# Report on Moriond QCD 2022 (and high energy interactions)

Overview of the conference

Focus on muon anomalous magnetic moment (g-2)

Sandrine Emery-Schrenk

Saclay, 22 avril 2022

https://moriond.in2p3.fr/2022/QCD/

Summary talks :

- Experimental : Jan Fiete Grosse-Oetringhaus (CERN)

https://moriond.in2p3.fr/QCD/2022/Saturday/Jan.pdf

- Theory : Kirill Melnikov (Karlsruhe)

https://moriond.in2p3.fr/QCD/2022/Saturday/Melnikov.pdf

# Particle physics is at the crossroads

Big, fundamental questions define the identify of particle physics

1. Unification of interactions
2. Nature of EW symmetry breaking
3. Origin of quark/lepton families
4. Masses and Yukawa couplings
5. Matter anti-matter asymmetry
6. Origin of dark matter
7. Connection to gravity

Connection?

Practical questions and challenges worth our current attention

1. Flavour anomalies
2. Muon anomalous magnetic moments
3. New developments in theory
4. Interplay of precision physics at the LHC and BSM searches

4. QCD dynamics

More details today

**Interplay experiments – theory**

Direct search for new physics : no discovery yet …

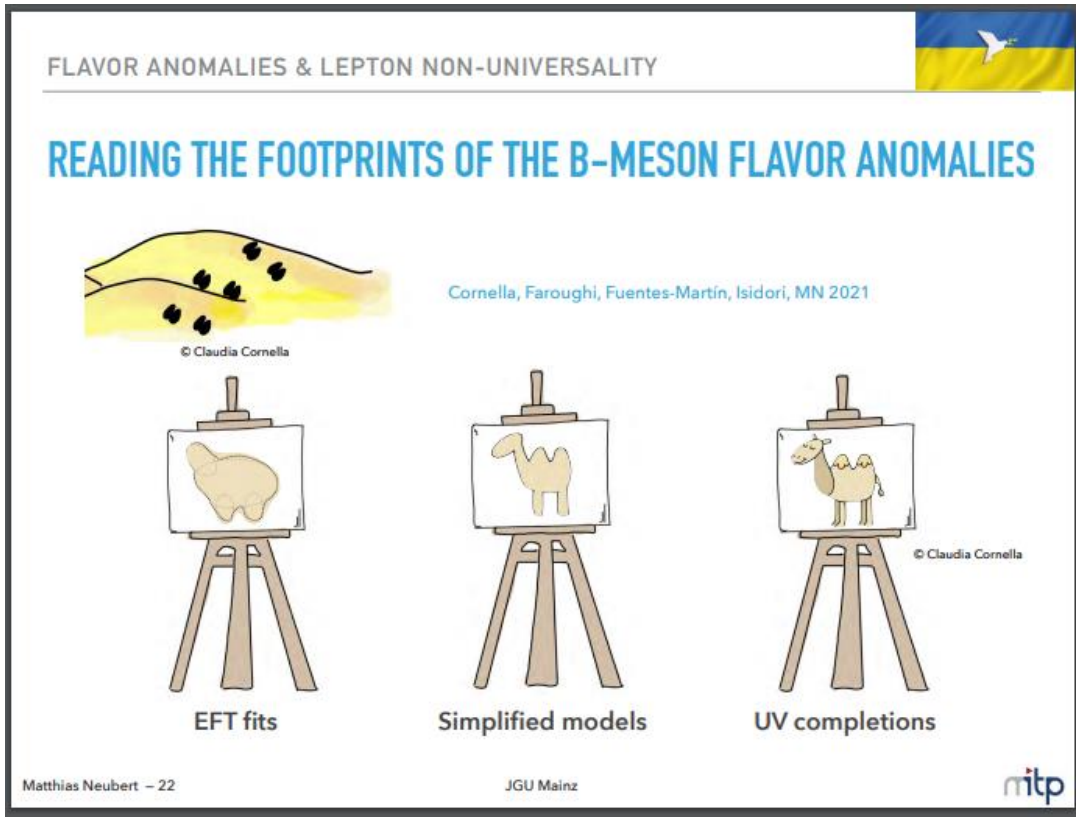
**Indirect search** :

compare precise measurements to Standard model (SM) precise predictions

➔ Important to understand and predict QCD effects to get precise SM predictions!

New physics theory models : different approaches :

Effective Field Theories or more specific models




Account for :

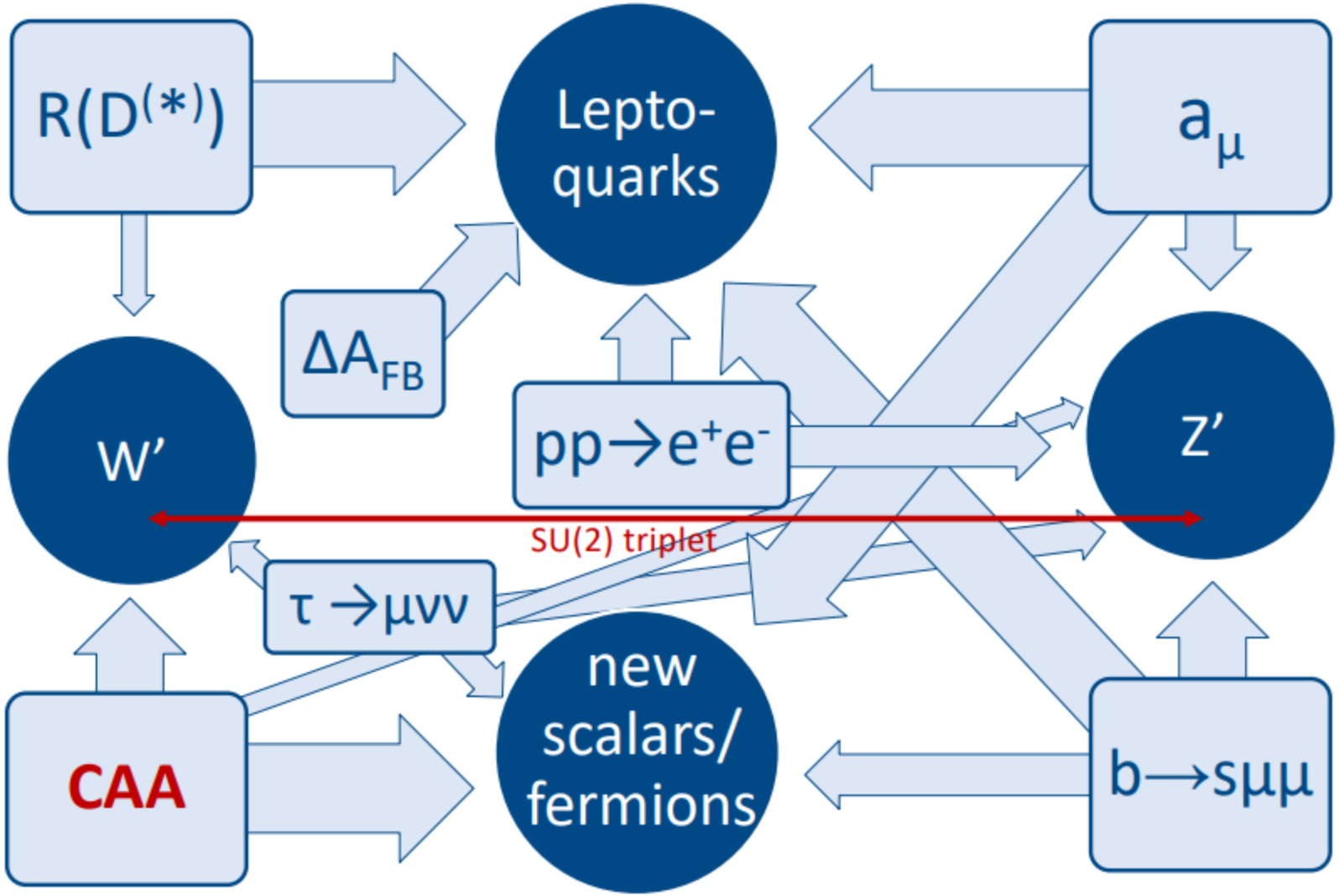
- various « anomalies » : flavour, g-2
- dark matter
- measurements consistant with standard model

« Classical » models like SUSY not ruled out but not favoured either…

More « contrived » models

Talk
Andreas Crivellin

# Conclusions



| | | | | |
|---|---|---|---|---|
| | **Higgs session, *chairperson Boaz Klima*** | | | |
| | **08:30 - 08:35** | Etienne Auge (Orsay) | Welcome | |
| | **08:35 - 08:40** | Bolek Pietrzyk (Annecy) | History and spirit of Moriond | |
| | **08:45 - 09:05** | Greg Landsberg (Brown) | Higgs Turns 10: The Childhood Story | pdf |
| | **09:05 - 09:20** | Liza Mijovic (Edinburgh) | Higgs highlights at ATLAS | pdf |
| | **09:25 - 09:40** | Jan Steggemann (Zürich, ETH) | Higgs highlights at CMS | pdf |
| | **09:45 - 10:00** | Adinda De Wit (Zürich Uni) | Higgs cross-section and properties at CMS and ATLAS | pdf |
| **S** | **10:05 - 10:25** | *Coffee Break* | | |
| **U** | **10:25 - 10:40** | Guillermo Nicolas Hamity (Edinburgh) | Exotic Higgs at ATLAS and CMS | pdf |
| **N** | **10:45 - 11:00** | Jose Santiago (Granada) | Connecting theory and experiment via effective field theories | pdf |
| **D** | **11:05 - 11:20** | Roberto Franceschini (Rome) | The landscape of future colliders | pdf |
| **A** | **11:25 - 11:40** | Rui Santos (Lisbon) | Impact of SM parameters and of the vacua of the Higgs potential in gravitational waves detection | pdf |
| **Y** | **Top session, *chairperson Andreas Meyer*** | | | |
| | **17:00 - 17:15** | Yang Qin (Manchester) | tt+X production at ATLAS and CMS | pdf |
| | **17:20 - 17:35** | Wolfgang Wagner (Wuppertal) | Top quark mass and cross-section at ATLAS and CMS | pdf |
| | **17:40 - 17:55** | Jan Van Der Linden (Karlsruhe) | Top quark properties at CMS and ATLAS | pdf |
| | **18:00 - 18:15** | Samuel May (Boston) | Single top and rare top quark production (including FCNC searches) at CMS and ATLAS | pdf |

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HIGGS and TOP physics also covered in Moriond EW conference

| | | | | |
|---|---|---|---|---|
| | **18:20 - 18:40** | *Coffee Break* | | |
| | **18:40 - 18:55** | Tomas Jezo (Muenster) | Hadronic W-boson decays in off-shell top-quark pair production and decay | pdf |

MONDAY

| Electroweak and g-2 session, *chairperson Bogdan Malaescu* | | | |
|---|---|---|---|
| 08:30 - 08:45 | Sonia Carra (Milano) | Electroweak Susy at ATLAS and CMS | pdf |
| 08:50 - 09:05 | Chris Pollard (Oxford) | Standard Model W,Z (+jet) at CMS and ATLAS | pdf |
| 09:10 - 09:25 | Andrea Massironi (Milano-Bicocca) | Standard Model multibosons at CMS and ATLAS | pdf |
| 09:30 - 09:45 | Miguel Ramos Pernas (Warvick) | QCD, electroweak physics, and searches for exotic signatures in the forward region at LHCb | pdf |
| | *g-2 mini-session* | | |
| 09:50 - 10:05 | Elia Bottalico (Pisa) | Status of the g-2 experiment | pdf |
| 10:10 - 10:30 | *Coffee Break* | | |
| 10:30 - 10:45 | Sandrine Emery (Saclay) | Exclusive hadronic cross sections and other recent hadronic BaBar results | pdf |
| 10:50 - 11:05 | Kalman Szabo (Wuppertal) | Lattice determination of the hadronic vacuum polarization contribution to g-2 | pdf |
| 11:10 - 11:25 | Zhiqing Zhang (IJCLab Orsay) | Dispersives approaches to hadronic vacuum polarization for g-2 | pdf |
| 11:30 - 11:45 | Jeremy Green (Trinity College Dublin) | Light-by-light contribution to the muon g-2: lattice QCD and dispersive approaches | pdf |

EW and g-2 physics also covered in Moriond EW conference

**MORE DETAILS IN THIS TALK**

# HEAVY FLAVOUR SESSIONS MONDAY and TUESDAY

## Heavy Flavour session, *chairperson Francesco Dettori*

| | | | |
|---|---|---|---|
| **17:00 - 17:15** | Maria Smizanska (Lancaster) | b-physics results at ATLAS | pdf |
| **17:20 - 17:35** | Yuta Takahashi (Zürich Uni) | b-physics result at CMS | pdf |
| **17:40 - 17:55** | Simone Devoto (Milano) | Heavy-quark production at NNLO | pdf |
| | *Spectroscopy* | | |
| **18:00 - 18:15** | Marco Pappagallo (Bari) | Heavy flavour spectroscopy at LHCb | pdf |
| **18:20 - 18:40** | *Coffee Break* | | |
| **18:40 - 19:00** | Giulio Mezzadri (Ferrara) | XYZ physics at BES III | pdf |
| **19:05 - 19:20** | Christoph Rosner (Mainz) | Precision measurement of nucleon form factors in time-like at BES III | pdf |

**TUESDAY**

## Heavy Flavour session, *chairperson Nazila Mahmoudi*

| | | | |
|---|---|---|---|
| | *CP violation* | | |
| **08:30 - 08:45** | Lais Soares Lavra (Clermont-Ferrand) | Mixing and CPV in beauty and charm at LHCb | pdf |
| **08:50 - 09:05** | Andreas Crivellin (Zurich U. and PSI) | The Cabibbo Angle Anomaly | pdf |
| **09:10 - 09:25** | Bernat Capdevila Soler (Torino) | Three loop calculations and inclusive Vcb | pdf |
| | *rare decays* | | |
| **09:30 - 09:45** | Maximillian Welsch (Bonn) | Latest results on semileptonic and electroweak penguin decays at Belle II | pdf |
| **09:50 - 10:05** | Francesco Dettori (Cagliari) | Rare and semileptonic decays of heavy hadrons (excluding LFU tests) at LHCb | pdf |
| **10:10 - 10:30** | *Coffee Break* | | |
| | *search for new physics - anomalies* | | |
| **10:30- 10:45** | Francesco Polci (Paris-Sorbonne) | Lepton flavour universality and lepton flavour violation tests at LHCb | pdf |
| **10:50 - 11:05** | Syuhei Iguro (Karlsruhe) | Interplay between the $R_D$ anomaly and the LHC | pdf |

## Heavy Flavour session, *chairperson Mathias Neubert*

| | | | |
|---|---|---|---|
| | *search for new physics - anomalies* | | |
| **17:00 - 17:15** | Nico Gubernari (Siegen) | $b \to s \mu\mu$: Standard Model predictions and Global Fits | pdf |
| **17:20 - 17:35** | Ben Allanach (Cambridge) | Simple Z' responsible for $b \to s \mu\mu$ anomalies | pdf |
| **17:40 - 17:55** | Mohamed Amine Boussejra (Lyon) | Flavour anomalies in supersymmetric scenarios with non-minimal flavour violation | pdf |
| **18:00 - 18:20** | *Coffee Break* | | |
| | *discussion session: Heavy Flavour and g-2 indirect search for New Physics, chair Mathias Neubert* | | |

g-2 discrepancy and flavour anomalies could be connected ?

| WEDNESDAY | | | | |
|---|---|---|---|---|
| | **New Phenomena session, *chairperson Pamela Ferrari*** | | | |
| | **08:30 - 08:45** | Petar Rados (Vienna) | Latest results on τ and dark sector physics at Belle II | pdf |
| | **08:50 - 09:05** | Julia Lynne Gonski (Columbia) | Highlights from searches of long-lived particles at ATLAS | pdf |
| | **09:10 - 09:25** | Lisa Benato (Hamburg) | Highlights from searches at CMS | pdf |
| | **09:30 - 09:45** | Indara Suarez (Boston) | Strong Susy at CMS and ATLAS | pdf |
| | **09:50 - 10:05** | Benedikt Maier (CERN) | Searches for exotic dark matter at CMS and ATLAS | pdf |
| | **10:10 - 10:30** | *Coffee Break* | | |
| | **10:30 - 10:45** | Francesco Guescini (Munich) | Searches for exotic heavy resonance at ATLAS and CMS | pdf |
| | **10:50 - 11:05** | Martin White (Adelaide Uni) | Recent BSM global fit results from the GAMBIT collaboration | pdf |
| | **11:10 - 11:25** | Krzysztof Rolbiecki (Warsaw) | LHC constraints on electroweakino dark matter revisited | pdf |
| | **11:30 - 11:45** | Joshua Ruderman (New York U.) | Pandemic Dark Matter | pdf |
| | **11:50 - 12:05** | Ubaid Tantary (Kent State) | N=4 supersymmetric Yang-Mills thermodynamics from effective field theory | pdf |
| | **New Phenomena session, *chairperson Jan Steggemann*** | | | |
| | **17:00 - 17:15** | Matthias Schott (Mainz) | Revival of the Search for QCD Instanton Processes | pdf |
| | **17:20 - 17:35** | Francesco Giuli (CERN) | Precision measurements of the Lepton-Charge and Forward-Backward Drell-Yan Asymmetries to Enhance the Sensitivity to Broad Resonances of New Gauge Sectors | pdf |
| | **17:40 - 17:55** | Mohammad Mahdi Altakach (Warsaw) | Probing a leptophobic top-colour model with cross section measurements and precise signal and background predictions: a case study | pdf |
| | **18:00 - 18:15** | Alexander Neuwirth (Muenster) | Soft gluon resummation for associated squark-gaugino production at the LHC | pdf |
| | **18:20 - 18:40** | *Coffee Break with the conference Very High Energy Phenomena in the Universe* | | |
| | | *Common session with the conference Very High Energy Phenomena in the Universe* | | |
| | **18:40 - 19:20** | Matthias Neubert (Mainz) | Lepton flavour non-universality | pdf |
| | **19:30 - 20:15** | Emmanuel Moulin (Irfu CEA-Saclay) | News from the very-high-energy gamma-ray sky | pdf |

**Common session with**
**« Very High Energy Phenomena in the Universe »**

Beyond Standard Model also in Moriond EW conference

## THURSDAY

### QCD session, *chairperson Giulia Zanderighi*

| | | | |
|---|---|---|---|
| 08:30 - 08:45 | Andrew Pilkington (Manchester) | SM highlight at ATLAS | pdf |
| 08:50 - 09:05 | Andrew Gilbert (Northwestern) | SM highlight at CMS | pdf |
| 09:10 - 09:25 | Matt Leblanc (CERN) | Standard Model QCD with jet and photons at ATLAS and CMS | pdf |
| 09:30 - 09:45 | Jeremy Wilkinson (GSI) | Charm quark hadronization studies in pp collisions with ALICE | pdf |
| 09:50 - 10:05 | Ezra Lesser (Berkeley) | Jet substructure in pp collisions with ALICE | pdf |
| 10:10 - 10:30 | *Coffee Break* | | |
| 10:30 - 10:45 | Giorgio Cerro (Southampton) | Spectral Clustering for Jet Physics | pdf |
| 10:50 - 11:05 | Rene Poncelet (Cambridge) | NNLO QCD corrections for three jet production | pdf |
| 11:10 - 11:25 | Tongzhi Yang (Zurich) | Di-lepton Rapidity Distribution in Drell-Yan Production at N3LO in QCD | pdf |
| 11:30 - 11:45 | Luca Rottoli (Zurich) | High precision predictions for Drell-Yan distributions | pdf |
| 11:50 - 12:05 | Luca Buonocore (Zurich Uni) | Mixed strong−electroweak corrections to the Drell−Yan process | pdf |

### QCD session, *chairperson Zhiqing Zhang*

| | | | |
|---|---|---|---|
| 17:00 - 17:15 | Giulia Zanderighi (Munich) | QCD correction to Lepton induced processes at the LHC | pdf |
| 17:20 - 17:35 | David d'Enterria (CERN) | QCD coupling from hadronic decays of W and Z bosons at N^3LO accuracy | pdf |
| 17:40 - 17:55 | Ignazio Scimemi (Madrid) | The vector bosons transverse momentum distributions | pdf |
| 18:00 - 18:15 | Gabor Veres (Eotvos Lorand, Hungary) | Standard Model soft QCD at CMS and ATLAS | pdf |
| 18:20 - 18:40 | *Coffee Break* | | |
| 18:40 - 18:55 | Anja Butter (Heilderberg) | Publishing Unbinned Differential Cross Section Results | pdf |
| 19:00 - 19:15 | Frederic Dreyer (Oxford) | Higher-order non-global logarithms from jet calculus | pdf |

SPECIFIC MORIOND QCD !

## FRIDAY

### Heavy Ion session, *chairperson Gabor Veres*

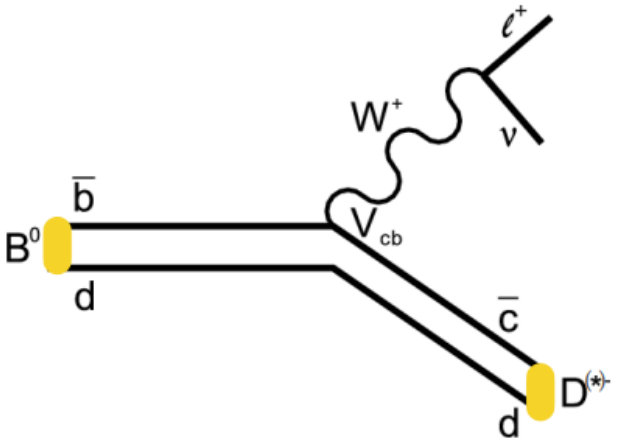
| | | | |
|---|---|---|---|
| 08:30 - 08:45 | Andre Govinda Stahl Leiton (CERN) | Hard probes in heavy ion physics at CMS and ATLAS | pdf |
| 08:50 - 09:05 | Tomasz Bold (Krakow) | Flow harmonics in heavy ion physics at ATLAS and CMS | pdf |
| 09:10 - 09:25 | Saverio Mariani (Firenze) | Heavy-ion and fixed-target physics at LHCb | pdf |
| 09:30 - 09:45 | Stefano Trogolo (CERN) | Constraining charm transport in the QGP and the spatial diffusion coefficient with ALICE | pdf |
| 09:50 - 10:05 | Sourav Kundu (CERN) | Light and hypernuclei production with ALICE | pdf |
| 10:10 - 10:30 | *Coffee Break* | | |
| 10:30 - 10:45 | Valeri Pozdiakov (CERN) | Photoproduction of vector mesons in ultra-peripheral heavy-ion collisions with ALICE | pdf |
| 10:55 - 11:10 | Tomas Truhlar (Prague) | Recent Star results | pdf |

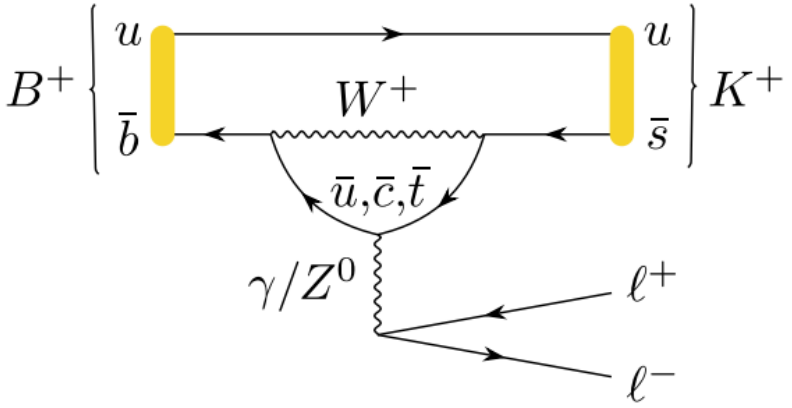
### Heavy ion session, *chairperson Marco Pappagallo*

| | | | |
|---|---|---|---|
| 17:00 - 17:15 | Niveditha Ram (Saclay) | Validation of the Glauber Model for centrality determination in small system collisions with PHENIX | pdf |
| 17:20 - 17:35 | Wojciech Brylinski (Warsaw) | News from the strong interactions program of NA61/SHINE | pdf |
| | *Proton structure mini-session* | | |
| 17:40 - 17:55 | Giacomo Magni (Nikhef) | Proton intrinsic charm | pdf |
| 18:00 - 18:15 | Claire Gwenlan (Oxford) | Impact of jet-production data on the next-to-next-to-leading-order determination of HERAPDF2.0 parton distributions | pdf |
| 18:20 - 18:40 | *Coffee Break* | | |
| 18:40 - 18:55 | Valerio Bertone (Paris) | Emergence of resummation scales in the evolution of the QCD strong coupling and PDFs | pdf |

# Flavour anomalies & lepton universality

LHC (LHCb but not only), BaBar, Belle, Belle II …




$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}; \quad \ell = e, \mu$$

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

https://moriond.in2p3.fr/QCD/2022/WednesdayAfternoon/Neubert.pdf

# TONIGHT . . .

Lepton non-universality


$\neq$

© Matthias Neubert



FLAVOR ANOMALIES & LEPTON NON-UNIVERSALITY

# TONIGHT . . .

Lepton non-universality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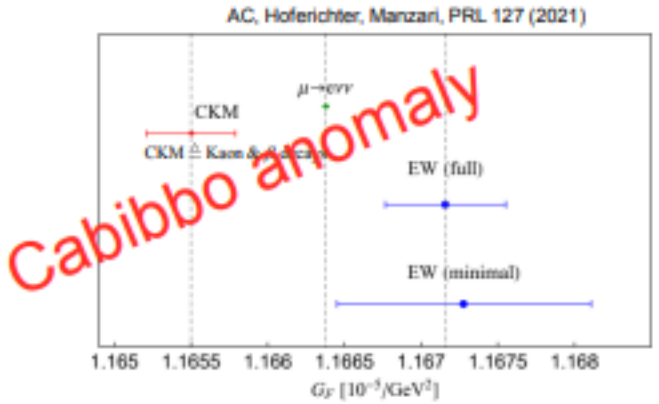
https://moriond.in2p3.fr/QCD/2022/WednesdayAfternoon/Neubert.pdf

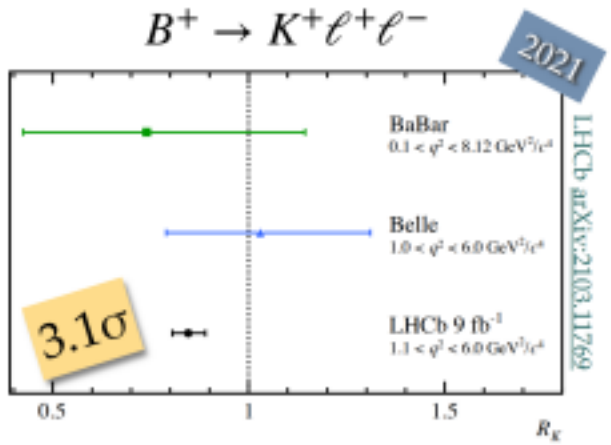
# Flavour physics

It is the time of multiple anomalies and high precision in flavour physics.




Cabibbo anomaly

Talk Andreas Crivellin



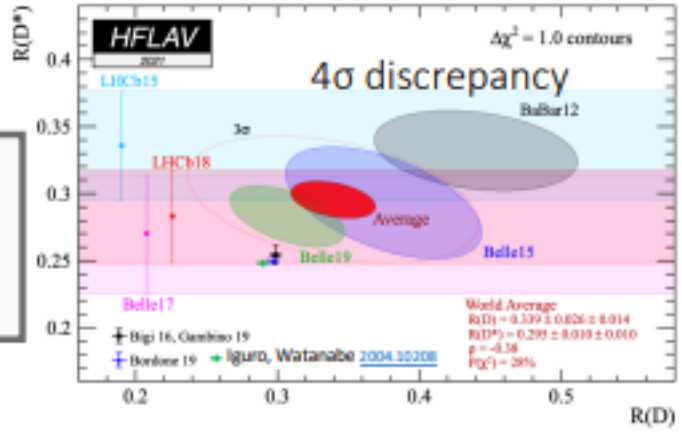

**Review by Neubert**

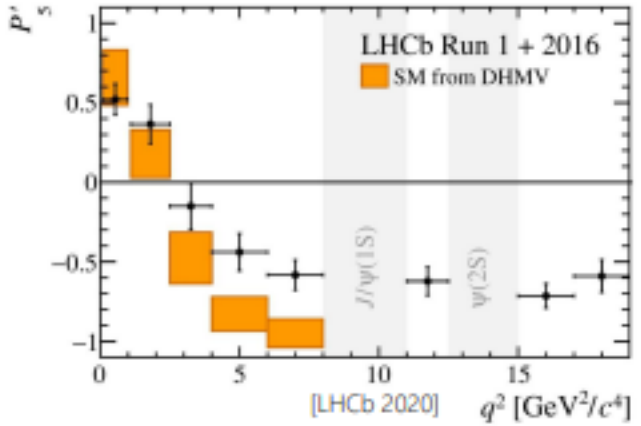
Lepton non universality

$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}\,; \quad \ell = e, \mu$$

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

Tensions between inclusive and exclusive $B$-meson decays:
$\Rightarrow \sim 1 - 3\sigma$



# Muon anomalous magnetic moment (g-2)

REFERENCES

- Apero DPhP – Georges Vasseur – May 7, 2021
- SFP - Journée division Champs et Particules – March 31, 2022 – talk from Michel Davier

https://indico.in2p3.fr/event/19850/timetable/

- Pour la Science hors-série N°114 February-March 2022 p 58 (also article on flavour anomalies)

Experimental result : see talk from Elia Bottalico

Dispersive approach results : see talk from Zhiqing Zhang

Lattice QCD result https://www.nature.com/articles/s41586-021-03418-1 (April 2021)
talk from Kalman Szabo

« Light by light » contribution : talk from Jeremy Green

**MORIOND QCD**

Future JPARC experiment : https://g-2.kek.jp/overview/

## Tuesday Morning (March 15, 8h30) : Precision & Cosmology

**511KeV constraints on feeble interactions**
Leonardo Mastrototaro

**g-2 Lattice review**
Laurent Lellouch

**Muon g-2 experiment**
Kevin Labe

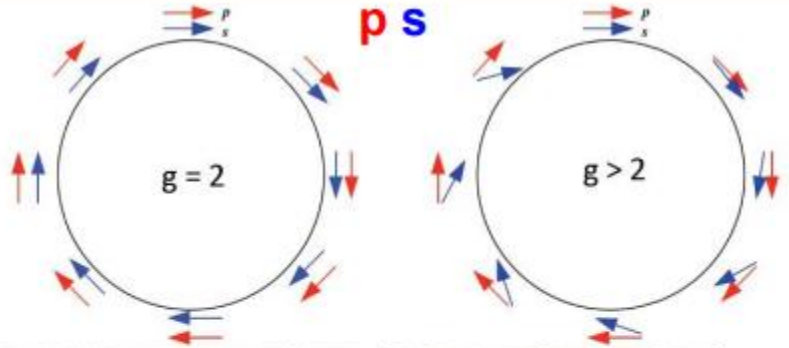
**Leptonic g-2 in 2HDM**
Fernando Cornet-Gomez

**Muon g−2 and B-anomalies from DM**
Marco Fedele

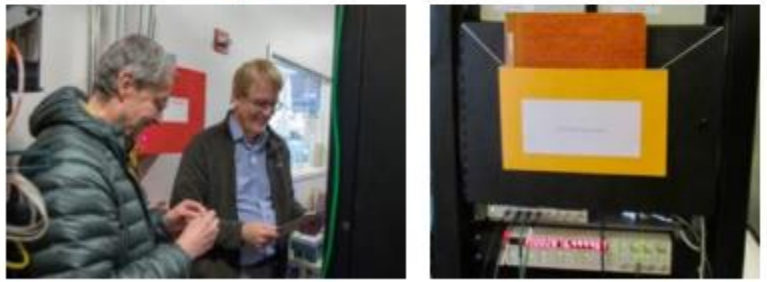
Moriond Electroweak

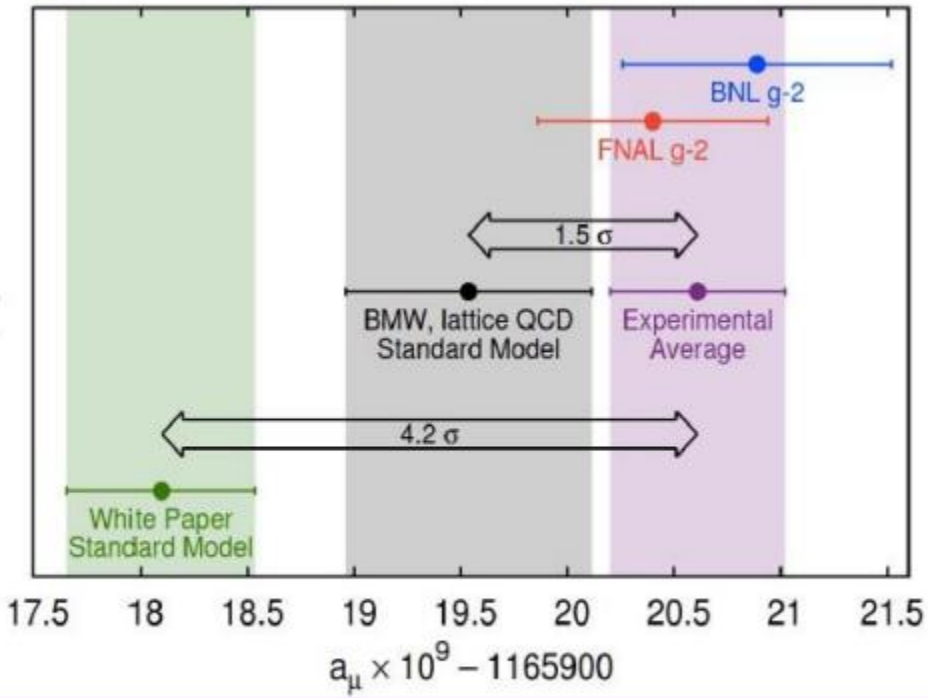
# g-2

$$\vec{\mu} = g\frac{q}{2m}\vec{S} \qquad a_\mu = \frac{g-2}{2}$$



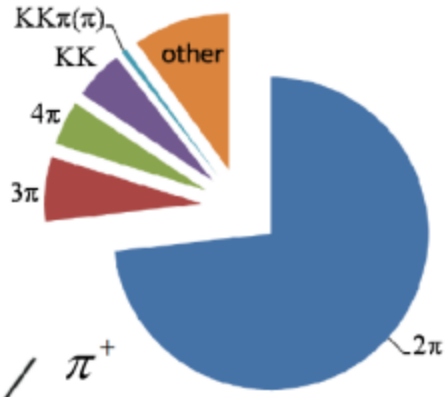

- Dedicated experiment to resolve long-standing difference between theory and experiment of intrinsic magnetic moment of the muon
- Quite special blind analysis ☺
  - Hardware clock frequency modification
- Run 1 result has confirmed discrepancy
  - 4.2σ to white paper theory initiative
  - But only 1.5σ to recent (2020) ab initio lattice QCD calculations
- Full results will have 8 times more data
  - Run 2/3 ongoing expected until end of the year
  - Alternative extraction planned with J-PARC experiment






**Bottalico**

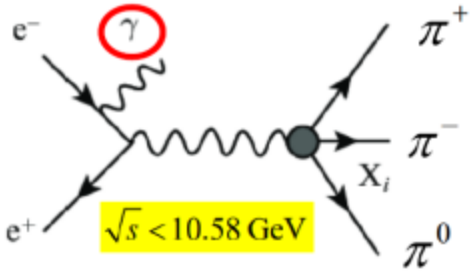
# Hadronic Corrections to $a_\mu$



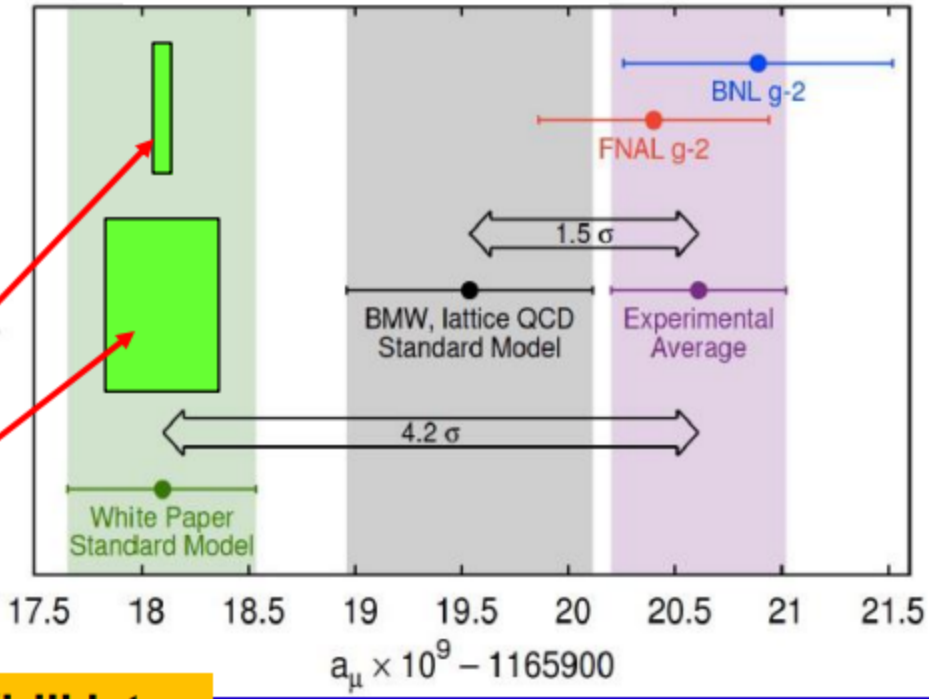

- Main theory uncertainty $a_\mu^{had}$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had} \qquad a_\mu^{\text{had LO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma^0_{\text{hadrons}}(s)$$

- New results from BaBar on $e^+e^- \rightarrow \pi^+\pi^-\pi^0$, $\pi^+\pi^-4\pi^0$, $\pi^+\pi$
  - Tag ISR photon → measure σ at all √s simultaneously
  - Uncertainty on $\pi^+\pi^-\pi^0$ reduced by factor 2
  - Only minor change of $a_\mu^{had}$




| (Rough) summary | $10^{-9}$ |
|---|---|
| Difference exp. g-2 and white paper | 2.5 |
| Current exp. uncertainty g-2 | ±0.54 |
| WP uncertainty | ±0.4 |
| Change by $\pi^+\pi^-\pi^0$ x-section | 0.015 |
| Discrepancy BaBar/KLOE (ππ) | ±0.28 |




**Bottalico Emery**

**More discussion by Kirill later**

# $e^+e^- \to \pi^+\pi^-\pi^0$ contribution to $a_\mu = (g-2)_\mu/2$

**Standard Model prediction**

(discrepancy with experimental measurement)

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

$$a_\mu^{\text{had LO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma^0_{\text{hadrons}}(s)$$

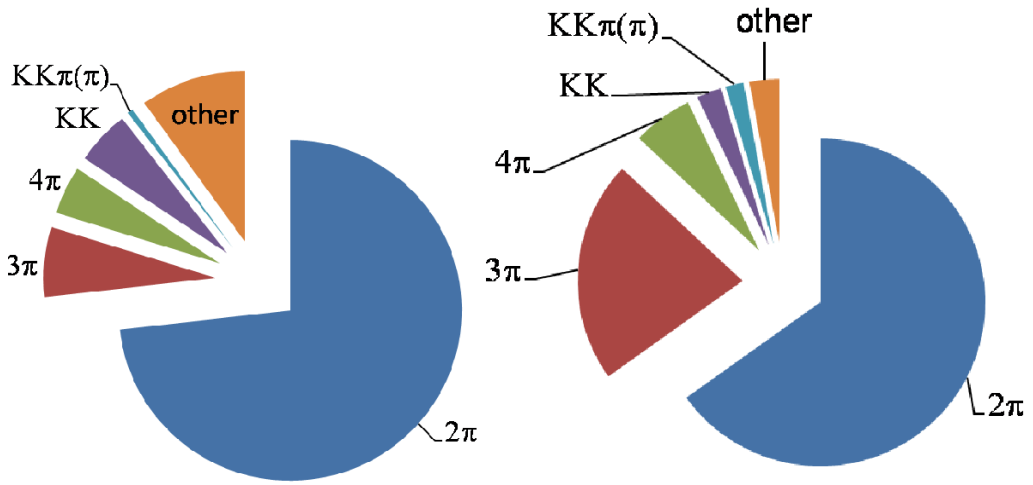
K(s) is a QED kernel and $\sigma^0_{hadrons}(s)$ the bare cross-section including final state radiation

Previous BaBar $\pi^+\pi^-\pi^0$: Phys. Rev. D **70**, 072004 (2004)

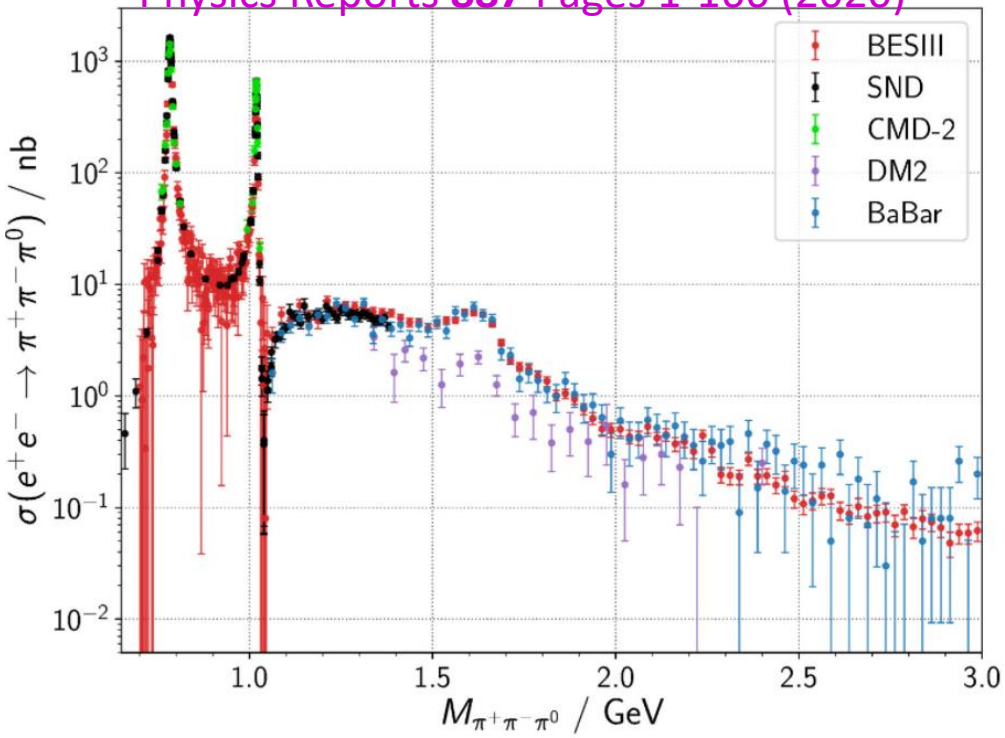
- **No result below 1.05 GeV**
- **Only used 89.3 fb$^{-1}$ (5 times less data)**

Error on $a_\mu^{had}$ also comes from differences with other experiments in cross sections measurements

$a_\mu^{had,LO\text{-}VP}$ $a_\mu^{had,LO\text{-}VP}$ error squared

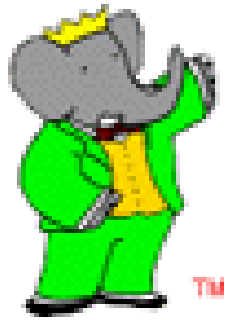



Physics Reports **887** Pages 1-166 (2020)



**THIS TALK**

**Red : First measurements**



| | | |
|---|---|---|
| $e^+e^- \to \pi^+\pi^-\pi^0$ | 469 fb $^{-1}$ | Phys. Rev. D 104, 11203 (2021) |
| $e^+e^- \to \pi^+\pi^-\, 4\pi^0$ (and $\pi^+\pi^-\, 3\pi^0\, \eta$) | 469 fb $^{-1}$ | Phys. Rev. D 104, 11204 (2021) |
| $2(\pi^+\pi^-)\pi^0\pi^0\pi^0$ and $2(\pi^+\pi^-)\pi^0\pi^0\eta$ | 469 fb$^{-1}$ | Phys. Rev. D 103, 092001 (2021) |
| $\pi^+\pi^-\pi^0\pi^0\pi^0$ and $\pi^+\pi^-\pi^0\pi^0\eta$ | 469 fb$^{-1}$ | Phys. Rev. D 98, 112015 (2018) |
| $\pi^+\pi^-\eta$ | 469 fb$^{-1}$ | Phys. Rev. D 97, 052007 (2018) |
| $\pi^+\pi^-\pi^0\pi^0$ | 454 fb$^{-1}$ | Phys. Rev. D 96, 092009 (2017) |
| $K^0_S K^\pm \pi^\mp \pi^0$ and $K^0_S K^\pm \pi^\mp \eta$ | 454 fb$^{-1}$ | Phys. Rev. D 95, 092005 (2017) |
| $K^0_S K^0_L \pi^0$, $K^0_S K^0_L \eta$, and $K^0_S K^0_L \pi^0 \pi^0$ | 469 fb$^{-1}$ | Phys. Rev. D 95, 052001 (2017) |
| $K^+K^-$ ($\gamma$ undetected) | 469 fb$^{-1}$ | Phys. Rev. D 92, 072008 (2015) |
| $K^0_S K^0_L$, $K^0_S K^0_L \pi^+\pi^-$, $K^0_S K^0_S \pi^+\pi^-$, and $K^0_S K^0_S K^+K^-$ | 469 fb$^{-1}$ | Phys. Rev. D 89, 092002 (2014) |
| $K^+K^-$ | 232 fb$^{-1}$ | Phys. Rev. D 88, 032013 (2013) |
| $p\bar{p}$ | 469 fb$^{-1}$ | Phys. Rev. D 87, 092005 (2013) |
| $p\bar{p}$ ($E_{cm}$ : 3.0 ÷ 6.5 GeV) | 469 fb$^{-1}$ | Phys. Rev. D 88, 072009 (2013) |
| $\pi^+\pi^-\pi^+\pi^-$ | 454 fb$^{-1}$ | Phys. Rev. D 85, 112009 (2012) |
| $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$, and $K^+K^-K^+K^-$ | 454 fb$^{-1}$ | Phys. Rev. D 86, 012008 (2012) |
| $\pi^+\pi^-$ | 232 fb$^{-1}$ | Phys.Rev.Lett. 103, 231801 (2009) |
| $K^+K^-\eta$, $K^+K^-\pi^0$ and $K^0_s K^\pm \pi^\mp$ | 232 fb$^{-1}$ | Phys. Rev. D 77, 092002 (2008) |
| $\Lambda\bar{\Lambda}$, $\Lambda\bar{\Sigma}^0$, and $\Sigma^0\bar{\Sigma}^0$ | 230, fb$^{-1}$ | Phys. Rev. D 76, 092006 (2007) |
| $2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$ and $K^+K^-\pi^+\pi^-\eta$ | 232 fb$^{-1}$ | Phys. Rev. D 76, 092005 (2007) |
| $3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$ and $K^+K^-2(\pi^+\pi^-)$ | 232 fb$^{-1}$ | Phys. Rev. D 73, 052003 (2006) |
| $\pi^+\pi^-\pi^0$ | 89 fb$^{-1}$ | Phys. Rev. D 70, 072004 (2004) |

Previous result

# $e^+e^- \to \pi^+\pi^-\pi^0$ contribution to $(g-2)_\mu$

| $M_{3\pi}$ GeV/c$^2$ | $a_\mu^{3\pi}\,[10^{-10}]$ | Ref. |
|---|---|---|
| 0.62 – 1.10 | $42.91 \pm 0.14 \pm 0.55 \pm 0.09$ | |
| 1.10 – 2.00 | $2.95 \pm 0.03 \pm 0.16$ | |
| < 2.00 | $45.86 \pm 0.14 \pm 0.58$ | PRD 104, 11203 (2021) |
| < 1.80 | $46.21 \pm 0.40 \pm 1.40$ | Eur. Phys. J. C 80, 241(2020) |
| < 1.97 | $46.74 \pm 0.94$ | Phys. Rev. D 101, 014029 (2020) |
| < 2.00 | $44.32 \pm 1.48$ | Springer Tracts Mod. Phys. 274, 1 (2017) |

Differences in 3π mass scales between experiments.

Estimated from differences in BaBar/SND/CMD-2 data

Calculations using Previous measurements (Not including the new BaBar result)

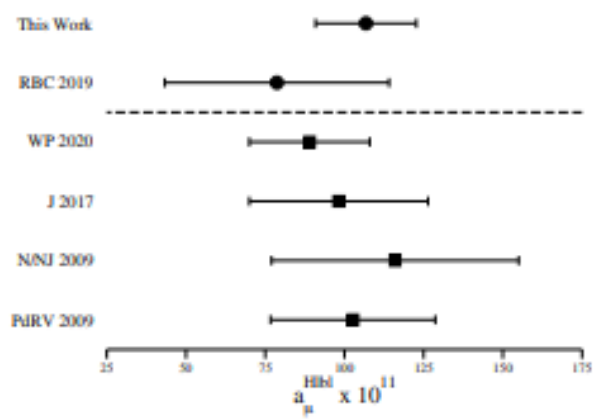
| Effect | Uncertainty (%) |
|---|---|
| Luminosity | 0.4 |
| Radiative correction | 0.5 |
| Detection efficiency | 1.1 |
| MC statistics | 0.15 |
| Background subtraction | 0.073 |
| Gaussian smearing | 0.0007 |
| Lorentzian smearing | 0.003 |
| Unfolding procedure | 0.045 |
| Total | 1.3 |

# Muon anomalous magnetic moment: HLBL

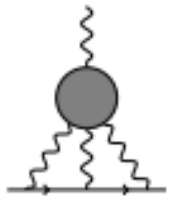
Hadronic light-by-light scattering is the least understood contribution. However, since it is fairly small, we do not need to know it with very high precision. The results are very stable since about 2009 (Glasgow consensus). New results are claimed to have smaller errors; whether this is justified, is hard to say.

An important message: lack of understanding of the HLBL contribution cannot be the sole reason for g-2 discrepancy.

Summary




- Lattice, dispersion theory, and old models are all in agreement.
- Combining lattice and dispersion (without charm) yields $a_\mu^{\mathrm{HLbL}} = 97.5(11.6)$.
- HLbL too small to explain the discrepancy with experiment.



hadronic light-by-light

| | |
|---|---|
| light conn,(2 + 2) | 107.4(11.3)(9.2)(6.0) |
| strange conn,(2 + 2) | −0.6(2.0) |
| (3 + 1) | 0.0(0.6) |
| (2 + 1 + 1) | 0.0(0.3) |
| (1 + 1 + 1 + 1) | 0.0(0.1) |
| $a_\mu^{\mathrm{HLbL}}$ (no charm) | $106.8(15.9) \times 10^{-11}$ |

Green

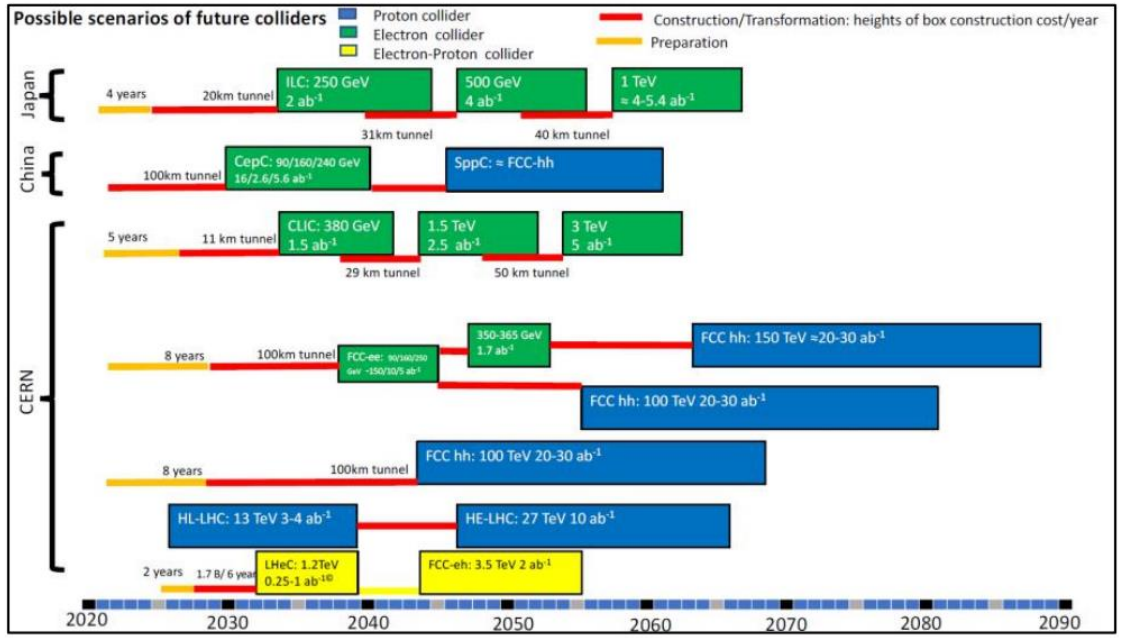
# Future

- LHC Run 3 is about to start
  - Big step for LHCb and ALICE (but not yet for Moriond 2023)
- BEPCII-U upgrade (BES III)
- Belle II (~1 year shutdown from summer '22)
- HL-LHC until ~2040
  - ATLAS/CMS/LHCb phase II, possible ALICE3
- And beyond?
- Roberto Franceschini said two true things

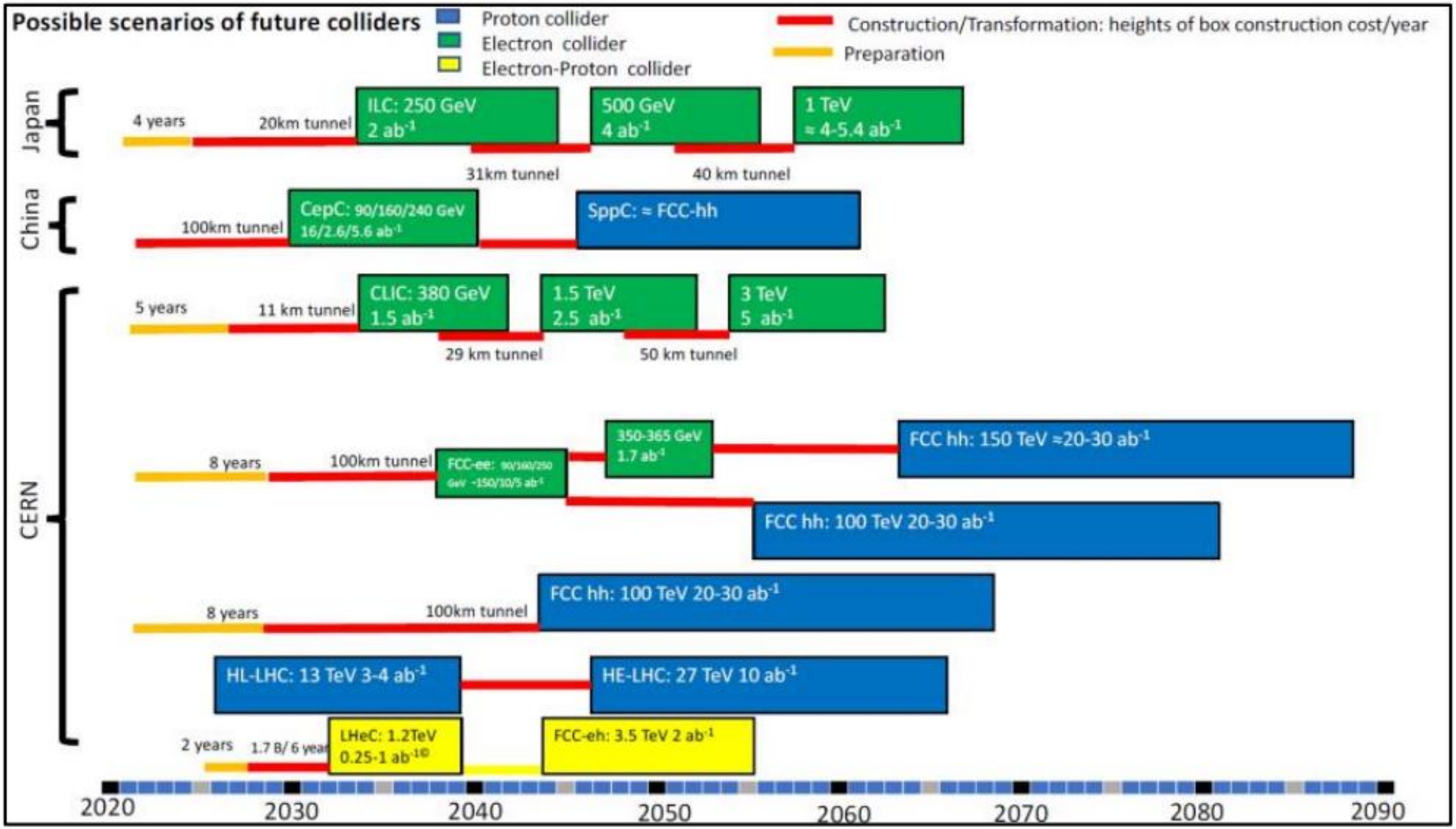
  *"There are enough proposals on the table",* ILC, CepC, CLIC, HE-LHC, FCC-ee, FCC-hh and…

  *… "I will not discuss cost"*

| LHC $L_{int}$ | Run 2 | Run 3 (estimate delivered) |
|---|---|---|
| ATLAS/CMS pp | 140 $fb^{-1}$ | x2 → 270 $fb^{-1}$ |
| LHCb pp | 6 $fb^{-1}$ | x4 → 23 $fb^{-1}$ |
| ALICE Pb-Pb | 1 $nb^{-1}$ | x8 → 8 $nb^{-1}$ |




**2020** **2050** **2090**




**2020** **2050** **2090**

# Back up

# READING THE FOOTPRINTS OF THE B-MESON FLAVOR ANOMALIES

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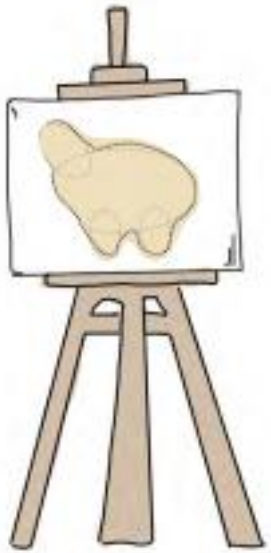
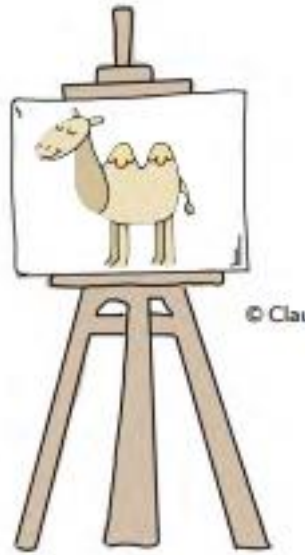
Cornella, Faroughi, Fuentes-Martín, Isidori, MN 2021



EFT fits

Simplified models



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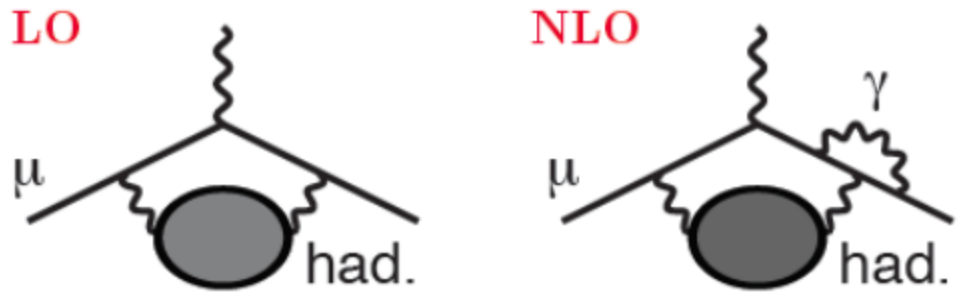
UV completions

# Hadronic contribution : vacuum polarization

- Non-perturbative
  - Dispersive approach using experimental data.
  - Progress with lattice QCD.




- Hadronic vacuum polarization correction large, $O(\alpha^2)$, and with the largest absolute uncertainty
  - relative uncertainty < 1%

$a_\mu^{HVP,LO} = (693.1 \pm 4.0)\ 10^{-10}$

$a_\mu^{HVP,NLO} = (-9.83 \pm 0.07)\ 10^{-10}$

$a_\mu^{HVP,NNLO} = (1.24 \pm 0.01)\ 10^{-10}$

# Theoretical calculation

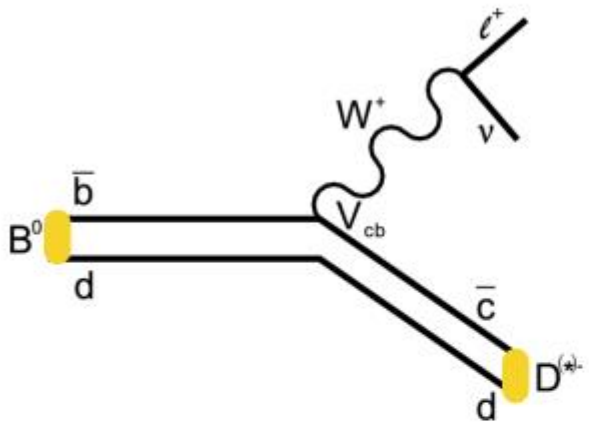
$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{hadronic}} + a_\mu^{\mathrm{NP?}}$$

- Prediction (g-2 theory initiative)
- $a_\mu^{SM} = (11\ 659\ 181.0 \pm 4.3)\ 10^{-10}$

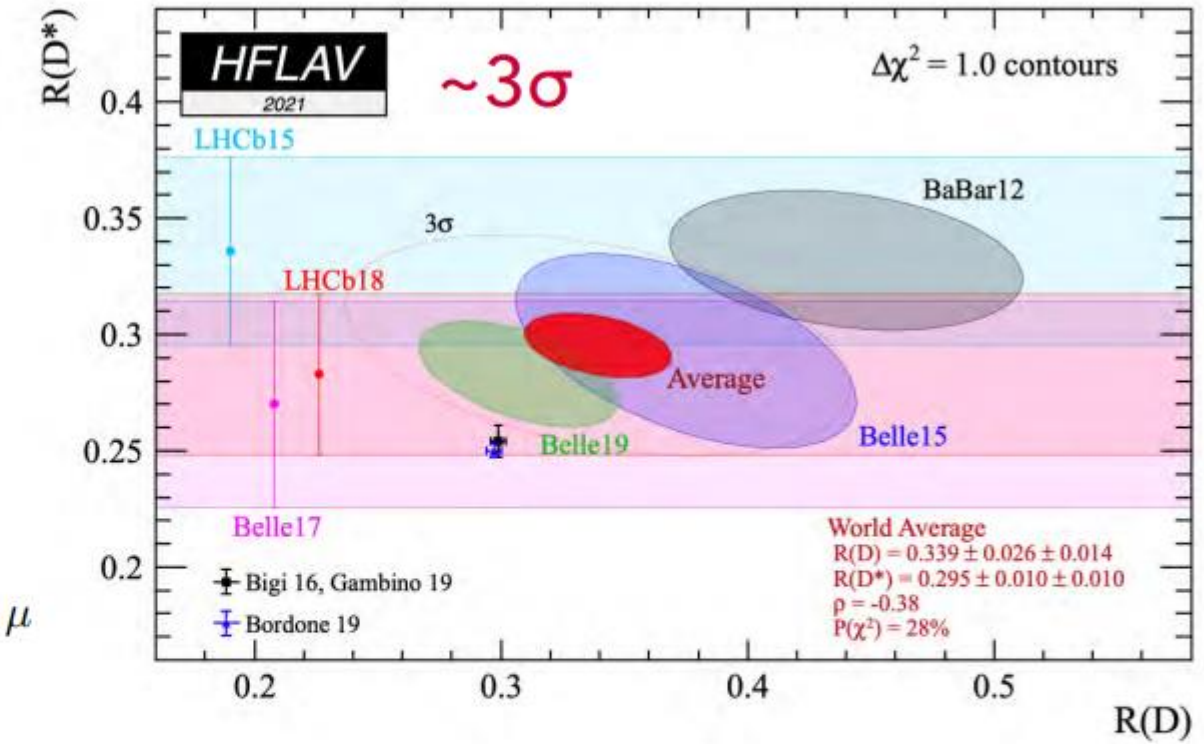
- BNL
- $a_\mu^{exp} = (11\ 659\ 208.9 \pm 6.3)\ 10^{-10}$

- Difference
- $\Delta a_\mu = (27.9 \pm 7.6)\ 10^{-10}$ **3.7 σ**

# CKM-FAVORED TREE-LEVEL DECAYS ($\tau \neq \mu, e$)

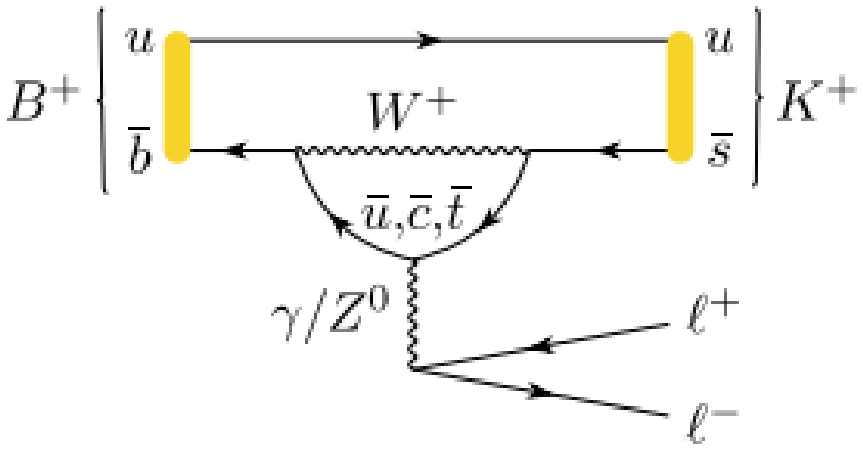



$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}; \quad \ell = e, \mu$$



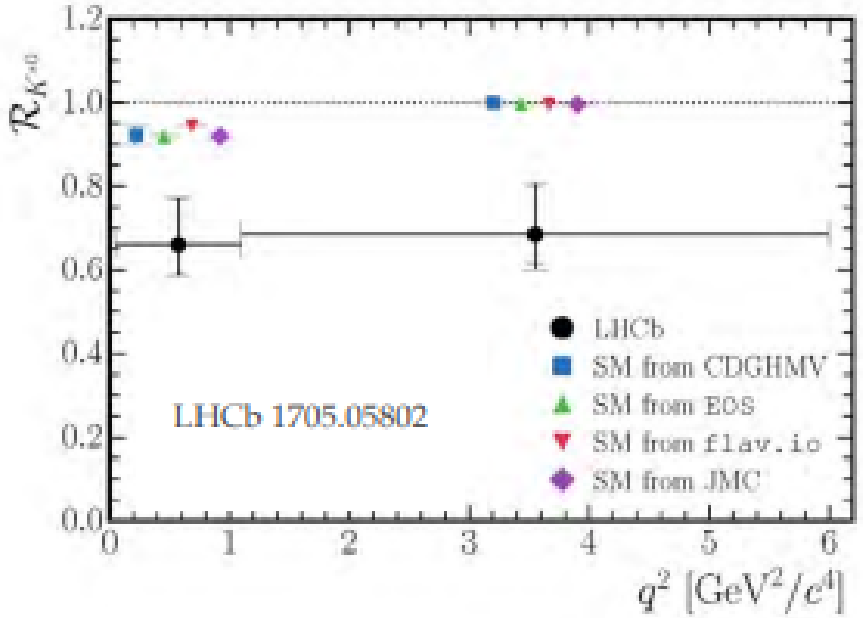

- need **tree-level new physics** without much CKM-like suppression
- difficult to account for effects much bigger than $v^2/\Lambda^2 \sim$ few %

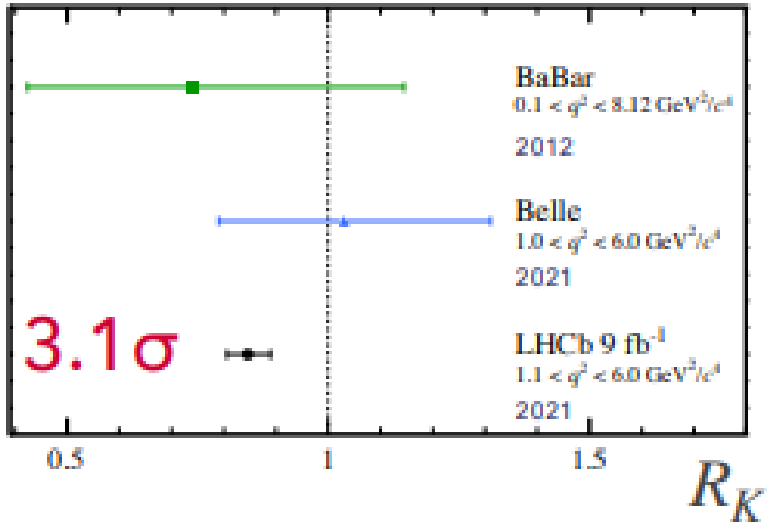
# RARE, LOOP-SUPPRESSED FCNC DECAYS ($\mu \neq e$)



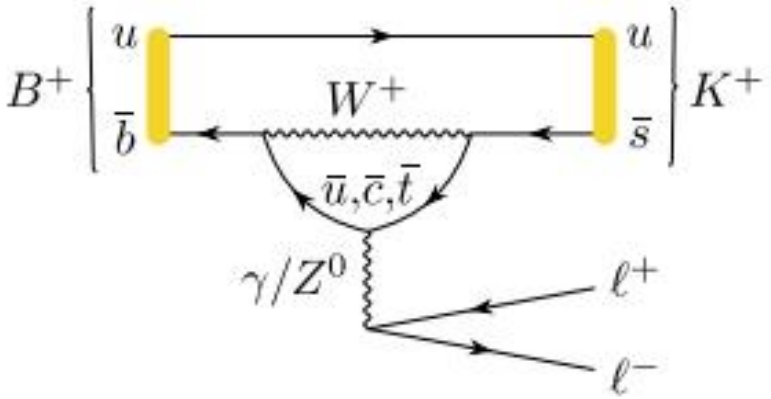

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

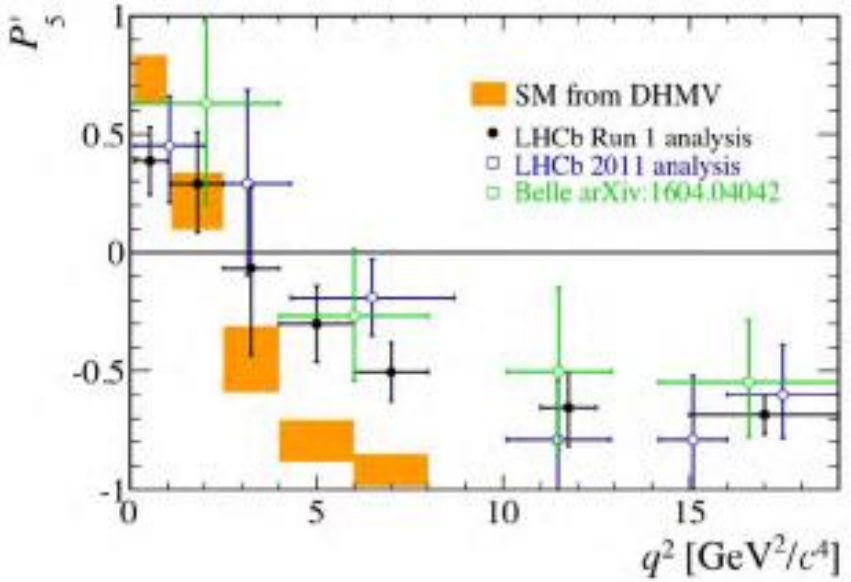
- need **new physics** at level of 10% of a strongly suppressed SM amplitude



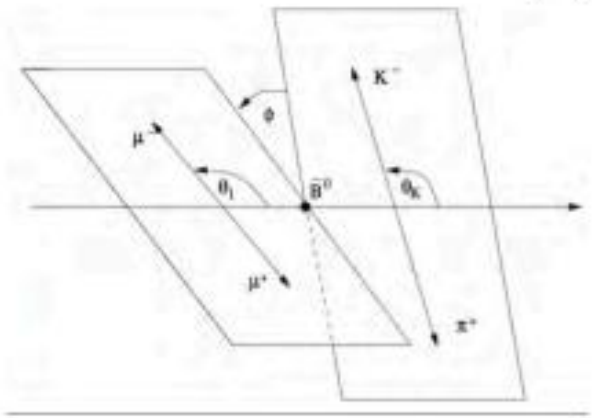



# RARE, LOOP-SUPPRESSED FCNC DECAYS ($\mu \neq e$)



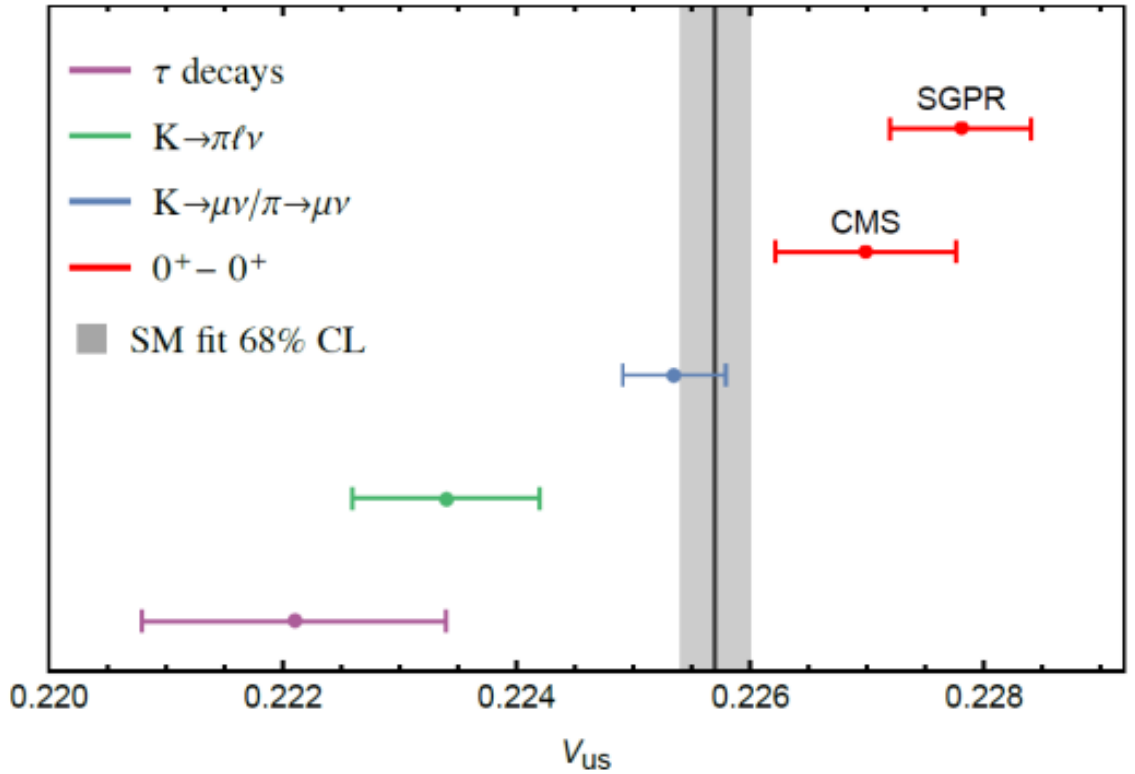

- first evidence for new physics from **angular observables**, in particular $P'_5$
- need **new physics** at level of 10% of a strongly suppressed SM amplitude
- but theoretically less clean



# Cabibbo Angle Anomaly

Talk of Chien-Yeah Seng on Monday

- $V_{ud}$ from super-allowed beta decays
- $V_{us}$ from Kaon and tau decays
- Disagreement leads to a (apparent) violation of CKM unitarity



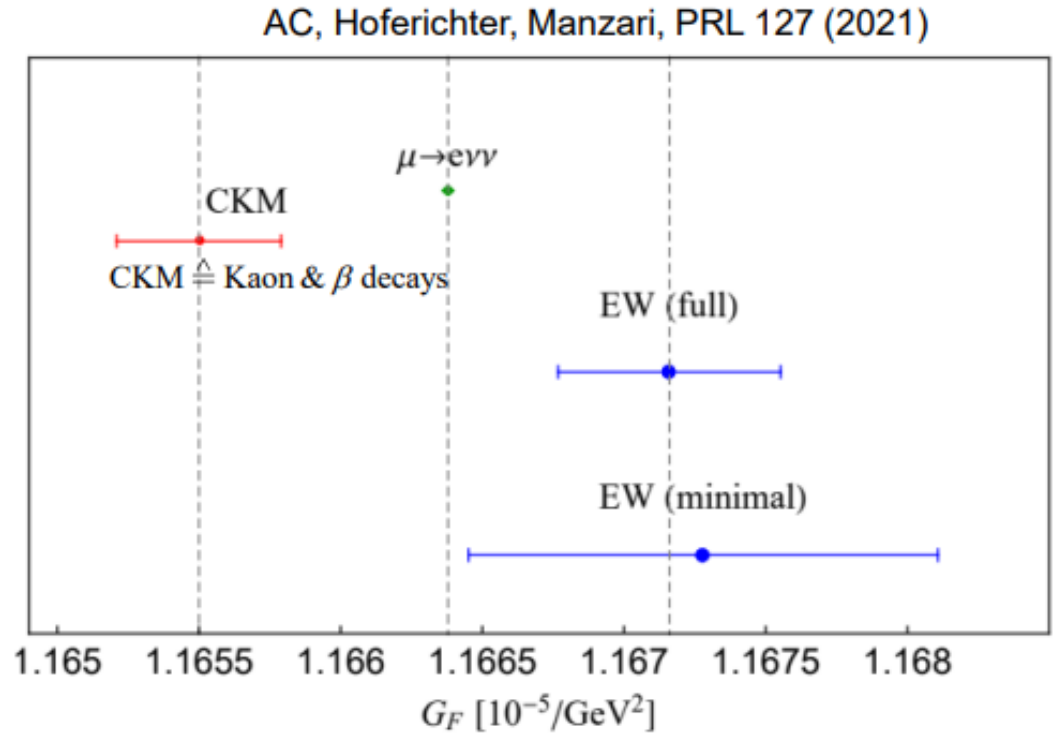

CMS, SGPR: radiative corrections

$$\left|V_{ud}^2\right|+\left|V_{us}^2\right|+\left|V_{ub}^2\right|=0.9985\pm0.0005,\ \left|V_{ud}^2\right|+\left|V_{cd}^2\right|+\left|V_{td}^2\right|=0.9970\pm0.0018$$

**Deficits in 1th row and column CKM unitarity**

# Correlations with EW fit

- The Fermi constant can be determined from:
  - The global EW fit (Z decays, α)
  - Kaon and beta decays (assuming CMK unitarity)
  - Muon decay




**CAA results in tensions in the Fermi constant**