NuFact 2013
Summary

Karol Lang
University of Texas at Austin
August 24, 2013

Confession

Past Workshop

1999 IPNL Lyon France http://www.ipnl.in2p3.fr/nufact99/
2000 UCBerkeley Monterey California USA
2001 Tsukuba Japan
2002 Imperial College London UK http://www.hep.ph.ic.ac.uk/NuFact02/
2003 Columbia University New York USA http://www.cap.bnl.gov/nufact03/
2004 Osaka University Japan
2005 INFN Frascati Italy http://www.lnf.infn.it/conference/2005/nufact05/
2006 UC Irvine California USA
2007 University of Okoyama Japan http://fphy.hep.okayama-u.ac.jp/nufact07/
2008 University of Valencia Spain http://ific.uv.es/nufact08/
2009 IIT and Fermilab Chicago USA http://nufact09.iit.edu/
2010 Tata Institute Mumbai India http://www.tifr.res.in/~nufact2010/
2011 Geneva Switzerland http://NUFACT11.unige.ch
2012 Jefferson Lab http://www.jlab.org/conferences/nufact12/

… I have not been the most attentive student… but:

"You can observe a lot by just watching." (Yogi Berra)

Summary of …

- WG1 – neutrino oscillations
- WG2 – neutrino-nucleon scatering
- WG3 – accelerator physics
- WG4 – Muon physics
- Plenaries
- IHEP visit
- Coffee breaks
- Posters
- Chitchats

NuFact2013 Agenda

	Sun 18	Mon 19	Tue 20	Wed 21	Thu 22	Fri 23	Sat 24
AM1 1.5 h		Plenary#1 overview	Plenary#4 Acc.+intro	Parallel#4 1-2-J34	Parallel#7 1-2-J34	Plenary#7 scat.	Plenary#8 Acc+WG rep.
break							
AM2 2 h		Plenary#2 osc.	Parallel#1	Plenary#5 Acc.+muon	Plenary#6 osc.	Parallel#8 1-2-J34	Plenary#9 WG rep.+Clos
Lunch							
PM1 2 h		Plenary#3 Acc.	Parallel#2 J12-3-4	Parallel#5	Free	Parallel#9 2-3-J14	
break		Poster					
PM2 1.5 h		IHEP tour	Parallel#3	Parallel#6		Parallel#10	
Evening		Reception	SPC	Banquet			

- AM1 8:30-10:00
- AM2 10:30-12:30
- PM1 13:30-15:30
- PM2 16:00-17:30

1-2-J34 means Joint session of WG3 and 4

- WG1: neutrino oscillation
- WG2: neutrino-nucleon scattering
- WG3: Accelerator physics
- WG4: Muon physics

Summary of …

- ~~WG1 – neutrino oscillations~~
- ~~WG2 – neutrino-nucleon scatering~~
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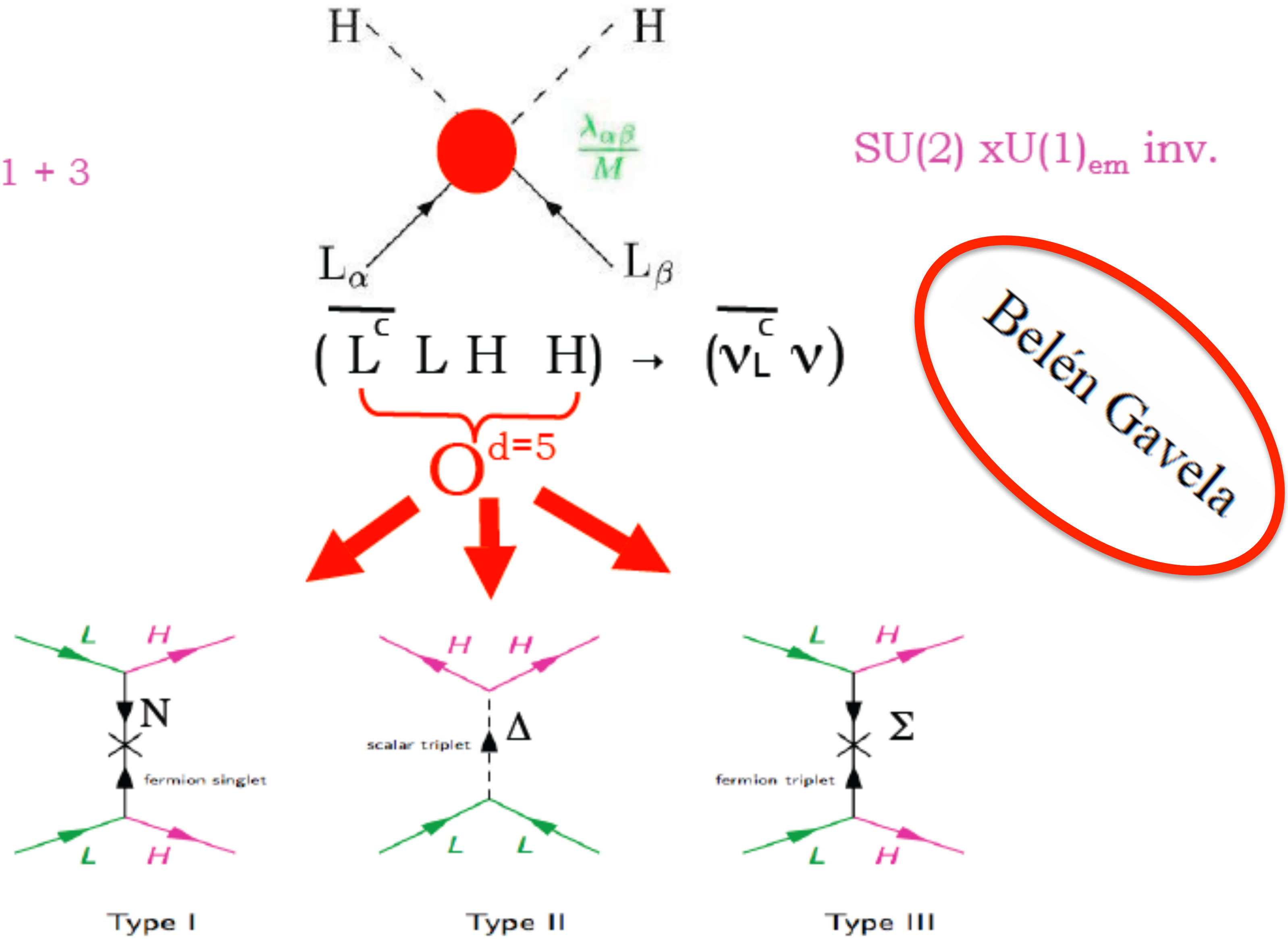
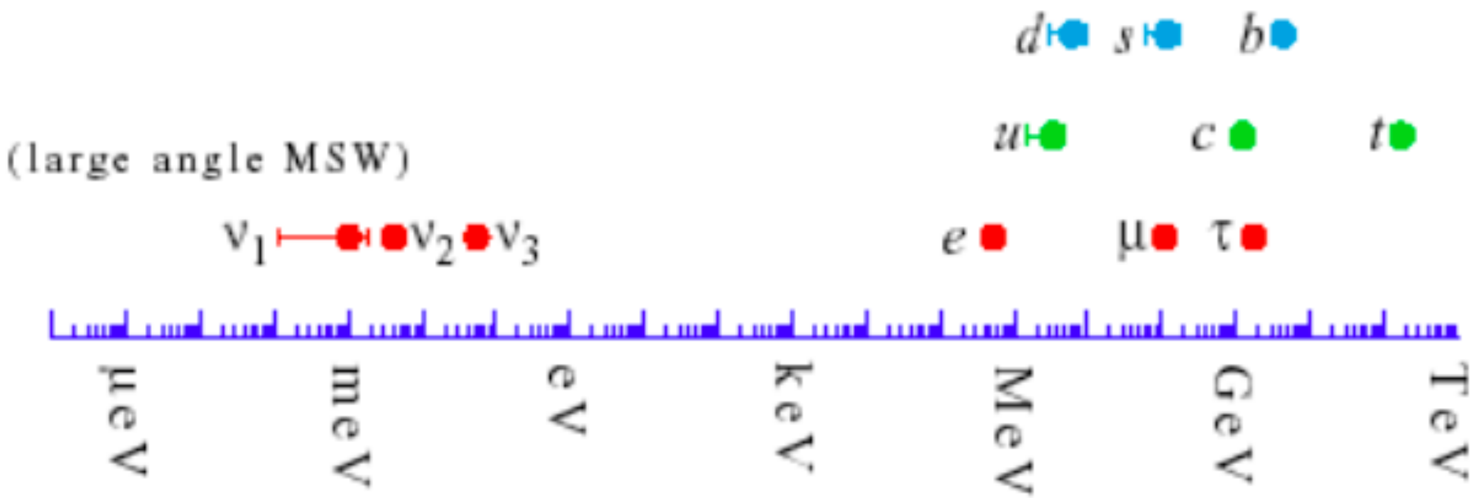
- WG1: neutrino oscillation
- WG2: neutrino-nucleon scattering
- WG3: Accelerator physics
- WG4: Muon physics

ν masses beyond the SM : tree level

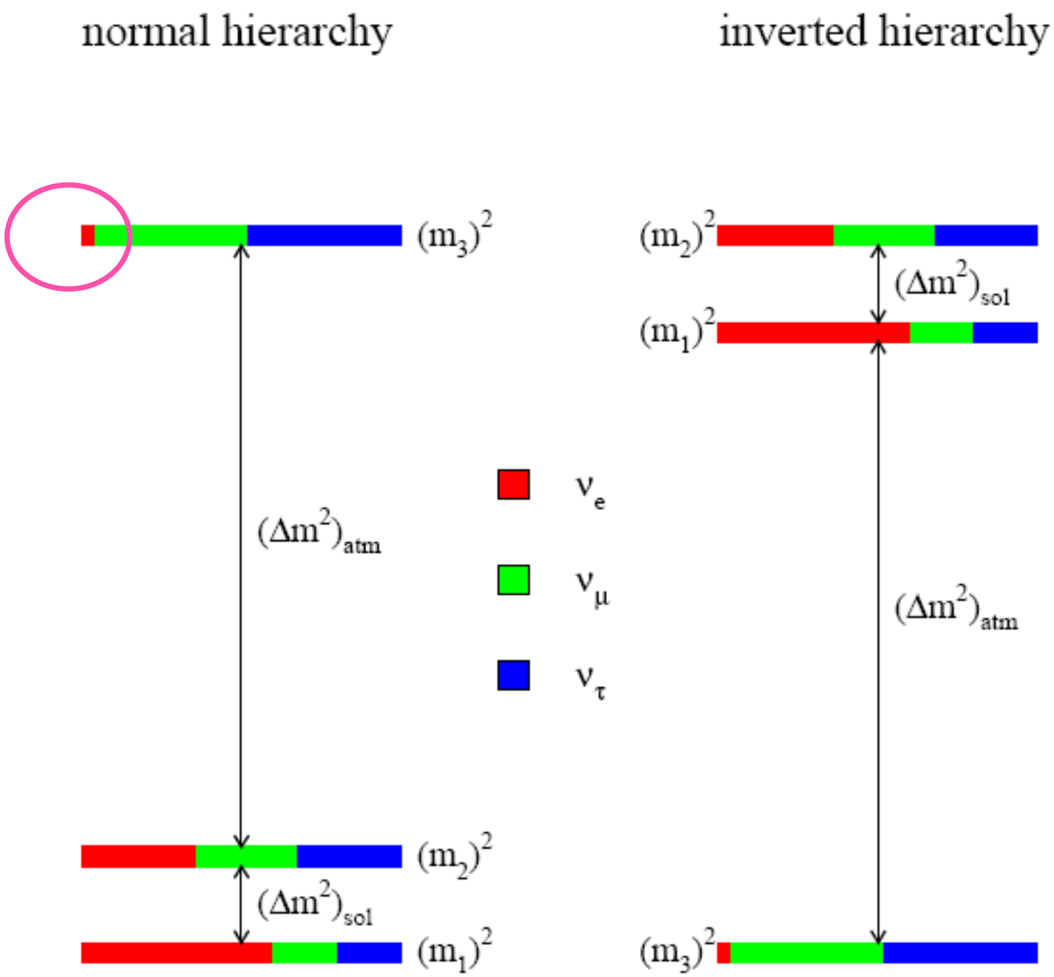
$2 \times 2 = 1 + 3$





Neutrinos lighter because Majorana?

Neutrino Mass

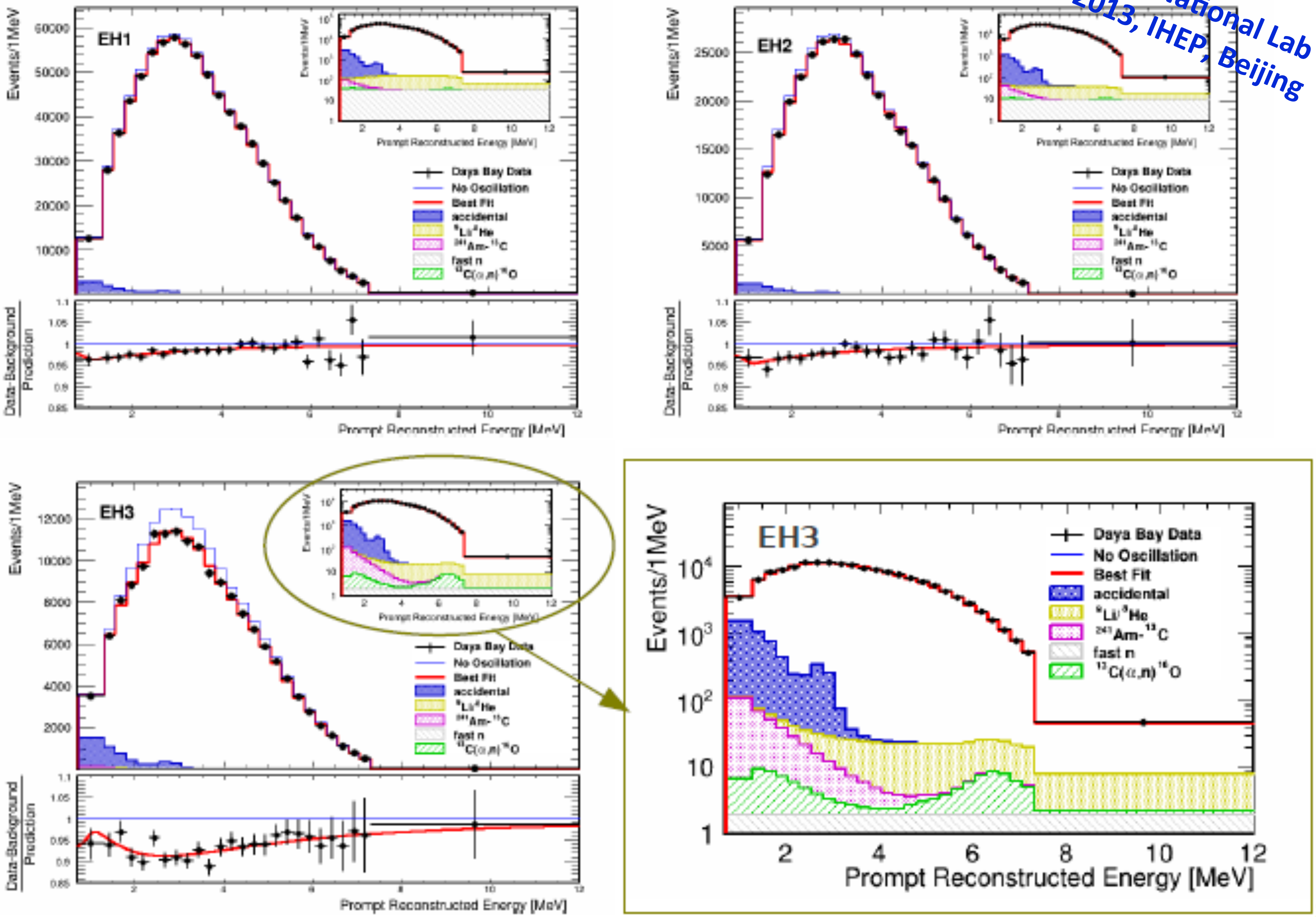


$\Delta m^2_{sol} \sim 7.5\text{x}10^{-5}\ eV^2$

$\Delta m^2_{atm} \sim 2.4\text{x}10^{-3}\ eV^2$

IBD Prompt Spectrum

Steve Kettell
Brookhaven National Lab
NuFact 2013, IHEP, Beijing

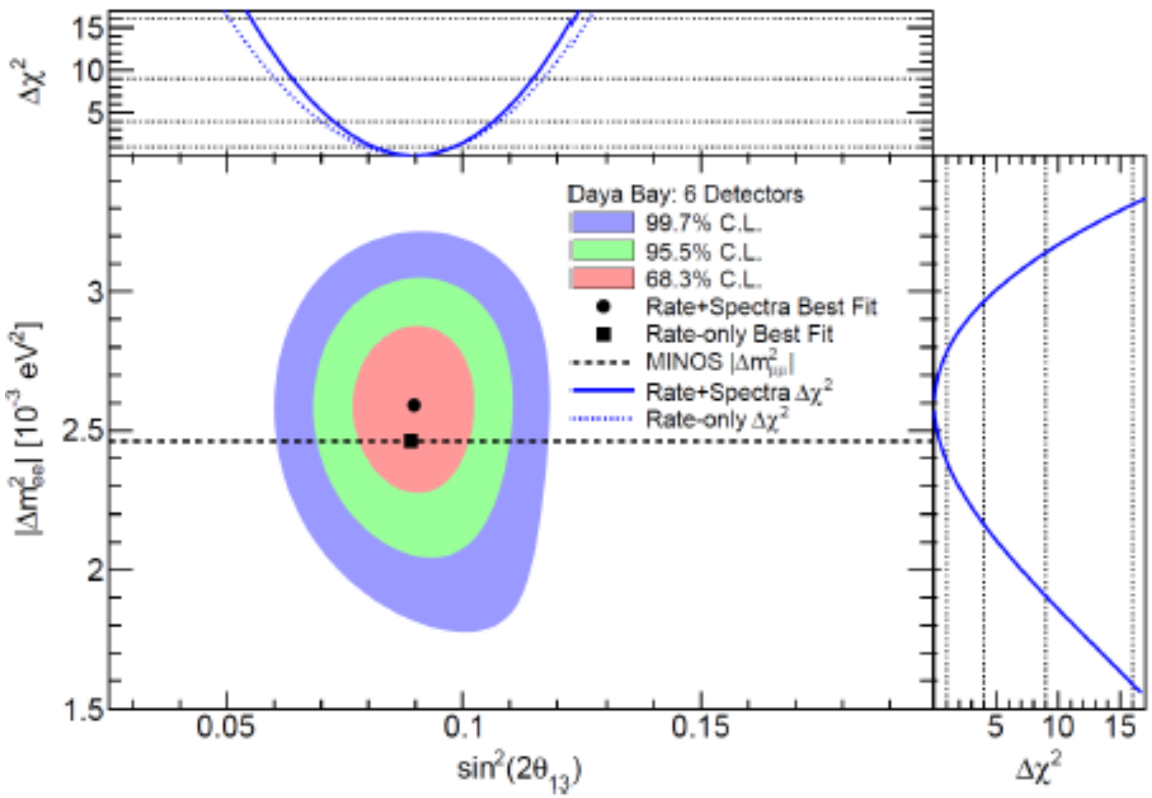


Spectrum distortion consistent with oscillation. Errors are statistical only.

Shape and mass splitting

Steve Kettell
Brookhaven National Lab
NuFact 2013, IHEP, Beijing

Rate and Spectral Analysis



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

$$\chi^2/NDF = 162.7/153$$

$$\sin^2 \Delta_{ee} = \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$$

$$\Delta m^2_{32} = 2.54^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

(Normal Mass Hierarchy)

$$\Delta m^2_{23} = 2.64^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

(Inverted Mass Hierarchy)

- Far vs. near relative measurement. [Absolute rate is not constrained.]
- Consistent results obtained by independent analyses, different reactor flux models.
- Result consistent with $|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3} (eV^2)$ result from MINOS.

Summary

Steve Kettell
Brookhaven National Lab
NuFact 2013, IHEP, Beijing

Accelerator experiments: ■ □
— normal, — inverted, $\delta_{CP}=0$, $\theta_{23}=45°$
Reactor experiments: ● ○ — ----
rate only, rate+shape, n-Gd, n-H

Dava Bav

$\sin^2 2\theta_{13}=0.090^{+0.008}_{-0.009}$
$|\Delta m^2_{ee}| = (2.59^{+0.19}_{-0.20})\times 10^{-3}$ eV^2

RENO

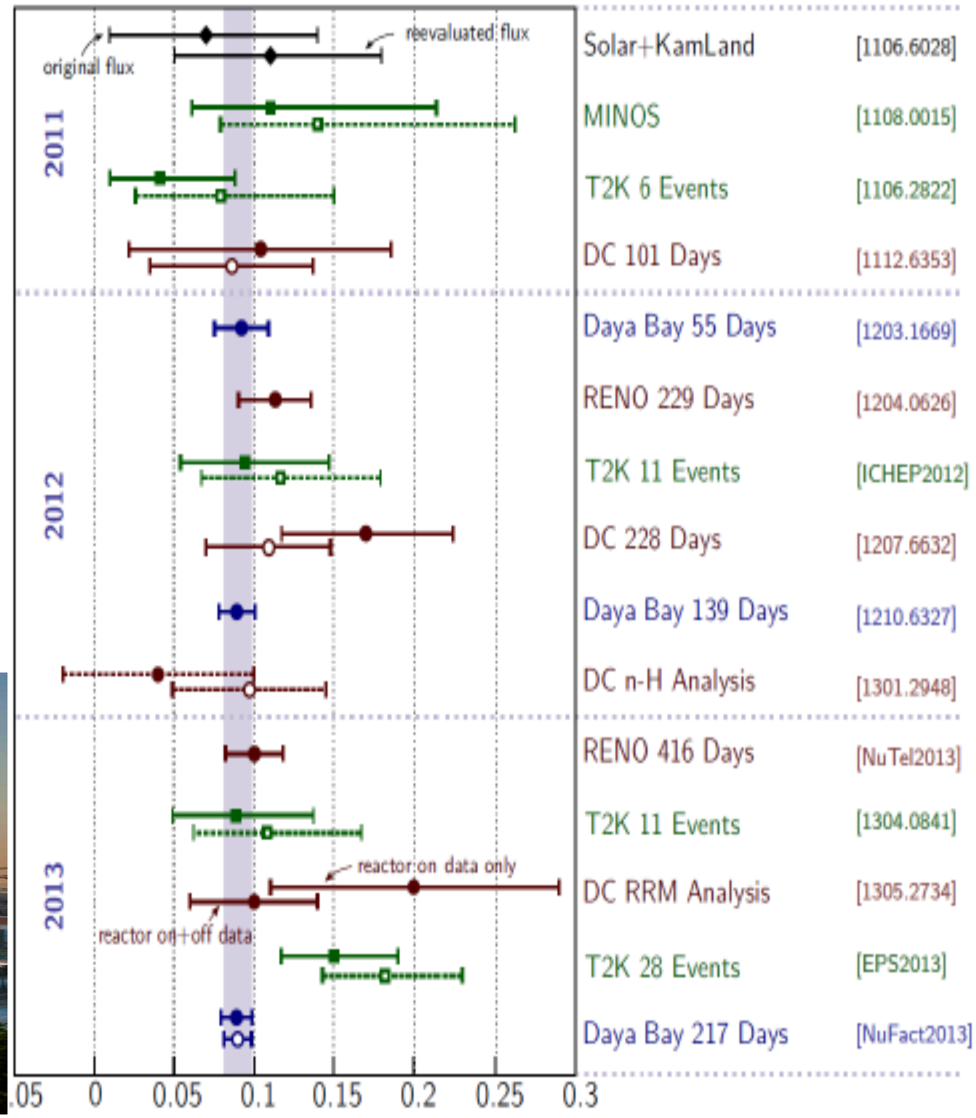
$\sin^2 2\theta_{13}=0.100\pm 0.010(\mathrm{stat})\pm 0.015(\mathrm{sys})$

Double Chooz

$\sin^2 2\theta_{13}=0.109\pm 0.030(\mathrm{stat})\pm 0.025(\mathrm{sys})$ n-Gd

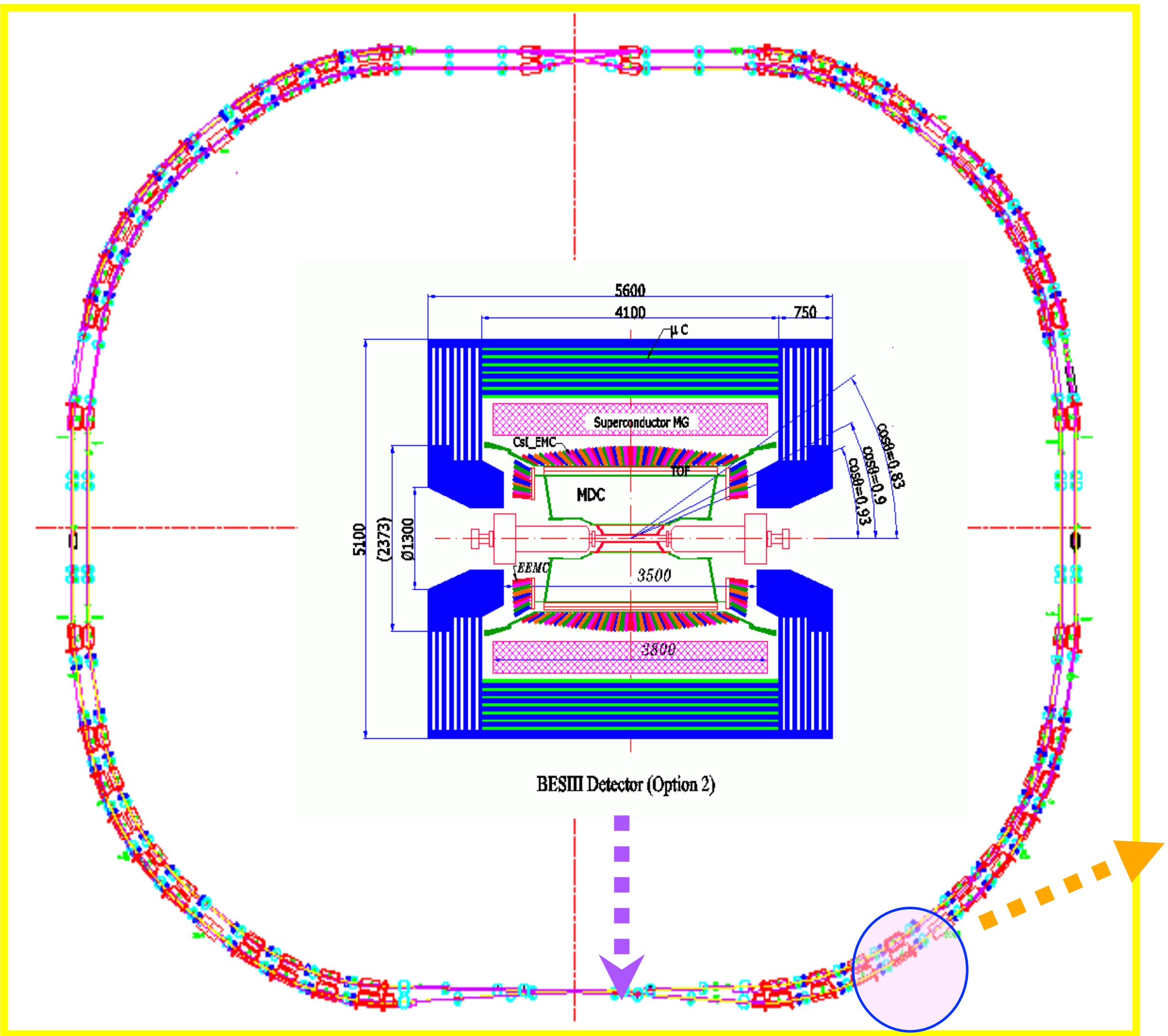
$\sin^2 2\theta_{13}=0.097\pm 0.034(\mathrm{stat})\pm 0.034(\mathrm{sys})$ n-H

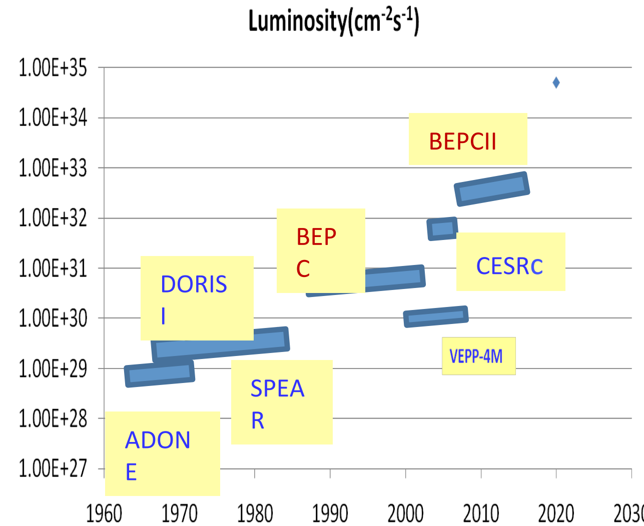
Electron neutrino contains 2 mass-splittings (3 mass states) and the large splitting agrees with that measured from muon neutrinos

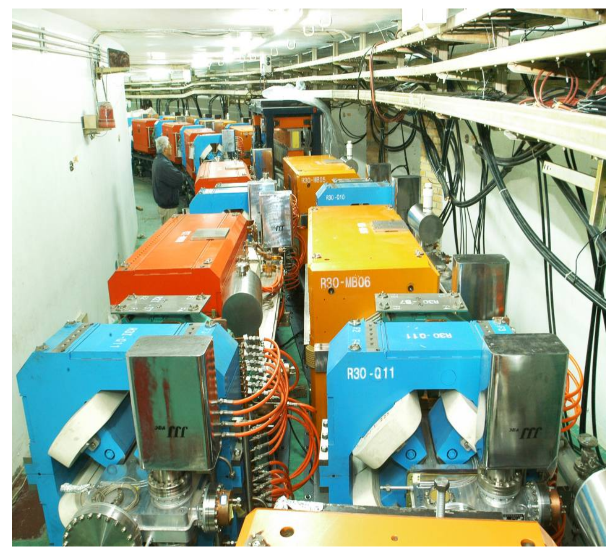


BEPCII/BESIII: Operational since 2009

A high lumi. e^+e^- collider at the τ-c energy region

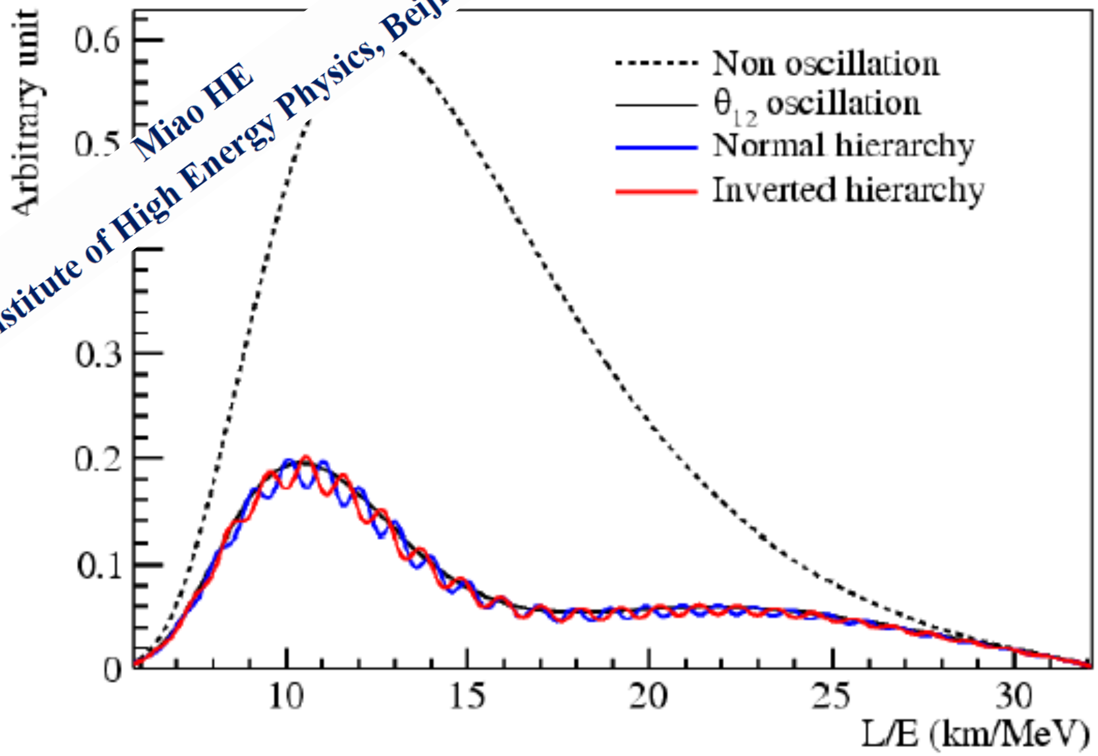







下山步道
Path to go downhill
1-4号车场
No.1-No.4 parking lots
登城
下山步道
Path to go downhill
卫生间
商店
Shop
卫生间
Toilet

Mass Hierarchy by Reactor neutrinos



$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$

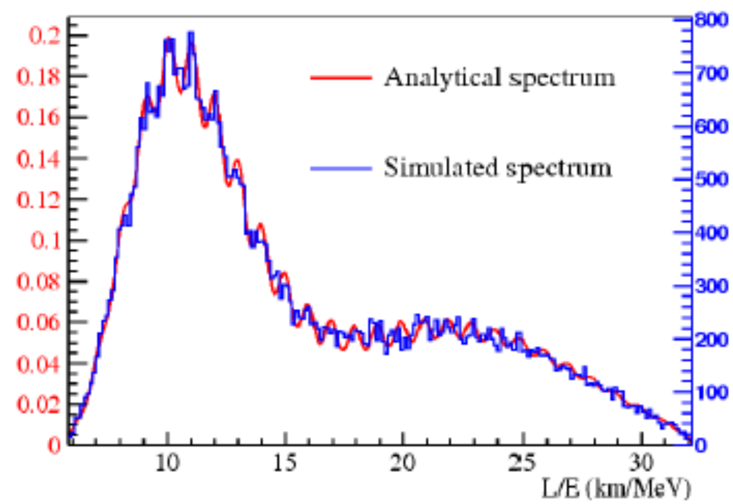
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

$$\Delta_{21} << \Delta_{31} \approx \Delta_{32}$$

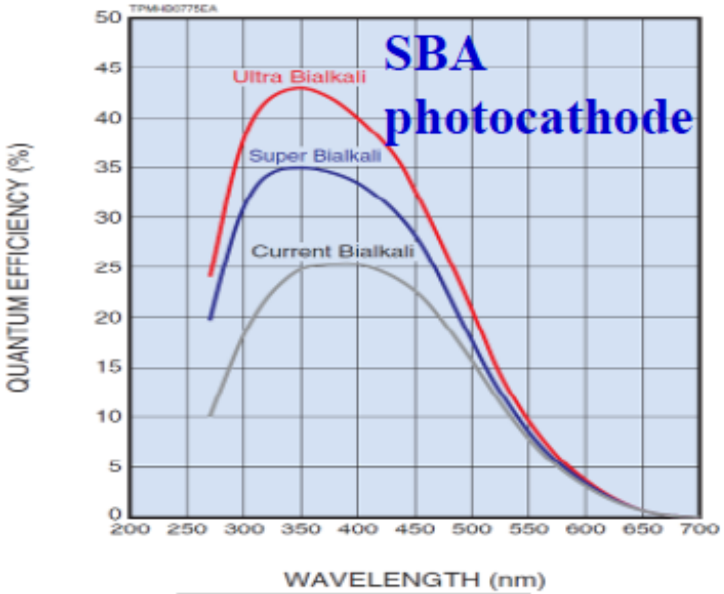
S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

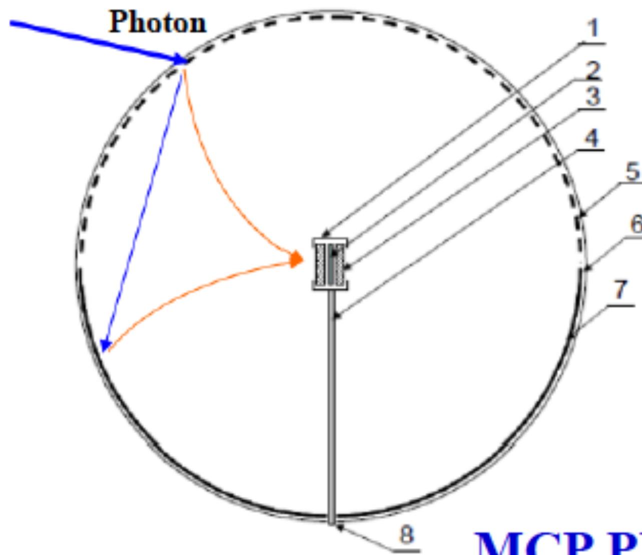
L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

Precision energy spectrum measurement: Looking for interference between P_{31} and P_{32}
➔ relative measurement



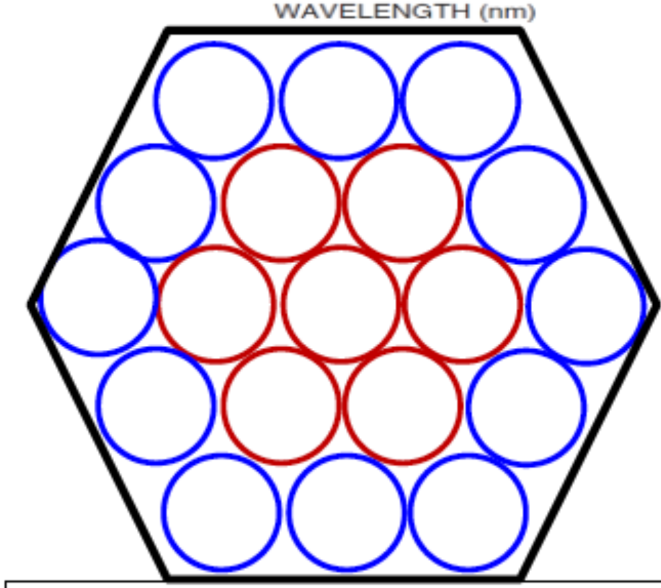
More Photoelectrons -- PMT





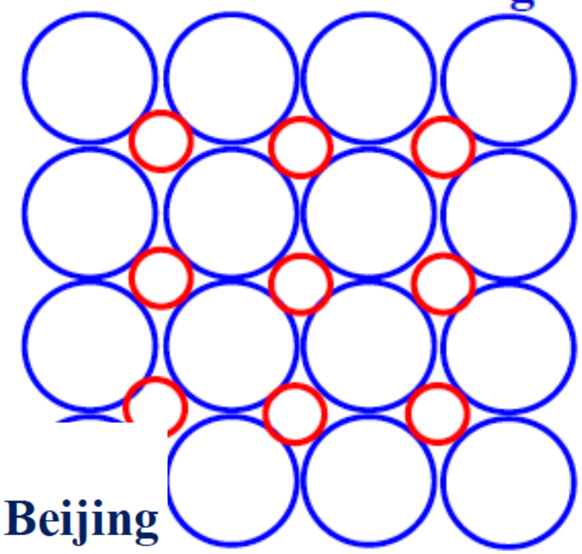
1.Insulated trestle table
2.Anode
3.MCP dodule
4.Bracket of the cables
5.Transmission Photoca
6.Glass shell
7.Reflection Photocatho
8.Glass joint

MCP PMT with reflection photocathode at bottom

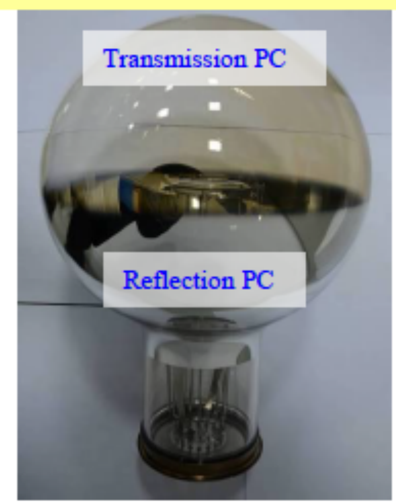


20" + 8" PMT

8" PMT better timing

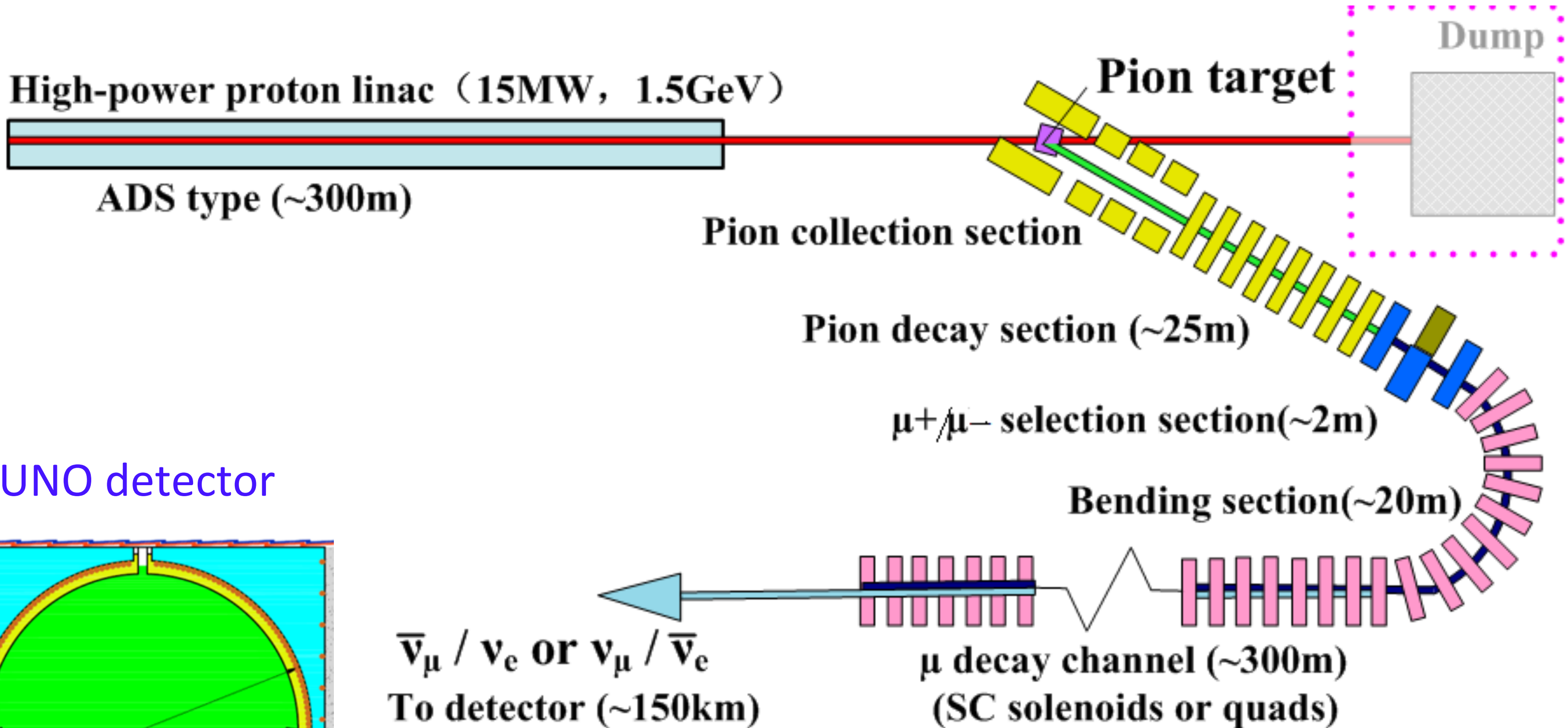


MCP-PMT prototype

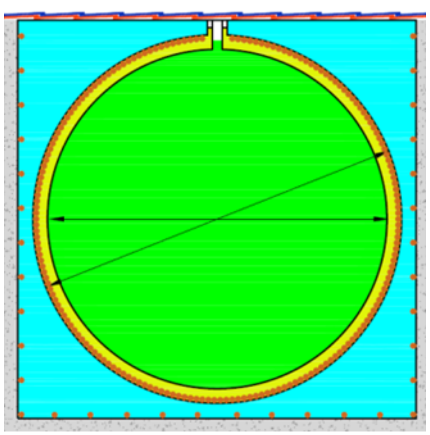


Miao HE
Institute of High Energy Physics, Beijing

China Superbeam Facility



JUNO detector



A possible detector: JUNO detector
(distance between CSNS and JUNO: ~150 km)

The next questions

- → Which θ_{23} octant ?
- → What is the mass hierarchy ?
- → Is CP Violated in the neutrino sector?

- → Are neutrinos Majorana type?
- → Are there (light) sterile neutrinos?

→ and then there are even more fundamental issues:

neutrino mass,

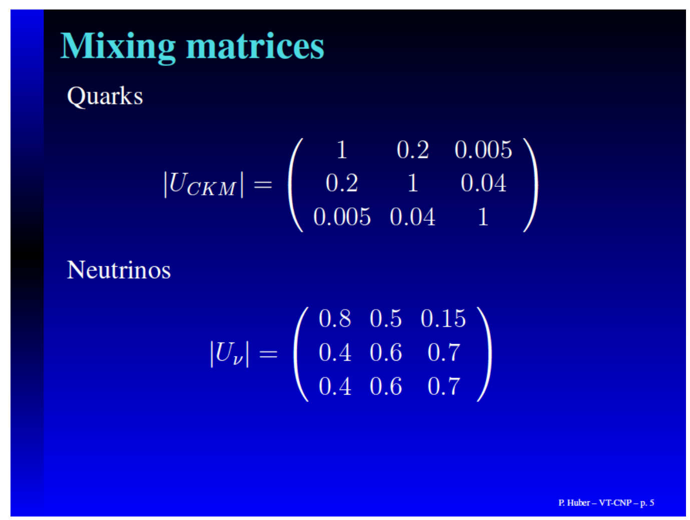
hierarchy problem,

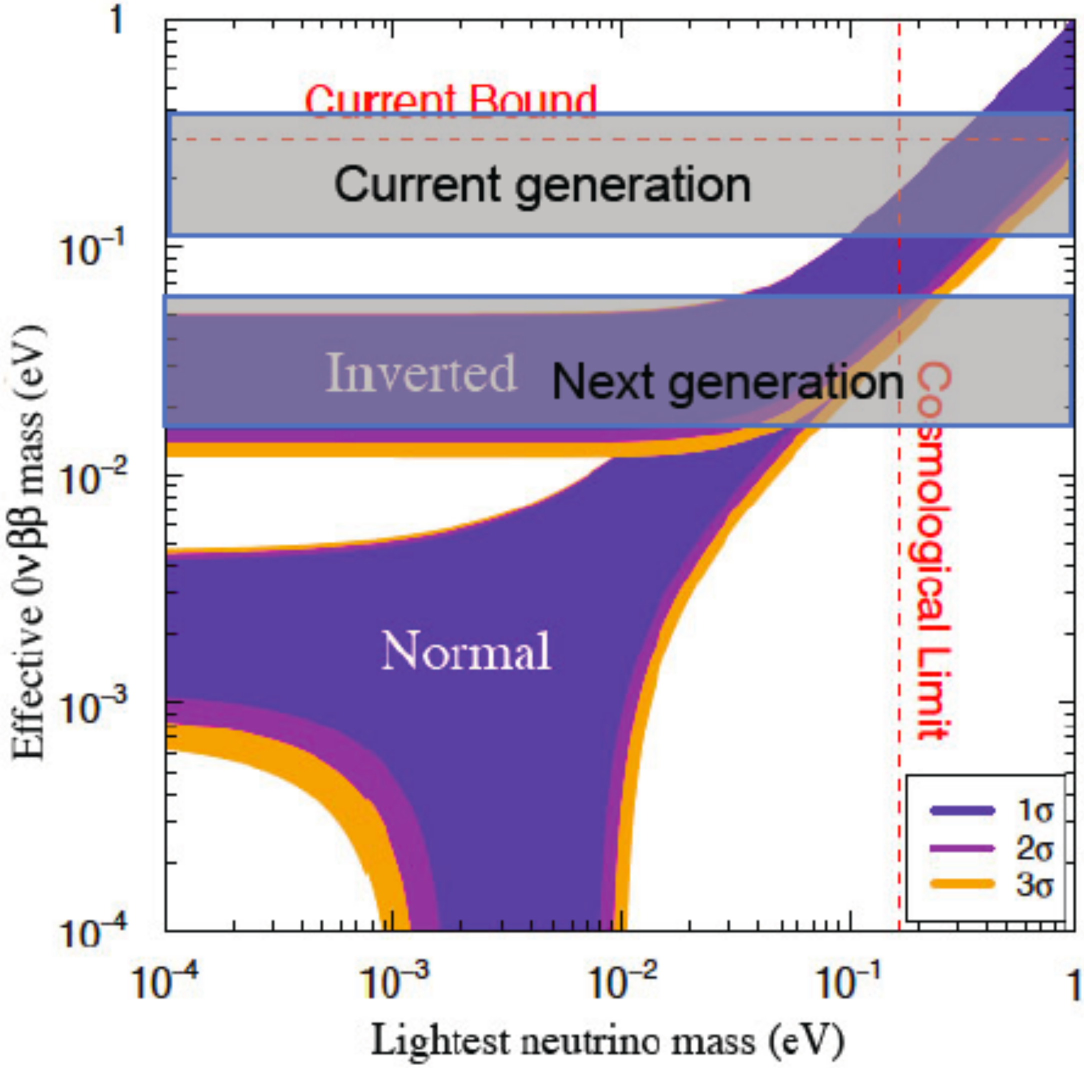
baryon asymmetry,
leptogenesis,

dark matter

inflation,

…





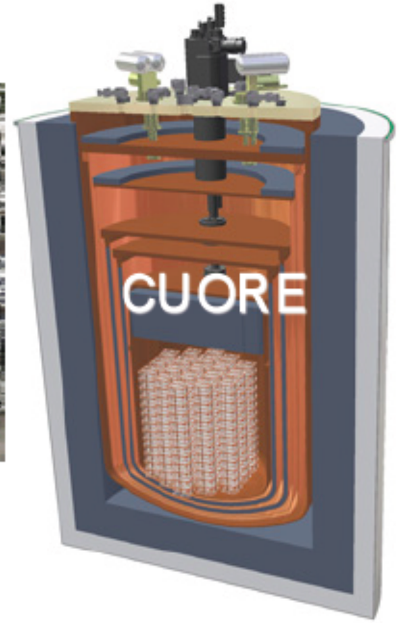
arXiv:1203.5250v1

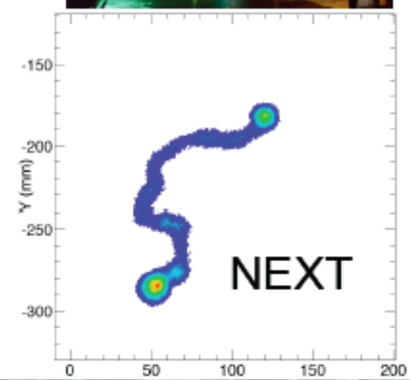
- CUORICINO
- NEMO-3
- EXO-200
- KamLAND-Zen
- GERDA

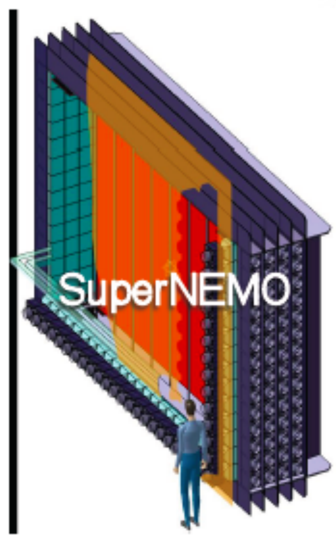
$$\langle m_{\beta\beta} \rangle = 140 - 930 \ \ \text{meV}$$

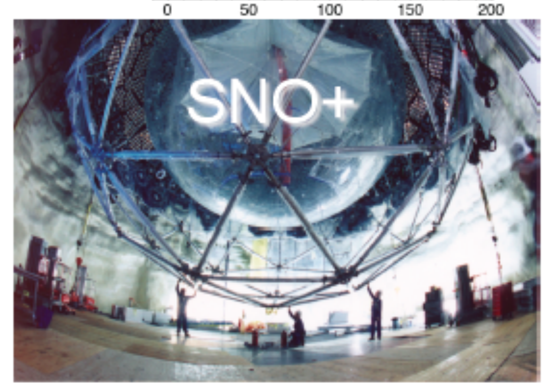
Liang Yang
University of Illinois at Urbana-Champaign

Probing the Inverted Mass Hierarchy?





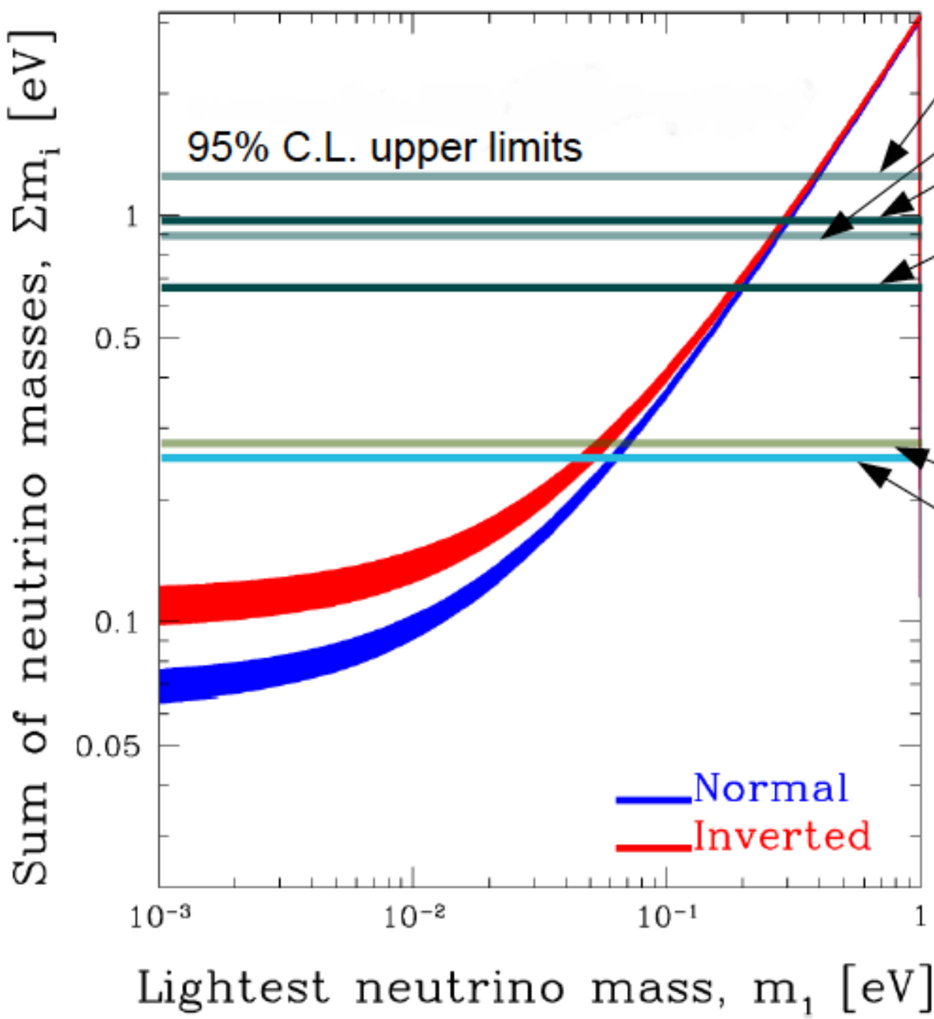




Yvonne Y. Y. Wong
The University of New South Wales
Sydney, Australia

Post-Planck...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\% \text{C.L.})$$

Best CMB-only bound

W7+ matter power spectrum + HST H_0

Planck + WP + (ACT ℓ > 1000 + SPT ℓ > 2000) + baryon acoustic oscillations

$$\sum m_\nu < 0.25 \text{ eV} \quad (95\% \text{C.L.})$$

Best minimal bound

Formally similar to the pre-Planck best minimal bound, but arguably less prone to issues of nonlinearities.

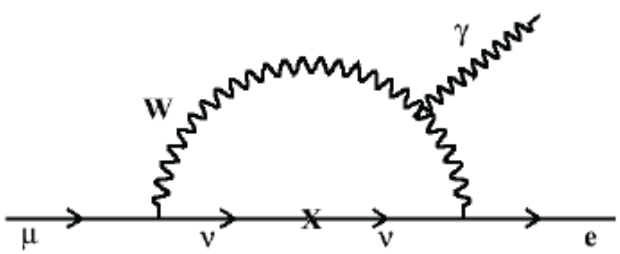
Many Exciting New Experiments and Pro

Sterile Neutrino Status
Carlo Giunti

- Reactor $\bar{\nu}_e$ Disappearance:
  - Nucifer (OSIRIS, Saclay), Stereo (ILL, Grenoble) [arXiv:1204.5379]
  - DANSS (Kalinin Nuclear Power Plant, Russia) [arXiv:1304.3696], POSEIDON (PIK, Gatchina, Russia) [arXiv:1204.2449]
  - SCRAAM (San Onofre, California) [arXiv:1204.5379]
  - CARR (China Advanced Research Reactor) [arXiv:1303.0607]
  - Neutrino-4 (SM-3, Dimitrovgrad, Russia), SOLID (BR2, Belgium), Hanaro (Korea) [D. Lhuillier, EPSHEP 2013]
- Radioactive Source ν_e and $\bar{\nu}_e$ Disappearance:
  - SOX (Borexino, Gran Sasso, Italy) [arXiv:1304.7721]
  - CeLAND (^{144}Ce@KamLAND, Japan) [arXiv:1107.2335]
  - SAGE (Baksan, Russia) [arXiv:1006.2103]
  - IsoDAR (DAEδALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
  - SNO+, Daya Bay, RENO [T. Lasserre, Neutrino 2012]
- Accelerator $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Appearance:
  - ICARUS/NESSIE (CERN) [arXiv:1304.2047, arXiv:1306.3455]
  - nuSTORM [arXiv:1308.0494]
  - OscSNS (Oak Ridge, USA) [arXiv:1305.4189, arXiv:1307.7097]

Luca Galli, Paul Scherrer Institut and INFN Pisa

- **cLFV forbidden** in the **Standard Model** with **vanishing neutrino masses**
- **extremely suppressed** in the SM extension with **neutrino oscillation**
  - *example:* ***BR(μ→ eγ) ≈ 10^{-50} not measurable*** *by any experiment*



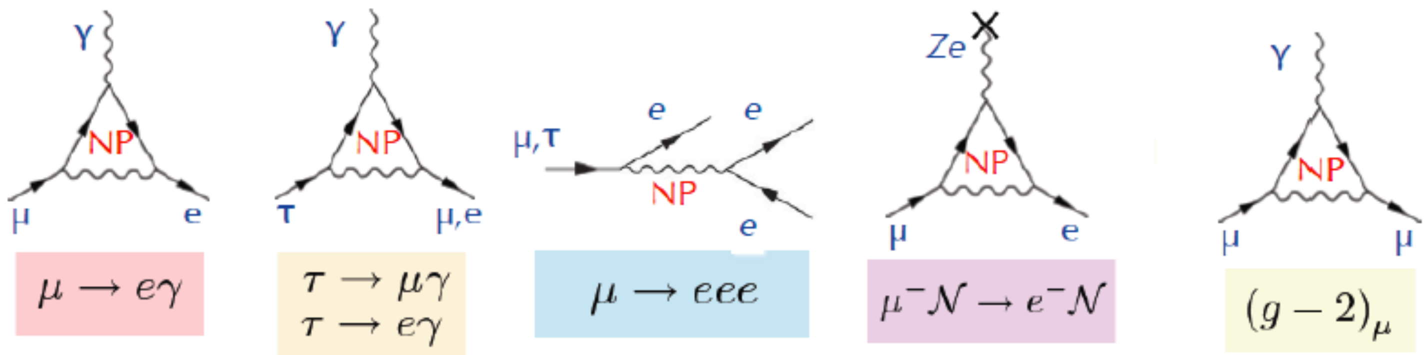
$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{3\alpha}{32\pi} \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

➡ ***μ→eγ*** as a **clean probe** of **new physics** beyond the Standard Model

cLFV zoology

Several **cLFV** (and μ physics) **processes sensitive** to **New Physics**



Lepton anomalous decay

$\mu \rightarrow e$ conversion in nuclei

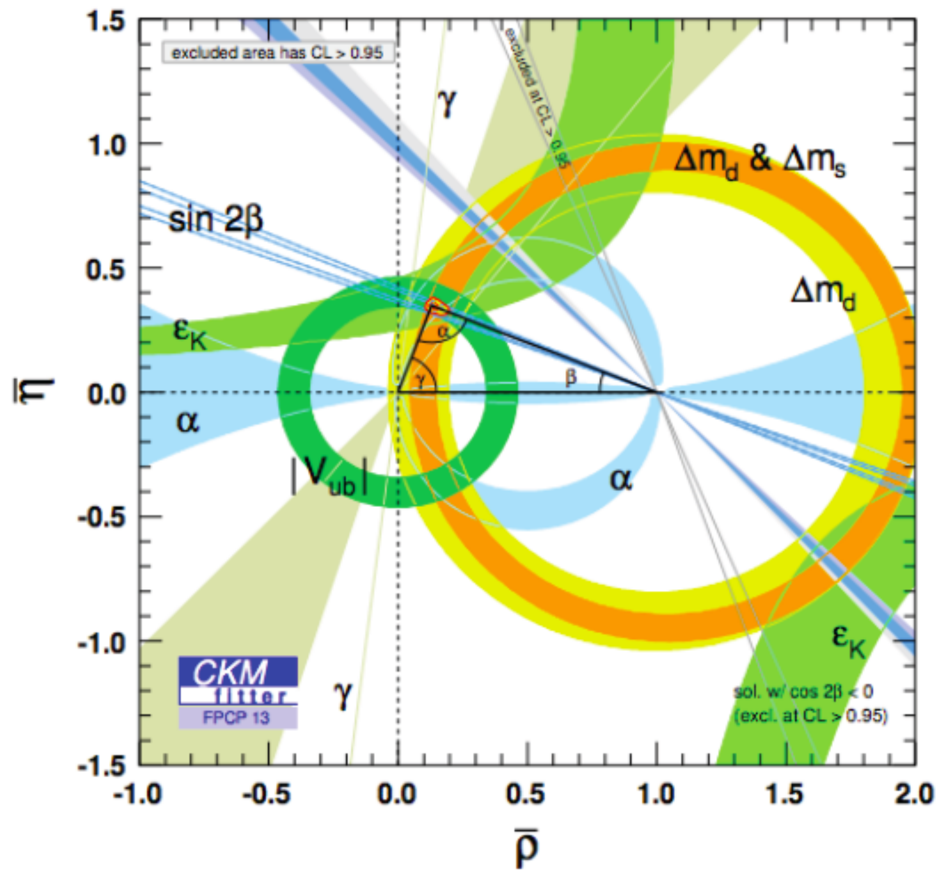
Anomalous magnetic moment

complementary processes to **define** the **nature** of NP

The coolest picture

Inspiration and Aspiration

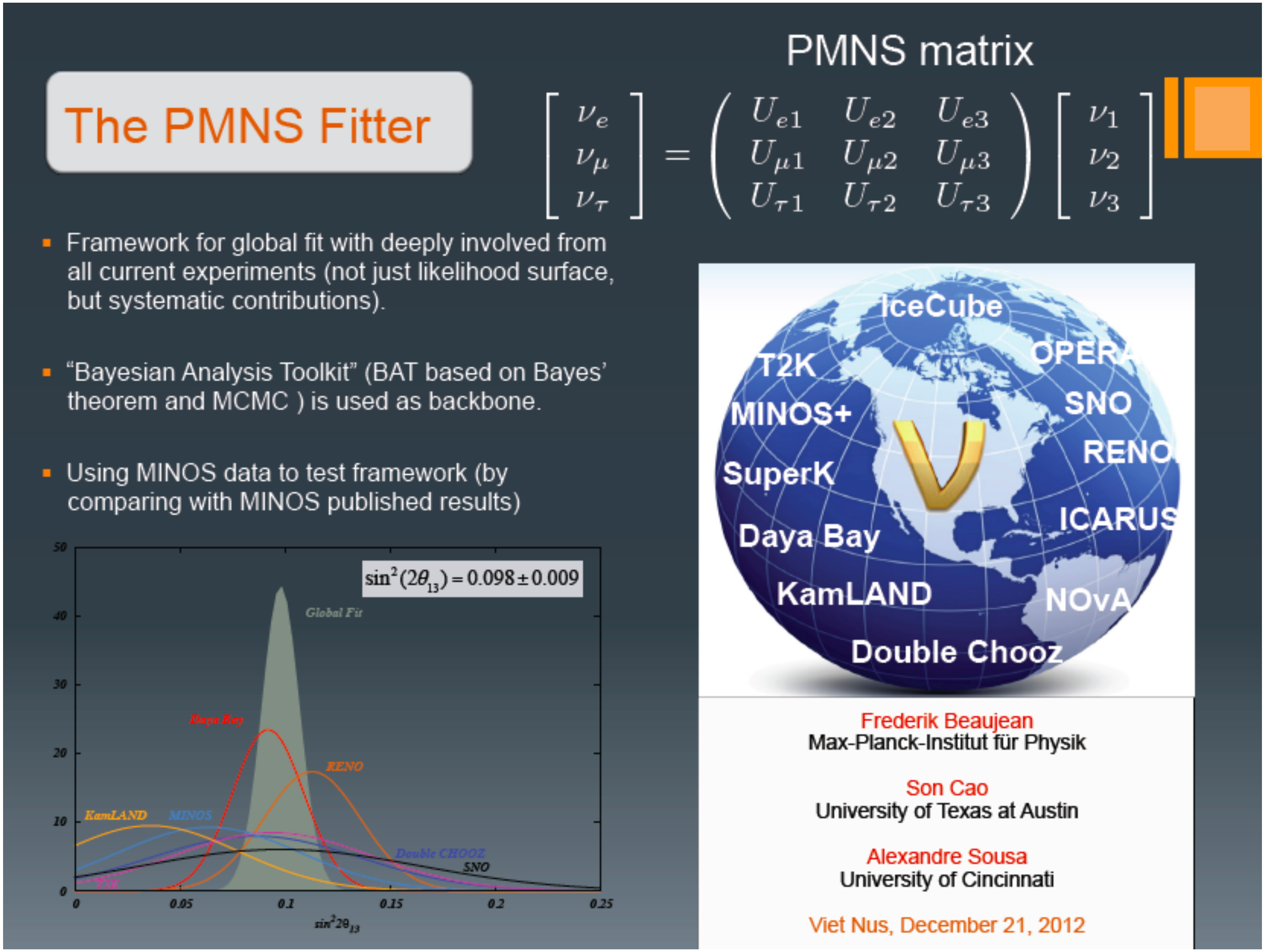
- The level of agreement between the measurements is often misinterpreted
- Allowed region is much larger if NP is included in the fit, more parameters, which changes the fit completely
- $\mathcal{O}(20\%)$ NP contributions to most loop processes (FCNS) are still allowed

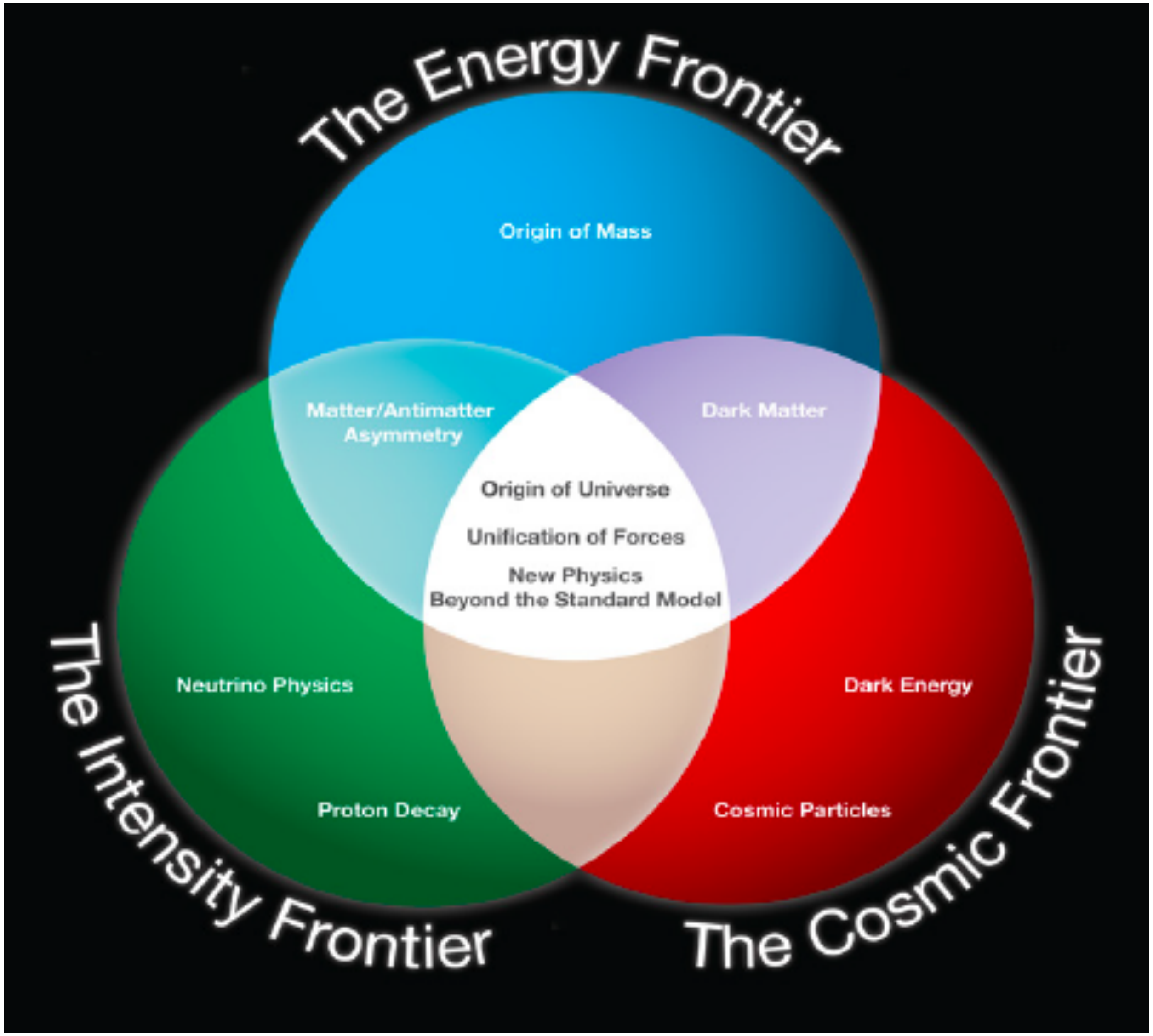


- Need experimental precision and theoretical cleanliness to increase NP sensitivity

Talk by Z. Ligeti at Snowmass-on-Missisipi, July-Aug 2013

Advertisement




The Energy Frontier
Origin of Mass
Matter/Antimatter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

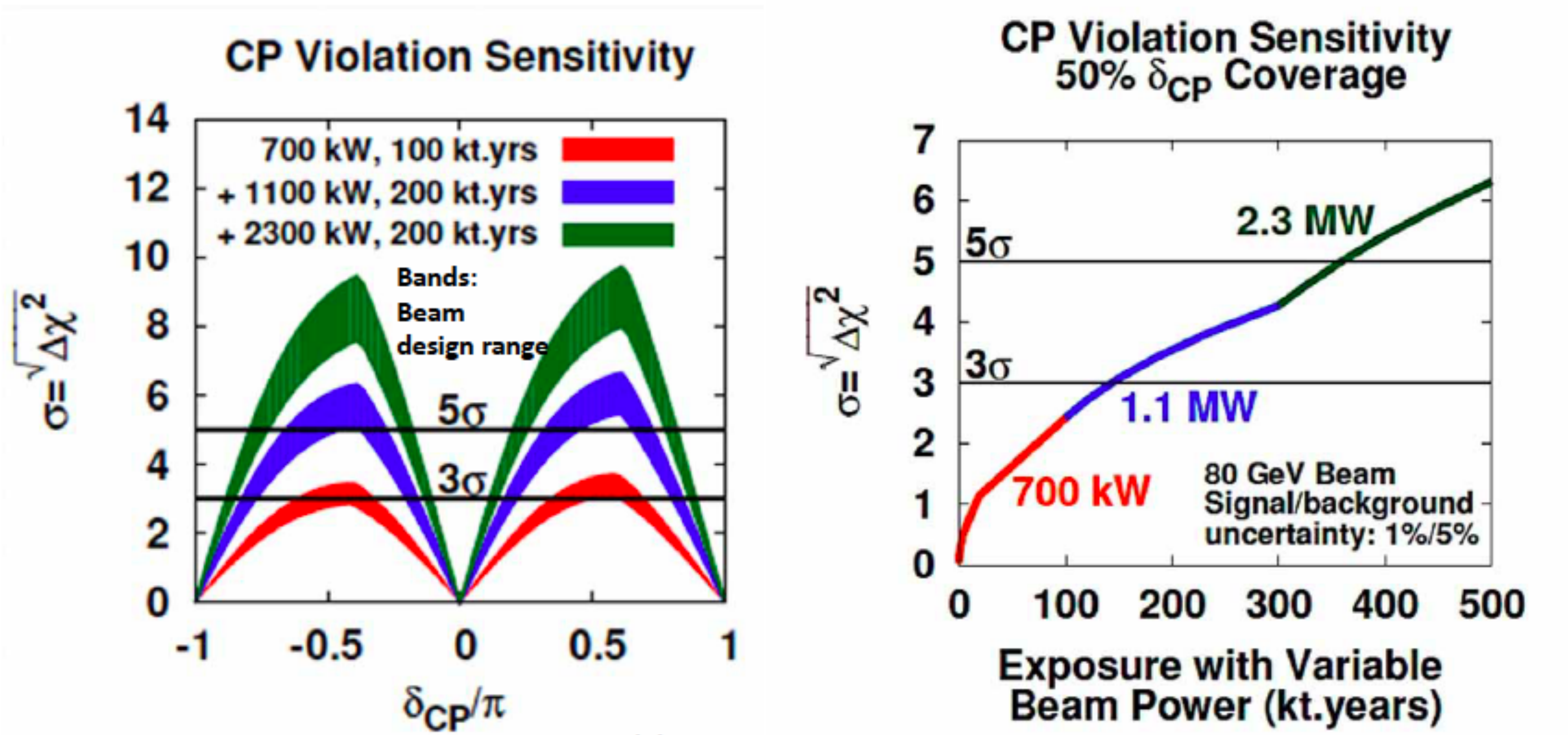
Summary of Snowmass 2013

André de Gouvêa

Northwestern University

- Nu1: Neutrino Oscillations and the Three-Flavor Paradigm (Mary Bishai, Karsten Heeger, Patrick Huber);
- Nu2: The Nature of the Neutrino: Majorana vs. Dirac (Steve Elliott, Lisa Kaufman);
- Nu3: Absolute Neutrino Mass (Hamish Robertson, Ben Monreal);
- Nu4: Neutrino Interactions (Jorge Morfin, Rex Tayloe);
- Nu5: Anomalies and New New Physics (Boris Kayser, Jon Link);
- Nu6: Astrophysical and Cosmological Neutrinos (Kara Hoffman, Cecilia Lunardini, Nikolai Tolich);
- Nu7: Neutrinos and Society (José Alonso, Adam Bernstein).

LBNE + Project X (1.1-2.3 MW) = Comprehensive Global Science Program



With 80 GeV MI protons source

- Long-range program in tandem with near detector neutrino interactions and non-accelerator physics

LBNE Design Status

LBNE has a well-developed design for the complete project:

- Neutrino beam at Fermilab for 700 kW operation, upgradeable to 2.3 MW
- Highly-capable near neutrino detector on the Fermilab site
- 34 kt fiducial mass LAr far detector at
  - A baseline of 1300 km
  - A depth of 4300 m.w.e. at the Sanford Underground Research Facility (SURF) in the former Homestake Mine in Lead, South Dakota

The most popular plot

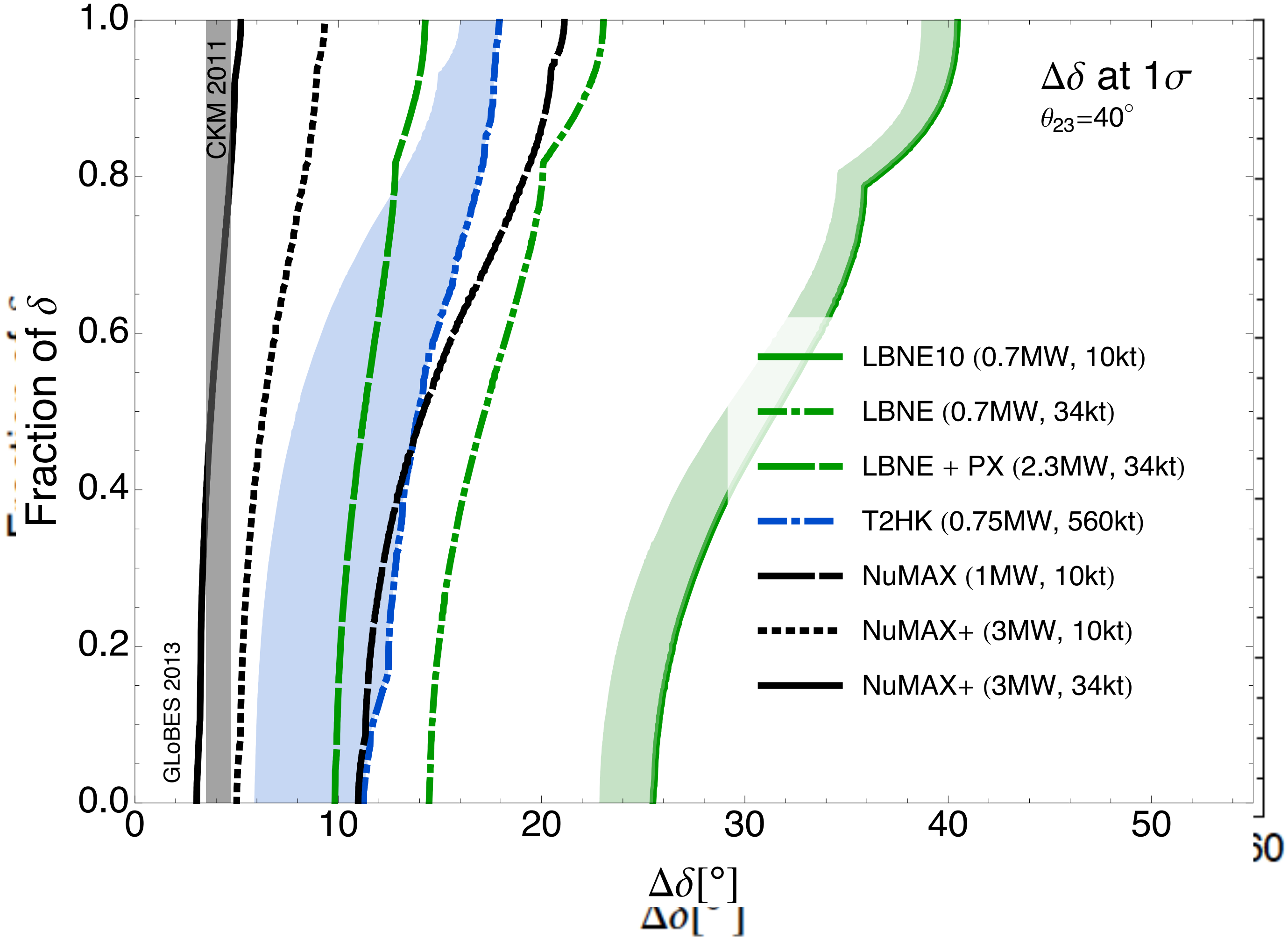
A NEW plot – THANKS to Pilar!

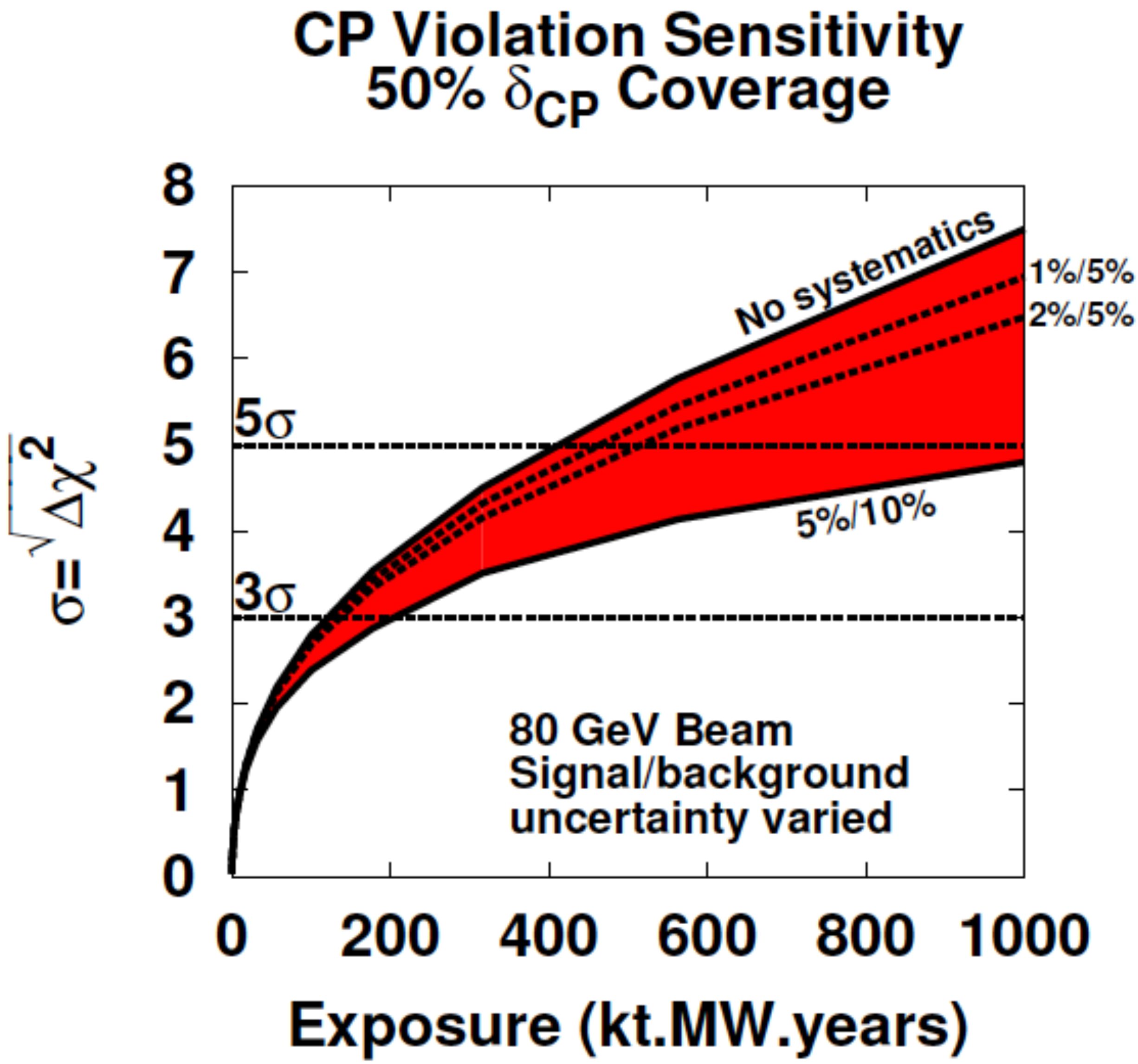
EURONU-WP6-12-53
FERMILAB-PUB-12-509-T
IDS-NF-036

Systematic uncertainties in long-baseline neutrino oscillations for large θ_{13}

September 27, 2012

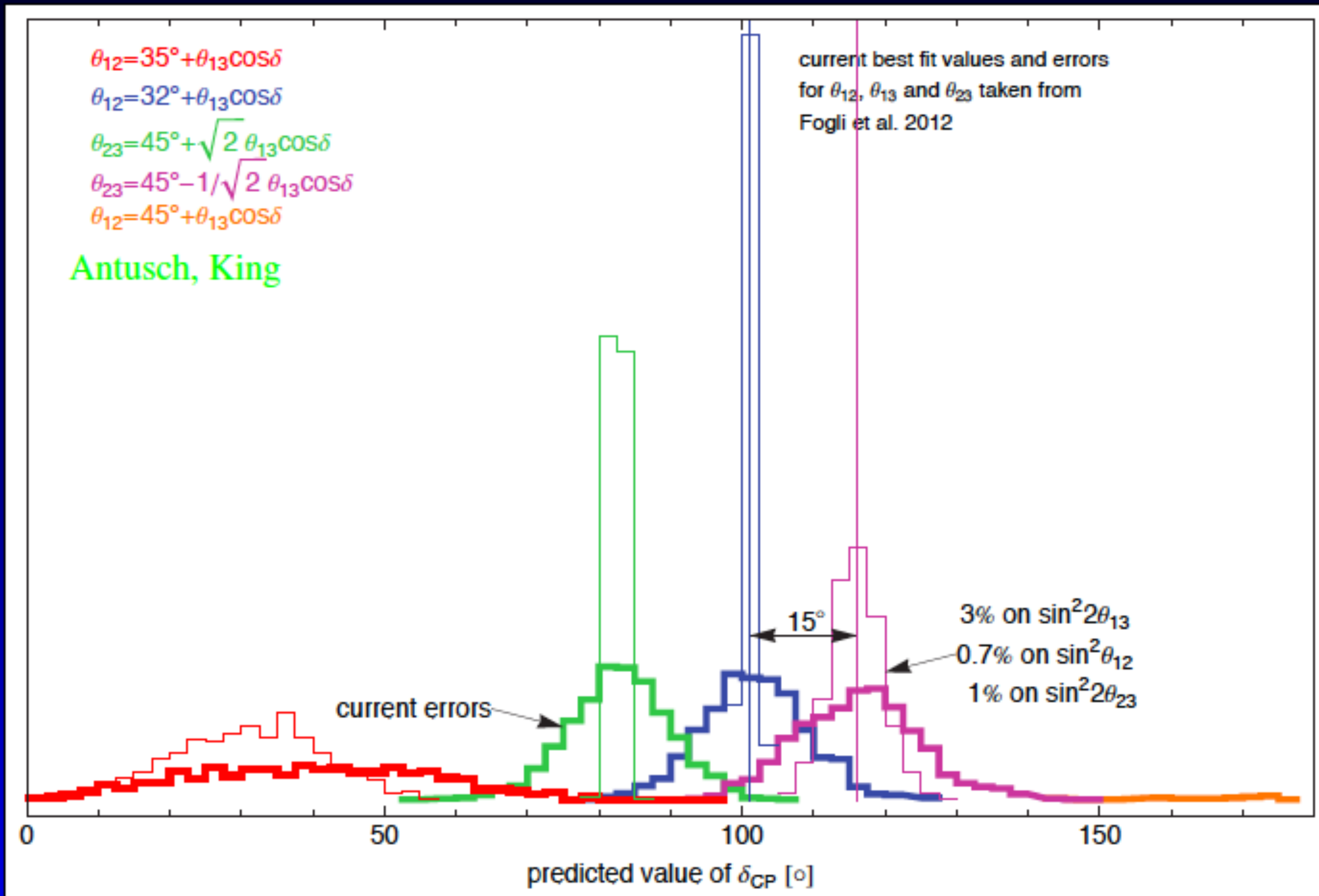
Pilar Coloma[a], Patrick Huber[b], Joachim Kopp[c], and Walter Winter[d]





CP Violation Sensitivity
50% δ_{CP} Coverage
$\sigma = \sqrt{\Delta\chi^2}$
Exposure (kt.MW.years)
No systematics
1%/5%
2%/5%
5%/10%
5σ
3σ
80 GeV Beam
Signal/background
uncertainty varied
0
1
2
3
4
5
6
7
8
0
200
400
600
800
1000

Sum rules

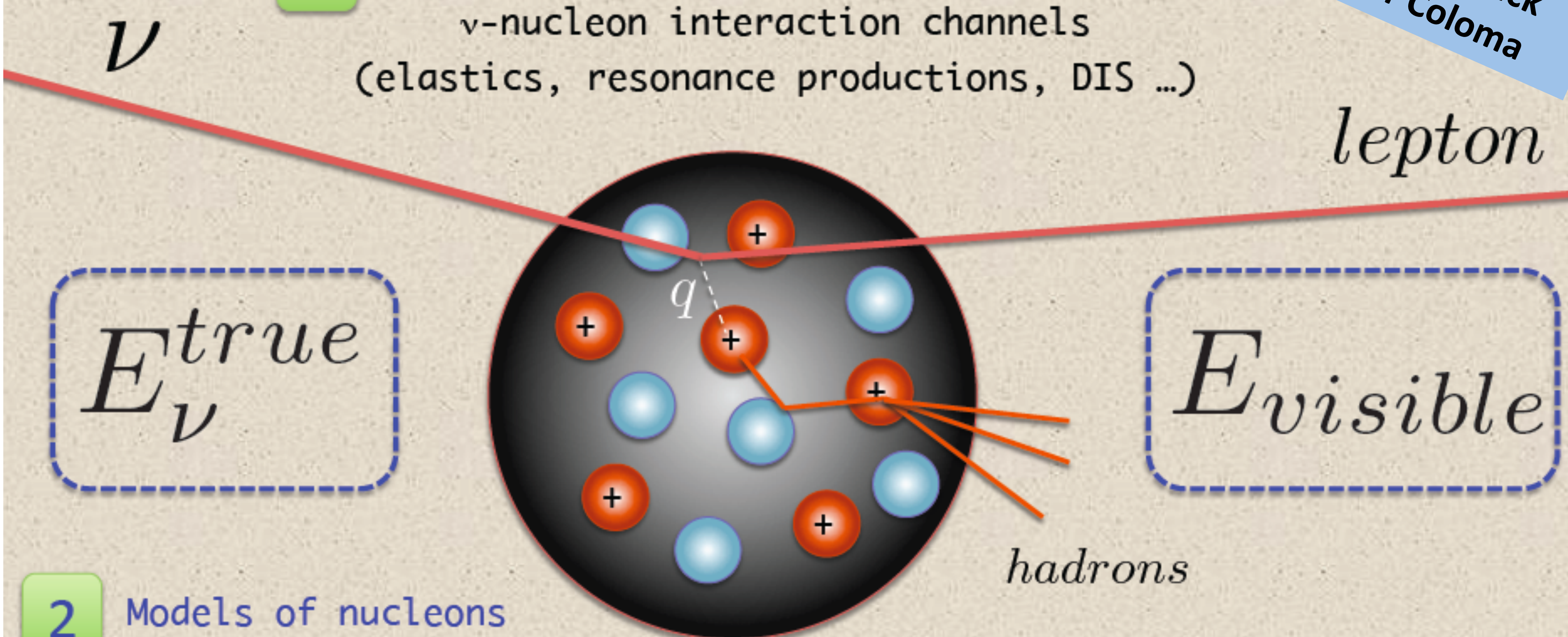


$3\,\sigma$ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like JUNO

Physics of GeV ν–N Interactions

Also from Jan Sobczyk, Patrick Huber, Pilar Coloma

1 Cross section models for all exclusive ν-nucleon interaction channels (elastics, resonance productions, DIS …)



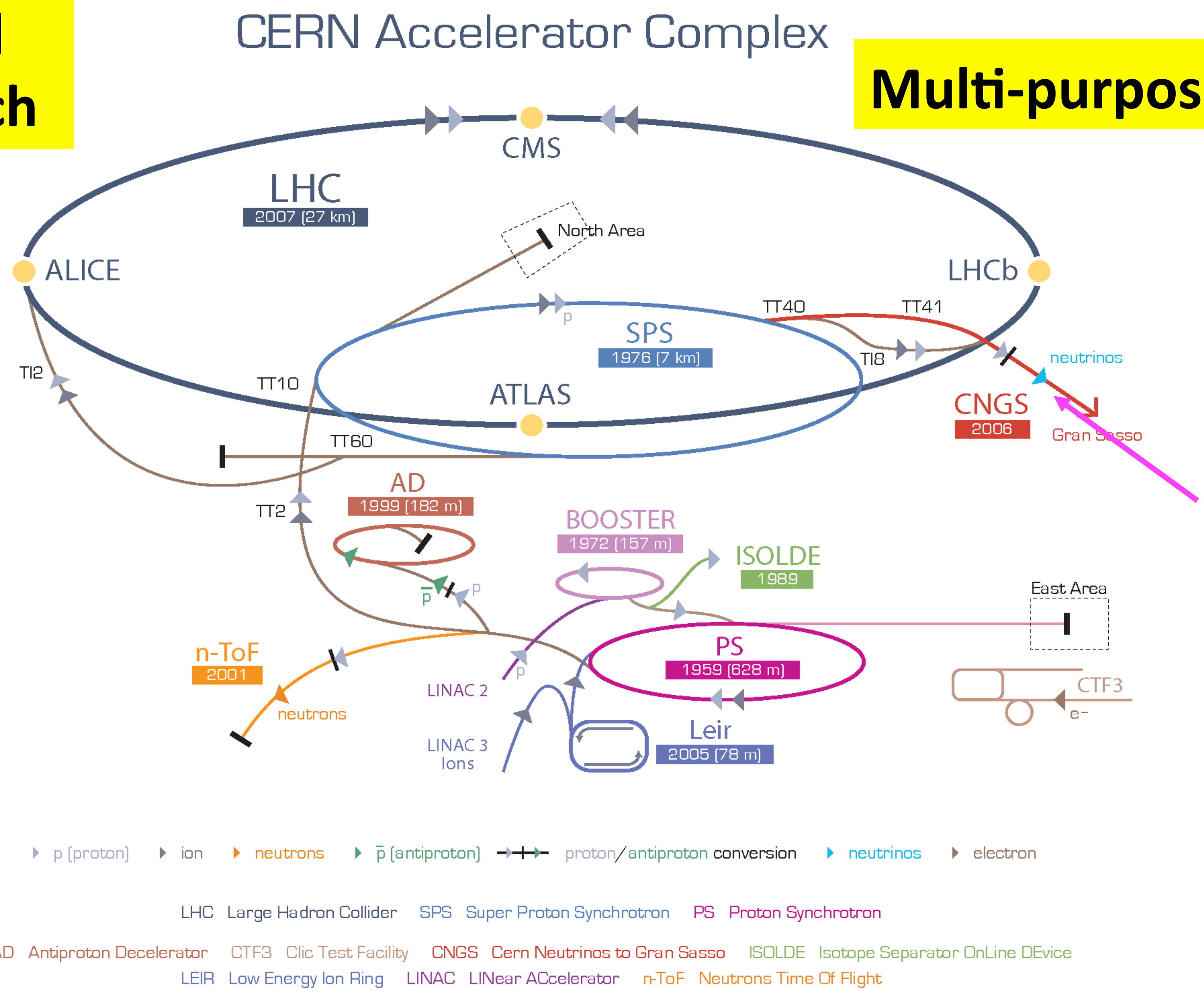
2 Models of nucleons within the nucleus (Relativist Fermi Gas, spectral functions, nucleon correlations, …)

3 Final state interaction models which alter the hadronic final state (rescattering, absorption, charge exchange, …)

CERN, a success story

Staged approach

Multi-purpose



"If you don't know where you are going, you might wind up someplace else." Yogi Berra

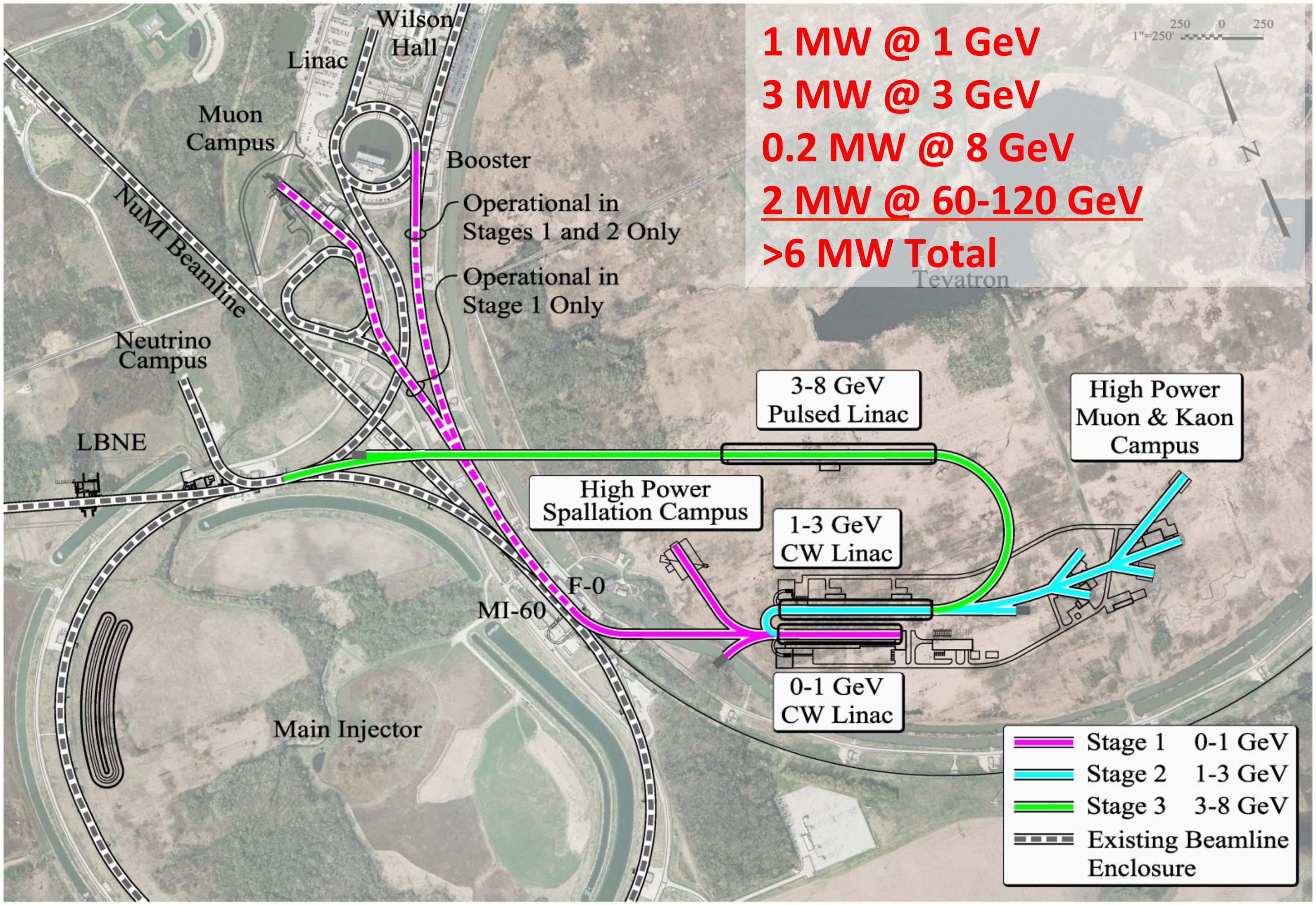
Staged Physics Program

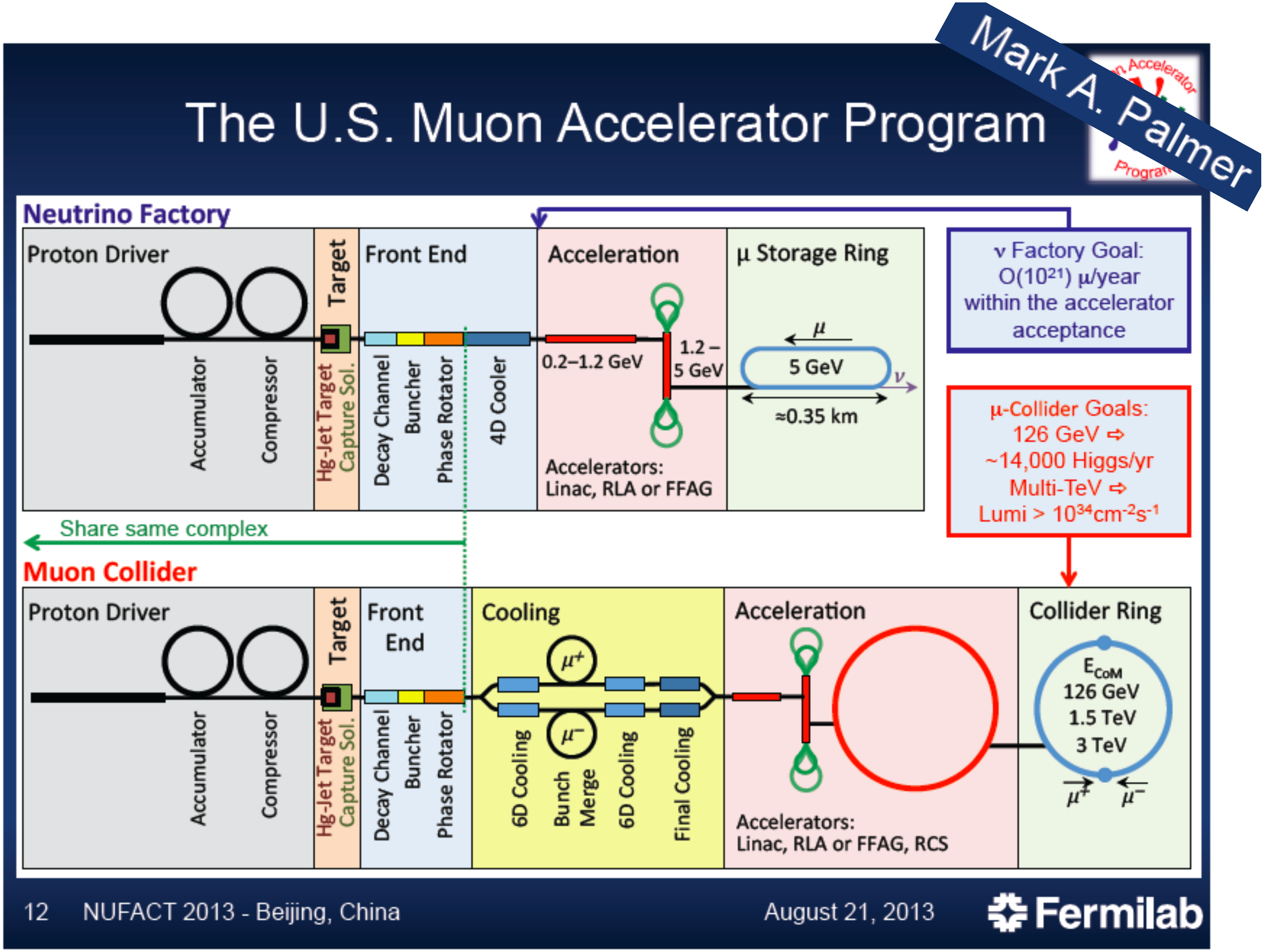
Steve Holmes @ Snowmass 2013

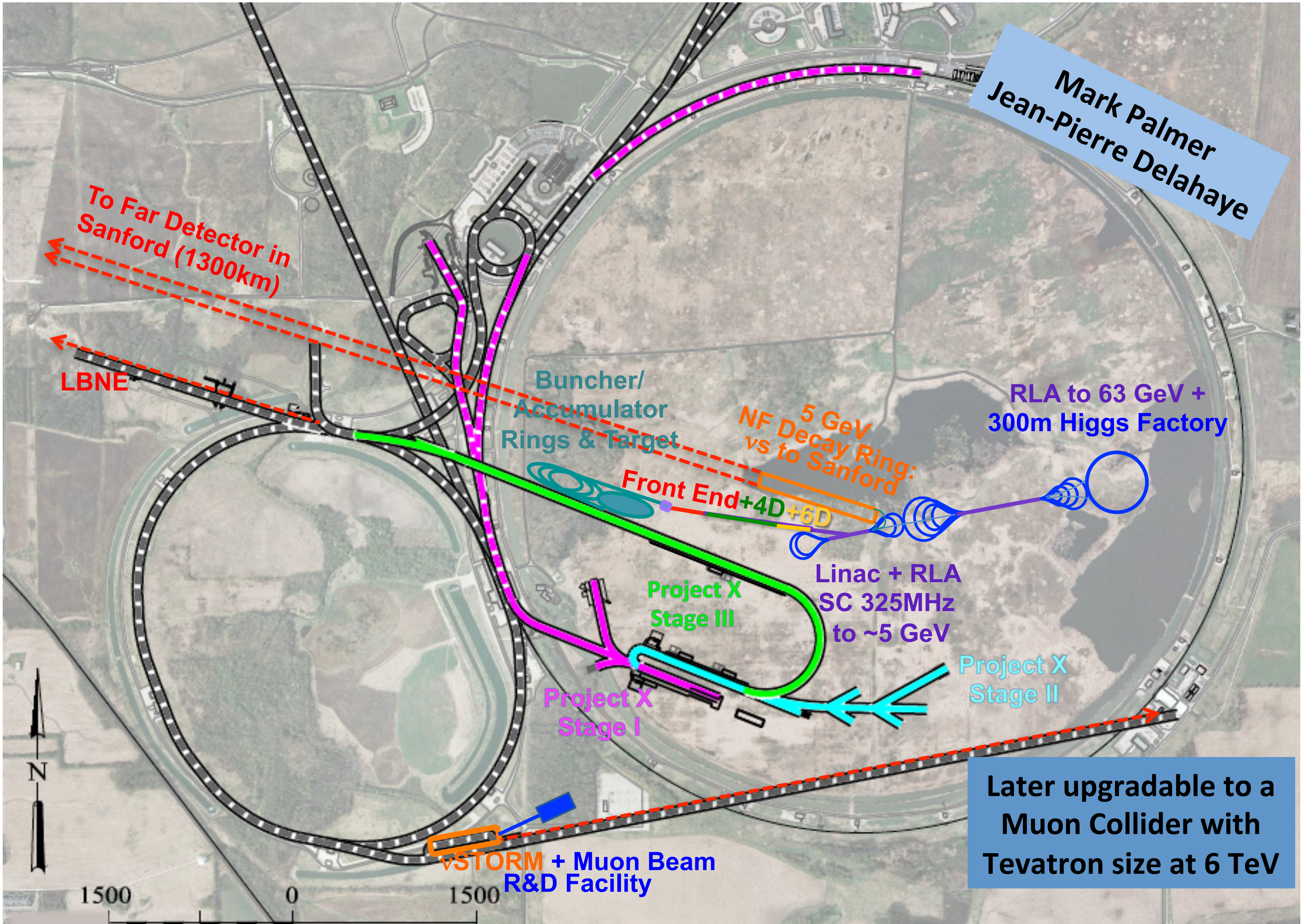
← Project X Campaign →

Program:	NOνA + Proton Improvement Plan	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
MuSR	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	9	9	9	9
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

Reference Design
Staging




Mark A. Palmer
The U.S. Muon Accelerator Program
Neutrino Factory
Proton Driver
Accumulator
Compressor
Target
Hg-Jet Target
Capture Sol.
Front End
Decay Channel
Buncher
Phase Rotator
4D Cooler
Acceleration
0.2–1.2 GeV
1.2 – 5 GeV
Accelerators:
Linac, RLA or FFAG
μ Storage Ring
μ
5 GeV
ν
≈0.35 km
ν Factory Goal:
O(10²¹) μ/year
within the accelerator acceptance
μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10³⁴cm⁻²s⁻¹
Share same complex
Muon Collider
Proton Driver
Accumulator
Compressor
Target
Hg-Jet Target
Capture Sol.
Front End
Decay Channel
Buncher
Phase Rotator
Cooling
μ+
μ−
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
Acceleration
Accelerators:
Linac, RLA or FFAG, RCS
Collider Ring
E CoM
126 GeV
1.5 TeV
3 TeV
μ+
μ−
12
NUFACT 2013 - Beijing, China
August 21, 2013
Fermilab



Mark Palmer
Jean-Pierre Delahaye
To Far Detector in Sanford (1300km)
LBNE
Buncher/ Accumulator Rings & Target
5 GeV NF Decay Ring: νs to Sanford
RLA to 63 GeV + 300m Higgs Factory
Front End+4D+6D
Linac + RLA SC 325MHz to ~5 GeV
Project X Stage III
Project X Stage II
Project X Stage I
νSTORM + Muon Beam R&D Facility
Later upgradable to a Muon Collider with Tevatron size at 6 TeV
1500 0 1500
N

Mark A. Palmer

The Muon Accelerator Program

By the end of this decade:

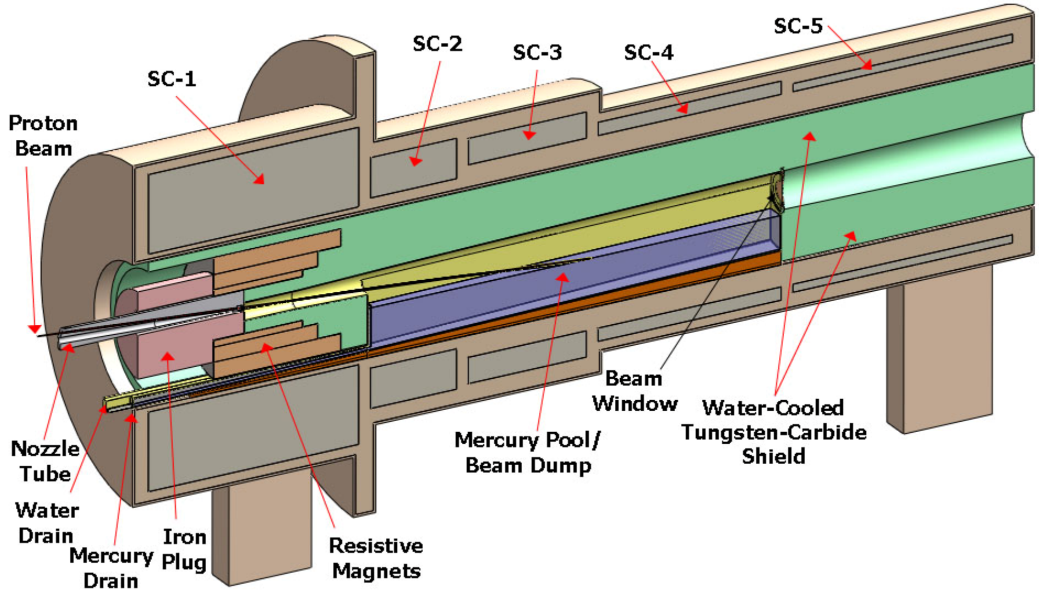
- *To deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility*

As well as…

- *To explore the path towards a facility that can provide cutting edge performance at both the Intensity Frontier and the Energy Frontier*
- *To validate the concepts that would enable the Fermilab accelerator complex to support these goals*

Neutrino Factory target baseline: free mercury jet

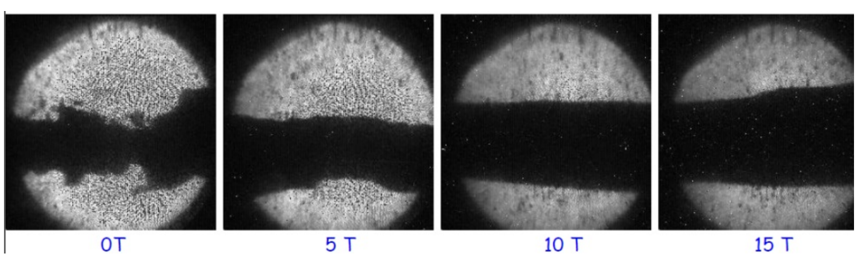
– see WG3 talk tomorrow … k McDonald

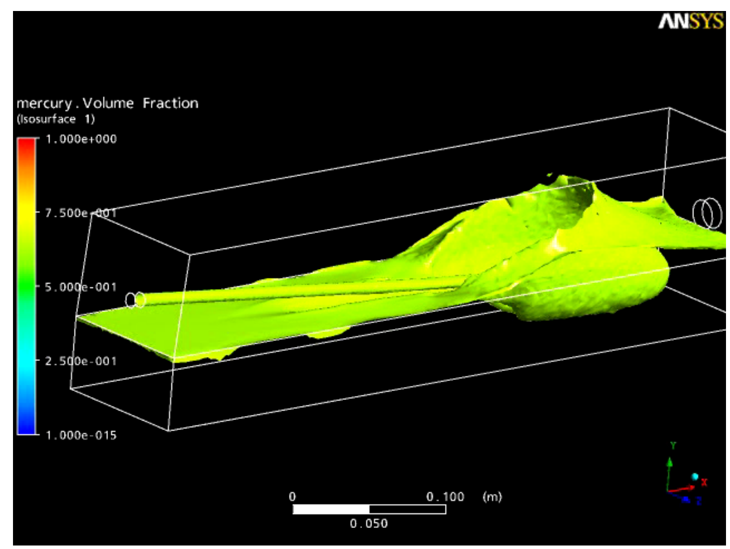


Baseline target system for a Neutrino Factory

But a liquid mercury target presents many challenges, e.g. interaction of mercury jet with dump, handling, disposal etc

MERIT mercury jet experiment at CERN demonstrated suppression of beam induced 'splash' with magnetic field





Conclusion

- Through the end of this decade, the primary goal of MAP is demonstrating the feasibility of key concepts needed for a neutrino factory and muon collider

⇨ Thus enabling an informed decision on the path forward for the HEP community

Mark A. Palmer

Muon Accelerator Program

A promising R&D program is in progress!

The short (realistic) version

Forget about

- CERN resources are fully challenged by LHC upgrades
- As a matter of fact the latest neutrino beam line fully funded by CERN had been WANF (Chorus, Nomad), more than 20 years ago. (CNGS had been funded by the largest part by external funding agencies, mainly INFN).
- The neutrino physics community is not converging to a single project and sometimes the different projects conflict.

Four large scale projects with high priority

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

- Full cost for a comprehensive accelerator based neutrino facility is large. Ideas for such facilities are being developed in Japan, the US and Europe.
- Consideration should include the physics potential from non-accelerator neutrino programme: i.e. sterile neutrino and mass hierarchy.
- Optimising the European contribution for neutrino physics vis a vie the European ambition of high energy frontier.

T. Nakada (European Strategy) ECFA-EPS Joint Session, Stockholm, Sweden, June 20, 2013 16

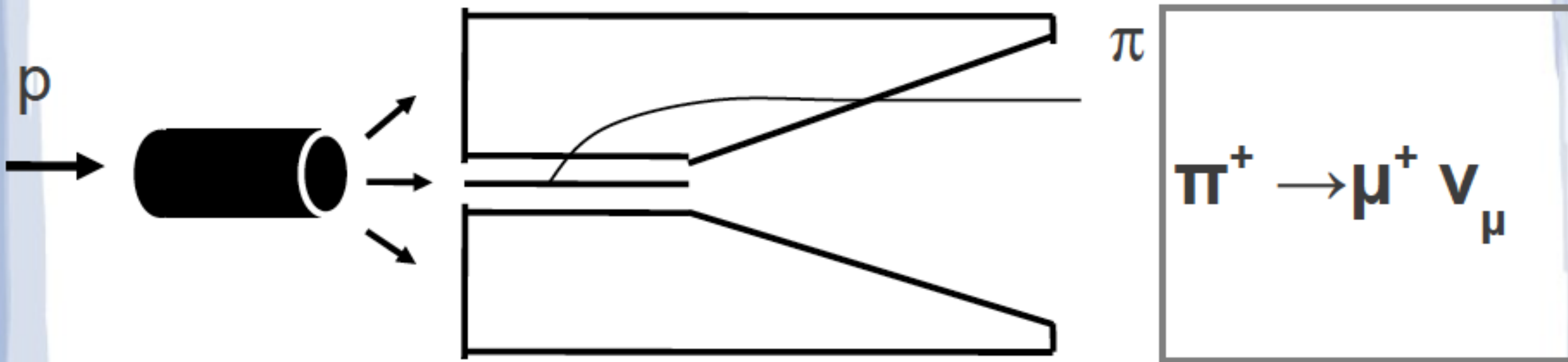
- Workers of the world, unite!
- Proletarier aller Länder vereinigt Euch!
- ***Пролетарии всех стран, соединяйтесь!***

From Marx and Engels

http://www.fnal.gov/directorate/icfa/neutrino_panel.html

Top page only at the moment. Site will go "live" Monday 26Aug13.

The neutrino (Super) beam



Primary proton beam on target

Focusing the pions with a magnetic device

Decay volume

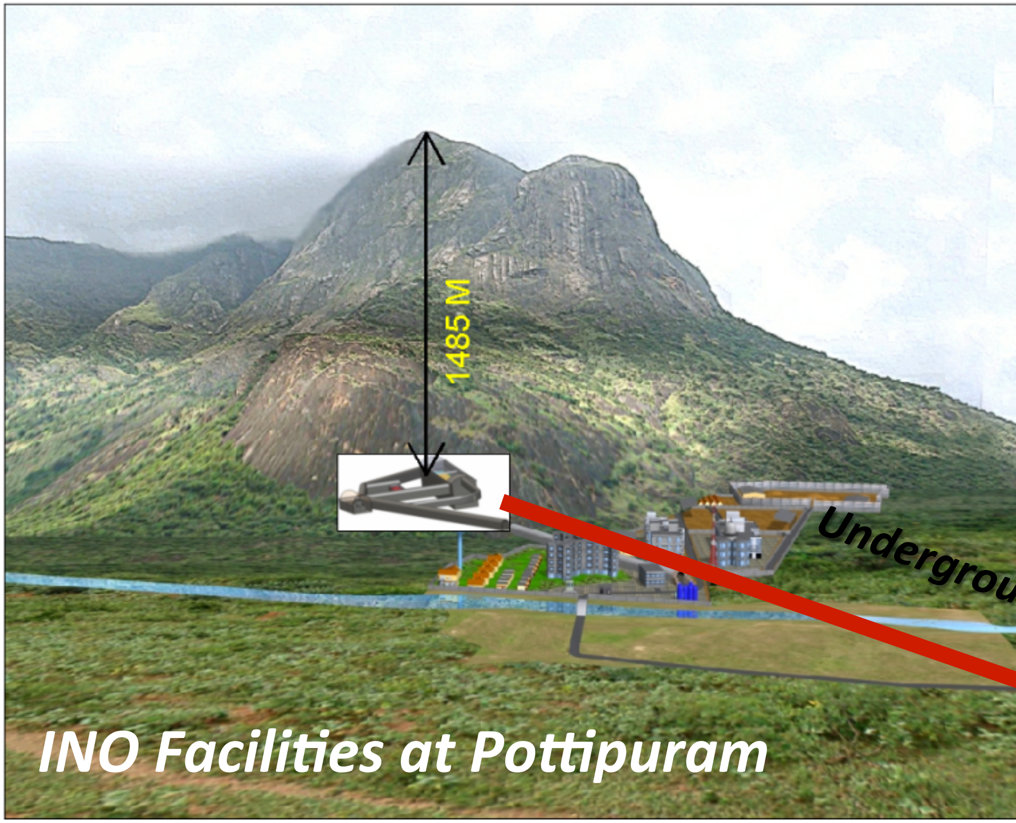
Conclusions-1

- A conventional neutrino beam with an increasing beam power towards the multi-MW range remains the primary tool for the further study of neutrino oscillations
- The EUROnu design study concluded that practical solutions exists for the target and horn
- Several aspects (target, horn cooling) require further prototyping to validate these solutions
- The devil is in the details: strips, cooling system, piping, remote replacement system

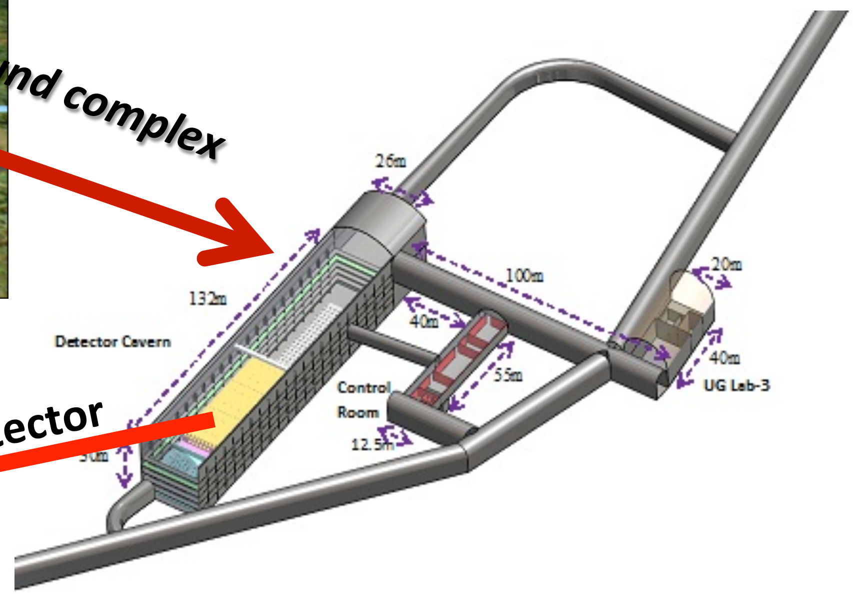
NUFACT 2013, Beijing Marco Zito 31

- The target system remain the primary area for further investigations towards <u>feasibility</u>
- The horn system has the potential for <u>boosted performances</u>

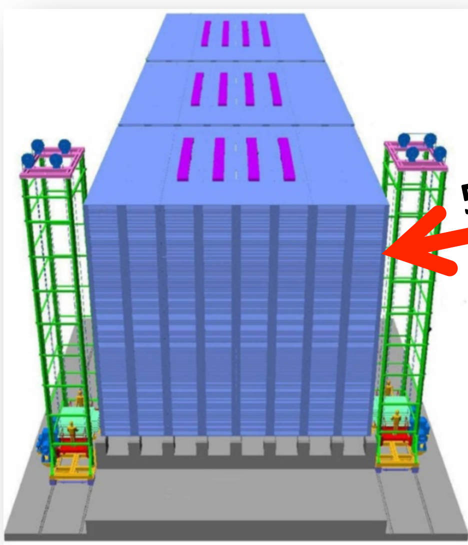
New kid on the block!



Underground complex



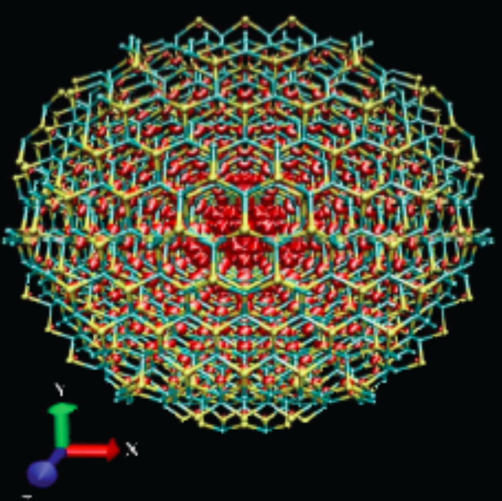
50 kton ICAL Neutrino Detector

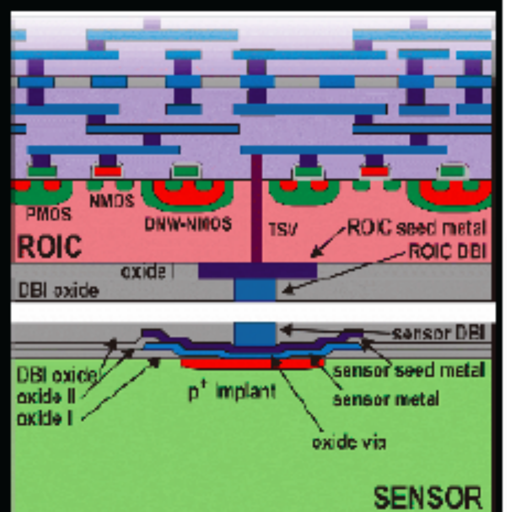


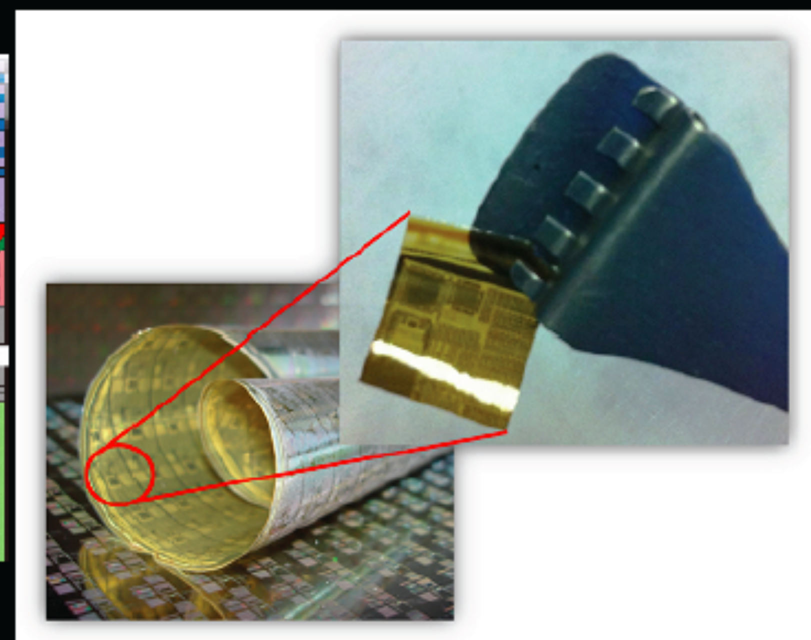
Funding Balance .... "The 1% Tax"

- What is the right balance between funding to support the needs of specific projects and funding to support generic detector development ?
- **What if 1% of the OHEP budget were set aside for the development of potentially transformative technologies ?**

- What technologies could be developed?



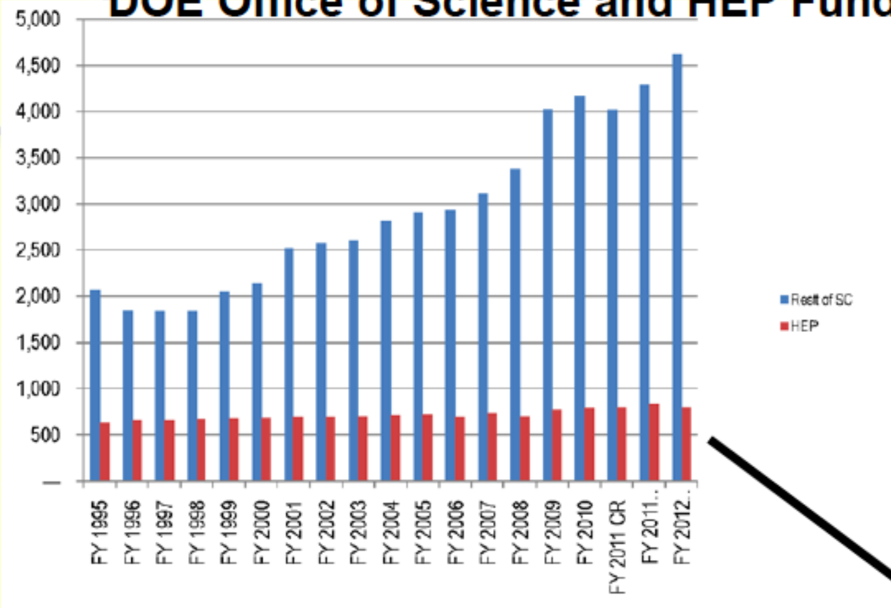




US HEP Funding

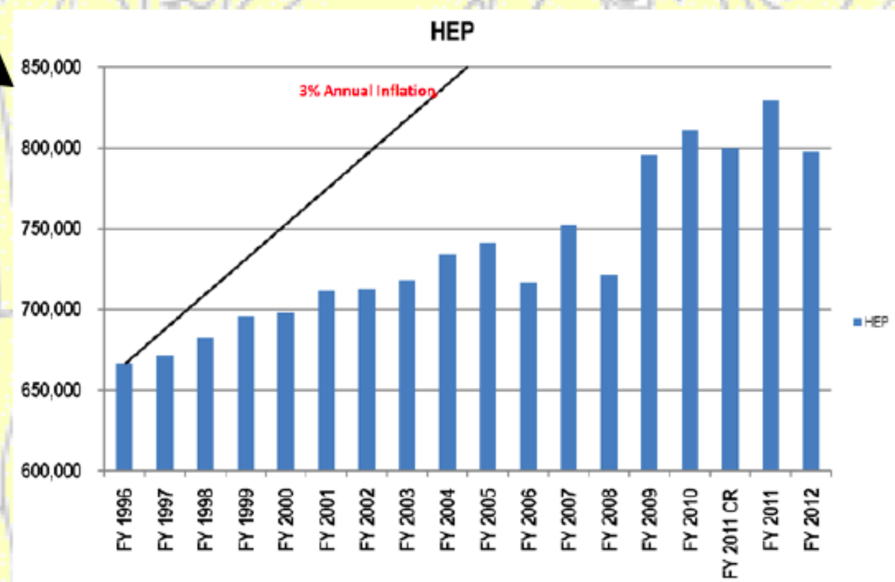
Eli Rosenberg
Iowa State University

DOE Office of Science and HEP Funding (M$)



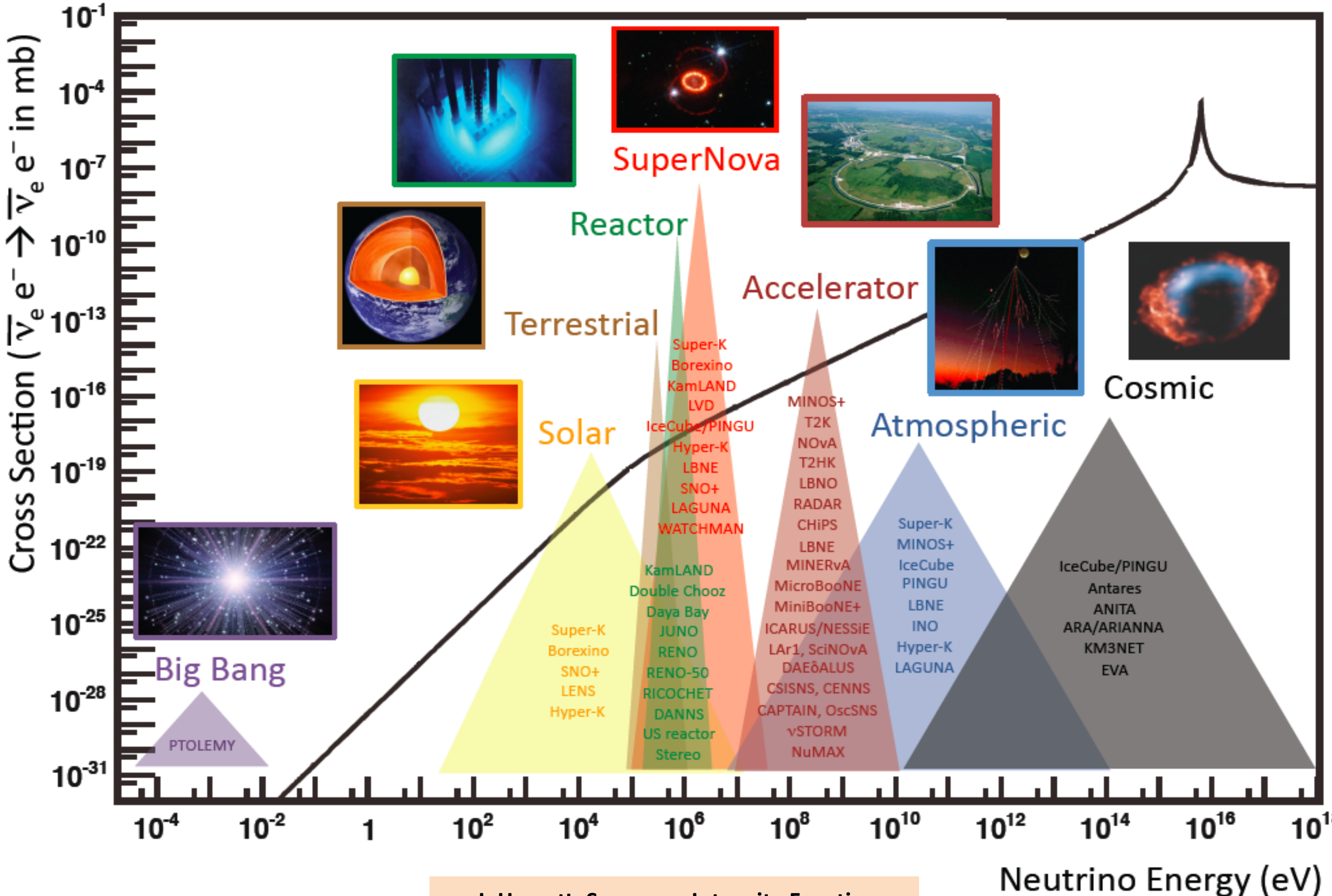
Discovery science is not a high priority

Energy independence and economic competiveness are



HEP is funding is likely to remain flat at best

"$800M is not exactly chicken feed"



J. Hewett, Summary Intensity Frontier
Snowmass on the Mississippi
From Formaggio and Zeller, Rev. Mod. Phys. 84, 1307-1341,2012

Bruno Pontecorvo (1913-1993)

- Solar neutrinos
  $^{37}Cl\ (\nu,e^-)\ ^{37}Ar$ (inverse beta)
- Different ν flavors, 1957
- Neutrino oscillations
- Accelerator produced ν beams
  $\pi \rightarrow \mu + \nu$, $K \rightarrow \mu + \nu$
- Sterile neutrinos
- …(and much more)

Born Aug 22, 1913

- This is a memorable NuFact
- Unforgettable hospitality
- Well organized and smoothly run!

- **THANKS to all!**

- My special thanks to Miao He

LOCAL ORGANIZING COMMITTEE

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Shinian Fu (IHEP)
Tao Hu (IHEP)
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Bon voyage!

再 见

zai jian