ATLAS Monophoton Results

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DARK MATTER AT THE LHC WORKSHOP
CHICAGO, SEPTEMBER 2013

Outline

- Introduction/Motivation
- LHC and ATLAS
- Monophoton Search
- WIMPS
- ADD LED

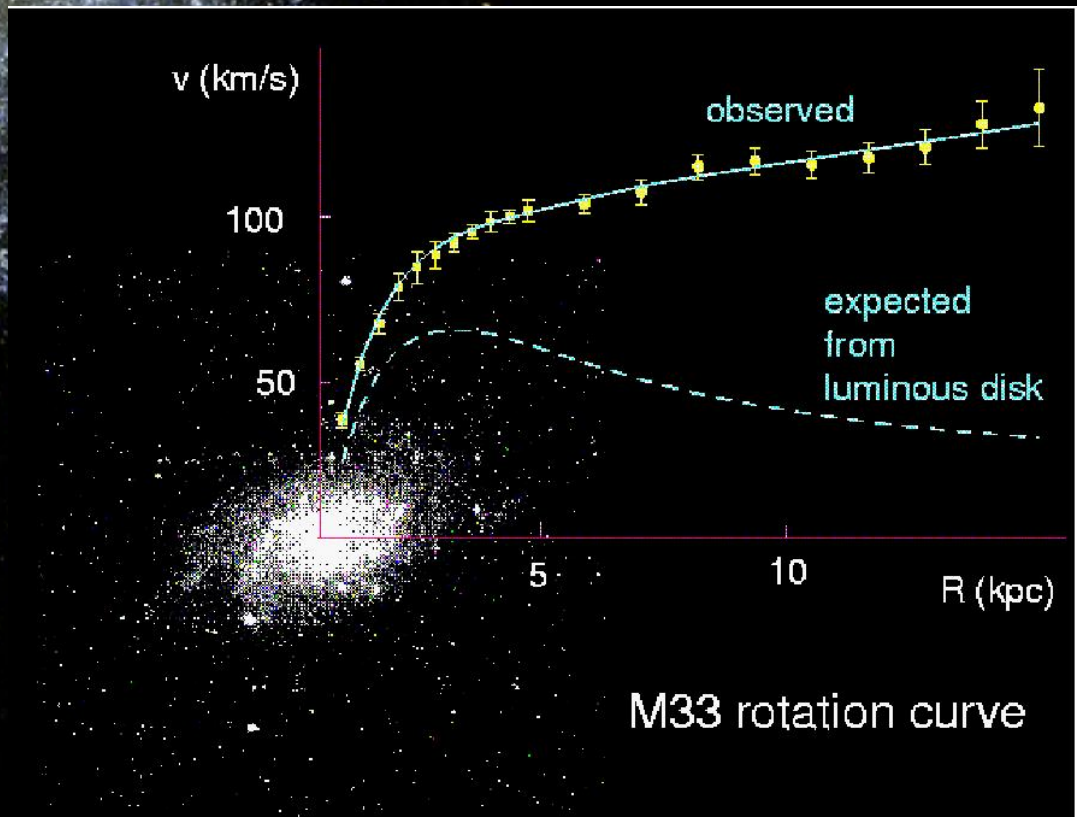
- Final notes

"Particles, particles, particles."

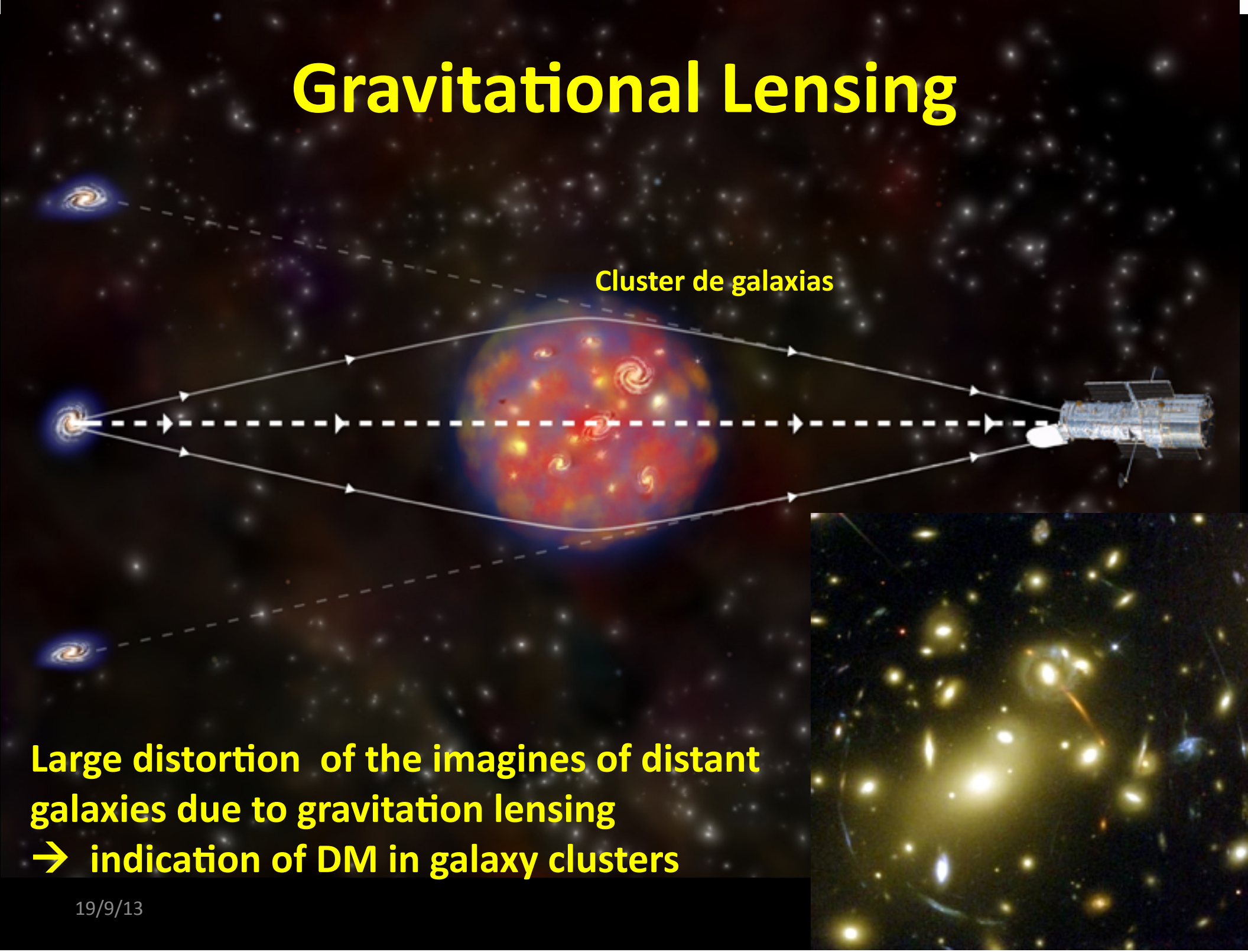
Galaxia M33

The rotation of the starts around the center of the galaxies are not consistent with the amount of mass observed $(L/M\ ratio)_{SUN}$

Spherical dark matter halo

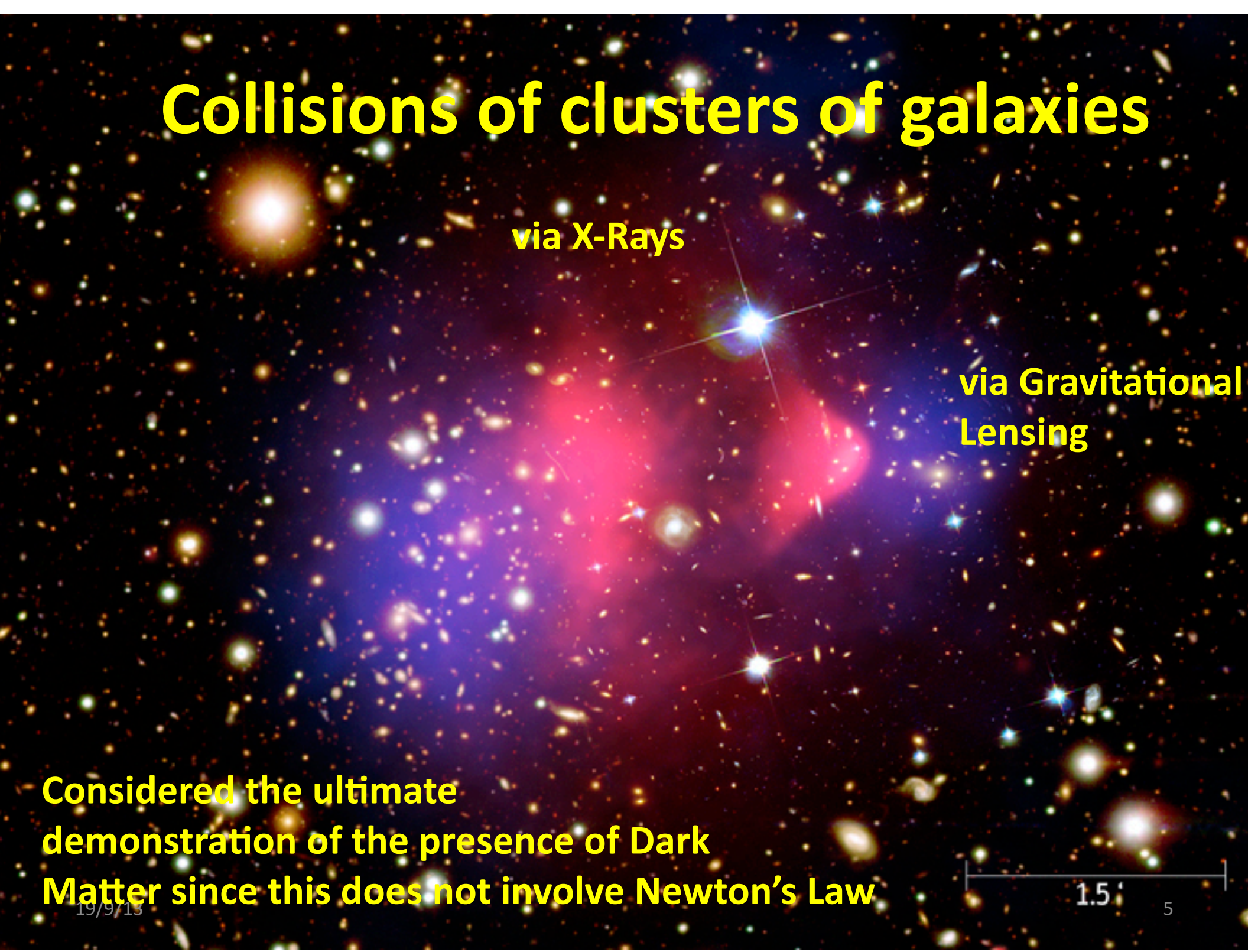


Gravitational Lensing



Large distortion of the imagines of distant galaxies due to gravitation lensing
→ indication of DM in galaxy clusters

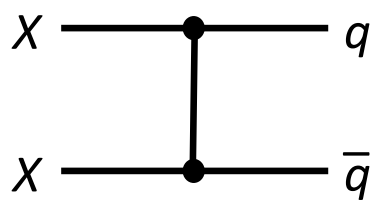
Collisions of clusters of galaxies



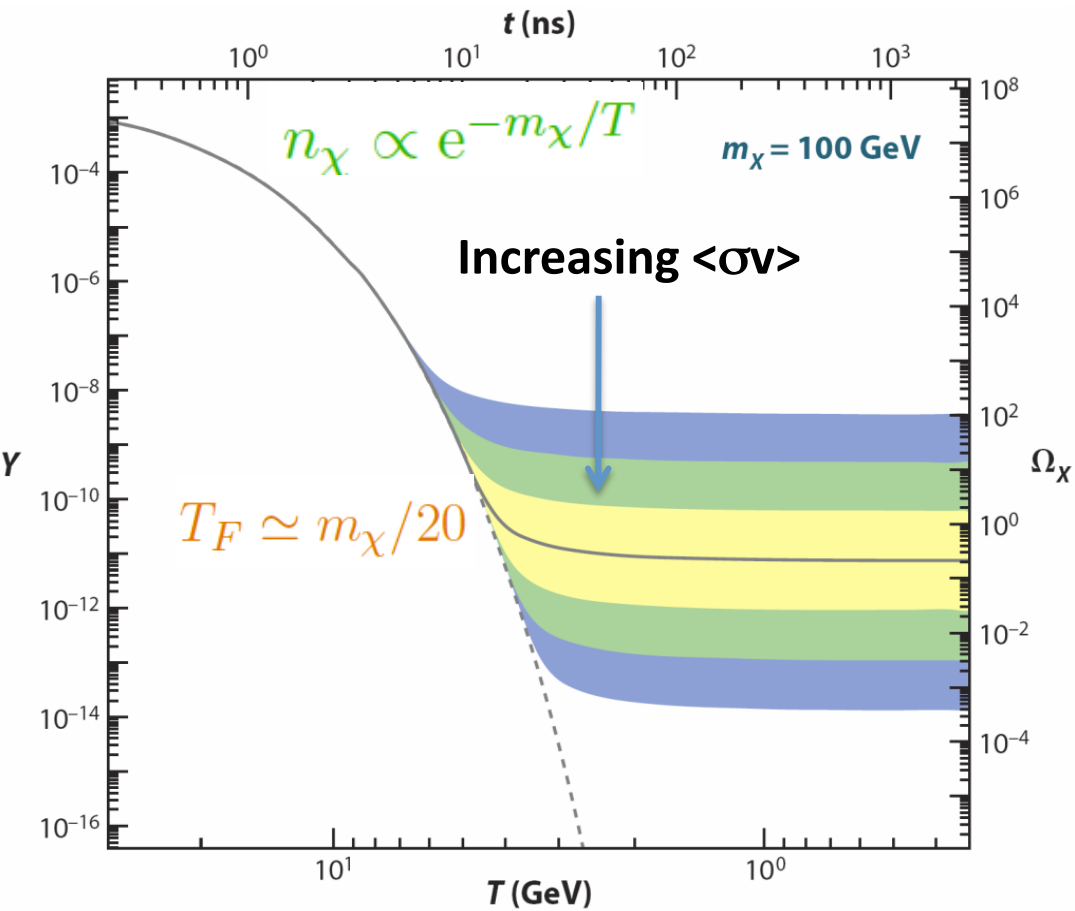
Considered the ultimate demonstration of the presence of Dark Matter since this does not involve Newton's Law

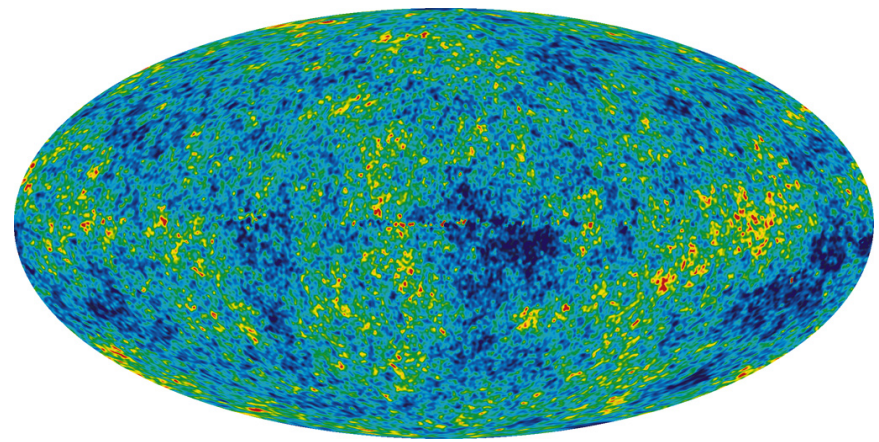
WMAP results

arXiv:1212.5226v2
(January 30th 2013)

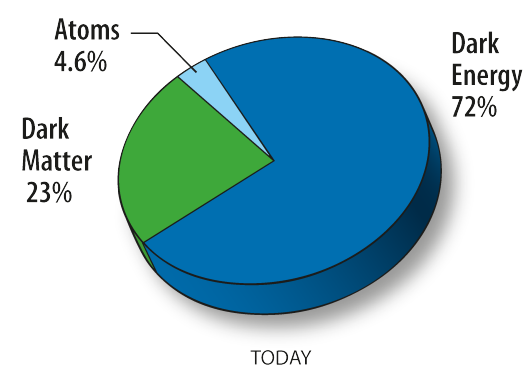


$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$





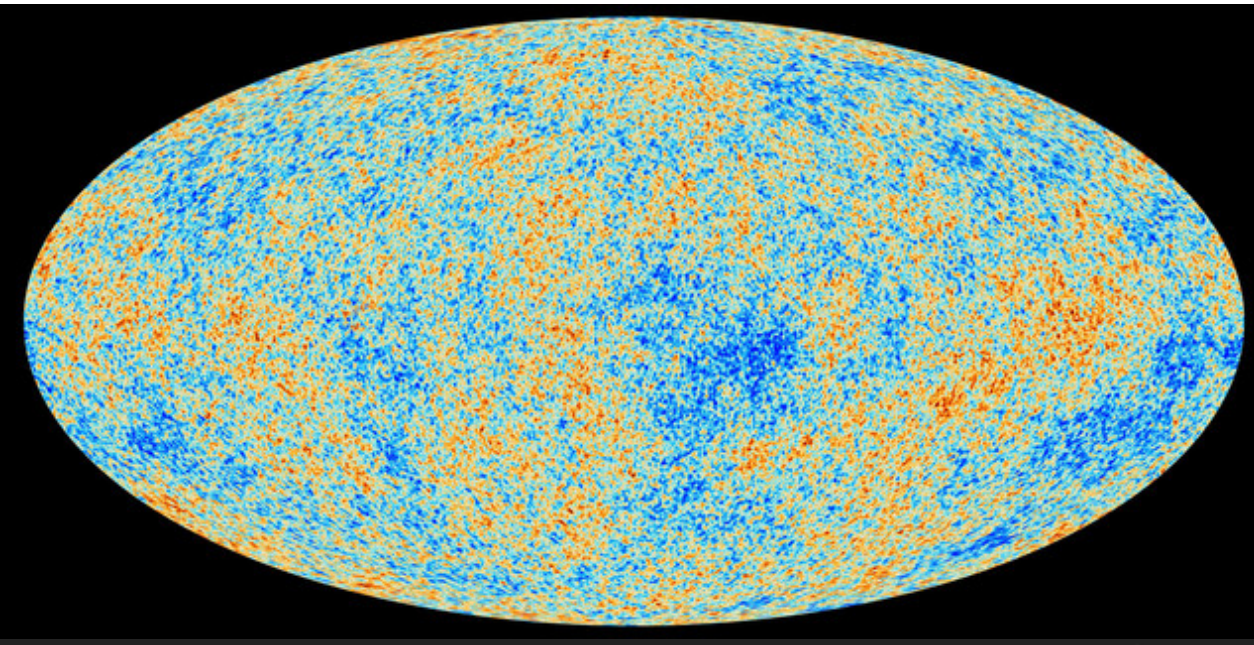
$$\Omega_\chi h^2 \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma(\chi\chi \to \mathrm{SM}) v \rangle}$$



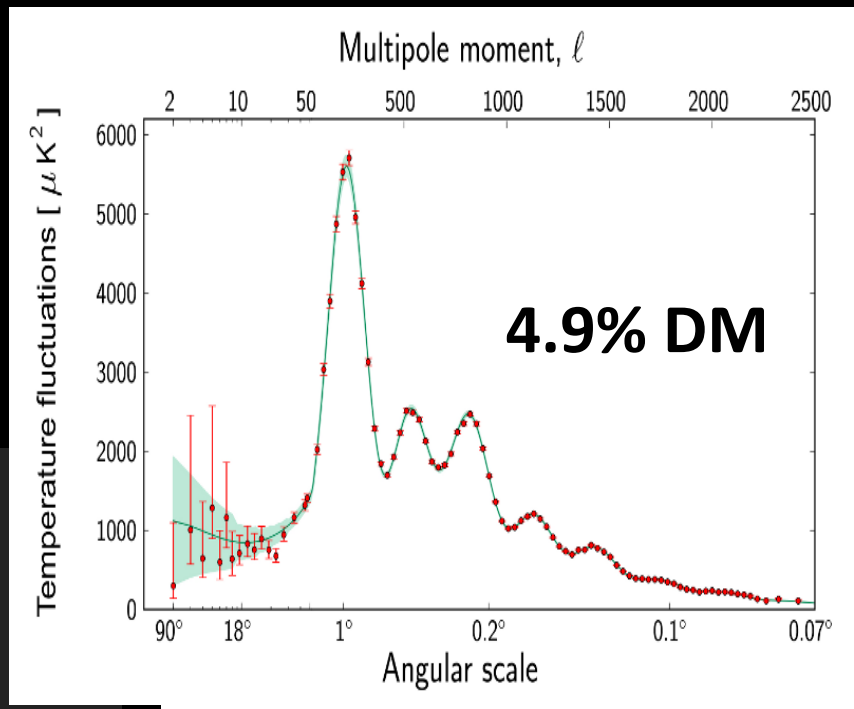
$$\langle \sigma(\chi\chi \to \mathrm{any}) v \rangle \simeq 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

WMAP : $\Omega_{CMD} h^2 \sim 0.1$

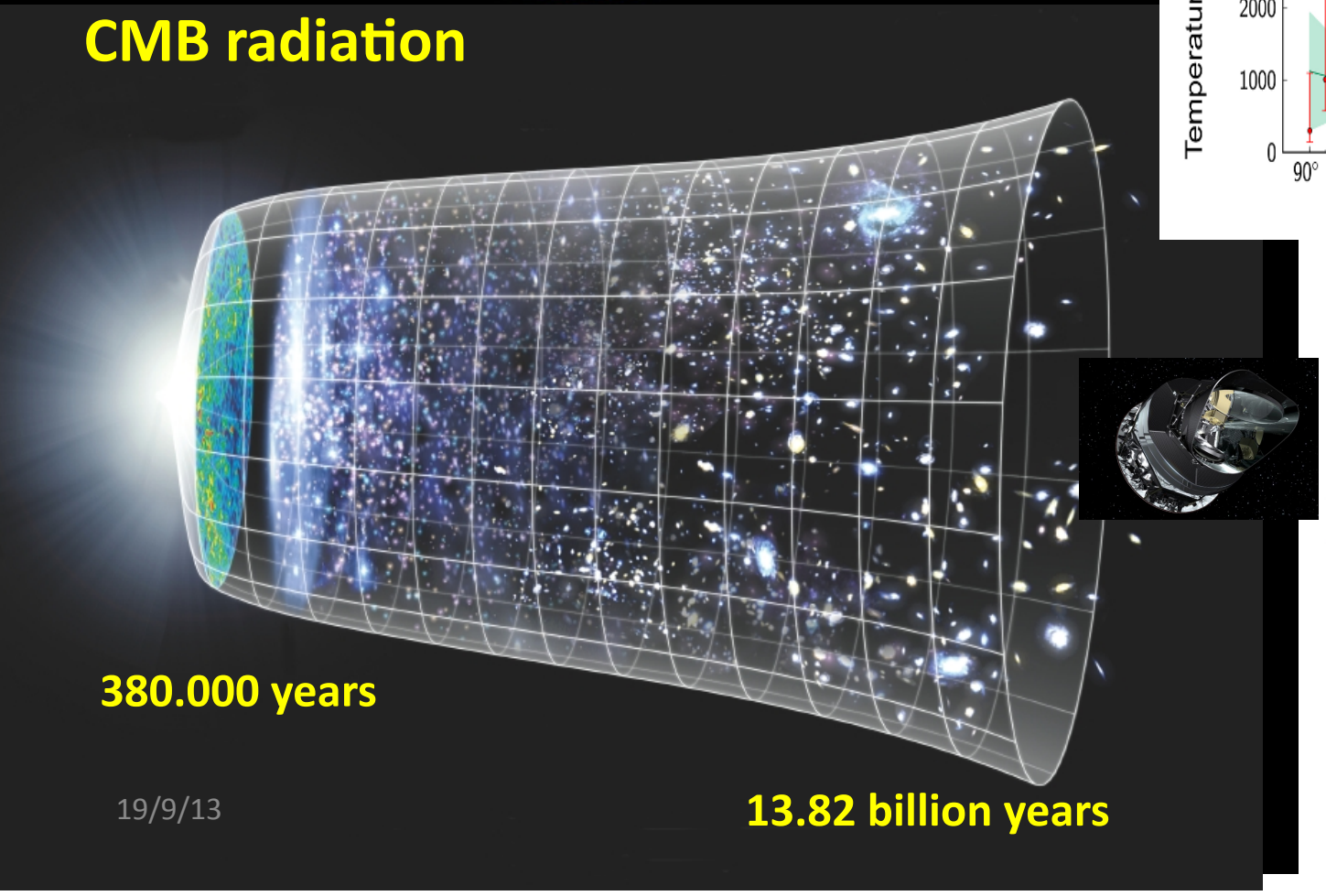
Weak scale for $\chi\chi$ annihilation cross section

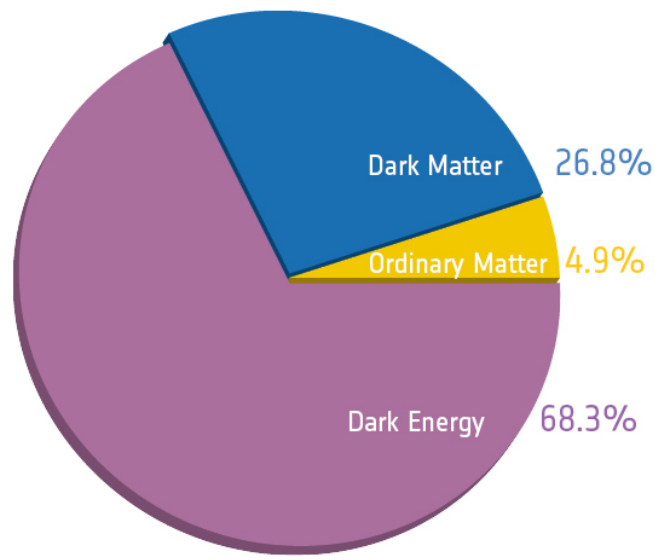


Planck (20 March 2013)
arXiv:1303.5062v1



CMB radiation





After Planck

Dark Matter Candidates

- Neutrinos ? ($\Omega_\nu h^2 < 0.0067$ @ 95%CL)
- Sterile Neutrinos
- Axions
- SUSY particles
  - Lightest neutralino
  - Sneutrinos
  - Gravitinos
  - Axinos
- KK states (UED)
- Wimpzillas
- ……
- ……

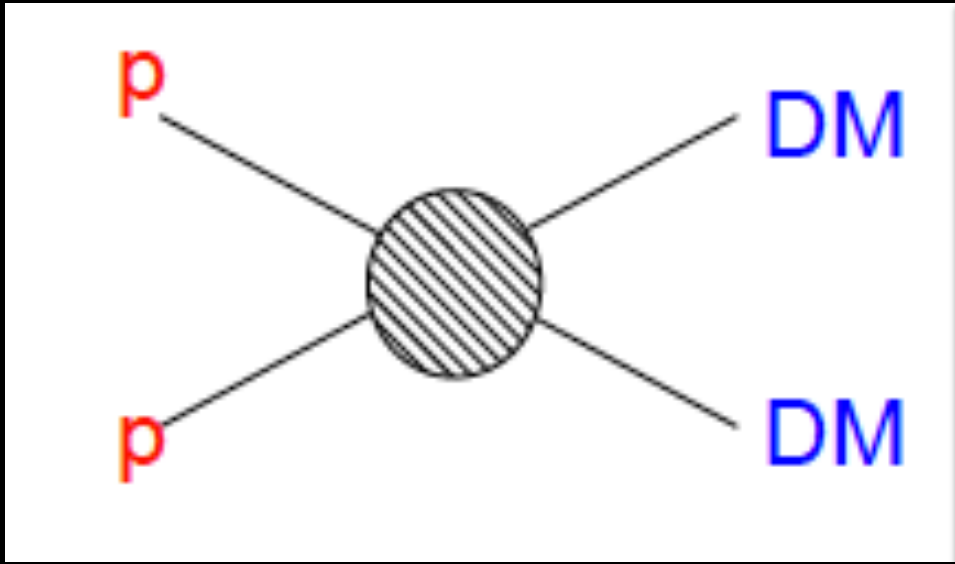
General requirements

- Electrically Neutral ("dark")
- Stable (lifetime larger than age of the Universe)
- Massive and Weakly interacting ($\Omega_{CDM} h^2 \sim 0.1$)

→WIMPS

Note: No reason DM should be made out of a single component (neutrinos exist)

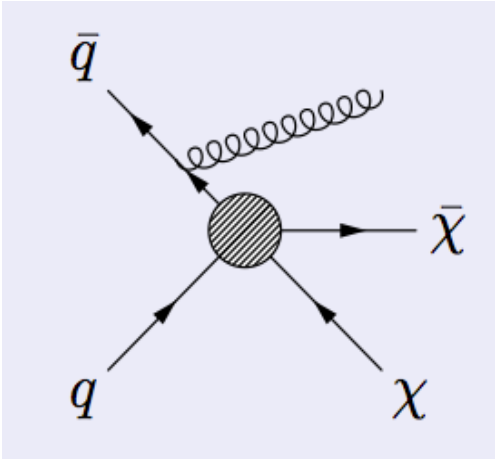
DM at the LHC

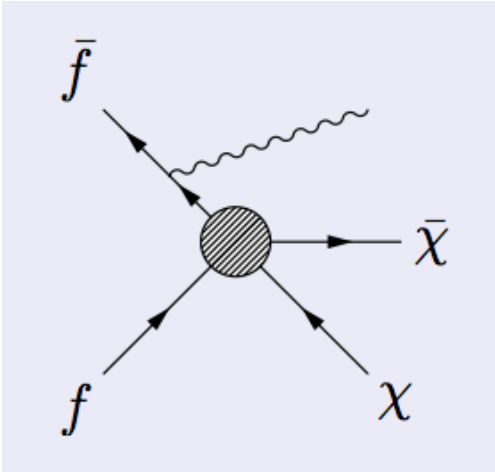


WIMP Pair Production at Colliders

At colliders (LHC) WIMPs can be produced in pairs leading to "nothing to detect" in the final state

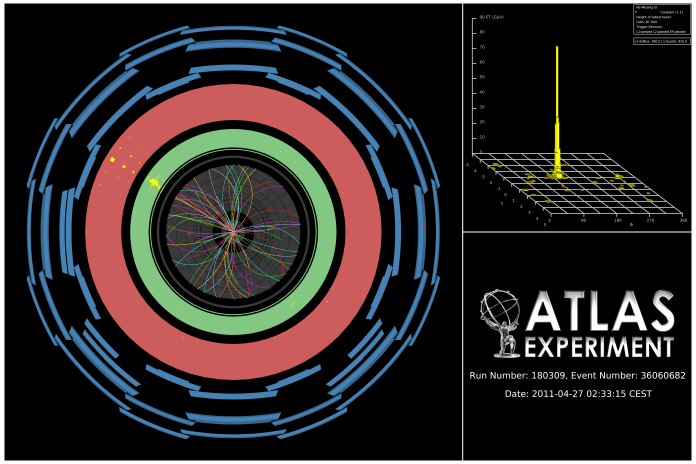
Such events are tagged via the presence of an energetic jet or a photon from initial state radiation

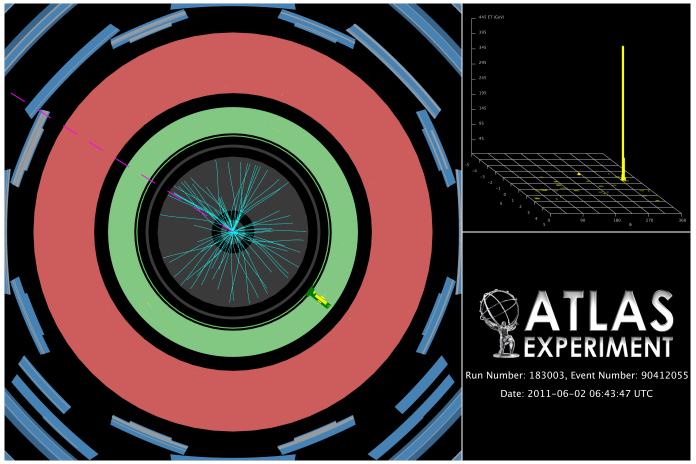




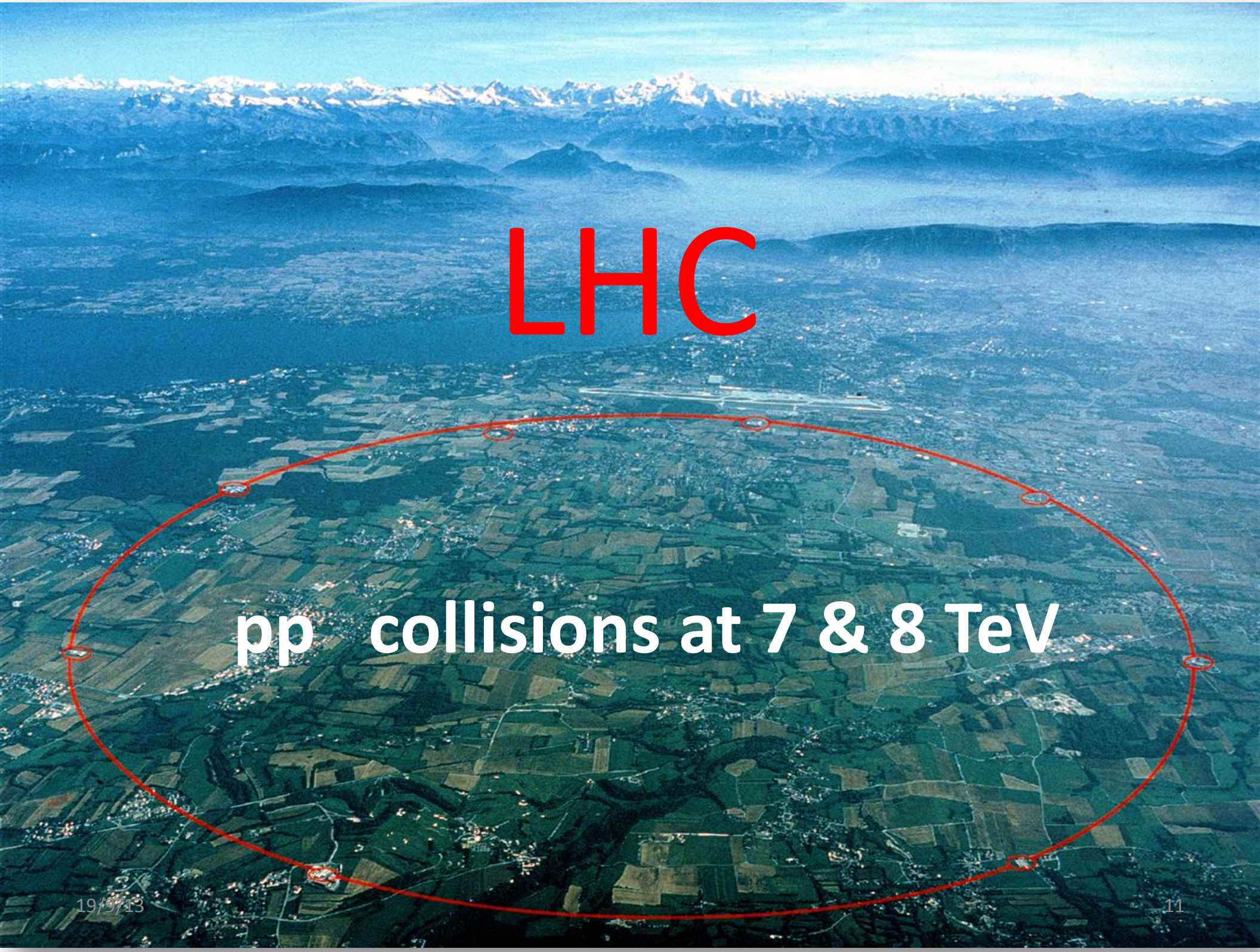
→Monojets and Monophotons

(complementary….but QCD wins in rate)



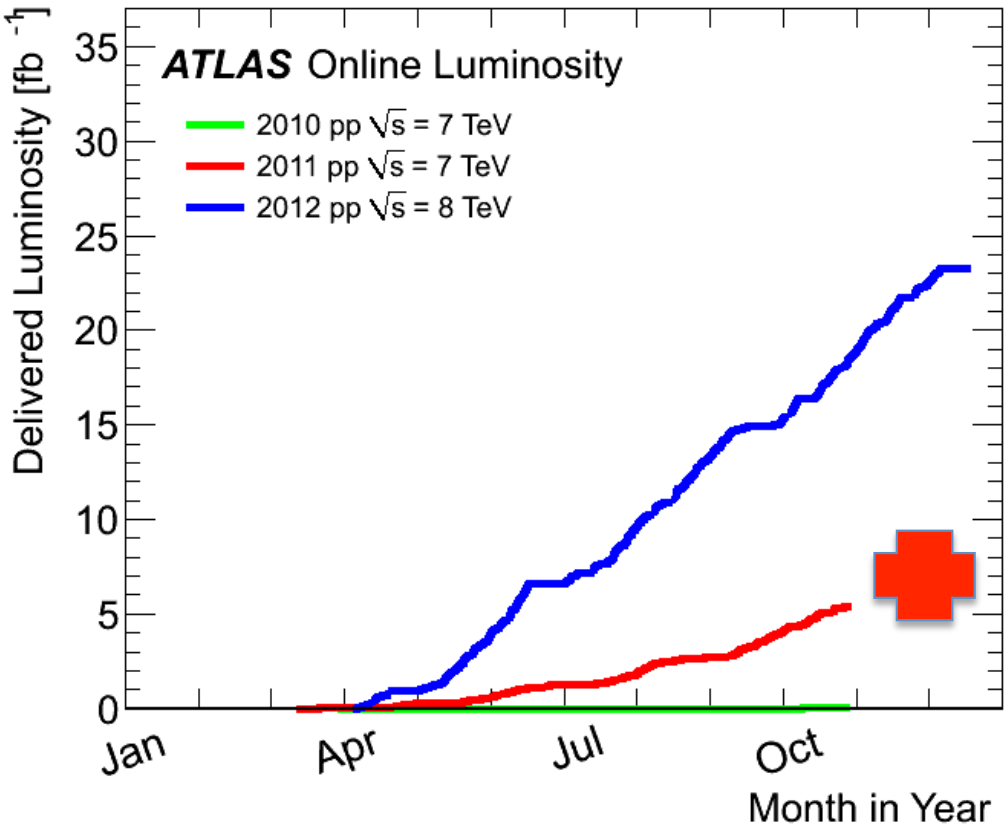


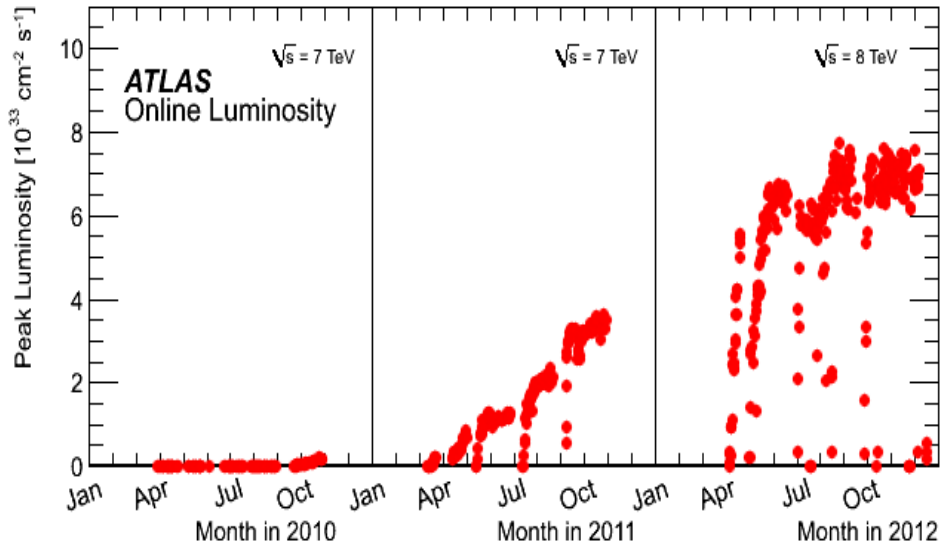
Rather spectacular and distinctive signature to search for new physics
(also relevant in searches for large extra spatial dimensions, etc…)


LHC
pp collisions at 7 & 8 TeV

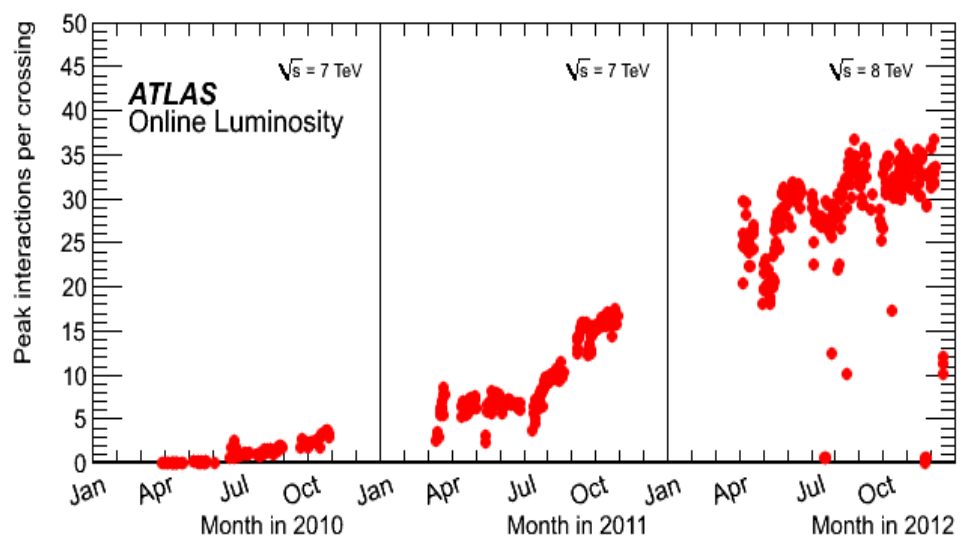
LHC Performance (2010-2012)

Spectacular LHC performance (rapid increase of data samples)





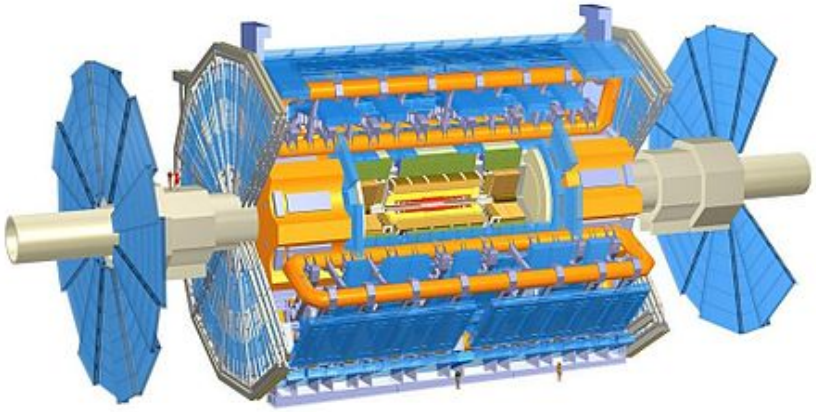
… rapid increase of pile-up conditions

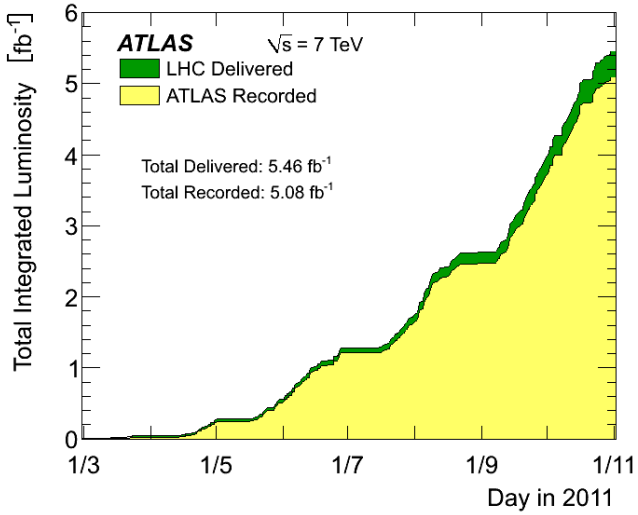


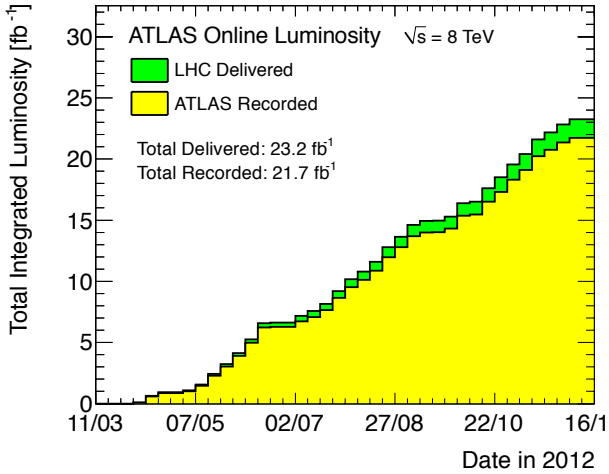
LHC ended pp run at 7+8 TeV after delivering more than 28 fb^{-1}

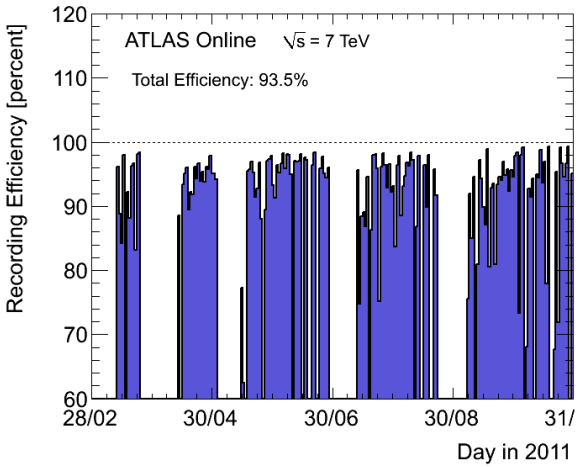
…will come back in 2015 with 13-14 TeV collisions

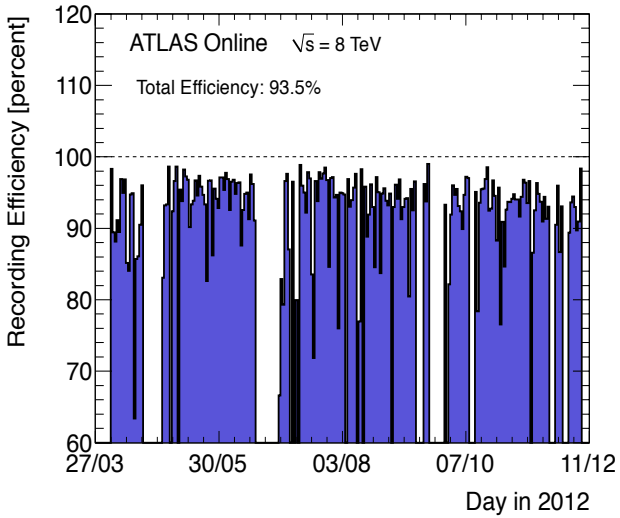
ATLAS



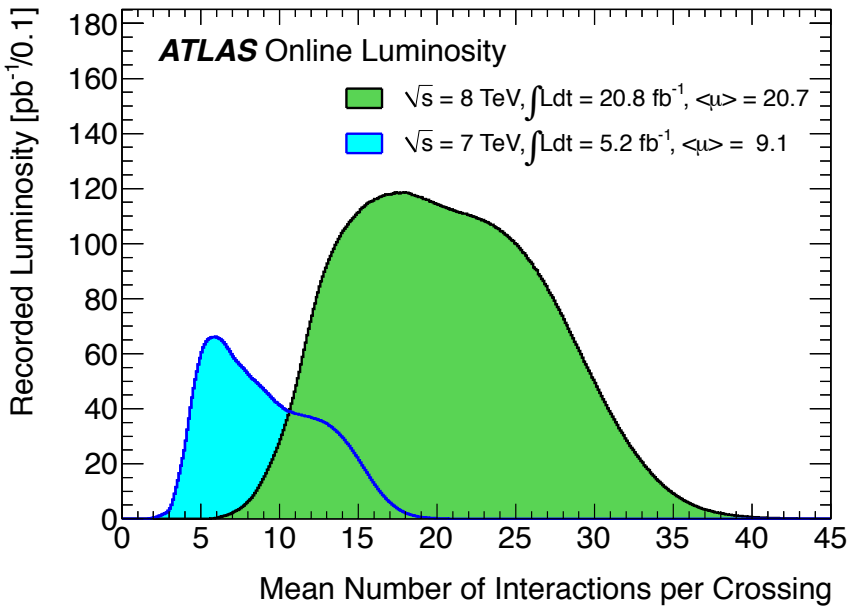




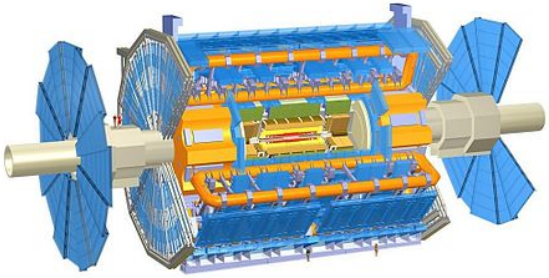




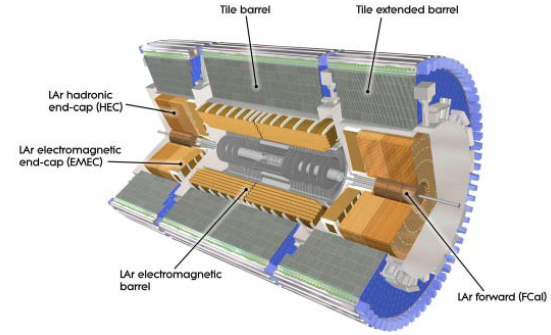
93.5% efficiency

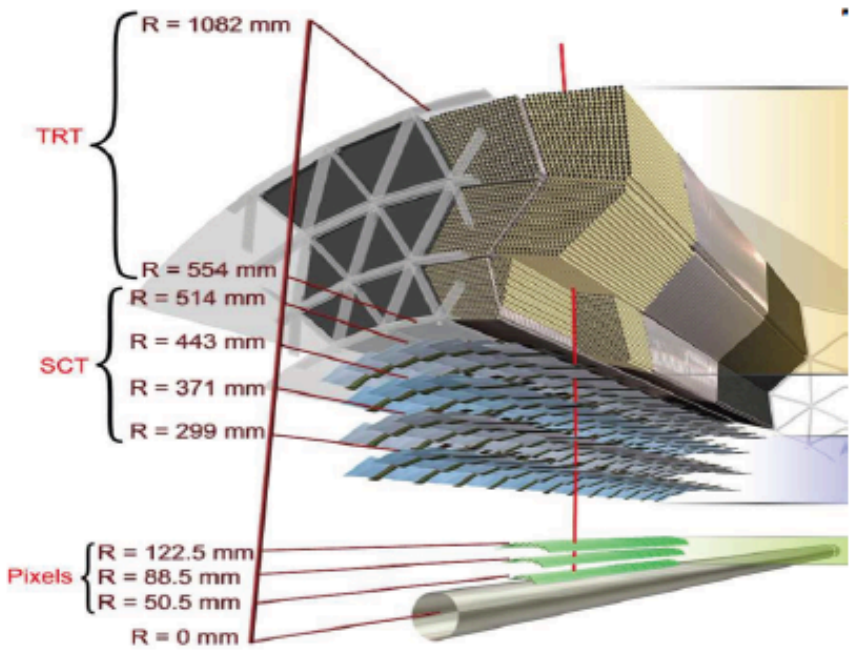


Challenging pile up conditions for the physics analysis



ATLAS
(relevant to photon ID)



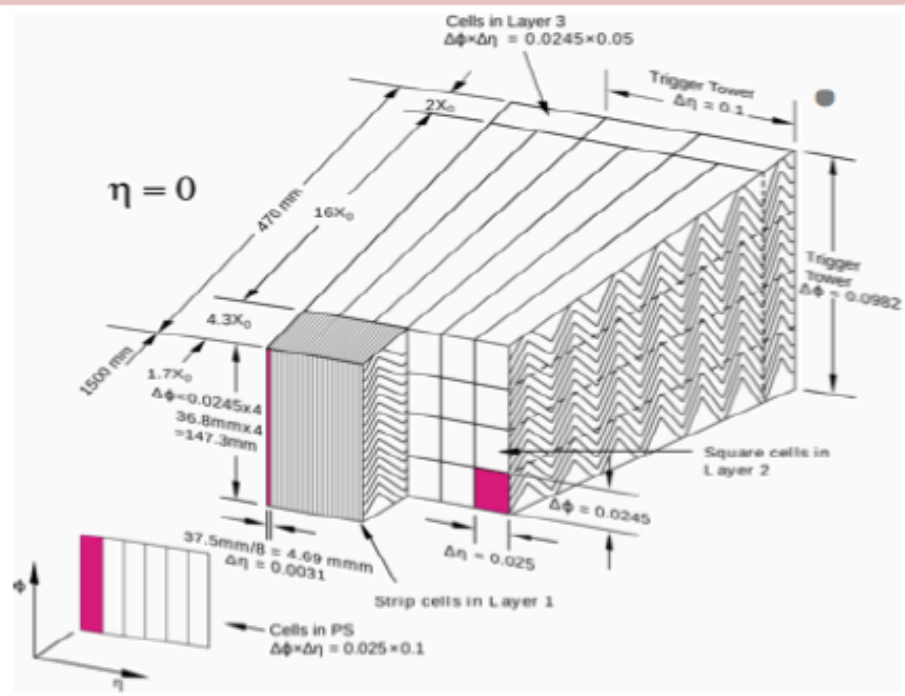


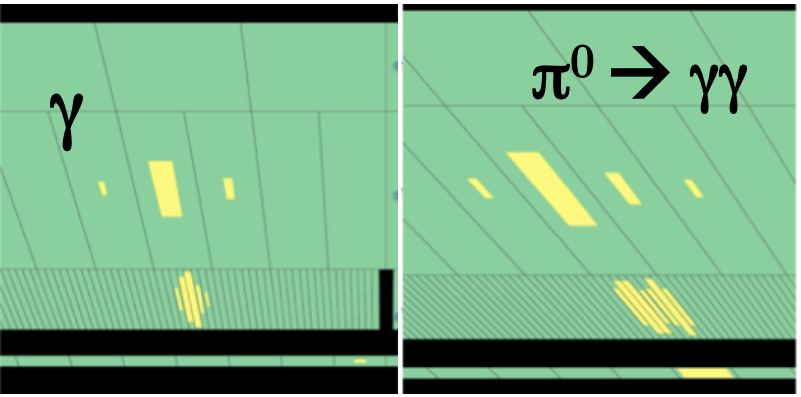
Inner Detector - Barrel (B)&End-cap (E) in 2T solenoidal magnetic field:

- Track reconstruction up to $|\eta|<2.47$;
- Conversion verticies reconstruction;
- e/γ and $e/\pi^{\pm}$ separation;
- Pixel: (B) 3 layers +(E) 2x3 disks $\sigma_{r\varphi}$~10 μm, σ_z~115 μm;
- Semi Conductor Tracker: (B) 4 layers +(E) 2x9 disks $\sigma_{r\varphi}$~17 μm, σ_z~580 μm;
- Transition Radiation Tracker: (B) 73 layers +(E) 2x160 layers σ_z~130 μm;

LAr lead sampling calorimeter with an 'accordion' geometry.

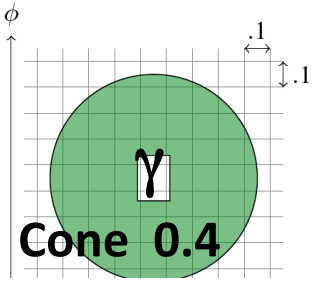
- 3 longitudinal layers with cell of $\Delta\eta \times \Delta\varphi$:
  - 1st layer (0.003÷0.006)x0.1;
  - 2nd layer 0.025x0.025;
  - 3rd layer 0.050x0.025.
- Presampler for $|\eta|<1.8$ $\Delta\eta \times \Delta\varphi$~0.025x0.1.
- Barrel-end-cap crack $|\eta|=1.37\div1.52$.
- $\sigma(E)/E=(10\text{-}17\%)(\eta)/\sqrt{E(\text{GeV})} \oplus (1.2\div1.8\%)$.

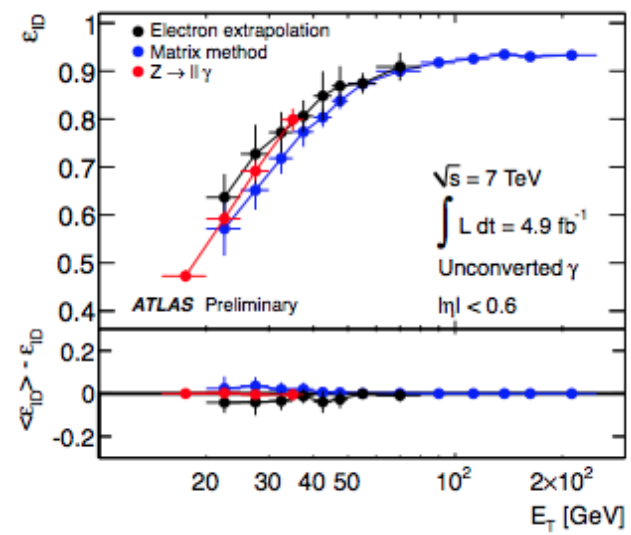




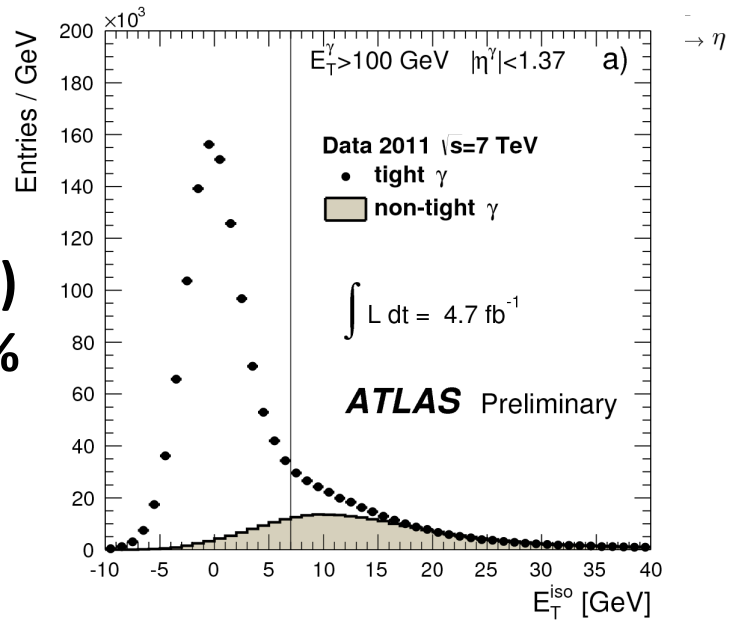
γ ID

ATLAS-CONF-2012-123
ATLAS-CONF-2013-022

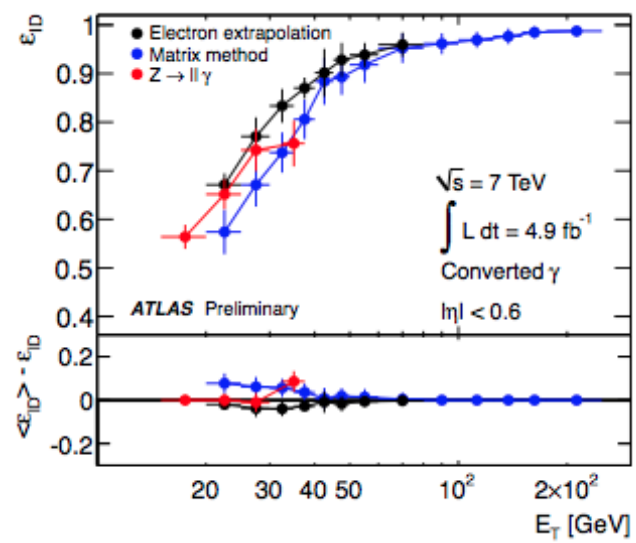




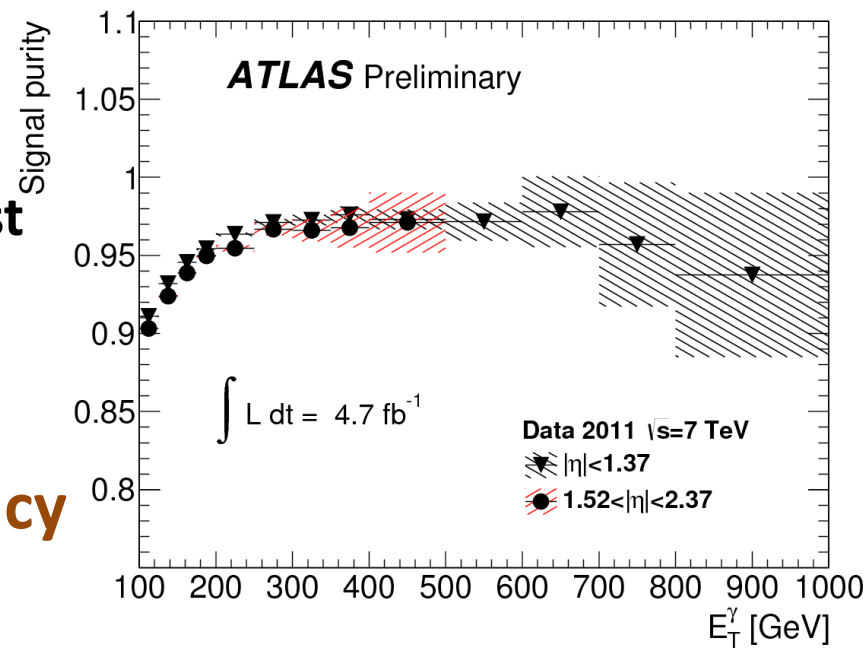
Slicing windown algoritm to determine the em-cluster (good photon– π^0 separation) E-scale known better than 1%



Reconstruction of both unconverted/converted photons



Photon isolation against multijet background



High purity/efficiency at large photon p_t

7 TeV
4.6 fb^{-1}

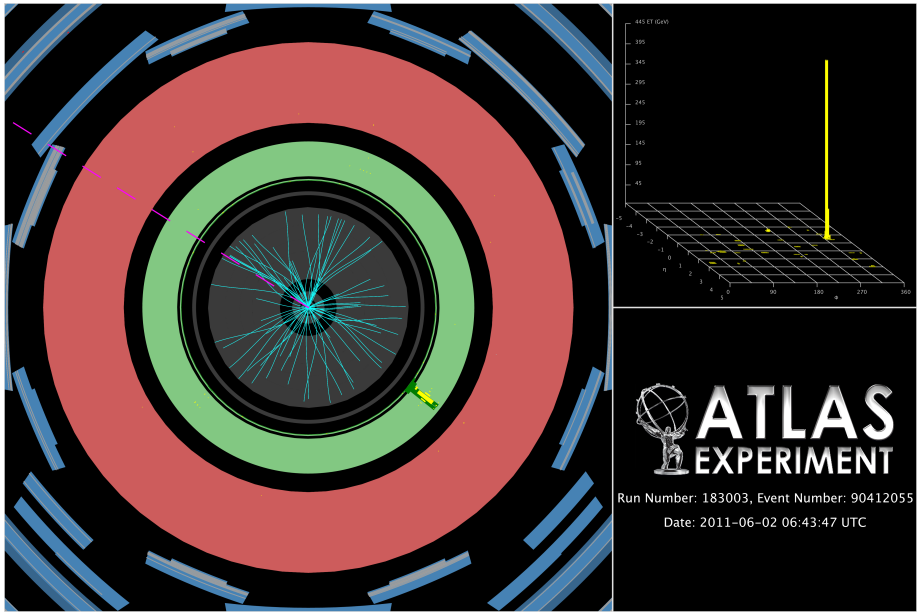
Monophotons

Event Selection

Events selected online with
E_t^{miss} > 70 GeV at the trigger level
(> 98% efficient for this analysis)

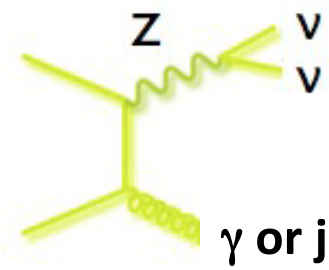
Well-reconstructed primary vertex
P_t^{γ} >150 GeV, $|\eta^{\gamma}|$ < 2.37, isolated
E_t^{miss} > 150 GeV
N^{jet} < 2 (p_T > 30 GeV) (anti-k_t 0.4)
$\Delta\phi$ (γ, E_T^{miss}) >0.4, $\Delta\phi$ (jet, E_T^{miss}) >0.4

Veto on leptons
(rejects W/Z backgrounds)
- No electrons with p_T > 20 GeV , $|\eta|$ < 2.47
- No muons with p_T > 10 GeV, $|\eta|$ < 2.4

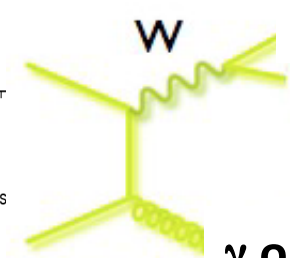


data sample: 116 events
(24% have one jet)

Backgrounds



γ or jet faking γ

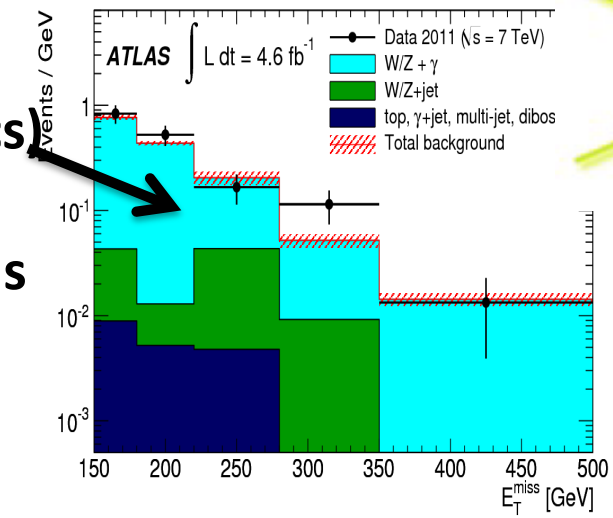


missed lepton

γ or jet faking γ

Background dominated by Z/W+γ processes (estimated using MC normalized in control regions)

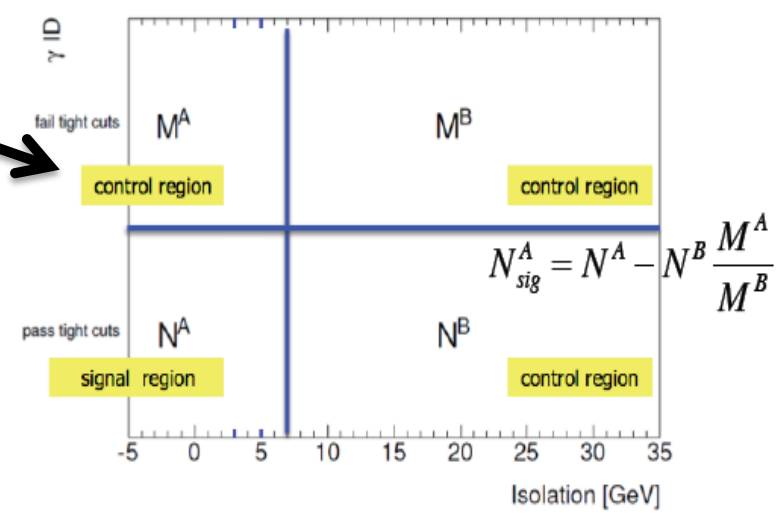
$\gamma + \mu + E_t^{miss}$ control sample (on top of signal region kinematics)



W/Z+jets with e or jets faking photons (determined from data)

k(W/Z+γ) ~1.1

e → γ (fake rate from data)
Jet → γ (isolation vs γ ID plane)



$$N_{sig}^{A} = N^{A} - N^{B}\frac{M^{A}}{M^{B}}$$

γ+jets and multijet background from data (using γ+jet sample with $\Delta\phi$ (jet, E_T^{miss}) < 0.4)

Small contributions from top, γγ, dibosons (Taken from MC normalized to NLO/NNLO)

Uncertainties

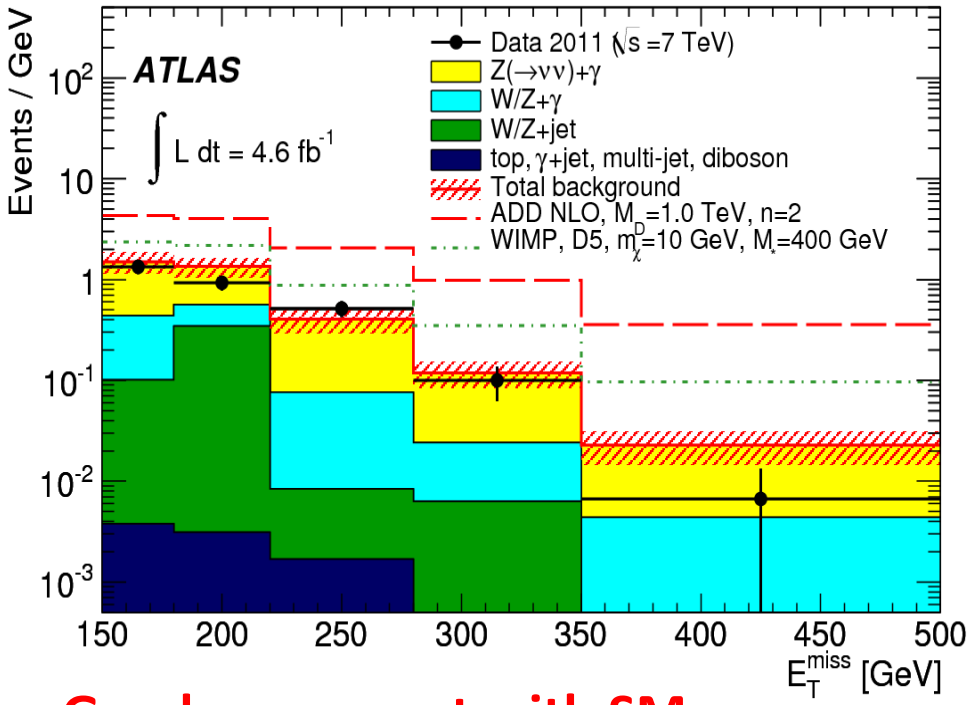
Source	Impact on total prediction	Note
γ E-scale	0.9%	
γ isolation/ID/resolution	1.1%	
Jet E-scale/resolution	0.9% - 1.2%	
Leptons	0.3%	
Low-pt jets/uncluster energy	0.8%	
Pileup subtraction	0.3%	
W/Z+γ modeling	**6.9%**	**Conservative (ALPGEN vs SHERPA)**
Others Sources	< 0.5%	Trigger, Luminosity, lepton p_t, normalization of small backgrounds (top, diboson) …
Statistical Component	**14%**	**Due to limited size control samples in data**

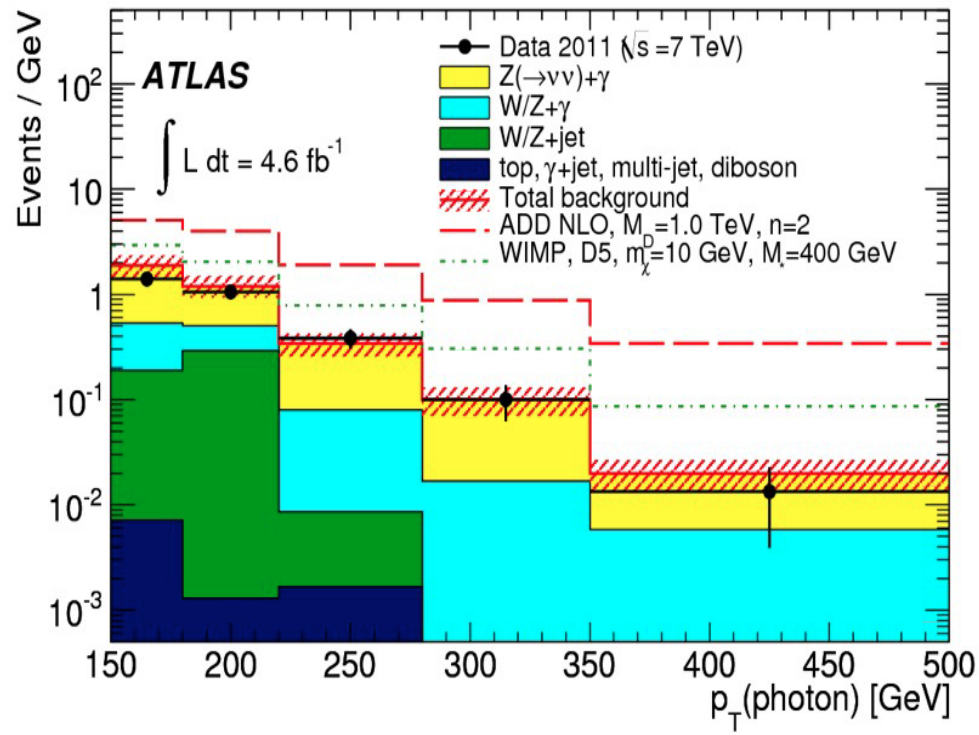
Some of the studies on systematics suffer from limited statistics in control samples

Room for improvement in the 8 TeV analysis

Results

Phys. Rev. Lett 110, 011802 (2013)





Good agreement with SM

Results translated into model-independent limits on σ x A x ε

σ x A x ε < 5.6 fb @ 90% CL

σ x A x ε < 6.8 fb @ 95% CL

Typical ε ~ 75%

Background source		Prediction	± (stat.)	± (syst.)
$Z(\to \nu\bar{\nu}) + \gamma$	68%	93	± 16	± 8
$Z/\gamma^*(\to \ell^+\ell^-) + \gamma$		0.4	± 0.2	± 0.1
$W(\to \ell\nu) + \gamma$	18%	24	± 5	± 2
W/Z + jets	13%	18	–	± 6
Top		0.07	± 0.07	± 0.01
$WW, WZ, ZZ, \gamma\gamma$		0.3	± 0.1	± 0.1
γ+jets and multi-jet		1.0	–	± 0.5
Total background		137	± 18	± 9
Events in data (4.6 fb^{-1})		116		

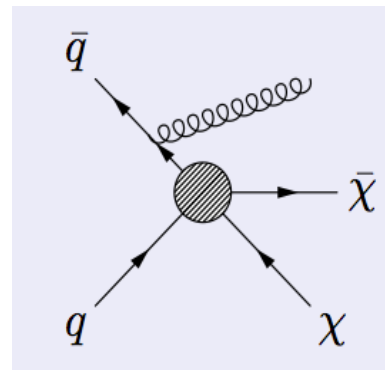
Effective Theory

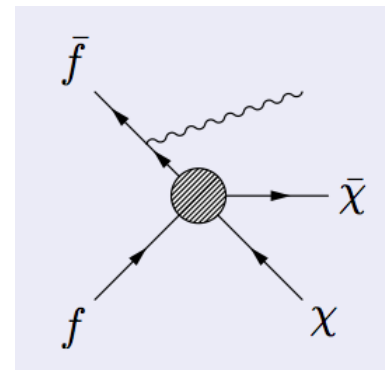
(model independent approach)

Effective Lagrangian approach (contact interaction) with parameters M_* and m_χ

$$M_*^2 \sim M^2/g_1 g_2$$

assuming the interaction is mediated by a heavy particle with mass M and couplings g_1 and g_2





Different operators are considered with different structures and here χ will be taken as Dirac fermions

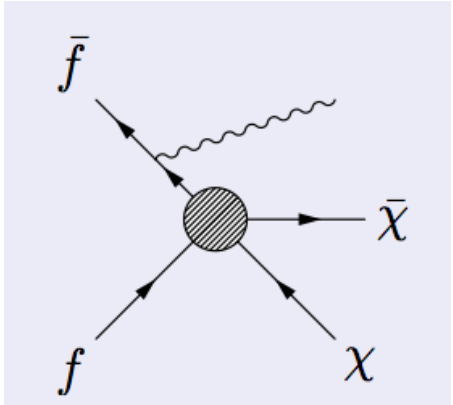
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Important note:

Not clear whether the effective approach under- or over-estimates the cross sections since this depends on the details of the unknown UV limit of the theory

Strictly speaking theory only applicable when M is much larger than the energy scale present in the reaction [$Q^2 \ll (4\pi M_*)^2$]

90% CL Limits on M_*



A x ε in the range between 11% (D1) and 23% (D9) (due to different E_t^{miss} spectrum)

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

On signal yields:

Experimental uncertainties (7%)

Theoretical uncertainties

ISR/FSR (4 % – 10%)

PDFs (5% - 30%)

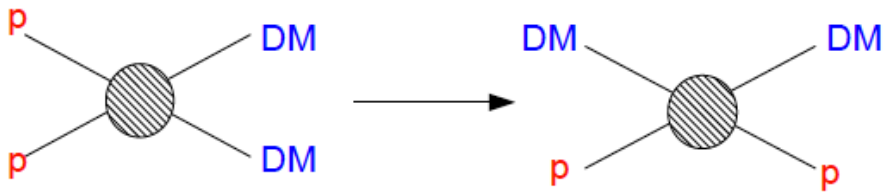
$\mu_{R,F}$ (8%)

$$\sigma^{D1} \propto (1/M^*)^6$$
$$\sigma^{D5,D8,D9} \propto (1/M^*)^4$$

WIMP MASS	M_* in D1 (GeV)	M_* in D5 (GeV)	M_* in D8 (GeV)	M_* in D9 (GeV)
1 GeV	> 31	> 585	> 585	> 794
1.3 TeV	> 5	> 156	> 100	> 188

Results are translated *into 90% CL limits* on M_* for different operators and as a function of WIMP mass

WIMP-nucleon cross section

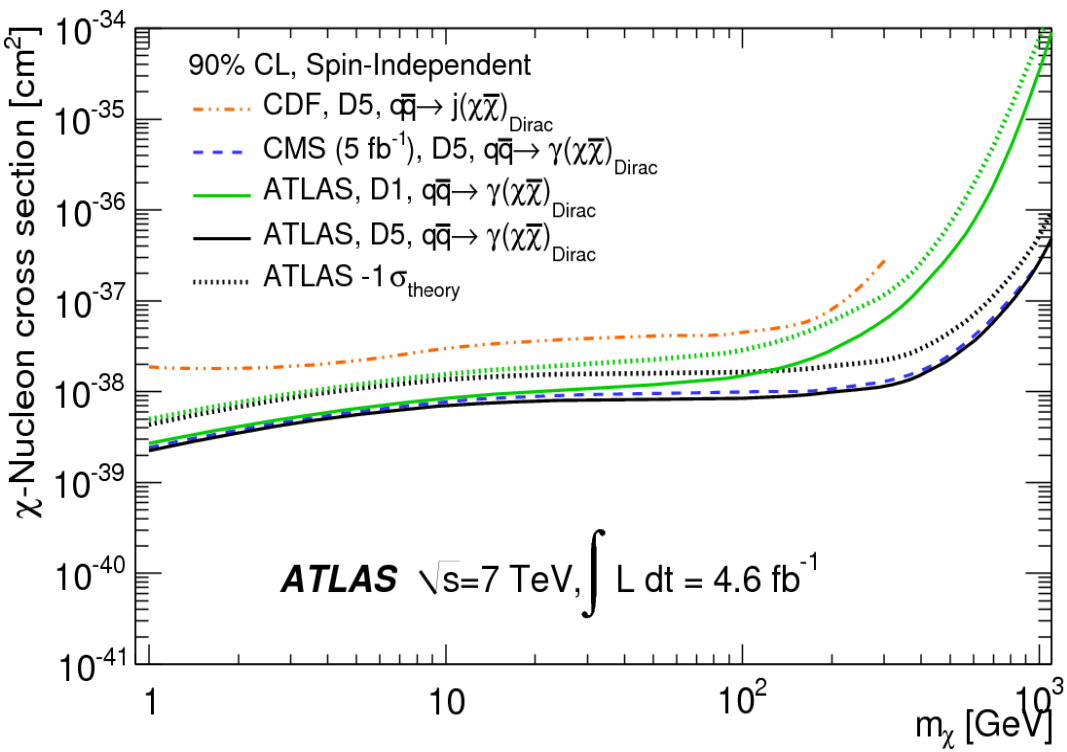


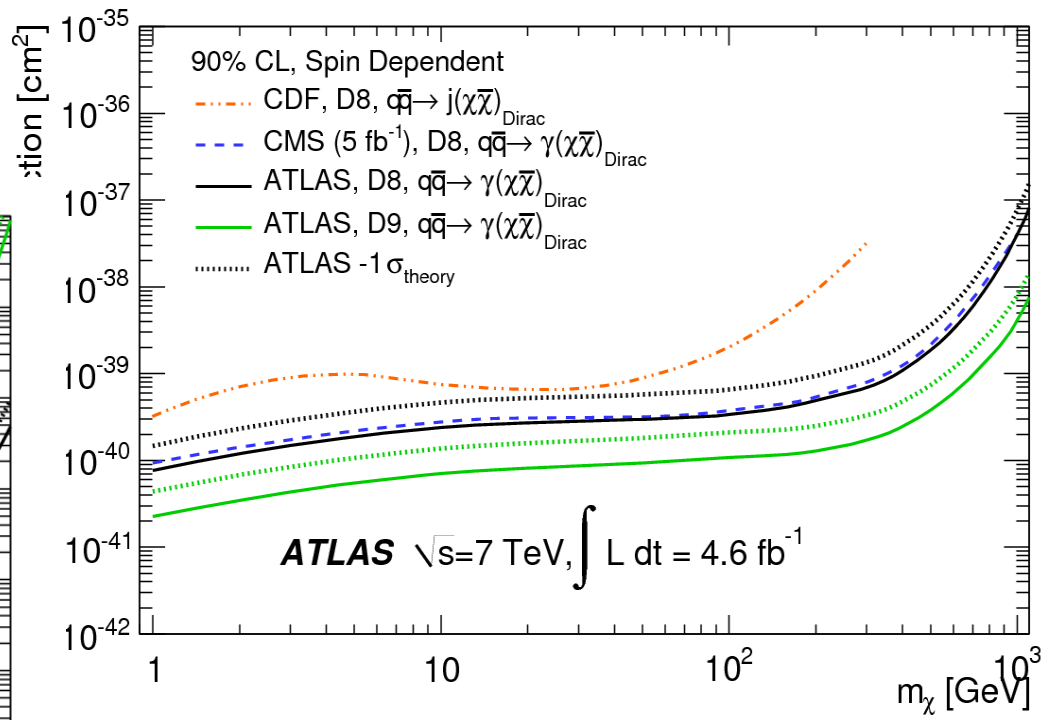
$$\sigma^{D1} = 1.60 \times 10^{-37} \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{20\ GeV}{M^*}\right)^6$$

$$\sigma^{D5} = 1.38 \times 10^{-37} \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{300\ GeV}{M^*}\right)^4$$

$$\sigma^{D8,D9} = 4.7 \times 10^{-39} \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{300\ GeV}{M^*}\right)^4$$

Different operators contribute either to spin-dependent or spin-independent WIMP-nucleon cross sections

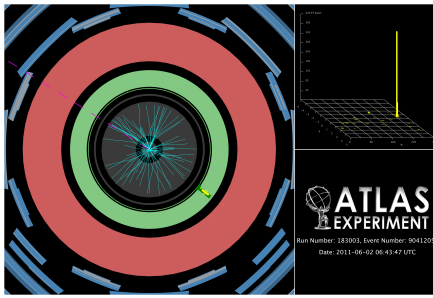


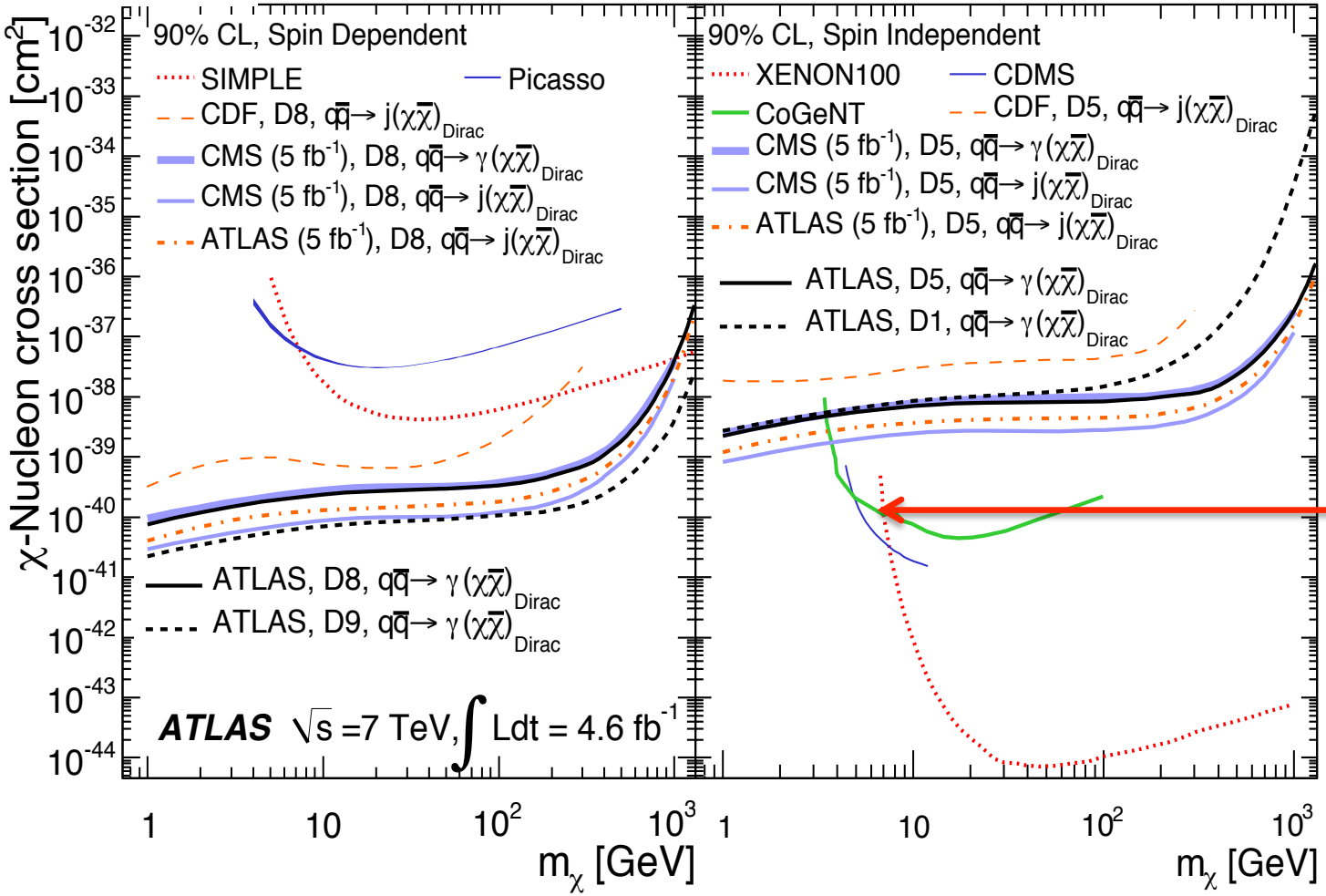


Within the assumption of the validity of the effective theory **the LHC results complement direct detection searches (particularly relevant at m_χ < 10 GeV)**

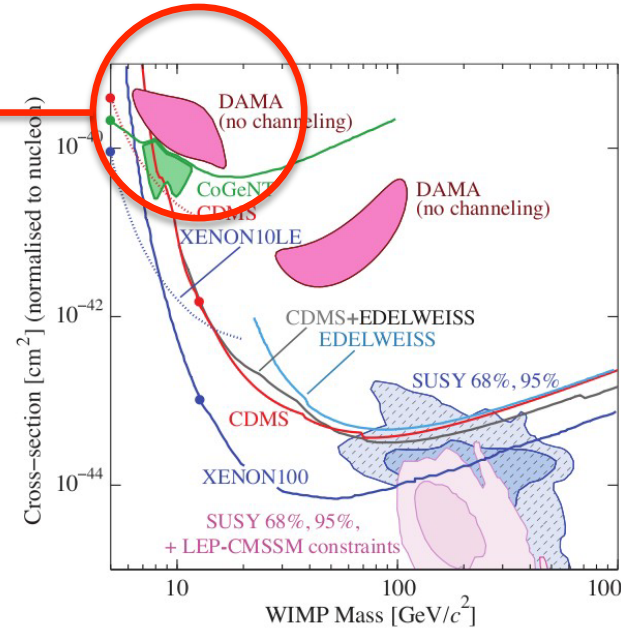
WIMPS

(monojets & monophotons)





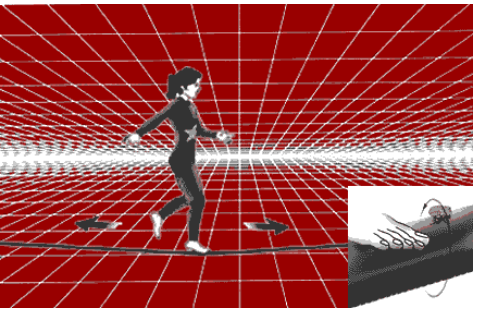
Not enough sensitivity yet to exclude/confirm the CoGeNT/DAMA excess at m_χ~10 GeV in case the of D1/D5 models



Very significant improvement on limits compared to Tevatron

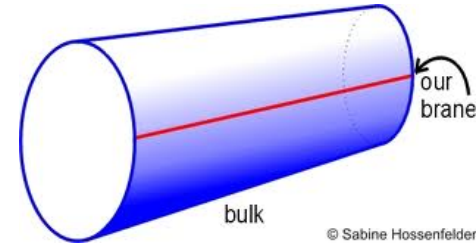
For m_χ < 100 GeV : WIMPS-nucleon cross sections above

3 x10^{-40} cm^2 (10^{-39} cm^2) are excluded for spin –dependent (spin-independent) operators



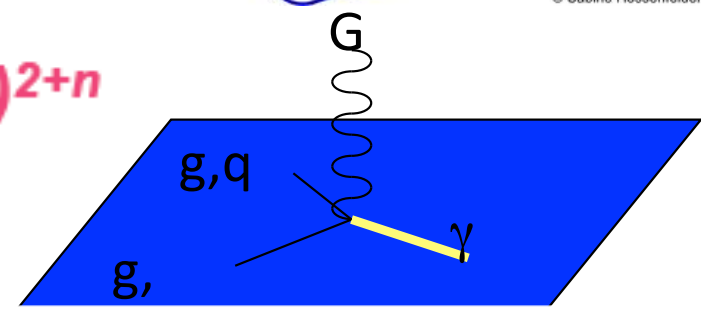
Large Extra Dimensions

Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale ~TeV)



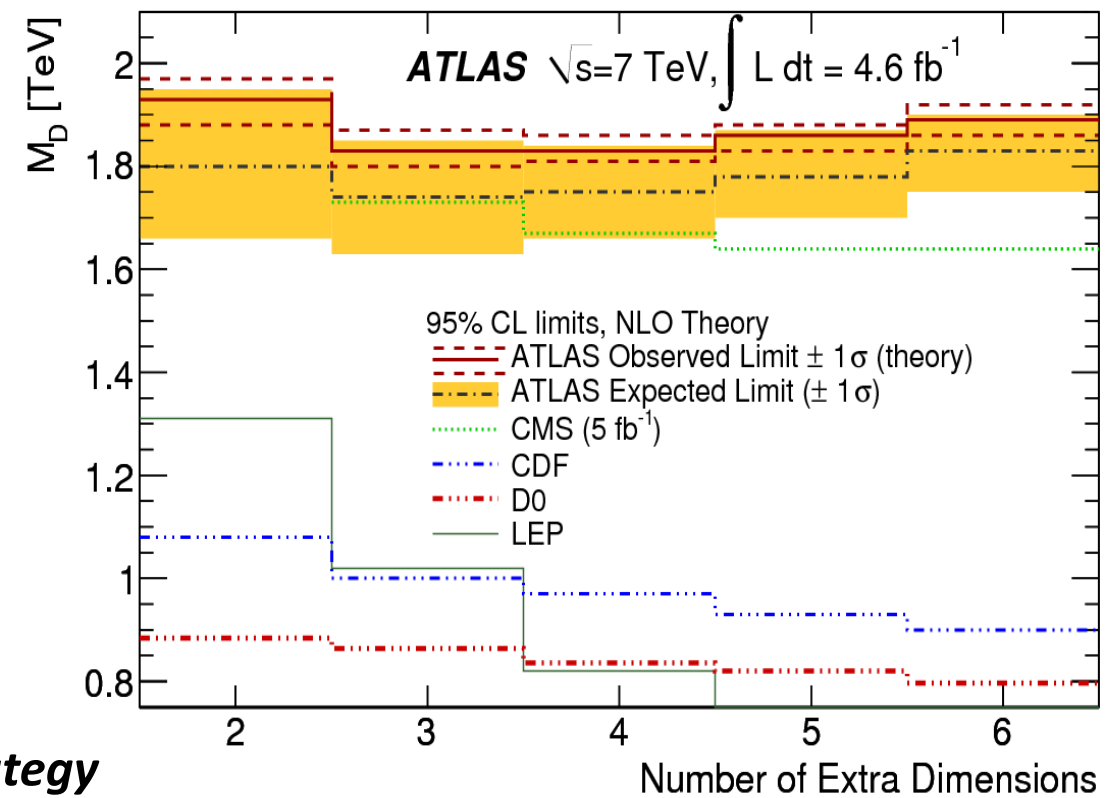
A x ε about 20%
(approx. independent on n and M_D)

$$(M_{PL})^2 \sim R^n (M_D)^{2+n}$$



On signal yields:
Experimental uncertainties (7%)
Theoretical uncertainties
ISR/FSR (4%)
PDFs (4% - 11% *as n increases*)
$\mu_{R,F}$ (9% - 5% *as n increases*)

***95% CL limits* on M_D vs n**



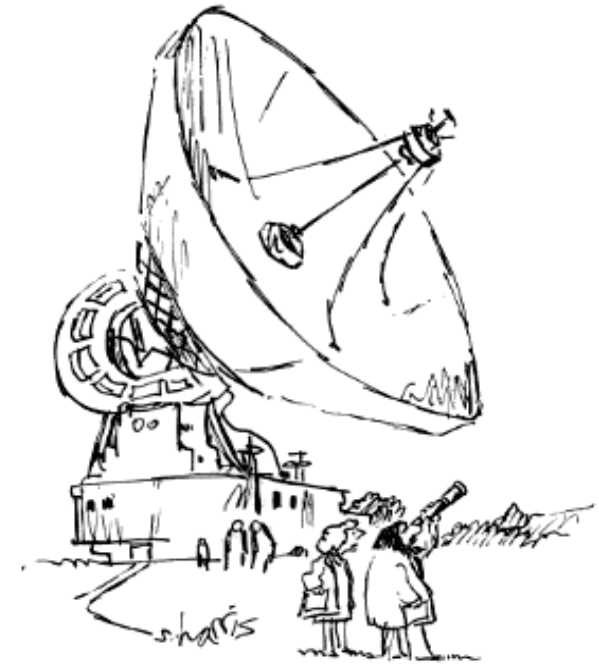
Limits on M_D beyond 1.9 TeV
(a real challenge for the model validity)

Note: Limits sensitive to the truncation strategy for s-hat > M_D^2 (15% to 75% of the ADD cross section as n increases)

… LHC probing phase space at large Q^2

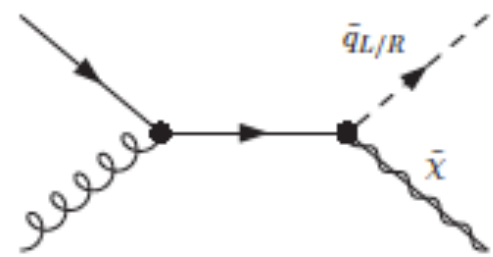
Final Notes

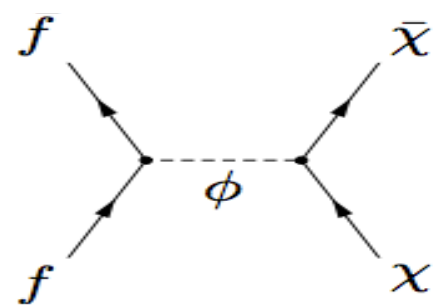
- **Very successful LHC operations**
- **More than 26 fb-1 of data on tape for ATLAS (7 TeV & 8 TeV)**
- **7 TeV results on monophotons**
- ***Within the effective lagrangian framework* the LHC DM searches are rather competitive & complement direct detection experiments**
- **Searches continue with 8 TeV dataset including all possible mono-X channels**



"Just checking."

..and more data bring new things and more direct access to DM





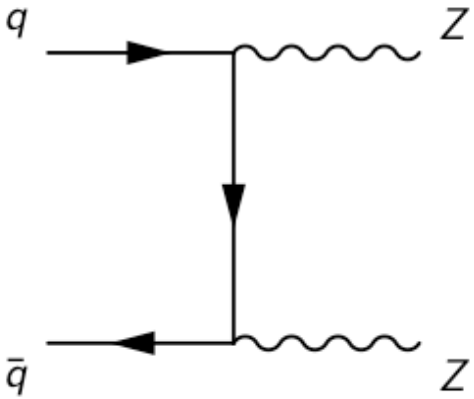
More Energy and More Data !

El LHC will almost double the centre-of-mass energy in 2015

8 TeV → 14 TeV
with increased luminosity

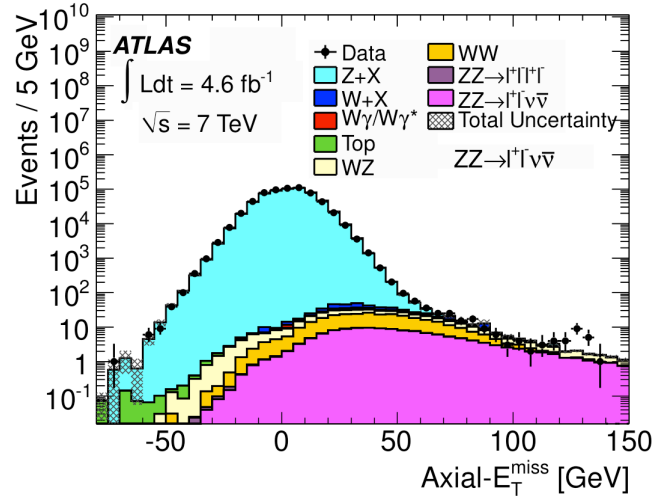
Ready for a new discovery ?

Backup Slides



Mono-Z
(ZZ → ll νν)

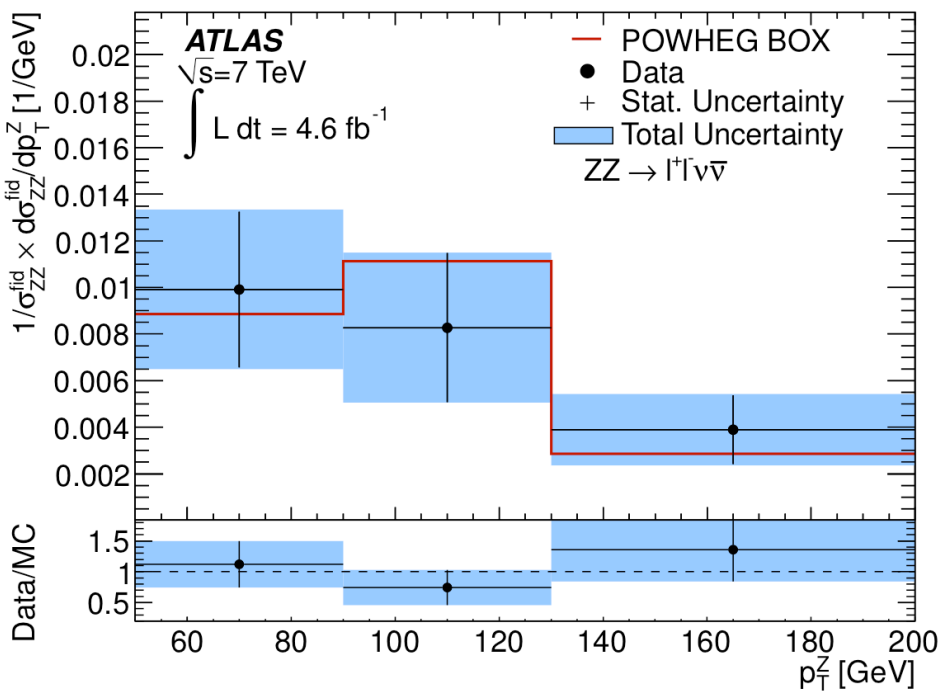
arXiv:1211.6096

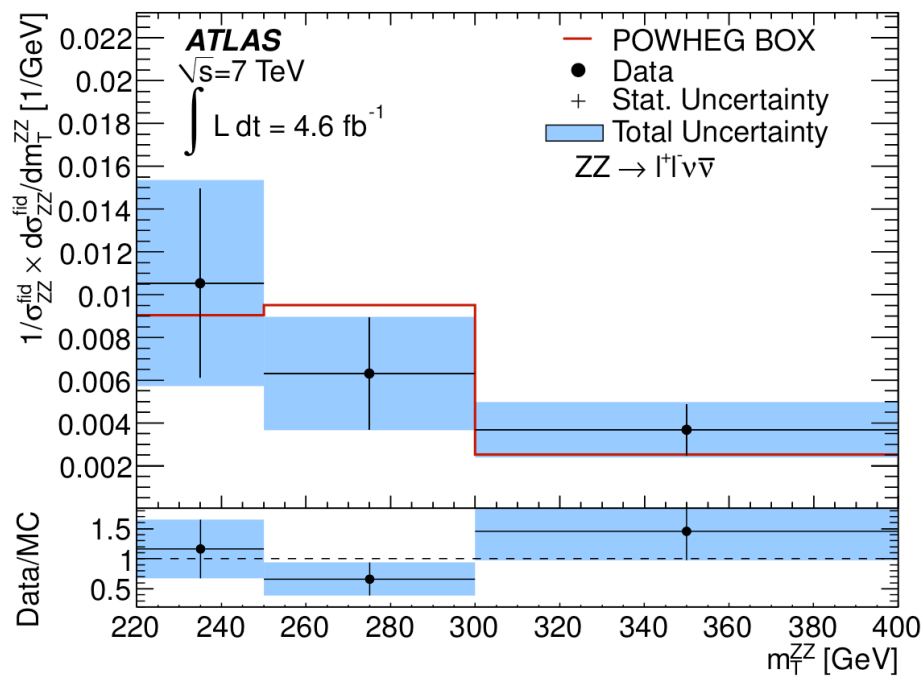


No jets with p_T above 25 GeV

$$(|p_T^{\nu\bar{\nu}} - p_T^Z|)/p_T^Z < 0.6$$

$$-p_T^{\nu\bar{\nu}} \times \cos(\Delta\phi(p_T^{\nu\bar{\nu}}, p_T^Z)) > 80 \text{ GeV}$$





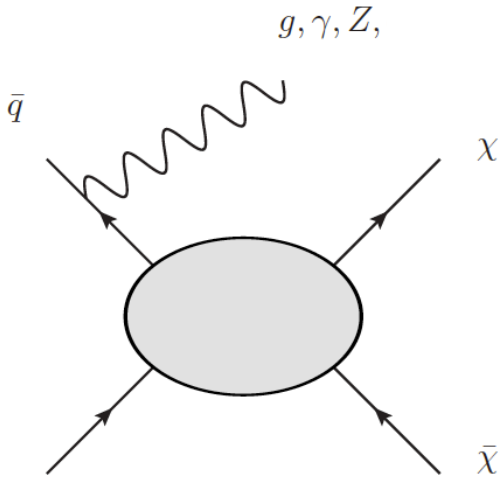
$$\sigma^{\text{fid}}_{ZZ\to\ell^+\ell^-\nu\bar{\nu}} = 12.7^{+3.1}_{-2.9}\ (\text{stat.})\ ^{+1.7}_{-1.7}\ (\text{syst.}) \pm 0.5\ (\text{lumi.})\ \text{fb}.$$

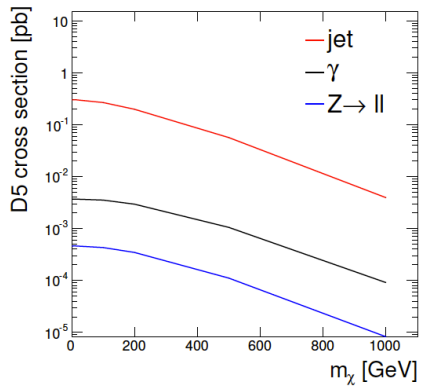
In good agreement with SM predictions

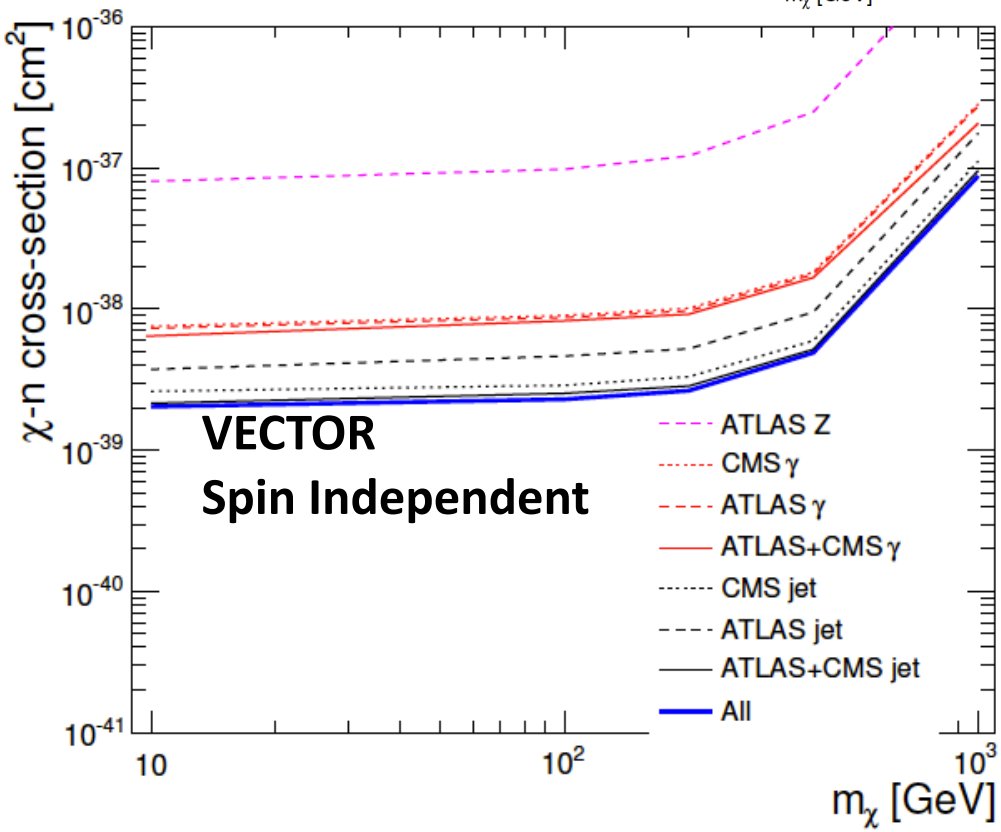
This can be used to put limits on χχ+Z

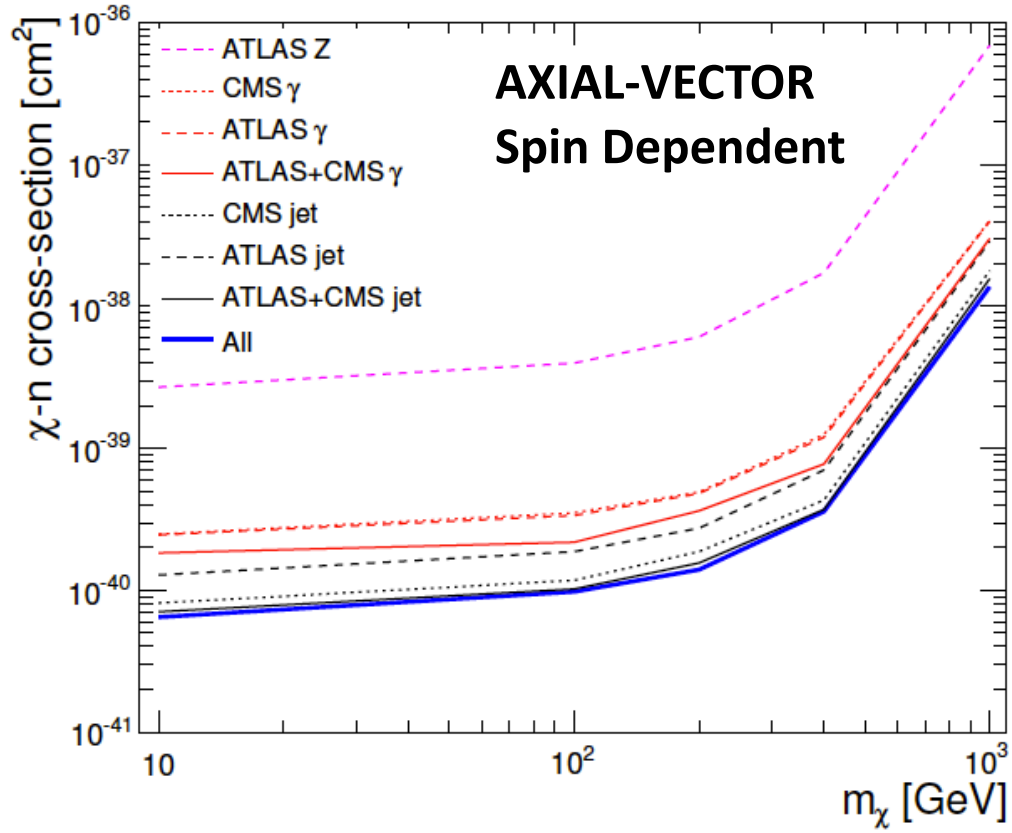
Un-official combination ATLAS & CMS Mono-X

Ning Zhou et al., arXiv:1302.3619

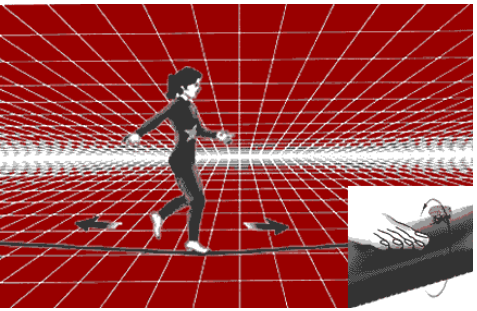






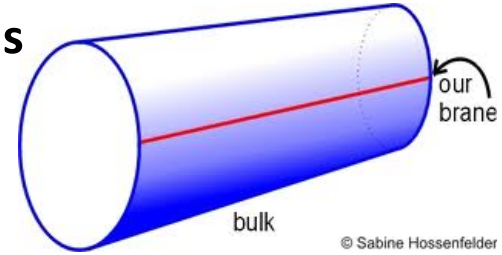


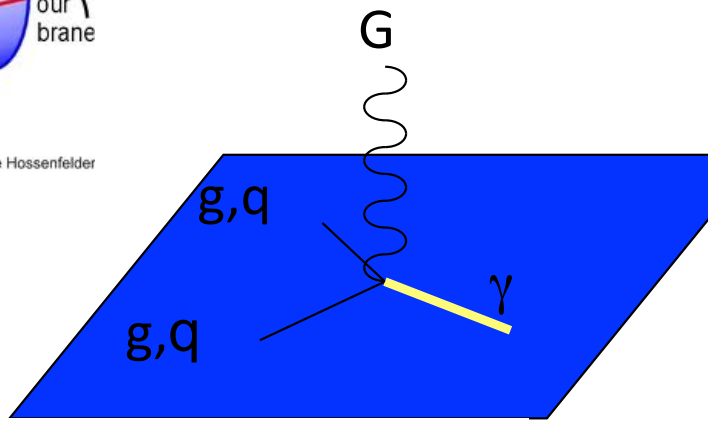
As expected the combination is totally dominated by the mono-jet results



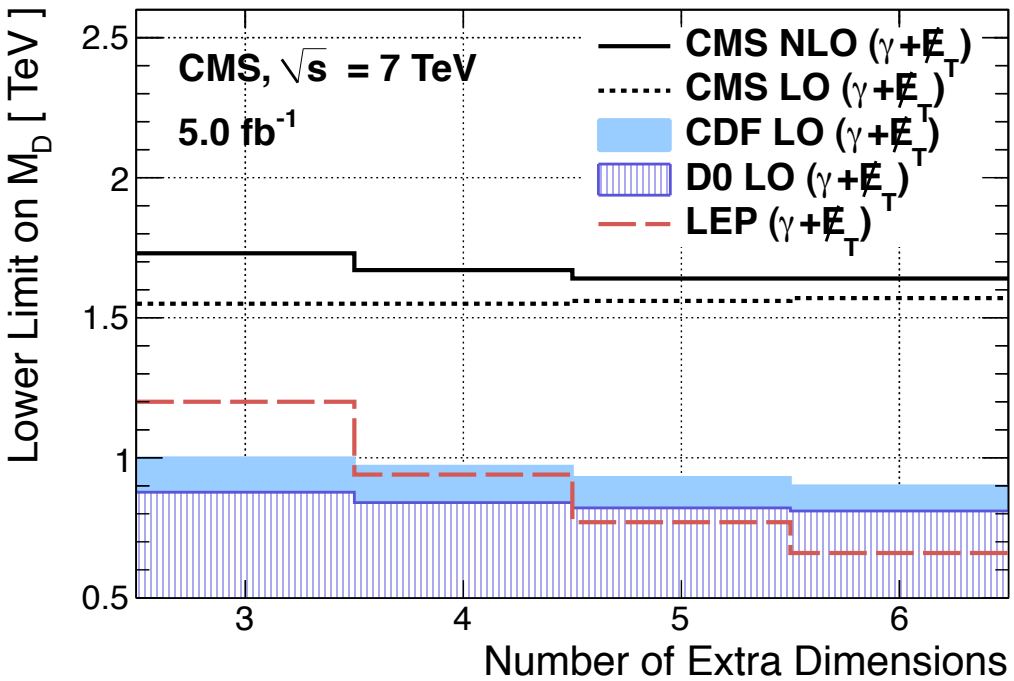
Large Extra Dimensions

Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale ~TeV)

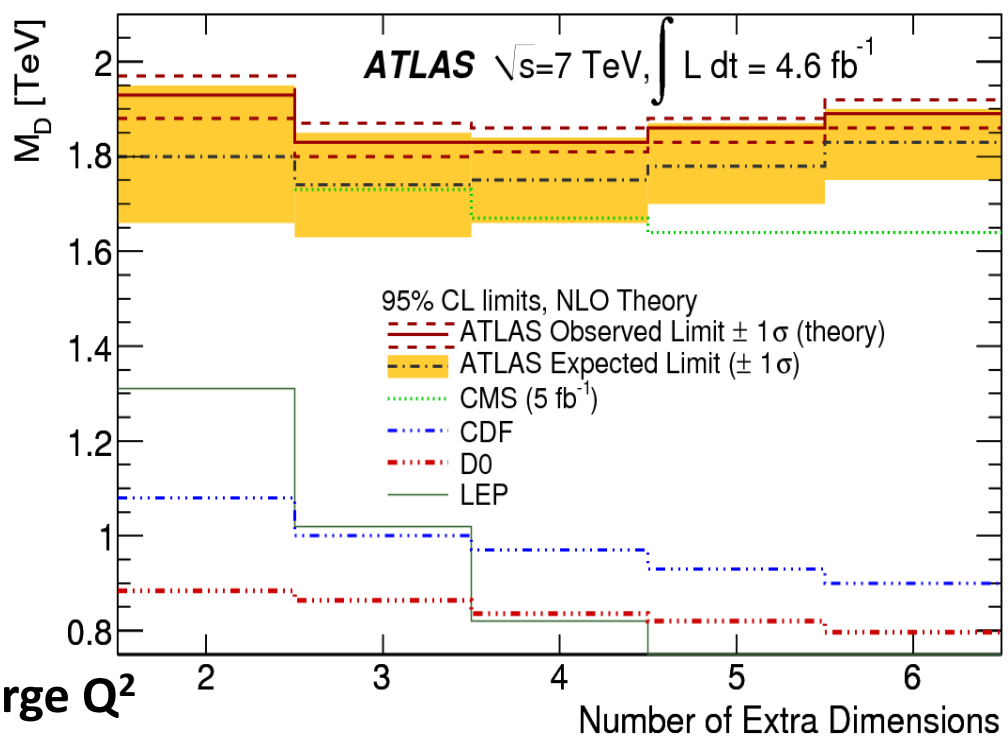




monophoton



$$(M_{PL})^2 \sim R^n (M_D)^{2+n}$$

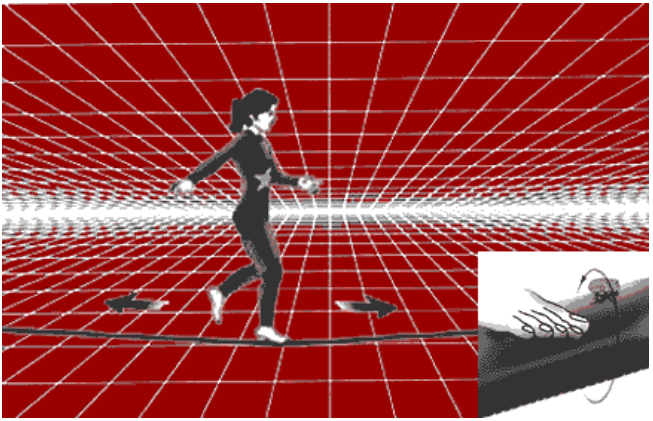


Limits on M_D beyond 1.5 TeV
(a real challenge of the model model validity)

Note: Limits sensitive to the truncation strategy for s-hat > M_D^2 … LHC probing phase space at large Q^2

Extra Dimensions

Alternative to solve Hierarchy Problem

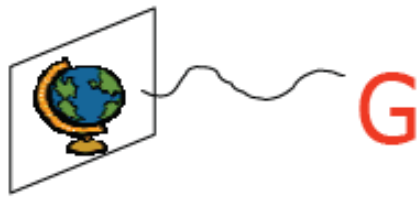


Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale ~ 1 TeV)

ADD

Arkani-Hamed, **D**imopoulos, **D**vali,
Phys Lett B429 (98)

Many large compactified EDs
In which G can propagate



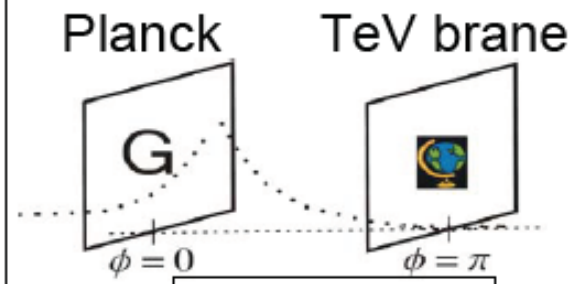
$$M_{Pl}^2 \sim R^n M_{Pl(4+n)}^{(2+n)}$$

Effective $M_{Pl} \sim 1\text{TeV} \rightarrow$ if compact space (R^n) is large

RS

Randall, **S**undrum,
Phys Rev Lett 83 (99)

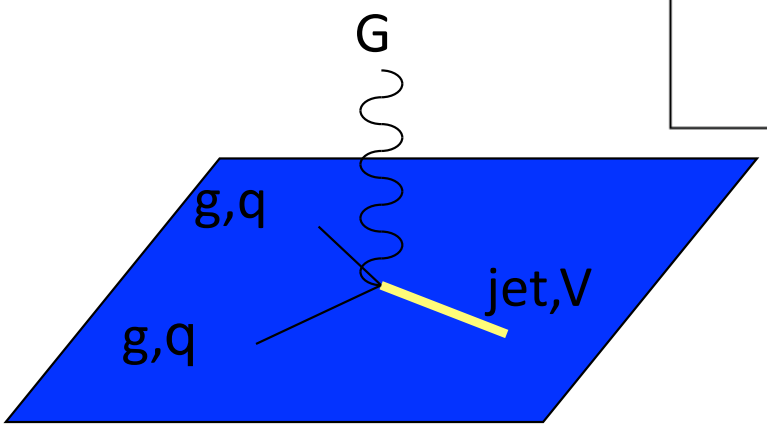
1 highly curved ED
Gravity localised in the ED



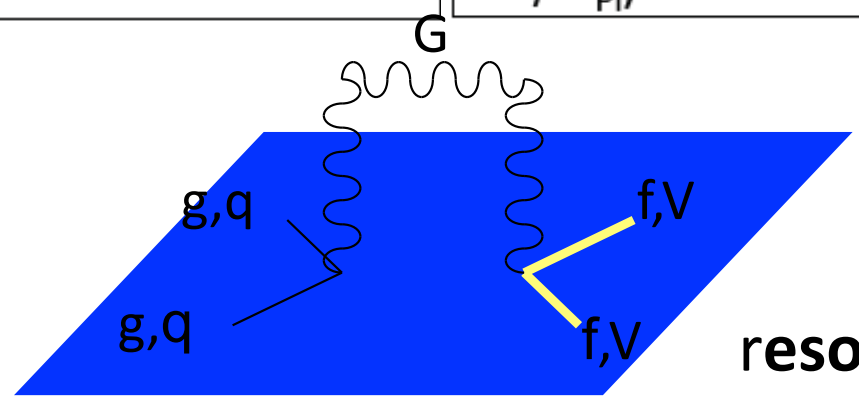
$$\Lambda_\pi = \overline{M}_{pl} e^{-kR_c\pi}$$

$\Lambda_\pi \sim$ TeV

if warp factor $kR_c \sim 11\text{-}12$
k/M_{Pl}, k: curvature scale



monojet/monophoton



resonances