The most recent ATLAS searches for TeV-scale gravity, for particles with charges up to 60e, and for magnetic monopoles.

ICHEP 2016, Chicago

Christopher Lester,
on behalf of the ATLAS Collaboration

Peterhouse / Cambridge

ATLAS search for particles with charges from 2e to 6e

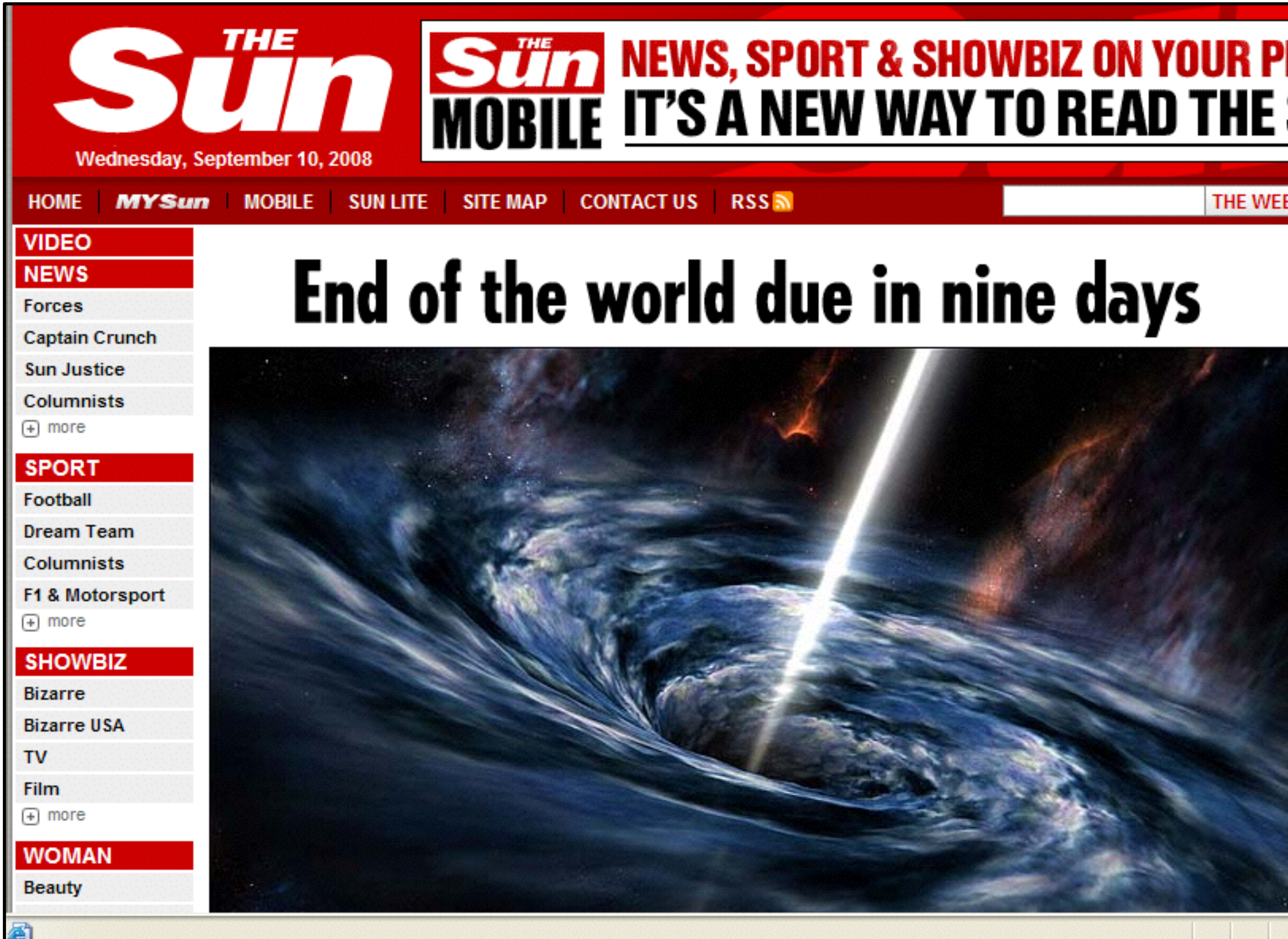
April 2015 - Run I

September 2015 - Run I

ATLAS search for particles with charges from 10e to 60e

ATLAS search for TeV-scale gravity signatures in high-mass final states with leptons and jets with the ATLAS detector at 13 TeV

June 2016
Run II


THE Sun
Wednesday, September 10, 2008
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Dream Team
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SHOWBIZ
Bizarre
Bizarre USA
TV
Film
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WOMAN
Beauty
End of the world due in nine days

In 2008 offered odds of **666,666,666:1** that

"there would be no tomorrow"

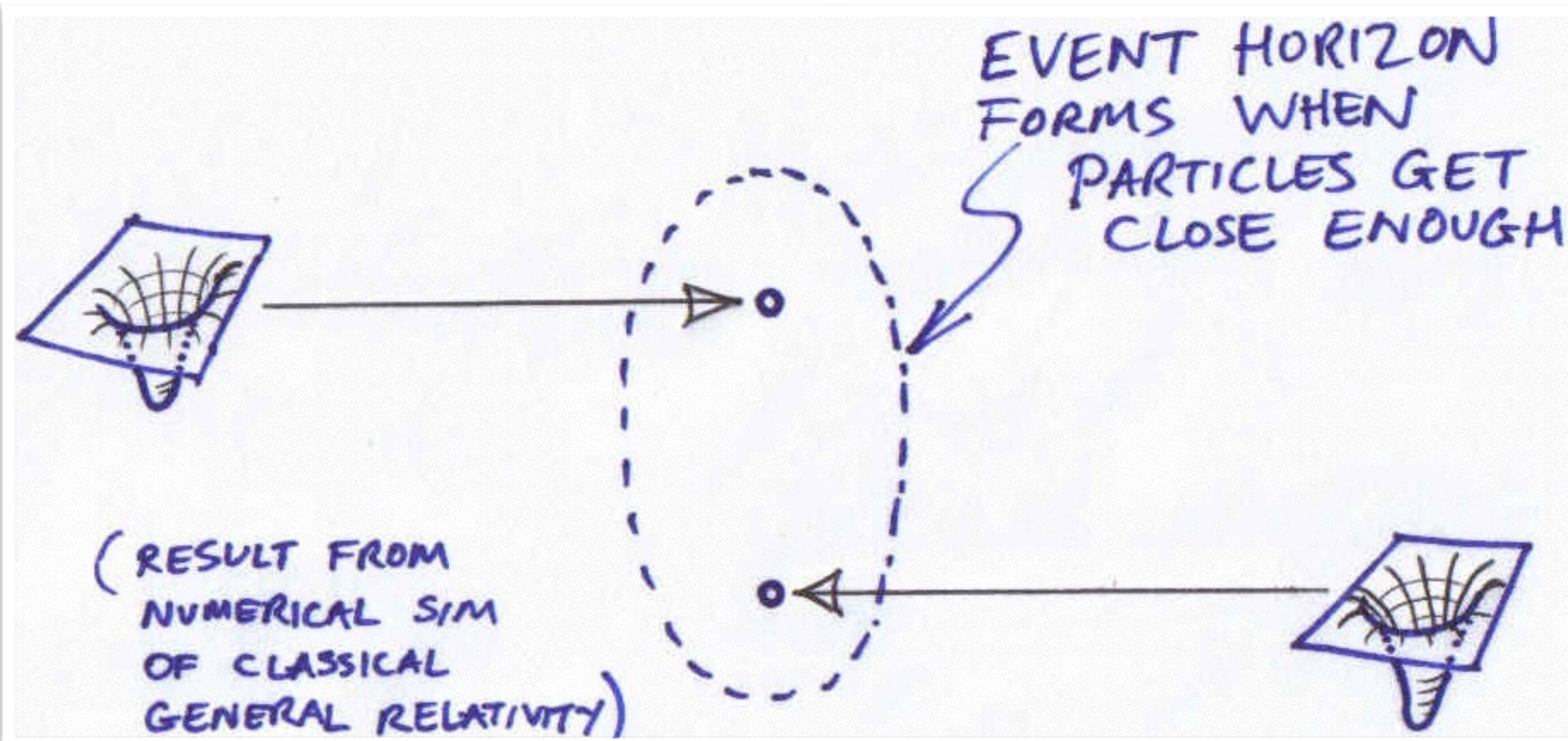
Rupert Adams of William Hill said:

"**As the end of the world is fairly depressing, we have decided to offer punters the opportunity to die extremely rich.**"

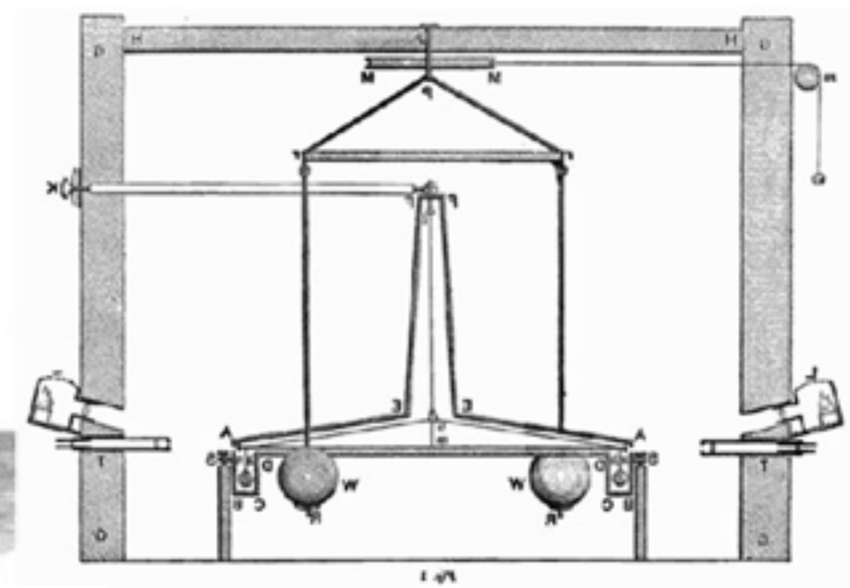
Text taken from a British News Paper, the `Daily Star', 10th Sept 2008:

Why the fuss?

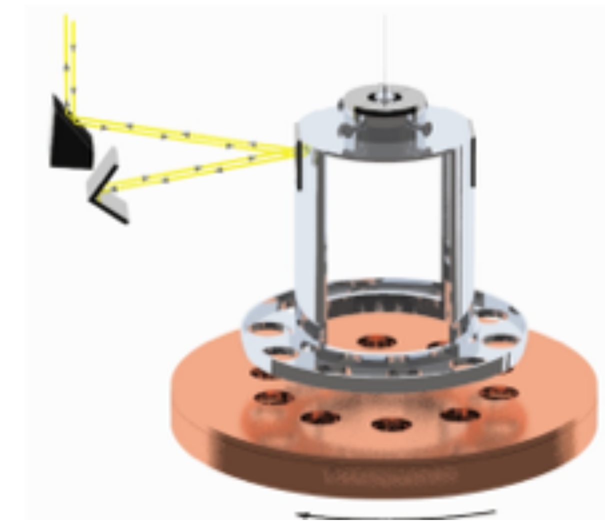
Black Hole Formation



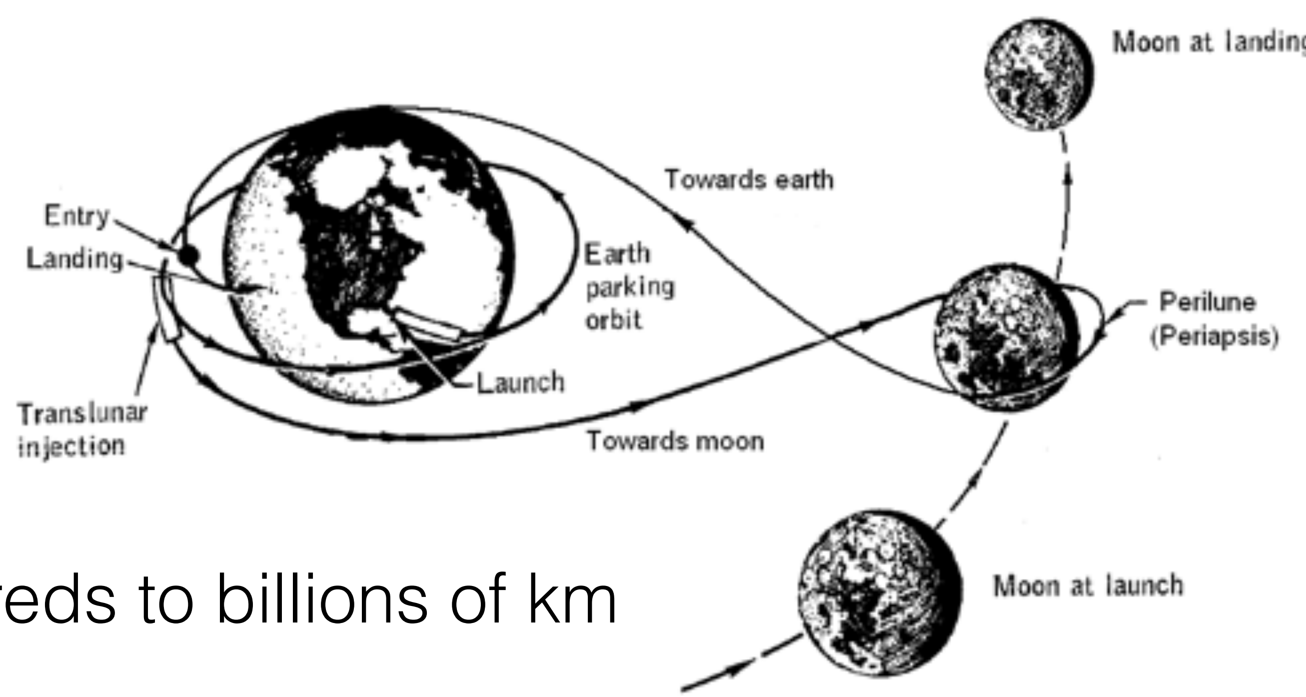
Gravity is $1/r^2$ and not very strong ?



~9 inches in 1798

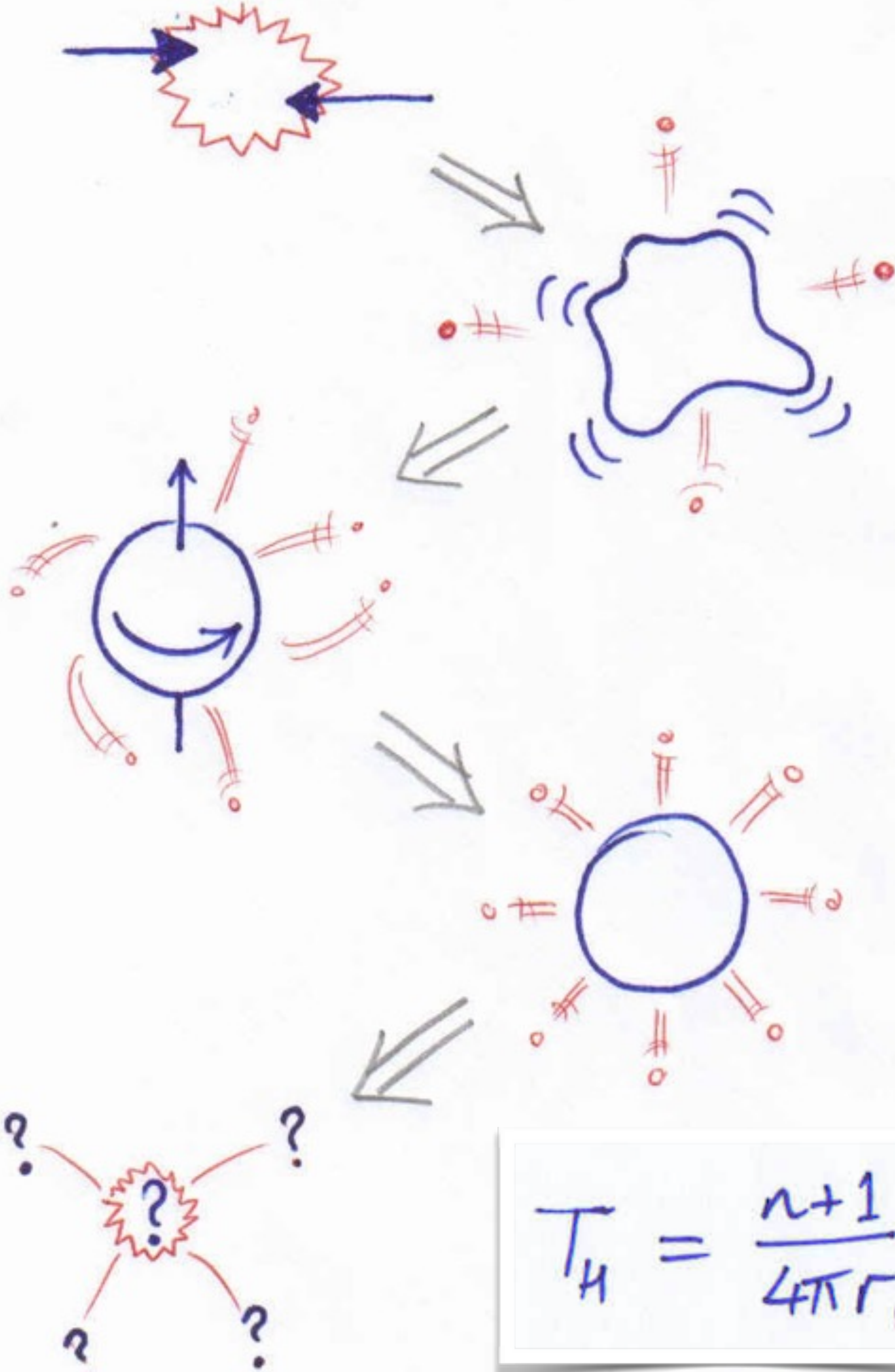


~0.01 mm in 2006



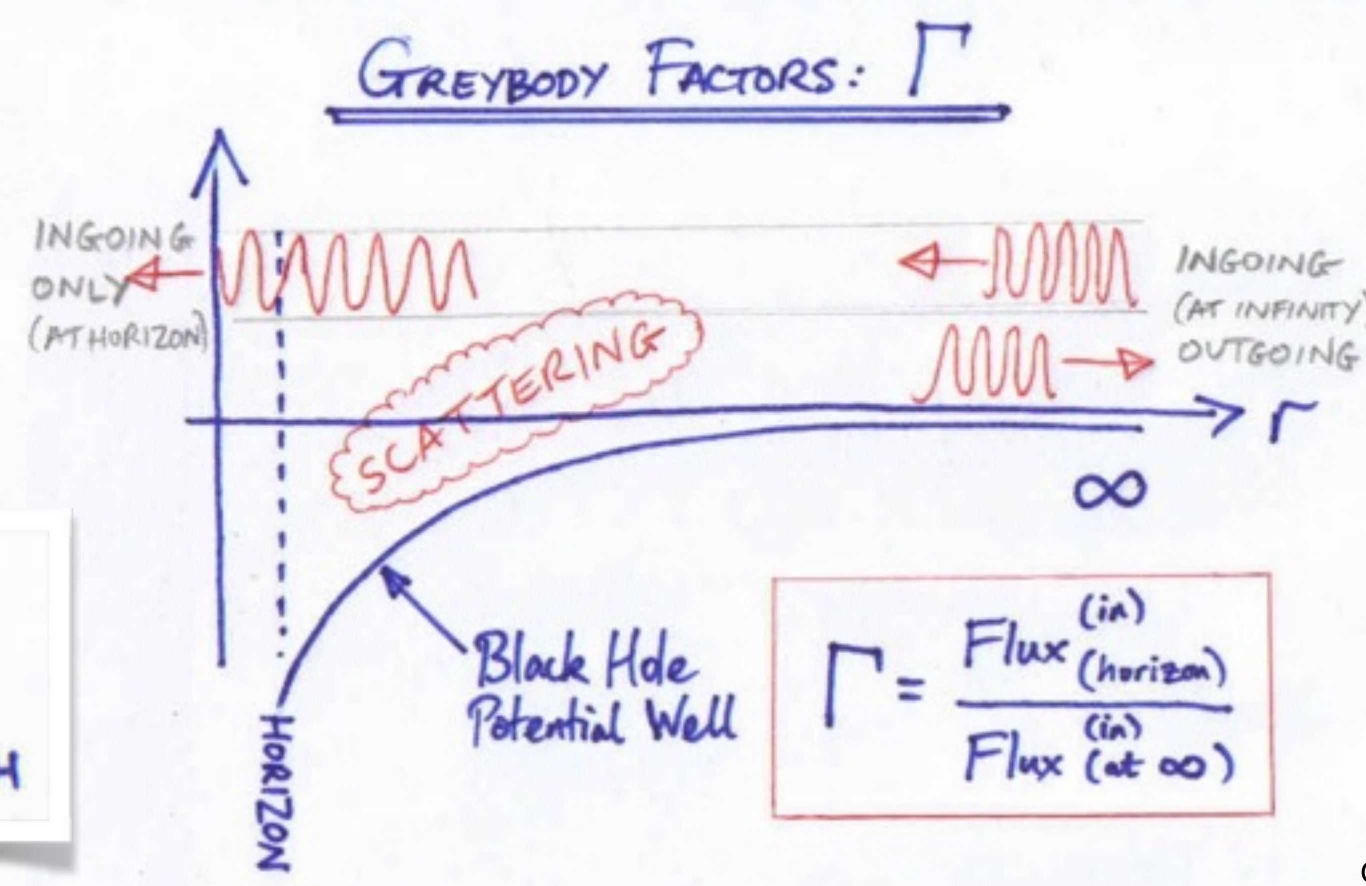
~hundreds to billions of km

Modifications at small scales (e.g. extra dimensions) might make some theorists happy.

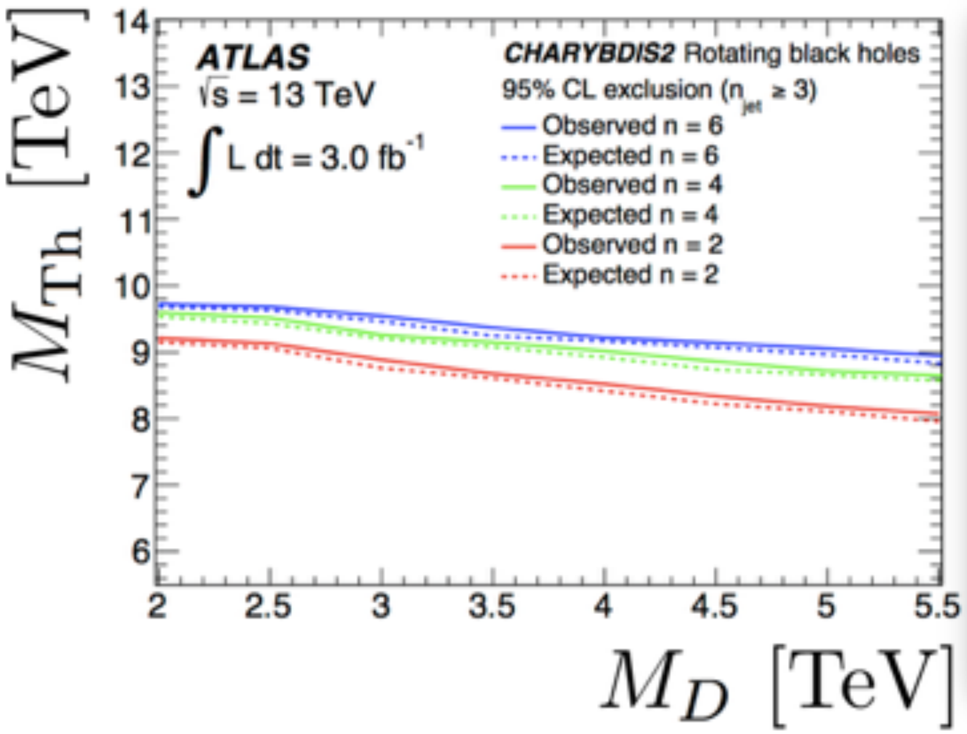


BLACK HOLE OF IGNORANCE

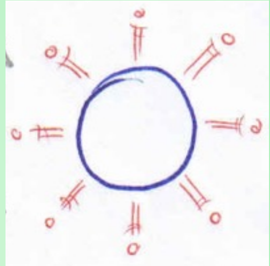
$$T_H = \frac{n+1}{4\pi r_{BH}}$$



Some important ATLAS TeV-scale gravity searches which are not covered in this talk:



Search for strong gravity in **multijet** final states produced in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector at the LHC



December 2015 Run-II, 13 TeV, 3.6/fb

10.1016/j.physletb.2016.01.032 arXiv: 1512.02586

Search for new phenomena in dijet mass and angular distributions from pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

December 2015 Run-II, 13 TeV, 3.6/fb

10.1016/j.physletb.2016.01.032 arXiv:1512.01530

Excludes, at 95% CL, **quantum black holes** with threshold masses below 8.3 TeV, 8.1 TeV, or 5.3 TeV in three different benchmark scenarios

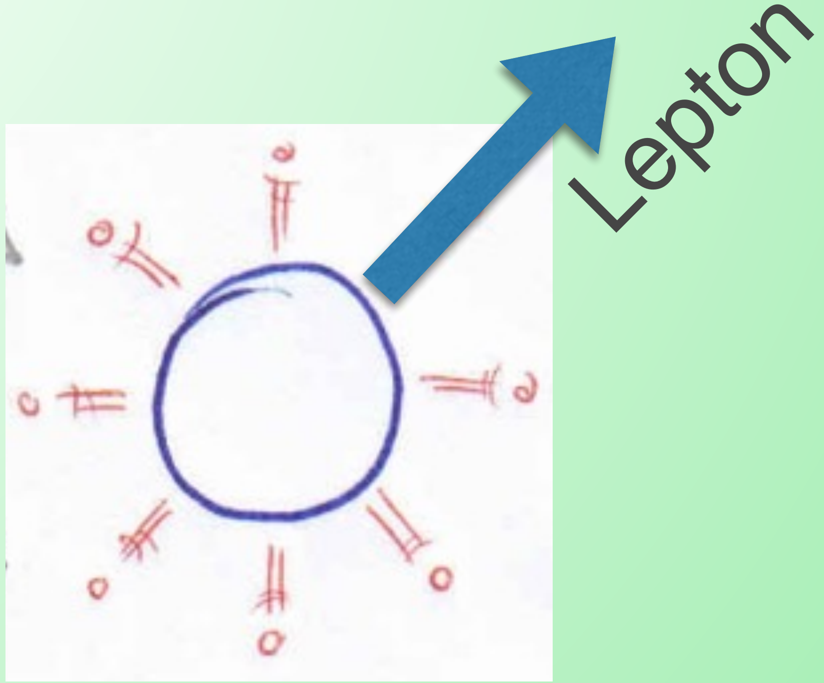
ATLAS search for TeV-scale gravity signatures in high-mass final states with leptons and jets with the ATLAS detector at 13 TeV

arXiv:1606.02265

Phys. Lett. B

doi:10.1016/j.physletb.2016.07.030

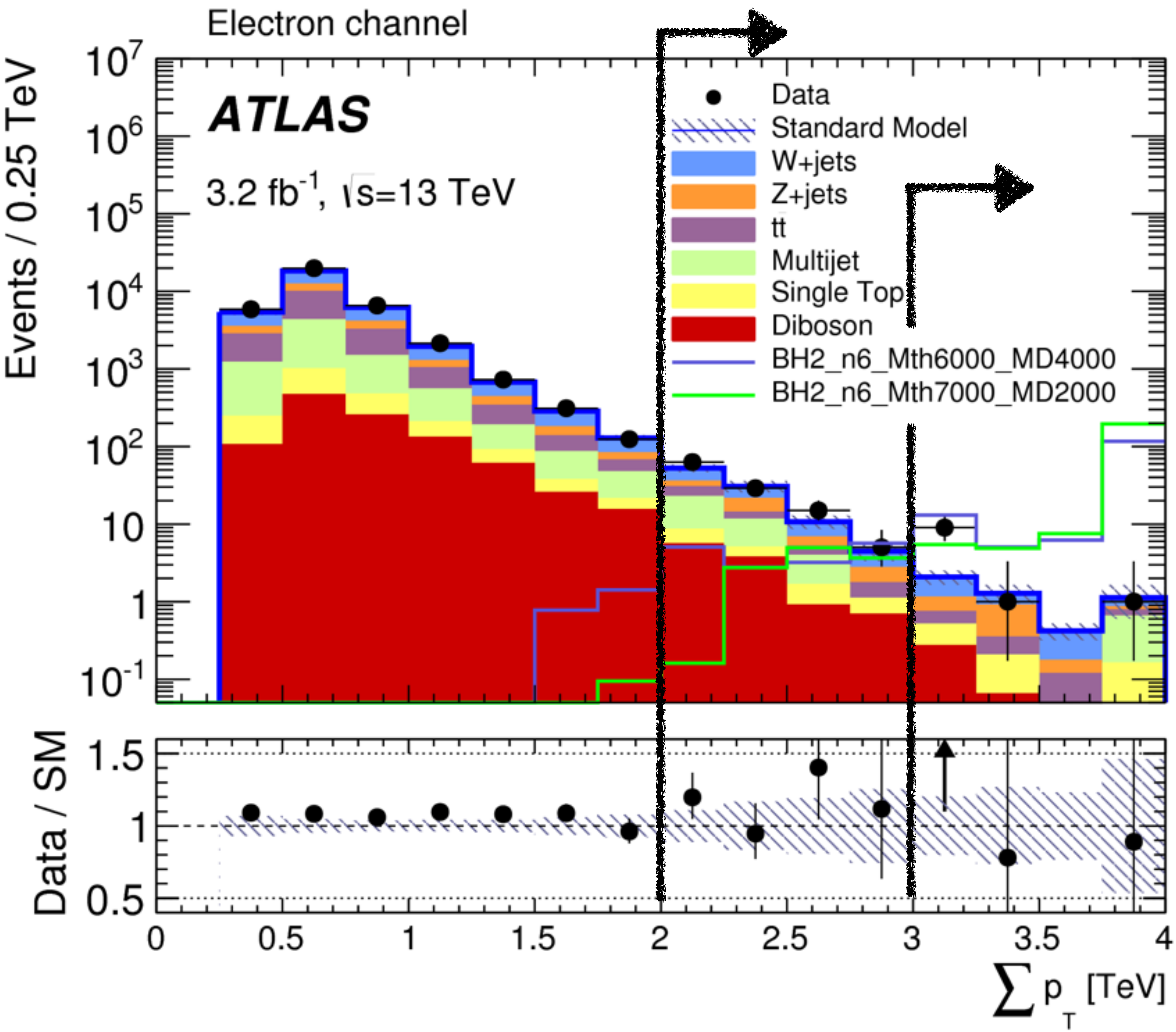
Run-II, 13 TeV, 3.2/fb

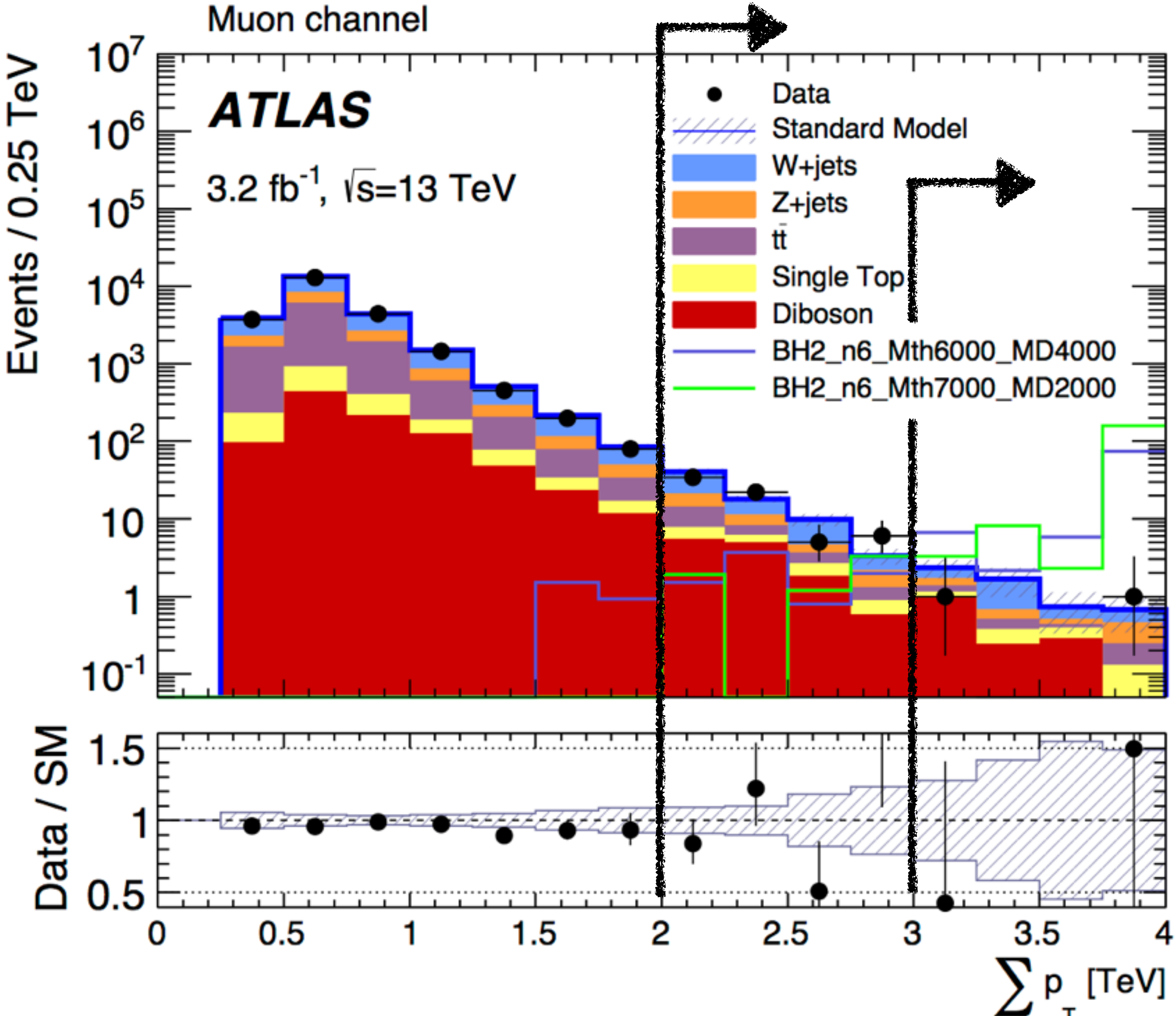


$$\sum p_{\mathrm{T}}$$

sum over jets & leptons with pT > 60 GeV.

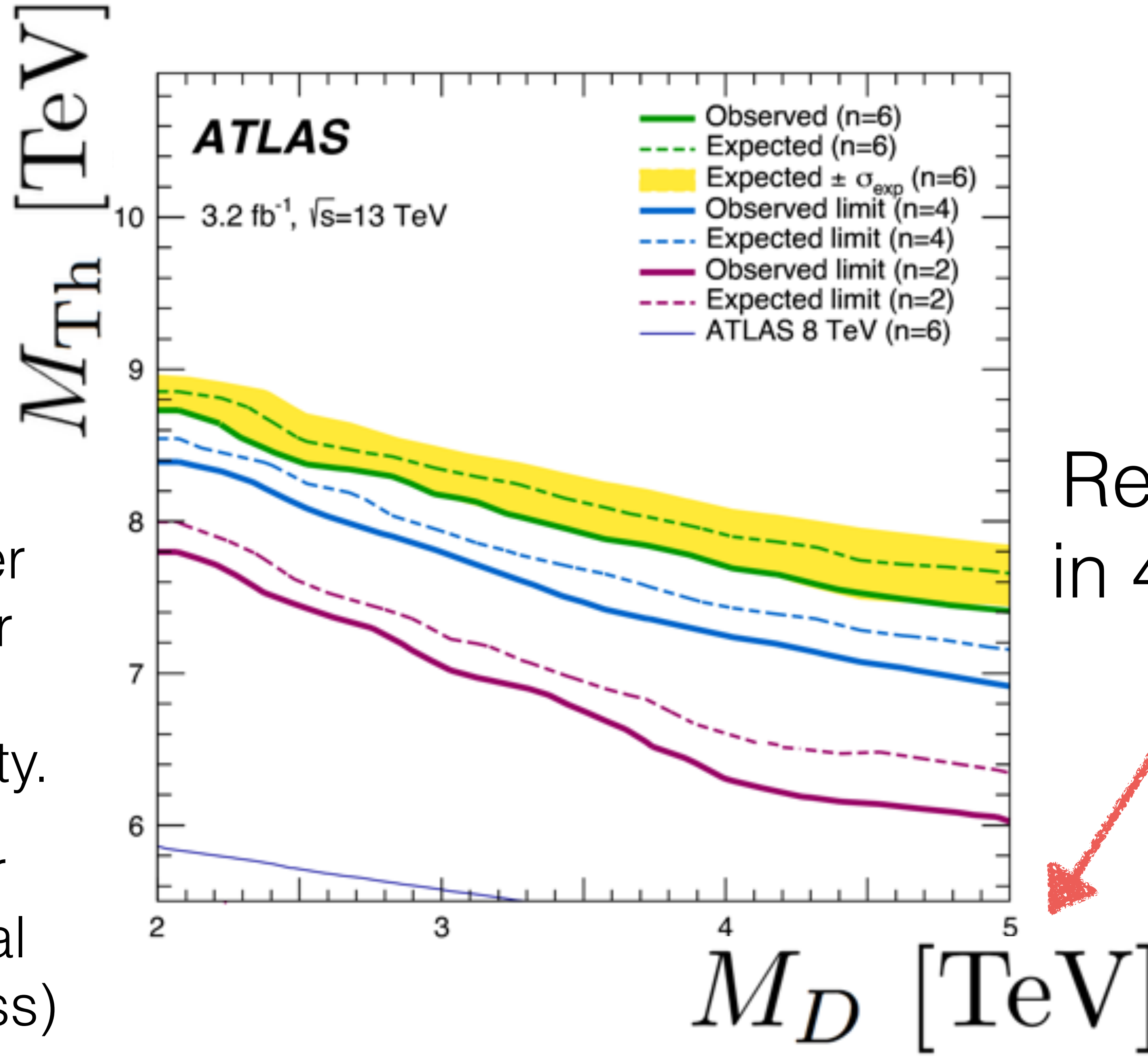
Selection	**Control Regions**			**Signal regions**
	Z**+jets**	W**+jets**	$t\bar{t}$	
$\sum p_{\mathrm{T}}$	750–1500 GeV			$> 2000(3000)$ GeV
Number of objects (leptons or jets)	≥ 3 objects with $p_{\mathrm{T}} > 60$ GeV			≥ 3 objects with $p_{\mathrm{T}} > 100$ GeV
Leading lepton (electron or muon)	Isolated with $p_{\mathrm{T}} > 60$ GeV			Isolated with $p_{\mathrm{T}} > 100$ GeV
$m_{\ell\ell}$	80–100 GeV	n/a		n/a
$E_{\mathrm{T}}^{\mathrm{miss}}$	n/a	> 60 GeV	n/a	
Number of leptons	$= 2$, opposite sign same flavour	$= 1$		≥ 1
Number of b-tagged jets	n/a	$= 0$	≥ 2	n/a
Number of jets	n/a		≥ 4	


Electron channel
ATLAS
3.2 fb^{-1}, $\sqrt{s}$=13 TeV
Data
Standard Model
W+jets
Z+jets
tt
Multijet
Single Top
Diboson
BH2_n6_Mth6000_MD4000
BH2_n6_Mth7000_MD2000
Events / 0.25 TeV
Data / SM
$\sum p_T$ [TeV]


Muon channel
ATLAS
3.2 fb^{-1}, $\sqrt{s}$=13 TeV
Events / 0.25 TeV
Data / SM
Data
Standard Model
W+jets
Z+jets
$t\bar{t}$
Single Top
Diboson
BH2_n6_Mth6000_MD4000
BH2_n6_Mth7000_MD2000
$\sum p_T$ [TeV]

No statistically significant excess of events seen thus far …

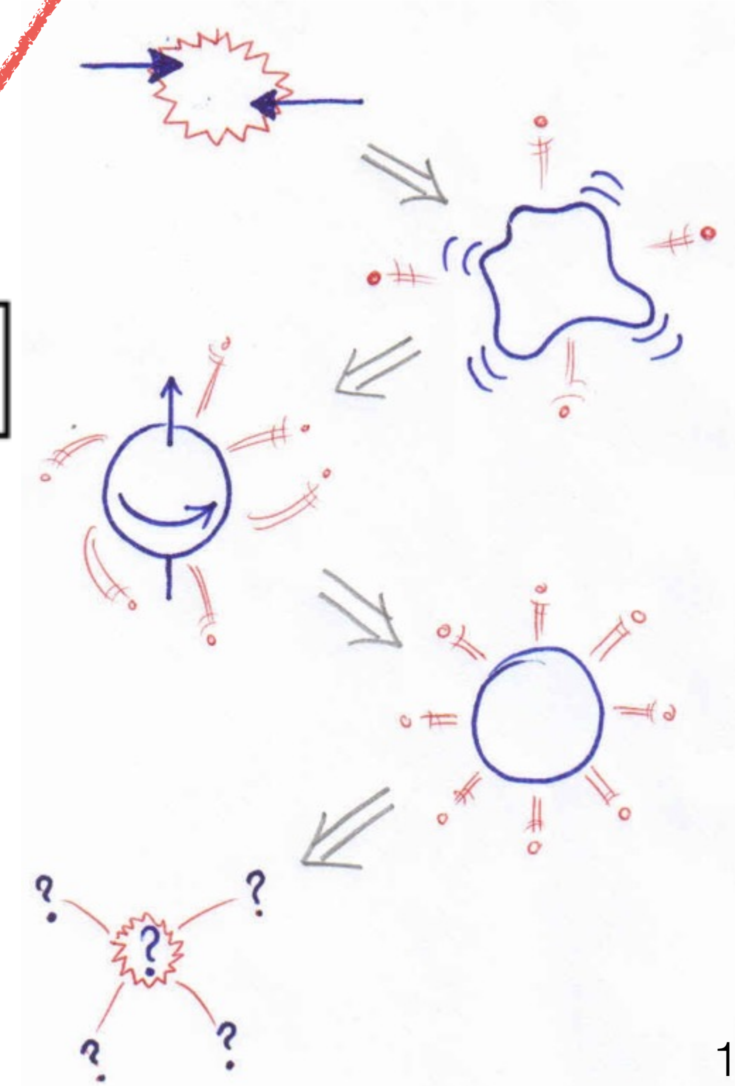
	SR-2TeV (electron)	SR-2TeV (muon)	SR-3TeV (electron)	SR-3TeV (muon)
Observed events	123	69	11	2
Expected bkg events	104 $\pm$ 9	78 $\pm$ 6	4.6 $\pm$ 0.8	5.3 $\pm$ 1.2
Expected $t\bar{t}$ events	13.8 $\pm$ 3.1	11.4 $\pm$ 2.5	0.65 $\pm$ 0.18	0.55 $\pm$ 0.15
Expected W+jets events	32.0 $\pm$ 3.5	33.9 $\pm$ 3.2	1.76 $\pm$ 0.31	2.0 $\pm$ 0.4
Expected Z+jets events	16.6 $\pm$ 1.5	12.6 $\pm$ 1.4	1.09 $\pm$ 0.18	0.77 $\pm$ 0.24
Exp. single-top-quark events	6.1 $\pm$ 0.9	5.2 $\pm$ 0.7	0.59 $\pm$ 0.18	0.54 $\pm$ 0.14
Expected diboson events	11.4 $\pm$ 1.4	14.5 $\pm$ 1.5	0.22 $\pm$ 0.18	1.5 $\pm$ 0.5
Expected multijet events	24 $\pm$ 7	0.0 $\pm$ 0.0	0.32 $\pm$ 0.24	0.0 $\pm$ 0.0



The parameter that hides our ignorance of quantum gravity.

(Threshold or minimum initial black-hole mass)

Real Planck scale in 4+n dimensions



A search has been performed for signatures of TeV-scale gravity in high-mass final states including at least one lepton in conjunction with at least two other leptons or hadronic jets each with $p_T > 100$ GeV, using 3.2 fb^{-1} of proton–proton collisions recorded by the ATLAS detector at the LHC at a centre-of-mass energy of 13 TeV. No significant deviation from the background predictions is observed. Upper limits are therefore set on the possible contribution of new physics processes in this class of final states at 12.1 fb (3.4 fb) at 95% CL for $\sum p_T > 2$ TeV (3 TeV). Constraints are placed on production of microscopic black holes in models with two to six extra space dimensions which substantially extend the excluded range of model parameters. The results of this analysis could potentially be used to constrain other models predicting new phenomena at the TeV scale involving decays to leptons and jets.

ATLAS search for particles with charges from 2e to 6e

Eur.Phys.J. C75 (2015) 362

arXiv: 1504.04188

Run-I, 8 TeV, 20.3/fb

The plan ....

Energy lost (per unit length) by a particle of charge z and speed βc traversing a medium containing nuclei with A nucleons and Z protons follows Bethe formula:

$$\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \left[\frac{1}{2\beta^2} \log\left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - 1 - \frac{1}{2\beta^2} \delta(\beta\gamma) \right]$$

Rate of loss is proportional to **square of particle charge**.

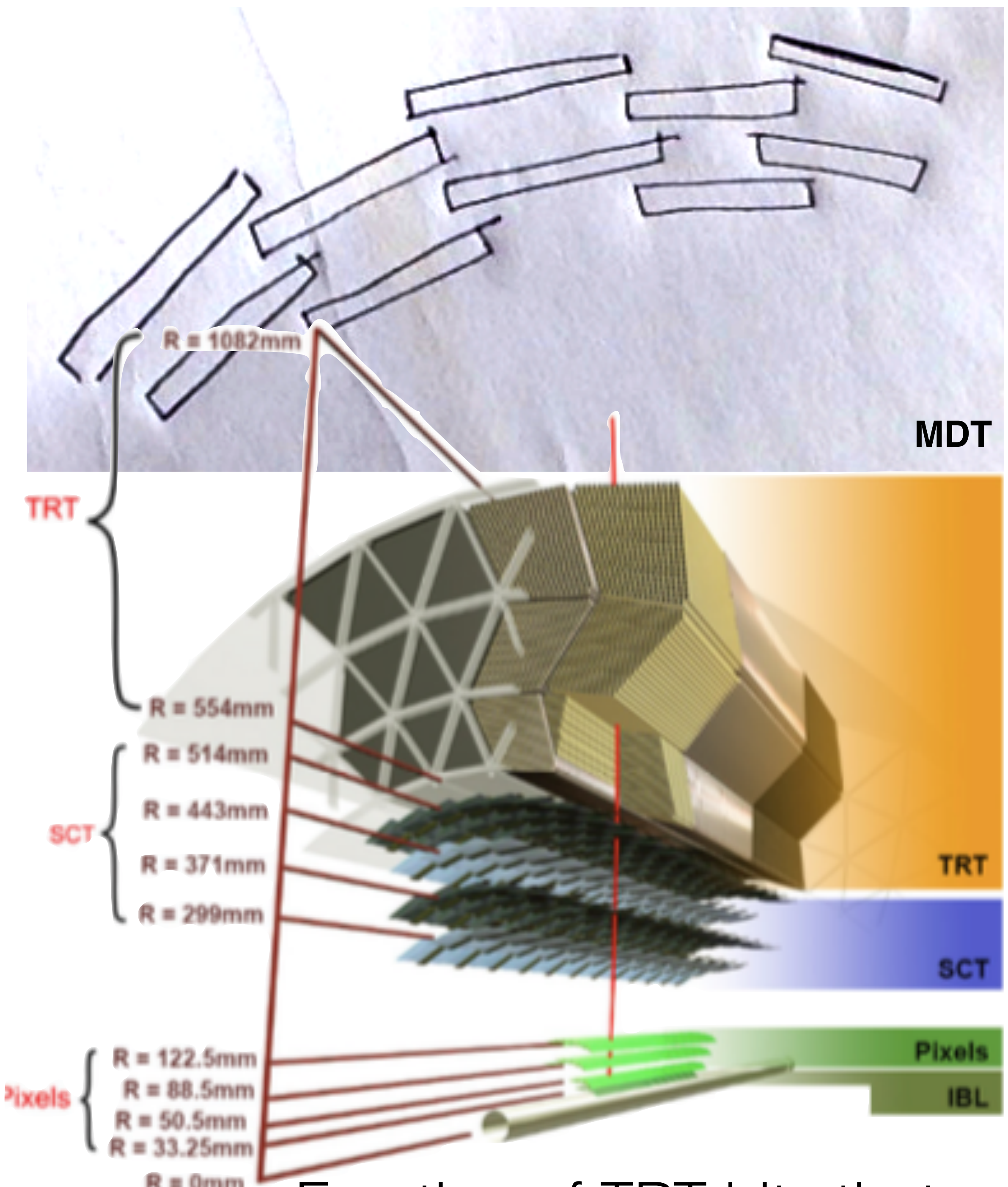
Mild dependence on other factors (e.g. more loss at low β).

So, build search for highly charged* particles from $\left\langle \frac{dE}{dx} \right\rangle$.

* and/or slow particles, so long as still “in-time”.

dE/dx "significance", S, and $\mathrm{TRT}\ f^{\mathrm{HT}}$

$$S = \frac{(\text{value of } \frac{dE}{dx} \text{ measured for candidate track}) - (\text{expected } \frac{dE}{dx} \text{ for a muon track of similar } p_T)}{(\text{typical resolution for muon track } \frac{dE}{dx} \text{ measurements})}$$



$$\boxed{S = \frac{\frac{dE}{dx} - \mu}{\sigma}}$$

Each part of ***S*** above has a value that depends on the part of the detector it was measured in. So have three variants of ***S***.

S_{MDT}, S_{TRT} — used in `**final selection**' for **background** estimation

S_{Pixels}, $\mathrm{TRT}\ f^{\mathrm{HT}}$ — define `**tight**' selection $\begin{cases} z = 2 \\ z \geq 3 \end{cases}$

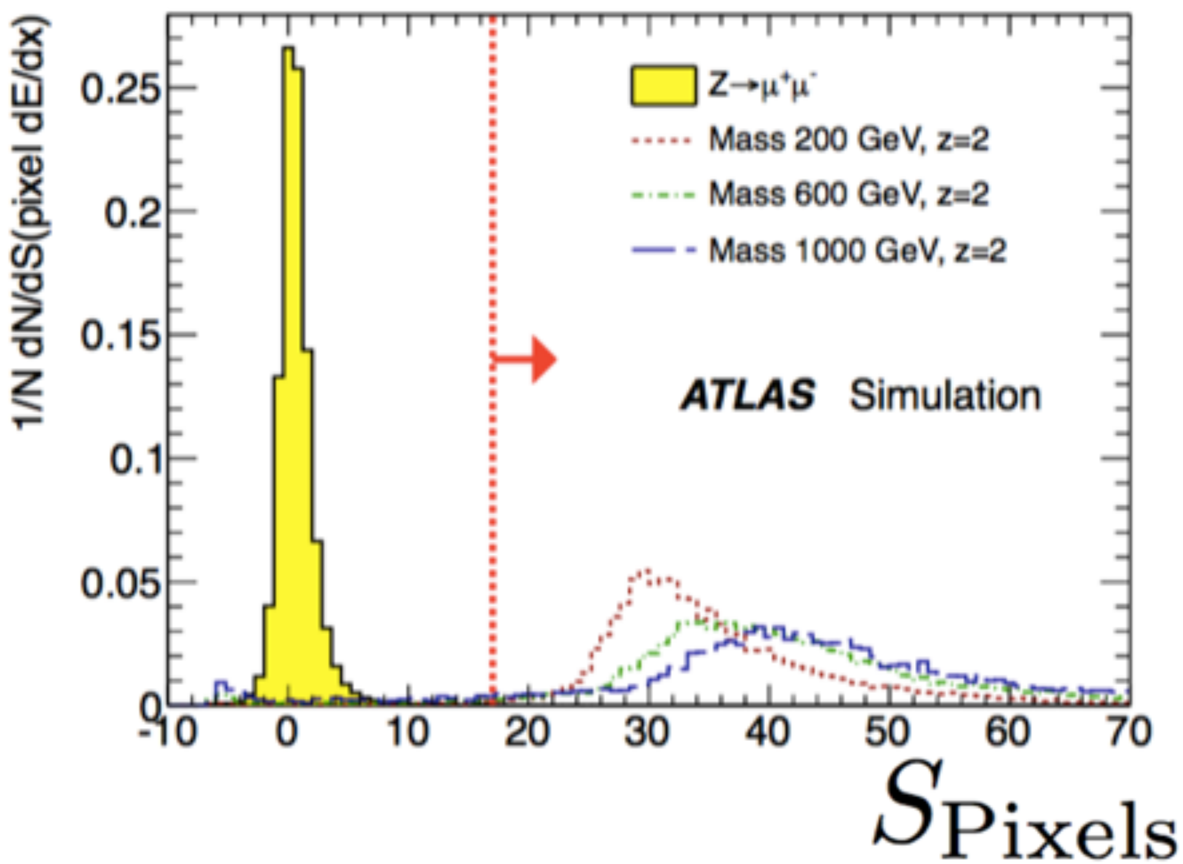
Fraction of TRT hits that are above the "High Threshold"

		Trigger and event selection	Candidate track selection	Tight and final selections ($z = 2$)	Tight and final selections ($z \geq 3$)
Requirements	Single-muon trigger case	≥ 1 trigger tight muon with $p_T/z > 36$ GeV ≥ 1 reconstructed muon with $p_T/z > 75$ GeV	Any muon with: $N_{\text{MDT hits}} \geq 7$ $p_T/z > 40$ GeV $\lvert\eta\rvert < 2.0$ $N_{\text{SCT hits}} \geq 6$ $N_{\text{TRT hits}} \geq 10$ $\lvert d_0\rvert < 1.5$ mm $\lvert z_0 \sin\theta\rvert < 1.5$ mm no other tracks within $\Delta R < 0.01$	Event passing preselection having a muon with:	Event passing preselection having a muon with:
				$S(\text{pixel } dE/dx) > 17$	$f^{HT} > 0.45$
	E_T^{miss} trigger case	trigger $E_T^{miss} > 80$ GeV ≥ 1 reconstructed muon with $p_T/z > 60$ GeV	Any muon with: $N_{\text{MDT hits}} \geq 7$ $p_T/z > 30$ GeV $\lvert\eta\rvert < 2.0$ $N_{\text{SCT hits}} \geq 6$ $N_{\text{TRT hits}} \geq 10$ $\lvert d_0\rvert < 1.5$ mm $\lvert z_0 \sin\theta\rvert < 1.5$ mm no other tracks within $\Delta R < 0.01$	$S(\text{MDT } dE/dx) > 5$ $S(\text{TRT } dE/dx) > 5$	$S(\text{MDT } dE/dx) > 7.2$ $S(\text{TRT } dE/dx) > 6$

`Tight' Selection

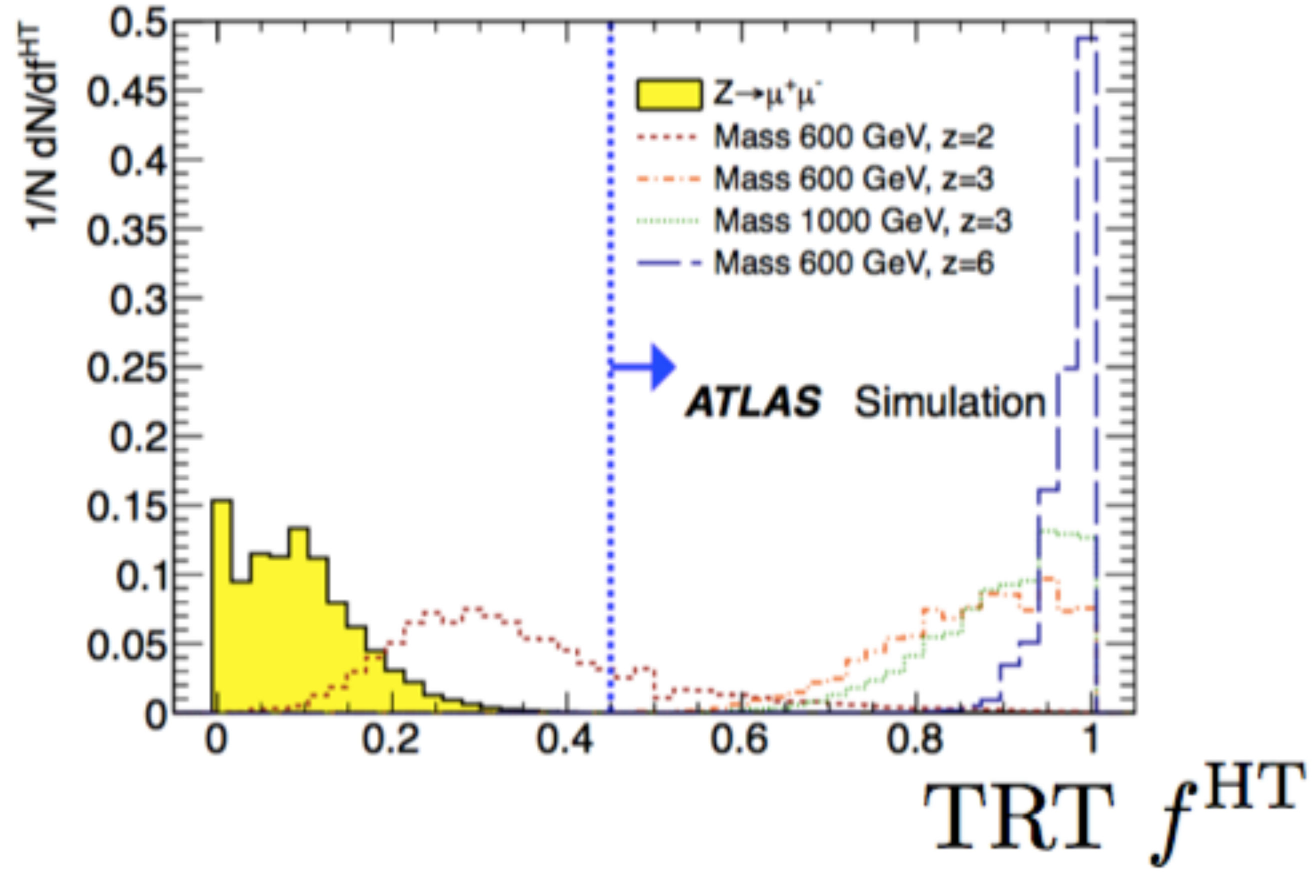
`Final' Selection

Tailoring search to size of charge



`Tight' Selection

$z = 2$

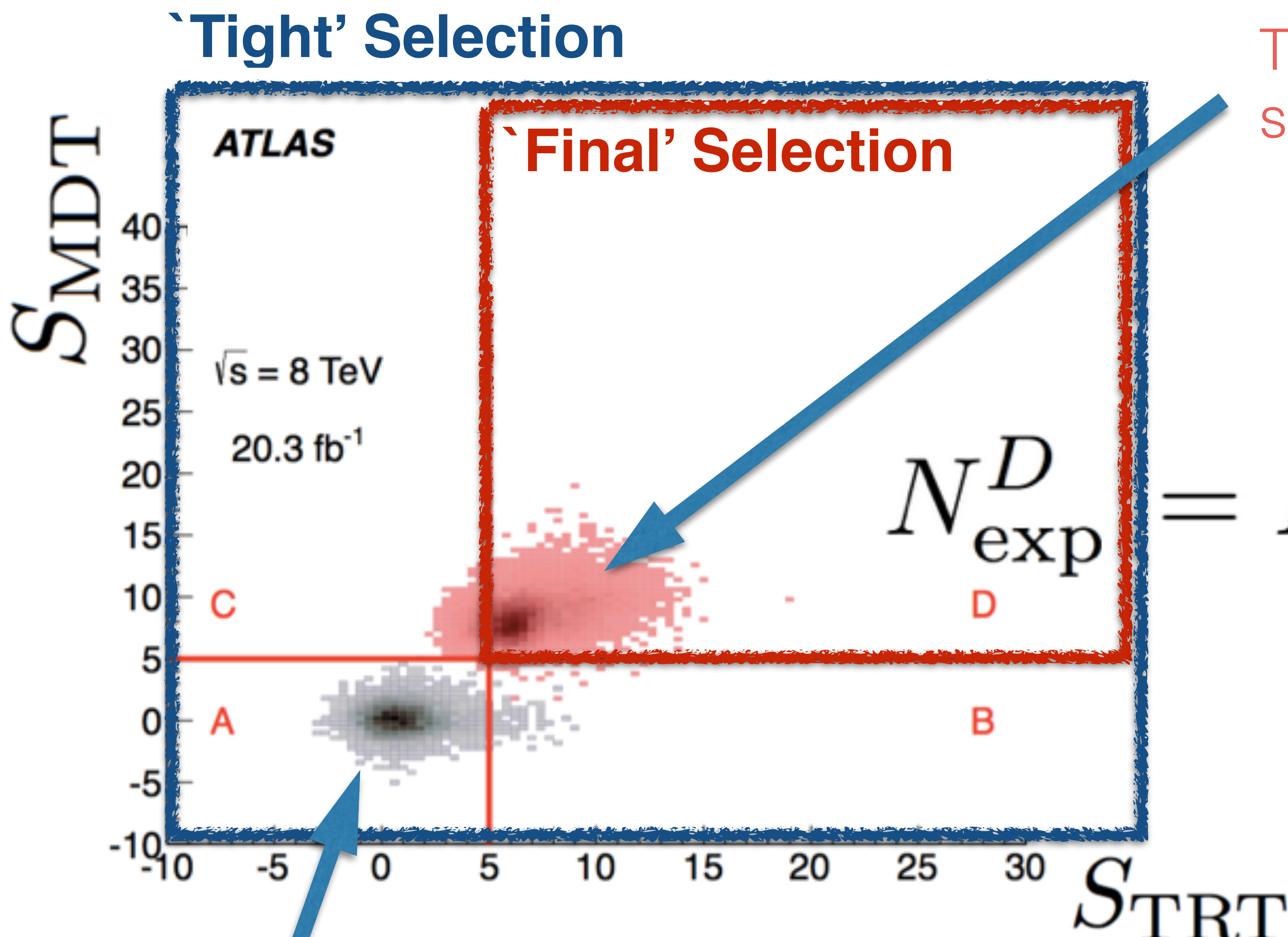


`Tight' Selection

$z \geq 3$

S_{Pixels} is a powerful discriminator for particles with z = 2. The tight signal region is defined to be the region with significance greater than 17. For higher values of z, the pixel readout saturates and the charge information for a particular pixel is lost. Therefore, to search for particles with z ≥ 3, $\mathrm{TRT}\ f^{\mathrm{HT}}$ is used as a discriminating variable instead.

How may uninteresting events are expected to pass final selection?



Tracks from potential signal with mass 600 GeV and z=2

Data tracks passing tight selection

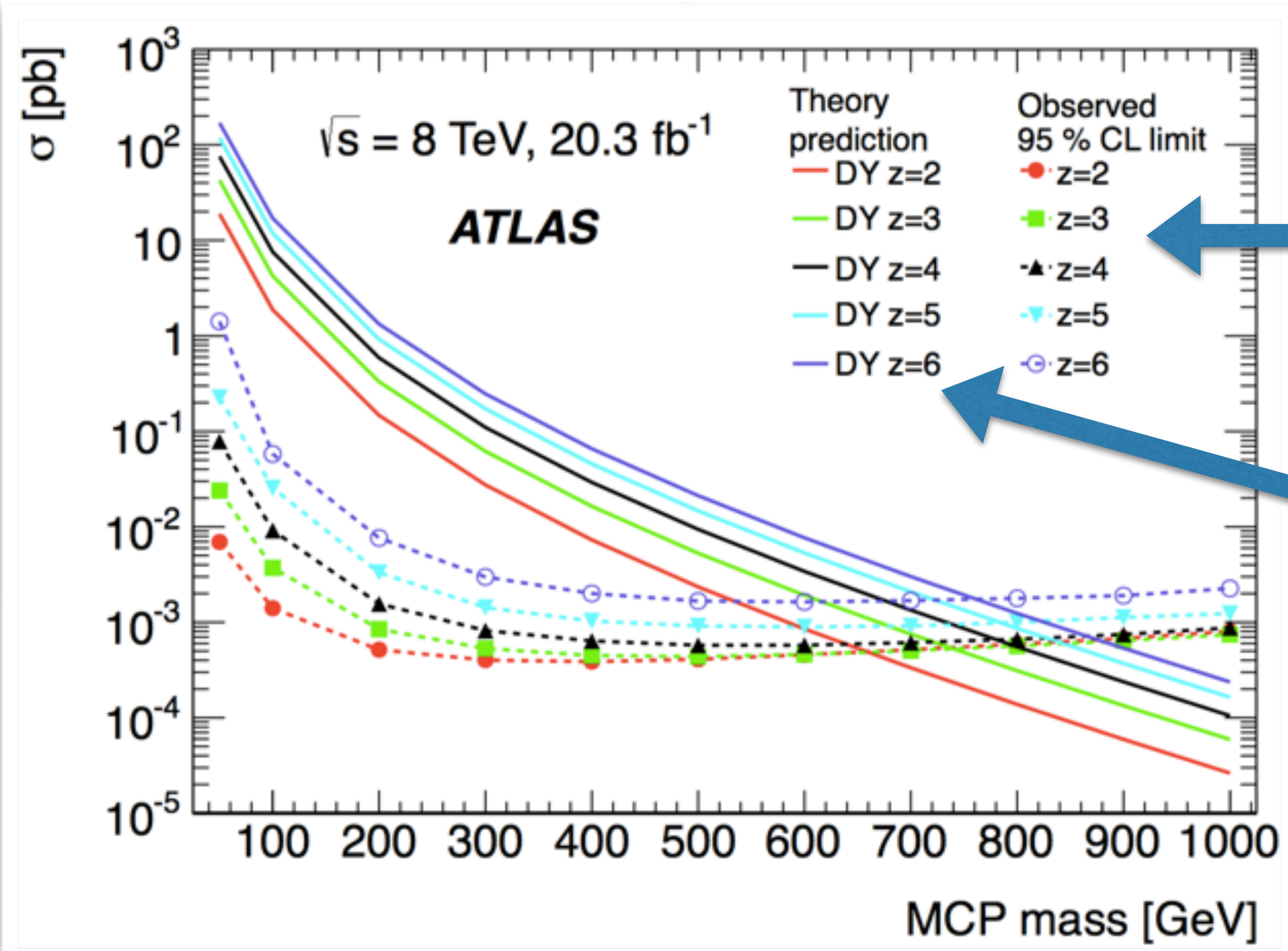
$$N^{D}_{\mathrm{exp}} = N^{B}_{\mathrm{obs}} \cdot f^{C/A}_{\mathrm{preselection}}$$

	$N^{\mathrm{B}}_{\mathrm{obs}}$	f	$N^{\mathrm{D}}_{\mathrm{exp}}$
$z = 2$	76	1.8×10^{-4}	0.013 ± 0.002
$z \geq 3$	1251	2.1×10^{-5}	0.026 ± 0.003

Alas, no events seen!

	$N^{\mathrm{D}}_{\mathrm{exp}}$	$N^{\mathrm{D}}_{\mathrm{obs}}$
$z = 2$	0.013±0.002	0
$z \geq 3$	0.026±0.003	0

So, limits are set:



$$z = \left| \frac{\text{charge of MCP}}{\text{charge of electron}} \right|$$

"**Theory prediction**" assumes a purely electromagnetic coupling, proportional to the electric charge of the MCPs. In this model, MCPs are produced in pairs via the Drell–Yan (DY) process, with only photon exchange included.

Theoretical cross-sections, and observed 95%-confidence upper limits on cross-sections for MCP (multi-charged particle) production.

Curves are shown as functions of the mass of the MCP for values of z between 2 and 6.

Present and Future

Run I, 8 TeV analysis excludes MCP masses below 650-800 GeV (charge dependent):

|q|	Mass limits [GeV]
2e	50-660
3e	50-740
4e	50-780
5e	50-785
6e	50-760

Run II at 13 TeV:

- for same mass, MCPs tend to be faster in 13 TeV running compared to 8 TeV so expect gain in muon trigger efficiency,
- late-muon trigger (2017?),
- insertable B-Layer installed.

Preliminary sensitivity estimates with 2015 and 2016 projected datasets indicate limits could be in range 900-1100 GeV (charge dependent).

ATLAS search for particles with charges from 10e to 60e

Phys. Rev. D 93, 052009 (2016)

arXiv:1509.08059

Run-I, 8 TeV, 7/fb

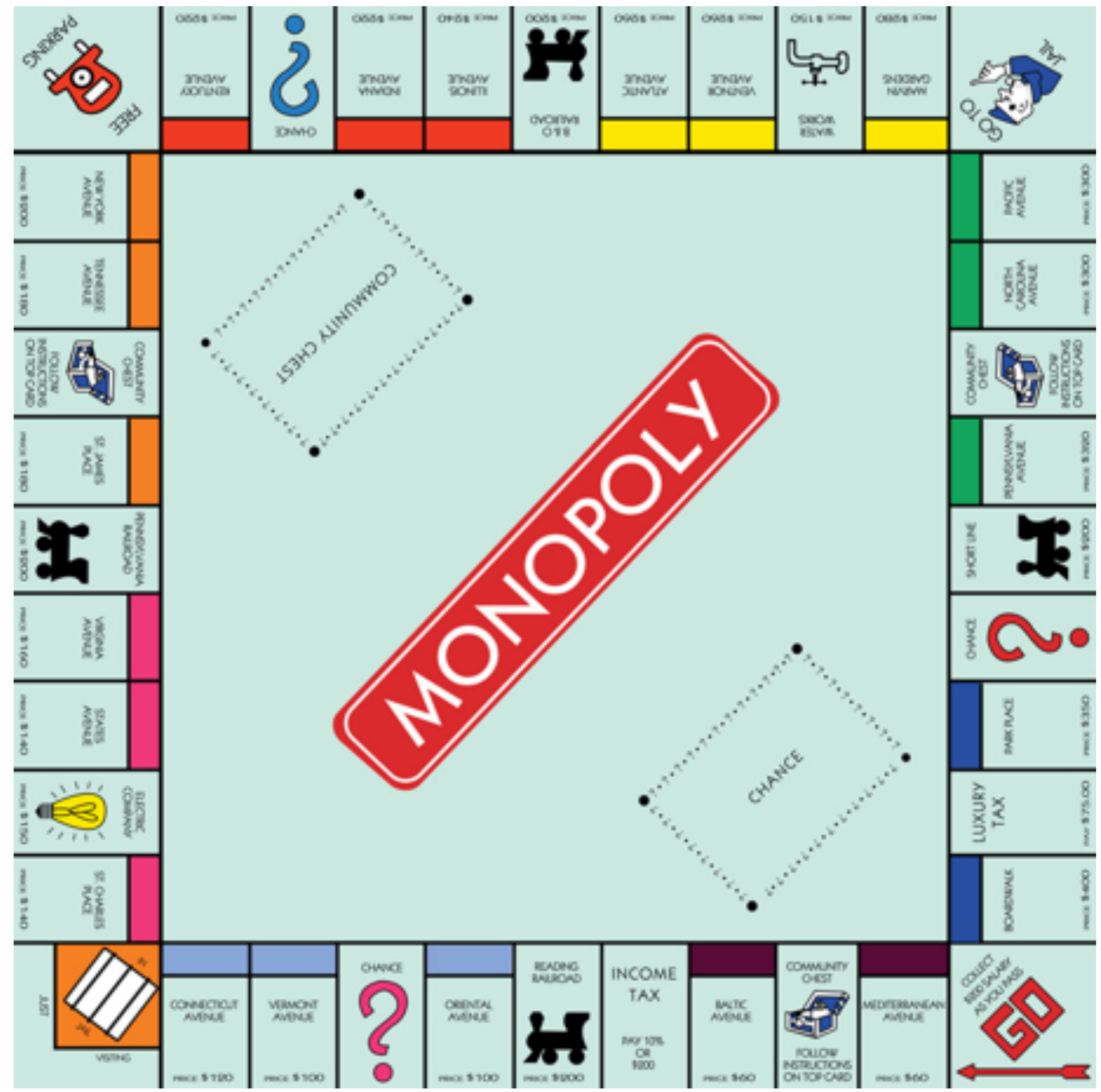
ATLAS search for particles with charges from ~~10e to 60e~~ Monopoles

Phys. Rev. D 93, 052009 (2016)

arXiv:1509.08059

Run-I, 8 TeV, 7/fb

… not these …



Magnetic Monopoles

Dirac condition:* $$e \cdot g_D = \frac{1}{2}\hbar c$$

Equivalently: $$g_D = \frac{e}{2\alpha} \approx \frac{137e}{2} = 68.5e$$

Moving **electric charge** creates **magnetic fields** in addition to its own **electric field**.
Moving **magnetic monopole** creates **electric fields** in addition to its own **magnetic field**.
(necessitates modified Bethe-Bloch to account for velocity dependent Lorentz force, monopole acceleration in ID solenoid magnetic field)

Nonetheless: to first order Monopoles traversing matter look like VERY HIGHLY CHARGED particles creating a lot of ionisation.

Q-balls? Strange matter? Stable Black Hole Remnants?

* (given some unspecified assumptions about units and the size of the smallest quanta of electric charge)

Can’t use previous search:

Super highly charged particles will not traverse much of the detector.

Ionisation losses will bring them to a halt!

Instead, must look for:

- significant ionisation in TRT
- large energy deposit in first layer of E-M calorimeter
- little energy deposited further out
- little `energy dispersion' (w)

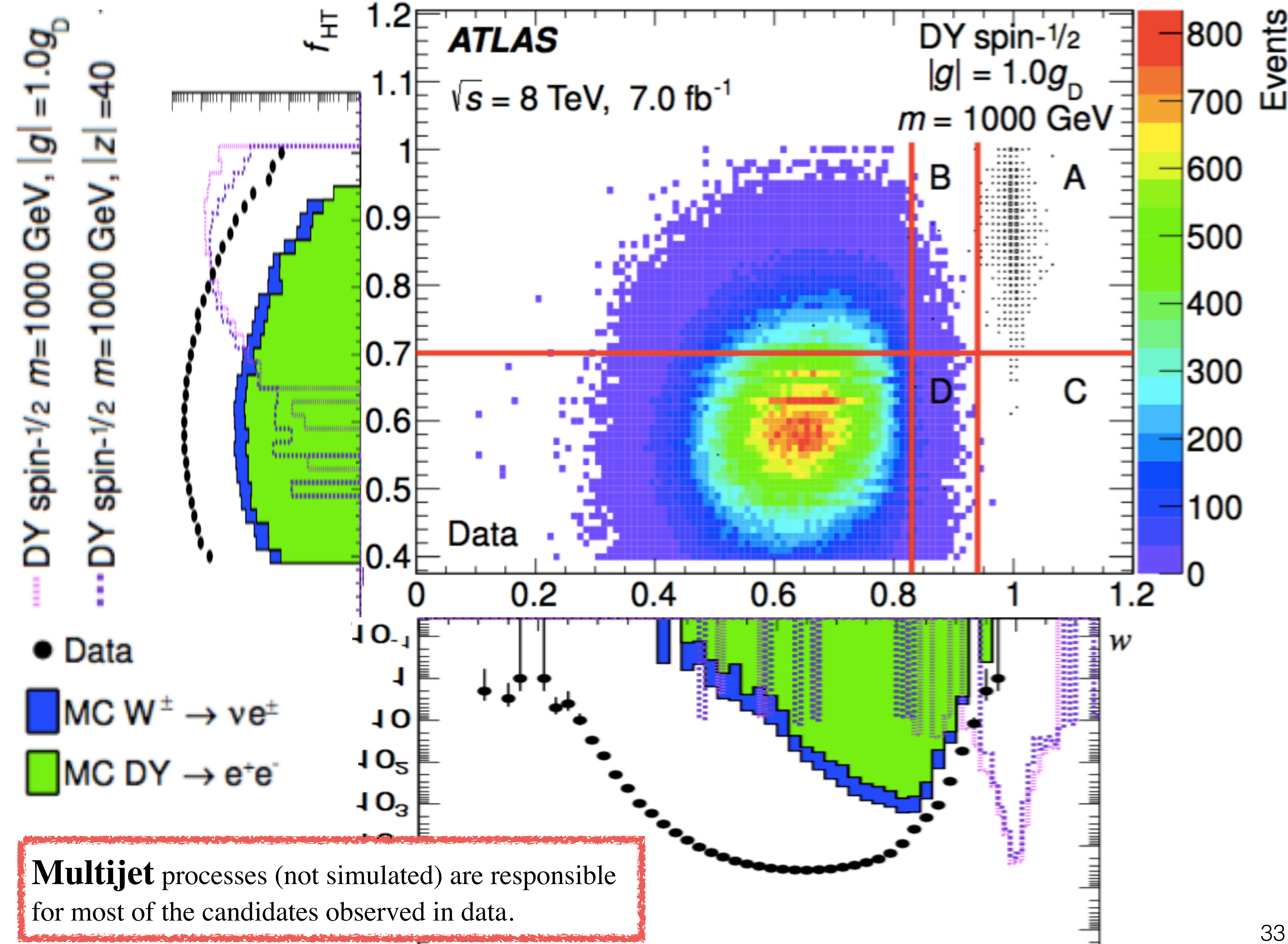
Bremsstrahlung and electron-positron pair creation is negligible for “heavily ionising particle” (HIP) so expect energy deposit in eCal to be narrower than from electron or photon.

Dedicated HIP trigger

ATLAS developed dedicated “stopping HIP” trigger for 8 TeV running.

Trigger “fires” if Region-of-Interest has:

- 18-20 GeV in first layer of E-M Calorimeter
- less than 1 GeV in hadron Calorimeter
- at least 20 high-threshold TRT hits
- at least 1/3 of TRT hits being high-threshold



Multijet processes (not simulated) are responsible for most of the candidates observed in data.

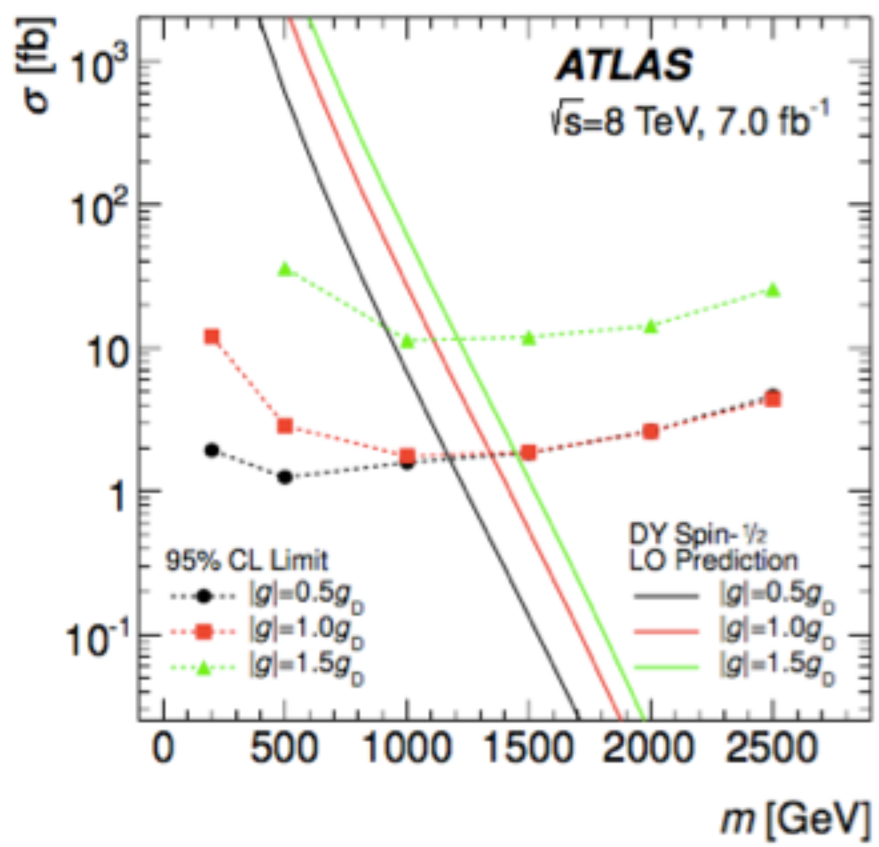
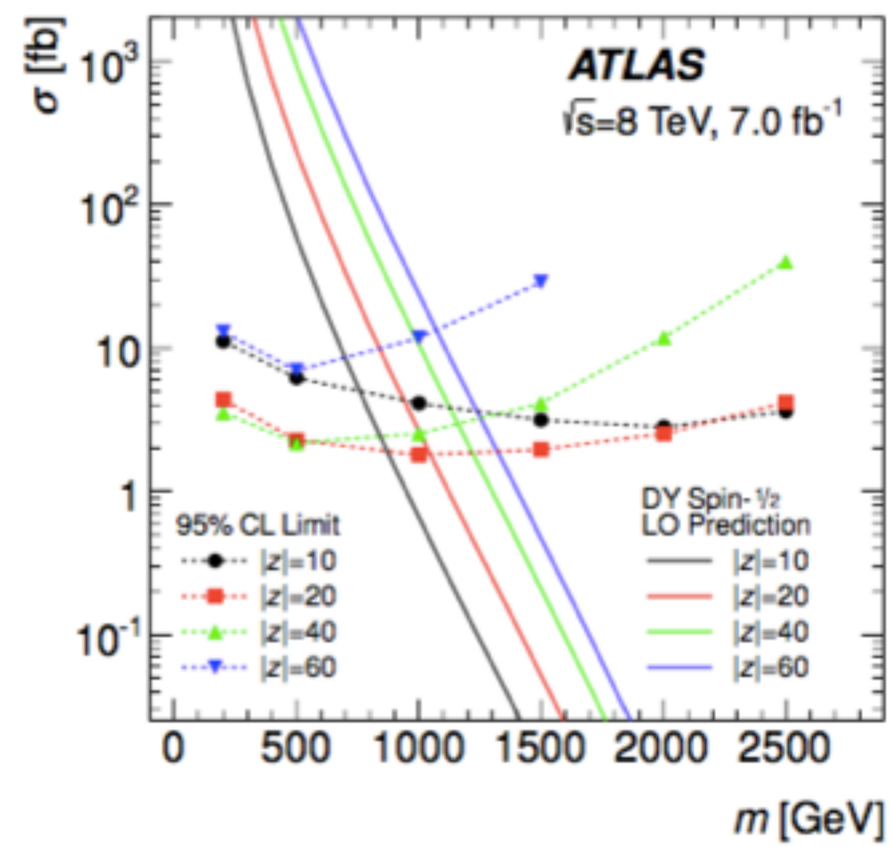
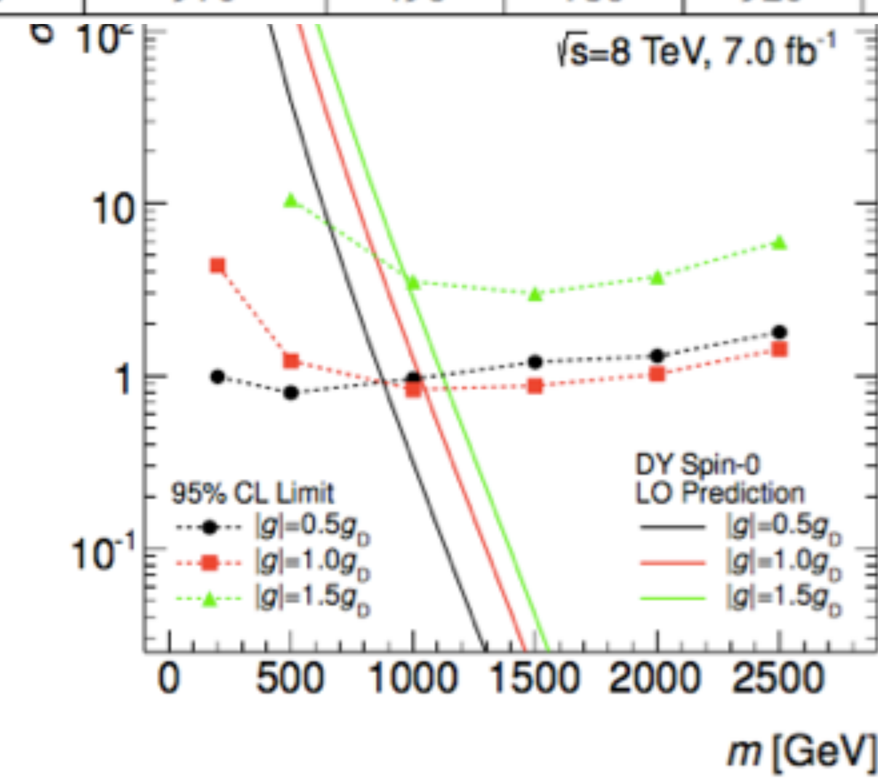
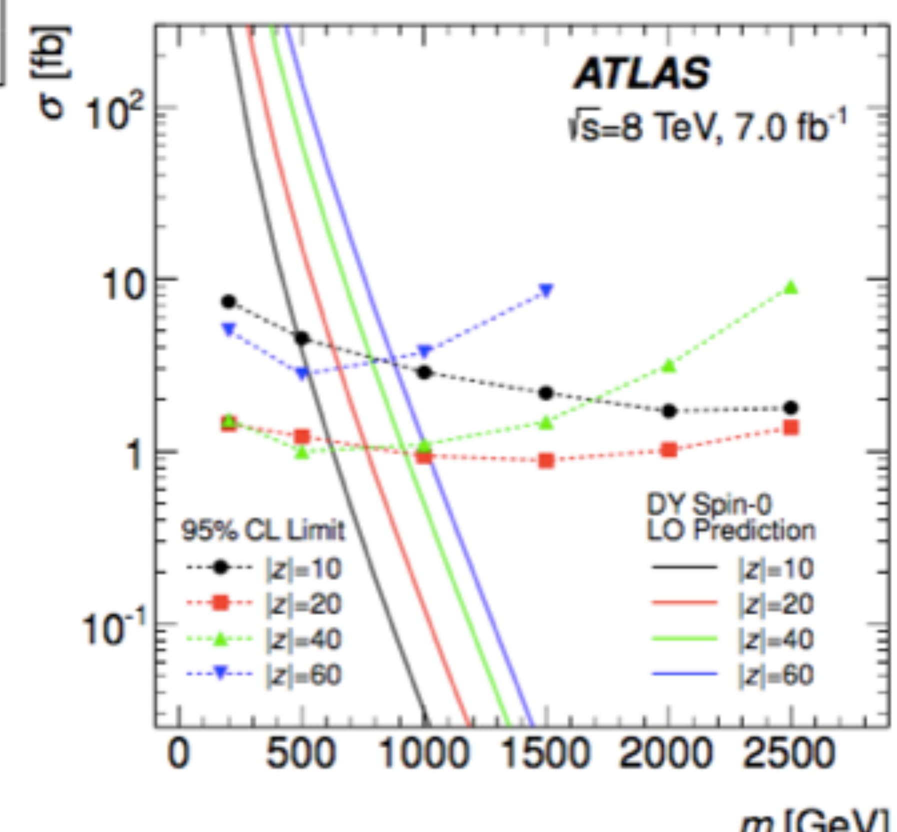
Alas, no event seen!

	Events in signal region
Expected	0.41 ± 0.24 (stat.) ± 0.16 (syst.)
Observed	0

(again)

This results in an upper limit on the number of signal events of 3.0 at 95% confidence level in the data sample.

95% CL CROSS SECTION LIMITS

	Magnetic Monopole	Generic HIP
Spin-1/2 HIP		
Spin-0 HIP		

	Drell-Yan Lower Mass Limits [GeV]						
	$\lvert g\rvert = 0.5g_D$	$\lvert g\rvert = 1.0g_D$	$\lvert g\rvert = 1.5g_D$	$\lvert z\rvert = 10$	$\lvert z\rvert = 20$	$\lvert z\rvert = 40$	$\lvert z\rvert = 60$
spin-1/2	1180	1340	1210	780	1050	1160	1070
spin-0	890	1050	970	490	780	920	880

Future monopole plans

- Run-II (13 TeV) work is in progress
- Hope to address electric charges up to 100e and magnetic charges up to 3 g_D


Also not found in ATLAS

The End

Fort Saint George pub in
Cambridge (UK).
Built in 16th Century.

150% older than Chicago,
but a lot smaller.

Back up slides

Electron channel	$t\bar{t}$ CR	W+jets CR	Z+jets CR	VR
Observed events	1201	3660	541	435
Fitted bkg events	1196 ± 34	3660 ± 60	558 ± 22	417 ± 24
Fitted $t\bar{t}$ events	990 ± 40	440 ± 80	2.97 ± 0.33	74 ± 12
Fitted W+jets events	37 ± 12	2090 ± 160	0.0 ± 0.0	147 ± 14
Fitted Z+jets events	11.3 ± 1.7	137 ± 19	515 ± 21	59 ± 4
Fitted single-top-quark events	76 ± 11	65 ± 11	0.17 ± 0.05	18.2 ± 2.3
Fitted diboson events	12.0 ± 2.4	257 ± 22	39.4 ± 3.5	42 ± 4
Fitted multijet events	70 ± 60	670 ± 130	0.0 ± 0.0	76 ± 19
MC exp. SM events	1210 ± 100	4190 ± 280	560 ± 40	480 ± 40
MC exp. $t\bar{t}$ events	1040 ± 70	460 ± 50	3.17 ± 0.24	103 ± 15
MC exp. W+jets events	45 ± 13	2630 ± 140	0.0 ± 0.0	183 ± 10
MC exp. Z+jets events	11.1 ± 1.5	141 ± 20	510 ± 40	58 ± 4
MC exp. single-top-quark events	78 ± 15	65 ± 14	0.18 ± 0.07	18.5 ± 3.3
MC exp. diboson events	12.1 ± 2.6	260 ± 30	40 ± 5	42 ± 5
Pre-fit multijet events	$27\ ^{+36}_{-27}$	630 ± 200	0.0 ± 0.0	76 ± 29

Muon channel	$t\bar{t}$ CR	W+jets CR	Z+jets CR	VR
Observed events	1010	2714	588	278
Fitted bkg events	1016 ± 31	2720 ± 50	572 ± 22	300 ± 18
Fitted $t\bar{t}$ events	910 ± 34	380 ± 70	3.01 ± 0.33	64 ± 10
Fitted W+jets events	25 ± 5	1910 ± 110	0.0 ± 0.0	131 ± 12
Fitted Z+jets events	6.8 ± 0.8	150 ± 32	529 ± 21	53 ± 5
Fitted single-top-quark events	68 ± 10	57 ± 10	0.18 ± 0.05	16.1 ± 2.1
Fitted diboson events	6.9 ± 1.6	223 ± 22	40.2 ± 3.4	35 ± 4
MC exp. SM events	1080 ± 70	3250 ± 170	540 ± 40	362 ± 27
MC exp. $t\bar{t}$ events	960 ± 60	400 ± 50	3.23 ± 0.25	89 ± 13
MC exp. W+jets events	31 ± 4	2400 ± 100	0.0 ± 0.0	165 ± 12
MC exp. Z+jets events	6.8 ± 0.8	160 ± 40	501 ± 35	55 ± 5
MC exp. single-top-quark events	70 ± 14	58 ± 13	0.16 ± 0.06	16.9 ± 3.1
MC exp. diboson events	7.2 ± 2.1	232 ± 29	39 ± 4	37 ± 5

	SR-2TeV (electron)	SR-2TeV (muon)	SR-3TeV (electron)	SR-3TeV (muon)
Observed events	123	69	11	2
Fitted bkg events	104 ± 9	78 ± 6	4.6 ± 0.8	5.3 ± 1.2
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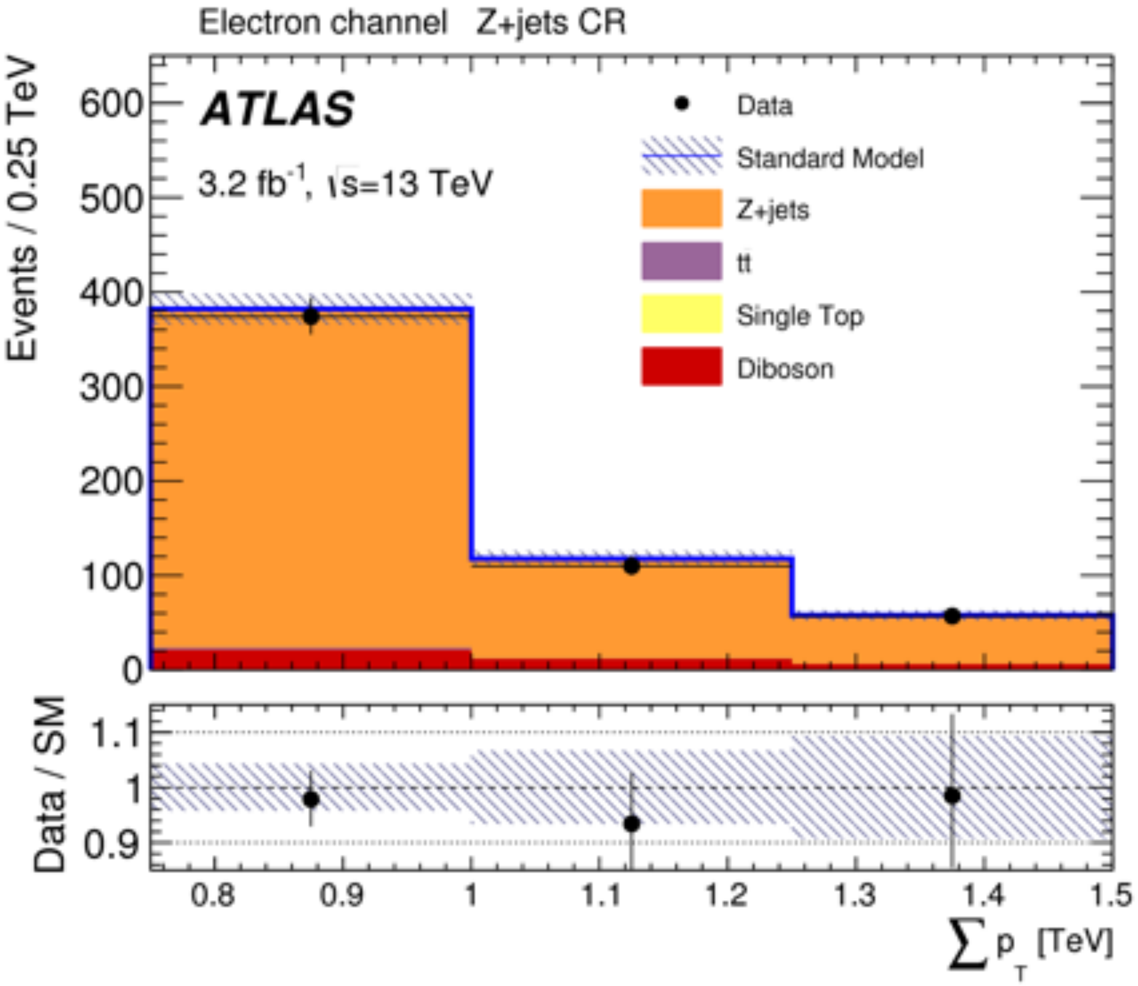
Fitted W+jets events	32.0 ± 3.5	33.9 ± 3.2	1.76 ± 0.31	2.0 ± 0.4
Fitted Z+jets events	16.6 ± 1.5	12.6 ± 1.4	1.09 ± 0.18	0.77 ± 0.24
Fitted single-top-quark events	6.1 ± 0.9	5.2 ± 0.7	0.59 ± 0.18	0.54 ± 0.14
Fitted diboson events	11.4 ± 1.4	14.5 ± 1.5	0.22 ± 0.18	1.5 ± 0.5
Fitted multijet events	24 ± 7	0.0 ± 0.0	0.32 ± 0.24	0.0 ± 0.0
MC exp. SM events	122 ± 15	95 ± 9	5.5 ± 1.1	6.9 ± 1.6
MC exp. $t\bar{t}$ events	22 ± 5	18 ± 4	1.07 ± 0.30	0.87 ± 0.23
MC exp. W+jets events	40.6 ± 3.5	43.6 ± 3.3	2.2 ± 0.4	2.7 ± 0.6
MC exp. Z+jets events	16.6 ± 1.6	13.1 ± 1.3	1.09 ± 0.19	0.91 ± 0.31
MC exp. single-top-quark events	6.4 ± 1.3	5.4 ± 1.0	0.58 ± 0.21	0.61 ± 0.17
MC exp. diboson events	12.1 ± 1.9	14.7 ± 1.9	0.36 ± 0.24	1.8 ± 0.5
Pre-fit multijet events	24 ± 10	0.0 ± 0.0	$0.19\,^{+0.24}_{-0.19}$	0.0 ± 0.0


Electron channel Z+jets CR
ATLAS
3.2 fb-1, √s=13 TeV
Data
Standard Model
Z+jets
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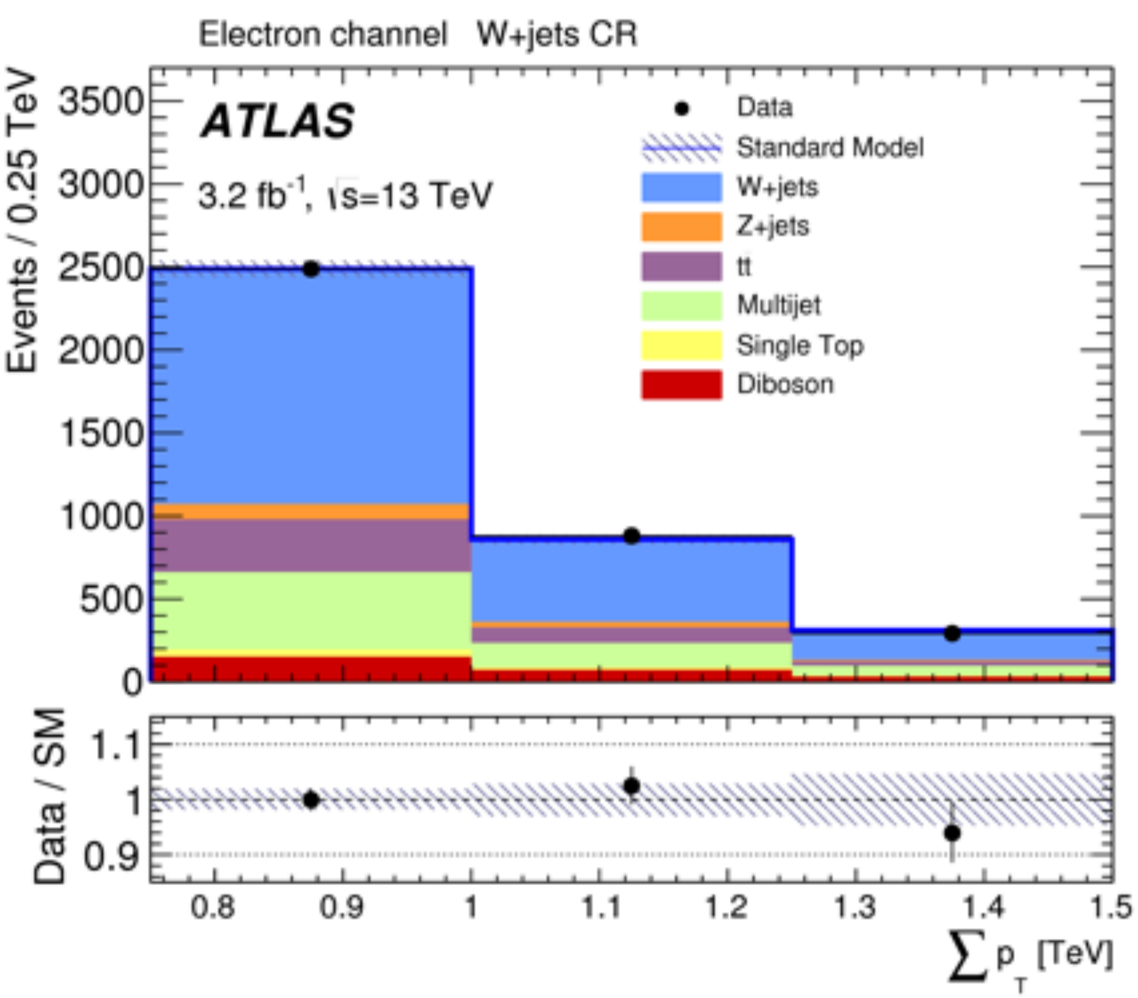
Single Top
Diboson
Events / 0.25 TeV
Data / SM
∑ pT [TeV]


Electron channel W+jets CR
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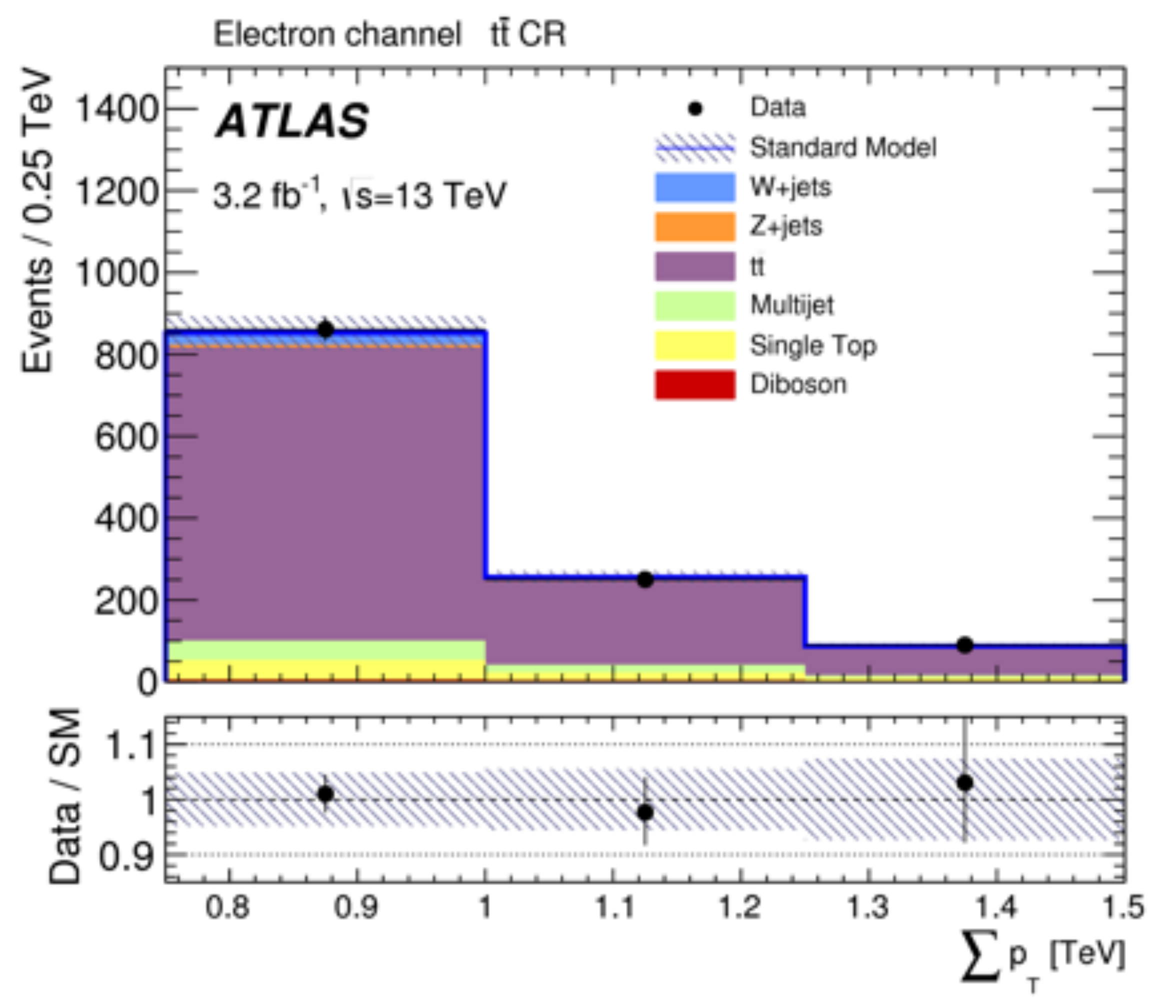
∑ pT [TeV]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Multijet
Single Top
Diboson
Events / 0.25 TeV
Data / SM
∑ pT [TeV]

World beater or planet eater? ... experiment will cause black holes some fear could destroy the planet

By PAUL SUTHERLAND
Sun Spaceman

Published: 01 Sep 2008

ADD YOUR COMMENTS

SCIENTISTS are trying to stop the most powerful experiment ever – saying the black holes it will create could destroy the world.

Dubbed by some the Doomsday test, it will be carried out next week in the Large Hadron Collider (LHC), located 300ft underground near the French-Swiss border.

The machine is 17 miles long and cost £4.4billion to create.

When its switch is pulled on September 10, this atom-smasher will become a virtual time machine, revealing what happened when the universe came into existence 14 billion years ago.

New particles of matter are expected to be discovered, new dimensions found beyond the four known, as scientists re-create conditions in the first **BILLIONTHS** of a second after the Big Bang.

Don't panic, there's time to try out every position in the Kama Sutra

WITH just nine days to go until the end of the world, here's what you could get up to before it's too late ...

1. Eat 27 Big Mac meals. Who's counting the calories?

2. Visit all seven continents.

3. Try out all 64 Kama Sutra positions.

4. Watch the entire box sets of Lost, Heroes and Prison Break.

5. Cruise the River Nile.

6. Drive to Switzerland for a ringside seat of doomsday.

Aberdeen Evening Express

Aberdeen Evening Express

September 10, 2008 Wednesday

'Doomsday machine' starts up

BYLINE: Albert Innes

SECTION: AGENCY; PA; home; Pg. 8

LENGTH: 164 words

SCIENTISTS hoping to unlock secrets of the universe today turned on a machine that some critics fear could cause the end of the world.
The £5 billion Large **Hadron Collider** (LHC) will smash protons one of the building blocks of matter - into each other at energies up to seven times greater than any achieved before.
Scientists expect to reproduce conditions that existed during the first billionth of a second after the Big Bang at the birth of the universe.
The LHC built under the Alps, could help scientists explain mass, gravity, mysterious "dark matter" and even create mini-black holes that blink in and out of existence in a fraction of a second.
But concerns have been voiced - in particular by German chemist Professor Otto Rossler - that black holes created by the LHC will grow uncontrollably and "eat the planet from the inside".
But those involved in the project insist they have reviewed all the evidence and concluded that it poses no risk to the universe.

British Press

Credits

- Some slide ideas are from Teresa Lenz.