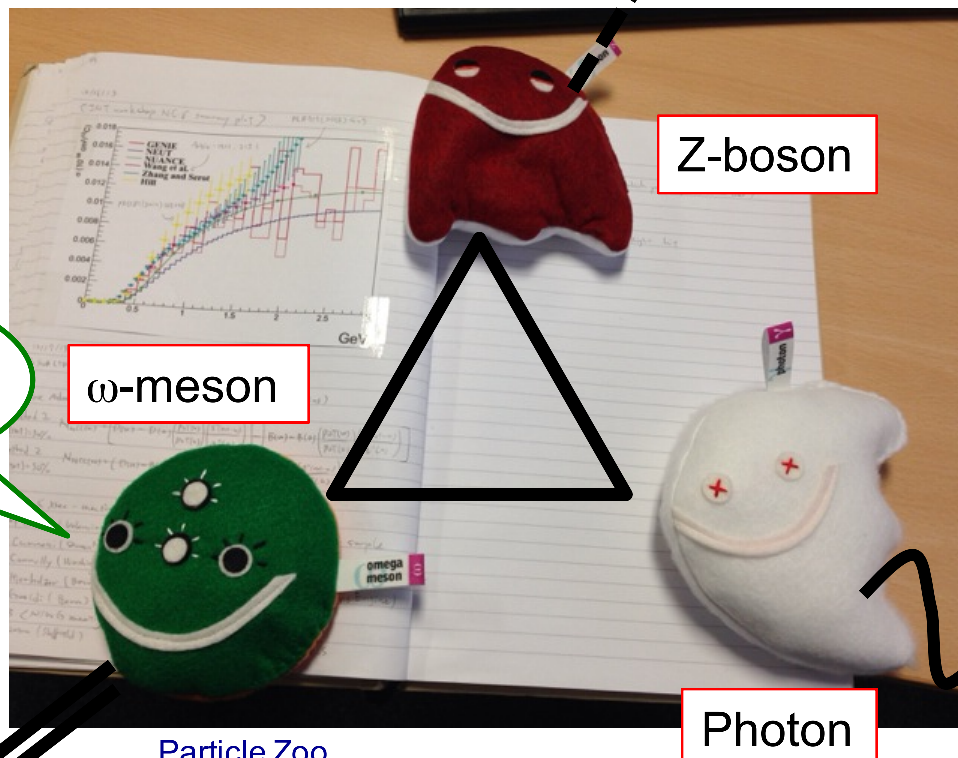
Single photon production in neutrino experiments

outline

1. Neutrino oscillation experiments
2. Motivation of ALPs search
3. Single photon search in neutrino experiments
4. Light WIMP in MiniBooNE
5. Conclusion

IoP astroparticle physics
facebook.com/IOPAPP/



Particle Zoo,
http://www.particlezoo.net/

Neutrino-induced
Anomaly mediated
photon production
PRL99(2007)261601

Queen Mary
University of London

Teppei Katori and Pierre Lasorak
Queen Mary University of London

ALPs workshop, Durham, Apr. 14, 2016

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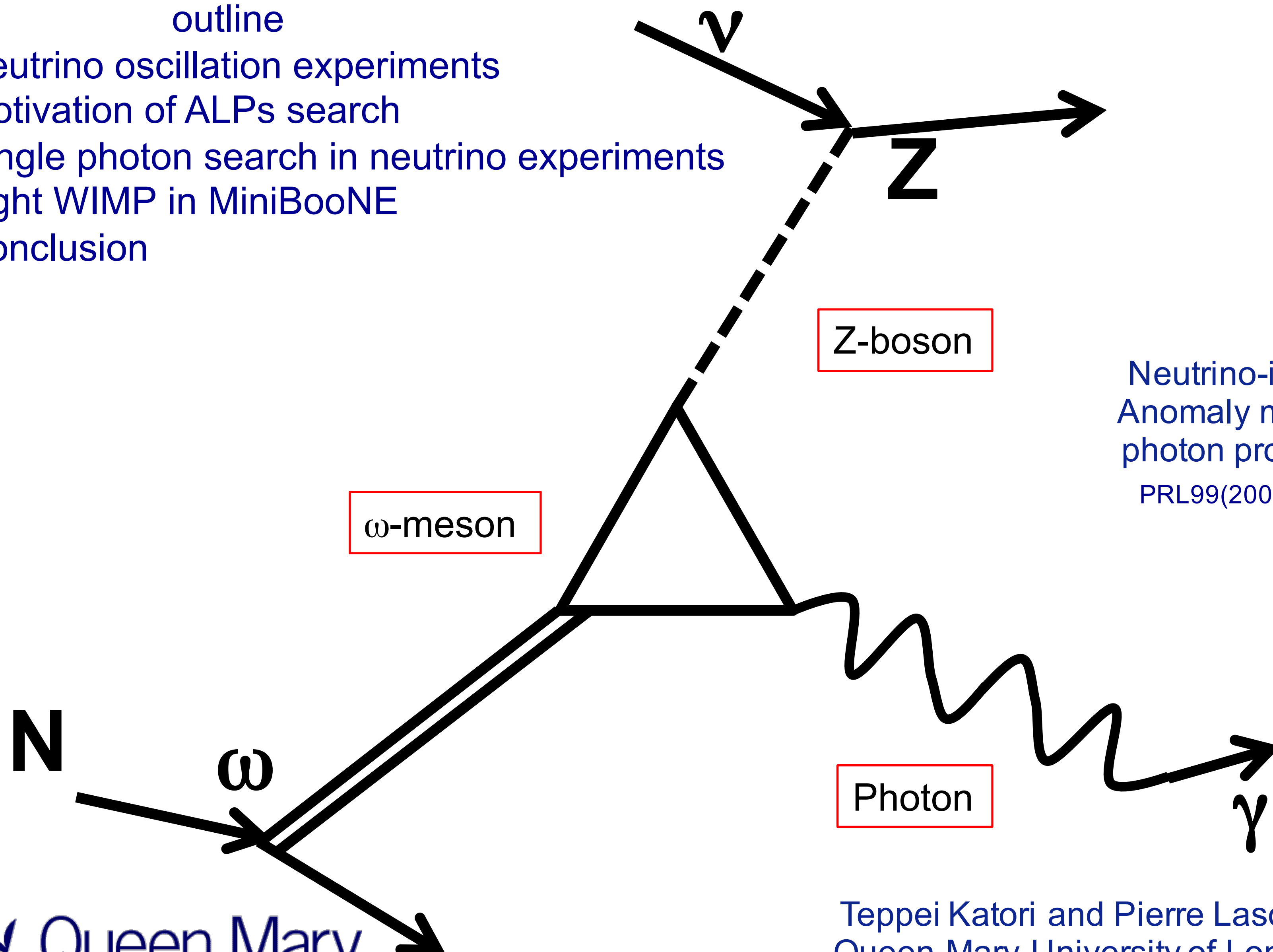

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1. Neutrino oscillation experiments

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5. Conclusion

1. Neutrino physics is the future of particle physics

P5 (particle physics project prioritization panel) recommend neutrinos to DOE

Contents

CERN → LHC
Fermilab → Neutrino

Table 1
Summary of Scenarios

Project/Activity	Scenarios: Scenario A	Scenario B	Senario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

1. CERN-USA, KEK-ICRR…

Political pacts are made to strengthen large collaborations…

CERN - USA

DUNE
- LArTPC detector
- argon target
- wideband 1-4 GeV

(on-axis beam)

Hyper-Kamiokande
- Water Cherenkov detector
- water target
- narrowband 0.6 GeV

(off-axis beam)

KEK - ICRR

1. Neutrino Standard Model (νSM)

Next goal of particle physics after Higgs discovery

- Establish νSM = "SM + 3 active massive neutrinos"

Unknown parameters of νSM

1. Dirac CP phase
2. θ_{23} (θ_{23}=40^o and 50^o are same for sin2θ_{23}, but not for sinθ_{23})
3. Mass ordering, normal $m_1<m_2<m_3$, or inverted $m_3<m_1<m_2$
4. Dirac or Majorana
5. Majorana phase (x2)
6. absolute neutrino mass

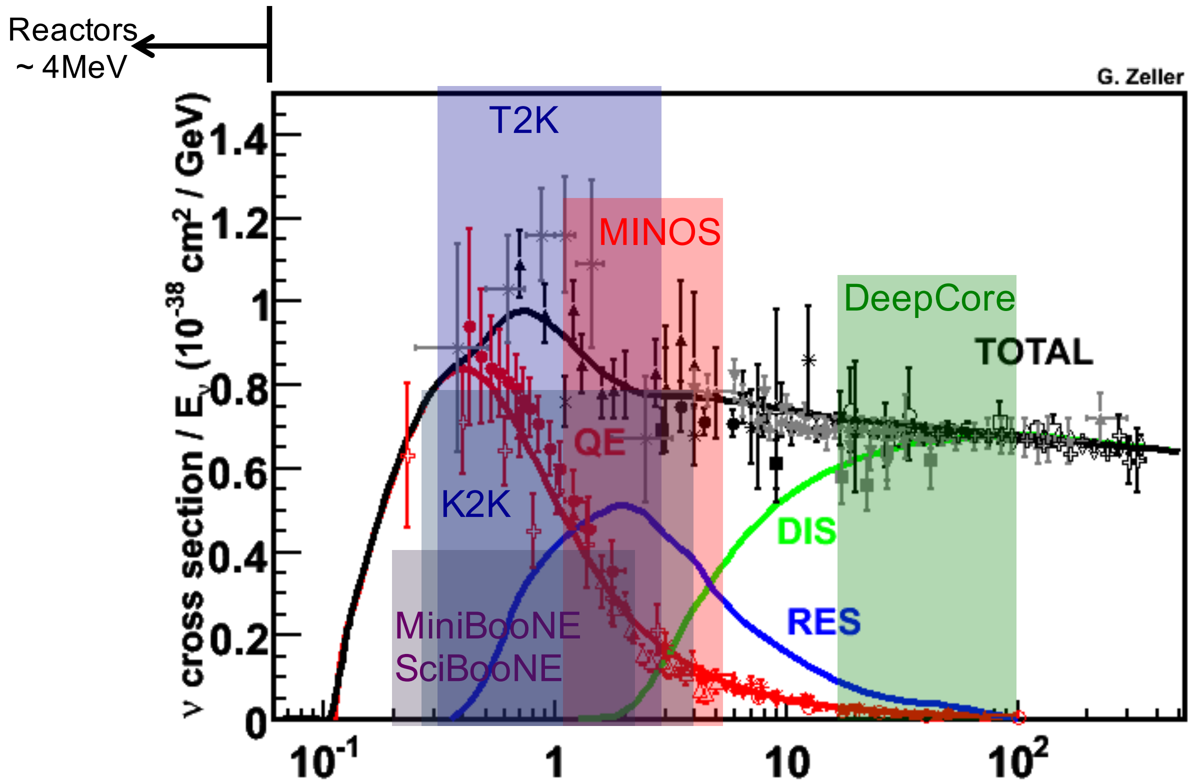
oscillation physics

There is a strong emphasis on 1-10 GeV energy region

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE…



ν_μCC cross section per nucleon

There is a strong emphasis on 1-10 GeV energy region

$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 (eV^2)\frac{L(km)}{E(GeV)}\right)$$

1. Next generation neutrino oscillation experiments

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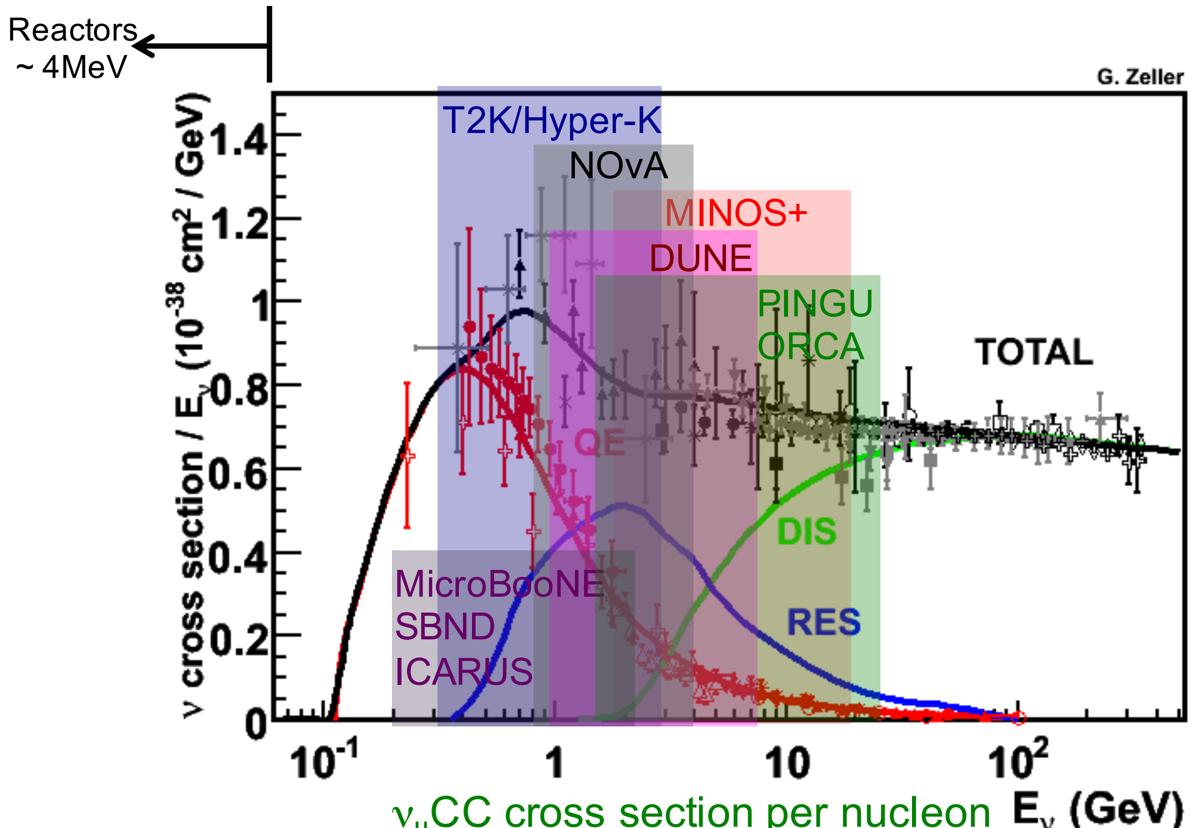

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1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE…

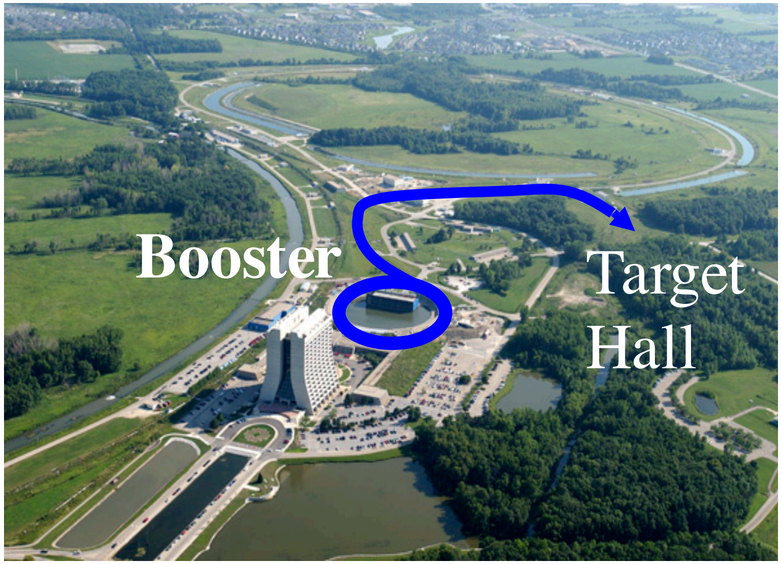
There is a strong emphasis on 1-10 GeV due to oscillation physics, but there are not many things to measure. We need more topics!

- T2K (~500 collaborators) ~ 10 papers/year

(oscillation=2, cross section=4, detector=1, others=2 in 2015)

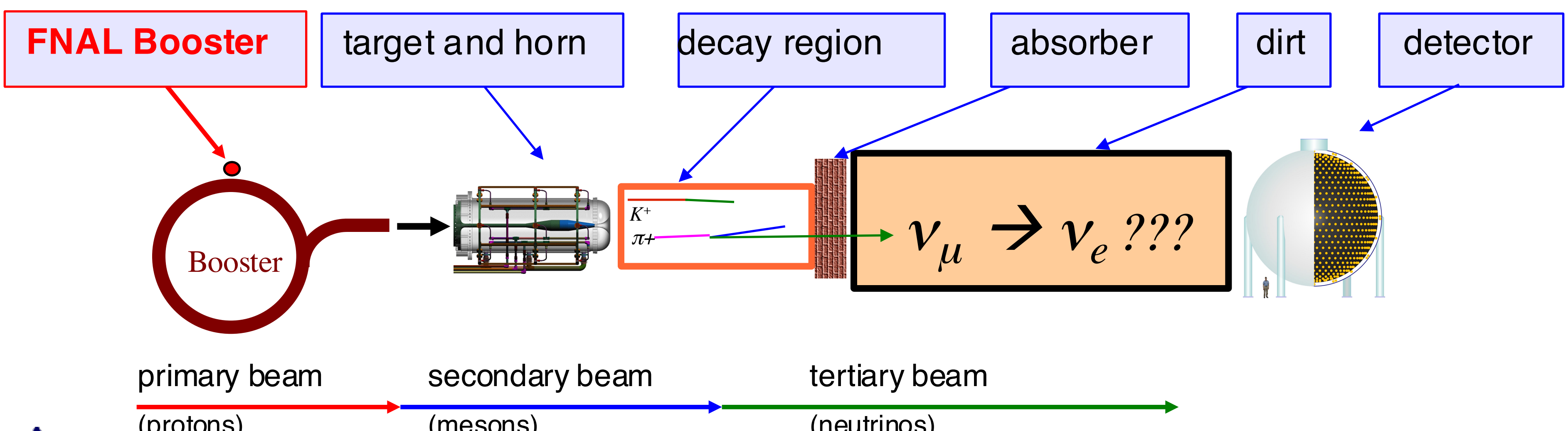
- CDF (~500 collaborators) ~ 50 papers/year

1. Neutrino beam



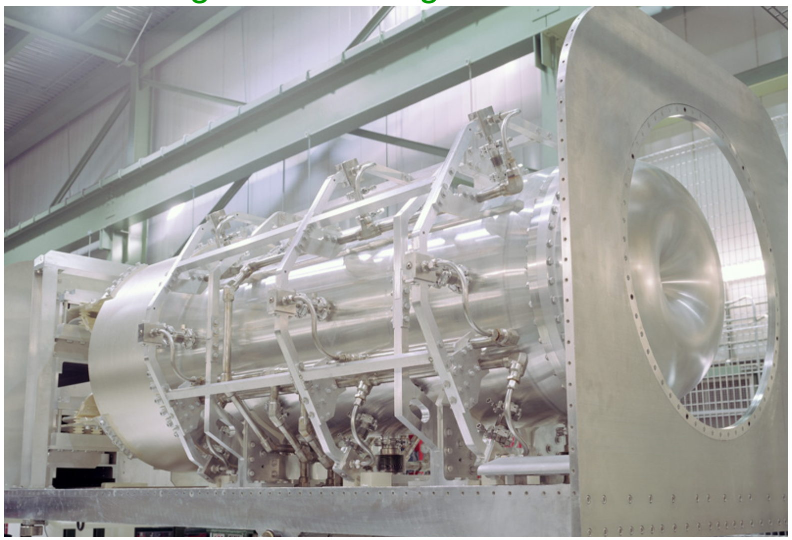
MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster



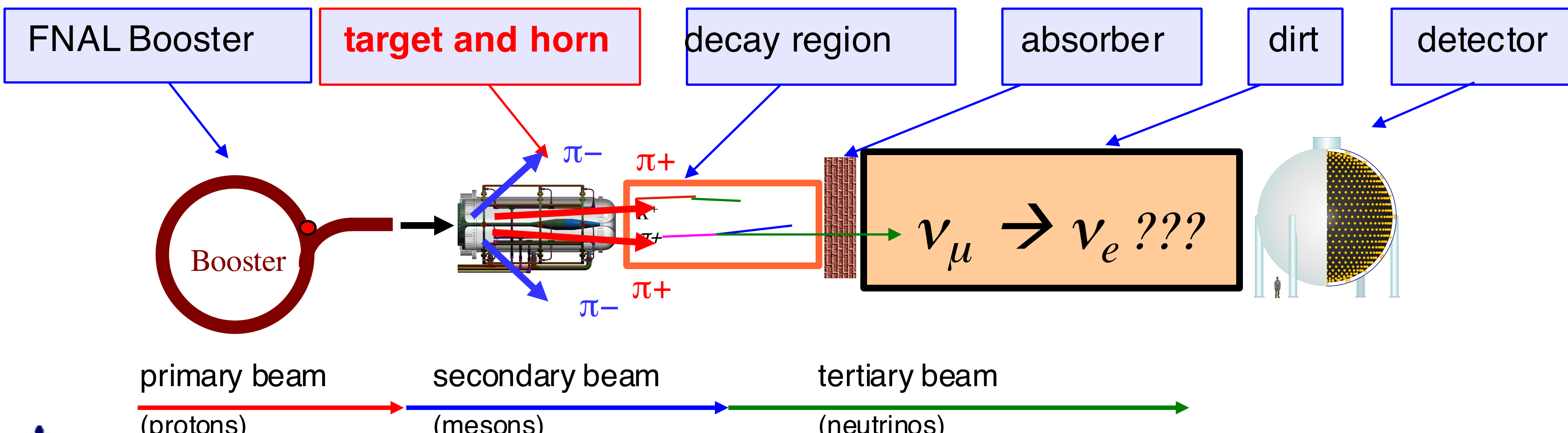
1. Neutrino beam

Magnetic focusing horn



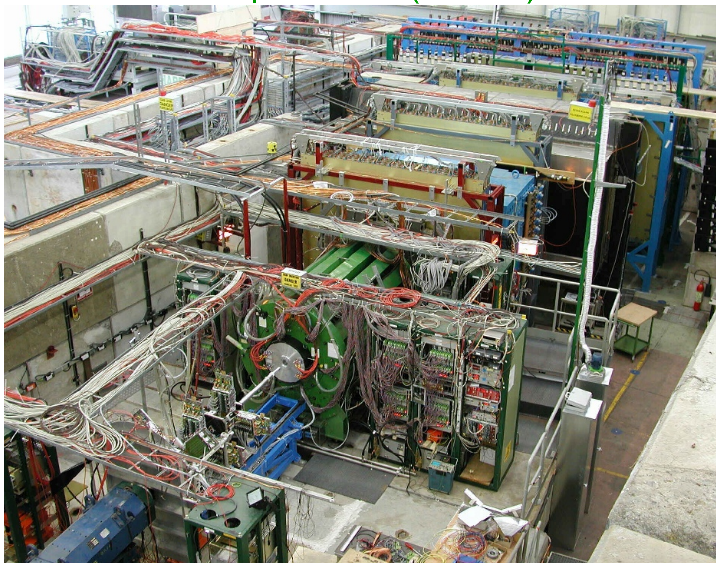
8GeV protons are delivered to a 1.7 λ Be target

within a magnetic horn (2.5 kV, 174 kA) that increases the flux by x6



1. Neutrino beam

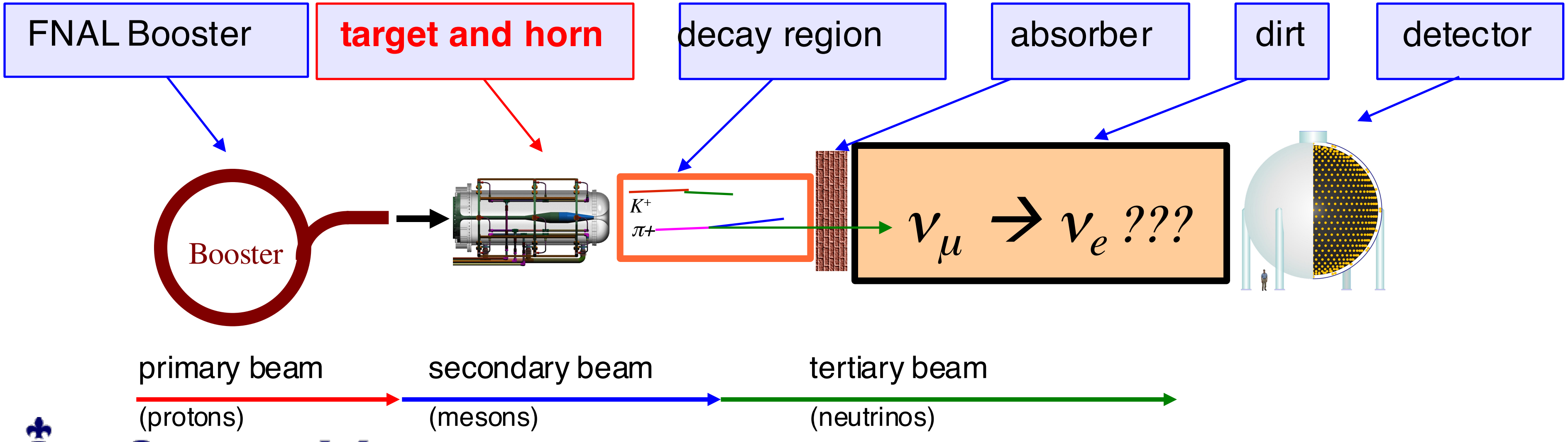
HARP experiment (CERN)



Modeling of meson production is based on the measurement done by HARP collaboration.

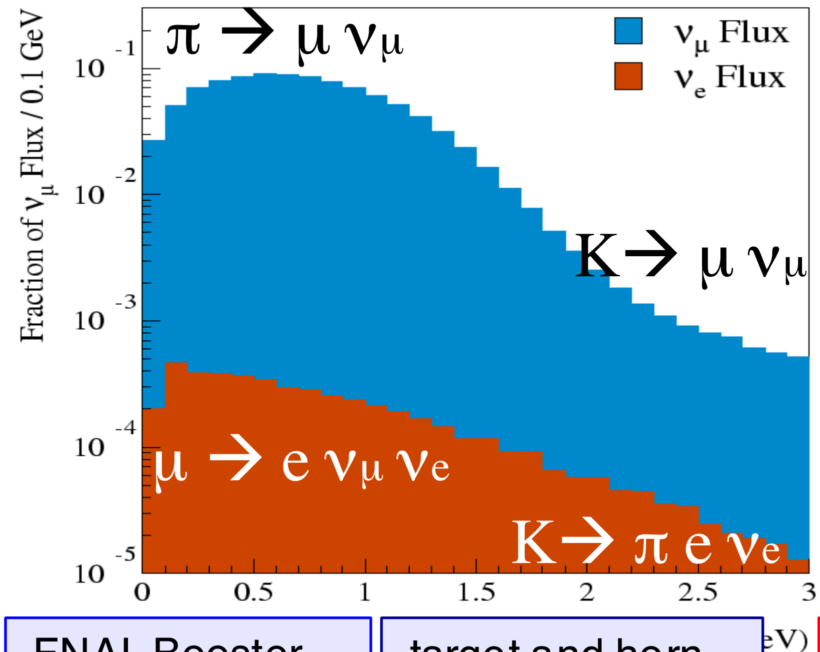
HARP,Eur.Phys.J.C52(2007)29

- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum



MiniBooNE,PRD79(2009)072002

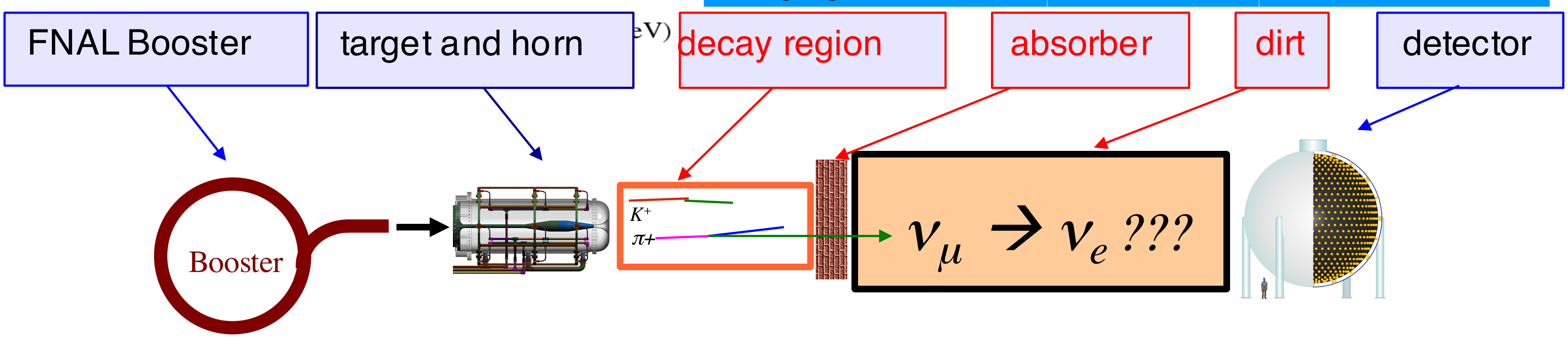
1. Neutrino beam



Neutrino flux from simulation by GEANT4

MiniBooNE is a ν_e (anti ν_e) appearance oscillation experiment, so we need to know the distribution of beam origin ν_e and anti ν_e (intrinsic ν_e)

	neutrino mode	antineutrino mode
intrinsic ν_e contamination	0.6%	0.6%
intrinsic ν_e from μ decay	49%	55%
intrinsic ν_e from K decay	47%	41%
others	4%	4%
wrong sign fraction	6%	16%



primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

Accelerator-based neutrino oscillation experiments are beamdump experiments

1. Neutrino oscillation experiments

2. Motivation of ALPs search in neutrino experiments

3. Single photon searches in neutrino experiments

4. Light WIMP search in MiniBooNE

5. Conclusion

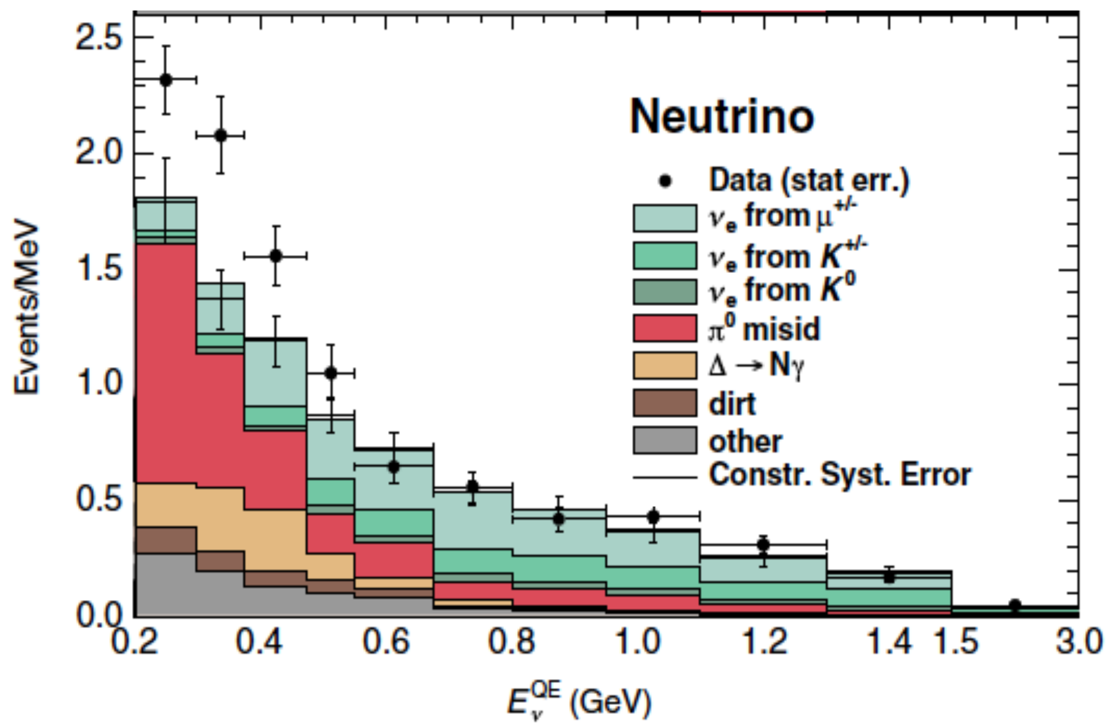
2. MiniBooNE

$$\nu_\mu \xrightarrow{oscillation} \nu_e + n \rightarrow e^- + p$$

$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow e^+ + n$$

Electron or photon?

- MiniBooNE observed excesses from final oscillation samples
- The largest misID background is photon from NCπ^o production
- Any high energy photon can be backgrounds



2. MiniBooNE

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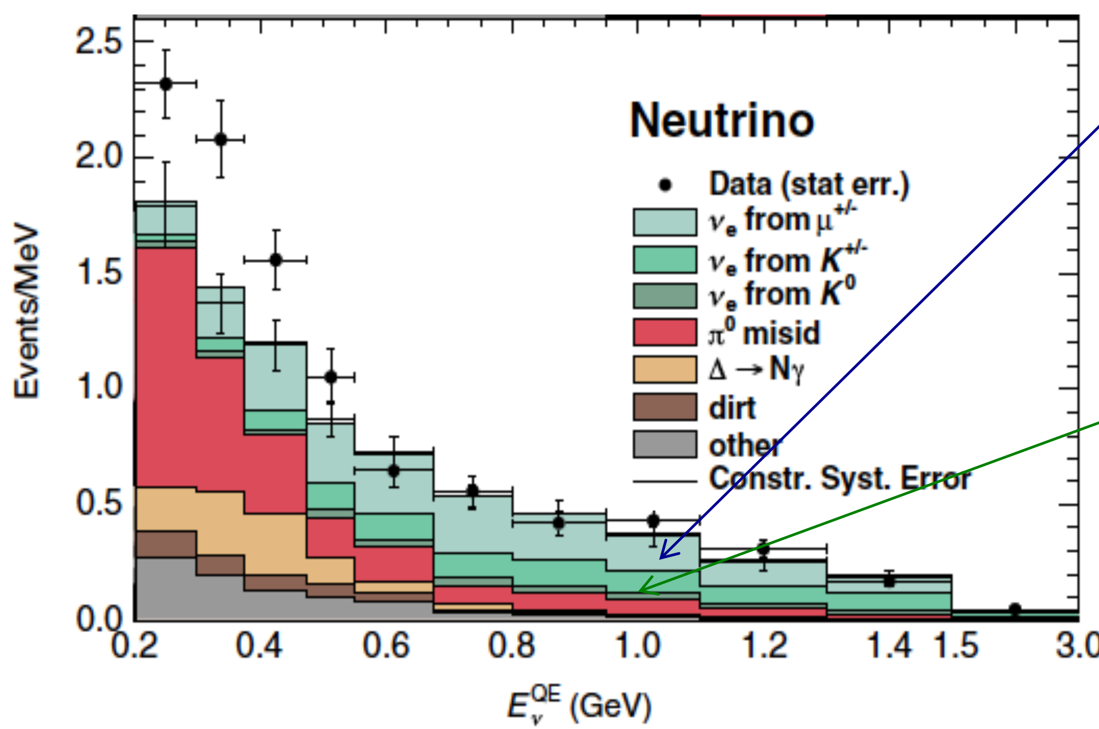


ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE

2. MiniBooNE

$$\nu_\mu \xrightarrow{oscillation} \nu_e + n \to e^- + p$$

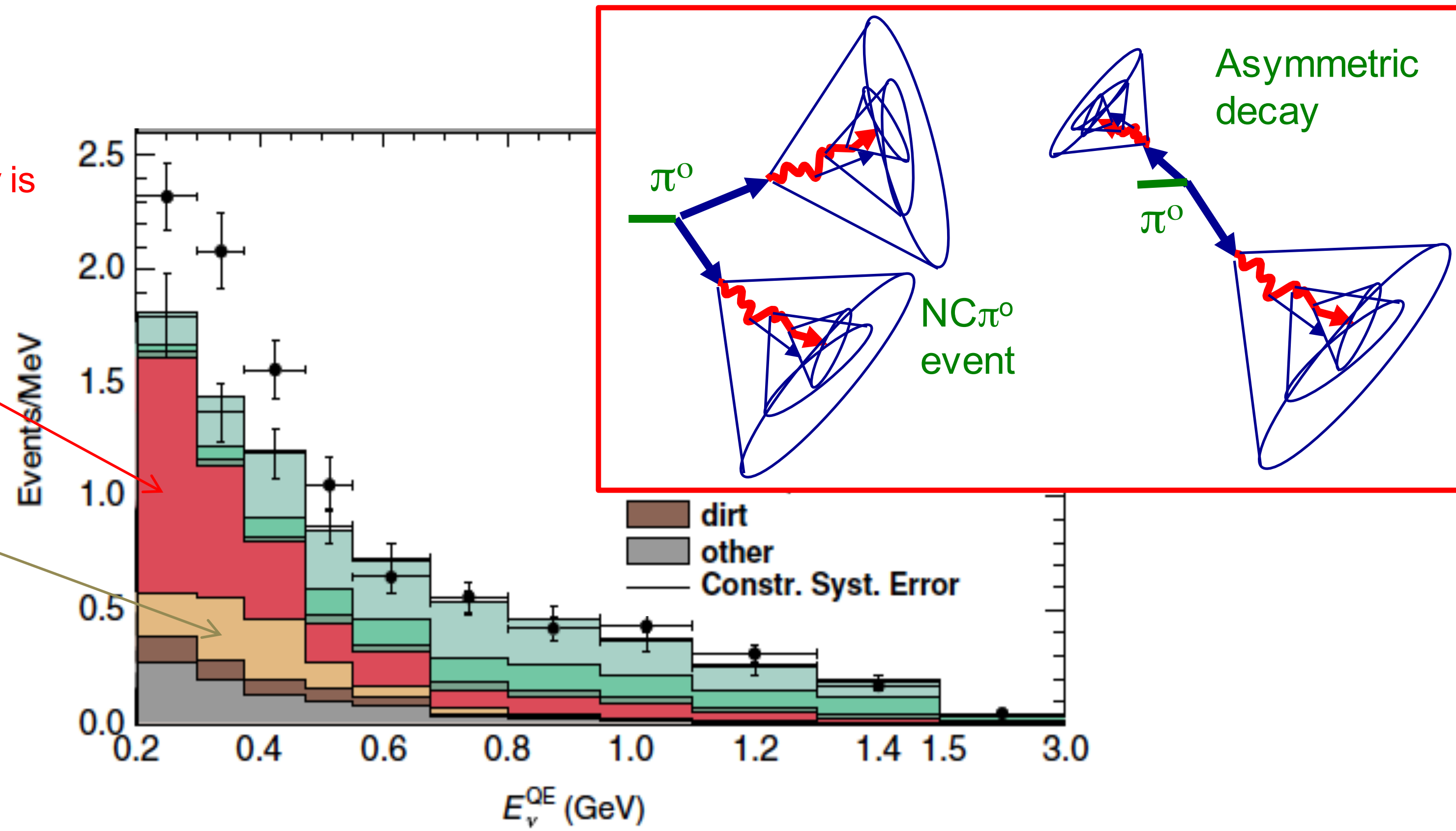
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \to e^+ + n$$

Electron or photon?

- MiniBooNE observed excesses from final oscillation samples
- The largest misID background is photon from NCπ^o production
- Any high energy photon can be backgrounds

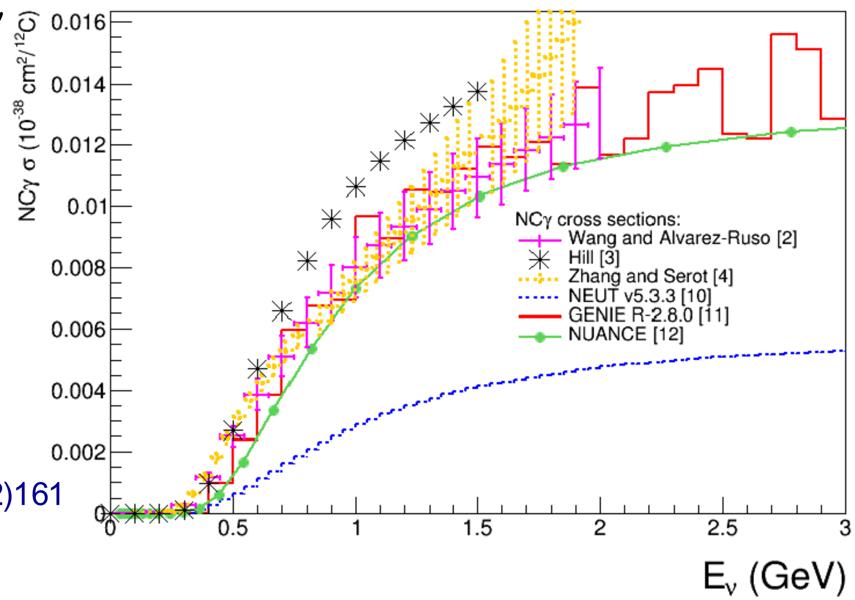
Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \to \gamma$)

Radiative Δ-decay ($\Delta \to N\gamma$) rate is constrained from measured NCπ^o



2. New photon sources within the Standard Model

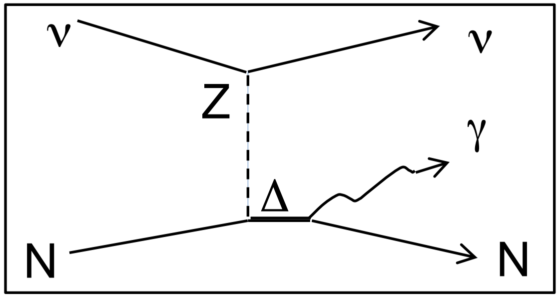
Neutral Current single photon production (NCγ)
- all generators estimate NCγ from radiative Δ-decay Δ→Nγ
- cross section is roughly ~0.5% of NC1π° channel
- state-of-the-art models tend to predict higher xs



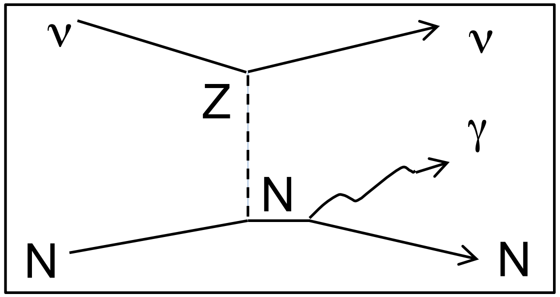
But probably these are not big enough to explain MiniBooNE excess

[2] Wang et al, PRC89(2014)015503
[3] Hill, PRD81(2010)013008
[4] Zhang and Serot, PLB719(2013)409
[10] NEUT, Acta Phys.Polon.B40(2009)2477
[11] GENIE, NIMA614(2010)87
[12] NUANCE, Nucl.Phys.Proc.Suppl.112(2002)161

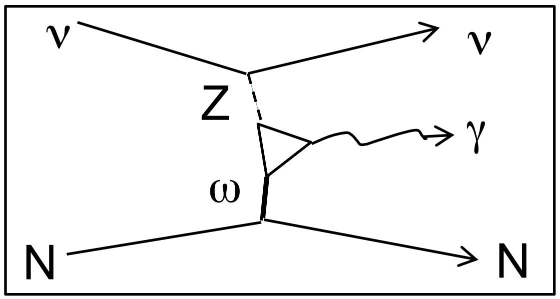
radiative Δ-decay



generalized Compton scattering



anomaly mediated triangle diagram

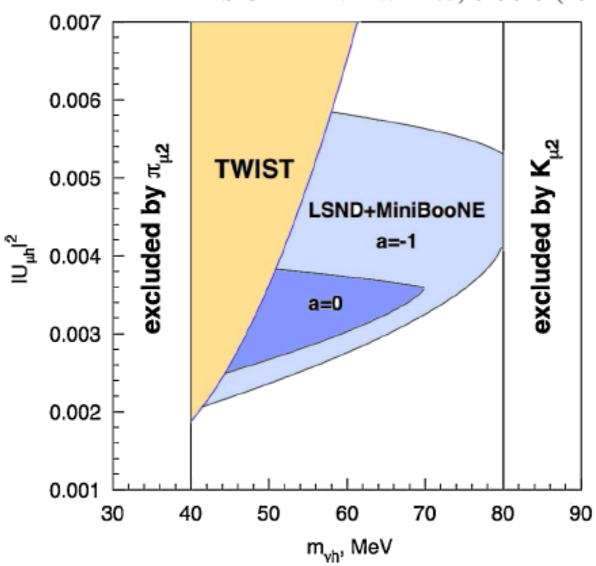


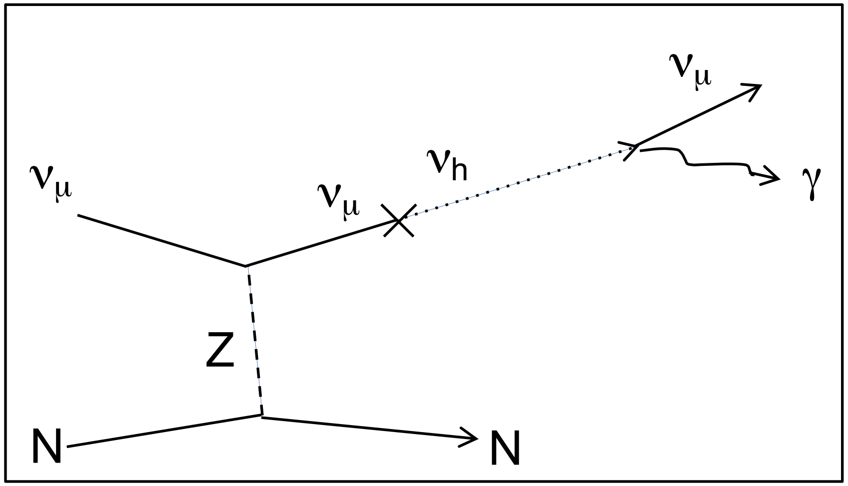
2. New photon sources Beyond the Standard Model

Heavy neutrino decay

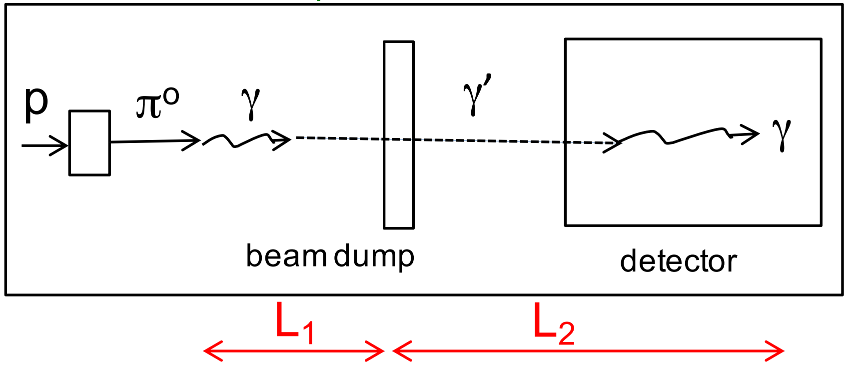
- A model designed to explain LSND, KARMEN, and MiniBooNE

PHYSICAL REVIEW D 83, 015015 (2011)





dark photon oscillation?



$$P_{\rm trans} = 16\chi^4\left[\sin\left(\frac{\Delta k L_1}{2}\right)\sin\left(\frac{\Delta k L_2}{2}\right)\right]^2$$

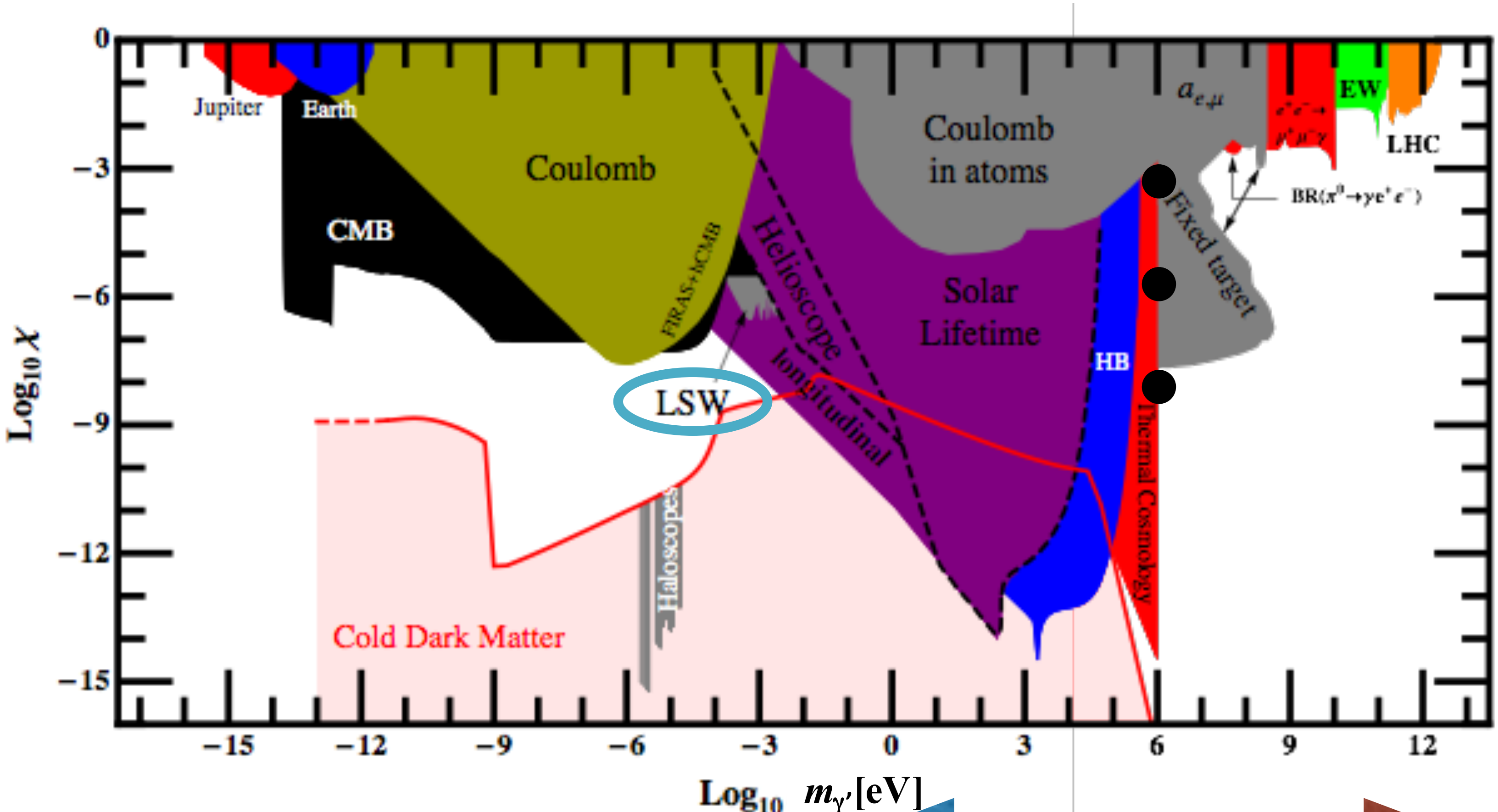
Photon-Dark photon oscillation

- Light-Shining-Through-the-Wall type experiment
- Neutrino experiments (=beamdump experiments)

may offer natural place to look for photon-dark photon oscillation

Pradler,EPS2015
Redondo, PRD77(2008)095001

2. Landscape of ALPs



$$\mathcal{L} = -\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} - \tfrac{1}{4}B^{\mu\nu}B_{\mu\nu} - \tfrac{1}{2}\chi F^{\mu\nu}B_{\mu\nu} + \tfrac{1}{2}m^2_{\gamma'}B_\mu B^\mu$$

Dark matter: Oscillation, Coulomb law deviations

Decay: “excesses”

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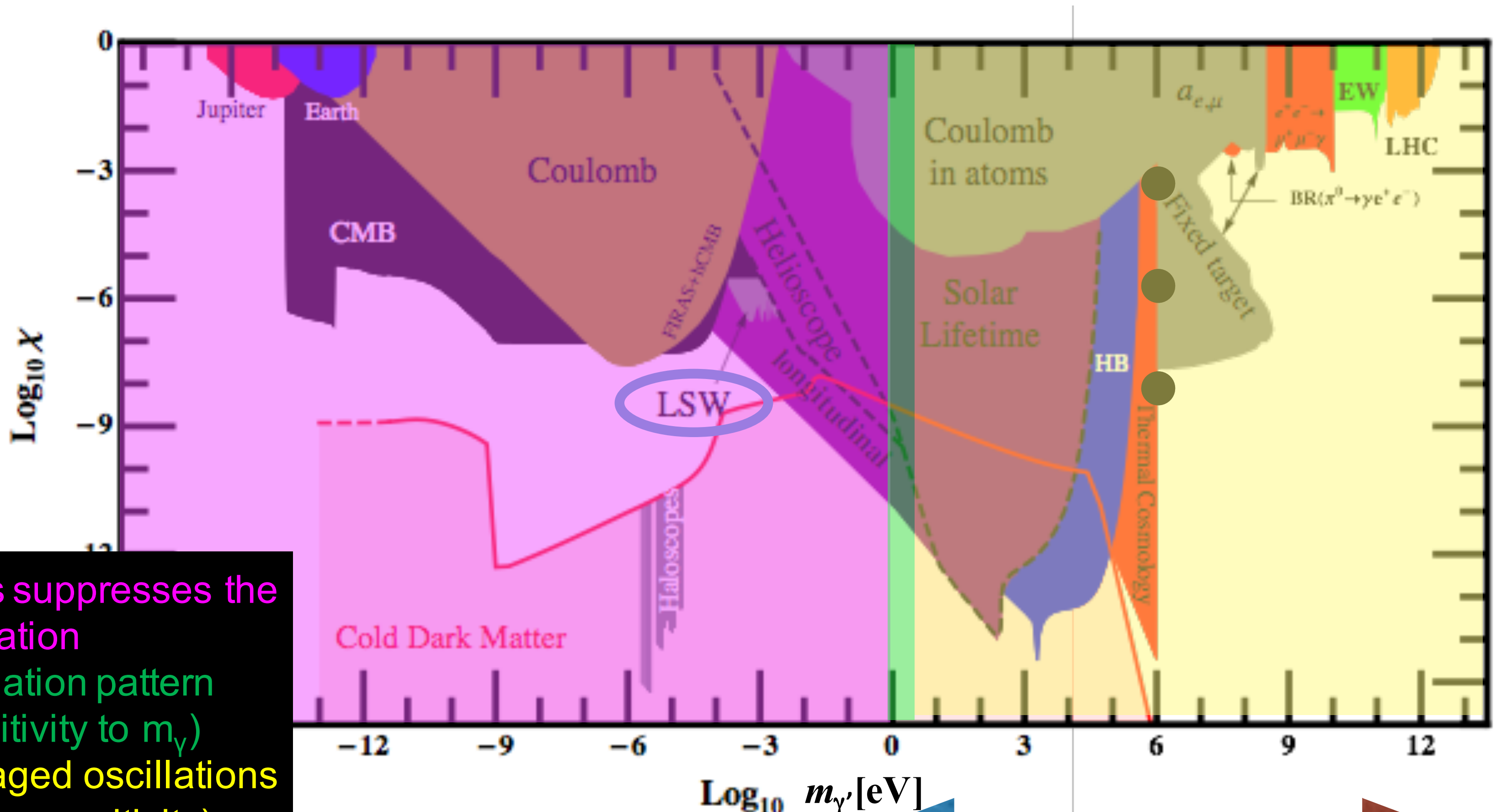
Pradler,EPS2015
Redondo, PRD77(2008)095001

2. Landscape of ALPs



Sines suppresses the oscillation
Oscillation pattern (sensitivity to m_γ)
Averaged oscillations (no m_γ sensitivity)

$$\mathcal{L} = -\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} - \tfrac{1}{4}B^{\mu\nu}B_{\mu\nu} - \tfrac{1}{2}\chi F^{\mu\nu}B_{\mu\nu} + \tfrac{1}{2}m_{\gamma'}^2 B_\mu B^\mu$$

Dark matter: Oscillation, Coulomb law deviations

Decay: “excesses”

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Pradler,EPS2015
Redondo, PRD77(2008)095001

2. Photon-Dark photon oscillation

$$P_{\text{trans}} = 16\chi^4\left[\sin\left(\frac{\Delta k L_1}{2}\right)\sin\left(\frac{\Delta k L_2}{2}\right)\right]^2$$

Sensitive of neutrino experiments

- Current LSW limit reaches $\chi \sim 10^{-6}$
- Oscillation probability ~ power 4 of coupling constant
- In T2K beamline, $\sim 10^{13}$ neutral pions are created in 10% total statistics (now)

→ T2K limit would be at best $\chi \sim 10^{-3}$

T2K, or any neutrino experiments are not competitive for dark photon oscillation measurements

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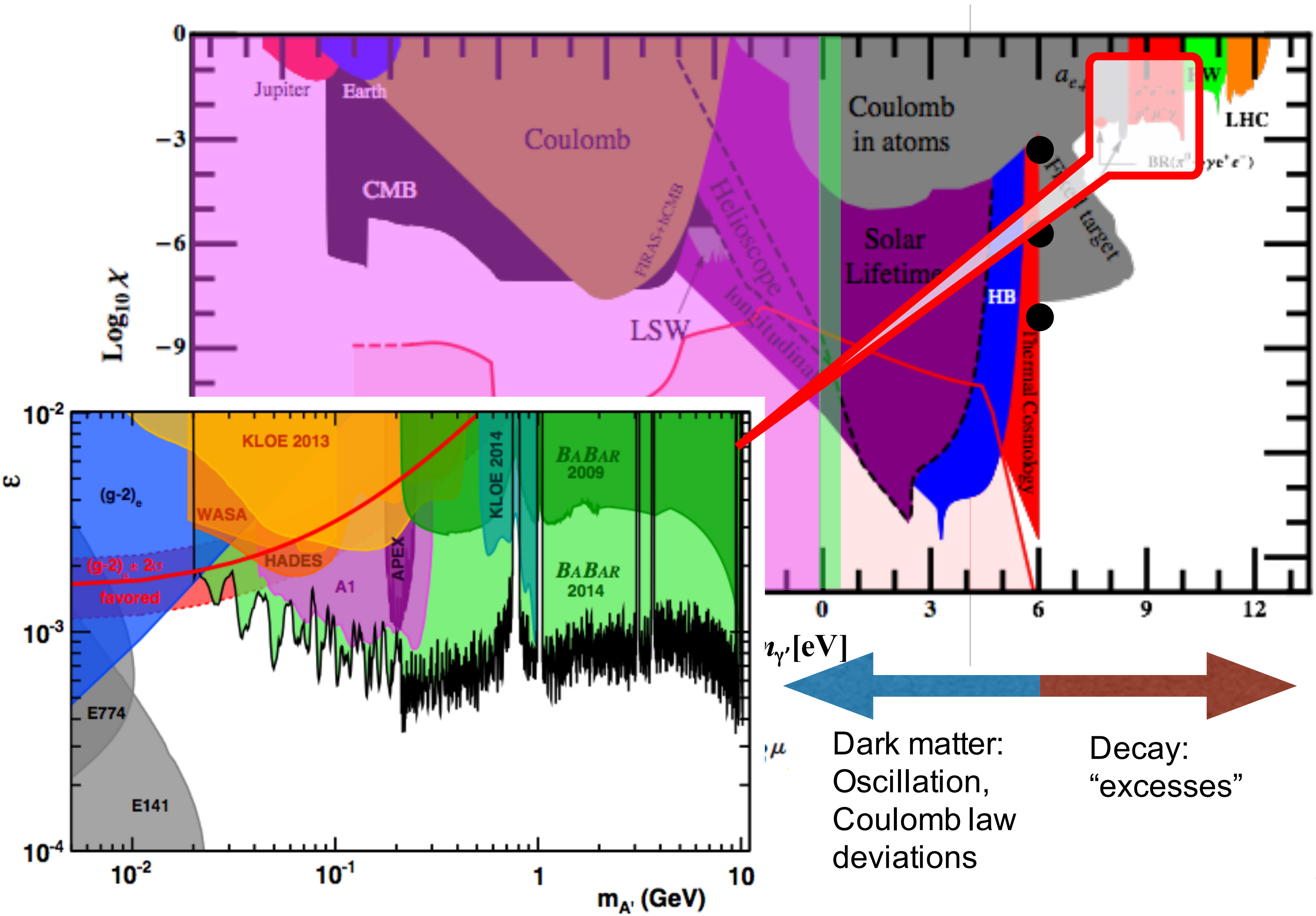
BABAR,PRL 113, 201801 (2014)

2. Landscape of ALPs



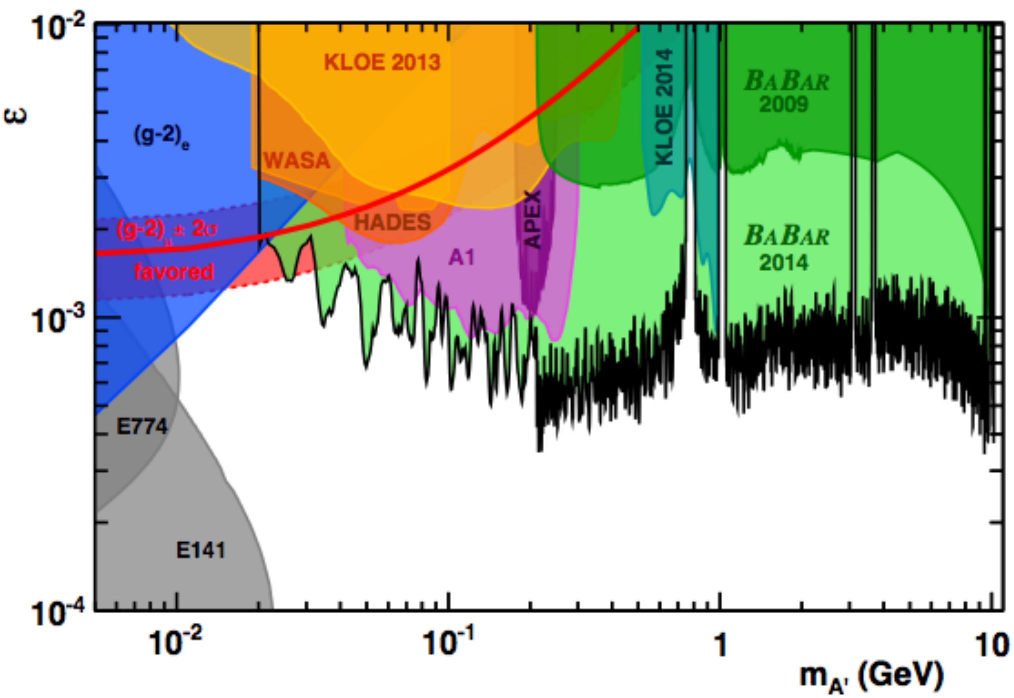
Dark matter:
Oscillation,
Coulomb law
deviations

Decay:
“excesses”

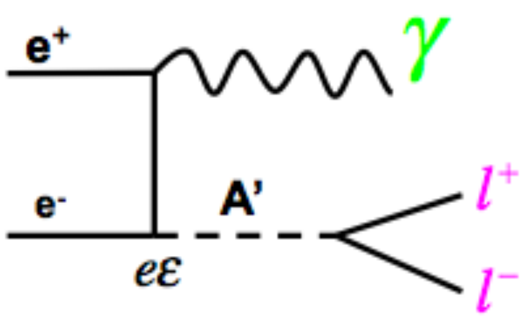
2. Dark photon decay

Any interesting models for neutrino experiments?
- current limit is ~10^{-3} in coupling constant
- there is no testable models for neutrino experiments

We (=T2K) are wondering what kind of models we can test in this region



Event signature in BABAR, but probably we should look for other topologies...



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5. Conclusion

Gargemelle, Phys.Lett.74B(1978)422
Gershtein et al.,Sov.J.Nucl.Phys33(1981)6

3. Bubble chamber experiments

ν_μ-e elastic scattering
- Important test of Standard Model
- Excess of gamma like events
- Earliest models are made to explain these, but Eν~25GeV.

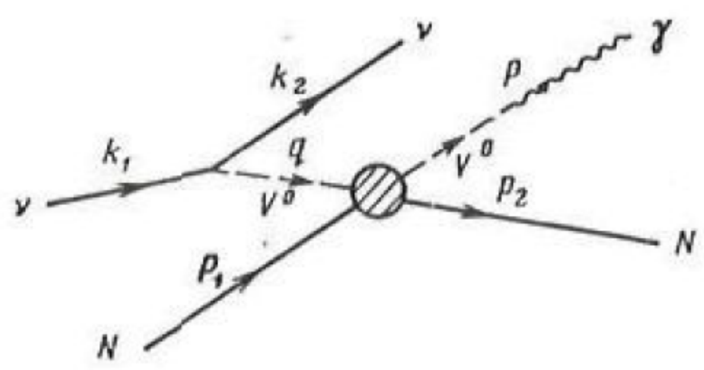
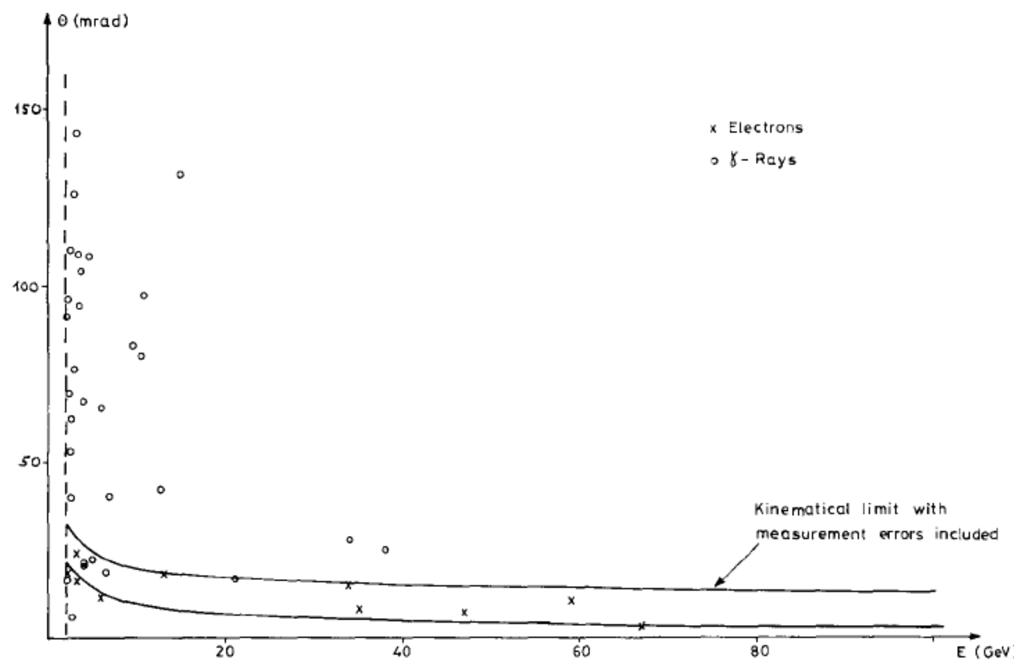


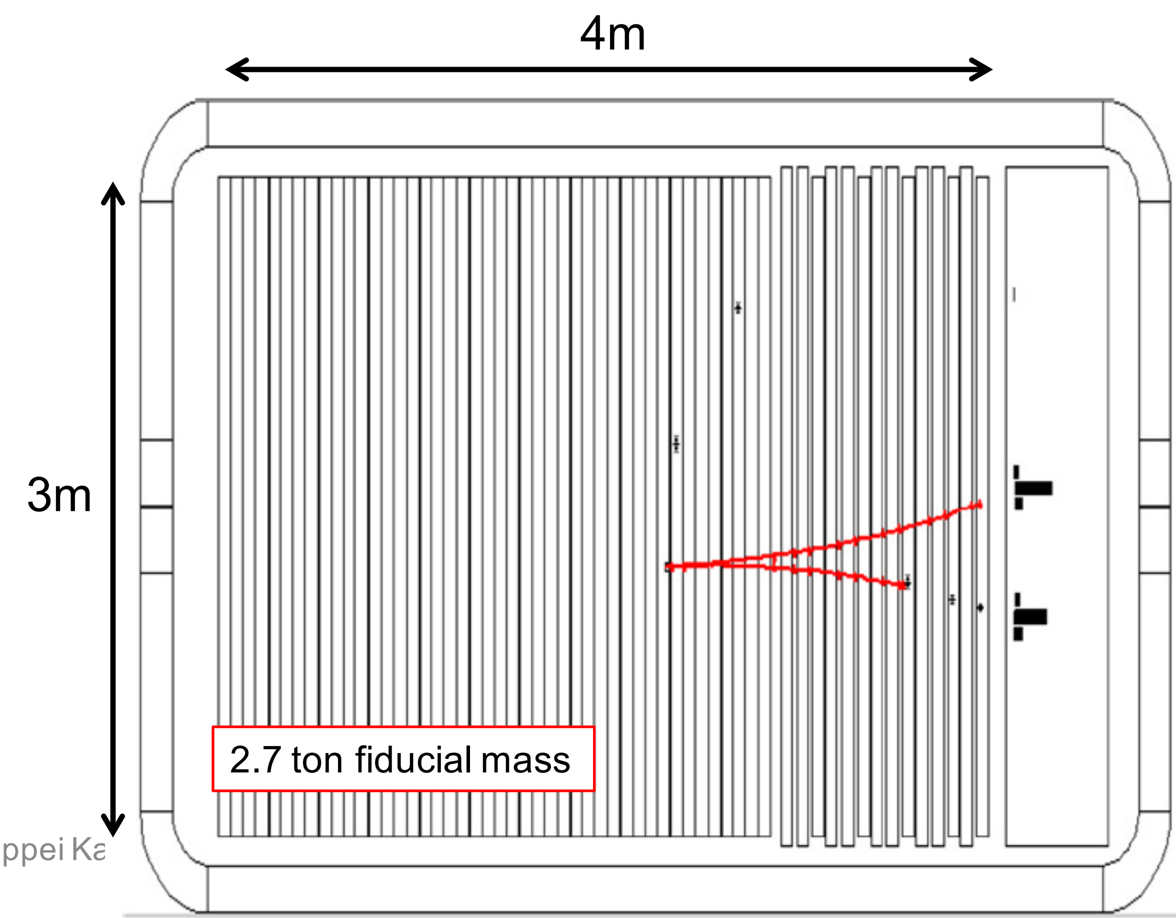
FIG. 1.



3. NOMAD

Selection of gamma event candidate

- single e^+-e^- pair
- fiducial cut
- W<50 MeV



3. NOMAD

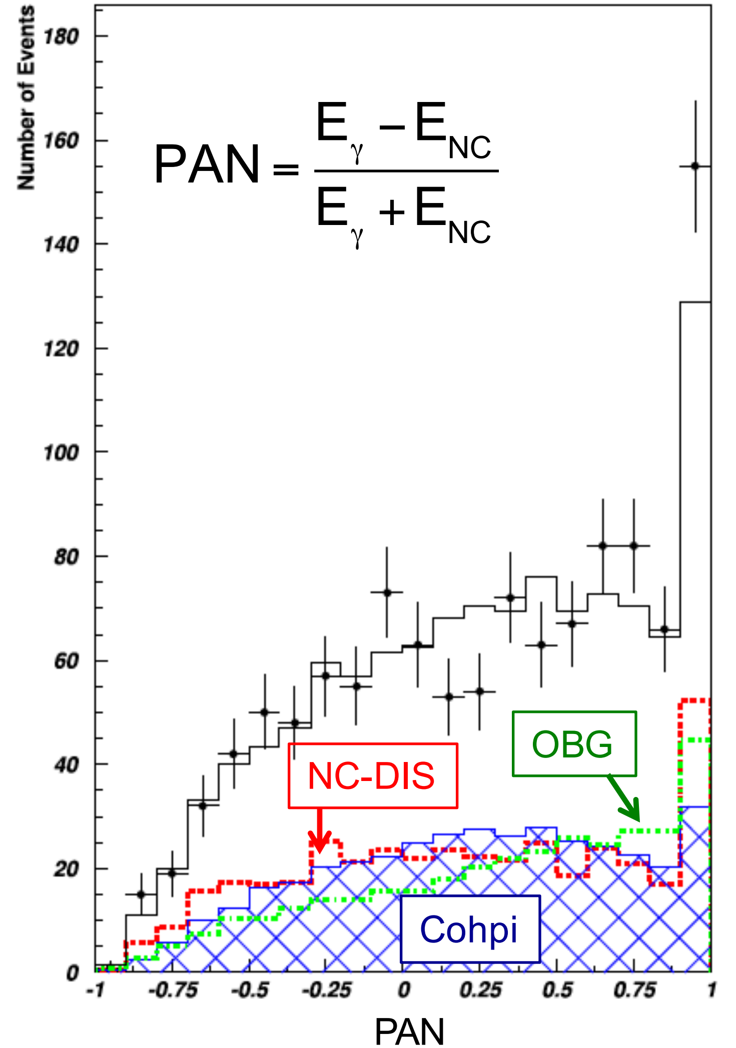
Selection of gamma event candidate

- single e^+-e^- pair
- fiducial cut
- W<50 MeV

3 major backgrounds

- NC coherent π^o production (Cohpi)
  → Cohpi model in MC is tuned to the distribution of measured 2γ sample
- outside of fiducial volume background (OBG)
  → Data sample outside of fiducial volume is used for normalization
- NC-DIS π^o production (NC-DIS)
  → Tune using the region $\zeta_\gamma=E_\gamma(1-\cos\theta_\gamma)>0.5$

no excess is found,
set limit, $xs(NC\gamma/CC) < 4\times10^{-4}$



3. NOMAD

Result

- no excess is found, set limit, xs($NC\gamma/CC$) < 4×10^{-4}

Lesson

- There will be 2 types of backgrounds, internal and external background

- internal background is dominated by $NC\pi^o$ production with single γ final state
- external background is γ coming from outside of the fiducial volume (also mostly π^o origin)

1. Neutrino oscillation experiments

2. Motivation

3. Past single photon searches

4. Future single photon searches

5. Conclusion

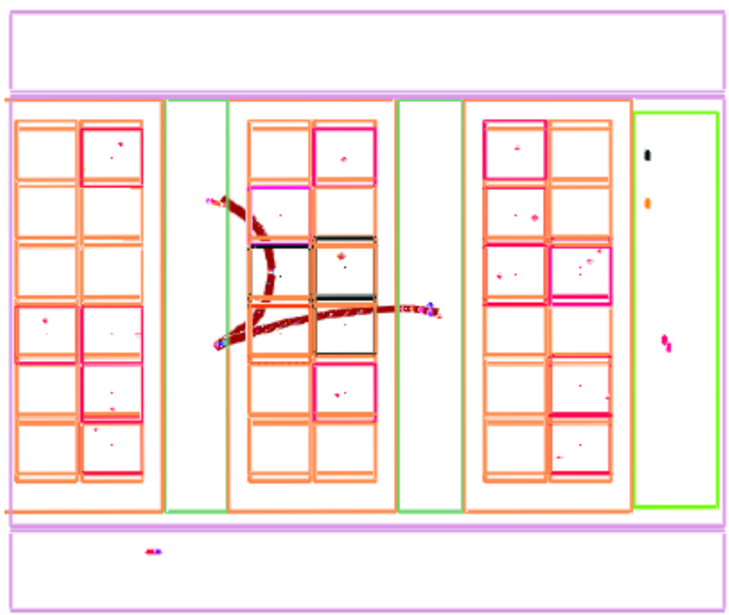
T2K, NIMA659(2011)106
Caravaca, PhD thesis (2014)

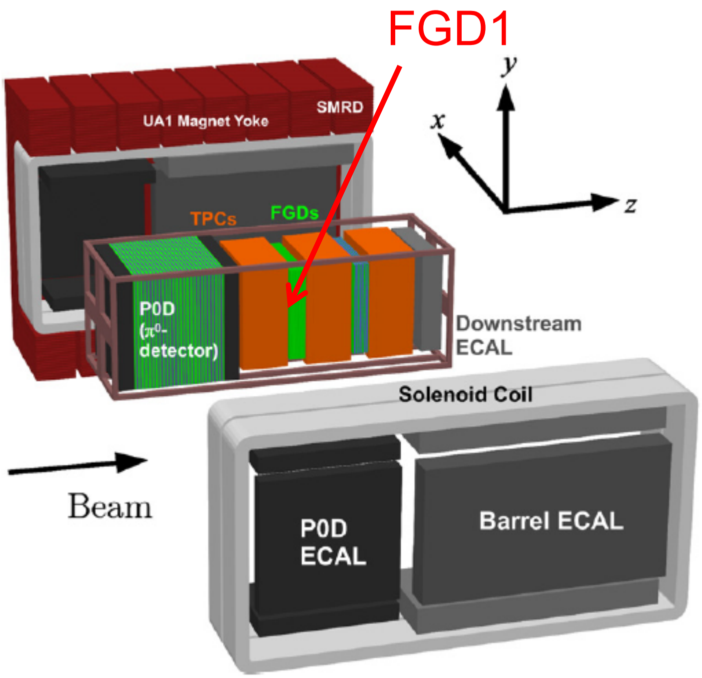
4. Single photon measurement in T2K

Fine Grained Detector (FGD1)

- The main vertex detector of ND280
- extruded scintillator+WLS fiber X-Y tracker
- $2.3 \times 2.4 \times 0.4 m^3$, fiducial volume (1.1 ton)

γ candidate in FGD1





4. Single photon measurement in T2K

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- extruded scintillator+WLS fiber X-Y tracker
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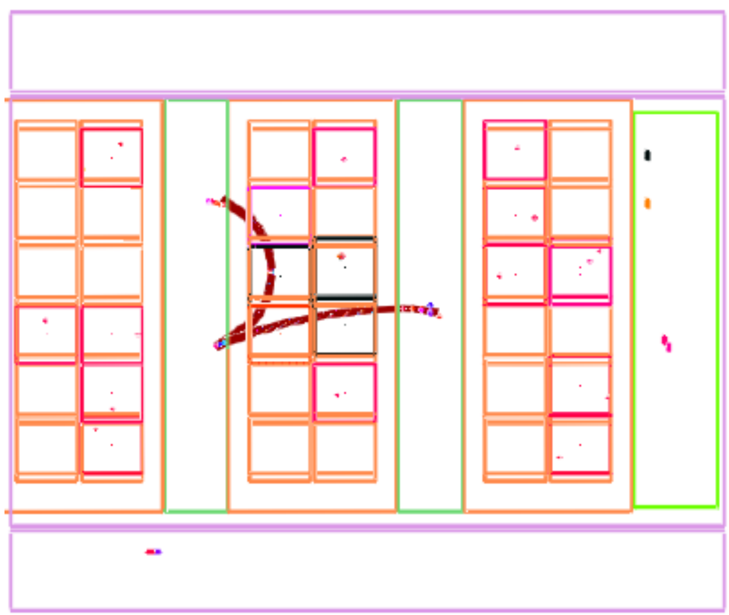
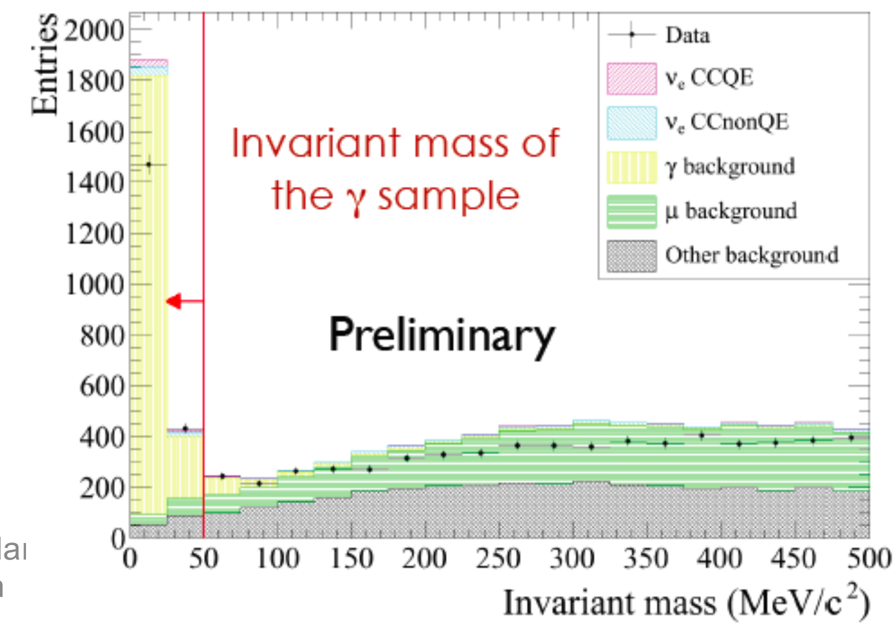
γ candidate in FGD1



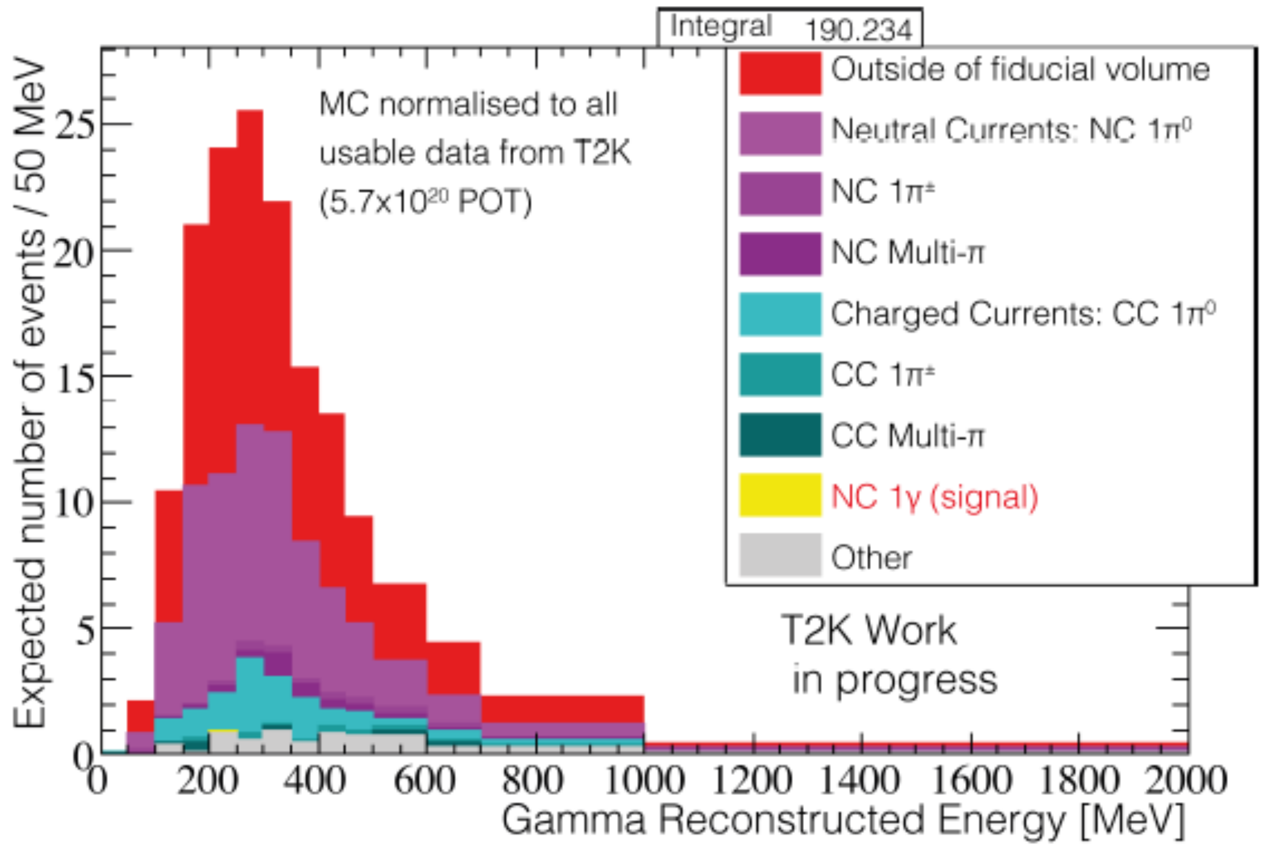
e^+ and e^- tracks are reconstructed, invariant mass is reconstructed
→ >95% purity gamma sample



4. Single photon measurement in T2K

Gamma selection in FGD1

- 95% pure gamma ray sample
  → half is $NC1\pi^o$ with one gamma missing (internal background)
  → other half is from outside of fiducial volume (external background)



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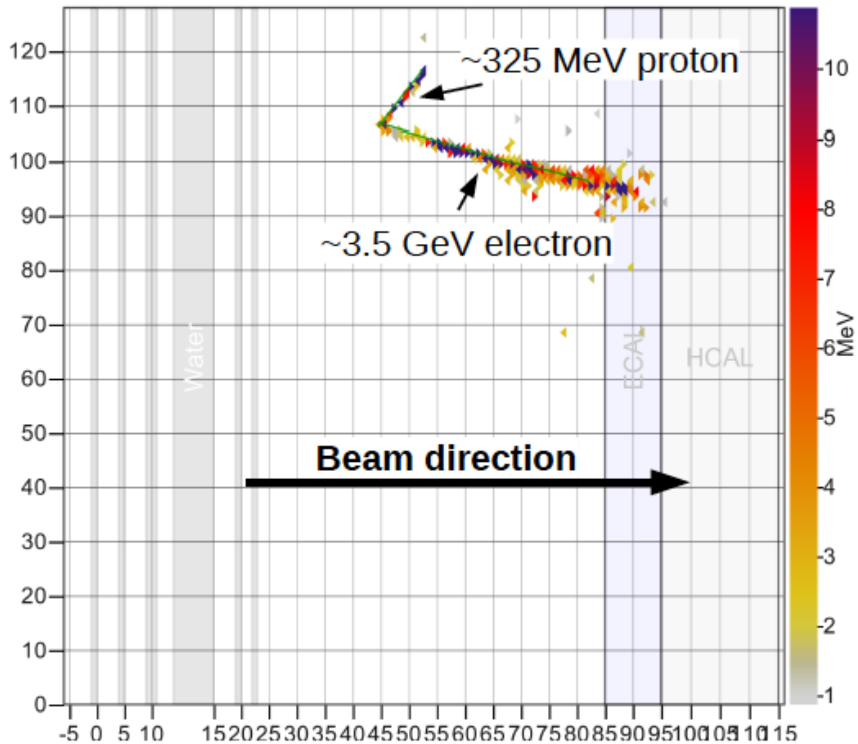
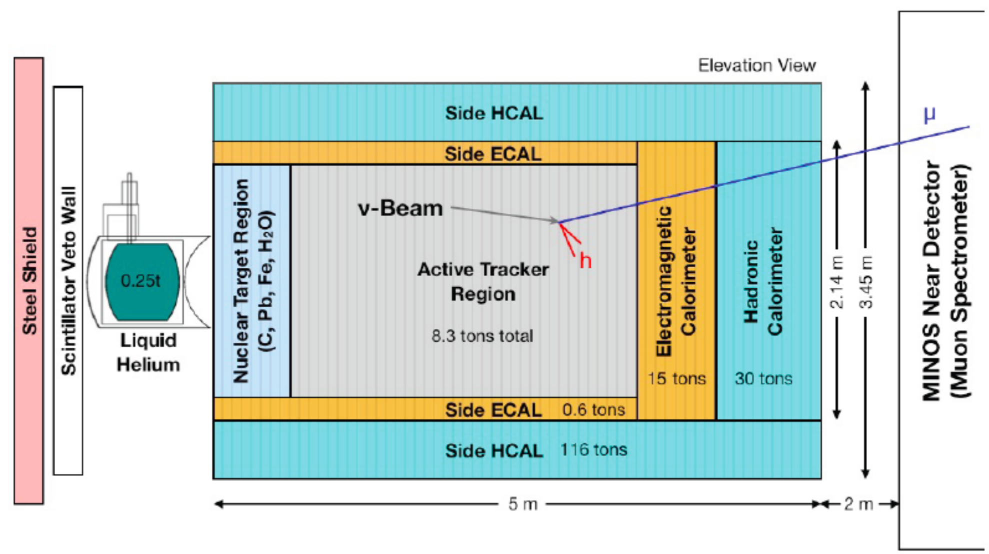
4. Single photon measurement in MINERvA

MINERvA ν_eCCQE analysis

- The main vertex detector is extruded scintillator+WLS fiber U-V tracker
- Fiducial volume is (5.57 ton)

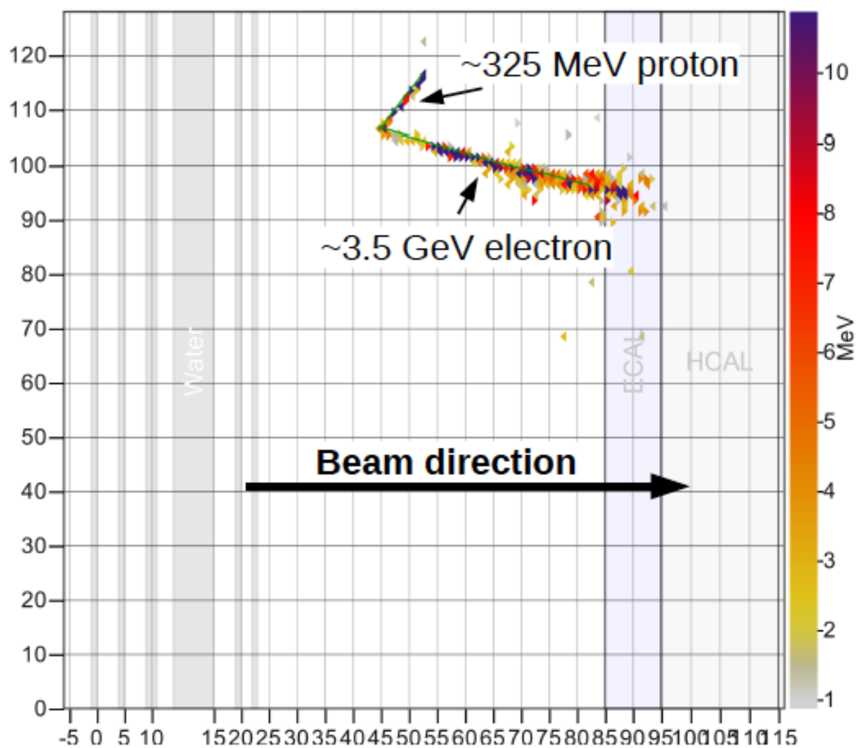


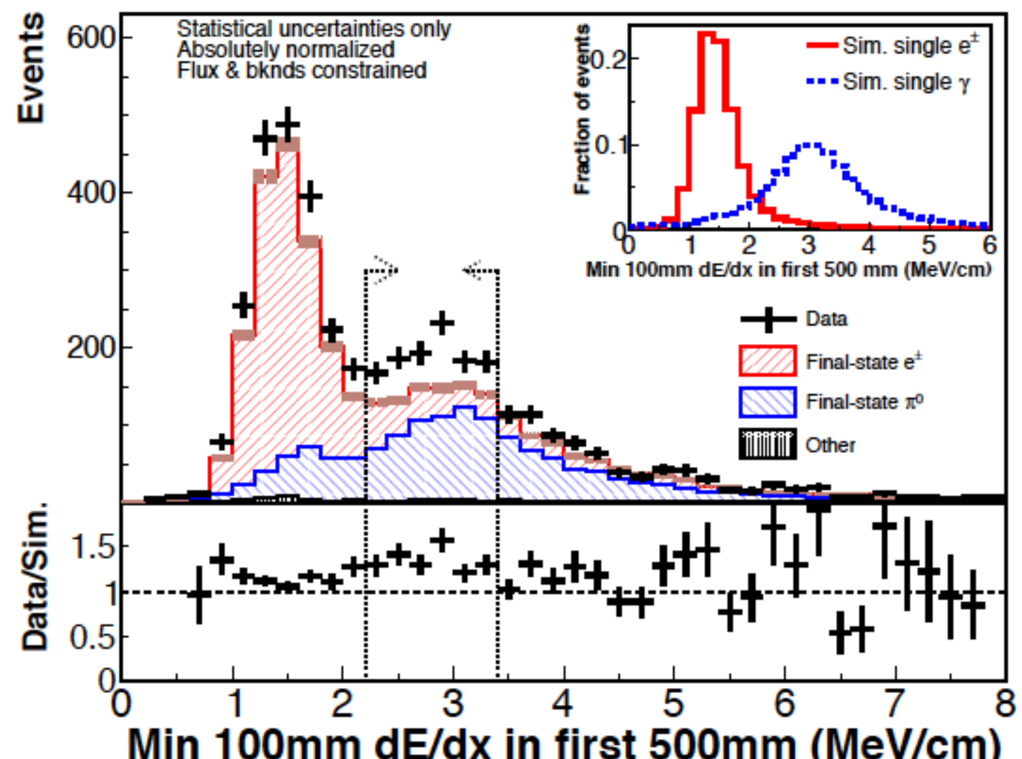


4. Single photon measurement in MINERvA

MINERvA ν_eCCQE analysis

- The main vertex detector is extruded scintillator+WLS fiber U-V tracker
- Fiducial volume is (5.57 ton)
- no magnetic field, but good e/γ separation by dE/dx
- photon samples are dominated various π^o background



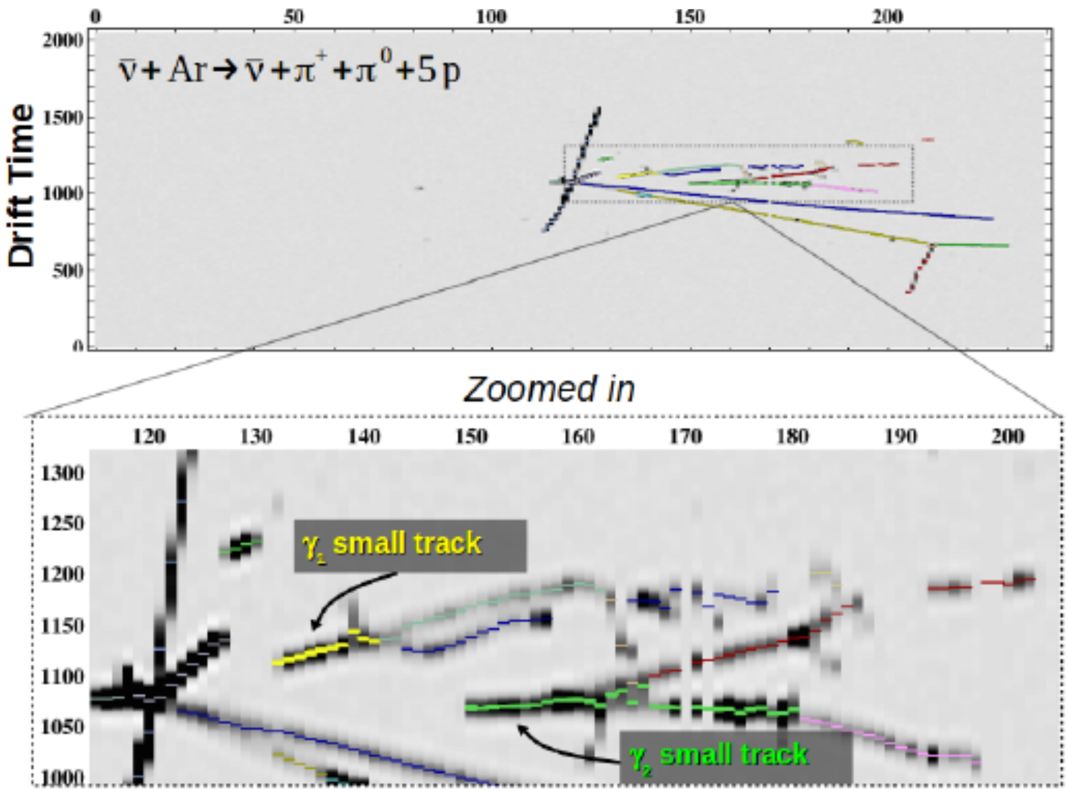


3. Single photon measurement in MicroBooNE

Liquid Argon Time Projection Chamber (LArTPC)

- Modern bubble chamber, amazing resolution
- 2.3x2.6x10.4m^3 (86 ton TPC volume), fiducial volume may be smaller than that
- ArgoNeuT demonstrated shower event measurement and π^o reconstruction

ArgoNeuT π^o candidate



3. Single photon measurement in MicroBooNE

Liquid Argon Time Projection Chamber (LArTPC)

- Modern bubble chamber, amazing resolution
- $2.3 \times 2.6 \times 10.4 m^3$ (86 ton TPC volume), fiducial volume may be smaller than that
- ArgoNeuT demonstrated shower event measurement and π^o reconstruction

LArTPC has excellent e/γ separation, but it's not clear how to remove single photon background from π^o

Seems all detectors have problem to reject photon background from π^o

	γ reconstruction	internal background	external background	status
NOMAD	magnet	DIS, RES, COH π^o	large	done
T2K	magnet	RES, COH π^o	very large	running
MINERvA	dE/dx	DIS, RES, COH π^o	large?	running
MicroBooNE	LArTPC	RES, COH π^o?	large?	running

1. Neutrino oscillation experiments

2. Motivation of ALPs search in neutrino experiments

3. Single photon searches in neutrino experiments

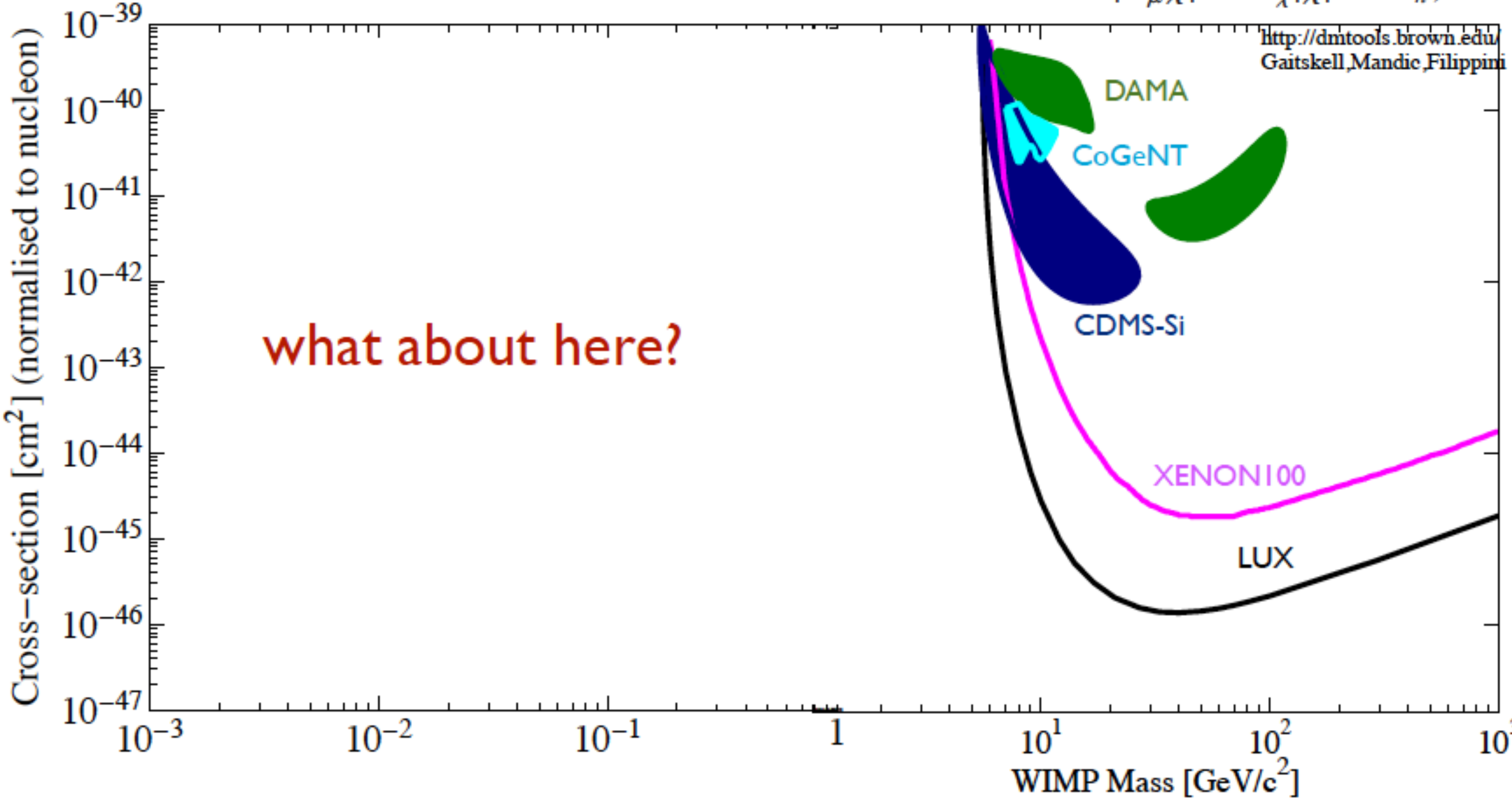
4. Light WIMP search in MiniBooNE

5. Conclusion

4. Light WIMP search in MiniBooNE

Light WIMP with new U(1) gauge boson (dark photon)
- Candidate of cold dark matter
- Not accessible with direct dark matter techniques

$$\mathcal{L}_{V,\chi} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu F^{\mu\nu} + |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'},$$



Thornton, arXiv:1411.4311

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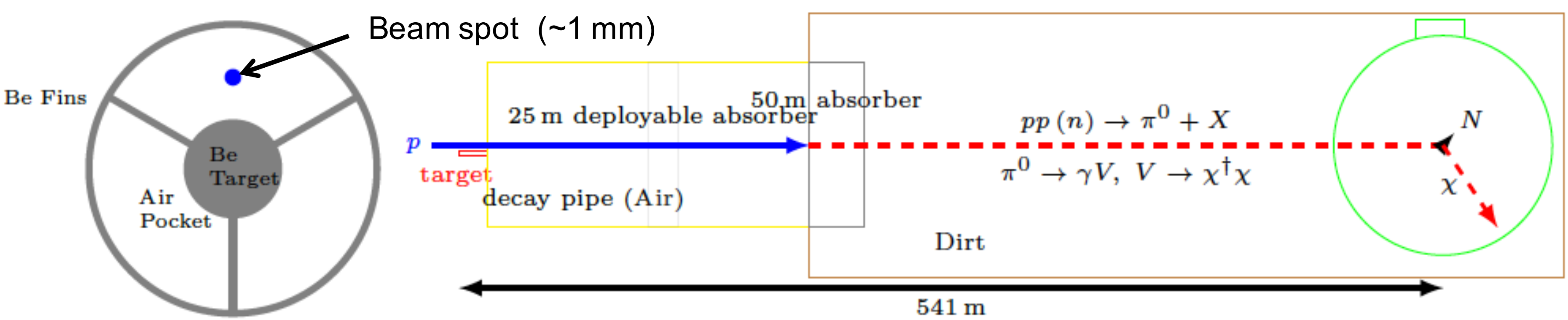
MiniBooNE beam dump mode

- beam is steered to avoid the target and hit the iron beam dump 50m away.
- event signature is nucleon recoil

$\chi + X \rightarrow \chi + NX'$ (scintillation)

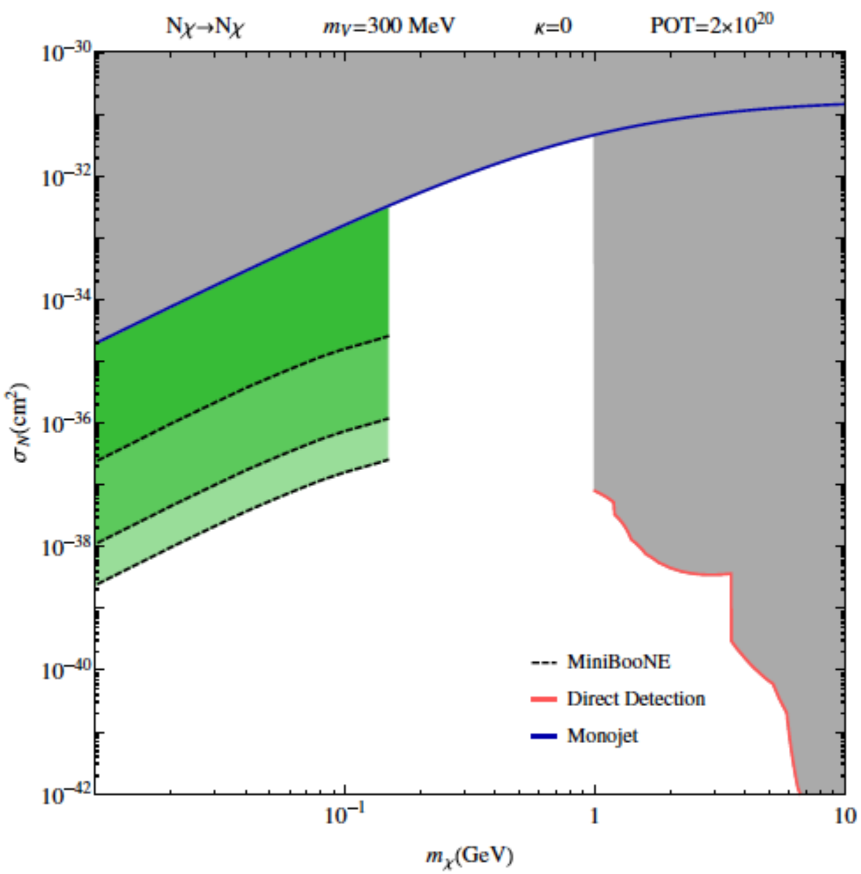


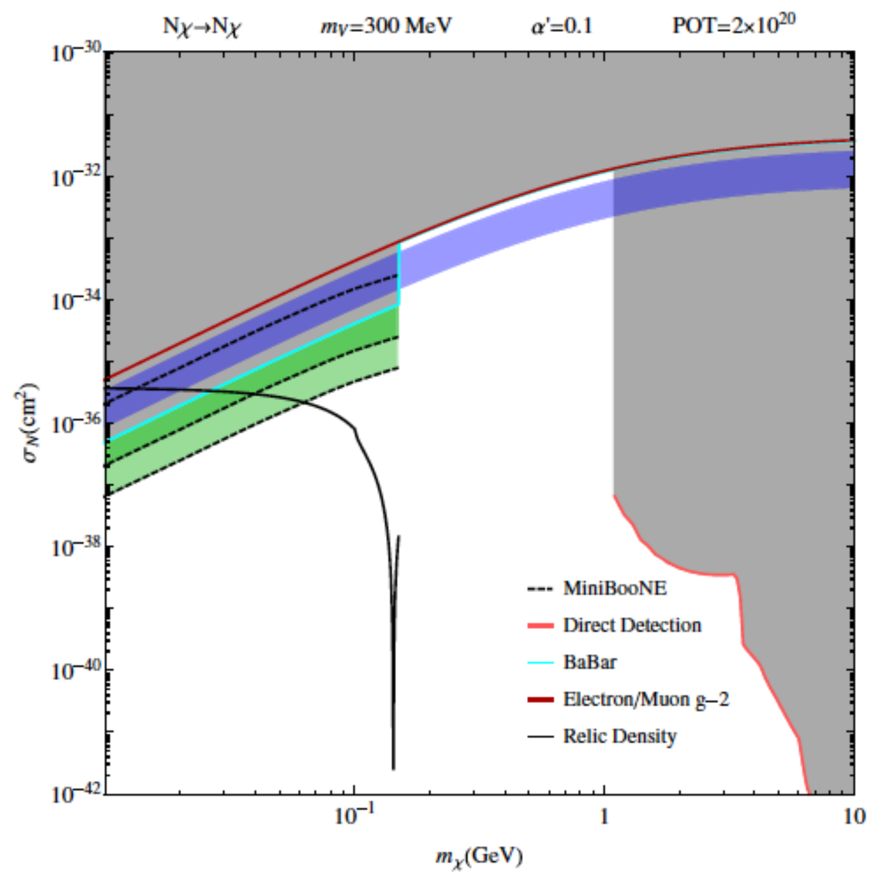
4. Light WIMP search in MiniBooNE

Phase space

$$\mathcal{L}_{V,\chi} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu F^{\mu\nu} + |D_\mu \chi|^2 - m_\chi^2|\chi|^2 + \mathcal{L}_{h'},$$

BATELL *et al.* PHYSICAL REVIEW D 90, 115014 (2014)





4. Light WIMP search in MiniBooNE

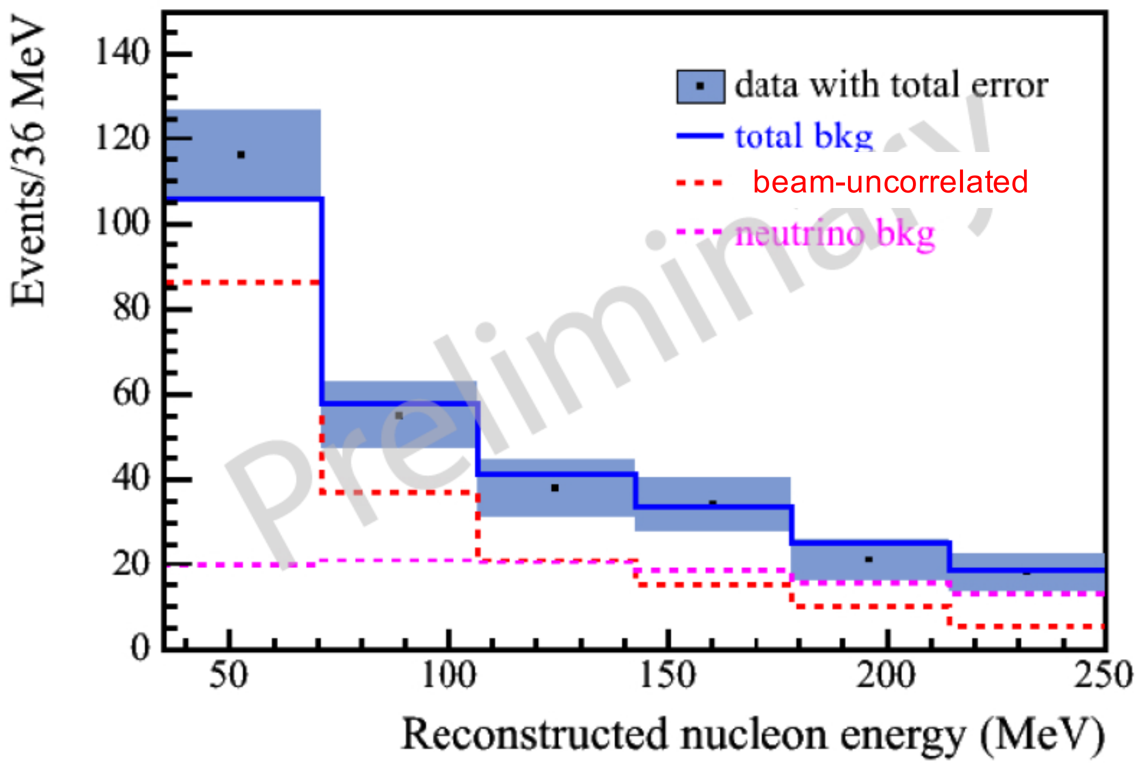
First 30% of beam-dump mode data
- Total data ~2E20POT
- The first result will be ~2016

$$\mathcal{L}_{V,\chi} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu F^{\mu\nu} + |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'},$$

Nucleon kinetic energy

2 types of backgrounds
- beam-uncorrelated events
- neutrino interactions (neutral current elastic scattering)

Very conservative systematic errors are assigned.



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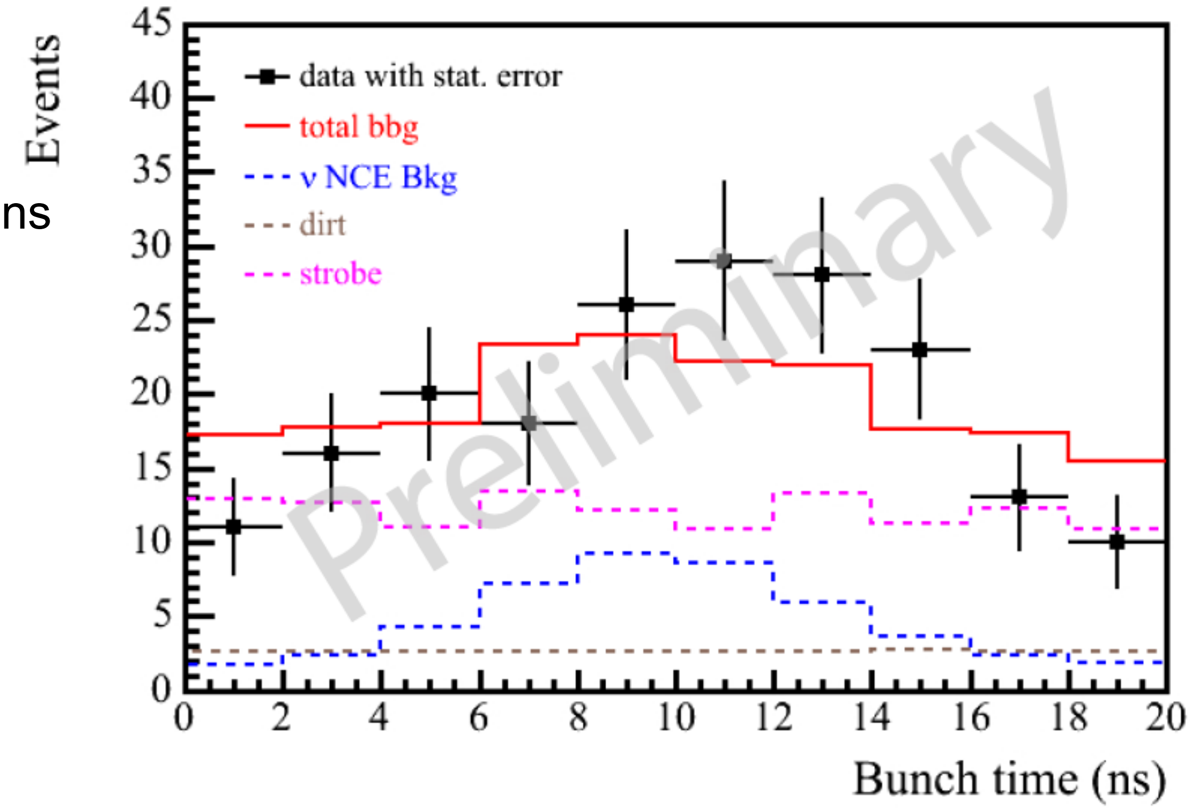
Dark matter TOF
- dark matter is slower than ν
- Booster bunch separation~19ns



5. Conclusions

Accelerator-based neutrino physics is the future of particle physics

Neutrino physics around 1-10 GeV does not have enough topics, and part of the community can contribute ALPs searches

There are many efforts to understand NC-like photon in neutrino detectors, both theoretically and experimentally, for ν_e appearance search

It is not clear any of near future neutrino experiments can perform interesting measurement on ALPs

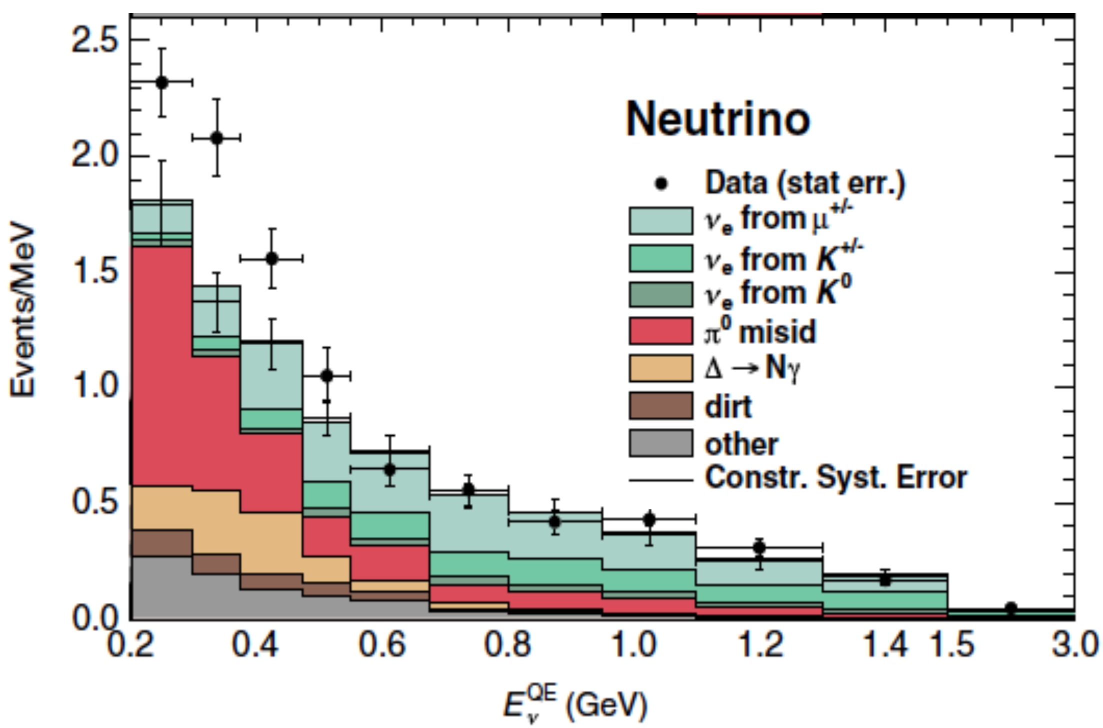
Thank you for your attention!

Backup

1. MiniBooNE

NCγ, as ν_e appearance background
- all generators estimate NCγ from radiative Δ-decay $\Delta \rightarrow N\gamma$
- cross section is roughly ~0.5% of NC1π^o channel

MiniBooNE
- Final oscillation paper estimates NCγ is roughly ~20% of NCπ^o background in ν_e candidate sample.
- To explain all excess by NCγ, NCγ cross section needs to be higher x2 to x3.

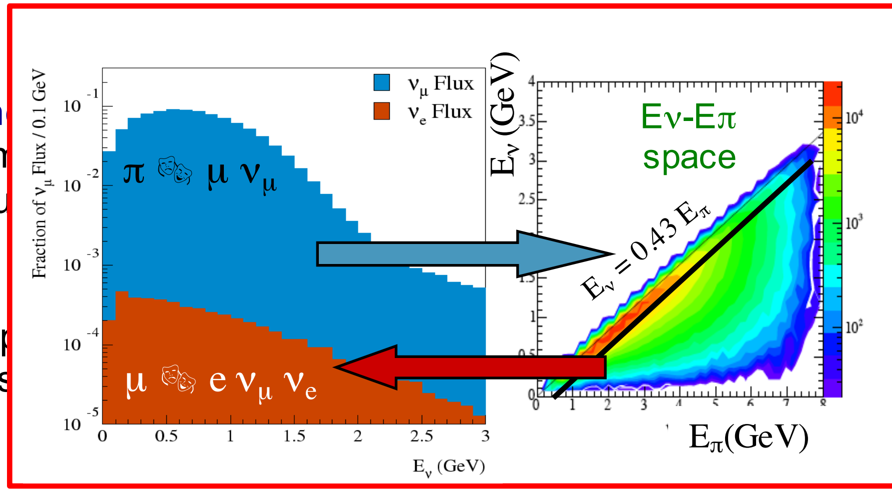


MiniBooNE Collaboration, PRL110(2013)161801

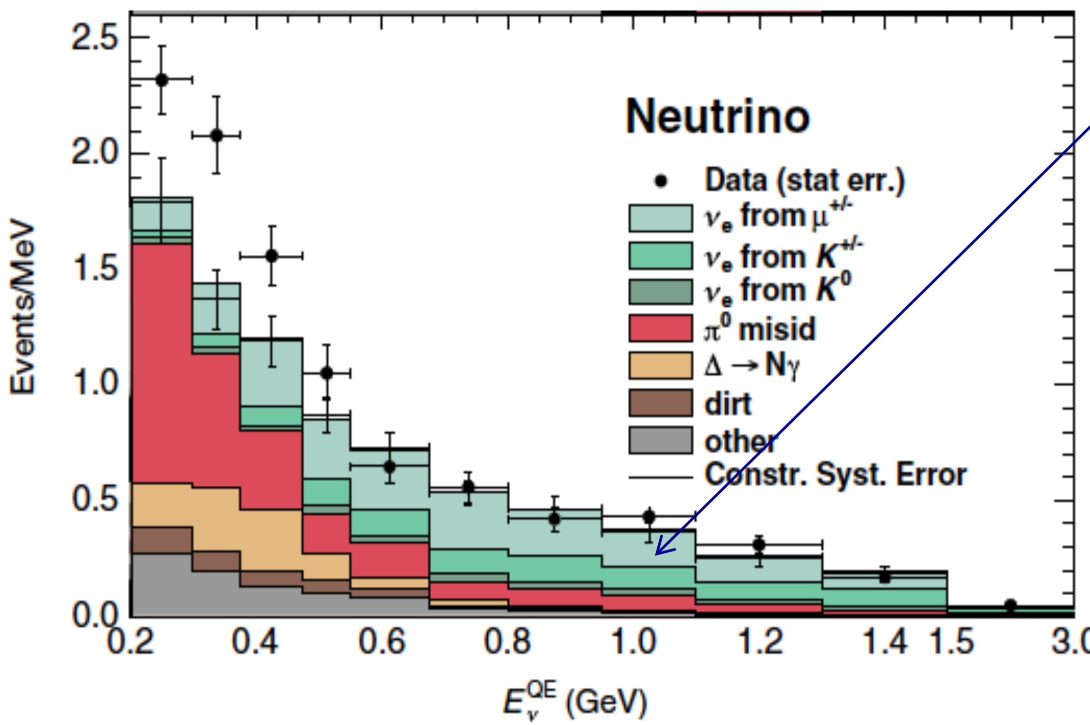
1. MiniBooNE

NCγ, as ν_e appearan
- all generators estim
- cross section is rou

MiniBooNE
- Final oscillation pap ... d in ν_e candidate sample.
- To explain all exces ... x3.



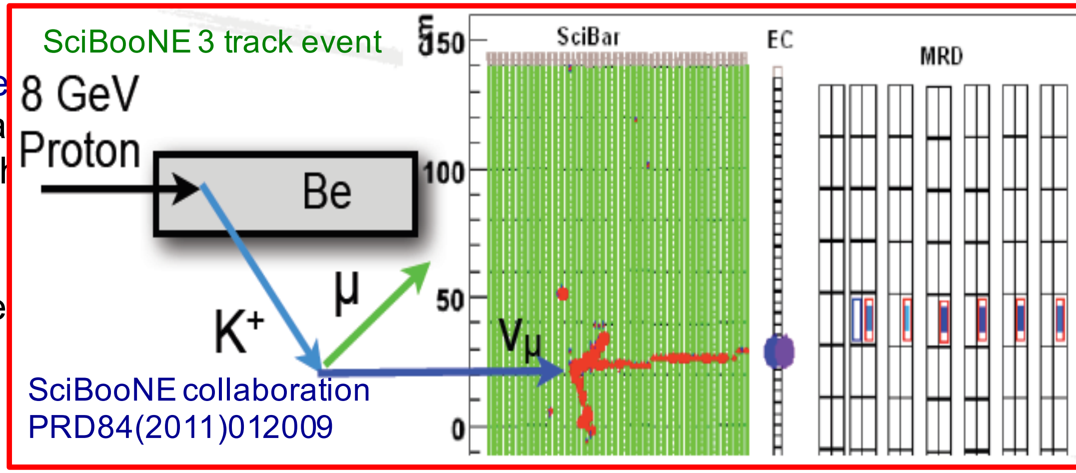
ν_e from μ decay is constrained from ν_μCCQE measurement



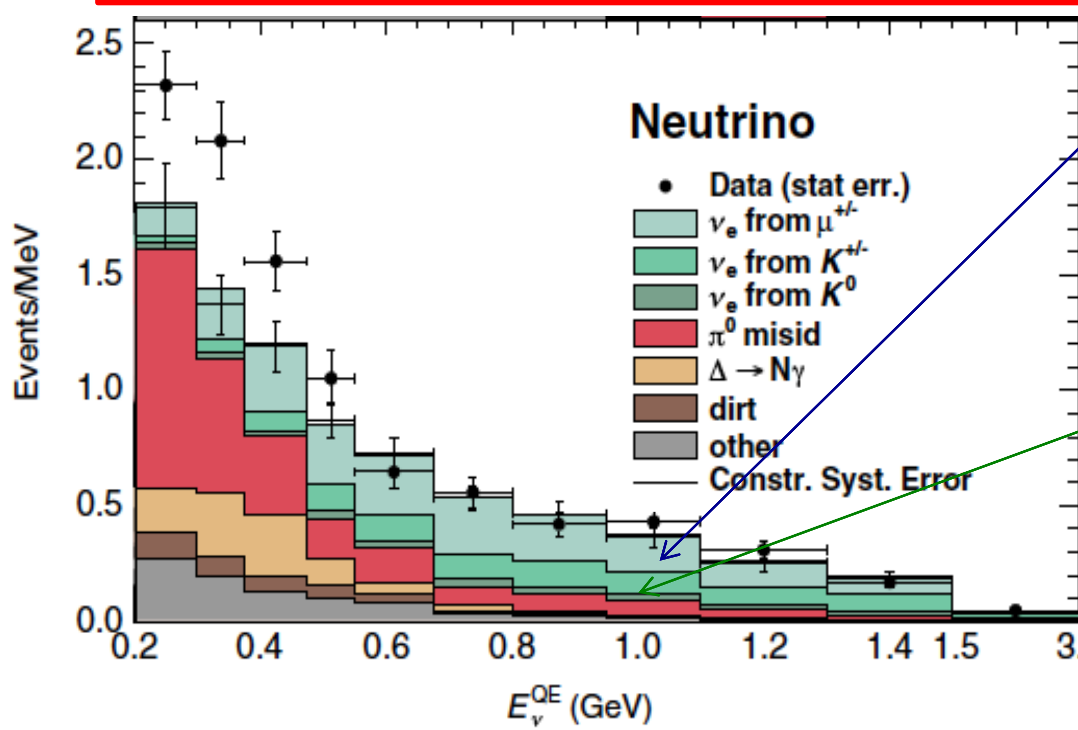
1. MiniBooNE

NCγ, as ν_e appearance
- all generators estima
- cross section is rough

MiniBooNE
- Final oscillation pape ate sample.
- To explain all excess



om μ decay is
strained from
ν_μCCQE measurement

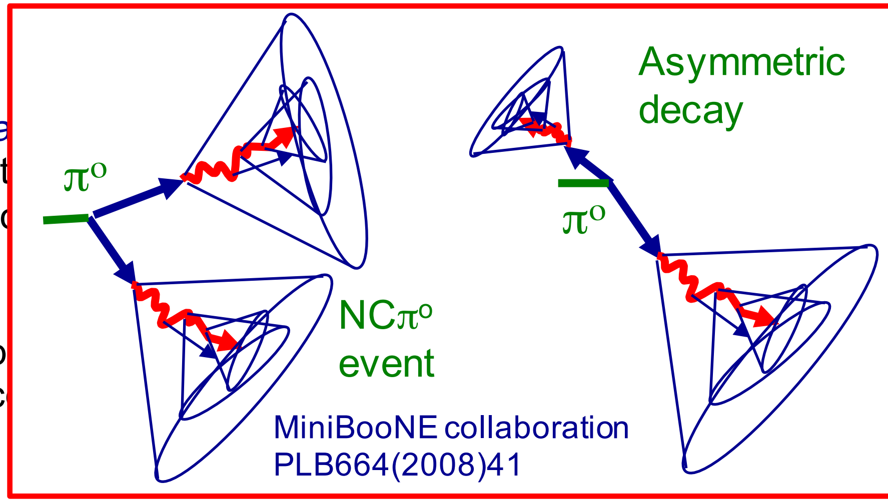


ν_e from K decay is
constrained from
high energy ν_μ event
measurement in
SciBooNE

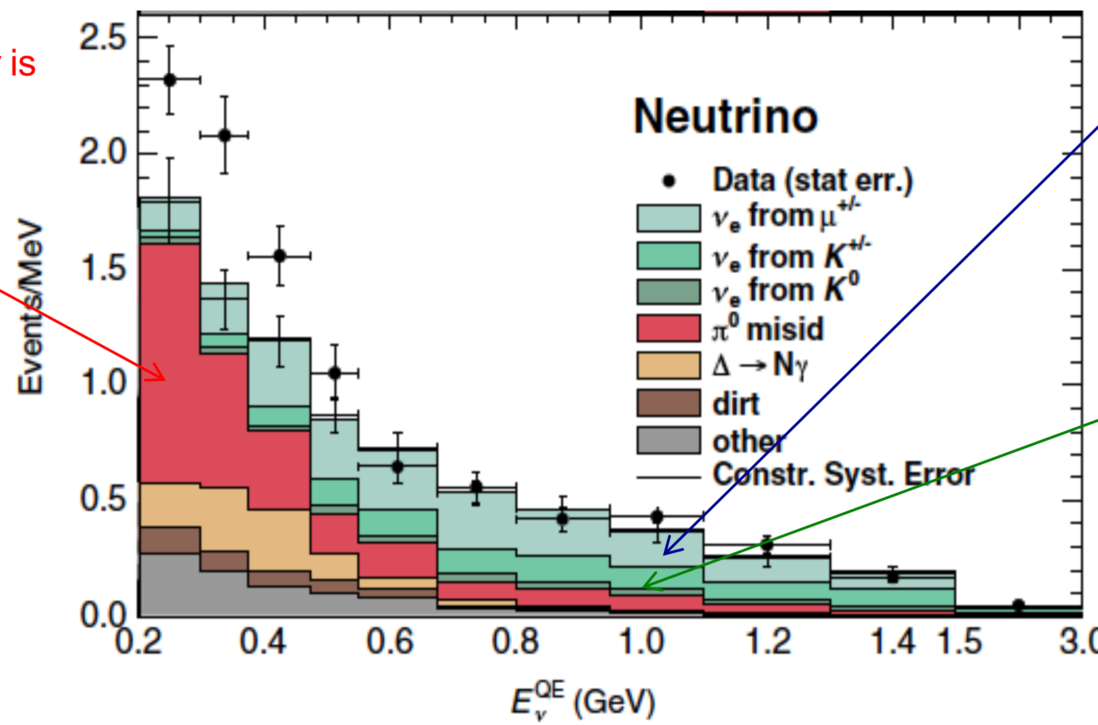
1. MiniBooNE

NCγ, as ν_e appeara
- all generators est
- cross section is ro

MiniBooNE
- Final oscillation p ... und in ν_e candidate sample.
- To explain all exc ... o x3.



Asymmetric πº decay is constrained from measured CCπº rate (πº→γ)



ν_e from μ decay is constrained from ν_μCCQE measurement

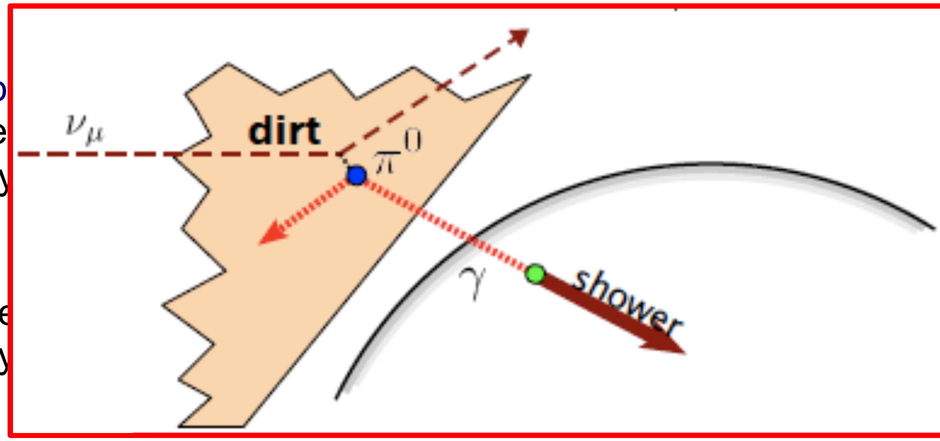
ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE

MiniBooNE Collaboration, PRL110(2013)161801

1. MiniBooNE

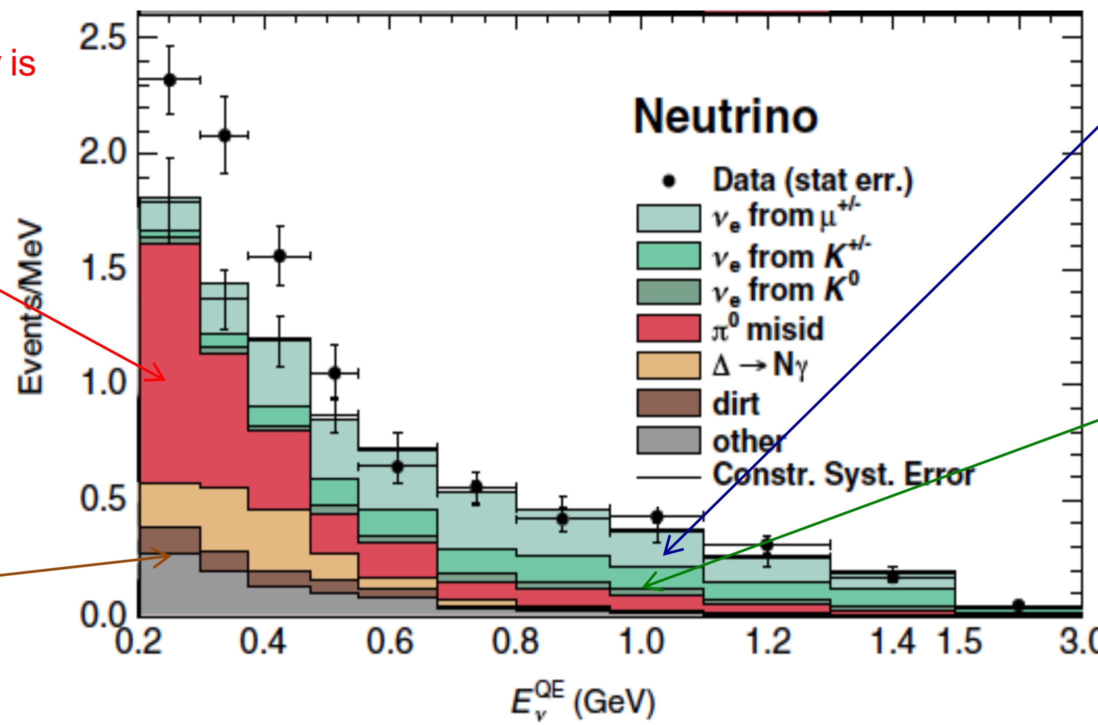
NCγ, as ν_e appearance b
- all generators estimate
- cross section is roughly

MiniBooNE
- Final oscillation paper e ... candidate sample.
- To explain all excess by



ν_e from μ decay is constrained from ν_μCCQE measurement

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)



ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE

dirt rate is measured from dirt enhanced data sample

1. MiniBooNE

NCγ, as ν_e appearance background
- all generators estimate NCγ from
- cross section is roughly ~0.5% of

$$\frac{N_C(\Delta \to N\gamma)}{N_C(\Delta \to N\pi^0)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^0}\varepsilon}$$

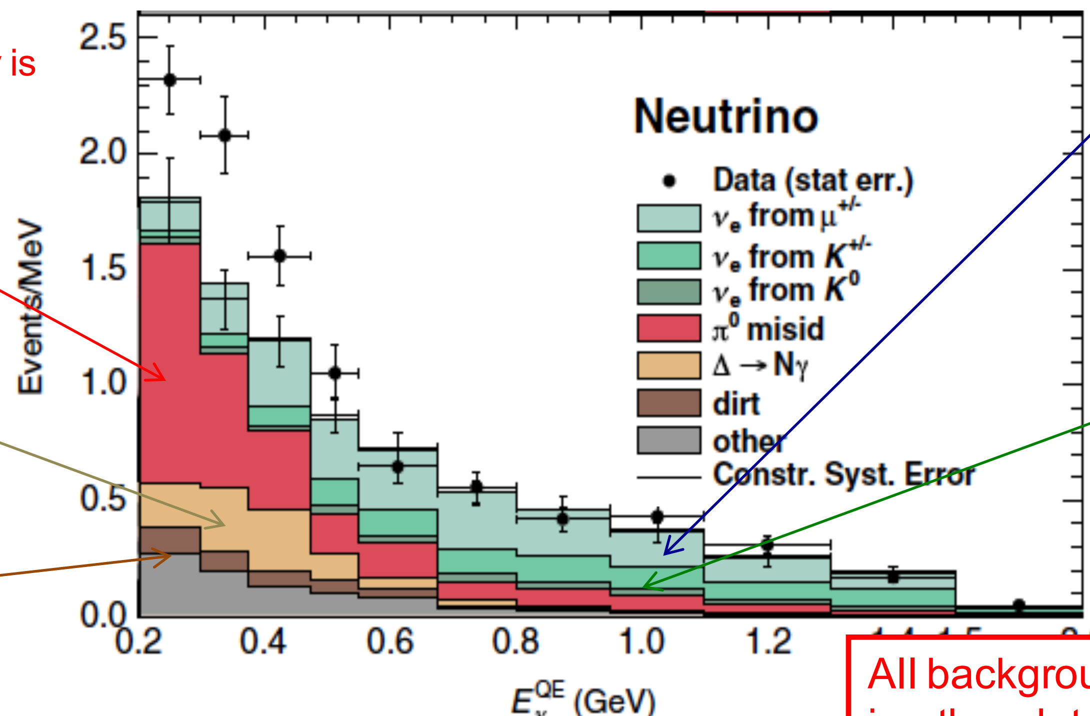
$\Gamma\gamma/\Gamma\pi$: NCγ to NCπ branching ratio
π^o fraction (=2/3)
ε: π escaping factor

MiniBooNE
- Final oscillation paper estimates N... und in ν_e candidate sample.
- To explain all excess by NCγ, NC... o x3.

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \to \gamma$)

Radiative Δ-decay ($\Delta \to N\gamma$) rate is constrained from measured NCπ^o

dirt rate is measured from dirt enhanced data sample



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_μ event measurement in SciBooNE

All backgrounds are measured in other data sample and their errors are constrained.

Queen Mary University of London

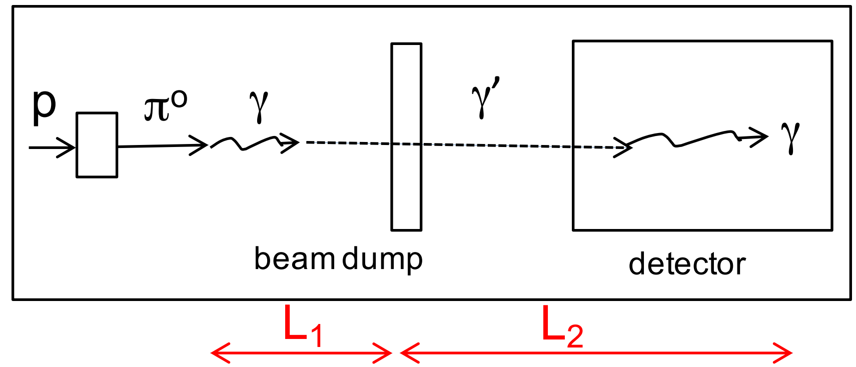
ALPS, PLB689(2010)149
T2K,PRD87(2013)012001

2. LSW experiment with magnetic field

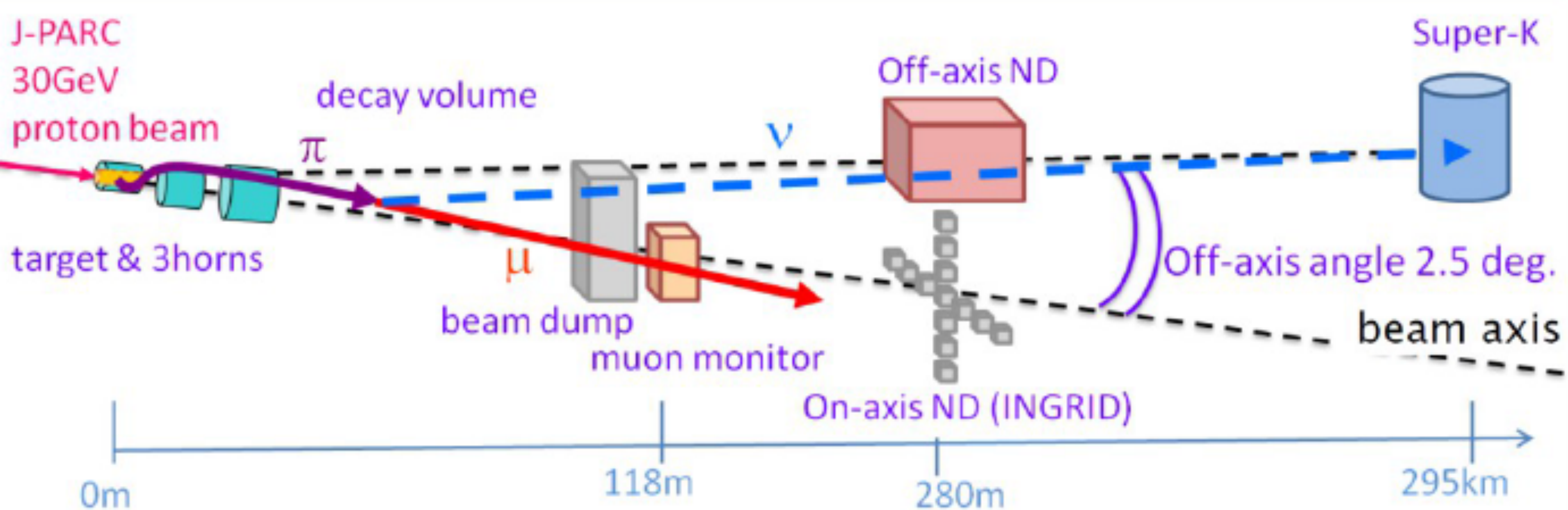
ALPs
- Light-Shining-Through-the-Wall type experiment
- photon-dark photon oscillation

T2K
- 1.7T toroidal field to focus mesons (total 6m horn)
- ~280m of dirt
- 0.2T dipole magnet in the near detector

dark photon oscillation?



$$P_{\rm trans} = 16\chi^4\left[\sin\left(\frac{\Delta k L_1}{2}\right)\sin\left(\frac{\Delta k L_2}{2}\right)\right]^2$$

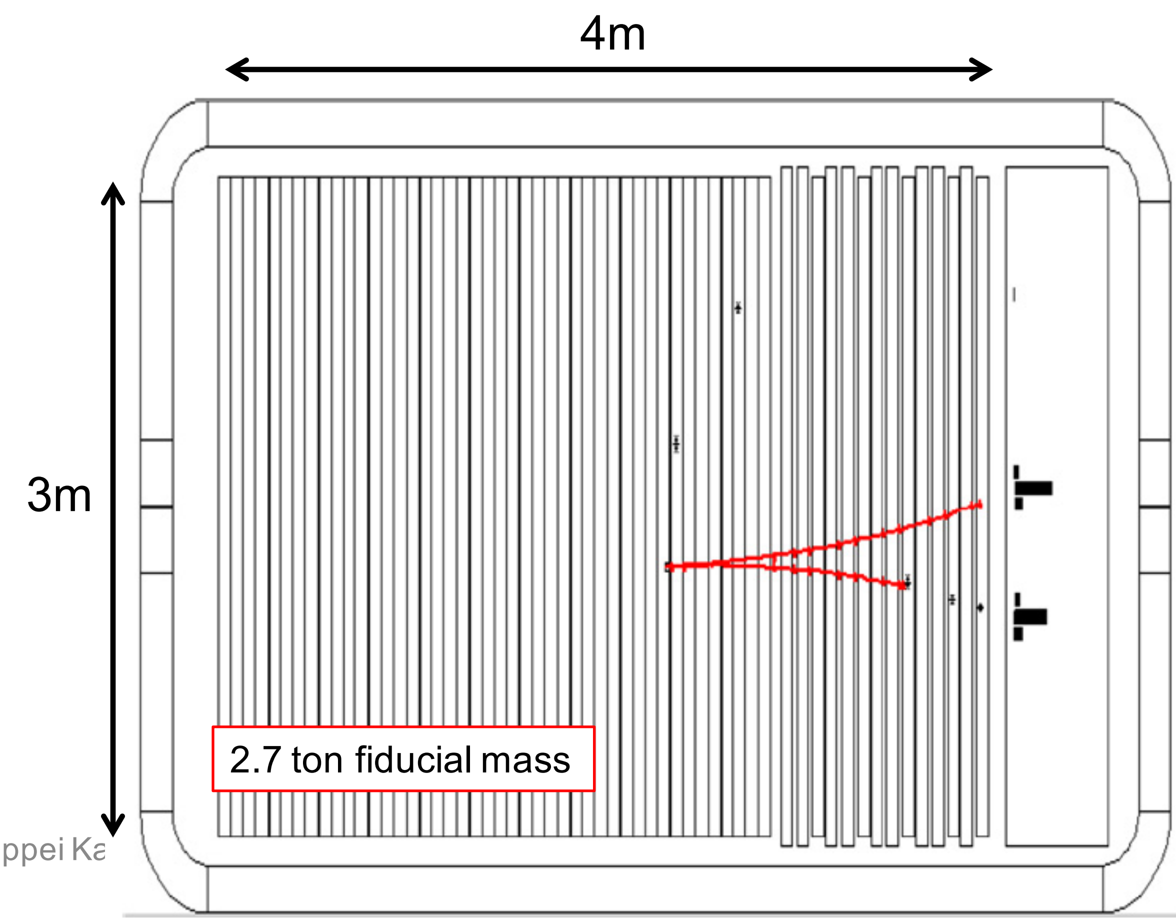


3. NOMAD

Single gamma search

Very simple, but robust analysis. They identified all issues on this measurement.

- single e^+-e^- pair
- fiducial cut
- W<50 MeV



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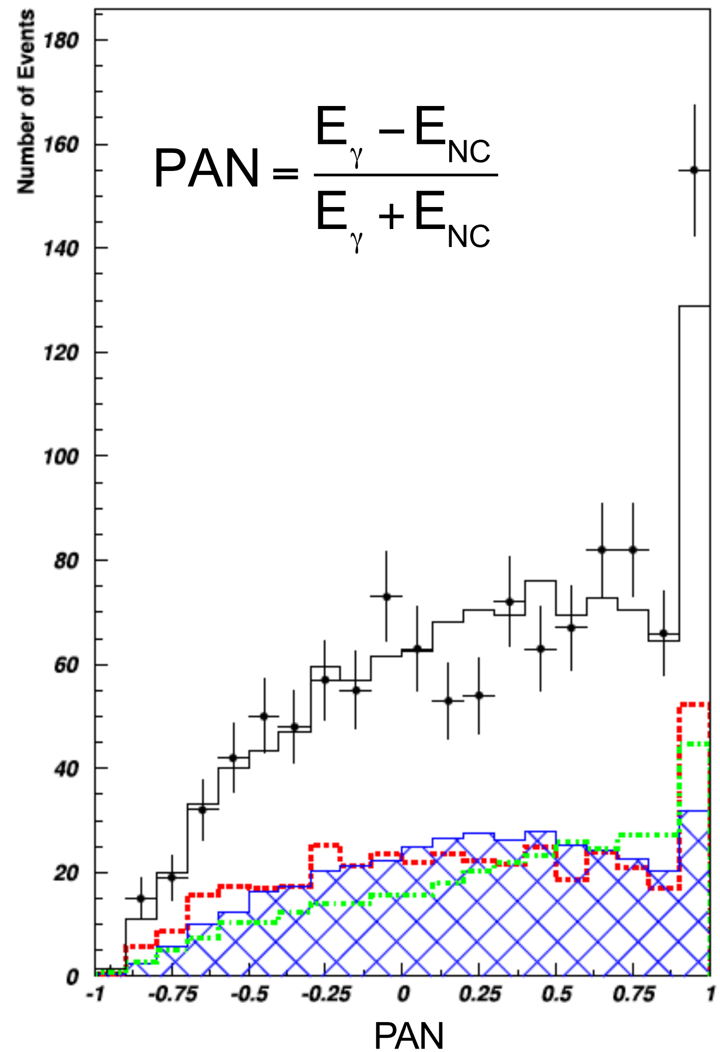
PAN=measure of energy asymmetry between E_γ and E_{NC}

- E_γ = measured gamma energy
- E_{NC} = ECAL energy deposit by neutral particles

PAN is big → less likely to be DIS and more interesting data



$$PAN = \frac{E_\gamma - E_{NC}}{E_\gamma + E_{NC}}$$

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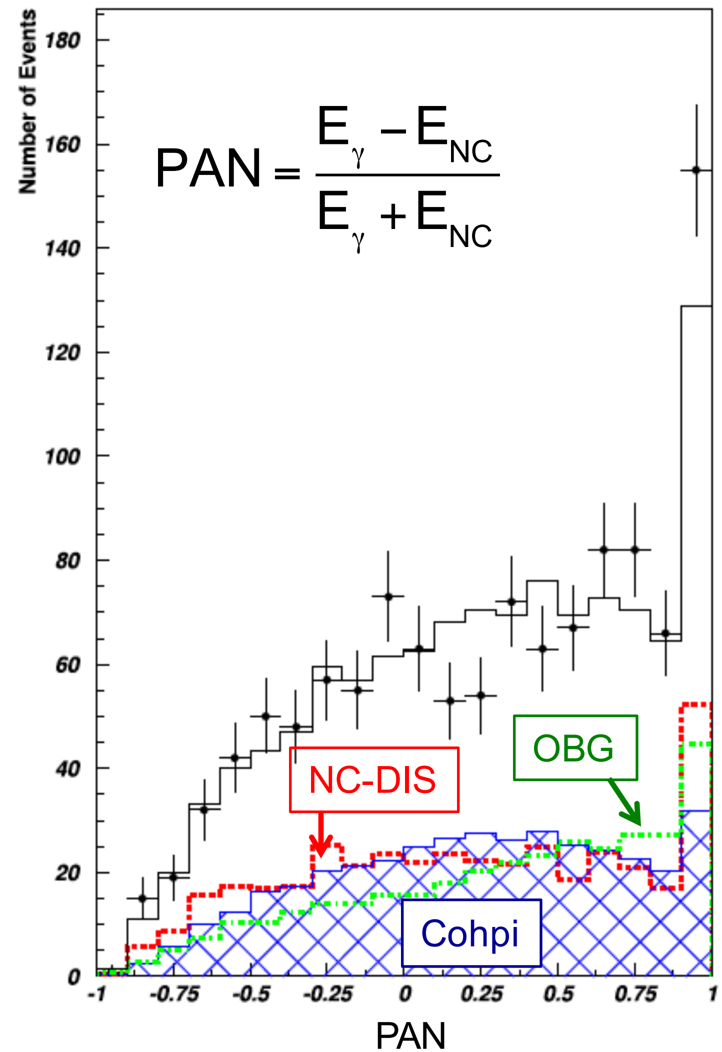
- E_γ = measured gamma energy
- E_{NC} = ECAL energy deposit by neutral particles

Signal box is defined to be PAN>0.9

3 major backgrounds

- NC coherent π^o production (Cohpi)
- outside of fiducial volume background (OBG)
- NC-DIS π^o production (NC-DIS)



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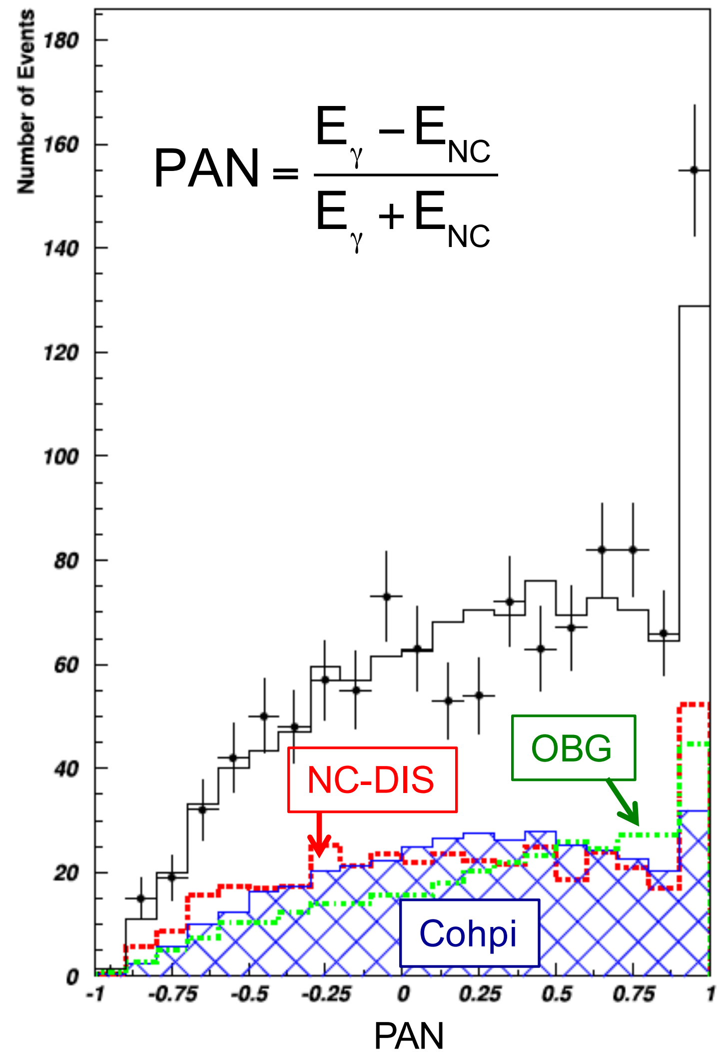
- E_γ = measured gamma energy
- E_{NC} = ECAL energy deposit by neutral particles

Signal box is defined to be PAN>0.9

3 major backgrounds
- NC coherent π^o production (Cohpi)
  → Cohpi model in MC is tuned to the distribution of measured 2γ sample
- outside of fiducial volume background (OBG)
  → Data sample outside of fiducial volume is used for normalization
- NC-DIS π^o production (NC-DIS)
  → Tune using the region $\zeta_\gamma = E_\gamma(1-\cos\theta_\gamma) > 0.5$



3. NOMAD

Result
- no excess, set limit, xs(NCγ/CC) < 4×10^{-4}

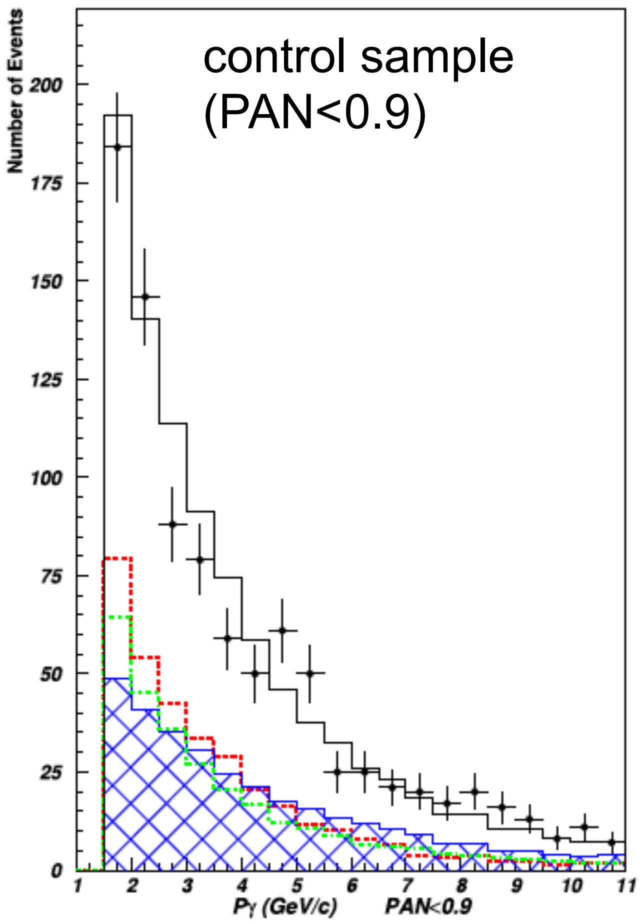


Fig. 3. Comparison of P_γ between data and MC in PAN < 0.9 region.

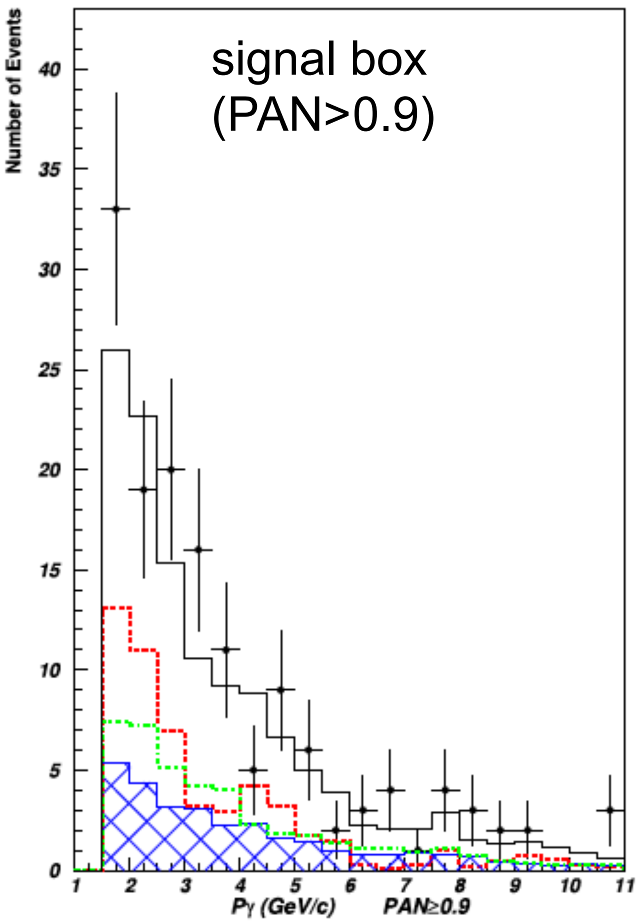


Fig. 5. Comparison of P_γ between data and MC in Box1, PAN ⩾ 0.9 region.

3. NOMAD

Result
- no excess, set limit, xs(NCγ/CC) < $4\text{x}10^{-4}$

Lesson
- There will be 2 types of backgrounds, internal and external background

- internal background is dominated by NCπ^o production with single γ final state
  → NCπ^o production rate needs to be constraint from the own data

(In general, NCγ cross section is ~0.5% of NCπ^o, so you need to reject 99% of π^o with 10% error, then NCγ would be ~2σ significance (assuming no other background)

- external background is γ coming from outside of the fiducial volume (also mostly π^o origin)
  → External background needs to be tuned from the own data
  → 3mx3mx4m is not big enough to suppressed external background