MilliQan : A new detector for milli-charged particles at the LHC

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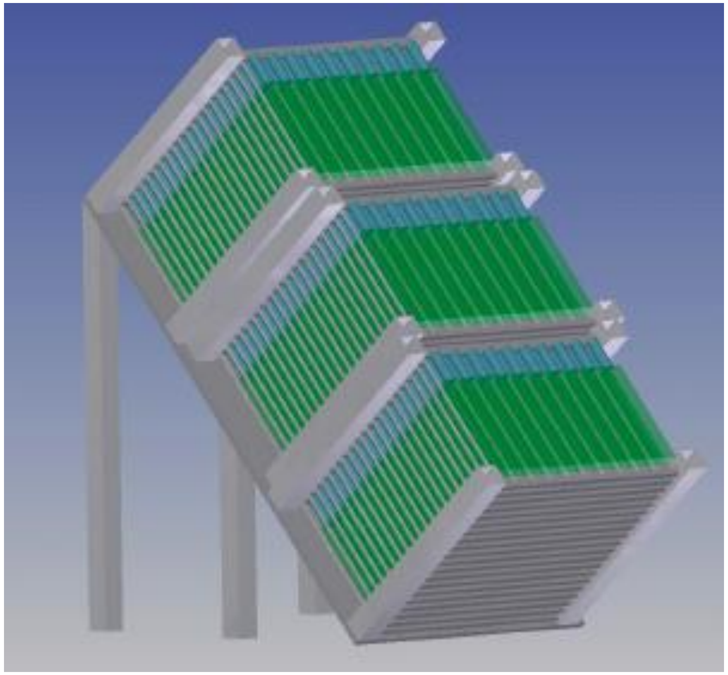
on behalf of the milliQan collaboration

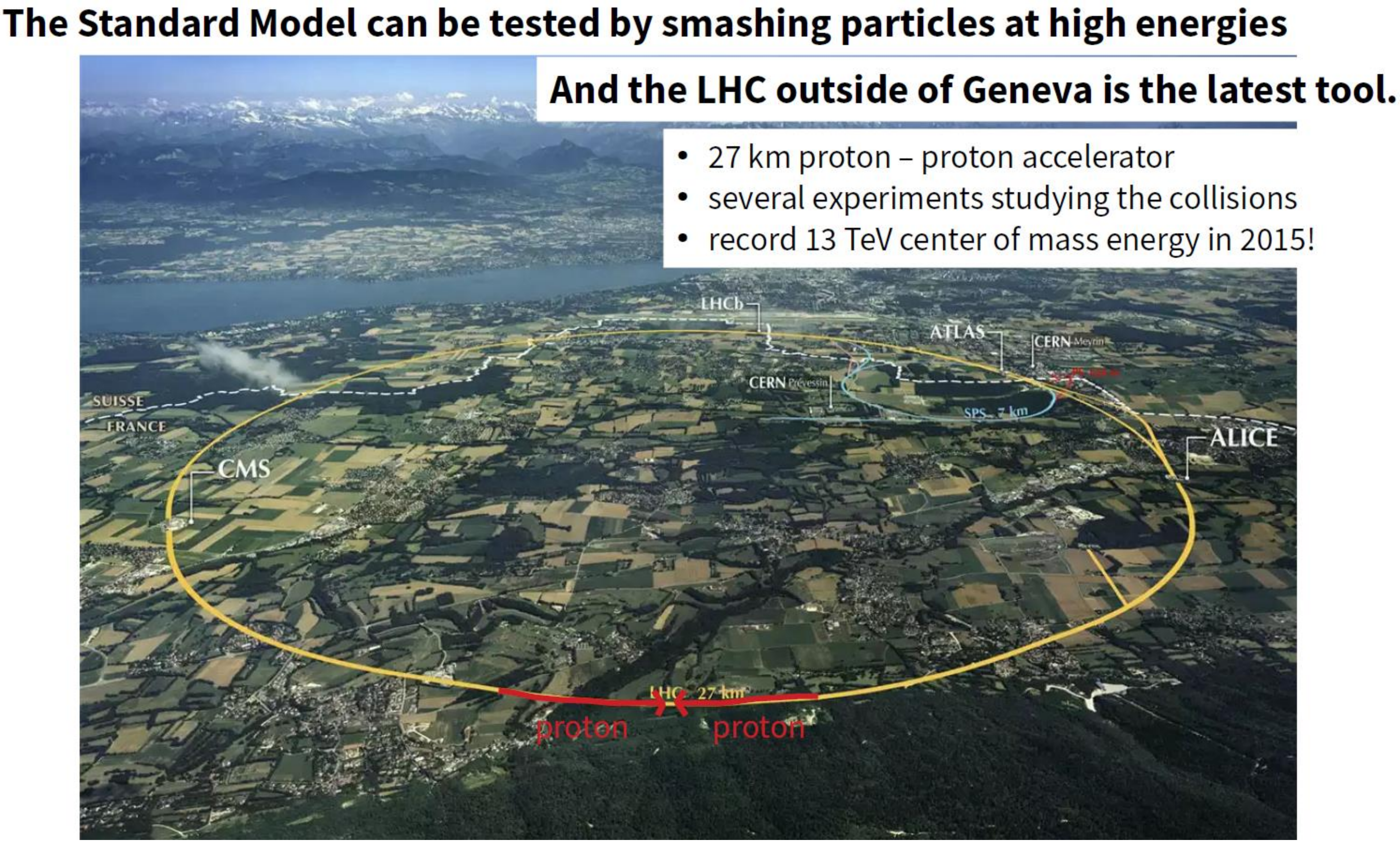
Fermilab Wine+Cheese

Sept. 8, 2017

http://theory.fnal.gov/jetp/



Large Hadron Collider (LHC)



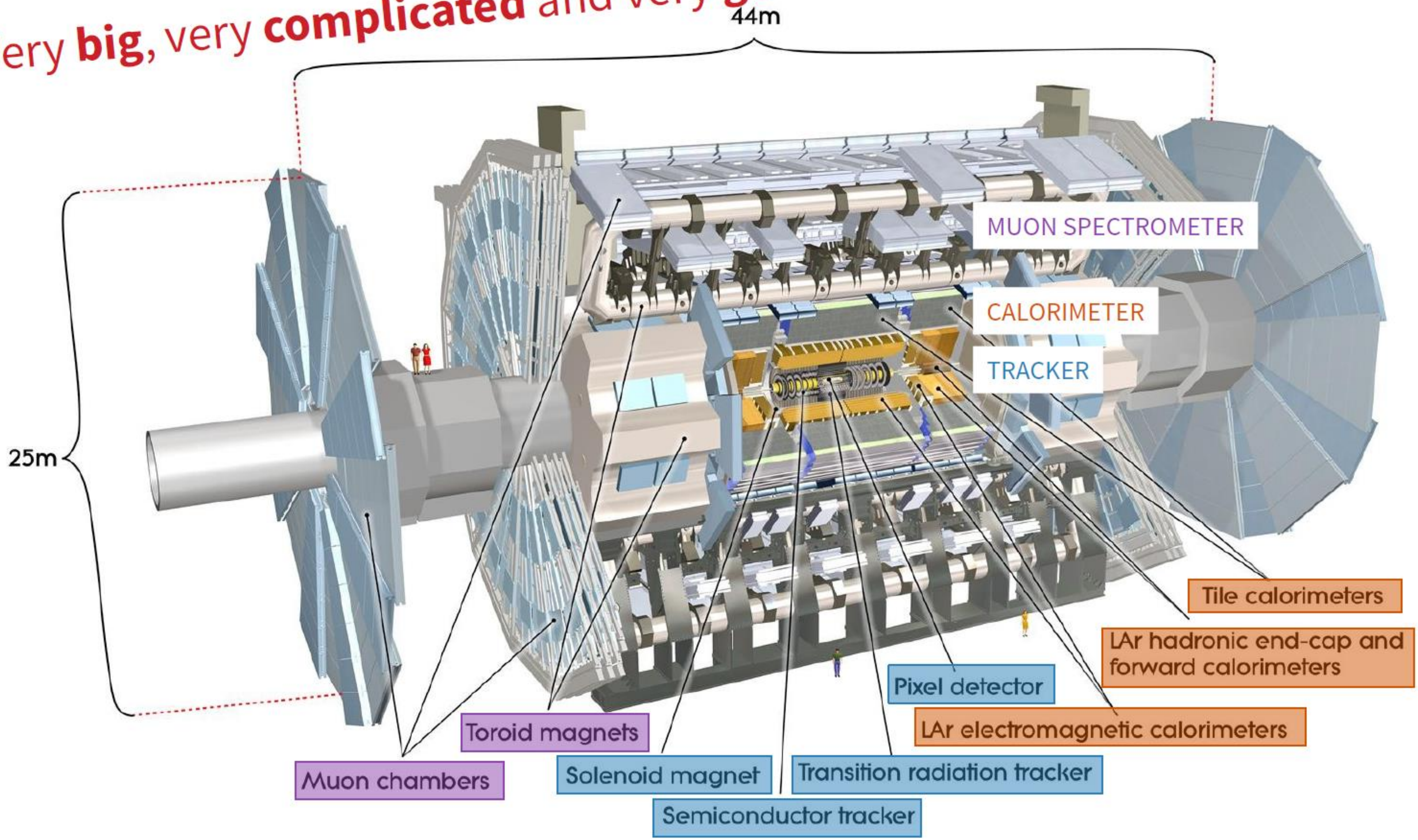
The Standard Model can be tested by smashing particles at high energies

And the LHC outside of Geneva is the latest tool.

- 27 km proton – proton accelerator
- several experiments studying the collisions
- record 13 TeV center of mass energy in 2015!

ATLAS Particle Detector

Very **big**, very **complicated** and very **general**!



MUON SPECTROMETER

CALORIMETER

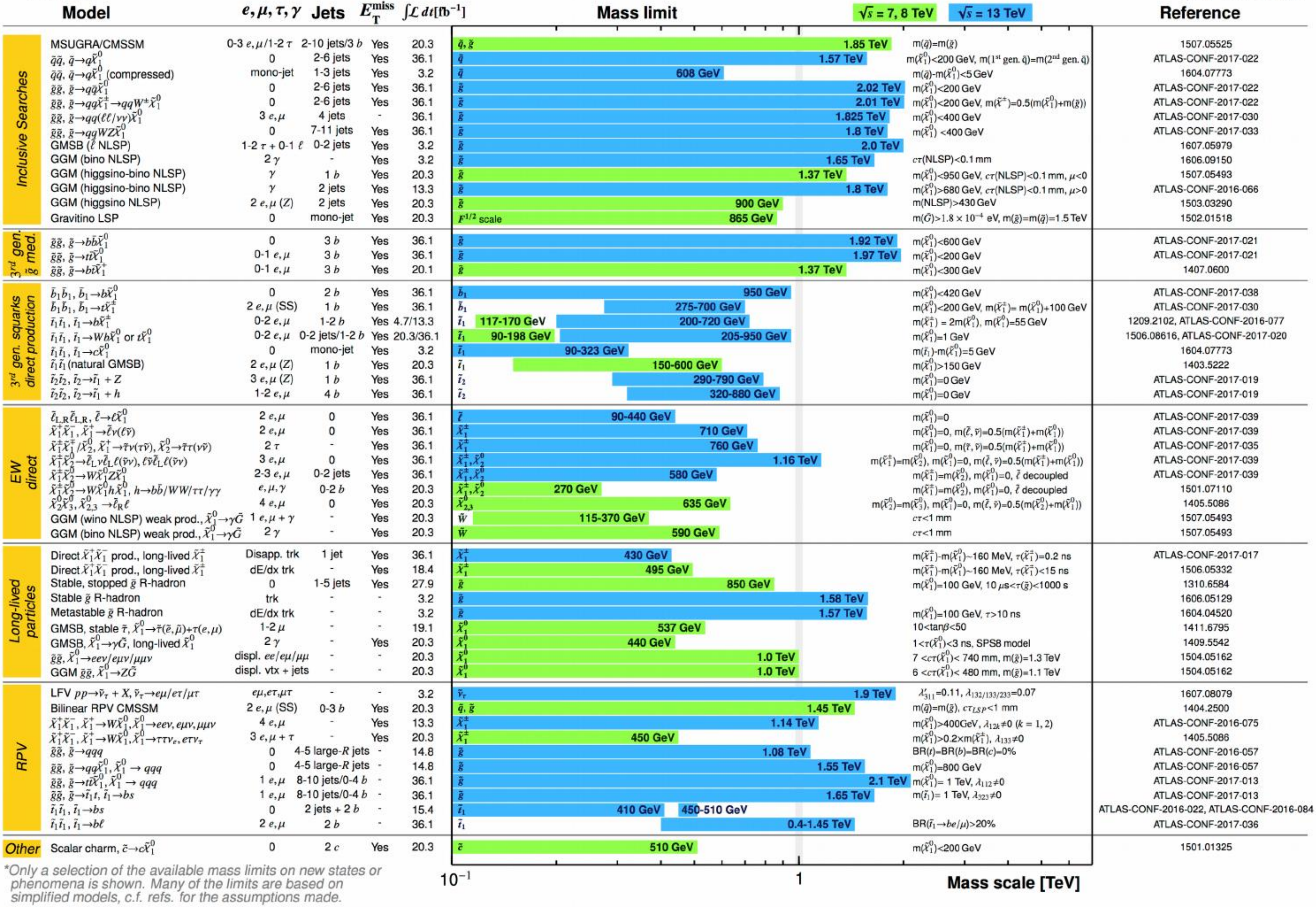
TRACKER

ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV



🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 🟩 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 🟦 1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 🟦 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 🟦 1.825 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 🟦 1.8 TeV	m($\tilde{\chi}_1^0$) <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 🟦 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 🟩 1.37 TeV	m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 🟦 1.8 TeV	m($\tilde{\chi}_1^0$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 🟩 900 GeV	m(NLSP)>430 GeV	1503.03290
	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
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.92 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.97 TeV	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 🟩 1.37 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$ 🟦 950 GeV	m($\tilde{\chi}_1^0$)<420 GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$ 🟦 275-700 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)= m($\tilde{\chi}_1^0$)+100 GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 205-950 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 🟦 90-323 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 🟩 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$ 🟦 290-790 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 🟦 320-880 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 🟦 90-440 GeV	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 710 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 760 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 🟦 1.16 TeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 🟦 580 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 🟩 270 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 🟩 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$ 🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	20.3	$\tilde{W}$ 🟩 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 🟦 430 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 🟩 495 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 🟩 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 🟦 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 🟦 1.57 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 🟩 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to eev/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 🟩 1.0 TeV	6 <$c\tau$($\tilde{\chi}_1^0$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$ 🟦 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 🟩 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 🟦 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 🟦 1.55 TeV	m($\tilde{\chi}_1^0$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 2.1 TeV	m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 🟦 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 🟦 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 🟩 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

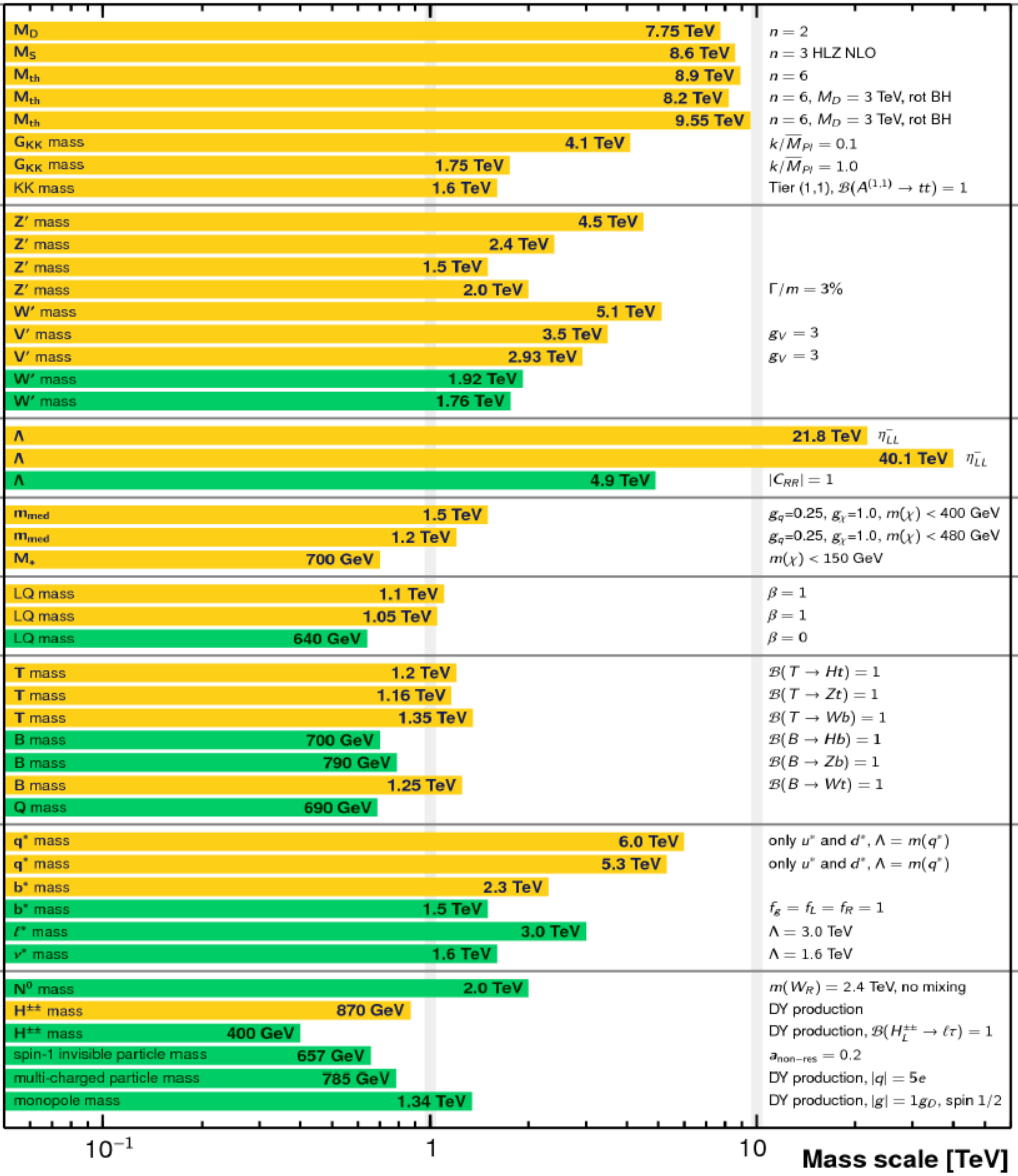
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	1 – 4 j	Yes	36.1	🟨 M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	🟨 G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	🟨 Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	3.2	🟨 Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	36.1	🟨 W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	36.7	🟨 V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV η_{LL}^{-}		1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ 40.1 TeV η_{LL}^{-}		ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	1 – 4 j	Yes	36.1	🟨 m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0\ e, \mu, 1\ \gamma$	≤ 1 j	Yes	36.1	🟨 m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	36.1	🟨 T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	🟩 B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	🟨 b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

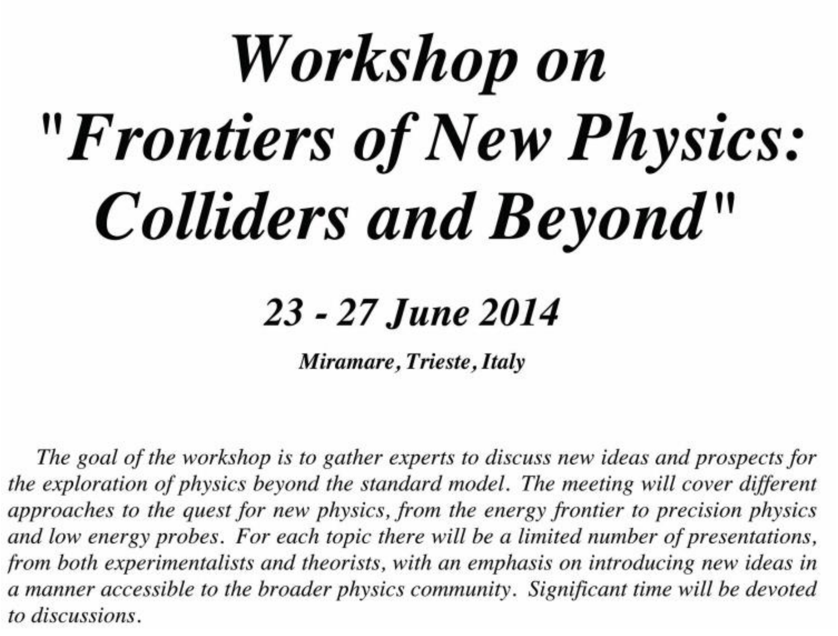
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Trieste 2014

Anything else we can look for at the LHC that we might be missing??

http://indico.ictp.it/event/a13203

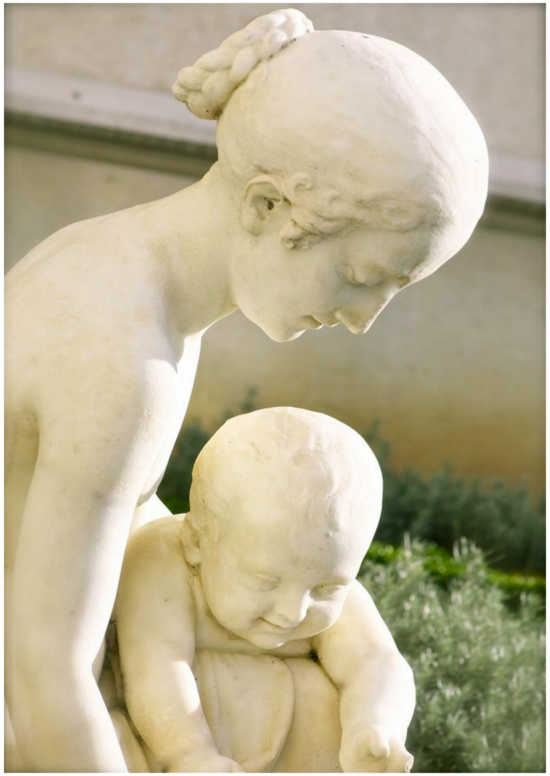


Workshop on
"Frontiers of New Physics:
Colliders and Beyond"

23 - 27 June 2014

Miramare, Trieste, Italy

The goal of the workshop is to gather experts to discuss new ideas and prospects for the exploration of physics beyond the standard model. The meeting will cover different approaches to the quest for new physics, from the energy frontier to precision physics and low energy probes. For each topic there will be a limited number of presentations, from both experimentalists and theorists, with an emphasis on introducing new ideas in a manner accessible to the broader physics community. Significant time will be devoted to discussions.



Trieste 2014

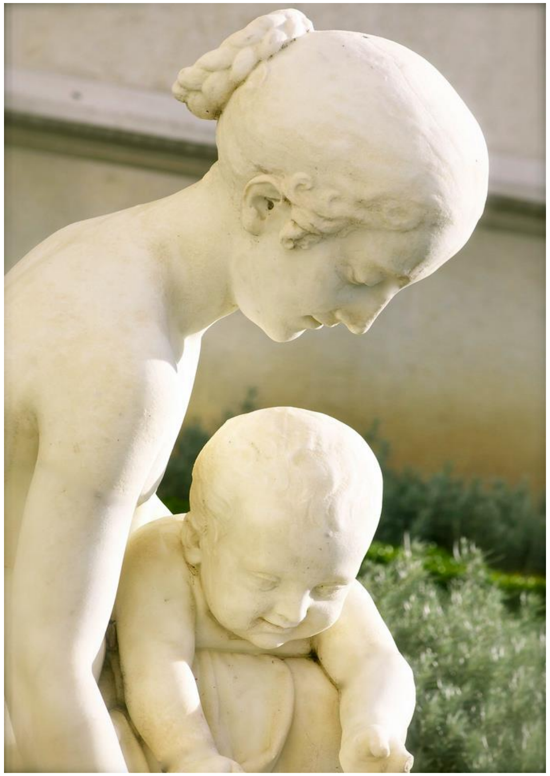
Anything else we can look for at the LHC that we might be missing??

“How about milli-charged particles?” – Itay Yavin

Low charge > little energy deposited > LHC detectors can’t see them!

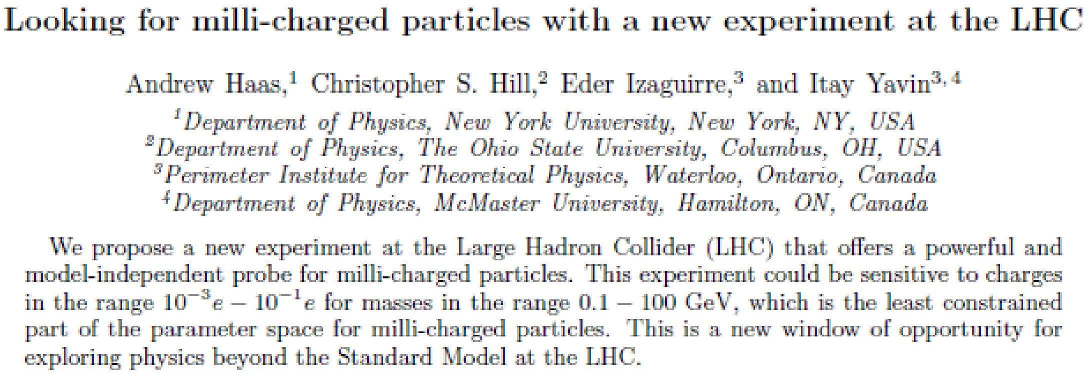
http://indico.ictp.it/event/a13203

By the end of the evening we had a basic design of a new detector finished!



Less than a year later completed a paper proposing the milliQan experiment idea:

Phys.Lett.B746 117 2015



Looking for milli-charged particles with a new experiment at the LHC

Andrew Haas,[1] Christopher S. Hill,[2] Eder Izaguirre,[3] and Itay Yavin[3,4]

[1] *Department of Physics, New York University, New York, NY, USA*
[2] *Department of Physics, The Ohio State University, Columbus, OH, USA*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada*
[4] *Department of Physics, McMaster University, Hamilton, ON, Canada*

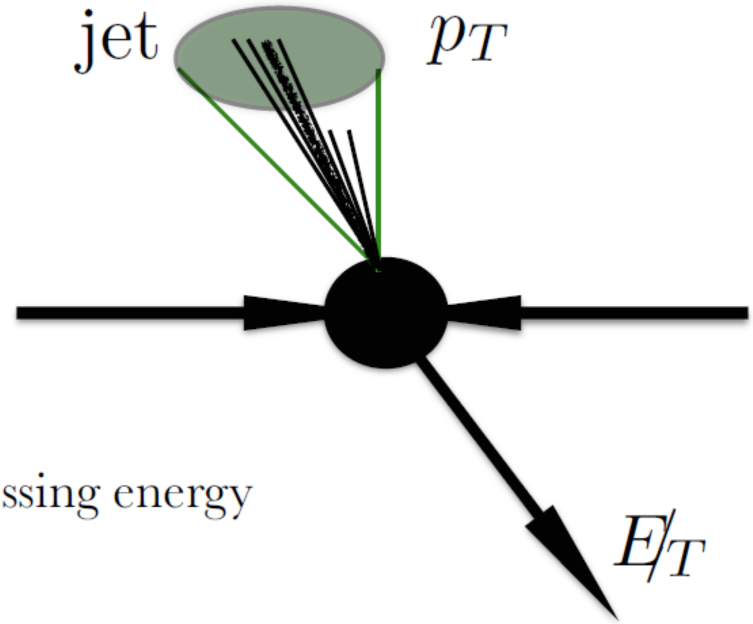
We propose a new experiment at the Large Hadron Collider (LHC) that offers a powerful and model-independent probe for milli-charged particles. This experiment could be sensitive to charges in the range $10^{-3}e - 10^{-1}e$ for masses in the range $0.1 - 100$ GeV, which is the least constrained part of the parameter space for milli-charged particles. This is a new window of opportunity for exploring physics beyond the Standard Model at the LHC.

Missing Energy to the rescue?

The mCPs could appear as missing energy instead

Momentum conservation implies $\vec{P}_{T,\mathrm{vis}} = -\vec{P}_{T,\mathrm{invis}}$

Can look for visible-energy + missing energy $pp \to j/\gamma/\ell + \bar{\psi}\psi$

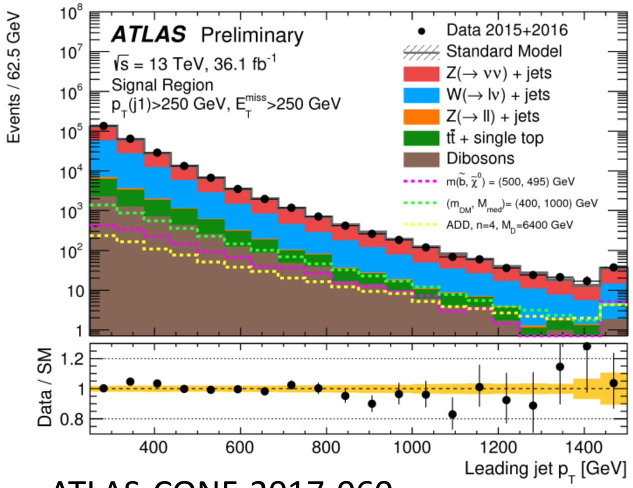


Example: 1 jet + missing energy

Slides from Eder Izaguirre

Darn Neutrinos

The limitations of looking for weakly-coupled new physics with missing energy: neutrinos (and mis-measured jets)



ATLAS-CONF-2017-060

Irreducible background from Z+jets

$$Z \to \nu\bar{\nu}$$

Additionally, from dijet production
Occasionally a jet's momentum is mis-measured giving missing energy + jet

Systematic uncertainties on these processes (jet energy scale, etc)
Unlikely to see a signal unless $S \gtrsim 0.1B$

Punchline: LHC jet + missing energy unlikely to improve sensitivity to mCPs beyond current bounds

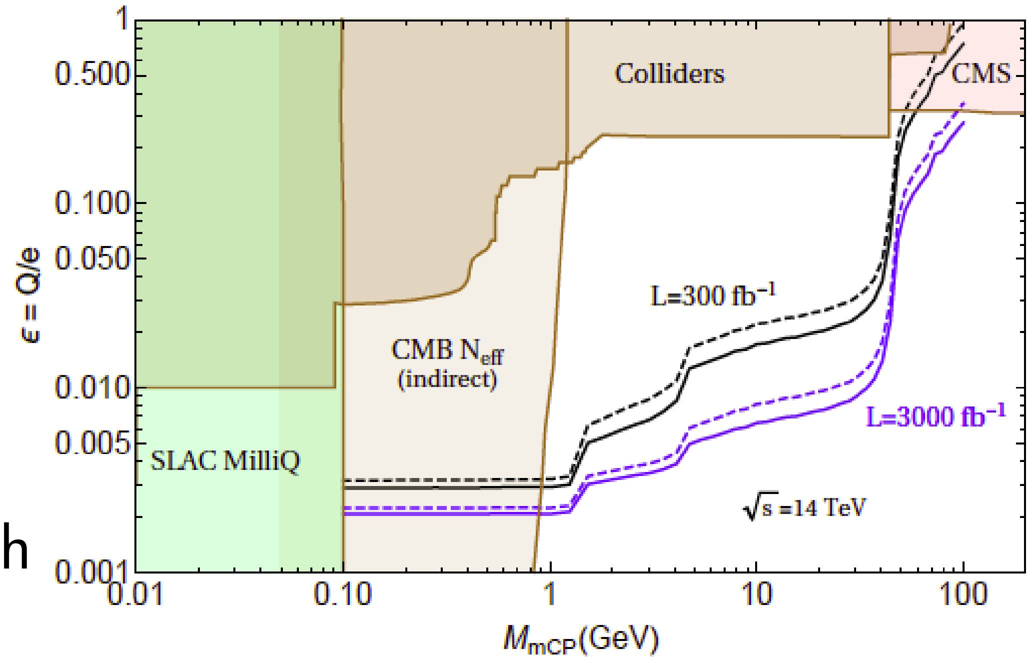
General Idea

Long history of searches for milli-charged particles (MCP)

MilliQan will probe for heavier MCP, 0.1 – 100 GeV, using a new detector at the LHC

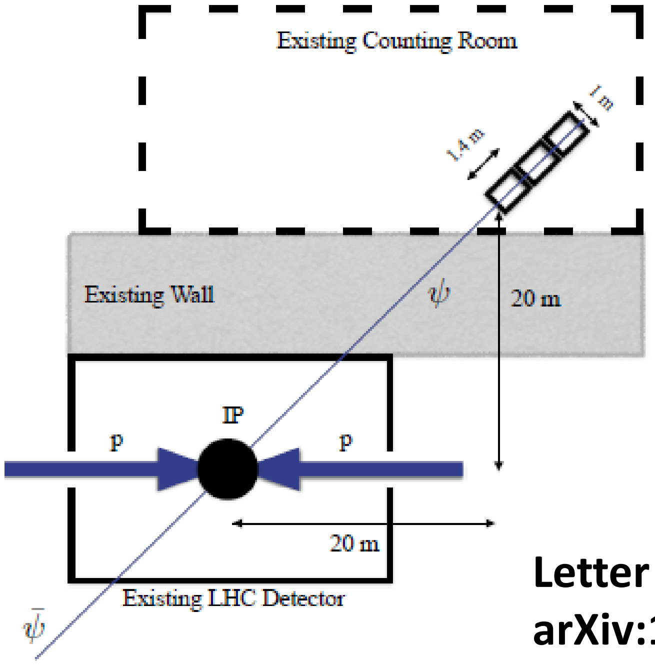
Produced via Drell-Yan and interact with detector via Bethe-Bloch

Cross-section and ionization $\propto \varepsilon^2$



Simple and model-independent

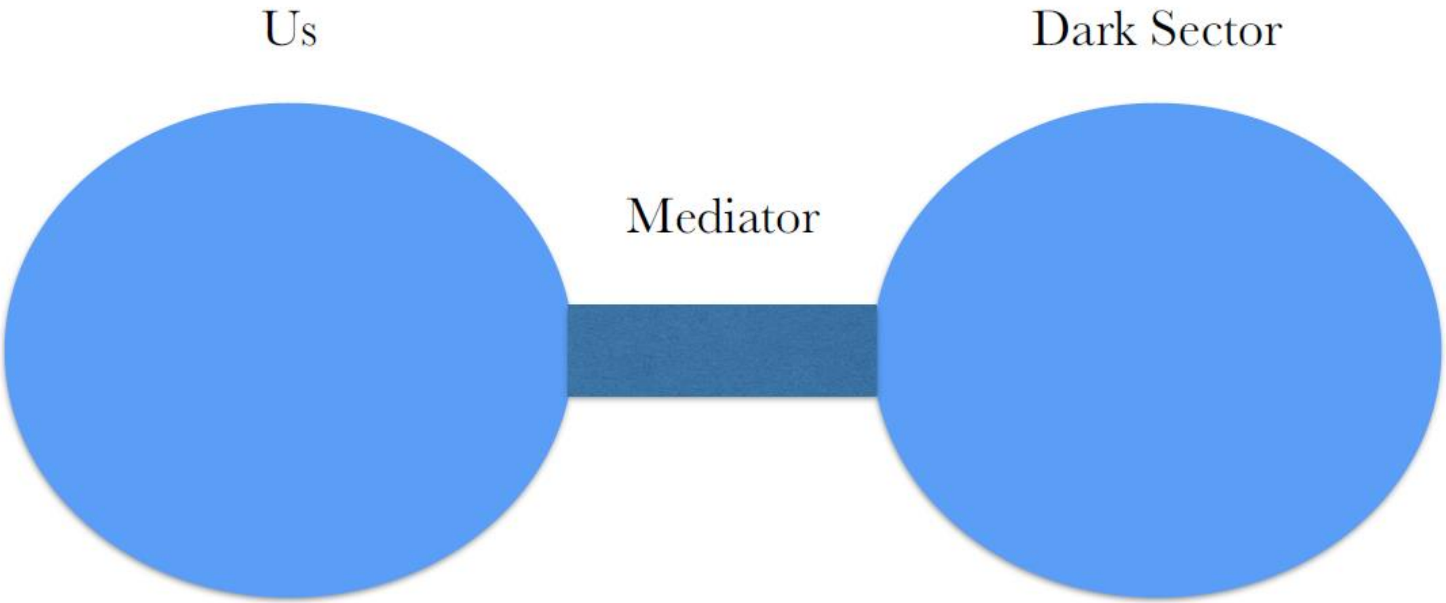
- With Q down to ~10^{-3}e, dE/dx is 10^{-6} MIP -> need large, sensitive, active area to see signal, $\mathcal{O}(1)$ PE.
- Install ~1 m x 1 m x 3 m scintillator array, pointing back to IP, in well shielded area of Point 5
- With triple coincidence, random background is controlled



Letter of intent: arXiv:1607.04669

Hidden Sector Paradigm

An increasingly popular effort to probe beyond the SM physics that lives in a "dark sector"



Us

Dark Sector

Mediator

Well-motivated by light DM
For light DM interactions between the DS and SM mediated by a light field

One organizing principle for probing it: focus on low-dimension operators:
vector portal, Higgs portal, neutrino portal

What are the generic properties one should expect from matter in the DS?
I will focus on the vector portal

Do Non-Quantized Charges Make Sense?

Theoretically consistent to add new particles with electric charge $Q = \epsilon e$

Could in principle add a new fermion with hypercharge $Y = 2\epsilon$

Or

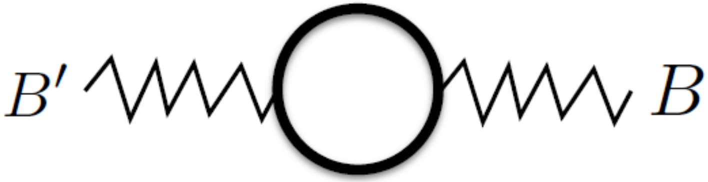
An elegant mechanism is that by Holdom, through the addition of a new massless U`(1) boson

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B^{\mu\nu'} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu}$$

Adding Particles with Non-Quantized Charge

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B^{'}_{\mu\nu}B^{\mu\nu'} - \frac{\kappa}{2}B^{'}_{\mu\nu}B^{\mu\nu}$$

The last term generically appears in SM extensions with a new massive field (mass M) charged under hypercharge and the new U`(1)



Induces a mixing

$$\kappa \sim 10^{-3} - 10^{-2}$$

Adding Particles with Non-Quantized Charge

If there are new fermions charged under the new U`(1)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}B^{'}_{\mu\nu}B^{\mu\nu'} - \frac{\kappa}{2}B^{'}_{\mu\nu}B^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie'B' + iM_{\text{mCP}})\psi$$

Standard trick: Redefine the gauge field

$$B' \to B' + \kappa B$$

Gets rid of "mixing term" and generates a hypercharge for the new fermions

After electro-weak symmetry breaking fermions acquire an EM charge (normalized to e)

$$Q = \kappa e' \cos\theta_W$$

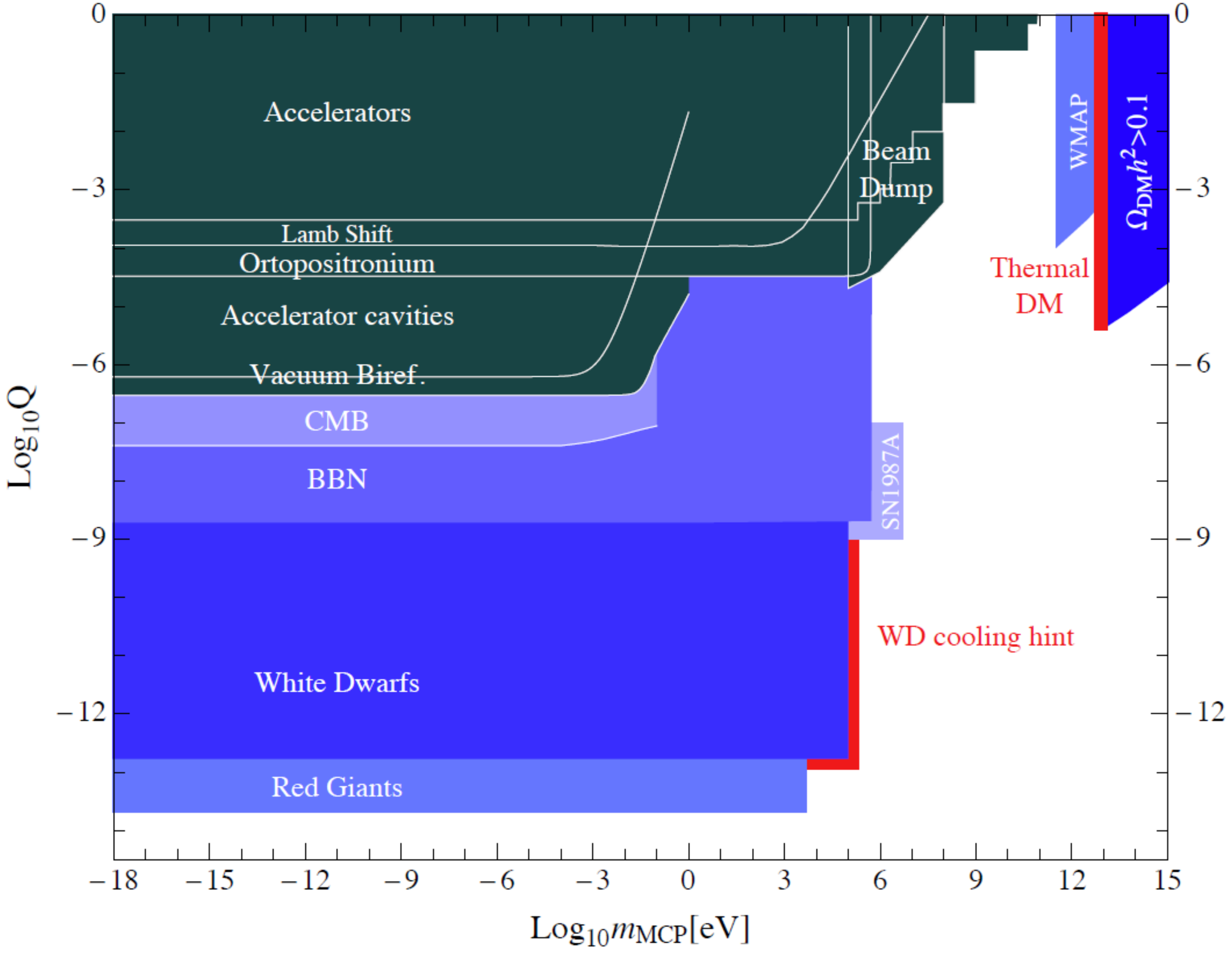
Status on Searches for Mini-charged Particles (mCPs)

A long history of direct and indirect searches for mCPs

For mCPs with mass below m_e one finds strong bounds from astrophysics and cosmology

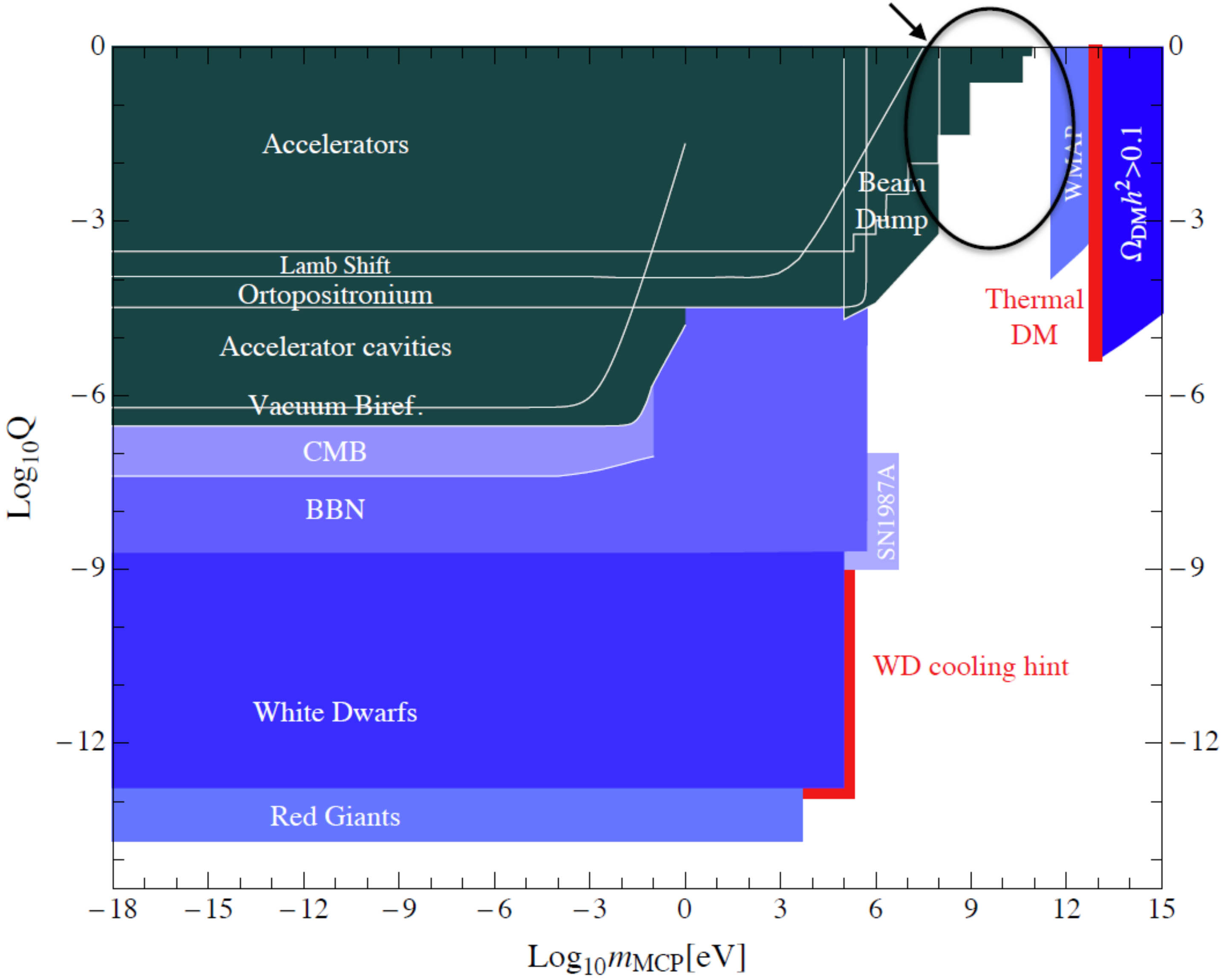
Astrophysics	Cooling and energy loss bounds from stars and SN
Cosmology	BBN and CMB number of effective relativistic degree of freedom bounds
Laboratory	Direct bound from the invisible decay of ortho-positronium
	Direct bound from the Lamb shift
	Direct constraint from accelerators: SLAC Milli-Charge experiment, E613, ASP, LEP More later on this

Status on Searches for Mini-charged Particles (mCPs)



Status on Searches for Mini-charged Particles (mCPs)

Least explored: GeV-100's GeV. The SM backyard!



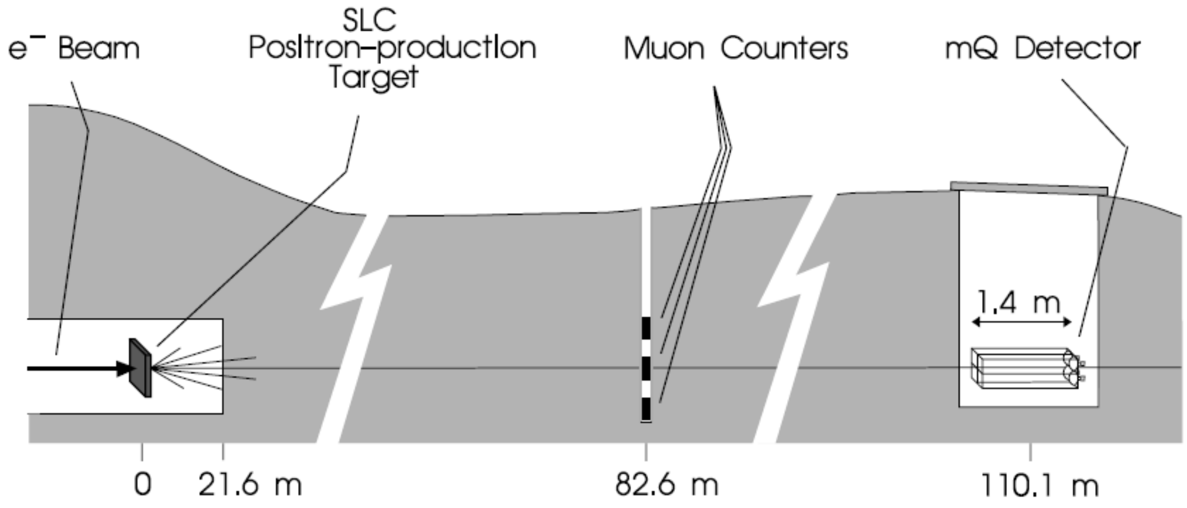
Lessons from the SLAC MilliCharge Experiment

Phys.Rev.Lett. 81 (1998) 1175-1178

29.5 GeV pulsed electron beam

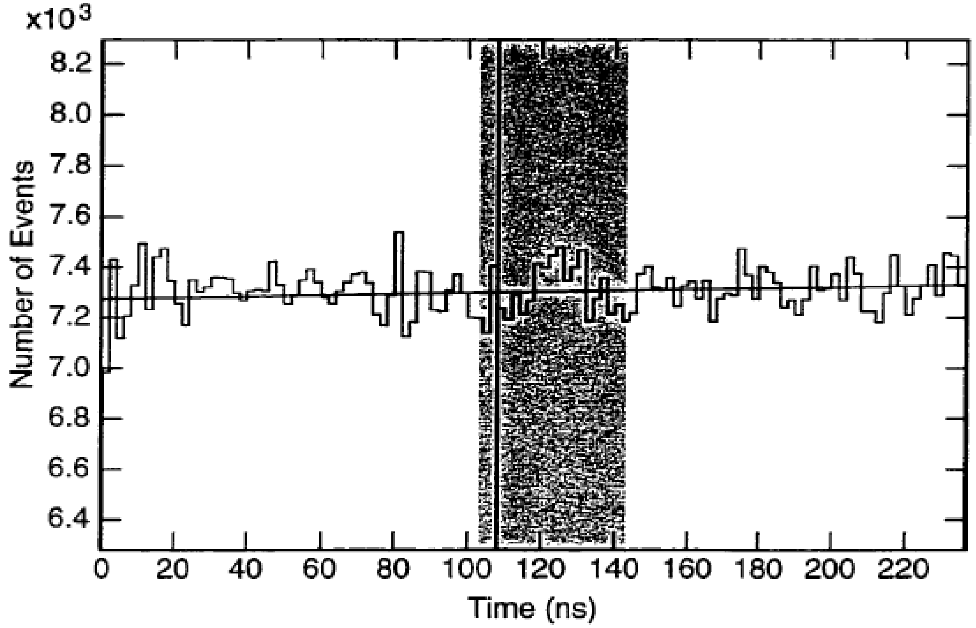
~ 10^{19} electrons on target

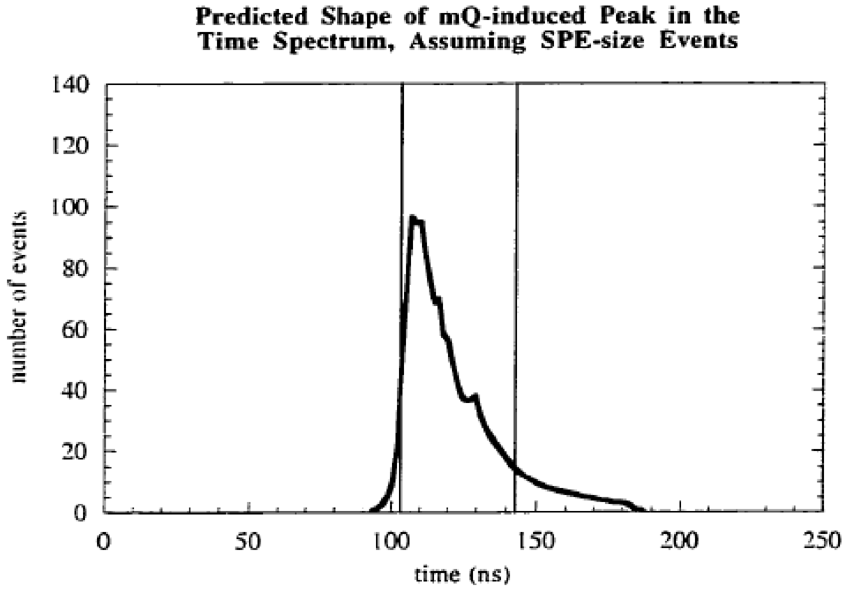
Good time resolution is essential, and tricky for small (SPE) pulses!



mQ detector

2x2 blocks of 21 cm x 21 cm x 130 cm plastic scintillator





What's in the Dark Sector?

EI, Itay Yavin, 1506.04760

Recall: Kinetic mixing communicating our sector with Dark Sector (DS)

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B^{'}_{\mu\nu} B^{\mu\nu'} - \frac{\kappa}{2} B^{'}_{\mu\nu} B^{\mu\nu}$$

Two cases studied in the literature

$$\frac{1}{2} m^2_{B'} B'^2$$

$m_{B'} = 0$ matter in DS is mCP: "Massless phase"

$m_{B'}$ non $-$ zero matter in DS is DM: "Massive phase"

What’s in the Dark Sector?

Our hyper-charge is a linear combination of a massless and a massive boson

What if that also is realized in the DS?
i.e. a “mixed phase”

$$B' = \cos\theta_{W'} A' - \sin\theta_{W'} Z'$$

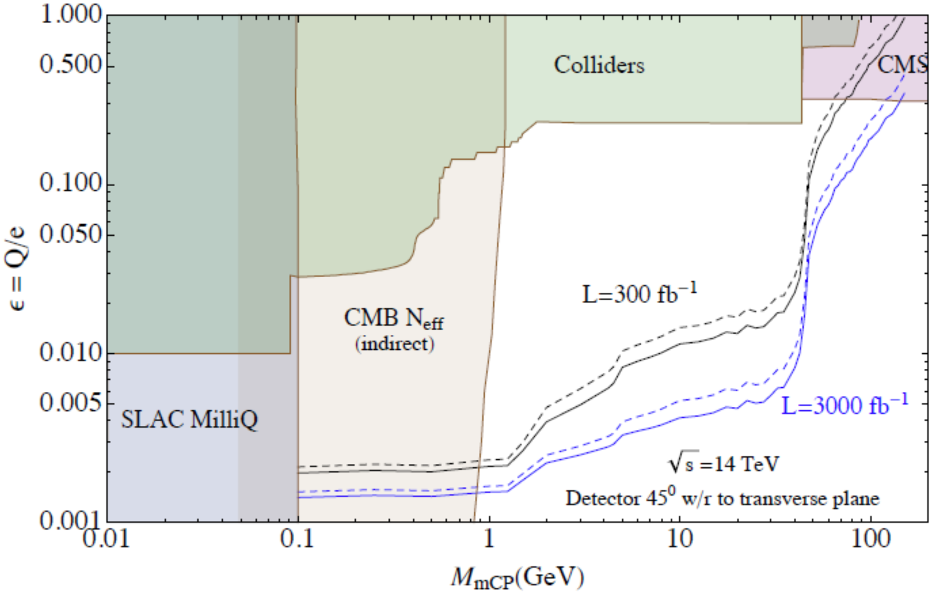
Opens up a new window into the DS
Produce the Z’ on-shell
Z’ decays to matter in the DS
Matter in the DS is still mCP!

Z’ couples to SM matter with strength $\epsilon_Z e = \kappa \cos\theta_W \sin\theta_{W'} e$

Matter in the DS charged under A’ acquires mill-charge $\epsilon_\gamma e = \kappa \cos\theta_W \cos\theta_{W'} e'$

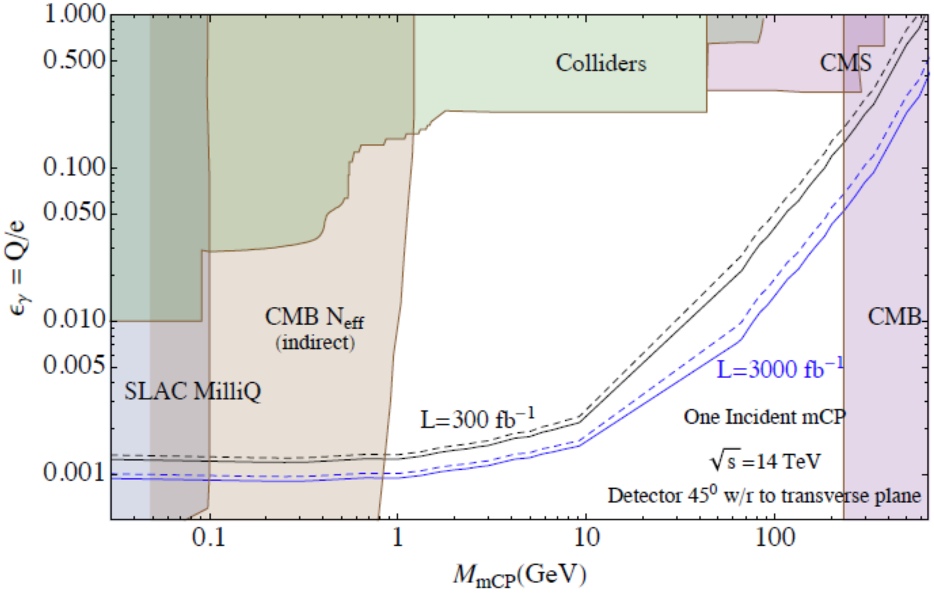
Looking for mCPs above GeV

Massless phase



Mixed phase

$M_{Z'} = 3M_{\rm mCP}, \theta_W{}' = \theta_W$



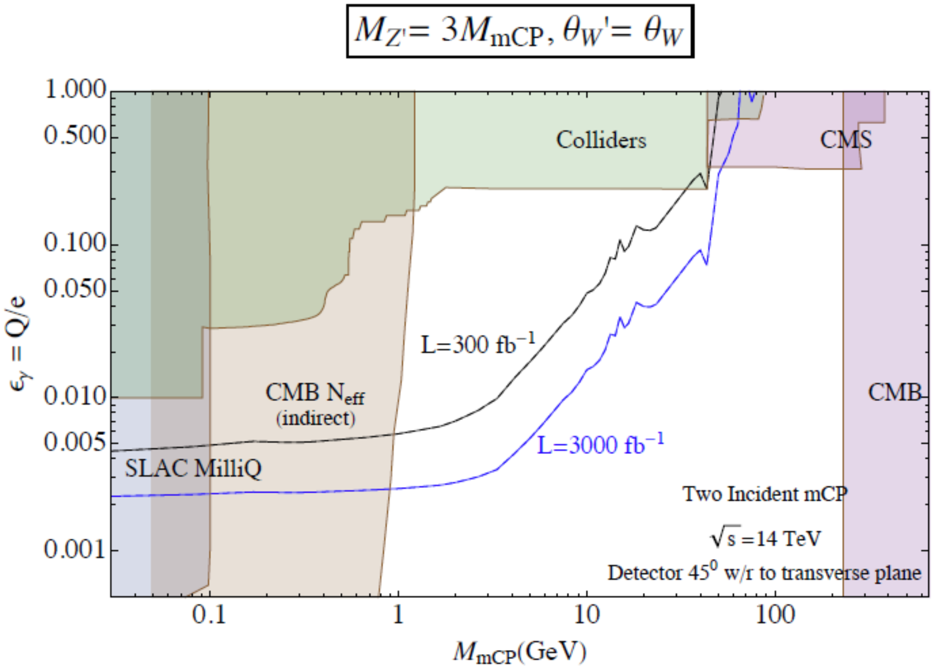
Note that mixed phase constraints at LHC experiment primarily sensitive to $\kappa_Z \kappa_\gamma$

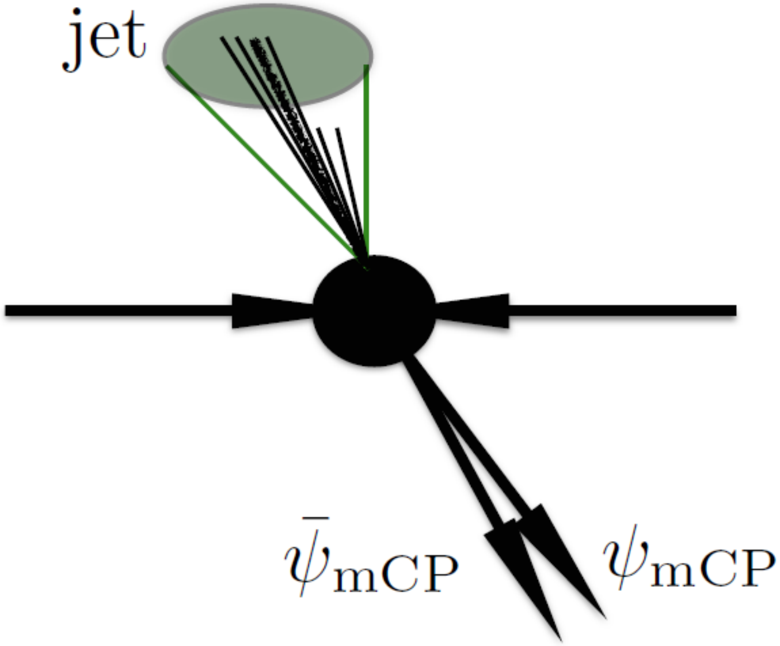
Unique Signature of the Mixed Phase

Mixed phase offers new striking signatures

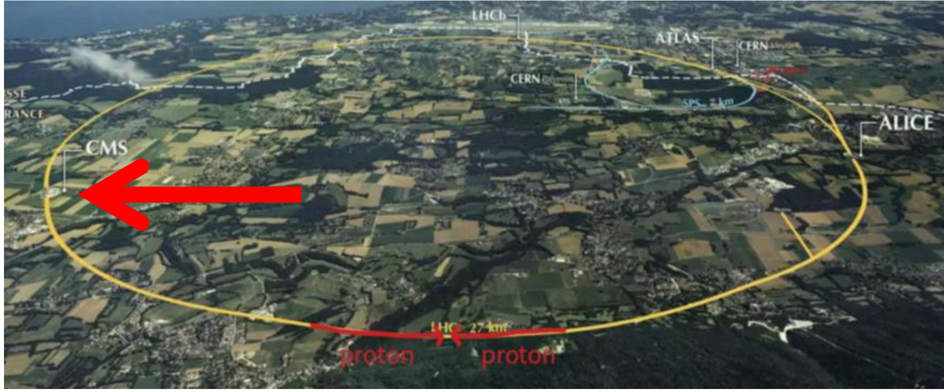
Two incident mCPs for boosted Z' when:

$$\Delta\theta(\bar{\psi}_{\mathrm{mCP}}, \psi_{\mathrm{mCP}}) < \Delta\theta_{\mathrm{det}}$$



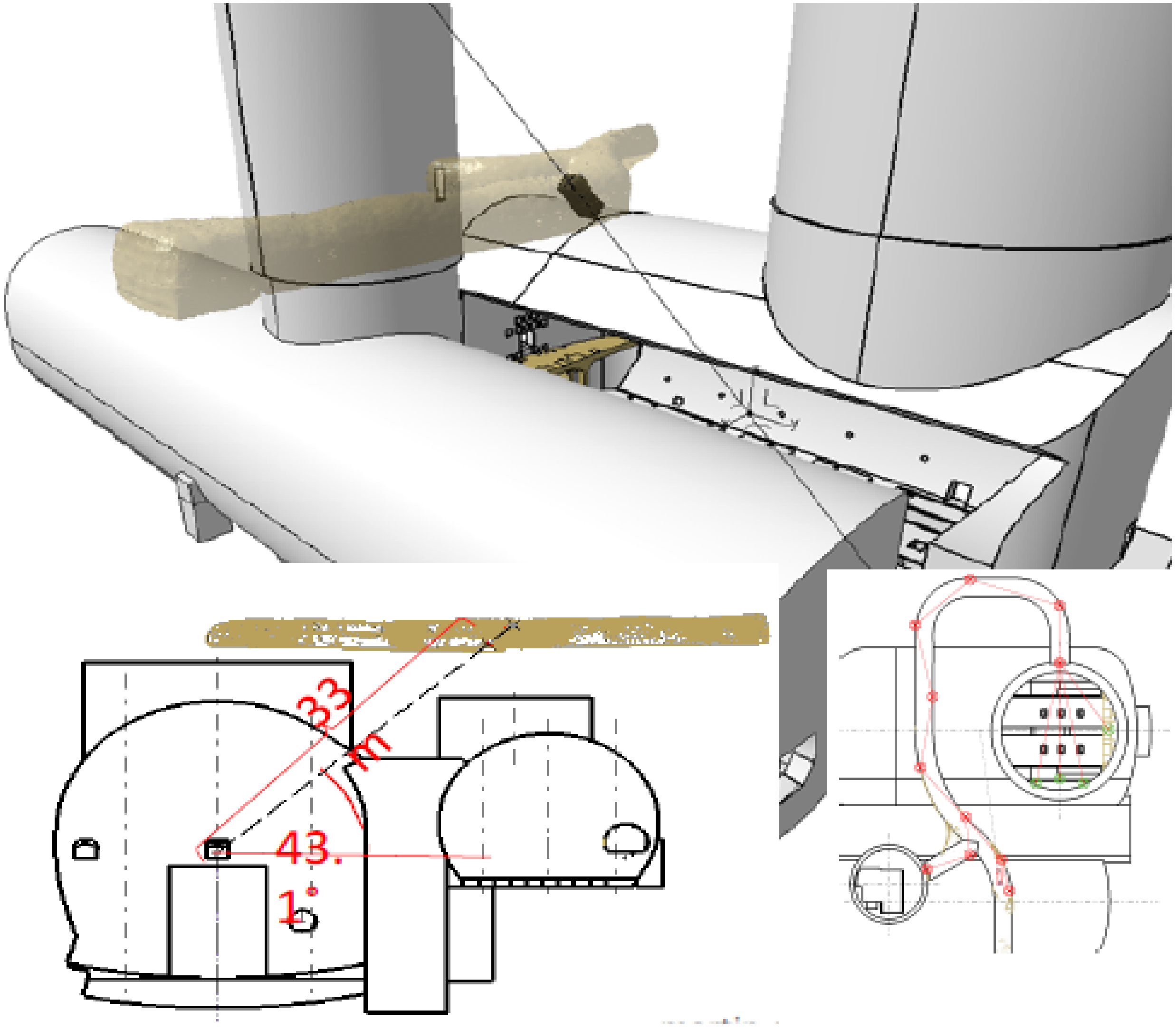


MilliQan location

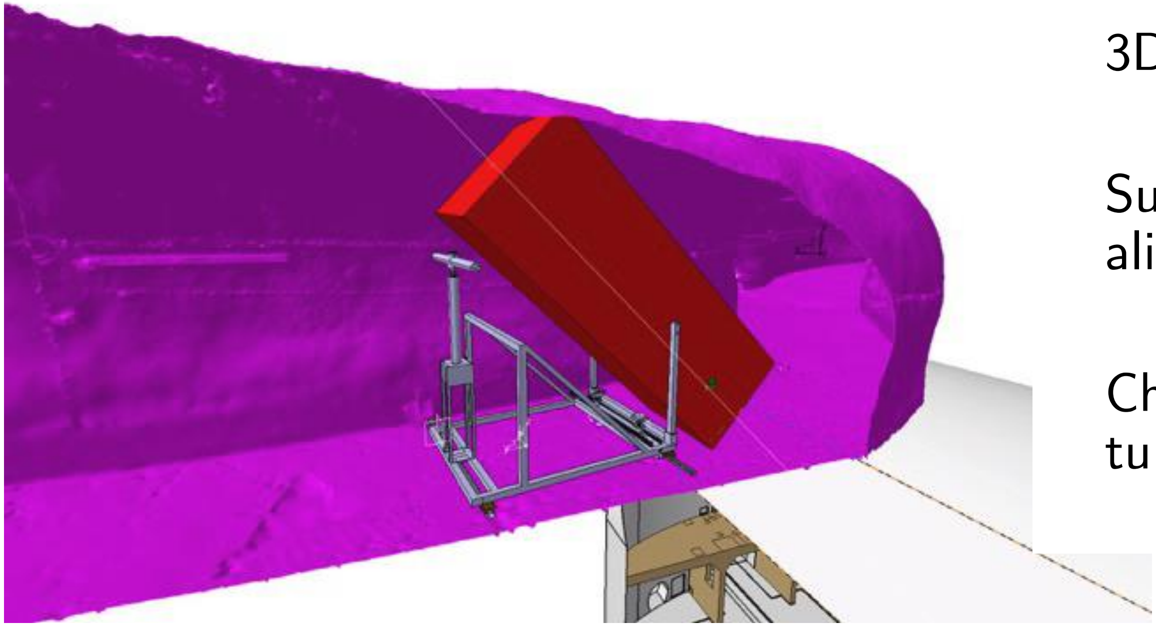


“Drainage Gallery”
an existing tunnel just above CMS

- Martin Gastal (CERN), and his team, have been particularly helpful
  - *3D drawings, surveys, B-field measurements, pictures, etc.*
- Now have precise details of location:
  - *33 m from IP*
  - *17 m through rock*
  - *Angle from horizontal plane is 43.1 deg*
  - *Clearance to gallery boundaries is ~30 mm!*



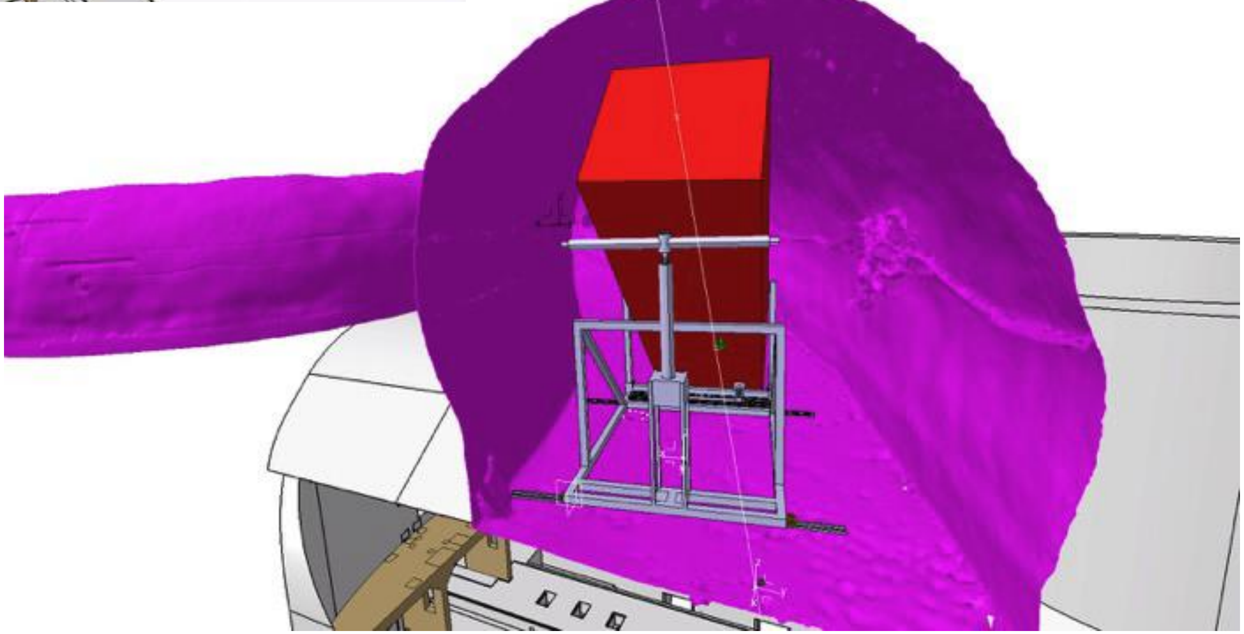
MilliQan location



3D laser scan of tunnel interior

Support structure to hold and align detector

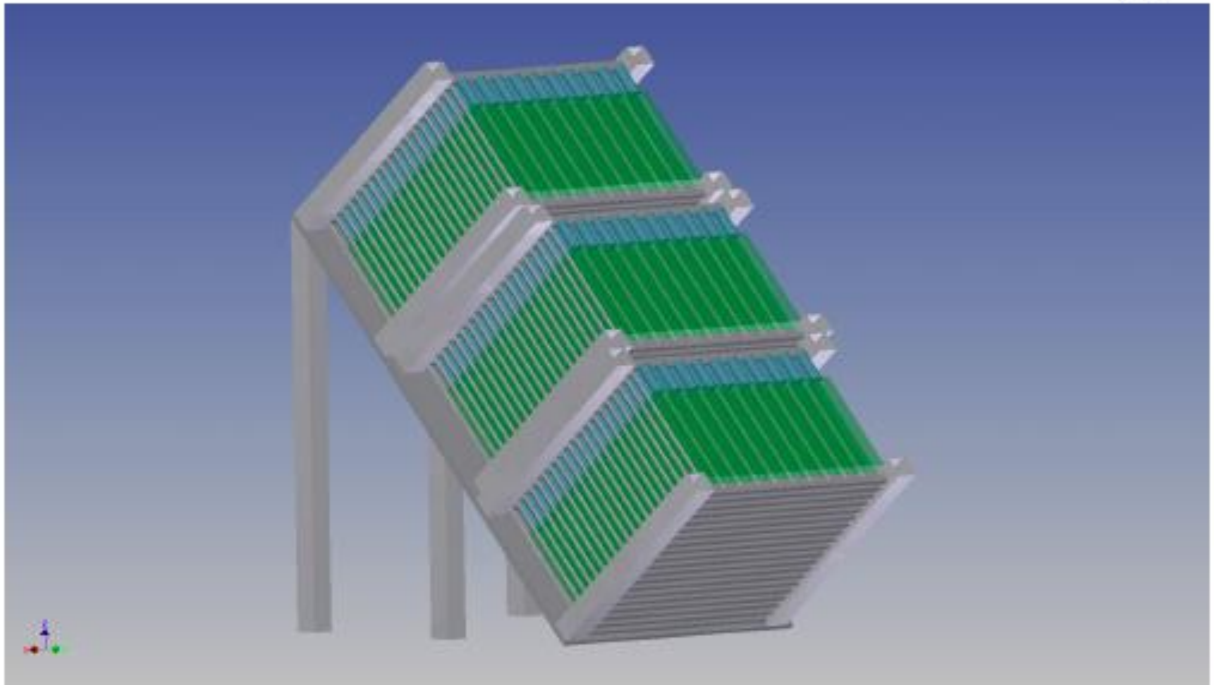
Challenge to fit 3m detector in tunnel, but it just fits

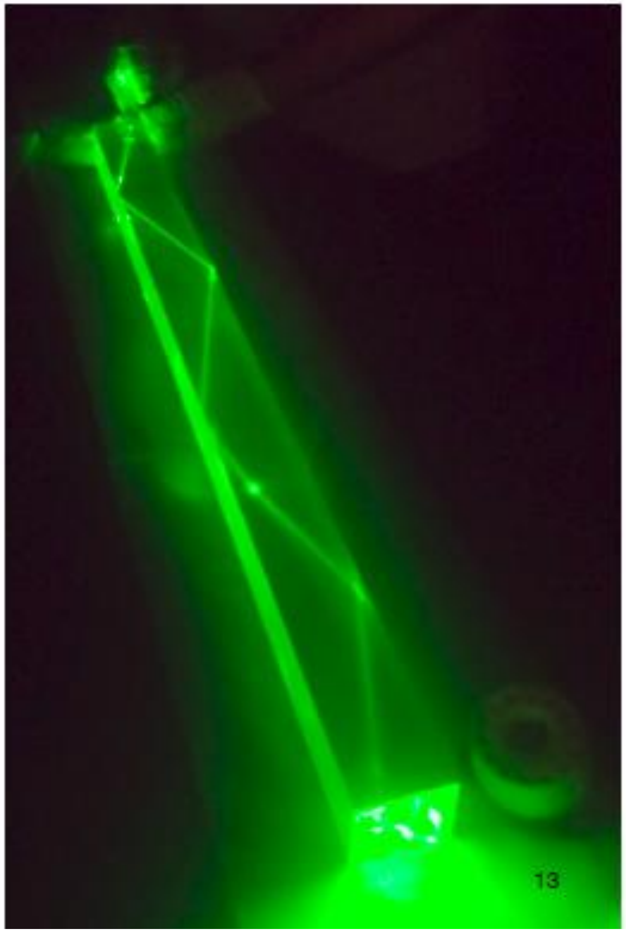


Detector idea

Aim to detect single photons in 3 adjacent large scintillators pointing back to IP, within a small time window (15 ns)

- Basic element is a 5 cm^2 x 80 cm bar pf plastic scintillator (BC 408) + PMT (HPK R7725)
- Arranged in a 20 x 20 x 3 array
  - *Supported by movable mechanical structure*
    - **Alignment to IP + retraction to allow passage through gallery**





Other Scintillators Considered

Light yield in bar given by (photon yield / keV) * density * length

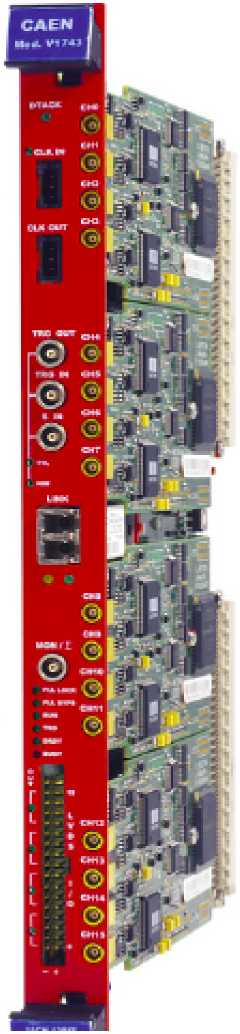
- Want high photon yield / keV > can go to lower charge (but limited by production cross-section too...)
- Want high density > can go to shorter bars / more layers
- Want it fast > lower backgrounds from smaller coincidence time window
- Want it cheap > can afford more bars / acceptance area

Material	Photons/keV	Density (g/cm^3)	* Length needed (cm)	Speed (ns)	Cost for 5x5 cm ($)	Notes
Plastic BC408	10	1.03	145	~2	~200	Current choice
NaI	38	3.67	11	~230	~800	Slow, fragile
LaBr3(Ce)	63	5.08	5	~16	~3000	Radioactive
Liquid Xe	62	2.95	8	~2 / ~34	~1000?	Cryogenic, ultraviolet

* Length needed to get 3 photons for charge 1/1000 e

Readout and trigger

Fantastic detail of each pulse from a triggered event
~1 ns timing resolution, even for tiny (single PE) pulses



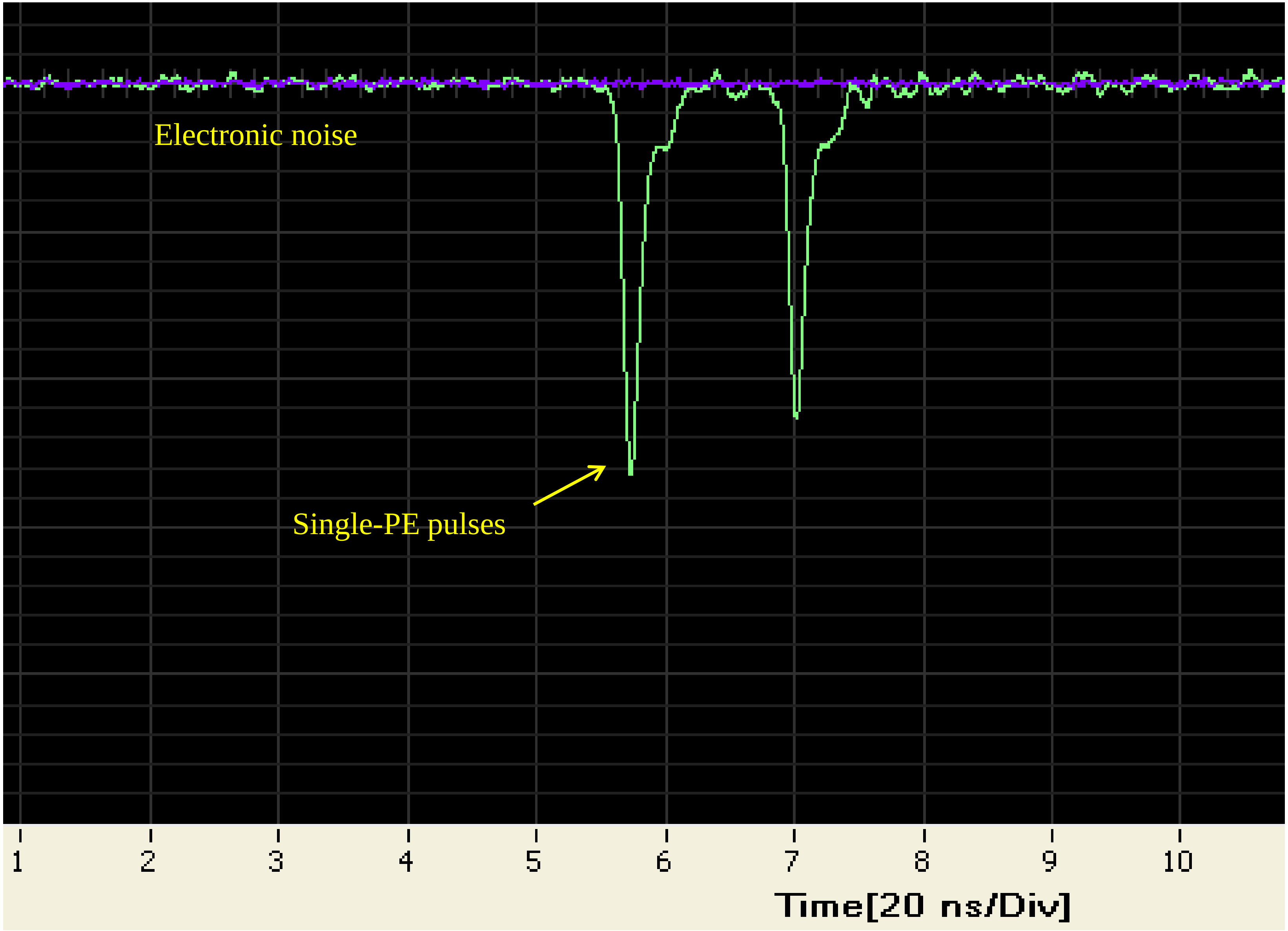
- Readout via CAEN V1743 12 bit digitizer
- 16 channels
  - *Sampled at 3.2 GS/s (a sample each 312.5 ps)*
  - *1024 analog buffer ring (320 ns long).*
  - *Analog noise is about 0.75 mV per channel, allowing good identification of and triggering on single PE signals*
- Trigger
  - *If 2 of 3 bars coincident in 15 ns window, self-triggers to read out whole detector*
    - **Completely separate from CMS trigger**
  - *Data will be read out via CAEN CONET 2 over 80 Mbps optical fiber to a PCI card in dedicated DAQ*
    - **Completely separate from CMS DAQ**

Will also interface with LHC clock to time-stamp events with bunch-crossing info!

Readout and trigger

Fantastic detail of each pulse from a triggered event

~1 ns timing resolution, even for tiny (single PE) pulses



Backgrounds

17m of rock removes all SM background from LHC collisions

- ~15 muons per minute at L=1.4E34, p>20 GeV makes it through the rock, but clearly not milli-charged (~1M PE actually saturates detector)
  - Can be used for rough check of alignment (discussed later)
- Middle layer offset to avoid glancing muons on edge of 3 bars

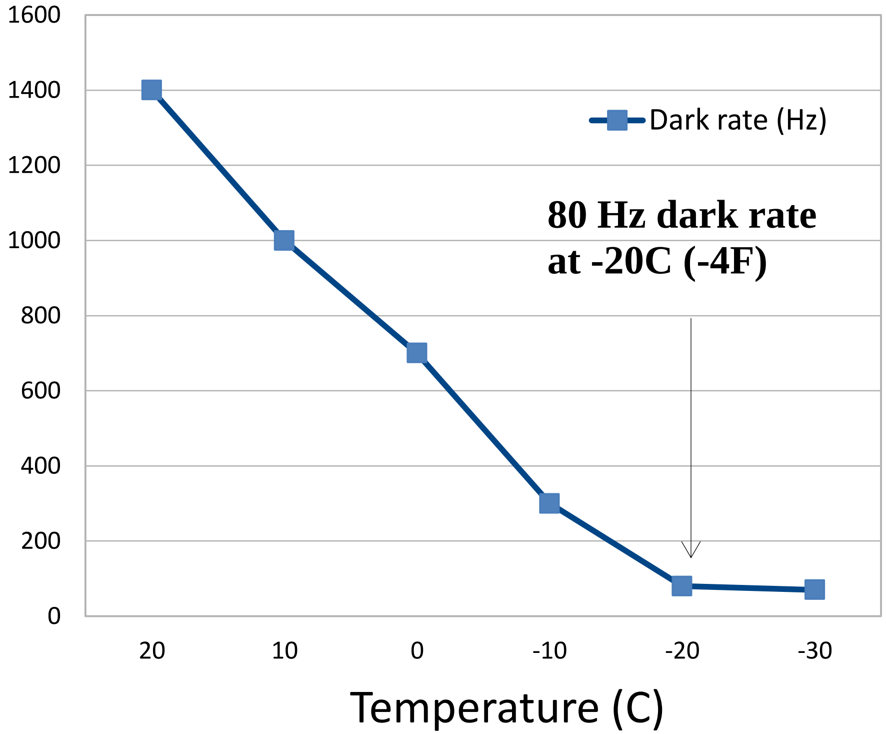
Cosmic rate ~100x smaller in tunnel than on surface

- Comparable to collider muon rate
- Worry about showers in rock with n, γ, etc. but will have *active vetos* and self-shielding from outer layer

Random dark-pulse background

- Need 3 coincident pulses
- ~50 events per year at room temp
- Greatly reduced by cooling to -20C

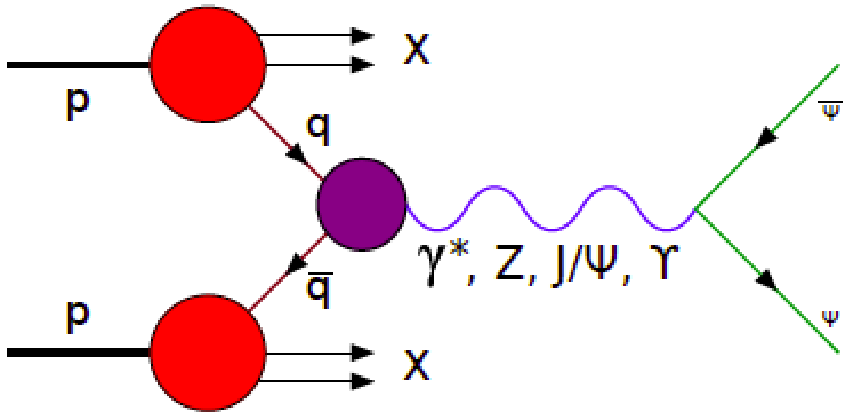
Backgrounds will be studied in situ from data: beam on/off, time relative to bunch crossing, pointing to IP or not, etc.



80 Hz dark rate at -20C (-4F)

Signal simulation

Detailed simulation, including CMS magnetic field (small effect)



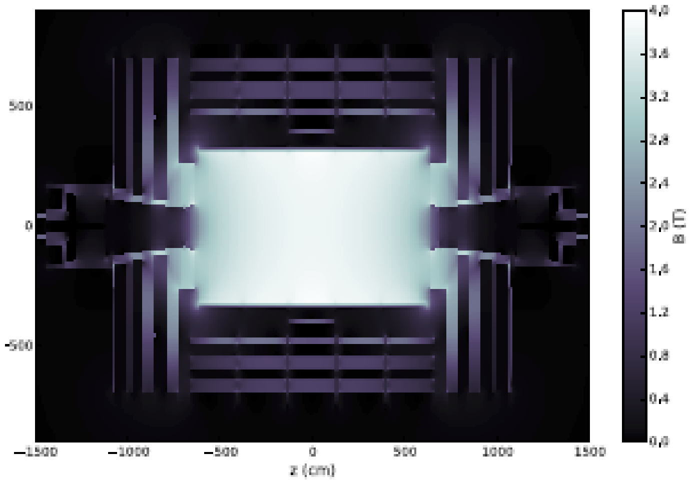
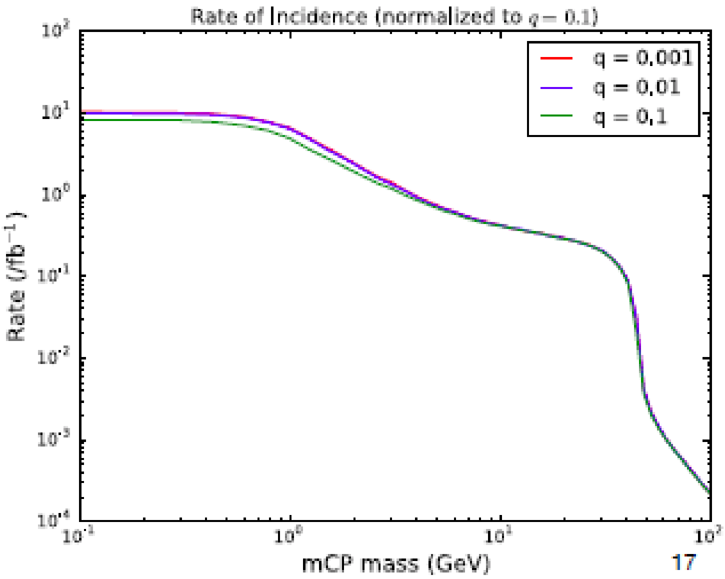


FIG. 2: Map of the CMS magnetic field in the r–z plane.

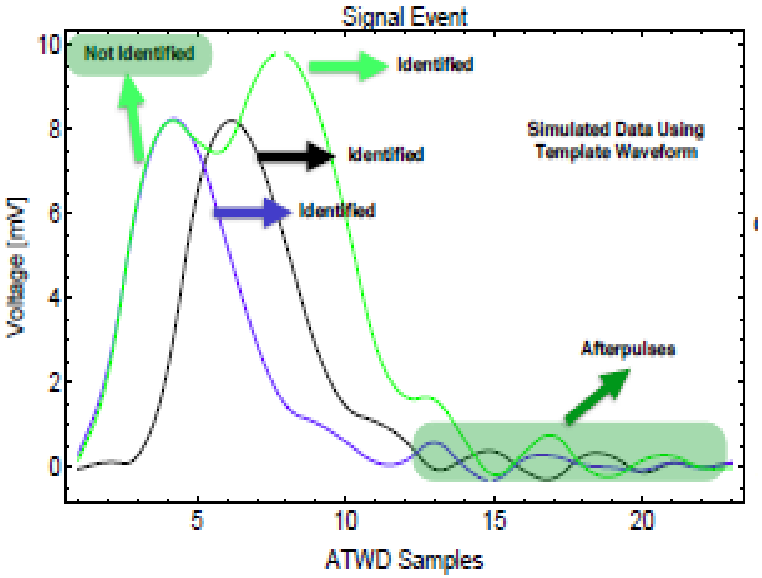
- Use madGraph + madOnia to simulate production via modified Drell-Yan
- Then propagate particles through parameterized simulation of material interactions with CMS & rock (full CMS simulation overkill)
  - *Used actual CMS B-field map though*
- Count rate of incidence on 1 m^2 face of milliQan detector

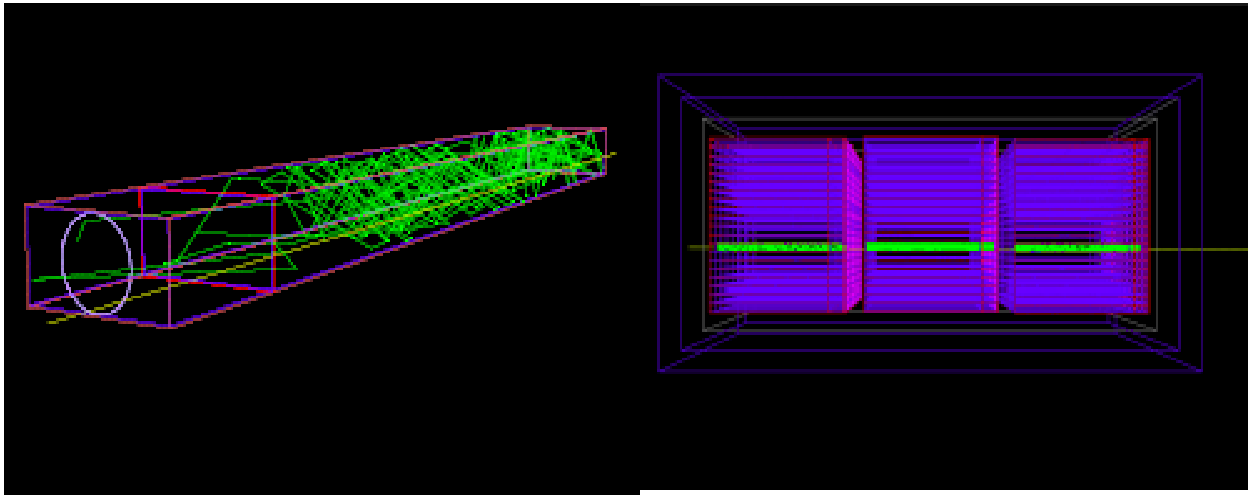


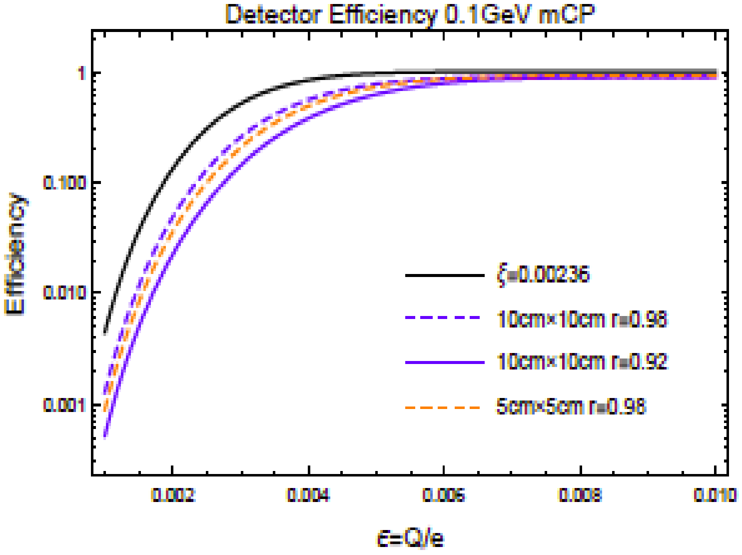
Signal simulation

Full Geant4 detector simulation

- Models reflectivity, the light attenuation length, and the shape of the scintillator. We input the PMT quantum efficiency, scintillator light emission spectrum, time constants, and digitized waveforms



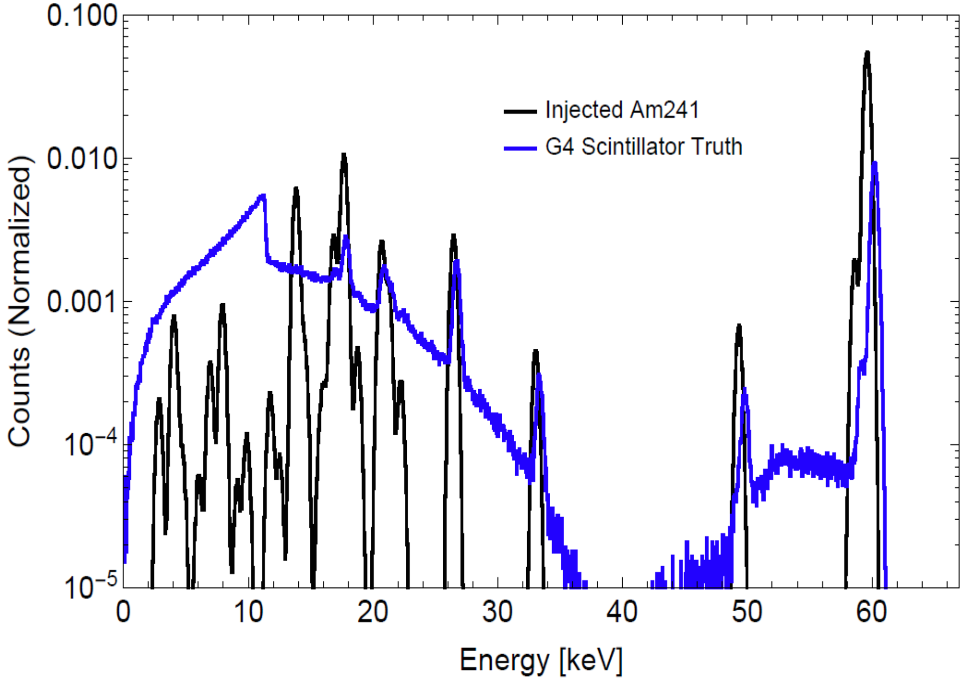




Efficiency Calibration

Am^{241}

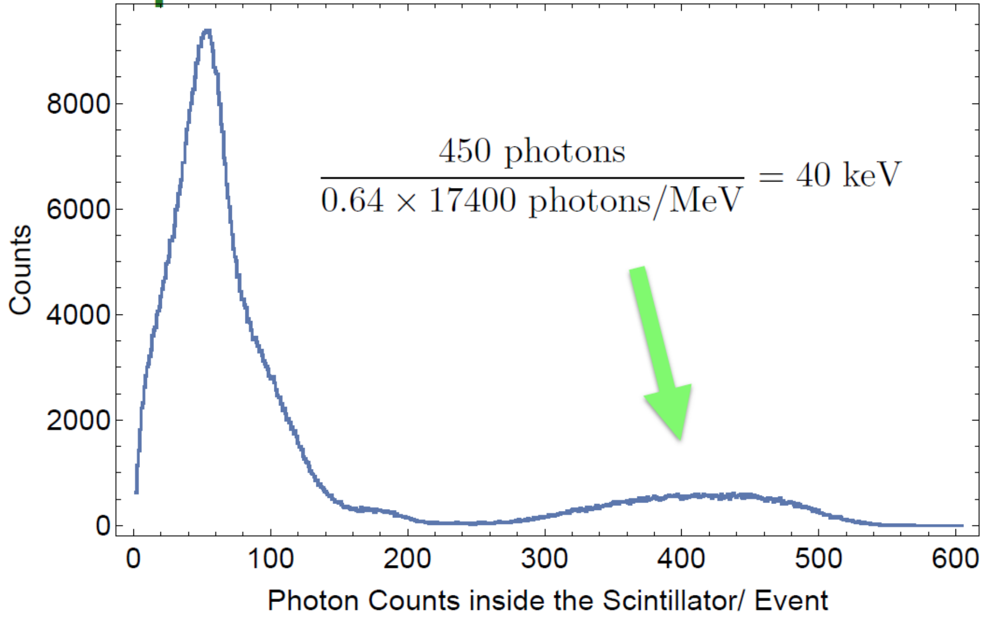
- Absolute calibration done using radioactive source, with known X-ray spectrum, at multiple points along each scintillator bar
- Full Geant4 simulation of X-rays in scintillator and creation / propagation of photons in bar
- By comparing to number of photo-electrons observed by PMT, can measure efficiency to ~25% accuracy
- Only done during accesses



LED pulsers

- PMT response monitored between calibrations via LED pulser system
- Can check *relative* efficiency during running periods, to ~few % accuracy

Truth Optical Photons Inside Scintillator



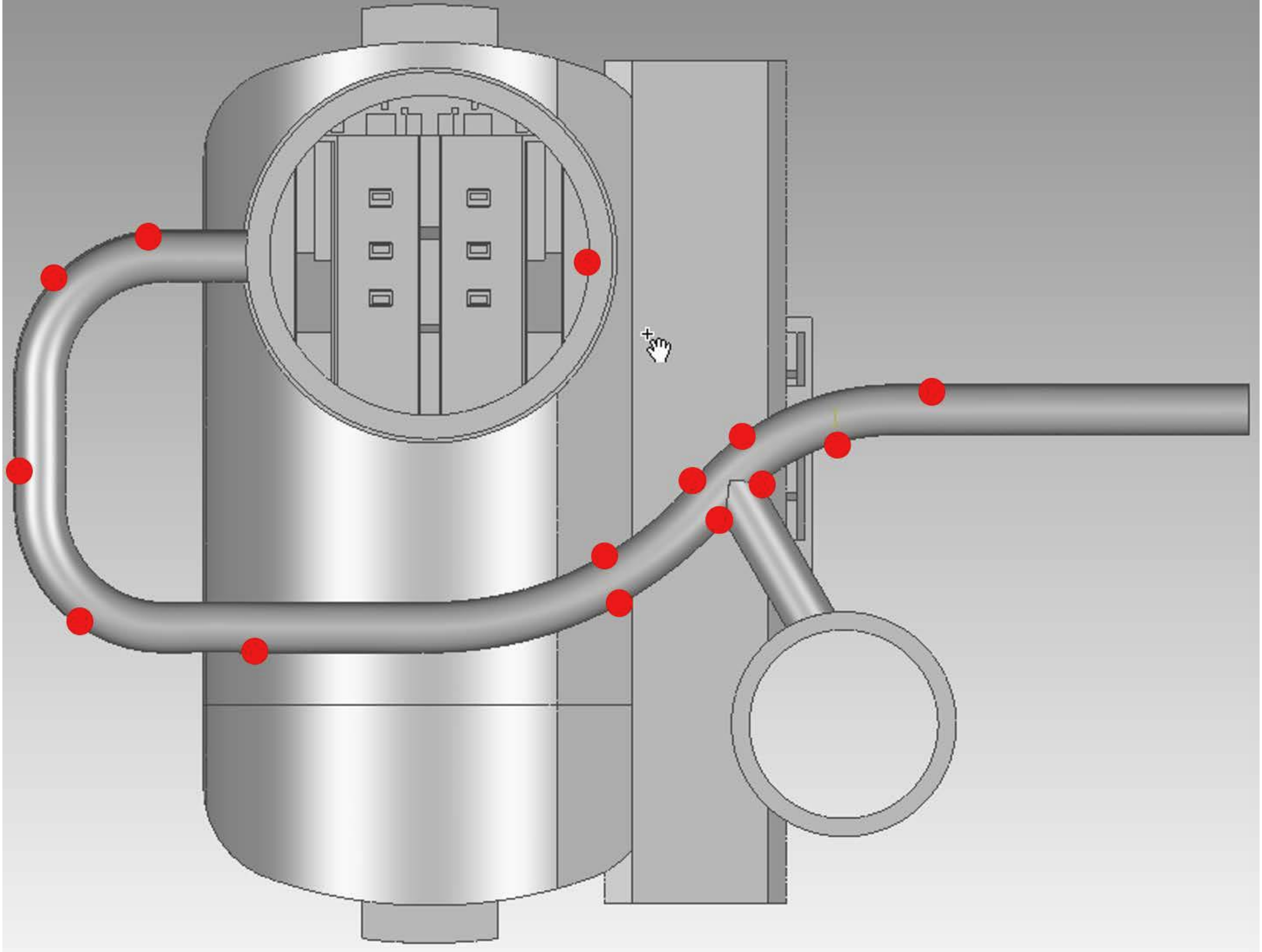
Put milliQan here!

Alignment

Special challenge, since far from IP with no line-of-sight!

CERN team heroically extended the CMS coordinate system into the tunnel, with ~mm precision

Center of milliQan goes here!



Alignment cross-check: **Measure muons from CMS collisions**

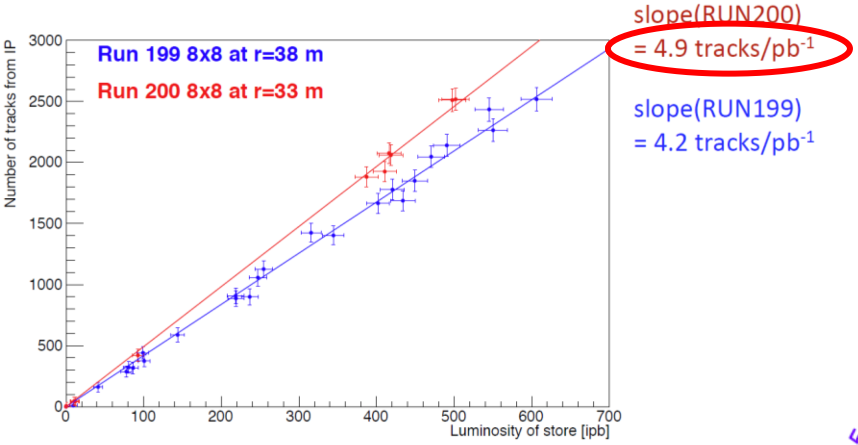
Two muon hodoscope detectors with arrays of 2x2x50 cm scintillator bars and SiPM readout

Rates agree with simulations to within 50%

About 10/hour with 1% mini-milliQan at L=1.4E34

Also can be used to "time-in" detector

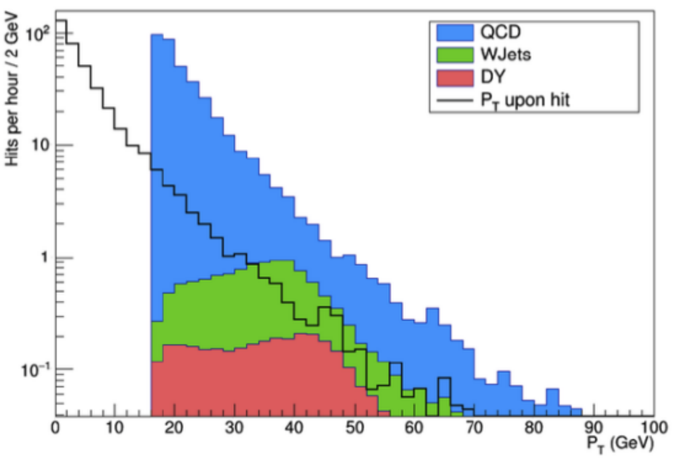
Number of muons vs Luminosity

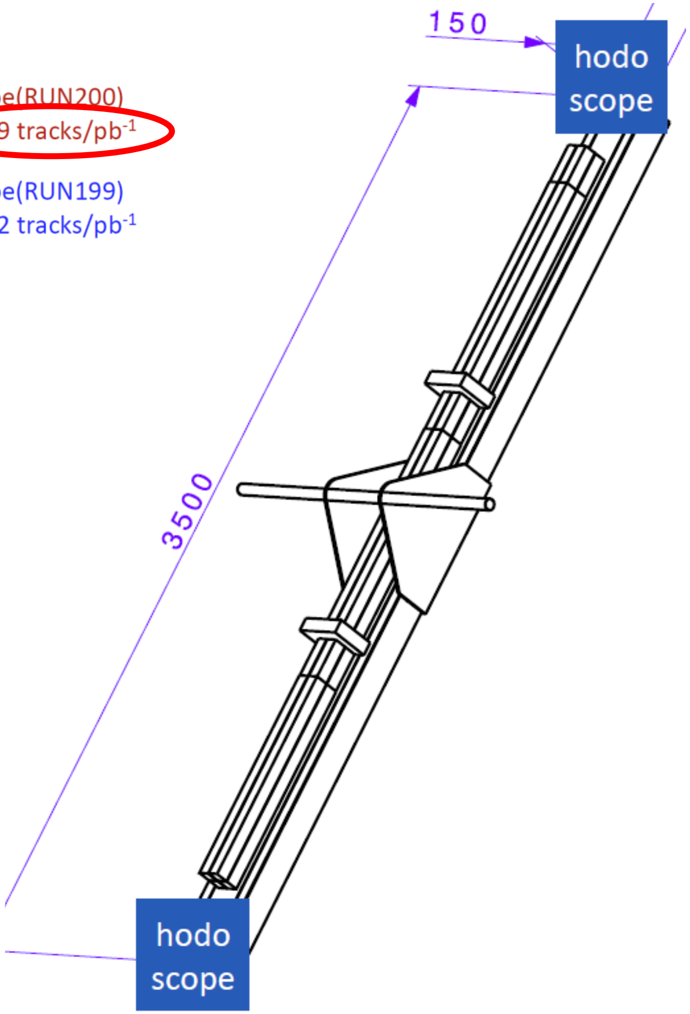


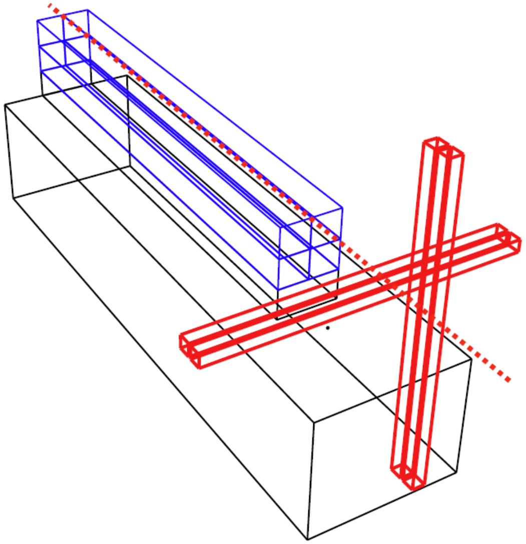
slope(RUN200) = 4.9 tracks/pb^{-1}

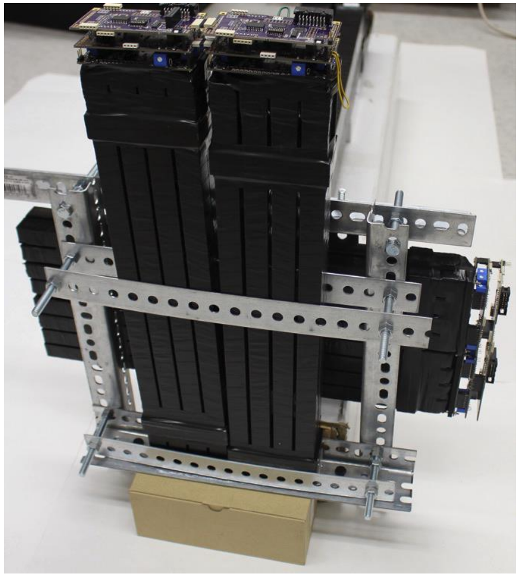
slope(RUN199) = 4.2 tracks/pb^{-1}

P_T (produced) of incident muons



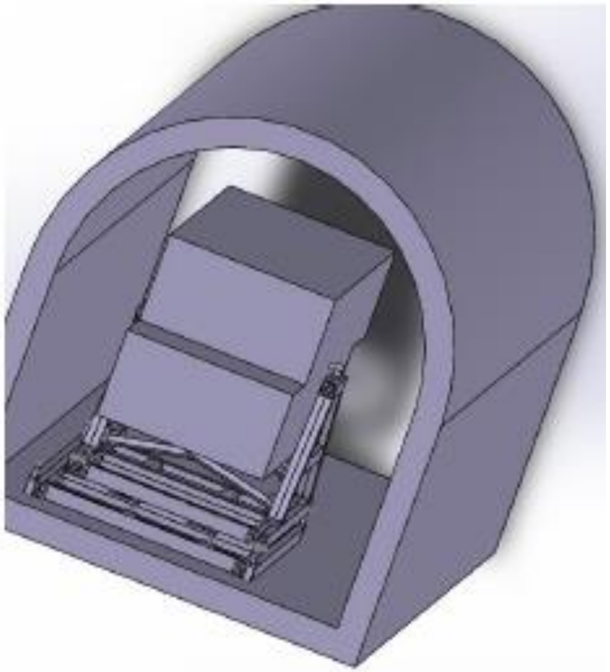


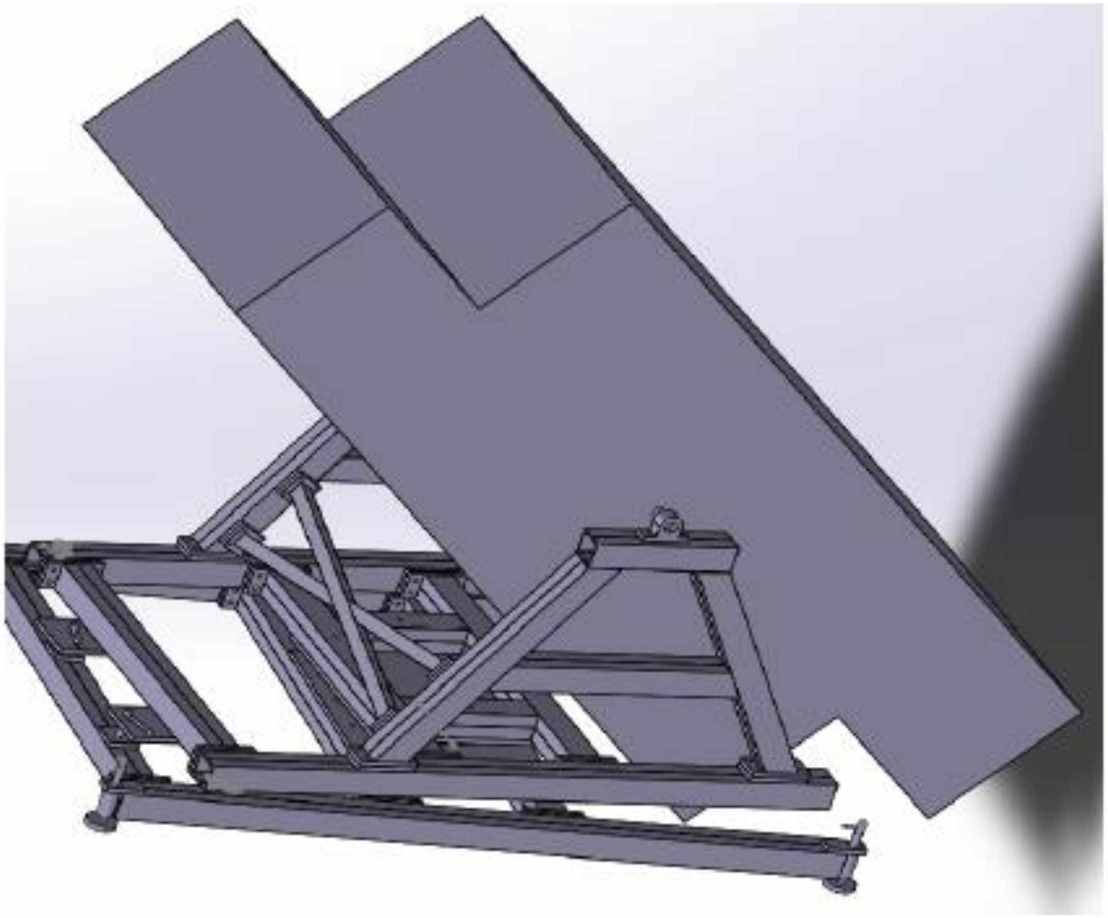


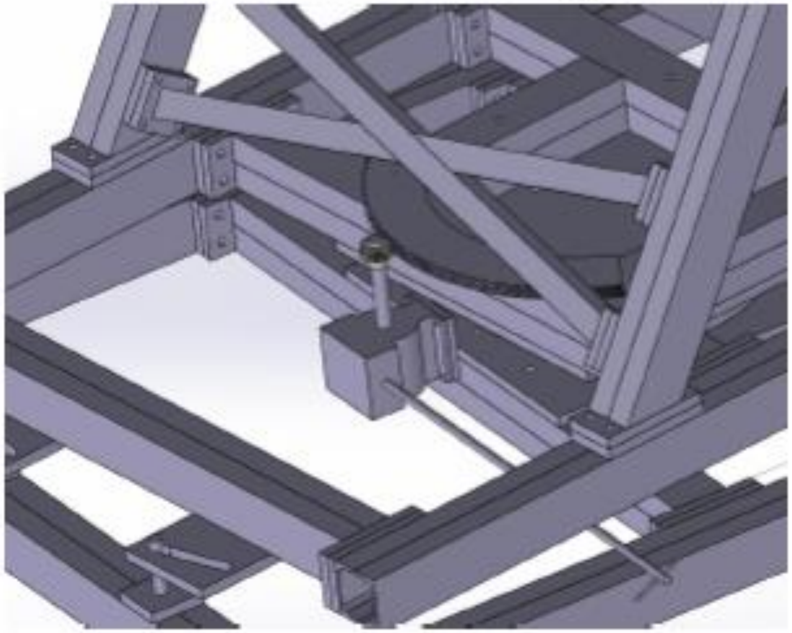


Support structure

- M. Gastal, R. Loos (CERN) working with engineers from Lebanese University on support structure
    - *Splitting in 2 gives much more clearance*







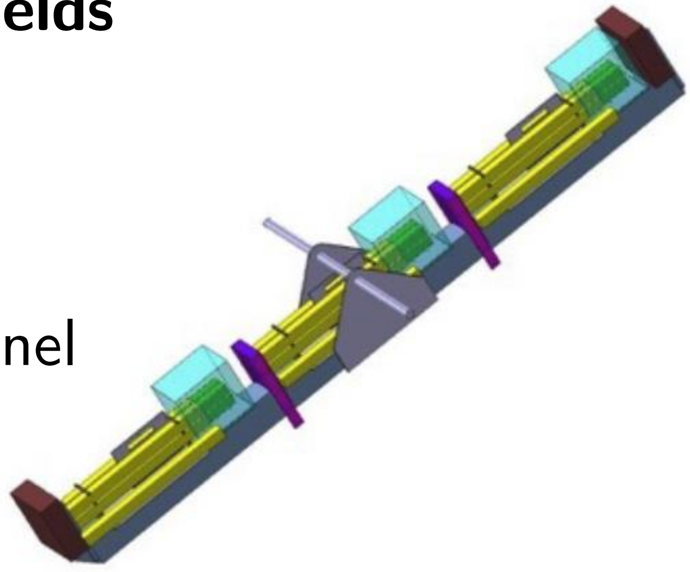
Support structure

Last month, in TS1, installed support structure in tunnel!

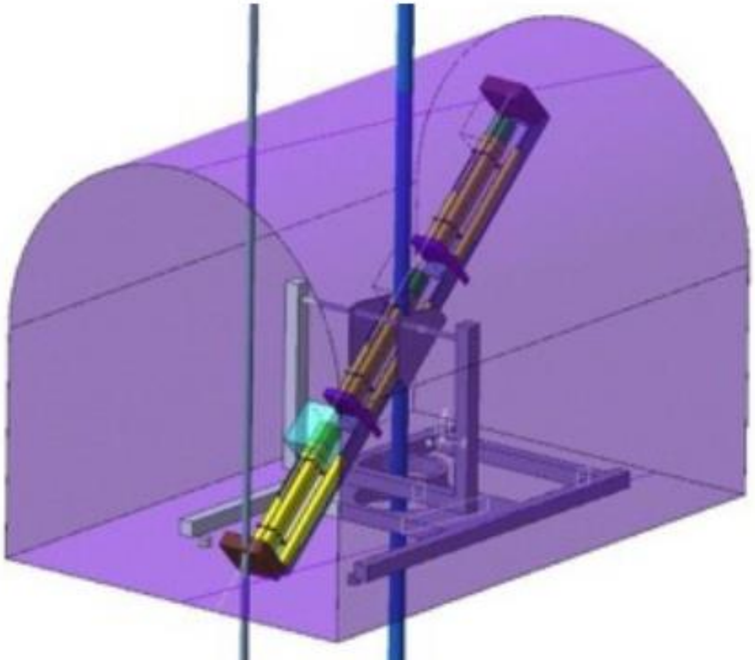
Can support, rotate, tilt, and align full 6-ton detector

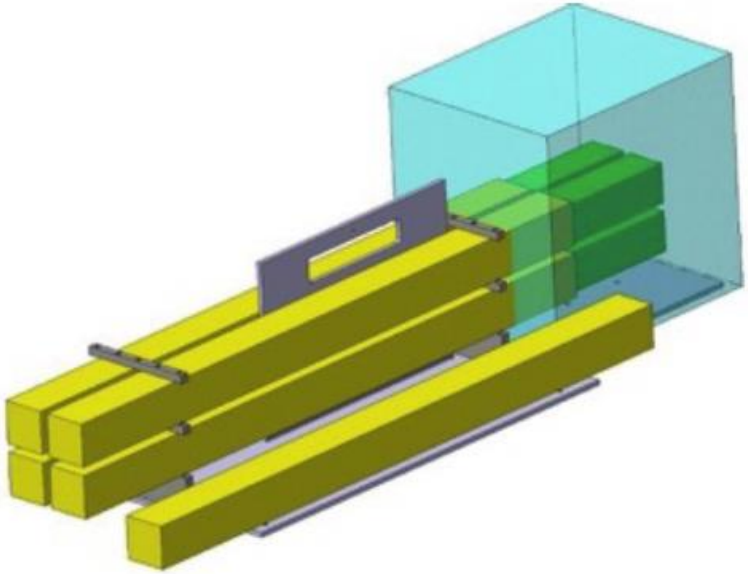
Next step: mini-milliQan demonstrator test

Fall 2017 – end of 2018:
1% test of milliQan in tunnel, with 12 full scintillators and PMTs, plus 2 hodoscopes, and some muon veto shields

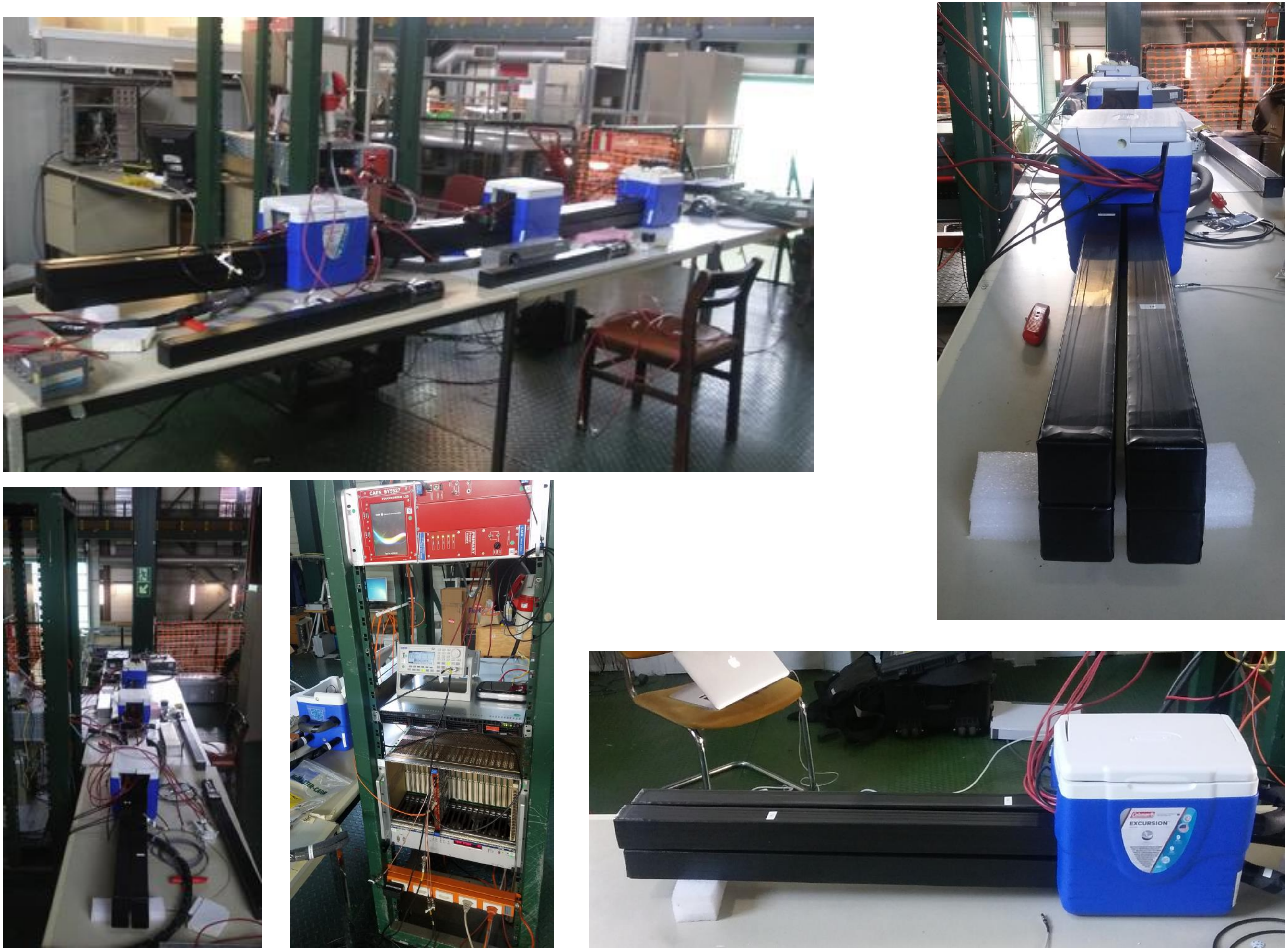


- Install in tunnel Sept. 18-20!!
- Get some collision data this year and should have plenty in 2018
- Learn about operating experiment in the tunnel
- Measure backgrounds, check alignment
- New heavy milli-charge particle sensitivity?





This week: 1% mini-milliQan commissioned in SX5



milliQan Collaboration

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Itay Yavin


Eder Izaguirre

THE UNIVERSITY OF CHICAGO


David Miller

KIT
Karlsruhe Institute of Technology

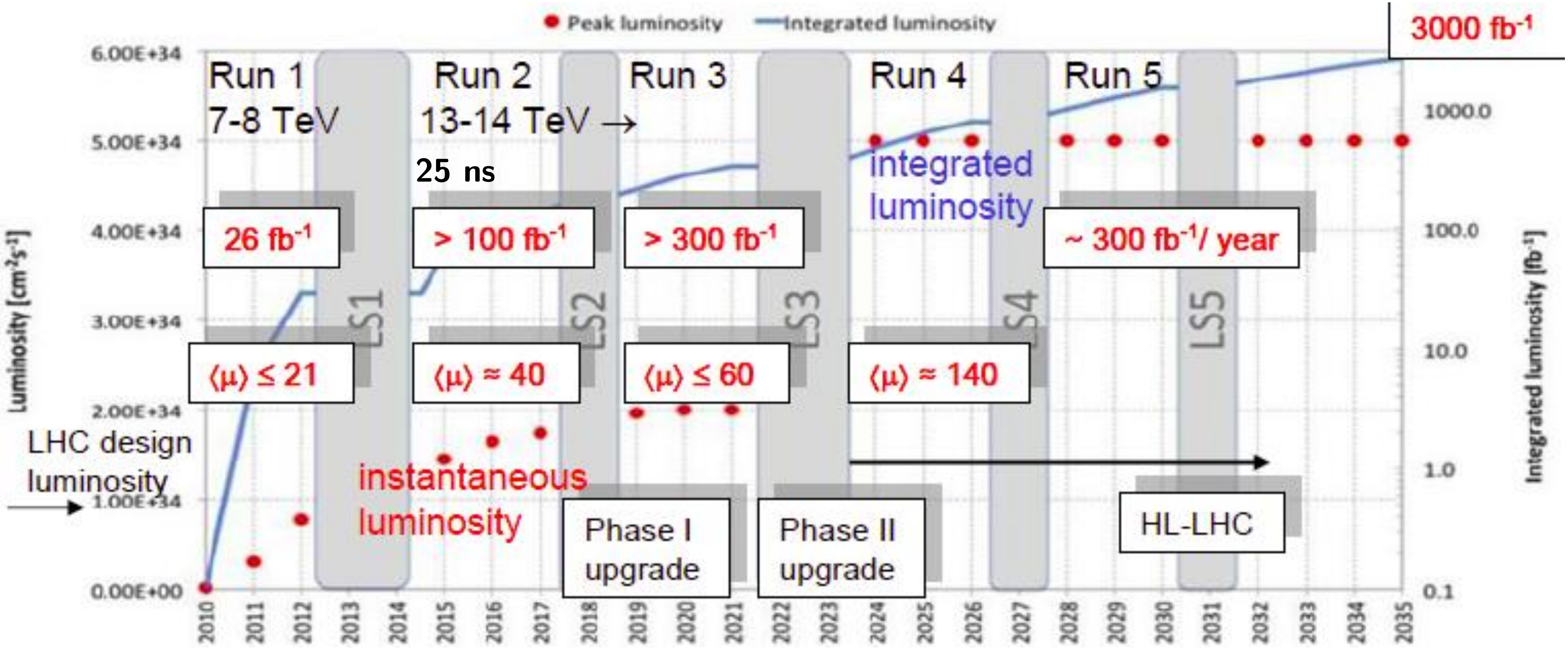

Ralf Ulrich

BROOKHAVEN NATIONAL LABORATORY

...plus many fantastic postdocs and students!

LHC and milliQan Schedule

- Higgs boson discovered in Run1
- Currently in Run2 -> Collect ~10/fb this year and ~40/fb by end of 2018
- Hope to complete full milliQan detector in time for Run3, collect ~300/fb
- Then HL-LHC milliQan upgrade ☺



Summary

MilliQan is a new LHC detector for milli-charged particles
Cover m = 0.1 – 100 GeV for q = 0.002 – 0.3 e by 2022

More generally, milliQan is the first detector sensitive to small ionization (single PE's) at the LHC (or any collider?)

- Potentially sensitive to other signals / models as well...

Detector design basically complete, and components tested in the lab

Thanks to support from CMS and CERN technical staff, milliQan is moving forward...

- Support structure and other infrastructure installed in the underground tunnel
- 1% milliQan test to be installed during TS2 (Sept. 18-20, 2017)!

Personal note: small collaboration and building a new experiment "from scratch" has been super fun and educational!