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*19<sup>th</sup> International Workshop on Neutrinos from Accelerators*

# Fully differential NLO predictions for rare and radiative lepton decays

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29<sup>TH</sup> SEPTEMBER 2017

Based on 1611.03617 and 1705.03782

Introduction

The radiative decay

Rare decay

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The radiative decay

Rare decay

- Radiative ( $\mu \rightarrow e\nu\bar{\nu} + \gamma$ ) and rare ( $\mu \rightarrow \nu\bar{\nu} + e^+e^-$ ) muon decays are a background to  $\mu \rightarrow e\gamma$  and  $\mu \rightarrow ee^+e^-$  searches.
- 4-Fermi interaction, fierzed at the Lagrangian

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

- Calculate decays at NLO fully differentially
- ⇒ Arbitrary distributions with arbitrary cuts.

Introduction

The radiative decay

Rare decay

- $3.5\sigma$  discrepancy between BaBar measurement and branching ratio NLO calculation [[Fael, Mercolli, Passera 2015](#)]
- Unlikely due to large logarithms or uncomputed higher order corrections

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Proposal:

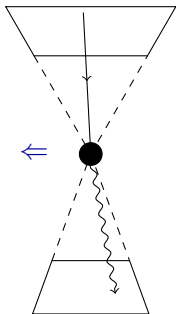
- Experimental cuts are very restrictive and unfolding of acceptance is not trivial
- Correct fiducial acceptance by simulating full cuts of boosted system

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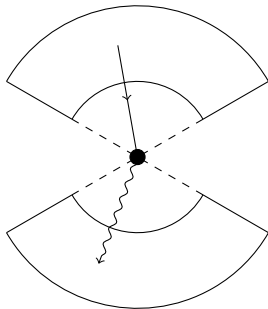
Proposal:

- Experimental cuts are very restrictive and unfolding of acceptance is not trivial
  - Correct fiducial acceptance by simulating full cuts of boosted system
  - Effect is large! Reduces discrepancy to  $1.2\sigma$
  - We **do not** claim that this is the full solution
- ⇒ Fully differential NLO corrections are very important!

Theorist's version of the MEG detector ( $B = 0$ )



$$E_\gamma > 40 \text{ MeV}$$

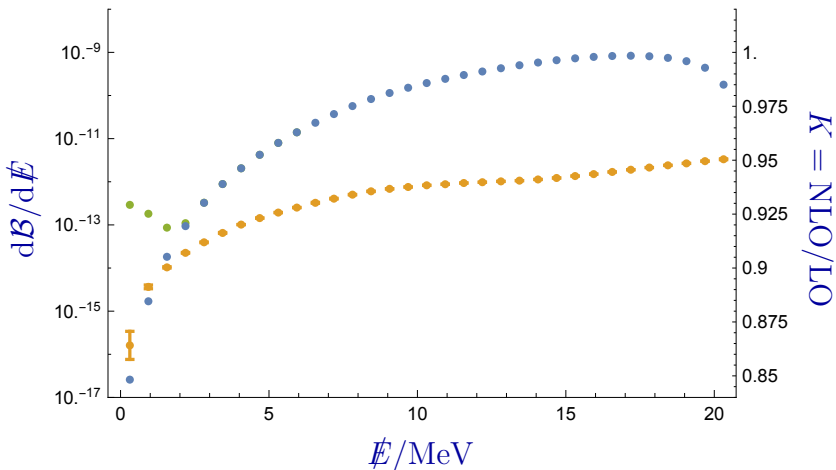


$$E_e > 45 \text{ MeV}$$

No 2<sup>nd</sup> photon  $E_{\gamma'} > 2 \text{ MeV}$  in the detector

# Invisible energy spectrum at MEG

•  $B_{NP} \simeq 4.2 \cdot 10^{-13}$



# $\pi\beta$ branching of $\mu \rightarrow e\nu\bar{\nu} + \gamma$

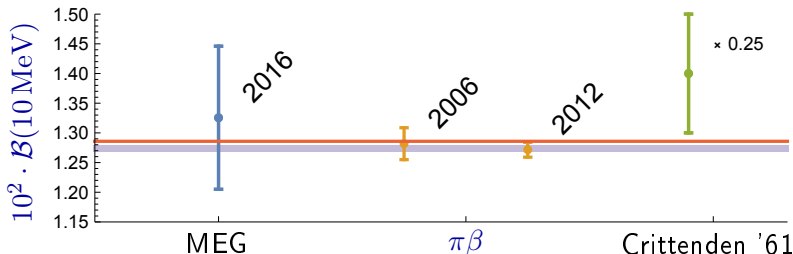
- $E_\gamma > 10 \text{ MeV}$  and  $\theta > 30^\circ$
- Our prediction  $\mathcal{B}_{\text{PSU}} = (4.26 - 0.04_{\text{NLO}}) \cdot 10^{-3}$  agrees perfectly with [Fael, Mercolli, Passera 2015]
- 2006:  $\mathcal{B}_{2006}^{\pi\beta} = 4.40(9) \cdot 10^{-3}$  (cf.  $\mathcal{B}_{\text{theo}}^{\pi\beta} = 4.3 \cdot 10^{-3}$ )
- 2012:  $\mathcal{B}_{2012}^{\pi\beta} = 4.37(4) \cdot 10^{-3}$  (cf.  $\mathcal{B}_{\text{theo}}^{\pi\beta} = 4.34 \cdot 10^{-3}$ )
- Assuming  $m_e = 0$ :  $\mathcal{B}_{\text{PSU}}^{m_e=0} = (4.35_{\text{LO}} + 0.06_{\text{NLO}}) \cdot 10^{-3}$

# Global comparison: $\mathcal{B}(10 \text{ MeV})$

- Relate all data using NLO Monte Carlo to  $E_\gamma > 10 \text{ MeV}$
- Compute kinematic acceptance  $\epsilon$

$$\mathcal{B}(10 \text{ MeV}) = \underbrace{\frac{\mathcal{B}_{\text{PSU}}(10 \text{ MeV})}{\mathcal{B}_{\text{PSU}}(\text{exp. cuts})}}_{\epsilon} \mathcal{B}_{\text{exp}}(\text{exp. cuts})$$

- $\epsilon_{\text{MEG}} \approx 2 \cdot 10^5$ ,  $\epsilon_{\pi\beta} \approx 3$
- Combined experimental  $\bar{\mathcal{B}}(10 \text{ MeV}) = 1.27(1) \cdot 10^{-2}$  ( $1\sigma$  above theory)

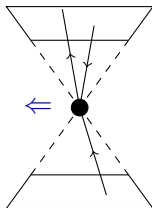


Introduction

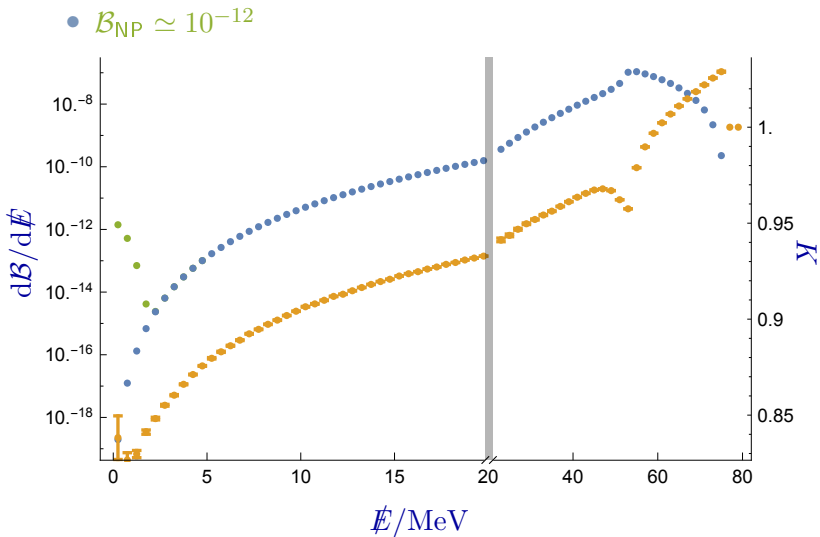
The radiative decay

Rare decay

- $4_{\text{Born}} + 40_{1\text{-loop}} + 20_{\text{real}}$  diagrams up to pentagons
- Good parametrisation of phase space very important
- Approximate Mu3e cuts  
 $E_{e^\pm} > 10 \text{ MeV}$ ,  
 $|\cos \angle(\vec{p}_{e^\pm}, \vec{e}_z)| < 0.8$



# Invisible energy spectrum at Mu3e



# BSM potential in $\mu \rightarrow e\nu\bar{\nu} + e^+e^-$

- **Very** preliminary!

$$\mathcal{A}(\mu \rightarrow e\nu\bar{\nu} + e^+e^-) = \left| \begin{array}{c} \gamma \\ \mu^+ \rightarrow \nu_e \bar{\nu}_\mu + e^+e^- \end{array} + \begin{array}{c} X \\ \mu^+ \rightarrow \nu_e \bar{\nu}_\mu + e^+e^- \end{array} \right|^2$$

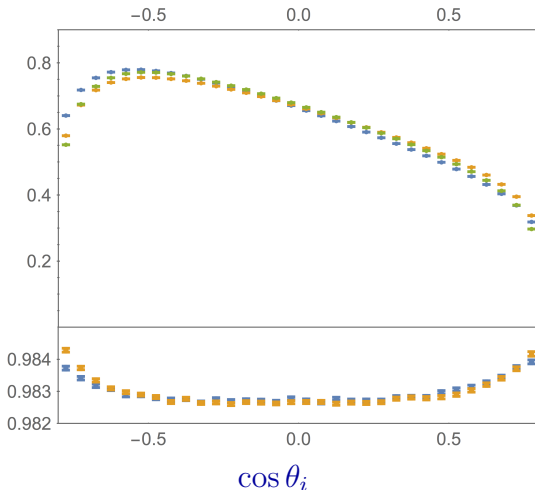
⇒ Looking for light new mediators

- Can New Physics be extracted from precise measurement of shapes in rare muon decay?
- NNLO uncertainties are likely to be very small.

# BSM potential in $\mu \rightarrow e\nu\bar{\nu} + e^+e^-$

- Distributions for the hard  $e^+$ , soft  $e^+$  and  $e^-$
- $K \approx 0.98 \Rightarrow$  shape very precise (small NNLO)

$d \log \mathcal{B} / d \cos \theta_i$



- Fully differential NLO prediction are available for both  $\ell \rightarrow l\nu\bar{\nu} + \gamma$  and  $\ell \rightarrow l\nu\bar{\nu} + l^+l^-$
- Radiative corrections can be extremely important when unfolding fiducial acceptance to 'PDG values'
- There is some confusion ( $\pi\beta$ , BaBar, treatment of 2<sup>nd</sup> photon)
- MEG & Mu3e: Corrections are negative, normally small (percent level) but can reach  $\mathcal{O}(10\%)$

## Rare & radiative lepton decays @ NLO

- Fully differential NLO prediction are available for both  $\ell \rightarrow l\nu\bar{\nu} + \gamma$  and  $\ell \rightarrow l\nu\bar{\nu} + l^+l^-$
- Arbitrary cuts and arbitrary distributions are possible
- Radiative corrections can be extremely important when unfolding fiducial acceptance to 'PDG values' (cf.  $3.5\sigma$  deviation in  $\tau \rightarrow e\nu\bar{\nu} + \gamma$  @ BaBar)
- MEG & Mu3e: Corrections are negative, normally small (percent level) but can get larger  $\mathcal{O}(10\%)$

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