

Test Beam Performance Measurements of Novel Thin Gap Detectors for the ATLAS Experiment Upgrade

2015 CAP Congress
Edmonton, AB

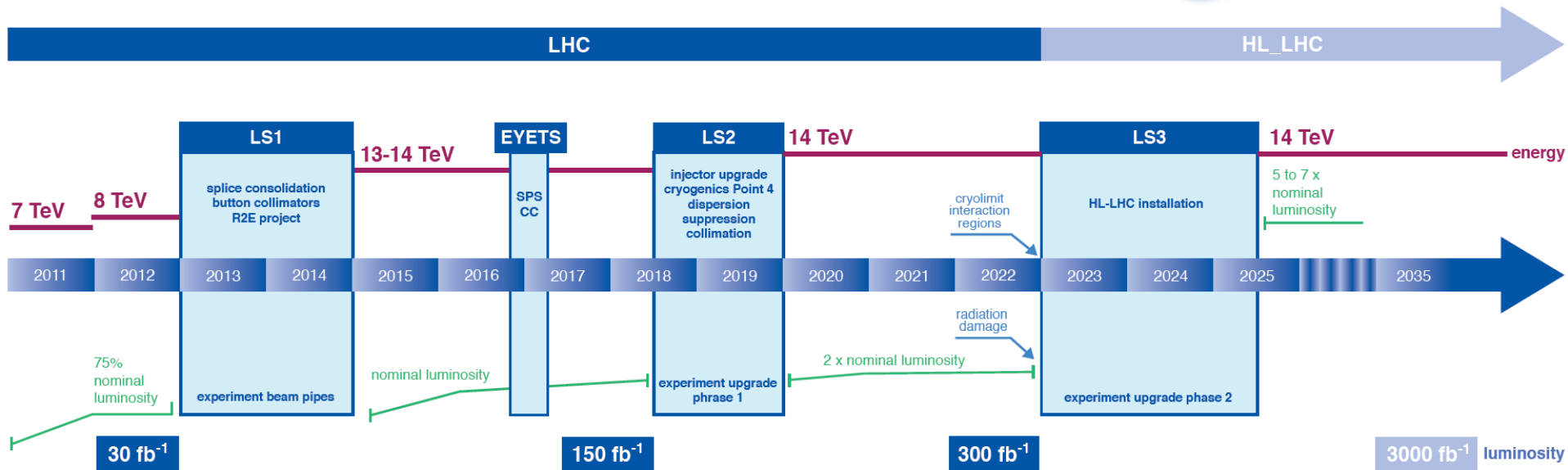
Sébastien Rettie, University of British Columbia & TRIUMF
on behalf of the ATLAS New Small Wheel Group



Outline

- Motivation
- The New Muon Small Wheel Upgrade
 - small-strip Thin Gap Chambers (sTGC)
- Full-size Prototype Test Beam at FNAL
 - Experimental Setup
 - Results
- Summary and Outlook

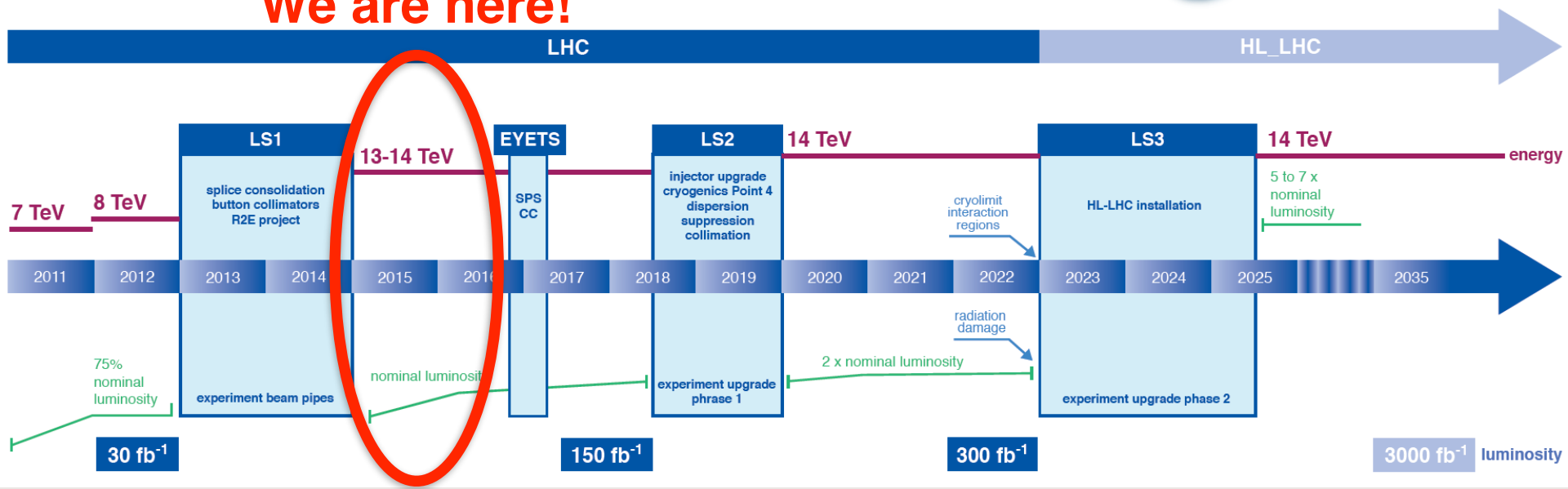
LHC / HL-LHC Plan



Harsher Conditions at the LHC

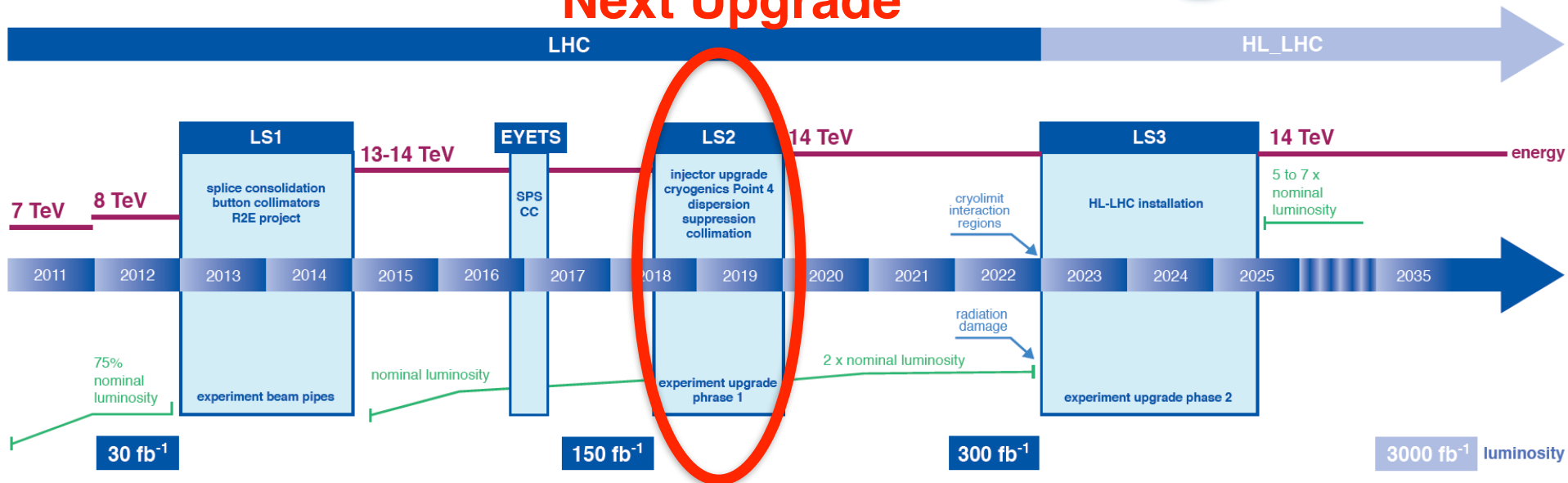
LHC / HL-LHC Plan

We are here!



Harsher Conditions at the LHC

LHC / HL-LHC Plan Next Upgrade



Trigger Bandwidth Limitations in ATLAS

- ATLAS subsystems level 1 readout bandwidth: 100 kHz.
- Allowed level 1 bandwidth for muon triggers: 20 kHz.
- Two options:

<i>Trigger Rate</i>	<i>Muon $p_T > 20$ GeV</i>	<i>Muon $p_T > 40$ GeV</i>
<i>Without NSW</i>	<i>60 kHz</i>	<i>29 kHz</i>
<i>With NSW</i>	<i>22 kHz</i>	<i>10 kHz</i>

Trigger Bandwidth Limitations in ATLAS

- ATLAS subsystems level 1 readout bandwidth: 100 kHz.
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- Two options:
 - Reduce number of events with real muons, but miss interesting events (e.g. $H \rightarrow \tau\tau$ with one τ decaying into a muon).

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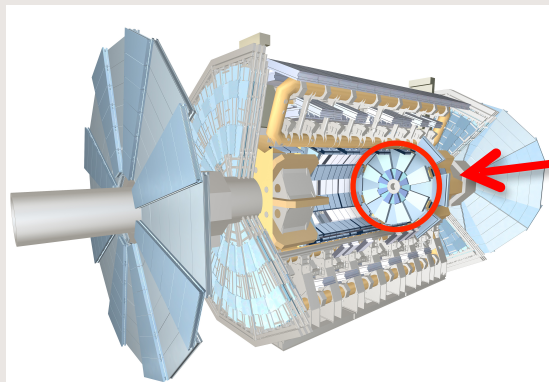
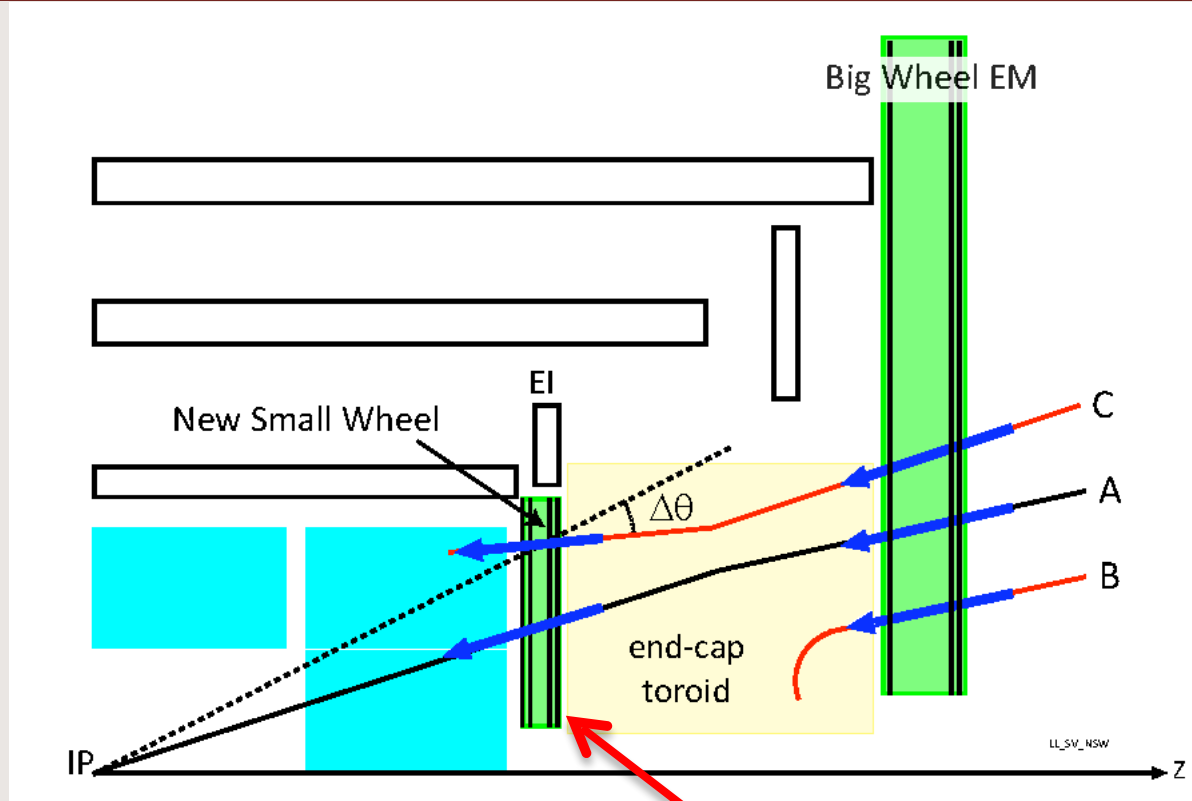
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- Two options:
 - Reduce number of events with real muons, but miss interesting events (e.g. $H \rightarrow \tau\tau$ with one τ decaying into a muon).
 - Improve the trigger system: New Small Wheel (NSW)!

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The New Muon Small Wheel (NSW)

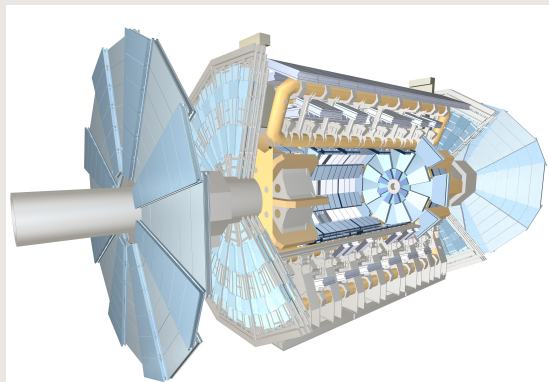
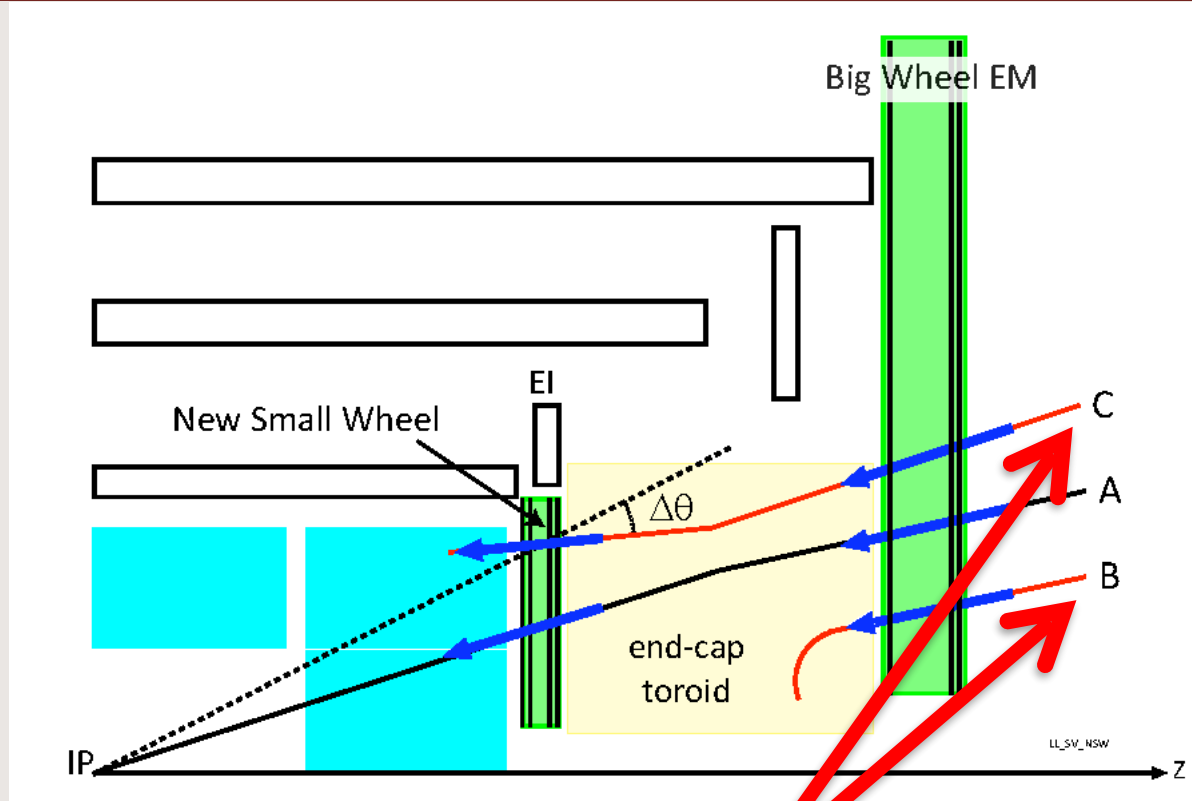
- Current Small Wheel triggers on A, B, and C tracks.
- NSW will only keep A tracks.
- B tracks will be rejected because there is no matching track in the NSW.
- C tracks will be rejected because the NSW track does not point to the interaction point.



“Small Wheel”

The New Muon Small Wheel (NSW)

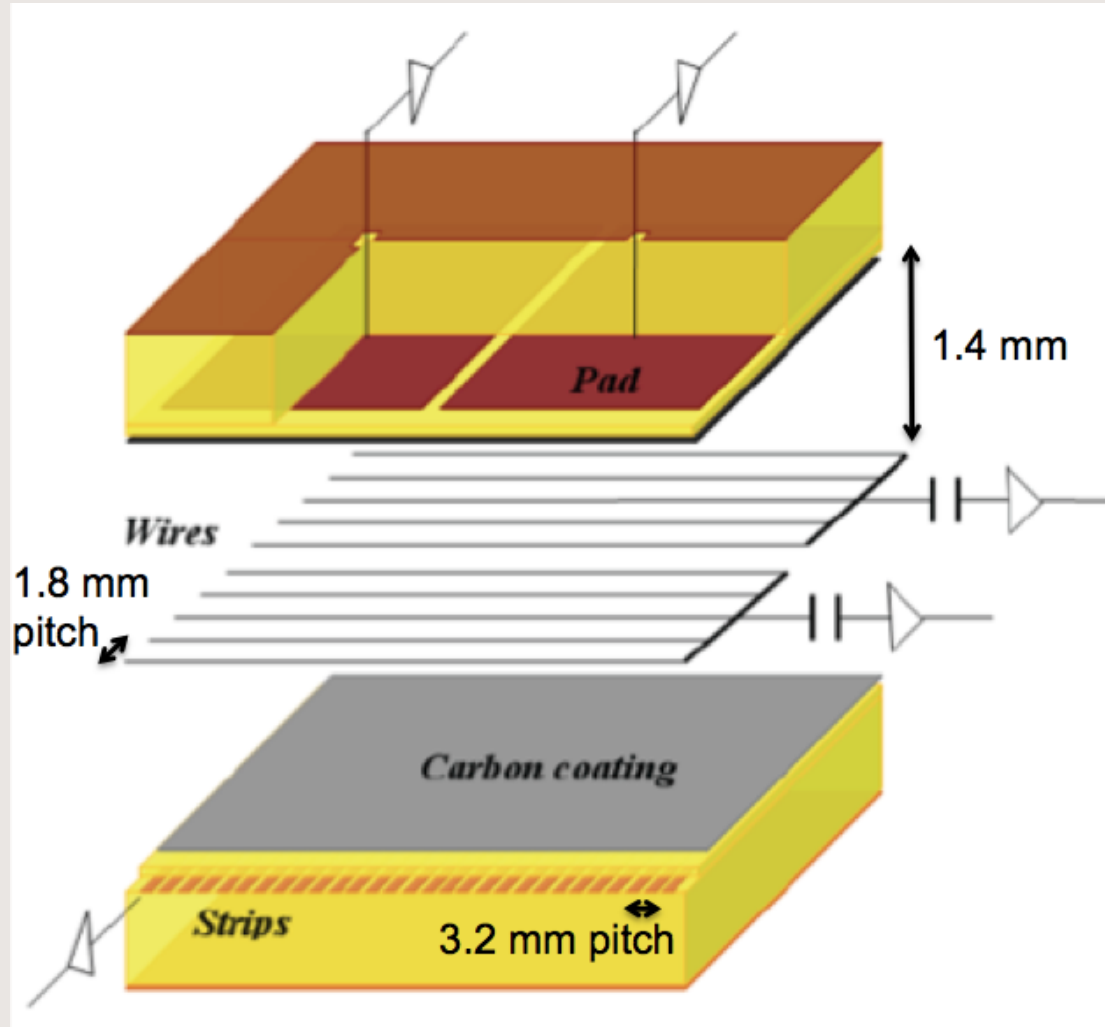
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Fake (unwanted) triggers

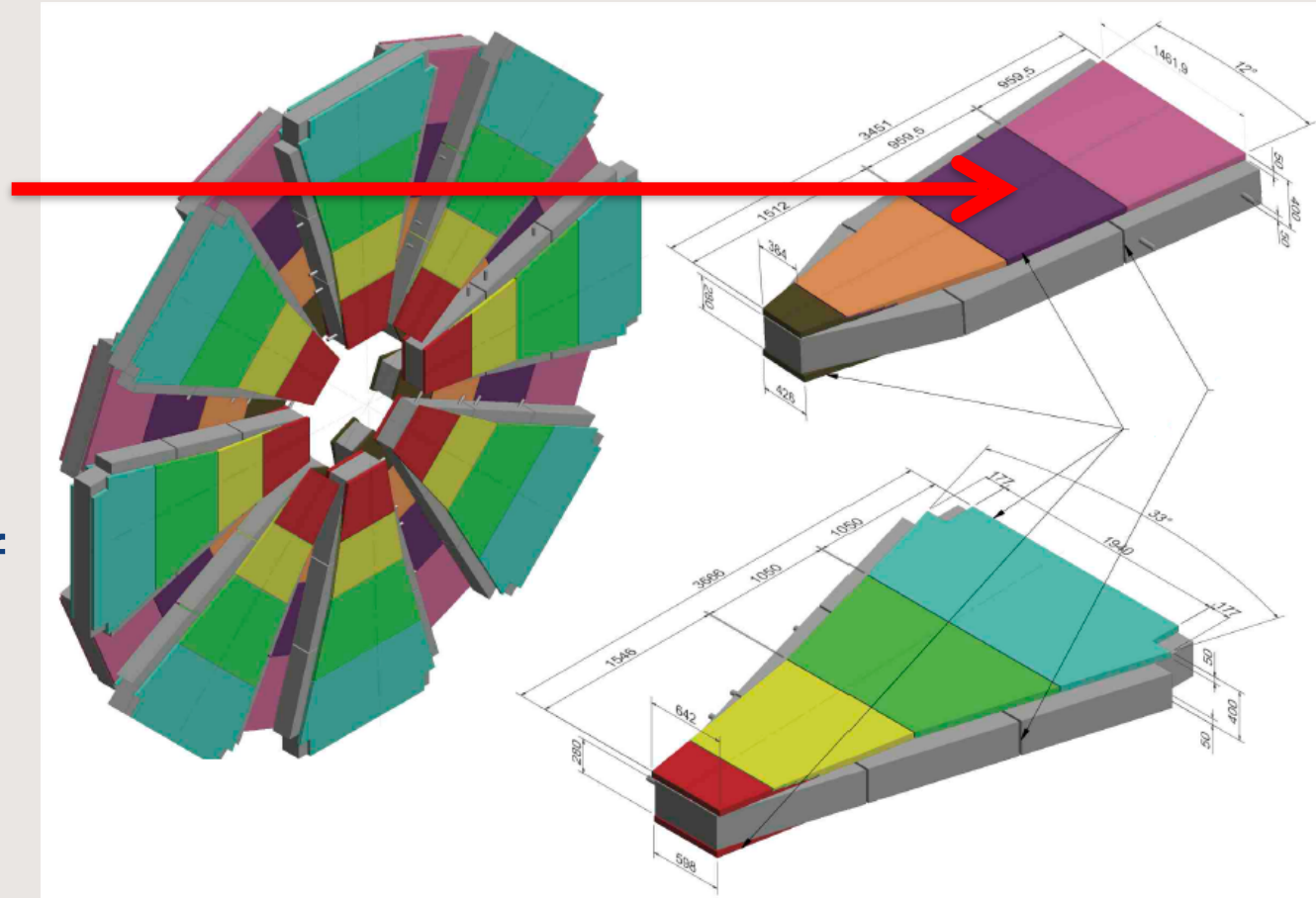
small-strip Thin Gap Chambers (sTGC)

- Gas mixture flows in sTGC: n-pentane / CO₂ (45% / 55%).
- Cathode: Pads and Strips.
- Anode: Wires.
- Readout the **pads** for **triggering**.
- Readout the **strips** and **wires** for **tracking**.
- Signal related to charge deposited on pads and strips.
- 64 channels per readout chip (VMM).



“Module -1”

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- Prototype sector of the NSW
- Composed of 4 sTGC layers

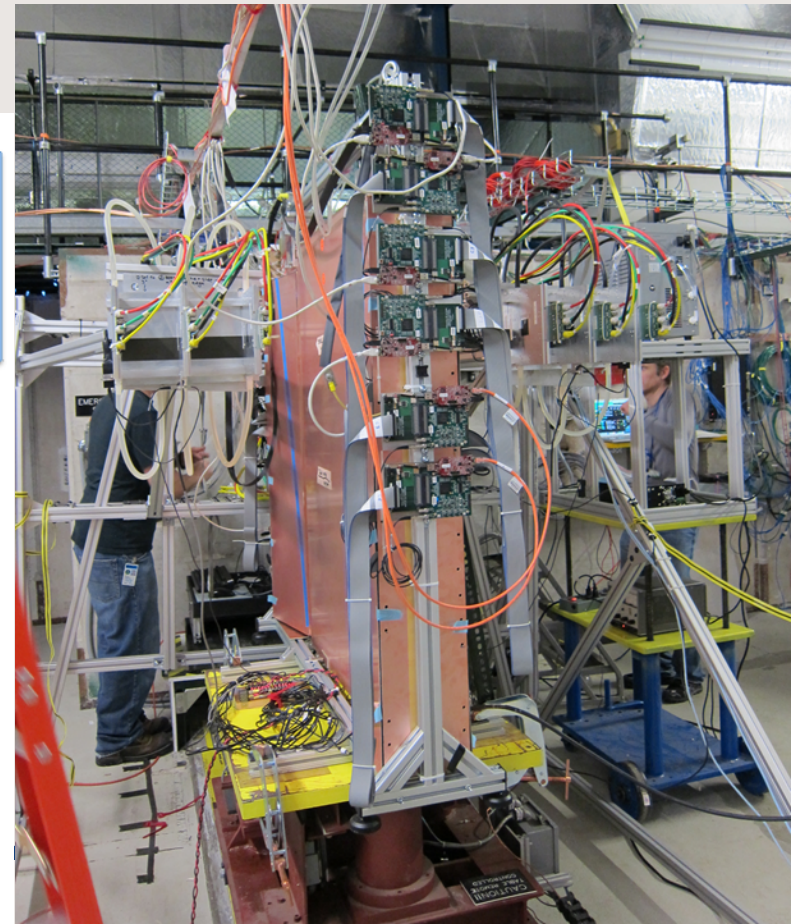
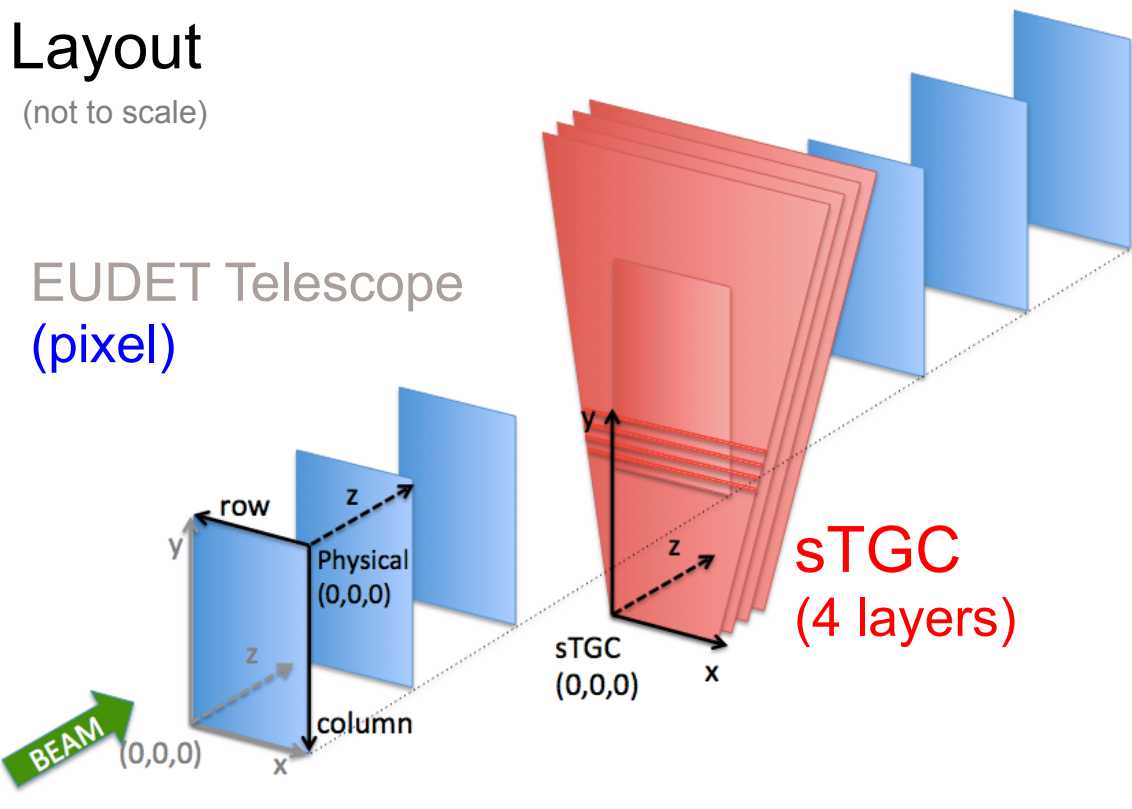


Fermilab Test Beam (May 2014)

- 32 GeV pion beam
- Pixel Telescope
- Module -1
- Readout (VMM1)
- Motion Table

Layout

(not to scale)

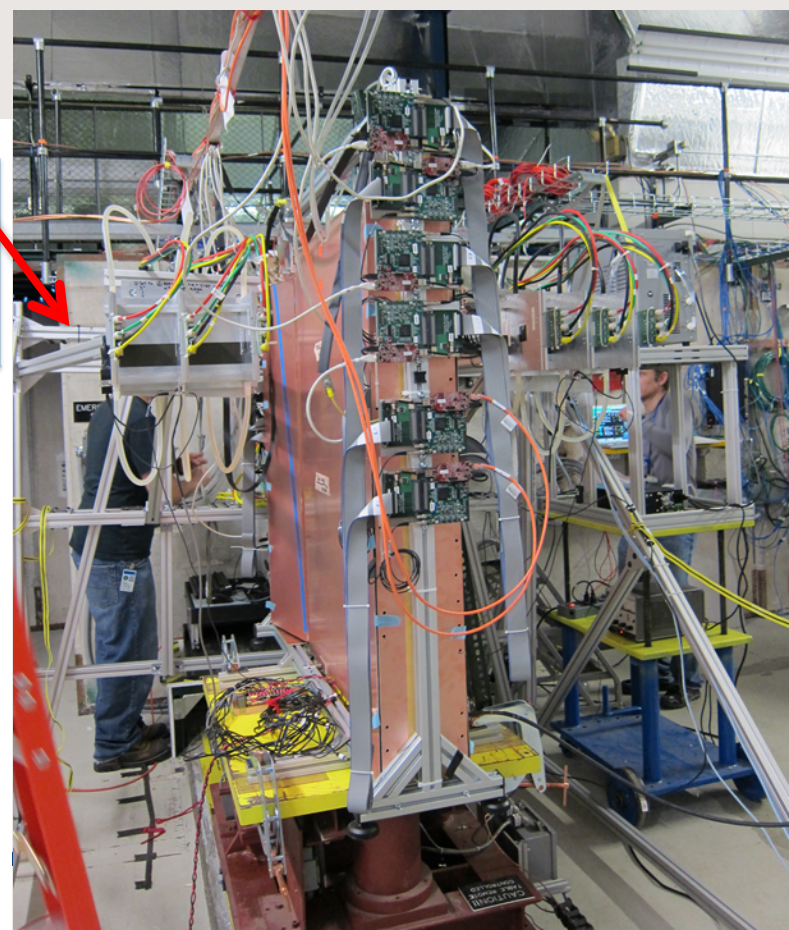
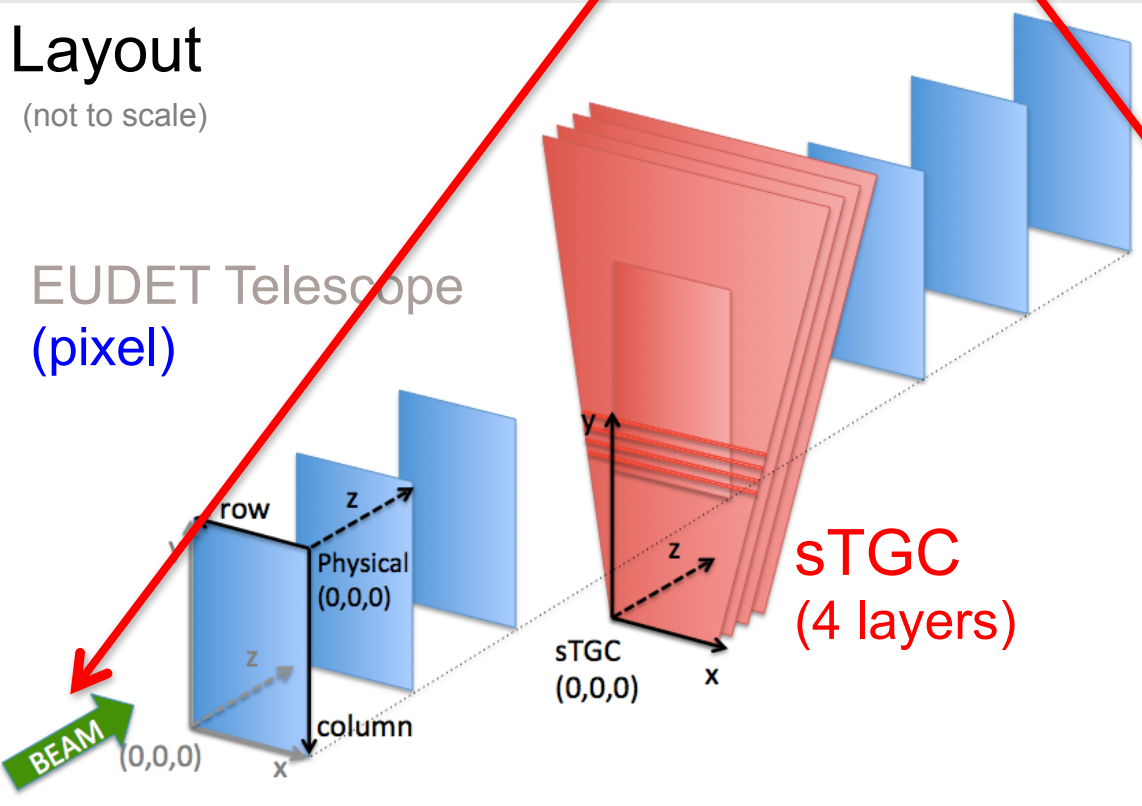


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EUDET Telescope
(pixel)

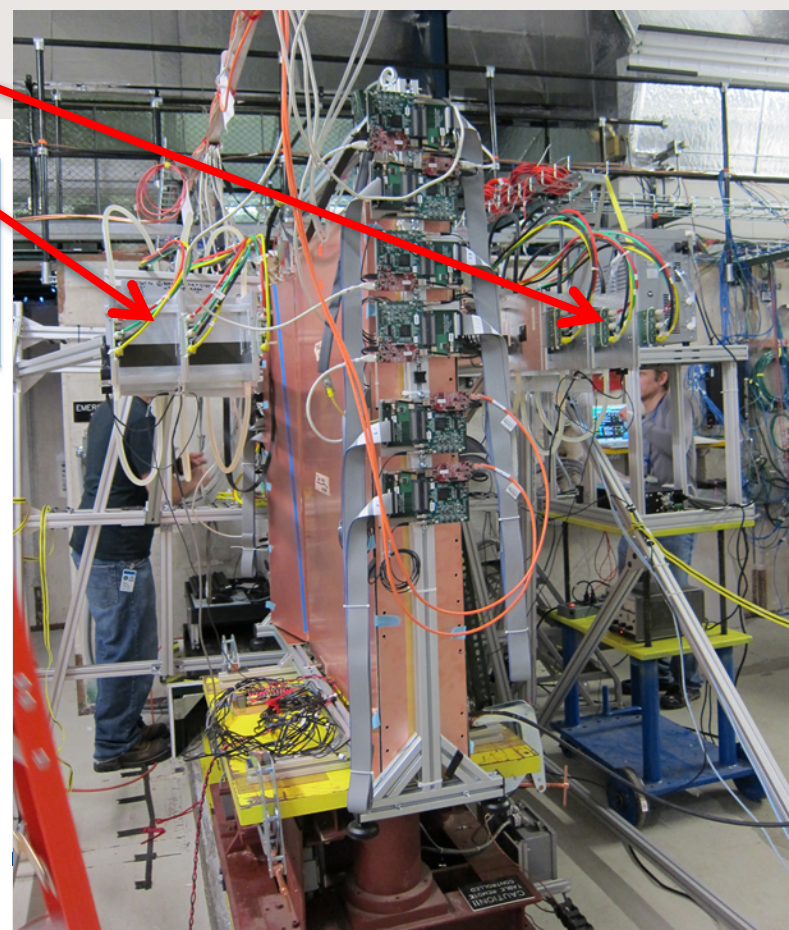
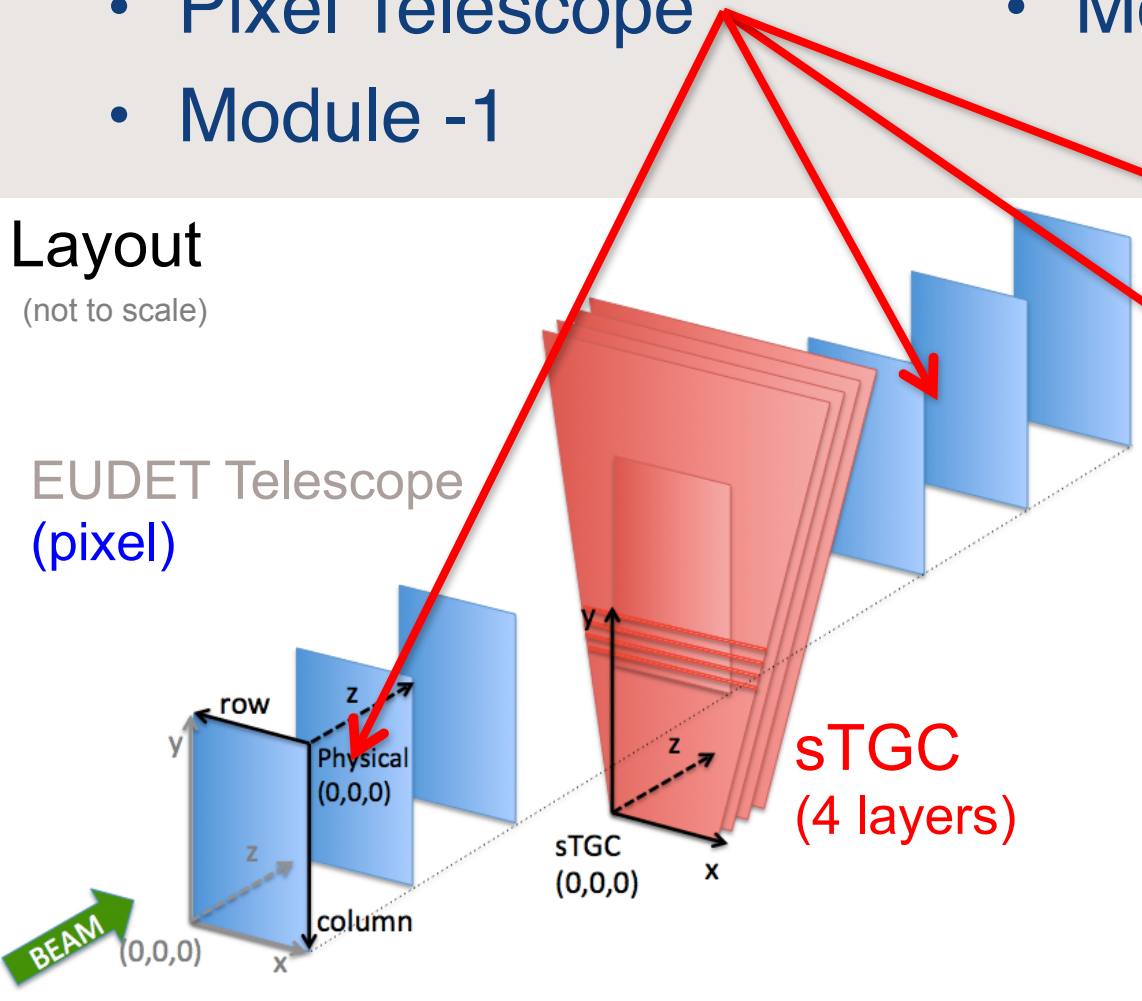


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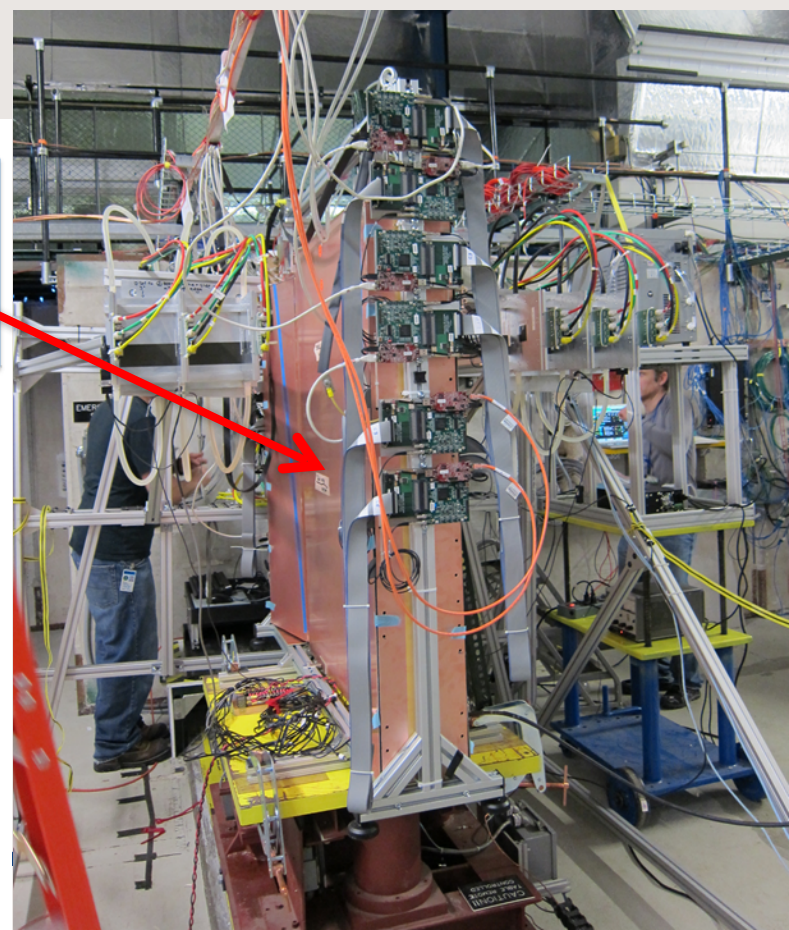
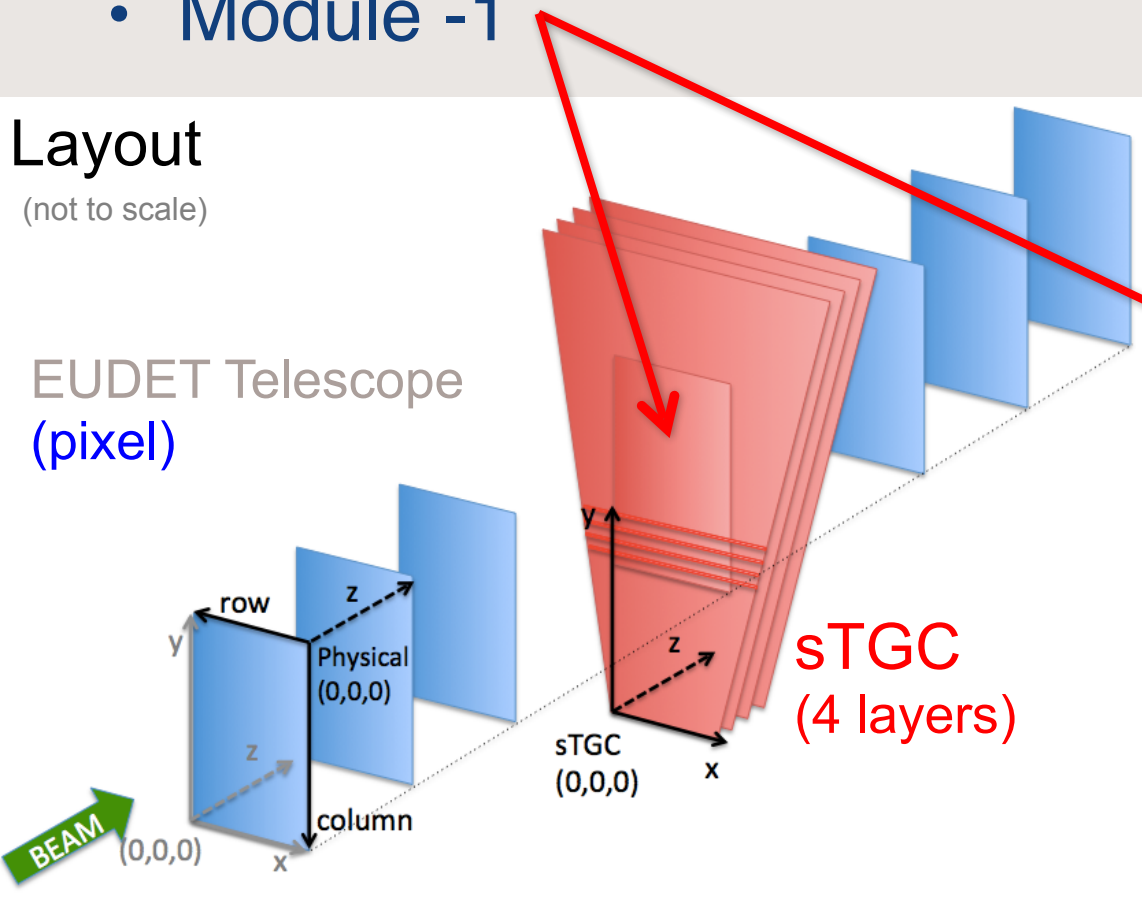


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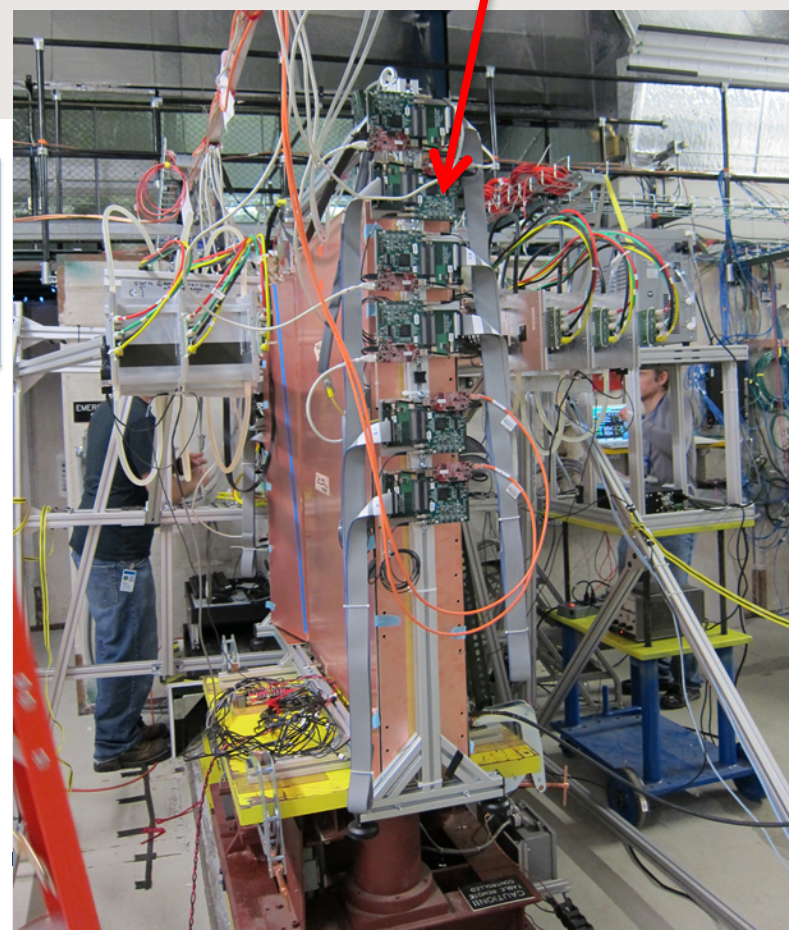
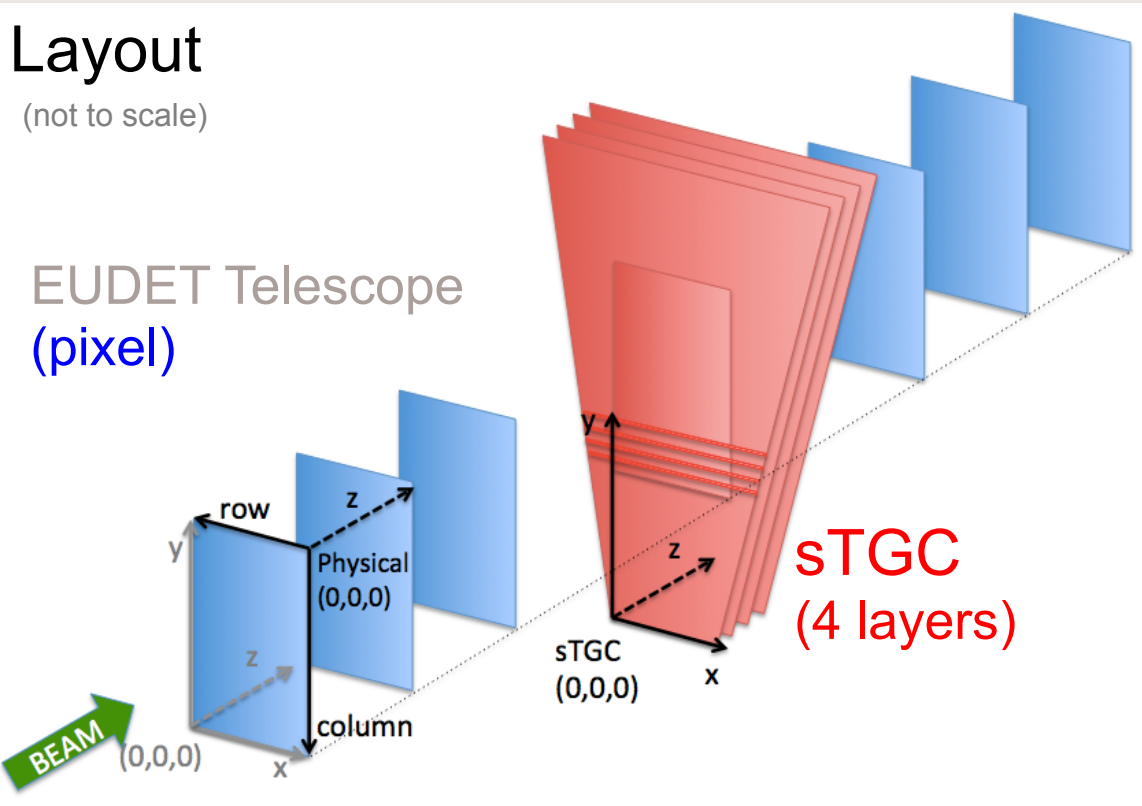


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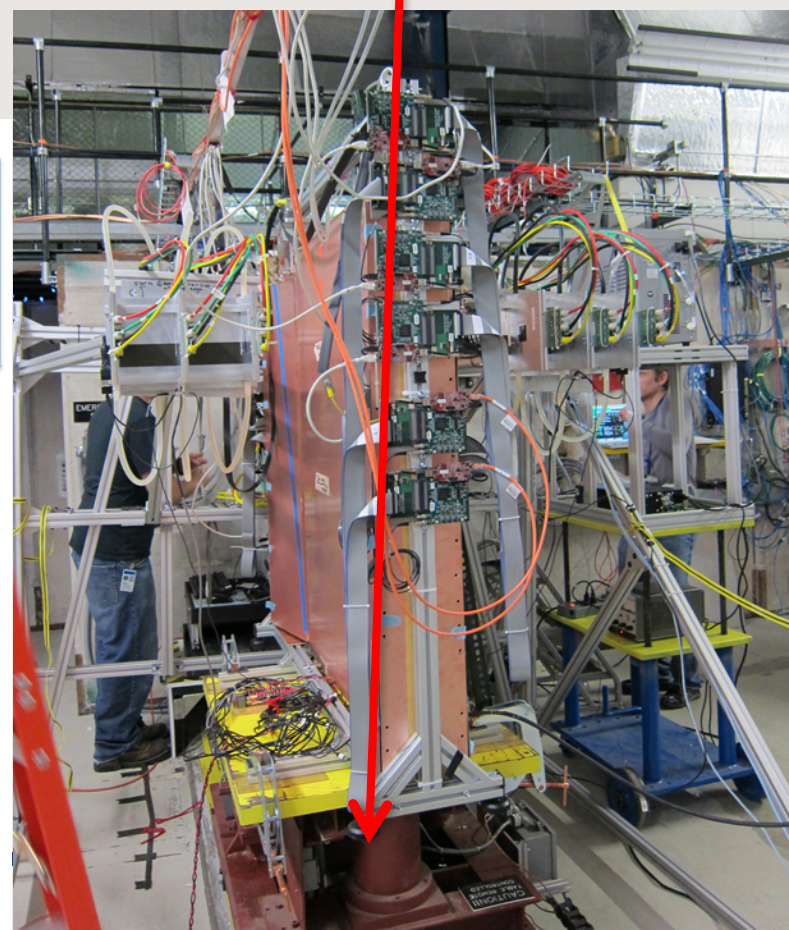
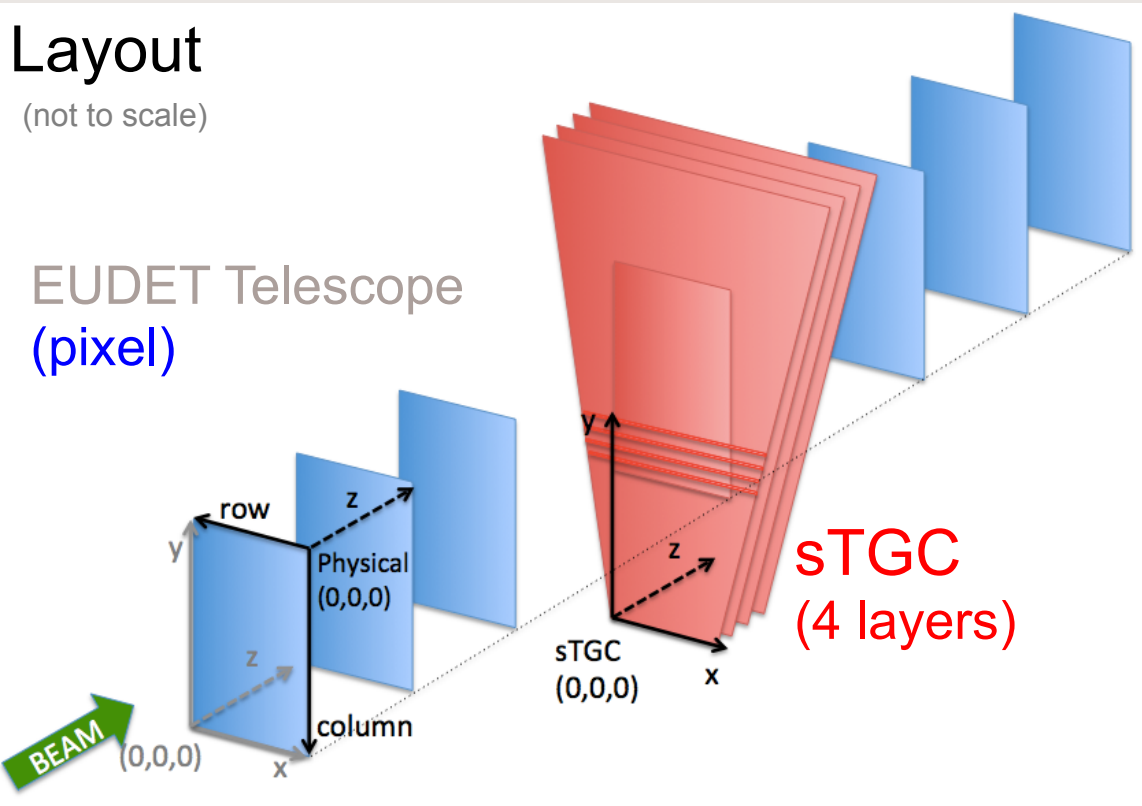


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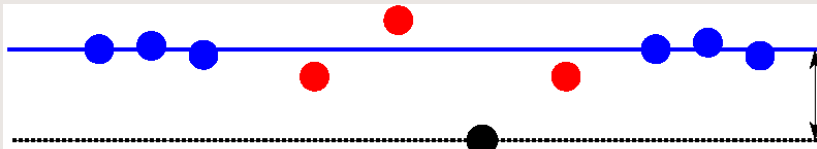
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EUDET Telescope (pixel)

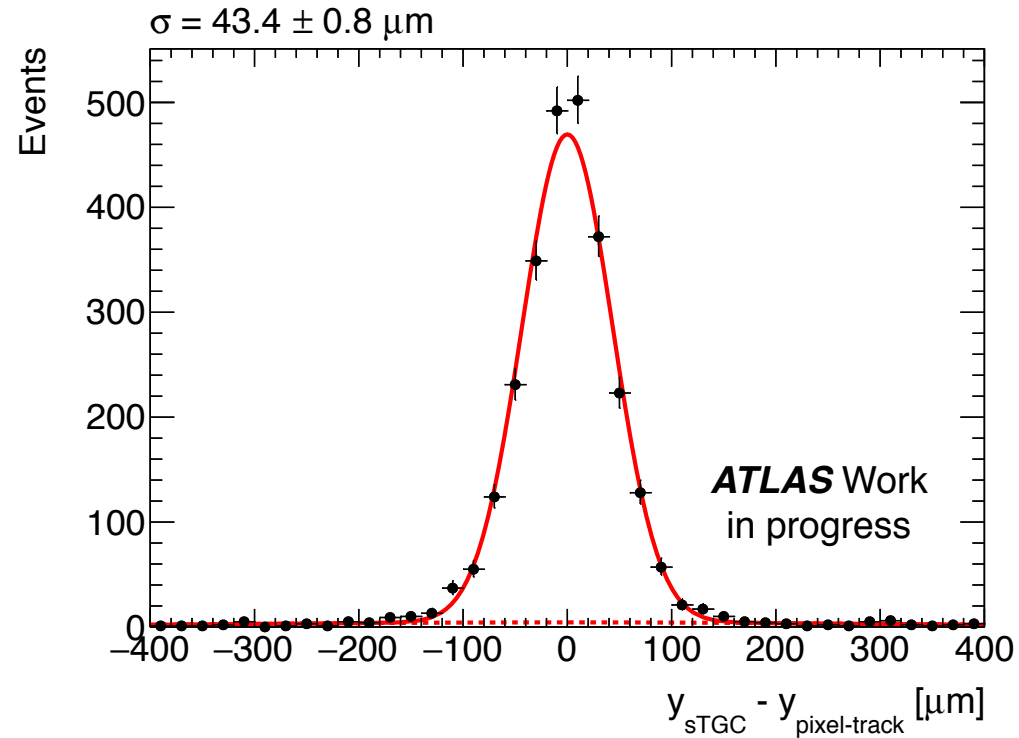


Pixel Telescope

- Each telescope plane has $\sim 5 \mu\text{m}$ resolution
- 6 telescope planes total

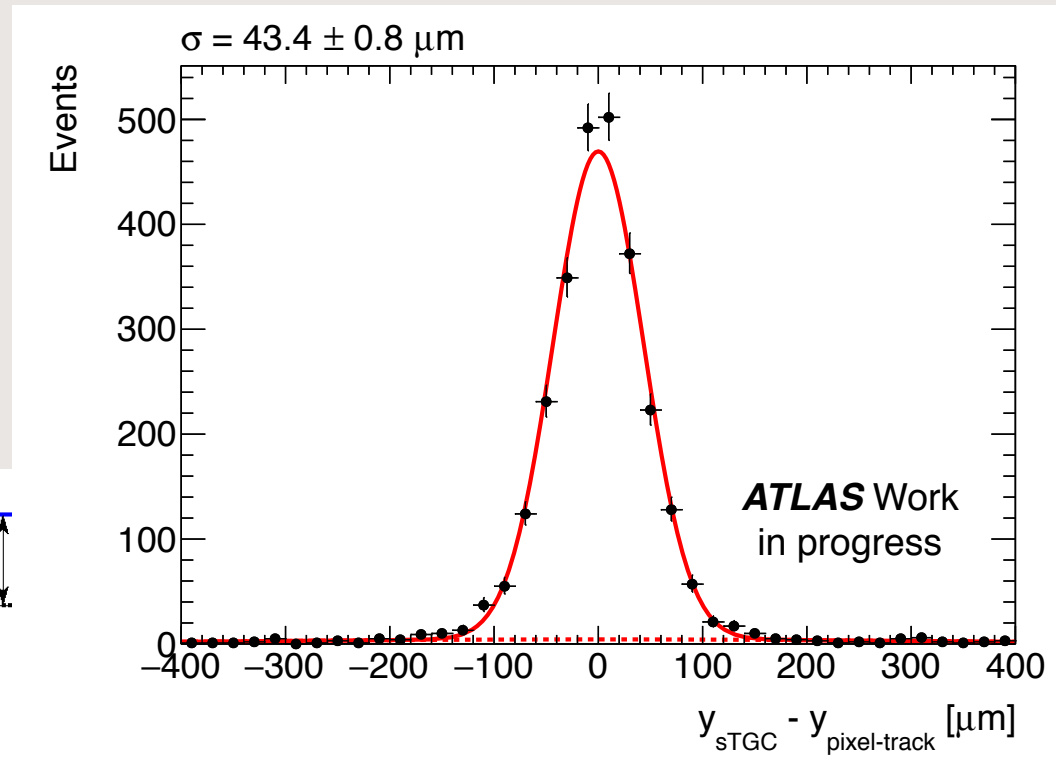
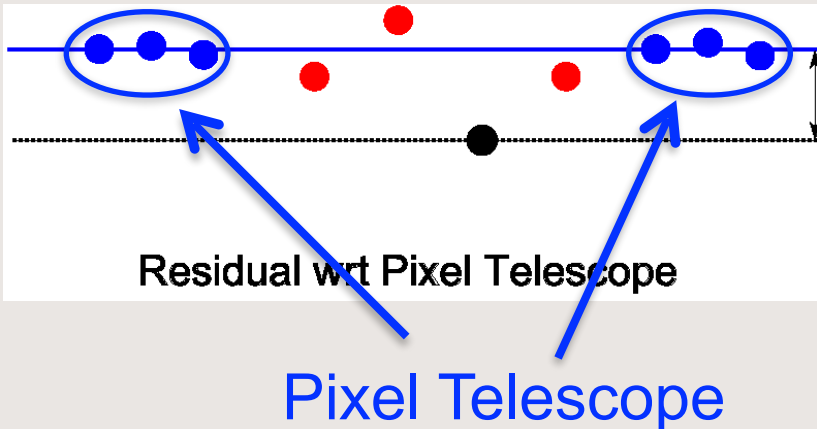


Residual wrt Pixel Telescope



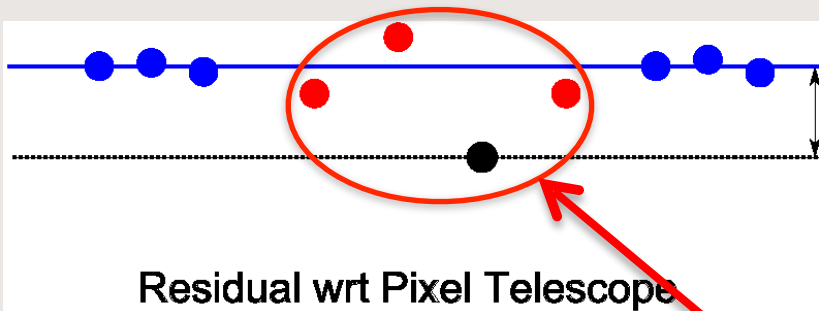
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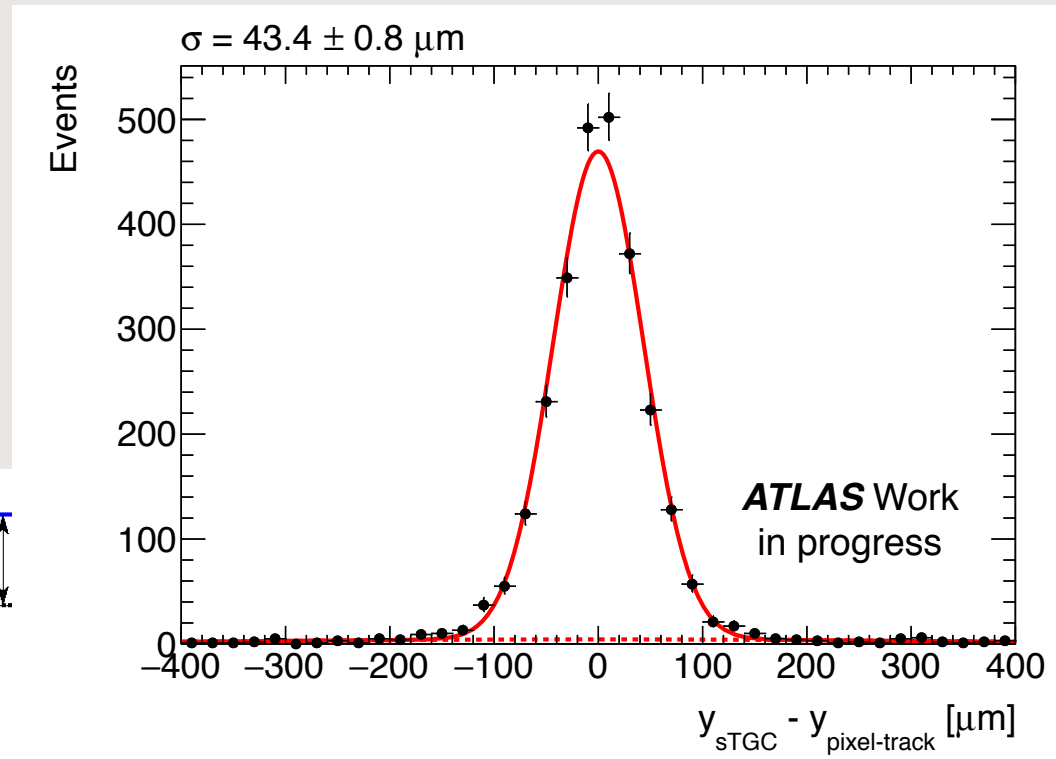


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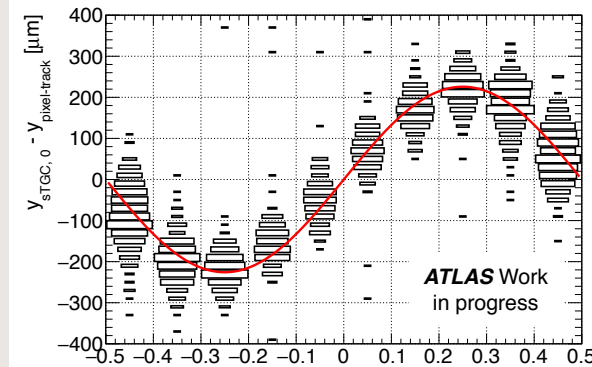
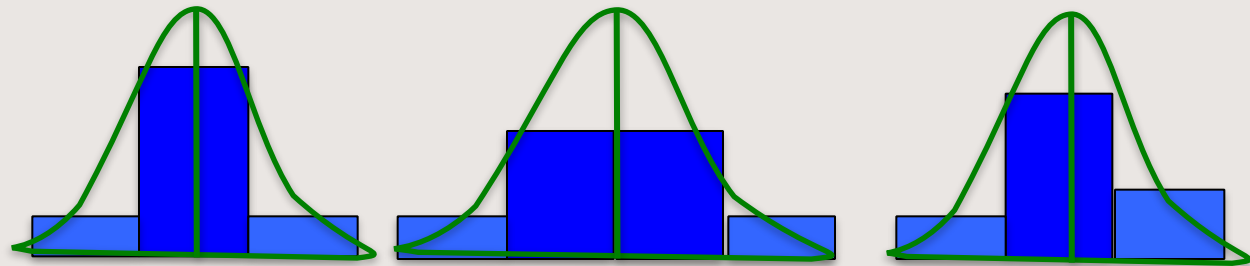


Module -1

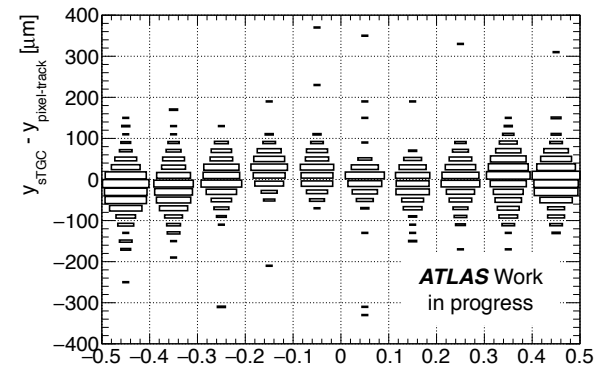


“S-shape” Correction

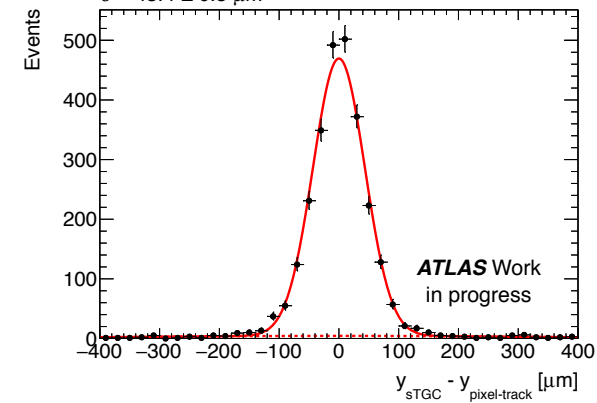
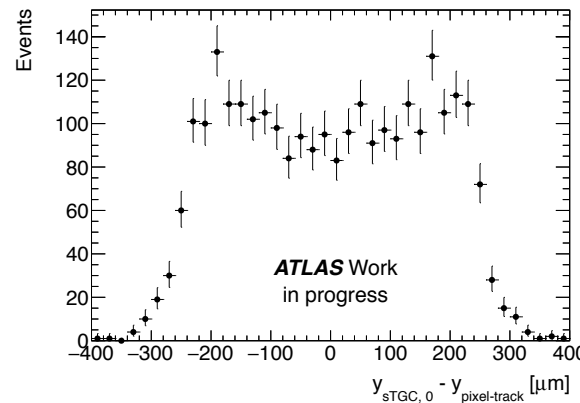
- Y-axis: difference between strip cluster mean and pixel track cluster
- X-axis: difference between strip cluster mean and closest gap
- Deviation of the expected hit position from the measured one depends on the hit position
- Differential non-linear effect



Before

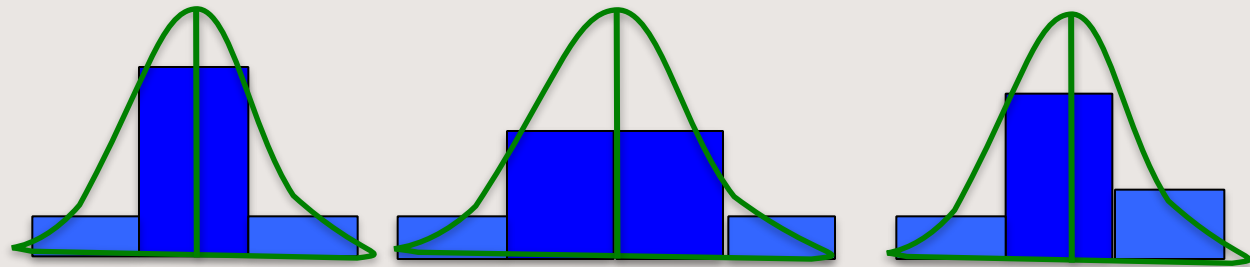


After

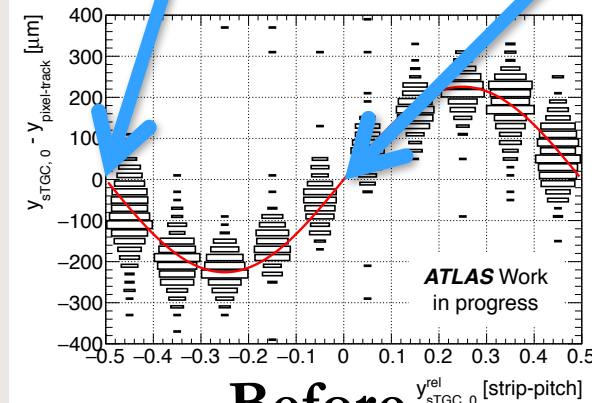


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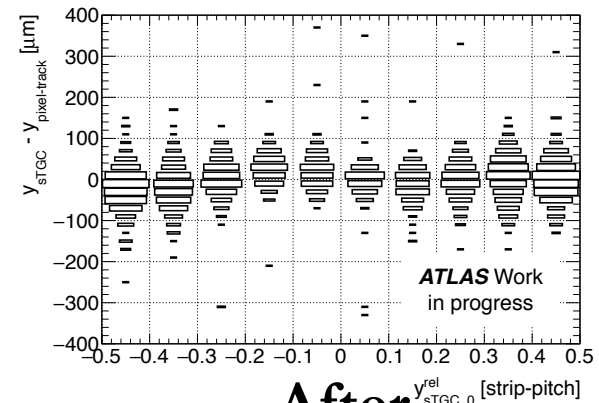
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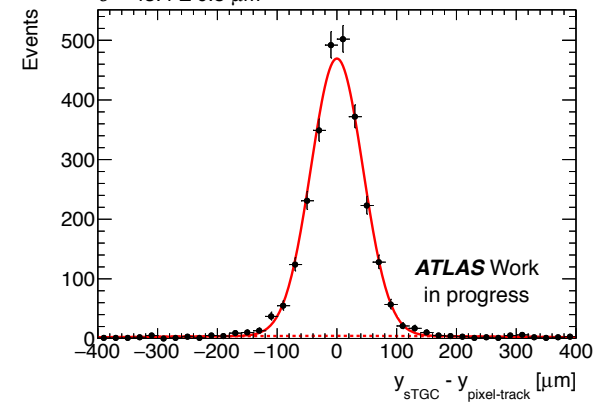
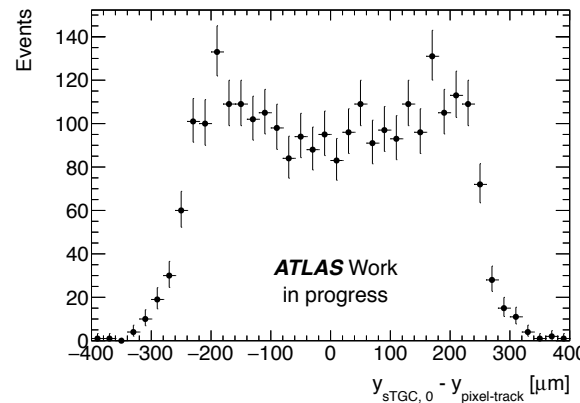
No deviation



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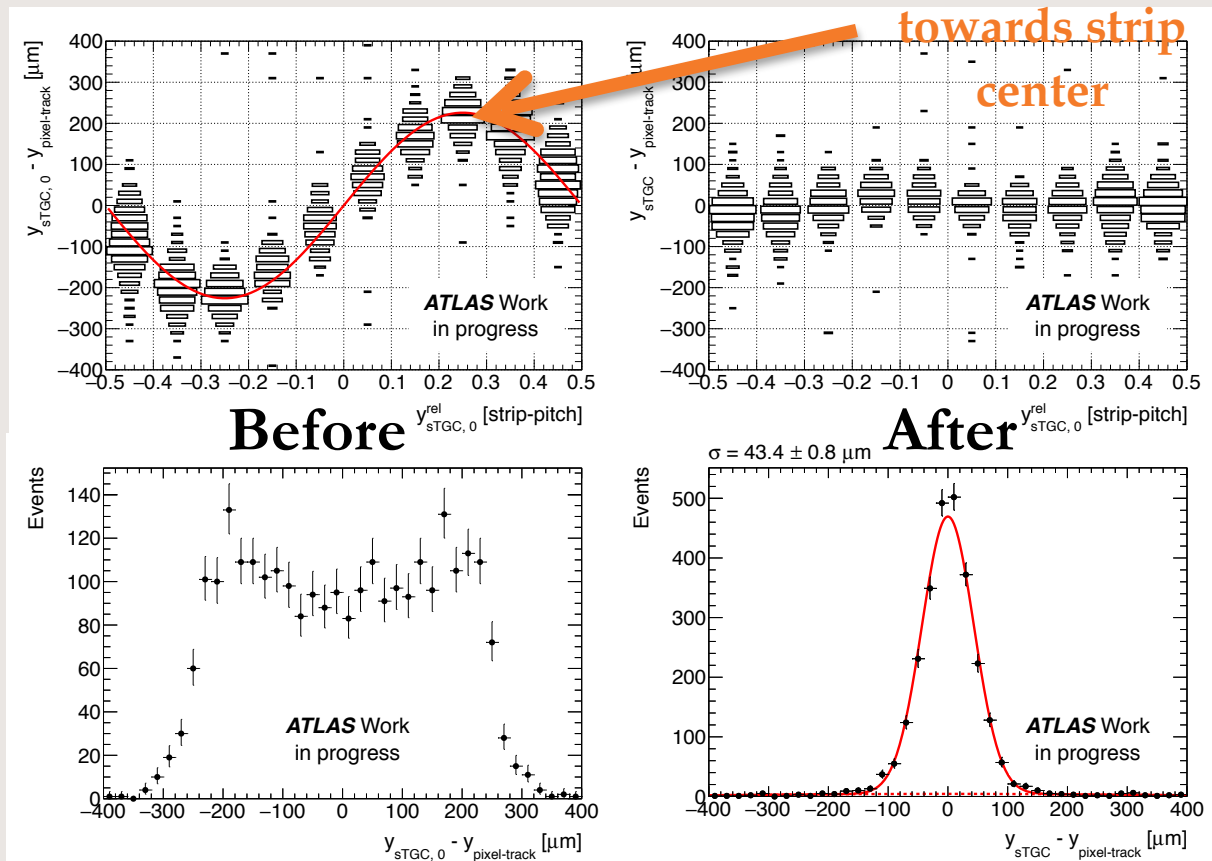
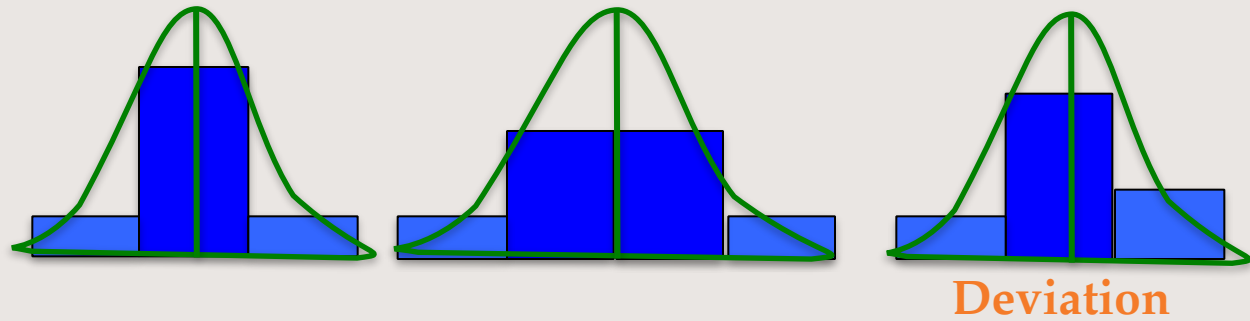


After



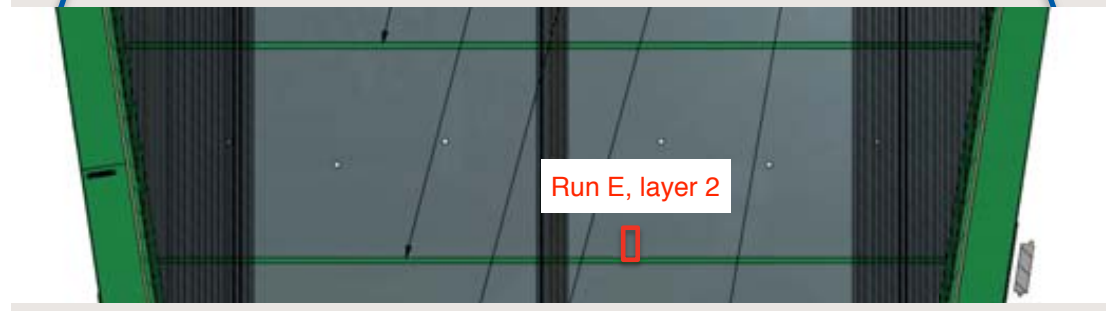
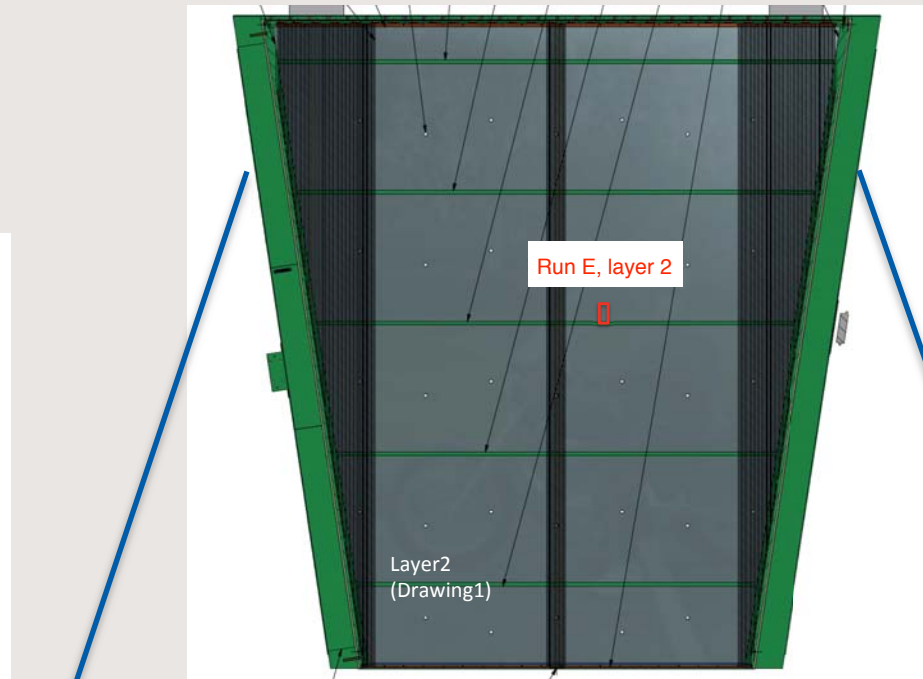
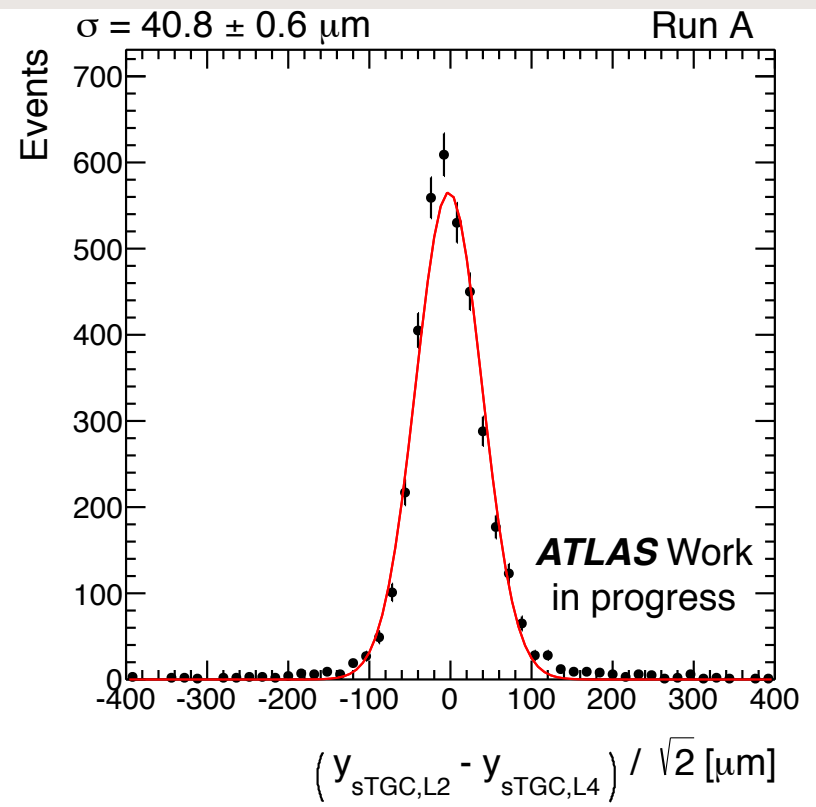
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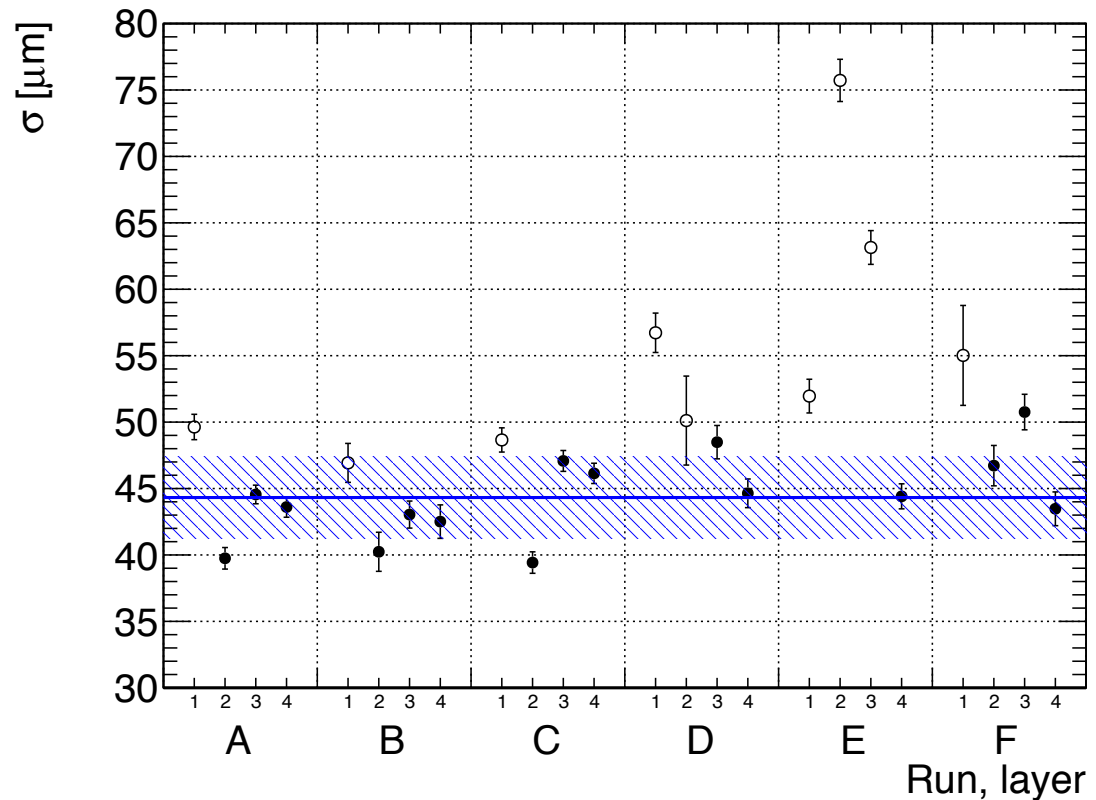




Pairwise Residuals

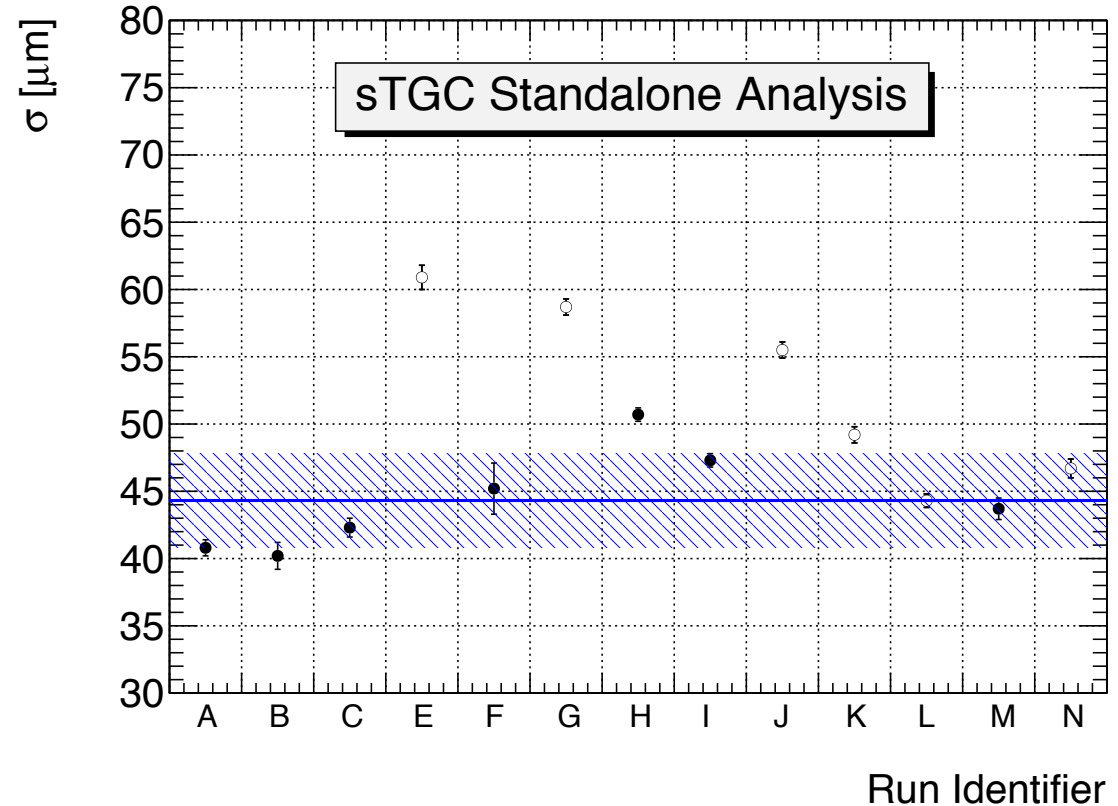
- Some runs have beam hitting module -1 wire support or spacer button.
- $(y_{\text{STGC},L_i} - y_{\text{STGC},L_j}) / \sqrt{2}$





-  **Nominal**
-  **Special**
 - “Per channel” pedestal corrections not available for layer 1.
 - Dead channel for run D layer 2.
 - Wire support and button in tested region for run E layers 2 and 3.

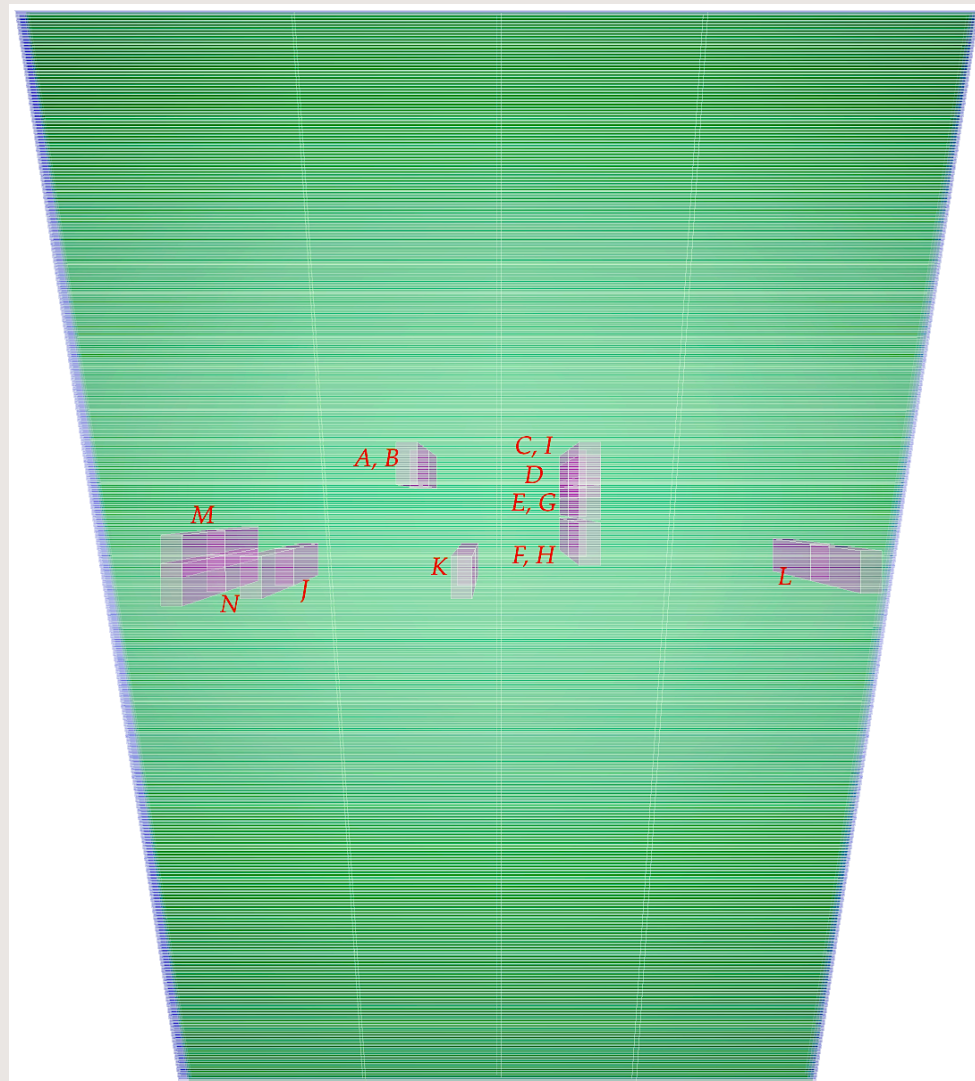


-  Nominal
-  Special
 - Wire support in tested region for runs E, G, J, K, L, N.
- Use pairwise residuals.
- Apply the “s-shape” correction extracted with the pixel telescope.
- Different runs probe different parts of the module -1.





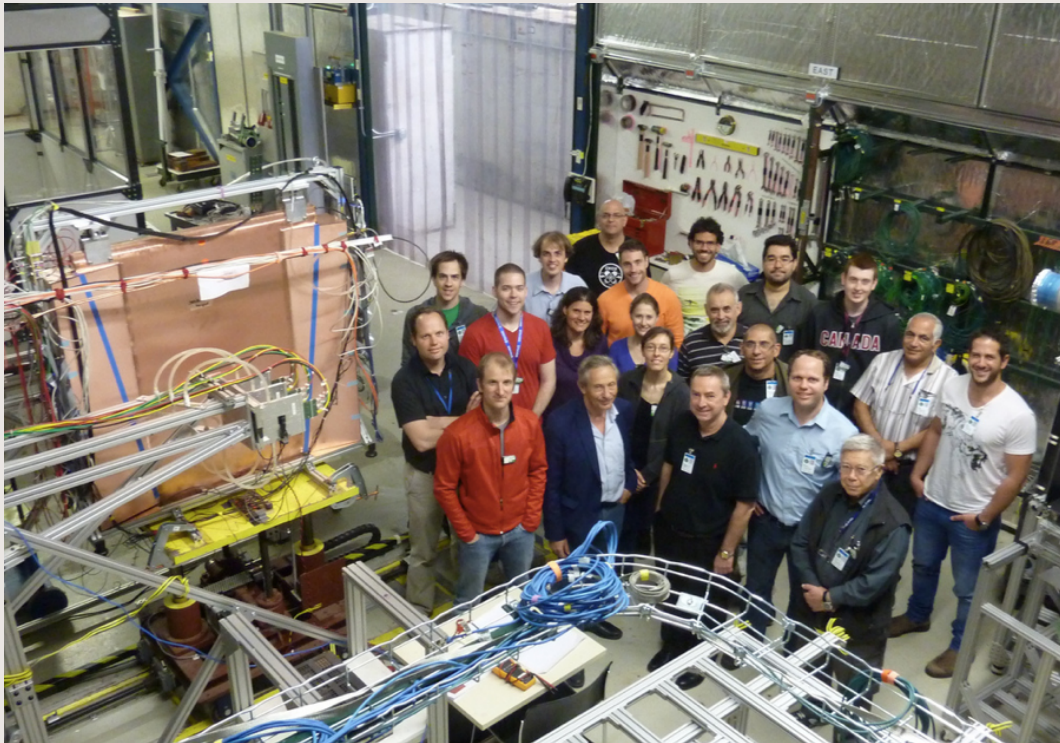
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Conclusion

- The NSW is a key Phase-1 upgrade.
- Achieved spatial resolution of “module -1” around 50 μm ; well within design requirement of 100 μm .
- NIM paper in preparation.
- Next steps: Construct a Canadian prototype and test it.

Thank you!



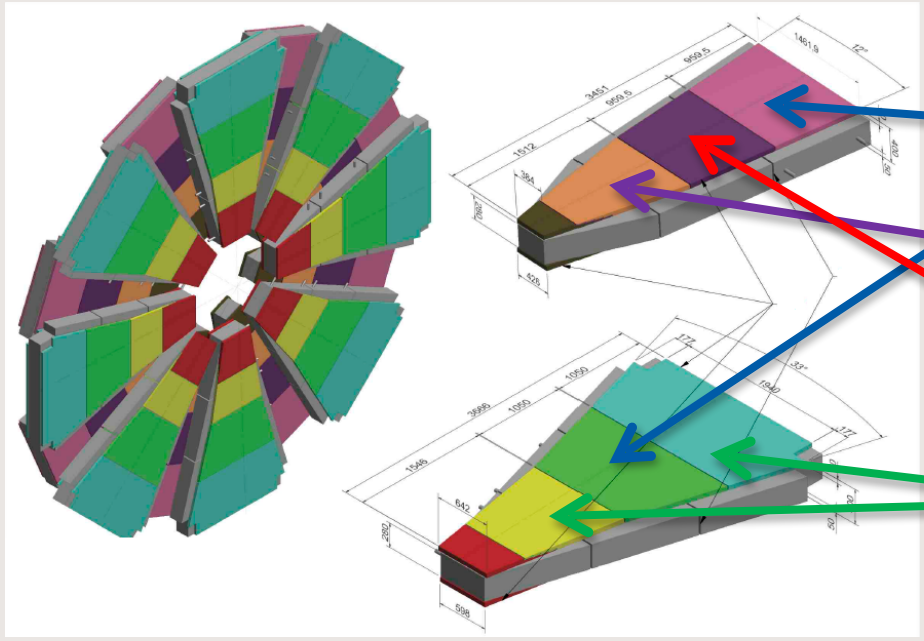
Merci!

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada
 Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

TRIUMF: Alberta | British Columbia |
 Calgary | Carleton | Guelph | Manitoba |
 McGill | McMaster | Montréal | Northern
 British Columbia | Queen's | Regina |
 Saint Mary's | Simon Fraser | Toronto |
 Victoria | Western | Winnipeg | York



Backup



- International effort

- Canada
 - 32 quadruplets + 8 spares
- Chile
 - 32 quadruplets + 4 spares
- China
 - 32 quadruplets + 4 spares
- Israel
 - 64 quadruplets + 8 spares

- TRIUMF

- Cathode board production: graphite spraying and chamber wall assembly.
- Quality control for all received parts.

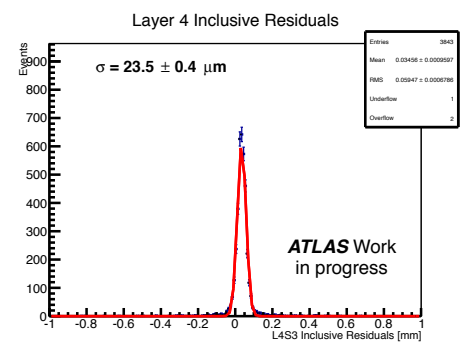
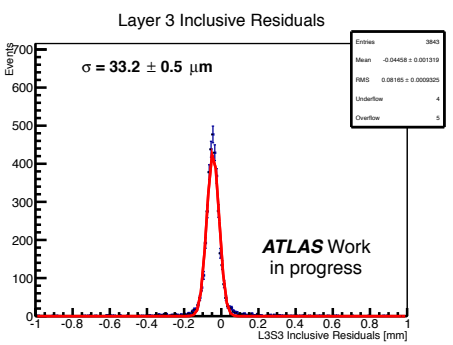
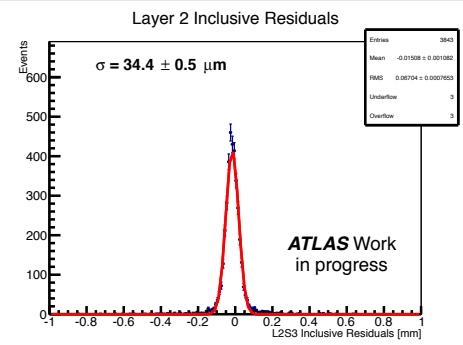
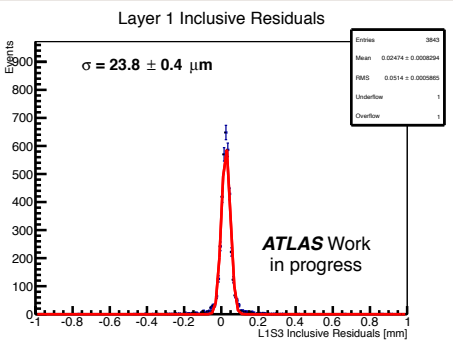
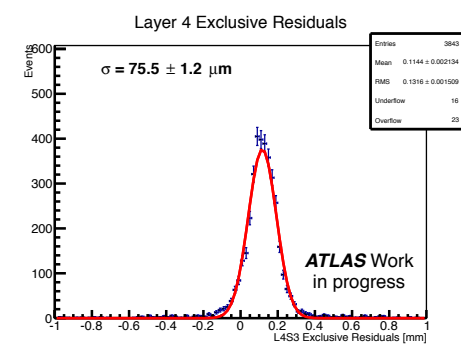
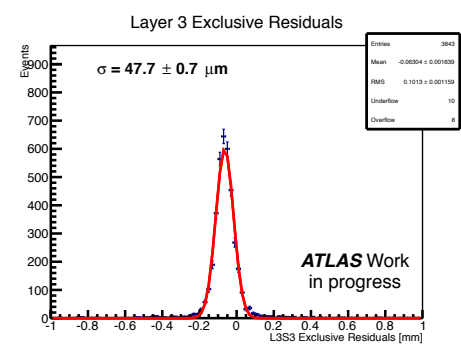
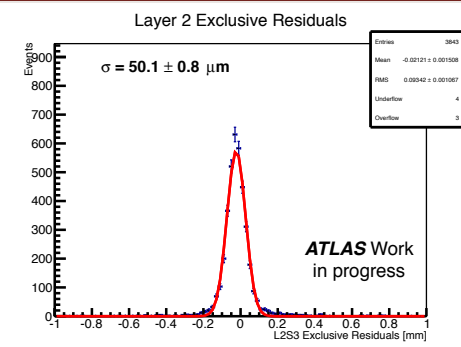
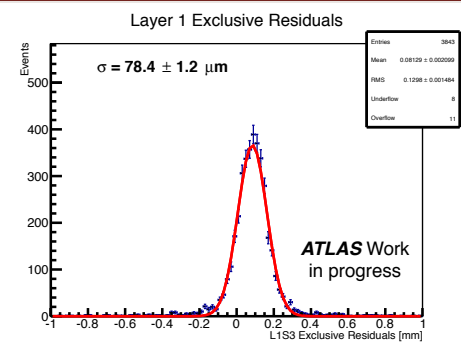
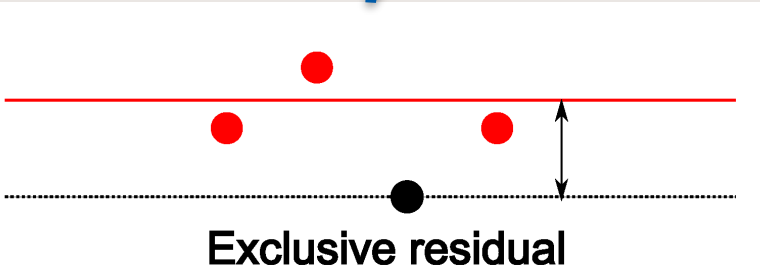
- Carleton

- Anode wire winding and quadruplet assembly.

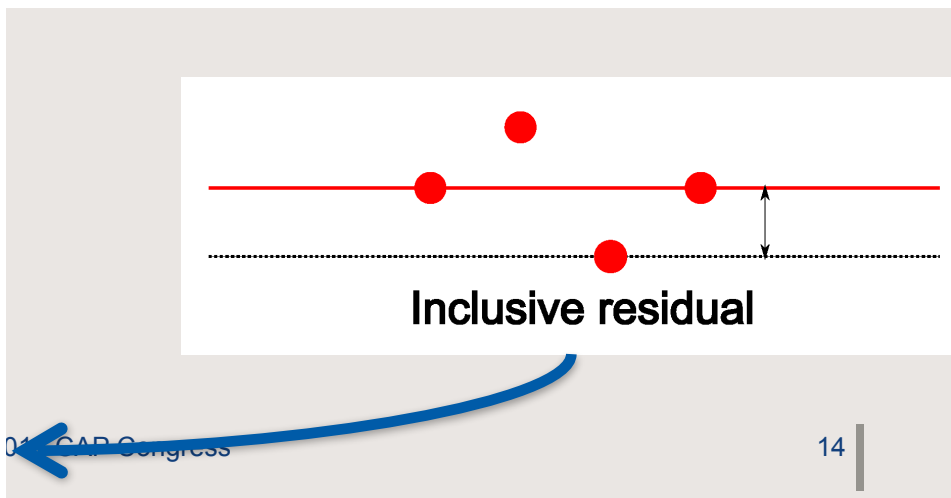
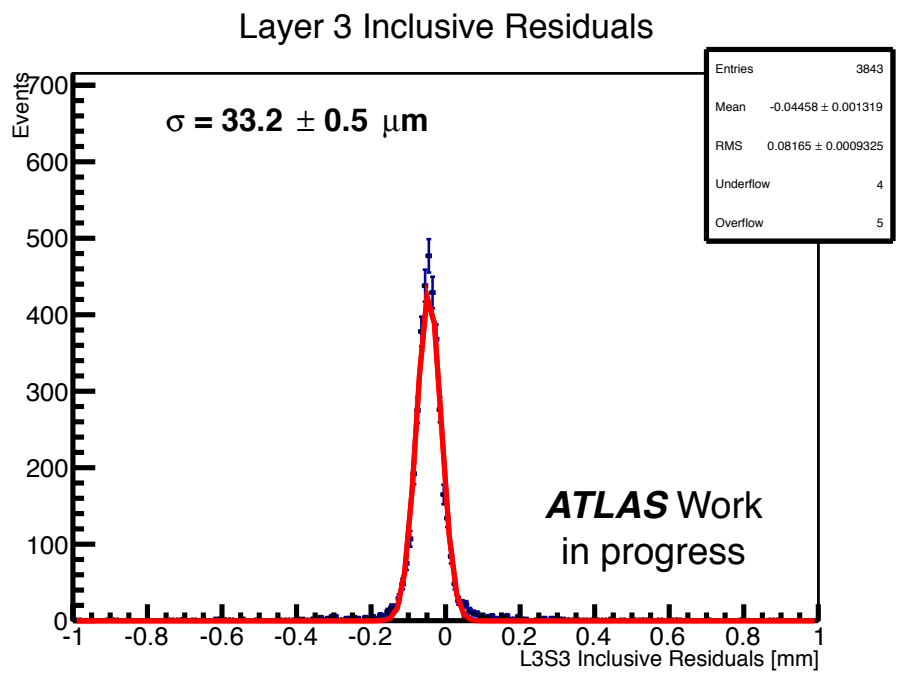
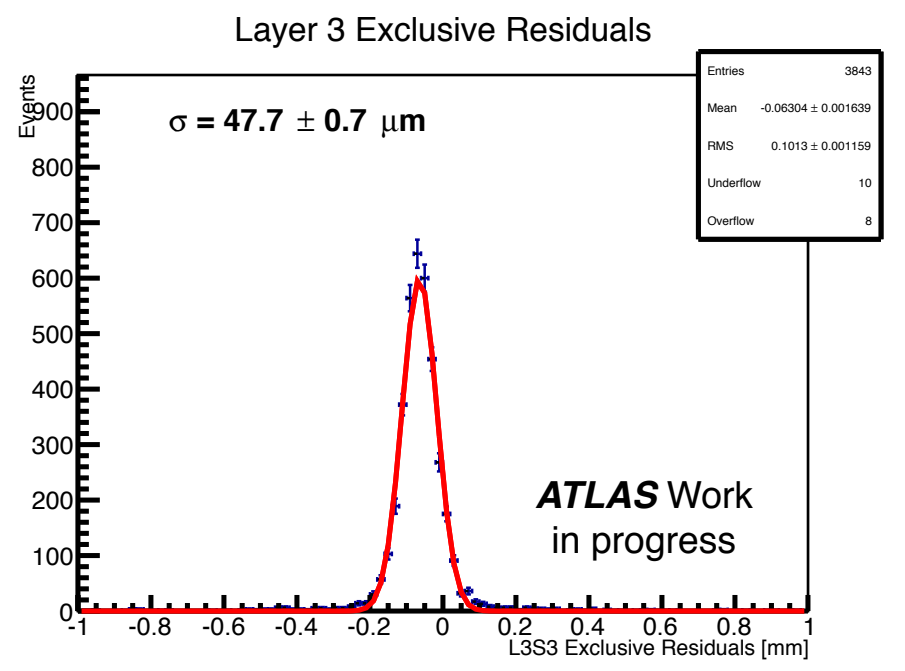
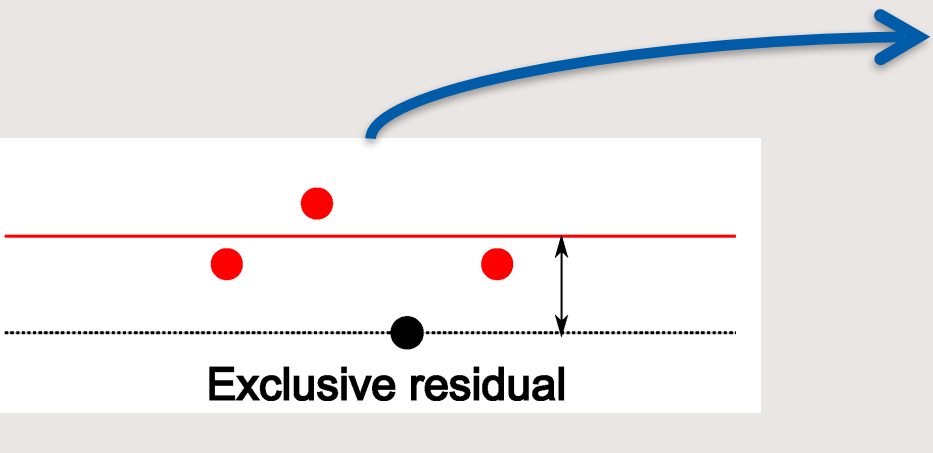
- McGill

- Cosmic ray testing.

Residuals

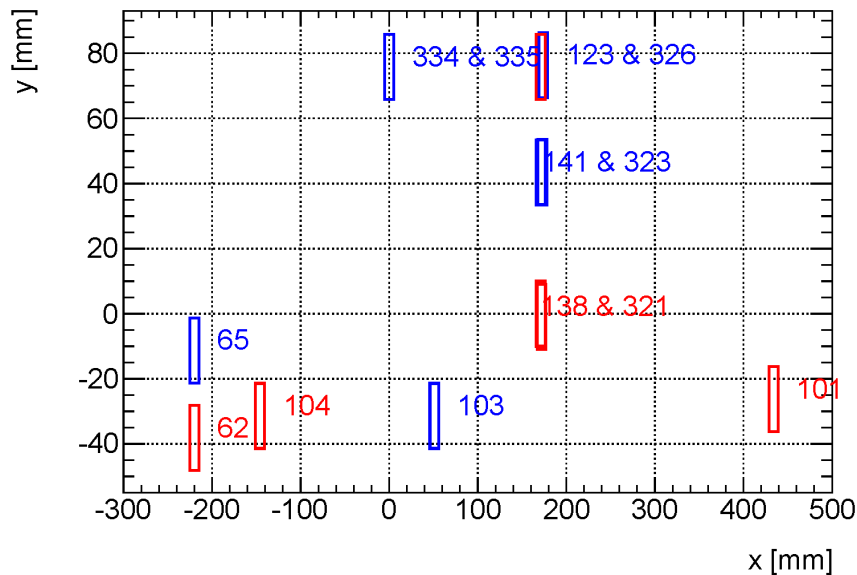
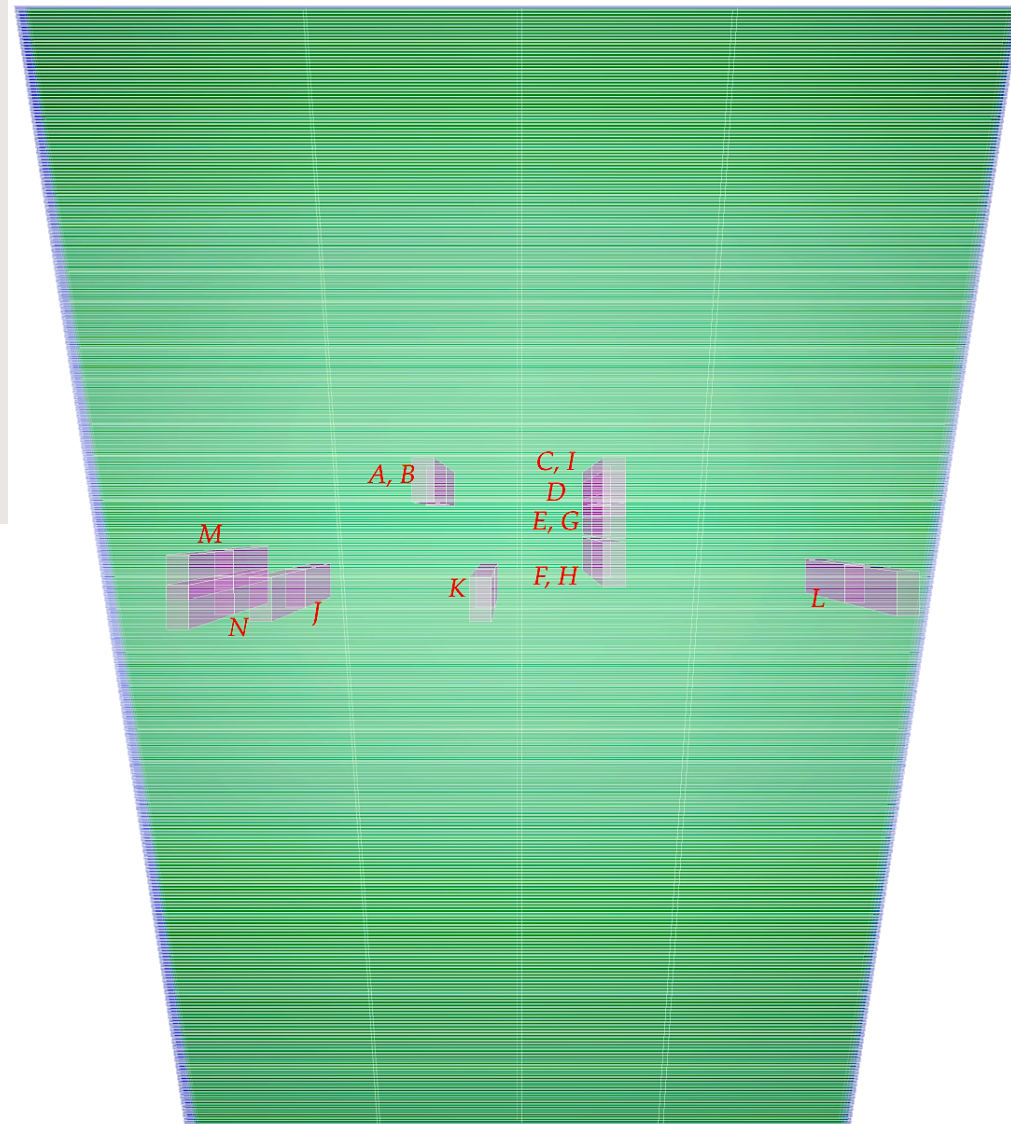


Residuals



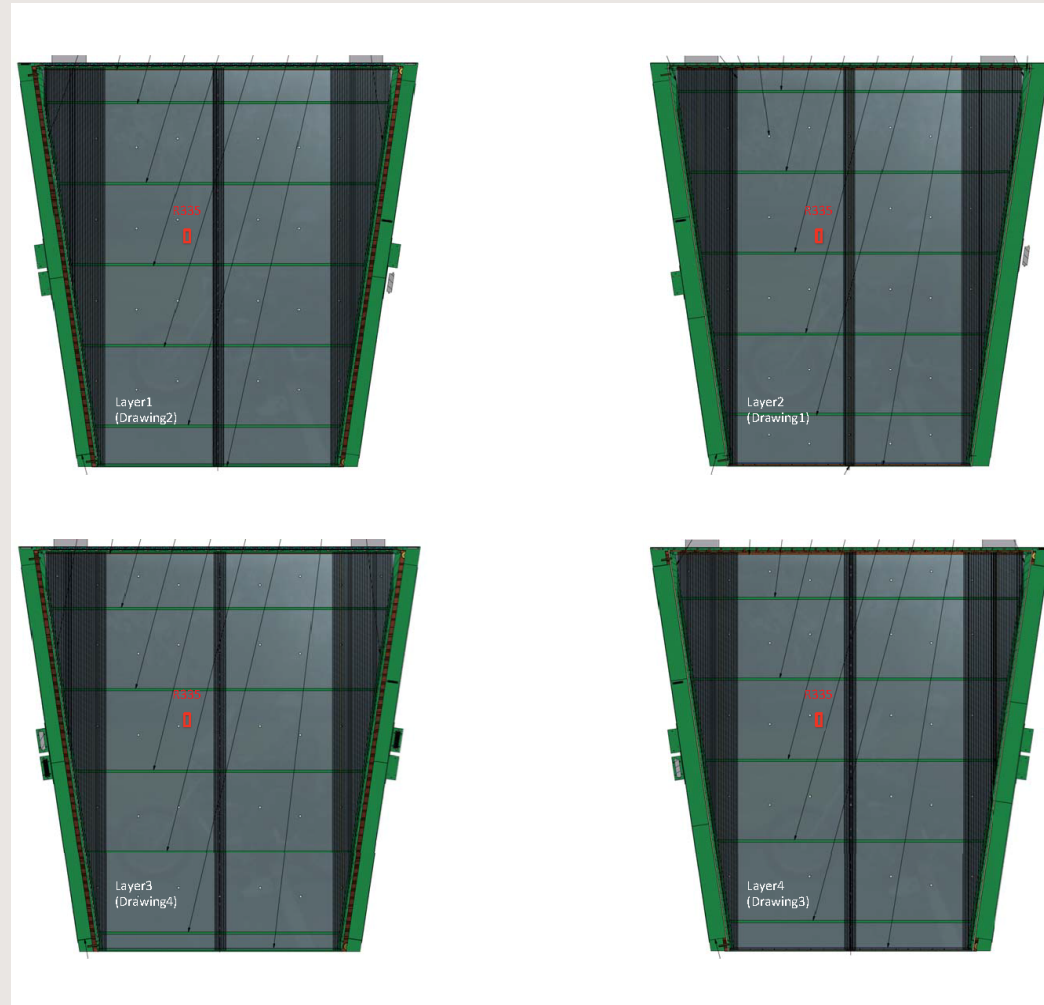
Good Runs

- Runs having good data that is analyzable

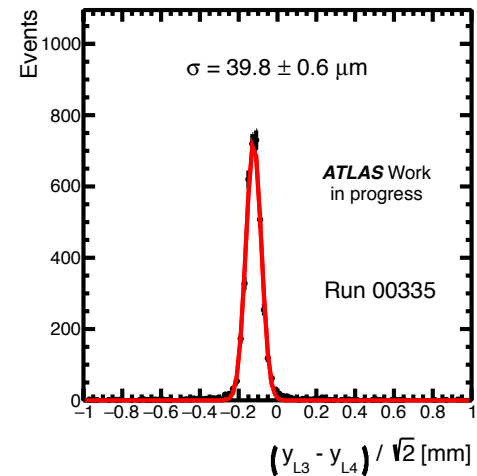
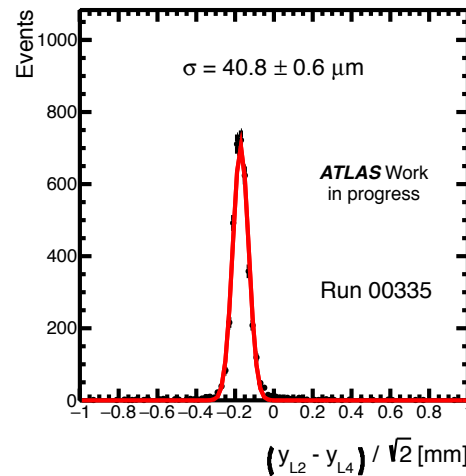
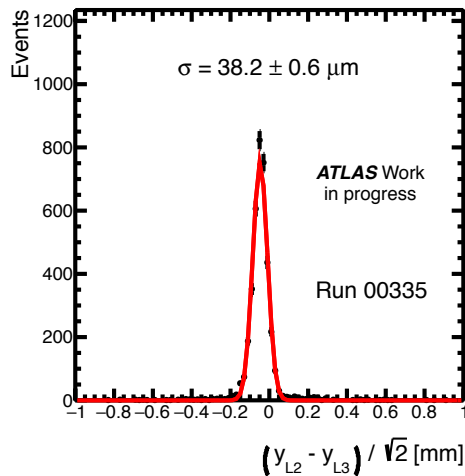
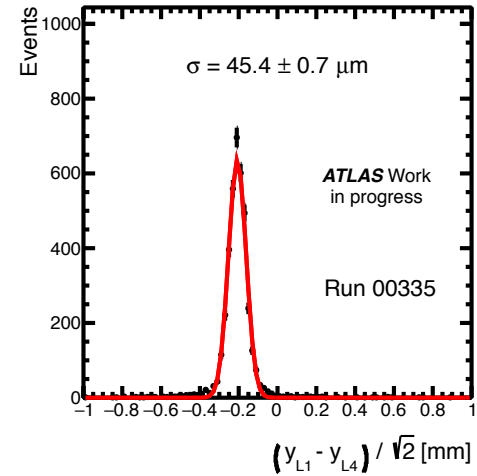
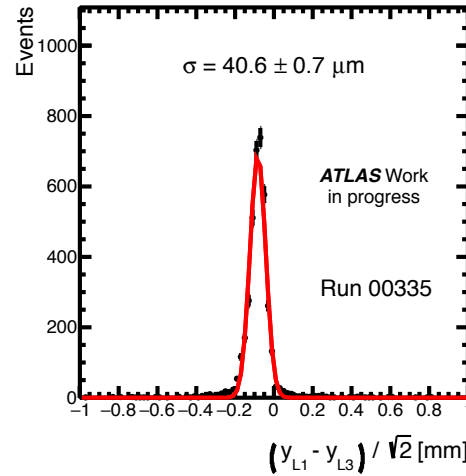
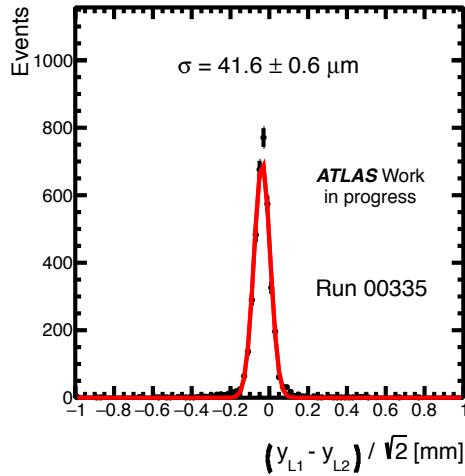


Runs 334 and 335

- All layers free of support structures

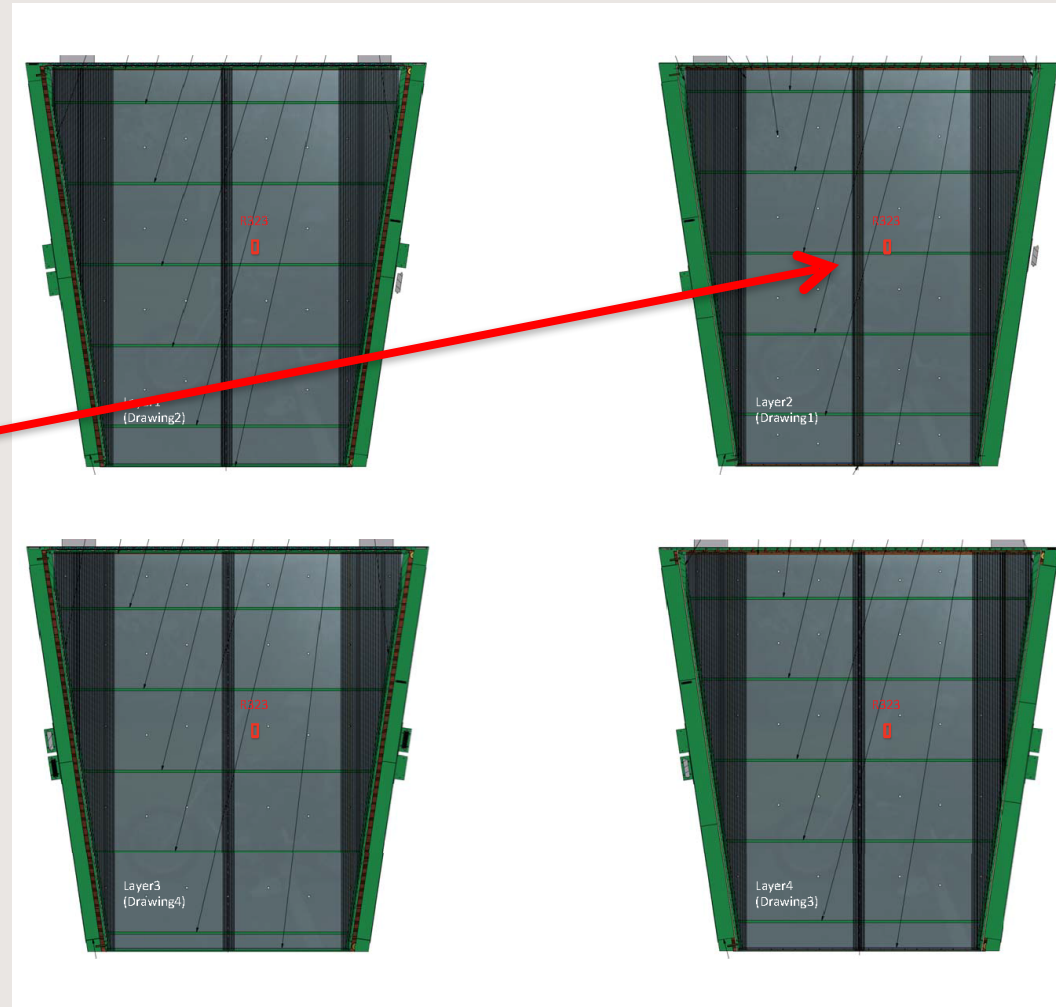


Run 335



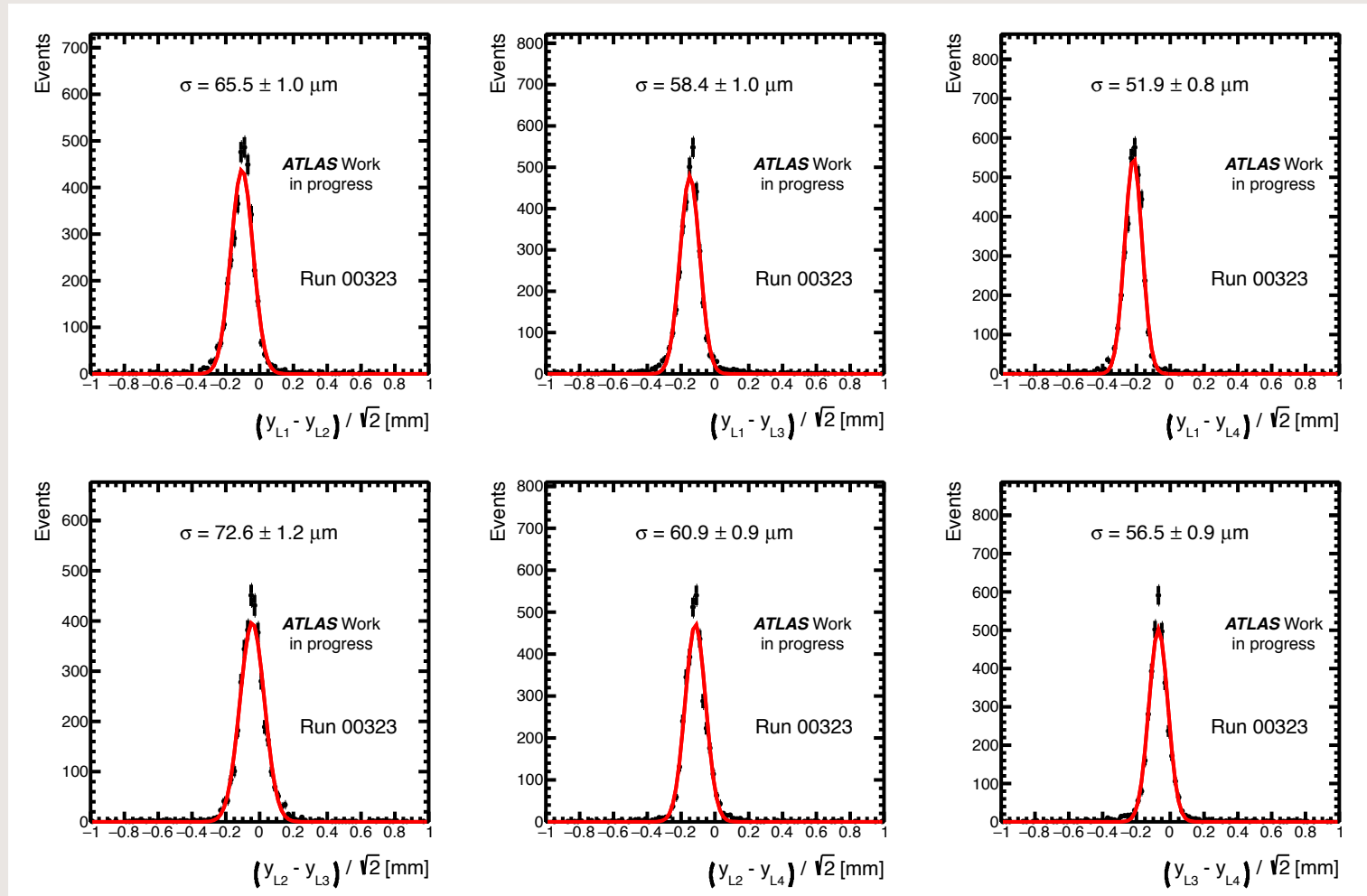
Run 323

- Layer 2 is being hit on support structure



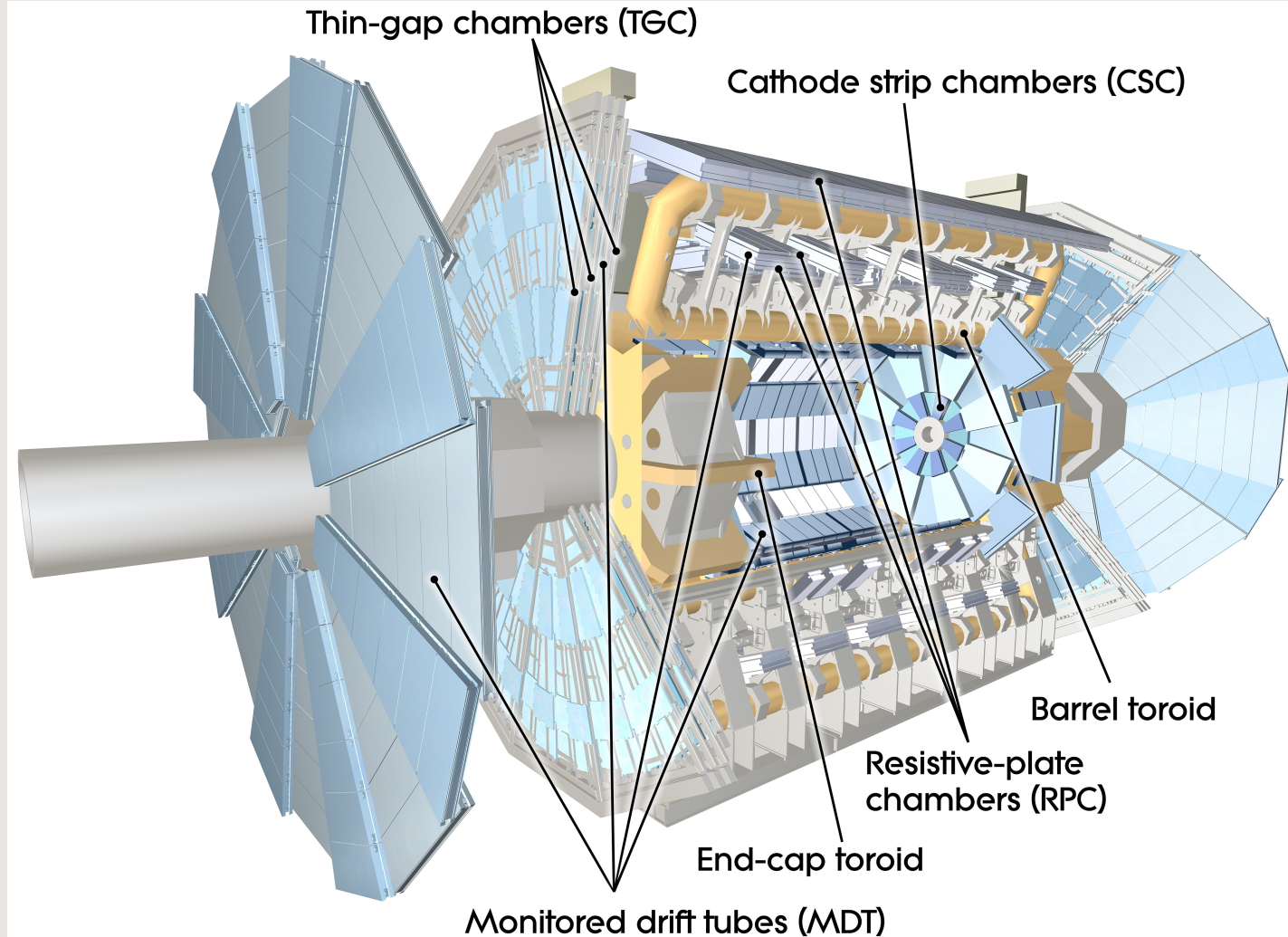
Run 323

- Residuals are systematically worse for pairing with layer 2.



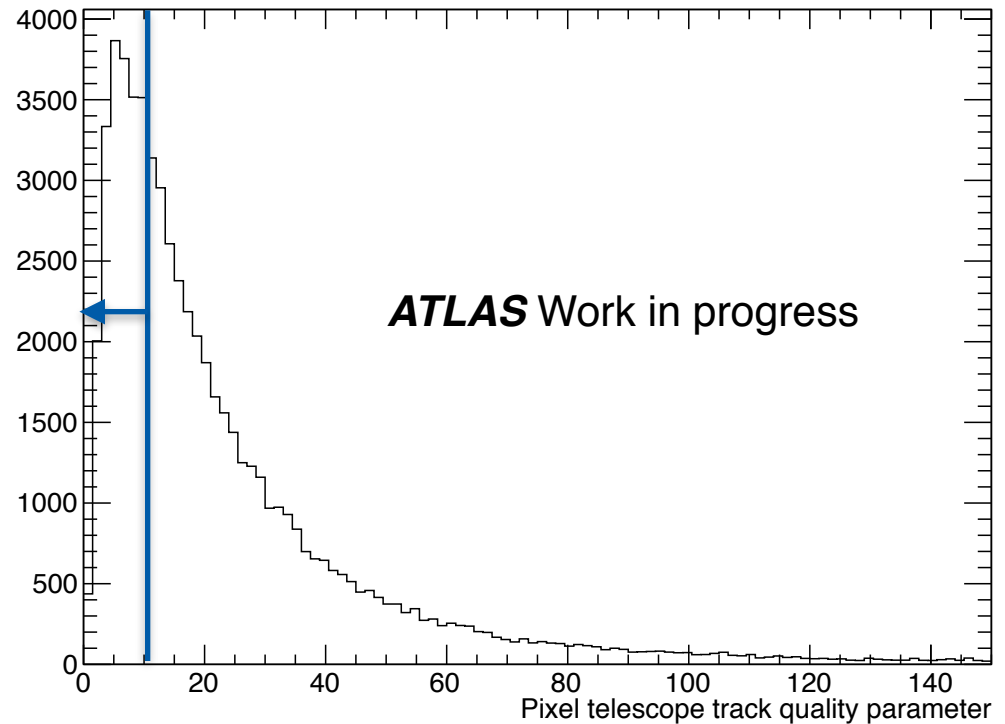
Fake Muons in ATLAS

- Fakes come mostly from activation in the end-cap toroid.



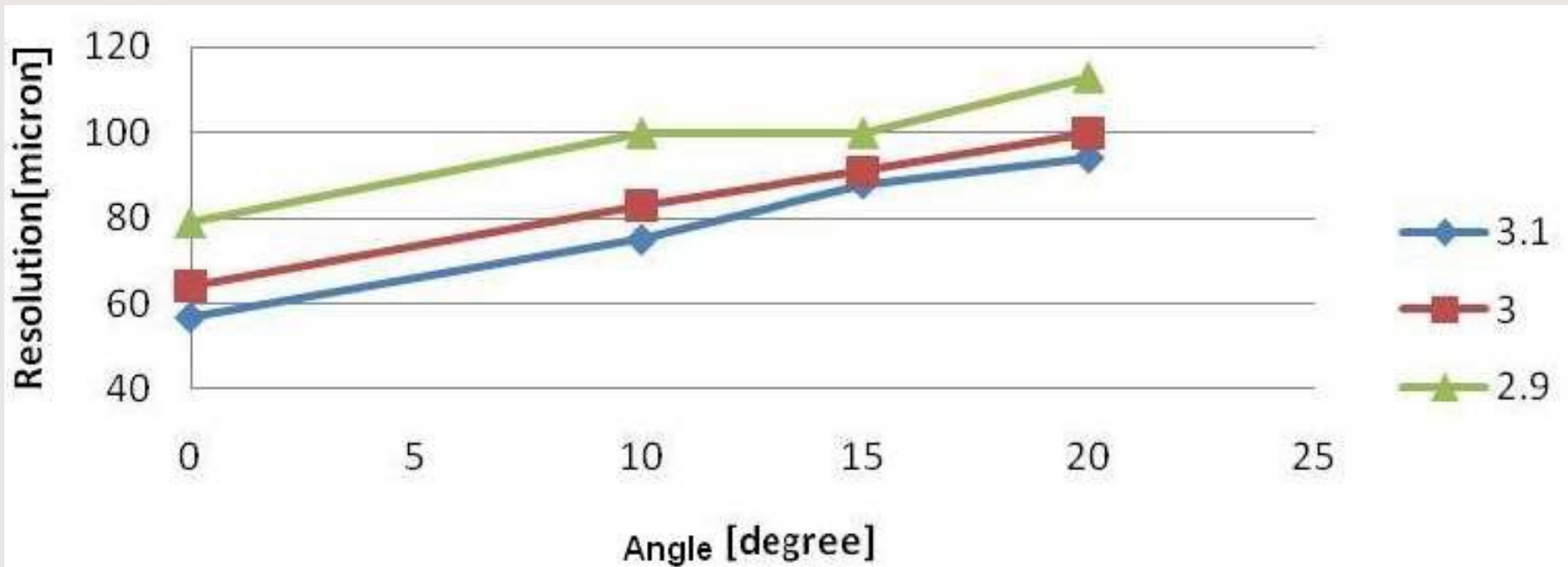
Pixel Tracks

- Require $\chi^2 < 10$
- Allows for very straight tracks
- Removes most multiple scattering events.



σ vs. Impact Angle

- From previous test beam efforts.
- For difference HV values.

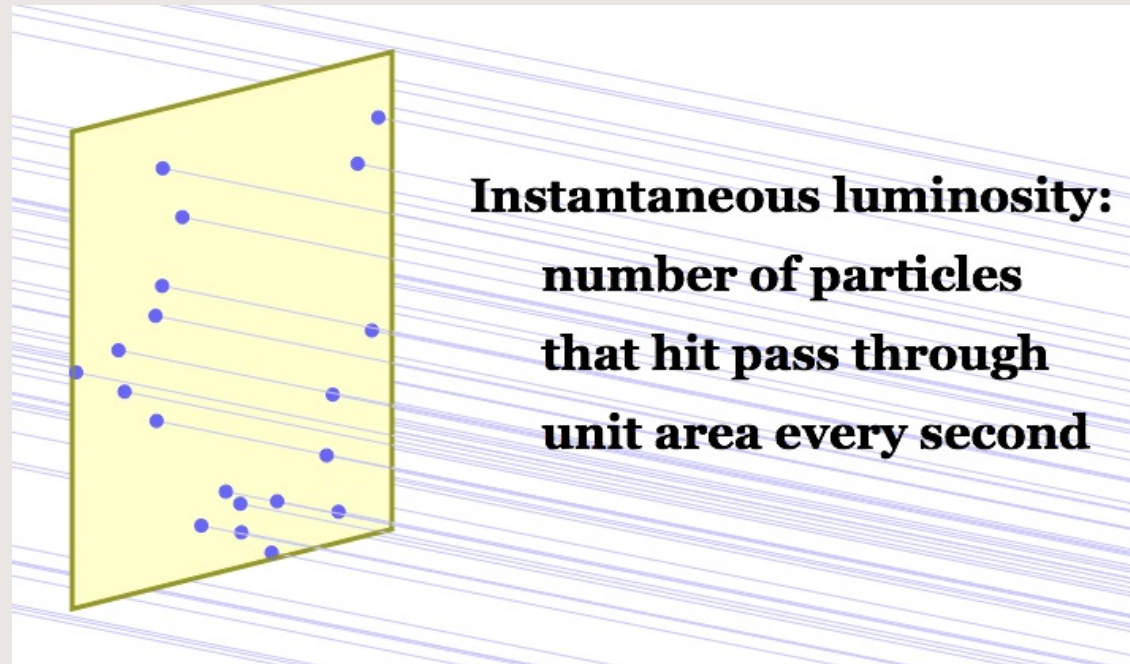


Event Selection

- Clustering
 - Only select cluster having 3, 4, or 5 hits
 - Require max bin of cluster not be next to zero bin
 - Require all bins close to max bin: $(bin - bin_{max}) < 2$
- Require all 4 layers be hit
- At most two 3-hit clusters in event
- TDO Cuts
- Corrections
 - “Per channel” pedestals applied, except for layer 1
 - -0.5 strip length offset for L2 and L4 by construction
 - $corr = -A * \sin(2\pi * yrel)$
 - A depends on size of cluster and layer of module -1
 - $yrel = mean_{cluster} - TMath::Nint(mean_{cluster})$

Instantaneous Luminosity

- The instantaneous luminosity is a measure of how many particles (blue) pass through a surface of unit area (yellow) in unit time (not shown.)

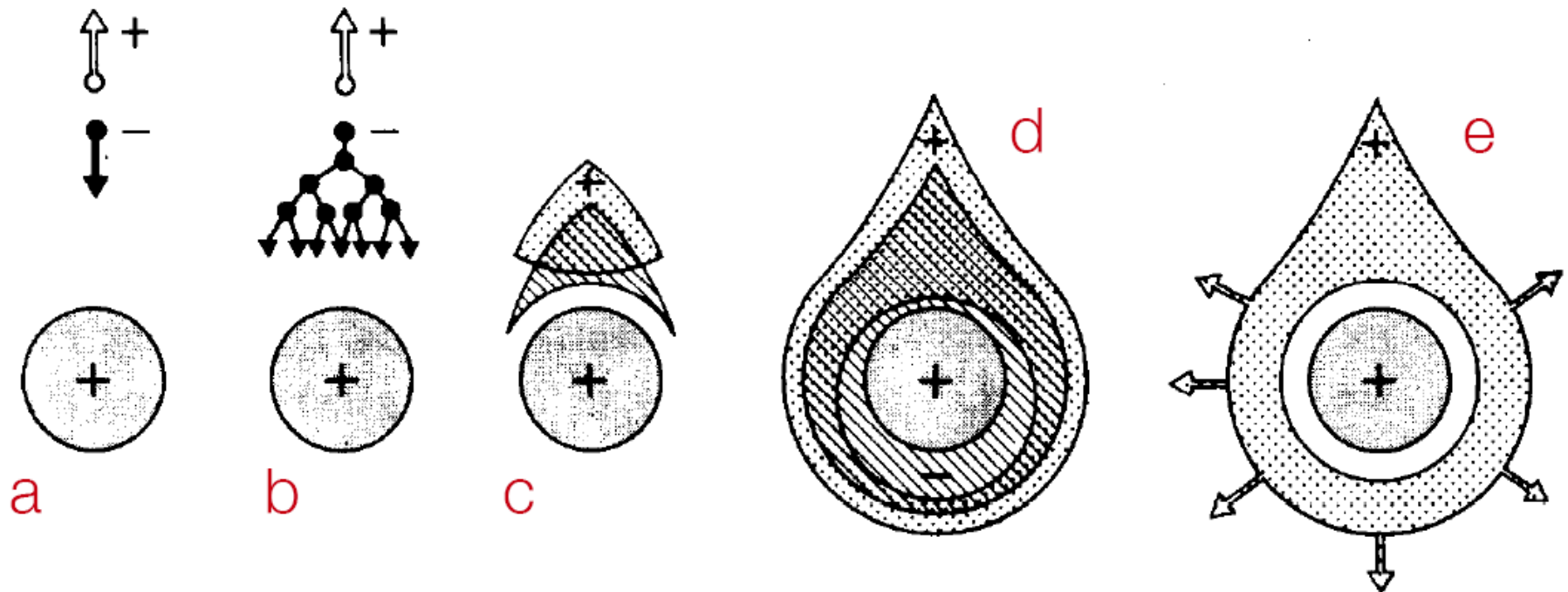


What is an inverse femtobarn?

- Measurement of particle-collision events per femtobarn; a measure of both the collision number and the amount of data collected.
- One inverse femtobarn corresponds to approximately 100 trillion (10^{12}) proton-proton collisions.
- Luminosity: ratio of the number of expected events detected per unit time to the interaction cross-section.

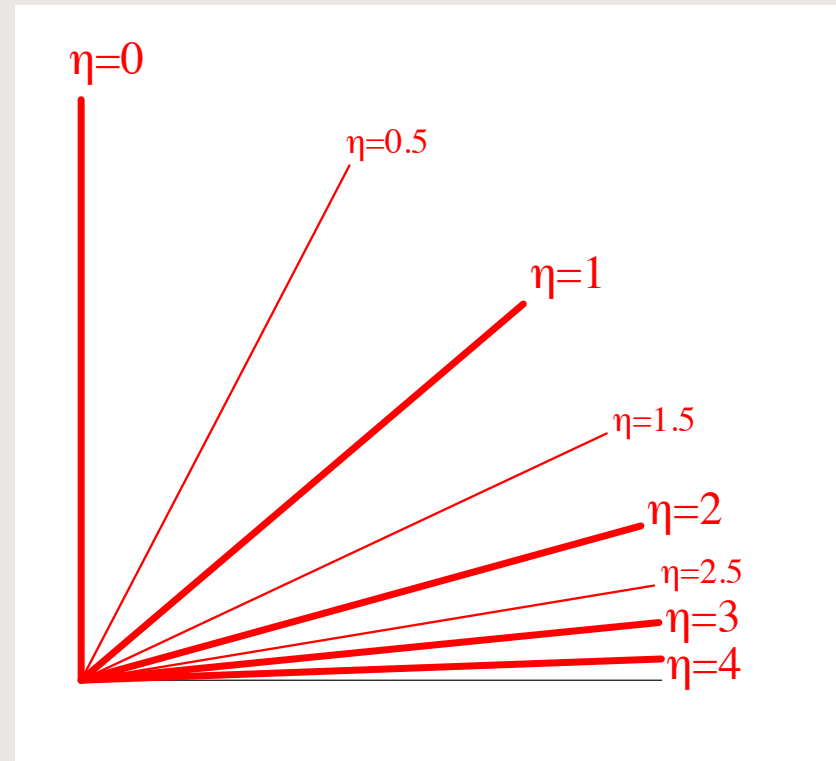
How Avalanches Form

- a. Electron is attracted to anode.
- b. Avalanche multiplication starts due to high E field.
- c. Lateral diffusion; Coulomb repulsion between same-charge particles.
- d. Drop-like avalanche is formed around the anode wire.
- e. Electrons are collected rapidly (~ 1 ns) and ions drift towards cathode. This generates the signal at the electrodes.



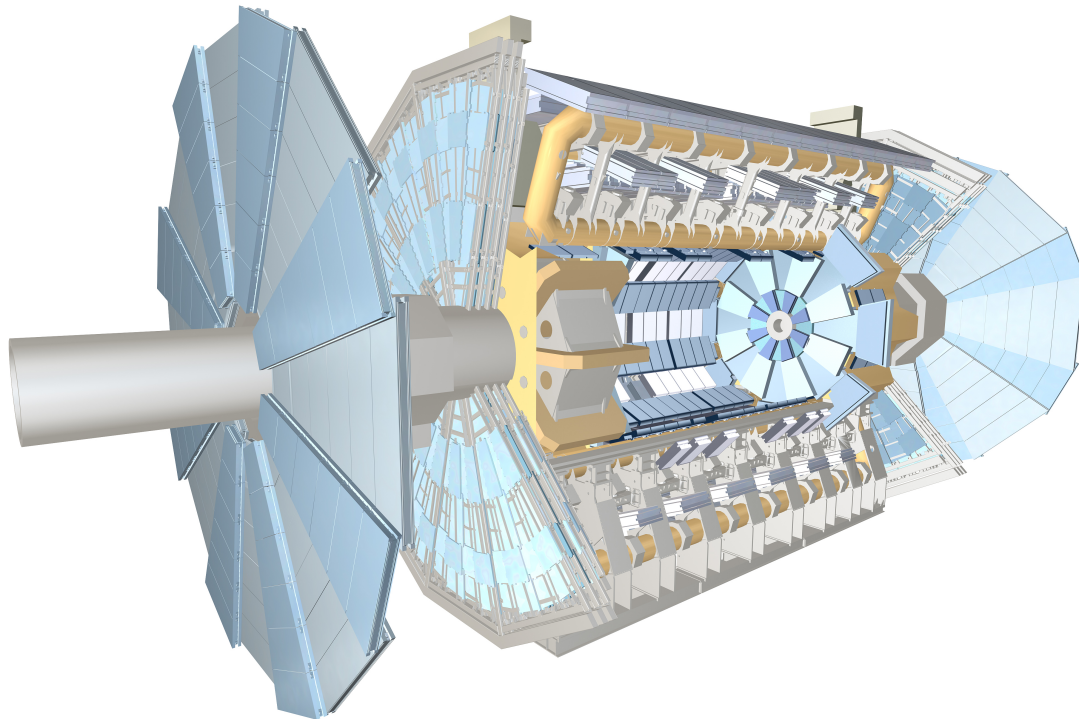
Pseudorapidity (η)

- $\eta = -\ln[\tan(\theta/2)]$
- NSW coverage is
 - $1.3 < \eta < 2.7$
 - $15 < \theta < 40$



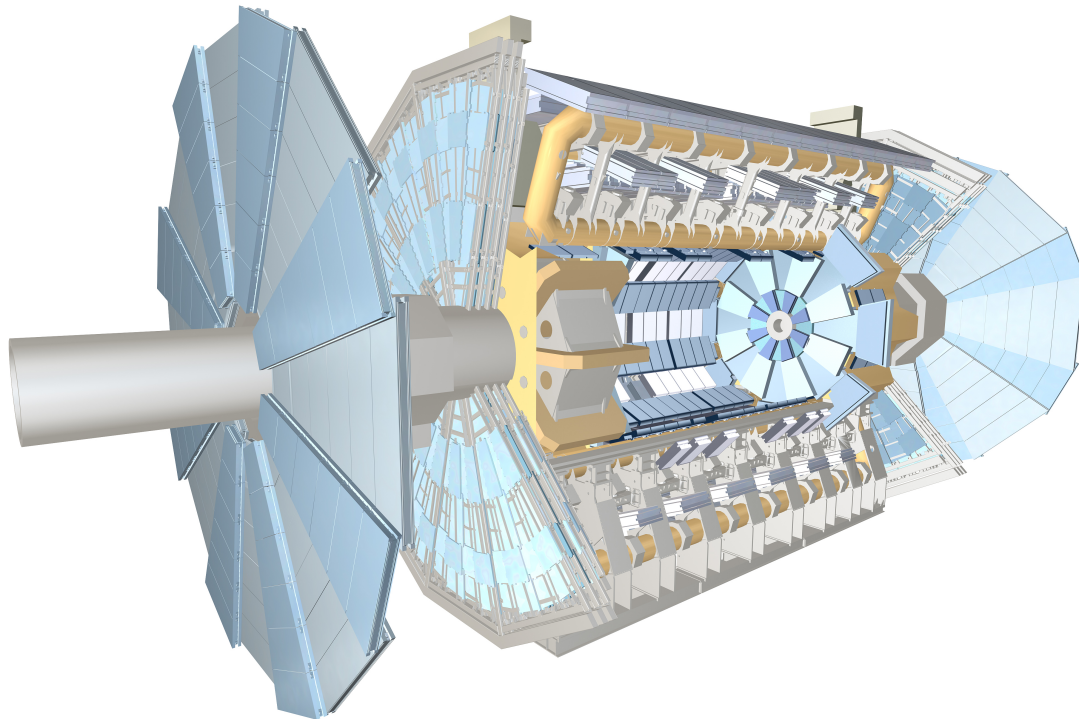
The ATLAS Detector at the LHC

- ATLAS is a multipurpose particle detector



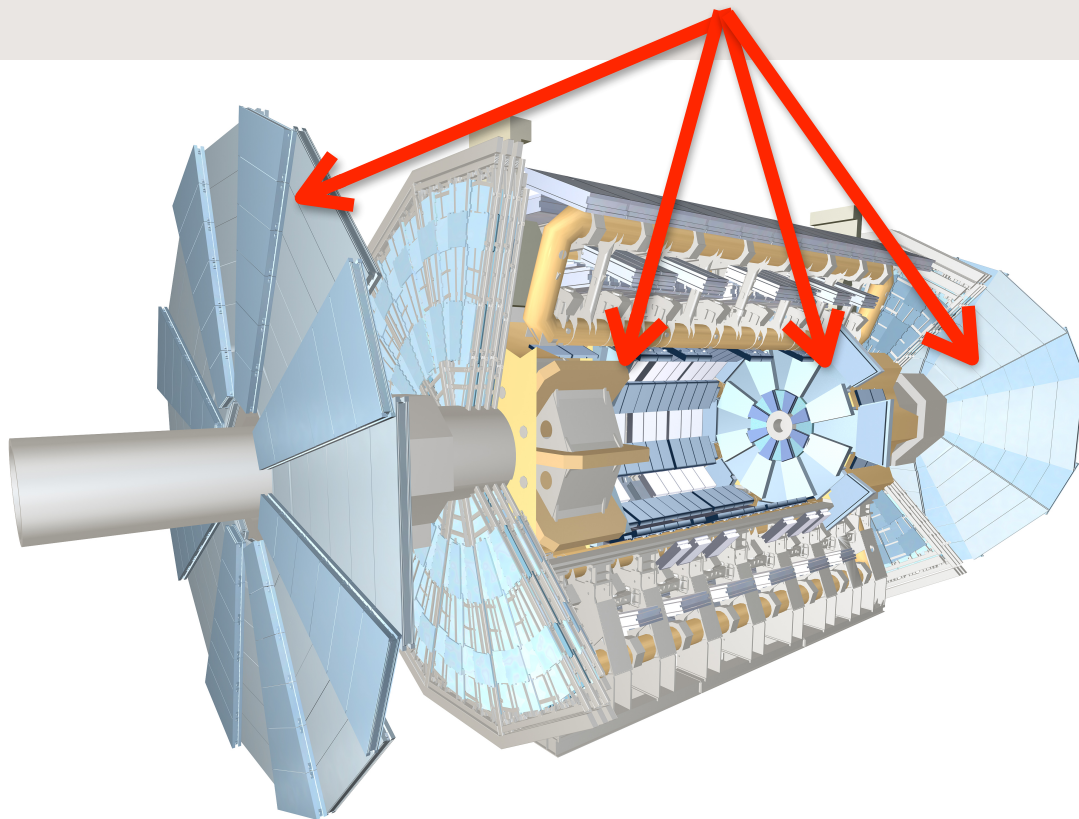
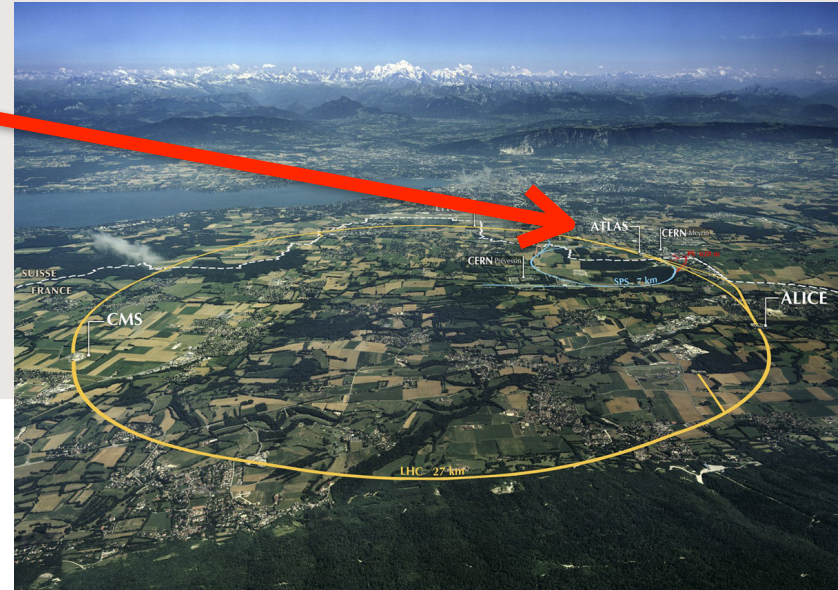
The ATLAS Detector at the LHC

- ATLAS is a multipurpose particle detector



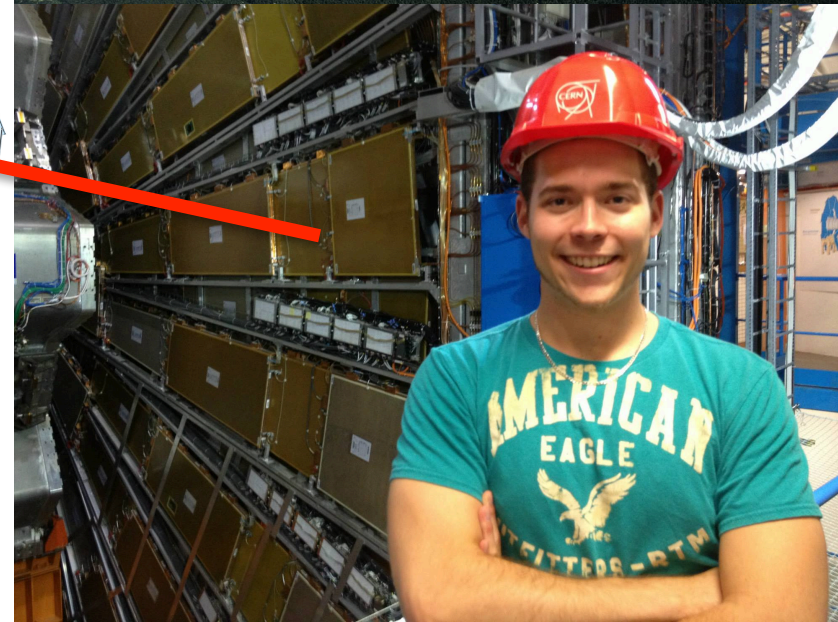
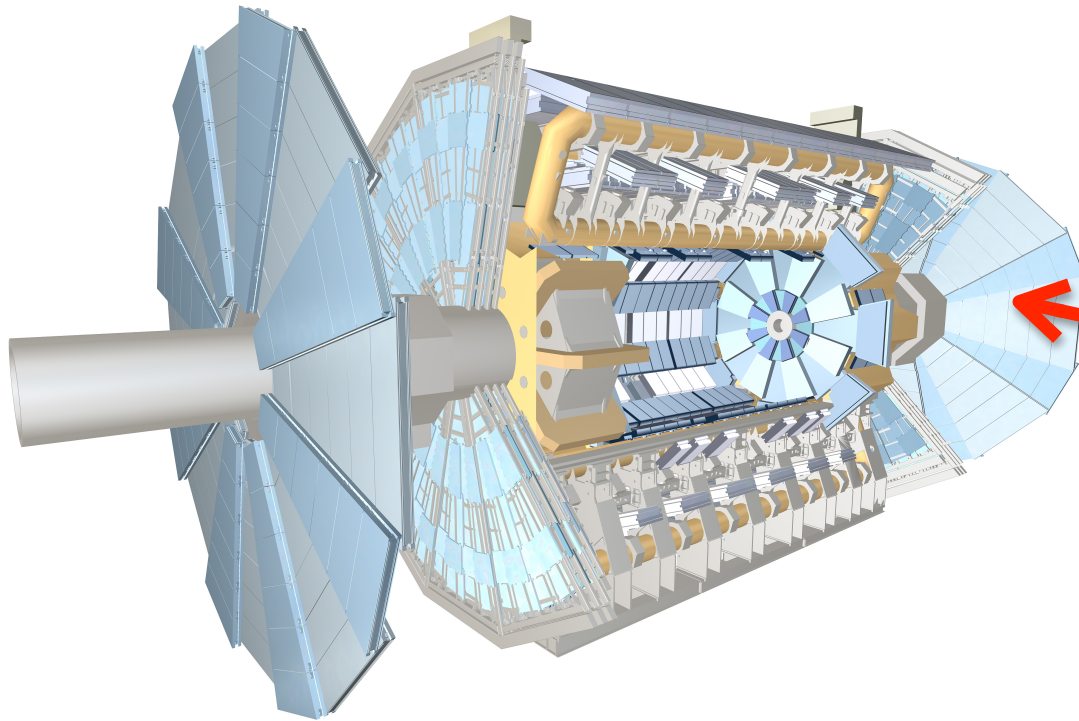
The ATLAS Detector at the LHC

- ATLAS is a multipurpose particle detector
- Endcap muon detectors



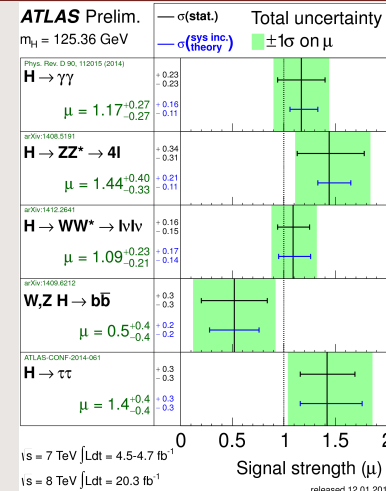
The ATLAS Detector at the LHC

- ATLAS is a multipurpose particle detector
- Endcap muon detectors



What Now?

- Higgs Precision Measurements
- Beyond the Standard Model Physics Searches
- SUSY, Extra dimensions, etc.
- All these searches need higher energy collisions, and more data



ATLAS SUSY Searches* - 95% CL Lower Limits
 Status: Feb 2015

Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{\text{miss}}^{\text{max}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive Searches	MSUGRA/CMSSM	0-2 jets	Yes	20.3	850 GeV	1405.7875		
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0-2 jets	Yes	20.3	850 GeV	1405.7875		
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ (compressed)	1 jet	Yes	20.3	250 GeV	1411.1559		
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0-2 jets	Yes	20.3	1.33 TeV	1405.7875		
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	1-2 jets	Yes	20	1.2 TeV	1501.03555		
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0-3 jets	Yes	20	1.36 TeV	1501.03555		
	GMSB (\tilde{g} NLSP)	$1.2 + 0.1 l$	0-2 jets	Yes	20.3	1.6 TeV	1407.0603	
	GGM (bino NLSP)	2 jets	Yes	20.3	619 GeV	ATLAS-CONF-2014-001		
	GGM (wino NLSP)	$1 \mu + \gamma$	Yes	4.8	800 GeV	ATLAS-CONF-2012-144		
	GGM (higgsino-bino NLSP)	γ	1 jet	Yes	4.8	890 GeV	1211.1167	
GGM (higgsino NLSP)	$2 e, \mu (Z)$	0-3 jets	Yes	5.8	890 GeV	ATLAS-CONF-2012-152		
Gravitino LSP	0 monojet	Yes	20.3	865 GeV	1502.01518			
3 rd gen. squarks direct production	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	0-3 jets	Yes	20.1	1.25 TeV	1407.0600		
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	0-7 jets	Yes	20.3	1.1 TeV	1308.1841		
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$0.1 e, \mu$	3 jets	Yes	20.1	1.34 TeV	1407.0600	
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$0.1 e, \mu$	3 jets	Yes	20.1	1.3 TeV	1407.0600	
	3 rd gen. squarks direct production	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	0-2 jets	Yes	20.1	$100\text{-}620 \text{ GeV}$	1308.2631	
		$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$2 e, \mu (SS)$	0-3 jets	20.3	$275\text{-}440 \text{ GeV}$	1404.2500	
		$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$1.2 e, \mu$	1-2 jets	Yes	4.7	$230\text{-}460 \text{ GeV}$	1209.2102, 1407.0583
		$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$2 e, \mu$	0-2 jets	Yes	20.3	$90\text{-}191 \text{ GeV}$	1403.4853, 1412.4742
		$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$0.1 e, \mu$	1-2 jets	Yes	20	$210\text{-}640 \text{ GeV}$	1407.0583, 1408.1122
		$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	0 monojet-tag	Yes	20.3	$90\text{-}240 \text{ GeV}$	1407.0600	
$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$		$2 e, \mu (Z)$	1 jet	Yes	20.3	$150\text{-}580 \text{ GeV}$	1403.5222	
$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$		$3 e, \mu (Z)$	1 jet	Yes	20.3	$290\text{-}600 \text{ GeV}$	1403.5222	
EW correct		$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$2 e, \mu$	0	Yes	20.3	$90\text{-}325 \text{ GeV}$	1403.5222
		$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$2 e, \mu$	0	Yes	20.3	$140\text{-}465 \text{ GeV}$	1403.5222
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$2 e, \mu$	0	Yes	20.3	$100\text{-}350 \text{ GeV}$	1402.7050	
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$3 e, \mu$	0	Yes	20.3	700 GeV	1402.7059	
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$2.3 e, \mu$	0-2 jets	Yes	20.3	420 GeV	1403.5294, 1402.7029	
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$4 e, \mu, \tau$	0-2 jets	Yes	20.3	250 GeV	1501.0710	
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$4 e, \mu$	0	Yes	20.3	620 GeV	1405.5086	
	Long-lived	Direct \tilde{t}_1, \tilde{b}_1 prod., long-lived \tilde{t}_1	Disapp	1 jet	Yes	20.3	270 GeV	1310.3675
		Stable \tilde{t}_1, \tilde{b}_1 prod., long-lived \tilde{t}_1	0-1.5 jets	Yes	27.9	832 GeV	1310.684	
		Stable \tilde{t}_1, \tilde{b}_1 prod., long-lived \tilde{t}_1	1 jet	Yes	19.1	537 GeV	1411.6795	
GMSB, stable $\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$		$1.2 e, \mu$	-	Yes	20.3	435 GeV	1411.6795	
GMSB, stable $\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$		2μ	-	Yes	20.3	435 GeV	1409.5542	
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ (RPV)		$1 \mu, \text{ displ. vtx}$	-	Yes	20.3	1.0 TeV	ATLAS-CONF-2013-092	
RPV		LFV $\tilde{g} \rightarrow \tilde{g} + X, \tilde{q} \rightarrow \tilde{q} + X$	$2 e, \mu$	-	4.6	1.61 TeV	1212.1272	
		LFV $\tilde{g} \rightarrow \tilde{g} + X, \tilde{q} \rightarrow \tilde{q} + X$	$1 \mu, e + \tau$	-	4.6	1.1 TeV	1212.1272	
		Bilinear RPV CMSSM	$2 e, \mu (SS)$	0-3 jets	Yes	20.3	450 GeV	1404.2500
		$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$4 e, \mu$	-	Yes	20.3	750 GeV	1405.5086
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$3 e, \mu + \tau$	-	Yes	20.3	450 GeV	1405.5086	
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	0-7 jets	Yes	20.3	916 GeV	ATLAS-CONF-2013-091		
	$\tilde{t}_1, \tilde{b}_1 \rightarrow t\tilde{g}, b\tilde{g}$	$2 e, \mu (SS)$	0-3 jets	Yes	20.3	850 GeV	1404.2500	
	Other	Scalar charm, $\tilde{t}_1 \rightarrow \tilde{t}_1^*$	0-2 jets	Yes	20.3	490 GeV	1501.0125	
		$\sqrt{s} = 7 \text{ TeV}$ full data	$\sqrt{s} = 8 \text{ TeV}$ partial data	$\sqrt{s} = 8 \text{ TeV}$ full data				

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

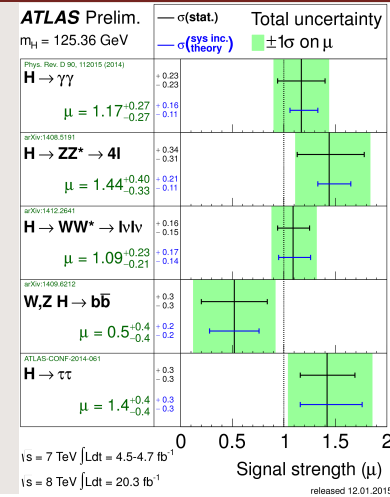
ATLAS Exotics Searches* - 95% CL Exclusion
 Status: March 2015

Model	ϵ, γ	Jets	$E_{\text{miss}}^{\text{max}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference	
Extra dimensions	ADD $G_{XX} + g/\eta$	-	≥ 1	Yes	20.3	M_{Pl}	
	ADD non-resonant $\ell\ell$	$2 e, \mu$	-	Yes	20.3	M_{Pl}	
	ADD OBH $\rightarrow \ell q$	$1 e, \mu$	1 jet	Yes	20.3	M_{Pl}	
	ADD OBH	-	2 jets	Yes	20.3	M_{Pl}	
	ADD BH high N_{eff}	$2 \mu (SS)$	-	Yes	20.3	M_{Pl}	
	ADD BH high $\sum \mu$	$\geq 1 e, \mu$	≥ 2 jets	Yes	20.3	M_{Pl}	
	ADD BH high multijet	-	≥ 2 jets	Yes	20.3	M_{Pl}	
	RS1 $G_{XX} \rightarrow \ell\ell$	$2 e, \mu$	-	Yes	20.3	M_{Pl}	
	RS1 $G_{XX} \rightarrow \gamma\gamma$	2μ	-	Yes	20.3	M_{Pl}	
	Bulk RS $G_{XX} \rightarrow ZZ \rightarrow q\bar{q}\ell\bar{\ell}$	$2 e, \mu$	2/1/1 J	Yes	20.3	M_{Pl}	
Bulk RS $G_{XX} \rightarrow WW \rightarrow q\bar{q}\nu\bar{\nu}$	$1 e, \mu$	2/1/1 J	Yes	20.3	M_{Pl}		
Bulk RS $G_{XX} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	-	4 jets	Yes	19.5	M_{Pl}		
2UED/3PPP	$1 e, \mu \geq 1 b, \geq 1 UQ$	$\geq 1 b, \geq 1 UQ$	Yes	20.3	M_{Pl}		
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	Yes	20.3	Z' mass	
	SSM $Z' \rightarrow \tau\tau$	2τ	-	Yes	19.5	Z' mass	
	SSM $W' \rightarrow \nu\bar{\nu}$	$1 e, \mu$	-	Yes	20.3	W' mass	
	EGM $W' \rightarrow WZ \rightarrow \ell\ell\ell\bar{\ell}$	$3 e, \mu$	-	Yes	20.3	W' mass	
	EGM $W' \rightarrow WZ \rightarrow q\bar{q}\ell\bar{\ell}$	$2 e, \mu$	2/1/1 J	Yes	20.3	W' mass	
	HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$	$1 e, \mu$	2 jets	Yes	20.3	W' mass	
	LRSM $W_2 \rightarrow tb$	$1 e, \mu$	2 b, 0 J	Yes	20.3	W_2 mass	
	LRSM $W_2 \rightarrow tb$	$0 e, \mu$	$\geq 1 b, 1 J$	Yes	20.3	W_2 mass	
	CI	CI $q\bar{q}$	-	2 jets	-	17.3	A
		CI $q\bar{q}\ell\bar{\ell}$	-	-	-	20.3	A
CI $u\bar{u}\ell\bar{\ell}$		$2 e, \mu (SS) \geq 1 b, \geq 1 J$	-	Yes	20.3	A	
DM		EFT D5 operator (Dirac)	$0 e, \mu \geq 1 J$	Yes	20.3	M_{Pl}	
		EFT D9 operator (Dirac)	$0 e, \mu, 1.5 \geq 1 J$	Yes	20.3	M_{Pl}	
		Scalar LQ 1 st gen	$2 e, \mu \geq 2 J$	-	1.0	M_{Pl}	
		Scalar LQ 2 nd gen	$2 e, \mu \geq 2 J$	-	1.0	M_{Pl}	
		Scalar LQ 3 rd gen	$1 e, \mu, 1 \tau$	1 b, 1 J	-	1.7	M_{Pl}
		LC	VLO $TT \rightarrow H\ell + X, Wb + X$	$1 e, \mu \geq 1 b, \geq 3 J$	Yes	20.3	T mass
			VLO $TT \rightarrow H\ell + X, Wb + X$	$2/3 e, \mu \geq 2/1 b$	Yes	20.3	T mass
	VLO $BB \rightarrow Zb + X$		$2/3 e, \mu \geq 2/1 b$	Yes	20.3	T mass	
	VLO $BB \rightarrow Wt + X$		$1 e, \mu \geq 1 b, \geq 5 J$	Yes	20.3	T mass	
	$T_{12} \rightarrow H\ell$		$1 e, \mu \geq 1 b, \geq 5 J$	Yes	20.3	T mass	
Heavy quarks	Excited quark $q^* \rightarrow q\gamma$		1 jet	-	20.3	q^* mass	
	Excited quark $q^* \rightarrow q\ell$		1 jet	-	20.3	q^* mass	
	Excited quark $q^* \rightarrow qW$		1 or 2 jets, 1 b, 2 J or 1 J	Yes	4.7	q^* mass	
	Excited lepton $\ell^* \rightarrow \ell\gamma$		$2 e, \mu, 1 \tau$	-	13.0	ℓ^* mass	
	Excited lepton $\ell^* \rightarrow \ell W, \gamma Z$		$3 e, \mu, \tau$	-	20.3	ℓ^* mass	
	Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 jet	-	20.3	q^* mass	
		Excited quark $q^* \rightarrow q\ell$	1 jet	-	20.3	q^* mass	
		Excited quark $q^* \rightarrow qW$	1 or 2 jets, 1 b, 2 J or 1 J	Yes	4.7	q^* mass	
		Excited lepton $\ell^* \rightarrow \ell\gamma$	$2 e, \mu, 1 \tau$	-	13.0	ℓ^* mass	
		Excited lepton $\ell^* \rightarrow \ell W, \gamma Z$	$3 e, \mu, \tau$	-	20.3	ℓ^* mass	
Other		LSTC $\tilde{g} \rightarrow W\gamma$	$1 e, \mu, 1 \tau$	-	Yes	20.3	M_{Pl}
		LRSM Micrans ν	$2 e, \mu (SS)$	-	Yes	20.3	M_{Pl}
		Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2 e, \mu (SS)$	-	Yes	20.3	M_{Pl}
		Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	Yes	20.3	M_{Pl}
		Monopole (non-res prod)	$1 e, \mu$	1 b	Yes	20.3	M_{Pl}
	Multi-charged particles	-	-	Yes	20.3	M_{Pl}	
	Magnetic monopoles	-	-	Yes	20.3	M_{Pl}	

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

What Now?

- Higgs Precision Measurements
- Beyond the Standard Model Physics Searches
- SUSY, Extra dimensions, etc.
- All these searches need higher energy collisions, and more data



released 12.01.2015

ATLAS SUSY Searches* - 95% CL Lower Limits
 Status: Feb 2015

Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{\text{miss}}^{\text{max}}$	$ \mathcal{L}_{\text{int}} \text{ [fb}^{-1}]$	Mass limit	Reference	
Inclusive Searches							
MSUGRA/CMSSM	0, 2, 6 jets	Yes	20.3	2	1455.7875	$m(\tilde{g})=0$ GeV, $m(\tilde{t}_1)=1.7$ TeV	
$\tilde{g}\tilde{g}, \tilde{g}\tilde{q} \rightarrow \tilde{g}q$	0, 2, 6 jets	Yes	20.3	2	1455.7875	$m(\tilde{g})=0$ GeV, $m(\tilde{t}_1)=1$ TeV, $m(\tilde{t}_2)=m(\tilde{t}_1)$	
$\tilde{g}\tilde{g}, \tilde{g}\tilde{q} \rightarrow \tilde{g}q$ (compressed)	1, 0, 1-jet	Yes	20.3	2	1411.1559	$m(\tilde{g})=0$ GeV, $m(\tilde{t}_1)=1$ TeV	
$\tilde{g}\tilde{g}, \tilde{g}\tilde{q} \rightarrow \tilde{g}q$	0, 2, 6 jets	Yes	20.3	2	1455.7875	$m(\tilde{g})=0$ GeV	
$\tilde{g}\tilde{g}, \tilde{g}\tilde{q} \rightarrow \tilde{g}q$	1, 2 jets	Yes	20	2	1501.03555	$m(\tilde{g})=0$ GeV, $m(\tilde{t}_1)=0.5m(\tilde{t}_2)$, $m(\tilde{t}_2)$	
$\tilde{g}\tilde{g}, \tilde{g}\tilde{q} \rightarrow \tilde{g}q$	2, 2 jets	Yes	20	2	1501.03555	$m(\tilde{g})=0$ GeV	
GMSB (\tilde{g} NLSP)	1-2 + 0-1 l	0-2 jets	Yes	20.3	2	1497.0603	$\tan\beta = 20$
GGM (bino NLSP)	2, 2 jets	Yes	20.3	2	1497.0603	$m(\tilde{g})=50$ GeV	
GGM (wino NLSP)	1, 2 jets	Yes	4.8	2	1497.0603	$m(\tilde{g})=200$ GeV	
GGM (higgsino-bino NLSP)	1, 0 jets	Yes	4.8	2	1497.0603	$m(\text{NLSP})=200$ GeV	
GGM (higgsino NLSP)	2, 2 jets	Yes	5.8	2	1497.0603	$m(\text{NLSP})=200$ GeV	
Gravitino LSP	0 monojet	Yes	20.3	2	1502.01518	$m(\tilde{g})=1.8 \times 10^{-4}$ eV, $m(\tilde{g}_2)=1.5$ TeV	
$\tilde{g}\tilde{g}$ scale							
$\tilde{g}\tilde{g}$ scale	0, 3, 4 jets	Yes	20.1	2	1497.0600	$m(\tilde{g})=400$ GeV	
$\tilde{g}\tilde{g}$ scale	0, 7-10 jets	Yes	20.3	2	1308.1841	$m(\tilde{g})=350$ GeV	
$\tilde{g}\tilde{g}$ scale	0, 1-4 jets	Yes	20.1	2	1497.0600	$m(\tilde{g})=400$ GeV	
$\tilde{g}\tilde{g}$ scale	0, 1-4 jets	Yes	20.1	2	1497.0600	$m(\tilde{g})=200$ GeV	
3rd gen. squarks direct production							
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	0, 2 jets	Yes	20.3	2	1300.2031	$m(\tilde{t}_1)=90$ GeV	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets (SS)	Yes	20.3	2	1484.2500	$m(\tilde{t}_1)=2m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	1, 2 jets	Yes	4.7	2	1209.2102, 1407.0583	$m(\tilde{t}_1)=2m(\tilde{t}_2), m(\tilde{t}_2)=45$ GeV	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets	Yes	20.3	2	1403.4853, 1412.4742	$m(\tilde{t}_1)=2m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	0, 1-2 jets	Yes	20	2	1407.0583, 1408.1122	$m(\tilde{t}_1)=2m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	0 monojet-tag	Yes	20.3	2	1497.0600	$m(\tilde{t}_1)=90$ GeV	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets	Yes	20.3	2	1403.5222	$m(\tilde{t}_1)=150$ GeV	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	3, 0 jets	Yes	20.3	2	1403.5222	$m(\tilde{t}_1)=200$ GeV	
3rd gen. squarks direct production							
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets	Yes	20.3	2	1490.5206	$m(\tilde{t}_1)=0$ GeV	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets	Yes	20.3	2	1490.5206	$m(\tilde{t}_1)=0$ GeV, $m(\tilde{t}_2)=0.5m(\tilde{t}_1)$, $m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets	Yes	20.3	2	1497.0600	$m(\tilde{t}_1)=0$ GeV, $m(\tilde{t}_2)=0.5m(\tilde{t}_1)$, $m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	3, 0 jets	Yes	20.3	2	1497.0600	$m(\tilde{t}_1)=0$ GeV, $m(\tilde{t}_2)=0.5m(\tilde{t}_1)$, $m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 3 jets	Yes	20.3	2	1403.5206, 1402.7029	$m(\tilde{t}_1)=m(\tilde{t}_2), m(\tilde{t}_1)=0, \text{ sleptons decoupled}$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 3 jets	Yes	20.3	2	1507.7110	$m(\tilde{t}_1)=m(\tilde{t}_2), m(\tilde{t}_1)=0, \text{ sleptons decoupled}$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	4, 0 jets	Yes	20.3	2	1490.5206	$m(\tilde{t}_1)=m(\tilde{t}_2), m(\tilde{t}_1)=0, \text{ sleptons decoupled}$	
EW correct							
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets	Yes	20.3	2	1490.5206	$m(\tilde{t}_1)=0$ GeV	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets	Yes	20.3	2	1490.5206	$m(\tilde{t}_1)=0$ GeV, $m(\tilde{t}_2)=0.5m(\tilde{t}_1)$, $m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets	Yes	20.3	2	1497.0600	$m(\tilde{t}_1)=0$ GeV, $m(\tilde{t}_2)=0.5m(\tilde{t}_1)$, $m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	3, 0 jets	Yes	20.3	2	1497.0600	$m(\tilde{t}_1)=0$ GeV, $m(\tilde{t}_2)=0.5m(\tilde{t}_1)$, $m(\tilde{t}_2)$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 3 jets	Yes	20.3	2	1403.5206, 1402.7029	$m(\tilde{t}_1)=m(\tilde{t}_2), m(\tilde{t}_1)=0, \text{ sleptons decoupled}$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 3 jets	Yes	20.3	2	1507.7110	$m(\tilde{t}_1)=m(\tilde{t}_2), m(\tilde{t}_1)=0, \text{ sleptons decoupled}$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	4, 0 jets	Yes	20.3	2	1490.5206	$m(\tilde{t}_1)=m(\tilde{t}_2), m(\tilde{t}_1)=0, \text{ sleptons decoupled}$	
Long-lived							
Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived \tilde{t}_1	Disapp. ltk	1 jet	Yes	20.3	110.3675	$m(\tilde{t}_1)=160$ MeV, $\tau(\tilde{t}_1)=0.2$ ns	
Stable, stopped R-hadron	0, 1-5 jets	Yes	27.9	2	160.6884	$m(\tilde{t}_1)=100$ GeV, $10 \mu\text{s} < \tau(\tilde{t}_1) < 1000$ s	
Stable R-hadron	Yes	19.1	2	1411.6795	$1.5 < \tau < 156$ ms, BR $_{\text{had}}=1, m(\tilde{t}_1)=108$ GeV		
GMSB, stable $\tilde{t}_1, \tilde{t}_1^* \rightarrow \tilde{t}_1, \tilde{t}_1^* + \tau(\tilde{t}_1)$	1, 2 jets	Yes	19.1	2	1411.6795	$10\text{-}100 \mu\text{s}$	
GMSB, stable $\tilde{t}_1, \tilde{t}_1^* \rightarrow \tilde{t}_1, \tilde{t}_1^* + \tau(\tilde{t}_1)$	2 jets	Yes	20.3	2	1490.5542	$2 < \tau < 10$ ns, SP82 model	
$\tilde{g}\tilde{g}, \tilde{g}\tilde{q} \rightarrow \tilde{g}q$	1, 0, displ. vtx	Yes	20.3	2	1490.5542	$1.5 < \tau < 156$ ms, BR $_{\text{had}}=1, m(\tilde{t}_1)=108$ GeV	
RPV							
LFV $\tilde{p}\tilde{p} \rightarrow \tilde{p}, \tilde{p} \rightarrow e + \mu$	2, 0 jets	Yes	4.6	2	1212.1272	$\tilde{A}_{12} = 0.10, \tilde{A}_{13} = 0.05$	
LFV $\tilde{p}\tilde{p} \rightarrow \tilde{p}, \tilde{p} \rightarrow e + \mu$	1, 1 jet + τ	Yes	4.6	2	1212.1272	$\tilde{A}_{12} = 0.10, \tilde{A}_{13} = 0.05$	
Bilinear RPV CMSSM	2, 0 jets	0-3 b	Yes	20.3	1484.2500	$m(\tilde{g})=0$ GeV, $\tau_{\text{had}} < 1$ ns	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	4, 0 jets	Yes	20.3	2	1490.5086	$m(\tilde{t}_1)=0.2m(\tilde{t}_2), \tilde{A}_{12} = 0$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	3, 0 jets + τ	Yes	20.3	2	1490.5086	$m(\tilde{t}_1)=0.2m(\tilde{t}_2), \tilde{A}_{12} = 0$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	0, 6-7 jets	Yes	20.3	2	1490.5086	$m(\tilde{t}_1)=0.2m(\tilde{t}_2), \tilde{A}_{12} = 0$	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2$	2, 0 jets (SS)	0-3 b	Yes	20.3	1494.2550	BR $_{\text{had}}=0.8m(\tilde{t}_1)=0.4m(\tilde{t}_2)$	
Other							
Scalar charm, $\tilde{t}_1 \rightarrow \tilde{t}_1^* \gamma$	0, 2 jets	Yes	20.3	2	1501.6125		

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

ATLAS Exotics Searches* - 95% CL Exclusion
 Status: March 2015

Model	ϵ, γ	Jets	$E_{\text{miss}}^{\text{max}}$	$ \mathcal{L}_{\text{int}} \text{ [fb}^{-1}]$	Mass limit	Reference
Extra dimensions						
ADD $G_{\text{XX}} + \dots$		≥ 1	Yes	20	5.25 TeV	$n=2$
ADD non-resonant $\ell\ell$	2, 0 jets	Yes	20	20	4.7 TeV	$n=3$ Planck
ADD OBH	1, 0 jets	Yes	20	20	5.2 TeV	5211.2008
ADD OBH	2, 0 jets	Yes	20	20	5.92 TeV	$n=6$
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets (SS)	Yes	20	20	4.7 TeV	$n=6, M_{\text{pl}}=3$ TeV, non-res BH
ADD BH $\rightarrow N_{\text{eff}}$	$\geq 1, 0$ jets	Yes	20	20	5.8 TeV	1304.4075
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	1404.4254
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	$n=6, M_{\text{pl}}=3$ TeV, non-res BH
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	$k/\bar{M}_{\text{pl}} = 0.1$
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	$k/\bar{M}_{\text{pl}} = 1.0$
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	$k/\bar{M}_{\text{pl}} = 1.0$
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	$k/\bar{M}_{\text{pl}} = 1.0$
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	BR = 0.925
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	ATLAS-CONF-2014-005
ADD BH $\rightarrow N_{\text{eff}}$	2, 0 jets	Yes	20	20	5.8 TeV	ATLAS-CONF-2015-029
Gauge bosons						
SSM $Z' \rightarrow \ell\ell$	2, 0 jets	Yes	20	20	2.9 TeV	1405.1123
SSM $Z' \rightarrow \tau\tau$	2, 0 jets	Yes	19.5	20	2.02 TeV	1500.0717
SSM $W' \rightarrow \ell\nu$	1, 0 jets	Yes	20	20	3.24 TeV	1407.7454
EGM $W' \rightarrow WZ \rightarrow \ell\ell\nu$	3, 0 jets	Yes	20	20	1.52 TeV	1406.4456
EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell\nu$	2, 0 jets	Yes	20	20	1.59 TeV	1406.0190
HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$	1, 0 jets	2b, 0 jets	Yes	20	1.47 TeV	1406.0190
LRSM $W' \rightarrow tb$	1, 0 jets	2b, 0 jets	Yes	20	1.92 TeV	1610.4100
LRSM $W'_2 \rightarrow tb$	0, 0 jets	2b, 0 jets	Yes	20	1.76 TeV	1610.4100
CI						
CI $q\bar{q}$	2, 0 jets	Yes	17.3	20	12.0 TeV	$\beta_2 = -1$
CI $u\bar{u}$	2, 0 jets	Yes	20	20	4.35 TeV	$ \mathcal{G} = 1$
CI $u\bar{u}$	2, 0 jets (SS) $\geq 1b, \geq 1l$	Yes	20	20	4.35 TeV	$ \mathcal{G} = 1$
DM						
EFT D5 operator (Dirac)	0, 0 jets	≥ 1	Yes	20	97 TeV	at 90% CL for $m(\chi) < 100$ GeV
EFT D9 operator (Dirac)	0, 0 jets	1, 1 jets	Yes	20	97 TeV	at 90% CL for $m(\chi) < 100$ GeV
LC						
Scalar LQ 1 st gen	2, 0 jets	≥ 1	Yes	1.0	660 GeV	$\beta = 1$
Scalar LQ 2 nd gen	2, 0 jets	≥ 1	Yes	1.0	685 GeV	$\beta = 1$
Scalar LQ 3 rd gen	1, 0 jets, 1 τ	1, 1 jets	Yes	1.7	534 GeV	$\beta = 1$
Heavy quarks						
VLO $TT \rightarrow Ht + X, Wb + X$	1, 0 jets	$\geq 1b, \geq 3l$	Yes	20	785 GeV	Isospin singlet
VLO $TT \rightarrow Zt + X, Wb + X$	2, 0 jets	$\geq 2b, \mu \geq 2l$	Yes	20	785 GeV	T in (TB) doublet
VLO $BB \rightarrow Zb + X$	2, 0 jets	$\geq 2b, \mu \geq 2l$	Yes	20	785 GeV	B in (TB) doublet