Marginal Events

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Summary

- Expected events for “golden” analysis
- Expected events for minimum bias analysis
- Significance evaluation:
  - P* method
  - Likelihood
- Δm^2_{23} measurement
- Absolute ν_τ cross-section measurement
- BDT Analysis + Significance evaluation (in progress)
- Lepton number measurement

“Golden” and “Minimum Bias” selections

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^T_{2ry} (GeV/c)	$>0.6\,(0.3)^*$	>0.15	/		>0.25	>0.1	>0.1	
p^T_{miss} (GeV/c)	$< 1\star$	/	$< 1\star$	/	/		/	
ϕ_{lH} (rad)	$>\pi/2\star$	/	$>\pi/2\star$	/	/		/	
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

Expected events for "golden" analysis

- **Efficiencies of 5th τ paper updated with $\Delta m^2_{23} = 0.0025$ eV^2 and final statistics (see back-up slides)**

Channel	**Expected Background**				**Expected Signal**	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.02	0.023	–	0.04	0.57	3
$\tau \to 3h$	0.18	0.003	–	0.18	0.80	1
$\tau \to \mu$	0.004	–	0.0002	0.004	0.66	1
$\tau \to e$	0.03	–	–	0.03	0.85	0
Total	0.23	0.03	0.0002	0.26 ± 0.05	2.9 ± 0.6	5

- **Efficiencies evaluated by myself (larger "new" MC production, different OpRelease version) also for ν_μ, $\Delta m^2_{23} = 0.0025$ eV^2 , final statistics (see back-up slides)**

Channel	**Expected Background**				**Expected Signal**	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.02	0.024	–	0.05	0.57	3
$\tau \to 3h$	0.20	0.003	–	0.21	1.09	1
$\tau \to \mu$	0.003	–	0.0002	0.003	0.55	1
$\tau \to e$	0.03	–	–	0.03	0.75	0
Total	0.27	0.03	0.0002	0.29 ± 0.06	3.0 ± 0.6	5

Expected events for minimum bias analysis

Channel	**Expected Background**				**Expected Signal**	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.15	1.28	–	1.43	2.82	6
$\tau \to 3h$	0.44	0.09	–	0.52	1.75	3
$\tau \to \mu$	0.008	–	0.02	0.03	1.09	1
$\tau \to e$	0.035	–	–	0.03	0.80	0
Total	0.63	1.37	0.02	2.0 ± 0.5	6.5 ± 1.3	10

Significance (I): P*method

http://operaweb.lngs.infn.it/Opera/publicnotes/OPERA_note_173.pdf

$$P^* = \prod_{i=1}^{channels} \mathcal{P}(n_i, b_i)$$

- Min bias Analysis → 14803 events over 1410065408 have P>P*.

  $P_{val} = 1.05 \cdot 10^{-5}$ → **4.25σ**

- Min bias Analysis 8 channels: 4 "golden"+4 "silver" (table in back-up) → 32 events over 1410065408 have P>P*.

  $P_{val} = 2.27 \cdot 10^{-8}$ → **5.47σ**

Significance (II): Likelihood

Roofit - Profile likelihood ratio one sided
Asymptotic calculator

- **<u>Min bias Analysis</u>** → $P_{val} = 2.41 \cdot 10^{-5}$ → **4.1σ**

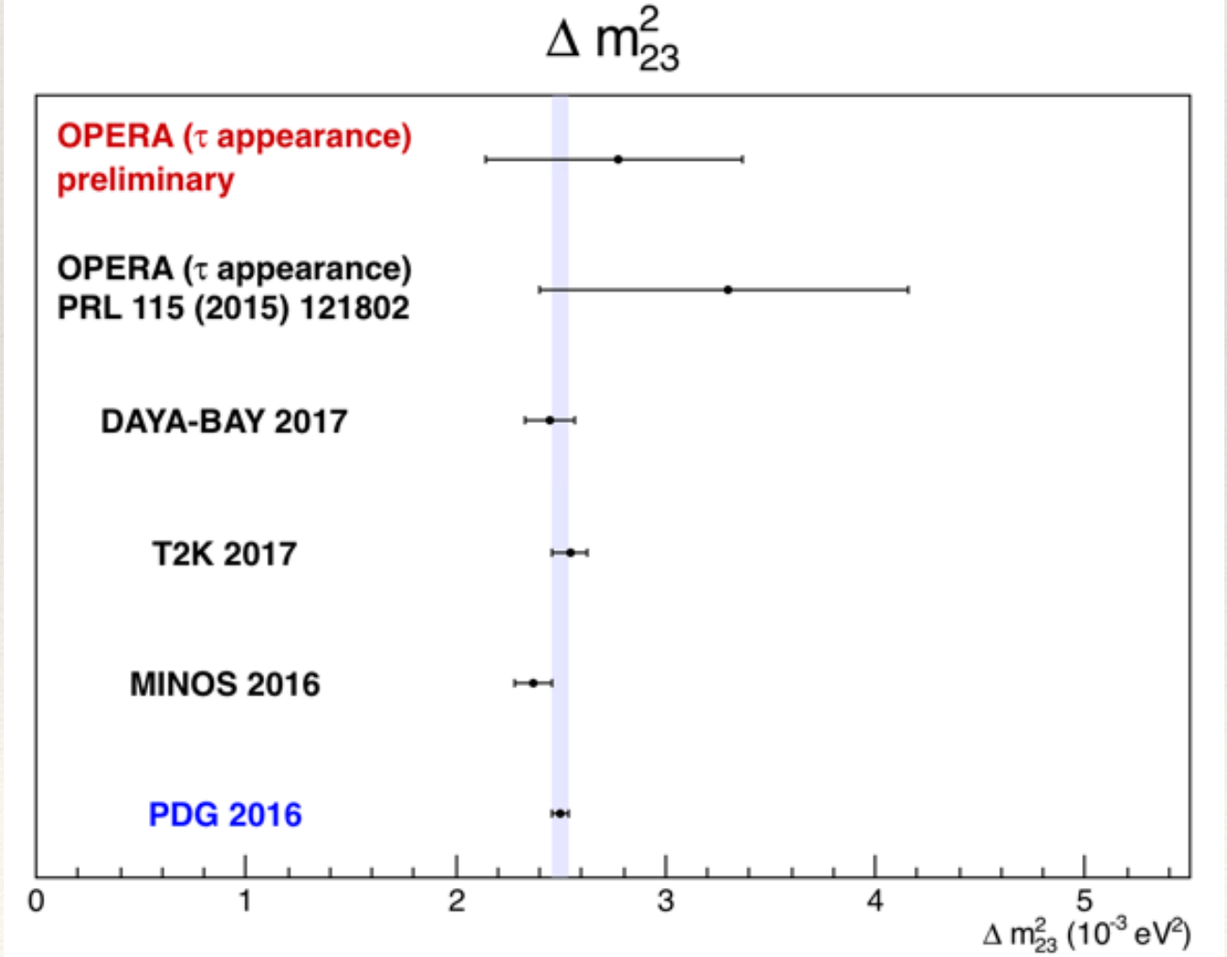
- **<u>Min bias Analysis 8 channels</u>**: 4 "golden"+4 "marginal" (table in back-up) → $P_{val} = 5.90 \cdot 10^{-9}$ → **5.7σ**

TO DO: Frequentist calculator. Crash after about 100M MC toy experiments to be solved

Δm^2_{23} measurement

	Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} (10^{-3} eV^2) (68% C.L)	(90% C.L)
PRL 115 (2015) 121802 $\Delta m^2_{23} = 2.44 \cdot (10^{-3}\ \text{eV}^2)$	2.56	0.25	5	$3.3^{+0.86}_{-0.90}$	[2.0; 5.0]
Preliminary $\Delta m^2_{23} = 2.5 \cdot (10^{-3}\ \text{eV}^2)$	6.5	2.0	10	2.8 ± 0.6	[1.84; 3.73]

Assuming maximal mixing and standard $\sigma_{\nu\tau}$



Agreement with *PDG 2016* value within 1σ

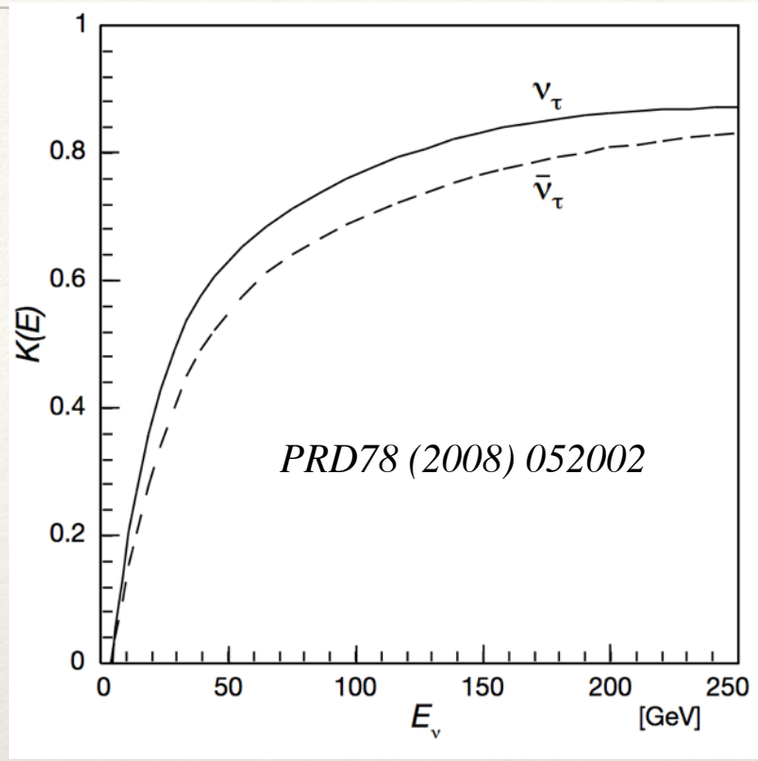
Latest (13/03/2017) global fit on $\Delta m^2_{23} = 2.52 \cdot 10^{-3}$ eV^2 (see: https://arxiv.org/pdf/1703.04471.pdf)

Absolute ν_τ cross-section measurement

$$\sigma_{\nu_\tau} = \sigma_{\nu_\tau}^{const} E K(E)$$

Until now, ν_τ cross section measured only by DONuT

DONuT could not distinguish ν_τ from anti-ν_τ



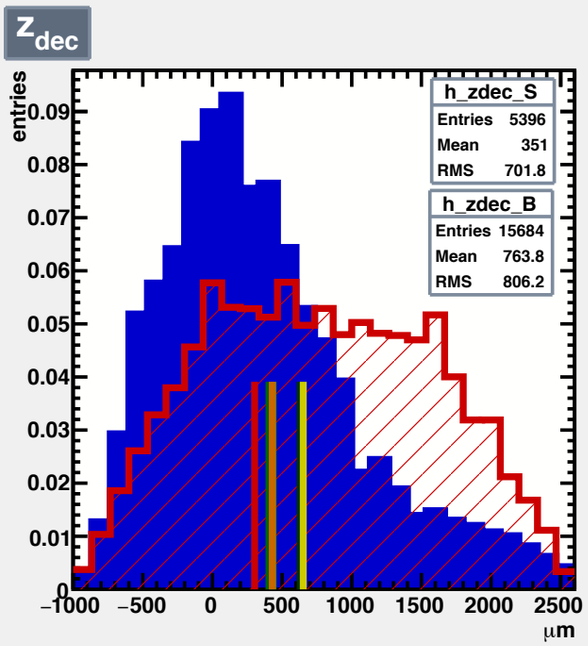
➤ OPERA: First measurement with ν_τ only

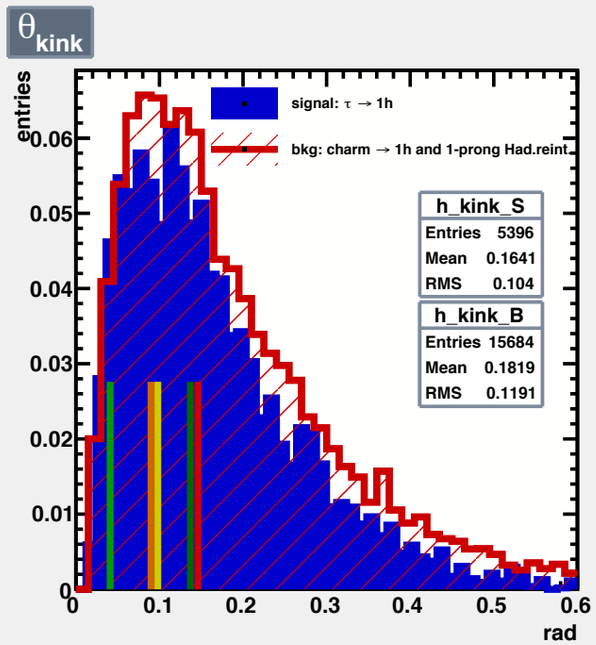
	Expected Signal	Expected Background	Observed ν_τ	$\sigma_{\nu_\tau}^{const}$ $(10^{-38}\text{cm}^2\text{GeV}^{-1})$ (68% C.L)	(90% C.L)
Preliminary $\Delta m^2_{23} = 2.5 \cdot (10^{-3}\ \text{eV}^2)$	6.5	2.0	10	$0.8^{+0.4}_{-0.3}$	$[0.36 - 1.49]$

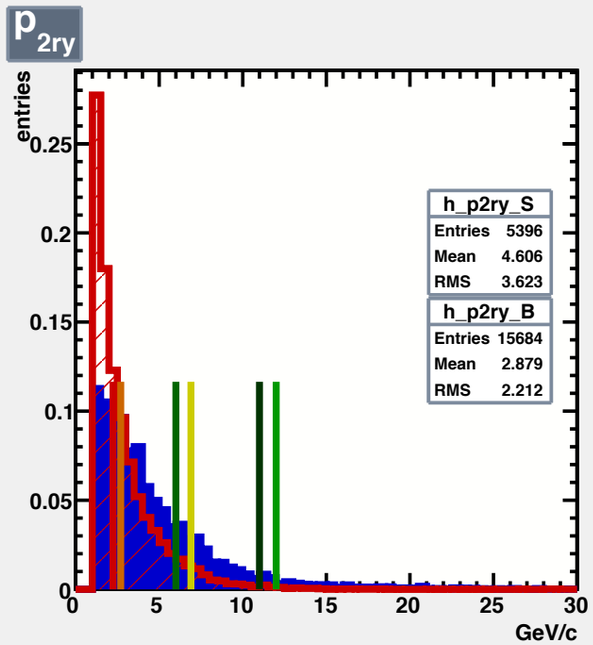
Assuming maximal mixing and PDG2016 Δm^2_{23}

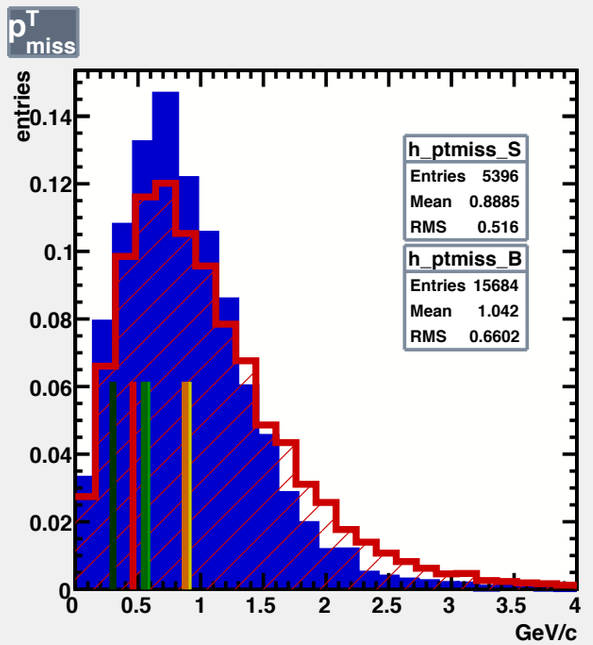
Agreement with SM value $0.67 \cdot 10^{-38} cm^2 GeV^{-1}$ within 1σ

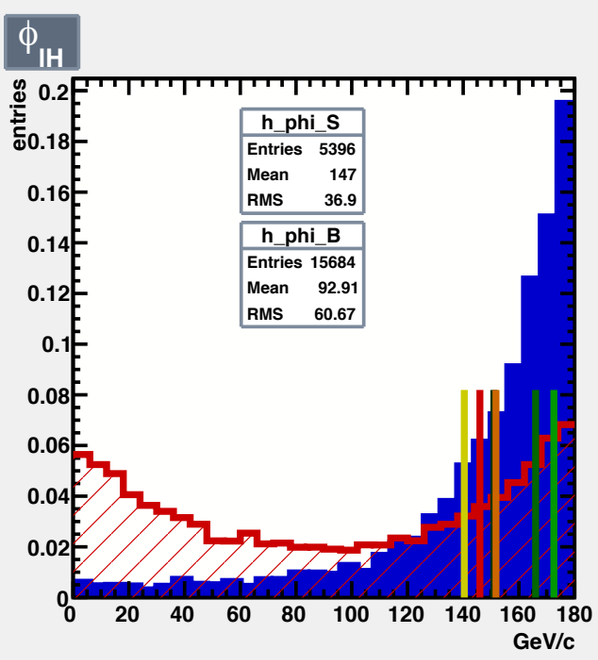
$\tau \rightarrow$ 1h Kinematical variables

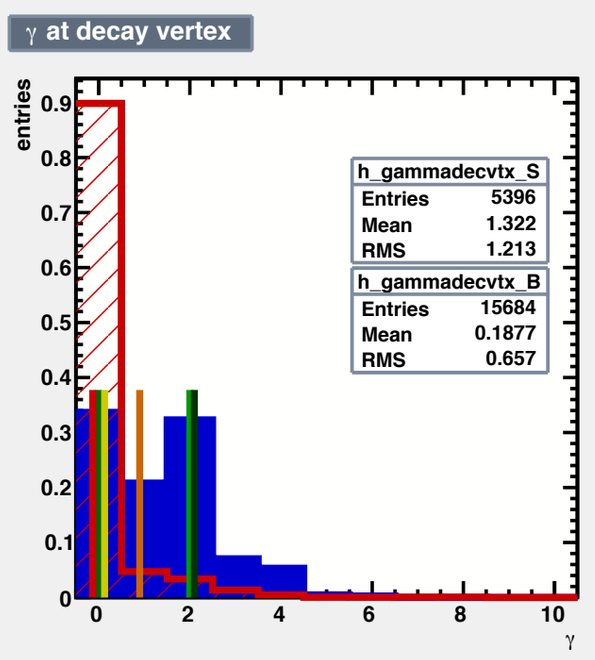


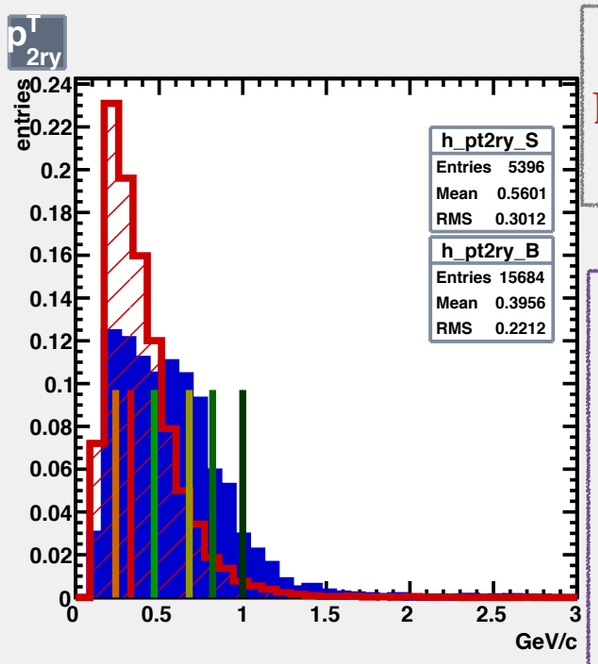












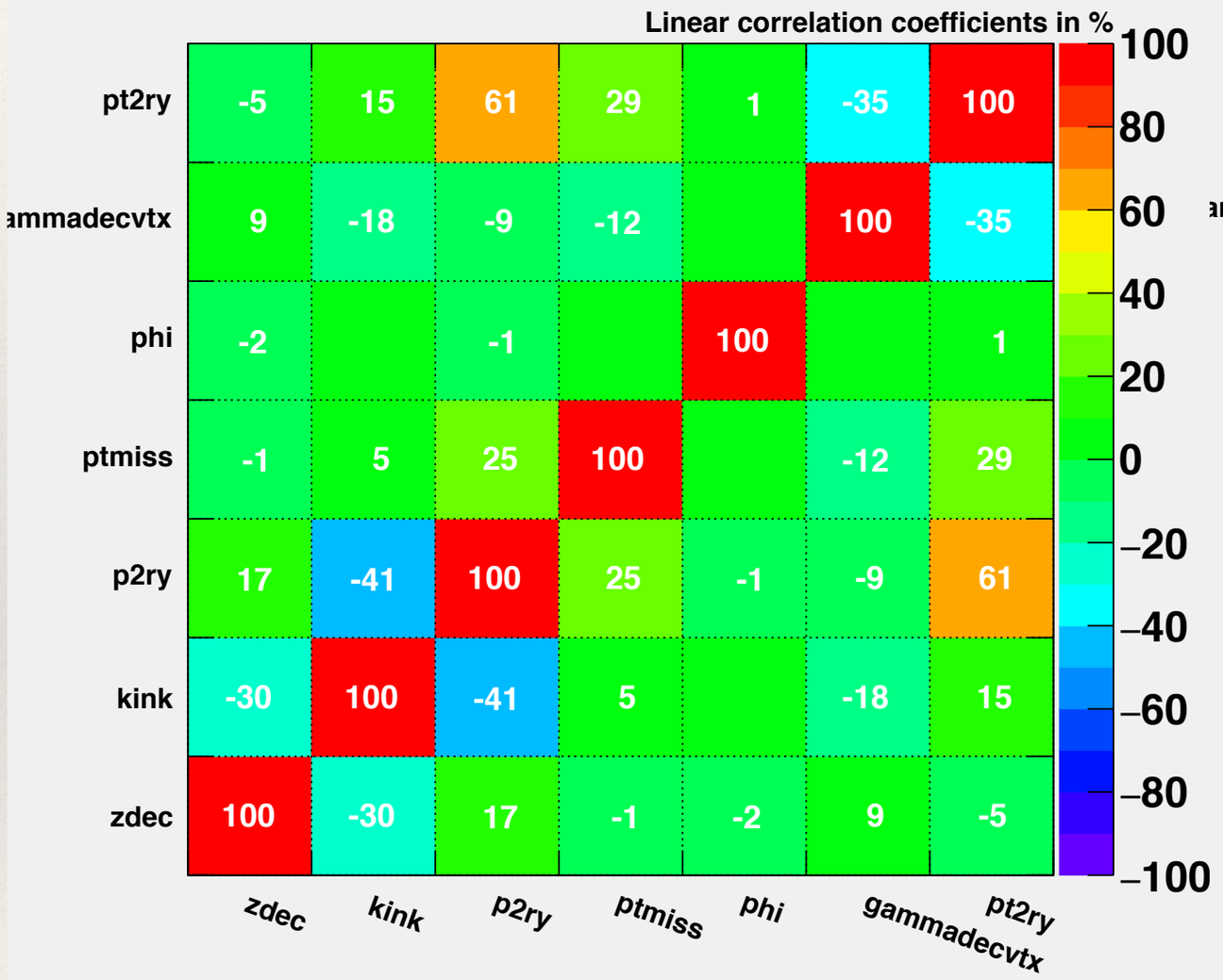
Signal: $\tau \rightarrow$1h (DIS + QE)
Background: charm$\rightarrow$1h (10%)
had reint (89%)

1st ν_τ candidate
4th ν_τ candidate
5th ν_τ candidate
Ev 11172035775 (Bern)
Ev 11143018505 (PD-BO)
Ev 9190097972 (Nagoya)

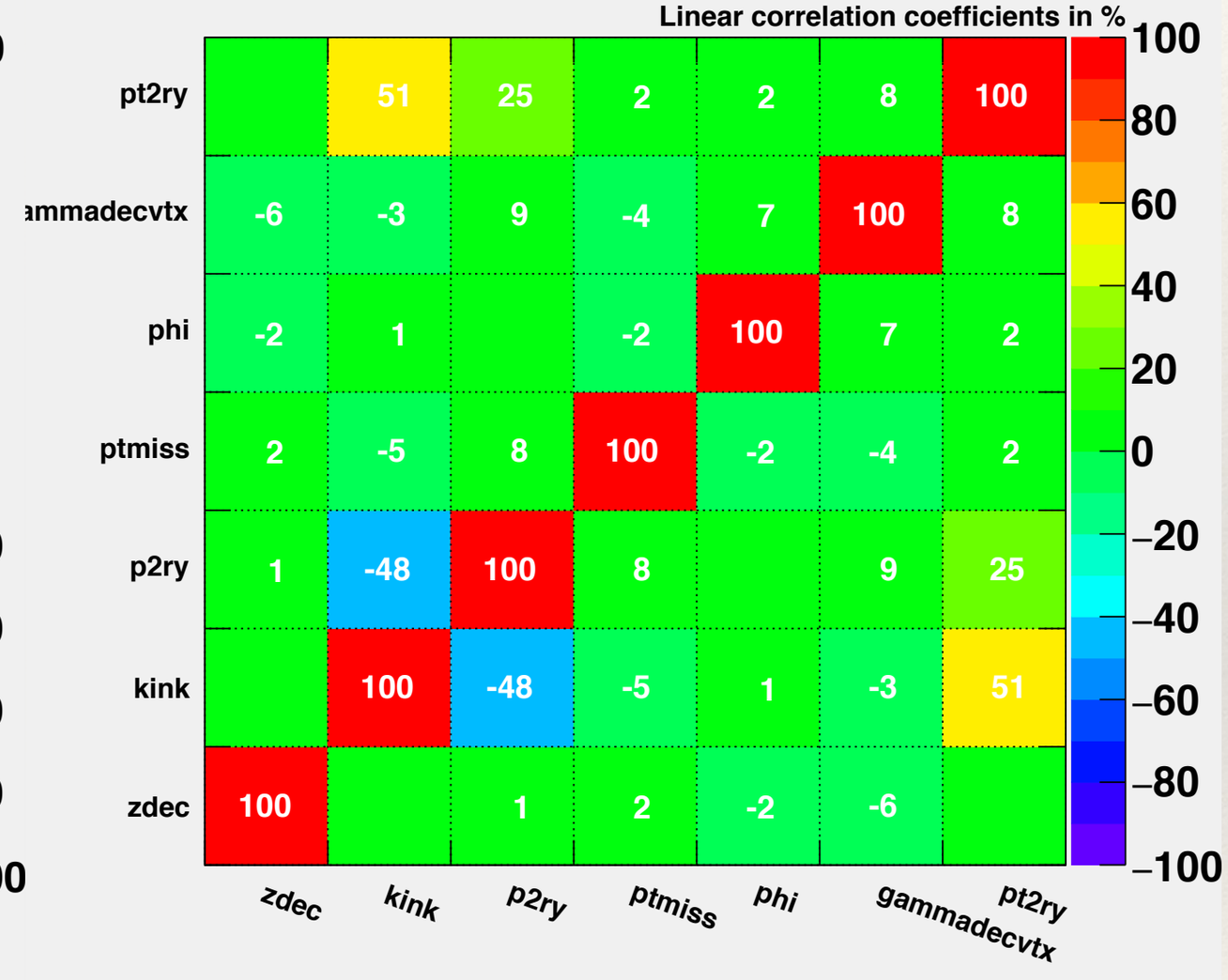
- τ distribution weighted for oscillation Probability
- charm distribution weighted for charm production Probability

τ → 1h Correlation Matrices

Correlation Matrix (signal)

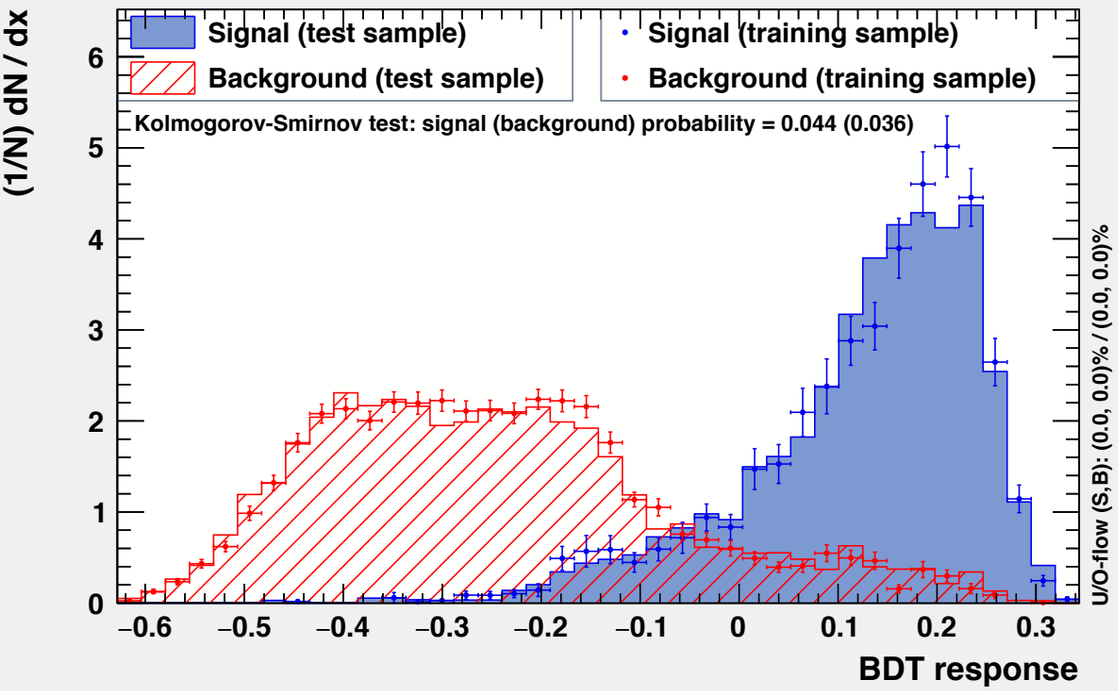


Correlation Matrix (background)

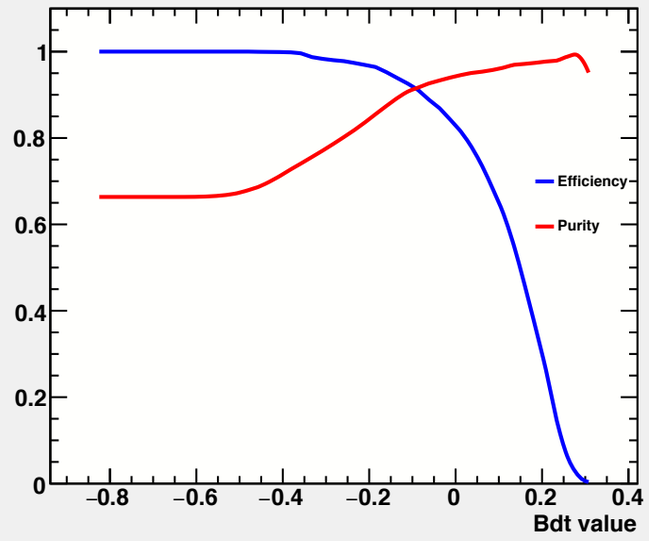


τ→1h RESULTS

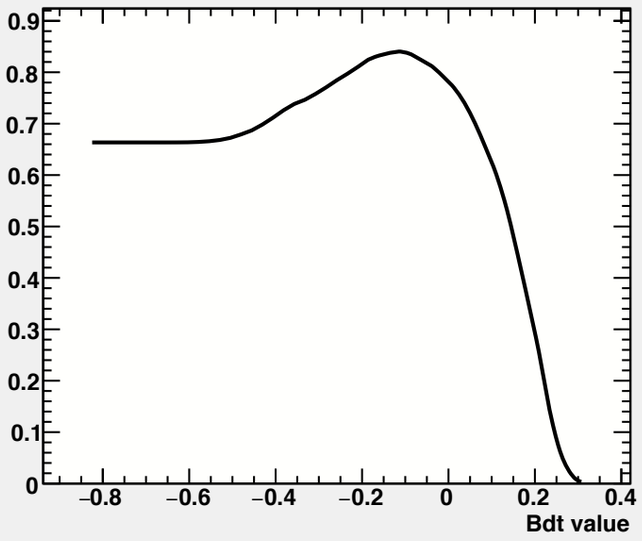
TMVA overtraining check for classifier: BDT



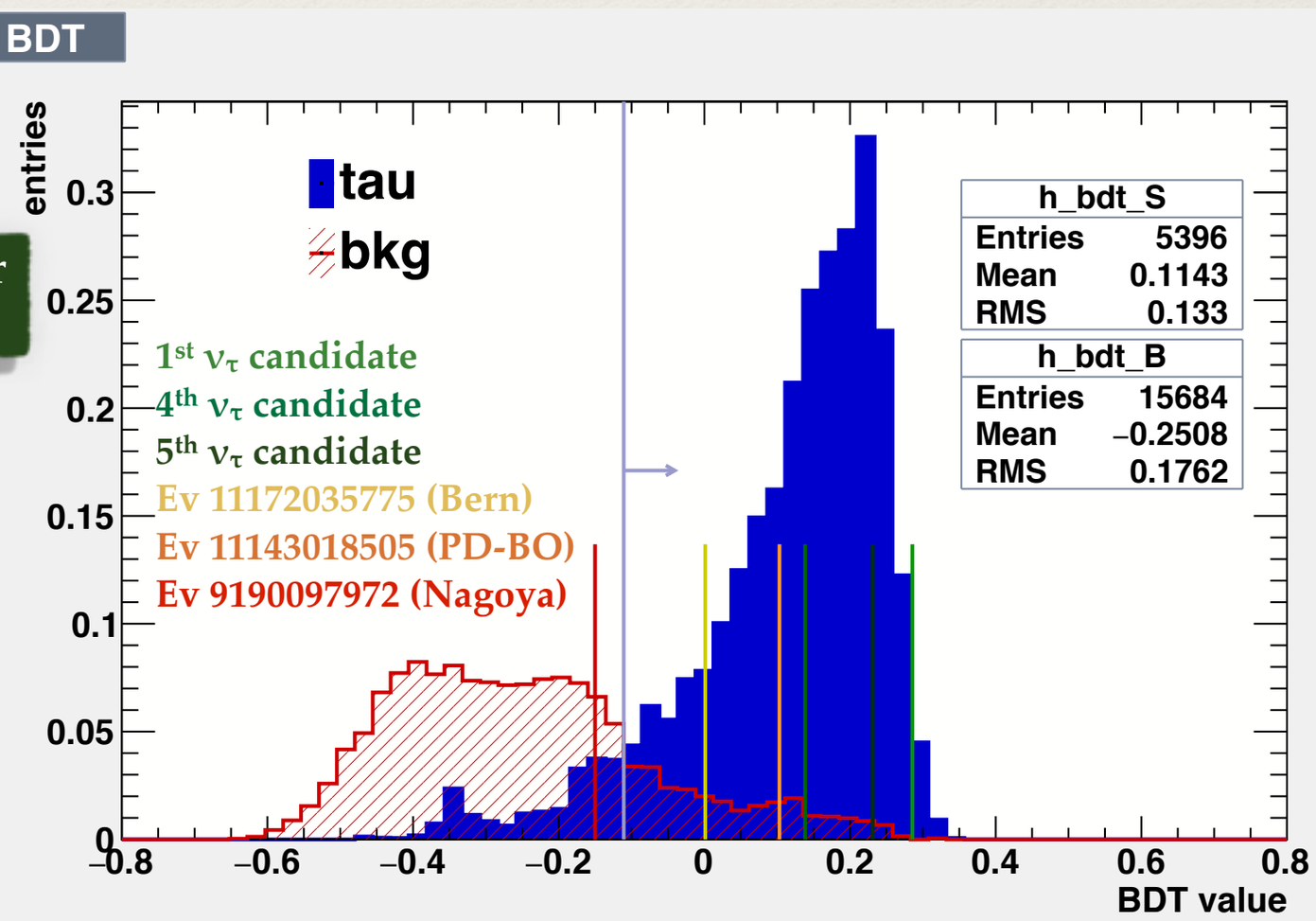
Efficiency and Purity vs cut



Efficiency*Purity



BDT



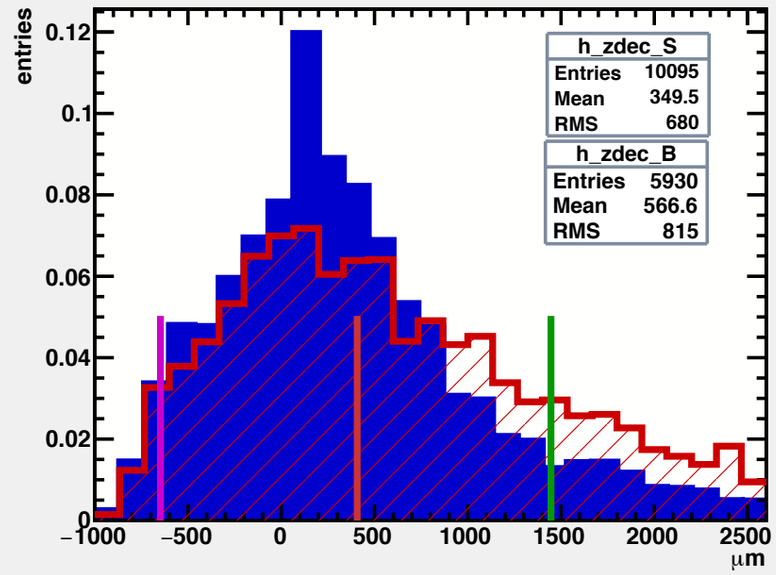
Signal & Bkg normalized for the number of expected events

signal = 93%
bkg = 19%

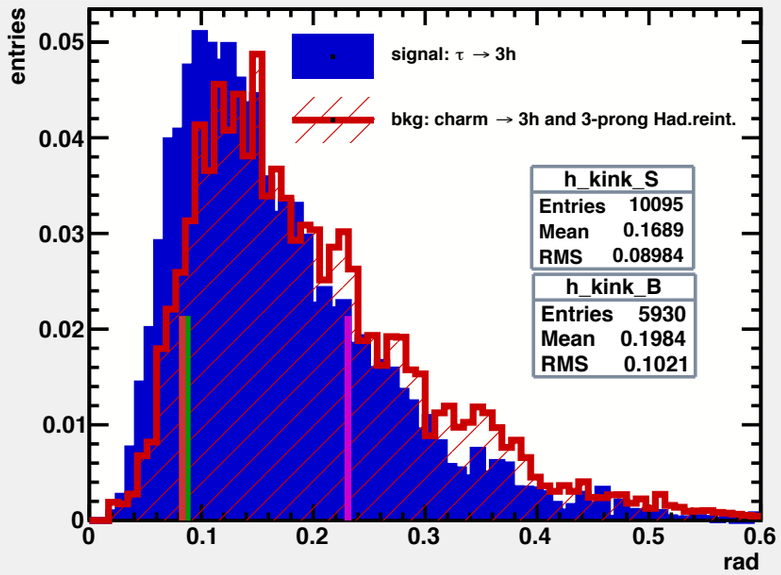
1.4 expected event of bkg for τ→1h ⇒
1 event classified as bkg:
good understanding of background

$\tau \rightarrow 3h$ Kinematical Variables

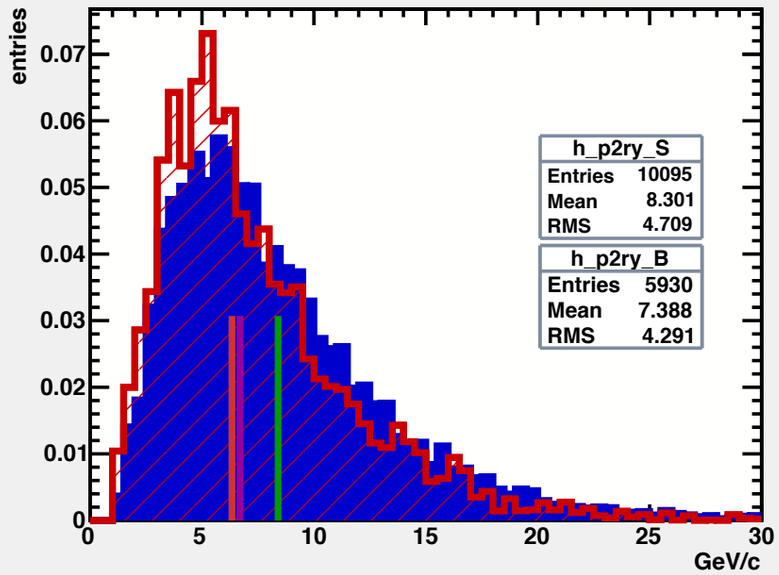
z_{dec}



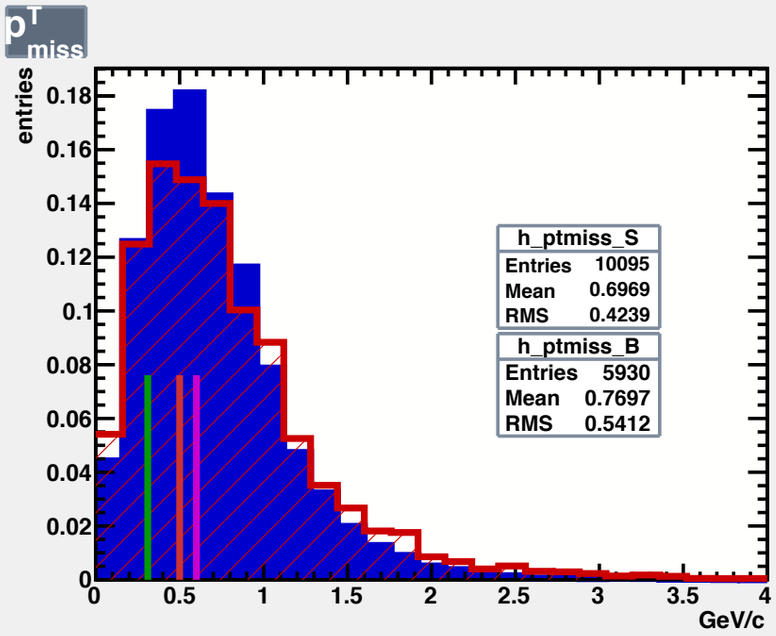
θ_{kink}



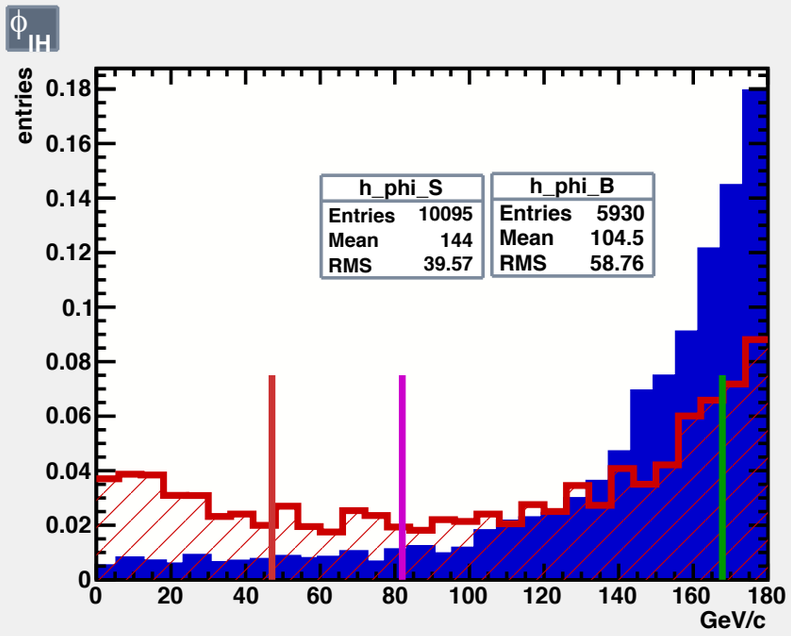
p_{2ry}



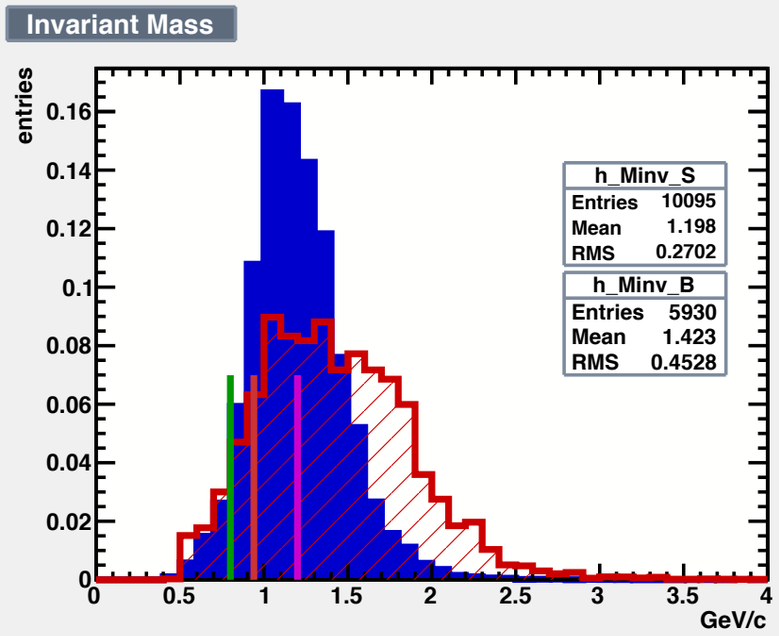
p^T_{miss}



ϕ_{IH}



Invariant Mass



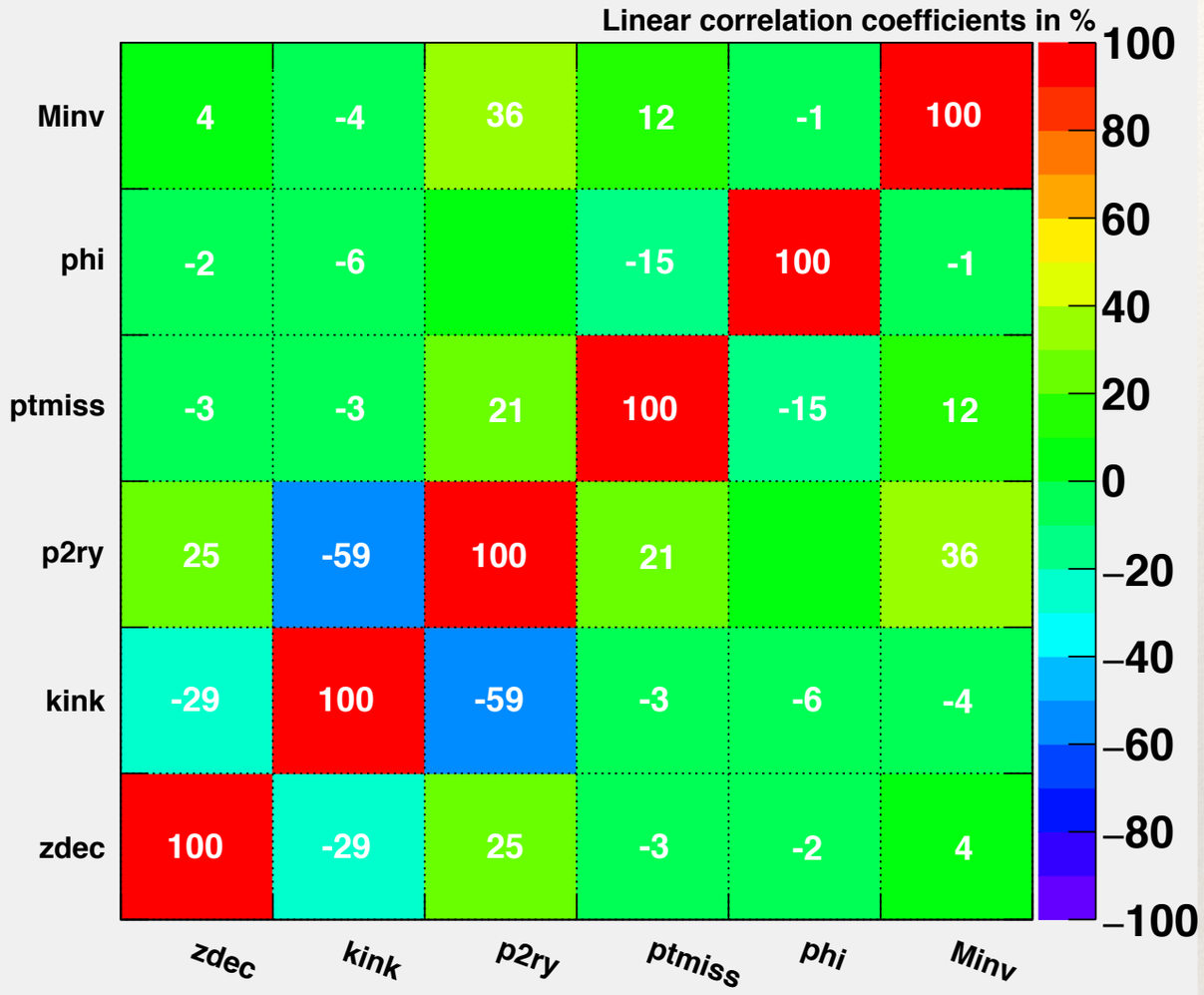
- τ distribution weighted for oscillation Probability
- charm distribution weighted for charm production Probability
- had reint weight = 1

Signal: $\tau \rightarrow 3h$ (DIS + QE)
Background: charm→3h (83%)
had reint (17%)

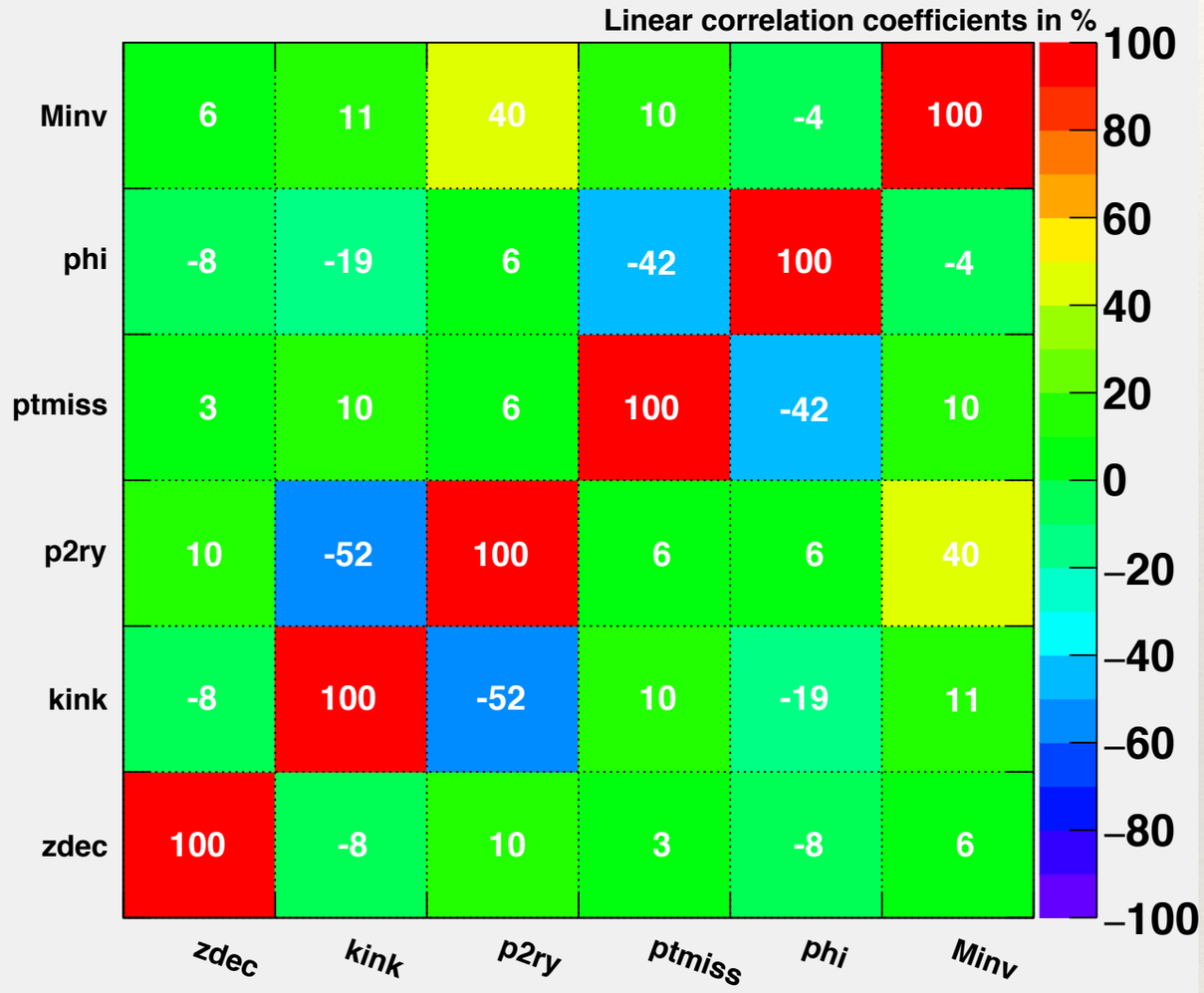
2nd ν_τ candidate
Ev 10123059807 (Bari)
Ev 11213015702 (Nagoya)

τ → 3h Correlation Matrices

Correlation Matrix (signal)



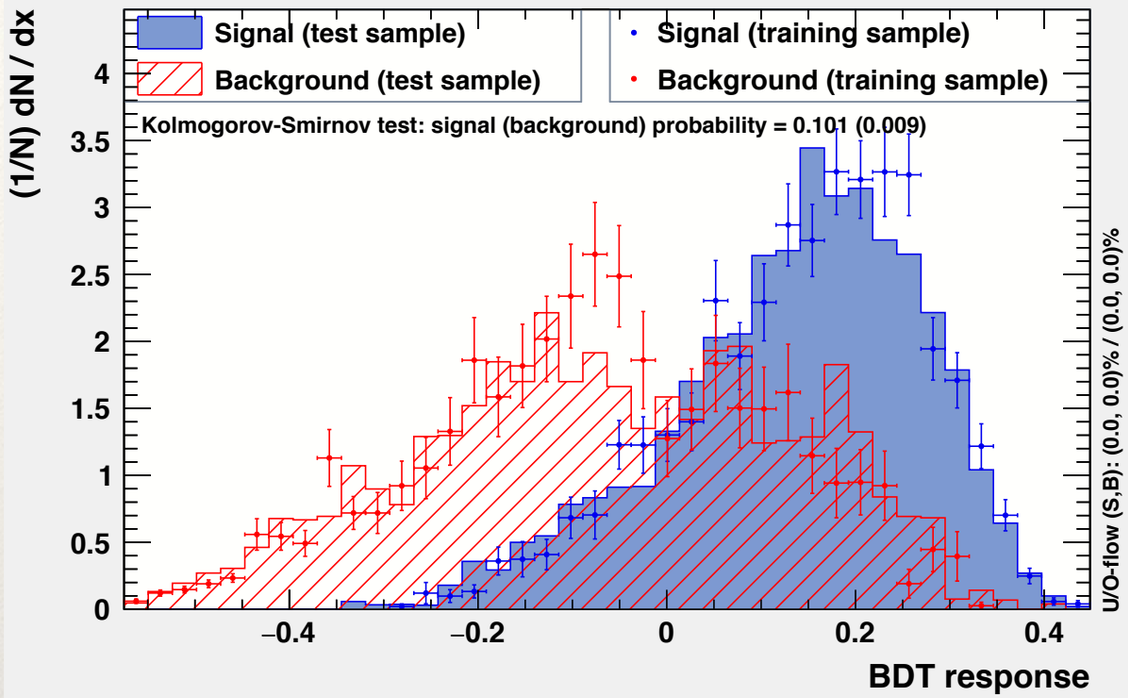
Correlation Matrix (background)



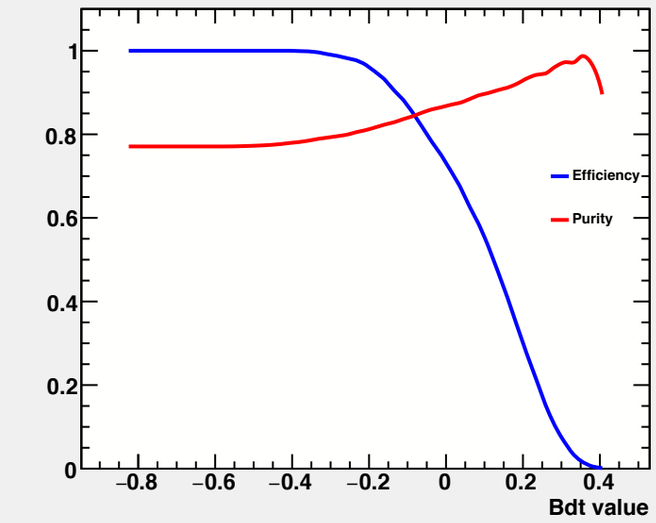
High correlation between Invariant mass and minimum invariant mass: the latter was eliminated from the analysis

τ → 3h RESULTS

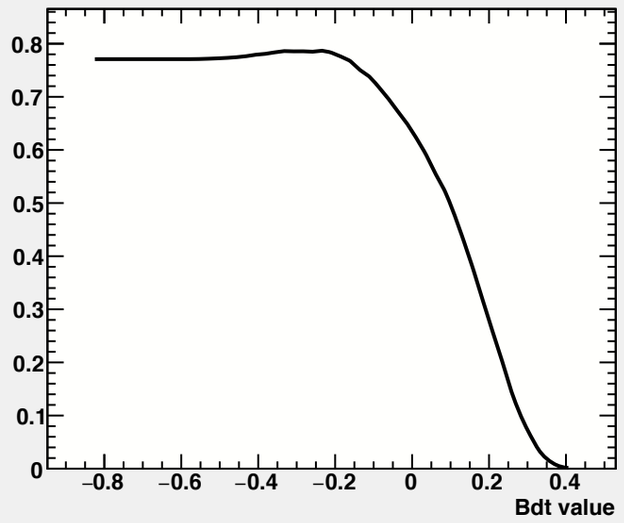
TMVA overtraining check for classifier: BDT



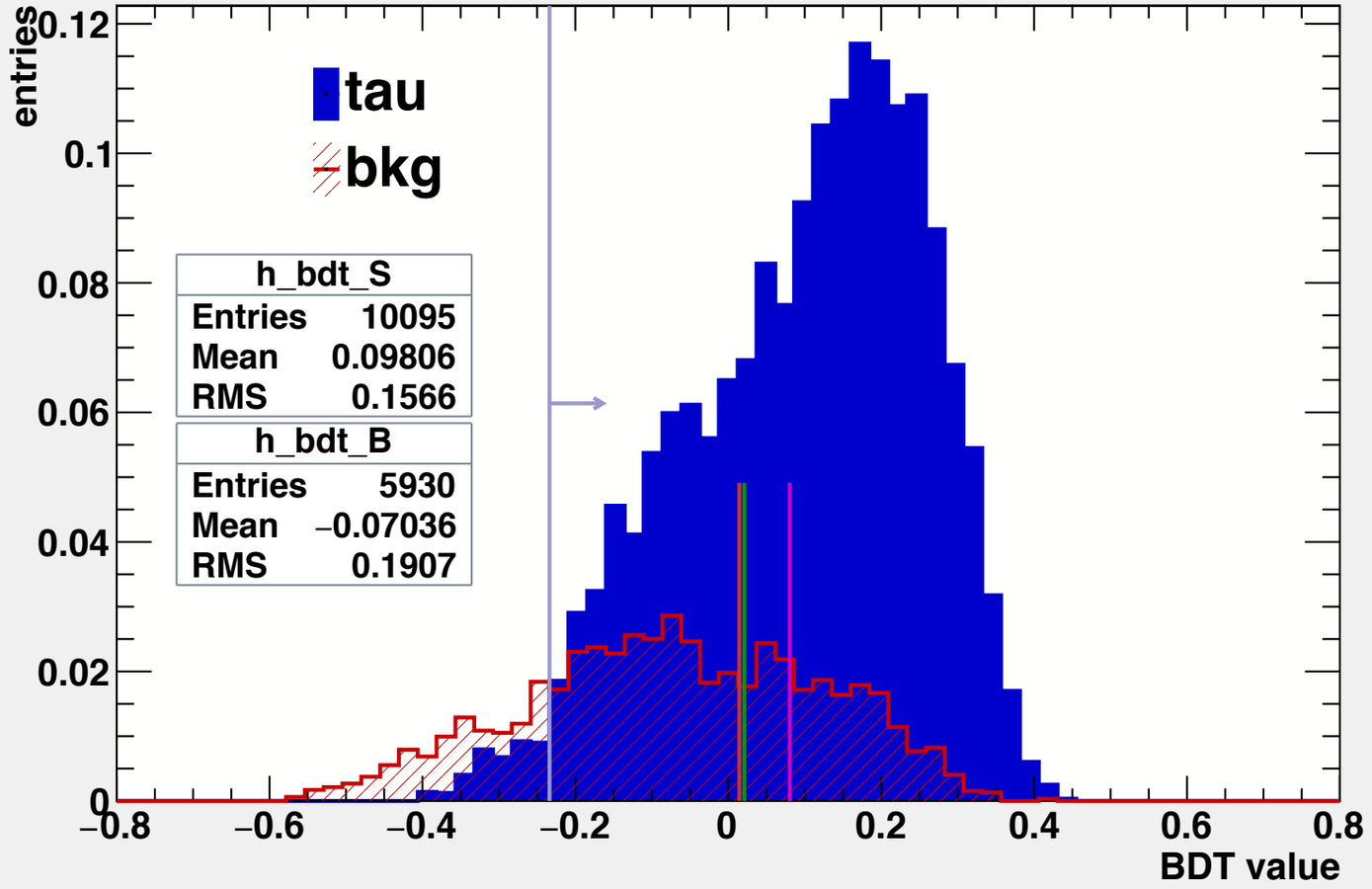
Efficiency and Purity vs cut



Efficiency*Purity



BDT



PROBLEM: low statistics!!

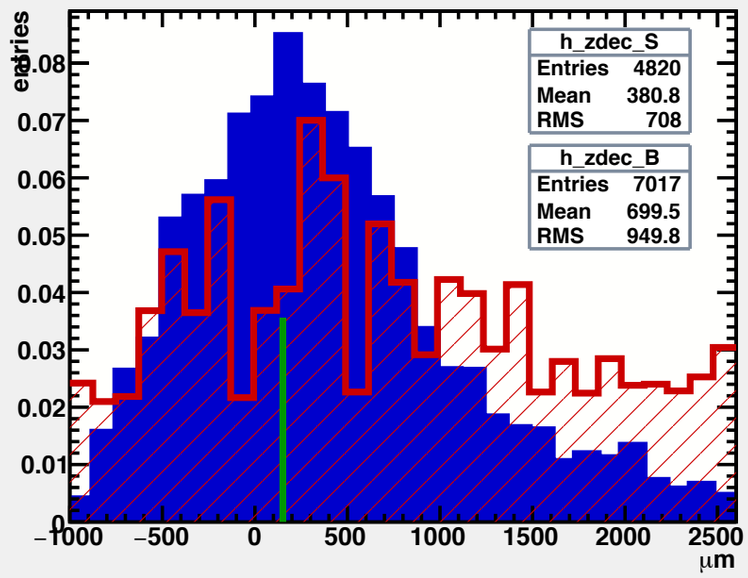
2nd ν_τ candidate
Ev 10123059807 (Bari)
Ev 11213015702 (Nagoya)

Signal & Bkg normalized for the number of expected events

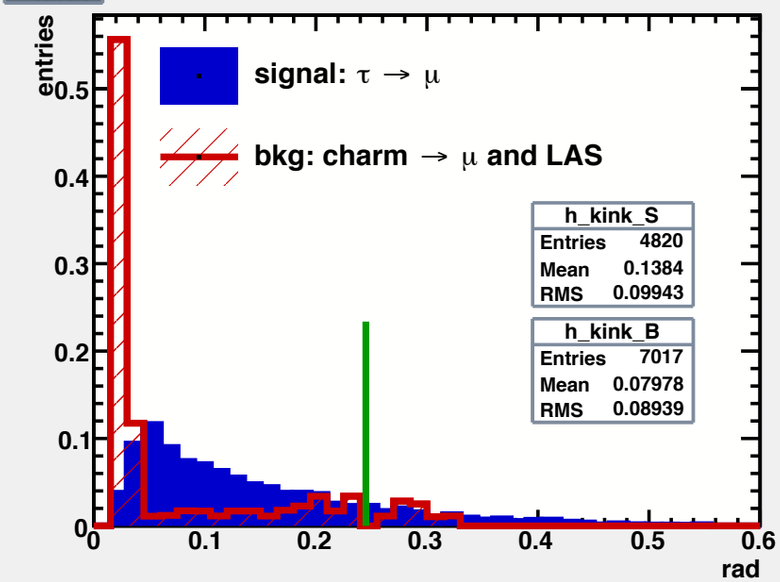
signal = 98%
bkg = 80%

τ→μ Kinematical Variables

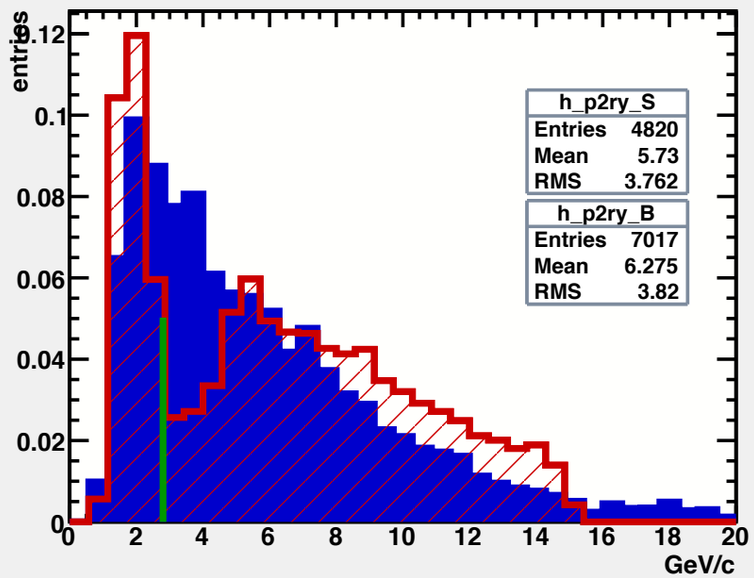
z_{dec}



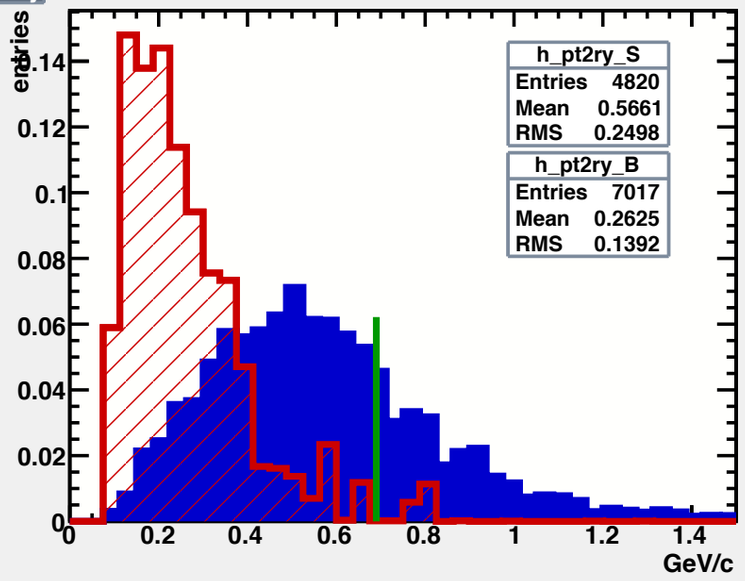
θ_{kink}



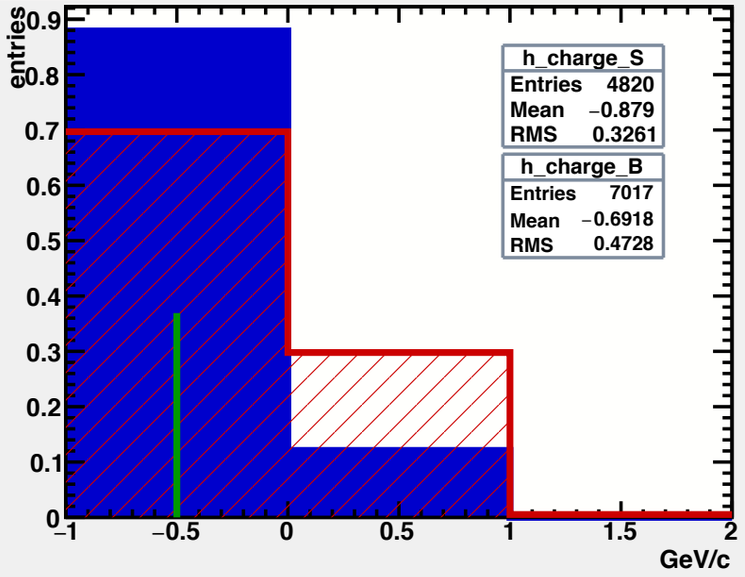
p_{2ry}



p^T_{2ry}



μ charge



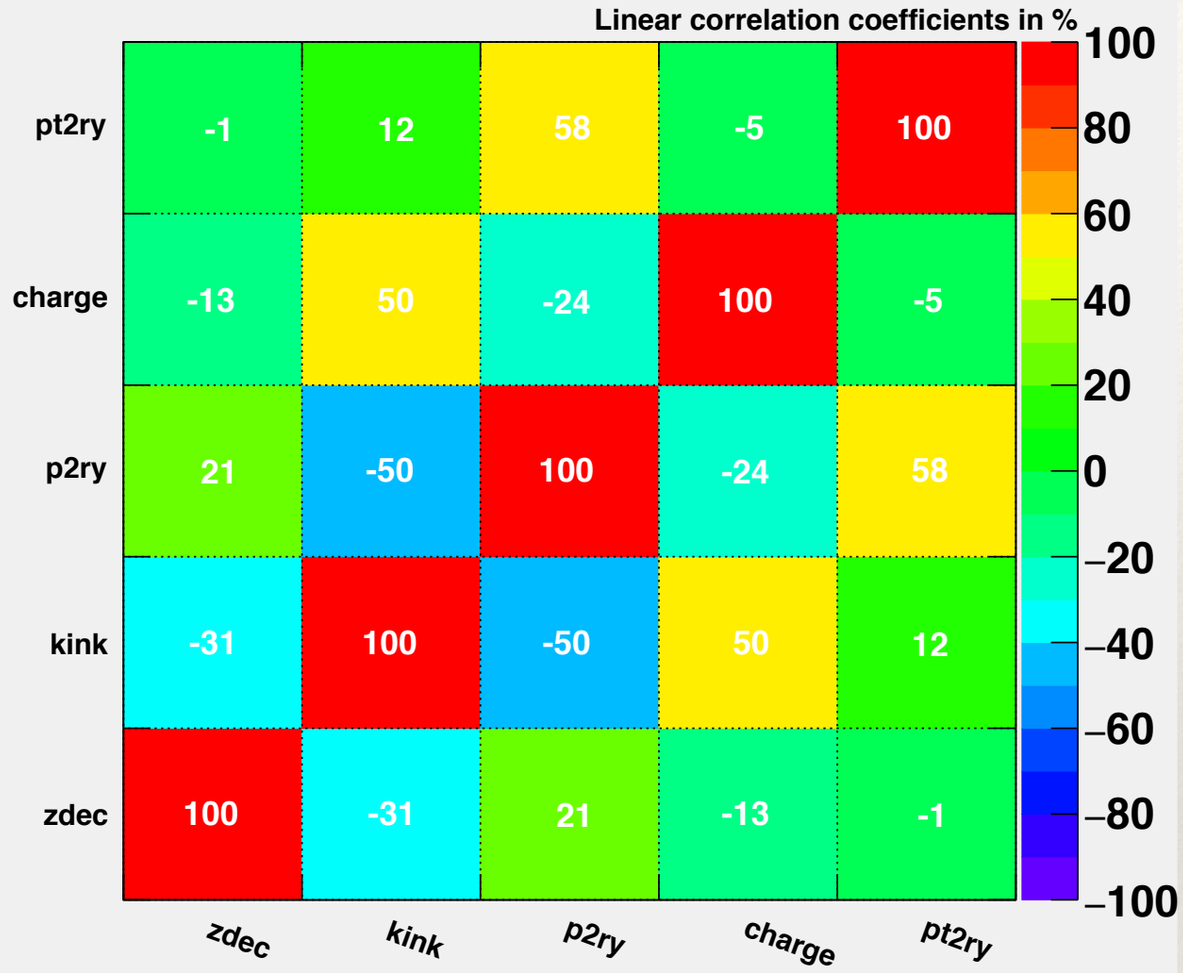
Signal: τ→μ (DIS + QE)
Background: charm→μ (32%)
LAS (68%)

3rd ν_τ candidate

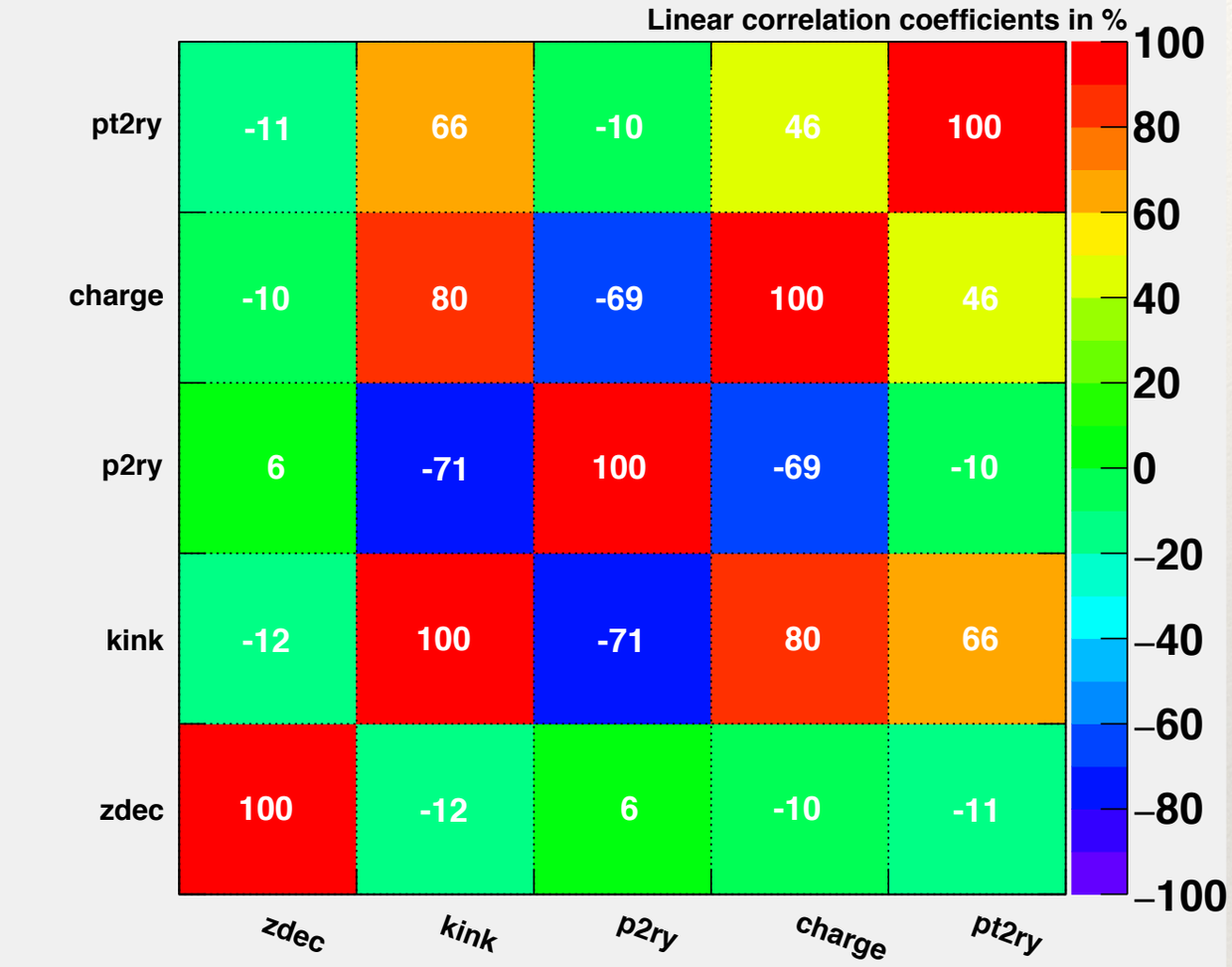
- τ distribution weighted for oscillation Probability
- charm distribution weighted for charm production Probability
- LAS weight = 1

τ→μ Correlation Matrices

Correlation Matrix (signal)

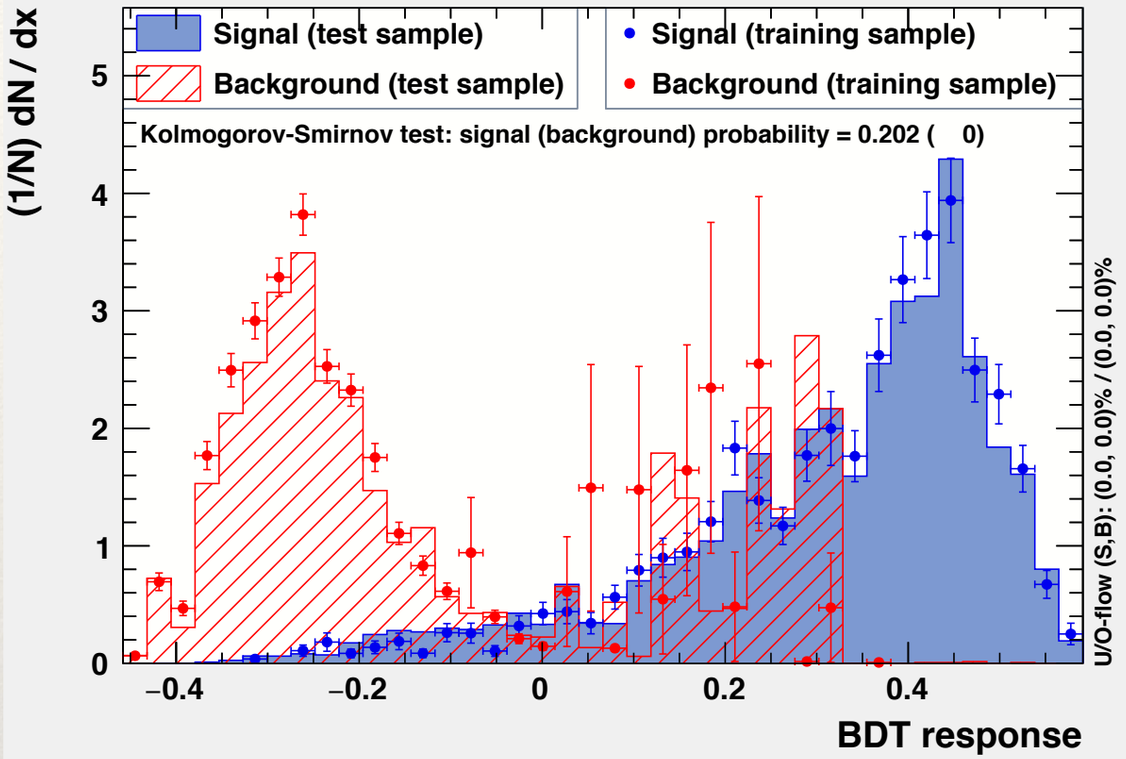


Correlation Matrix (background)



$\tau \rightarrow \mu$ RESULTS

TMVA overtraining check for classifier: BDT

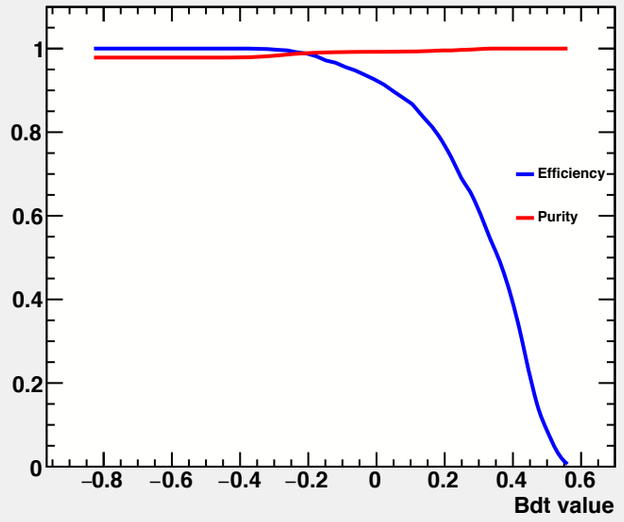


PROBLEM: low statistics, especially for charm!!

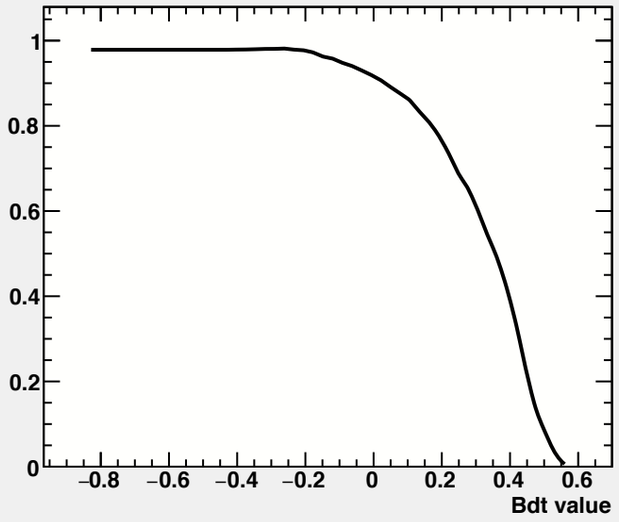
Signal & Bkg normalized for the number of expected events

signal = 99.6%
bkg = 66%

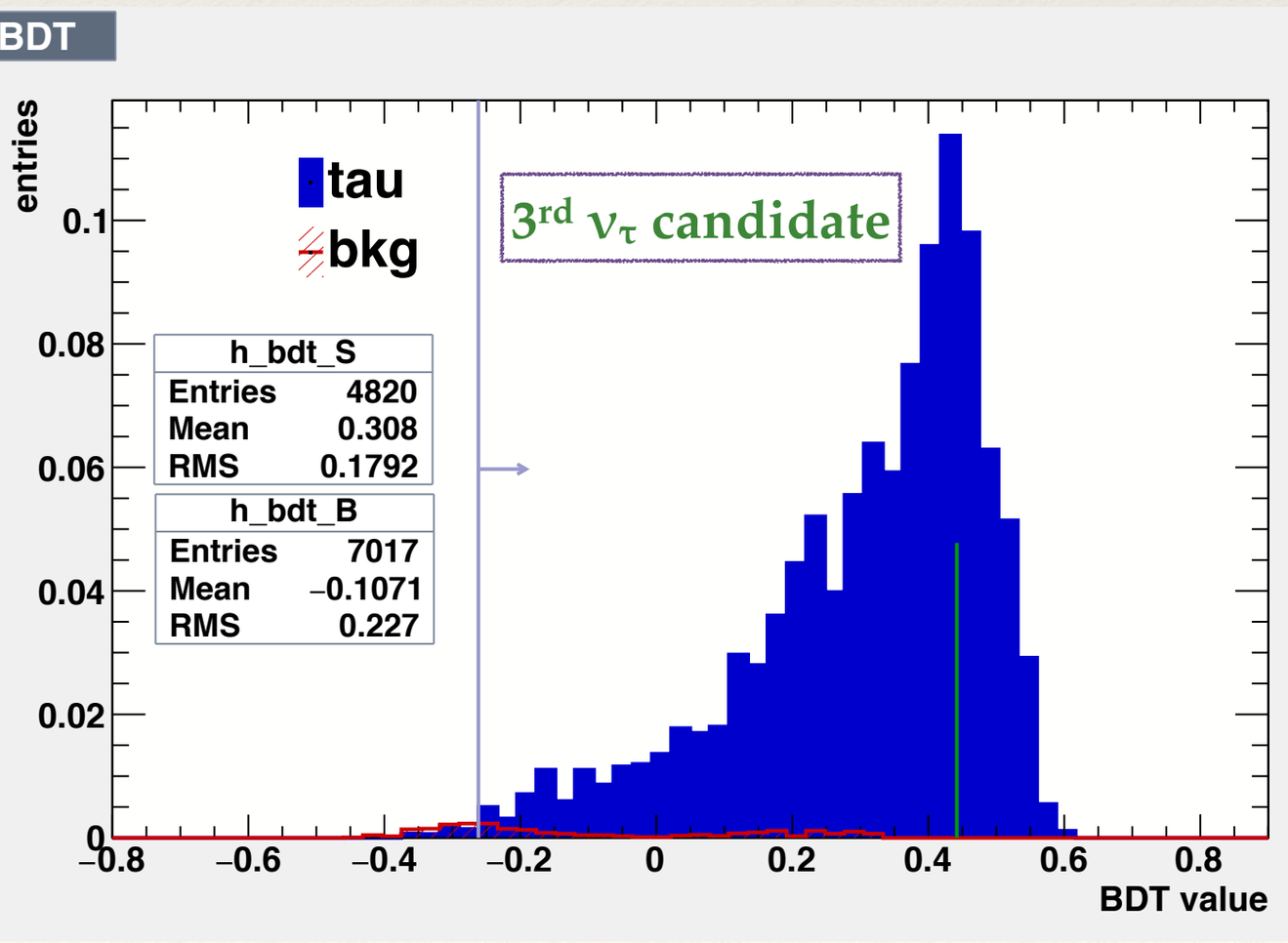
Efficiency and Purity vs cut



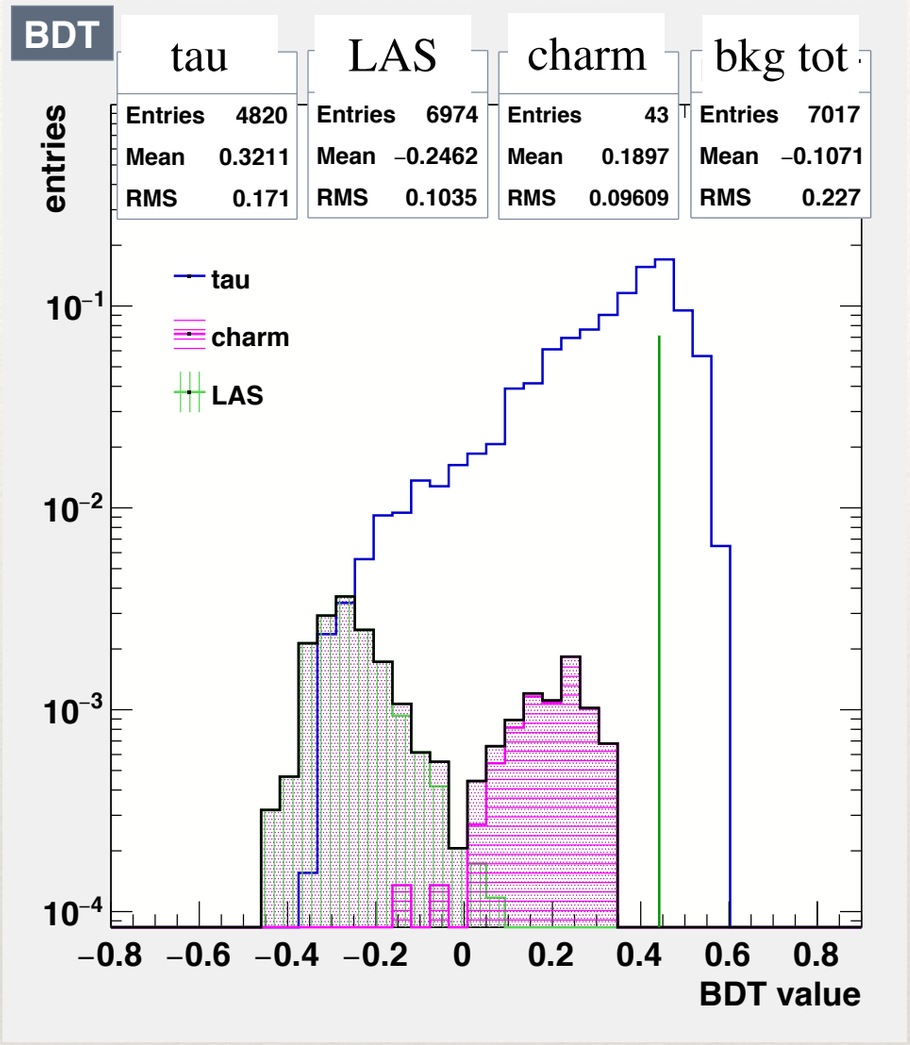
Efficiency*Purity

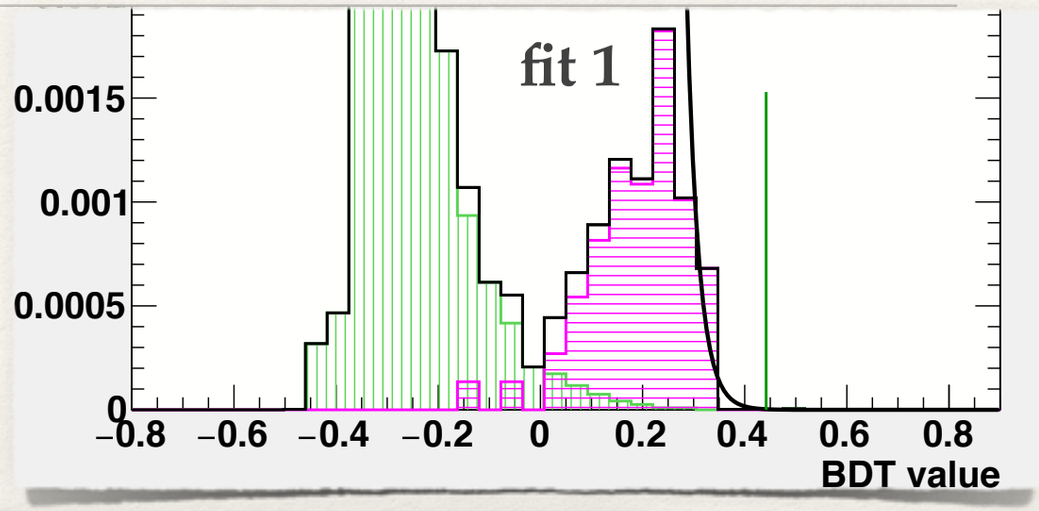


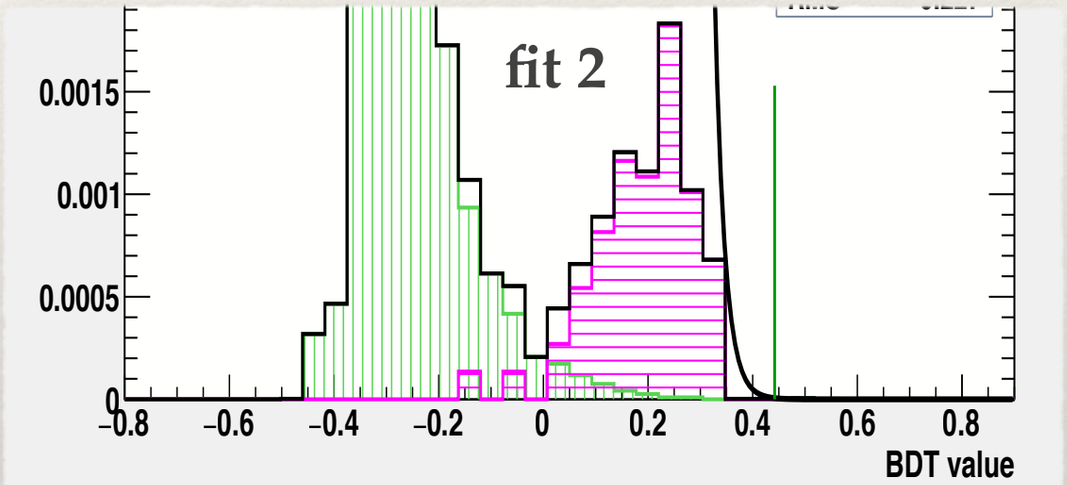
BDT

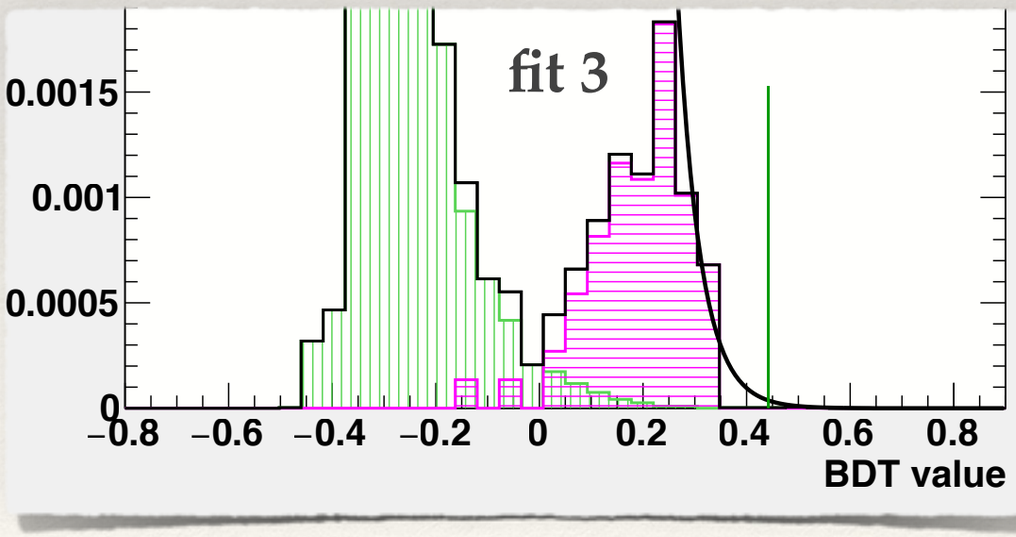


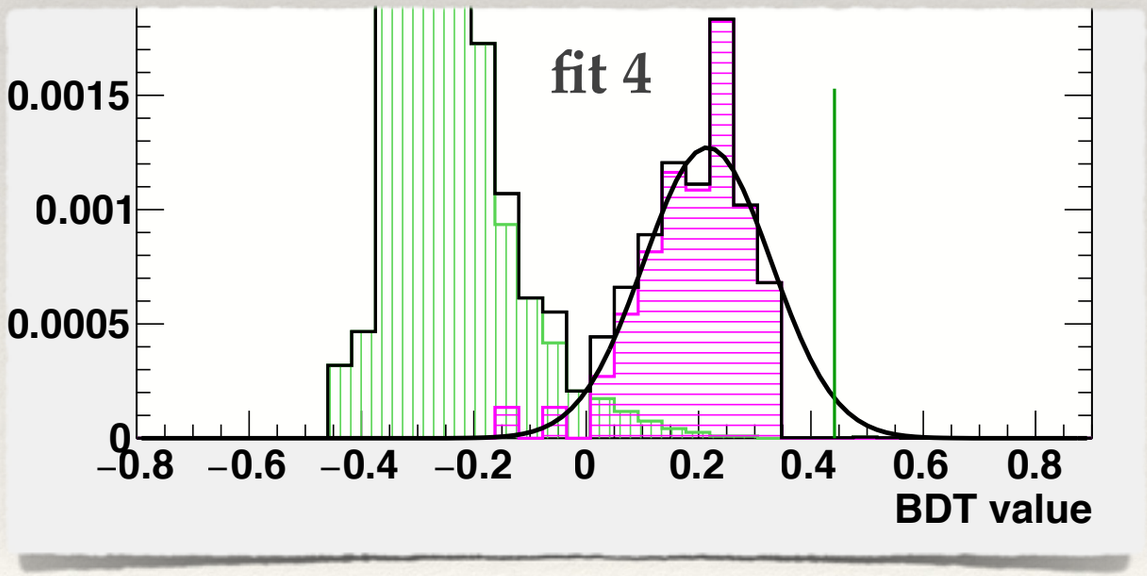
$\tau \to \mu$ RESULTS











LEPTON NUMBER MEASUREMENT

Likelihood test for background only hypothesis:
Poisson + BDT

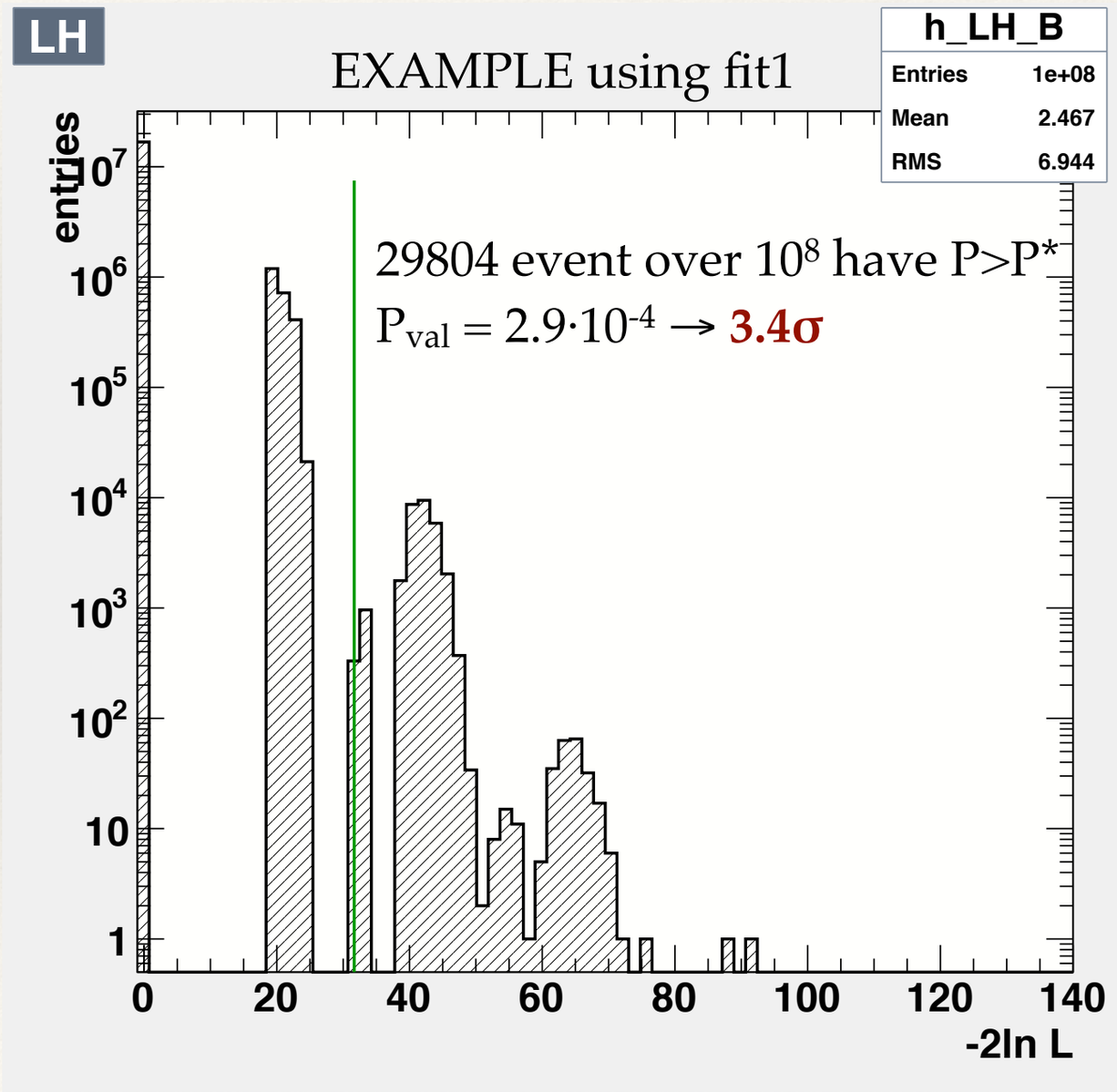
$$\mathcal{L} = \text{Poisson}(n|b) \cdot \prod_{i=1}^{n} f(BDT_i)$$

(Syst. errors on b not taken into account at the moment)

Pseudo Experiments: 10^8

fit	P*	P	σ
1	31.6678	2.9804E-04	3.43
2	33.0272	2.9473E-04	3.44
3	27.9158	2.9804E-04	3.43
4	24.8093	2.97748E-04	3.43

Preliminary significance: **3.4σ**

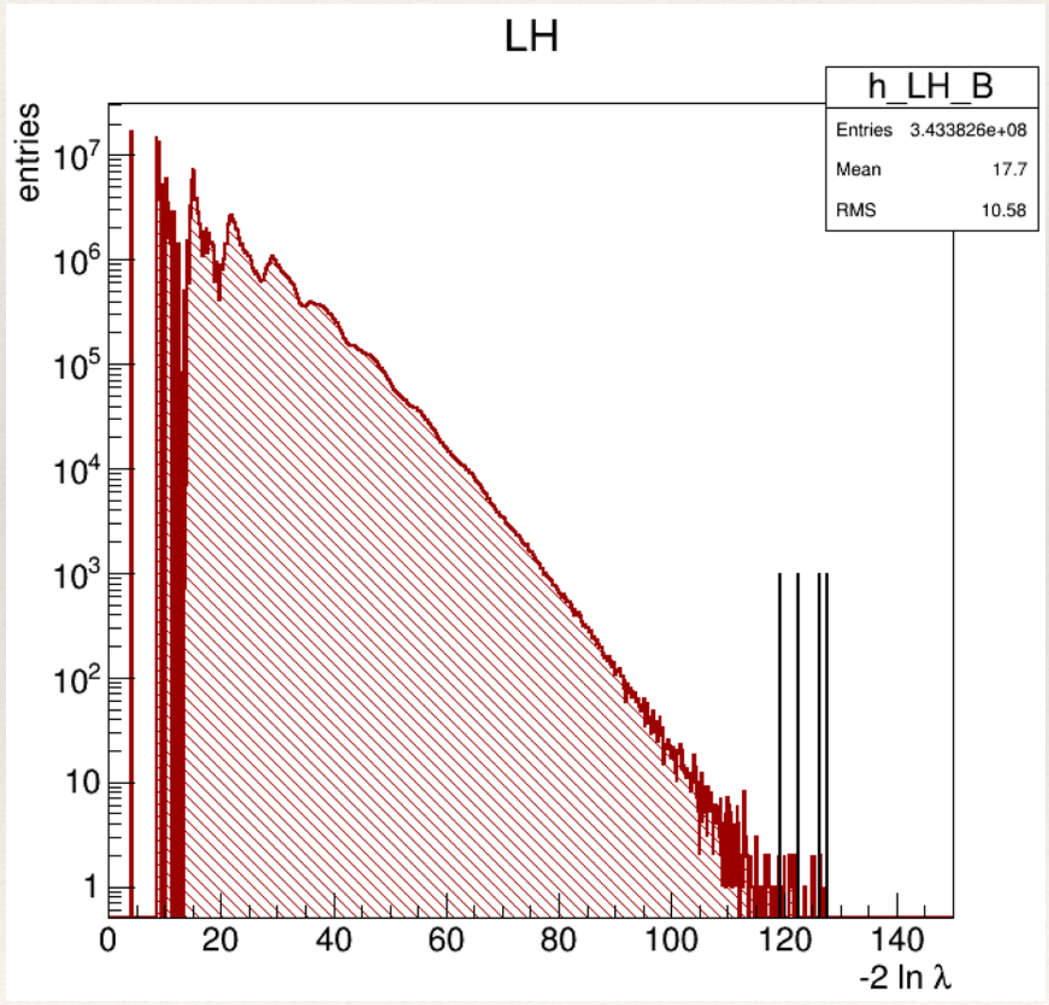


Significance (III)

Significance obtained combining the discriminating power of the BDT analysis and Poisson with the Likelihood method:

$$\mathcal{L} = \prod_{ch=1}^{4} \left(\frac{b_{ch}^{n_{ch}} e^{-b_{ch}}}{n_{ch}!} \cdot \prod_{i=1}^{n_{ch}} f(BDT_{ch_i}) \right)$$

fit	P*	N exp P>P*	P	σ
1	126.309	4	1.4561E-08	5.55
2	127.668	1	2.9122E-09	5.82
3	122.557	10	2.9122E-08	5.42
4	119.45	25	7.28051E-08	5.26



Conclusions

- Cross check with efficiencies used for tau articles performed → Good agreement reached
- Δm^2_{23} and absolute ν_τ cross-section measurement: agreement with PDG2016 value / SM prediction within 1σ
- BDT analysis: more statistics is needed
- Minimum bias analysis significance > 5σ with P*-method, Likelihood (8 channels mode) and BDT

Back-up

8 channels

minimum bias analysis 8 channels						
	charm	had reint	las	tot bkg	Expected signal	Observed
τ→1h	0.02	0.024	0.00	0.05	0.57	3
τ→μ	0.003	0.00	0.0002	0.003	0.55	1
τ→3h	0.20	0.003	0.00	0.21	1.09	1
τ→e	0.03	0.00	0.00	0.03	0.75	0
τ→1h	0.13	1.26	0.00	1.39	2.25	3
τ→μ	0.005	0.00	0.02	0.02	0.54	0
τ→3h	0.23	0.08	0.00	0.31	0.66	2
τ→e	0.00	0.00	0.00	0.00	0.04	0
Totale	0.63	1.37	0.02	2.02	6.46	10

Final sample

Run year	0μ DS	1μ DS
2008	150	543
2009	255	1024
2010	278	1001
2011	291	1031
2012	223	807
TOTAL	1197	4406

ν_μ efficiencies

	v	err	v	err
1μ	46.47	0.24	13.39	0.33
0 μ	2.99	0.08	30.47	0.44

Marginal Events

LAB	Event ID	Ev Class	Topology	zdec	DL	ptmiss	phi	P_t (GeV/c)	P_{dau} Total (GeV/c)	psum	kink	massa inv	m min inv	γ at decvtx	TFD
1st cand	9234119599	0μ	kink	435 ±35	1135 ±35	$0,52^{+0,32}_{-0,17}$	173±2	$0,47^{+0,24}_{-0,12}$	12^{+6}_{-3}	$24,3^{+3,9}_{-2,7}$	0,041±0,002	/	/	2	DONE
2nd cand	11113019758	0μ	trident	1446 ±10	1466 ±10	0,31±0,11	167,8±1,1	/	8,4±1,7	$12,7^{+1,7}_{-2,3}$	0,0874±0,0015	0,80± 0,12	0,96 ±0,13	0	DONE
3rd cand	12123032048	1μ	kink	151 ±10	376 ±10	/	/	0,69±0,05	2,8 [2,6; 3,0]	$6,8^{+0,9}_{-0,6}$	0,245±0,005	/	/	0	DONE
4th cand	12254000036	0μ	kink	406 ±30	1090 ±30	$0,55^{+0,3}_{-0,2}$	166^{+2}_{-31}	$0,82^{+0,3}_{-1,6}$	6,0 [4,8; 8,2]	$14,4^{+3,9}_{-2,7}$	0,137+0,004	/	/	0	DONE
5th cand	12227007334	0μ	kink	630 ±30	960 ±30	0,3±1	151±1	$1^{+1,1}_{-0,4}$	11^{+14}_{-4}	12^{+14}_{-4}	0,090±0,002	/	/	0	DONE
Bo-Pd	11143018505	0μ	kink	429,6	1160	0.876	151,8	0.24	2,7 [2,13; 3,70]	23.2	0.090	/	/	1	DONE
Bern	11172035775	0μ	kink	652	1100	0,90 [0,79;1,16]	140.4	0,68 [0,56; 0,90]	6,9 [5,7; 9,2]	32.2	0.098	/	/	0	NOT NEED
Nagoya	9190097972	0μ	kink	10	822	0,46	142,8	0,33	2,2 [1,6; 3,6]	9,6	0.146	/	/	0	NOT NEED
Bari	10123059807	0μ	trident	-648	140	>0,6	82	/	6,7	16,4	0.231	1,2	2	0	DONE
Nagoya	11213015702	0μ	trident	407	256	0,5	47,1	>0,40	> 6,3	>6.78	0.083	0.94	1.42	2	NOT NEED