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Neutrino Tridents at Near Detectors

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In collaboration with
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Zahra Tabrizi and Renata Zukanovich Funchal (U-São Paulo)

Physics Opportunities in the Near
DUNE Detector Hall
Fermilab, Nov 2018

Based on arXiv:1807.10973

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Fermilab

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NORTHWESTERN UNIVERSITY
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1851

Outline

- Introduction
- Trident Cross Section
- Events in LAr Detectors (DUNE ND)
- Conclusions

Introduction

Near Detector Program

Neutrino sector under scrutiny

Precision measurements in the neutrino sector → Reduce systematic uncertainties

- Flux
- CC and NC cross sections
- Backgrounds

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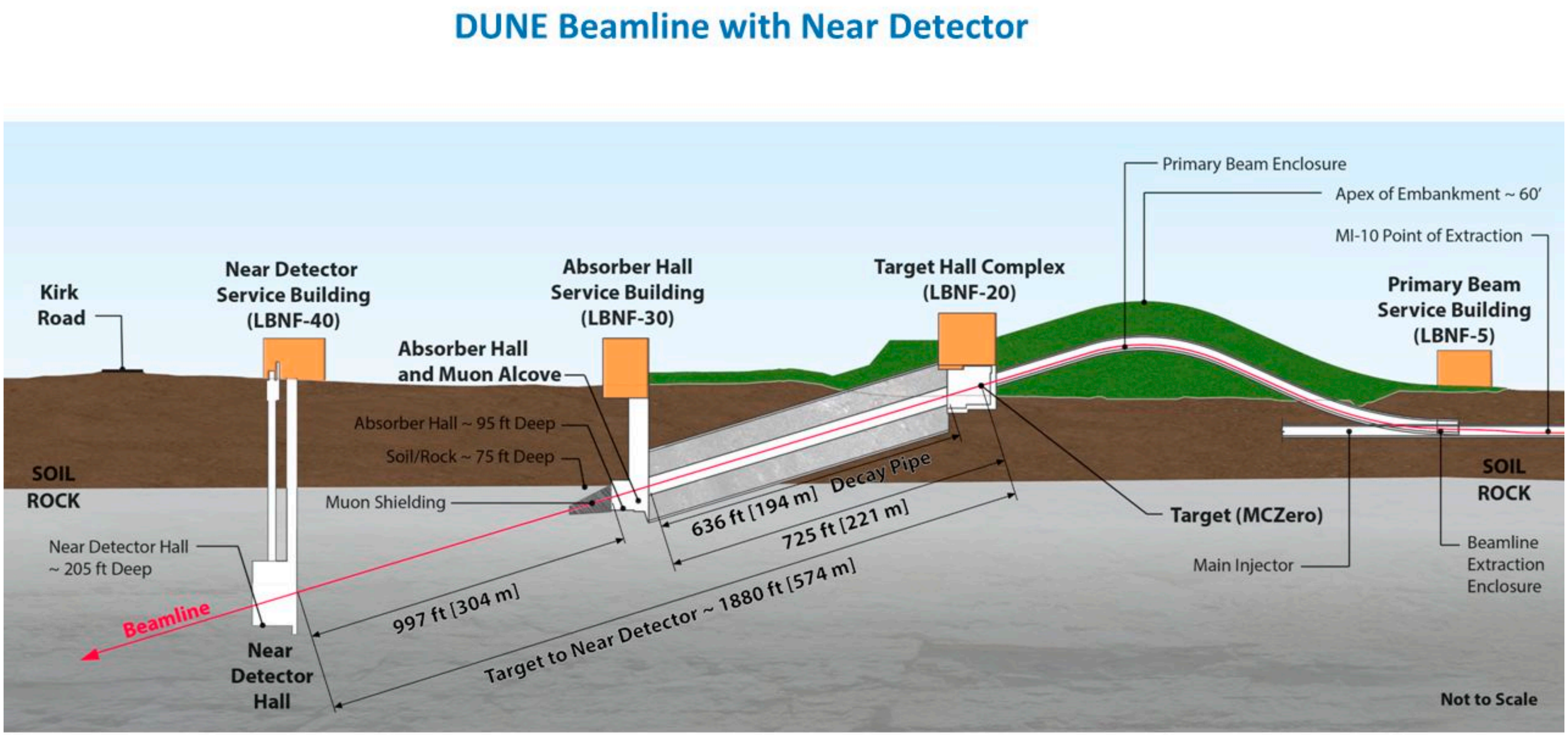
High beam luminosity + Large fiducial mass → Ideal places to investigate rare neutrino interactions

$\sigma < 10^{-44}$ cm^2

- Test SM predictions
- Search for BSM physics

DUNE ND

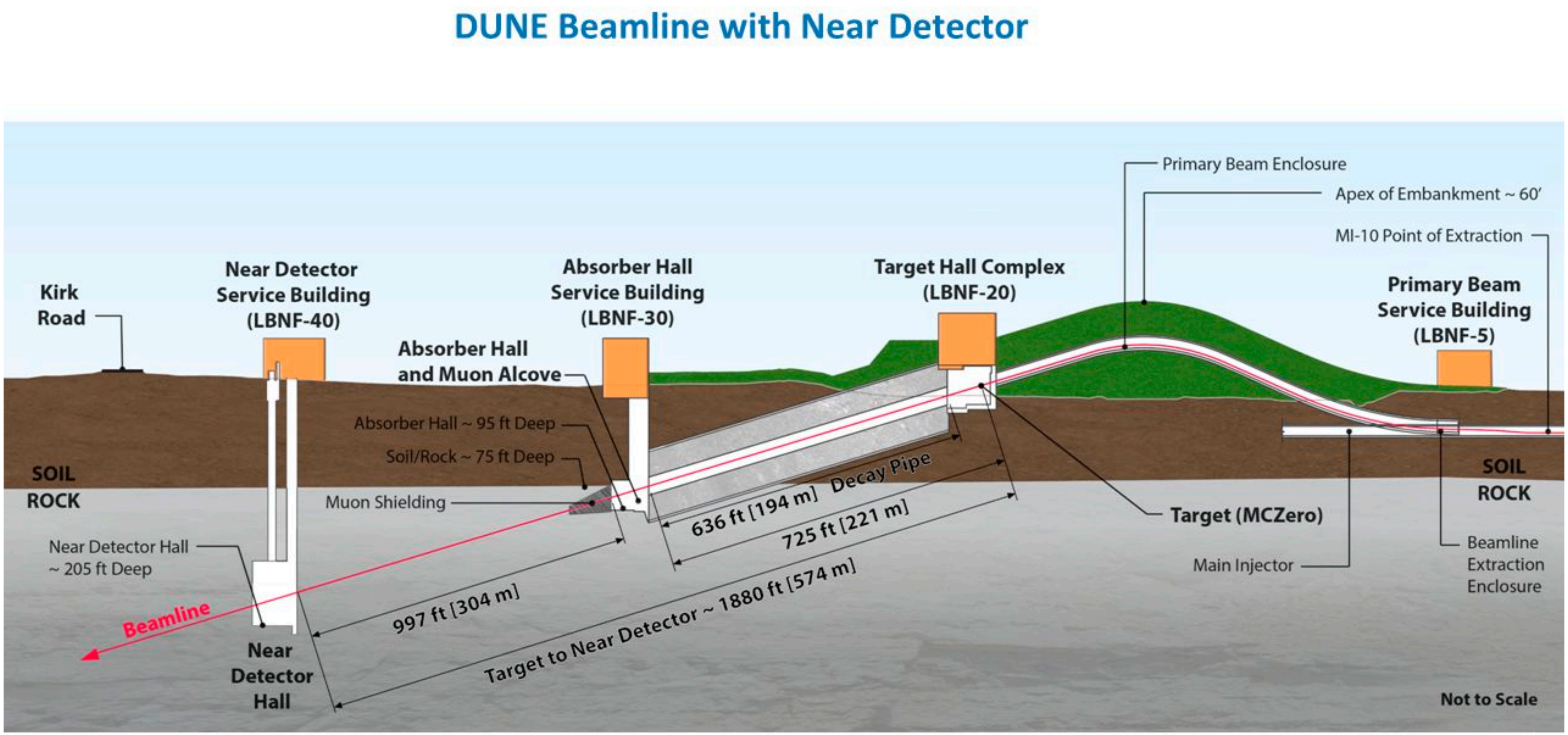


Events per ton-year

ν_μ CC Total	1.64×10^6
ν_μ NC Total	5.17×10^5
$\nu_\mu - e$	135

Alan's talk

DUNE ND



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What about rare neutrino scatterings?

Alan's talk

Trident Inelastic Scattering

M. A. Kozhushner et. al.1962
W. Czyz et al. 1964
Lovseth et al, 1971

Production of a charged lepton pair from the inelastic neutrino scattering in the Coulomb field of the nucleus

$$\nu_\alpha + \mathscr{H} \to \nu_{\alpha \,\mathrm{or}\, \kappa(\beta)} + \ell^-_\beta + \ell^+_\kappa + \mathscr{H}$$

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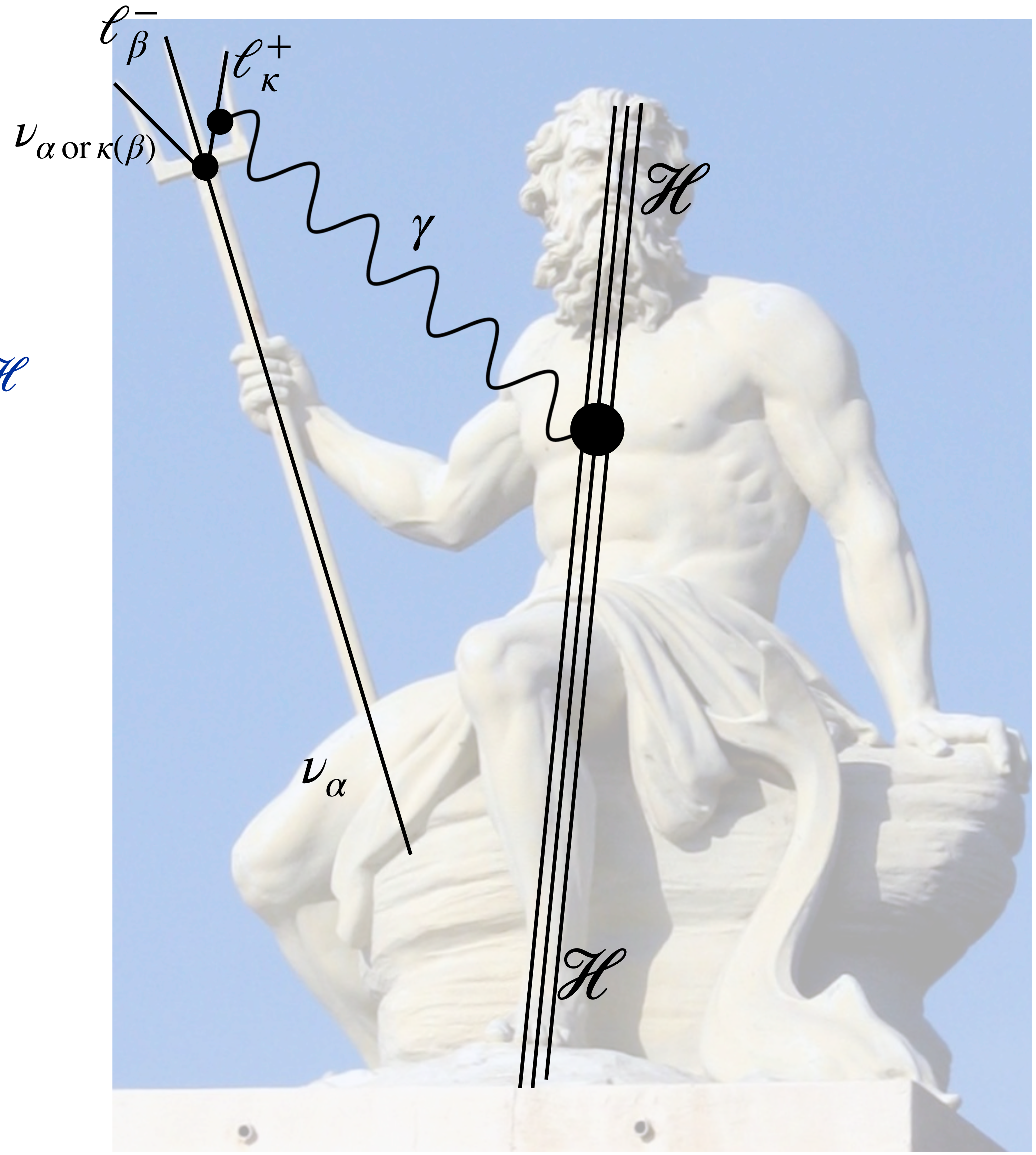

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$$\nu_\mu \to \nu_\mu \mu^+ \mu^-$$

CHARM II

PLB 245 (1990) 271

$$\frac{\sigma_{\text{CHARM II}}}{\sigma_{\text{SM}}} = 1.58 \pm 0.57$$

CCFR

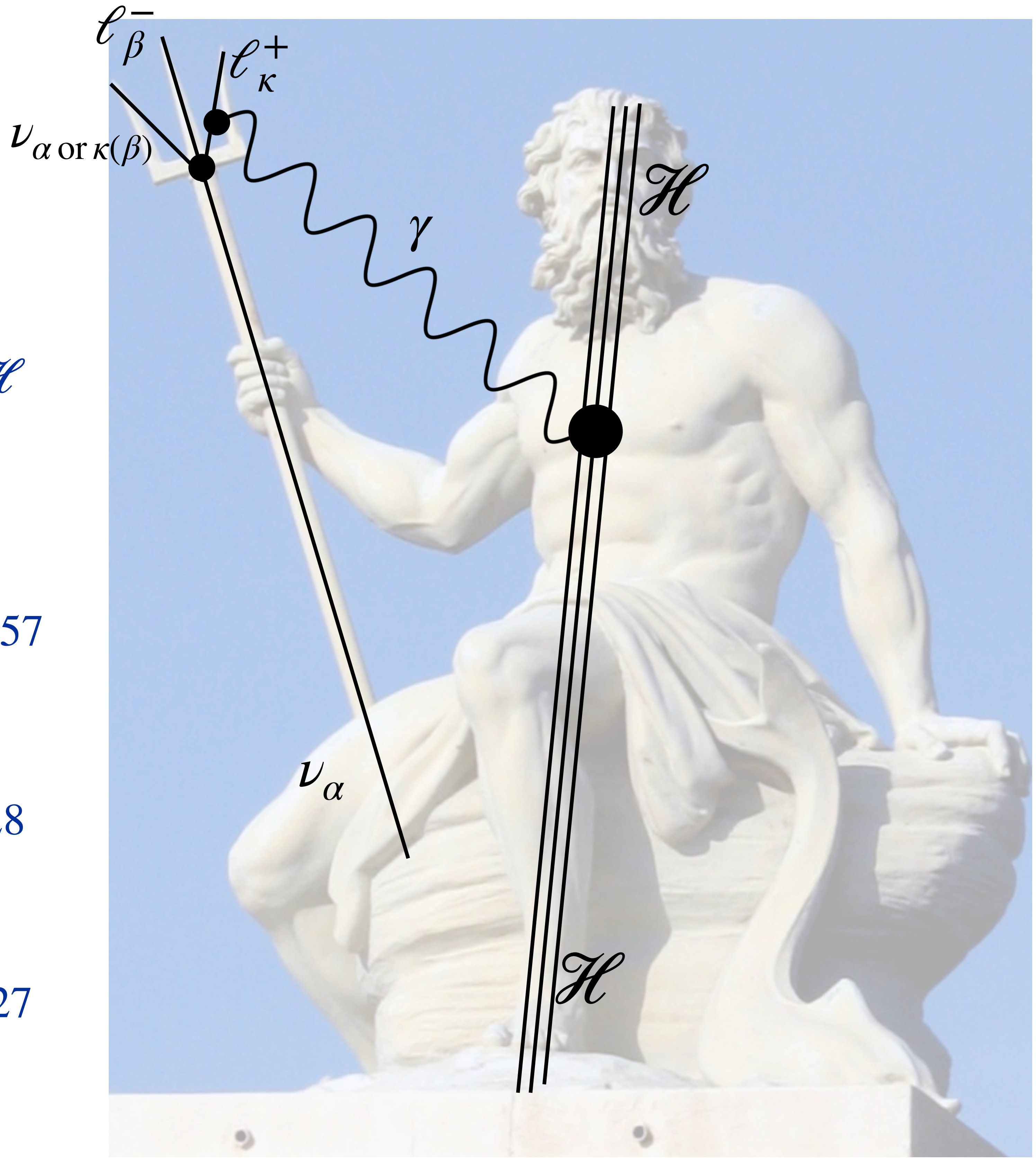
PRL 66 (1991) 3117

$$\frac{\sigma_{\text{CCFR}}}{\sigma_{\text{SM}}} = 0.82 \pm 0.28$$

NuTeV

Vancouver 1998, High energy physics, vol. 1

$$\frac{\sigma_{\text{NuTeV}}}{\sigma_{\text{SM}}} = 0.67 \pm 0.27$$



Trident Inelastic Scattering

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Z' constraints from trident

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Rates at DUNE ND

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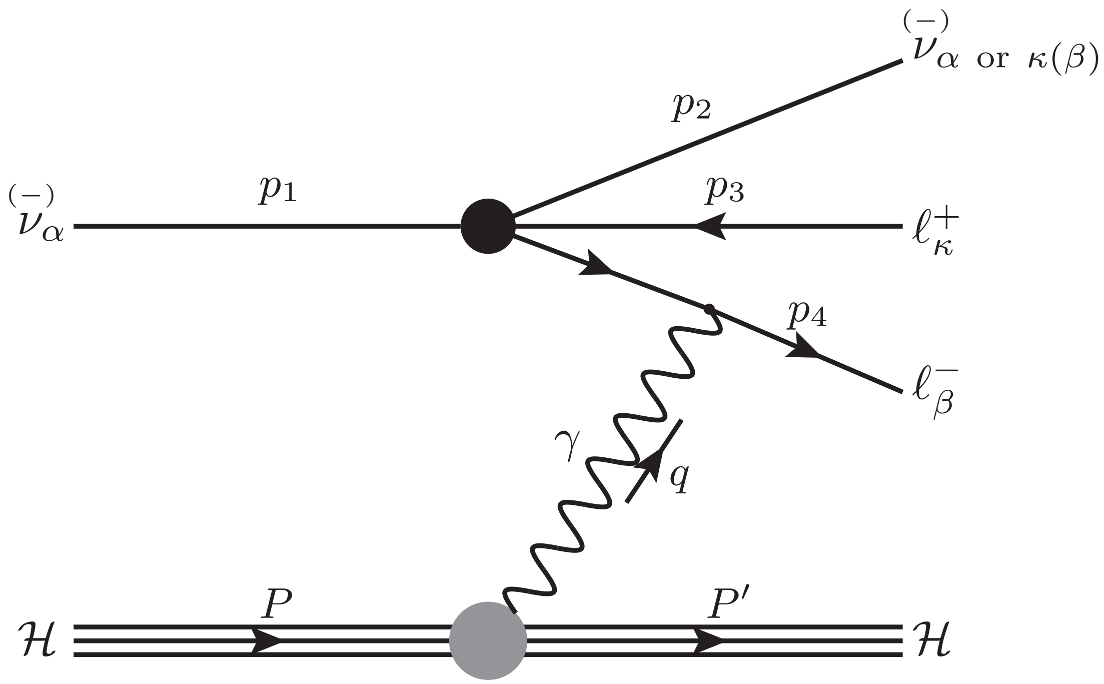
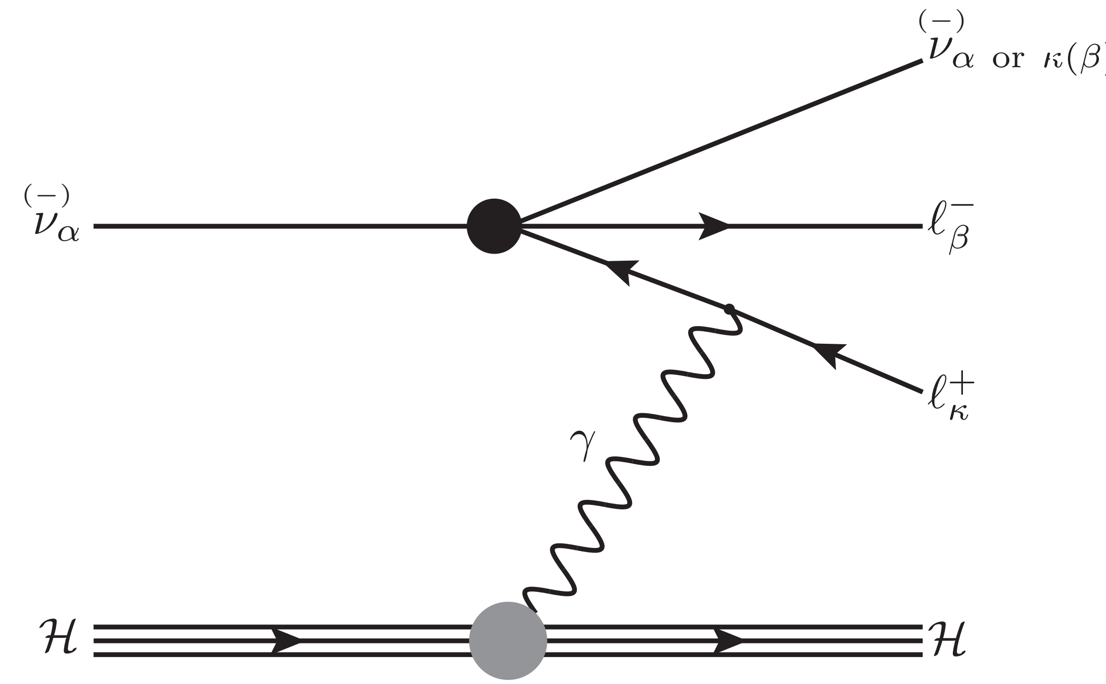
Equivalent Photon Approximation (EPA) → Overestimates the cross section in some cases by more than 200%.

Trident Cross Sections

$$\nu_\alpha(p_1) + \mathscr{H}(P) \to \nu_{\alpha\,\mathrm{or}\,\kappa(\beta)}(p_2) + \ell^-_\beta(p_4) + \ell^+_\kappa(p_3) + \mathscr{H}(P')$$





(Anti)Neutrino	SM Contributions
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_\mu \mu^- \mu^+ \mathcal{H}$	CC + NC
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_e e^\pm \mu^\mp \mathcal{H}$	CC
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_\mu e^- e^+ \mathcal{H}$	NC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_e e^- e^+ \mathcal{H}$	CC + NC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_\mu \mu^\pm e^\mp \mathcal{H}$	CC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_e \mu^- \mu^+ \mathcal{H}$	NC

→ Observed!

4-point limit

$$V_{\alpha\beta\kappa}(A_{\alpha\beta\kappa}) \equiv g_V^\beta(g_A^\beta)\delta_{\beta\kappa} + \delta_{\alpha\beta}$$

Interference between CC and NC

Trident Production

Differential cross sections

$$\frac{\mathrm{d}^2\sigma_{\nu \mathrm{X}}}{\mathrm{d}Q^2\mathrm{d}\hat{s}} = \frac{1}{32\pi^2(s - M_{\mathscr{H}}^2)^2}\frac{\mathrm{H}_{\mathrm{X}}^{\mu\nu}\ \mathrm{L}_{\mu\nu}}{Q^4}$$

Trident Production

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Momentum Transfer

$$s \equiv (p_1 + P)^2$$

Center-of-mass energy of the total system

$$\hat{s} \equiv (p_1 + q)^2$$

Center-of-mass energy of the neutrino-photon system

Trident Production

Differential cross sections

It depends on scattering regime ← Hadronic Tensor

$$\frac{d^2\sigma_{\nu X}}{dQ^2 d\hat{s}} = \frac{1}{32\pi^2(s - M_{\mathscr{H}}^2)^2} \frac{H_X^{\mu\nu} L_{\mu\nu}}{Q^4}$$

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Center-of-mass energy of the neutrino-photon system

We can separate photon contributions

$$\frac{d^2\sigma_{\nu X}}{dQ^2 d\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}\,Q^2}\left[h_X^T(Q^2,\hat{s})\,\sigma_{\nu\gamma}^T(Q^2,\hat{s}) + h_X^L(Q^2,\hat{s})\,\sigma_{\nu\gamma}^L(Q^2,\hat{s})\right]$$

Transversal Longitudinal

Scattering Regimes

Coherent

Scattering Regimes

Coherent

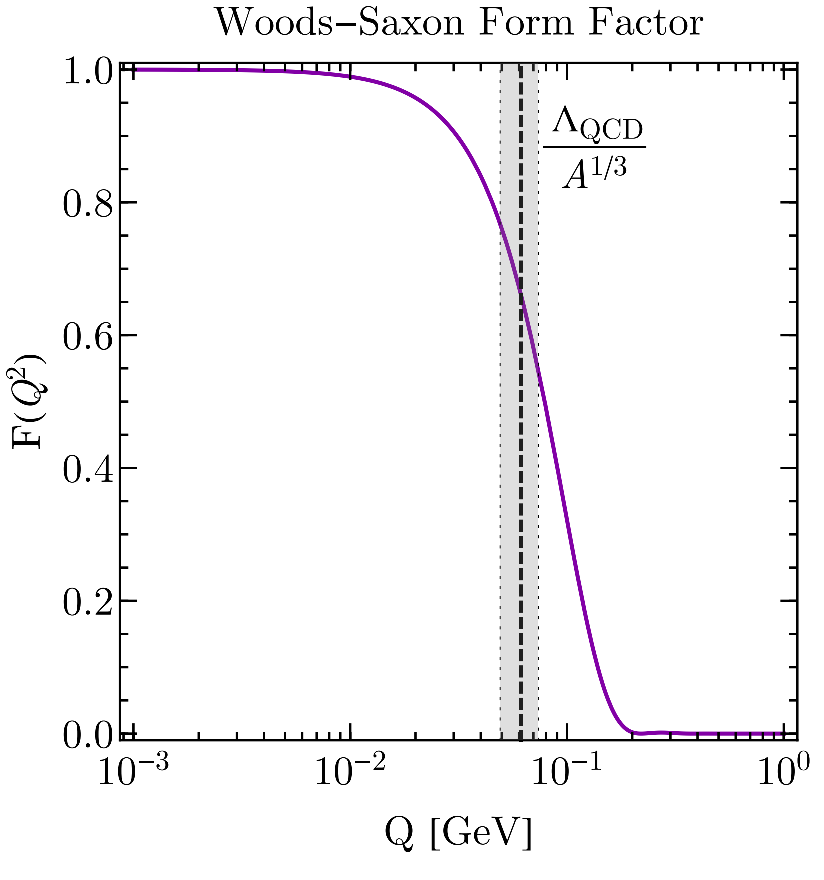
$$\mathrm{H}_{\mathrm{c}}^{\mu\nu} = 4Z^2 e^2 \left| F(Q^2) \right|^2 \left(P^\mu - \frac{q^\mu}{2} \right) \left(P^\nu - \frac{q^\nu}{2} \right)$$

Scattering Regimes

Coherent

$$H_c^{\mu\nu} = 4Z^2e^2\left|F(Q^2)\right|^2\left(P^\mu - \frac{q^\mu}{2}\right)\left(P^\nu - \frac{q^\nu}{2}\right)$$

Cut on Q



Scattering Regimes

CC • CC+NC • NC

Coherent

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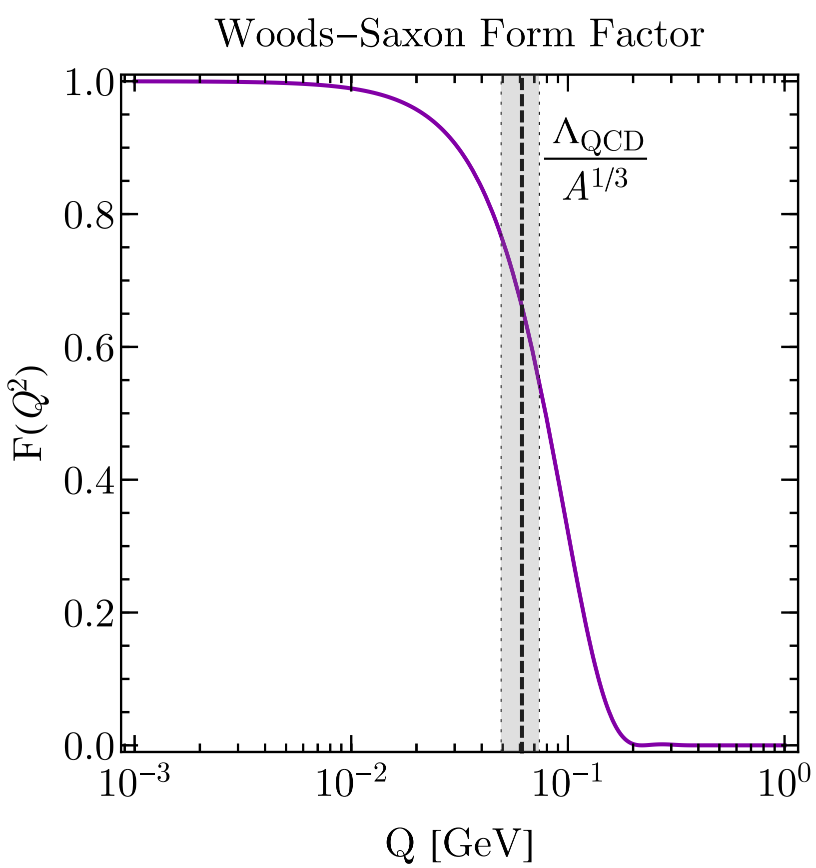
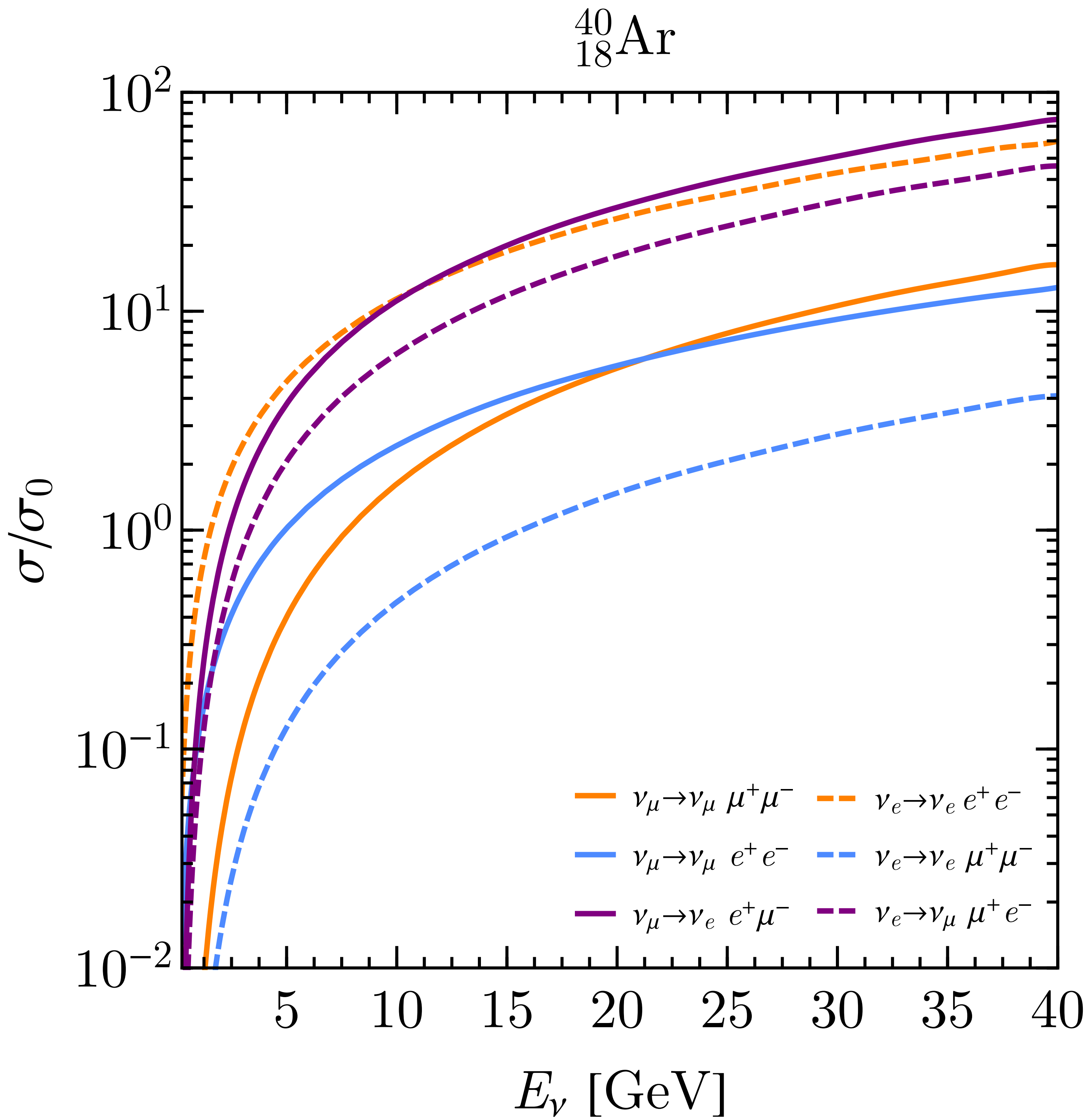




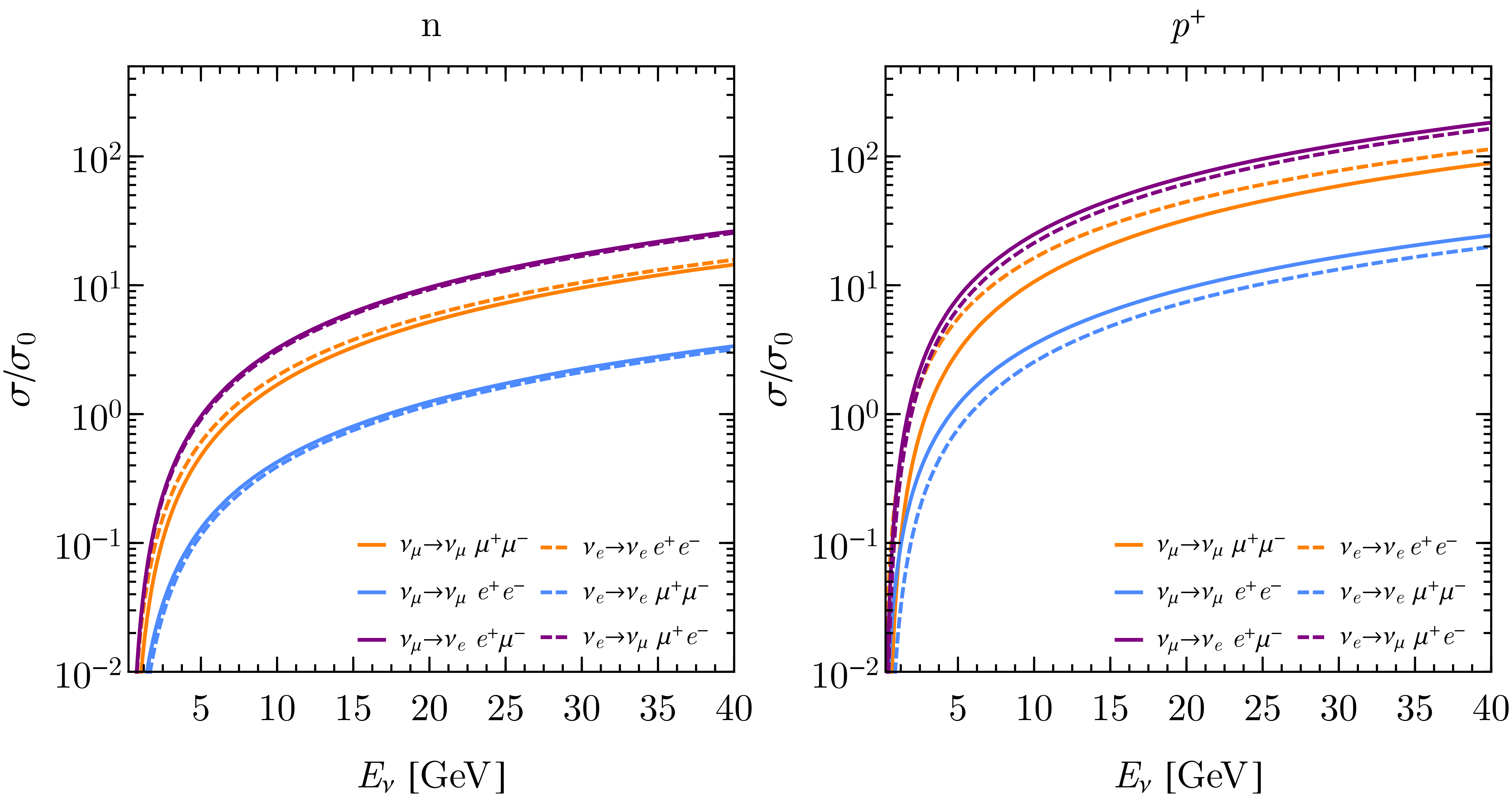
$\sigma_0 = Z^2 \cdot 10^{-44}\ \mathrm{cm}^2$

Scattering Regimes

Diffractive

$$\frac{d^2\sigma_{\nu d}}{dQ^2 d\hat{s}} \to f(|\vec{q}|)\frac{d^2\sigma_{\nu d}}{dQ^2 d\hat{s}}$$

$$H_d^{\mu\nu}(P,P') = Z\,H_p^{\mu\nu}(P,P') + (A-Z)\,H_n^{\mu\nu}(P,P')$$



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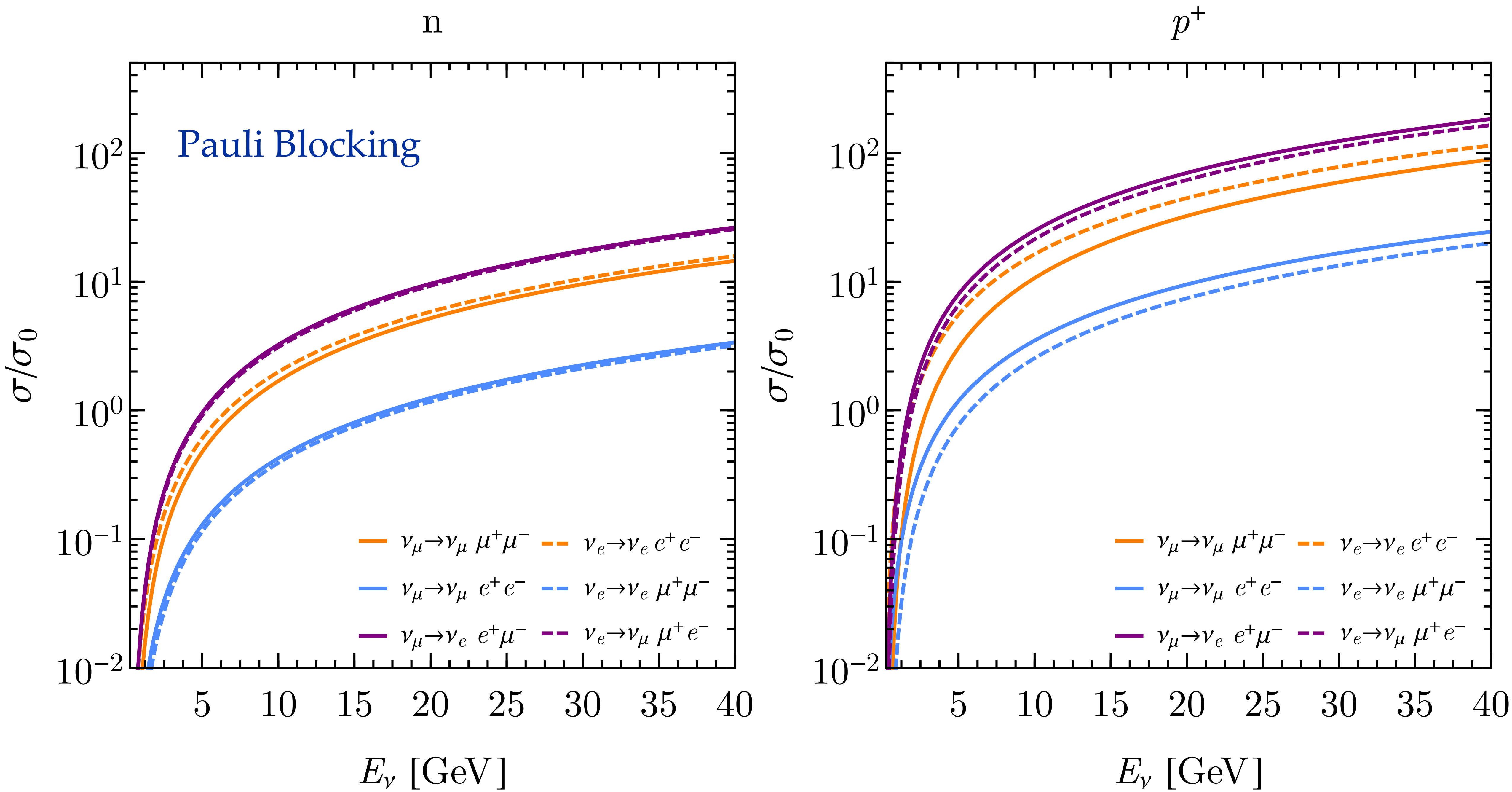

Equivalent Photon Approximation (EPA)

Can we obtain an approximate cross section?

Fermi, 1924
Weizsacker, Williams, 1934

EPA

$$\sigma_{\rm t}(P_i + C_s \to P_f + C_s) \approx \int dP(Q^2, \hat{s})\, \sigma_\gamma(P_i + \gamma \to P_f; \hat{s}, Q^2 = 0)$$

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Energy spectrum of
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Incoming particle with a real photon

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Incoming particle with a real photon

Assumptions

- ✴ Longitudinal contribution can be neglected $\sigma^{\mathrm{L}}_{\nu\gamma}(Q^2, \hat{s}) \approx 0$
- ✴ Transverse contribution can be taken as on-shell $\sigma^{\mathrm{T}}_{\nu\gamma}(Q^2, \hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0,\hat{s})$

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Trident case

$$\sigma_{\rm EPA} = \int_{m_L^2}^{\hat{s}_{\rm max}} \int_{(\hat{s}/2E_\nu)^2}^{Q^2_{\rm max}} \sigma^{T}_{\nu\gamma}(0,\hat{s})\, dP(Q^2, \hat{s})$$

Photon spectrum

$$dP(Q^2, \hat{s}) = \frac{Z^2 e^2}{4\pi^2} |F(Q^2)|^2 \frac{d\hat{s}}{\hat{s}} \frac{dQ^2}{Q^2}$$

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Kinematical Limits

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Does it work?

EPA

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QED

Fermi Limit of the SM

EPA

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QED

$$\sigma_\gamma^{\rm QED}(P_i + \gamma \to P_f; \hat{s}, 0) \propto \frac{1}{\hat{s}}$$

Decreases with increasing transferred four-momentum

On-shell >> off-shell

Fermi Limit of the SM

EPA

Does it work?

$$\sigma_t(P_i + C_s \to P_f + C_s) \approx \int dP(Q^2, \hat{s})\, \sigma_\gamma(P_i + \gamma \to P_f; \hat{s}, Q^2 = 0)$$

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Fermi Limit of the SM

$$\sigma_\gamma^{\mathrm{FL}}(P_i + \gamma \to P_f; \hat{s}, 0) \propto G_{\mathrm{F}}^2\, \hat{s}$$

Increases with increasing transferred four-momentum

On-shell << off-shell

EPA

Does it work?

$$\sigma_{\rm t}(P_i + C_s \to P_f + C_s) \approx \int dP(Q^2, \hat{s})\, \sigma_\gamma(P_i + \gamma \to P_f; \hat{s}, Q^2 = 0)$$

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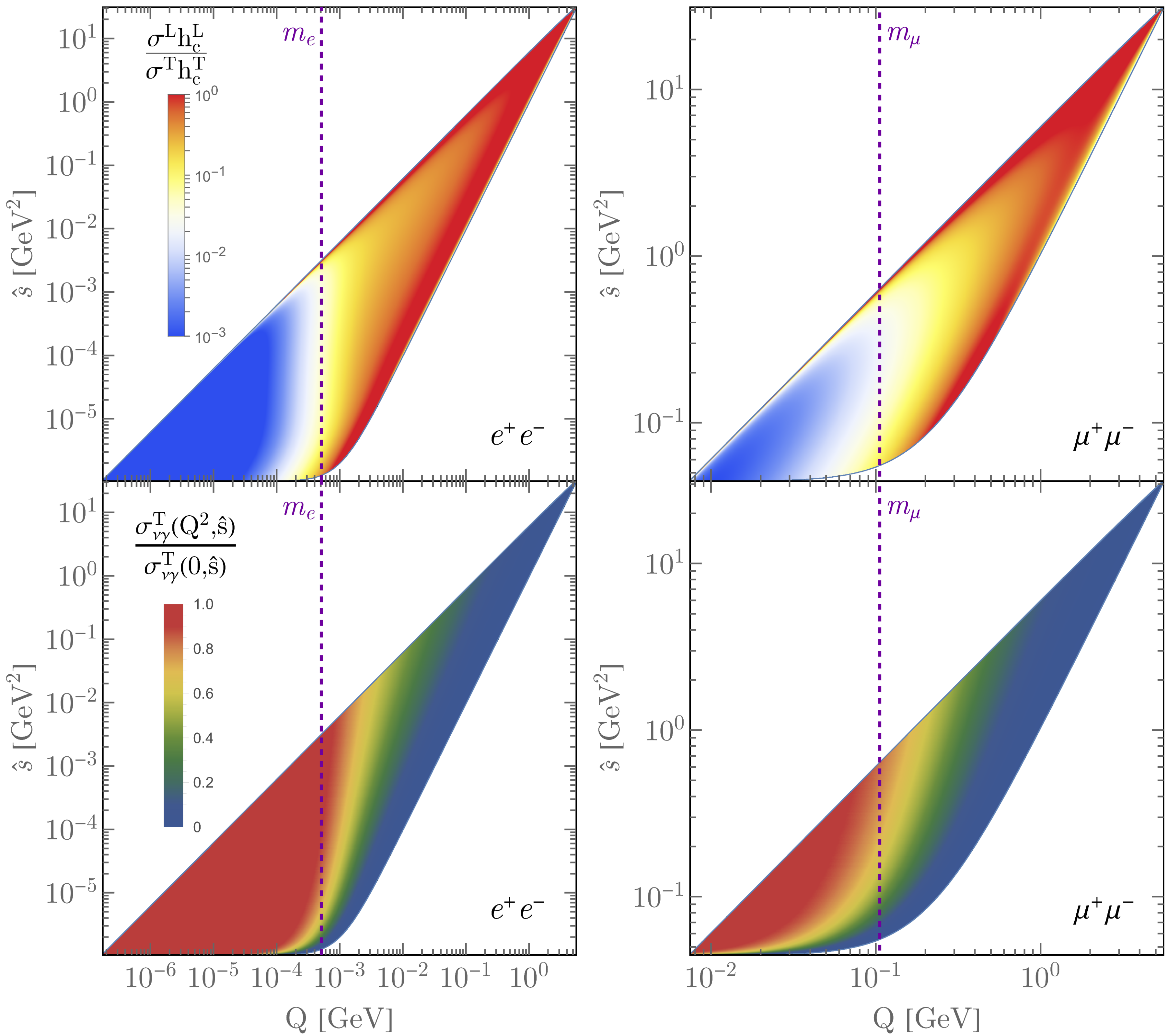

Kinematically allowed region

$E_\nu = 3$ GeV

EPA

EPA not valid for trident, right?

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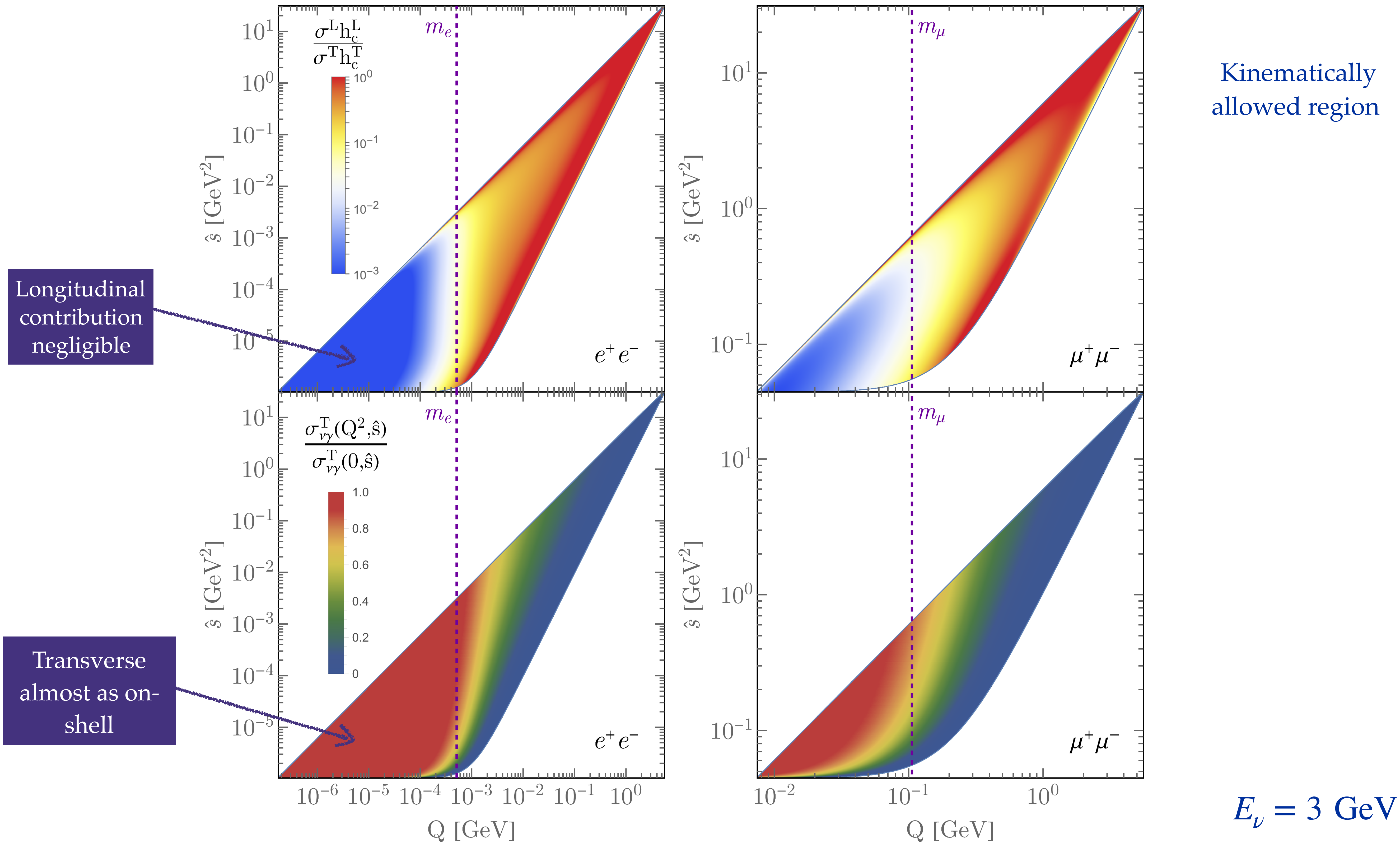


EPA

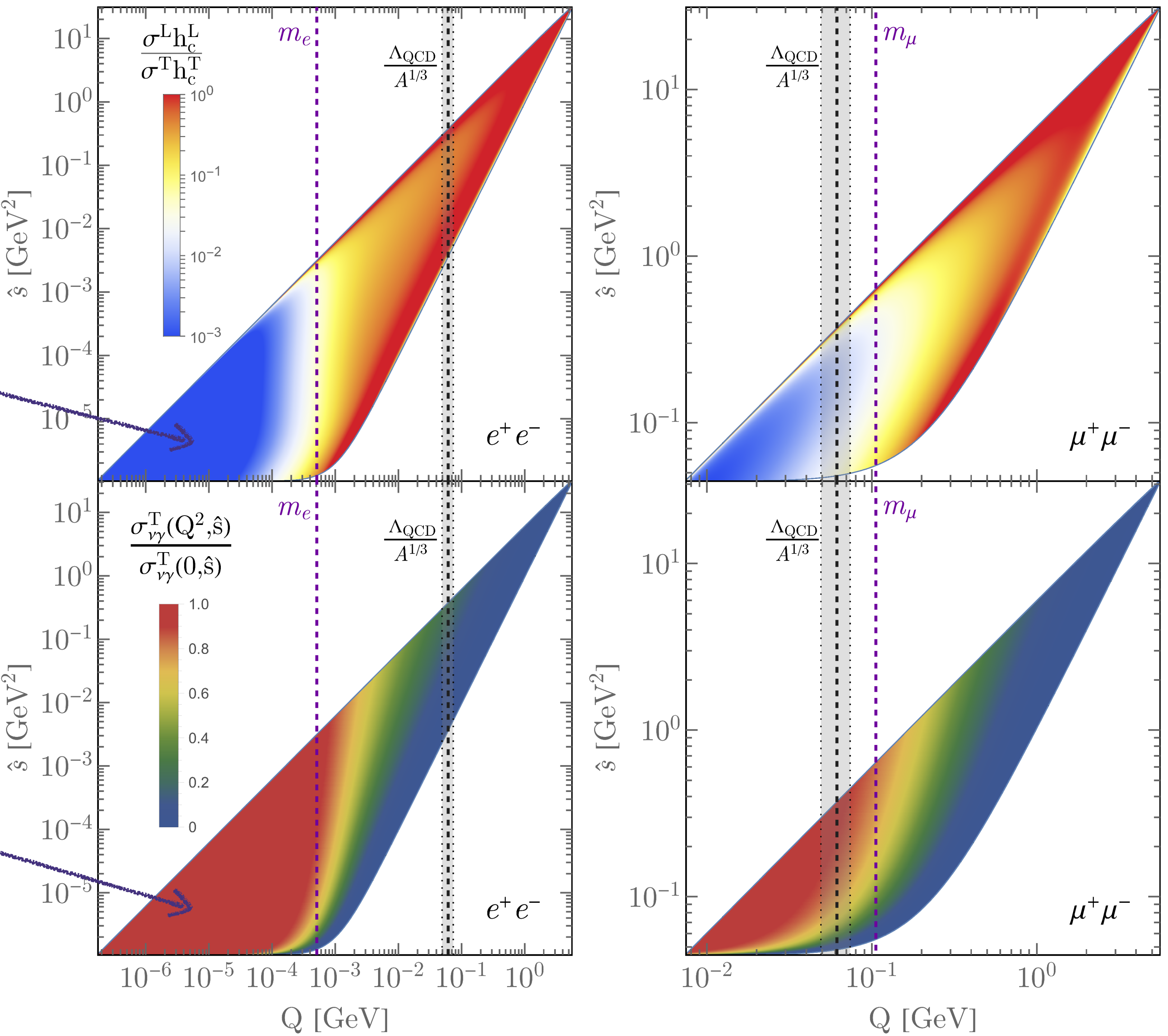
EPA not valid for trident, right?

Physical cutoff on the momentum integration

$\frac{\sigma^{T}_{\nu\gamma}(Q^2,\hat{s})}{\sigma^{T}_{\nu\gamma}(0,\hat{s})}$ $\frac{\sigma^{L}(Q^2,\hat{s})\,h^{L}_{c}(Q^2,\hat{s})}{\sigma^{T}(Q^2,\hat{s})\,h^{T}_{c}(Q^2,\hat{s})}$

Kinematically allowed region

Longitudinal contribution negligible



Transverse almost as on-shell

Form factor cuts the Q integration in a region which EPA works reasonably

$E_\nu = 3$ GeV

EPA

EPA not valid for trident, right?

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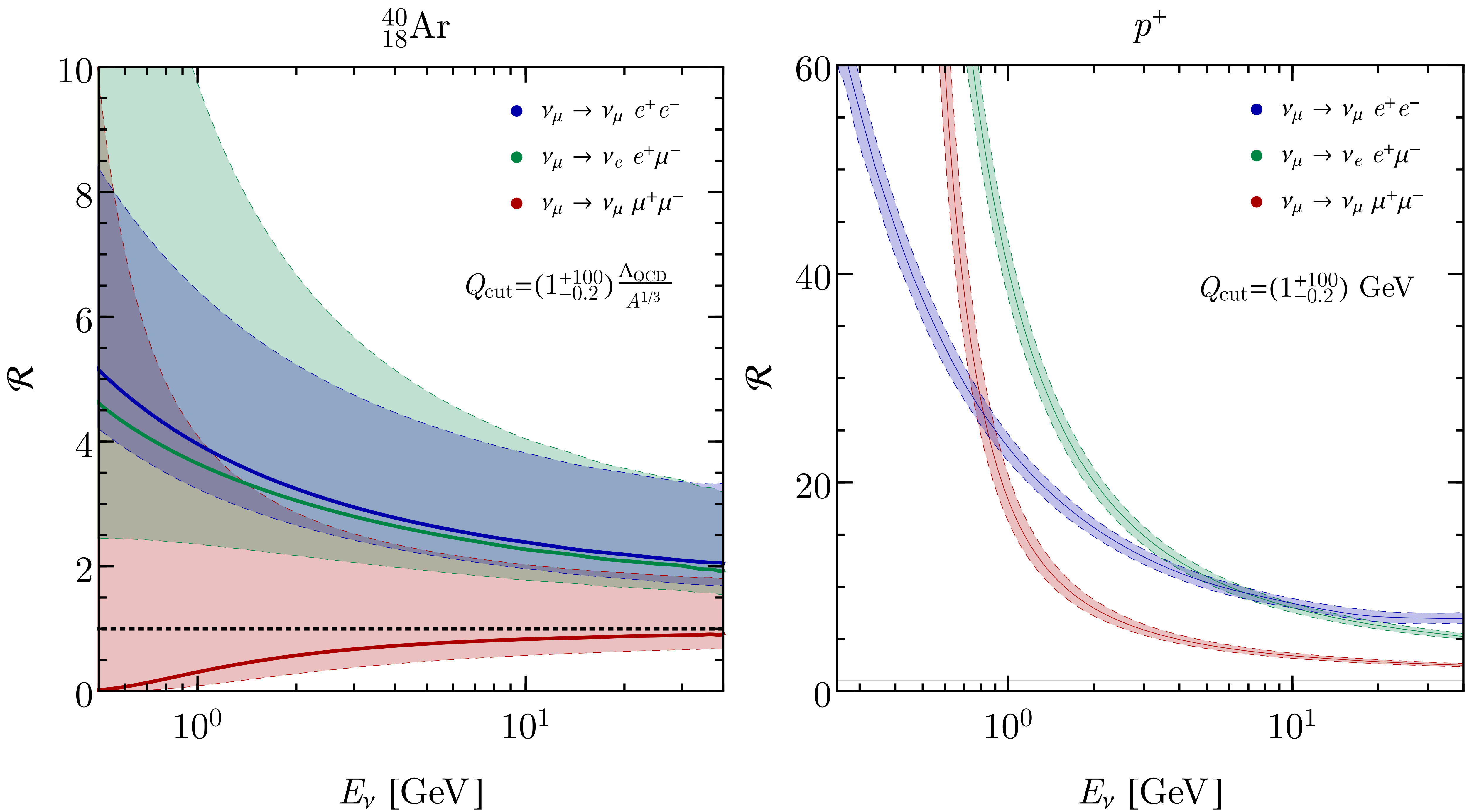
EPA not valid for trident, right?

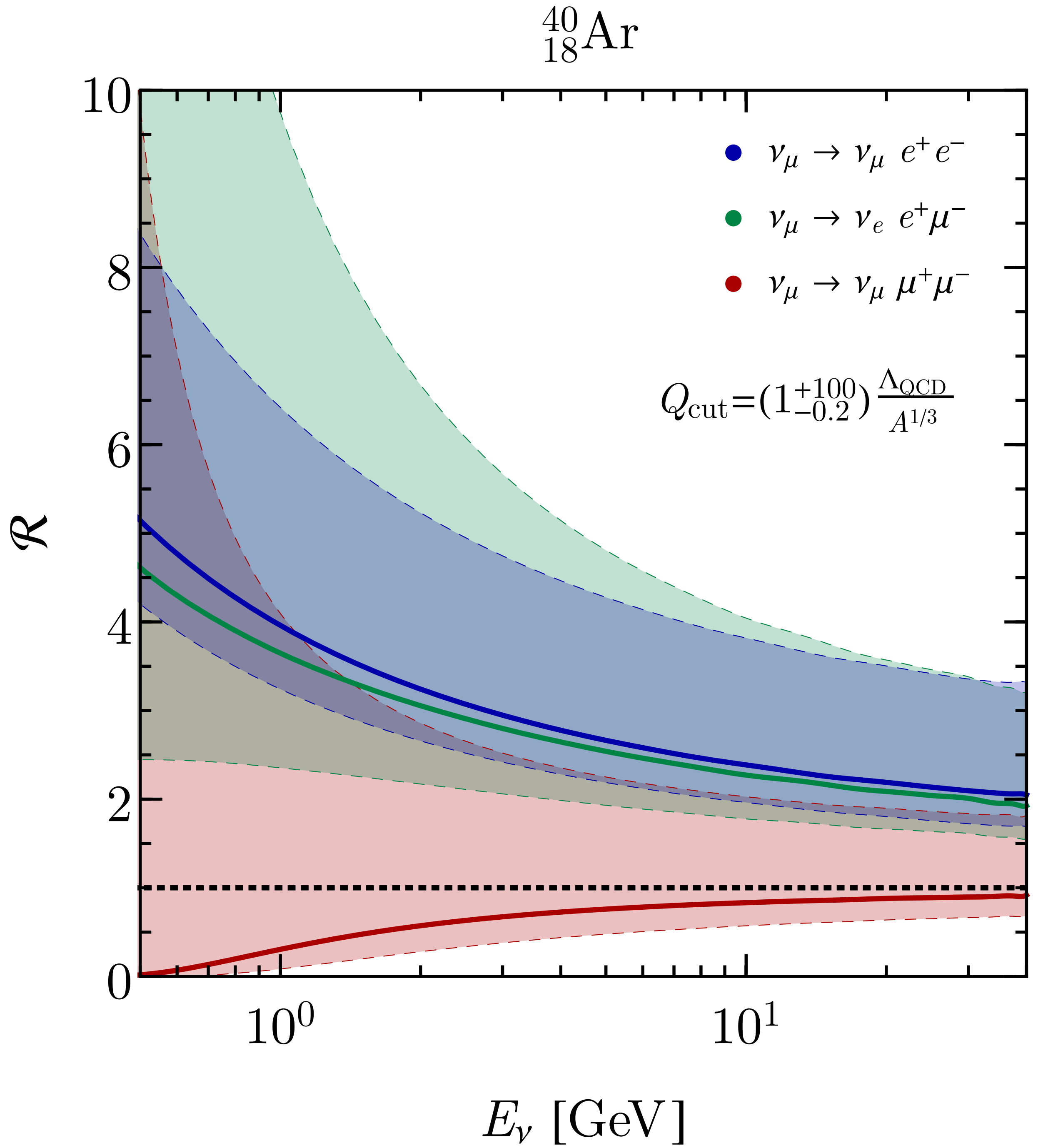
$$\mathcal{R} = \frac{\sigma_{\rm EPA}(E_\nu)|_{Q_{\rm cut}}}{\sigma_{\rm 4PS}(E_\nu)}$$

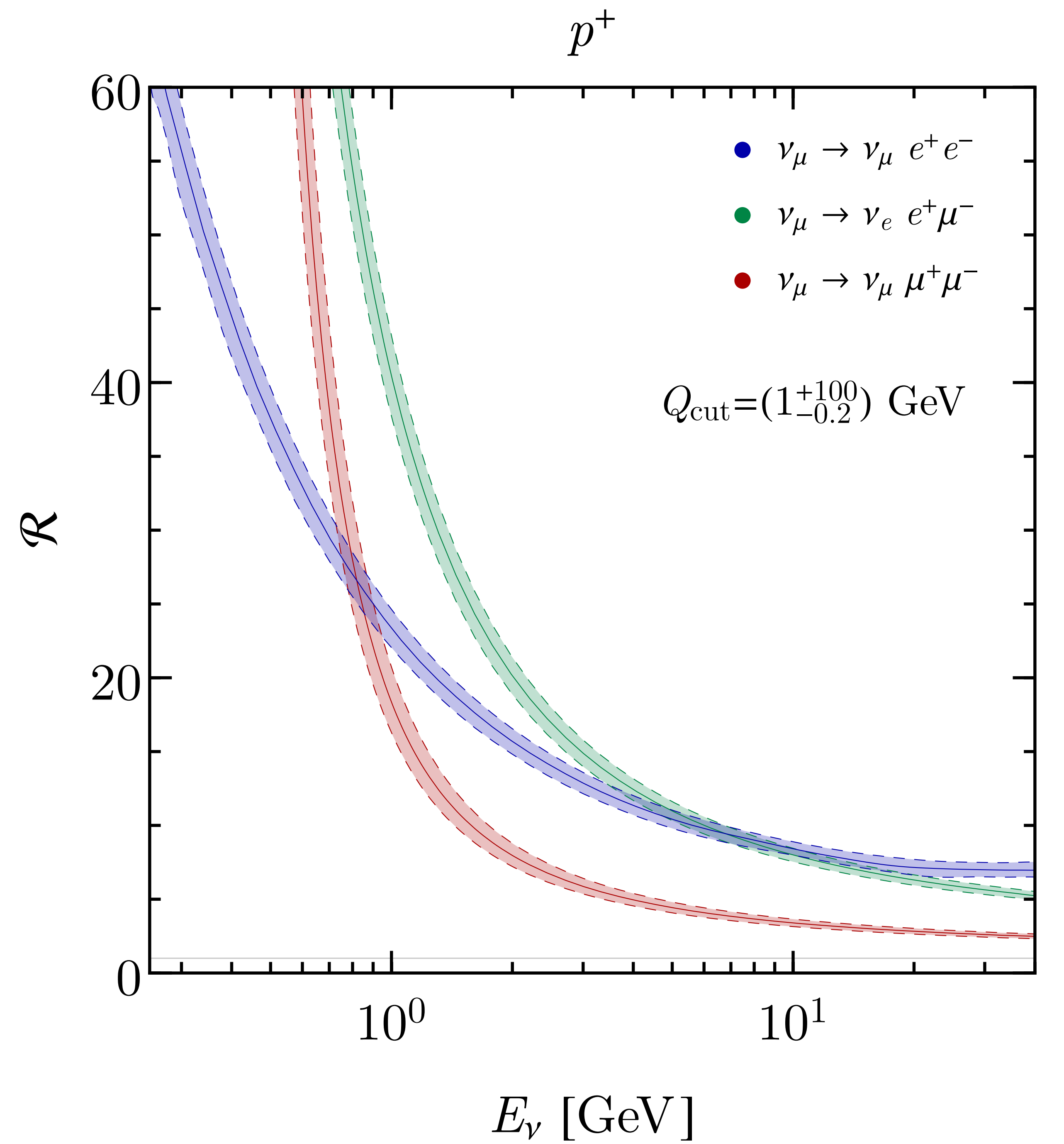


EPA

EPA not valid for trident, right? Yes.

$$\mathscr{R} = \frac{\sigma_{\rm EPA}(E_\nu)|_{Q_{\rm cut}}}{\sigma_{\rm 4PS}(E_\nu)}$$





Compute the full 4PS cross sections

Events in LAr Detectors

Rates

$$N_{\mathrm{X}}^{\psi} = \mathrm{Norm} \times \int dE_\nu \, \sigma_{\nu \mathrm{X}}(E_\nu) \frac{d\phi_\nu(E_\nu)}{dE_\nu} \epsilon(E_\nu)$$

Rates

$$N_X^{\psi} = \text{Norm} \times \int dE_\nu \, \sigma_{\nu X}(E_\nu) \frac{d\phi_\nu(E_\nu)}{dE_\nu} \epsilon(E_\nu)$$

$$\text{Exposure [POT]} \times \frac{\text{Fiducial Detector Mass} \times \text{N}_\text{A}}{m_\text{T}} \left[\text{target particles}\right]$$

Assuming 100% efficiency

Rates

$$N_X^{\psi} = \text{Norm} \times \int dE_\nu \, \sigma_{\nu X}(E_\nu) \frac{d\phi_\nu(E_\nu)}{dE_\nu} \epsilon(E_\nu)$$

$$\text{Exposure [POT]} \times \frac{\text{Fiducial Detector Mass} \times \text{N}_\text{A}}{m_\text{T}} \left[\text{target particles}\right]$$

Assuming 100% efficiency

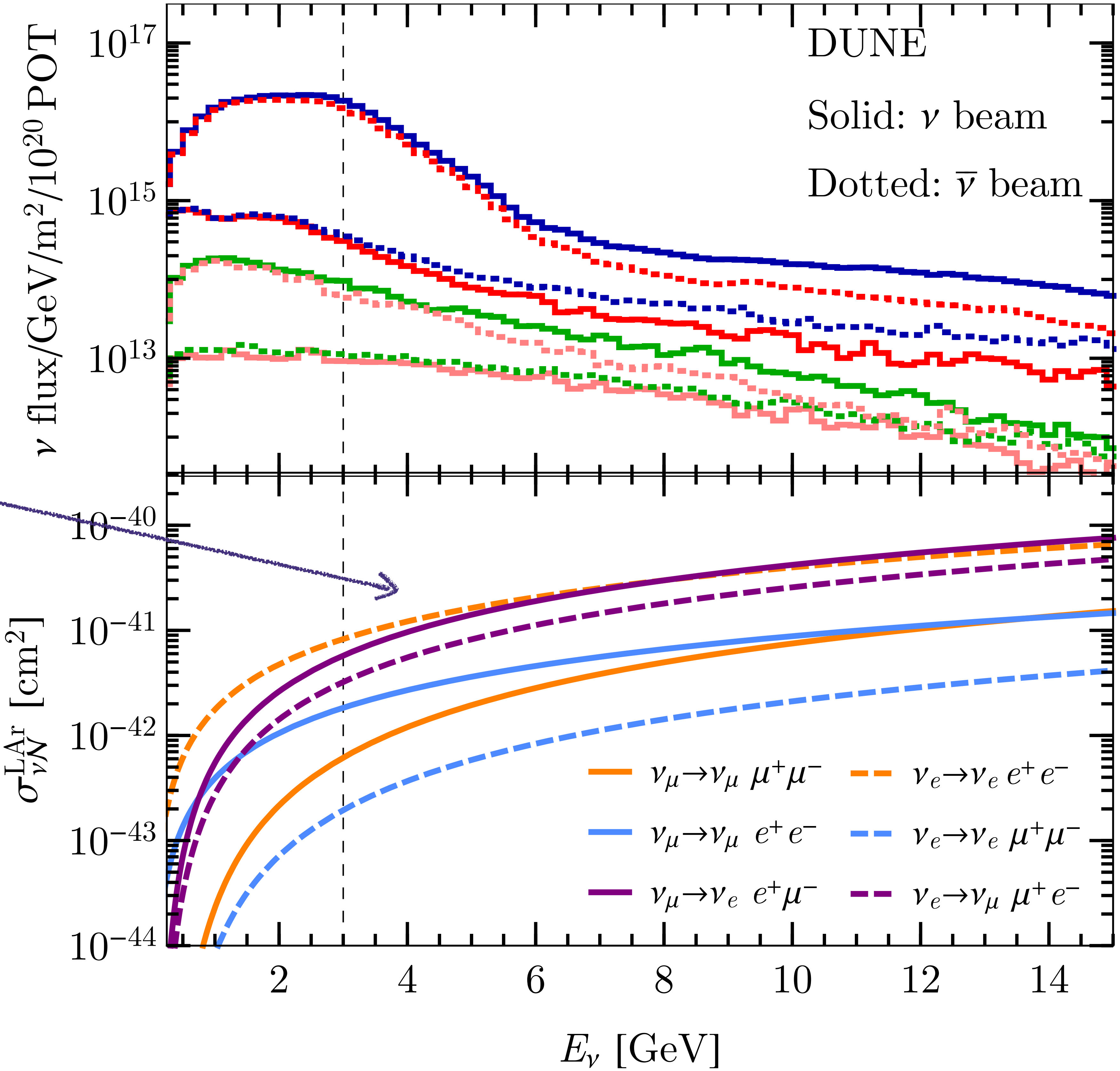
Experiment	Baseline (m)	Total Exposure (POT)	Fiducial Mass (t)	E_ν (GeV)
SBND	110	6.6×10^{20}	112	$0-3$
μBooNE	470	1.32×10^{21}	89	$0-3$
ICARUS	600	6.6×10^{20}	476	$0-3$
DUNE	**574**	$12.81\ (12.81) \times 10^{21}$	**50**	$0-40$
νSTORM	50	10^{21}	100	$0-6$

ν mode $\bar{\nu}$ mode

$$\text{Exposure} = 1.83 \times (3 + 2 \times 2) \times 10^{21}\ \text{POT}$$

Rates

Higher cross sections at DUNE ND



Rates

Exposure $= 1.83 \times (3 + 2 \times 2) \times 10^{21}$ POT

Channel	SBND	μBooNE	ICARUS	DUNE ND	νSTORM ND
Total $e^{\pm}\mu^{\mp}$	10	0.7	1	2993 (2307)	191
	1	0.1	0.1	391 (299)	23
Total $e^{+}e^{-}$	6	0.4	0.7	1007 (800)	114
	0.2	0.0	0.02	64 (49)	6
Total $\mu^{+}\mu^{-}$	0.4	0.0	0.0	286 (210)	11
	0.3	0.0	0.0	143 (108)	6

Not seen yet (Total $e^{\pm}\mu^{\mp}$)

Not seen yet (Total $e^{+}e^{-}$)

Coherent

Diffractive

Large contributions of diffractive events

Compare order of magnitudes

ν mode

$\bar{\nu}$ mode

Kinematical Distributions

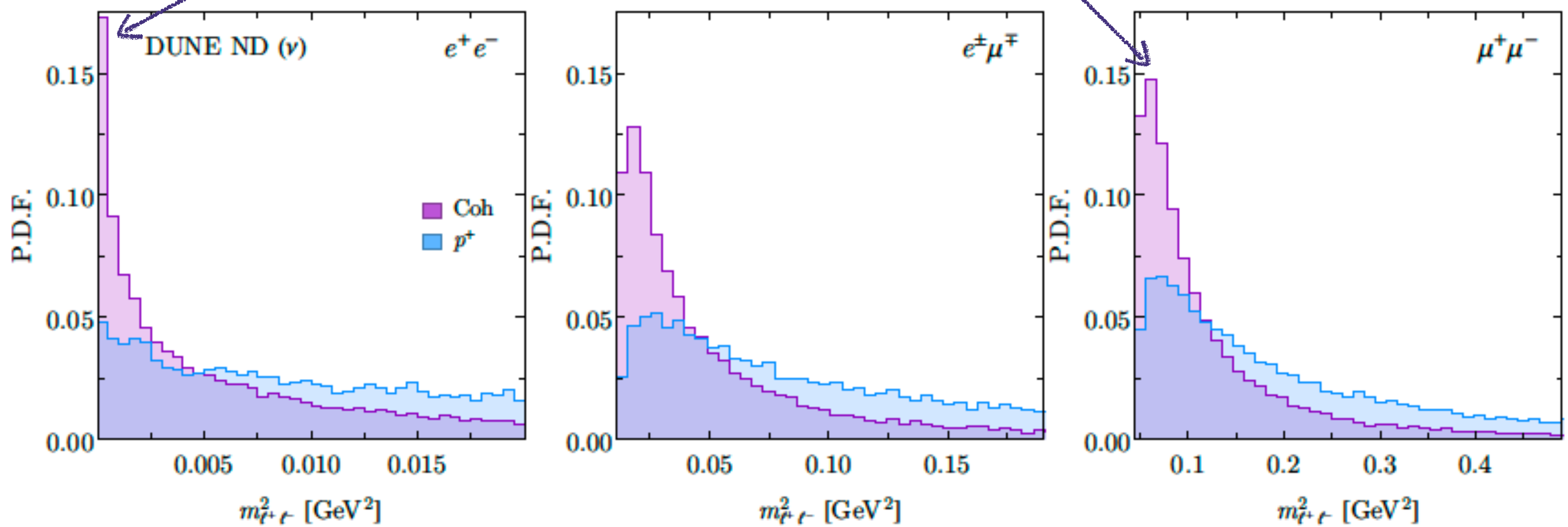
EPA gives also misleading distributions

Invariant charged lepton masses $m^2_{\ell^+\ell^-}$

Tool for background suppression

Small values

Peaked distributions

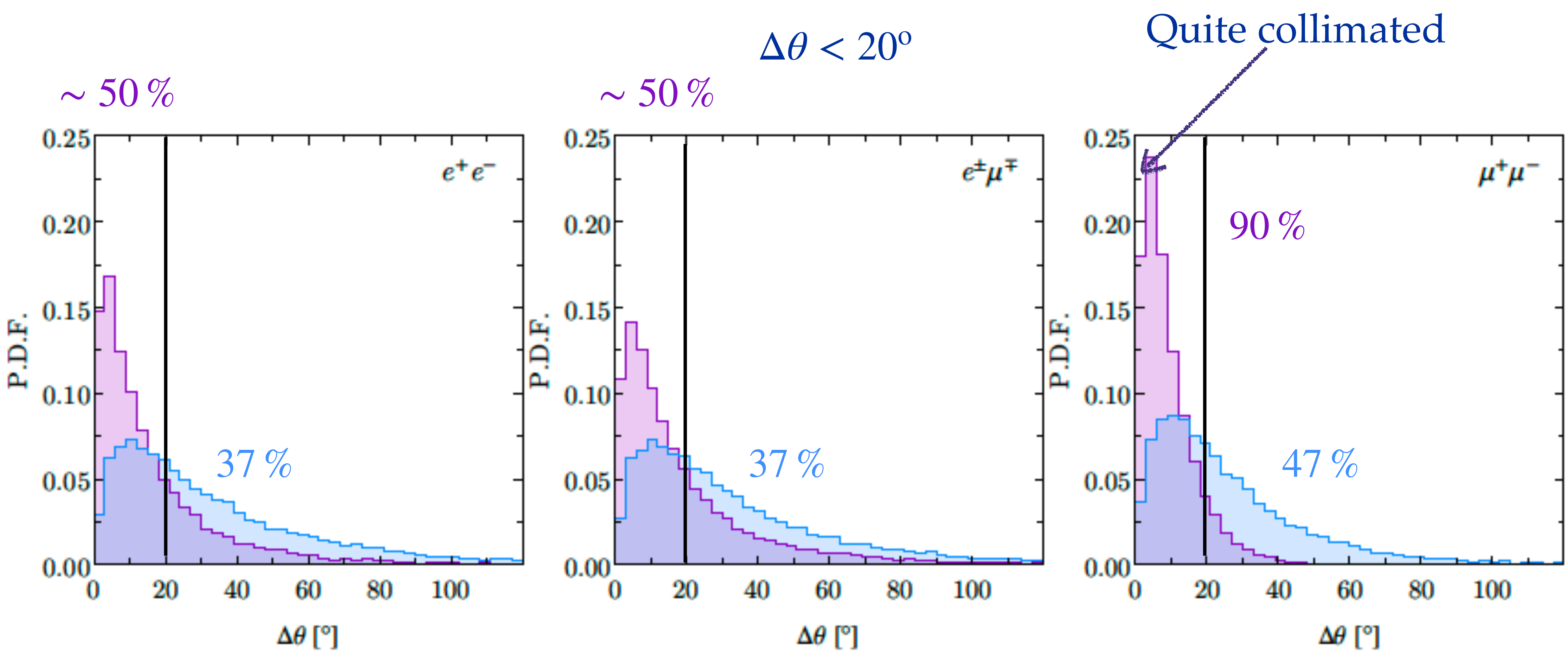


Flux integrated distributions

All channels with same final states

Kinematical Distributions

Separation angle $\Delta\theta$



Flux integrated distributions

All channels with same final states

Backgrounds?

Goal: Reach suppressions of order $\mathcal{O}(10^{-6} - 10^{-5})$

- misID $\mu^+\mu^- \longrightarrow \nu_\mu CC1\pi^\pm$

  $e^+e^- \longrightarrow NC\pi^0$

  $e^\pm\mu^\mp \longrightarrow CC\pi^0$

  $CC\gamma \quad \nu_e CC\pi^\pm$

misID	Rate
γ as $e^\pm$	0.05
γ as e^+e^-	0.1 (w/ vertex) 1 (no vertex + overlapping)
$\pi^\pm$ as $\mu^\pm$	0.1

A more careful analysis is needed

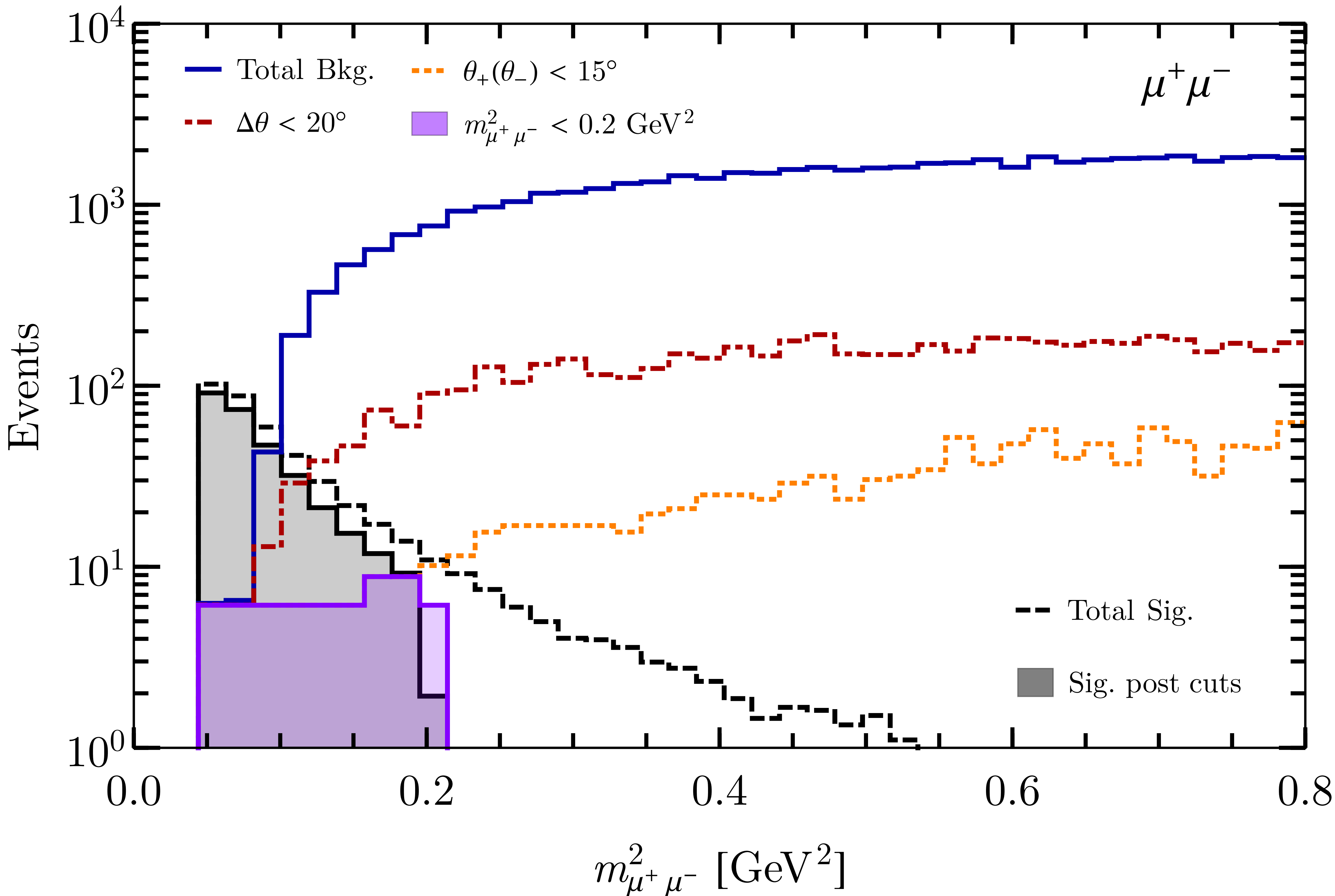
- No hadronic activity
- $m^2_{\mu^+\mu^-} < 0.2\ \text{GeV}^2, \Delta\theta < 20^\circ, \theta_\pm < 15^\circ$

Channel	N_B^{misID}/N_{CC}	N_B^{had}/N_{CC}	N_B^{kin}/N_{CC}	ϵ_{sig}^{coh}	ϵ_{sig}^{dif} [11]
$e^\pm\mu^\mp$	$1.67\ (1.62) \times 10^{-4}$	$2.68\ (4.31) \times 10^{-5}$	$4.40\ (3.17) \times 10^{-7}$	0.61 (0.61)	0.39 (0.39)
e^+e^-	$2.83\ (4.19) \times 10^{-4}$	$1.30\ (2.41) \times 10^{-4}$	$6.54\ (14.1) \times 10^{-6}$	0.48 (0.47)	0.21 (0.21)
$\mu^+\mu^-$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$	0.66 (0.67)	0.17 (0.16)

misID — Hadronic veto — Kinematic cuts

Efficiencies after cuts

Backgrounds?



GENIE simulation

Conclusions

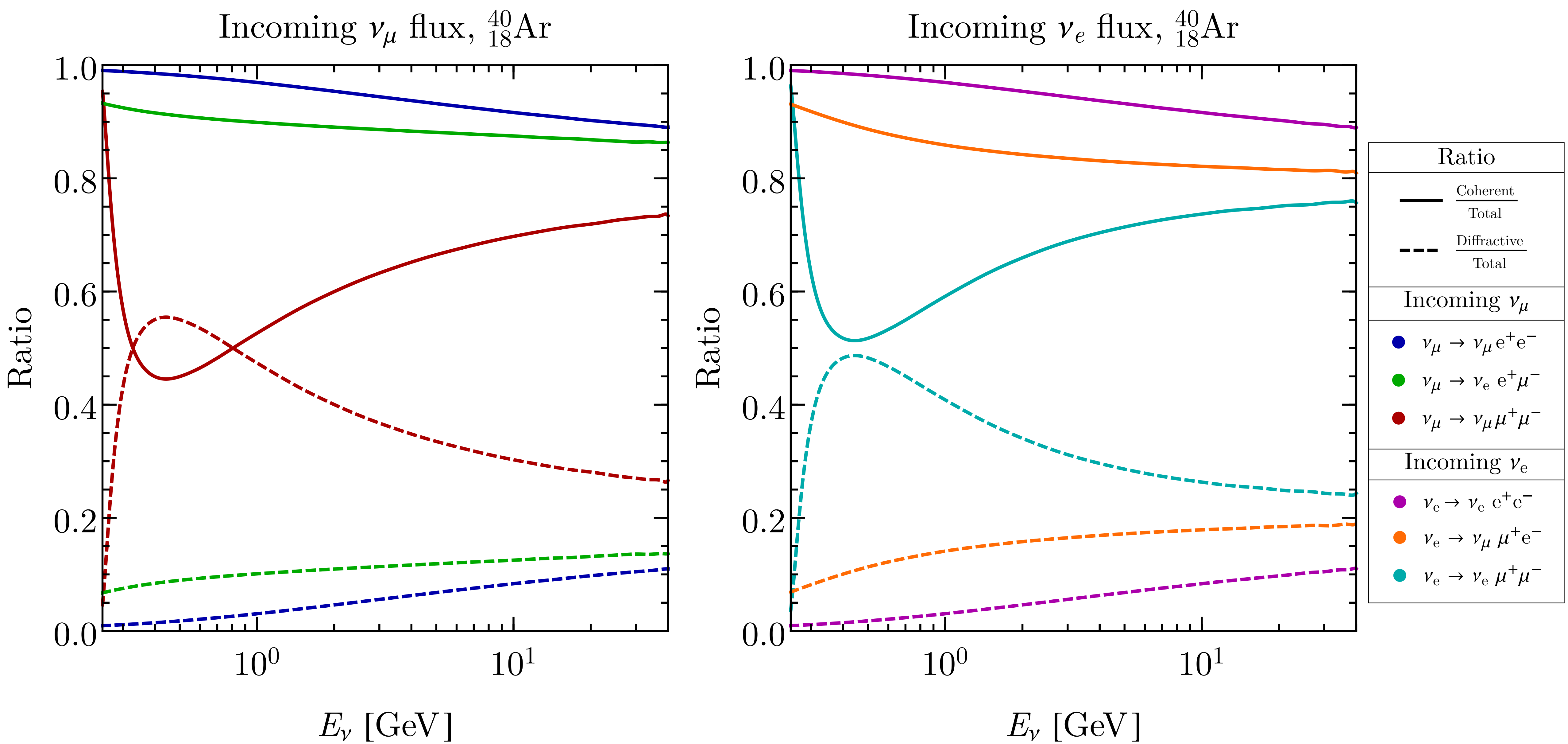
- A full 4PS computation is required to obtain correct estimates for the number of events.
- Let us stress that the EPA gives a reasonable result for the dimuon channel due to a serendipitous behavior of the Form Factor.
- EPA can artificially suppress the coherent scattering contribution and increase the diffractive one giving rise to an incorrect rate and distributions of observable quantities.
- We have estimated the background for each trident channel via a Monte Carlo simulation using GENIE, and identified the dominant contributions arising primarily from particle misidentification.
- Reduction of ~6 orders of magnitude x CC in the background is necessary to observe trident events at DUNE ND. A more careful analysis is needed.

Thank you!

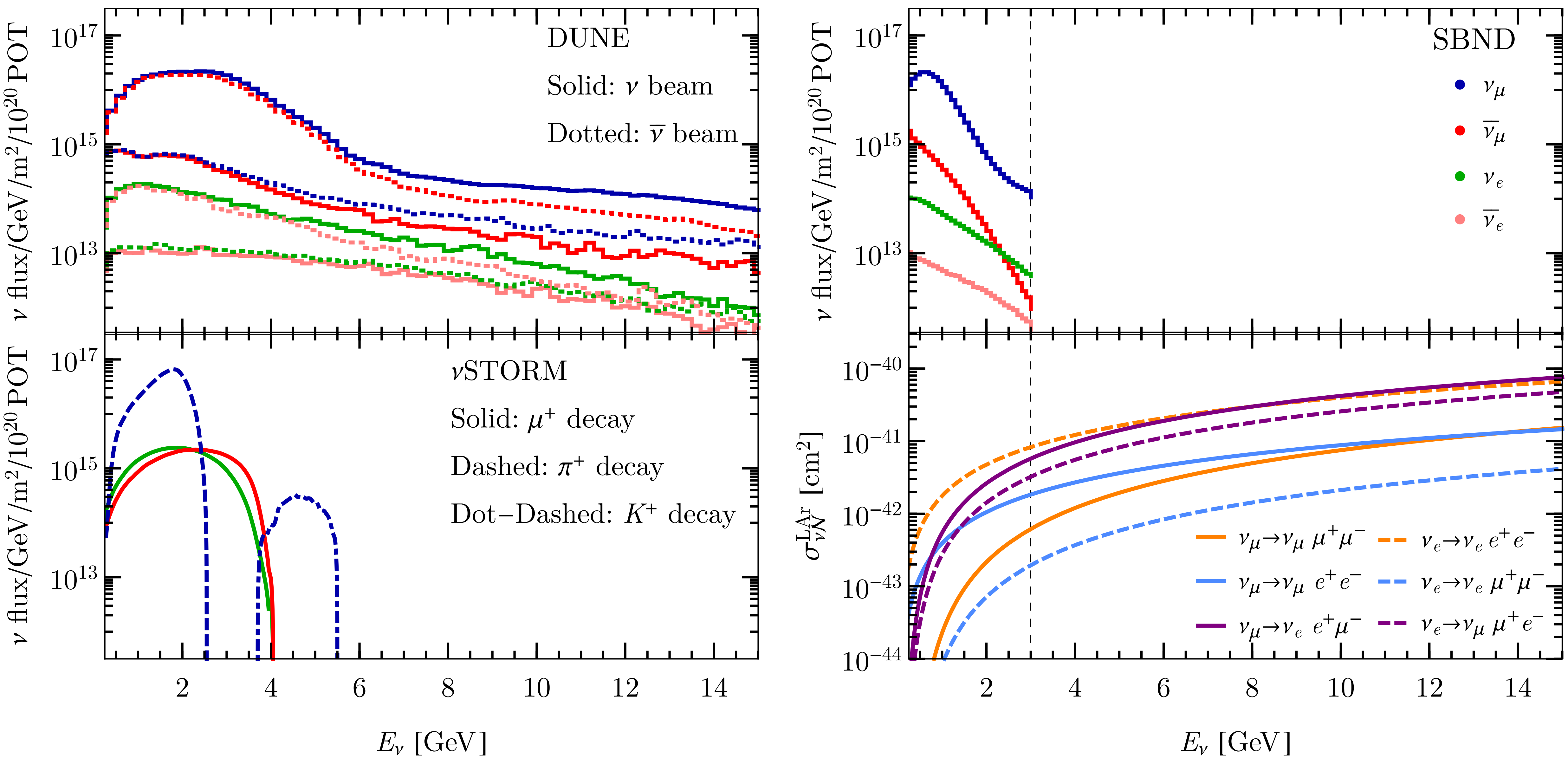
Backup

Coherent vs Diffractive

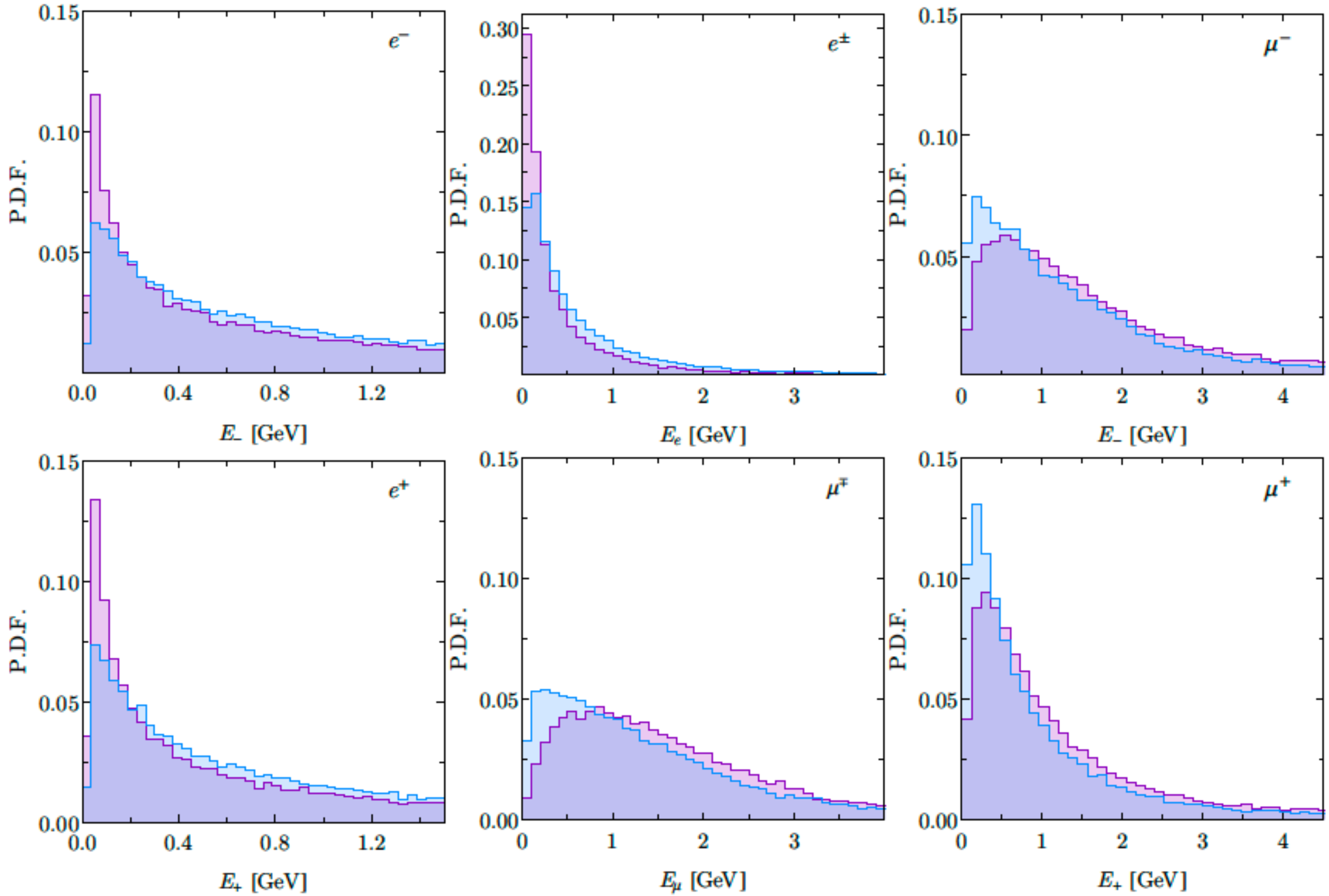
$$\sigma_{\nu\mathcal{N}} = \sigma_{\nu c} + \sigma_{\nu d} \qquad \frac{\sigma_{\nu c}}{\sigma_{\nu\mathcal{N}}} \qquad \frac{\sigma_{\nu d}}{\sigma_{\nu\mathcal{N}}}$$



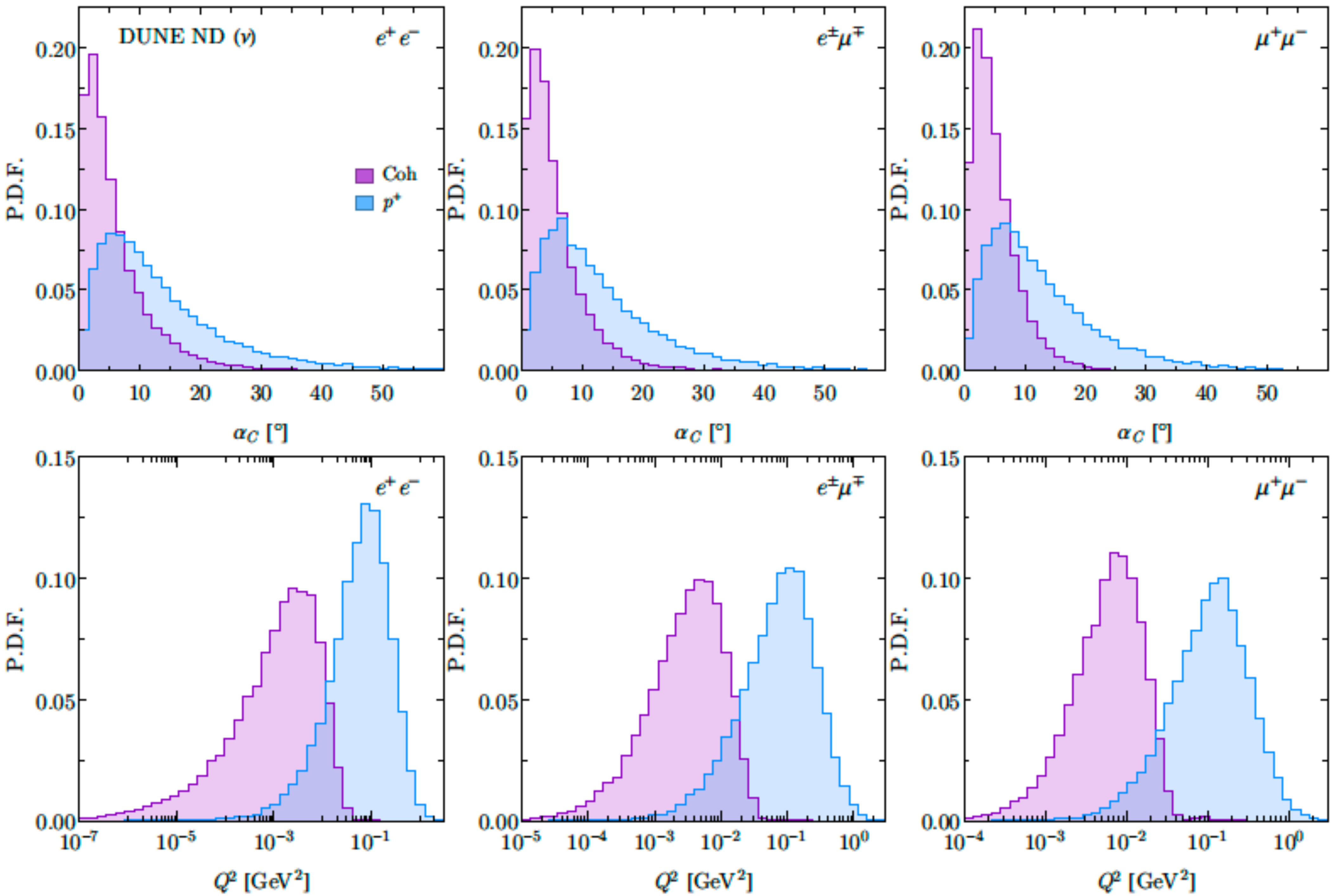
Rates


DUNE
Solid: ν beam
Dotted: ν̄ beam
νSTORM
Solid: μ+ decay
Dashed: π+ decay
Dot−Dashed: K+ decay
SBND
ν_μ
ν̄_μ
ν_e
ν̄_e
ν flux/GeV/m2/1020 POT
σ^LAr_νN [cm2]
E_ν [GeV]
ν_μ→ν_μ μ+μ−
ν_μ→ν_μ e+e−
ν_μ→ν_e e+μ−
ν_e→ν_e e+e−
ν_e→ν_e μ+μ−
ν_e→ν_μ μ+e−

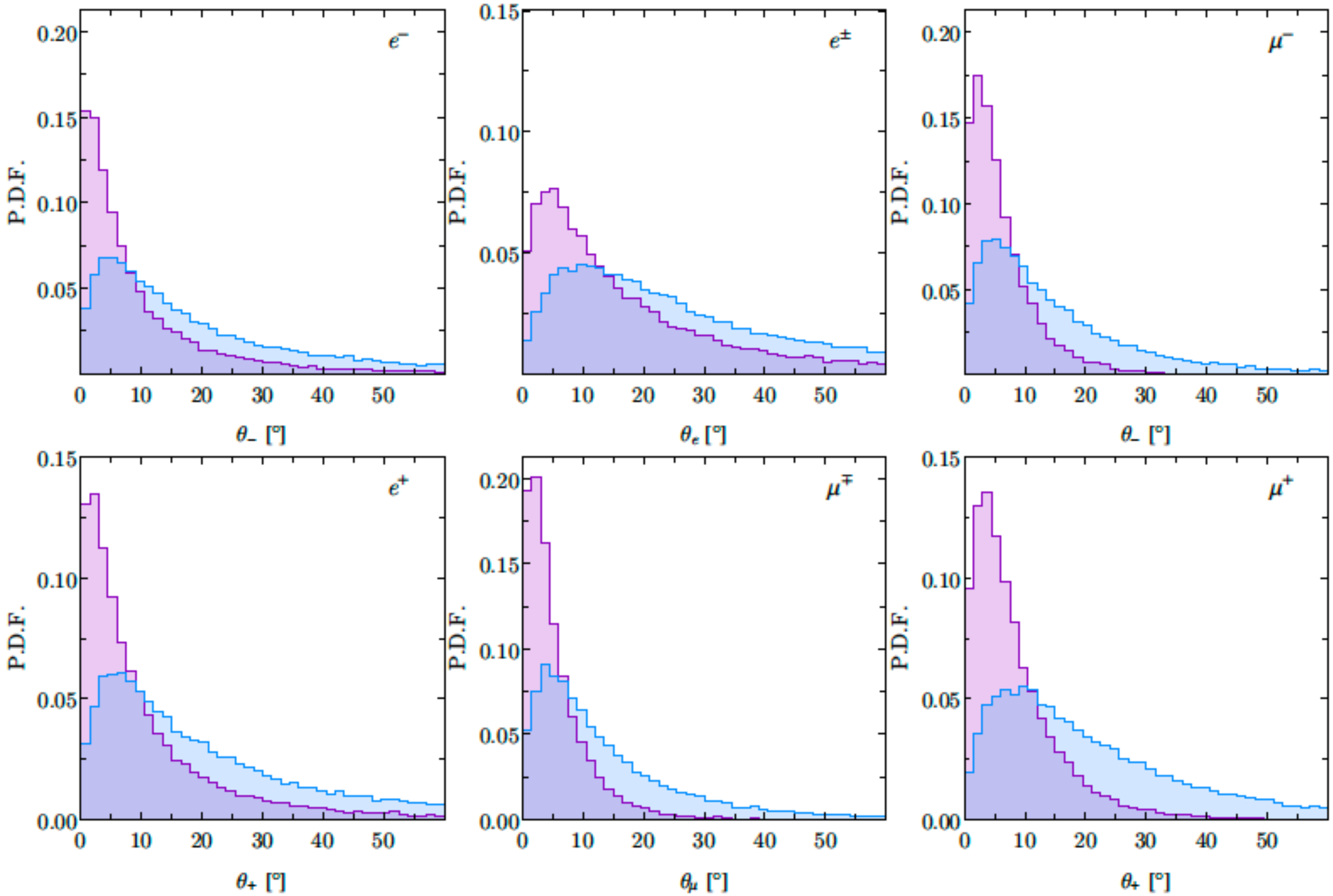
Kinematical Distributions



Kinematical Distributions



Kinematical Distributions



Events at other ND facilities

Rates

$$N_{\rm X}^{\psi} = \text{Norm} \times \int dE_\nu \, \sigma_{\nu \rm X}(E_\nu) \frac{d\phi_\nu(E_\nu)}{dE_\nu} \epsilon(E_\nu)$$

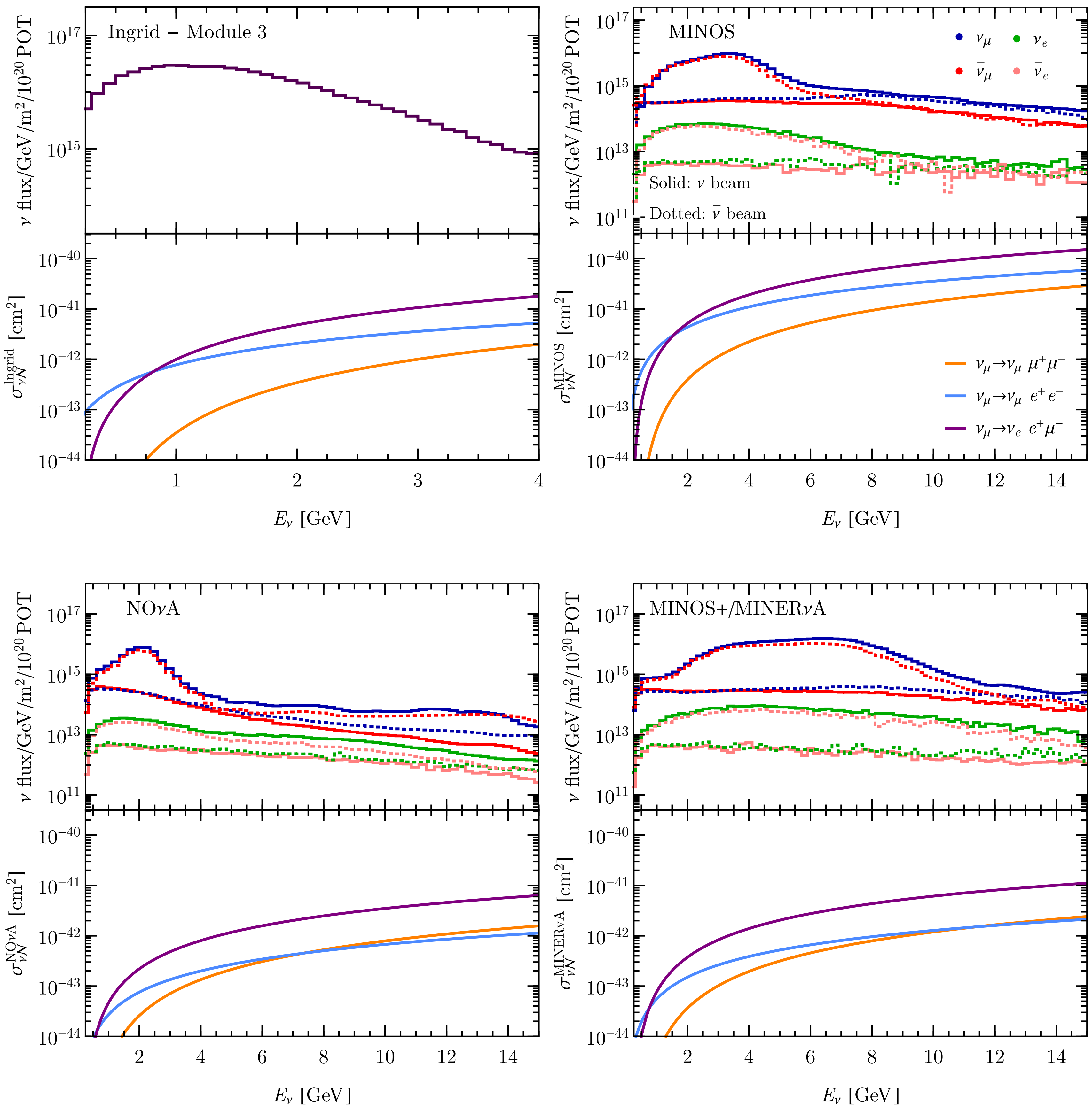
Fraction

$$\sigma_{\nu \rm X}^{\rm FAC} = \sum_i f_i \, \sigma_{\nu \rm X}^i$$

Cross section for the component

Experiment	Material	Baseline (m)	Exposure (POT)	Fiducial Mass (t)	E_ν (GeV)
INGRID	Fe	280	3.9×10^{21} [10^{22}] T2K-I [T2K-II]	99.4	$0 - 4$
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6	$0 - 20$
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ $[36(36)] \times 10^{20}$ [NOνA-II]	231	$0 - 20$
MINERνA	CH, H_2O, Fe, Pb, C	1035	$12(12) \times 10^{20}$	7.98	$0 - 20$

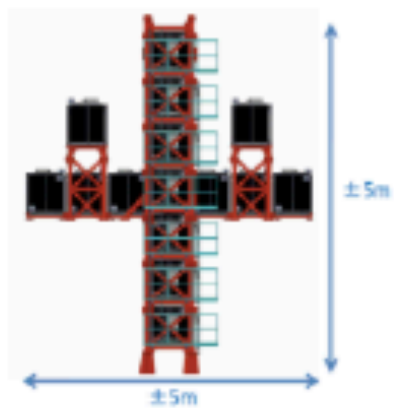
Rates

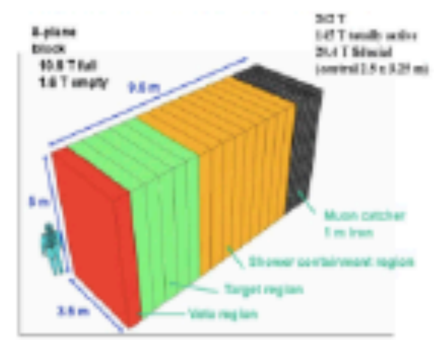


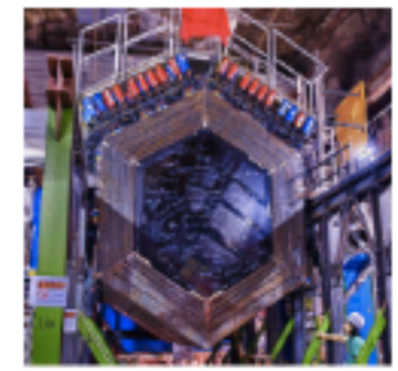
Ingrid – Module 3
MINOS
Solid: ν beam
Dotted: ν̄ beam
NOνA
MINOS+/MINERνA
ν_μ
ν_e
$\bar{\nu}_\mu$
$\bar{\nu}_e$
$\nu_\mu \to \nu_\mu\ \mu^+\mu^-$
$\nu_\mu \to \nu_\mu\ e^+e^-$
$\nu_\mu \to \nu_e\ e^+\mu^-$
ν flux/GeV/m²/10²⁰ POT
$\sigma_{\nu N}^{\rm Ingrid}$ [cm²]
$\sigma_{\nu N}^{\rm MINOS}$ [cm²]
$\sigma_{\nu N}^{\rm NO\nu A}$ [cm²]
$\sigma_{\nu N}^{\rm MINER\nu A}$ [cm²]
E_ν [GeV]

Rates

INGRID







Channel	T2K-I	T2K-II	MINOS	MINOS+	NOνA-I	NOνA-II	MINERνA
Total $e^{\pm}\mu^{\mp}$	563	1444	222 (56)	730	83 (72)	340 (374)	149 (102)
	96	246	46 (11)	151	25 (22)	102 (114)	56 (39)
Total e^+e^-	277	711	61 (15)	62	29 (22)	119 (114)	39 (27)
	24	62	9 (2)	8	4 (4)	16 (21)	10 (7)
Total $\mu^+\mu^-$	30	76	26 (6)	86	9 (9)	37 (47)	18 (13)
	21	54	15 (3)	49	8 (8)	34 (36)	18 (13)