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Decoherence in neutrino oscillations and the Gallium anomaly

Thomas Schwetz
Karlsruhe Institute of Technology, Institute for Astroparticle Physics

Outline

- Motivation: reactor and gallium anomalies, general decoherence effects in reactor experiments

- A QFT calculation of standard decoherence effects in reactor and radioactive source experiments
  w. Raphael Krüger, arXiv:2303.15524

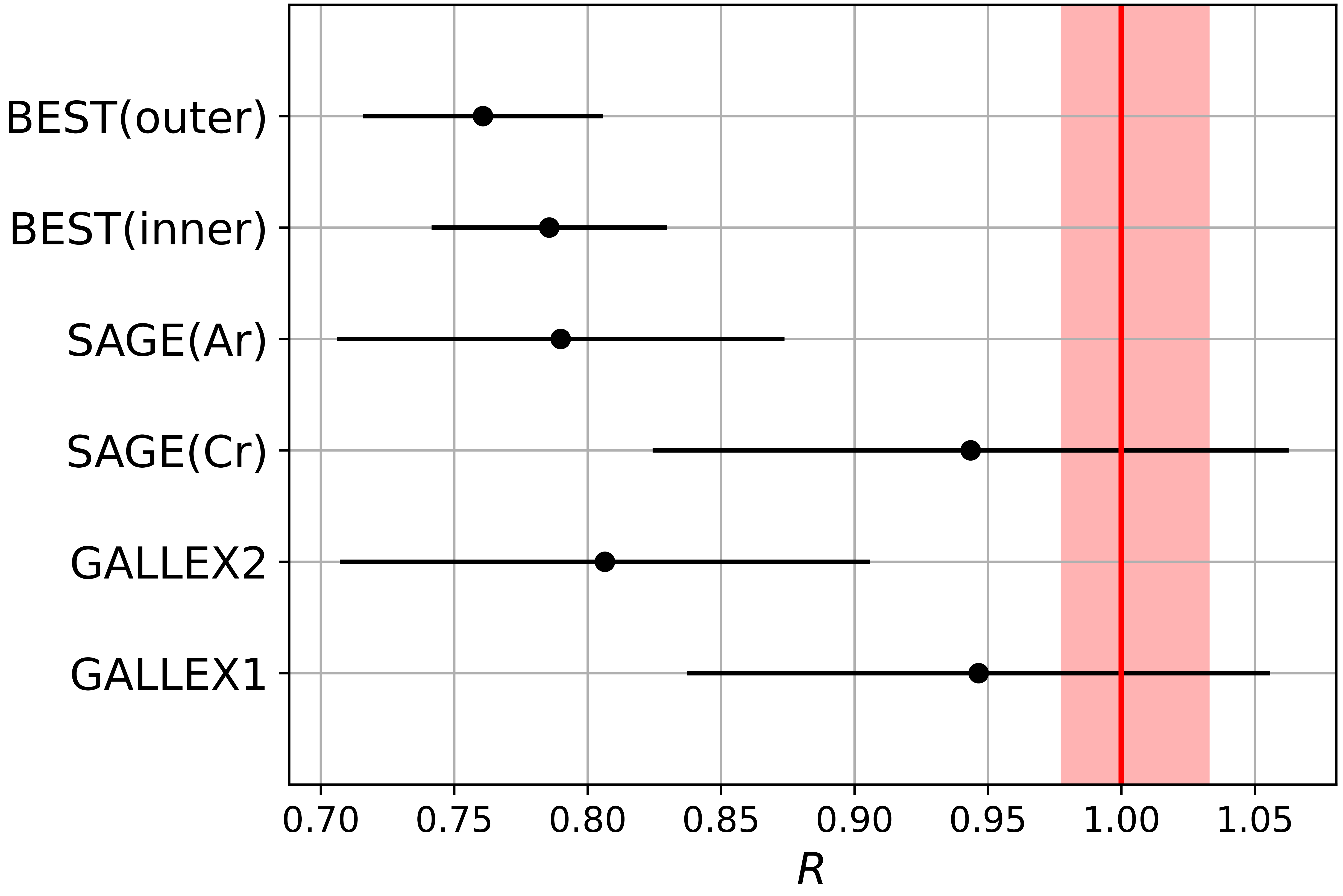
- An explanation of the gallium anomaly in terms of new physics quantum decoherence without sterile neutrinos
  w. Yasaman Farzan, arXiv:2306.09422

The gallium anomaly

electron capture decay: ${}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e$

$$E_\nu = 750\,\mathrm{keV}\,(90\%)\,\&\,430\,\mathrm{keV}\,(10\%)$$

	$\chi^2_{\rm null}/\mathrm{dof}$	p-value
CS1, BEST	32.1/2	1.1×10^{-7} (5.3σ)
CS1, all	36.3/6	2.4×10^{-6} (4.7σ)
CS2, BEST	34.7/2	2.9×10^{-8} (5.5σ)
CS2, all	38.4/6	9.4×10^{-7} (4.9σ)

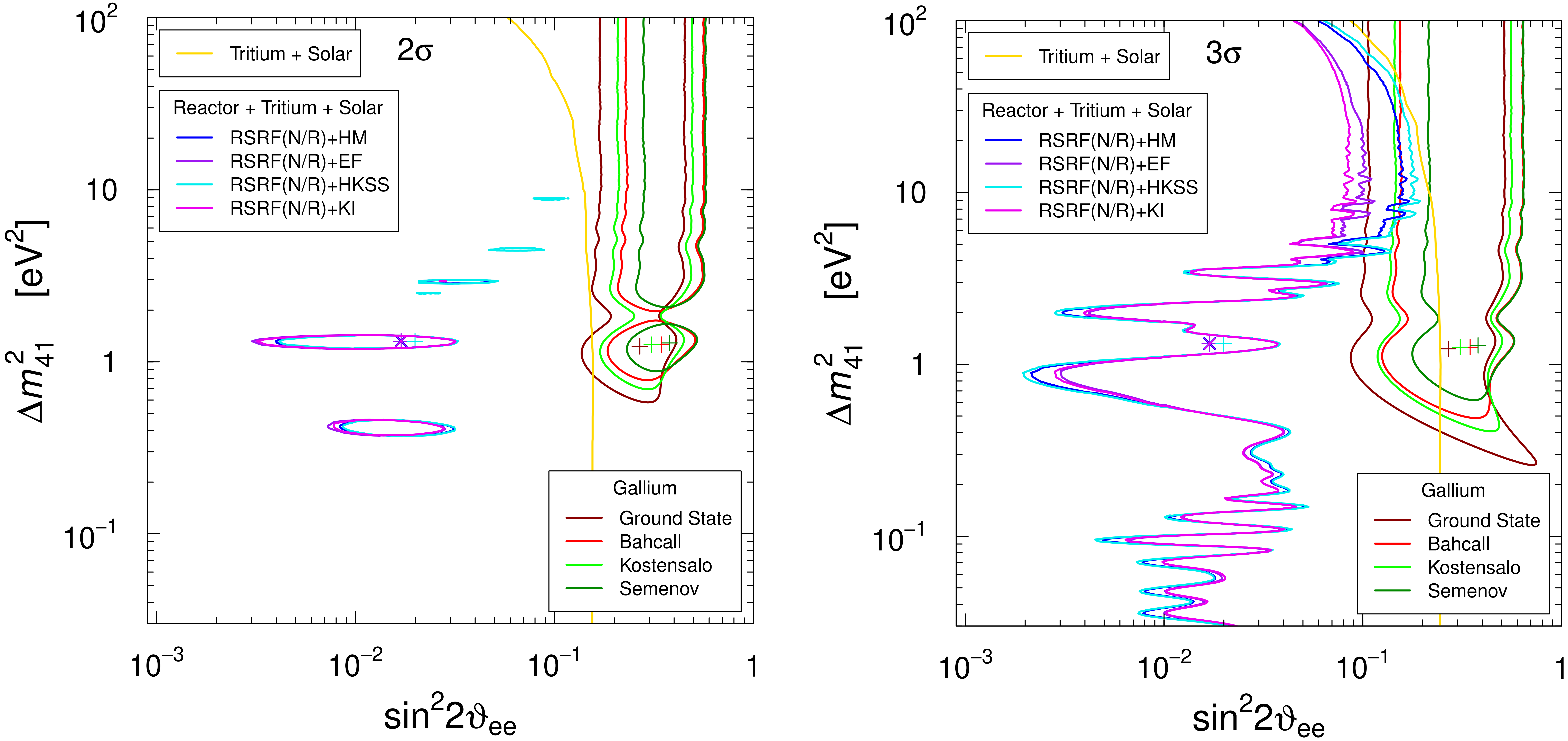


R = observed detection rate / predicted rate

Farzan, TS, 2306.09422
cross sections CS1, CS2 from
Haxton et al., 2303.13623

eV sterile neutrino oscillations disfavoured

- solar neutrinos, reactor experiments (and cosmology)



Giunti, Li, Ternes, Tyagi, Xin, 2209.00916

see also Berryman, Coloma, Huber, TS, Zhou, 2111.12530; Goldhagen, Maltoni, Reichard, TS, 2109.14898; Brdar, Gehrlein, Kopp, 2303.05528

severe tension of $4-5\sigma$

Can quantum decoherence have an effect on the gallium/reactor tension?

- Arguelles, Bertolez-Martinez, Salvado, Impact of Wave Packet Separation in Low-Energy Sterile Neutrino Searches [2201.05108]
- Arguelles, Conrad et al., New Clues About Light Sterile Neutrinos: Preference for Models with Damping Effects in Global Fits [2211.02610]

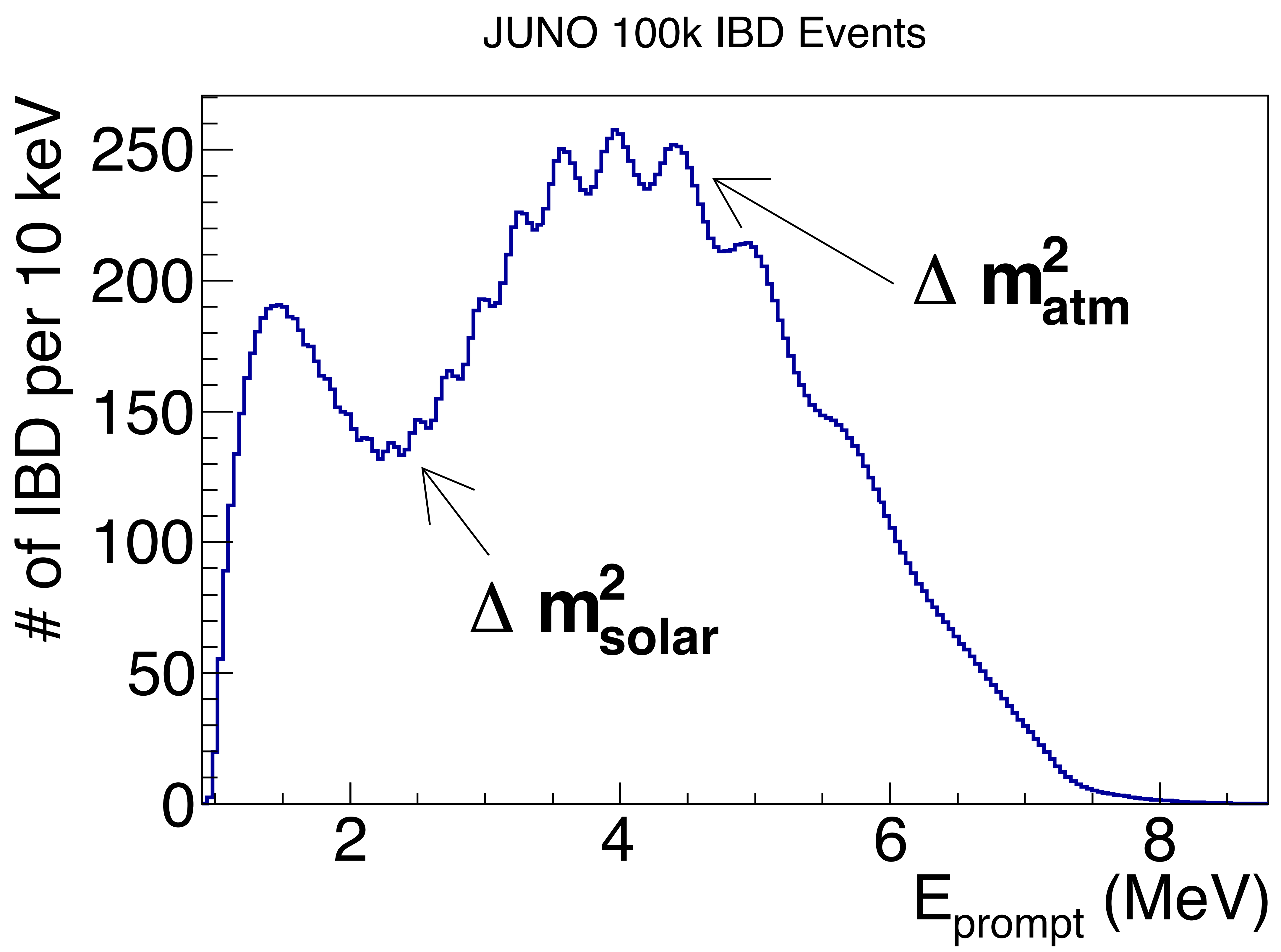
- Akhmedov, Smirnov, Damping of neutrino oscillations, decoherence and the lengths of neutrino wave packets, [2208.03736]; Jones, Comment on... [2209.00561], Akhmedov, Smirnov, Reply to comment... [2210.01547]

- Jones, Marzec, Spitz, The Width of a Beta-decay-induced Antineutrino Wavepacket [2211.00026]

Can quantum decoherence effects show up in future reactor experiments?

- High-precision reactor experiment
  JUNO coll., 1507.05613

- decoherence effects in JUNO?
  Gouvea, Romeri, Ternes, 2005.03022;
  Wang et al. (JUNO) 2112.14450;
  Marzec, Spitz, 2208.04277



Our goal:

- perform a QFT calculation of the oscillation amplitude, taking into account localization of external particles for reactor and gallium experiments

- „first principle“ calculation of decoherence effects

R. Krüger, T. Schwetz, 2303.15524 (EPJC)

Decoherence in neutrino oscillations

lecture by A. Smirnov

large literature (very incomplete selection):

- S. Nussinov, Solar Neutrinos and Neutrino Mixing, PLB 63 (1976) 201;
- B. Kayser, On the Quantum Mechanics of Neutrino Oscillation, PRD 24 (1981) 110;
- C. Giunti, C. W. Kim, U. W. Lee, When Do Neutrinos Really Oscillate?: Quantum Mechanics of Neutrino Oscillations, PRD 44 (1991) 3635;
- J. Rich, The Quantum Mechanics of Neutrino Oscillations, PRD 48 (1993) 4318;
- K. Kiers, S. Nussinov, N. Weiss, Coherence Effects in Neutrino Oscillations, PRD 53 (1996) 537;
- W. Grimus and P. Stockinger, Real Oscillations of Virtual Neutrinos, PRD 54 (1996) 3414;
- C. Giunti, C.W. Kim, U.W. Lee, When Do Neutrinos Cease to Oscillate?, PLB 421 (1998) 237;
- C. Giunti and C. W. Kim, Coherence of Neutrino Oscillations in the Wave Packet Approach, PRD 58 (1998) 017301;
- L. Stodolsky, The Unnecessary Wave Packet, PRD 58 (1998) 036006;
- W. Grimus, P. Stockinger, and S. Mohanty, The Field Theoretical Approach to Coherence in Neutrino Oscillations, PRD 59 (1999) 013011;
- C. Y. Cardall, Coherence of Neutrino Flavor Mixing in Quantum Field Theory, PRD 61 (2000) 073006;
- M. Beuthe, Oscillations of Neutrinos and Mesons in Quantum Field Theory, Phys. Rept. 375 (2003) 105; [hep-ph/0109119].
- E. K. Akhmedov and A. Y. Smirnov, Paradoxes of Neutrino Oscillations, Phys. Atom. Nucl. 72 (2009) 1363; [0905.1903].
- E. K. Akhmedov and J. Kopp, Neutrino Oscillations: Quantum Mechanics vs Quantum Field Theory, JHEP 04 (2010) 008;
- D. Hernandez and A. Yu. Smirnov, Active to sterile neutrino oscillations: Coherence and MINOS results, PLB706 (2012) 360;
- E. Akhmedov, D. Hernandez, and A. Smirnov, Neutrino Production Coherence and Oscillation Experiments, JHEP 04 (2012) 052;.
- B. J. P. Jones, Dynamical Pion Collapse and the Coherence of Conventional Neutrino Beams, PRD 91 (2015), no. 5 053002

The „standard oscillation formula“

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta} = \langle \nu_\beta | \quad \text{propagation} \quad | \nu_\alpha \rangle$$

$$= \sum_{i,j} U_{\beta j} \langle \nu_j | \quad e^{-i(E_i t - p_i x)} \quad | \nu_i \rangle U^*_{\alpha i} = \sum_i U_{\beta i} U^*_{\alpha i} e^{-i(E_i t - p_i x)}$$

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$$\to \quad P_{\nu_\alpha \to \nu_\beta} = \left| \mathcal{A}_{\nu_\alpha \to \nu_\beta} \right|^2 = \sum_i |U_{\beta i} U^*_{\alpha i}|^2 + \underbrace{\sum_{i \neq j} U_{\beta j} U^*_{\alpha j} U^*_{\beta i} U_{\alpha i} e^{-i\phi_{ji}}}_{\text{interference terms}}$$

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$$\rightarrow \quad P_{\nu_\alpha\to\nu_\beta} = \left|\mathcal{A}_{\nu_\alpha\to\nu_\beta}\right|^2 = \sum_i |U_{\beta i}U^*_{\alpha i}|^2 + \underbrace{\sum_{i\neq j} U_{\beta j}U^*_{\alpha j}U^*_{\beta i}U_{\alpha i}e^{-i\phi_{ji}}}_{\text{interference terms}}$$

with phase differences:

$$\phi_{ji} = (E_j - E_i)t - (p_j - p_i)x \quad \text{with} \quad E_i^2 = p_i^2 + m_i^2$$

after some hand waving: $\phi_{ji} \approx \frac{\Delta m^2_{ji} L}{2\,E}$ with $\Delta m^2_{ji} \equiv m_j^2 - m_i^2$

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2-flavour: $P = \frac{1}{2}\sin^2 2\theta\left(1 - \cos\frac{\Delta m^2 L}{2E}\right)$

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- production and detection regions are localised in space $\rightarrow$
  inconsistent with plane wave ansatz for neutrino propagation $\propto e^{-i(E_i t - p_i x)}$
- plane waves correspond to states with exact energy/momentum $\rightarrow$
  neutrino mass states are distinguishable particles
  why is the sum in the amplitude coherent (inside modulus)?

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  why is the sum in the amplitude coherent (inside modulus)?

Two approaches:

- assume wave-packets for neutrinos
- QFT approach, neutrino as internal line, wave-packets for external particles

- relation of the two approaches e.g., Akhmedov, Kopp, JHEP (2010) [1001.4815]

Decoherence

$$P_{\nu_\alpha \to \nu_\beta} = \sum_i |U_{\beta i} U^*_{\alpha i}|^2 + \xi \underbrace{\sum_{i \neq j} U_{\beta j} U^*_{\alpha j} U^*_{\beta i} U_{\alpha i} e^{-i\phi_{ji}}}_{\text{interference terms}} \qquad \phi_{ji} \approx \frac{\Delta m^2_{ji} L}{2\,E}$$

decoherence: $0 \leq \xi \leq 1 \to$ damping of interference terms

Decoherence

$$P_{\nu_\alpha \to \nu_\beta} = \sum_i |U_{\beta i} U^*_{\alpha i}|^2 + \xi \underbrace{\sum_{i \neq j} U_{\beta j} U^*_{\alpha j} U^*_{\beta i} U_{\alpha i} e^{-i\phi_{ji}}}_{\text{interference terms}} \qquad \phi_{ji} \approx \frac{\Delta m^2_{ji} L}{2E}$$

decoherence: $0 \leq \xi \leq 1 \to$ damping of interference terms

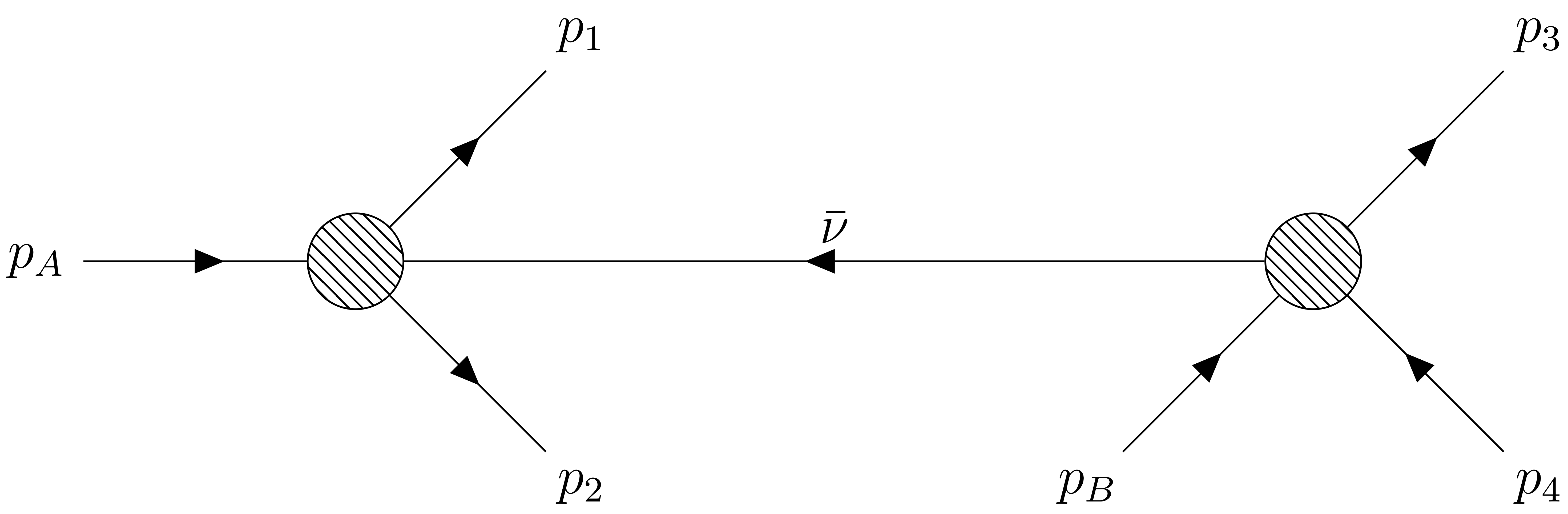
- "Quantum" decoherence:
  $\xi < 1$ appears already at amplitude level:

$$|\mathcal{A}|^2 = \sum_{ij} \mathcal{A}^*_j \mathcal{A}_i$$

- "Classical" decoherence:
  $\xi < 1$ due to averaging of the probability:

$$\overline{P} \propto \int dx \, |\mathcal{A}(x)|^2 \,, \qquad x = L, E$$

QFT approach to neutrino oscillations

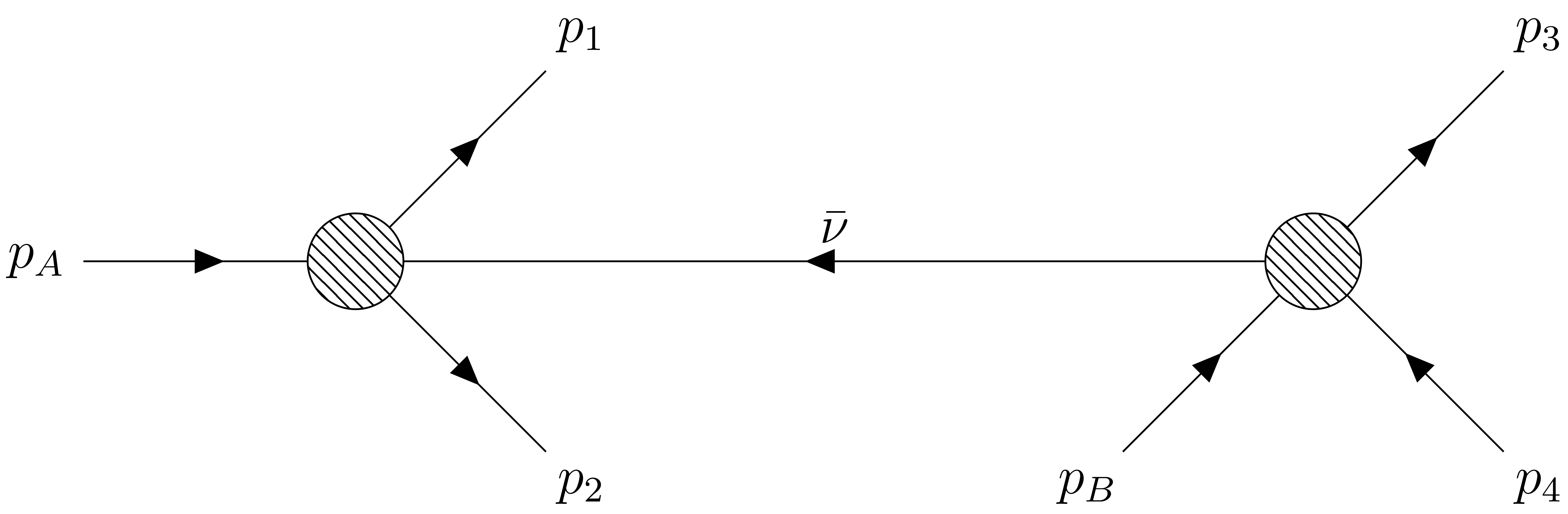


- Feynman diagram for joint process of production, propagation, detection

- early papers:
  Rich,1993; Giunti,Kim,Lee,Lee,1993; Grimus,Stockinger,1996; Kiers,Weiss,1998

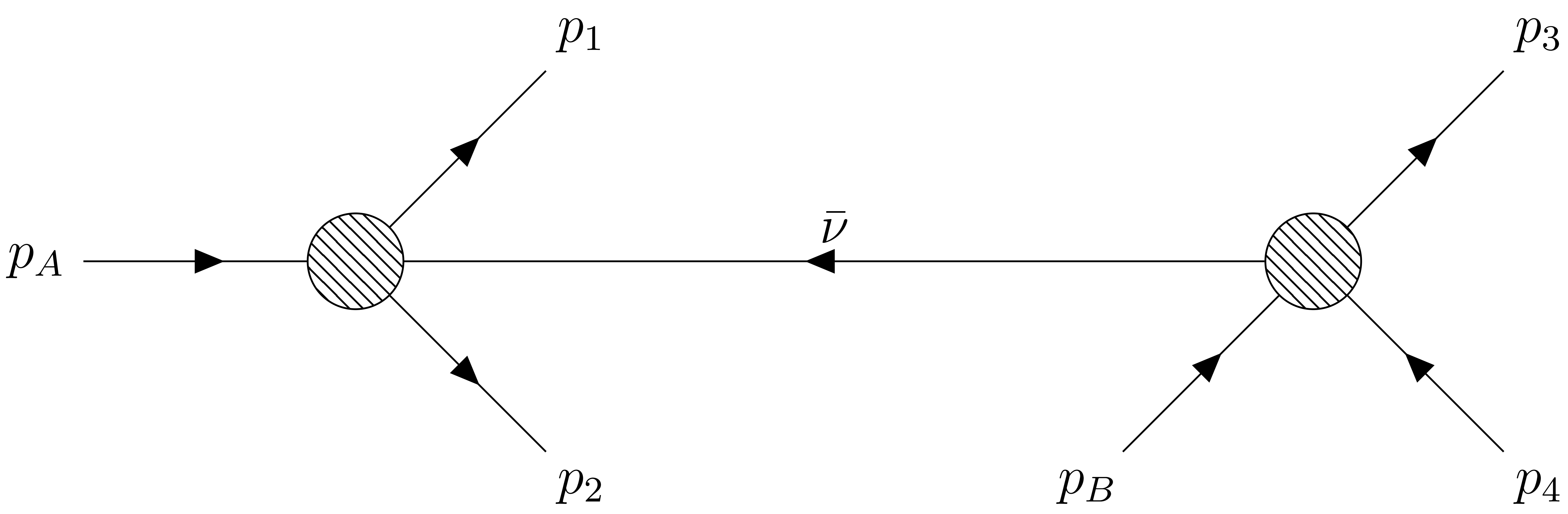
- review paper: M. Beuthe, Phys. Rept. 375 (2003) 105 [hep-ph/0109119]

QFT approach to neutrino oscillations



- macroscopic separation of the two vertices
- wave packets for external particles

QFT approach to neutrino oscillations



reactor experiments:

- production: $A \to A' + e^- + \bar{\nu}_e$
- detection: $\bar{\nu}_e + p \to n + e^+$
- $\Rightarrow A + p \to A' + n + e^- + e^+$

Gallium source experiments:

- production: $\mathrm{Cr} \to \mathrm{V} + \nu_e$
- detection: $\mathrm{Ga} + \nu_e \to \mathrm{Ge} + e^-$
- $\Rightarrow \mathrm{Cr} + \mathrm{Ga} \to \mathrm{V} + \mathrm{Ge} + e^-$

QFT approach to neutrino oscillations

- coherence properties of oscillation amplitude is determined by localization of external particles and their velocities
- assume Gaussian wave packets in momentum space:

$$|\phi\rangle = \int d\tilde{\mathbf{k}} \phi(\mathbf{k}) |\mathbf{k}\rangle \qquad \phi(\mathbf{k}) = \left(\frac{2\pi}{\sigma^2}\right)^{3/4} e^{-\frac{(\mathbf{k}-\mathbf{p})^2}{4\sigma^2}}$$

The oscillation amplitude

$$i\mathcal{A}_{\alpha\beta} \propto \sum_j U_{\alpha j} U^*_{\beta j} \int \frac{d^4 p}{(2\pi)^4} i\tilde{\mathcal{M}}_P \frac{\not{p} - m_j}{p^2 - m_j^2 + i\epsilon} i\tilde{\mathcal{M}}_D \, e^{-ip(x_D - x_P)}$$

$$\times \prod_{I=P,D} \frac{\pi^2}{\sigma_{pI}^3 \sigma_{EI}} \exp\left[-\frac{(\mathbf{p}-\mathbf{p}_I)^2}{4\sigma_{pI}^2} - \frac{(p^0 - E_I - \mathbf{v}_I(\mathbf{p}-\mathbf{p}_I))^2}{4\sigma_{EI}^2}\right]$$

effective momentum and energy spreads for neutrino production and detection processes

The oscillation amplitude

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$$\times \prod_{I=P,D} \frac{\pi^2}{\sigma^3_{pI}\sigma_{EI}} \exp\left[-\frac{(\mathbf{p}-\mathbf{p}_I)^2}{4\sigma^2_{pI}} - \frac{(p^0 - E_I - \mathbf{v}_I(\mathbf{p}-\mathbf{p}_I))^2}{4\sigma^2_{EI}}\right]$$

effective momentum and energy spreads for neutrino production and detection processes

generalizations for reactor & gallium configurations:

- finite life-time of decaying particles
- interactions with environment (effect in analogy to collisional line broadening)

The oscillation amplitude

$$i\mathcal{A}_{\alpha\beta} \propto \sum_j U_{\alpha j} U^*_{\beta j} \int \frac{d^4 p}{(2\pi)^4} i\tilde{\mathcal{M}}_P \frac{\not{p} - m_j}{p^2 - m_j^2 + i\epsilon} i\tilde{\mathcal{M}}_D \, e^{-ip(x_D - x_P)}$$

$$\times \prod_{I=P,D} \frac{\pi^2}{\sigma_{pI}^3 \sigma_{EI}} \exp\left[-\frac{(\mathbf{p} - \mathbf{p}_I)^2}{4\sigma_{pI}^2} - \frac{(p^0 - E_I - \mathbf{v}_I(\mathbf{p} - \mathbf{p}_I))^2}{4\sigma_{EI}^2} \right]$$

- perform integral over neutrino momentum $\int d^3 p$ taking into account macroscopic separation of source and detector: $L = |\mathbf{x}_D - \mathbf{x}_P| \to \infty$
Grimus, Stockinger, 1996 $\to$ neutrinos go onshell $\mathbf{p}_j = \hat{\mathbf{l}}\sqrt{p_0^2 - m_j^2}$

The oscillation amplitude

$$i\mathcal{A}_{\alpha\beta} \propto \sum_j U_{\alpha j} U^*_{\beta j} \int \frac{d^4p}{(2\pi)^4} i\tilde{\mathcal{M}}_P \frac{\not{p} - m_j}{p^2 - m_j^2 + i\epsilon} i\tilde{\mathcal{M}}_D \, e^{-ip(x_D - x_P)}$$

$$\times \prod_{I=P,D} \frac{\pi^2}{\sigma_{pI}^3 \sigma_{EI}} \exp\left[-\frac{(\mathbf{p} - \mathbf{p}_I)^2}{4\sigma_{pI}^2} - \frac{(p^0 - E_I - \mathbf{v}_I(\mathbf{p} - \mathbf{p}_I))^2}{4\sigma_{EI}^2} \right]$$

- square the amplitude and perform a time average due to unobserved time of neutrino production
- perform the integral over the neutrino energy $\int dp_0$

…after some algebra:

$$\overline{|\mathcal{A}_{\alpha\beta}|^2} \propto \exp\left[i\frac{\Delta m^2 L}{2E_0}\right] \quad \text{standard oscillation phase}$$

$$\times \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2}{4E_0\sigma_m}\right)^2\right] \quad \text{localization decoherence } \xi_{\rm loc}$$

$$\times \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2 L\sigma_{\rm en}}{2E_0^2}\right)^2\right] \quad \text{energy decoherence } \xi_{\rm en}$$

$\sigma_m, \sigma_{\rm en}$ are calculable from localization properties of initial and final state particles

$$\frac{1}{\sigma_m^2} \equiv \sum_{I=P,D}\left(\frac{1}{\sigma_{pI}^2} + \frac{v_I^2}{\sigma_{EI}^2}\right), \qquad \frac{1}{\sigma_{\rm en}^2} \equiv \sum_{I=P,D}\frac{1}{\sigma_{I,\rm eff}^2}$$

$$\frac{1}{\sigma_{I,\rm eff}^2} \equiv \frac{1}{\sigma_{pI}^2} + \frac{(1-v_I)^2}{\sigma_{EI}^2}, \qquad E_0 \equiv \sigma_{\rm eff}^2 \sum_{I=P,D}\frac{E_I}{\sigma_{I,\rm eff}^2}$$

- Localization decoherence:

$$\xi_{\rm loc} = \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2}{4E_\nu\sigma_m}\right)^2\right] = \exp\left[-2\pi^2\left(\frac{\delta_{\rm loc}}{L_{\rm osc}}\right)^2\right] \quad \text{with} \quad \sigma_m\delta_{\rm loc} = \frac{1}{2}$$

  - energy/momentum uncertainty be large enough that individual mass states cannot be identified: $\sigma_m \gg \Delta m^2/E_\nu$
  - production/detection regions be localized better than oscillation length: $\delta_{\rm loc} \ll L_{\rm osc}$

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  - production/detection regions be localized better than oscillation length: $\delta_{\rm loc} \ll L_{\rm osc}$

- Energy decoherence:

$$\xi_{\rm en} = \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2 L \sigma_{\rm en}}{2E_\nu^2}\right)^2\right] = \exp\left[-2\pi^2\left(\frac{L}{L_{\rm osc}}\frac{\sigma_{\rm en}}{E_\nu}\right)^2\right]$$

  - the neutrino energy needs to be well defined $\sigma_{\rm en} \ll E_\nu$
  - can be interpreted as neutrino wave packet separation ($v_j \approx 1 - m_j^2/2E_\nu^2$)

Classical averaging

$$\overline{P} \propto \int dx \, |\mathcal{A}(x)|^2 \,, \qquad x = L, E$$

- Classical averaging of $|\mathscr{A}|^2$ over space and energy has the same effect as intrinsic QM decoherence:

$$\delta^2_{\rm loc} \to \delta^2_{\rm loc} + \delta^2_{\rm clas} \,, \quad \sigma^2_{\rm en} \to \sigma^2_{\rm en} + \sigma^2_{\rm clas}$$

- indistinguishable phenomenologically
  Kiers, Nussinov, Weiss, 1996; Stodolsky, 1998; Ohlsson, 2001
- quantum mechanical uncertainties provide a fundamental lower bound on the uncertainty
- to observe QM decoherence, classical averaging effects have to be suppressed down to the quantum level

Classical averaging

- classical averaging due to experimental reasons: size of production region, finite detector resolutions (in space and energy),...

- fundamental averaging effects due to experimental configuration and physics principles:
  - phase space integrals of unobserved particles:
    reactor experiments:
    momenta of outgoing particles in the source, neutron in the detector
    gallium: momenta of all outgoing particles (counting experiment)
  - gallium experiments: Doppler broadening of the decay line from $\mathrm{Cr} \to \mathrm{V} + \nu_e$
    due to thermal motion of source particles

Numerical estimates for gallium and reactors

R. Krüger, TS, 2303.15524

- nuclei localization: inter-atomic distances in cristal lattice or fluid
- velocities: either thermal velocities or velocities for typical kin. energies of outgoing particles
- electron/positron localization: distance the particle travels until it deposits one mean excitation energy (integrating $\langle dE/dx \rangle$ Bethe equation)

	Particle	δ_x [nm]	σ [eV]	v
Reactor (P)	N	0.24	410	1×10^{-6}
$N \to N' + e^- + \overline{\nu}_e$	N'	0.24	410	4×10^{-5}
	e^-	260	0.38	0.99
Reactor (D)	p	0.1	990	5×10^{-6}
$p + \overline{\nu}_e \to n + e^+$	n	5×10^6	2×10^{-5}	5×10^{-3}
	e^+	320	0.3	0.99
Gallium (P)	Cr	0.20	480	7×10^{-7}
$\text{Cr} \to \text{V} + \nu_e$	V	0.20	480	2×10^{-5}
Gallium (D)	Ga	0.27	370	6×10^{-7}
$\text{Ga} + \nu_e \to \text{Ge} + e^-$	Ge	0.27	370	1×10^{-5}
	e^-	310	0.32	0.83

s. also Akhmedov, Smirnov, 2208.03736

Numerical estimates for gallium and reactors

R. Krüger, TS, 2303.15524

- localization decoherence:

for reactor and gallium experiments dominated by hadronic particles

$$\sigma_m \simeq (400 - 500)\,\mathrm{eV}\,, \qquad \delta_{\mathrm{loc}} = \frac{1}{2\sigma_m} \simeq 0.2\,\mathrm{nm}$$

$$-\ln \xi_{\mathrm{loc}} = \frac{1}{2}\left(\frac{\Delta m^2}{4E_\nu \sigma_m}\right)^2 \approx 1.3 \times 10^{-19} \left(\frac{\Delta m^2}{1\,\mathrm{eV}^2}\right)^2 \left(\frac{1\,\mathrm{MeV}}{E_\nu}\right)^2 \left(\frac{500\,\mathrm{eV}}{\sigma_m}\right)^2$$

$\Rightarrow$ QM localization decoherence irrelevant for all practical purposes: $\xi_{\mathrm{loc}} = 1$

Note: classical spatial averaging is relevant and needs to be taken into account

Numerical estimates for gallium and reactors

R. Krüger, TS, 2303.15524

- energy decoherence:

including phase space integration and Doppler broadening:

$$\sigma_{\mathrm{en}} \approx 0.5\,\mathrm{eV}\,, \qquad \delta_{\mathrm{en}} \approx 200\,\mathrm{nm}$$

$$-\ln \xi_{\mathrm{en}} = 2\pi^2 \left(\frac{L}{L_{\mathrm{osc}}} \frac{\sigma_{\mathrm{en}}}{E_\nu} \right)^2 \approx 4.9 \times 10^{-12} \left(\frac{L}{L_{\mathrm{osc}}} \right)^2 \left(\frac{1\,\mathrm{MeV}}{E_\nu} \right)^2 \left(\frac{\sigma_{\mathrm{en}}}{0.5\,\mathrm{eV}} \right)^2$$

$\Rightarrow$ QM energy decoherence (“wave packet separation”) irrelevant for all practical purposes: $\xi_{\mathrm{en}} = 1$

Note: classical energy averaging is relevant and needs to be taken into account

Summary energy decoherence

R. Krüger, TS, 2303.15524
s. also Akhmedov, Smirnov, 2208.03736

- our result: $\sigma_{\rm en} \approx 0.5\,{\rm eV}\,, \quad \delta_{\rm en} \approx 200\,{\rm nm}$

- energy resolution of typical reactor neutrino detectors:

$$(0.03 - 0.06)\,{\rm MeV}\sqrt{E/{\rm MeV}} \quad \Rightarrow \quad \sigma_{\rm clas} \simeq 0.1\ {\rm MeV}$$

  about 6 orders of magnitude larger than $\sigma_{\rm en}$!

- QM decoherence negligible — dominated by classical averaging (holds also for JUNO)

- phenomenological constraint is dominated by classical energy resolution:
  $\sigma < 0.47\,{\rm MeV}, \delta > 2.1 \times 10^{-4}\,{\rm nm}$ [Gouvea,Romeri,Ternes, 2005.03022, 2104.05806]

Any decoherence effect on top of classical averaging will point towards new physics!

Barenboim, Mavromatos, Sarkar, Waldron-Lauda, 2006
Fogli, Lisi, Marrone, Montanino, Palazzo, 2007
Farzan, TS, Smirnov, 2008; Bakhti, Farzan, TS, 2015
Guzzo, de Holanda, Oliveira, 2014
Hellmann, Pas, Rani, 2022
Banks, Kelly, McCullough, 2023
…

Decoherence explanation of the gallium anomaly

Y. Farzan, TS, 2306.09422

- three SM neutrinos (no steriles)
- modified QM evolution:

$$H = \frac{1}{2E_\nu} \text{diag}(m_1^2, m_2^2, m_3^2) \, ,$$

$$\frac{d\rho}{dt} = i[\rho, H] - \{\rho, D^2\} + 2D\rho D$$

$$D = \text{diag}(d_1, d_2, d_3) \, ,$$

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$$\frac{d\rho}{dt} = i[\rho, H] - \{\rho, D^2\} + 2D\rho D$$

$$D = \mathrm{diag}(d_1, d_2, d_3)\,,$$

- damping of interference terms:

$$P_{ee} = \sum_{i=1}^{3} |U_{ei}|^4 + \sum_{i\neq j} |U_{ei}|^2 |U_{ej}|^2 e^{-\gamma_{ij} L} e^{-i\phi_{ij}}$$

$$\gamma_{ij} = (d_i - d_j)^2$$

Karlsruher Institut für Technologie

UV origin?

$$P_{ee} = \sum_{i=1}^{3} |U_{ei}|^4 + \sum_{i \neq j} |U_{ei}|^2 |U_{ej}|^2 e^{-\gamma_{ij} L} e^{-i\phi_{ij}}$$

phenomenological ansatz:

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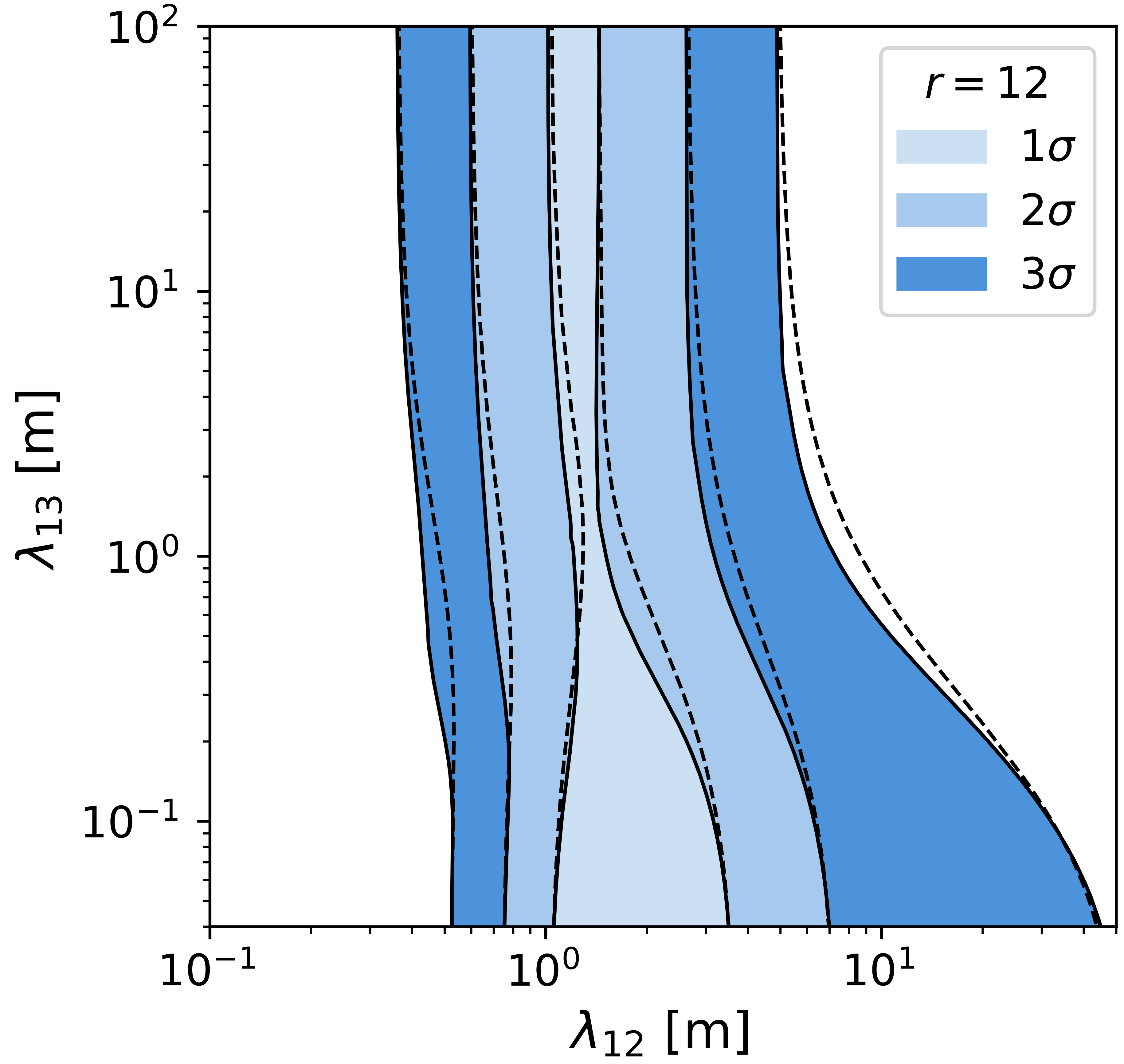
- $r \neq 1$ violates Lorentz invariance
- localization and energy decoherence $r = 2$ or 4, but have different L dependence (L^0 or L^2)
- $r = -2$: quantum gravity models
- $r = -1$: cross section like behaviour
- $r = 2$: light cone fluctuations
- $r = 1$: phenomenologically similar to invisible neutrino decay

Decoherence explanation of the gallium anomaly

Y. Farzan, TS, 2306.09422

	$r = 12$				
	$\chi^2_{\rm min}/\text{dof}$	p-val.	$\Delta\chi^2$	$\#\sigma$	λ_{12} [m]
BEST	2.2/1	0.14	32.5	5.4	1.44
all	9.2/5	0.10	29.2	5.0	1.74



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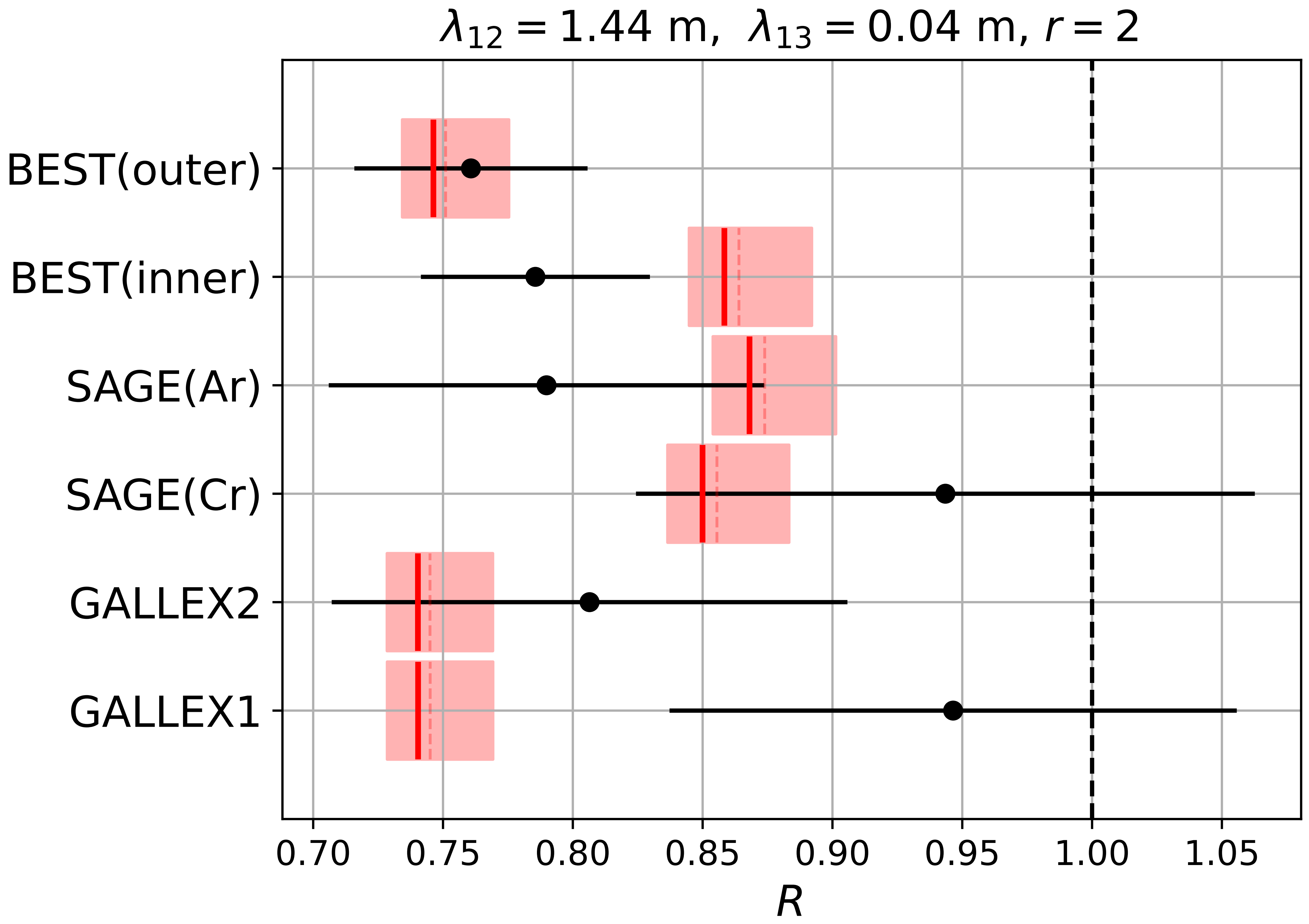
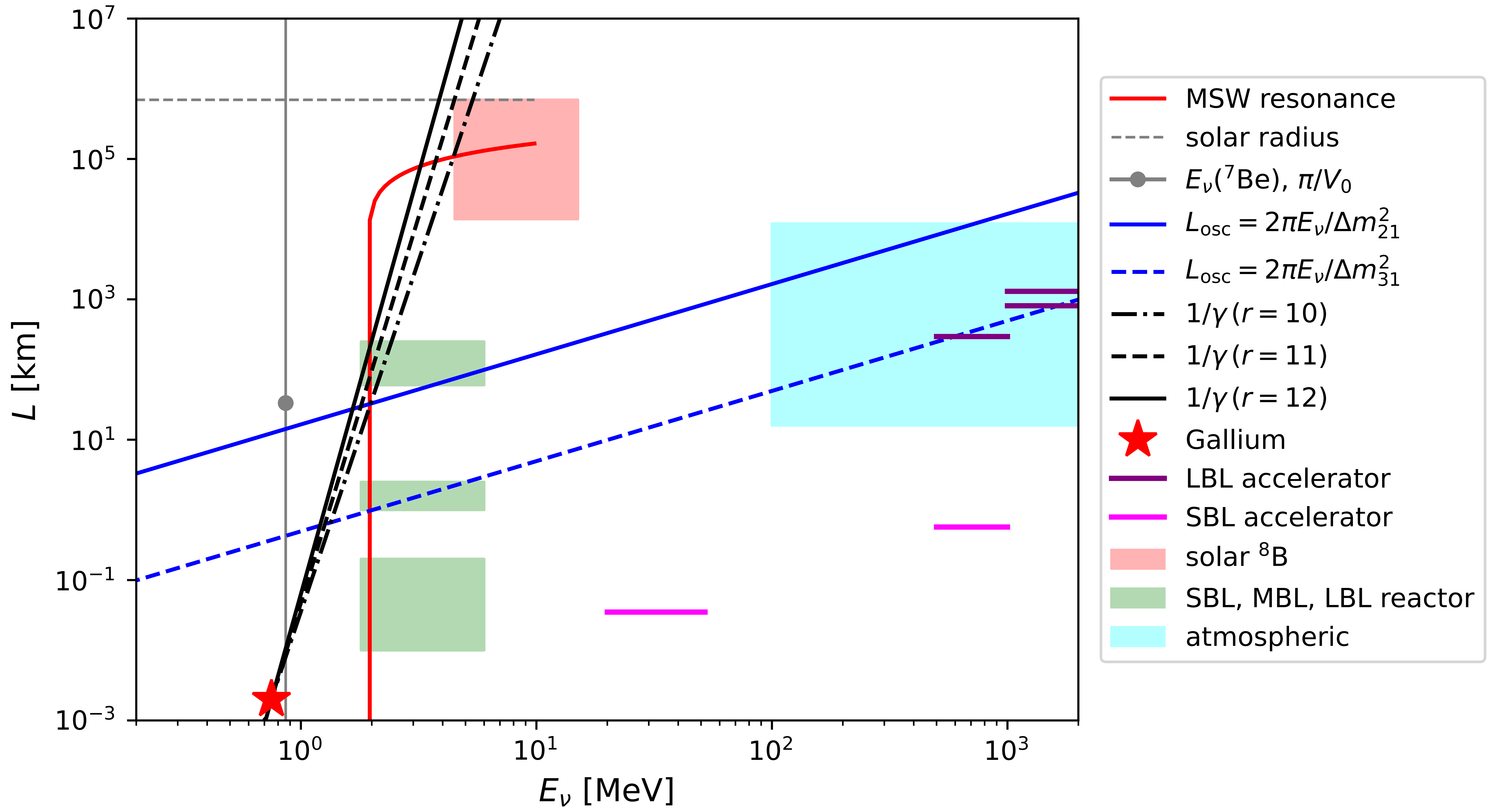
$$P_{ee}^{\rm gal} \approx 1 - \frac{1}{2}\sin^2 2\theta_{13} - \frac{1}{2}\cos^4\theta_{13}\sin^2 2\theta_{12}\left(1 - e^{-\gamma_{12}L}\right)$$



Consistency with other oscillation data



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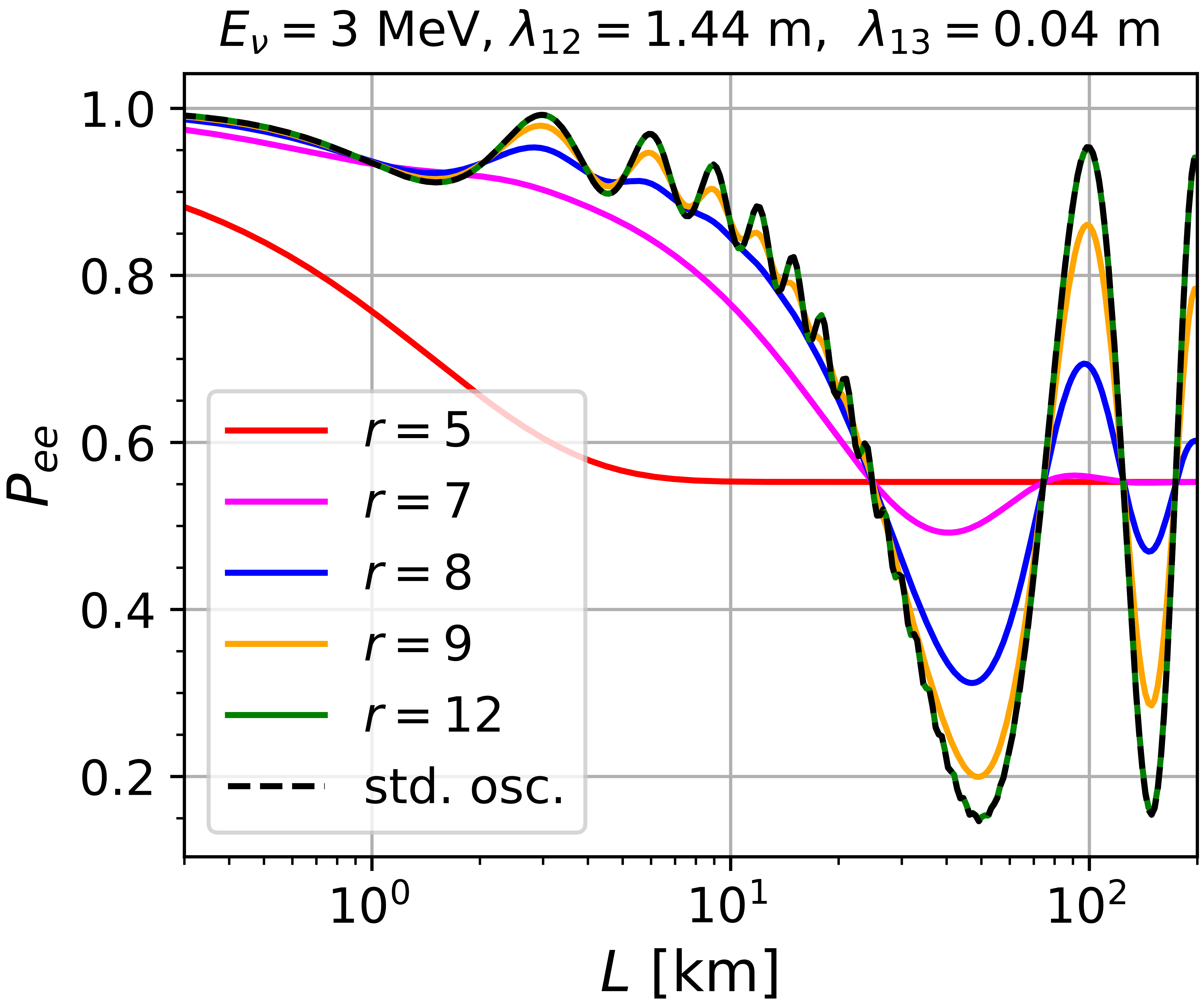

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- predict distance dependence in gallium exps. (still compatible with BEST) slightly modified MSW transition region in $P_{ee}(E_\nu)$ for solar neutrinos
- no effect predicted in MiniBooNE or SBL reactors
- expect standard three-neutrino neutrino cosmology

Can be combined with decoherence explanation of LSND

Bakhti, Farzan, TS [1503.05374]

assume Gaussian energy dependence:

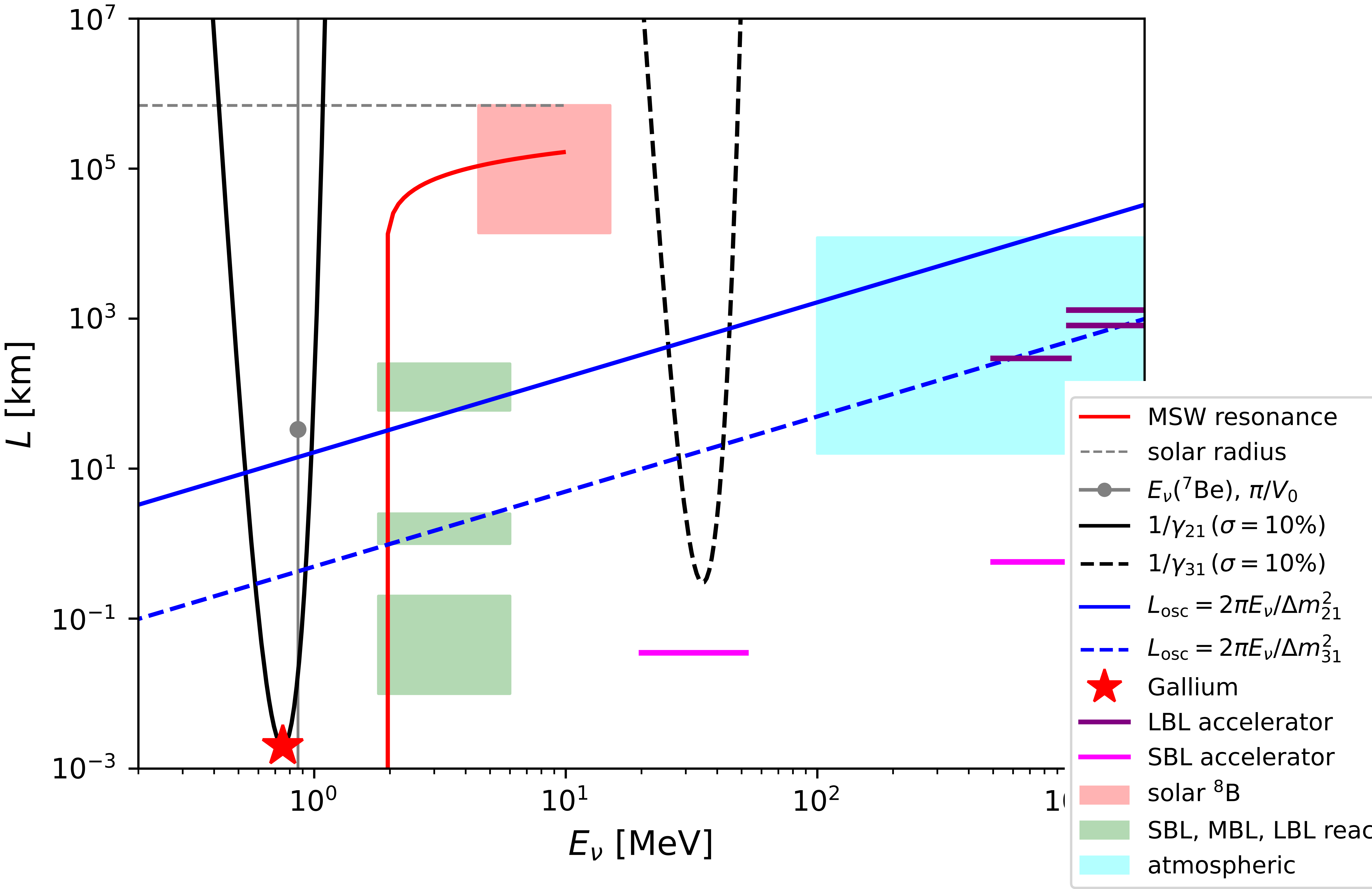
$$d_1 \approx 0$$

$$d_{2,3} = \frac{1}{\sqrt{\lambda_i}} \exp\left[-\frac{(E_\nu - E_i)^2}{2(0.1E_i)^2}\right]$$

$$\lambda_2 = 2\,\mathrm{m}, E_2 = 0.75\,\mathrm{MeV}$$

$$\lambda_3 = 300\,\mathrm{m}, E_3 = 35\,\mathrm{MeV}$$

$$\gamma_{ij=(d_i-d_j)^2}$$



Summary

- BEST results make gallium anomaly highly significant $\approx 5\sigma$
  difficult to explain without being in conflict with other data

- QFT framework to study decoherence effects
  standard QM localization/wave packet effects are negligible

- presented an explanation in terms of new-physics decoherence, consistent with oscillation data, cosmology, and potentially compatible with an LSND explanation

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Thank you for your attention

Backup

Single vertex case

transition probability $i \to f$:

$$P_{if} = |\langle \phi_f | iT | \phi_i \rangle|^2 \equiv |i\mathcal{A}|^2$$

definition of the matrix element for momentum states:

$$\left(\prod_f \langle \mathbf{k}_f | \right) iT \left(\prod_i |\mathbf{k}_i\rangle \right) = (2\pi)^4 \delta^{(4)} \left(\sum_f k_f - \sum_i k_i \right) i\mathcal{M} \, ,$$

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$$= \int d^4x \prod_f \int d\tilde{\mathbf{k}}_f \phi_f^*(\mathbf{k}_f) e^{ik_f x} \prod_i \int d\tilde{\mathbf{k}}_i \phi_i(\mathbf{k}_i) e^{-ik_i x}\, i\mathcal{M}$$

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Single vertex case

$$iA \propto i\mathcal{M}\,\frac{\pi^2}{\sigma_p^3\sigma_e}\exp\left[-\frac{(\Delta\mathbf{p})^2}{4\sigma_p^2}-\frac{(\Delta E-\Delta\mathbf{p}\mathbf{v})^2}{4\sigma_e^2}\right]$$

with

$$\Delta\mathbf{p}\equiv\sum_i \mathbf{p}_i-\sum_f \mathbf{p}_f\,,\qquad \Delta E\equiv\sum_i E_{p_i}-\sum_f E_{p_f}$$

and effective momentum and energy spreads:

$$\sigma_p^2\equiv\sum_{i,f}\sigma_{i,f}^2\,,\qquad \sigma_e^2\equiv\sigma_p^2(\Sigma-\mathbf{v}^2)$$

and a weighted velocity and velocity-squared:

$$\mathbf{v}\equiv\frac{1}{\sigma_p^2}\sum_{i,f}\sigma_{i,f}^2\mathbf{v}_{i,f}\,,\qquad \Sigma\equiv\frac{1}{\sigma_p^2}\sum_{i,f}\sigma_{i,f}^2\mathbf{v}_{i,f}^2\,,\qquad \mathbf{v_i}\equiv\left.\frac{\partial E_i}{\partial\mathbf{k}_i}\right|_{\mathbf{k}_i=\mathbf{p}_i}$$