Flavour: what’s next?

A collection of slides for discussion

New Quarkonium states

- The most highly cited paper by the Belle collaboration is the 2003 paper on the discovery of the X(3872), which has almost 900 citations as of March 2014. Of Belle's 15 most highly cited papers, 5 are on quarkonium physics.
- The 4th most highly cited paper by the BaBar collaboration is their 2005 paper on the discovery of the Y(4260), which has 500 citations as of March 2014. Of Babar's 30 most highly cited papers, 9 are on quarkonium physics.

The spectroscopy of quarkonia states above the open-heavy-flavor threshold is a field that had a dramatic progress in the last years, and others are expected through experiments at the intensity frontier. This will trigger theoretical efforts to understand the results.

There are lots of XYZ states

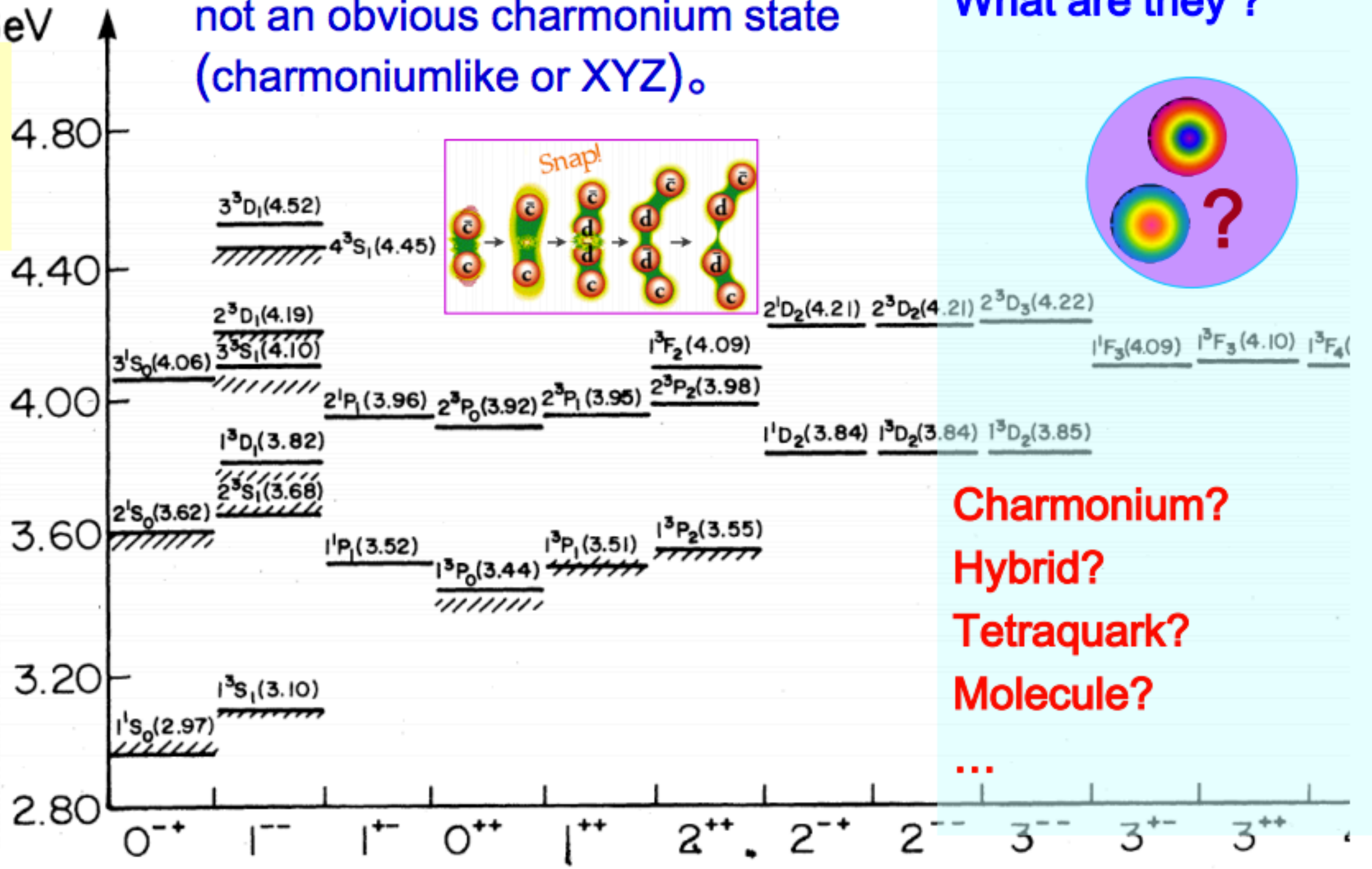
Charmonium in the final state, but not an obvious charmonium state (charmoniumlike or XYZ)。

Z(4430)
Z(4250)
Z(4050)
Z(3900)

X(3872)

XYZ(3940)

X(3915)
X(4160)
Y(4008)
Y(4140)
Y(4260)
Y(4360)
X(4350)
Y(4660)



What are they ?

Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

Not all of them are charmonia!

Giovanni Punzi

Consider an "Extreme Flavor" experiment

- Current/foreseen experiments only exploit a fraction of the enormous production of HF at HL-LHC
  - ATLAS/CMS:
    - Full LHC lum: 3000 fb^{-1}
    - But limited efficiency due to lepton, hi-pt requirements
  - LHCb:
    - High efficiency, also on hadronic/charm events
    - But limited luminosity: 50fb^{-1} vs 3000 fb^{-1}
- What physics could we get from the analysis of samples of ~10^{14} b-quarks and ~10^{15} c-quarks per year ?
- Don't have an immediate answer, and the question does need to be addressed, but *"The great advances in science usually result from new tools rather than from new doctrines."* (Dyson)

Ingredients for an "Extreme Flavor" experiment

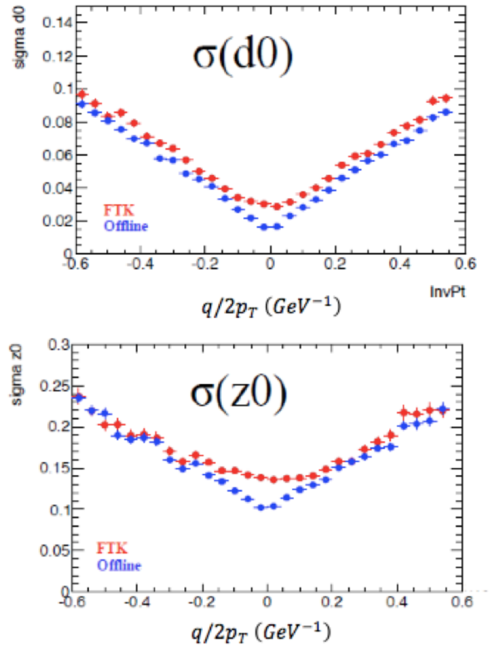
1. Detector with strong tracking capability at high-lum
   - Technologically within reach.
2. Detector readout at 40MHz
   - Doable thanks to progress of telecom technology (e.g. LHCb upgrade)
3. Real-time event reconstruction at 40MHz
   - Get tracks and other complex primitives (complete decay trees ?) straight out of the detector [see talk by G.P. et al. @INSTR-14, and L1-tracking R&D@CMS/ATLAS]
4. Offline-grade reconstruction and calibration in real-time.
   - Exploit progress in CPU processing power
5. *Physics analysis* "in real time".
   - Ability to do precision measurements from reduced-size stored samples.
   - Overcome the "event" concept: only save statistical summaries ("histograms")
   - Need superior real-time detector calibration, and well-chosen control samples.
   - Special systematic-control methods (e.g. CDF [PRD 85.012009 (2012), appendix B]

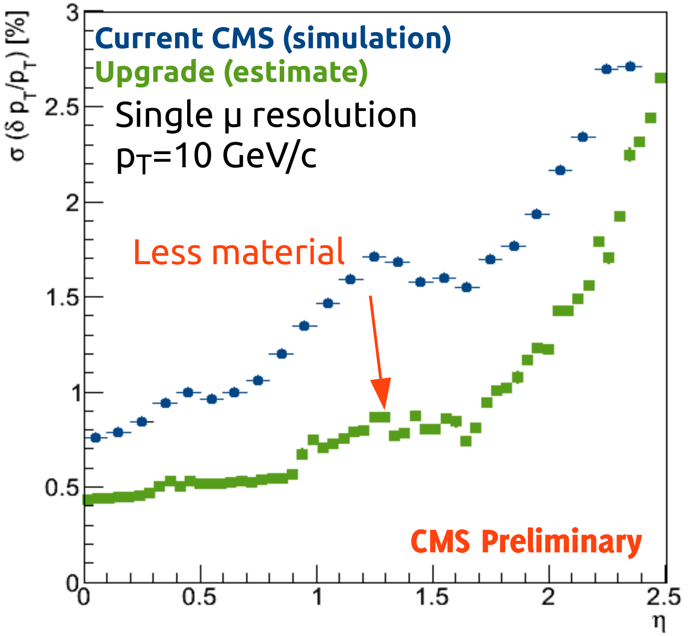
Fabrizio Palla

Phase 2 ATLAS and CMS upgrade

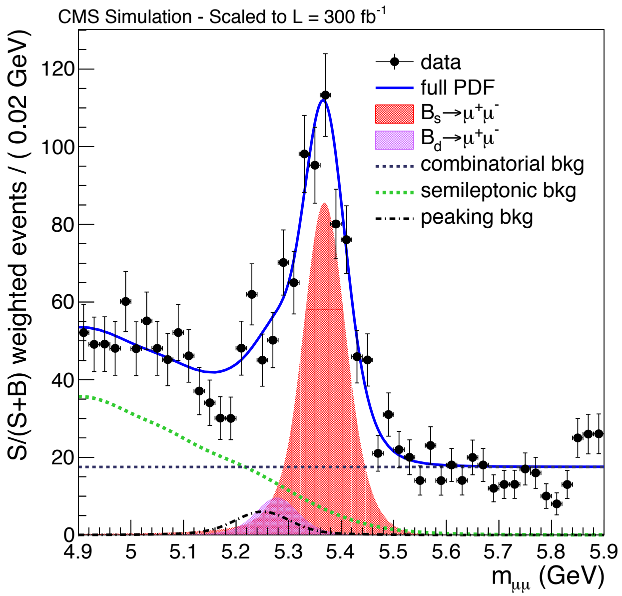
Improved Trackers for ATLAS and CMS open up new possibilities

- **Lower material budget, improved resolution, extended acceptance**
- **L1 Track Trigger based on Associative Memories**
  - **CMS: standalone p_T>2 GeV, 1 mm z resolution, option to use VDET under study, can trigger on B-physics**
  - **ATLAS: Calorimeter and Muon seeded, use VDET, p_T>~5 GeV (need low p_T muon thresholds)**
- **Incredible statistics (250 fb^{-1} per year, for 10 years) – factor 10 more than LHC Run1**

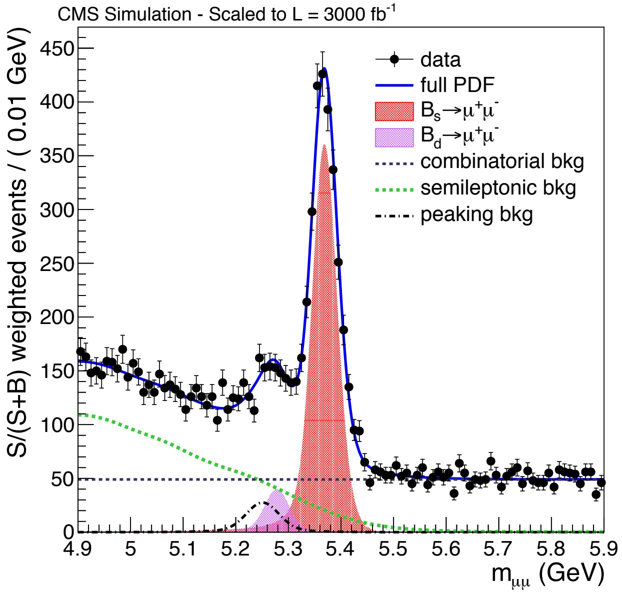




Effects on $B_{s/d} \to \mu\mu$



CMS PAS
FTR-13-022



Improved Tracker

L (fb^{-1})	No. of $\mathrm{B_s^0}$	No. of $\mathrm{B^0}$	$\delta\mathcal{B}/\mathcal{B}(\mathrm{B_s}^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}/\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-)$	$\mathrm{B^0}$ sign.	$\delta \frac{\mathcal{B}(\mathrm{B^0}\to\mu^+\mu^-)}{\mathcal{B}(\mathrm{B_s^0}\to\mu^+\mu^-)}$
20	16.5	2.0	35%	>100%	0.0–1.5 σ	>100%
100	144	18	15%	66%	0.5–2.4 σ	71%
300	433	54	12%	45%	1.3–3.3 σ	47%
3000	2096	256	12%	18%	5.4–7.6 σ	21%

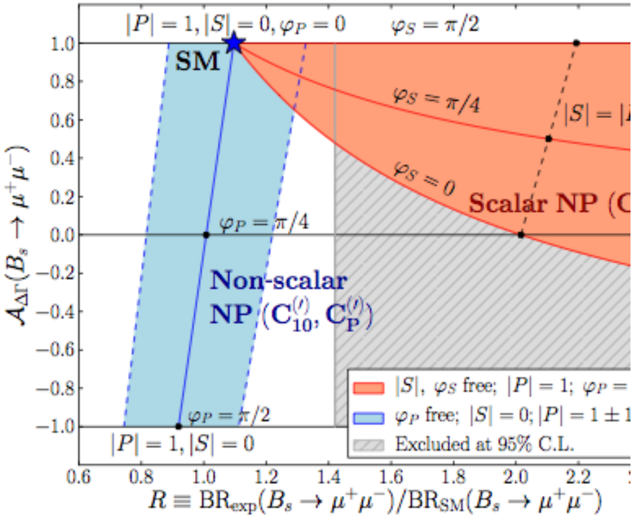
$B_{s/d} \rightarrow \mu\mu$: Beyond the BR

- Measure effective lifetime

$$\tau_{\mu^+\mu^-} \quad = \quad \frac{\int_0^\infty t \langle \Gamma(B_s^0(t) \to \mu^+\mu^-)\rangle dt}{\int_0^\infty \langle \Gamma(B_s^0(t) \to \mu^+\mu^-)\rangle dt}$$

→ determine $\mathcal{A}_{\Delta\Gamma} y_s$

$$\mathcal{A}_{\Delta\Gamma} y_s \quad = \quad \frac{(1-y_s^2)\tau_{\mu^+\mu^-} - (1+y_s^2)\tau_{B_s^0}}{2\tau_{B_s^0} - (1-y_s^2)\tau_{\mu^+\mu^-}}$$



→ new constraints on different new physics operators

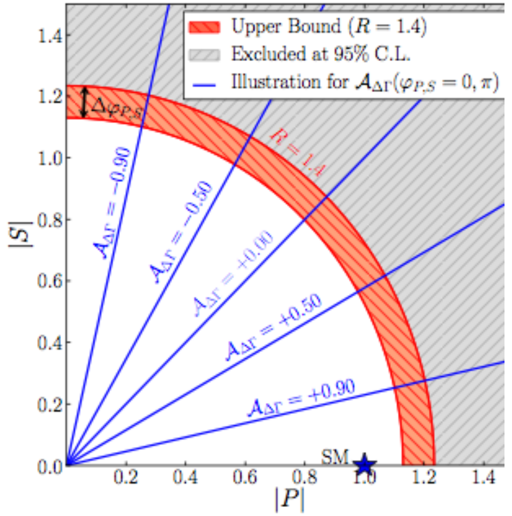
$$R \quad \equiv \quad \frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{exp}}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}}}$$

$$= \quad \left[\frac{1 + \mathcal{A}_{\Delta\Gamma} y_s}{1 - y_s^2}\right]$$

$$= \quad \left[\frac{1 + y_s \cos 2\phi_P}{1 - y_s^2}\right] |P|^2 + \left[\frac{1 - y_s \cos 2\phi_S}{1 - y_s^2}\right] |S|^2$$

→ resolve ambiguity with

$$|S| \quad = \quad |P| \sqrt{\frac{\cos 2\phi_P - \mathcal{A}_{\Delta\Gamma}}{\cos 2\phi_S + \mathcal{A}_{\Delta\Gamma}}}$$



Other observables

- ratio of branching fractions with very small SM uncertainties

$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0 \to \mu^+\mu^-)} = \frac{\tau(B^0)}{\tau(B_s^0)} \frac{m(B^0)}{m(B_s^0)} \frac{f_{B^0}^2}{f_{B_s^0}^2} \left|\frac{V_{td}}{V_{ts}}\right|^2 = \frac{\hat{B}_d}{\hat{B}_s} \frac{\tau(B^0)}{\tau(B_s^0)} \frac{\Delta m(B^0)}{\Delta m(B_s^0)}$$

  - ▷ only after observation of $B^0 \to \mu^+\mu^- \ldots$

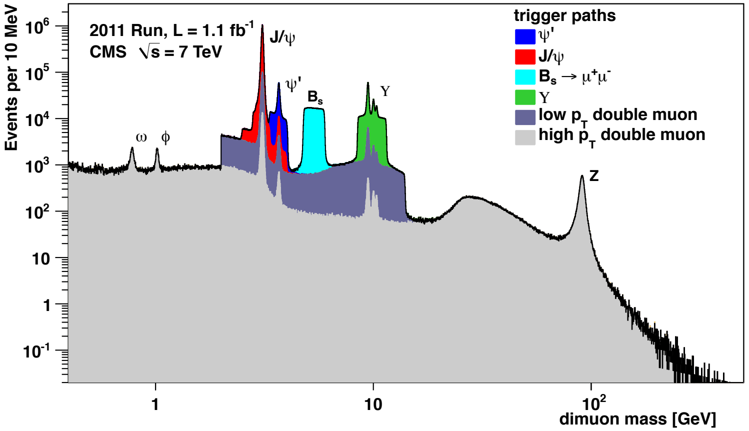
- CP asymmetry (time dependent and tagged!)

$$\frac{\Gamma(B_s^0(t) \to \mu^+\mu^-) - \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)}{\Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)} = \frac{\mathcal{S}_{CP} \sin(\Delta m_s t)}{\cosh(y_s t/\tau_{B_s^0}) + \mathcal{A}_{\Delta\Gamma} \sinh(y_s t/\tau_{B_s^0})}$$

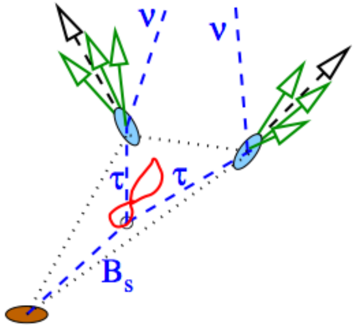
  - ▷ in SM: zero
  - ▷ also possible for $B^0 \to \mu^+\mu^- \ldots$

$B_s \to \tau\tau$, $B_s \to \mu\tau$

- BR($B_s \to \tau\tau$)$|_{SM}$~8×10^{-7}. No limits as in HFAG/PDG
- Forbidden in SM. B($B_d \to \mu\tau$) < 2.2×10^{-5} (BABAR, PR, D77, 091104)
- Can trigger on $\tau \to 3$ prongs and μ at L1, with some invariant mass cuts like CMS does now for other modes



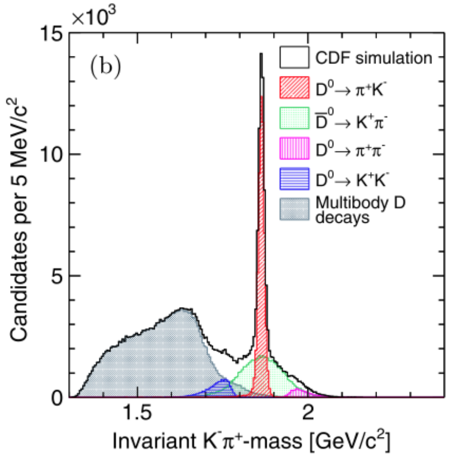
- **Problem in reconstructing the taus**
  - Neutrino missing, and tau production vertex not known, but some techniques might be used to solve numerically and iteratively
    - see *Nucl. Instrum. Meth.* **A569** (2006) 824–828, arXiv:hep-ph/0607294



- Can use better Tracker and improved VDET
  - Need to perform detailed studies

Hadronic modes

- **Having a capability to fully reconstruct tracks with good resolutions at L1 (including impact parameters, thanks to the VDET), one might think of getting enough events for fully hadronic decays of the B and D.**
  - **Possible measurements on B and D CP violation studies doable even in absence of a particle-id (see what CDF did PHYSICAL REVIEW D 85, 012009 (2012)) thanks to excellent momentum resolution (1% at CDF, similar or even better at ATLAS/CMS – multiple scattering dominated)**



Nicolo’ Cartiglia

PicoSecond Tracking

Can we build a 4-D tracking system for concurrent time and position measurement?

Goal:

- **50 micron**
- **10 picosecond**

From the same Pixel

(many layers, better resolution)

Sensor:

- Fast and Large signal
- Low noise

Timing depends upon:

- Noise
- dV/dt
- Rise time

A possible solution:

Thin silicon sensor (50 micron) with low internal gain

➔ This is traditional silicon sensor, with 10 x Signal

(not APD or SiPM-like, they don't go into breakdown)

And it should be:

- Radiation hard
- Low Mat. Budget
- Non-Magnetic
- Cheap
- Photon blind

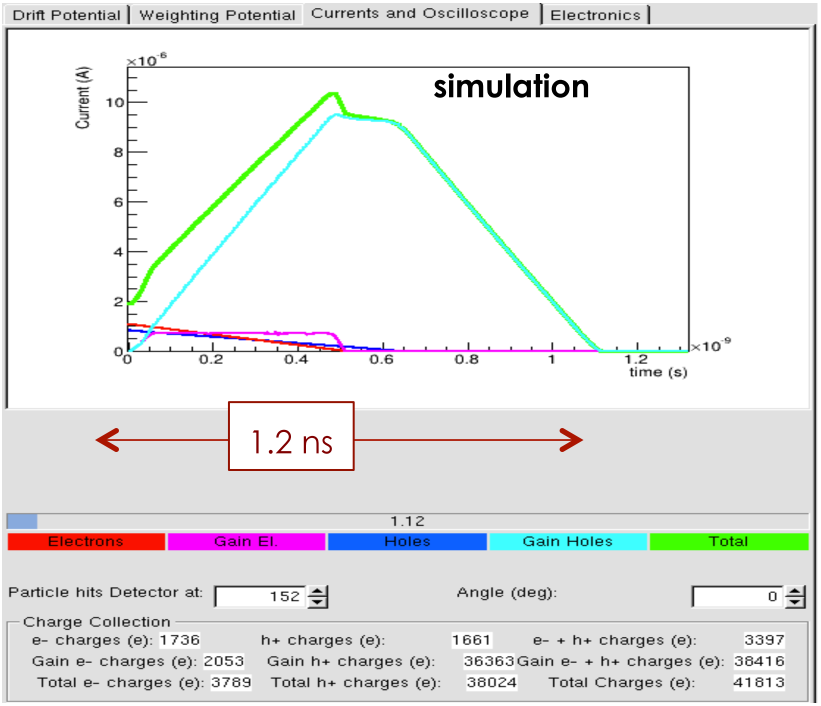
Ultra-Fast Silicon Detector (INFN - gruppo V)

UFSD: pixelated silicon detector with low internal gain (LGAD)

UFSD gain: Add an extra deep p+ implant

➔ High local field generates multiplications

- 50 μ thick Si. detector
- Large Signal: ~40k e/h (as in a 500 μ Si det.)
- Very short signal (~1 ns)

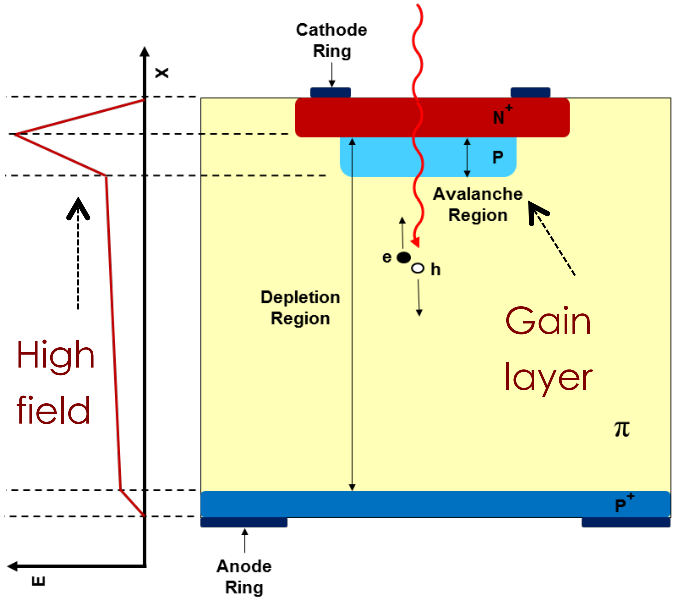


Particle hits Detector at: 152

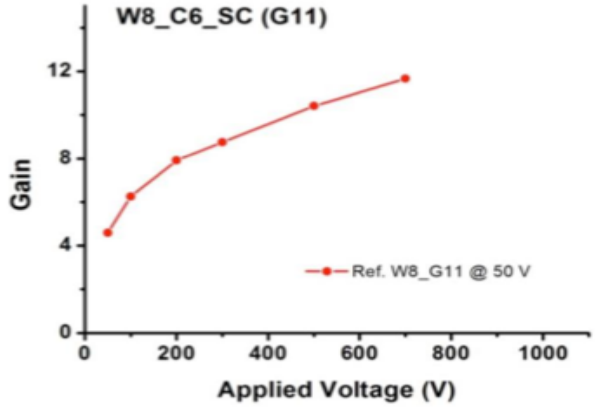
Angle (deg): 0

Charge Collection

e- charges (e):	1736	h+ charges (e):	1661	e- + h+ charges (e):	3397
Gain e- charges (e):	2053	Gain h+ charges (e):	36363	Gain e- + h+ charges (e):	38416
Total e- charges (e):	3789	Total h+ charges (e):	38024	Total Charges (e):	41813



Prototype UFSD shows good gain (~ 10)



Status and outlook

Status:

- UFSD Prototypes exist and show strong gain (5-20)
- New Collaboration with FBK started, design ready by summer
- Collaboration on electronics with CAEN and Saclay
- Production of 50 micron-thick, UFSD microstrips and small pixels under way

What can we do with Picosecond Tracking?

- Very good Time-of-Flight
  => Much lighter than Magnet on satellite for momentum measurements
- Fight background
  => New generation of NA62 (100 ps precision)
- Pile-up rejection
  => Help at HI-LHC in forward direction
- Resolve tracking ambiguities
  ⇒ More information always help in tracking..
- **Your ideas here…**

Cecilia Tarantino et al.

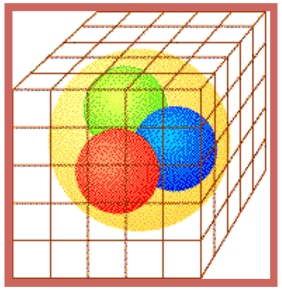
Improved accuracy in (well known) Lattice inputs
~2000→ Today→ ~2030 (What Next Era)

- Unquenching (N_f=2,2+1 and first 2+1+1),
- $M\pi \lesssim 200$ MeV and first $M\pi = M\pi^{phys}$

Thanks to improvements in:

Computational power, algorithms, Lattice actions

Hadronic Parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]	FLAG 2013 [1310.8555]
$\hat{B}_K$	0.86(15) [17%]	0.77(1) [1.3%]
f_{Bs}	238(31) MeV [13%]	228(5) MeV [2%]
f_{Bs}/f_B	1.24(7) [6%]	1.20(2) [1.7%]
B_{Bs}	1.34(12) [9%]	1.33(10) [7%]
$\hat{B}_{Bs}/B_B$	1.00(3) [3%] (quenched, $\mu_l > m_s/2$,…)	1.06(11) [10%]
$F_{D^*}(1)$	0.91(3) [3%]	0.90(2) [2%]
$B \to \pi$	-- [20%]	-- [10%]
$\overline{m}_c(m_c)$	1.26(24) GeV [19%] PDG'02	1.35(4) GeV [3%] ETMC'14 (N_f=2+1+1)
$\overline{m}_b(m_b)$	4.26(21)GeV [5%] PDG'02	4.29(12)GeV [3%] ETMC'13 (N_f=2)



- N_f=2+1+1
- $M\pi = M\pi^{phys}$
- …
- $M_B \approx M_B^{phys}$

~2030

1% level for all these quantities and even better

BUT

When going below 1% previously neglected effects have to be included:

Electromagnetism: $O(\alpha_{e.m.}) \approx 1/100$

Isospin breaking: $O[(m_d - m_u)/\Lambda_{QCD}] \approx 1/100$

They have started to be studied for the simplest observables (m_u/m_d, $M_n - M_p$, f_K/f_π)

More unpredictable but more surprising progresses can occur for the observables that today are very difficult (or unfeasible)

A new method to compute IB effects has been formulated and applied by the RM123 Collaboration [1110.6294,1303.4896]

$$M^2_{\pi^+} - M^2_{\pi^0} = 1.44(13)(16) \times 10^3\ \mathrm{MeV}^2$$

$$\frac{\hat{m}_u}{\hat{m}_d}(\overline{MS}, 2\ \mathrm{GeV}) = 0.50(2)(3)$$

$$\left[\frac{F_{K^+}/F_{\pi^+}}{F_K/F_\pi} - 1\right]^{QCD} = -0.0040(3)(2)$$

$$[M_n - M_p]^{QCD} = 2.9(6)(2)\ MeV\ .$$

Long distance contributions to $K \to \pi \nu \bar{\nu}$ and $K \to \pi l^+ l^-$ have been shown to be computable on the Lattice in an exploratory study by G.Isidori, G. Martinelli and P.Turchetti [hep-lat/0506026]

$K \to \pi \pi$ is being studied by RBC/UKQCD [1206.5142,1212.1474]
- $\Delta I=3/2$ [20%] (too difficult until few years ago)
- $\Delta I=1/2$ [investigated with unphysical kinematics] (unfeasible until few years ago)

Δm_K is being studied by RBC/UKQCD (unfeasible until few years ago) [1212.5931]

What Next?

Predictions for the What Next Era require
a (highly) non-linear extrapolation taking into account:
✖ Progresses in computational power, algorithms, Lattice actions and new ideas
✖ Small effects, neglected so far, that become relevant

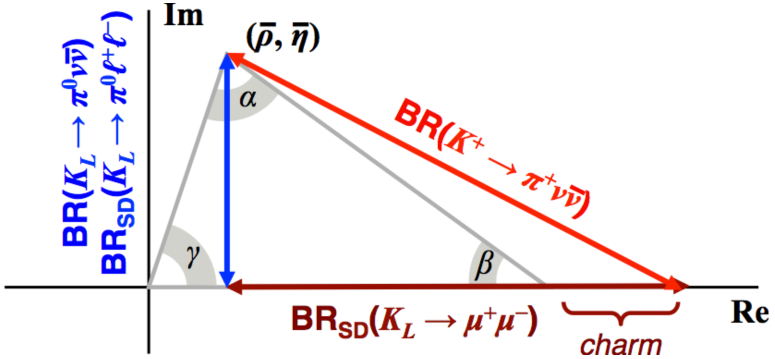
We will try!

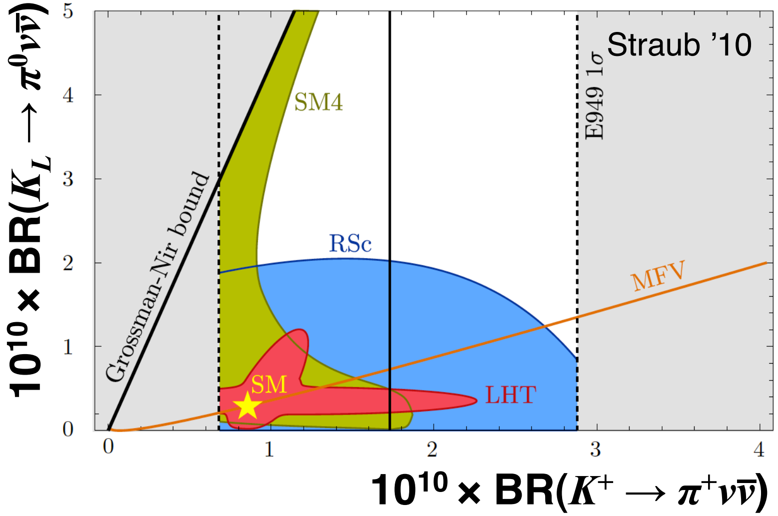
Matthew Moulson

Experimental status of $K \to \pi\nu\bar{\nu}$

Reminder: Important to measure both K^+, K_L

- New physics affects channels differently
- With both BRs unitarity triangle overconstrained





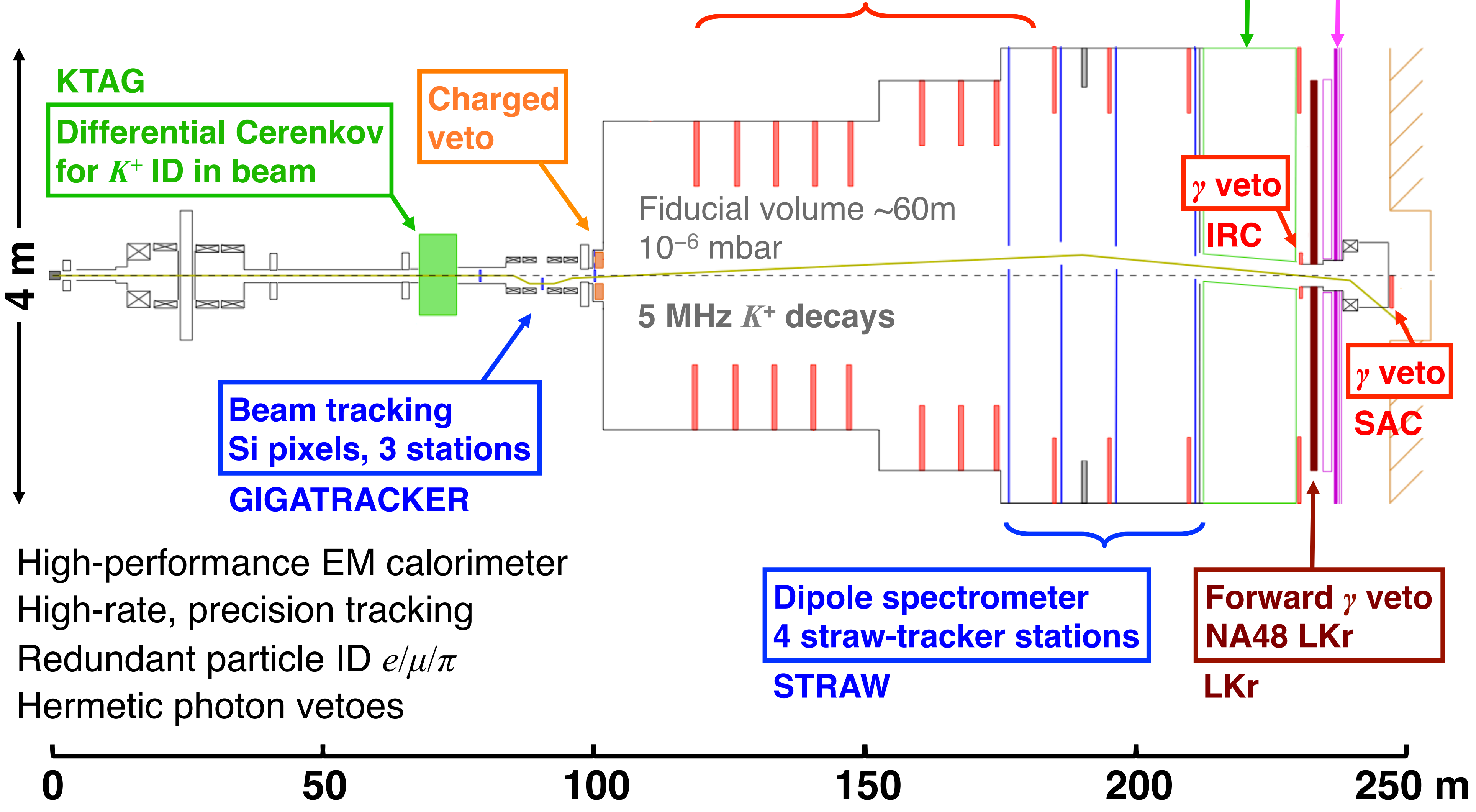
Experiments running, planned, or proposed

Expt.	Primary beam (E GeV)	Secondary beam (E GeV)	Start date + run years	SM events	Status
NA62	**SPS (450)**	**positive (75)**	**2014+2**	**100**	**Ready**
ORKA	FNAL MI (95)	K^+ (0.6)	2020+5	1000	Proposal
KOTO	**JPARC-I (30)**	**neutral (2 peak)**	**2013+3**	**~3**	**Running**
KOTO/2	JPARC-II (30)	neutral (~2 peak)	2025?	>100	Concept
FNAL K_L	Project X (3)	neutral (0.7 peak)	2030?	1000	Concept

$K_L \to \pi^0\nu\bar{\nu}$ < $K^+ \to \pi^+\nu\bar{\nu}$ < **ballistic**

The NA62 experiment at the SPS

75 GeV positive secondary beam
750 MHz total beam rate
50 MHz K^+ into experiment



LAV
Large angle photon vetoes
OPAL lead glass

RICH
RICH μ/π ID
1 atm Ne

MUV
μ veto
Fe/scint

KTAG
Differential Cerenkov for K^+ ID in beam

Charged veto

Fiducial volume ~60m
10^{-6} mbar

5 MHz K^+ decays

γ veto
IRC

γ veto
SAC

Beam tracking
Si pixels, 3 stations
GIGATRACKER

Dipole spectrometer
4 straw-tracker stations
STRAW

Forward γ veto
NA48 LKr
LKr

High-performance EM calorimeter
High-rate, precision tracking
Redundant particle ID $e/\mu/\pi$
Hermetic photon vetoes

Beyond NA62: From K^+ to K_L

Acceptance for $K_L \to \pi^0 \nu\bar{\nu} > 10\%$
Rejection > 10^{12} for main K decays

Goal: 100 signal evts, S/B ~ 10
2 yr equivalent data in 2014-2017

NA62 will run as much as possible until LS2 (2018): *What next?*

NA62 Italy subset has **PRIN funding** for feasibility studies for a K_L experiment

FERRARA, FIRENZE, FRASCATI, NAPOLI, PERUGIA, PISA, TOR VERGATA, TORINO

Questions to answer:

- **What are the advantages of a $K_L \to \pi^0 \nu\bar{\nu}$ experiment at high energy?**
- How intense a neutral beam can be obtained? What will be its composition?
- Can an upstream photon absorber eliminate direct (beam) photons?
- Is the performance of the NA48 LKr calorimeter suitable?
- Can we add a preshower detector to the LKr for extra geometrical constraints?
- What performance will be required of the large-angle photon veto systems?
- How will charged particles be vetoed?
- How do we stop photons from escaping downstream through the beam pipe?
- What baseline architecture should be adopted for triggering/data acquisition?

PRIN studies: $K_L \to \pi^0 \nu\bar{\nu}$ at the SPS

Beam: 400 GeV p+Be, 2.4 × 10^{12} ppp
Extracted at 2.4 ± 0.15 mrad
Mean $p(K_L)$ = 110 GeV

Extrapolating for $K_L \to \pi^0 \nu\bar{\nu}$:
10× increased intensity
Angular bite ±0.20 mrad

SPS intensity is not a problem

6 × 10^{11} K_L decay/yr
K_L decays in FV: **500 kHz**

vs.

Beam neutrons: **800 MHz**
Beam photons: **2 GHz**

Beam sweeper: May require innovative approach: Iridium monocrystal?

Large angle photon vetoes: 26 new LAV stations, scintillator/tile design
Hermetic coverage to at least 100 mrad

Small angle photon vetoes: Prototypes under development:
Converter + NA62 Gigatracker (Si pixel)-based veto
Dense inorganic Cerenkov crystal veto

Expected results with 2 yrs of data:
$\pi^0 \nu\bar{\nu}$ cand. with 2γ on LKr, nothing else
Vertex in FV with $p_\perp(\pi^0) > 0.1$ GeV

7.8 signal events
6.0 ± 1.7_{st} $\pi\pi^0$ background

Nominally 2× better than KOTO (JPARC)

Franco Grancagnolo

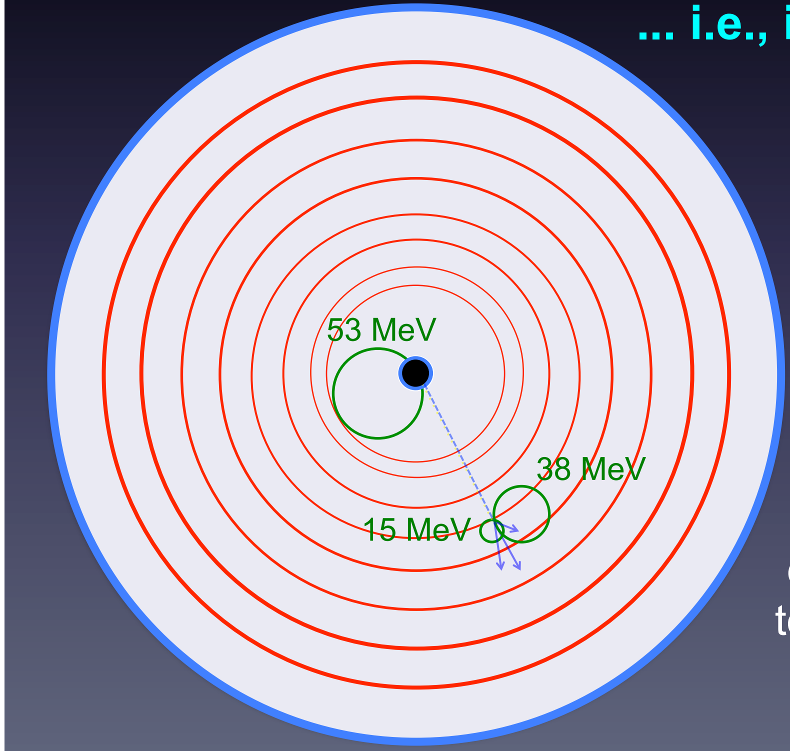
How to improve the $\mu \rightarrow e\gamma$ limit?

With respect to the MEG upgrade, despite the excellent energy resolution of the liquid xenon calorimeter, a sensible improvement can only be obtained by changing the approach to **the measurement of the photon.**

Geometric acceptance, energy resolution and position (angle) resolution can all simultaneously be improved by turning the calorimeter measurement into a tracking measurement:

allowing the photon to convert and reconstructing the electron pair…

… i.e., in a large drift chamber inside the KLOE magnet



Inner radius = 10 cm ($p_{t\,min}$ = 9 MeV/c) to allow for vertex detector

Outer radius = 245 cm

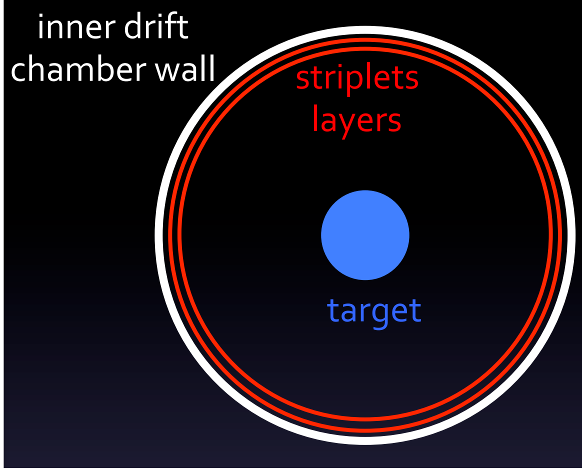
1st super-layer up to r = 60 cm to fully contain $p_t \leq 53$ MeV/c electrons (≈100 ± stereo layers)

Successive super-layers of 16 stereo layers of increasing cell size (from 0.8 to 2.2 cm) separated by **radiator shells** to track electron pairs from photon conversion (2.1 X_0 total)

Total number of drift cells ≈ 110,000 (x10 KLOE)

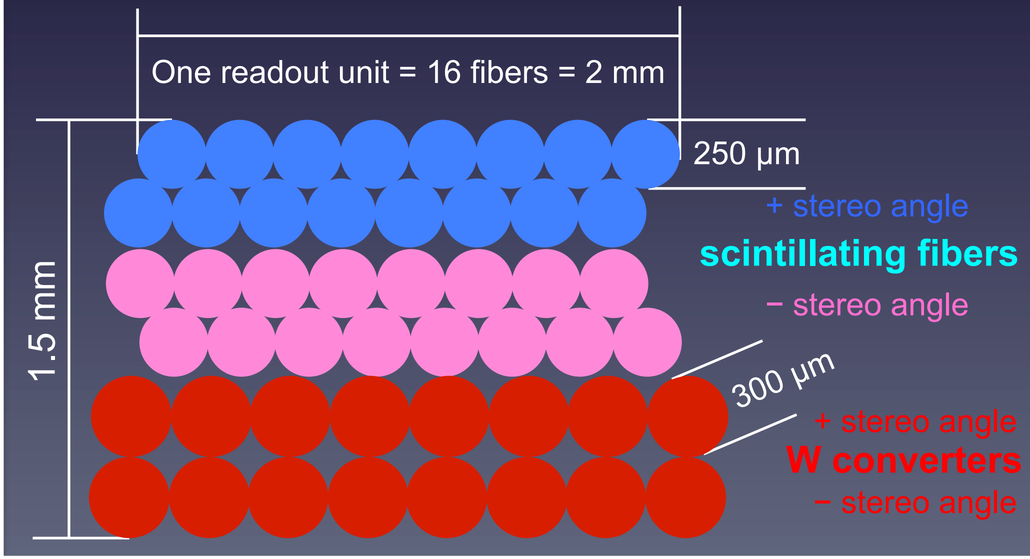
Additional sub-detectors

Low-mass Vertex Detector



- 80 μm × 2 mm striplets
  (occ. ≈ 0.5% for 10^9 μ/s at 10 cm) (3 μs double pulse resolution)
- Only 2 layers:
  just to extrapolate track to vertex in the target.
- 16 cm long:
  to match drift chamber acceptance.
- 6 × 10^5 striplets / layer
  no standalone tracking required.
- Total of $2 \times 10^{-3} X_0$.
  8 mrad / layer ➔ broken line fitting

Timing Counters system



- W converter shells made of bundles of W wires at the same stereo angles as the drift chamber wires, with no loss of active volume.
- Layers of scintillating fibers (same orientation of the W wires) for triggering and defining the conversion point.
  1 Million fibers (250 μm).
- By grouping 16 fibers together (2 mm azimuthal granularity) one ends up with 64,000 channels. Reading out both ends, besides the conversion time, gives all 3 coordinates of the conversion point.

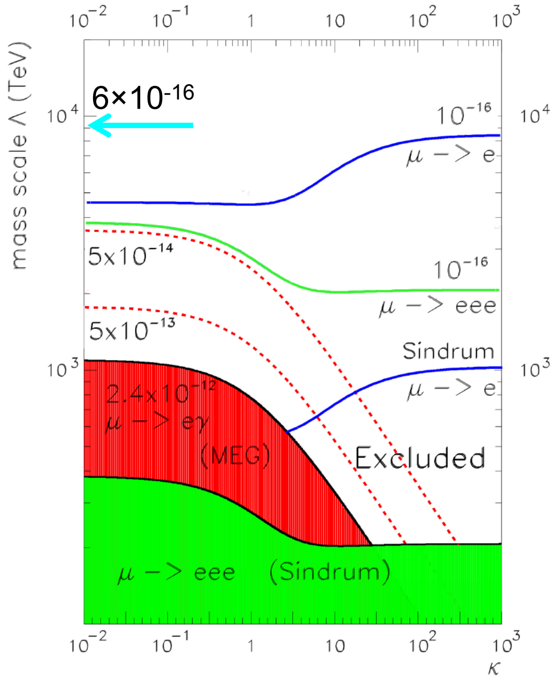
Expected performance

$$N_{sig} = R_\mu \times T \times \Omega \times B_r \times \varepsilon_\gamma \times \varepsilon_e \times \varepsilon_s$$

$$N_{bkg} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$$

arXiv:1301.7225 [physics.ins-det]

	MEG [2013] **5.7×10^{-13}**	**MEG upgrade** **6×10^{-14}**	**This approach** **6×10^{-16}**
R_μ	$= 3.3 \times 10^7\ \mu^+/s$	$= 7 \times 10^7\ \mu^+/s$	$= 3 \times 10^8\ \mu^+/s$
T	$= 1.1 \times 10^7$ s	$= 2 \times 10^7$ s	$= 5 \times 10^7$ s
Ω	= 11 %	= 11 %	= 90 %
ε_γ	= 63%	= 69%	= 80%
ε_e	= 40%	= 90%	= 90%
ε_s	= 65%	= 65%	= 65%
ΔE_γ	= 1.7% (900 KeV)	= 1.1% (600 KeV)	= 0.5% (250 KeV)
ΔP_e	= 306 KeV	= 130 KeV	= 120 KeV
$\Delta\Theta_{e\gamma}$	= 17 mrad	= 8 mrad	= 2 mrad
$\Delta t_{e\gamma}$	= 122 ps	= 84 ps	= 150 ps



de Gouv^ea and Vogel (2013), arXiv:1303.4097 [hep-ph]

Further improvements:

The large reduction in the background rate cannot be fully exploited because of the limitations imposed by the drift chamber occupancy in the inner layers (25%).

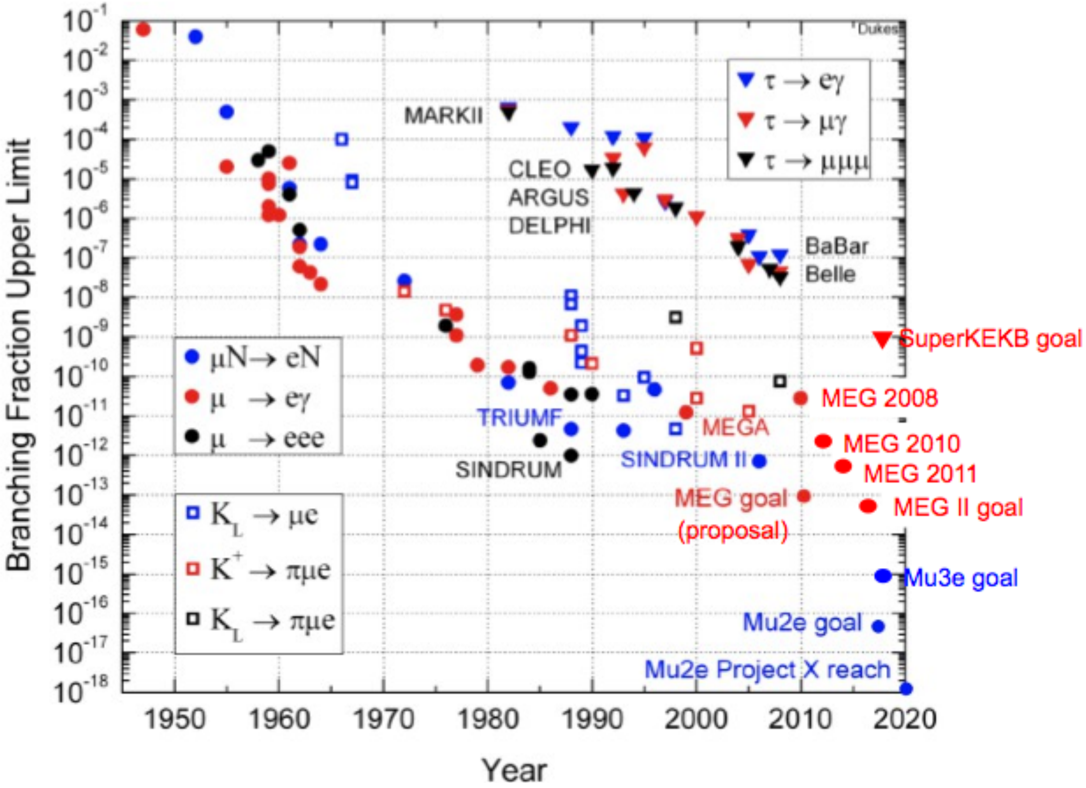
To overcome this (and gain a further factor 50, down to **1.2×10^{-17}**) one can think of replacing the inner super-layer with a higher granularity detector (e.g., cylindrical GEM's) and/or adoptimg a not uniform magnetic field to sweep out high transverse momentum tracks.

Moreover, the high tracking efficiency in the inner super-layer allows also for setting a limit on the **eee decay** with similar values.

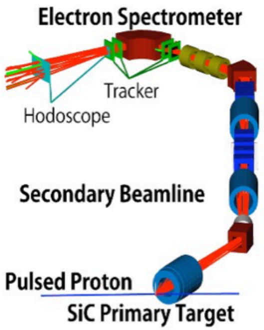
Giovanni Signorelli, Alessandro Baldini

Ballistic

- La proiezione balistica della CLFV ci porta ad avere esplorato nel 2020, se tutto va bene, un grosso spazio dei parametri delle teorie esistenti
- MEG dovrebbe dare il risultato finale entro quest'anno e poi MEGII

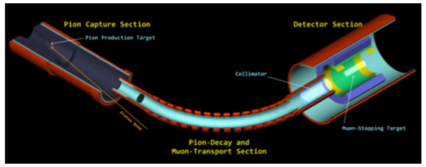


In the next decade...

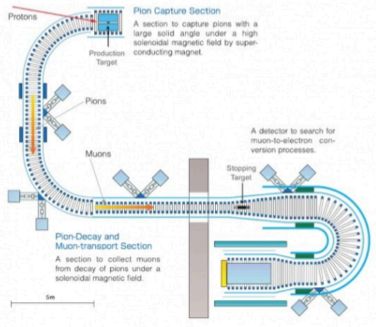


DeeMee DAQ

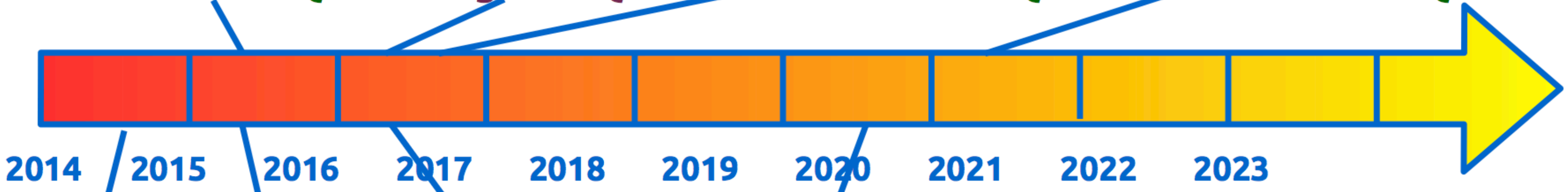
g-2 DAQ



COMET-I DAQ



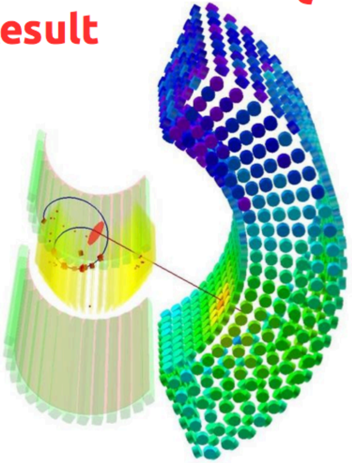
COMET-II DAQ



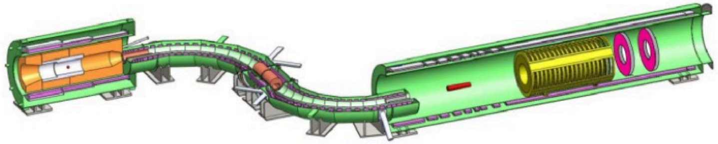
2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

MEG
Final Result

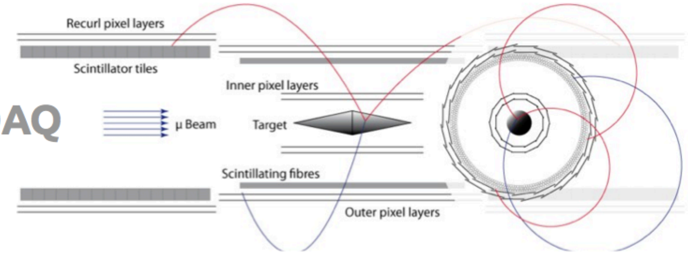
MEG2 DAQ

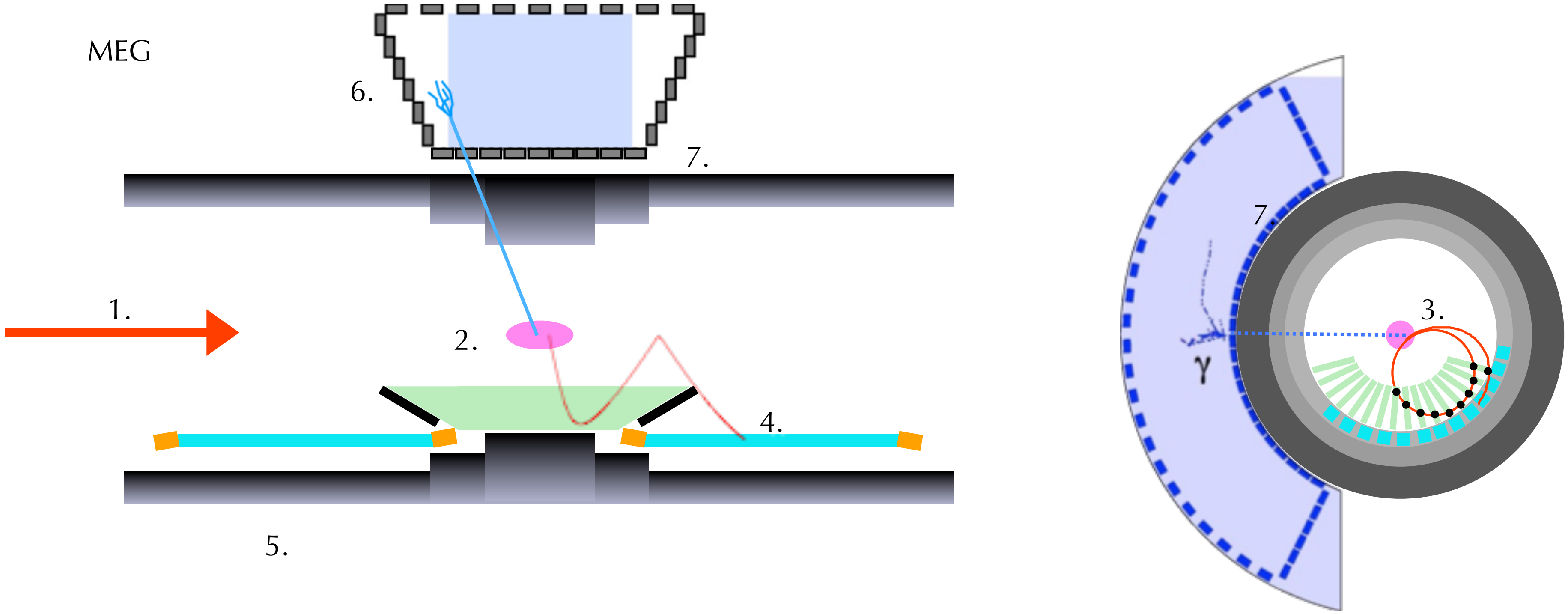


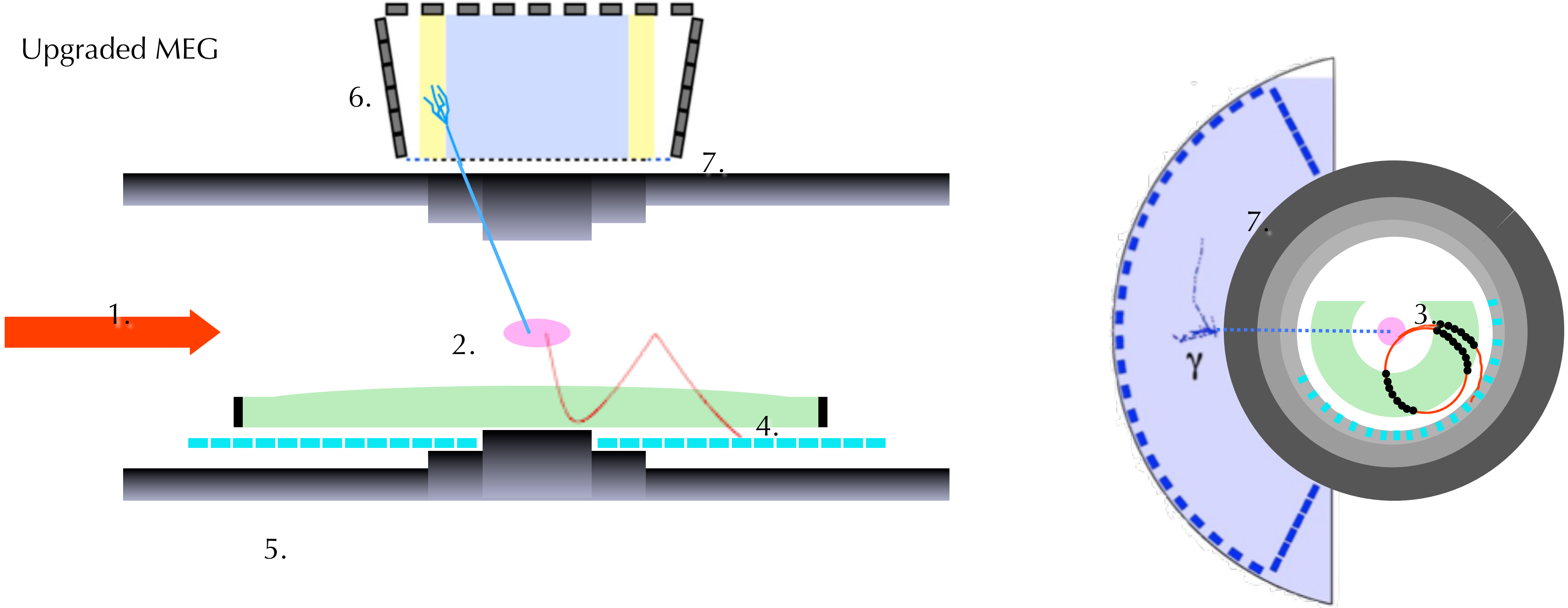
Mu2e DAQ



Mu3e DAQ

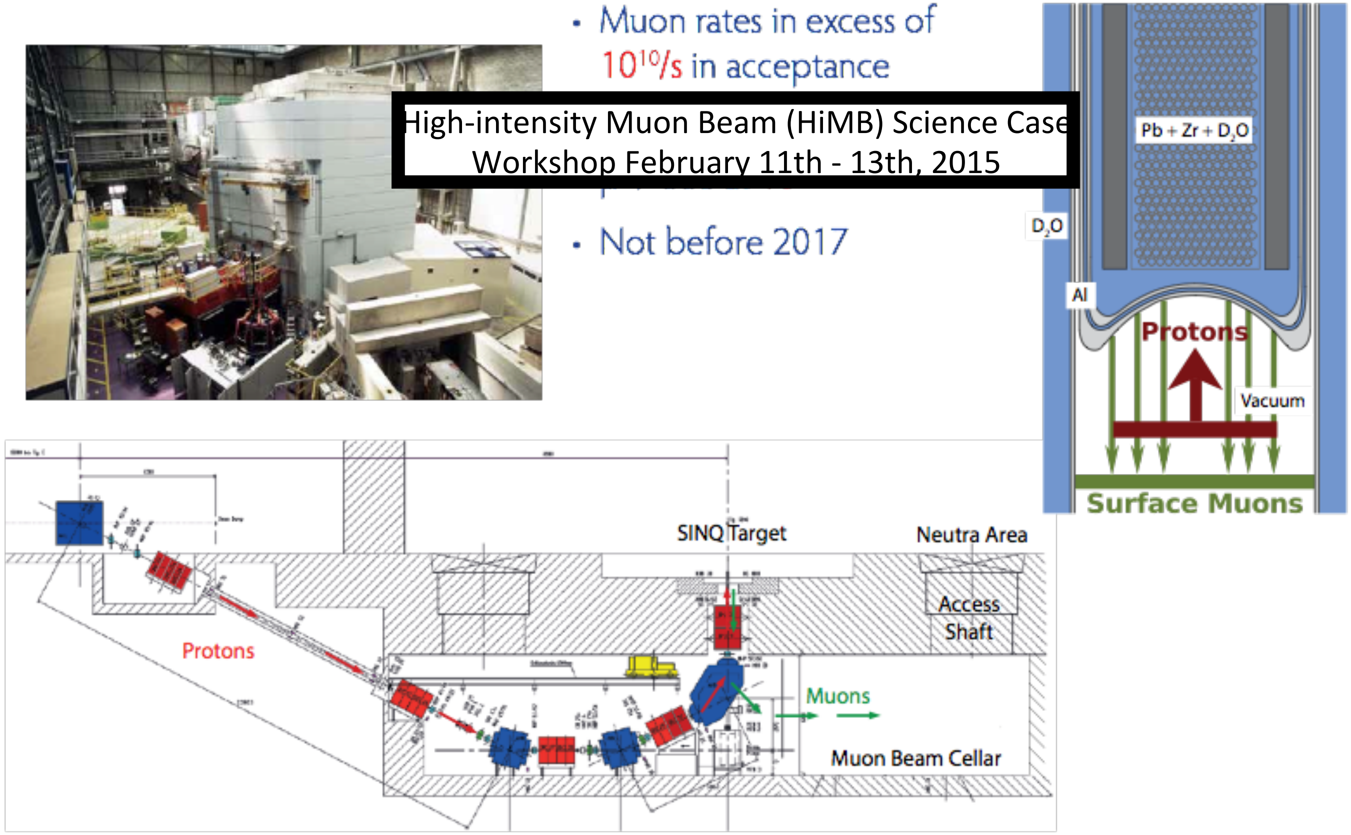



MEG
6.
7.
1.
2.
4.
5.
7
3.
γ


Upgraded MEG
6.
7.
1.
2.
4.
5.
7
3.
γ

High Intensity Muon Beam at PSI

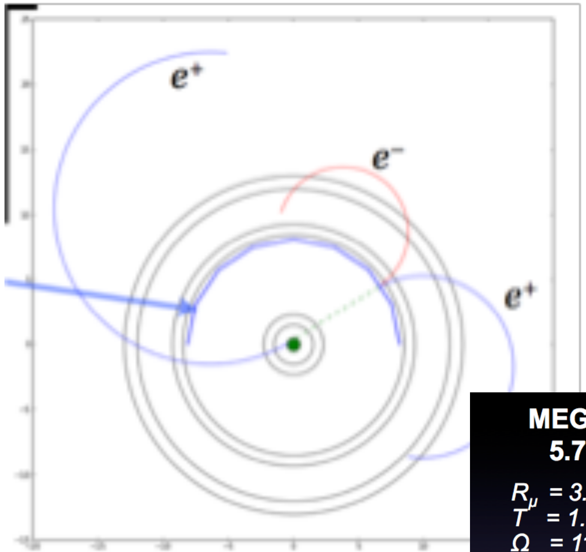
- Fuori da questo main stream è in fase di progettazione una nuova linea continua di muoni al PSI ad alta intensità (HIMB), presi dal bersaglio terminale per la produzione di neutroni (SINQ)
- Un rate superiore a 10^{10} μ/sec dovrebbe essere possibile
- Tempi scala 2017 ~ 2018
- Un workshop al PSI per lo studio dei casi di fisica

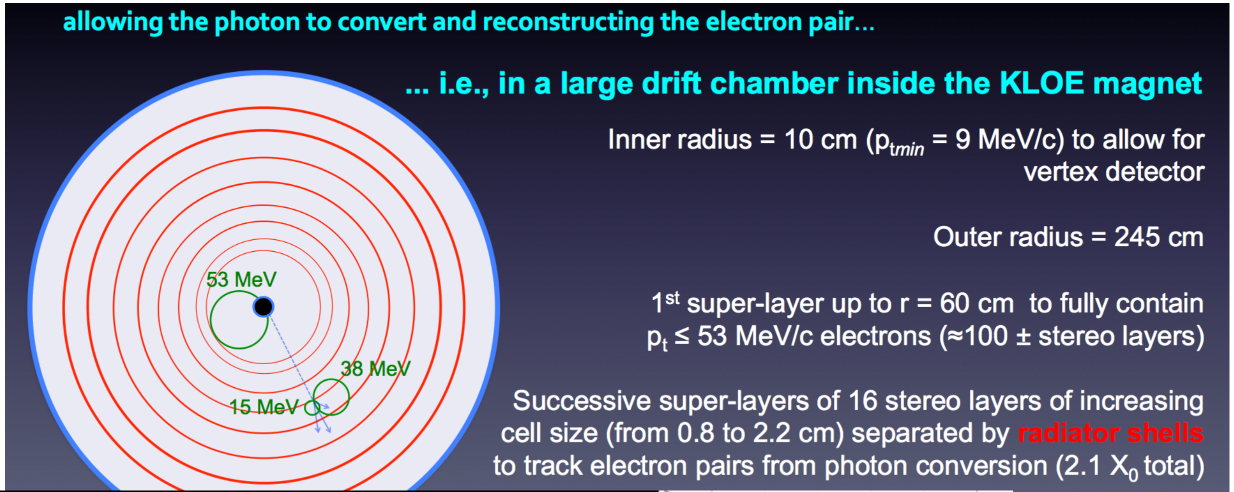

- Muon rates in excess of 10^{10}/s in acceptance
- Not before 2017

High-intensity Muon Beam (HiMB) Science Case
Workshop February 11th - 13th, 2015

Ultimate sensitivity

- Ha senso domandarsi quale sia la sensibilità limite di esperimenti quali $\mu \to e\gamma$, $\mu \to 3e$ e da cosa sia limitata
  - rate di accidentali
  - sostenibilità dei rivelatori
- Procedere oltre le stime "back of the envelope"





allowing the photon to convert and reconstructing the electron pair…

… i.e., in a large drift chamber inside the KLOE magnet

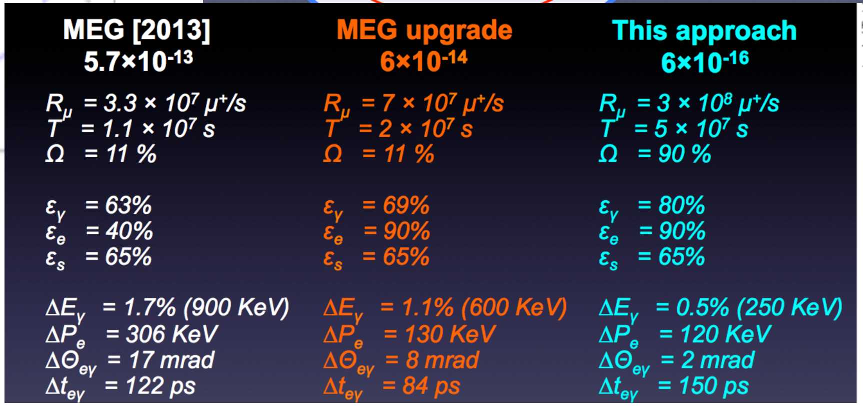
Inner radius = 10 cm (p_{tmin} = 9 MeV/c) to allow for vertex detector

Outer radius = 245 cm

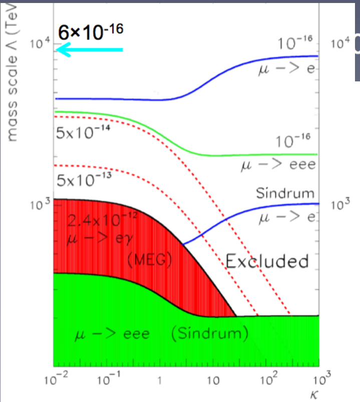
1st super-layer up to r = 60 cm to fully contain $p_t \leq 53$ MeV/c electrons (≈100 ± stereo layers)

Successive super-layers of 16 stereo layers of increasing cell size (from 0.8 to 2.2 cm) separated by radiator shells to track electron pairs from photon conversion (2.1 X_0 total)

000 (x10 KLOE)



MEG [2013] **5.7×10^{-13}**	**MEG upgrade** **6×10^{-14}**	**This approach** **6×10^{-16}**
$R_\mu = 3.3\times10^{7}\ \mu^+/s$	$R_\mu = 7\times10^{7}\ \mu^+/s$	$R_\mu = 3\times10^{8}\ \mu^+/s$
$T = 1.1\times10^{7}$ s	$T = 2\times10^{7}$ s	$T = 5\times10^{7}$ s
Ω = 11 %	Ω = 11 %	Ω = 90 %
ε_γ = 63%	ε_γ = 69%	ε_γ = 80%
ε_e = 40%	ε_e = 90%	ε_e = 90%
ε_s = 65%	ε_s = 65%	ε_s = 65%
ΔE_γ = 1.7% (900 KeV)	ΔE_γ = 1.1% (600 KeV)	ΔE_γ = 0.5% (250 KeV)
ΔP_e = 306 KeV	ΔP_e = 130 KeV	ΔP_e = 120 KeV
$\Delta\Theta_{e\gamma}$ = 17 mrad	$\Delta\Theta_{e\gamma}$ = 8 mrad	$\Delta\Theta_{e\gamma}$ = 2 mrad
$\Delta t_{e\gamma}$ = 122 ps	$\Delta t_{e\gamma}$ = 84 ps	$\Delta t_{e\gamma}$ = 150 ps

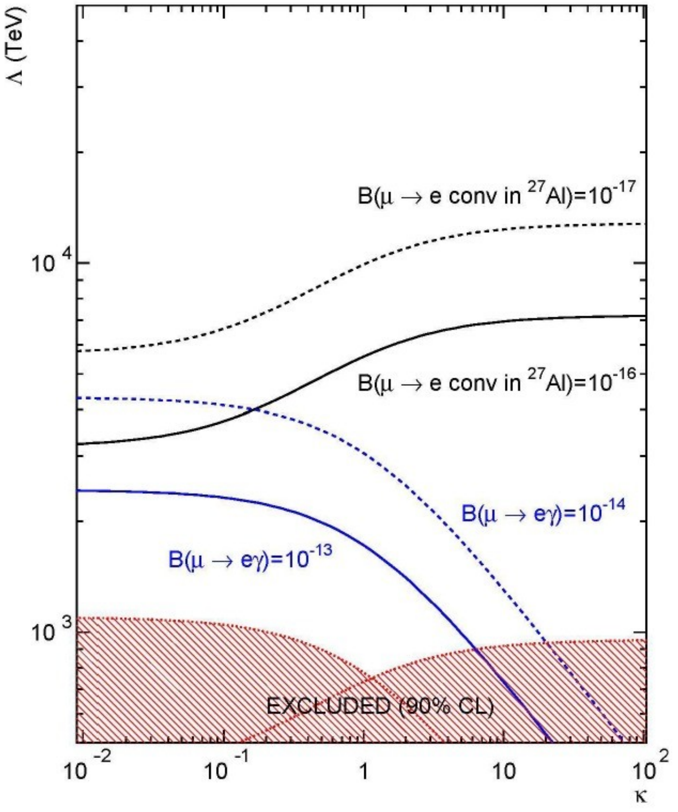


Roberto Carosi & Stefano Miscetti

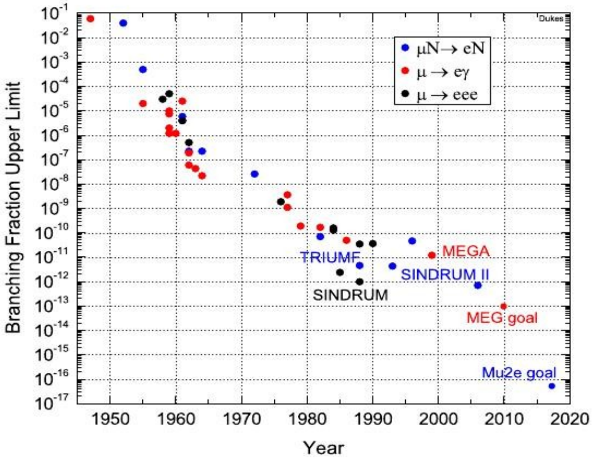
Mu2e at What Next

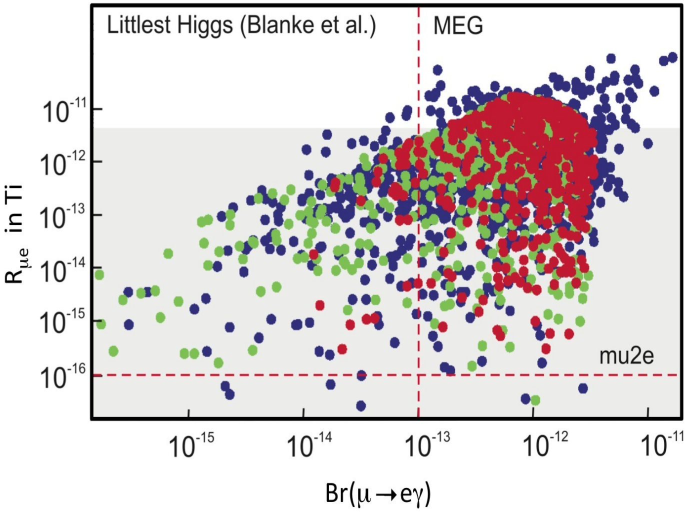
- Mu2e si propone di musurare il processo CLFV di conversione $\mu^- \rightarrow e^-$ con una precisione di ~2×10^{-17} (s.e.)
  - B.R. ~10^{-15} → 40 eventi di segnale (fondo ~0.5 ev.)
  - Previsone SM: ~10^{-54} → un segnale implica nuova fisica
- Esplorazione della (eventuale) fisica “Beyond Standard Model” e sensibilità ai vari parametri.
- Links:
  - Mu2e web site: http://mu2e.fnal.gov
  - Presentazione al Physics Advisory Committee, Fermilab, gennaio 2014: http://www.fnal.gov/directorate/program_planning/Jan2014PACPublic/2014-January-PAC-140123.pdf
  - http://arxiv.org/abs/1211.7019 (Conceptual Design Report)
- Piani:
  - CD2 quest'anno
  - Costruzione 2015-2018,
  - Partenza 2019,
  - 3 anni presa dati
- Prossima decade:
  - Mu2e a PIP-2, miglioramento x10 di sensibilità (s.e.) (arXiv:1307.1168, 1311.5278)

Interesse di Mu2e



Quadro storico

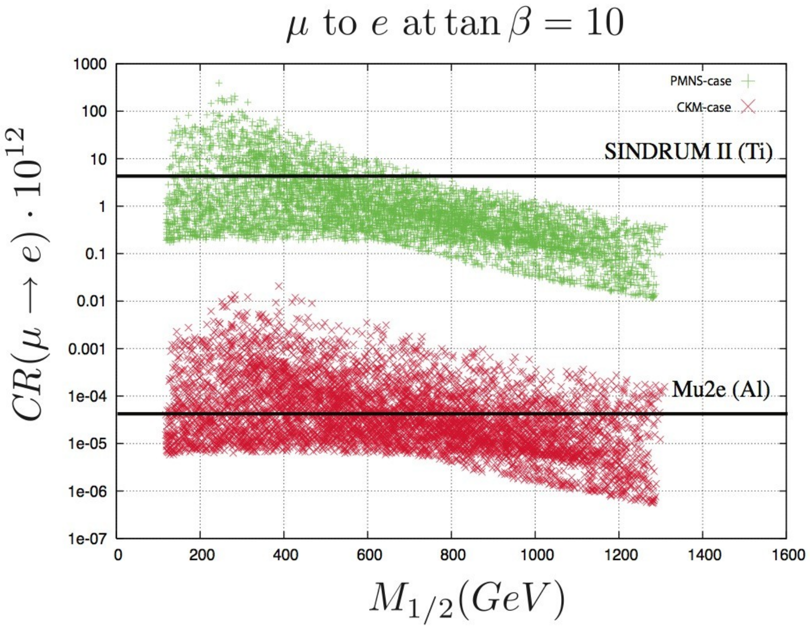


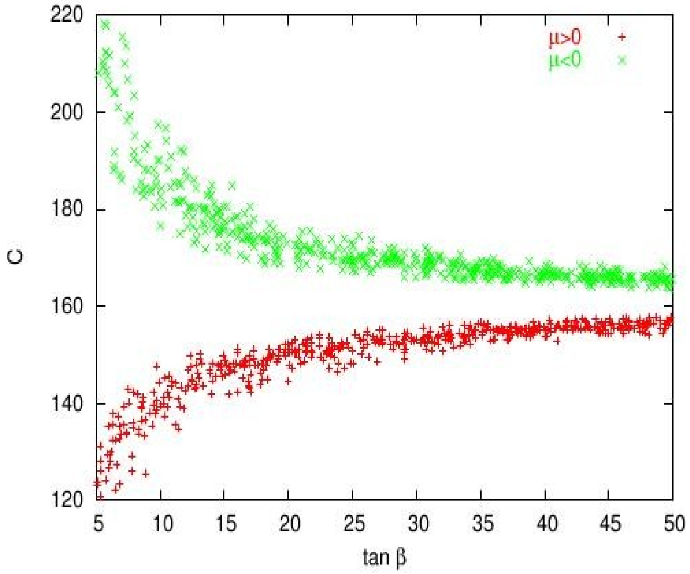


κ: peso relativo tra termini “contact” (compositeness, Leptoquarks, new heavy bosons,...) e “loops” (supersymmetry, Heavy neutrinos, two Higgs doublets,...)

Blanke et al, JHEP 705, 013 (2007)
Red: PMNS; Green: CKM; Blue: gen. scan of the parameters.

Mu2e & LHC





C = rate decad./rate convers.

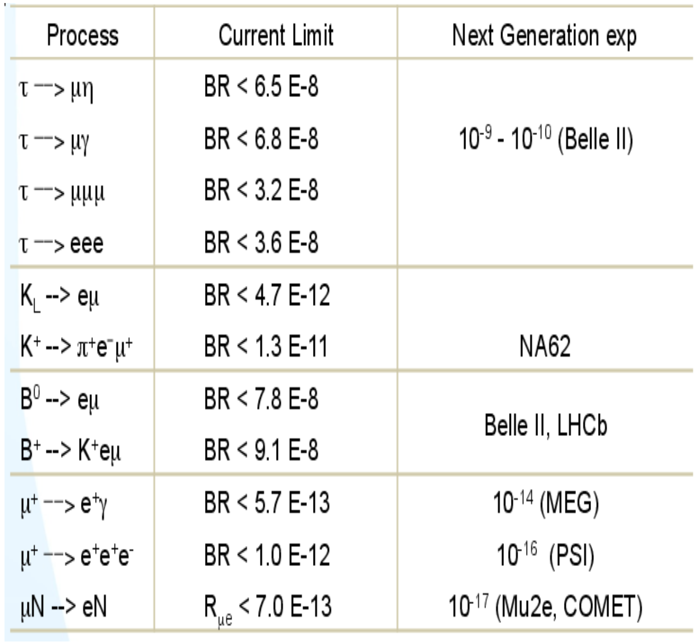
Calibbi et al, PRD 74, 116002 (2006)

Yaguna et al., Int J Mod Phys A21, 1283 (2006)

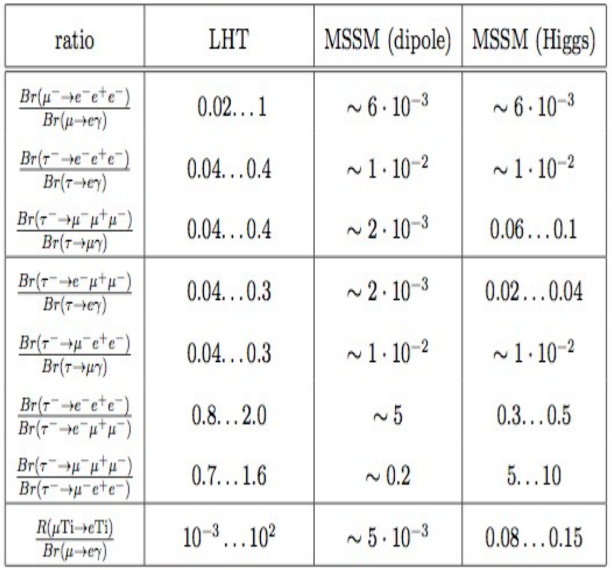
- *Sensibilità ai parametri in caso di scoperta*
- *Esplorazione di scale di energia più alte altrimenti (~10^4 TeV)*

("Complementare" a LHC)

Mu2e & altri processi CLFV



Process	Current Limit	Next Generation exp
τ --> $\mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II)
τ --> $\mu\gamma$	BR < 6.8 E-8	
τ --> $\mu\mu\mu$	BR < 3.2 E-8	
τ --> eee	BR < 3.6 E-8	
K_L --> eμ	BR < 4.7 E-12	
K^+ --> $\pi^+e^-\mu^+$	BR < 1.3 E-11	NA62
B^0 --> eμ	BR < 7.8 E-8	Belle II, LHCb
B^+ --> $K^+e\mu$	BR < 9.1 E-8	
μ^+ --> $e^+\gamma$	BR < 5.7 E-13	10^{-14} (MEG)
μ^+ --> $e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
μN --> eN	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)



ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

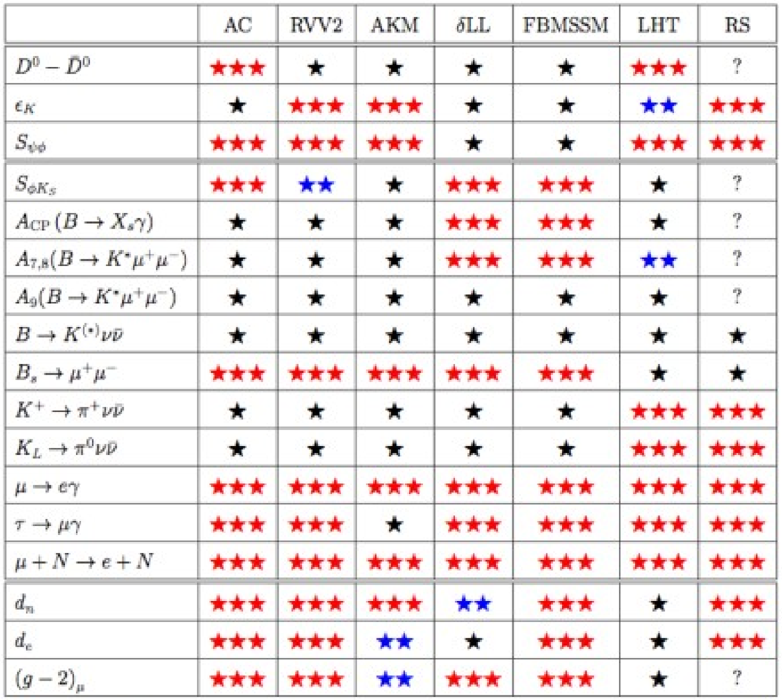
Table 3: *Comparison of various ratios of branching ratios in the LHT model* ($f = 1\,\mathrm{TeV}$) *and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

Blanke et al, arXiv:0909.5454v2[hep-ph]

Più sensibile a CLFV rispetto ad altri decadimenti (τ, B,...)

Mu2e e altri processi CLFV

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub



	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

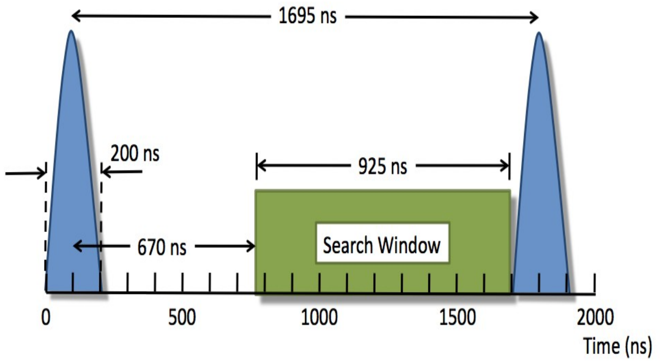
★★★ Discovery Sensitivity

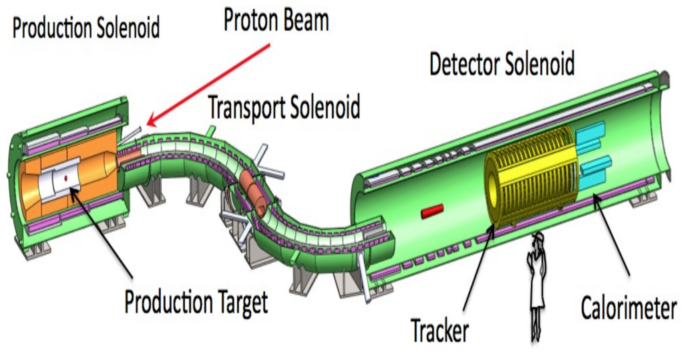
arXiv:0909.1333[hep-ph]

Mu2e

Mu2e - futuro

- Presa dati ~2020, per 4 anni: risultato nel 2025?
- Tecnica sperimentale, innovazioni rispetto al passato:
  - Fascio di protoni più intenso
  - Fascio di protoni impulsato (elim. fondi “prompt”)
  - Trasporto dei m con percorso ad “S” (elim. fondi diretti)
  - Campi magnetici non uniformi (specchi magnetici) per aumentare l' accettanza
  - Rivelatore con tracker ad alta precisione, calorimetro a cristalli (INFN) e veto per i raggi cosmici
- Quindi, la struttura del fascio e dei magneti è complessa e costosa
  - INFN Genova in prima linea con la realizzazione del prototipo del “transport solenoid”
- Una misura più precisa è possibile solo con un fascio di protoni molto più intenso
  - Mu2e-2 a PIP-2 (arXiv:1307.1168, 1311.5278)
- ...e dopo una validazione della tecnica attuale

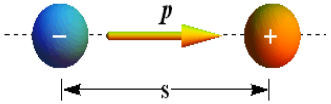




Paolo Lenisa

EDM of fundamental particles

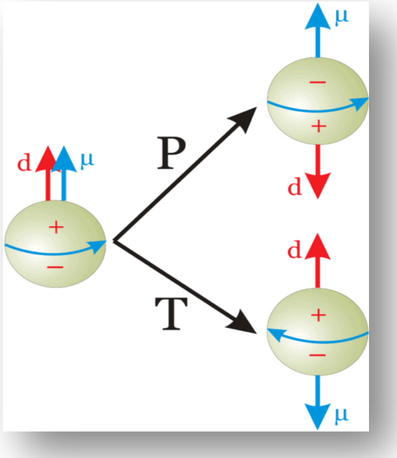
An electric dipole is caused by a permanent charge separation inside the particle volume



Molecules have large EDM because of degenerated ground states with different parity

Elementary particles (including hadrons) have a definite partiy and cannot have EDM

Unless P and T reversal are violated



: magnetic dipole moment
: electric dipole moment
(both aligned with spin)

Permanent EDMs violate P and T
Assuming CPT to hold, CP violated also

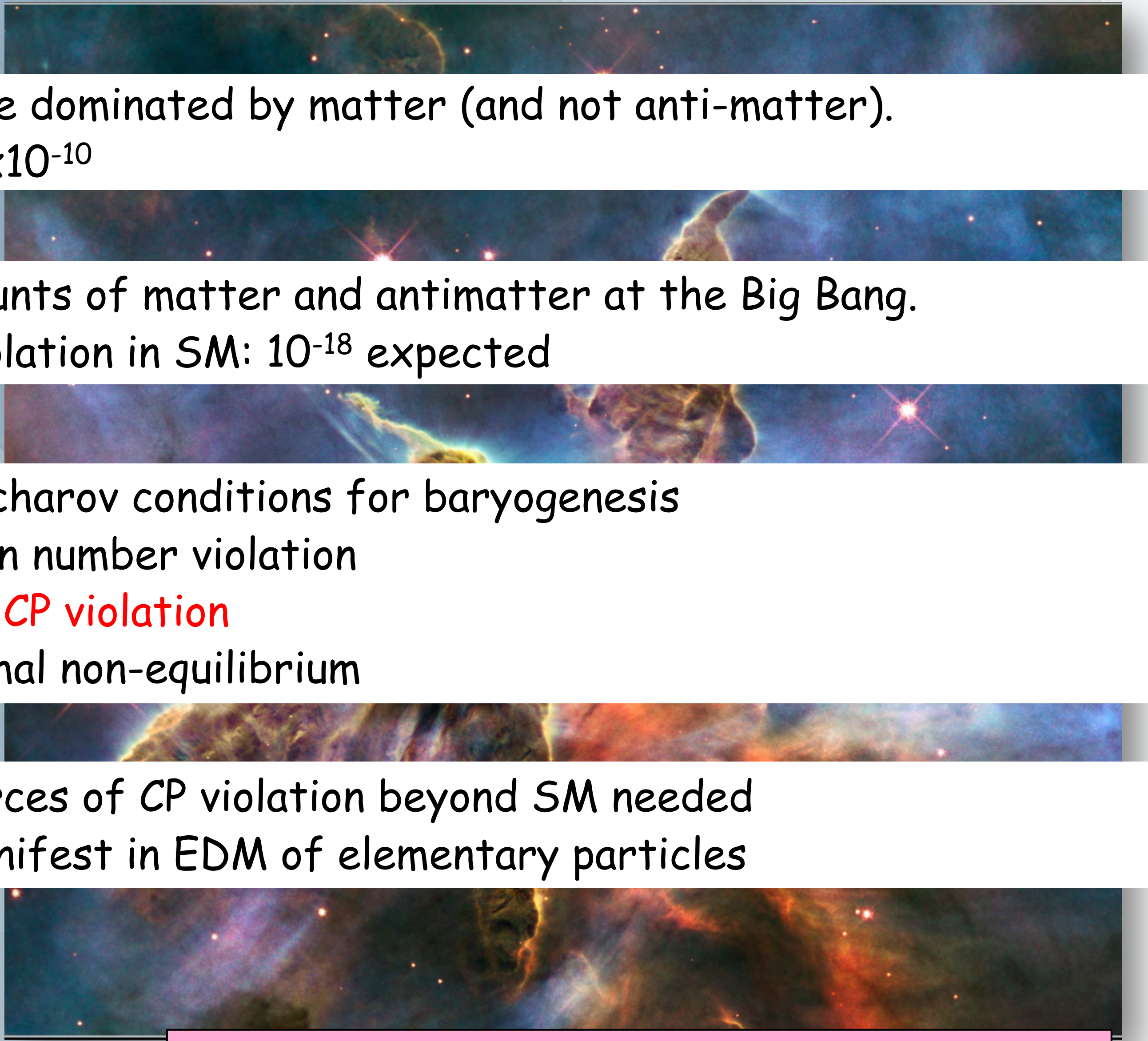
CP violation

- .Universe dominated by matter (and not anti-matter).
  - $= 6 \times 10^{-10}$

- Equal emounts of matter and antimatter at the Big Bang.
  - CP violation in SM: 10^{-18} expected

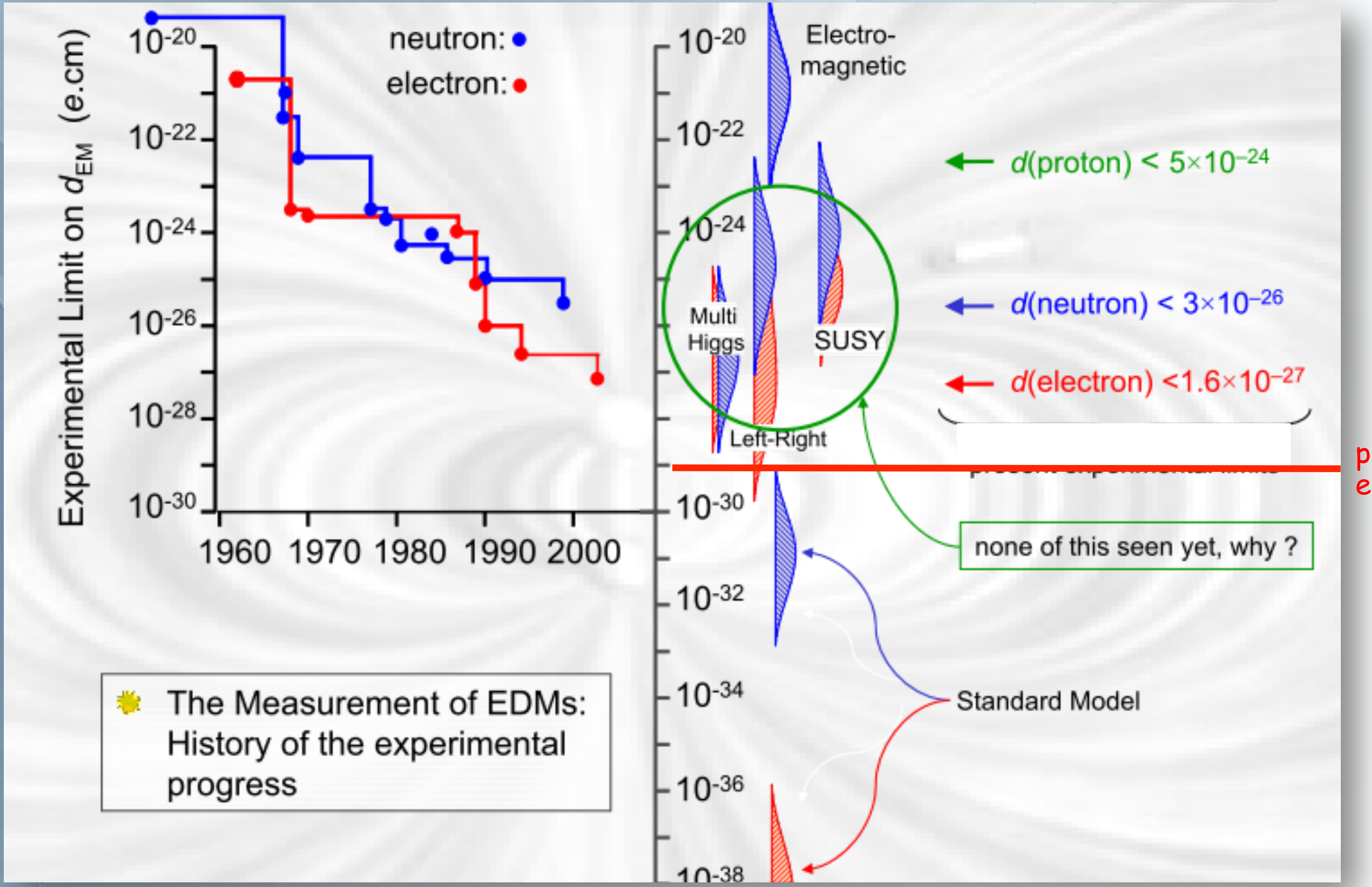
- 1967: 3 Sacharov conditions for baryogenesis
  - Baryon number violation
  - C and CP violation
  - Thermal non-equilibrium

- New sources of CP violation beyond SM needed
- Could manifest in EDM of elementary particles



Carina Nebula (Largest-seen star-birth regions in the galaxy)

Theoretical predictions



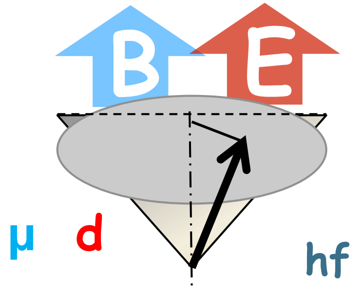
planned experiments

No Standard Model Background!

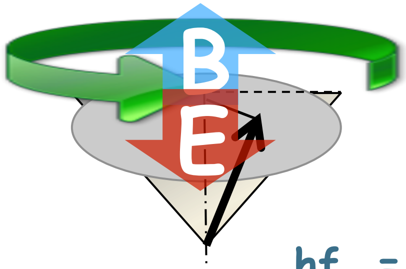
EDM searches: state of the art

- EDM searches: only upper limits yet
- E-fields accelerate charged part. → search limited to neutral systems

- „Traditional“ approach: precession frequency measurement in B and E fields



$hf_+ = 2\mu B + 2dE$



$hf_- = 2\mu B - 2dE$

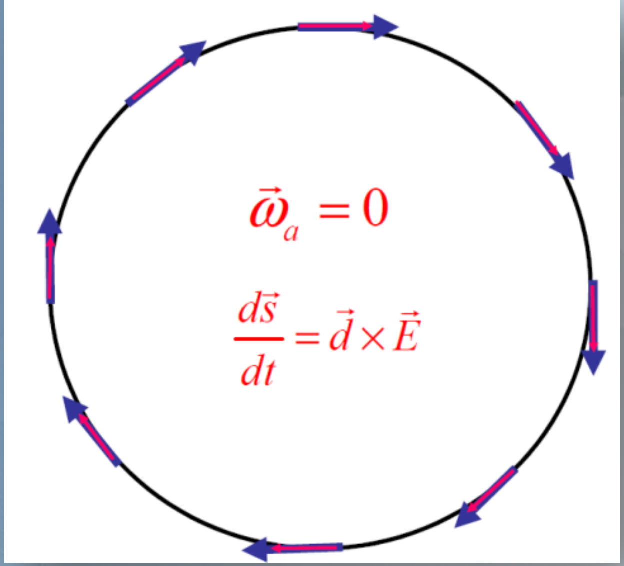
Particle	**System**	**Limit**	**Goal**	**SM prediction**
Barions				
Neutron	-	$<3\cdot 10^{-26}$	10^{-28}	10^{-32}
Proton	^{199}Hg	$7.9\cdot 10^{-25}$	10^{-29}	10^{-32}
Deuteron	-	-	10^{-29}	
Leptons				
Electron	ThO	$8.9\cdot 10^{-29}$	10^{-29} *	10^{-38}
Muon		1.9×10^{-19}	-	10^{-38}
Tau	$e^+e^- \rightarrow \tau^+\tau^-$	1×10^{-16}		

No direct measurement of electron or proton EDM yet

EDM of charged particles: use of storage rings

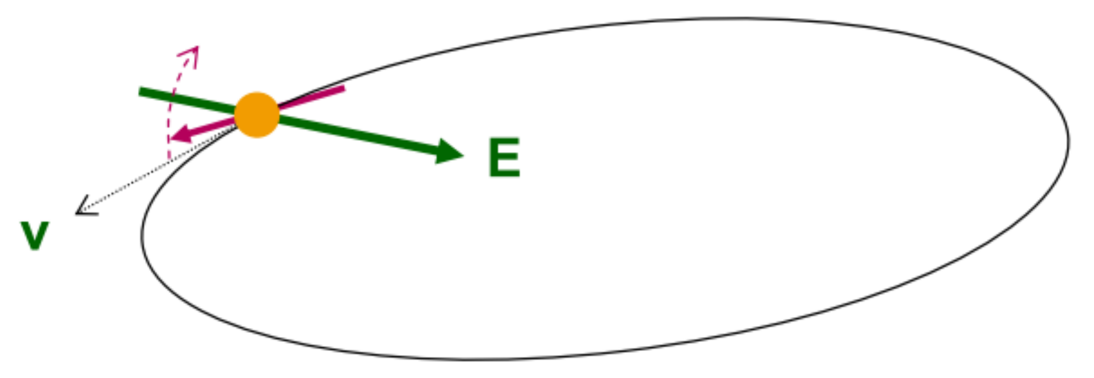
PROCEDURE

1. Place particles in a storage ring
2. Align spin along momentum (→freeze horizontal spin precession)
    - (Proton/electron: all electric ring)
3. Search for time development of vertical polarization



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$



Technological challenges

- SYSTEMATIC ERROR PLAN
  - Control of magnetic fields (< 1fT)
  - Beam position monitors (< 10 nm)

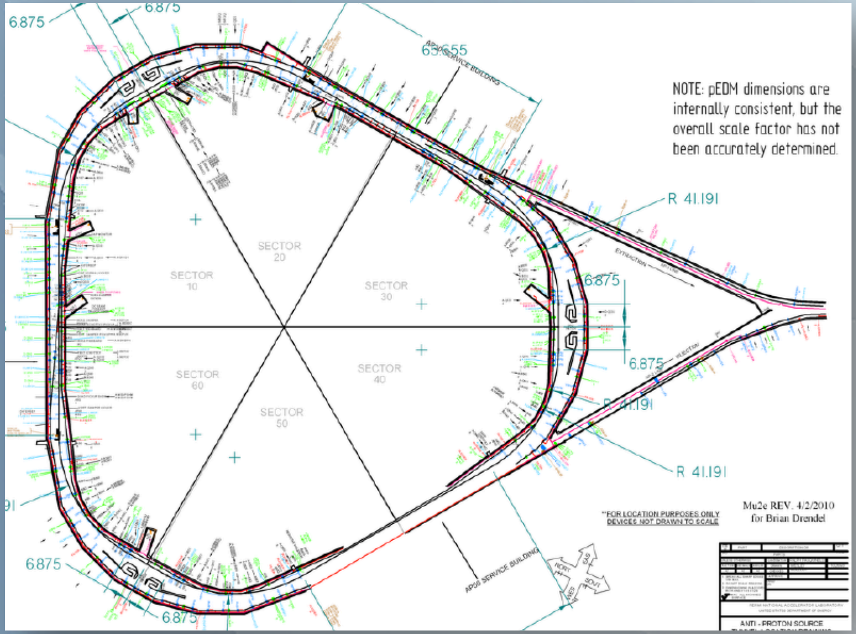
- ELECTRIC FIELD, as large as practical (no sparks).

- POLARIMETER
  - Large sensitivity to polarization (0.5).
  - High efficiency (> 1%).
  - Managing of systematic errors (< 10^{-6}).

- POLARIZED BEAM
  - Polarization must remain parallel to velocity.
  - Polarization must last a long time (> 1000 s).

Storage ring projects

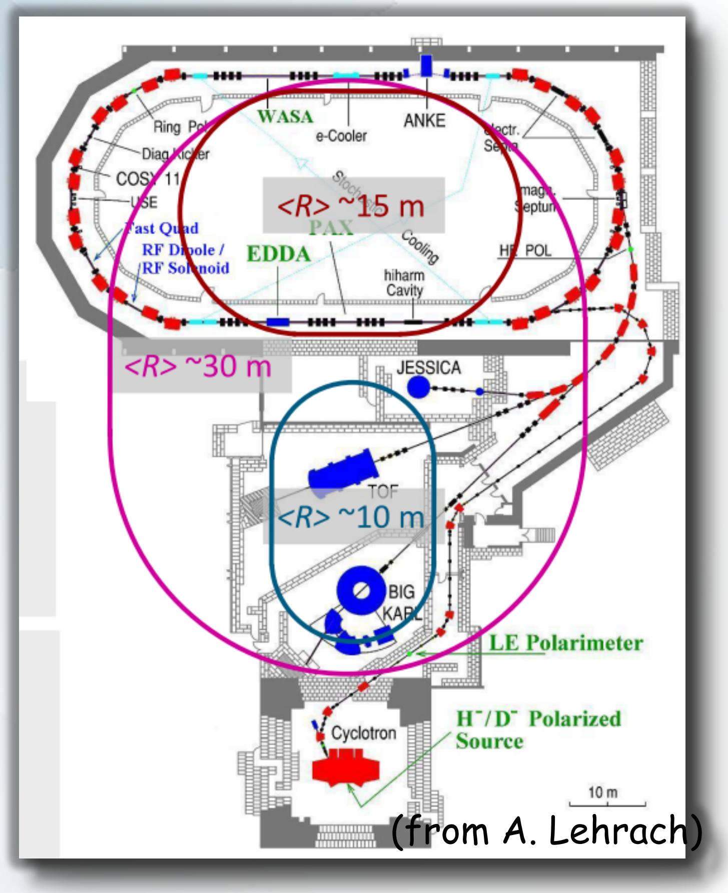
FNAL: Proton all electric ring



NOTE: pEDM dimensions are internally consistent, but the overall scale factor has not been accurately determined.

CW and CCW propagating beams

FZ-Jülich: deuteron and proton in a combined E-B machine



(from A. Lehrach)

All electric electron-EDM storage ring (at LNF?)

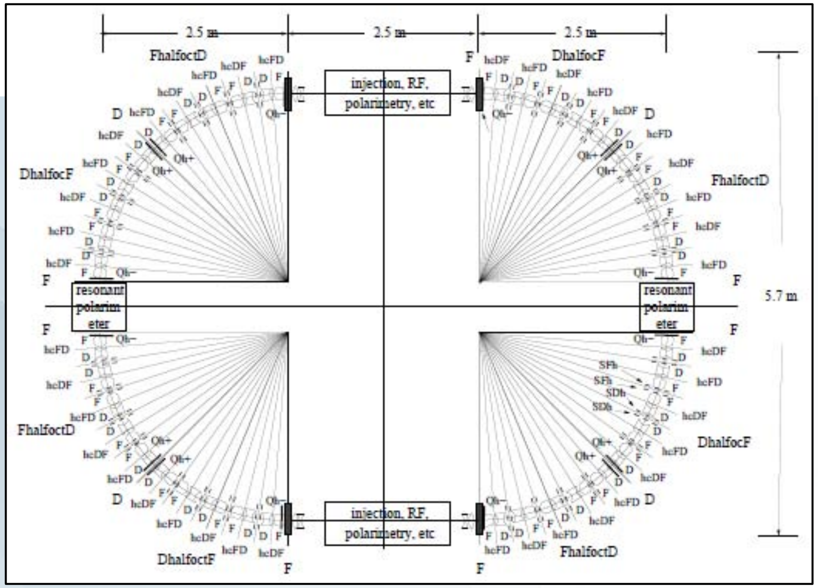
- First ever DIRECT measurement of electron EDM.

- Compact
    - Magic energy for electron: 14.5 MeV (γ=29.4)
    - E = 2-6 MeV/m → $2\pi R$ = 50 - 20 m

- Technical challenge, modest investment.

- Mandatory step for larger machines (proton and deuteron → $2\pi R$ > 250 m).

- Open issue: polarimetry.



(from R. Talman)