Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions

Jun 7 – 9, 2023
University of Zurich

Experimental Inputs

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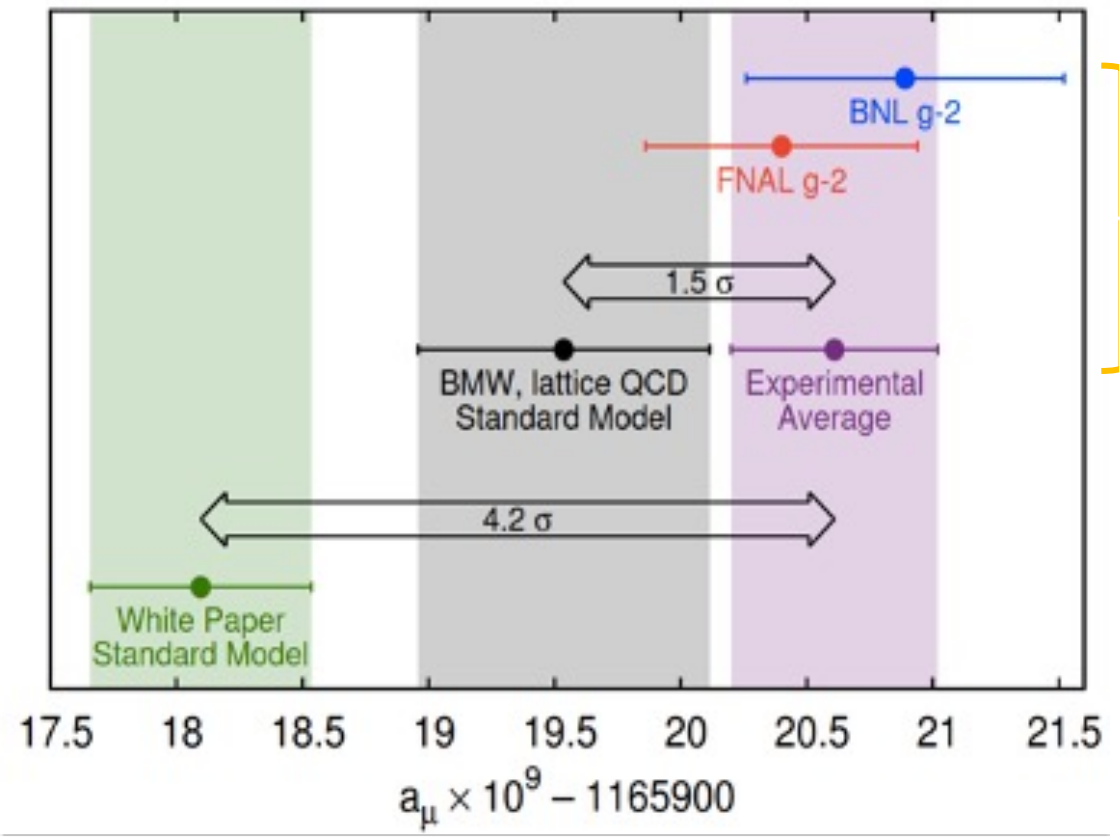
Muon g-2: SM value vs Experimental measurement



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{hadronic}$$

- In 2021 FNAL confirms BNL result (final exp. precision goal 140 ppb

$$\mathbf{a}_\mu(\mathbf{FNAL}) = 116592040(54) \cdot 10^{-11} \ (460\,\text{ppb})$$
$$\mathbf{a}_\mu(\mathbf{BNL}) = 116592089(63) \cdot 10^{-11} \ (540\,\text{ppb})$$
$$\mathbf{a}_\mu(\mathbf{Exp}) = 116592061(41) \cdot 10^{-11} \ (350\,\text{ppb})$$

[Phys. Rev. Lett. **126**, no.14, 141801 (2021)]

- 4.2σ tension with SM from dispersive approach and 1.5σ tension with SM from lattice QCD
- Theory uncertanty dominated by hadronic term, now known to 0.57%:

From the White Paper (Physics Reports 887 (2020) 1):

$$a_\mu^{\text{had}}(LO) = 693.1(4.0) \times 10^{-10}$$

Experimental Technique

1. Inject polarized muons into a magnetic storage ring
2. Muons circulate around the ring at the cyclotron frequency:

$$\vec{\omega}_C = \frac{q}{\gamma m_\mu}\vec{B}$$

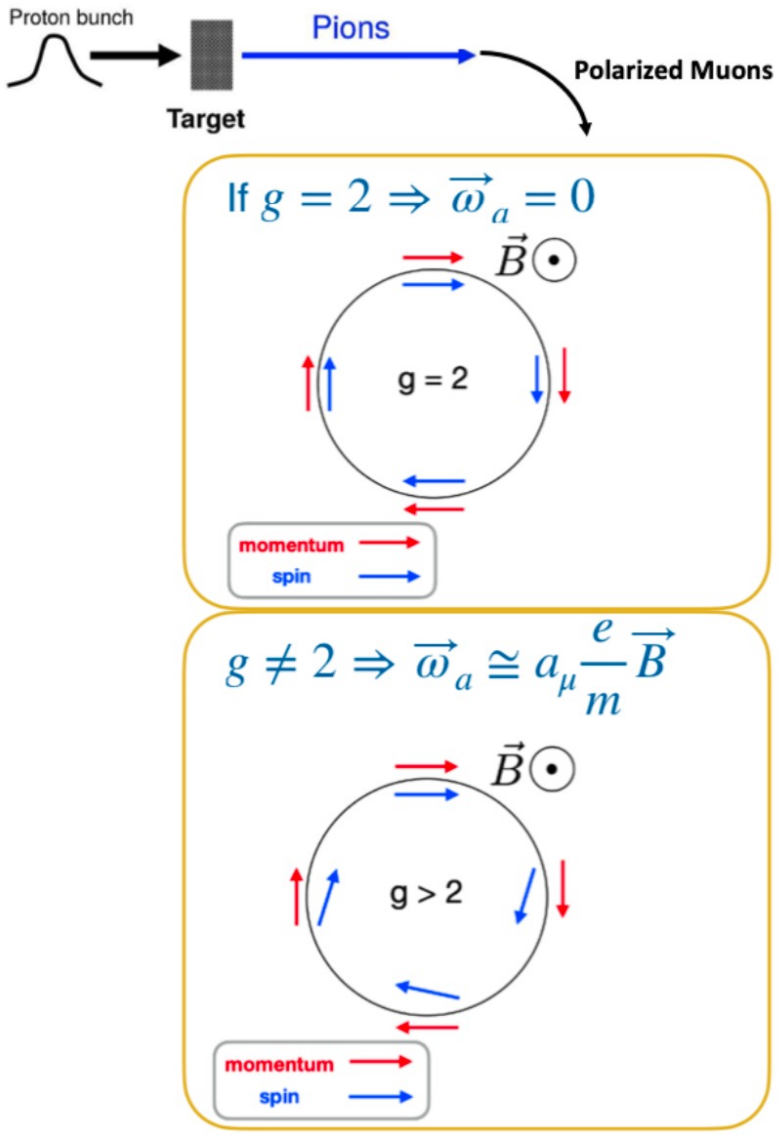
3. Muon spin precession frequency (Larmor) is given by:

$$\vec{\omega}_S = \frac{q}{\gamma m_\mu}\vec{B}(1+\gamma a_\mu)$$

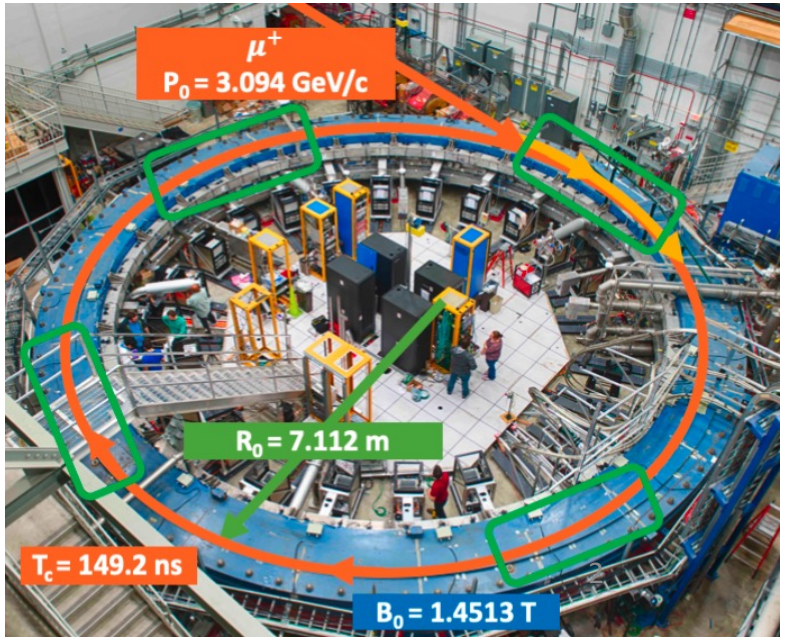
4. Muon anomaly is related to **anomalous precession frequency**:

$$\vec{\omega}_a \cong \vec{\omega}_S - \vec{\omega}_C \cong a_\mu \frac{q}{m_\mu}\vec{B}$$

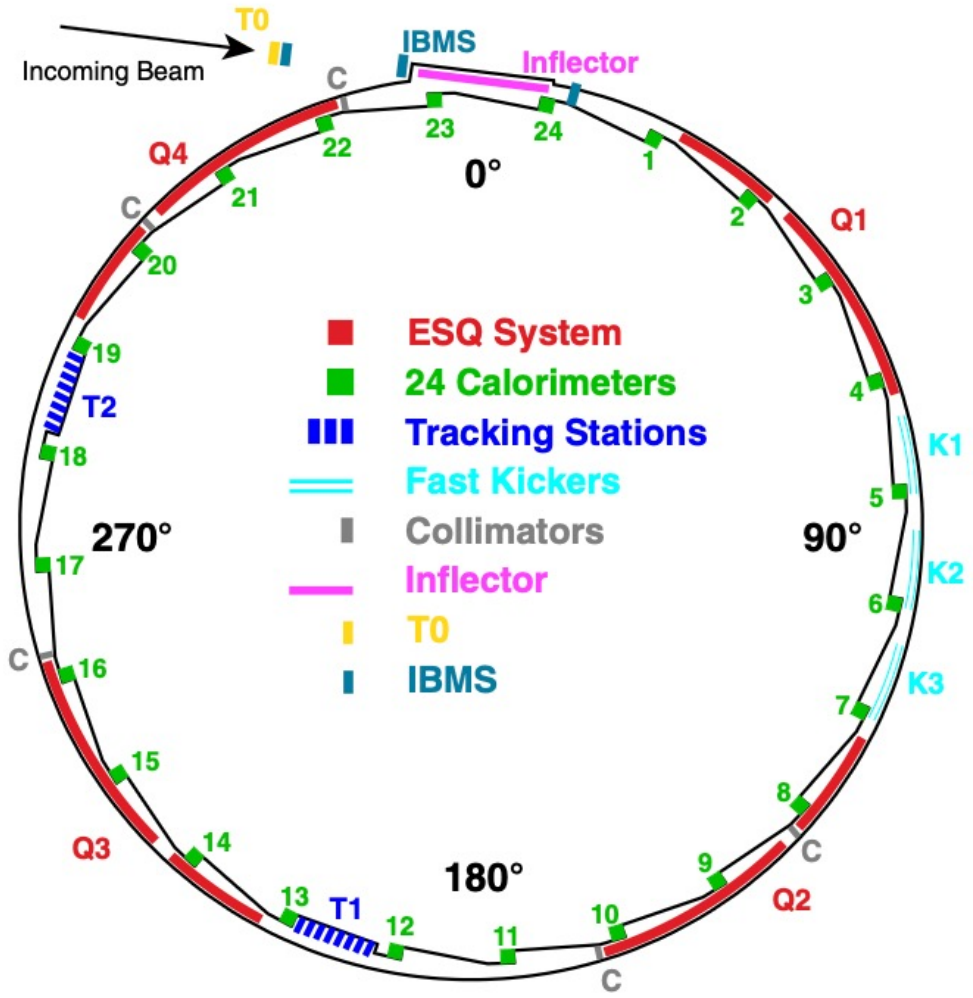
5. Measure B and ω_a to extract the anomaly



FNAL and BNL experiments use the same experimental technique, also in summer 2013 BNL storage ring was moved to FNAL



FNAL Muon g-2 Experiment



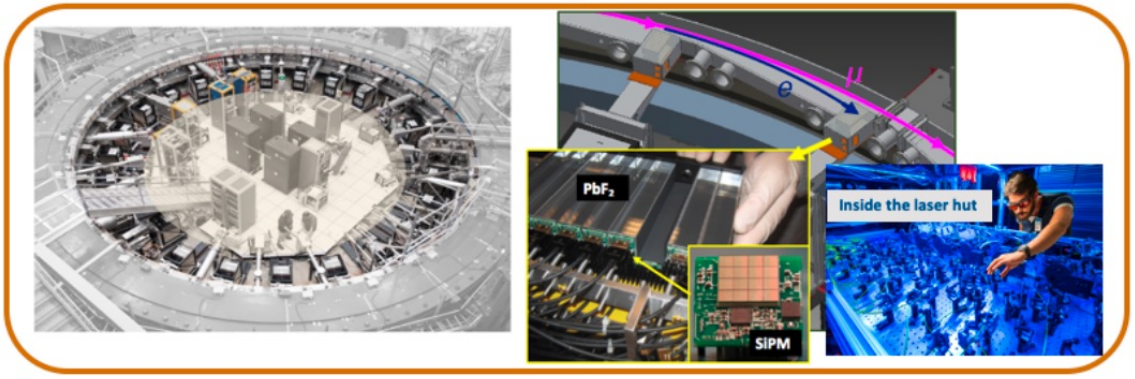
- **3.1 GeV/c polarized μ^+ beam** (from FNAL AD) injected into the **storage ring** (same of BNL but achieved 50ppm uniformity thanks to active and passive shimming) trough **inflector**; beam time and spatial profiles measured by **T0** and **IBMS**
- Beam deflected by 3 fast-pulsed **kicker magnets** into storage orbit
- Beam vertically focused by 4 **ElectroStatic Quadrupoles**:

$$\vec{\omega}_a \cong -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \underbrace{\frac{1}{\gamma^2-1}}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

~ 0 if γ=29.3 *i.e.*, p_μ=3.094 GeV/c

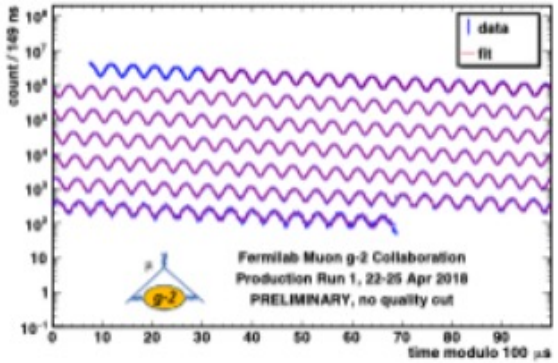
E −field component cancels out (at first order) when muons at *magic momentum*

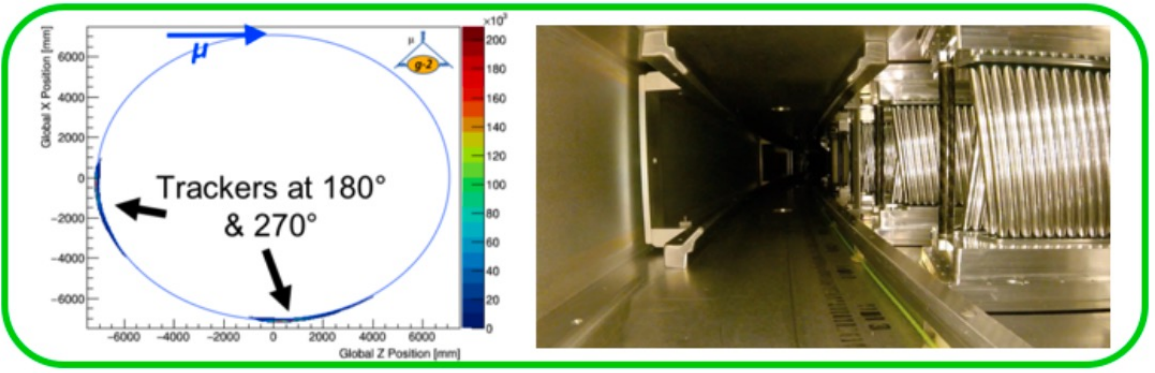
Detectors and Probes



24 Calos around the ring

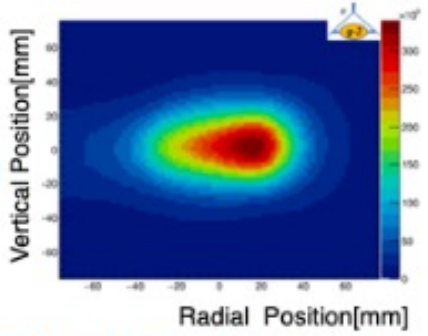
- Each made of 6×9 PbF_2 crystals read out by large-area SiPMs
- 1296 channels individually calibrated by 405nm-laser system



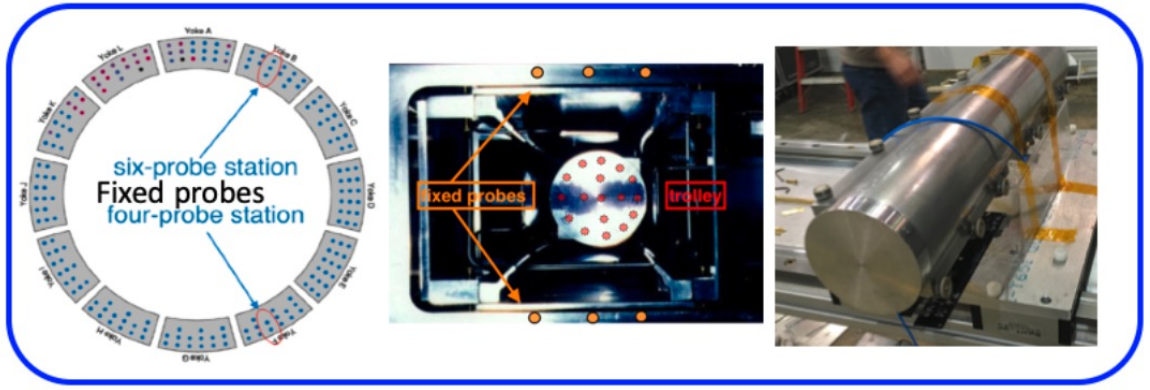


2 in-vacuum straw trackers

- Each with 8 modules consisting of 128 gas filled straws

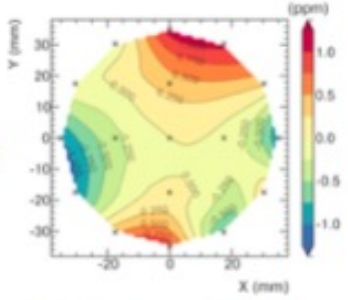


Muon distribution in the storage ring



2 types of field probes

- 378 fixed NMR probes above and below storage region
  - → measure B-field 24/7
- Trolley with 17-probe NMR
  - → 2D profile of B over the entire azimuth when beam is OFF



Map the magnetic field

Measuring the muon anomaly

fundamental factors
(combined uncertainty 25 ppb):

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

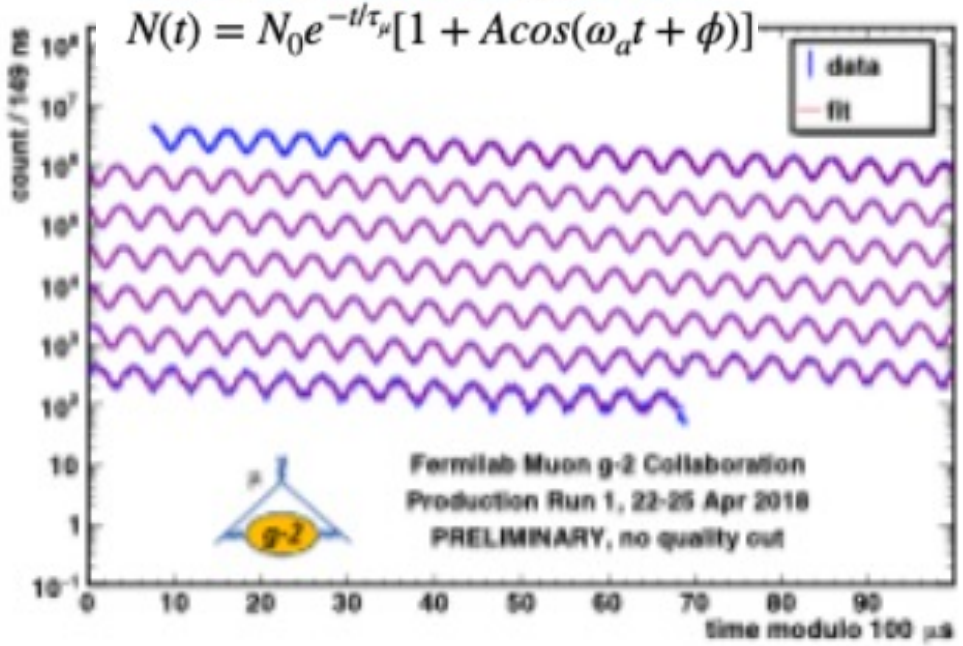
$\mu'_p(T_r)/\mu_e(H)$ from [Metrologia **13**, 179 (1977)]
$\mu_e(H)/\mu_e$ from [Rev. Mod. Phys. **88** 035009 (2016)]
m_μ/m_e from [Phys. Rev. Lett. **82**, 711 (1999)]
$g_e/2$ from [Phys. Rev. A **83** 052122 (2011)]

ratio of frequencies (R_μ) measured by us

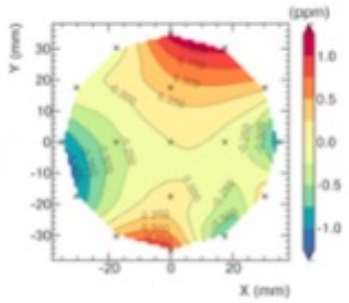
ω_a: muon anomalous precession frequency

Extract from decay positron time spectra

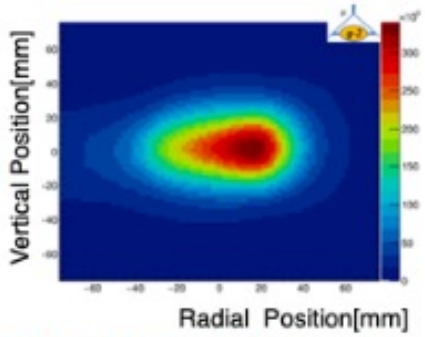
$N(t) = N_0 e^{-t/\tau_\mu}[1 + A\cos(\omega_a t + \phi)]$



$\tilde{\omega}'_p(T_r)$: magnetic field B in terms of (shielded) proton precession frequency (proton NMR $\hbar\omega_P = 2\mu_p B$) **and** weighted by the muon distribution
(shielded = measured in spherical water sample at $T_r = 34.7\,°C$)



Map the magnetic field



Muon distribution in the storage ring

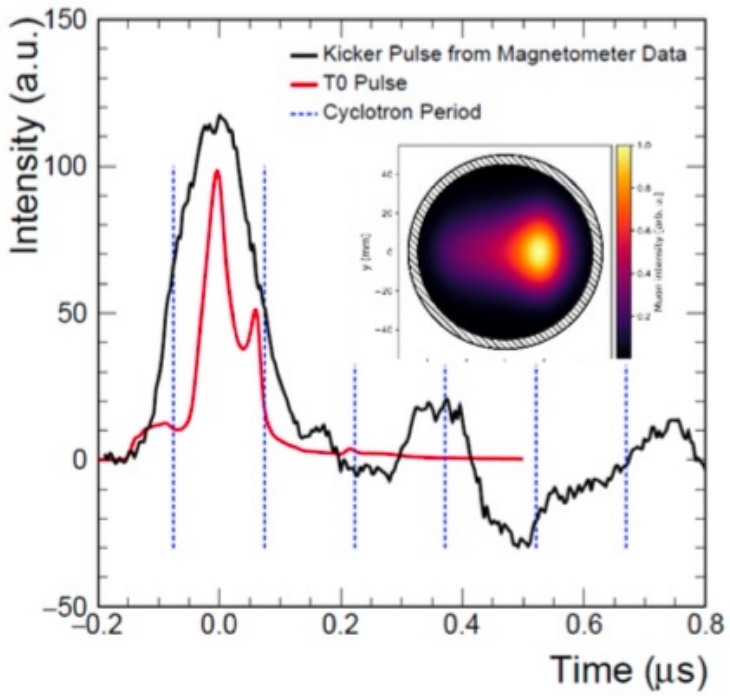
Run-1 Dataset

Statistics:

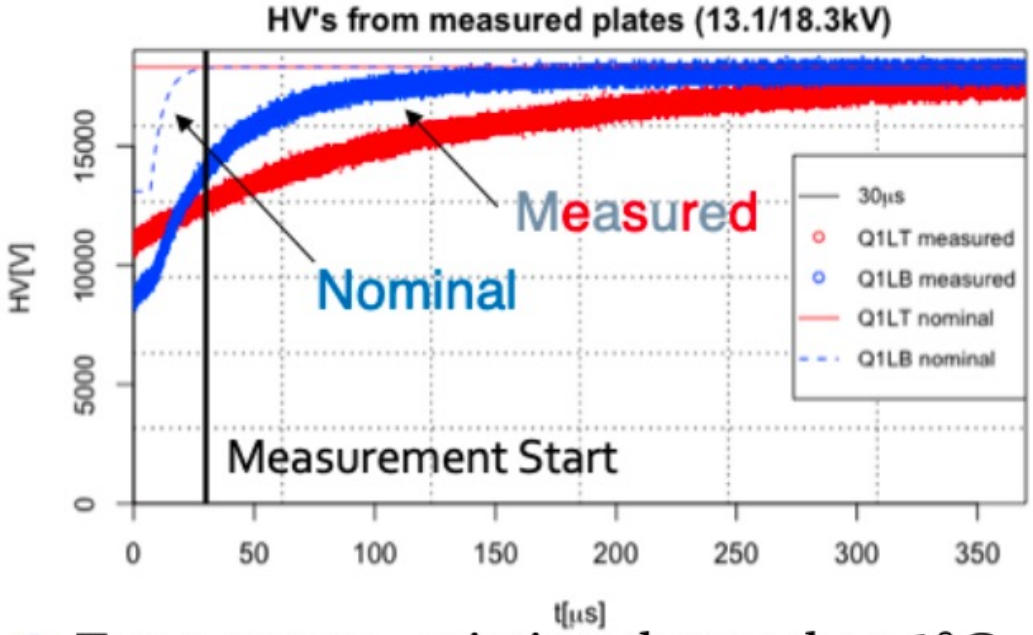
- March 26 – July 7 2018 : **Run1**
- **1.2 × BNL** after data quality selection

Main challenges:

- Non-ideal kick
  - → low amplitude and ringing
  - → beam not centered in storage region



- 2 of 32 HV Quad resistors were damaged
  - → slow recovery time



- Temperature variations larger than 1°C

Run1 Results

First **FNAL** $g-2$ result :

$$a_\mu = 116592040(54) \times 10^{-11} \ (462 \text{ ppb})$$

f_{clock} : blinded clock
ω_a^{meas} : measured precession frequency

C_e : electric field correction
C_p : pitch correction
C_{ml} : muon loss correction
C_{pa} : phase-acceptance correction

$$R_\mu = \left(\frac{\overbrace{f_{clock} \cdot \omega_a^{meas}}^{\omega_a} \cdot \overbrace{(1 + C_e + C_p + C_{ml} + C_{pa})}^{\text{beam dynamics corrections}}}{\underbrace{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi)}_{\widetilde{\omega}'_p(T_r)} \cdot \underbrace{(1 + B_k + B_q)}_{\text{field corrections}}} \right)$$

f_{calib} : absolute magnetic field calibration
$\omega'_p(x,y,\phi)$: field maps
$M(x,y,\phi)$: muon beam distribution

B_k : transient field from eddy current in kicker
B_q : transient field from quad vibration

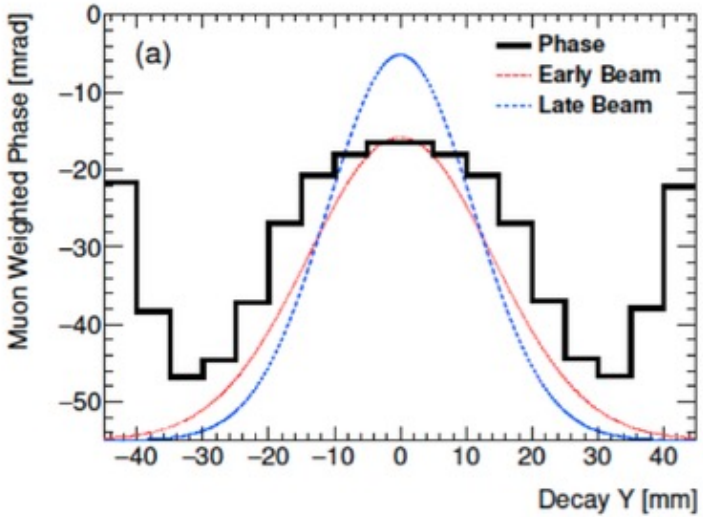
Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	434
ω_a^m (systematic)	...	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle$	...	56
B_k	−27	37
B_q	−17	92
$\mu'_p(34.7°)/\mu_e$	...	10
m_μ/m_e	...	22
$g_e/2$	...	0
Total systematic	...	157
Total fundamental factors	...	25
Totals	544	462

- Run-1 result uncertainty is **statistics dominated**
- Major systematic uncertainties: **PA and field transients**
- **Next**: reduce as much as possible the experimental uncertainty on g-2 !

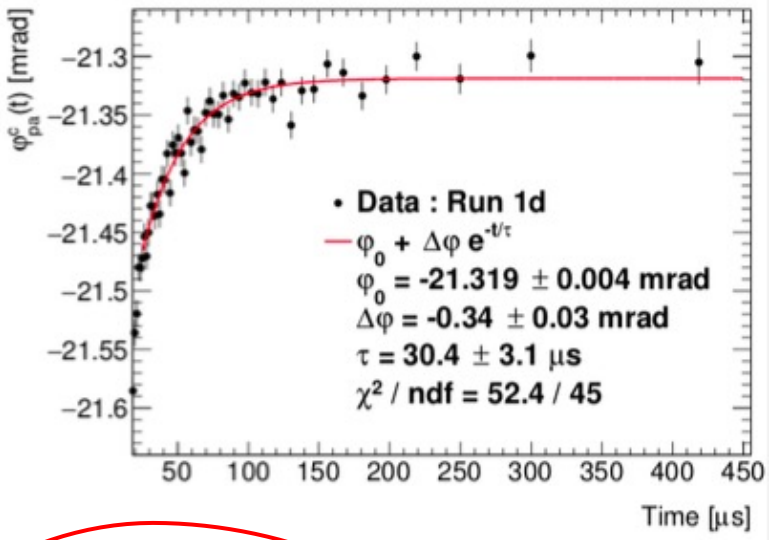
Run-1 Main Syst. Uncertainties

Phase acceptance

- phase changes due to early to late variations of the beam
- worsened by damaged quads resistors
- measured using tracker data and simulations



$C_{pa} \sim 200\,\text{ppb} \quad \delta_{C_{pa}} \sim 80\,\text{ppb}$



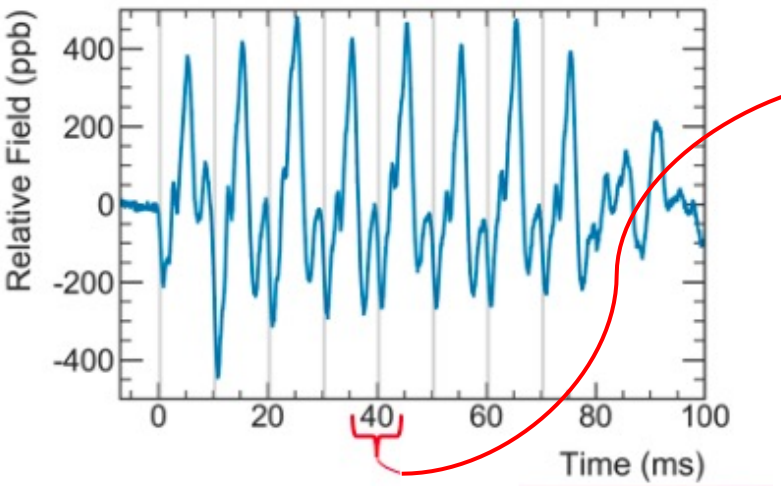
Quads transient field

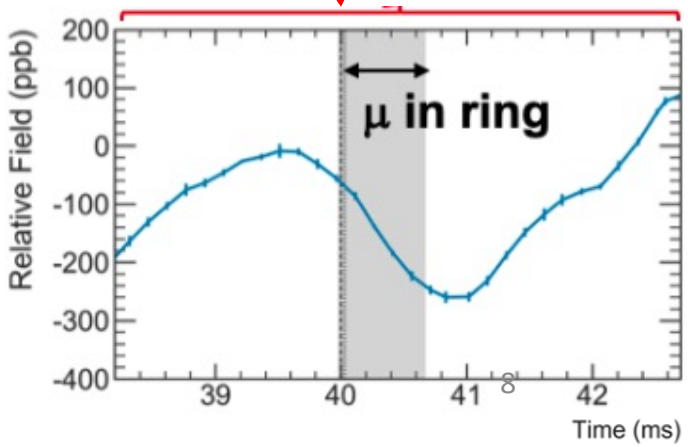
- due to mechanicals vibrations from pulsing the quads
- mapped using special NMR probes

$B_q \sim 17\,\text{ppb} \quad \delta_{B_q} \sim 92\,\text{ppb}$

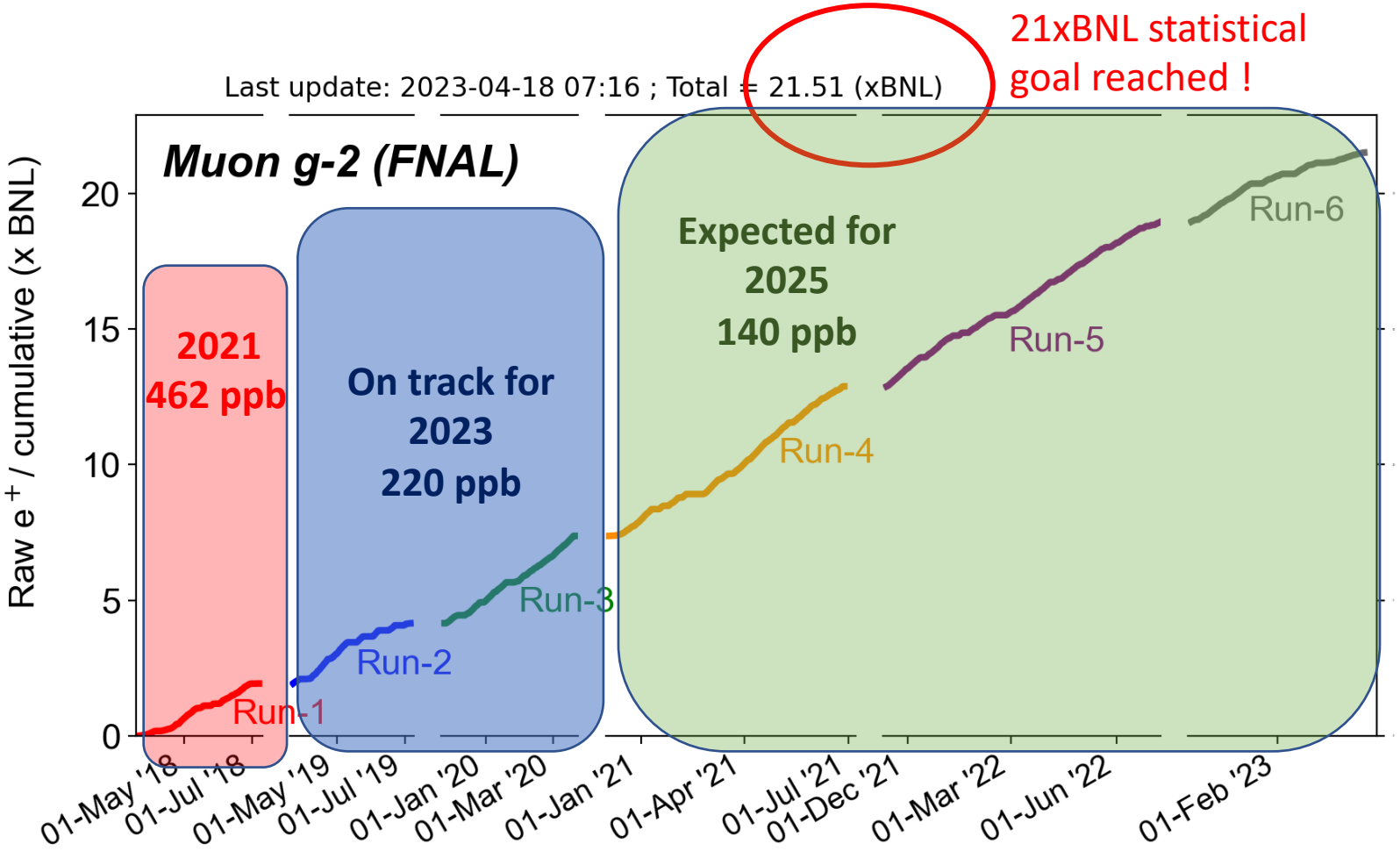
→ δ_{B_q} dominated by incomplete map

→ expected to be reduced by factor 2 for Run 2 and after





Status of FNAL Muon g-2 Exp.



On track for ~140 ppb total uncertainty

Improvements after Run1:

- Quad resistors are fixed, so reduced C_{PA}, reduced muon losses, and can take longer measurements of B_q
- Full kick, muons on central orbit. Reduced C_E and δC_E
- Magnet insulation, so less field drift from temperature variations

Run4 and beyond Improvements:

- New Radio Frequency System mounted on quadrupoles which reduces Beam Betatron oscillations
  - damps beam oscillations in the first 10 μs
  - Tested during Run-4 and in use during Run-5 and Run-6
- Improved knowledge of the time-momentum correlation with simulation and a new detector

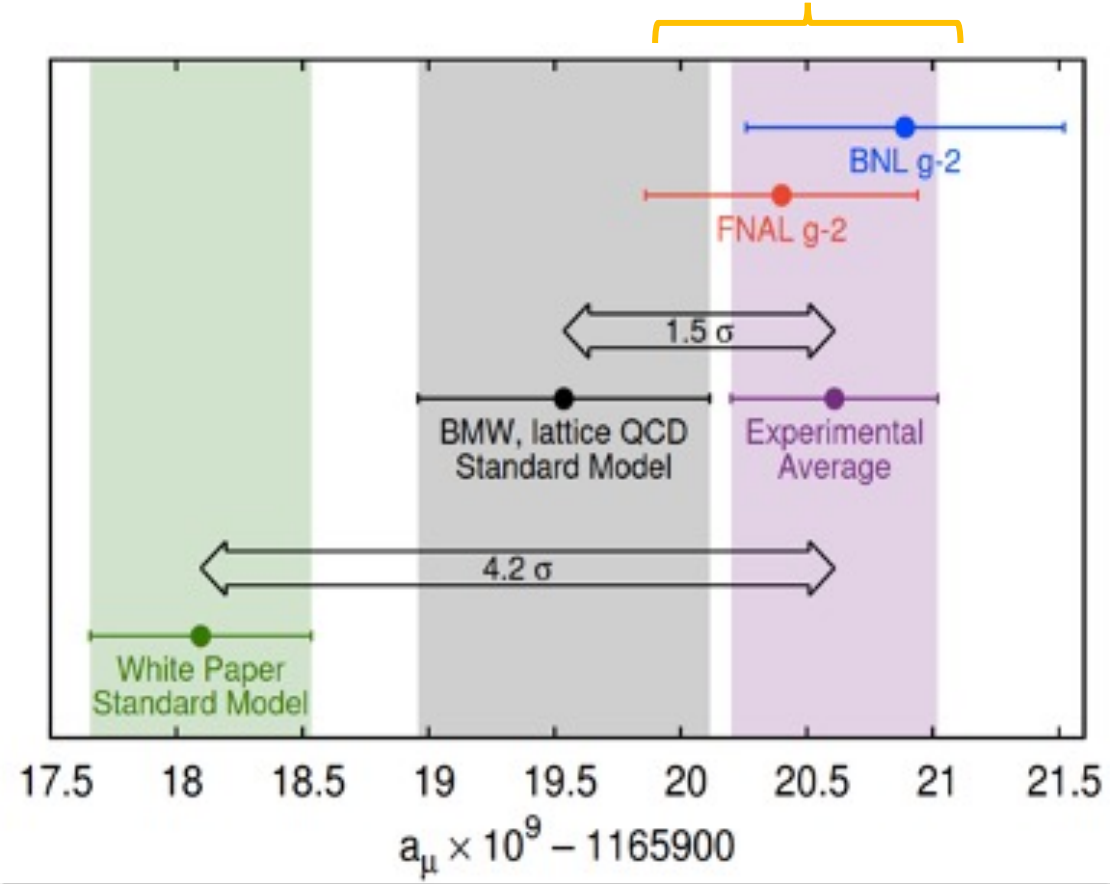
Improvements in the analysis

- Reconstruction algorithms, pileup…

Muon g-2: SM value vs Experimental measurement

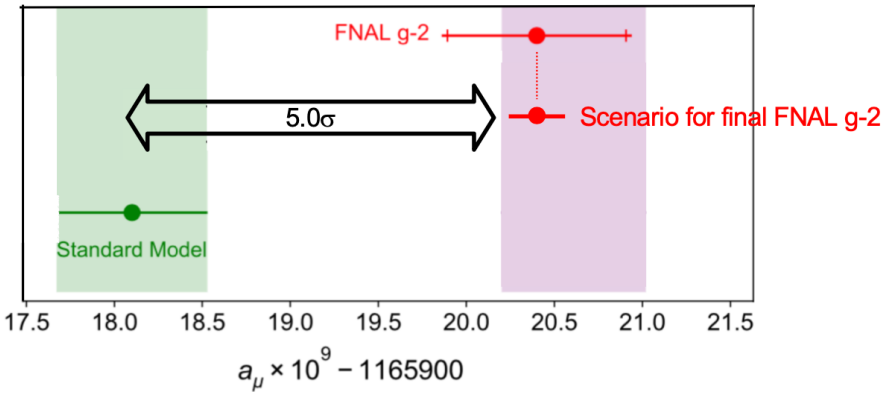
$a_\mu(\mathbf{FNAL}) = 116592040(54) \cdot 10^{-11}$ (460 ppb)
$a_\mu(\mathbf{BNL}) = 116592089(63) \cdot 10^{-11}$ (540 ppb)
$a_\mu(\mathbf{Exp}) = 116592061(41) \cdot 10^{-11}$ (350 ppb)

[Phys. Rev. Lett. **126**, no.14, 141801 (2021)]

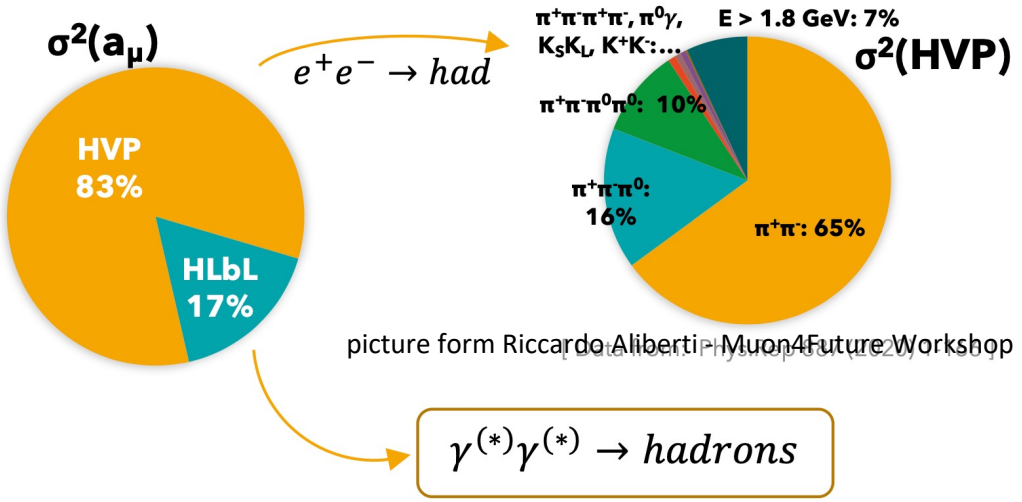


$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{hadronic}$$

- Final FNAL exp. precision goal 140 ppb



- SM uncertainty dominated by hadronic term:



picture form Riccardo Aliberti - Muon4Future Workshop

Needs to be reduced to 0.23% to match Fermilab precision

Hadronic Vacuum Polarization Contribution to g-2

From optical theorem (unitarity) and analyticity:

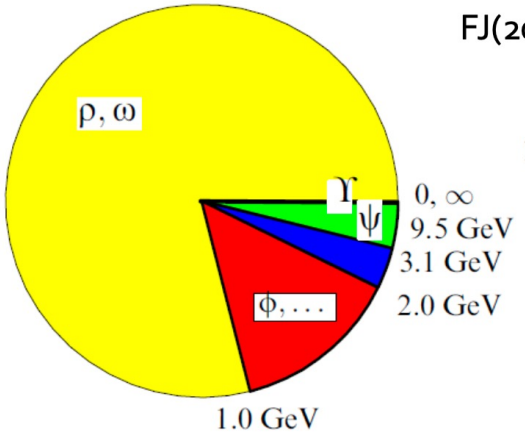
$$a_\mu^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty}\frac{ds}{s}\,K(s)\,R(s)$$

$$R(s) = \frac{\sigma(e^+e^-\to hadrons)}{\sigma(e^+e^-\to\mu^+\mu^-)}$$

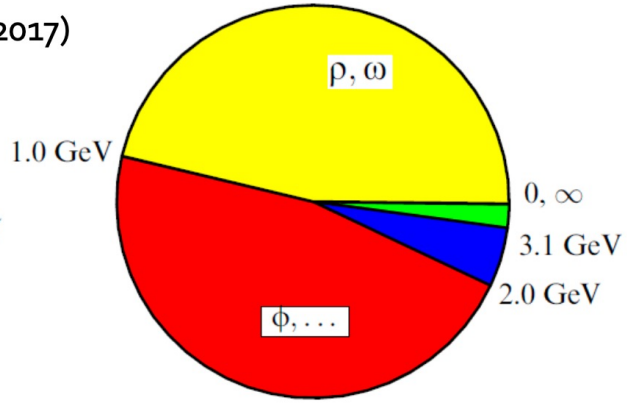
- **Data Driven approach**: K(s) known kernel function, needed e^+e^- into hadrons data to evaluate R(s)

- main contributions from low energies: $\sqrt{s} \lesssim 2\text{GeV}$

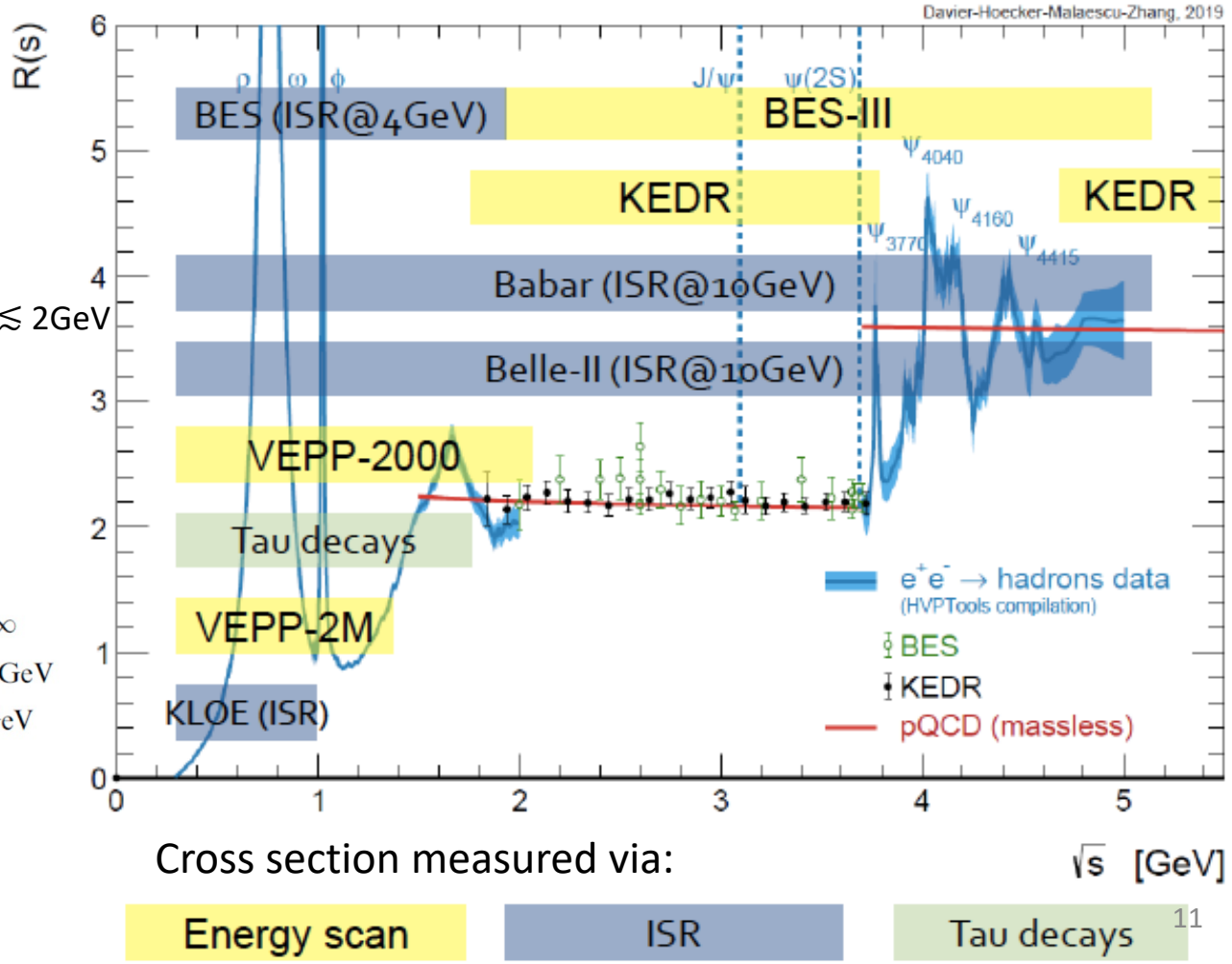
FJ(2017)



Contribution to the integral

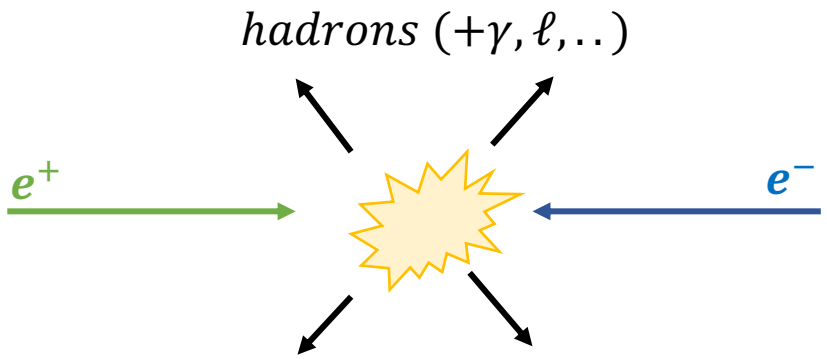


Contribution to the error of integral



Energy scan approach

- Direct measurment of $\sigma(e^+e^- \to hadrons)$
- performed at electron-positron collider by collecting data at different beam energy
- At each energy point:



$$\sigma = \frac{N_{obs} - N_{bg}}{\varepsilon \cdot \int \mathcal{L} dt}$$

1. select **final states with hadrons** and subtract **backgrounds**

2. correct for the **detection efficiency** (kinematical limits of detector) calculated usually using MC simulation

- need knowledge of energy and angular distributions of final particles (including all correlations)
- High energy: **inclusive approach -** total cross section is measured directly
- Low energy: **exclusive approach** (different ε per each final and intermediate hadronization states) – measured single cross sections and sum them

3. normalized to **luminosity integral**

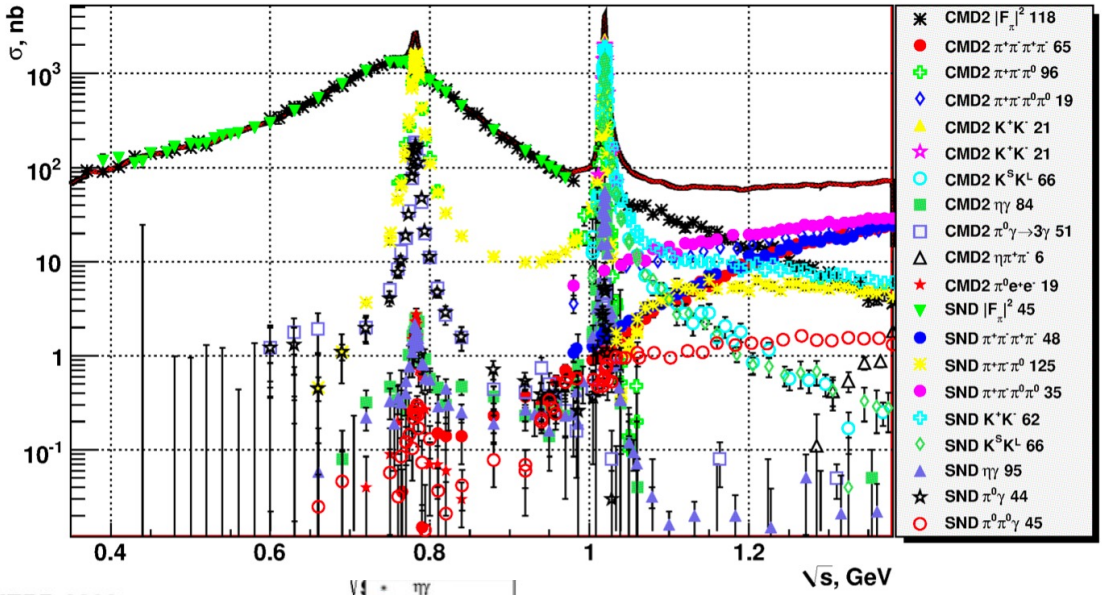
- Use process with known cross section to measure the luminosity

$$\int \mathcal{L} dt = \frac{N_{obs} - N_{bg}}{\varepsilon \cdot \sigma_{known}}$$

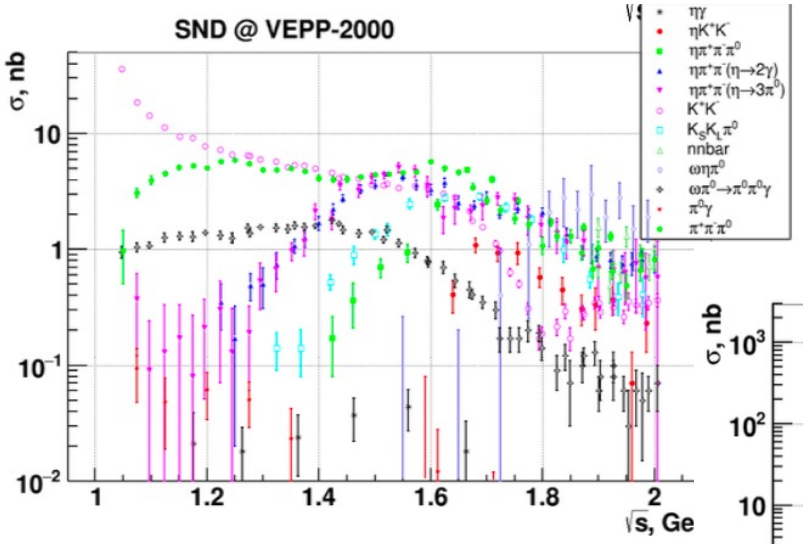
- $e^+e^- \to \mu^+\mu^-$ *Has many advantages, but relatively small cross section and large background*
- $e^+e^- \to \gamma\gamma$ *Natural for final states with neutrals*
- $e^+e^- \to e^+e^-\gamma$
- $e^+e^- \to e^+e^-\gamma\gamma$ *Often used for online measurement*

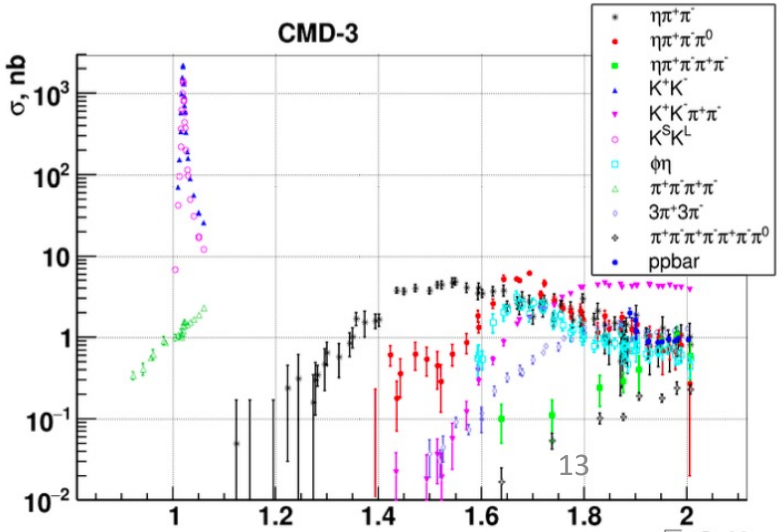
Energy Scan Measurements

- **VEPP-2M (1993-2000) :**
  - Energy range: 0.36 – 1.4 GeV
  - Luminosity up to 5 10^{30} $cm^{-2}s^{-1}$
  - **Detectors:** SND, CMD-2



- **VEPP-2000 (2011-2013) (2017-now)**
  - Energy range: 0.32-2.0 GeV
  - Luminosity 10^{32} $cm^{-2}s^{-1}$
  - 2013-2017 major upgrade :
  - **Detectors:** SND, CMD-3





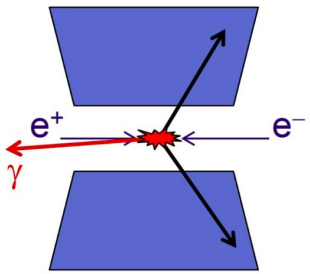
Initial State Radiation (ISR) Approach

- $\sigma(e^+ + e^- \to X)$ in the energy range is extracted looking for $e^+ + e^- \to X + \gamma$ events at a single energy point:
- Emission angle of γ_{ISR}:

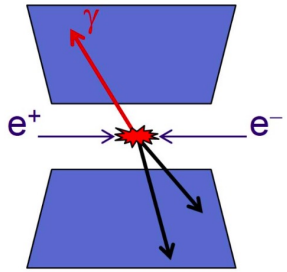
$$\frac{dN_{X(\gamma)\gamma_{ISR}}}{d\sqrt{s'}} = \frac{dL^{eff}_{ISR}}{d\sqrt{s'}} \varepsilon_{X(\gamma)}(\sqrt{s'})\sigma_{X(\gamma)}(\sqrt{s'})$$

Effective luminosity: $\frac{dL^{eff}_{ISR}}{d\sqrt{s'}} = L_{ee}\frac{dW}{d\sqrt{s'}}$

Radiator function – probability to radiate ISR photon (with radiative corrections)



- Small (γ_{ISR} not detected but reconstructed in the final state) => **untagged ISR**



- Large (γ_{ISR} detected) => **tagged ISR**

	Tagged ISR	Untagged ISR
Normalization to e^+e^-	KLOE-2010 ($\pi^+\pi^-$) BABAR (most channels)	KLOE-2005 ($\pi^+\pi^-$) KLOE-2008 ($\pi^+\pi^-$) BABAR ($p\bar{p}$)
Normalization to $\mu^+\mu^-(\gamma)$	BABAR ($\pi^+\pi^-$)* BES-III ($\pi^+\pi^-$) CLEO-c ($\pi^+\pi^-$)	KLOE-2012 ($\pi^+\pi^-$)

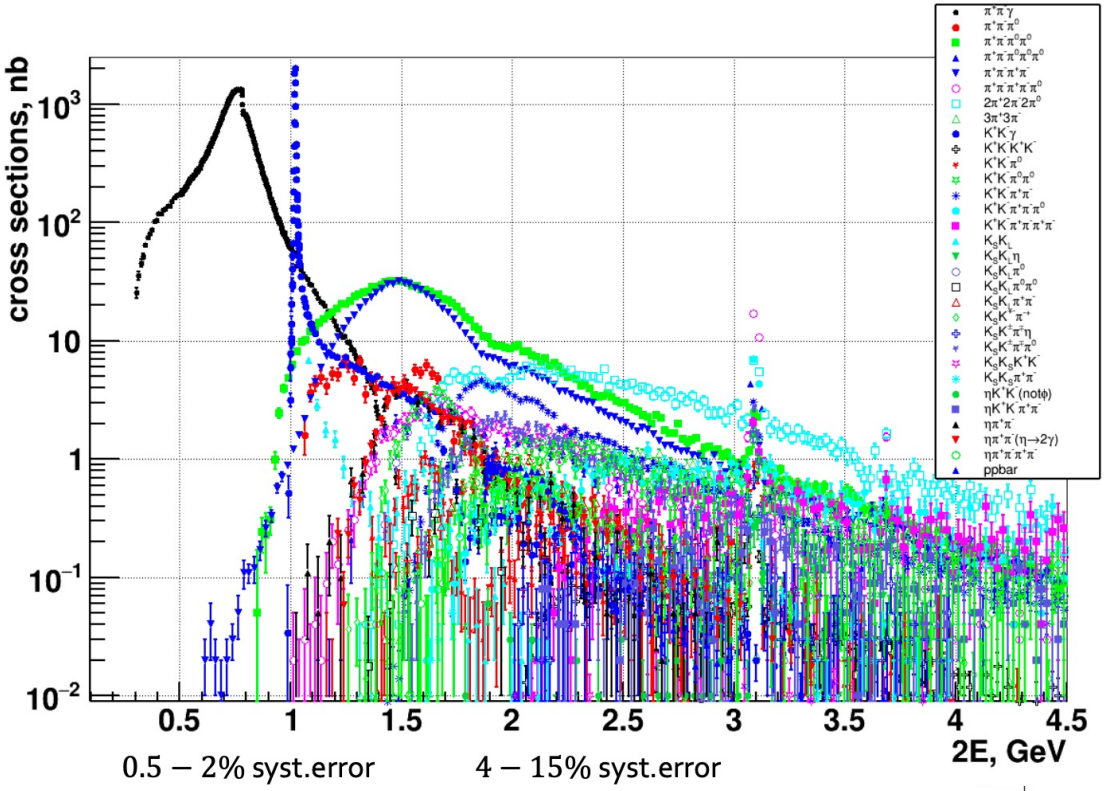
Slide from Ivan Logashenko - Data Input to HVP

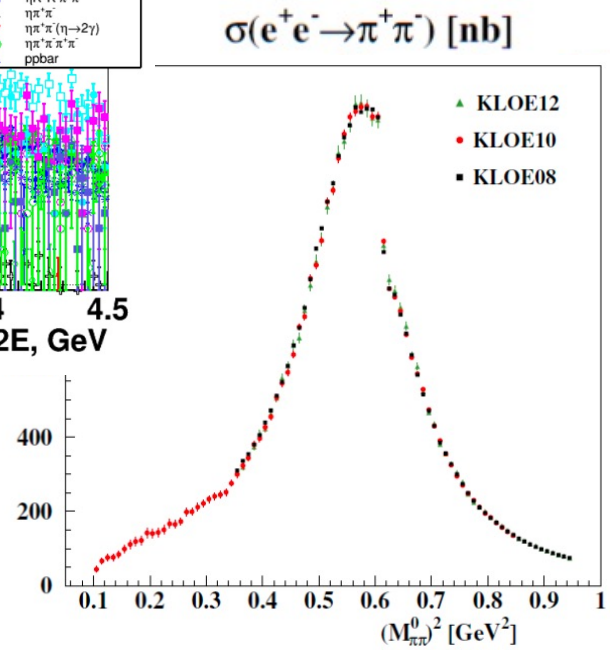
ISR Measurements

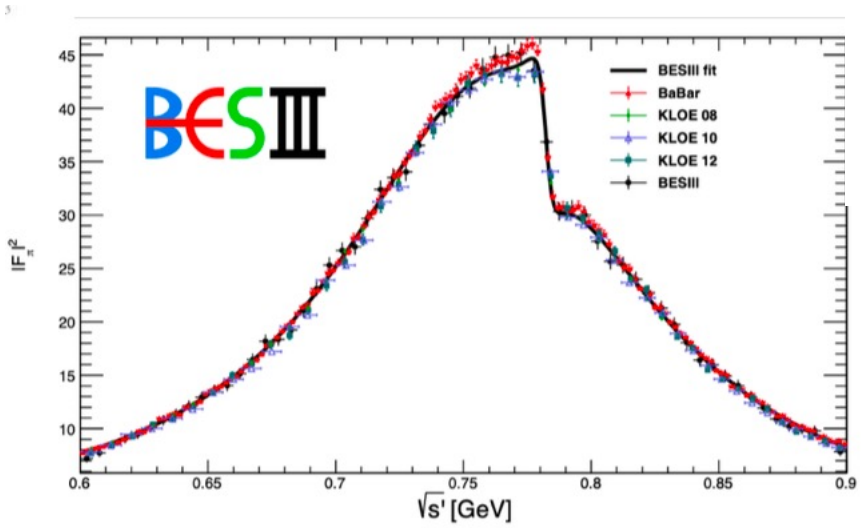
- **BaBar Experiment:**
  - asymmetric e^+e^- collider at SLAC with 9 GeV e^- and 3.1 GeV e^+
  - between 1999-2008 collected 500 fb^{-1}

- **KLOE Experiment:**
  - DAFNE phi-facility in Frascati
  - Data collected between 2000-2006

- **BES-III Experiment:**
  - BEPC-II collider in Beijing with c.m. energy range from 2 to 5 GeV
  - Still collecting data
  - Previous experiments BES-I and BES-II







From measured cross section to a_μ input to calculation

"Visible" cross section
$\sigma(e^+e^-(\gamma) \to X(\gamma))$

Here we correct for all detector effects

Adjust for radiative corrections (ISR, FSR)
$\sigma(e^+e^- \to X)$

This one is used to get parameters of the resonances (mass, width,…)

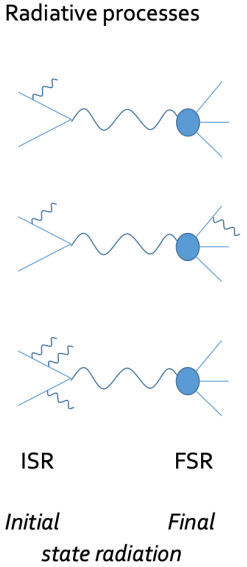
Adjust for vacuum polarization and return back FSR
$\sigma^0(e^+e^- \to X(\gamma))$

This one is used in the a_μ integral

Radiative Corrections (RC):

- to accunt for processes with photons emmitted by any of the particles
- Impact both cross-sections and final state

$$\sigma = \frac{N_{obs} - N_{bg}}{\varepsilon(\delta) \cdot (1+\delta) \cdot \int \mathcal{L} dt}$$

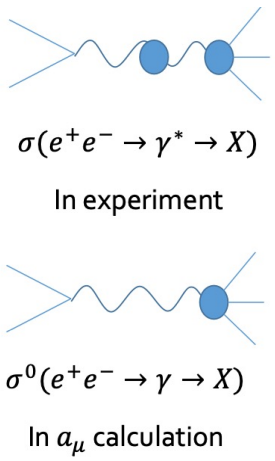


Vacuum polarization (VP):

- To account for higher order effects (loop corrections) in the experiment:

$$\sigma^0(e^+e^- \to X) = \sigma(e^+e^- \to X) \times \frac{|\alpha(s)|^2}{\alpha^2}$$

- Not needed if $e^+e^- \longrightarrow \mu^+\mu^-$ is used for the luminosity measurements



Inclusive R(s) Measurements

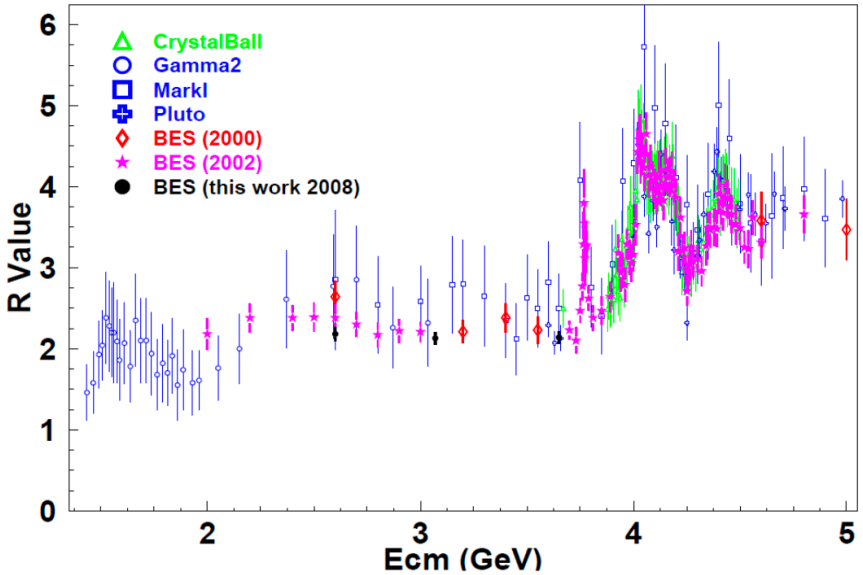
- For cms energies > 2 GeV (large QED background below, low multiplicities)
- Select events with at least one hadron in the final state and any other particle:

$$\sigma_{\mathrm{mh}}^{\mathrm{obs}}(s) = \frac{N_{\mathrm{mh}} - N_{\mathrm{res.bg}}}{\int \mathcal{L}\,\mathrm{d}t}$$

$$R = \frac{\sigma_{\mathrm{mh}}^{\mathrm{obs}}(s) - \sum \varepsilon_{\mathrm{bg}}(s)\,\sigma_{\mathrm{bg}}(s) - \sum \varepsilon_{\psi}(s)\,\sigma_{\psi}(s)}{\varepsilon(s)\big(1+\delta(s)\big)\,\sigma_0^{e^+e^-\to\mu^+\mu^-}(s)}$$

PRL88(2002)101802
PLB677(2009)239

Depends on:
- event selection
- luminosity measurement
- calculation of radiative corrections
- evaluation of detector efficiency



Generally achieved 3% precision, main difficulty is modelling of hadronic events to evaluate efficiencies and radiative corrections => dedicated MC generators

Next talk:

Feasibility Studies for an Inclusive R-Measurement using ISR with BESIII *Thomas Lenz*

Monte Carlo generators

- In the last 20 years there has been a lot of effort to improve MC generators and RC to $e^+e^- \rightarrow leptons/hadrons$ at low energy : reached accuracy of 0.2 - 0.5%

MC generators for exclusive channels (exact NLO + Higher Order terms in some approx)

MC generator	Channel	Precision	Comment
MCGPJ (VEPP-2M, VEPP-2000)	$e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$	0.2%	photon jets along all particles (collinear Structure function) with exact NLO matrix elements
BabaYaga@NLO (KLOE, BaBar, BESIII)	$e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma$	0.1%	QED Parton Shower approach with exact NLO matrix elements
BHWIDE (LEP)	$e^+e^- \rightarrow e^+e^-$	(0.1%?)	Yennie-Frautschi-Suura (YFS) exponentiation method with exact NLO matrix elements

MC generators for ISR (from approximate to exact NLO)

MC generator	Channel	Precision	Comment
EVA (KLOE)	$e^+e^- \rightarrow \pi^+\pi^-\gamma$	O(%)	Tagged photon ISR at LO + Structure Function FSR: point-like pions
AFKQED (BaBar)	$e^+e^- \rightarrow \pi^+\pi^-\gamma, \ldots$	depends on the event selection (can be as good as Phokhara)	ISR at LO +Structure Function
PHOKHARA (KLOE, BaBar BESIII)	$e^+e^- \rightarrow \pi^+\pi^-\gamma, \mu^+\mu^-\gamma, 4\pi\gamma, \ldots$	0.5%	ISR and FSR(sQED+Form Factor) at NLO
KKMC	$e^+e^- \rightarrow f^+f^-(n)\gamma$	High accuracy only for muon pairs	YFS exponentiation for soft photons + hard part and sub-leading terms in some approximation

- New data and improved evaluation of a_μ^{HLO} requires improvement on MC generators at ~0.1% → **NNLO needed!**

Inputs to White Paper for the HVP Calculation

- Merging of KNT, DHMZ estimates + input from ChPT/dispersive fits: CHHKS for 2π, 3π channels; determinations from FJ17 and BDJ10 (assuming hadronic models in global fit) not considered

	DHMZ19	KNT19	Difference
$\pi^+\pi^-$	507.85(0.83)(3.23)(0.55)	504.23(1.90)	3.62
$\pi^+\pi^-\pi^0$	46.21(0.40)(1.10)(0.86)	46.63(94)	−0.42
$\pi^+\pi^-\pi^+\pi^-$	13.68(0.03)(0.27)(0.14)	13.99(19)	−0.31
$\pi^+\pi^-\pi^0\pi^0$	18.03(0.06)(0.48)(0.26)	18.15(74)	−0.12
K^+K^-	23.08(0.20)(0.33)(0.21)	23.00(22)	0.08
$K_S K_L$	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.06)(0.04)(0.07)	4.58(10)	−0.17
Sum of the above	626.08(0.95)(3.48)(1.47)	623.62(2.27)	2.46
[1.8, 3.7] GeV (without $c\bar{c}$)	33.45(71)	34.45(56)	−1.00
J/ψ, $\psi(2S)$	7.76(12)	7.84(19)	−0.08
[3.7, ∞) GeV	17.15(31)	16.95(19)	0.20
Total $a_\mu^{\mathrm{HVP,\,LO}}$	$694.0(1.0)(3.5)(1.6)(0.1)_\psi(0.7)_{\mathrm{DV+QCD}}$	692.8(2.4)	1.2

reasonable agreement

→ $a_\mu^{HVP,LO} = 693.1(2.8)_{\mathrm{exp}}(2.8)_{\mathrm{syst}}(0.7)_{\mathrm{pQCD}} = 693.1(4.0) \times 10^{-10}$ Whitepaper estimate

experimental uncertainties: dominated by 2π uncertainty

KLOE/BABAR tension: leaving out KLOE or BABAR, respectively

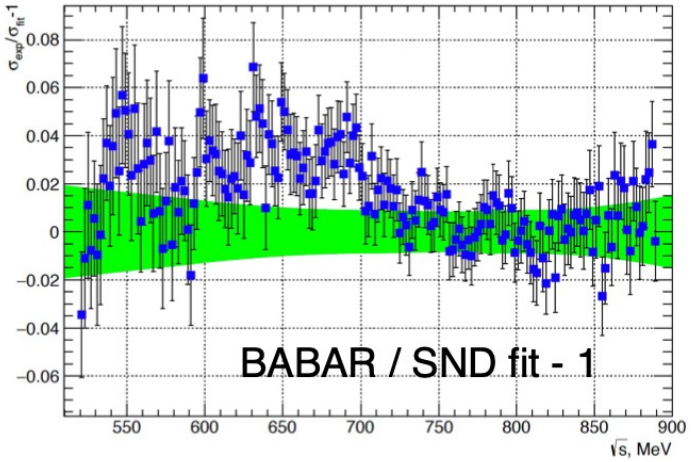
energy region [1.8;3.7] GeV; usage of pQCD by DHMZ, while KNT follows data-driven approach

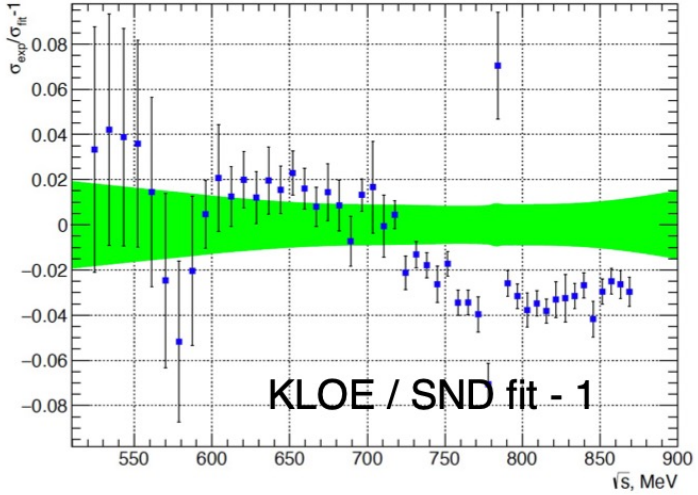
Hadronic Cross Sections Data after the White Paper

- BESIII $\pi^+\pi^-$, (600 < √s < 900) MeV, update of covariance matrix
  → central value unchanged, reduction of statistical error

- New SND analysis of $\pi^+\pi^-$ channel, (525 < √s < 883) MeV
  → systematic uncertainty > 600 MeV: 0.8%

Measurement	$a_\mu(\pi\pi) \times 10^{10}$
This work	$409.79 \pm 1.44 \pm 3.87$
SND06	$406.47 \pm 1.74 \pm 5.28$
BaBar	$413.58 \pm 2.04 \pm 2.29$
KLOE	$403.39 \pm 0.72 \pm 2.50$



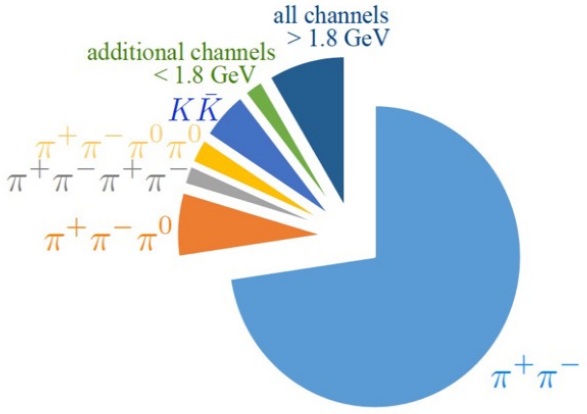


- New BABAR data on $\pi^+\pi^-4\pi^0$, $2(\pi^+\pi^-)3\pi^0$, $KK\pi\pi\pi$

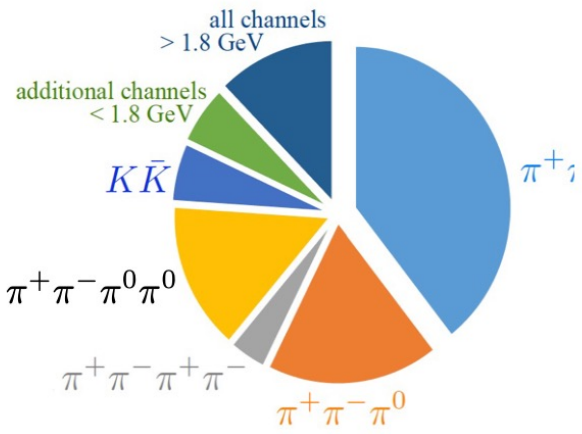
- New BABAR analysis of $\pi^+\pi^-\pi^0$ channel, (0.62 < √s < 3.5) GeV
  → systematic uncertainty < 1.1 GeV: 1.3%
  → fit to $M_{3\pi}$ including $\omega(782)$, $\omega(1420)$, $\omega(1680)$, $\phi(1020)$, $\rho(770)$

The $e^+e^- \to \pi^+\pi^-$ channel

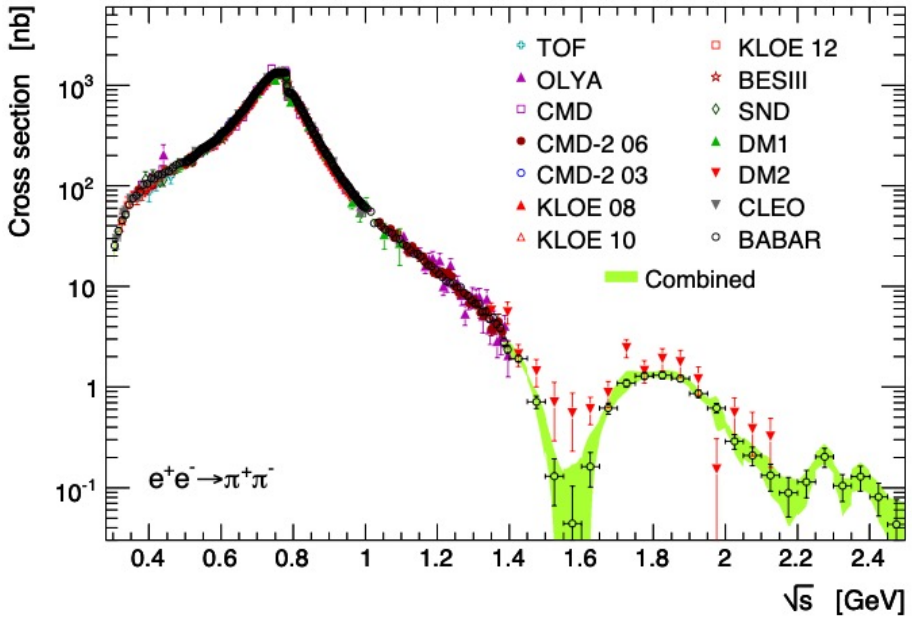
- Largest contributor to both HVP and σ_{HVP}

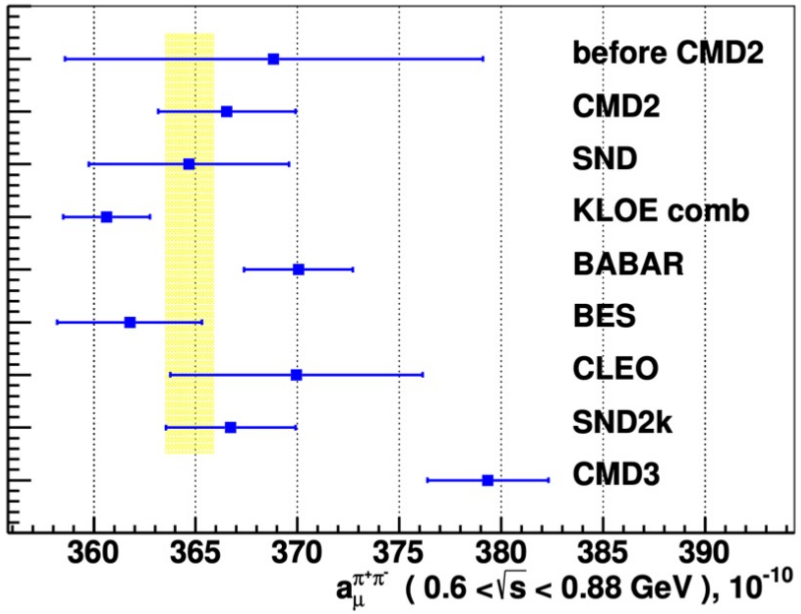


Contributions to HVP integral



Contributions to HVP error





- Measurement from KLOE, BaBar and BES-III ISR with $\delta a / a \leq 1\%$
- Long Standing KLOE-BaBar discrepancy
- Feb 2023: new CMD-3 energy scan measurement in tension with most of the previous results. After next talk:

The “updated” Hadronic Vacuum Polarization Puzzle

- Discrepancy between Lattice QCD calculation and data-driven dispersive estimate

- Discrepancy within data-driven dispersive estimate on the $e^+e^- \to \pi^+\pi^-$ channel

Tomorrow talks :

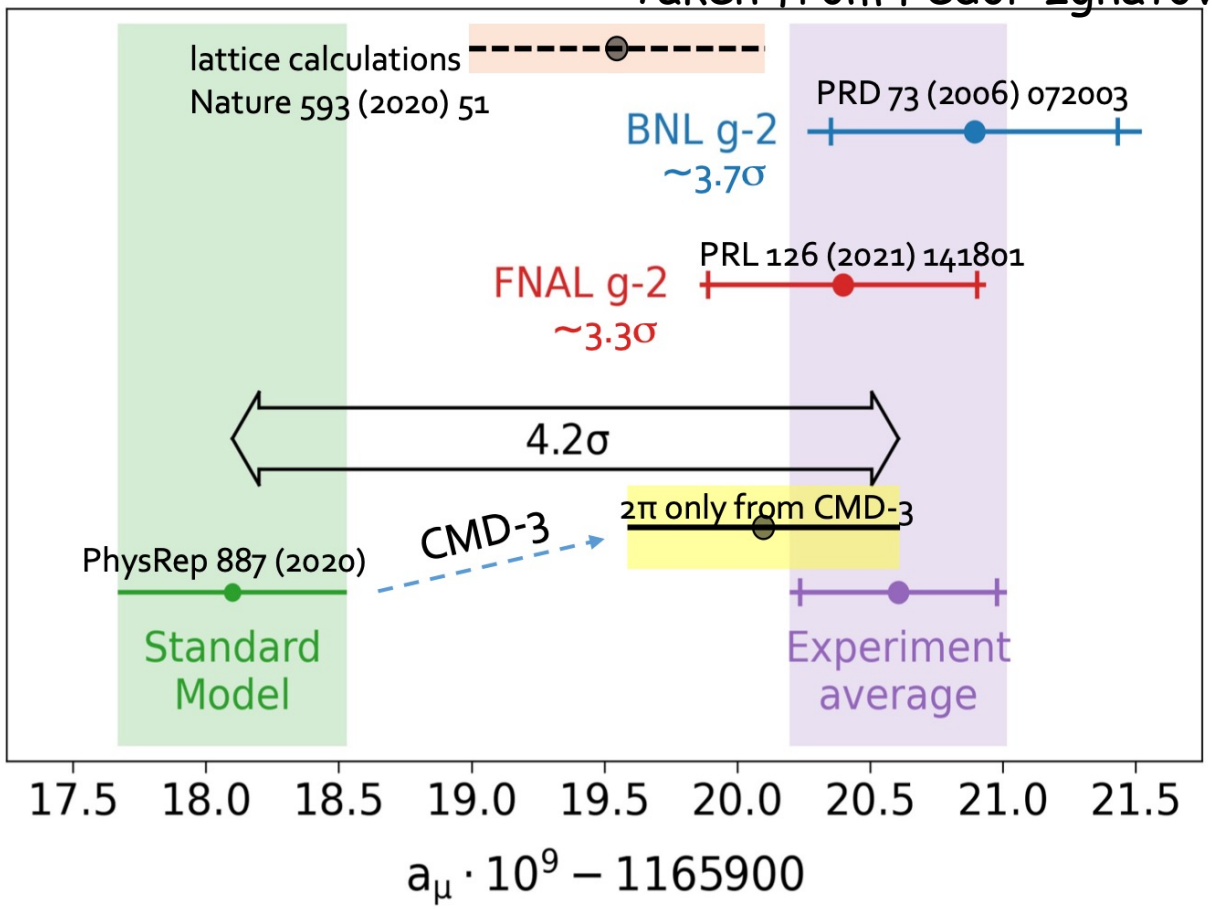
Status of dispersive approach	*Thomas Teubner*
Lattice overview	*Letizia Parato*

- Another data driven evaluation of a_μ^{HLO} is to move from **time-like** to **space-like: MUonE**

Dedicated MUonE talks on Friday:

Experimental MUonE	*Giovanni Abbiendi*
KOL-F-101, University of Zurich	15:00 - 15:20
Lattice MUonE	*Javad Komijani*
KOL-F-101, University of Zurich	15:30 - 15:40
Theoretical MUonE	*Marco Rocco*
KOL-F-101, University of Zurich	15:50 - 16:10

Taken from Fedor Ignatov



PrecisionSM: annotated database for low-energy hadronic cross sections in e^+e^- collisions

Deliverable of the STRONG2020 European project (http://www.strong-2020.eu)

Steps used to make the annotated database:

1. **DATA COLLECTION**: inputs of hadronic e^+e^- data published
2. **UPLOAD DATA IN PUBLIC REPOSITORY** → HEPData.net ⇄ InspireHEP.net

   - Collaboration point-of-contact (or STRONG2020 coordinator) submits data
   - Reviewer appointed for cross-checks: no mistakes, HEPData.net prescriptions
   - If validated: data is posted, can be catalogued and used
3. **CATALOGUE DATA IN ACCESSIBLE WAY**: https://precision-sm.github.io
4. Website files on GitHub

   -Created with Nikola static website generator
5. **PROVIDE EXAMPLES of TOOLS TO ELABORATE DATA**

Inputs collected for $e^+e^- \to \pi^+\pi^-$ data

- Inputs considered so far are $\pi^+\pi^-$ channels from the following experiments:
  - ✦ BaBar (WG contact persons: A. Lusiani, B. Malaescu)
  - ✦ BESIII (WG contact persons: A. Denig, C. Redmer)
  - ✦ KLOE (WG contact person: S. Mueller)
  - ✦ Novosibirsk Exp.: CMD2, CMD3, OLYA, CMD, TOF, VEPP, SND (WG contact person: F. Ignatov, M. Achasov)
  - ✦ Old Exp. at Frascati and Orsay, CLOE (WG contact person: G. Venanzoni)

- Almost all of them are **finalized**, only few **in preparation** (inserted on HEPData.net)
- We thank the Points-of-Contact of the experiments who are helping us very much!!

PrecisionSM webpage (link)

PrecisionSM Contents Docs About RSS feed Search

Low energy e^+e^- channels database

- Measurements Database:
  - $e^+e^- \to \pi^+\pi^-$
- HEPData submissions
  - cured by PrecisionSM
- HEPData submissions checks
- Plots

Contents © 2023 PrecisionSM Group - Powered by Nikola

Database for $e^+e^- \to \pi^+\pi^-$ channels

Input data

Experiment	Year	Reference (link to INSPIRE-HEP)	Link to Hepdata	Details	Status
BESIII (BEPC, Beijing)	2016	Phys.Lett.B 753(2016) 629-638 [errata: Phys.Lett.B 812 (2021) 135982]	ins1385603	details	Finalized
BaBar (SLAC, Stanford U.)	2016	Phys.Rev.D 86 (2012) 032013		details	In Preparation
CLEO (CESR, Cornell U.)	2018	Phys.Rev.D 97 (2018) 3, 032012	ins1643020	details	Finalized
CLEO (CESR, Cornell U.)	2013	Phys.Rev.Lett. 110 (2013) 2, 022002	ins1189656	details	Finalized
CLEOc (CESR, Cornell U.)	2005	Phys.Rev.Lett. 95 (2005) 261803	ins693873	details	Finalized
KLOE (DAPHNE, Frascati)	2017	JHEP 03 (2018) 173		details	In Preparation
KLOE (DAPHNE, Frascati)	2012	Phys.Lett.B 720 (2013) 336-343		details	In

KLOE (DAPHNE, Frascati), 2017

- status: **in preparation**
- hepdata: 1634981
- method: Direct
- quotes:
  - $d\sigma/dQ^2(\pi^+\pi^-\gamma)$ (stat, syst)
  - $\sigma_{\pi^+\pi^-}$ (stat, syst)
  - F_π (stat, syst)
- energy[GeV]: 0.32 - 0.97
- radiative corrections:
  - VP corr. updated to 'alphaQED16.tar.gz' package by F. Jegerlehner (2016)
  - Remaining are in inspirehep-797438, inspirehep-859660, inspirehep-1208095
- comment:
  - combination of KLOE08, KLOE10 and KLOE12 data;
  - updates for inspirehep-797438, inspirehep-859660, inspirehep-1208095

Annotate:

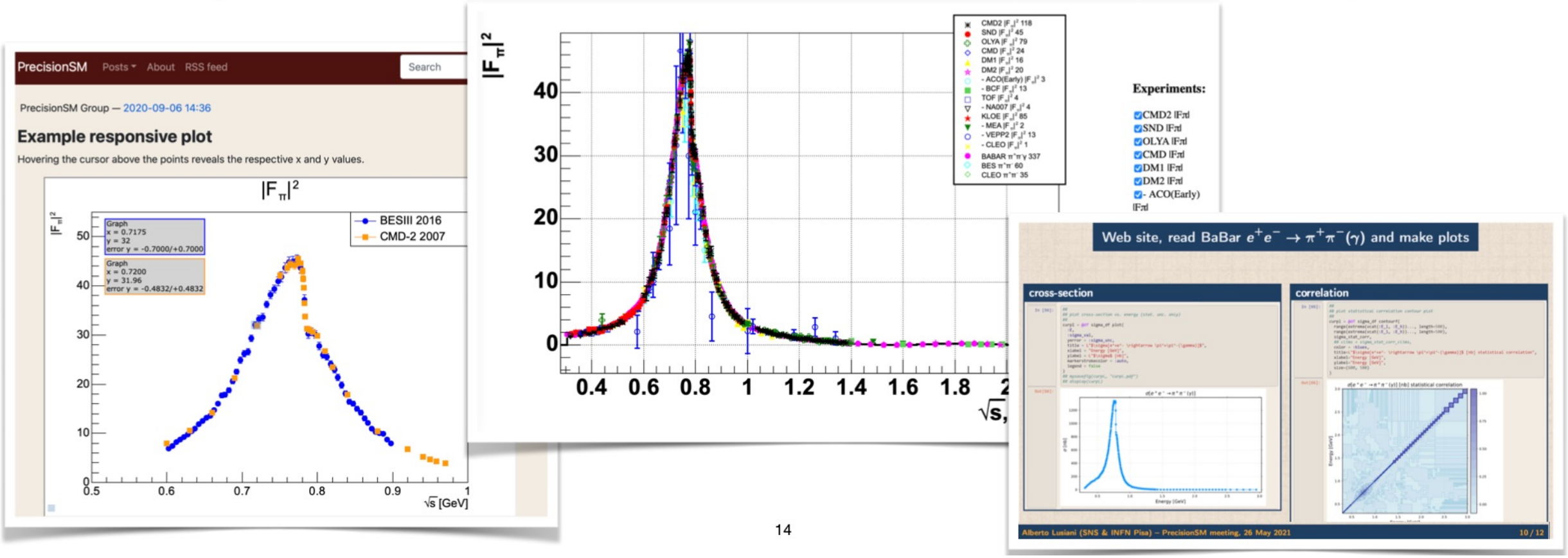
- available data
- energy ranges
- treatment of RC
- …
- Yaml file with info available for download

714, Sov.J.Nucl.Phys. 33 (1981) 368-	ins167191	details	Finalized
05-208	ins75634	details	Finalized
28-332	ins69313	details	Finalized
19, Phys.Lett.B 25 (1967) 6, 433-435	ins57008	details	Finalized

(download)

PrecisionSM webpage (link) tools to elaborate the data

- Examples of code to build responsive plots and notebooks are already available:



Summary

- **FNAL Muon g-2** Run-1 data produced a result with 460 ppb, there is more data to analyze and so far we are on track for the **140 ppb uncertainty goal**
- Experimental measurement is tension of $\mathbf{4.2\sigma}$ with SM from dispersive approach and only $\mathbf{1.5\sigma}$ with SM from lattice QCD
- There is a **tension between data-driven and lattice calculations**, **MUonE** is a third way to get $\boldsymbol{a_\mu^{HLO}}$ and could contribute to the resolution of the puzzle
- Accuracy of the HVP contribution to muon g-2 from dispersive approach is limited by 2-pion channel; **major challenge** is to solve the KLOE-BABAR-BESIII puzzle and the new CDM-3 measurement
- STRONG2020 is contributing with **PrecisionSM database**: a database for low-energy hadronic cross sections with relevant information (RC treatment, systematic errors, …)

Thank you!

Acknowledgements

- some material of this talk was taken from the following presentations :
  - Ivan Logashenkov *“Data Input to Hadronic Vacuum Polarization “* (International Physics School on Muon Dipole Moments and Hadronic Effects)
  - Achim Denig *“Status of R and gamma-gamma measurements”* (FCCP2022)
  - *Graziano Venanzoni “Radio MonteCarLow and Strong2020 activities”* (NePSI23)
  - Lorenzo Cotrozzi *“The Strong2020 and RadioMonteCarlow activities”* (New Frontiers in Lepton Flavor 2023)
  - Riccardo Aliberti *“R Measurements Experimental Inputs to HVP”* (Muon4Future 2023)