Focus on **active or approved** experiments, which are in design phases

Many other efforts are **in development**

I will try to tell you what each experiment is designed to deliver
Recent, Present and Future Projects Worldwide

**Muons**

- **Lifetime: Fermi constant**
  - **MuLan:** Status: complete $\delta\tau_{\mu} = 1.0 \text{ ppm}; \quad \delta G_F = 0.5 \text{ ppm}$

- **Decay: Michel parameters**
  - **TWIST:** Status: complete $\rho, \delta, \eta, P_{\mu \xi}$

- **Capture: fundamental hadronic parameters**
  - **MuCap (g_P):** Status: complete $\delta g_P = 7\%$
  - **MuSun (L1a):** Status: data taking

- **Anomalous magnetic moment**
  - **g-2** Status: ~CD0 this month; design and construction
  - **EDM** Status: parasitic to g-2

- **Charged Lepton Flavor Violation**
  - **MEG ($\mu \rightarrow e\gamma$):** Status: $BR < 10^{-12};$ data taking; upgrade plans
  - **Mu2e ($\mu A \rightarrow eA$):** Status: CD-1; design and construction
  - **COMET ($\mu A \rightarrow eA$):** Status: in design, approved for phase 1
Recent, Present and Future Projects Worldwide

- **Pions**
  - Lepton universality: $\pi \rightarrow e^\nu$
    - PEN Status: data taking complete; analysis in progress
    - PIENU Status: data taking

- **Dark Photons**
  - APEX (Hall A) Status: test run published
  - HPS (Hall B) Status: tested with photon beam
  - DarkLight (FEL) Status: test run complete

- **EDMs** $\rightarrow$ Brad Filippone

- **PVES** $\rightarrow$ Kent Paschke
Recent, Present and Future Projects Worldwide

**Neutrons**
- **Lifetime**
  - NIST – beam technique  Status: In progress
  - LANSE – Ultracold traps  Status: planning
  - Munich – magneto-grav trap  Status: construction
- **Decay parameters (many efforts)**
  - PERKEO II (“big A”)  Status: complete (2012) \( \delta A/A \sim 5 \times 10^{-3} \)
  - UCNA ("big A"; B, b later)  Status: complete (2012) and future running
  - aCORN (“little a”)  Status: in progress
  - N\(_{ab}\) (“little a, little b”)  Status: in construction

**Nuclei** (incomplete; mostly covered elsewhere)
- **0+ \( \rightarrow \) 0+**
  - Many new results  Status: complete, but new set of nuclei
- **He-6 System**
  - Lifetime  Status: complete  \( \delta \tau_{\text{He-6}} = 3 \times 10^{-4} \)
  - e-\(\nu\) correlation (“little a”)  Status: in progress
  - E spectrum (“little b”)  Status: planning

**Paul Trap at ANL**
- \(^8\text{B}\) and \(^8\text{Li}\)  Status: data taking on Li complete. B planning
Precision Physics and Beyond the Standard Model
Exploration: An example (of course, quite speculative and not implied as true)

We often claim the low-energy observables (both limits and signals) will be part of the conversation and interpretation of, say, LHC results

Observations at the LHC
- \( h \rightarrow \gamma \gamma \) production rate is too high by \(~40-50\%\)
- Higgs rates in \( ZZ^* \) and \( WW^* \) are consistent with the SM

Theoretical SUSY model that fits observations
- light stau with large left-right mixing
- light Bino
- heavy higgsinos

Other consequences
- Predicts Muon Anomaly exactly
- Compatible with thermal dark matter
- Predicts small deviations in \( h \rightarrow \gamma Z \) and \( h \rightarrow \tau \tau \)
- Predicts measureable violations of Lepton Non-Universality in \( \tau-\mu \) and \( \tau-e \)
- Predicts NO violation in the \( \mu-e \) sector

Correlation between the Higgs Decay Rate to Two Photons and the Muon \( g - 2 \)
Gian F. Giudice\(^a\), Paride Paradisi\(^a\) and Alessandro Strumia\(^a,b\)
arXiv:1207.6393v1

Post Higgs paper (others exist too)
Chapter 1: Muons

(well) Beyond Schwinger
2010: Michel Parameter / Muon Decay: TWIST

\[ \rho = 0.74977 \pm 0.00012 \text{ (stat)} \pm 0.00023 \text{ (syst)} \]
\[ \delta = 0.75049 \pm 0.00021 \text{ (stat)} \pm 0.00027 \text{ (syst)} \]
\[ P_\mu \pi^0 = 1.00084 \pm 0.00029 \text{ (stat)} -0.00063 \text{ (syst)} +0.00165 \]

Results mostly constrain right-handed muon terms

- summary of all terms (pre-TWIST in parentheses)
  \[ |g_{RR}^S| < 0.35 \text{ (0.66)} \]
  \[ |g_{RR}^V| < 0.017 \text{ (0.033)} \]
  \[ |g_{RR}^T| \equiv 0 \]
  \[ |g_{LR}^S| < 0.050 \text{ (0.125)} \]
  \[ |g_{LR}^V| < 0.023 \text{ (0.060)} \]
  \[ |g_{LR}^T| < 0.015 \text{ (0.036)} \]
  \[ |g_{RL}^S| < 0.420 \text{ (0.424)} \]
  \[ |g_{RL}^V| < 0.105 \text{ (0.110)} \]
  \[ |g_{RL}^T| < 0.105 \text{ (0.122)} \]
  \[ |g_{LL}^S| < 0.550 \text{ (0.550)} \]
  \[ |g_{LL}^V| > 0.960 \text{ (0.960)} \]
  \[ |g_{LL}^T| \equiv 0 \]

\[ Q_R^\mu = \frac{1}{4} |g_{LR}^S|^2 + \frac{1}{4} |g_{RR}^S|^2 + |g_{LR}^V|^2 + |g_{RR}^V|^2 + 3 |g_{LR}^T|^2 \]
\[ = \frac{1}{2} \left[ 1 - \frac{1}{3} \xi - \frac{16}{9} \xi \delta \right] \]
\[ < 8.2 \times 10^{-4} \text{ (90\%C.L.)} \]

2011: Muon lifetime / Fermi constant: MuLan*

The most precise particle or nuclear or atomic lifetime ever measured

\[ \tau(\text{MuLan}) = 2196980.3 \pm 2.2 \ \text{ps} \ (1.0 \ \text{ppm}) \]

\[ \Delta \tau(\text{R07} - \text{R06}) = 1.3 \ \text{ps} \]

\[ G_F(\text{MuLan}) = 1.16637875(62) \times 10^{-5} \ \text{GeV}^{-2} \ (0.5 \ \text{ppm}) \]

*US led effort at PSI
2012: Muon Capture on Proton: MuCap*

Measured: $\Lambda_S = (714.9 \pm 5.4_{\text{stat}} \pm 5.0_{\text{syst}}) \, \text{s}^{-1}$

Determined: $g_P(\text{MuCap}) = 8.04 \pm 0.56$

Compare to: $g_P(\text{Theory}) = 8.26 \pm 0.23$

First unambiguous determination of $g_P$ and clarification of longstanding puzzle between fundamental QCD-based prediction and expt.

*US led effort at PSI
Several fundamental astrophysics processes depend on weak interaction in deuterium

Basic solar fusion: \( p + p \rightarrow d + e^+ + \nu \)

Sudbury Neutrino Observatory: \( \nu_e + d \rightarrow p + p + e^- \) (CC)  
\( \nu_x + d \rightarrow p + n + \nu_x \) (NC)

Tiny cross sections, predictions rely on theory

Idea: replace \( e^- \) by \( \mu^- \), calibrate in muon capture reaction

*US led effort at PSI  
model-independent connection via EFT
Muon forms atom, overlap with nucleus enhanced. Short range EW interaction leads to small, but observable rate.

\[ \mu^- + d \rightarrow \nu + n + n \] (~0.1% compared to decay)

Capture rate is deduced from $\mu^+/\mu^-$ lifetime difference.

![Cryo-TPC diagram](image)

- Muon coming to rest
- Delayed fusion
- Muon lifetime difference
- Log(counts) vs time
- $\mu^+$, no capture
- $\mu^-$

![Data plot](image)

- Theory
- Exp
- Goal
FNAL initiates Muon Campus concept to serve new g-2, Mu2e and parasitic EDM experiments

For g-2, achieves
1) Long decay channel
2) Rapid ring cycle
3) No hadronic flash

For Mu2e, achieves
1) Ideal proton bunches for mu formation
2) High intensity / Extinction
Muon Anomaly: The g-2 Experiment*

What is nature trying to tell us?

- Magnitude and sign have important implications
- 1-D UED models predict “tiny” effects
- SUSY models – many predict large contributions as observed
- The “Uninvented” – sets a stringent experimental constraints for any new models, together with other low- and high-energy data

Last g-2 experimental results have > 2000 citations. It’s highly relevant in helping shape the New Standard Model we hope to discover.
The anomaly is obtained from three well-measured quantities.

\[ \alpha \mu = \frac{\mu_\mu}{\mu_p} \frac{\omega_a}{\omega_p} \]

\[ \omega_a = \frac{q}{m} a \mu B \]

- Momentum
- Spin

\[ \mu \mu = 3.18334524(37) \quad (120 \text{ ppb}) \]
\[ = 3.18334539(10) \quad (31 \text{ ppb}) \]
Method and Goal

- Build on a proven technique
- Use existing unique storage ring
- Obtain more muons
- Control systematic errors
- New team built from E821 experts, augmented by significant new strengths
- VERY strong Nuclear Physics community effort here

GOAL

Experimental uncertainty: 63 → 16 x 10^{-11}
  0.1 ppm statistical
  0.1 ppm systematic

Theory uncertainty: 51 → 30 x 10^{-11}

Future: $\Delta a_\mu(\text{Expt} - \text{Thy}) = xx \pm 34 x 10^{-11}$

(If xx remains 296, the deviation from zero would be close to 9\sigma)
Muon-to-Electron Conversion: Mu2e*

The SM theory is clear: It won’t happen

\[ \mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L) \]

*Nuclear / Particle / Accelerator collaboration at Fermilab
Method and Goal

- **Make muonic Al atoms.**
  - 40% will decay “in orbit”;
  - 60% will capture (junk emitted)

- **Look for** mono-energetic $e^-$, at muon mass (~104 MeV)

- **Severe high rates implies tracking issues**

- **Avoid fake backgrounds:** Goal single event sensitivity $< 2 \times 10^{-17}$

\[ R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))} \]
How it is done
(note: somewhat similar project COMET starting in Japan)

This experiment is in R&D and Pre-Construction Mode with CD1 approval
Chapter 2: Pions & Photons

Silicon strip tracker inside an evacuated dipole for excellent vtx & mom resolution
\[ B_{\text{calc}} = \frac{\Gamma(\pi \rightarrow e\bar{\nu}(\gamma))}{\Gamma(\pi \rightarrow \mu\bar{\nu}(\gamma))_{\text{calc}} } = \begin{cases} 
1.2352 (5) \times 10^{-4} \\
1.2354 (2) \times 10^{-4} \\
1.2352 (1) \times 10^{-4} 
\end{cases} \]

Current Expt. World Avg. = \(1.230 \pm 0.004\) \times 10^{-4} \ x \ 10 \ \text{improvement}

\[ \frac{\delta B}{B} \simeq 5 \times 10^{-4} \]

PEN data taking complete. Analysis in progress

PiENu data taking

\*at PSI  \quad **at TRIUMF
A’, a massive neutral vector boson
- kinematically mixes with $\gamma$
- $\alpha' = \varepsilon \alpha_{e.m.}$  $\varepsilon = 10^{-2} - 10^{-6}$
- Mass in the MeV-GeV region

- Can explain g-2 discrepancy
- Can explain cosmic positron data

2010 → … Dark Photon searches: @JLab
Method: Produce $A'$ with electron beam
Detect pair decays (narrow peak above background)

APEX in Hall A
Simplest using existing spectrometers

Heavy Photon Search @ Hall B
Physics reach: $\epsilon < 10^{-4}$; mass 20-800 MeV
Parasitic test run complete 2012
Plan for physics run in 12 GeV era

DarkLight @ the JLab FEL
- FEL beam (~1mA, 100 MeV) incident on a H2 gas jet target.
- Collect 1/ab in ~ 60 days of beam time
- High acceptance detector inside a 0.5 T solenoid

Successful Test Run (July 2012)
Seeking funding
Chapter 3: Neutrons & Nuclei
1. **DDH model** - uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 7 weak meson coupling constants

\[ f_\pi, h_\rho^0, h_\rho^1, h_\rho^2, h_\omega^0, h_\omega^1 \]

- Observables can be written as their combinations

\[ A = a_\rho f_\pi^1 + a_\omega h_\omega^0 + a_\rho h_\rho^1 + a_\rho h_\rho^2 + a_\omega h_\omega^0 + a_\omega h_\omega^1 \]

\[ A_\gamma \approx -0.11 f_\pi^1 \]

\[ f_\pi \approx 4.5 \times 10^{-7} \]

2. **Lattice QCD**
- J. Wasem, PRC C85 (2012)

\[ f_\pi = 1.099 \pm 0.505 \pm 0.058 \pm 0.006 \times 10^{-7} \ (m_\pi \sim 589 \text{MeV}) \]

3. **Effective Field Theory** (hybrid and pure)
- model-independent

- NN potentials are expressed in terms of 12 parameters, whose linear combinations give us 5 low energy coupling constants

- connect to 5 parity-odd S-P NN amplitudes

\[ A_\gamma^{np} \approx -0.27 C_6^\pi - 0.09 m_N \rho_t \]

**Curious result**
Method and Status: On floor at the FnPB (SNS)

- Already taken hydrogen data at the $5 \times 10^{-8}$ $A_\gamma$ level.

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi} \left(1 + A_\gamma \cos \theta\right)$$

$A_\gamma$ – directional asymmetry in the gammas emitted from cold neutron capture on protons

- 200 MW-days, starting next month, needed to reach goal of $1 \times 10^{-8}$
The Neutron as a Fundamental Laboratory

\[ n \rightarrow p^+ + e^- + \nu'_e \]

neutron lifetime \( \tau \approx 15 \text{ min} \)
\( \beta \)-endpoint energy: \( E_{\text{max}} = 782 \text{ keV} \)

\[
dW \propto \frac{1}{\tau_n} \frac{1}{F(E_e)} \left[ 1 - a \frac{p_e \cdot p_V}{E_e \cdot E_V} + b \frac{m_e}{E_e} + \frac{\sigma_n \cdot p_v}{E_v} \right]
\]

\[
\tau_n \propto \frac{1}{(g_A^2 + 3g_V^2)}
\]

\[
a = \frac{1 - \left( \frac{g_A}{g_V} \right)^2}{1 - 3 \left( \frac{g_A}{g_V} \right)^2}
\]

\[
b = 0
\]

\[
A = -2 \left( \frac{g_A}{g_V} \right)^2 + \left( \frac{g_A}{g_V} \right)
\]

\[
B = 2 \left( \frac{g_A}{g_V} \right)^2 - \left( \frac{g_A}{g_V} \right)
\]

Neutron beta decay measurements give:

\[
\left( g_A^2 + 3g_V^2 \right) / g_V
\]
Neutron Decay Correlations

\[ \frac{g_A}{g_V} \]

Neutron Lifetime

\[ g_A^2 + 3g_V^2 \]

Nuclear \( O^+ \rightarrow O^+ \) Decays, CKM Unitarity

Neutron Decay Correlations

\[ g_V \]
2007 picture: Lifetime and Correlations combine in a confused picture for the physics of \( g_A \) or unitarity

\[ g_V \equiv G_F V_{ud} f(0) \]
This well-known plot of **Neutron Lifetime versus Time** illustrates just how difficult this measurement is:

Reanalysis of bottle experiments by Serebrov, et al.

Serebrov et al.,

(878.5 ± 0.7 ± 0.3) seconds

PDG 2010 average:

\( \tau_n = 885.7 \pm 0.8 \) seconds
2012: \( n \) Lifetime Update: PDG

As Kumar \( n \) Committee recommended, an improved BEAM-method at 1-s precision is very important.
Big Bang Nucleosynthesis

Thermal Equilibrium

\[
\begin{align*}
    p + \bar{v}_e & \leftrightarrow n + e^+ \\
    n + v_e & \leftrightarrow p + e^-
\end{align*}
\]

\[n/p \sim e^{-Q/T}\]

After Freezeout

n/p decreases due to neutron decay

\[n \rightarrow p + e^- + \bar{v}_e\]

Nucleosynthesis

\[T \sim 0.1 \text{ MeV}\]

Light elements are formed.

\[p + n \rightarrow d + \gamma\]
\[d + d \rightarrow ^4\text{He} + \gamma\]

almost all neutrons present \(\rightarrow ^4\text{He}\)

Neutron lifetime dominates theoretical uncertainty in \(^4\text{He}\) abundance.

Kolb and Turner, The Early Universe, 1990
2009 - 13 UCNA: big “A” with Ultracold Neutrons

\[ R = R_0 (1 + \frac{v}{c} P \ A(E) \ \cos \theta) \]

- Only expt. using ultracold neutrons for angular correlation measurements
- Scintillator + MWPC detector package
- Very low background (see plot)

<table>
<thead>
<tr>
<th>Year</th>
<th>Statistics</th>
<th>( \delta A/A )</th>
<th>Published</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>2 M</td>
<td>4.5%</td>
<td>2009</td>
</tr>
<tr>
<td>2008/2009</td>
<td>24 M</td>
<td>1.4%</td>
<td>2010</td>
</tr>
<tr>
<td>2010/2011</td>
<td>65 M</td>
<td>&lt;1%</td>
<td>Fall 2012</td>
</tr>
</tbody>
</table>
The ILL efforts have defined the field for a long time.

MUND et al (2012) = $-1.2767(16)$

Not in PDG yet
Tests of CKM Unitarity via nuclear beta, muon and Kaon decays at the 0.06% level
2012 Picture: Lifetime and Correlations in better shape, but lifetime and Asymmetry still in tension

\[ g_V \equiv G_F V_{ud} f(0) \]
2015- Nab – future and beyond

- Measure the electron-neutrino parameter $a$ in neutron decay with accuracy of \[ \frac{\Delta a}{a} \approx 10^{-3} \]
  or $\approx 50 \times$ better than:
  
  $-0.1054 \pm 0.0055$  Byrne et al ’02
  
  current results: $-0.1017 \pm 0.0051$  Stratowa et al ’78
  
  $-0.091 \pm 0.039$  Grigorev et al ’68

- Measure the Fierz interference term $b$ in neutron decay with accuracy of \[ \Delta b \approx 3 \times 10^{-3} \] Never measured in n decay

- Nab will be followed by the abBA/PANDA polarized program to measure $A$, electron, and $B/C$, neutrino/proton, asymmetries with $\approx 10^{-3}$ relative precision, an independent measurement of $\lambda$. 
Nab principles of measurement

- Collect and detect both electron and proton from neutron beta decay.
- Measure $E_e$ and $\text{TOF}_p$ and reconstruct decay kinematics
- Segmented Si det’s:

Nab experiment at FnPB/SNS
Toward Exotica with Nuclei
(just a few examples)

Argonne

$^8$Li decay kinematics
- Pure GT decay
- Characteristic $\beta-\alpha-\alpha$ coincidence

Seattle Tandem van de Graaff

$\rightarrow 10^9$ $^6$He atoms/s
$\rightarrow$ Lifetime
$\rightarrow$ Decay correlations with MOT
Probing exotic scalar and tensor CC couplings

\[ \mathcal{L}_{CC} \supset -\frac{G_F V_{ud}}{\sqrt{2}} \left[ \epsilon_S \bar{\ell}(1-\gamma_5)\nu \cdot \bar{u} d + \epsilon_T \bar{\ell} \sigma_{\mu\nu}(1-\gamma_5)\nu \cdot \bar{u} \sigma^{\mu\nu}(1-\gamma_5)d \right] \]

- **Current**: $0^+ \rightarrow 0^+$ (b) constrains $\epsilon_S$; $\pi \rightarrow e \nu \gamma$ constrains $\epsilon_T$ [green band]
- **Future**: neutron b, B @ $10^{-3}$ level (Nab; UCNB,b, abBA, ...) [red band], $^6$He (b) [yellow band]

$\Lambda_S = 3.2$ TeV

$\Lambda_S = 5$ TeV

$\Lambda_T = 7$ TeV

$\Lambda_T = 5$ TeV

$g_S = 0.8 (4)$

$g_T = 1.05(35)$

Bhattacharya, Cirigliano, Coh Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011
Neutron experiments mostly from Kumar report priorities; others R&D

Many of these are approximate and depend on actual funding profiles
Charge (nEDM and PVES added for completeness)

1. What major scientific discoveries have occurred in your research area since the 2007 LRP was drafted?
   1. TWIST Michel parameters agree with SM; pushes out $W_R$
   2. $G_F$ to 0.5 ppm (best EW measured parameter)
   3. $g_P$ measurement confirms theory after more than 40 years controversy
   4. $g-2$ signal now about 3.5 $\sigma$, owing to improved SM theory
   5. $A$ in $n$ beta decay measured precisely by 2 independent experiments
   6. $V_{ud}$, when combined with $V_{us}$ and $V_{ub}$ satisfies CKM unitarity to 0.06%.
   7. emiT measures D coefficient $n$ beta decay to $(-0.96 \pm 1.89 \pm 1.01) \times 10^{-4}$

2. What compelling and unique science is to be done in the next 5 years?
   1. $g-2$ experiment to 0.14 ppm on schedule
   2. $f_\pi$ from NPDGamma
   3. $n$ lifetime from Beam technique
   4. Qweak result
   5. nEDMs emerging from ?? experiment
   6. Improved $n$ beta decay parameters from neutrons and nuclei.
   7. Perhaps not designed for “5 $\sigma$” discovery, but null results at 90% C.L. will constrain exotic theories at sensitive levels
3. What science would you expect to pursue in the program in “2020” and beyond?
   1. Mu2e experiment
   2. US nEDM
   3. Moller at 11 GeV
   4. Storage ring EDM of proton
   5. Smaller efforts that might be proposed: e.g., abBA, n lifetime, muon EDM, …)
   6. AND, it DEPENDS ON WHAT WE FIND!!

4. What is the international context, and how does it affect your vision?
   1. Unique Muon Campus at FNAL will dominate on g-2 and Mu2e, but JPARC can be very competitive with COMET and possible little g-2
   2. PSI owns stopping muon experiments (MEG, MuSun, mu → eee, …)
   3. Neutron sources highly competitive
   4. nEDM very intense competition
   5. PVES rather unique in US program

5. Manpower, resources, etc.
   1. Sustaining effort of research groups and enabling travel and detector, electronics, daq purchases essential
   2. Continue to support MRIs for strategic opportunities (recent example: Nab)
   3. Make room for a few “big” projects in the future. This field can defend it.
Summary

- A lot of superb and diverse projects
- Scale from small $ to large $$$
- A wide variety of facilities used.
  - Often nuclear physics does not have to ‘provide the beam’
    - SNS, PSI, Fermilab, Solar Neutrinos; Reactor Neutrinos, just hiding underground and ducking the cosmics rays, … and so on
  - Important science, highly leveraged
- International competition is very active
  - Sometimes they are ahead
  - Sometimes the US is ahead
  - Very often, it’s close and depends on support

This talk featured contributions from MANY people in the field, but I did not cover everything. Apologies