Effective theories, dark matter and neutrinos

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Aspen Winter Meeting
15 January 2016

Features work of the following students

M. Solon,
(2015 Sakurai thesis award
U.Chicago→UC Berkeley/LBNL)

A. Meyer
(U.Chicago/FNAL)

Thanks also: J. Arrington, M. Bauer, M. Betancourt, C. Blanco, T. Cohen, R. Gran, A. Kronfeld, G. Lee, G. Paz, M. Wetstein, and many others.

Will discuss 3 “The Effective Theories” of WIMP dark matter

- heavy WIMP expansion
- heavy mediator expansion
- low velocity expansion

and the relation between 3 aspects of Neutrino Physics

- neutrino models
- cross sections (particle physics)
- cross sections (nuclear physics)

cf. talks of S. Pascoli, M. Messier, K Heeger, …

Two questions that I hope this talk will help introduce and address:

- What can the particle theorist do about neutrino cross sections at ~GeV energies?
- Isn’t this messy/nuclear physics?

Will see:

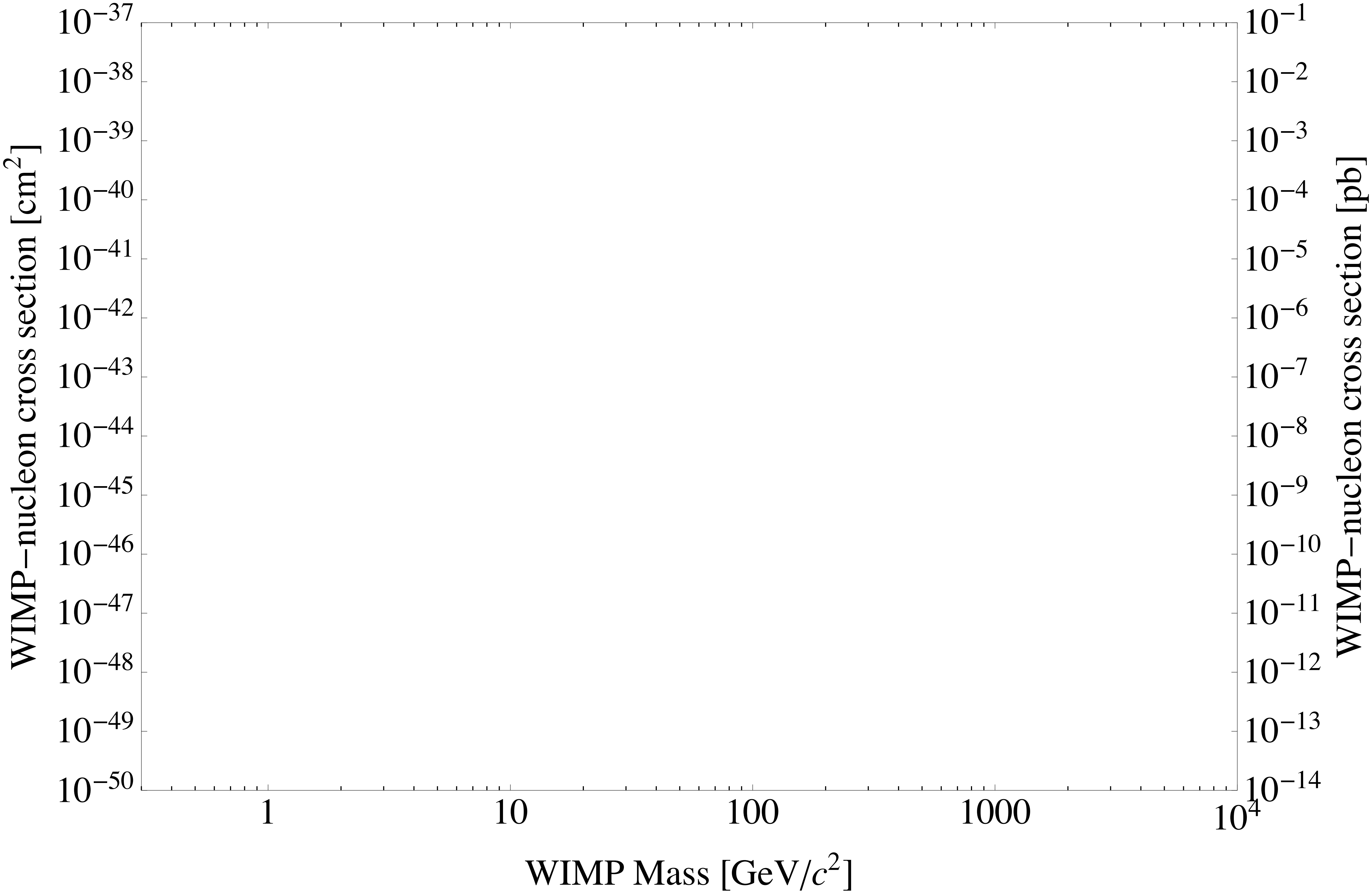
- interesting and solvable problems
- new tools, techniques and experimental handles available

Need to go where the physics takes us. Nobody said that probing high scales was going to be easy

Part 1:
The "The Effective Theories" of WIMP dark matter

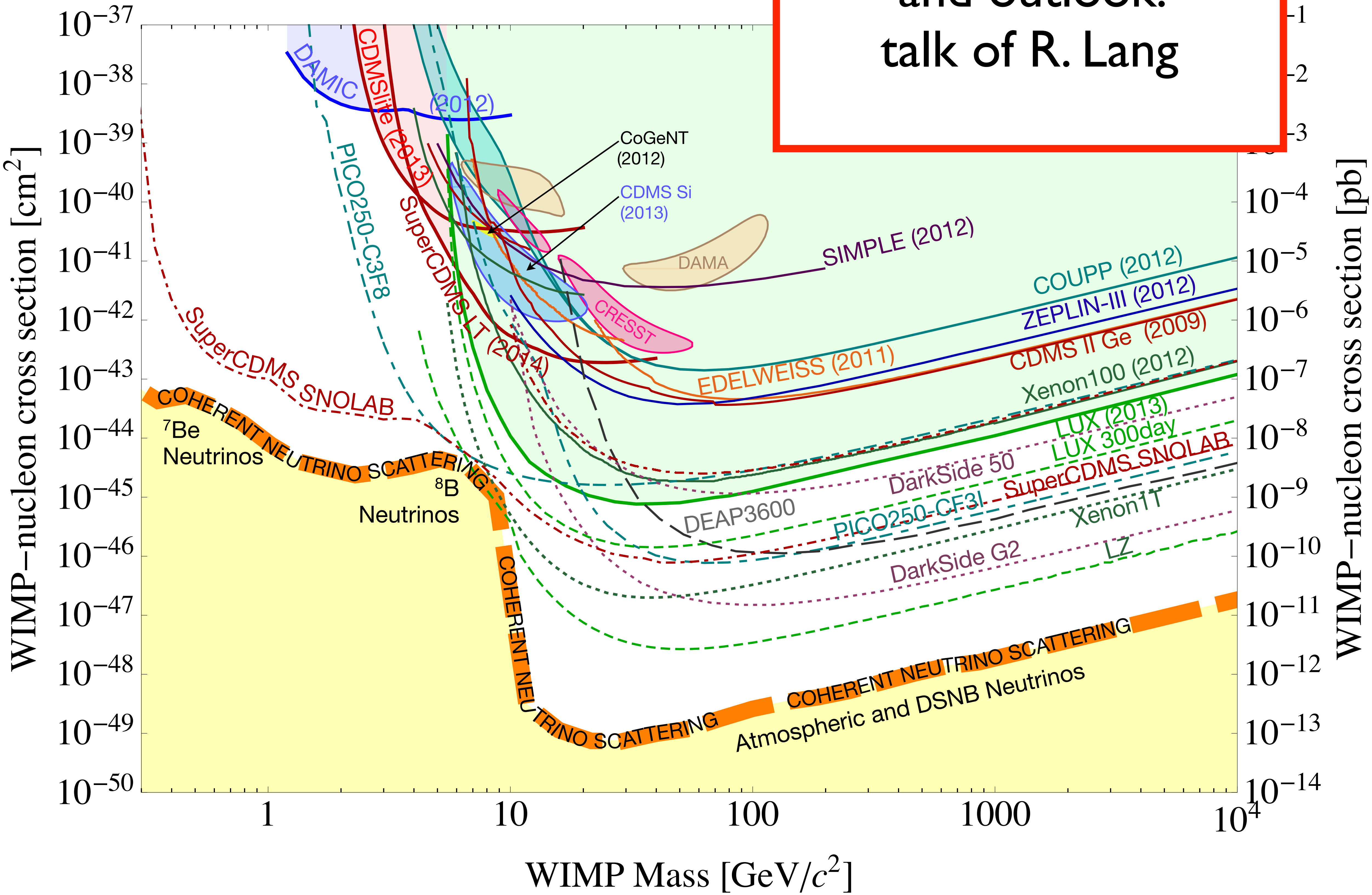
- heavy WIMP expansion
- heavy mediator expansion
- low velocity expansion

A lot of space...



A lot of space remaining...

experimental status and outlook: talk of R. Lang



The "The Effective Theories" of WIMP dark matter

→

- heavy WIMP expansion
- heavy mediator expansion
- low velocity expansion

DM EFT 1: Heavy WIMP expansion

- Present null results may point to $\gtrsim$ TeV WIMP mass
- This regime has important challenges and simplifications

Take as basic WIMP:	SU(3)	x SU(2)	x U(1)	spin
	1	3	0	s

Many results independent of WIMP spin, and elementary vs. composite nature of WIMP (e.g. wino, composite scalar, …)

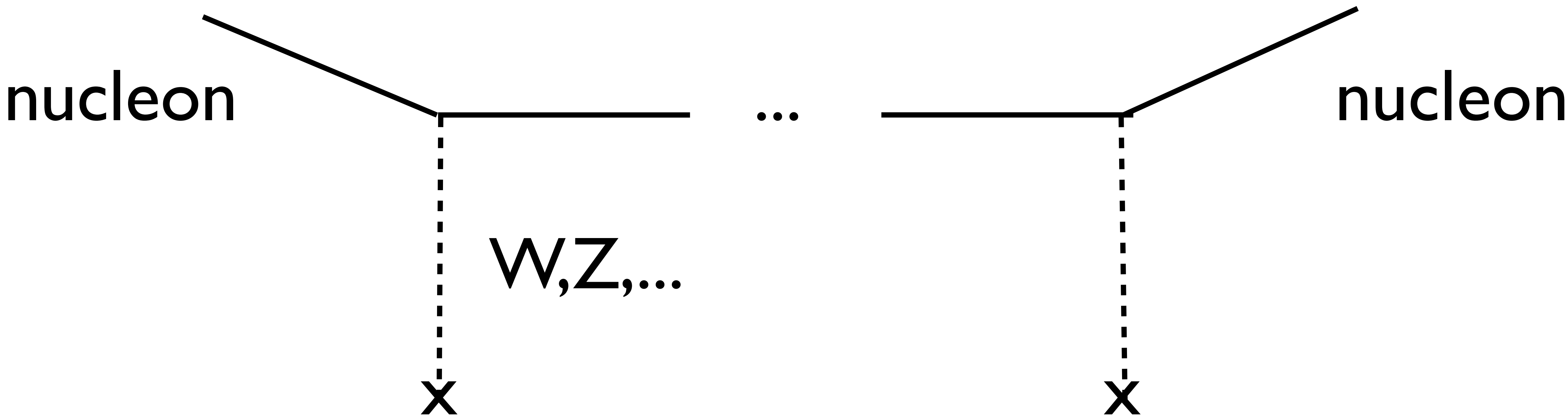
Direct detection

Many manifestations of heavy particle symmetry:

- hydrogen/deuterium spectroscopy $E_n(H) = -\frac{1}{2} m_e (Z\alpha)^2 + \ldots$ $(m_e Z\alpha) \ll m_e$

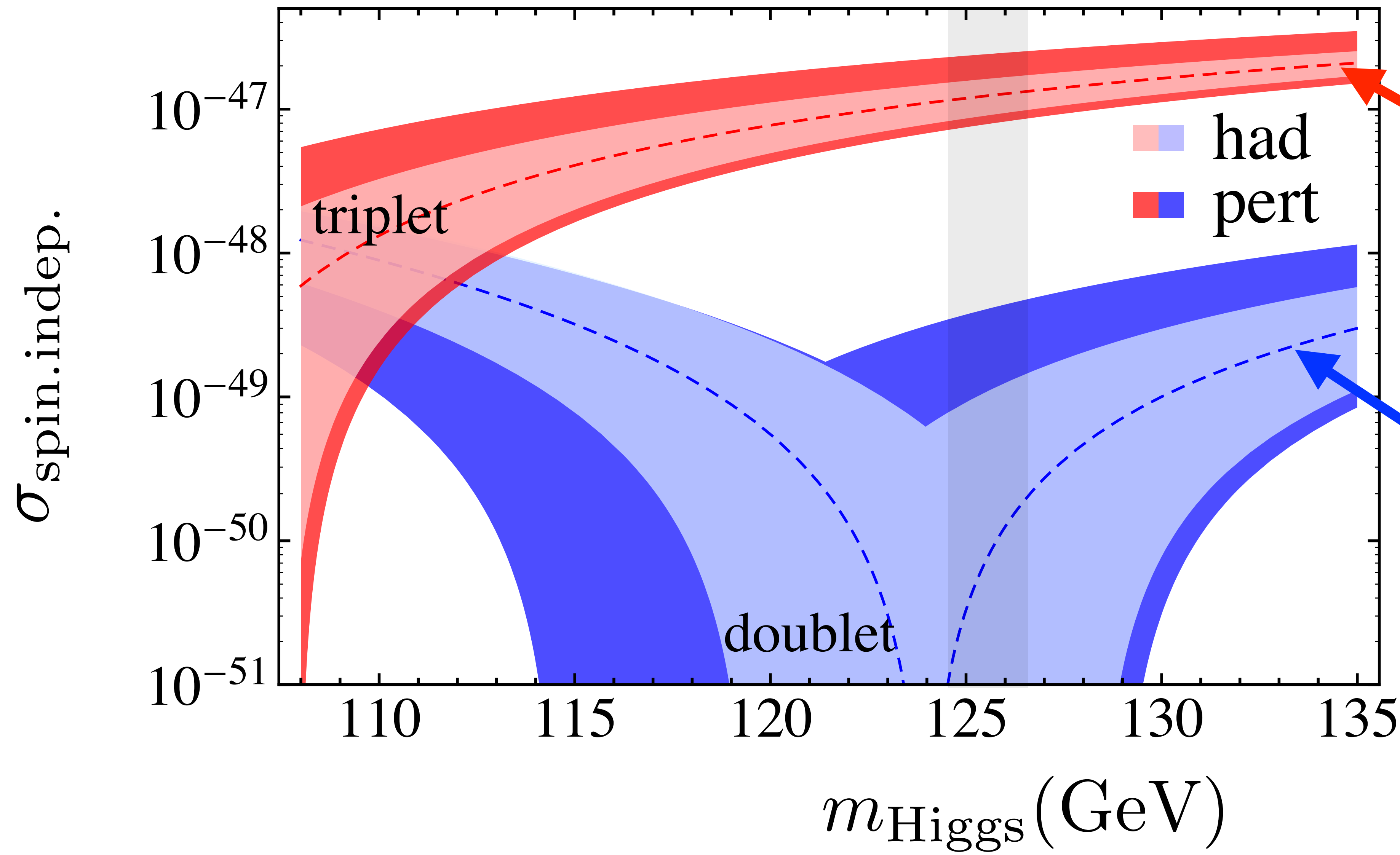
- heavy meson B/B* transitions $F^{B\to D}(v' = v) = 1 + \ldots$ $\Lambda_{\rm QCD} \ll m_{b,c}$

- DM interactions $\sigma(\chi N \to \chi N) = ?$ $m_W \ll m_\chi$



basic problem in SM physics: scattering of nucleon from SU(2)xU(1) source

Benchmarks: large mass, low velocity limit



R. Hill, M. Solon (2014)

(3,0) of SU(2)xU(1)

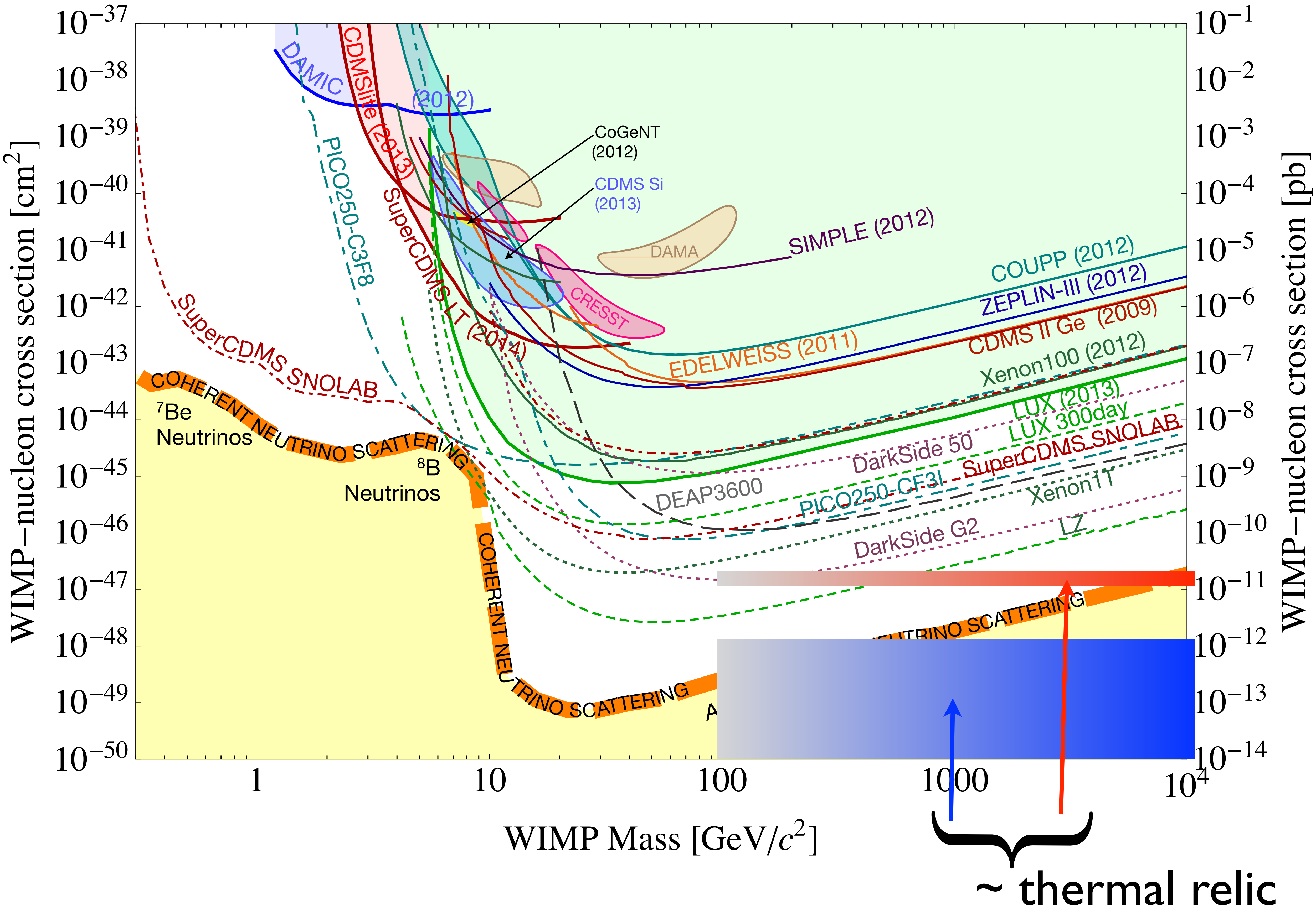
(2,1/2) of SU(2)xU(1)

Suppressed versus dimensional estimate (~10^{-45}cm^2)

- bino/wino, bino/higgsino admixtures *Hill, Solon 1309.4092, 1401.3339, 1409.8290*

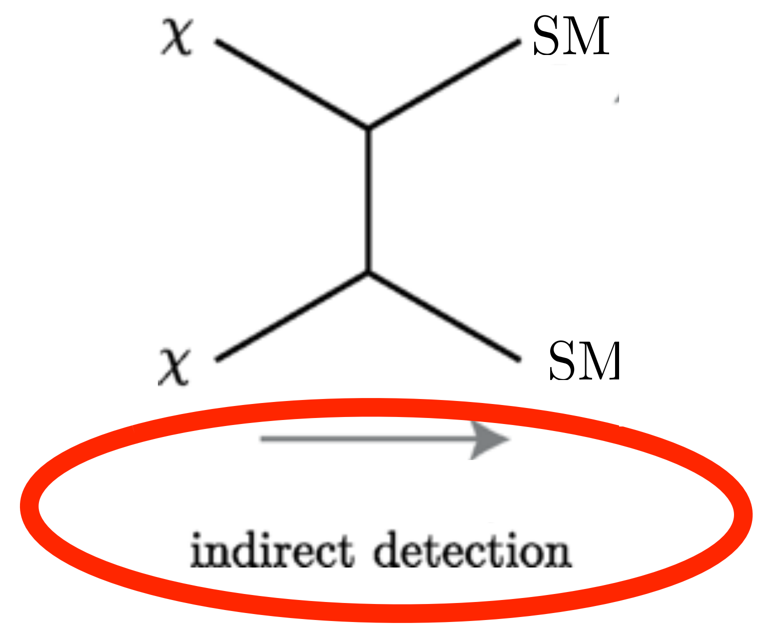
(backup slide)

- bino/sfermion admixtures *Berlin, Robertson, Solon, Zurek 1511.05964*
- 1/M power corrections *C.-Y. Chen, A. Wijangco …*



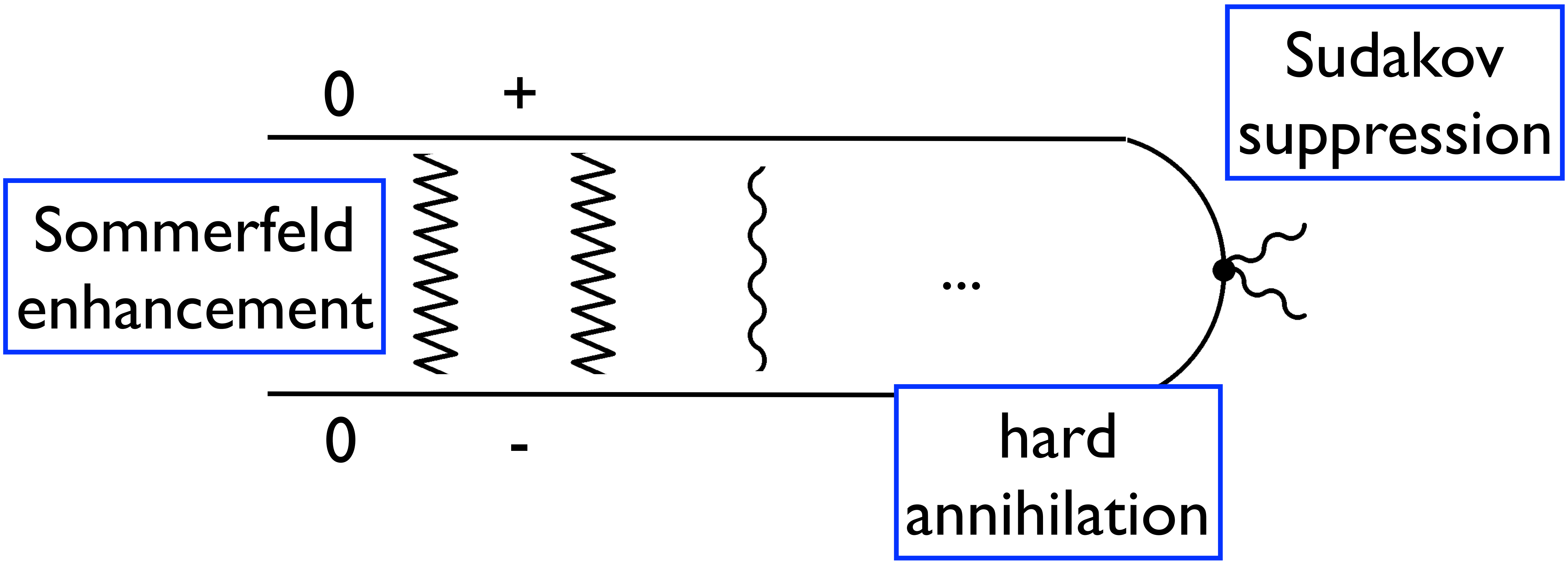
Strong motivation for pushing to neutrino floor at TeV mass

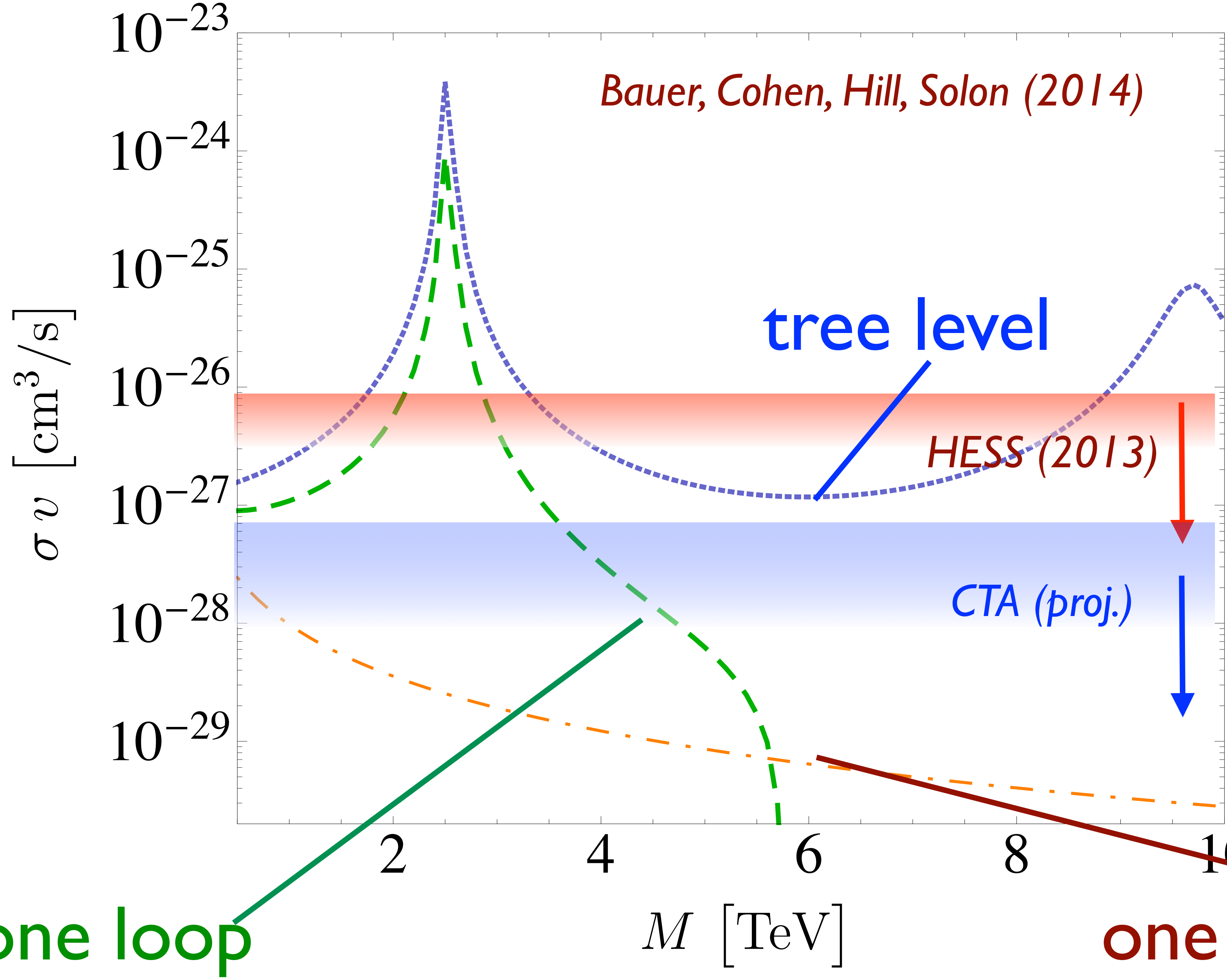
Indirect detection



Recall basic WIMP: SU(3) x SU(2) x U(1)
1 3 0

Photon line signal for heavy WIMP annihilation:





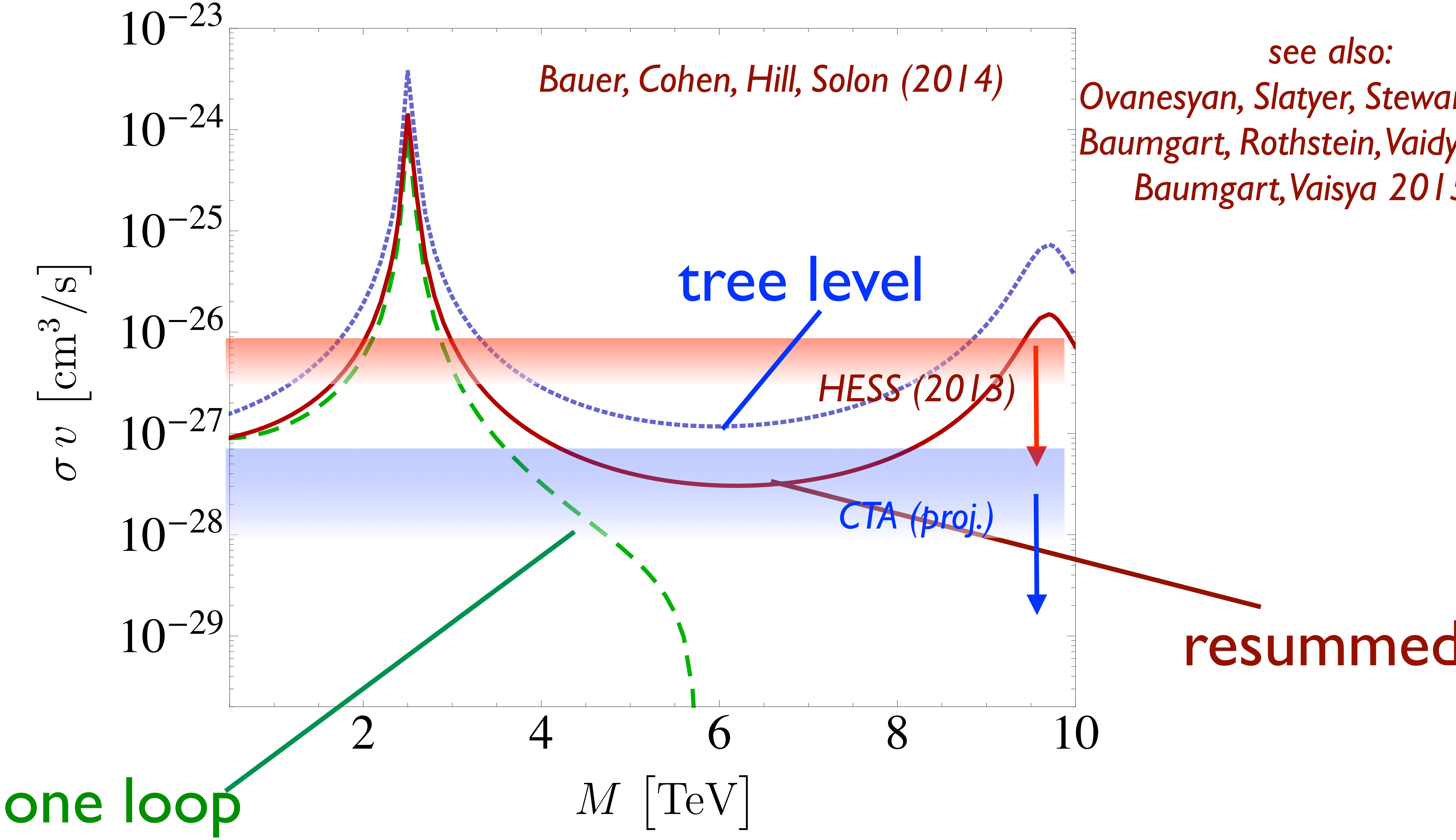
see also:
Ovanesyan, Slatyer, Stewart 2014,
Baumgart, Rothstein, Vaidya 2014,
Baumgart, Vaisya 2015, …

Photon line signal
for “wino”
annihilation

one loop

one loop, neglect
wavefunction enhancement

Multi-scale field theory problem, breakdown of naive perturbation theory



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The "The Effective Theories" of WIMP dark matter

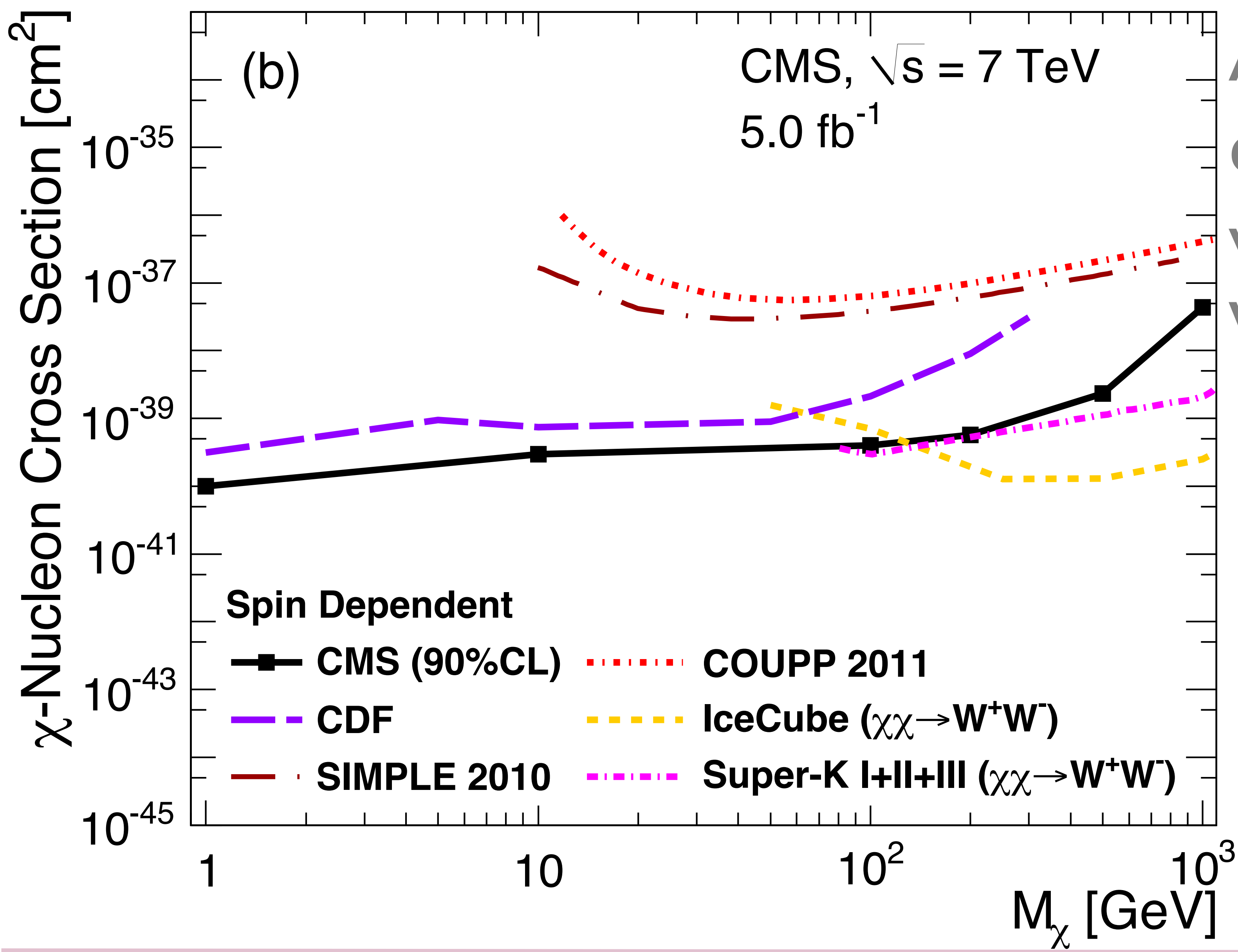
- heavy WIMP expansion
- → heavy mediator expansion
- low velocity expansion

Heavy Mediator expansion

Set-up: $$\mathcal{L} \sim c_i \frac{1}{\Lambda^{d-4}} O_{\rm SM} \times O_{\rm WIMP}$$

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2010, …

Majorana fermion: 10 operators through d=7



Axial-vector quark contact interaction with Dirac fermion WIMP

→ other examples, simplified model extensions: talks of T. Tait, F. Maltoni

The “The Effective Theories” of WIMP dark matter

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- heavy mediator expansion
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Velocity expansion

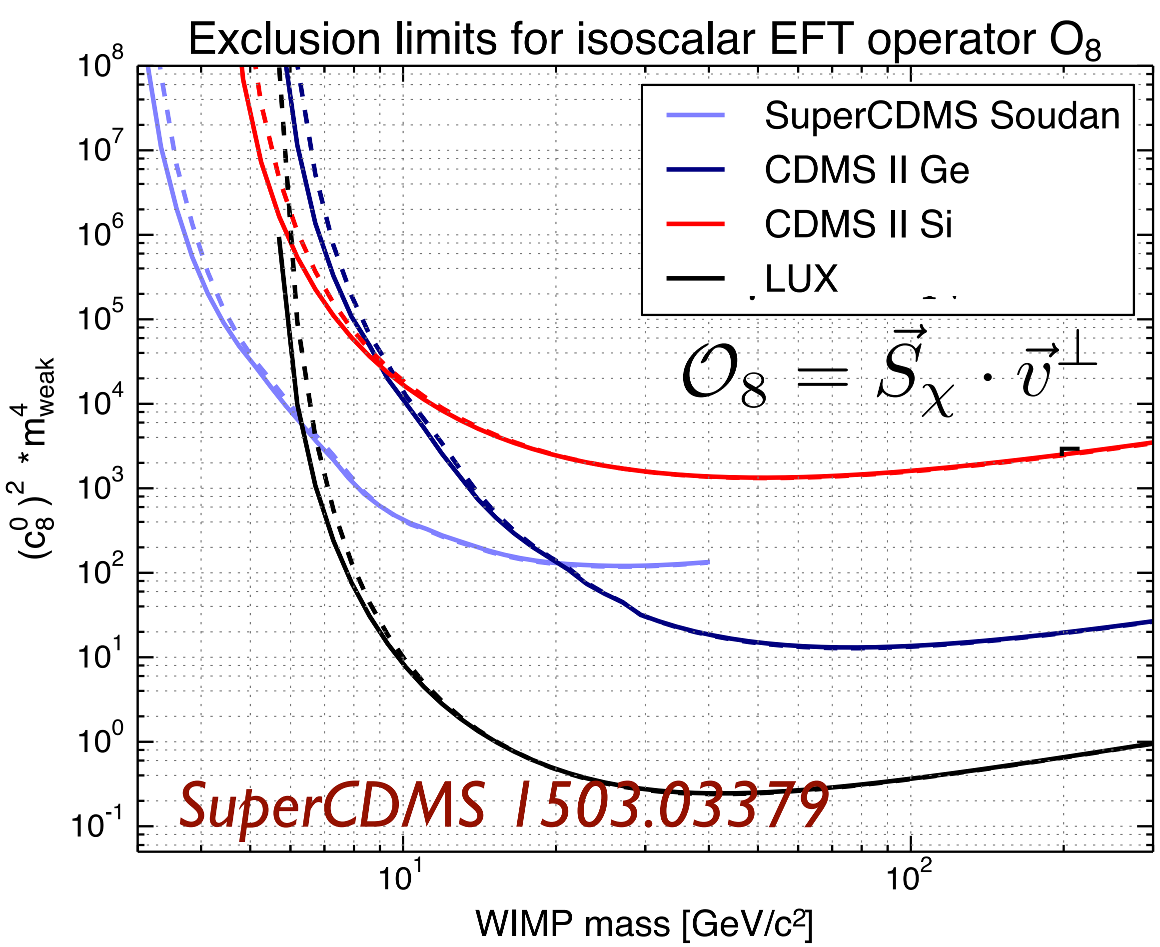
Set-up

$$\mathcal{L} = N^\dagger\left\{i\partial_t + \frac{\partial^2}{2m_N} + \dots\right\}N + \chi^\dagger\left\{i\partial_t + \frac{\partial^2}{2m_\chi} + \dots\right\}\chi$$

$$+ \sum_i \frac{c_i}{\Lambda^{d-4}} N^\dagger(\dots)N\chi^\dagger(\dots)\chi$$

Fitzpatrick, Haxton, Katz, Lubbers, Xu (2012), …

20 contact operators through $1/M^4$



SuperCDMS 1503.03379

- tracing simplified models to non.rel. ops

Dent, Krauss, Newstead, Sabharwal 1505.03117

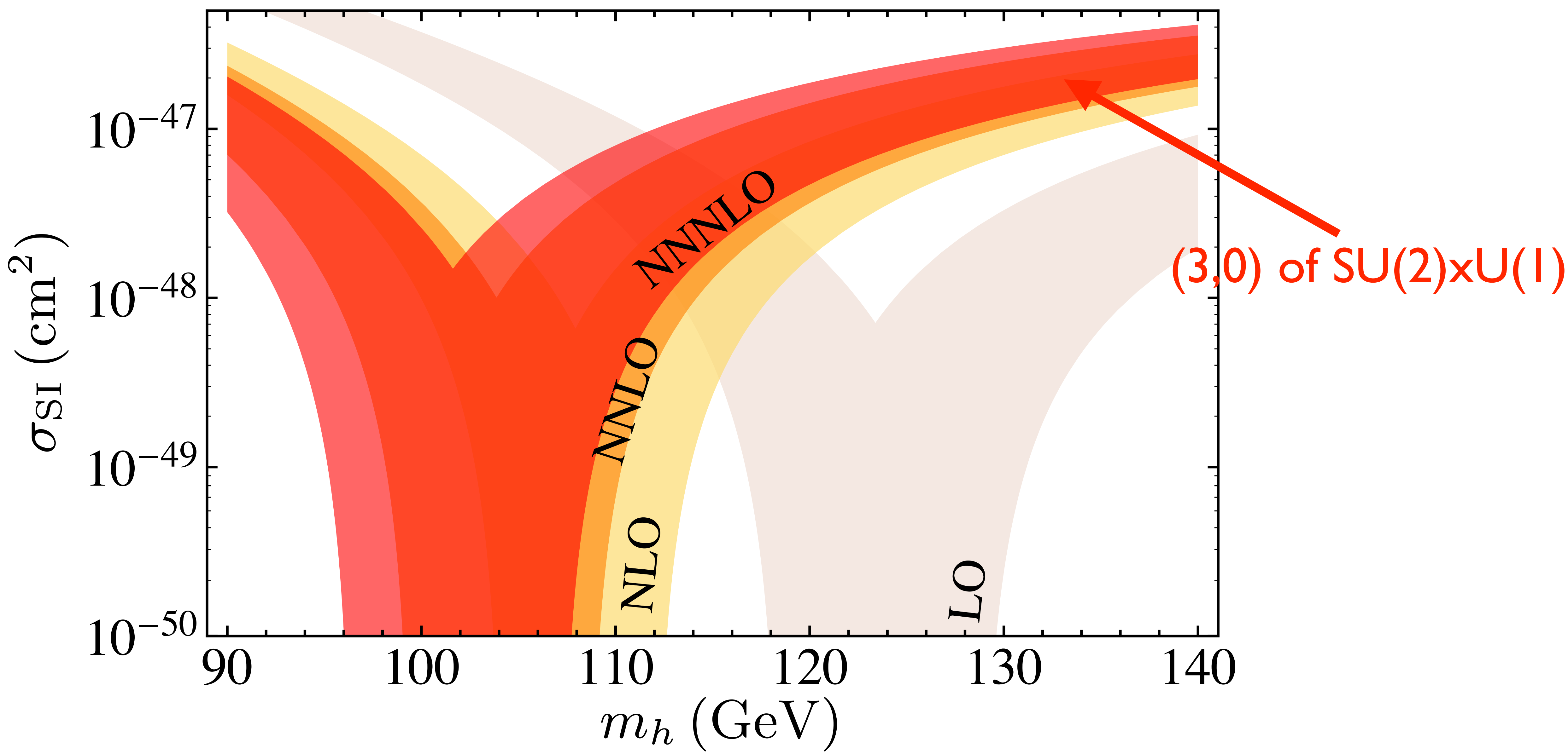
- related phenomenology

Gluscevic, Gresham, McDermott, Peter 1506.04454

Novel detector responses possible, especially for low-mass WIMPs

QCD aspects of WIMP-nucleus scattering

perturbative QCD corrections:



NLO corrections essential for correct order of magnitude

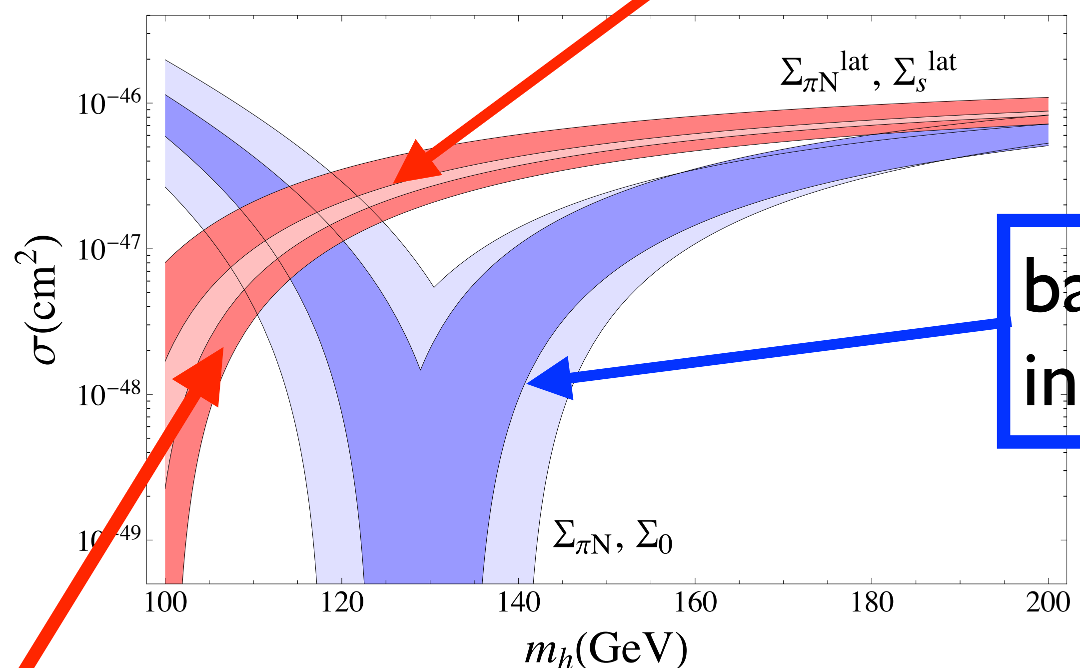
QCD aspects of WIMP-nucleus scattering

nonperturbative matrix elements: important impact from lattice QCD

lattice QCD inputs

Durr et al. 1109.4265

Junnarkar and Walker-Loud, 1301.1114



baryon spectroscopy inputs

Borasoy and Meissner, hep-ph/9607432

Pavan et al. hep-ph/0111066

(3,0) of SU(2)xU(1)

- recent work in n_f=2 chiral perturbation theory *Crivellin, Hoferichter, Procura (2014)*

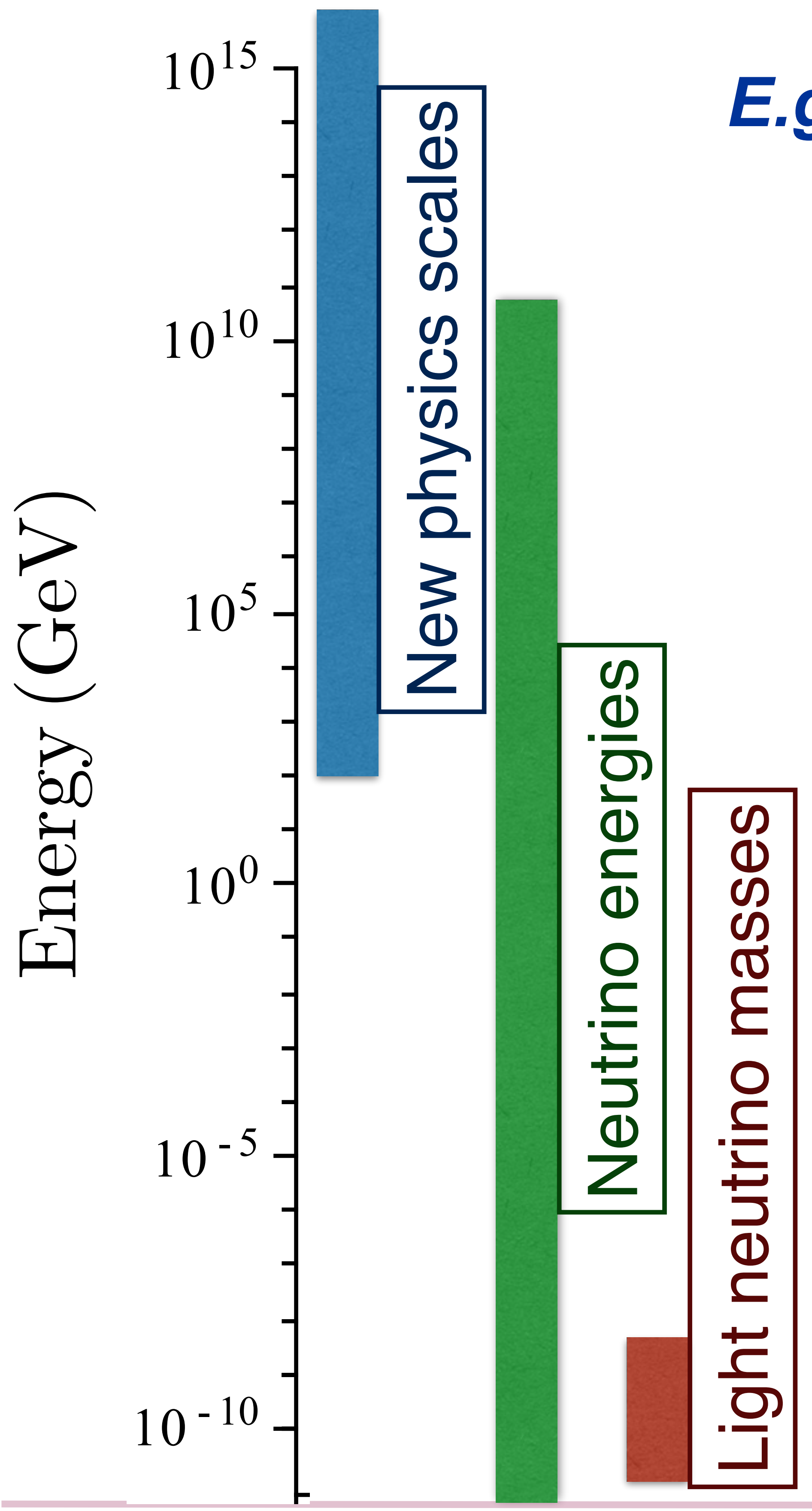
Hoferichter, Ruiz de Elvira, Kubis, Meissner (2015)

Part 2:
The particle physics of neutrino cross sections

DM $\leftrightarrow$ neutrinos

- Compelling physics problems
- Particle/nuclear interplay
- Lattice QCD providing critical inputs

Neutrino physics covers a vast range of energy scales



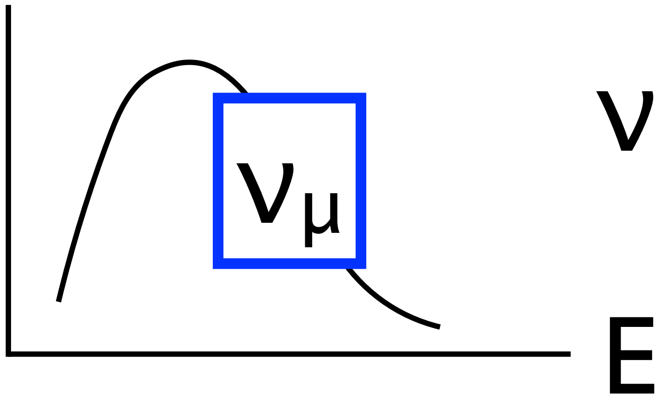
E.g., at DUNE, NOvA, MINOS, T2K, …

- ***Probing $\Lambda_{New\ Physics}$ ~ 10^{15}GeV***
- ***Neutrino energies ~ GeV***
- ***Neutrino masses ~ 10^{-10} GeV***

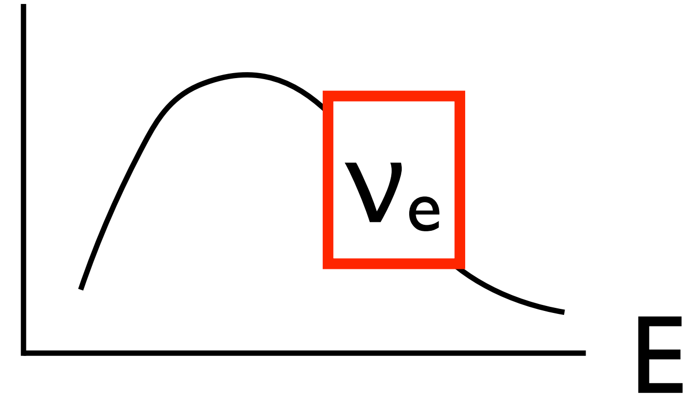
Exploiting this window on high scale physics demands a dedicated theory effort

probability of $\nu_\mu \rightarrow \nu_e$ $\Rightarrow$ fundamental neutrino properties

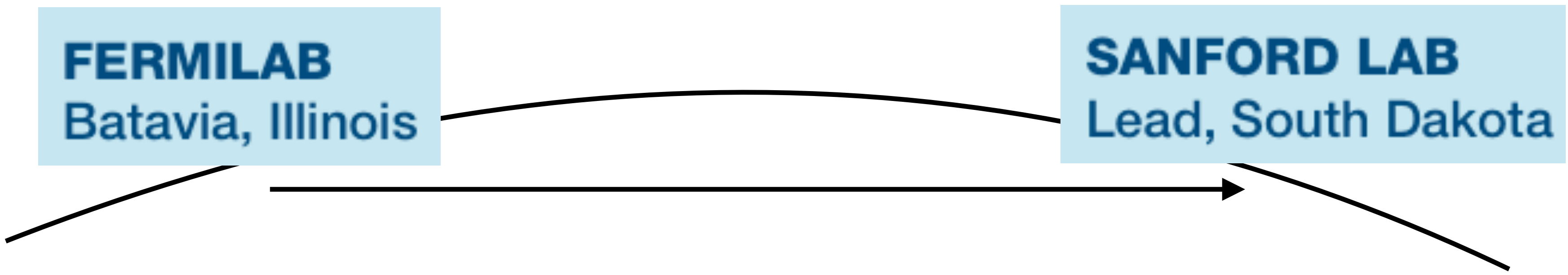
ν_μ flux



$$\nu_e \text{ flux} = \frac{\nu_e \text{ event rate}}{\text{cross section}}$$



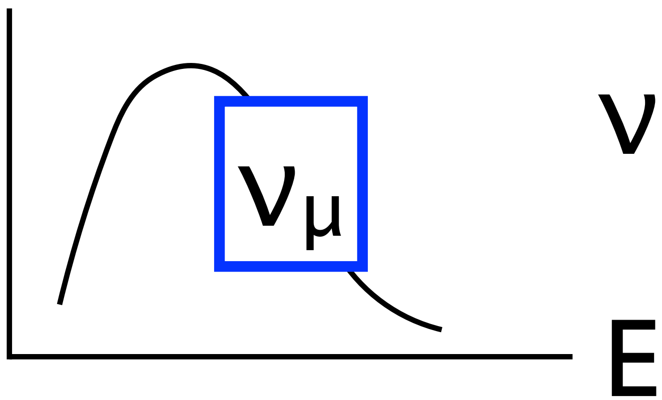
E.g. DUNE



Cross section translates observed event rate to ν_e appearance prob.

probability of $\nu_\mu \to \nu_e$ $\Rightarrow$ fundamental neutrino properties

ν_μ flux



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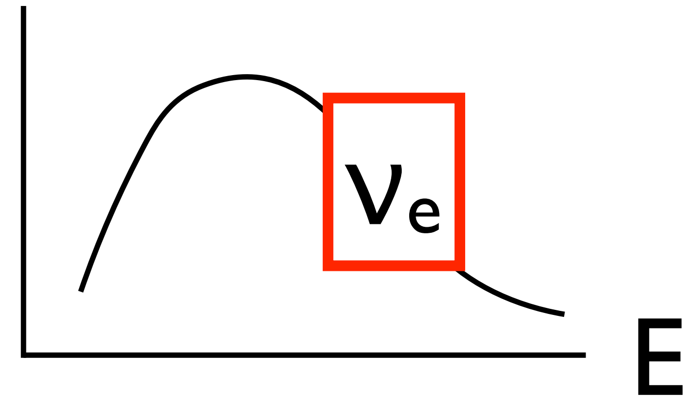

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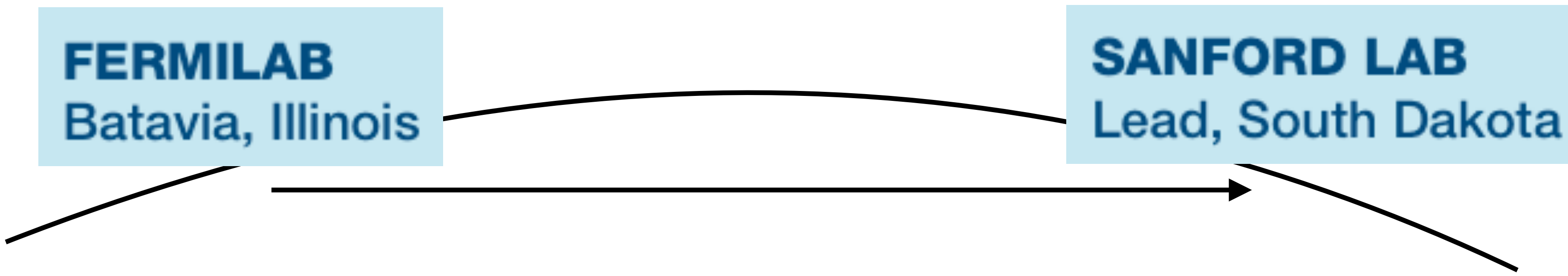
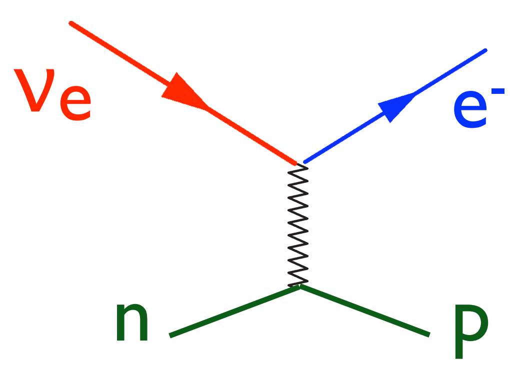


Cross section translates observed event rate to ν_e appearance prob.

Basic signal process: charged current quasi elastic scattering

(large event sample, "reconstructible" neutrino energy, theoretically "clean")



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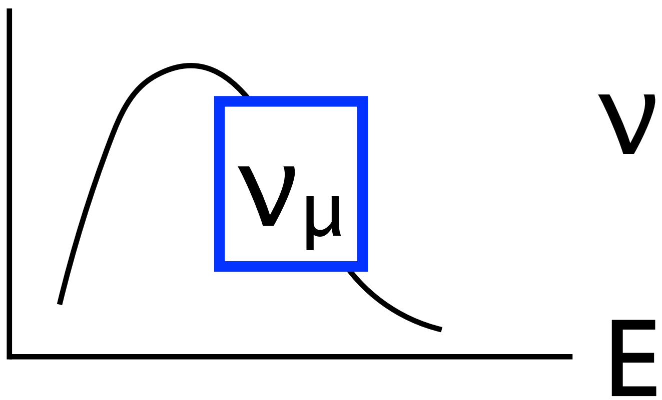

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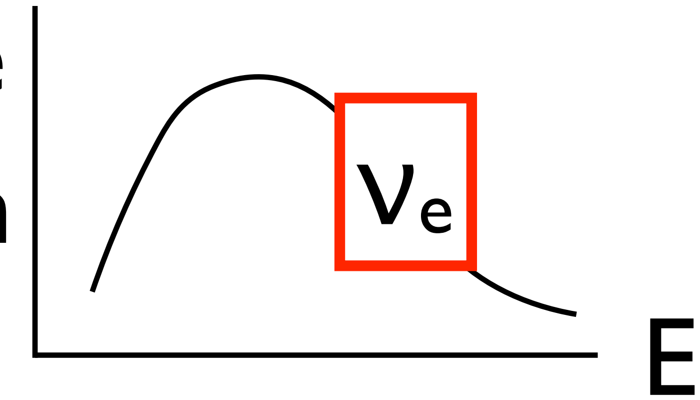

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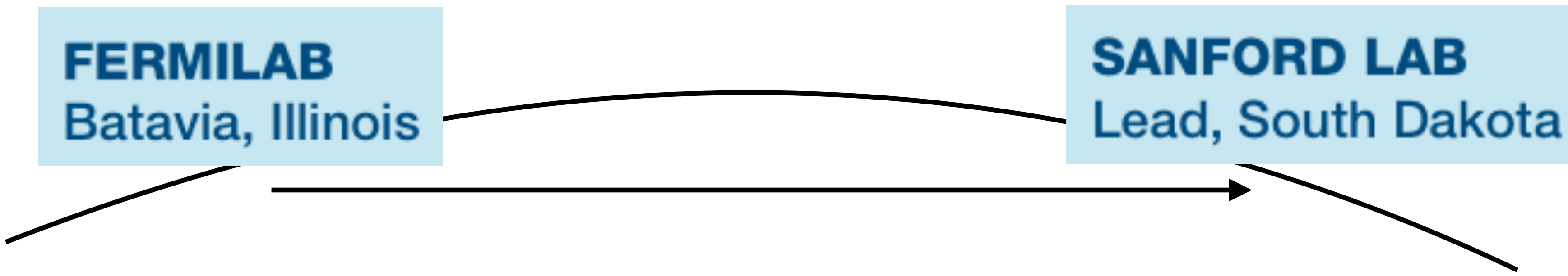

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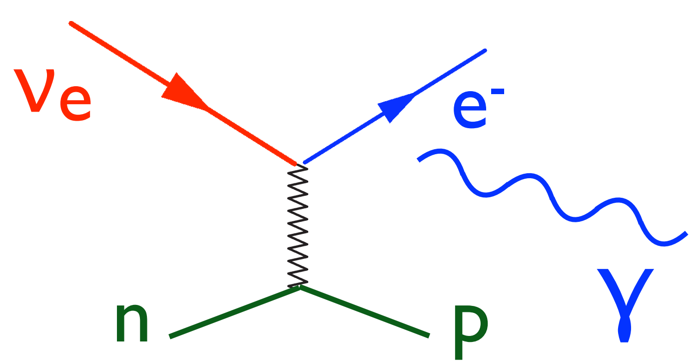
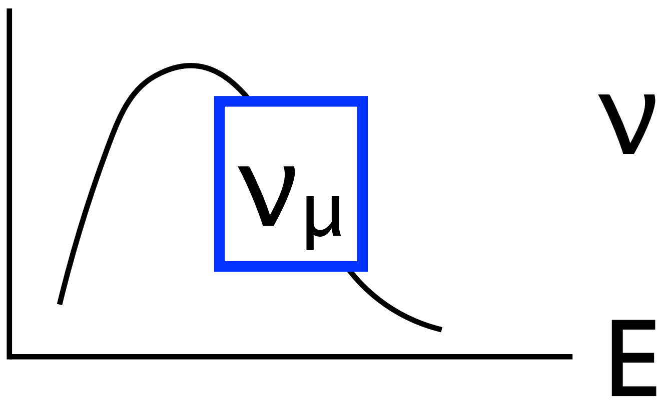


radiative corrections

probability of $\nu_\mu \to \nu_e$ $\Rightarrow$ fundamental neutrino properties

ν_μ flux



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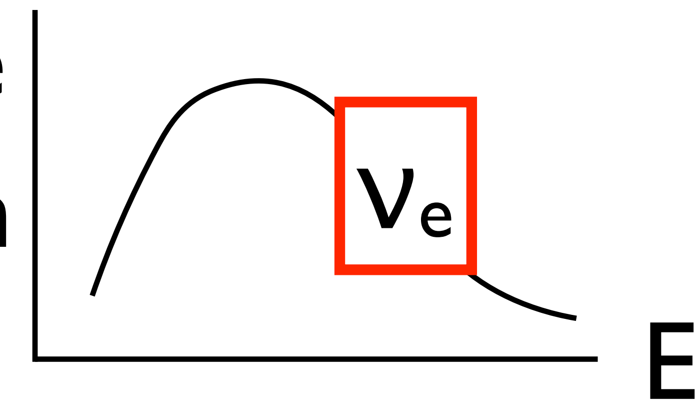

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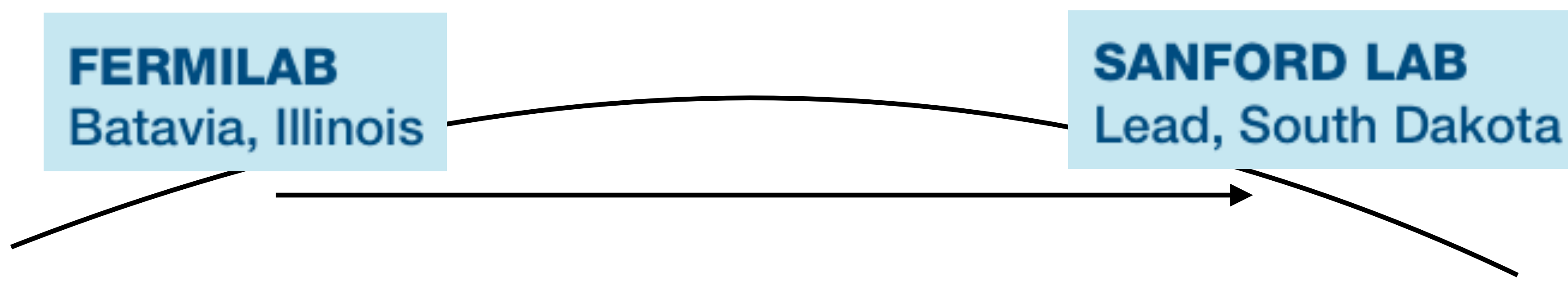

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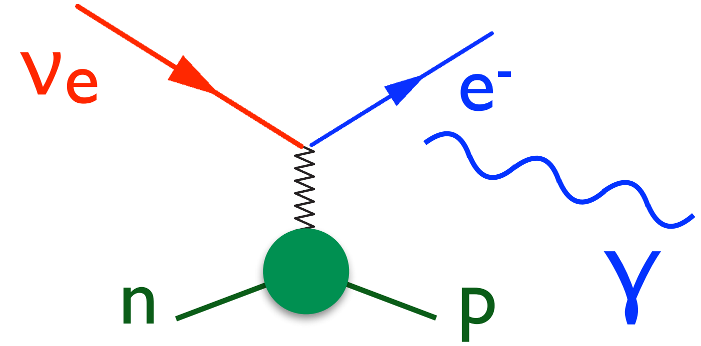
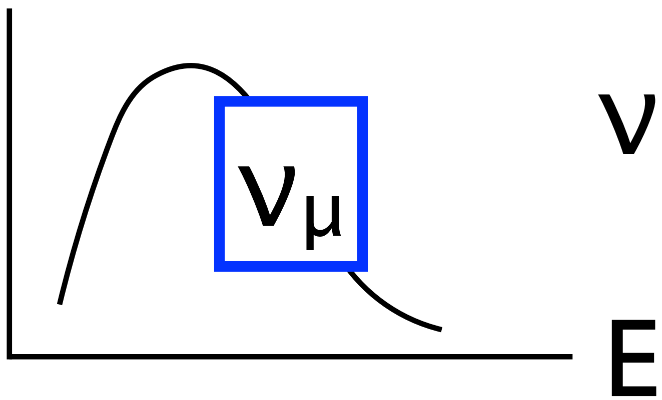


radiative corrections

hadronic amplitudes

probability of $\nu_\mu \to \nu_e$ ⇒ fundamental neutrino properties

ν_μ flux



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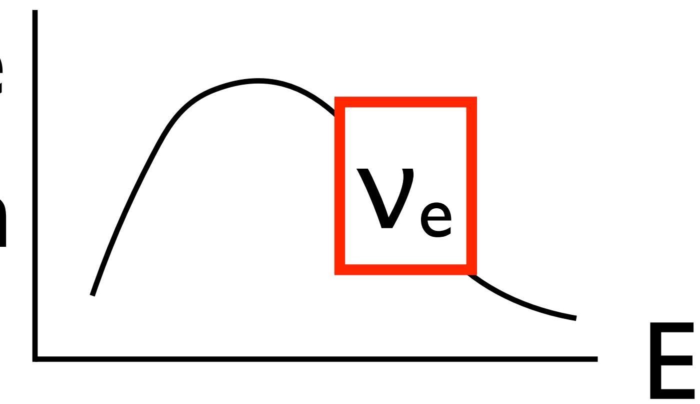

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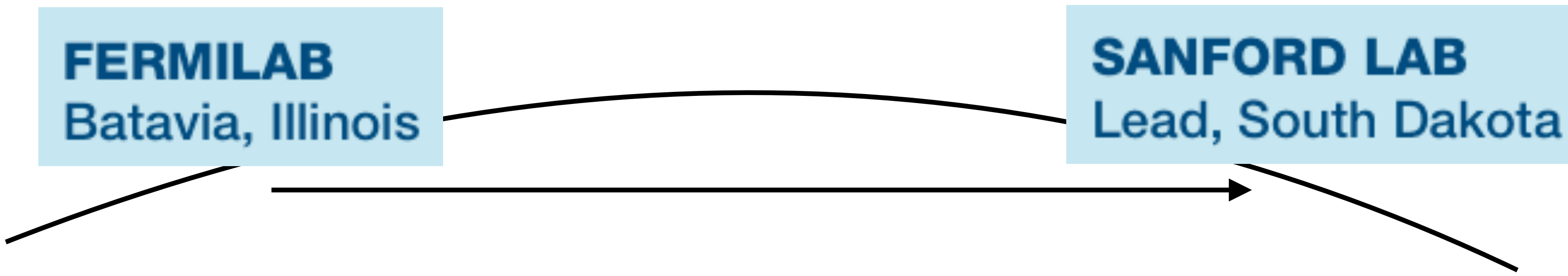

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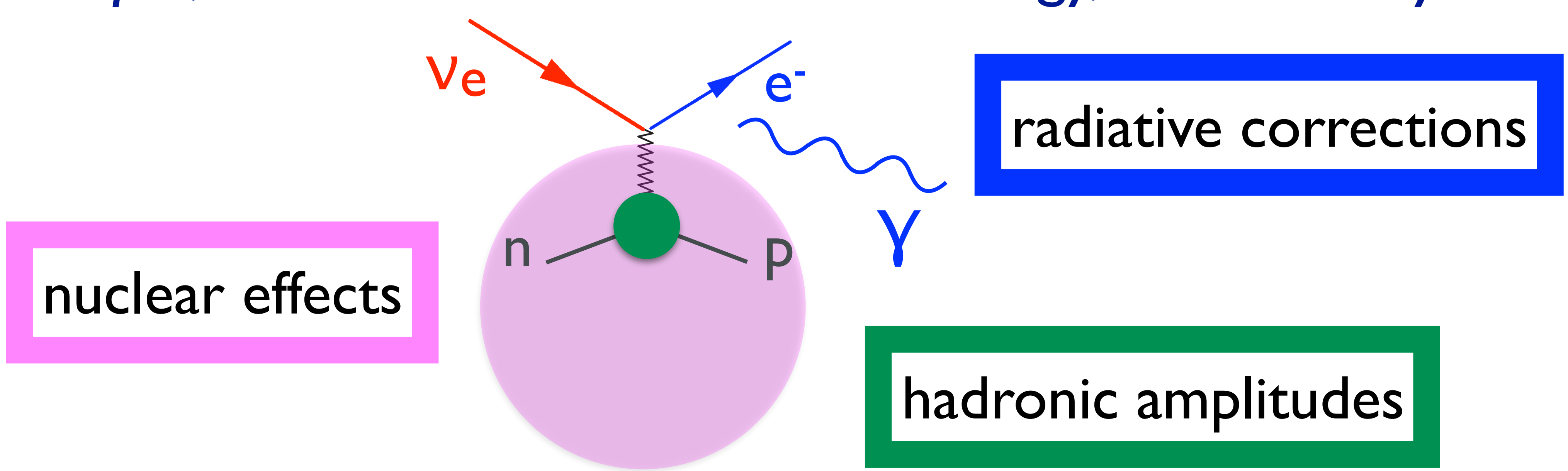
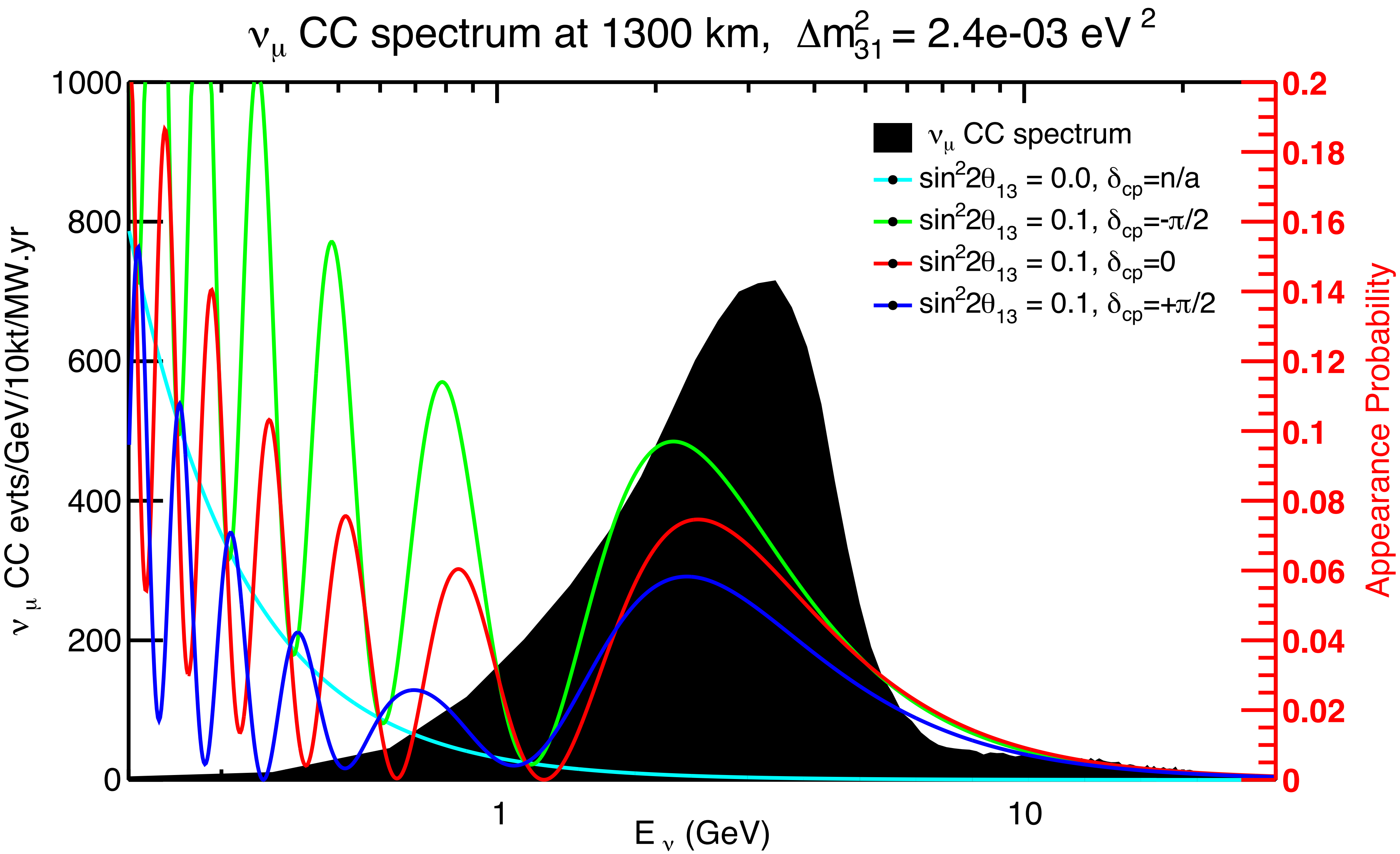
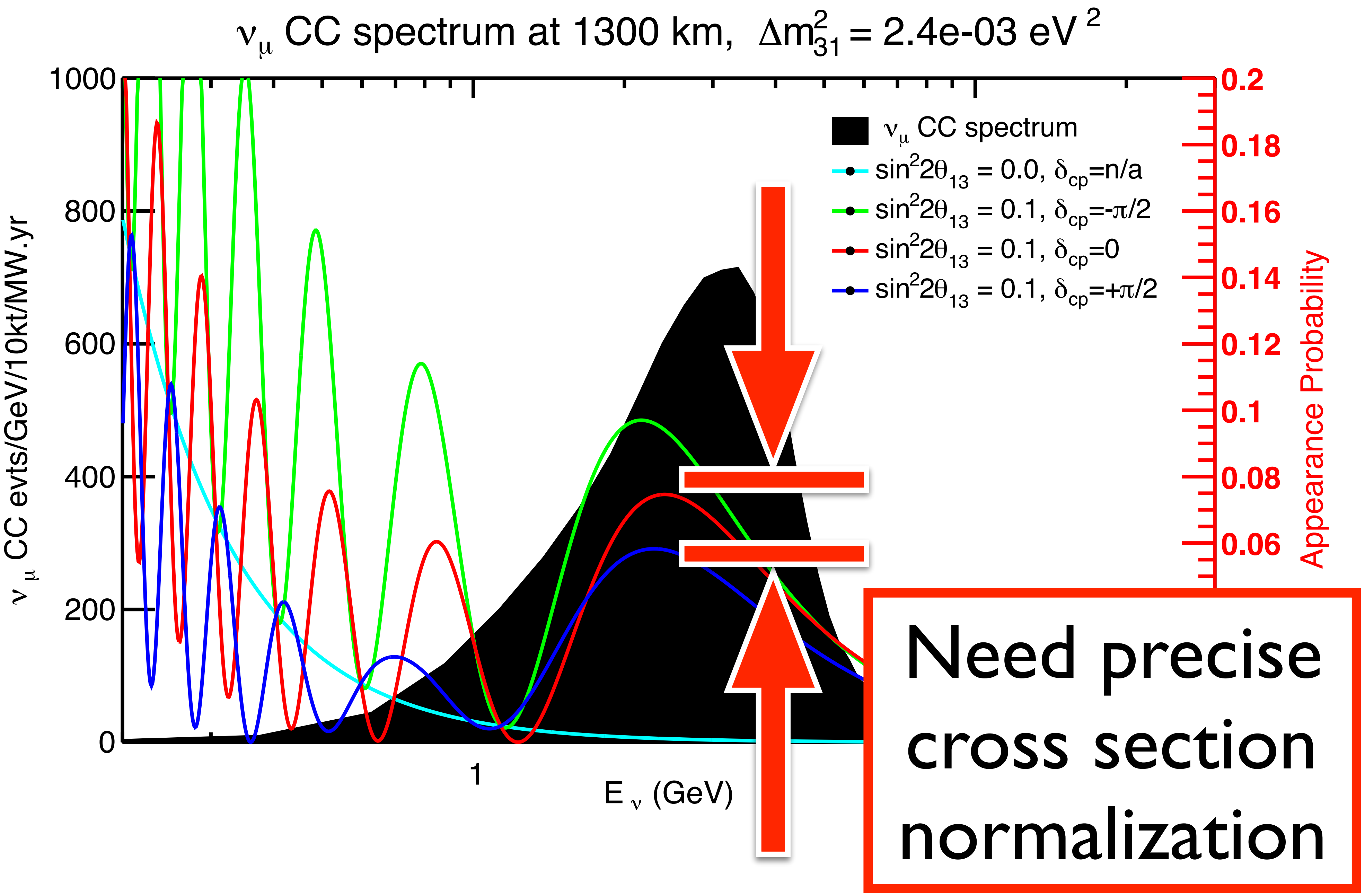




LBNE, 1307.7335
cf. Coloma, Huber et al., 1307.1243, 1311.4506;
Lalakulich and Mosel, 1311.7288



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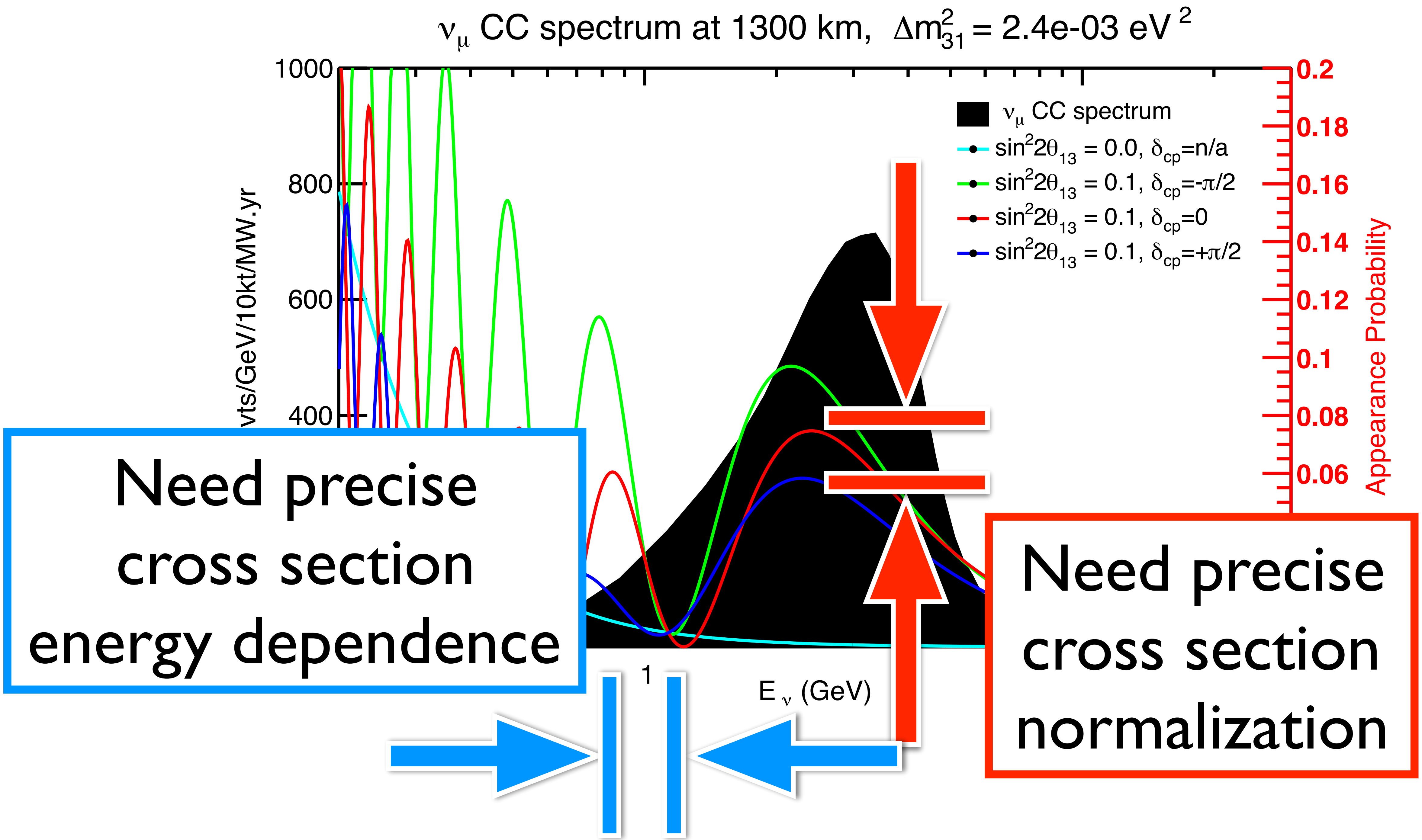

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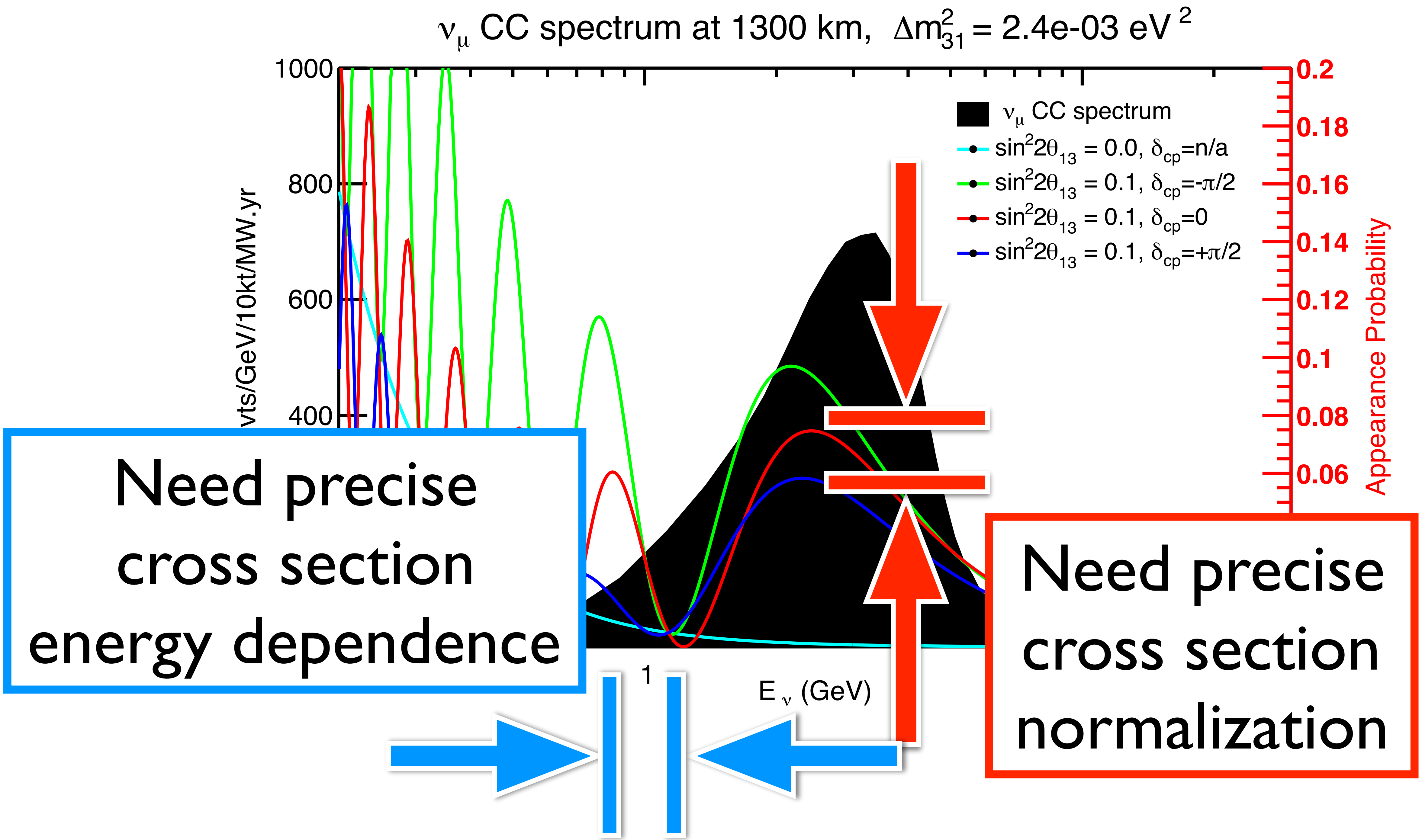

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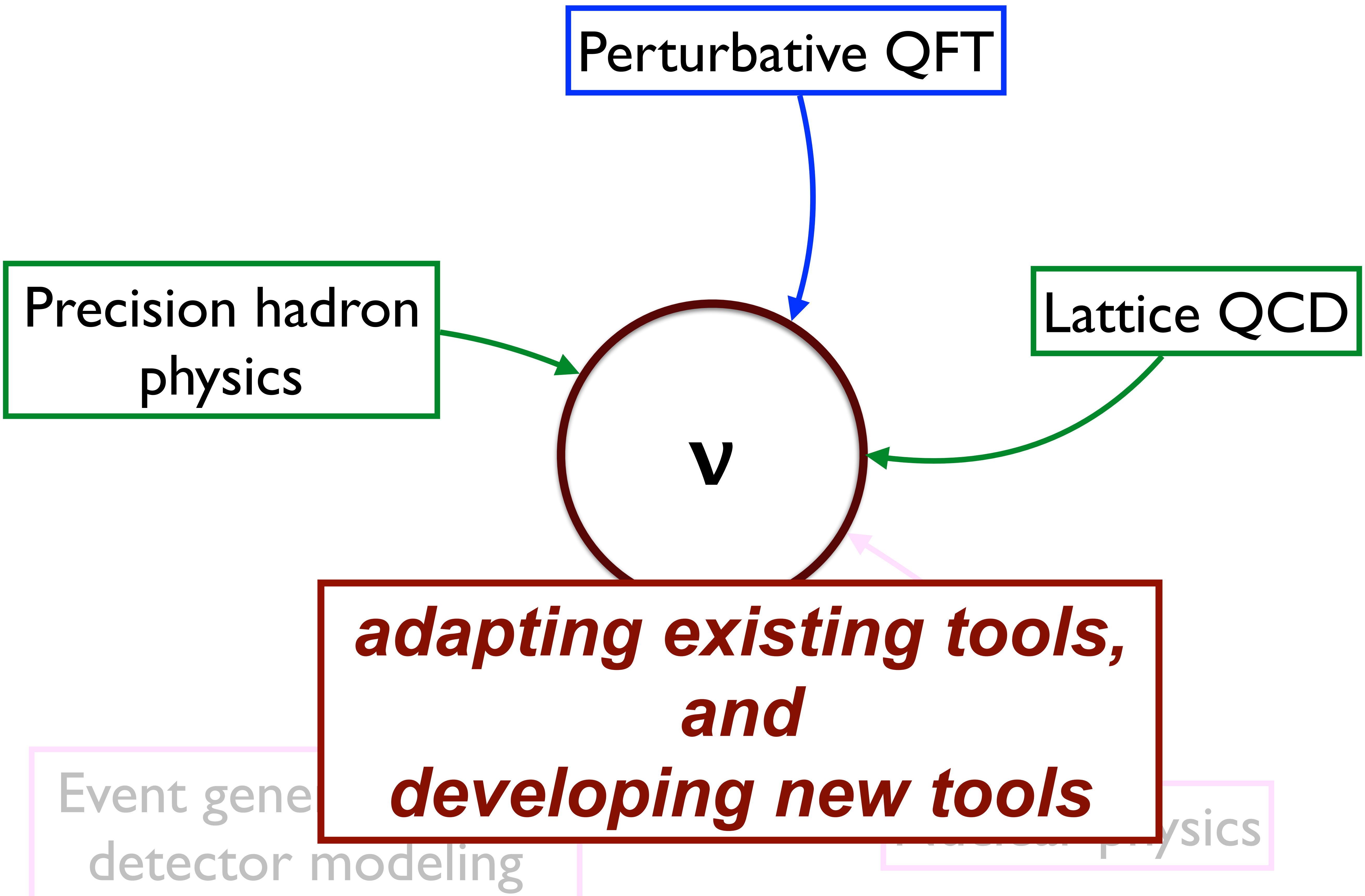
Many related activities and applications, over a wide energy range:

- **sterile neutrino searches**
- **reactor, supernova, astrophysical, solar, cosmological ν's**
- **proton decay, …**

Focus here on ~GeV ν cross sections for oscillation experiments

This is a challenging problem. HEP Theory is…



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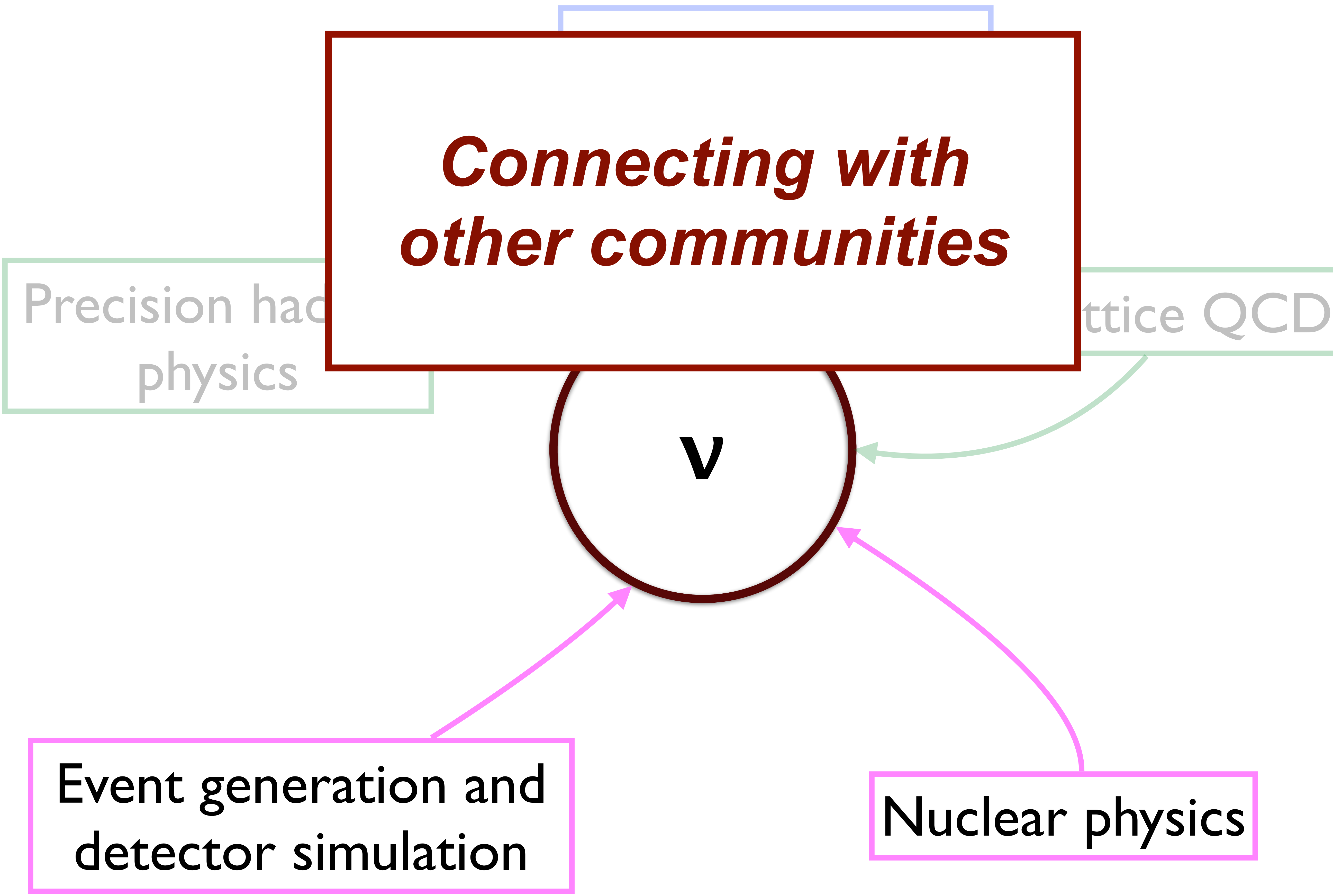
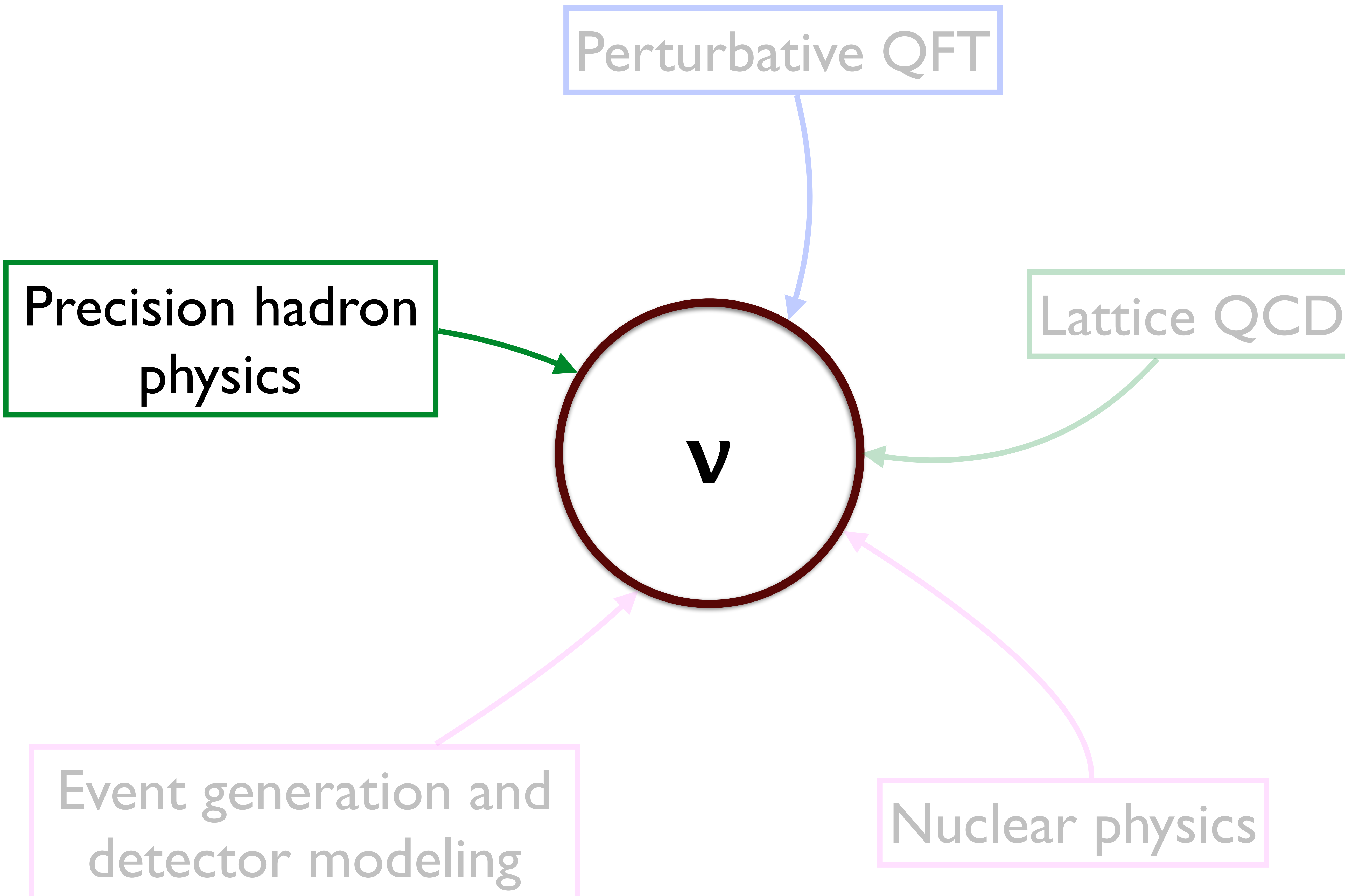
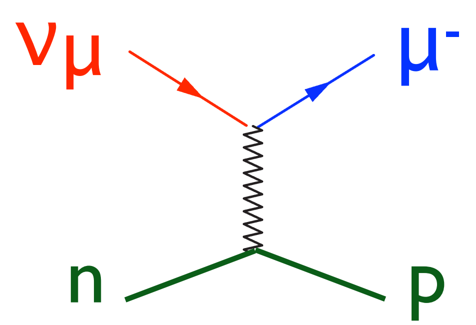


Begin with elementary targets



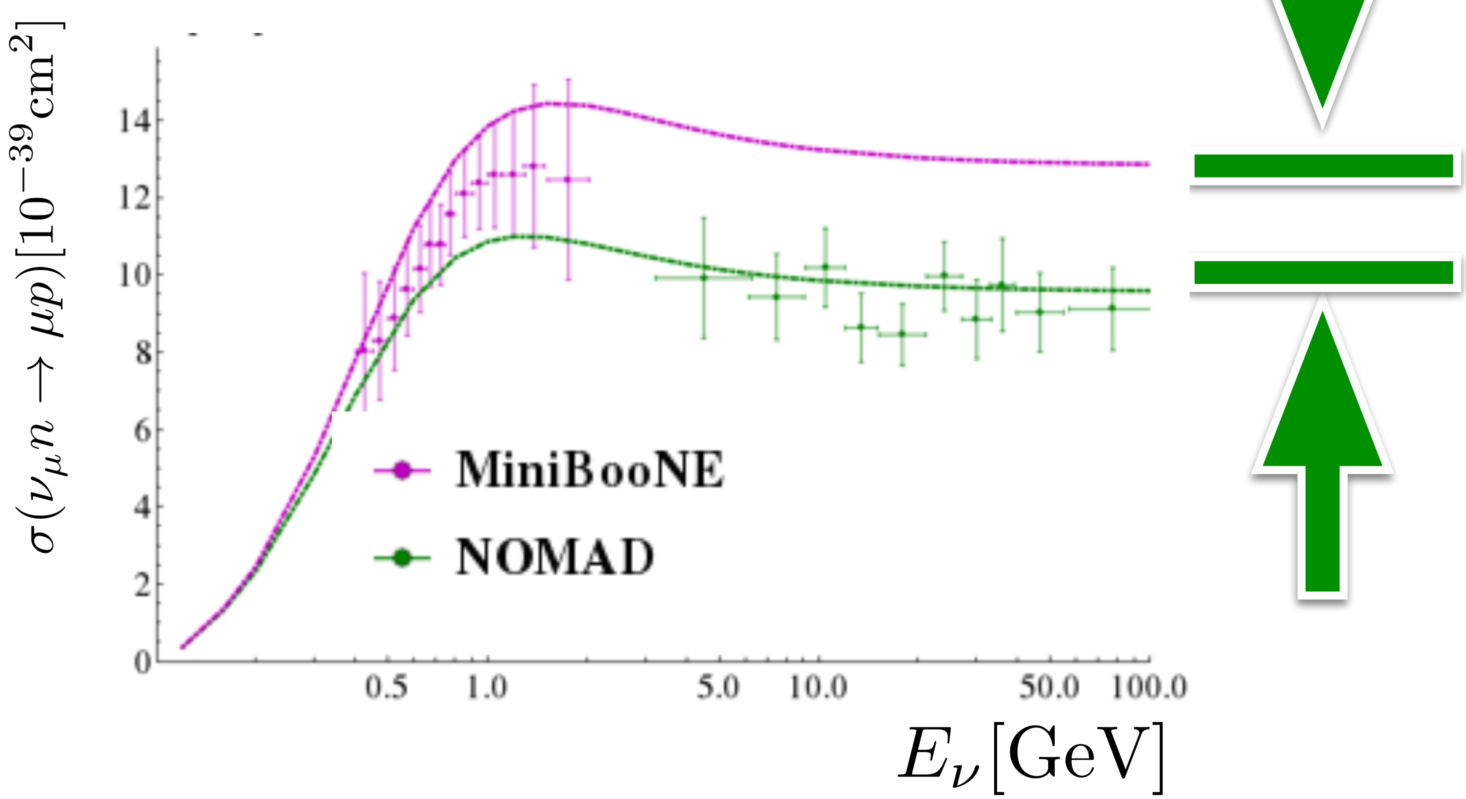
Return to the basic process



$$\sigma(\nu n \to \mu p) = |\cdots F_A(q^2) \cdots|^2$$

poorly known axial-vector form factor

Large uncertainties in nucleon-level amplitudes, the basic building block for complete nuclear cross sections.



Different nucleon-level cross sections inferred from carbon data

But, different:

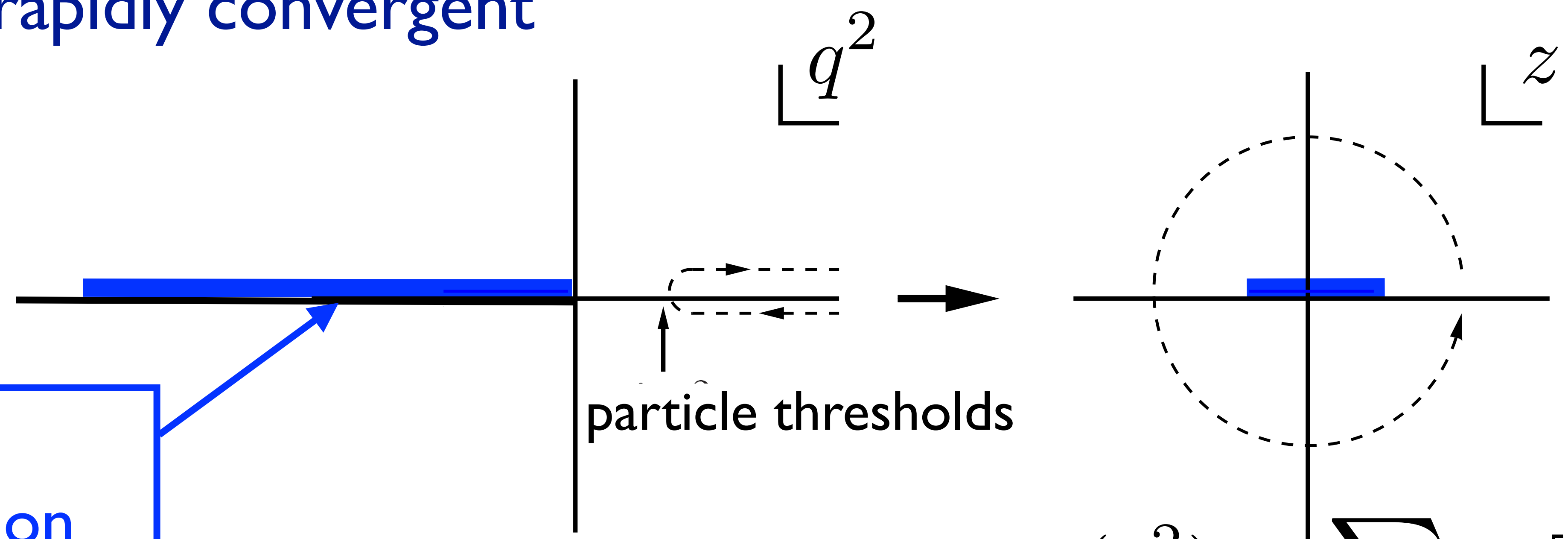
- ***nucleon form factors***
- ***nuclear corrections***

Need elementary targets to break degeneracies

HEP toolbox is being applied to precision lepton-nucleon scattering

Basic problem: don't know form factor shapes, so don't know what we're constraining

Underlying QCD tells us that Taylor expansion in appropriate variable is rapidly convergent



experimental kinematic region

$$F(q^2) = \sum_k a_k [z(q^2)]^k$$

coefficients in rapidly convergent expansion encode nonperturbative QCD

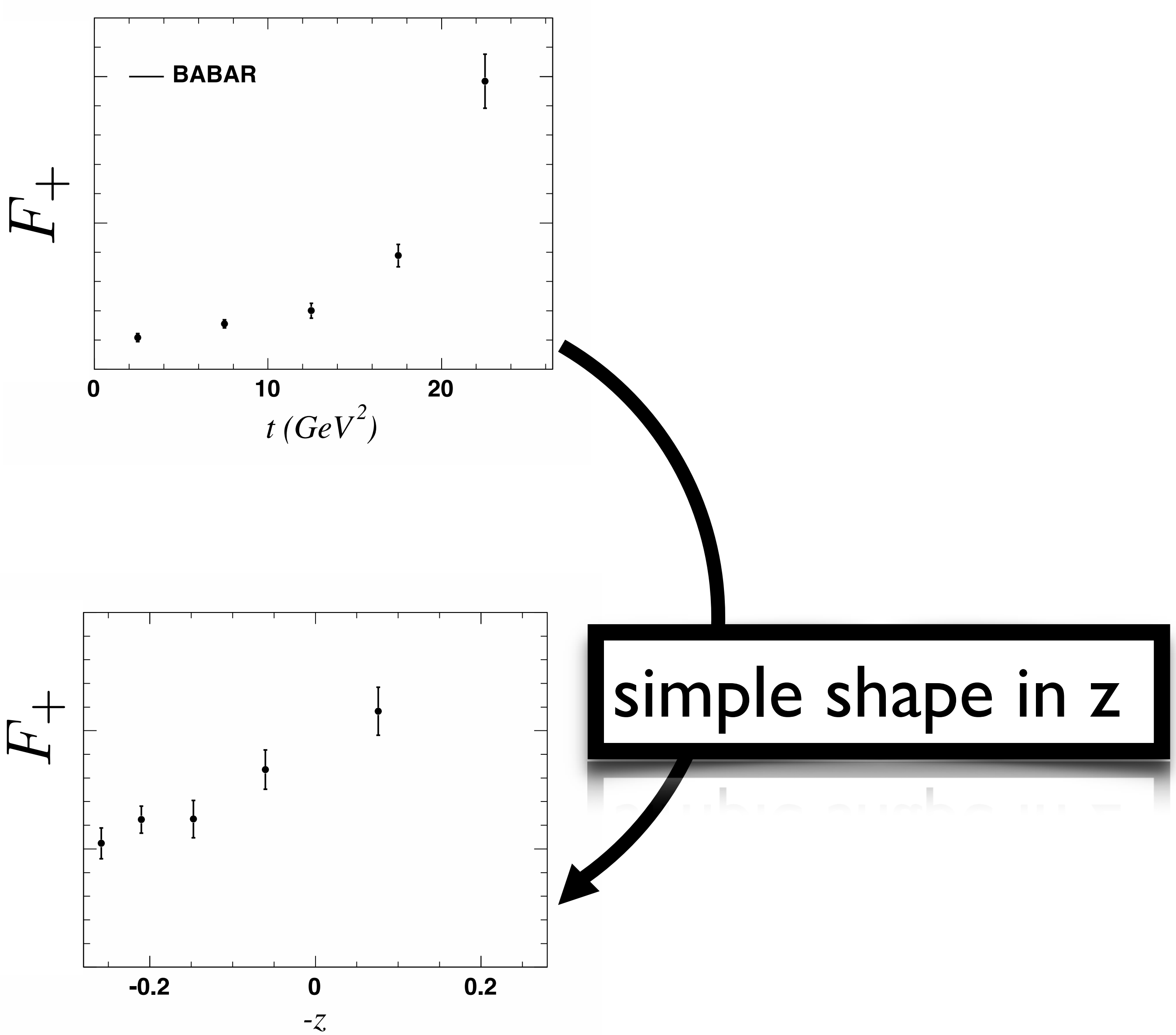
Systematically improvable, quantifiable uncertainties

This approach has been very successful in other processes

E.g., B→πeν: |z|<0.28

$$\frac{d\mathcal{B}}{dq^2} \sim |V_{ub}|^2 |F_+(q^2)|^2$$

Becher, RJH hep-ph/0509090



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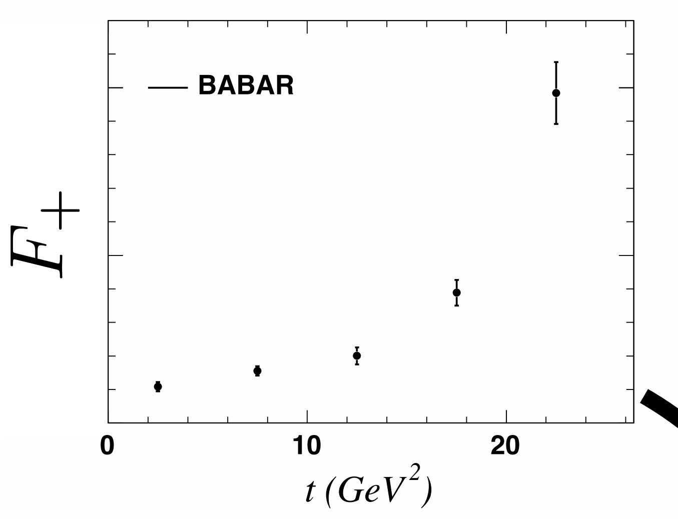
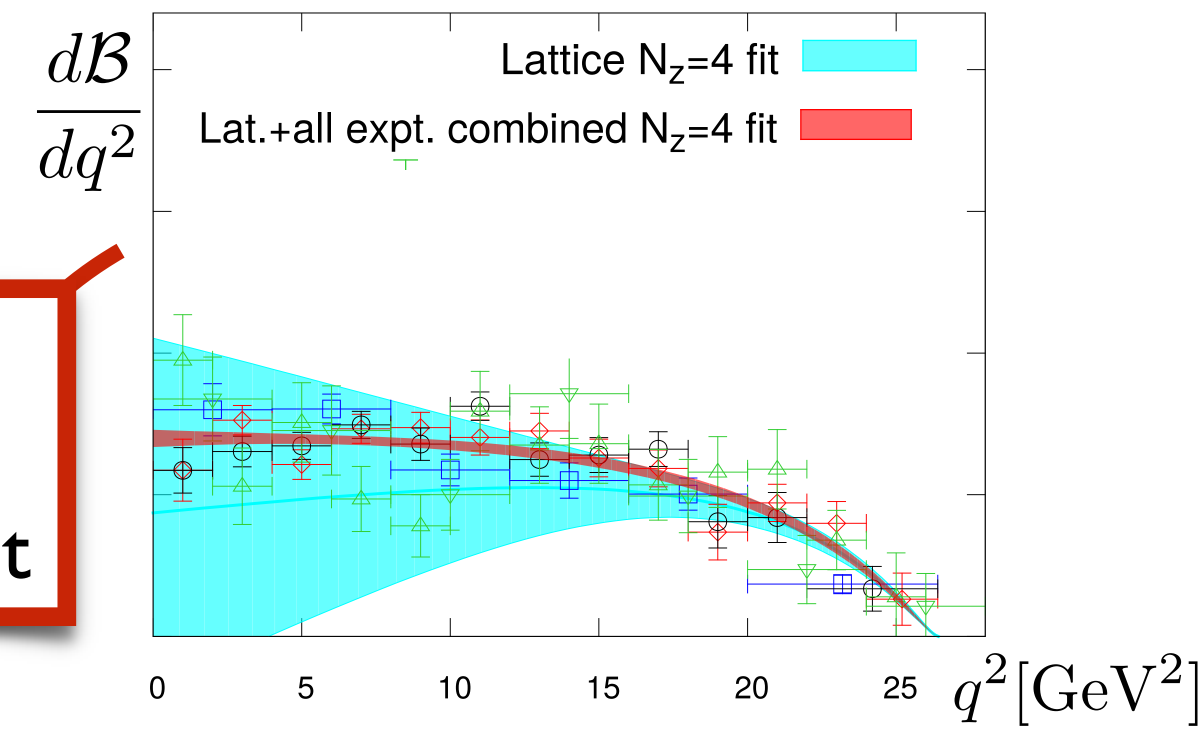
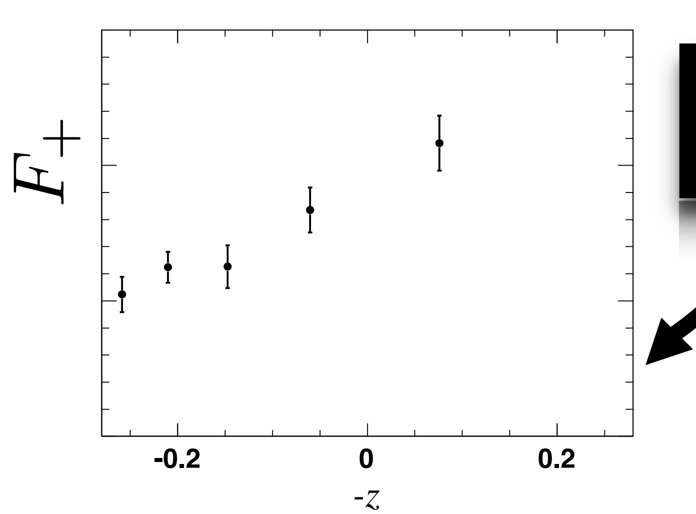


Fermilab lattice/MILC 1503.07839



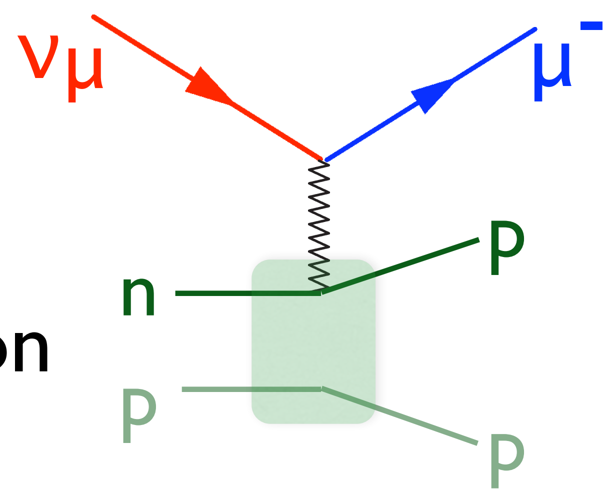
systematic combination of lattice, experiment



simple shape in z

world's best determination of $|V_{ub}|$

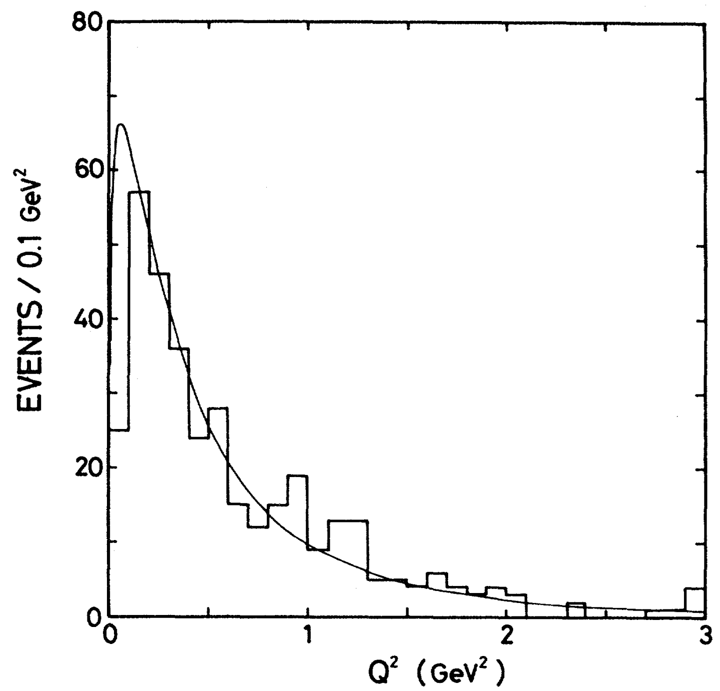
Adapt these tools for neutrino - hadron scattering



deuteron

E.g., $\nu_\mu + n \to \mu^- + p$,
$0 < Q^2 < 3\ \text{GeV}^2$

$|z|<0.35$

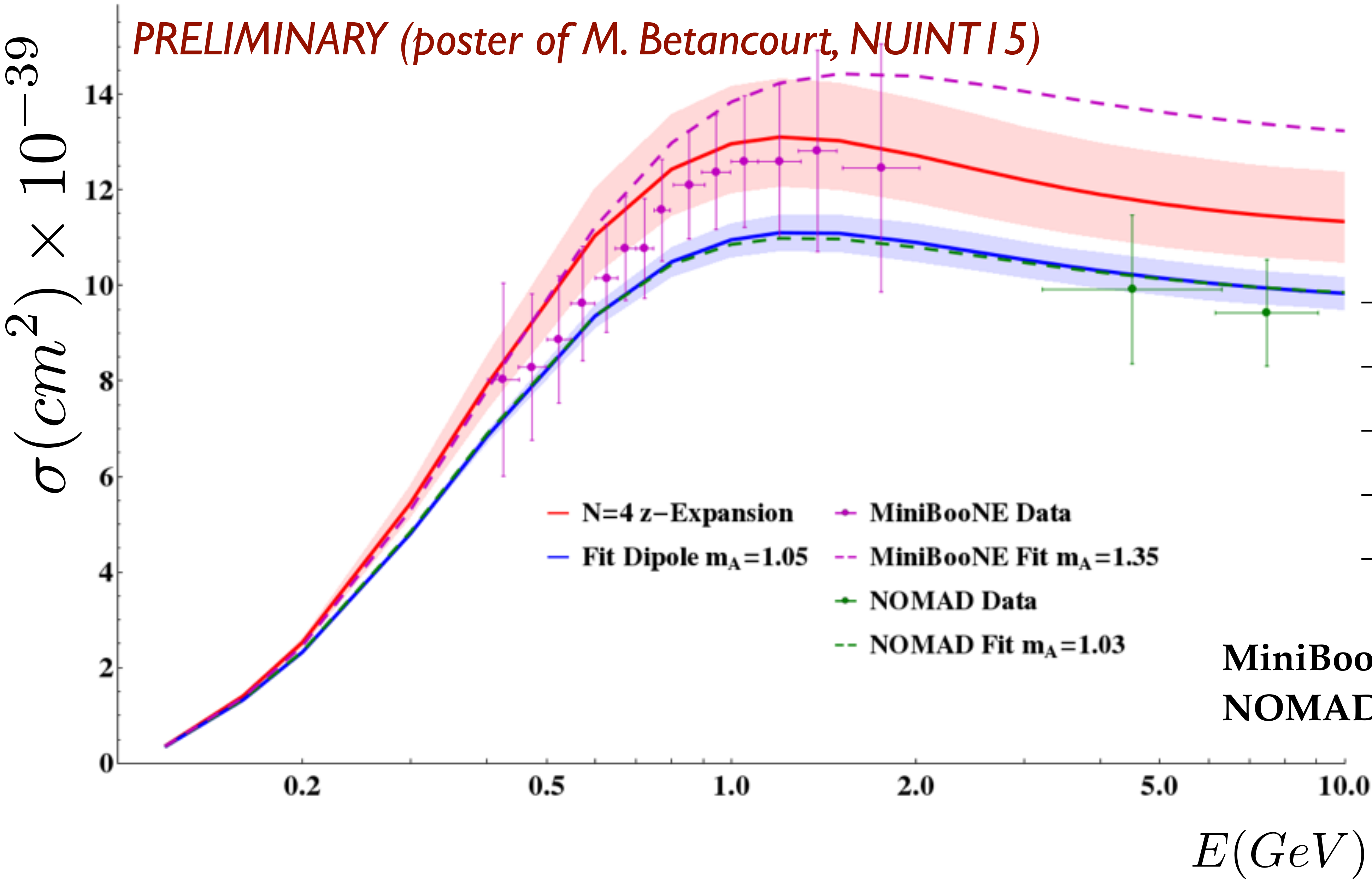


[Fermilab 15-foot deuterium bubble chamber, PRD 28, 436 (1983)]

Revisit deuterium bubble chamber data

- small(-ish) nuclear effects
- small(-ish) experimental uncertainties
- small statistics, ~3000 events in world data

M. Betancourt, R. Gran, RJH, A. Meyer,
PRELIMINARY (poster of M. Betancourt, NUINT15)



Dipole

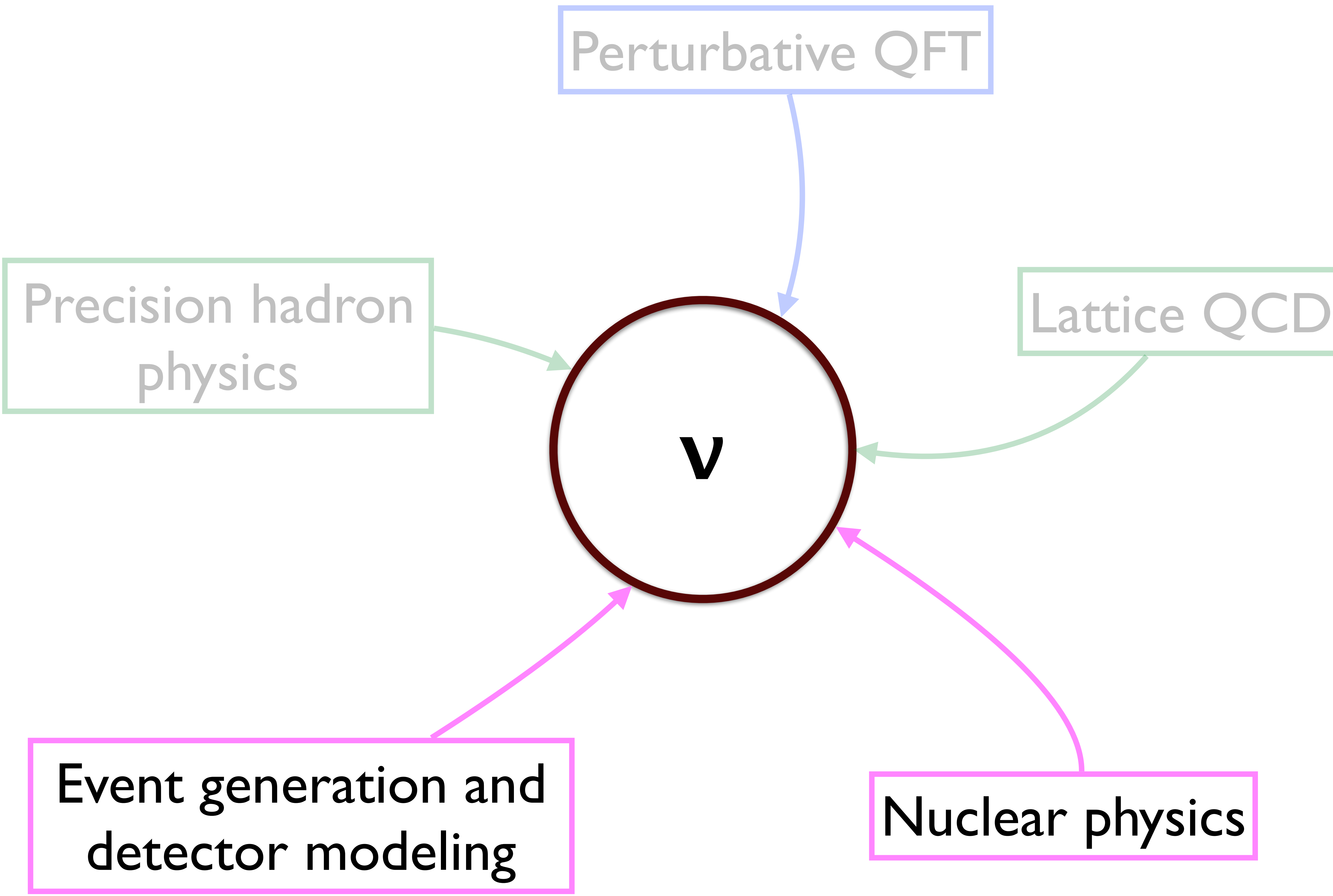
χ^2/DOF	$168/122$
m_A	$1.05(4)$

z-Expansion

χ^2/DOF	$167/119$
a_1	$2.36^{+0.21}_{-0.19}$
a_2	$-0.61^{+0.42}_{-0.39}$
a_3	$-5.4^{+1.6}_{-1.7}$
a_4	$5.2^{-2.2}_{+2.5}$

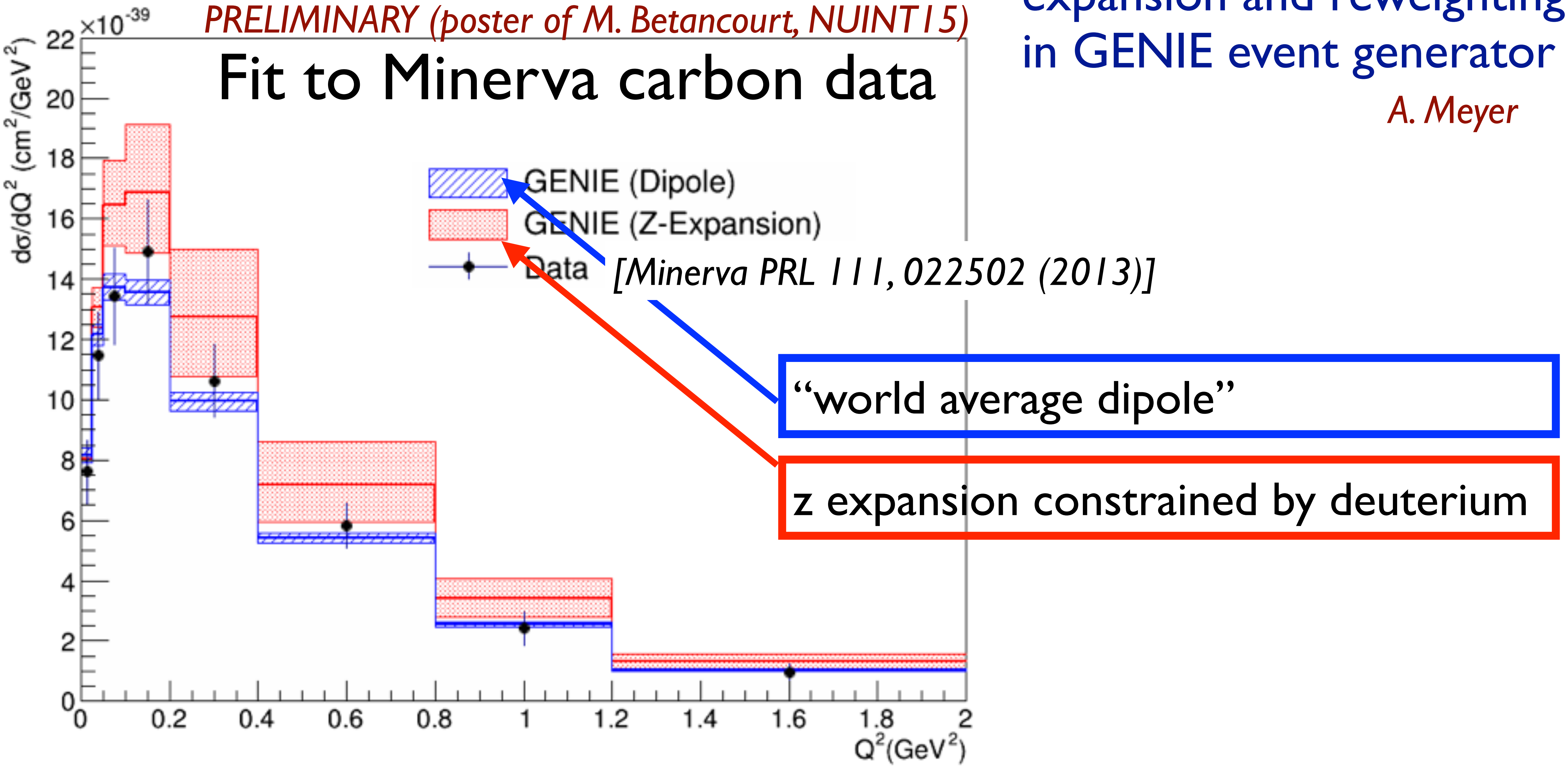
MiniBooNE: Phys. Rev. D 81 (2010)
NOMAD: Eur. Phys. J. C 63 (2009)

$\Rightarrow$ ***nucleon-level amplitudes and cross sections with complete error budget !***


Perturbative QFT
Precision hadron physics
Lattice QCD
ν
Event generation and detector modeling
Nuclear physics

Propagate errors to nuclear cross sections

PRELIMINARY (poster of M. Betancourt, NUINT15)



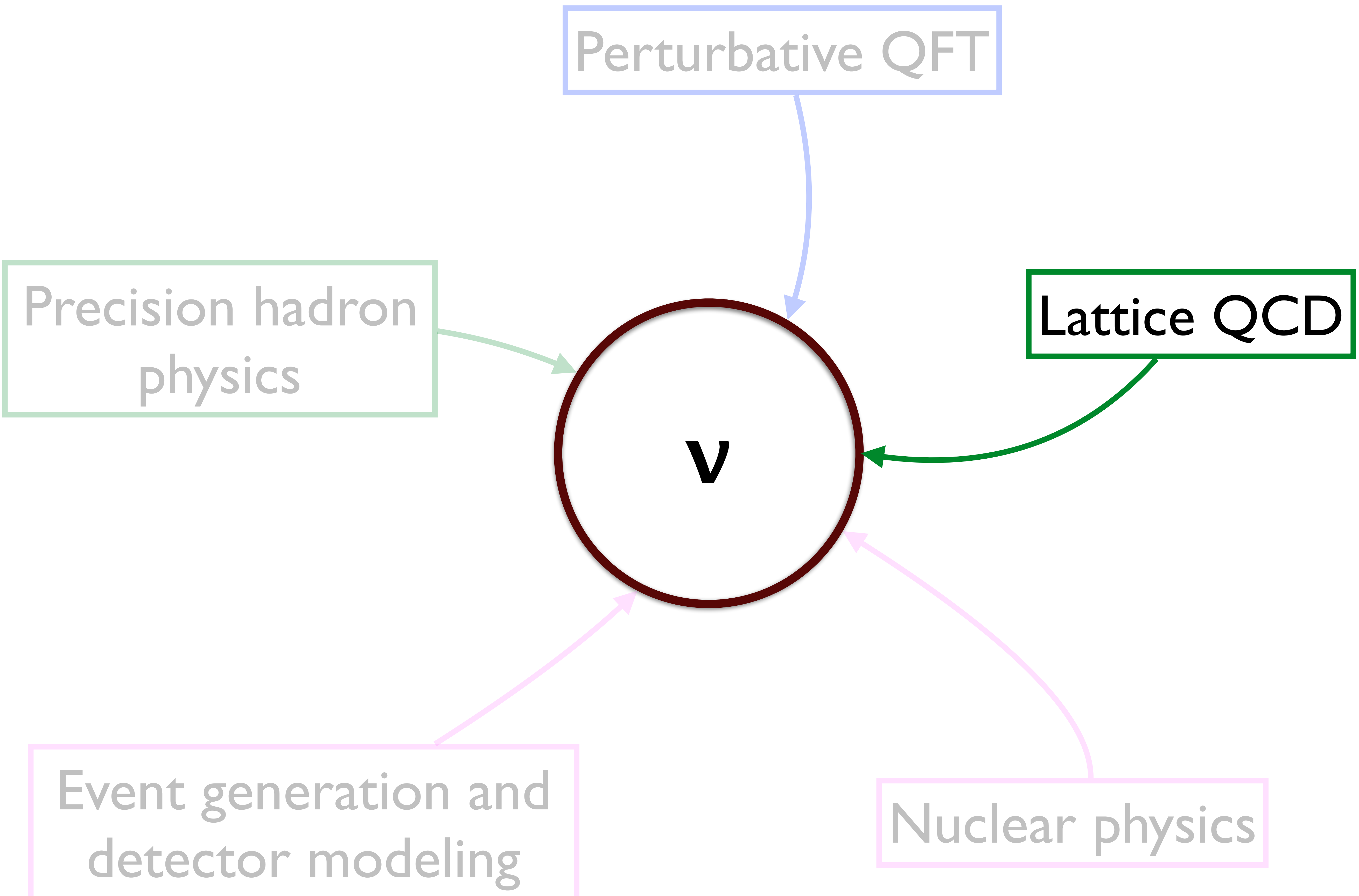
New module for z expansion and reweighting in GENIE event generator

A. Meyer

⟹ **Robust constraints on nuclear parameters (cf. parton distribution function determination at colliders)**

(example: backup slide)

⟹ **Robust errors propagated to oscillation observables**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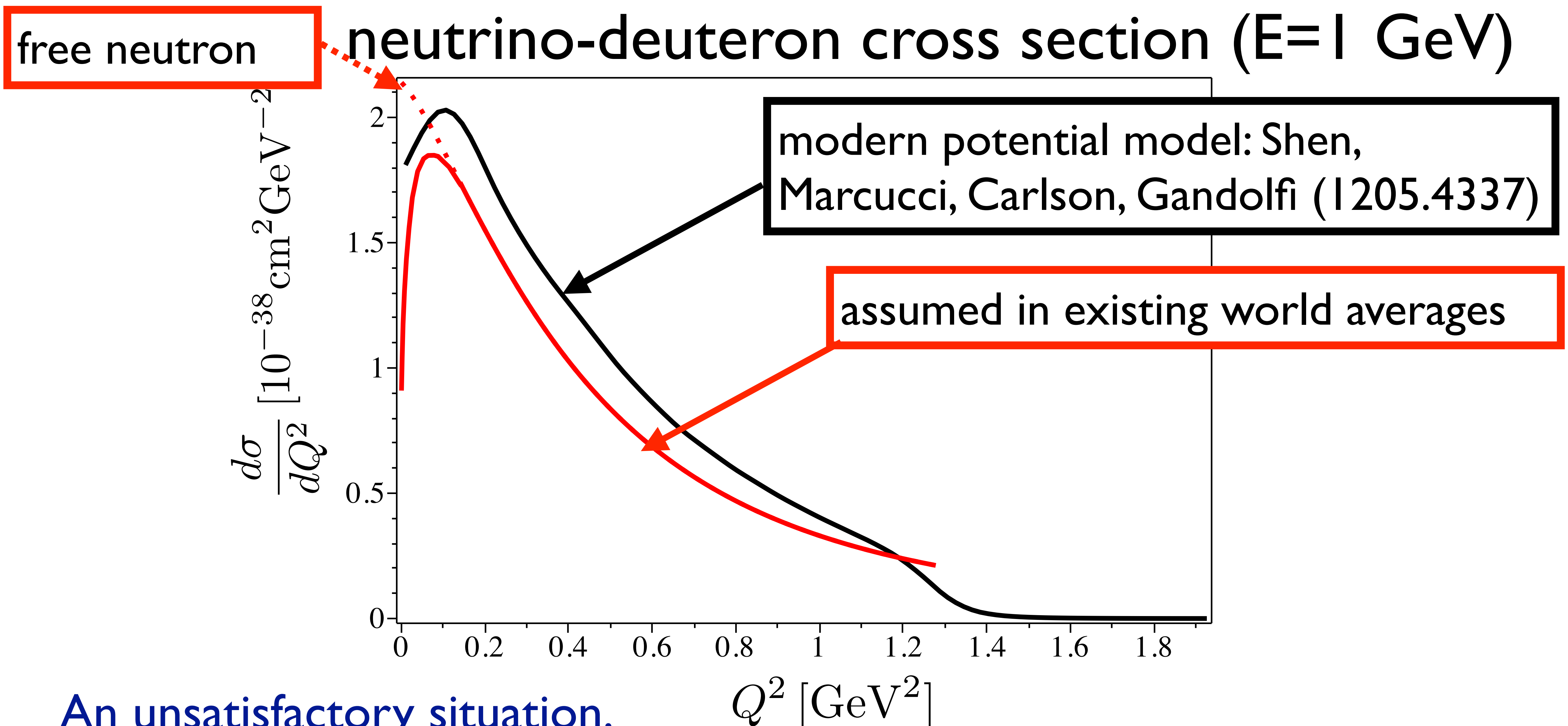
Realistic error bars for $F_A(q^2)$ from deuterium are significant

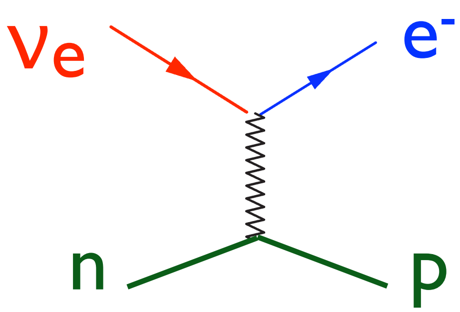
Model dependence in deuteron corrections (and possibly issues with experimental systematics)



An unsatisfactory situation.

(Important impacts beyond long baseline ν's: 0νββ, muon capture, …)

Lattice QCD can constrain nucleon-level amplitudes from first principles



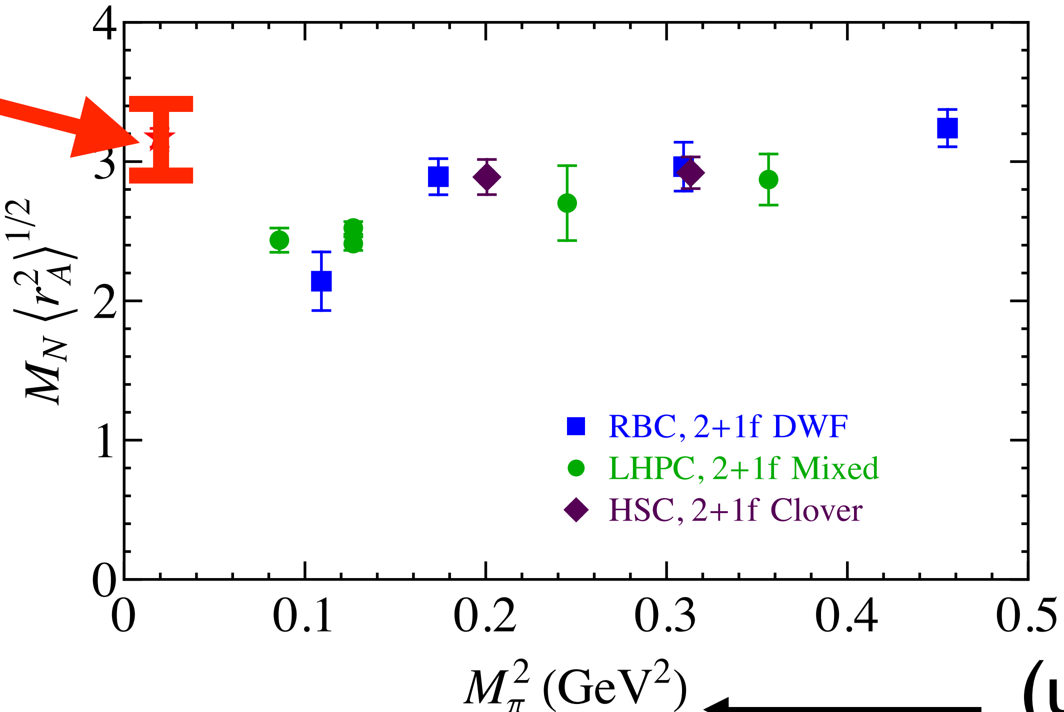
$$\sigma(\nu n \to ep) = |\cdots F_A(q^2) \cdots|^2$$

A prime target is the nucleon axial form factor

deuterium

illustrative:
dipole m_A=1.0(1)

$$\left.\frac{dF_A}{dq^2}\right|_{q^2=0} \propto r_A^2$$



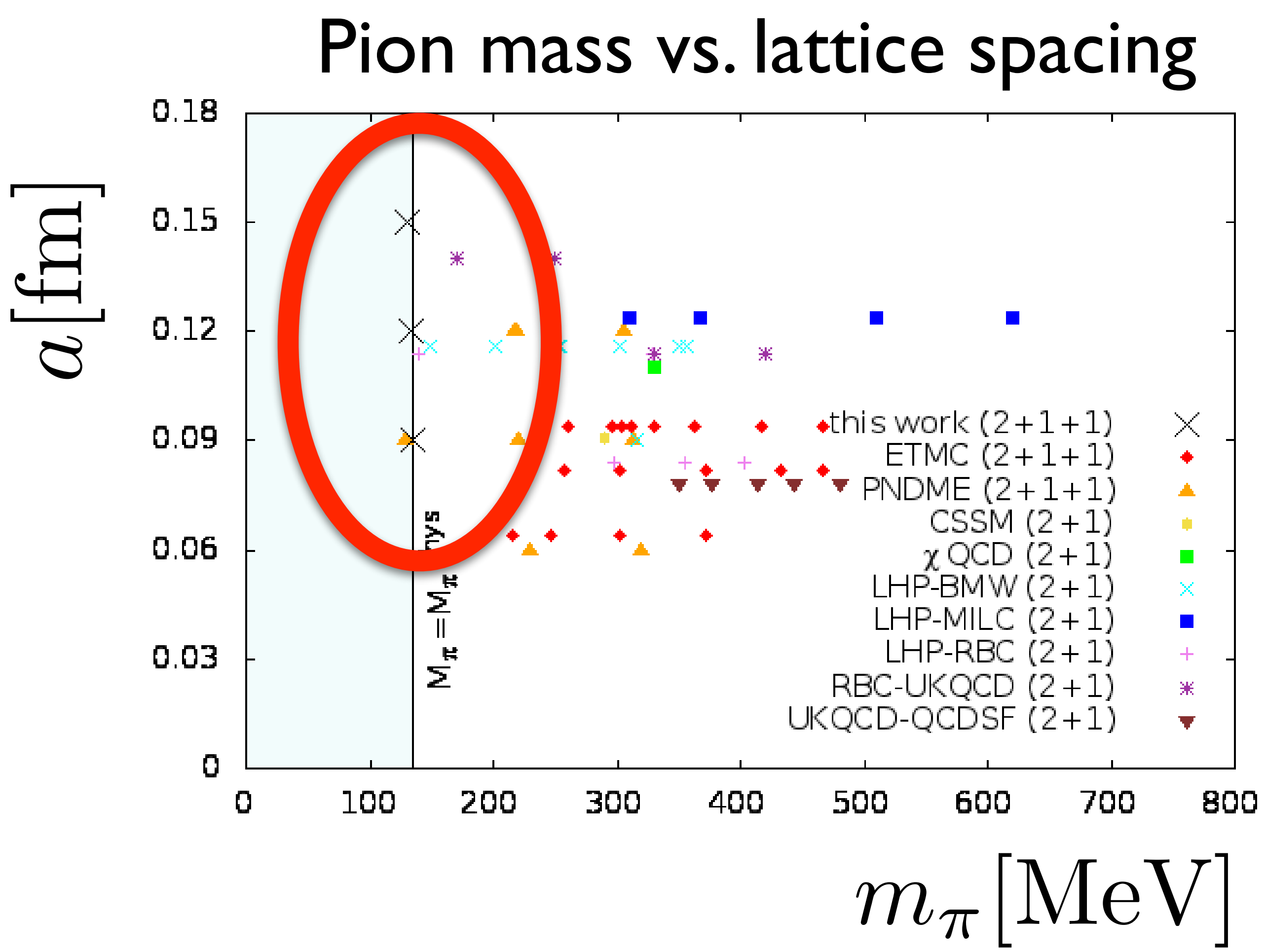
compilation from
Lin and Cohen 1104.4319

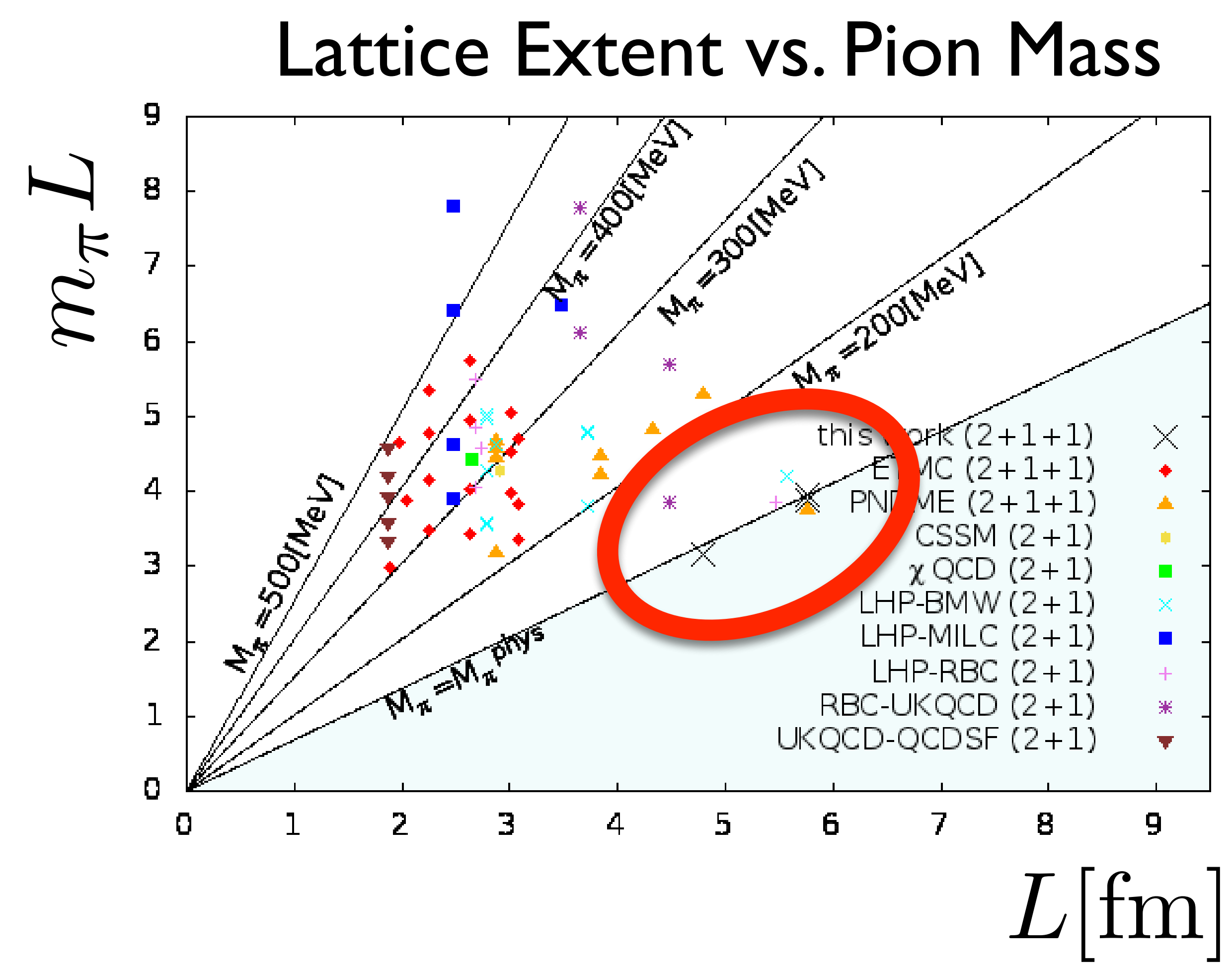
(unphysical) pion mass

Lattice QCD is poised to compete with deuterium data.

Need lighter quarks, bigger and finer lattices

A. Meyer, RJH, A. Kronfeld, Fermilab lattice and MILC collaborations

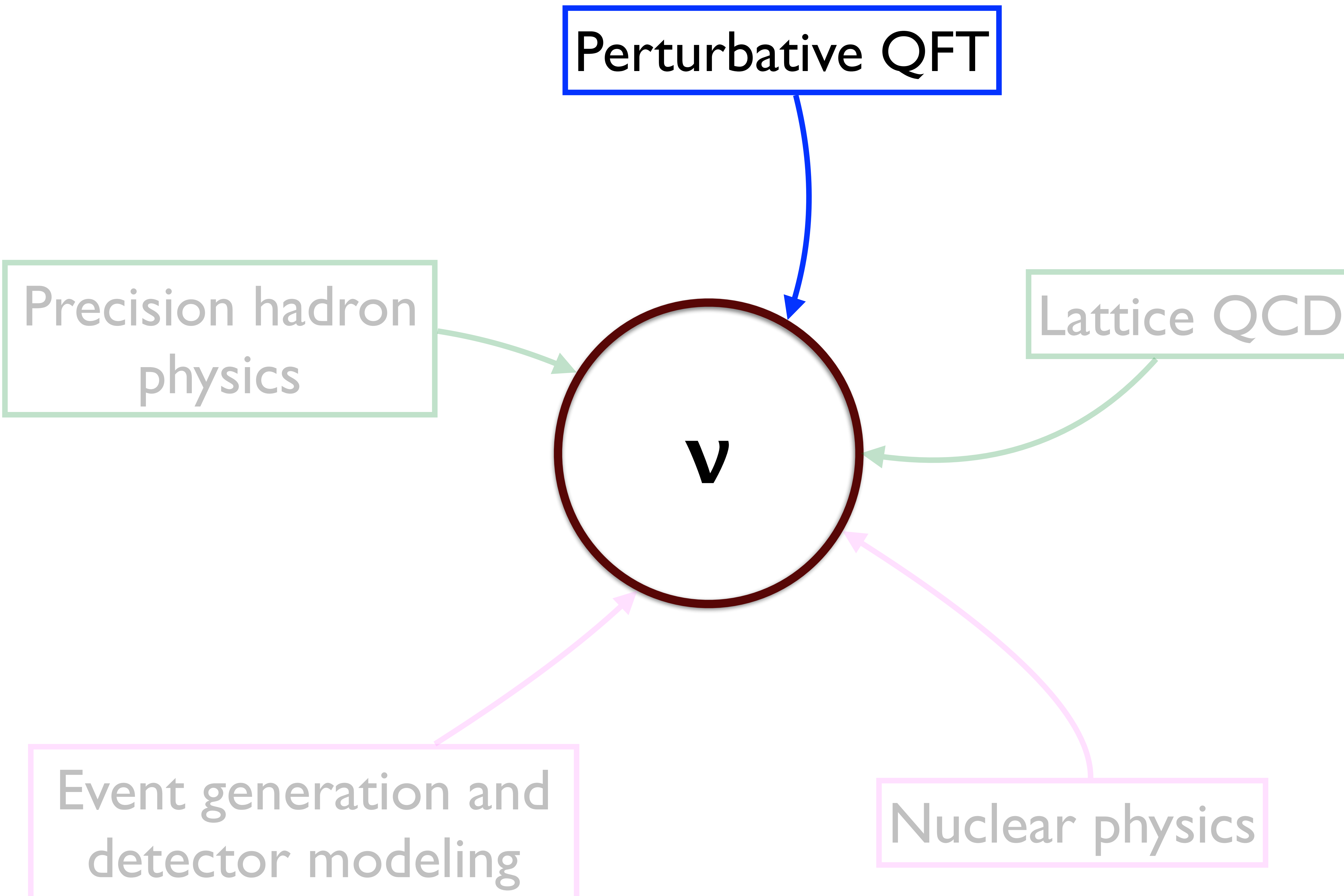




Big lattices, multiple spacings, physical quark masses

<u>Other targets</u>: neutral currents; resonance couplings and form factors; pion final states

<u>Advantages</u>: independent of detector-dependent radiative corrections and nuclear effects (and for lattice QCD: no underground safety hazard)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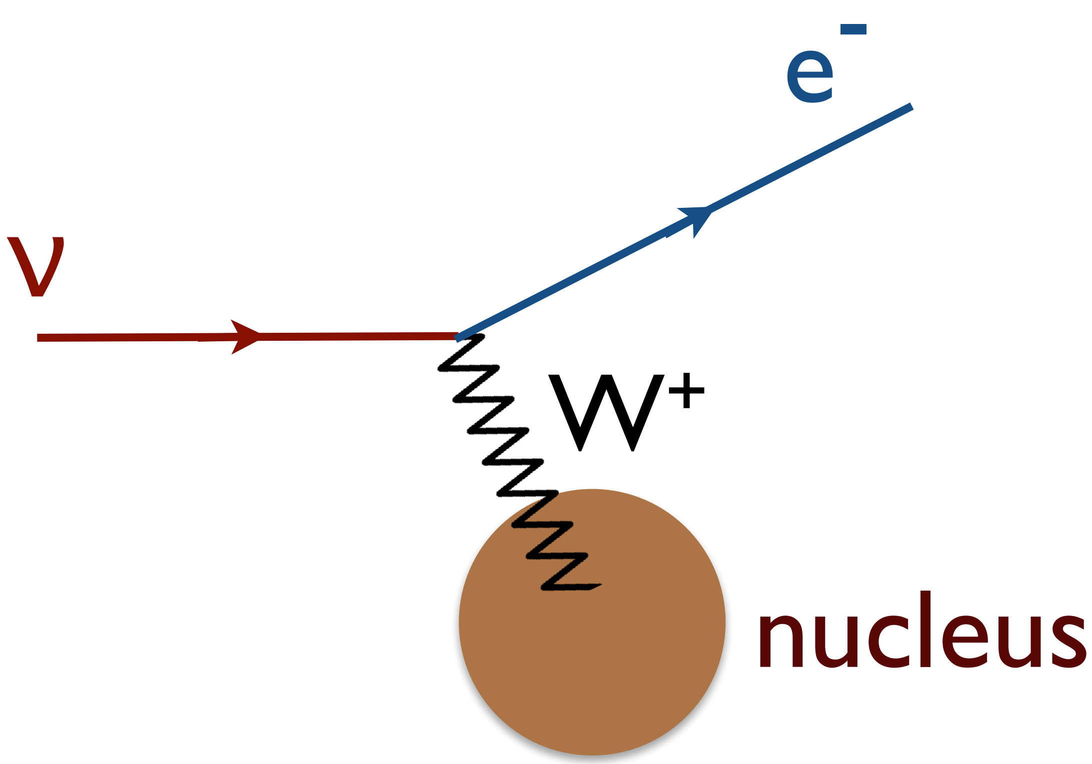
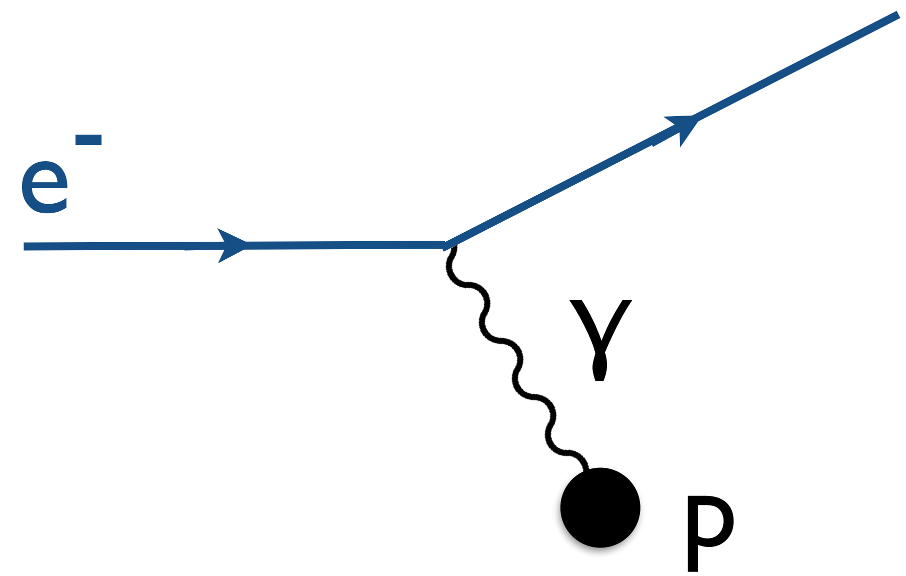
Consider related process: elastic electron-proton scattering:

- *inputs to neutrino cross sections (vector form factors)*
- *a proving ground for both theory and experiment*



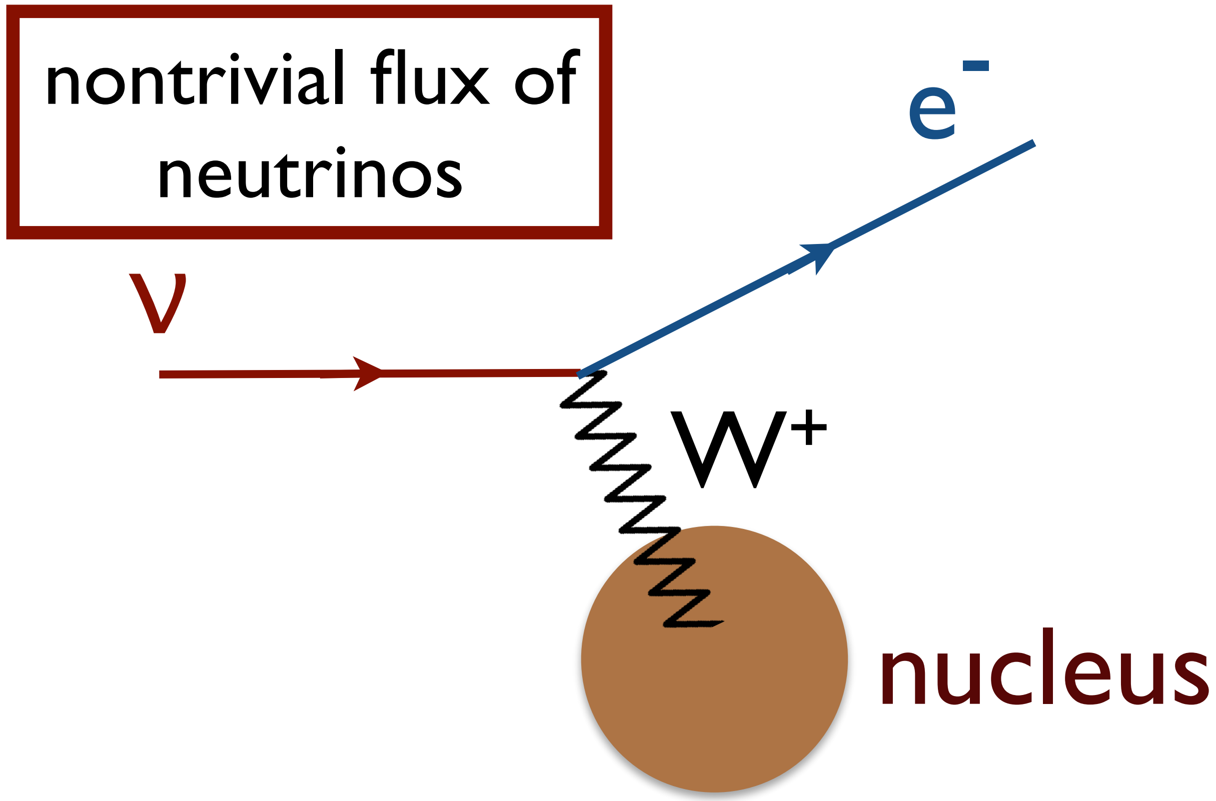


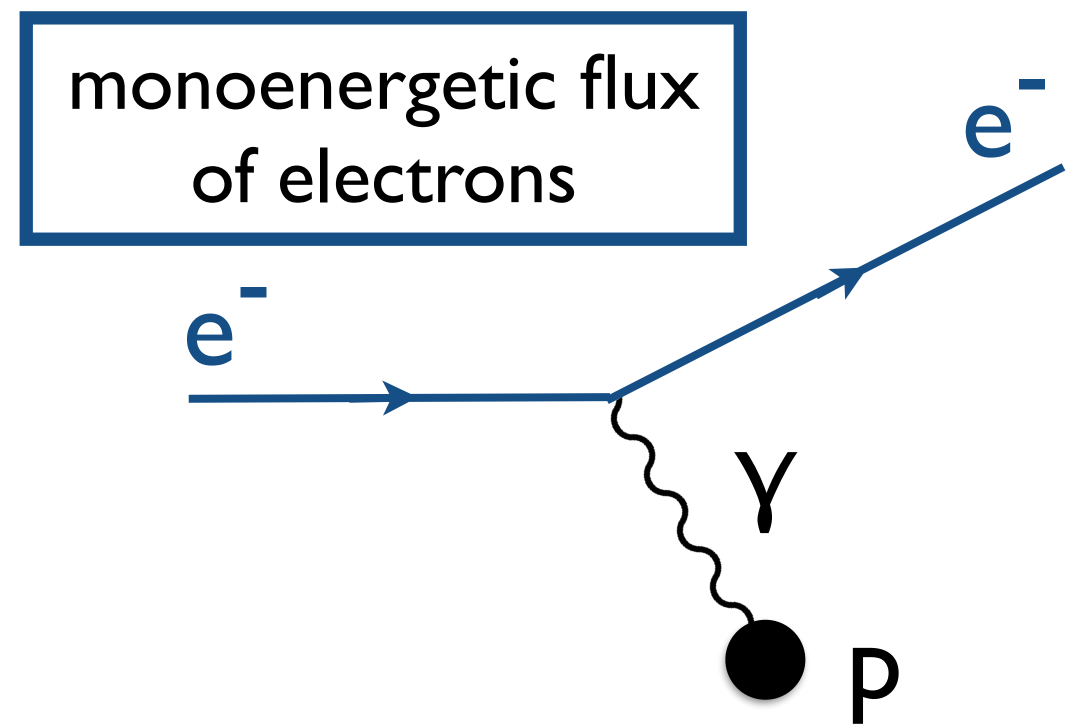
Do we understand this problem with controllable uncertainties?

Look at related process: elastic electron-proton scattering:

- inputs to neutrino cross sections (vector form factors)

- a proving ground for both theory and experiment





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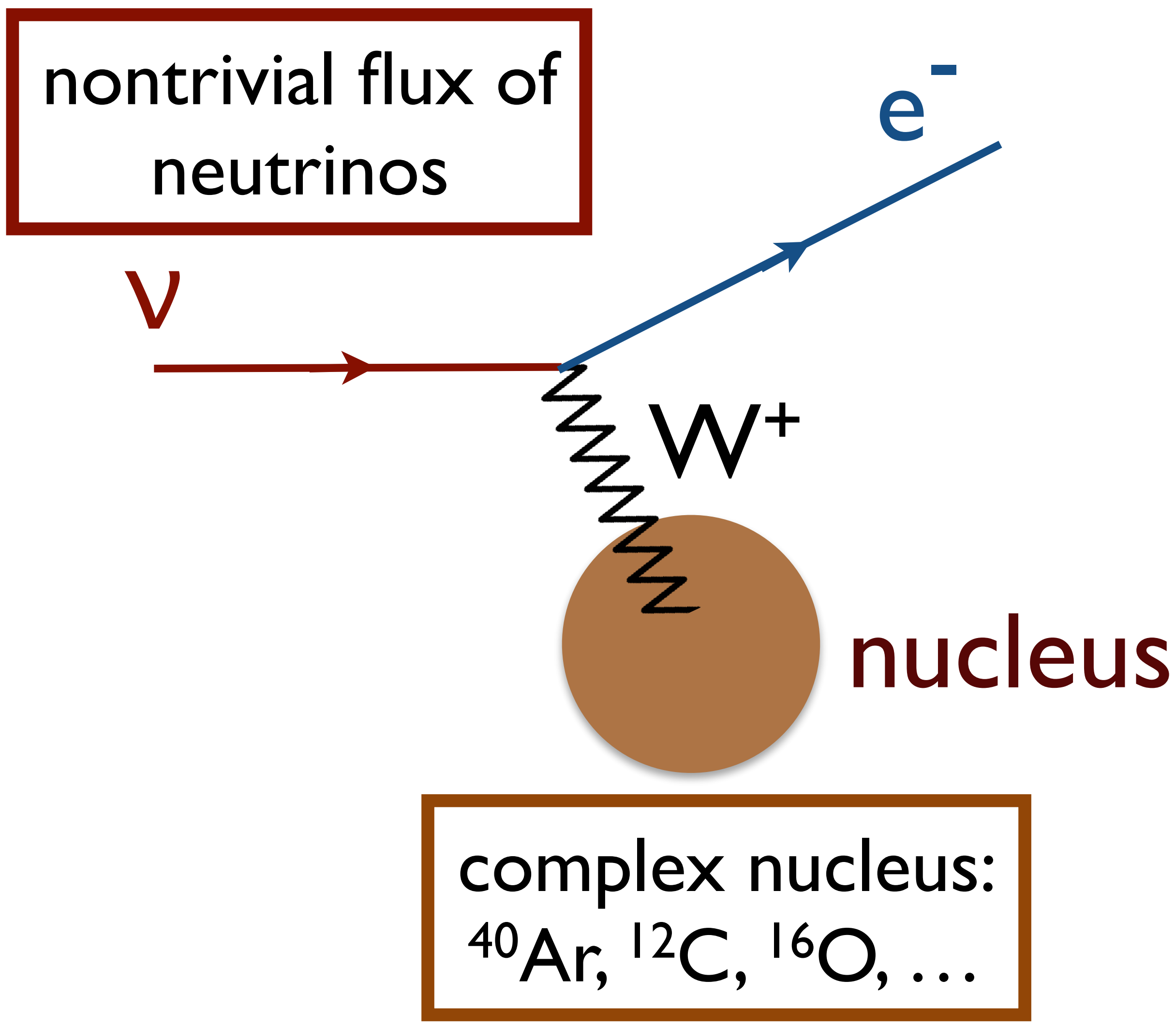

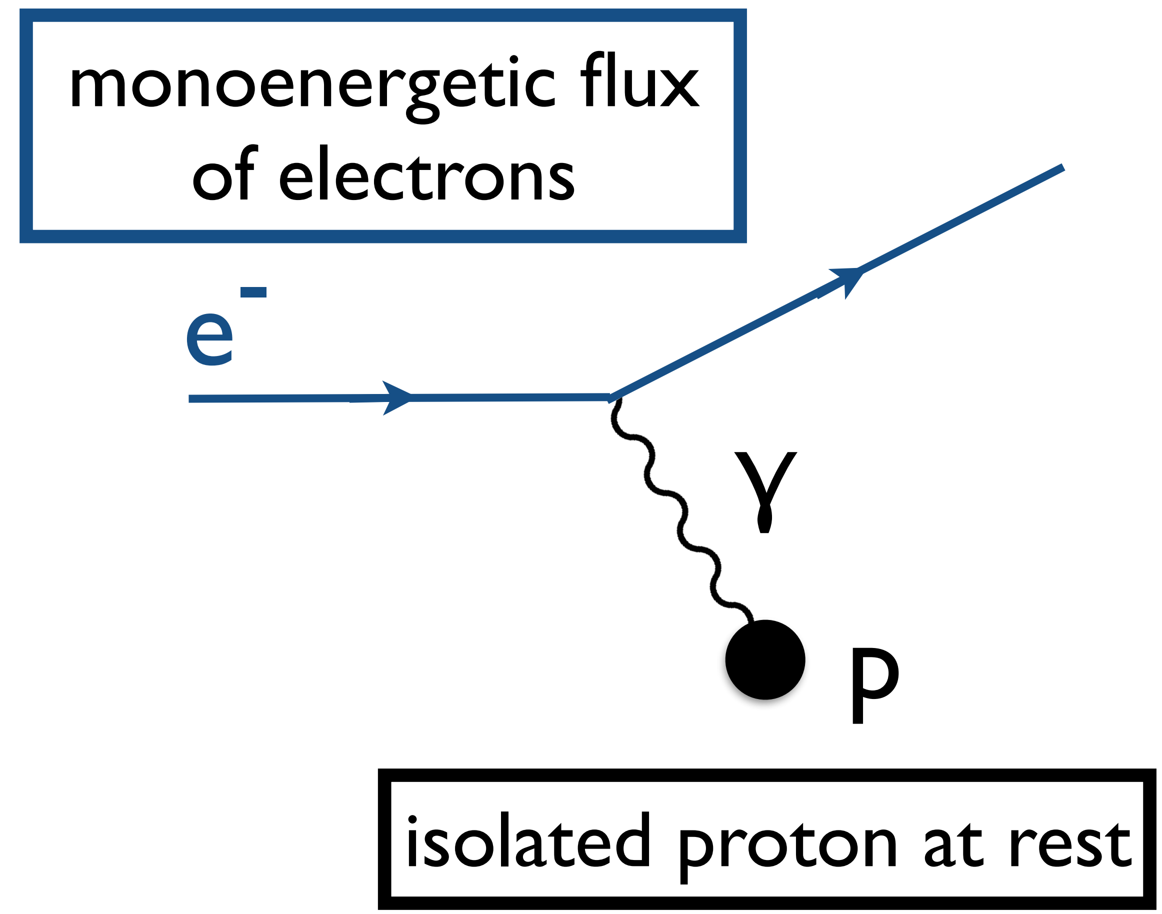

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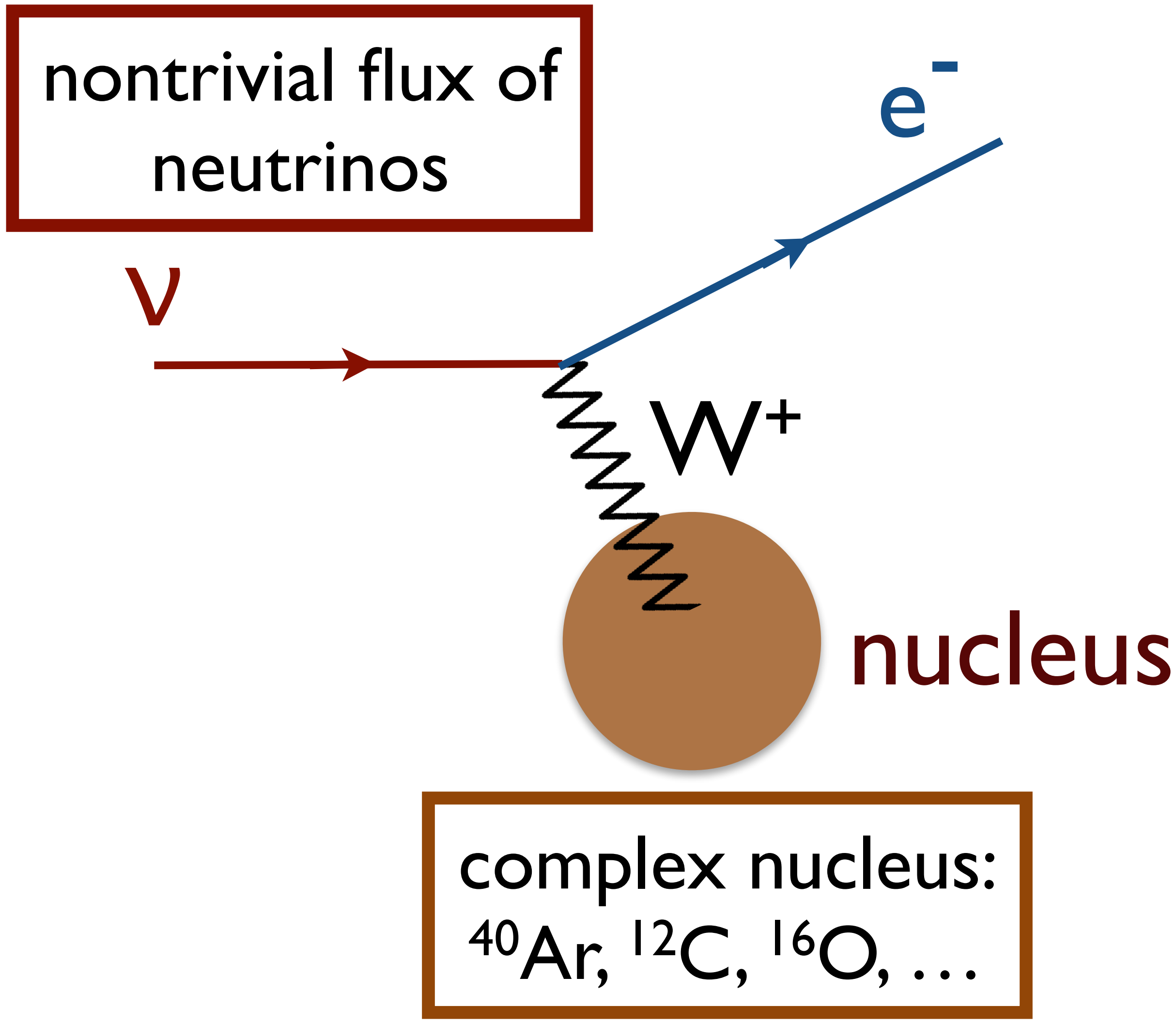

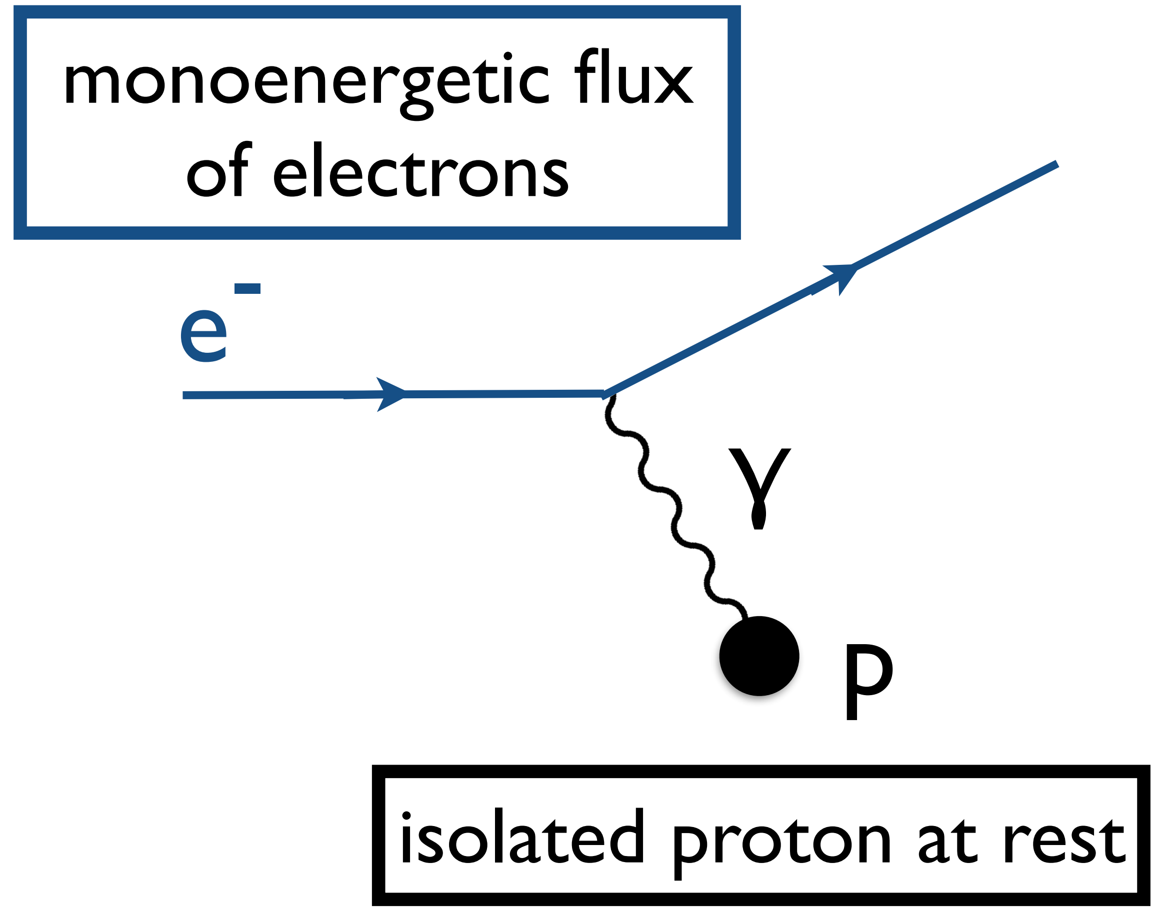

Do we understand this problem with controllable uncertainties?

Some facts about the Rydberg constant puzzle (a.k.a. proton radius puzzle)

1) It has generated a lot of attention and controversy

The New York Times

2) The *most mundane* resolution necessitates:

- 5σ shift in fundamental Rydberg constant
- discarding or revising decades of results in e-p scattering and hydrogen spectroscopy

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This *is* HEP's problem:

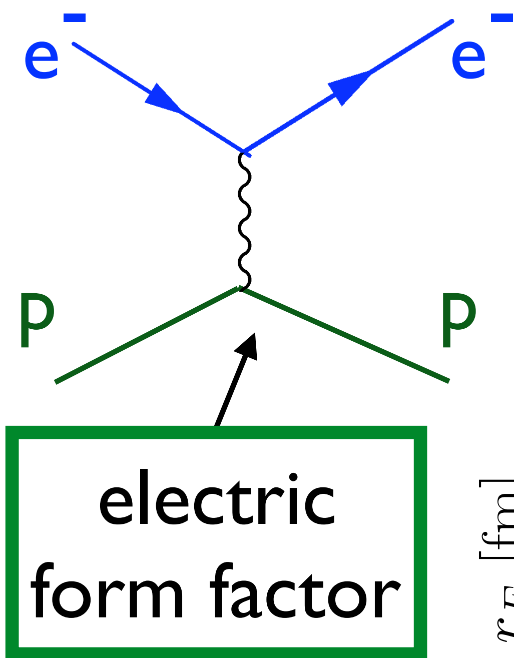
"The good news is that it's not my problem"

3) Systematic effects in electron-proton scattering impact neutrino-nucleus scattering, *at a level large compared to DUNE precision requirements*

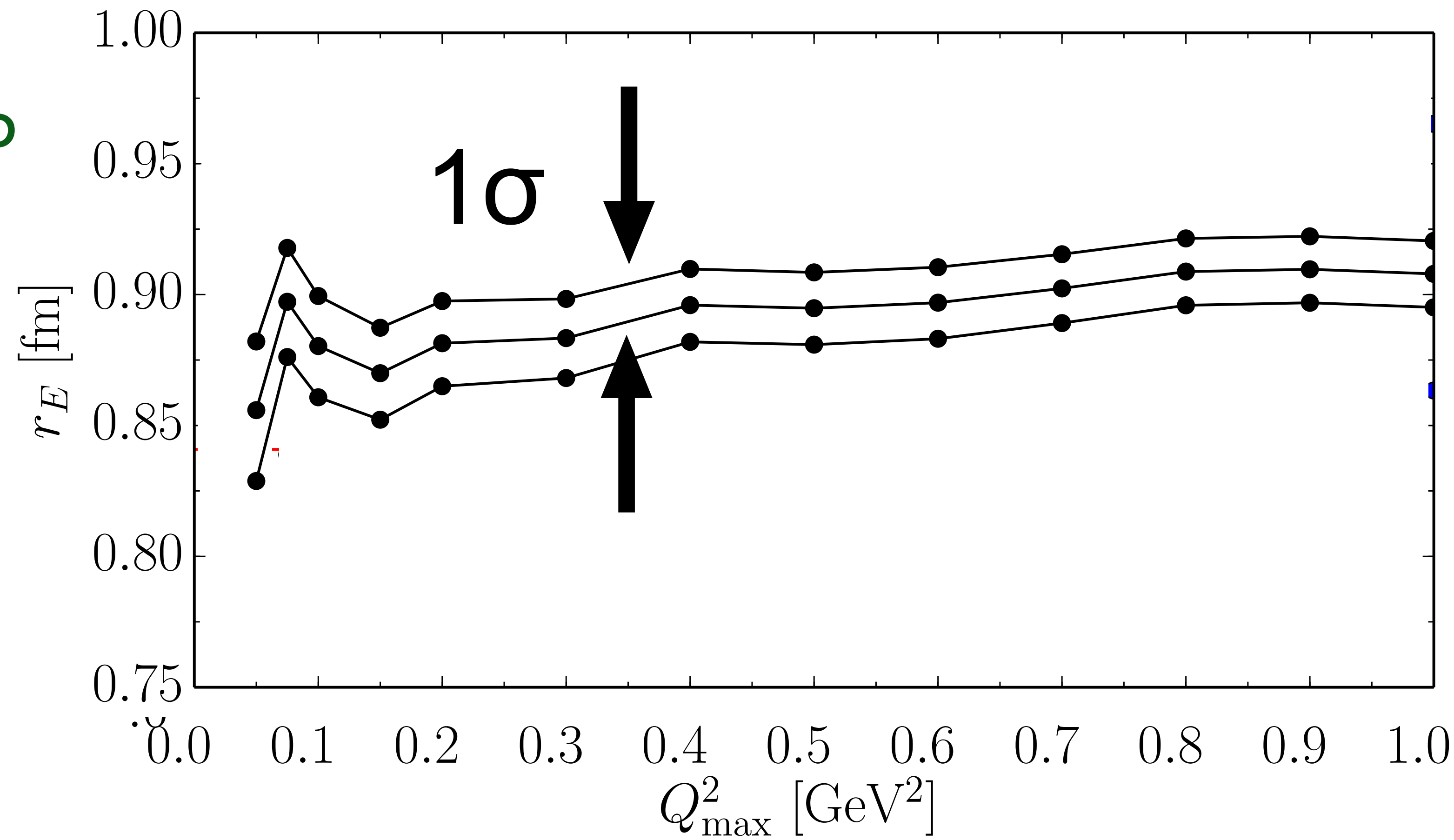
New analysis: G. Lee, J. Arrington, RJH 1505.01489

World e-p scattering dominated by 2010 MAMI A1 dataset: $0 < Q^2 < 1$ GeV^2 ($|z|<0.32$)

(details: backup slide)



$$\frac{dF_E}{dq^2} \propto r_E^2$$



- Unexpected Q^2 dependence of extracted radius, and potentially large radiative corrections
- For both e-p and ν-N: large logarithms upset naive perturbation theory
- Work in progress to implement complete radiative corrections

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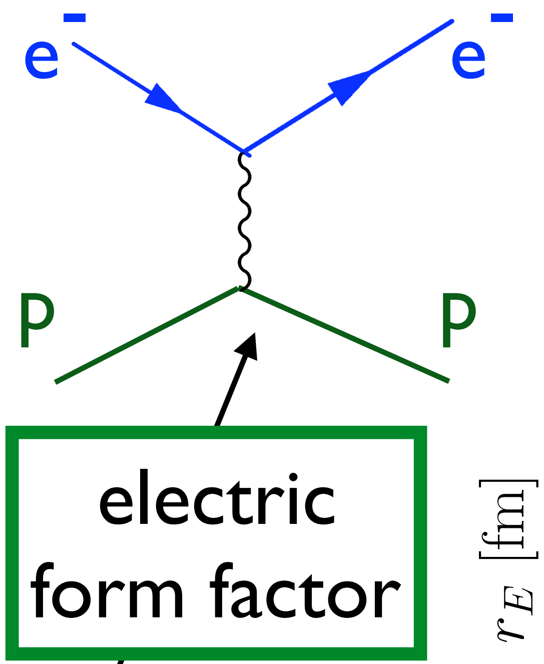

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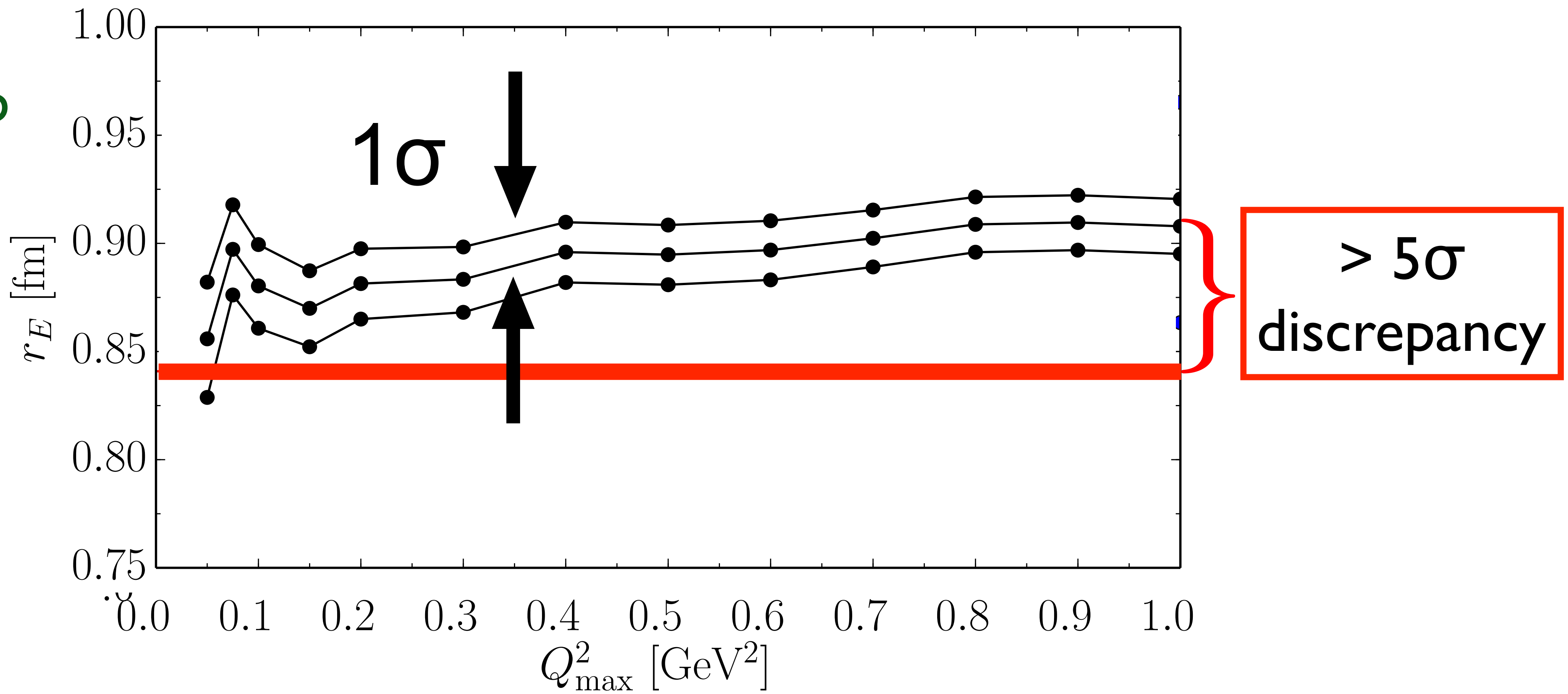

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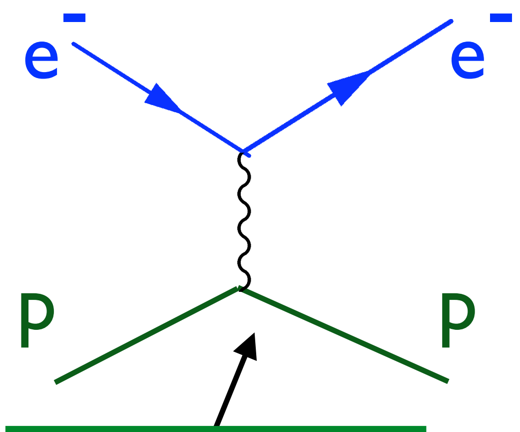
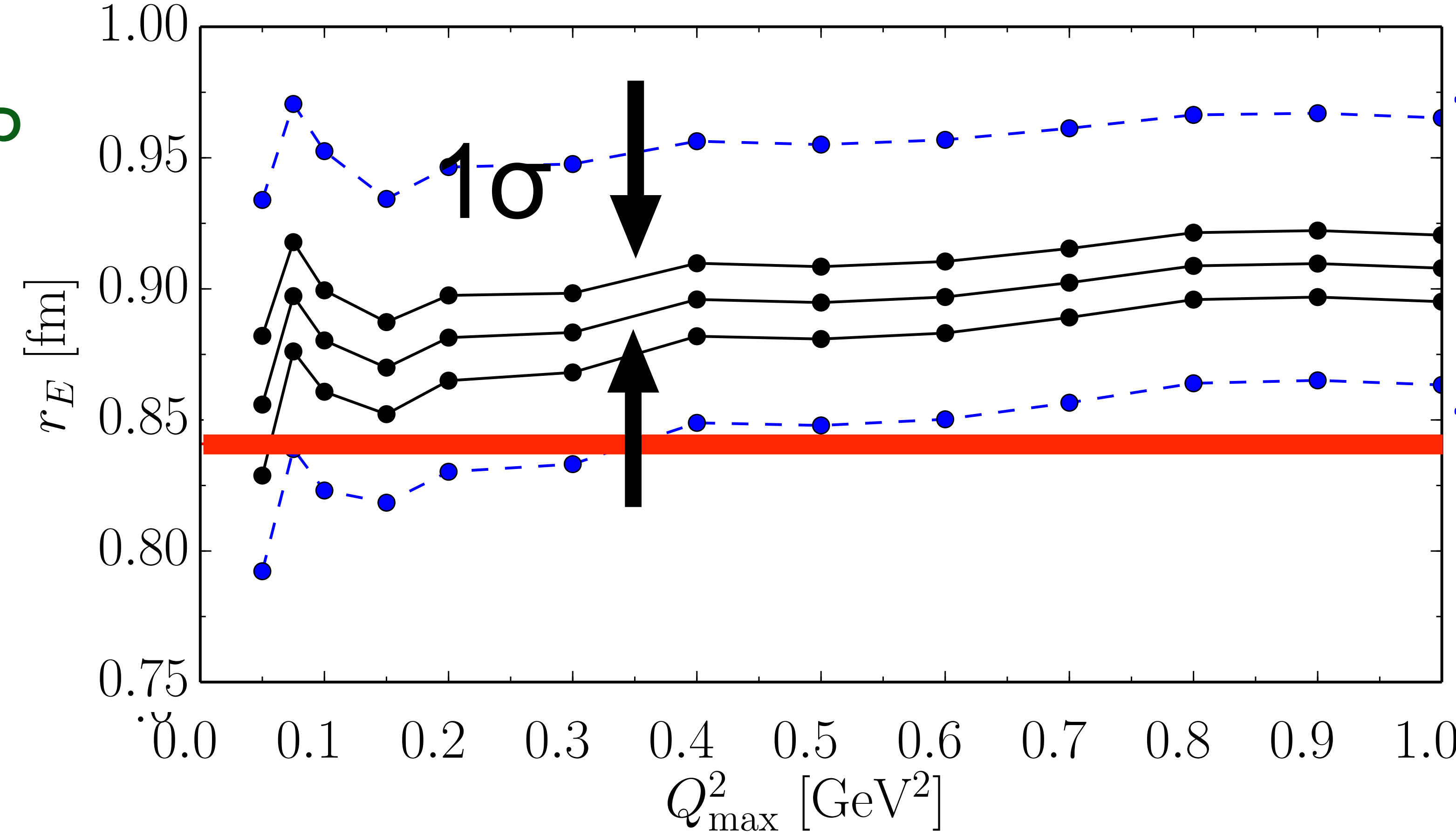


electric form factor

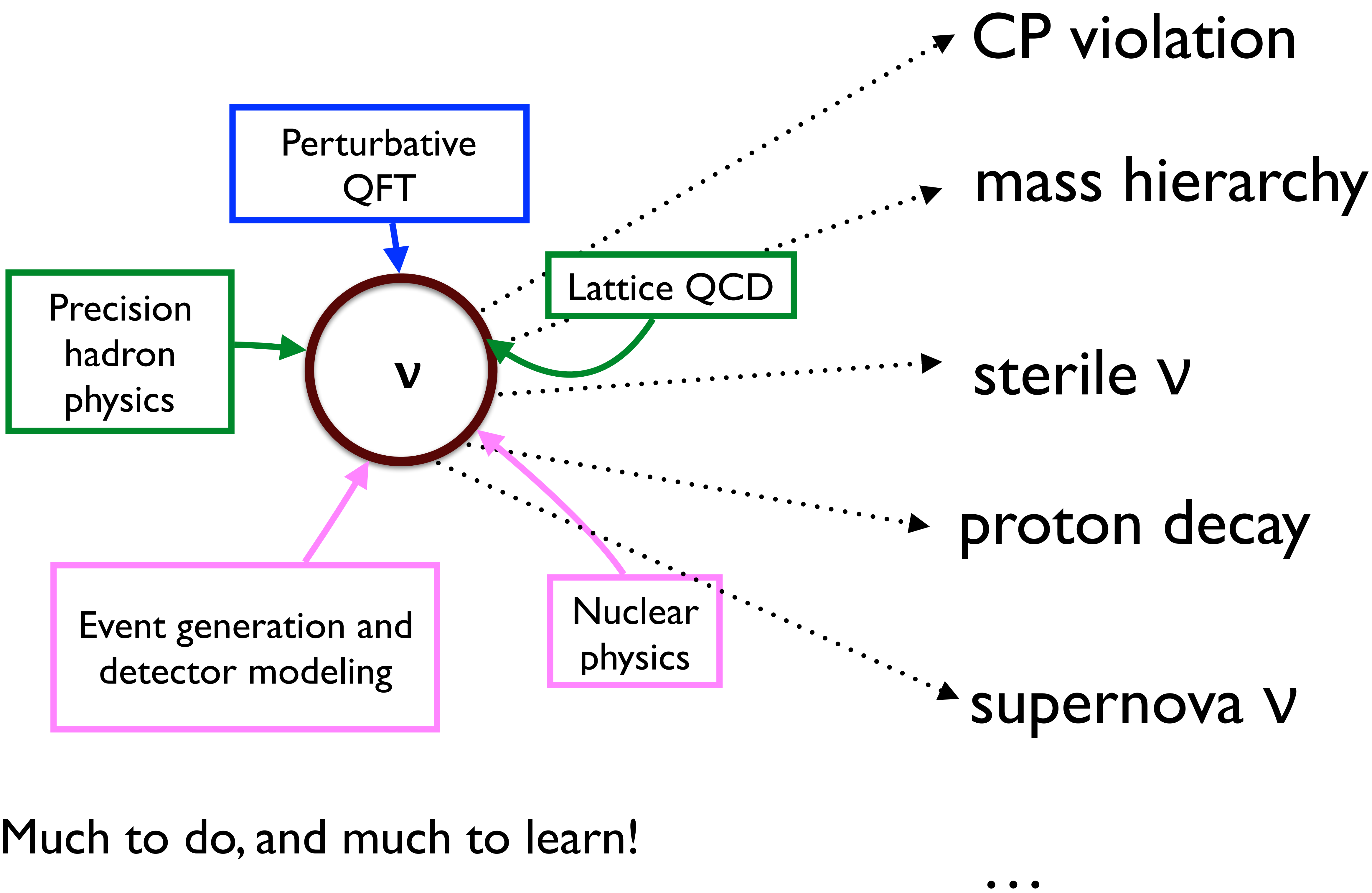
$$\frac{dF_E}{dq^2} \propto r_E^2$$



potentially large uncertainty from radiative corrections

- Unexpected Q^2 dependence of extracted radius, and potentially large radiative corrections
- For both e-p and ν-N: large logarithms upset naive perturbation theory
- Work in progress to implement complete radiative corrections

A systematic framework is being constructed to map elementary-target/ lattice data through to oscillation observables



Much to do, and much to learn!

Cross sections key to discoveries in the neutrino sector

Particle theory has a critical role to play

- precision hadron physics: *building on CKM studies*
- radiative corrections: *renormalization, soft-collinear effective theory*
- lattice QCD

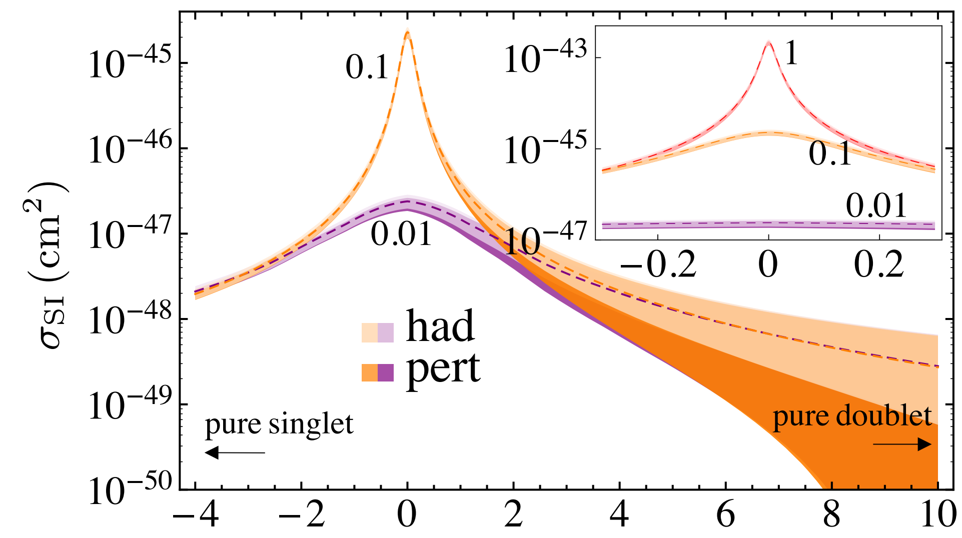
Important connections: other intensity frontier initiatives

- lattice QCD & baryons: *neutrinos, DM, proton radius puzzle, nEDM, …*
- radiative corrections: *neutrinos, g-2, proton radius puzzle, CKM, …*
- nuclear effects and hadronic final state: *energy reconstruction in ν-N scattering; atmospheric bkgd. to proton decay, …*

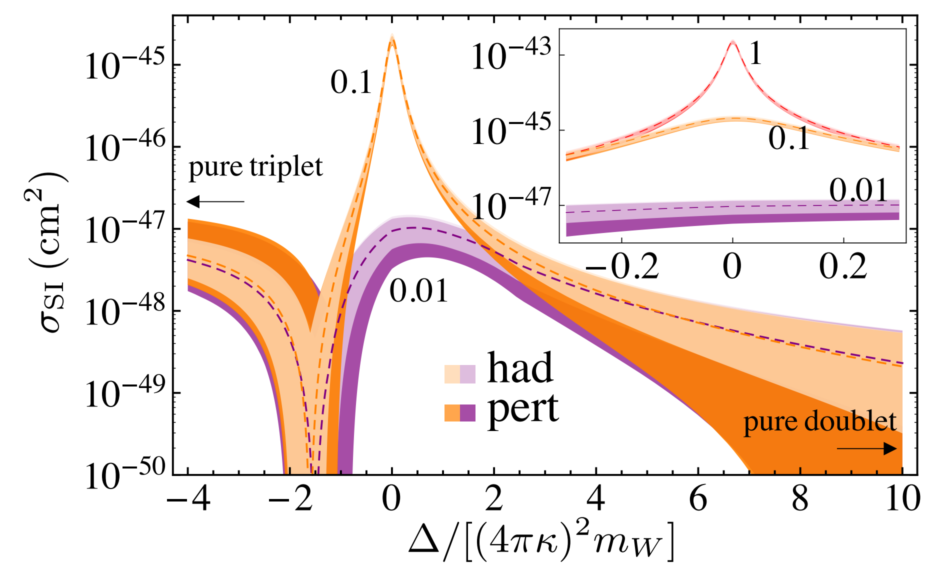
backup

Additional states in the dark sector

singlet-doublet (e.g., bino-higgsino)



triplet-doublet (e.g., wino-higgsino)

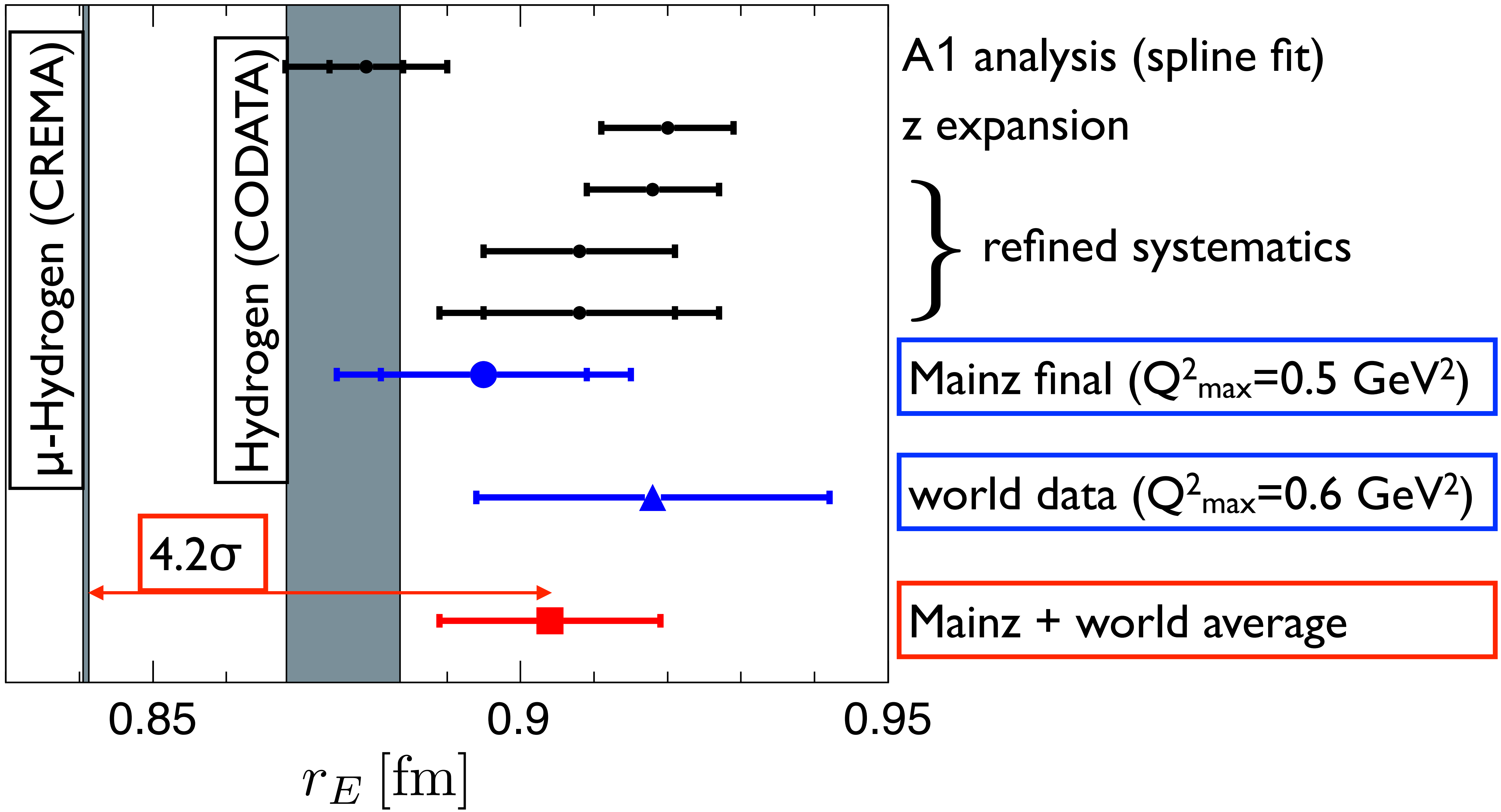


Δ: mass splitting of multiplets, in units where tree/loop crossover occurs at ~1

interplay of mass-suppressed (tree level) and loop suppressed contributions

experimental landscape: electron-proton scattering

G. Lee, J. Arrington, RJH, 2015



r_E^{Mainz} = 0.895(14)(14)

r_E^{world} = 0.918(24)

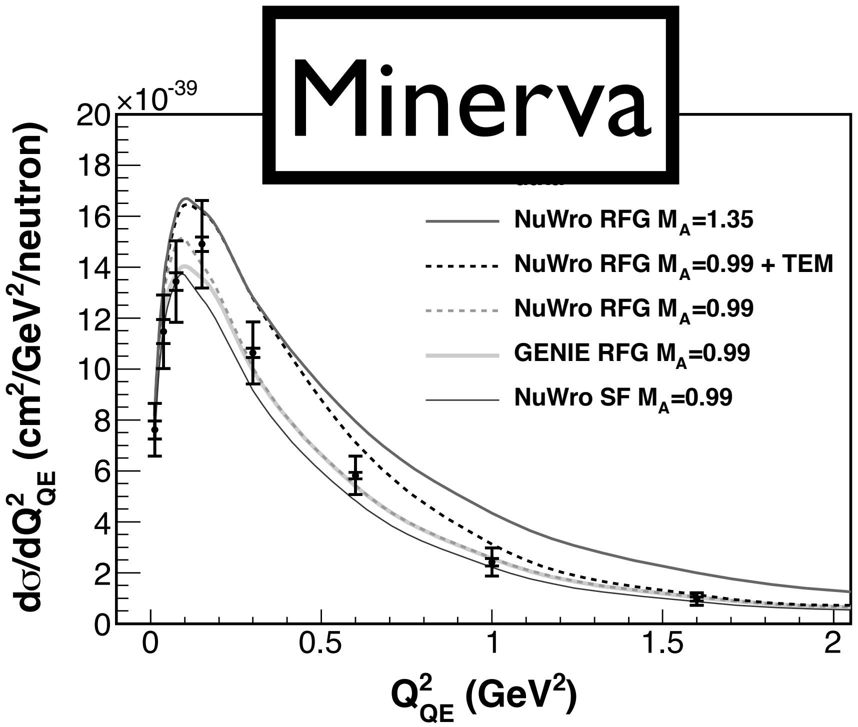
simple average: $r_E^{avg.}$ = 0.904(15)

Sample application of elementary target data: constrain and validate nuclear models

Can we constrain a simple nuclear model for two-body contributions ?

$$\sigma = \sigma_{1-\text{body}} + f\sigma_{2-\text{body}}$$

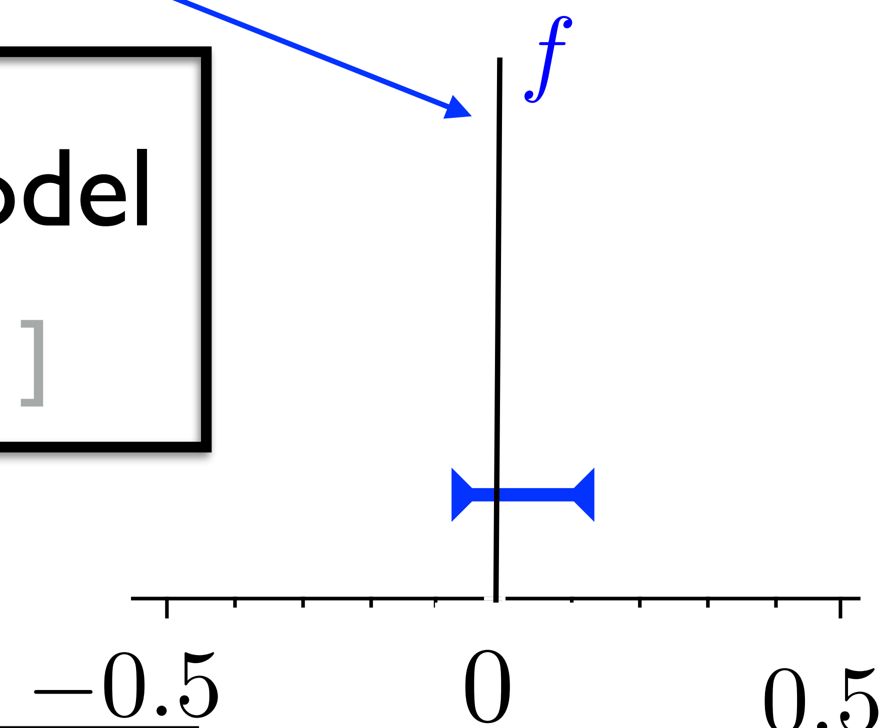
(GENIE MEC model)

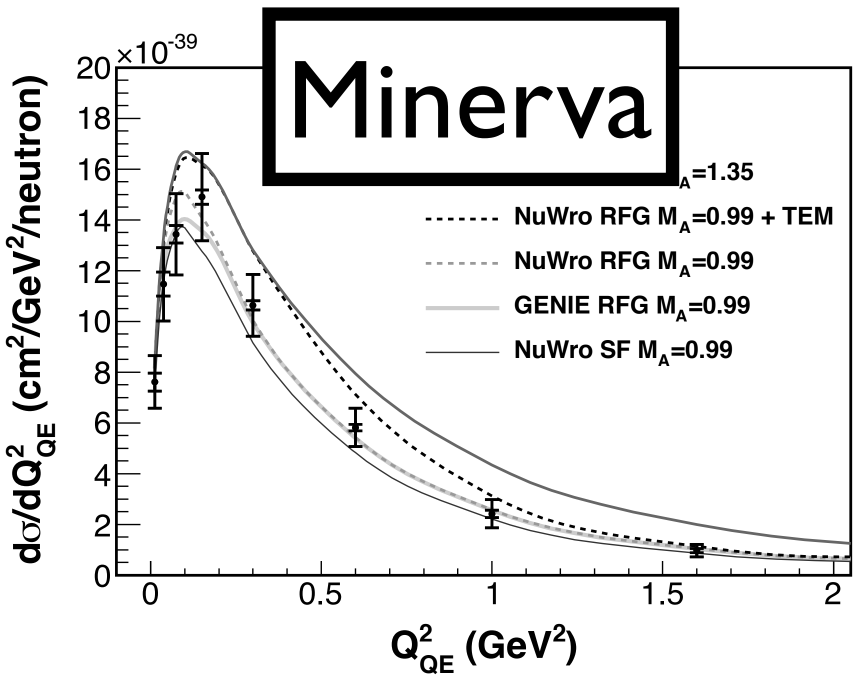


+

F_A = dipole model

[m_A=1.01(2)]





+

F_A = model-independent

large nucleon-level uncertainties

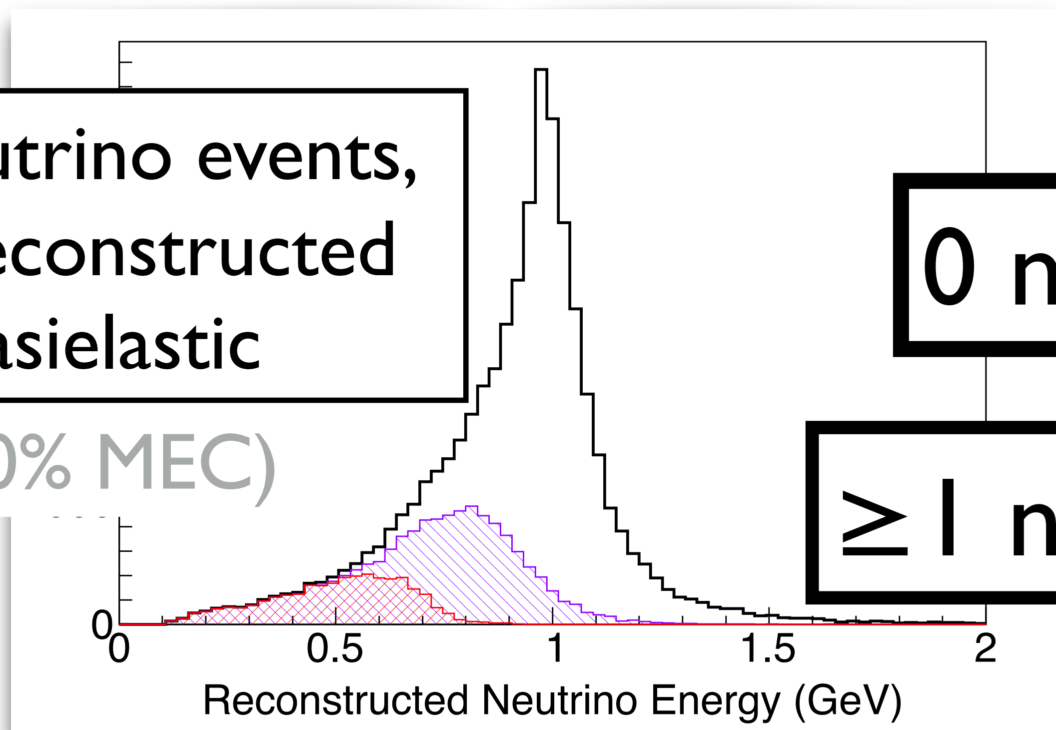
Addressing energy reconstruction biases

cf. colliders: define event classes to isolate underlying parton mechanisms (vector boson fusion, gluon fusion,…)

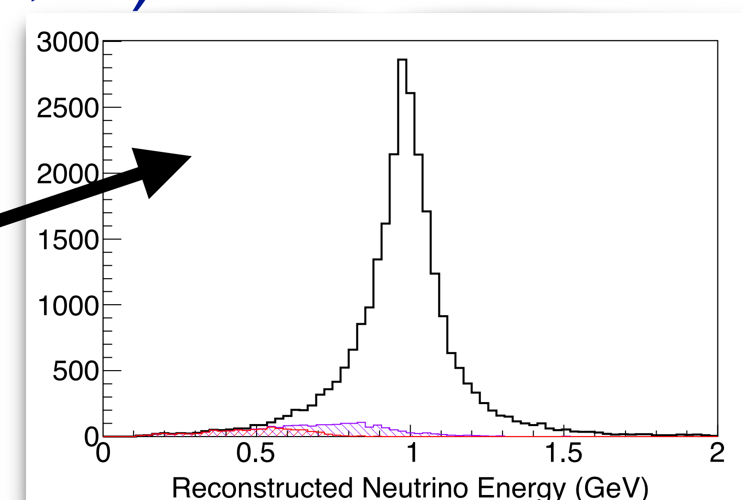
for neutrinos: define event classes with (in)sensitivity to underlying nucleon-level mechanisms (multinucleon processes,…)

1 GeV neutrino events, 0 pions, reconstructed as quasielastic

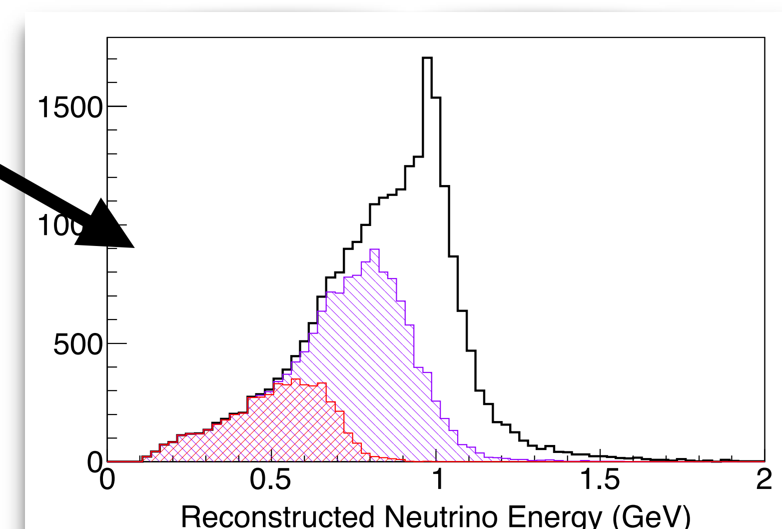
(GENIE, +30% MEC)



0 neutron



≥ 1 neutron



C. Blanco, M. Wetstein, RJH

Capitalize on new detector technologies

- final state protons in LArTPC
- final state neutrons (ANNIE)
- simple flux (stored muons); multiple fluxes ("nuPRISM"), …