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Muon decay

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Outline

Motivation

Polarisation and γ^5

The radiative decay

The rare decay

Outlook

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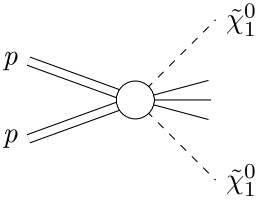
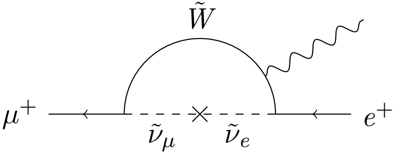
New physics: lightning introduction





Direct search

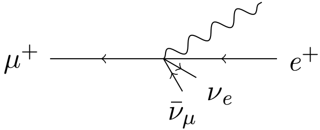
Sensitive up to $\mathcal{O}\left(10^3\,\text{GeV}\right)$

Indirect search

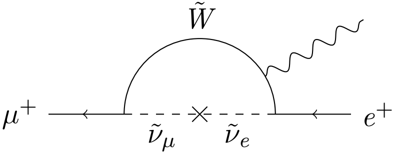
Sensitive up to $\mathcal{O}\left(10^{13}\,\text{GeV}\right)$[1]

[1] Model dependent

Importance of background



Radiative decay
$(\mu \to \nu\bar{\nu}e + \gamma)$
$E_{\nu\bar{\nu}} < \Delta E_{\text{exp.}}$



LFV decay
$(\mu \to e\gamma)$

Status quo

	Experimental	Theoretical (4-Fermi)
Normal $\mu \to \nu\bar{\nu}e$	TWIST[1] $\mathcal{O}\left(10^{-4}\right)$	NLO (polarised, MC) [Arbuzov 2001] NNLO (unpolarised, analytic) [Anastasiou, Melnikov, and Petriello 2007]
Radiative $\mu \to \nu\bar{\nu}e + \gamma$	MEG $\mathcal{O}\left(1\%\right)$	NLO (polarised, MC) [Fael, Mercolli, and Passera 2015]
Rare $\mu \to \nu\bar{\nu}e + e^+e^-$	Mu3e[2] $\mathcal{O}\left(10\%\right)$	LO (polarised, MC)

[1] Michel parameters
[2] Proposed

Open theoretical issues

Use muon as toy process: clean QED

- γ^5: Treatment in dim-reg?
- Regularisation scheme dependency
- Large logs, esp. $\tau \to \nu\bar{\nu}e + \gamma$ (3.5σ deviation!) [Fael, Mercolli, and Passera 2015]
- No NLO for rare decay

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Polarisation

- Two equivalent ways of introducing polarisations dependence
  - "Closing the trace" $u(p)\bar{u}(p) = (\not{p} + m)\dfrac{1+\gamma^5 \not{s}}{2}$
  - Massive spinor helicity formalism

$$u_\pm(p) = \left|\ell^\pm\right\rangle + \frac{m}{\left\langle \ell^\pm | n^\mp \right\rangle}\left|n^\mp\right\rangle$$

$$\left|k^\pm\right\rangle = \frac{1\pm\gamma^5}{2}u(k)$$

n is related to s [See Ellis' lecture]

- Both introduce a γ^5!

Treatment of γ^5

- $\gamma^5 = \mathrm{i}\gamma^0\gamma^1\gamma^2\gamma^3$ is not well defined in d dimensions
- There are at two sources of γ^5:
  - The 4-Fermi vertex $j^\mu_{V-A}(a,b) = \bar\psi_a\gamma^\mu(1-\gamma^5)\psi_b$: [Berman and Sirlin 1962]

    $$j^\mu_{V-A}(a,b) = \underbrace{\bar\psi_a\gamma^\mu\psi_b}_{j^\mu} - \bar\psi_a\gamma^\mu\psi_b'$$

    $\psi_b' = \gamma^5\psi_b$ corresponds to an electron with $m=-m_e$.
  - Polarisation: Spinor helicity formalism in FDH (external particles in $d=4$)

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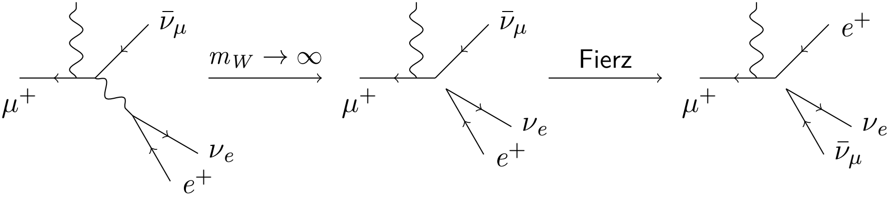
Fully differential NLO predictions for MEG @ PSI

- 4-Fermi interaction, fierzed at the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathsf{QED}} + \frac{G_F}{\sqrt{2}} j_{V-A}(\mu, e) \cdot j_{V-A}(\nu_\mu, \nu_e)$$



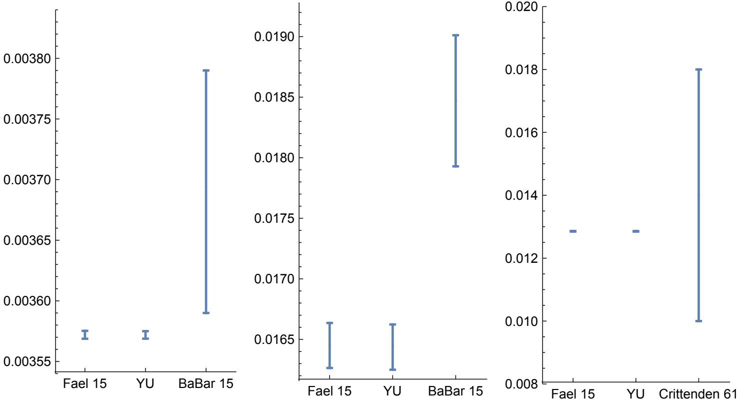
Implementation

- Get amplitudes from GoSam [Cullen et al. 2014]
- FKS subtraction [Frixione, Kunszt, and Signer 1996]
- Custom phase spaces for increased stability and FKS
- (Almost) original VEGAS for integration [Lepage 1980]

Branching ratio: Experimental comparison

$$\delta\mathrm{BR}^{\mathrm{NNLO}} \approx \frac{\alpha}{\pi} \log\frac{m}{M} \log\frac{\omega_0}{M} \mathrm{BR}^{\mathrm{NLO}}$$

[Fael, Mercolli, and Passera 2015]

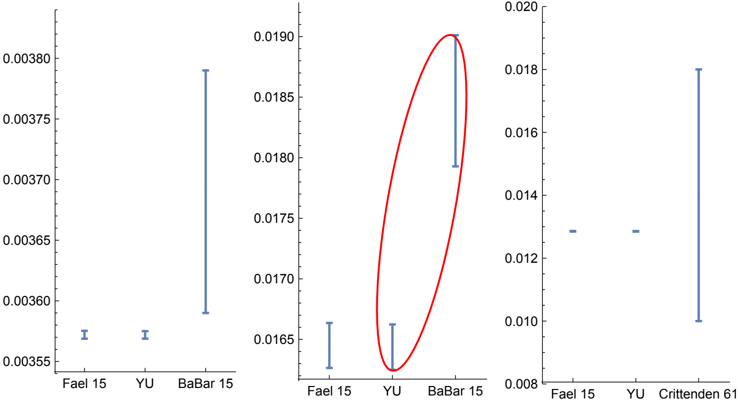


$\tau \to \nu\bar{\nu}\mu + \gamma$ $\qquad$ $\tau \to \nu\bar{\nu}e + \gamma$ $\qquad$ $\mu \to \nu\bar{\nu}e + \gamma$

Branching ratio: Experimental comparison

$$\delta \mathrm{BR}^{\mathrm{NNLO}} \approx \frac{\alpha}{\pi} \log \frac{m}{M} \log \frac{\omega_0}{M} \mathrm{BR}^{\mathrm{NLO}}$$

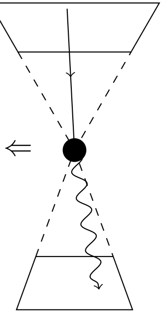
[Fael, Mercolli, and Passera 2015]

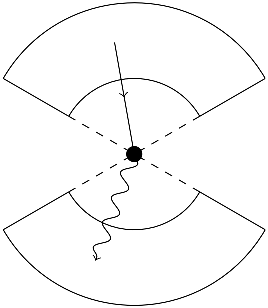


$\tau \to \nu\bar{\nu}\mu + \gamma$ $\tau \to \nu\bar{\nu}e + \gamma$ $\mu \to \nu\bar{\nu}e + \gamma$

MEG geometry

Theorist's version of the MEG detector @ PSI





$E_\gamma >$ 40 MeV $\quad |\cos\theta_e| < 0.5 \quad E_e >$ 45 MeV

$\cos\theta_e$ ***distribution***

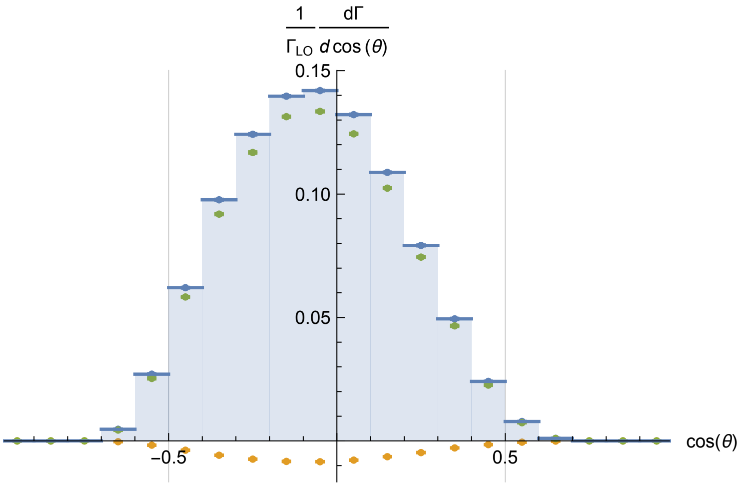


Fig.: Angular distribution:

$\cos\theta_e$ ***distribution***

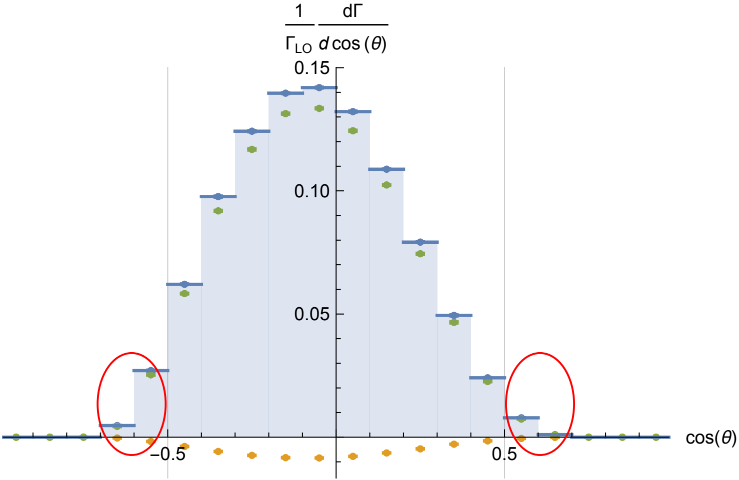


Fig.: Angular distribution: MEG cuts on the electron loose 4.10 % of the events

$\cos\theta_e$ ***distribution***

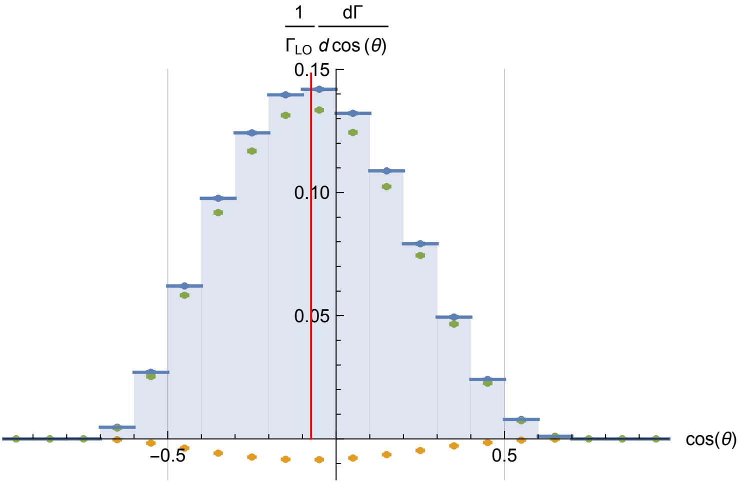


Fig.: Angular distribution: Polarised source $\langle\cos\theta_c\rangle \approx -0.063 < 0$ corresponding to $\langle\theta_c\rangle \approx 93.62°$

Neutrino spectrum

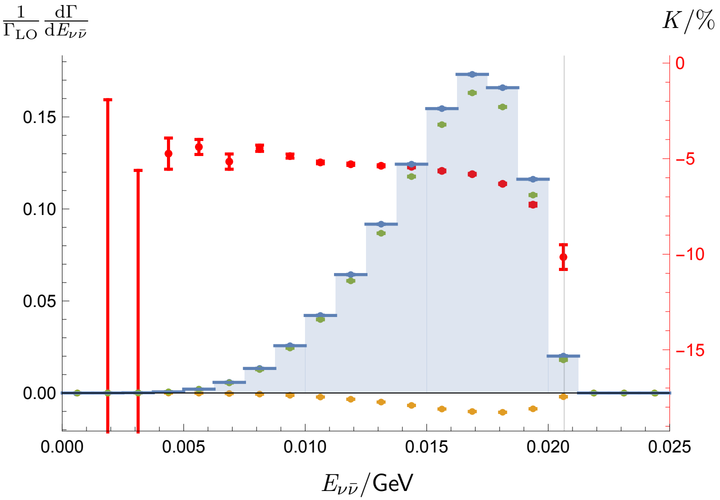


Fig.: Neutrino spectrum:

Neutrino spectrum

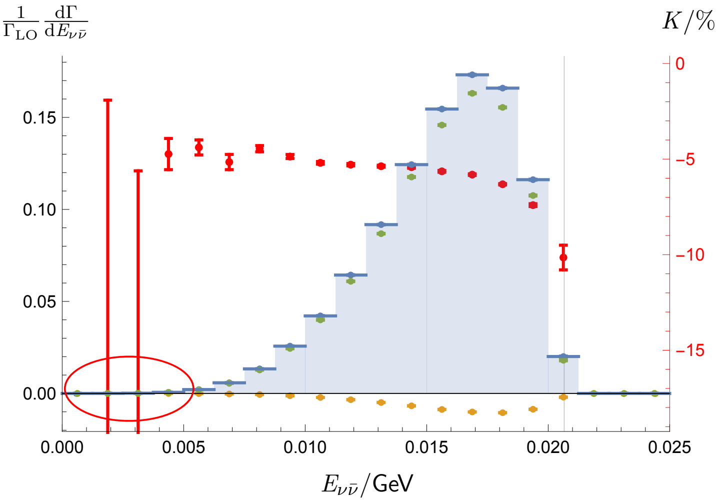


Fig.: Neutrino spectrum: Experimental resolution $\approx 2\,\text{MeV} \Rightarrow$ low energy neutrino are important (below $5\,\text{MeV}$: 7.2×10^{-4})

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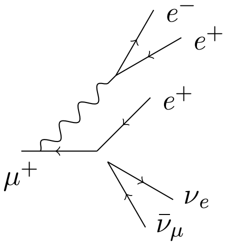
NLO branching ratios for Mu3e @ PSI

- $4_{\text{Born}} + 40_{\text{1-loop}} + 20_{\text{real}}$ diagrams up to pentagons
- A lot but not *that* many
- Use same approach (GoSam, FKS, VEGAS)
- Phase space more important than ever
- Mu3e cuts $E_e > 10\,\text{MeV}$



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Preliminary results

	LO	NLO only	K-factor
$\mathcal{B}$(no cuts)	3.605×10^{-5}	0.007×10^{-5}	$-0.19\,\%$
$\mathcal{B}(E > 10\,\text{MeV})$	2.309×10^{-6}	-0.041×10^{-6}	$-1.78\,\%$

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Conclusion and outlook

Conclusion

- New fully differential NLO predictions for the radiative decay for MEG
- New NLO predictions for the rare decay for Mu3e

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- New fully differential NLO predictions for the radiative decay for MEG
- New NLO predictions for the rare decay for Mu3e

Work to be done

- Predict / Resume large logs $\log\frac{m}{M}\log\frac{\omega_0}{M}$ @ NLO and possibly NNLO

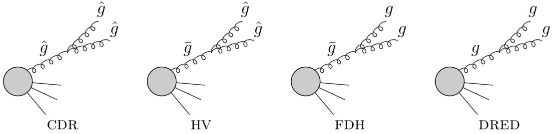
$\Rightarrow$ Solve 3.5σ discrepancy

- Produce distributions for the rare decay @ NLO

A slide from Andrea Visconti

1. Variants of dimensional regularisation:
   - CDR (”conventional dimensional regularization”)
   - HV (”’t Hooft Veltman”)
2. Variants of dimensional reduction:
   - DRED (”original/old dimensional reduction”)
   - FDH (”four-dimensional helicity scheme”)

	CDR	HV	FDH	DRED
internal gluon	$\hat{g}^{\mu\nu}$	$\hat{g}^{\mu\nu}$	$g^{\mu\nu}$	$g^{\mu\nu}$
external gluon	$\hat{g}^{\mu\nu}$	$\bar{g}^{\mu\nu}$	$\bar{g}^{\mu\nu}$	$g^{\mu\nu}$



$g = Q4D$, $\hat{g} = QD - \text{dim.}$, $\bar{g} = 4 - \text{dim.}$