Istituto Nazionale di Fisica Nucleare

Sezione di Bologna

Measurement of the leading hadronic contribution to the muon g-2 via space-like data

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(INFN – Bologna)

EPS-HEP, 5-12 July 2017, Venice (Italy)

Work done in collaboration:

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Presented to the "Physics Beyond Collider" CERN Study Group http://pbc.web.cern.ch/

Reference papers:

Phys.Lett. B746 (2015) 325

A new approach to evaluate the leading hadronic corrections to the muon g-2 ☆

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Eur.Phys.J.C 77 (2017) 139

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

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Outline

- Muon anomalous magnetic moment $a_\mu = (g_\mu-2)/2$
  - introduction and status
- New approach to determine the leading hadronic contribution a_μ^{HLO} from the space-like region
- Proposal for a measurement of a_μ^{HLO} with $\mu e \rightarrow \mu e$ at CERN
- Detector considerations
- On-going work and plans
- Conclusions

Muon anomalous magnetic moment

Dirac equation - the magnetic dipole moment of a spin ½ particle (l = e, μ) is:

$$\vec{M}_l = g_l \frac{e}{2m_l}\vec{S}$$

gyromagnetic ratio $g_l = 2$

QED – loop corrections give rise to the anomaly:

$$a_l \equiv \frac{g_l - 2}{2}$$

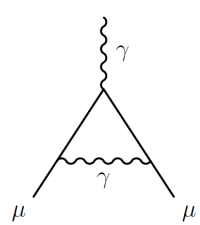
This observable can be both precisely measured experimentally and predicted in the Standard Model, providing powerful tests of the SM.

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

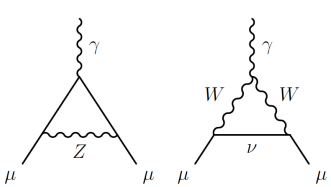
$$= (11659180.2 \pm 4.9) \times 10^{-10}$$

0.4 ppm

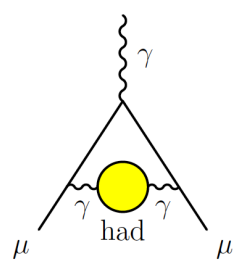
Davier, Hoecker, Malaescu, Zhang,
Eur.Phys.J. C71 (2011) 1515 / err. C72 (2012) 1874



QED corrections known up to 5 loops, rel. precision ~7x10^{-10}
Leading order term (Schwinger) = $\alpha/2\pi$ ~ 0.00116



EWK corrections ~ 10^{-9}
rel. uncertainty less than 1%



Hadronic LO contribution
-not calculable by pQCD-
$a_\mu^{HLO} = (692.3 \pm 4.2) \times 10^{-10}$
rel. uncertainty 0.6%

Dominant Theoretical uncertainty

Measurement of a_μ

E821 experiment at BNL : Bennett et al, Phys.Rev.D73 (2006) 072003

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10}$$

Precise measurement : 0.54 ppm
Dominated by statistics

$$\boxed{a_\mu^{E821} - a_\mu^{SM} \sim (28 \pm 8)\times 10^{-10}}$$

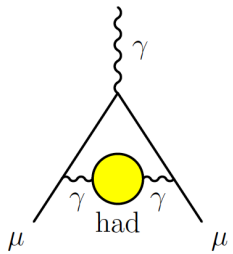
Intriguing discrepancy with Standard Model: about 3.5 σ

Sensitive to new physics (Supersymmetry, dark photons)

New experiments in preparation at Fermilab and J-PARC are targeting **a reduction of the experimental error by a factor of 4**

Theoretical precision should be improved as well

a_μ^{HLO}: standard approach



Dispersion relations, optical theorem:

$$a_\mu^{HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{\hat{K}(s) R_{had}(s)}{s^2}$$

$R_{had}(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$
K smooth function

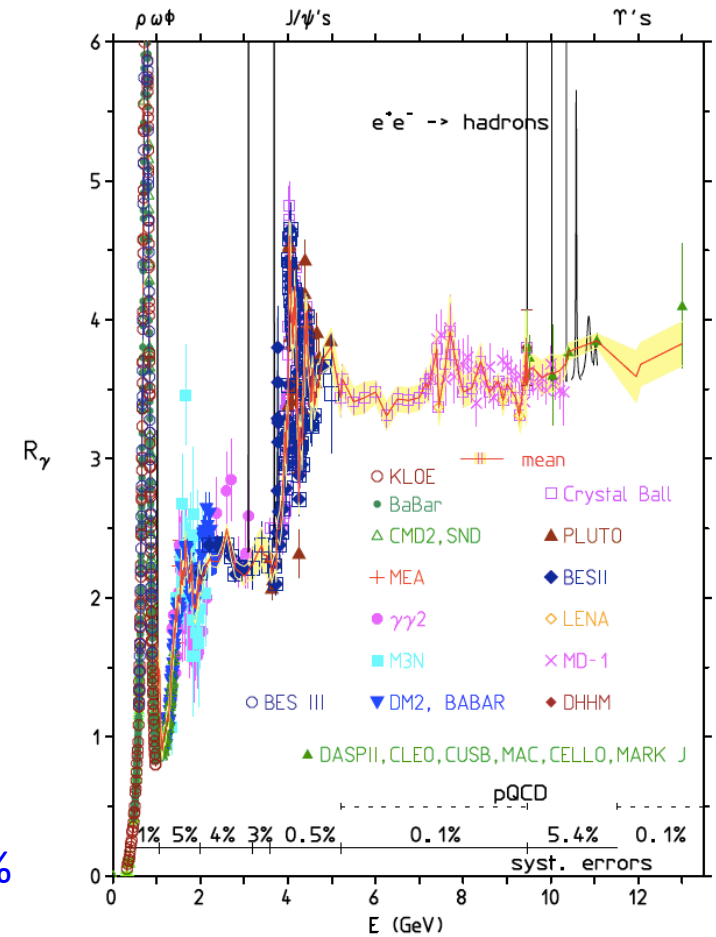
Traditionally the integral is calculated by using the experimental measurements up to an energy cutoff, beyond which perturbative QCD can be applied.

Main contribution: low-energy region ($1/s^2$ enhancement), highly fluctuating due to hadron resonances and thresholds effects

$$a_\mu^{HLO} = (692.3 \pm 4.2) \times 10^{-10}$$

Rel. uncertainty 0.6%

F.Jegerlehner, EPJ Web Conf. 118 (2016) 01016



Alternative evaluations by lattice QCD not yet competitive, though expected to improve

a_μ^{HLO}: alternative approach (space-like data)

C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni Phys.Lett. B746 (2015) 325

-Initially proposed for use with Bhabha scattering data from flavour factories-

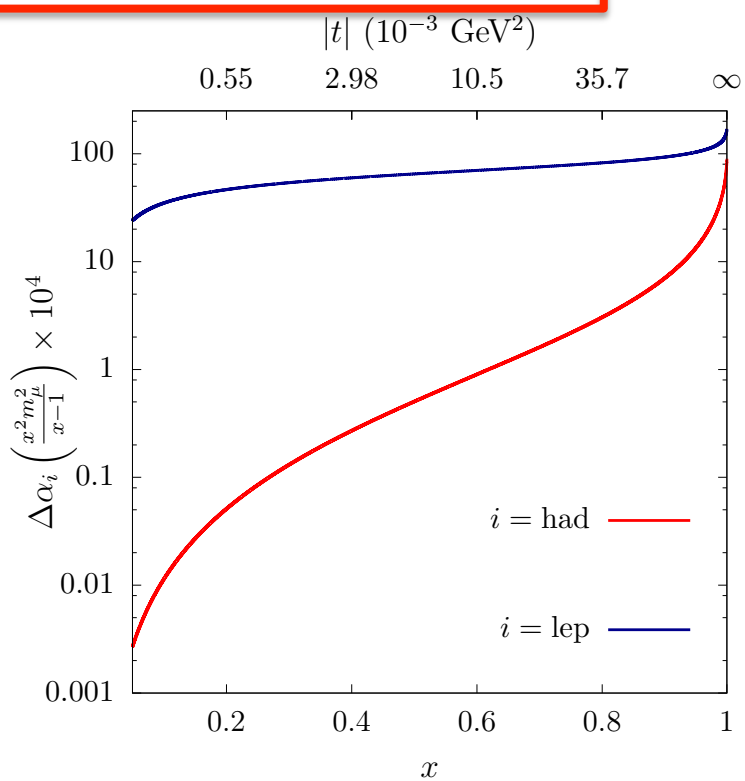
$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

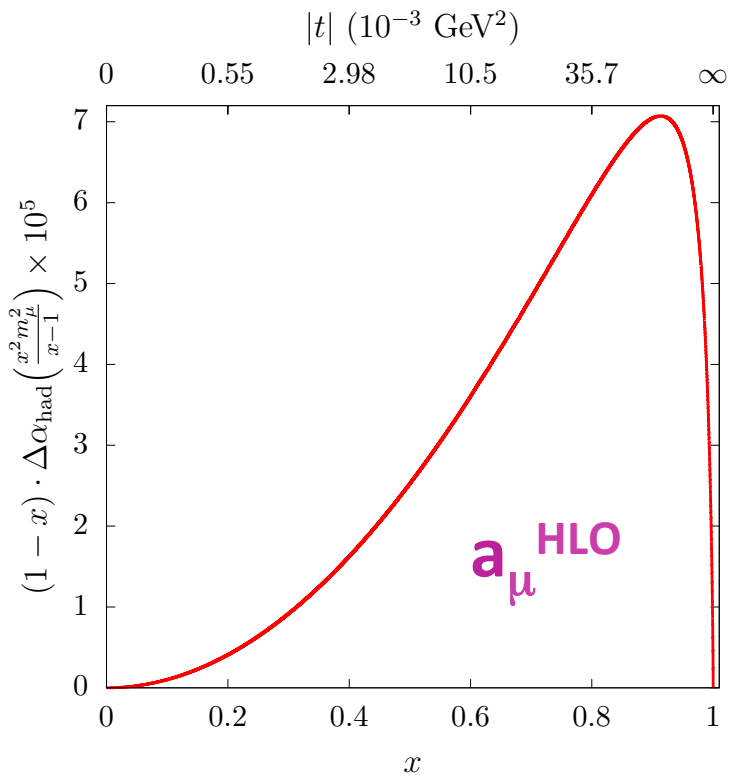
$$t(x) = -\frac{x^2 m_\mu^2}{1-x} \qquad 0 \le -t < \infty \qquad 0 \le x < 1$$

$\Delta\alpha_{had}$ is the hadronic contribution to the running of α in the space-like region (t<0)

$$\alpha(t) = \frac{\alpha}{1-\Delta\alpha(t)}$$

$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had}$$





Integrand function smooth: no resonances

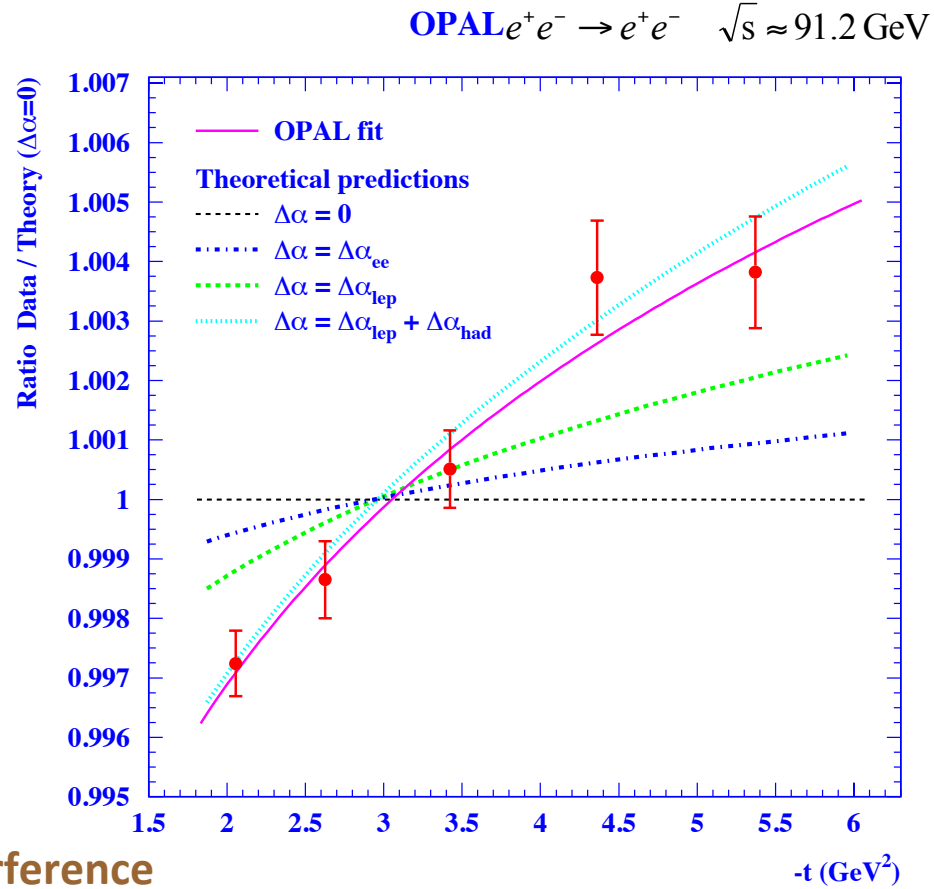
Low-energy enhancement: peak of the integrand at x=0.914 -> t=-0.108GeV^2 → $\Delta\alpha_{had}$ ~ 0.8x10^{-3}

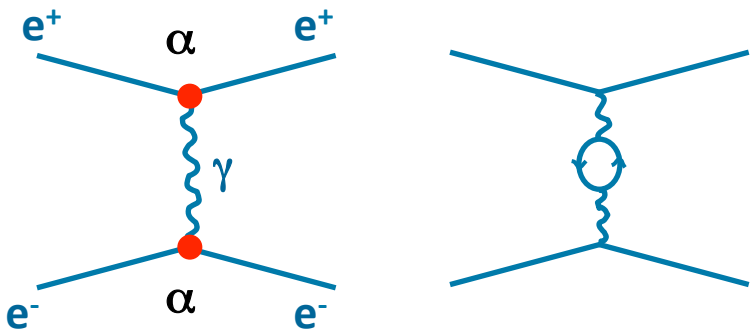
Measurement of $\Delta\alpha_{had}(t)$ spacelike at LEP

OPAL measurement: Bhabha scattering at small angle, with $1.8 < -t < 6.1$ GeV^2

about 10^7 events
precision at the per mille level

G.Abbiendi et al, Eur.Phys.J. C 45 (2006) 1





$$\frac{d\sigma}{dt} = \frac{d\sigma^{(0)}}{dt}\left[\frac{\alpha(t)}{\alpha_0}\right]^2 (1+\varepsilon)(1+\delta_\gamma) + \delta_Z$$

Born term for t-channel single γ exchange

$$\left(\frac{1}{1-\Delta\alpha(t)}\right)^2$$

Effective coupling factorized

Photonic radiative corrections

s-channel γ exchange correction

Z interference correction

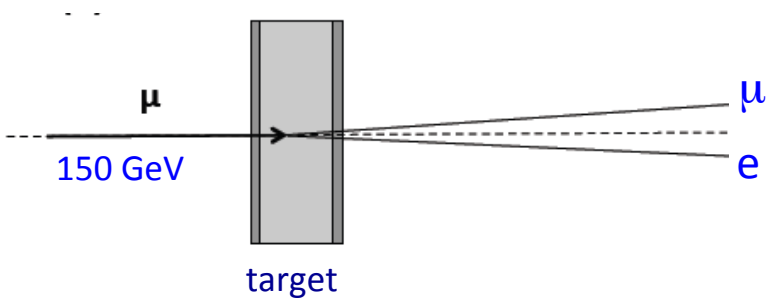
Other measurements in the space-like region by L3, VENUS

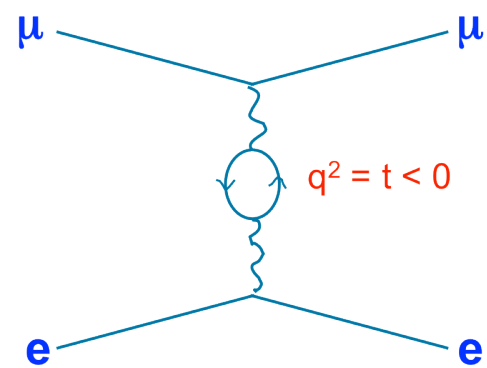
Experimental Proposal

Elastic scattering $\mu e \rightarrow \mu e$ with a μ beam of E=150 GeV on atomic electrons of a fixed target with low Z (Be or C)

- From the measured differential cross section determine $\Delta\alpha_{had}(t)$ and then a_μ^{HLO} by the space-like approach

G.Abbiendi, C.M.Carloni Calame, U.Marconi, C.Matteuzzi, G.Montagna, O.Nicrosini, M.Passera, F.Piccinini, R.Tenchini, L.Trentadue, G.Venanzoni, Eur.Phys.J.C 77 (2017) 139





$$\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \approx \frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

running of α

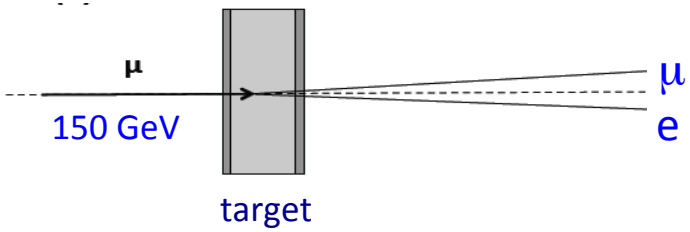
$$\Delta\alpha(t) = \underline{\Delta\alpha_{lep}(t)} + \Delta\alpha_{had}(t)$$

known from QED to be measured !

Leading mechanism. Higher-order corrections to be considered as well…

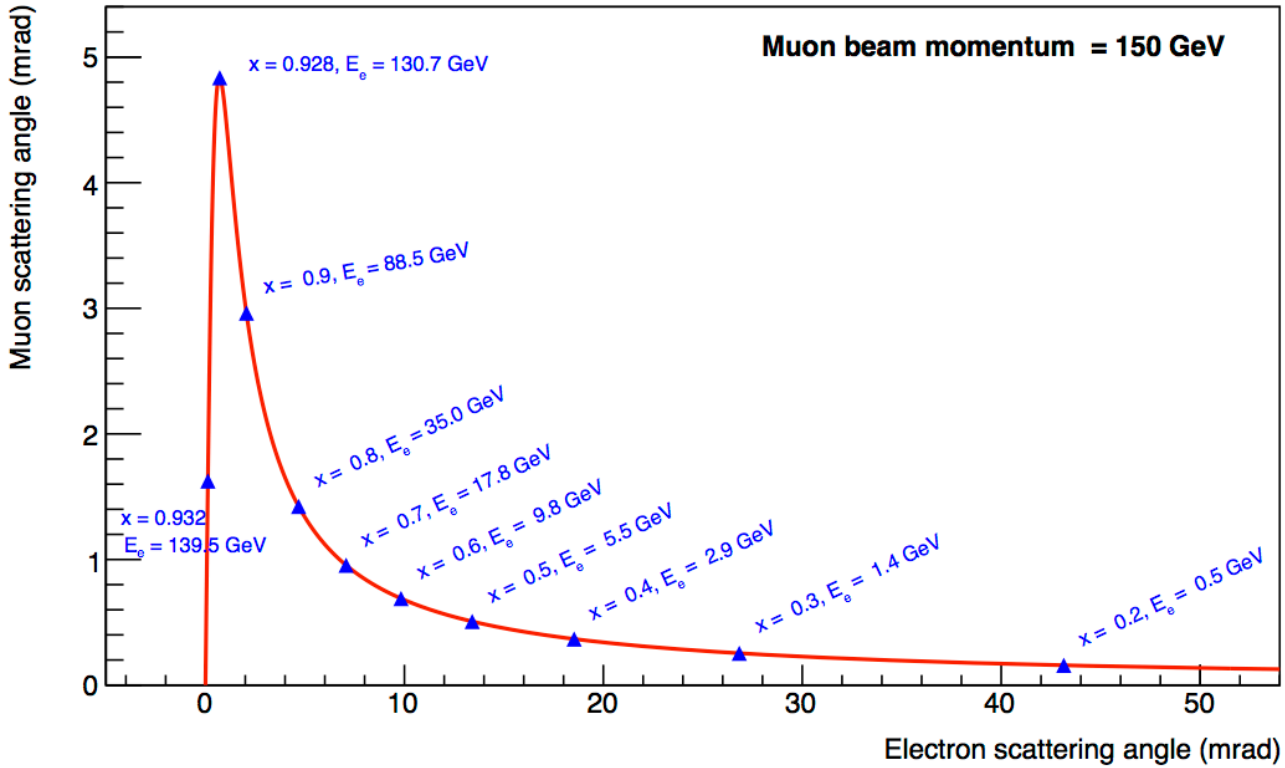
Experimental proposal

Elastic scattering μe→μe with a μ beam of E=150 GeV on atomic electrons of a fixed target with low Z



- Only t-channel at LO: running coupling $\alpha^2(t)$ factorized in the cross section
  - Instead Bhabha scattering at flavour factories involves both s- and t- channel diagrams
- Simple kinematics determined from the initial muon energy and either one energy or angle of the scattered particles, e.g. $t \cong -2m_e E_e$
  - Or incoming muon energy determined from both θ_e and θ_μ
- For beam E=150 GeV the phase space extends up to: $x<0.932$, $-t<0.143$ GeV^2 corresponding to 87% of the a_μ^{HLO} integral.
  - The remaining 13% can be calculated by time-like data plus pQCD and/or Lattice QCD
- Boosted kinematics: $\theta_e<32$mrad (for $E_e>1$ GeV), $\theta_\mu<5$mrad the whole acceptance can be covered with one 10x10cm^2 silicon sensor at 1m distance from the target, reducing many systematic errors

Elastic scattering μe→μe

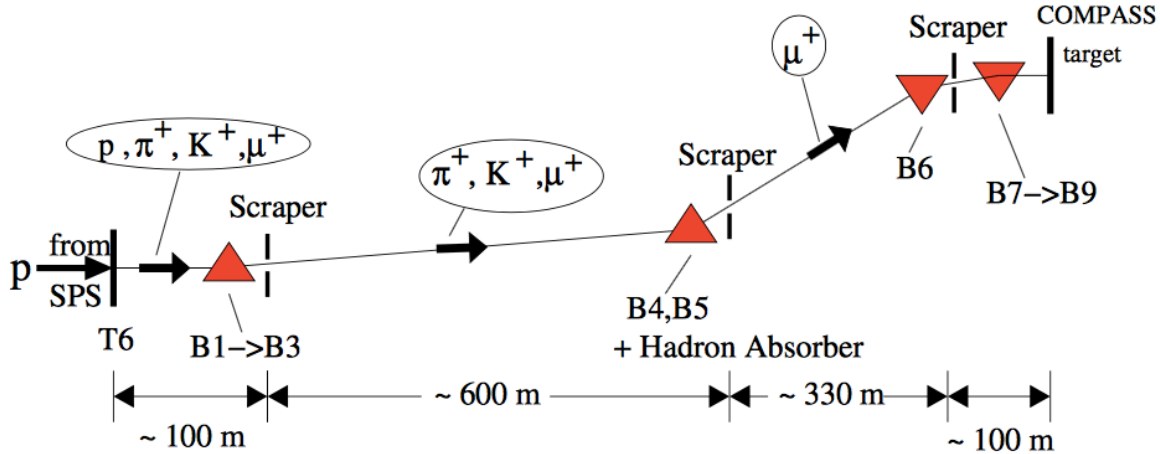


- The scattering angles θ_e and θ_μ are correlated: important constraint to select elastic events, rejecting radiative or inelastic processes.
  - Ambiguity for scattering angles of 2-3 mrad to be solved by pID

- Similar technique already used in the past by the NA7 experiment (pion form factor from πe elastic scattering:

  S.R.Amendolia et al, Phys.Lett.B146(1984)116 / Nucl.Phys.B277(1986)168

CERN muon beam M2



From SPS

COMPASS exp. P.Abbon et al, Nucl.Instrum.Meth.A 577 (2007) 455

Table 3
Parameters and performance of the 160 GeV/c muon beam

Beam parameters	Measured
Beam momentum $(p_\mu)/(p_\pi)$	(160 GeV/c)/(172 GeV/c)
Proton flux on T6 per SPS cycle	1.2×10^{13}
Focussed muon flux per SPS cycle	2×10^{8}
Beam polarisation	$(-80 \pm 4)\%$
Spot size at COMPASS target $(\sigma_x \times \sigma_y)$	$8 \times 8\,\mathrm{mm}^2$
Divergence at COMPASS target $(\sigma_x \times \sigma_y)$	0.4×0.8 mrad
Muon halo within 15 cm from beam axis	16%
Halo in experiment $(3.2 \times 2.5\,\mathrm{m}^2)$ at $\lvert x, y\rvert > 15$ cm	7%

Spill duration: 4.8 s
within the SPS cycle of 16.8 s

High average intensity
> 10^7 μ/s

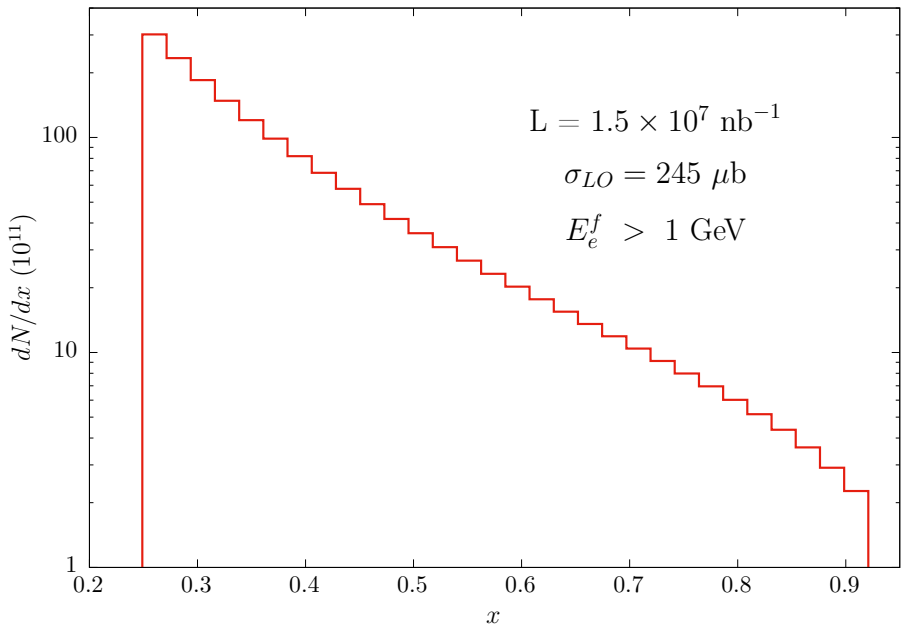
Choice of the target and setup

Two contrasting needs:

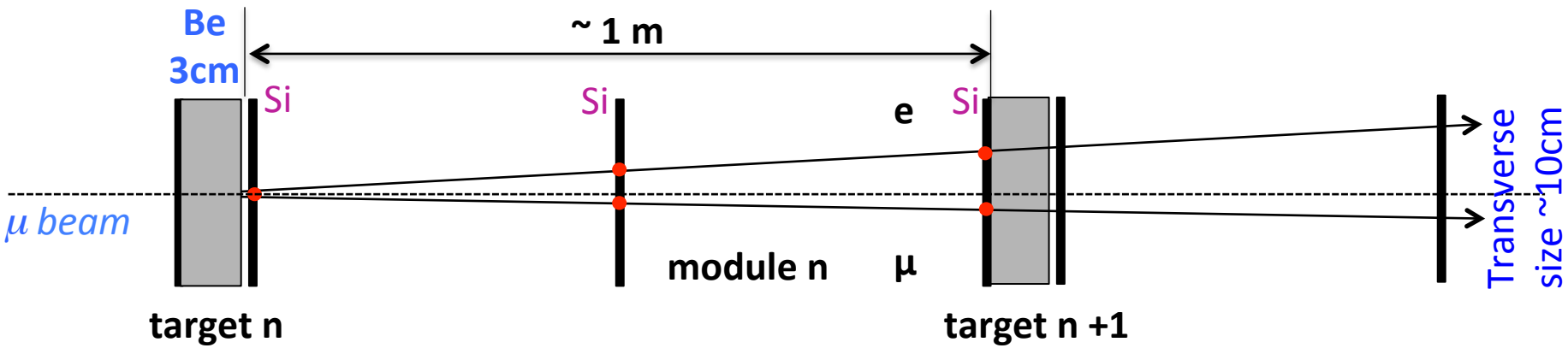
- Large statistics of events at the peak to reach the necessary sensitivity (hence enough target material)
- Minimal distortions of the outgoing e/μ trajectories within the target material and small rate of radiative events (low Z)

The solution is a modular apparatus, a sequence of N identical modules:

- Considering a 150 GeV μ beam with I=1.3x10^{7}μ/s *(available at CERN, M2/NorthArea)*
- 20 Be layers, 3cm thick.
- In 2 years of data-taking (running time 2x10^{7}s/y) an integrated luminosity of 1.5x10^{7}nb^{-1} can be reached
- From a simplified simulation of the experiment we estimate a 0.3% statistical sensitivity on a_μ^{HLO} (current precision 0.6%)



Detection technique



Sequence of 20 modules, each one:

Target + 3 pairs of orthogonal Si strip planes (size: 1m x 0.1m x 0.1m)

measuring angles with high resolution ~0.02 mrad

In addition Particle ID to solve the e/μ ambiguity at angles ~2-3 mrad:

downstream calorimeter + muon detector

Whole acceptance contained in the detector, within single Si sensors ~10x10cm^2

Incoming muon direction determined from the previous module; incoming momentum to be measured with a dedicated subdetector (as in COMPASS or NA62)

The role of Multiple Scattering

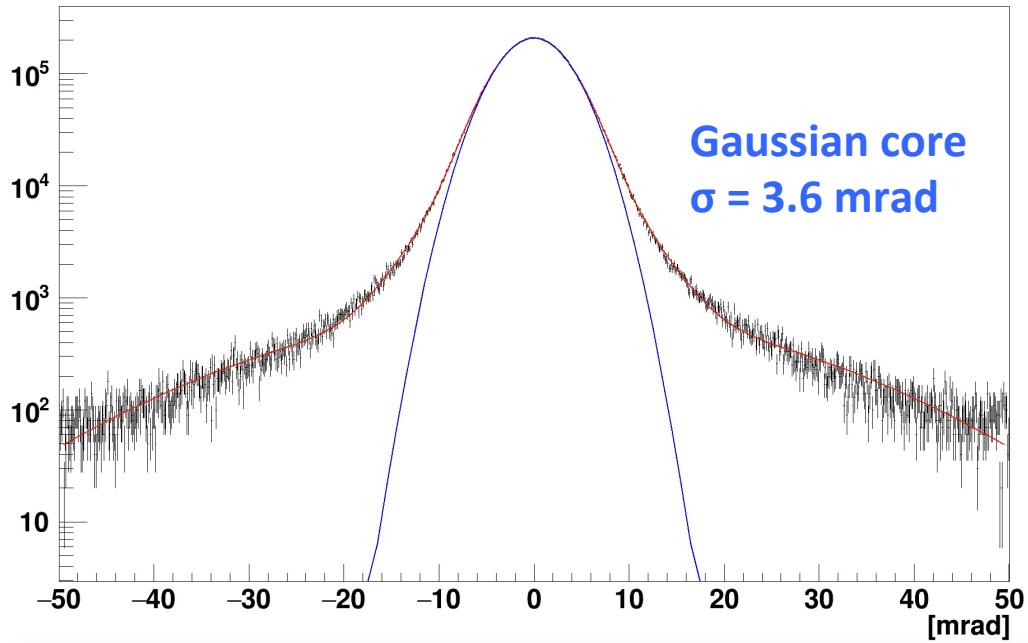
Main systematic effect for low energy electrons
It **breaks** the μ-e angular correlation, moving events out of the kinematic constraint.
It also causes **acoplanarity**, while two-body events are planar

Highland formula (PDG):
3.593 mrad

$$\sigma = \frac{13.6}{\beta pc} z \sqrt{\frac{d}{X_0}} \left[1 + 0.038 \ln\left(\frac{d}{X_0} \right) \right]$$

Non-Gaussian tails ~ 3%

GEANT4, 1 GeV electrons, 3cm Be target



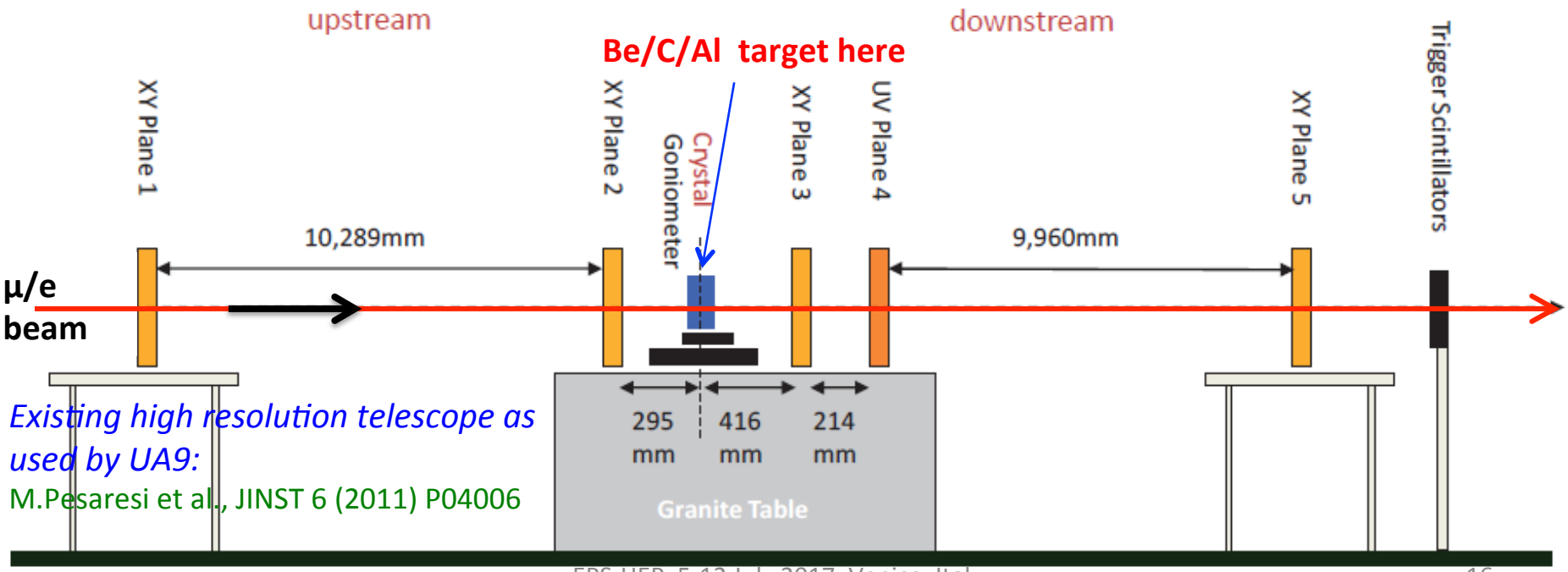
Vertices of the **μ + e → μ + e** collisions will be uniformly distributed inside the target along the direction of the beam axis.
The observable angles (electron and muon angles) depend therefore on the particles' path length inside the material and on their energies.
We need a MSC model to relate the observed angles to the scattering ones.

Test Beam

- At CERN SPS in the H8 Beam Line (27 Sep-3 Oct 2017)
- Existing setup (used by CMS and UA9): 5 pairs of Si strips planes (measuring orthogonal coords), 2 before and 3 after the target
  - Planes 2,3,4,5 to be housed on top of the table, to increase the angular acceptance from ~2mrad to ~20mrad
- μ beam at max intensity E~150-160 GeV or electron beam with E>~12 GeV
- Max rate: 10 kHz

Purposes:

- With e beam: test Multiple Scattering modeling of GEANT by comparing different thickness of C target (0.2 / 2 cm) or different materials (Be, Al)
- With μ beam: identify/reconstruct elastic μe scattering events



Existing high resolution telescope as used by UA9:
M.Pesaresi et al., JINST 6 (2011) P04006

Theory developments

A fully exclusive MC generator describing the μe scattering with all the relevant radiative corrections is a mandatory tool. This will be obtained in steps:

1. NLO QED corrections are already available in literature
2. Resummation of LL corrections to all orders, matched with NLO corrections.
   - Similar approach as in the BabaYaga MC for Bhabha scattering
   - But additional non-trivial issue: mass effects in this case are important.
3. NNLO QED corrections and matching with resummation of LL corrections at higher orders
   - some classes of NNLO corrections re-usable from existing Bhabha calculations (S.Actis et al, Eur. Phys. J. C 66 (2010) 585 and references therein)
   - some new due to different mass scales (**m_μ** and **m_e**).

Impact of LL corrections to μe expected to be smaller than in Bhabha, as:

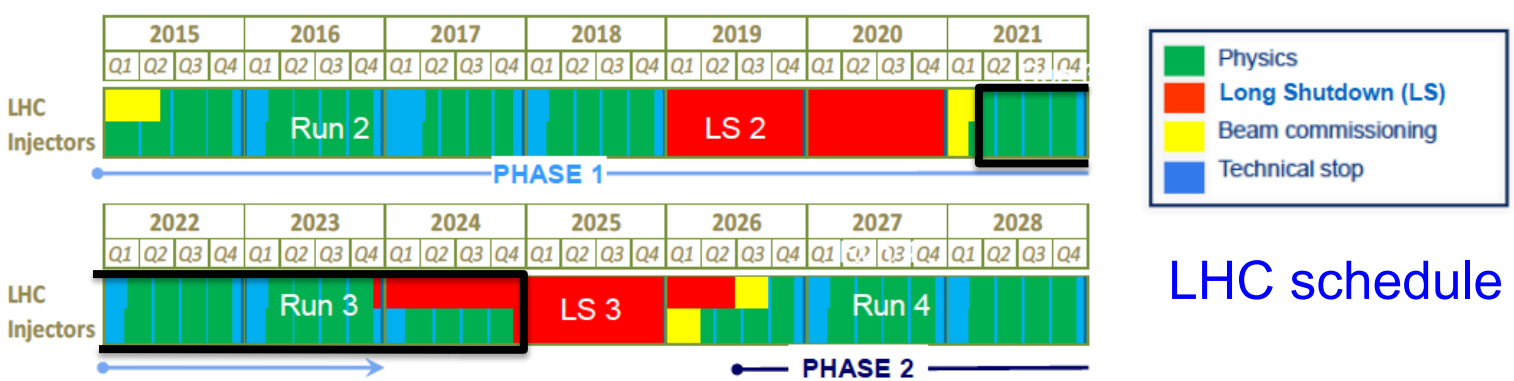
$$L_\mu = \log\left(\frac{s}{m_\mu^2}\right) \cong 2.7 \qquad L_e = \log\left(\frac{s}{m_e^2}\right) \cong 13 \qquad s = 0.165\ \mathrm{GeV}^2$$

Forthcoming Theory workshops: Padova, 4-5 September 2017

Mainz, 19-23 February 2018

Plans

- **2017 - 2019**
  - Detector optimization studies
  - Test beams (first on 27 Sep-3 Oct 2017 at CERN)
  - First prototype of a detector module
  - Theoretical developments
  - Physics Beyond Colliders CERN Study Group (final report by end 2018)
  - Forming a collaboration
  - Letter of Intent to the SPSC
- **2020**
  - Detector construction and installation (maybe a staged version of the detector)
- **2021 – 2024**
  - Start the data taking after LS2 to measure a_μ^{HLO} (not necessarily to the ultimate precision)



LHC schedule

Conclusions

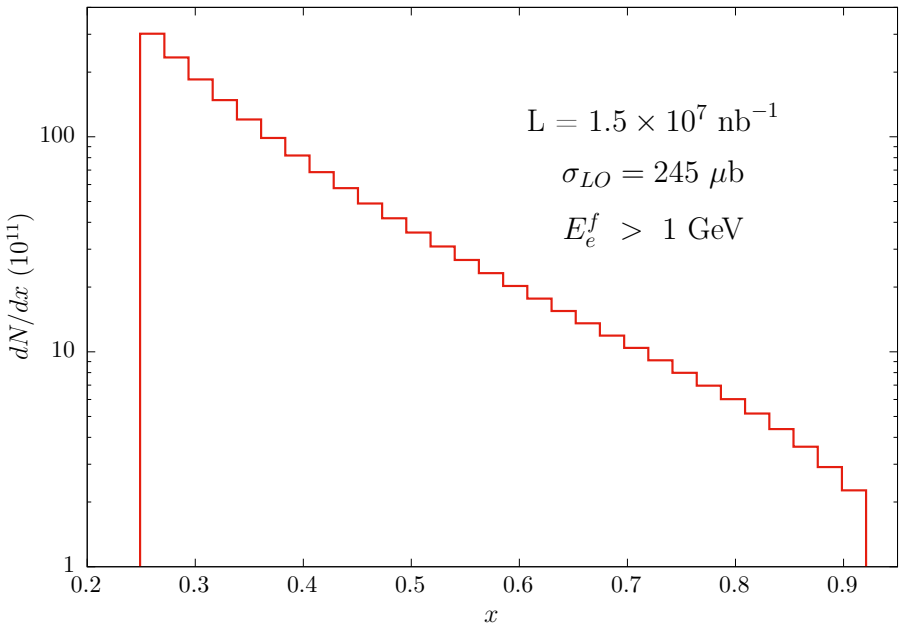
- Proposal of a new experiment to measure the leading hadronic contribution to the muon g-2, aiming at results in the same period of the new g-2 measurements from Fermilab and J-PARC.
  - New approach, space-like, from μe scattering, competitive and independent from the standard time-like approach
- On-going studies of systematic errors from multiple scattering effects
  - In collaboration with GEANT4 developers
  - Test beam at CERN
- On-going theoretical developments: two-loop calculations and accurate MC generator describing multi-photon emission

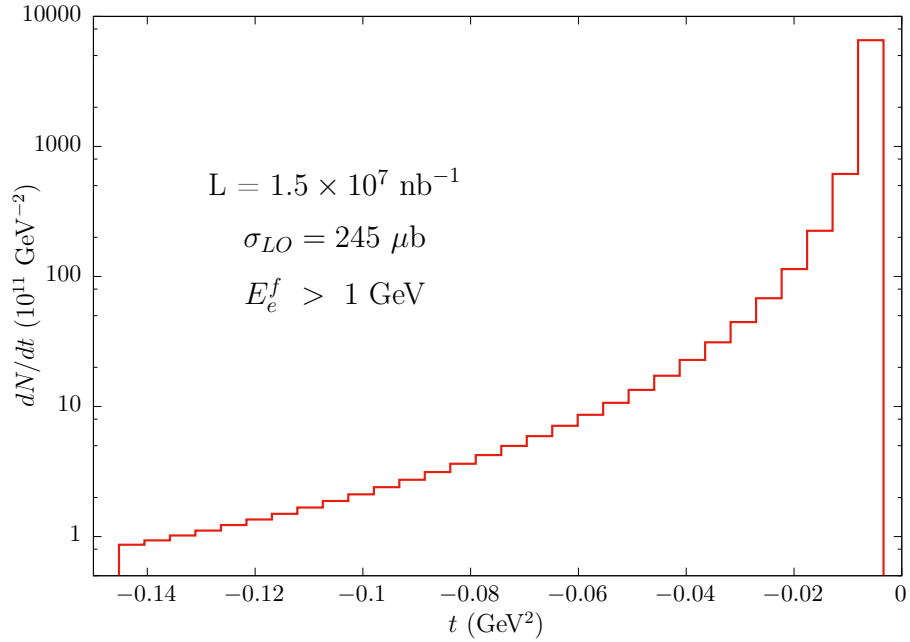
- Plans for next year:
  - proto-experiment at CERN M2 - will require only one detector module
  - starting a Collaboration

contact us if you are interested !

BACKUP

Statistical sensitivity

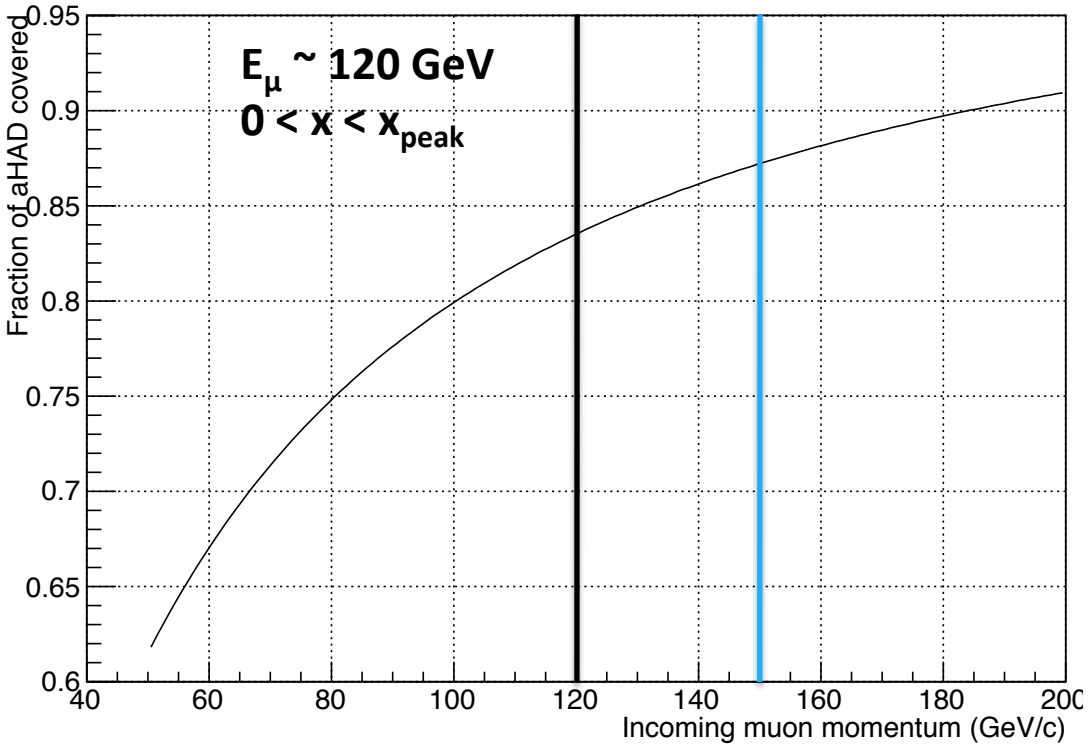


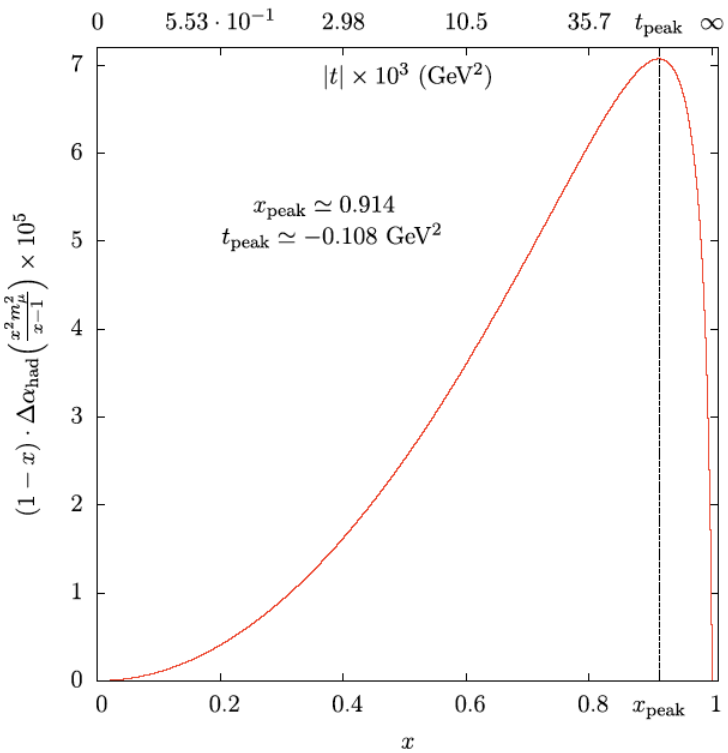


Distribution of μe elastic scattering events as a function of x and t, for an integrated luminosity equivalent to two years of data-taking: ~4×10^{12} events

Optimal Muon Beam Momentum

Fraction of the a_μ^{HLO} integral as a function of the muon beam momentum:
p_μ = 150 GeV → 87% of the integral (0 < x <0.93)

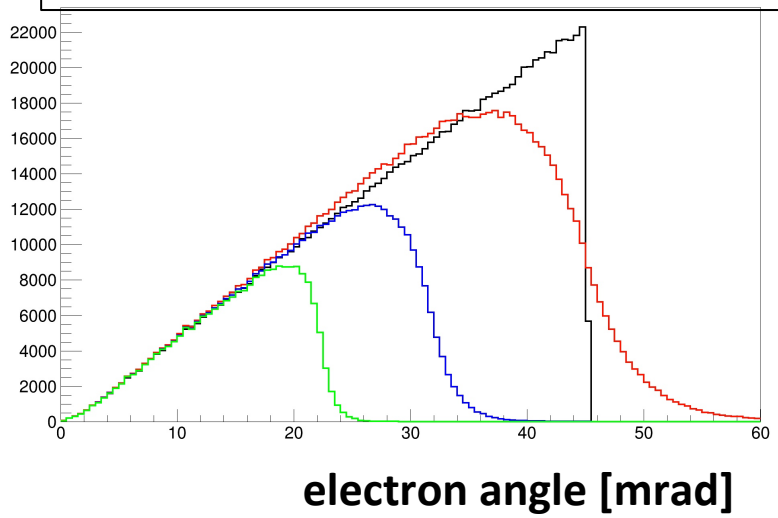




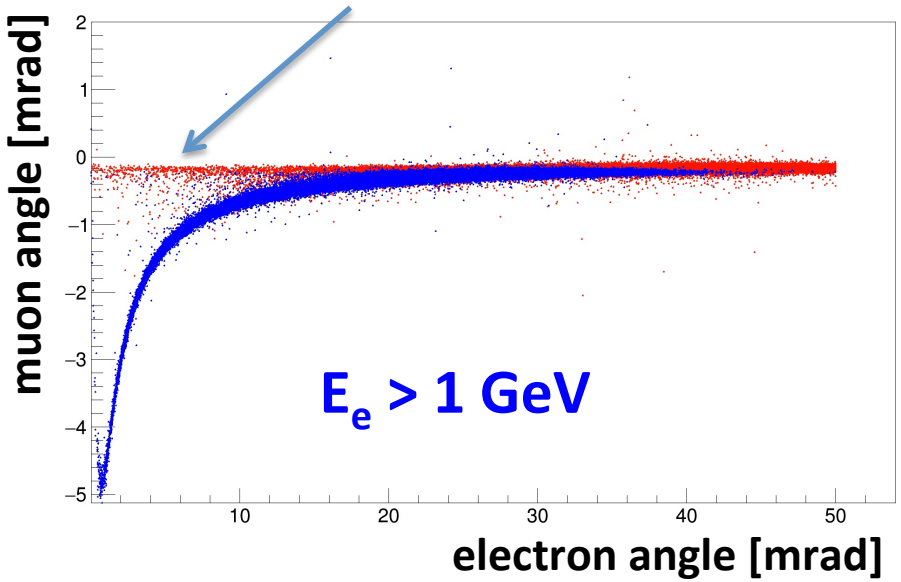
Beyond the kinematic limit the integral can be determined using pQCD & time-like data, and/or lattice QCD results.

Resolution models

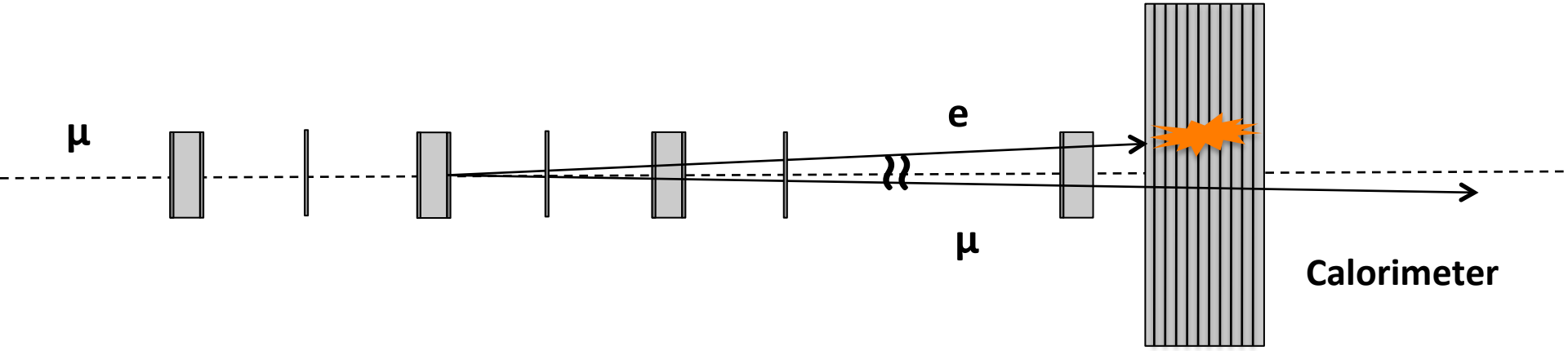
LO differential cross section
observable angular distribution
observable angular distribution, E_e > 1 GeV
observable angular distribution, E_e > 2 GeV



low energy electron scattered away from the original direction



Detector design/optimization



- Modeling MSC effects
  - Geant4 is the tool: likely to be tuned on data.
- Target material and geometry
  - Best low Z material and geometry.
  - Active target to determine vertex positions.
- Electromagnetic calorimeter needed to:
  - Perform the PID: muon/electron discrimination.
    -- PID capabilities also reconstructing the electromagnetic shower in the tracking system.
  - Measure E_e to get rid of events with $E_e < 1$ GeV
  - Triggering : (muon in) AND (ECAL E > E_{th})
    -- There is an alternative trigger condition: (muon in) AND (2 prongs into a given module)

Systematics

- Acceptance
- Tracking
- Trigger
- PID
- Effects of E_e energy cut

Affordable by means of GEANT4 based simulations

- Uncertainty in the location of interaction vertices: Segmented/ active target to resolve the vertex position
- Uncertainty in the muon beam momentum:
  Scattering kinematic to determine the beam momentum
- Effects of Multiple Scattering:
  It requires dedicated measurements (test beam) and simulation improvements (Geant model)
- Definition of the signal (needs a dedicated MC generator for μe describing multi-photon emission)
- Theoretical uncertainties on the μe cross section (see next)

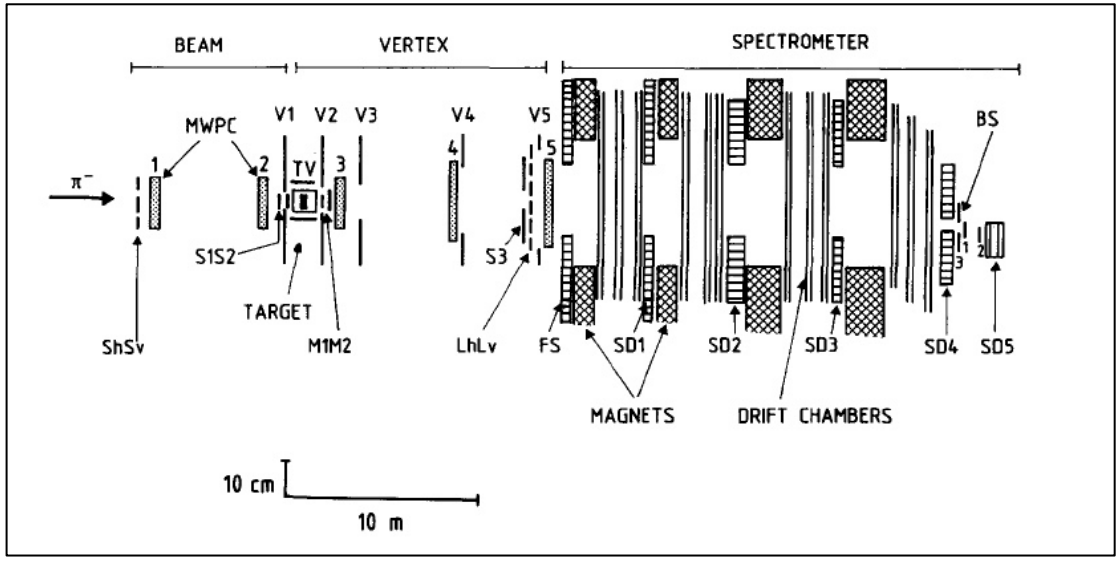
All the systematic effects must be known to ensure an error on the cross section < 10ppm

NA7 experiment

A MEASUREMENT OF THE SPACE-LIKE PION ELECTROMAGNETIC FORM FACTOR

S.R.Amendolia et al, Phys.Lett.B146(1984)116 / Nucl.Phys.B277(1986)168

"The pion form factor has been measured in the space-like q^2 region 0.014 to 0.26 $(GeV/c)^2$ by **scattering 300 GeV pions from the electrons of a liquid hydrogen target"**



Target: 28 cm liquid Hydrogen
X_0 (liquid H_2) = 890.5 cm

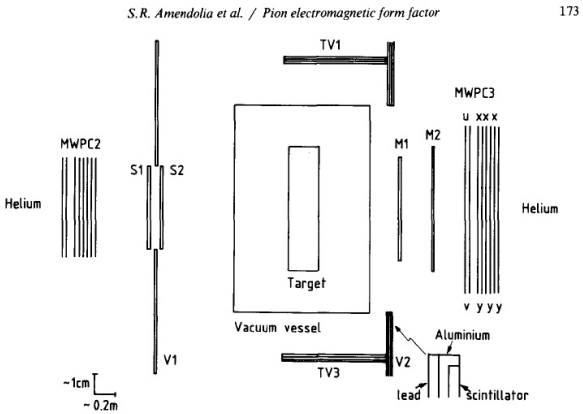
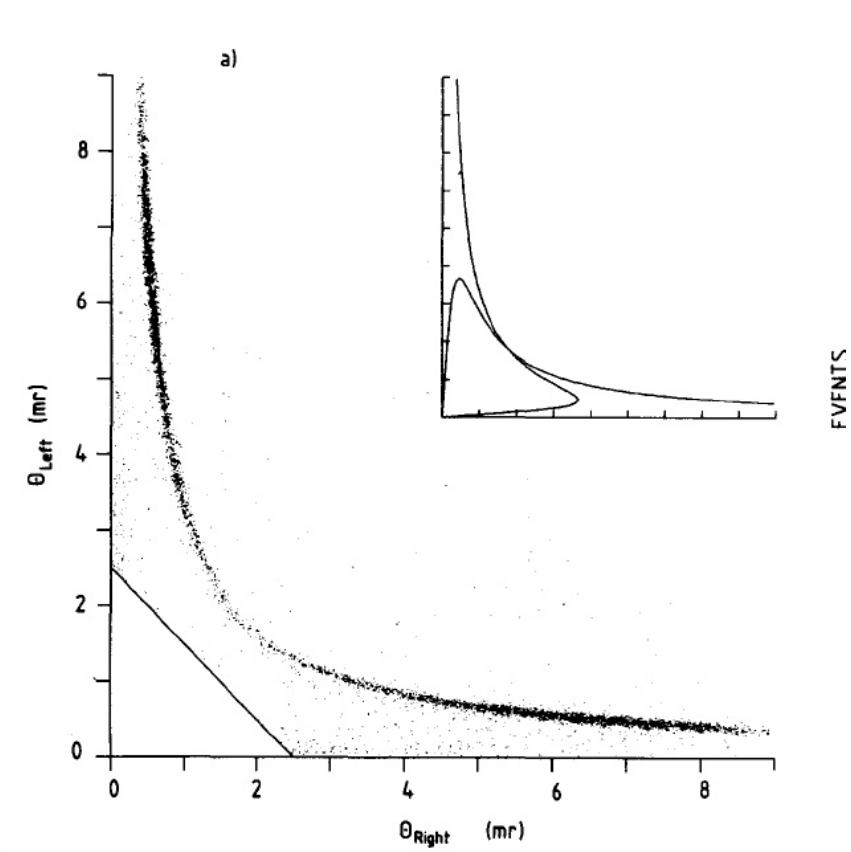


Fig. 4. Apparatus surrounding the target.

"**The q^2 variable for the final sample was determined from the angles alone**, up to the kinematic ambiguity which was resolved using the shower detectors. In this procedure the only rejection criterion involving the momenta was a cut against electrons of less than 1 GeV/c"

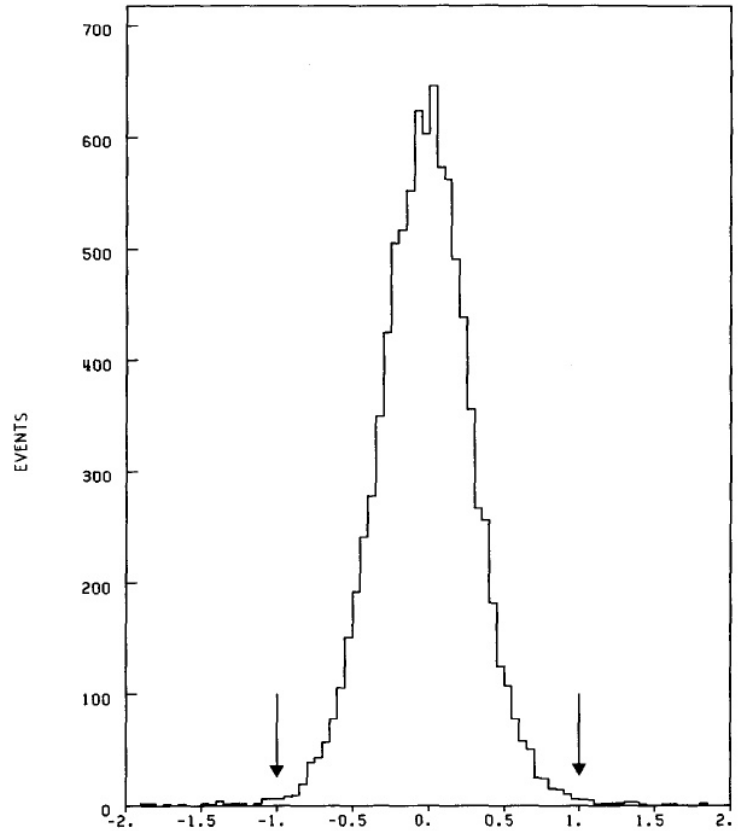
NA7 experiment

Elastic scattering in the (θ_R,θ_L) plane



"The scatter distribution of the measured polar angles of the right and left-going particles (θ_R,θ_L). Our estimate of q^2 was made from the point on the theoretical kinematic curve nearest to these angle coordinates".

Acoplanarity

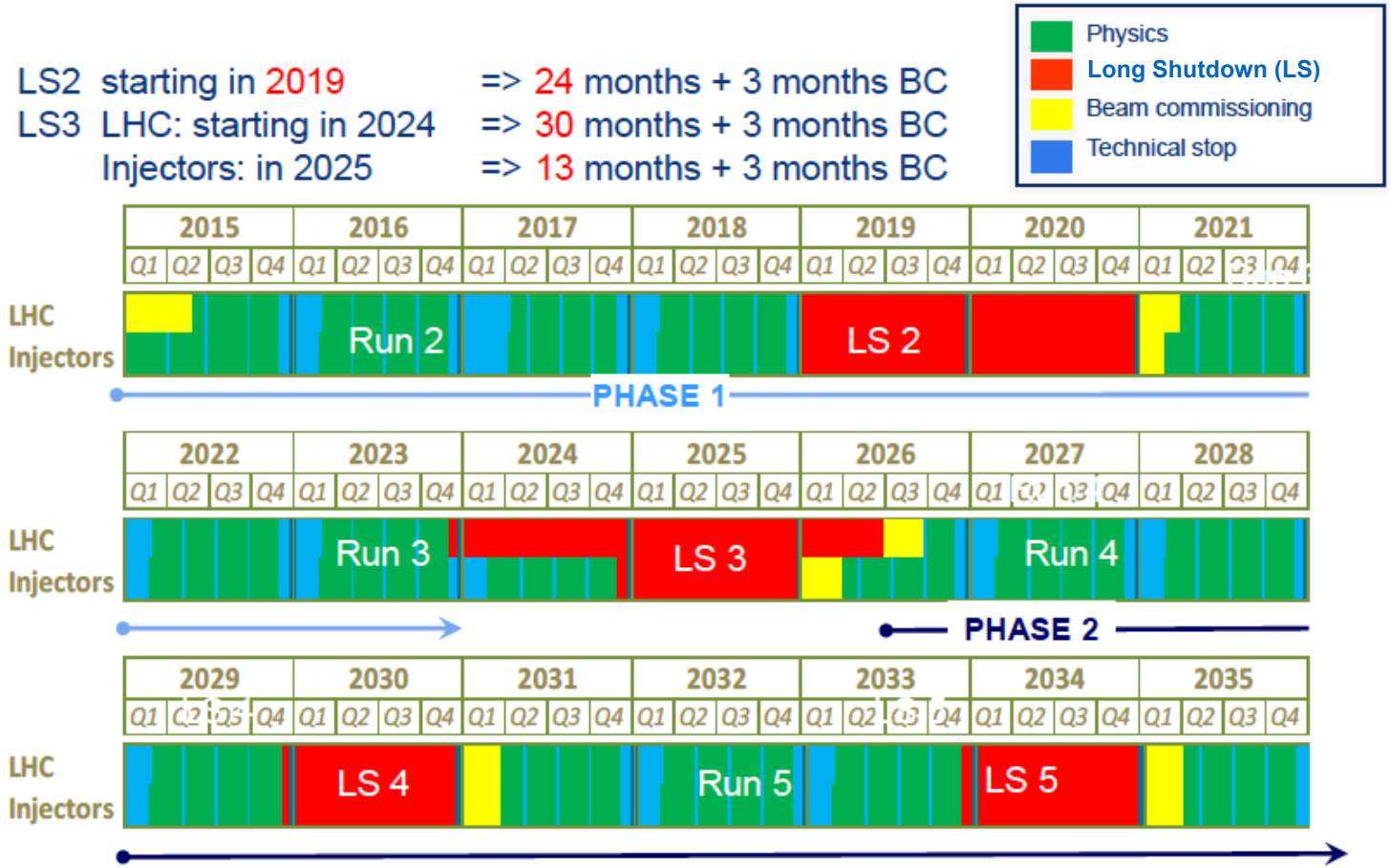


"A fraction of the hadronic background was rejected by requiring coplanarity of the incident and scattered tracks"

Experiment proposed to CERN

- Idea presented to the "Physics Beyond Collider Study Group" http://pbc.web.cern.ch/
- C. Matteuzzi and G. Venanzoni experiment representatives.
- Physics Beyond Collider Study Group will select experiments aiming to:
  - Enrich and diversify the CERN scientific program
  - Exploit the unique opportunities offered by CERN's accelerator complex and scientific infrastructure
  - Complement the laboratory's collider programme (LHC, HL-LHC and possible future colliders).
  - The scientific findings will be collected in a report to be delivered by the end of 2018. This document will also serve as input to the next update of the European Strategy for Particle Physics.

LHC roadmap, according to MTP 2016-2020*



**outline LHC schedule out to 2035 presented by Frederick Bordry to the SPC and FC June 2015*