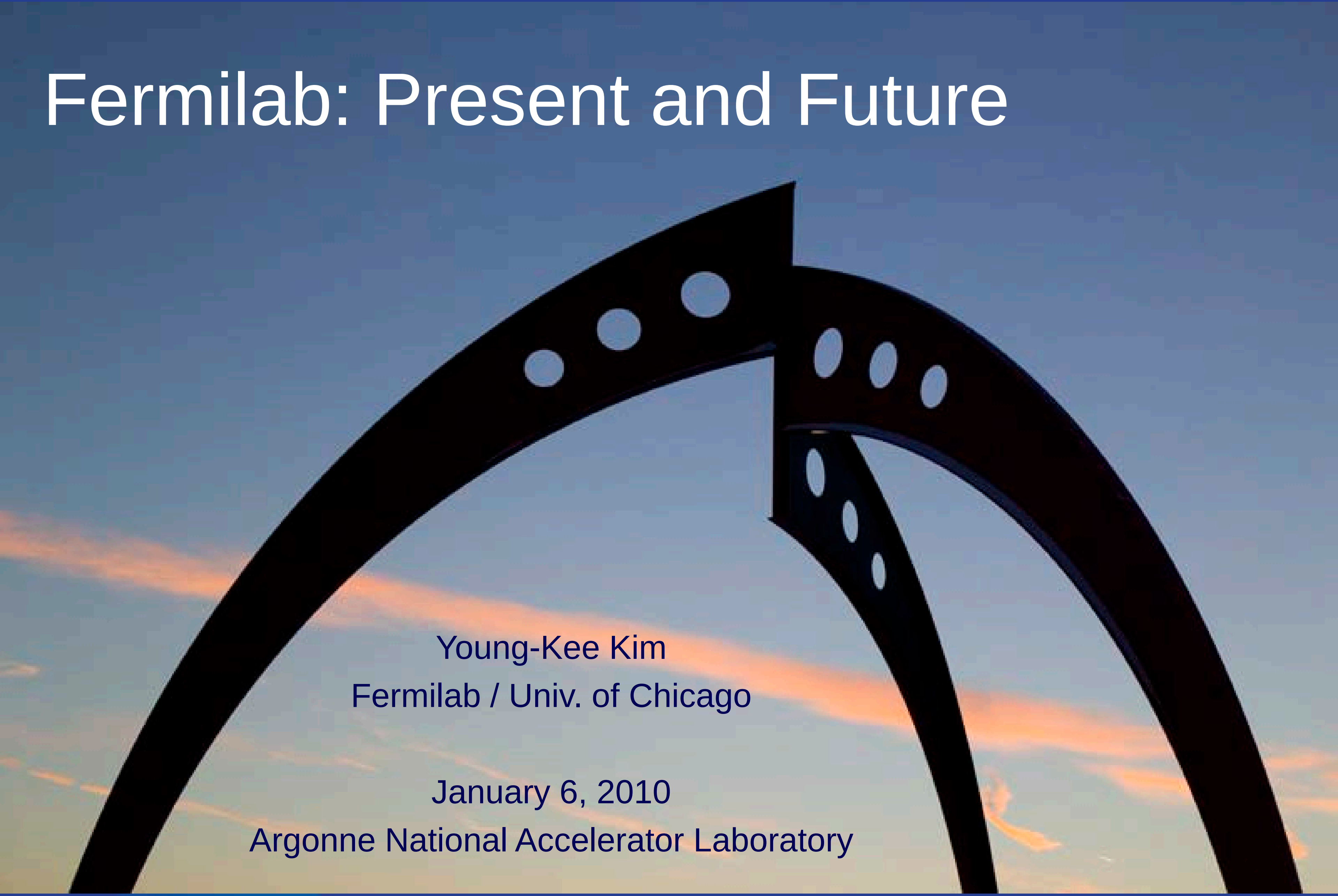


Fermilab: Present and Future

Young-Kee Kim
Fermilab / Univ. of Chicago

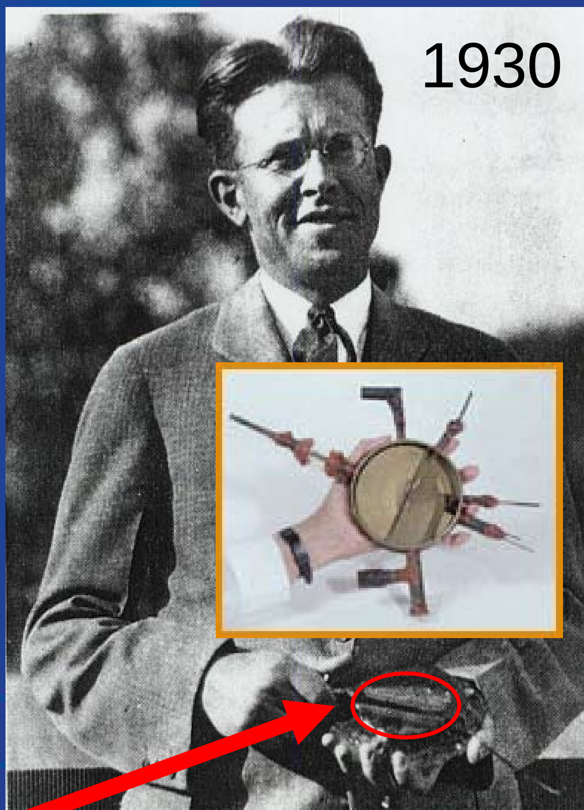
January 6, 2010
Argonne National Accelerator Laboratory

What is the world made of?
What holds the world together?
Where did we come from?

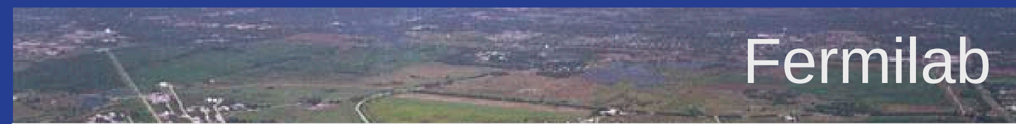
the smallest things in the world
interactions (forces) between them
the Universe’s past, present, and future

Particle Physics: physics where
small and big things meet,
inner and outer space meet

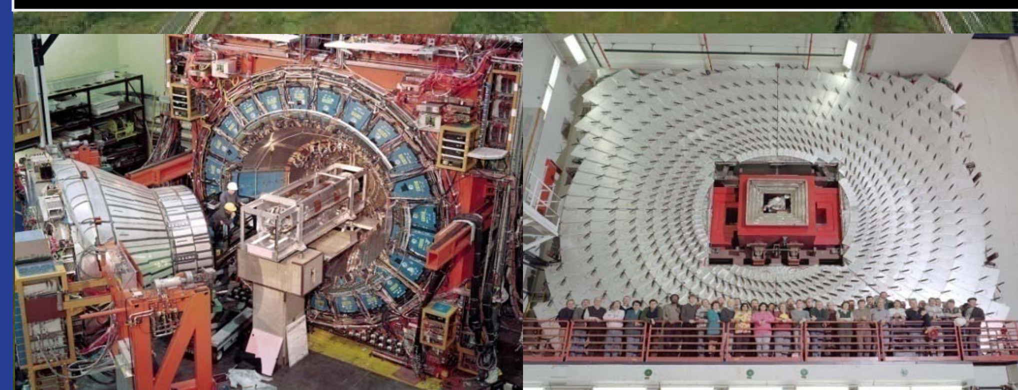
Many generations of Accelerators created with higher and higher energy and intensity beams



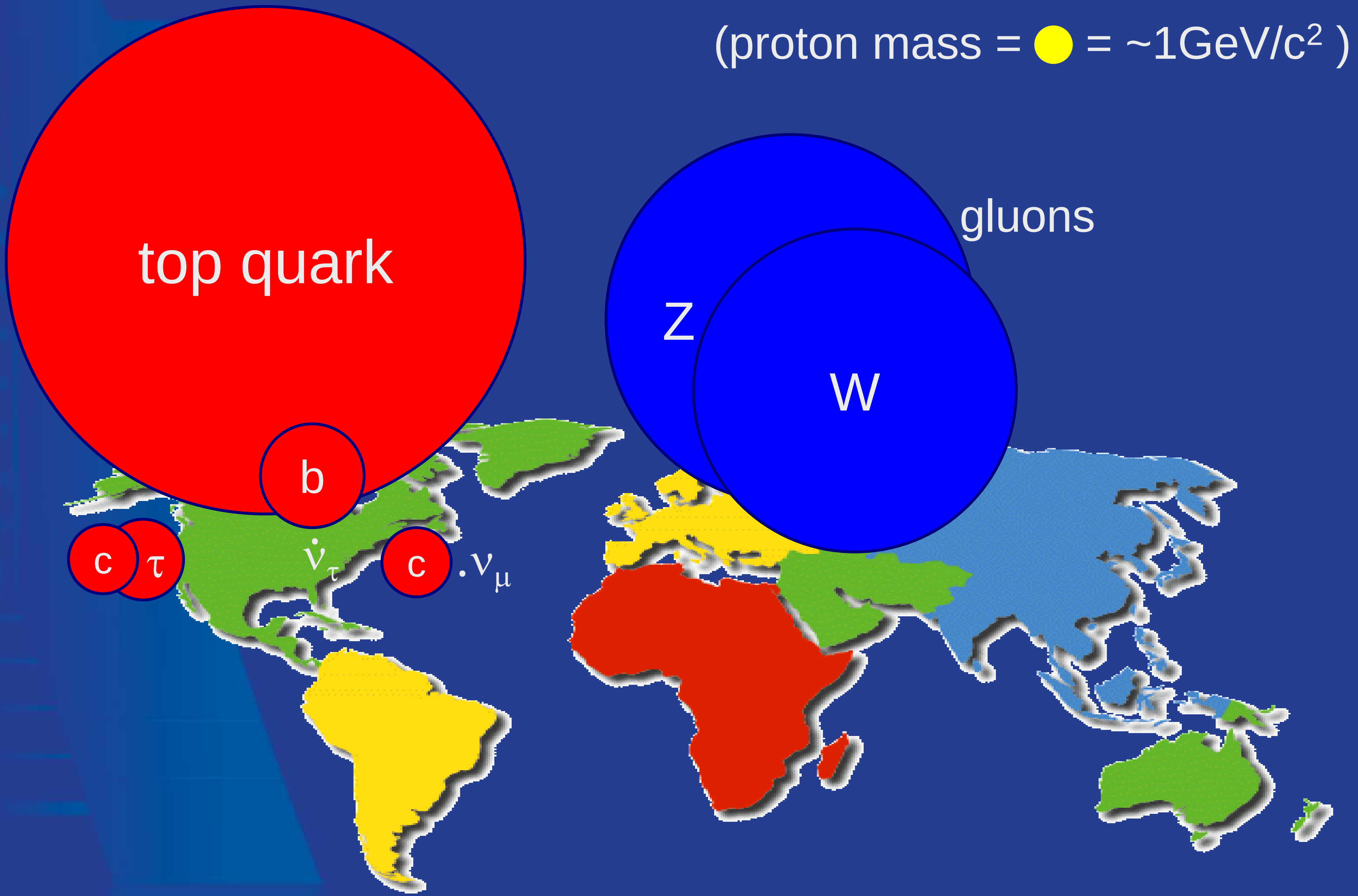
Ernest Lawrence
(1901 - 1958)



~2000 Scientists
Fermilab experiments using accelerators
> 2 publications every week
~2 Ph.D.s every week

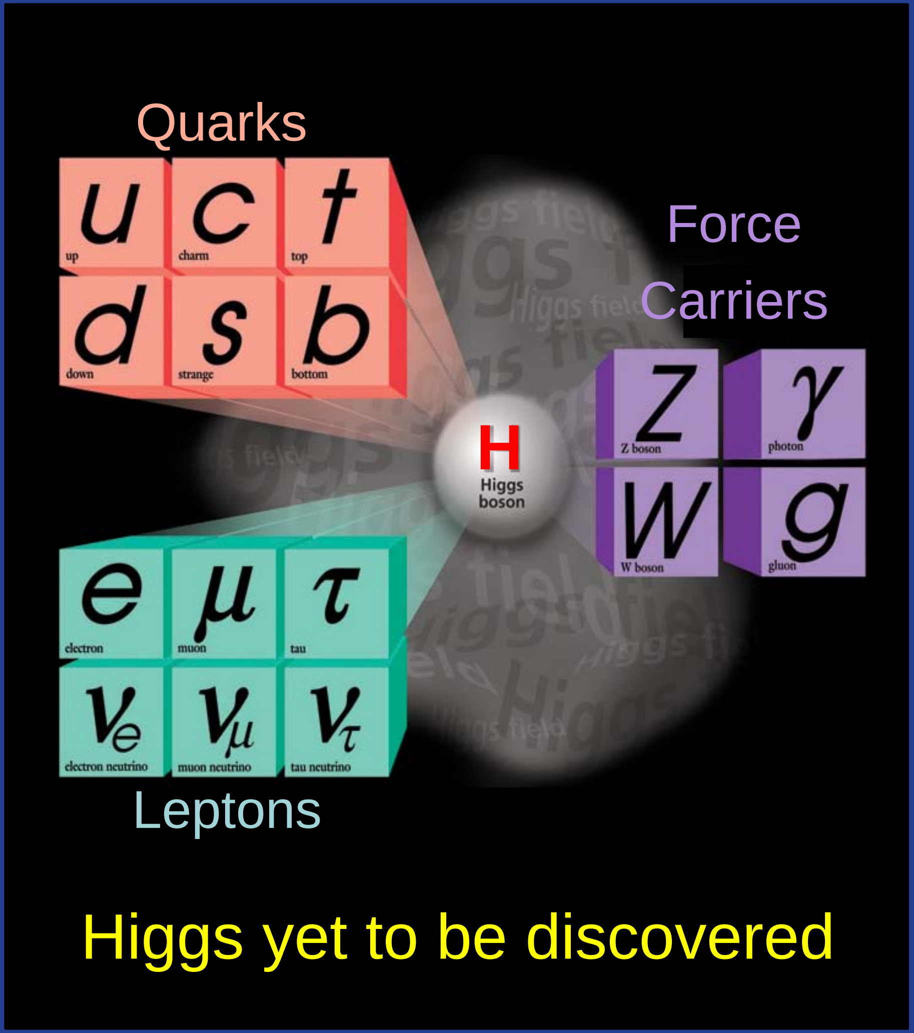


Tevatron: x10^4 bigger, x10^6 higher energy
Intense neutrino beams



(proton mass = ● = ~1GeV/c²)
top quark
gluons
Z
W
b
c
τ
ν_τ
c
ν_μ

- Present theory (Standard Model) is a remarkable intellectual construction
- Particle experiments ever done fits in the framework
- But huge questions remain unanswered.
- New physics is required to answer: e.g.
  - Supersym. extension of SM, extra dimensions, ….



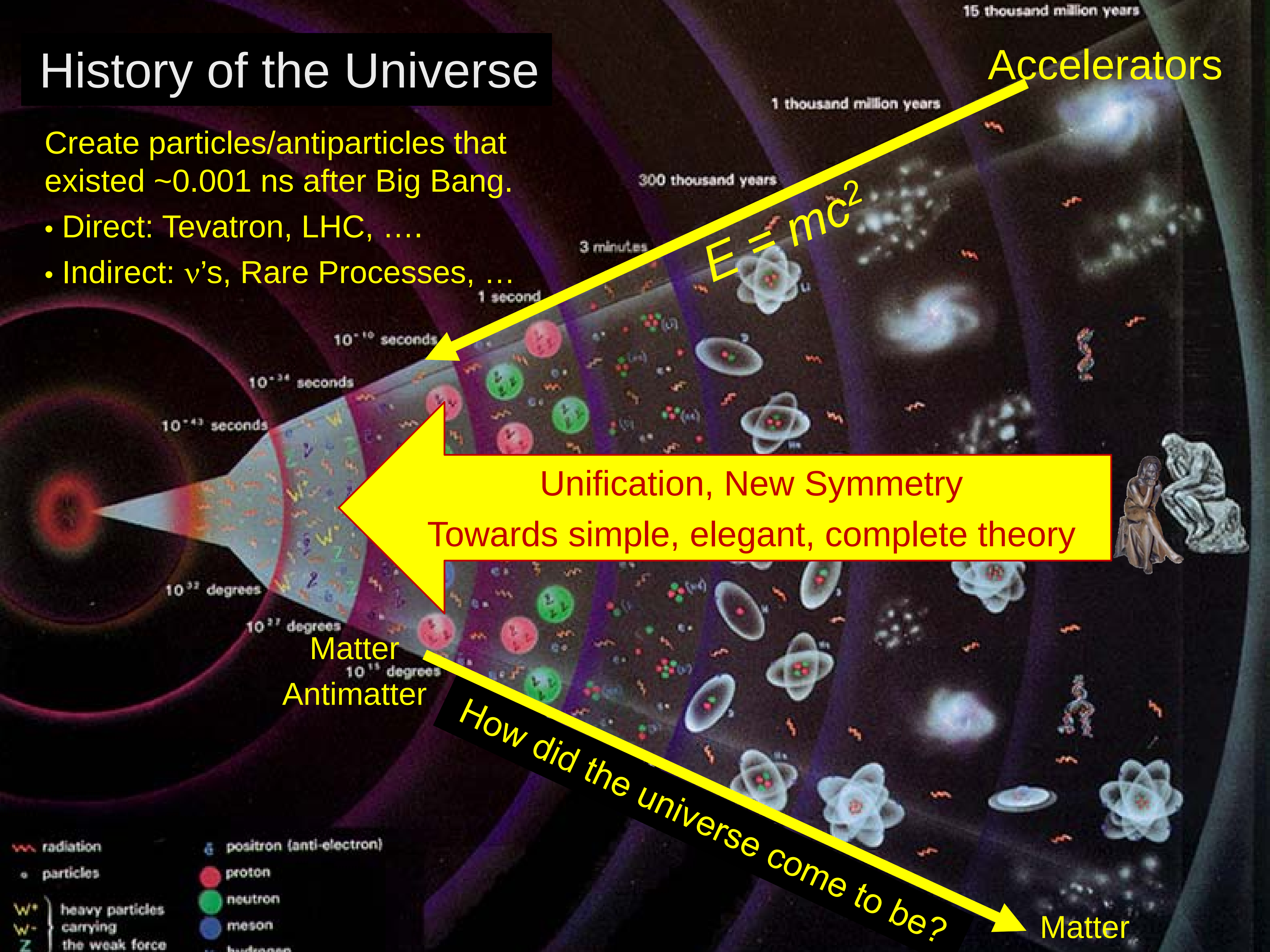
1. What is the origin of mass for fundamental particles?
2. Why are there so many kinds of particles?
3. Do all the forces become one?
4. Are there extra dimensions of space?
5. What are neutrinos telling us?
6. What happened to the antimatter?
7. What is dark matter?
8. How can we solve the mystery of dark energy?
9. How did the universe come to be?
10. Are there undiscovered principles of nature:
    new symmetries, new physical laws?

Evolved Thinker

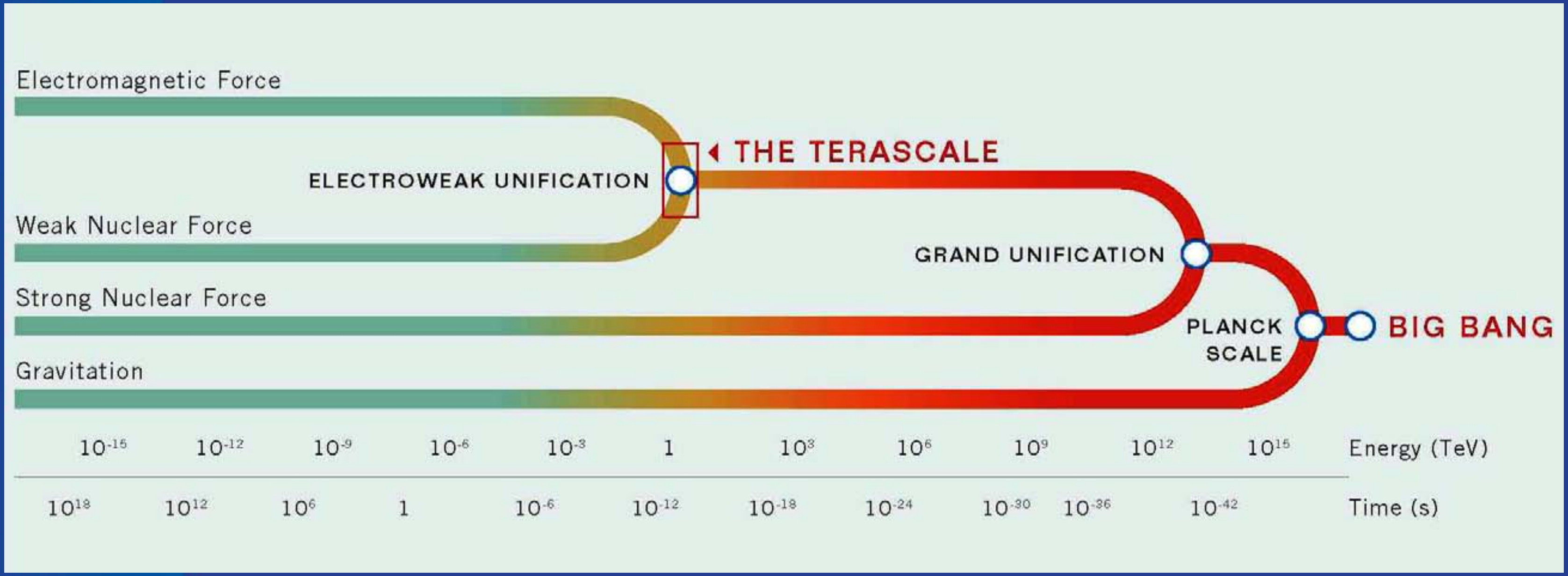
History of the Universe

Create particles/antiparticles that existed ~0.001 ns after Big Bang.

- Direct: Tevatron, LHC, ….
- Indirect: ν's, Rare Processes, …



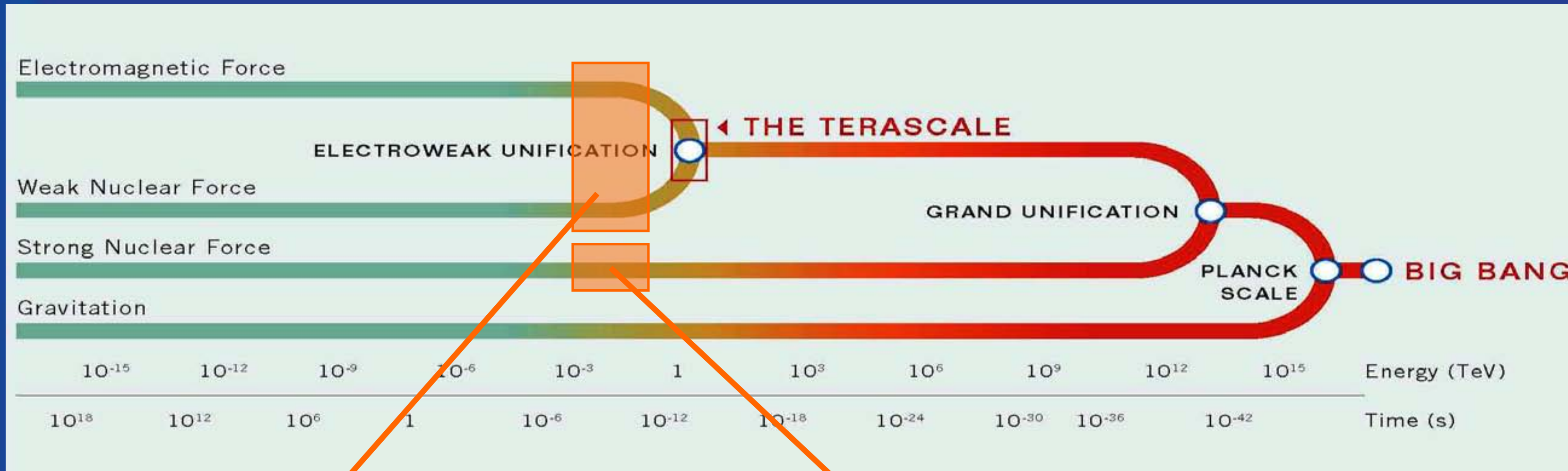
Unification

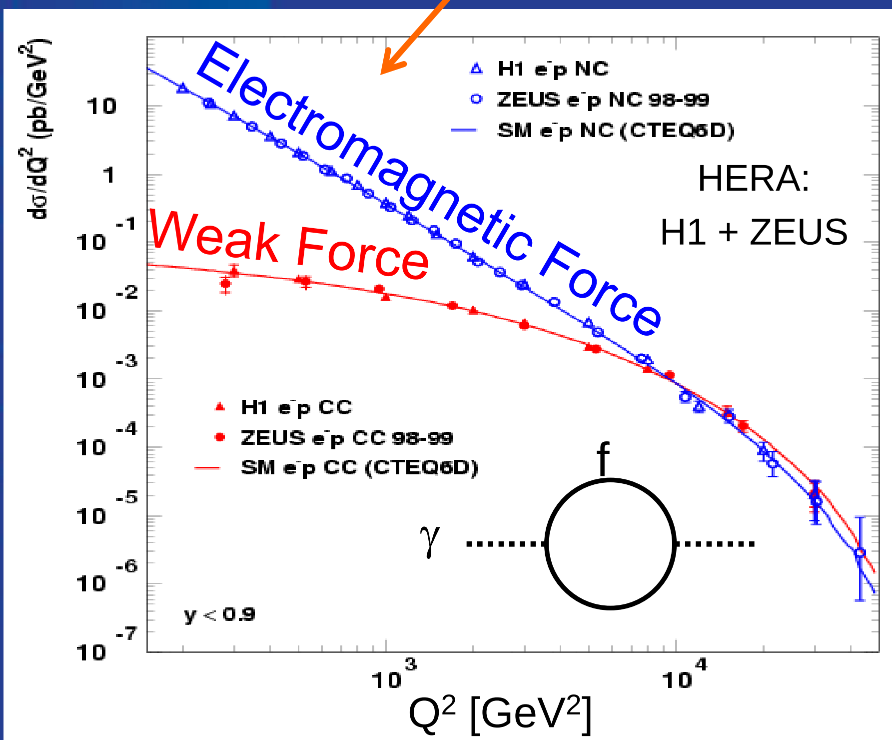


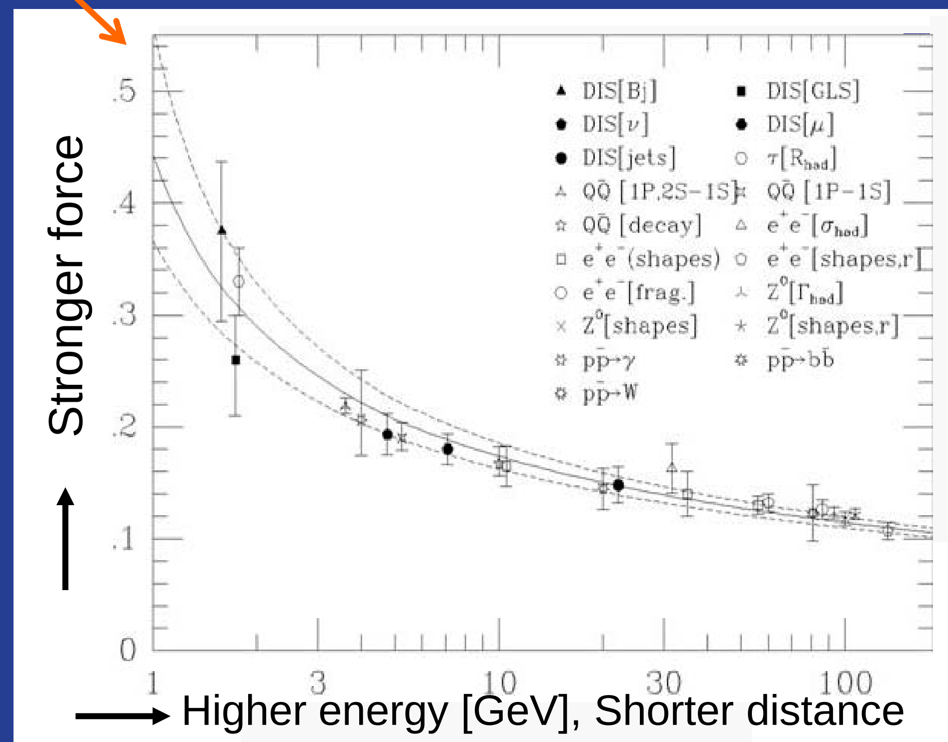
2.3×10^{-13} GeV	1TeV = 10^{3}GeV	10^{16}GeV	10^{19}GeV	Energy
(2.7K)	(10^{16}K)	(10^{29} K)	(10^{32}K)	Temp
12×10^{9} y	10^{-11} s	10^{-38} s	10^{-41} s	Time

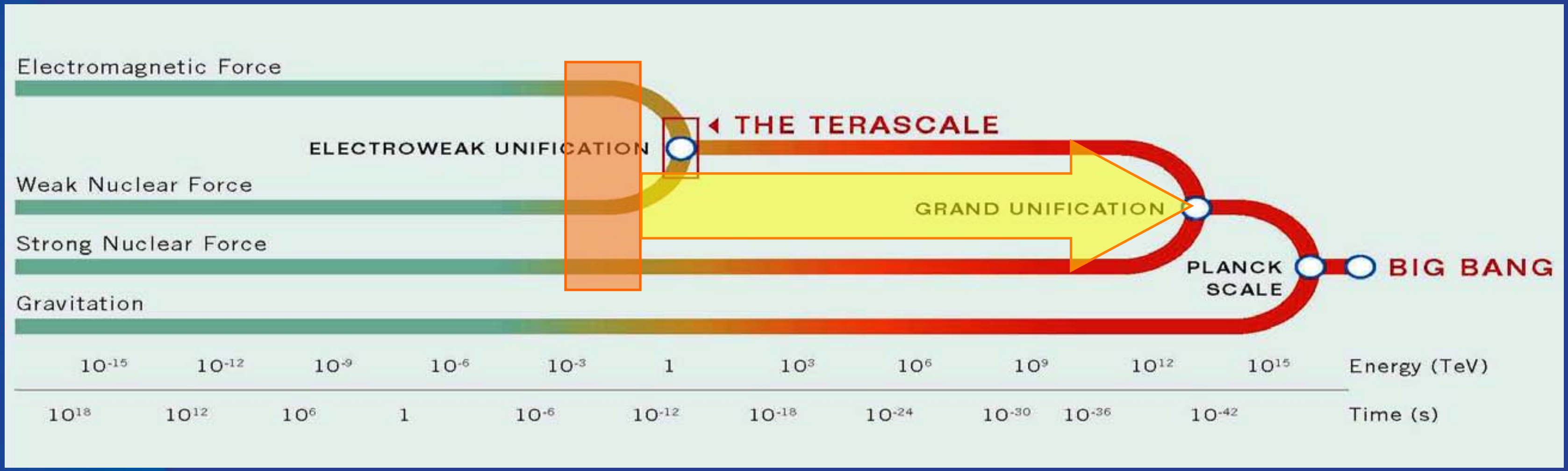
We want to believe that there was just one force after the Big Bang.

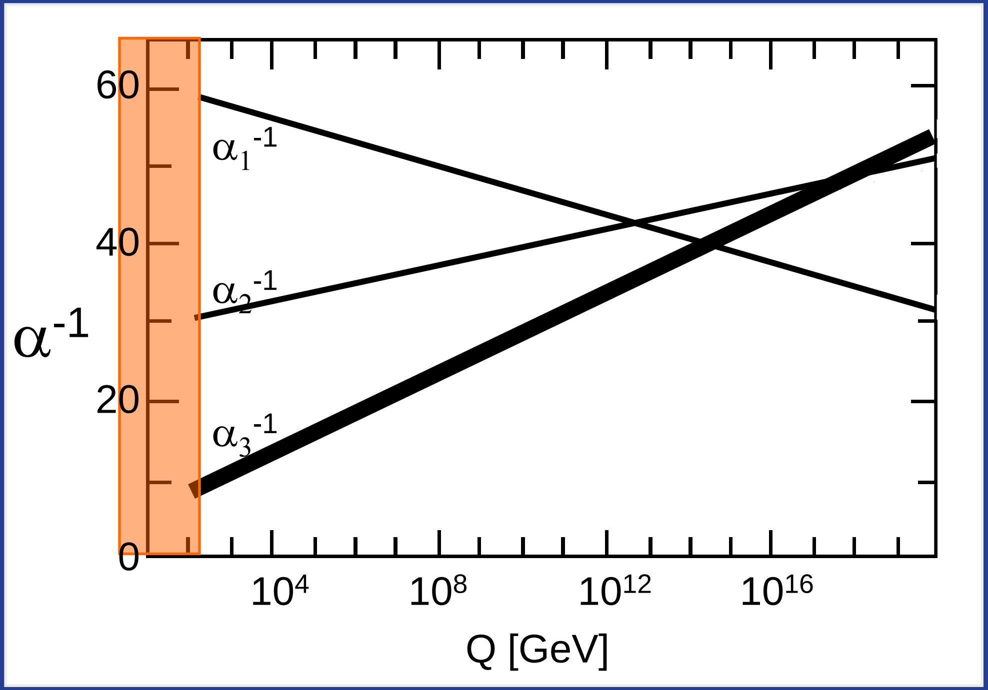
As the universe cooled down,
the single force split into the four that we know today.


Electromagnetic Force
ELECTROWEAK UNIFICATION
THE TERASCALE
Weak Nuclear Force
GRAND UNIFICATION
Strong Nuclear Force
PLANCK SCALE
BIG BANG
Gravitation
10⁻¹⁵ 10⁻¹² 10⁻⁹ 10⁻⁶ 10⁻³ 1 10³ 10⁶ 10⁹ 10¹² 10¹⁵ Energy (TeV)
10¹⁸ 10¹² 10⁶ 1 10⁻⁶ 10⁻¹² 10⁻¹⁸ 10⁻²⁴ 10⁻³⁰ 10⁻³⁶ 10⁻⁴² Time (s)


dσ/dQ² (pb/GeV²)
Electromagnetic Force
Weak Force
H1 e⁻p NC
ZEUS e⁻p NC 98-99
SM e⁻p NC (CTEQ6D)
HERA:
H1 + ZEUS
H1 e⁻p CC
ZEUS e⁻p CC 98-99
SM e⁻p CC (CTEQ6D)
f
γ
y < 0.9
Q² [GeV²]

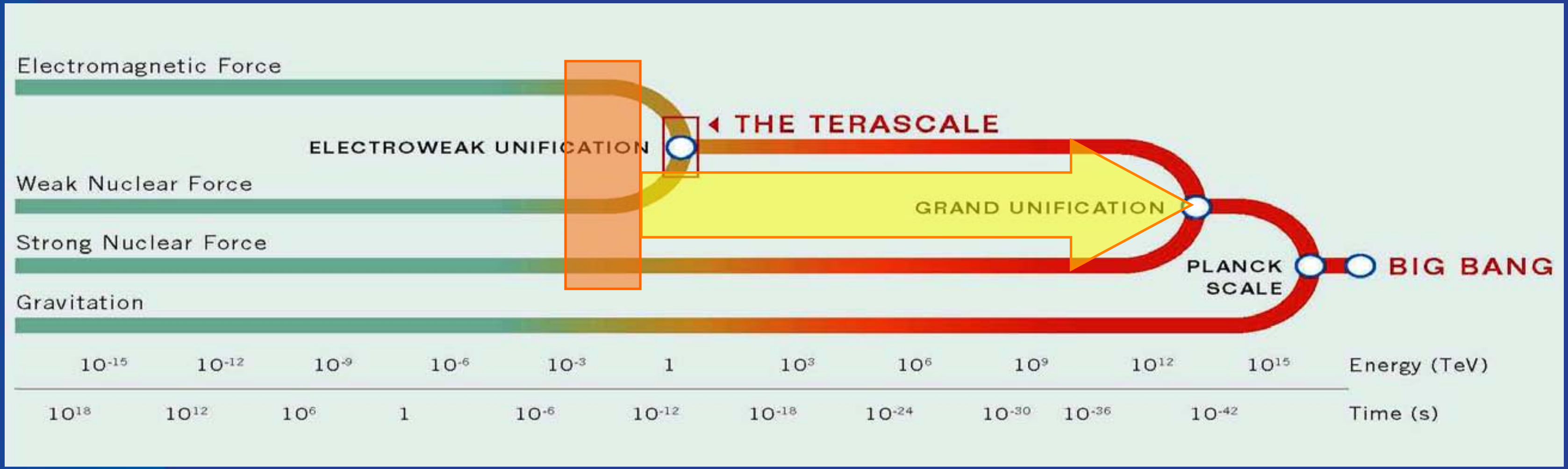

Stronger force
DIS[Bj]
DIS[GLS]
DIS[ν]
DIS[μ]
DIS[jets]
τ[R_had]
QQ̄ [1P,2S−1S]
QQ̄ [1P−1S]
QQ̄ [decay]
e⁺e⁻[σ_had]
e⁺e⁻(shapes)
e⁺e⁻[shapes,r]
e⁺e⁻[frag.]
Z⁰[Γ_had]
Z⁰[shapes]
Z⁰[shapes,r]
pp̄→γ
pp̄→bb̄
pp̄→W
Higher energy [GeV], Shorter distance

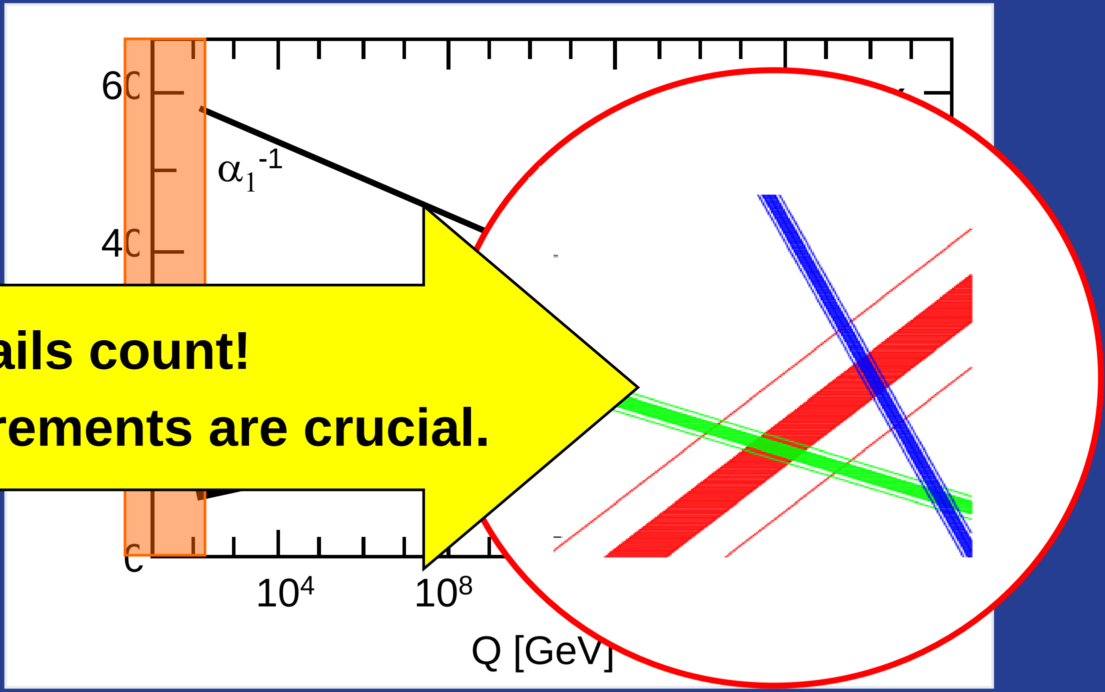




The Standard Model fails to unify the strong and electroweak forces.

Fermilab



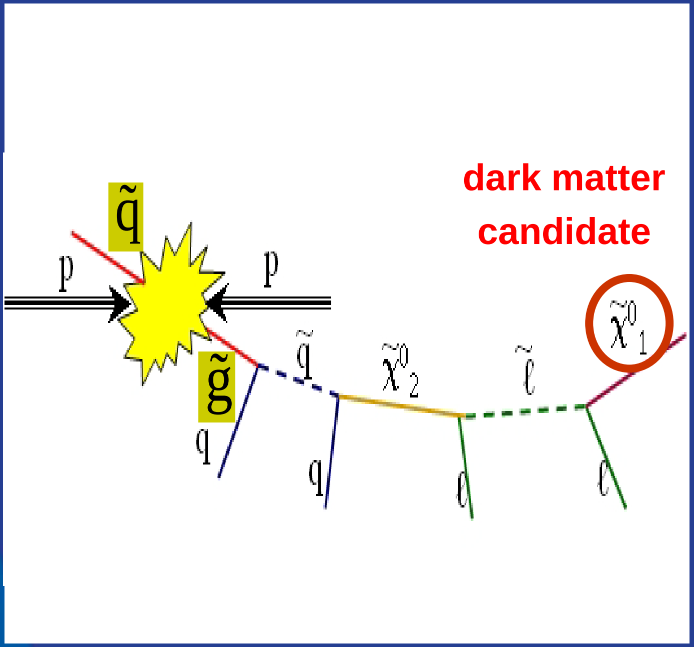


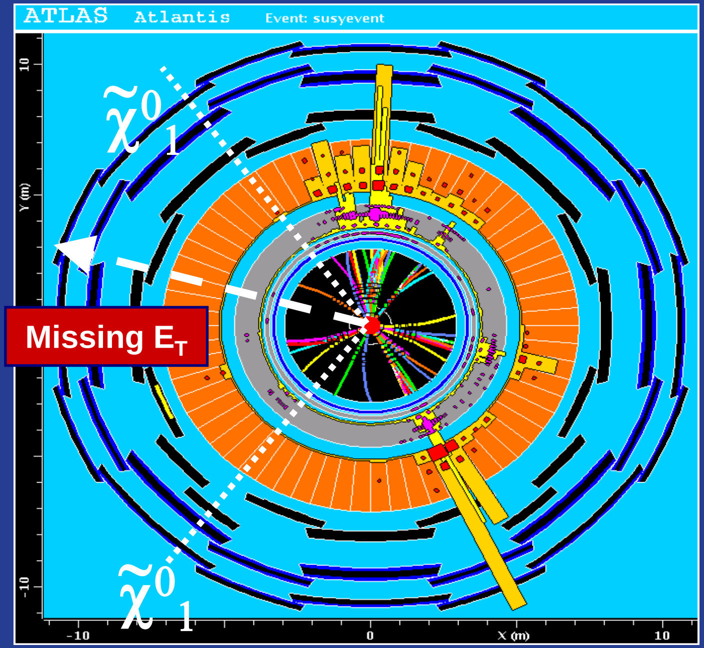
But details count!

Precision measurements are crucial.

Early discovery at LHC

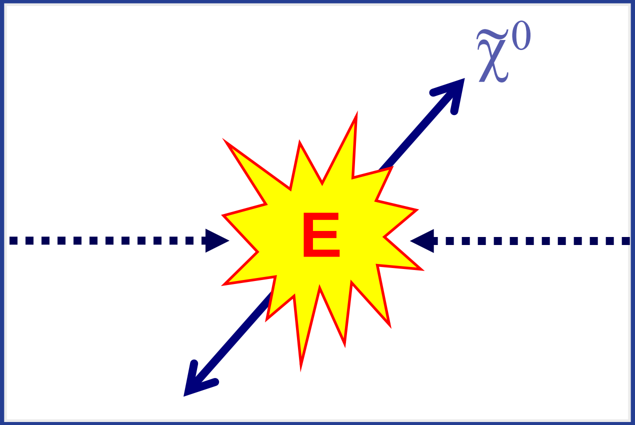
LHC could discover strongly coupled SUSY

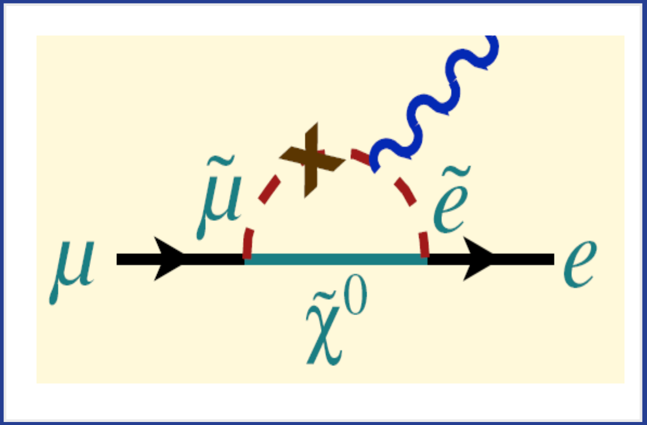




A host of new particles: fit roughly some masses,
make assumption on couplings

Energy Frontier ⟷ Intensity Frontier





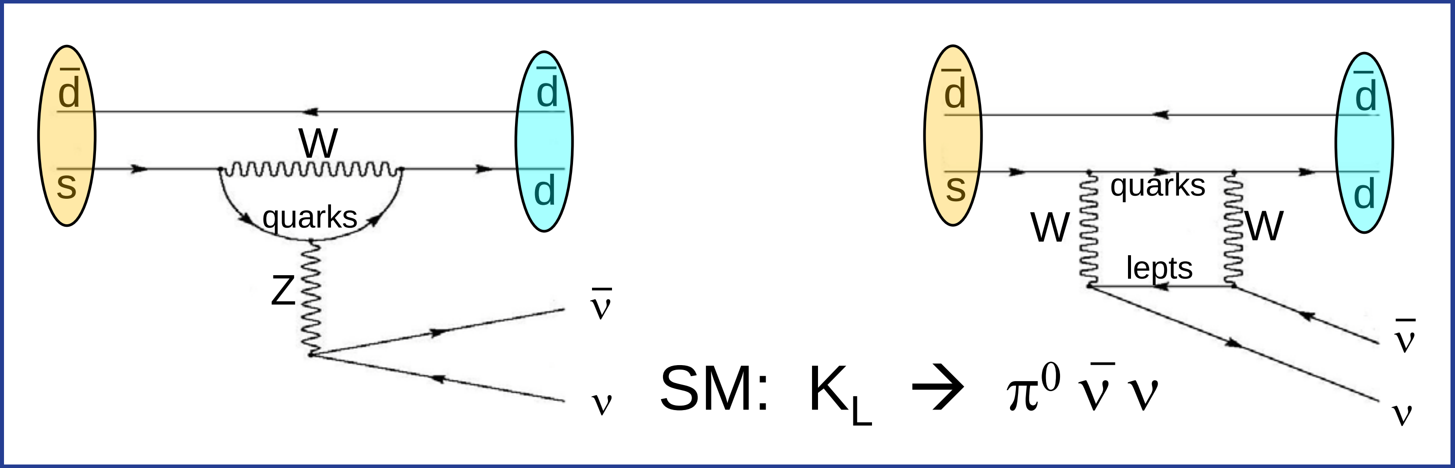
The Intensity Frontier can probe
new physics at a scale >> TeV.

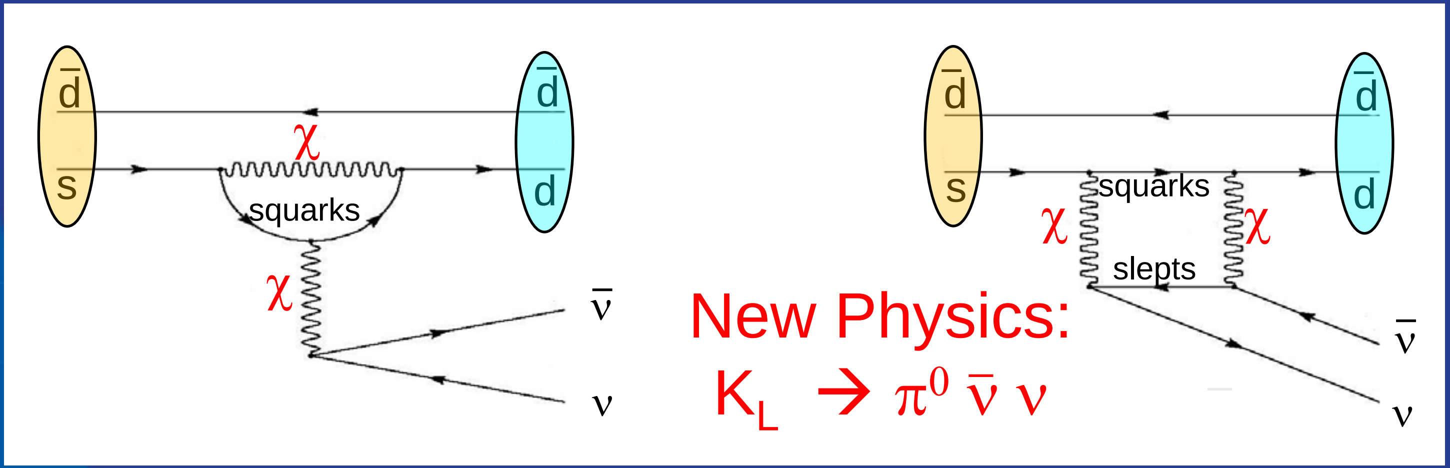
Muon to electron conversion: $\mu N \rightarrow eN$

Neutrinos change from one kind to another.

Do charged leptons do, too?

Intensity: Large effects in kaon decay rates



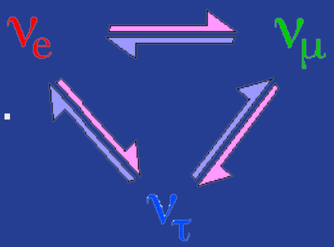


Fermilab

Interplay:Energy Frontier ⟷ Intensity Frontier

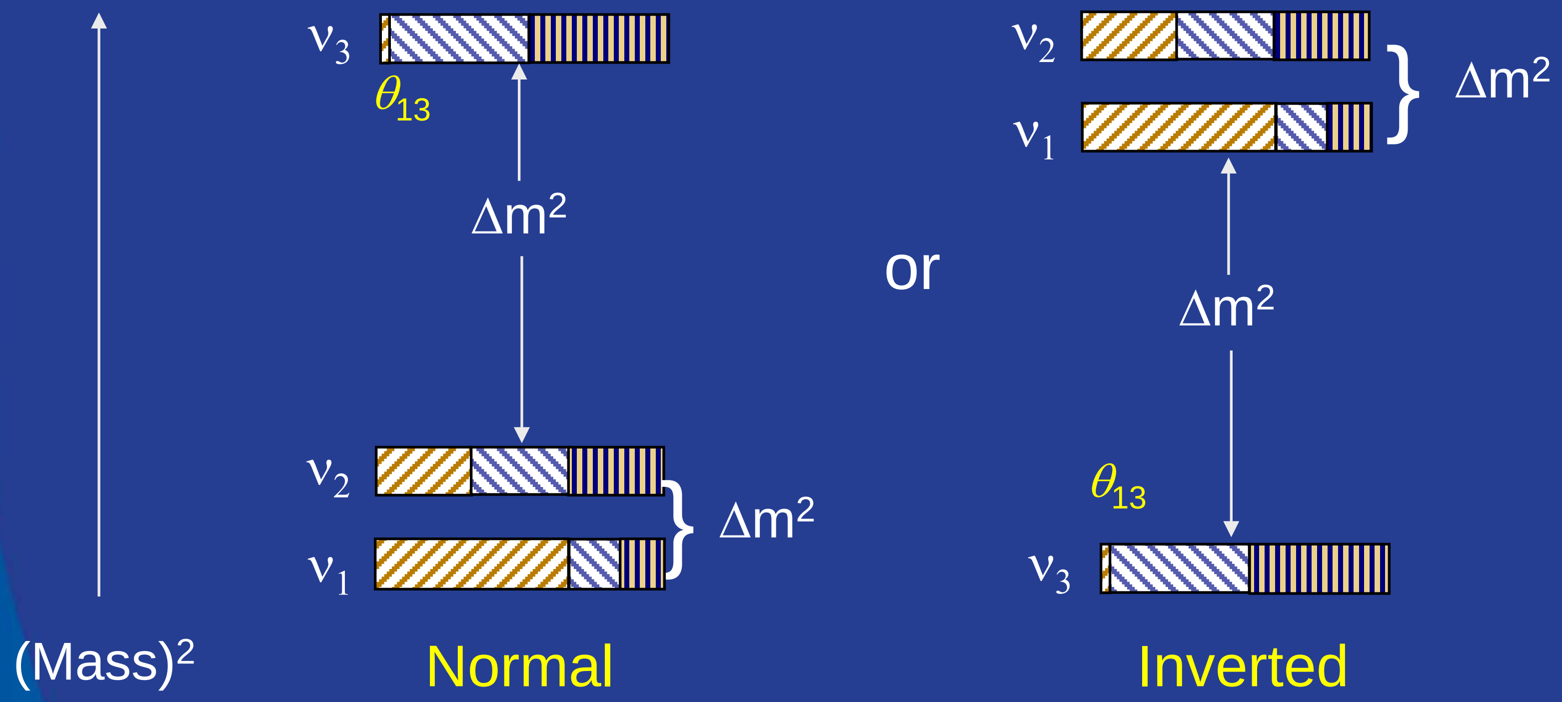
Nothing	→	Only handle on the next energy scale
LHC		Intensity Frontier
Lots	⟷	Determine/verify structure of new physics. Anything beyond?

Intensity Frontier: Neutrinos



- Recent Discoveries
  - produced much excitement.
  - the only new physics seen so far in the lab.
- Behave so different from other particles
  - Mass, Oscillation pattern, $\nu = \bar{\nu}$ possibility
- A Matter-Dominate Universe
  - Require Matter-Antimatter Asymmetry (CP Violation)
  - Quarks can not explain. Maybe the leptons can.
- Unification
  - ν mass, mixing point toward new symmetries (unification)
- Cosmic Connection
  - ~10^9 neutrinos / nucleon or electron in the Universe.
  - Neutrino mass affects large scale structure.

The neutrino spectrum: unknowns



θ_{13}

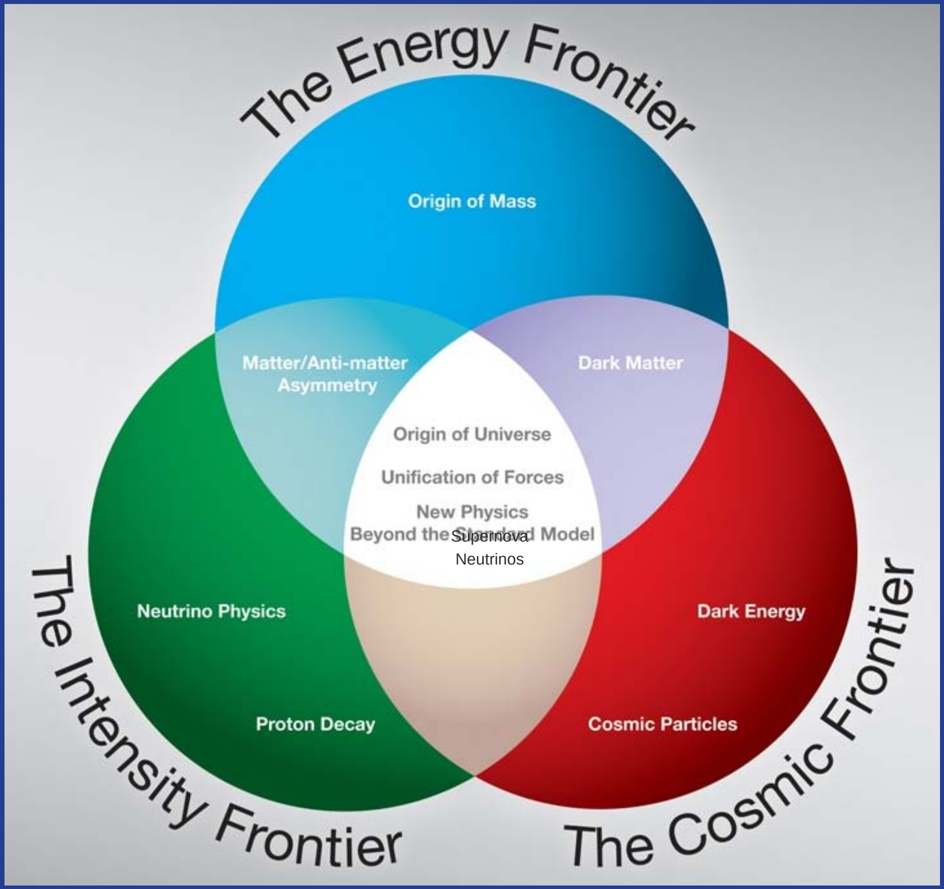
Mass Hierarchy

Matter – Antimatter Asymmetry Phase δ

$\nu = \bar{\nu}$?

Particle Physics at the Three Frontiers

Endorsed by the US Particle Physics Community



Fermilab

Particle Physics

- Global enterprise
- Many laboratories have changed missions. A few principle particle physics laboratories in the world
- Important and healthy to maintain expertise, long term stability, and support in all three regions, and to engage the world wide community
- More coordination and collaboration

US Particle Physics Today

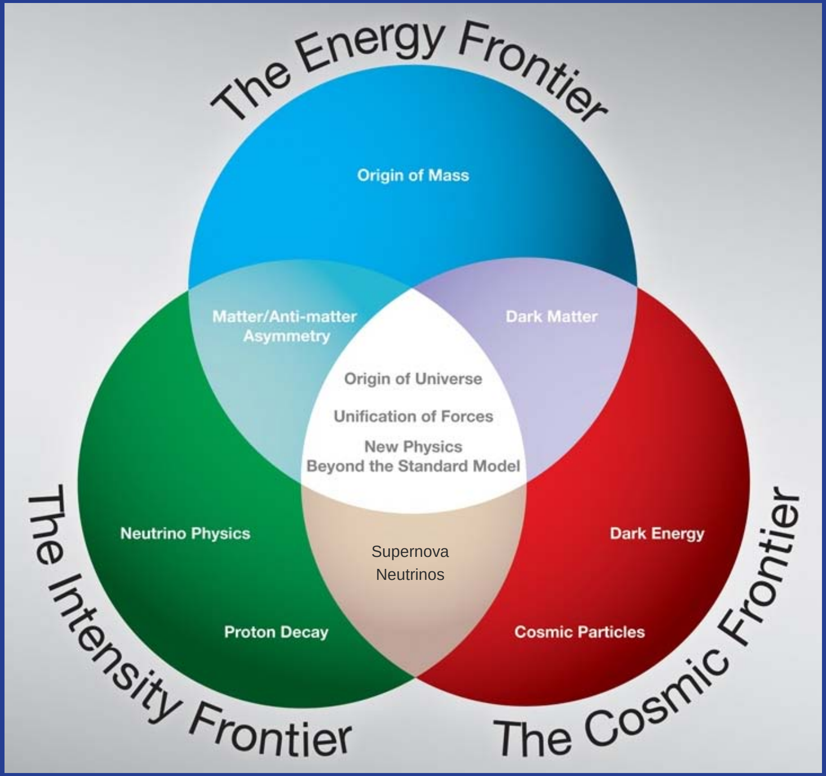
- National Laboratories
  - Fermilab
    - Single mission – particle physics
  - Other laboratories: ANL, BNL, LANL, LBNL, SNAL, …
    - Multi missions including particle physics
    - Particle physics is not the primary mission
- Universities

- We need to maintain expertise and uniqueness in laboratories and universities

Fermilab Programs at Three Frontiers (Now)

Hadron Colliders:
Tevatron
LHC

Neutrinos



Dark Matter,
Dark Energy,
UHE Particles
from Space

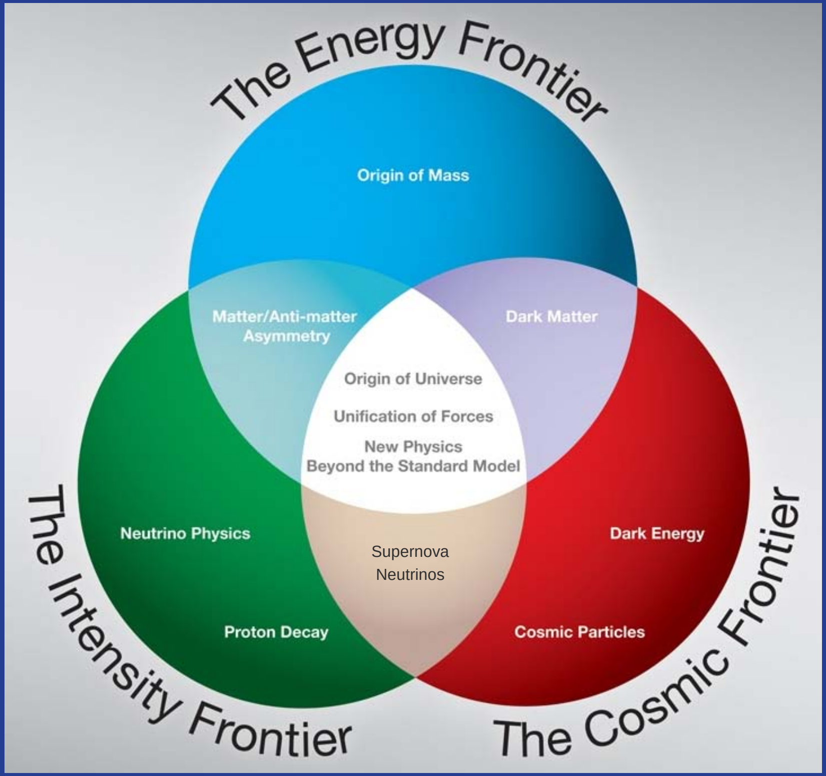
http://www.fnal.gov/pub/science/frontiers/

Fermilab Programs at Three Frontiers (Future)

Hadron Colliders:

LHC

Project X:
Neutrinos
Rare Processes
Precision Meas.s
Nuclear Physics



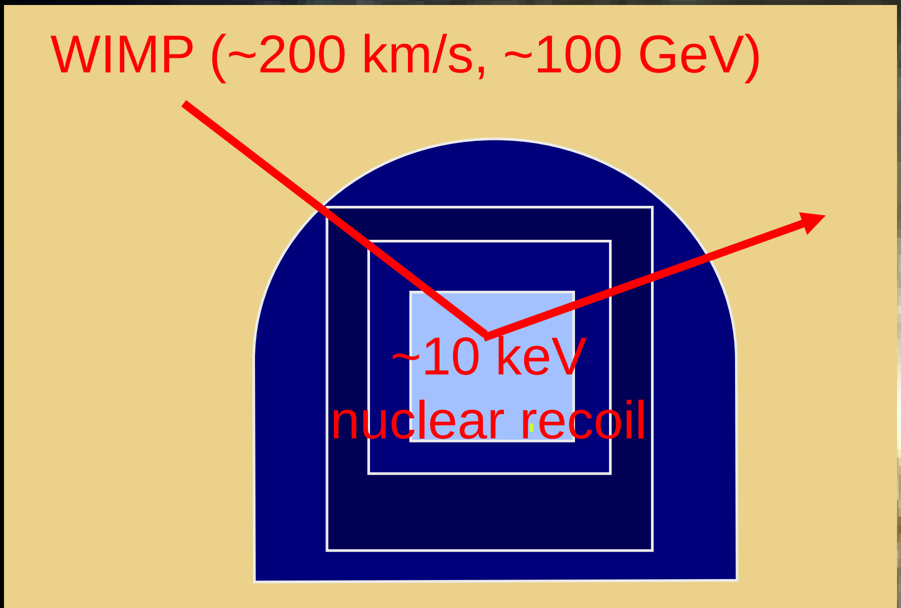
Lepton Colliders:
Sub-TeV: ILC
Multi-TeV: μ Collider
(CLIC)

Dark Matter,
Dark Energy,
UHE Particles
from Space

http://www.fnal.gov/pub/science/frontiers/

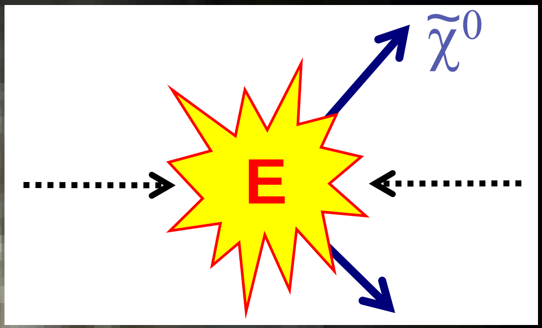
Cosmic Frontier: Dark Matter

Underground experiments may detect Dark Matter candidates.

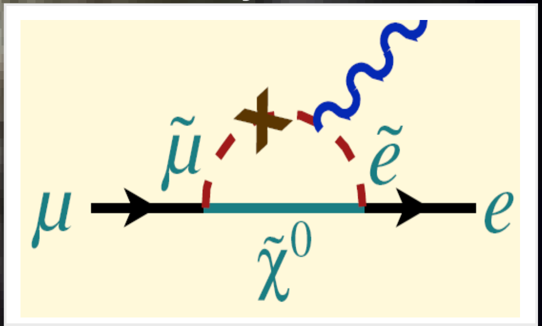


Cosmic Frontier

Energy Frontier



Intensity Frontier

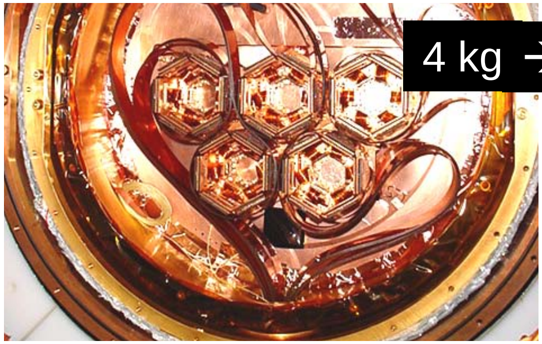


Accelerators can produce dark matter in the laboratory and understand exactly what it is.

Dark Matter Searches – Underground Detectors

CDMS

Low temp. Ge / Si crystals



4 kg → 15 kg → 100 kg

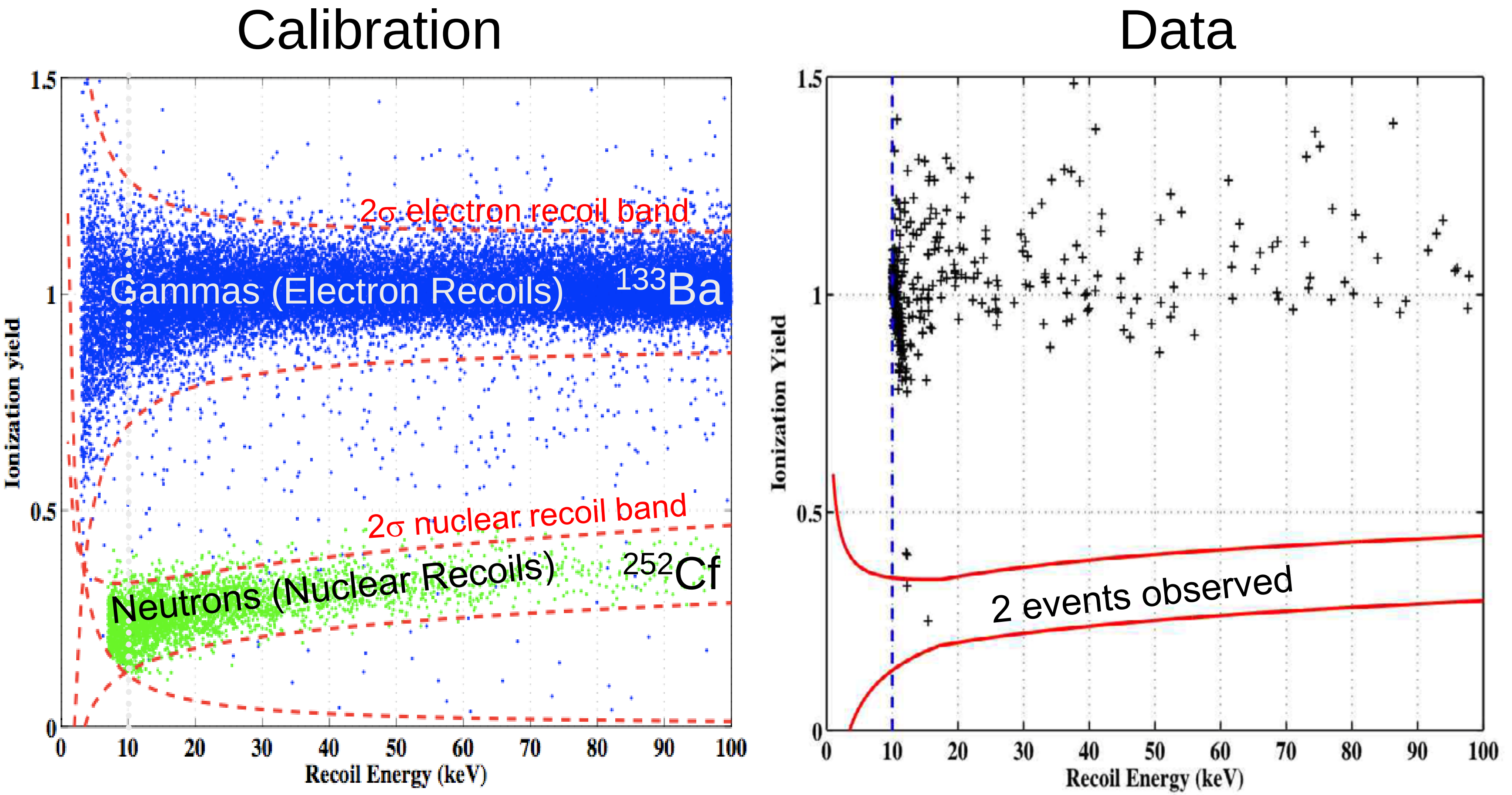
World's

Best Limits

UPP

F I Bubble Chamber

CDMS (4 kg) Results



Ionization yield = E_{charge} / E_{phonon}

0.8 ± 0.2 background expected

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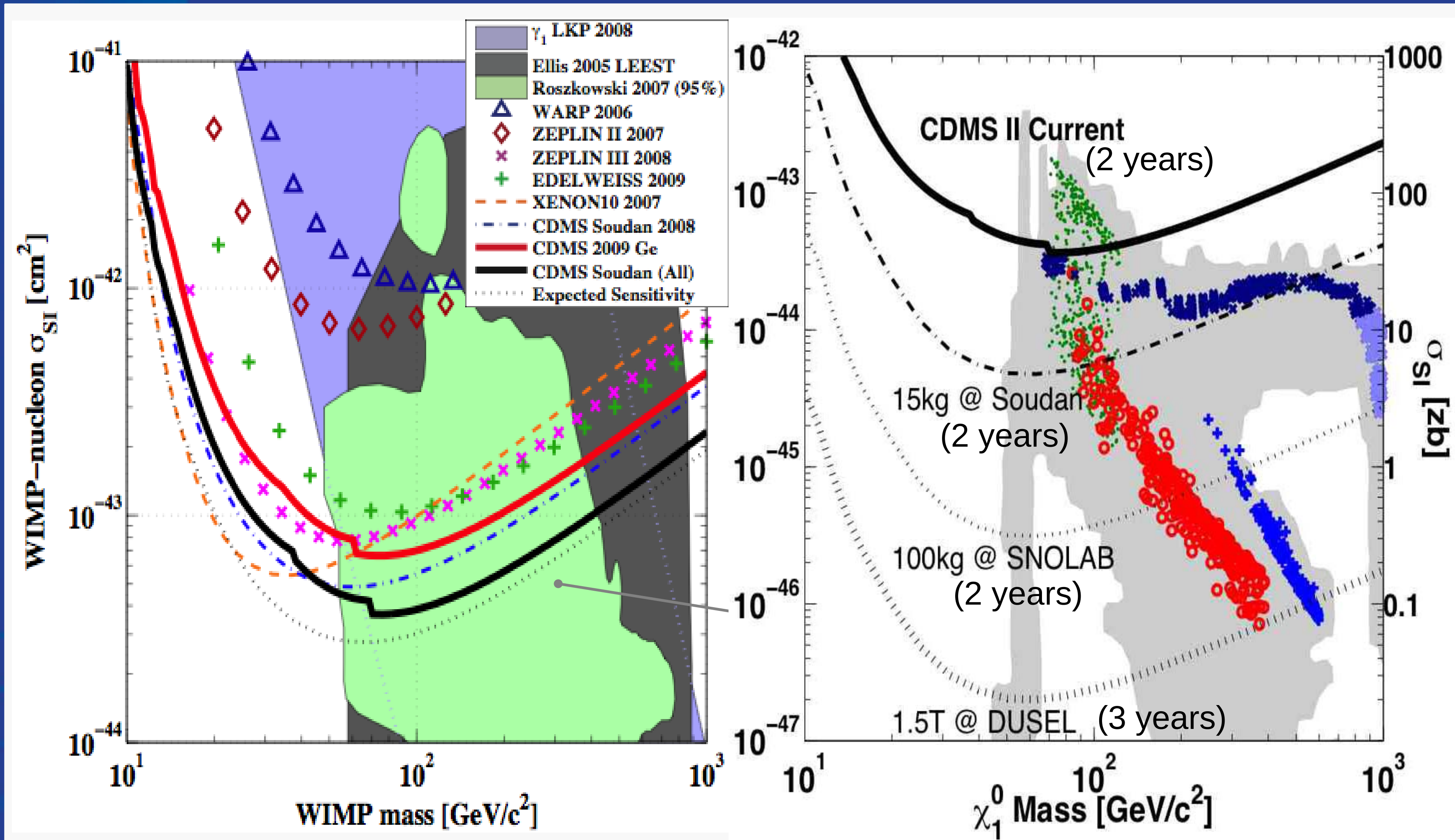
90% CL Limit: Present and Future



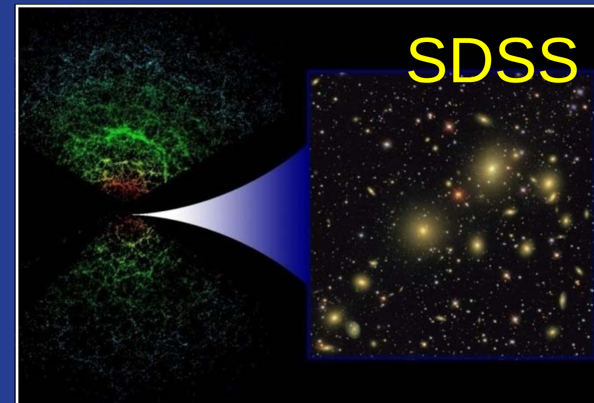
Fermilab

Cosmic Frontier: Probing Dark Energy

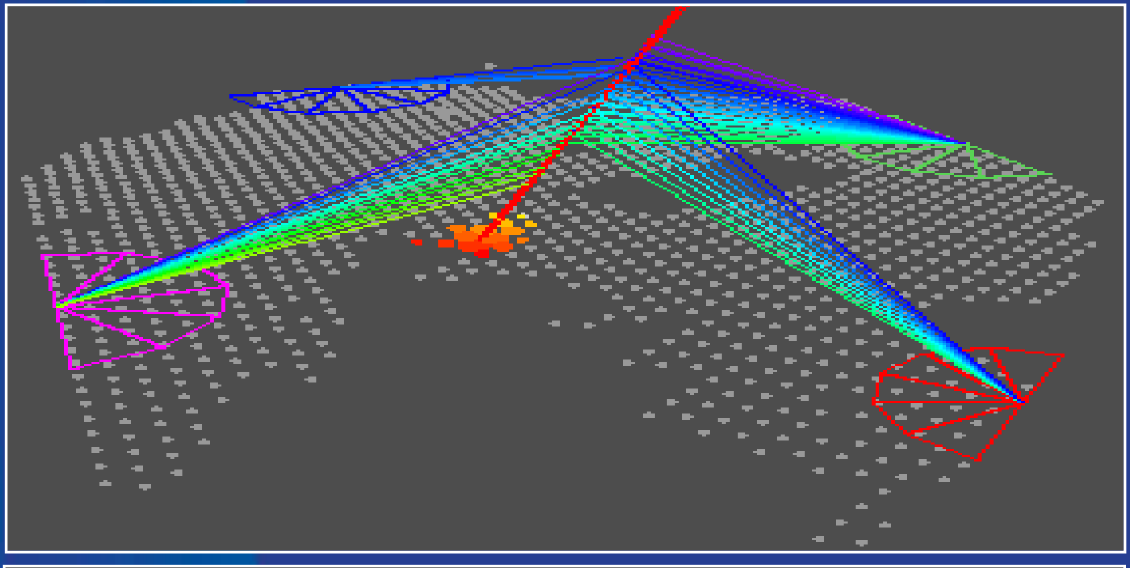
1. SDSS (Sloan Digital Sky Survey)
   - 2.5 meter telescope in New Mexico
   - Ranks as the facility with the highest impact in astronomy for the 3rd year in a row.
   - Power spectrum of galaxies constrain dark energy density parameter.

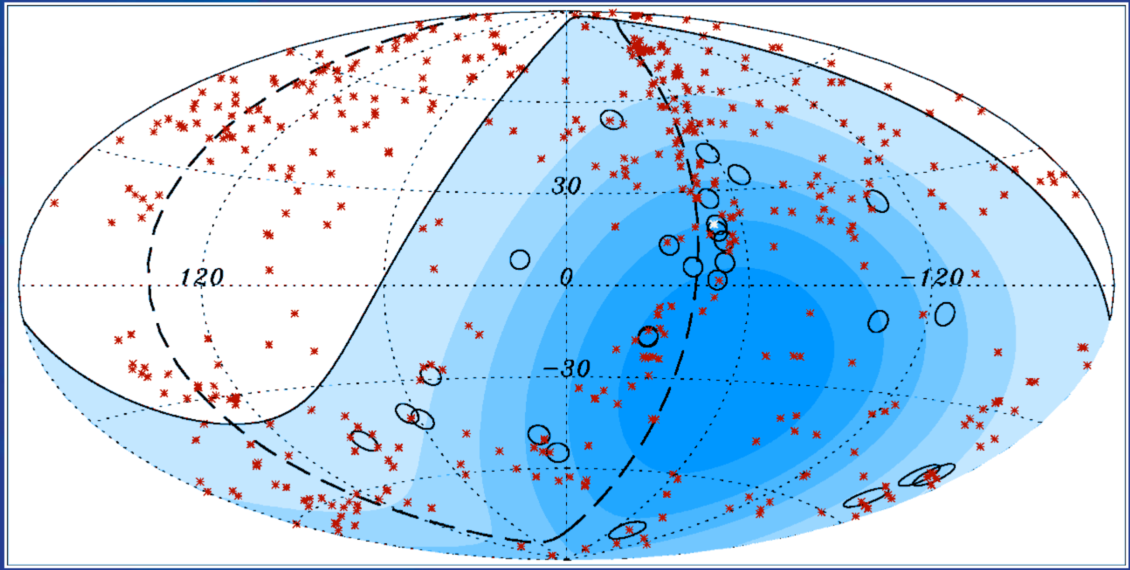
2. DES (Dark Energy Survey)
   - 4 meter telescope in Chile
   - DES Camera under construction
   - Operation: 2011 – 2016

3. JDEM (Joint Dark Energy Mission)
   - Space telescope
   - Fermilab Goal: Science Operation Center



Cosmic Frontier: High Energy Particles from Space





Auger Observatory
studies ultra-high energy cosmic rays.

o – Cosmic rays with E > 57,000,000 TeV

Correlation

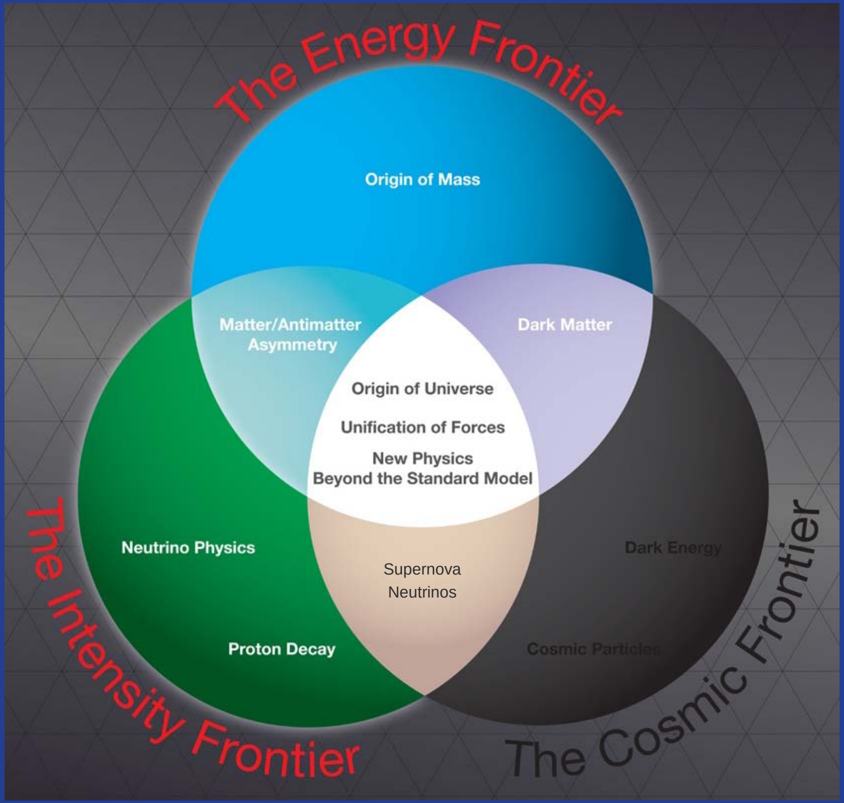
x – Active Galactic Nuclei

Fermilab

Energy and Intensity Frontiers

Energy-Intensity Integrated Program

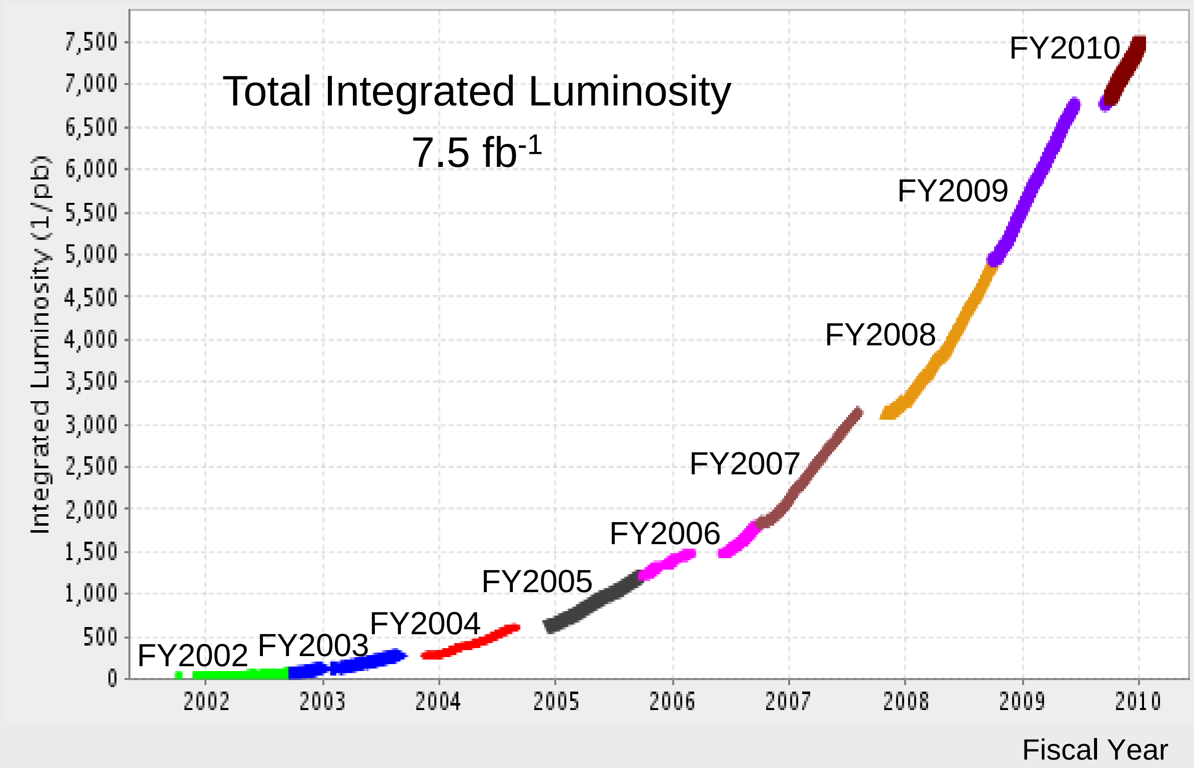
Today: operates Tevatron & highest power ν beams



Future: continue to have the integrated plan

The Energy Frontier: The Tevatron (1985 – 2011)

Progress: the Tevatron

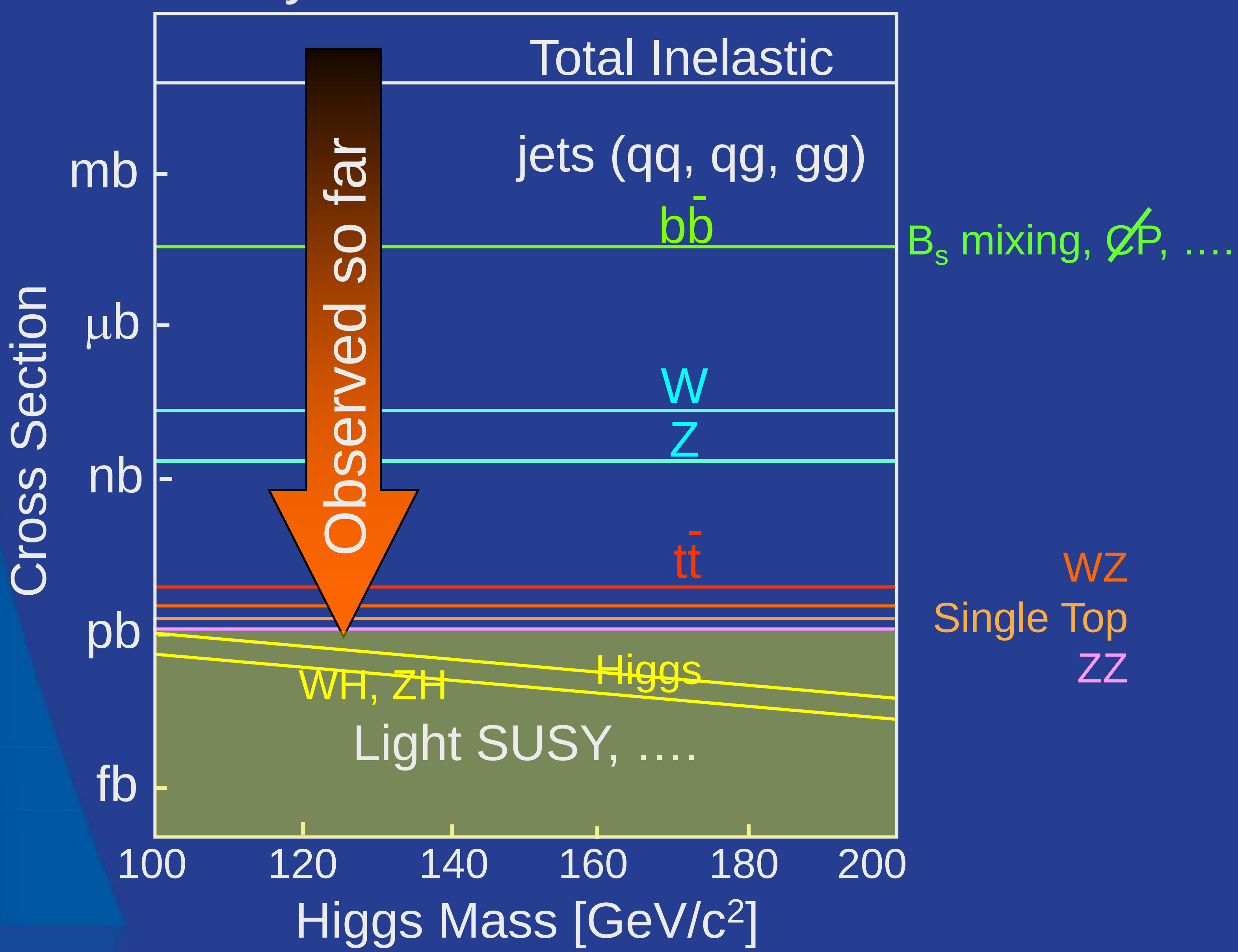


~100 publications / year, ~60 Ph.D.s / year

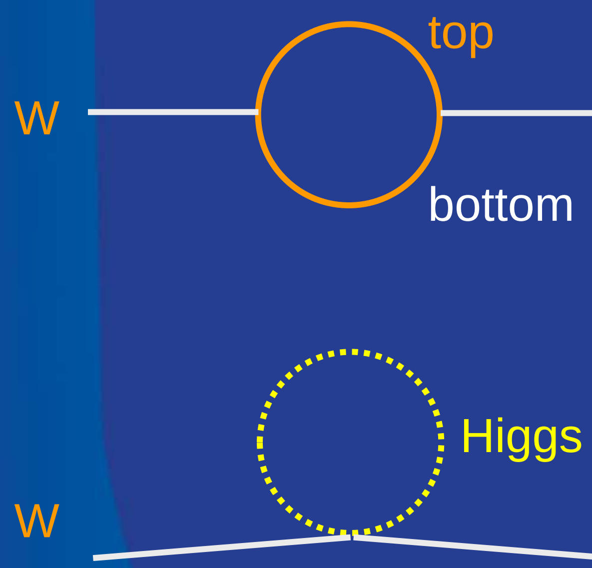
Plan to run through FY2011: 7.5 fb^{-1} (now) → 12 fb^{-1}

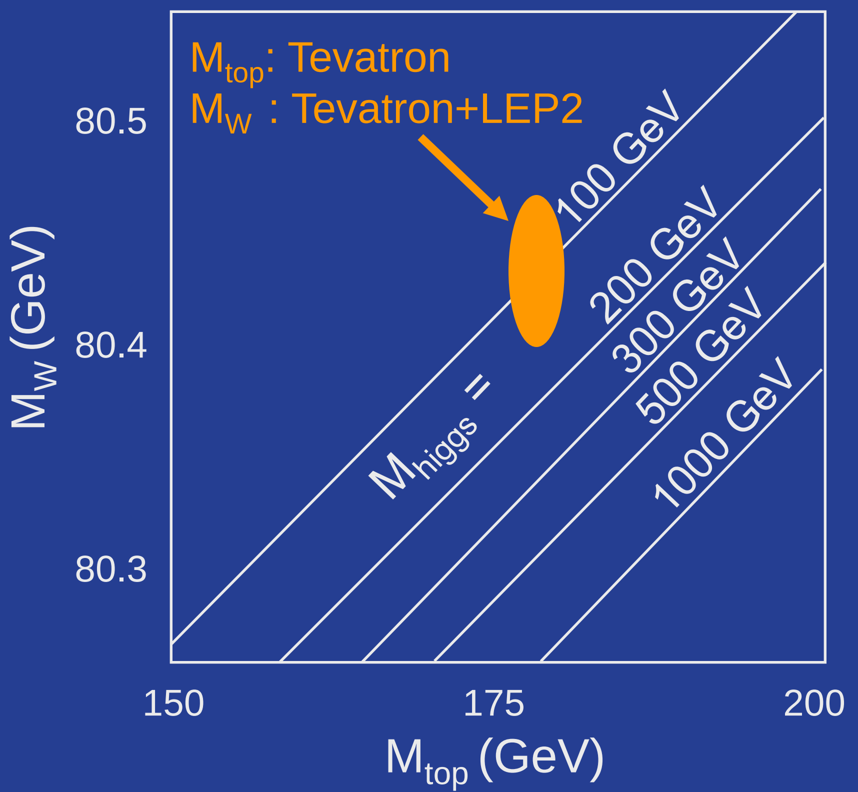
DZero

Physics at the Tevatron



The Tevatron Predicts Higgs Mass via Quantum Corrections





$m_H = 87^{+35}_{-26}$ GeV ($m_{top} = 173.1 \pm 1.3$ GeV)

Favors "light" Higgs in the range where Tevatron has good potential.

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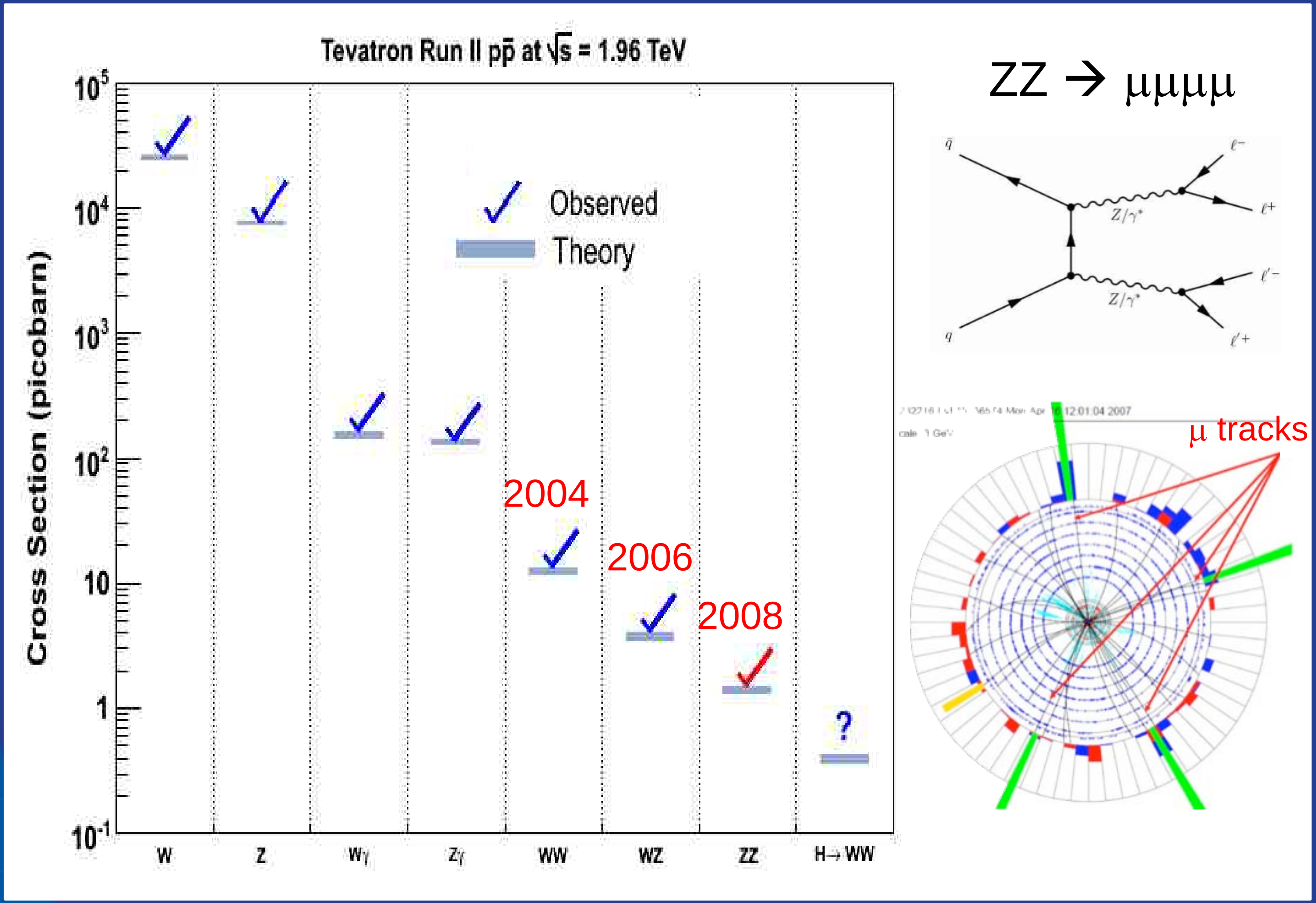
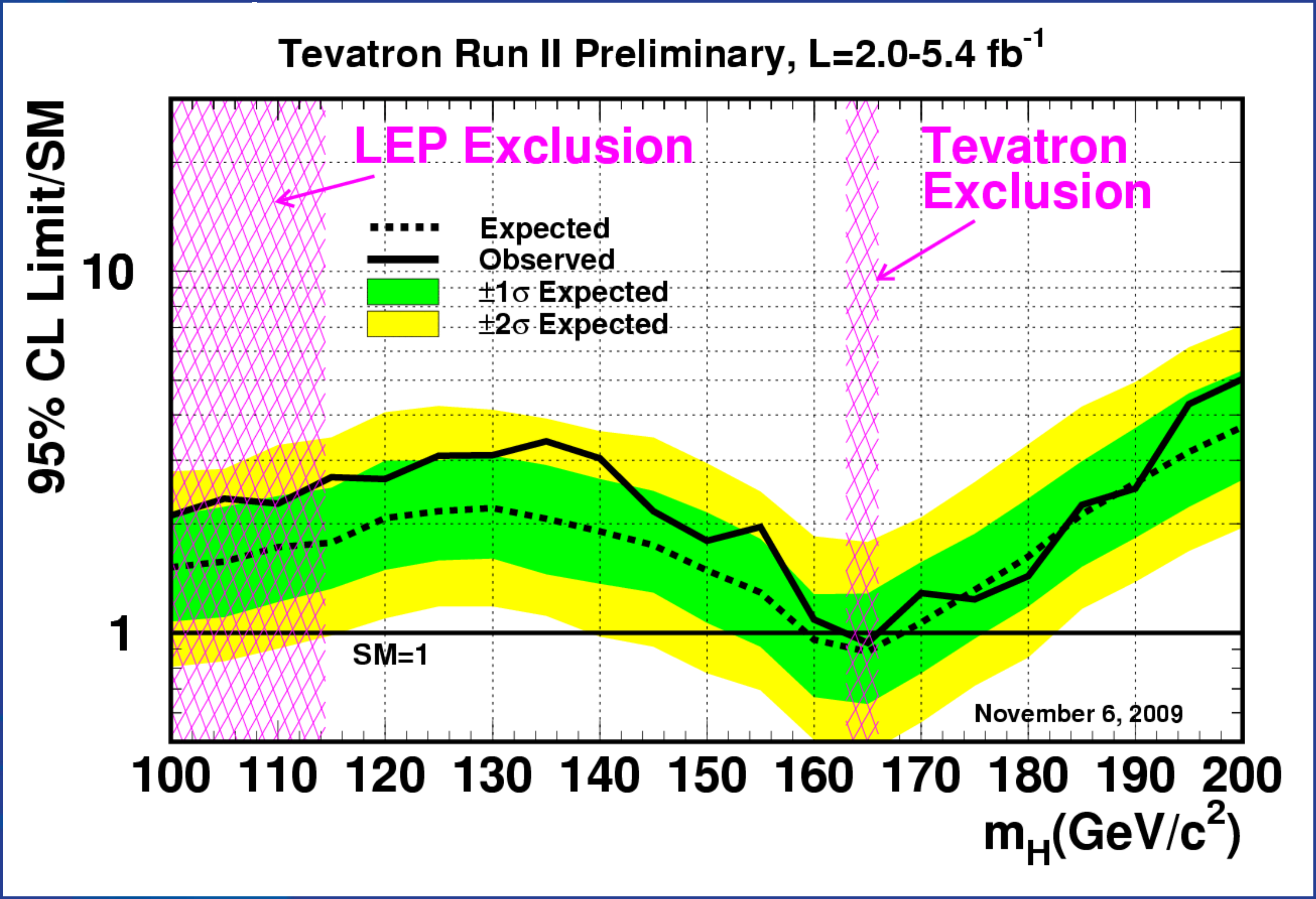
Observations: rare SM processes



Diboson production: more luminosity allows access to smaller cross sections

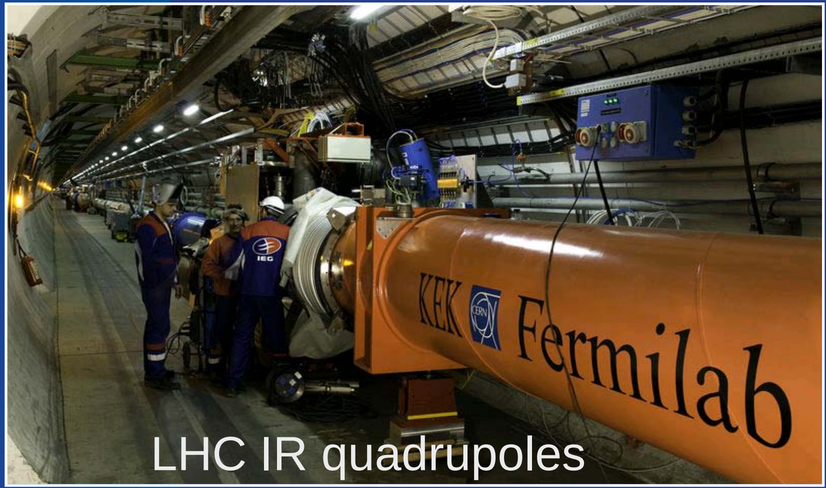
The Higgs Search

- The SM Higgs (if it exists) is being produced NOW at the Tevatron! We have enough energy
  - Just not that often & it's buried in "backgrounds"
  - It's a story of luminosity, passion, persistence and luck
  - We know how to look for it and we are in fact closing in!
- Over the last years, there's been a dramatic infusion of people, effort and ideas, aimed at finding the Higgs


Tevatron Run II Preliminary, L=2.0-5.4 fb^{-1}
95% CL Limit/SM
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
10
1
SM=1
November 6, 2009
100 110 120 130 140 150 160 170 180 190 200
m_H(GeV/c^2)

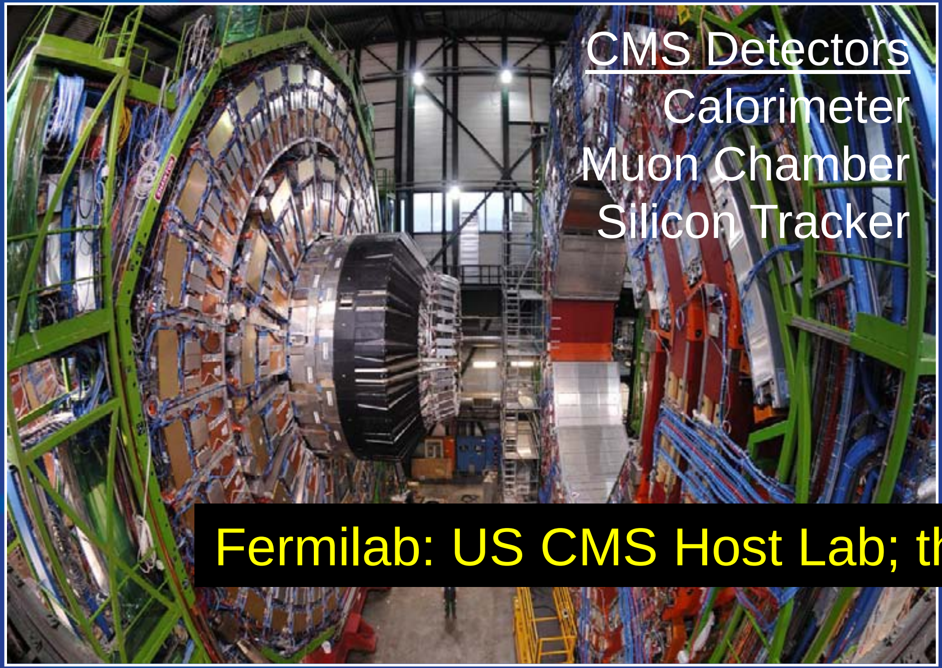
Fermilab and LHC:

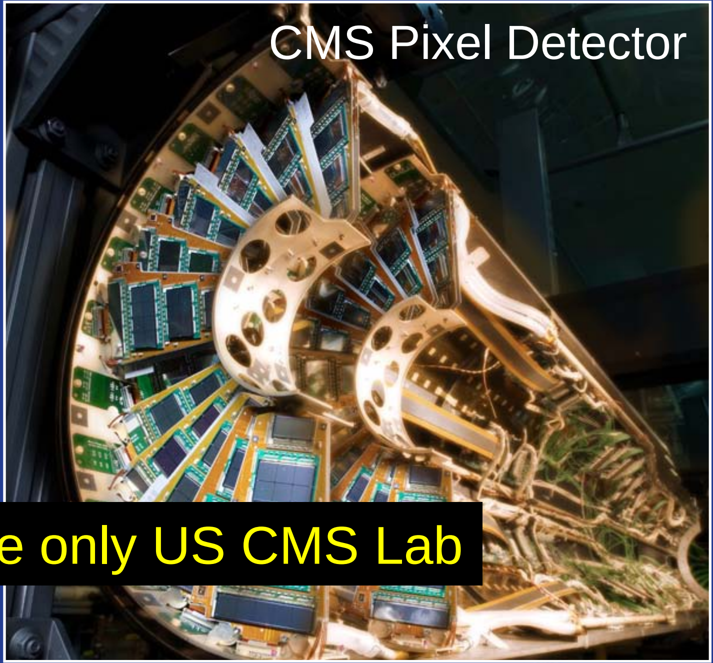
Accelerator and Detector Design/Engineering/Construction and Upgrades



LHC IR quadrupoles

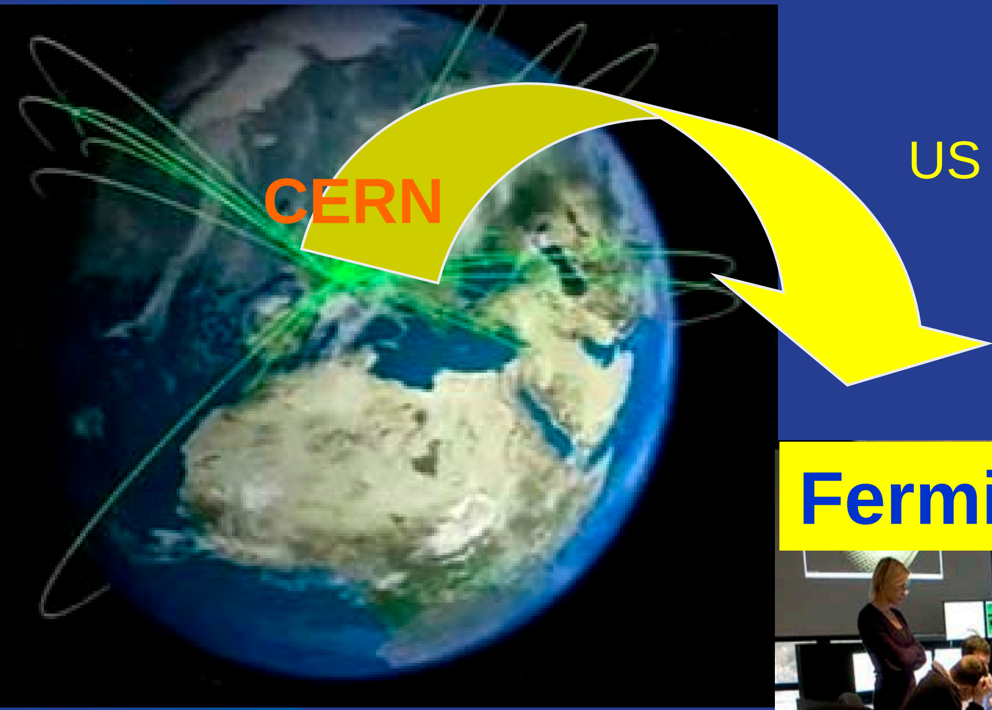

LHC upgrade
3.4m Nb3Sn prototype


CMS Detectors
Calorimeter
Muon Chamber
Silicon Tracker


CMS Pixel Detector

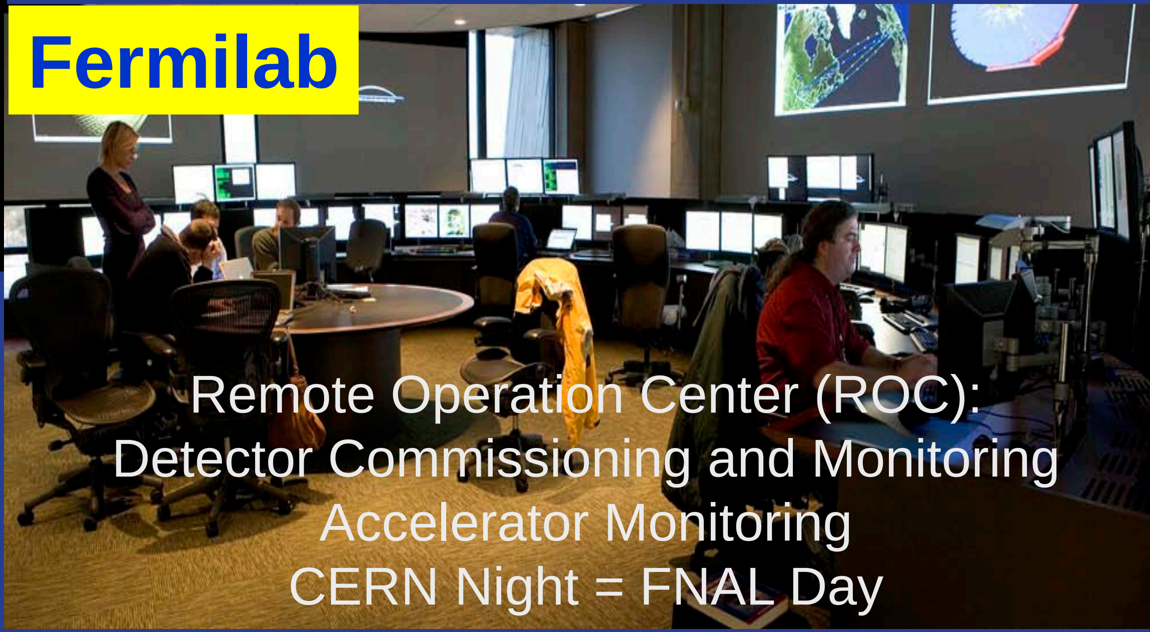
Fermilab: US CMS Host Lab; the only US CMS Lab

Fermilab and LHC



US CMS Host Lab; the only US CMS Lab

CMS Tier-1 Computing Center
LHC Physics Center
Support US CMS Community



Remote Operation Center (ROC):
Detector Commissioning and Monitoring
Accelerator Monitoring
CERN Night = FNAL Day

To make being at Fermilab as good as being at CERN.
Requires critical mass (~100 Fermilab + University Scientists at Fermilab).

Supporting the LHC Community

CERN-Fermilab Hadron Collider Physics Summer School

1st	Fermilab	August 9-18, 2006
2nd	CERN	June 6-15, 2007
3rd	Fermilab	August 12-22, 2008
4th	CERN	June 8-17, 2009
5th	Fermilab	Summer 2010

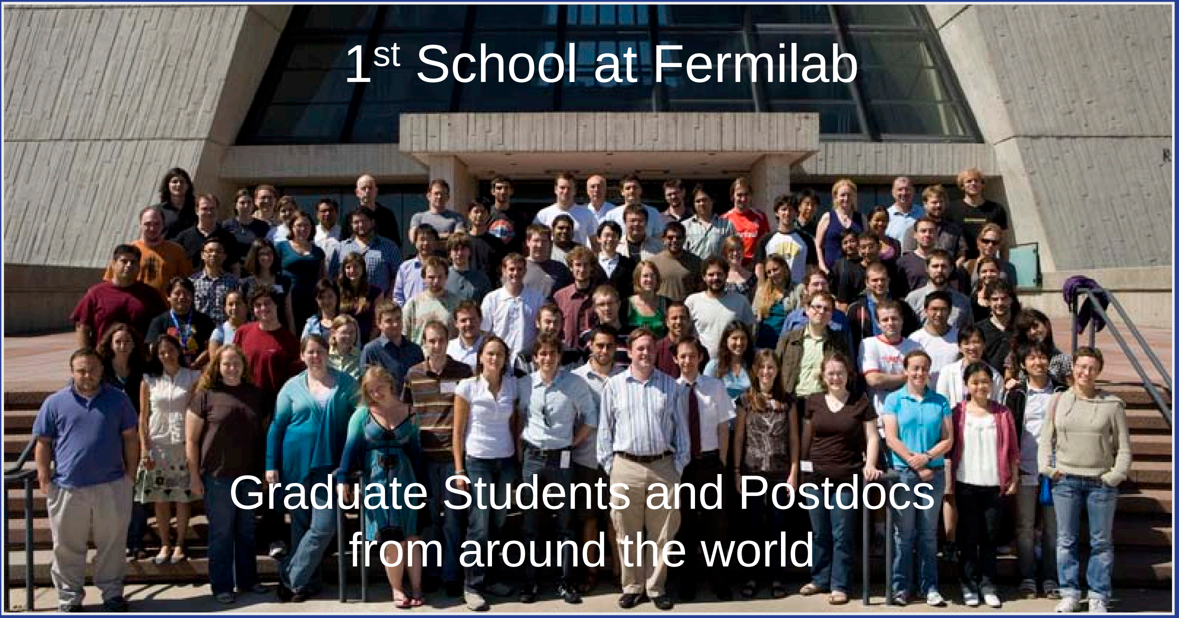
Fermilab

International Neutrino Summer School

Merging various neutrino schools into one coherent school

Rotating in three regions

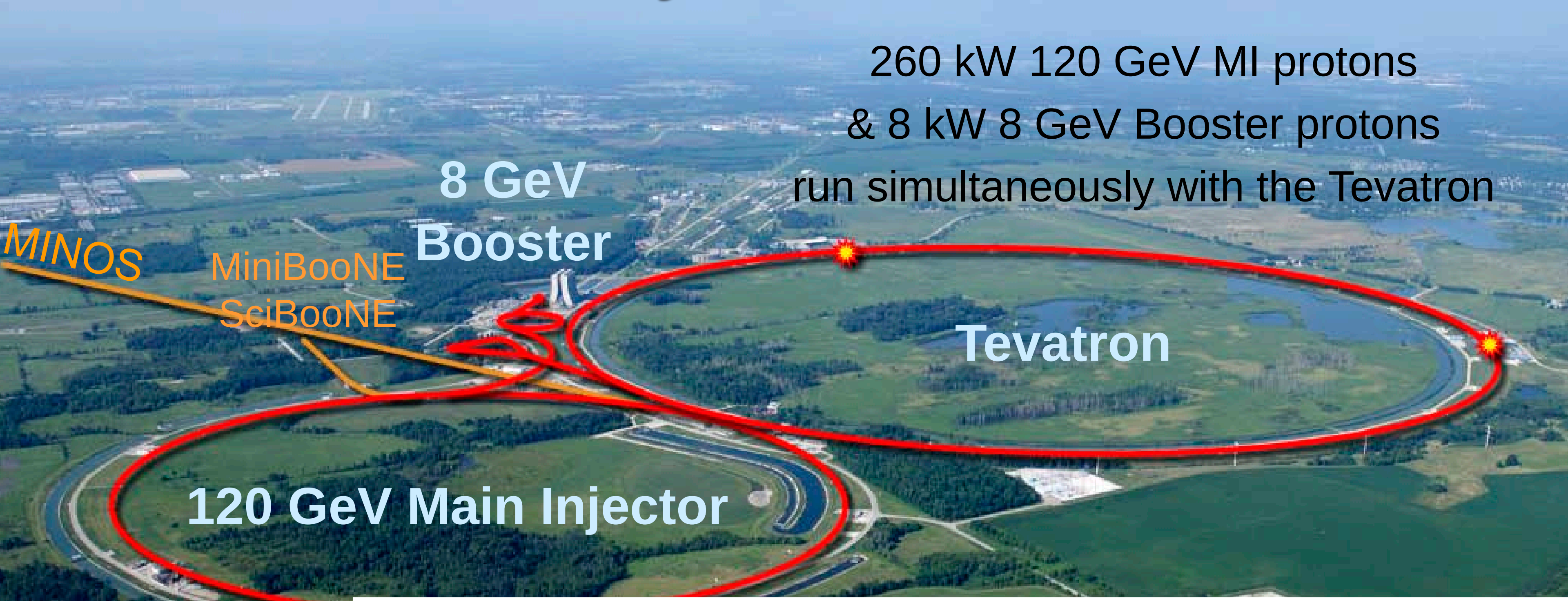
1st	Fermilab	July 6-18, 2009
2nd	KEK	2010
3rd	Europe	2011

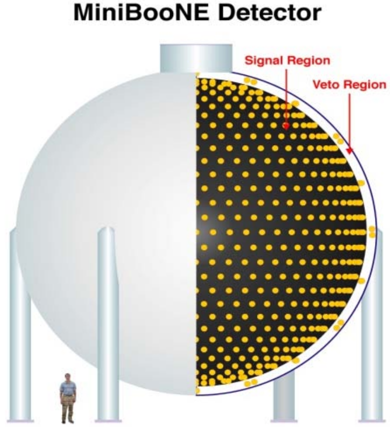


Fermilab

The Intensity Frontier: Neutrinos

260 kW 120 GeV MI protons
& 8 kW 8 GeV Booster protons
run simultaneously with the Tevatron





Neutrino beam from 8 GeV Booster

MiniBooNE: Excludes “4th gen.” ν
Low Eng Excess in ν, Now running anti-ν

SciBooNE: ν – Matter Interactions

MicroBooNE: 170 ton LAr TPC

Neutrino beam from 120 GeV MI

Best Δm^2_{23}
θ_{13} ?
…

Global fit:

θ_{13} = 0 disfavored by ~2σ

Central value $\sin^2 2\theta_{13}$=0.08

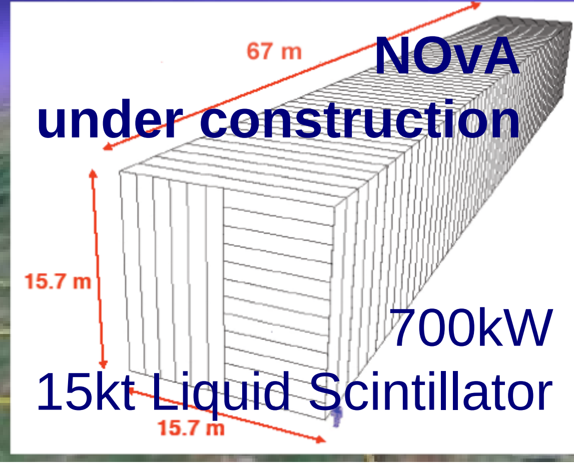
735 km
2.5 msec

Lead, SD

MiniBooNE
SciBooNE

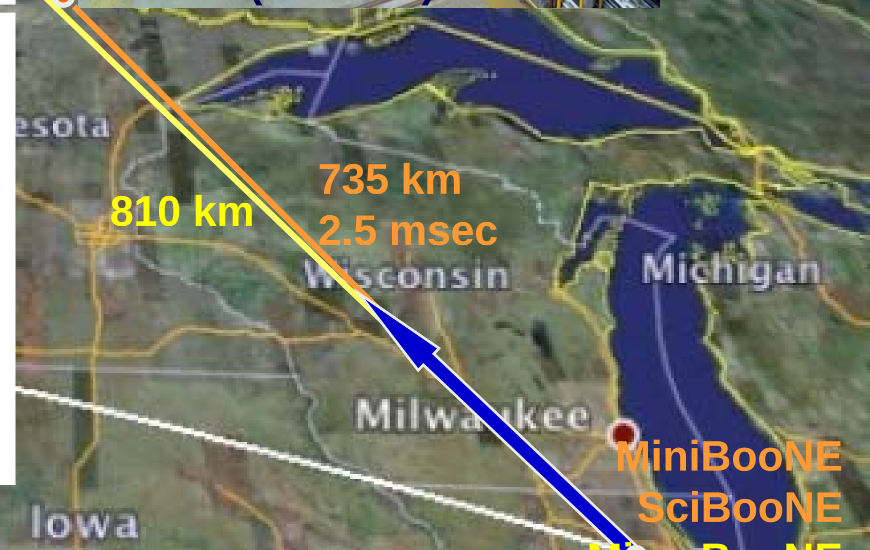
MINOS
MINERvA
ArgoNeuT

MINERvA: Ops. w/ Partial Det.(2009)
ν – Matter Interactions



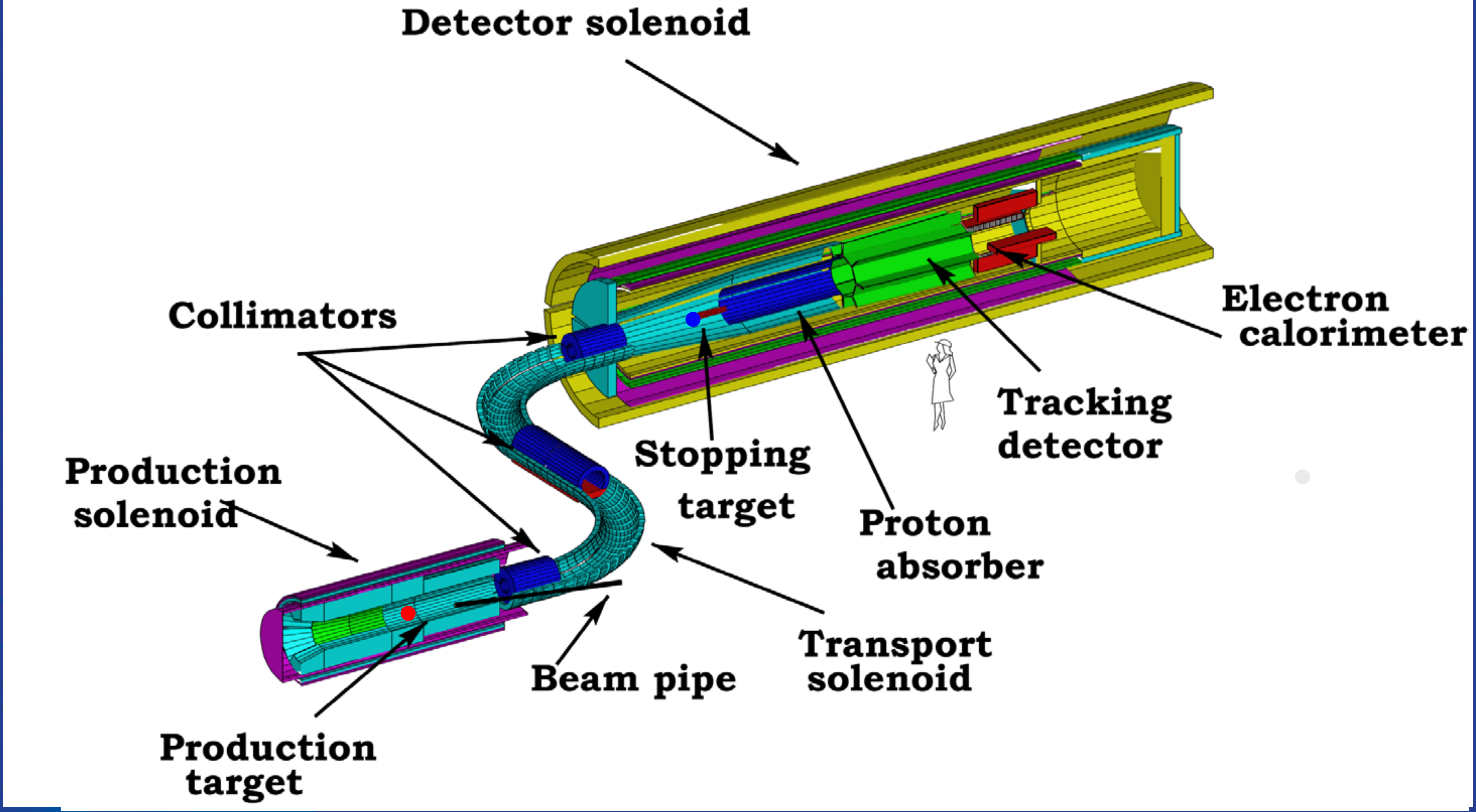
NOvA: Data Taking in FY12-13

- θ_{13}
- Mass Ordering:
  the only near term project in the world sensitive to mass ordering
- improved precision: 2-3
- …



MINERvA: Ops. w/ Full Det.(2010)
ν – Matter Interactions

Muon to e Conversion ($\mu N \rightarrow eN$)

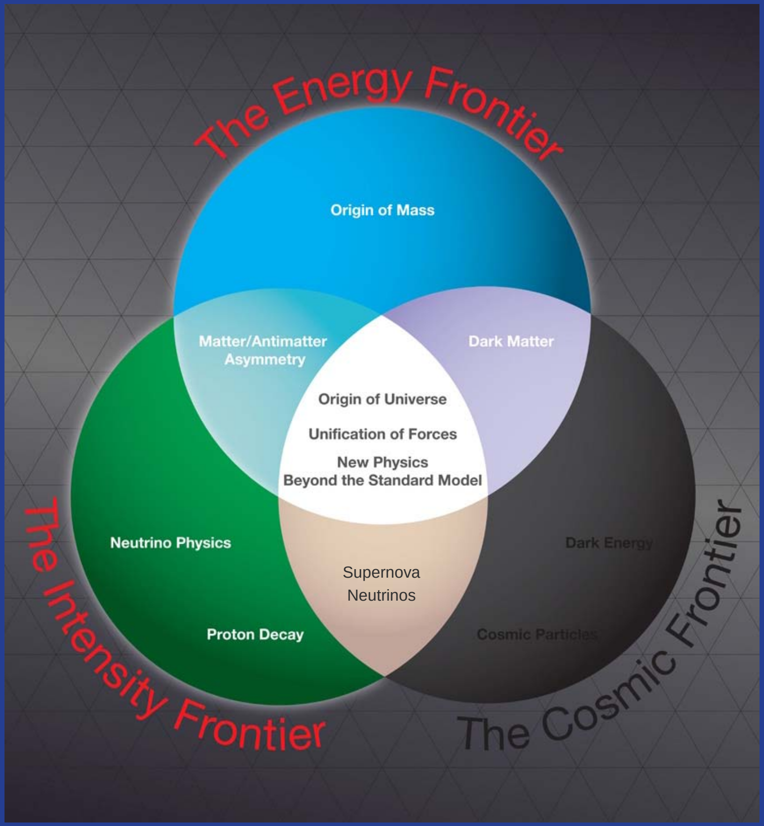


Muon g-2, $K^+ \rightarrow \pi^+\nu\nu$ (1000 events) under consideration

Project X: intense proton accelerator

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

- The intensity frontier answers fundamental questions
- Project X is the key
- Project X can lead us back to the energy frontier



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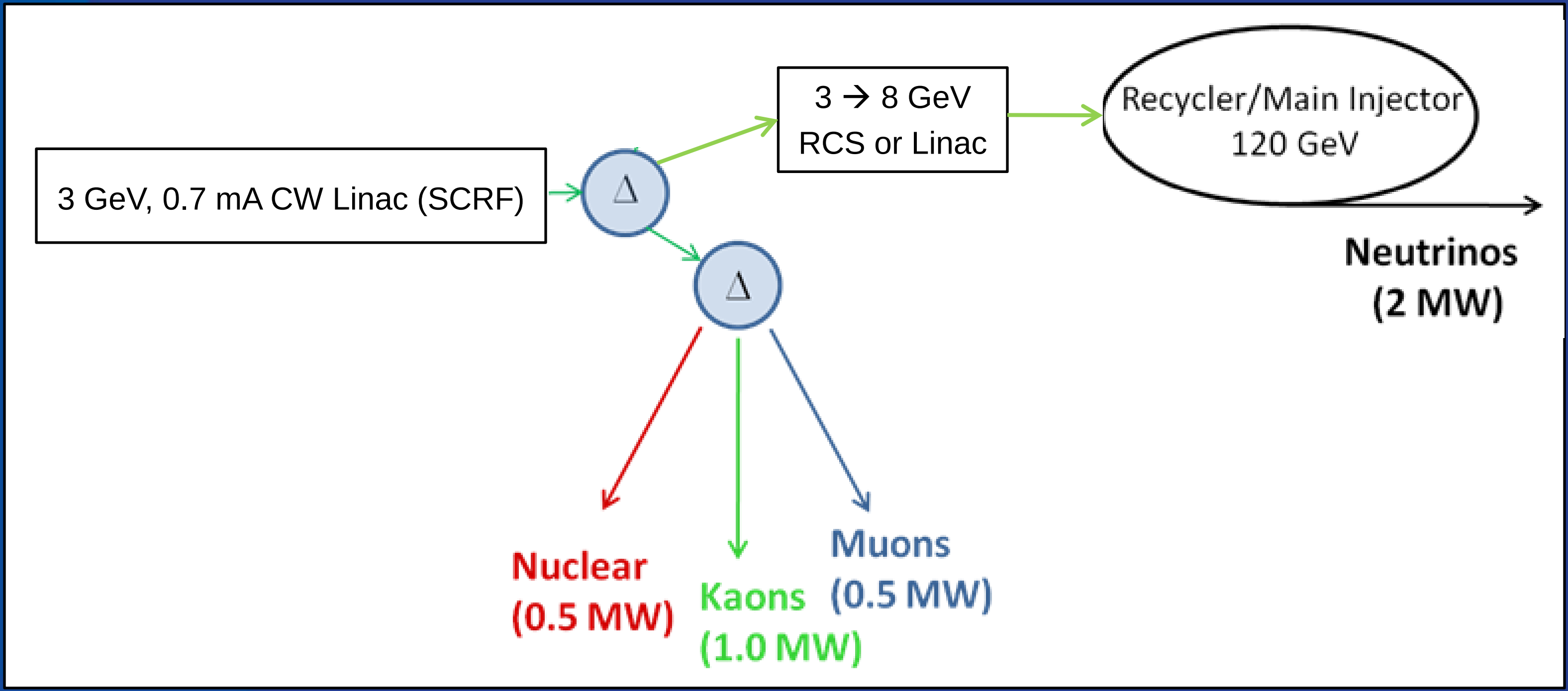
Evolution of Project X: 3 Simultaneous Beams

- 3 GeV protons, 2 MW CW (continuous pulses at 325 MHz)
  - Rare processes + precision measurements
  - flexible time patterns + pulse intensities
- 8 GeV protons, 20 – 200 kW: rare processes + precision meas.s
- 60 – 120 GeV protons, 2 MW (to Homestake) for neutrinos



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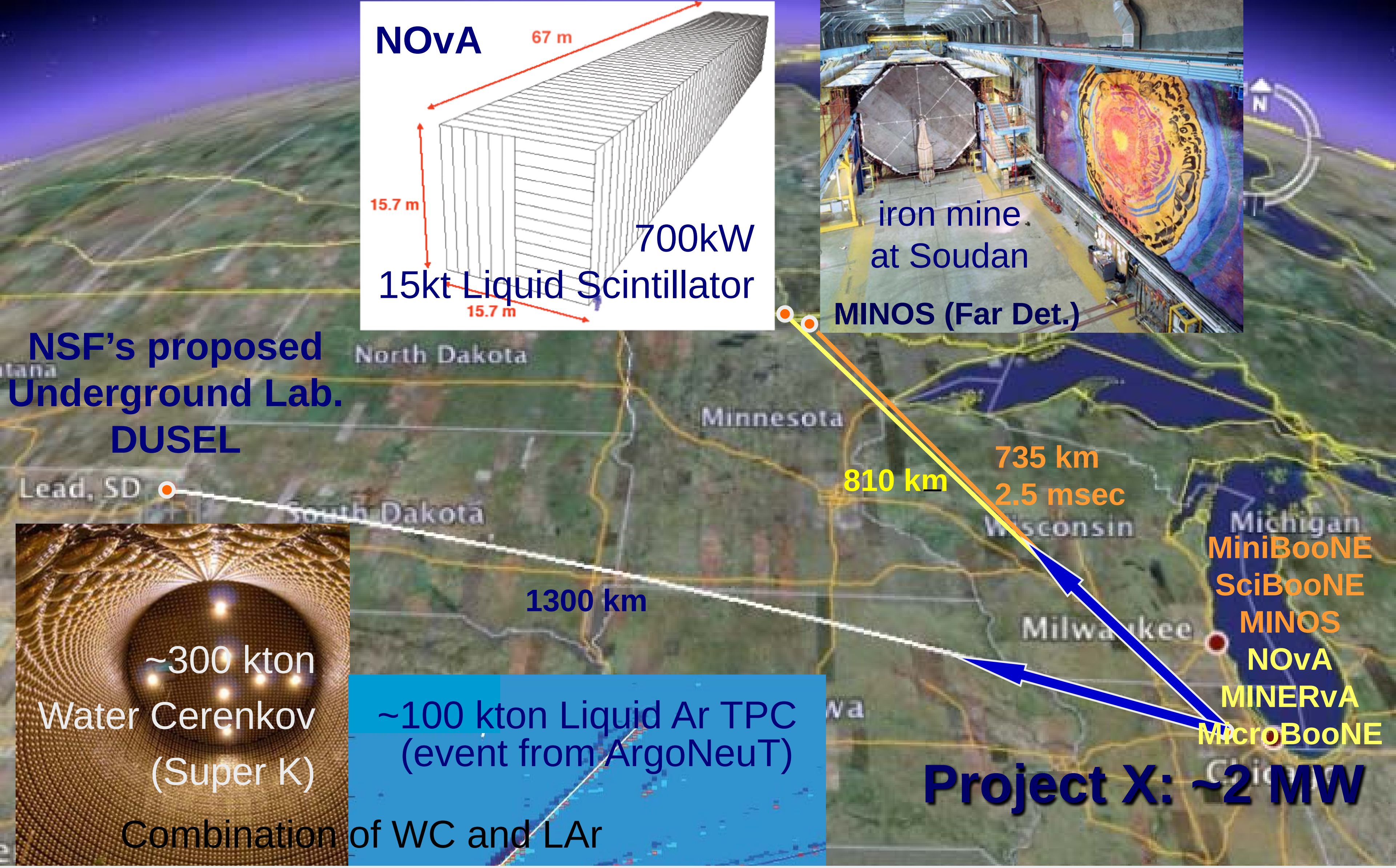
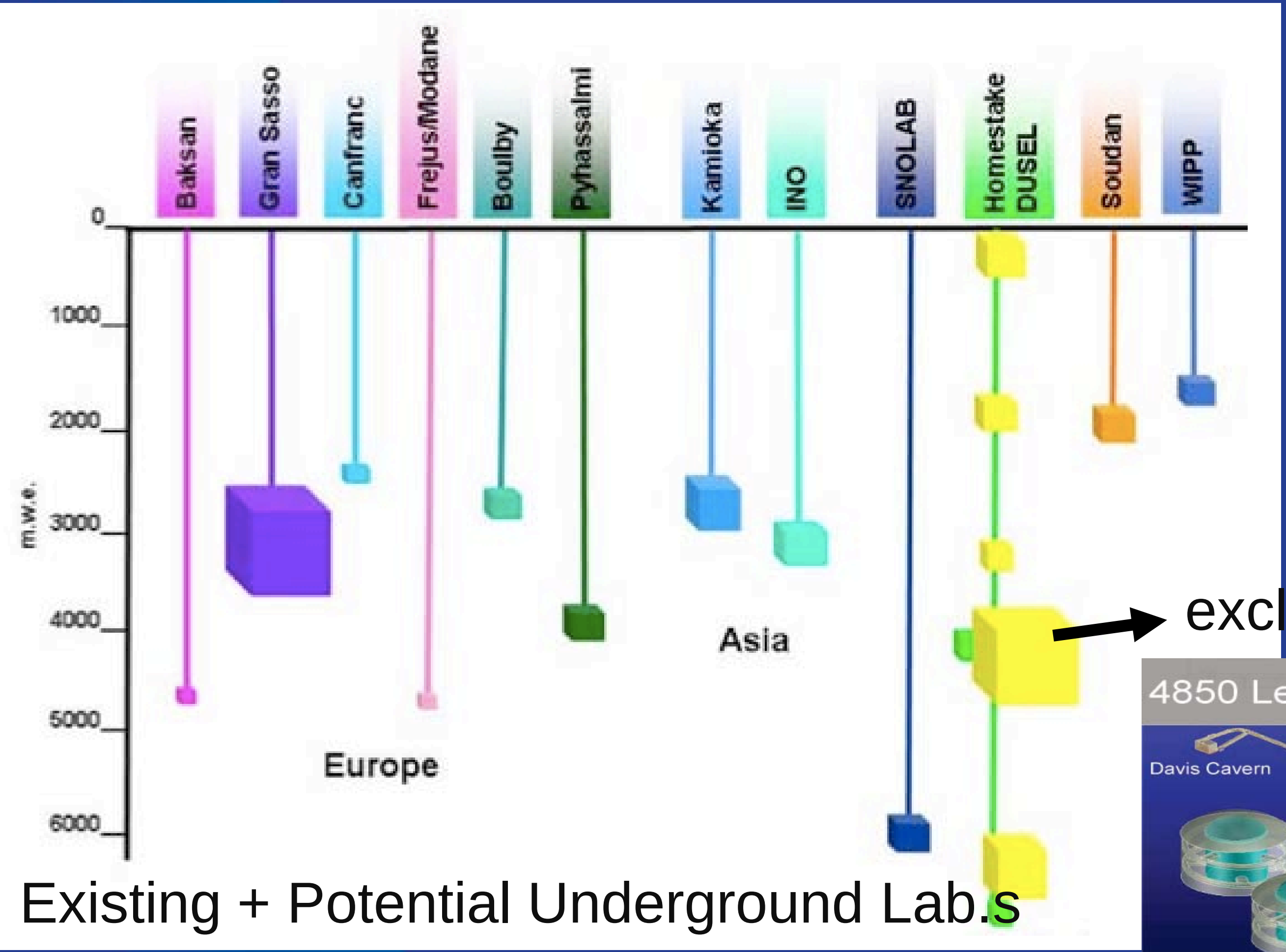


Matter – Antimatter Asymmetry with Neutrinos

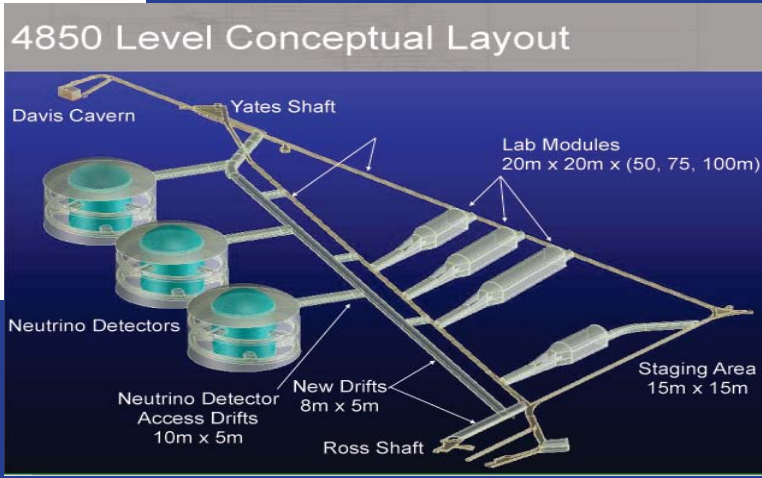
Proton Decay

Supernovae Neutrinos

The Intensity Frontier: Fermilab → DUSEL Option



excluding the big cavern



Existing + Potential Underground Lab.s

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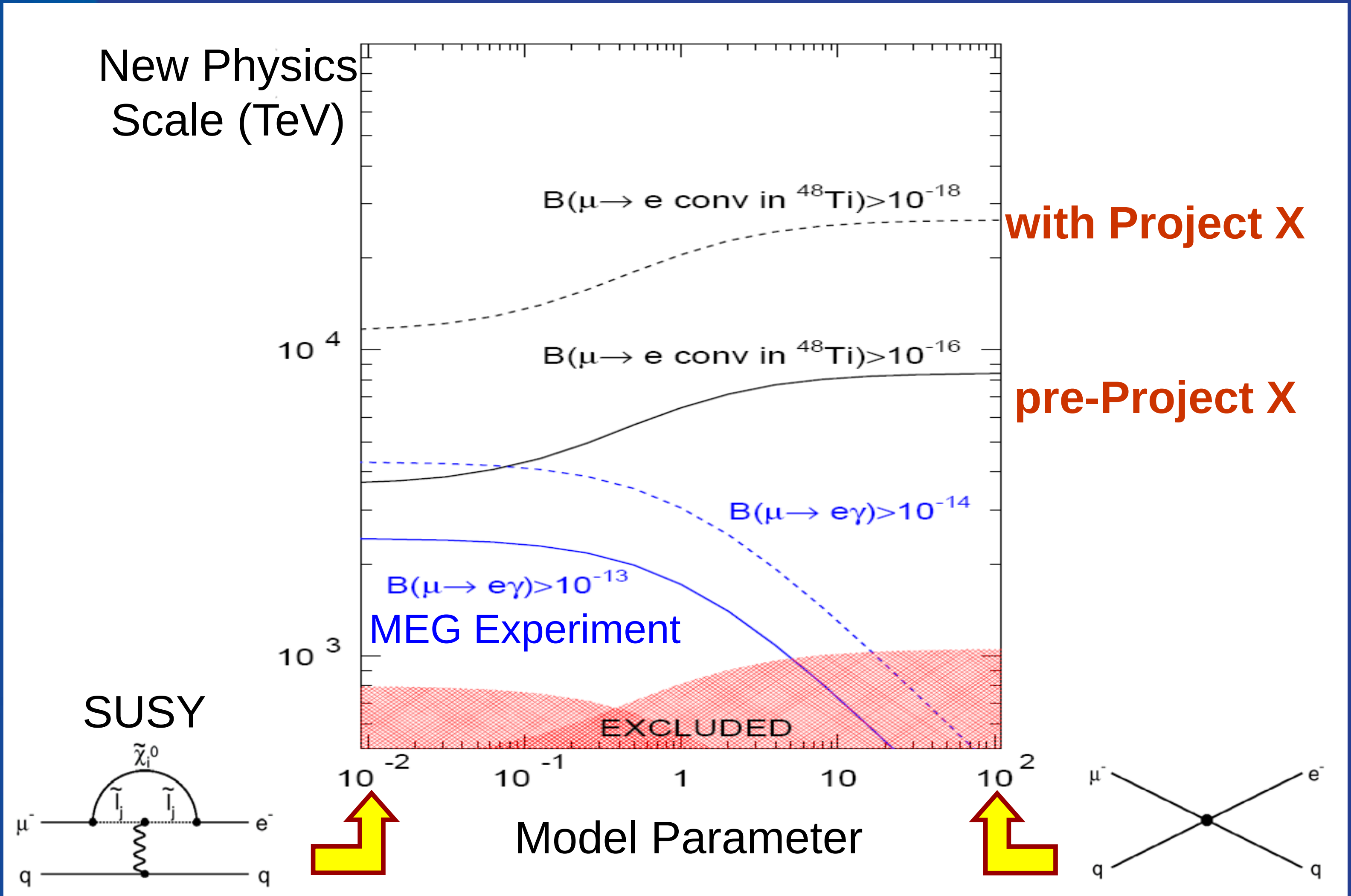
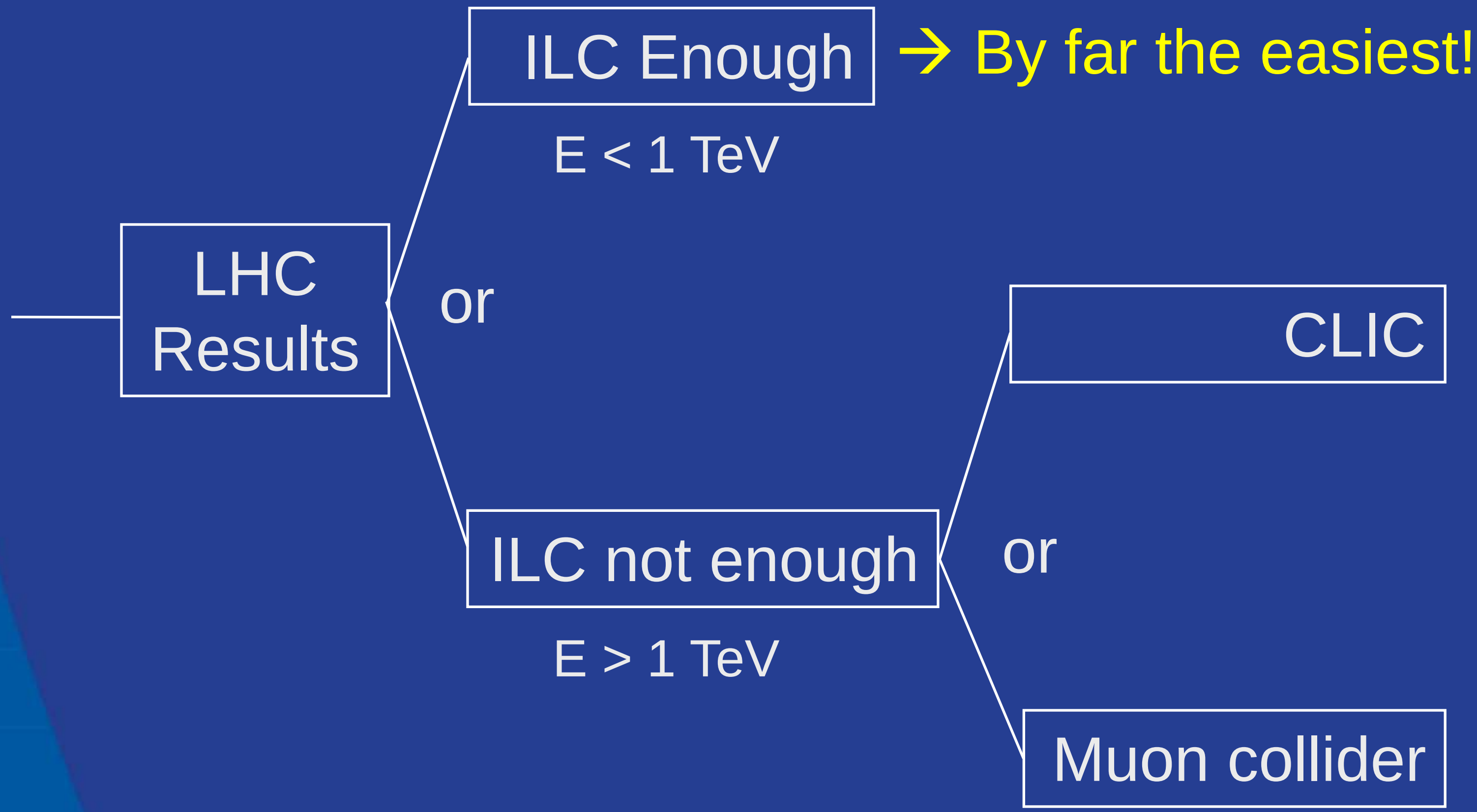
Mu2e can probe ~10^4 TeV



A path back to the energy frontier?

Lepton colliders beyond LHC



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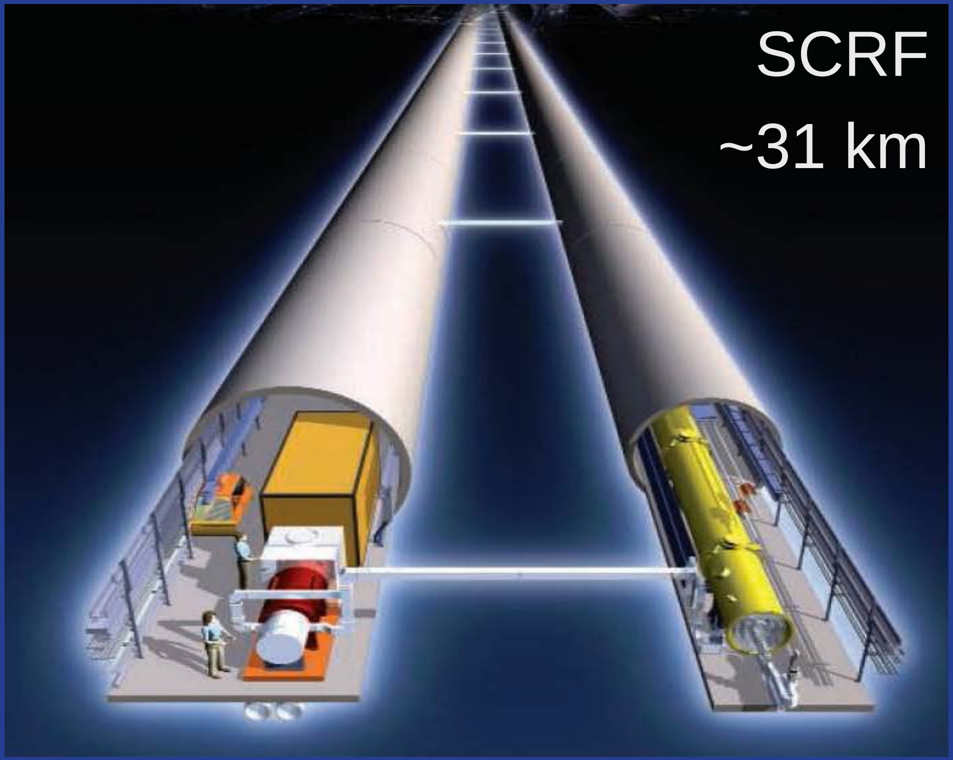
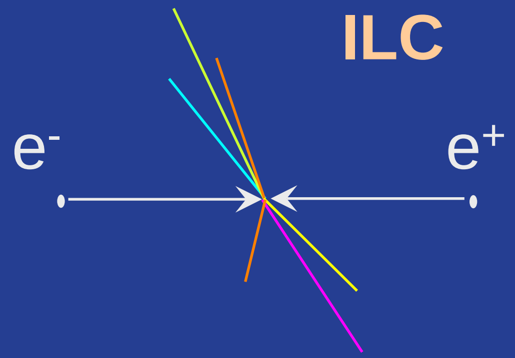
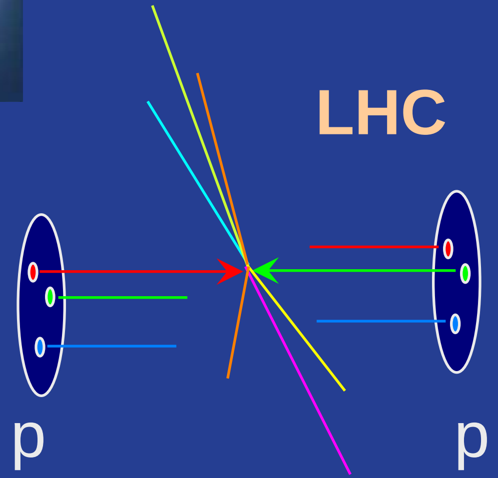
International Linear Collider (ILC)







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Muon Collider Conceptual Layout

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

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

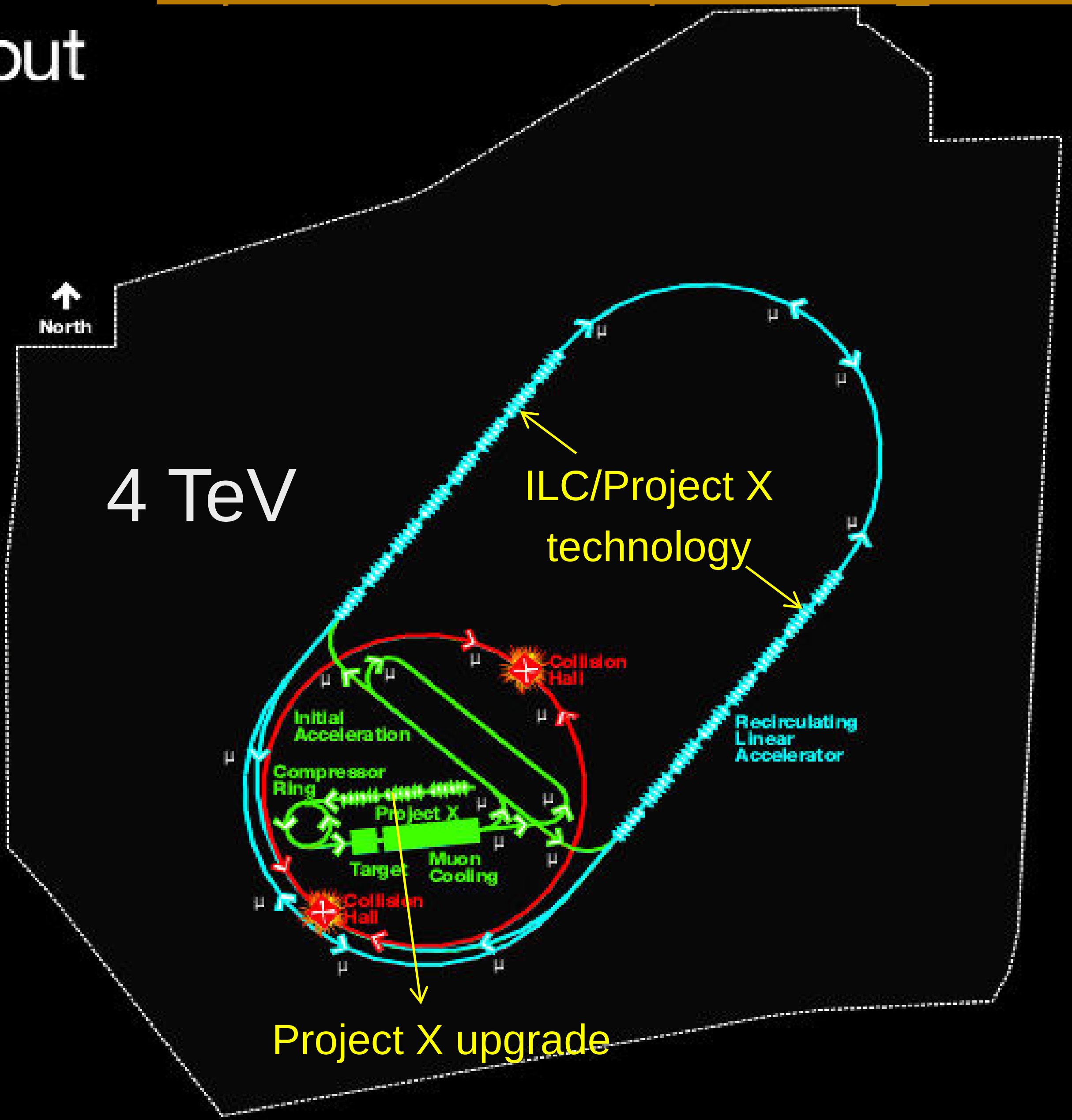
Target
Collisions lead to muons with energy of about 200 MeV.

Muon Cooling
Reduce the transverse motion of the muons and create a tight beam.

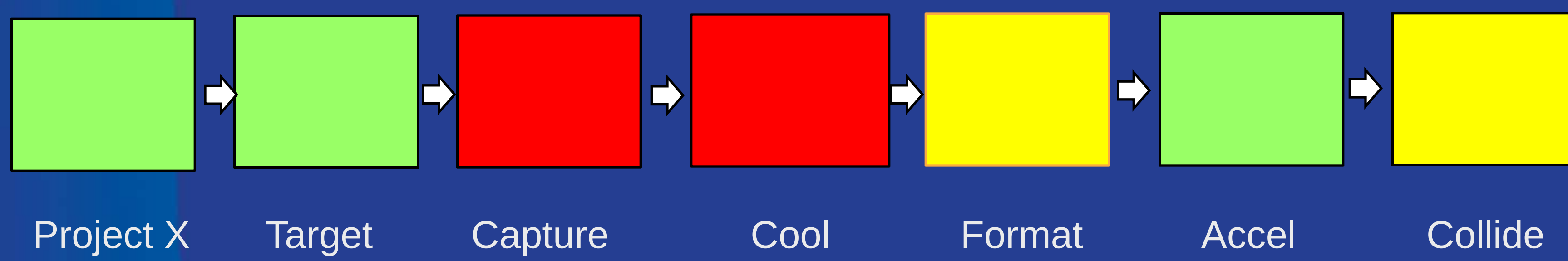
Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Located 100 meters underground. Muons live long enough to make about 1000 turns.



Muon collider functional layout



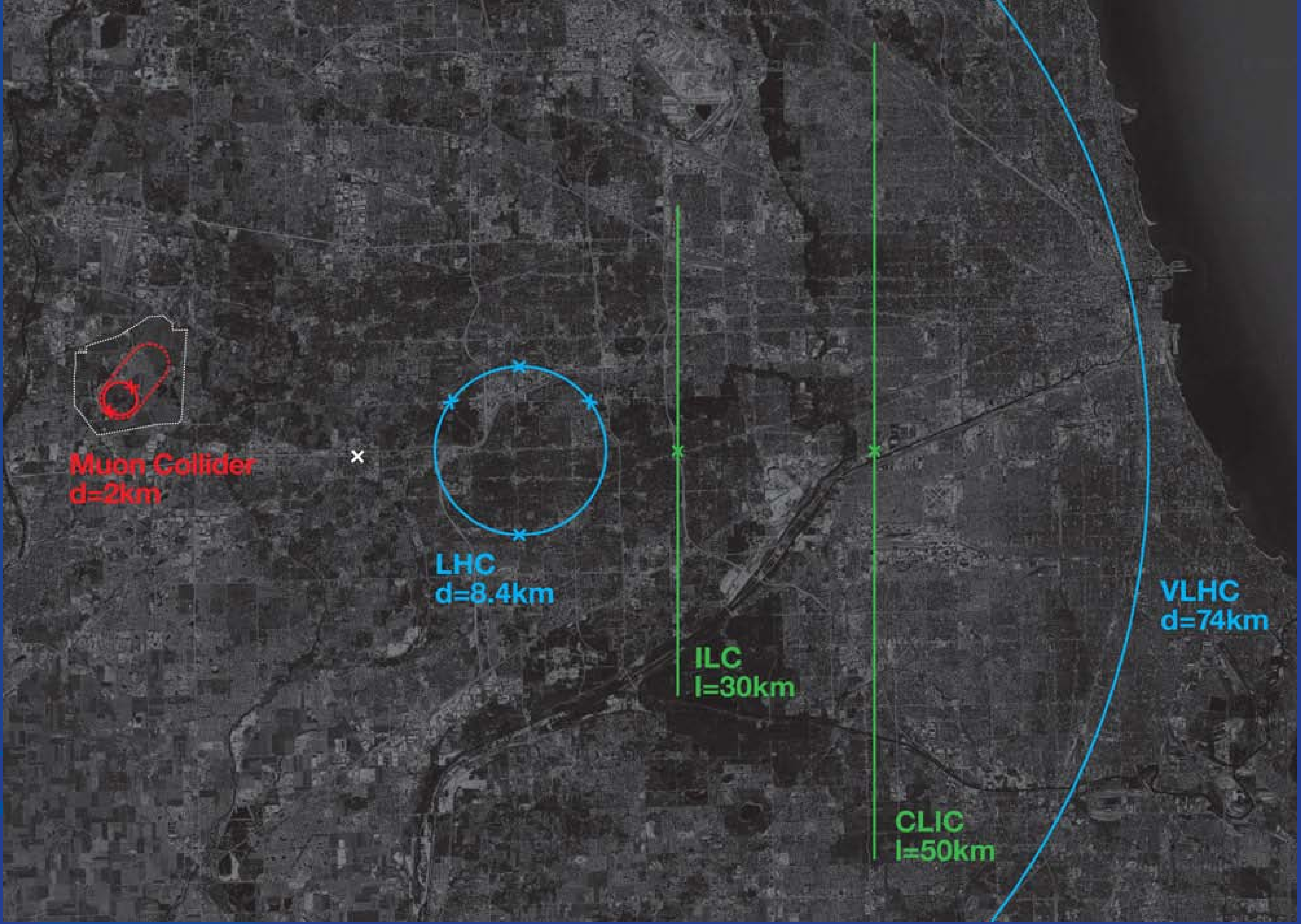
Color indicates degree of needed
R&D (difficulty) and demonstration

ILC / Project X / Muon Collider technology at Fermilab

System Test Facility with beams

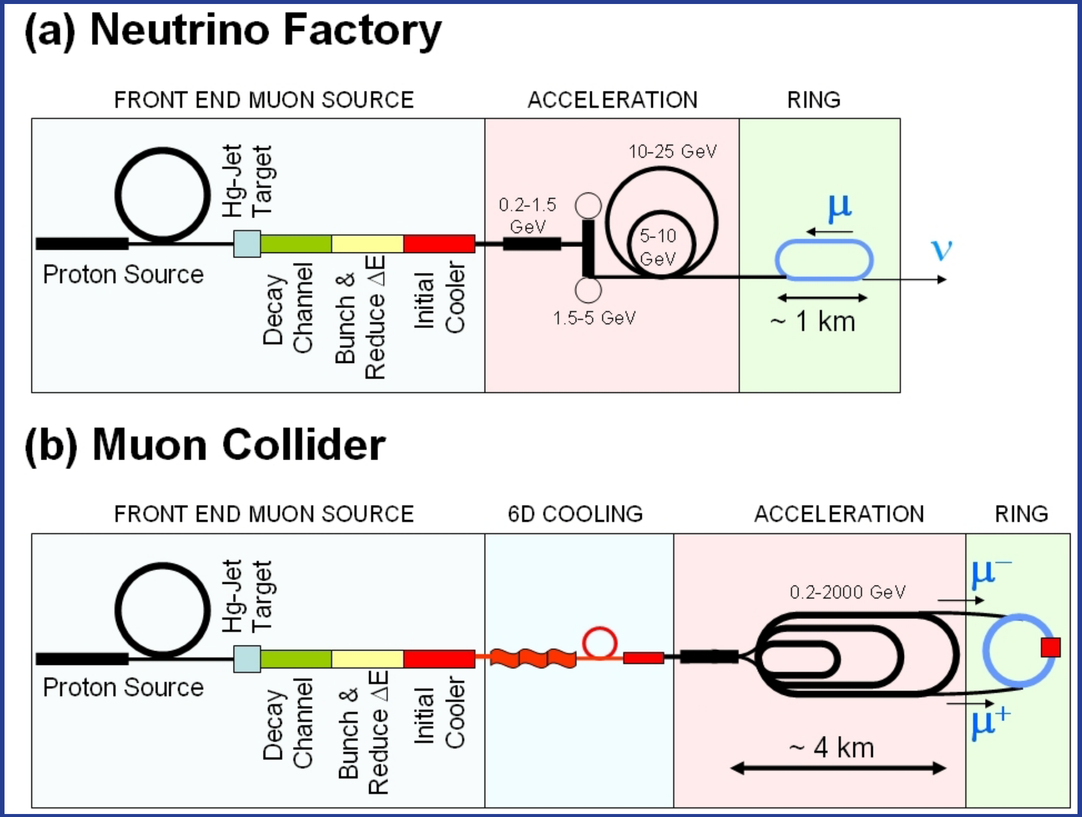
Comparison of Particle Colliders

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



Evolution of ν Program: Neutrino Factory

- Muon Colliders & Neutrino Factories require similar, & potentially identical, muon sources:



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Project X

- Would be a fantastic machine at the intensity frontier for neutrino physics, kaon physics, muon physics, and nuclear physics
- Would develop and exercise the technologies to position the US to host a global facility at the energy frontier (or contribute to one elsewhere)
  - ILC and muon collider

US Strategy

Detector Synergy:
ILC/CLIC/μ Collider

Energy Frontier

Tevatron — (LHC) — ILC / μ Collider

protons

technology

injector

Intensity Frontier

NuMI (260kW) → NuMI (700kW) → **Project X** → injector → ν Factory

2 MW (120GeV) for ν

Booster

+ 2MW(3GeV) + 200kW(8GeV)

MINOS — NOvA — 1300km baseline ν

MiniBooNE — WC / LAr

SciBooNE — MINERvA — (+Proton Decay,..)

ArgoNeuT — MicroBooNE

Mu2e — Mu2e II

μ g-2 — μ g-2 II

K^+ — $(K^0/K_L, K^+)$ II

EDM (μ, Λ, Σ^+) II

Nuclear Physics

….

time →

Closing Remarks

- Compelling Questions in Particle Physics
  - Require three interrelated frontiers
    - The Energy Frontier
    - The Intensity Frontier
    - The Cosmic Frontier

- Fermilab: Current and Future
  - A balanced program at 3 interrelated frontiers
  - Project X (intense proton source)
    - Intensity Frontier Facility (broad physics program)
    - A path back to the Energy Frontier
      - ILC technology
      - Front end of a muon collider (and/or ν factory), Acceleration technology for a muon collider

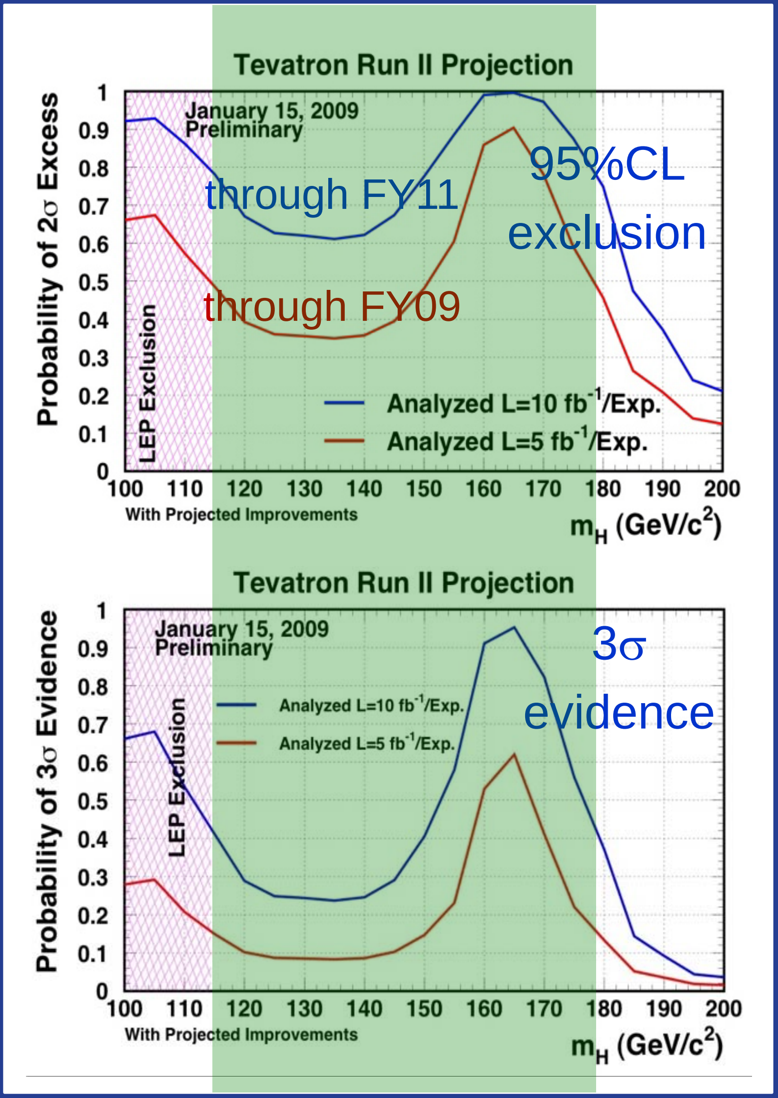
END

and some luck

Higgs reach with continued analysis improvement

running through
FY09 (red)
FY11(blue)

Favored mass region



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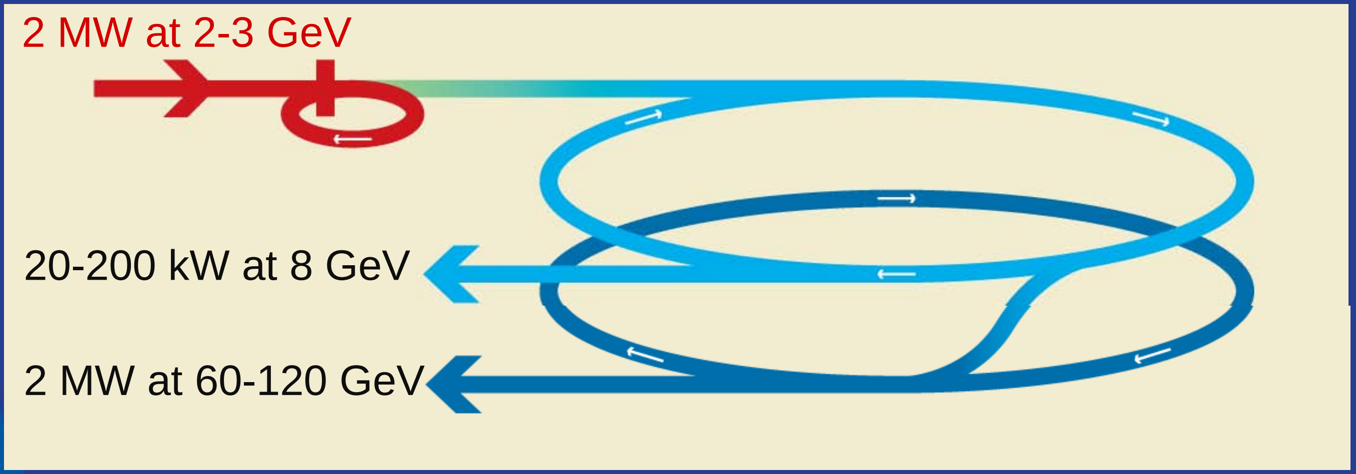
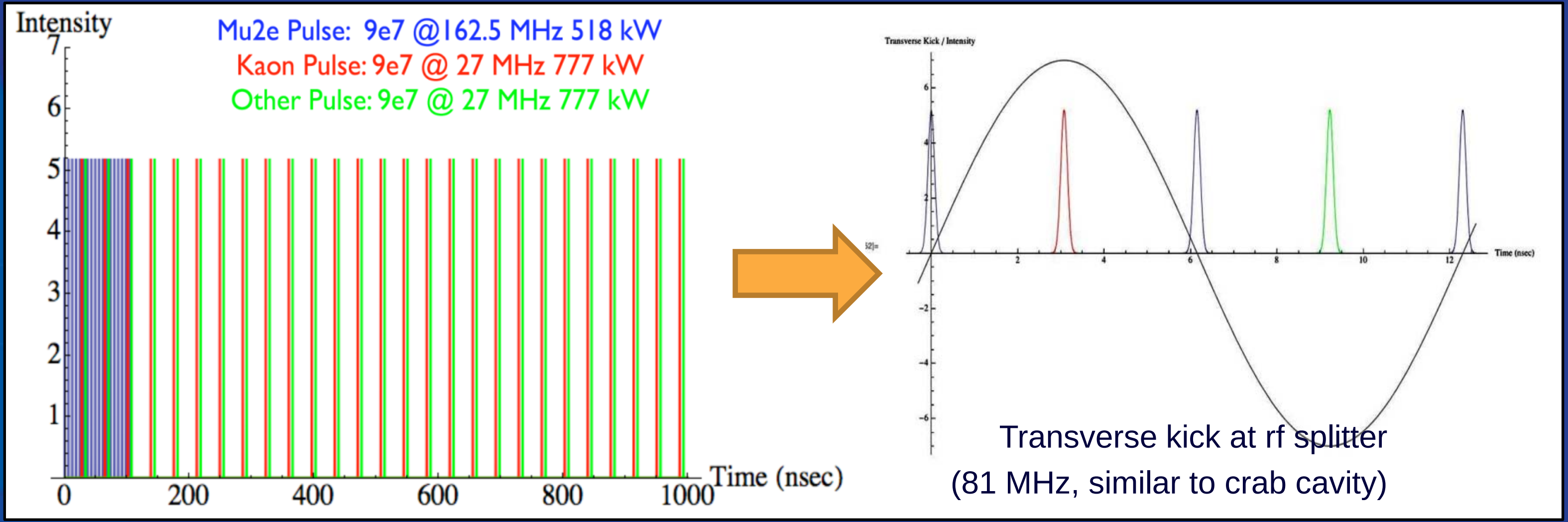
Evolution of Project X: 3 Simultaneous Beams

- 2 MW CW (continuous pulses at 325 MHz) 2-3 GeV protons
  - rare processes and precision measurements
  - flexible time patterns and pulse intensities
- 20 – 200 kW 8 GeV protons
  - rare processes and precision measurements
- 2 MW 60 – 120 GeV protons (to Homestake) for neutrinos



Flexible bunch format

- Variable H^- ion source provides current 1 to 10 mA DC
- Variable bunch formats:
    1. Ion source at 1 mA, no beam chopping: 1.9×10^7 protons per bunch at 325 MHz rate
    2. Ion source at 10 mA, 90% beam chopping: 1.9×10^8 protons per bunch at 32.5 MHz rate (1 mA ave current)
    3. Bunch-by-bunch chopping example (ion source at 4.7 mA), chopping and rf splitting for 3 experiments



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Other applications

- Nuclear Physics
  - Can drive an ISOL target for Nuclear Physics applications. Totally complementary program for nuclear EDMs and fundamental experiments on atomic traps just with ISOL target
- Muon Spin Rotation
  - Currently done in Rikken, PSI and TRIUMF
  - Would produce the most intense muon beams available, including, polarization and monochromatization

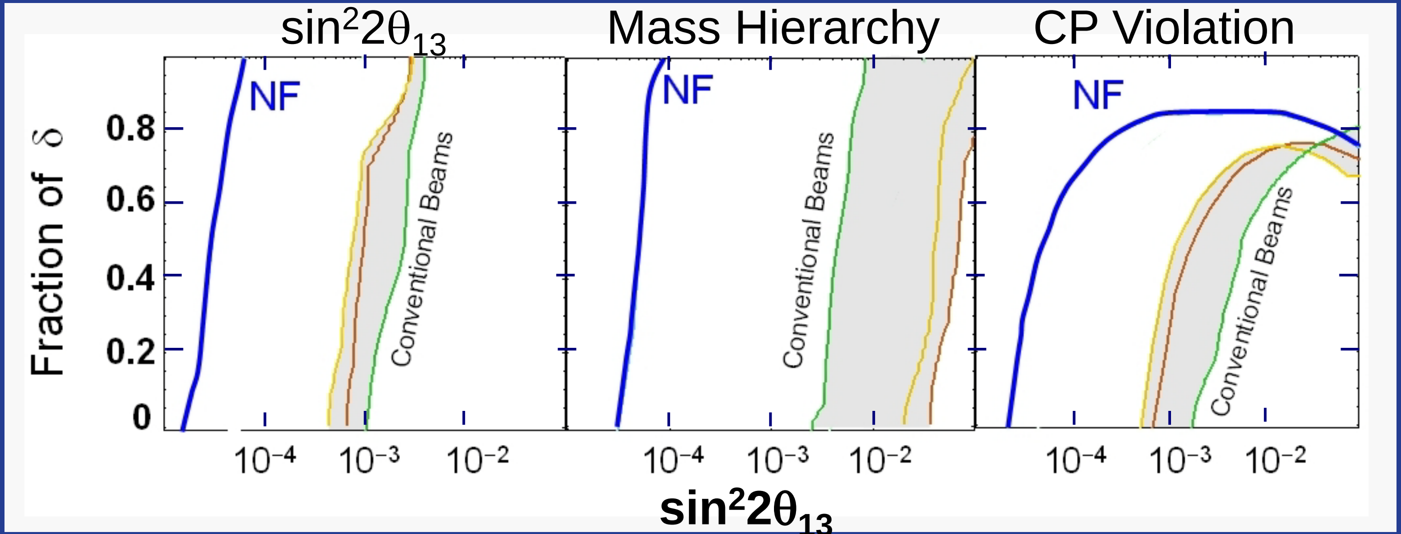
Muon experiments

- Next generation $\mu \rightarrow e$ conversion experiment, new techniques for higher sensitivity and/or other nuclei.
- $\mu \rightarrow 3e$
- Next generation (g-2) if motivated by theory, next round, LHC
- Other:
  - μ edm.
  - $\mu^+ e^- \rightarrow \mu^- e^+$
  - $\mu^- A \rightarrow \mu^+ A'$
- Systematic study of radiative μ capture on nuclei.

Evolution of ν Program: Neutrino Factory

International Design Study

- If $\sin^2 2\theta_{13}$ is small
  - Choose a NF energy of 25 GeV & a very long baseline (e.g. ~3000km) – up to ~ x100 improvement in sensitivity compared to a superbeam



- If θ_{13} is large (>.005)
  - A 4 GeV NF aimed at Homestake gives clean reach into CP violation, mass hierarchy and any unusual features

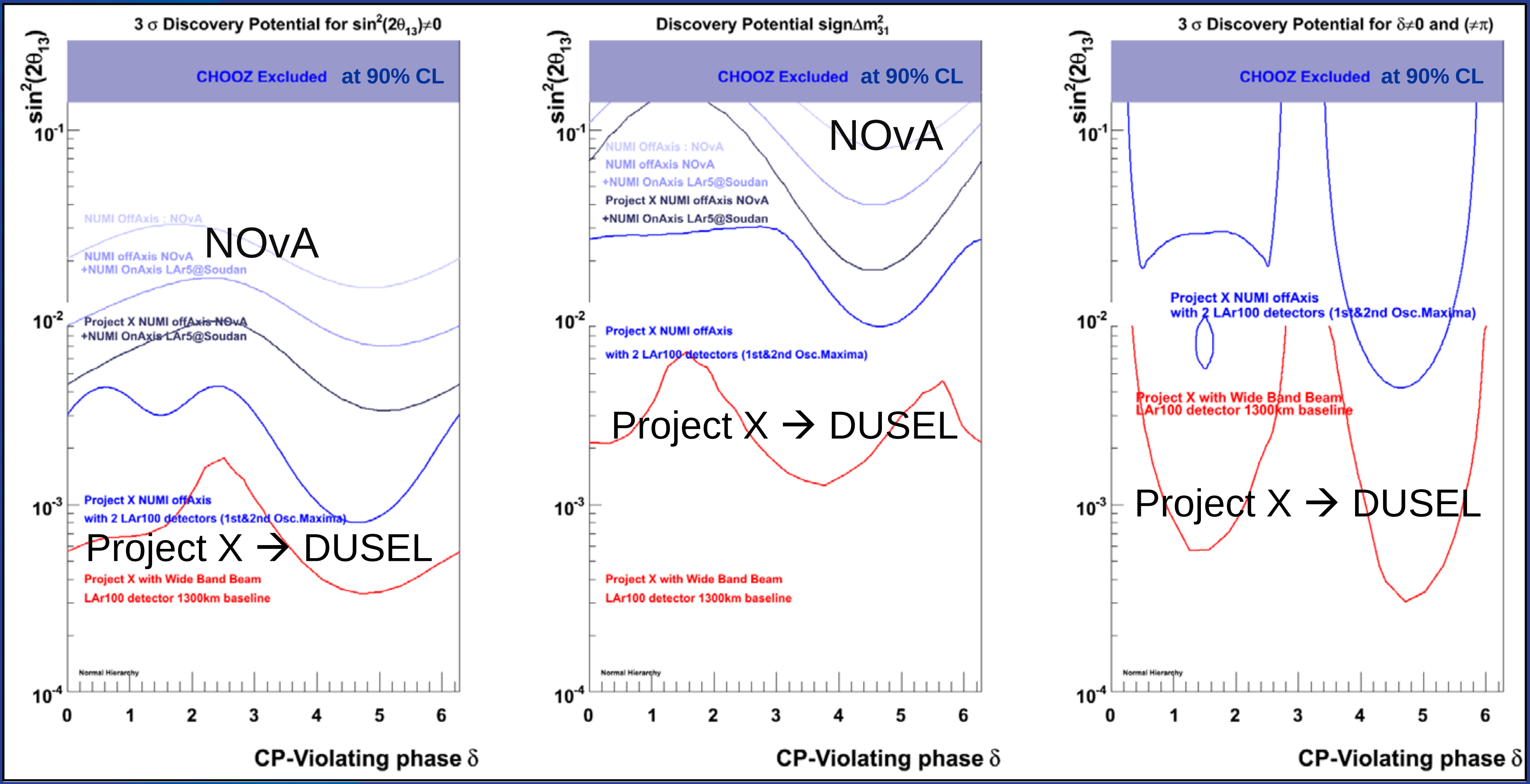
Fermilab

Multi-TeV Lepton Colliders

- Muon Collider Approach: Fermilab's Focus
  - Based on a secondary beam: we have experience basing colliders on antiprotons. For μ's we must do it in 20 msec.
  - Advantages: narrow energy spread (no beamstrahlung) and small physical footprint (no synchrotron radiation)
  - No new methods of acceleration, but new method of deceleration!: muon cooling
- CLIC Approach: CERN's Focus
  - Advantages: stable particles, polarization
  - Two-beam accelerator scheme
- Physics/detector
  - ILC-CLIC-Muon Collider Synergy

The 3σ reach (2 MW, 100 kton LAr TPC)

$\sin^2 2\theta_{13}$ | Mass Hierarchy | CP Violation



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