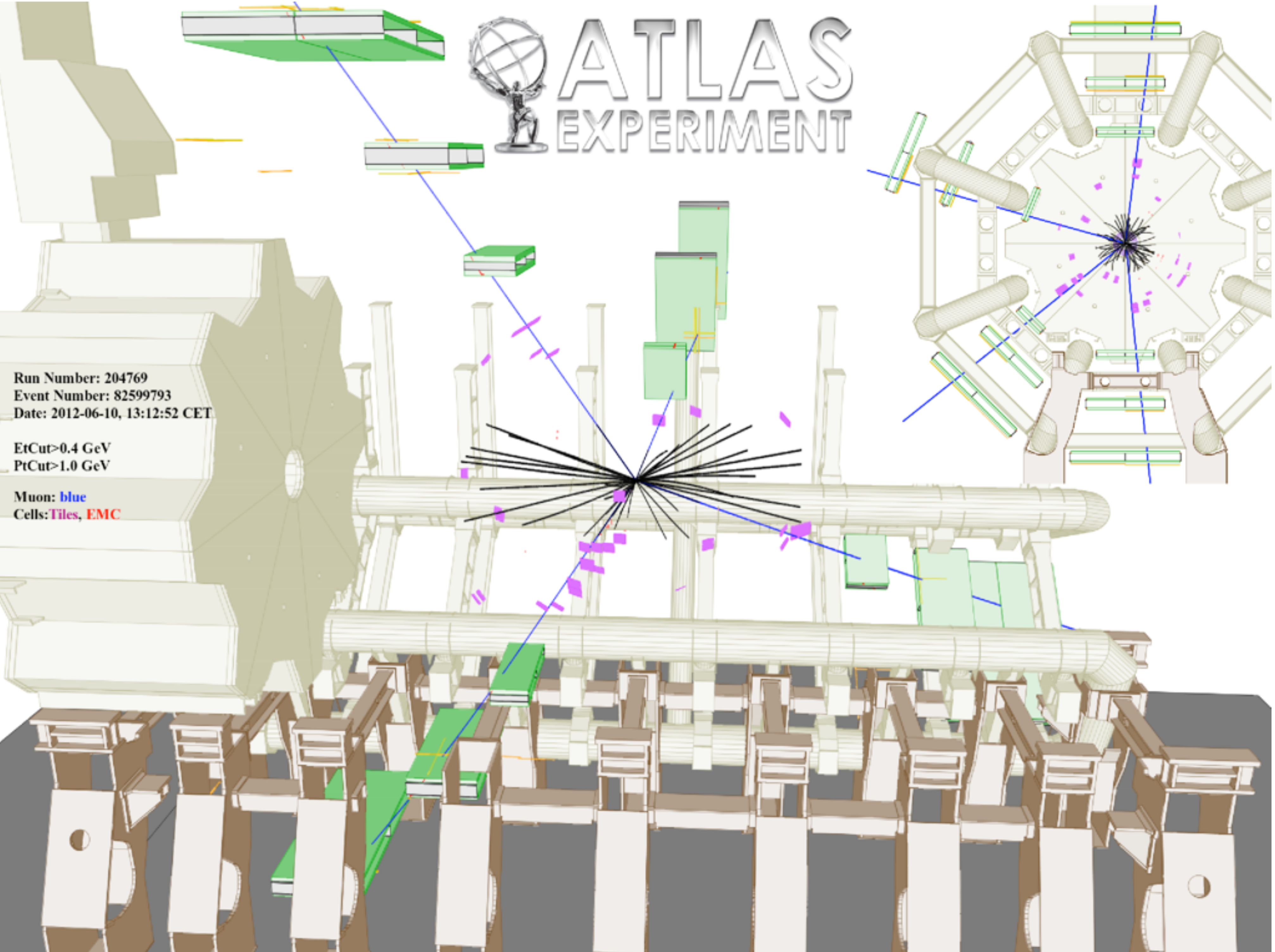


Search for Dark Matter in Higgs + MET final states with ATLAS

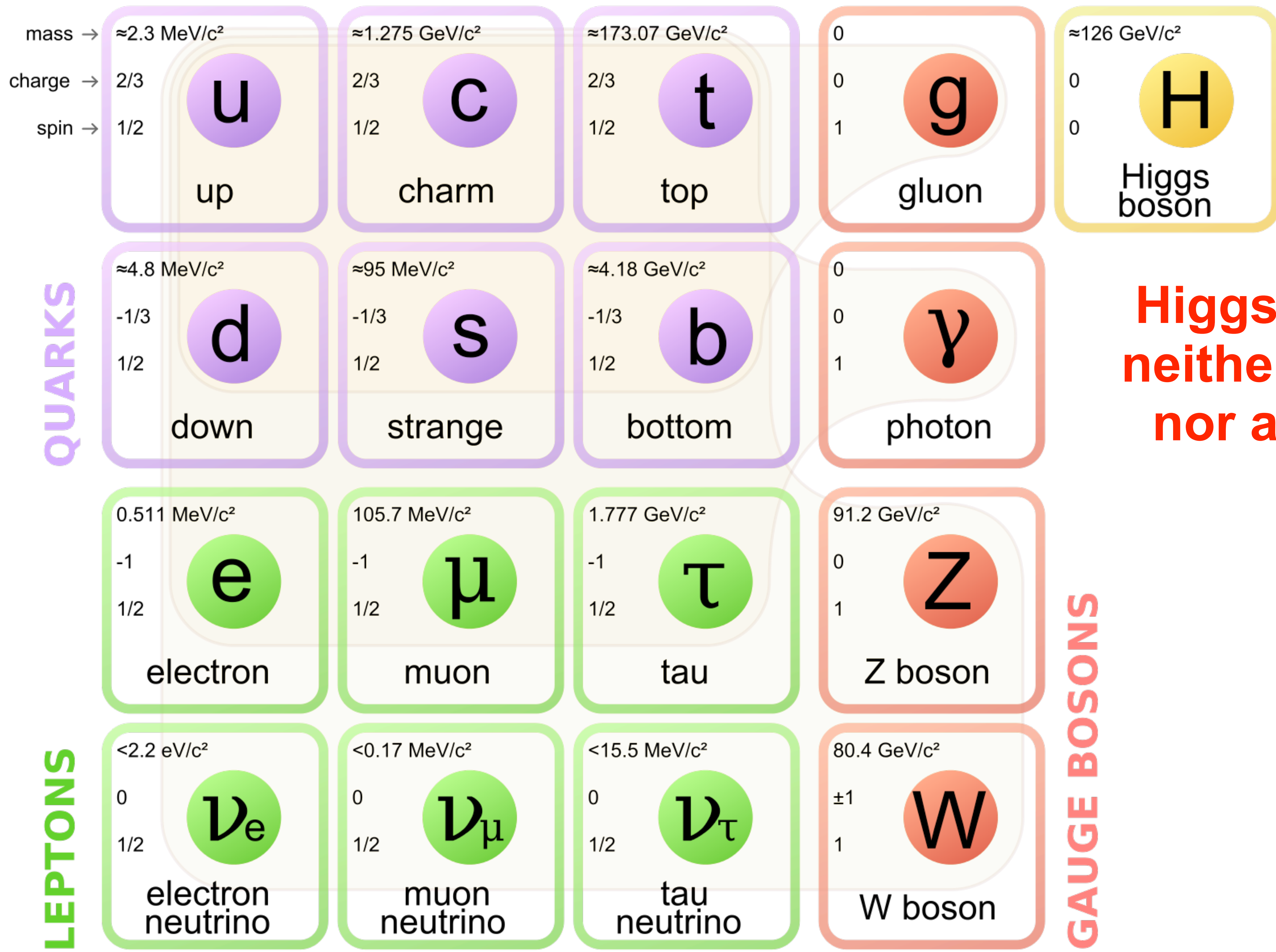
K. Nikolopoulos
University of Birmingham

UNIVERSITY OF BIRMINGHAM

HEP2016

13th May 2016, Thessaloniki, Greece

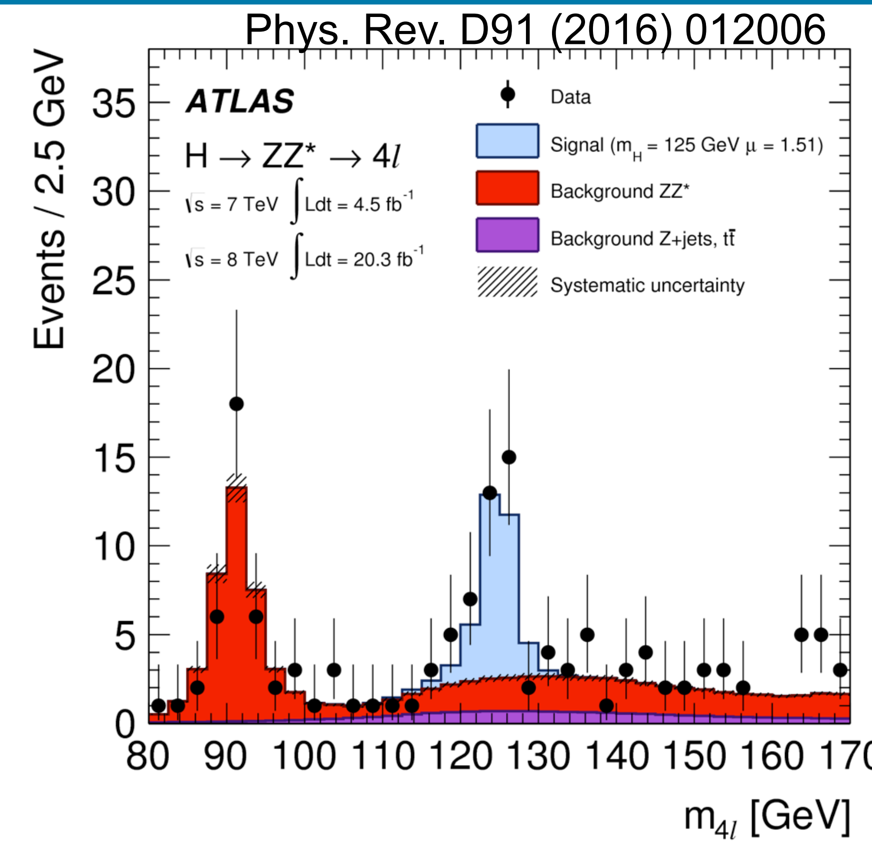
The Standard Model



Higgs boson neither Matter nor a Force

Matter **Forces**

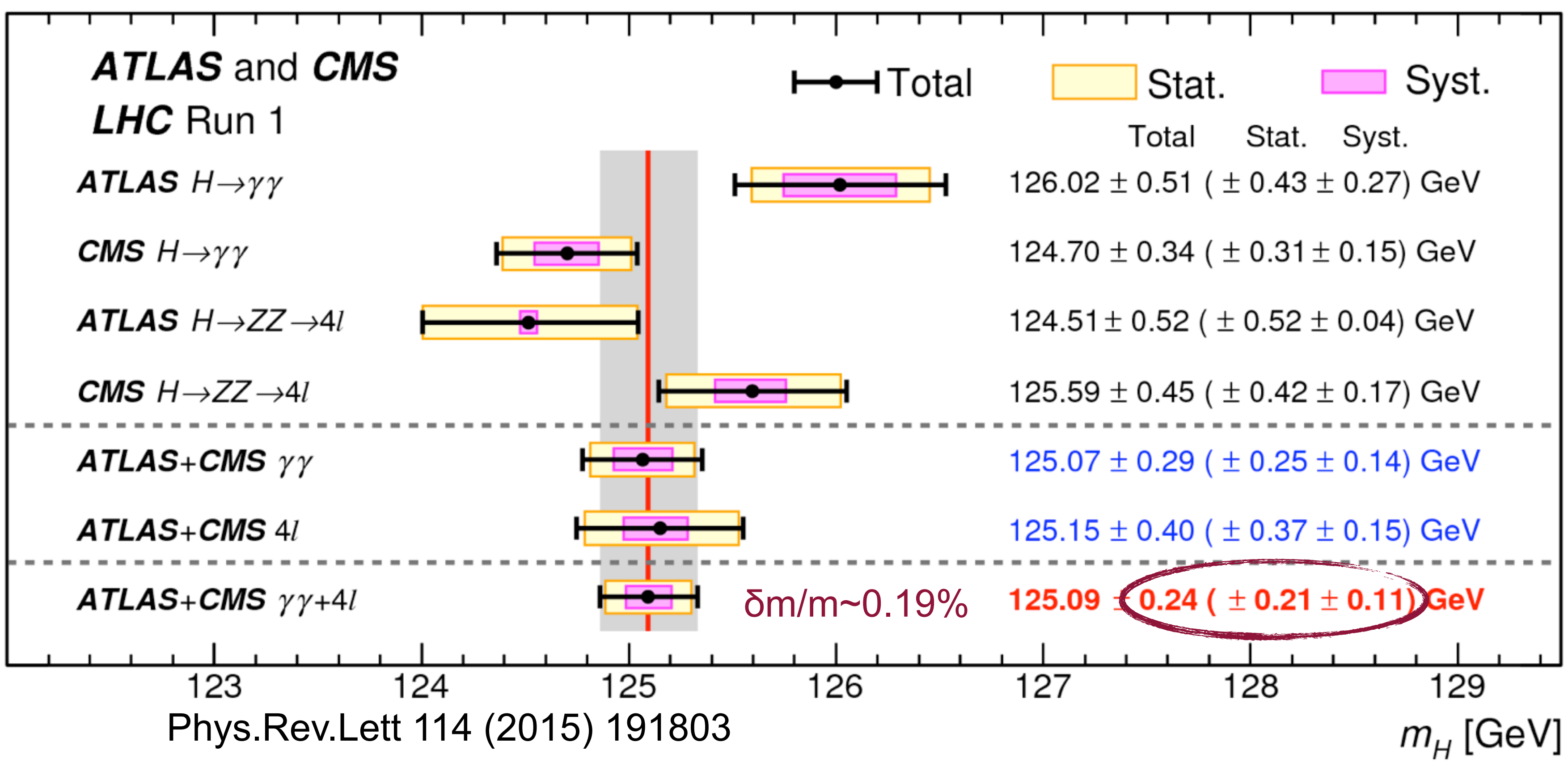
Higgs boson



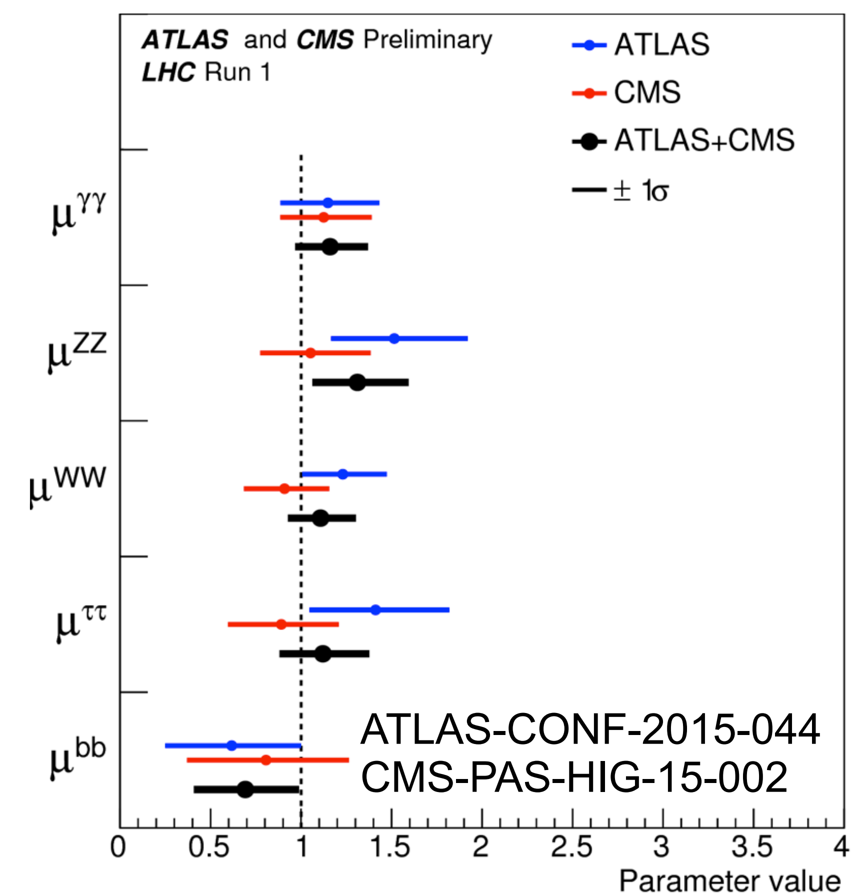
July 2012

Higgs boson observation

Standard Model is now complete!



Phys.Rev.Lett 114 (2015) 191803

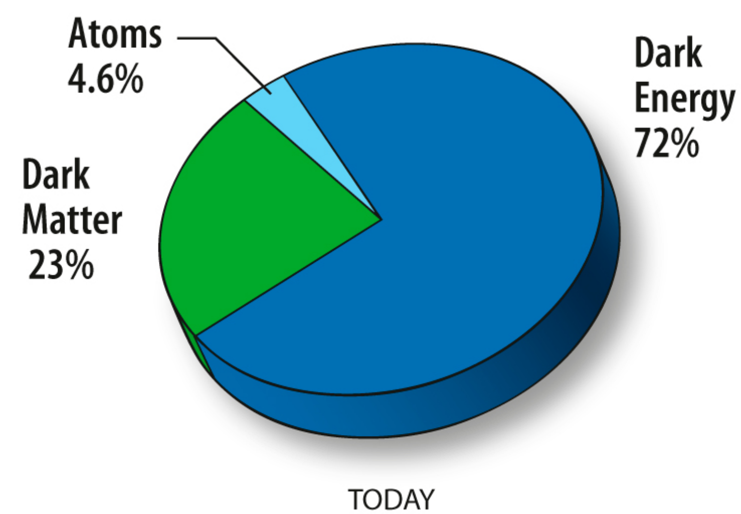


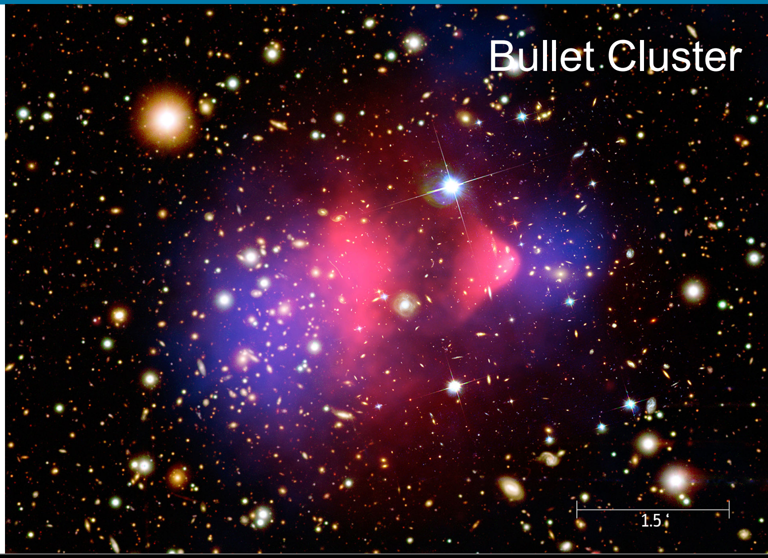
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

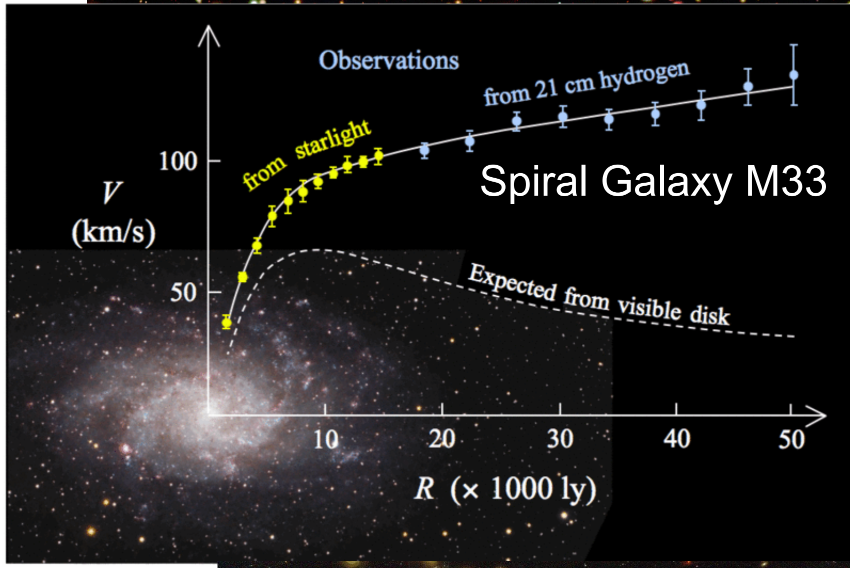
Dark Matter

SM only describes ~5% of matter-energy content of universe, no explanation for:

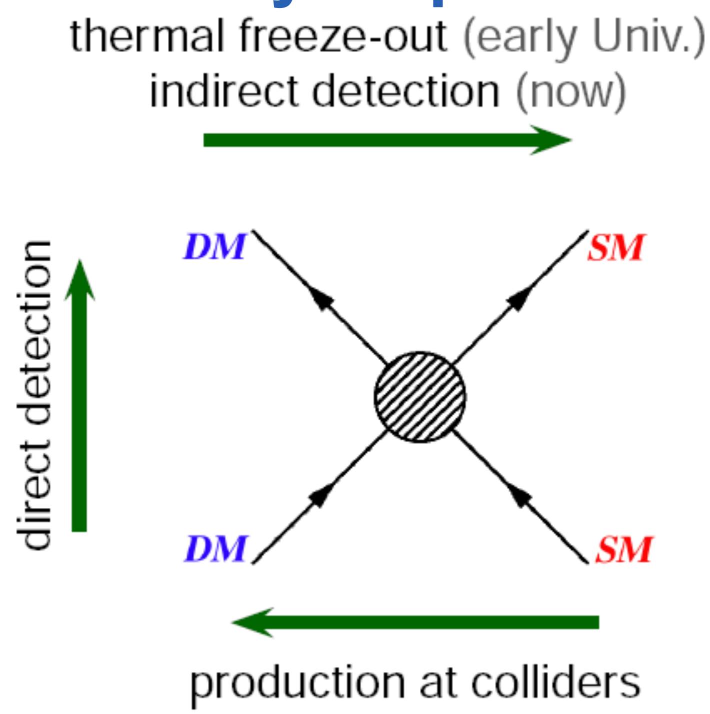
- ❑ origin of electroweak scale
- ❑ fermion mass hierarchy
- ❑ neutrino masses
- ❑ baryogenesis



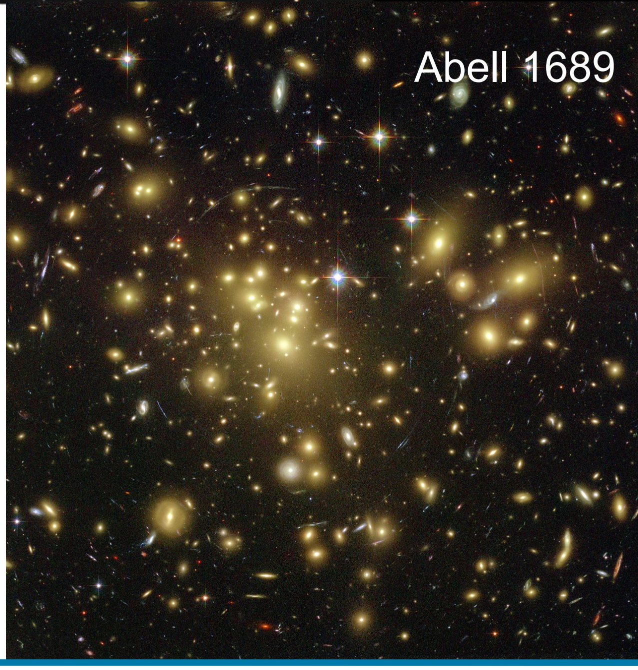




- **Cosmological observations evidence for Dark Matter**
- **Particle content of DM is not known**
- **LHC complementary to direct observation experiments**
  - **DM may be produced, and escape undetected**



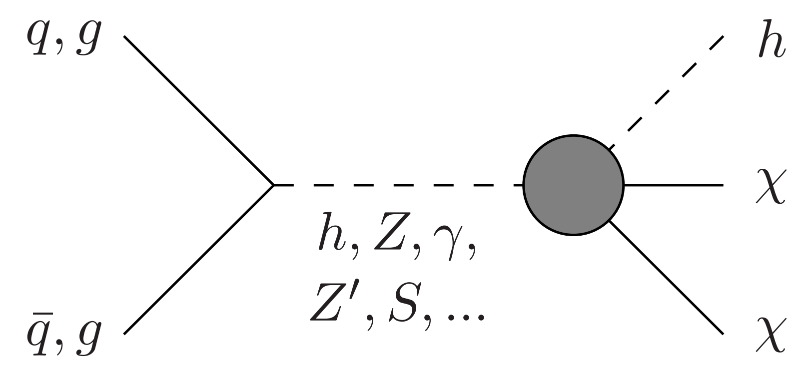
The Higgs boson a can be a tool for new discoveries

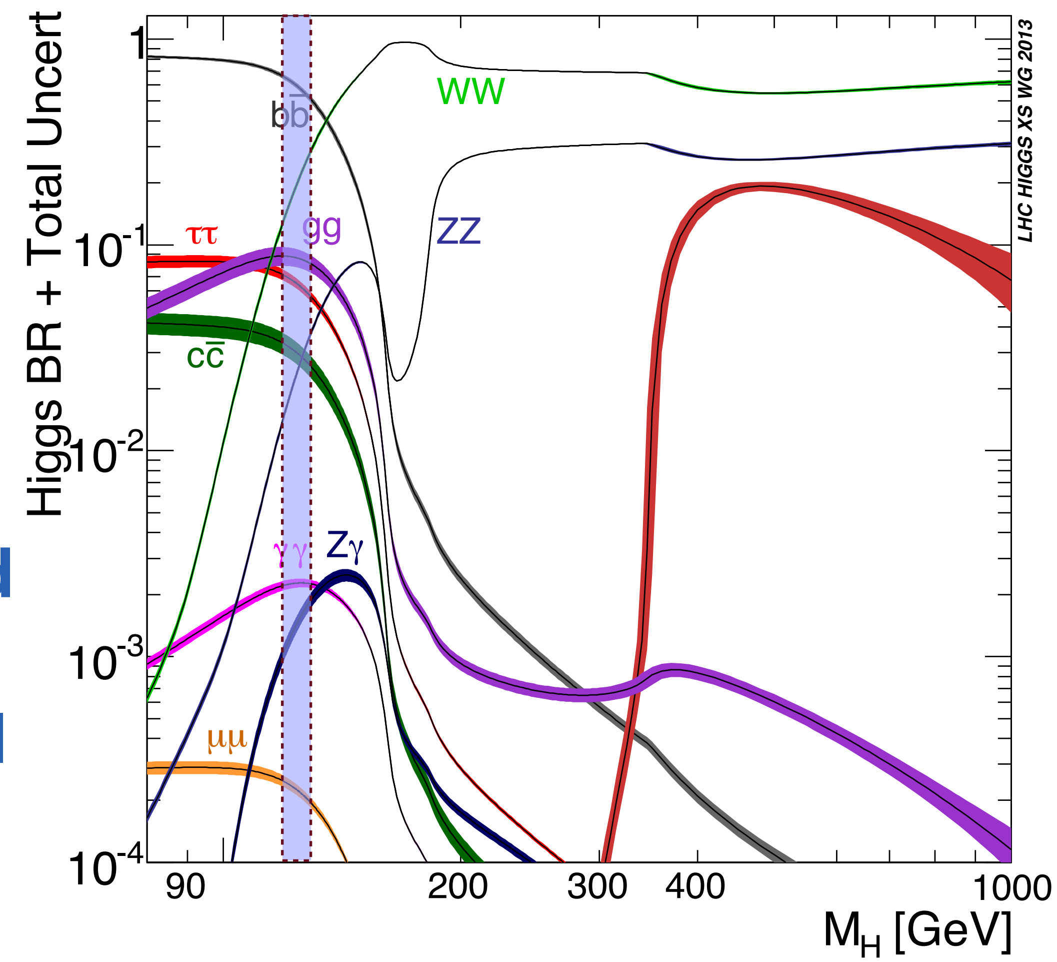


mono-boson searches

K. Hamano DM@LHC'16

Mono-photon	8 TeV	ATLAS: arXiv:1411.1559[hep-ex] CMS: arXiv:1410.8812
	13 TeV	ATLAS: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-05/
Mono-Z/W (hadr)	8TeV	ATLAS: arXiv:1309.4017[hep-ex] CMS: CMS PAS EXO-12-055
	13 TeV	ATLAS: ATLAS-CONF-2015-080
Mono-Z(ll)	8 TeV	ATLAS: arXiv: 1404.0051[hep-ex] CMS: arXiv: 1511.09375
Mono-W(lv)	8 TeV	ATLAS: arXiv:1407.7495[hep-ex] CMS: arXiv:1408.2745[hep-ex]
Mono-H(bb)	8 TeV	ATLAS: arXiv:1510.0621[hep-ex]
	13 TeV	ATLAS: ATLAS-CONF-2016-019
Mono-H(gamgam)	8 TeV	ATLAS: arXiv:1506.01081[hep-ex]
	13 TeV	ATLAS: ATLAS-CONF-2016-011

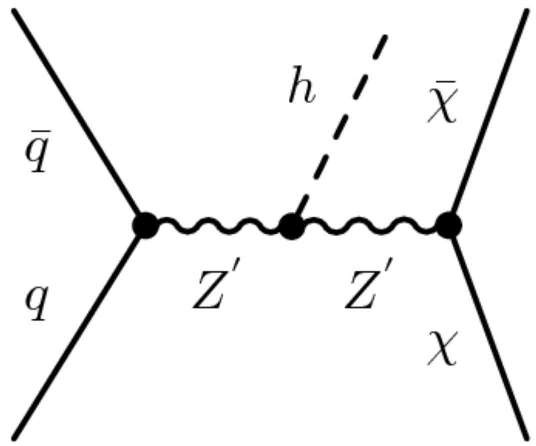




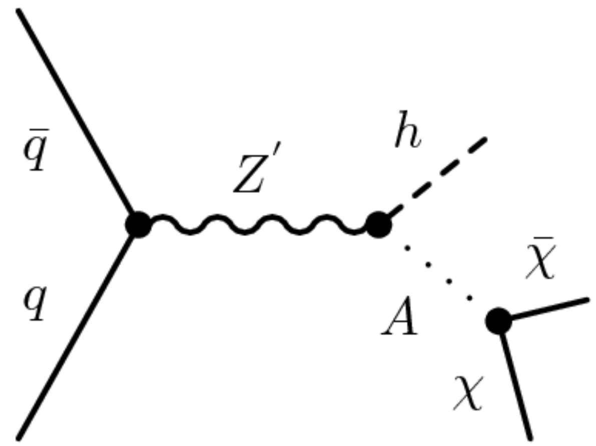
- **Initial State Higgs emission Yukawa suppressed**
  - **Higgs boson part of DM interaction**
- **Higgs boson emission by mediator in s-channel**
- **H→bb: Larger branching ratio**
- **H→γγ: Clean signature**

Interpretation Models

- Interpretations based on **Dark Matter Forum** recommendation [arXiv:1507.00966 [hep-ex]]
- Complete theories predicting DM particles
    - SUSY, extra dimensions, …
- **Simplified models**
  - Limited number of new particles/interactions
    - Building blocks of more complete theories
  - DM: Dirac particles
  - Mediator (narrow): Vector, axial-vector, scalar, pseudo-scalar
  - Two vector mediator models studied:



$\{M_{\mathrm{med}}, m_\chi, g_\chi, g_{\mathrm{q}}, \sin\theta, g_{hZ'Z'}\}$

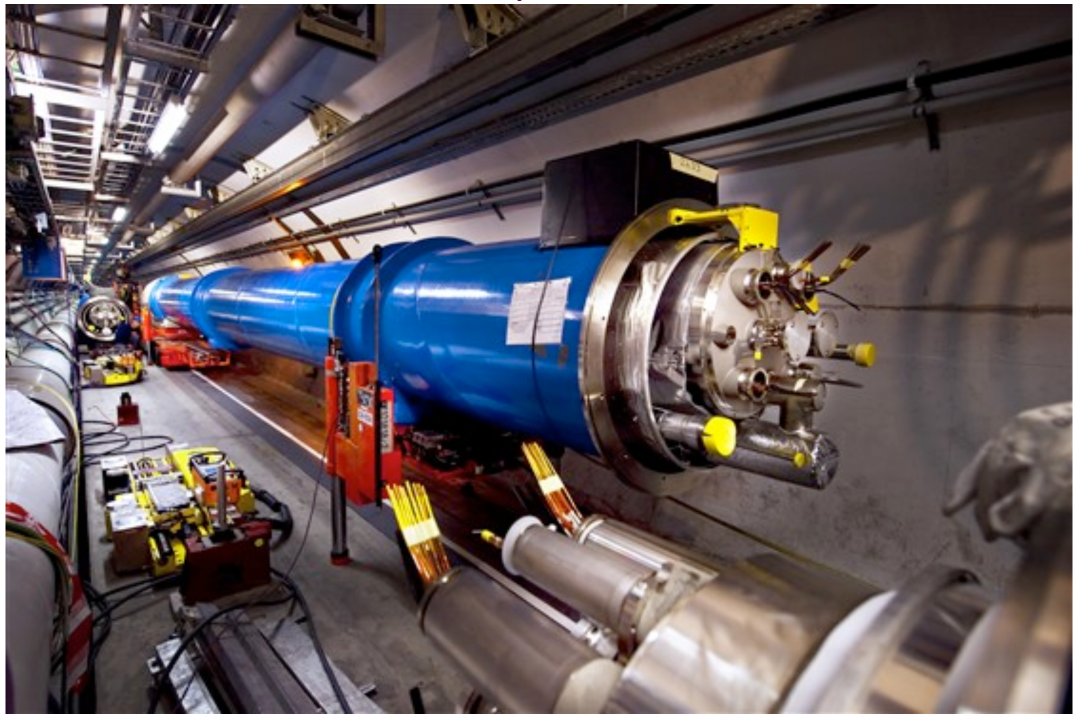


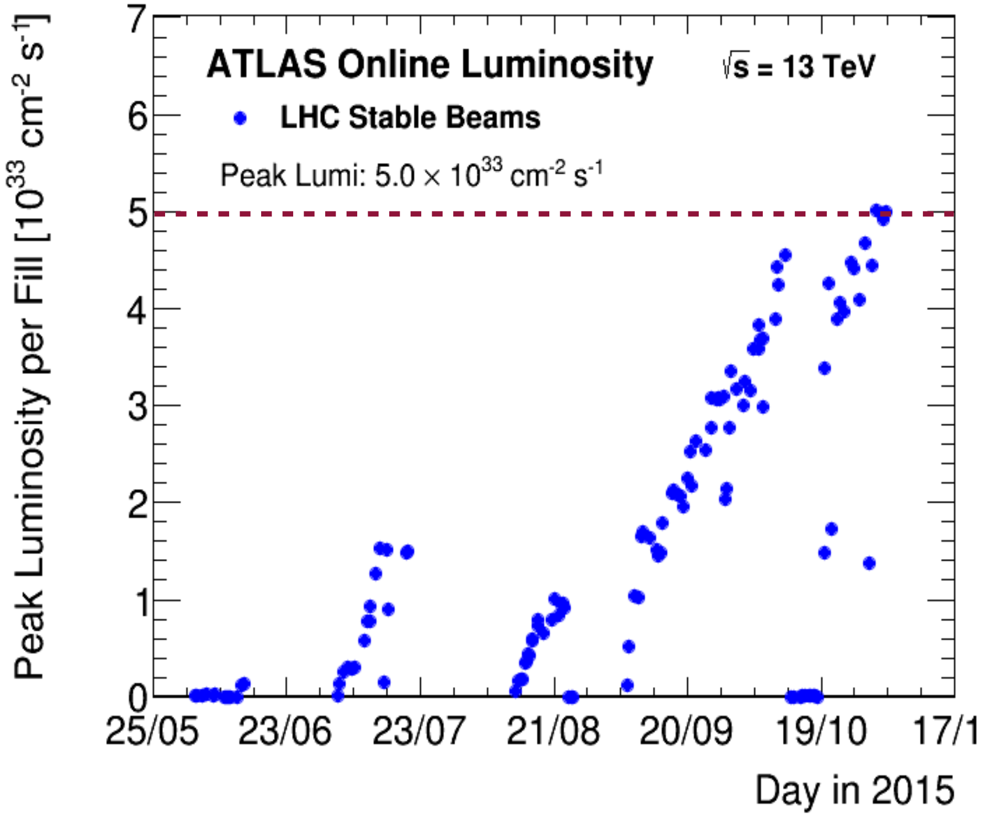
Z'+2HDM

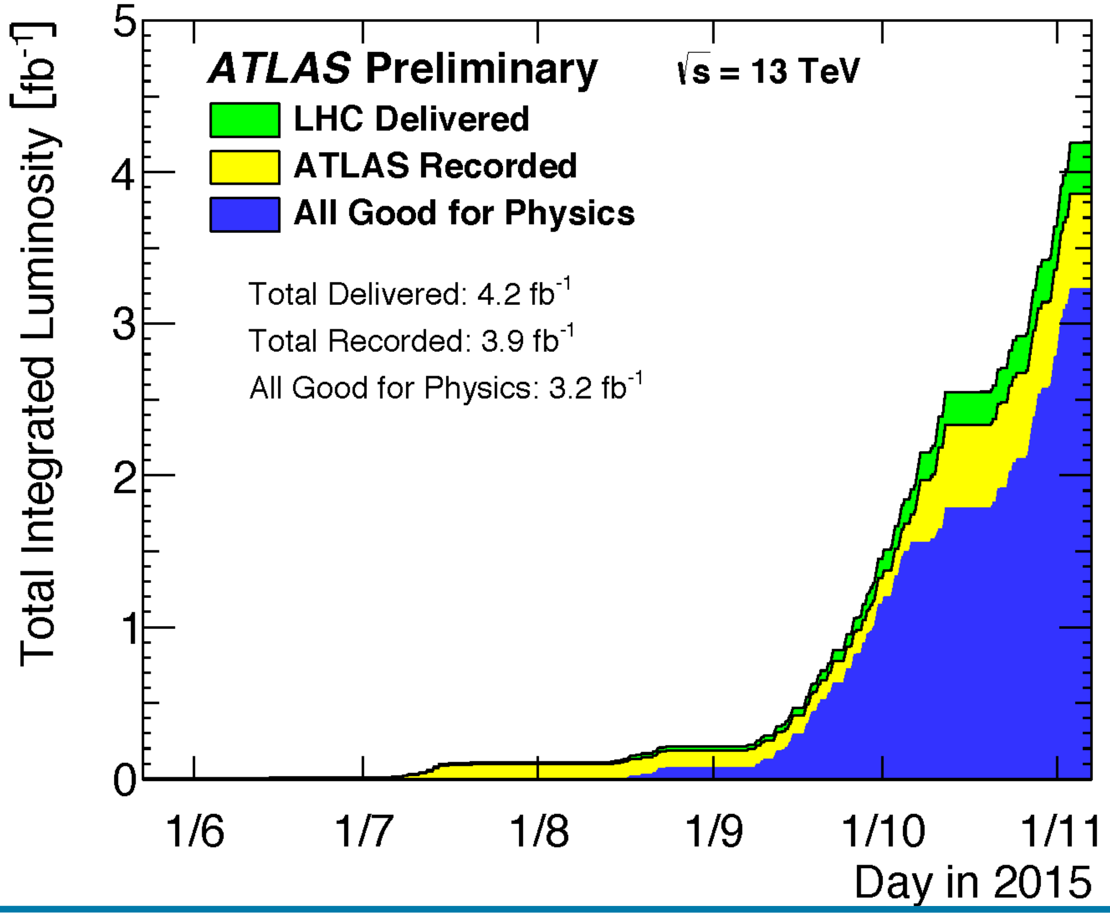
- **Effective field theory**
  - Mediator integrated out
  - Less model dependent
    - Two parameters: DM mass, effective energy scale/coupling strength
  - Variety of operators
  - Holds for momentum transfer < mediator mass
    - Potentially an issue for 13 TeV searches

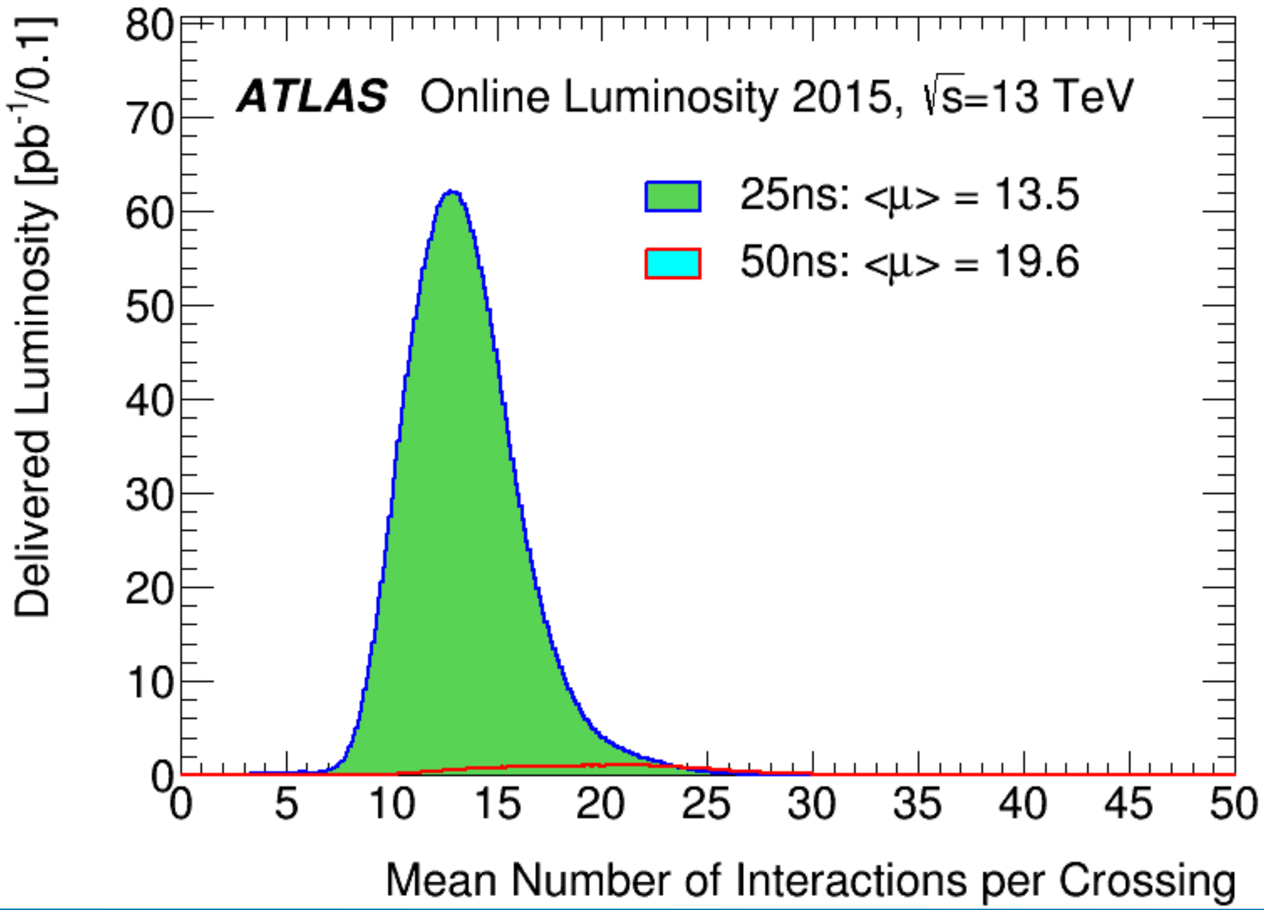
Large Hadron Collider Run 2

1232 superconducting dipoles with B field of (up to) 8.3T
1.9K → the coolest place in the universe!

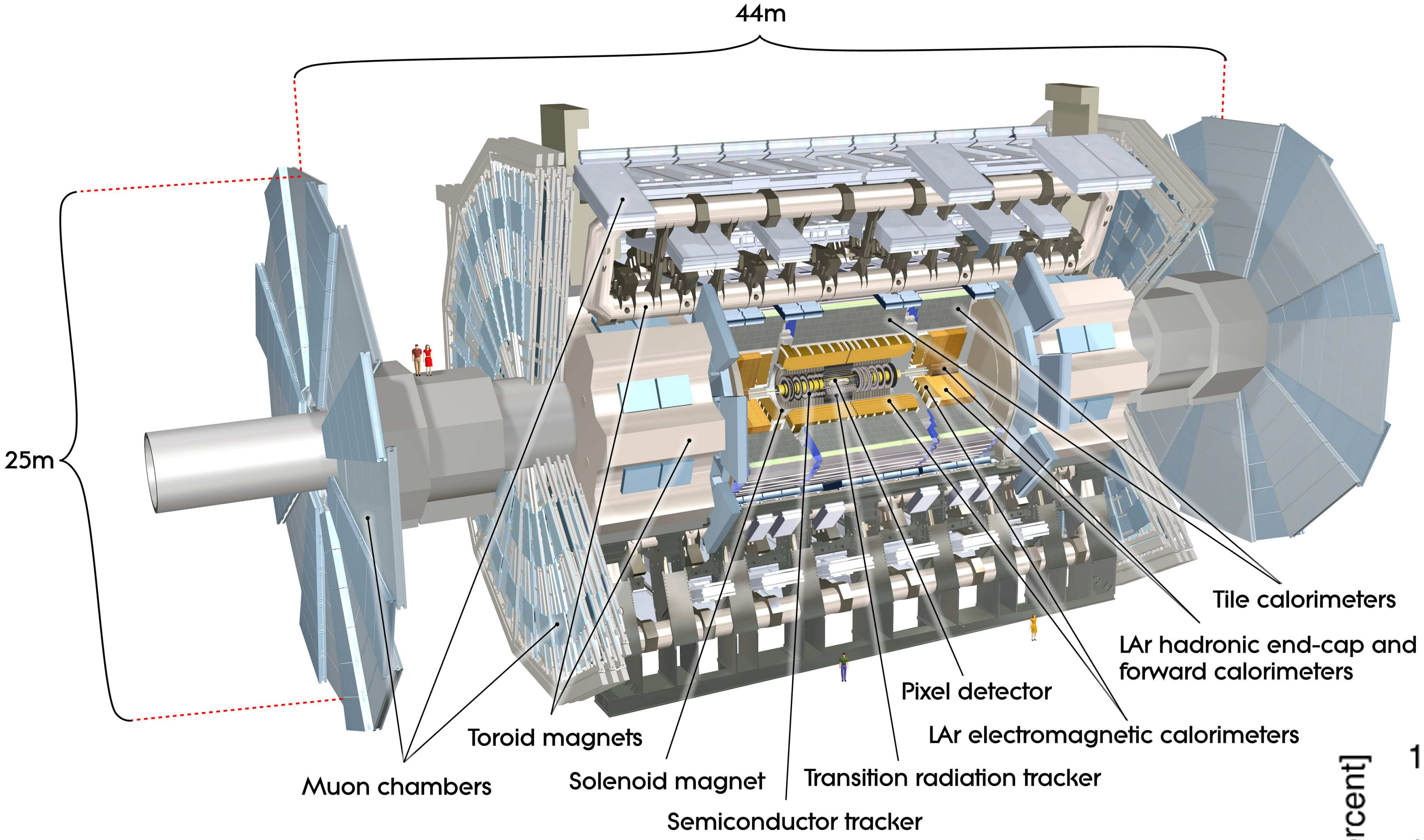








A Toroidal LHC ApparatuS



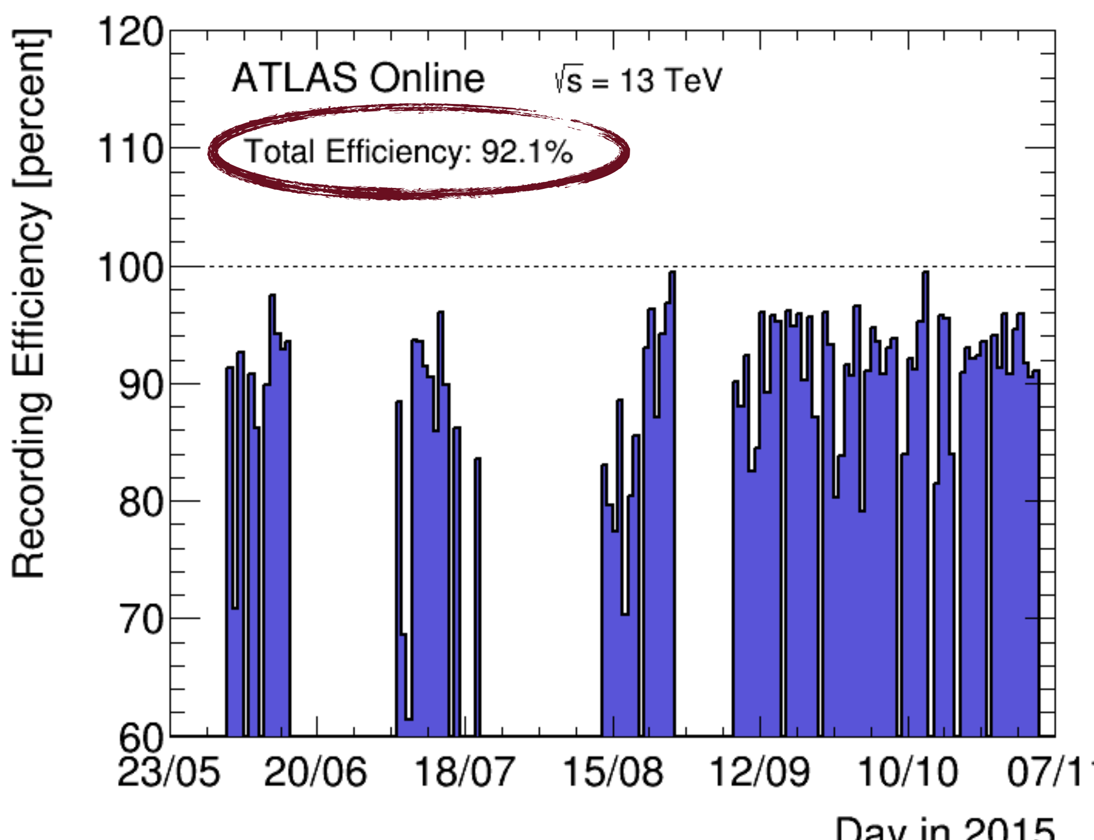
	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling Liquid Argon
Hadron Calorimetry	plastic scintillator (barrel) Liquid Argon(endcap)
Muon	independent system with trigger capabilities
Trigger	3 Level Implementation from 40 MHz to 400 Hz

ATLAS pp 25ns run: August-November 2015

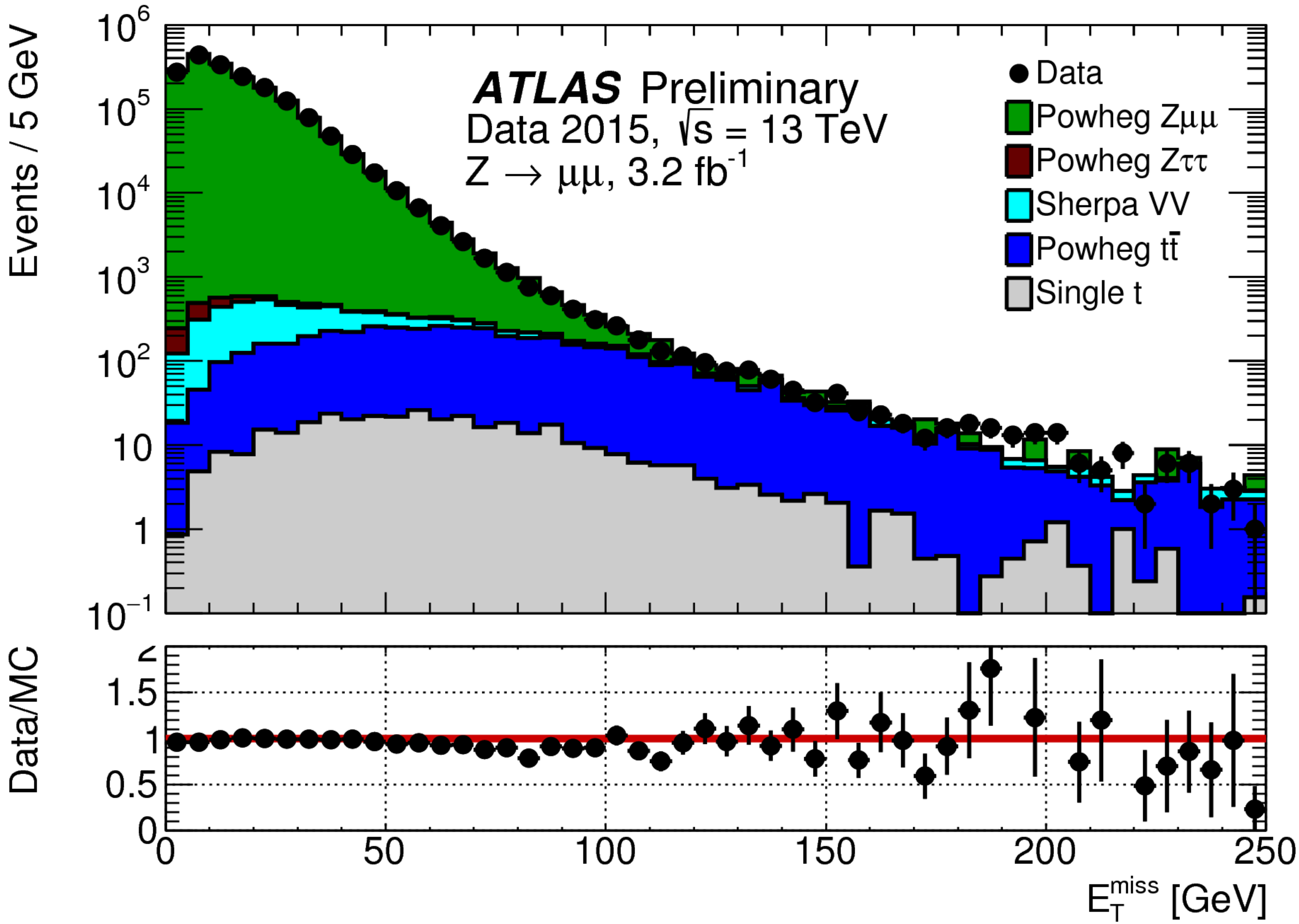
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
93.5	99.4	98.3	99.4	100	100	100	100	100	100	97.8

All Good for physics: 87.1% (3.2 fb^{-1})

Luminosity weighted relative detector uptime and good data quality (DQ) efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}$=13 TeV between August-November 2015, corresponding to an integrated luminosity of 3.7 fb^{-1}. The lower DQ efficiency in the Pixel detector is due to the IBL being turned off for two runs, corresponding to 0.2 fb^{-1}. Analyses that don't rely on the IBL can use those runs and thus use 3.4 fb^{-1} with a corresponding DQ efficiency of 93.1%.



ATLAS performance overview

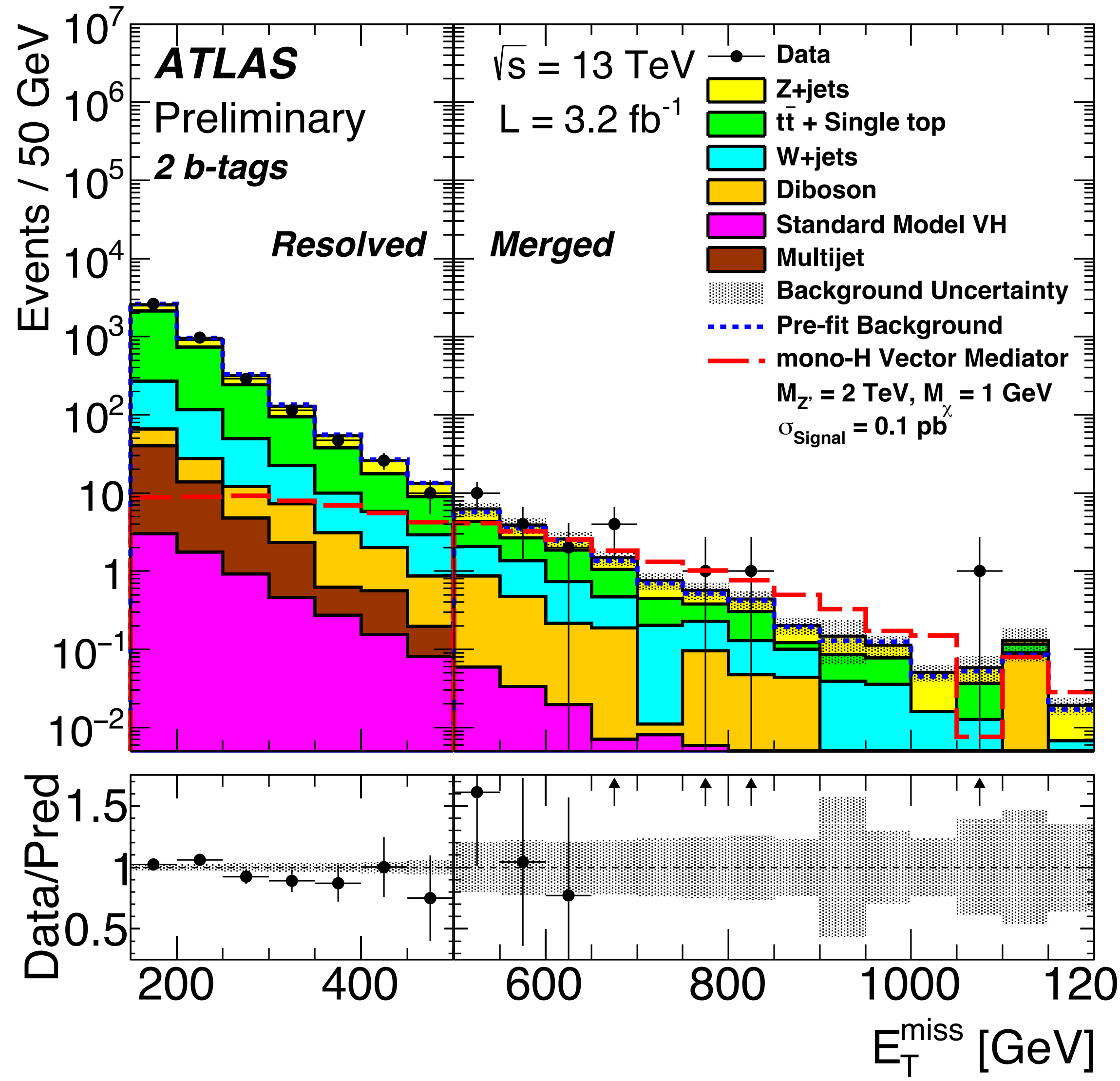


$H \rightarrow bb$ + MET

Event Selection

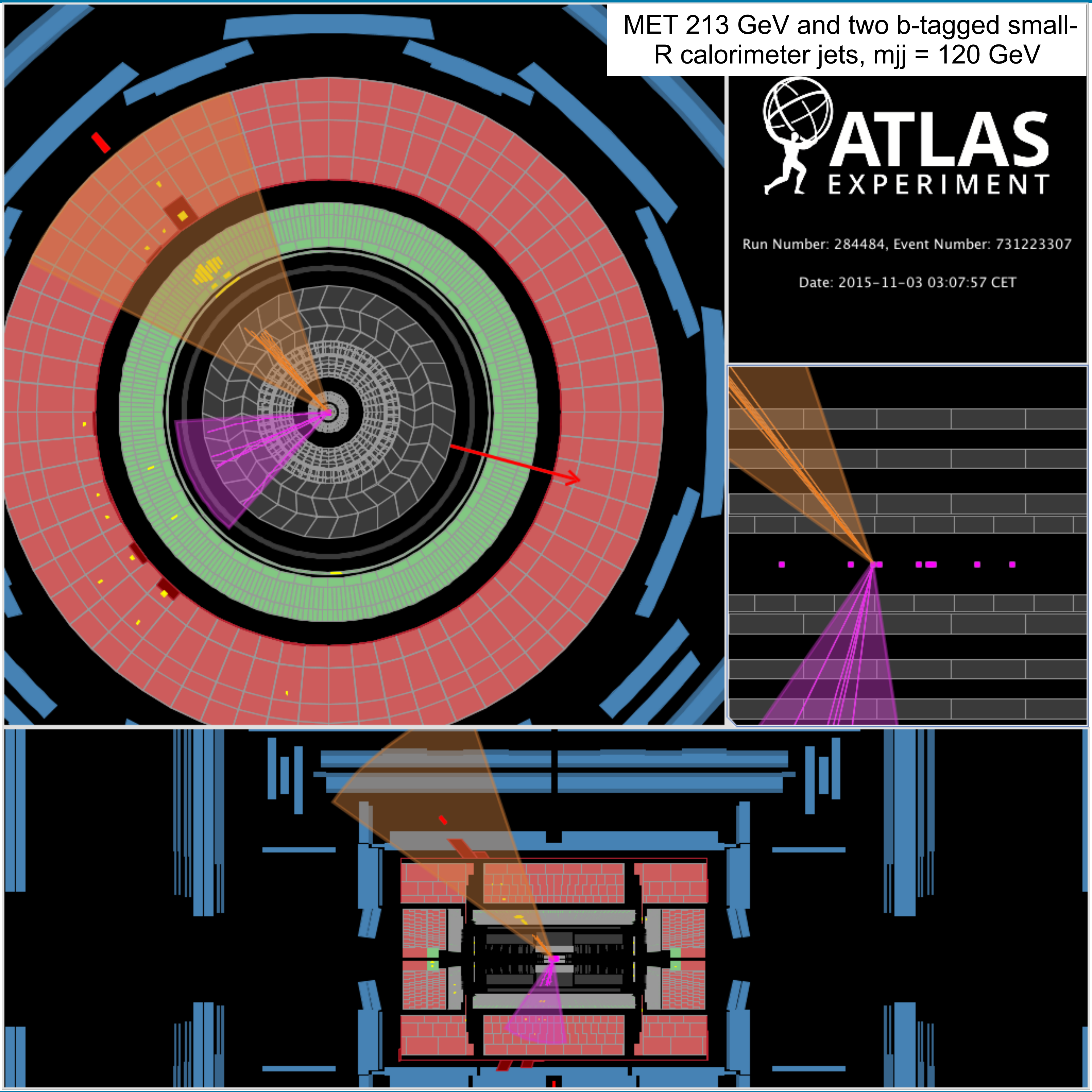
ATLAS-CONF-2016-019

- 13 TeV, 3.2 fb^{-1}, MET trigger
- MET>150 GeV, and track based MET $p_T$miss>30 GeV
- Lepton veto
  - no isolated electron or muon with p_T>7 GeV
- Higgs boson candidate
  - Resolved Region (MET<500 GeV)
    - Two small-R jets (R=0.4)
    - Leading jet p_T>45 GeV
  - Merged Region (MET>500 GeV)
    - One large-R jet (R=1.0)
  - 1 or 2 b-tagged jets
- Other topological requirements in resolved region
  - Aim to suppress multi-jet background
  - min[Δφ(MET,jets)] > 20° → no jets near met
  - Δφ(MET,$p_T$miss) < 90° → MET and track-met align
  - Δφ(MET,Higgs) > 120° → MET and Higgs back-to-back
  - Δφ(j_1,j_2) <140° → jets comprising Higgs not back-to-back
- Final discriminant: m_{jj} or m_J in bins of MET and b-tags



ATLAS-CONF-2016-019

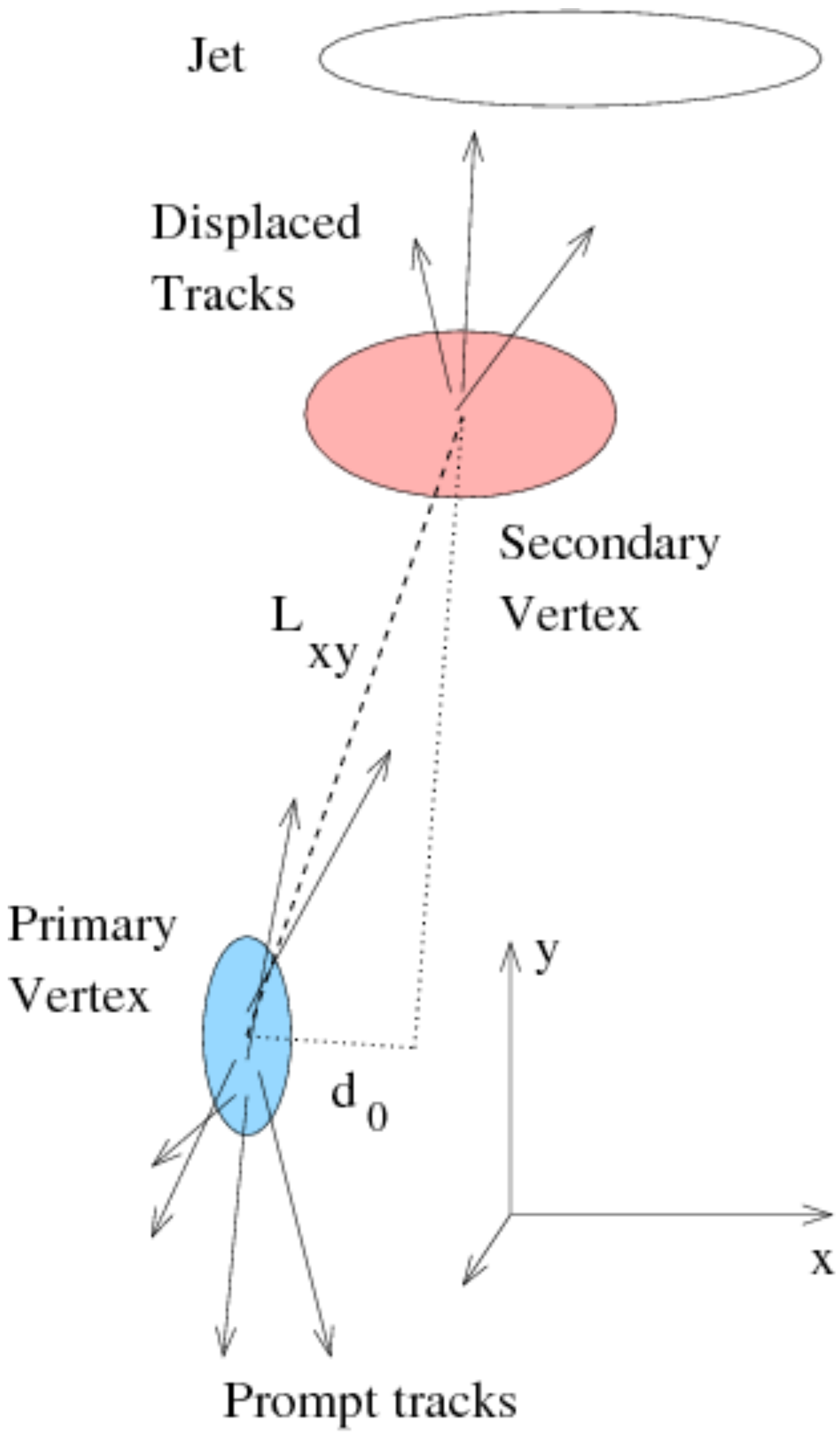
Resolved candidate



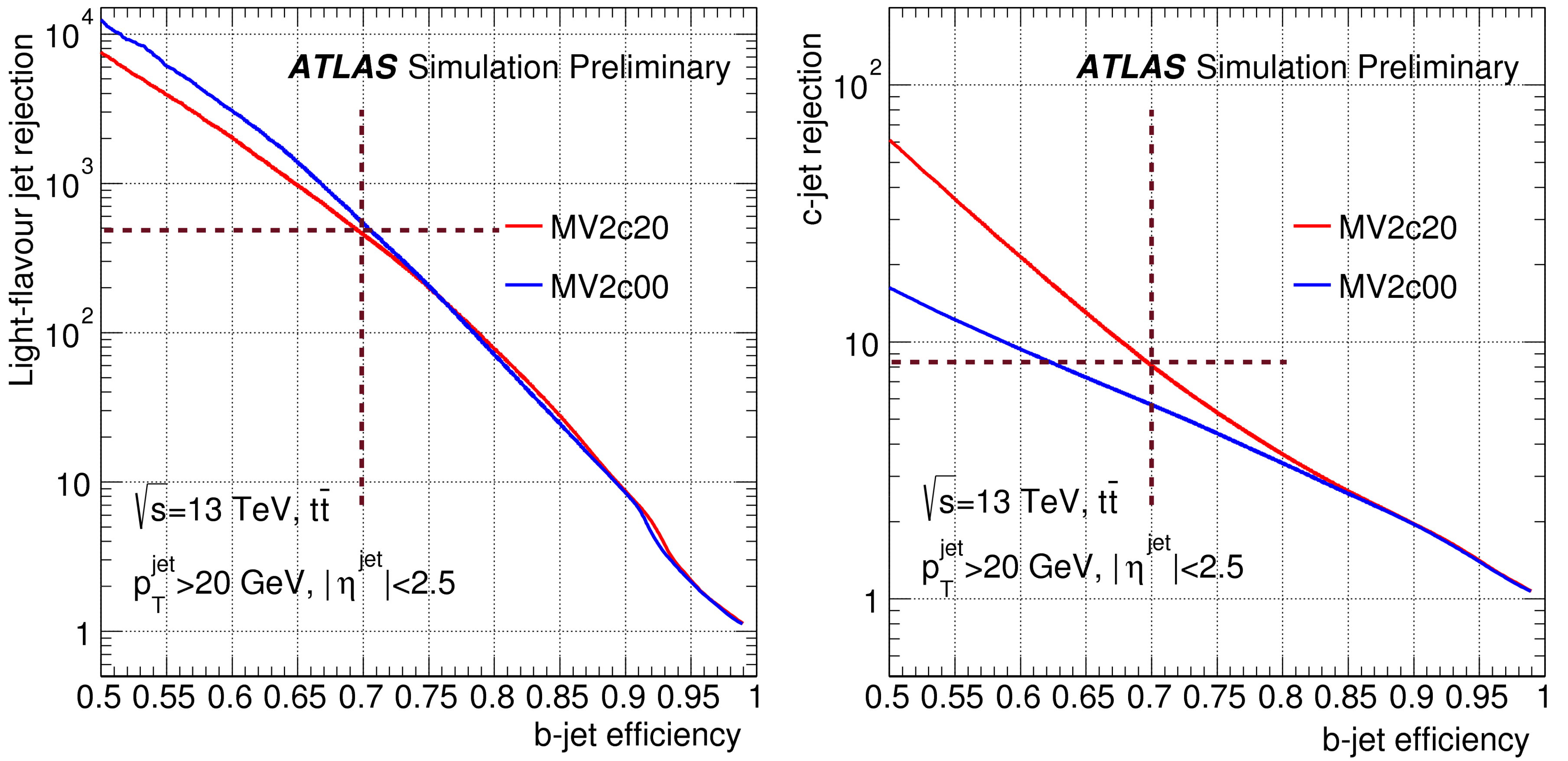
ATLAS-CONF-2016-019

Flavour tagging

ATLAS-PHYS-PUB-2015-022

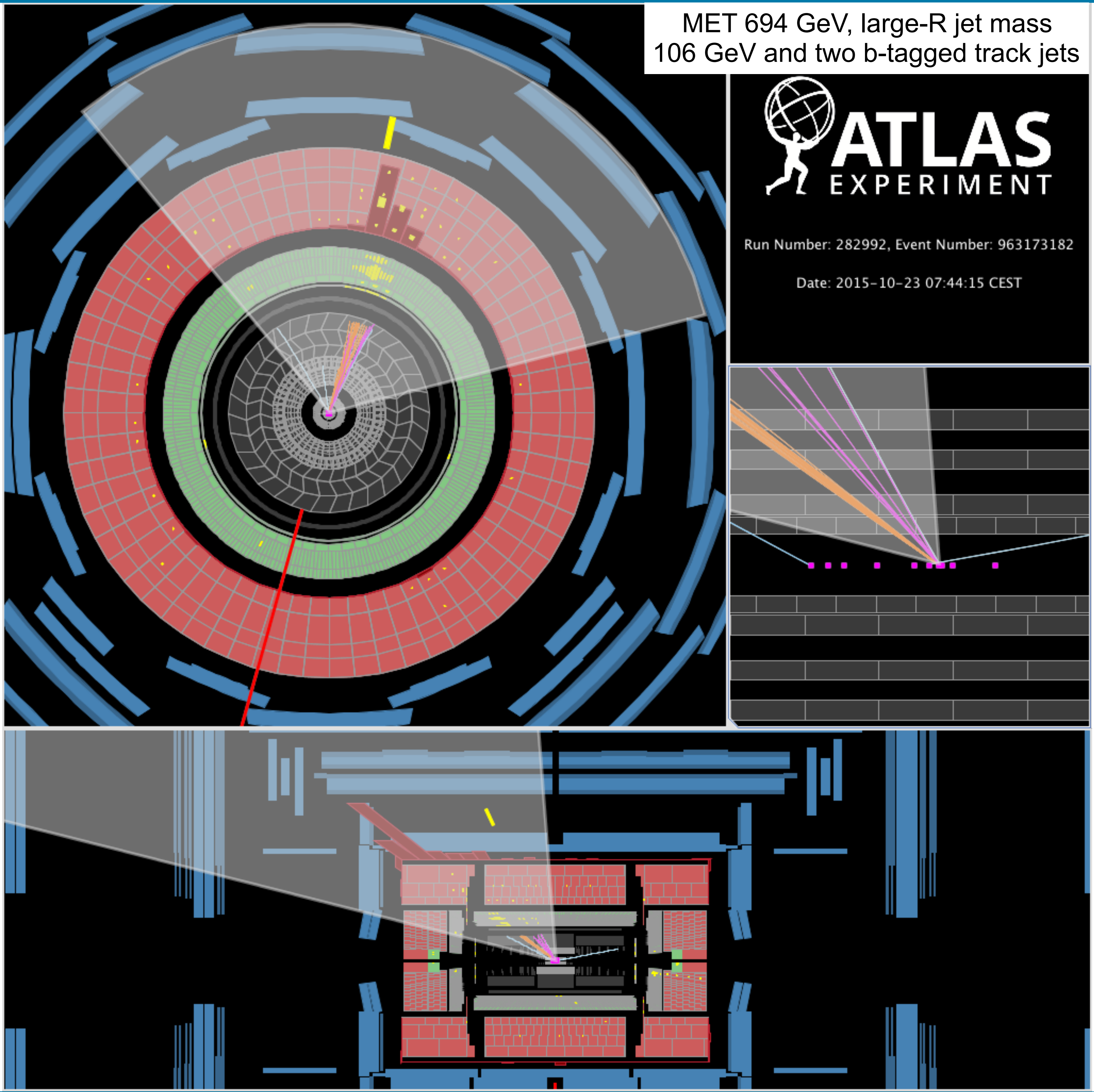


cτ = 492 μm



For 70% efficiency in identifying small-R (track) jets containing a b-hadron, misidentification probabilities:
~12(18)% for charm-quark jets and
~0.2(0.6)% for light-flavour jets
[from simulated ttbar events]

Merged candidate



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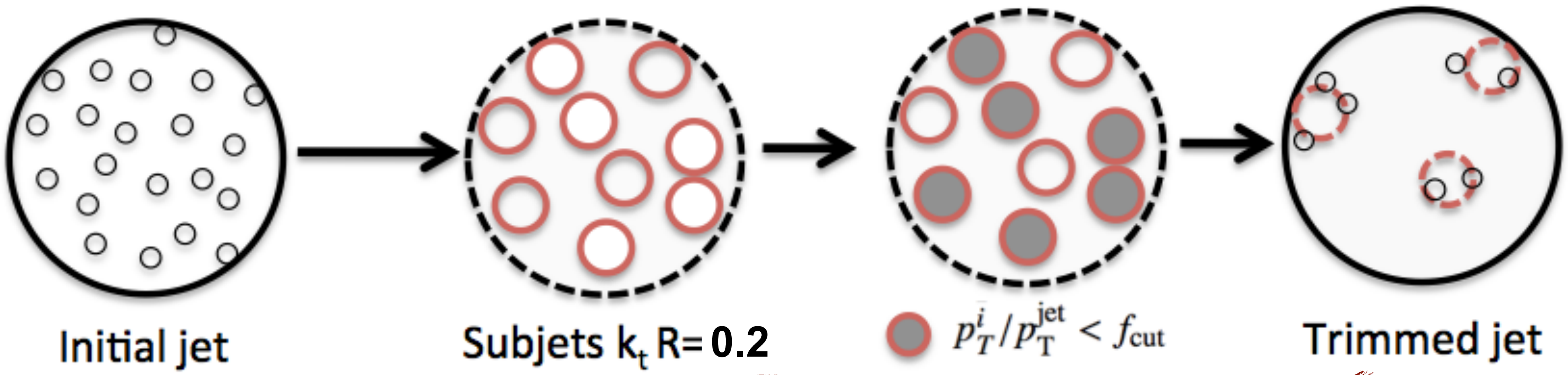
Large-R jets and substructure

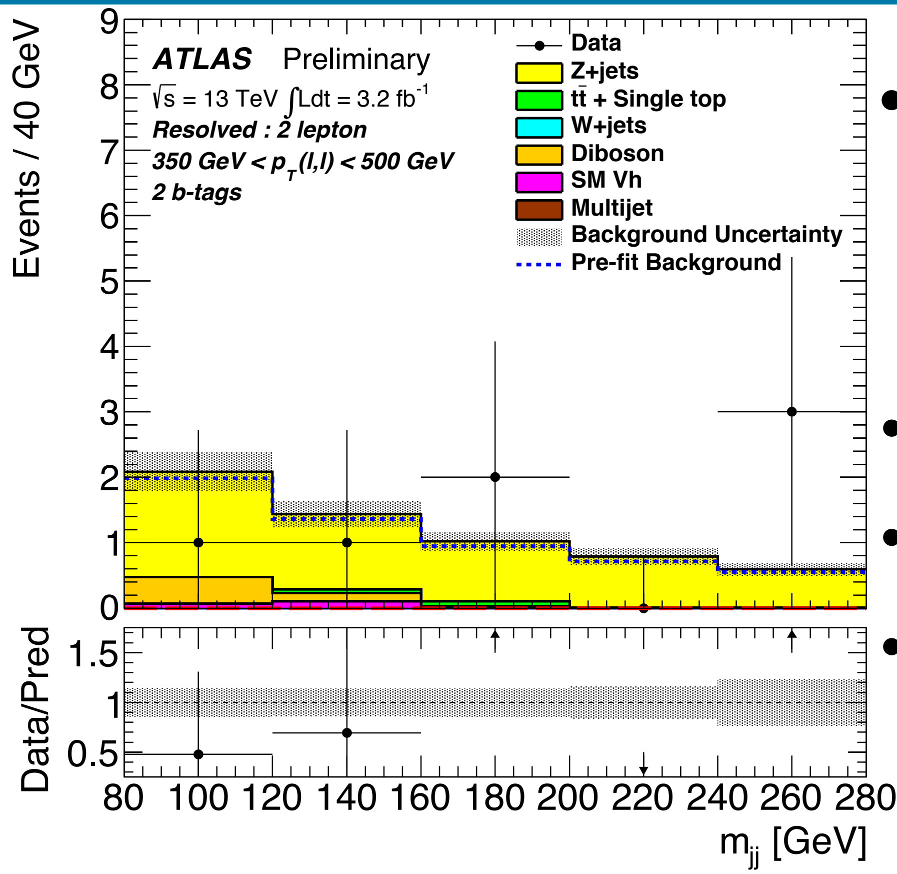


Begin from an anti-kT jet with radius parameter R=1.0
(small radius jets R=0.4)

Subjets are constructed with the kT algorithm with R_{sub}=0.2

Subjets with pT <5% of the large-R jet, are removed

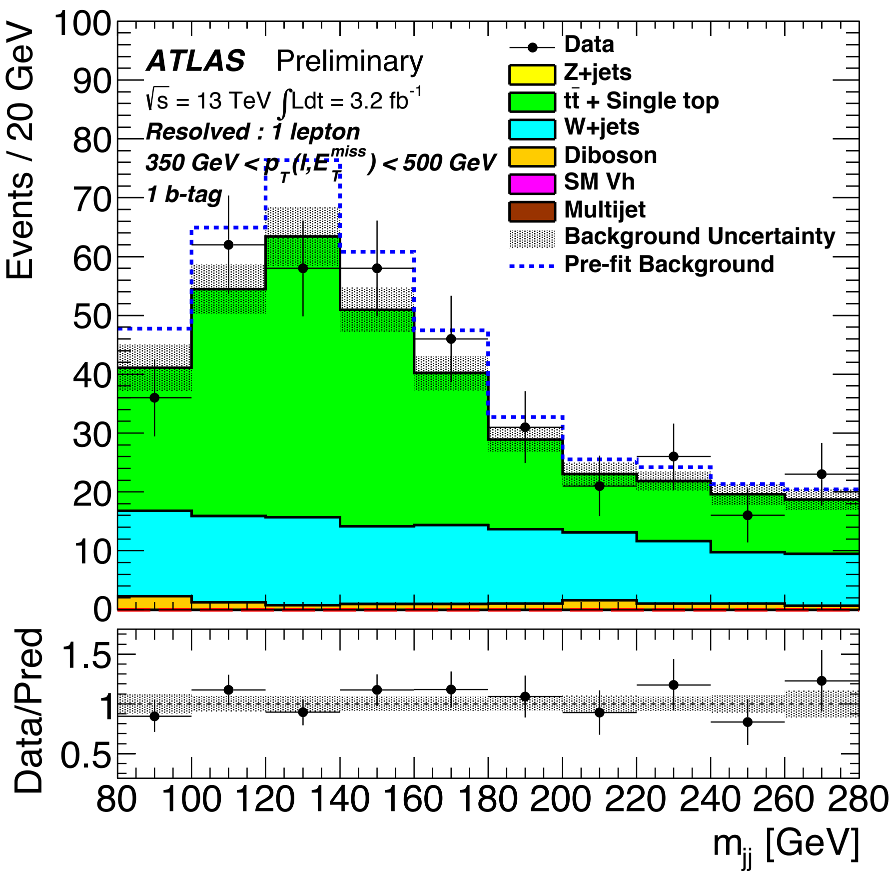
Background Control Regions

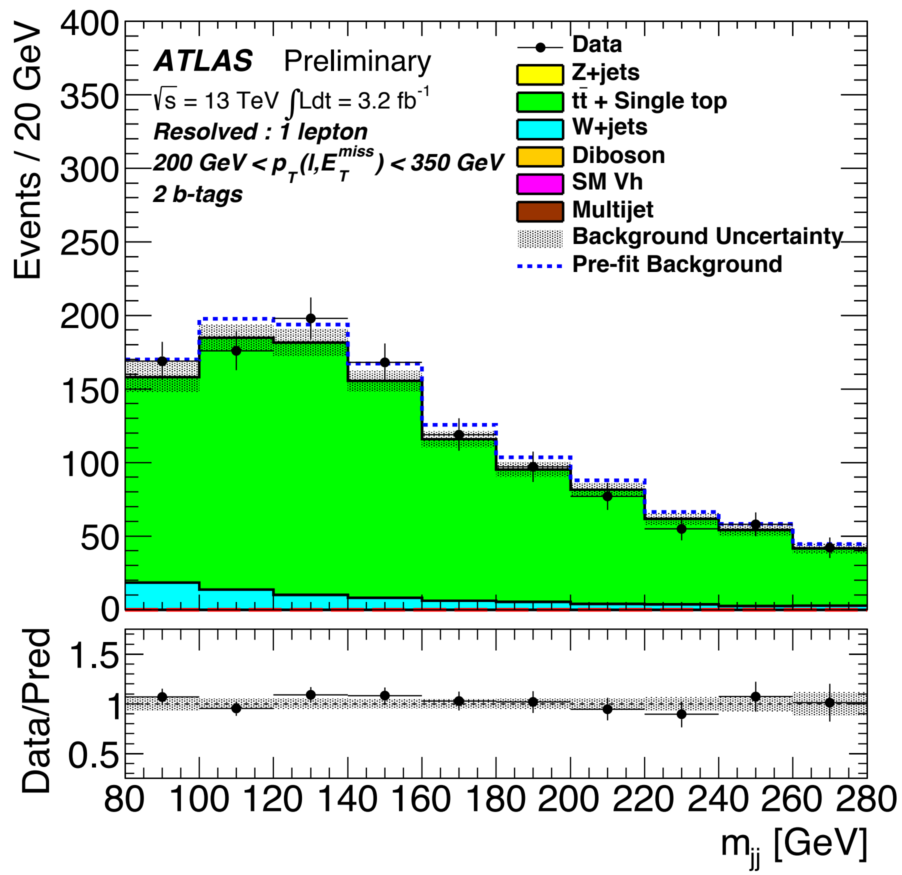


ATLAS-CONF-2016-019

- **Main backgrounds: normalisation from data**
  - Control regions in simultaneous maximum likelihood fit
  - Observed Higgs boson production is also a background
- **W+jets** and **ttbar**: one-muon control region
- **Z+jets**: two-lepton control region
- **Multi-jet** background (resolved region):

  derived from control region dominated by multi-jets





ATLAS-CONF-2016-019

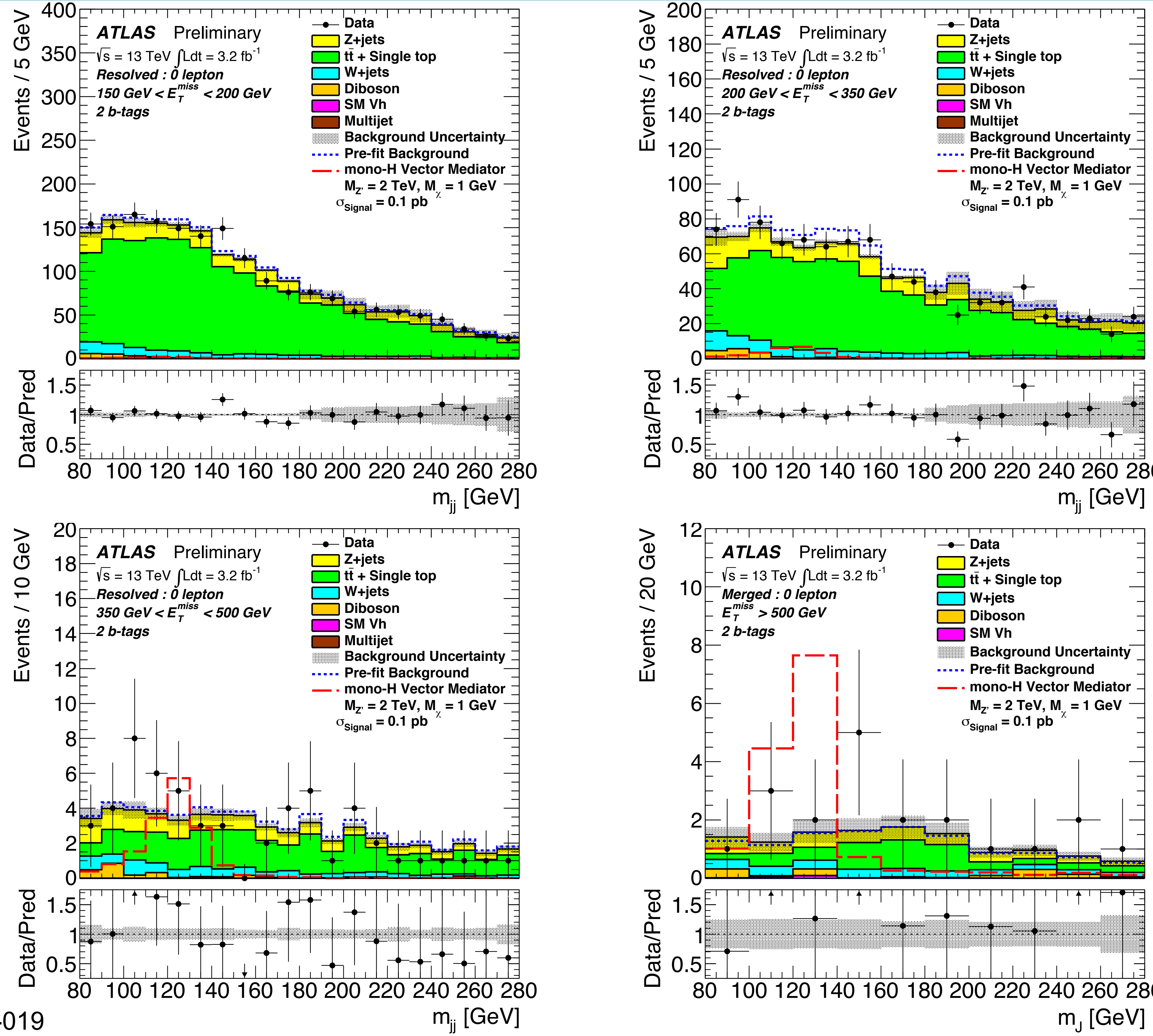
Systematic Uncertainties

ATLAS-CONF-2016-019

Source of uncertainty	Impact (%)
Total	23.0
Statistical	20.5
Systematic	10.3
Experimental Uncertainties	
b-tagging	6.6
Luminosity	4.4
Jets+E_T^{miss}	2.8
Leptons	0.4
Theoretical and Modeling Uncertainties	
Top	5.1
Z+jets	3.4
Signal	2.6
W+jets	1.5
Diboson	0.6
Multijet	0.5
Vh (h$\rightarrow b\bar{b}$)	0.4

Table 1: The percentage impact of the various sources of uncertainty on the expected production cross section for signal expectation using the vector mediator model with $m_{Z'} = 2000$ GeV and $m_\chi = 1$ GeV, normalised with a cross section of 0.1 pb.

Signal Regions



ATLAS-CONF-2016-019

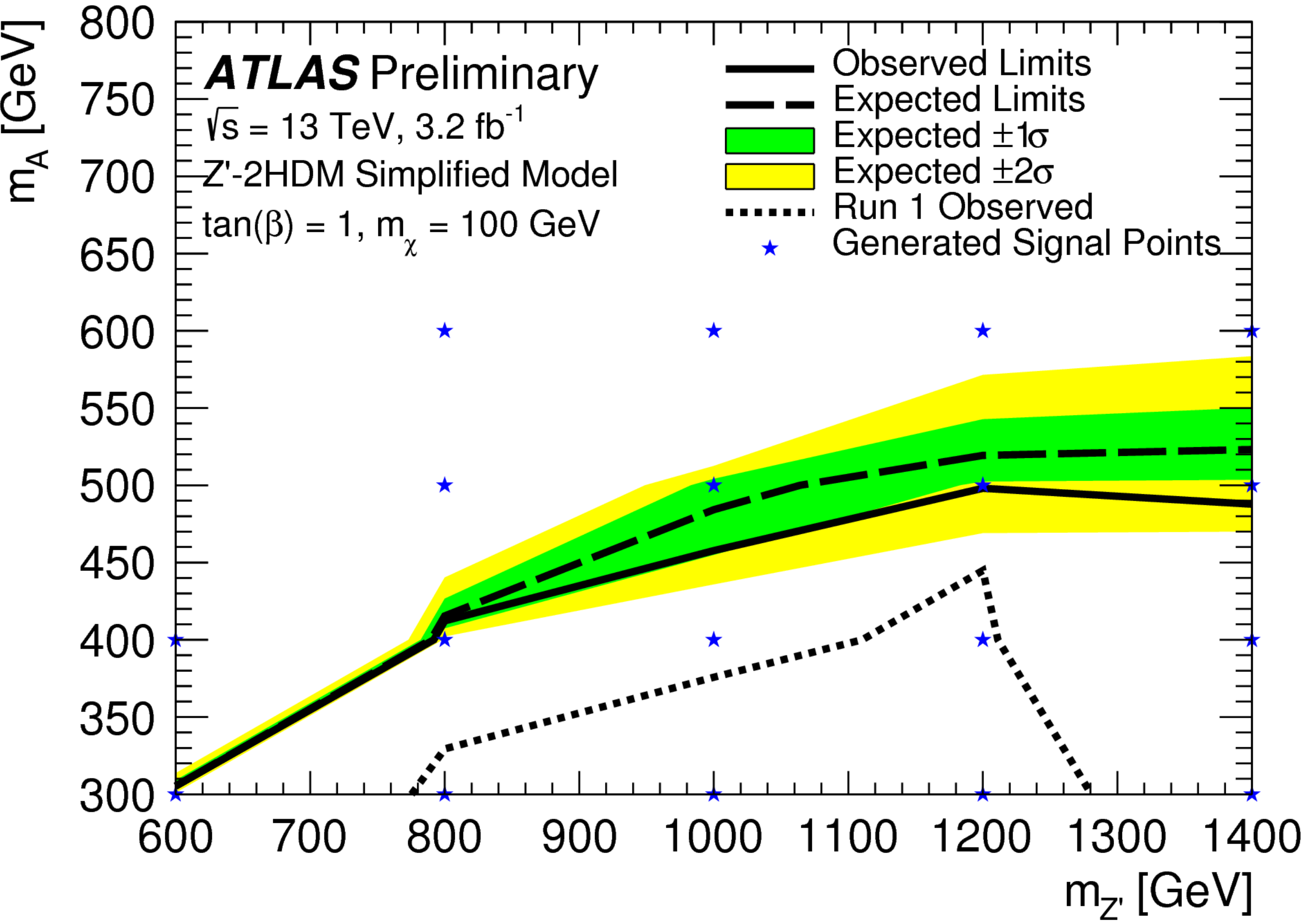
Event Yields in categories

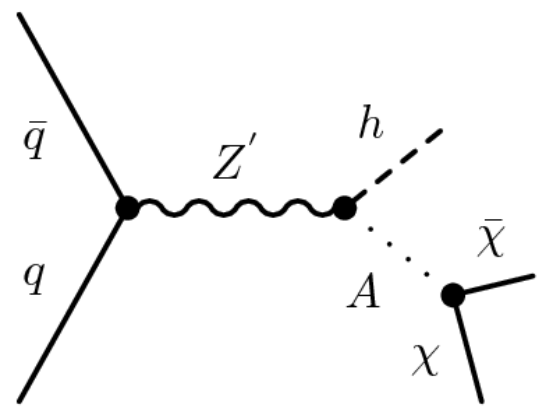
ATLAS-CONF-2016-019

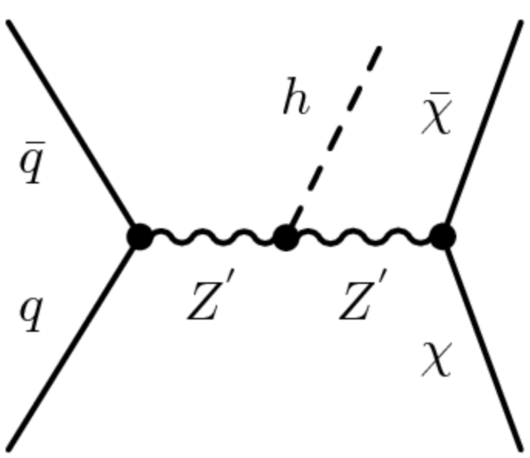
E_T^{miss} (GeV)	Resolved			Merged
	150–200	200–350	350–500	>500
$Z + jets$	259 ± 27	171 ± 13	14.6 ± 1.2	3.80 ± 0.44
$W + jets$	95 ± 28	70 ± 22	7.5 ± 2.4	2.48 ± 0.71
$t\bar{t}$ & Single top	1444 ± 44	656 ± 25	30.8 ± 1.4	4.83 ± 0.88
Multijet	21 ± 10	11 ± 5	0.58 ± 0.27	–
Diboson	17.8 ± 1.6	18.7± 1.0	2.53 ± 0.22	1.20 ± 0.12
$SMVh$	2.8 ± 1.3	2.8 ± 1.4	0.46 ± 0.23	0.15 ± 0.08
Tot. Bkg.	1840 ± 33	930 ± 20	56.5 ± 2.1	12.5 ± 1.3
Data	1830	942	56	20
Exp. Signal	80 ± 8	245 ± 18	161 ± 12	149 ± 34

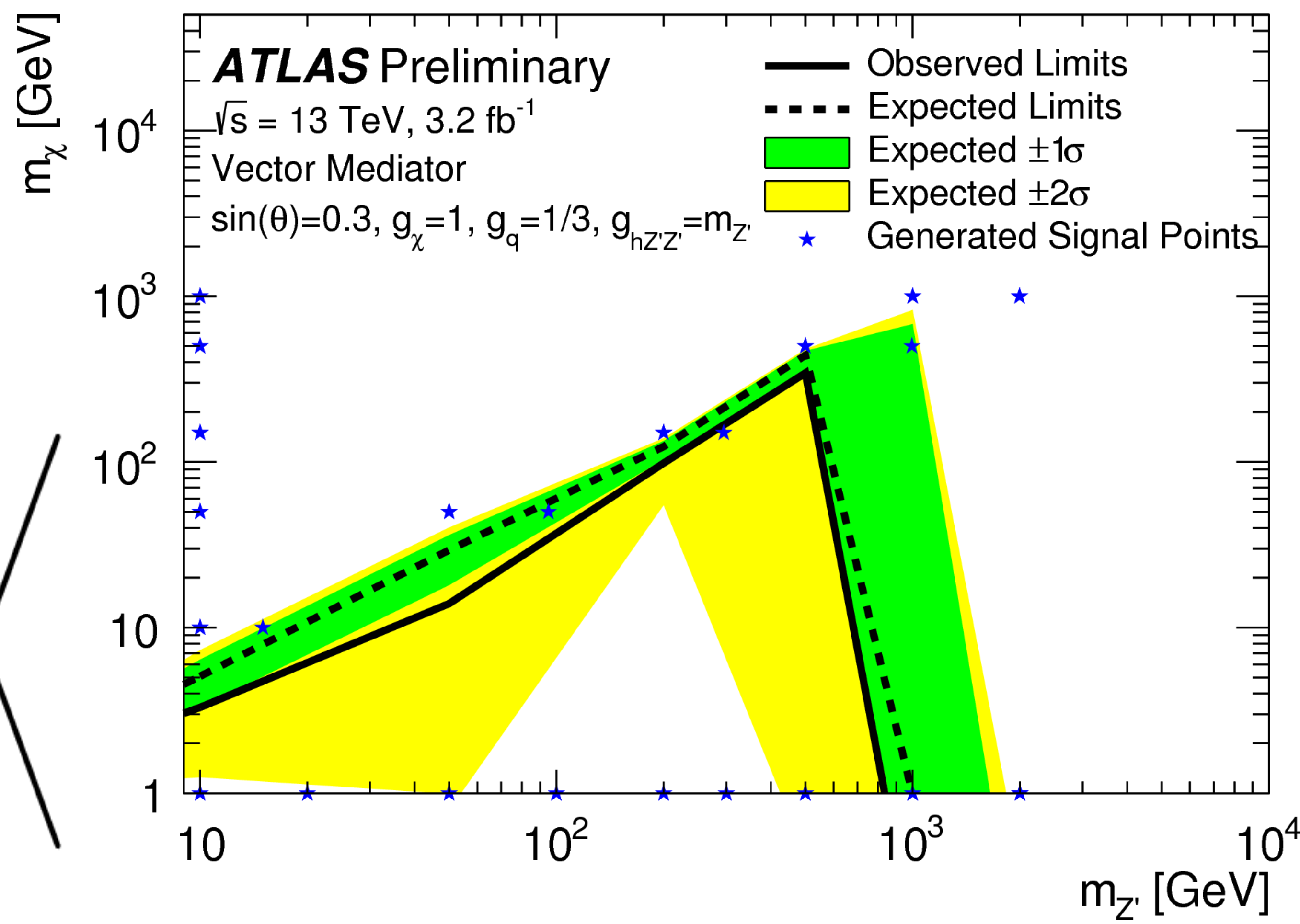
Table 2: The numbers of predicted background events following the profile likelihood fit for each background process, the sum of all background components, and observed data in the 2 b-tag signal region of the resolved and merged channels for each E_T^{miss} region. Statistical and systematic uncertainties are combined. The uncertainties on the total background take into account the correlation of systematic uncertainties among different background processes. An example signal expectation using the vector mediator model with $m_{Z'} = 2000$ GeV and $m_\chi = 1$ GeV, normalised with a cross section of 1 pb is also listed.

Interpretation of Results: Simplified Models



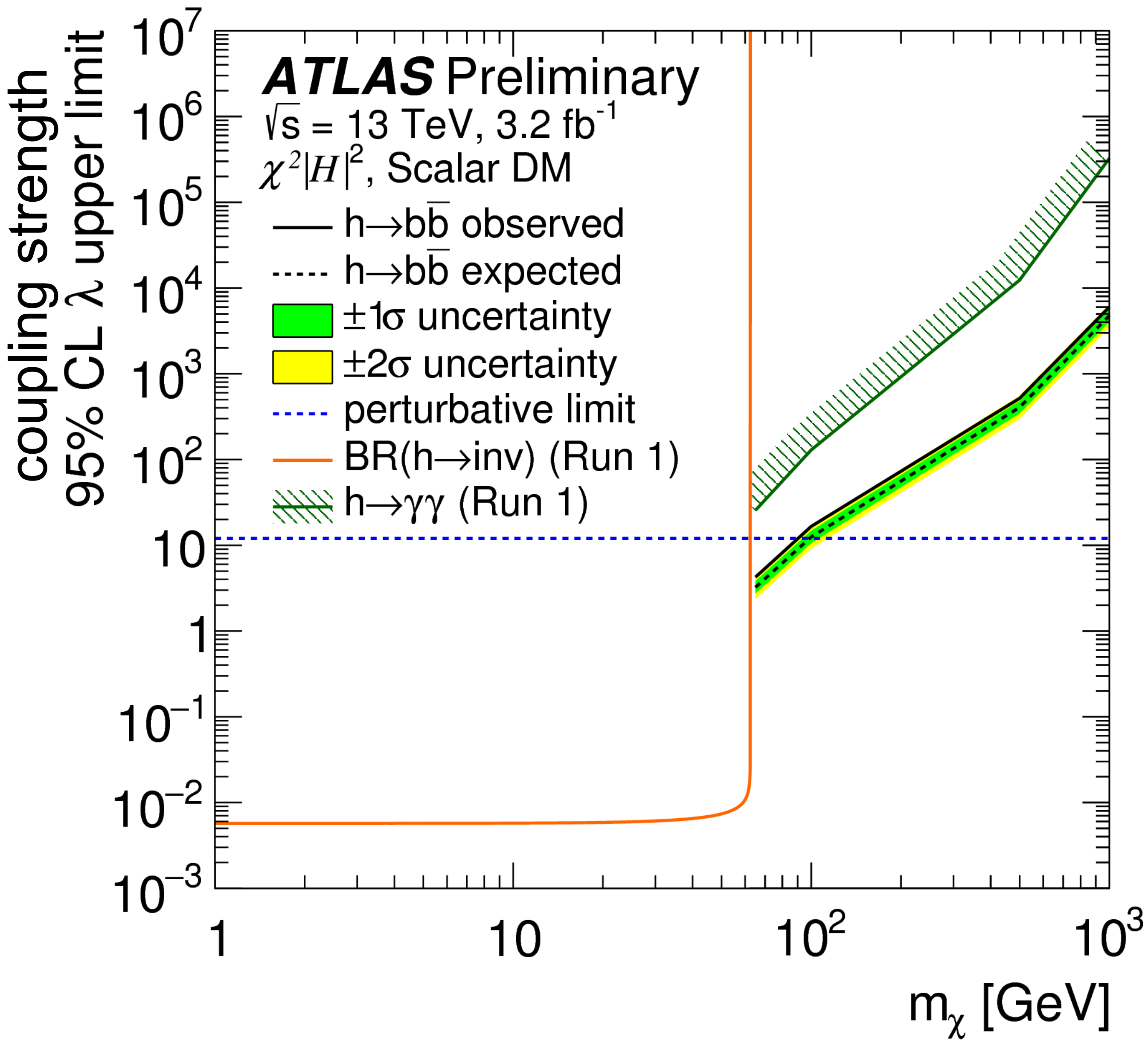


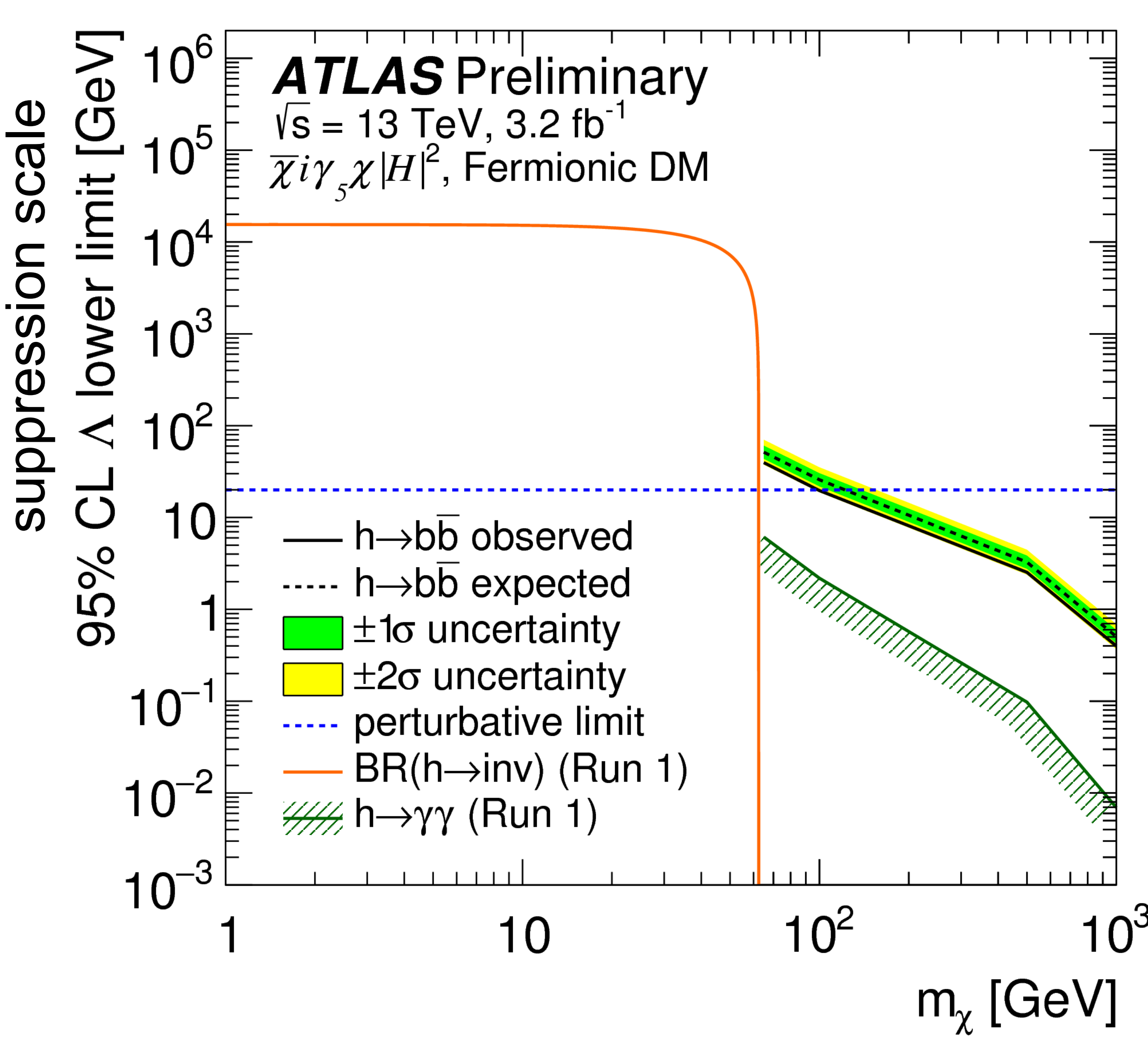




ATLAS-CONF-2016-019

Interpretation of Results: EFT



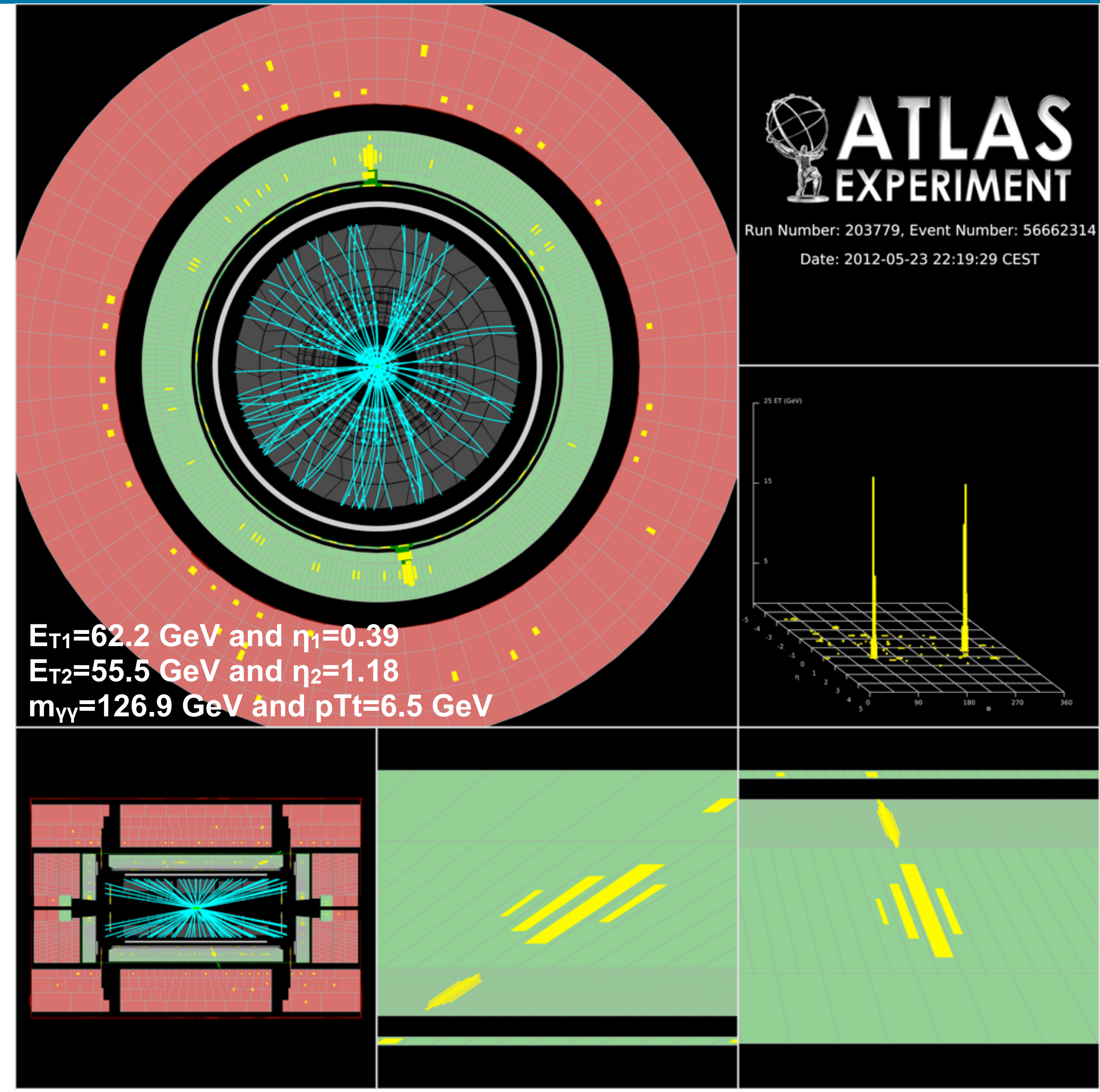


ATLAS-CONF-2016-019

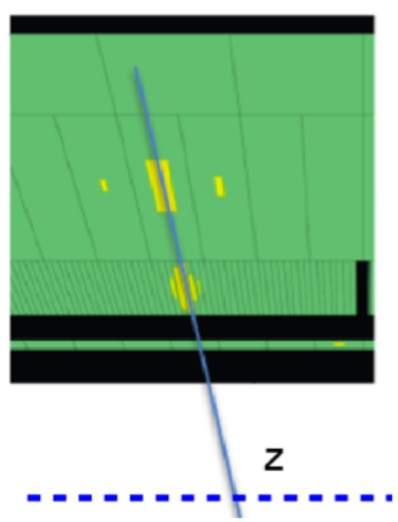
$H \rightarrow \gamma\gamma$ + MET

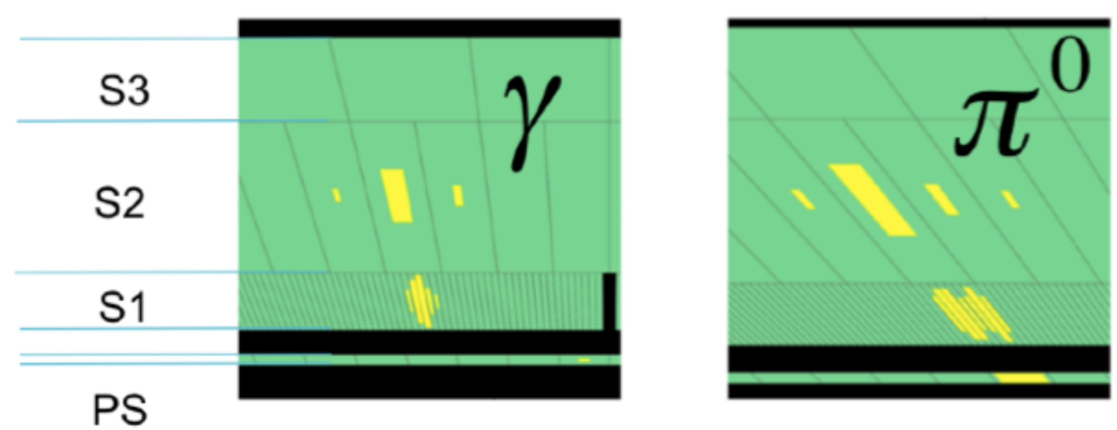
Event Selection

- 13 TeV, 3.2 fb^{-1}, photon trigger
- Higgs selection follows $H \rightarrow \gamma\gamma$
  - two isolated photons
  - $E_T^{\gamma}/m_{\gamma\gamma} > 0.35, 0.25$
  - tight identification
  - mass window 105-160 GeV
- Background from data side-bands
- Signal and background parametrised à la $h\rightarrow\gamma\gamma$
  - Statistical uncertainty dominant



$$\boxed{m^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)}$$

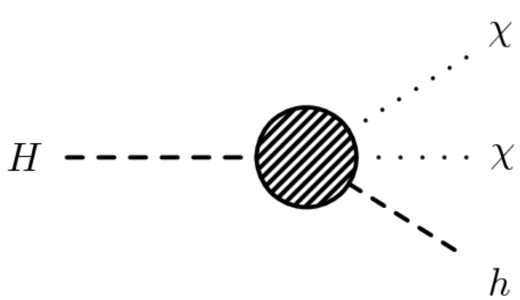


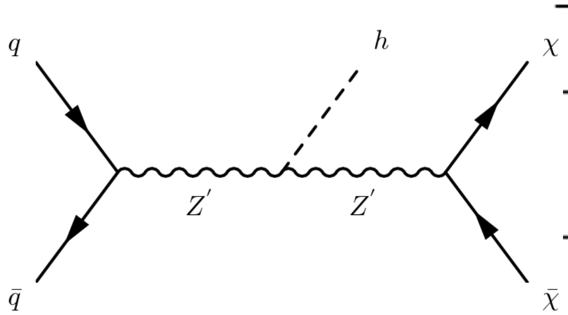


Event categorisation

- Four categories, aiming at:
  - Simplified Z' model
  - Heavy Scalar
    - $2m_h < m_H < 2m_{top}$
- $p_T$hard vector sum of all jets and photons in the event

Category	E_T^{miss} [GeV]	p_T^{hard} [GeV]	$p_T^{\gamma\gamma}$ [GeV]
High E_T^{miss}, high $p_T^{\gamma\gamma}$	> 100	-	> 100
High E_T^{miss}, low $p_T^{\gamma\gamma}$	> 100	-	≤ 100
Intermediate E_T^{miss}	> 50 and ≤ 100	> 40	-
Rest	-	-	> 15





Category	Intermediate	High E_T^{miss}, High $p_T^{\gamma\gamma}$	High E_T^{miss}, Low $p_T^{\gamma\gamma}$	Rest
Data	111	0	6	2477
Heavy scalar, $m_H = 275\ GeV$, $m_\chi = 60\ GeV$				
Yields	16.2 ± 2.3	3.41 ± 0.45	3.83 ± 0.58	26.5 ± 3.6
Selection Eff(%)	11.0 ± 1.6	2.31 ± 0.31	2.59 ± 0.39	17.9 ± 2.4
Z'_B model, $m_{Z'} = 10\ GeV$, $m_\chi = 1\ GeV$				
Yields	1.54 ± 0.21	1.56 ± 0.20	0.21 ± 0.03	1.03 ± 0.14
Selection Eff(%)	15.8 ± 2.1	16.0 ± 2.1	2.19 ± 0.33	10.6 ± 1.4
Backgrounds				
SM Higgs boson	5.2 ± 1.6	0.51 ± 0.09	0.23 ± 0.19	98 ± 16
Non-resonant	110.7 ± 3.7	1.51 ± 0.43	3.95 ± 0.70	2372 ± 17

Systematic Uncertainties

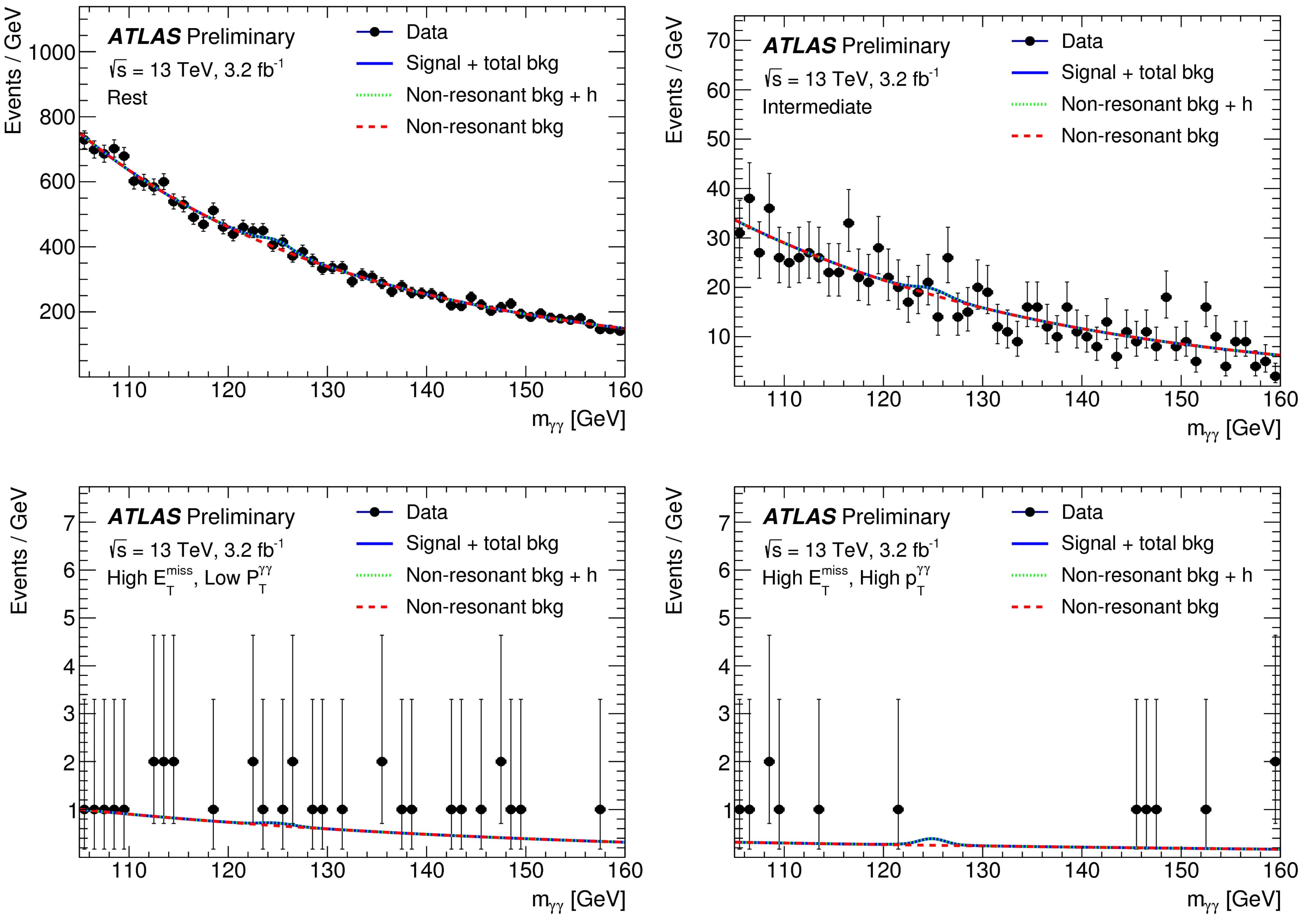
ATLAS-CONF-2016-011

Source	Maximum uncertainty (%)
Experimental	
Luminosity	5
Trigger efficiency	0.4
Vertex selection	3.6 (Intermediate), 20 (High $E_{\mathrm{T}}^{\mathrm{miss}}$)
Photon identification efficiency	2.8
Photon energy scale	1
Photon energy resolution	2
Photon isolation efficiency	4
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	1 (Rest), 20 (Intermediate and High $E_{\mathrm{T}}^{\mathrm{miss}}$)
Pile-up reweighting	4.5
Theoretical	
QCD scale uncertainty of ggH p_{T} spectrum	10 - 20
Modelling of ggH $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum	25
PDF	9
MPI	1 (Intermediate), 50 (High $E_{\mathrm{T}}^{\mathrm{miss}}$)
BR($h \to \gamma\gamma$)	4.9

Table 4: Breakdown of the dominant systematic uncertainties. The impact of uncertainties on the yield of the SM Higgs boson processes is shown. All production modes of the SM Higgs boson are considered together unless otherwise stated. Representative values for the impact on the four analysis categories are shown, unless a given source has very different impacts on different categories, in which cases the largest and the smallest impacts are shown separately.

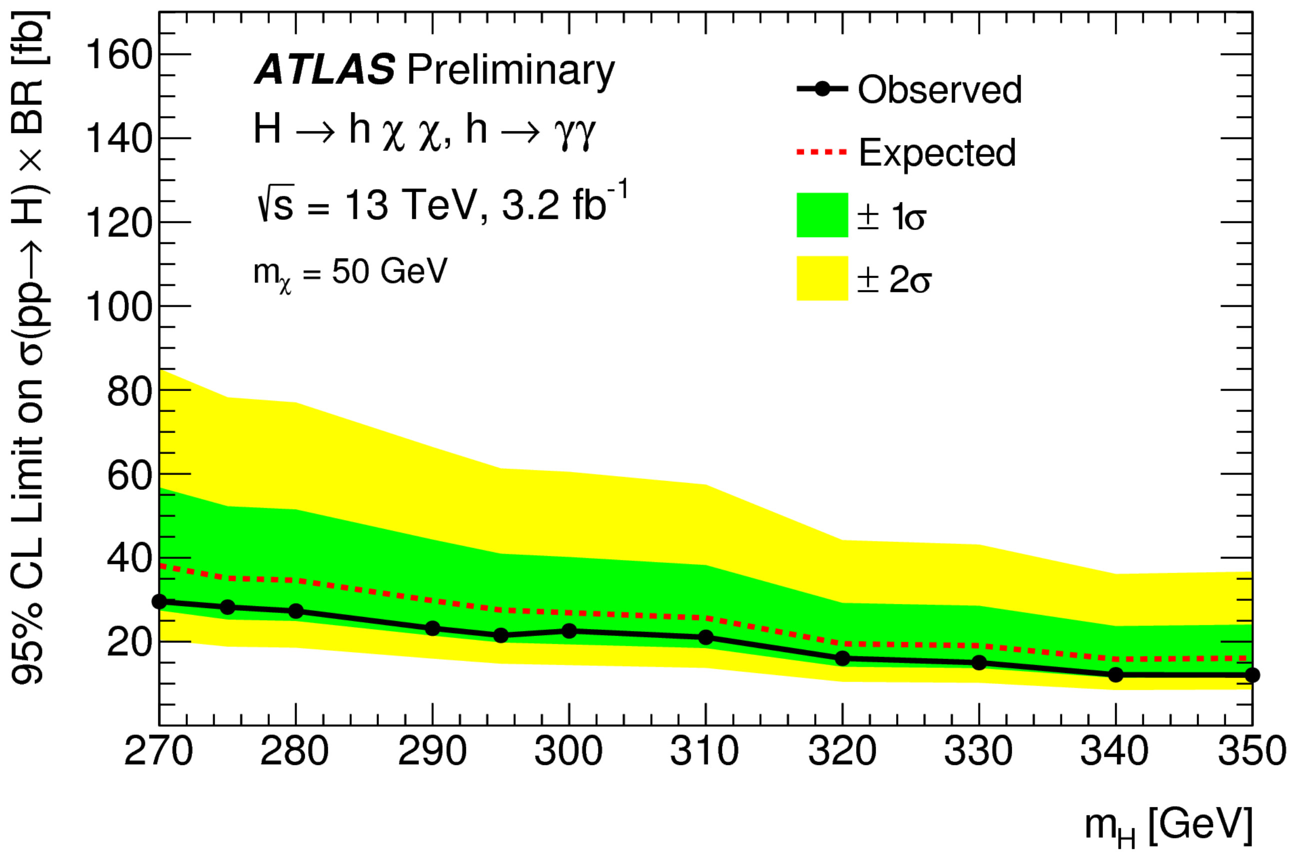
Signal Regions

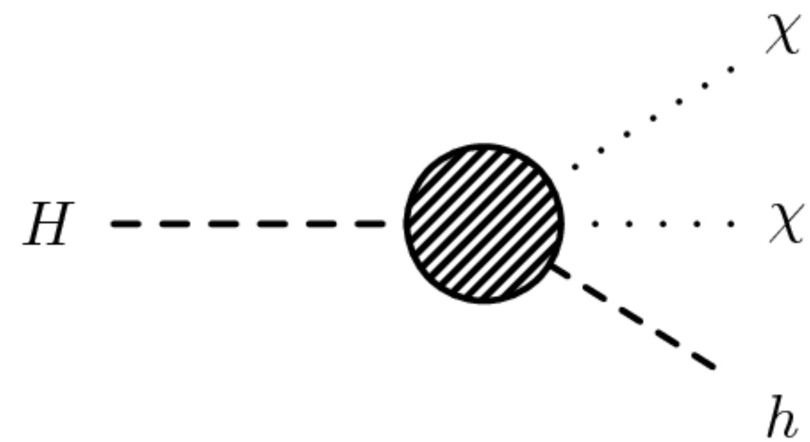
ATLAS-CONF-2016-011

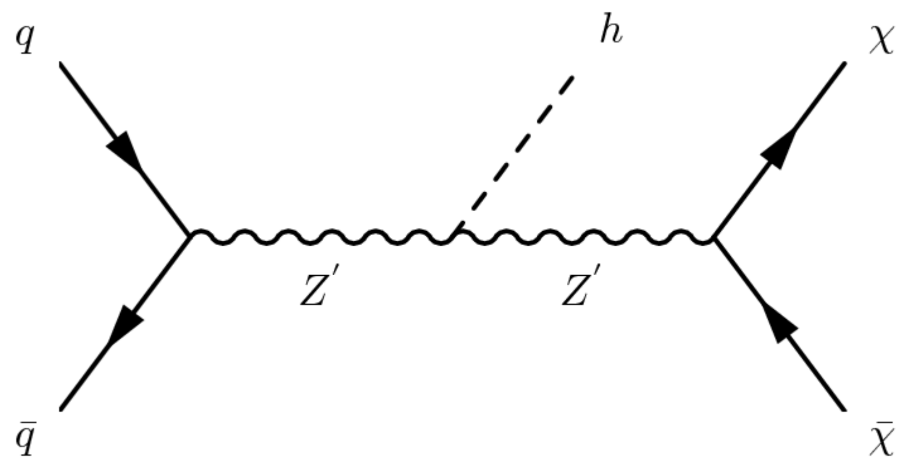


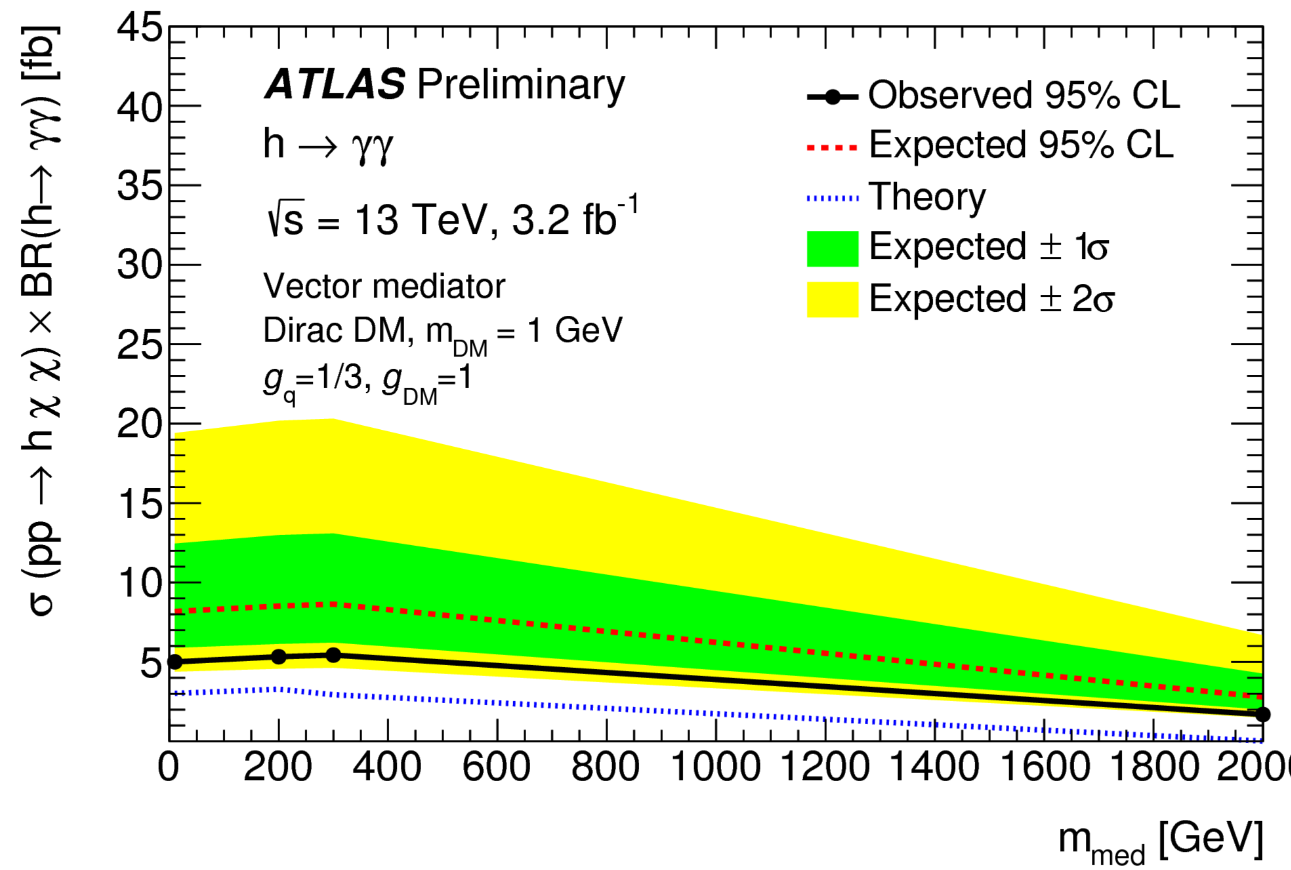
Interpretation of Results: Simplified Models

ATLAS-CONF-2016-011

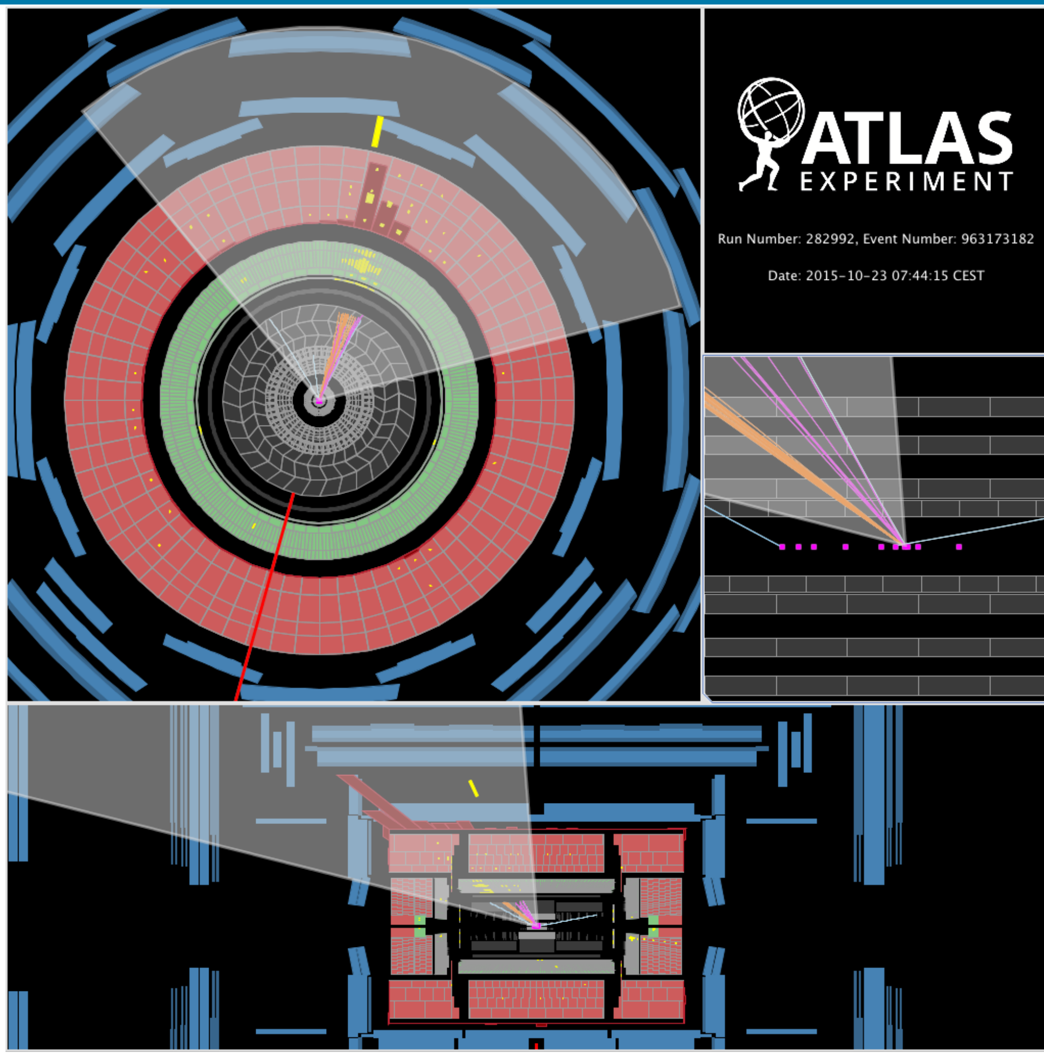








Summary

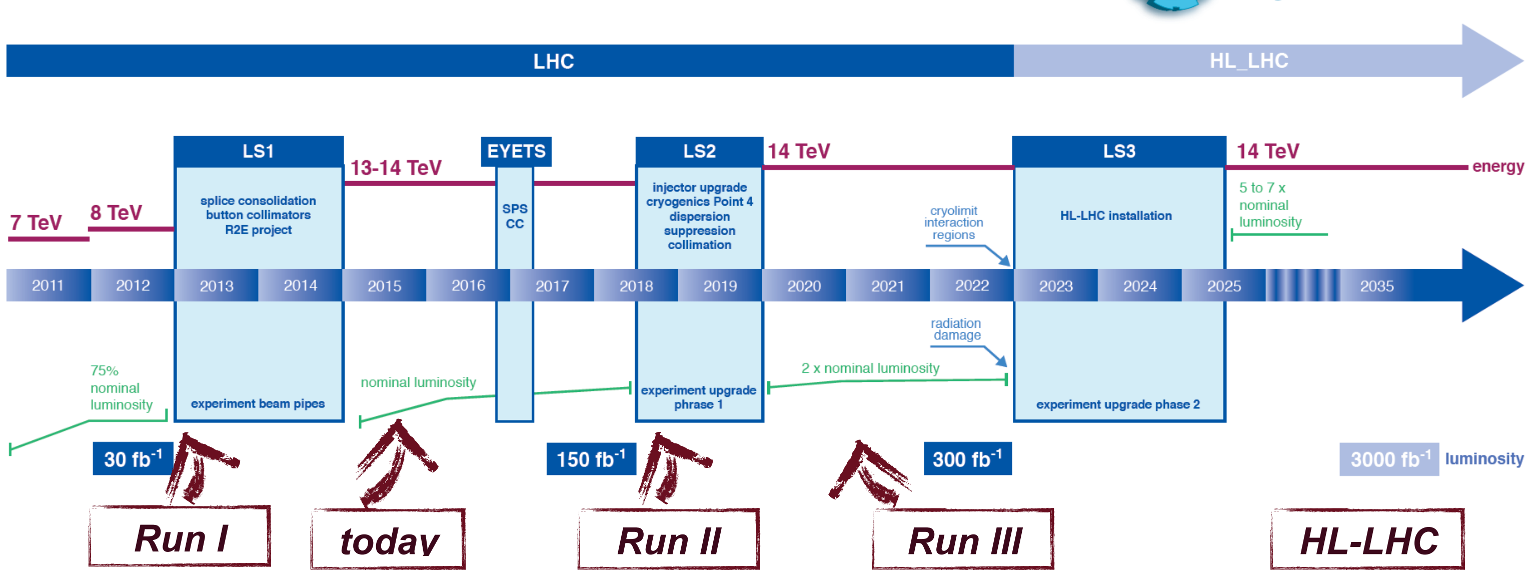


Higgs sector landscape transformed since July 4th, 2012!

Observed Higgs boson now a tool for probing New Physics!

- Precision property measurements
  (fiducial/differential cross-sections, couplings, etc.)
- Anomalous/rare production/decays
  (FCNC, LFV, h→Qγ, …)
- Extended sectors
  (H→hh, A→Zh, h→aa,…)
- Probe for Dark Matter

LHC / HL-LHC Plan



Latest H(→bb/γγ)+MET searches presented

On-going Run 2 will provide substantially enhanced sensitivity in all of these directions!