FYST11 Lecture 12
BSM II

Thanks to G. Brooijmans, T. Rizzo, L. Covi, M. Maggiore

Lab exercise

Remember

March 2: working in groups

March 6: presenting

March 8: computer exercise

Wednesday March 8 we will meet in H321.

I will soon (?) get a list of people with accounts there from this course, will let you know

If you already have account on those machines but forgot username/pw, send an email to kurslab_admin@fysik.lu.se

Today & Monday

- Why go Beyond the SM?
  - What are the problems with the SM?
  - What direct measurements points to physics BSM
- Some attempts at solutions
  - Supersymmetry
  - Extended Higgs sector
  - Extra dimensions
  - A few others
- Searches for DM, gravitational waves

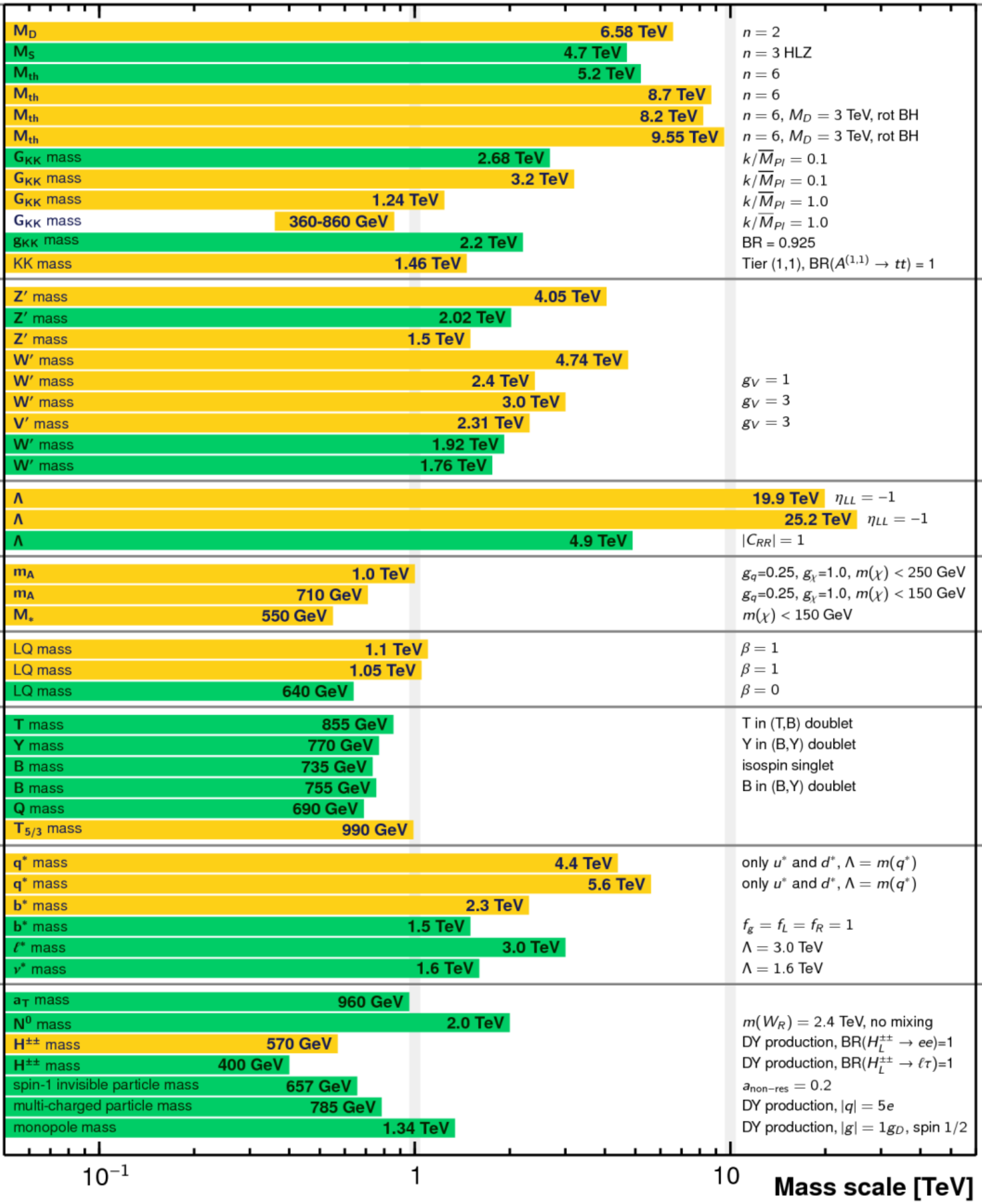
ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$

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



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	🟨 M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	🟩 M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	🟨 M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	3.2	🟨 G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	1 J	Yes	13.2	🟨 G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	–	4 b	–	13.3	🟨 G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	🟩 g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	🟨 KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \rightarrow tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	13.3	🟨 Z' mass 4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	🟩 Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	13.3	🟨 W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	🟨 W' mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model B	–	2 J	–	15.5	🟨 W' mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			3.2	🟨 V' mass 2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \rightarrow tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	🟨 Λ 19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	🟨 Λ 25.2 TeV	$\eta_{LL} = -1$	1607.03669
	CI $uutt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	🟨 m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	🟨 m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \rightarrow Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \rightarrow Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \rightarrow WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
	VLQ $T_{5/3} T_{5/3} \rightarrow WtWt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	3.2	🟨 $T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	3.2	🟨 q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \rightarrow qg$	–	2 j	–	15.7	🟨 q^* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	8.8	🟨 b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	🟩 a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow ee$	2 e (SS)	–	–	13.9	🟨 $H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

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

Parity Restoration: Signals

- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances (Z') offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with p_T
  - $t\bar{t}$ decays visible
  - ν_R is presumably heavy, W' may not decay to leptons
    - Only dijet or diboson
    - If ν_R lighter than W'/Z', ν_R decays become important
- Note: many kinds of Z' - review by Langacker

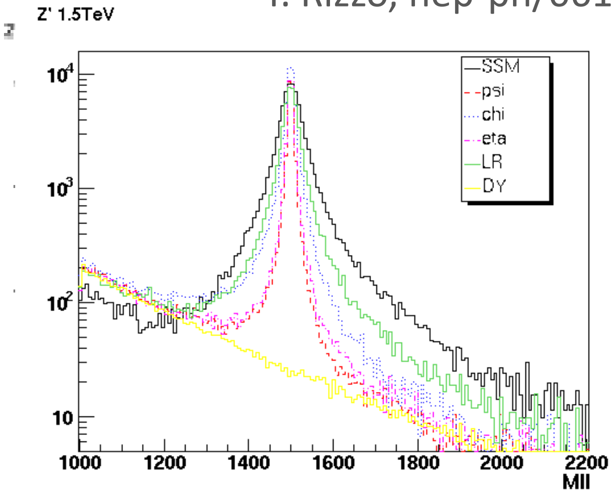
arXiv:0801.1345

  - W'/Z' would also require new fermions…

Z' Production and Decay

- Production from u, d quarks is dominant at LHC
  - Couplings vary by model
  - E.g. for LR symmetric models, $\kappa = g_R/g_L$ drives production cross-section (convolute with PDFs) and branching ratios
- Decays somewhat similar to Z (but almost no BR to light neutrinos, decays to top open up), plot assumes ν_R heavier

T. Rizzo, hep-ph/0610104



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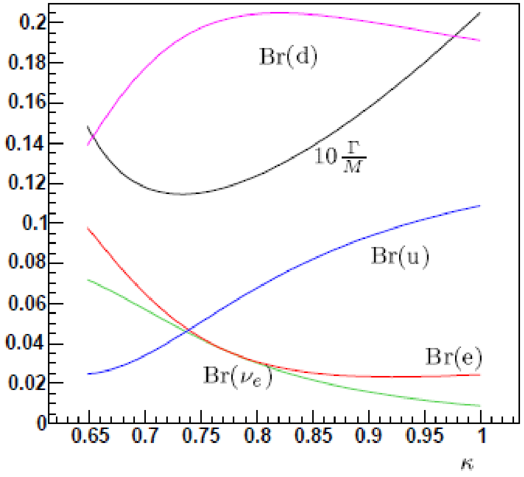
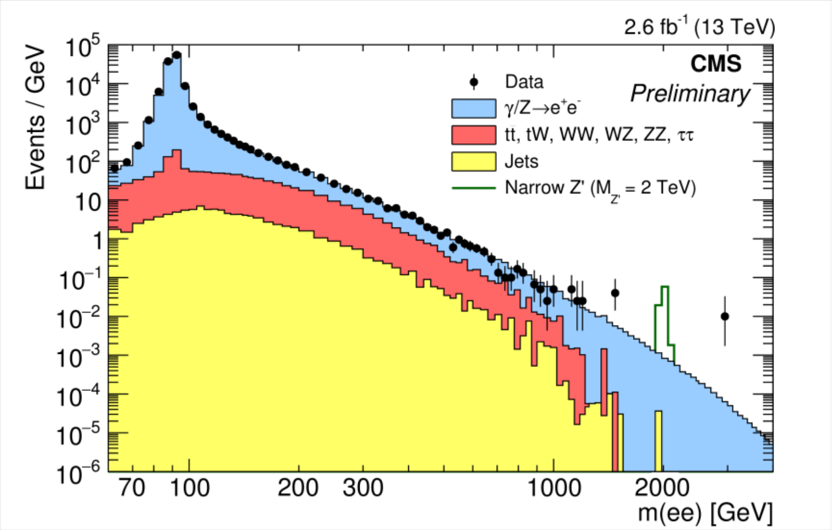
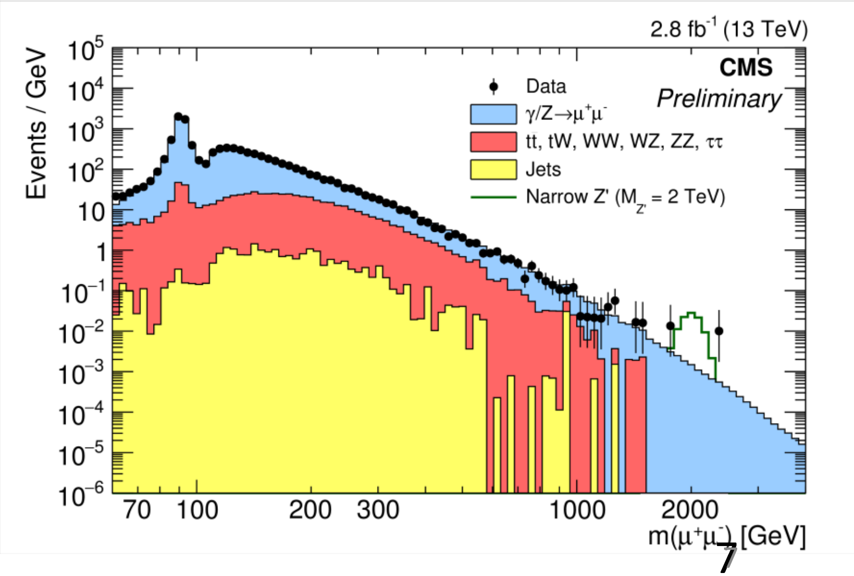


Z’ → ee/μμ

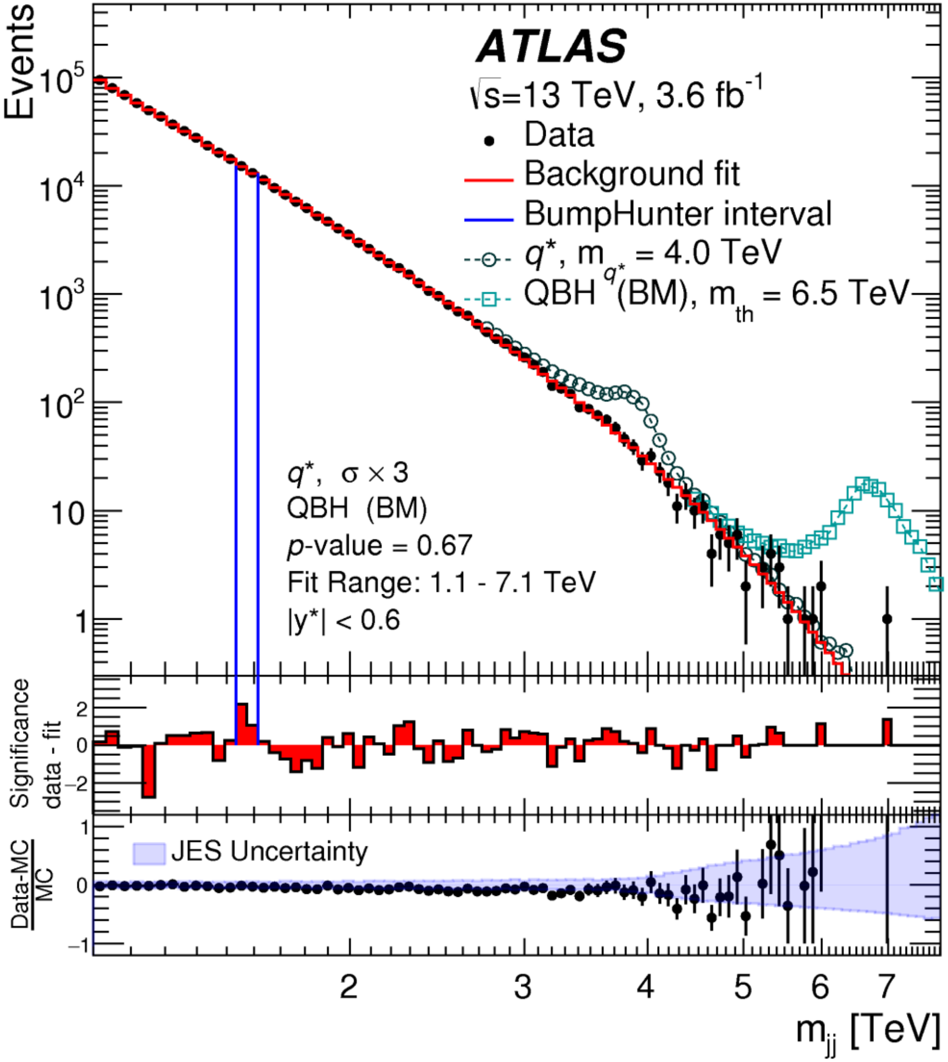
- ❖ Most promising channels:
  - Backgrounds very low!
  - “Self-calibrating”
  - In ee, at high masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
- ❖ LHC extended Tevatron reach immediately!





Dijets

- SM background obviously much larger
  - But single source
  - And opens the door to strongly interacting objects



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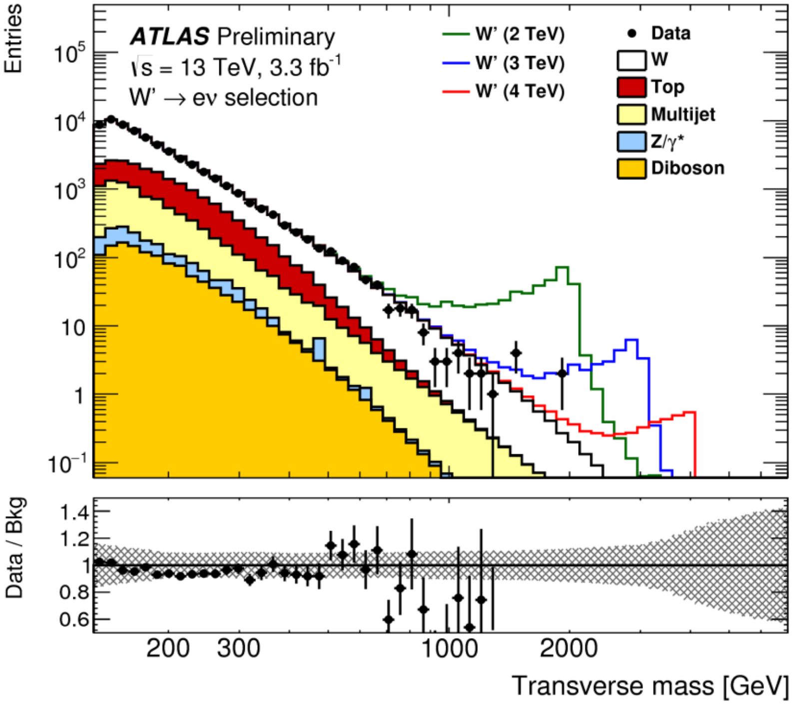
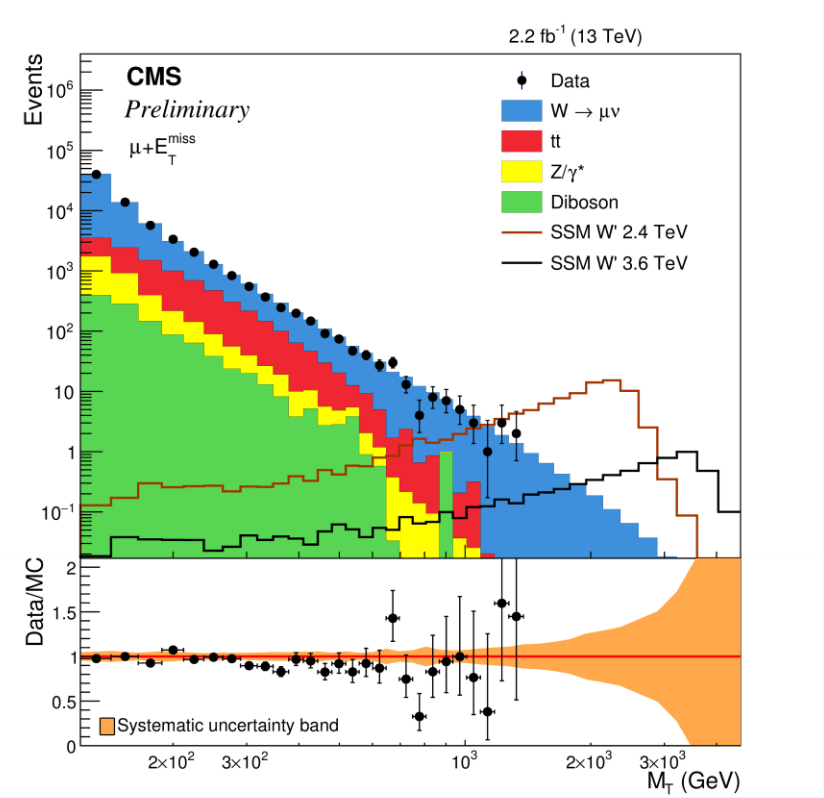
W’ →μν / eν

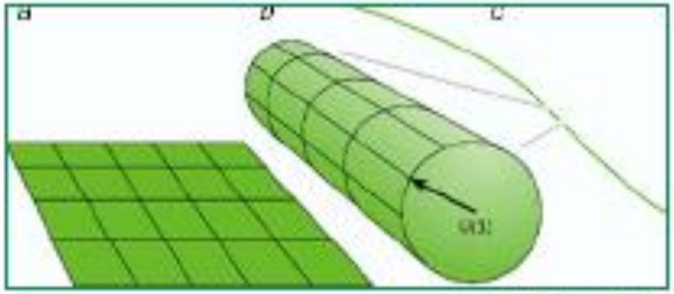
Another very simple selection: lepton + MET





Extra Dimensions

- A promising approach to quantum gravity consists in adding extra space dimensions: string theory
  - Additional space dimensions are hidden, presumably because they are compactified



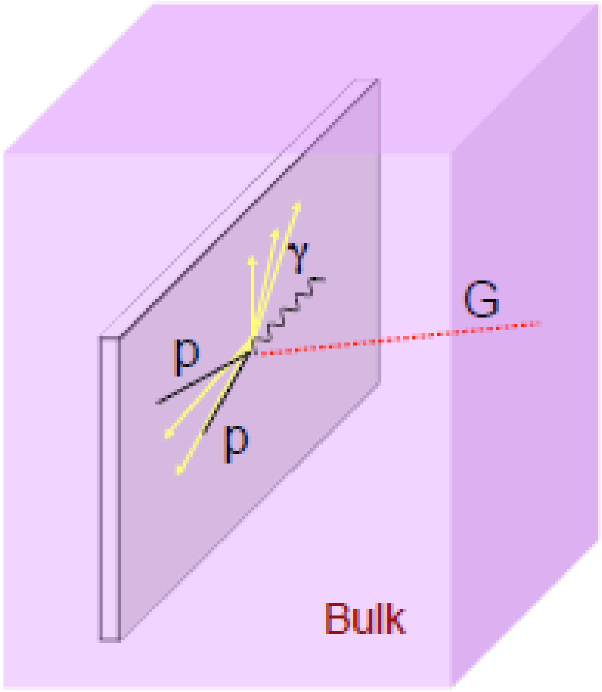
Source: PhysicsWorld

- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In '90 Antoniadis realized they may be much larger...

Phys Lett B246:377-384 1990

ADD extra dimensions

- "Large extra dimension" scenario (developed by Arkani-Hamed, Dimopoulos and Dvali): Phys.Lett. B429 (1998) 263-272
  - Standard model fields are confined to a 3+1 dimensional subspace ("brane")
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton "goes through"

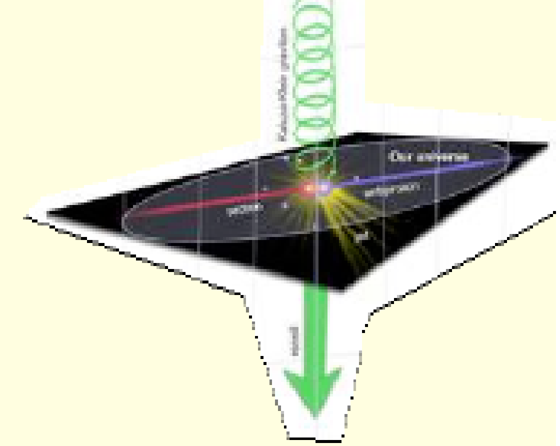


Drawing by K. Loureiro

ADD signatures

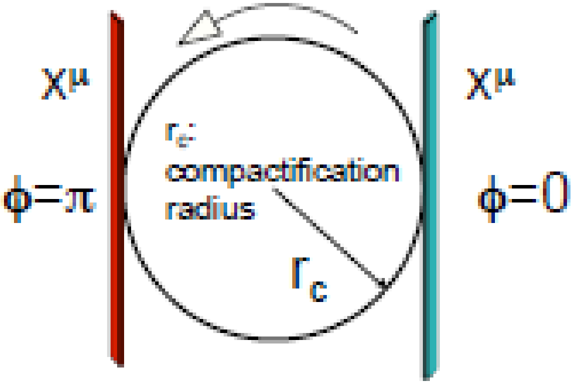
- Edges of extra dimensions identified
  - Boundary conditions
  - Momentum along extra dimension is quantized
  - Looks like mass to us
  - Very small separations → looks like continuum
  - Called Kaluza-Klein tower
- Coupling to single graviton very weak, but there are *lots* of them!
  - Large phase space → observable cross-section
    - Impacts all processes (graviton couples to energy-momentum)

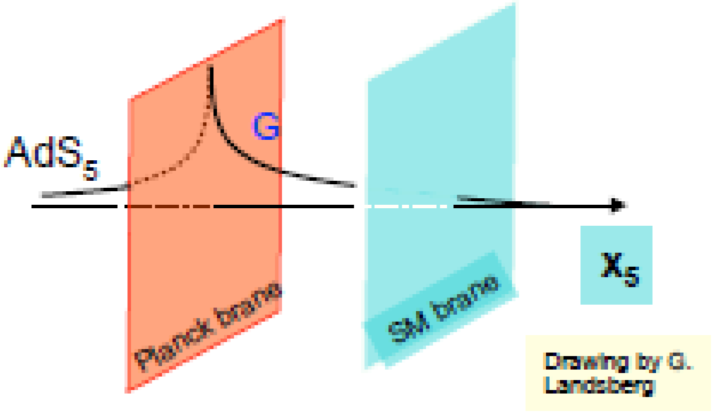
- ❖ Consider processes that involve the bulk (i.e. gravitons)
  - Translational invariance is broken
    - ➡ Momentum is not conserved ...
    - ... because graviton disappears in bulk right away
- ❖ Look for p p → jet/photon + nothing (i.e. $\not{E}_T$), or deviations in high mass/angular behavior in standard model processes
  - Graviton has spin 2, couples to energy-momentum!



Warped extra dimensions

- “Simple” Randall-Sundrum model:
  - SM confined to a brane, and gravity propagating in an extra dimension
  - As opposed to the original ADD scenario, the metric in the extra dimension is “warped” by a factor $\exp(-2kr_c\phi)$
  - (Requires 2 branes)



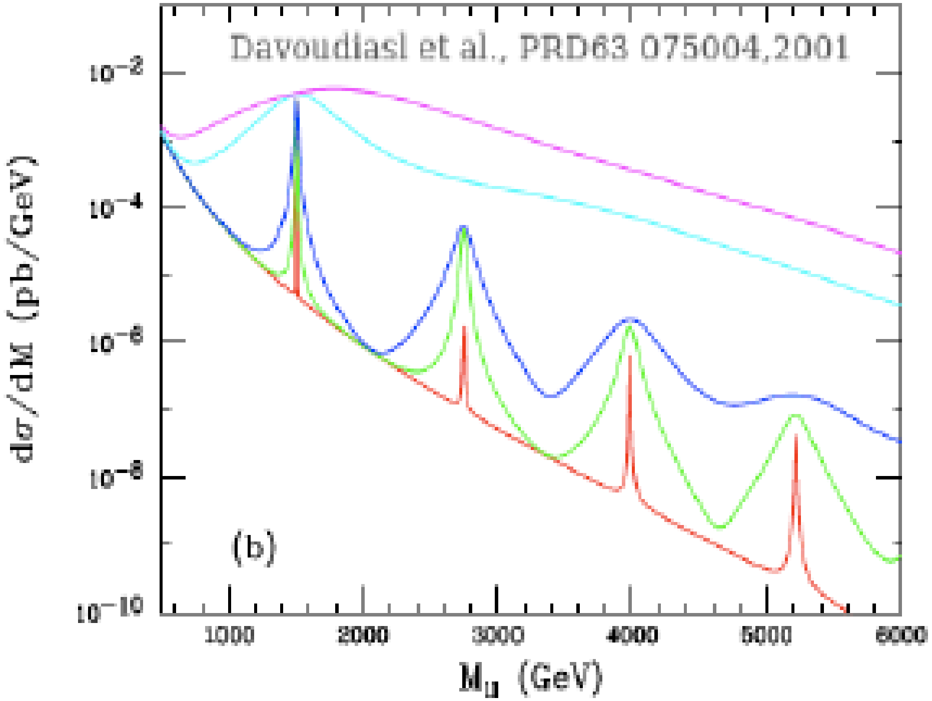


Drawing by G. Landsberg

Graviton excitations

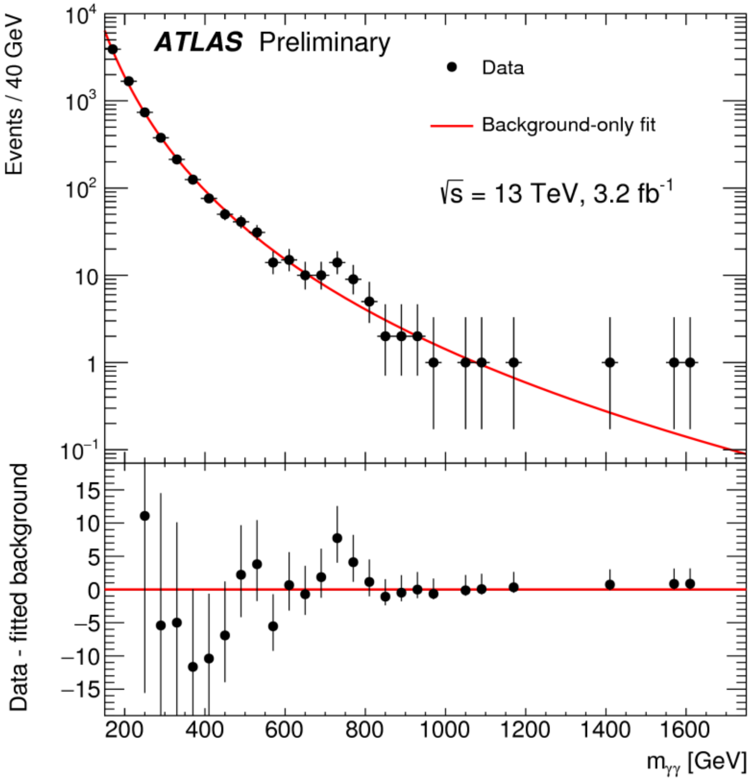
- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function
    - ➡ Smoking gun!

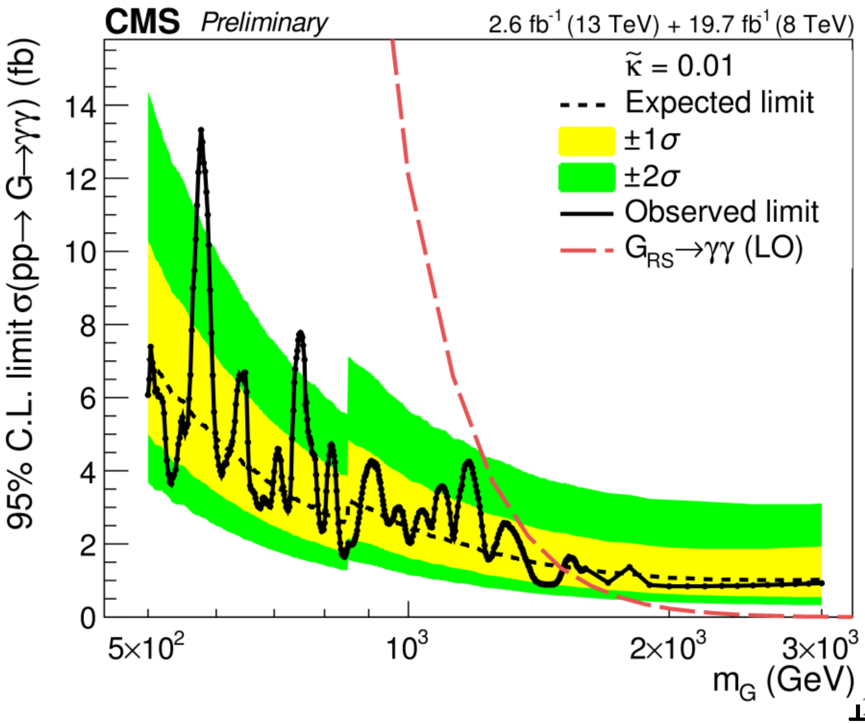
(BRs also different than Z':
e.g. γγ allowed)



Example

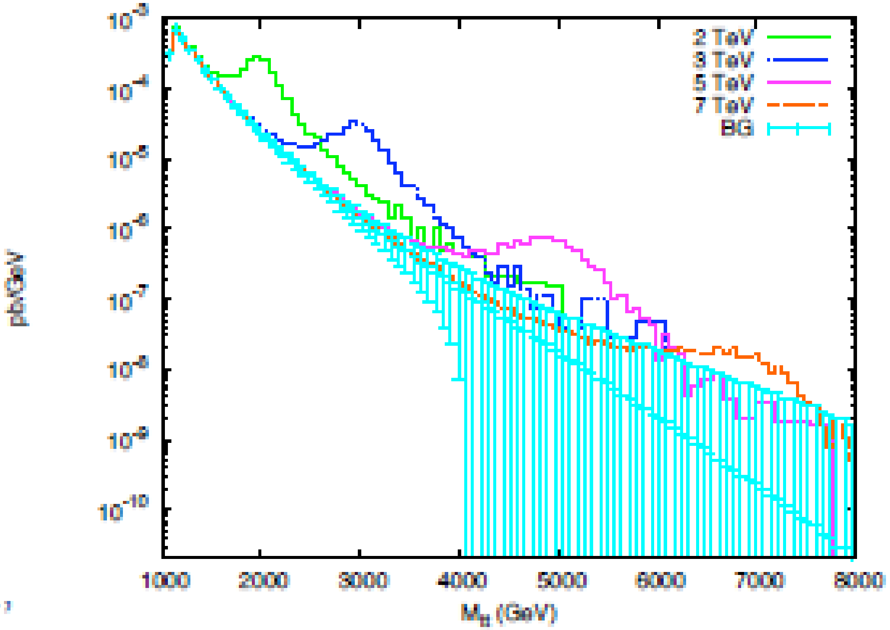
The infamous γγ bump is an example of a search for RS gravitons:





Gauge boson excitations

- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)



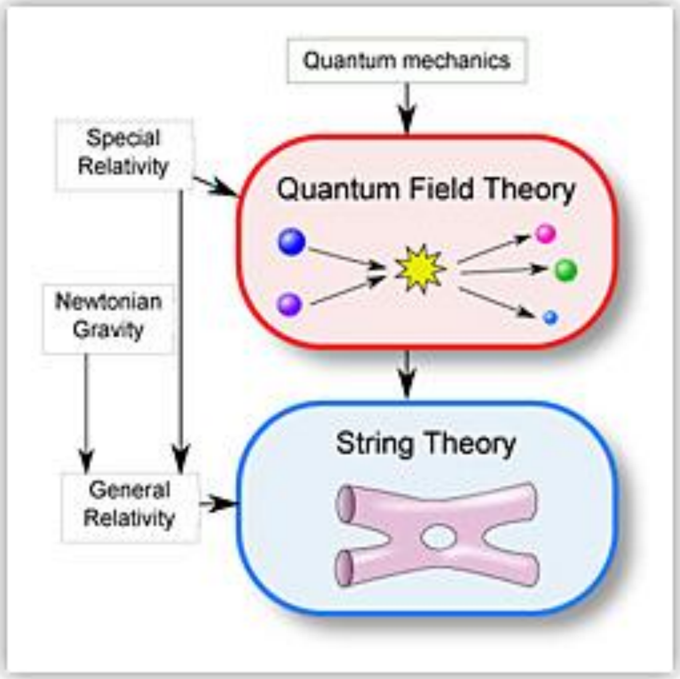
B. Lillie et al., JHEP 0709:074,2007

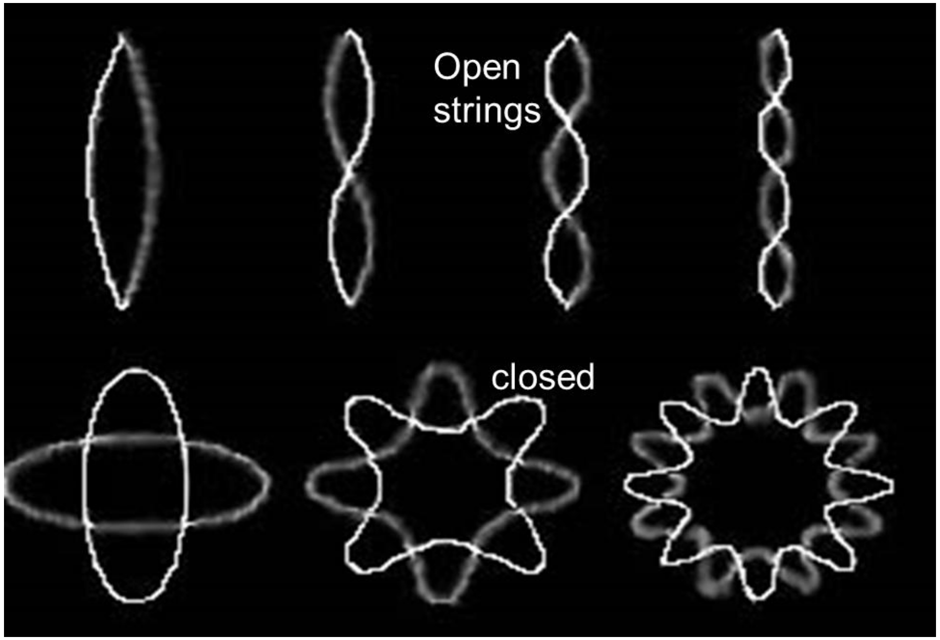
(super)Strings

Avoid infinities from point-like particles

Different vibration modes = different particles

One fundamental parameter: *string size*





Great idea but we have not yet understood how to test it at current ”low” energies

Extra dimensions a must
Supersymmetry a plus

A hidden (“dark”) sector?

Rather than being heavy, could new particles be light but *very* weakly interacting?

e.g. new, light “hidden sector” of particles which are singlets wrt gauge group of the SM

- Several possibilities for renormalisable singlet operators which each involve some hidden sector particle **mixing** with some SM “portal particle” :
  - **Vector portal** – new U(1) B_{mn} – massive vector photon (paraphoton, secluded photon…) mixing with regular photon → $eB_{mn}F^{mn}$
  - **Higgs portal** – new scalar field
  - **Axial portal** – new axial-vector field a – Axion Like Particles (to distinguish from Peccei–Quinn axion)
  - **Neutrino portal** – new heavy neutral leptons (HNL) → $YH^{T}N'L$

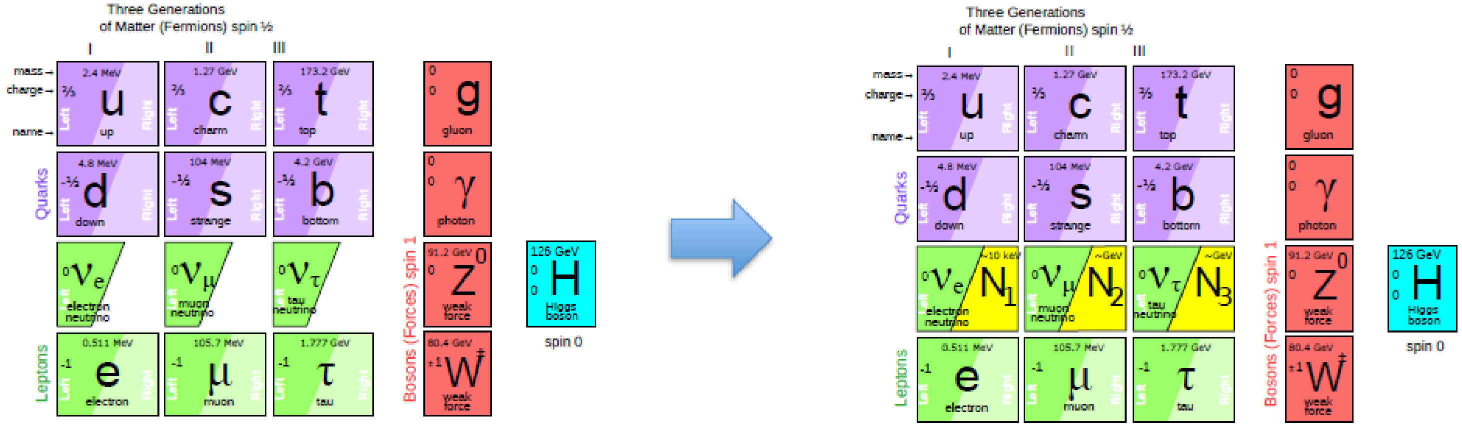
- E.g. The **neutrino Minimal Standard Model** (**nMSM**) aims to explain :
  - Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter

by adding three right-handed, Majorana, Heavy Neutral Leptons (HNL), **N_1, N_2 and N_3**

The Neutrino Portal

- The **neutrino Minimal Standard Model** (**νMSM**) [T.Asaka, M.Shaposhnikov, Phys. Lett B620 (2005) 17] aims to explain
  - Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter

  by adding three right-handed, Majorana, Heavy Neutral Leptons (HNL), **N_1, N_2 and N_3**



- **N_1** – mass in keV region, (warm) dark matter candidate
- **$N_{2,3}$** – mass in 100MeV – GeV region – generate neutrino masses via see-saw mech. and produce baryon asymmetry of the Universe

Dark Matter Searches

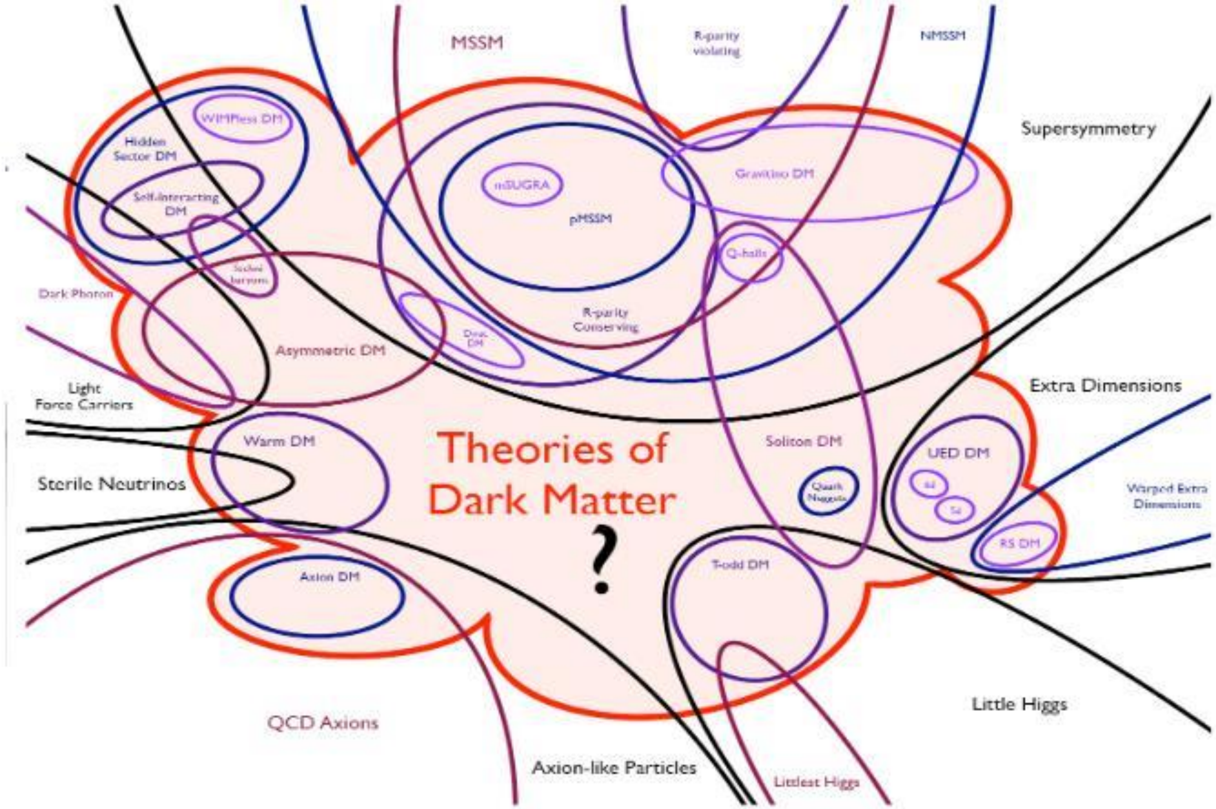
Lots of models, this is not a unique search!

Typically divided in two ”classes”:

WIMP: weakly interacting massive particle (elementary particle)

MACHO: Massive Compact Halo Objects (planets, dwarf stars, something large)

The energy scale(s) of new physics



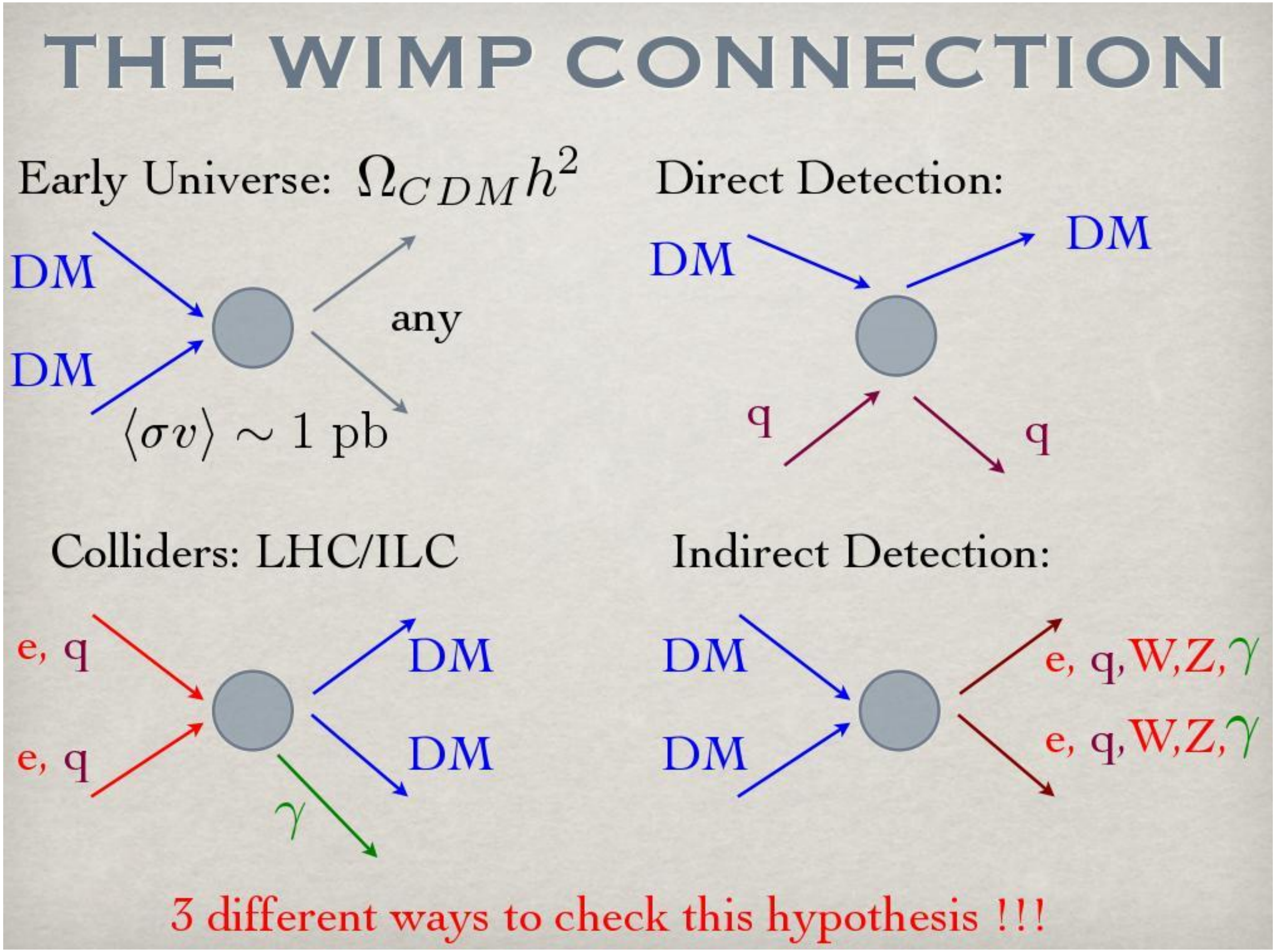
T. Tait, DM@LHC '14

The prediction about the mass scale of DM comes with large error bars:

(WIMPS) $10^{-22}\,\mathrm{eV} < m_{DM} < 10^{20}\,\mathrm{GeV}$ (MACHOs)

(ALPs) (Wimpzillas, Q-balls)

or even black holes ~10000 x M_{Sun}



THE WIMP CONNECTION

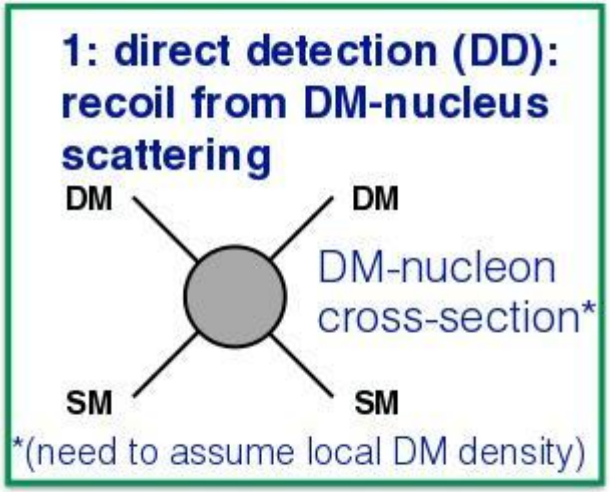
Early Universe: $\Omega_{CDM}h^2$

Direct Detection:

Colliders: LHC/ILC

Indirect Detection:

3 different ways to check this hypothesis !!!

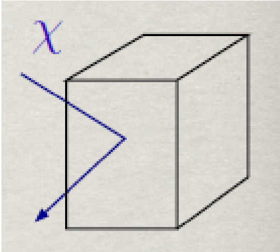


1: direct detection (DD): recoil from DM-nucleus scattering

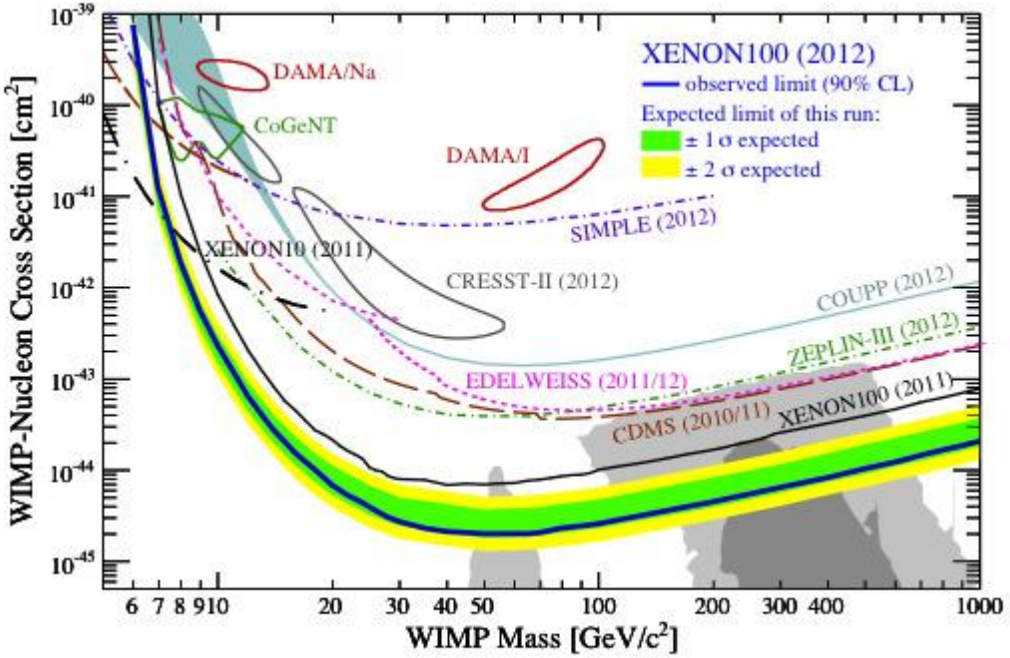
DM-nucleon cross-section*

*(need to assume local DM density)

Underground searches (experiments: DAMA, Xenon etc

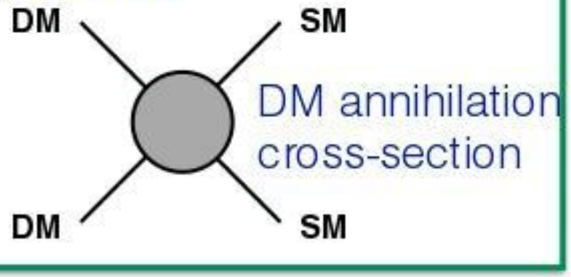


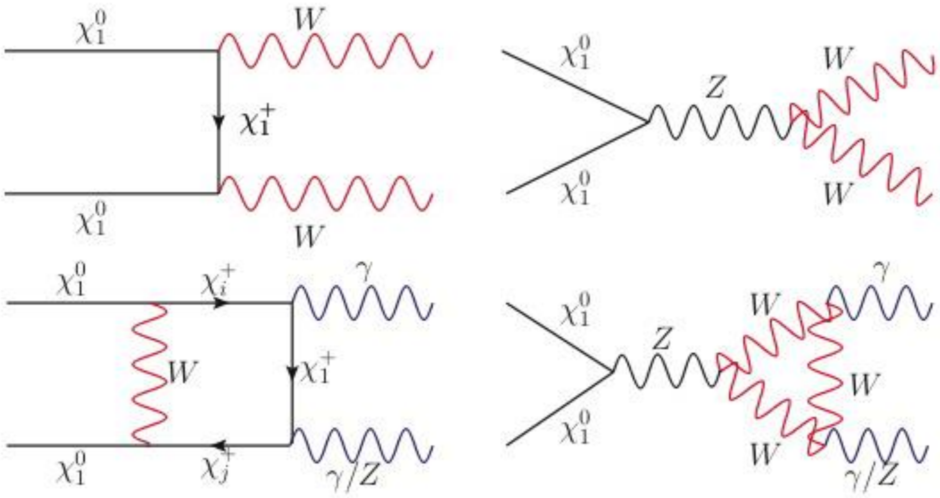
WIMP scatters off nuclei
Looking for annual modulation / DM ”wind”

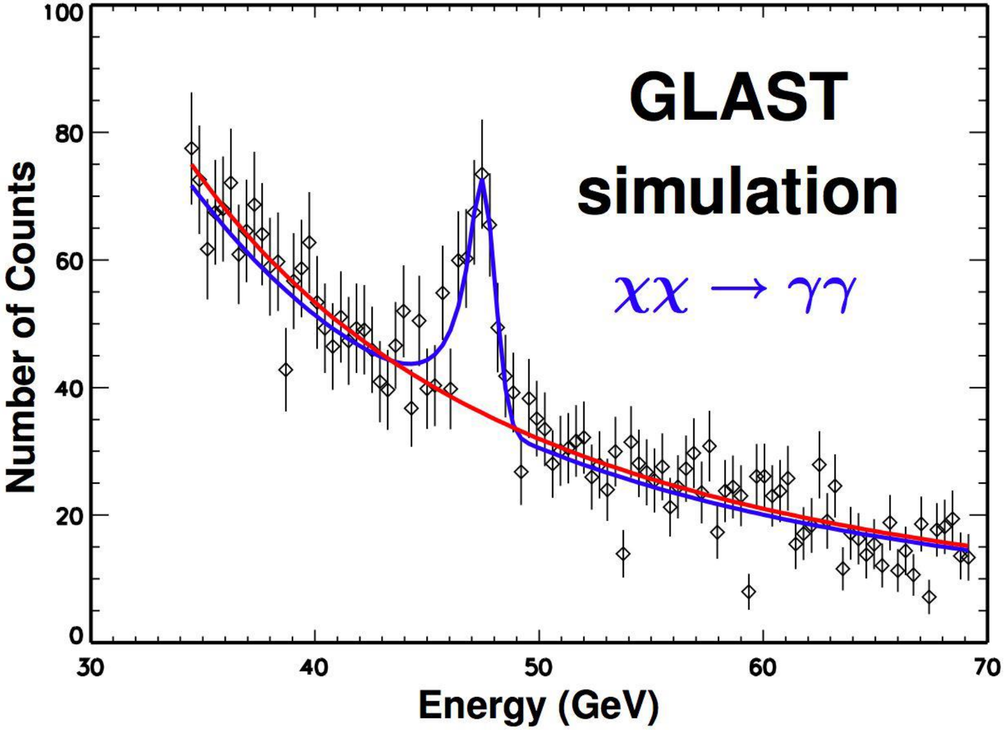


Cross section depends on exchange particle:
 Z exchange ruled out
Now looking for H exchange

2: indirect detection (ID): DM-DM annihilation products



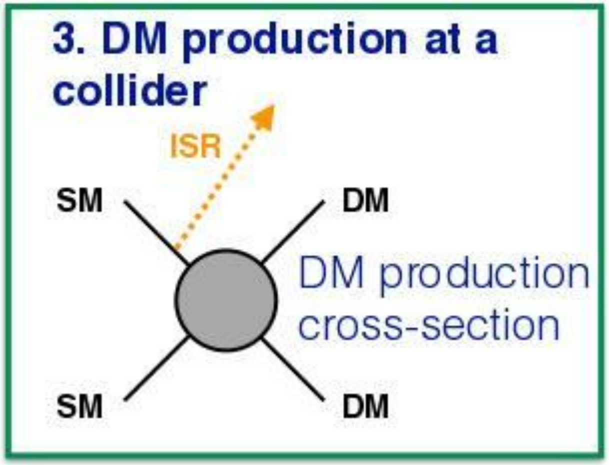




Look for annihilation signals!
Measure decay products

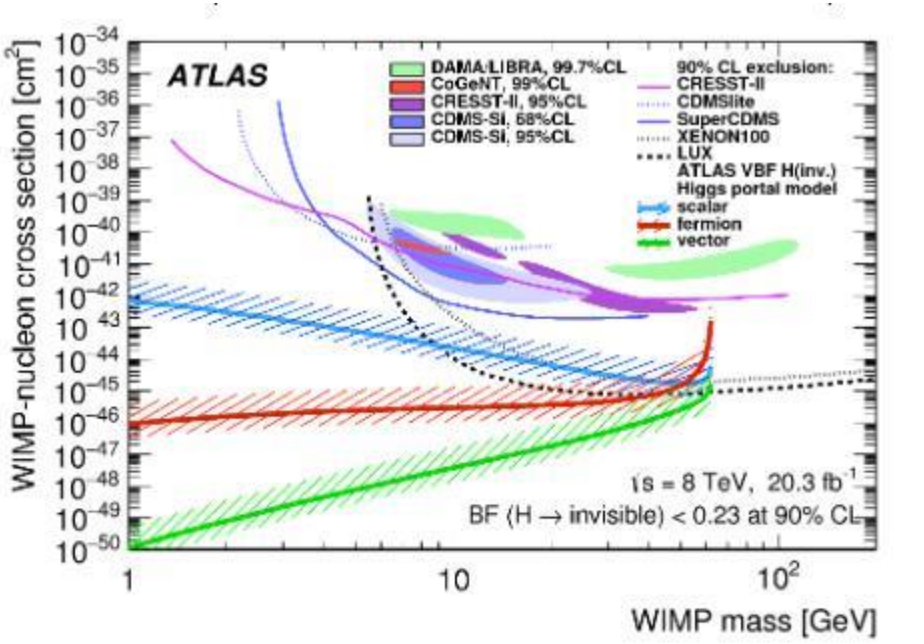
Experiments: FERMI, PAMELA, AMS etc

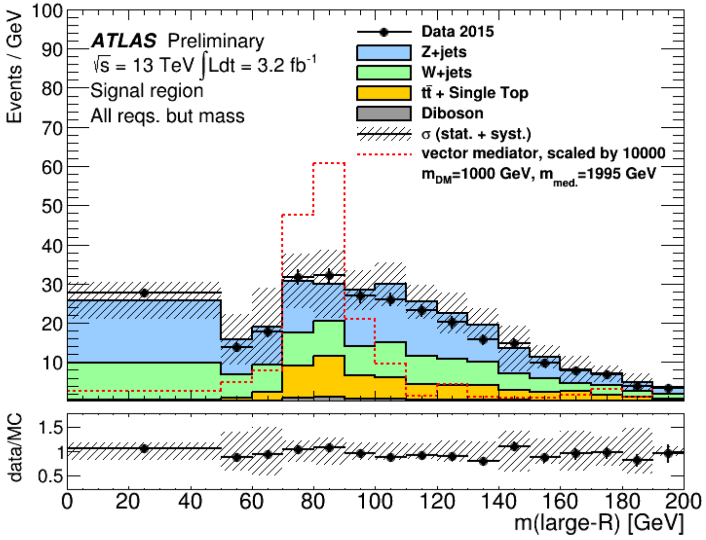
At the LHC



No Dark Matter interaction with the detector ⇒ signature is missing energy

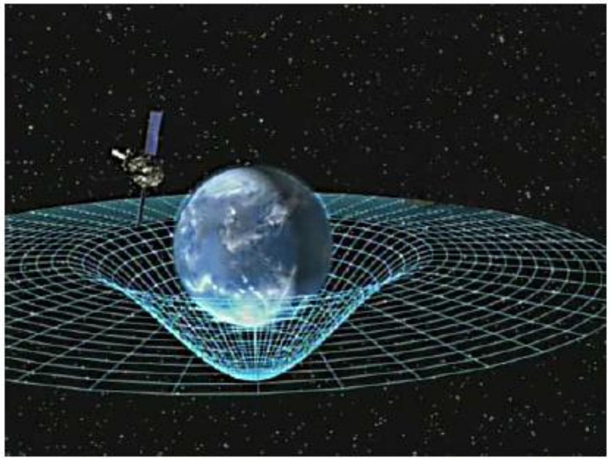
Use initial state radiation (ISR) to detect it! (e.g jets, γ, W, Z, H)





Gravitation

The basic intuitive picture:



Credit:NASA

More formally:

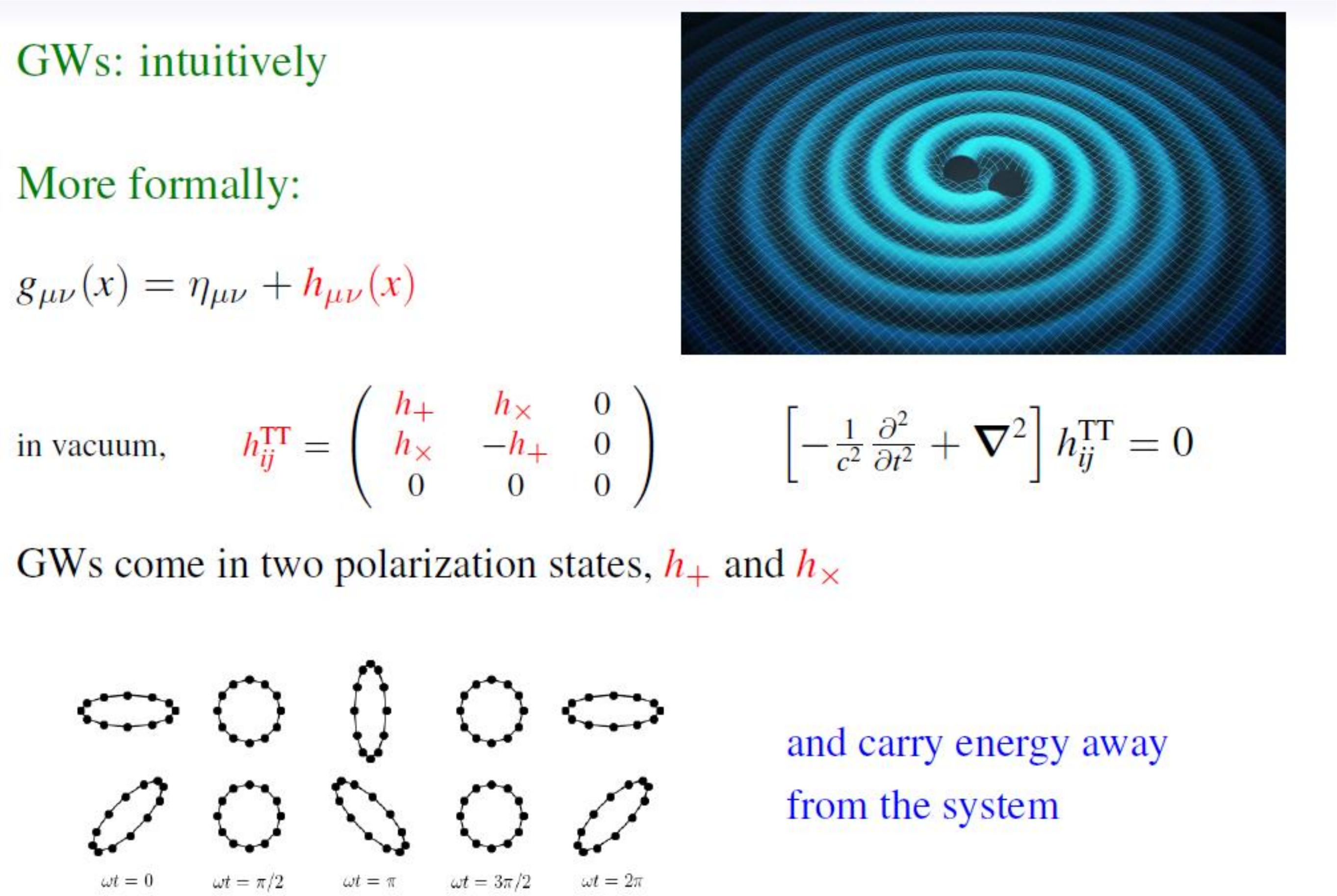
Flat space: $ds^2 = -c^2dt^2 + d\mathbf{x}^2 = \eta_{\mu\nu}\, dx^\mu dx^\nu$ $\eta_{\mu\nu} = (-1, 1, 1, 1)$

Curved space $ds^2 = g_{\mu\nu}(x)\, dx^\mu dx^\nu$

Einstein eqs. $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$

Gravitational waves

Black holes merging



GWs: intuitively

More formally:

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x)$$

in vacuum, $h_{ij}^{\mathrm{TT}} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$ $\left[-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \nabla^2\right] h_{ij}^{\mathrm{TT}} = 0$

GWs come in two polarization states, h_+ and $h_\times$

and carry energy away from the system

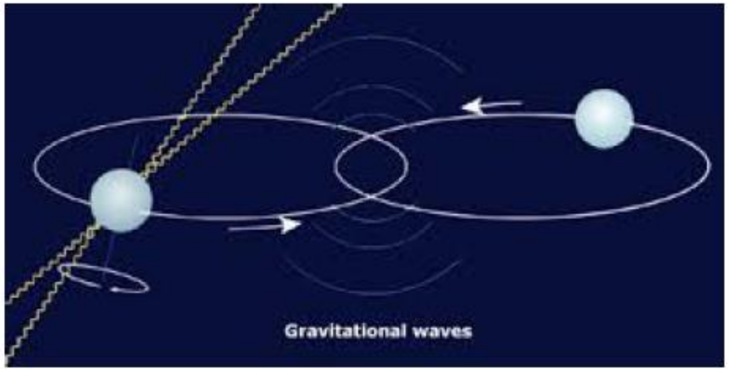
In fact we already observed gravitational waves before

Hulse-Taylor binary pulsar

NS-NS binary

a NS observed as pulsar
($P \simeq 59$ ms)

discovered 1974



Pulsars are clocks with exceptional intrinsic stability
(comparable to atomic clocks)

Timing residuals affected by various effects due to GR

(e.g. Roemer, Einstein and Shapiro time delays)

Detecting gravitational waves

Direct GW detection aims at opening a new window in astrophysics and cosmology

This has been made possible by 40+ years of work, including

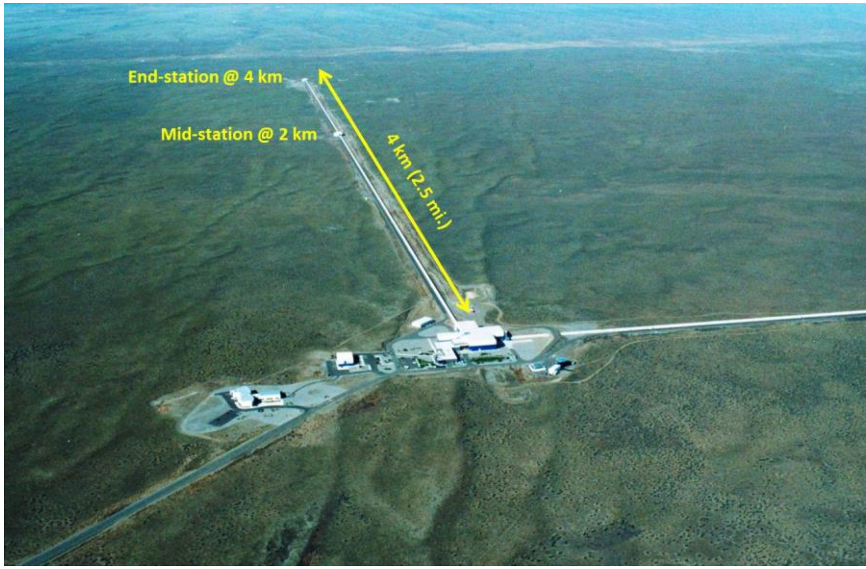
- Experimental ‘miracles’

  the event detected by LIGO has $h_{\rm max} \simeq 1 \times 10^{-21}$

  $\frac{\Delta L}{L} = (1/2)h, \quad L = 4\ km \quad \Rightarrow \quad \Delta L = 2 \times 10^{-3}$ fm !!!

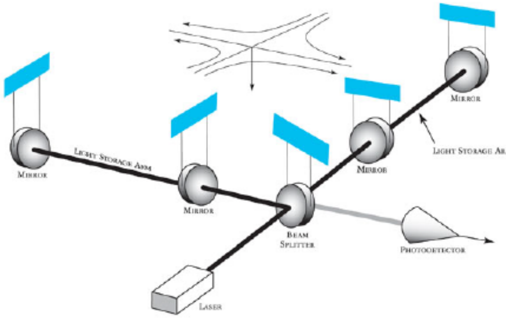
- Theoretical breakthroughs

  predicting the waveform for BH-BH coalescence



LIGO Livingston inferometer

How can we possibly measure $\Delta L = 10^{-3}$ fm???



- laser beam size $\sim$ 12 cm. Even if $\Delta L = 10^{-3}$ fm, we measure a coherent displacement of all atoms in the mirror! A better figure is given by the phase shift in the interferometer,

$$\Delta\phi = \frac{4\pi\mathcal{F}}{\lambda_L} h_0 L \sim 10^{-8} \text{ rad}$$

- does not detect a mirror motion $x(t)$ but $\tilde{x}(f)$ in a selected range of frequencies $\sim$ 10Hz – 3kHz. We are only sensitive to GW frequencies in this range

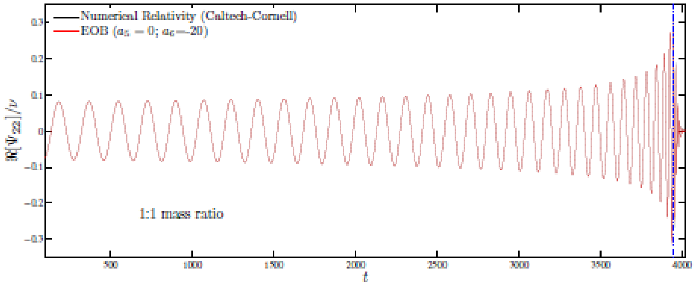
What does a BH merger look like?

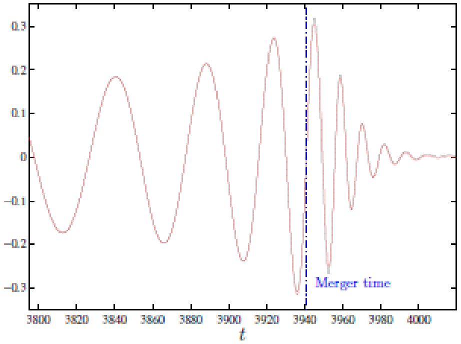
Accurate predictions of the waveform are crucial for

- extracting the signal from the noise
- perform parameter estimation, i.e. extracting the physics from the event

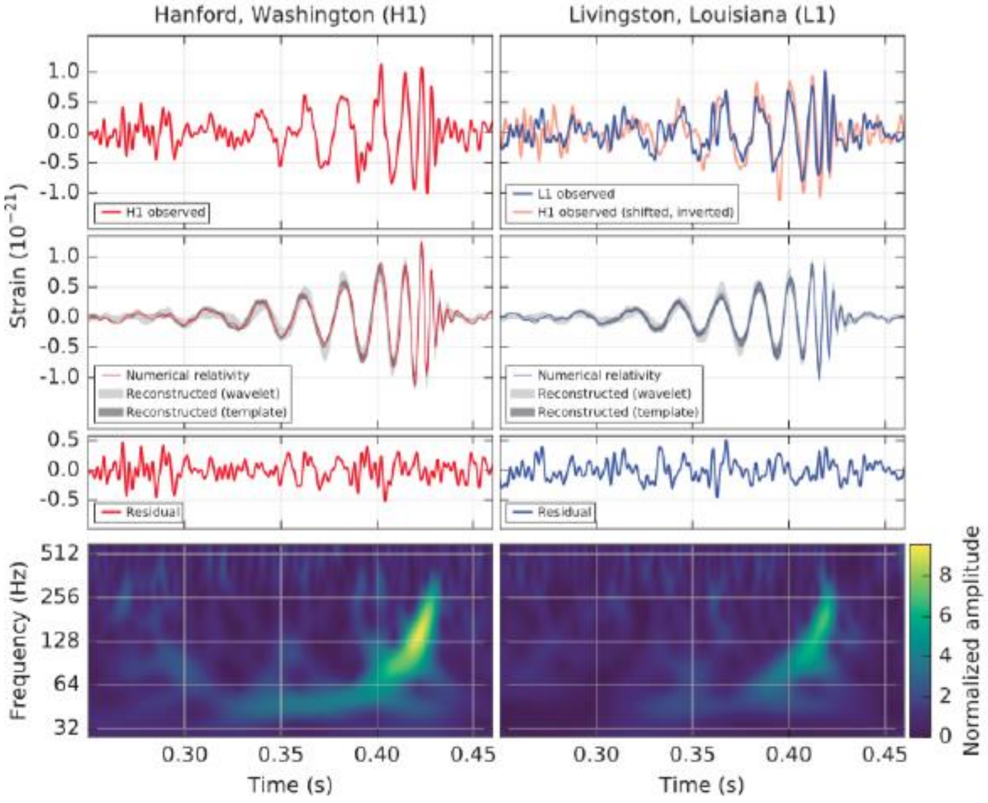
Three phases: inspiral-merger-ringdown

Thanks to decades of theoretical work, the waveform is fully under control





First observation
Sept. 2016

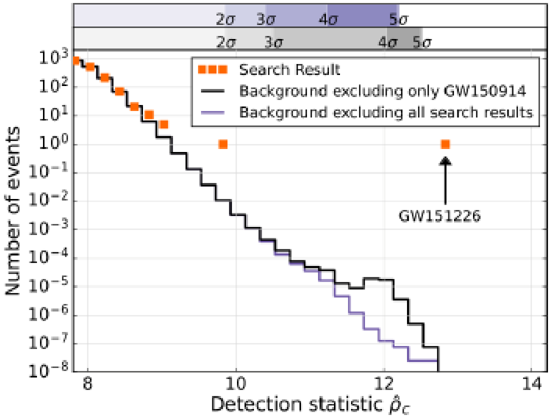


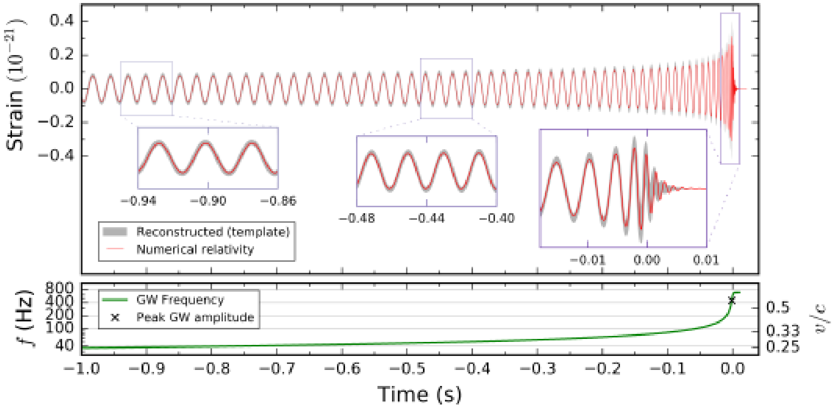
Abbott et al, PRL 116, 061102 (2016)

parameter estimation from matched filtering:

primary BH mass	$36^{+5}_{-4}\,M_\odot$
secondary BH mass	$29^{+4}_{-4}\,M_\odot$
final BH mass	$62^{+4}_{-4}\,M_\odot$
final BH spin $\hat{a} \equiv Jc/(GM^2)$	$0.67^{+0.05}_{-0.07}$
luminosity distance	410^{+160}_{-180} Mpc
source redshift	$0.09^{+0.03}_{-0.04}$

A second detection on Dec. 26, 2015



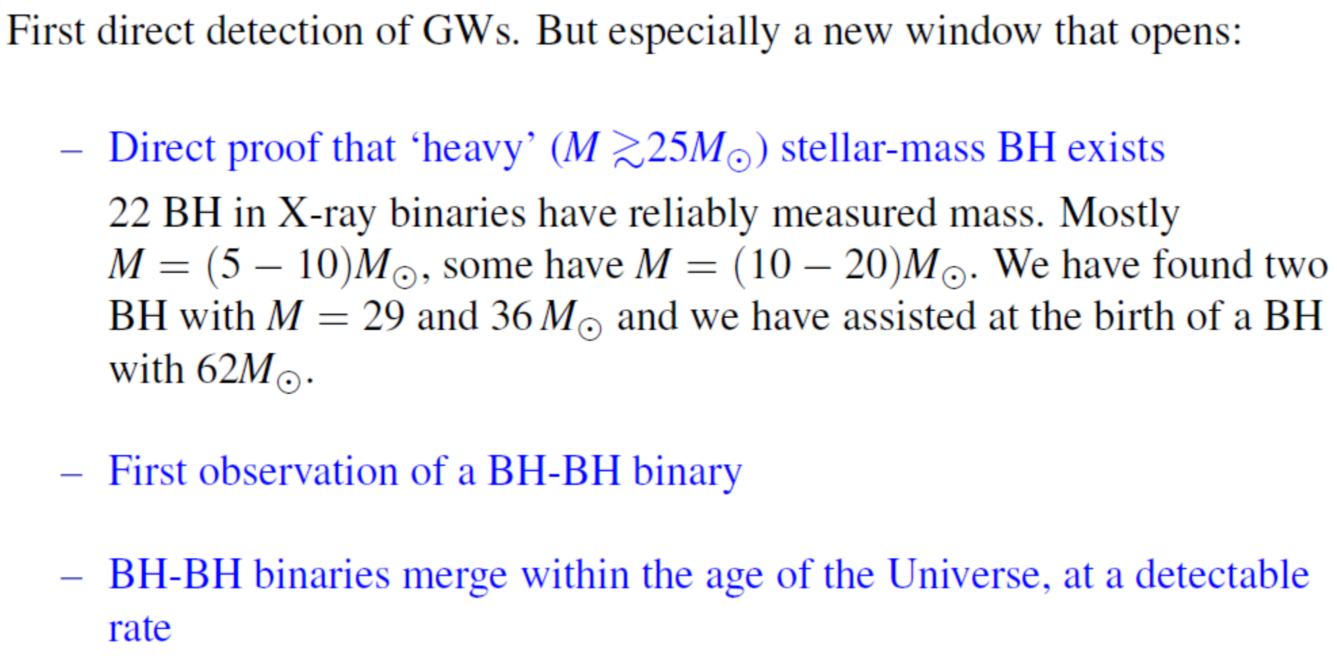


significance $> 5.3\sigma$

$14.0 M_\odot + 7.5 M_\odot$, many more inspiral cycles

How is this estimated?

Why is this important?



First direct detection of GWs. But especially a new window that opens:

- Direct proof that ‘heavy’ ($M \gtrsim 25 M_\odot$) stellar-mass BH exists

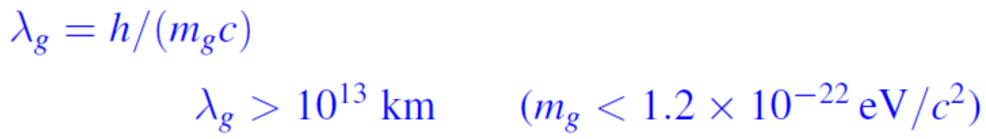
  22 BH in X-ray binaries have reliably measured mass. Mostly $M = (5-10)M_\odot$, some have $M = (10-20)M_\odot$. We have found two BH with $M = 29$ and $36\,M_\odot$ and we have assisted at the birth of a BH with $62 M_\odot$.

- First observation of a BH-BH binary

- BH-BH binaries merge within the age of the Universe, at a detectable rate

Tests of General Relativity

Mass limits on (massive) gravitons:



$$\lambda_g = h/(m_g c)$$

$$\lambda_g > 10^{13}\ \mathrm{km} \qquad (m_g < 1.2 \times 10^{-22}\,\mathrm{eV}/c^2)$$

Summary/outlook

- Many problems with current Standard model
- Many new models to take over

  Some important models not mentioned, for instance:
  - GUT models
  - Technicolor
  - Hidden valleys
- The LHC energy scale is tuned to be sensitive to many of these, complementary to other current searches
- Several potential signatures requires new ”objects”, ie lepton-jets, long-lived heavy particles, ”quirks” etc
- Several good ideas but Nature decides which (if any) are true!