MUonE: Theory Status

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INFN Padova

Flavour Changing and Conservation Process
23rd September, 2022

Fellini
Fellowship for Innovation at INFN
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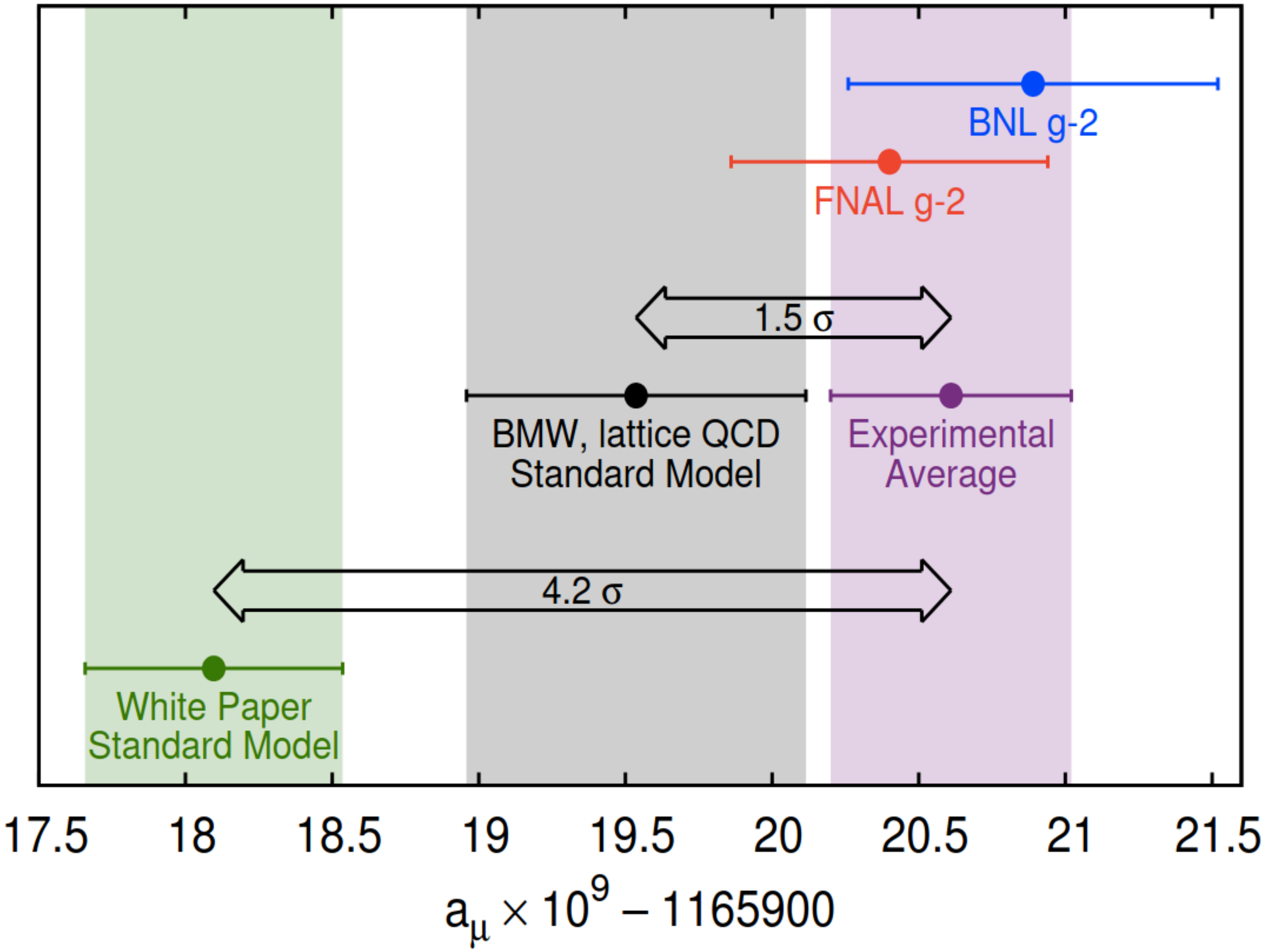
G.A. 754496

Istituto Nazionale di Fisica Nucleare

Motivation

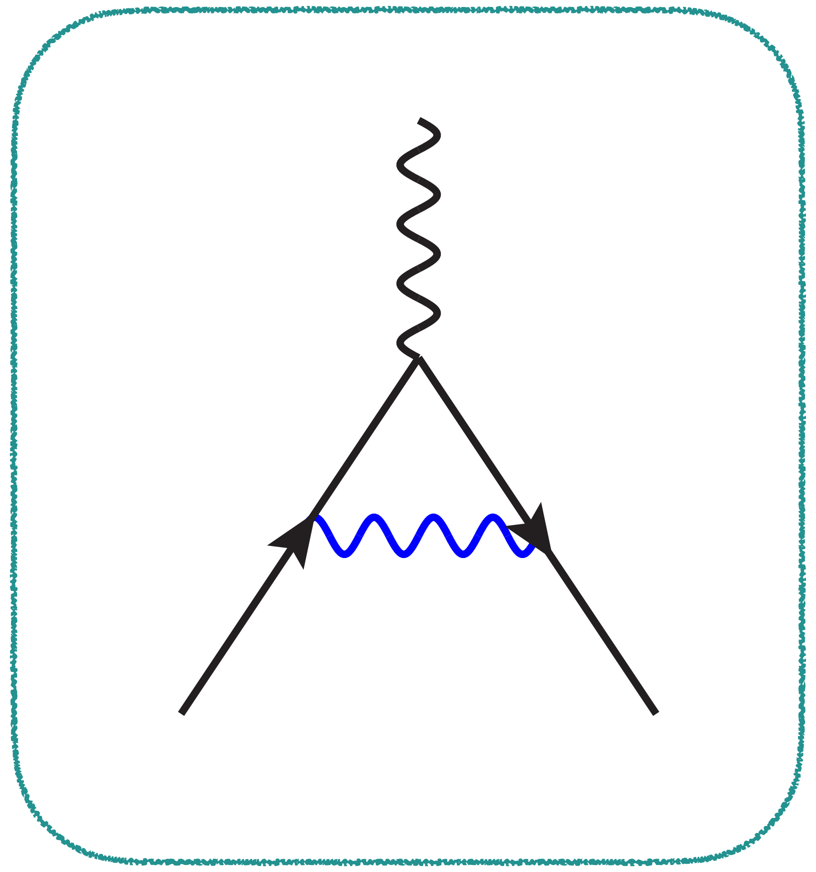


$a_\mu^{EXP} = (116592089 \pm 63) \times 10^{-11}$ [0.54ppm] BNL E821

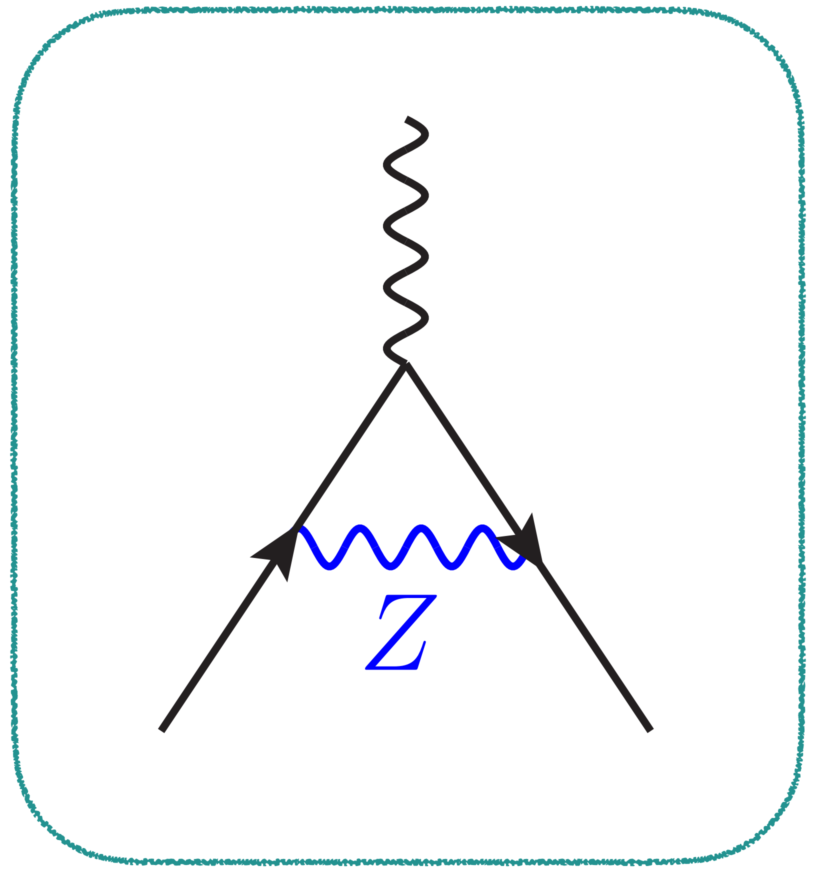
$a_\mu^{EXP} = (116592040 \pm 54) \times 10^{-11}$ [0.46ppm] FNAL E989 Run 1

$a_\mu^{EXP} = (116592061 \pm 41) \times 10^{-11}$ [0.35ppm] WA

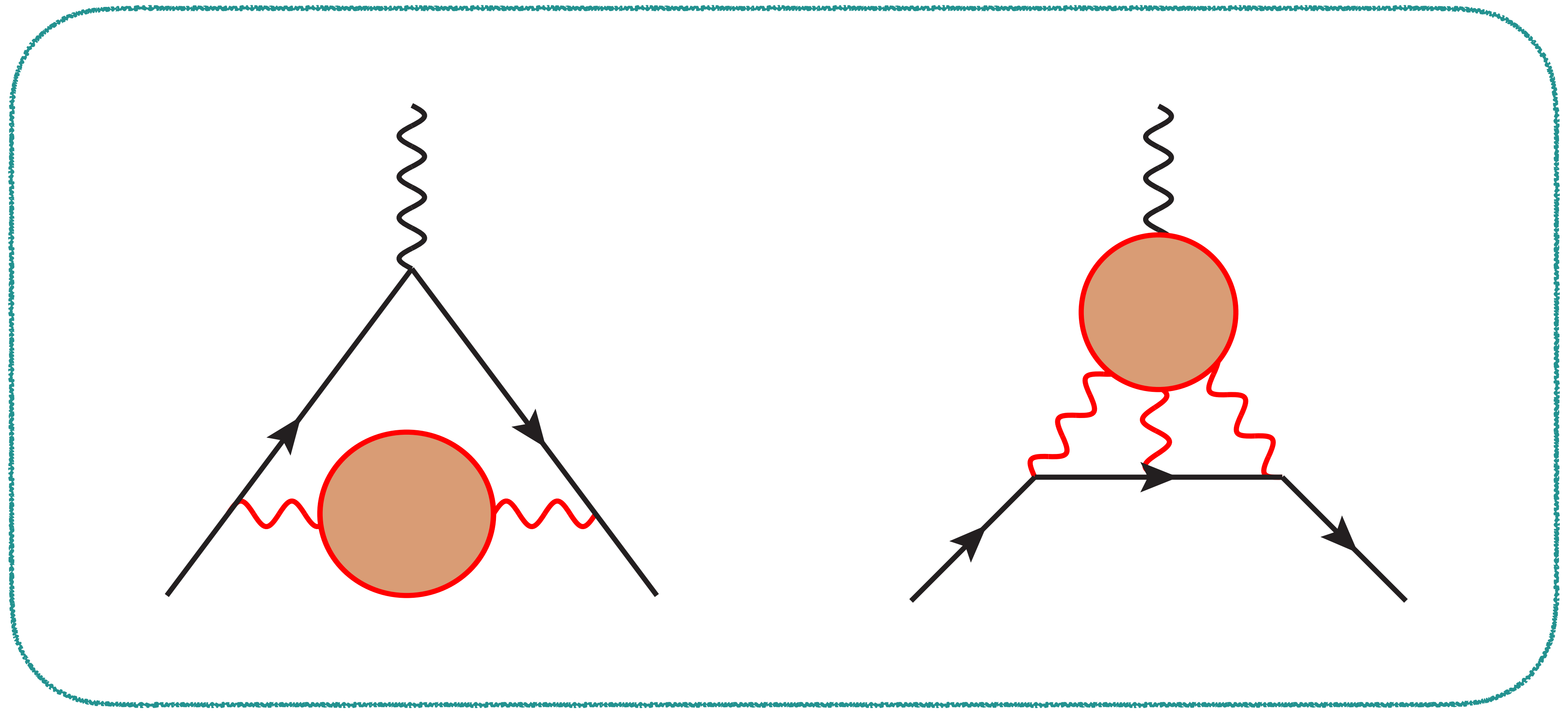
Anomalous Magnetic Moment of Muon



$$a_\mu^{\mathrm{QED}}$$



$$a_\mu^{\mathrm{EW}}$$



$$a_\mu^{\mathrm{had}}$$

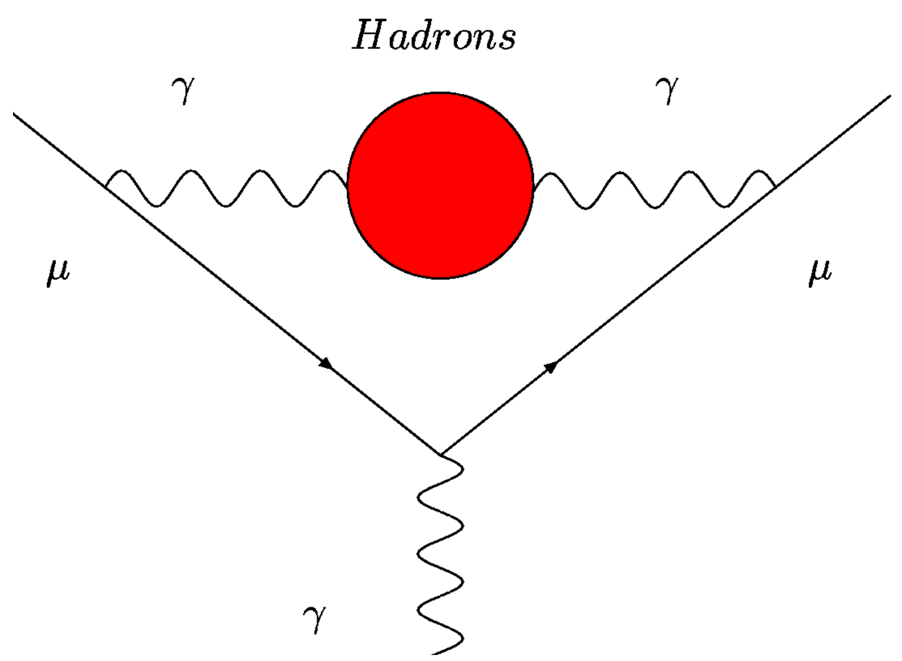
$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{had}}$$

$$a_\mu^{\mathrm{had}} = a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLbL}}$$

$$\boxed{a_\mu^{\mathrm{SM}} = 116591810(43) \times 10^{-11}}$$

Motivation

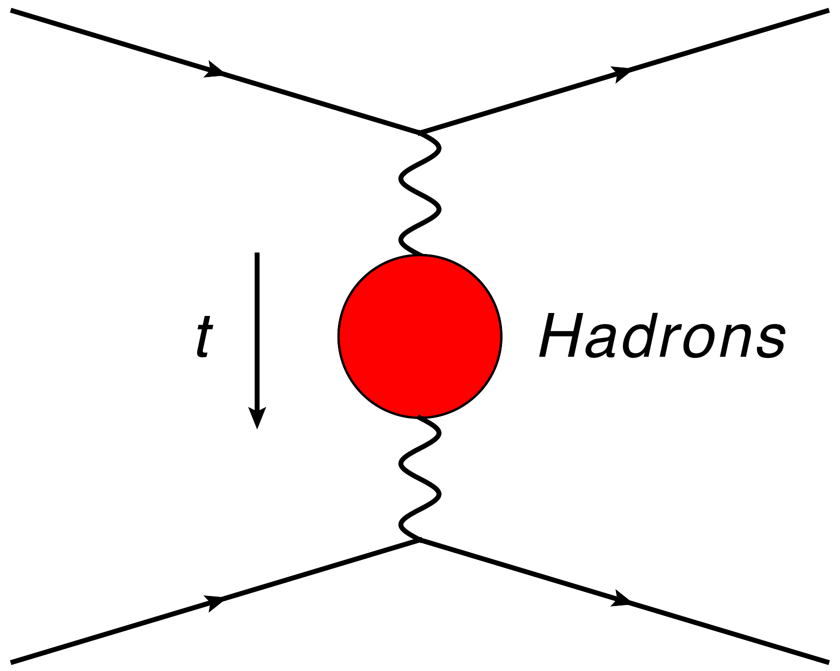
- **Leading hadronic contribution computed via the usual dispersive (timelike) formula:**



$$a_\mu^{\mathrm{HLO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{\mathrm{had}}^{(0)}(s)$$

$$K(s) = \int_0^1 dx\, \frac{x^2\,(1-x)}{x^2 + (1-x)\,(s/m_\mu^2)}$$

- **Alternatively, simply exchanging the x and s integrations:**



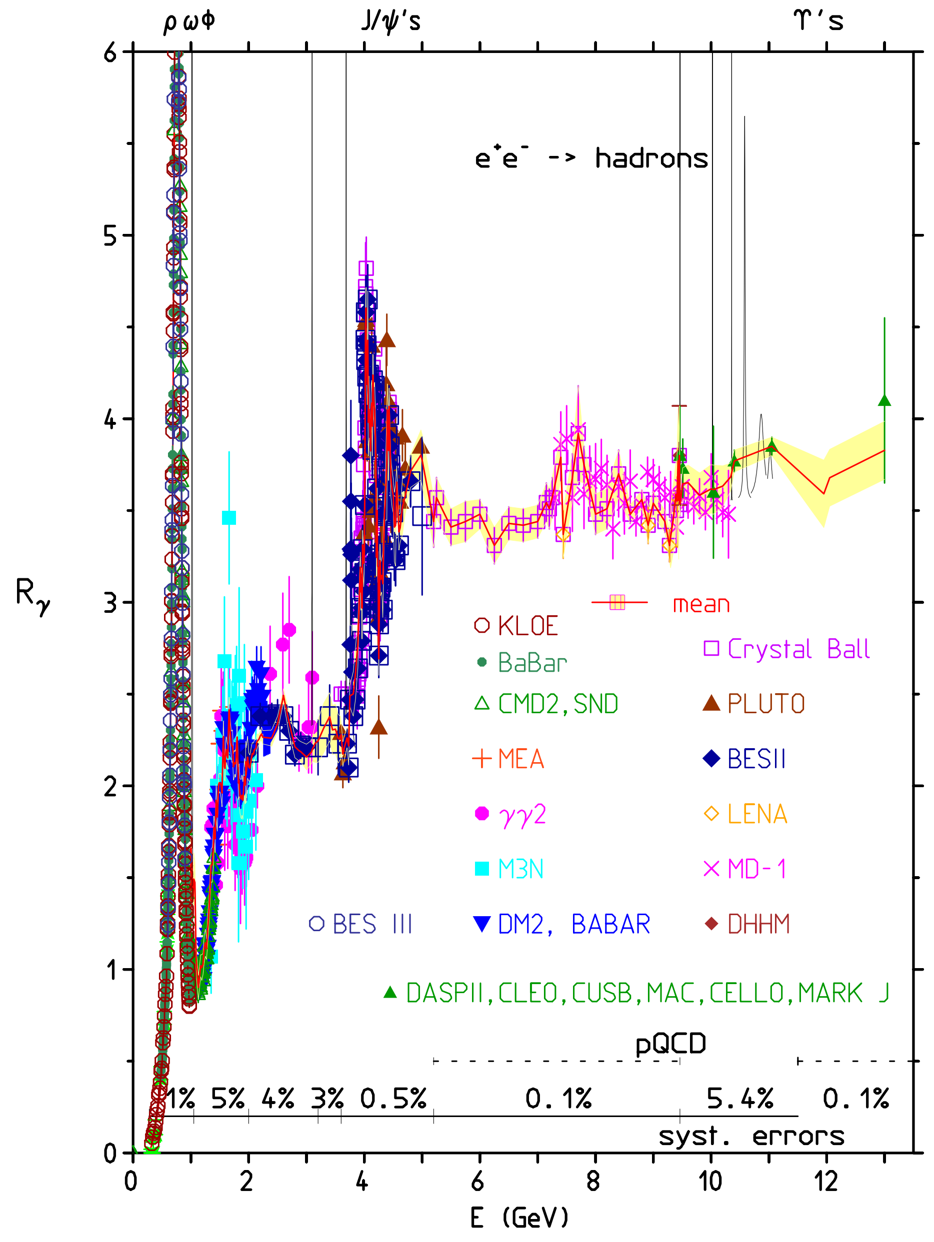
$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

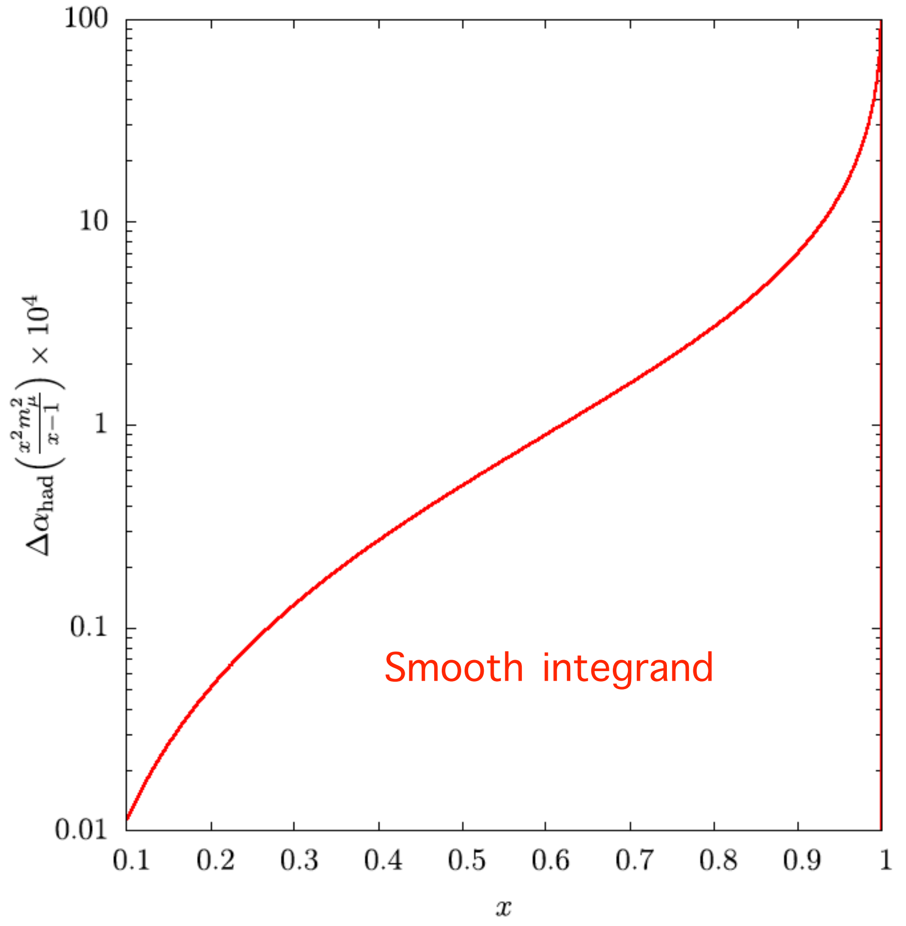
$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

Lautrup, Peterman, de Rafael, 1972

$\Delta\alpha_{\mathrm{had}}(t)$ is the hadronic contribution to the space-like running of α: proposal to measure a_μ^{HLO} via scattering data!

Carloni Calame, MP, Trentadue, Venanzoni, 2015





- ☑ **Smooth integrand**
- ☑ **Inclusive measurement**
- ☑ **Direct interplay with lattice QCD**

MUonE Experiment

MUonE Experiment

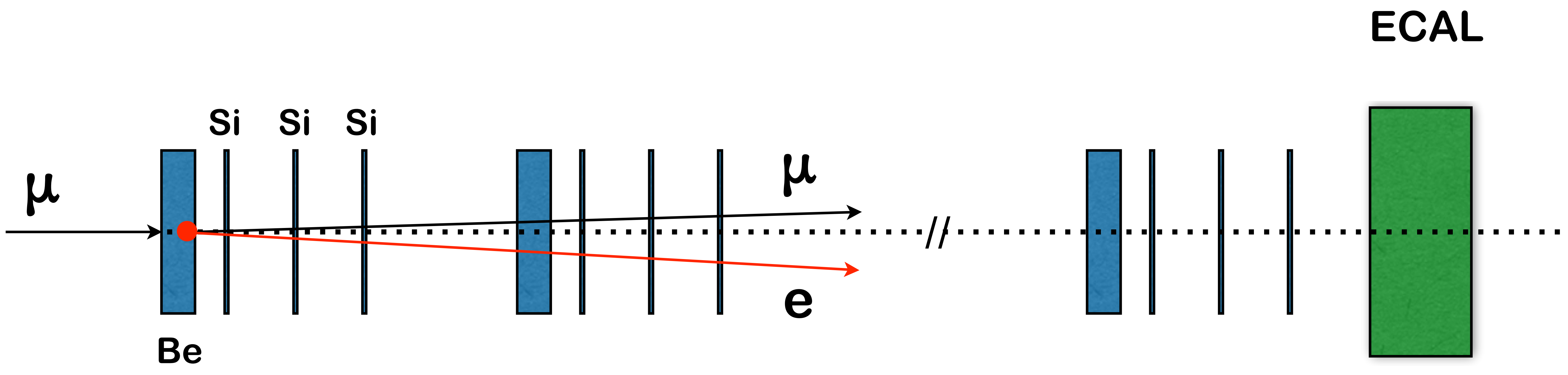
Eur. Phys. J. C (2017) 77:139
DOI 10.1140/epjc/s10052-017-4633-z

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

G. Abbiendi[1,a], C. M. Carloni Calame[2,b], U. Marconi[3,c], C. Matteuzzi[4,d], G. Montagna[2,5,e], O. Nicrosini[2,
M. Passera[6,g], F. Piccinini[2,h], R. Tenchini[7,i], L. Trentadue[8,4,j], G. Venanzoni[9,k]



- Scattering of a 160 GeV muon beam (available at CERN's North Area) on a fixed electron target (Beryllium).

- Modular apparatus: each station has one layer of Beryllium (target) followed by three thin Silicon strip detectors.

- $\Delta\alpha_{\rm had}(t)$ Can be measured via the elastic scattering

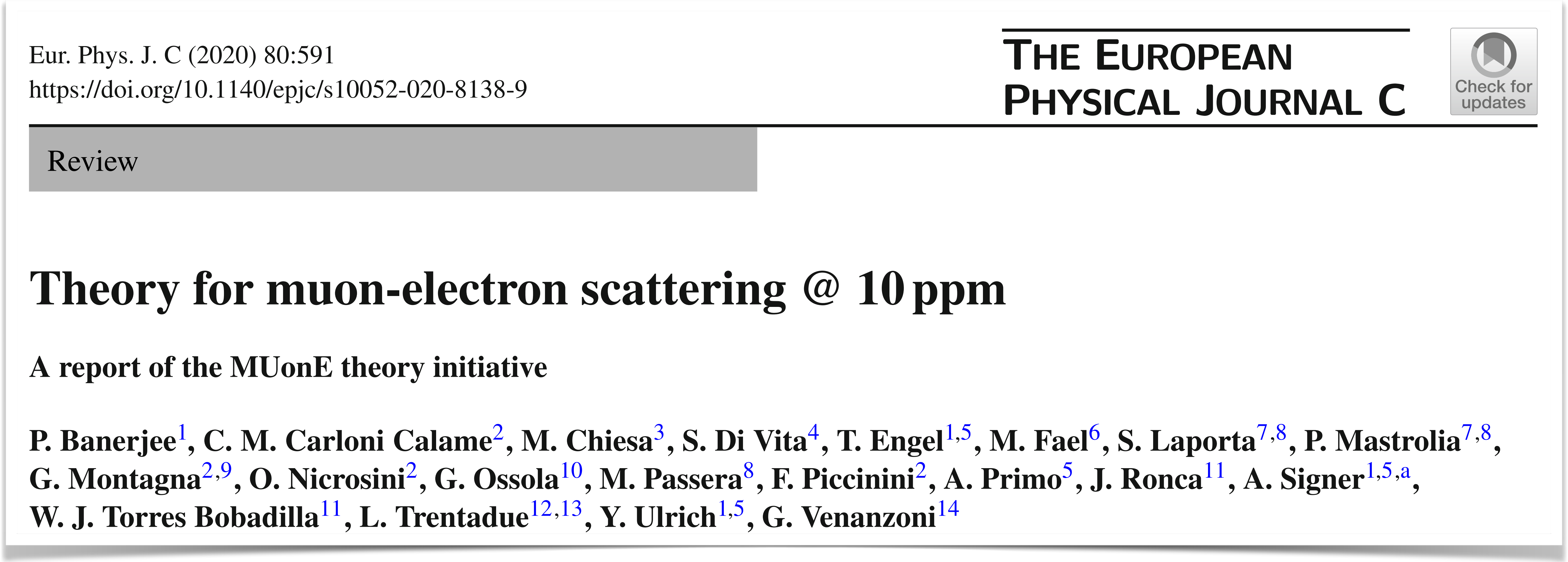
Muon-Electron Scattering at 10 PPM

[Banerjee, Engel, Signer, Ulrich (2020)]

[Banerjee, Engel, Schalch, Signer, Ulrich (2021)]

[Budassi, Carloni Calame, Chiesa, Del Pio, Hasan, Montagna, Nicrosini, Piccinini (2021)]

[Carloni Calame, Chiesa, Hasan, Montagna, Nicrosini, Piccinini (2020)]


Eur. Phys. J. C (2020) 80:591
https://doi.org/10.1140/epjc/s10052-020-8138-9
THE EUROPEAN PHYSICAL JOURNAL C
Check for updates

Review

Theory for muon-electron scattering @ 10 ppm

A report of the MUonE theory initiative

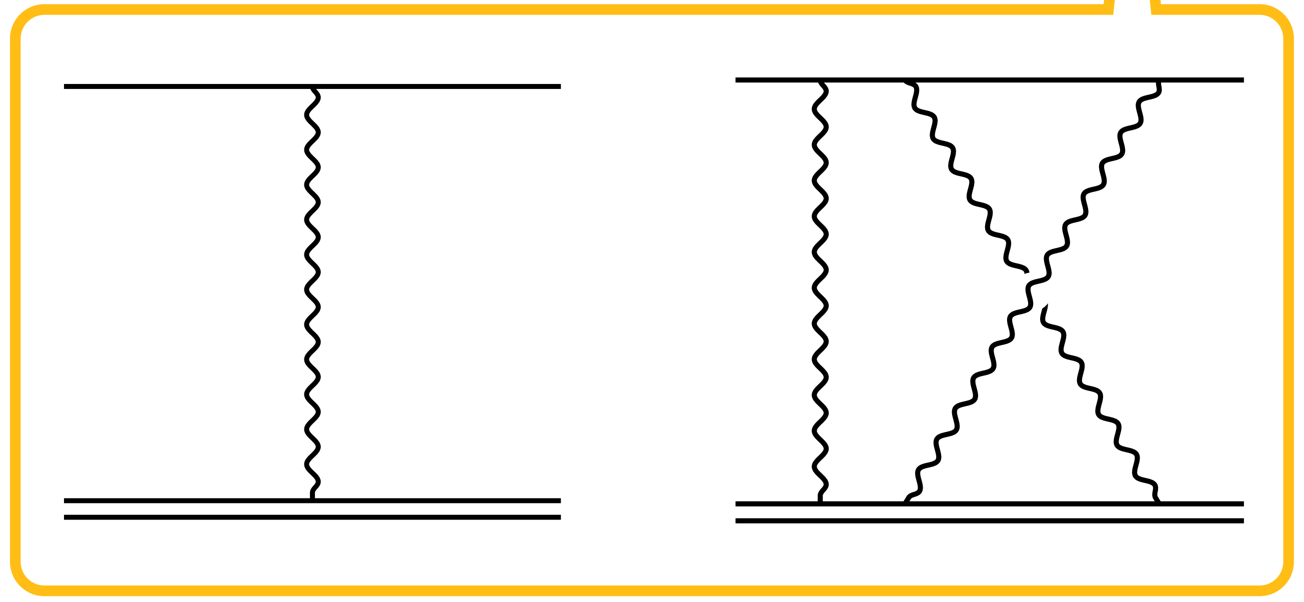
P. Banerjee[1], C. M. Carloni Calame[2], M. Chiesa[3], S. Di Vita[4], T. Engel[1,5], M. Fael[6], S. Laporta[7,8], P. Mastrolia[7,8], G. Montagna[2,9], O. Nicrosini[2], G. Ossola[10], M. Passera[8], F. Piccinini[2], A. Primo[5], J. Ronca[11], A. Signer[1,5,a], W. J. Torres Bobadilla[11], L. Trentadue[12,13], Y. Ulrich[1,5], G. Venanzoni[14]

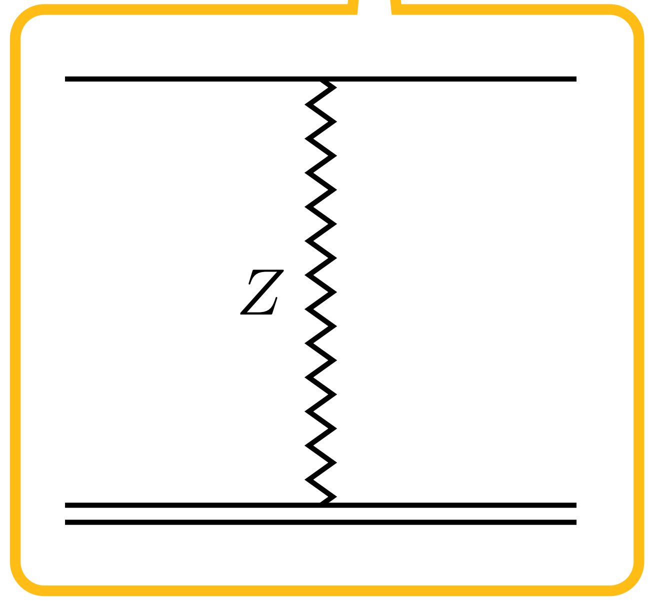
[Masiero, Paradisi, Passera (2020)]

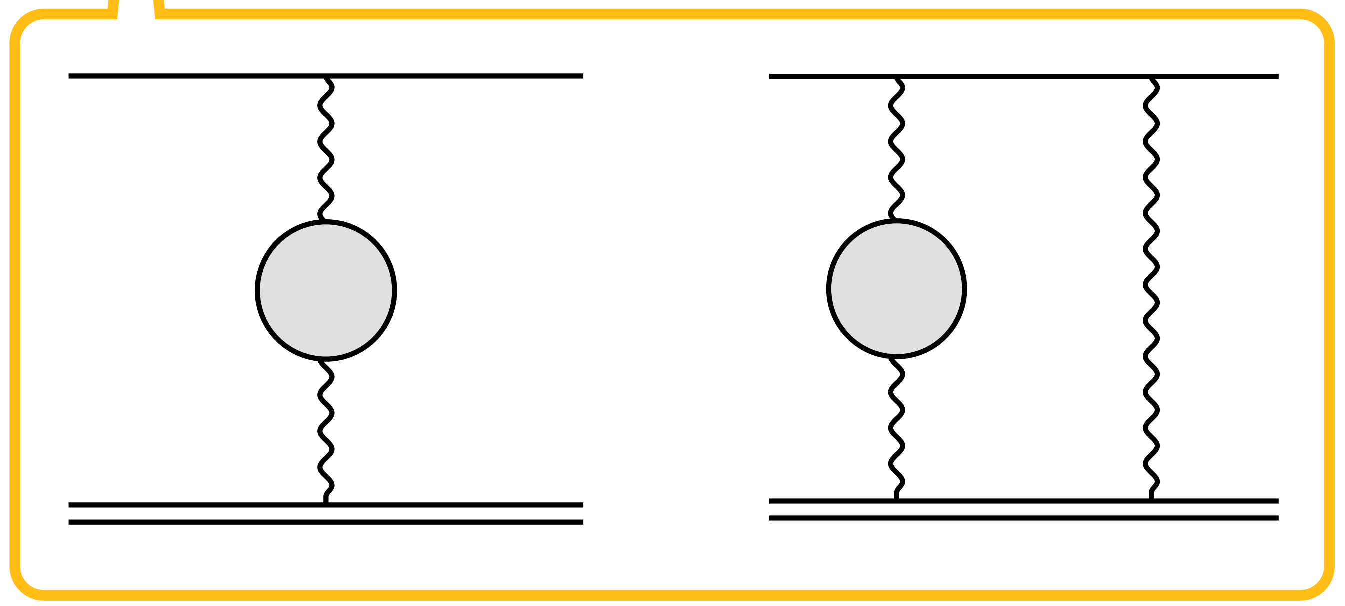
[Dev, Rodejohann, Xu, Zhang (2020)]

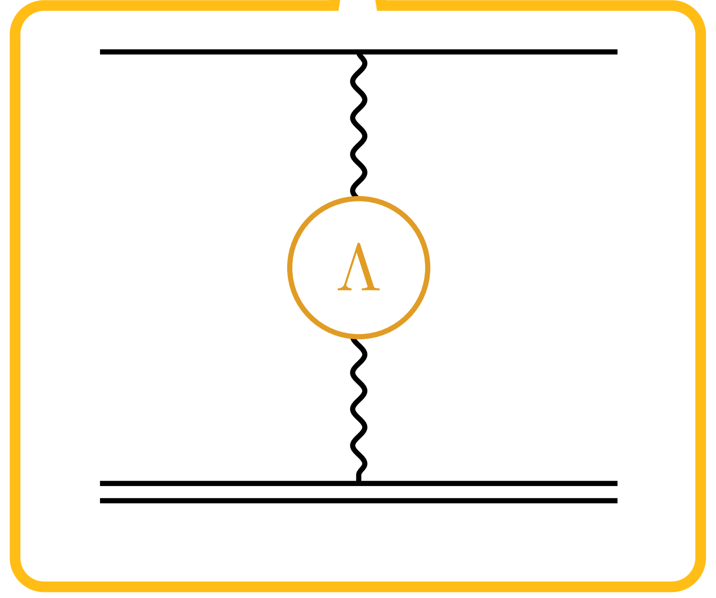
$$\sigma = \sigma_{\text{QED}} + \sigma_{\text{EW}} + \sigma_{\text{had}}$$

New Physics Effect

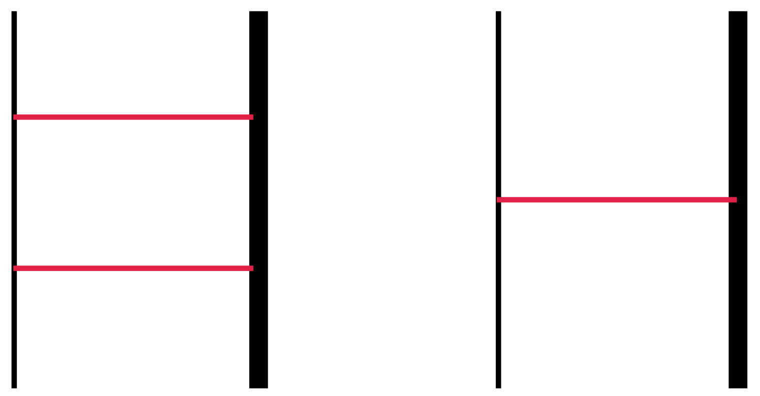


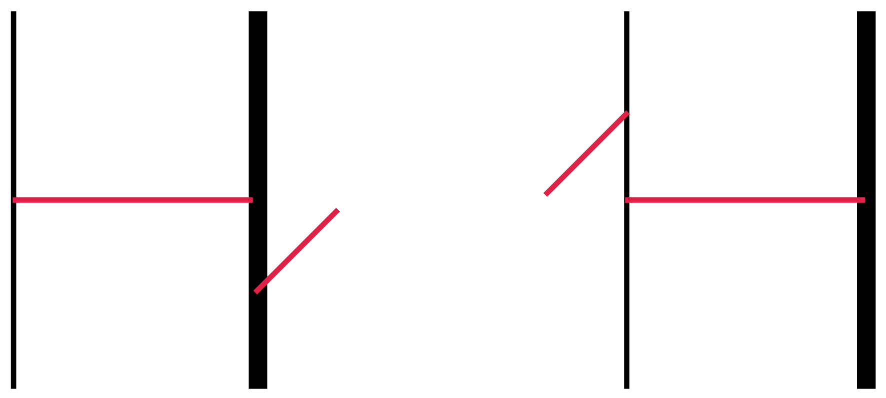






Muon-Electron Scattering at NLO





✦ Full set of QED NLO corrections computed and checked

✦ Fully differential fixed-order MC @ NLO ready

Muon Electron Scattering with Multiple Electromagnetic Radiation (MESMER)

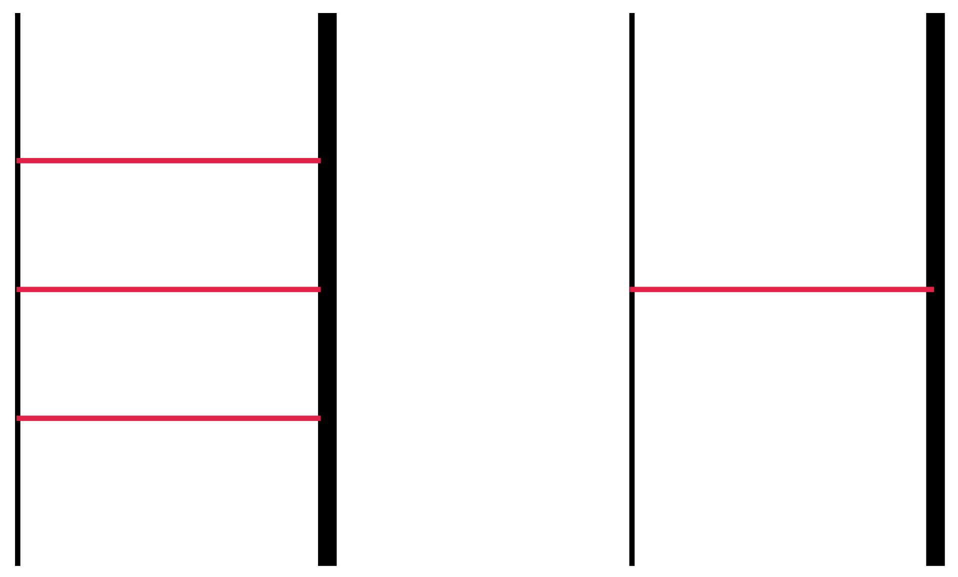
github.com/cm-cc/mesmer

✦ EW NLO corrections known but not required at 10ppm level

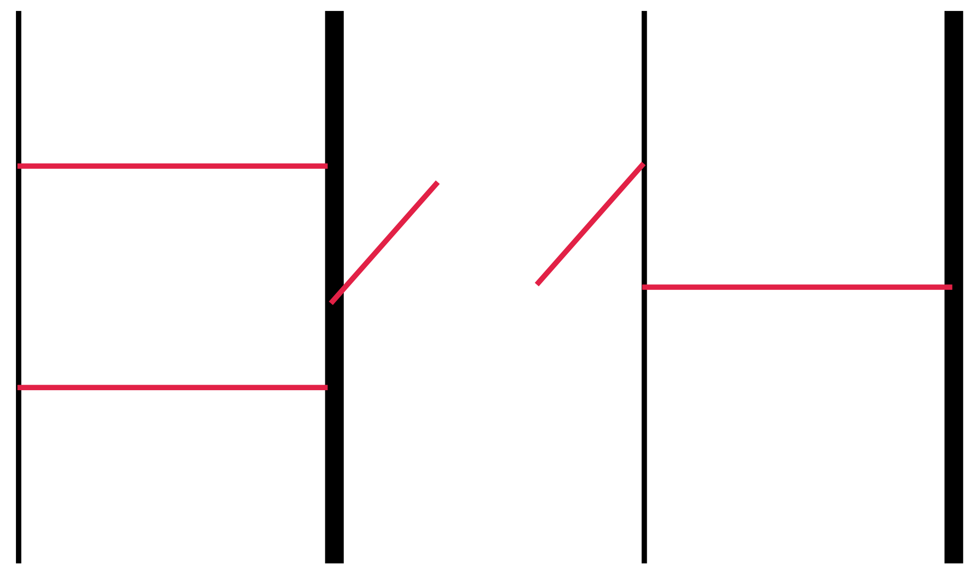
$$\frac{\sigma_{\rm EW}}{\sigma_{\rm QED}} \sim \left(\frac{s}{M_Z^2}\right)^2 \sim 10^{-5}$$

[Alacevich, Carloni Calame, Chiesa, Montagna, Nicrosini, Piccinini (2019)]

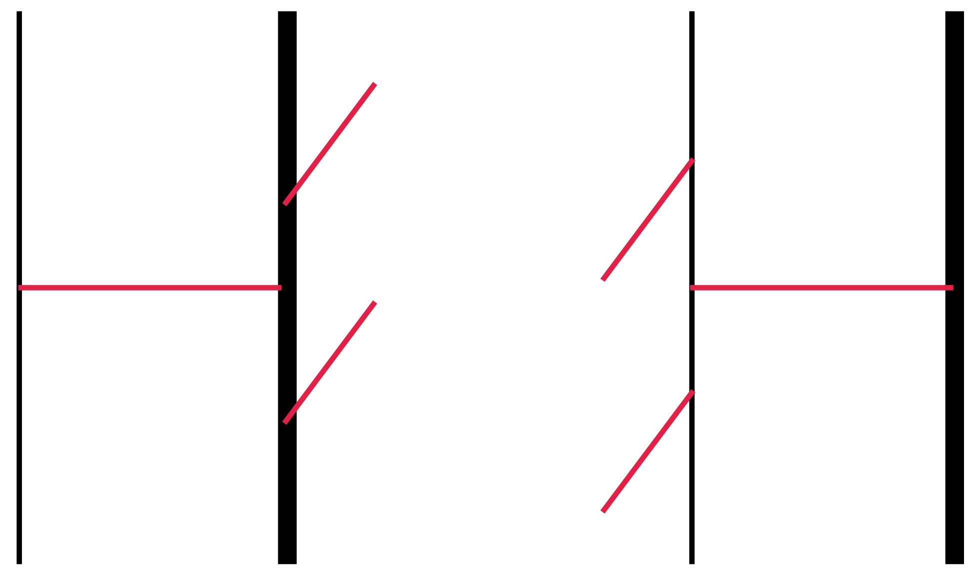
Muon-Electron Scattering [NNLO]



Double Virtual



Real Virtual



Double Real

$$\int \left[\frac{VV_4}{\epsilon^4} + \frac{VV_3}{\epsilon^3} + \frac{VV_2}{\epsilon^2} + \frac{VV_1}{\epsilon^1} + VV_0 \right] d\phi_2$$

$$\int \left[\frac{RV_2}{\epsilon^2} + \frac{RV_1}{\epsilon^1} + RV_0 \right] d\phi_3$$

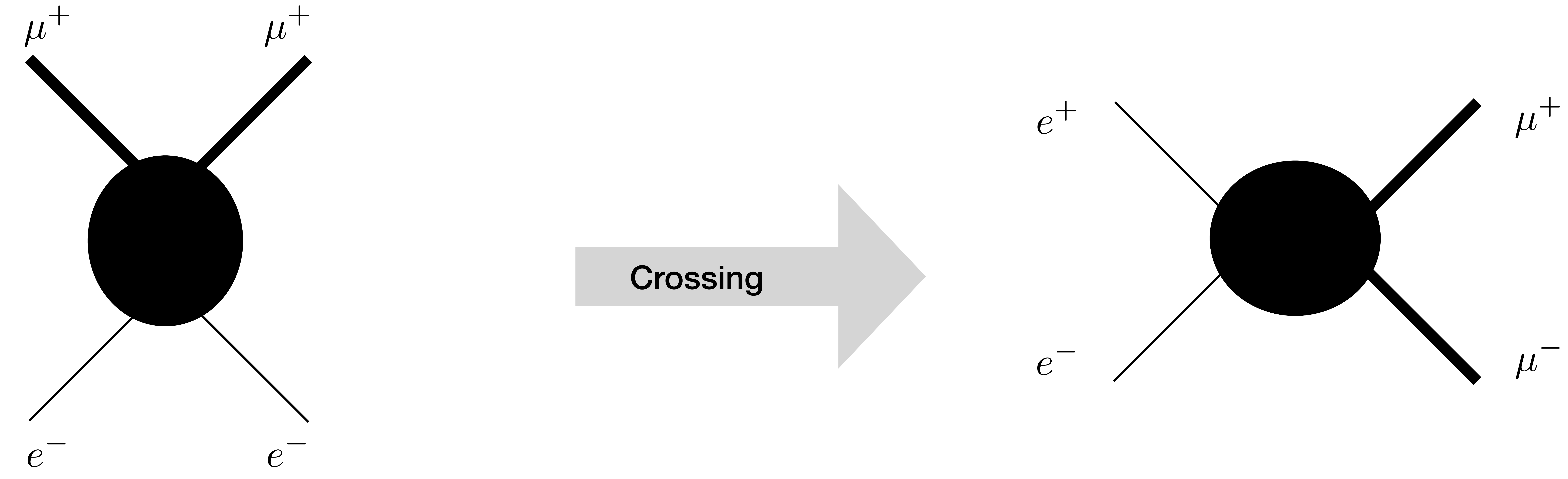
$$\int \left[RR_0 \right] d\phi_4$$

Double Virtual

Di-Muon Production

The two-loop four-fermion scattering amplitude in QED

R. Bonciani,[1,*] A. Broggio,[2,†] S. Di Vita,[3,4] A. Ferroglia,[5,6,‡] M. K. Mandal,[7,8,§] P. Mastrolia,[8,7,¶] L. Mattiazzi,[7,8,‖] A. Primo,[9,**] J. Ronca,[10,††] U. Schubert,[11,‡‡] W. J. Torres Bobadilla,[12,§§] and F. Tramontano[10,¶¶]



$e^- + \mu^+ \to e^- + \mu^+$

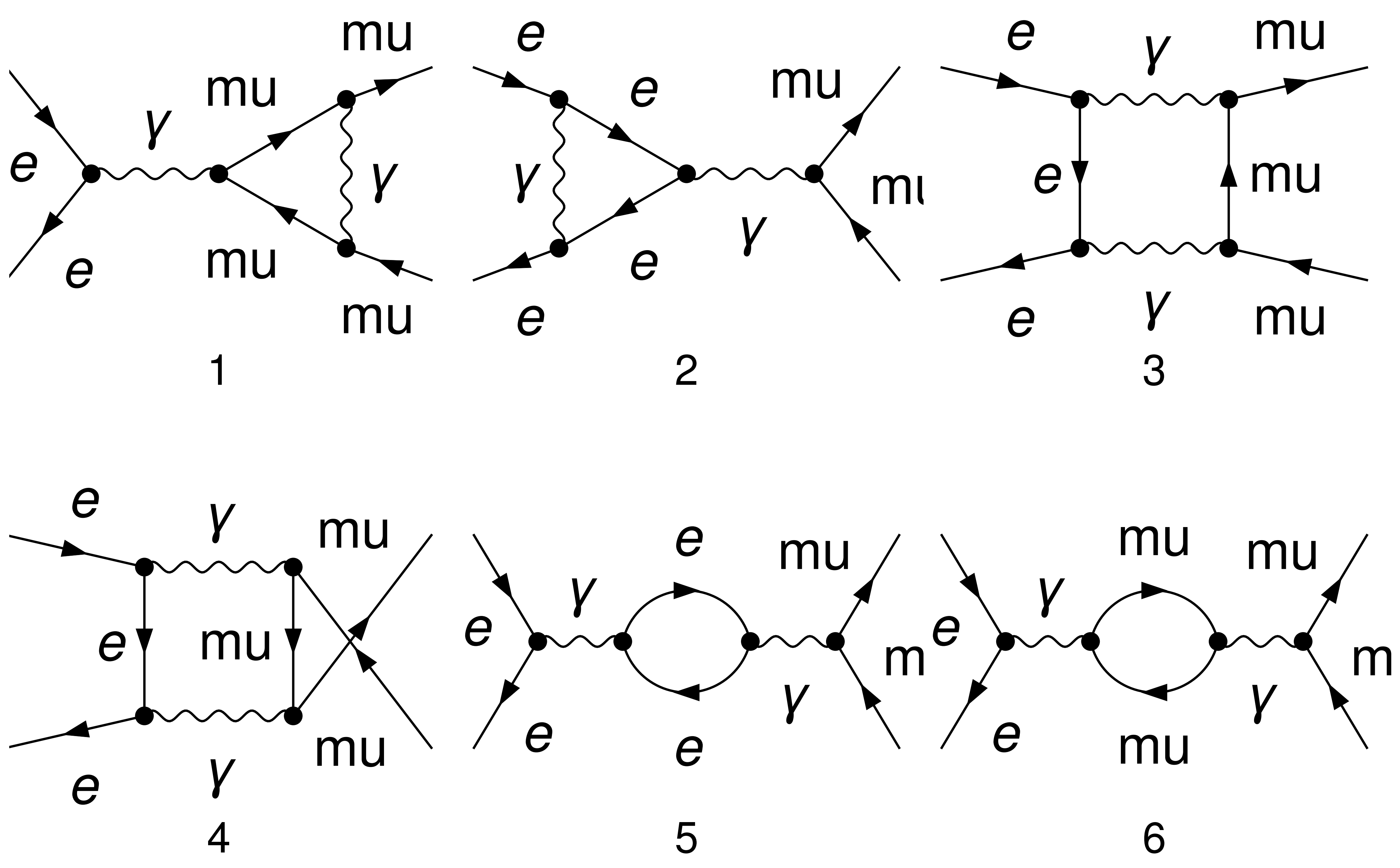
$e^- + e^+ \to \mu^- + \mu^+$

1-Loop Diagrams

[Bonciani, Broggio, Di Vita, Ferroglia, MKM, Mastrolia, Mattiazzi, Primo, Ronca, Schubert, Torres Bobadilla, Tramontano (2021)]

6 Diagrams

$$\mathcal{M}^{(1)} = A^{(1)} + n_l\, B_l^{(1)} + n_h\, C_h^{(1)}$$



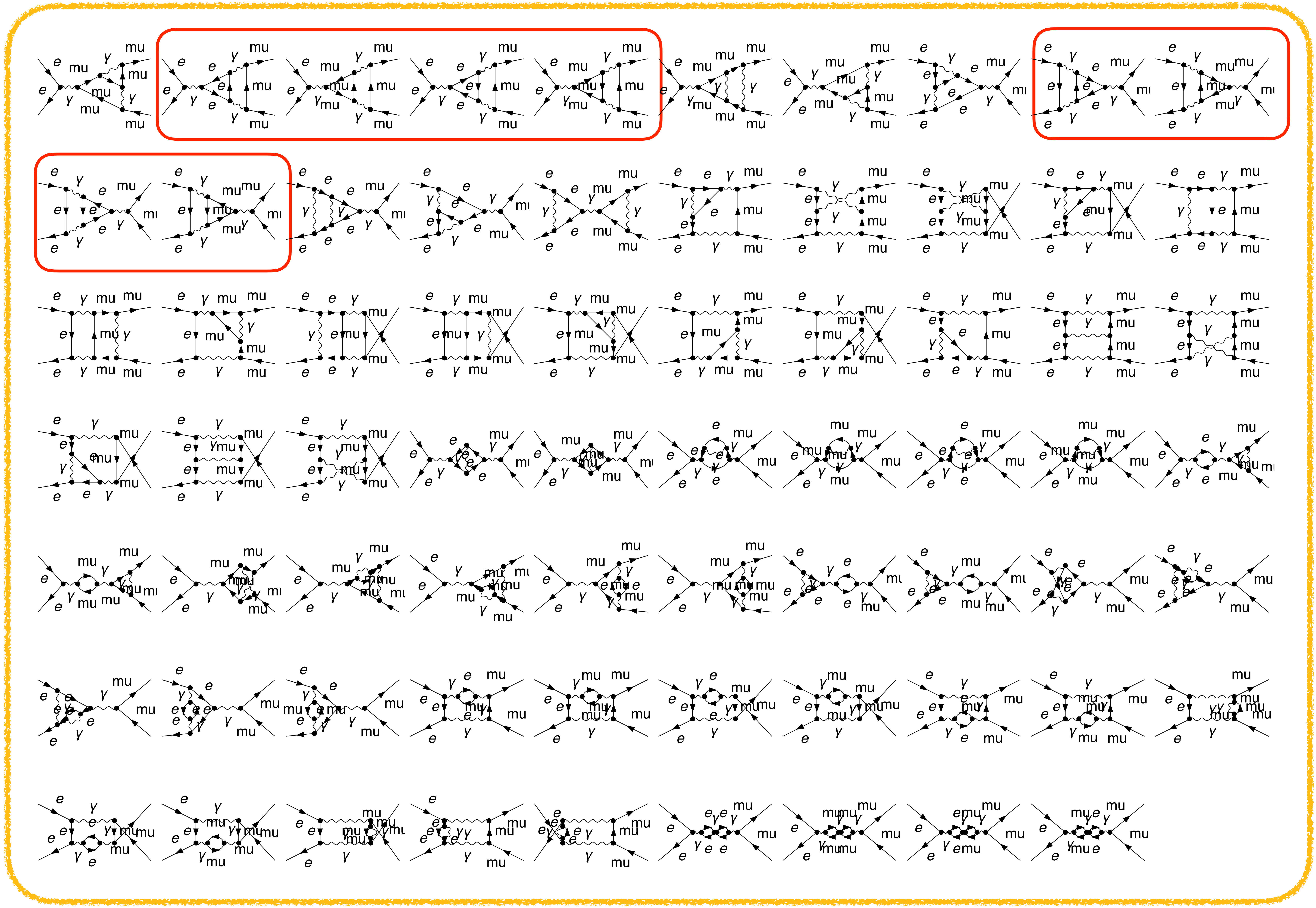
2-Loop Diagrams

[Bonciani, Broggio, Di Vita, Ferroglia, MKM, Mastrolia, Mattiazzi, Primo, Ronca, Schubert, Torres Bobadilla, Tramontano (2021)]

69 Diagrams

0 Due to Furry's Theorem

$$\mathcal{M}^{(2)} = A^{(2)} + n_l\, B_l^{(2)} + n_h\, C_h^{(2)} + n_l^2 D_l^{(2)}$$
$$+ n_h\, n_l\, E_{hl}^{(2)} + n_h^2\, F_h^{(2)}$$



Computation of the Loop Amplitude

Mathematica Based Package AIDA [Mastrolia, Peraro, Primo, Ronca, Torres Bobadilla (To be Published)]

Generation of Diagram by FeynArts

↓

Spin sums, Dirac Algebra, Trace by FeynCalc

↓

Adaptive Integrand Decomposition

↓

IBP Reduction via Reduze and KIRA

↓

Master Integral evaluation
Ginac, handyG

$$\mathcal{M}_{\mathrm{b}}^{(n)} = (S_\epsilon)^n \int \prod_{i=1}^{n} \frac{d^d k_i}{(2\pi)^d} \sum_G \frac{N_G}{\prod_{\sigma \in G} D_\sigma}$$

$$\mathcal{M}_{\mathrm{b}}^{(n)} = \mathbb{C}^{(n)} \cdot \mathbf{I}^{(n)}$$

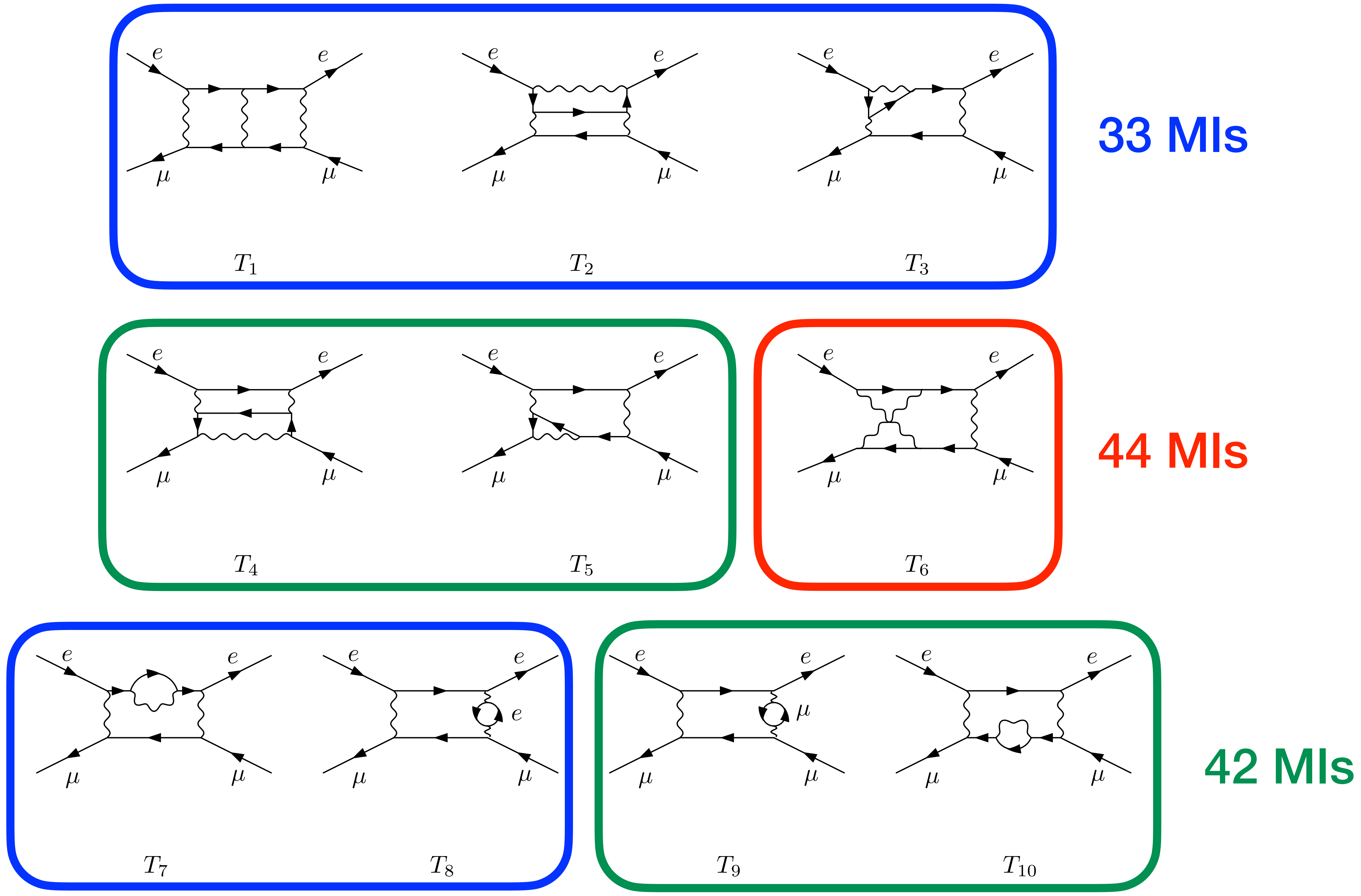
Master Integrals

Master Integrals

- The differential equation method has been the most successful in the computation of the MIs

[Kotikov (1990)] [Gehrmann, Remiddi (1999)]

[Henn (2013)] [Argeri, Di Vita, Mastrolia, Mirabella, Schlenk, Schubert, Tancredi (2014)]



[Bonciani, Ferroglia, Gehrmann, von Manteuffel (2008-13)]

[Mastrolia, Passera, Primo, Schubert (2017)]

[Di Vita, Laporta, Mastrolia, Primo, Schubert (2018)]

[MKM, Mastrolia, Ronca, Torres Bobadilla (2022)]

Generalized Polylogarithms

$$G(w_n, \ldots, w_1; \tau) \equiv \int_0^\tau \frac{dt}{t - w_n} G(w_{n-1}, \ldots, w_1; t)$$

$$G(w_1; t) \equiv \log(1 - t/w_1)$$

UV Renormalization

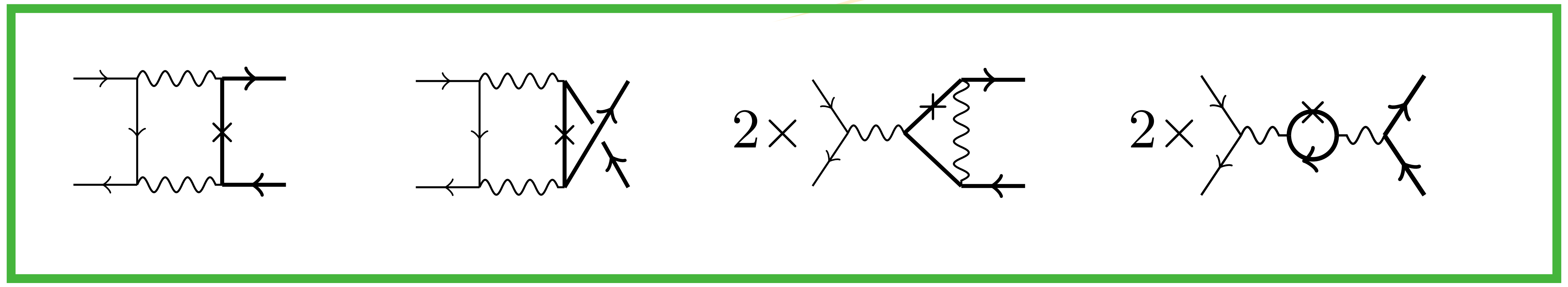
Renormalized Amplitude

$$\mathcal{A}(\alpha) = 4\pi\alpha\left[\mathcal{A}^{(0)} + \left(\frac{\alpha}{\pi}\right)\mathcal{A}^{(1)} + \left(\frac{\alpha}{\pi}\right)^2\mathcal{A}^{(2)}\right]$$

$$\mathcal{A}^{(0)} = \mathcal{A}_{\mathrm{b}}^{(0)}$$

$$\mathcal{A}^{(1)} = \mathcal{A}_{\mathrm{b}}^{(1)} + \left(\delta Z_\alpha^{(1)} + \delta Z_F^{(1)}\right)\mathcal{A}_{\mathrm{b}}^{(0)}$$

$$\mathcal{A}^{(2)} = \mathcal{A}_{\mathrm{b}}^{(2)} + \left(2\delta Z_\alpha^{(1)} + \delta Z_F^{(1)}\right)\mathcal{A}_{\mathrm{b}}^{(1)} + \left(\delta Z_\alpha^{(2)} + \delta Z_F^{(2)} + \delta Z_f^{(2)} + \delta Z_F^{(1)}\delta Z_\alpha^{(1)}\right)\mathcal{A}_{\mathrm{b}}^{(0)} + \delta Z_M^{(1)}\mathcal{A}_{\mathrm{b}}^{(1,\text{mass CT})}$$



$$\delta Z_f^{(2)} = n_h\left(\frac{L_\mu}{8} + \frac{1}{16\epsilon} - \frac{5}{96}\right)$$

[Czakon, Mitov, Moch (2007)]

IR Factorization

$$\mathcal{M}^{(1)}\Big|_{\text{poles}} = \frac{1}{2} Z_1^{\text{IR}}\, \mathcal{M}^{(0)}\Big|_{\text{poles}}$$

$$\mathcal{M}^{(2)}\Big|_{\text{poles}} = \frac{1}{8}\left[\left(Z_2^{\text{IR}} - \left(Z_1^{\text{IR}}\right)^2\right)\mathcal{M}^{(0)} + 2\, Z_1^{\text{IR}}\, \mathcal{M}^{(1)}\ \right]\Big|_{\text{poles}}$$

[Becher, Neubert (2009)]

[Hill (2017)]

IR Renormalization Factor

$$\ln Z_{\text{IR}} = \frac{\alpha}{4\pi}\left(\frac{\Gamma_0'}{4\epsilon^2} + \frac{\Gamma_0}{2\epsilon}\right) + \left(\frac{\alpha}{4\pi}\right)^2\left(-\frac{3\beta_0\Gamma_0'}{16\epsilon^3} + \frac{\Gamma_1' - 4\beta_0\Gamma_0}{16\epsilon^2} + \frac{\Gamma_1}{4\epsilon}\right) + \mathcal{O}\left(\alpha^3\right)$$

$$\Gamma'\left(\alpha\right) \equiv \frac{\partial}{\partial \ln \mu}\Gamma\left(\alpha\right) = \sum_{n=0}^{\infty}\Gamma_i'\left(\frac{\alpha}{4\pi}\right)^{n+1}$$

$$\Gamma = \gamma_{\text{cusp}}\left(\alpha\right)\ln\left(-\frac{s}{\mu^2}\right) + 2\gamma_{\text{cusp}}\left(\alpha\right)\ln\left(\frac{t-M^2}{u-M^2}\right) + \gamma_{\text{cusp,M}}\left(\alpha, s\right) + 2\gamma_h\left(\alpha\right) + 2\gamma_\psi\left(\alpha\right)$$

Cusp Anomalous dimension

Anomalous dimension

Numerical Result of the 2-Loop Amplitude

[Bonciani, Broggio, Di Vita, Ferroglia, MKM, Mastrolia, Mattiazzi, Primo, Ronca, Schubert, Torres Bobadilla, Tramontano (2021)]

- At 2 Loop there are 4063 GPLs up to weight 4 $\quad G(w_n, \ldots, w_1; \tau) \equiv \int_0^\tau \frac{dt}{t - w_n} G(w_{n-1}, \ldots, w_1; t)$

- 18 Letters $\quad w_i = w_i(x, y, z)$

$$\boxed{\begin{aligned} -t/M^2 &= x \\ -s/M^2 &= (1-y)^2/y \\ -(u-M^2)/(t-M^2) &= z^2/y \end{aligned}}$$

- The GPLs are evaluated by Ginac [PolyLogTools interface] and HandyG

[Vollinga, Weinzierl (2004)] [Duhr, Dulat (2019)]

[Naterop, Signer, Ulrich (2019)]

☑ We have obtained complete agreement between the predicted IR poles and the 2-Loop UV renormalized amplitude

☑ We recovered the Abelian part of the QCD result of $q\bar{q} \to t\bar{t}$ at 1- and 2-Loop

[Czakon (2008)]

[Bonciani, Ferroglia, Gehrmann, Maitre, Studerus (2008)]

[Bärnreuther, Czakon, Fiedler (2014)]

[MKM, Mastrolia, Ronca, Torres Bobadilla (2022)]

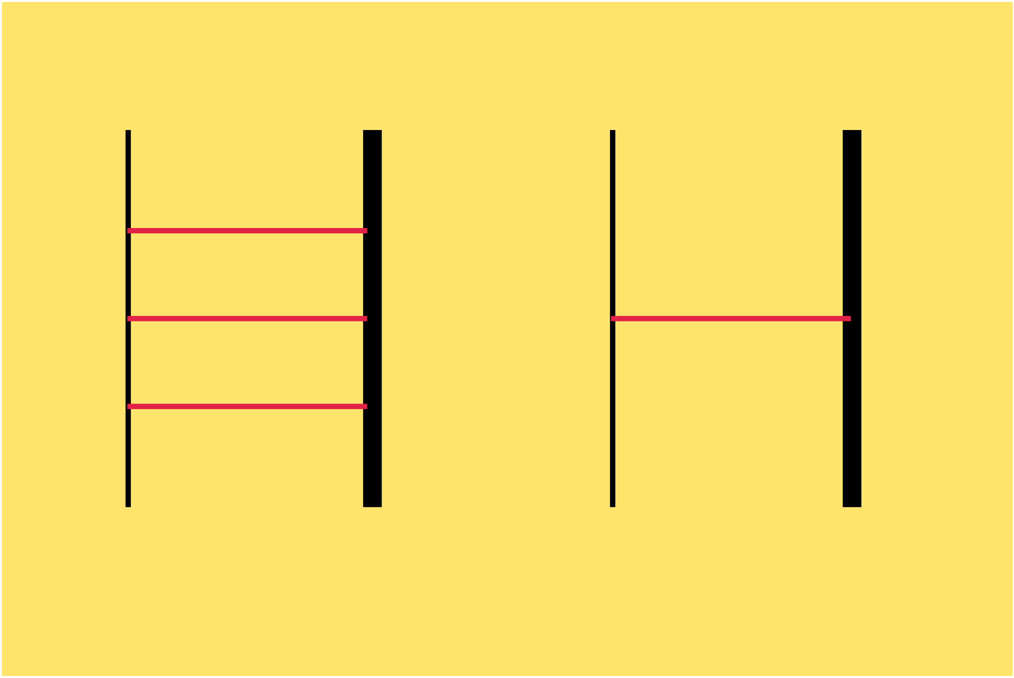
☑ n_h contributions were checked independently

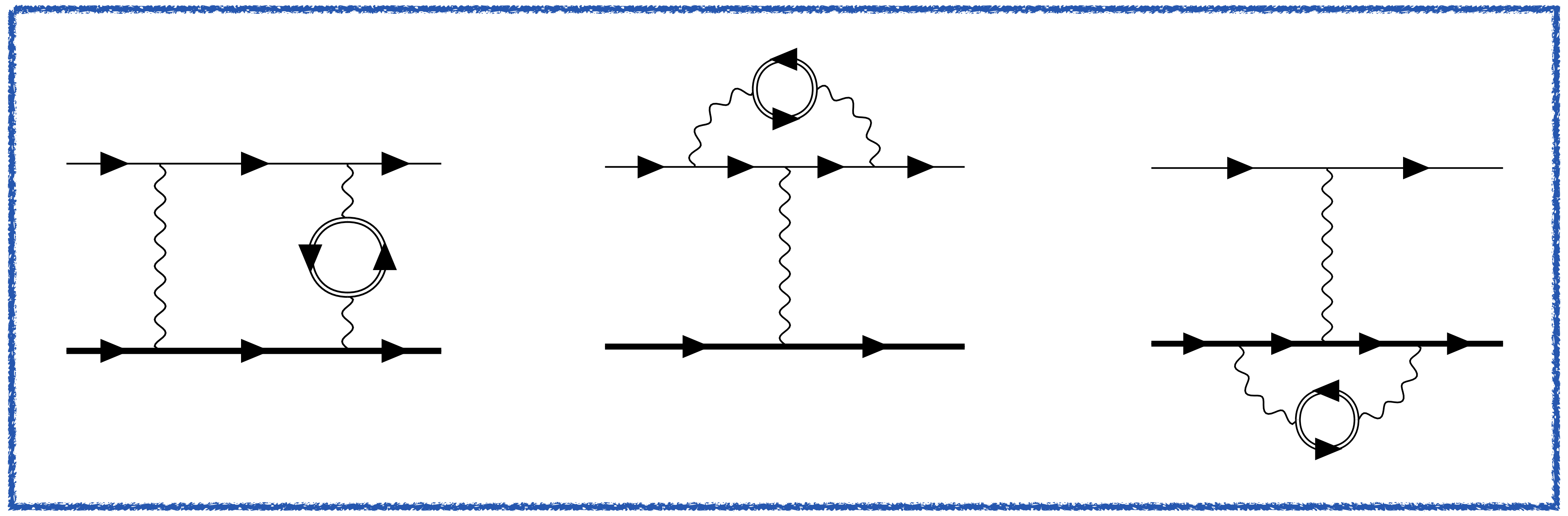
[Fael, Passera (2019)]

[Fael (2018)]

Towards Complete NNLO

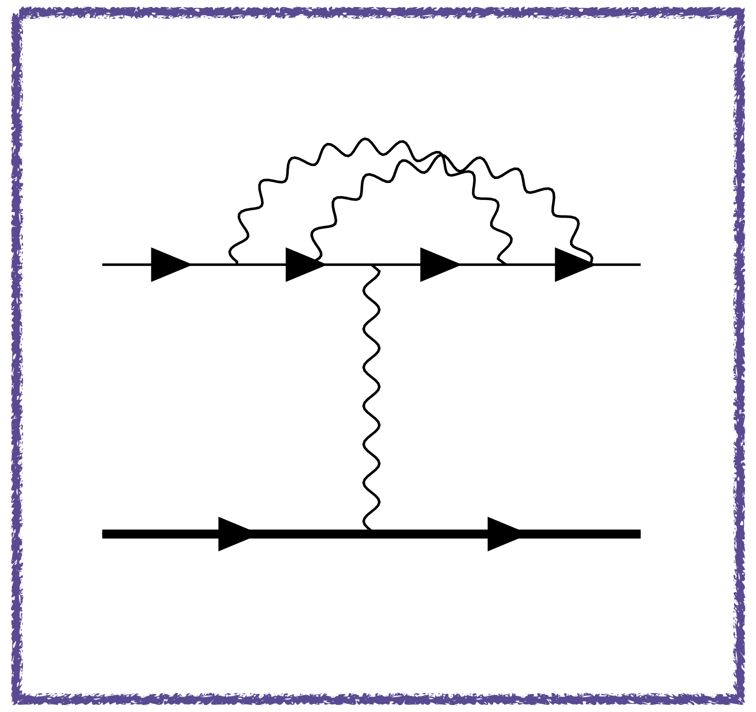
Towards Complete NNLO cross-section

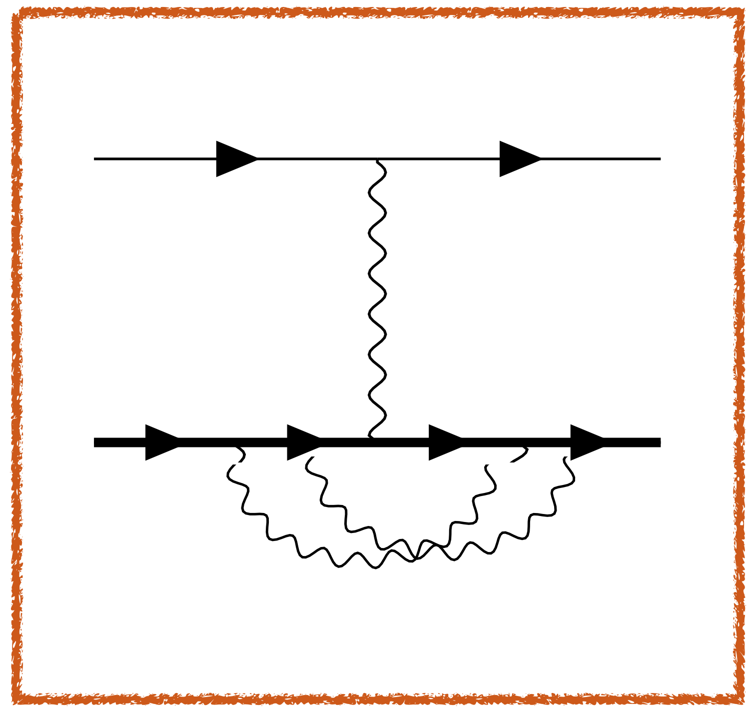




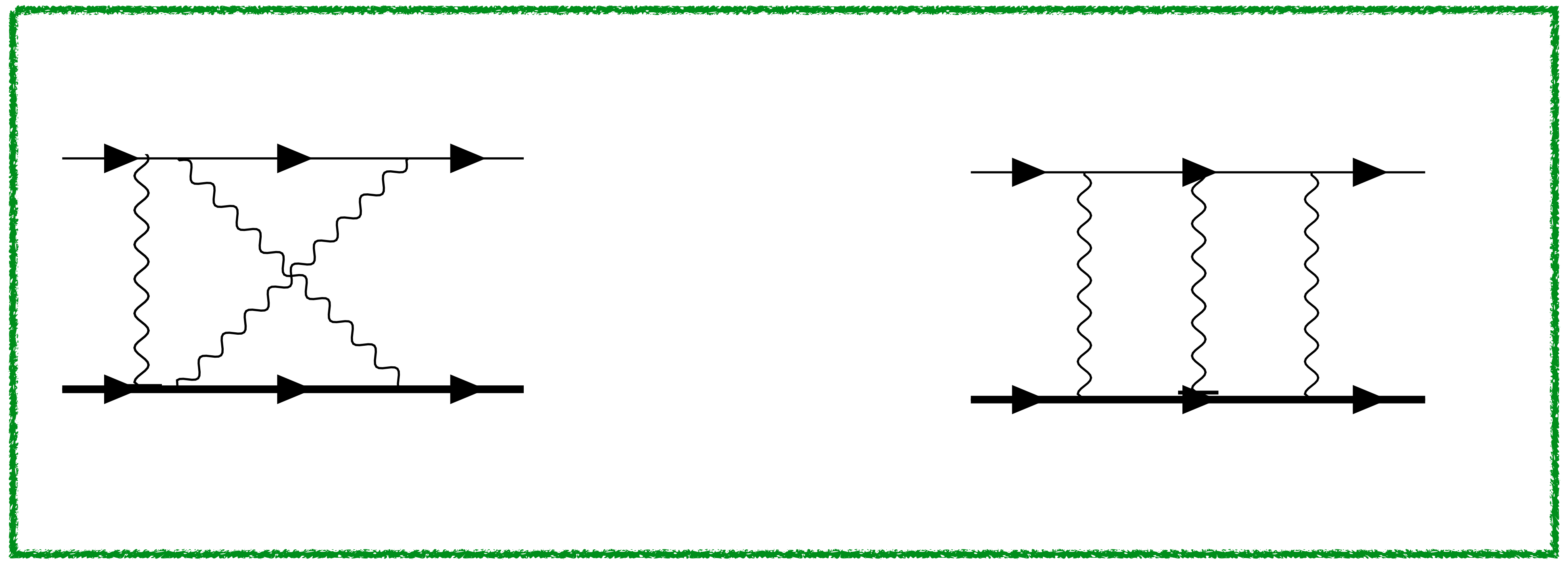
VP

Electronic





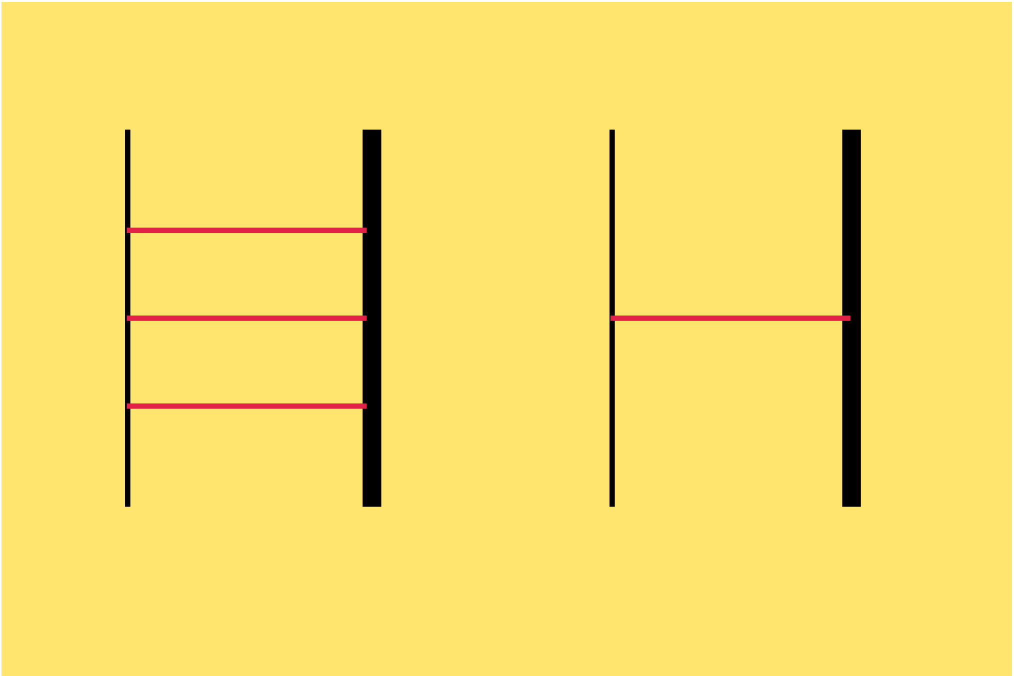
Muonic



Mixed

Towards Complete NNLO cross-section [VV]

[Broggio, Engel, Ferroglia, MKM, Mastrolia, Passera, Rocco, Ronca, Signer, Torres Bobadilla, Ulrich, Zoller (In Progress)]



[Mitov, Moch (2006)]

[Penin (2006)]

[Becher, Melnikov (2007)]

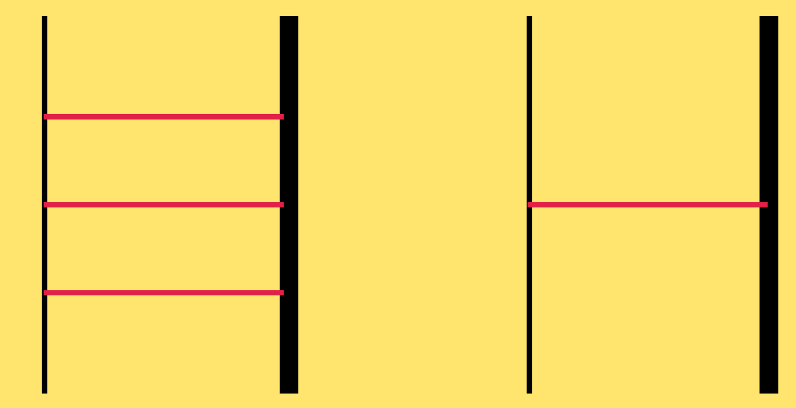
[Engel, Gnendiger, Signer, Ulrich (2018)]

- The complete two loop virtual amplitude is available with massless electron.
- Leading electron mass effects are restored through massification
- The two loop virtual correction can be divided as
  - ✦ Diagrams with closed fermionic loop [VP] ⇒ VP contribution computed exactly with electron mass
  - ✦ Diagrams with no fermionic loops
    - ✦ Correction on the electron line [`electronic`] ⇒ Known using massive vertex formfactor
    - ✦ Correction on the muon line [`muonic`] ⇒ Known using massive vertex formfactor
    - ✦ Mixed corrections [`mixed`] ⇒ Employed the idea of Massification

Massification

Towards Complete NNLO cross-section [VV]

[Broggio, Engel, Ferroglia, MKM, Mastrolia, Passera, Rocco, Ronca, Signer, Torres Bobadilla, Ulrich, Zoller (In Progress)]



[Mitov, Moch (2006)]

[Penin (2006)]

[Becher, Melnikov (2007)]

[Engel, Gnendiger, Signer, Ulrich (2018)]

Massification

VP contribution computed exactly with electron mass

Known using massive vertex formfactor

Known using massive vertex formfactor

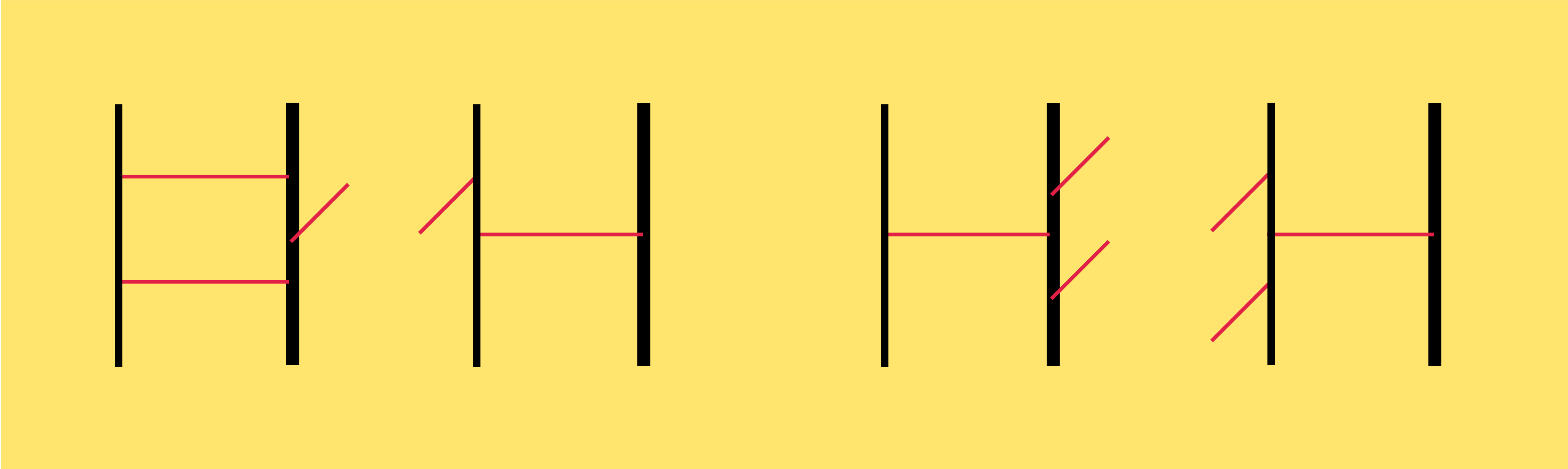
Employed the idea of Massification

☑ VP contribution has been checked independently [Fael, Passera (2019)] [Fael (2018)]

☑ Vertex corrections has been checked independently

Carloni Calame, Chiesa, Hasan, Montagna, Nicrosini, Piccinini (2020)

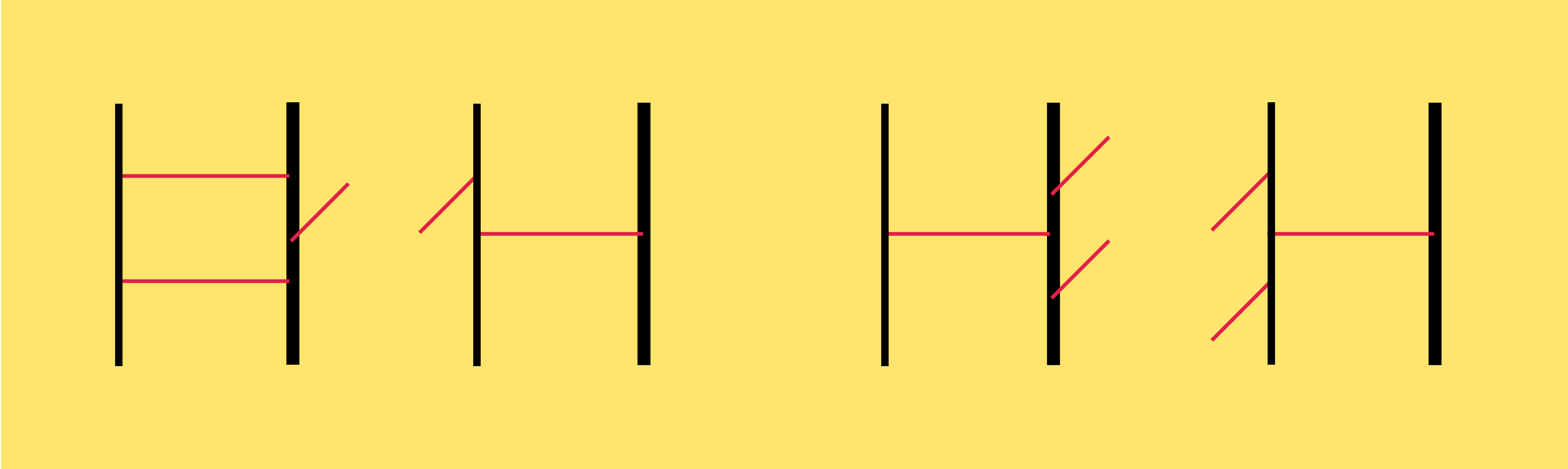
Towards Complete NNLO cross-section [RV+RR]

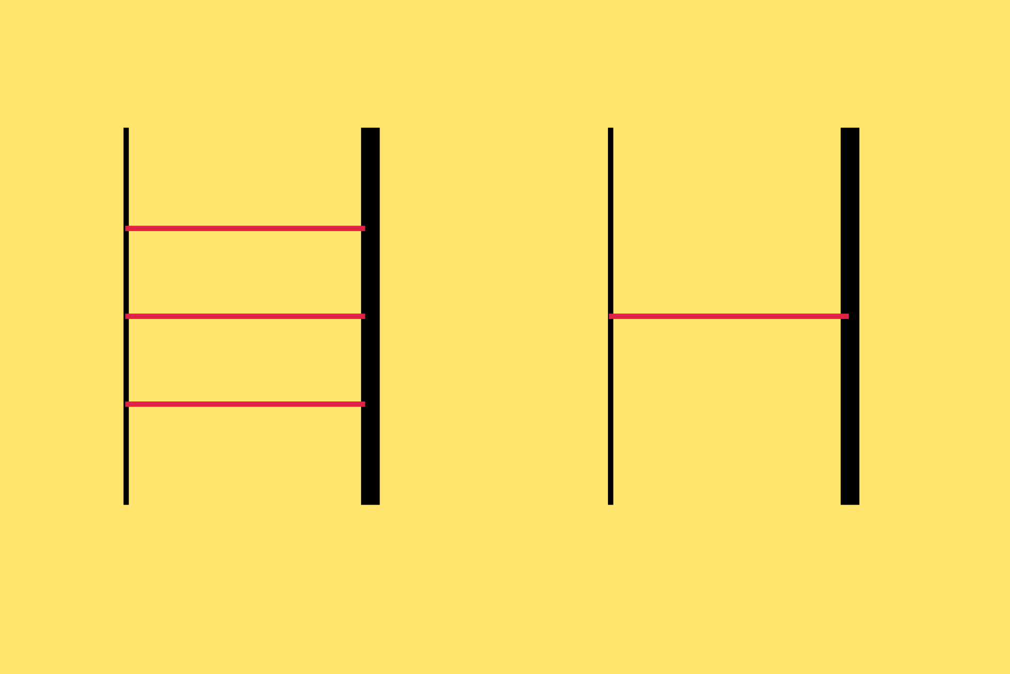


- ☑ Computed via OpenLoops assisted with next-to-soft stabilization   Buccioni, Pozzorini, Zoller
- ☑ One Loop generalization of the LBK theorem helped to obtain the soft expansion to NLP   [Banerjee, Engel, Schalch, Signer, Ulrich (2021)] [Engel, Signer, Ulrich (2021)]
- ☑ All components have been implemented within the McMule Framework for their efficient and stable evaluation
  Banerjee, Coutinho, Engel, Gurgone, Hagelstein, Kollatzsch, Naterop, Rocco, Schalch, Sharkovska, Signer, Ulrich
- ☑ Dedicated comparison with the MESMER from Pavia group for the Real-virtual and double Real contribution
  Budassi, Carloni Calame, Chiesa, Del Pio, Hasan, Montagna, Nicrosini, Piccinini (2021)

Towards Complete NNLO cross-section

[Broggio, Engel, Ferroglia, MKM, Mastrolia, Passera, Rocco, Ronca, Signer, Torres Bobadilla, Ulrich, Zoller (In Progress)]





$\alpha = 1/137.035999084$ $\quad m_e = 0.510998950\,\mathrm{MeV}$

$m_\mu = 105.658375\,\mathrm{MeV}$ $\quad m_\tau = 1776.86\,\mathrm{MeV}$

On-Shell Renormalization scheme

θ_e Scattering angle of electron

θ_μ Scattering angle of muon

$t_e = (p_1 - p_3)^2$ $\quad t_\mu = (p_2 - p_4)^2$

Cuts

S1 :: $E_e > 1\,\mathrm{GeV},\ \theta_\mu > 0.3\,\mathrm{mrad}$

S2 :: $E_e > 1\,\mathrm{GeV},\ \theta_\mu > 0.3\,\mathrm{mrad},\ 0.9 < \theta_\mu/\theta_\mu^{\mathrm{el}} < 1.1$

Elasticity Cut

Total Cross-section

[Broggio, Engel, Ferroglia, MKM, Mastrolia, Passera, Rocco, Ronca, Signer, Torres Bobadilla, Ulrich, Zoller (In Progress)]

	$\sigma/\mu b$	$\sigma/\mu b$	$\delta K^{(i)}\%$	$\delta K^{(i)}\%$
	S1	**S2**	**S1**	**S2**
$\sigma^{(0)}$	106.44356	106.44356		
$\sigma_e^{(1)}$	-0.61211	-4.66041	-0.57505	-4.37830
$\sigma_{e\mu}^{(1)}$	-0.21404	-0.16016	-0.20108	-0.15047
$\sigma_\mu^{(1)}$	-0.02842	-0.16133	-0.02670	-0.15156
$\sigma_{\text{had}}^{(1)}$	0.01597	0.01597	0.01500	0.01500
$\sigma_{\text{vp}}^{(1)}$	1.57105	1.57105	1.47594	1.47594
σ_1	107.16003	103.03269		
$\sigma_e^{(2)}$	0.00089	0.06594	0.00083	0.06400
$\sigma_{e\mu}^{(2)}$	0.00094	0.01925	0.00088	0.01869
$\sigma_\mu^{(2)}$	-0.00005	0.00001	-0.00004	0.00001
$\sigma_{\text{vp}}^{(2)}$	-0.01393	-0.07376	-0.01300	-0.0715
σ_2	107.14788	103.10397		

Preliminary

$$K^{(i)} = 1 + \delta K^{(i)} = \frac{\sigma_i}{\sigma_{i-1}}$$

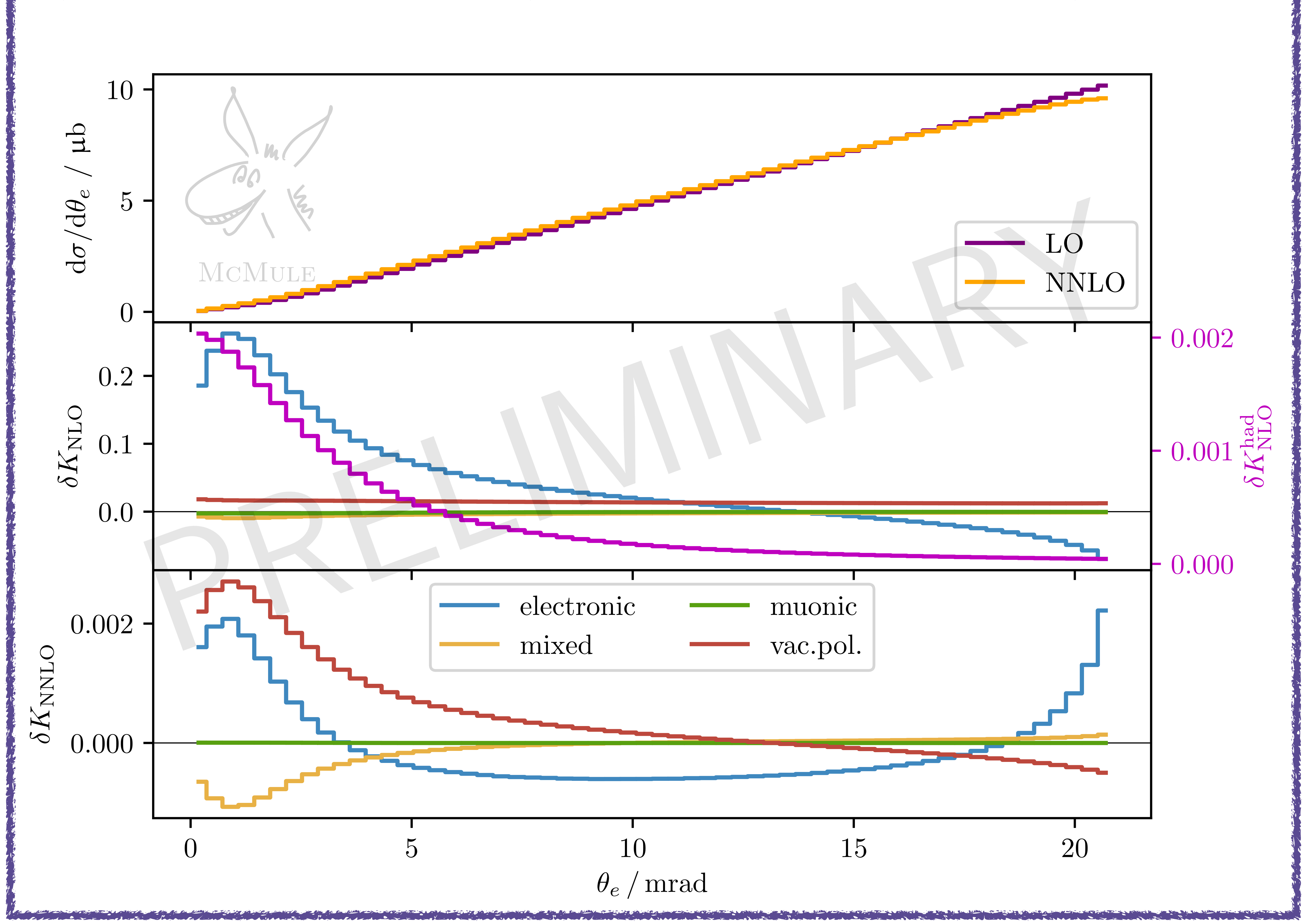
$$\sigma_2 = \sigma^{(0)} + \sigma^{(1)} + \sigma^{(2)}$$

$$\sigma_1 = \sigma^{(0)} + \sigma^{(1)}$$

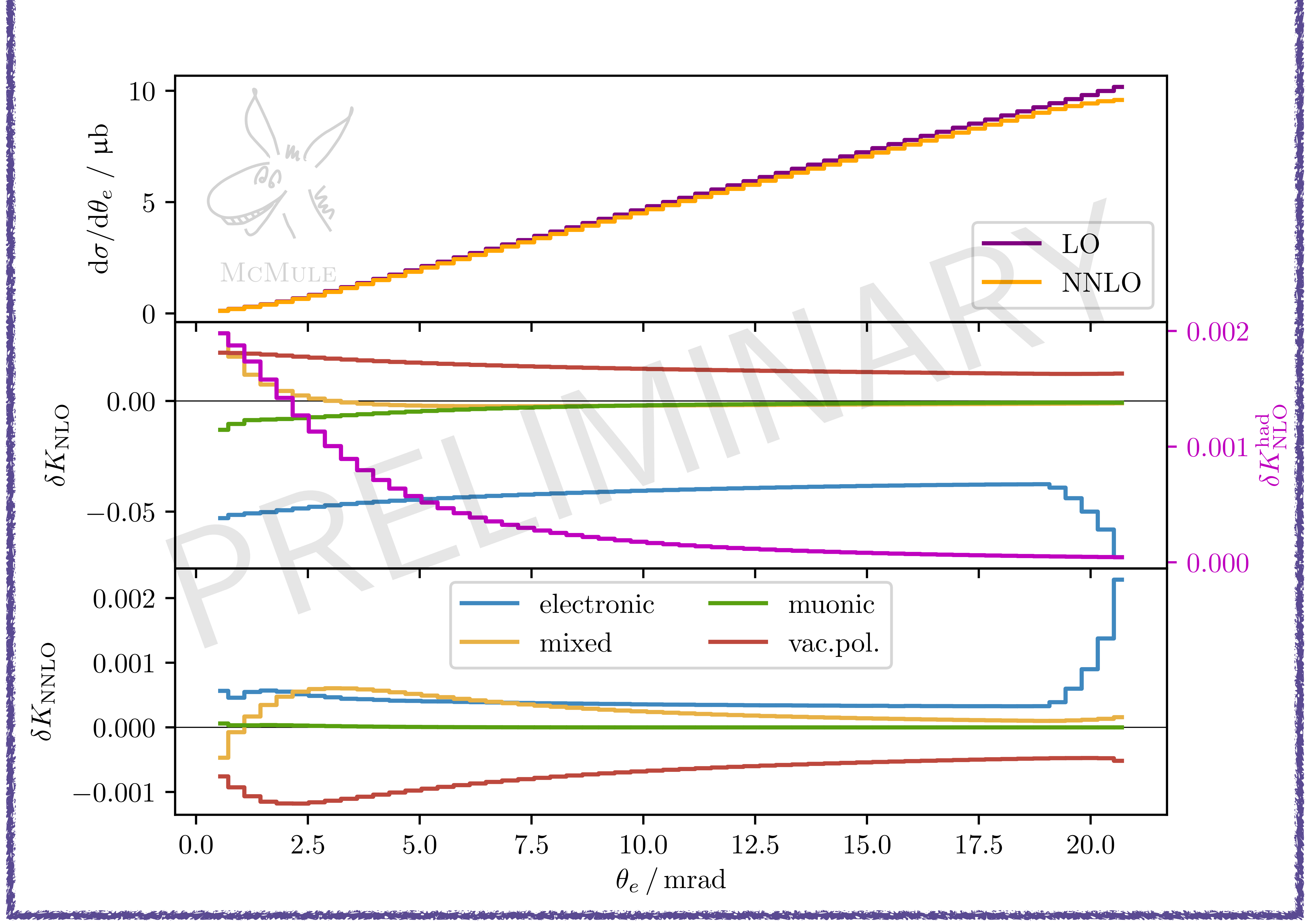
- ✦The results are split into purely electronic, muonic, mixed, and VP corrections
- ✦All three leptons as well as the hadronic contribution are included in the VP

Differential distribution for θ_e

[Broggio, Engel, Ferroglia, MKM, Mastrolia, Passera, Rocco, Ronca, Signer, Torres Bobadilla, Ulrich, Zoller (In Progress)]



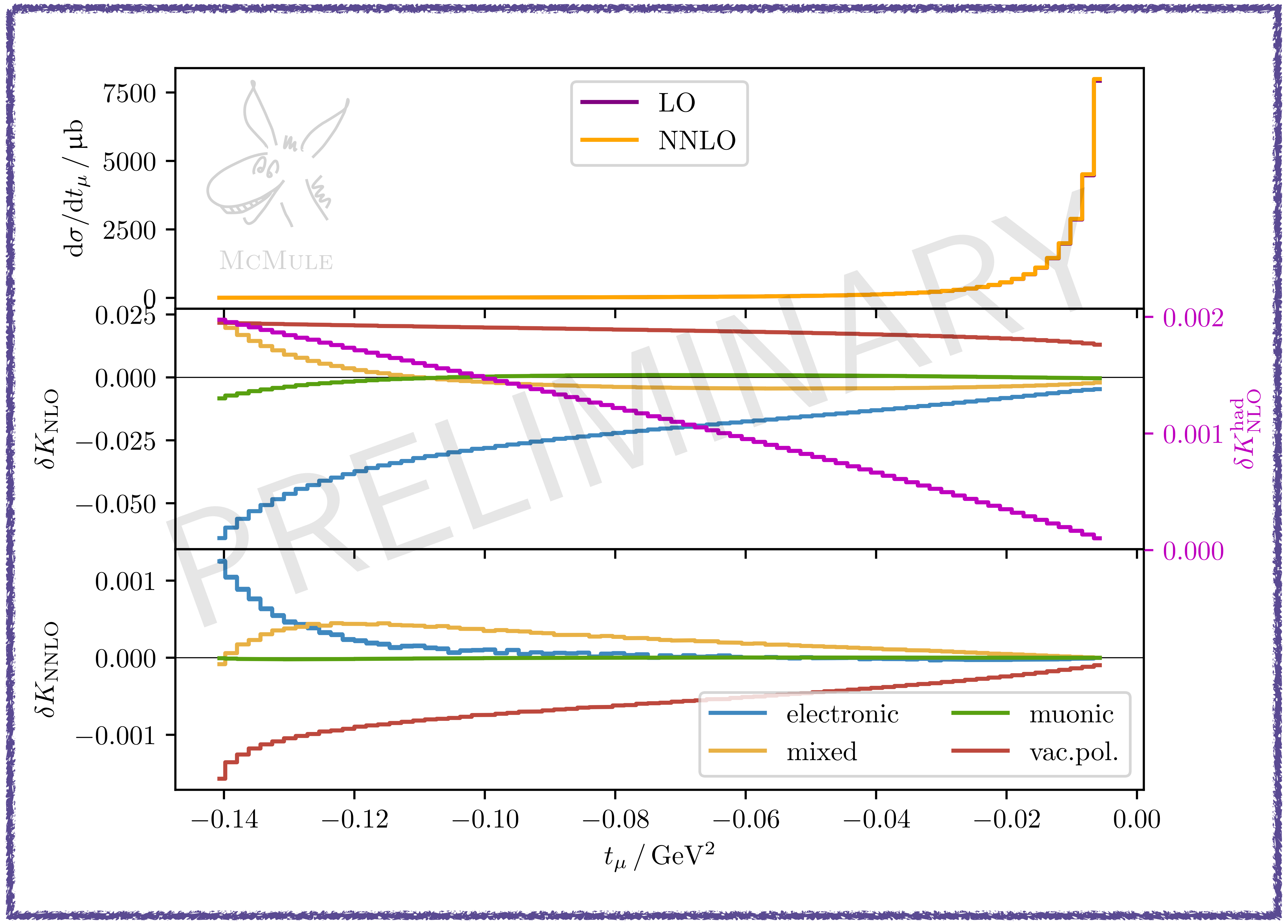
S1



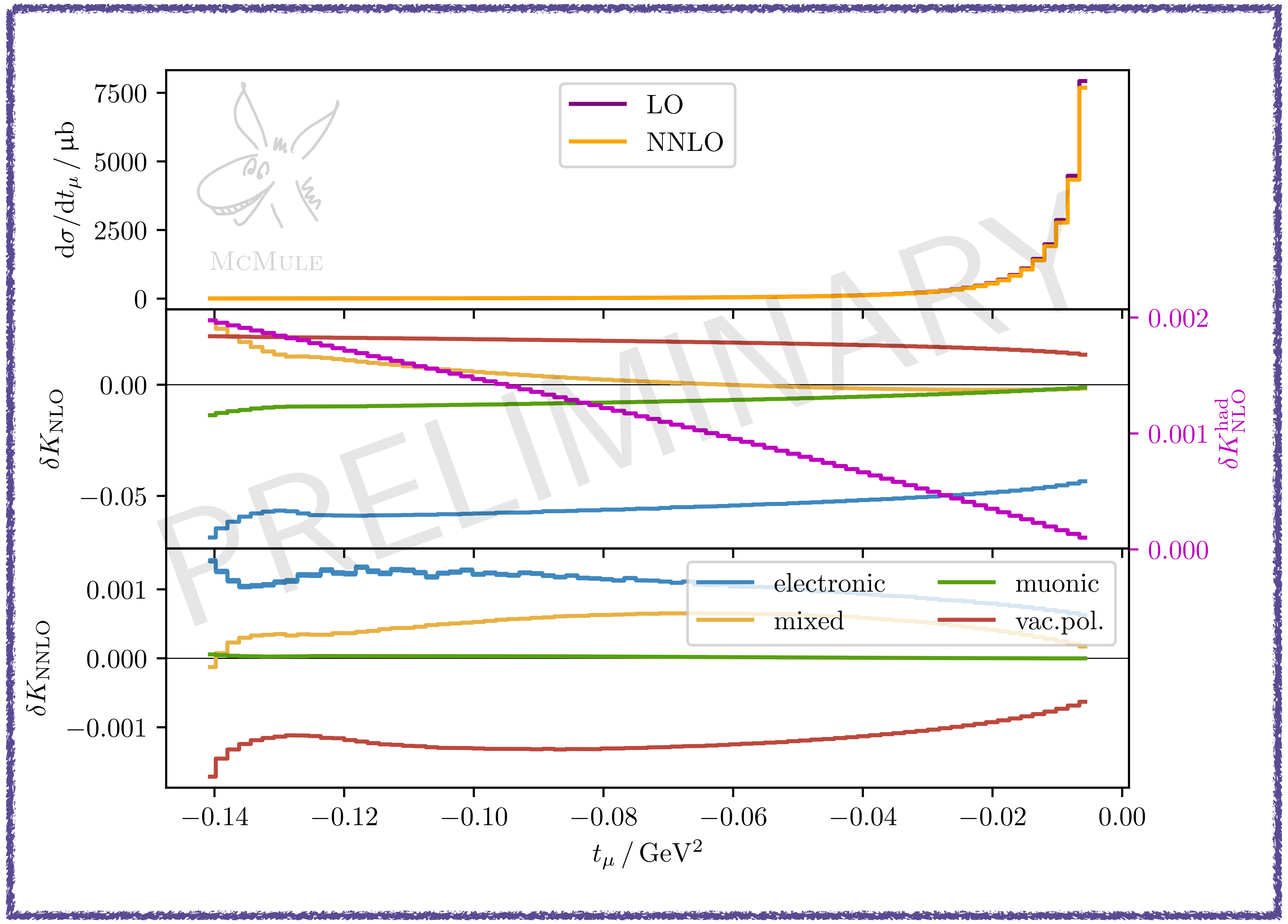
S2

Differential distribution for t_μ

[Broggio, Engel, Ferroglia, MKM, Mastrolia, Passera, Rocco, Ronca, Signer, Torres Bobadilla, Ulrich, Zoller (In Progress)]

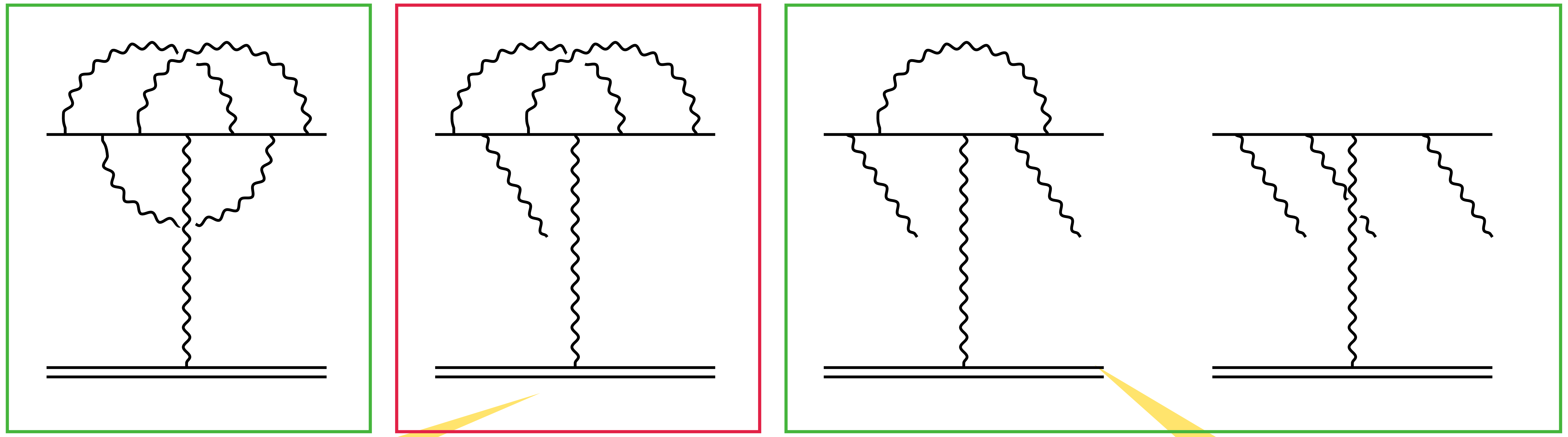


S1



S2

MUonE : Dominant Three-Loop Corrections



Main Bottleneck

2-Loop 5 point process

[Buccioni, Pozzorini, Zoller (2017)]

Openloop can be used

Next-To-Soft Stabilization will be useful

[Engel, Signer, Ulrich (2021)]

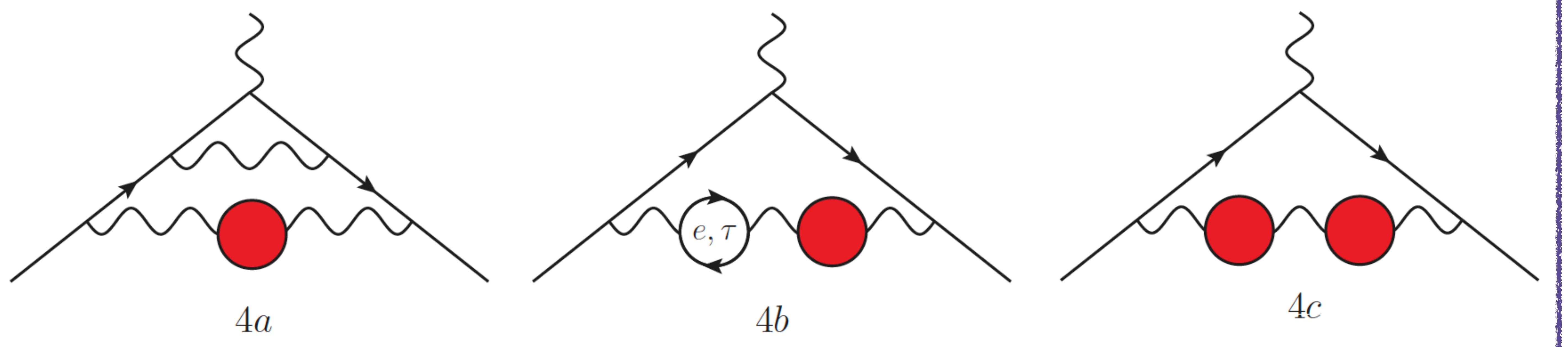
[Banerjee, Engel, Schalch, Signer, Ulrich (2021)]

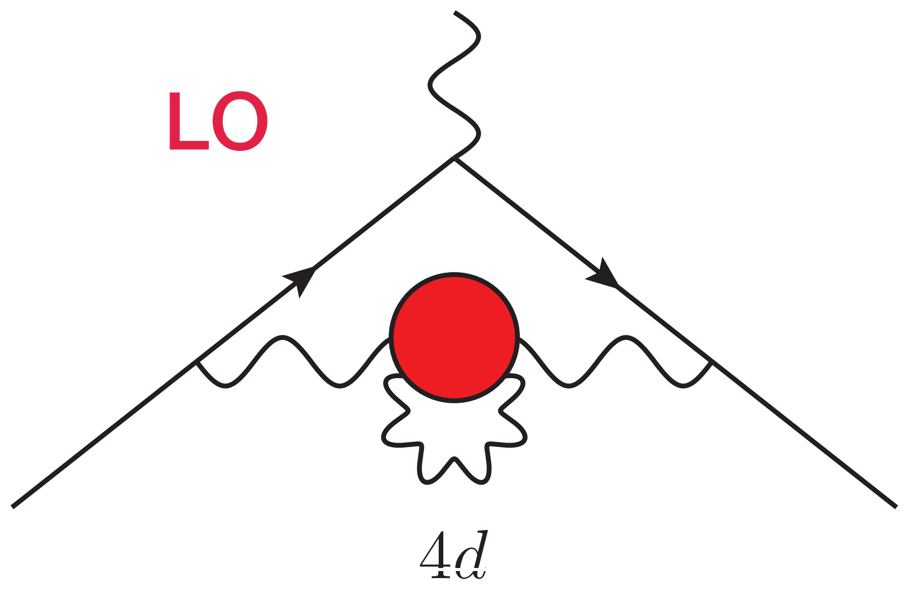
- ☑ Massive vector form factors to three loops computed very recently [Fael, Lange, Schönwald, Steinhauser (2022)]
- ☑ Subtraction scheme is ready: FKS3 [Engel, Signer, Ulrich (2019)]
- ☑ Dedicated N3LO kick-off workshop, Aug 2022 at IPPP, Durham to investigate the feasibility

Y. Ulrich, https://conference.ippp.dur.ac.uk/event/1104

HVP NLO contribution to Muon g-2 with MUonE

[Nesterenko (2021)]
[Balzani, Laporta, Passera (2021)]





$$a_\mu^{\mathrm{HVP}}(\mathrm{LO}) = -\frac{\alpha}{\pi^2}\int_{-\infty}^{0}\frac{\mathrm{d}t}{t}\,\Pi_{\mathrm{h}}(t)\,\mathrm{Im}K^{(2)}(t/m^2) = \frac{\alpha}{\pi}\int_0^1 \mathrm{d}x\,(1-x)\,\Delta\alpha_{\mathrm{h}}(t(x))$$

LO Kernel

[Krause (1996)],
[Keshavarzi, Nomura, Teubner (2019)]

$$a_\mu^{\mathrm{HVP}}(\mathrm{NLO}) = -98.3(7)\times 10^{-11}$$

Timelike Region

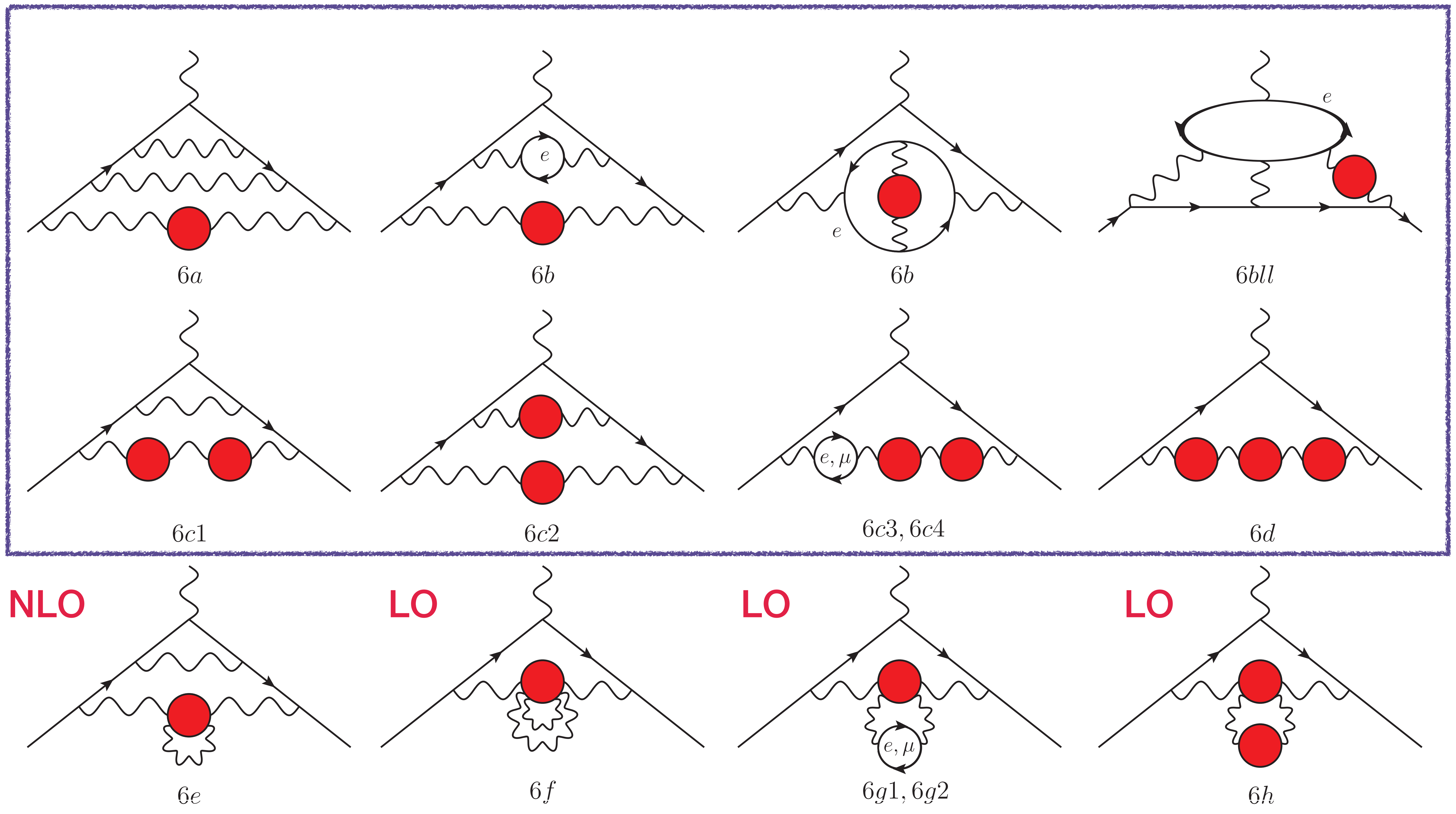
$$a_\mu^{(4a)} = \left(\frac{\alpha}{\pi}\right)^2\int_0^1 \mathrm{d}x\,\kappa^{(4)}(x)\,\Delta\alpha_{\mathrm{h}}(t(x)), \qquad \kappa^{(4)}(x) = \frac{2-x}{x\,(x-1)}\,2F^{(4)}(x-1)$$

$$F^{(4)}(u) = R_1(u) + R_2(u)\ln(-u) + R_3(u)\ln(1+u) + R_4(u)\ln(1-u) + \\ + R_5(u)\left[4\mathrm{Li}_2(u) + 2\mathrm{Li}_2(-u) + \ln(-u)\ln\left((1-u)^2(1+u)\right)\right]$$

NLO Kernel

HVP NNLO contribution to Muon g-2 with MUonE

[Balzani, Laporta, Passera (2021)]



[Kurz, Liu, Marquard, Steinhauser (2014)]

$$a_\mu^{\mathrm{HVP}}(\mathrm{NNLO}) = 12.4(1) \times 10^{-11}$$

Timelike Region

☑The NNLO space-like kernels are available for MUonE

☑The NLO & NNLO space-like kernels can also be used in lattice QCD computation

MUonE Theory Papers

C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni, PLB 746 (2015) 325 [1504.02228 [hep-ph]]
P. Mastrolia, M. Passera, A. Primo, U. Schubert, JHEP 1711 (2017) 198 [1709.07435 [hep-ph]]
S. Di Vita, S. Laporta, P. Mastrolia, A. Primo, U. Schubert, JHEP 1809 (2018) 016 [1806.08241 [hep-ph]]
M. Alacevich et al, JHEP 02 (2019) 155 [1811.06743 [hep-ph]]
M. Fael, JHEP 1902 (2019) 027 [1808.08233 [hep-ph]]
M. Fael and M. Passera, PRL 122 (2019) 192001 [1901.03106 [hep-ph]]
P. Banerjee et al. [The MUonE TI], EPJC 80 (2020) 591 [2004.13663 [hep-ph]]
C. M. Carloni Calame et al, JHEP 11 (2020) 028 [2007.01586 [hep-ph]]
P. Banerjee, T. Engel, A. Signer, Y. Ulrich, SciPost Phys. 9 (2020) 027 [2007.01654 [hep-ph]]
R. Bonciani et al, PRL 128 (2022) 022002 [2106.13179 [hep-ph]]
E. Budassi et al, JHEP 11 (2021) 098 [2109.14606 [hep-ph]]
A.V. Nesterenko, JPG 49 (2022) 055001 [2112.05009 [hep-ph]]
E. Balzani, S. Laporta, M. Passera, arXiv:2112.05704 [hep-ph]
M. Fael, F. Lange, K. Schönwald, M. Steinhauser, PRL128 (2022) 172003 [2202.05276 [hep-ph]]
M. Fael, F. Lange, K. Schönwald, M. Steinhauser, PRD 106 (2022) 034029 [2207.00027 [hep-ph]]
D. Greynat and E. de Rafael, JHEP 05 (2022) 084 [2202.10810 [hep-ph]]
E. Budassi, C.M. Carloni Calame, C.L. Del Pio, F. Piccinini, PLB 829 (2022) 137138 [2203.01639 [hep-ph]]

NP:

P.S.B. Dev, W. Rodejohann, X. J. Xu, Y. Zhang, JHEP05 (2020), 053 [2002.04822 [hep-ph]]
A. Masiero, P. Paradisi, M. Passera, PRD102 (2020) 7, 075013 [2002.05418 [hep-ph]]
U. Schubert, C. Williams, PRD100 (2019) 3, 035030
K. Asai, K. Hamaguchi, N. Nagata, S.Y. Tseng, J. Wada, arXiv:2109.10093 [hep-ph]
I. Galon, D. Shih, I.R. Wang, arXiv:2202.08843 [hep-ph]
G. Grilli di Cortona, E. Nardi, PRD 105 (2022) 11, L111701 [2204.04227 [hep-ph]]

Conclusion

- Independent determination of the HVP contribution to the anomalous magnetic moment of Muon compared to dispersive and lattice results
- Fully differential fixed-order MC @ NLO ready
- EW NLO corrections known but not required at 10ppm level
- Fully analytic evaluation of the two-loop QED amplitude completed
- Massification of the two-loop QED amplitude has been done and combined with Real-Virtual and Real-Real piece
- Two independent MC (MESMER, McMule) at NNLO in progress
- First step towards investigating dominant N3LO corrections
- New NLO and NNLO space-like kernels for HVP are ready
- Possible new physics searches, etc

Thank You

Back up

Scattering Process

$$e^-(p_1)\mu^\pm(p_2) \to e^-(p_3)\mu^\pm(p_4) + X(p_5)$$

$$s = m^2 + M^2 + 2mE_2$$

γ

e^+e^-

$\mu^+\mu^-$

$\pi^+\pi^-$

π^0

Budassi, Carloni Calame, Chiesa, Del Pio, Hasan, Montagna, Nicrosini, Piccinini (2021)

Budassi, Carloni Calame, Del Pio, Piccinini (2022)

✦ Elastic events are required

$$\theta_\mu^{\mathrm{el}*} = \pi - \theta_e^{\mathrm{el}*}$$ **COM Frame**

$$\tan\theta_\mu^{\mathrm{el}} = \frac{2\tan\theta_e^{\mathrm{el}}}{(1+\gamma^2\tan^2\theta_e^{\mathrm{el}})(1+g_\mu^*) - 2}$$

$$g_\mu^* = \frac{E_2 m + M^2}{E_2 m + m^2} \qquad \gamma = \frac{E_2 + m}{\sqrt{s}}$$

LAB Frame