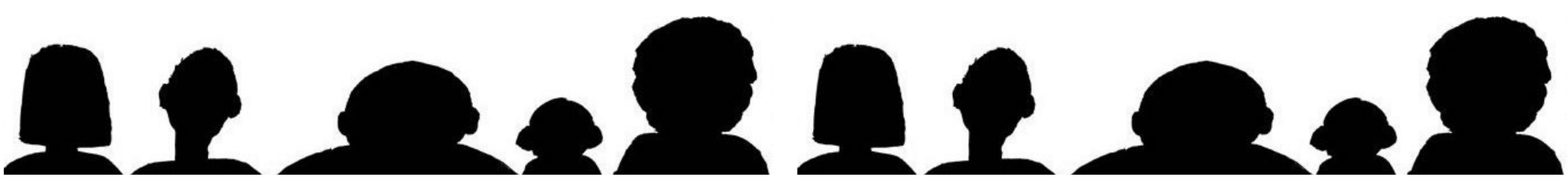
Trinity College Dublin
The University of Dublin

LATTICE 18
East Lansing, MI, USA

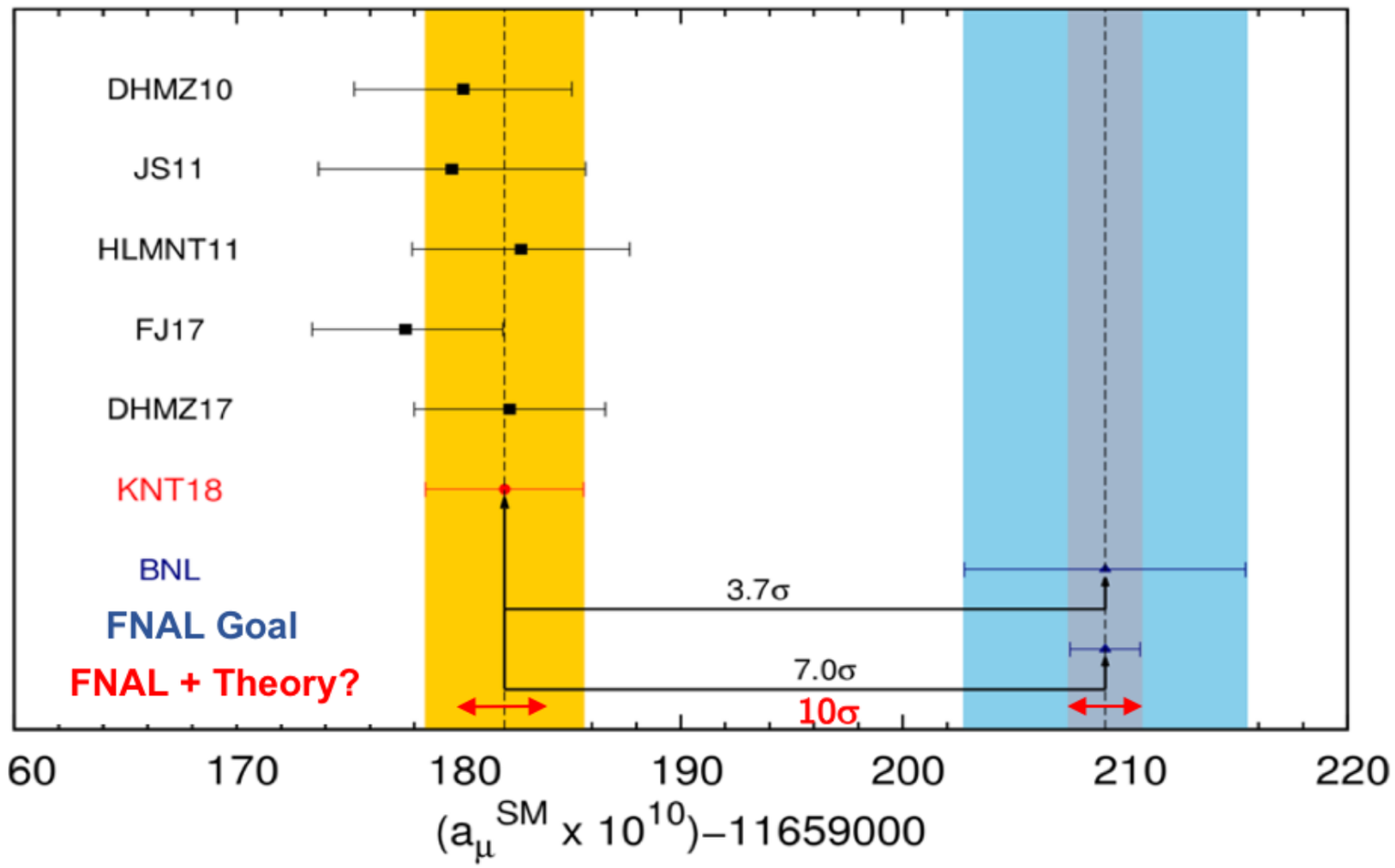
Leading hadronic contribution to muon g-2 from lattice QCD and the MUonE experiment

Marina Krstić Marinković
Trinity College Dublin

in collab. w. **N. Cardoso** (IST, Lisbon)
and μONe exp. and th. effort

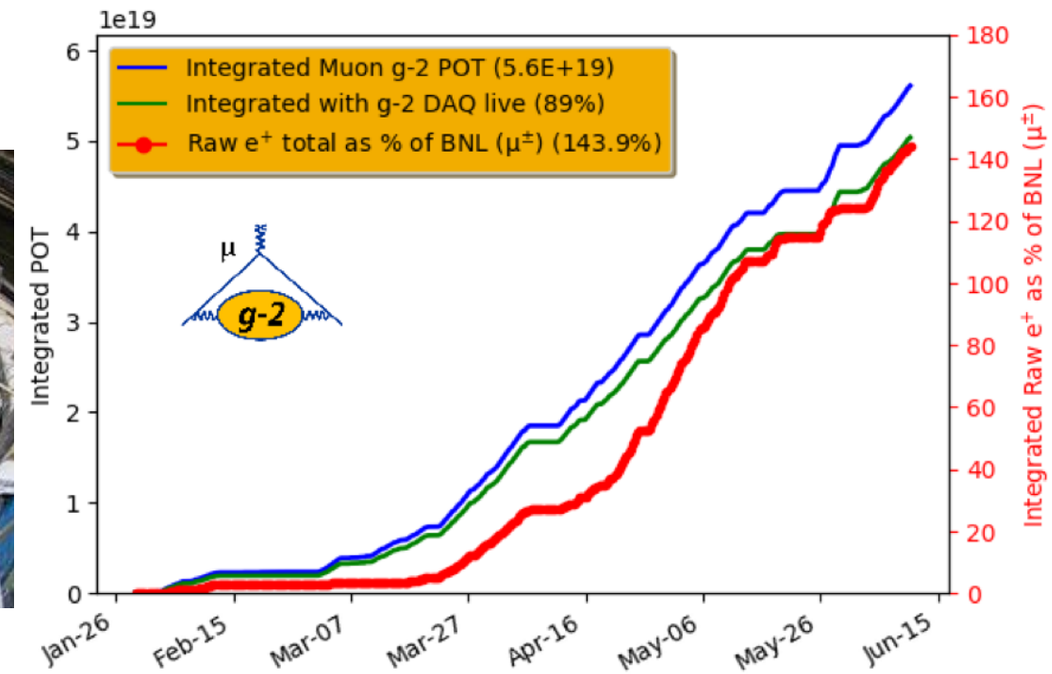


Muon g-2 Status



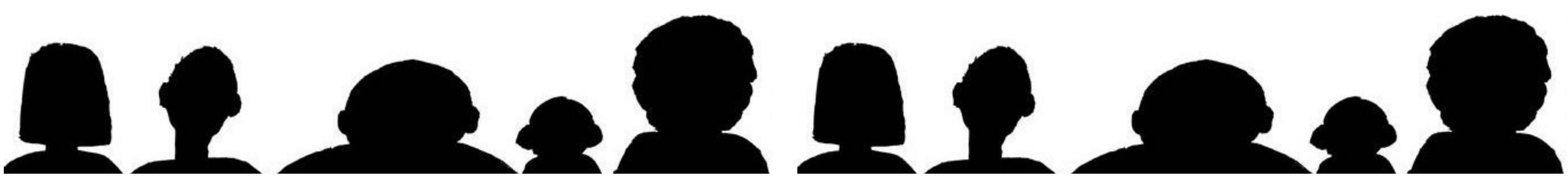
Keshavarzi, Nomura, Teubner, Phys.Rev. D97 (2018) no.11, 114025 [arxiv:1802.02995]

a_μ from the experiment: FNAL E989



- a_μ^{exp} = 11659208.0(6.3) × 10 $^{-10}$(0.54ppm) [**BNL, 2006-2008**]
- New experiments (J-PARC, FNAL) expected to **perform 4× more precise measurement (E 989@FNAL by Jun 2020)**
- **Sucessful commissioning run in 2017!**

D. Kawall (@Mainz, Muon g-2 Theory Initiative): Data set comparable to BNL statistics [June 2018]
https://indico.him.uni-mainz.de/event/11/contributions



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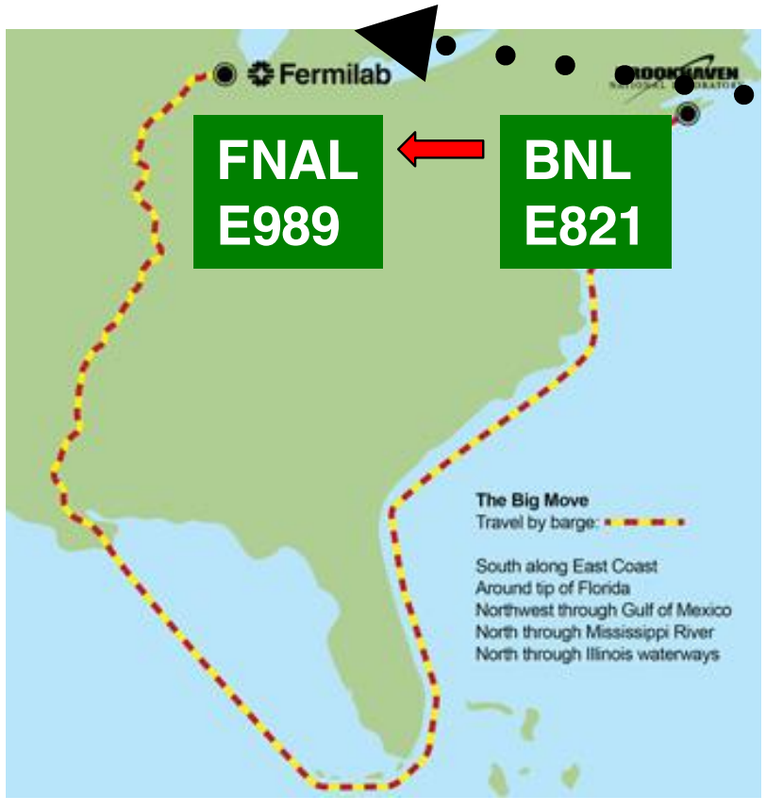

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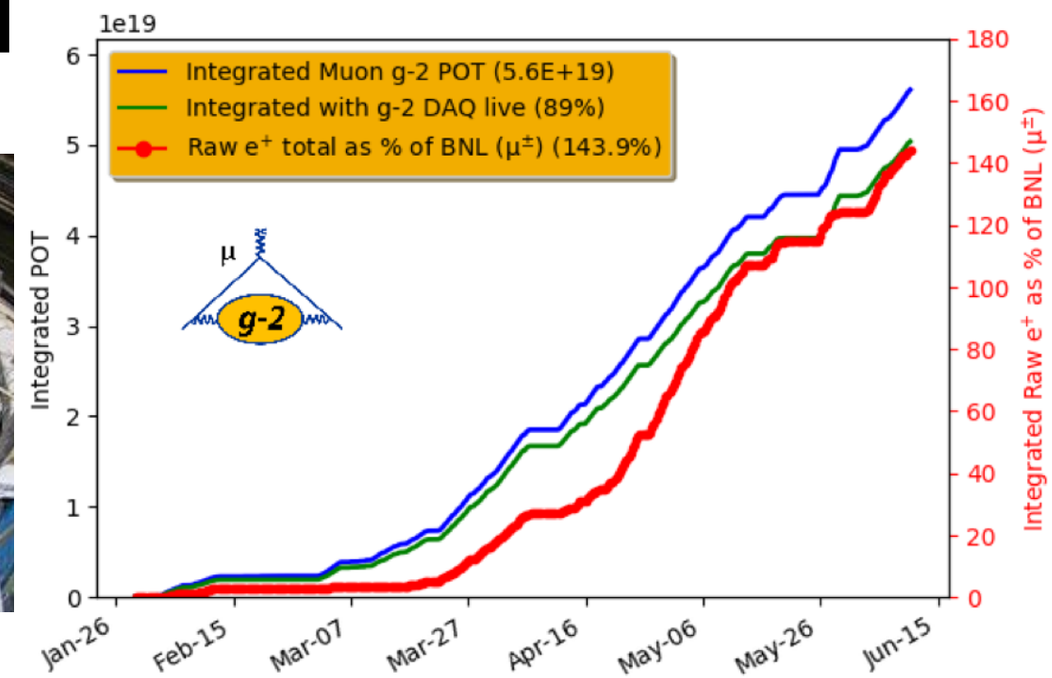

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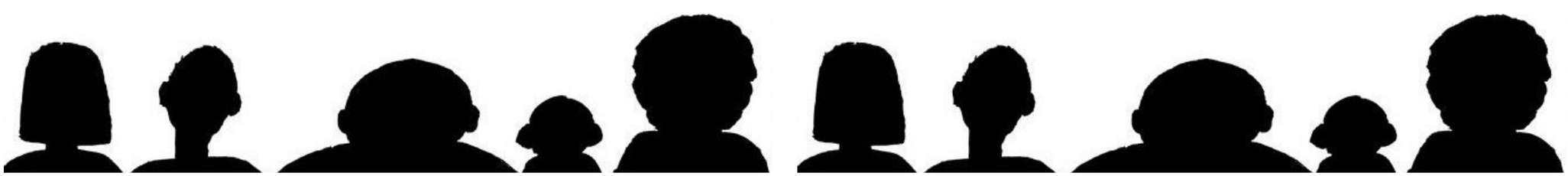
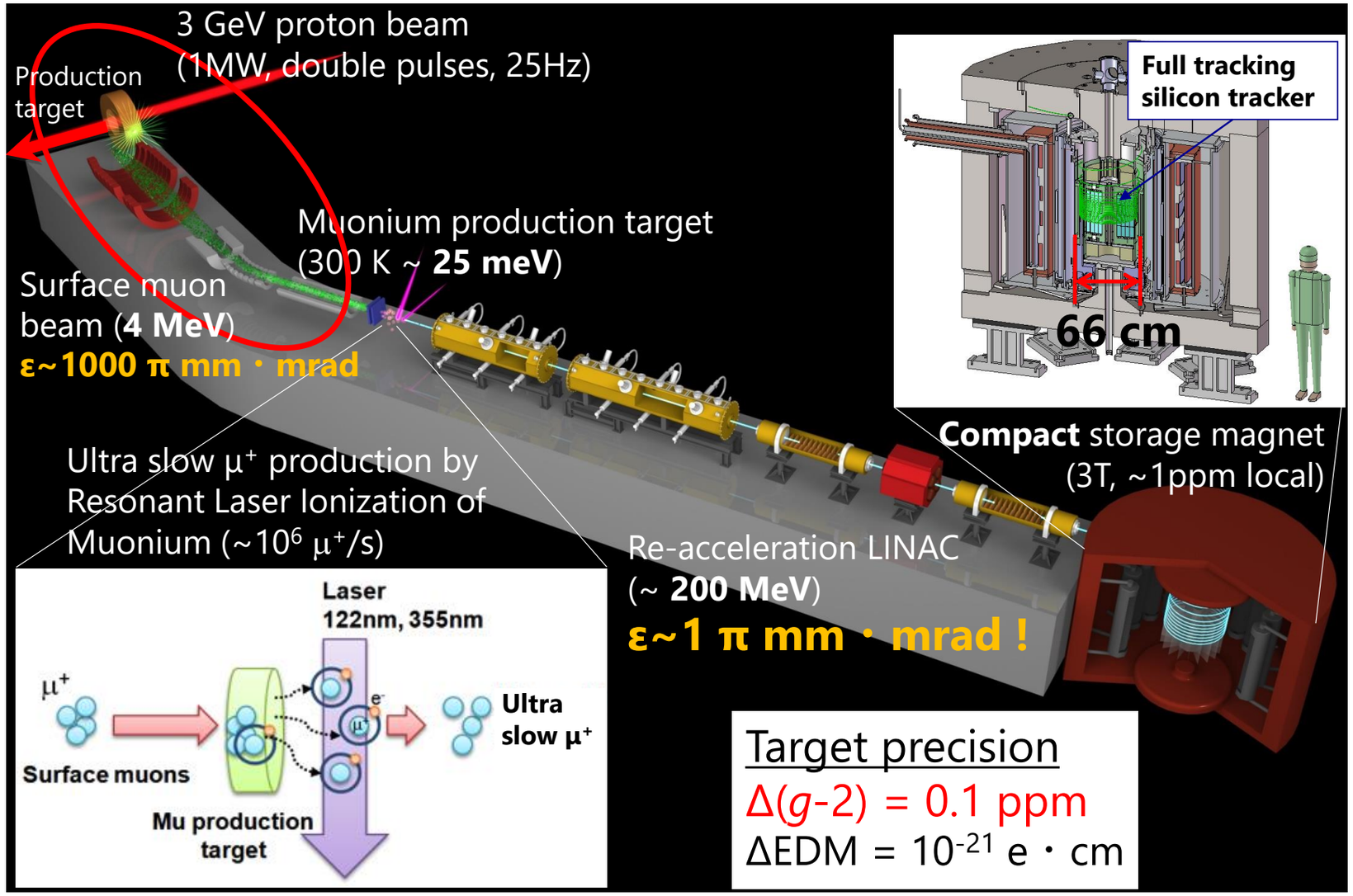
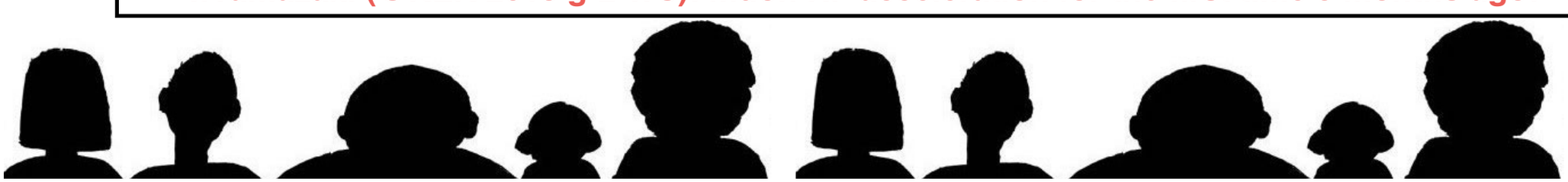


a_μ from the experiment: J-PARC E34



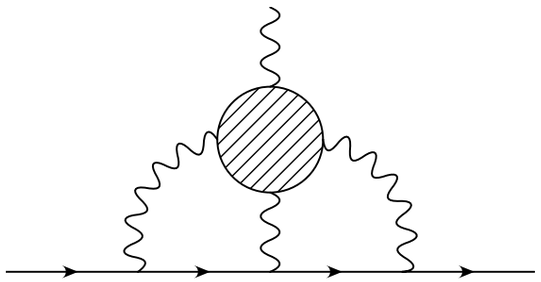
$$\vec{\omega_a} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta_\mu}{2}\left(\beta \times \vec{B} + \frac{E}{c}\right)\right]$$

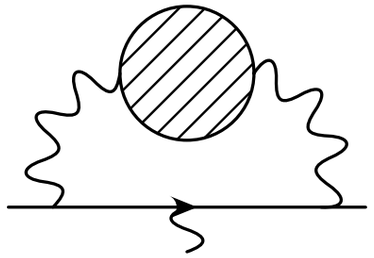
T.Yamazaki (@KEK 2018 g-2 WS): muon RF acceleration for the first time 5 months ago!



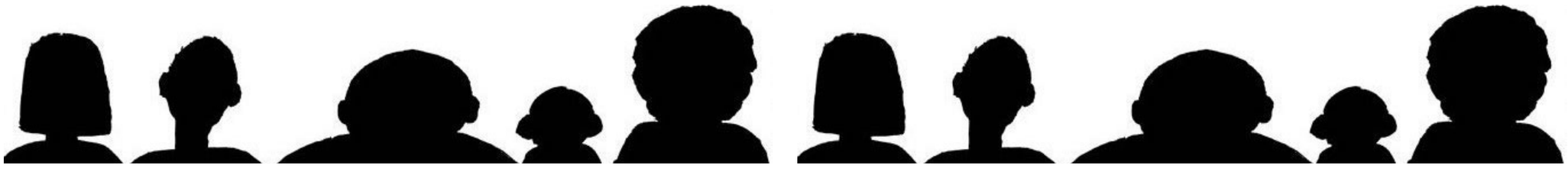
Muon g-2 Status

	2011		2017	
QED	11658471.81 (0.02)	$\longrightarrow$	11658471.90 (0.01)	[arXiv:1712.06060]
EW	15.40 (0.20)	$\longrightarrow$	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 **(2.60)**	[EPJ Web Conf. 118 (2016) 01016]
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]
	HLMNT11		**KNT18**	
LO HVP	694.91 (4.27)	$\longrightarrow$	693.27 **(2.46)**	[Phys.Rev. D 97 (2018)
NLO HVP	-9.84 (0.07)	$\longrightarrow$	-9.82 (0.04)	[Phys.Rev. D 97 (2018)
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144]
Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)	[Phys.Rev. D 97 (2018)
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)	[Phys.Rev. D 97 (2018)
Δa_μ	3.3σ	$\longrightarrow$	3.7σ	[Phys.Rev. D 97 (2018)



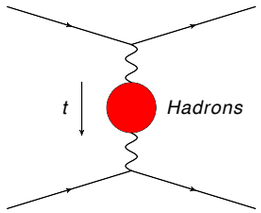


A. Keshavarzi@Mainz. Muon g-2 Theory Initiative WS. 18-22



MUonE project

- **A high precision measurement of $a_\mu^{had,\,LO}$ with a 150 GeV μ beam on e^- target at CERN**

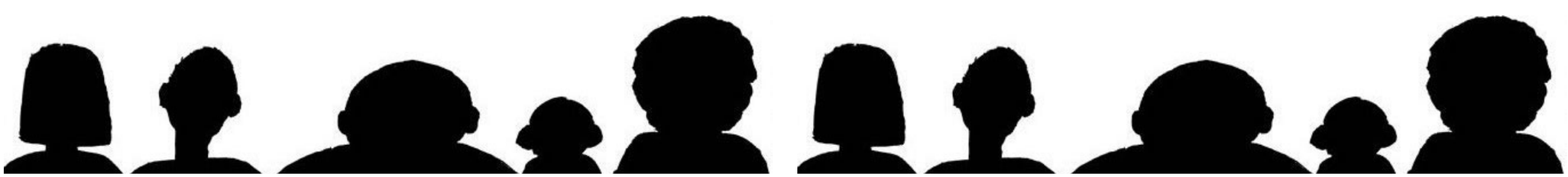


➡ **In space-like (Euclidean) momenta region**

➡ **Obtain $a_\mu^{had,\,LO}$ by utilising the running of α_{QED} in a space-like process**

$$a_\mu^{\mathbf{had,LO}} = \frac{\alpha}{\pi}\int_0^1 \mathbf{dx(1-x)\Delta\alpha_{had}[Q^2(x)]}$$

[Lautrup, de Rafael '69]



MUonE project

> 40 Scientists and growing …!

- A high precision measurement of $a_\mu^{HVP, LO}$ with a 150 GeV μ beam on e^- target at CERN

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➡ Obtain $a_\mu^{had, LO}$ by utilising the running of α_{QED} in a space-like process

$$a_\mu^{\mathbf{had,LO}} = \frac{\alpha}{\pi}\int_0^1 \mathbf{dx(1-x)\Delta\alpha_{had}[Q^2(x)]}$$

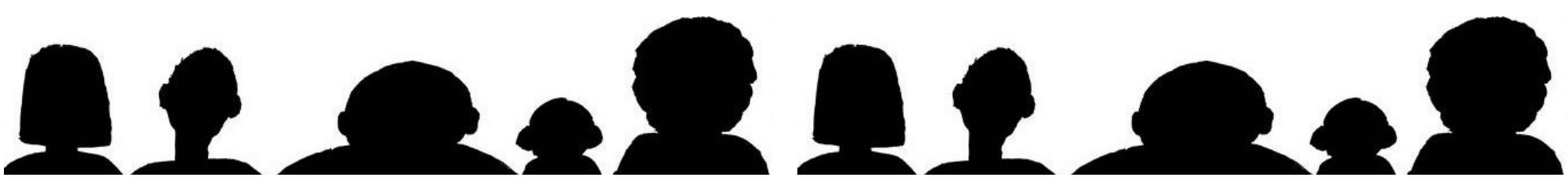
[Lautrup, de Rafael '69]

➡ Proposal to measure precisely the Q^2 - dependent fine-structure constant:

$$\alpha(Q^2) = \frac{\alpha(O)}{1-\Delta\alpha(Q^2)}$$

[Phys.Lett. B746 (2015) 325-329 by Carloni, Passera,Trentadue, Venanzoni] @e+e- detector

[Eur.Phys.J. C77 (2017) no.3, 139 by Abbiendi et al.] Physics Beyond Colliders@CERN



MUonE: space-like evaluation of $a_\mu^{\text{had, LO}}$

➡ **The running contributions can be split into the hadronic and the leptonic part:**

$$\Delta\alpha(Q^2) = \Delta\alpha_{had}(Q^2) + \Delta\alpha_{lep}(Q^2)$$

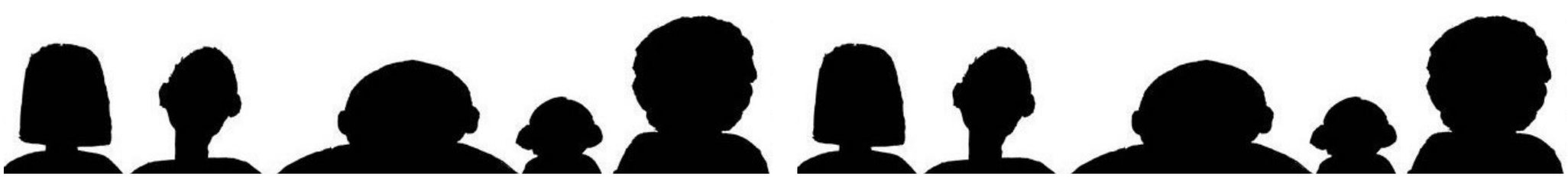
➡ **MUonE will measure total $\Delta\alpha(Q^2)$ in low-Q^2 region**

➡ **Subtracting the purely leptonic part gives leading order HVP:**

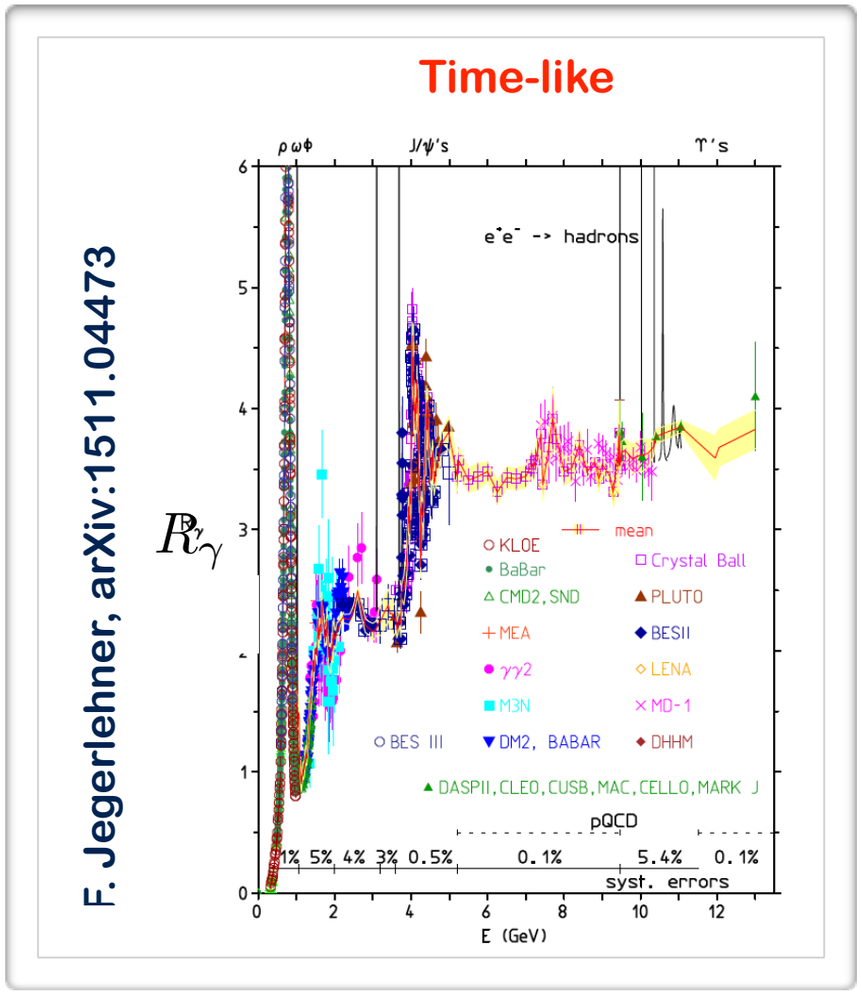
$$\Delta\alpha(Q^2) - \Delta\alpha_{lep}(Q^2) \equiv \Delta\alpha_{had}(Q^2) \longrightarrow a_\mu^{\text{had,LO}} = \frac{\alpha}{\pi}\int_0^1 \mathrm{d}x(1-x)\Delta\alpha_{\text{had}}[Q^2(x)]$$

known up to three loops [Steinhauser '98]

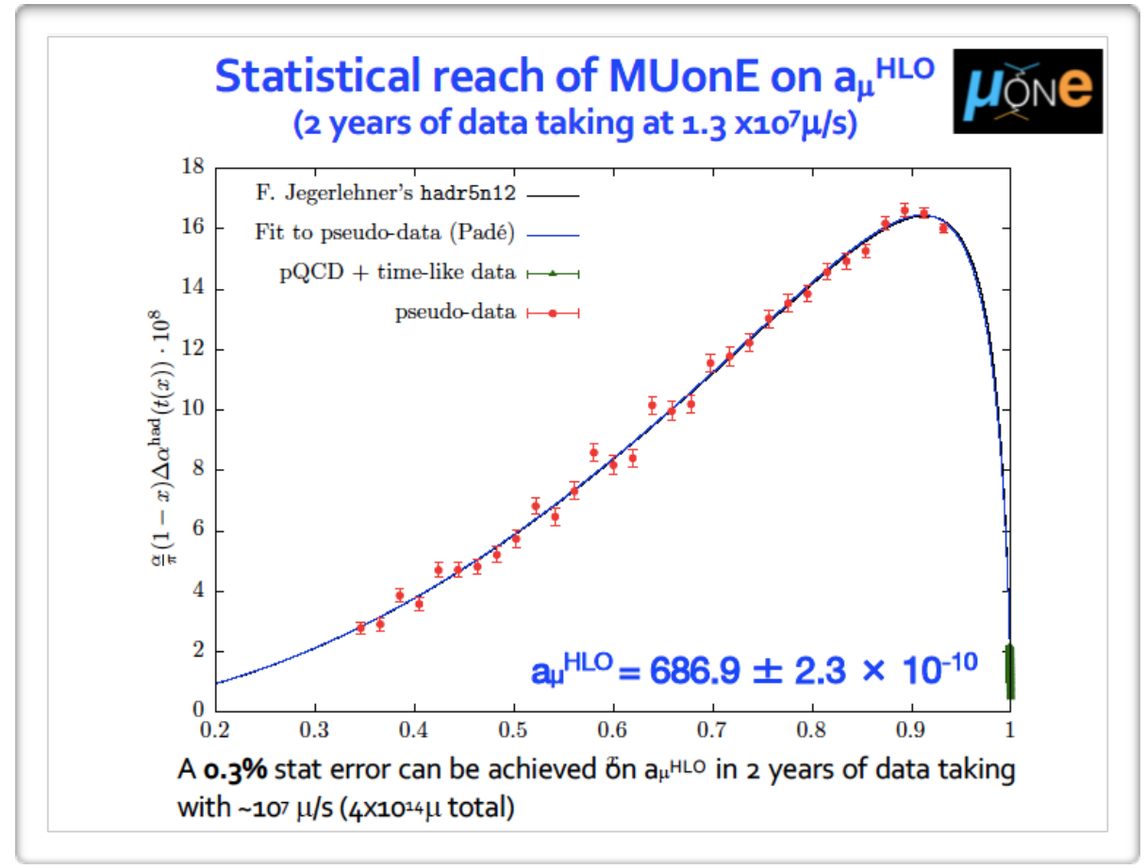
for some Q^2 four loops [Baikov et al. '13, Sturm '13]



MUonE: space-like evaluation of $a_\mu^{had,\ LO}$



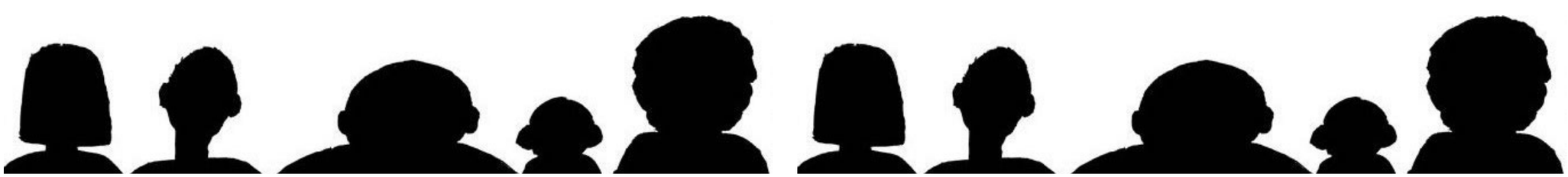
Space-like



➡ combination of many exp. data sets

➡ smooth integrand

➡ single experiment enough - but high accuracy needed (one-loop effect)



MUonE experimental setup

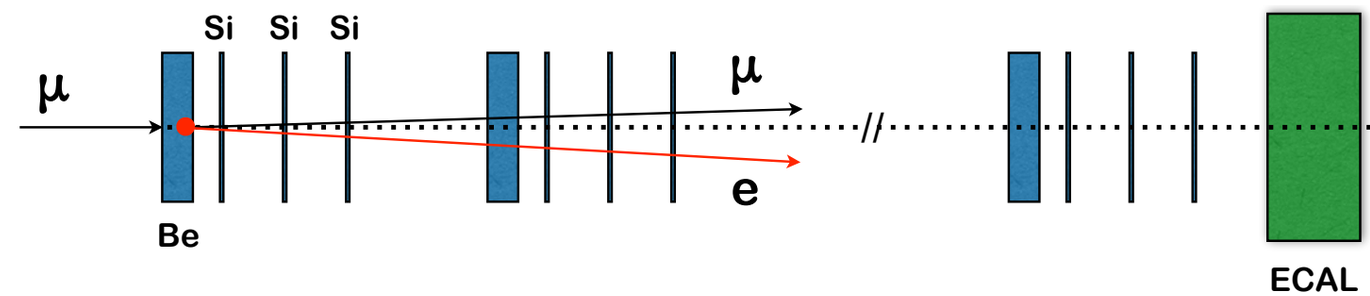
- **A high precision measurement of $a_\mu^{HVP, LO}$ with a 150 GeV μ beam on e^- target at CERN**

➡ ≈60 modules (distributed target) each ~ 0.5m length

[Eur.Phys.J. C77 (2017) no.3, 139 by Abbiendi et al.]

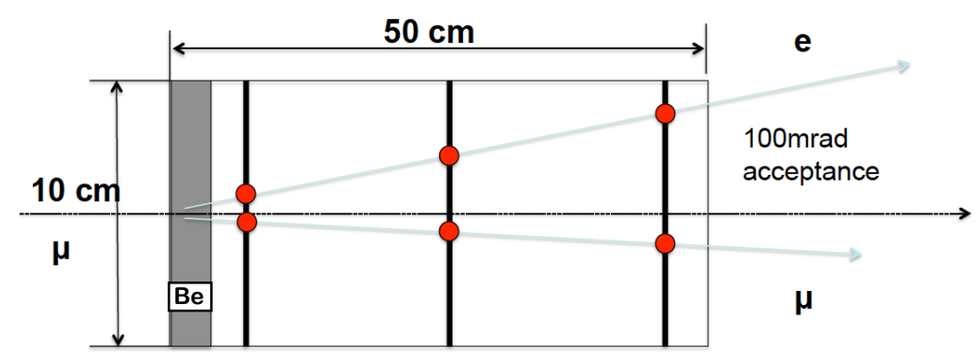
➡ Modular apparatus: each module has ≈1 cm

Beryllium target and 3/4 state-of-the-art Silicon strips detectors

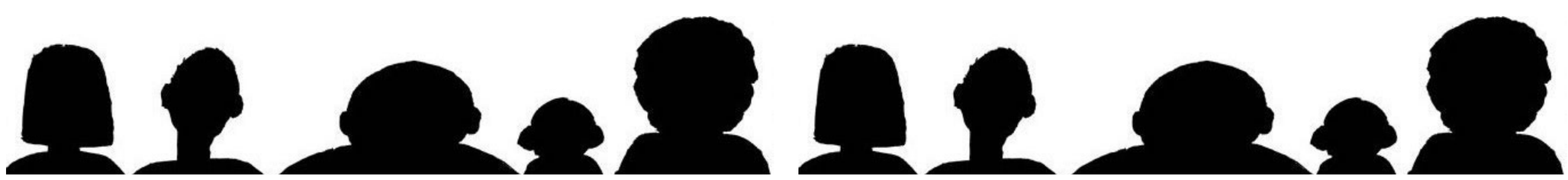


➡ Signal angular region: $\theta_e \leq 45 \text{ mrad} \quad \theta_\mu \leq 5 \text{ mrad}$

➡ Expected intrinsic angular resolution: 0.02 mrad



➡ Main challenge: multiple scattering (tests in progress)



MUonE experimental tests in progress

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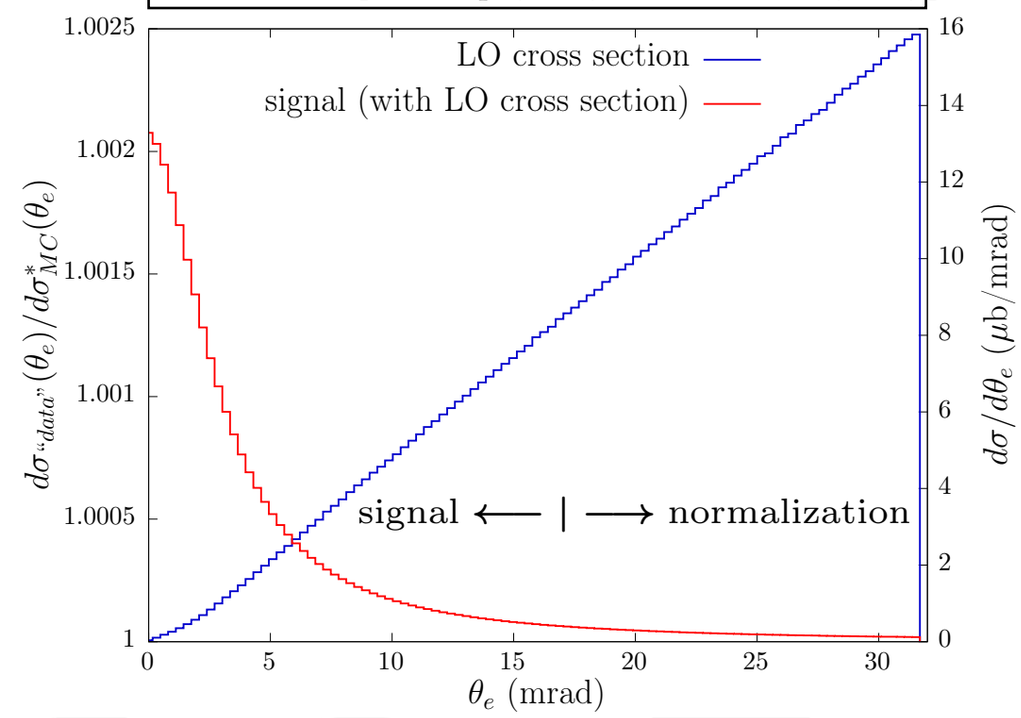
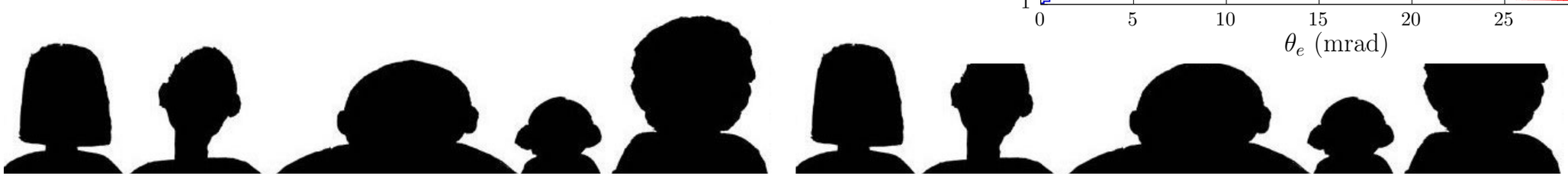
➡ **Expected intrinsic angular resolution:** 0.02 mrad

➡ **Main challenge: multiple scattering (tests in progress)**

$$\text{The Signal} \equiv \frac{dN_{data}(O_i)}{N_{data}^{norm}} \times \frac{\sigma_{MC}^{norm}}{d\sigma_{MC}^{*}(O_i)} \simeq 1 + 2[\Delta\alpha_{lep}(Q^2) + \Delta\alpha_{had}(Q^2)]$$

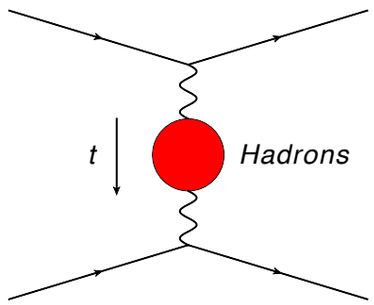




MUonE: theoretical effort underway

[0.001,0.14] GeV^2

➡ **Theory in low-Q^2 [dominating HVP integral]: To extract $\Delta\alpha_{had}(t)$ from this measurement, the ratio of the SM cross sections in the signal and normalisation regions must be known at ≲ 10ppm!**



[NNLO amp.: Di Vita, Laporta, Mastrolia, Ossola, Passera, Primo, Schubert, Torres … Mastrolia et al. JHEP 11 (2017), Di Vita et. al arXiv:1806.08241]

[NNLO had. contributions Fael, Passera]

[Fixed-order NNLO+ Resumation Broggio, Signer, Ulrich]

[MC@NNLO Carloni, Montagna, Nicrosini, Piccinini,Czyz…]

[…]

[0.14,4] GeV^2

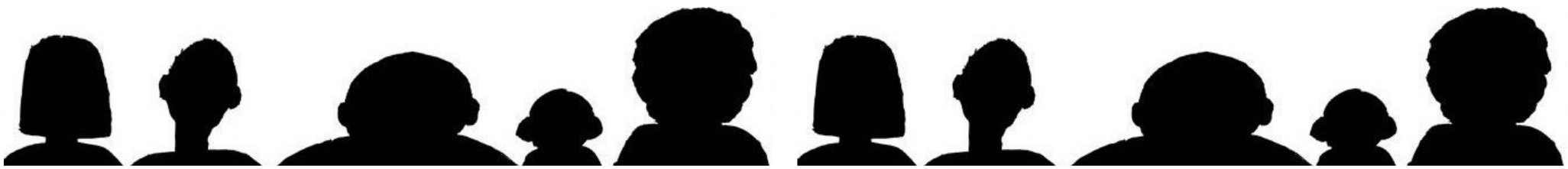
➡ **Theory in intermediate-Q^2: Lattice QCD or analytic continuation of the R-ratios**

[4, ∞] GeV^2

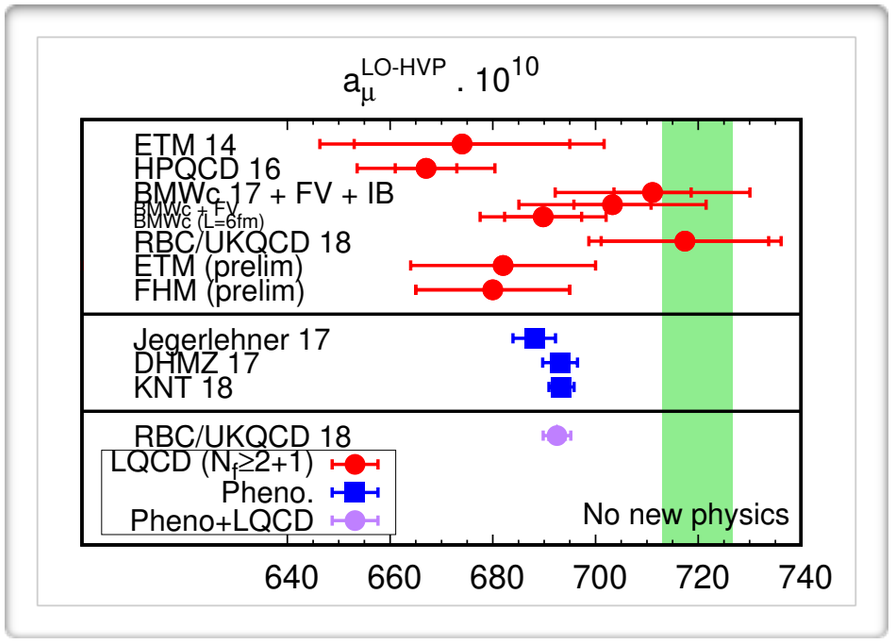
➡ **Theory in high-Q^2: PT** √

[Chetyrkin et al. '96]

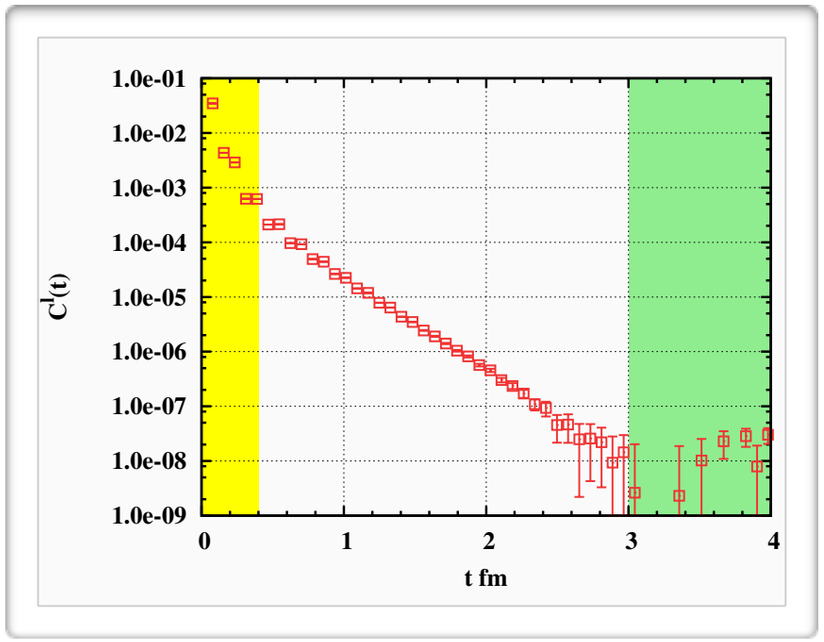
[Harlander&Steinhauser '02]



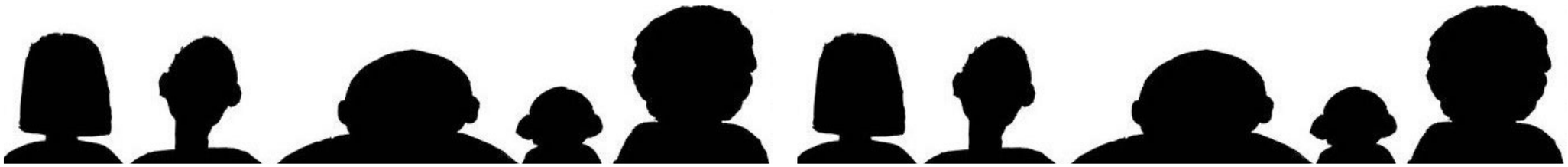
Lattice determinations of HVP



[K. Miura @ LAT2018]



- ➡ Progress in lattice determinations of HVP [K. Miura, Wed. 9am]
- ➡ Complementary approach: interplay between exp. and lattice determinations of HVP
- ➡ @Granada: C. Lehner: a connection of lattice HVP to the R-ratio data [C.LEHNER, FRI 14.00]
- ➡ In this talk: demonstrate what can lattice do for μONe @ CERN Physics Beyond Colliders and vice versa

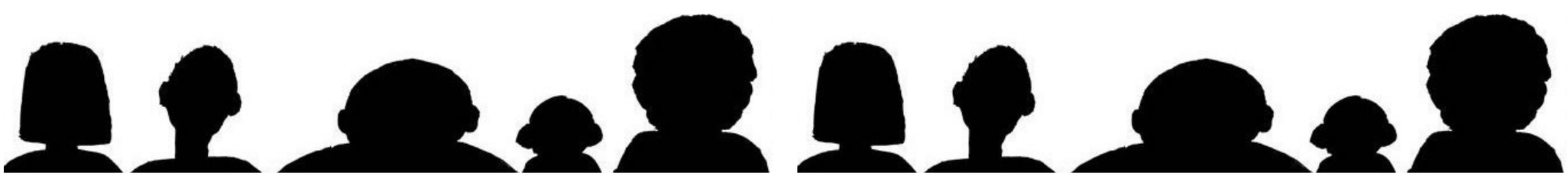


MUonE: space-like evaluation of $a_\mu^{\text{had, LO}}$

➡ **Subtracting the purely leptonic part gives leading order HVP:**

$$\Delta\alpha(Q^2) - \Delta\alpha_{lep}(Q^2) \equiv \Delta\alpha_{had}(Q^2) \longrightarrow a_\mu^{\mathbf{had,LO}} = \frac{\alpha}{\pi}\int_0^1 \mathbf{dx}(\mathbf{1-x})\boldsymbol{\Delta}\alpha_{\mathbf{had}}[\mathbf{Q^2(x)}]$$

$$Q^2 = \frac{x^2 m_\mu^2}{1-x}$$



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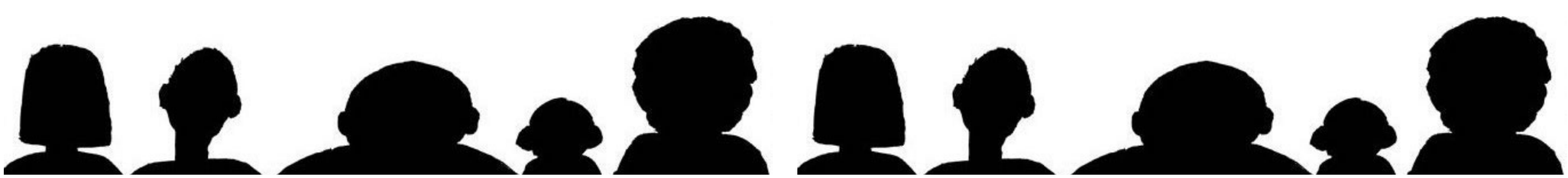
[Lautrup, de Rafael '69]

[T. Blum '03]

$$Q^2 = \frac{x^2 m_\mu^2}{1-x}$$

$$a_\mu^{\mathbf{had,LO}} = \frac{\alpha}{\pi}\int_0^\infty \mathbf{dQ^2}\sqrt{\frac{\mathbf{1}}{\mathbf{Q^2(4m_\mu^2+Q^2)}}}\left(\frac{\sqrt{\mathbf{4m_\mu^2+Q^2}}-\sqrt{\mathbf{Q^2}}}{\sqrt{\mathbf{4m_\mu^2+Q^2}}+\sqrt{\mathbf{Q^2}}}\right)^{\mathbf{2}}\hat{\mathbf{\Pi}}(\mathbf{Q^2})$$



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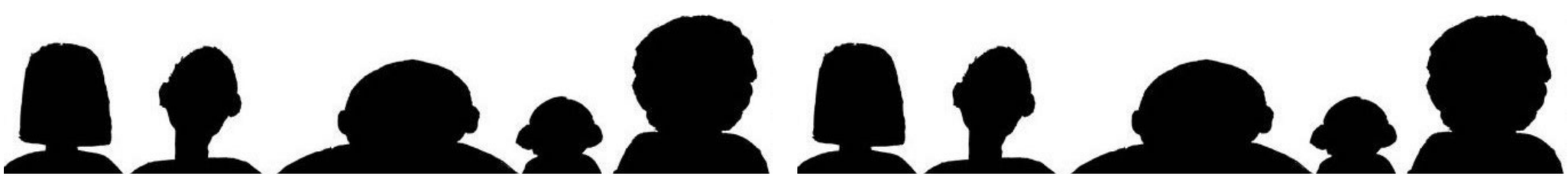
[Lautrup, de Rafael '69]

[T. Blum '03]

$$Q^2 = \frac{x^2 m_\mu^2}{1-x}$$

$$a_\mu^{\mathbf{had,LO}} = \left(\frac{\alpha}{\pi}\right)^{\mathbf{2}}\int_0^\infty \mathbf{dQ^2}\underbrace{\sqrt{\frac{1}{Q^2(4m_\mu^2+Q^2)}}\left(\frac{\sqrt{4m_\mu^2+Q^2}-\sqrt{Q^2}}{\sqrt{4m_\mu^2+Q^2}+\sqrt{Q^2}}\right)^2}\ \hat{\mathbf{\Pi}}(\mathbf{Q^2})$$

$$a_\mu^{\mathbf{had,LO}} = \left(\frac{\alpha}{\pi}\right)^{\mathbf{2}}\int_0^\infty \mathbf{dQ^2}\mathbf{f}(\mathbf{Q^2})\hat{\mathbf{\Pi}}(\mathbf{Q^2})$$



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$$Q^2 = \frac{x^2 m_\mu^2}{1-x}$$

[Lautrup, de Rafael '69]

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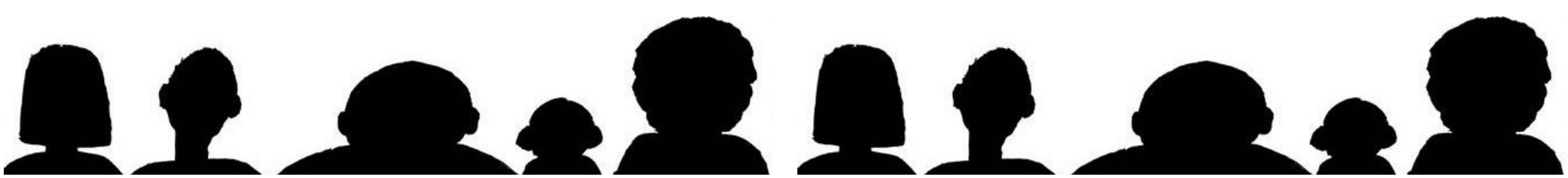
$$a_\mu^{\mathbf{had,LO}} = \left(\frac{\alpha}{\pi}\right)^{\mathbf{2}}\int_0^\infty \mathbf{dQ^2}\underbrace{\sqrt{\frac{1}{Q^2(4m_\mu^2+Q^2)}}\left(\frac{\sqrt{4m_\mu^2+Q^2}-\sqrt{Q^2}}{\sqrt{4m_\mu^2+Q^2}+\sqrt{Q^2}}\right)^2}\ \hat{\mathbf{\Pi}}(\mathbf{Q^2})$$

➡ **f(Q²) diverges as** $Q^2 \longrightarrow 0$

➡ **Dominant contribution to the integral:** $Q^2 \approx m_\mu^2$

$$a_\mu^{\mathbf{had,LO}} = \left(\frac{\alpha}{\pi}\right)^{\mathbf{2}}\int_0^\infty \mathbf{dQ^2}\mathbf{f(Q^2)}\hat{\mathbf{\Pi}}(\mathbf{Q^2})$$



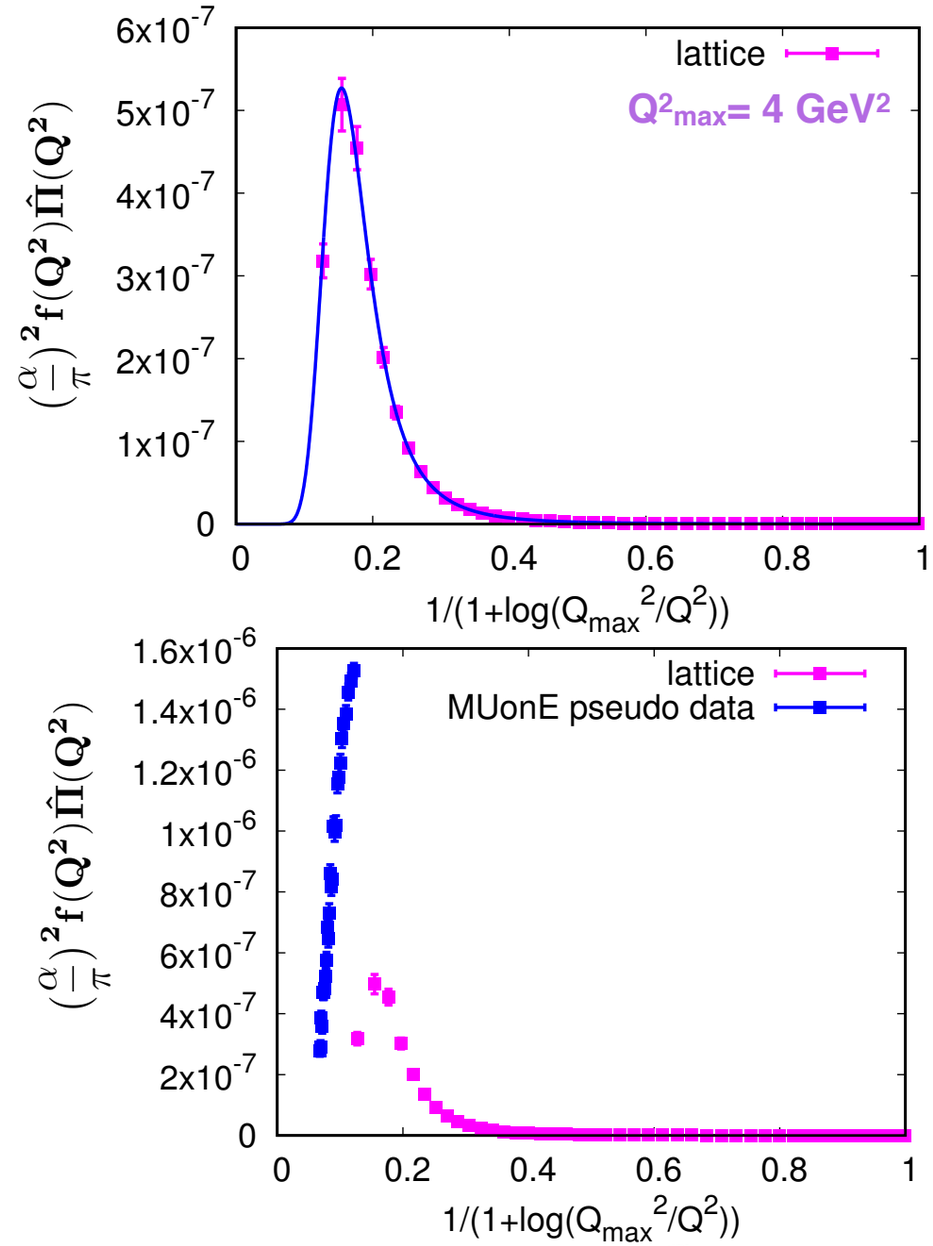
MUonE: space-like evaluation of $a_\mu^{\text{had, LO}}$

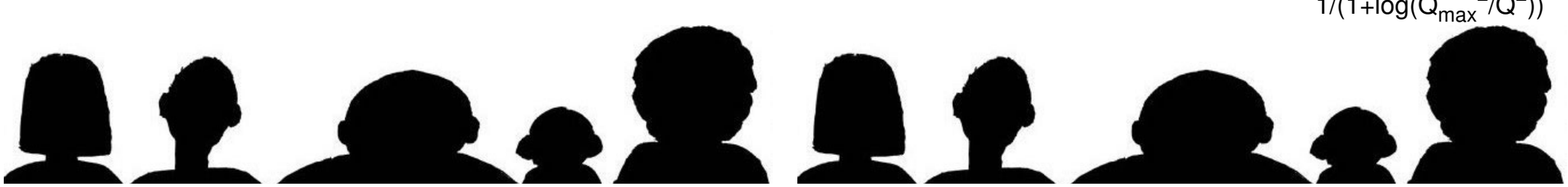
- ➡ Lattice: also Euclidean mom.
- ➡ smooth integrand

$$a_\mu^{\mathbf{had,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty \mathbf{dQ^2 f(Q^2)\hat{\Pi}(Q^2)}$$

- ➡ $\mathbf{\hat{\Pi}(Q^2) = 4\pi^2(\Pi(Q^2) - \Pi(0))}$ accessible directly
- ➡ Low-Q^2 not covered (momenta quantization & limitation in lattice sizes)
- ➡ Deterioration of signal/noise as Q^2—>0

Space-like

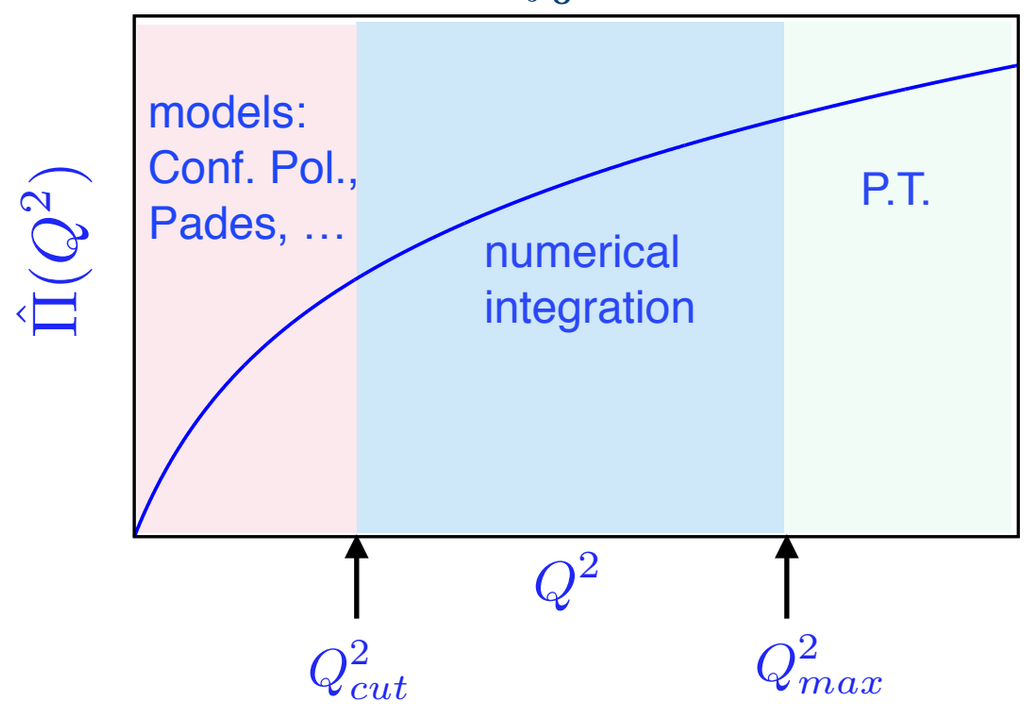




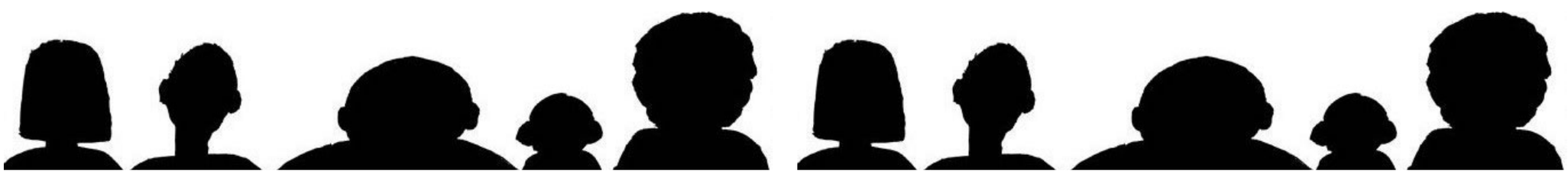
Hybrid method: separate integration ranges to control the systematics

Phys. Rev. D 90, 074508 (2014), [M. Golterman, K. Maltman, S. Peris]

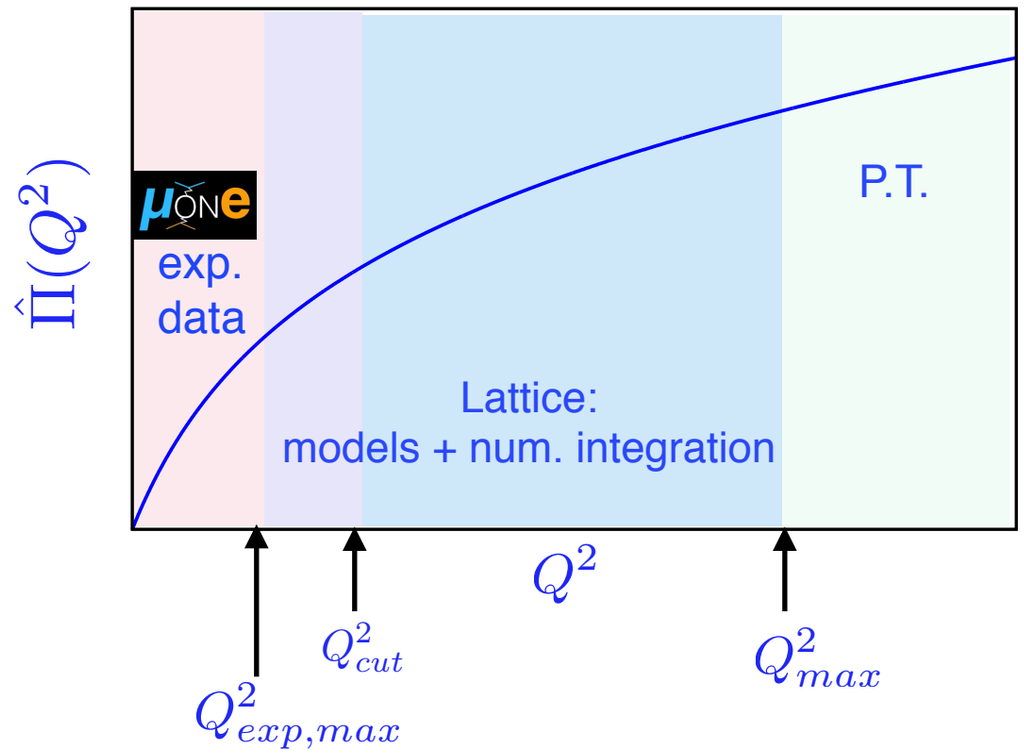
$$a_\mu^{\mathbf{had,LO}} = \left(\frac{\alpha}{\pi}\right)^{\mathbf{2}} \int_{\mathbf{0}}^{\infty} \mathbf{dQ^2 f(Q^2)\hat{\Pi}(Q^2)}$$



- ➡ Motivated by the observation that the systematics error grows with Q^2_{cut}
- ➡ Physically motivated τ-model for I=1 HVP: 80% of HVP from Q^2<0.1GeV^2, 90% from Q^2<0.2GeV^2
- ➡ Applied for determining strange quark HVP [RBC/UKQCD, JHEP 1604 (2016)]
- ➡ Compared with TMR method for light/strange/charm HVP [CLS/Mainz, JHEP 1710 (2017)]



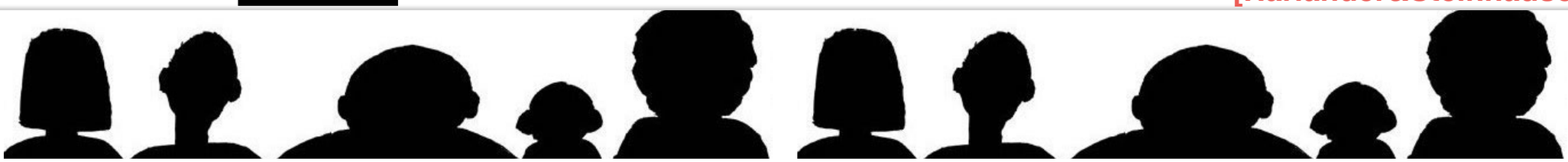
Hybrid method: MUonE experiment +lattice



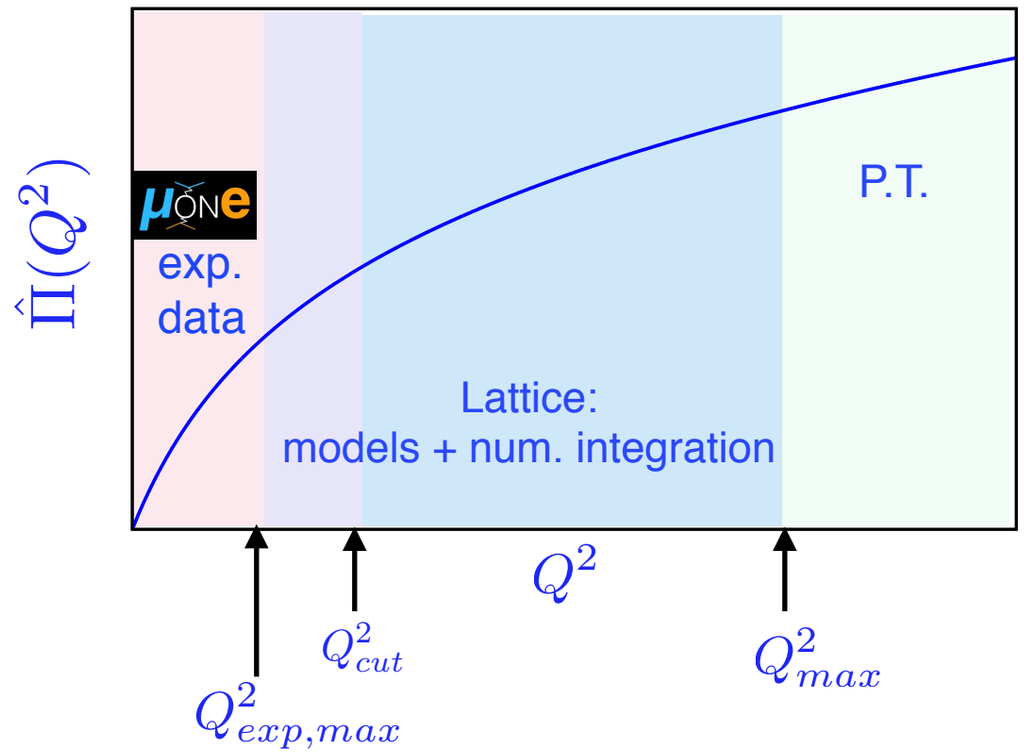
$$a_\mu^{had,LO} = \underbrace{\frac{\alpha}{\pi}\int_0^{0.93\ldots} dx(1-x)\Delta\alpha_{had}[Q^2(x)]}_{I_0} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2 \int_{0.14}^{Q^2_{max}} dQ^2 f(Q^2)\times\hat{\Pi}(Q^2)}_{I_1} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2 \int_{Q^2_{max}}^{\infty} dQ^2 f(Q^2)\times\hat{\Pi}_{pert.}(Q^2)}_{I_2}$$

- lattice QCD
- R-ratios

[Chetyrkin et al. '96]
[Harlander&Steinhauser '02]



Hybrid method: MUonE experiment +lattice



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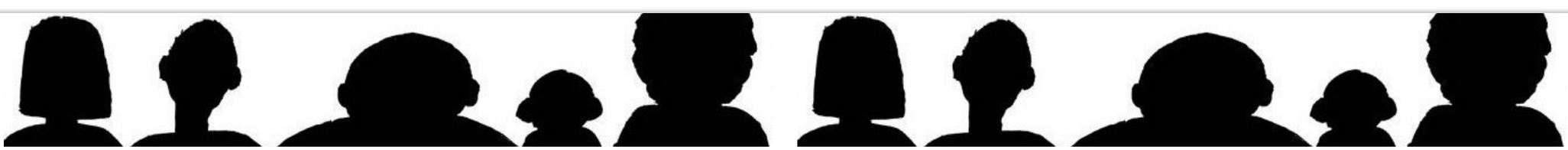
- **lattice QCD**
- **R-ratios**

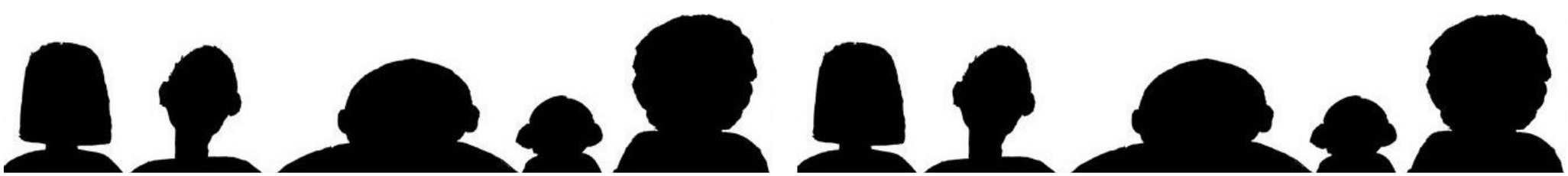
- I_1 **contribution to the HVP from the lattice: control of systematics easily attainable**



HVP: Intermediate-Q^2 range integration

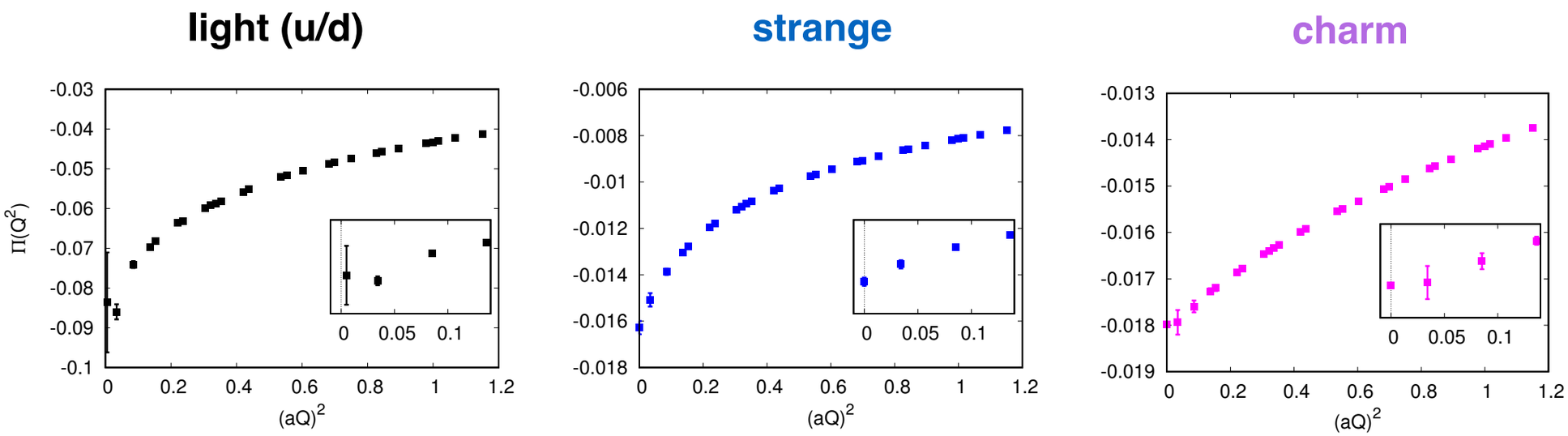
$$a_\mu^{had,LO} = \underbrace{\frac{\alpha}{\pi}\int_0^{0.93\ldots} dx(1-x)\Delta\alpha_{had}[Q^2(x)]}_{I_0} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2 \int_{0.14}^{Q^2_{max}} dQ^2 f(Q^2)\times\hat{\Pi}(Q^2)}_{I_1} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2 \int_{Q^2_{max}}^{\infty} dQ^2 f(Q^2)\times\hat{\Pi}_{pert.}(Q^2)}_{I_2}$$

- $\mathcal{I}_1$ on CLS ensembles with N_f=2 O(a) improved Wilson fermions (A5,E5,F6,G8,N6,O7)
- m_π≈180-440MeV, continuum extrapolation (0.05-0.09fm), chiral extrapolation to $m_{\pi,phys}$
- Partially quenched: s, c (κ_s,κ_c taken from [CLS/Mainz, JHEP 1710 (2017)])
- Neglecting isospin breaking effects ($m_u \neq m_d$ and $\alpha_{em} \neq 0$) and disconnected contribution
- $m_\pi L \geq 4$, long-distance effects effects in $\mathcal{I}_1$ not yet explored explicitly
- VP function from the off-diagonal component of the conserved-conserved current correlator: $\Pi(Q^2) = \frac{\Pi_{\mu\nu}(Q)}{p_\mu p_\nu}$



HVP: Intermediate-Q^2 range integration

m_π = 311 MeV
$L^3xT=48^3x96$
a=0.066fm
N_{cfg}=60
N_{meas}=480

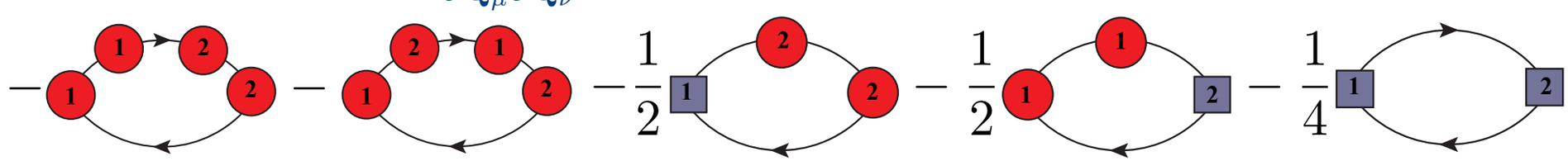


➡ Statistical precision in I_1 (still) determined by $\Pi(0)$ $\boxed{\hat{\Pi}(Q^2) = 4\pi^2(\Pi(Q^2) - \Pi(0))}$

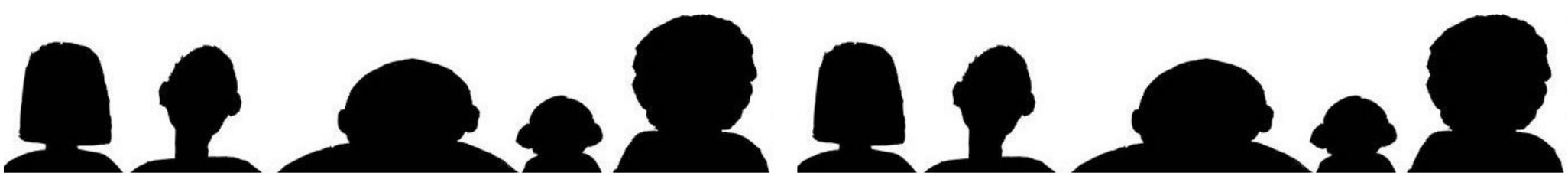
➡ Expansion of the quark propagator around zero spatial momentum

➡ Strange & Charm contributions: $\Pi(0) = -\frac{\partial \Pi_{\mu\nu}(Q)}{\partial Q_\mu \partial Q_\nu}|_{Q^2=0}$ [de Divitiis, Petronzio, Tantalo; Phys.Lett. B718 (2012)]

$\Pi(0) =$



➡ Light contribution: Q^2—> 0 extrapolation



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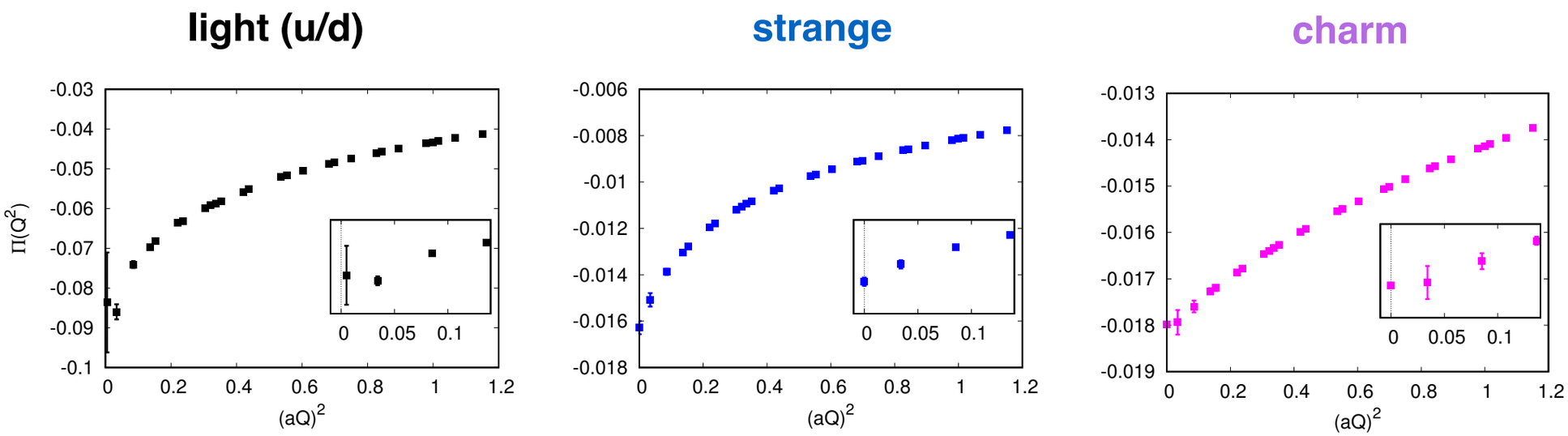

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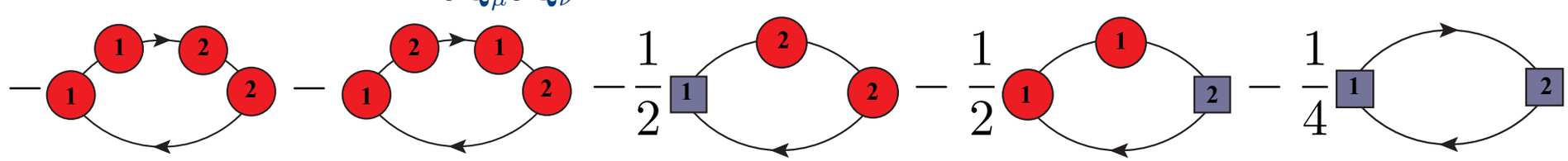
➡Expansion of the quark propagator around zero spatial momentum

"derivative method"/"Rome method"

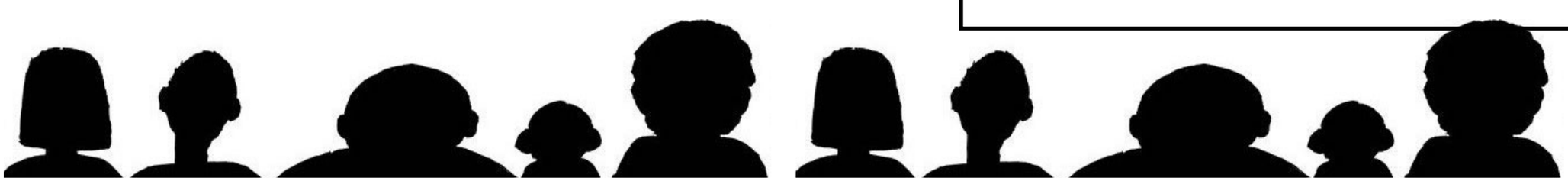
➡Strange & Charm contributions: $\Pi(0) = -\frac{\partial \Pi_{\mu\nu}(Q)}{\partial Q_\mu \partial Q_\nu}|_{Q^2=0}$ [de Divitiis, Petronzio, Tantalo; Phys.Lett. B718 (2012)]

$\Pi(0) =$



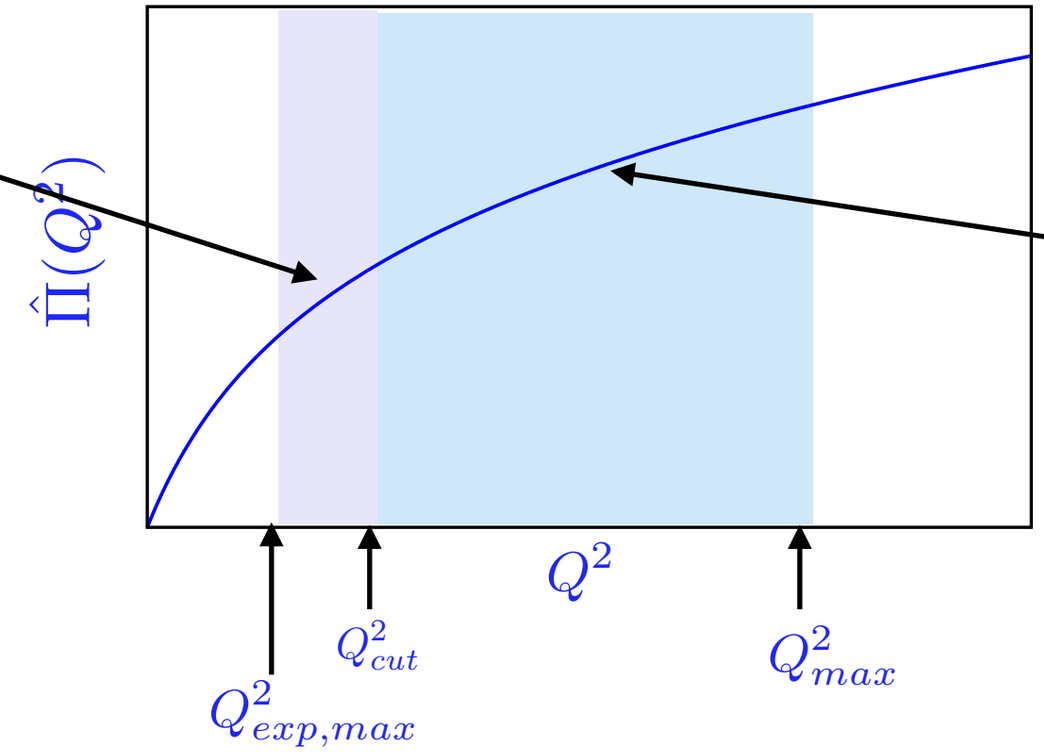
➡Light contribution: Q^2—> 0 extrapolation

recently applied on nuclear charge&axial radius
[N. Hasan et al. Phys.Rev. D97 (2018) no.3, 034504]



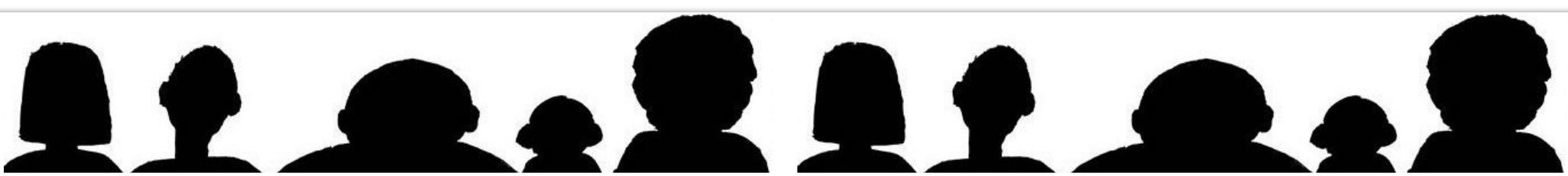
HVP: Intermediate-Q^2 range integration

Padé/conformal polynomial fits
[0.14, Q^2_{cut}] GeV^2

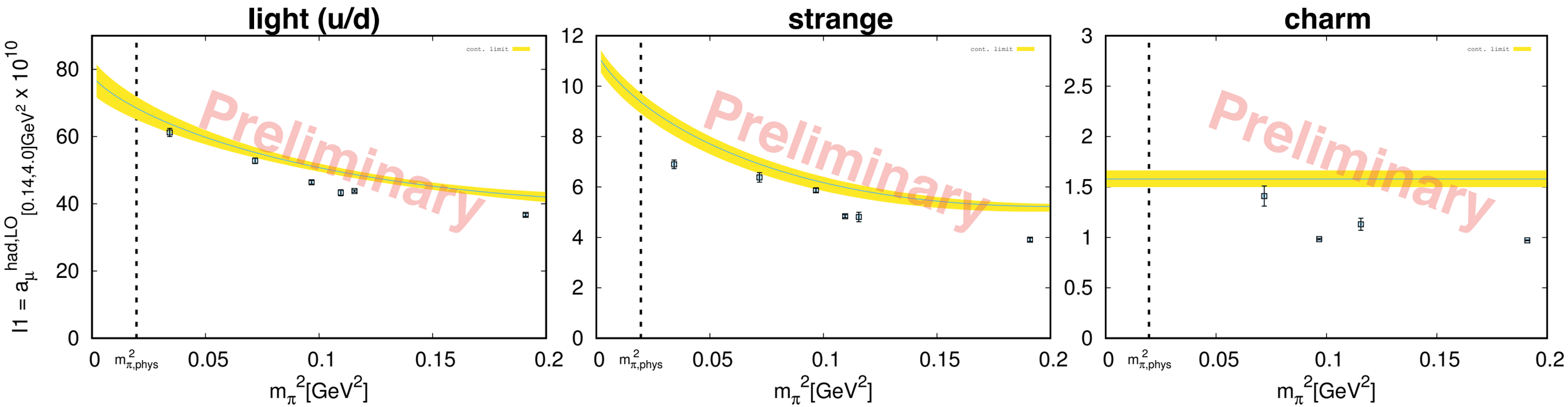


Numerical integration
[Q^2_{cut},4.0]GeV^2, Q^2_{cut} = 0.5-1.0 GeV^2
[Golterman et al.
Phys. Rev. D 90, 074508 (2014)]

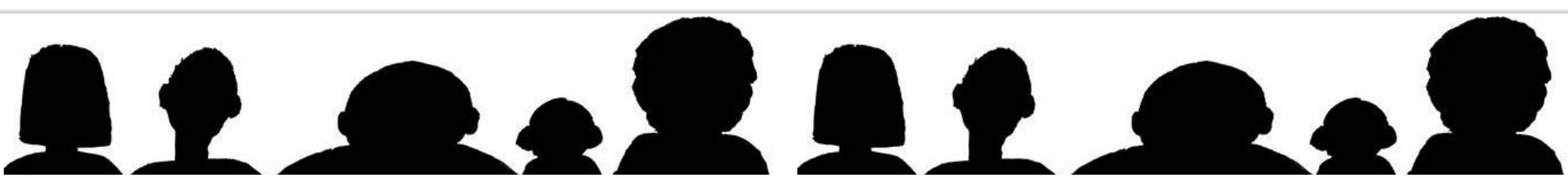
- Unlike for LO HVP at the full Q^2-range —> important to get $\Pi(Q^2)$ at high-Q^2 correctly
  - [M. CÈ, FRI 15.40, CLS/Mainz,LAT15: arXiv:1511.04751, ETM JHEP 1511 (2015)]
  - NLO HVP [HPQCD/Fermilab: Chakraborty, Davies, Koponen, Lepage,V.d.Water; arXiv:1806.08190]
- Padé approximants guaranteed to converge to the actual $\hat{\Pi}(Q^2)$[Aubin, Blum,Golterman,Peris Phys.Rev. D86 (2012)]
- Higher order Pade's needed, if fitting momenta Q^2>0.5GeV^2

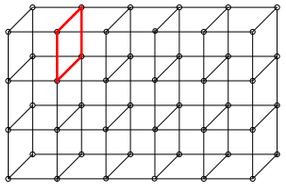


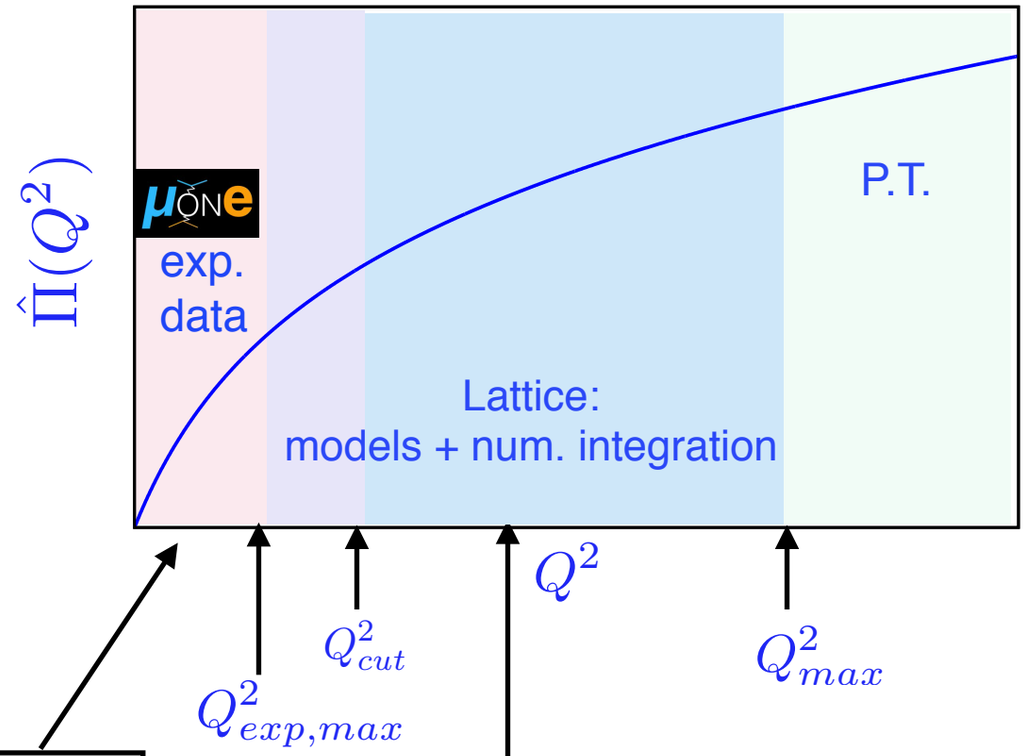
HVP: Intermediate-Q^2 range integration



- Continuum + chiral extrapolation: $\alpha_1 + \alpha_2 m_\pi^2 + \alpha_3\ m_\pi^2 ln(m_\pi^2) + \alpha_4\ a$ (light/strange)
- Preliminary result $I_1^{u,s,c}$=79.5(3.5)x10^{-10}; 4% uncertainty in I_1 corresponds to ≈0.5% in the full HVP
- Further work: more statistics at near physical m_π, O(a) improved vector current [T.Harris, H. Meyer Phys.Rev. D92 (2015)]
- Additional caveats: cutoff effects, isospin breaking corrections, finite volume effects, disconnected contribution

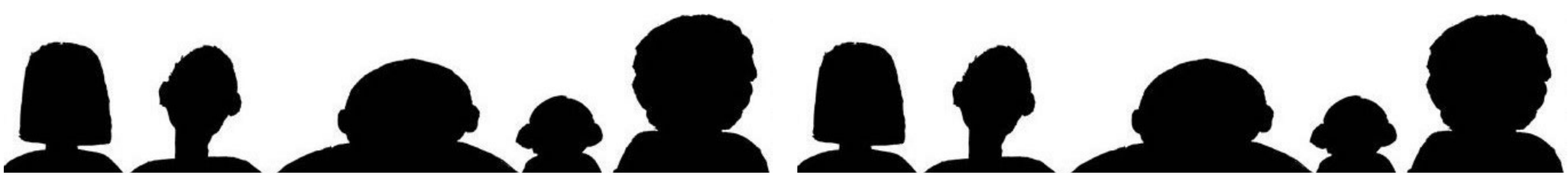


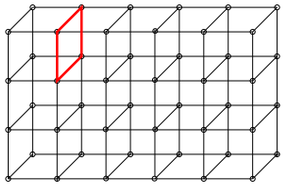
Hybrid strategy for the HVP: μONE +  + P.T.

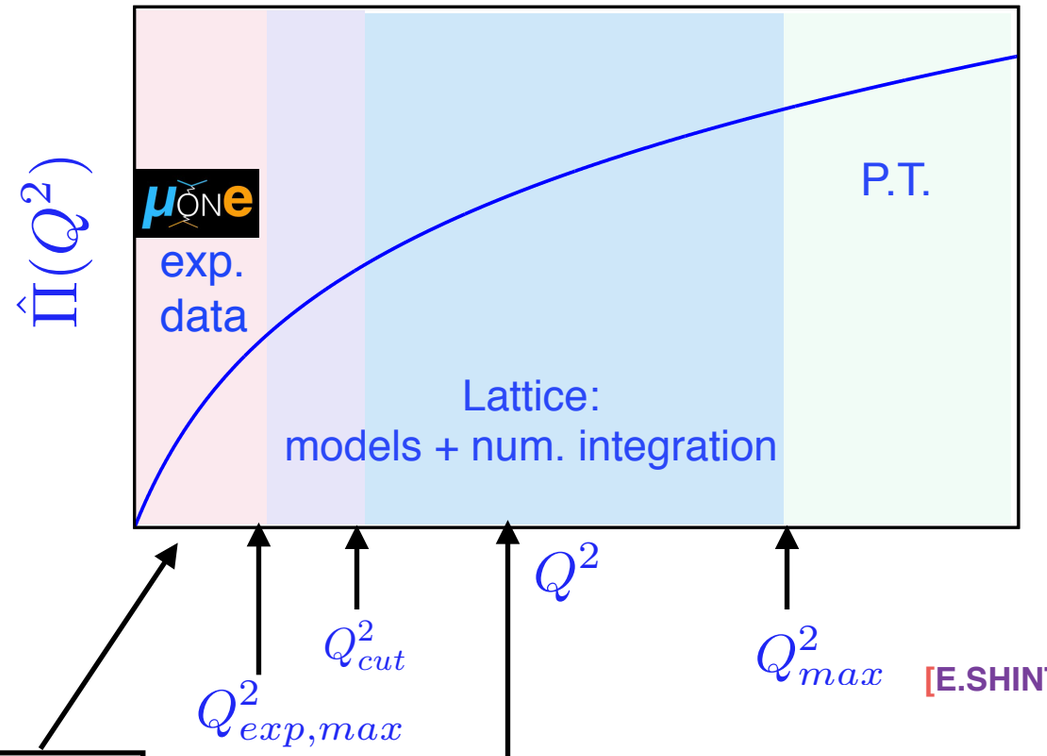


- Low momentum region
  - Experiment (NLO, NNLO, radiative corrections …)

- continuum limit: a—> 0
- finite volume corrections
- chiral extrapolation
- isospin breaking corrections ($m_u \neq m_d$ and $\alpha_{em} \neq 0$)



Hybrid strategy for the HVP: μONE +  + P.T.

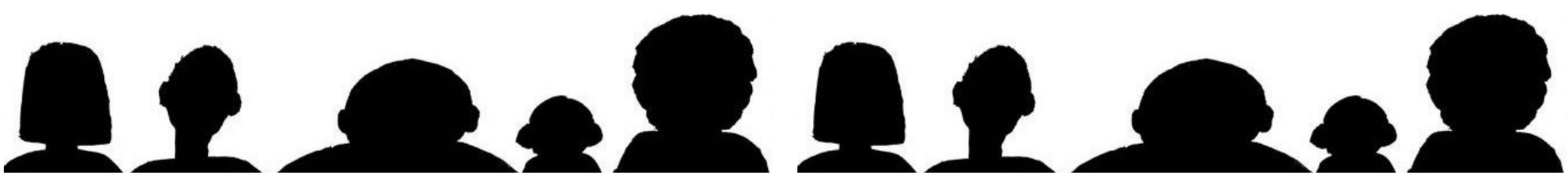


[E.SHINTANI TUE 16.30, T.BLUM, FRI 16.30, H.WITTIG FRI 16.50]

- Low momentum region
  - Experiment (NLO, NNLO, radiative corrections …)

- continuum limit: a—> 0
- finite volume corrections
- chiral extrapolation
- isospin breaking corrections ($m_u \neq m_d$ and $\alpha_{em} \neq 0$)

[A.RISCH TUE 16.30, V..GUELPERS, FRI 14.40, M.BRUNO FRI 15.00, J. ZANOTTI FRI 15.20,D.GIUSTI FRI 17.10]

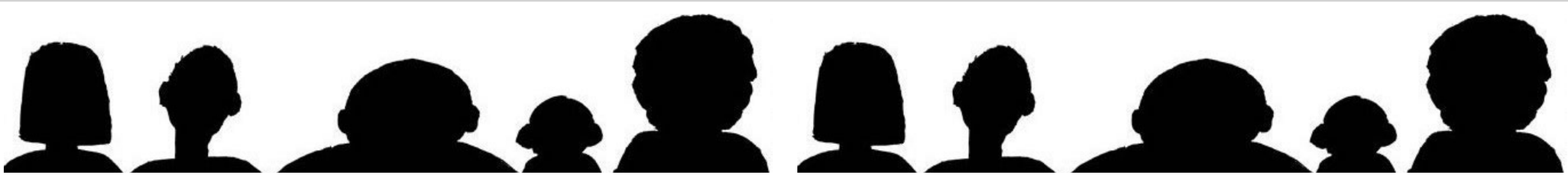


Summary & Outlook

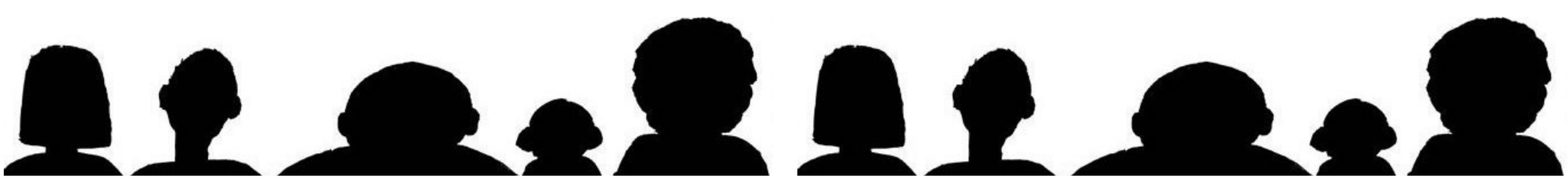
- MUONE experiment: space-like mu-e scattering [setup and status]
- In the 2-3 years, 0.3% statistical uncertainty in HVP expected
- Measuring the running of α_{QED} in the $Q^2 \in [0.001, 0.14]$ GeV^2 which dominates the HVP

- Hybrid method [Golterman et. al.'14] (Exp.+Lat.+P.T.): $I = I_0 + I_1 + I_2$
- I_1 from the lattice, CLS ensembles with Nf=2 O(a) improved Wilson fermions
- Outlook: cross-checks with different lattice discretizations, TMR, use $m_{\pi,phys}$, revisit strategy for a_μ^{light}

- Useful input from the lattice community: for $\hat{\Pi}(Q^2)$ at fixed momentum transfer (a—>0; V—> ∞ limit)
- Muon g-2 Theory Initiative [~Fermilab '16, [KEK/UConn. '17], Mainz '17] white paper in preparation
- In the mean time: have a look @ [H.Meyer, H. Wittig PPNP Review, arXiv:1807.XXXXX —> NEW!!! Lattice & Muon g-2]
- MUonE: L.O.I. to SPSC@CERN due for submission next year - welcome to join us!



Thank you!



Acknowledgements

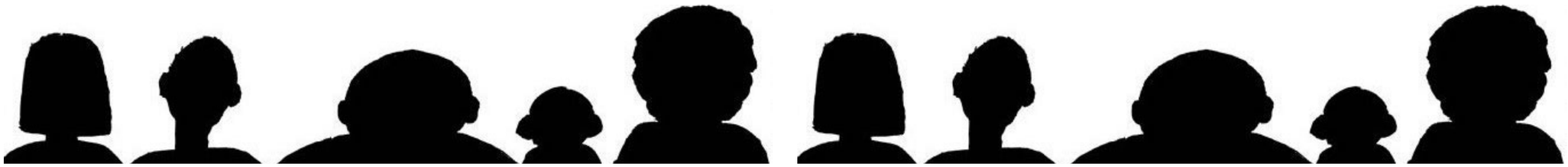
- This work was supported by TCHPC (Research IT, Trinity College Dublin).

- Most calculations were performed on the Lonsdale and Kelvin clusters maintained by the Trinity Centre for High Performance Computing. This cluster was funded through grants from Science Foundation Ireland.

- Part of the simulations reported in this talk were performed on a dedicated PC cluster at CERN. We are grateful to the CERN IT Department for technical support.

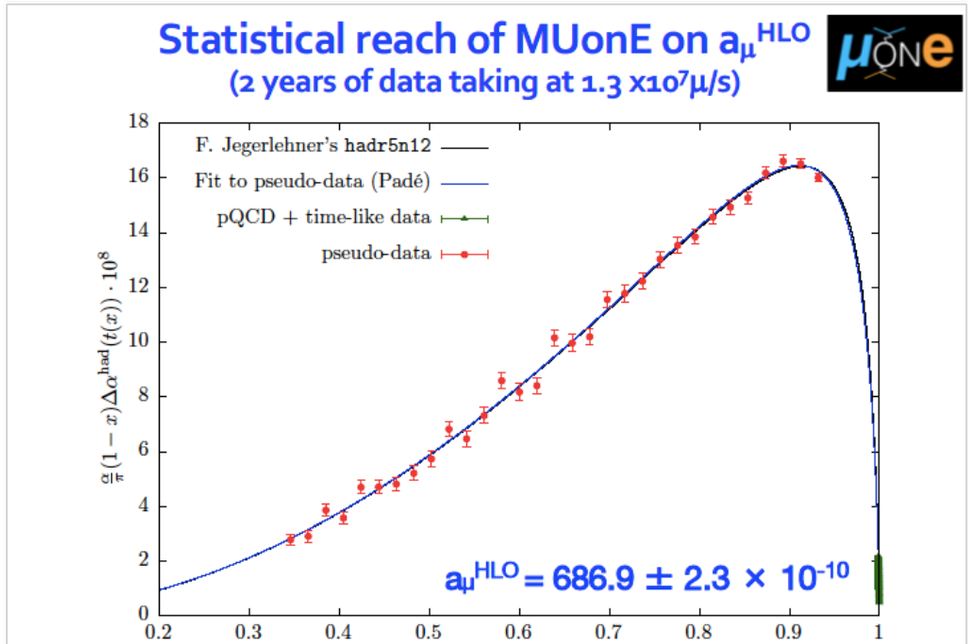
- We acknowledge Santander Supercomputacion support group at the University of Cantabria for providing access to Altamira Supercomputer at the Institute of Physics of Cantabria (IFCA-CSIC), member of the Spanish Supercomputing Network, for performing simulations/analyses.

- This work was supported by a grant from the Swiss National Supercomputing Centre (CSCS) under project ID s642.

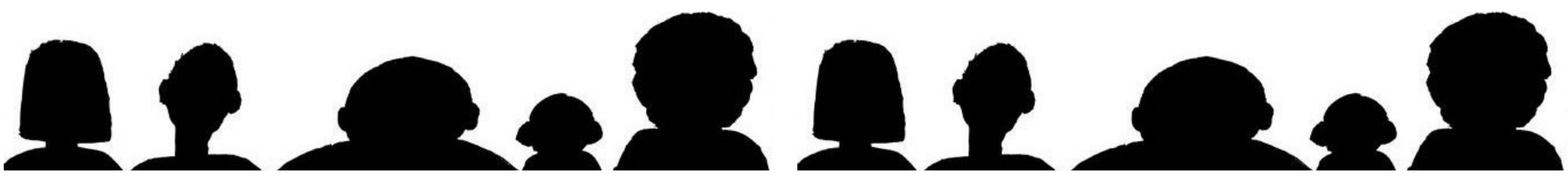


The projected Accuracy of the MUonE experiment

- ➡ Attempt to estimate the total uncertainty after MUonE has collected the data
- ➡ Pseudo data generated by using the MC simulations of the relevant cross sections
- ➡ Error only statistical
- ➡ Is combined fit of experimental and lattice data going to give even better precision?

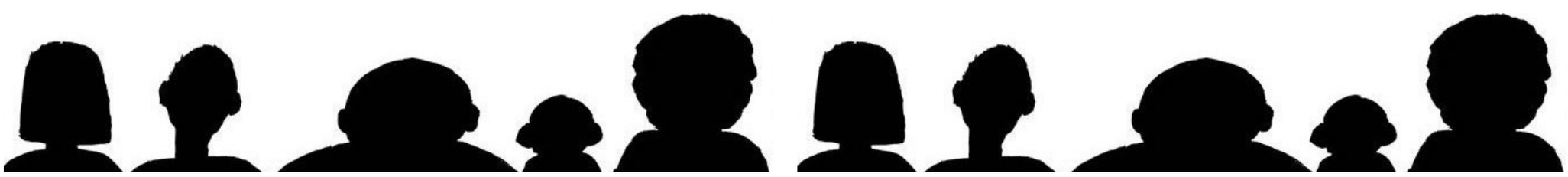


A **0.3%** stat error can be achieved on a_μ^{HLO} in 2 years of data taking with ~10^7 μ/s (4x10^{14}μ total)

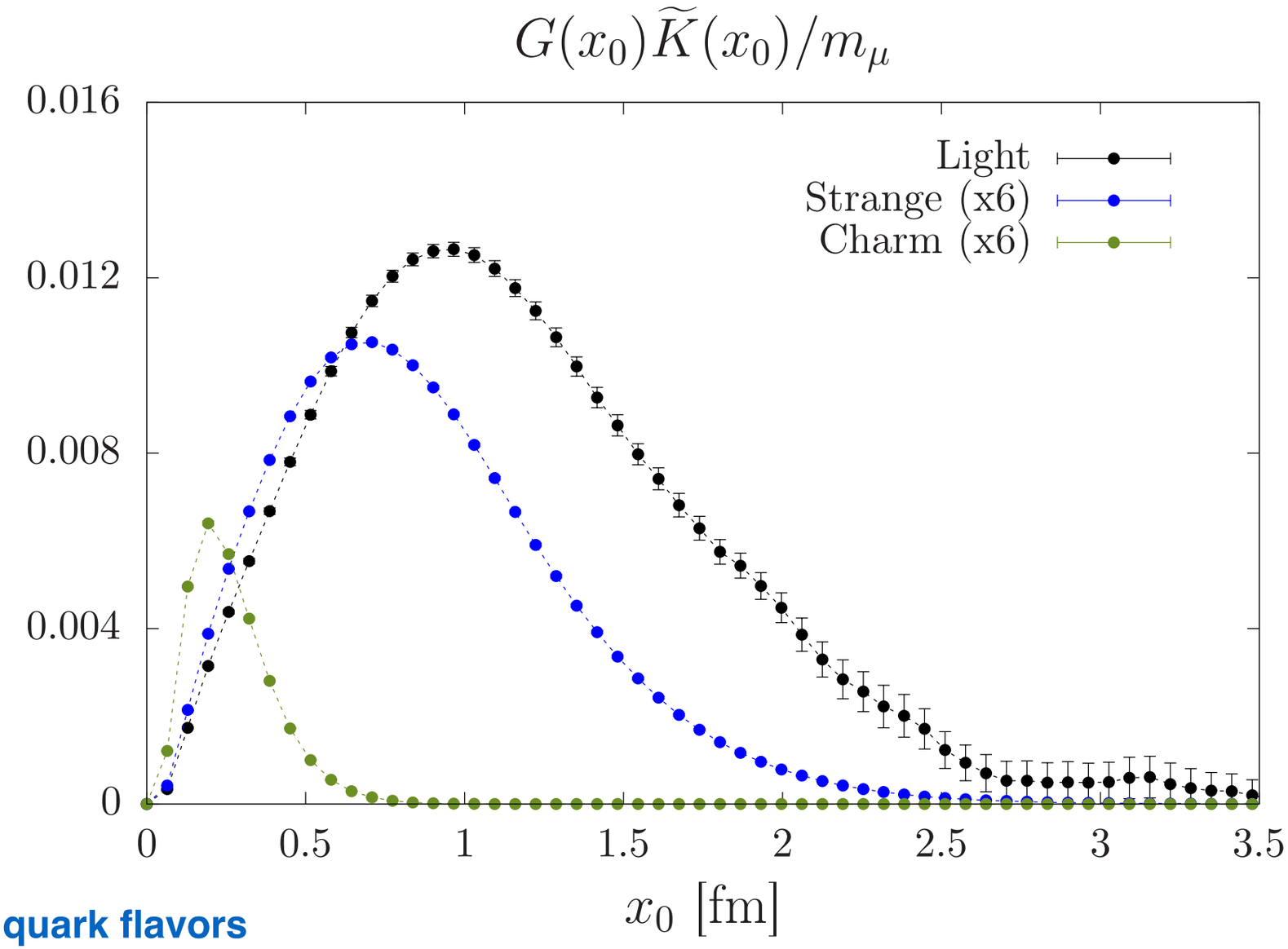


Measured CLS Nf=2 gauge ensembles

Nf=2	β	L/a	a[fm]	m_π[MeV]	N_{cfg}	N_{meas}
A5	5.2	32	0.0755(11)	331	100	800
E5	5.3	32	0.0658(10)	437	78	702
F6	5.3	48	0.0658(10)	311	60	480
G8	5.3	64	0.0658(10)	185	25	100
N6	5.5	48	0.0486(6)	340	30	270
O7	5.5	64	0.0486(6)	268	40	640

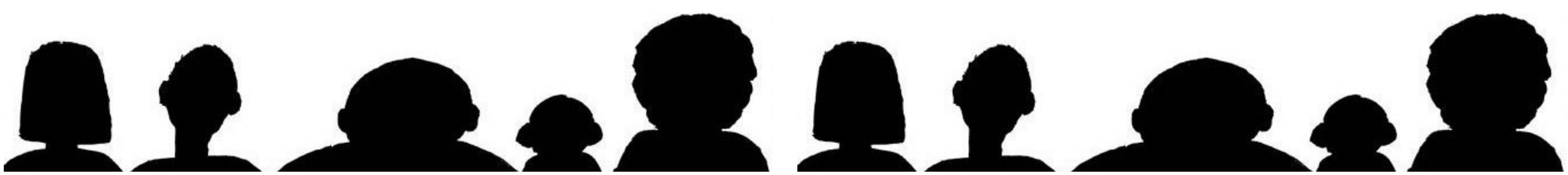


Long distance contributions



- For different quark flavors

- [H. Meyer @ Mainz, Muon g-2 Theory Initiative] CLS/Mainz Nf=2+1

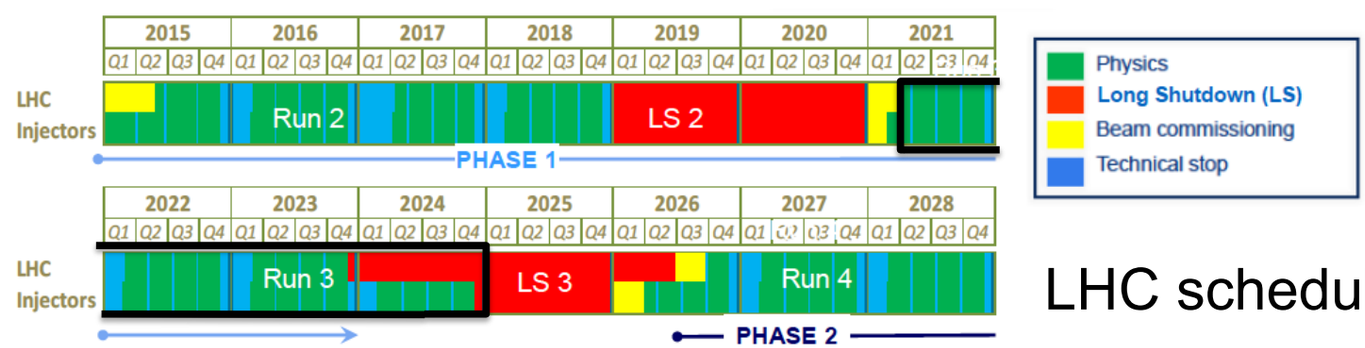


MUonE Timeline

from G. Venanzoni's talk at Physics Beyond Colliders WG meeting, June 13-14 2018

- **2018-2019**
  - Detector optimization studies: simulation; Test Run at CERN (2018); Mainz/Desy with few GeV e- (2019); Fermilab with 60 GeV μ (TBC)
  - Theoretical studies
  - Set up a collaboration
  - Letter of Intent to the SPSC
- **2020-2021**
  - Detector construction and installation

  2021–2024
  - Data taking: staged detector for a first (pilot) run +2 years with full detector



LHC schedule