"BEYOND STANDARD MODEL AT LHC (ATLAS), Mu2e, COMET, MUON g-2"

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Problems of the Standard Model

Dark Matter: There is a particle that exists and is floating around making up 80% of the mass of our Universe and galaxy.

Baryon Asymmetry: We don't understand why there is more matter than anti-matter in the Universe. We know that the Standard Model inside Inflationary Big Bang Cosmology doesn't produce anywhere near enough of an excess.

Strong CP problem According to quantum chromodynamics there could be a violation of CP symmetry in the strong interactions. However, there is no experimentally known violation of the CP-symmetry in strong interactions.

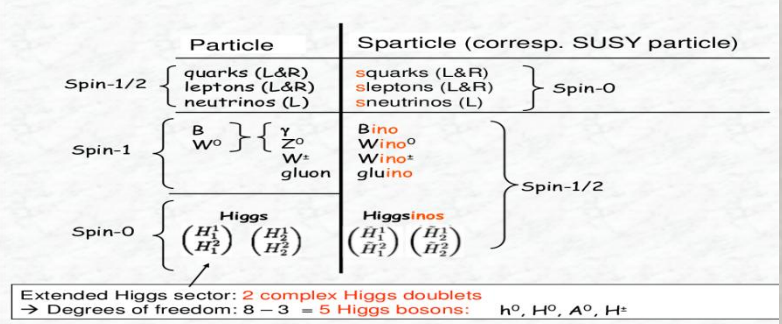
Inflation: There needs to be an inflationary field that reheats the Standard Model.

Origin of Masses: The problem is complicated because mass is strongly connected to gravitational interaction, and no theory of gravitational interaction reconciles with the SM.

Neutrino oscillation : observation of the phenomenon implies that the neutrino has a non-zero mass, which was not included as part of the original SM.

SM is inconsistent with that of general relativity, to the point that one or both theories break down under certain conditions (for example within known space-time singularities like the Big Bang and black hole event horizons).

BSM models



	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
Spin-1	$\left.\begin{matrix}B\\W^0\end{matrix}\right\}\left\{\begin{matrix}\gamma\\Z^0\end{matrix}\right.$ $W^\pm$ gluon	Bino Wino^0 Wino$^\pm$ gluino	Spin-1/2
Spin-0	Higgs $\begin{pmatrix}H_1^1\\H_1^2\end{pmatrix}$ $\begin{pmatrix}H_2^1\\H_2^2\end{pmatrix}$	Higgsinos $\begin{pmatrix}\tilde{H}_1^1\\\tilde{H}_1^2\end{pmatrix}$ $\begin{pmatrix}\tilde{H}_2^1\\\tilde{H}_2^2\end{pmatrix}$	

Extended Higgs sector: 2 complex Higgs doublets
→ Degrees of freedom: 8 − 3 = 5 Higgs bosons: h^0, H^0, A^0, $H^\pm$

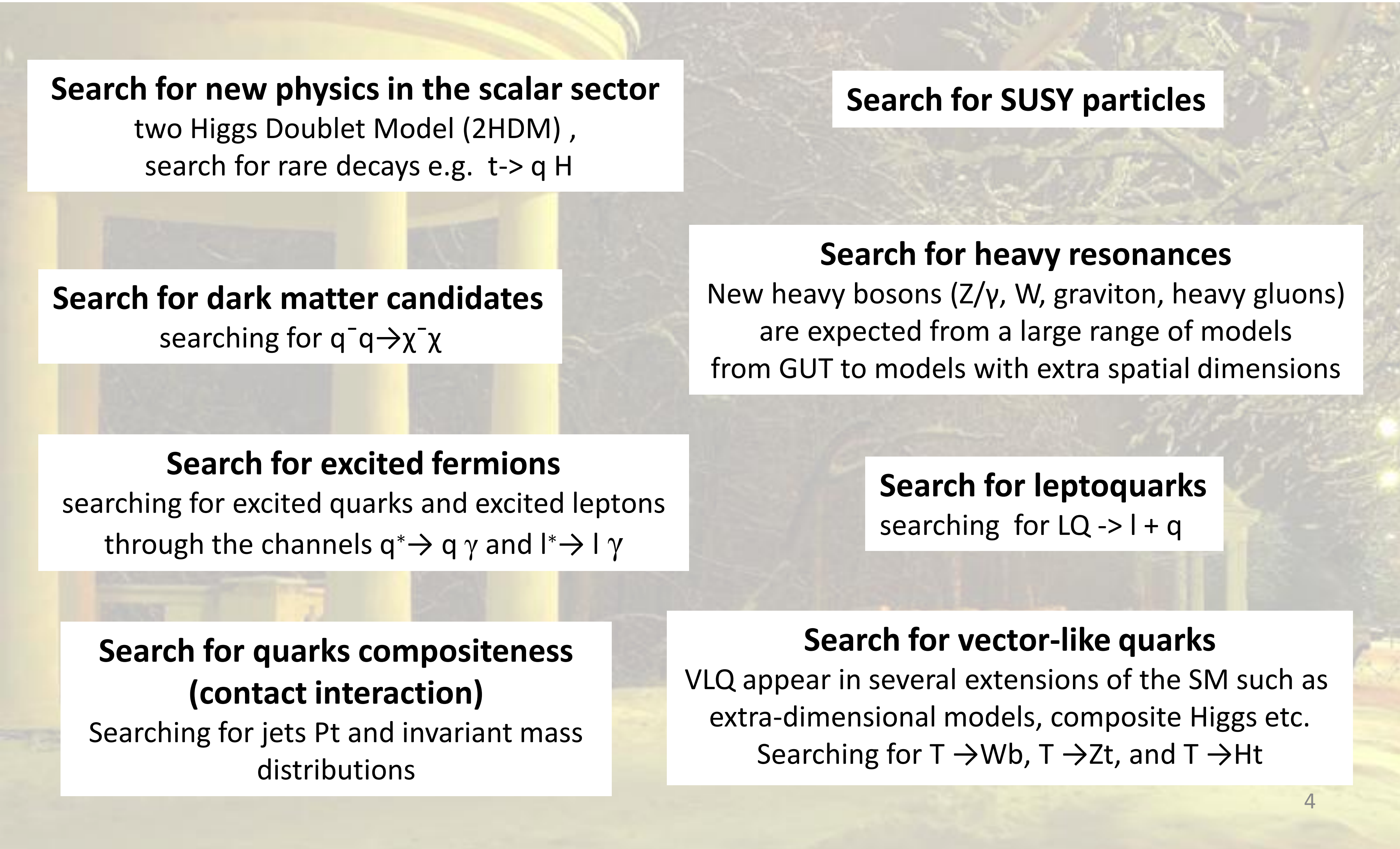
1. **Supersymmetry.** It is one of the best motivated extension of the SM. The theory proposes a new symmetry between bosons (integer spin) and fermions (half integer spin).

2. **Grand Unified Theories.** Attempt at unifying the electroweak and strong interactions at high energy. They are based on larger symmetry groups, like SU(5), SO(10), E6. The full symmetry is restored at very high energies. Typical scales of 10^{16} GeV emerge from the different running (meeting point) of the strong, weak and electromagnetic couplings.

3. **Additional spatial dimension(s).** An option to attack the hierarchy problem, i.e. the huge difference in scale between the gravitational interaction ($M_{Pl}=1.2\times10^{19}$ GeV) and the other fundamental interactions ($M_{ewk}\approx100$ GeV), relies on modifying the space-time structure of our universe.

4. **Dynamical symmetry breaking. (technicolor, compositeness, Little Higgs…)** Another class of theories introduce a new strong interaction that breaks the gauge symmetry of the SM. The scalar particles are bound states of fermions charged under the strong interaction, similar to pions in QCD.

Search for Exotics Physics beyond the SM with the ATLAS Detector



Search for new physics in the scalar sector
two Higgs Doublet Model (2HDM) ,
search for rare decays e.g. t-> q H

Search for SUSY particles

Search for heavy resonances
New heavy bosons (Z/γ, W, graviton, heavy gluons)
are expected from a large range of models
from GUT to models with extra spatial dimensions

Search for dark matter candidates
searching for $q\bar{q}\rightarrow\chi\bar{\chi}$

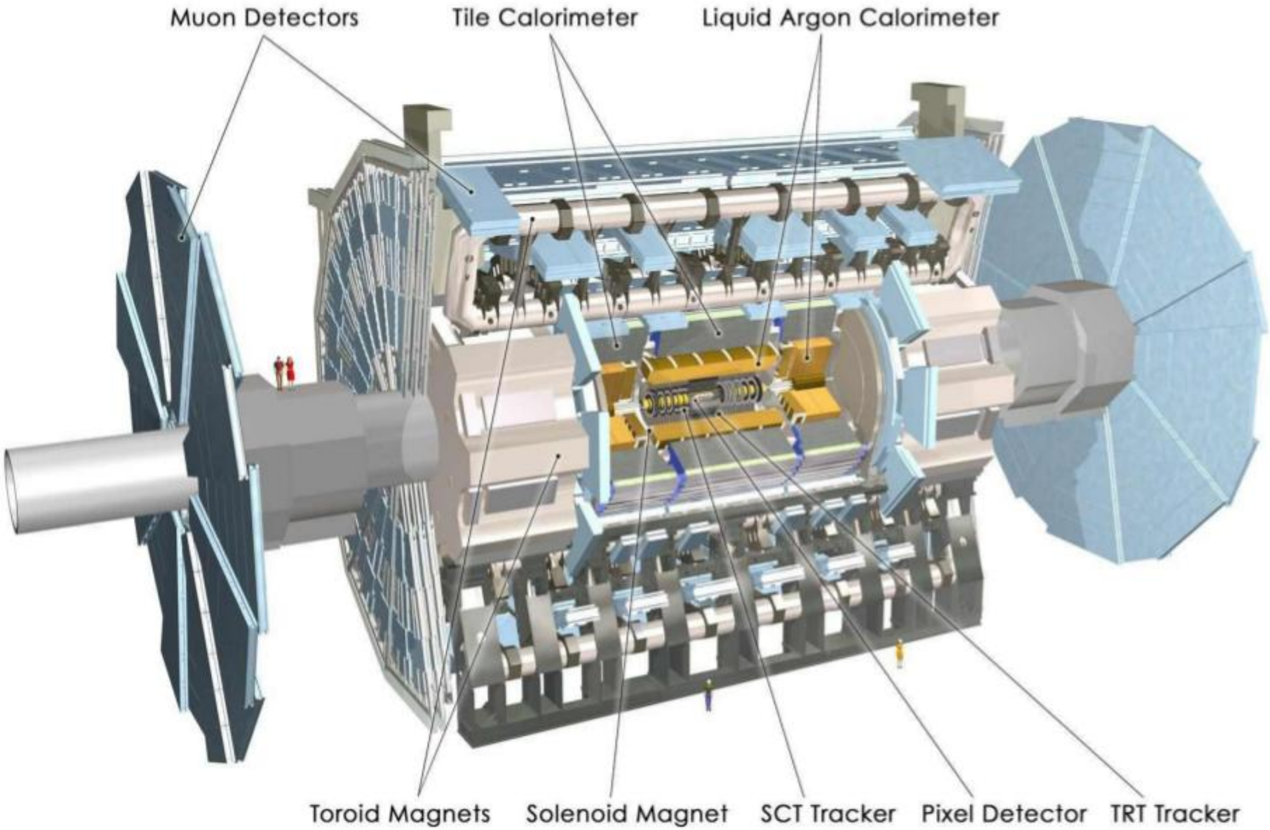
Search for excited fermions
searching for excited quarks and excited leptons
through the channels $q^* \rightarrow q\,\gamma$ and $l^* \rightarrow l\,\gamma$

Search for leptoquarks
searching for LQ -> l + q

Search for quarks compositeness (contact interaction)
Searching for jets Pt and invariant mass distributions

Search for vector-like quarks
VLQ appear in several extensions of the SM such as
extra-dimensional models, composite Higgs etc.
Searching for T →Wb, T →Zt, and T →Ht

ATLAS Detector



e / γ	calorimeter, tracking, $\gamma \rightarrow e^+e^-$
μ	muon system, tracking
tau	BDT: collimation, isol, shower profile
jets	anti-Kt (R=0.4)
E_T^{miss}	objects + topo clusters in calo
b-jets	lifetime-related Neural Net
Z / W	$Z \rightarrow \ell\ell$ / $W \rightarrow \ell\nu$, qq'
top	$t \rightarrow b W$

The DLNP and JINR participation in ATLAS

The international collaboration ATLAS was established about 20 years ago to carry out a new-generation multipurpose experiment aimed at studying fundamental properties of matter in collisions of 14-TeV protons at the LHC.

Since 1995 the following important works were carried out at JINR: Creation, mounting and adjustment of the elements of the ATLAS Muon Detector System, Liquid-Argon and Barrel Tile Calorimeters, Inner Detector. Calibration, preparation for data-taking and running of the calorimeters. Participation in the development on the Trigger TDAQ and creation of the ATLAS Grid at JINR (the best in Russia). Calculation of the magnet system, etc.

- **Search for high-mass resonances decaying to dielectron or dimuon final states from the analysis pp collisions at a center-of-mass ener of 8 TeV corresponding to an integrated luminosity of 20.3 fb^{-1} in the dielectron chann and 20.5 fb^{-1} in the dimuon channel.**
- **Search for supersymmetry in final states containing at least one isolated lepton (electron or muon), jets, and large missing transverse momentum**

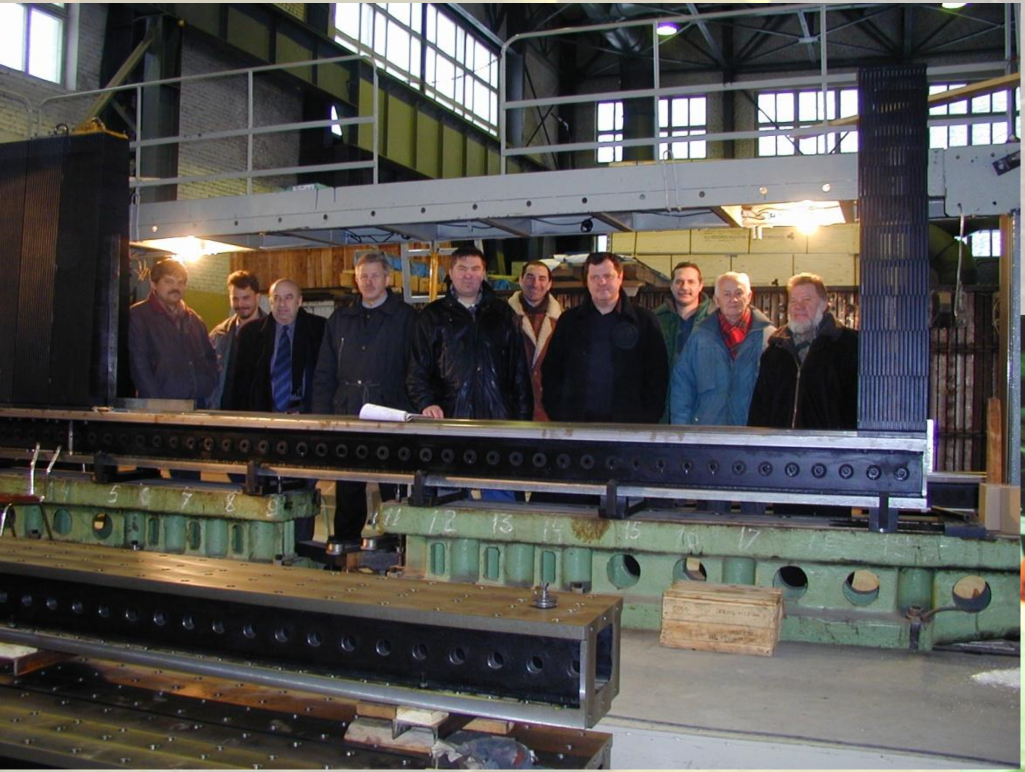
Publications:

ATLAS Collaboration, Phys. Rev. D 90, 052005 (2014).

ATLAS Collaboration, ATL-COM-PHYS-2014-929, to be submitted to JHEP.

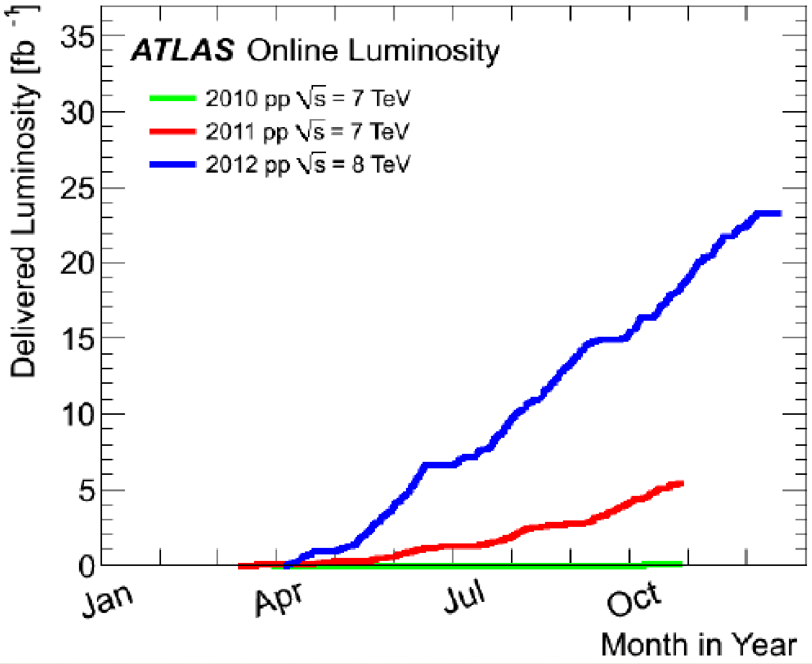
The DLNP Created of the ATLAS Barrel Tile Cal

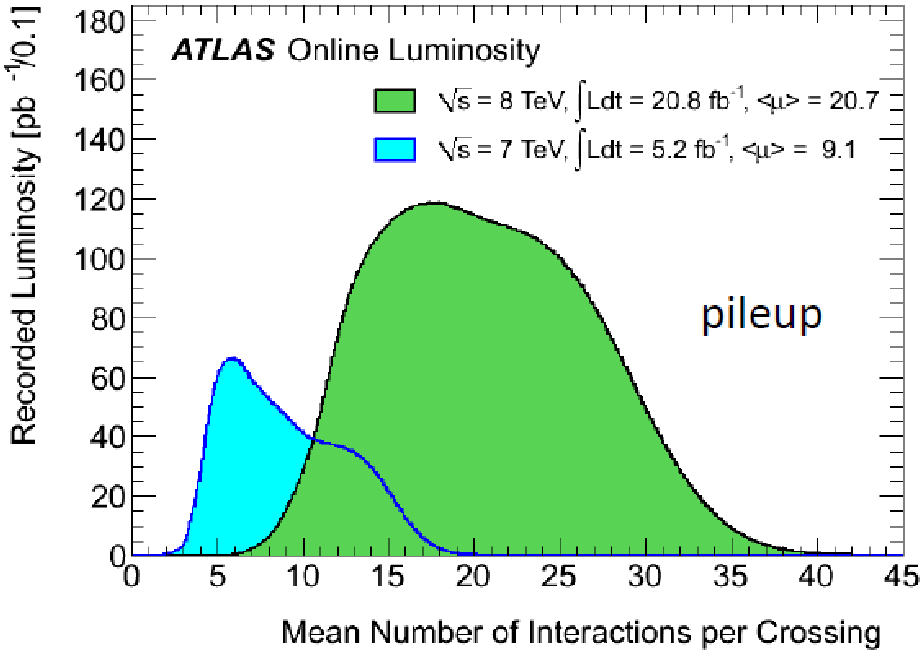
- milestones over the period **1994–2002**:
- R&D for calorimeter structure elements; manufacture of prototypes.
- Industrial production of ≅ 300 000 steel nuclear absorbers, girders.
- Manufacture of 65 modules; development and application of precision technologies, including the laser technique.



Data Taking (pp Mode)

Year	√s	BC	Delivered	Good Qual
2010	7 TeV	50 ns	0.048 fb^{-1}	0.045 fb^{-1}
2011	7 TeV	50 ns	5.46 fb^{-1}	4.5 fb^{-1}
2012	8 TeV	50 ns	22.8 fb^{-1}	20.3 fb^{-1}
2015	13 TeV	25 ns	~40 fb^{-1}	



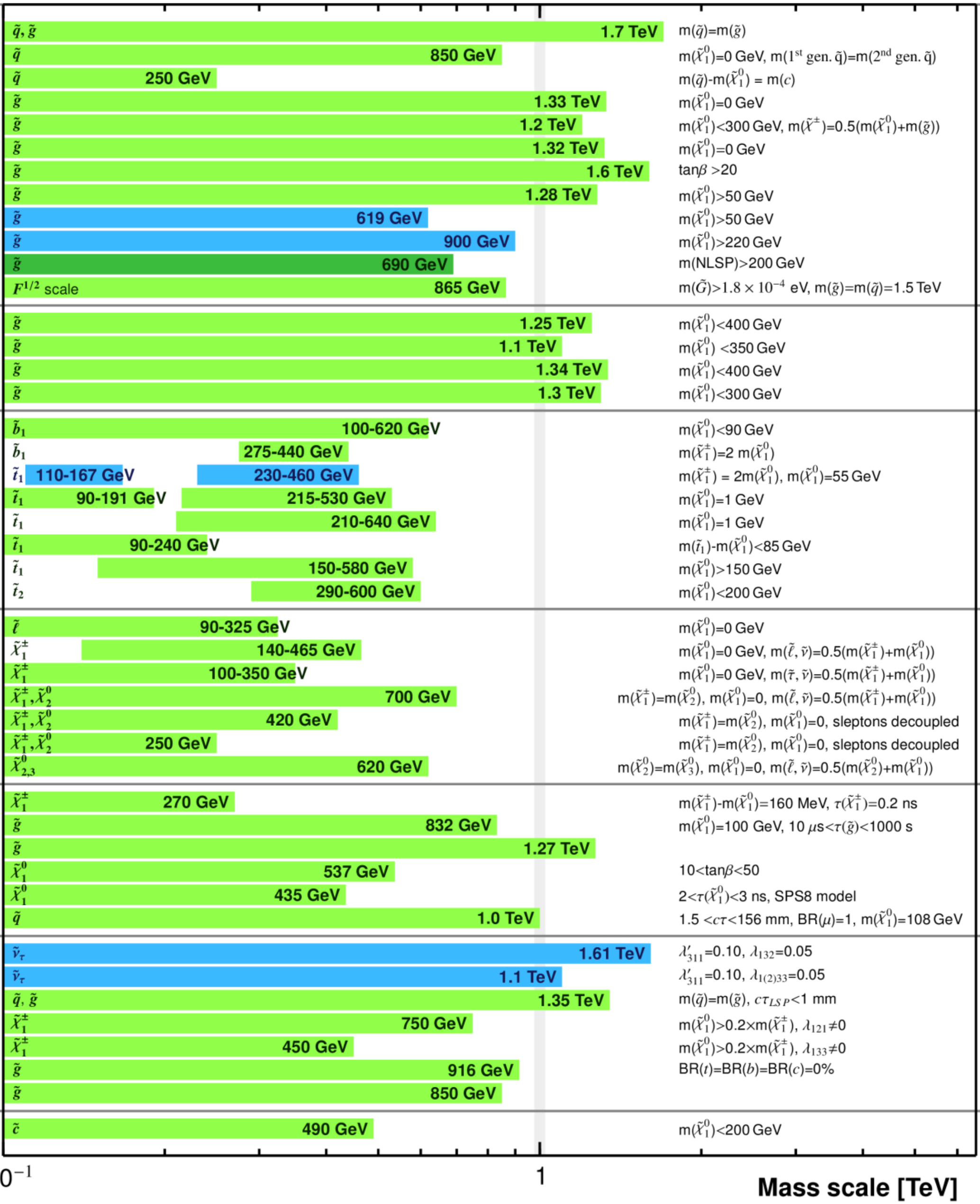


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma$, $\tilde{q}\rightarrow q\tilde{\chi}^0_1$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$) = m(c)	1411.1559
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}^0_1$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}^\pm_1\rightarrow qqW^\pm\tilde{\chi}^0_1$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	m($\tilde{\chi}^0_1$)<300 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	m($\tilde{\chi}^0_1$)=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	m($\tilde{\chi}^0_1$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}^0_1$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}^0_1$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}^0_1$)<400 GeV	1407.0600
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}^0_1$) <350 GeV	1308.1841
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}^0_1$)<400 GeV	1407.0600
	$\tilde{g}\rightarrow b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}^0_1$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}^0_1$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}^\pm_1$)=2 m($\tilde{\chi}^0_1$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV 230-460 GeV	m($\tilde{\chi}^\pm_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV 215-530 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow t\tilde{\chi}^0_1$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1$ 140-465 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 100-350 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1407.0350
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 700 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\rightarrow W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 420 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\rightarrow W\tilde{\chi}^0_1 h\tilde{\chi}^0_1$, $h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 250 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\rightarrow\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$ 620 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^\pm_1$ 270 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=160 MeV, τ($\tilde{\chi}^\pm_1$)=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 435 GeV	2<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}$, $\tilde{\chi}^0_1\rightarrow qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}^0_1$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 750 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^\pm_1$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^\pm_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\rightarrow\tilde{t}_1 t$, $\tilde{t}_1\rightarrow bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

🟦 $\sqrt{s}$ = 7 TeV full data 🟩 $\sqrt{s}$ = 8 TeV partial data 🟩 $\sqrt{s}$ = 8 TeV full data

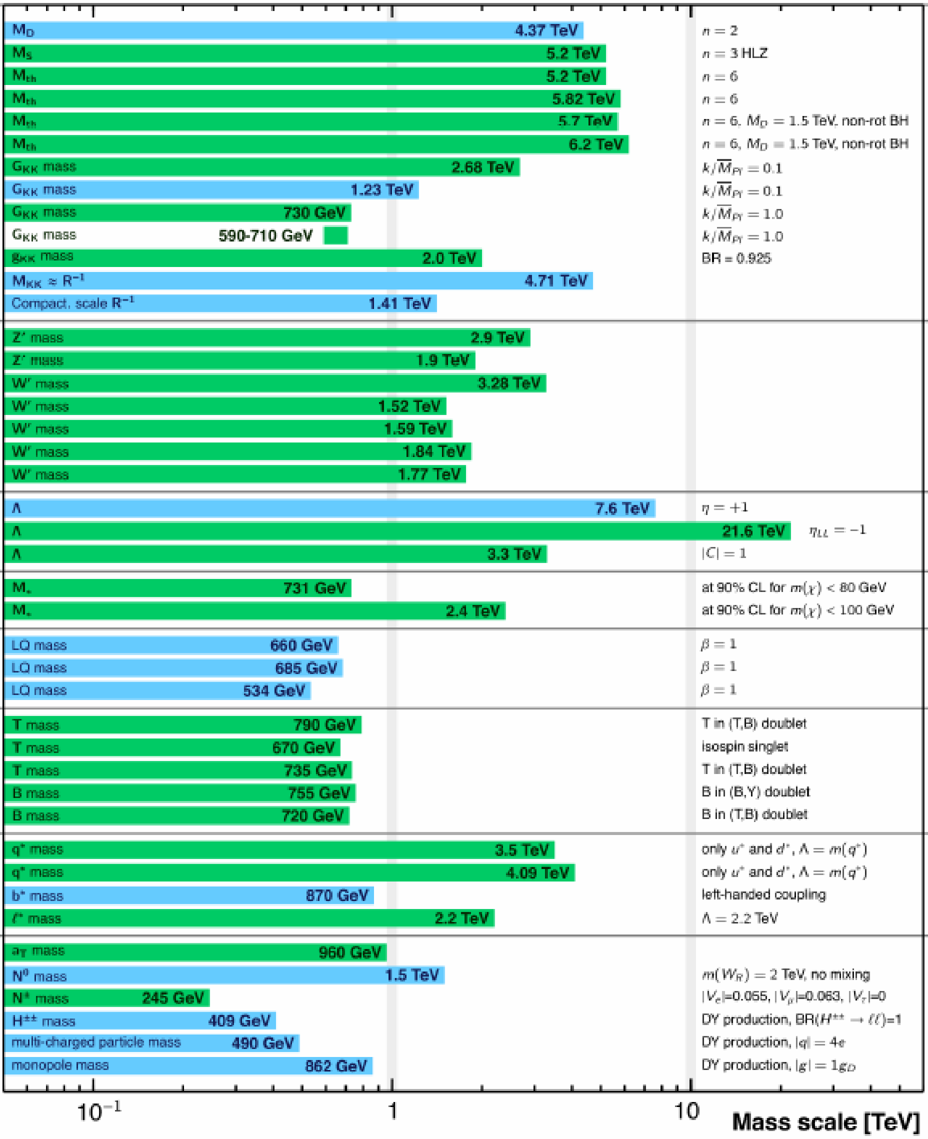
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (1.0 - 20.3) fb^{-1} $\sqrt{s}$ = 7, 8 TeV



	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	🟦 M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	2e, μ	–	–	20.3	🟩 M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH → ℓq	1 e, μ	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	🟩 M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	🟩 M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	🟩 M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	2 e, μ	–	Yes	4.7	🟦 G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	2 e, μ	2 j / 1 J	–	20.3	🟩 G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV 🟩	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	14.3	🟩 g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	2 e, μ	–	–	5.0	🟦 $M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	2 γ	–	Yes	4.8	🟦 Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	🟩 Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	🟩 Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	🟩 W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	3 e, μ	–	Yes	20.3	🟩 W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	🟩 W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	14.3	🟩 W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	🟦 Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	🟩 Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 Λ 3.3 TeV	$\|C\| = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	0 e, μ	1-2 j	Yes	10.5	🟩 M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	🟩 M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	🟦 LQ mass 660 GeV	$\beta = 1$	1112.4826
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	🟦 LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	🟦 LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 4 j	Yes	14.3	🟩 T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	14.3	🟩 T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	🟩 T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	🟩 q* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	🟩 q* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	🟦 b* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	🟩 ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	🟩 a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	2 e, μ	2 j	–	2.1	🟦 N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	2 e, μ	–	–	5.8	🟩 $N^\pm$ mass 245 GeV	$\|V_e\|$=0.055, $\|V_\mu\|$=0.063, $\|V_\tau\|$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	4.7	🟦 $H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	🟦 multi-charged particle mass 490 GeV	DY production, $\|q\| = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	🟦 monopole mass 862 GeV	DY production, $\|g\| = 1g_D$	1207.6411

🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

Short summary

So far no hints of new physics beyond the SM have been found at the LHC.

The SUSY searches allow to probe the gluino mass up to around 1.3 TeV while the squark masses are probed up to roughly 700 GeV.

The exotica program has not shown any excess and limits are set on the mass scale for a lot of scenarios.

Both SUSY and Exotica searchers will benefit from the higher center-of-mass energy and the increased luminosity in the next years and afterwards using the HL-LHC program

Sensitivity to High Mass Scales

High energy experiments

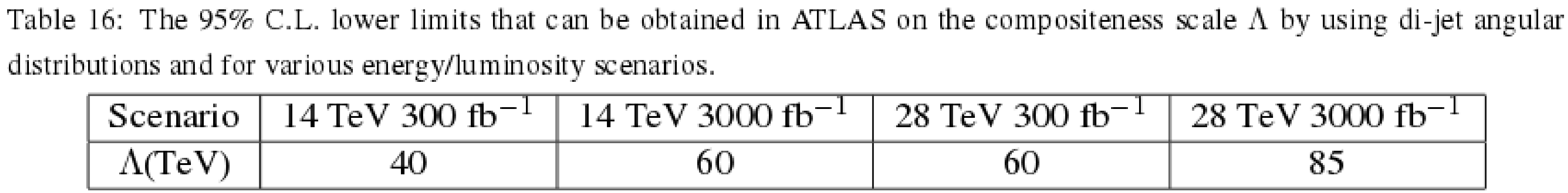


Table 16: The 95% C.L. lower limits that can be obtained in ATLAS on the compositeness scale Λ by using di-jet angular distributions and for various energy/luminosity scenarios.

Scenario	14 TeV 300 fb^{-1}	14 TeV 3000 fb^{-1}	28 TeV 300 fb^{-1}	28 TeV 3000 fb^{-1}
Λ(TeV)	40	60	60	85

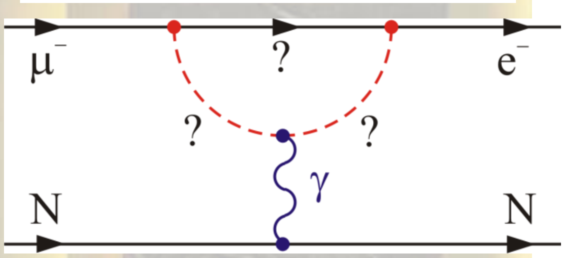
Of course, the high-energy frontier is not the only option to look for BSM physics. Rather than manifesting itself through new particles as external states, BSM can modify processes with only SM external particles through virtual effects.

BSM particles can act in a similar way and modify couplings and cross sections of SM particles. The size of these deviations from the SM depends crucially on the mass scale of the BSM particles and their coupling to SM particles.

Precision muon experiments : Sensitivity to High Mass Scales

$$\mathrm{L_{CLFV}} = \frac{m_\mu}{\boxed{(\kappa+1)}\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \boxed{\frac{\kappa}{(1+\kappa)}}\Lambda^2\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

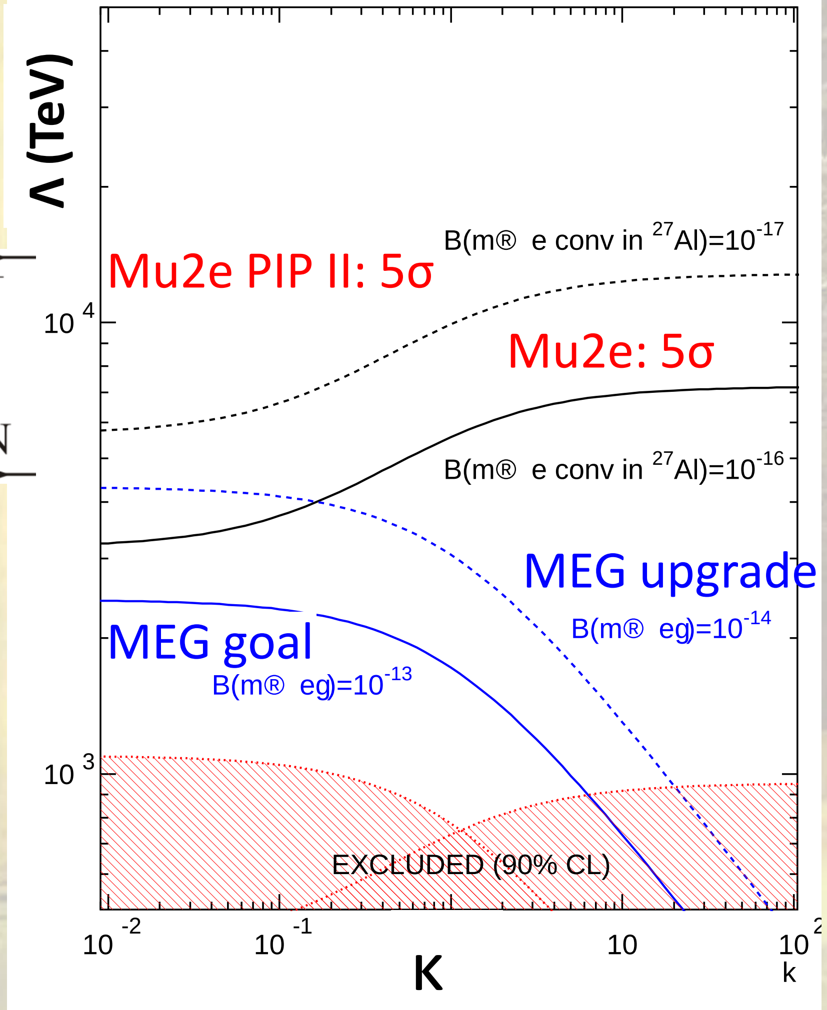
Loops dominate for κ << 1



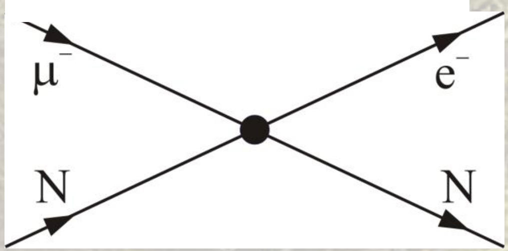
μ→eγ

μN→eN

μ→eee



Contact terms dominate for κ >> 1



~~μ→eγ~~

μN→eN

μ→eee

Mu2e, COMET

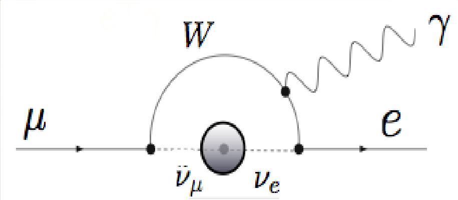
Search for neutrinoless conversion of a muon into an electron in the field of a nucleus

$$\boxed{\mu^- N \rightarrow e^- N}$$

Charged Lepton Flavor Violation

Mu2e : SM prediction and New Physics

The BR of CLFV processes in the Standard Model



$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U_{\mu i}^{*}U_{ei}\frac{\Delta m_{1i}^{2}}{M_W^2}\right|^2 < 10^{-54}$$

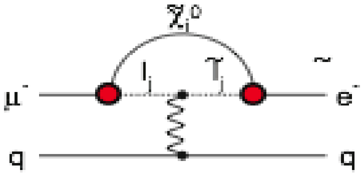
Mu2e sensitivity is $6*10^{-17}$

NP

Sensitive to mass scales up to O(10,000 TeV)

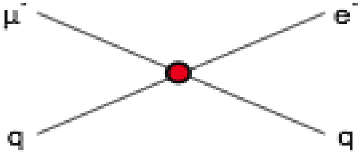
Supersymmetry

rate ~ 10^{-15}



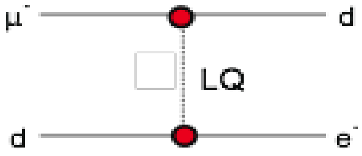
Compositeness

Λ_c ~ 3000 TeV



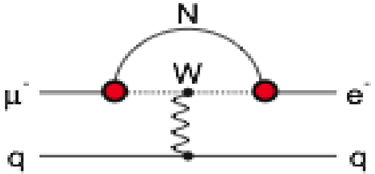
Leptoquark

M_{LQ} = 3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



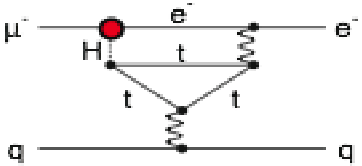
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ $8\text{x}10^{-13}$



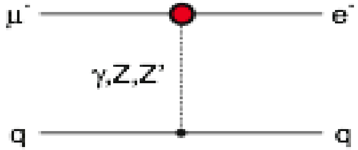
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4}g(H_{\mu\mu})$



Heavy Z' Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c^2



$$\mathrm{L_{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Flavour Physics of Leptons and Dipole Moments, Eur.Phys.J.C57:13-182,2008

Search for new physics in Mu2e experiment

JINR team

Artikov A.M., Atanov N.V., Atanova O.S., Azaryan N.S., Baranov V.Yu., Batusov Yu.A., Budagov J.A., Chokheli D., Davydov Yu.I., Demin D.L., FlyaginV.B., Glagolev V.V., Guskov D.S., Kazakov D.I., Kharzheev Yu.N., Kozlov G.A., Kolomoets V.I., Kolomoets S.M., Korenkov V.V., Kulchitsky Y.A., Kuchinsky N.A., Lyablin M.V., Romanov V.M., Sazonova A.V., Shalyugin A.N., Simonenko A.V., Studenov S.N., Suhanova A.K., Suslov I.A., Tarasov O.V., Tereschenko V.V., Tereschenko S.V., Titkova I.V., Usubov Z.U., Uzhinsky V.V.,

Flavor Violation

- We’ve known for a long time that quarks mix → (Quark) Flavor Violation
  - Mixing strengths parameterized by CKM matrix
- In last 15 years we’ve come to know that neutrinos mix → Lepton Flavor Violation (LFV)
  - Mixing strengths parameterized by PMNS matrix
- Why not charged leptons?
  - Charged Lepton Flavor Violation (CLFV)

The great-grandparents of the Mu2e (MELC, 1992; MECO, 1997) are INR scientists V.M. Lobashev and R.M. Djilkibaev

Владимир Михайлович Лобашёв
(29.07.1934—03.08.2011)

Mu2e Muon-to Electron Conversion

Mu2e will measure the ratio of the coherent neutrinoless muon-to-electron conversion rate to muon capture rate

muon converts to electron in the field of a nucleus

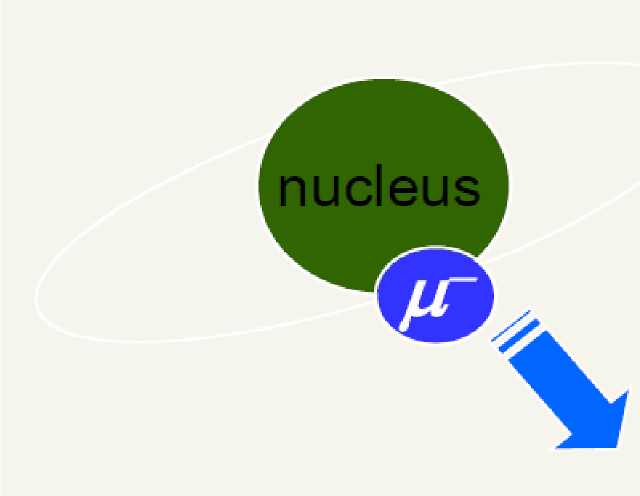
$$\mu^- N \rightarrow e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

- Charged Lepton Flavor Violation (CLFV)
  - manifest Beyond-Standard-Model physics
  - SES of 2.3×10^{-17}, 0.4 evt bkg; 6×10^{-17} at 90% CL

Requires about 10^{18} stopped muons; about 10^{20} protons on target

The Measurement Method



- Stop negative muons in an aluminum target
- The stopped muons form muonic atoms
  - 207x smaller radius than inner e⁻ in Al–>
  - well inside electron orbits →

    muon forms a hydrogen-like atom, unaffected by e's
  - hydrogenic 1S : Bohr radius ~20 fm, BE~500 keV
  - Nuclear radius ~ 4 fm →

    muon and nuclear wavefunctions overlap significantly
- Three main things can happen (numbers for case of Al):
  - Muon decays (40%): $\mu^- \to e^- + \overline{\nu}_e + \nu_\mu$
  - Muon captures on the nucleus (60%): $\mu^- + {}^{27}_{13}Al \to X + \nu_\mu (capture)$

  (capture is roughly sum of reactions with protons in nucleus: $\mu^- + p \to \nu_\mu + n$)
  - Muon to electron conversion: $\mu^- + {}^{27}_{13}Al \to {}^{27}_{13}Al + e^-$
- Muon lifetime in 1S orbit of aluminum ~864 ns

  (40% decay, 60% nuclear capture), compared to 2.2 μsec in vacuum
- Look for 105 MeV conversion electron signal $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$ E_e=104.96 MeV

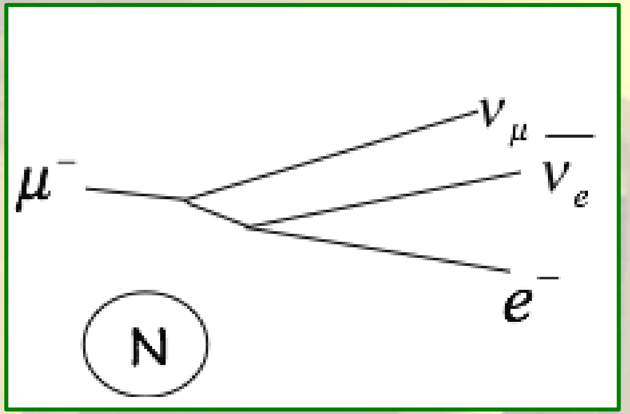
Backgrounds

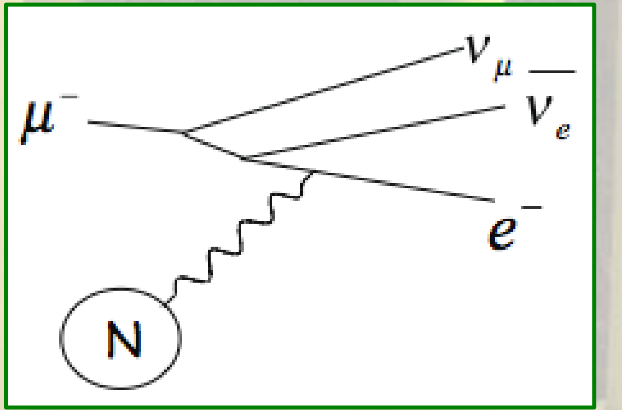
- Stopped Muon induced
  - Muon decay in orbit (DIO)
- Out of time protons or long transit-time secondaries
  - Radiative pion capture; Muon decay in flight
  - Pion decay in flight; Beam electrons
  - Anti-protons
- Secondaries from cosmic rays

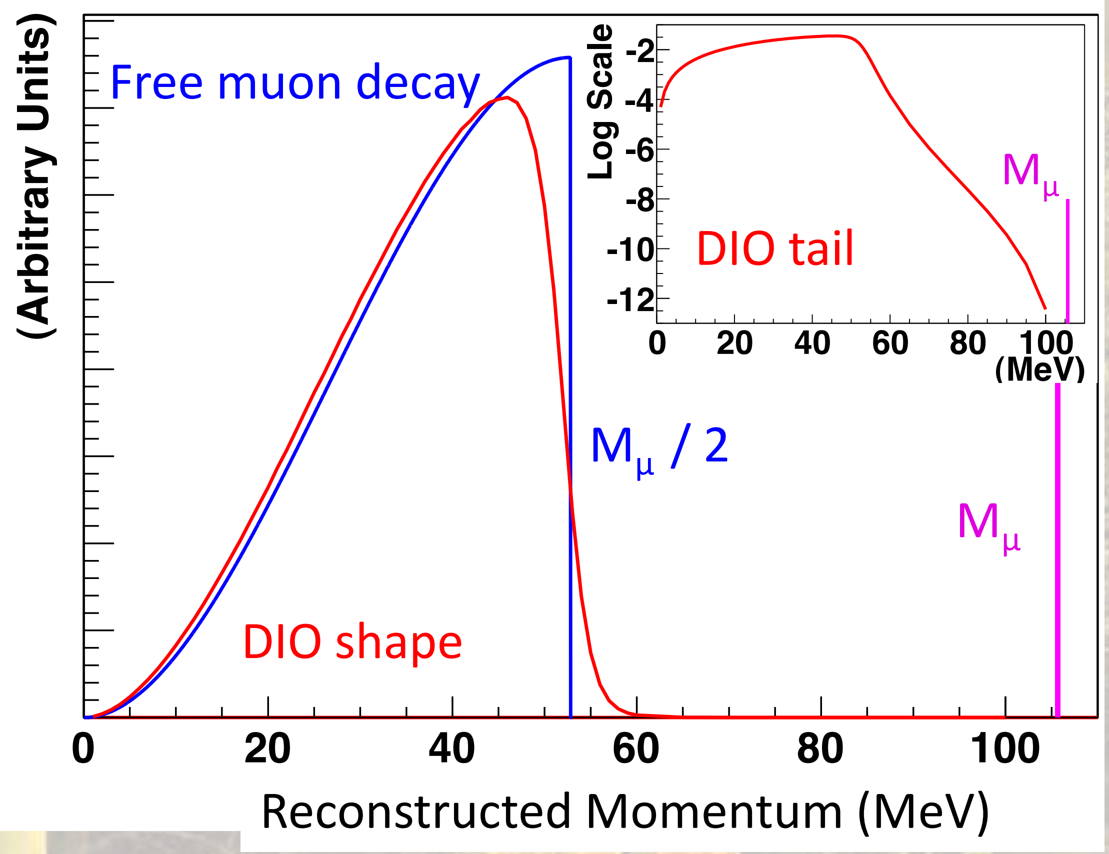
- Mitigation:
  - Excellent momentum resolution
  - Excellent extinction plus delayed measurement window
  - Thin window at center of TS absorbs anti-protons
  - Shielding and veto

Decay–in-Orbit: Dominant Background

DIO: Decay in orbit

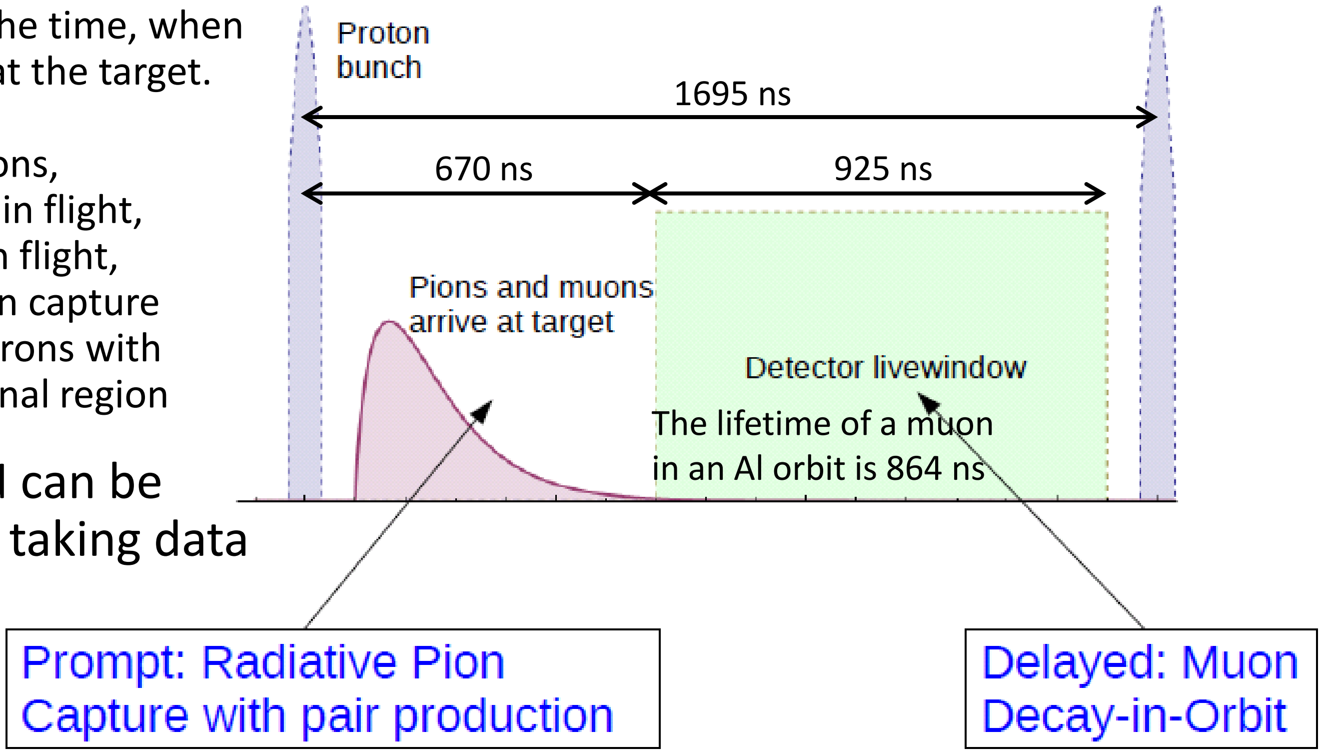






Prompt Background Suppression

- Prompt background
  - Happens around the time, when the beam arrives at the target.
  - Sources
    - beam electrons,
    - muon decay in flight,
    - pion decay in flight,
    - radiative pion capture
  - May creaste electrons with energies in the signal region



- Prompt background can be suppressed by not taking data during the first 670 ns after the peak of the proton pulse.

- However, this prompt background cannot be eliminated entirely, since some of the protons arrive “out of time”.
  - A ratio of 10^{-10} is required for the beam between pulses vs. the beam contained in a pulse.

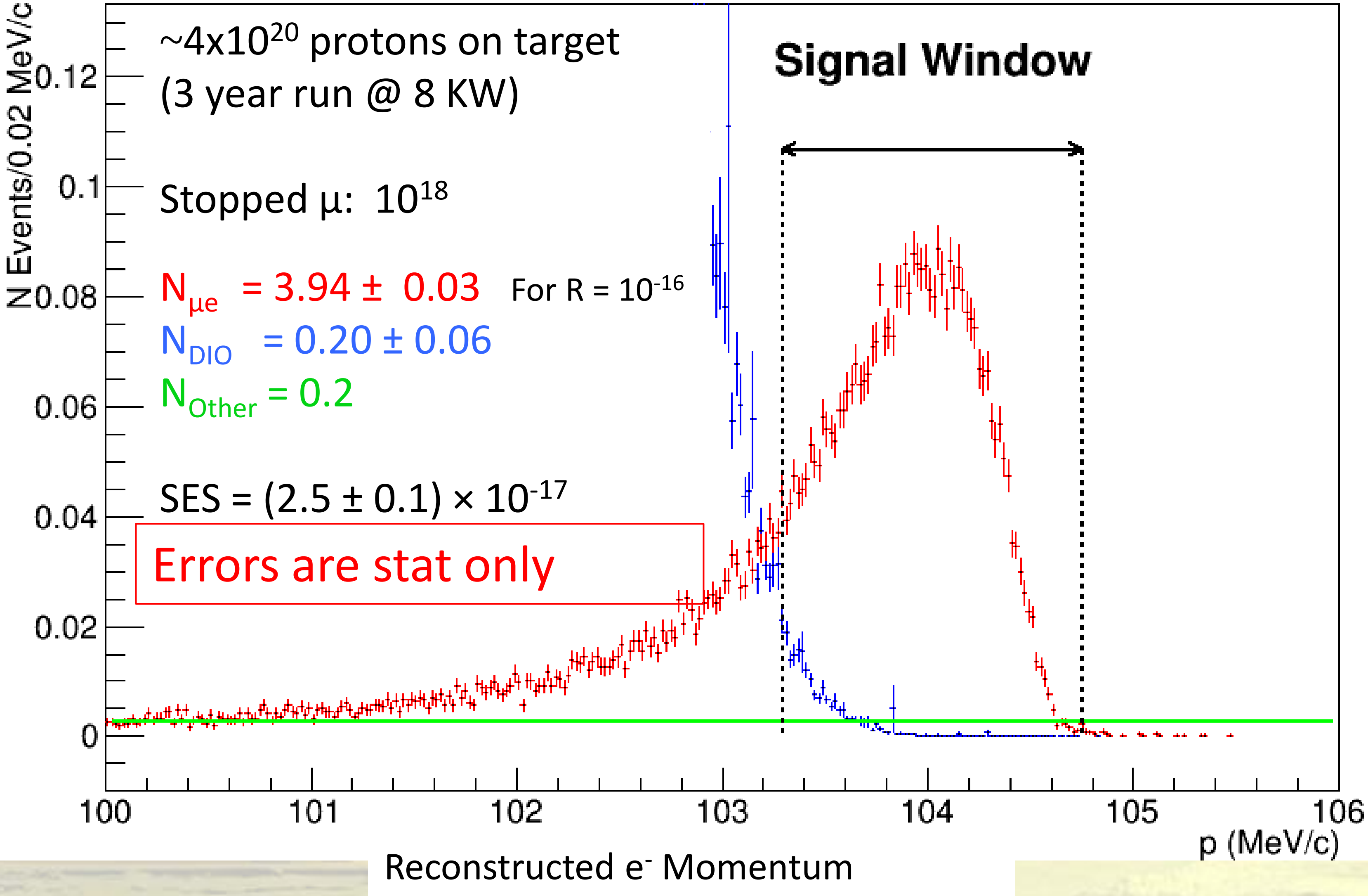
Backgrounds for 3 Year Run

Source	Events	Comment
μ decay in orbit (DIO)	0.20 ± 0.06	
Anti-proton capture	0.10 ± 0.06	
Radiative π^- capture*	0.04 ± 0.02	From protons during detection time
Beam electrons*	0.001 ± 0.001	
μ decay in flight*	0.010 ± 0.005	With e^- scatter in target
Cosmic ray induced	0.050 ± 0.013	Assumes 10^{-4} veto inefficiency
Total	**0.4 ± 0.1**	

All values preliminary; some are stat error only.

- *** scales with extinction: values in table assume extinction = 10^{-10}**

Signal Sensitivity for 3 Year Run



~4x10^{20} protons on target
(3 year run @ 8 KW)

Stopped μ: 10^{18}

$N_{\mu e}$ = 3.94 ± 0.03 For R = 10^{-16}

N_{DIO} = 0.20 ± 0.06

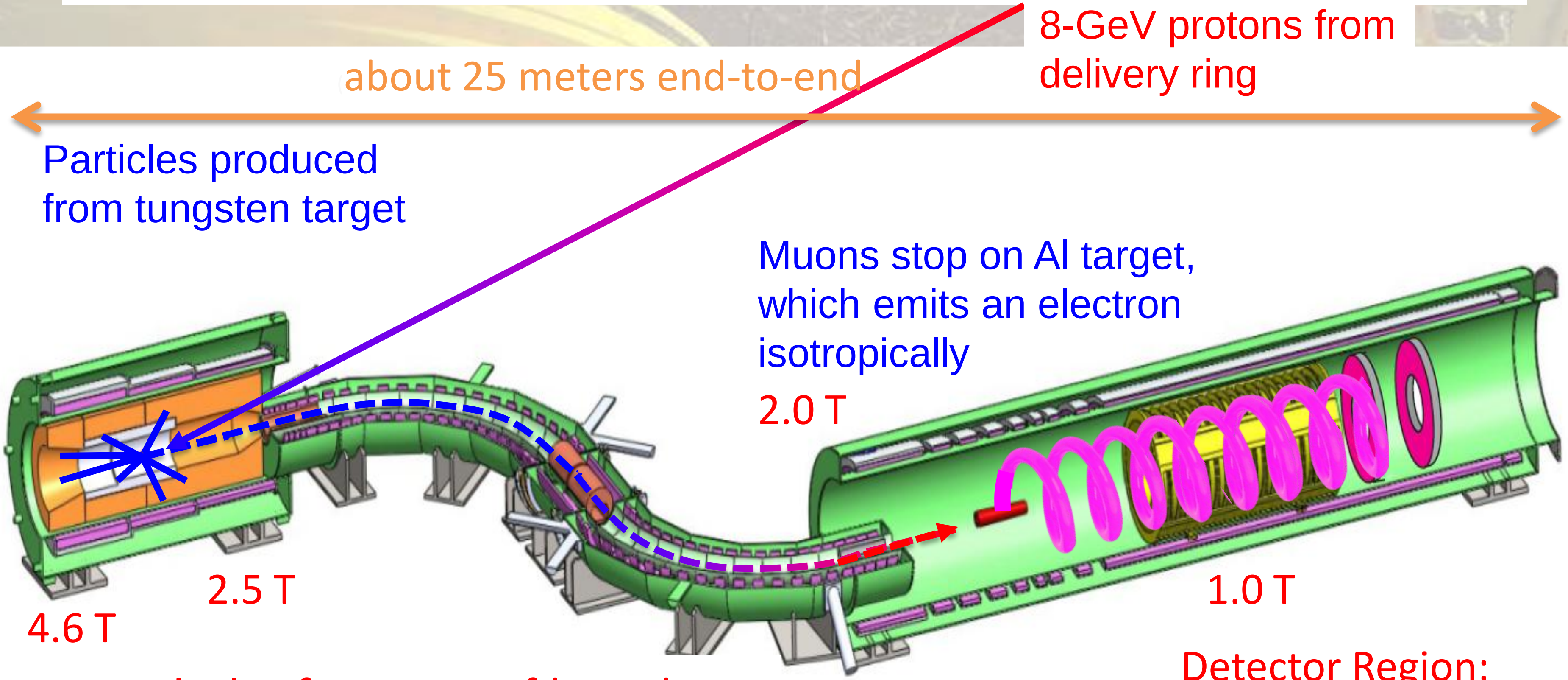
N_{Other} = 0.2

SES = (2.5 ± 0.1) × 10^{-17}

Errors are stat only

Reconstructed e$^-$ Momentum

Baseline Mu2e Apparatus



8-GeV protons from delivery ring

Particles produced from tungsten target

Muons stop on Al target, which emits an electron isotropically

Graded B for most of length

Detector Region: Uniform Field 1T

S-shaped solenoid:

- transports particles to detector area, and
- allows remaining pions to decay to muons
- collimator selects negatively-charged particles

Tracker/calorimeter detect electron signature

The Mu2e Tracker

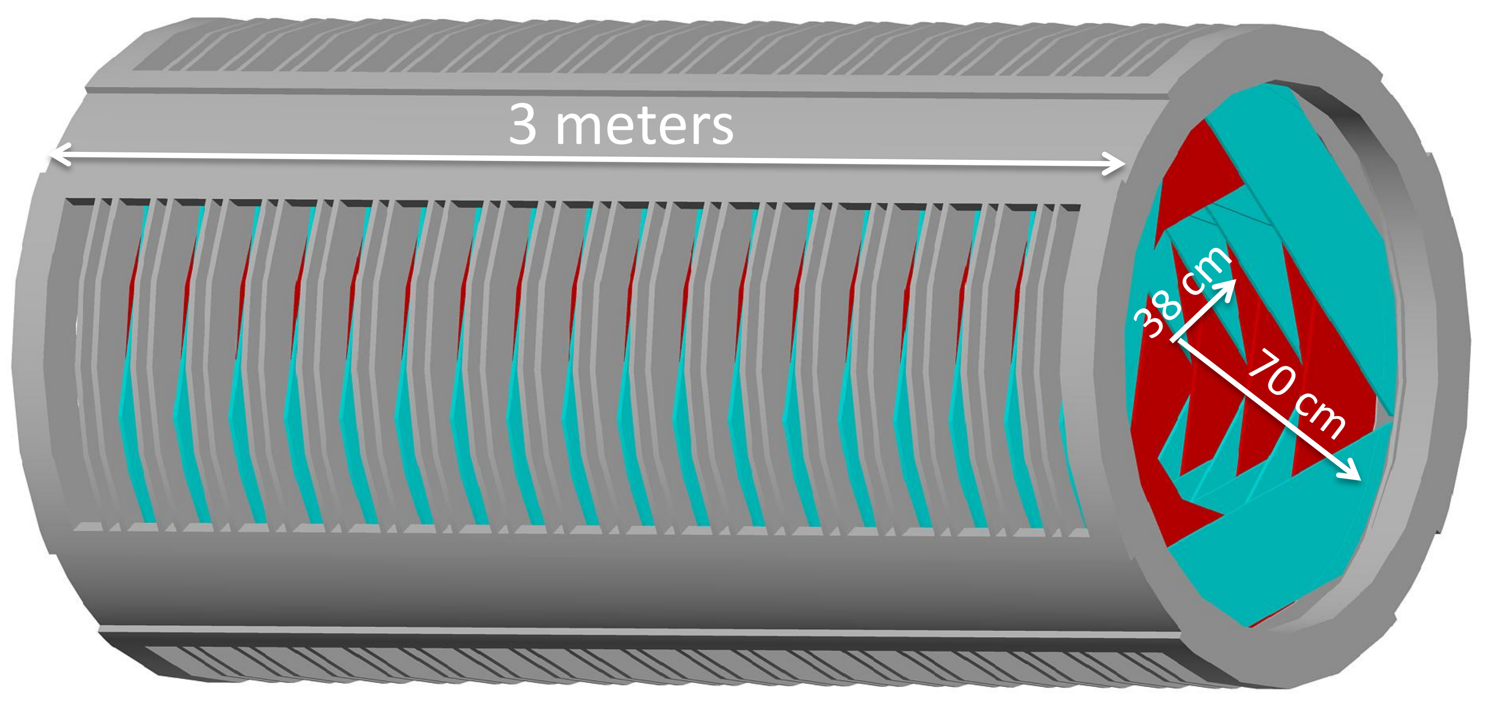
- Will employ straw technology
  - Low mass
  - Can reliably operate in vacuum
  - Robust against single-wire failures

5 mm diameter straw

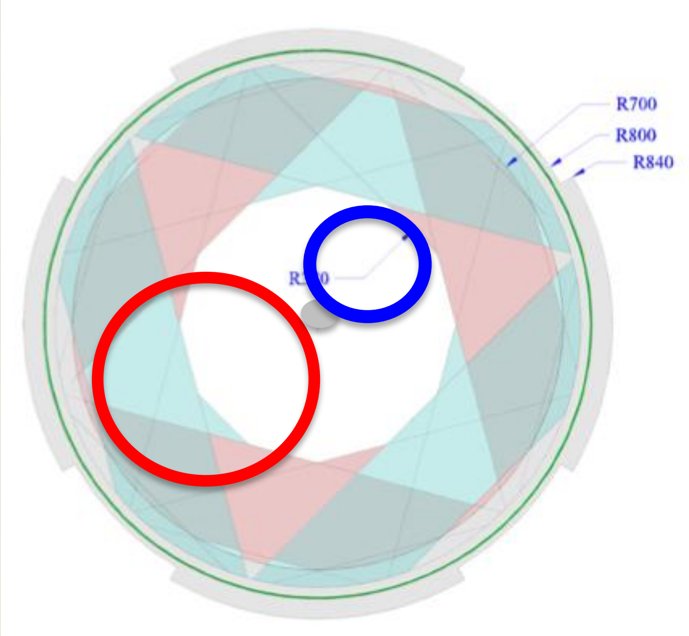
- **Spiral wound**
- **Walls: 12 μm Mylar + 3 μm epoxy + 200 Å Au + 500 Å Al**
- **25 μm Au-plated W sense wire**
- **33 – 117 cm in length**
- **80/20 Ar/CO2 with HV < 1500 V**

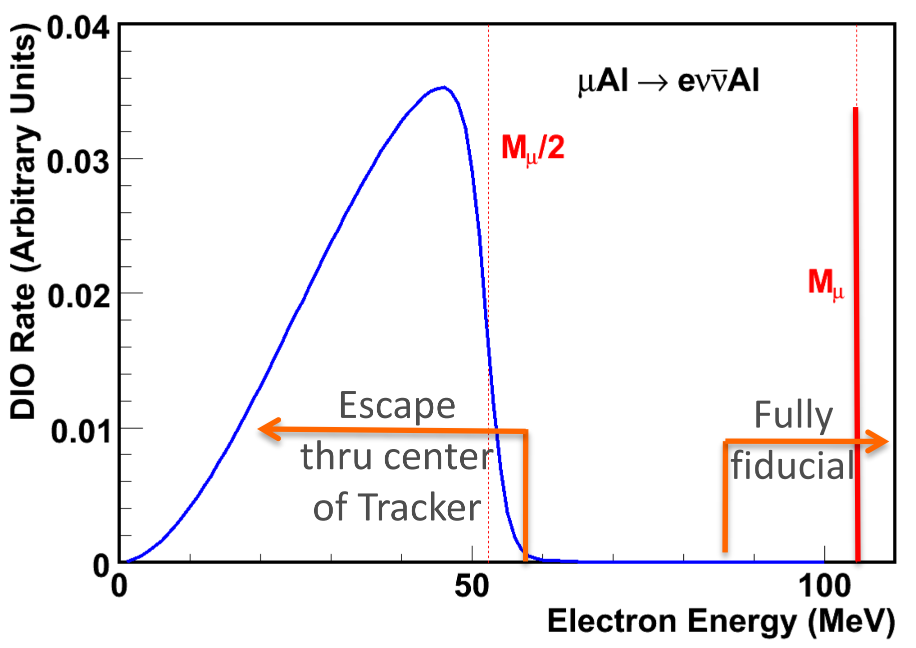
The Mu2e Tracker

- 18-20 “stations” with straws transverse to beam
- Naturally moves readout and support to large radii, out of active volume



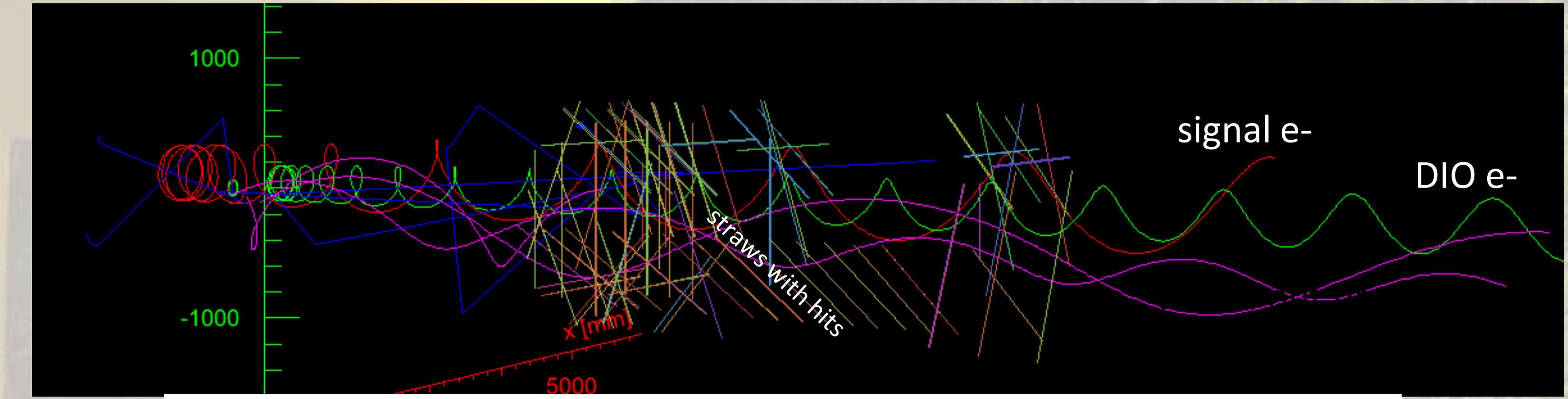
The Mu2e Tracker





- Inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum

Mu2e Pattern Recognition



(particles with hits within +/-50 ns of signal electron t_{mean})

- We use timing information to look in +/- 50 ns windows – significant reduction in occupancy and significant simplification for Patt. Rec.

Mu2e Calorimeter

The Calorimeter consists of two disks with 1650 BaF_2 hexagonal crystals
(30 mm x 200 mm):

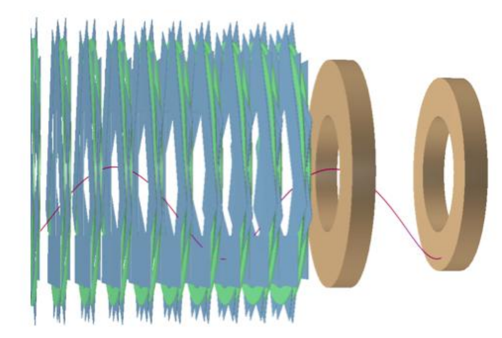
→ R_{inner} = 351 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)

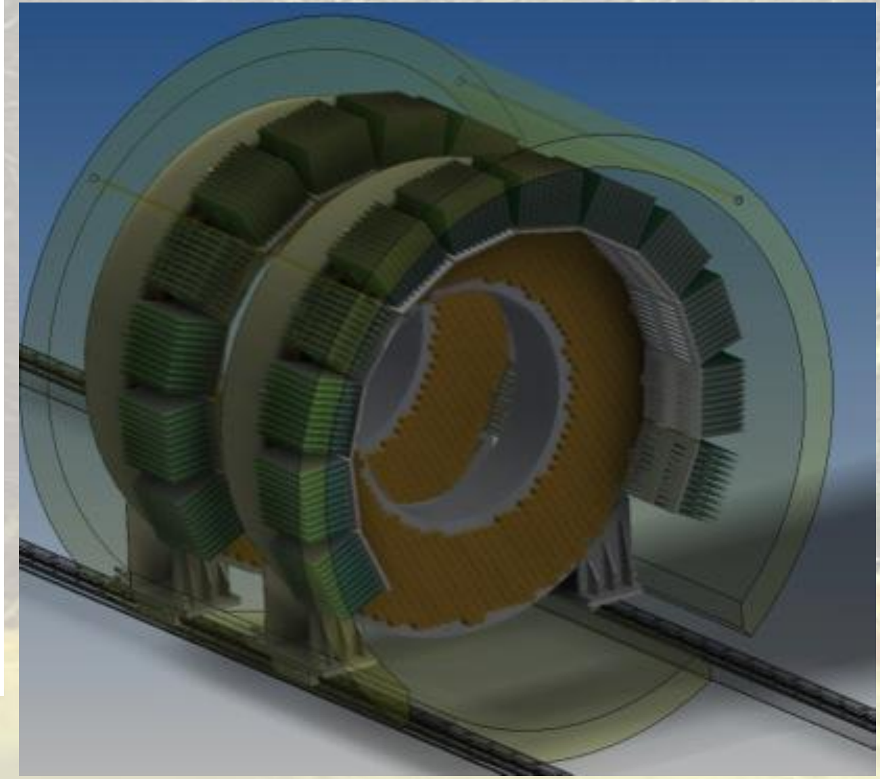
→ The distance between disks is optimized at ½ wavelength (70 cm)

→ Each crystal is readout by two large area APD's (9x9 mm^2) (3300 total)

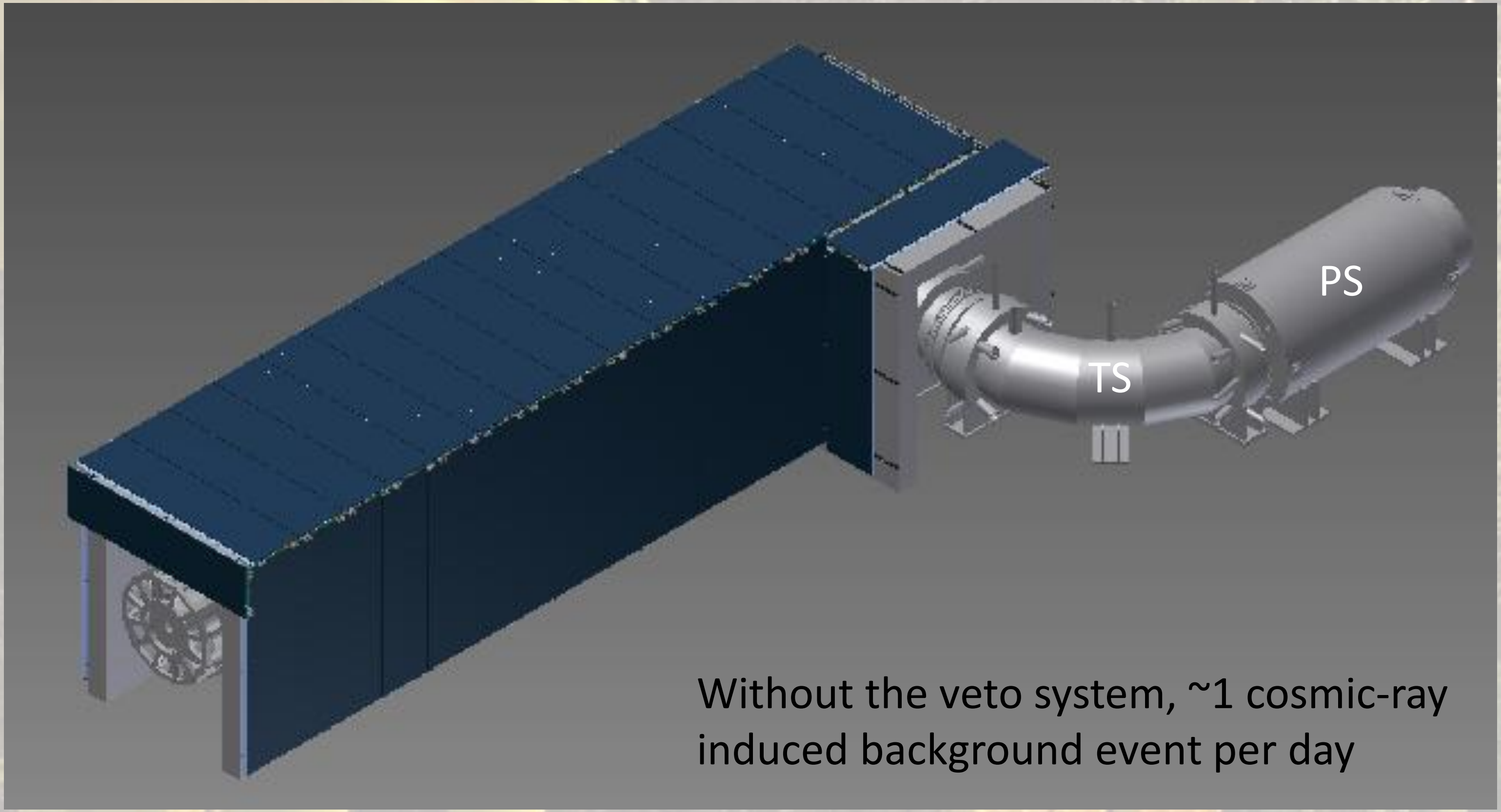
→ Analog FEE and digital electronics are located in near-by electronics crates

→ Radioactive source and laser systems provide absolute calibration as well as fast and reliable monitoring capability





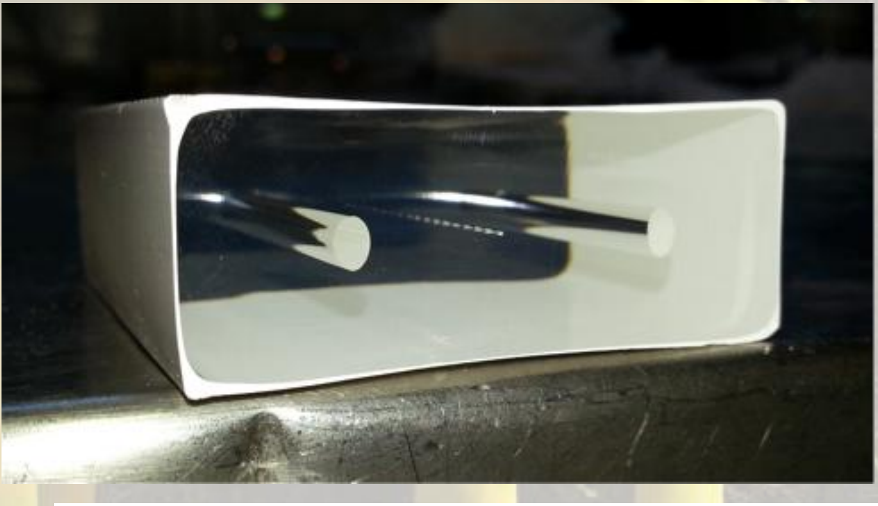
Mu2e Cosmic-Ray Veto

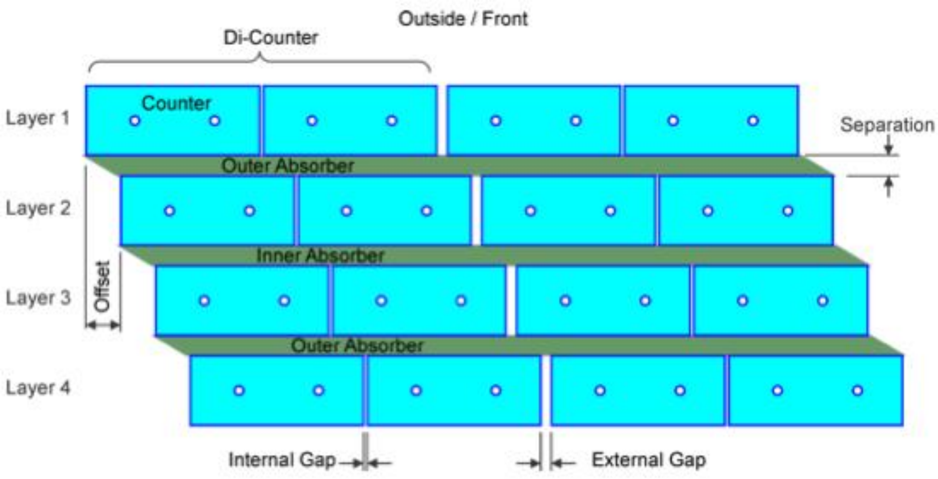


Without the veto system, ~1 cosmic-ray induced background event per day

- Veto system covers entire DS and half TS

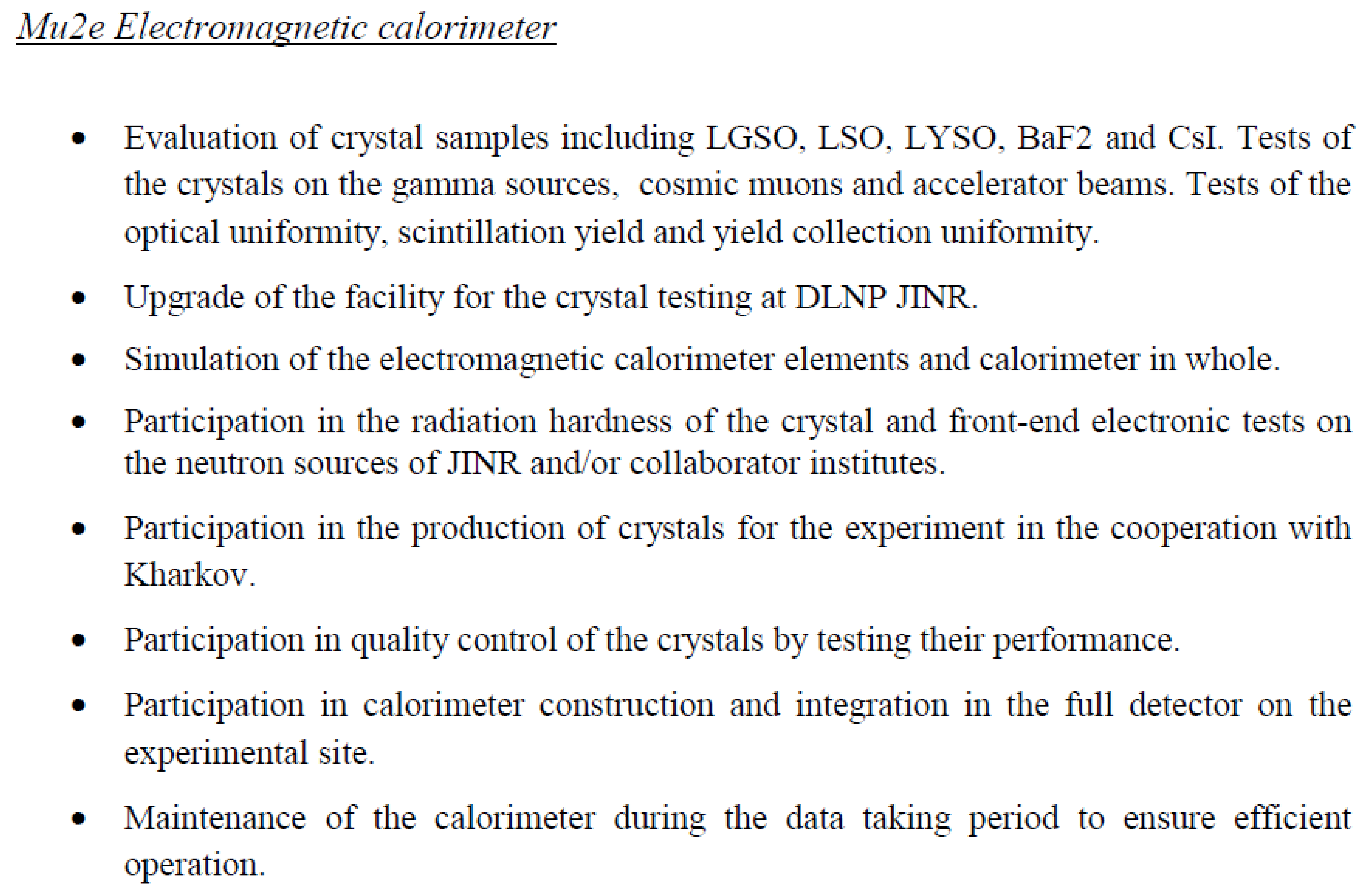
Mu2e Cosmic-Ray Veto





- Will use 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved ε > 99.4% (per layer) in test beam

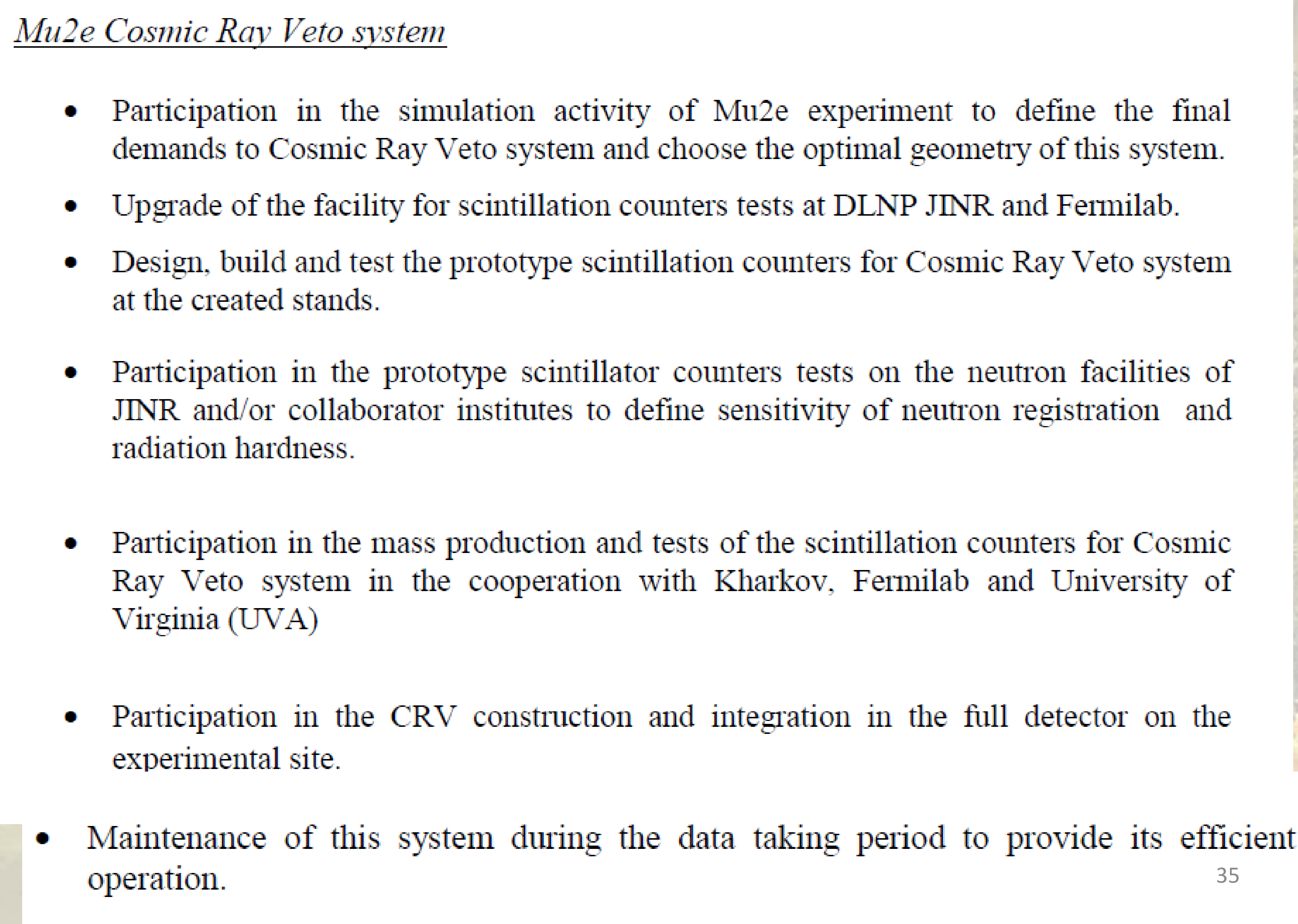
JINR CONTRIBUTION



Mu2e Electromagnetic calorimeter

- Evaluation of crystal samples including LGSO, LSO, LYSO, BaF2 and CsI. Tests of the crystals on the gamma sources, cosmic muons and accelerator beams. Tests of the optical uniformity, scintillation yield and yield collection uniformity.
- Upgrade of the facility for the crystal testing at DLNP JINR.
- Simulation of the electromagnetic calorimeter elements and calorimeter in whole.
- Participation in the radiation hardness of the crystal and front-end electronic tests on the neutron sources of JINR and/or collaborator institutes.
- Participation in the production of crystals for the experiment in the cooperation with Kharkov.
- Participation in quality control of the crystals by testing their performance.
- Participation in calorimeter construction and integration in the full detector on the experimental site.
- Maintenance of the calorimeter during the data taking period to ensure efficient operation.

JINR CONTRIBUTION



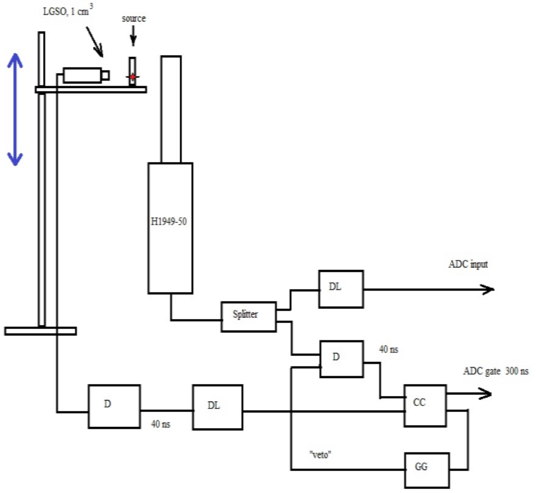
Mu2e Cosmic Ray Veto system

- Participation in the simulation activity of Mu2e experiment to define the final demands to Cosmic Ray Veto system and choose the optimal geometry of this system.
- Upgrade of the facility for scintillation counters tests at DLNP JINR and Fermilab.
- Design, build and test the prototype scintillation counters for Cosmic Ray Veto system at the created stands.
- Participation in the prototype scintillator counters tests on the neutron facilities of JINR and/or collaborator institutes to define sensitivity of neutron registration and radiation hardness.
- Participation in the mass production and tests of the scintillation counters for Cosmic Ray Veto system in the cooperation with Kharkov, Fermilab and University of Virginia (UVA)
- Participation in the CRV construction and integration in the full detector on the experimental site.
- Maintenance of this system during the data taking period to provide its efficient operation.

DLNP scintillators test laboratory

JINR Mu2e: Comparison of 3 crystals - Setup and methods

Chairman of the Egyptian Atomic Energy Authority Professor Atef A. Abdel-Fattah and Vice-Chairman of the Authority Professor Samy Sh. Soliman attend our Lab.



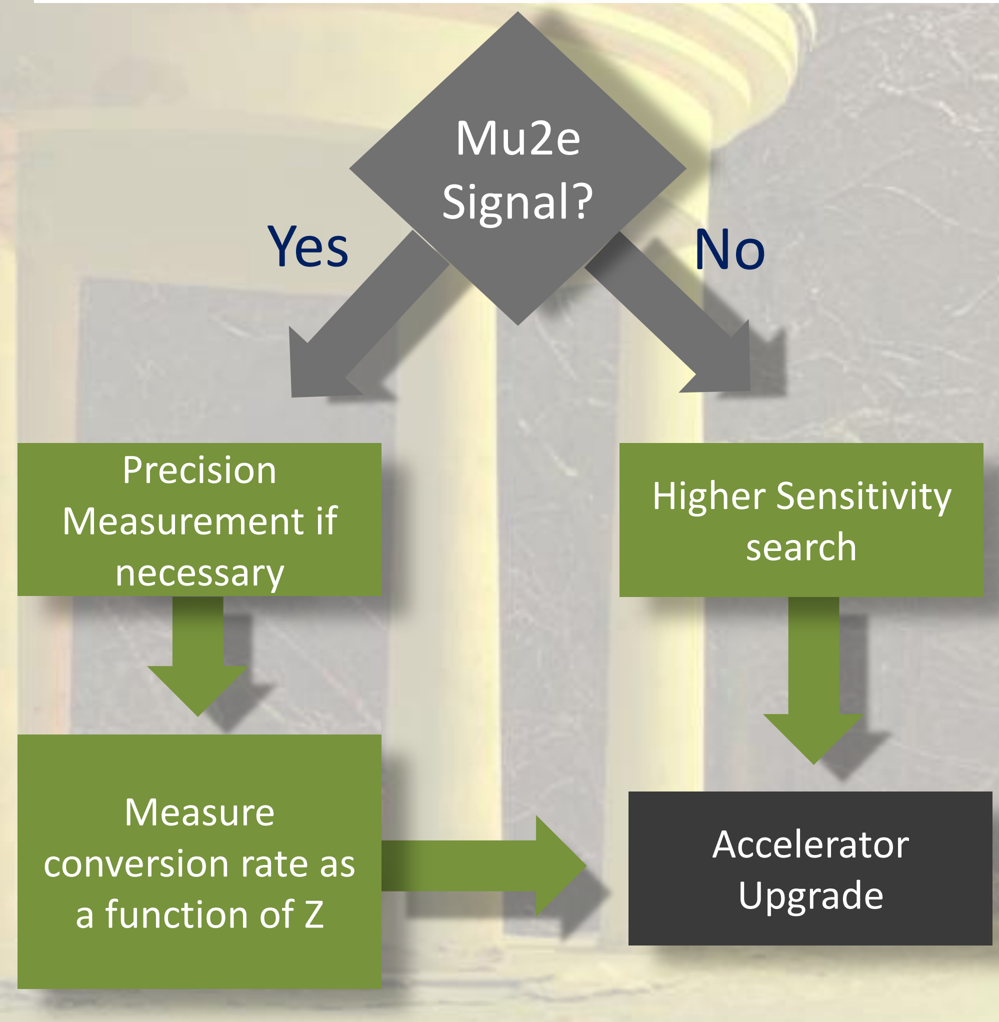
LRU measurements:

- **^{22}Na source was used for the measurements**
- Source and trigger PMT moved along the crystals

Energy resolution measurements

- Sources were placed over the crystals irradiating their far ends
- Data were taken in self triggering mode and in coincidence with Hamamatsu 5783 PMT

What next?



Mu2e Signal?

Yes

No

Precision Measurement if necessary

Higher Sensitivity search

Measure conversion rate as a function of Z

Accelerator Upgrade

- A next-generation Mu2e experiment makes sense in all scenarios
  - – Push sensitivity or
  - – Study underlying new physics
  - – Will need more protons → upgrade accelerator

Muon g-2

Muon magnetic dipole momentum precise measurement

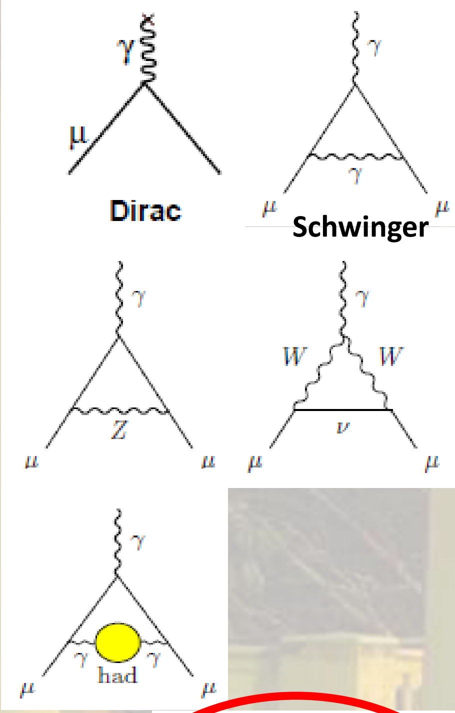
$$\vec{\mu}_\mu = \frac{gQe}{2m_\mu}\vec{S}$$

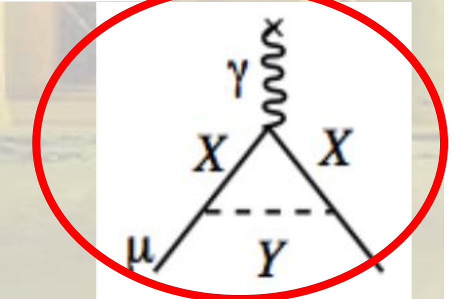
$$g = 2(1 + a)$$

muon g-2: SM prediction and New Physics

g-2: $\vec{\mu} = g\frac{e}{2m}\vec{s}$ Dirac: $g = 2$ Schwinger (1948): $a \equiv (g-2)/2 = \alpha/(2\pi)$

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





Several groups have produced hadronic compilations over the years.
Here: Hagiwara+Liao+Martin+Nomura+T

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	-9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

(Numbers taken from HLMNT11, arXiv:1105.3149)

Mu2e and Muon g-2 work together

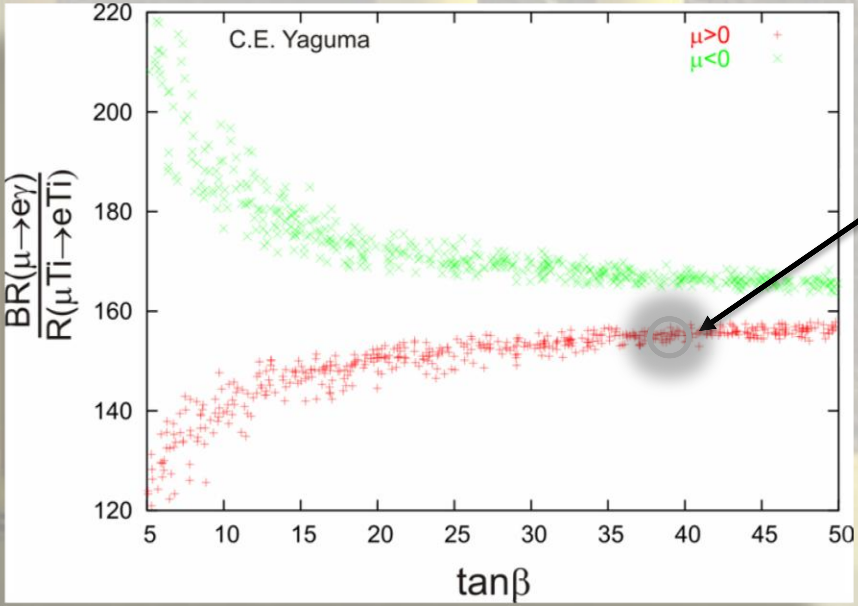
Example:

SUSY contributes to a_μ= (g-2)/2

- From g-2 we know tan β
- From g-2 we know also know μ>0
- From Mu2e we measure R(μ N → e N) and take the ratio to the MEG result

$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\text{GeV}}{M_{SUSY}}\right)^2 \tan\beta \, \text{sign}(\mu)$$

We use this match to prediction as a way to disentangle, or validate, or interpret manifestations of SUSY



MSSM/msugra/seesaw

g-2 selects which curve we should be on, and gives us the value of tan β

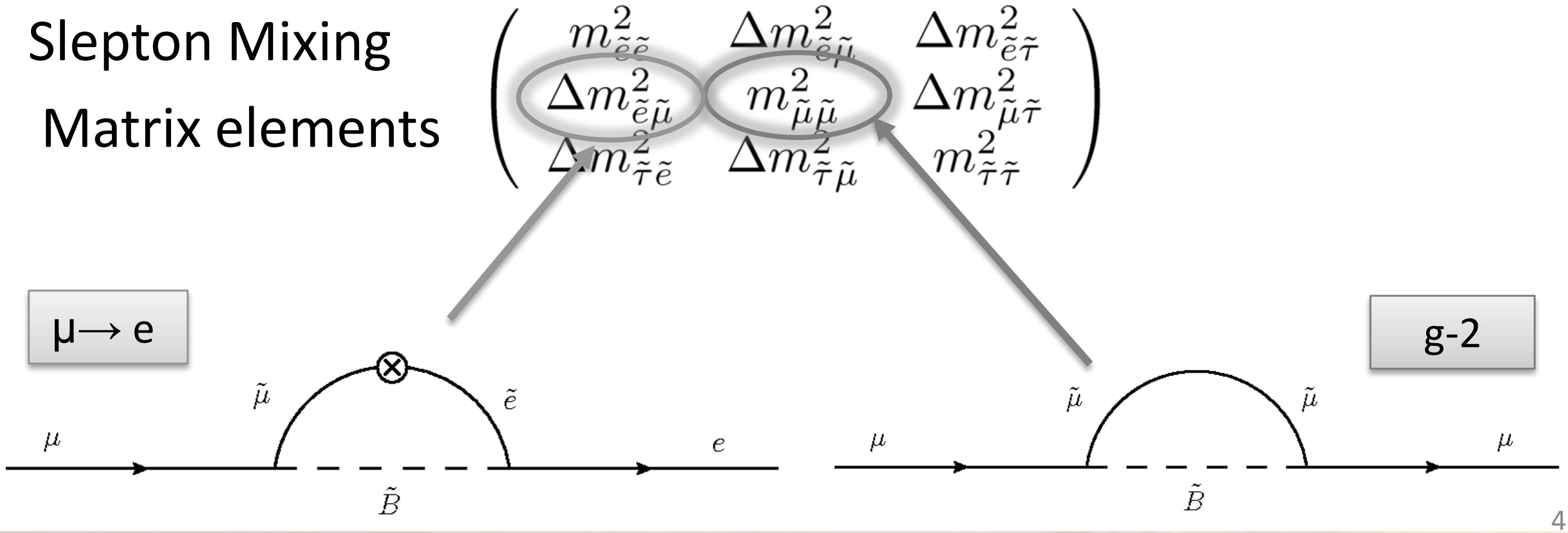
tan β - the ratio of the vacuum expectation values of the two Higgs doublets

Sign(μ) - the sign of the higgsino mass parameter

Mu2e and Muon g-2 work together

Gives us access to Slepton Mixing Matrix elements

Slepton Mixing Matrix



$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{e}\tilde{\mu}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

μ→ e

g-2

Muon g-2 Experiment Goal

$$\vec{\mu}_\mu = \frac{gQe}{2m_\mu}\vec{S}$$

Goal:

Measurement of the value of muon anomalous magnetic moment, a_μ, to an uncertainty of $\boxed{16}\times10^{-11}$ (0.14 ppm) where, $a_\mu = \frac{g_\mu - 2}{2}$

Present Situation:

$$a_\mu^{SM} = 116591834(49) \times 10^{-11}\ (0.42\ \text{ppm})$$

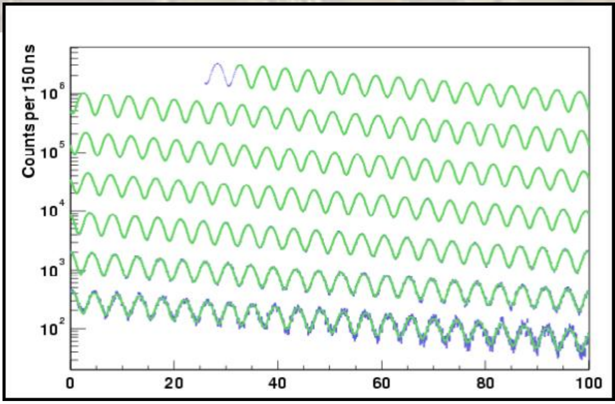
$$a_\mu^{exp} = 116592089(\boxed{63}) \times 10^{-11}\ (0.54\ \text{ppm})$$

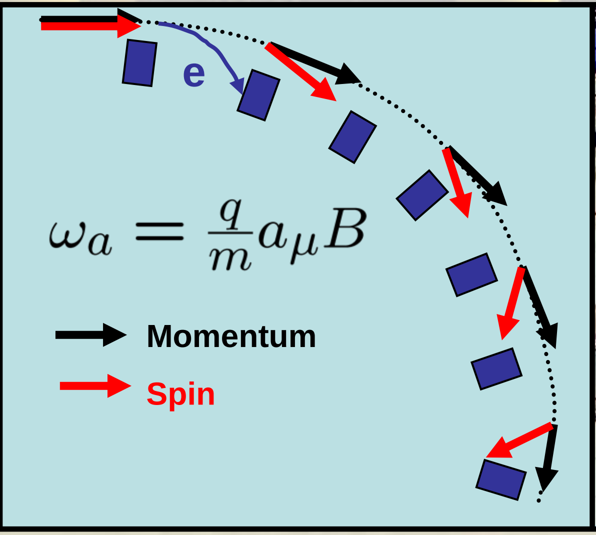
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} = (\boxed{255} \pm 80) \times 10^{-11}$$

Physics beyond the standard model

g-2 Experimental Technique

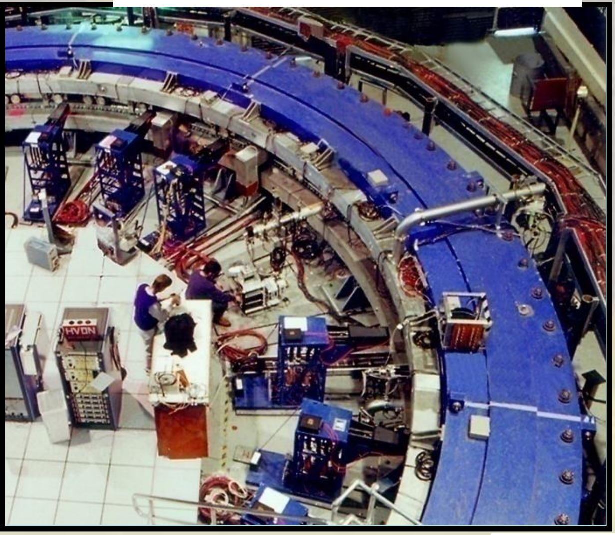
- Capture 3.094 GeV/c muons in a uniform magnetic field
- Measure the precession frequency of the muon spin
- The precession frequency, under special circumstances, is proportional to a_μ

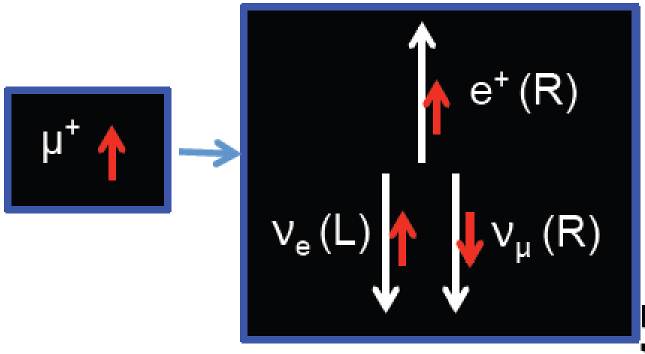




$$\omega_a = \frac{q}{m} a_\mu B$$

muon storage ring





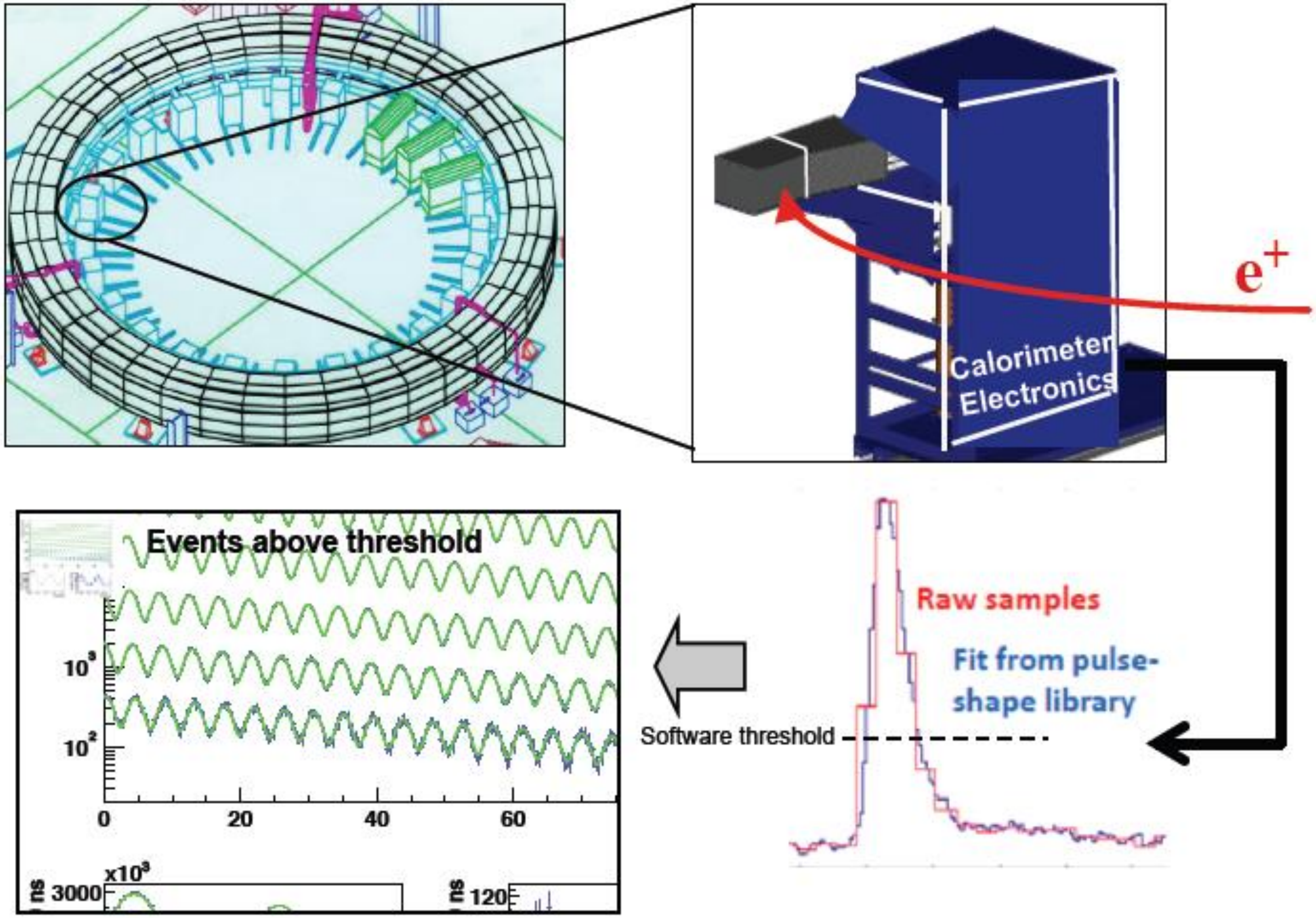
Highest energy positrons occur when muon spin and momentum are aligned (decay is boosted)

Positron direction follows muon spin

g-2 Experimental Technique

An “event” is an isolated positron above a threshold

24 calorimeter and tracker stations are located inside muon ring to detect positrons



How to achieve a fourfold improvement ?

New Experimental Goal: 63 → 16 x 10^{-11}

Statistics:	0.46 → 0.10 ppm
Systematics on Precession:	0.21 → 0.07 ppm
Systematics on Field:	0.17 → 0.07 ppm

21 x BNL

- **Need counts**
  - Note: E821 was already "rate limited"
    - Cleaner beam
    - Inject more often
    - Run longer
- **Reduce systematics**
  - Note: Many scale with counts; others were "good enough"
    - Modern detectors / electronics / DAQ critical
    - Improved field intrinsic uniformity
    - Better environment (building)
    - Improved injection

JINR CONTRIBUTION

JINR participation in G-2 DAQ:

* Support of MIDAS (Maximum Integrated Data Acquisition System)
* Online parallel data preprocessing and compression using GCPU (NVIDIA CUDA) technology
* Real time software emulation of the DAQ frontends
* Development of online analyzer software for express data analysis to produce physics histograms
* Real time visualization of the experiment: event display, raw data & physics histograms, slow control data
* Online automatic data quality control
* Integration of the online analysis with the MIDAS slow control & alarm systems
* Development of run sequencer software to control different modes of the experiment (calibration, tests, data taking etc)
* Customized experiment control web interface
* Miscellaneous database support for MIDAS ODB (Fast Online Database), logging of run parameters, slow control data archiving

Summary

Precise muon experiments :

- Improve sensitivity by a factor of 10^4
- Provide *discovery capability* over wide range of New Physics models
- Are complementary to LHC, heavy-flavor, and neutrino experiments

BRAZIL-JINR FORUM
June 18, 2015

DLNP Conference Hall

9.30 D.V. Naumov (DLNP JINR) “Baikal GVD and TAIGA – perspectives in neutrino and gamma astronomy”

10.00 D.S. Shkirmanov (BLTP JINR) “Quantum Field Theory of Neutrino Oscillations and Reactor AntiNeutrino Anomaly”

10.30 S.A. Kotov (DLNP JINR) “R&D of particle detectors”

11.00-11.20 Coffee-break

11.20 N.V.Anphimov (DLNP JINR) “R&D of ECAL and Photo-Detectors”

11.50 G.V. Mitsin (DLNP JINR) “Applied Research: Radiotherapy and associated diagnostics”

12.20 Yu. A. Usov (DLNP JINR) “Method to reach Ultra Low Temperatures and its use in Experimental Physics”

12.50-15.00 Lunch

15.00 Round Table: Discussion of possible collaborations between DLNP JINR and Brasil

18.00 Excursion to Phasotron and Medical Technical Complex for proton Therapy (DLNP JINR)

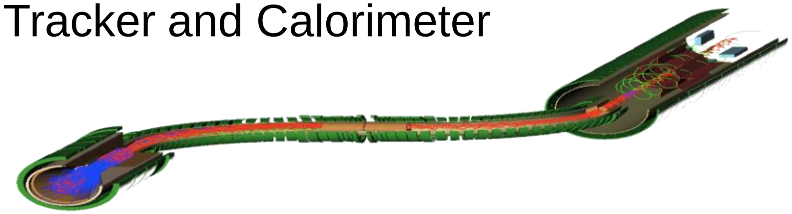
BACKUP

Mu2e / COMET comparison

- Mu2e employs Booster batches left unused by the Fermilab neutrino program
  - **Mu2e will run simultaneously with NOvA and the short-baseline neutrino program at Fermilab**
  - All these program can simultaneously get the protons they need to meet their physics goals
  - **Mu2e can run at lower beam power**
    - **Saves significant money, reduces detector rates, simplifies solenoids, strengthens physics program**

- **COMET cannot run simultaneously with the JPARC neutrino program**
  - Either one or the other can take data
  - **Forces COMET to plan for higher beam power in order to minimize the amount of required beam time**
    - More complicated solenoid system, need to mitigate detector rates with a C-shaped detector solenoid, which significantly reduces their acceptance for e+

Mu2e / COMET comparison

	Mu2e	COMET
approval/ funding	**ranked among the very top priorities for the U.S. HEP program** P5 Report 2014 "Complete the Mu2e and g-2 projects." Mu2e is *fully funded in all budget scenarios* The DOE is committed to completing Mu2e	**COMET phase-II funding has not been identified** and Japan has clearly stated that their top priorities are Belle-II, long baseline neutrinos, and ILC
Operation Condition	**Mu2e will run simultaneously with NOvA and the short-baseline neutrino program at Fermilab**	**COMET cannot run simultaneously with the JPARC neutrino program. It forces COMET to plan for higher beam power in order to minimize the amount of required beam time**
Detector	Straight Solenoid with gradient field Tracker and Calorimeter 	C-shape Solenoid with gradient field Tracker and Calorimeter 

Mu2e is equally sensitive to e- and e+ and thus have an additional physics channel $\mu^- N \rightarrow e^+ N'$ and will be able to measure in situ some background components (e.g. $\pi^- N \rightarrow \gamma N' \rightarrow e^- e^+ N'$)

the COMET solenoids, particularly their production solenoid, is more technically risky (e.g. they will use a 9 (!) layer coil, Mu2e is 3 layer).

Mu2e Calorimeter

	LSO:Ce/LYSO:Ce	BaF_2	CsI
Density (g/cm^3)	7.40	4.89	4.51
Melting point (°C)	2050	1280	621
Radiation Length (cm)	1.14	2.03	1.86
Molière Radius (cm)	2.07	3.10	3.57
Interaction Length (cm)	20.9	30.7	39.3
Z_{eff}	64.8	51.6	54.0
dE/dX (MeV/cm)	9.55	6.52	5.56
Emission Peak[a] (nm)	420	300 220	310
Refractive Index[b]	1.82	1.50	1.95
Relative Light Yield[a]	100	42 4.8	4.2
LY in 1st ns (photons)	740	960	100
Decay Time[a] (ns)	40	650 0.9	26
d(LY)/dT[c] (%/°C)	-0.2	-1.9 0.1	-1.4

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C)

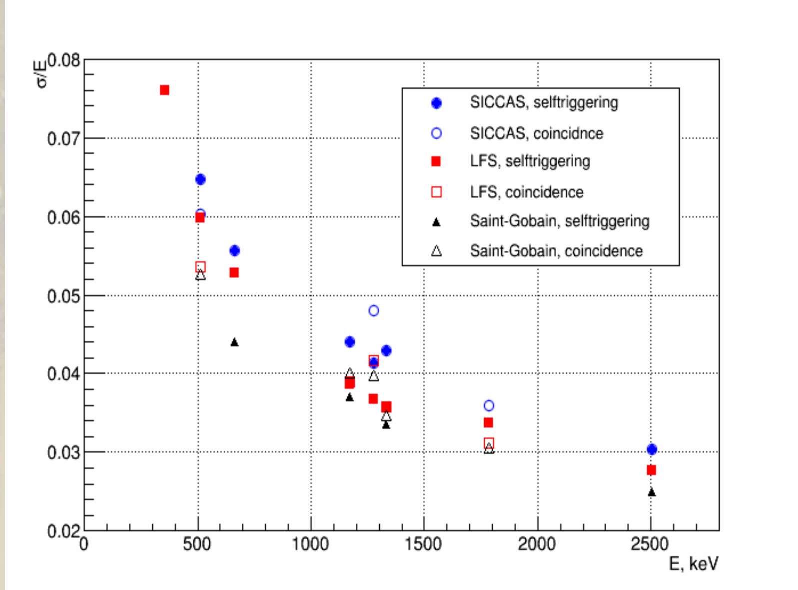
Mu2e Calorimeter

Barium Fluoride (BaF_2)

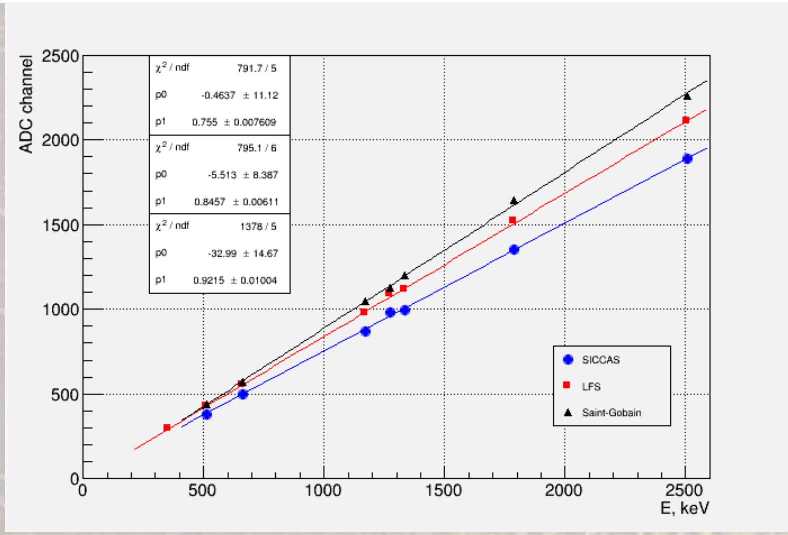
- Radiation hard, non-hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be “solar”-blind
- Crystal dimension: hexagonal faces of 33 mm across flats, 200 mm length (10 X_0)

	BaF_2
Density (g/cm^3)	4.89
Radiation length (cm)	2.03
Moliere Radius (cm)	3.10
Interaction length (cm)	30.7
dE/dX (MeV/cm)	6.52
Refractive index	1.50
Peak luminescence (nm)	220 (300)
Decay time (ns)	1 (650)
Light yield (rel. to NaI)	5% (42%)
Variation with temperature	0.1% (-1.29)% / °C

JINR R&D



Energy resolutions of LYSO:Ce crystals from Saint-Gobain and SICCAS and LFS crystal from Zecotek.



Energy response linearity of the same three crystals in the 511-2500 keV energy range.

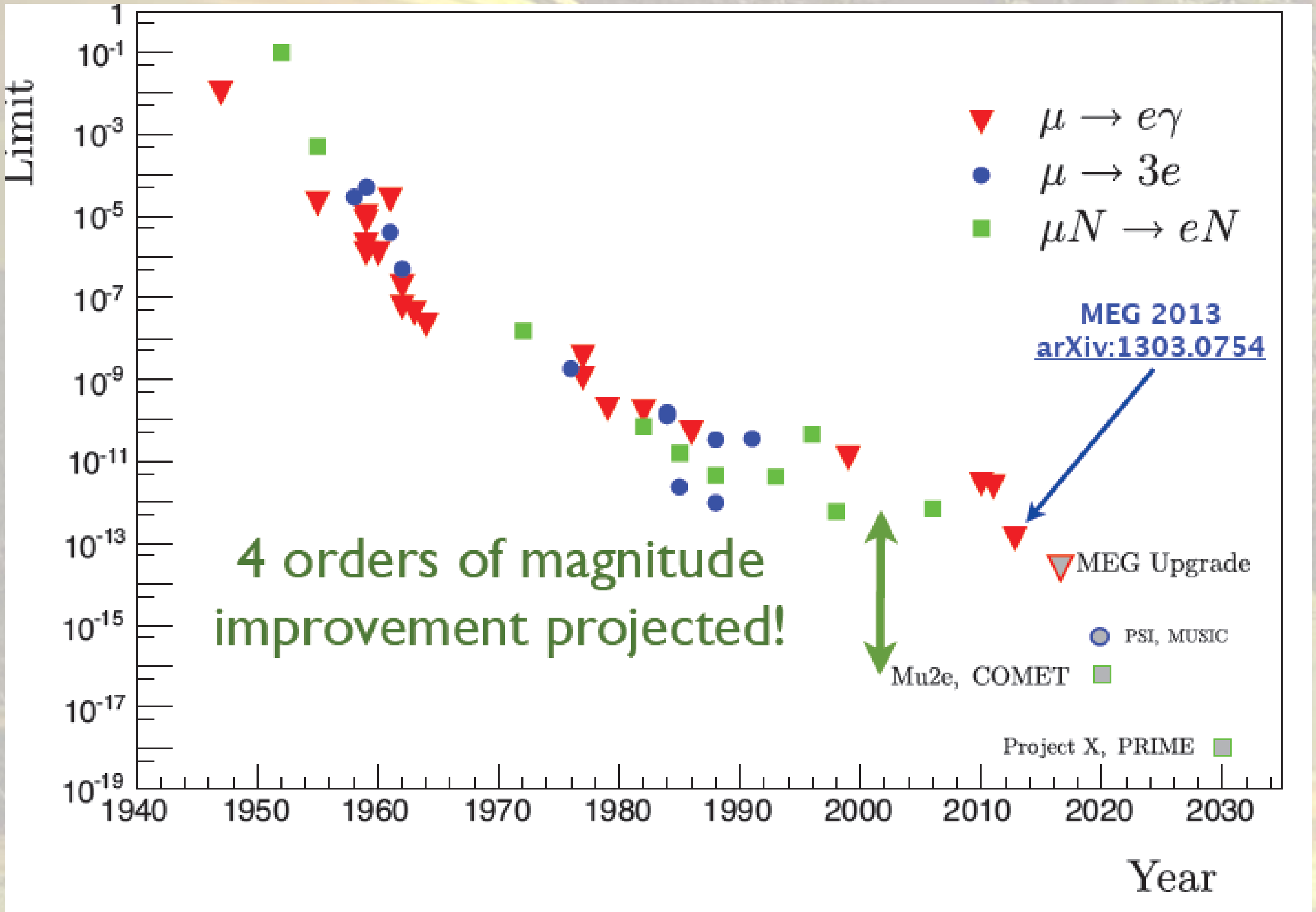
- **R.J. Abrams et al., “Mu2e Conceptual Design Report”, arXiv:1211.7019 (2012).**
- **J. Budagov et al., “The calorimeter project for the Mu2e experiment”, Nucl. Instr.&Meth. A718(2013) 56-59.**
- **O. Sidletskiy et al., “Evaluation of LGSO:Ce scintillator for high energy physics experiments”, Nucl. Instr.&Meth. A735(2014) 620-623.**
- **K. Afanaciev et al., “Response of LYSO:Ce scintillation crystals to low energy gamma-rays”, JINR preprint E13-2013-141, Dubna, 2013. Submitted to Nucl. Instr.&Meth. A.**
- **Z. Usubov, “Electromagnetic calorimeter simulation for future μ→e conversion experiments”, arXiv:1212.4322 (2012).**
- **Z. Usubov, “Light output simulation of LYSO single crystal”, arXiv:1305.3010 (2013).**

Comparison of COMET Phase-I / Phase-II and Mu2e

90% C.L. upper limit is $7x10^{-13}$ (SINDRUM)

	S.E. sensitivity	BG events at aimed sensitivity	running time (sec)	Year	Comments
COMET Phase-I	$3x10^{-15}$	0.03	$1.5x10^{6}$	~2016	Proposal (2012)
COMET Phase-II	$3x10^{-17}$	0.34	$2x10^{7}$	~2019	CDR (2009)
Mu2e	$3x10^{-17}$	0.4	3x ($2x10^{7}$)	~2019	J. Miller's talk at SSP2012

Status of CLFV Searches



MEG 2013
arXiv:1303.0754

4 orders of magnitude improvement projected!