Project X: Accelerator and Experiments:

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Fermilab
Jan 22, 2010-Aspen

Physics of Project X:

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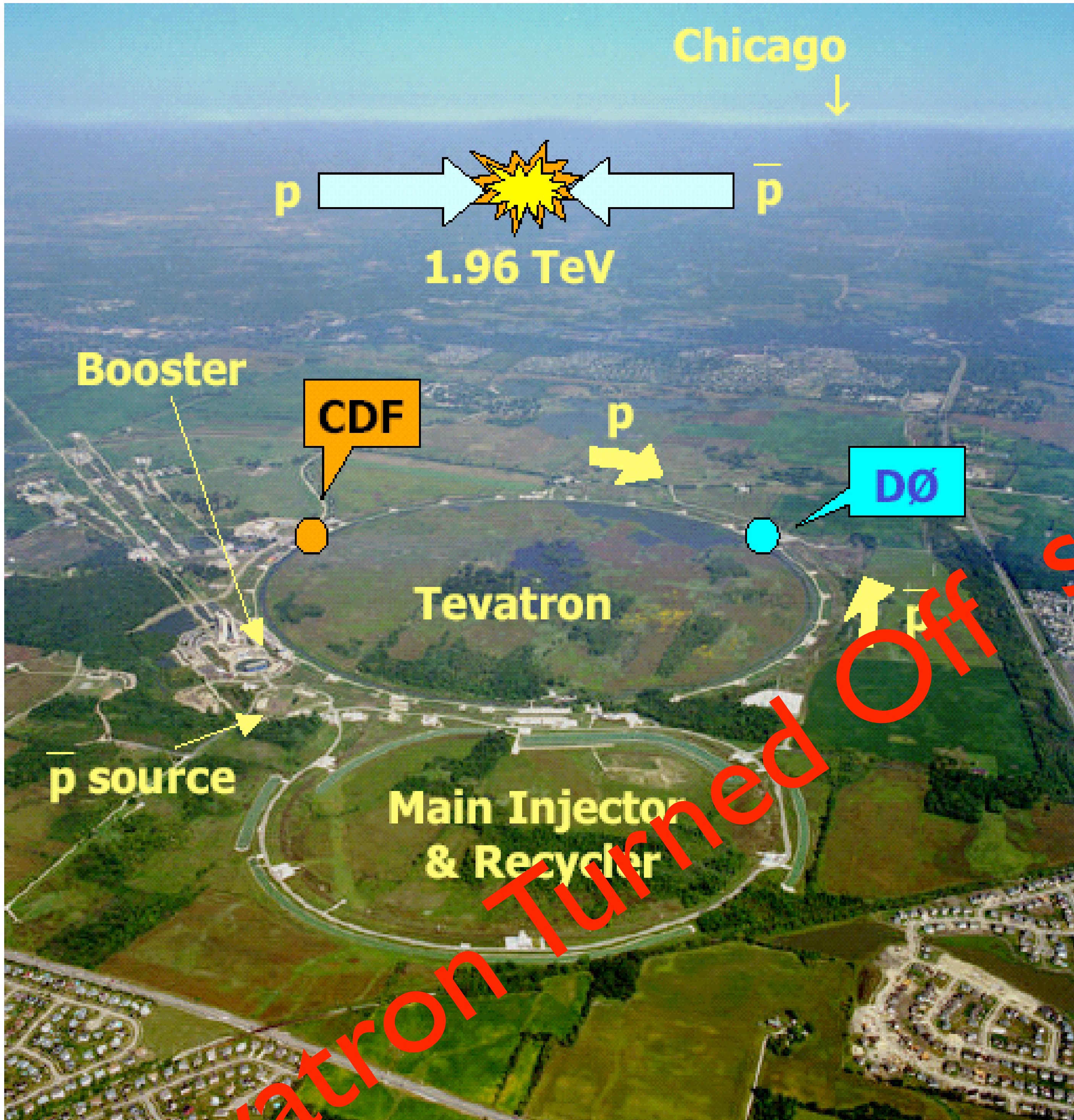
Jan 22, 2010-Aspen

Tevatron: CDF & D0

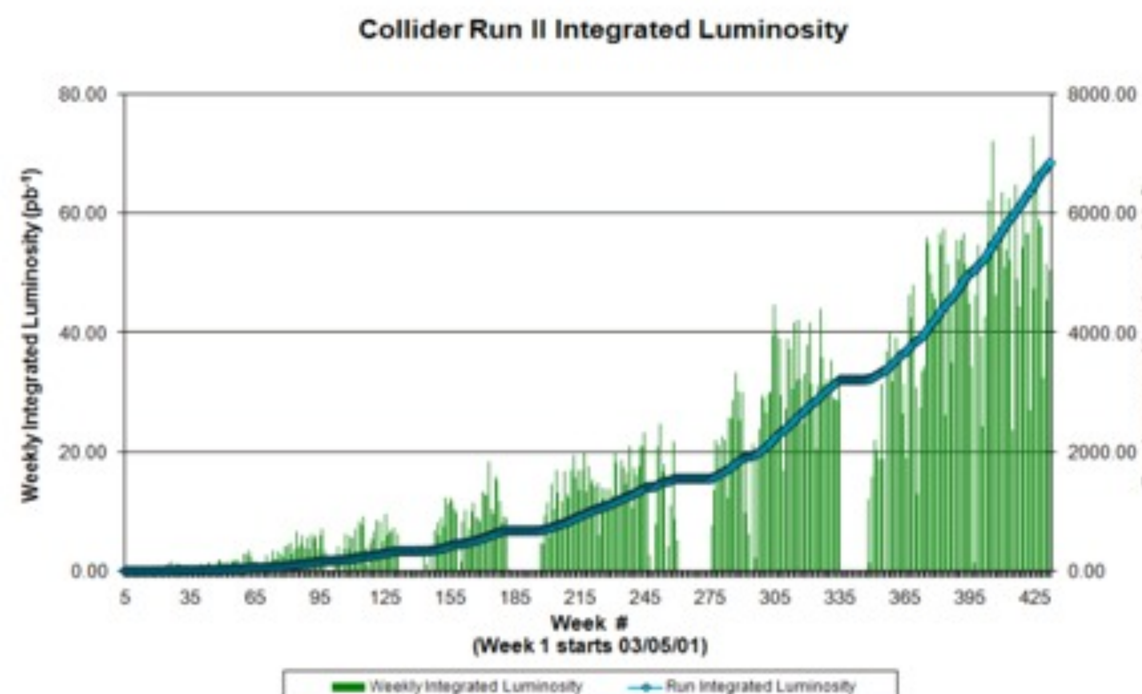
Tevatron Turned Off sometime in 2011



- 36x36 bunches
- bunch crossing 396 ns
- Run II started in March 2001
- Peak Luminosity:3.5E32 cm^{-2} sec^{-1}
- Run II delivered: ~7 fb^{-1}

Peak Intergrated Luminosity:

$$3.5 \times 10^{32}\ cm^{-2} sec^{-1} \times 3 \times 10^{7} sec \approx 10 fb^{-1}/yr$$



Peak $\bar{p}$ Collection Rate:

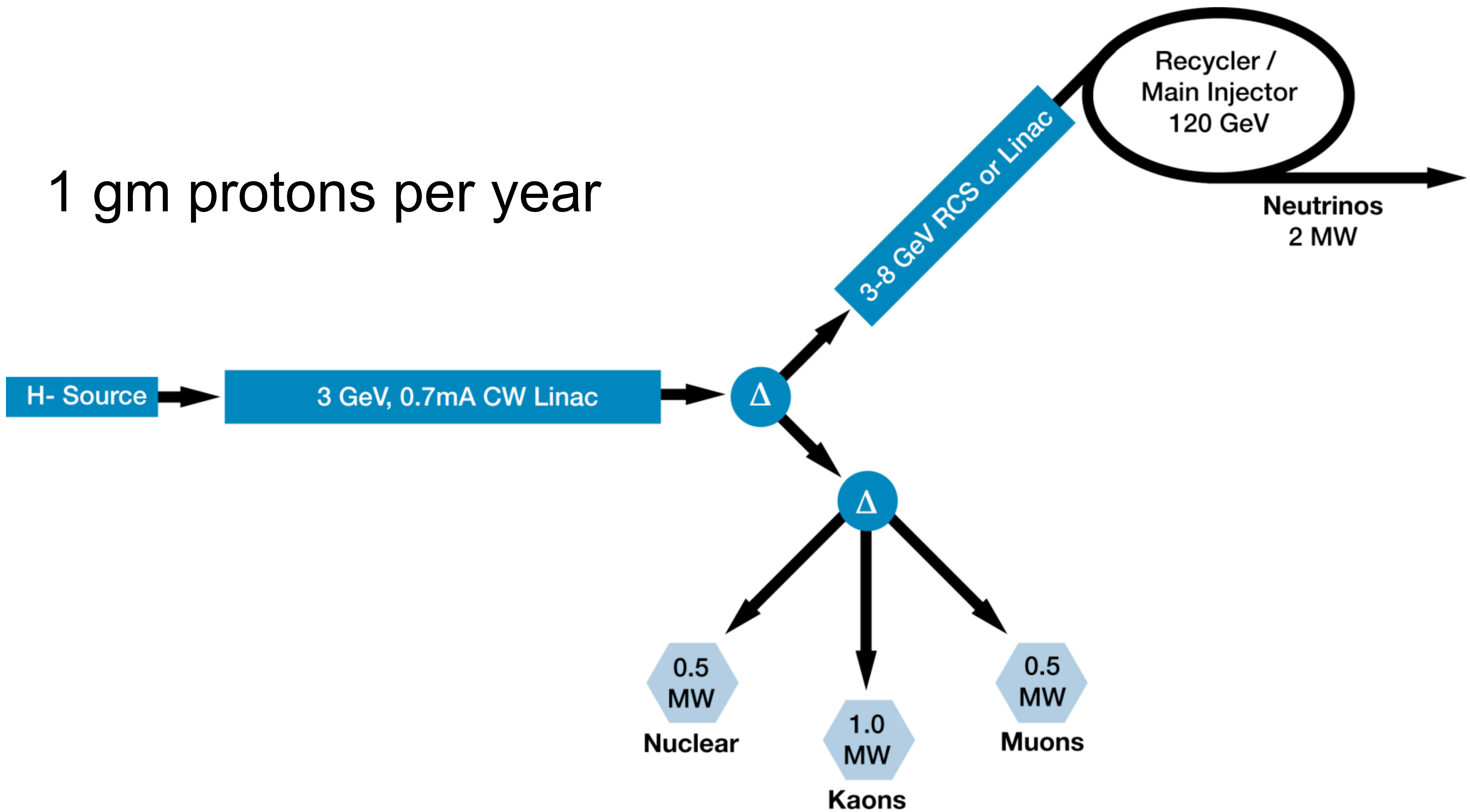
$$7 \times 10^{7}/sec$$

Peak $\bar{p}$ Burn Rate:

$$2 \times 3.5 \times 10^{32}\ cm^{-2} sec^{-1} \times 100\ mb = 7 \times 10^{7}/sec$$

Project X: (Proton Driver)

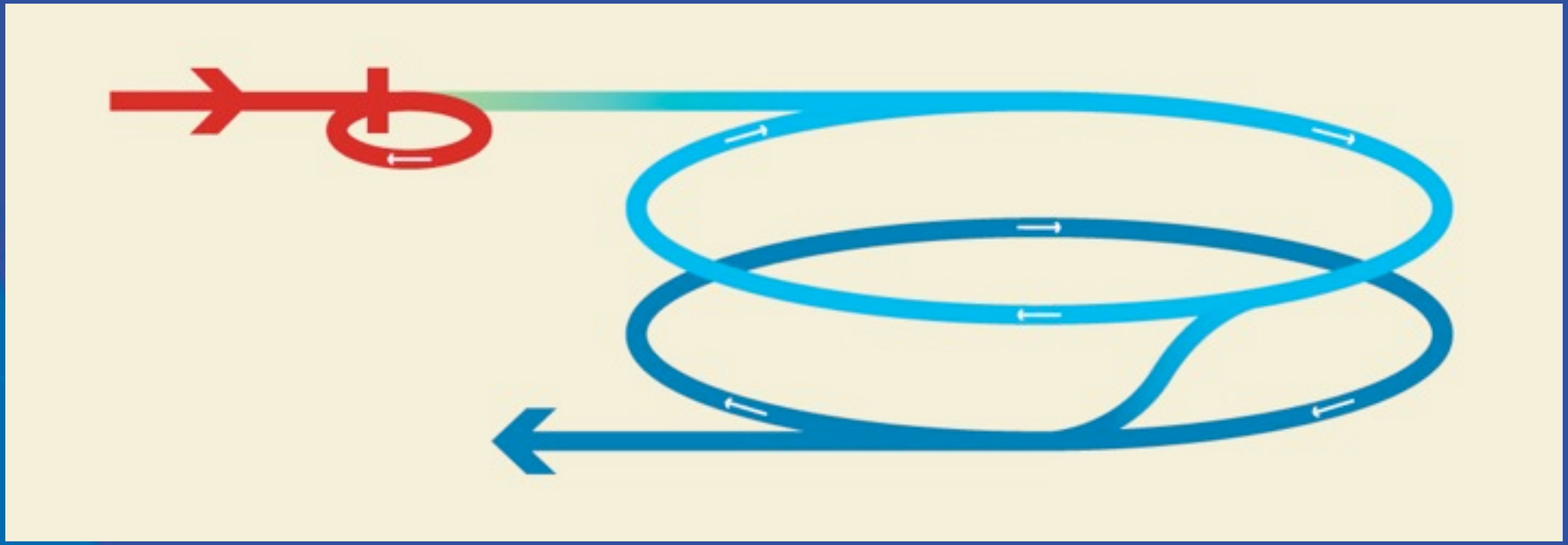
1 gm protons per year



Project X and LBNE to Homestake

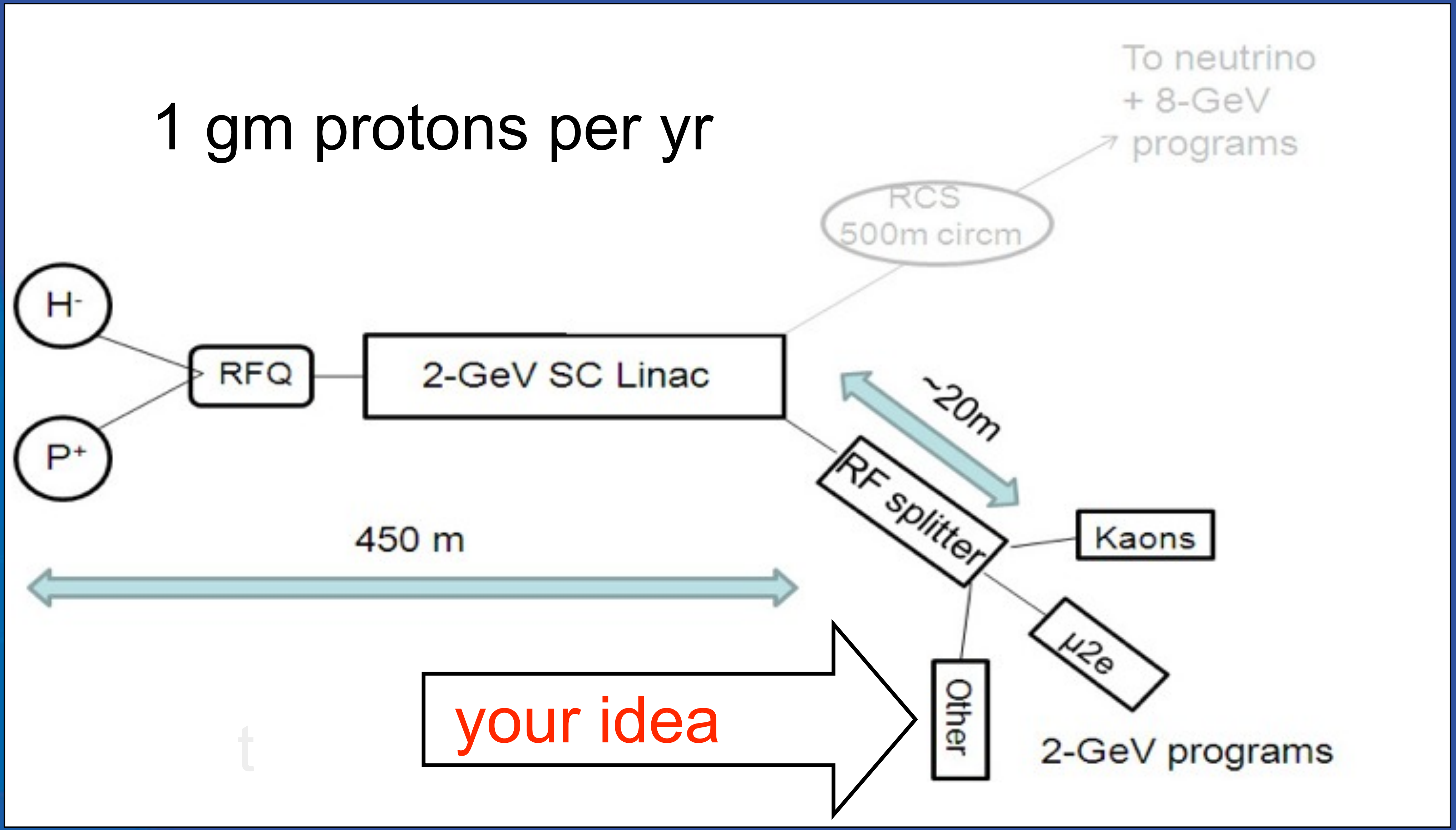
- 5% of the time line, the 3 GeV linac feeds a simple Rapid Cycling Synchrotron (RCS), 500m circumference, to strip, accumulate and boost the energy to 8 GeV

- Six pulses of the SAB are transferred to the recycler, filling the existing recycler, and every 1.4 sec transferred to the Main Injector for acceleration to high energies (60 GeV to 120 GeV)



Project X and 2 GeV beams

- The greatest potential for rare processes comes from 2 MW continuous beam. Intensity experiments need continuous beam: pile up is the main limitation in pulsed beams



Neutrinos:

Mixing Matrix:

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ | Atmos. L/E $\mu \leftrightarrow e$ | Solar L/E $e \to \mu, \tau$ | $0\nu\beta\beta$ decay

500km/GeV | 15km/MeV

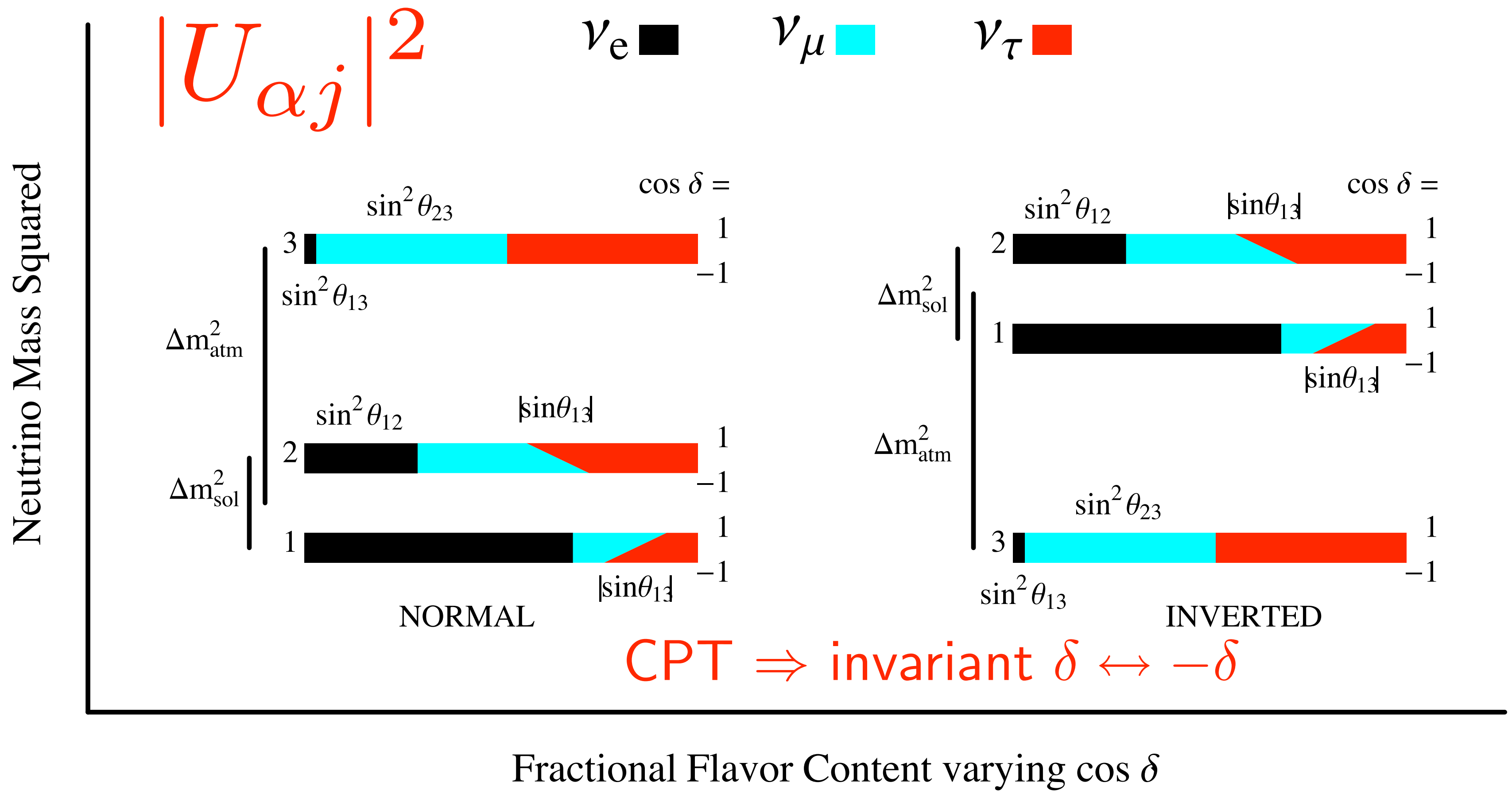
solar/KamLAND

Reactor/LBL

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Atmospheric Nus

Neutrinos



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$\sin^2\theta_{12} \sim 1/3$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$\sin^2\theta_{23} \sim 1/2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sin^2\theta_{13} < 3\%$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

$$0 \leq \delta < 2\pi$$

At 2σ we have the following limits:

$$
\begin{aligned}
\sin^2\theta_{13} &< 0.04 \\
\left|\sin^2\theta_{12} - \frac{1}{3}\right| &< 0.04 \\
\left|\sin^2\theta_{23} - \frac{1}{2}\right| &< 0.12
\end{aligned}
$$

Close to Tri-Bi-Maximal: accident or symmetry ?

In numerous models:

$$\sin^2\theta_{13},\ \left|\sin^2\theta_{12} - \tfrac{1}{3}\right|,\ \left|\sin^2\theta_{23} - \tfrac{1}{2}\right| \ \sim\ \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^n$$

Experiment has probed down to n $\approx 1/2$ to 1 !!!

$$
\begin{array}{ccccccc}
 & & & \text{CP} & & & \\
 & \nu_\mu \longrightarrow \nu_e & & \Longleftrightarrow & & \bar{\nu}_\mu \longrightarrow \bar{\nu}_e & \\
\text{T} & \Updownarrow & & \text{CPT across diagonals} & & \Updownarrow & \text{T} \\
 & \nu_e \longrightarrow \nu_\mu & & \Longleftrightarrow & & \bar{\nu}_e \longrightarrow \bar{\nu}_\mu & \\
 & & & \text{CP} & & &
\end{array}
$$

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\,|^2$$

$\updownarrow$ CP violation !!!

$$\Delta_{ij} = \delta m^2_{ij} L/4E$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \sin\Delta_{21}$

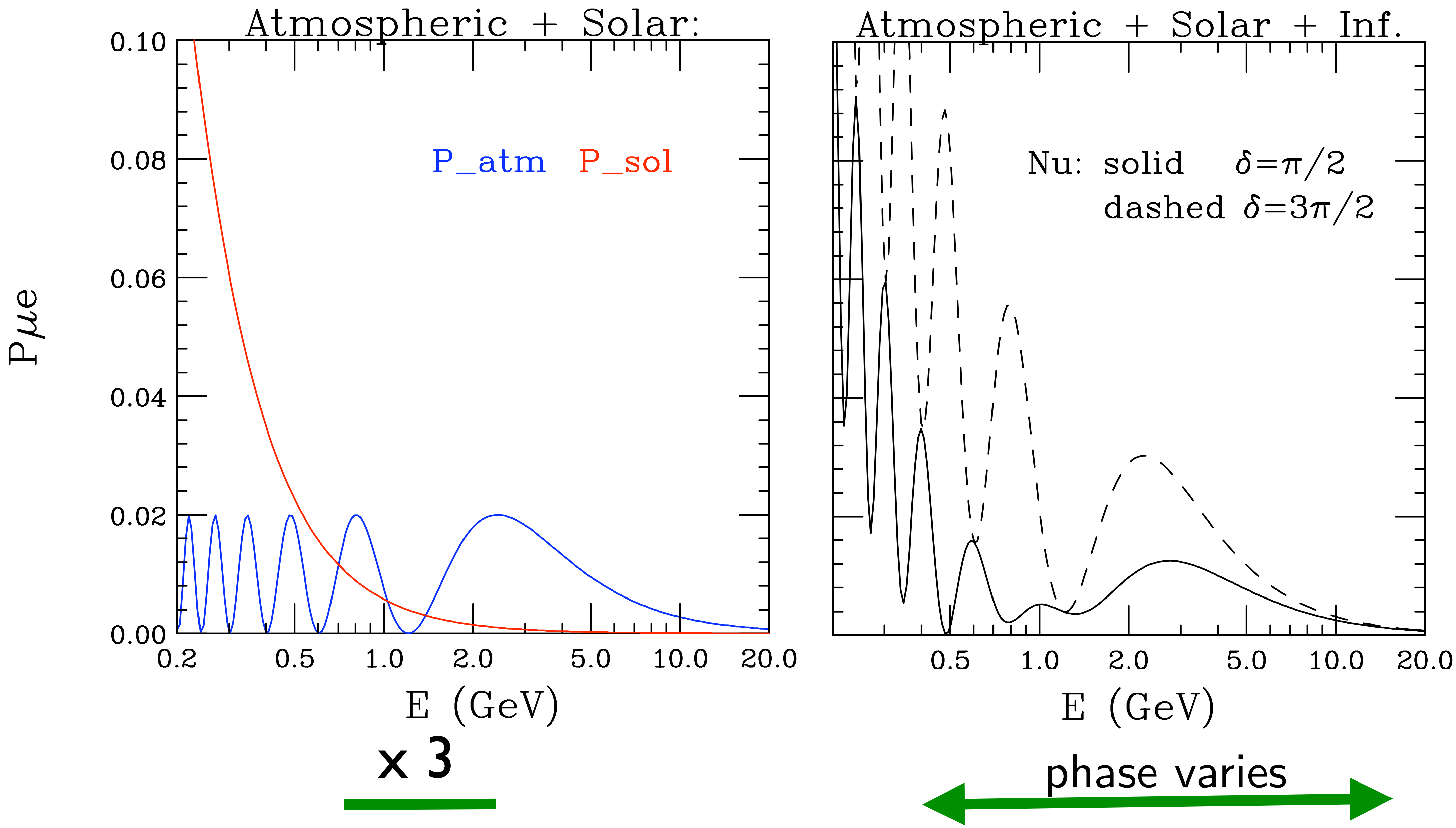
$$\boxed{P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32}\pm\delta) + P_{sol}}$$

only CPV

$$\cos(\Delta_{32}\pm\delta) = \cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta$$

$$P(\nu_\mu \rightarrow \nu_e) \;\approx\; |\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$



In Matter:

$$P_{\mu\to e} \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}|^2$$

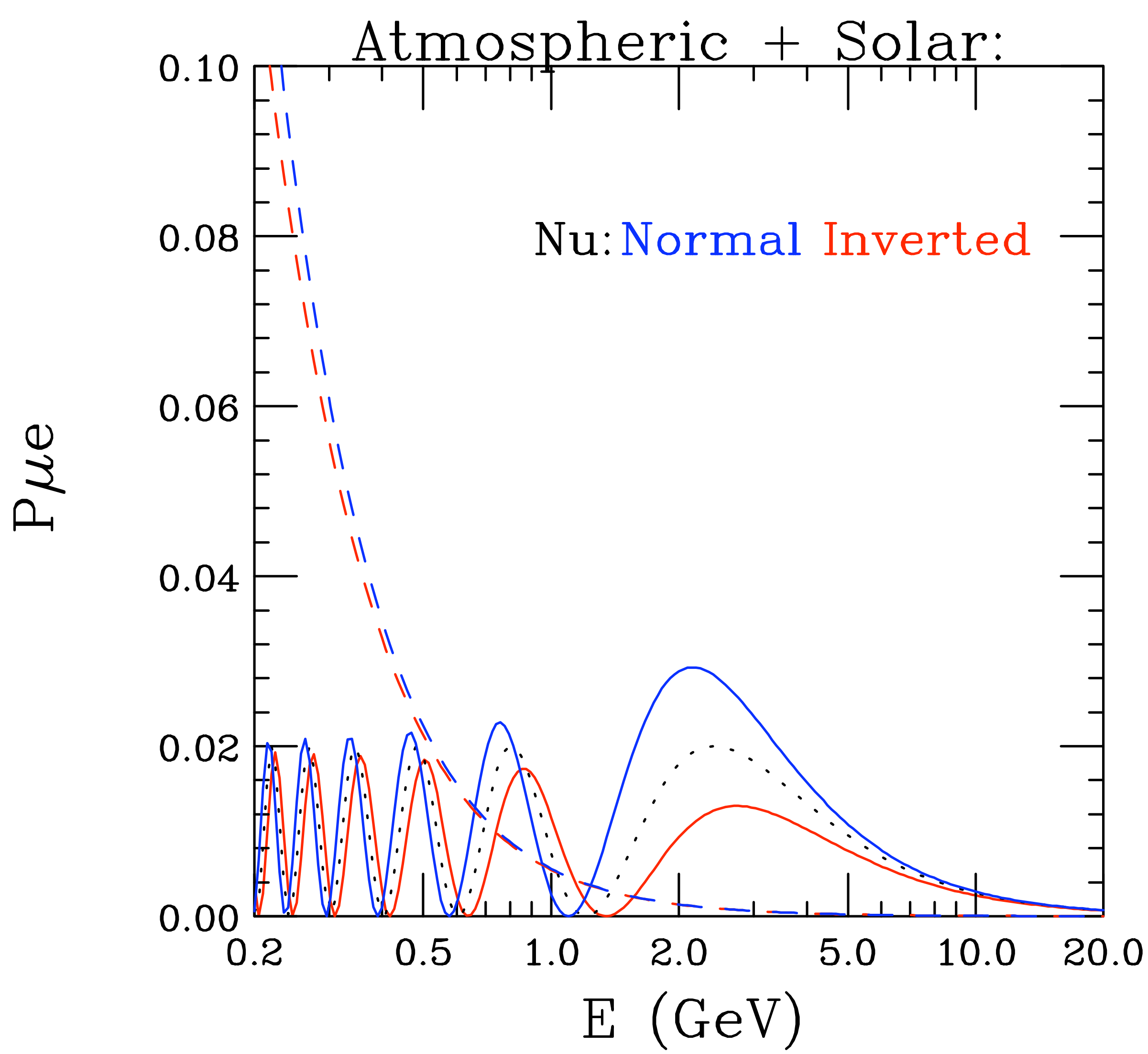
where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\,\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\,\Delta_{31}$

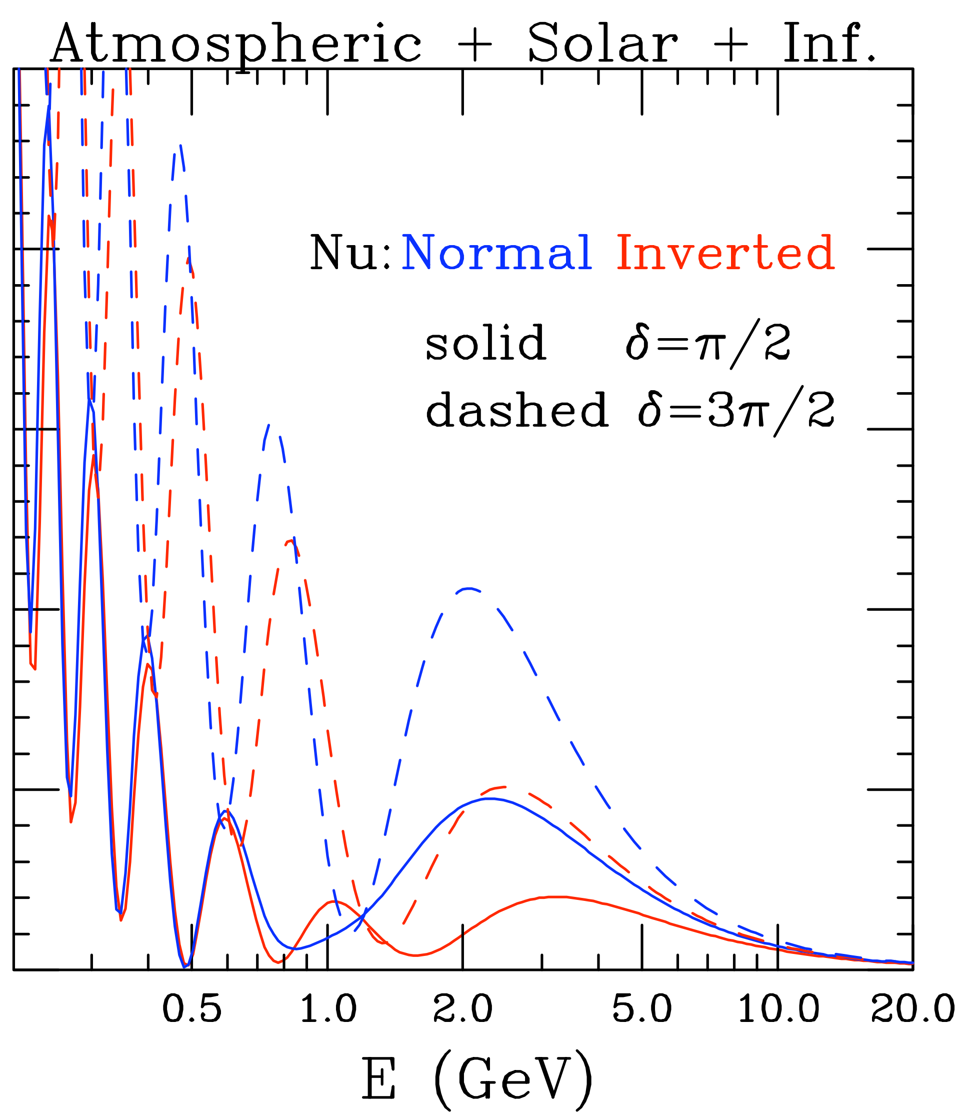
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\,\frac{\sin(aL)}{(aL)}\,\Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





$\nu_\mu \longrightarrow \nu_e$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad \approx \quad & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& +2\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13} \\
& *\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21} \\
& *(\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta) \\
& +\cos^4\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2
\end{aligned}
$$

CPV

CPC

$$(\Delta_{31}-aL) = \Delta_{31}\left(1-\frac{aL}{\Delta_{31}}\right) = \Delta_{31}\left(1-\frac{2\sqrt{2}G_F N_e E}{\delta m_{31}^2}\right)$$

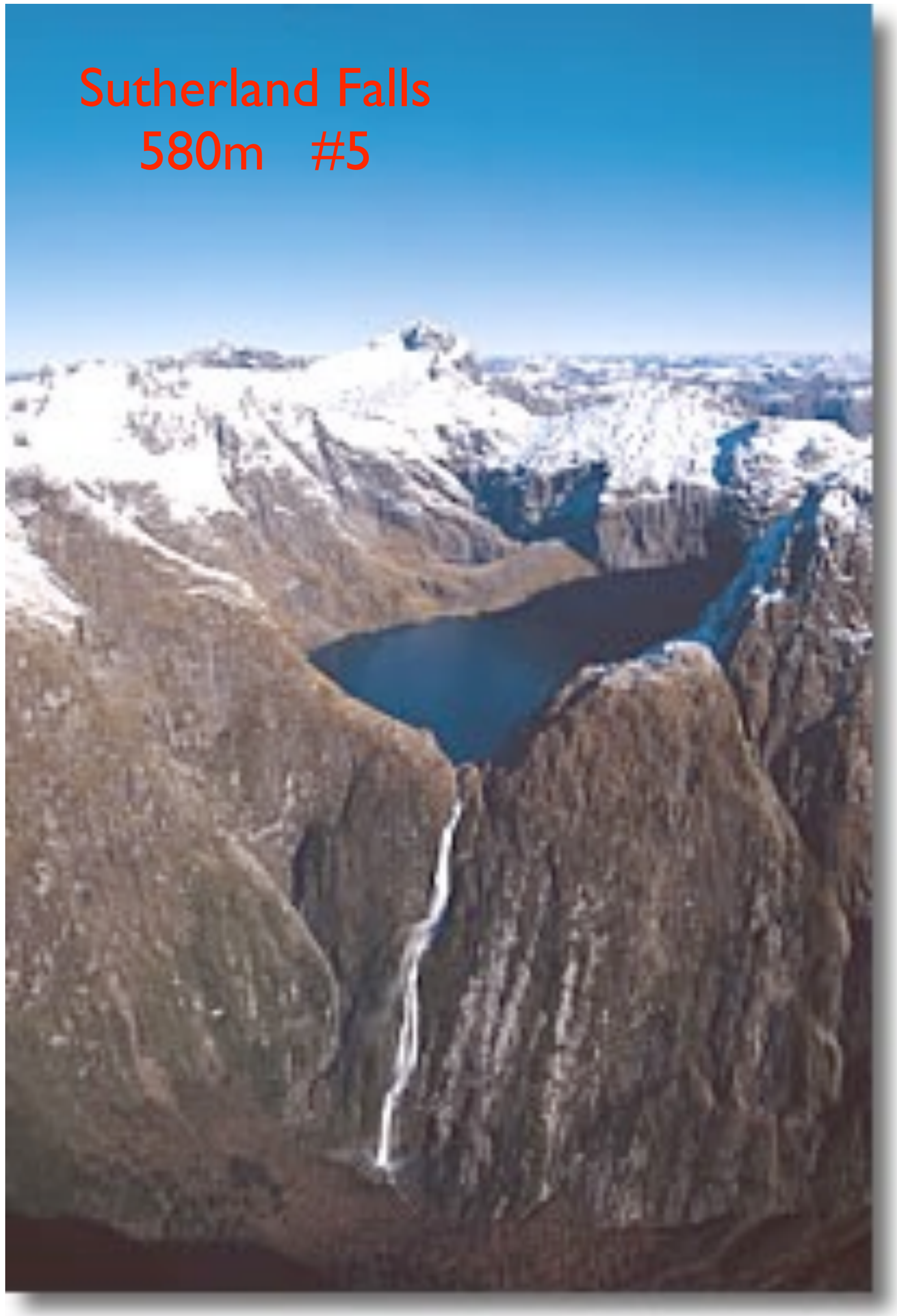
$$\Delta_{32} \approx \Delta_{31}$$

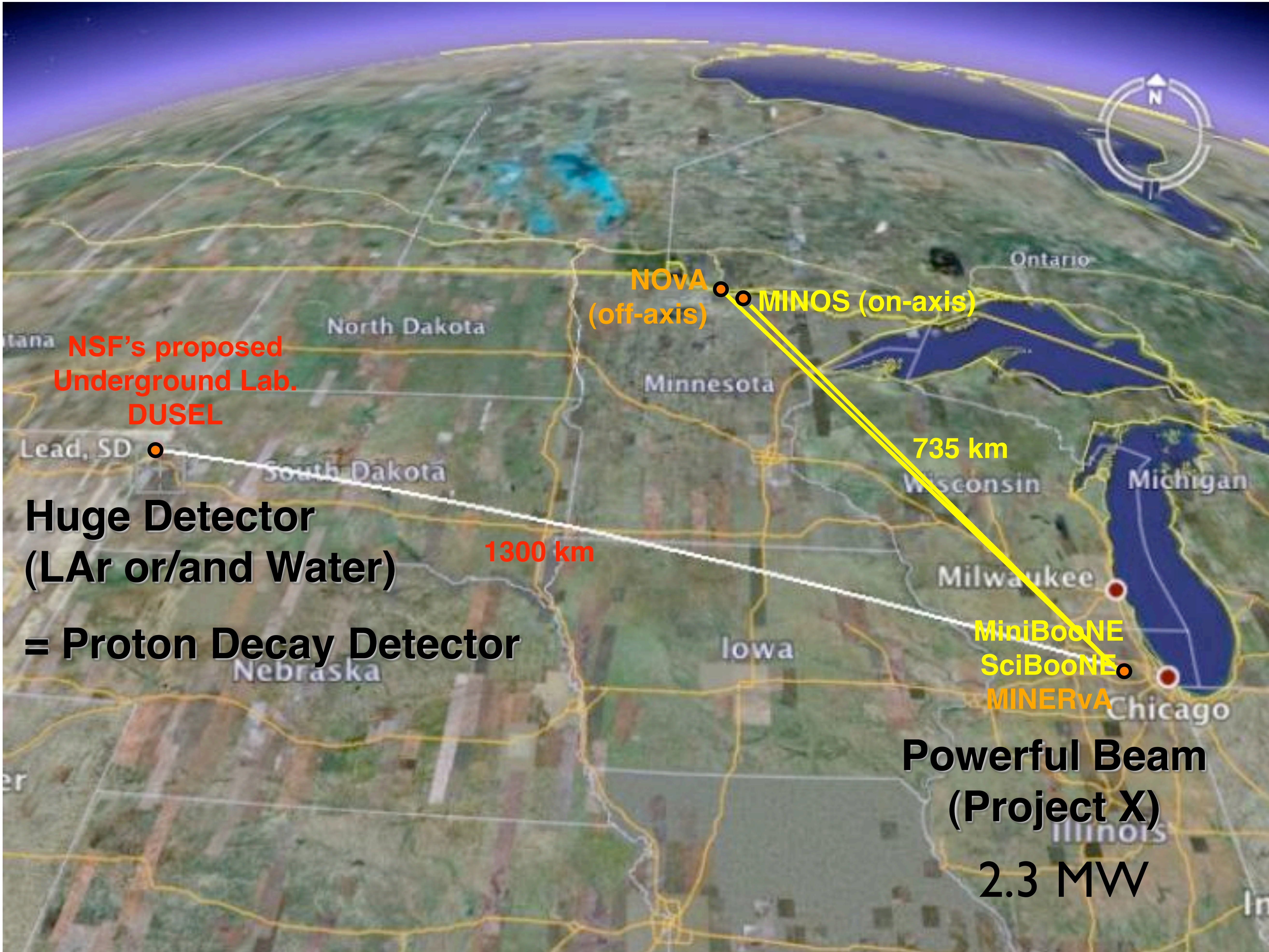
$$J = \sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}\sin\delta$$

$\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\rightarrow e} \approx |\ \sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

Sensitivity to
CPV
and
Mass Hierarchy !!!

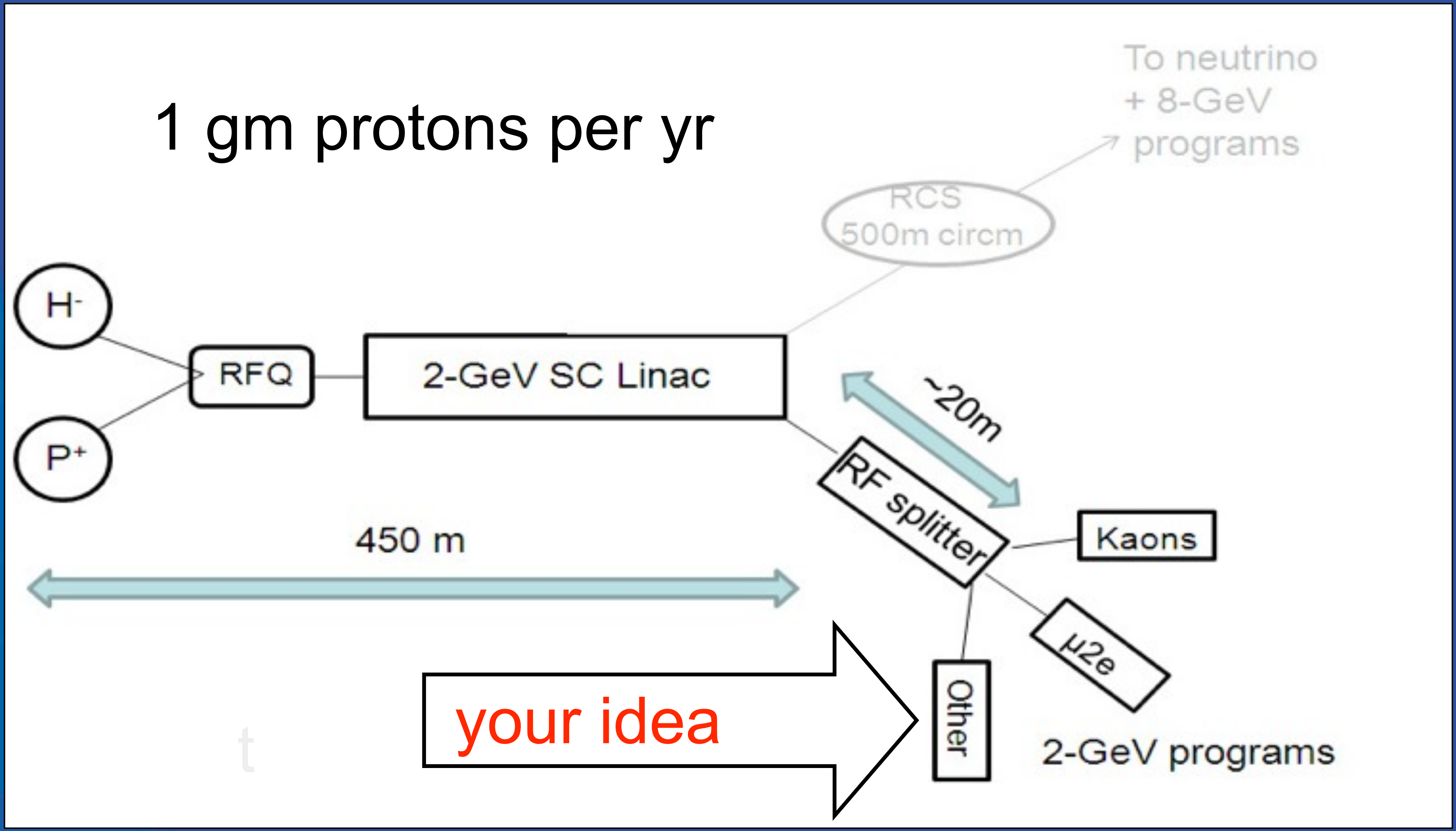




NOvA
(off-axis)
MINOS (on-axis)
NSF's proposed
Underground Lab.
DUSEL
Lead, SD
North Dakota
Minnesota
Ontario
South Dakota
735 km
Wisconsin
Michigan
Huge Detector
(LAr or/and Water)
1300 km
= Proton Decay Detector
Nebraska
Iowa
Milwaukee
MiniBooNE
SciBooNE
MINERvA
Chicago
Powerful Beam
(Project X)
Illinois
2.3 MW

Project X and 2 GeV beams

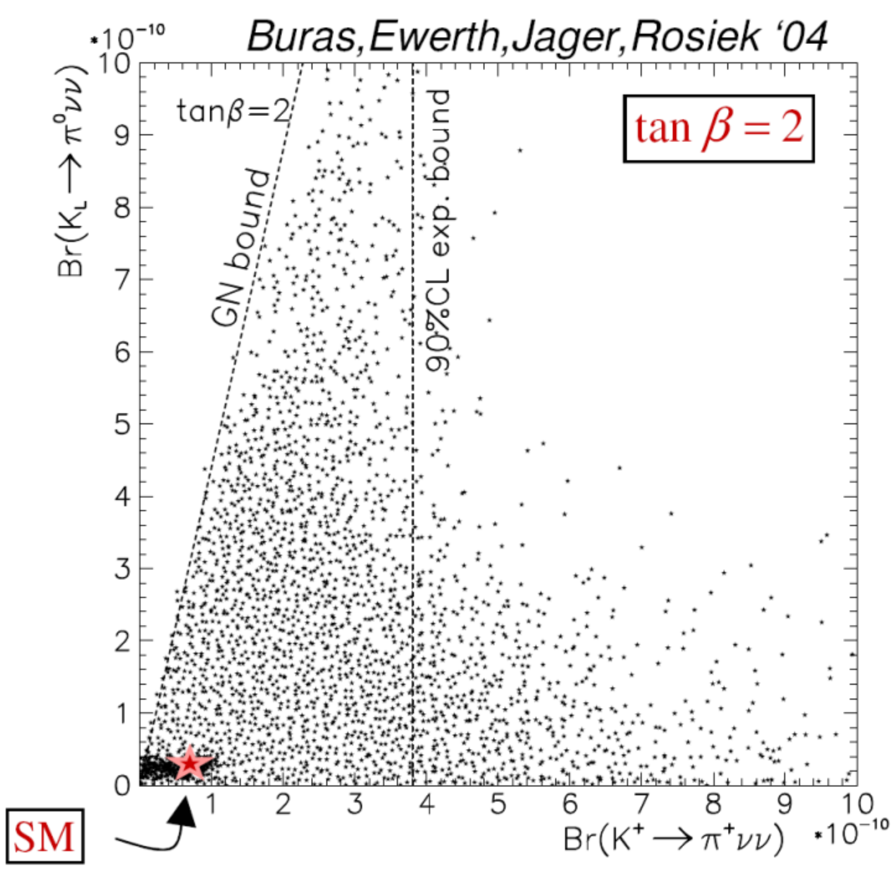
- The greatest potential for rare processes comes from 2 MW continuous beam. Intensity experiments need continuous beam: pile up is the main limitation in pulsed beams

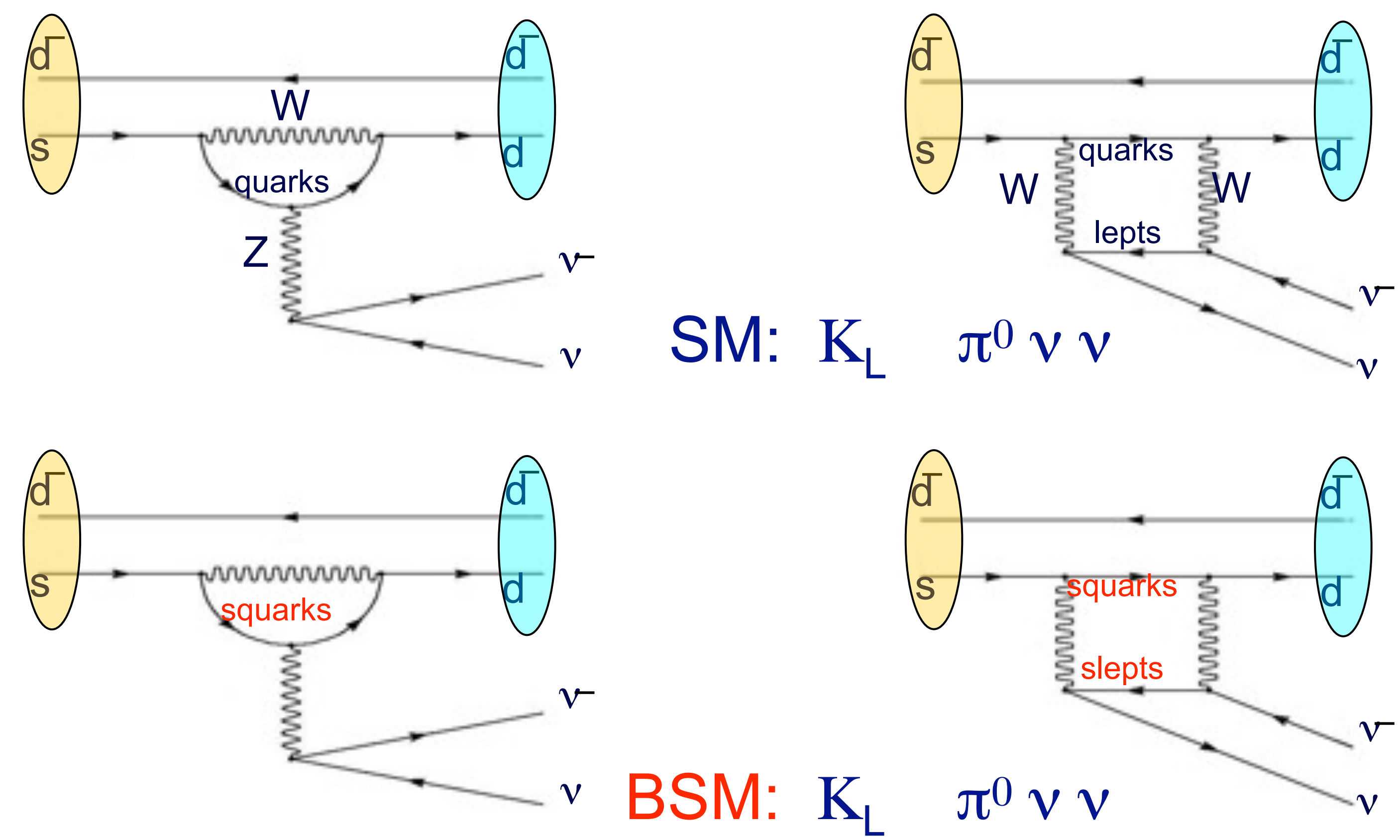


Kaons

$$K^+ \to \pi^+ \nu \bar{\nu}$$
$$K_L \to \pi^0 \nu \bar{\nu}$$

	Theo(SM)$\times 10^{10}$	Exp.$\times 10^{10}$	Experiment
$K^+ \to \pi^+ \nu \bar{\nu}$	0.85 ± 0.07	$1.73^{+1.15}_{-1.05}$	BNL-E787/949
$K_L \to \pi^0 \nu \bar{\nu}$	0.28 ± 0.04	< 670	KEK-391





For Statistical Uncertainties $\approx$ Theoretical Uncertainties

$\sim$ 1000 events needed in K^+ and K_L !

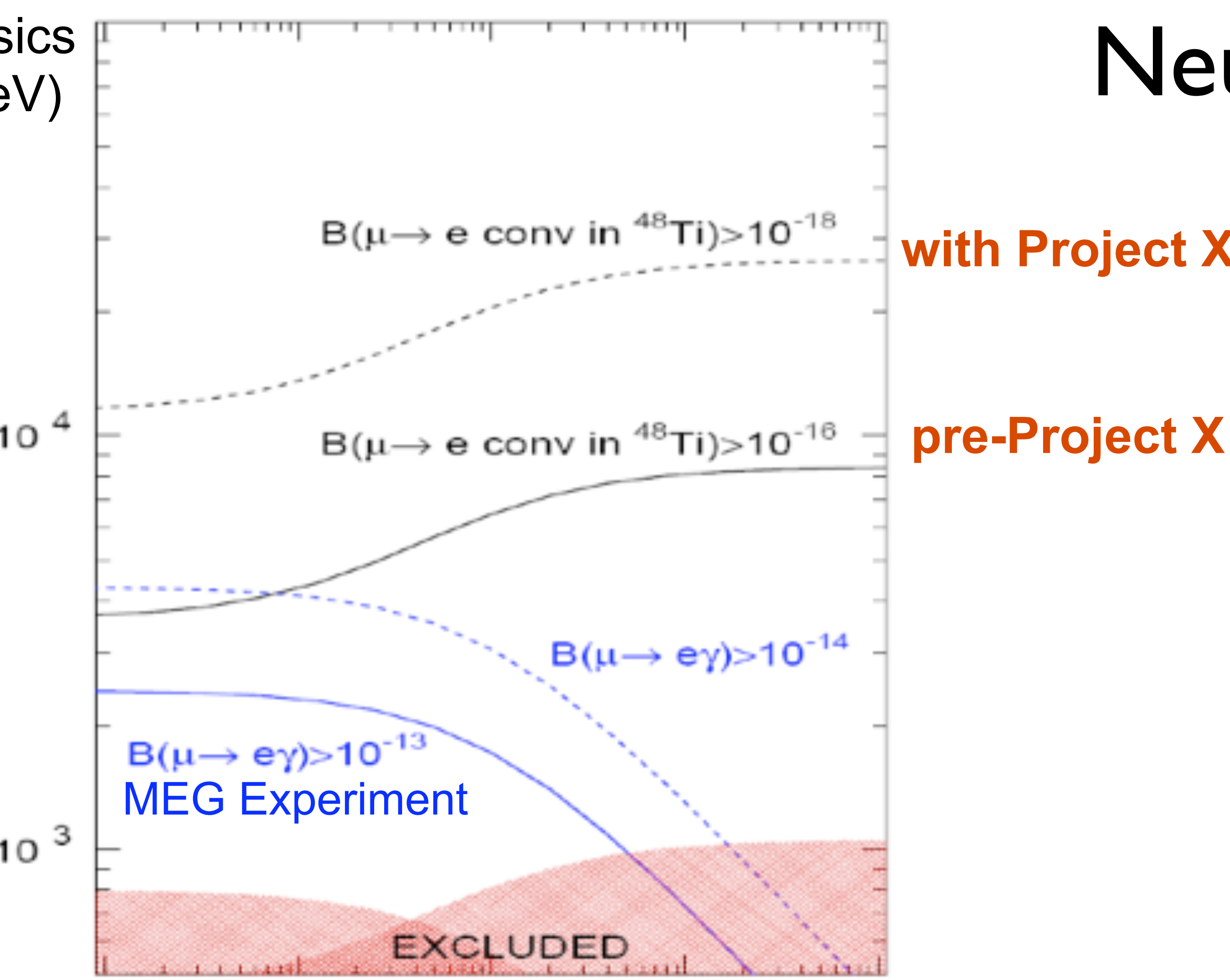
Project X

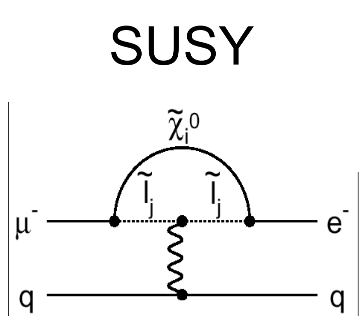
Muons

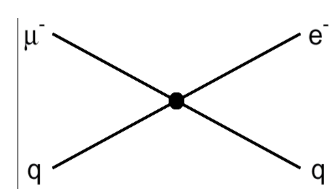
$$\mu + N \rightarrow e + N$$

$$(g-2)_\mu$$

Neutrino Factory

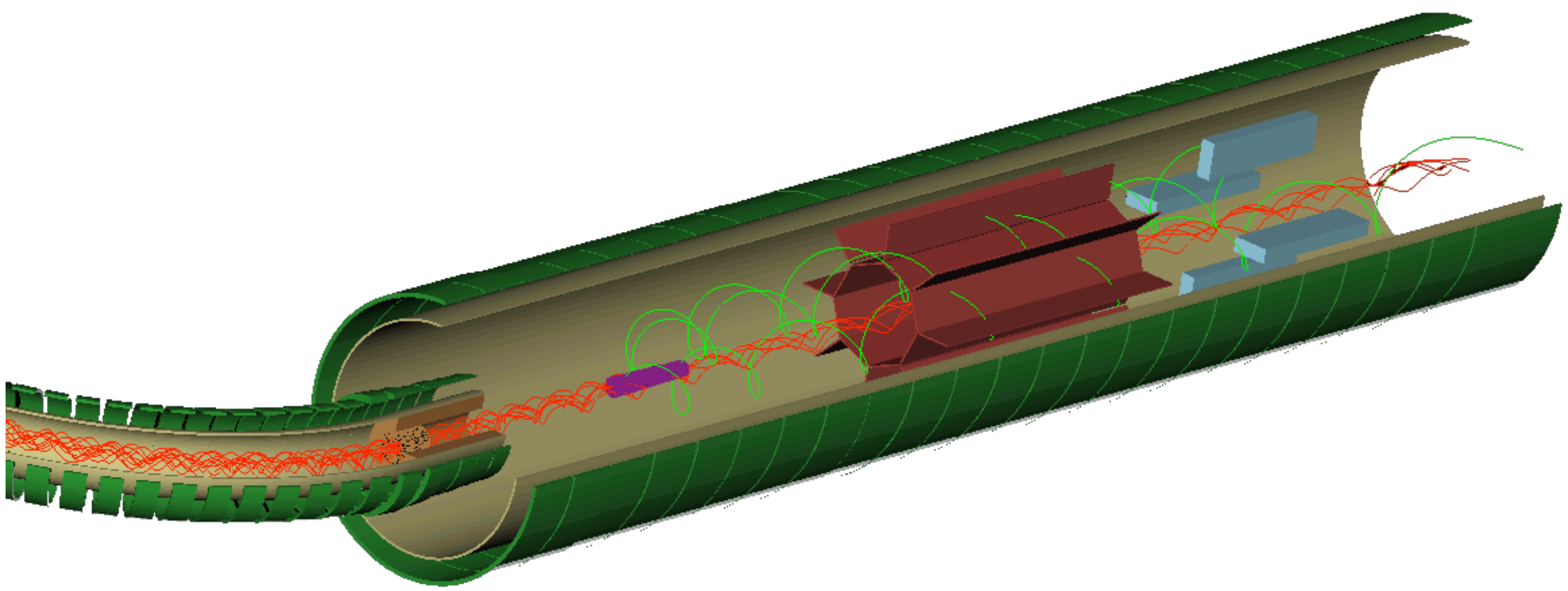






Mu2e can probe $10^3 - 10^4$ TeV

The Mu2e Detector in Detail



Further in the Future:

Muon Collider
and
Neutrino Factory

Lepton colliders beyond LHC

LHC Results

or

ILC Enough → By far the easiest!

ILC not enough

or

CLIC

Muon collider

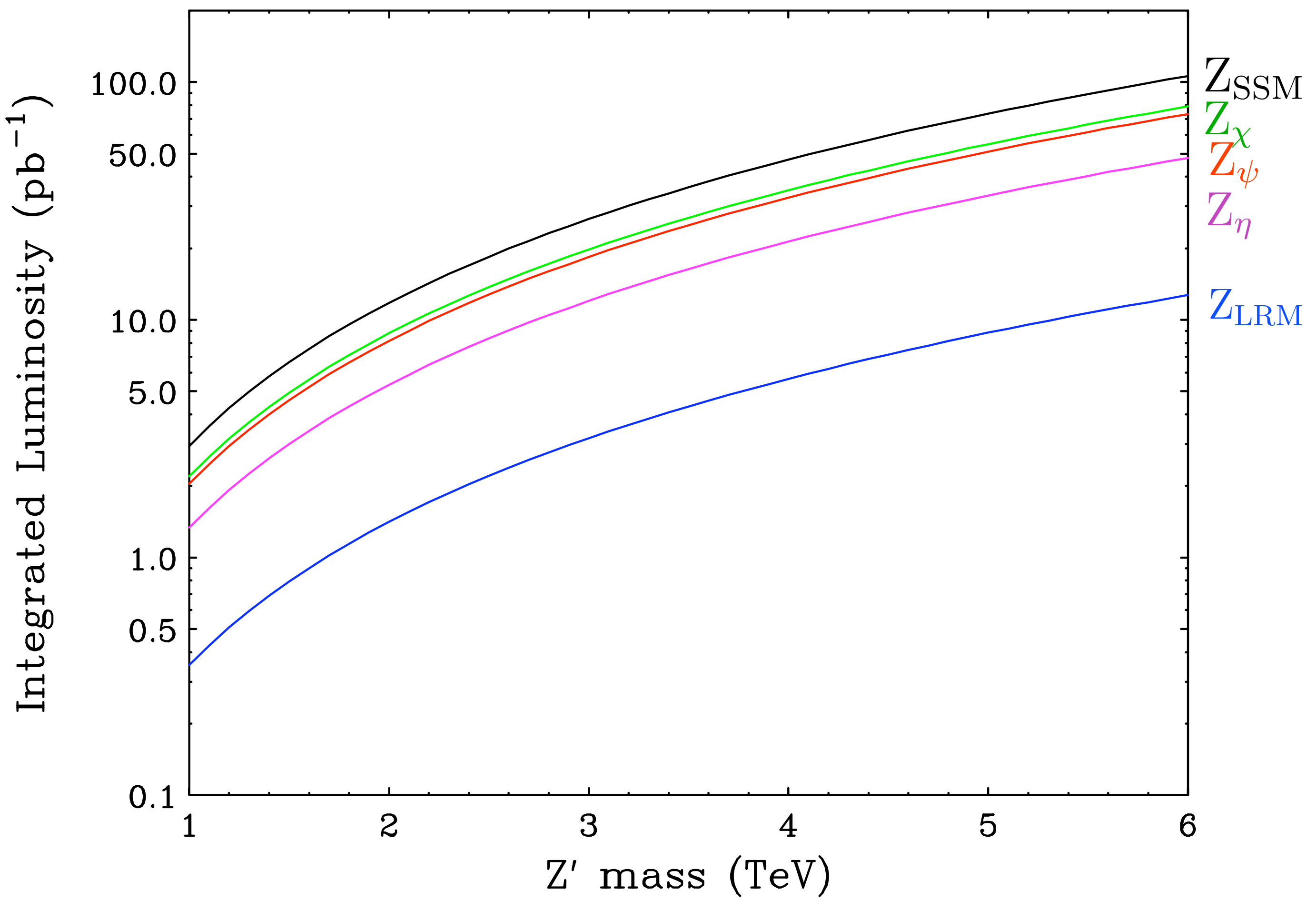
Minimum Luminosity for Physics:

- Assuming a new gauge boson: Z′
  - examples: SSM, E6, LRM
  - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

- For a narrow resonance with $2\Delta E_{beam} / \Gamma_{resonance} << 1$:

$$\rightarrow R_{\mathrm{peak}} = (2J+1)3\frac{B(\mu^+\mu^-)B(visible)}{\alpha_{\mathrm{EM}}^2}$$

The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z′ events on the peak

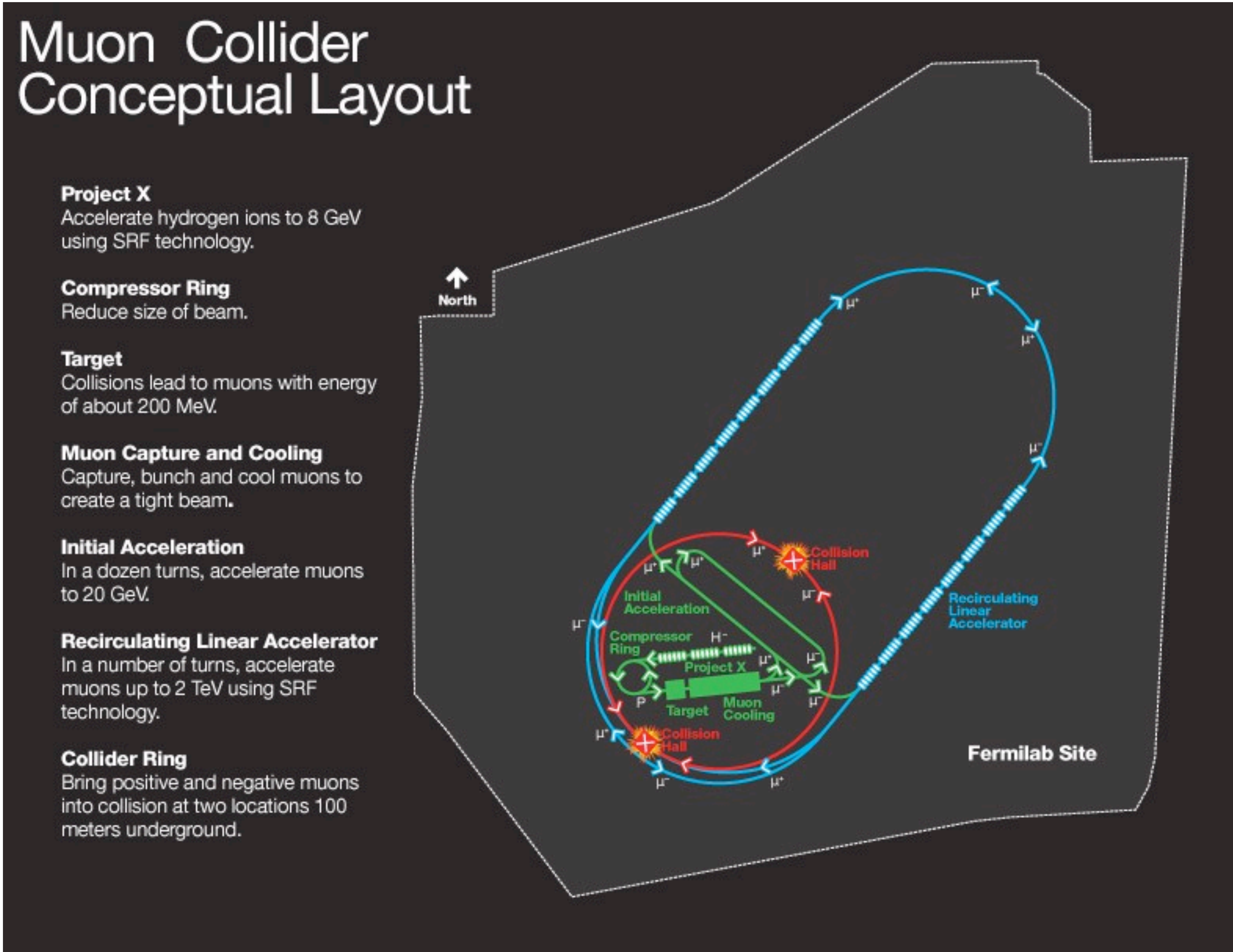


Hence minimum luminosity -> 0.5-5.0 x 10^{30} cm^{-2} sec^{-1}

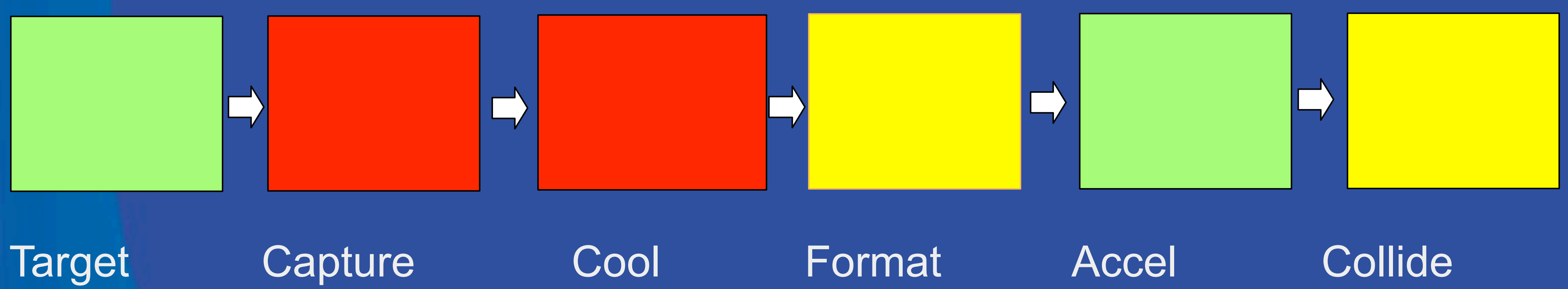
for M(Z′) -> 1.5-5.0 TeV

E. Eichten, "The Basics of Muon Collider Physics" (Fermilab-Pub-09-225-T)

4 TeV


Muon Collider
Conceptual Layout
Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.
Compressor Ring
Reduce size of beam.
Target
Collisions lead to muons with energy of about 200 MeV.
Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.
Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.
Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.
Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.
North
Collision Hall
Initial Acceleration
Compressor Ring
H⁻
Project X
P
Target
Muon Cooling
Collision Hall
Recirculating Linear Accelerator
Fermilab Site
μ⁺
μ⁻

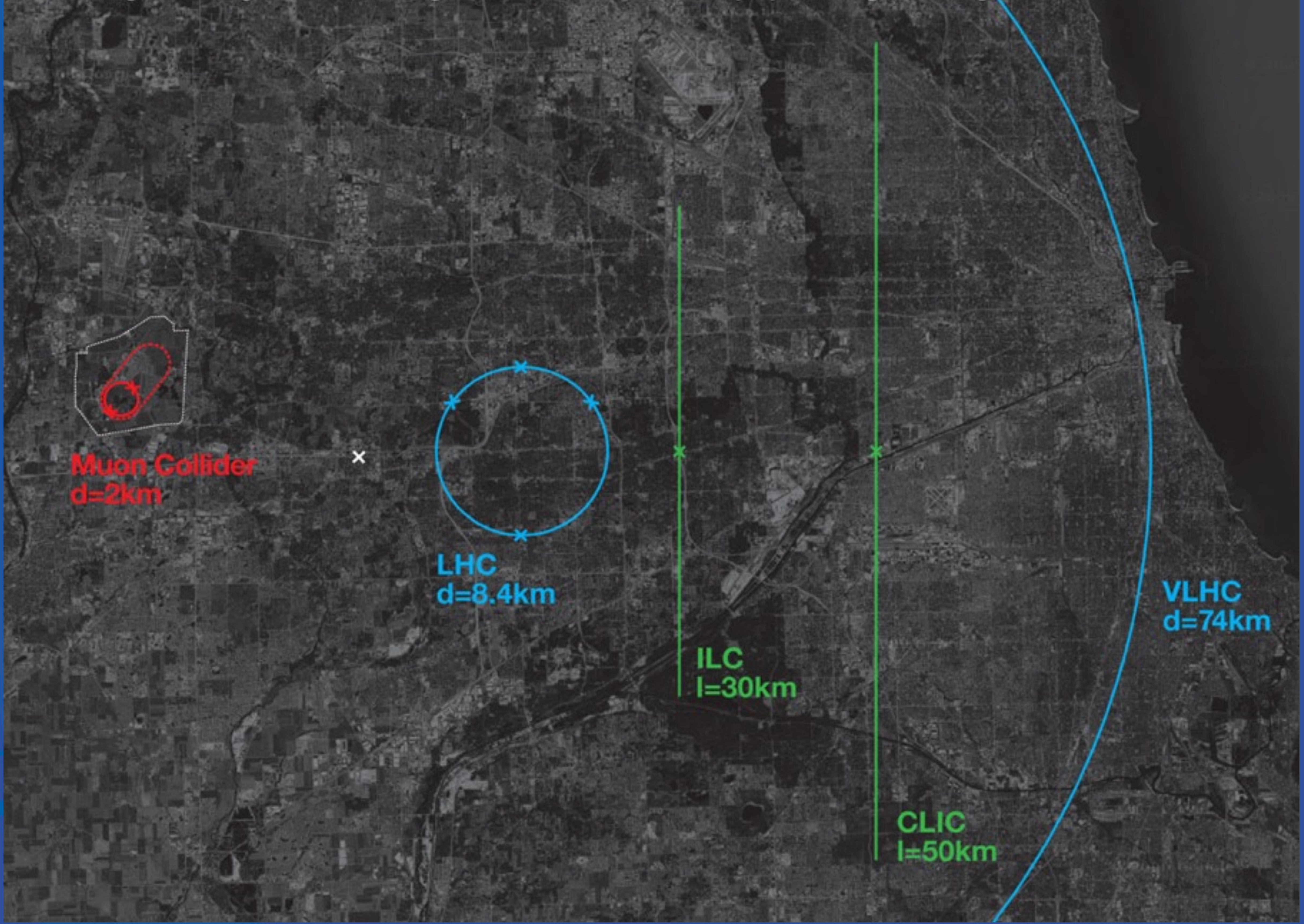
Muon collider functional layout



Color indicates degree of needed R&D (difficulty) and demonstration

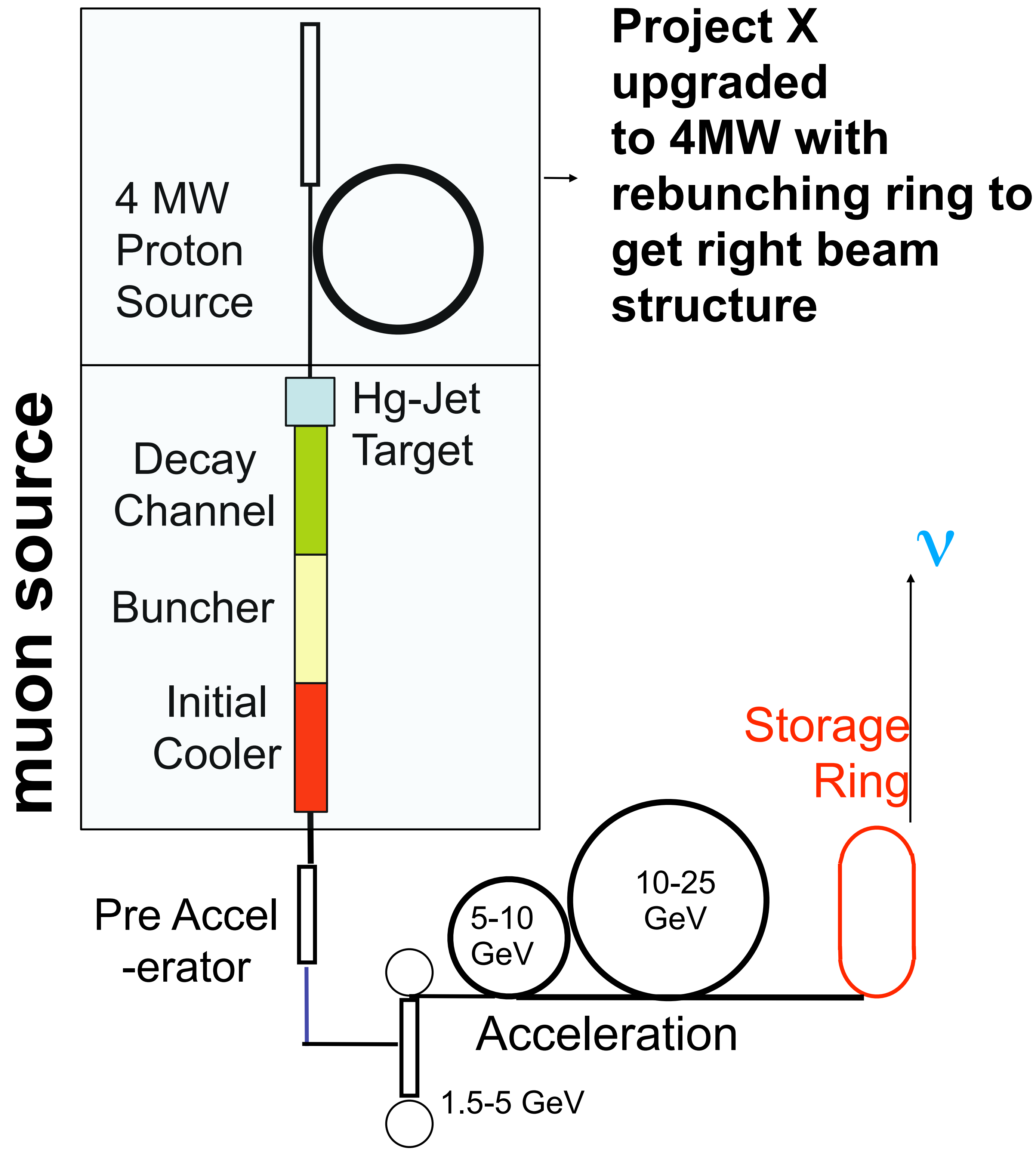
Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.



Neutrino Factory Schematic

- Proton Source
  - primary beam on production target
- Target, Capture, and Decay
  - create π; decay into μ
- Bunching & Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce transverse emittance
- Acceleration
  - 130 MeV $\rightarrow E_{NF}$
- Storage Ring
  - store for 500 turns; long straight section



Project X in a nutshell:

http://www.fnal.gov/pub/projectx/

Highly flexible 3 GeV proton continuous wave linac with a beam power of 2 MW. This can be used for:

- Neutrino Physics: Long Baseline - LBNE (θ_{13}, mass hiearchy, CPV) short baseline - $\sin^2\theta_W$, anomalous couplings of neutrinos, LSND, ...
- Kaon Physics: Precision measurements of $K_L \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$. Also precision measurements of K^0 and $\bar{K}^0$ system, CPT tests.
- Muon Physics: (g-2), electric dipole moments, $\mu \to e$ conversion, muon cooling leading to Neutrino Factory and maybe a Muon Collider.
- Nuclear Physics: EDM measurements of unstable deformed nuclei.

At Fermilab, our revolution has already started !!!