Lattice QCD: an Enabling Technology for Project X

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What is Project X?

- A stoner movie from this year?
- A roller coaster at Legoland?
- A high-power proton accelerator?

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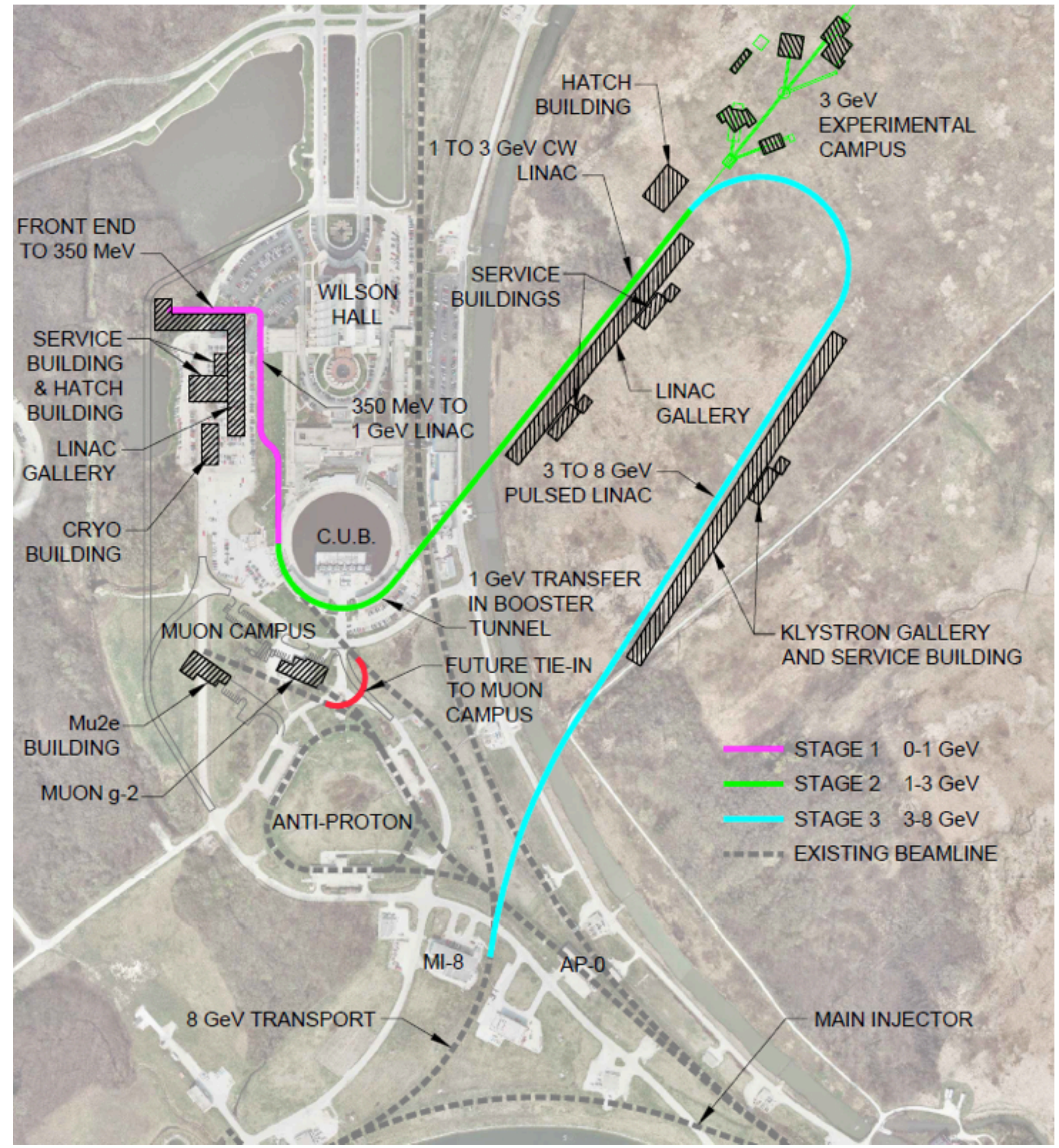
LEGO
TECHNIC TEST TRACK
PROJECT X
DOWN

What is Project X?

- A stoner movie from this year?
- A roller coaster at Legoland?
- A high-power proton accelerator?



Fermilab Accelerator Complex

- 400 MeV Linac (pulsed)
- 8 GeV Booster (pulsed synchrotron)
- 120 GeV Main Injector (can run at 60 GeV)
- The Recycler (storage ring in MI tunnel)
- Tevatron (now mothballed)
- Project X replaces the Linac and Booster with an 8 GeV linac based on superconducting RF (~TESLA/ILC).

Current Fermilab Experimental Program

- 8 GeV Booster
  - Booster ν beam: MiniBooNE, SciBooNE; MicroBooNE
  - Muon campus: New Muon *g*–2, Mu2e
- 120 GeV Main Injector
  - NuMI beam: MINOS, MINERvA, ArgoNeut; NOvA; MINOS+
  - Fixed target: SeaQuest, MIPP; ORKA
  - Homestake beam: LBNE
- (CMS; astrophysics projects; analysis of “finished” experiments)

Run(ning)
Construction
CD-x
Proposed

Beam Requirements

- Different kinds of experiments require different kinds of beams:
  - neutrinos want as many protons as possible in widely spaced bunches;
  - rare kaons want (very) slow spill to avoid two coincident decays;
  - other programs somewhere between these extremes.
- Leads to tension between neutrino program and others.
- Project X Stages 1 and 2 have a “continuous wave” to solve this problem.

Project X

http://projectx.fnal.gov/
https://indico.fnal.gov/event/projectxps12/

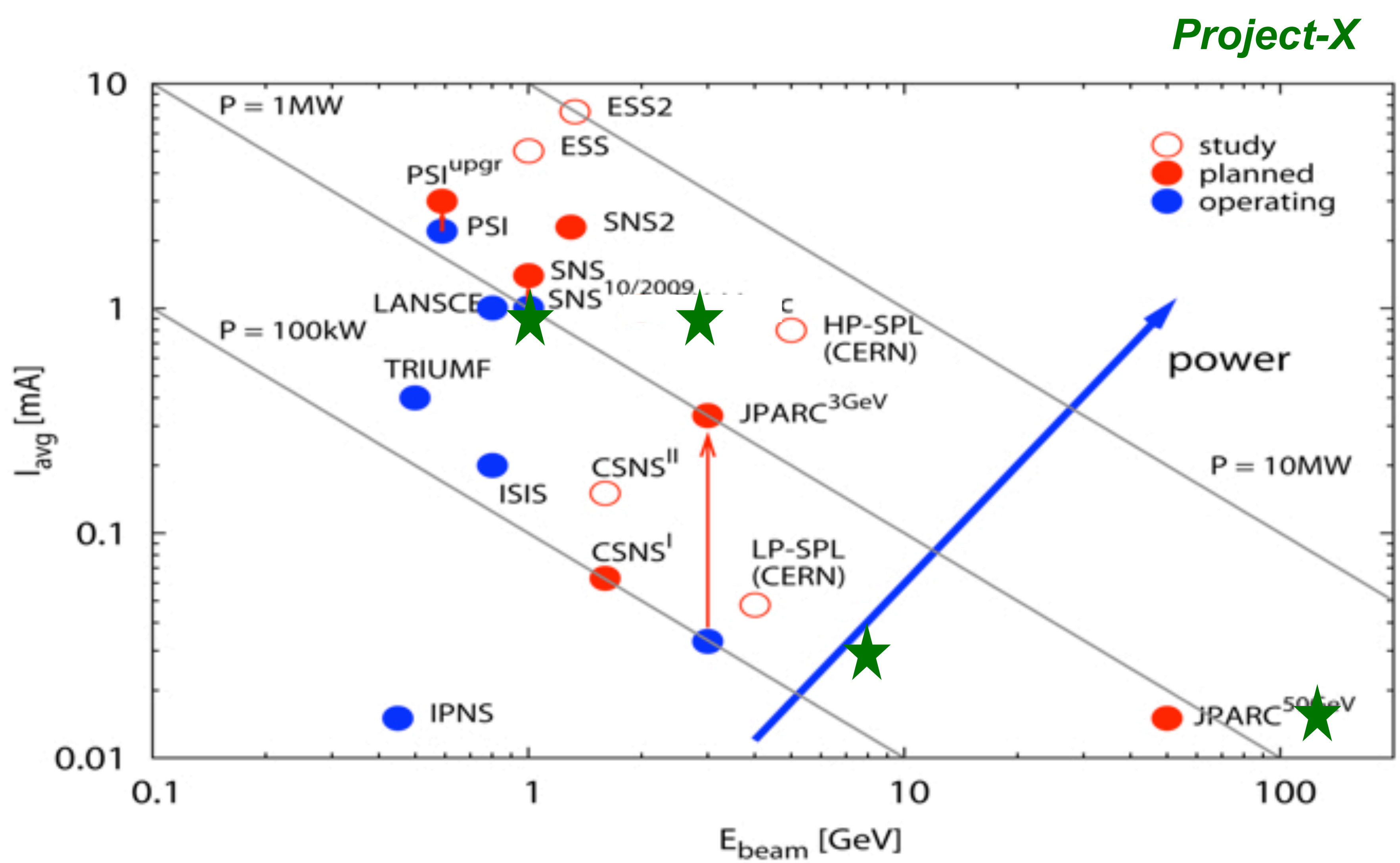
Example Power Staging Plan

Project X

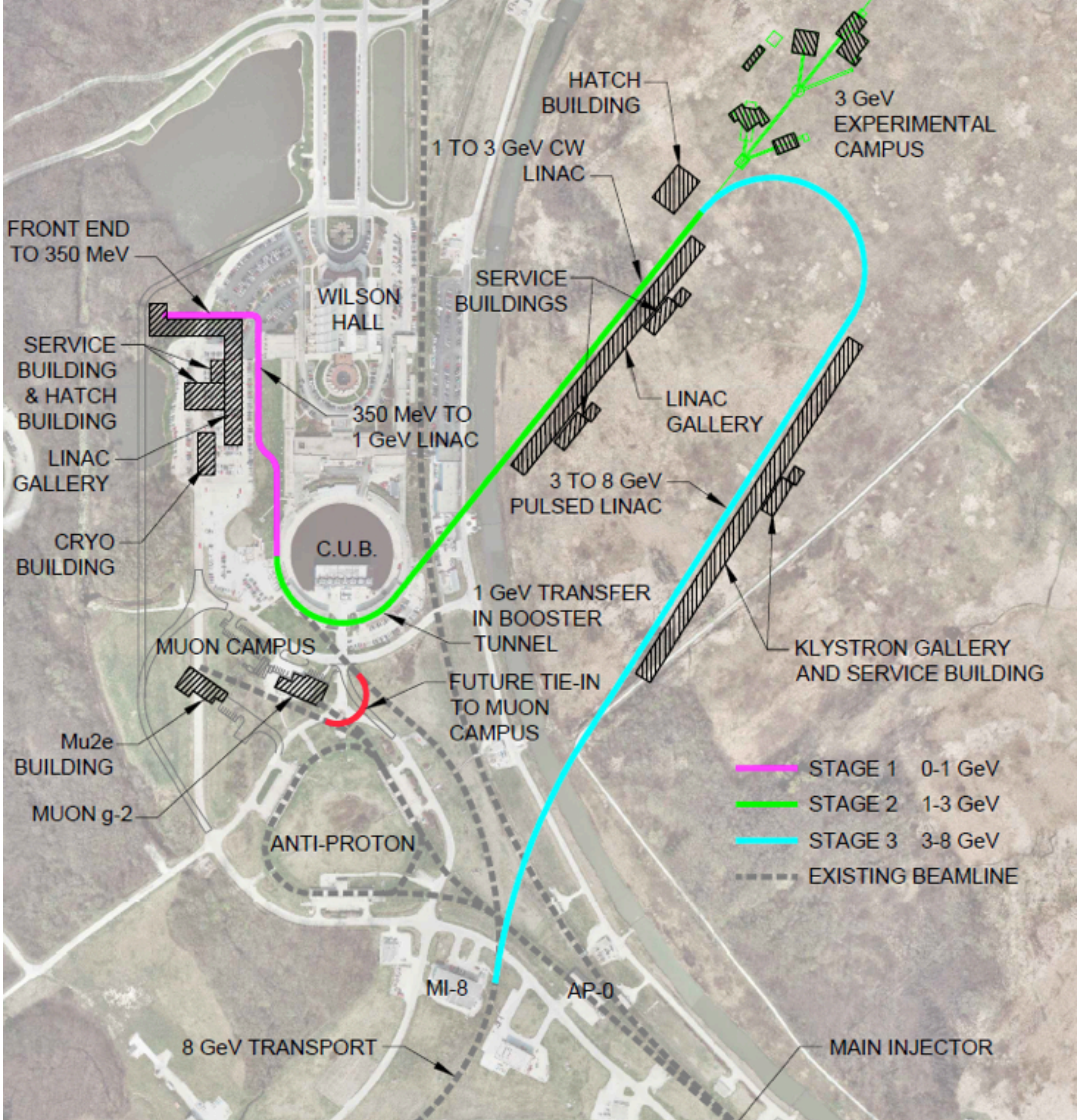
Program	Present complex	Stage 1 1 GeV CW Linac	Stage 2 3 GeV CW Linac	**Stage 3** **Project X RDR**	Stage 4 (beyond RDR)
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1–3 GeV Muon	none	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW**	0-75 kW**	1100 kW	1870 kW	1870 kW
Nuclear EDMs	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutrons	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs	4	8	8	8	8
Total max power	735 kW	2222 kW	4284 kW	6492 kW	11870kW

*** Operating point depends on Main Injector energy for neutrinos.**
**** Operating point depends on Main Injector slow-spill duty factor.**

The Landscape

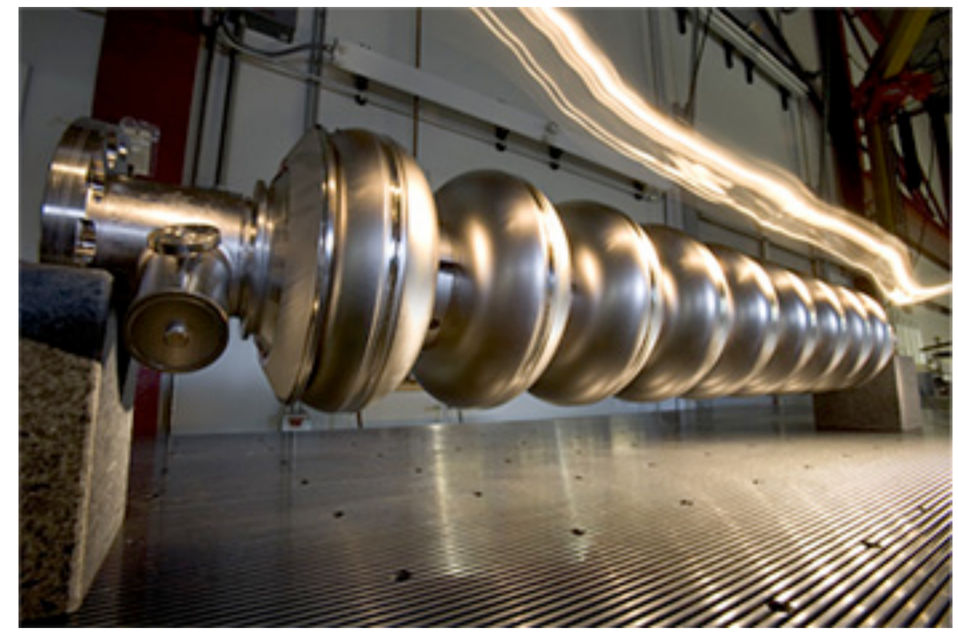


M. Seidel (PSI); S. Holmes (Fermilab)


HATCH BUILDING
3 GeV EXPERIMENTAL CAMPUS
1 TO 3 GeV CW LINAC
FRONT END TO 350 MeV
WILSON HALL
SERVICE BUILDINGS
SERVICE BUILDING & HATCH BUILDING
LINAC GALLERY
350 MeV TO 1 GeV LINAC
LINAC GALLERY
3 TO 8 GeV PULSED LINAC
CRYO BUILDING
C.U.B.
1 GeV TRANSFER IN BOOSTER TUNNEL
MUON CAMPUS
KLYSTRON GALLERY AND SERVICE BUILDING
FUTURE TIE-IN TO MUON CAMPUS
Mu2e BUILDING
MUON g-2
STAGE 1 0-1 GeV
STAGE 2 1-3 GeV
STAGE 3 3-8 GeV
EXISTING BEAMLINE
ANTI-PROTON
MI-8
AP-0
8 GeV TRANSPORT
MAIN INJECTOR

Accelerating Cavities

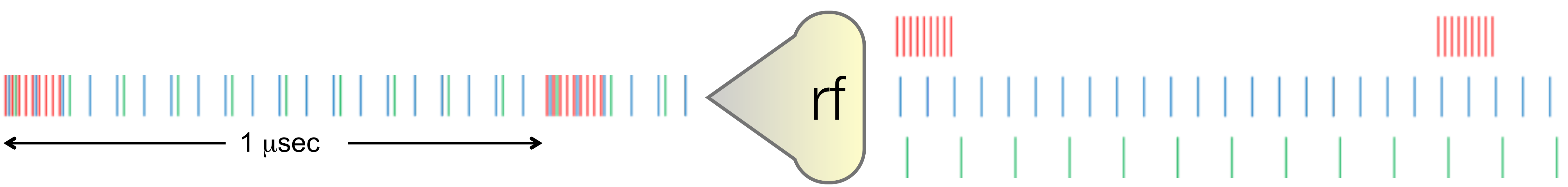
- Superconducting niobium.
- Pioneered by DESY/TESLA:
  - being used for European XFEL.
- Developed further for ILC (DESY, Saclay, Fermilab, JLab, Cornell, KEK, …).
- Can also accelerate protons (lots of them).
- For low energies—$\beta < 1$—need cavities with "boutique" shape & frequency.



- ν = 1.3 GHz , λ = 23 cm

Continuous Wave + Beam Splitter

- The first two Stages (1 GeV & 1–3 GeV) can be filled with any beam structure needed by the experiments. Example:
  - muon pulses: 80 MHz, 100 ns 700 kW
  - kaon pulses: 20 MHz 1540 kW
  - nuclear pulses: 10 MHz 770 kW



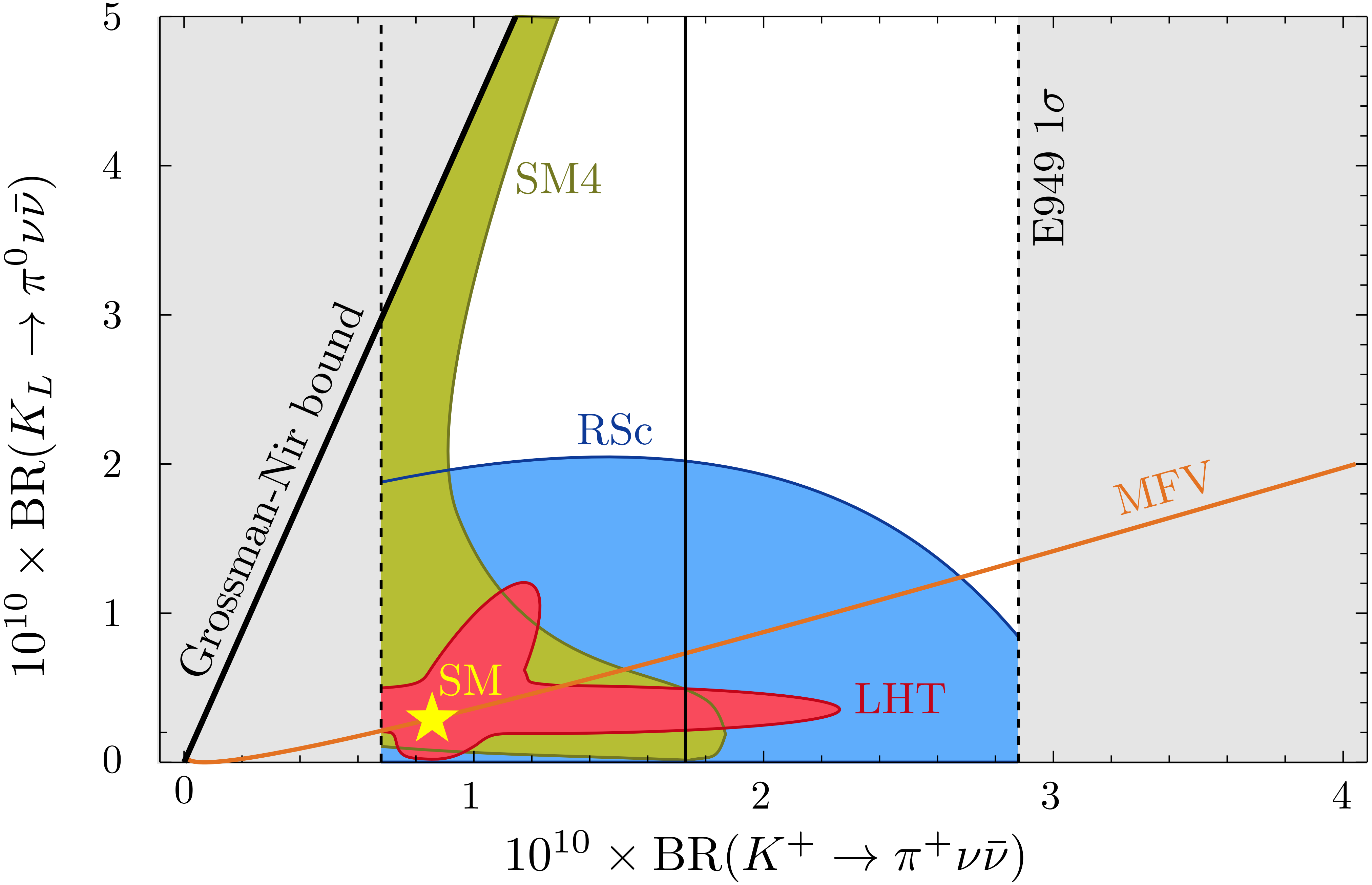
- Upstream splitter for 3–8 GeV (Stage 3) & Main Injector.

Lattice QCD Opportunities

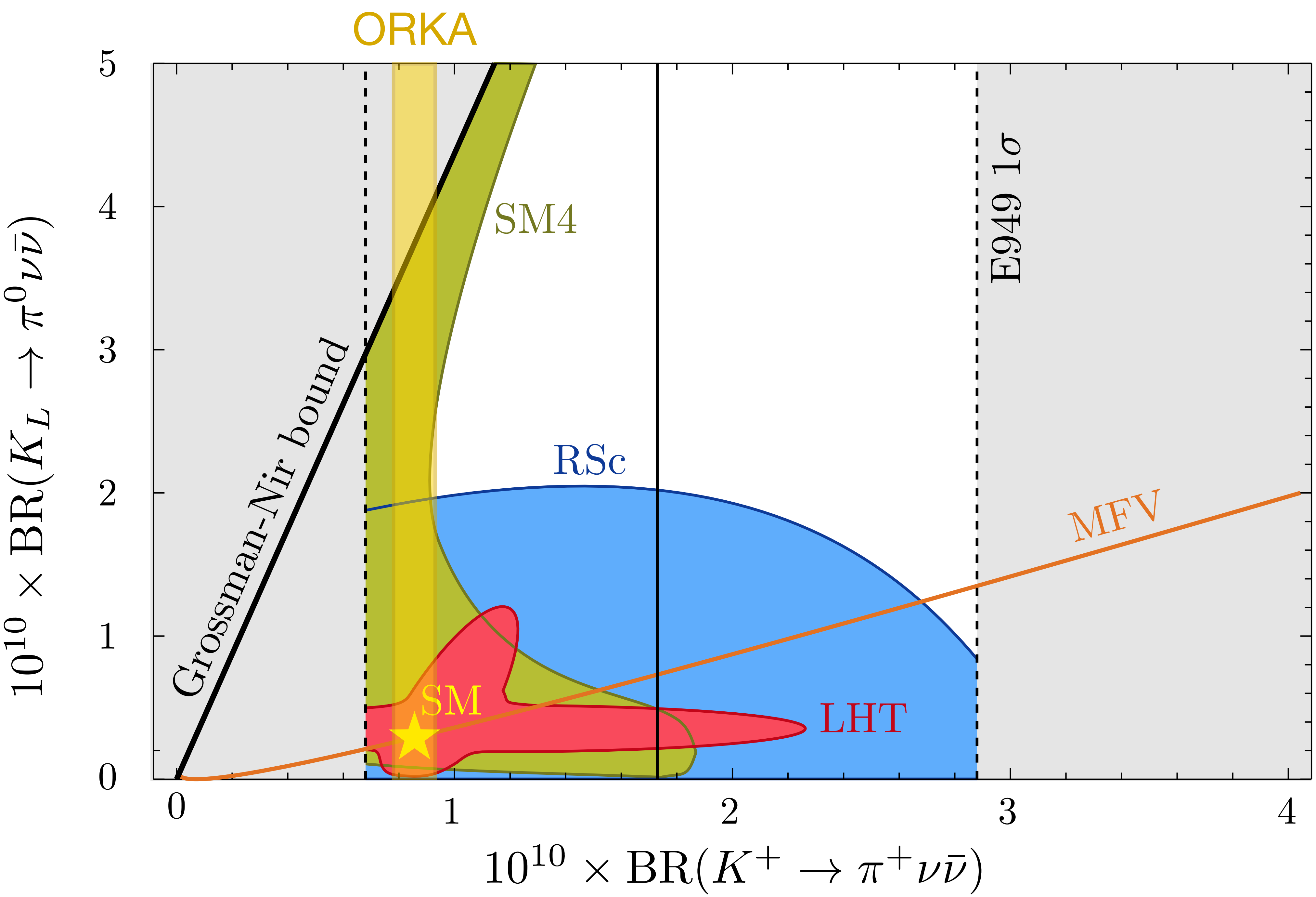
Experiments

- Kaon experiments: rare decays using secondary beams from MI or booster.
- Hadronic physics: with 120 GeV proton beams, or secondary beams.
- Electric dipole moments: nucleons, radioisotopes, ..., produced at 1 or 3 GeV.
- Muon experiments: from secondary booster beam.
- Neutron-antineutron oscillations: from neutrons produced at 1 or 3 GeV.
- Proton decay: in conjunction with large, underground neutrino detectors.
- Neutrinos: long- and short baseline oscillations; neutrino scattering.

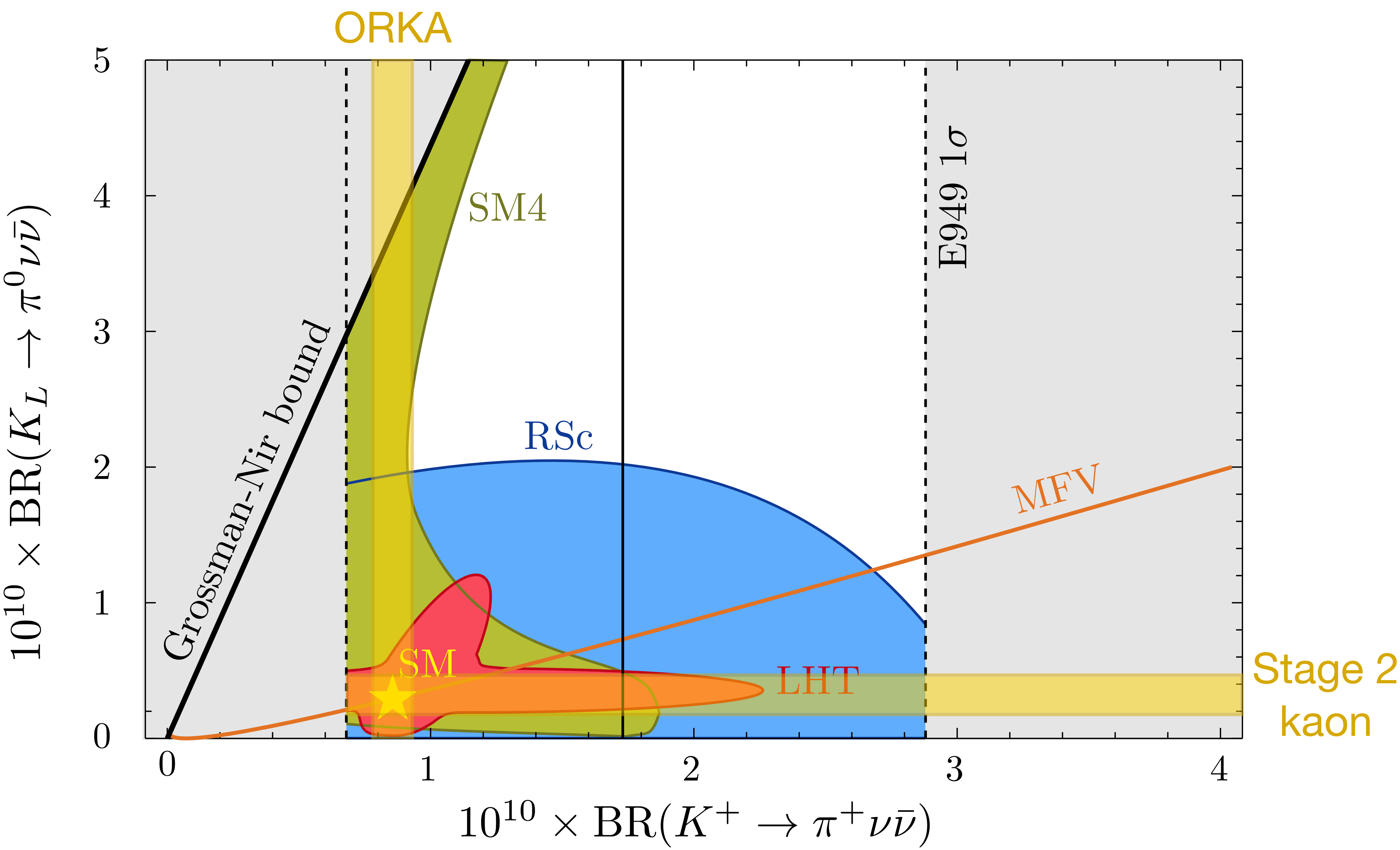
Rare Kaon Decays



Rare Kaon Decays

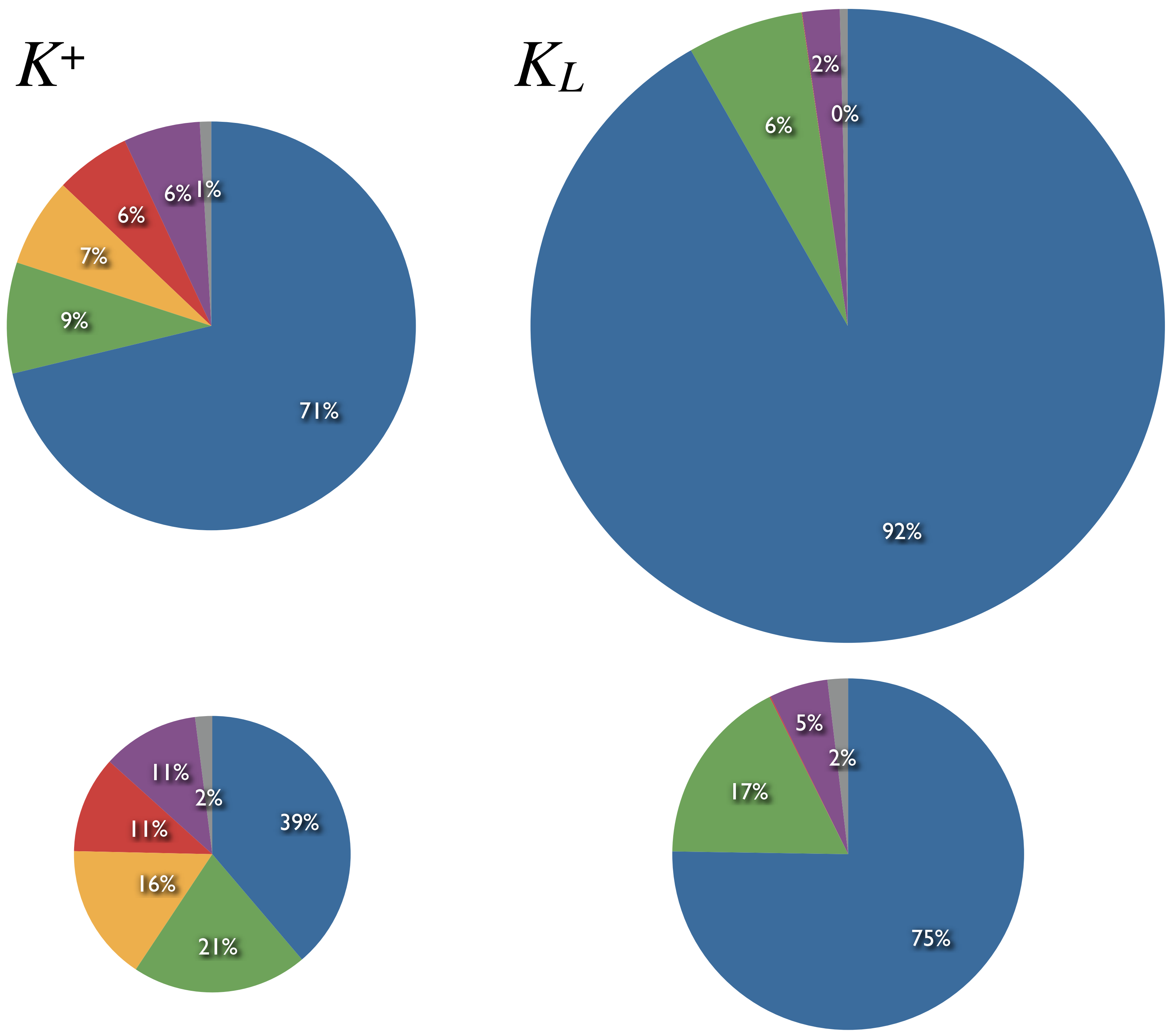


Rare Kaon Decays



Relative Error Budgets

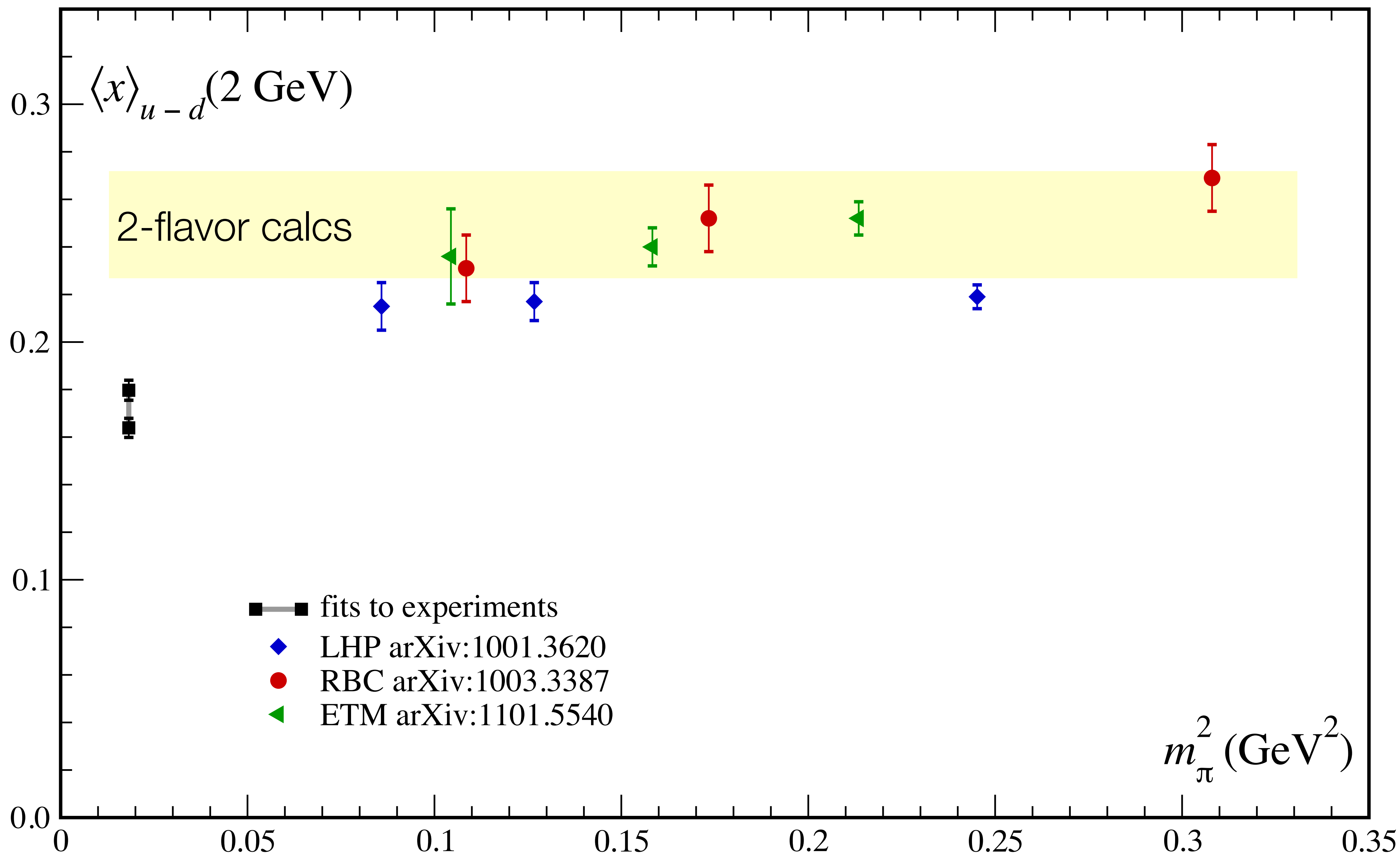
- Top pies show current status
- Blue error is CKM, esp. V_{cb} and V_{ub}
- Bottom pies assume CKM errors ÷ 2



Hadron Structure

cf., Paul Reimer

- Moments of parton densities:



Neutron Decay

- Stage 1 of PX (the 1 GeV linac) has a power similar to SNS:
  - source of ultra-cold neutrons for beta decay, neutron EDM, and neutron-antineutron oscillations.
- Next generation neutron beta-decay experiments will be sensitive to scalar and tensor interactions: compute g_A, g_S, g_T:

$$\begin{aligned} \langle p|\bar{u}\gamma^\mu\gamma^5 d|n\rangle &= g_A \bar{u}_p \gamma^\mu \gamma^5 u_n \\ \langle p|\bar{u}d|n\rangle &= g_S \bar{u}_p u_n \\ \langle p|\bar{u}\sigma^{\mu\nu} d|n\rangle &= g_T \bar{u}_p \sigma^{\mu\nu} u_n \end{aligned}$$

(neglecting small stuff).

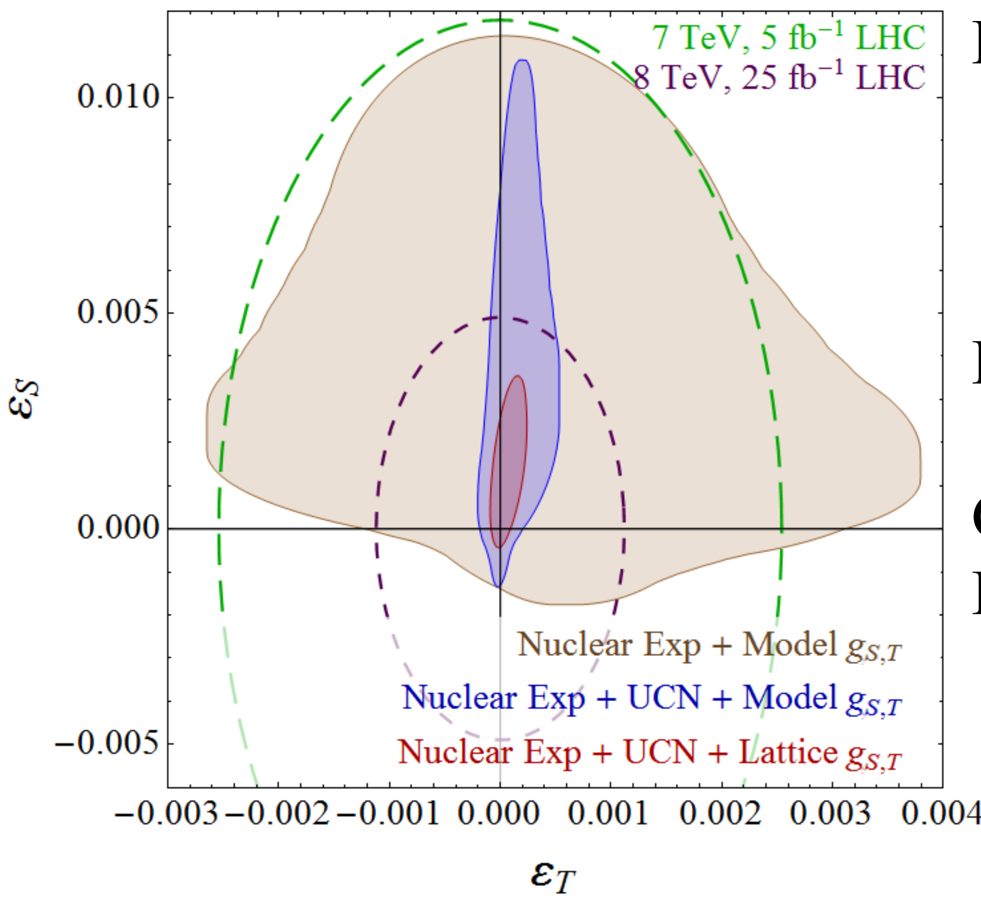
g_S, g_T, g_A on the Lattice

Saul Cohen

High-Energy Constraints

§ Constraints from high-energy experiments?

LHC current bounds and near-term expectation



Estimated though effective *L*

$$\mathcal{L} = -\frac{\eta_S}{\Lambda_S^2} V_{ud} (\overline{u} d)(\overline{e} P_L \nu_e) - \frac{\eta_T}{\Lambda_T^2} V_{ud} (\overline{u} \sigma^{\mu\nu} P_L d)(\overline{e} \sigma_{\mu\nu} P_L \nu_e)$$

Looking at high transverse mass in $e\,\nu + X$ channel

Compare with *W* background

Estimated 90% C.L. constraints on

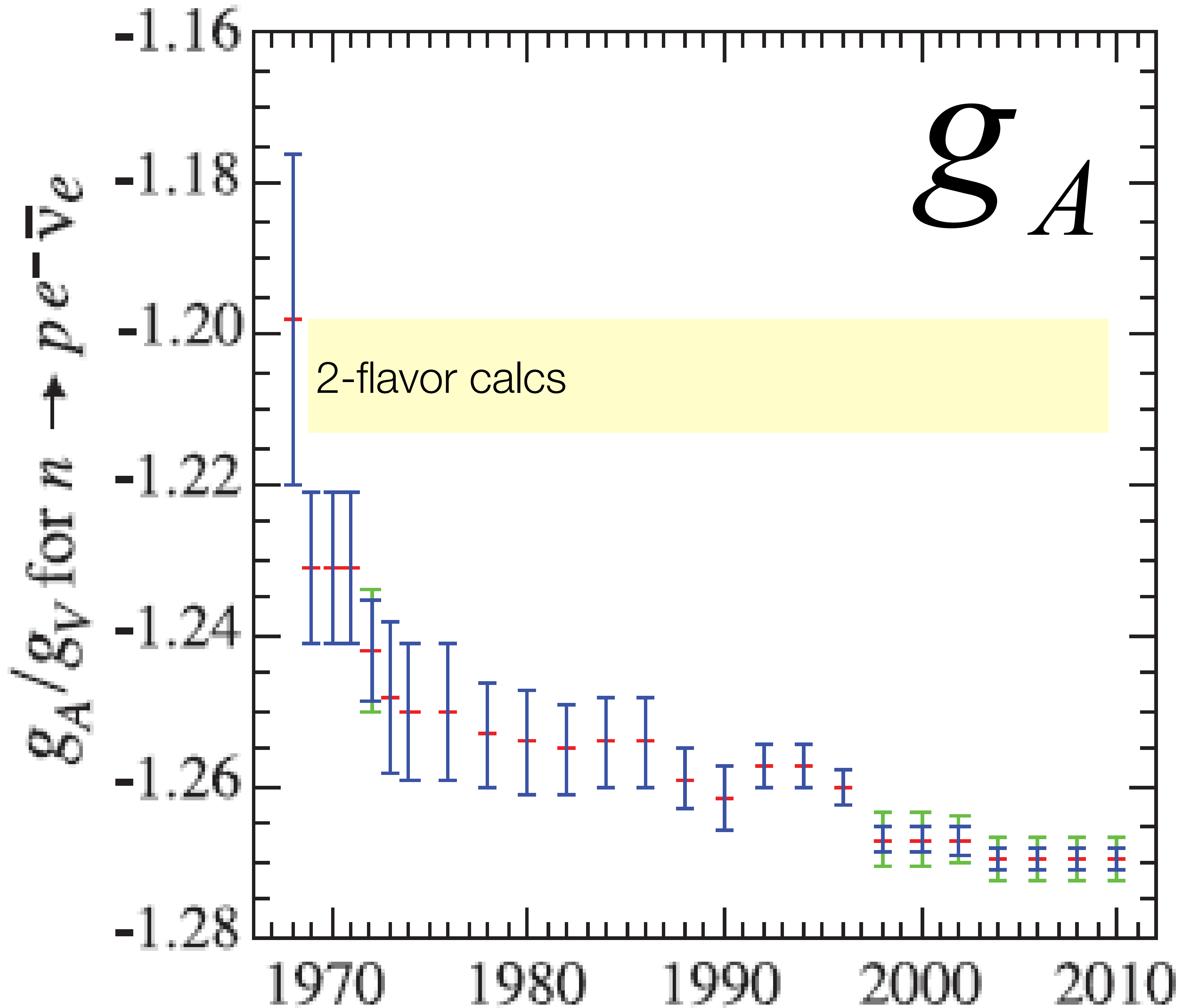
$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

HWL, 1112.2435; 1109.2542

T. Bhattacharya et al, 1110.6448

Nucleon Structure in the Lab: g_A and g_V

Brad Plaster



Proton Decay

- Although not directly related to Project X, big underground neutrino detectors (e.g., liquid argon) can also be used for proton decay.

$$\langle \pi \ell | q q q \ell | p \rangle$$

- Many groups have worked on this.

- Interesting to get to the physical point:

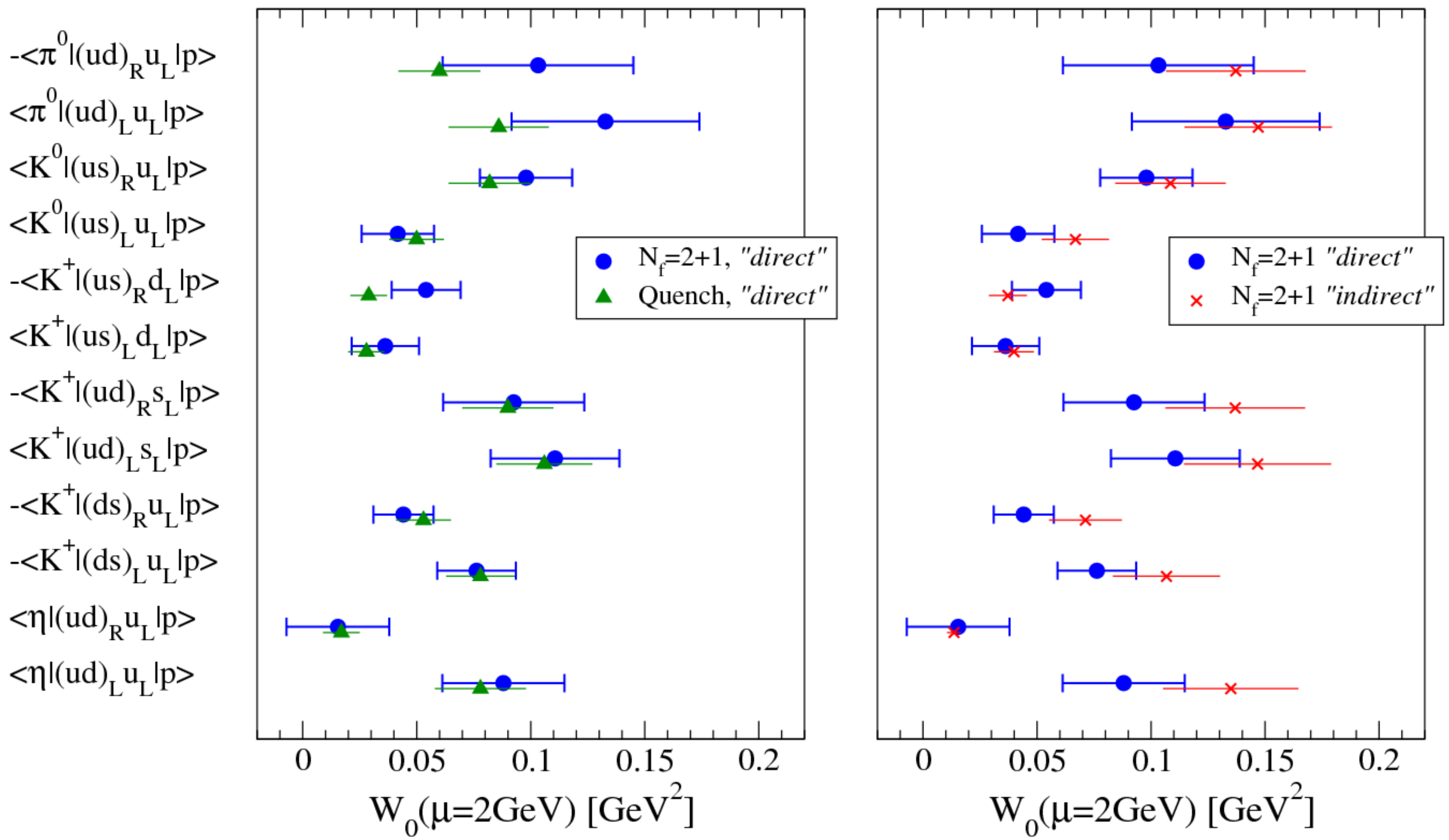
    - Chiral bag model suggests extremely strong suppression in chiral limit [Martin & Stavenga]

Proton Decay

Taku Izubuchi

In full QCD

RBC/UKQCD in prep.



- There is no significant discrepancy between each results.
- Statistical and systematic errors are still large.

Neutron-Antineutron Transitions

Michael Buchoff

$\mathcal{P}_i$: basis of 6-quark operators

VERY Preliminary Results

	Lattice	MIT Bag Model
$\langle\overline{n}\vert\mathcal{P}_1\vert n\rangle$	$1.57(\pm0.85)(+0.25)(-0.30)$	-6.56
$\langle\overline{n}\vert\mathcal{P}_2\vert n\rangle$	$-0.20(\pm0.14)(+0.14)(-0.12)$	1.64
$\langle\overline{n}\vert\mathcal{P}_3\vert n\rangle$	$-0.24(\pm0.26)(+0.10)(-0.07)$	2.73
$\langle\overline{n}\vert\mathcal{P}_4\vert n\rangle$	$-0.02(\pm0.39)(+0.07)(-0.18)$	-6.36
$\langle\overline{n}\vert\mathcal{P}_5\vert n\rangle$	$0.34(\pm0.82)(+0.27)(-0.57)$	9.64
$\langle\overline{n}\vert\mathcal{P}_6\vert n\rangle$	$-2.07(\pm1.10)(+1.28)(-0.77)$	-28.92
	$\times10^{-5}$ GeV^6	$\times10^{-5}$ GeV^6

Electric Dipole Moments

Tanmoy Bhattacharya

- Both strong and BSM CP violation contribute to nucleon EDM

$$
\begin{aligned}
d_n &\approx \frac{8\pi^2}{M_n^3}\left[-\frac{2m_*}{3}\frac{\partial\langle\bar{q}\sigma q\rangle_F}{\partial F}\left(\bar{\Theta} + g_s\frac{\langle\bar{q}G\sigma q\rangle}{2\langle\bar{q}q\rangle}\sum\frac{d_q^G}{m_q}\right)\right.\\
&\quad + \frac{\langle\bar{q}q\rangle}{3}\left(4\,d_d^\gamma - d_u^\gamma\right)\\
&\quad \left. + g_s\frac{\langle\bar{q}G\sigma q\rangle}{6\langle\bar{q}q\rangle}\left(4\,d_d^G\frac{\partial\langle\bar{d}\sigma d\rangle_F}{\partial F} - d_u^G\frac{\partial\langle\bar{u}\sigma u\rangle_F}{\partial F}\right)\right]\\
&\approx \left(\frac{4}{3}d_d^\gamma - \frac{1}{3}d_u^\gamma\right) - \frac{2e\langle\bar{q}q\rangle}{M_n f_\pi^2}\left(\frac{2}{3}d_d^G + \frac{1}{3}d_u^G\right),
\end{aligned}
$$

- Strong CP flips sign for need both to disentangle!

EDM Experiments

- Neutron: trap neutrons: “standard”
- Proton: store two counter-circulating proton beams in an *electrostatic* storage ring; see http://www.bnl.gov/edm/ for details.
- The intense PX beam can also produce heavy ions, leading to atomic and nuclear EDMs that get at electron EDM.
- The muon source enables muon EDM.

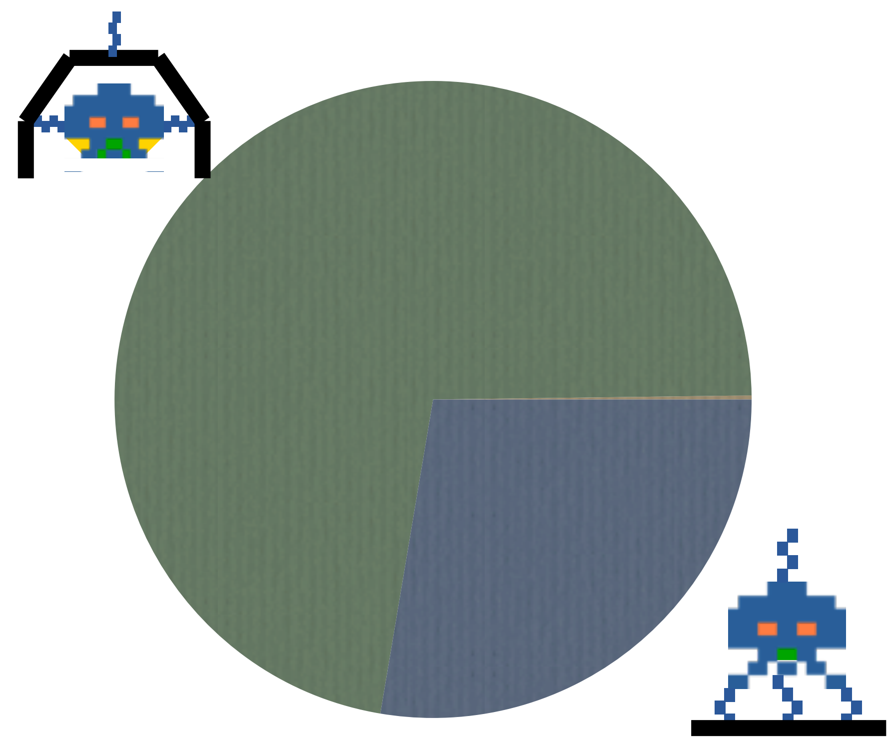
Error Budgets for Muon $(g-2)$

error ∝ perimeter; area ∝ weight in sum in quadrature

stats
syst

BNL E821 → FNAL E989

HL×L
HVP
EW

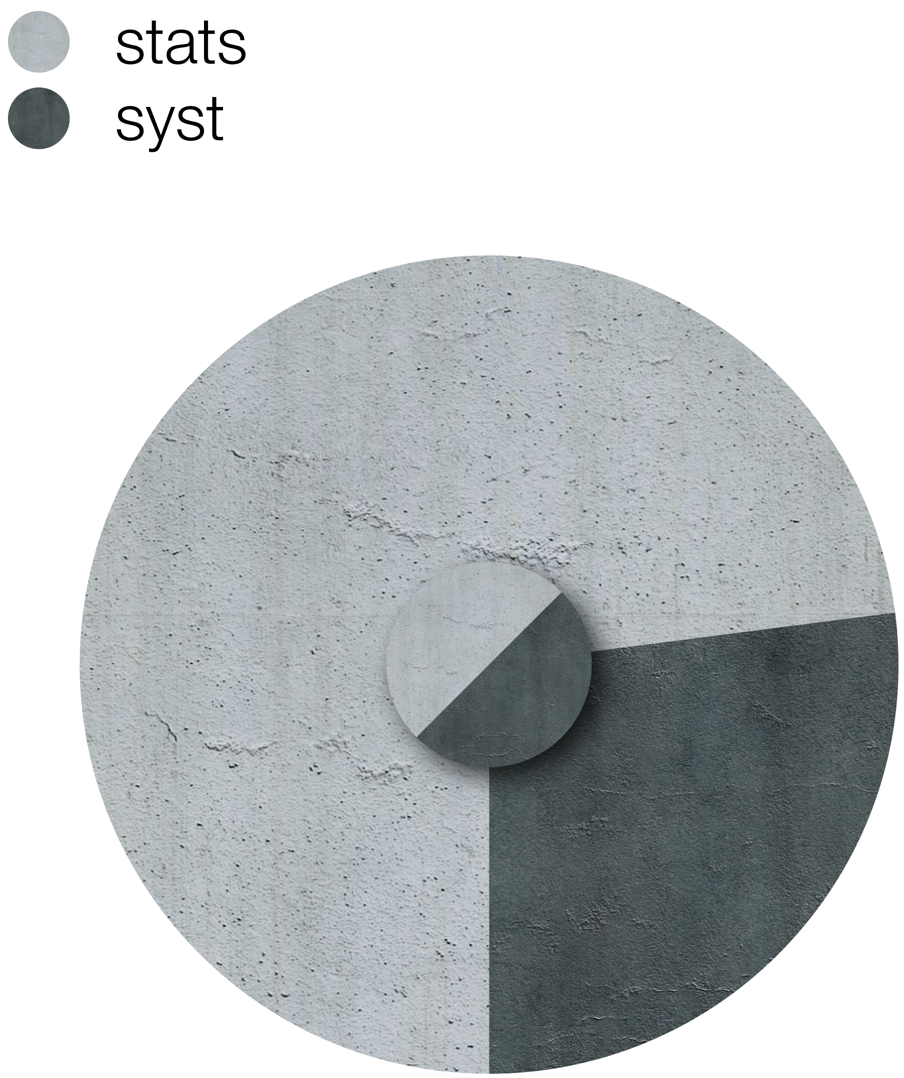


Standard Model Calculation

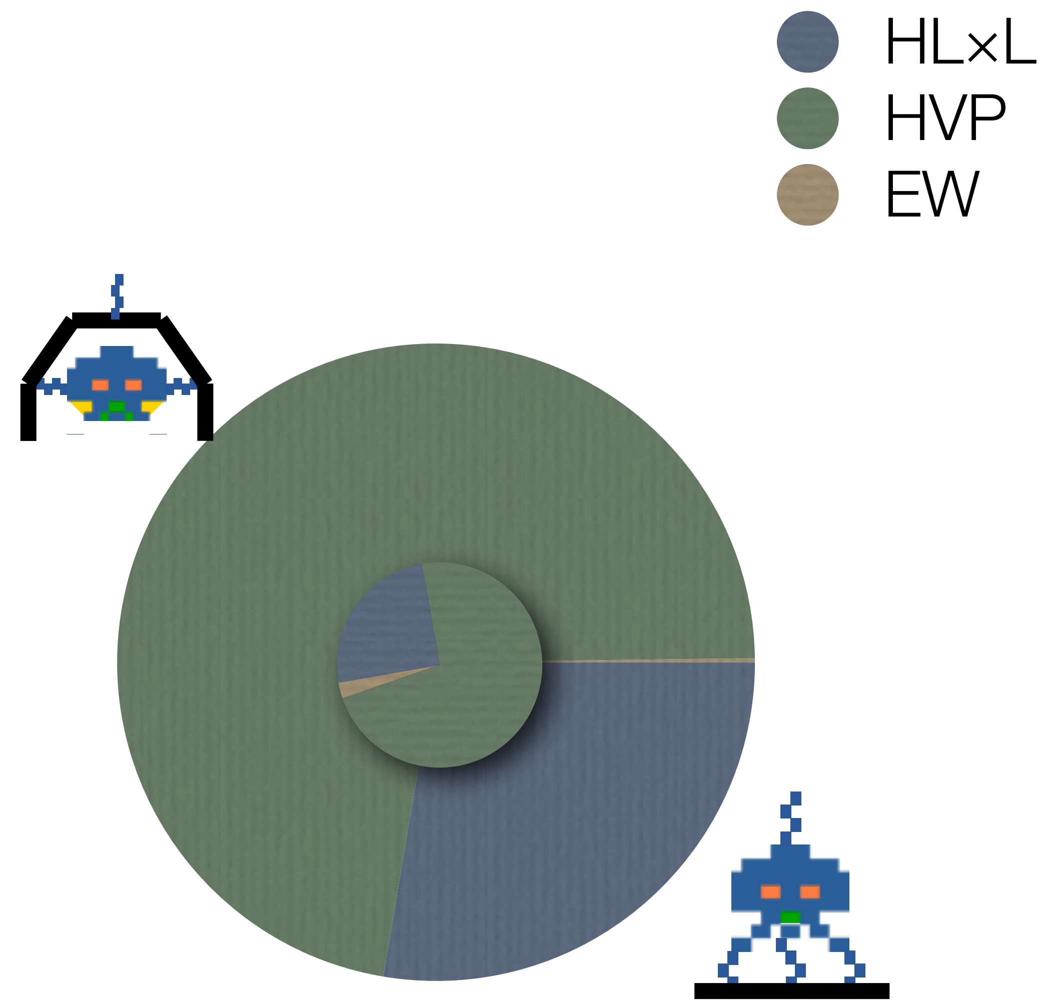
25

Error Budgets for Muon $(g - 2)$

error ∝ perimeter; area ∝ weight in sum in quadrature



BNL E821 → FNAL E989

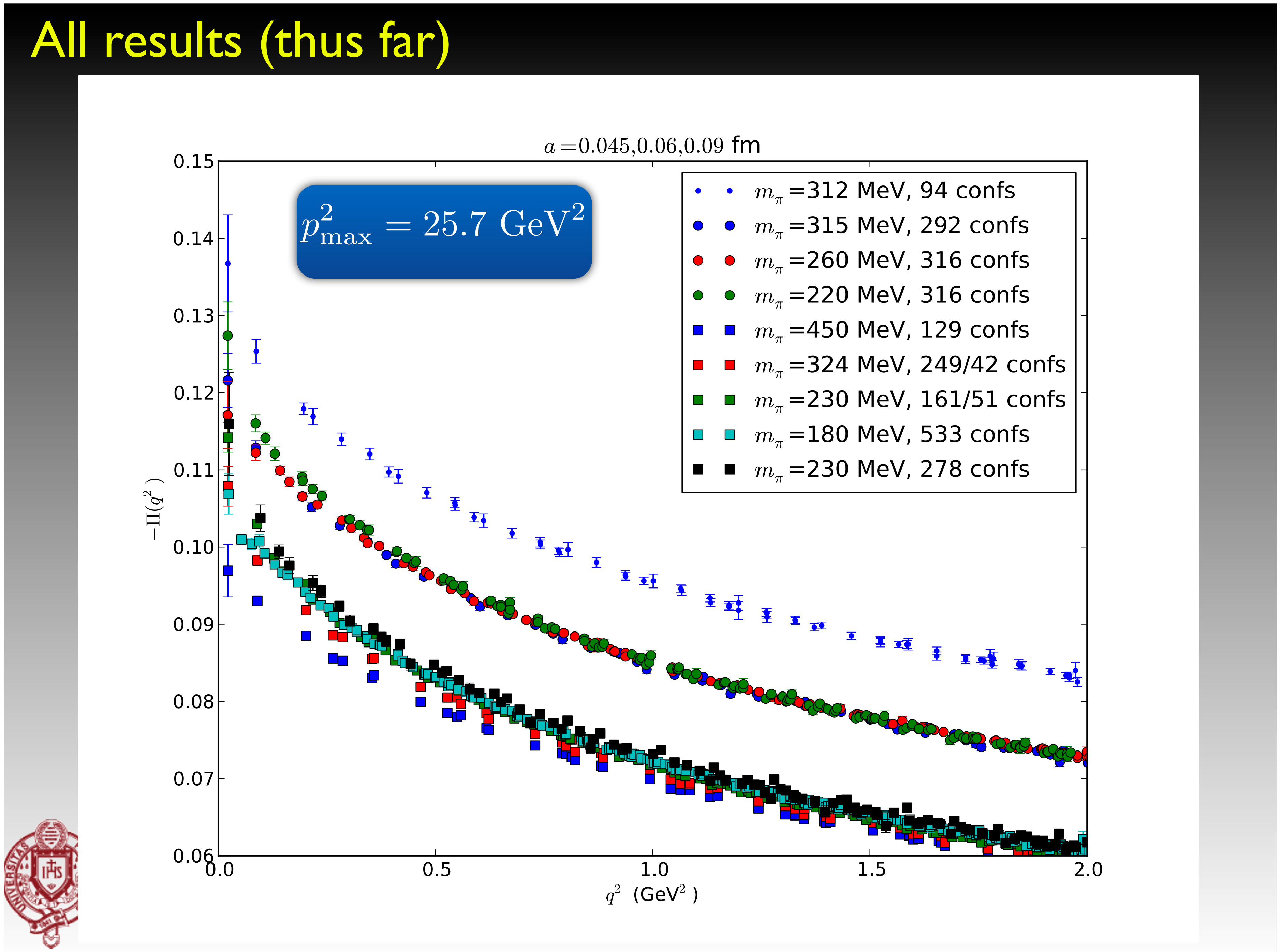


Standard Model Calculation

25

Muon g–2: Hadronic Vacuum Polarization

Christopher Aubin

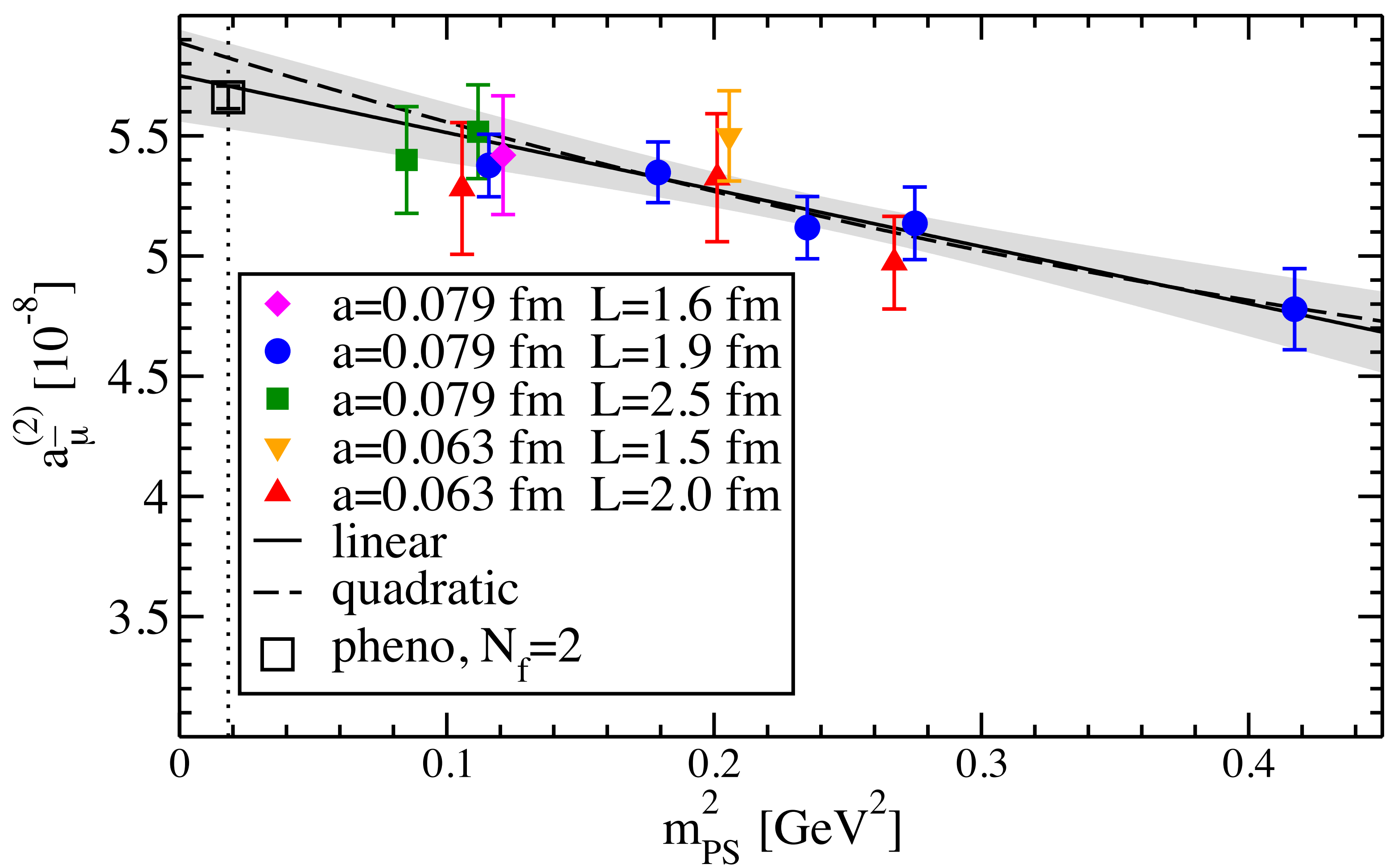


Muon g–2: Hadronic Vacuum Polarization

Dru Renner

Leading-order correction to a_μ

modified method lead to reliable well-controlled calculation of $a_\mu^{(2)}$



use of $N_f = 2$ was the only substantially weak part of calculation

Muon g–2: Hadronic Light-by-Light

Tom Blum

$a_\mu(\mathrm{HLbL})$ in 2+1f lattice QCD+QED (PRELIMINARY)

Signal may be emerging in the model ballpark:

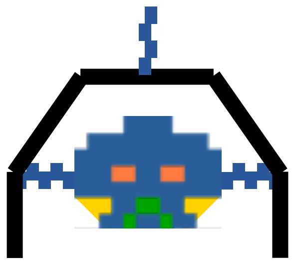
- $F_2(0.18\ \mathrm{GeV}^2) = (0.142 \pm 0.067) \times \left(\frac{\alpha}{\pi}\right)^3$
- $F_2(0.11\ \mathrm{GeV}^2) = (0.038 \pm 0.095) \times \left(\frac{\alpha}{\pi}\right)^3$
- $a_\mu(\mathrm{HLbL/model}) = (0.084 \pm 0.020) \times \left(\frac{\alpha}{\pi}\right)^3$

Lattice size 24^3, $m_\pi = 329$ MeV, $m_\mu \approx 190$ MeV

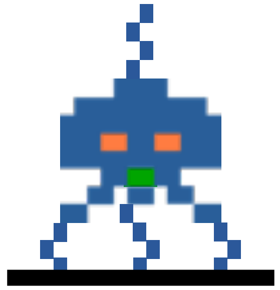
model value/error is "Glasgow Consensus" (arXiv:0901.0306 [hep-ph])

Muon g–2: Summary

- HVP will proceed and do well on the timescale of E989.



- HLxL needs more ideas from more people.



Muon Capture (needed for Mu2e)

- Coherent: low-energy limit of pn form factor.
- Incoherent contribution (quasi-informed guess)
  - low-energy scale ~ 100 MeV
  - nuclear effective theory (Kaplan, Savage, Wise, …), to reduce nuclear physics to nucleon-nucleon interactions
  - used, e.g., to assess strangeness content of neutron stars (NPLQCD).

Neutrino Experiments

- Deeply inelastic neutrino scattering → hadron structure moments of PDFs.
- Several other hadronic issues in neutrino physics:
  - neutrino cross sections;
  - matter effects;
  - π and K production in target.
- Some topics for the future; one for now!

Slide from lecture by Petr Vogel (Caltech)

NNPSS-TSI 2010

QE scattering at ~ 1 GeV, need to take into account the nucleon structure characterized by form factors

Vector ff can be determined in electron scattering, under control

Nucleon current
$$j^\mu = [F_1^V(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_\nu - F_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2)q^\mu\gamma^5]\tau^\pm$$

Pseudoscalar ff ~$(m_l/M)^2$, small

axial form factor

$$F_A(Q^2) = \frac{1.267}{(1+Q^2/M_A^2)^2}$$

$F_A(Q^2=0)$ from β decay

- Q^2 dependence can only be measured in ν scattering
- not as well measured
- assumed to have dipole form

(function of a single parameter "axial mass" = M_A)

must be measured experimentally!

Conclusions

Physics Opportunities

- Kaon experiments
- Hadronic physics
- Electric dipole moments (nucleon)
- Muon experiments: Mu2e; g-2
- Neutron-antineutron oscillations
- Proton decay
- Neutrino experiments

- V_{cb} and V_{ub}
- Moments of PDFs; spectroscopy.
- Nucleon matrix elements
- Nucleon matrix elements; HLxL
- Nucleon matrix elements—6 quark
- Nucleon matrix elements—3 quark
- Nucleon matrix elements

Nucleon Matrix Elements

Nucleon Matrix Elements
(which are hard)