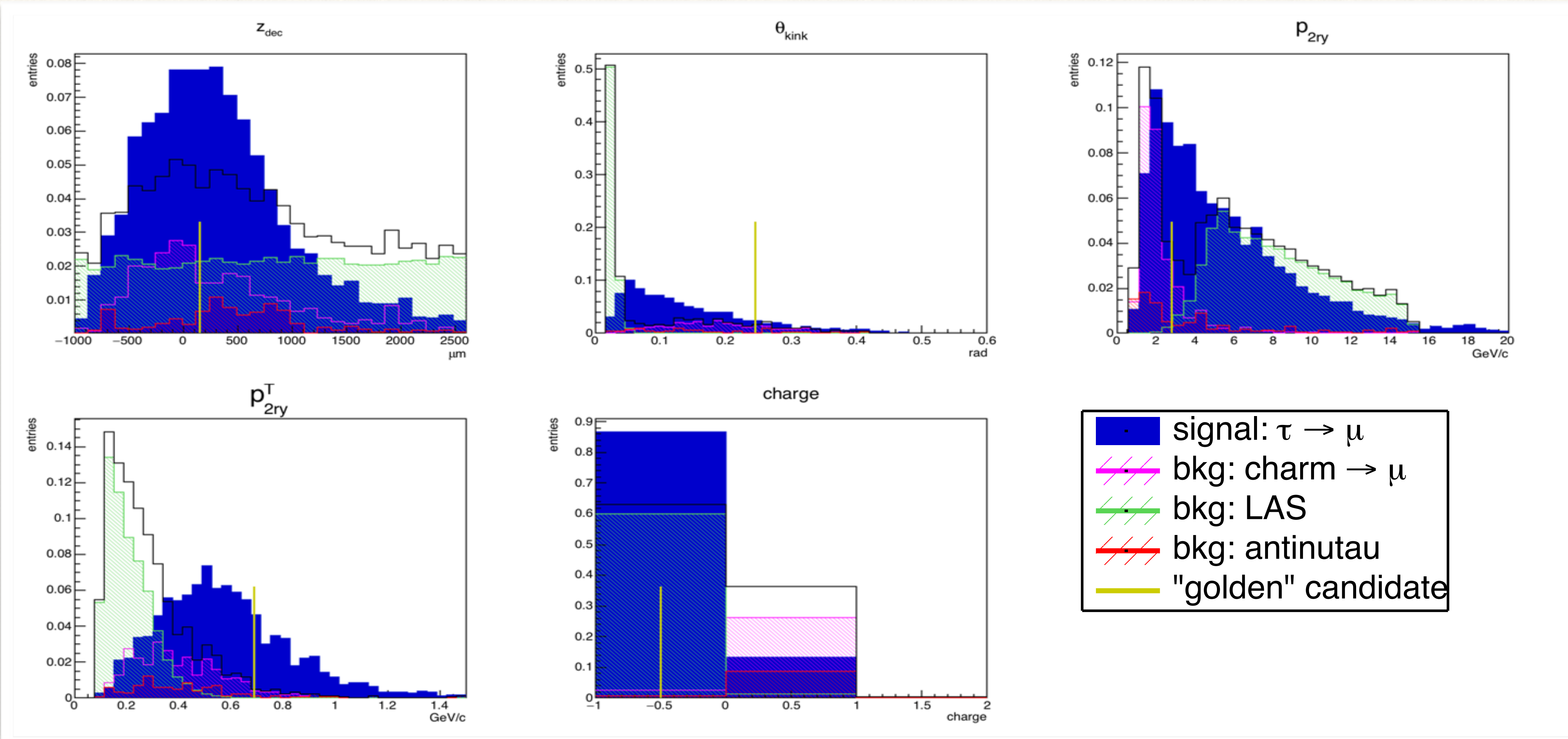
$$\langle\sigma\rangle_{meas} = (1.2^{+0.6}_{-0.5})\ \langle\sigma\rangle_G$$



ν_τ lepton number

- Lepton number of ν_τ has never been observed
- Muon decay channel: ν can be distinguished from $\bar{\nu}$?
- CNGS beam: 2% contamination of $\bar{\nu}_\mu$ which could oscillate into $\bar{\nu}_\tau$
- Expected $\bar{\nu}_\tau$ with $\tau^+ \rightarrow \mu^+$ with misidentified or not measured charge $= 0.0024 \pm 0.0005$

ν_τ lepton number observation



- Extended likelihood function
- Significance of having observed a $\tau^- \to \mu^-$: **3.7 σ**
- Assumption: lepton number is conserved in the neutrino interaction

First observation of ν_τ lepton number

Summary of OPERA final results on ν_τ appearance

- **New strategy for the ν_τ selection**
- 5603 fully analysed ν events: **10 ν_τ candidates** satisfying the looser criteria
- Multivariate analysis to fully exploit event features
- **ν_τ appearance significance improved: 6.1σ**
- The number of observed ν_τ candidates after bkg subtraction is a function of $\Delta m^2_{23} \cdot \sigma_{\nu\tau}$
  - $\Delta m^2_{23} = 2.7^{+0.7}_{-0.6} \cdot 10^{-3} eV^2$ at 68% C.L. ➙ **first measurement in appearance mode**
  - $<\sigma_{\nu\tau}>$ **CC** $= 5.1^{+2.4}_{-2.0} \cdot 10^{-36} cm^2/GeV$ ➙ **first measurement ever**
- **First observation of the ν_τ lepton number** with a significance of 3.7σ

- Paper published on PRL on 22nd May 2018 Ref: Phys. Rev. Lett. 120, 211801

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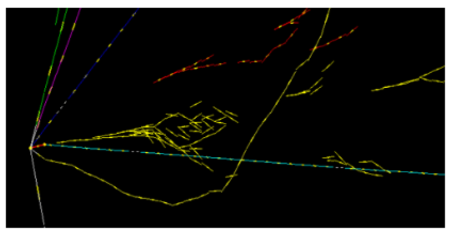

Physics NEWS AND COMMENTARY

OPERA's 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)

Current Issue

Vol. 120, Iss. 21 — 25 May 2018

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PHYSICAL REVIEW LETTERS **120**, 211801 (2018)

Editors' Suggestion Featured in Physics

Final Results of the OPERA Experiment on ν_τ Appearance in the CNGS Neutrino Beam

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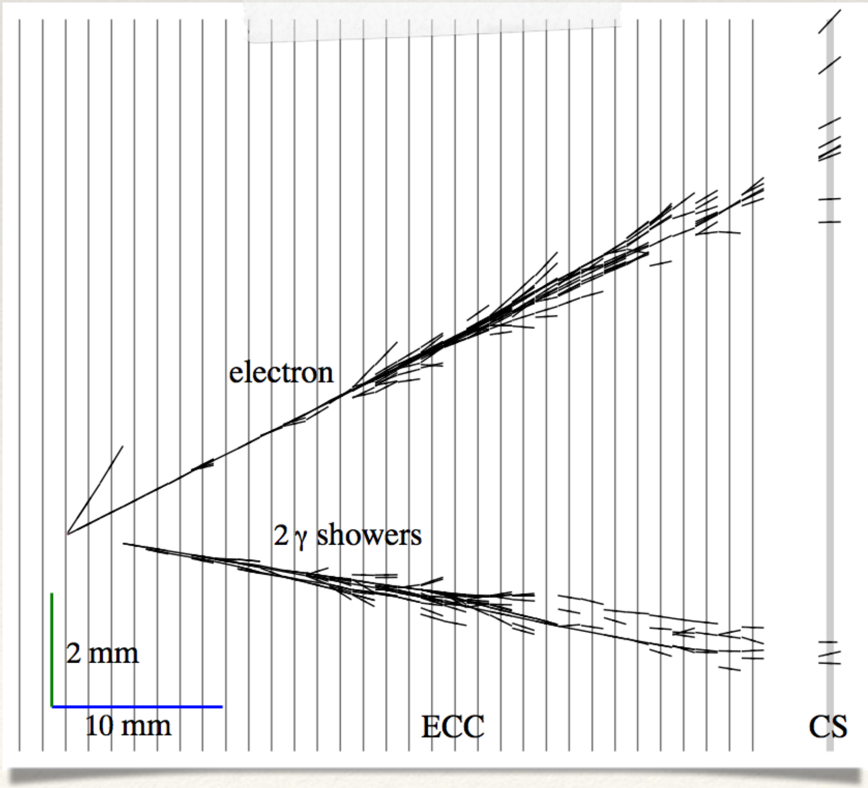
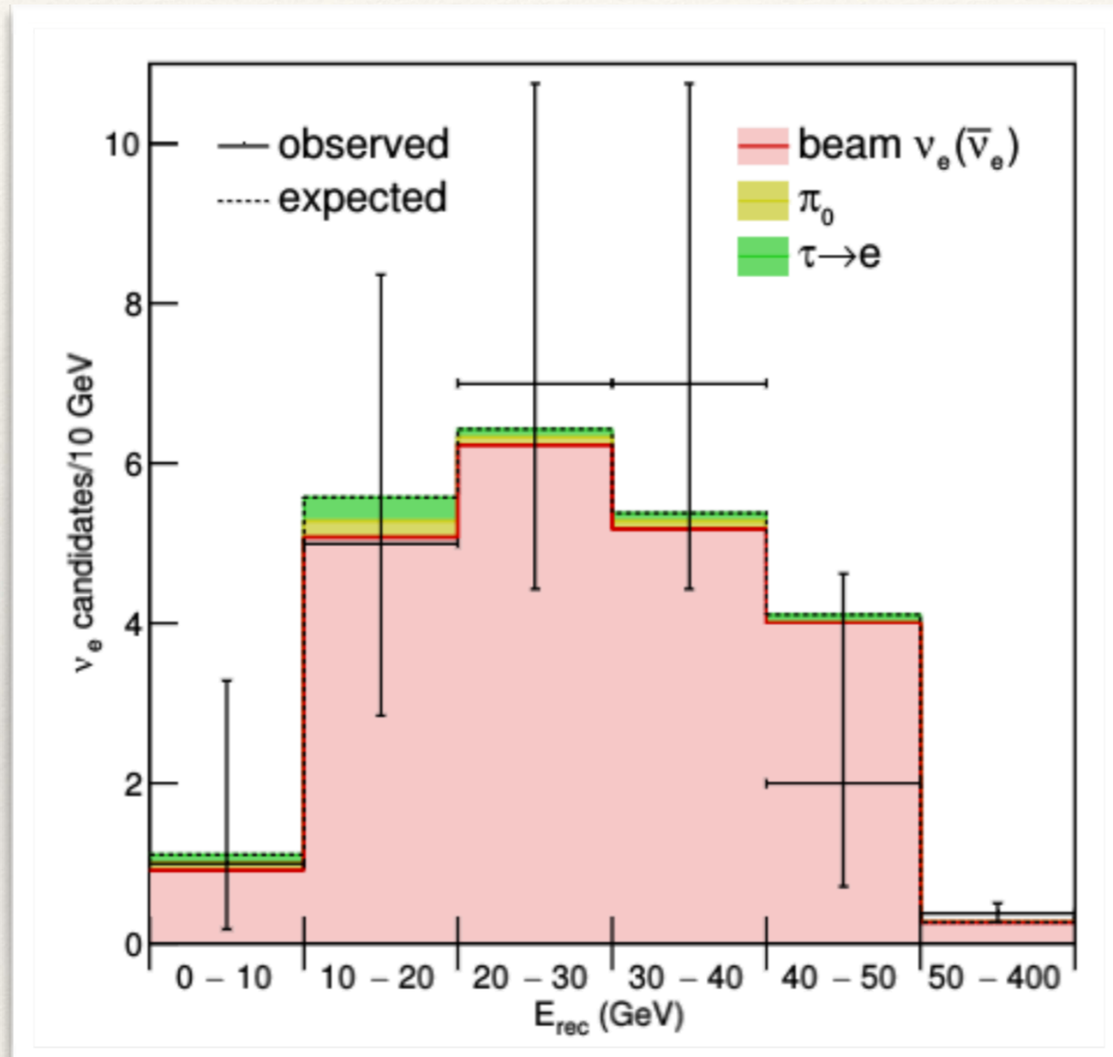
(OPERA Collaboration)

OPERA final results for $\nu_\mu \rightarrow \nu_e$ oscillations search



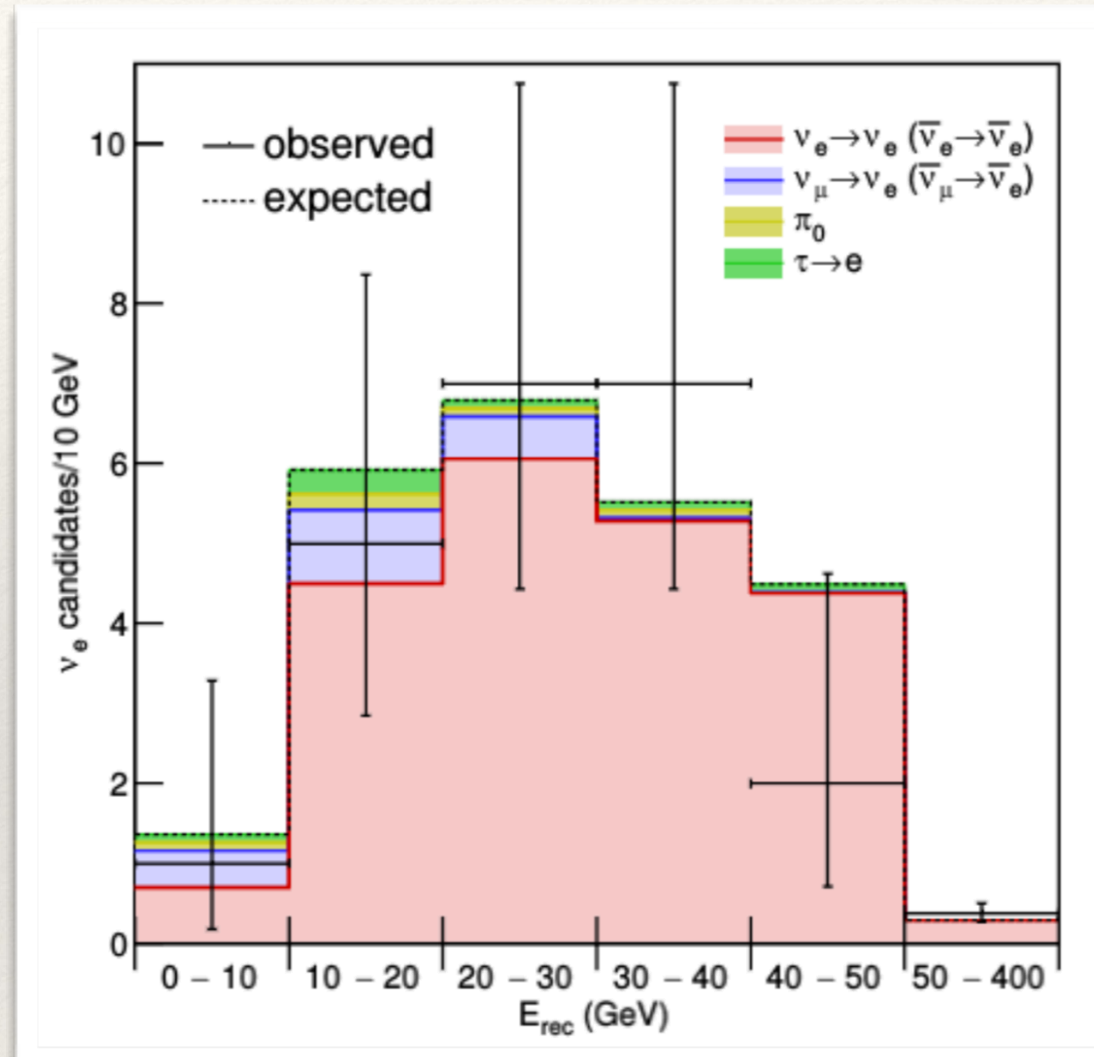
Reconstructed energy distributions of the observed ν_e candidates

No oscillation hypothesis



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

3 neutrino flavour mixing

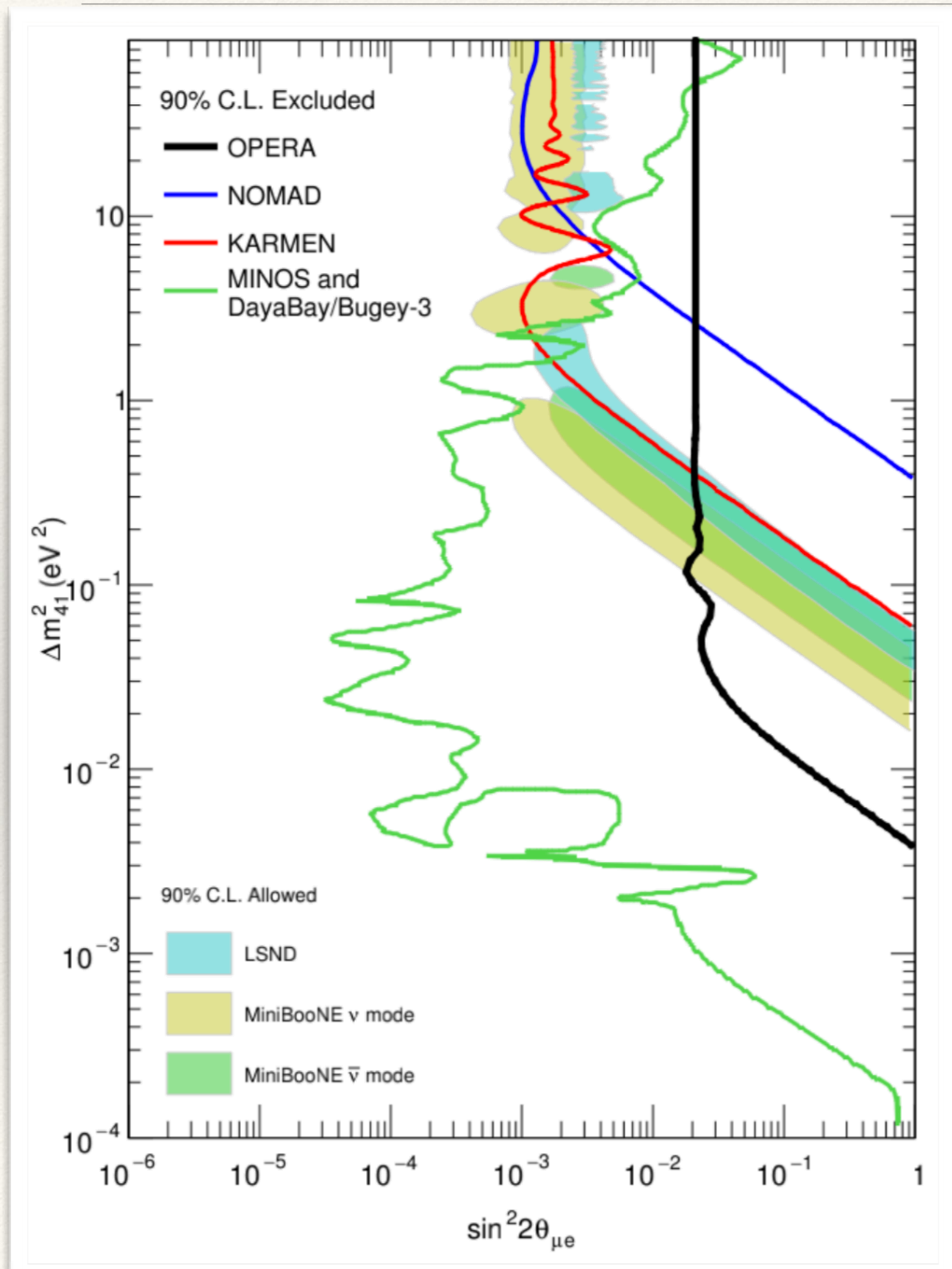


- $N_{exp} = 34.3 \pm 0.5$ (stat.) ± 3.4 (syst.)

- $N_{obs} = 35$

Ref: *arXiv:1803.11400*

Final results for $\nu_\mu \rightarrow \nu_e$ oscillations search



Ref: *arXiv:1803.11400*

- 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 $\Delta m^2_{41} \gtrsim$? 0.1 eV^2 at 90%C.L.

- OPERA is the only appearance experiment excluding neutrino mass difference down to $4\times10^{-3}\ eV^2$

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