Neutrino Scattering Measurements on Hydrogen and Deuterium: A Snowmass White Paper

NuSTEC board meeting, 7 December 2021

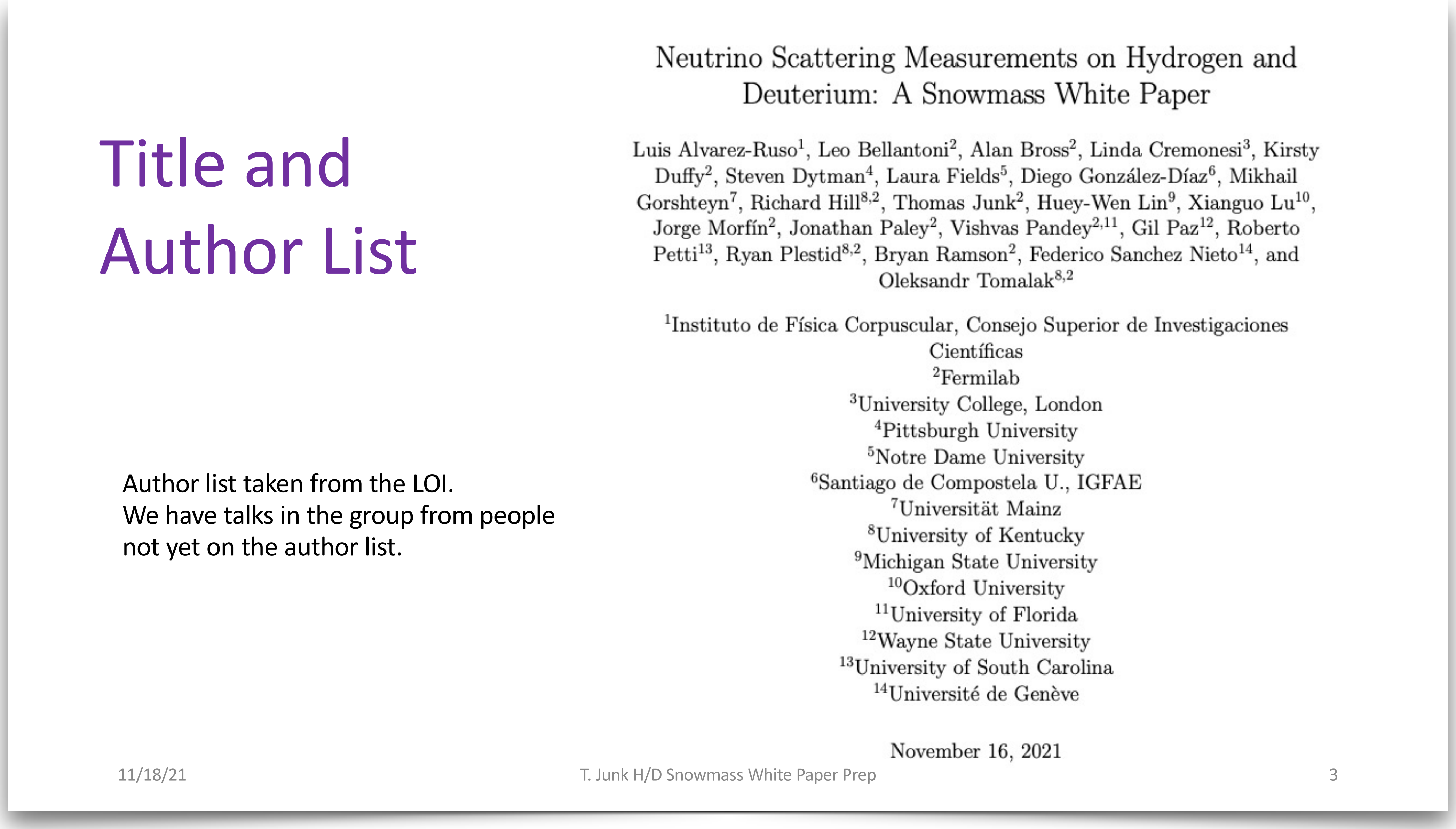
Richard Hill, U. Kentucky and Fermilab

Thomas Junk, Fermilab

overview

- administration
- theory
- experiment

administration



Title and Author List

Author list taken from the LOI.
We have talks in the group from people not yet on the author list.

Neutrino Scattering Measurements on Hydrogen and Deuterium: A Snowmass White Paper

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[11]University of Florida
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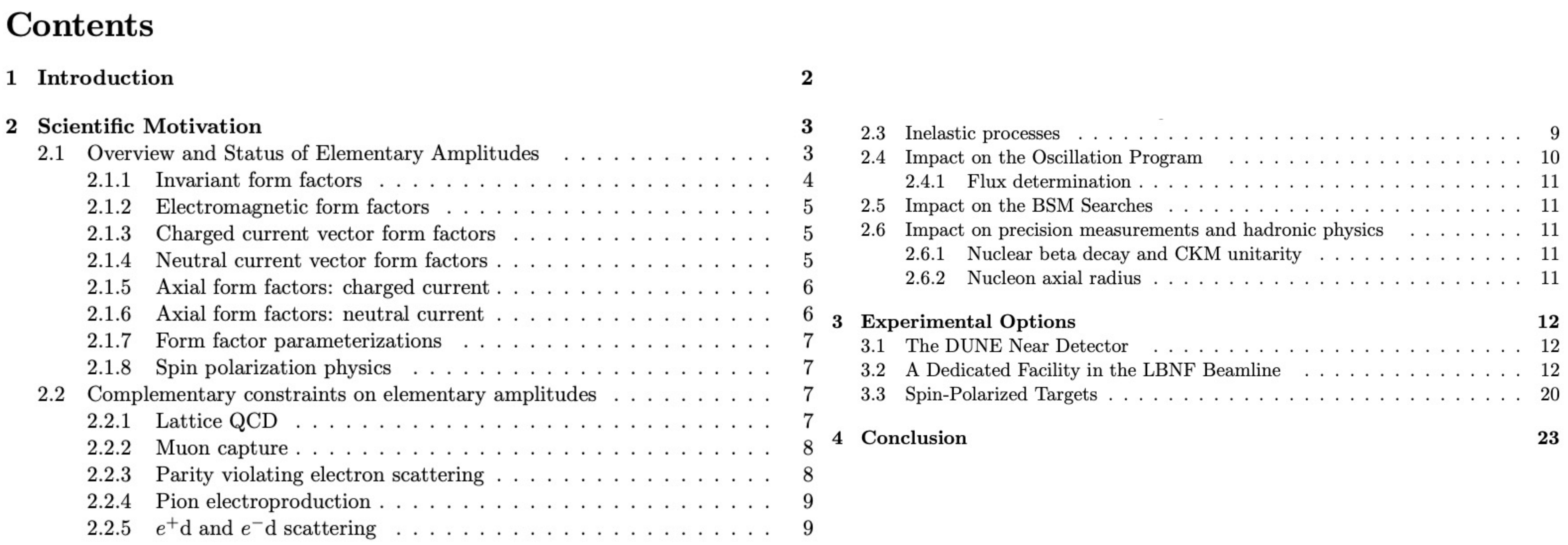
[14]Université de Genève

November 16, 2021

11/18/21 T. Junk H/D Snowmass White Paper Prep 3

- please get in touch for editable overleaf link, slides from previous working group meetings and mailing list for announcements

Current Status, cont'd



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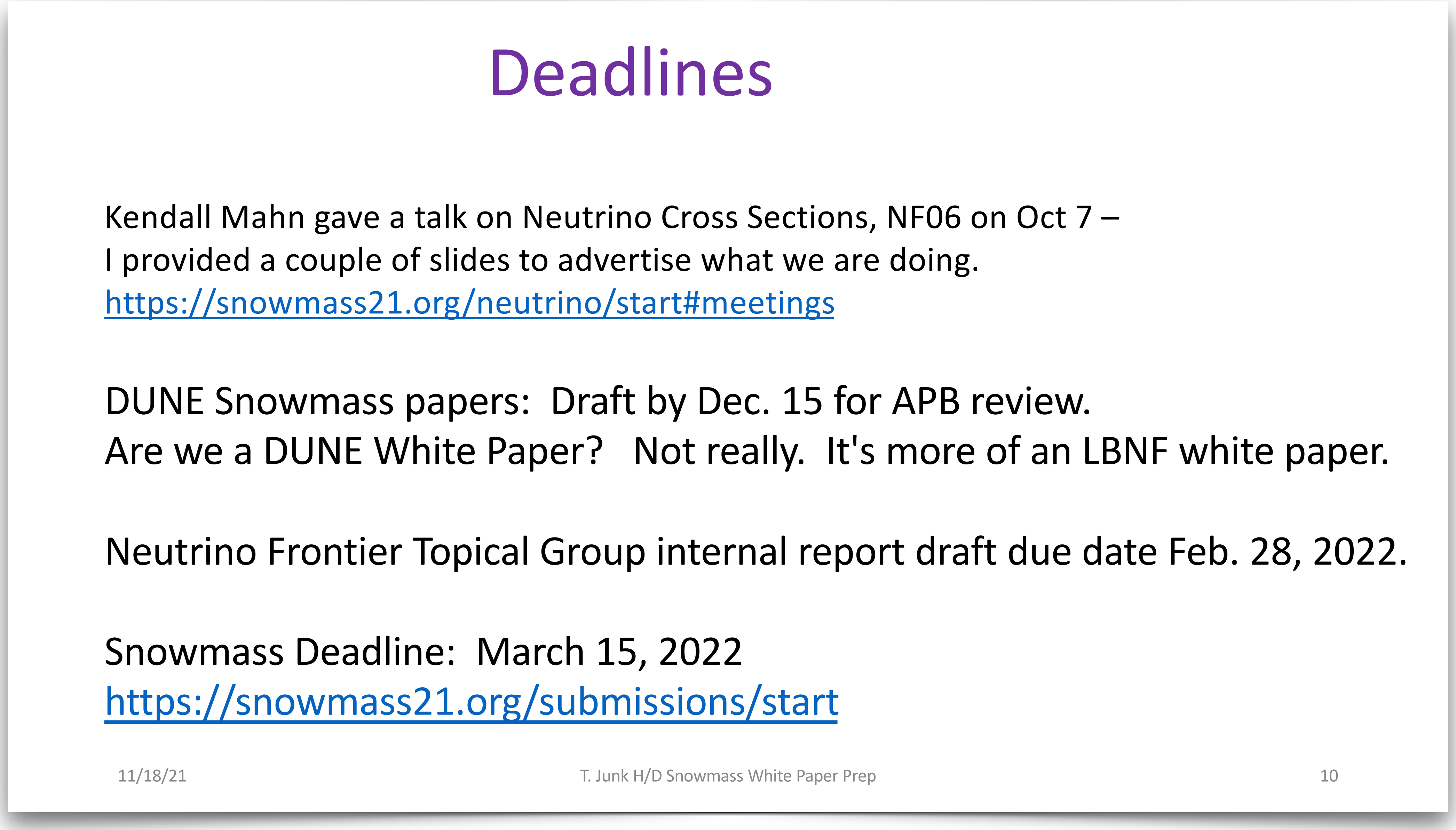


Deadlines

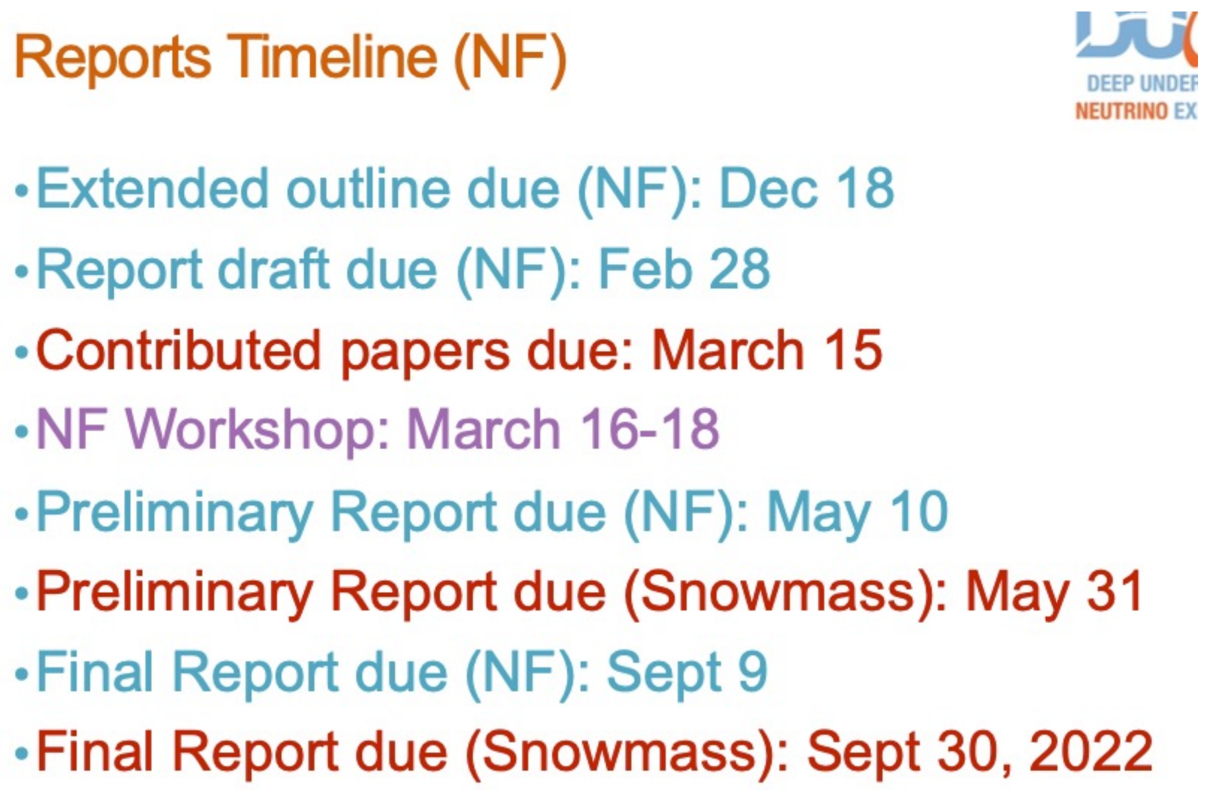
Kendall Mahn gave a talk on Neutrino Cross Sections, NF06 on Oct 7 –
I provided a couple of slides to advertise what we are doing.
https://snowmass21.org/neutrino/start#meetings

DUNE Snowmass papers: Draft by Dec. 15 for APB review.
Are we a DUNE White Paper? Not really. It's more of an LBNF white paper.

Neutrino Frontier Topical Group internal report draft due date Feb. 28, 2022.

Snowmass Deadline: March 15, 2022
https://snowmass21.org/submissions/start

A Snowmass Timeline Slide from Elizabeth Worcester with Longer Timescales



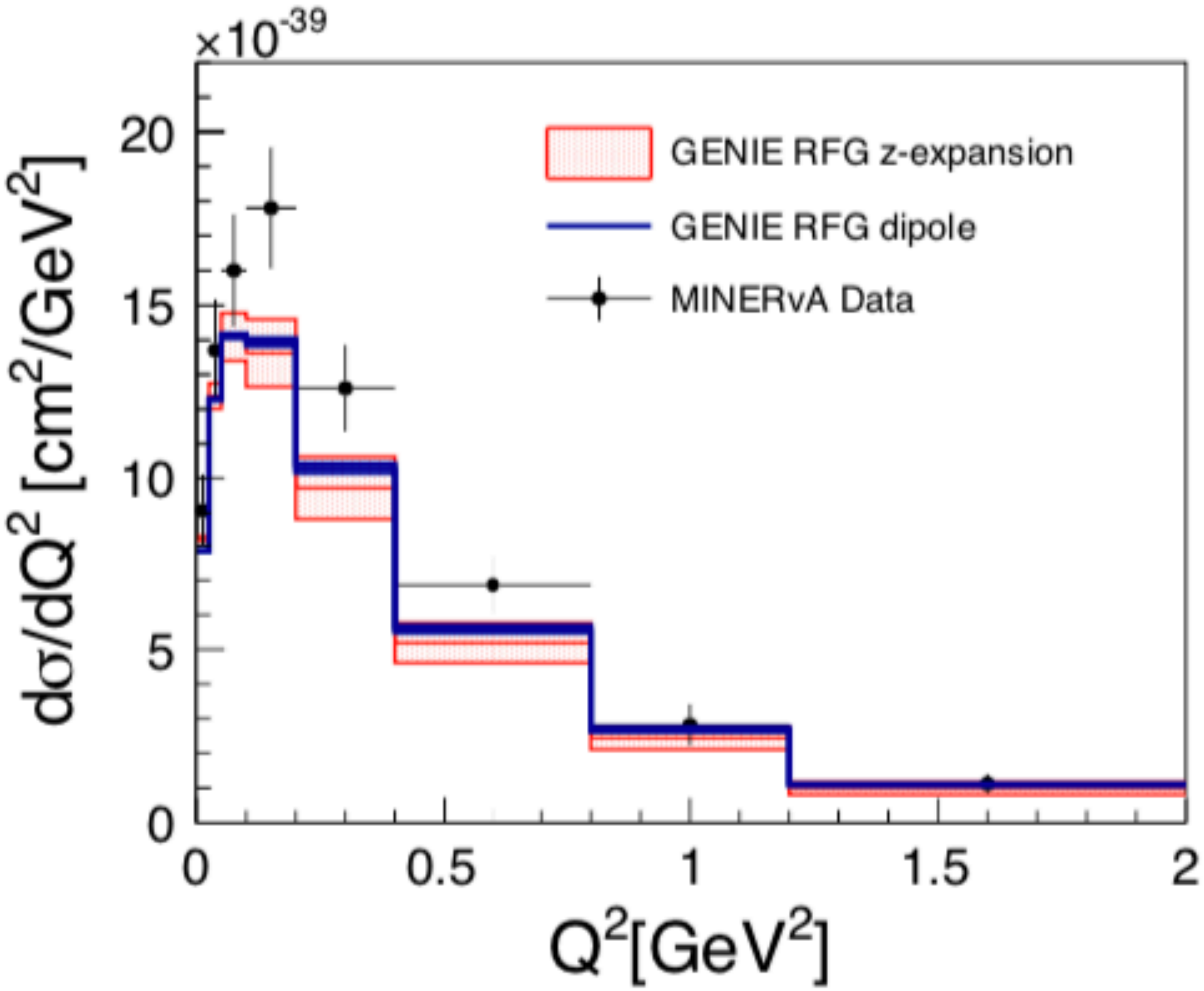
Reports Timeline (NF)

- Extended outline due (NF): Dec 18
- Report draft due (NF): Feb 28
- Contributed papers due: March 15
- NF Workshop: March 16-18
- Preliminary Report due (NF): May 10
- Preliminary Report due (Snowmass): May 31
- Final Report due (NF): Sept 9
- Final Report due (Snowmass): Sept 30, 2022

theory/motivation

- Why new H/D data?
    - We have only very imprecise data for neutrino-nucleon interactions
    - Better data would impact many areas of precision measurements in and beyond Standard Model, in and beyond the DUNE era
    - Direct measurements on H/D desirable from both theory and experimental perspectives
- Why NuSTEC?
    - nucleon level interactions are the natural meeting point of **particle and nuclear**
    - important interplay of **theory and experiment** to motivate, collect, analyze, and apply new precision data
    - NuSTEC lives at the particle-nuclear and theory-experiment interfaces

Cross sections for the oscillation program



plot from Meyer et al 1603.03048

- uncertainties from elementary nucleon-level amplitudes limit absolute cross section predictions, degenerate with nuclear modeling uncertainties

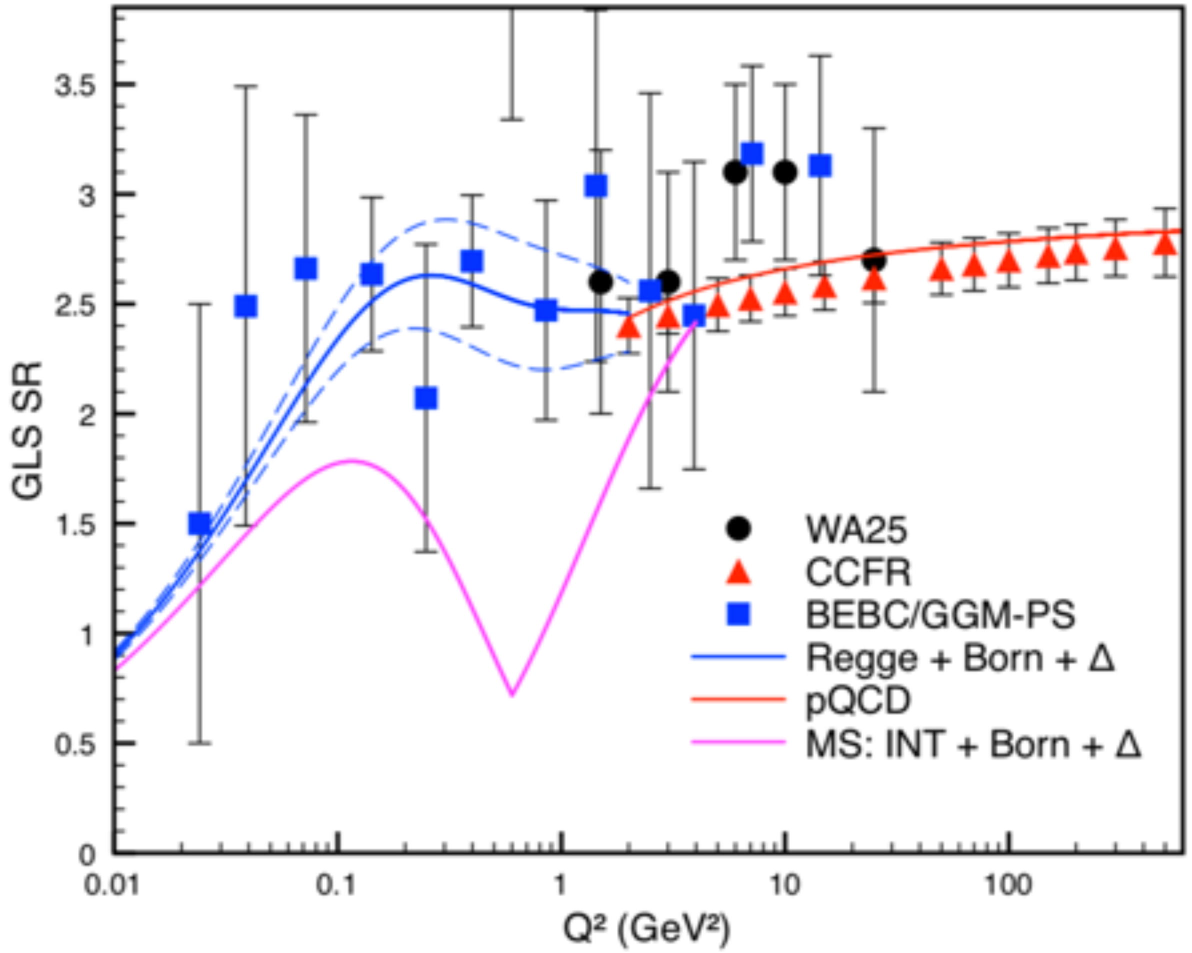
- similar situation for pion production and inelastic processes

cf. Wilkinson et al. 1411.4482, and T. Katori and J. Morfin SIS/DIS discussion

Cross sections beyond the oscillation program

≳ 3 sigma unitarity violation from V_{ud}

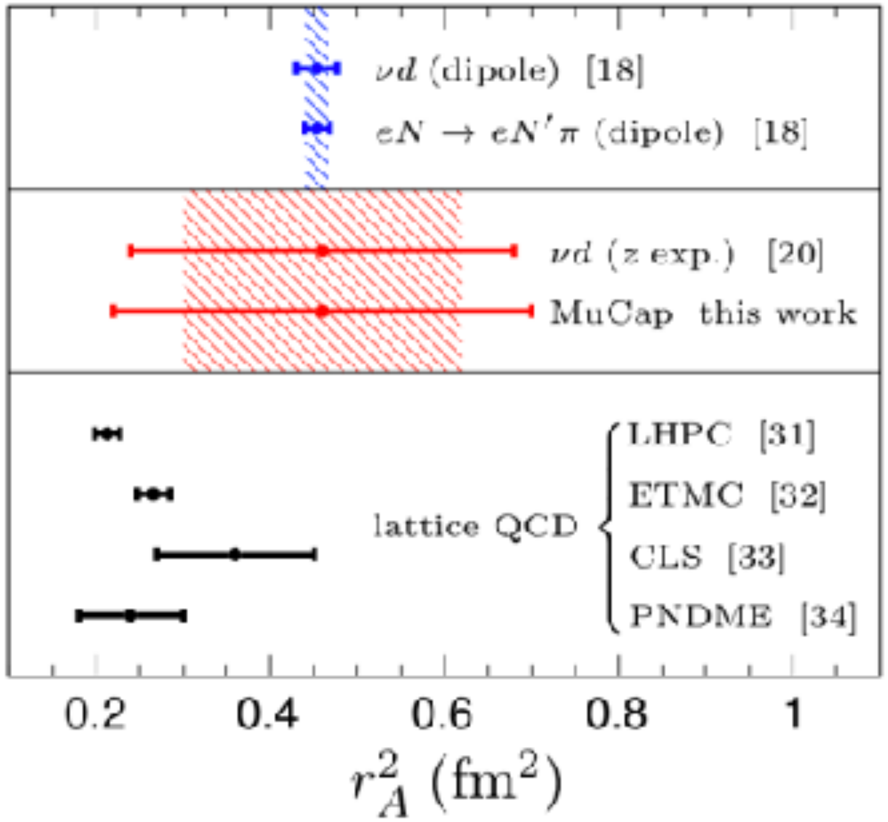
radiative corrections sensitivity to F_3 structure function for inclusive neutrino scattering



plot from Seng, Gorchtein, Patel, Ramsey-Musolf, 1807.10197

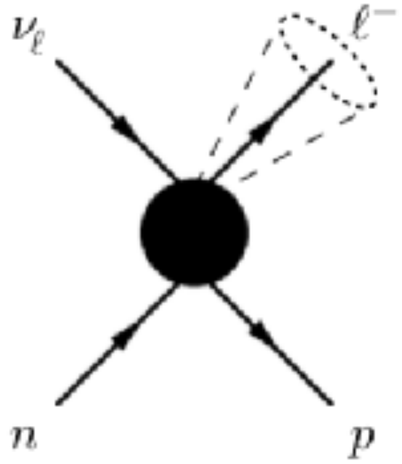
competing measurements of hadron structure (e.g. nucleon axial radius) from

- neutrino scattering
- electroproduction
- muon capture
- lattice QCD
- PV electron scattering
- …



plot from Hill, Kammel, Marciano, Sirlin, 1708.08462

Radiative corrections

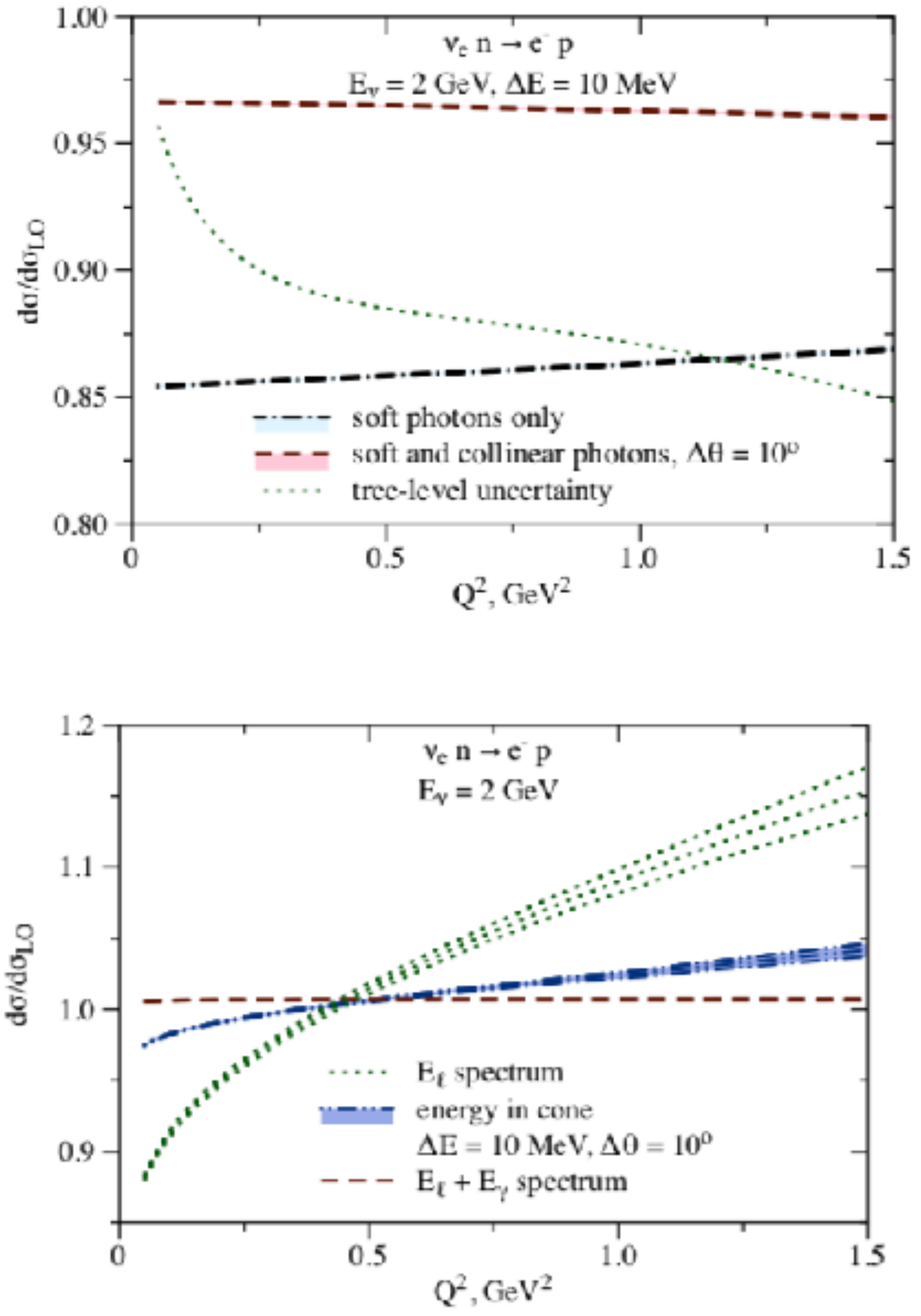


- radiative corrections are enhanced by large logarithms, but these enhancements computable in perturbation theory

$$\lambda \sim \frac{m_\ell^2}{E_\nu^2} \sim (\Delta\theta)^2 \sim \frac{\Delta E}{E_\nu} \sim \%$$

- size of corrections dependent on analysis strategy. Important flavor ratios insensitive to hadron and nuclear uncertainty

- nucleon-level data: update old D data; explore and validate exclusive/inclusive analysis strategies; complementarity with lattice QCD



plot from O. Tomalak, Q. Chen, Hill, McFarland 2105.07939

New physics searches

tonne-scale H detector can probe new models, e.g. very light and very weakly interacting

- lepto-phobic or hadro-philic, or
- xsec/nucleon larger on free nucleon (e.g. spin/isospin coupling, or absence of Pauli blocking, etc., or
- signal involves small nucleon recoil, or
- …

R. Plestid talk in H/D working group and work in progress

precision nucleon-level data constrains BSM contributions to second class currents

K. Borah (FNAL URA scholar) and O. Tomalak, work in progress

Complementarity with lattice QCD

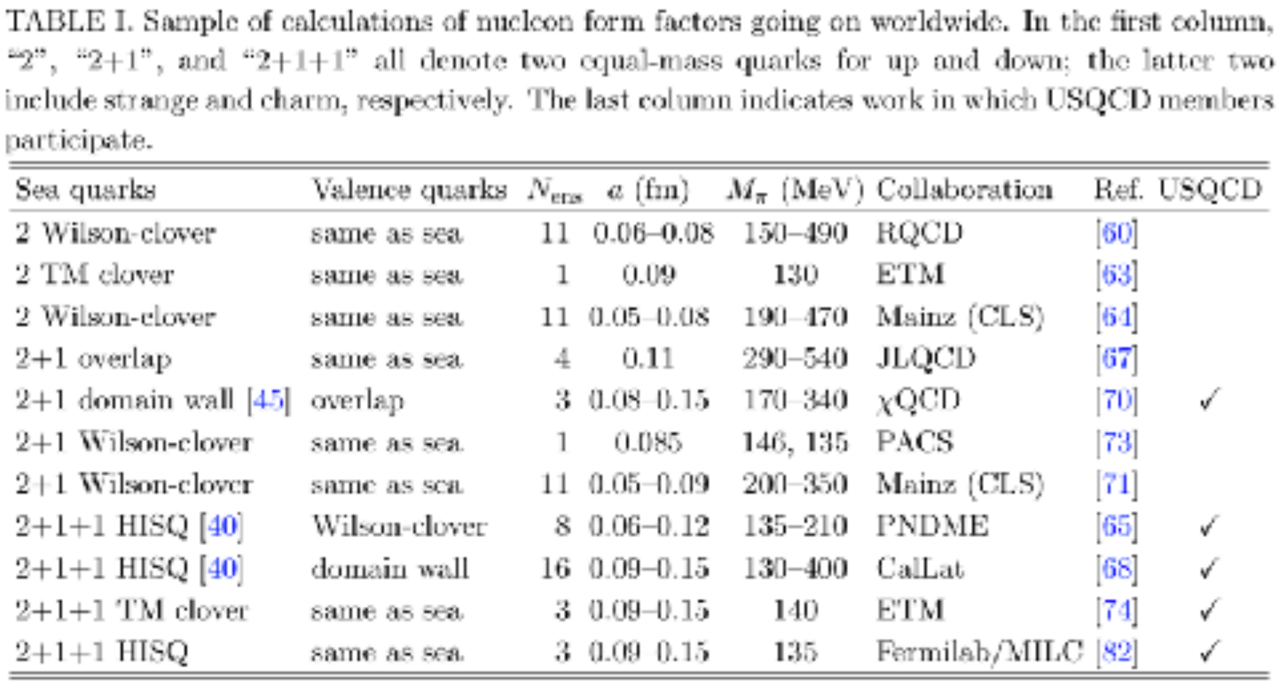
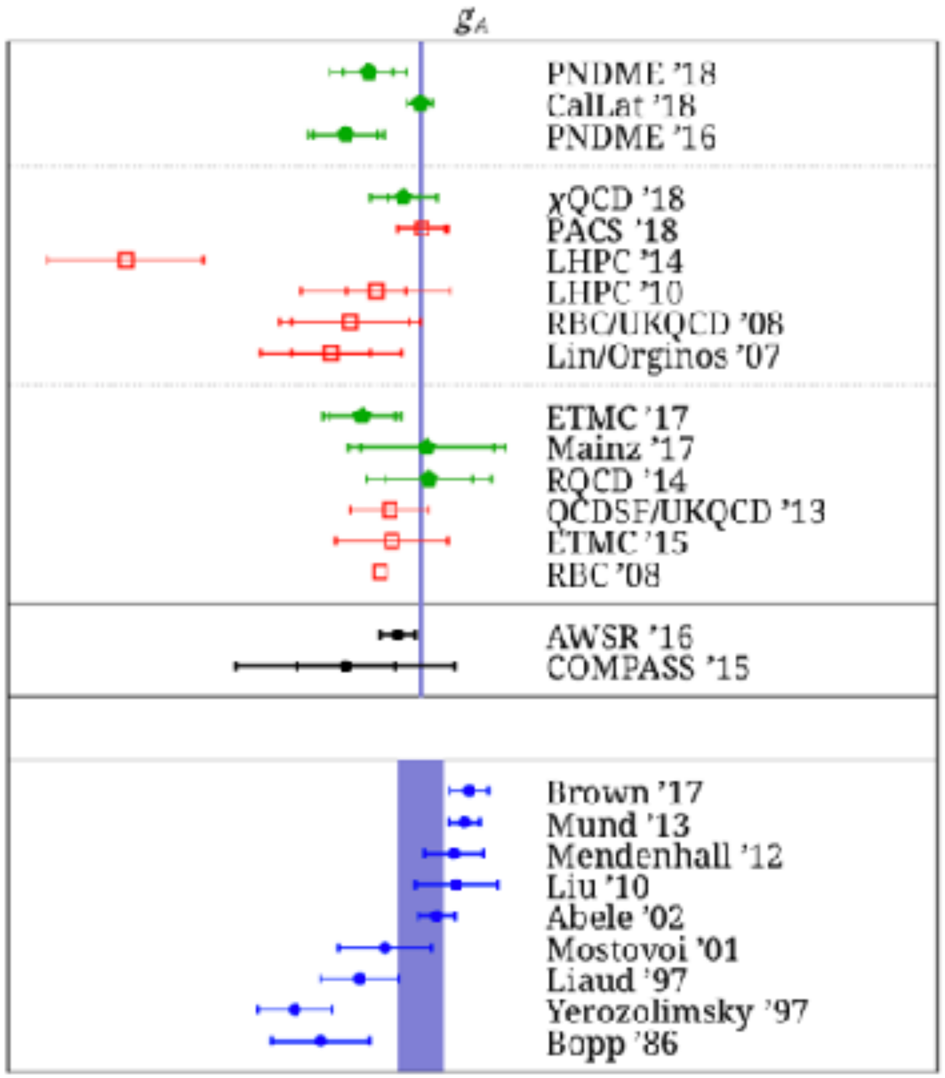


TABLE I. Sample of calculations of nucleon form factors going on worldwide. In the first column, "2", "2+1", and "2+1+1" all denote two equal-mass quarks for up and down; the latter two include strange and charm, respectively. The last column indicates work in which USQCD members participate.

Sea quarks	Valence quarks	N_{ens}	a (fm)	M_π (MeV)	Collaboration	Ref.	USQCD
2 Wilson-clover	same as sea	11	0.06–0.08	150–490	RQCD	[60]	
2 TM clover	same as sea	1	0.09	130	ETM	[63]	
2 Wilson-clover	same as sea	11	0.05–0.08	190–470	Mainz (CLS)	[64]	
2+1 overlap	same as sea	4	0.11	290–540	JLQCD	[67]	
2+1 domain wall [45]	overlap	3	0.08–0.15	170–340	χQCD	[70]	✓
2+1 Wilson-clover	same as sea	1	0.085	146, 135	PACS	[73]	
2+1 Wilson-clover	same as sea	11	0.05–0.09	200–350	Mainz (CLS)	[71]	
2+1+1 HISQ [40]	Wilson-clover	8	0.06–0.12	135–210	PNDME	[65]	✓
2+1+1 HISQ [40]	domain wall	16	0.09–0.15	130–400	CalLat	[68]	✓
2+1+1 TM clover	same as sea	3	0.09–0.15	140	ETM	[74]	✓
2+1+1 HISQ	same as sea	3	0.09–0.15	135	Fermilab/MILC	[82]	✓

from Kronfeld et al. USQCD white paper on lattice QCD and neutrino-nucleus scattering



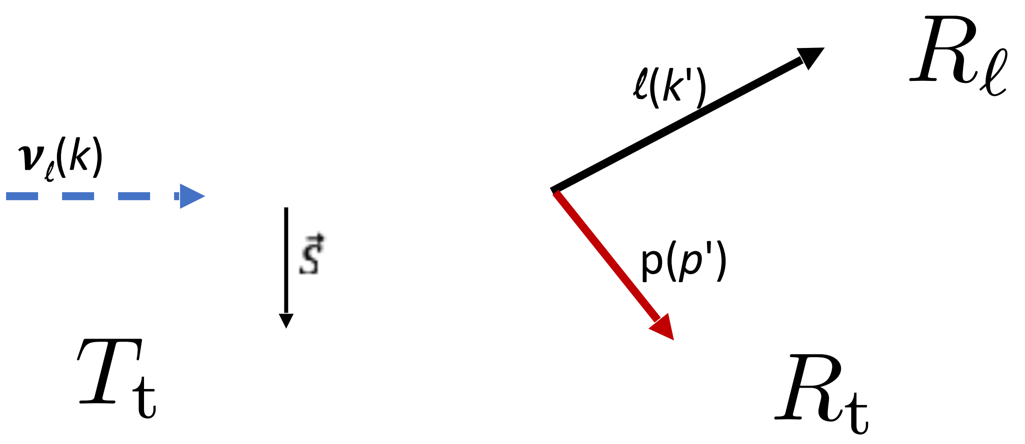
plot from Gupta et al. 1806.09006

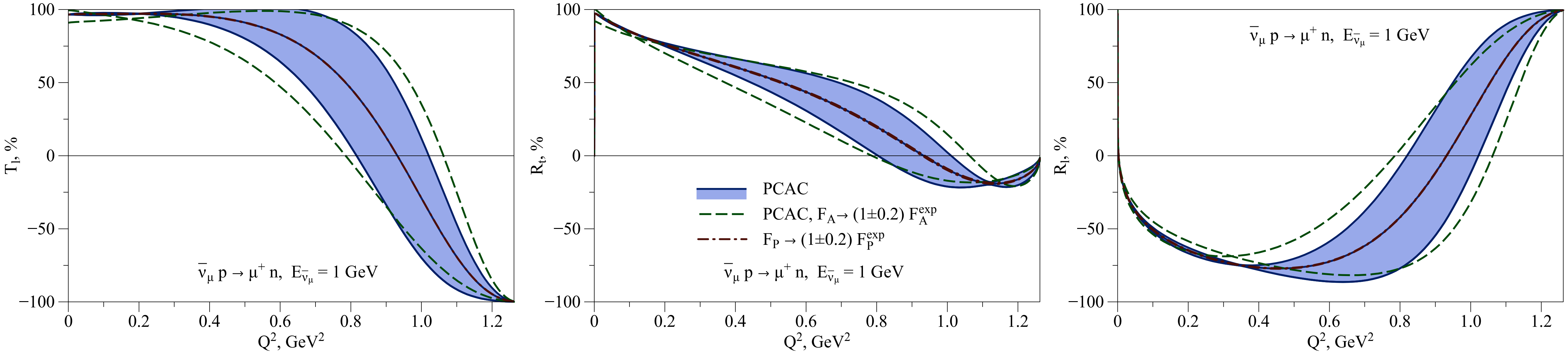
- comparison of experiment and lattice gives either tests of both, or more precision when combined, since kinematic coverage is different

- constraints on BSM contributions (absent in lattice)

- constraints on structure-dependent QED radiative corrections

Polarization asymmetries

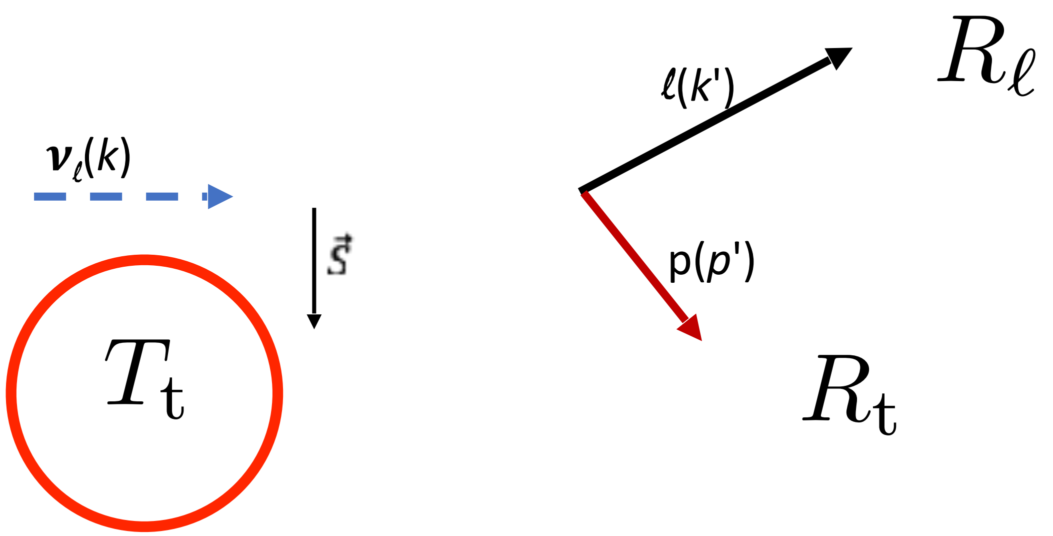


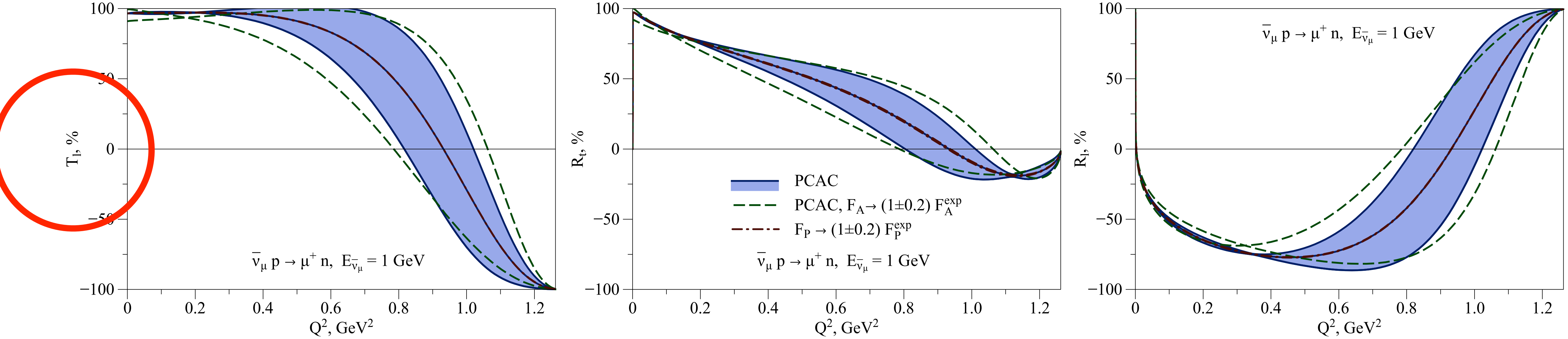


plots from O. Tomalak,2008.03527

- transverse target (or recoil target, recoil lepton) asymmetries would give access to important measurements and constraints both in and beyond Standard Model

Polarization asymmetries





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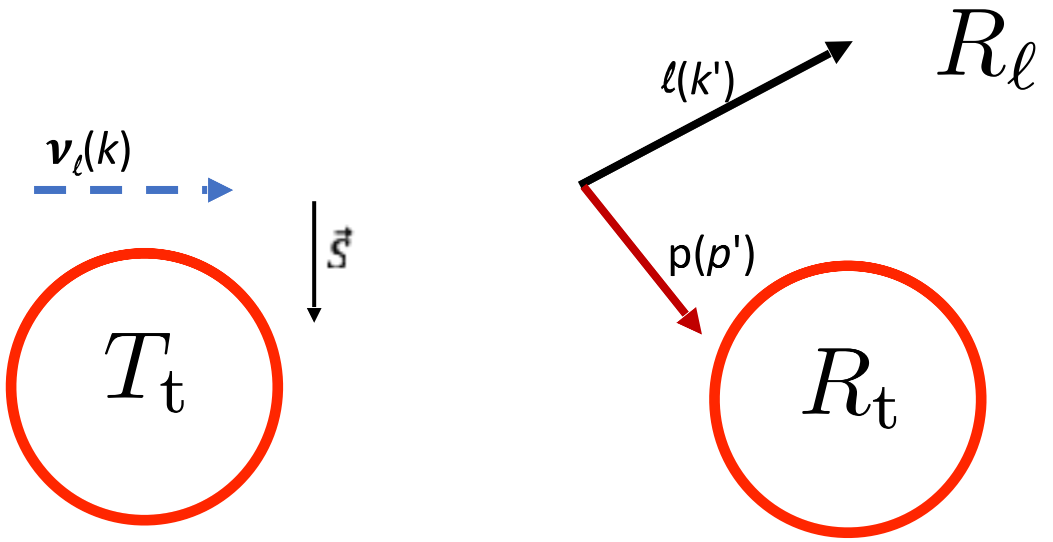
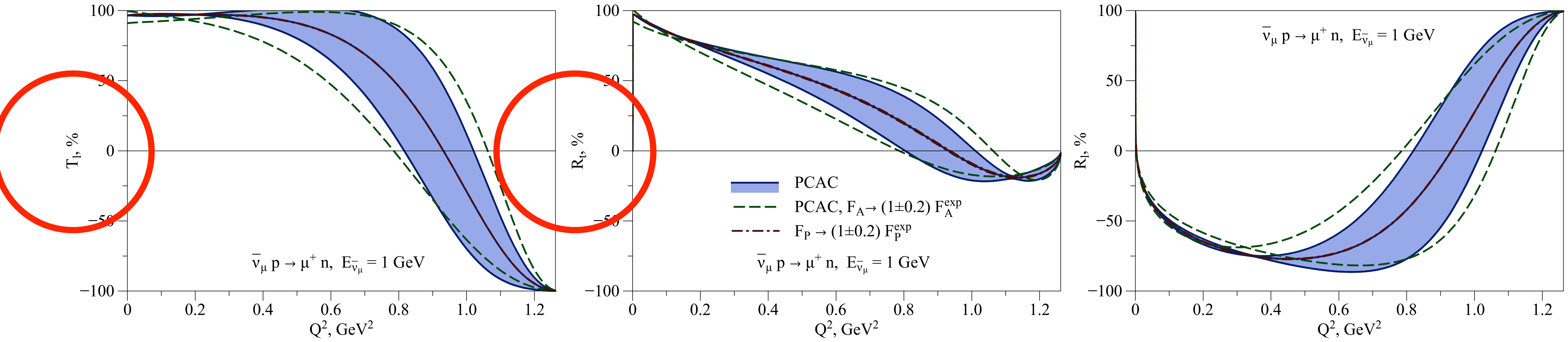
Polarization asymmetries





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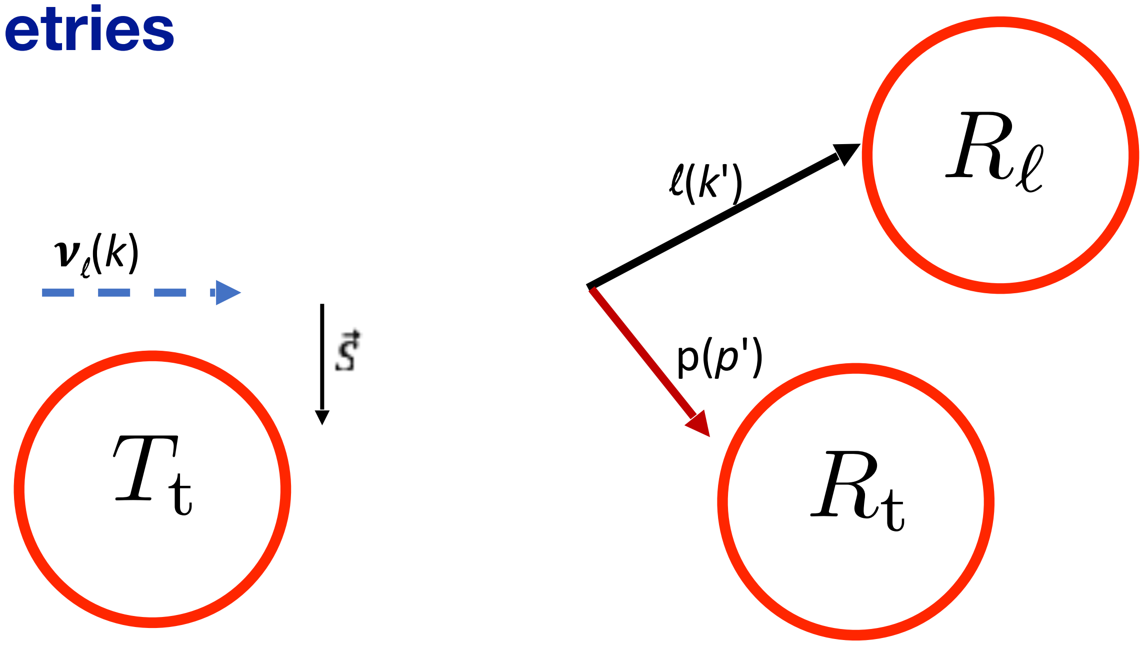
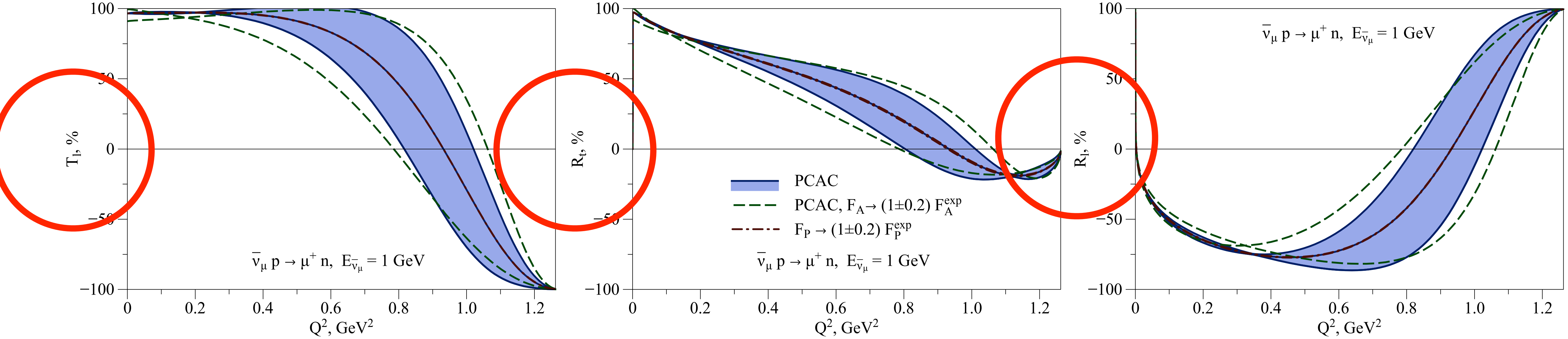
Polarization asymmetries





plots from O. Tomalak,2008.03527

- transverse target (or recoil target, recoil lepton) asymmetries would give access to important measurements and constraints both in and beyond Standard Model

experiment

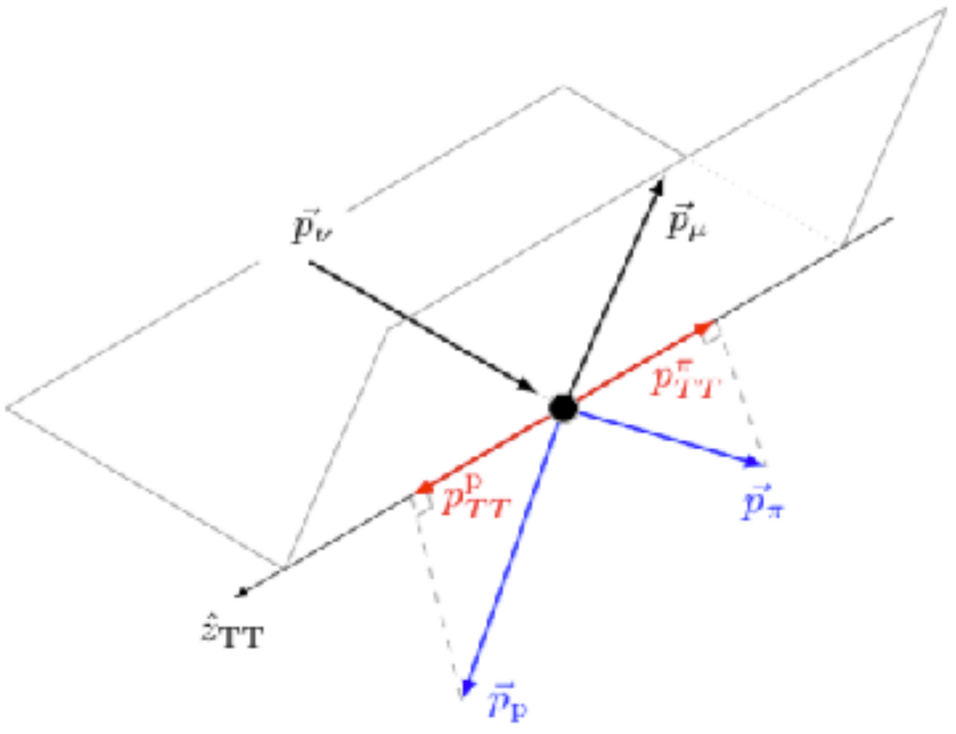
(slides from T. Junk, U. Kentucky nuclear seminar Feb. 2021)

Transverse Kinematics for Separating Hydrogen Interactions from Heavier Nuclei

X.-G. Lu, D. Coplowe, R. Shah, G. Barr, D. Wark and A. Weber, PRD **92**, 051302 (2015) (arXiv: 1507.00967)

X.-G. Lu, L. Pickering, S. Dolan, G. Barr, D. Coplowe, Y. Uchida, D.Wark, M.O. Wascko, A. Weber, and T. Yuan, Phys. Rev. C94, 015503 (2016), (arXiv:1512.05748)

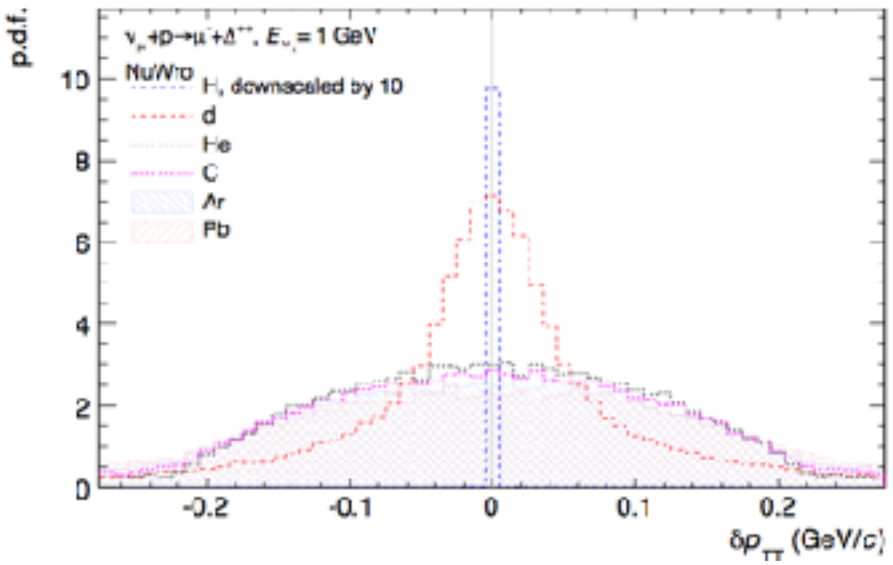
H. Duyang, B. Guo, S. R. Mishra and R. Petti, arXiv:1809.08752

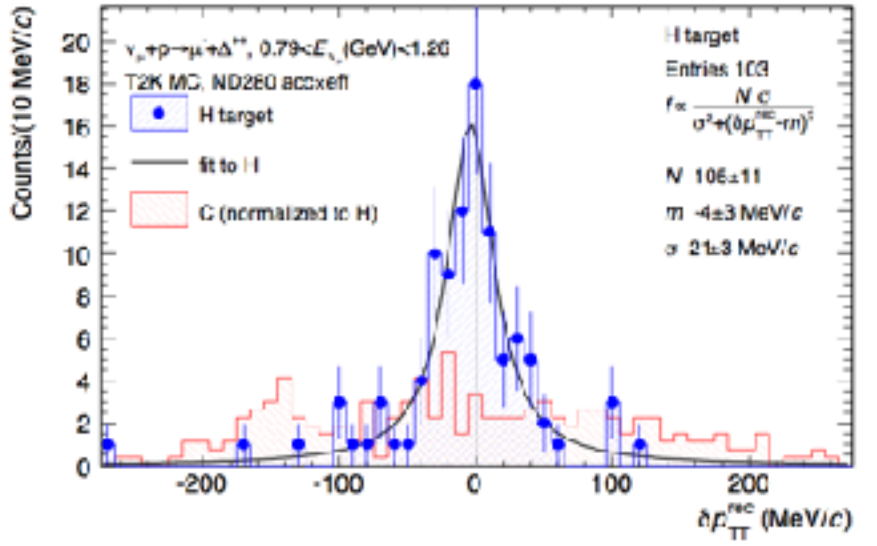


(a) $\delta p_{TT} = p^{\pi}_{TT} + p^{p}_{TT}$.

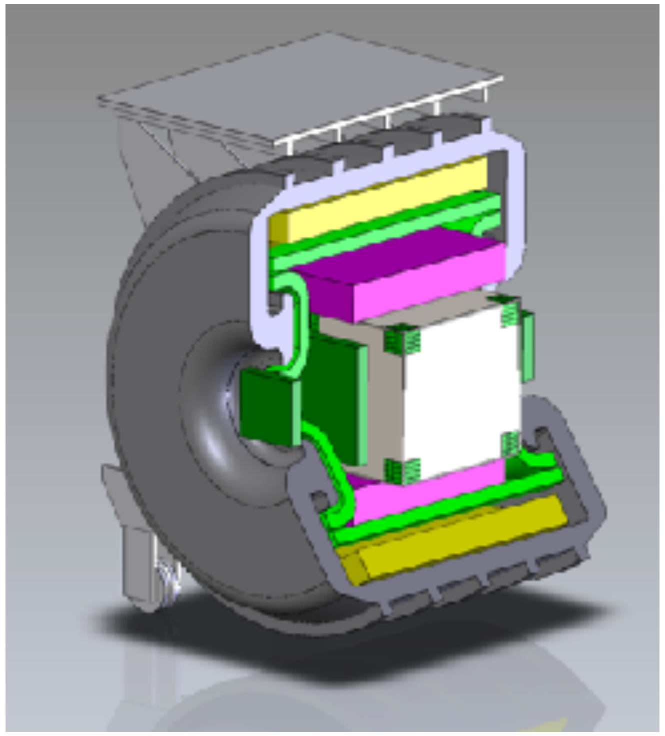
Lack of Fermi motion with a proton target means transverse momentum sums to zero.

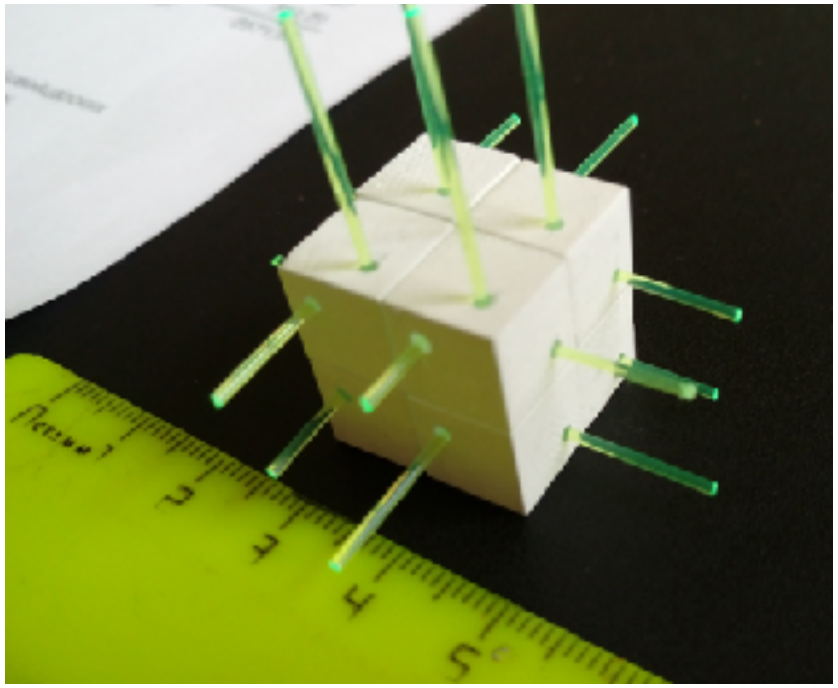
"transverse" is perpendicular to both the neutrino and the lepton





Option 1: Use the SAND Detector's Plastic Scintillator as a Hydrogen Target

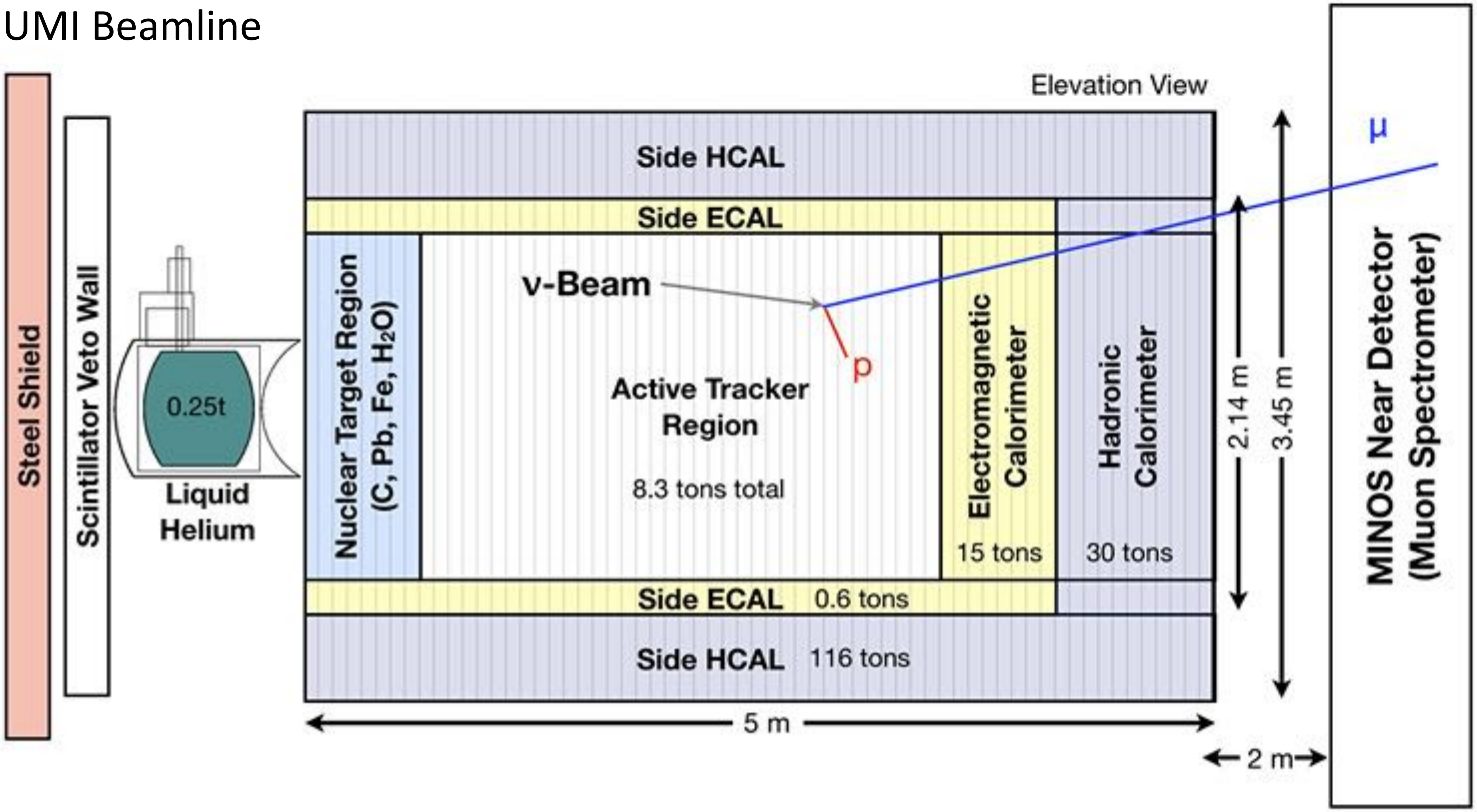




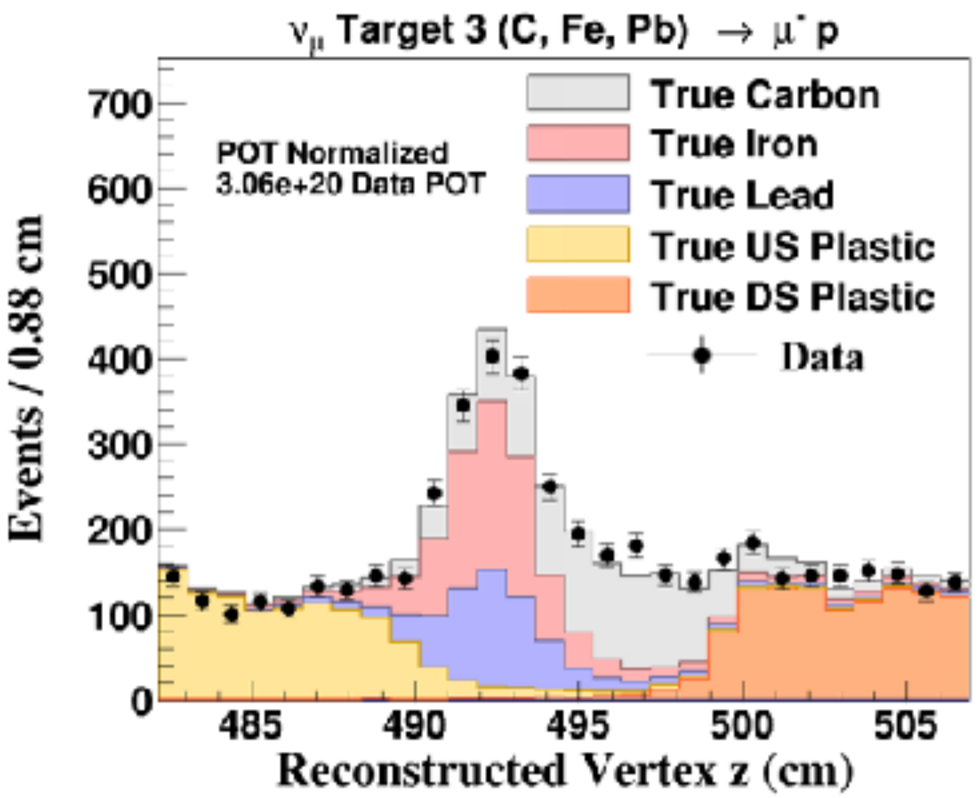
- SAND has a 3D scintillating tracker (3DST) – Dominantly polystyrene $(CH)_n$
- Challenges in using it to measure interactions on hydrogen:
  - Can do better with the hydrogen ratio: CH vs CH_2
  - Need to subtract interactions on carbon
    - A great idea – include a pure carbon target in the detector
  - Deuterated plastic is *very* expensive. Maybe it is cheaper in bulk, but we're not optimistic.

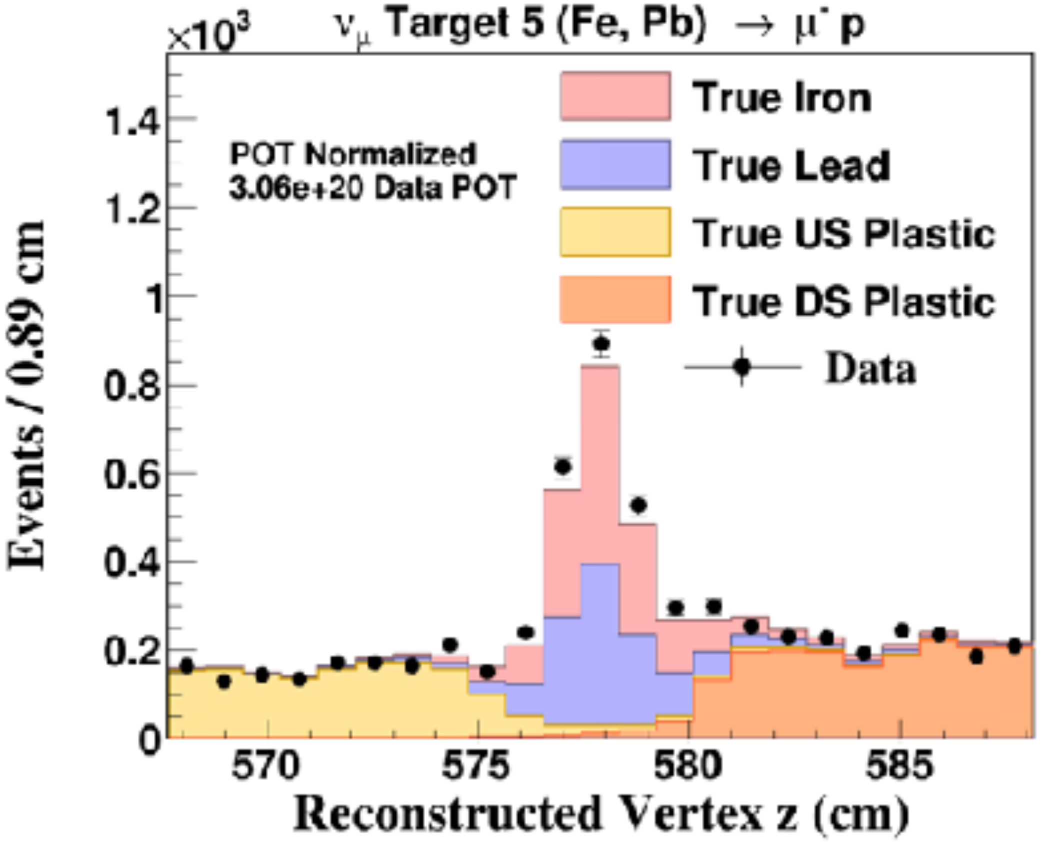
The MINERvA Detector

In the NUMI Beamline



MINERvA's Measurement of Reactions on Different Nuclei





Vertex resolution not spectacular for separating contributions.

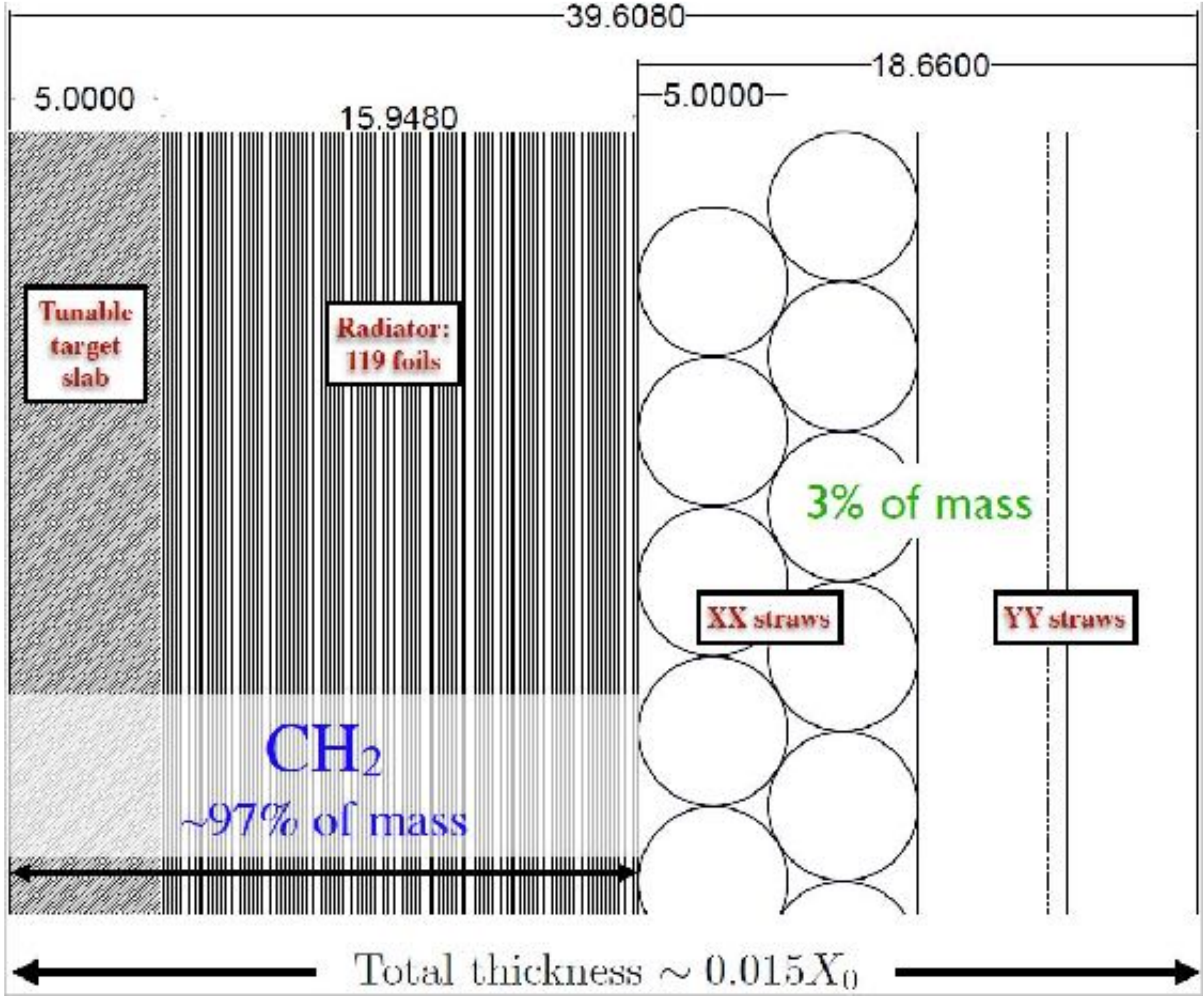
Direct Measurement of Nuclear Dependence of Charged Current
Quasielastic-like Neutrino Interactions using MINERvA
Phys. Rev. Lett. 119, 082001 (2017)

Straw-Tube Tracker Design for SAND

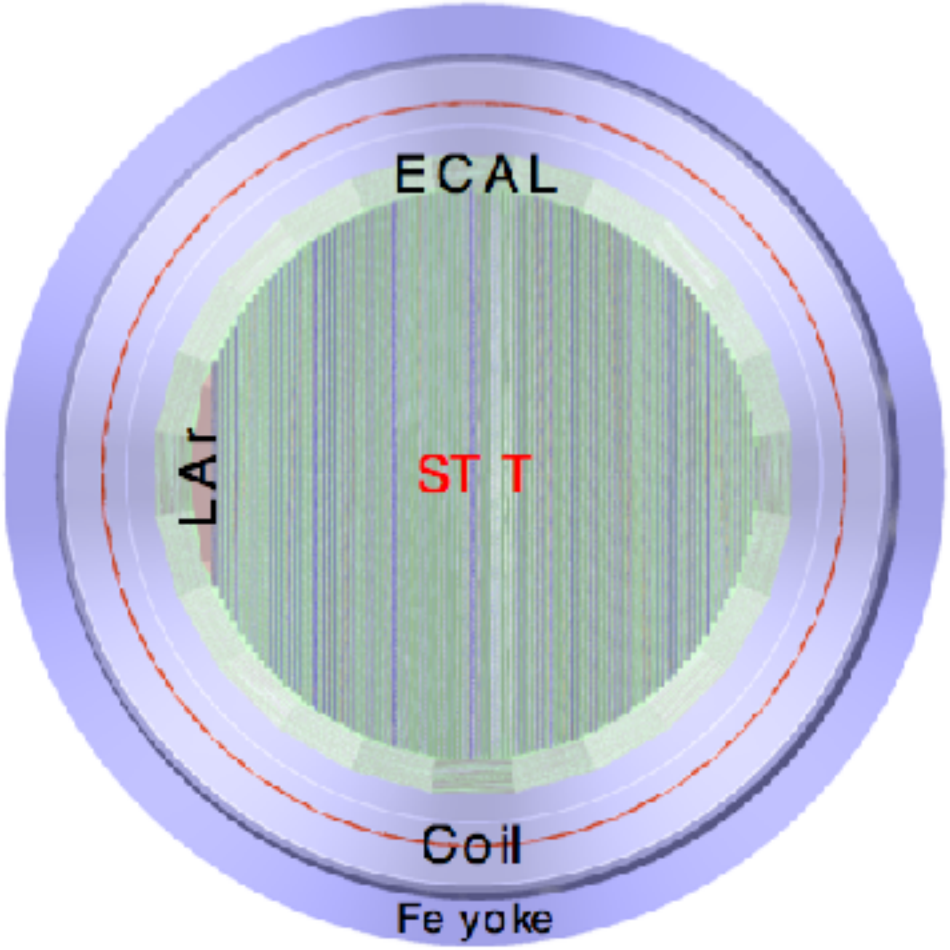
Polypropylene $(CH_2)_n$ target

Much better vertex resolution (c.f. NOMAD) than the 3DST

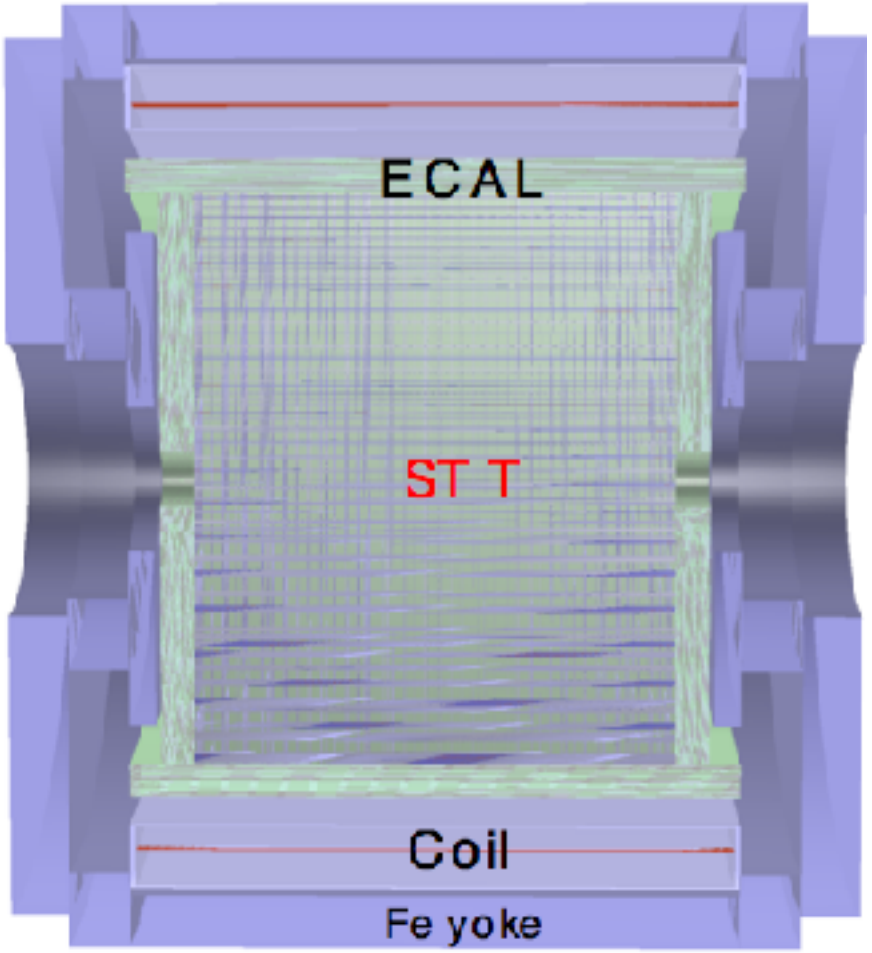
Estimated resolution: 0.1 mm to 0.6 mm, depending on which coordinate (R. Petti)



Replacing the 3DST with a STT

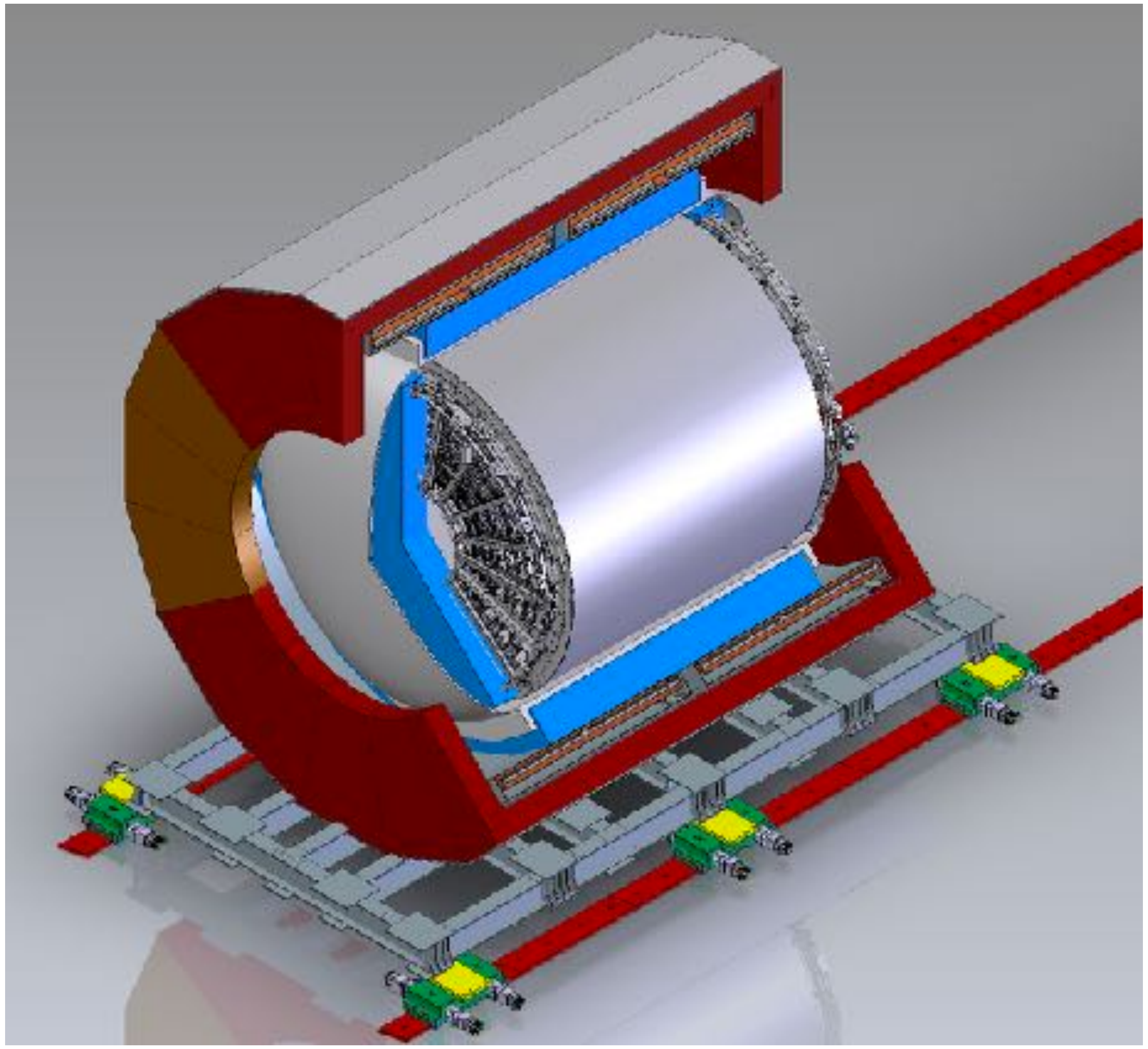


YZ view (beam -0.101 rad along Z)



XY view (B along X)

Option 2: Use a Hydrogen-Rich Gas in the High-Pressure Gas TPC



- ND-GAr is studying the use of P10 gas: 90% Ar, 10% CH_4 at 10 Atm.
  - 97% of interactions are on Ar.
  - Most of the rest are on C.

- One could add H_2 or D_2 to the gas mixture,
  but it has to be a very small amount,
  to keep flammability down

- Safety requirements restrict us to 40 kg of flammable liquid or gas underground, or the entire facility would have to be built under explosion-proof electrical guidelines.

- The ND Hall has high-voltage power supplies and benefits from flexibility in design and operation

- Other options: hydrogen-rich but less flammable gases or liquids, e.g. Tetramethylsilane: $(CH_3)_4Si$ [S.X. Wu, B.G. Leandro, M. Weber and G.Gratta, Nucl. Inst. Meth. A 972 (2020) 163904 (arXiv:1911.12887)]

Option 3: Build a H_2/D_2 Bubble Chamber in a Dedicated Hall

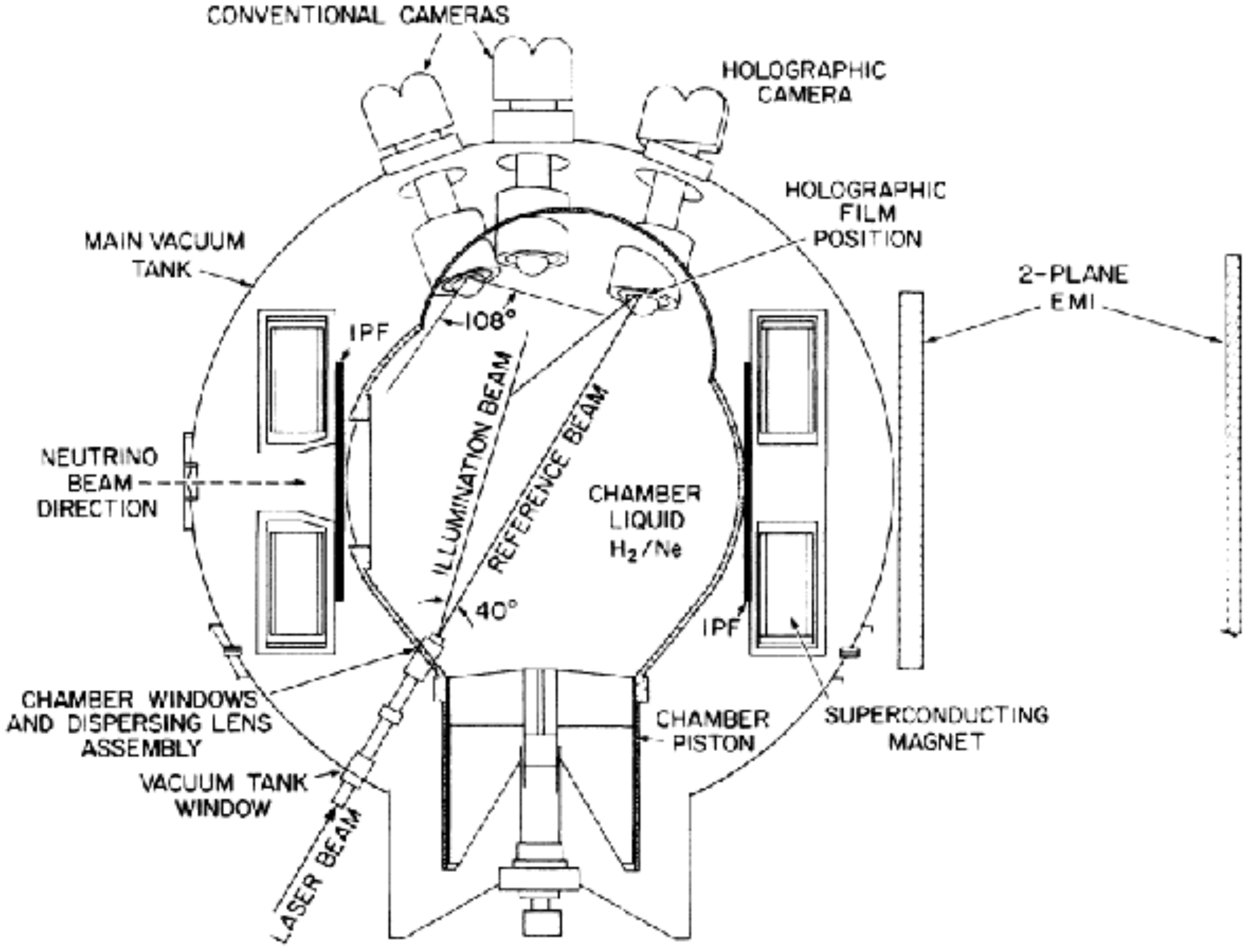
- 40 kg limit on flammable gas/liquid doesn't let us have much.
- One option – run a 40 kg dewar of liquid hydrogen for 20 years – get 800 kg-year exposure.
  -- We would still need a calorimeter and muon system.

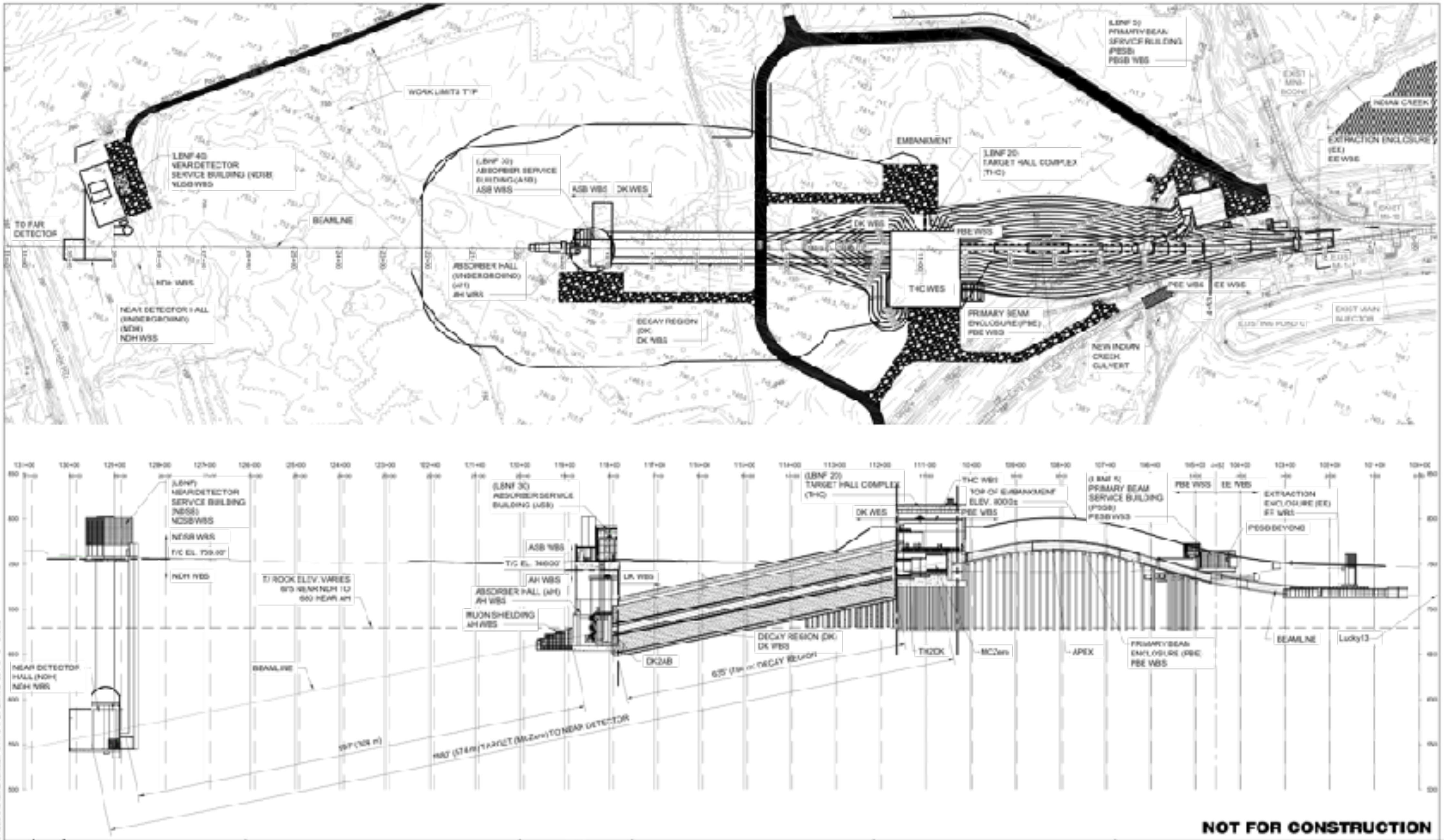
- Not much room in the ND hall left over – detectors must move for the Prism analysis to work

- Electrons drift in a liquid hydrogen TPC, but *very slowly*. (Seconds... Requires incredibly low electronegative impurity fractions)
  Y. Sakai, H. Böttcher, and W. F. Schmidt, Journal of Electrostatics **12**, 89-96 (1982).

- Bubble chambers are battle-tested, but they are:
  - Slow
  - Mechanical
  - Old-style analyses required human scanners.

FNAL 15' Bubble Chamber





NOT FOR CONSTRUCTION

00	12/21/18	PRELIMINARY DESIGN SET - 60%
REV.	DATE	DESCRIPTION
REVISIONS		

AECOM

303 East Wacker Drive Suite 1400
Chicago, IL 60601
312-373-7700 tel 312-373-6800 fax
www.aecom.com

TRUE NORTH

SCALE:

PLAN VIEW & PROFILE HORIZONTAL SCALE (22x34)

1" = 100'-0"

PROFILE VERTICAL SCALE (22x34)

1" = 10'-0"

Fermilab

Long-Baseline Neutrino Facility

DESIGNED	H. ZHU	2020
DRAWN	D. EGGERDING	2020
CHECKED	F. LOBIS	2020

PROJECT NO. 6-15-10

LBNF NEAR SITE CONVENTIONAL FACILITIES

PRELIMINARY SITE DESIGN

FINAL GRADING PLAN AND PROFILE

DRAWING NO. **C-301** REV. 00

6-15-10

Bubble Chamber Challenges and Opportunities

- It has to be underground! Or at least in a 150-ft deep shaft.
  Digging for neutrinos!
- Rock muons – 6/m^2/spill at 1.2 MW – 120/spill in 15' bubble chamber. And <1 neutrino interaction.
- H_2 and D_2 are still explosive.
- Magnet, flashlamps, electronic cameras and all kinds of instrumentation will be needed – explosion proof!
- For personnel safety – would like no access to bubble chamber hall when there is any H_2 or D_2 in the system
  - Difficult to maintain – what if something breaks and you need to fix it? Could be months to drain and re-fill.
- Large, heavy pier needed as ballast for piston.
  - Bolt it to the floor!
  - Had originally wanted to lower it down a shaft just big enough for a bubble chamber, but that doesn't work.
- Additional detectors for calorimetry and muon ID are needed.
- Idea – install it on the surface (low rate, not representative of the neutrinos produced on axis)

Polarized Target Options

- Nearly impossible to polarize the protons in H_2 molecules just by lowering temperature and raising B.
  - Lowest-energy state @B=0 is Ortho-hydrogen (opposite nuclear spins, symmetric spatial wavefunction).
  - Need Para-hydrogen (same nuclear spins, asymmetric (L=1) spatial wave function)
  - Need enormous B fields (10^5 T)and very low temperatures.

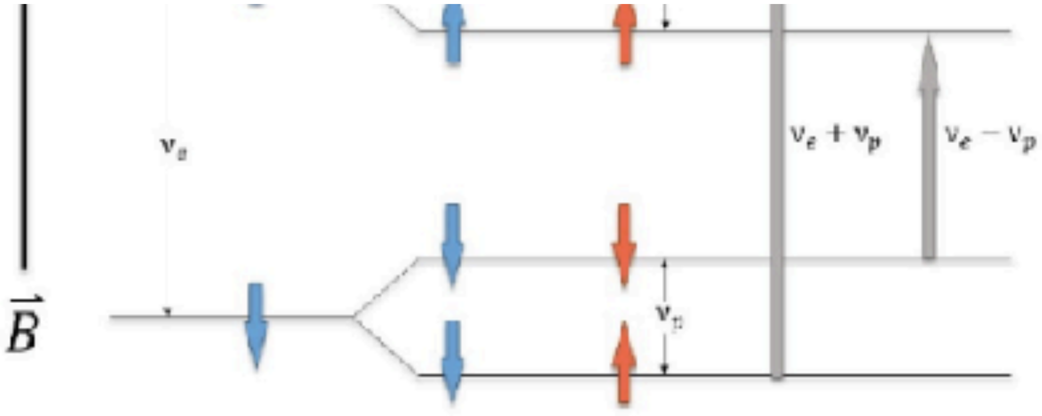
    A. Misra and A. Panda, J Low Temp Phys (2011) 163: 311–316

- Materials used in polarized targets so far:
  - LiH (COMPASS)
  - NH_3 (SMC and SpinQuest)
  - Butanol (SMC and the FroST target at JLAB)

- Review article: St. Goertz, W. Meyer and G. Reicherz, Progress in Particle and Nuclear Physics **49**, 403-489 (2002). All targets for charged-particle beams so far.

Dynamic Nuclear Polarization (DNP) Target

$\mu_e \sim 1000\mu_p$



e-relaxation time: ~ms
p-relaxation time: ~10 mins

- Dynamic Nuclear Polarization
  - Dope target material with paramagnetic centers:

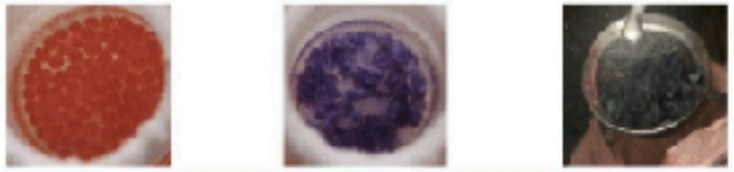
    chemical or irradiation doping to just the right density (10^{19} spins/cm^3)
  - Polarize the centers: Just stick it in a magnetic field
  - Use microwaves to transfer this polarization to nuclei:

    mutual electron-proton spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other
- Optimize so that DNP is performed at *B/T* conditions where electron t_1 is short (ms) and nuclear t_1 is long (minutes or hours)

$$P_{TE} = \frac{e^{\frac{\mu B}{kT}} - e^{\frac{-\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}} = \tanh\left(\frac{\mu B}{kT}\right)$$

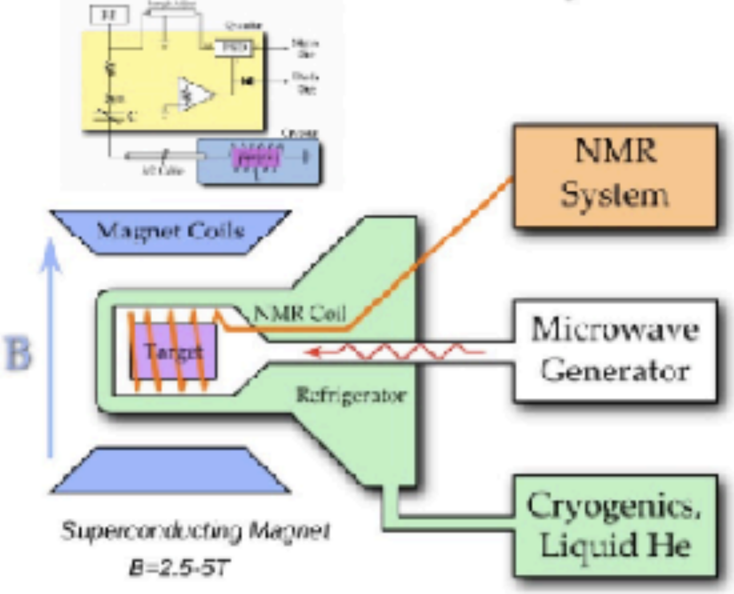
Successful material for DNP characterized by three measures:

1. Maximum polarization
2. Dilution factor
3. Resistance to ionizing radiation



Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.6	25.0
Polarization (%)	90-95	90-95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^6LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	40	50	55
Rad. Resistance	moderate	high	very high
Comments	*Easy to produce and handle*	*Works well at 5T/1K*	*Slow polarization, but long T_1*

General System



Polarization Detection

Tuned To Larmor of spin species
Proton (42.6 MHz/T)

Larmor-ESR
50-185 GHz
~140 GHz at 5T

T=0.03-1K

Slide from Dustin Keller

Polarized Target Challenges

- Large mass needed for neutrino interactions.
  Previous targets have had masses of tens to hundreds of grams.
- Large magnetic field and low temperature.
  SpinQuest has 5T and 1K. Easier to do in small volumes
- RF is needed to transfer polarization from electrons to nuclei
- We need to be able to measure how polarized the target is and monitor it over time.
- We want to measure low-momentum particles from the interactions.
  Tens of MeV to tens of GeV, mostly on the low side.
- Particles of interest will stop inside the target – common feature of neutrino experiments.
  Detector has to be *inside* the target.
- Polarization must be switchable from + to -. Bonus: transverse polarization.

On the positive side, at least it does not have to be radiation hard! And no beam heating!

summary

- lots of exciting physics goals: neutrinos and beyond neutrinos, SM and BSM
- please join and contribute to white paper if you haven’t already