Neutrino tridents at the LHC

Possibilities for trident detection at FPF

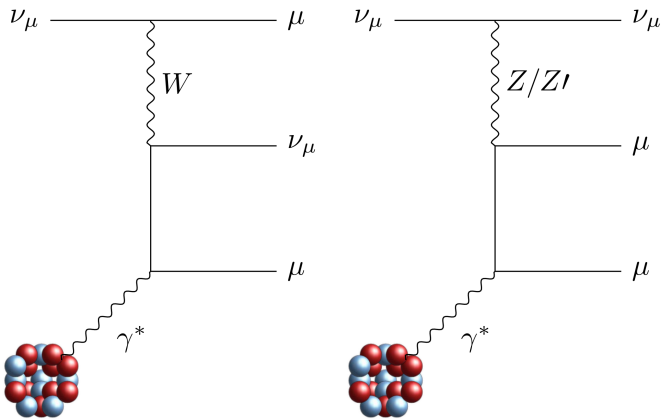
Wolfgang Altmannshofer, ***Toni Mäkelä****, Subir Sarkar,*
Sebastian Trojanowski, Keping Xie, Bei Zhou

FPF7
February 29 – March 1, 2024

NATIONAL SCIENCE CENTRE
POLAND

Neutrino tridents

- Neutrino-induced charged lepton production in Coulomb fields of heavy nuclei



SM

$$\nu_\ell N \to \nu_\ell N \ell^+ \ell^- \qquad (W, Z)$$

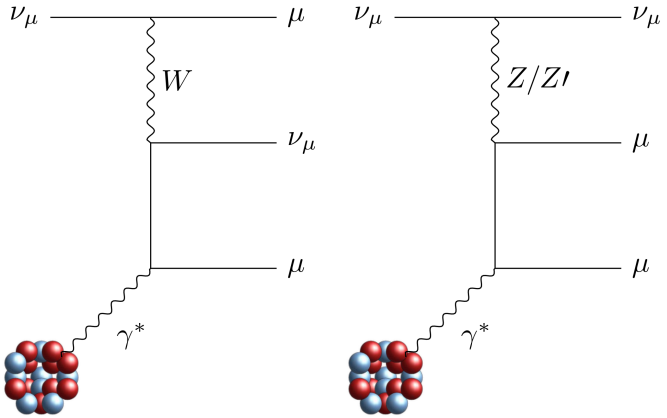
$$\nu_\ell N \to \nu_\ell N \ell'^+ \ell'^- \qquad (Z)$$

$$\nu_\ell N \to \nu_{\ell'} N \ell'^+ \ell^- \qquad (W)$$

BSM: also *Z'*

Neutrino tridents

- Neutrino-induced charged lepton production in Coulomb fields of heavy nuclei



SM

$$\nu_\ell N \to \nu_\ell N \ell^+ \ell^- \qquad (W, Z)$$

$$\nu_\ell N \to \nu_\ell N \ell'^+ \ell'^- \qquad (Z)$$

$$\nu_\ell N \to \nu_{\ell'} N \ell'^+ \ell^- \qquad (W)$$

BSM: also *Z'*

- Observations claimed at
  - CHARM II, 3σ, E_ν~20 GeV
  - CCFR, 3σ
  - NuTeV

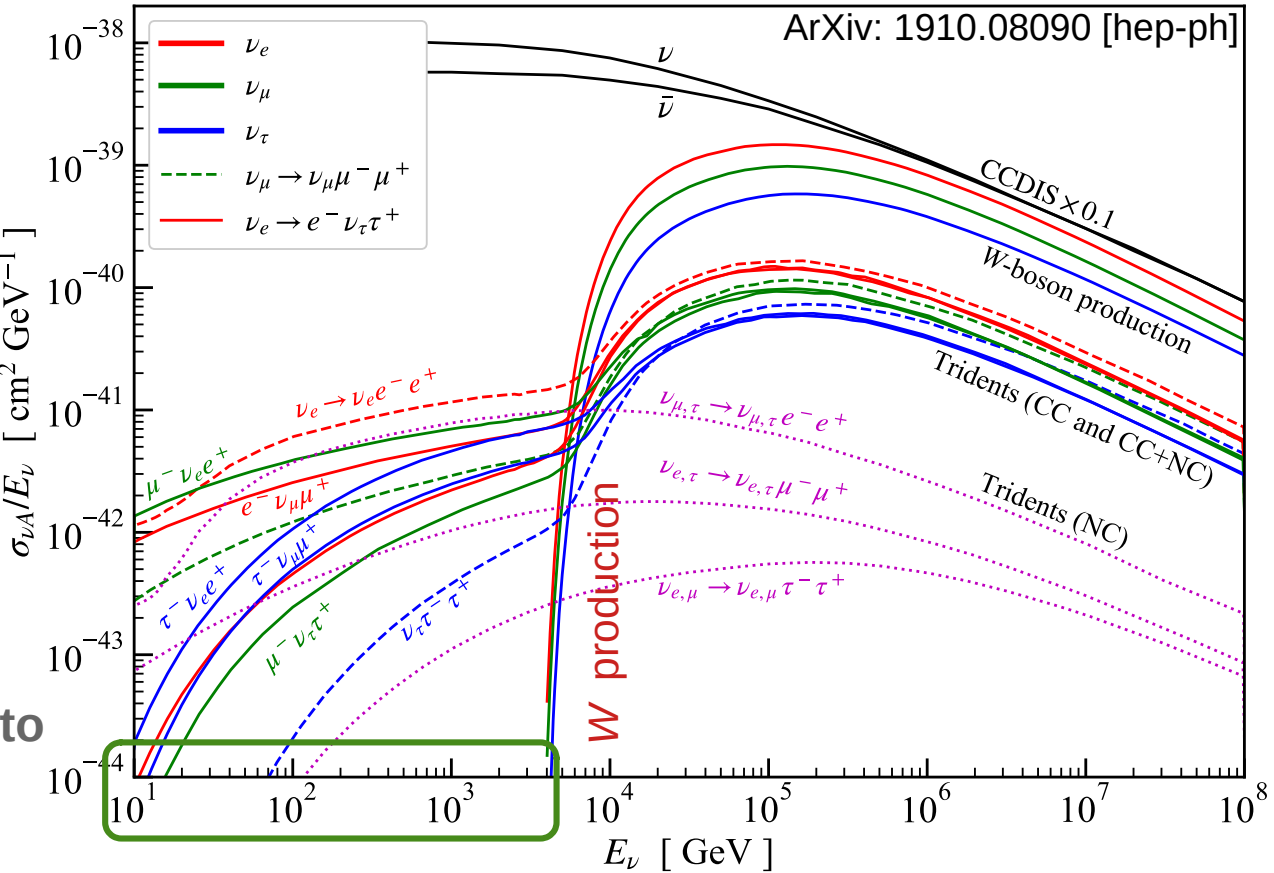
  } E_ν~160 GeV

- NuTeV identified additional b.g. (diffractive charm) not considered in other measurements
  - How conclusive are the results?

Neutrino tridents

- Rare, cross section orders of magnitude below DIS
- **LHC forward experiments**: region of interest up to ~5 TeV
  - New E_ν range, but well below W production

Trident processes computed using codes of 1406.2332 [hep-ph] and 1902.06765 [hep-ph], many thanks to W. Altmannshofer!



The SM trident signal

- Consider processes with **two muons in the final state**
  - Background: DIS dimuon production, incoming ν_μ
  - Trident signal: incoming ν_e, ν_μ, ν_τ (ν_μ dominates)

High-Z targets optimal for trident processes!

Name	Mass [tons]	Target	On(Off)-Axis	Neutrino Tridents, $\nu N \to \nu N' \ell\ell$						
				$\mu^+\mu^-$	$\mu^+\mu^-$ $(f_s = 0.5)$	e^+e^-	$\tau^+\tau^-$	$e^\pm\mu^\mp$	$e^\pm\tau^\mp$	$\mu^\pm\tau^\mp$
Run 3										
FASERν	1.1	W	On	0.23	0.55	0.24	0.0031	0.84	0.034	0.060
SND@LHC	0.83	W	Off	0.026	0.06	0.03	0.0002	0.10	0.004	0.005
HL-LHC (Forward Physics Facility)										
FASERν2	20	W	On	41	99	44	0.5	152	6.2	10
AdvSND@LHC	5	W	Off	2.2	5.3	2.7	0.02	8.9	0.3	0.4
FLArE	10	LAr	On	4.2	10	4.3	0.06	15	0.7	1.1
FLArE-100	100	LAr	On	27	63	28	0.3	95	4.0	6.5
NuTeV-like (Fe)	95	Fe	On	24	57	22	0.4	103	3.9	6.7

The SM trident signal

- Consider processes with **two muons in the final state**
  - Background: DIS dimuon production, incoming ν_μ
  - Trident signal: incoming ν_e, ν_μ, ν_τ (ν_μ dominates)

High-Z targets optimal for trident processes!

Also other charged lepton pairs possible at FPF

Name	Mass [tons]	Target	On(Off)-Axis	Neutrino Tridents, $\nu N \to \nu N' \ell\ell$						
				$\mu^+\mu^-$	$\mu^+\mu^-$ $(f_s = 0.5)$	e^+e^-	$\tau^+\tau^-$	$e^\pm\mu^\mp$	$e^\pm\tau^\mp$	$\mu^\pm\tau^\mp$
Run 3										
FASERν	1.1	W	On	0.23	0.55	0.24	0.0031	0.84	0.034	0.060
SND@LHC	0.83	W	Off	0.026	0.06	0.03	0.0002	0.10	0.004	0.005
HL-LHC (Forward Physics Facility)										
FASERν2	20	W	On	41	99	44	0.5	152	6.2	10
AdvSND@LHC	5	W	Off	2.2	5.3	2.7	0.02	8.9	0.3	0.4
FLArE	10	LAr	On	4.2	10	4.3	0.06	15	0.7	1.1
FLArE-100	100	LAr	On	27	63	28	0.3	95	4.0	6.5
NuTeV-like (Fe)	95	Fe	On	24	57	22	0.4	103	3.9	6.7

The SM trident signal

- Consider processes with **two muons in the final state**
  - Background: DIS dimuon production, incoming ν_μ
  - Trident signal: incoming ν_e, ν_μ, ν_τ (ν_μ dominates)

High-Z targets optimal for trident processes!

Also other charged lepton pairs possible at FPF

Name	Mass [tons]	Target	On(Off)-Axis	Neutrino Tridents, $\nu N \to \nu N' \ell\ell$						
				$\mu^+\mu^-$	$\mu^+\mu^-$ $(f_s = 0.5)$	e^+e^-	$\tau^+\tau^-$	$e^\pm\mu^\mp$	$e^\pm\tau^\mp$	$\mu^\pm\tau^\mp$
Run 3										
FASERν	1.1	W	On	0.23	0.55	0.24	0.0031	0.84	0.034	0.060
SND@LHC	0.83	W	Off	0.026	0.06	0.03	0.0002	0.10	0.004	0.005
HL-LHC (Forward Physics Facility)										
FASERν2	20	W	On	41	99	44	0.5	152	6.2	10
AdvSND@LHC	5	W	Off	2.2	5.3	2.7	0.02	8.9	0.3	0.4
FLArE	10	LAr	On	4.2	10	4.3	0.06	15	0.7	1.1
FLArE-100	100	LAr	On	27	63	28	0.3	95	4.0	6.5
NuTeV-like (Fe)	95	Fe	On	24	57	22	0.4	103	3.9	6.7

Assuming enhanced strangeness scenario of arXiv: 2202.03095 [hep-ph]

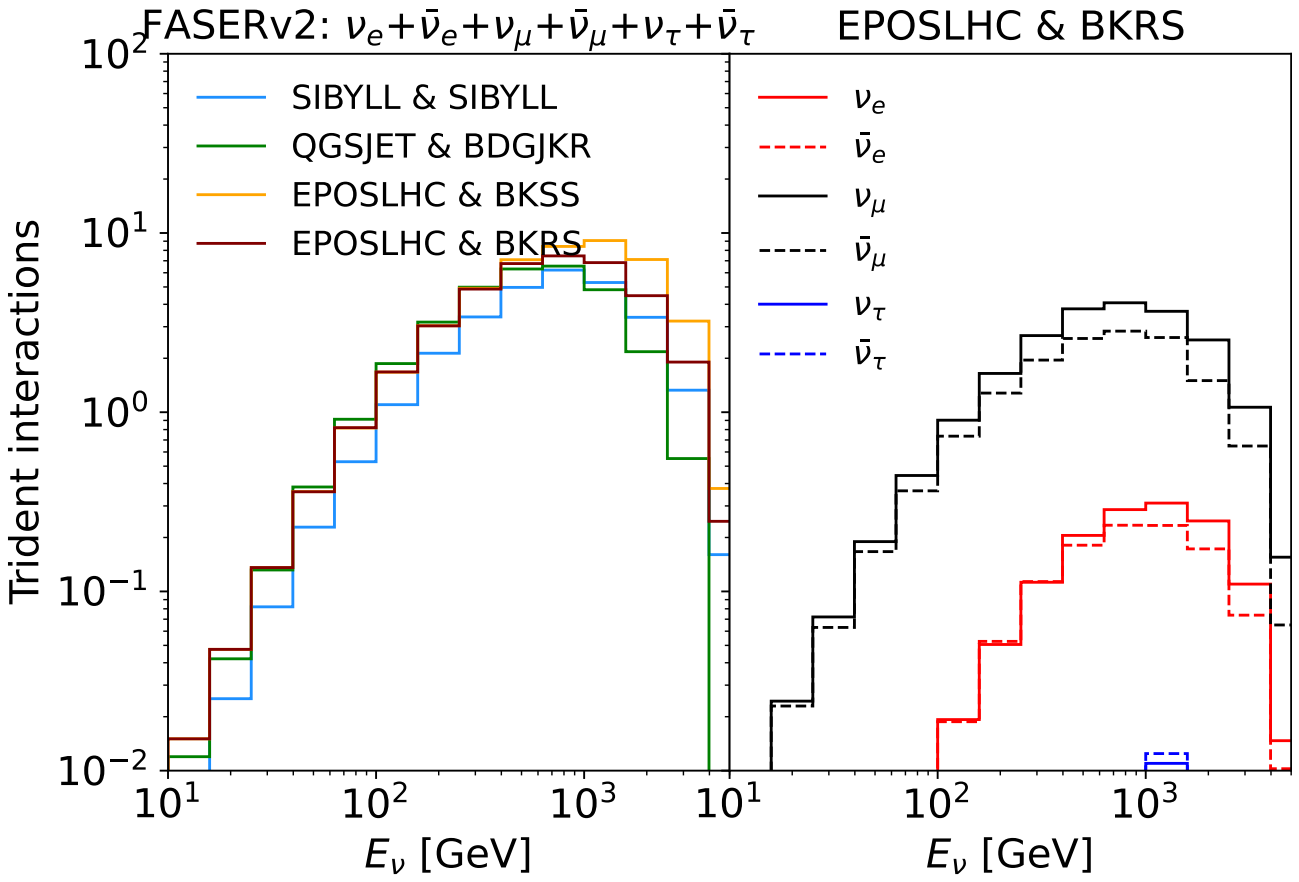
The SM trident signal

- Spectrum uncertainties via a Fisher information approach, based on the predictions:

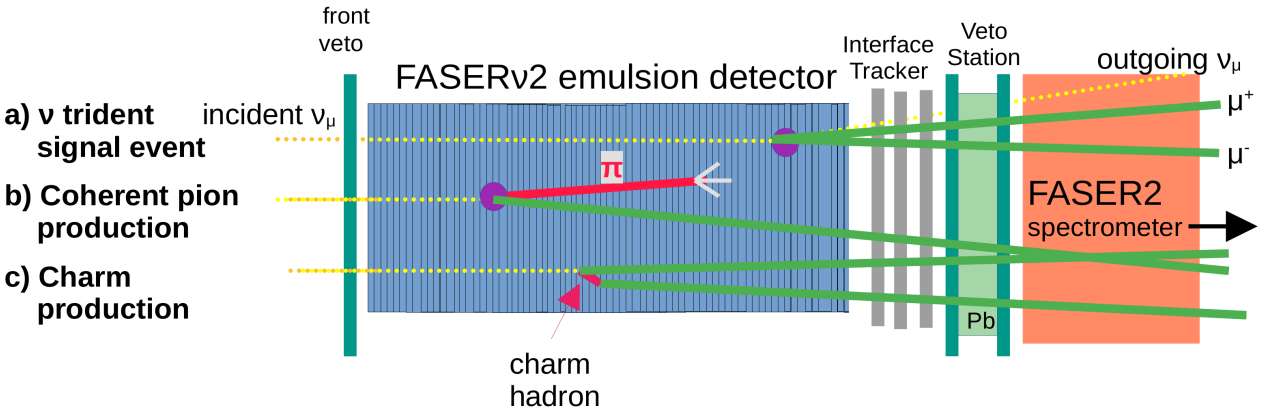
Light mesons (π, K)	Charm hadrons (D, Λ_c)
SIBYLL 2.3d	SIBYLL 2.3d
EPOS-LHC	BKSS k_T BKRS (NLO)
QGSJET II-04	BDGJKR (NLO)

- Baseline: EPOS+BKRS

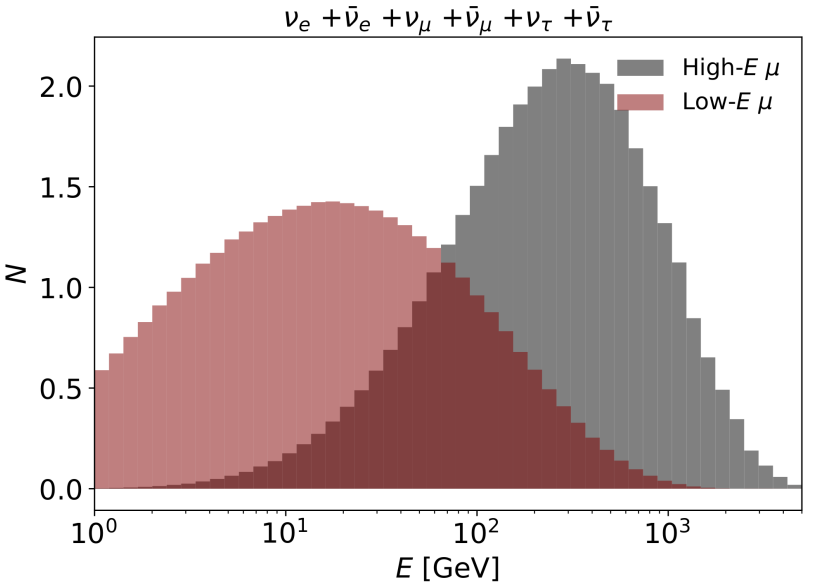
Many thanks to WG2, M. Fieg and F. Kling for their efforts!



Experimental signatures

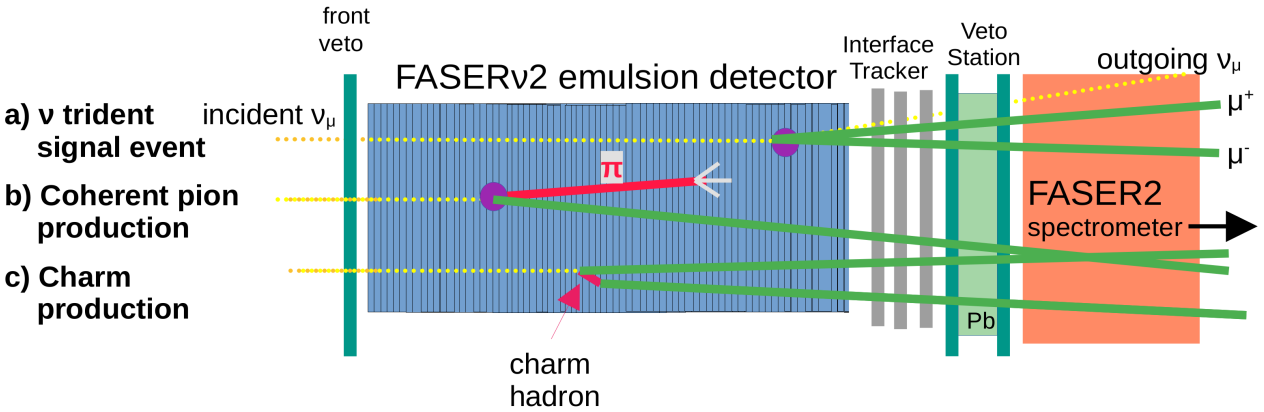


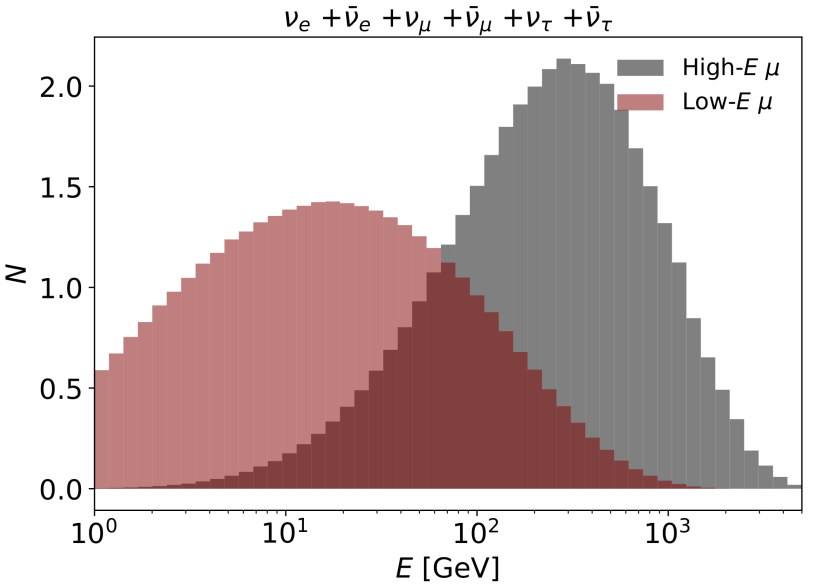
- The signal is seen as two muons originating from the same vertex, must be distinguished from other processes



- Expect a high- and low-E muon in signal events

Experimental signatures





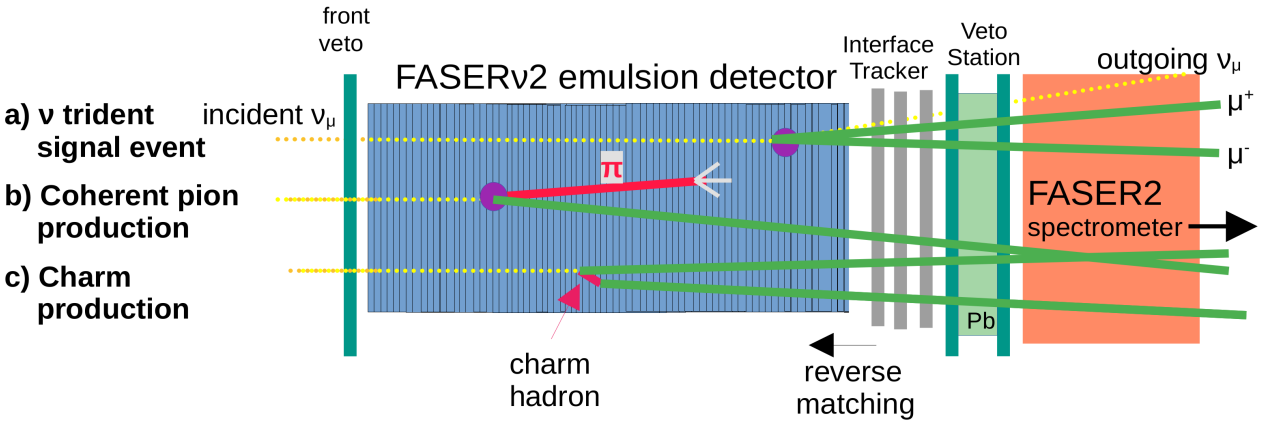
- The signal is seen as two muons originating from the same vertex, must be distinguished from other processes

To resolve the signal, apply the cuts:

- Require exactly 2 muon tracks
- Maximum decay length: 2 cm
- Max. angle between muons: 0.1 rad

- Expect a high- and low-E muon in signal events

Experimental signatures

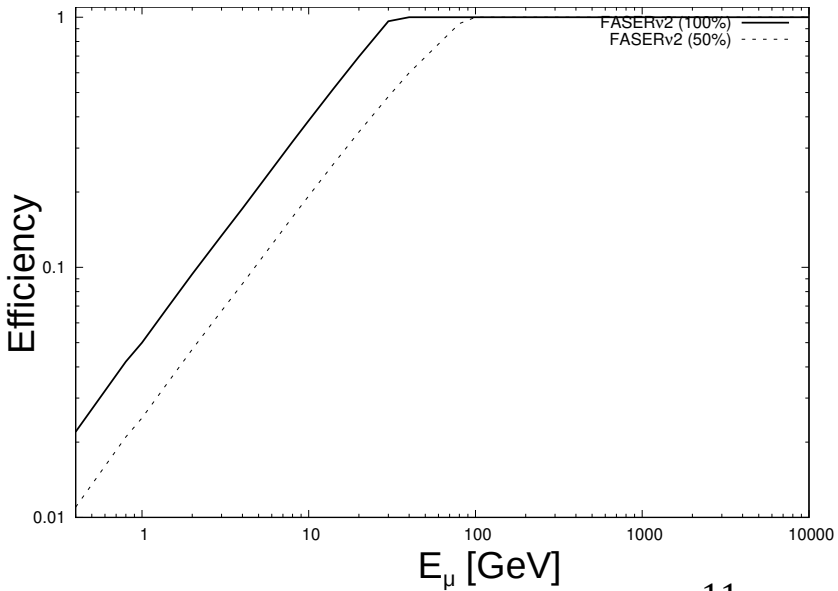


- The signal is seen as two muons originating from the same vertex, must be distinguished from other processes

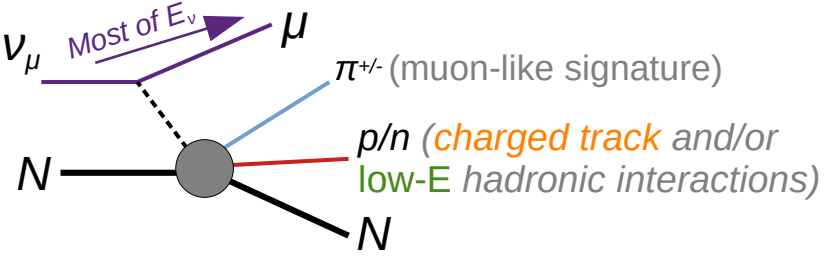
To resolve the signal, apply the cuts:

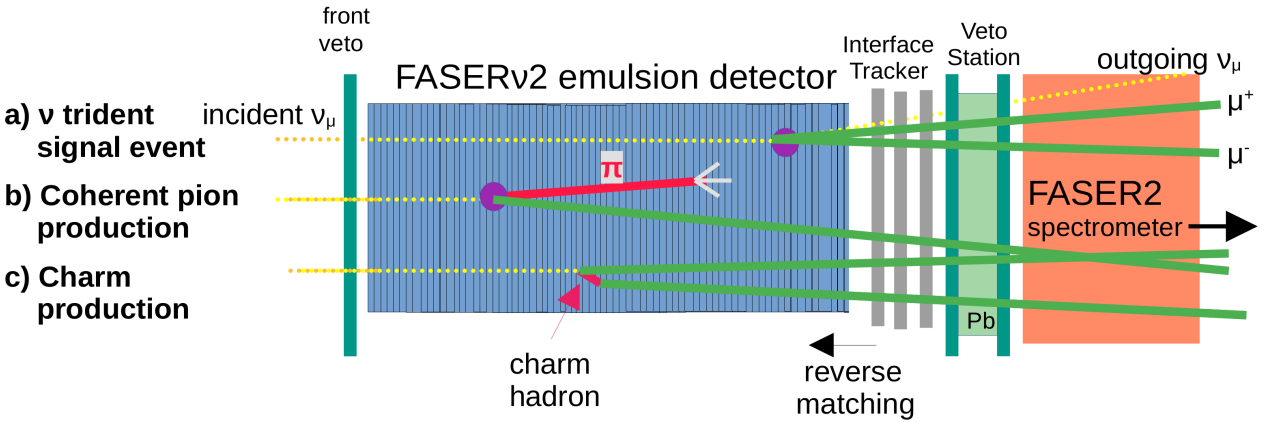
- Require exactly 2 muon tracks
- Maximum decay length: 2 cm
- Max. angle between muons: 0.1 rad

- Reverse matching at FASERν2
  - Acceptance accounting for μ energy loss



Experimental signatures



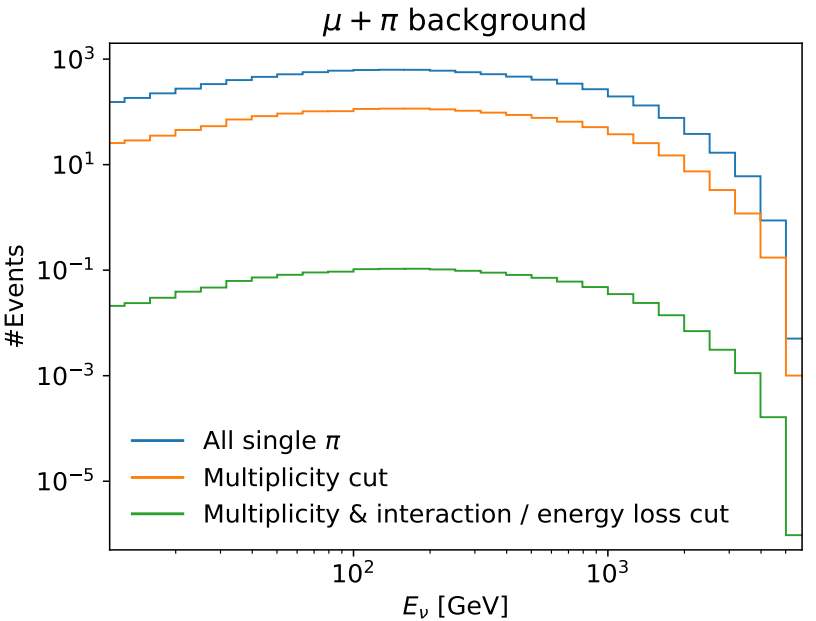


- The signal is seen as two muons originating from the same vertex, must be distinguished from other processes

To resolve the signal, apply the cuts:

- Require exactly 2 muon tracks
- Maximum decay length: 2 cm
- Max. angle between muons: 0.1 rad

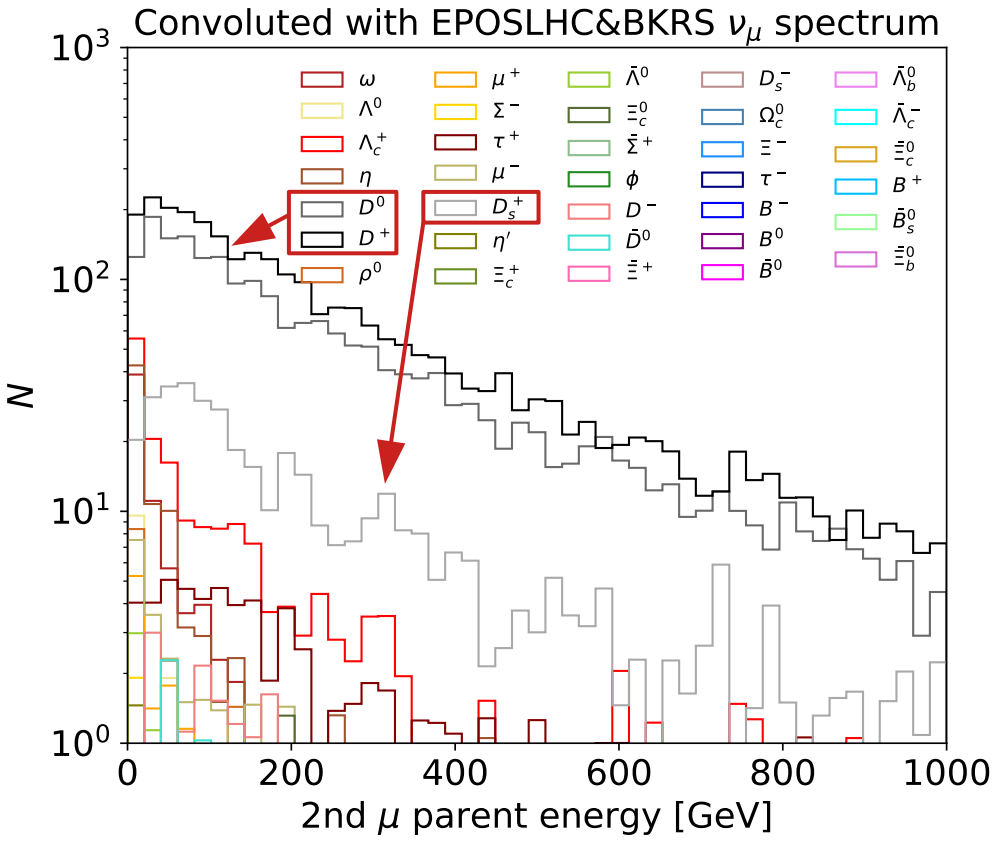
- Single+pion background made negligible by charged track multiplicity cut and energy loss effects



Dimuon background

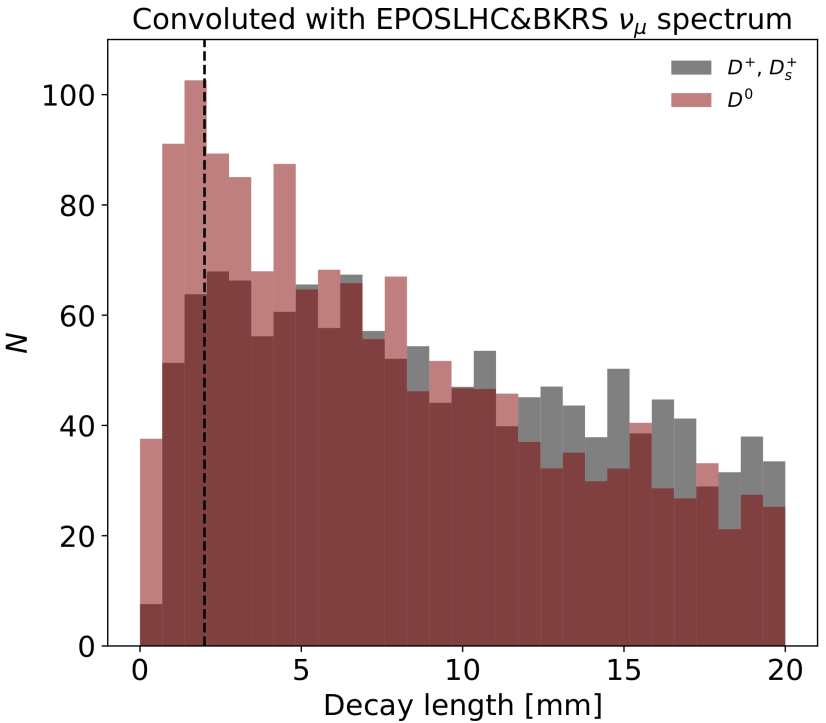
- Non-trident SM processes resulting in 2(+) muons in the final state
- Mostly *D* mesons
  - lightest charmed hadrons

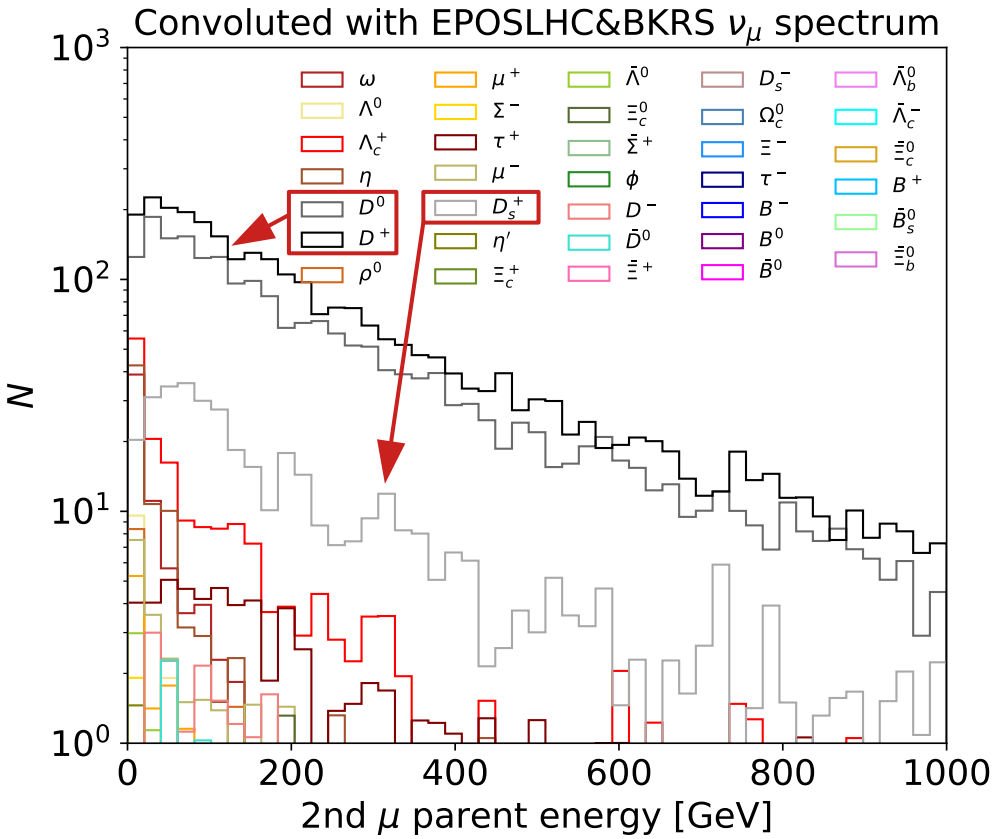
Background sample computed using Pythia8, many thanks to B. Zhou!



Dimuon background

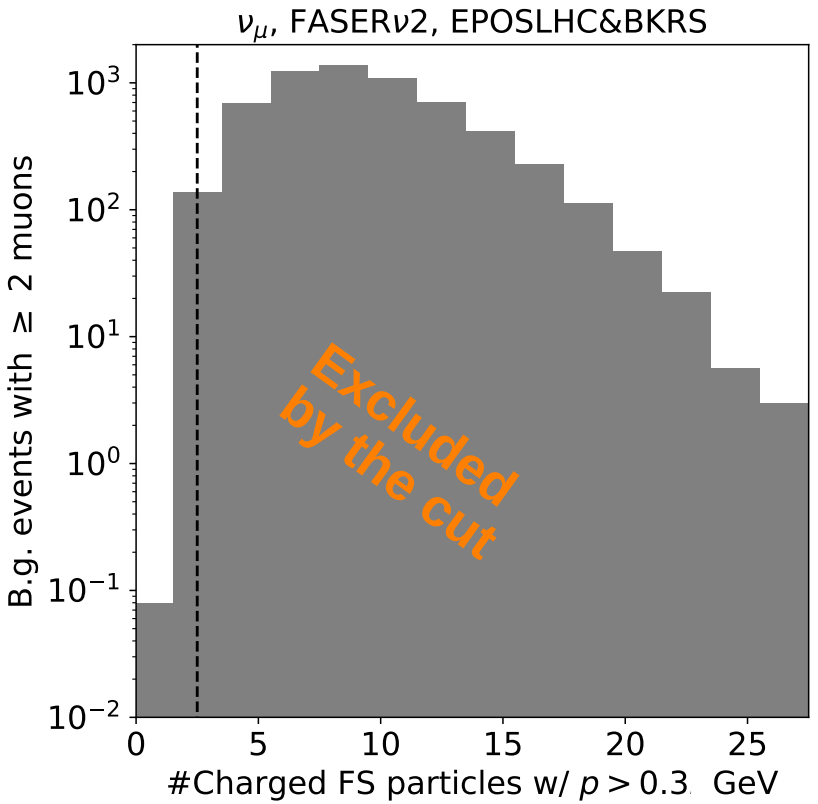
- Additionally, decay length cut effective against *D* meson backgrounds at high-*E*

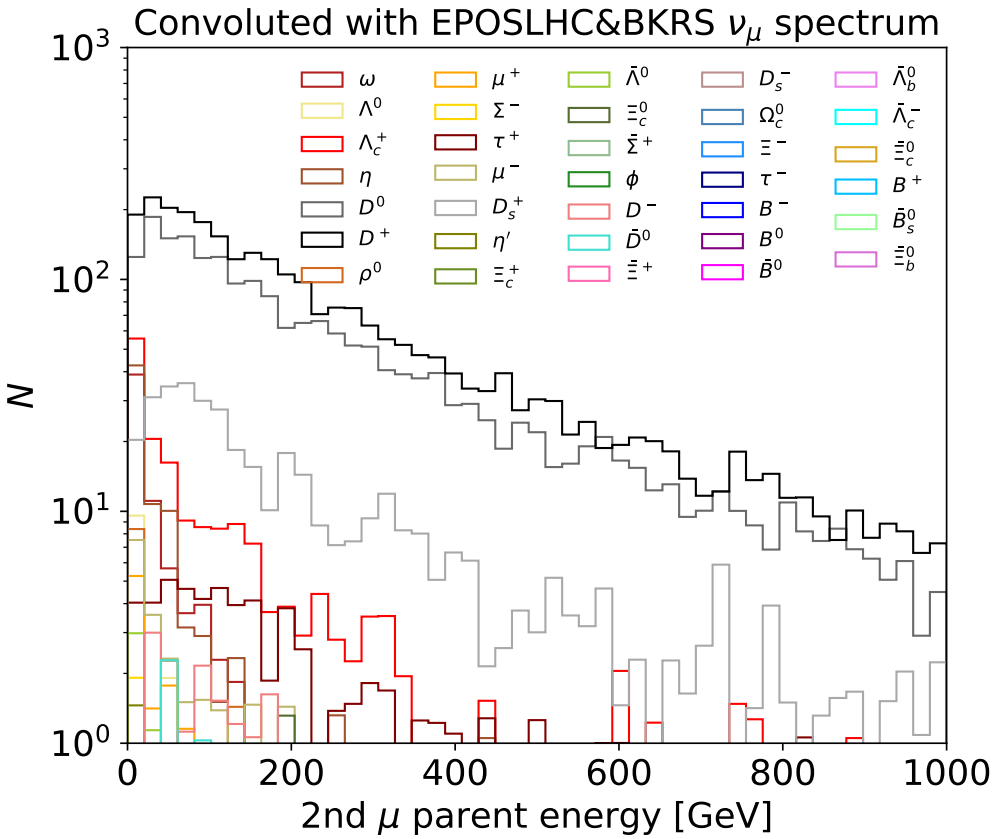




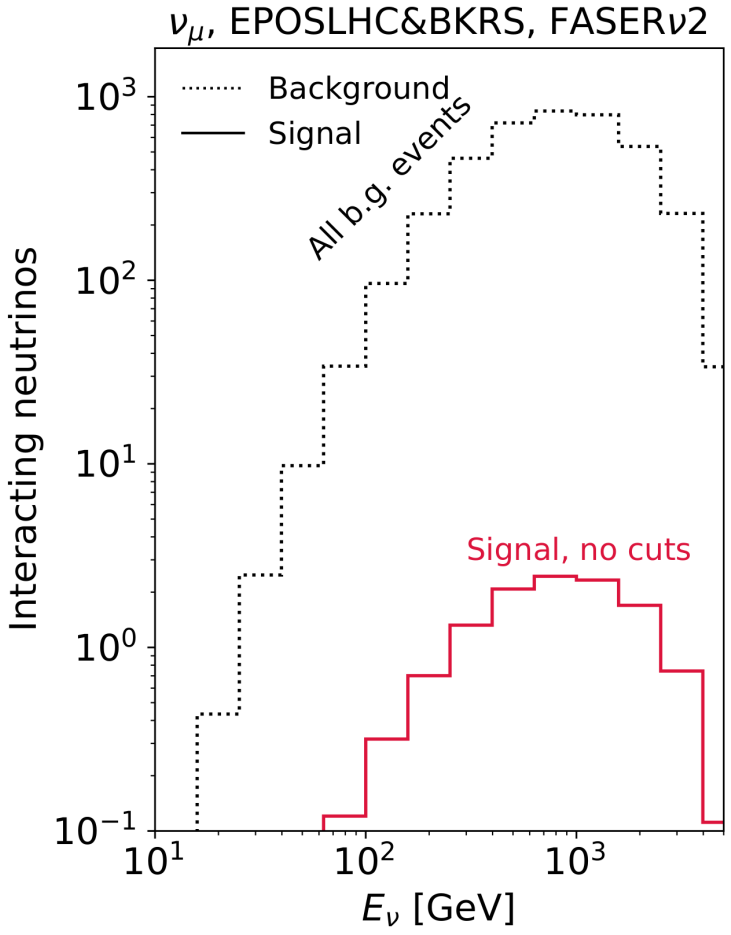
Dimuon background

- Charged track multiplicity cut particularly effective against b.g.



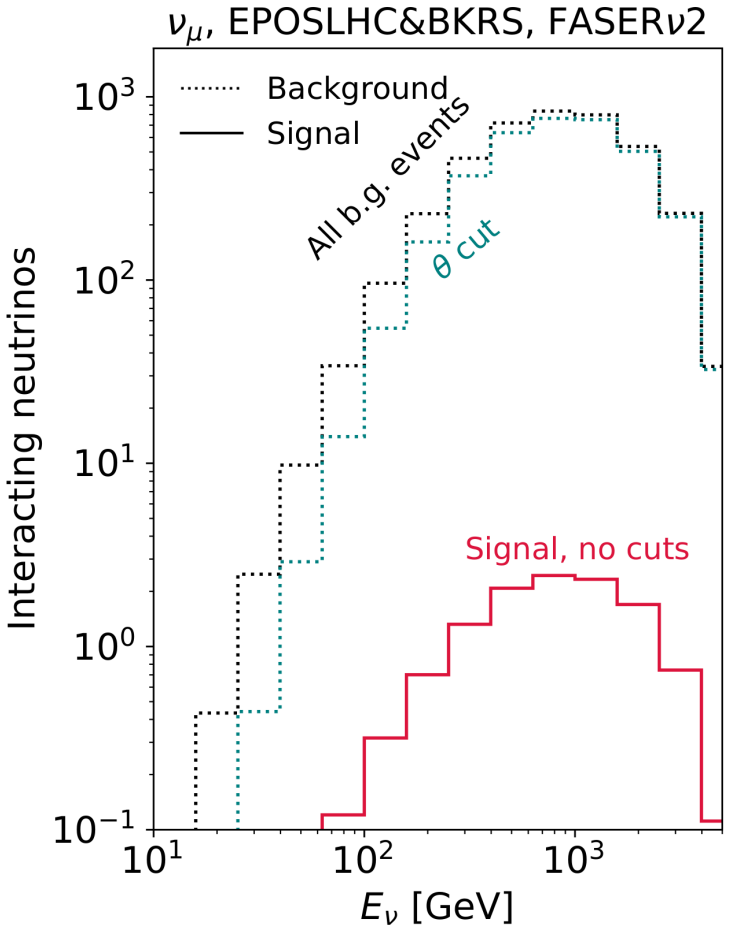


Background vs signal



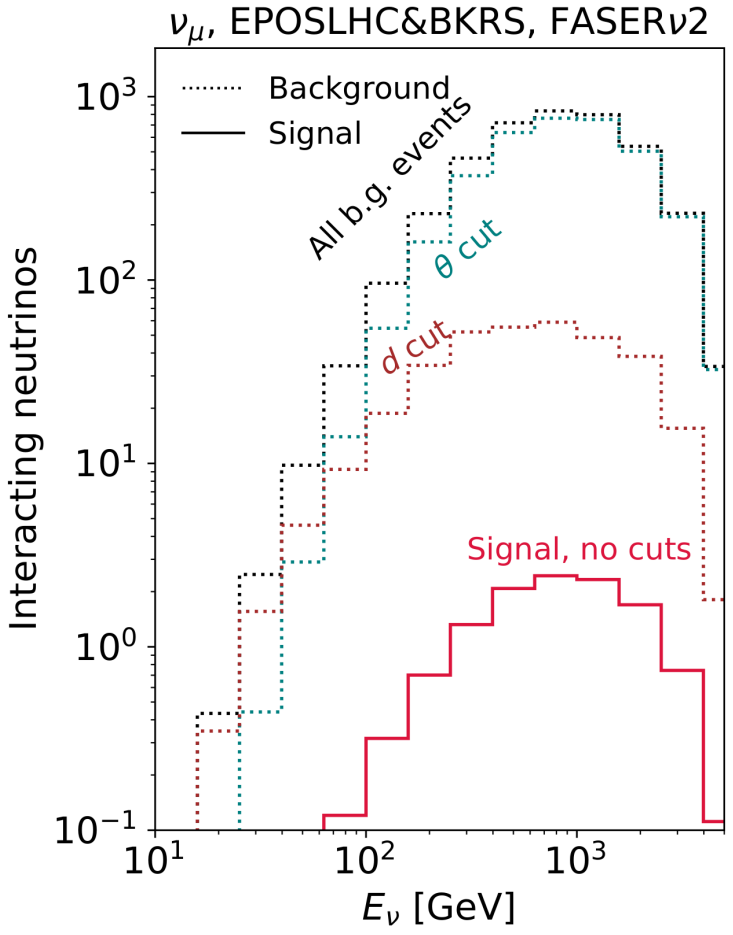
NCBJ

Background vs signal



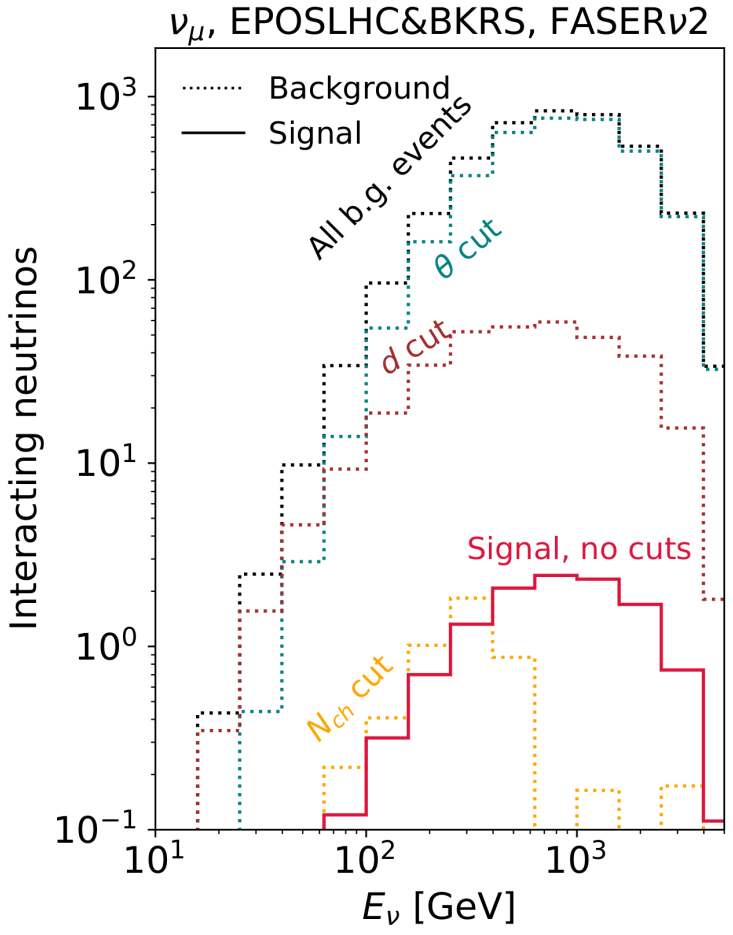
NCBJ

Background vs signal



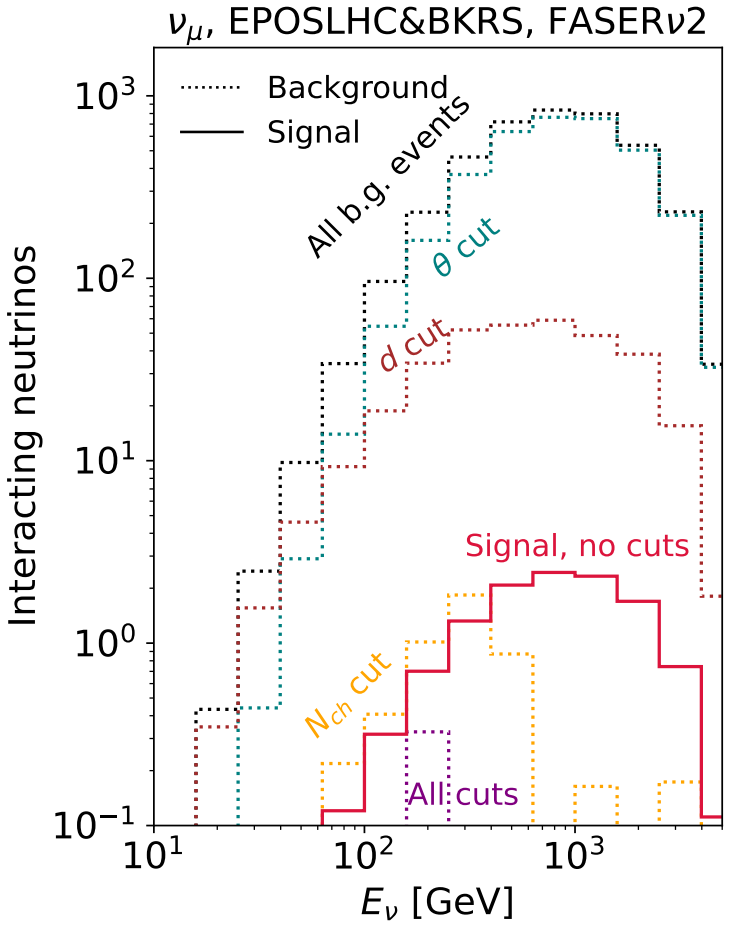
NCBJ

Background vs signal



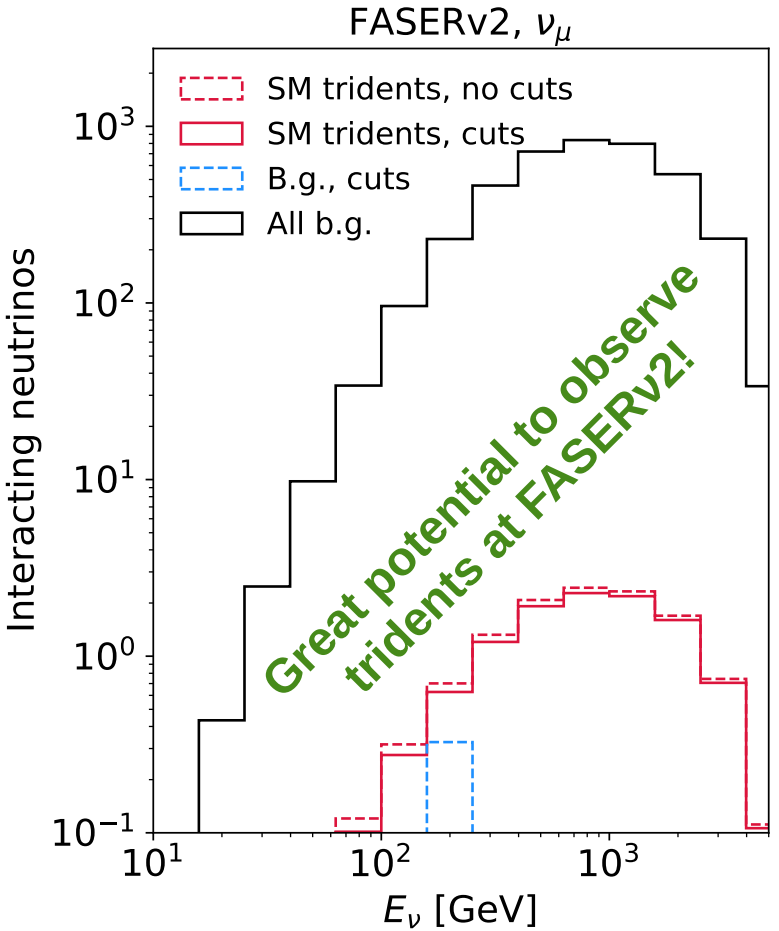
NCBJ

Background vs signal



The cuts annul the background

Effect on signal negligible!



NCBJ

Summary and outlook

- Trident production is a rare process, conclusive observation elusive
  - Probe physics at the EW scale and below
  - WIP: possibilities as a handle to BSM: e.g. gauged L_μ-L_τ?
- SM tridents already a promising case for the FPF
  - Potential for conclusive observation at FASERν2
    - Backgrounds constrained very precisely
    - Also non-$\mu^+\mu^-$ final states, no prior observations
  - WIP: Investigate prospects at a NuTeV-like detector (Fe/Pb/...)

Thanks for your attention!