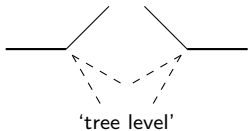

LTP seminar

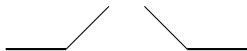
Higher order corrections for muons

Yannick Ulrich

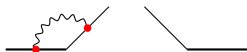
Paul Scherrer Institut / Universität Zürich

20TH MAY 2019

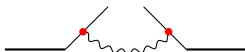
 α^0
(LO)



'tree level'

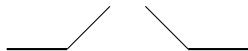
 α^0
(LO)

'virtual one-loop'

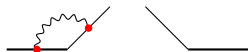


'real correction'

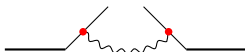
 α^1
(NLO)



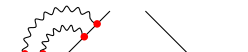
'tree level'

 α^0
(LO)

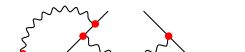
'virtual one-loop'



'real correction'

 α^1
(NLO)

'virtual two-loop'



'real-virtual'



'double real'

 α^2
(NNLO)

- MEG, Mu3e, MUonE, MUSE etc. need to understand relevant (background) SM processes **very precisely**
- **naive** estimate: for each order, $\alpha \sim 1/137$.

- MEG, Mu3e, MUonE, MUSE etc. need to understand relevant (background) SM processes **very precisely**
- **naive** estimate: for each order, $\alpha \sim 1/137$.
- more realistic estimate: for each order, $\alpha \log^i \frac{m_e^2}{m_\mu^2} \sim 1/12$

- MEG, Mu3e, MUonE, MUSE etc. need to understand relevant (background) SM processes **very precisely**
 - **naive** estimate: for each order, $\alpha \sim 1/137$.
 - more realistic estimate: for each order, $\alpha \log^i \frac{m_e^2}{m_\mu^2} \sim 1/12$
- ⇒ minimal requirement:
- NLO for $\mu \rightarrow e\nu\bar{\nu}\gamma$, $\mu \rightarrow e\nu\bar{\nu}ee$ (PiBeta, MEG, Mu3e)
 - NNLO for $\mu \rightarrow e\nu\bar{\nu}$ (TWIST, MEG_J)
 - at the very least NNLO for $\mu e \rightarrow \mu e$ and $\mu p \rightarrow \mu p$ (MUonE, MUSE)

$$\mu \rightarrow e\nu\bar{\nu} + \gamma$$

and

$$\mu \rightarrow e\nu\bar{\nu} + e^+e^-$$

[Pruna, Signer, YU 16, Pruna, Signer, YU 17, YU 17]

$E_\gamma > 10 \text{ MeV}$ 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]

$E_\gamma > 10 \text{ MeV}$ 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. $\mathcal{B}_{\text{theo}}^{\pi\beta} = 4.3 \cdot 10^{-3}$)

$E_\gamma > 10 \text{ MeV}$ 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. $\mathcal{B}_{\text{theo}}^{\pi\beta} = 4.34 \cdot 10^{-3}$)

$E_\gamma > 10 \text{ MeV}$ 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 $m_e = 0$: $\mathcal{B}_{\text{PSU}}^{m_e=0} = (4.35_{\text{LO}} + 0.06_{\text{NLO}}) \cdot 10^{-3}$
- $3.7\sigma \rightarrow \sim 1\sigma$

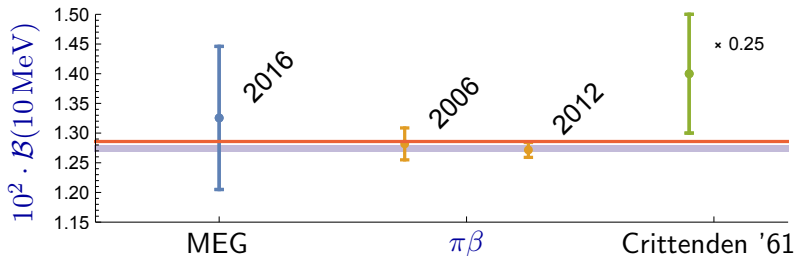
\Rightarrow details matter!!

Relate all data using NLO Monte Carlo to $E_\gamma > 10 \text{ MeV}$

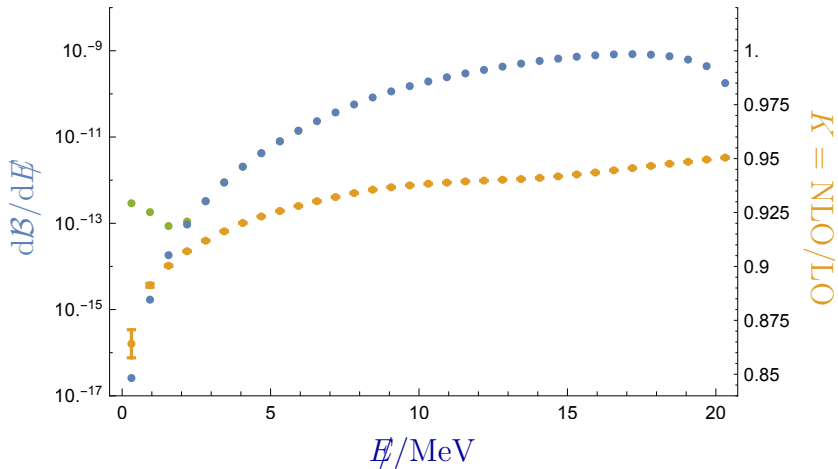
- Compute kinematic acceptance ϵ

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

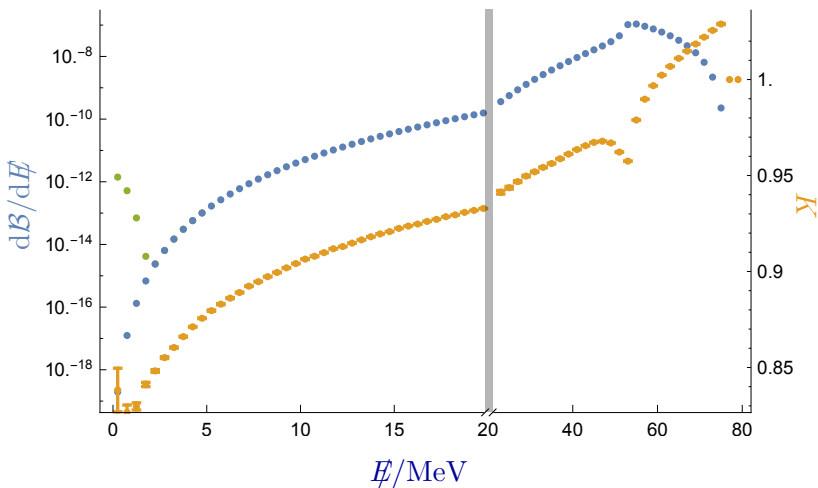
- $\epsilon_{\text{MEG}} \approx 2 \cdot 10^5$, $\epsilon_{\pi\beta} \approx 3$
- combined experimental $\bar{\mathcal{B}}(10 \text{ MeV}) = 1.27(1) \cdot 10^{-2}$



exactly one photon $E_\gamma > 40\text{MeV}$ in the detector. $\mathcal{B}_{\text{NP}} \simeq 4.2 \cdot 10^{-13}$



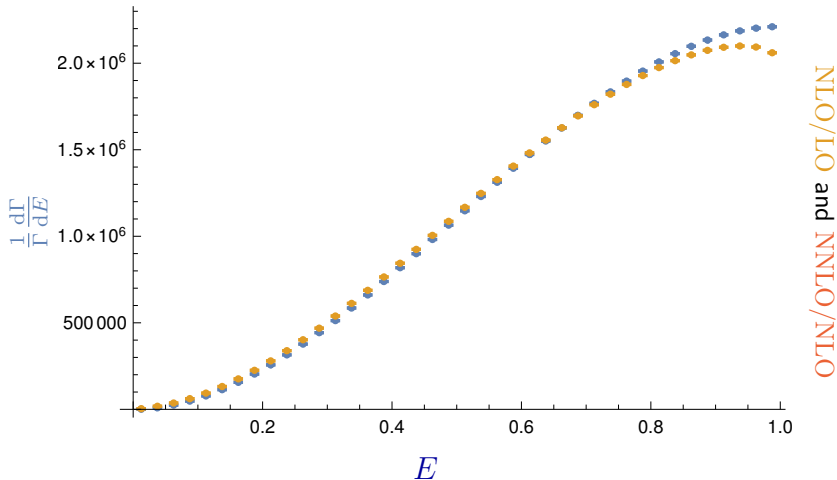
assuming $E > 10\text{MeV}$ and geometry cuts. $\mathcal{B}_{\mu \rightarrow 3e} \simeq 10^{-12}$



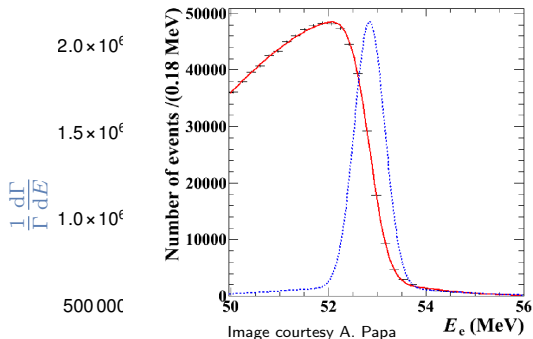
$$\mu \rightarrow e \nu \bar{\nu}$$

[Engel, Gnendiger, Signer, YU 18, Banerjee, Engel, Signer, YU soon]

Majoron with $m_J \sim 0$, $\mathcal{B}_{\mu \rightarrow e J} \sim 2 \times 10^{-3}$



Majoron with $m_J \sim 0$, $\mathcal{B}_{\mu \rightarrow e J} \sim 2 \times 10^{-3}$

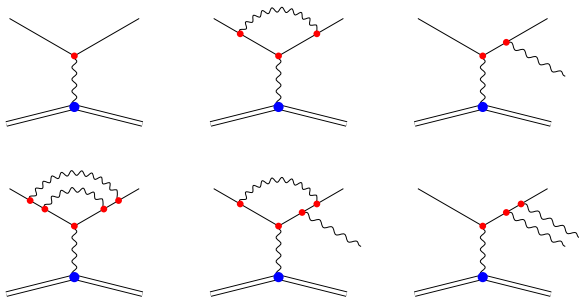


$$\mu e \rightarrow \mu e$$

and

$$\mu p \rightarrow \mu p$$

- leptonic NNLO done [Bucoveanu, Spiesberger 18]
- second calculation using new methods in progress [Banerjee, Engel, Signer, YU soon-ish]
- hadronic correction \Rightarrow someone else's problem



- recent proposal to measure a_μ^{HLO} with μe scattering
- LTP Colloquium Graziano Venanzoni
28th March
- requires theoretical uncertainties below $10^{-5} \Rightarrow$ at least NNLO (electronic contribution almost done)
- $\mathcal{O}(\alpha^3 \log^3 \frac{m_e^2}{m_\mu^2}) \gg 10^{-5}$
- NNLO not enough \Rightarrow resummation and exploratory N³LO studies



details matter!

- $\mu \rightarrow e\nu\bar{\nu}\gamma$ and $\mu \rightarrow e\nu\bar{\nu}ee$ at NLO
- input into PiBeta reanalysis \Rightarrow current best value
- $\mu \rightarrow e\nu\bar{\nu}$ at NNLO: large corrections at the endpoints
- $\mu e \rightarrow \mu e$ and $\mu p \rightarrow \mu p$ at NNLO: ongoing