The Intensity Frontier

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Undergraduate Lecture Series – Fermilab

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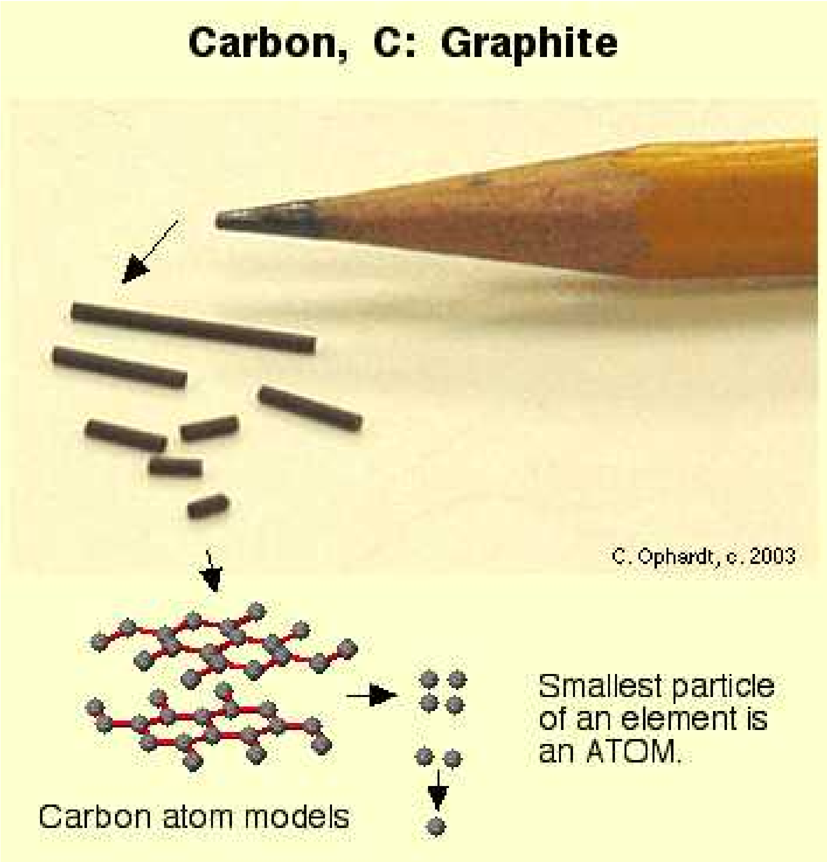
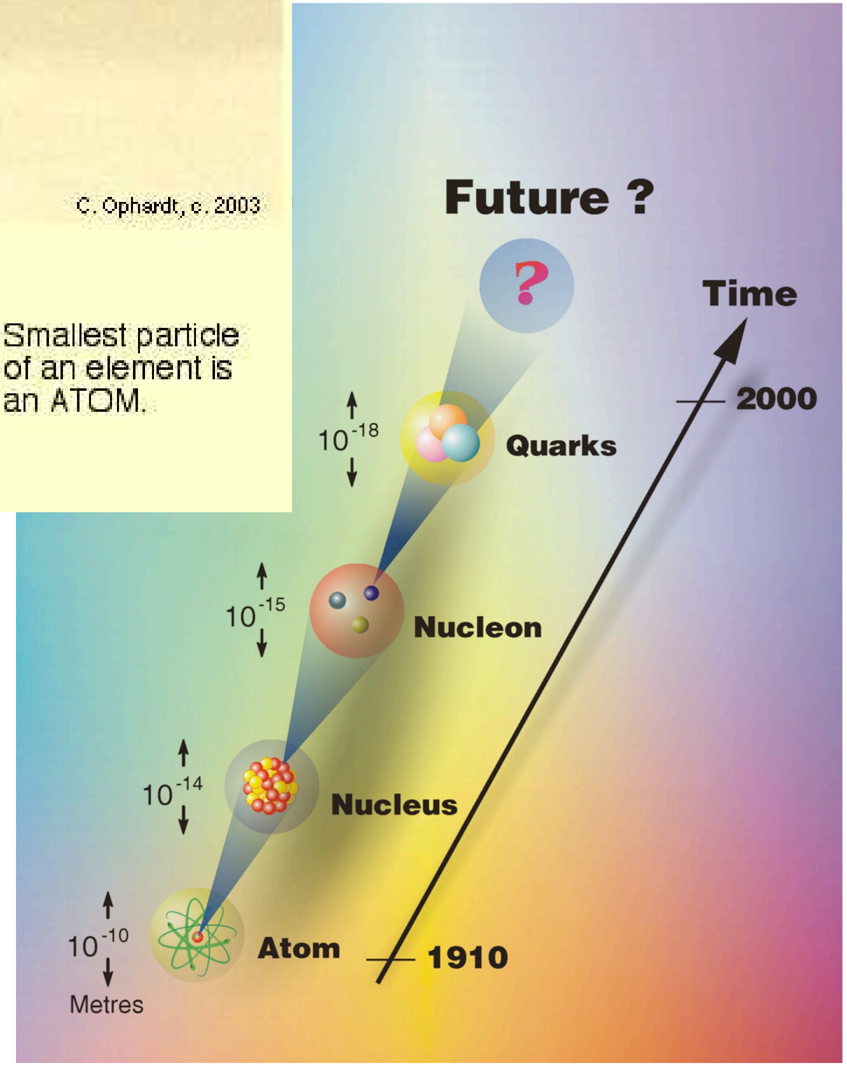
Outline

1. The Frontiers of Particle Physics
2. The Intensity Frontier
3. Neutrinos
4. Muons et al



- What are basic ingredients of matter?
- How do they interact with one another?

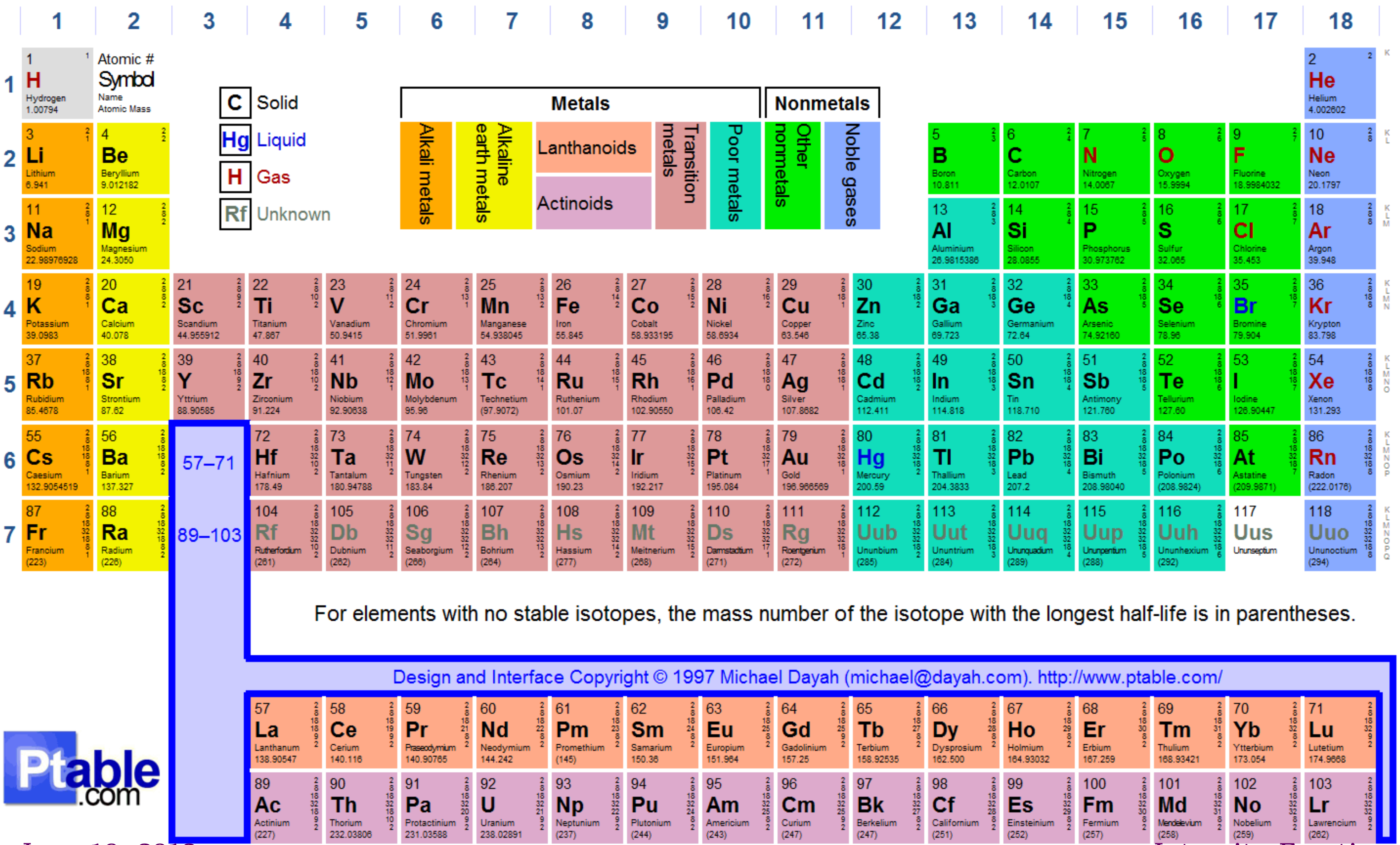


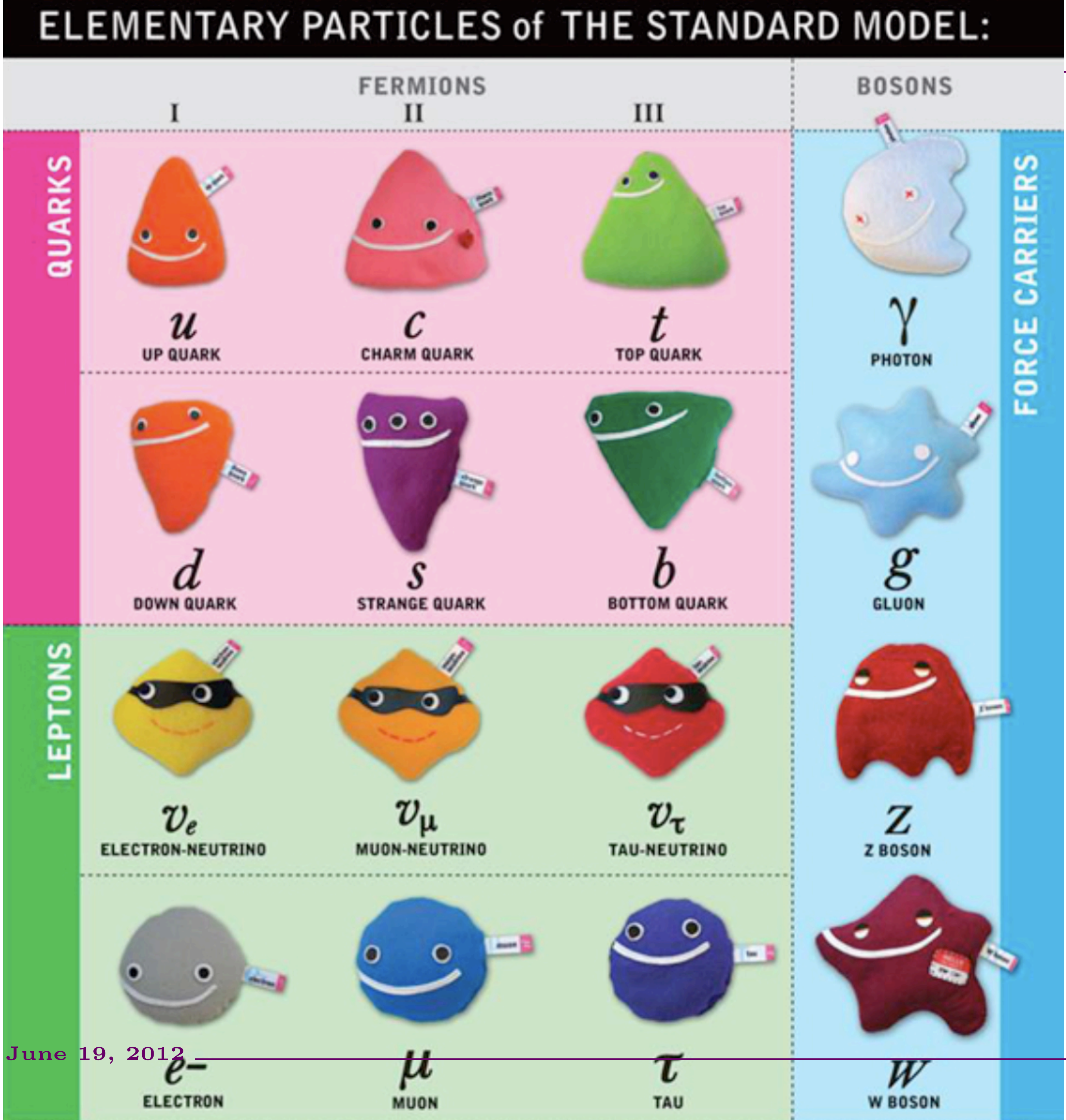
Particle Physics

Questions:

- What are the most fundamental laws that describe all natural phenomena (at least in principle)?
- And several more pragmatic question:
  - how do stars shine?
  - heavy elements?
  - ...

Periodic Table of Elements





Particle Zoo:

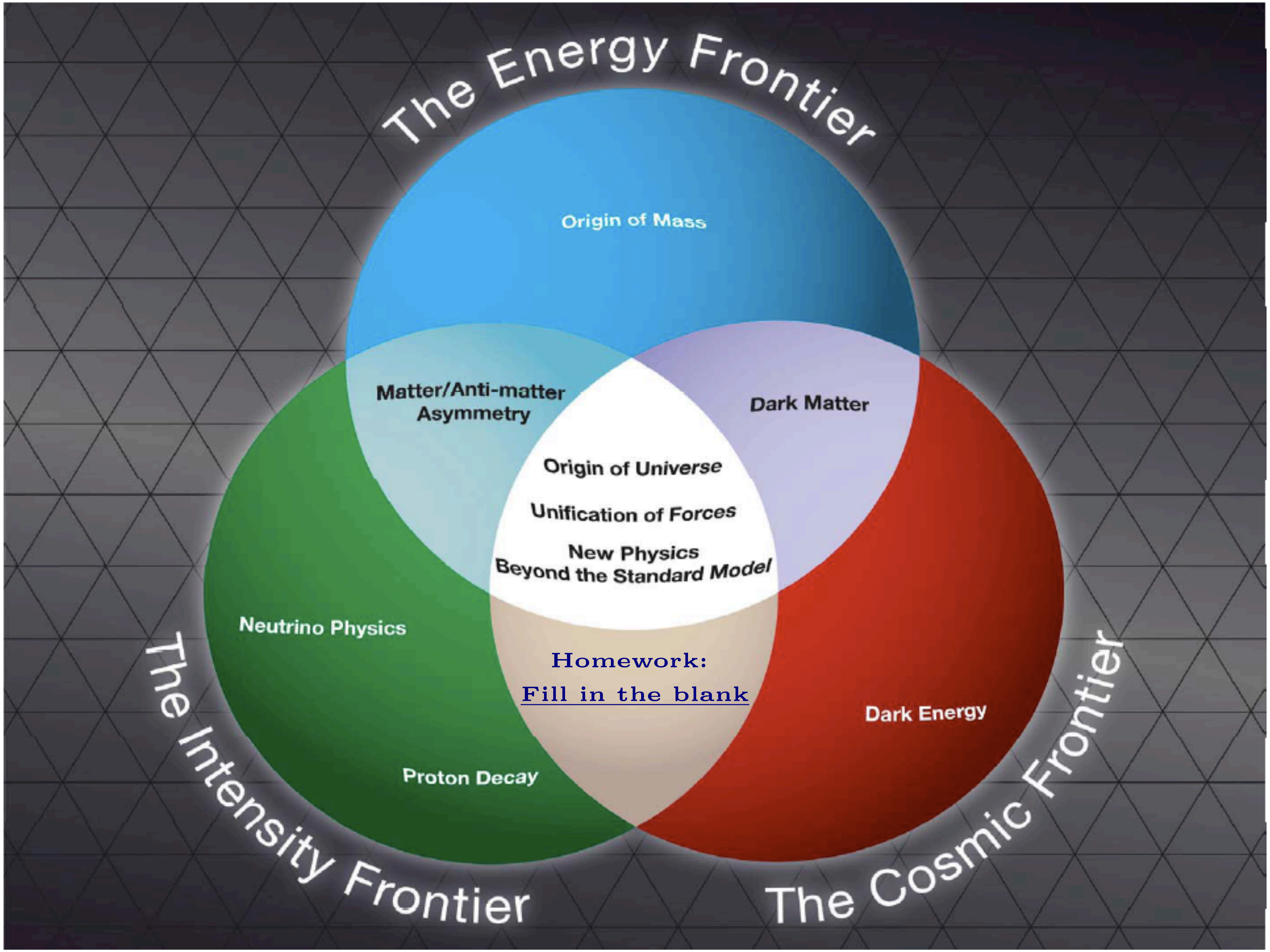
New periodic table

http://www.particlezoo.net

What We Know We Don't Know: A Few Solid Clues for What Lies Beyond

1. What is the physics responsible for electroweak symmetry breaking? → Higgs Boson (?)
2. What is most of the matter in the universe? → Dark Matter (?)
3. Where do *neutrino* masses come from?

The Research Frontiers of Particle Physics



There will be dedicated lectures on the Energy Frontier and the Cosmic Frontier I am going to concentrate on the Intensity Frontier.

Boundaries are very fuzzy. To me,

"The Intensity Frontier consists of research efforts where one aims at probing nature through precision studies of the properties and fundamental interactions of its basic constituents. While many of these efforts – especially the ones pertinent to Fermilab – revolve around particle accelerators, the energy of the accelerator is not 'as high as possible' but is rather dictated by the physics question one is interested in addressing. Instead, it is the intensity and "quality" (purity, time and space profile, etc) of the accelerated beam, that determine the reach of intensity frontier experiments. Past, current, and future Intensity Frontier experiments include studies of neutrino oscillations, searches for rare muon, pion, and kaon processes, precision measurements of muon properties, heavy flavor (charm and bottom) factories and the LEP1 experiments (the energy was fixed at a special value, the Z-pole mass)."

[AdG, N. Saoulidou, Ann. Rev. Nucl. Part. Sci. 60, 513-538 (2010).]

Cosmic Frontier

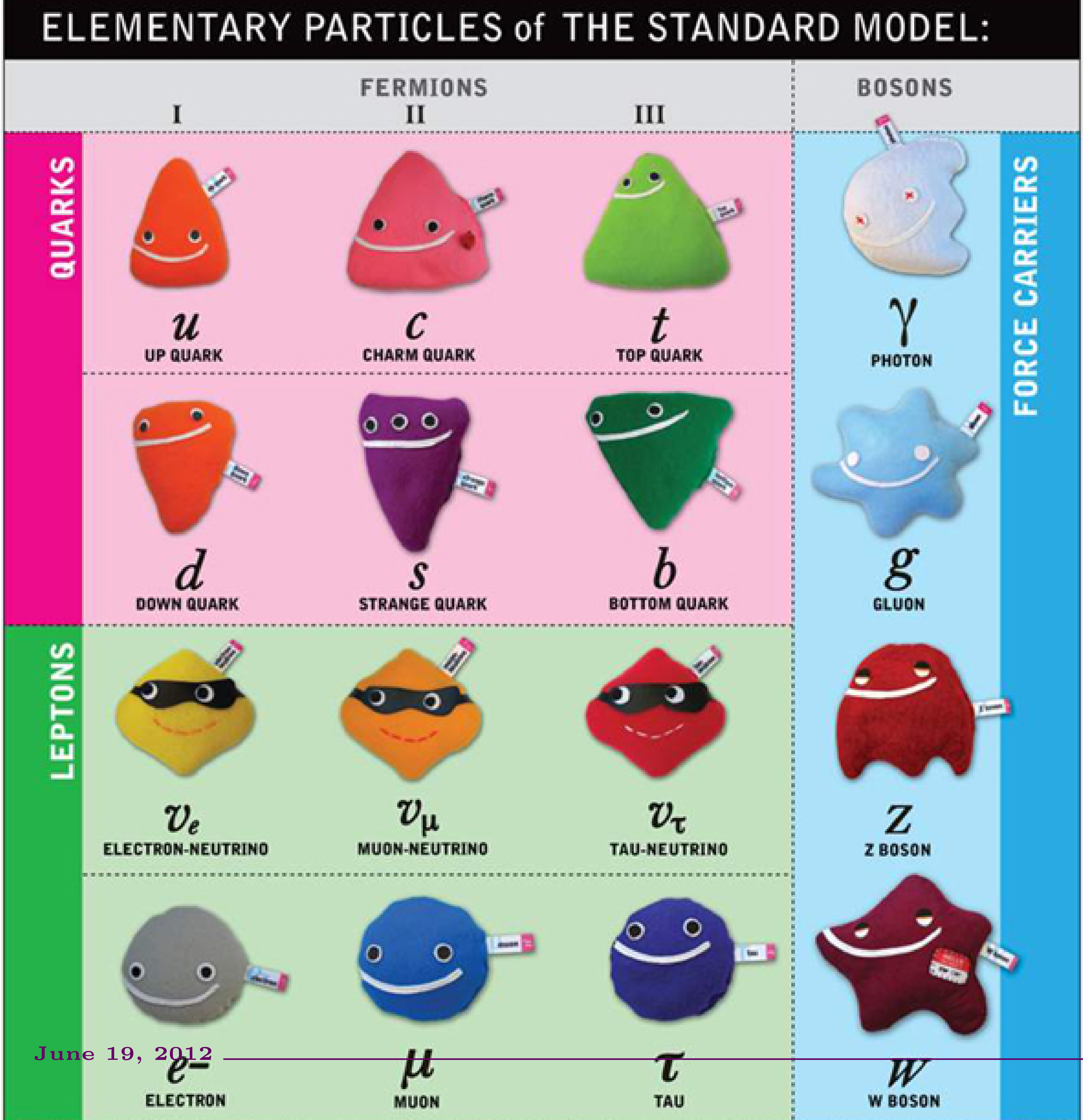
(What is most of the matter in the universe?)

Intensity Frontier

(Where do neutrino masses come from?)

Energy Frontier

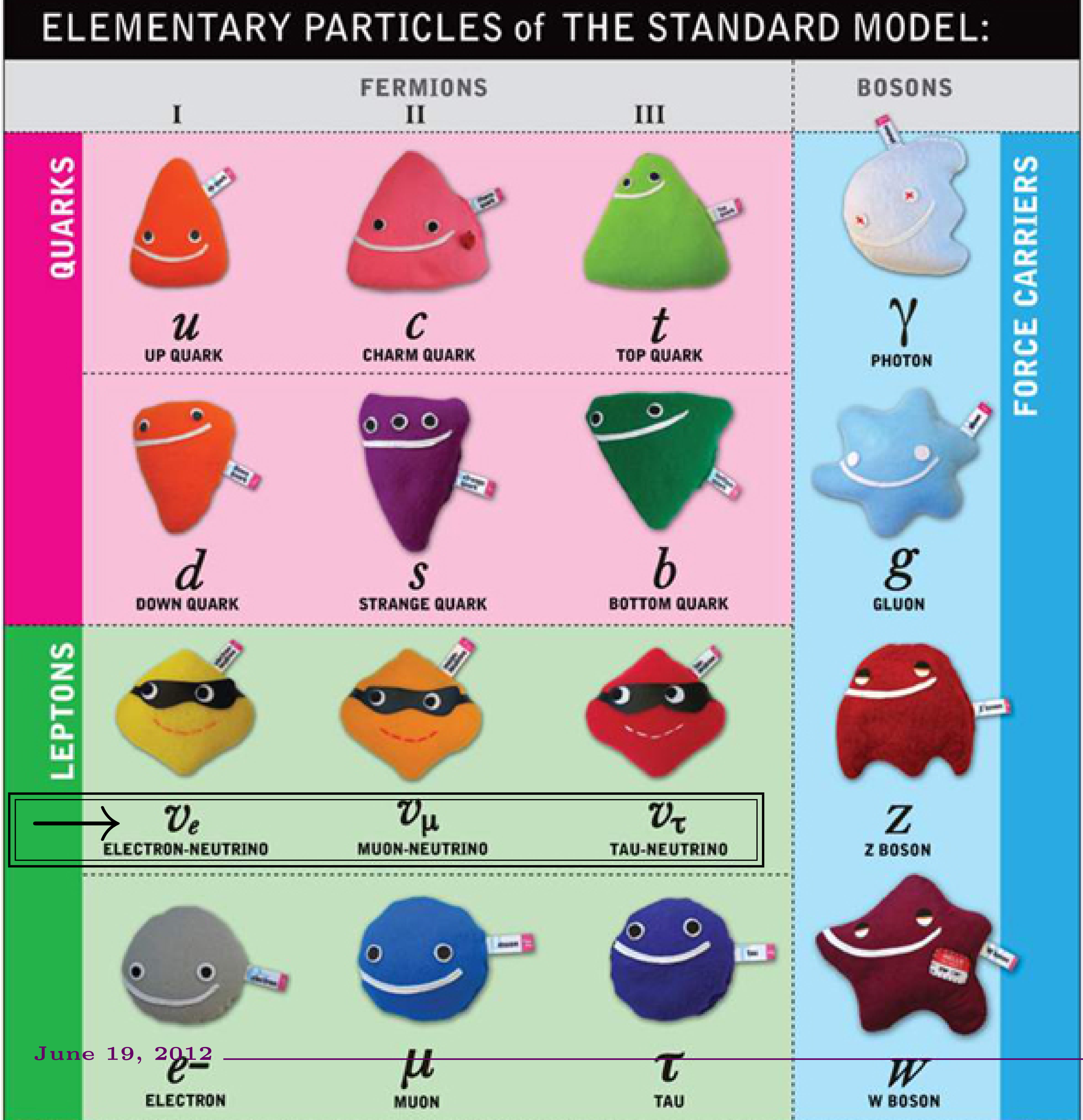
(What is the Physics of Electroweak Symmetry Breaking?)



Intensity Frontier

Study the properties of the basic ingredients in as much detail as possible.

http://www.particlezoo.net

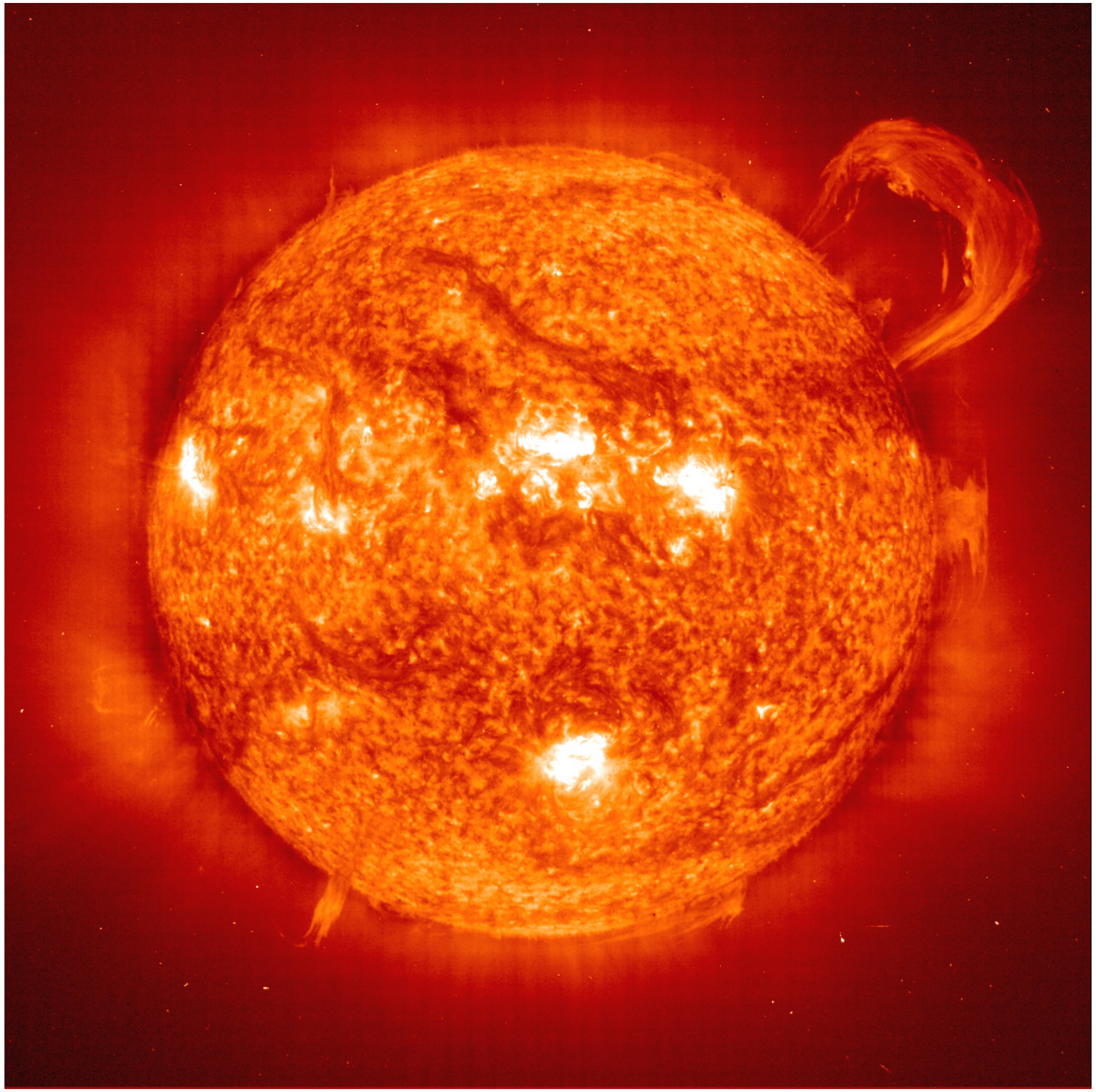


Neutrinos are Among a Handful of Known Fundamental, Point-Like Particles.

neutrino = ν ('nu')

http://www.particlezoo.net

Neutrinos are Very, Very Abundant.

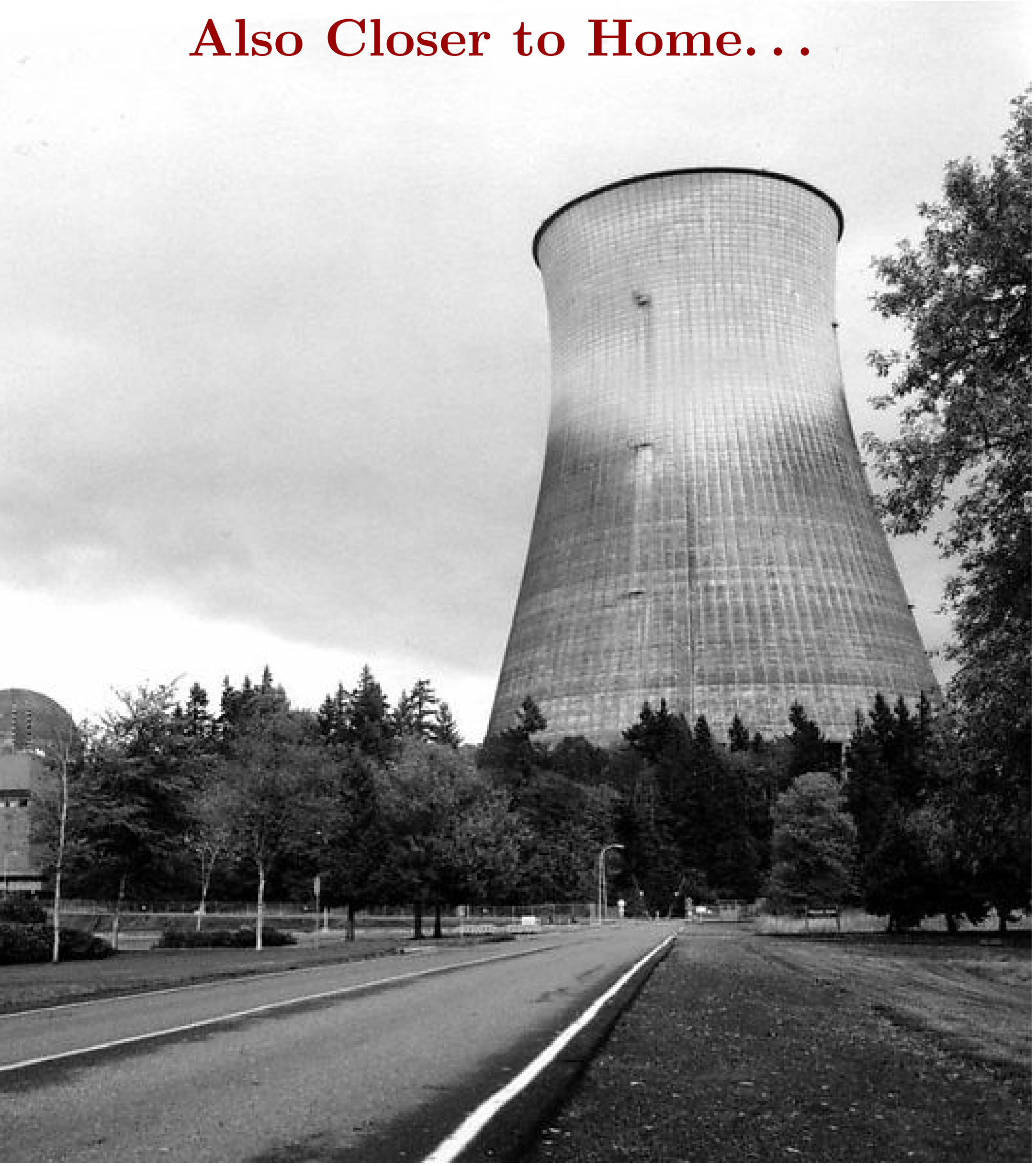


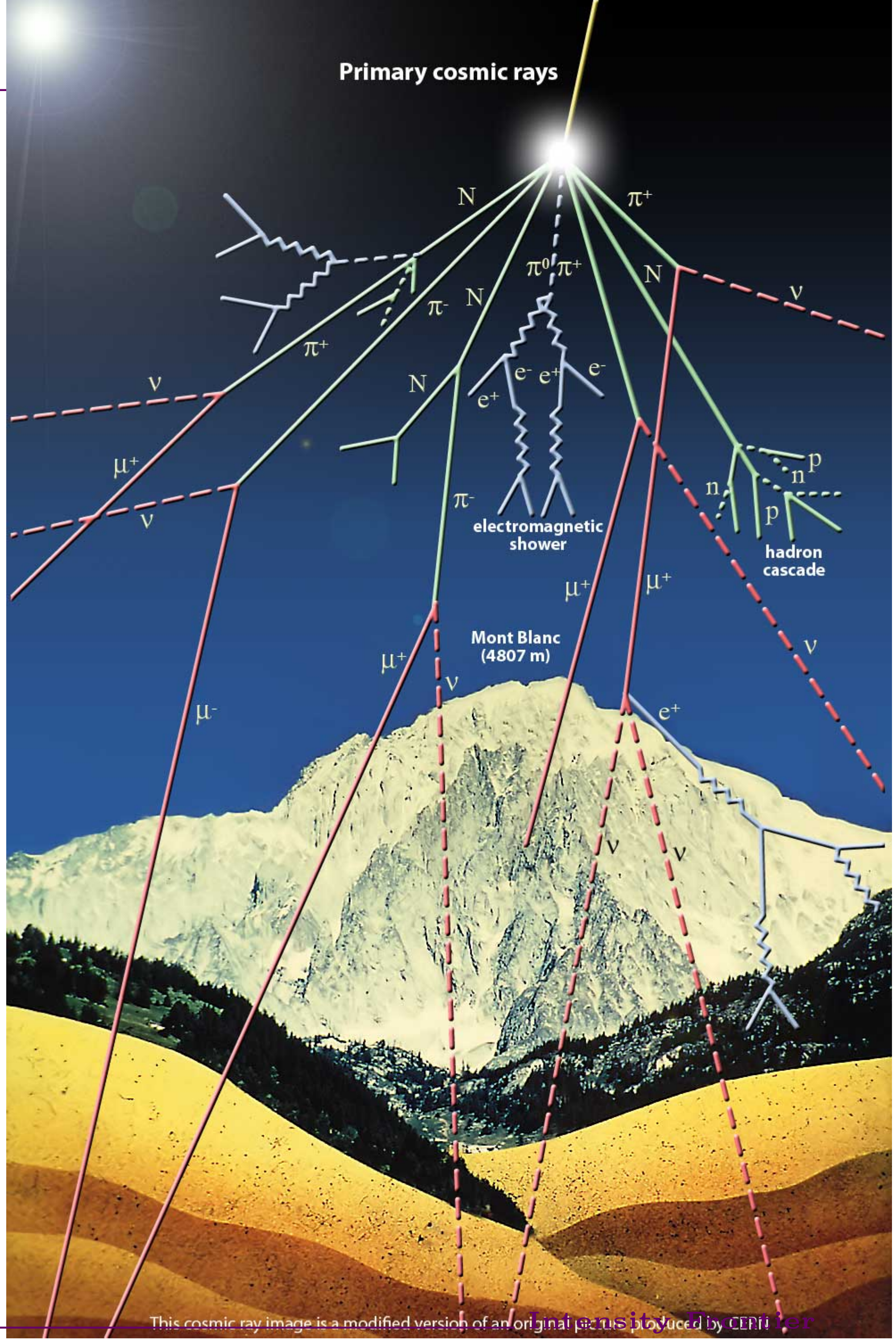
Reaction	Termination (%)	Neutrino Energy (MeV)
$p+p \to {}^2\text{H}+e^+ + \nu_e$	99.96	< 0.423
$p+e^- + p \to {}^2\text{H}+\nu_e$	0.044	1.445
${}^2\text{H}+p \to {}^3\text{He}+\gamma$	100	–
${}^3\text{He}+{}^3\text{He} \to {}^4\text{He}+p+p$	85	–
${}^3\text{He}+{}^4\text{He} \to {}^7\text{Be}+\gamma$	15	–
${}^7\text{Be}+e^- \to {}^7\text{Li}+\nu_e$	15	0.863(90%) 0.386(10%)
${}^7\text{Li}+p \to {}^4\text{He}+{}^4\text{He}$		–
${}^7\text{Be}+p \to {}^8\text{B}+\gamma$	0.02	–
${}^8\text{B} \to {}^8\text{Be}^* + e^+ + \nu_e$		< 15
${}^8\text{Be} \to {}^4\text{He}+{}^4\text{He}$		–
${}^3\text{He}+p \to {}^4\text{He}+e^+ + \nu_e$	0.00003	< 18.8

Note: Adapted from Ref. 12. Please refer to Ref. 12 for a mor
nation.

around 100 billion go through
your thumb every second!

Also Closer to Home. . .

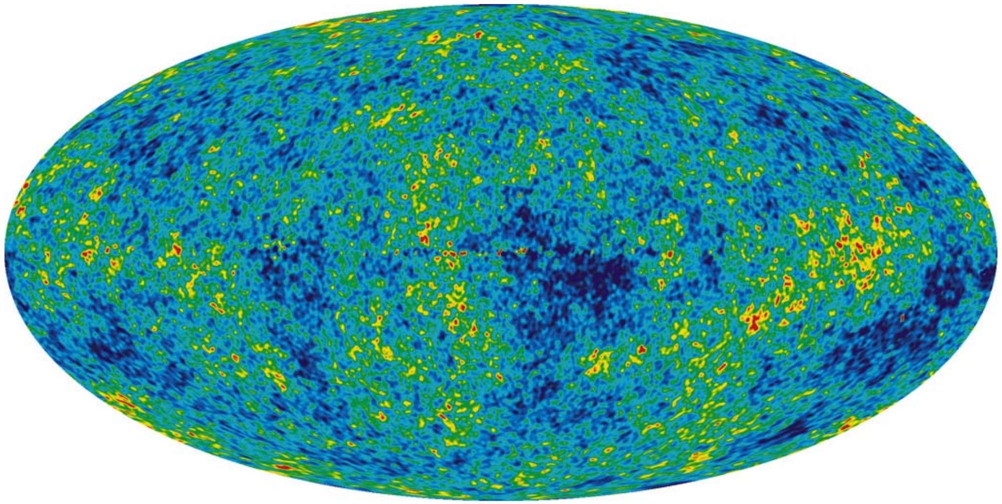


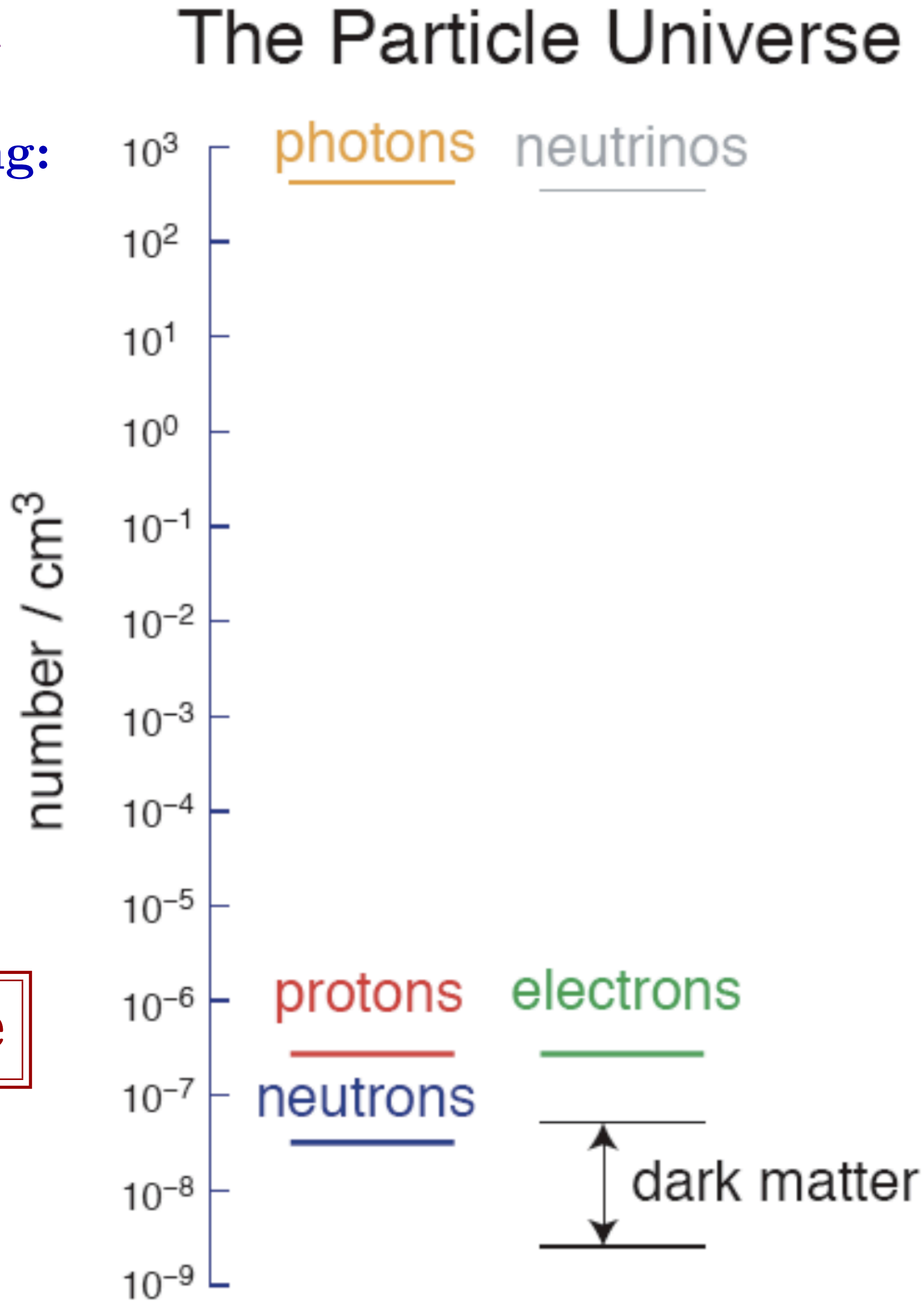


. . . And Much Further Away.

Supernova: 100 times more energy released in the form of neutrinos!

Neutrinos are Relics of the Big Bang:





Neutrinos are Everywhere

However, Neutrinos Are Really Hard To Detect:

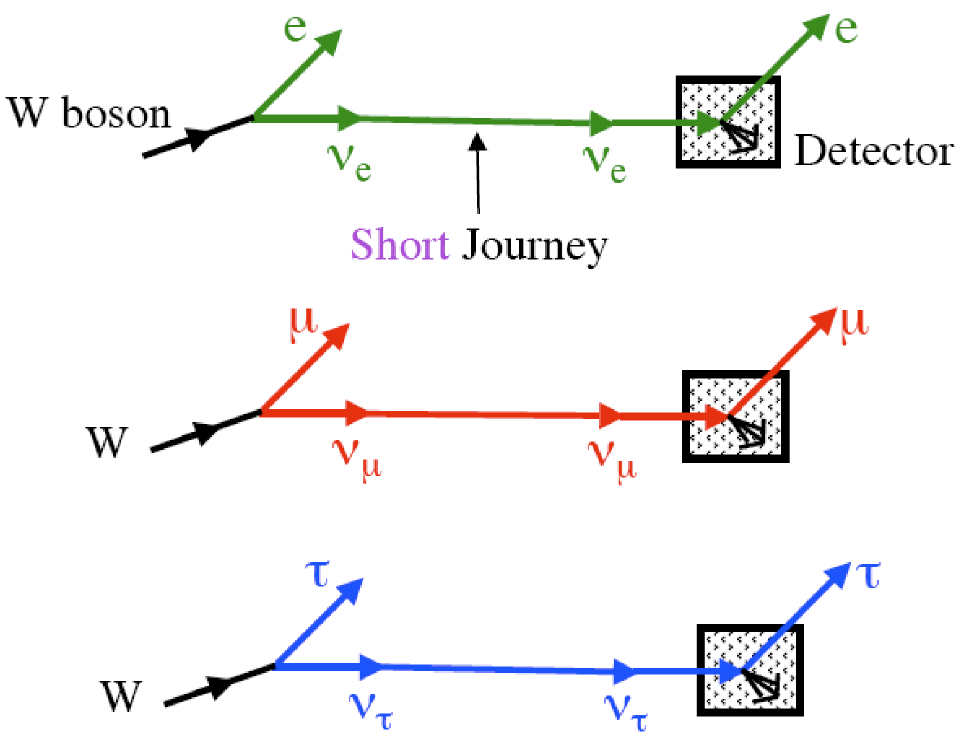
Neutrinos have no charge (unlike, say, the electrons) and don't interact via the strong nuclear forces (unlike, say, a neutron).

They interact only via the WEAK force – which, as it turns out, is really weak.

You need a wall of lead as thick as the solar system in order to stop a neutrino produced in the Sun!

How did we get around this? With lots and lots of neutrinos, and really big detectors!

Until recently ($\sim$ 1998), this is how we pictured neutrinos:



- come in three flavors (see figure);
- interact only via weak interactions;
- have ZERO mass;
- 2 degrees of freedom:
  - left-handed state ν,
  - right-handed state $\bar{\nu}$;
- neutrinos carry lepton number:
  - $L(\nu) = +1$,
  - $L(\bar{\nu}) = -1$.

Over the past decade, the picture changed dramatically. We have discovered that neutrino masses are not zero. In more detail, this is what we discovered:

- Neutrinos Mix.
- Neutrinos Oscillate. This means they can change their flavor after propagating a long distance (depends on the neutrino energy. Oftentimes, it is hundreds of miles).

Both of these phenomena occur only if the neutrino masses are not zero, and different from one another.

Mass-Induced Neutrino Flavor Oscillations

Neutrino Flavor change can arise out of several different mechanisms. The simplest one is to appreciate that, once **neutrinos have mass**, **leptons can mix**. If neutrinos have mass, there are two different ways to define the different neutrino states.

(1) Neutrinos with a well defined mass:

$$\nu_1, \nu_2, \nu_3, \ldots \qquad \text{with masses} \quad m_1, m_2, m_3, \ldots$$

(2) Neutrinos with a well defined flavor:

$$\nu_e, \nu_\mu, \nu_\tau$$

These are related by a unitary transformation:

$$\nu_\alpha = U_{\alpha i}\nu_i \qquad \alpha = e, \mu, \tau, \quad i = 1, 2, 3$$

U is a unitary mixing matrix.

Massive Neutrinos Are Mixtures of Flavor Neutrinos

ν_1

ν_2

ν_3

ν_1	ν_2	ν_3
20% orange (ν_μ)	32% orange (ν_μ)	48% orange (ν_μ)
60% yellow (ν_e)	36% yellow (ν_e)	4% yellow (ν_e)
20% red (ν_τ)	32% red (ν_τ)	48% red (ν_τ)

electron-neutrino

muon-neutrino

tau-neutrino

electron-antineutrino

The Propagation of Massive Neutrinos

Neutrino mass eigenstates are eigenstates of the free-particle Hamiltonian:

$$|\nu_i\rangle = e^{-i(E_i t - \vec{p_i}\cdot\vec{x})}|\nu_i\rangle, \qquad E_i^2 - |\vec{p}_i|^2 = m_i^2$$

The neutrino flavor eigenstates are linear combinations of ν_i's, say:

$$\begin{aligned} |\nu_e\rangle &= \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle. \\ |\nu_\mu\rangle &= -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle. \end{aligned}$$

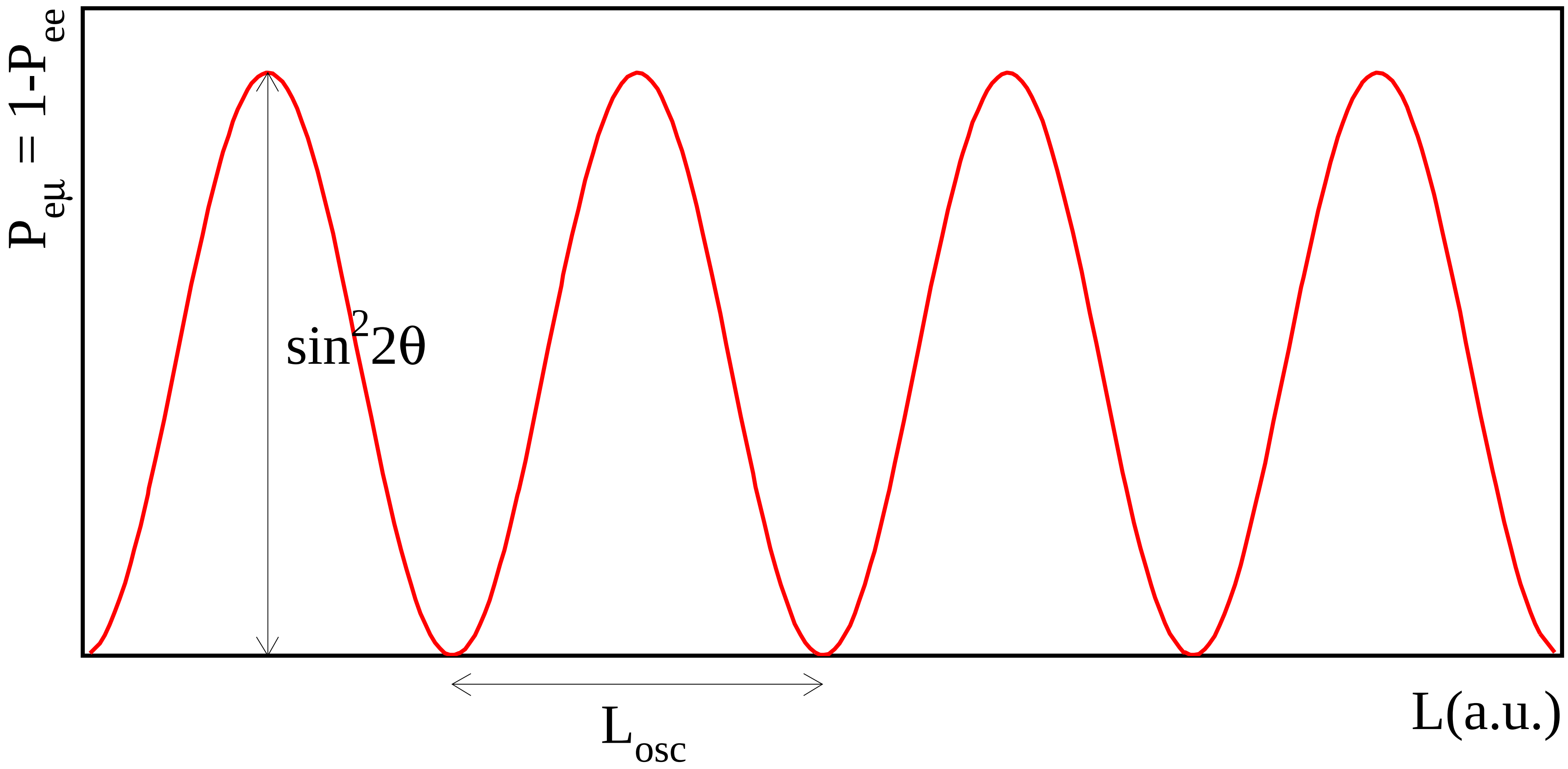
If this is the case, a state produced as a ν_e evolves in vacuum into

$$|\nu(t,\vec{x})\rangle = \cos\theta e^{-ip_1x}|\nu_1\rangle + \sin\theta e^{-ip_2x}|\nu_2\rangle.$$

It is trivial to compute $P_{e\mu}(L) \equiv |\langle\nu_\mu|\nu(t,z=L)\rangle|^2$. It is just like a two-level system from basic undergraduate quantum mechanics! In the ultrarelativistic limit (always a good bet), $t \simeq L$, $E_i - p_{z,i} \simeq (m_i^2)/2E_i$, and

$$\boxed{P_{e\mu}(L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}$$

oscillation parameters: $\begin{cases} \pi\frac{L}{L_{\rm osc}} \equiv \frac{\Delta m^2 L}{4E} = 1.267\left(\frac{L}{\rm km}\right)\left(\frac{\Delta m^2}{\rm eV^2}\right)\left(\frac{\rm GeV}{E}\right) \\ \text{amplitude } \sin^2 2\theta \end{cases}$



NuMI Beamline

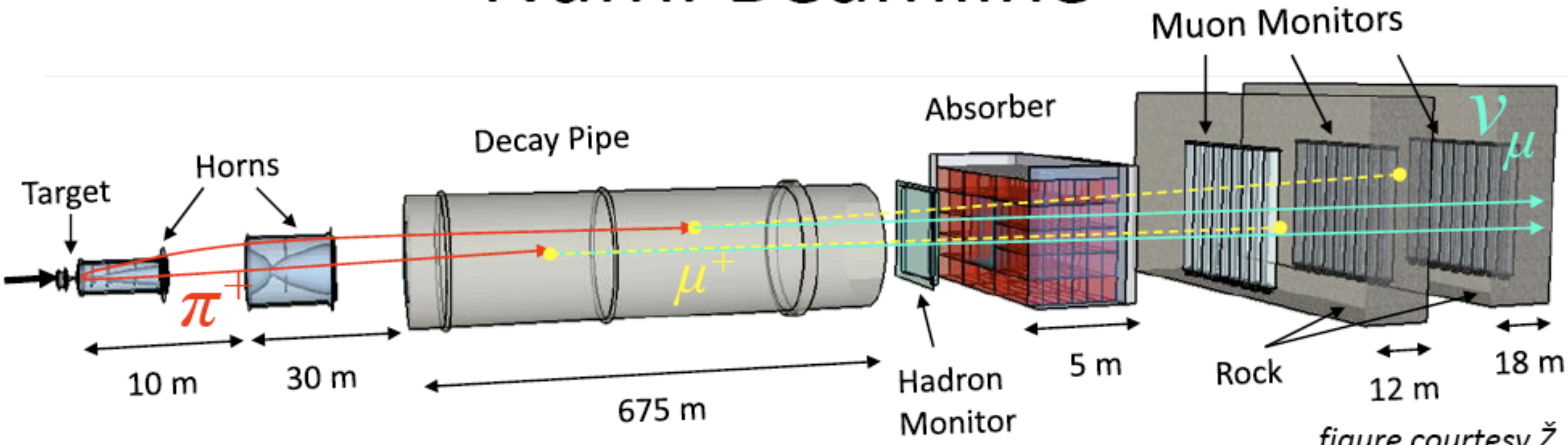
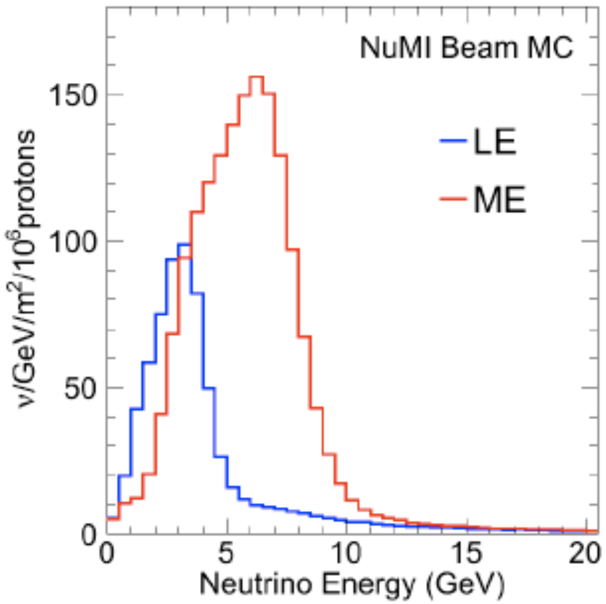
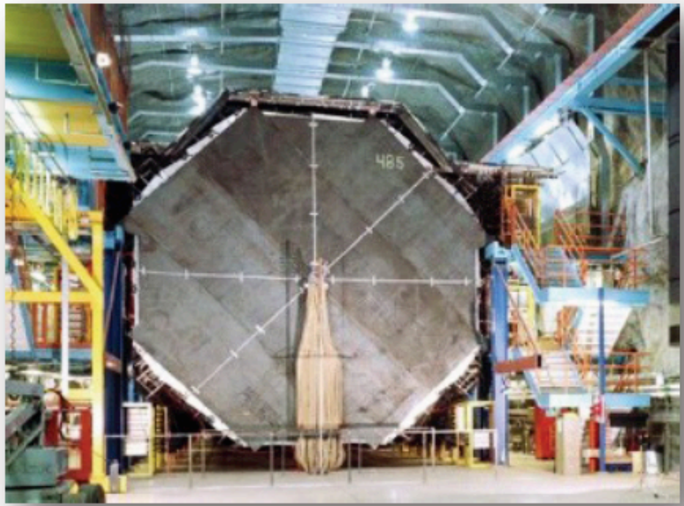


figure courtesy Ž. Pavlović

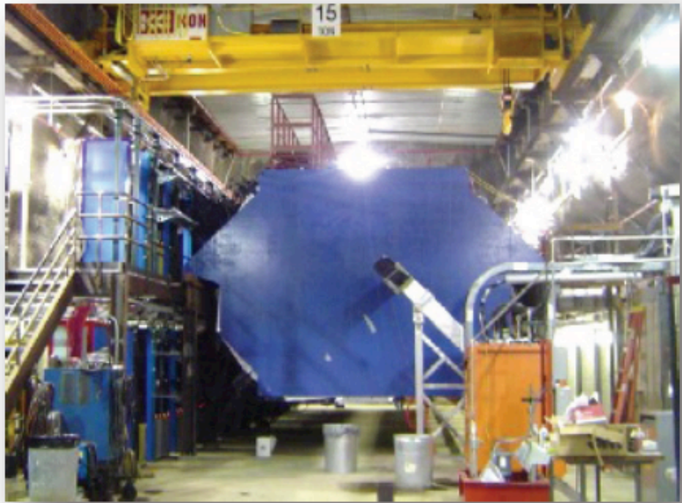


- 120 GeV P Beam → C target ⟶ π^{+-} & K^{+-}
- ~35x10^{12} protons on target (POT) per spill at 120 GeV with a beam power of 300-350 kW at ~0.5 Hz
- 2 horns focus π^+ and K^+ only (or π^- and K^-)
- Mean E_ν increased by moving target and one horn
- π^+ and K^+ → $\mu^+\nu_\mu$
- Absorber stops hadrons not μ
- μ absorbed by rock, ν ⟶ detector

MINOS: 2 magnetized iron-scintillator tracking calorimeters



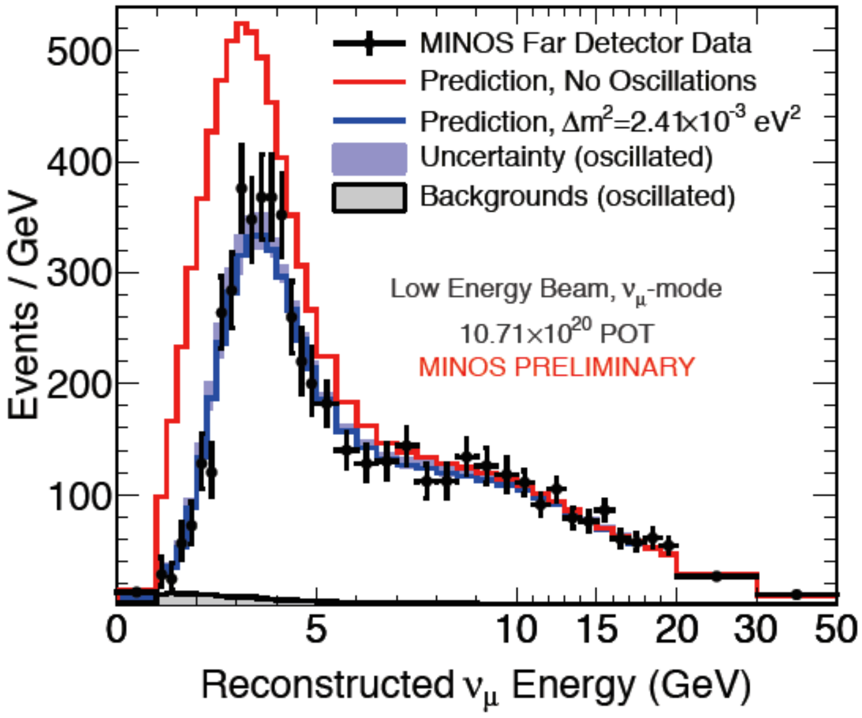
NIMA **596** 190 (2008)

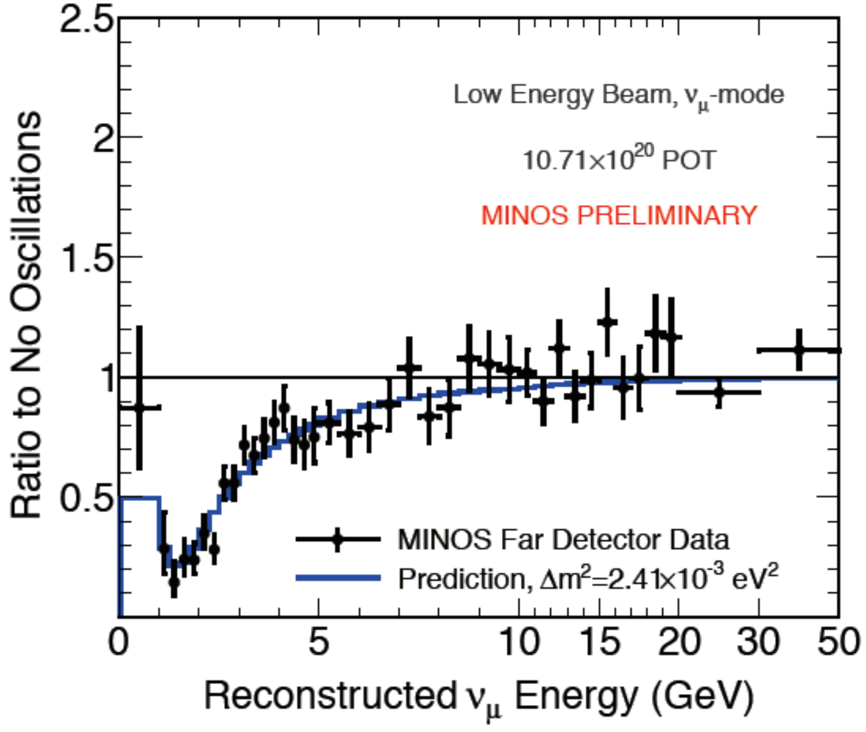


Functionally equivalent

- Magnetized steel planes $\langle B \rangle = 1.3$ T
- 1×4.1 cm^2 scintillator strips
- 2.54 cm steel sheets
- Moliere radius = 3.7 cm
- Sampling = 1.4 radiation lengths

Muon neutrino oscillation results



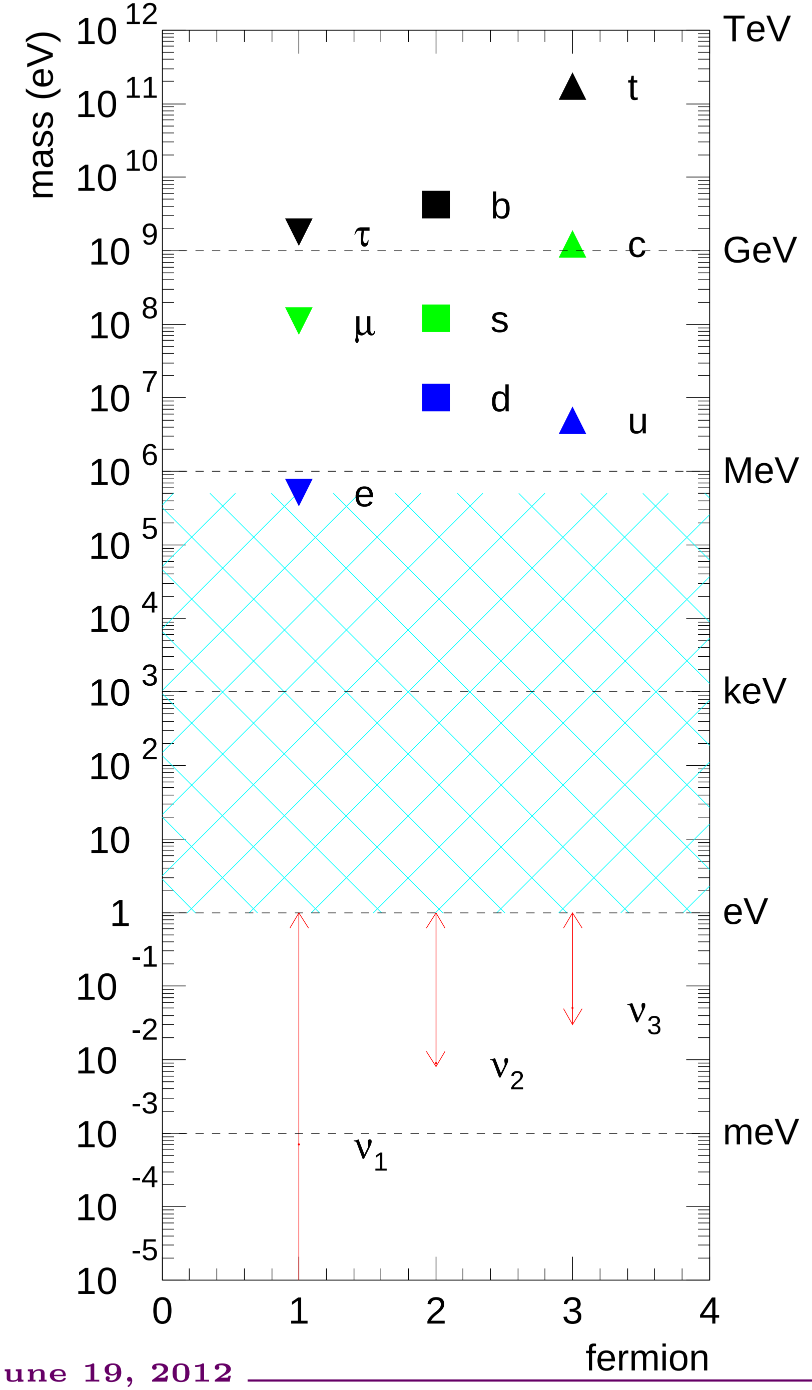


Observed: 2894

Predicted (no oscillations): 3564

$$\left|\Delta m^2\right| = 2.41^{+0.11}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

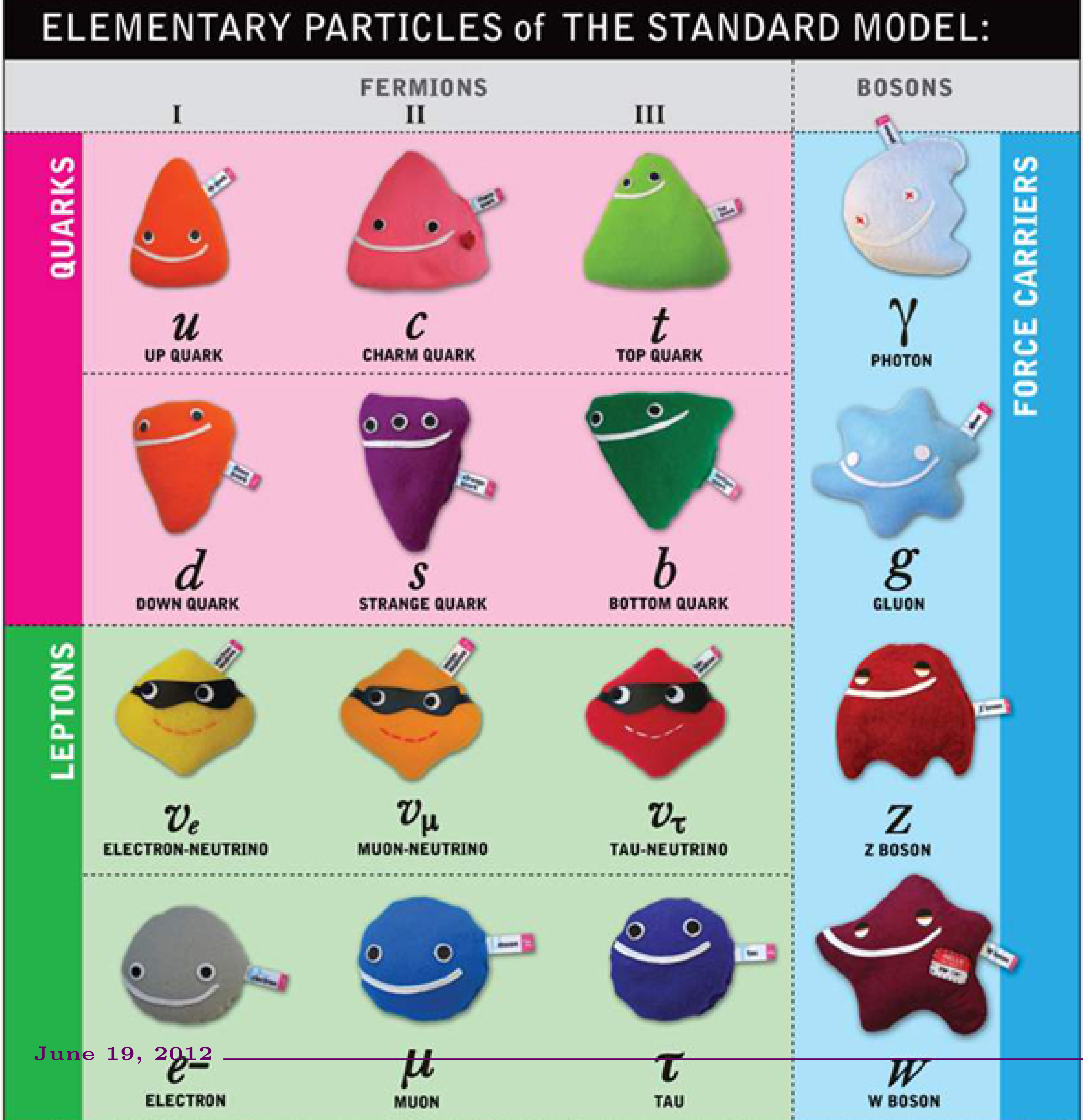
$$\sin^2(2\theta) = 0.937^{+0.044}_{-0.047}$$



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



This is much more than a pretty picture. It is a very powerful, predictive model.

http://www.particlezoo.net

- Result of over 50 years of particle physics theoretical and experimental research.
- Theoretical formalism based on the marriage of Quantum Mechanics and Special Relativity – Relativistic Quantum Field Theory.
- Very Powerful – once we specify the model ingredients: field content (matter particles) and the internal symmetries (interactions), the dynamics of the system is uniquely specified by a finite set of free parameters.

Given the known ingredients of the model and the known rules, we can predict that the neutrino masses are exactly zero.

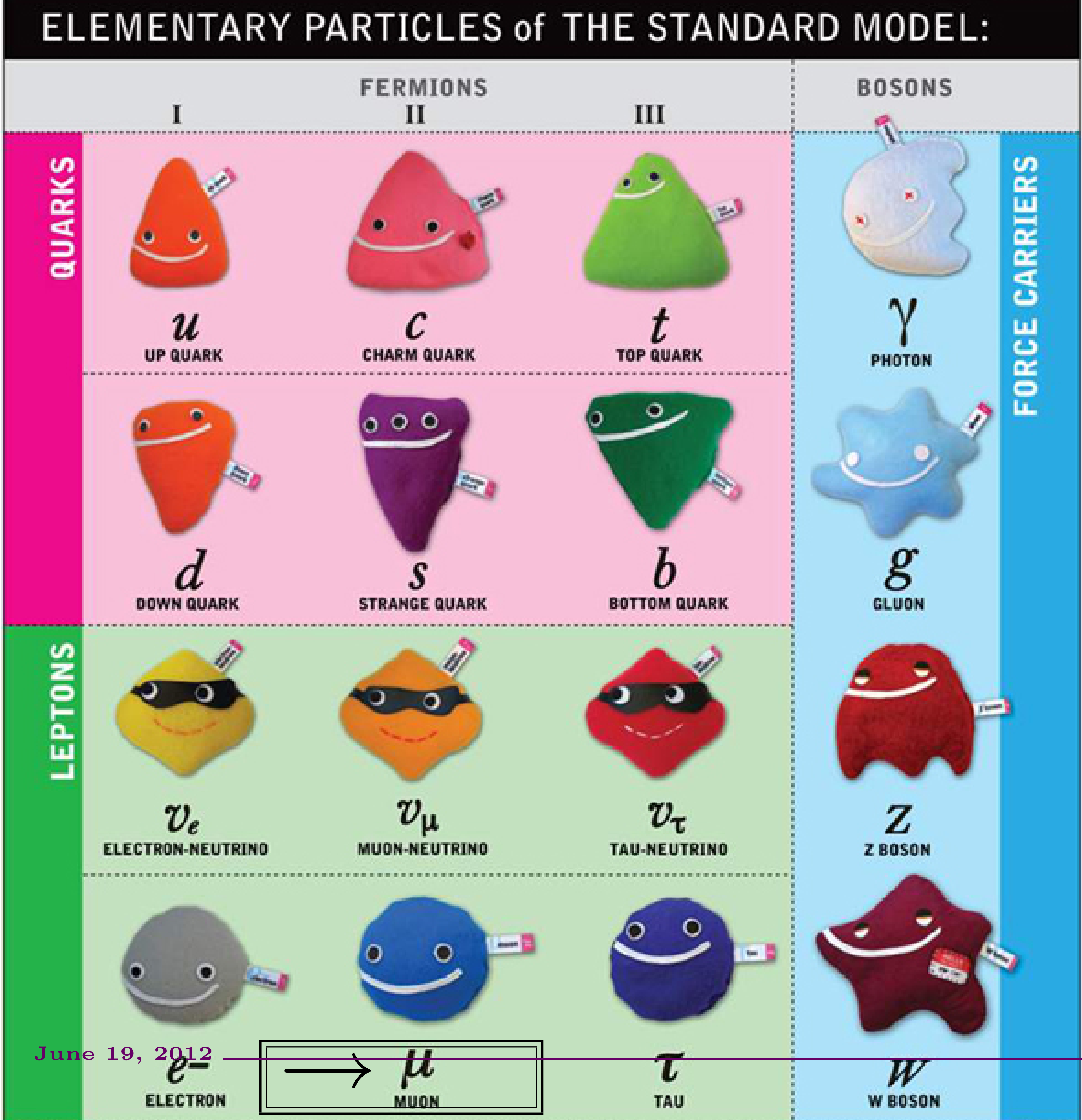
Neutrino masses require new ingredients or new rules. We are still try to figure out what these new ingredients are.

On the plus side, we probably know what they could be. . .

(Some of the) Ongoing Neutrino Physics Activity at FERMILAB

- MINOS;
- MiniBooNE;
- Minerνa;
- NOνA;
- MINOS+;
- MicroBooNE.

plus lots of plans for the future!



The Muon is Among a Handful of Known Fundamental, Point-Like Particles.

$$\text{muon} = \mu$$

('mu')

http://www.particlezoo.net

Citation: W.-M. Yao et al. (Particle Data Group), J. Phys. G 33, 1 (2006) (URL: http://pdg.lbl.gov)

μ $J = \frac{1}{2}$

μ MASS (atomic mass units u)

The primary determination of a muon's mass comes from measuring the ratio of the mass to that of a nucleus, so that the result is obtained in u (atomic mass units). The conversion factor to MeV is more uncertain than the mass of the muon in u. In this datablock we give the result in u, and in the following datablock in MeV.

VALUE (u)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.1134289264±0.0000000030	MOHR	05	RVUE	2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.1134289168±0.0000000034	[1] MOHR	99	RVUE	1998 CODATA value
0.113428913 ±0.000000017	[2] COHEN	87	RVUE	1986 CODATA value

[1] MOHR 99 make use of other 1998 CODATA entries below.
[2] COHEN 87 make use of other 1986 CODATA entries below.

μ MASS

2002 CODATA gives the conversion factor from u (atomic mass units, see the above datablock) as 931.494 043 (80). Earlier values use the then-current conversion factor. The conversion error dominates the masses given below.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
105.6583692±0.0000094	MOHR	05	RVUE		2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.6583568±0.0000052	MOHR	99	RVUE		1998 CODATA va
105.658353 ±0.000016	[3] COHEN	87	RVUE		1986 CODATA va
105.658386 ±0.000044	[4] MARIAM	82	CNTR	+	
105.65836 ±0.00026	[5] CROWE	72	CNTR		
105.65865 ±0.00044	[6] CRANE	71	CNTR		

[3] Converted to MeV using the 1998 CODATA value of the conversion const: 931.494013 ± 0.0000037 MeV/u.
[4] MARIAM 82 give m_μ/m_e = 206.768259(62).
[5] CROWE 72 give m_μ/m_e = 206.7682(5).
[6] CRANE 71 give m_μ/m_e = 206.76878(85).

"Who Ordered That?"

The muon is the best known unstable fundamental particle.

The muon is also the heaviest fundamental particle we can directly work with. It is a unique, priceless resource for physicists.

μ MEAN LIFE τ

Measurements with an error > 0.001×10^{-6} s have been omitted.

VALUE (10^{-6} s)	*DOCUMENT ID*		*TECN*	*CHG*
2.19703 ±0.00004 OUR AVERAGE				
2.197078±0.000073	BARDIN	84	CNTR	+
2.197025±0.000155	BARDIN	84	CNTR	−
2.19695 ±0.00006	GIOVANETTI	84	CNTR	+
2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

Citation: W.-M. Yao et al. (Particle Data Group), J. Phys. G 33, 1 (2006) (URL: http://pdg.lbl.gov)

μ $\qquad J = \frac{1}{2}$

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ANS: "We did!"

μ MEAN LIFE τ

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2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

The Muon Magnetic Dipole Moment

The magnetic moment of the muon is defined by $\vec{M} = g_\mu \frac{e}{2m_\mu}\vec{S}$.

The Dirac equation predicts $g_\mu = 2$, so that the anomalous magnetic moment is defined as (note: dimensionless)

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

In the standard model, the (by far) largest contribution to a_μ comes from the one-loop QED vertex diagram, first computed by Schwinger:

$$a_\mu^{QED}(1-\text{loop}) = \frac{\alpha}{2\pi} = 116,140,973.5 \times 10^{-11}$$

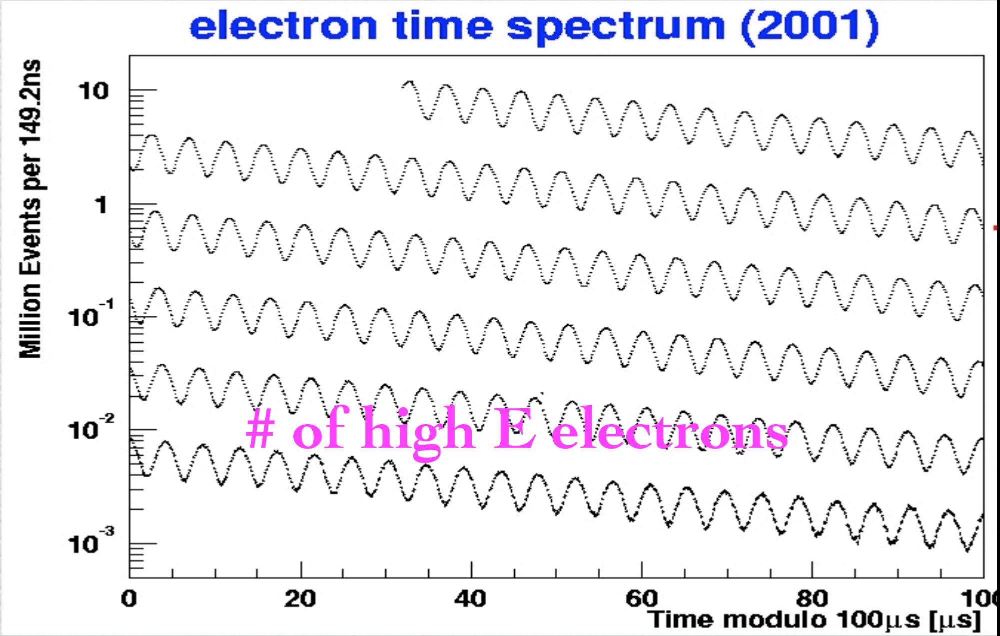
The theoretical estimate has been improved significantly since then, mostly to keep up with the impressive experimental reach of measurements of the $g-2$ of the muon.

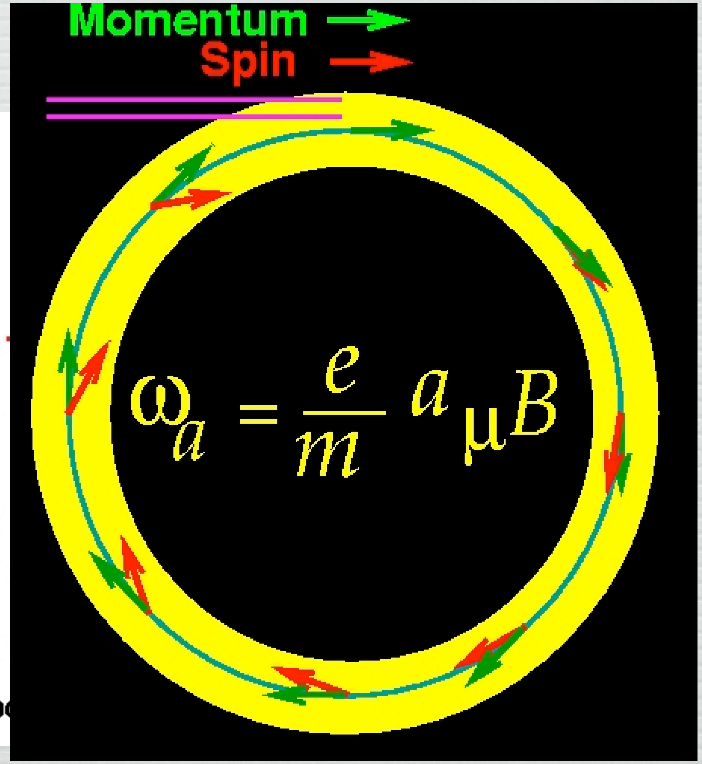
Spin Precession w.r.t. Momentum Vector

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

(g-2)/2

$$\gamma_{\text{magic}} = 29.3$$
$$p_{\text{magic}} = 3.09\ \text{GeV/c}$$





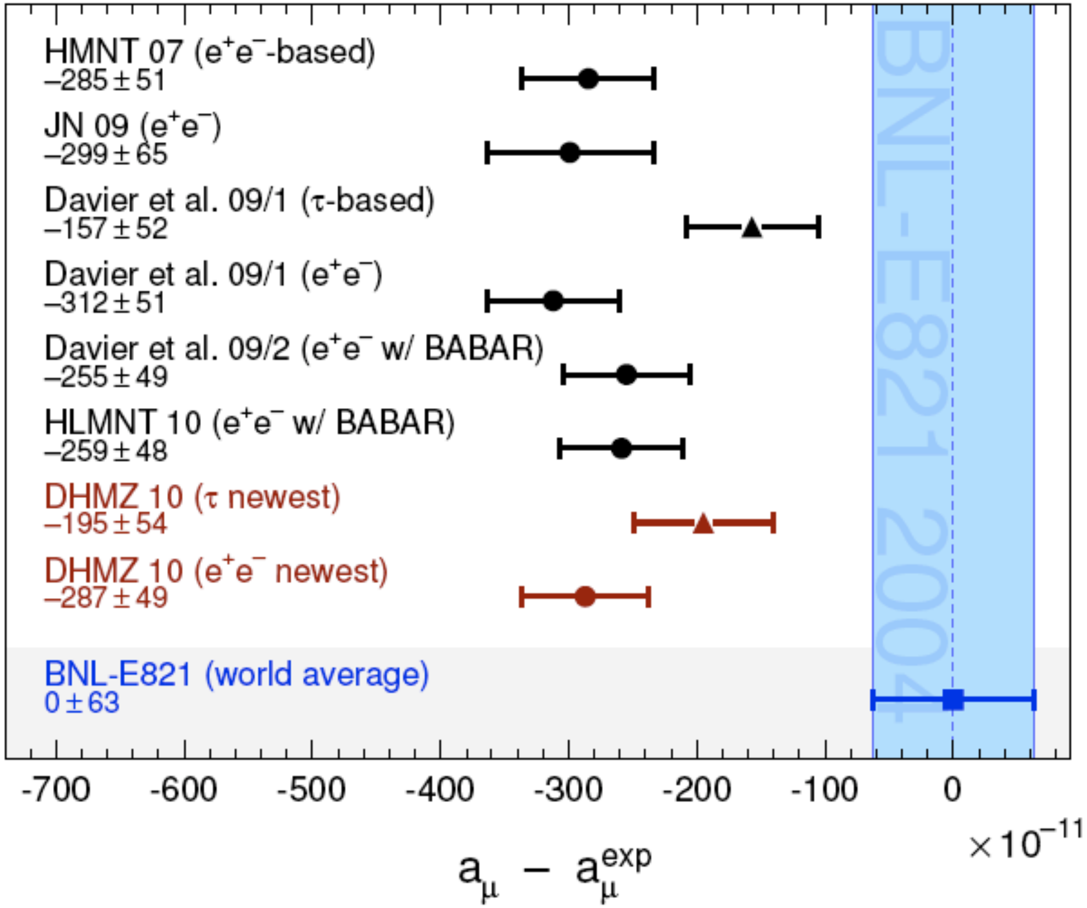


FIG. 9: Compilation of recent results for $a_\mu^{\rm SM}$ (in units of 10^{-11}), subtracted by the central value of the experimental average [12, 57]. The shaded vertical band indicates the experimental error. The SM predictions are taken from: this work (DHMZ 10), HLMNT (unpublished) [58] (e^+e^- based, including BABAR and KLOE 2010 $\pi^+\pi^-$ data), Davier *et al.* 09/1 [15] (τ-based), Davier *et al.* 09/1 [15] (e^+e^--based, not including BABAR $\pi^+\pi^-$ data), Davier *et al.* 09/2 [10] (e^+e^--based including BABAR $\pi^+\pi^-$ data), HMNT 07 [59] and JN 09 [60] (not including BABAR $\pi^+\pi^-$ data).

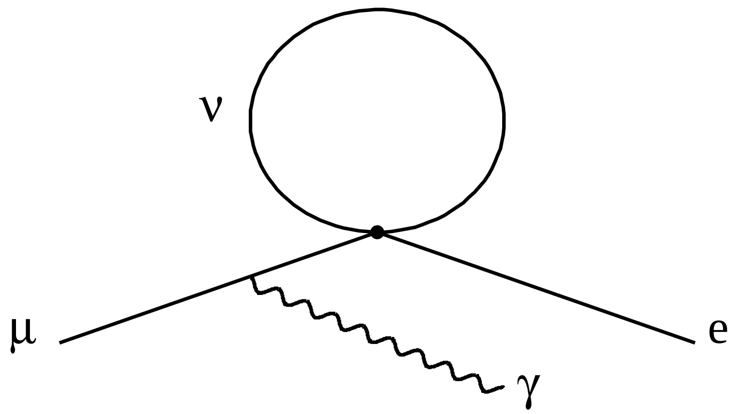
NOTE: $a_\mu^{LbL} = 105 \pm 26 \times 10^{-11}$

[Davier *et al*, 1010.4180]

Δa_μ: we need to dig a little more!

This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

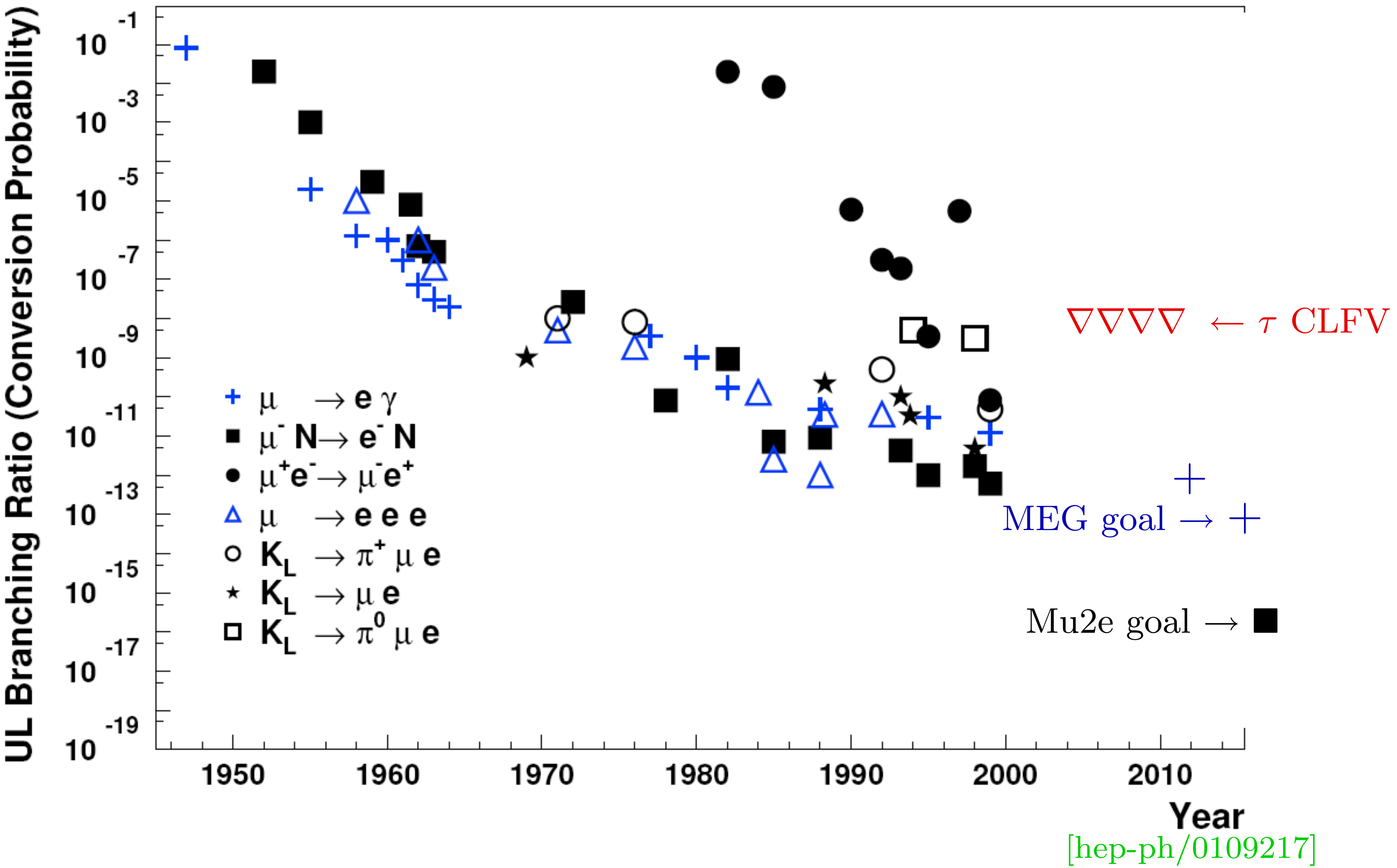
Ever since it was established that $\mu \to e\nu\bar{\nu}$, people have searched for $\mu \to e\gamma$, which was thought to arise at one-loop, like this:



The fact that $\mu \to e\gamma$ did not happen, led one to postulate that the two neutrino states produced in muon decay were distinct, and that $\mu \to e\gamma$, and other similar processes, were forbidden due to symmetries.

To this date, these so-called individual lepton-flavor numbers seem to be conserved in the case of charged lepton processes, in spite of many decades of (so far) fruitless searching…

60+ Years of Searches for Charged-Lepton Flavor violation (μ and e)



SM Expectations?

In the old SM, the rate for charged lepton flavor violating processes is trivial to predict. It vanishes because individual lepton-flavor number is conserved:

- $N_\alpha(\text{in}) = N_\alpha(\text{out})$, for $\alpha = e, \mu, \tau$.

But individual lepton-flavor number are NOT conserved– ν oscillations!

Hence, in the νSM (the old Standard Model plus operators that lead to neutrino masses) $\mu \to e\gamma$ is allowed (along with all other charged lepton flavor violating processes).

These are Flavor Changing Neutral Current processes, observed in the quark sector ($b \to s\gamma$, $K^0 \leftrightarrow \bar{K}^0$, etc).

Unfortunately, we do not know the νSM expectation for charged lepton flavor violating processes $\to$ **we don't know the νSM Lagrangian !**

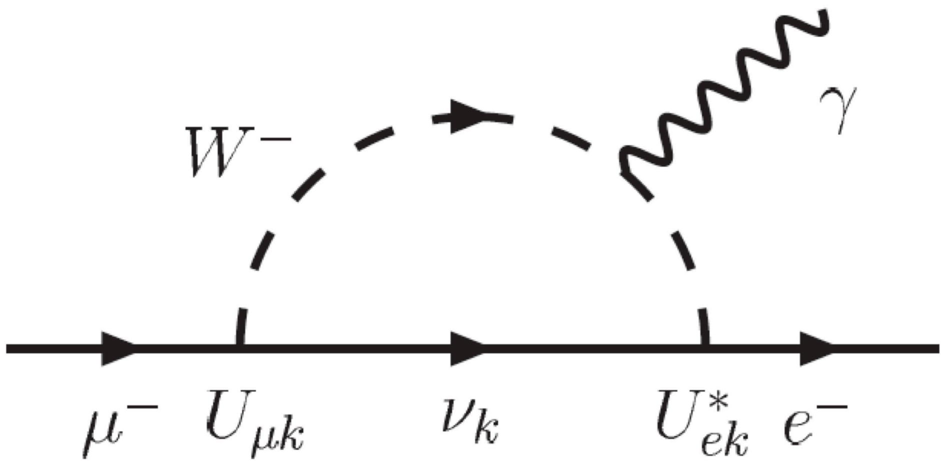
One contribution known to be there: active neutrino loops (same as quark sector).

In the case of charged leptons, the **GIM suppression is very efficient**…

$$\text{e.g.: } Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

[$U_{\alpha i}$ are the elements of the leptonic mixing matrix,

$\Delta m^2_{1i} \equiv m^2_i - m^2_1$, $i = 2, 3$ are the neutrino mass-squared differences]

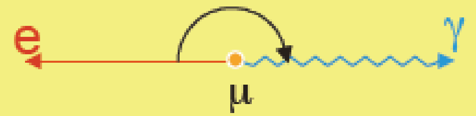


Principal Features of $\mu^+ \to e^+\gamma$ Experiment

- Stop μ^+ in thin target
  - Measure energies of e^+ (E_e) and γ (E_γ)
  - Measure angle between e^+ and γ ($\Delta\theta$)
  - Measure time between e^+ and γ (Δt)

Kinematics

$\theta_{e\gamma} = 180°$



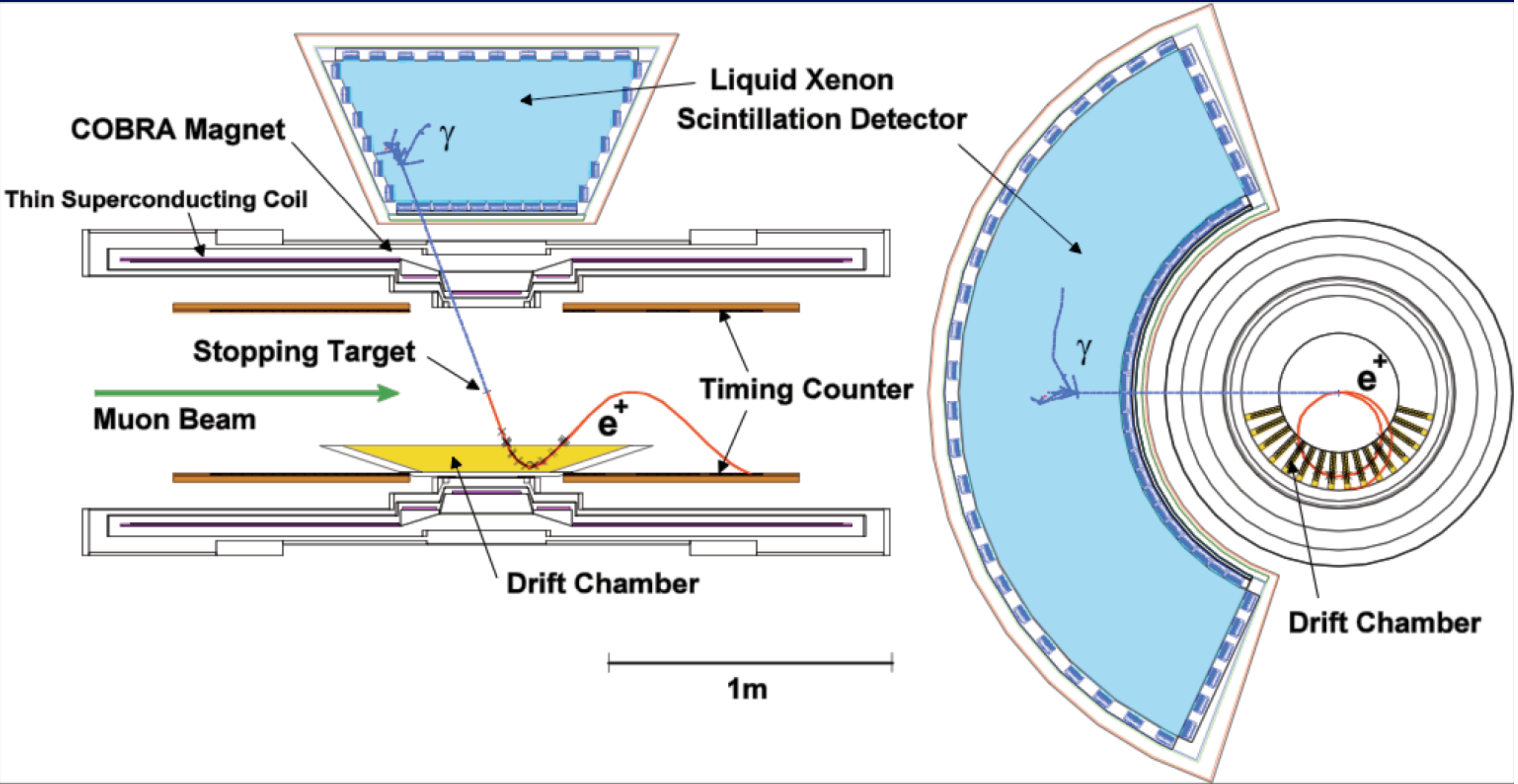
E_e = 52.8 MeV E_γ = 52.8 MeV

- Background from radiative decay – $\mu \to e\nu\nu\gamma$
  - Heavily suppressed for $E_\nu \to 0$, photon opposite electron
  - Not dominant background when rate high enough to reach 10^{-13} sensitivity

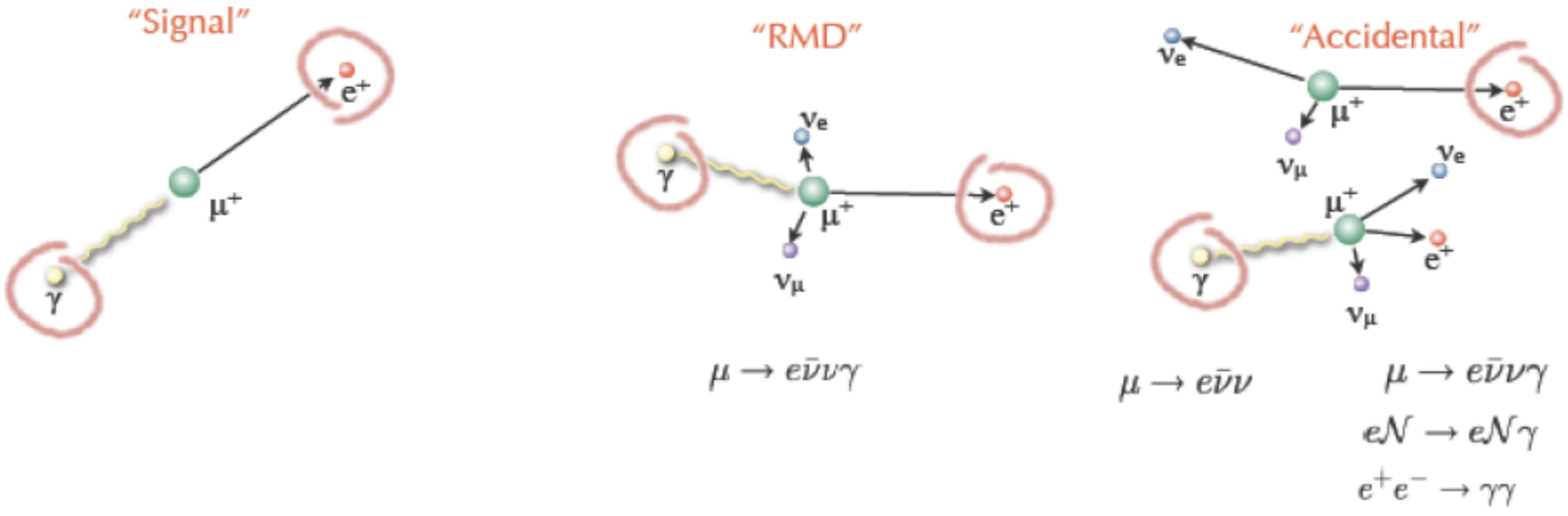
- Main source of background:
  - Accidental coincidences of e^+ from Michel decay ($\mu^+ \to e^+ \nu_e \nu_\mu$) + random γ from radiative decay or annihilation in flight
  - E_e distribution peaks near 53 MeV ($x = E_e / E_{max}$)
  - E_γ distribution in interval dy near y=1 given by $dN_\gamma \propto (1-y)dy$ ($y = E_\gamma / E_{max}$)

$\Rightarrow$ background/signal $\propto \Delta E_e \times (\Delta E_\gamma)^2 \times \Delta t \times (\Delta\theta)^2 \times$ Rate

The MEG Experiment

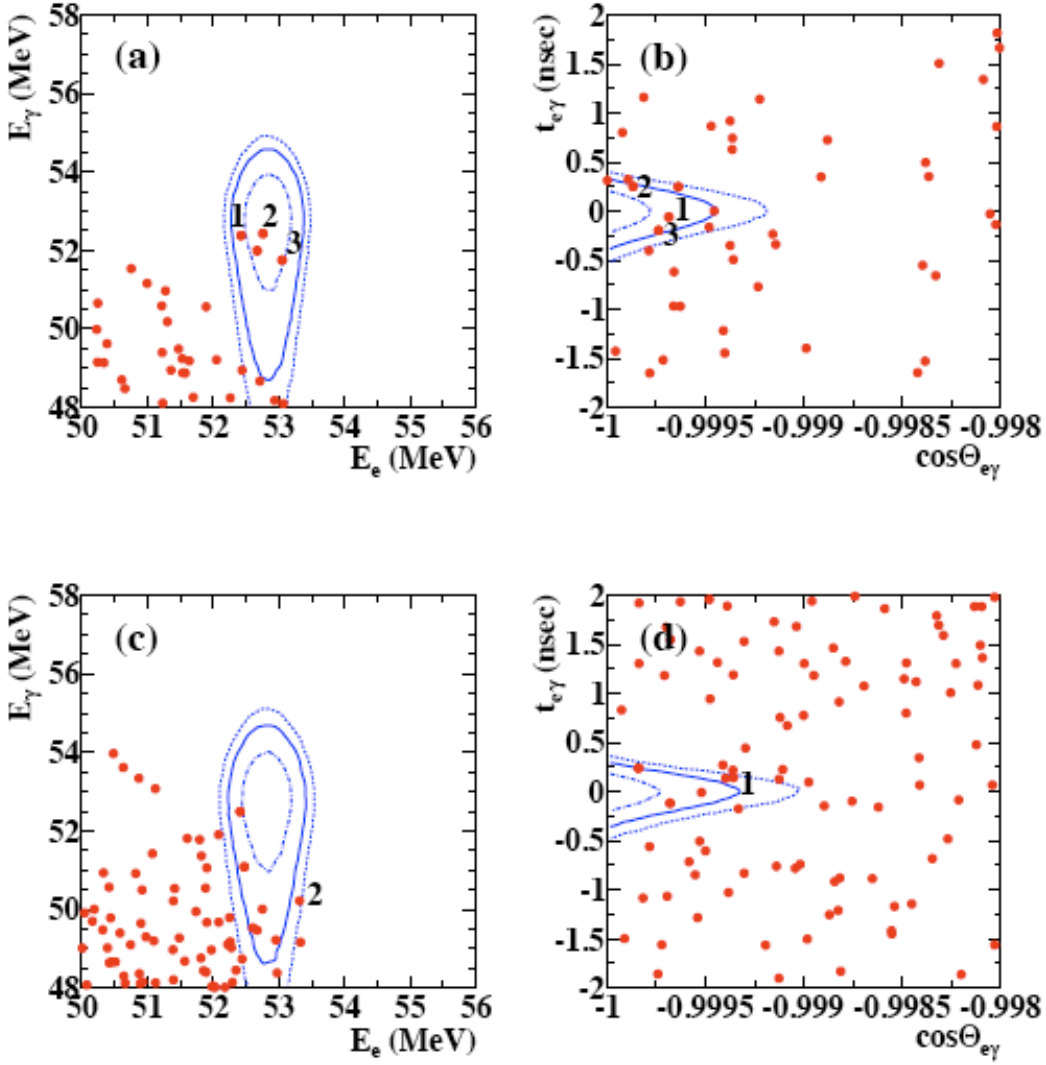


W. Molzon, UC Irvine NuFact 2006 - Status of the MEG Experiment August 28, 2006 5



$\Uparrow$

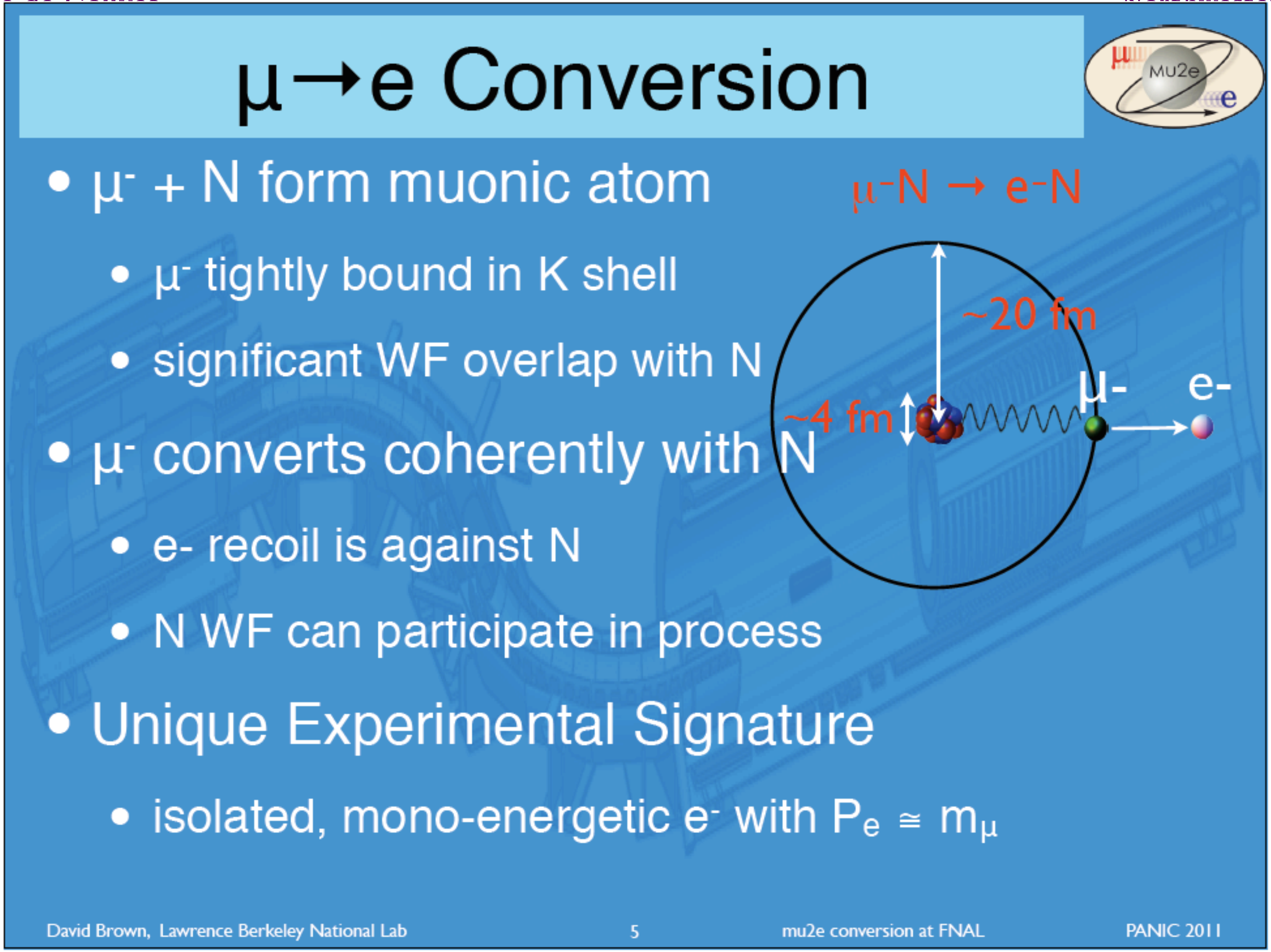
Dominant Background



$$\mathbf{Br}(\mu \to e\gamma) < 2.4 \times 10^{-12}\ \mathbf{(90\%\ CL)}$$

FIG. 1: Event distributions in the analysis region of (a) E_γ vs E_e and (b) $t_{e\gamma}$ vs $\cos\Theta_{e\gamma}$ for 2009 data and of (c) E_γ vs E_e and (d) $t_{e\gamma}$ vs $\cos\Theta_{e\gamma}$ for 2010 data. The contours of the PDFs (1-, 1.64- and 2-σ) are shown, and a few events with the highest signal likelihood are numbered for each year. (The two highest signal likelihood events in 2010 data appear only in (c) or (d).)

[MEG Coll. arXiv:1107.5547]


μ→e Conversion
Mu2e
μ
e
• μ- + N form muonic atom
• μ- tightly bound in K shell
• significant WF overlap with N
• μ- converts coherently with N
• e- recoil is against N
• N WF can participate in process
• Unique Experimental Signature
• isolated, mono-energetic e- with Pe ≅ mμ
μ-N → e-N
~20 fm
~4 fm
μ-
e-
David Brown, Lawrence Berkeley National Lab
5
mu2e conversion at FNAL
PANIC 2011

The Mu2e Experiment

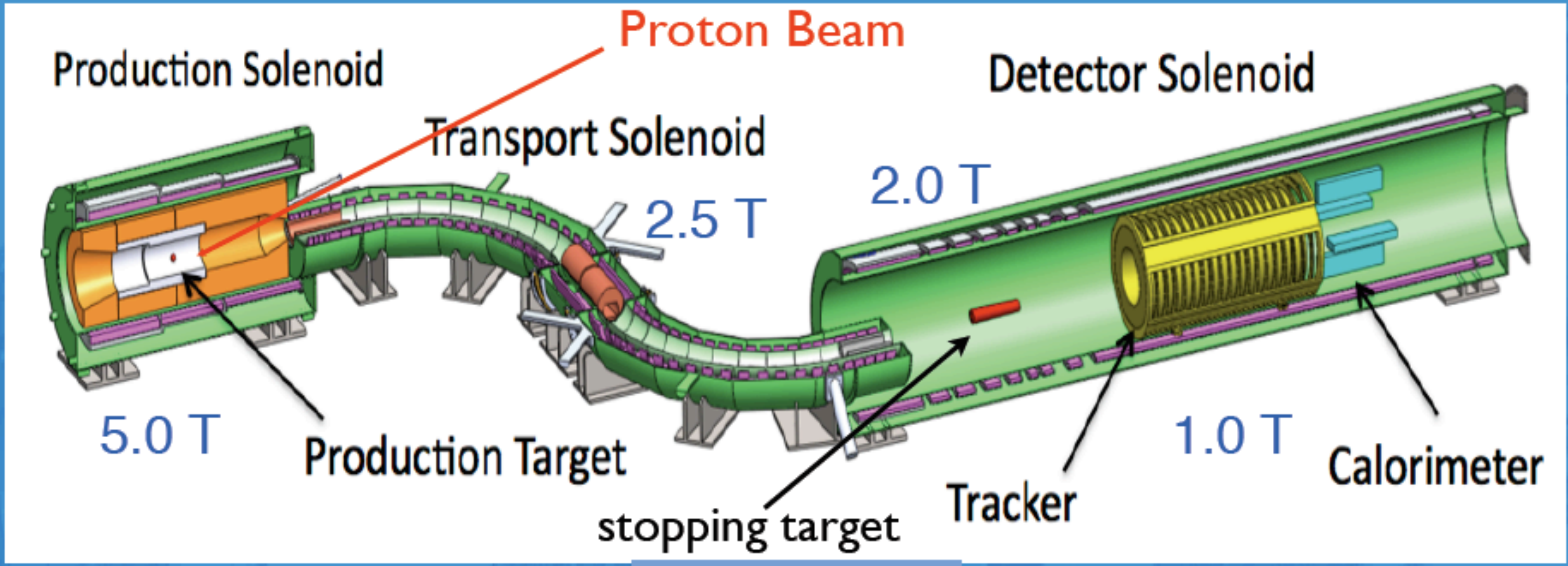
- Experimental Goal: Measure the ratio $R_{\mu e}$

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

- 90% C.L. sensitivity to $R_{\mu e} > 6\times10^{-17}$
  - 4 orders of magnitude better than current limits
- Requires ~ 10^{18} stopped muons
  - ~ 4×10^{20} protons on target (2 year run @ 25 KW)
- Requires negligible (<1) background events
  - Many challenges for beamline and detector design

David Brown, Lawrence Berkeley National Lab 7 mu2e conversion at FNAL PANIC 2011

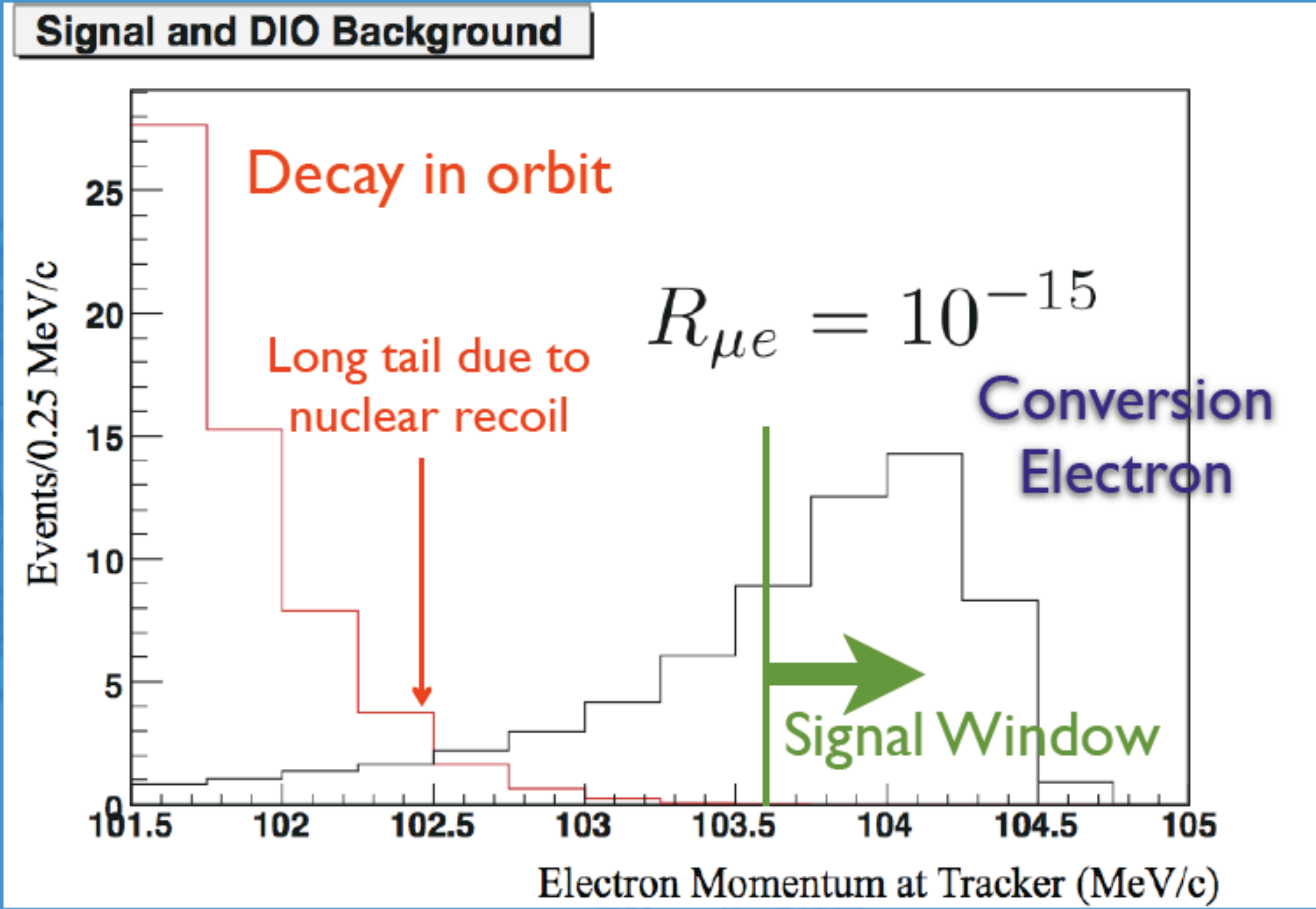
Mu2e Apparatus



~ 20 meters

- Proton delivery beamline
- SC solenoids for muon collection, transportation, and analysis
- Primary (proton) and secondary (muon) targets
- Active devices: tracker, calorimeter, Cosmic Ray veto

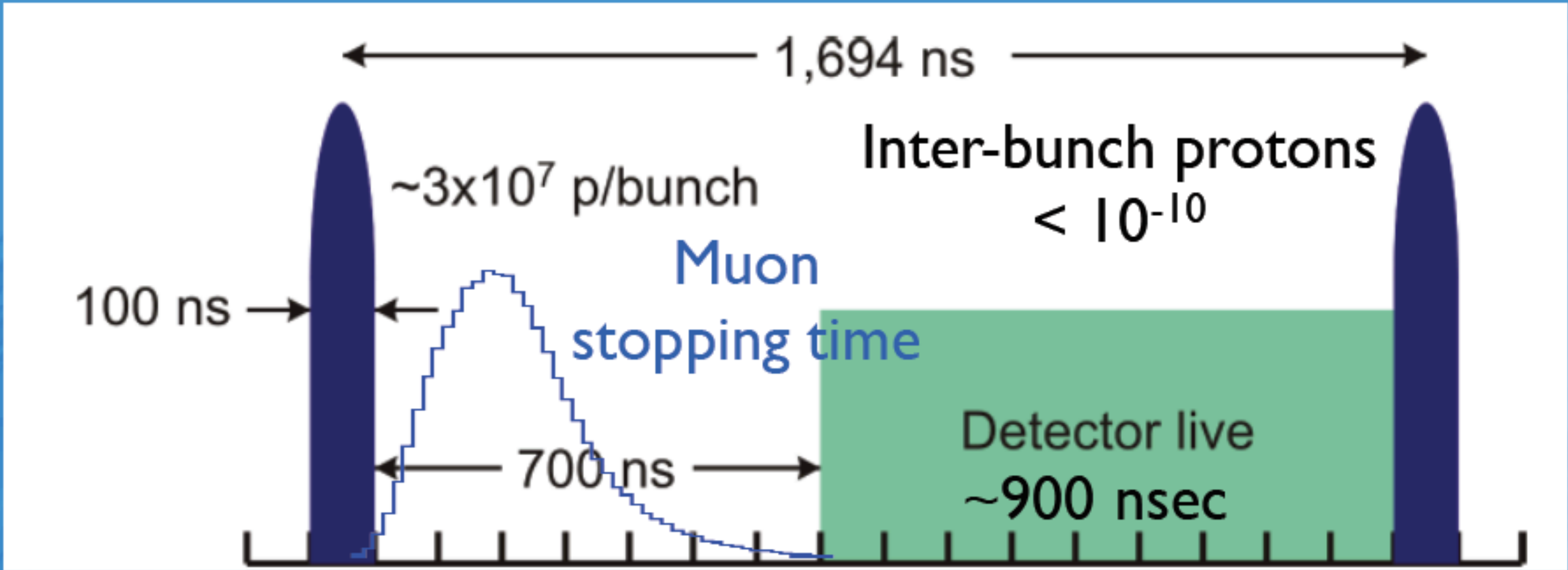
Momentum Sensitivity



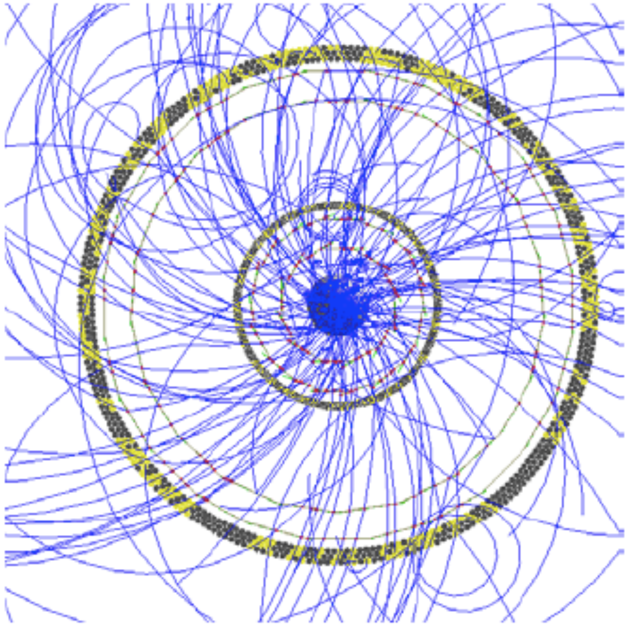
Shanker, Phys.Rev D25, 1847 (1982)

New calculation by Czarnecki etal agrees within 30% arXiv:1106.4756v1

Beam Timing

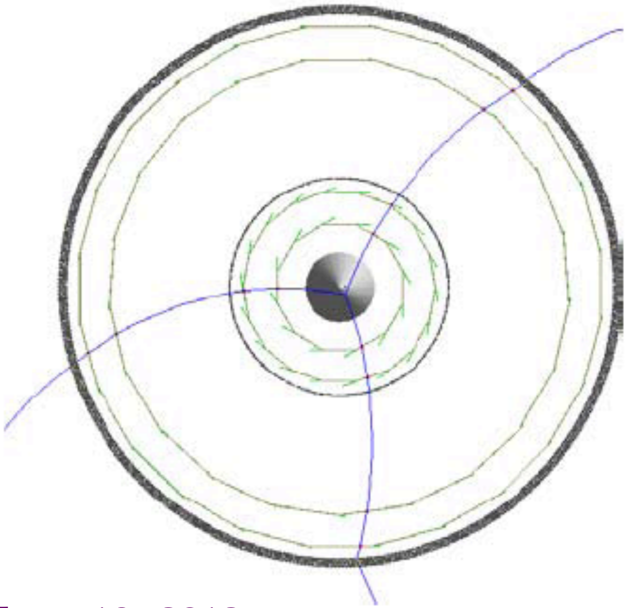


- Prompt pions decay rapidly
  - τ = 26 nsec
- Muons survive to reach the stopping target
  - Stopped muon lifetime on Al ~800 nsec



- The silicon detector is read out with 10 MHz (power consumption)
- Hundred electron tracks in one frame
- Can be resolved by scintillating fibre tracker
- Resolution ~ 100 ps - on average one electron

$$\boxed{\mu^+ \to e^+ e^+ e^-}$$



Backgrounds: – $\mu^+ \to e^+\nu\nu\gamma^*(\to e^+e^-)$
– accidentals (like $\mu \to e\gamma$)

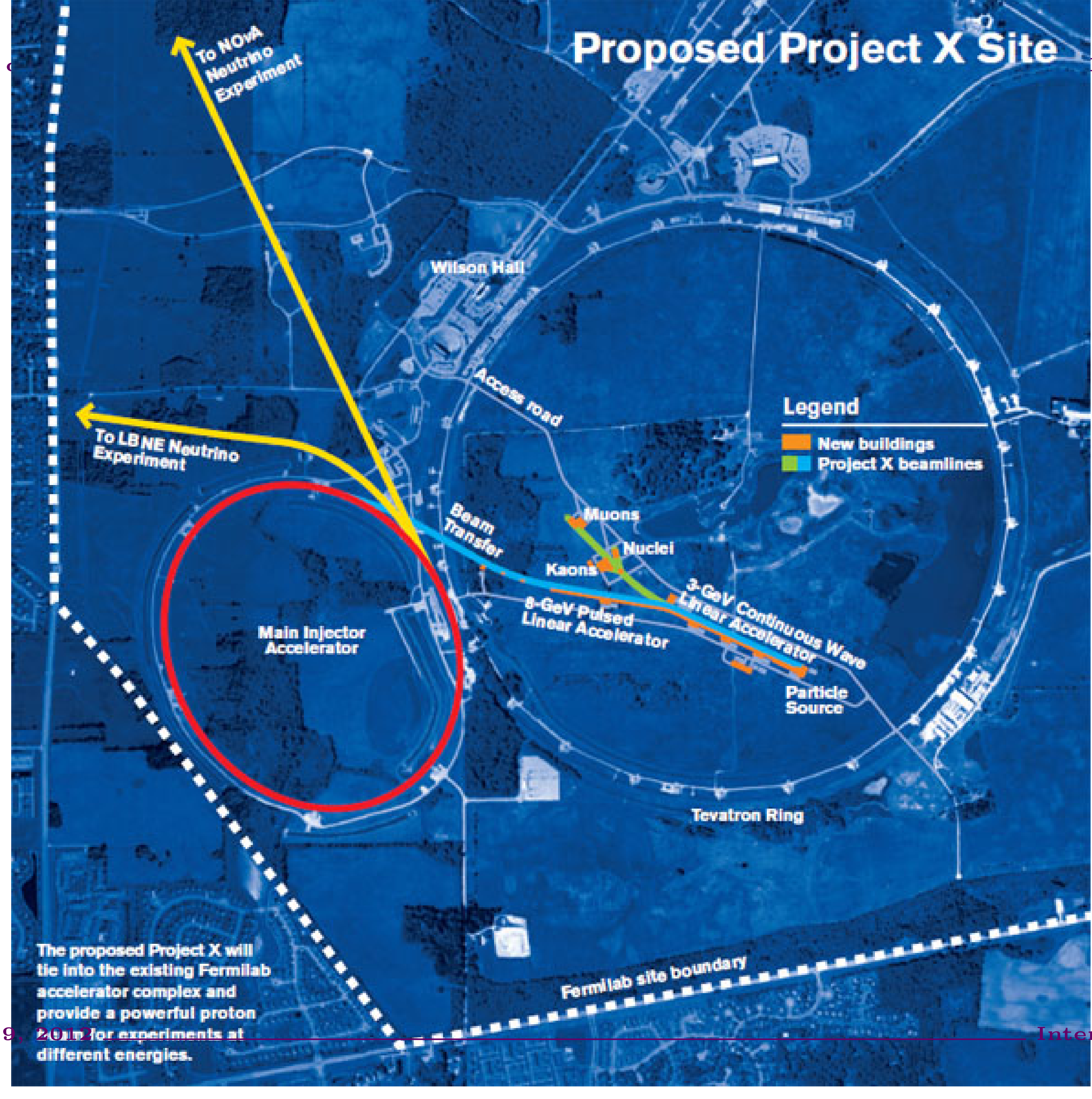
Handle: – vertexing, needs excellent tracking

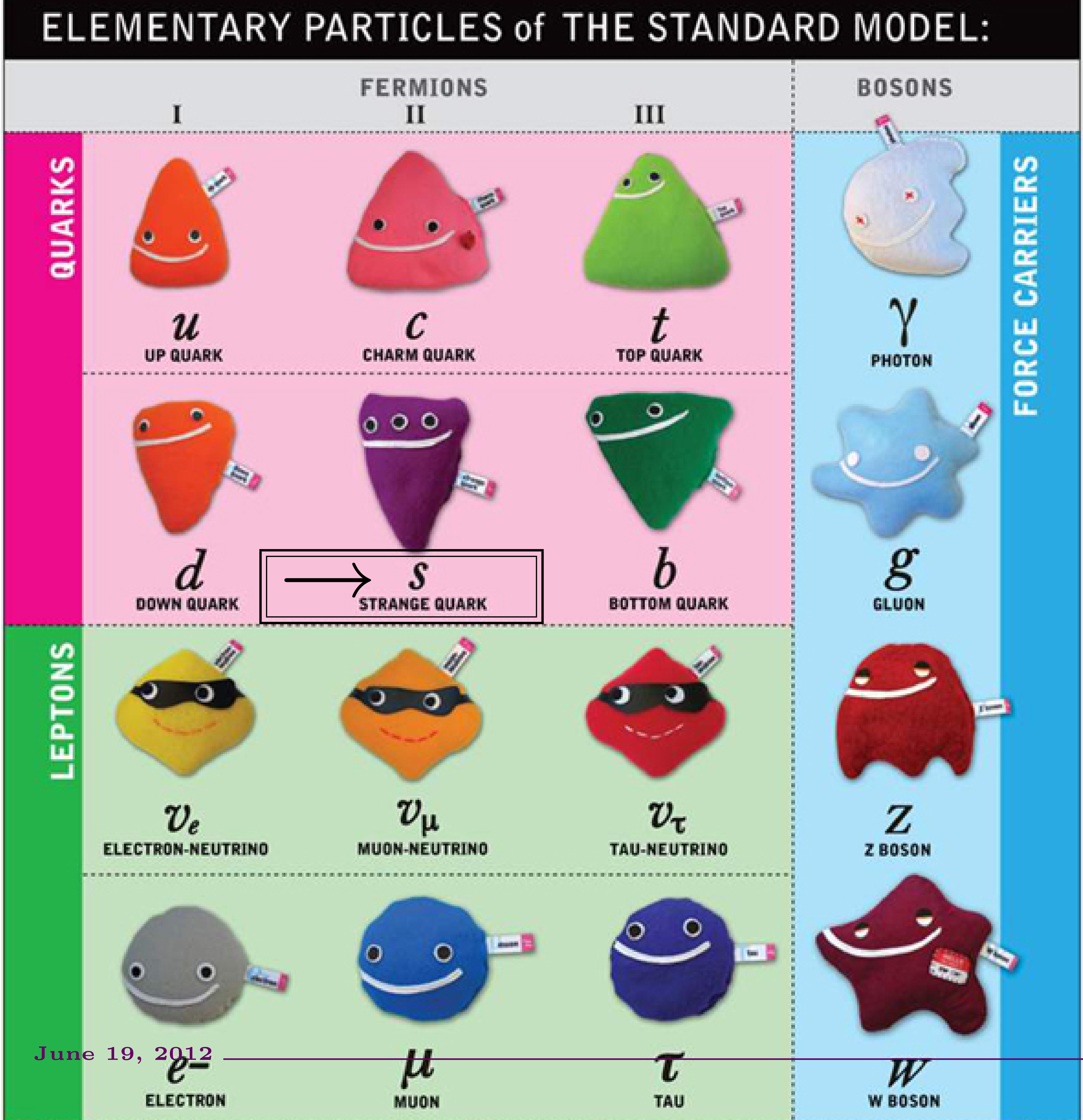
Yet to hit a wall. Proposal at PSI (?)

[N. Berger at NuFact'11]

What Will Happen in the Near Future ...

- Mu2e and COMET: $\mu \to e$-conversion at 10^{-16}.
- $g-2$ measurement a factor of 3–4 more precise.
- Project X-like: $\mu \to e$-conversion at 10^{-18} (or precision studies?).
- Project X-like: deeper probe of muon edm.
- Muon Beams/Rings: $\mu \to e$-conversion at 10^{-20}? Revisit rare muon decays ($\mu \to e\gamma$, $\mu \to eee$) with new idea?


Proposed Project X Site
To NOvA Neutrino Experiment
To LBNE Neutrino Experiment
Wilson Hall
Access road
Legend
New buildings
Project X beamlines
Beam Transfer
Muons
Nuclei
Kaons
3-GeV Continuous Wave Linear Accelerator
8-GeV Pulsed Linear Accelerator
Main Injector Accelerator
Particle Source
Tevatron Ring
Fermilab site boundary
The proposed Project X will tie into the existing Fermilab accelerator complex and provide a powerful proton for experiments at different energies.



Strange Quark is Among a Handful of Known Fundamental, Point-Like Particles.

http://www.particlezoo.net

The Kaon is bound state of a $s\bar{u}$ (charged Kaon) or $s\bar{d}$ (neutral Kaon)

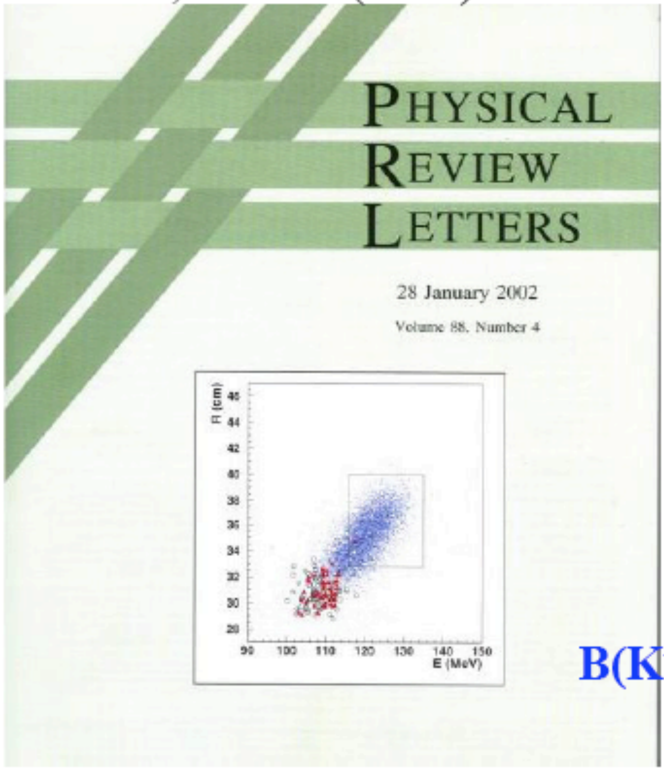
Sensitivity Frontier of Kaon Physics Today

- CERN NA62: 100×10^{-12} measurement sensitivity of $K^+ \to e^+ \nu$
- Fermilab KTeV: 20×10^{-12} measurement sensitivity of $K_L \to \mu\mu ee$
- Fermilab KTeV: 20×10^{-12} search sensitivity for $K_L \to \pi\mu e$, $\pi\pi\mu e$
- BNL E949: 20×10^{-12} measurement sensitivity of $K^+ \to \pi^+ \nu\bar{\nu}$
- BNL E871: 1×10^{-12} measurement sensitivity of $K_L \to e^+ e^-$
- BNL E871: 1×10^{-12} search sensitivity for $K_L \to \mu e$

Probing new physics above a 10 TeV scale with 20-50 kW of protons.

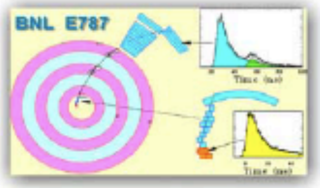
E787

PRL **88**, 041803 (2002)


PHYSICAL REVIEW LETTERS

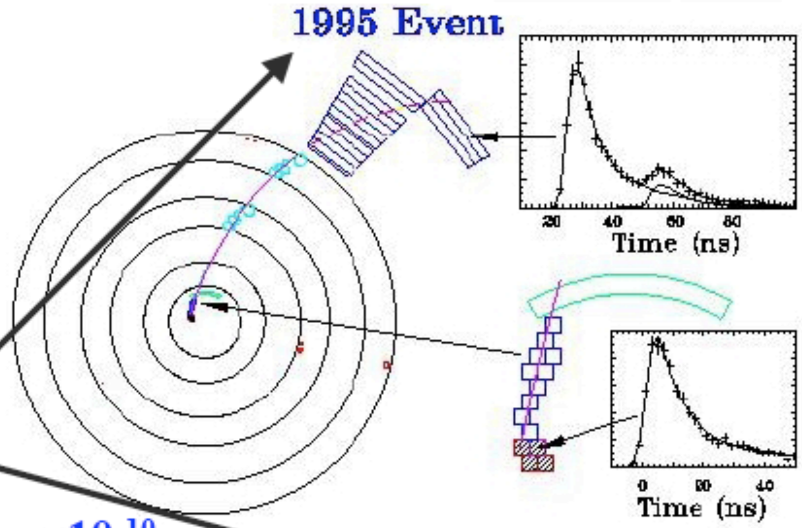
28 January 2002

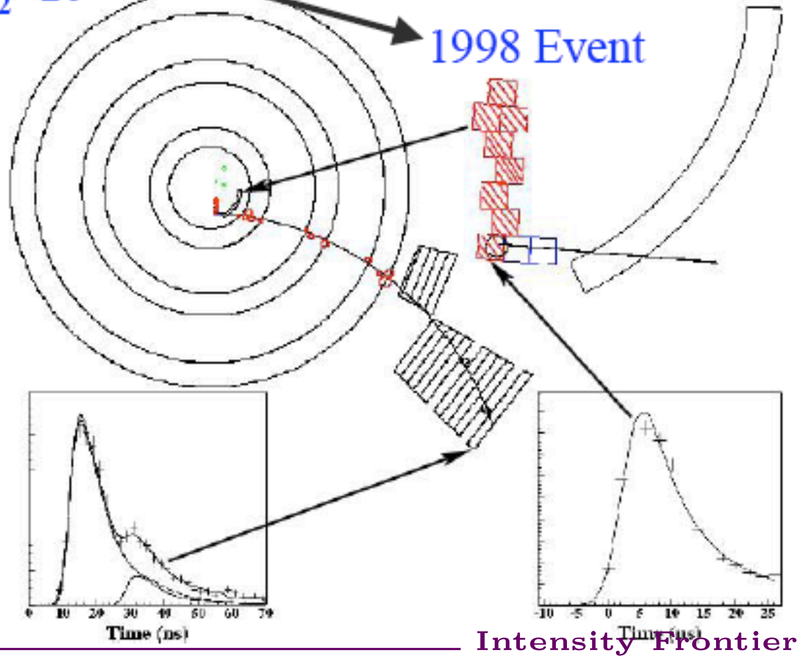
Volume 88, Number 4



Two events above the $K_{\pi 2}$ (pnn1)

$B(K^+ \to \pi^+ \nu \nu) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$





Below $K_{\pi 2}$ (pnn2) limit:

1996: PL **B537**, 211 (2002)

1997: PR **D70**, 037102 (2004)

$140 < p_\pi < 195$ MeV/c

1 candidate event with an expected background of 1.22 +/- 0.24 events.

Background limited, with S/N<0.2

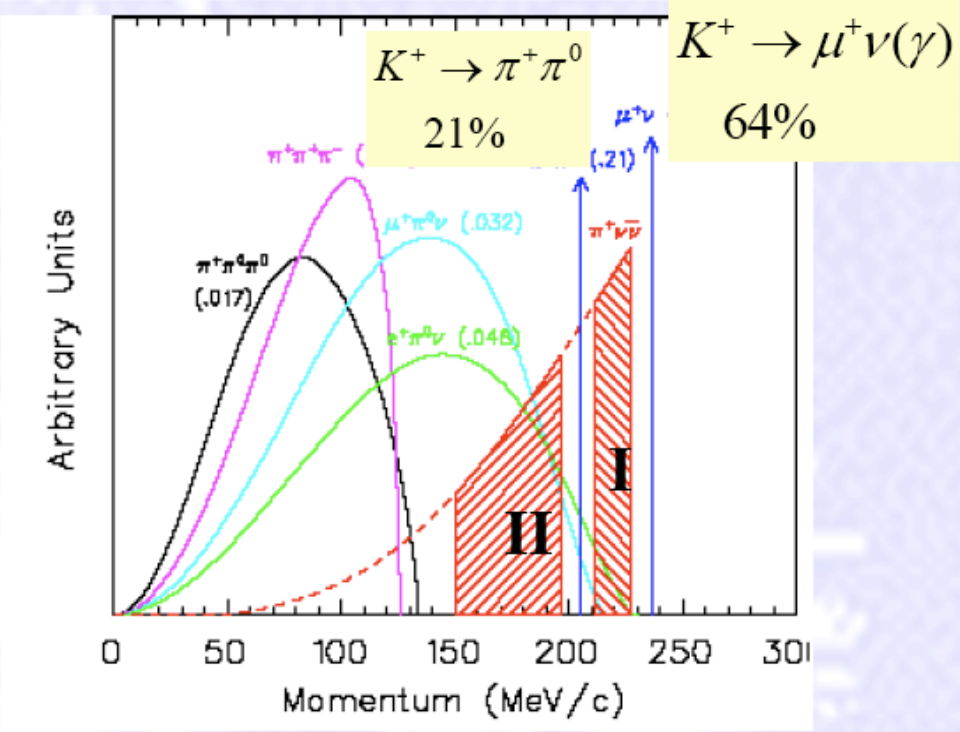
Set an upper limit of $B(K^+ \to \pi^+ \nu \nu) < 22 \times 10^{-10}$

WIN09 September 18, 2009

Special Features of Measuring

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

Experimentally weak signature with background processes exceeding signal by $>10^{10}$



Determine everything possible about the K^+ and π^+

* π^+/μ^+ particle ID better than 10^6 (π^+ - μ^+ - e^+)

Eliminate events with extra charged particles or ***photons***

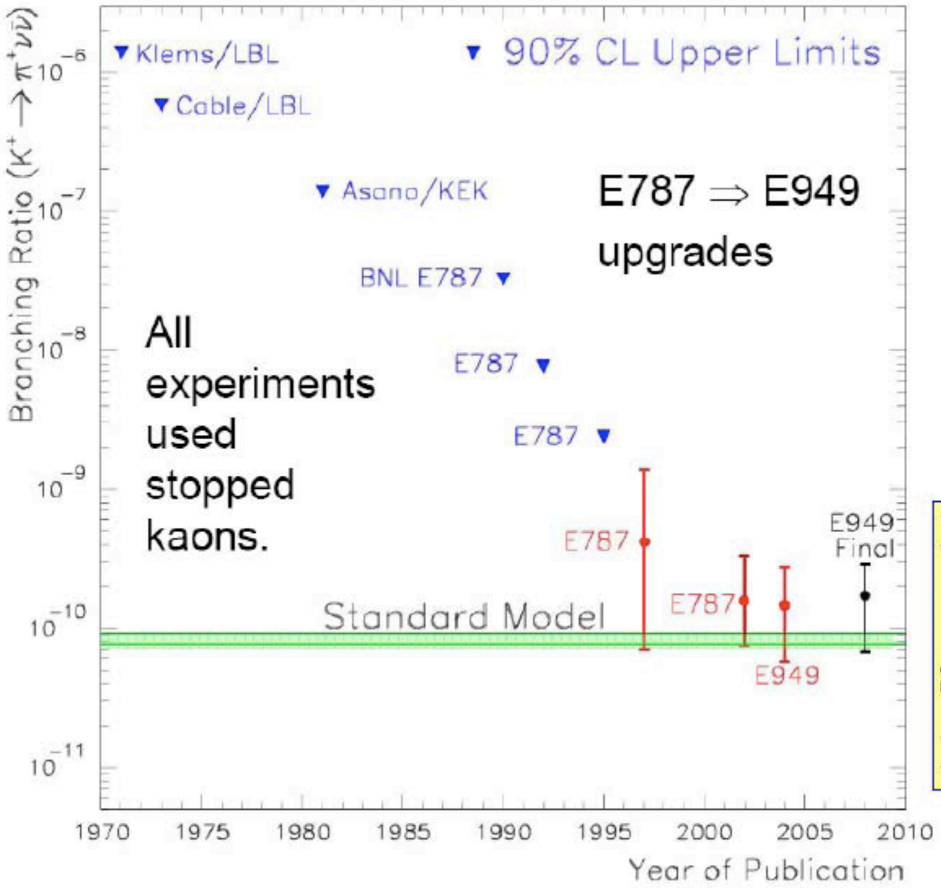
* π^0 inefficiency $< 10^{-6}$

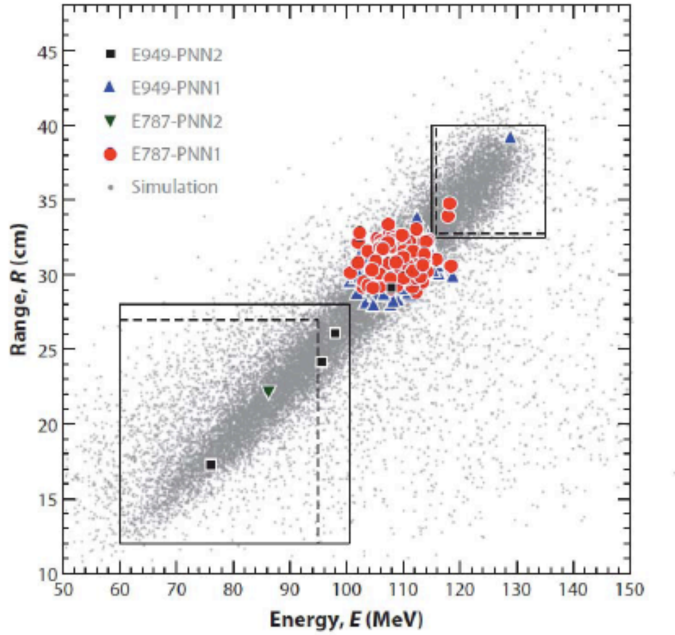
Suppress backgrounds well below the expected signal (S/N~10)

* Predict backgrounds *from data*: dual independent cuts
* Use "Blind analysis" techniques
* Test predictions with outside-the-signal-region measurements

Evaluate candidate events with S/N function

$K^+ \to \pi^+ \nu \bar{\nu}$ History



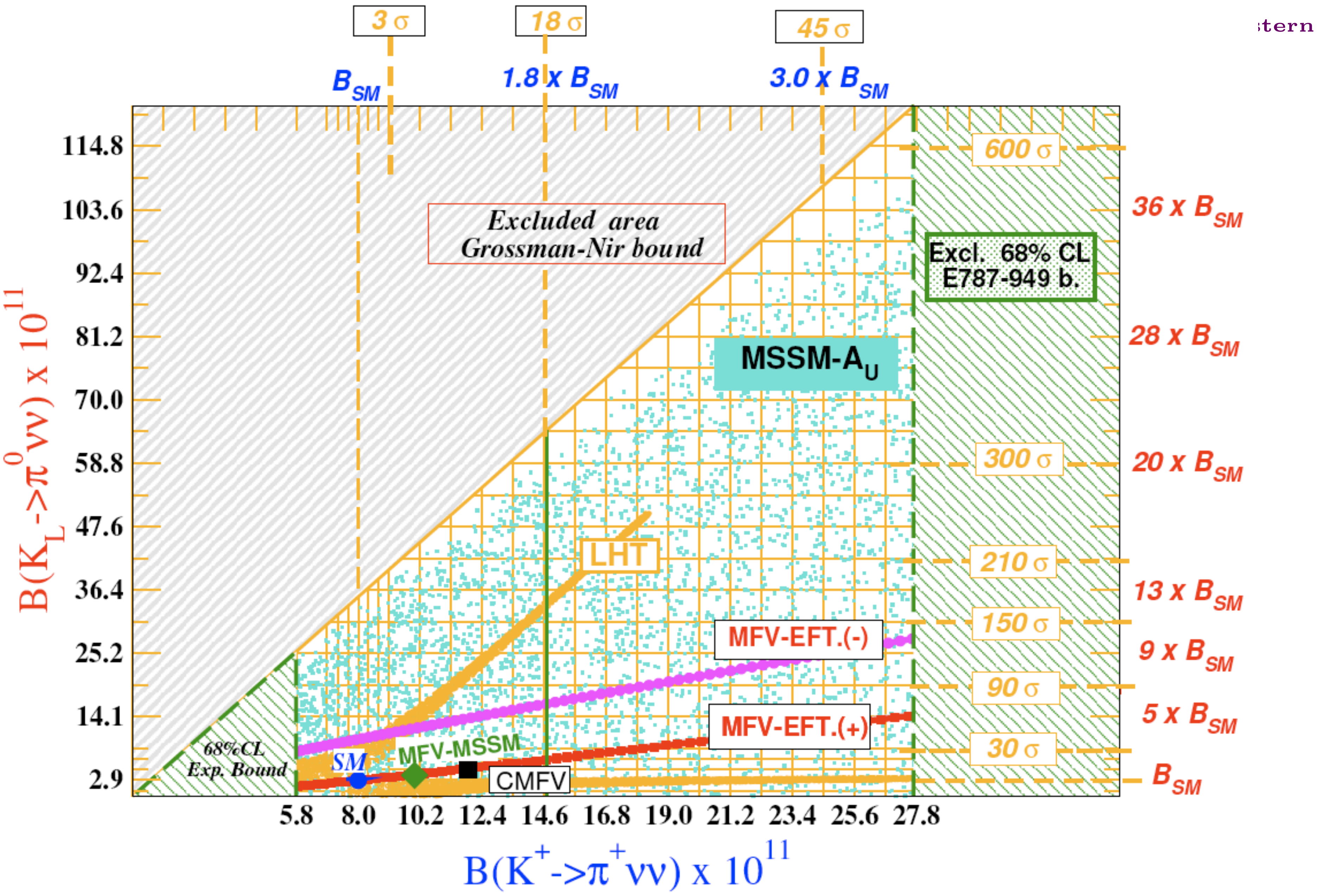


E787/E949 Final: 7 events observed

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} x 10^{-10}$$

Standard Model:

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = (0.78 +\!- 0.08) \; x 10^{-10}$$



large data samples may teach us a lot . . . depending on where we are late in this decade

$K \to \pi\nu\bar{\nu}$... Past, Present, Future

Facility (Experiment)	Proton Power	Kaon Decay/stop rate	Kaon Properties	$K \to \pi\nu\bar{\nu}$ Sensitivity
BNL AGS (E787/E949):	50kW	1×10^{6} K^{+}/sec	Pure stopped K^{+} source	7 events
CERN (NA62):	20kW	10×10^{6} K^{+}/sec	Un-separated 1- GHz $K^{+}/\pi^{+}/p^{+}$ beam	80 events
Fermilab: (ORKA):	**75kW**	**9×10^{6} K^{+}/sec**	**Pure stopped K^{+} source**	**1000 events**
Project-X $K^{+}\to\pi\nu\bar{\nu}$	1500 kW	100×10^{6} K^{+}/sec	Pure stopped K^{+} source	>1000 events

$K_L \to \pi^0 \nu\bar{\nu}$ has never been observed.

"nothing in – nothing out". Very hard experimentally!

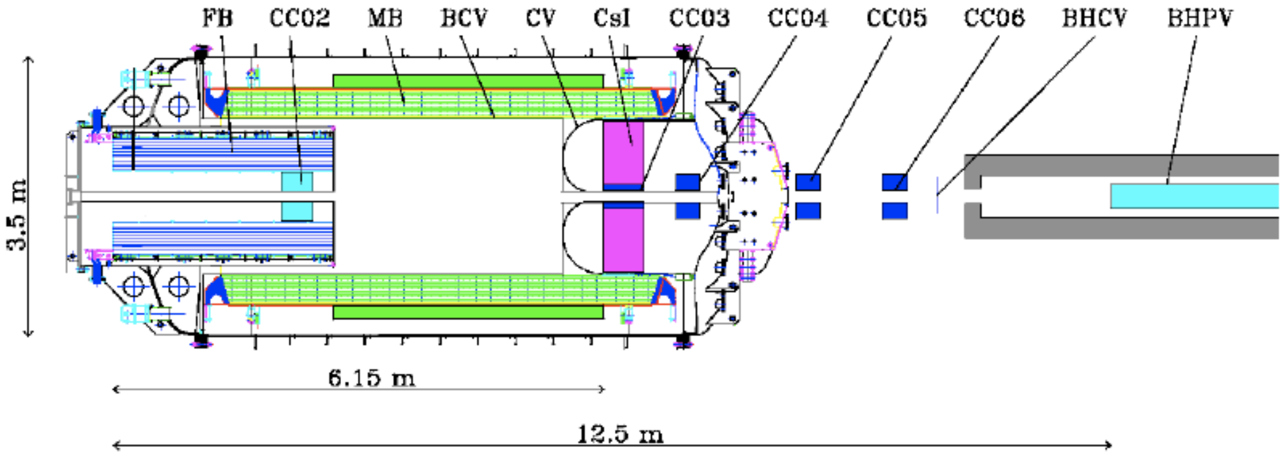


Figure 5: The K^OTO detector.

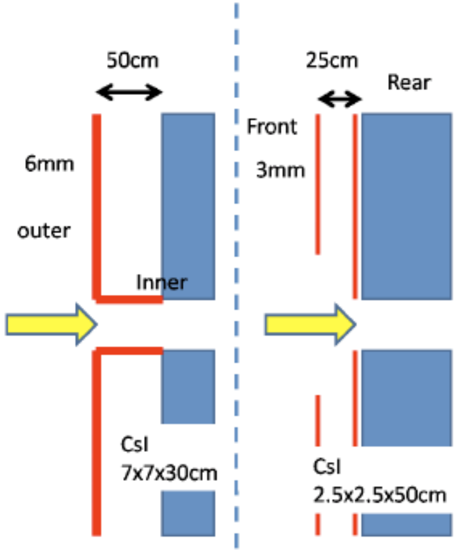
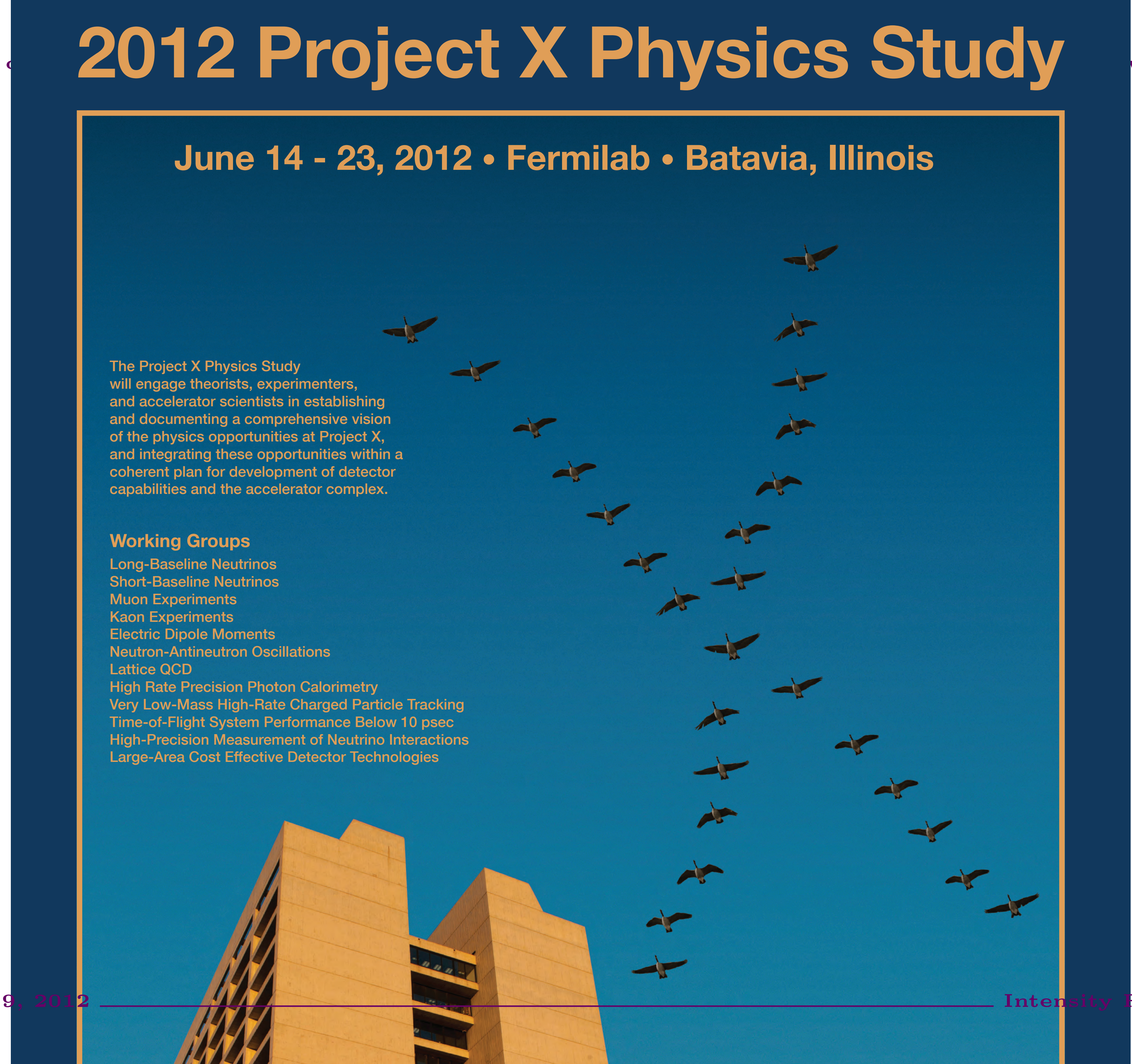
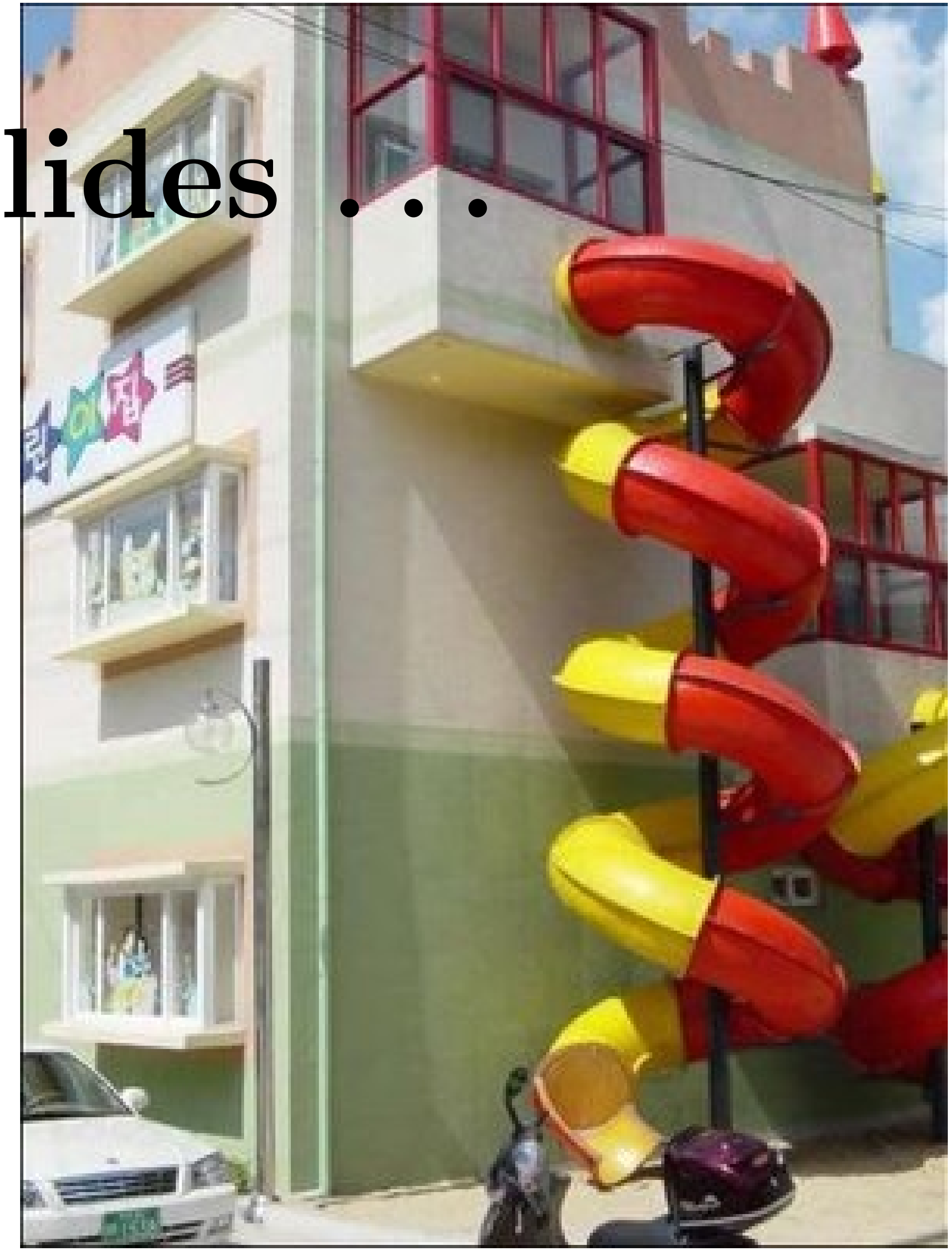


Figure 6: The CV at E391a (left) and at K^{O}TO (right).

goal of the KOTO experiment in J-PARC – around 50 events, assuming SM rate.

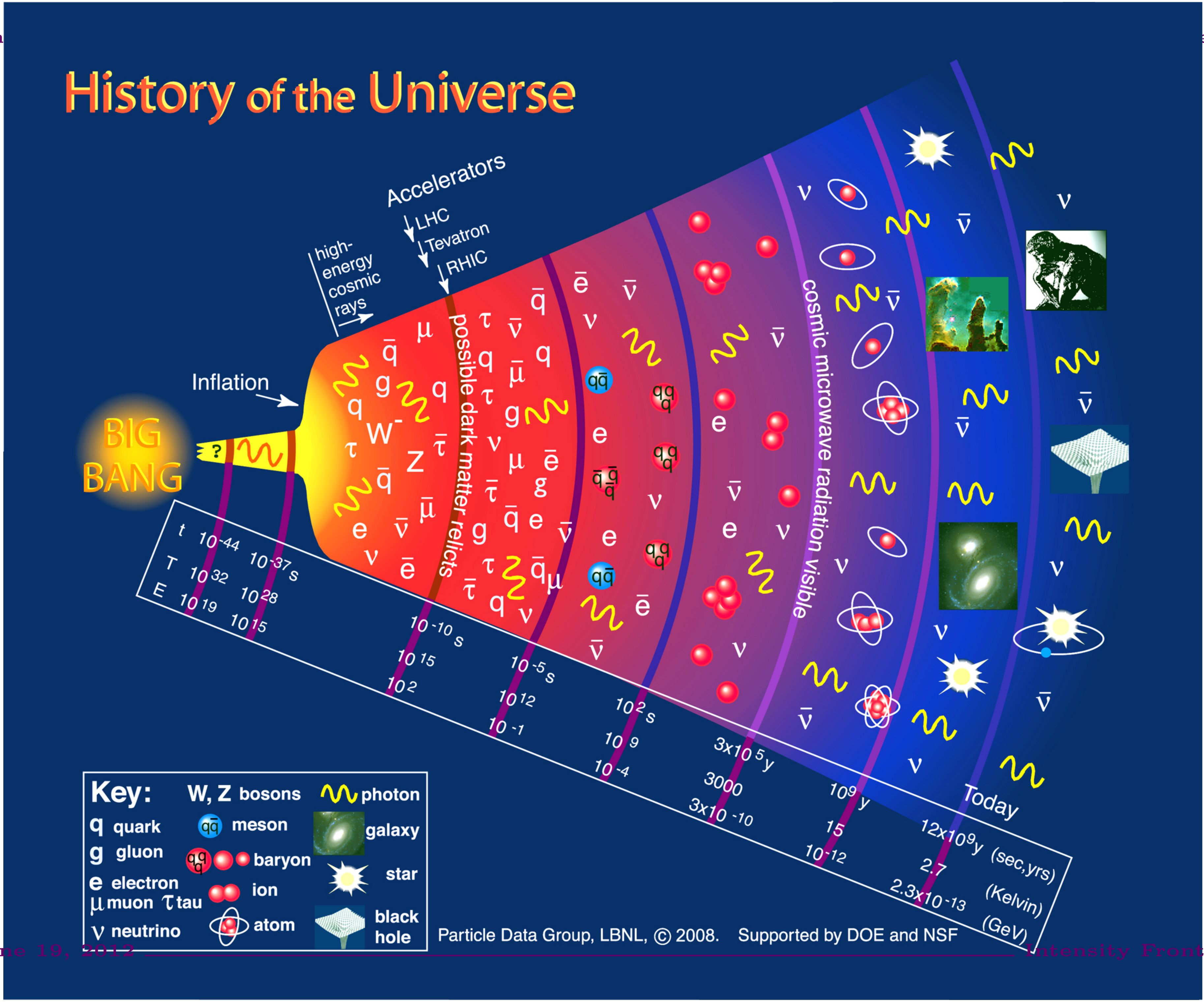

2012 Project X Physics Study
June 14 - 23, 2012 • Fermilab • Batavia, Illinois
The Project X Physics Study will engage theorists, experimenters, and accelerator scientists in establishing and documenting a comprehensive vision of the physics opportunities at Project X, and integrating these opportunities within a coherent plan for development of detector capabilities and the accelerator complex.
Working Groups
Long-Baseline Neutrinos
Short-Baseline Neutrinos
Muon Experiments
Kaon Experiments
Electric Dipole Moments
Neutron-Antineutron Oscillations
Lattice QCD
High Rate Precision Photon Calorimetry
Very Low-Mass High-Rate Charged Particle Tracking
Time-of-Flight System Performance Below 10 psec
High-Precision Measurement of Neutrino Interactions
Large-Area Cost Effective Detector Technologies

Backup Slides . . .



"I have done something very bad today by proposing a particle that cannot be detected; it is something that no theorist should ever do."

- Wolfgang Pauli


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF