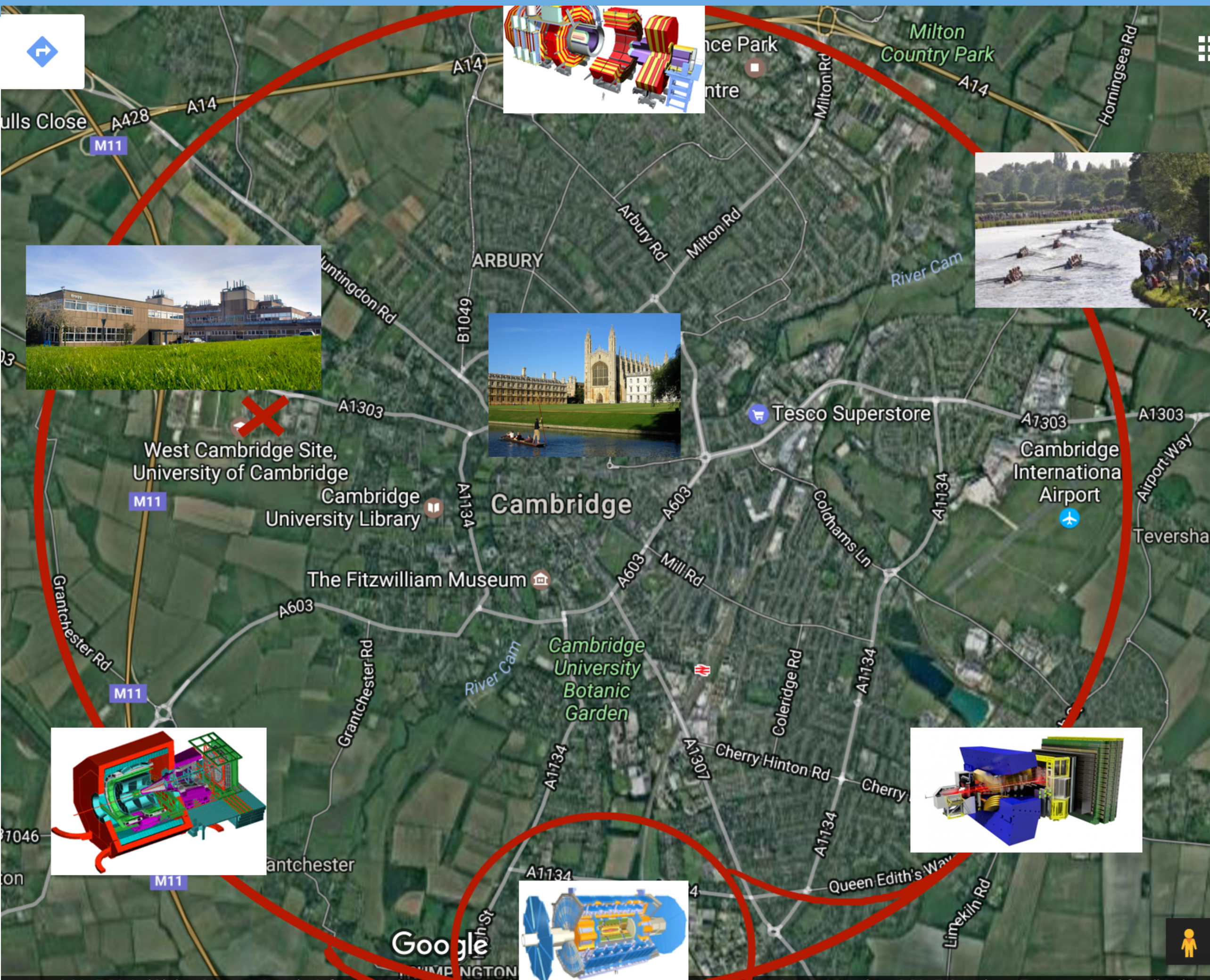
BSM searches and detector developments

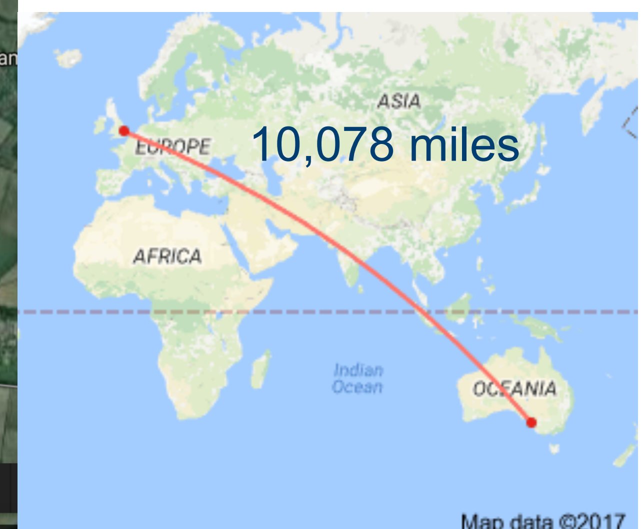
CoePP workshop 2017

Dr Sarah Williams- University of Cambridge

Introduction



- Despite housing the world's forth oldest surviving university, the city of Cambridge would fit comfortably inside the LHC ring….



Activities in the Cambridge HEP group

High Energy Physics group:

- ATLAS
- LHCb
- Theory
- MicroBooNE
- DUNE
- Linear collider

- In the next ~ 30 minutes, will try and discuss **some** of the ongoing activities within the group, with a particular focus on the LHC experiments.

What the U.K media had to say about the LHC last year (sourced from https://www.theguardian.com)

April 2016

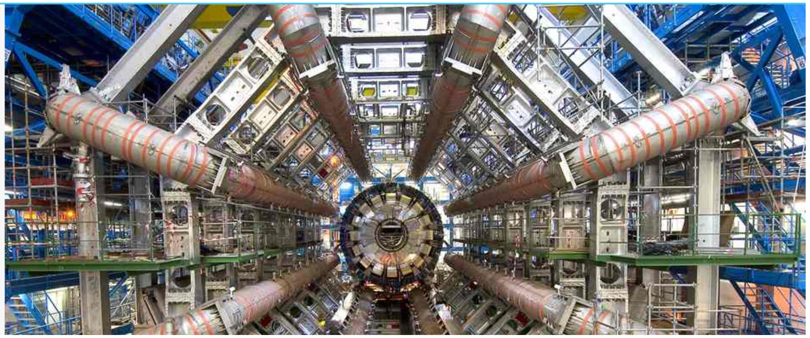
Large Hadron Collider on paws after creature chews through wiring

LHC expected to be out of action for a week while transformer connections are replaced following visit from hungry fouine

August 2016

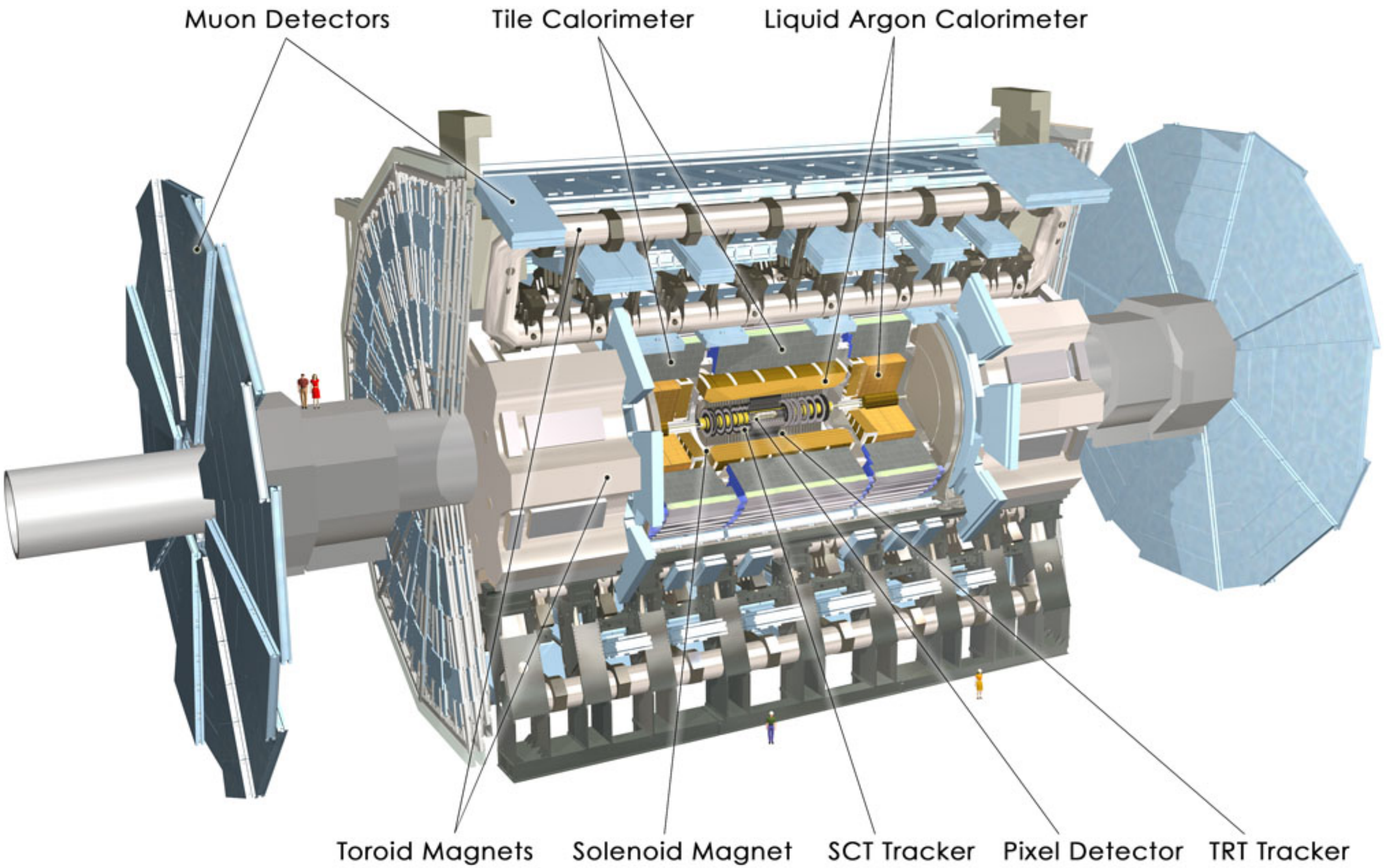
Blip flop as tantalising bump in Large Hadron Collider data disappears

Hopes for a new particle are dashed, as new data shows no trace of the anomaly, suggesting that its appearance was a statistical fluke



Weasels aside, the large increase in size of the 13 TeV dataset in 2016 has increased the potential sensitivity of the LHC experiments to new physics scenarios. This talk will first summarise several new research efforts related to BSM physics that are ongoing within the ATLAS and LHCb groups, and will be followed by a quick look ahead to ongoing detector development work…

ATLAS results…



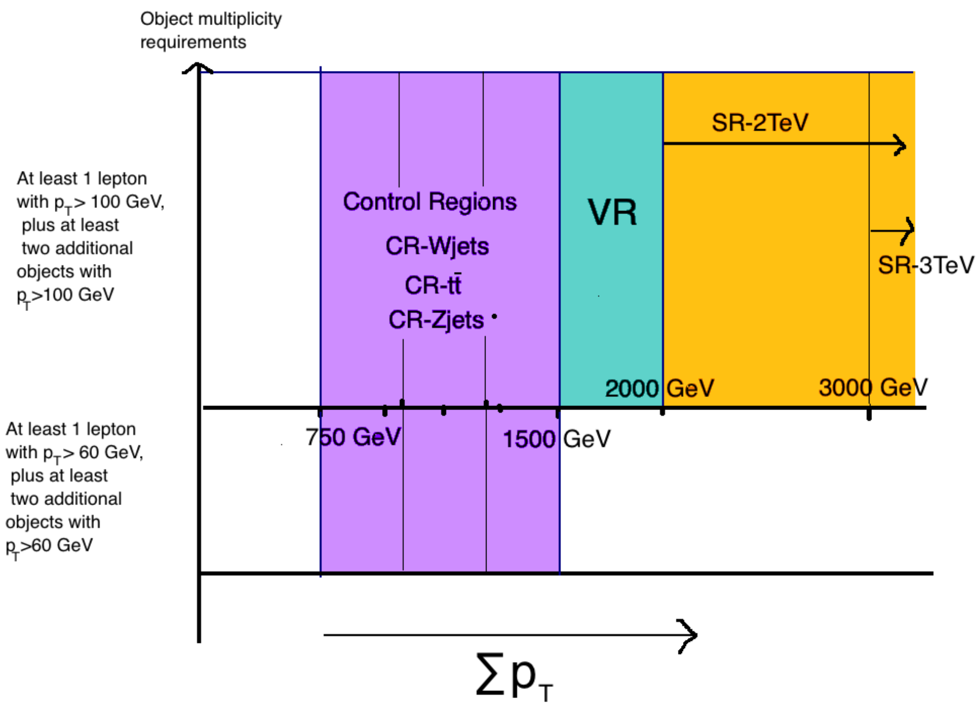
Reminder of typical ATLAS search strategy

- Define one or more "signal regions" using a set of event selection criteria designed to select signal whilst suppressing the SM backgrounds (note as analyses become more sophisticated these are often binned).

- Dominant SM backgrounds are estimated using data-driven methods (often by extracting normalisation from "control regions").

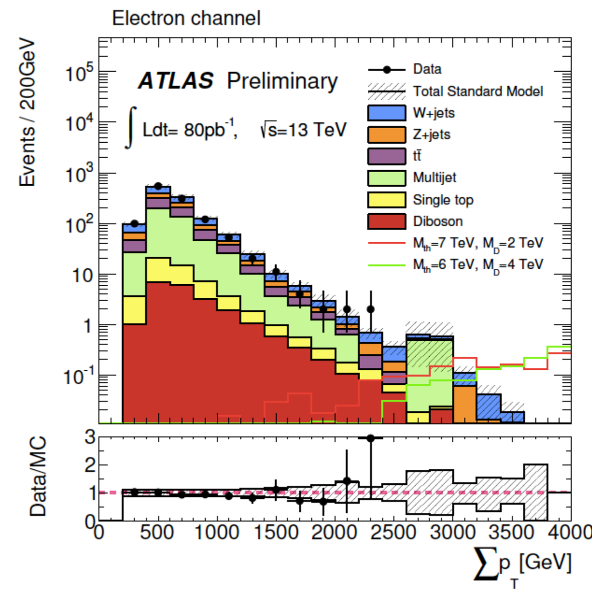
- Background estimates often checked using dedicated "validation regions".

- Excesses in the SRs could be a sign of new physics



Extending the reach of BSM searches in ATLAS

- At the time of the last CoePP workshop the first results based on 3.2 fb^{-1} of 2015 data were in the process of being released.
- The energy increase relative to run-I meant for some scenarios the run-II sensitivity exceeded previous limits with very small datasets.
- E.g. the search for TeV-gravity signatures in events with three high p_T objects (including a lepton) exceeded the previous limits with only 80 pb^{-1}

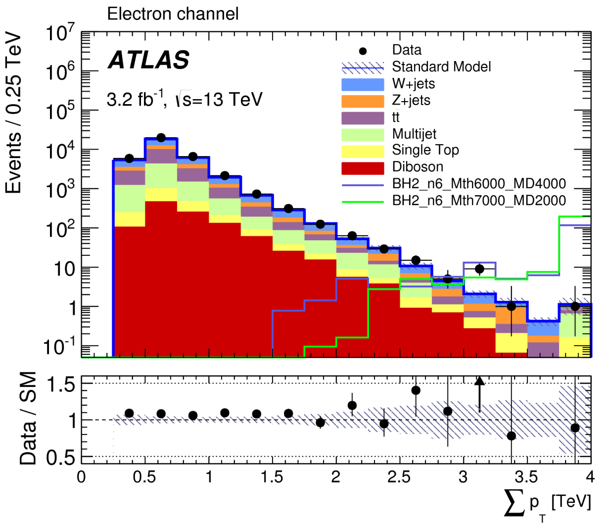


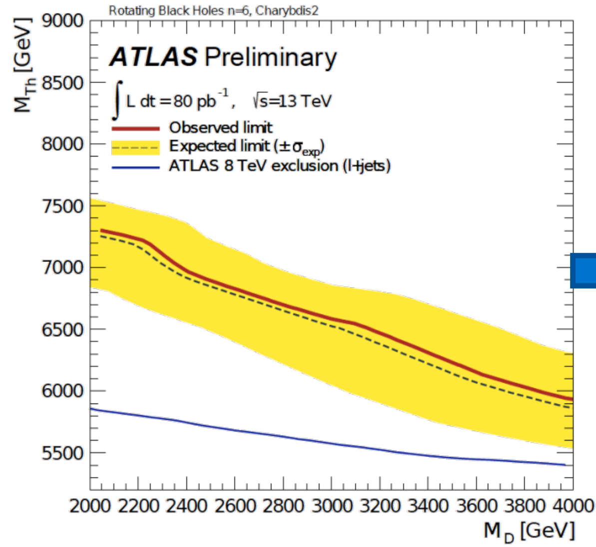
Analysis looked for an excess of events at high Σp_T which could be caused by microscopic black holes or other gravitational states

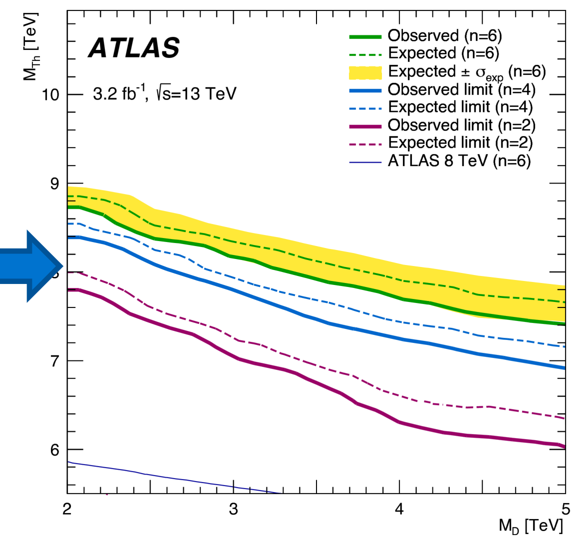
ATLAS-CONF-2015-046

Constraints on TeV-gravity signatures in ATLAS

Search using full 2015 dataset also saw no excess above the SM expectation -> set limits as a function of m_D (planck mass) and m_{TH} (threshold mass) for rotating black hole production in n=2,4,6 extra dimensions



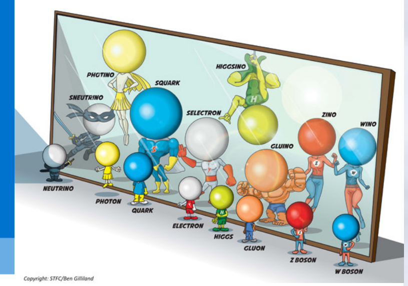




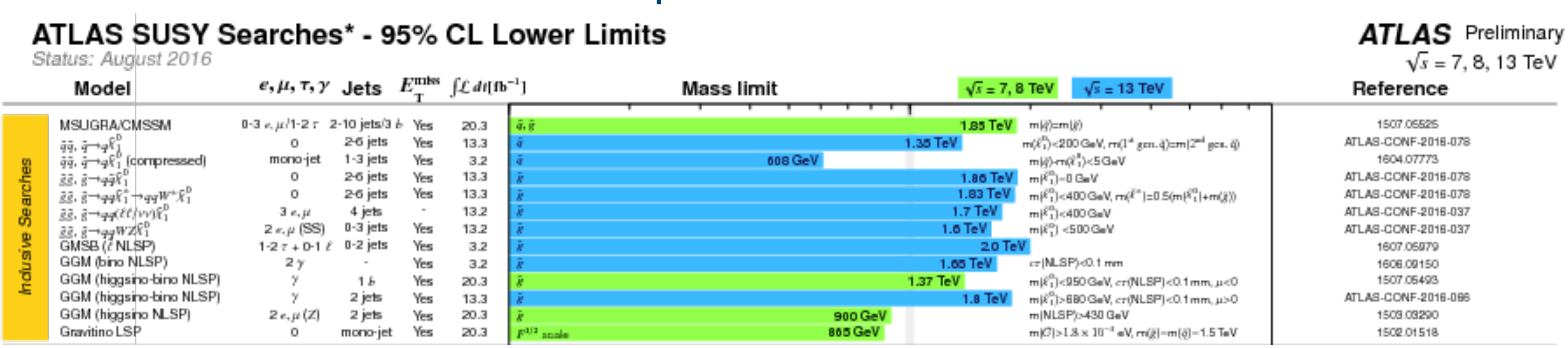
- Increase in sensitivity with more data small compared to gain with centre-of-mass energy.
- Significant improvement in sensitivity would require improved techniques and larger datasets.

PLB 760 (2016) 520-537

What about SUSY?



- Early run-II SUSY searches in ATLAS were also focussed on strongly produced sparticle production which has a higher production cross-section.
- Exclusion limits for squark and gluino production extend beyond 1TeV in most scenarios considered.
- SUSY searches within the Cambridge group are more focussed on electroweak production…



Quick reminder

- Electroweak SUSY refers to production processes that cannot be mediated by the strong interaction-> production of charginos, neutralinos, and sleptons.
- Charginos and neutralinos are the mass eigenstates of the bino, wino and higgsinos, and the exact mixing can greatly impact the phenomenology.
- Searches often based on simplified models in the pMSSM to focus on particular signatures, usually involving leptonic final states.

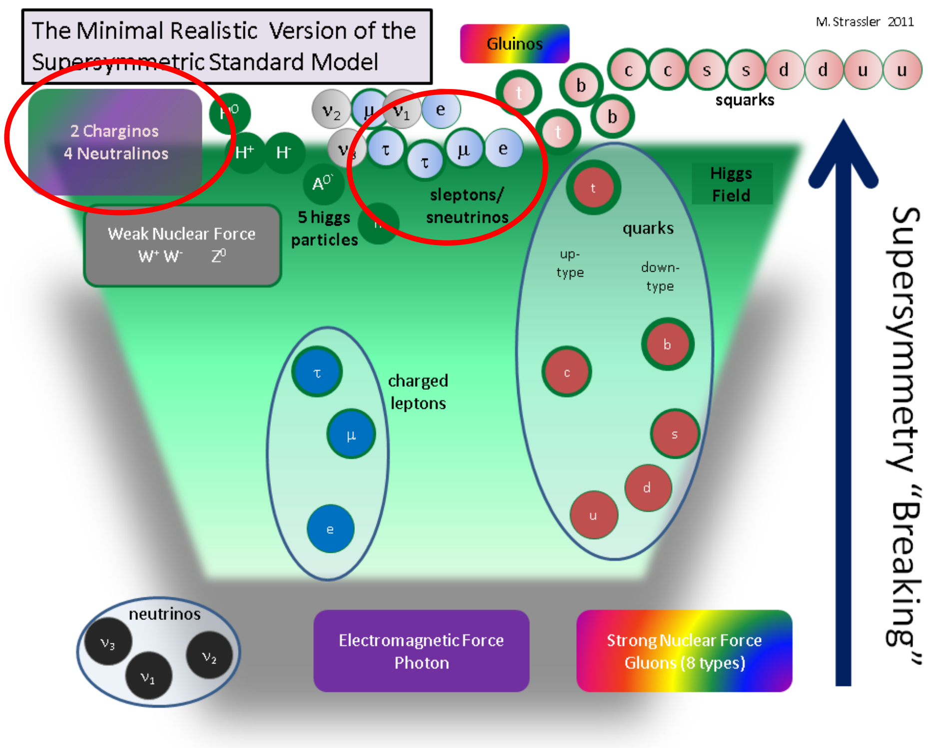
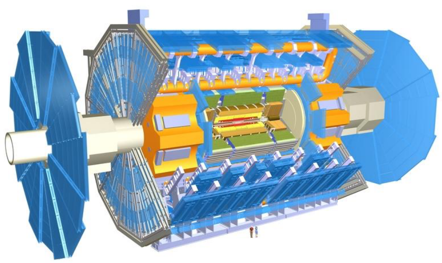
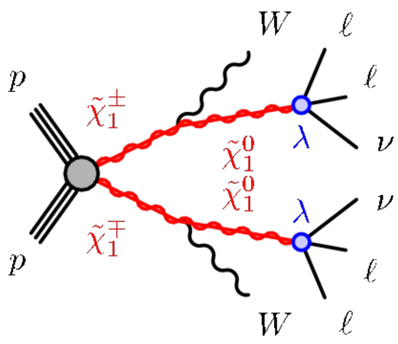


Image credit Matt Hassler

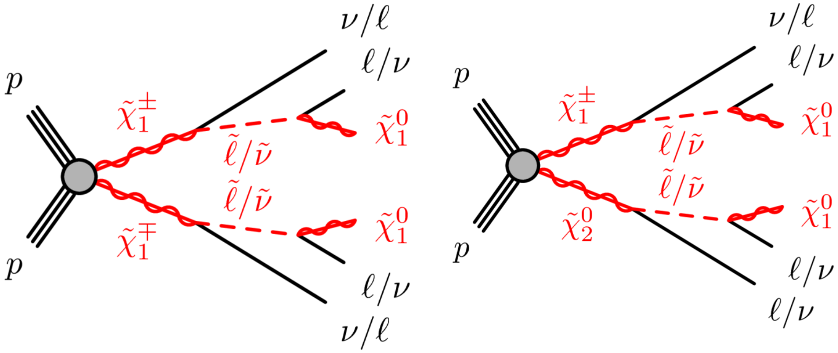
Electroweak SUSY searches in ATLAS



- Potentially the primary discovery channel if strongly produced sparticles are heavy and so out of reach.
- Also relevant to the issue of naturalness in SUSY.
- Cambridge group is active in searches for the electroweak production of SUSY particles in 2,3 and 4-lepton final states.
- First results based on run-II datasets were released as conference notes in August/September 2016 (ATLAS-CONF-2016-075 and ATLAS-CONF-2016-096)



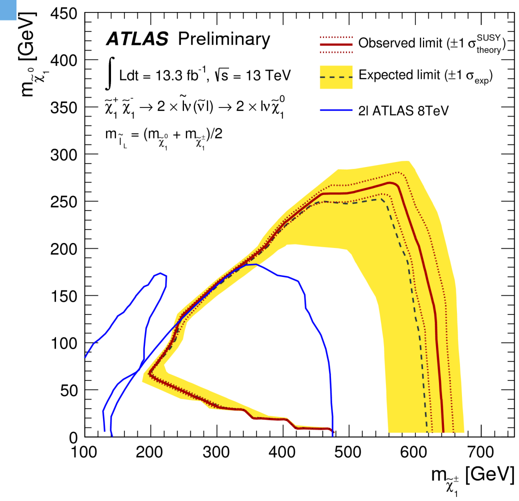
4-lepton events can target chargino pair production with indirect RPV decays of the LSP

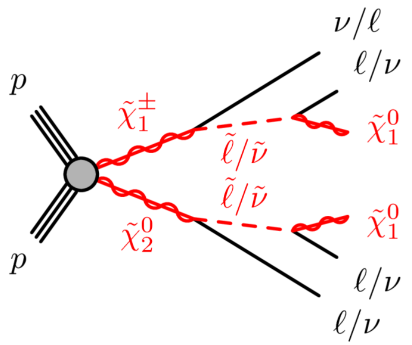


2/3-lepton events could be sensitive to chargino pair production/ chargino-neutralino production decaying to leptons

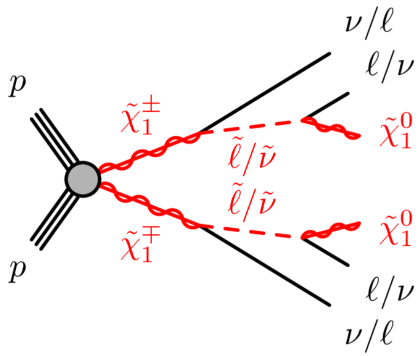
Electroweak SUSY in multi-lepton final states- 2/3l

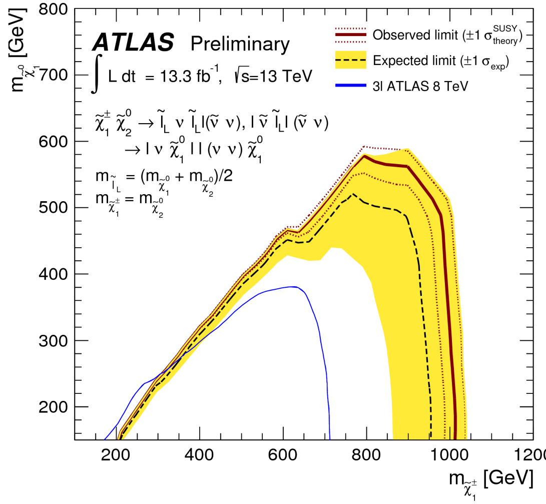
- Big ongoing effort within the group, with strong involvement also from the Adelaide ☺ (hence I won't say too much in this talk)
- First public result based on 13.3 fb^{-1} of 2015/2016 data targeted only (wino-like) chargino pair and chargino-neutralino production decaying via intermediate sleptons to a (bino-like) neutralino LSP.
- First results greatly exceeded run-I limits…





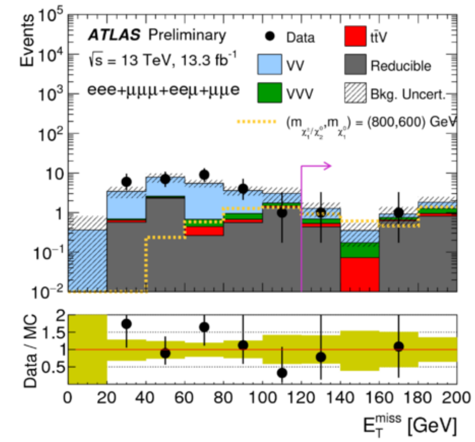
ATLAS-CONF-2016-096



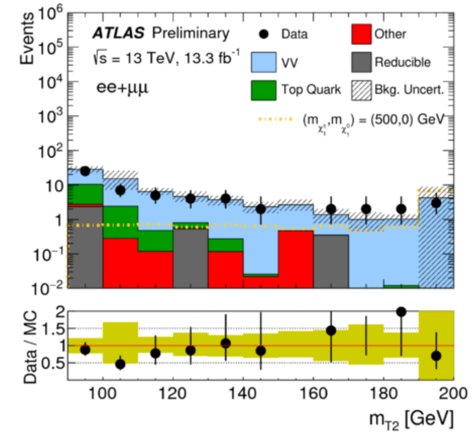


Electroweak SUSY in multi-lepton final states- 2/3l

- Both 2l and 3l channels relied on jet vetos to suppress SM backgrounds.
- Additional selections applied to reduce dominant diboson (WW/WZ backgrounds).
- 2l channel relied on hard cuts on the "stransverse mass" m_{T2} whereas 3l channel used the third lepton p_T and E_T^{miss} to target different regions of parameter space.



ATLAS-CONF-2016-096

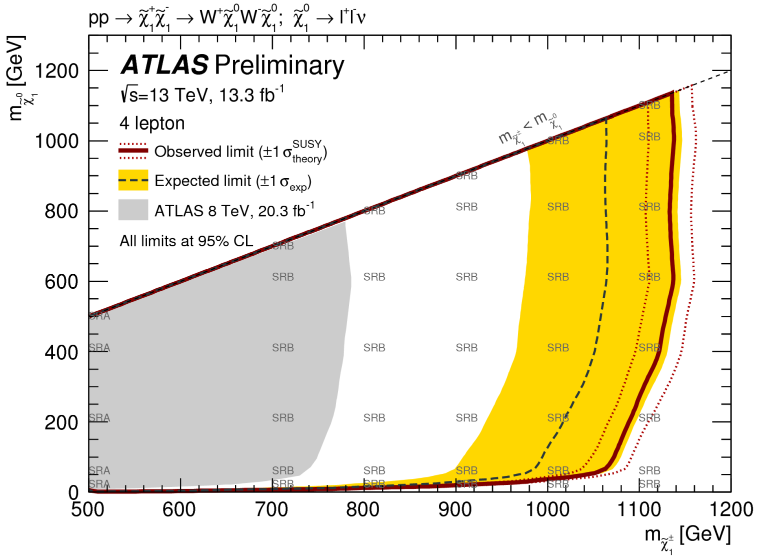


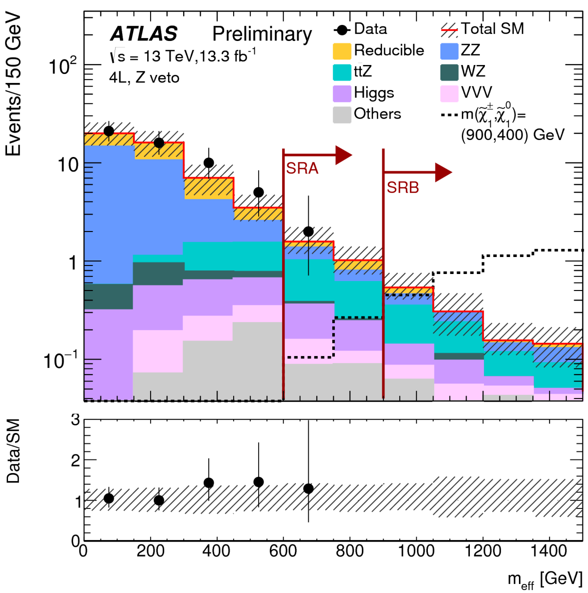
Variable	SR2ℓ	
lepton	$\ell^+\ell^-$	
lepton flavour	SF	DF
central light jets	0_{20}	0_{30}
central b-jets	0_{20}	0_{20}
forward jets	0_{30}	0_{30}
$\|m_{\ell\ell} - m_Z\|$ [GeV]	> 10	–
m_{T2} [GeV]	$> 90,\ 120,\ 150$	

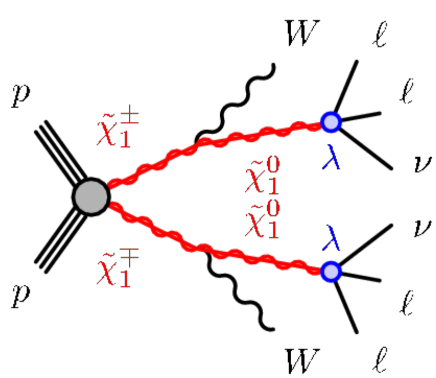
Variable	SR3ℓ-I	SR3ℓ-H
lepton	$\ell^+\ell^-\ell$	
b-tagged jet	veto	
$m_T >$	110	
m_{SFOS}	$\notin [81.2, 101.2]$	>101.2
$p_T^{3^{rd}\ell} >$	30	80
$E_T^{miss} >$	120	60

Electroweak SUSY in multi-lepton final states- 4l

- In addition to model-independent limits, first search using run-II data interpreted results in a simplified model of chargino production with indirect RPV decays.
- Backgrounds supressed by vetoing events containing a leptonic Z-boson decay.
- Searched for excesses of events at high "effective mass" m_{eff} (scalar sum of the E_T^{miss} and p_T's of all leptons and selected jets)





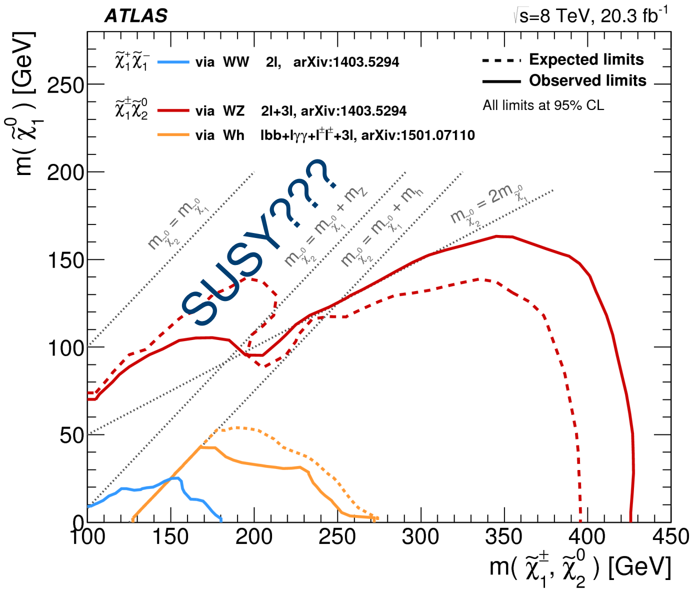


ATLAS-CONF-2016-075

Electroweak SUSY in multi-lepton final states- outlook

- There's a lot of activity in this area now the data is coming in quickly. Need to work to overcome experimental obstacles to probe more challenging regions of phase space with large SM backgrounds. Looking forward to:

1. Considering new scenarios
2. Improved search techniques (new variables? Improved object definitions?)
3. (lets be optimistic?) a discovery?



The large datasets in 2016, and expected in 2017 should open up the possibility to target new, previously unexplored regions of SUSY parameter space.

Something slightly different…

Dark matter interpretations of ATLAS searches for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV proton-proton collisions

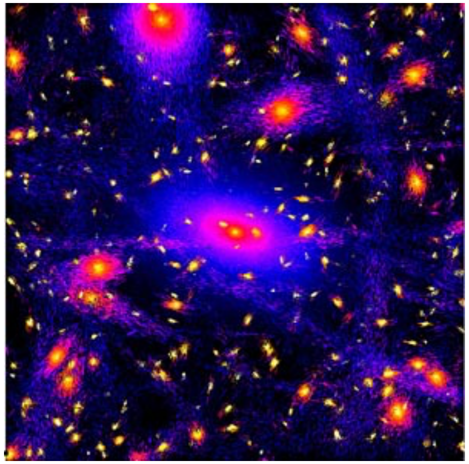


Image credit: M. Zemp

- Reinterpretation of four ATLAS run-I electroweak SUSY searches performed as part of a STA ("short term attachment") project involving ATLAS and three theorists.
- Examined the impact of the ATLAS results on models selected using an initial likelihood scan in a 5D effective MSSM that focussed on the electroweak and higgs sector (parametrised by M_1, M_2, μ, tanβ and m_A).

Reinterpretation of ATLAS run-I electroweak SUSY searches

$$\ln \mathcal{L}_{\text{Joint}} = \ln \mathcal{L}_{\text{EW}} + \ln \mathcal{L}_{\text{B}} + \ln \mathcal{L}_{\Omega_\chi h^2} + \ln \mathcal{L}_{\text{DD}} + \ln \mathcal{L}_{\text{Higgs}} + \ln \mathcal{L}_{\text{LEP-}\tilde{\chi}_1^\pm},$$

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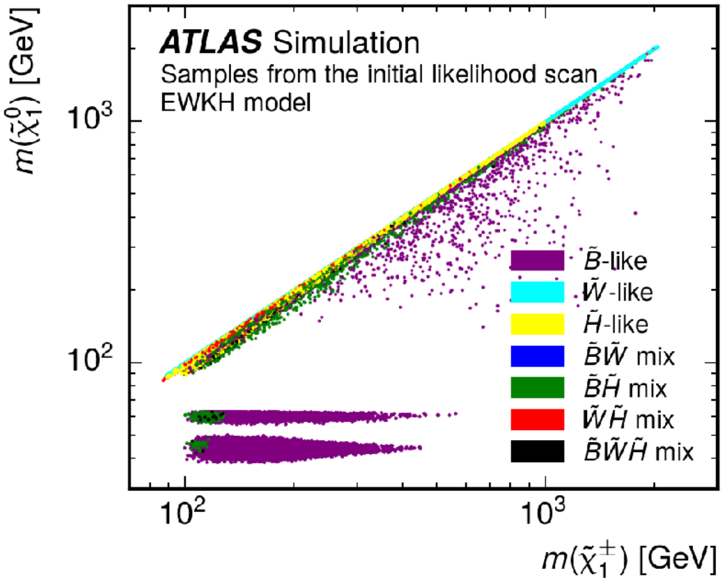
Initial likelihood scan included:

- Electroweak precision observables (mainly from LEP)
- B-physics constraints
- The cosmological relic dark matter density
- Direct detection constraints
- The ATLAS Higgs mass measurement
- The LEP2 limit on the chargino mass.



Models within 95% CL of initial scan concentrated in several distinct regions of parameter space in the chargino-LSP mass plane.

Results presented in terms of fraction of models excluded by ATLAS in different regions of parameter space…

Reinterpretation of ATLAS run-I electroweak SUSY searches

- Unsuprising observation: ATLAS had best sensitivity in regions corresponding to the simplified models used in run-I.

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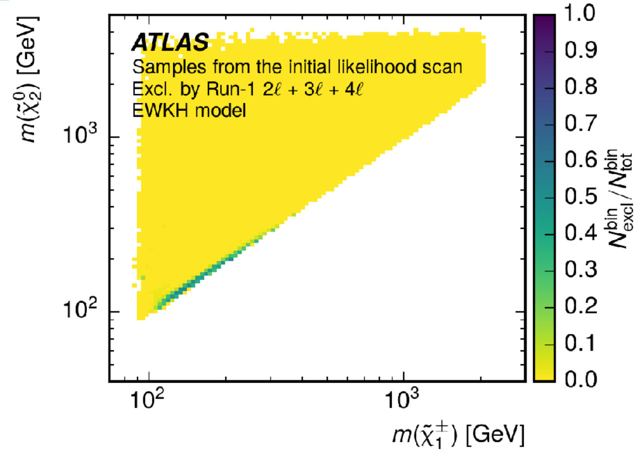
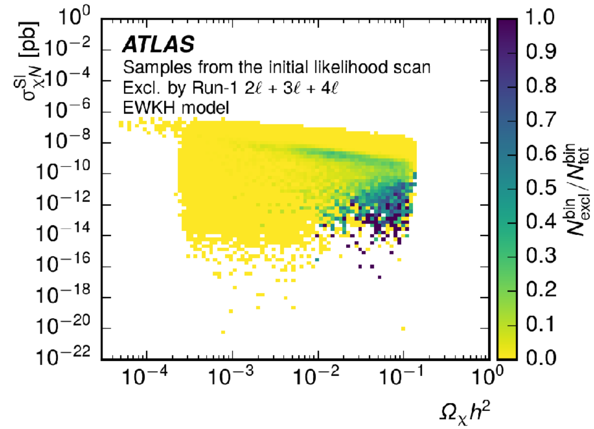


Useful messages from the analysis:

- Collider results can provide complimentary information to other constraints.

- There are still lots of regions of parameter space to explore, but they will be challenging (more compressed, non-bino LSP content). There's lots to do in run-II!



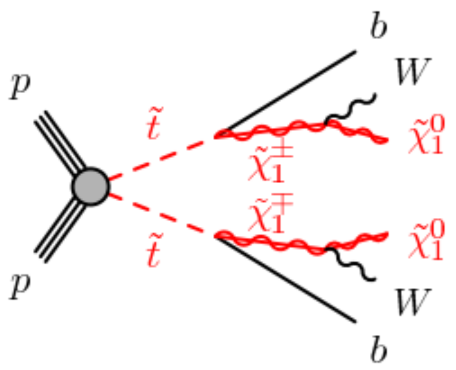
- Collaboration with theorists is essential, and finding ways to do this effectively is important.

(Nice to see the GAMBIT talk ☺)

Other SUSY activities

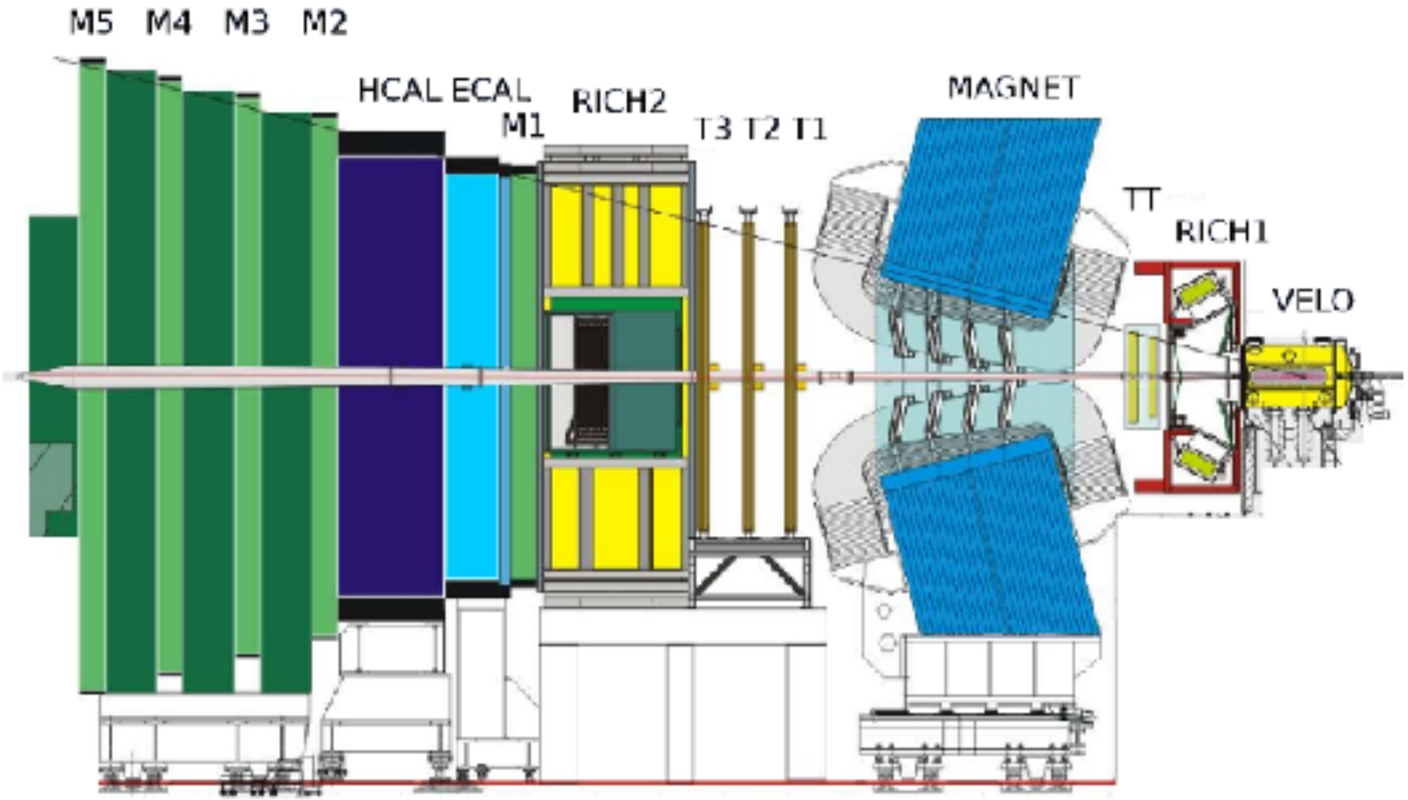
ATLAS-CONF-2016-050

- Also have a student working on third generation searches.
- Focused on stop pair production with decays to b+chargino in the 1-lepton channel.
- First public result considered several simplified models with different assumptions on the masses of the stop, chargino and LSP
- Improved analysis based on full 2015+2016 dataset expected soon

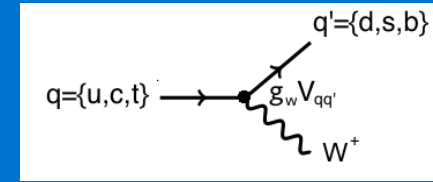


Variable	bC2x_diag	bC2x_med	bCbv
Number of (jets, b-tags)	($\geq$ 4, $\geq$ 2)	($\geq$ 4, $\geq$ 2)	($\geq$ 2, = 0)
Jet p_T > [GeV]	(70 60 55 25)	(170 110 25 25)	(120 80)
b-tagged jet p_T > [GeV]	(25 25)	(105 100)	–
E_T^{miss} [GeV]	> 230	> 210	> 360
$H_{T,sig}^{miss}$	> 14	> 7	> 16
m_T [GeV]	> 170	> 140	> 200
am_{T2} [GeV]	> 170	> 210	–
$\lvert\Delta\phi(\text{jet}_i, \vec{p}_T^{miss})\rvert (i = 1)$	> 1.2	> 1.0	> 2.0
$\lvert\Delta\phi(\text{jet}_i, \vec{p}_T^{miss})\rvert (i = 2)$	> 0.8	> 0.8	> 0.8
Leading large-R jet mass [GeV]	–	–	[70, 100]
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	–	–	> 1.2

LHCb results



CKM matrix as a probe for new physics



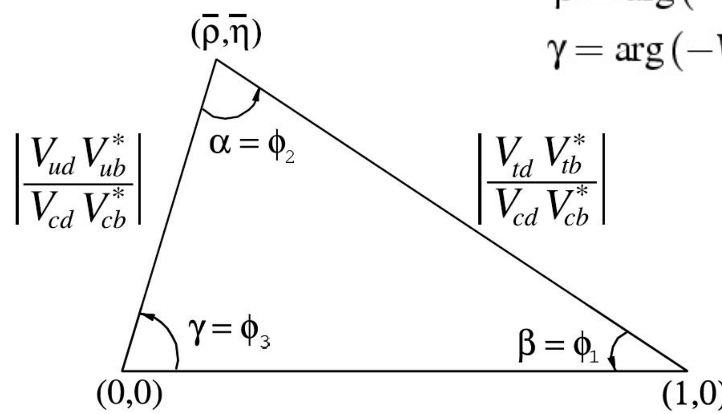
- Quark mixing in SM described by the 3x3 unitary CKM matrix-> imaginary phase in Wolfenstein parametrisation gives height to the unitarity triangle-> source of CP violation in the SM.

$$\hat{V}_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4).$$

$$\alpha = \arg\left(-V_{td}V_{td}^*/V_{ud}V_{ub}^*\right)$$
$$\beta = \arg\left(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right)$$
$$\gamma = \arg\left(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right)$$

- SM implies $\alpha + \beta + \gamma = 180°$

- Heavy flavour decays are sensitive to new physics and can be used to extract CKM matrix elements.



Accurate determination of the CKM parameters is a primary goal in flavour physics to test the SM and as a potential gateway to new physics…

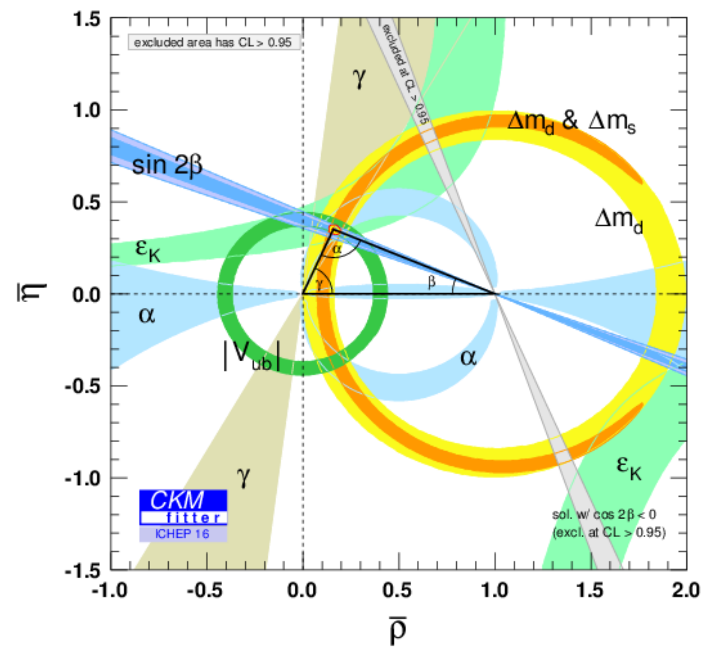
The unitary triangle- γ

Angles in the unitarity triangle can be measured through CP-violating asymmetries where processes with amplitudes with different weak phases interfere…

- The angle γ is the least well-known in the unitarity triangle and provides an excellent probe for new physics.
- Measured through tree-level B-decays, where decays via D^0 and $\overline{D^0}$ to the same final state interfere.
- Status as of summer 2016 (acc. CKMfitter)

γ [deg]	65.40 [+0.97 -1.16]
γ [deg] (meas. not in the fit)	65.33 [+0.96 -2.54]
γ [deg] (dir. meas.)	72.1 [+5.4 -5.8]

- Expected LHCb sensitivity (run 4) ~ 1°.



CKM angles- measuring γ

Currently have group members working on both the combination and one of the analyses that feeds into the measurement. Latest combination result (world's most precise single experiment measurement):

$$\gamma = (72.2^{+6.8}_{-7.3})^{\circ}$$

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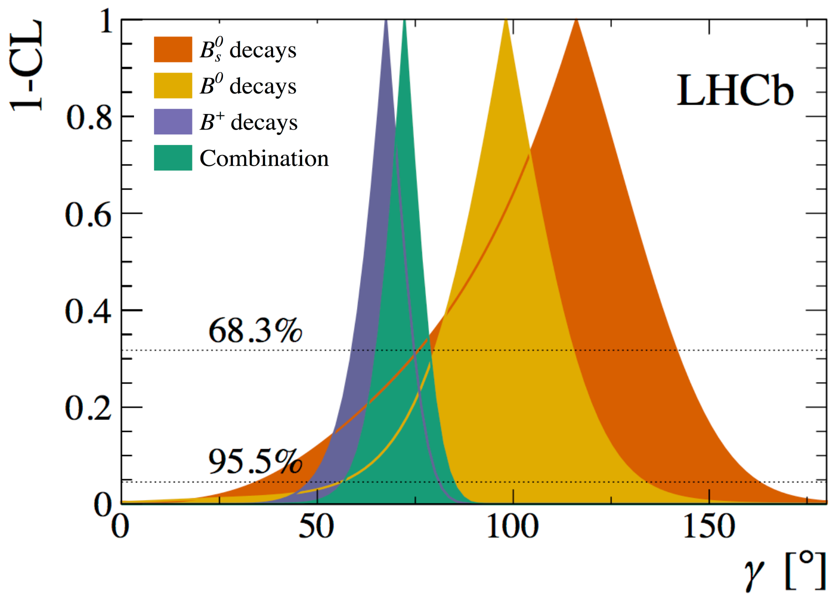
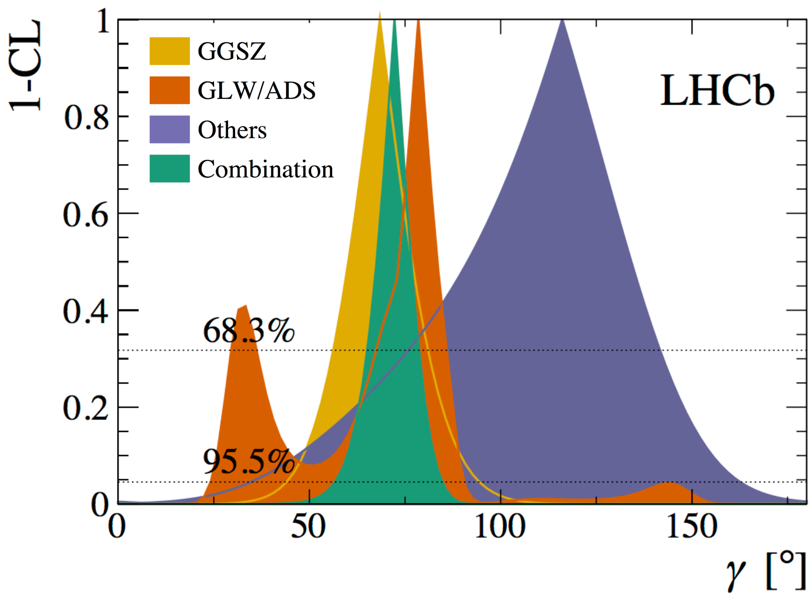
B decay	D decay	Method	Ref.	Status since last combination [28]
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS	[44]	Updated to 3 fb^{-1}
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[44]	Updated to 3 fb^{-1}
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[45]	New
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[46]	As before
$B^+ \to DK^+$	$D \to K^0_S K^-\pi^+$	GLS	[47]	As before
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS	[48]	New
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[49]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[50]	New
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[51]	New
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$	TD	[52]	As before

Note: three main methods to measure γ- named after theorists who proposed the final state:

1. GLW method
2. ADS method
3. GGSZ method

CKM angles- measuring γ





- LH plot shows results split by initial state, RH plot shows the combination split by method.
- Analyses with best standalone sensitivity (GLW/ADS) can typically have multiple solutions-> combination is essential!

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Measurement of γ using $B^0 \to DK^{*0}$ with $D \to K_S^0\pi^+\pi^-$

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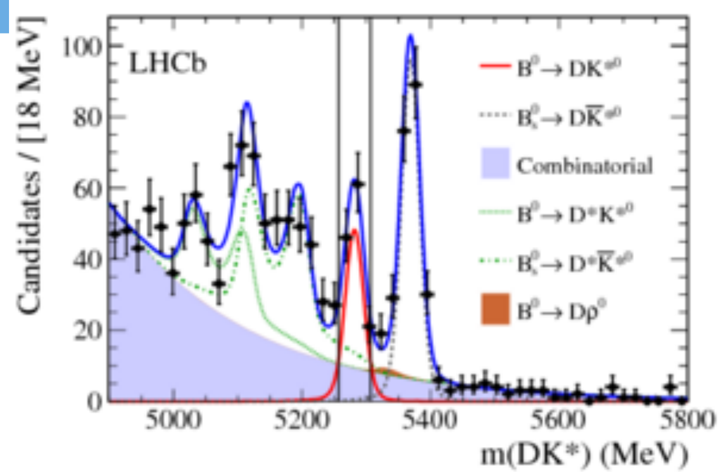
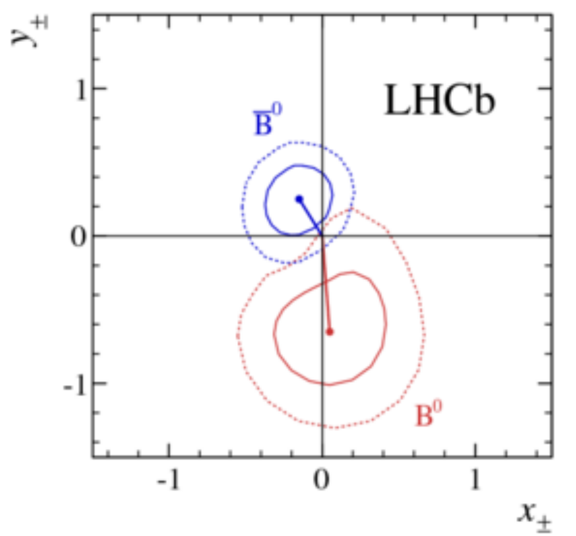
- As opposed to measuring ratios of widths of specific processes, model dependent GGSZ analysis exploits interference patterns across the Dalitz plot of three-body decays $\mathbf{D} \to K_S^0\pi^+\pi^-$.

- Large interference effects so good sensitivity to gamma, but statistics low (small branching fraction).

$$\gamma = (80^{+21}_{-22})^\circ$$

- Process $B^0 \to DK^{*0}$ also interesting as new physics may only affect B^0 modes not B^+ modes.





$B_S \to \mu^+\mu^-$ ongoing work

- Branching fractions of $B_S^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are low in the SM.
- Their values and in particular the ratio of their branching fractions are very sensitive to new physics and provide strong discrimination between BSM theories.
- After first observation of $B_S^0 \to \mu^+\mu^-$ in 2014, work now ongoing to provide accurate measurements of the lifetime and branching fraction

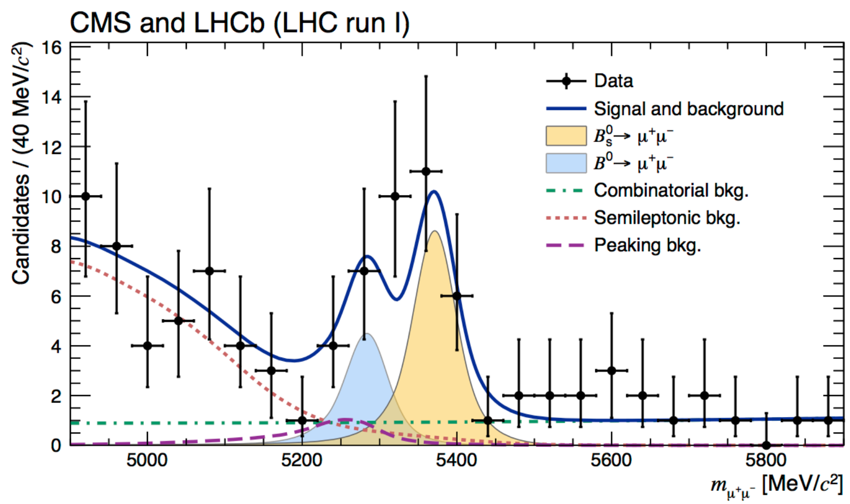
Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

CMS Collaboration & LHCb Collaboration

Nature 522 (2015) 68

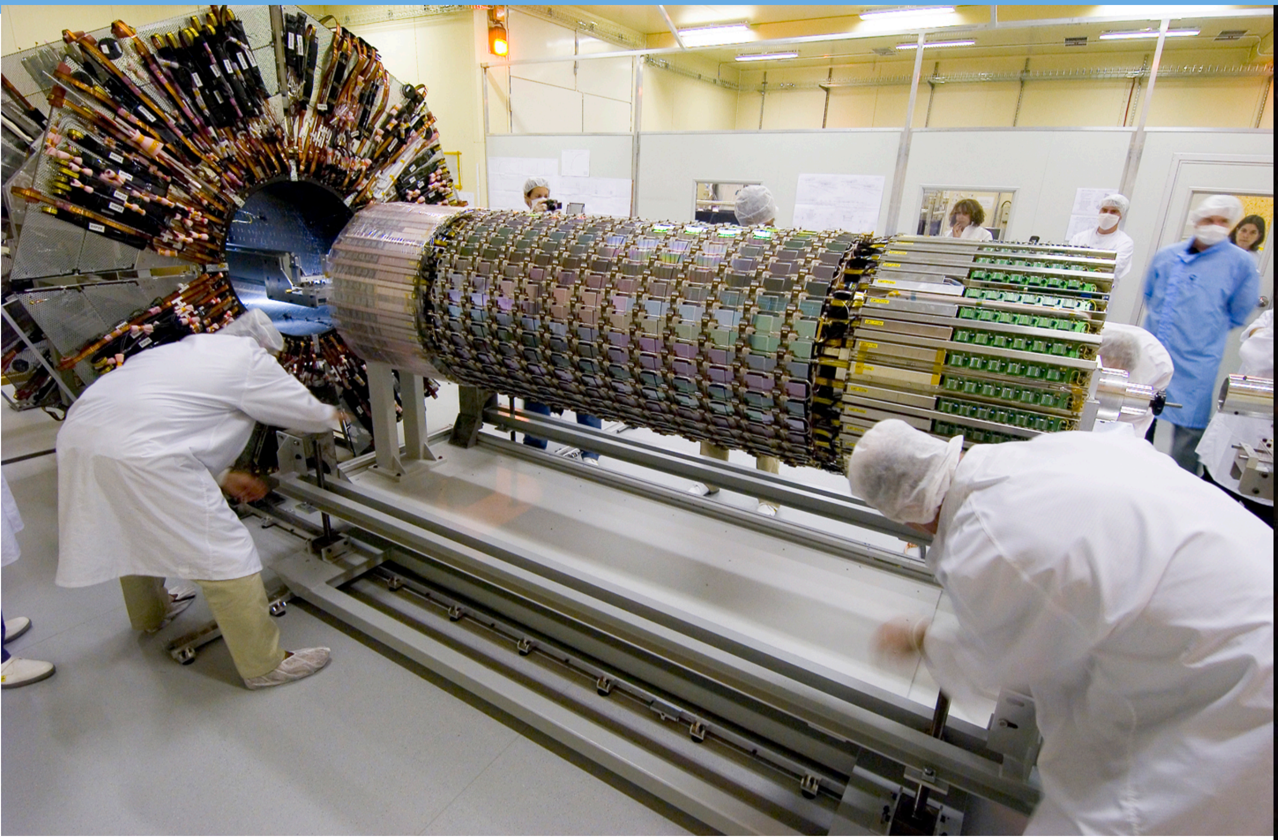
Affiliations | Contributions | Corresponding authors

Nature **522**, 68–72 (04 June 2015) | doi:10.1038/nature14474
Received 12 November 2014 | Accepted 31 March 2015 | Published online 13 May 2015



Preliminary update presented last week at CERN seminar: https://indico.cern.ch/event/580619/ -> paper expected soon!

Detector developments



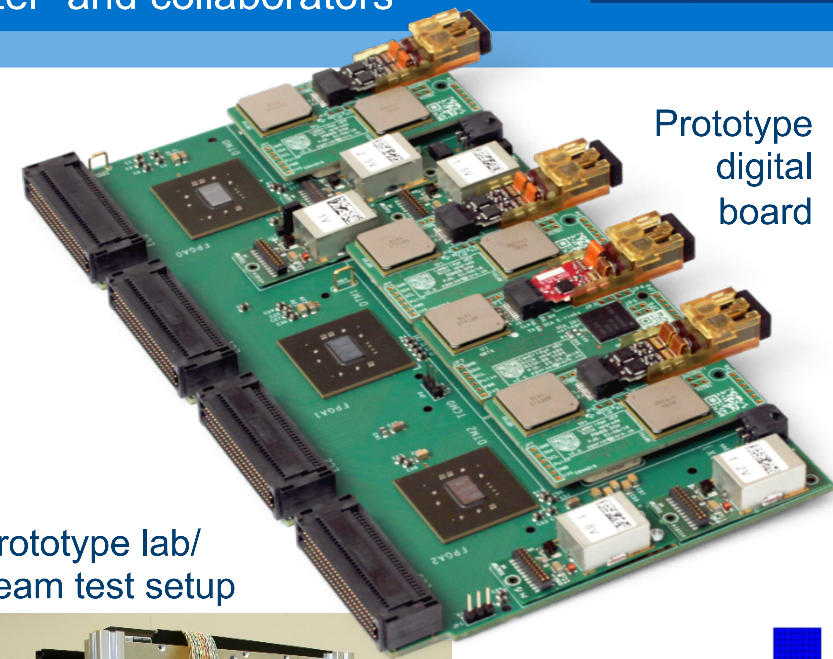
- As well as continued detector responsibilities for the RICH detector (LHCb) and the SCT (ATLAS), currently active in several LHC upgrade projects…

LHCb RICH upgrade

Steve Wotton, Philip Garsed, Floris Keizer and collaborators

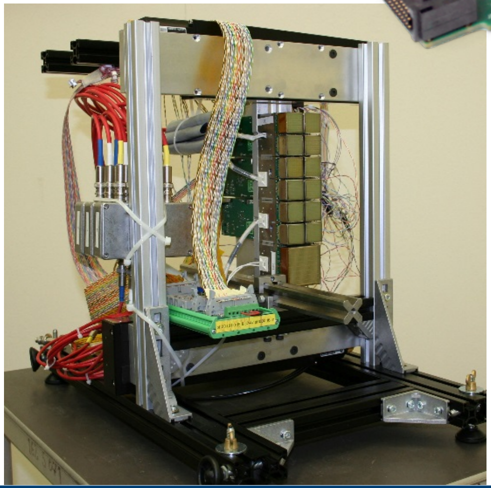
Group is responsible for digital board for LHCb RICH upgrade:

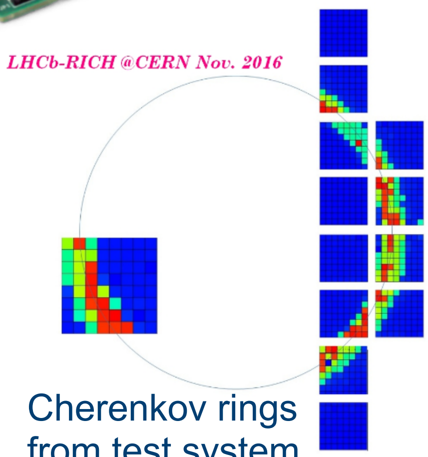
- RICH1 and RICH2 are used for particle ID in LHCb. Upgrading from 1 to 40MHz operation.
- 456 digital boards will read out 209,000 front end channels @ 40 MHz
- Data synchronised and transmitted to surface over 3400x 4.8 Gbps fibre links
- Prototype design largely complete; system tests well underway
- Installation in 2019/2020



Prototype digital board

Prototype lab/ beam test setup





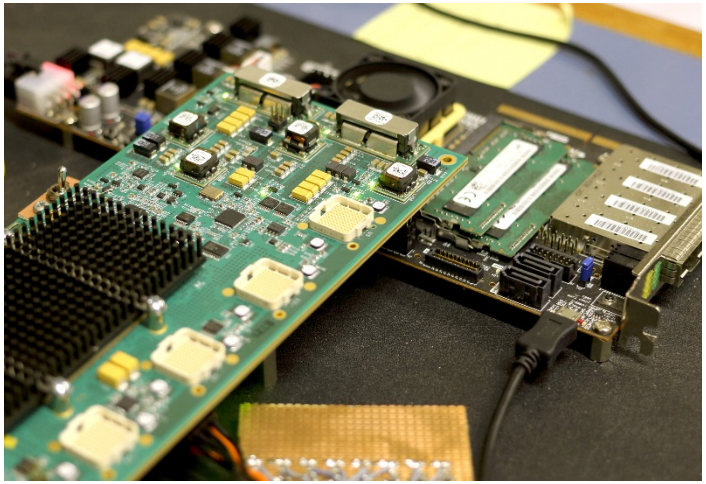
Cherenkov rings from test system

ATLAS L1-Calo Readout driver (ROD)

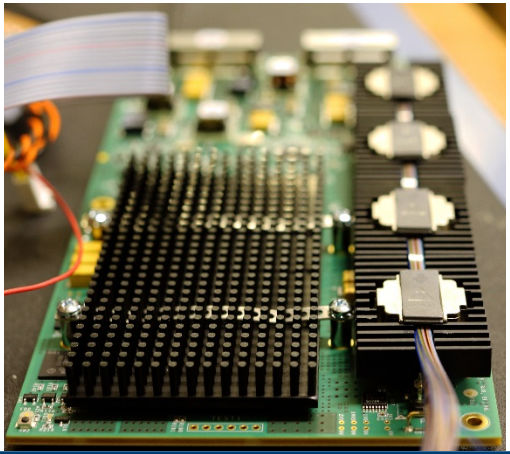
Ed Flaherty, Philip Garsed and collaborators

Also responsible for the read-out driver for the ATLAS L1 calorimeter upgrade.

- Builds events from data from feature extractor boards on triggered events
- Assembled events are packetised and transmitted for analysis and storage
- 8 ROD boards per system, each with a throughput of 200 Gbps
- Based on Xilinx Virtex-7 FPGA
- Working prototype has been operating for a year. Currently developing firmware and software
- Installation in 2019/2020



ROD board in test system



ROD board showing Virtex-7 FPGA and Minipod fibre transceivers

Conclusions

- Have given a (very brief) overview of some of the activities within the group in the last ~ year.
- The LHC is definitely in a search phase at the moment, but as we push exclusion limits higher we will need to work more to get the most out of our data.
- Hopefully this time next year there will be even more news, and maybe some hints of new physics.
- Thank you for inviting me to this very interesting workshop, and for now- any questions?