

Elementary Particle Physics: theory and experiments

Discovery of the Higgs boson

- **Measurements: mass, spin, couplings**

Searches for New Physics

- **Supersymmetry**
- **Exotic models**
- **Dark Matter**
- **Unconventional signatures**

The Higgs field and Standard Model

Higgs Field

- Has non-zero vacuum expectation value
- Lead to electroweak symmetry breaking

Higgs Mechanism

- Can explain non-zero gauge boson masses
- Remarkably can also produce fermion masses

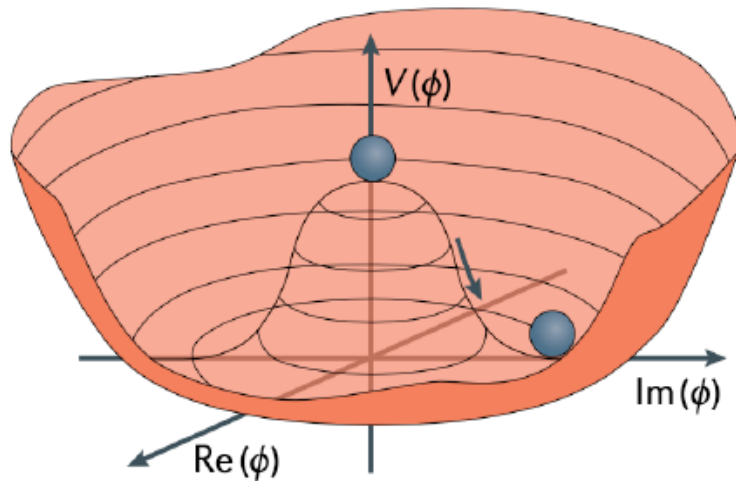
Higgs Boson Particle

- Excitation of the Higgs field
- Unique chance to probe the Higgs field



Englert and Brout & Higgs
& Guralnik, Hagen and Kibble

The Higgs potential



$$|\phi|_{\min} = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{\nu}{\sqrt{2}}, \nu = 246 \text{ GeV}$$

When $\mu^2 < 0$ the potential has a minimum at:

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

$$\lambda = m_H^2/2\nu^2 \approx 0.13$$

Measurement of λ is crucial to reconstruction the Higgs potential and therefore test the Higgs mechanism

Baryogenesis requires a first order electroweak phase transition, which would lead to a modification to the Higgs potential ...

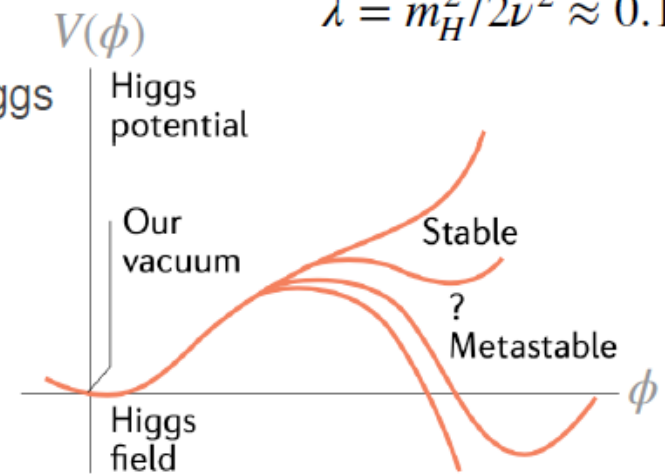


Image credit: *Nature Reviews Physics* 3.9 (2021)

Higgs self-coupling

- Direct exploring the potential at each Higgs field value ϕ is not possible.

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \supset \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$

Mass term

$\kappa_\lambda = \lambda_{\text{HHH}}/\lambda_{\text{SM}}$

self-coupling

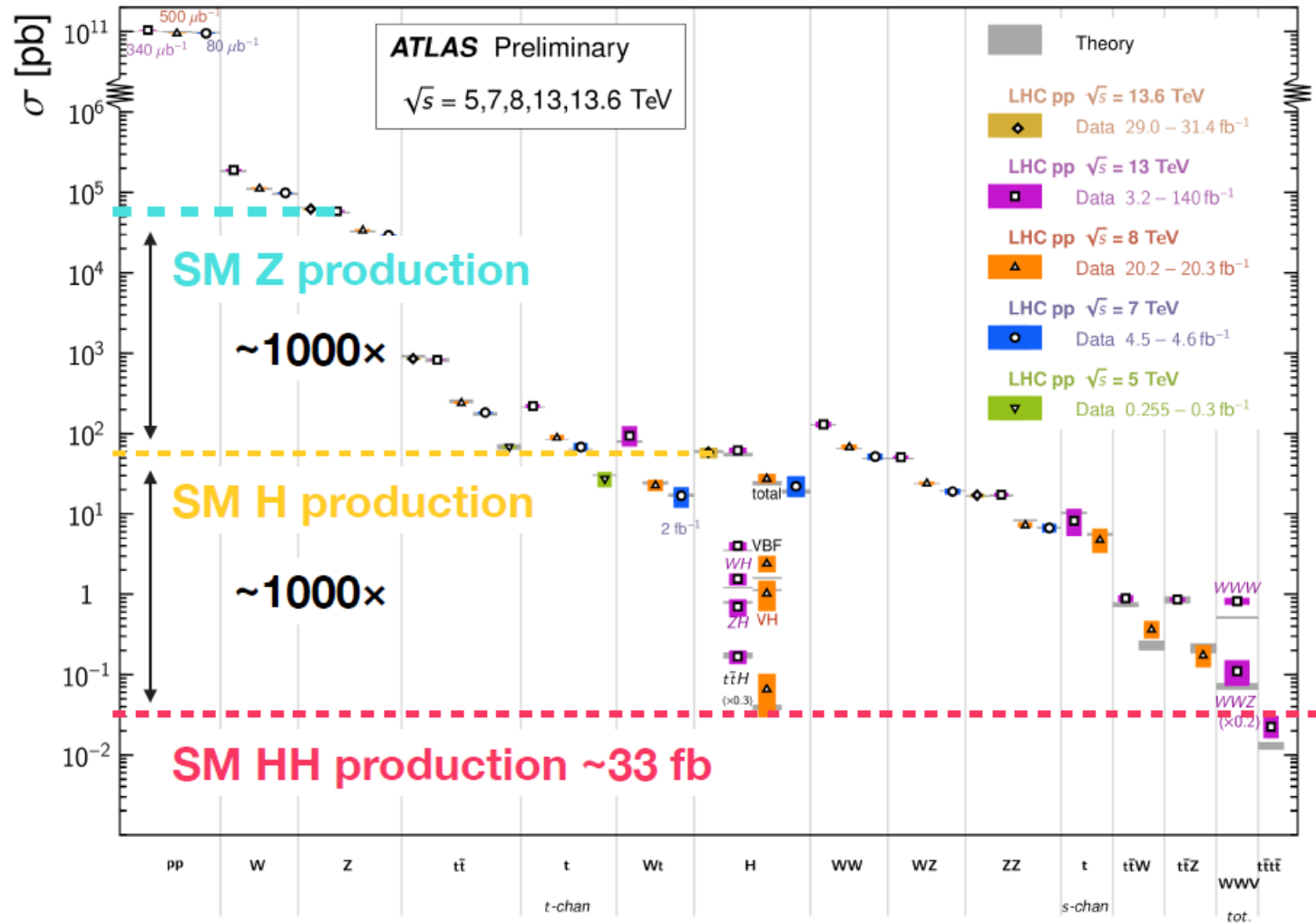
- Probing the Higgs-self coupling is a key towards pinning down exact shape of the potential.

Study of Higgs boson pair production (HH) can shed light

Higgs cross-sections

Standard Model Total Production Cross Section Measurements

Status: October 2023

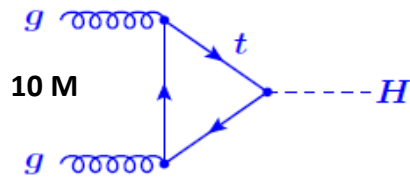


Discovery of the Higgs boson

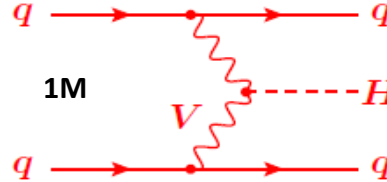
- Measurements: mass, spin, couplings

The Higgs Boson at the LHC

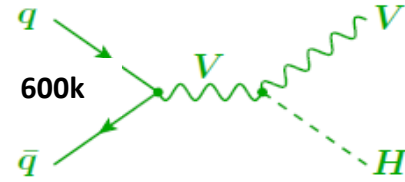
Production



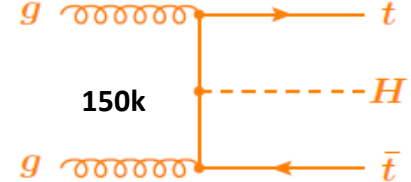
Main production channel



2 forward jets,
little central
hadronic activity



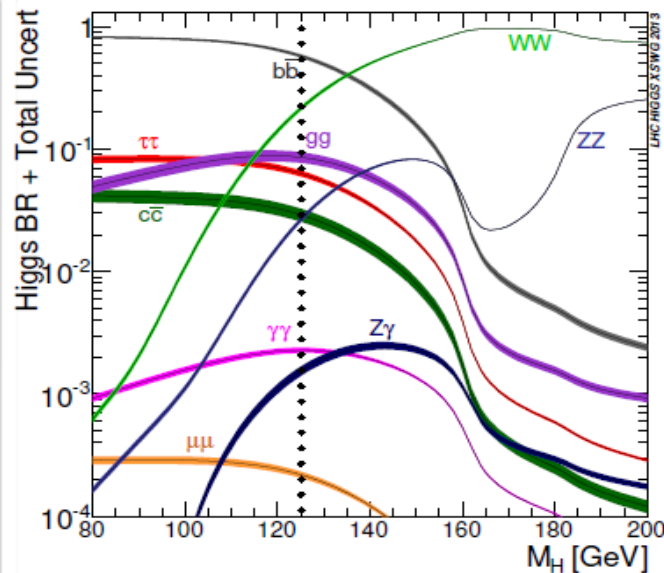
Tag W and Z
decays



Tag 2 top quarks

#Higgs produced at
13 TeV (2015-2017)

Decays



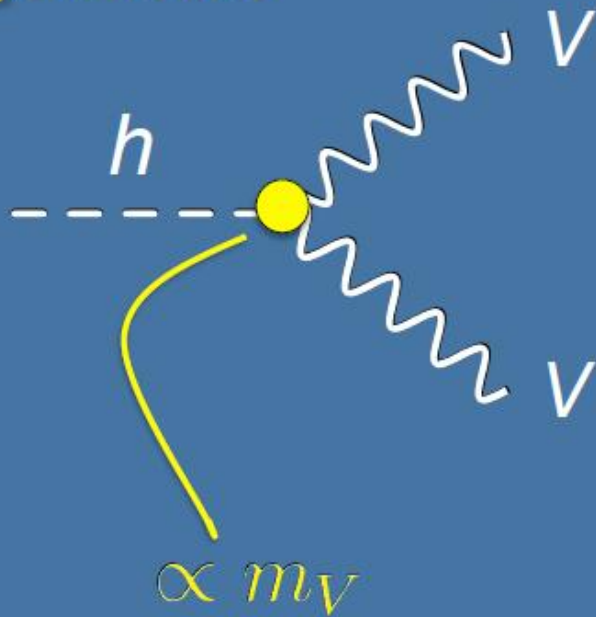
5 main channels at the LHC

Decay branching fractions for
 $m_H = 125$ GeV

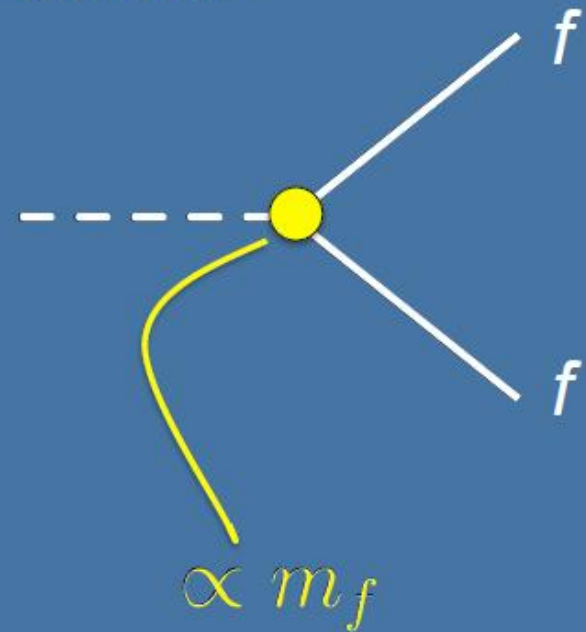
- $H \rightarrow bb$: 58 %
- $H \rightarrow WW^*$: 21%
- $H \rightarrow \tau^+\tau^-$: 6.3%
- $H \rightarrow ZZ^*$: 2.6%
- $H \rightarrow \gamma\gamma$: 0.2%

Higgs boson couplings

Gauge bosons

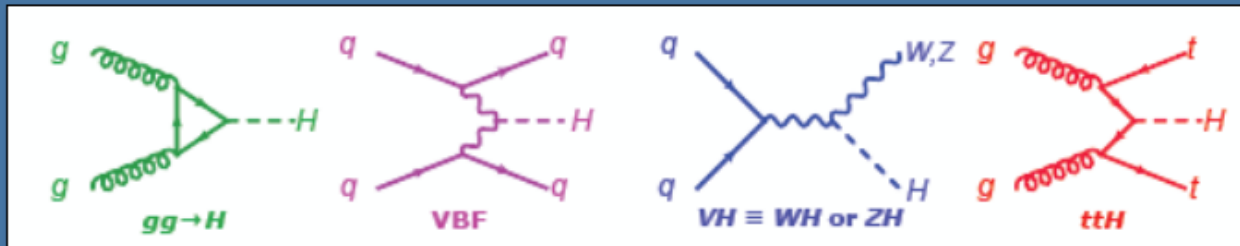


Fermions

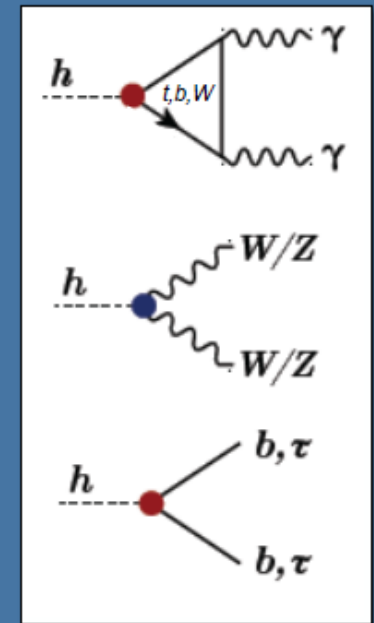


Higgs boson properties are fixed in the Standard Model (m_h)

Higgs boson phenomenology

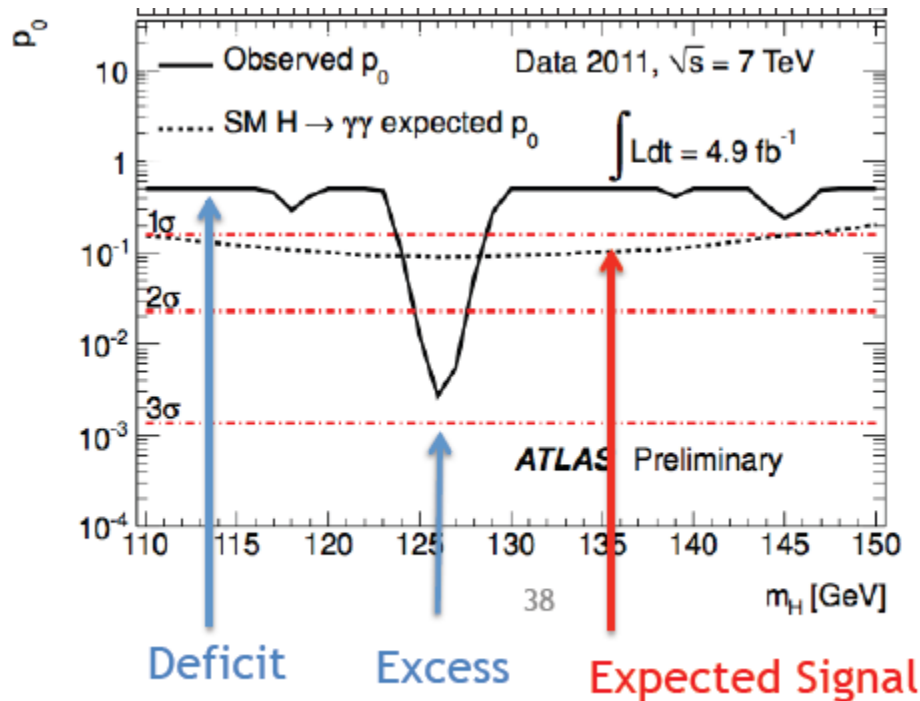


‘production & decay matrix’
sensitivity to different Higgs properties

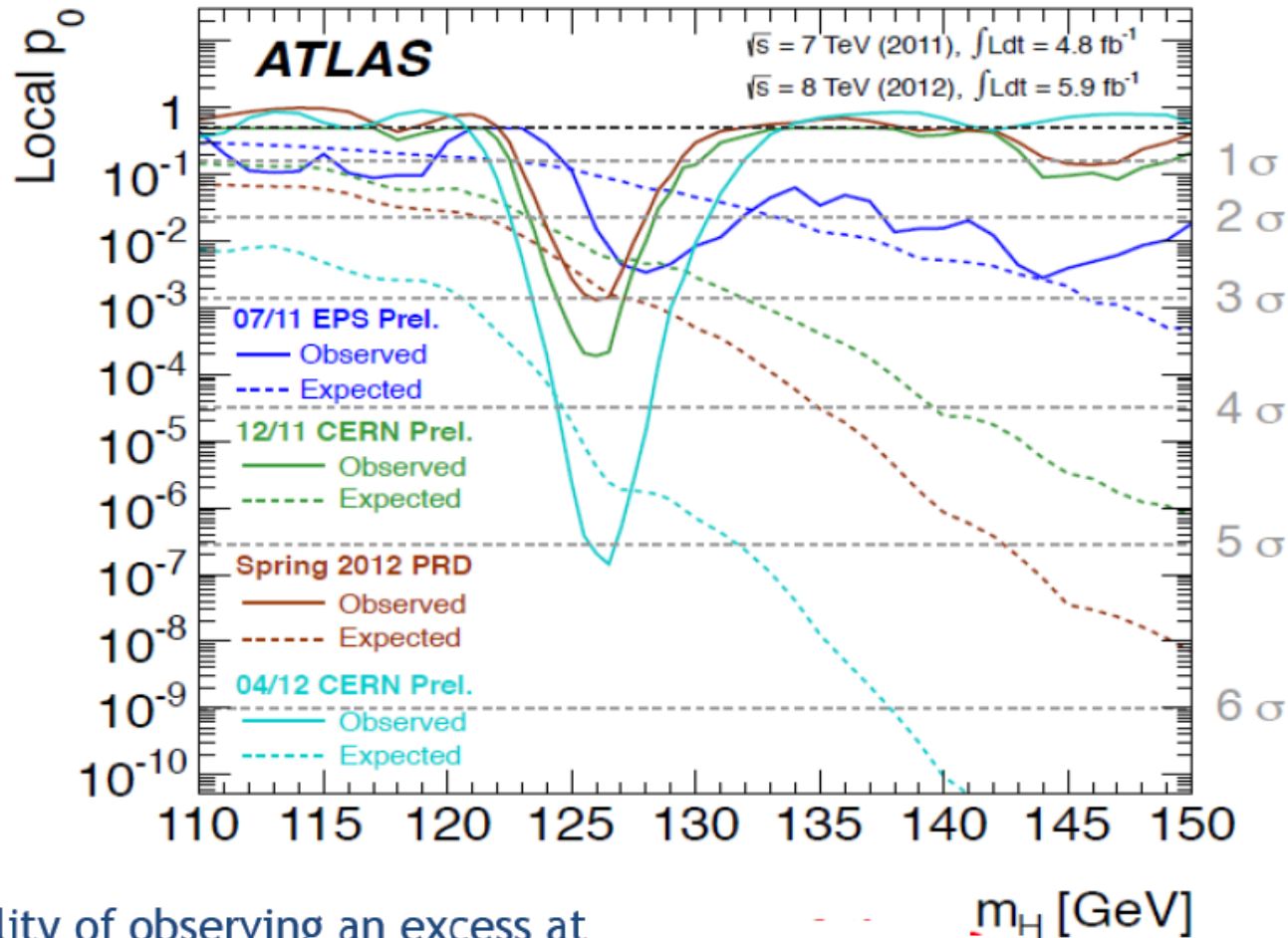


Local p_0

Probability that the background can produce a fluctuation greater than or equal to the excess observed in data. Equivalent in terms of number of standard deviations is called local significance.



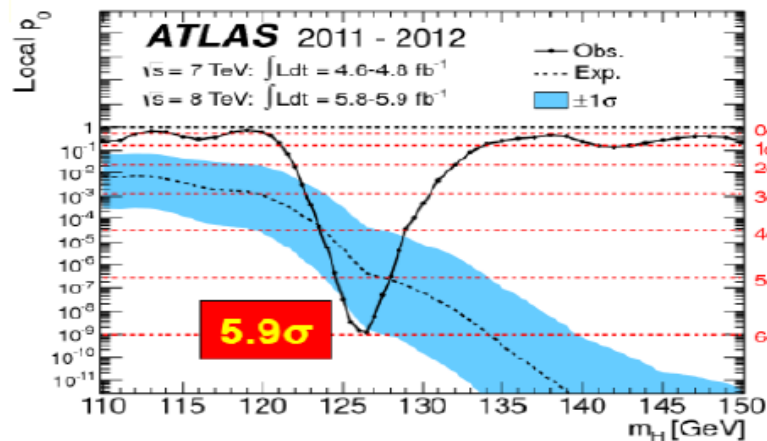
Birth of a particle



Probability of observing an excess at
 one specific mass
 (in absence of signal)...

Higgs-like particle – 4 July 2012

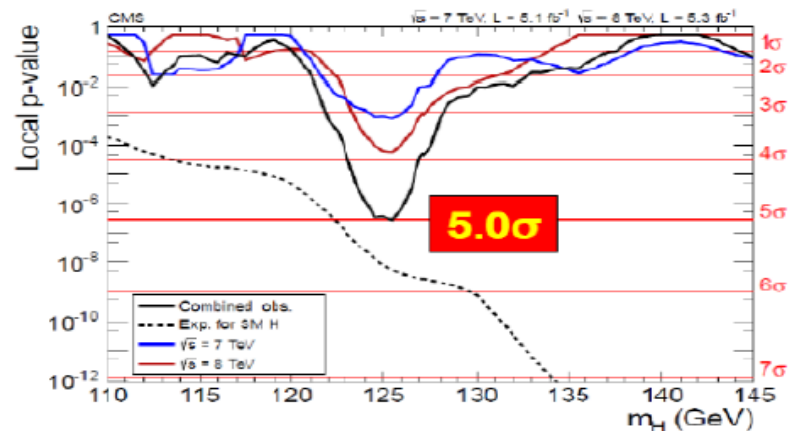
- We are living in a privileged moment in the history of High Energy Physics: **first fundamental scalar**
- The discovery came at half of the design energy, much more severe pile-up and one-third of integrated luminosity than was originally judged as



ATLAS [PLB 716 \(2012\) 1-29](#), Sept 17 (2012)

Largest local excess:
5.9 σ at $m_H = 126.5 \text{ GeV}$

$H \rightarrow \gamma\gamma, bb, \tau\tau, WW(l\nu l\nu, l\nu q\bar{q}), ZZ(4l, ll\nu\nu, llq\bar{q})$



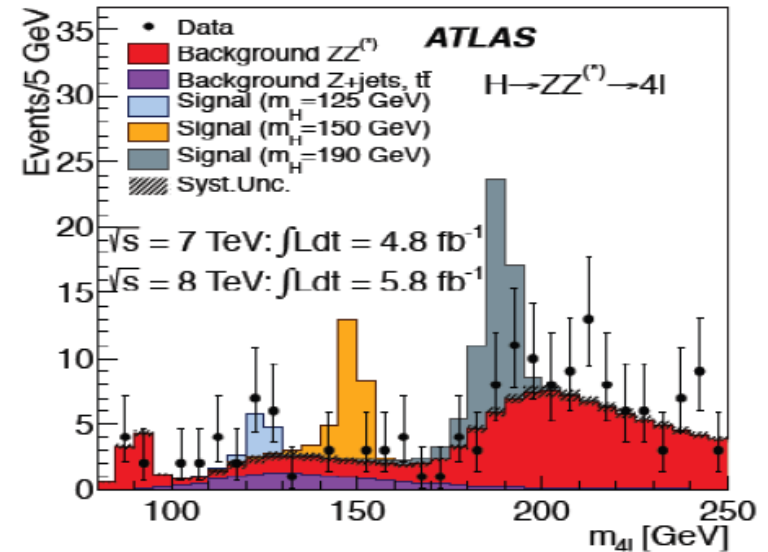
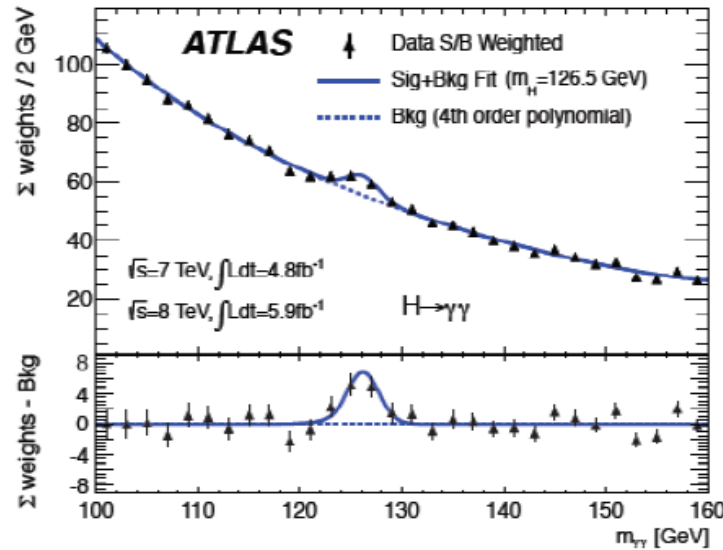
CMS [PLB 716 \(2012\) 30-61](#), Sept 17 (2012)

Largest local excess:
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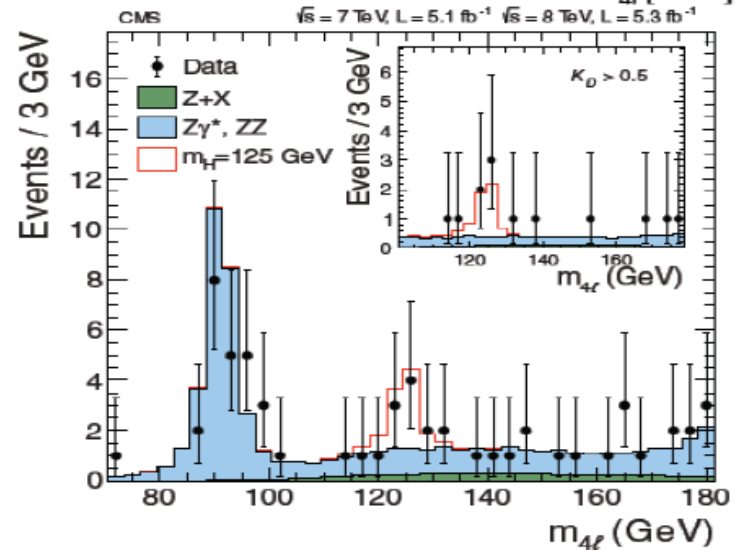
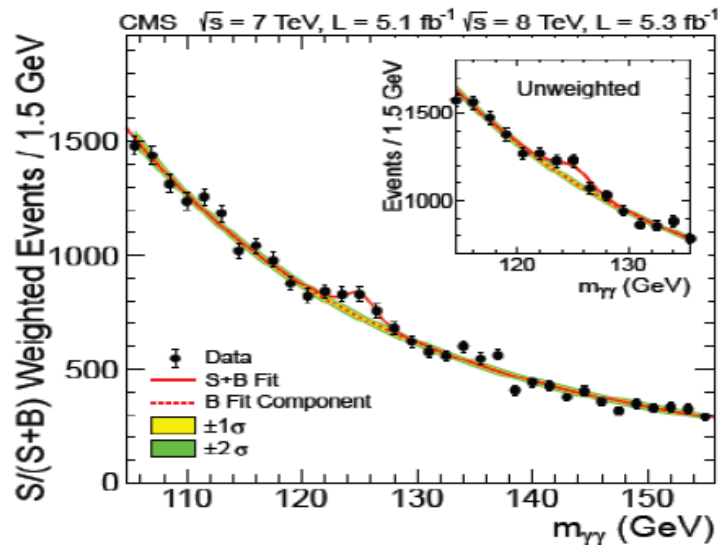
$H \rightarrow \gamma\gamma, bb, \tau\tau, WW(l\nu l\nu), ZZ(4l, ll\tau\tau, ll\nu\nu, llq\bar{q})$

Higgs-like particle – 4 July 2012

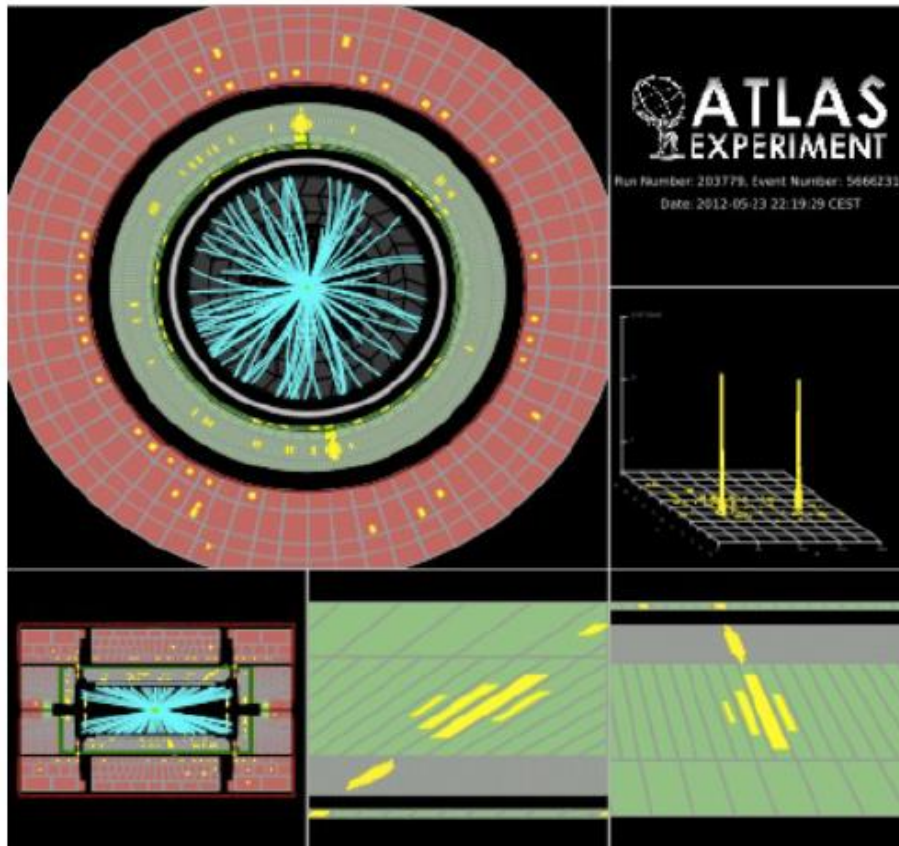
Phys.Lett. B716 (2012) 1-29



Phys.Lett. B716 (2012) 30-61



H- $\gamma\gamma$: events signature



Simple event signature

- ☐ Two high pT photons
 $p_{T_1} > 40$ GeV and $p_{T_2} > 30$ GeV
- ☐ High trigger efficiency
~99%
- ☐ High event selection efficiency
despite high jet-jet & γ -jet
production
~40%
- ☐ High signal over background
~3-10 % (depending on sub-category)

Invariant mass reconstruction $m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$

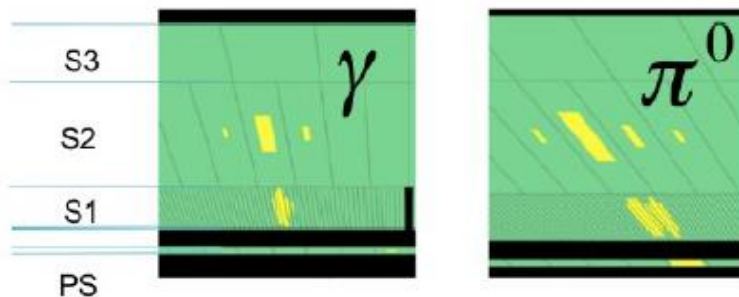
- ☐ Good energy calibration
- ☐ Robust primary vertex reconstruction

→ Excellent invariant mass resolution ~1.6 GeV with 90% of events within $\pm 2\sigma$

Shower shapes and vertex reconstr.

Photon ID 2 – Photon shower shapes and background rejection

π^0 - γ Rejection



- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

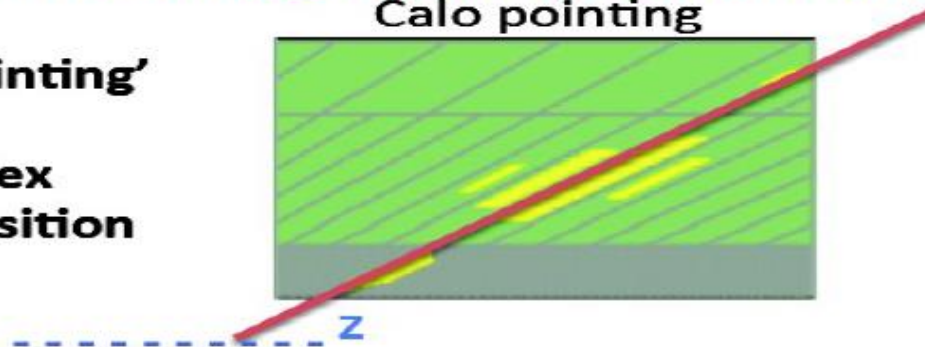
Vertex Reconstruction

$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$$

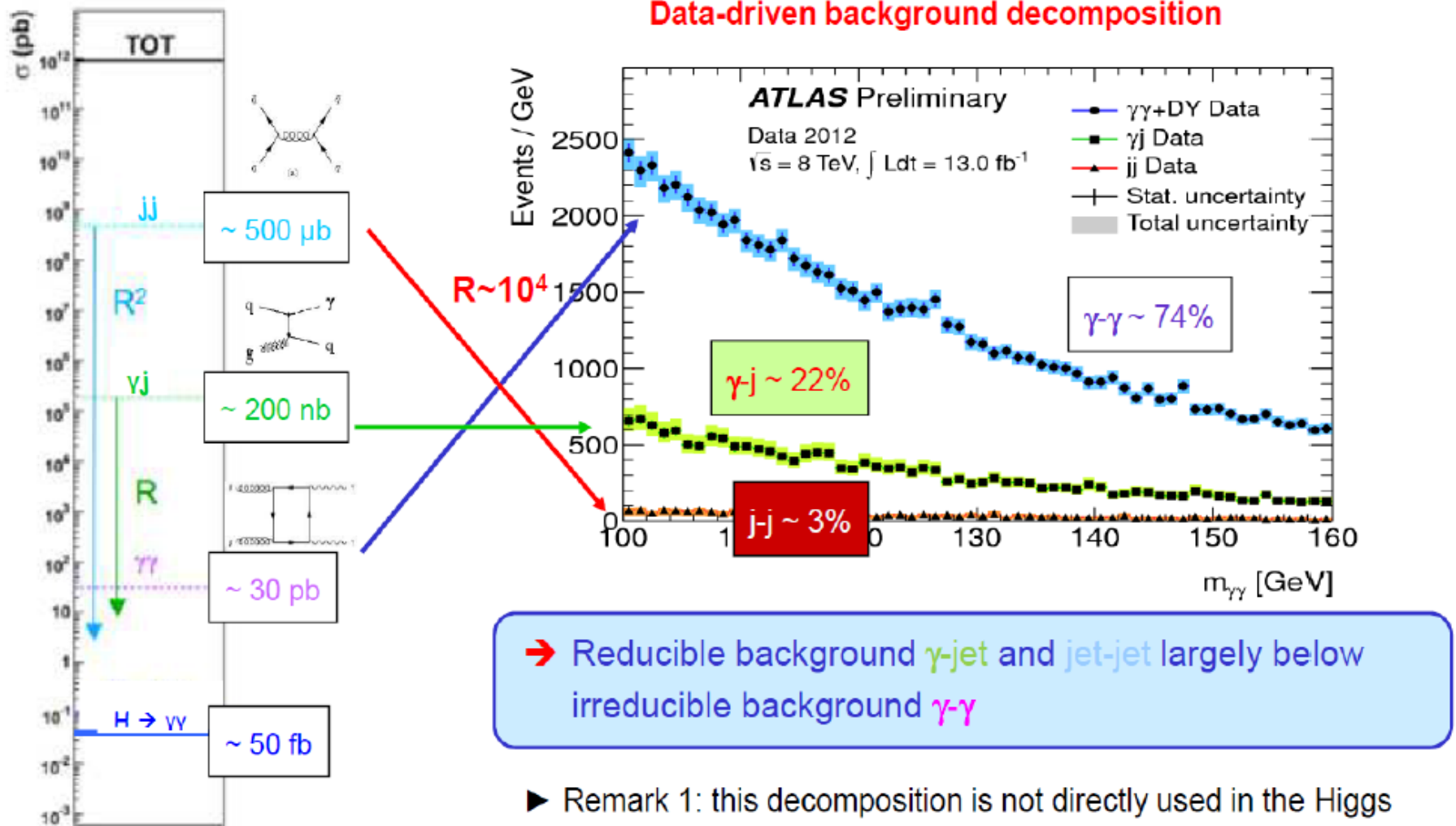
□ Vertex reconstructed through likelihood combination

- Calorimeter 'pointing'
- Σ tracks pT^2
- Conversion vertex
- Mean vertex position

Calo pointing

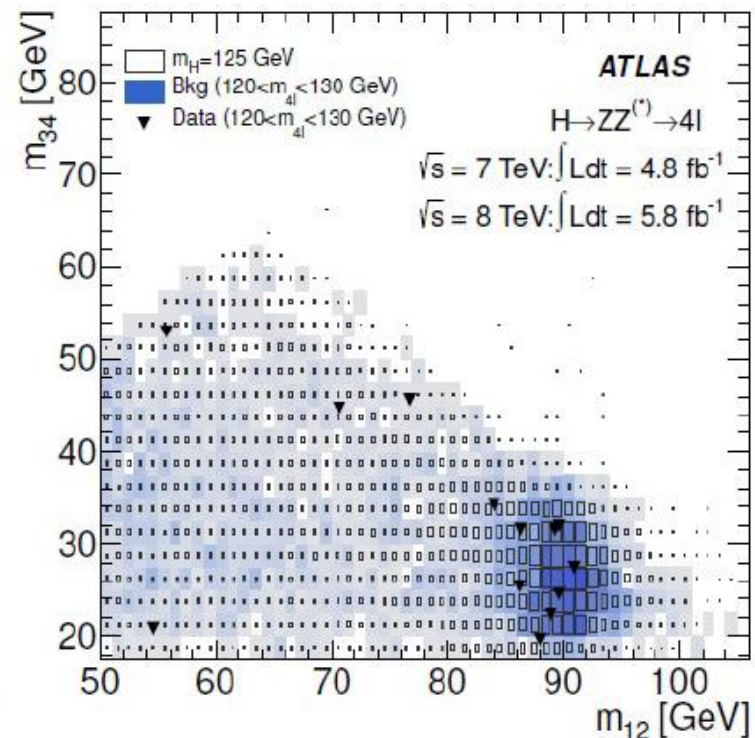
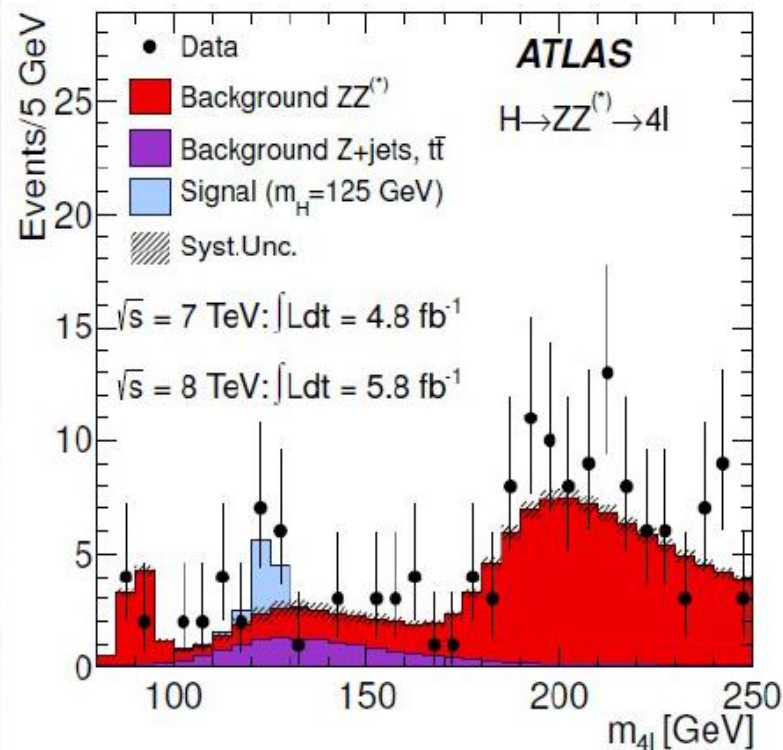


H $\rightarrow\gamma\gamma$: background rejection



- Remark 1: this decomposition is not directly used in the Higgs search: the background is extrapolated from data sidebands
- Remark 2: Drell-Yan $\sim$ negligible for $m_{\gamma\gamma} > 100 \text{ GeV}$ ($\sim 1\%$)

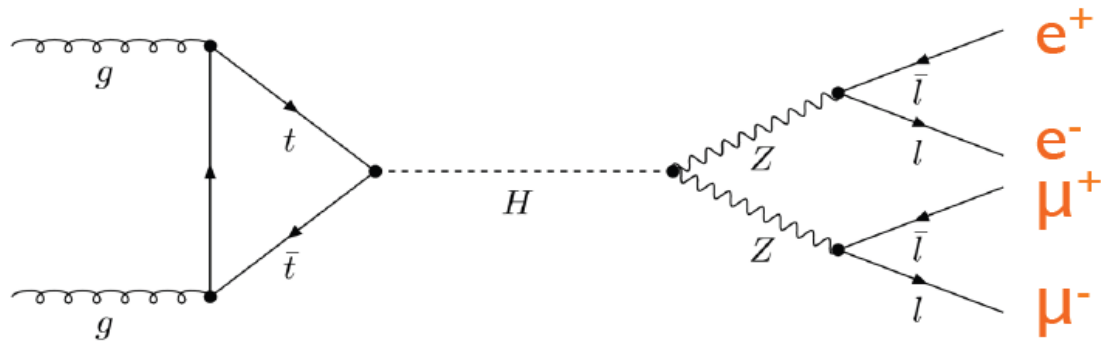
The golden channel: $H \rightarrow ZZ, Z \rightarrow l\bar{l}$



In a $m_{4\ell}$ window
 around 120-130 GeV:

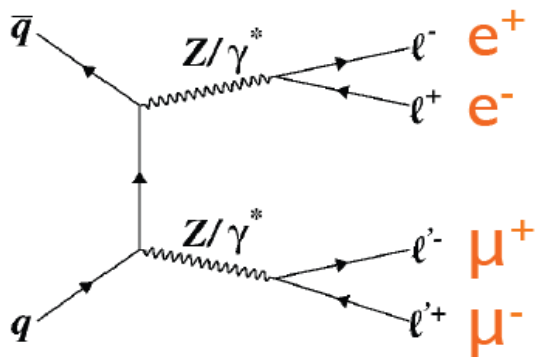
	Signal	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	Observed
4μ	2.09 ± 0.30	1.12 ± 0.05	0.13 ± 0.04	6
$2e2\mu/2\mu2e$	2.29 ± 0.33	0.80 ± 0.05	1.27 ± 0.19	5
$4e$	0.90 ± 0.14	0.44 ± 0.04	1.09 ± 0.20	2

Signal and background



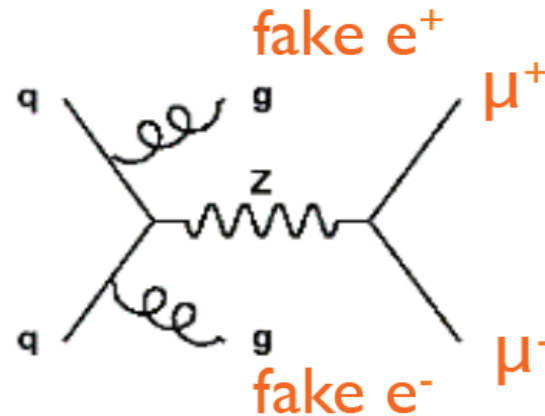
Irreducible background

The final state is exactly the same, but it does not come from the particle you are looking for



Reducible background

The final state looks like the same, but some of the particles fake what you are looking for



4e candidate. $m_{4\ell} = 124.6$ GeV, $m_{12} = 70.6$ GeV, $m_{34} = 44.7$ GeV.

e_1 : $P_T = 24.9$ GeV, $\eta = -0.33$, $\phi = 1.98$

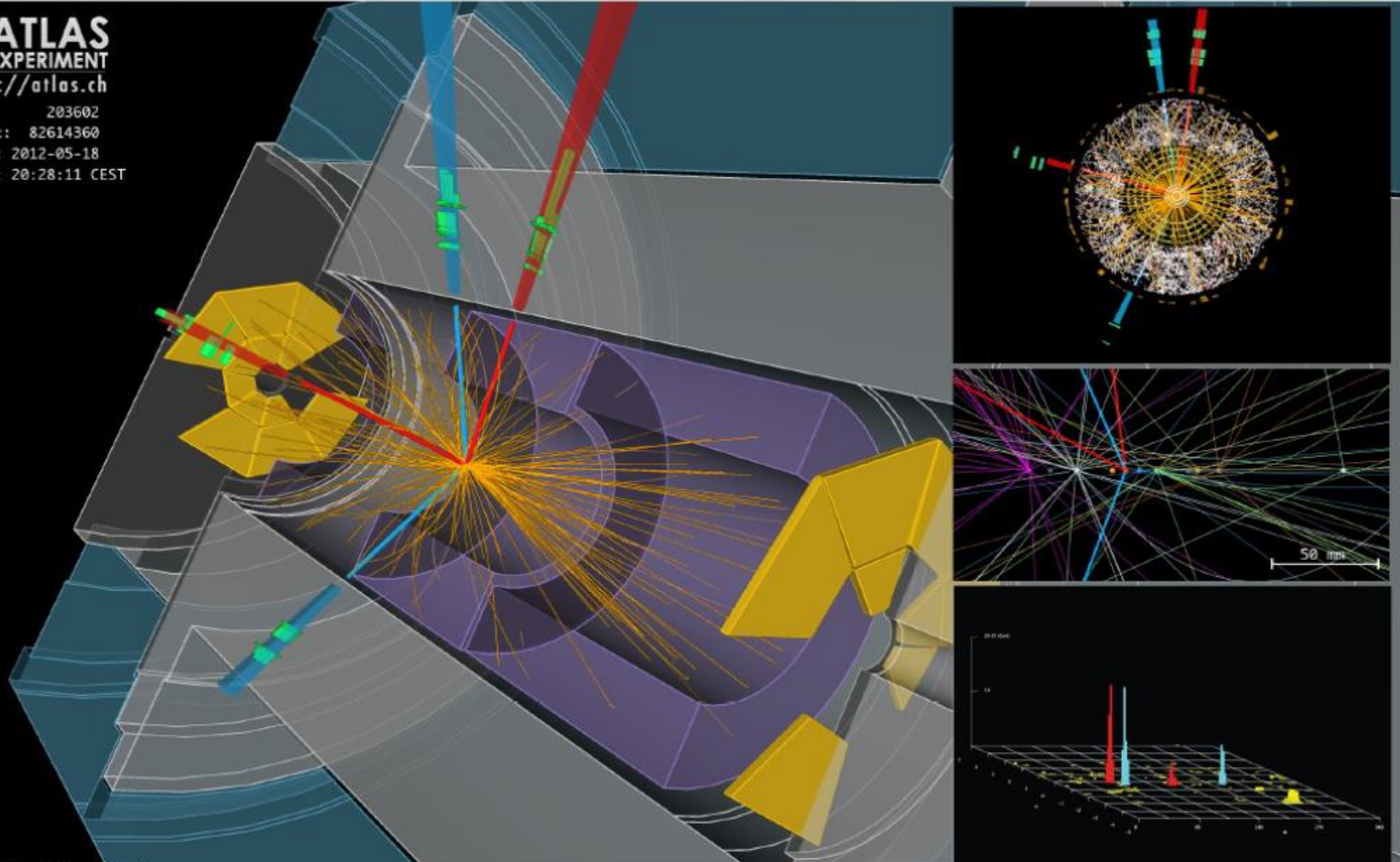
e_2 : $P_T = 53.9$ GeV, $\eta = -0.40$, $\phi = 1.69$

e_3 : $P_T = 61.9$ GeV, $\eta = -0.12$, $\phi = 1.45$

e_4 : $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$

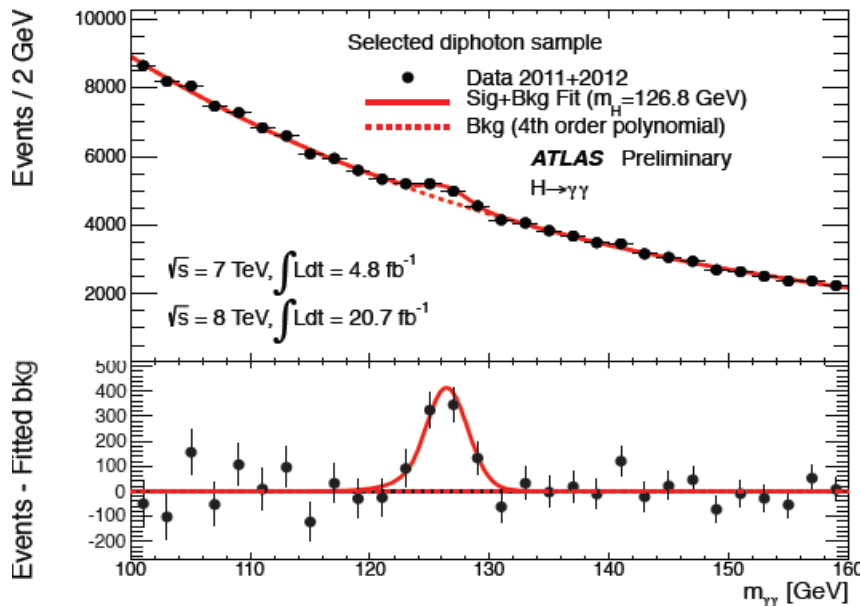
ATLAS
EXPERIMENT
<http://atlas.ch>

Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST



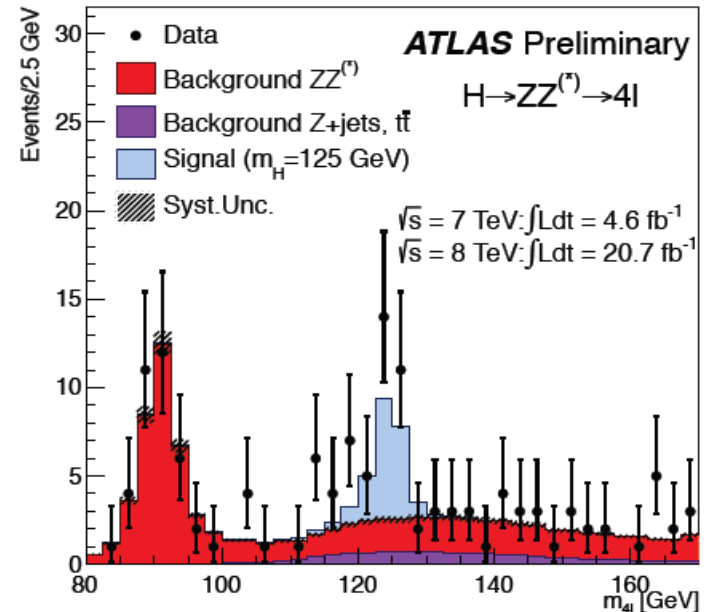
Higgs like signal with 7 TeV and 8 TeV data

$H \rightarrow \gamma\gamma$



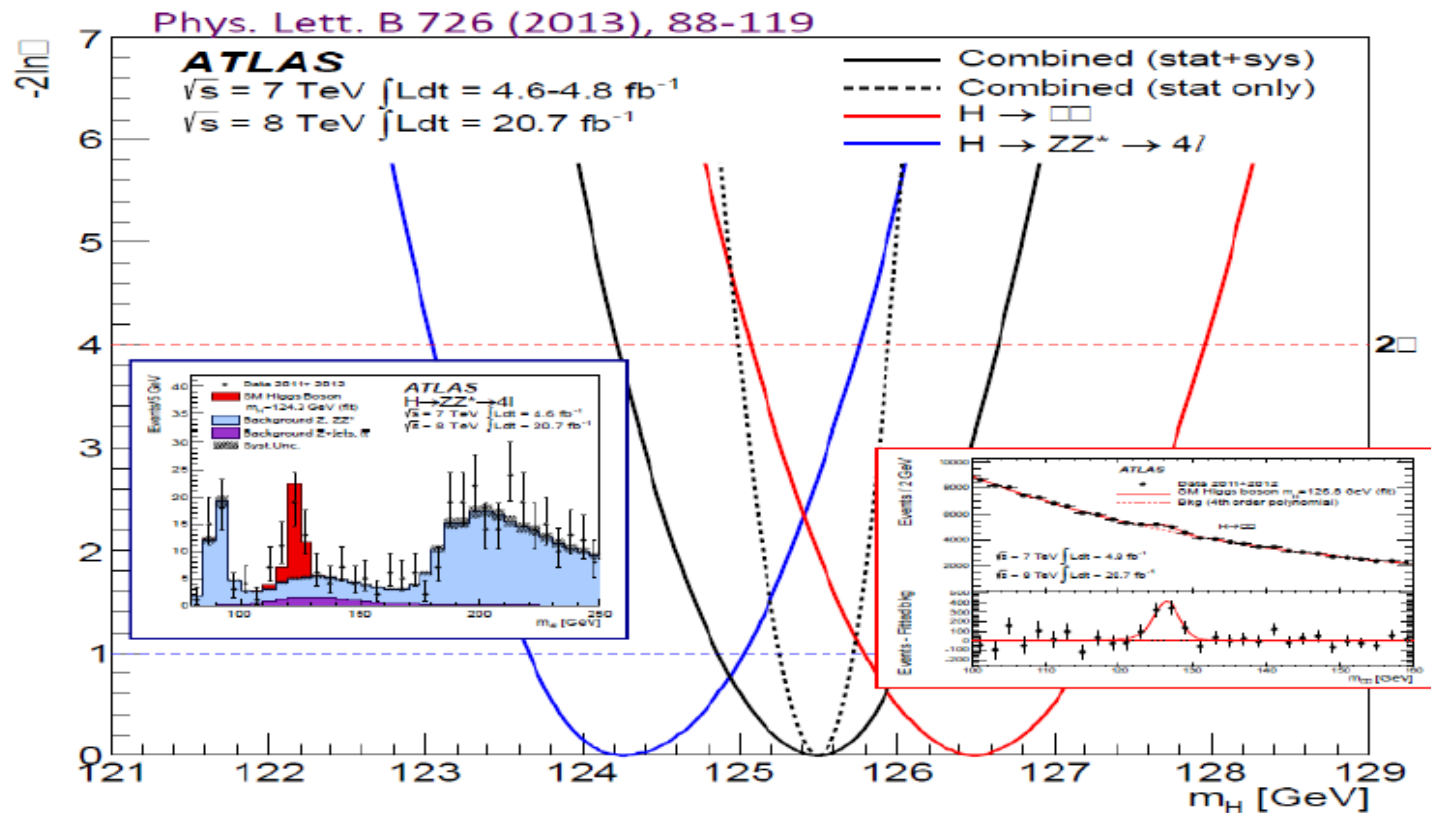
- Signal significance = 7.4σ
- $m_H = 126.8 \pm 0.2$ (stat) ± 0.7 (syst) GeV
- $\mu = 1.65 \pm 0.34$ (deviation w.r.t. SM at 2.3σ)

$H \rightarrow 4l$



- Signal significance = 6.6σ
- $m_H = 124.3^{+0.6}_{-0.5}$ (stat) $^{+0.6}_{-0.3}$ (syst) GeV
- $\mu = 1.7 \pm 0.34$

Mass measurement



$$4\ell: M_H = 124.3 \pm 0.6_{\text{stat}} \pm 0.4_{\text{sys}} \text{ GeV}$$

$$\gamma\gamma: M_H = 126.8 \pm 0.2_{\text{stat}} \pm 0.7_{\text{sys}} \text{ GeV}$$

$$\text{Combined: } M_H = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{sys}} \text{ GeV}$$

Nobel price for predicting Higgs particle

2013 NOBEL PRIZE IN PHYSICS

François Englert
Peter W. Higgs



© The Nobel Foundation. Photo: Lovisa Engblom.

THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES
AND SCALAR PARTICLES



8 October 2013

The Royal Swedish Academy of Sciences
has decided to award the Nobel Prize in
Physics for 2013 to

François Englert and Peter Higgs

*“for the theoretical discovery of a
mechanism that contributes to our
understanding of the origin of mass of
subatomic particles, and which recently was
confirmed through the discovery of the
predicted fundamental particle, by the
ATLAS and CMS experiments at CERN’s Large
Hadron Collider”*

Entrance of the Higgs into PDG

2013

Higgs Bosons — H^0 and $H^\pm$

A REVIEW GOES HERE – Check our WWW List of Reviews

CONTENTS:

H^0 (Higgs Boson)

- H^0 Mass
- H^0 Spin
- H^0 Decay Width
- H^0 Decay Modes
- H^0 Signal Strengths in Different Channels
 - Combined Final States
 - W^+W^- Final State
 - ZZ^* Final State
 - $\gamma\gamma$ Final State
 - $b\bar{b}$ Final State
 - $\tau^+\tau^-$ Final State

Standard Model H^0 (Higgs Boson) Mass Limits

- H^0 Direct Search Limits
- H^0 Indirect Mass Limits from Electroweak Analysis

Searches for Other Higgs Bosons

- Mass Limits for Neutral Higgs Bosons in Supersymmetric Models
 - H^0 (Higgs Boson) Mass Limits in Supersymmetric Models
 - A^0 (Pseudoscalar Higgs Boson) Mass Limits in Supersymmetric Models
- H^0 (Higgs Boson) Mass Limits in Extended Higgs Models
 - Limits in General two-Higgs-doublet Models
 - Limits for H^0 with Vanishing Yukawa Couplings
 - Limits for H^0 Decaying to Invisible Final States
 - Limits for Light A^0
 - Other Limits
- $H^\pm$ (Charged Higgs) Mass Limits
 - Mass limits for $H^{\pm\pm}$ (doubly-charged Higgs boson)
 - Limits for $H^{\pm\pm}$ with $T_3 = \pm 1$
 - Limits for $H^{\pm\pm}$ with $T_3 = 0$

NODE=S055
NODE=S055

NODE=S055CNT
NODE=S055CNT

H^0 (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

NODE=S055CNT

NODE=S055210

NODE=S055210

H^0 MASS

UNDE(GeV)

125.0±0.4 OUR AVERAGE

	DOCUMENT ID	TECN	COMMENT
125.0±0.4±0.4	¹ CHATRCHYAN13J	CMS	p.p. 7 and 8 TeV
126.0±0.4±0.4	² AAD	12N ATLAS	p.p. 7 and 8 TeV
••• We do not use the following data for averages, fits, limits, etc. •••			
126.2±0.0±0.2	³ CHATRCHYAN13J	CMS	p.p. 7 and 8 TeV
125.3±0.4±0.5	⁴ CHATRCHYAN12N	CMS	p.p. 7 and 8 TeV

¹ Combined value from ZZ and $\gamma\gamma$ final states.

² AAD 12N obtain results based on $4.6\text{--}4.8\text{ fb}^{-1}$ of p.p. collisions at $E_{\text{CM}} = 7\text{ TeV}$ and $5.0\text{--}5.9\text{ fb}^{-1}$ at $E_{\text{CM}} = 8\text{ TeV}$. An excess of events over background with a local significance of 5.9σ is observed at $m_{H^0} = 126\text{ GeV}$. See also AAD 12DA.

³ Result based on $ZZ \rightarrow 4\ell$ final states in 5.1 fb^{-1} of p.p. collisions at $E_{\text{CM}} = 7\text{ TeV}$ and 1.2 fb^{-1} at $E_{\text{CM}} = 8\text{ TeV}$.

⁴ CHATRCHYAN 12N obtain results based on $4.9\text{--}5.1\text{ fb}^{-1}$ of p.p. collisions at $E_{\text{CM}} = 7\text{ TeV}$ and $5.1\text{--}5.3\text{ fb}^{-1}$ at $E_{\text{CM}} = 8\text{ TeV}$. An excess of events over background with a local significance of 5.0σ is observed at about $m_{H^0} = 125\text{ GeV}$. See also CHATRCHYAN 12DY.

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NODE=S055HBM

OCCUR=2

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NODE=S055HBM;LINKAGE=AA

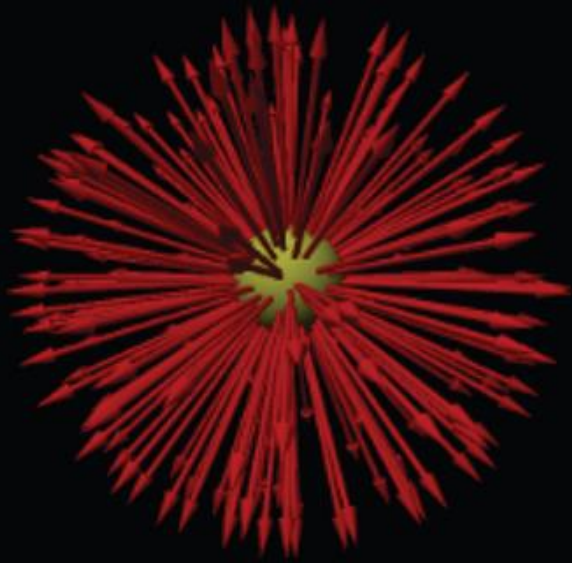
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NODE=S055HBM;LINKAGE=CH

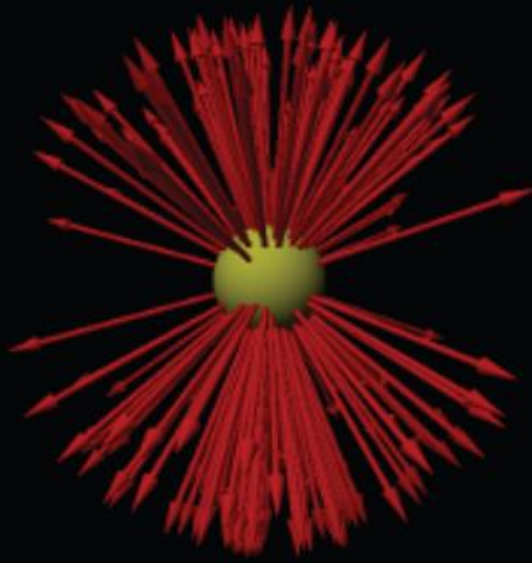
Inaugural entrance of
the Higgs boson in the
PDG particle listing !

H^0

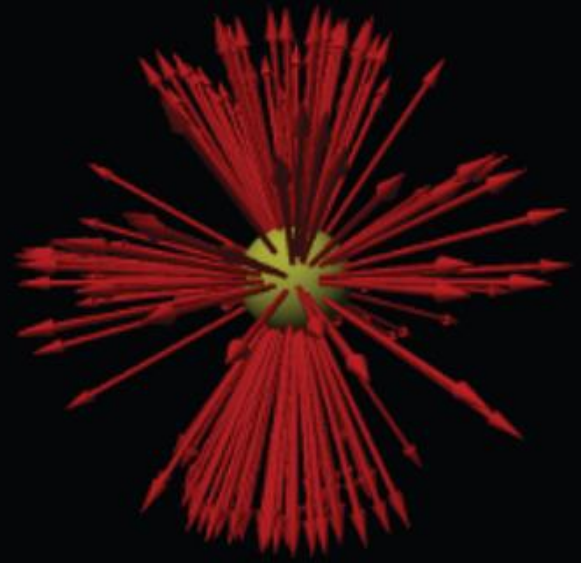
How we can recognize spin?



spin 0



spin 1

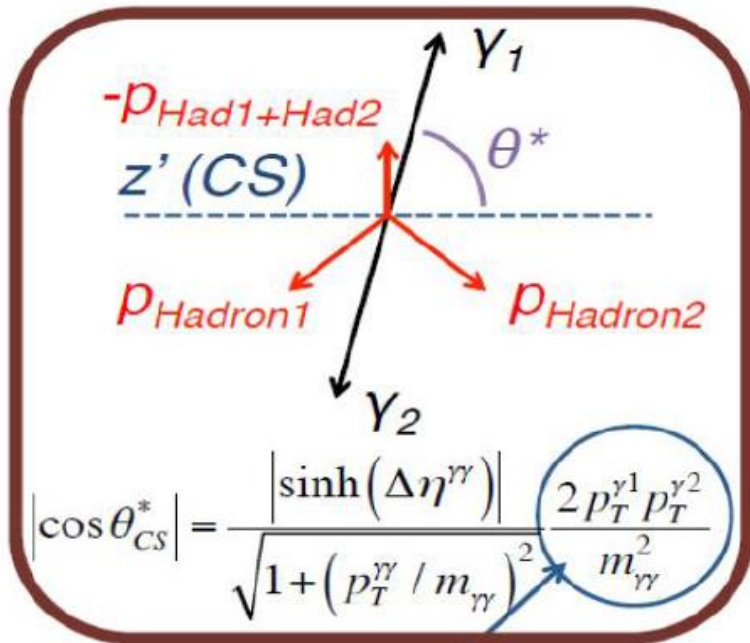


spin 2

Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

Spin observables for $H \rightarrow \gamma\gamma$

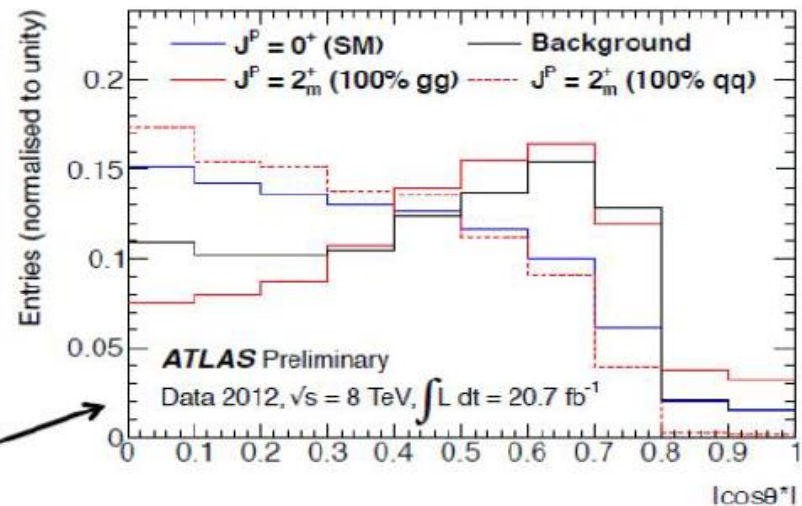
Separate 0^+ and 2^+ spin hypotheses using the angular correlation of the two photons



Collins-Soper frame used to get reference axis z' for $\cos(\theta^*)$

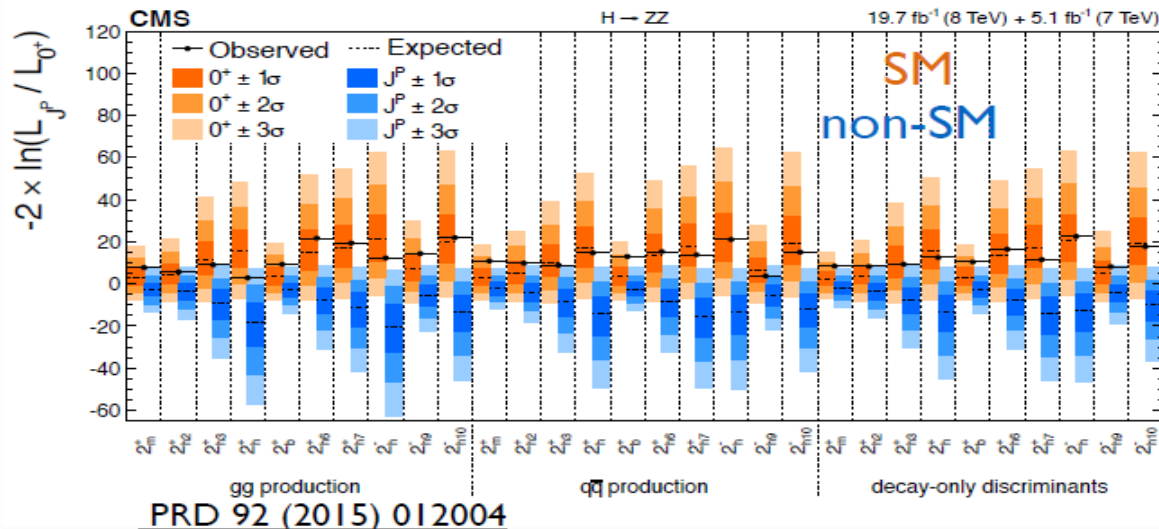
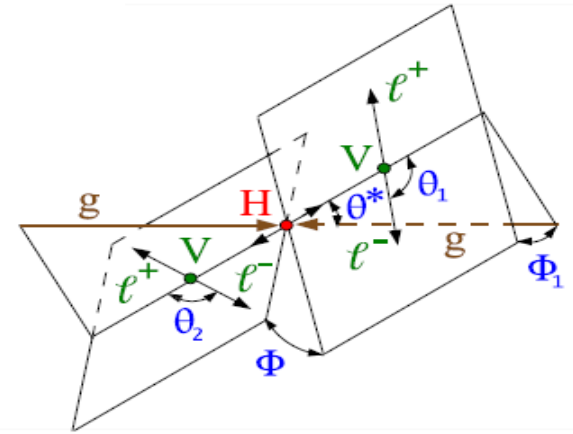
- z -axis bisects angle between the momenta of colliding hadrons
- Minimizes impact of ISR
- Better 0^+ / 2^+ discrimination

Relative p_T cuts on the photons remove most correlation with $m_{\gamma\gamma}$
 $qq \rightarrow 2^+$ very similar to SM $gg \rightarrow 0^+$



Spin study with $H \rightarrow 4l$

- SM predicts $J^{PC} = 0^{++}$
- Angular distributions sensitive to J^P
- Wide range of alternative quantum numbers excluded at $>99\%$ CL
- All observations consistent with expectations for the SM Higgs boson



Tests of
alternative J^P
hypotheses in ZZ

Higgs boson decay width

$$m_h = 125 \text{ GeV} \rightarrow \Gamma_h = 4.07 \text{ MeV}$$

$$\tau_h = 1.62 \cdot 10^{-22} \text{ [s]}$$

A deviation would imply a decay to non-SM particles

Differential Higgs production cross-section

$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

Γ_h cannot be accessed directly (experimental resolution $\sim 1\text{-}2 \text{ GeV}$)

A

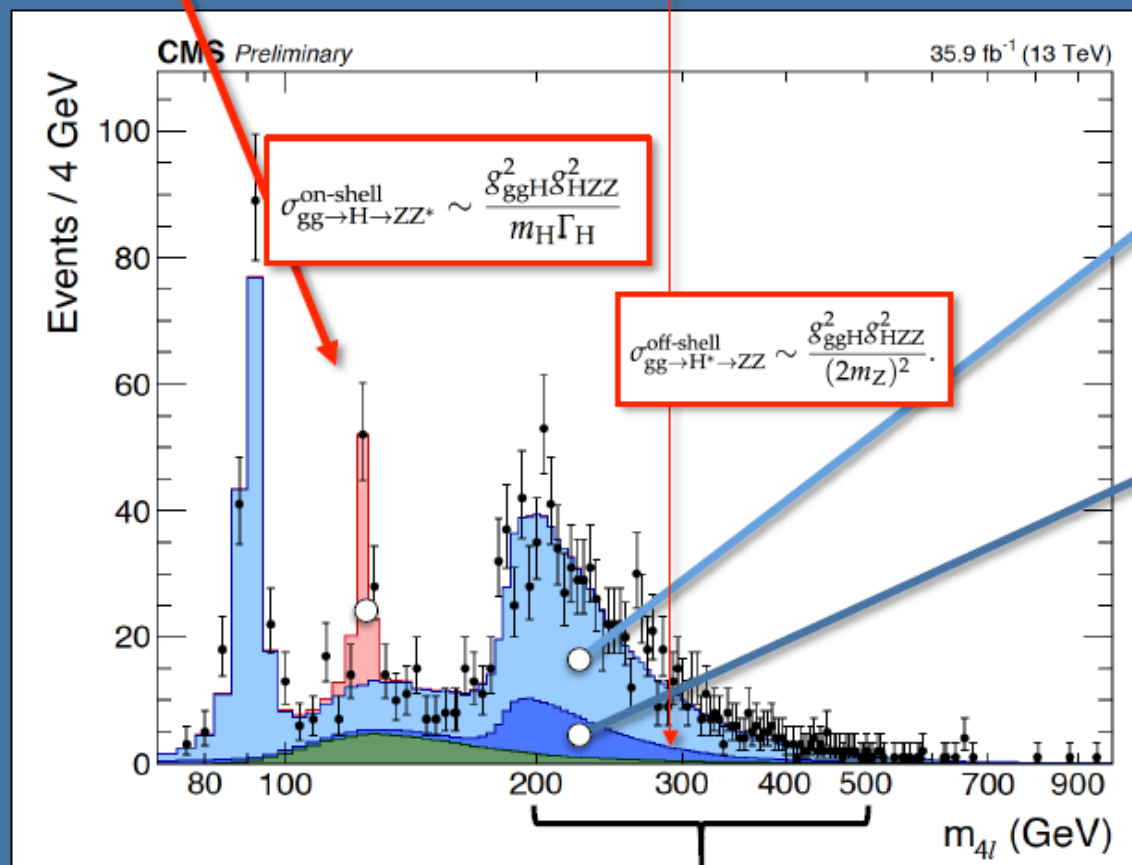
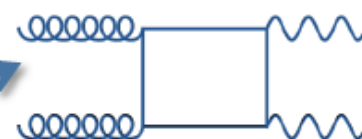
higgs $\rightarrow$ ZZ

Indirect measurement

B

qq $\rightarrow$ ZZ

C

gg $\rightarrow$ ZZ

Interference between **A** and **C** : $(A+C)^2 = A^2 + C^2 + 2AC$

tiny ←

→ *accessible*

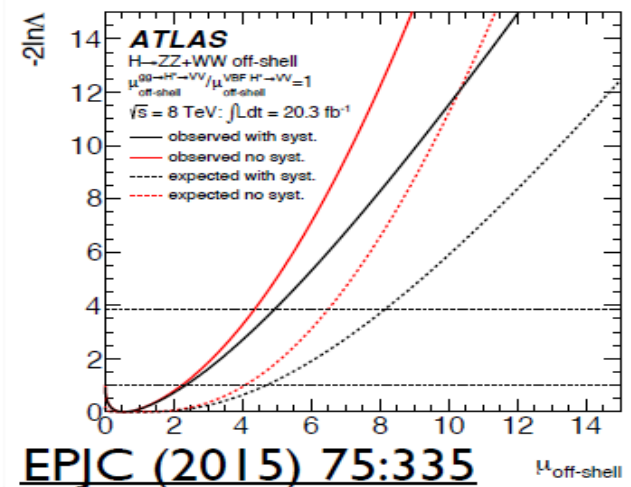
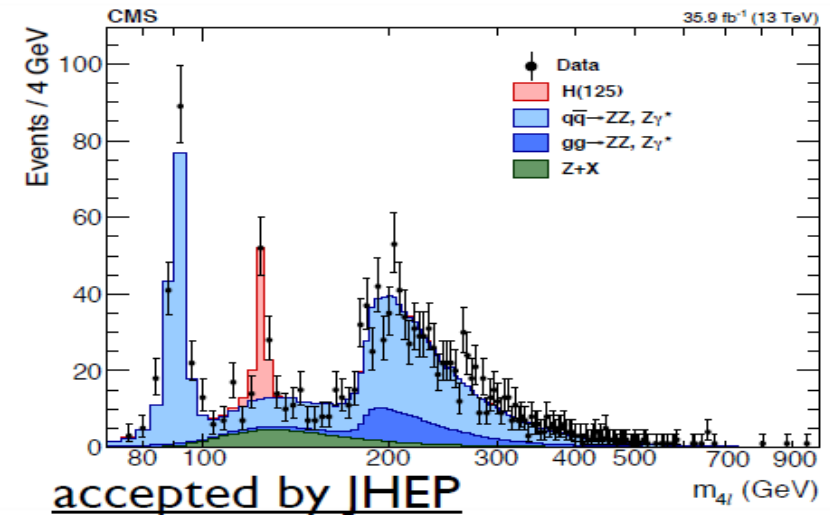
Higgs boson decay width

Total width

- Lower bound on total width from decay measurements
- Direct experimental measurements probe 3 orders of magnitude larger than SM width ($\Gamma=4$ MeV)
- Indirect constraint* on the width via measurement of ratio of off-peak to on-peak cross-section
 - CMS: $\Gamma < 13$ MeV
 - ATLAS: $\Gamma < 22$ MeV

*N. Kauer and G. Passarino, JHEP (2012) 2012: 116

*F. Caola and K. Melnikov, PRD88 (2013) 054024

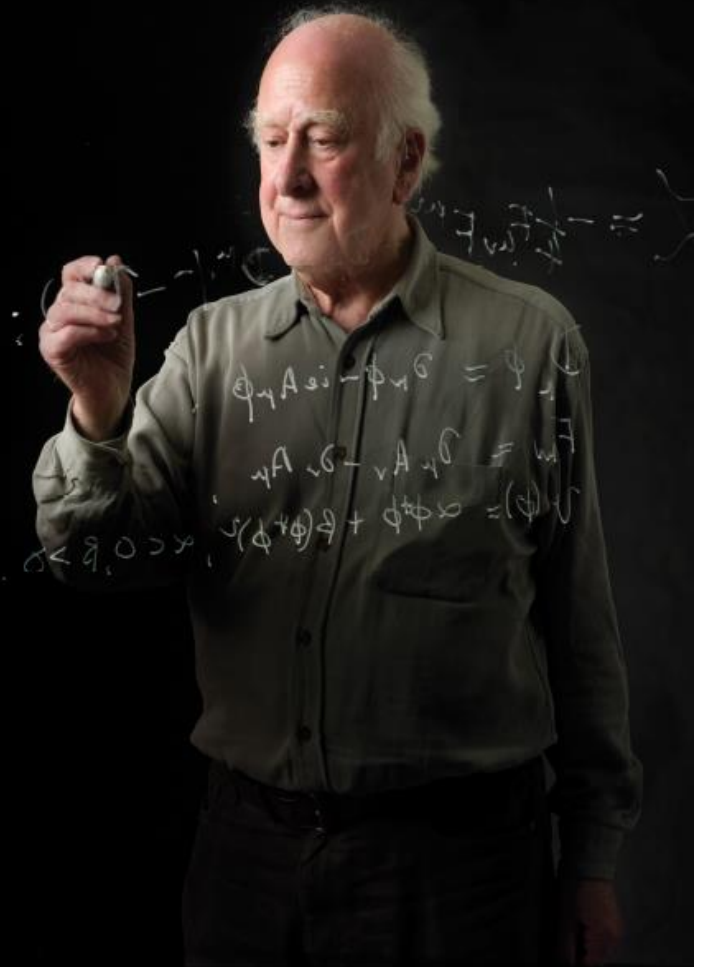


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c$$

$$+ \bar{\psi}_i \gamma_{ij} \psi_j \phi + h.c$$

$$+ |D_\mu \phi|^2 - V(\phi)$$



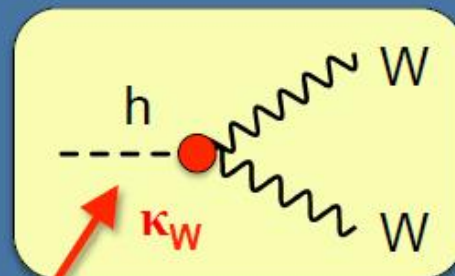
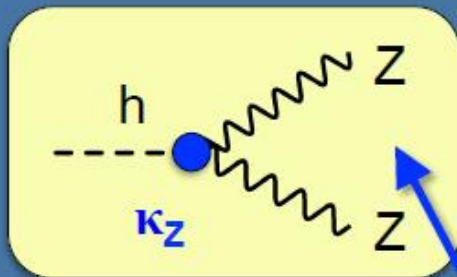
Couplings: kappa-framework

Scale factor for each (fundamental) coupling:

$$\sigma(i \rightarrow h \rightarrow f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_h^2 \Gamma_h^{SM}}$$

$$\begin{aligned} \mathcal{L} = & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ & - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f \bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f \bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f \bar{f} \right) H \end{aligned}$$

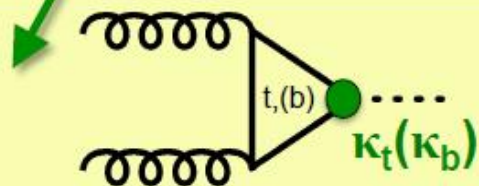
Scale Higgs boson couplings (wrt SM): production & decay



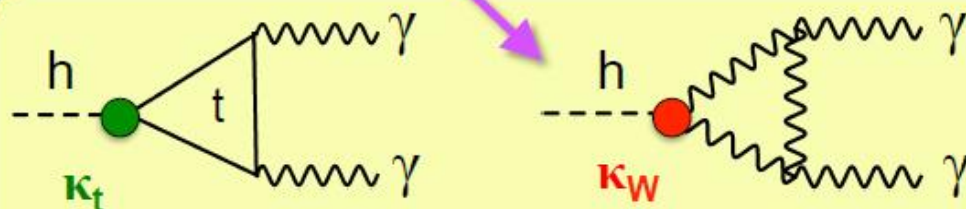
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$

$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$

$$+ \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f \bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f \bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f \bar{f} \right) H$$



$$\kappa_g^2 \propto 1.06 \kappa_t^2 - 0.07 \kappa_t \kappa_b + 0.01 \kappa_b^2$$



$$\kappa_\gamma^2 \propto 1.59 \kappa_W^2 - 0.66 \kappa_W \kappa_t + 0.07 \kappa_t^2$$

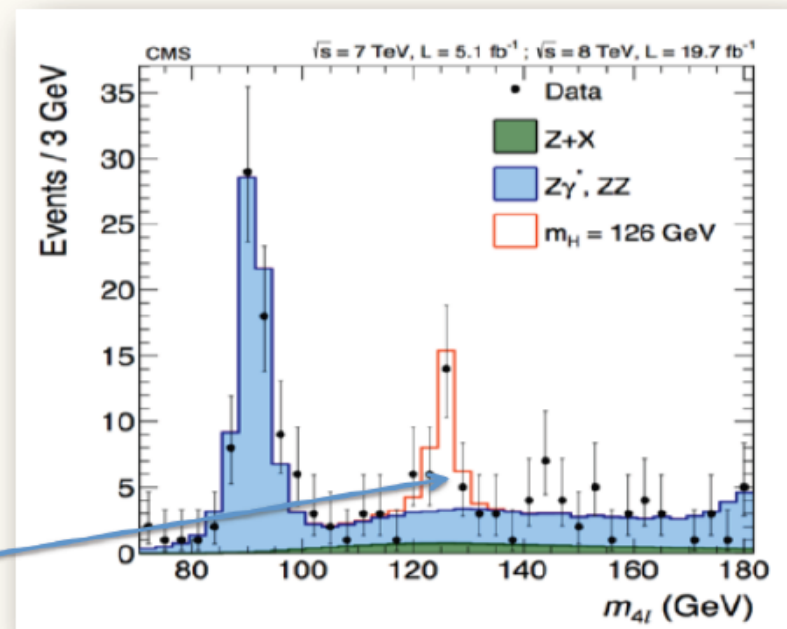
What do we measure?

We measure event yields

We want to derive couplings and signal strengths

The first thing we want to measure is the the “signal strength” per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B



$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \epsilon_p^i \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

$$\mu^{ZZ}(@125.5 \text{ GeV}) = 1.44^{+0.40}_{-0.35}$$

$$\mu^{ZZ}(@125.6 \text{ GeV}) = 0.93^{+0.26+0.13}_{-0.23-0.09}$$

6.6σ (4.4 exp) ATLAS

6.8σ (6.7 exp) CMS

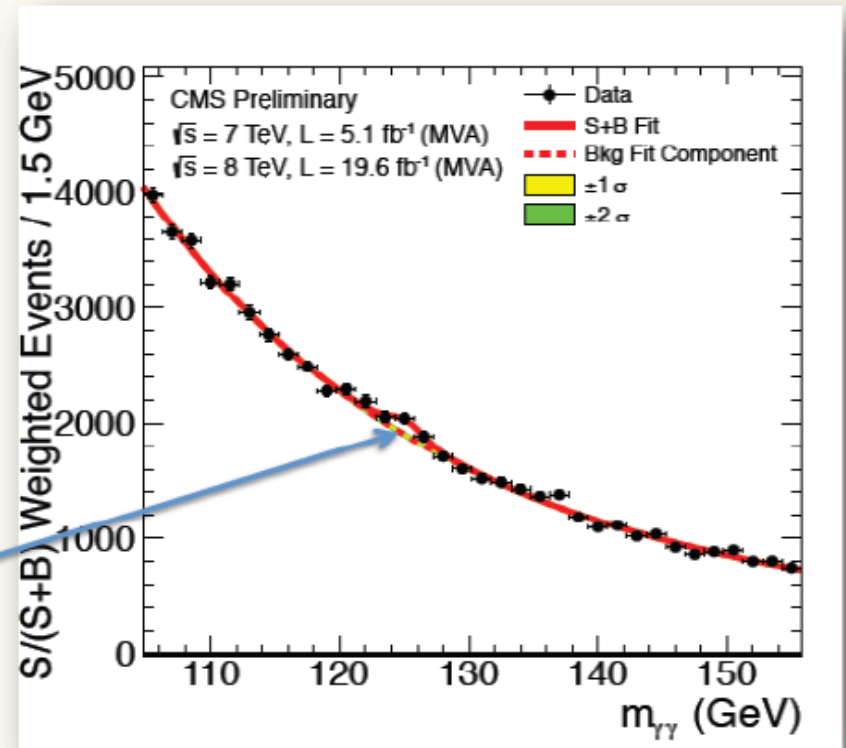
What do we measure?

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$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

Higgs boson decay channels

Significance

7.4σ (4.3σ)

6.6σ (4.4σ)

3.8σ (3.8σ)

4.1σ (3.2σ)

0.36σ (1.64σ)

Obs. (*Exp.*)

Combined

3.2σ (4.2σ)

6.8σ (6.7σ)

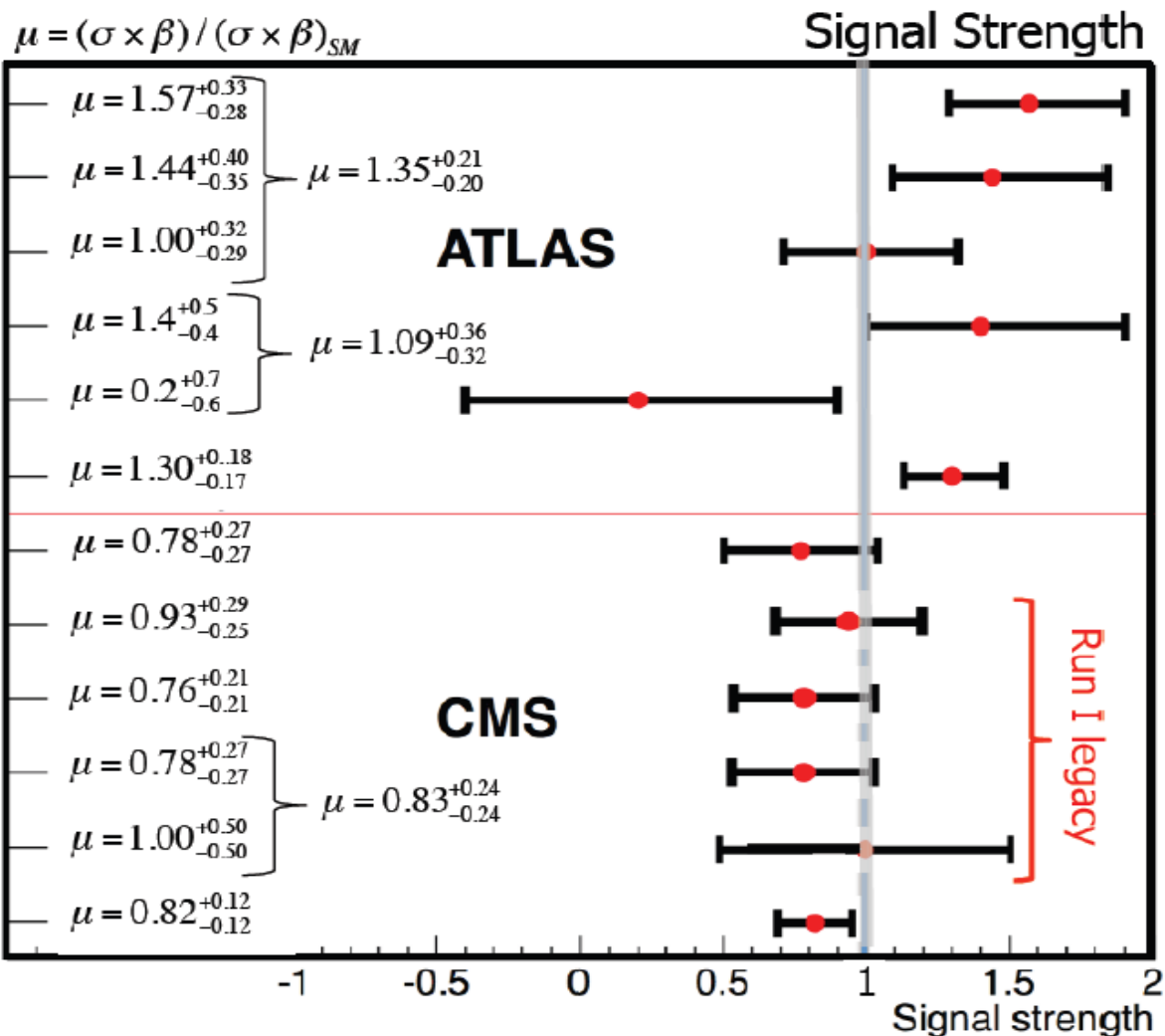
4.3σ (5.8σ)

3.3σ (3.7σ)

2.1σ (2.1σ)

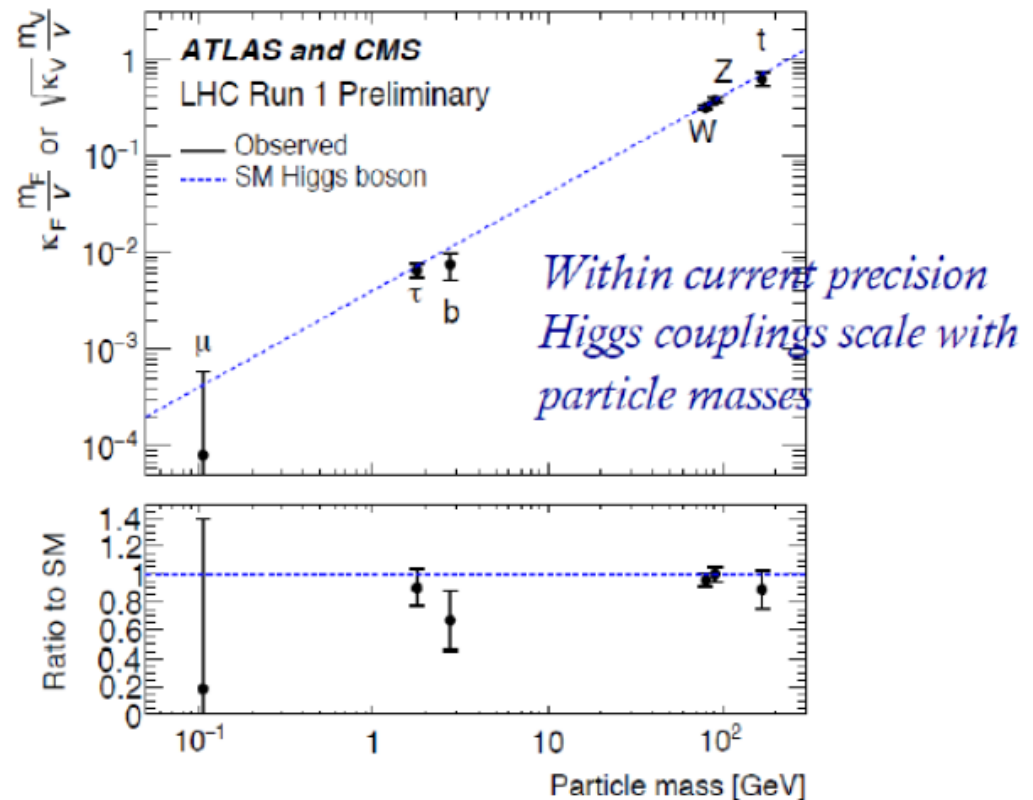
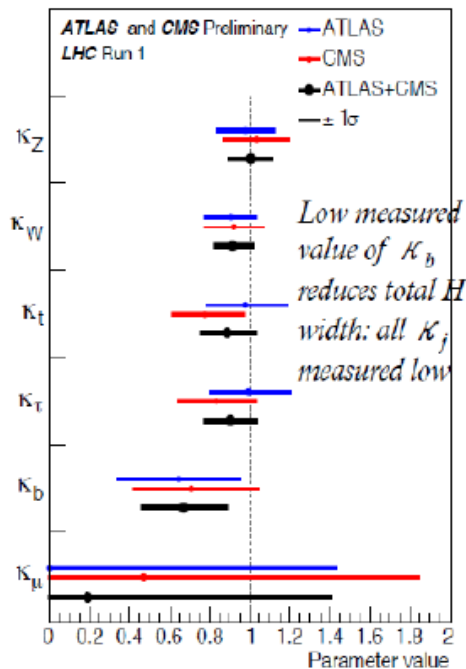
Obs. (*Exp.*)

Combined
(private)

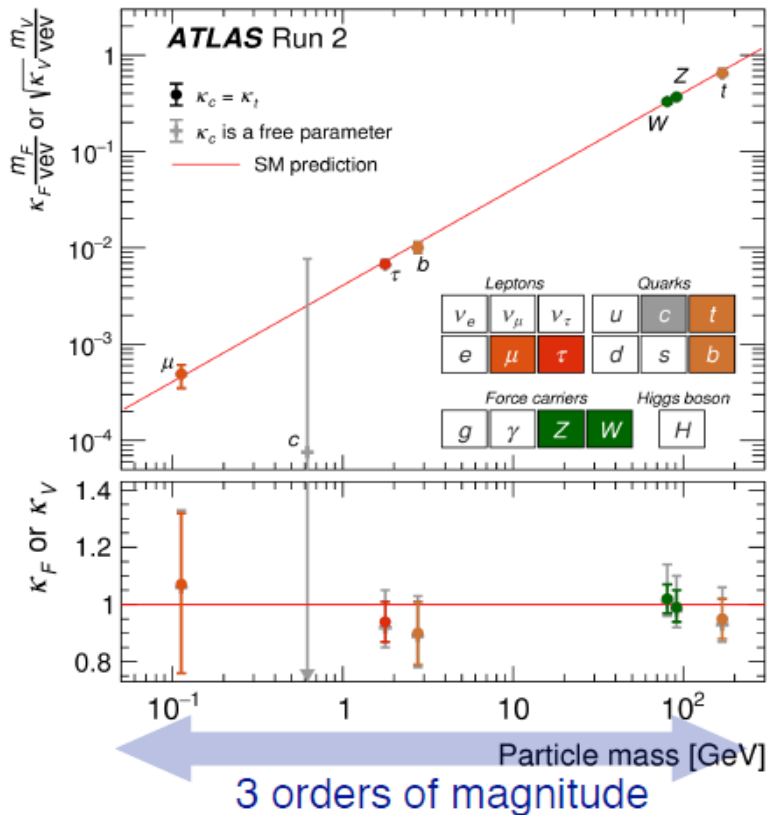


Constraints on three-level Higgs couplings

- Assume only SM physics in loops, no invisible or unseen BSM Higgs decays
- Fit for scaling parameters for Higgs couplings to W, Z, b, t, τ , μ



What we have learned since discovery



- All main production modes (ggF, VBF, VH, ttH+tH) established at $> 5\sigma$
- Couplings to gauge bosons and 3rd gen. charged fermions **observed, evidence** for $H \rightarrow Z\gamma$
- Couplings to 2nd gen. charged fermions: **evidence** for $H \rightarrow \mu\mu$; first constraints on $H \rightarrow cc$;
- Mass measured to $< 0.1\%$
- $J^{CP} = 0^{++}$ (alternative hypotheses excluded at $> 99.9\%$ C.L.)

But still very little knowledge about the shape of the Higgs potential.

ATLAS combination

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^*$	$H \rightarrow WW^*$	$H \rightarrow \tau\tau$	$H \rightarrow b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 $\ell + 2 \tau_{\text{had}}$ $t\bar{t}H$ multilepton 2 opposite-sign $\ell + 1 \tau_{\text{had}}$ $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 4 ℓ (except $H \rightarrow ZZ^* \rightarrow 4\ell$) $t\bar{t}H$ leptonic, $H \rightarrow ZZ^* \rightarrow 4\ell$ $t\bar{t}H$ hadronic, $H \rightarrow ZZ^* \rightarrow 4\ell$			$t\bar{t}H$ 1 ℓ , boosted $t\bar{t}H$ 1 ℓ , resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH	VH 2 ℓ VH 1 ℓ , $p_T^{\ell+E_T^{\text{miss}}} \geq 150 \text{ GeV}$ VH 1 ℓ , $p_T^{\ell+E_T^{\text{miss}}} < 150 \text{ GeV}$ VH E_T^{miss} , $E_T^{\text{miss}} \geq 150 \text{ GeV}$ VH E_T^{miss} , $E_T^{\text{miss}} < 150 \text{ GeV}$ $VH+VBF$ $p_T^{j1} \geq 200 \text{ GeV}$ VH hadronic (2 categories)	VH leptonic 0-jet, $p_T^{4\ell} \geq 100 \text{ GeV}$ 2-jet, $m_{jj} < 120 \text{ GeV}$			2ℓ , $75 \leq p_T^V < 150 \text{ GeV}$, $N_{\text{jets}} = 2$ 2ℓ , $75 \leq p_T^V < 150 \text{ GeV}$, $N_{\text{jets}} \geq 3$ 2ℓ , $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 2$ 2ℓ , $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} \geq 3$ 1ℓ $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 2$ 1ℓ $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 3$ 0ℓ , $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 2$ 0ℓ , $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 3$
VBF	VBF , $p_T^{\gamma\gamma jj} \geq 25 \text{ GeV}$ (2 categories) VBF , $p_T^{\gamma\gamma jj} < 25 \text{ GeV}$ (2 categories)	2-jet VBF, $p_T^{j1} \geq 200 \text{ GeV}$ 2-jet VBF, $p_T^{j1} < 200 \text{ GeV}$	2-jet VBF	VBF $p_T^{\tau\tau} > 140 \text{ GeV}$ ($\tau_{\text{had}}\tau_{\text{had}}$ only) VBF high- m_{jj} VBF low- m_{jj}	VBF , two central jets VBF , four central jets $VBF + \gamma$
ggF	2-jet, $p_T^{\gamma\gamma} \geq 200 \text{ GeV}$ 2-jet, $120 \text{ GeV} \leq p_T^{\gamma\gamma} < 200 \text{ GeV}$ 2-jet, $60 \text{ GeV} \leq p_T^{\gamma\gamma} < 120 \text{ GeV}$ 2-jet, $p_T^{\gamma\gamma} < 60 \text{ GeV}$ 1-jet, $p_T^{\gamma\gamma} \geq 200 \text{ GeV}$ 1-jet, $120 \text{ GeV} \leq p_T^{\gamma\gamma} < 200 \text{ GeV}$ 1-jet, $60 \text{ GeV} \leq p_T^{\gamma\gamma} < 120 \text{ GeV}$ 1-jet, $p_T^{\gamma\gamma} < 60 \text{ GeV}$ 0-jet (2 categories)	1-jet, $p_T^{4\ell} \geq 120 \text{ GeV}$ 1-jet, $60 \text{ GeV} \leq p_T^{4\ell} < 120 \text{ GeV}$ 1-jet, $p_T^{4\ell} < 60 \text{ GeV}$ 0-jet, $p_T^{4\ell} < 100 \text{ GeV}$	1-jet, $m_{\ell\ell} < 30 \text{ GeV}$, $p_T^{\ell_2} < 20 \text{ GeV}$ 1-jet, $m_{\ell\ell} < 30 \text{ GeV}$, $p_T^{\ell_2} \geq 20 \text{ GeV}$ 1-jet, $m_{\ell\ell} \geq 30 \text{ GeV}$, $p_T^{\ell_2} < 20 \text{ GeV}$ 1-jet, $m_{\ell\ell} \geq 30 \text{ GeV}$, $p_T^{\ell_2} \geq 20 \text{ GeV}$ 0-jet, $m_{\ell\ell} < 30 \text{ GeV}$, $p_T^{\ell_2} < 20 \text{ GeV}$ 0-jet, $m_{\ell\ell} < 30 \text{ GeV}$, $p_T^{\ell_2} \geq 20 \text{ GeV}$ 0-jet, $m_{\ell\ell} \geq 30 \text{ GeV}$, $p_T^{\ell_2} < 20 \text{ GeV}$ 0-jet, $m_{\ell\ell} \geq 30 \text{ GeV}$, $p_T^{\ell_2} \geq 20 \text{ GeV}$	Boosted, $p_T^{\tau\tau} > 140 \text{ GeV}$ Boosted, $p_T^{\tau\tau} \leq 140 \text{ GeV}$	

$$\mu = 1.11_{-0.08}^{+0.09} = 1.11 \pm 0.05 \text{ (stat.) }_{-0.04}^{+0.05} \text{ (exp.) }_{-0.04}^{+0.05} \text{ (sig. th.) }_{-0.03}^{+0.03} \text{ (bkg. th.)}$$

Searches for New Physics

- Supersymmetry
- Exotic models
- Dark Matter
- Unconventional signatures

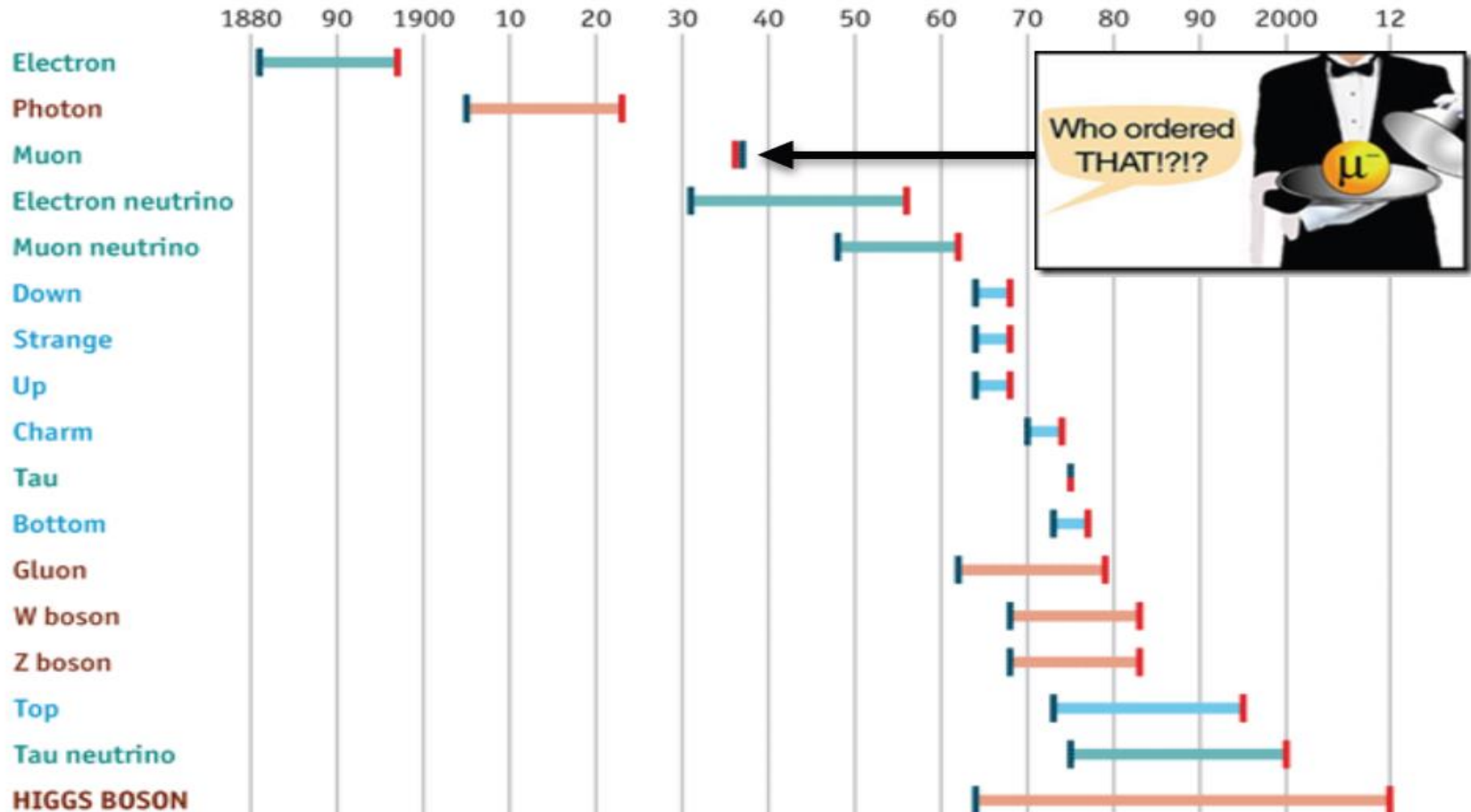
Uncharted discoveries?

The Standard Model of particle physics

Years from concept to discovery

Leptons
Bosons
Quarks

Theorised/explained
Discovered



Source: *The Economist*

Many unanswered questions ...

Why there are 3 families of particles? Are there more?

Why is the top quark so heavy?

Why there's more matter than anti-matter?

How do neutrinos get mass?

Are there more forces?

1960: SLAC u up quark	1954: Brookhaven & SLAC c charm quark	1985: Fermilab t top quark	1979: DESY g gluon
1968: SLAC d down quark	1977: Manchester University s strange quark	1977: Fermilab b bottom quark	1923: Washington University γ photon
1960: Savannah River Plant ν_e electron neutrino	1962: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1963: CERN W W boson
1927: Cavendish Laboratory e electron	1937: Caltech and Harvard μ muon	1976: SLAC τ tau	1983: CERN Z Z boson
			2012: CERN H Higgs boson

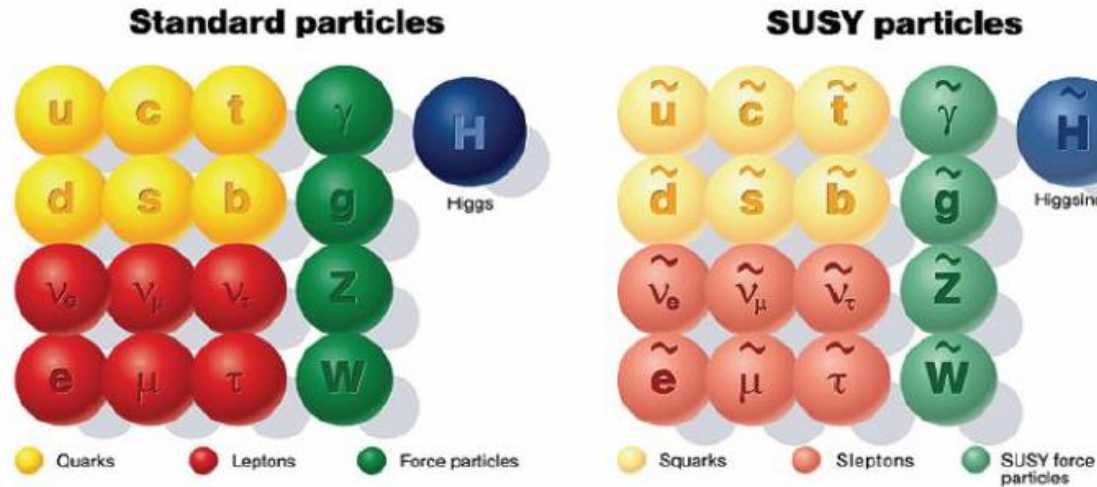
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

... and as many possible answers to probe!

- Super-symmetry?



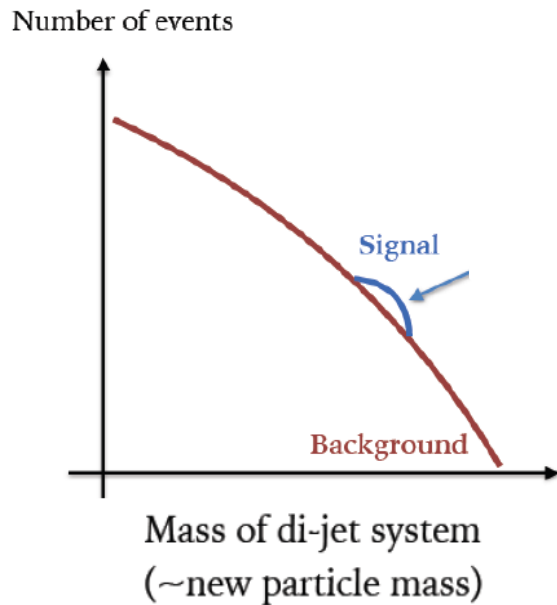
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- ...



How would new phenomena manifest itself?

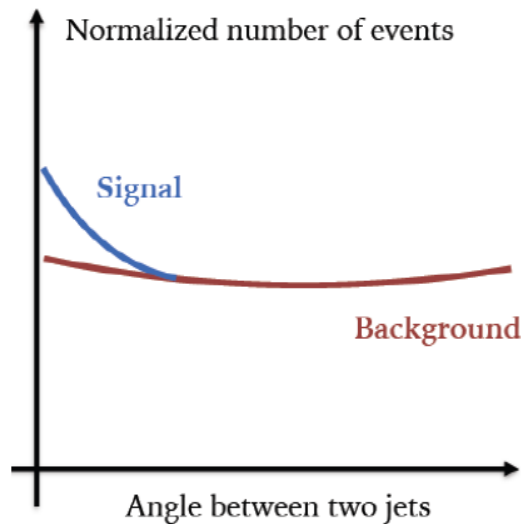
New particles:

resonant excess (bump) over Standard Model background



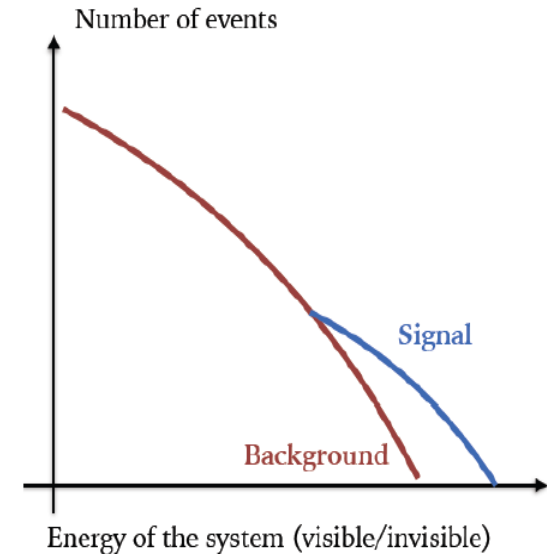
New interactions:

more central production ($\sim$ Rutherford experiment)

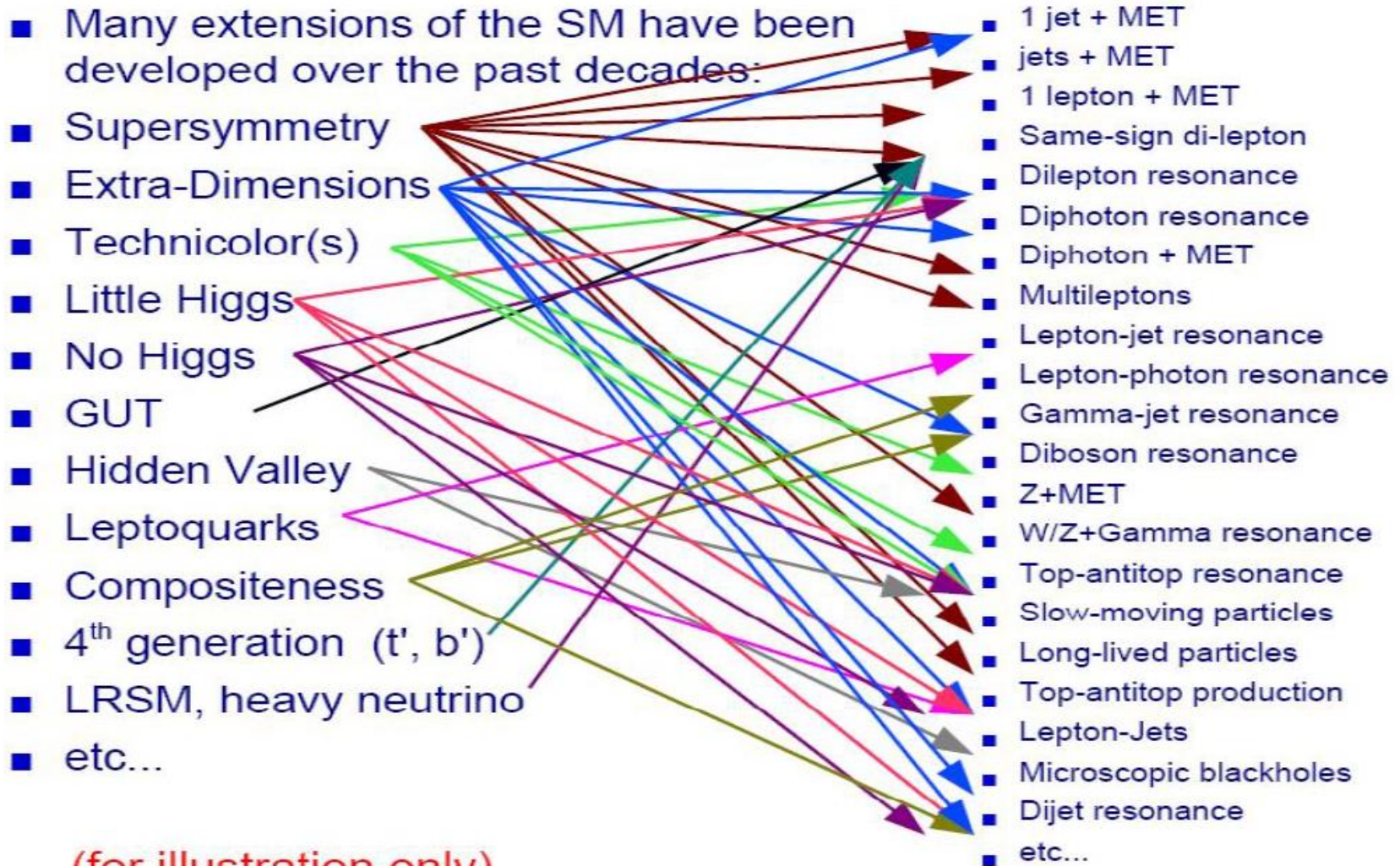


New particles and states:

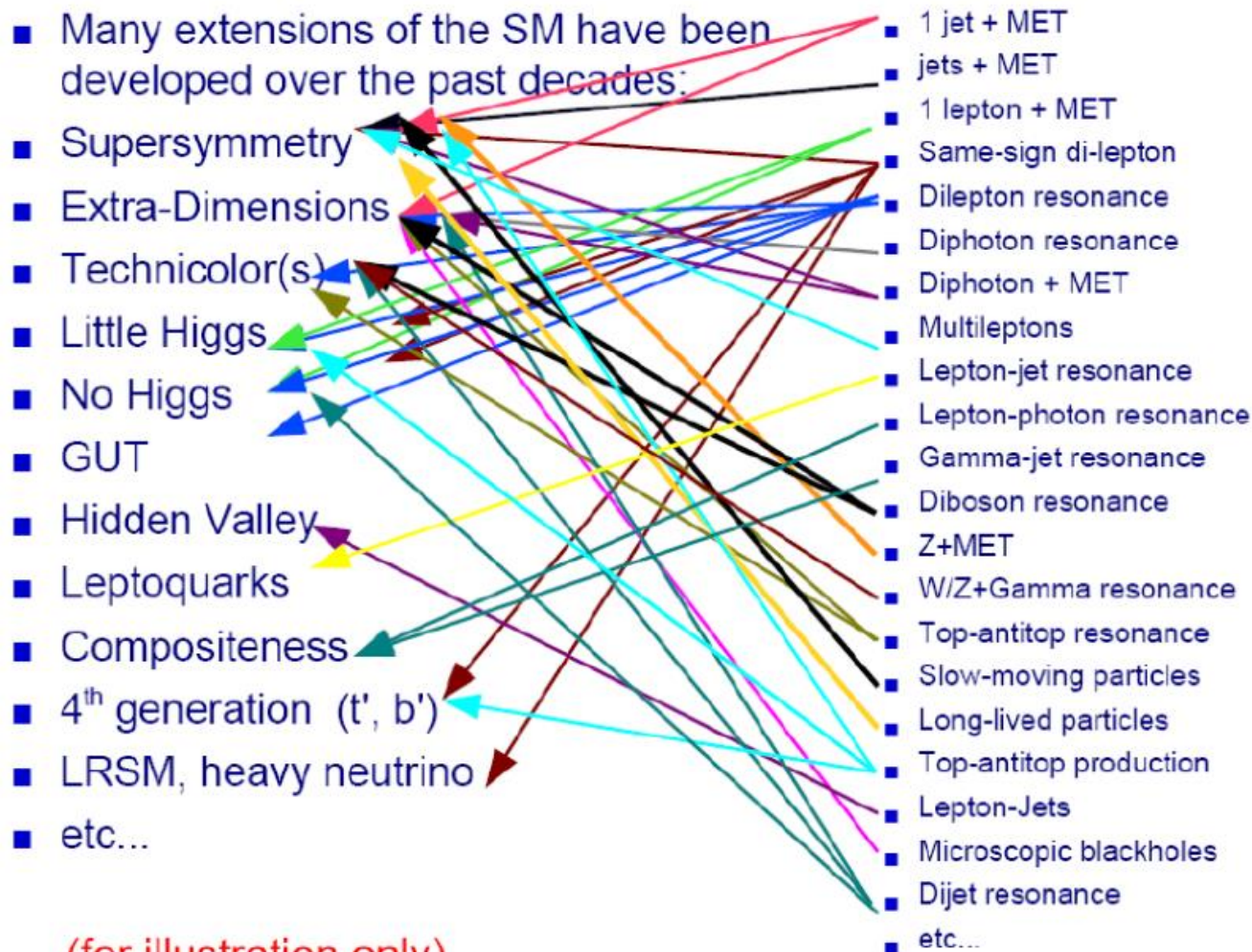
larger multiplicity of objects at high masses



Long list of models and signatures



Long list of models and signatures



(for illustration only)

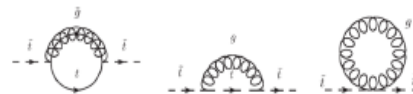
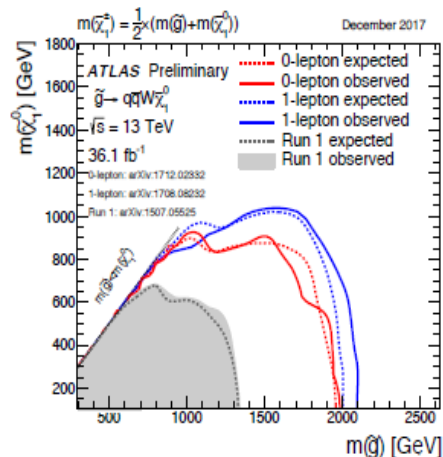
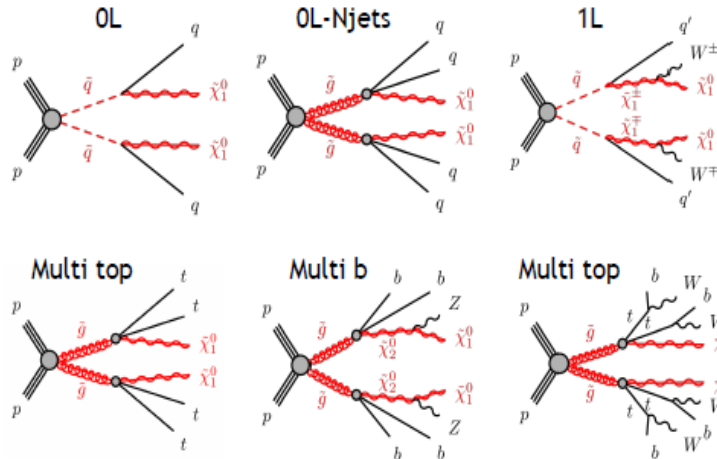
A complex 2D problem

Experimentally, a **signature standpoint** makes a lot of sense:

- Practical
- Less model-dependent
- Important to cover every possible signature

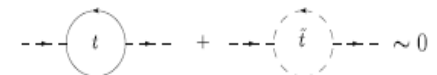
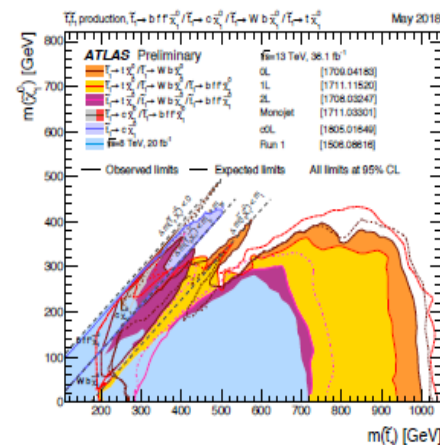
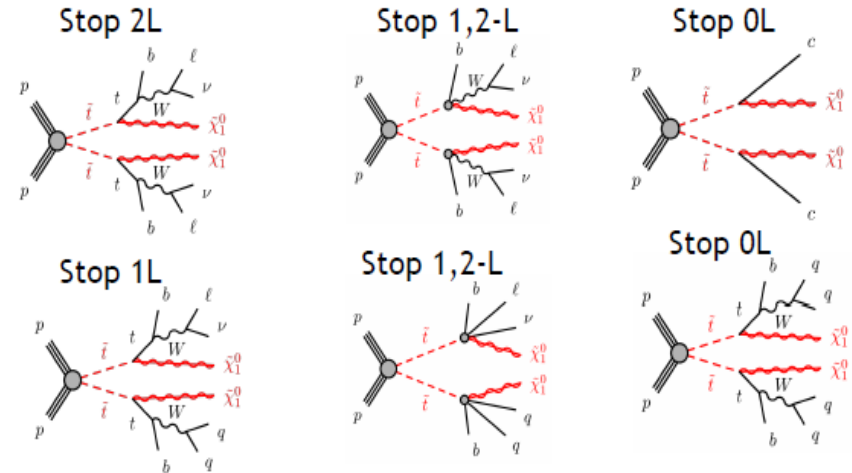
Strongly produced SUSY searches

Squarks and gluinos



Stop also a scalar requires light gluinos to be light enough: for gluinos $> 1.8 \text{ TeV}$ ~tuning of Factor of 30

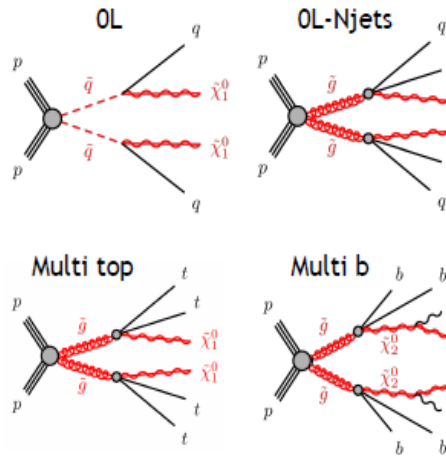
Stop



Not so natural SUSY: Stops $> 800 \text{ GeV}$ ~Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

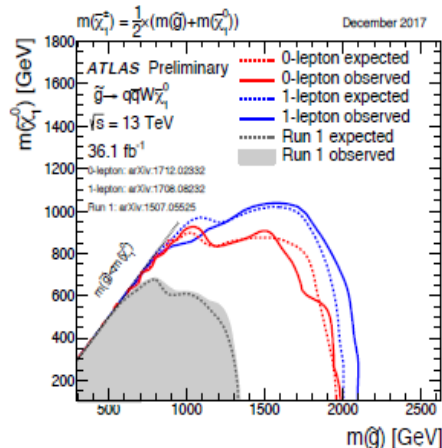
Strongly produced SUSY searches

Squarks and gluinos

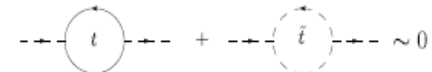
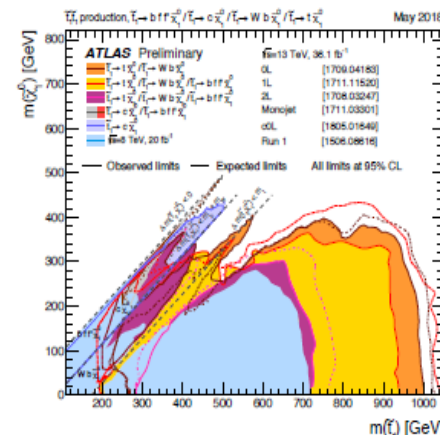
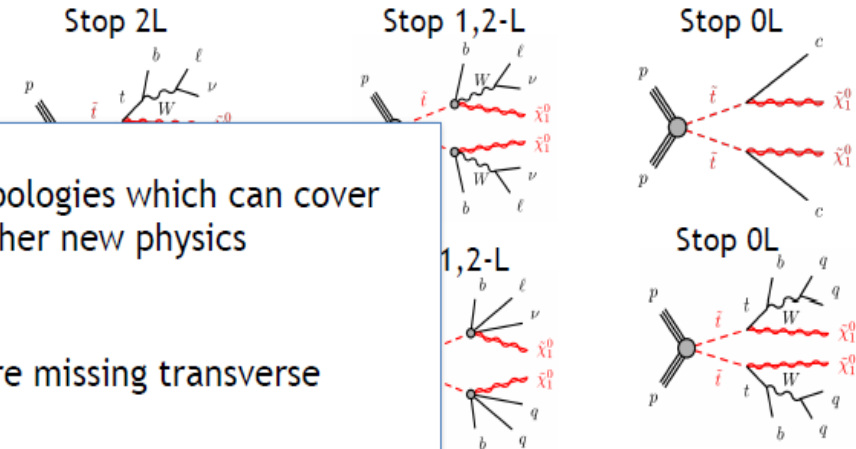


Large number of topologies which can cover different SUSY or other new physics scenarios

All signatures feature missing transverse energy!



Stop also a scalar requires light gluinos to be light enough: for gluinos > 1.8 TeV $\sim$ tuning of Factor of 30



Not so natural SUSY: Stops > 800 GeV $\sim$ Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

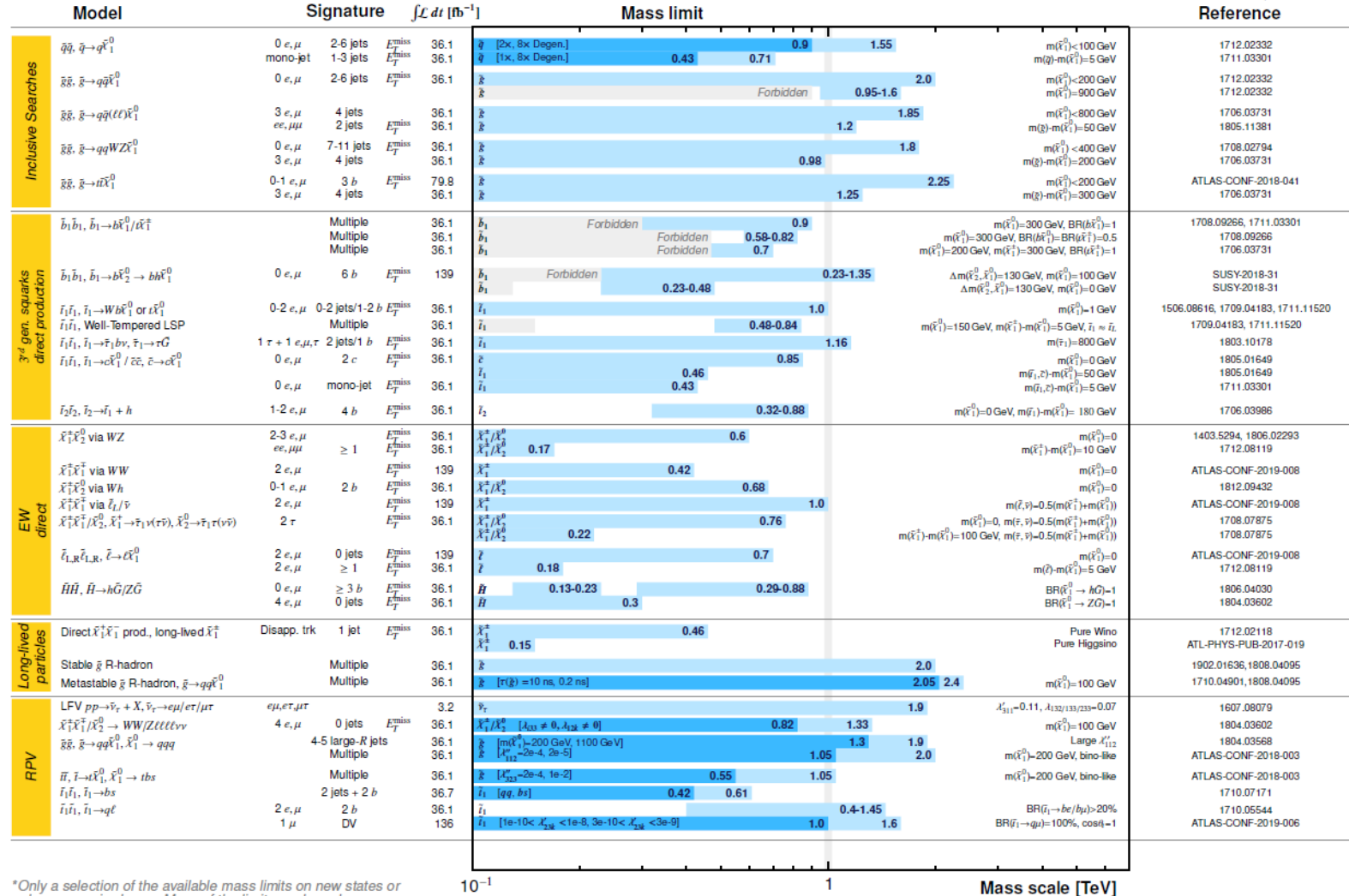
SUSY Searches Overview (2019)

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$

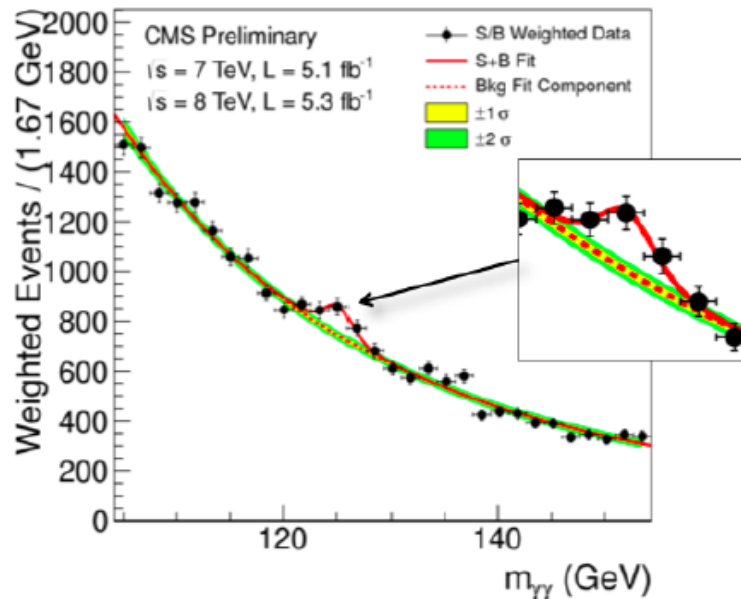


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

What characterizes Exotics Searches

No precise model to guide us

Standard Model:
Predicted Higgs boson

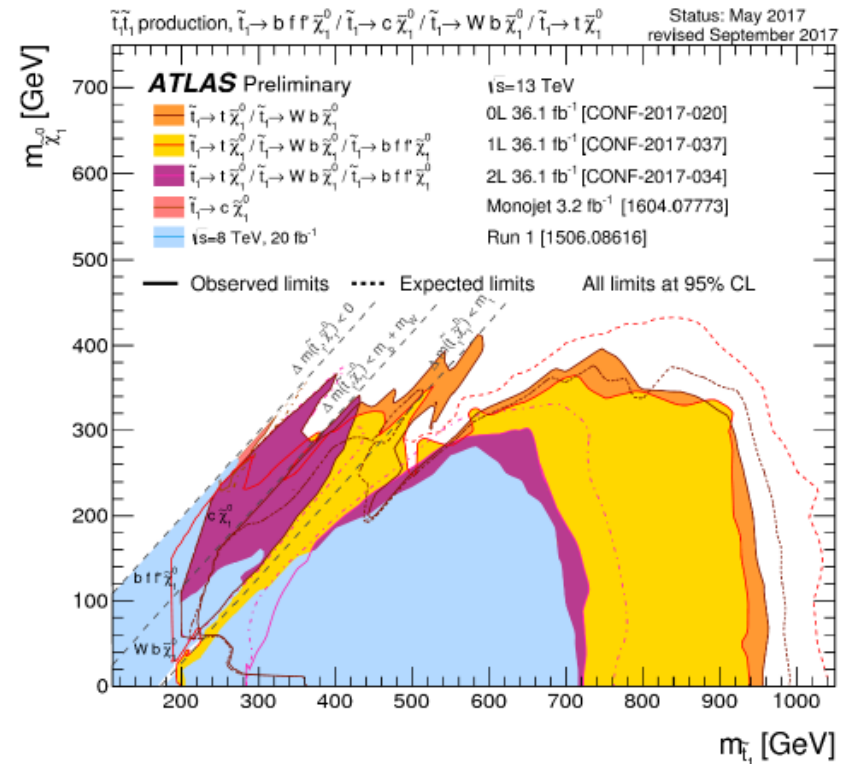


[Phys. Lett. B 716 \(2012\) 1-29](#)

[Phys. Lett. B 716 \(2012\) 30-61](#)

No unified parameter phase space

Supersymmetry Searches:



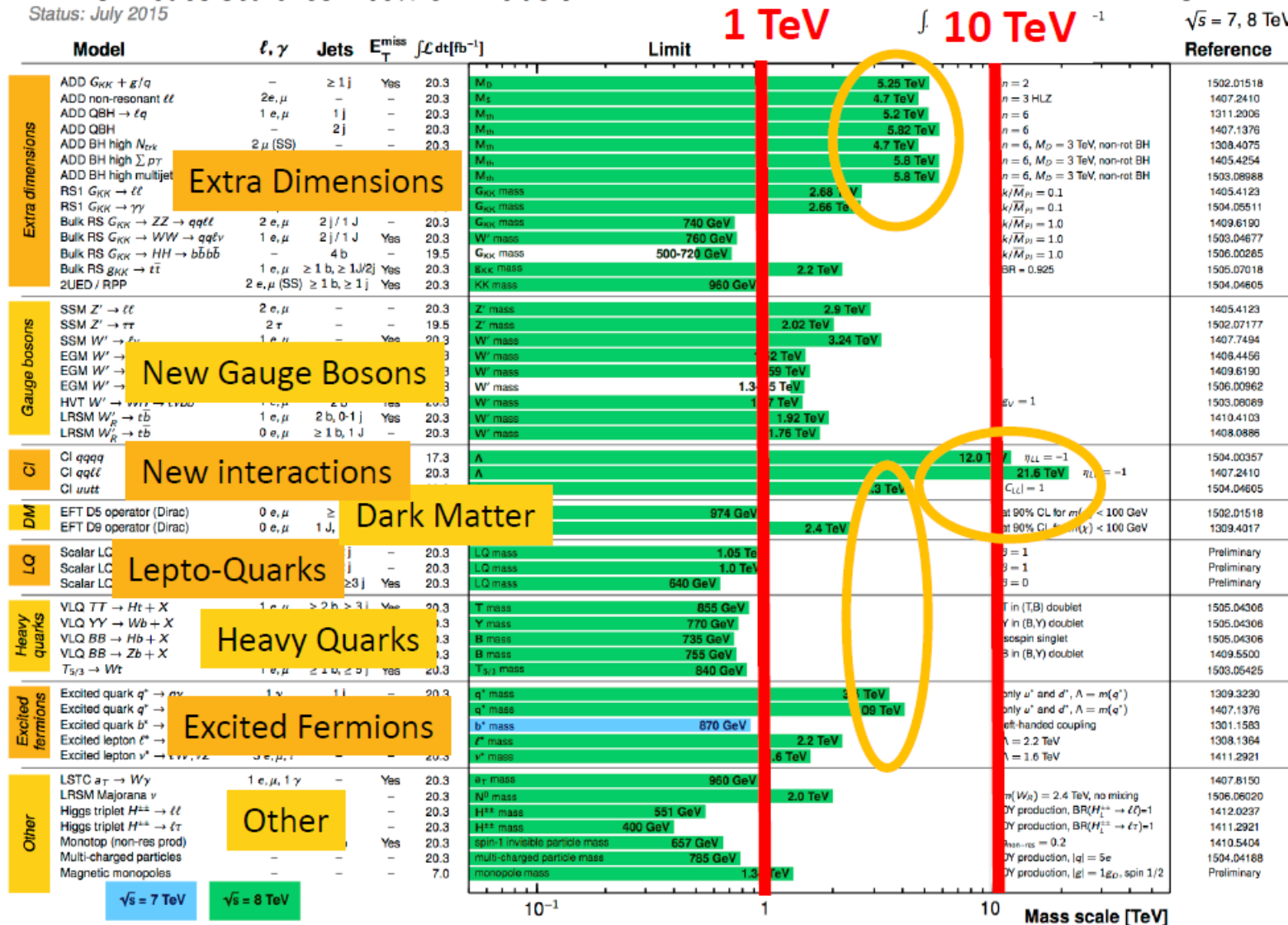
Exploration range of LHC by mid 2015

ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

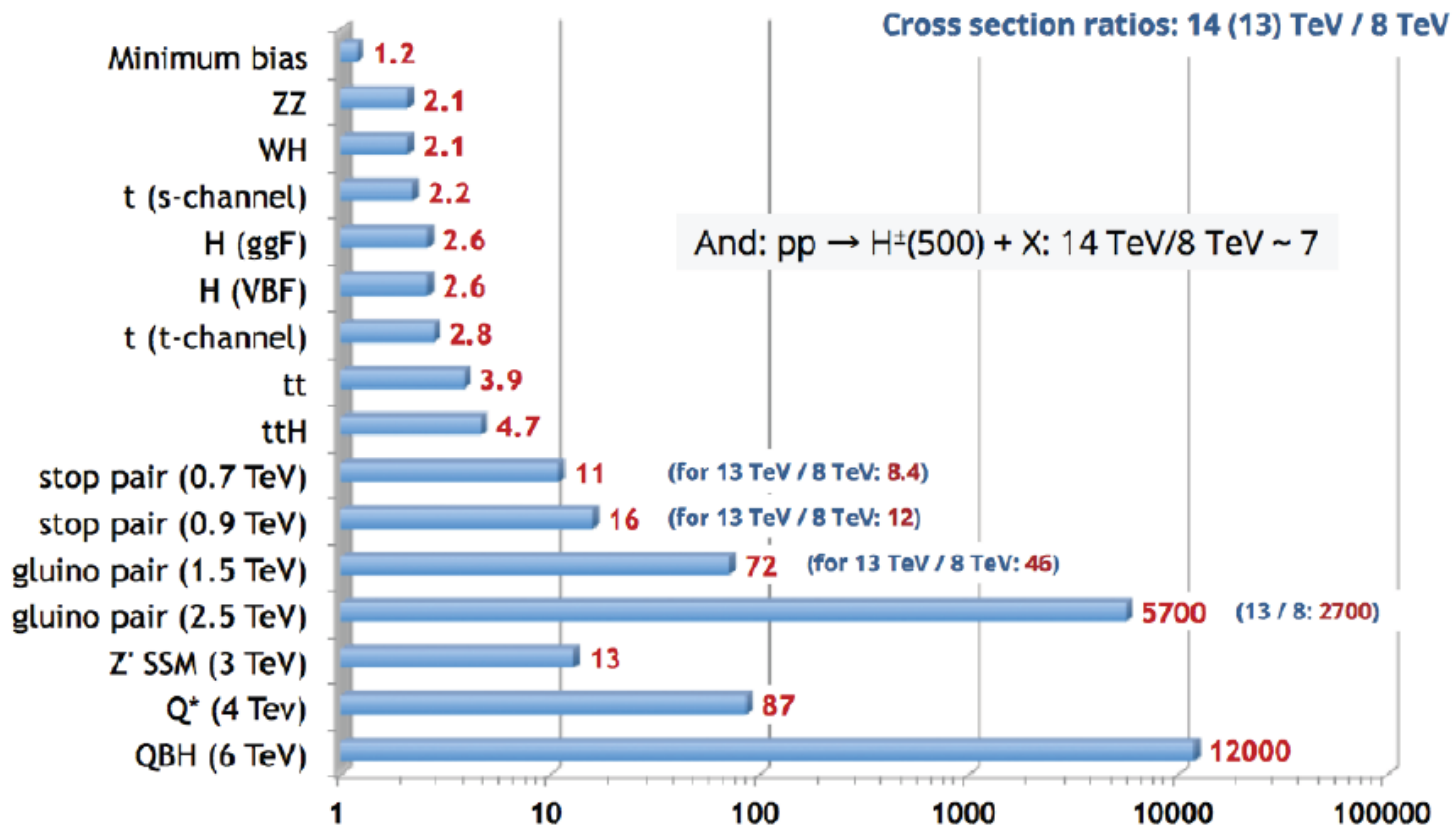
$\sqrt{s} = 7, 8 \text{ TeV}$



*Only a selection of the available mass limits on new states or phenomena is shown.

LHC Run II

Hugely increased potential for discovery of heavy particles at 13 TeV
Perfect occasion for young motivated physicists: join the search!



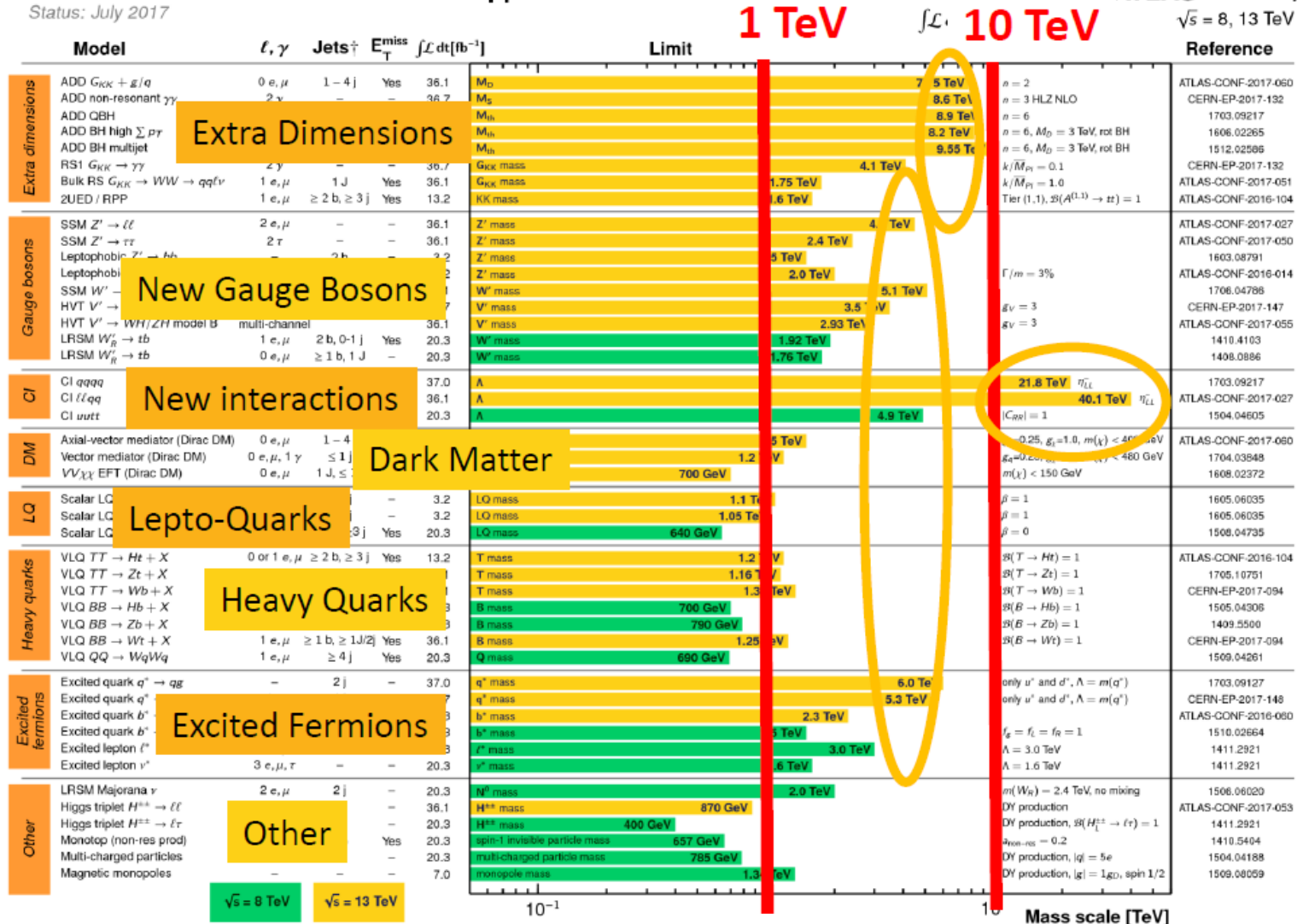
Exploration range of LHC by mid 2017

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limit

Status: July 2017

ATLAS Preliminary

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



*Only a selection of the available mass limits on new states or phenomena is shown.

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

Exploration range of LHC by mid 2019

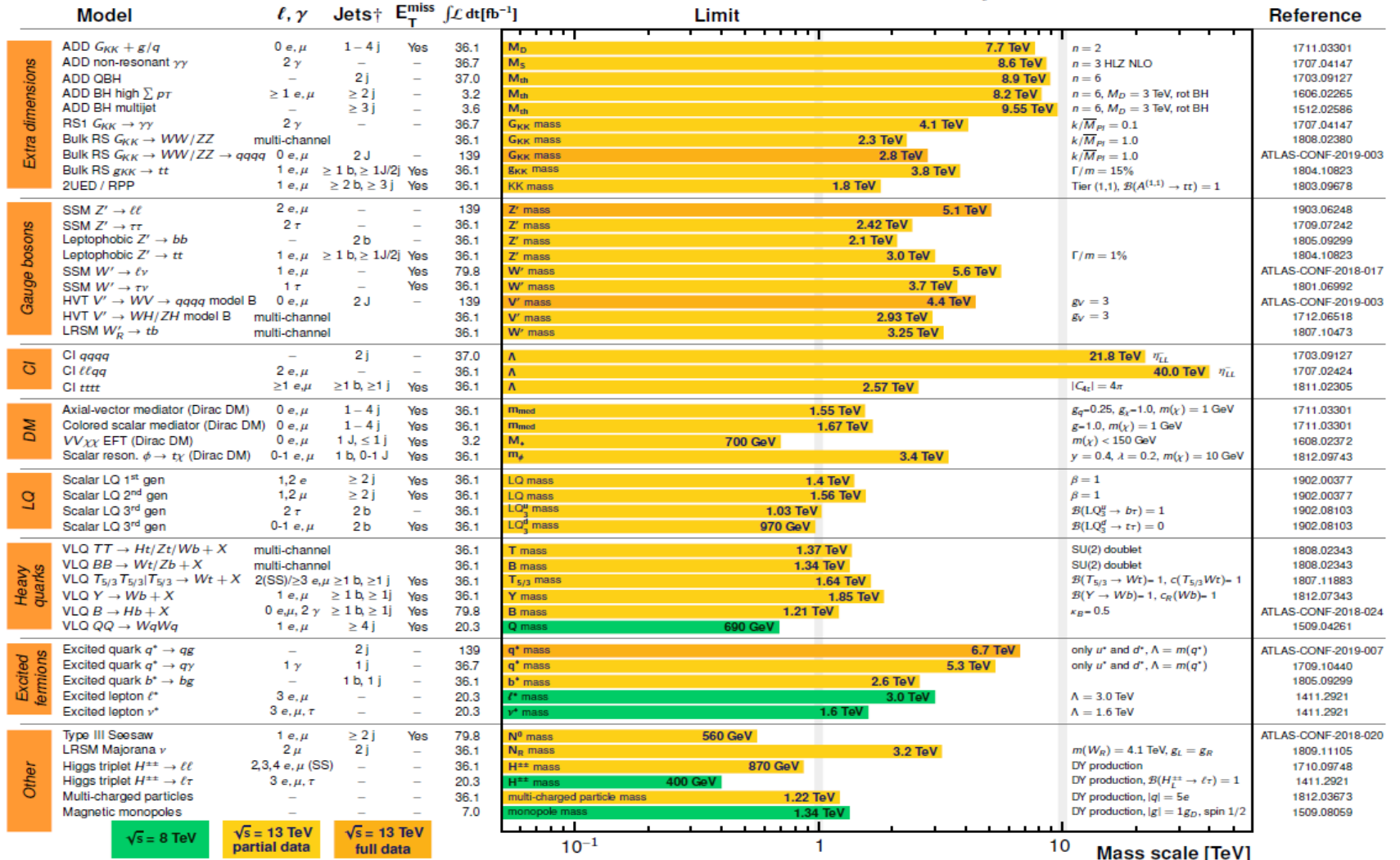
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: March 2019

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$

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



*Only a selection of the available mass limits on new states or phenomena is shown.

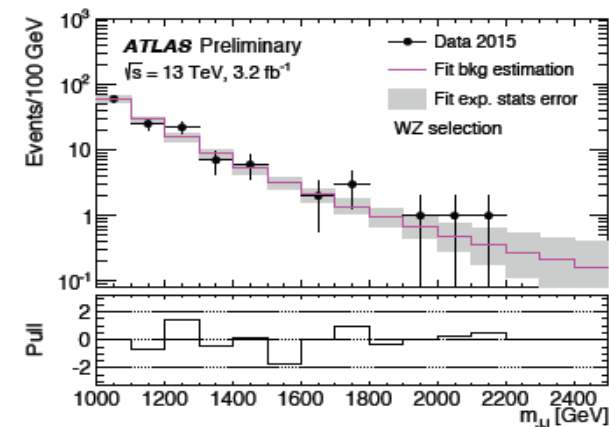
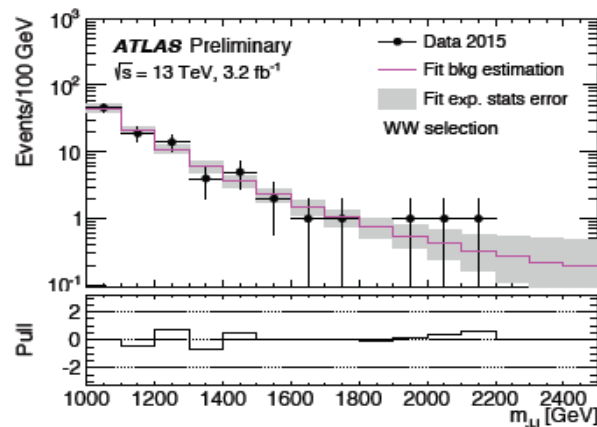
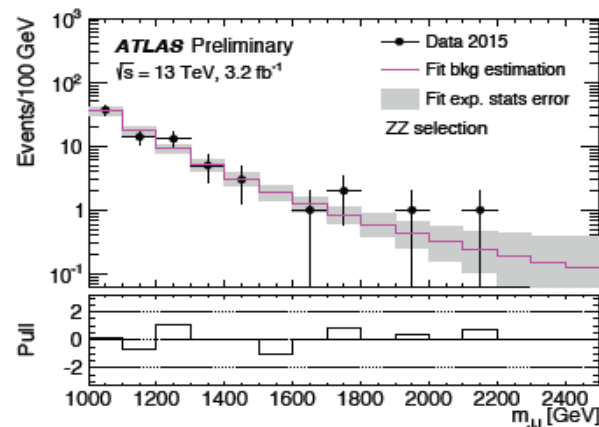
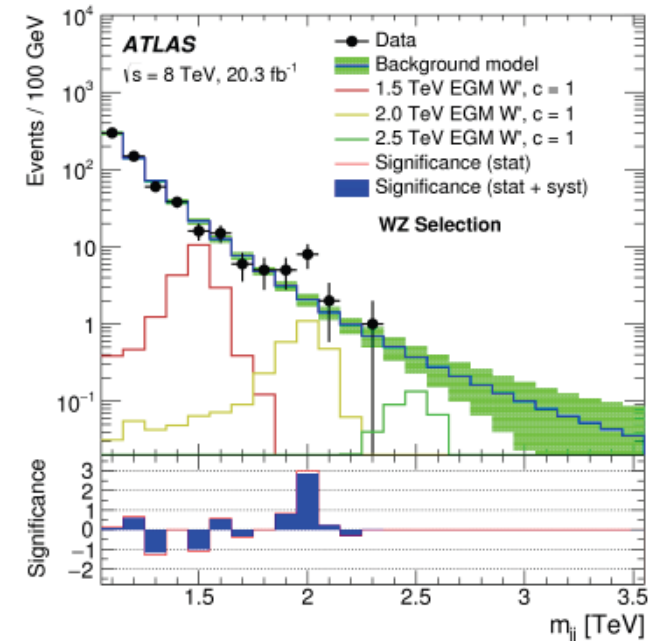
†Small-radius (large-radius) jets are denoted by the letter j (J).

Fully hadronic Diboson Searches

[ATLAS-CONF-2015-073](#)

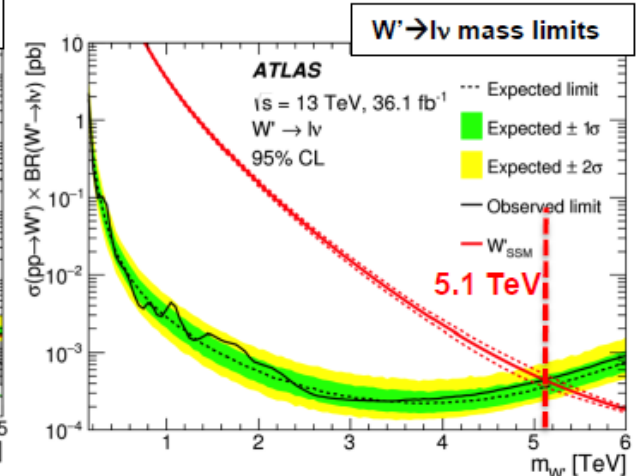
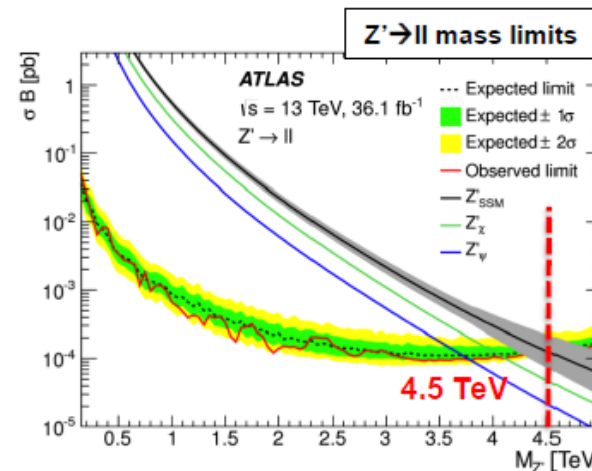
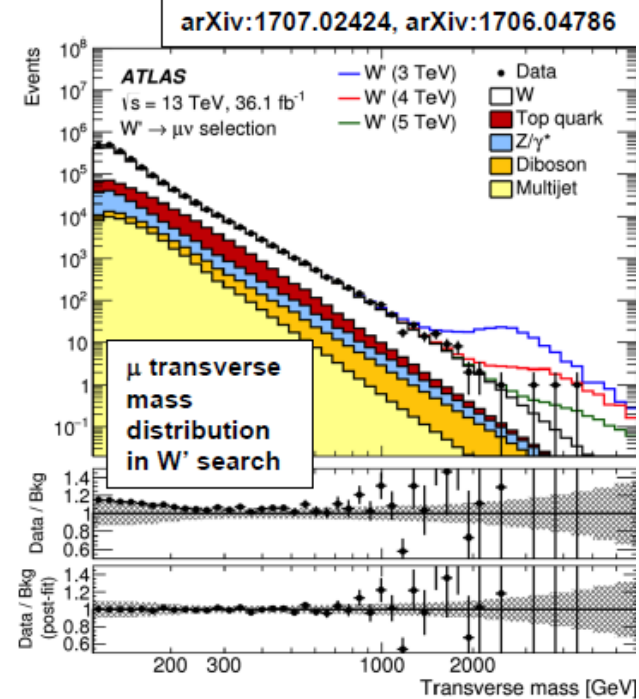
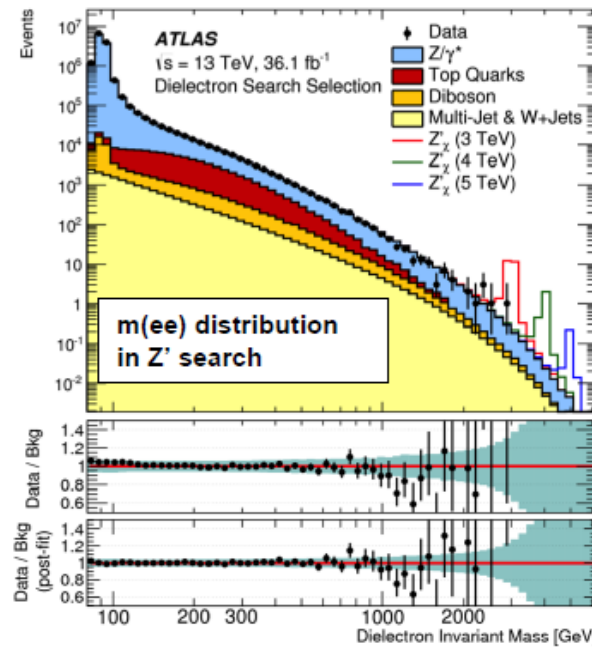
- **Modest excess at Run-1: 3.4σ local / 2.5σ global**
- **Analysis very similar to Run 1**, with functional fit of the background
- **No significant excess is observed**
however sensitivity not high enough for conclusive probe of the Run 1 excess

Run-1



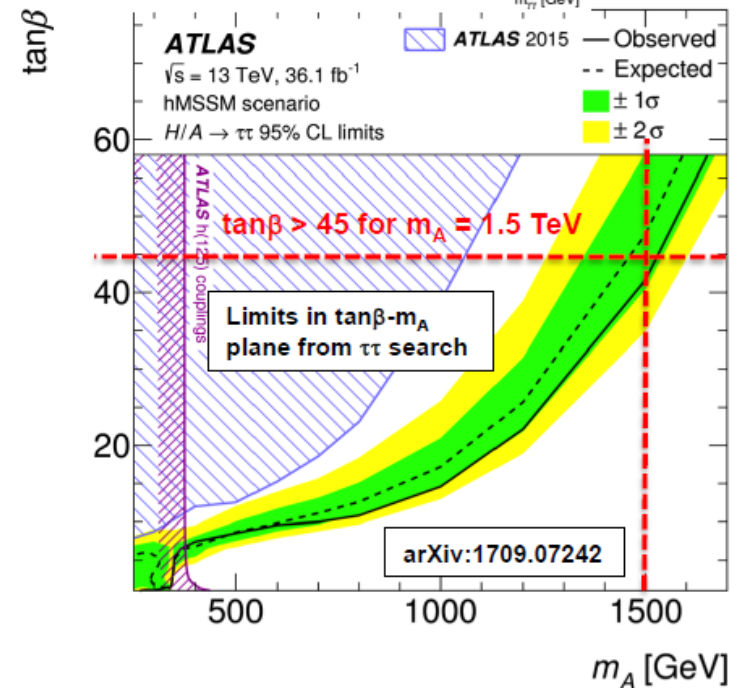
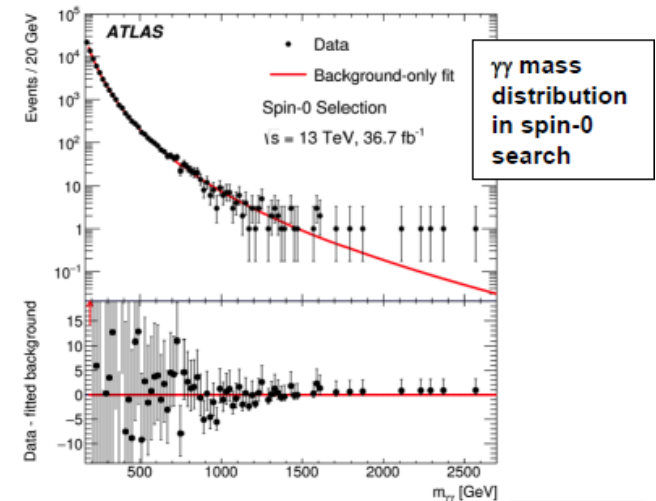
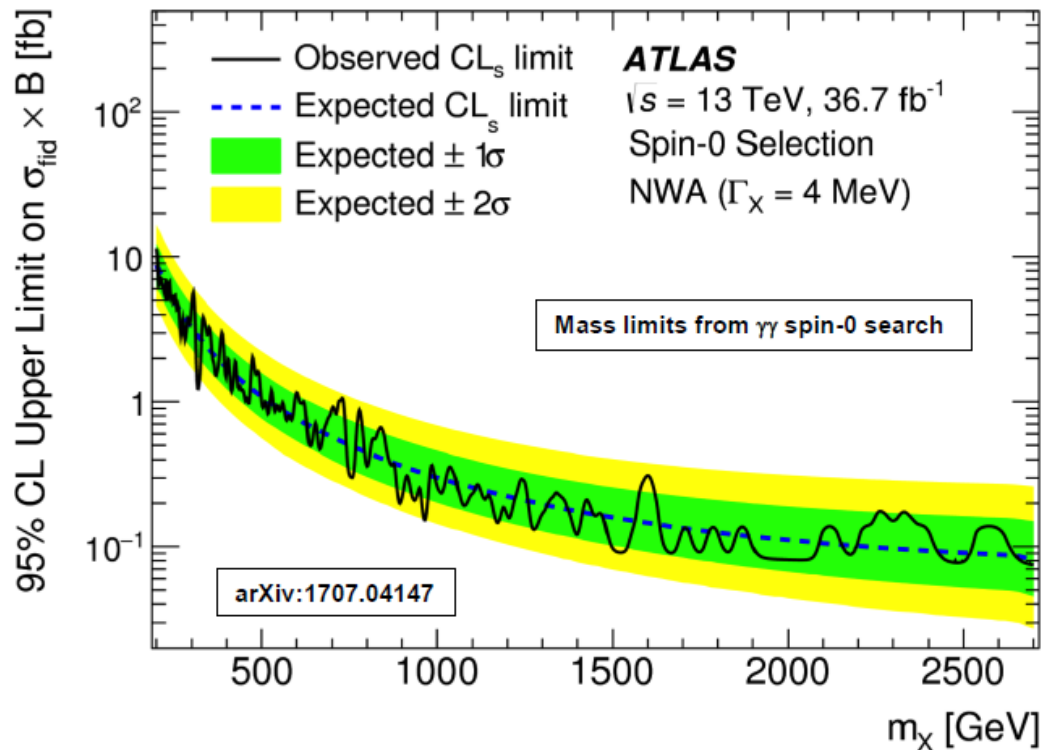
Resonance Searches (Dilepton, Lepton+ETmiss)

- Searches for new resonances decaying to lepton pairs (e.g. Z') or lepton+ E_T^{miss} (e.g. W')
- Signature is peak in invariant mass distribution (dilepton) or transverse mass distributions (lepton+ E_T^{miss})
- No significant excess over SM expectation
- 95% CL exclusion limits extracted in various new physics Z' and W' scenarios, e.g. the Sequential Standard Model (SSM)

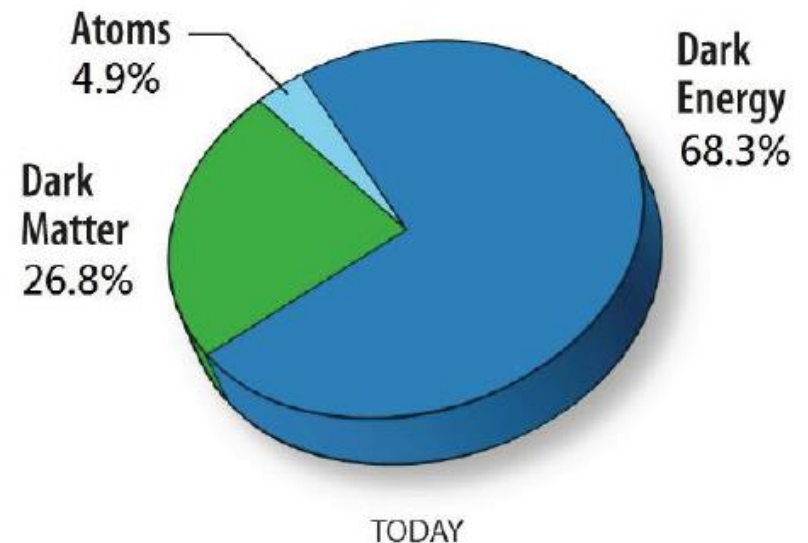
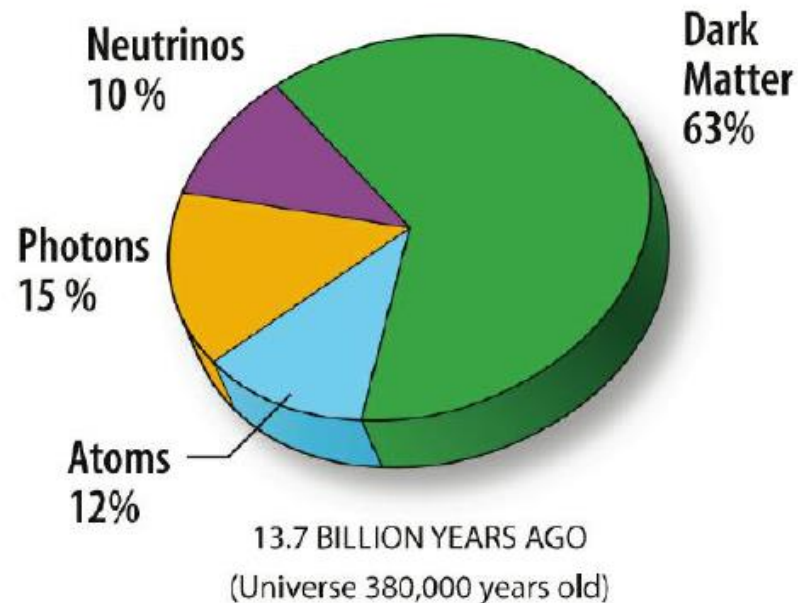


Resonance Searches ($\gamma\gamma$, $\tau\tau$)

- Diboson resonance searches also sensitive to new heavy scalars, e.g. Higgs bosons.
- Searches also conducted with $\gamma\gamma$ and $\tau\tau$ final states
- $\gamma\gamma$ search also targets spin-2 (graviton) production with a dedicated selection
- $\tau\tau$ searches sensitive to SUSY Higgs (H/A) models
- No significant excesses over SM expectation



What do we know about Dark Matter

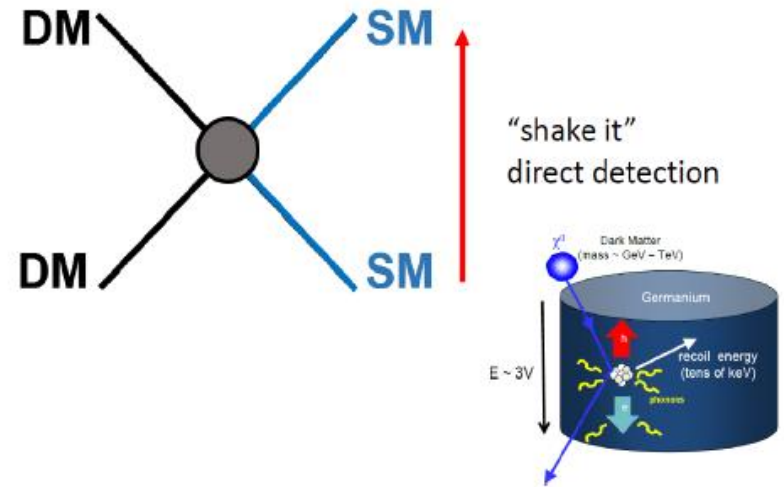
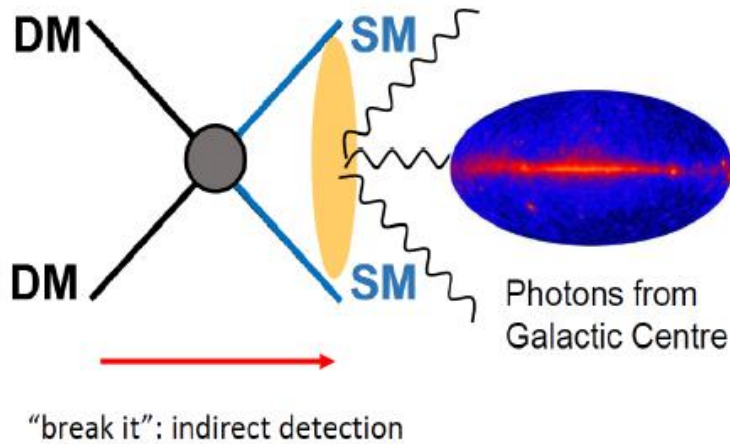


Strong astrophysical evidence for the existence of dark matter

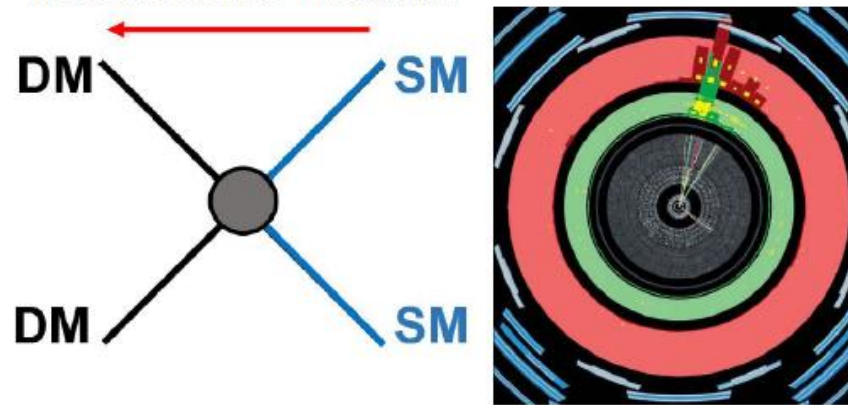
What do we know about Dark Matter

- **Massive**
- **Non-relativistic (slow)**
- **Long lived (old)**
- **No electric or colour charge**
- **Very weakly interacting with ordinary matter**
- **Subject to gravity interactions**

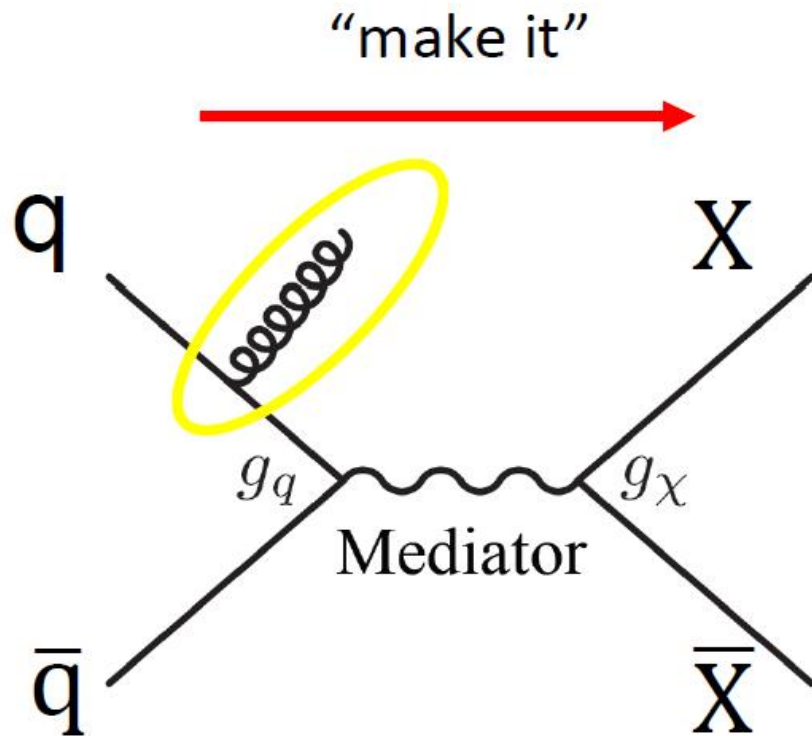
Experimental detection of Dark Matter



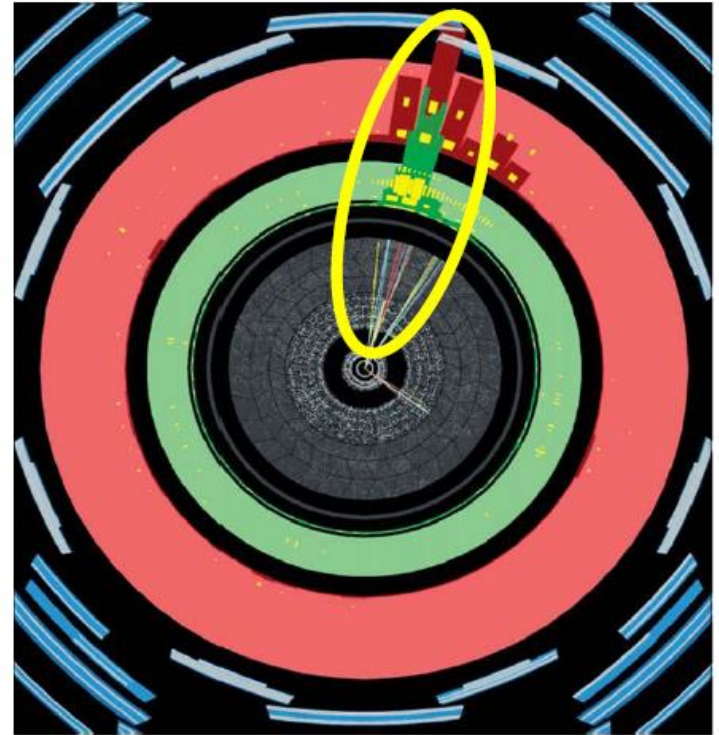
“make it”: Collider Production



Dark Matter searches at Colliders

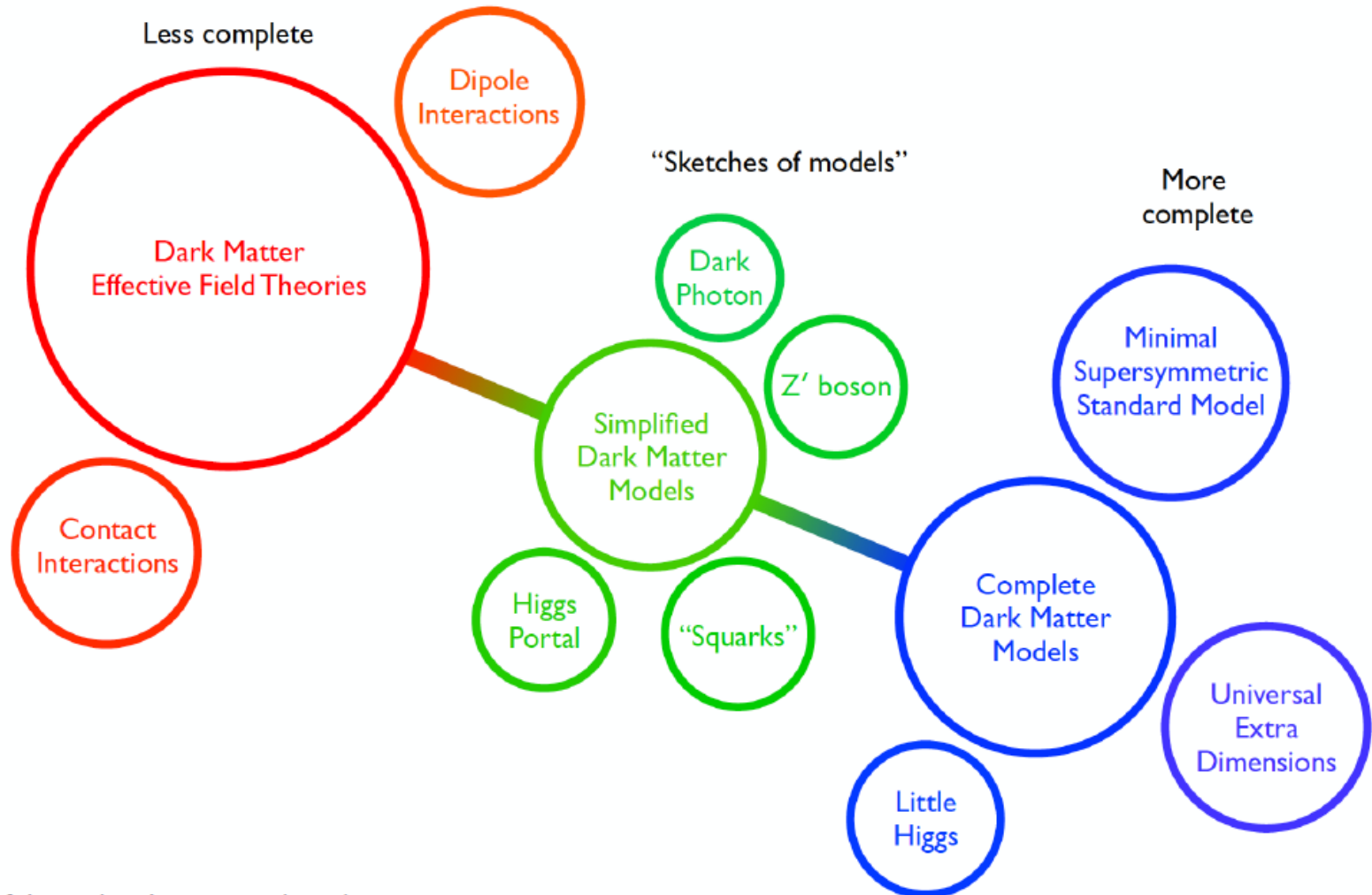


g_q and g_X coupling strengths

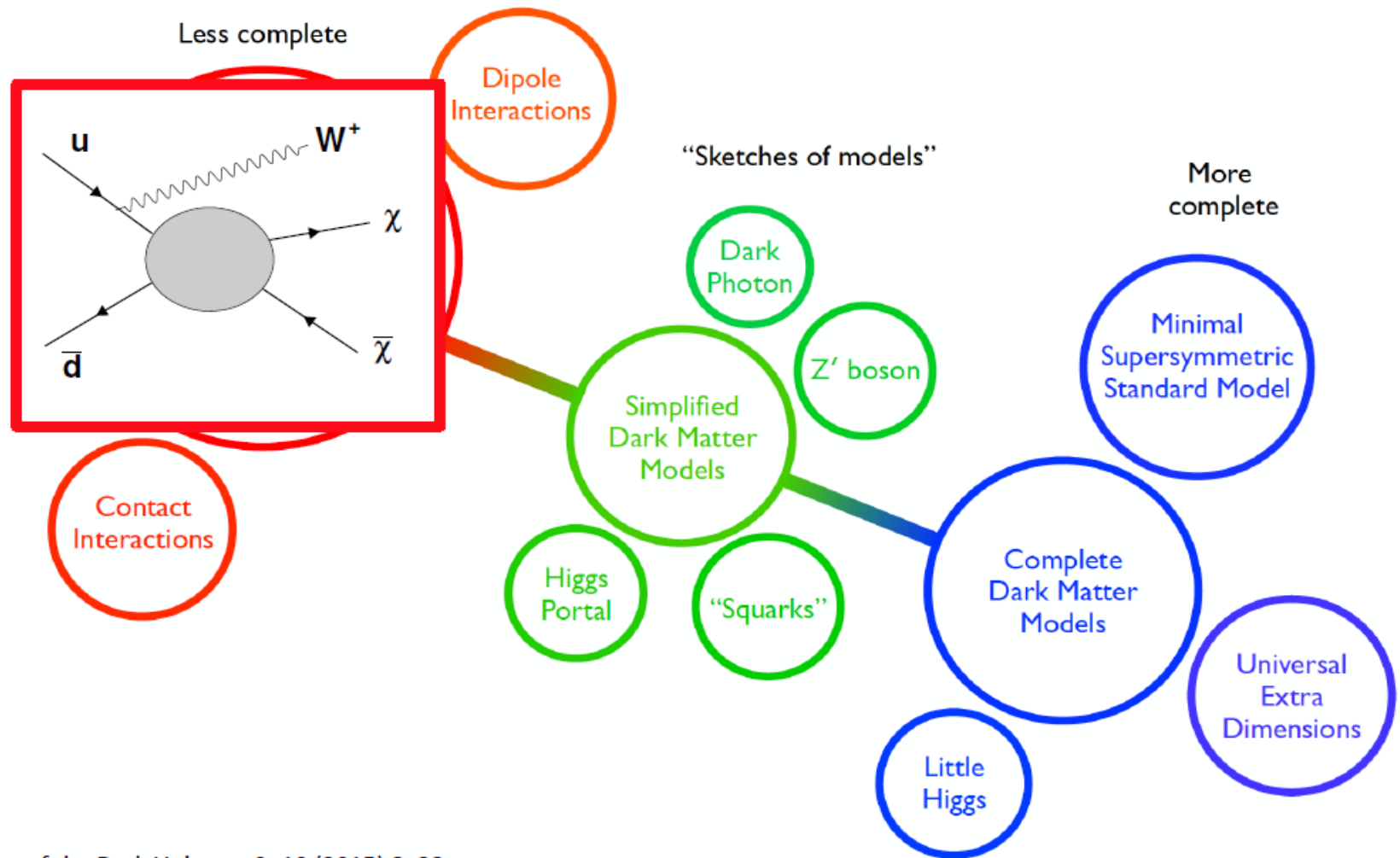


Empty detector + something

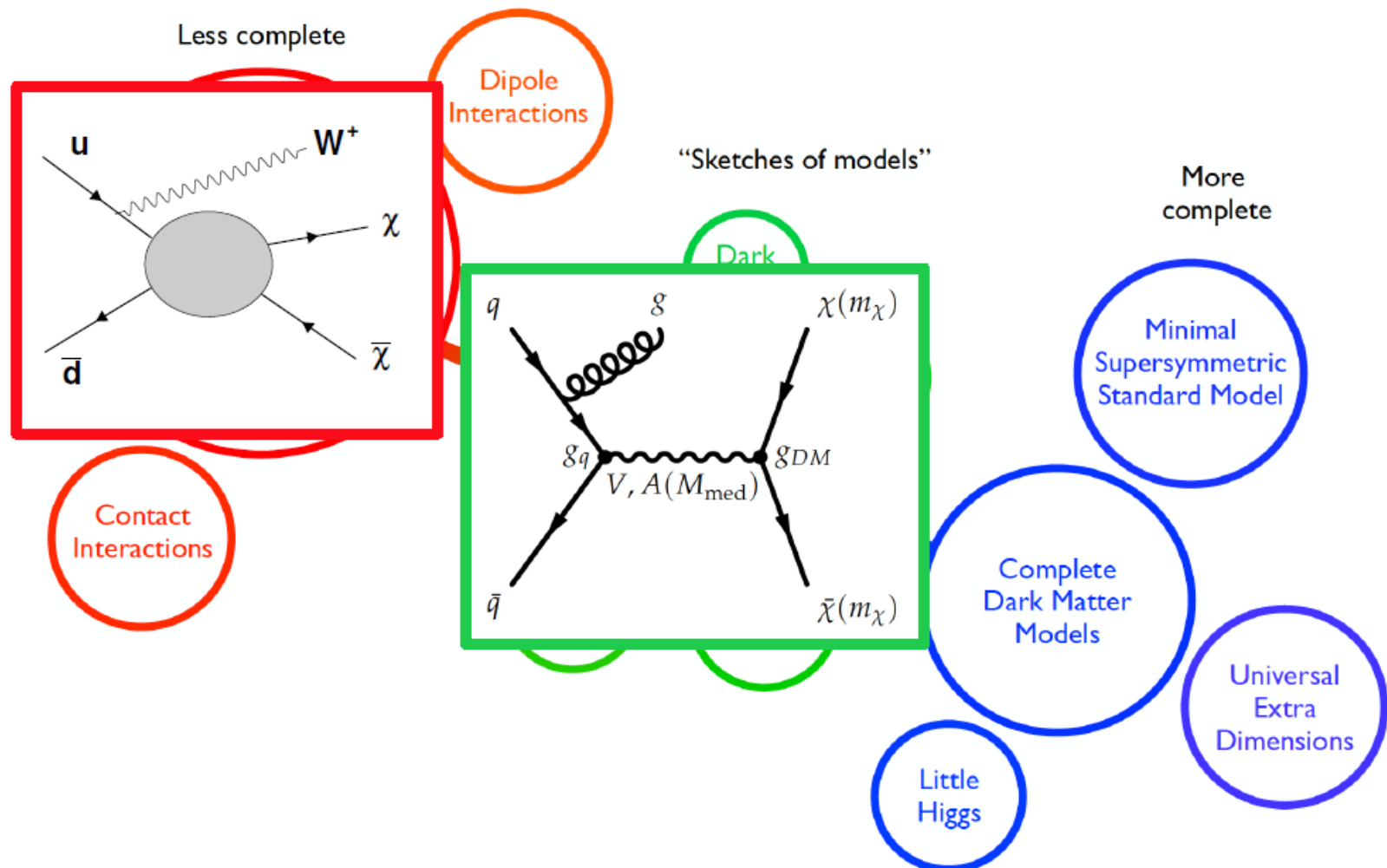
Dark Matter theory space



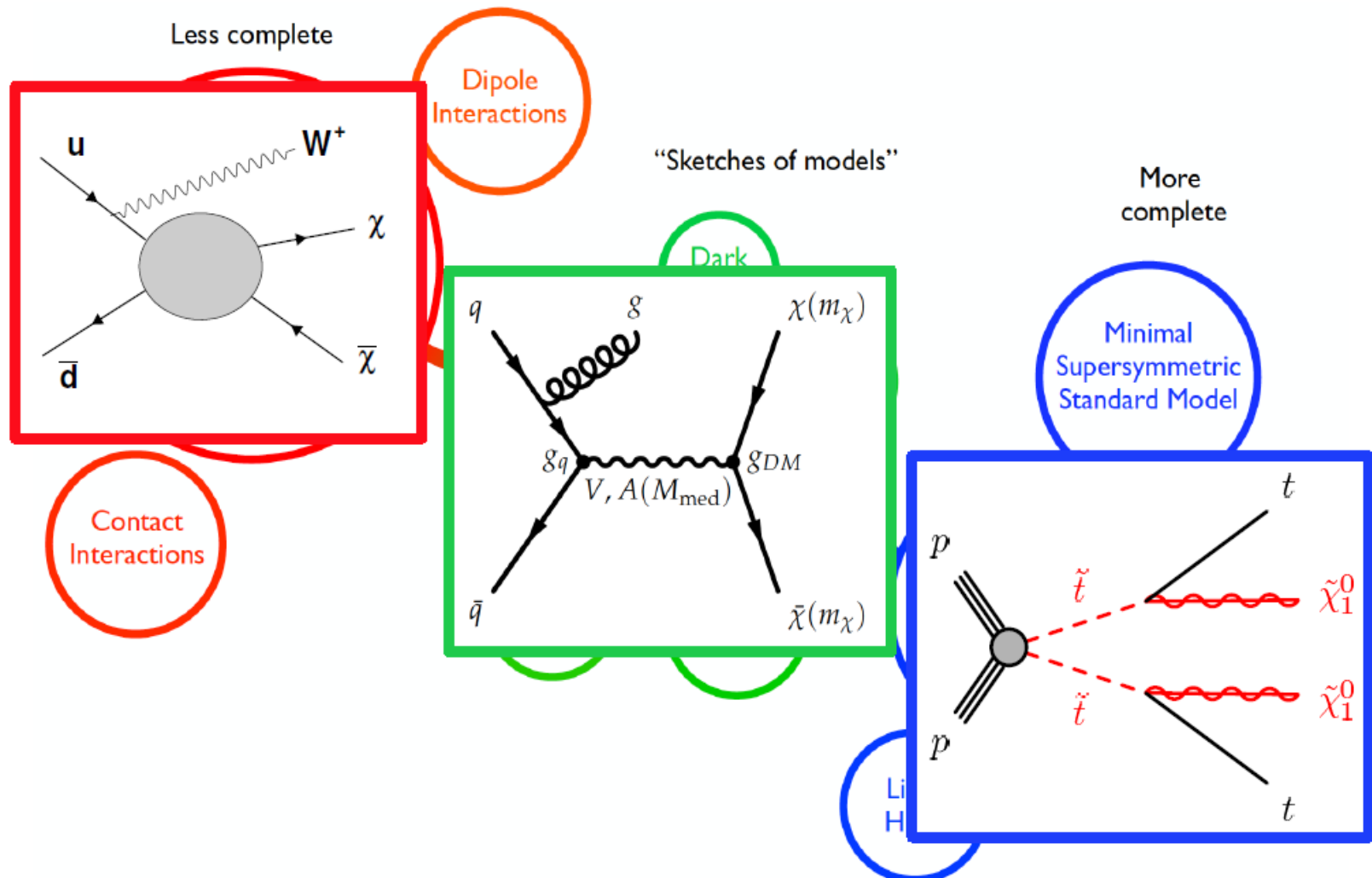
Dark Matter theory space



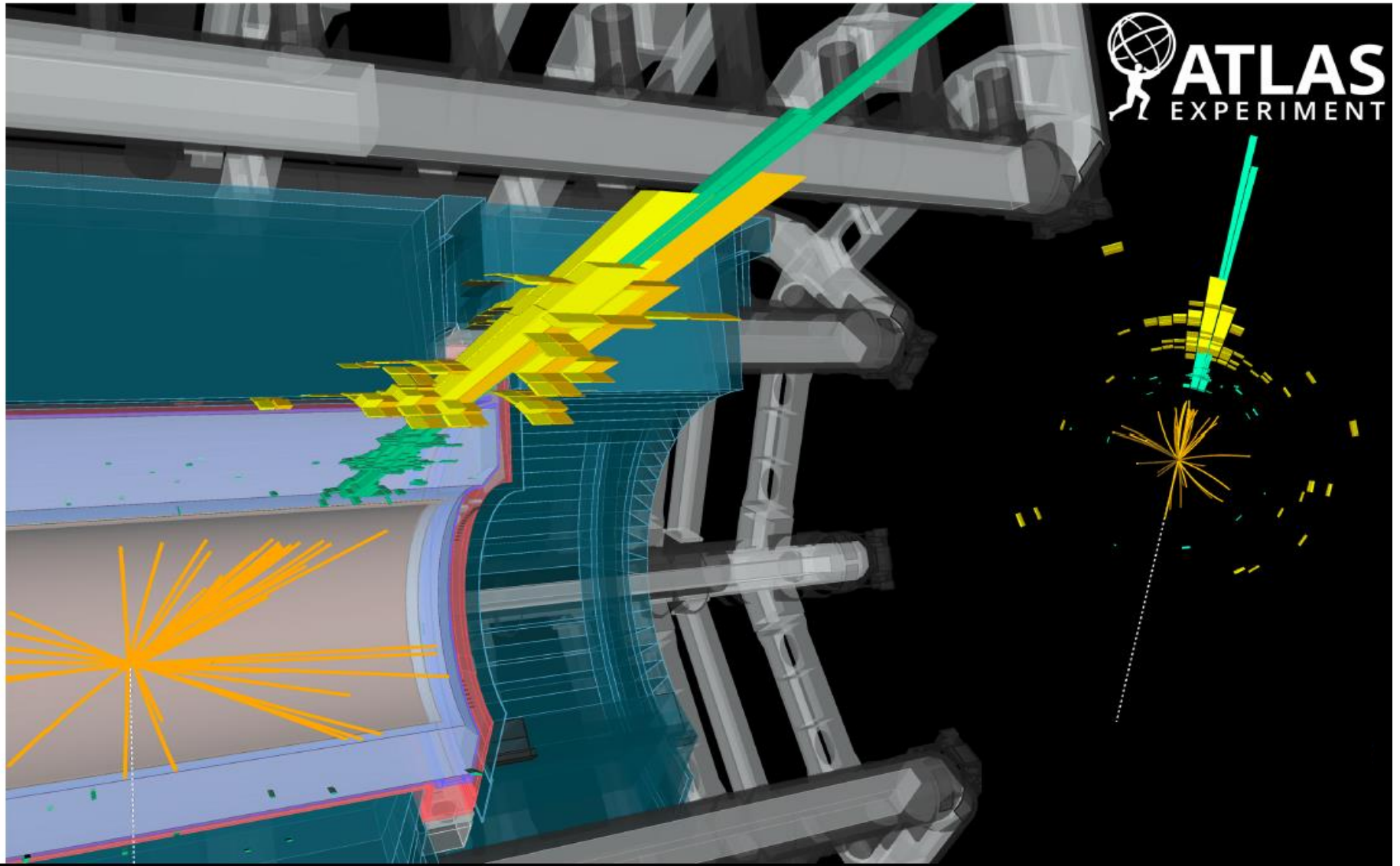
Dark Matter theory space



Dark Matter theory space

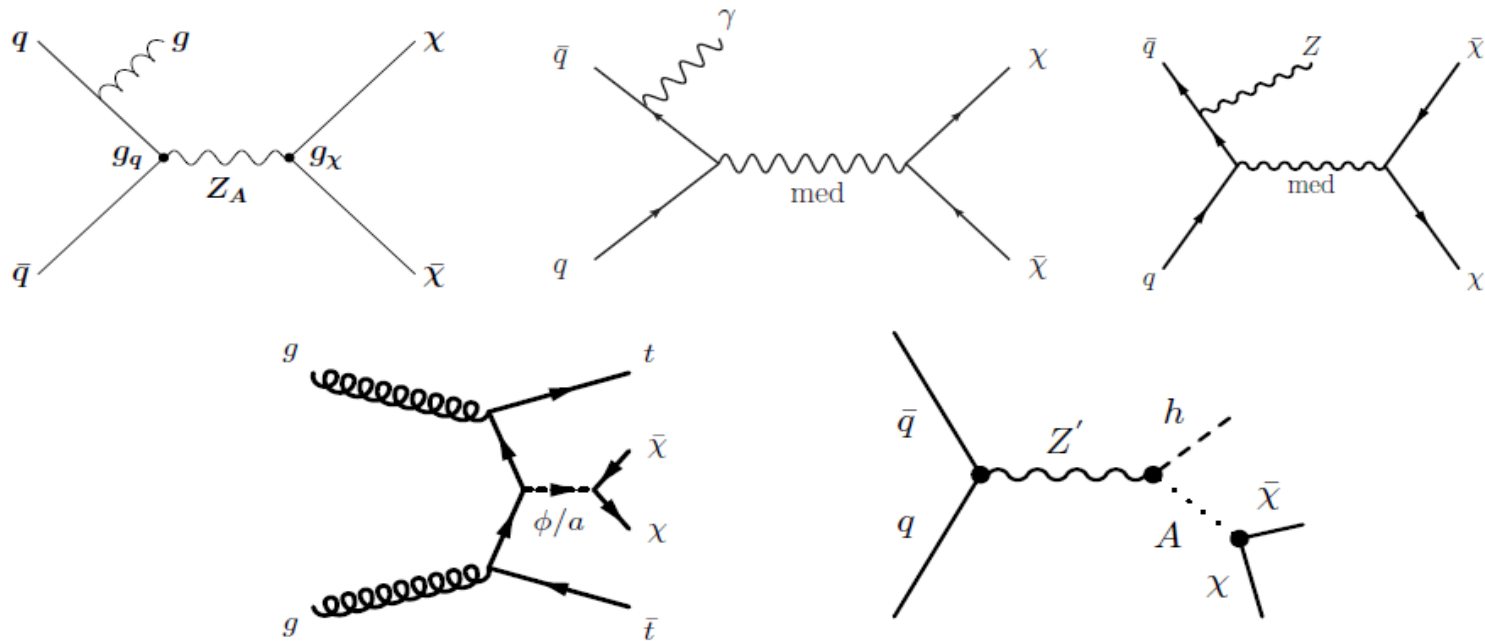


Searches for DM with ($E_T^{\text{miss}} + X$) Signatures



$(E_T^{\text{miss}} + X)$ or Mono- X Signatures

SM-DM mediator decays to DM pairs $\chi\bar{\chi}$ when $M_{\text{med}}/2 > m_\chi$.
 DM escapes detection $\Rightarrow E_T^{\text{miss}} + X$ signature where
 $X = \text{SM particles that tag the event, } X = \text{jet}, \gamma, V, t, b, h \dots$



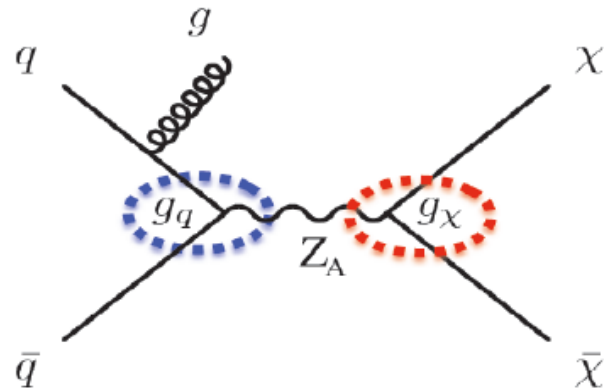
Mediators: vector, axial-vector, scalar, pseudoscalar

Parameters: $m_{\text{med}}, m_\chi, g_q, g_\chi$

Simplified Model

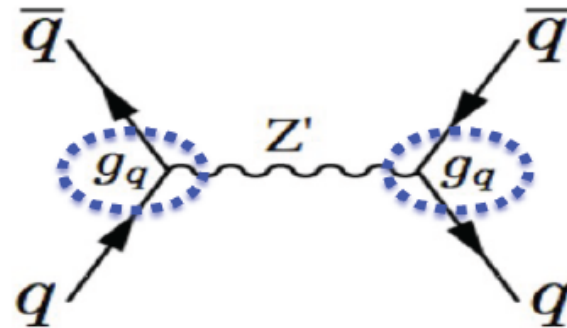
Simplified Model

$SM \rightarrow \text{mediator} \rightarrow DM$



→ Mono-X signature
 $E_T^{miss} + \text{jet, W/Z/H, } \gamma, \dots$

$SM \rightarrow \text{mediator} \rightarrow SM$



→ resonant production
 Dijet, ditop, dilepton.....

spin 0

spin 1

Charge

$Q=0$ for s-channel

Lorentz structure

Scalar

$$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$$

Vector

$$g_q \sum_q V_\mu \bar{q} \gamma^\mu q$$

Pseudoscalar

$$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f} \gamma^5 f$$

Axial-vector

$$g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma^5 q$$

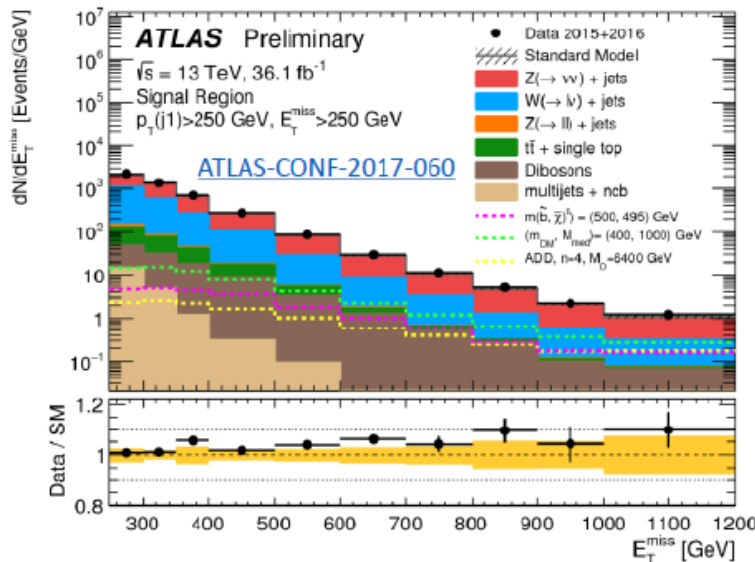
Coupling

$\propto \text{mass}$

$\propto \text{charge}$

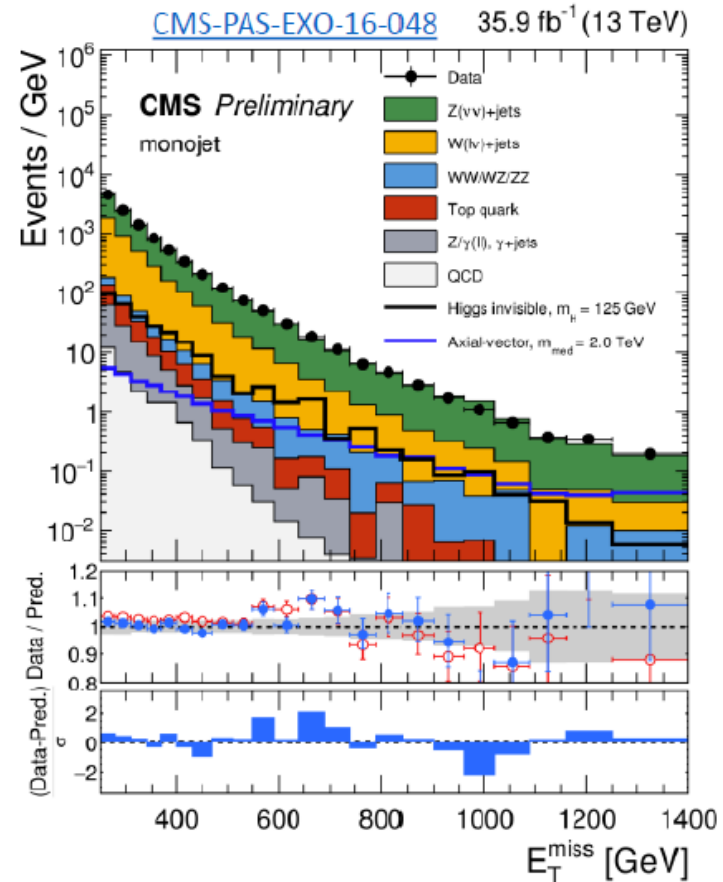
Mono-X searches

Mono-jet



ATLAS

- $E_T^{\text{miss}} > 250 \text{ GeV}, \Delta\phi(\text{jet}, p_T^{\text{miss}}) > 0.4$
- Jet $p_T > 250 \text{ GeV}, |\eta| < 2.4$
- $N_{\text{jets}} \leq 4$

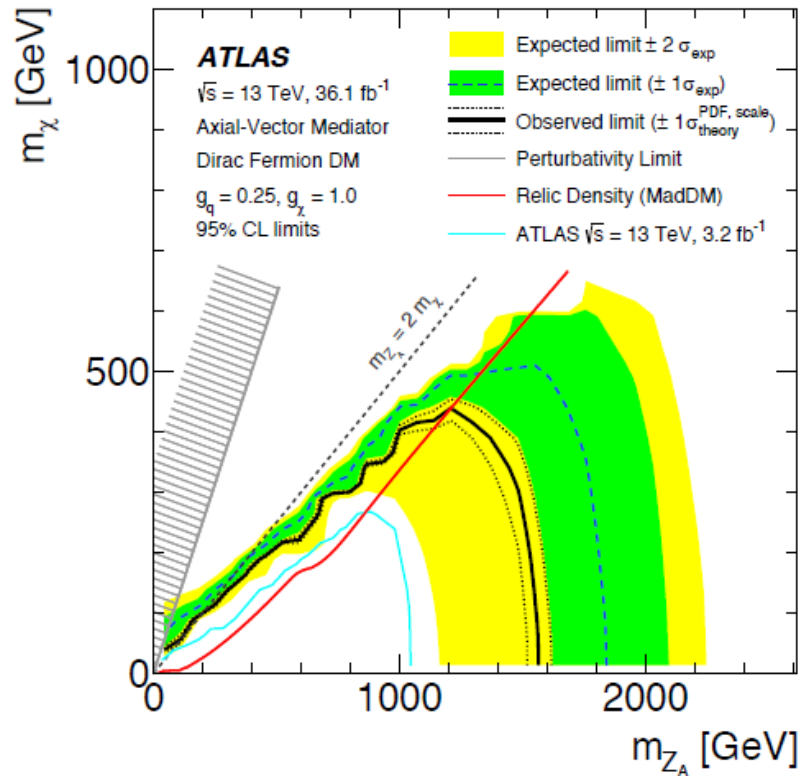


CMS

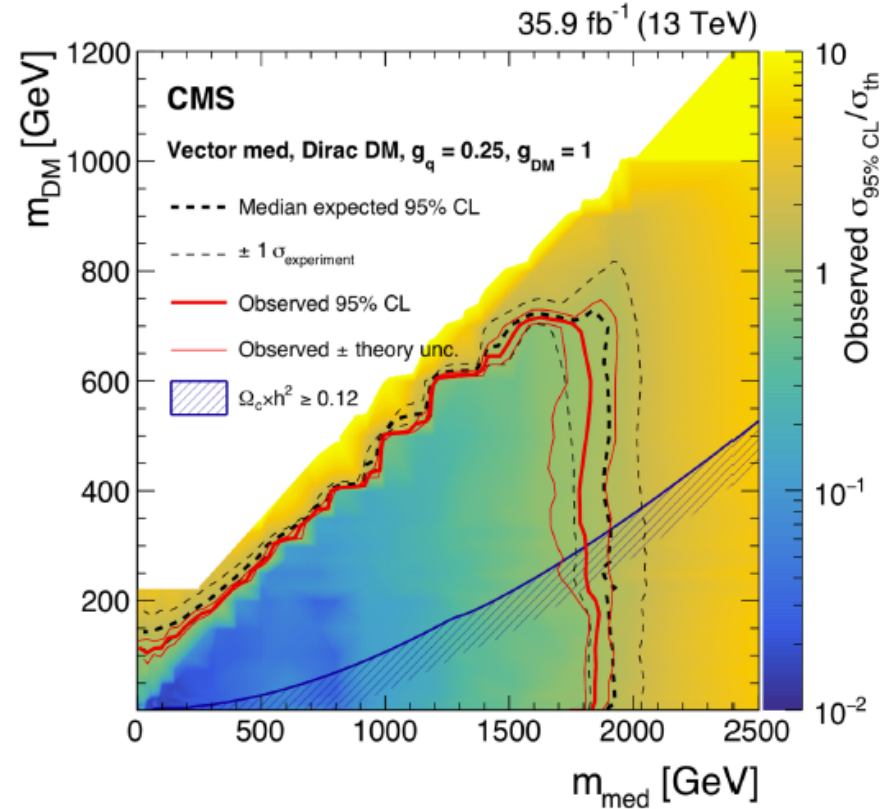
- $E_T^{\text{miss}} > 250 \text{ GeV}$
- Jet $p_T > 100 \text{ GeV}, |\eta| < 2.5$

Mono-X searches

Axial-Vector Mediator



Vector Mediator

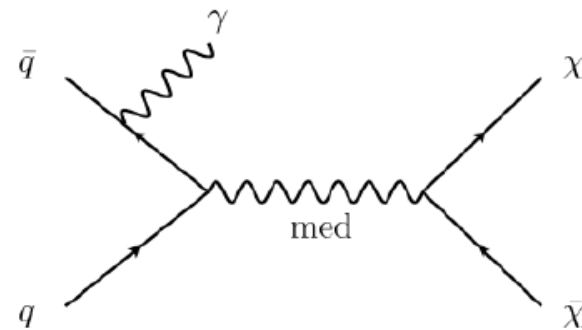
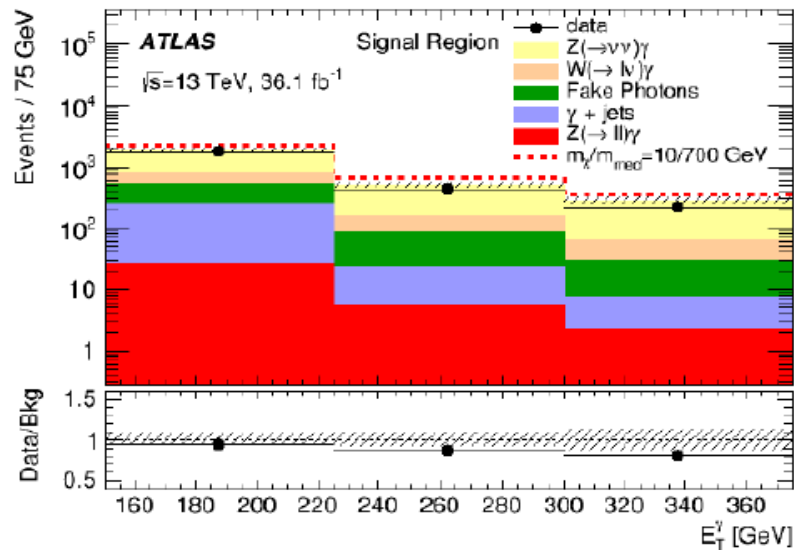


For couplings $g_q = 0.25$, $g_\chi = 1.0$, axial-vector and vector mediators excluded up to 1.8 TeV (1.55 TeV) by CMS (ATLAS) for $m_\chi \sim 1 \text{ GeV}$.

JHEP 01 (2018) 126
 arXiv:1712.02345

Mono-X searches

Mono-photon

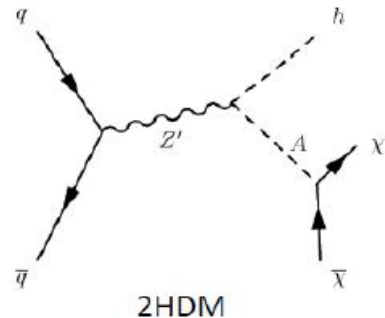
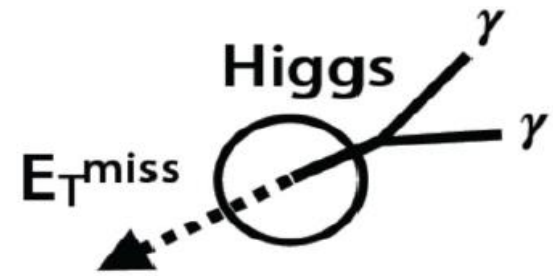
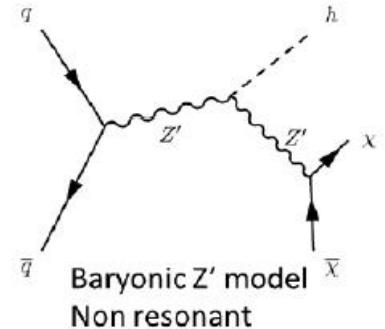
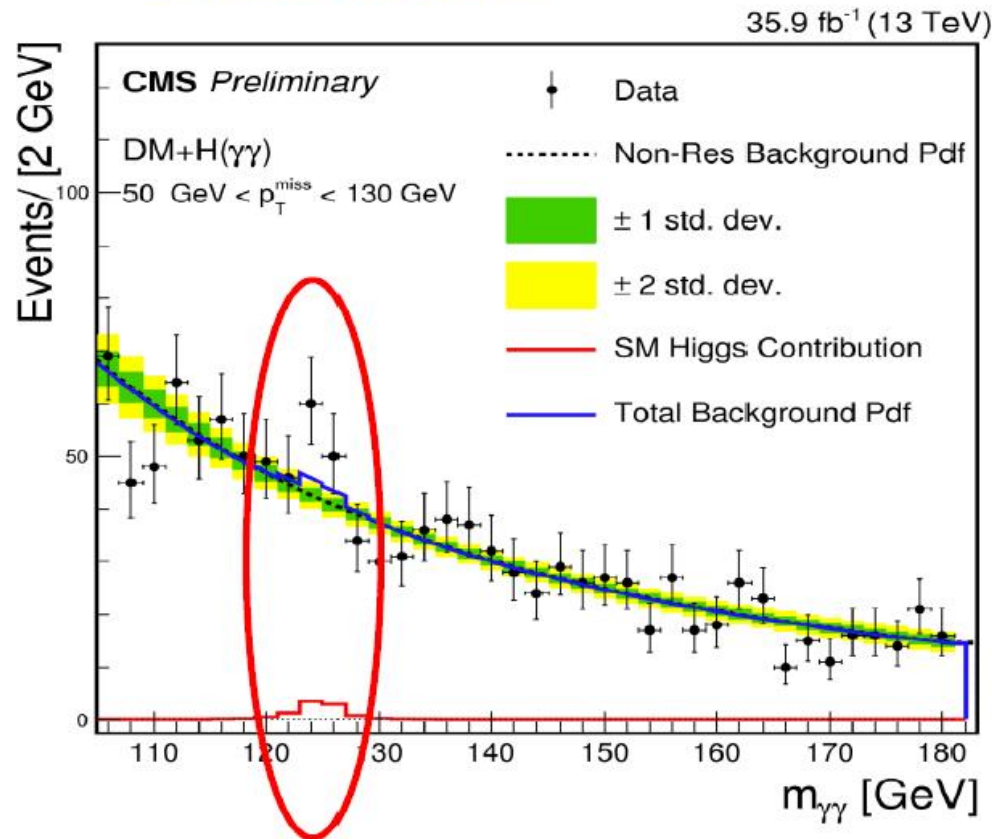


- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{\text{miss}}/\sqrt{\sum E_T} > 8.5 \text{ GeV}^{1/2}$
- $\Delta\phi(\text{photon}, E_T^{\text{miss}}) > 0.4$
- $N_{\text{jets}}(p_T > 30 \text{ GeV}, |\eta| < 4.5) \leq 1$

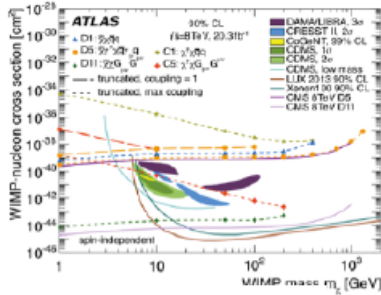
Mono-X searches

Mono-Higgs

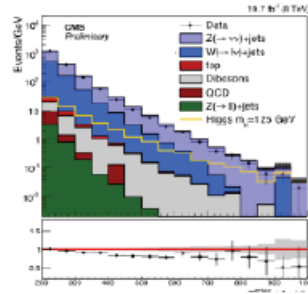
[CMS-PAS-EXO-16-054](#)



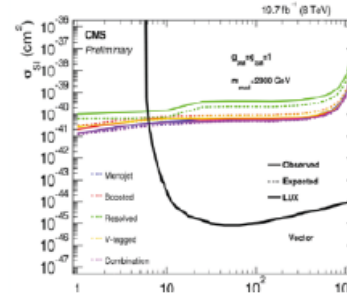
Plenty of mono-signatures



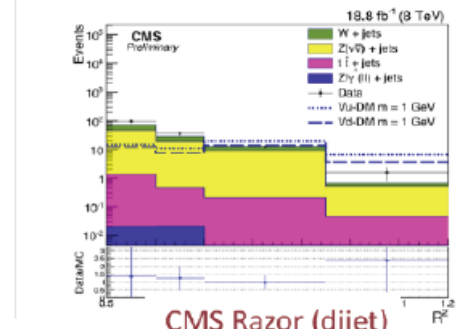
ATLAS Monojet
EPJC (2015) 75:299



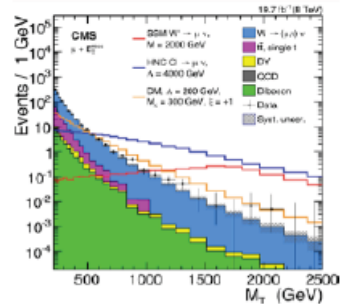
CMS j/V (mono/dijet)
PAS-EXO-12-055



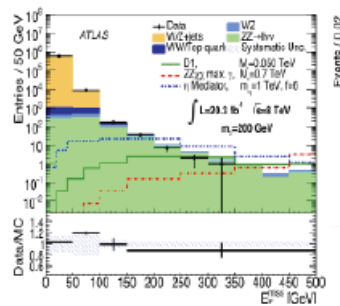
CMS j/V (mono/dijet)
PAS-EXO-12-055



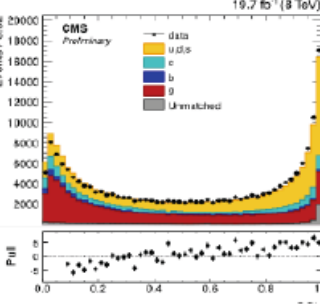
CMS Razor (dijet)
PAS-EXO-14-004



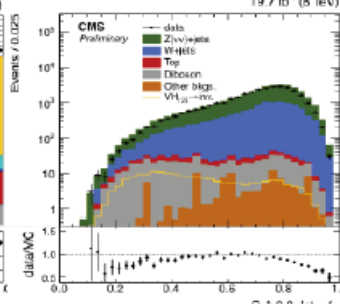
CMS, ATLAS MonoW
PRD 91, 092005, JHEP 09 (2014) 037 (2015)



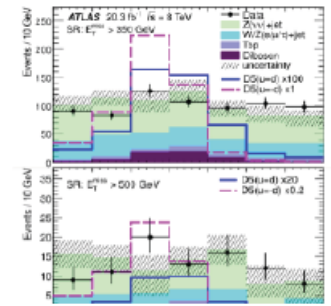
CMS, ATLAS MonoZ
EXO-12-054, PRD 90, 012004 (2014)



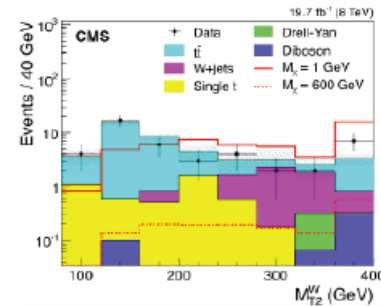
CMS MonoV (resolved)
PAS-EXO-12-005, PAS-JME-14-002



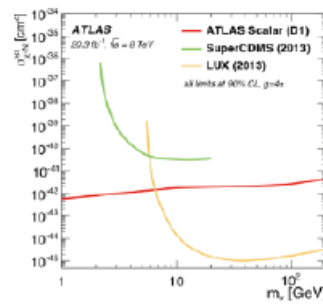
CMS MonoV (boosted)
EXO-12-005/JME-14-002



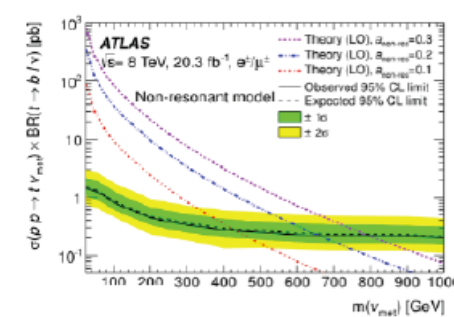
ATLAS MonoV (boosted)
ATLAS, PRL 112, 041802 (2014)



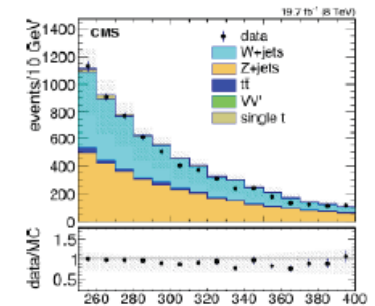
CMS TopPairs
CMS, JHEP 06 (2015) 121



ATLAS TopPairs
ATLAS, EPJC (2015) 75:92

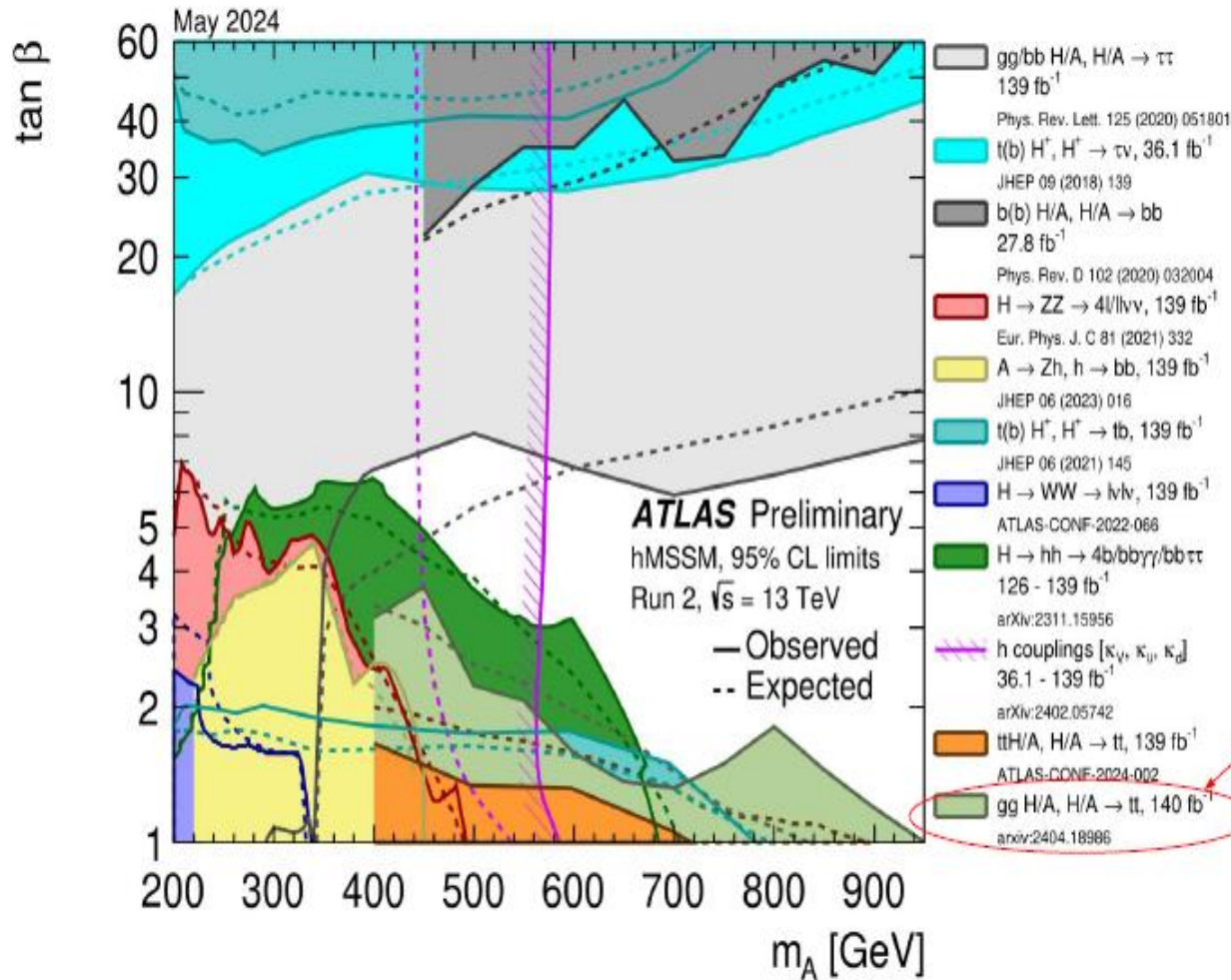


CMS MonoTop
CMS, PRL 114 (2015) 101801



ATLAS MonoTop
ATLAS, JHEP 11 (2014) 118

Heavy Higgs summary plot

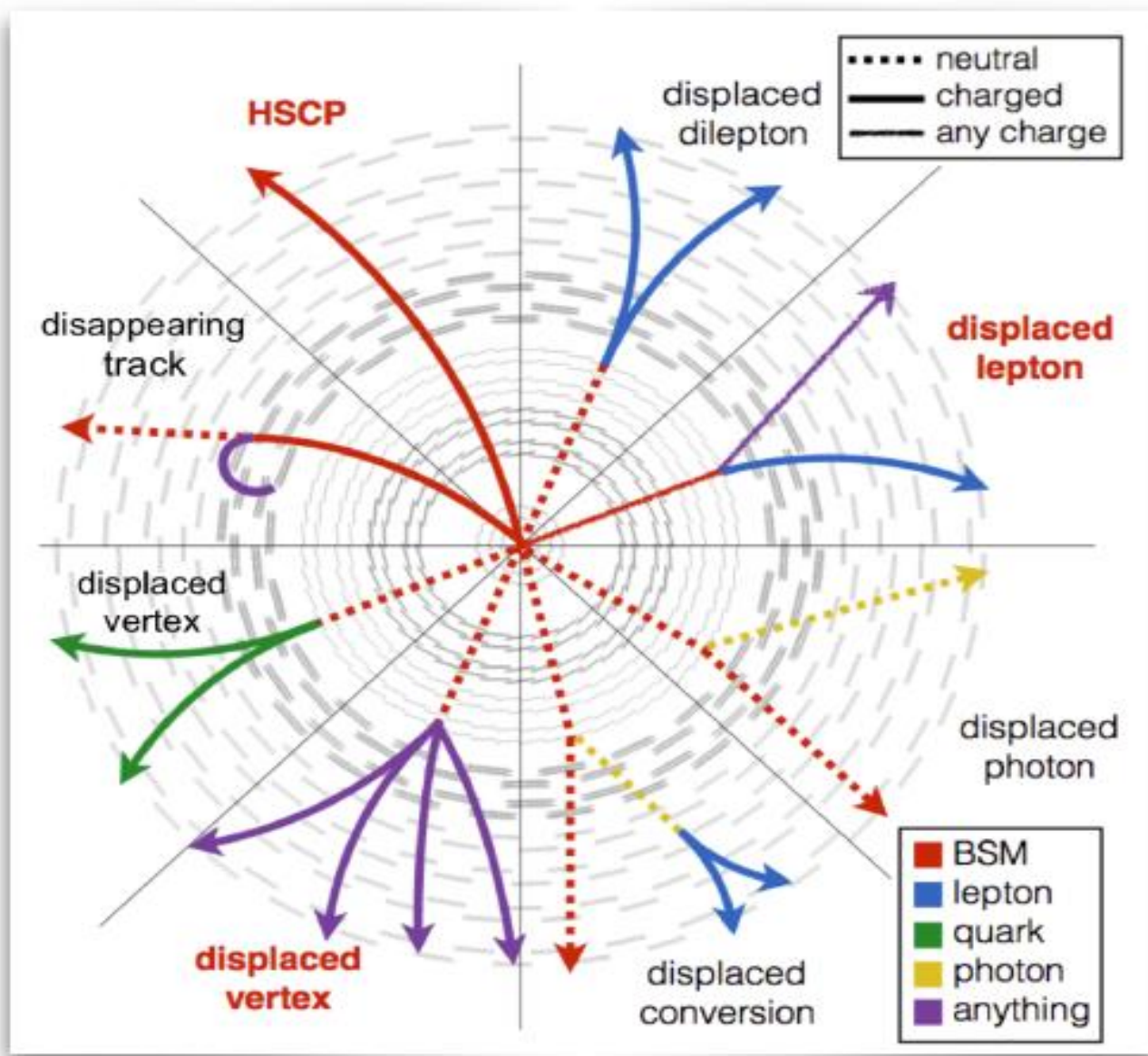


Excluded regions of $[m_A, \tan\beta]$ plane excluded in the hMSSM via direct searches for heavy Higgs bosons

- gg $H/A, H/A \rightarrow tt$ adds to exclusion at low $\tan\beta$!

[ATL-COM-PHYS-2024-195](#)

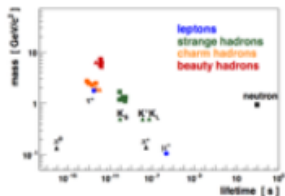
Unconventional signatures



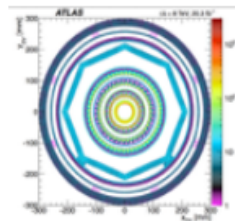
Unconventional signatures: challenges

- ▶ **Trigger**: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
 - First step in every search for LLPs: make sure that interesting events are saved!
 1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger on MET)
 2. Design and develop a new trigger. Need to keep trigger rates under control and within budget
- ▶ **Object identification** algorithms assume prompt particles. Need to adapt them
- ▶ **Backgrounds**: usually instrumental background such as miss-identified leptons (“fakes”) and non-collision backgrounds (NCB) have to be taken into account

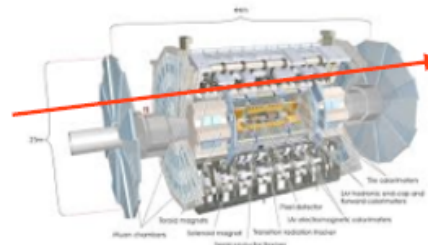
weak decays of heavy flavour



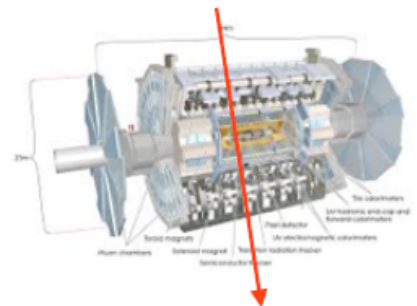
material interactions



beam halo muons



cosmic muons

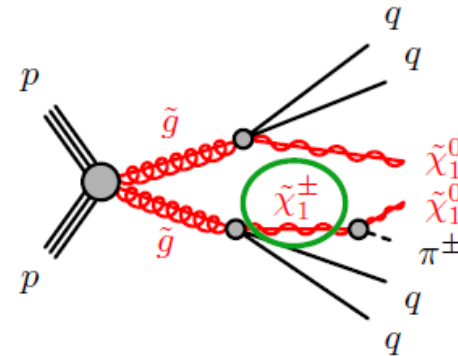
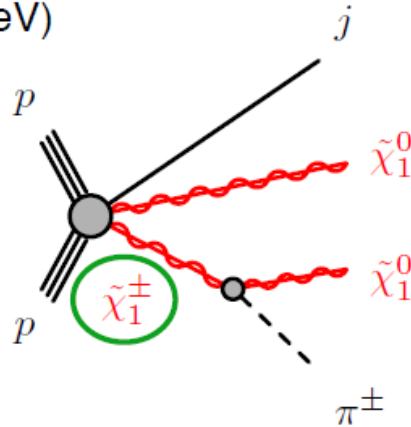


- **Systematic** uncertainties: can't use standard recommendations for object reconstruction nor trigger

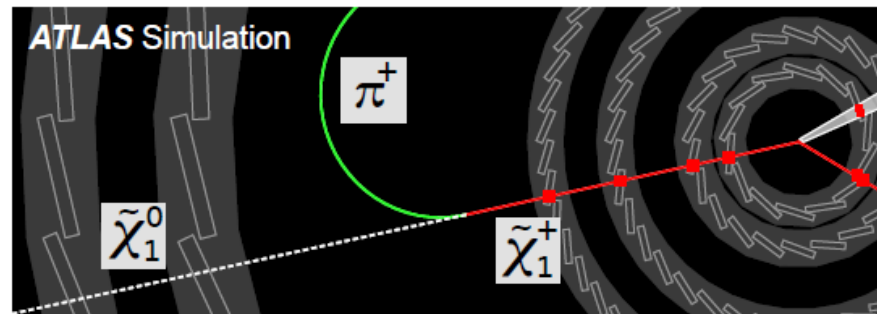
Unconventional signatures: disappearing tracks

LLP

- ▶ Search for disappearing track + MET + jets
- ▶ **Signature:** Chargino track “disappears” when it decays, into MET
 - ▶ Low momentum pion track (~ 0.1 GeV) is hard to reconstruct
 - ▶ Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks
- ▶ **Benchmark model:** AMSB model with almost degenerate neutralino and chargino $\Delta m \sim \mathcal{O}(100 \text{ MeV})$



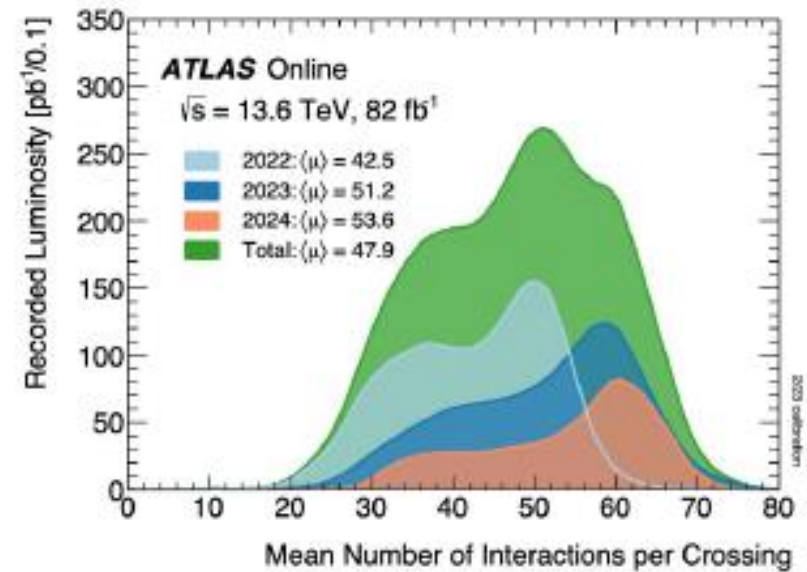
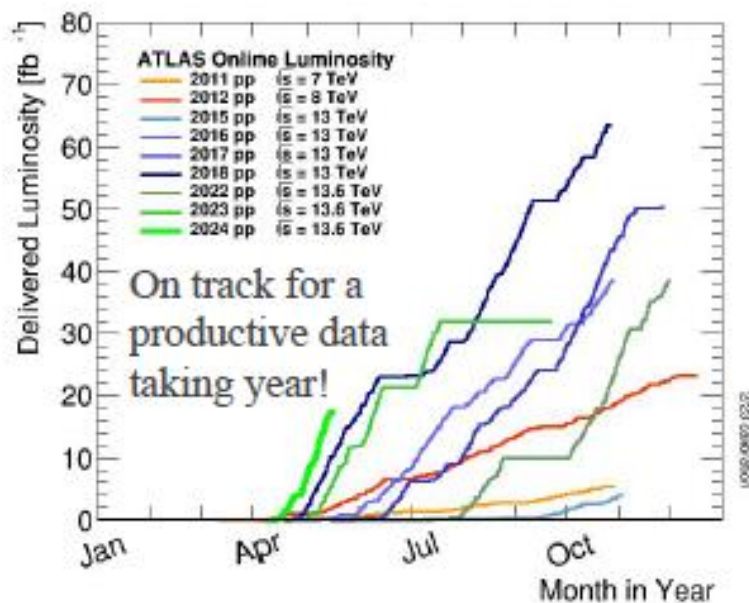
- ▶ Search sensitive to LLP lifetime of 10ps to 10 ns



Summary (Exotic Searches)

- Searches for Exotic searches
 - All major search channels reached 1 TeV scales
 - Quite a few at 10 TeV
 - New probe: Higgs boson → emerging field
- Dark Matter Searches are thriving at the LHC
- For vector and axial vector interactions
 - Dark Matter masses up 400 GeV – 700 GeV (mono-jet) excluded
 - Mediator mass up to 1.6 – 1.8 TeV (mono-jet) excluded
 - Mediator mass up to 1.2 TeV (mono-photon) excluded
 - Mediator mass up to 0.7 TeV (mono-Z) excluded
- LHC searches complement DD experiments
 - $m_{\text{DM}} < O(10 \text{ GeV})$

ATLAS experiment: 2024 data taking



2024 LHC schedule

Activity	Duration [days]	Ratio [%]
Beam Commissioning & Intensity ramp-up	41	15.8
Scrubbing	3	1.2
25 ns physics (>1200 bunches)	147.5	56.9
Special physics runs (incl. setting-up)	2	0.8
Pb-Pb ions & p-p ref. setting-up	6	2.3
Pb-Pb ions physics & p-p ref. run	23	8.9
Technical stop	9	3.5
Technical stop recovery	2	0.8
Other scheduled stops	2.5	1.0
Machine Development	23	8.9
Total:	259	100

