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

Prof. dr hab. Elżbieta Richter-Wąs

The Higgs field and Standard Model

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

↓

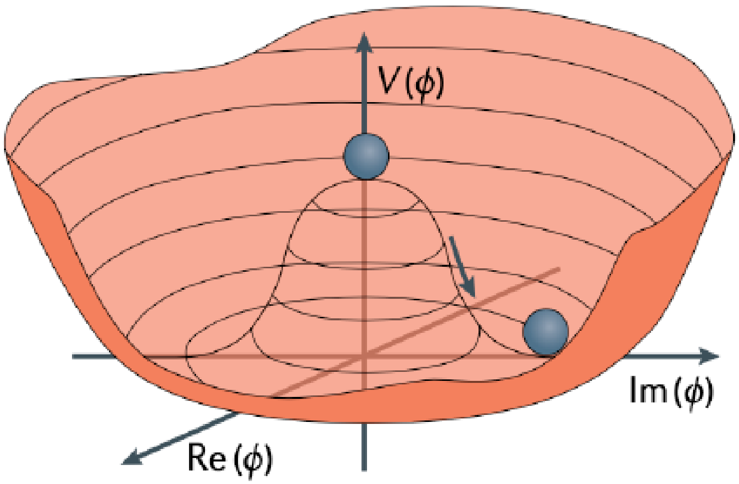
Higgs Mechanism
- Can explain non-zero gauge boson masses
- Remarkably can also produce fermion masses

↓

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



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

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 ...

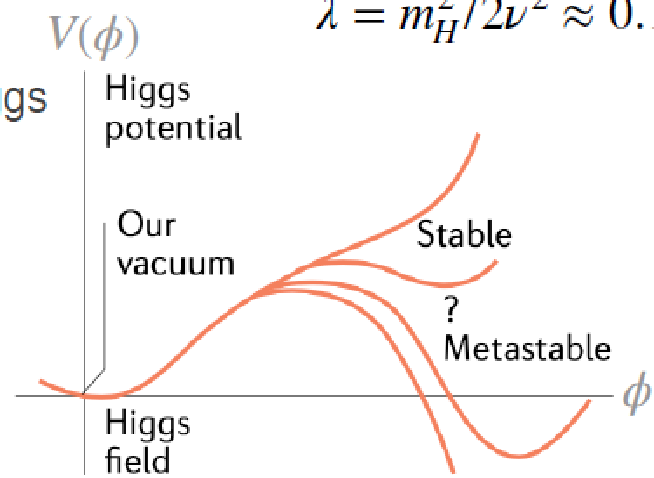
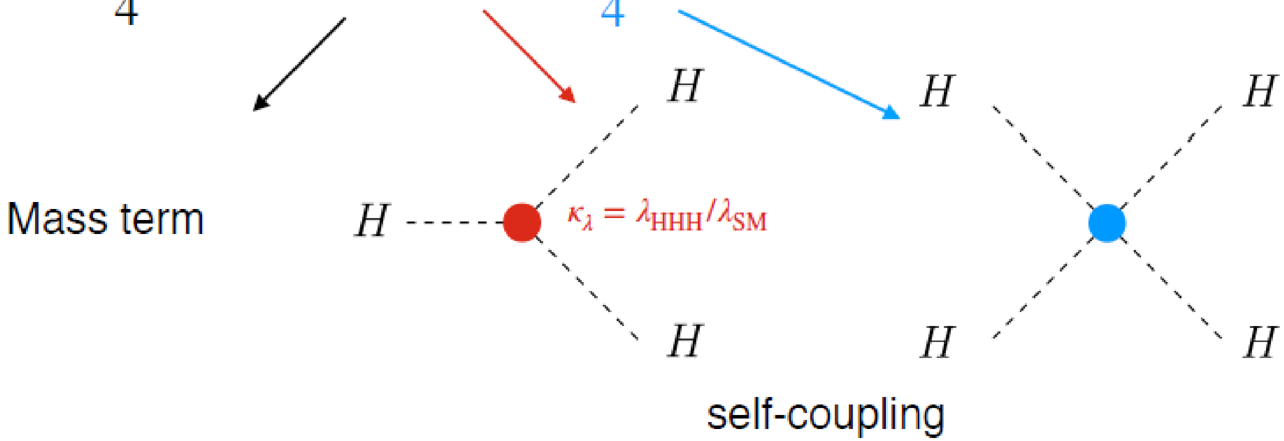


Image credit: Nature Reviews Physics 3.9 (2021)

Higgs self-coupling

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

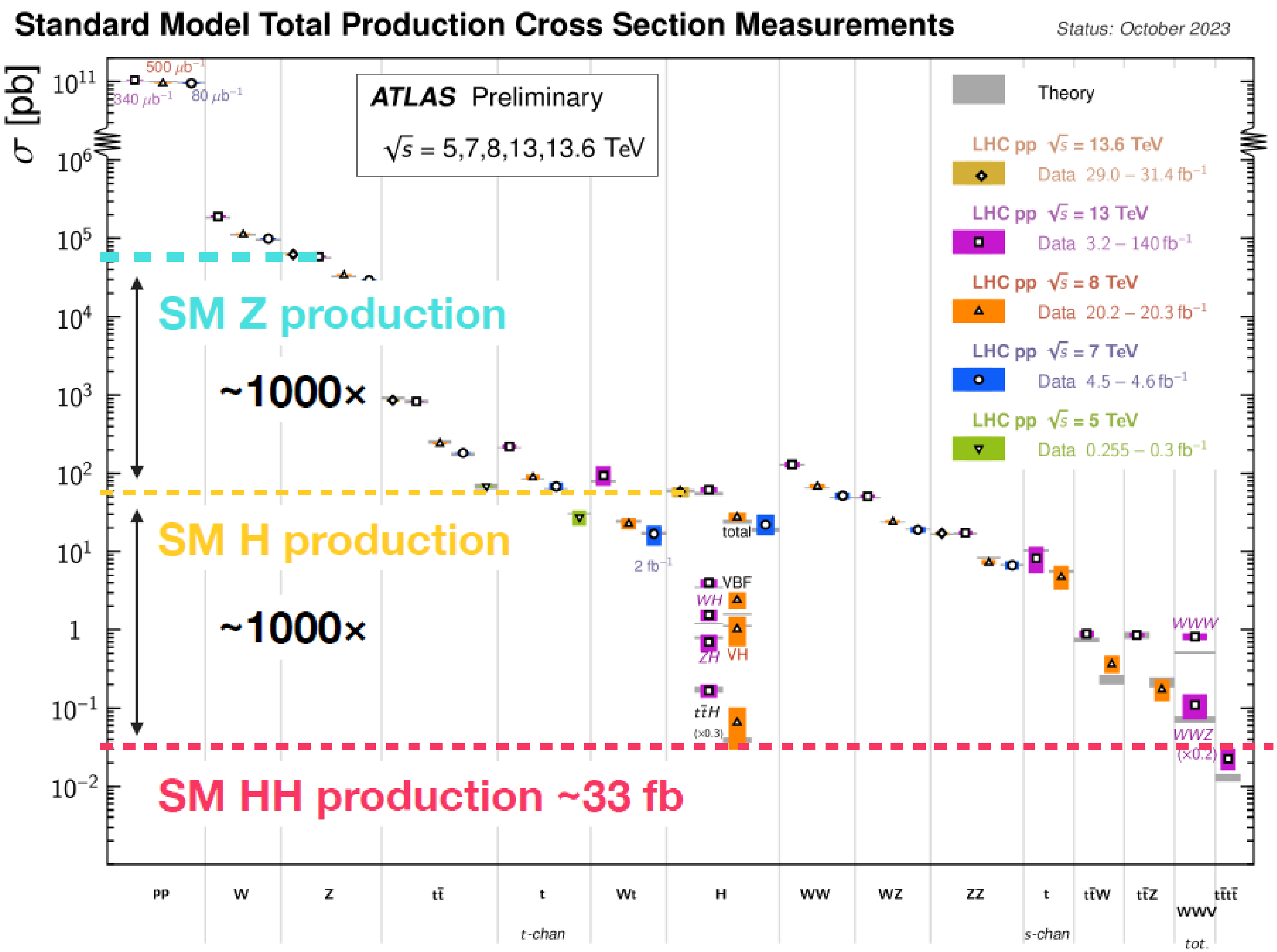
$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \supset \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$



- 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



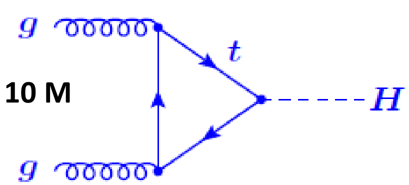
Discovery of the Higgs boson

- Measurements: mass, spin, couplings

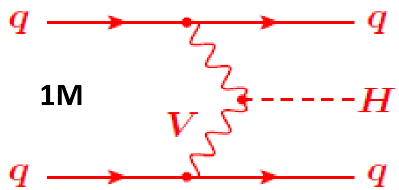
The Higgs Boson at the LHC

Production

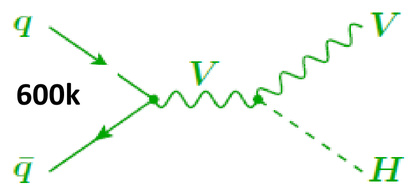
#Higgs produced at 13 TeV (2015-2017)



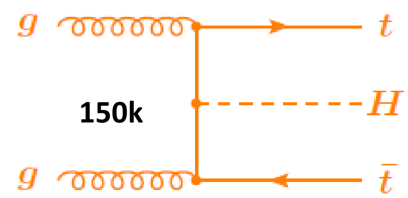
Main production channel



2 forward jets, little central hadronic activity

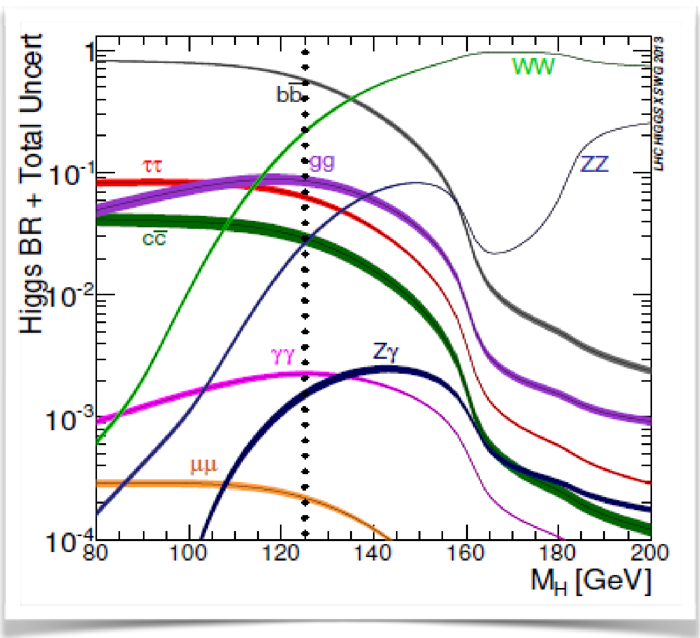


Tag W and Z decays



Tag 2 top quarks

Decays



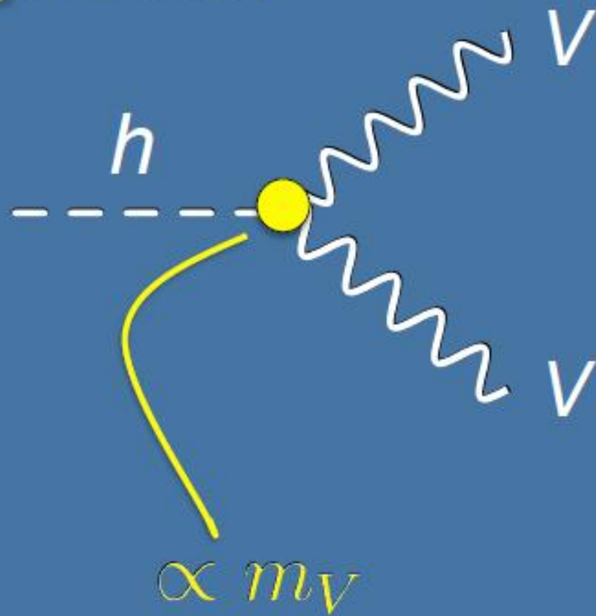
5 main channels at the LHC

Decay branching fractions for m_H = 125 GeV

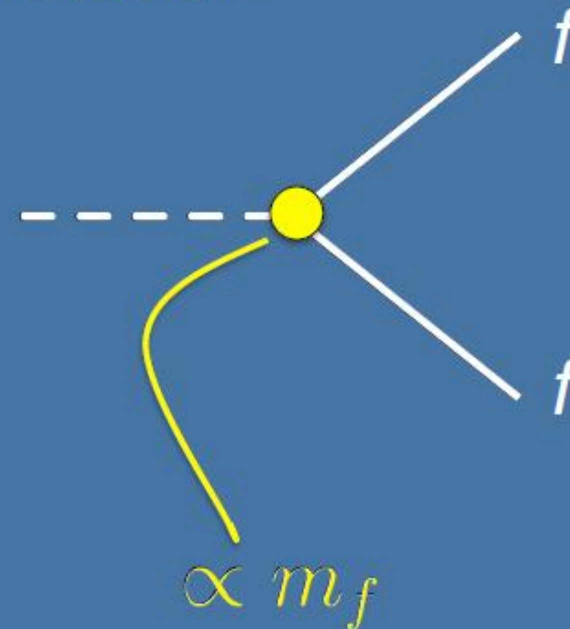
- $H \to bb$: 58 %
- $H \to WW^*$: 21%
- $H \to \tau^+\tau^-$: 6.3%
- $H \to ZZ^*$: 2.6%
- $H \to \gamma\gamma$: 0.2%

Higgs boson couplings

Gauge bosons

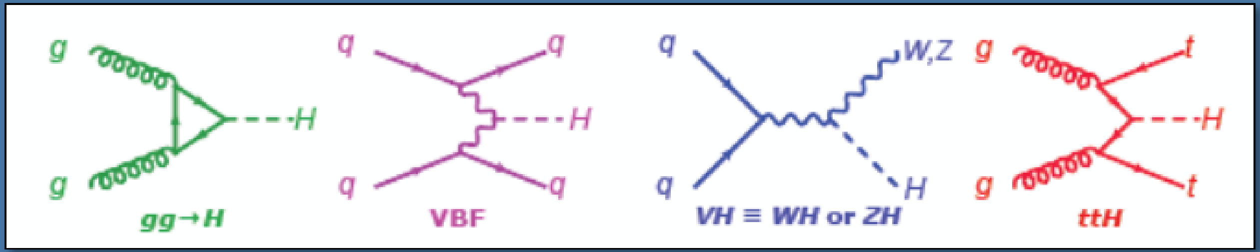


Fermions



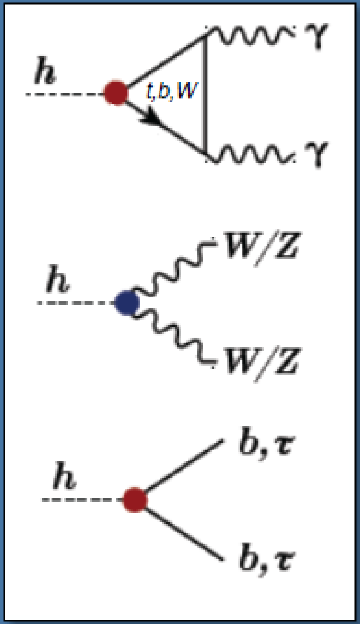
Higgs boson properties are fixed in the Standard Model (m_h)

Higgs boson phenomenology



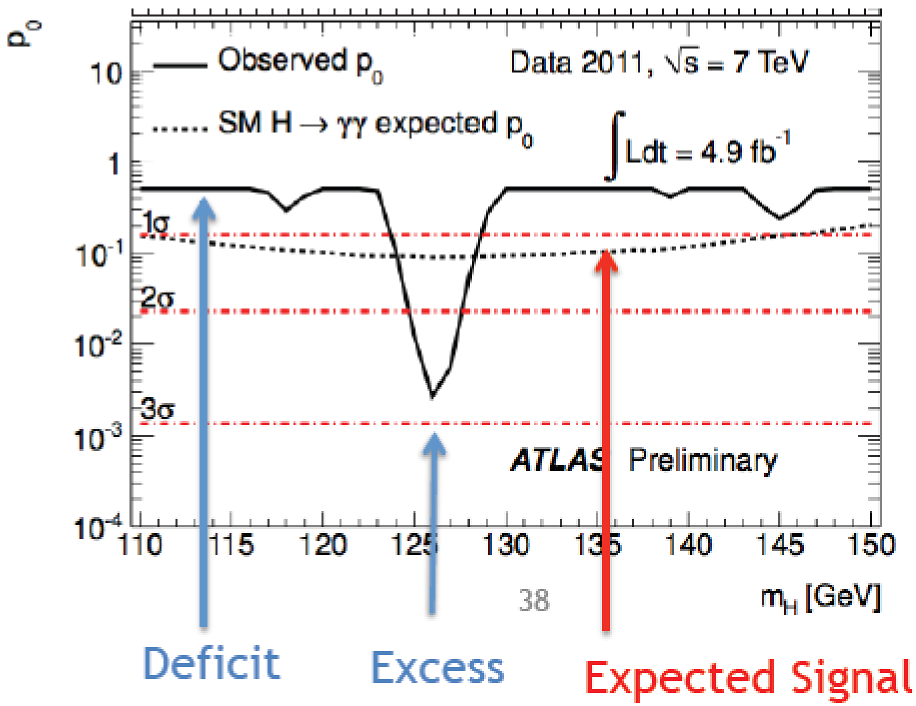
‘production & decay matrix’

sensitivity to different Higgs properties

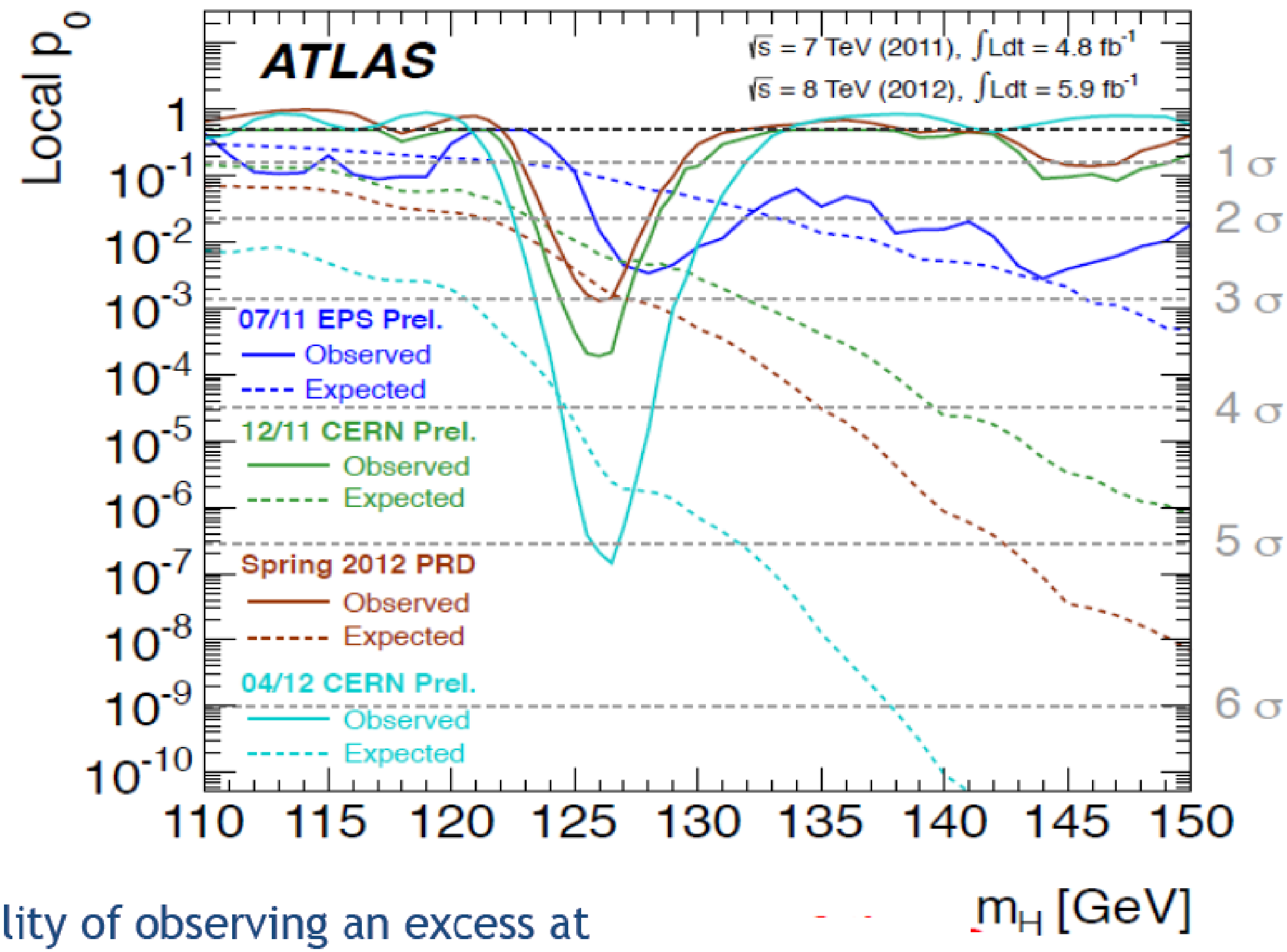


Local p_0

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.



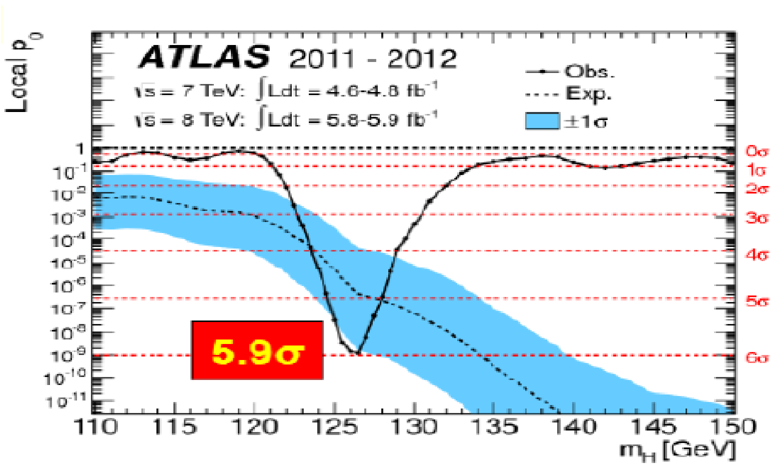
Birth of a particle

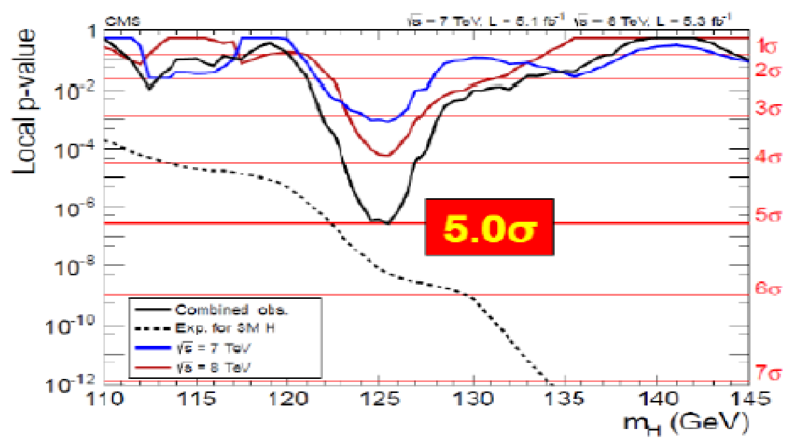


Probability of observing an excess at one specific mass (in absence of signal)...

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:
5.9σ at m_H= 126.5 GeV

H→γγ, bb, ττ, WW(lνlν, lνqq), ZZ(4l, llνν, llqq)

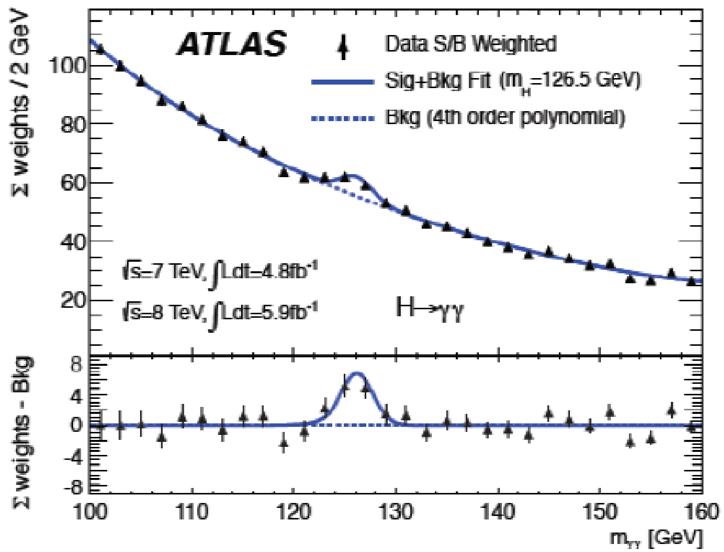
CMS *PLB 716 (2012) 30-61, Sept 17 (2012)*

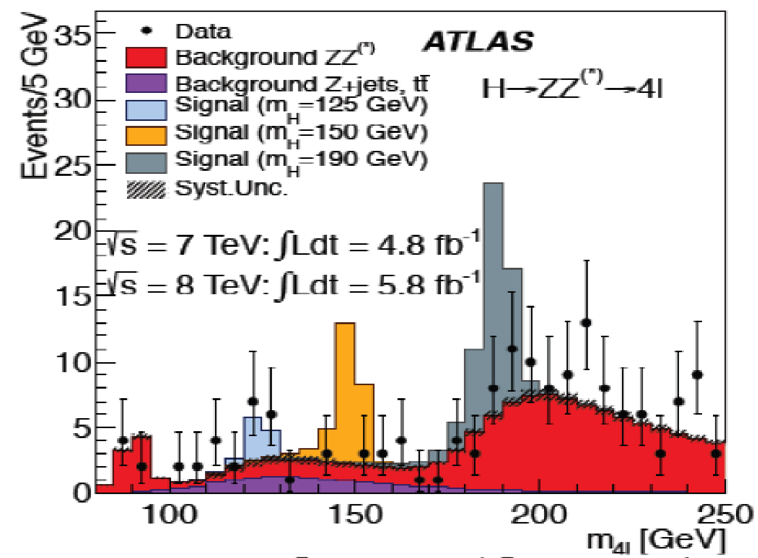
Largest local excess:
5.0σ at m_H= 125.5 GeV

H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)

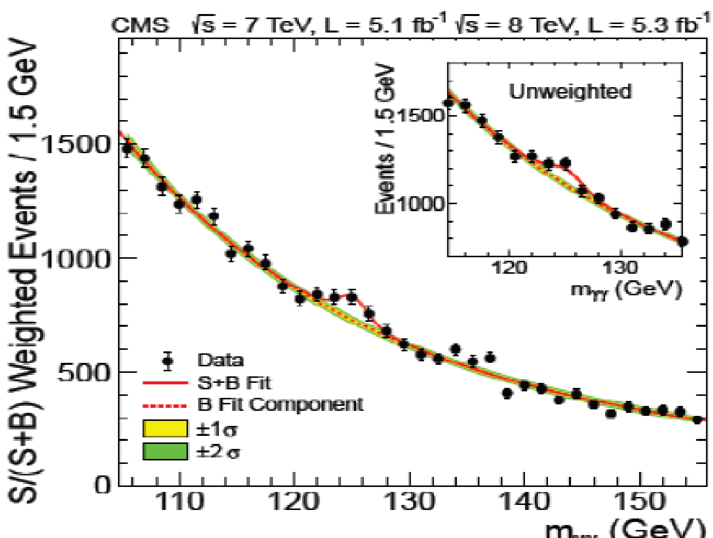
Higgs-like particle – 4 July 2012

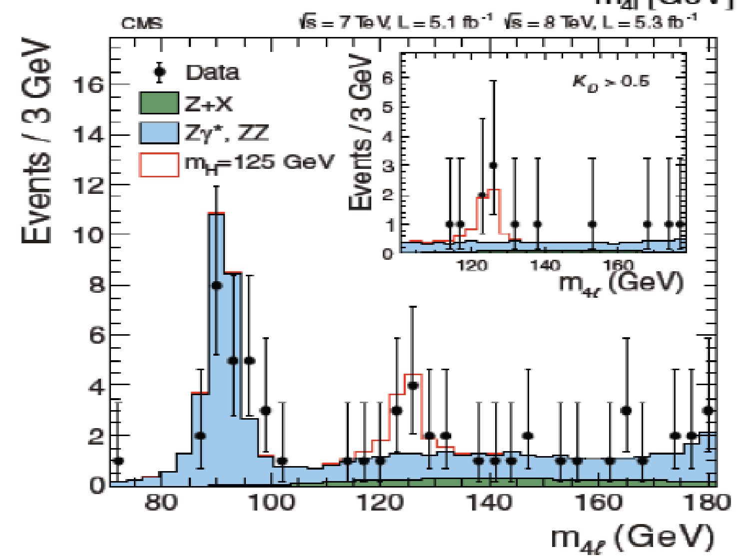
Phys.Lett. B716 (2012) 1-29



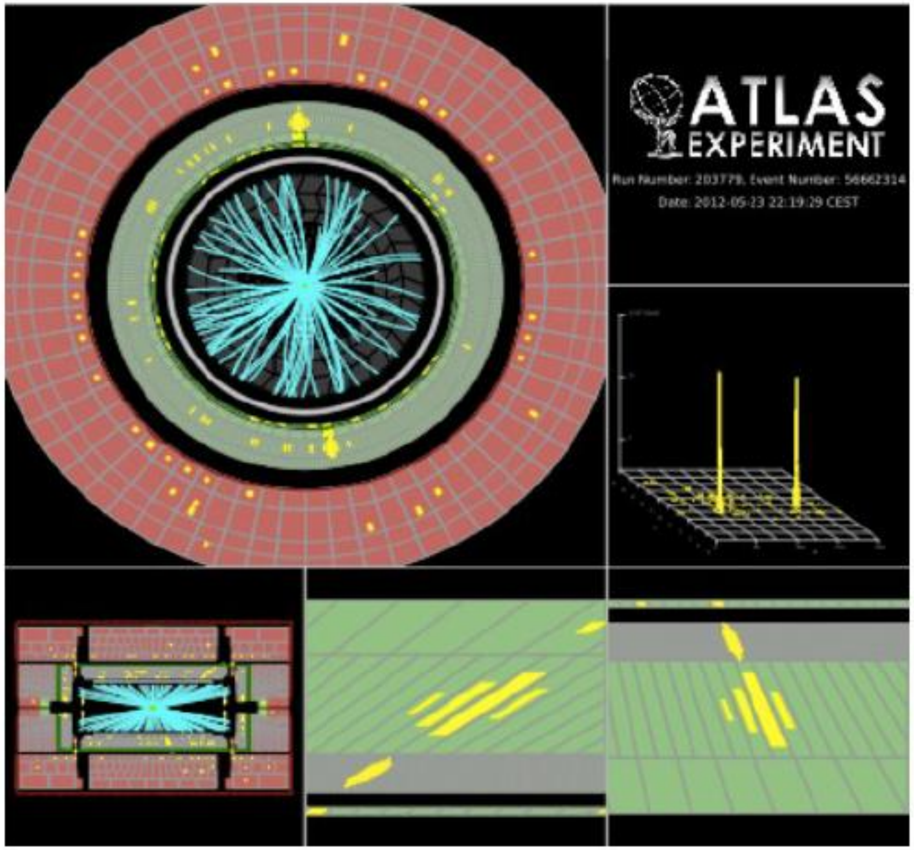


Phys.Lett. B716 (2012) 30-61





H->γγ: events signature



Simple event signature

- ❑ Two high pT photons
$pT_1 > 40$ GeV and $pT_2 > 30$ 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)

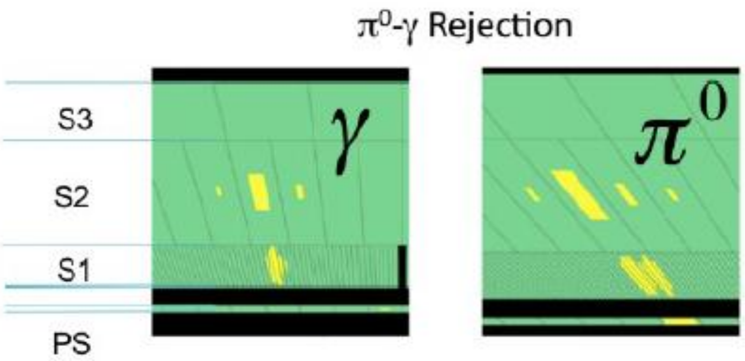
Invariant mass reconstruction $m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos\alpha)$

- ❑ Good energy calibration
- ❑ Robust primary vertex reconstruction

→ Excellent invariant mass resolution ~1.6 GeV with 90% of events within ±2σ

Shower shapes and vertex reconstr.

Photon ID 2 – Photon shower shapes and background rejection



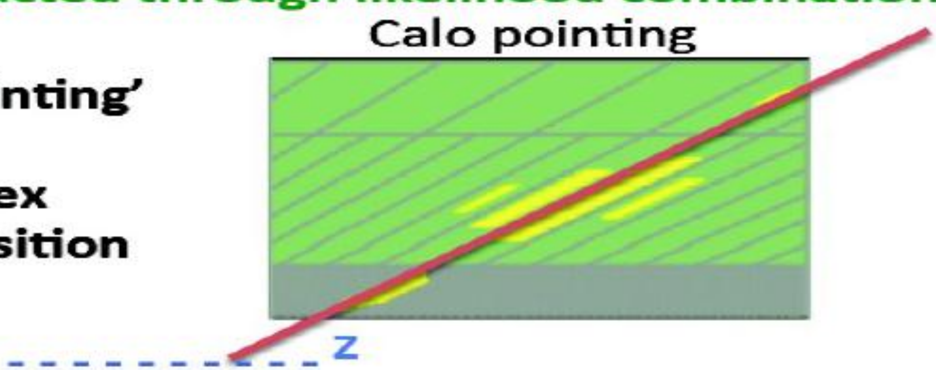
- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

Vertex Reconstruction

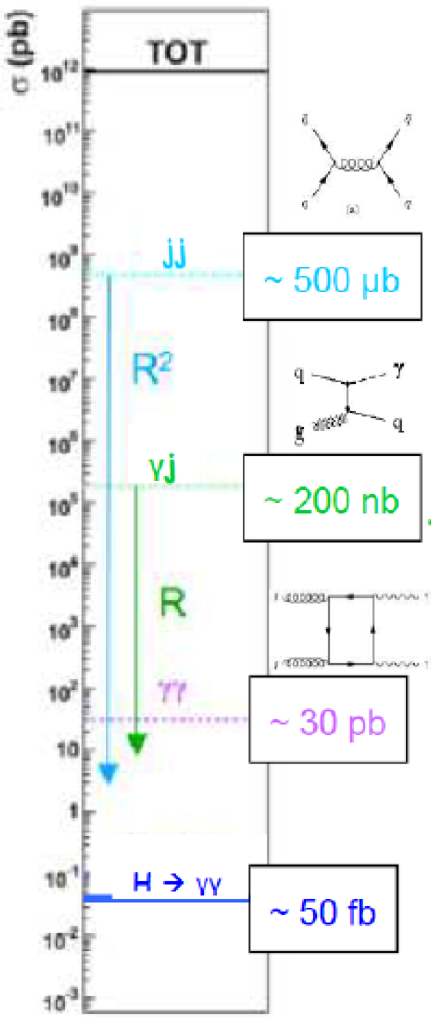
$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$$

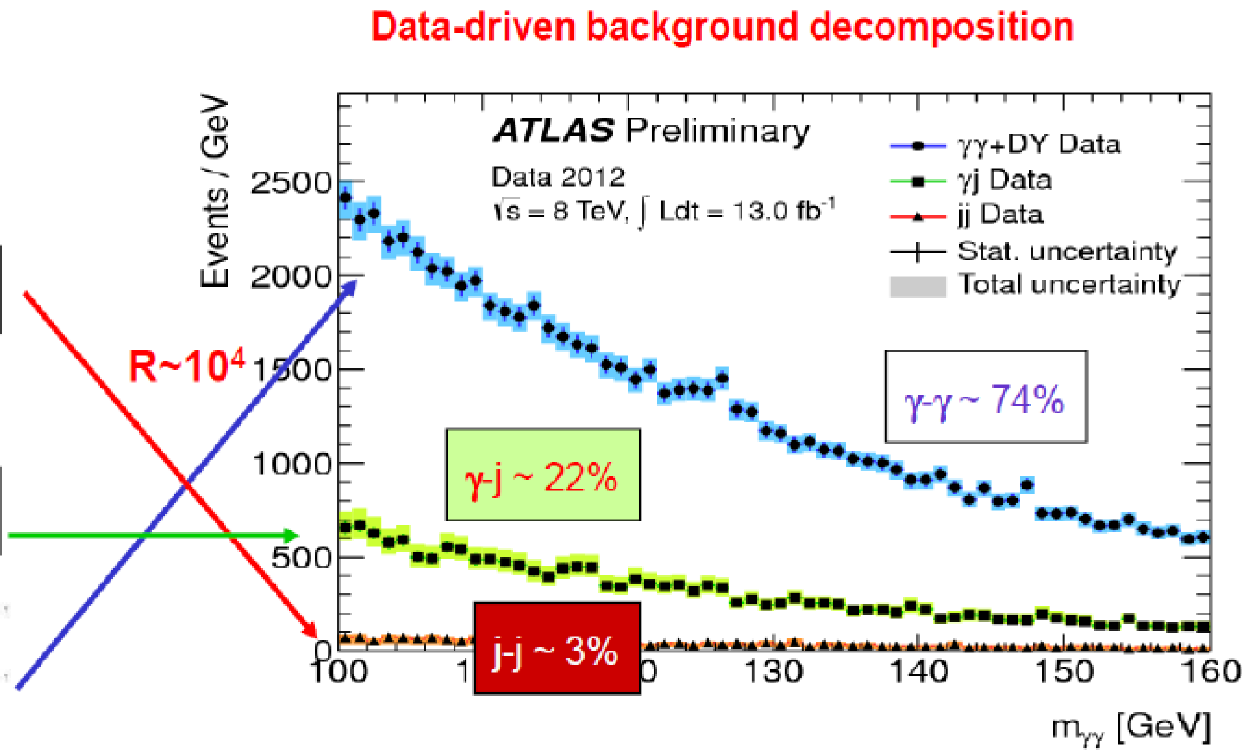
❑ **Vertex reconstructed through likelihood combination**

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



H->γγ: background rejection

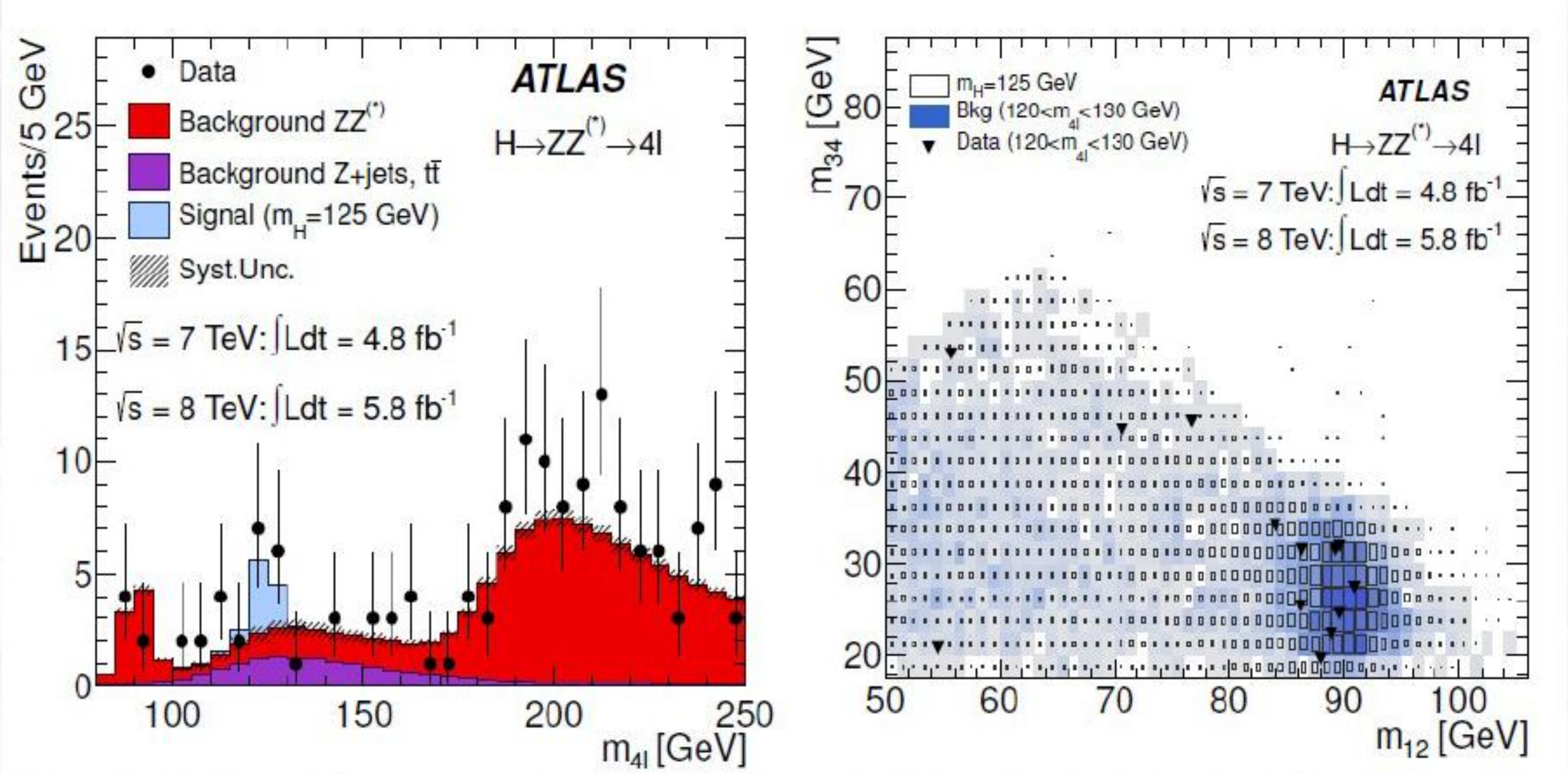




➔ Reducible background γ-jet and jet-jet largely below irreducible background γ-γ

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

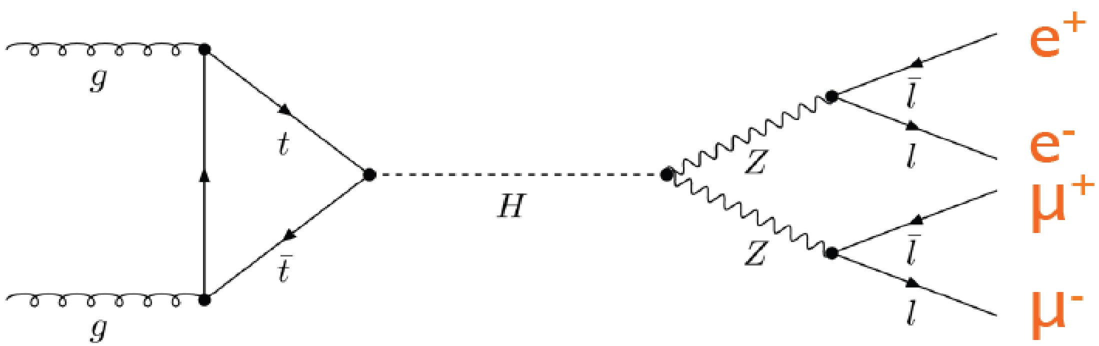
The golden channel: H->ZZ, Z->ll



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

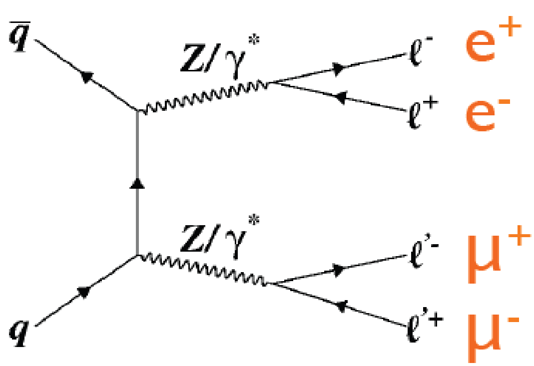
	Signal	$ZZ^{(*)}$	$Z+\text{jets}, t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

Signal and background



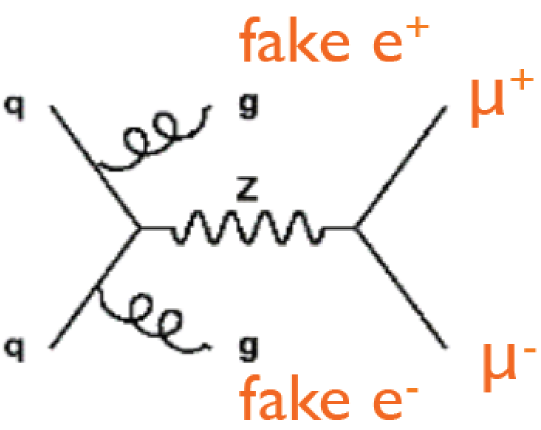
Irreducible background

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



Reducible background

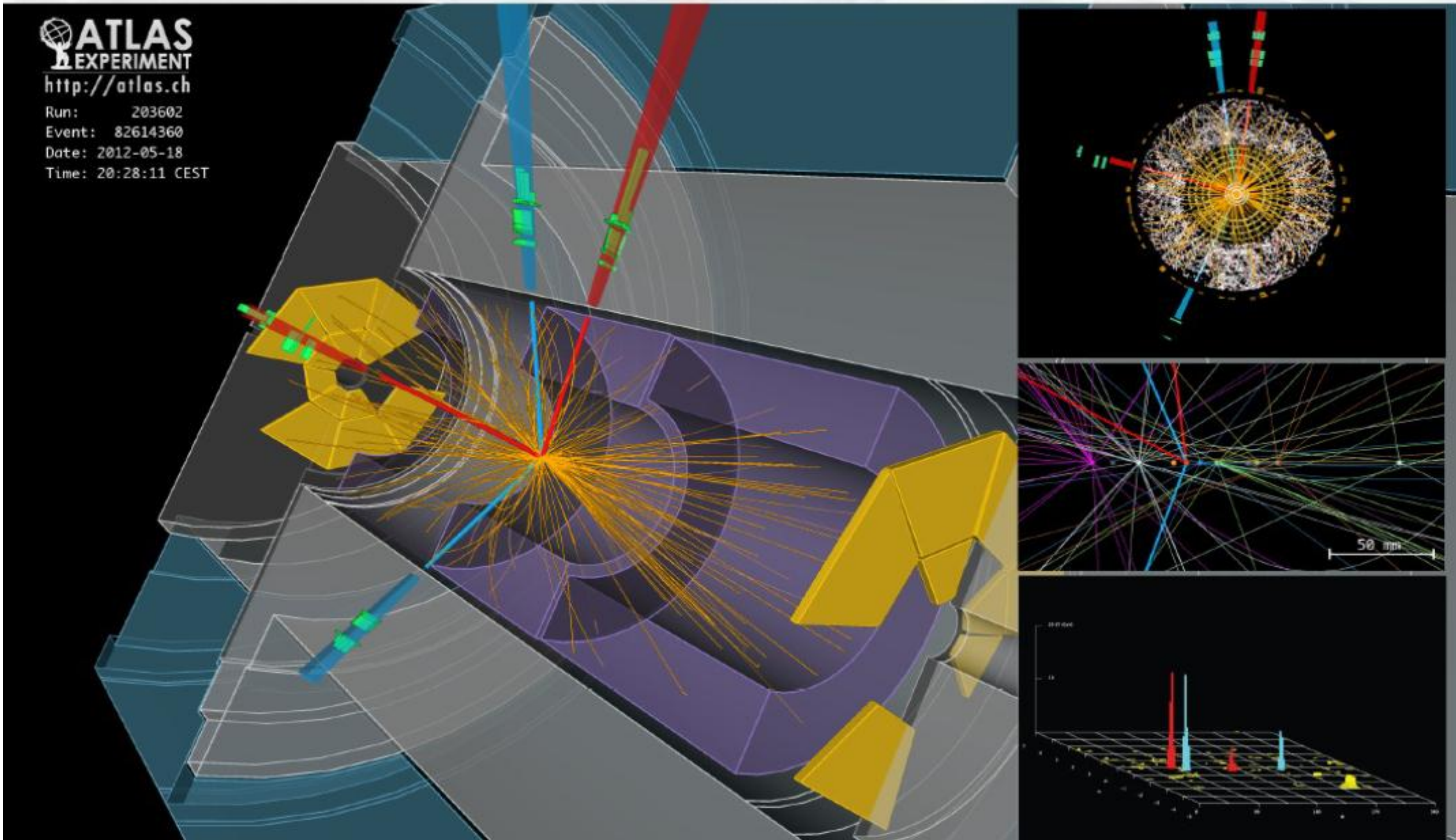
The final state looks like the same, but some f the particle fakes what you are looking for



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

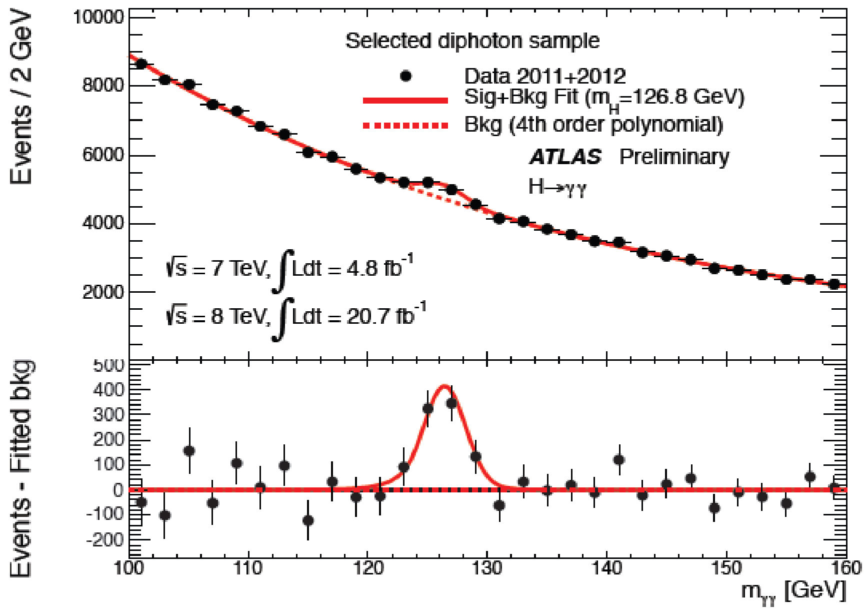
e_1: $P_T = 24.9$ GeV, $\eta = -0.33$, $\phi = 1.98$ e_2: $P_T = 53.9$ GeV, $\eta = -0.40$, $\phi = 1.69$

e_3: $P_T = 61.9$ GeV, $\eta = -0.12$, $\phi = 1.45$ e_4: $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$



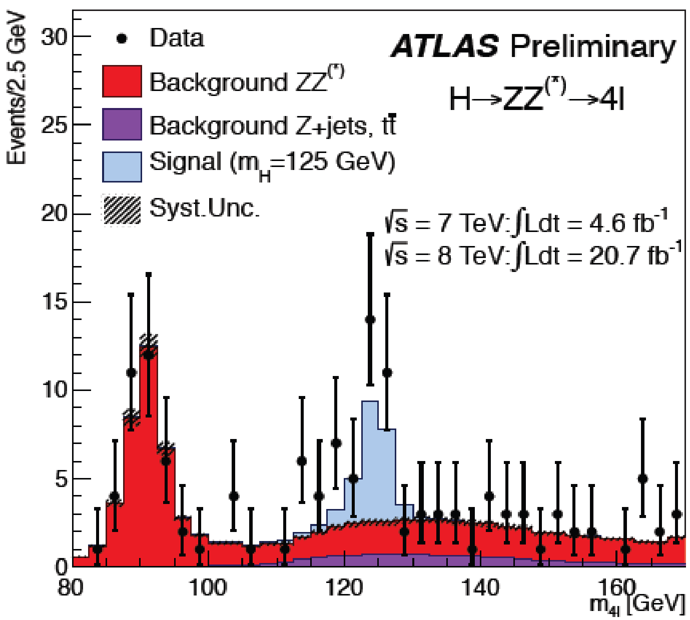
Higgs like signal with 7 TeV and 8 TeV data

H→γγ



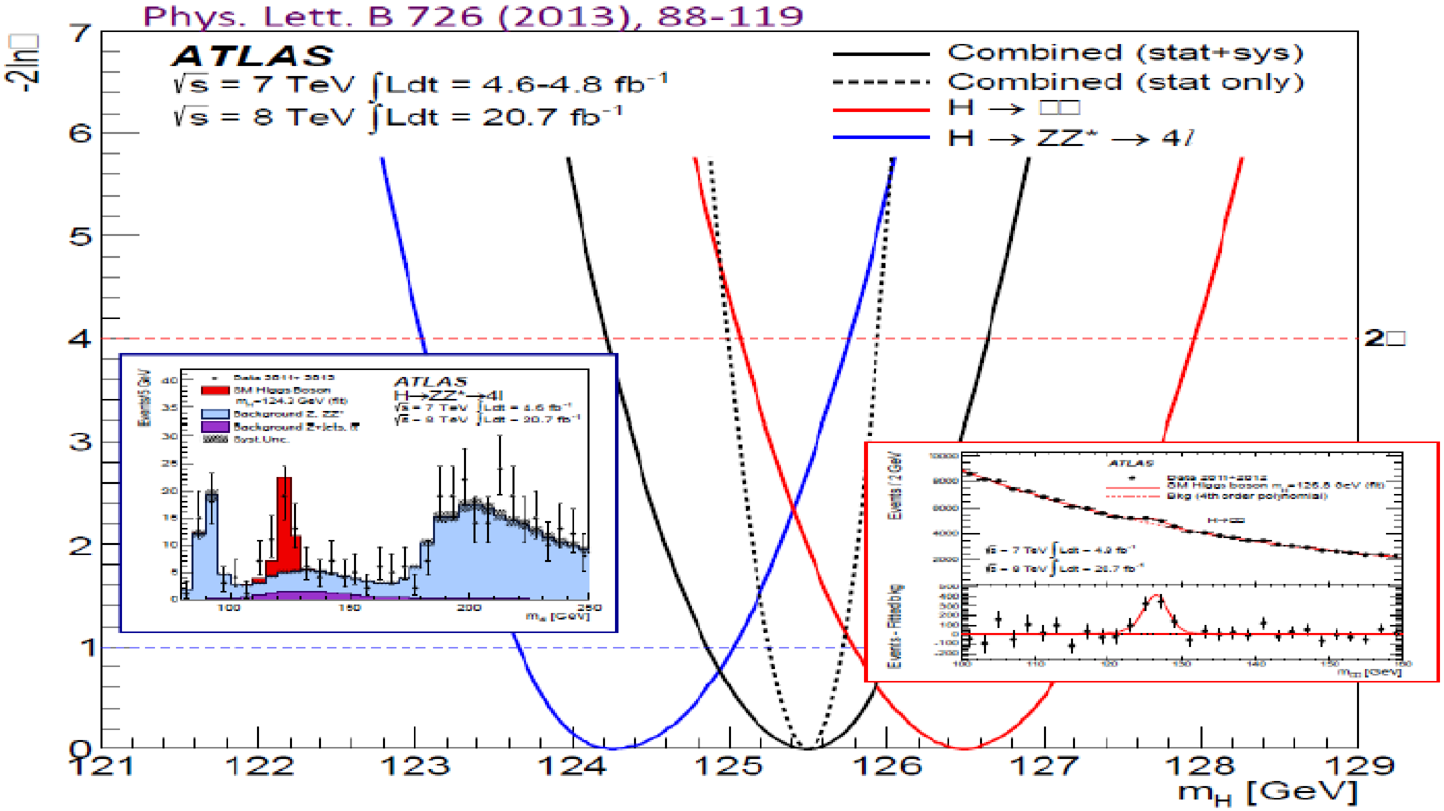
- Signal significance = 7.4 σ
- m_H = 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
- μ = 1.65 ± 0.34 (deviation w.r.t. SM at 2.3σ)

H→4l



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

Mass measurement

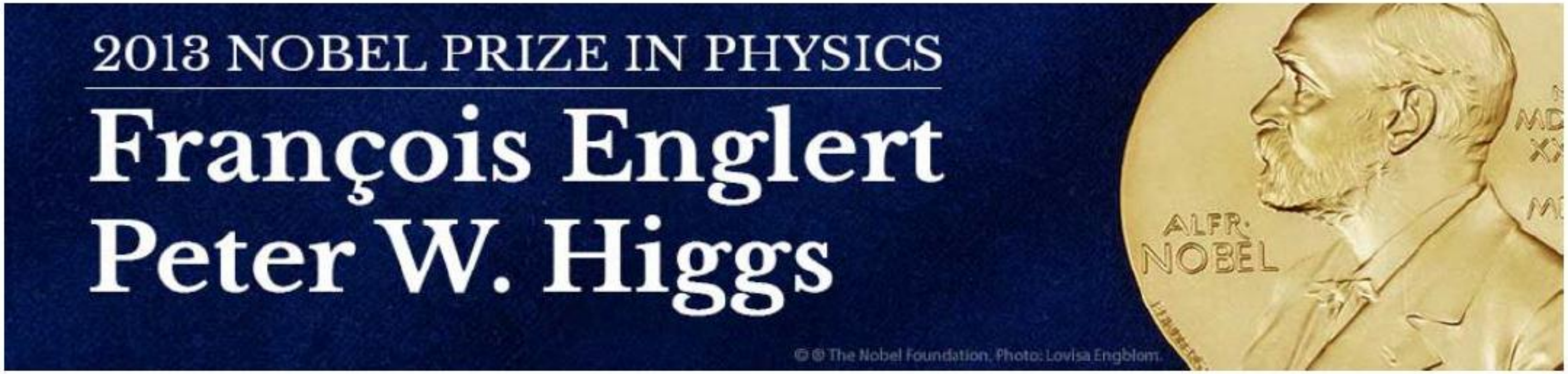


4ℓ: M_H = 124.3 ± **0.6**$_{stat}$ ± 0.4$_{sys}$ GeV

γγ: M_H = 126.8 ± 0.2$_{stat}$ ± **0.7**$_{sys}$ GeV

Combined: M_H = 125.5 ± 0.2$_{stat}$ ± 0.6$_{sys}$ GeV

Nobel price for predicting Higgs particle



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

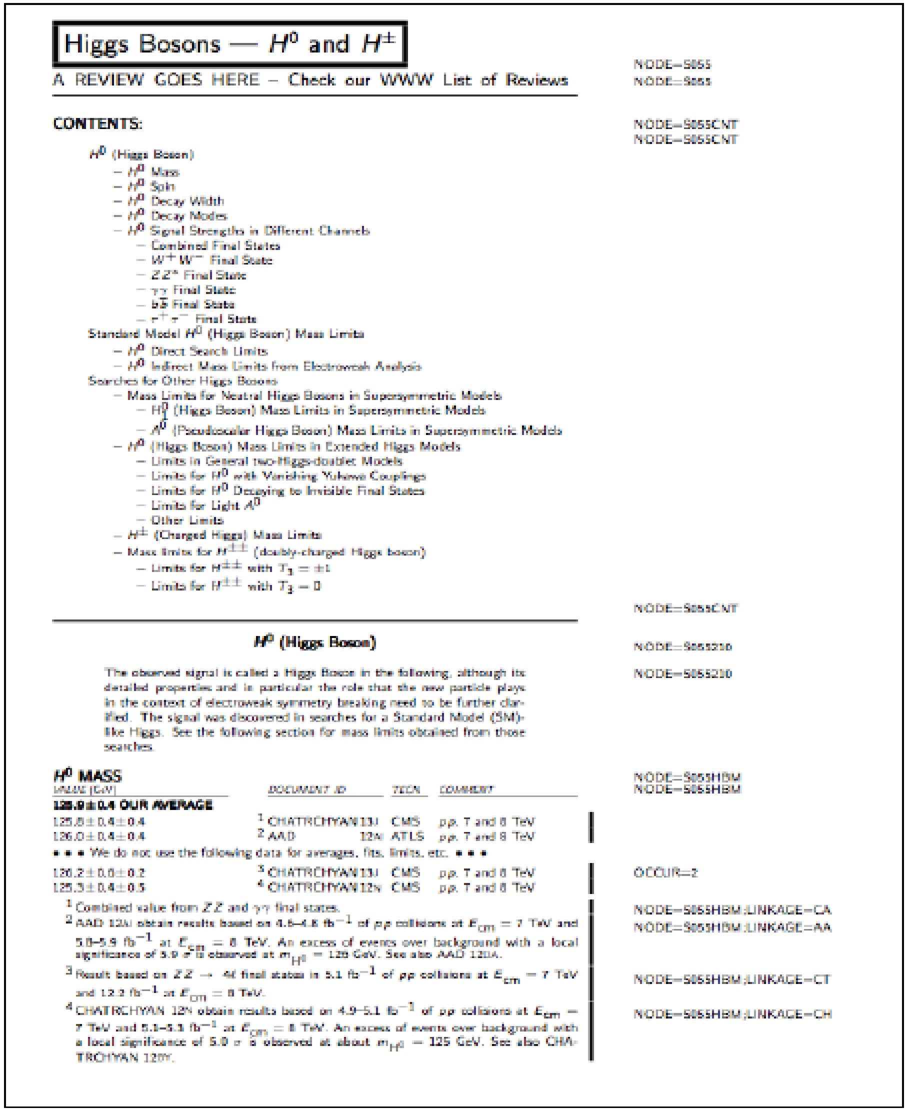
8 October 2013

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



Higgs Bosons — H^0 and $H^\pm$

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055
NODE=S055

CONTENTS:

NODE=S055CNT
NODE=S055CNT

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210

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=S055210

H^0 MASS

NODE=S055HBM
NODE=S055HBM

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT	
125.9±0.4 OUR AVERAGE				
125.8±0.4±0.4	[1] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV	
126.0±0.4±0.4	[2] AAD 12AI	ATLS	pp, 7 and 8 TeV	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
126.2±0.6±0.2	[3] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV	OCCUR=2
125.3±0.4±0.5	[4] CHATRCHYAN 12N	CMS	pp, 7 and 8 TeV	

[1] Combined value from ZZ and $\gamma\gamma$ final states. NODE=S055HBM;LINKAGE=CA

[2] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.8–5.9 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.9 σ is observed at m_{H^0} = 126 GeV. See also AAD 12DA. NODE=S055HBM;LINKAGE=AA

[3] Result based on $ZZ \to 4\ell$ final states in 5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 12.2 fb^{-1} at E_{cm} = 8 TeV. NODE=S055HBM;LINKAGE=CT

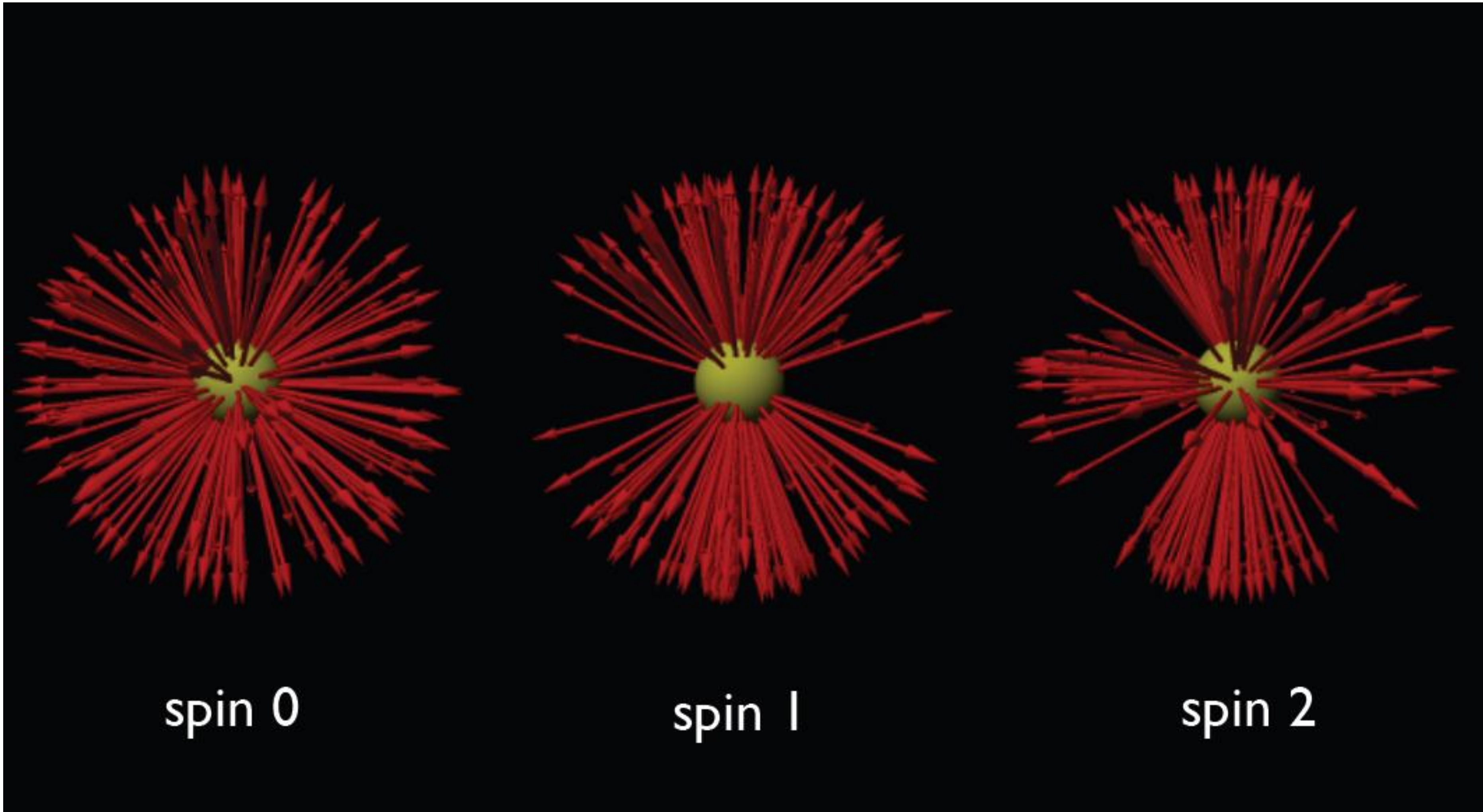
[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.1–5.3 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.0 σ is observed at about m_{H^0} = 125 GeV. See also CHATRCHYAN 12BY. NODE=S055HBM;LINKAGE=CH

2013

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

$$H^0$$

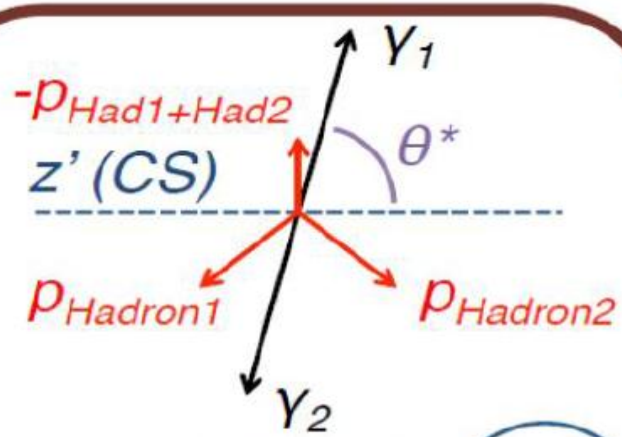
How we can recognize spin?



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->γγ

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



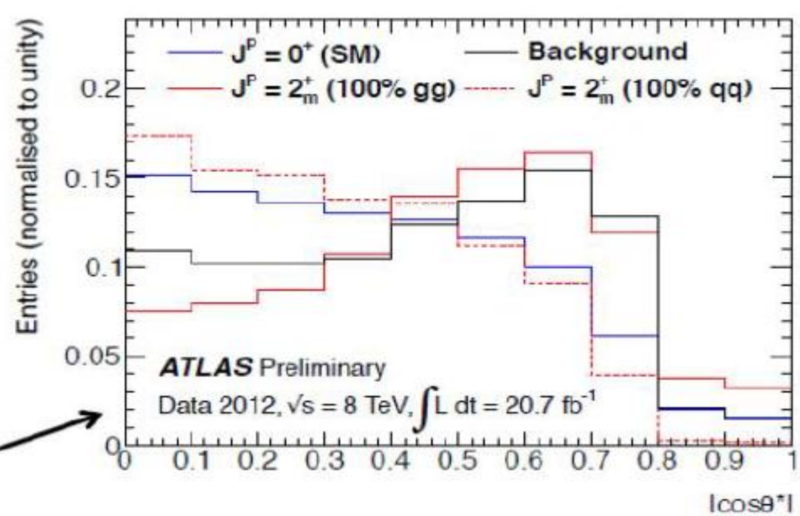
$$\left|\cos\theta^*_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

Relative p_T cuts on the photons remove most correlation with $m_{\gamma\gamma}$

qq→2⁺ very similar to SM *gg*→0⁺

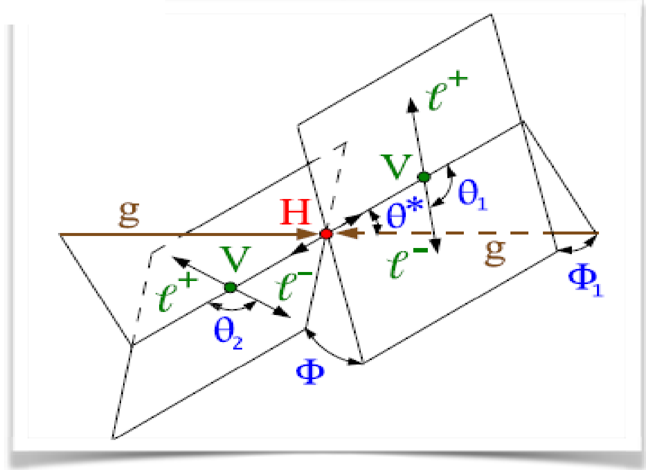
Collins-Soper frame used to get reference axis z' for cos(θ*)

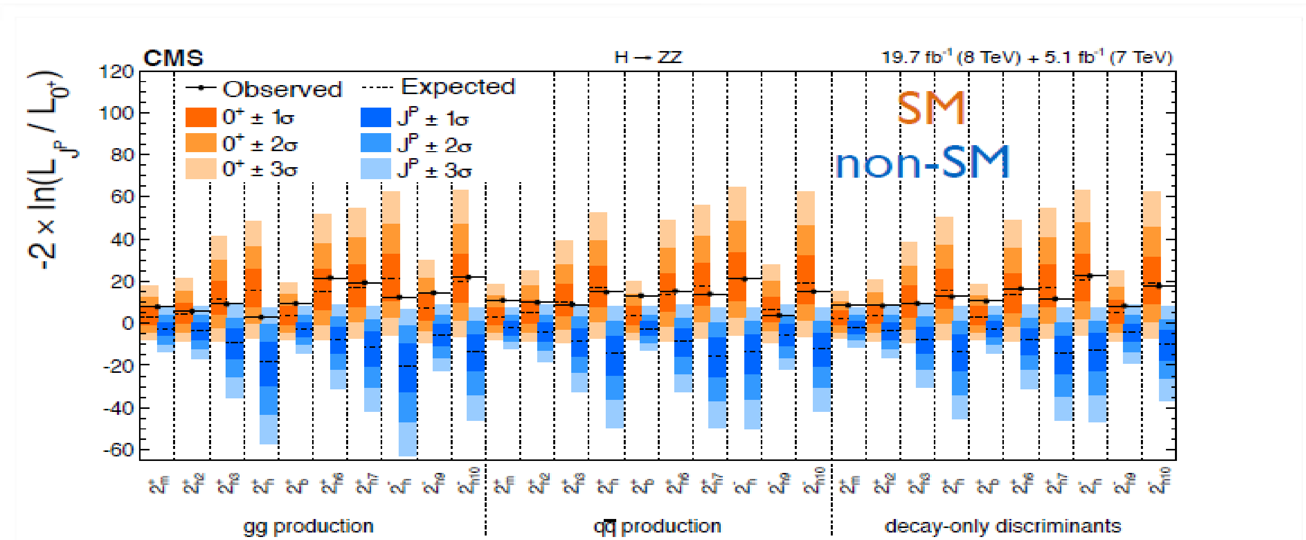
- z-axis bisects angle between the momenta of colliding hadrons
- Minimizes impact of ISR
- Better 0⁺ / 2⁺ discrimination



Spin study with H->4l

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





PRD 92 (2015) 012004

Tests of alternative J^P hypotheses in ZZ

Higgs boson decay width

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

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

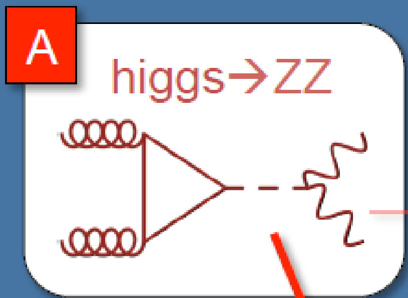
A deviation would imply a decay to non-SM particles

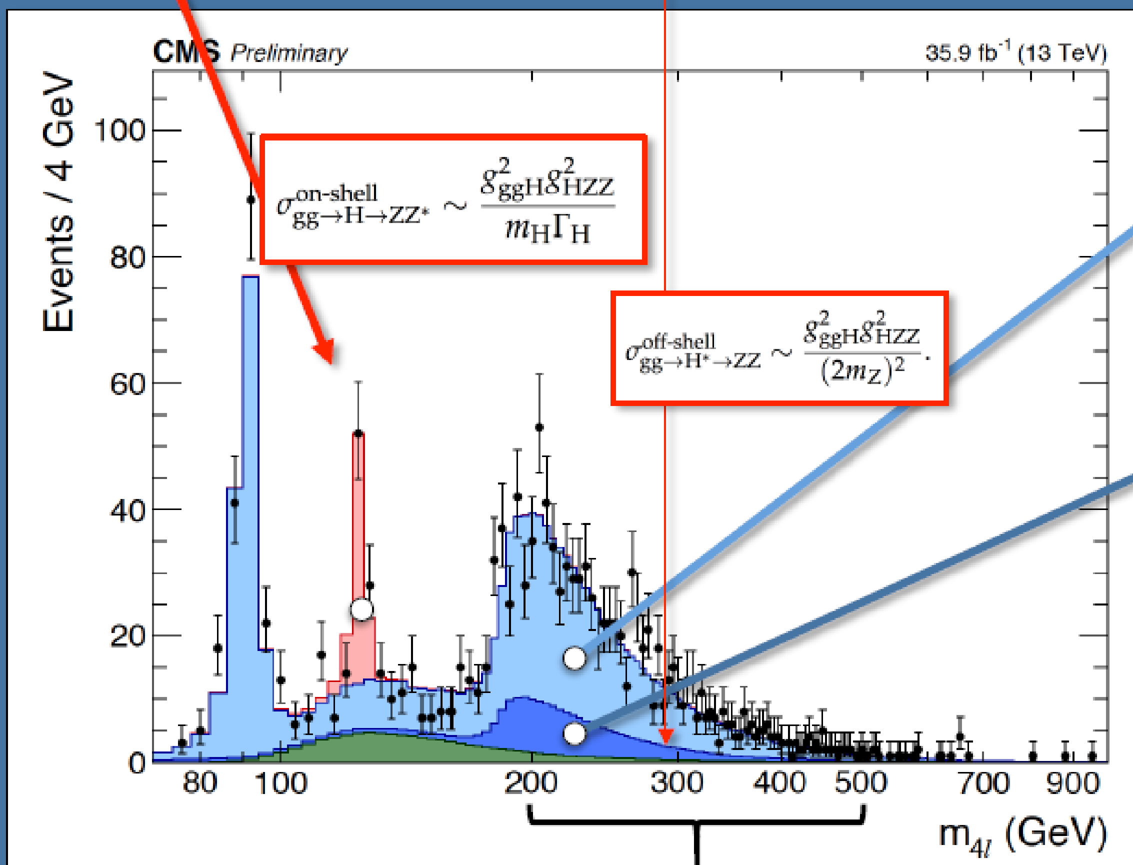
Differential Higgs production cross-section

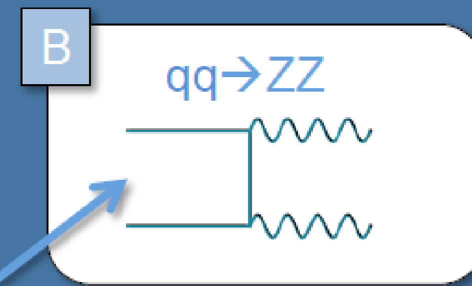
$$\frac{\mathrm{d}\sigma_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}}}{\mathrm{d}m^2_{\mathrm{ZZ}}} \sim \frac{g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}}}{(m^2_{\mathrm{ZZ}} - m^2_{\mathrm{H}})^2 + m^2_{\mathrm{H}}\Gamma^2_{\mathrm{H}}},$$

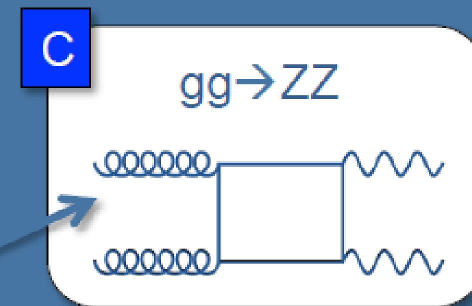
Γ_h cannot be accessed directly (experimental resolution ~ 1-2 GeV)

Indirect measurement









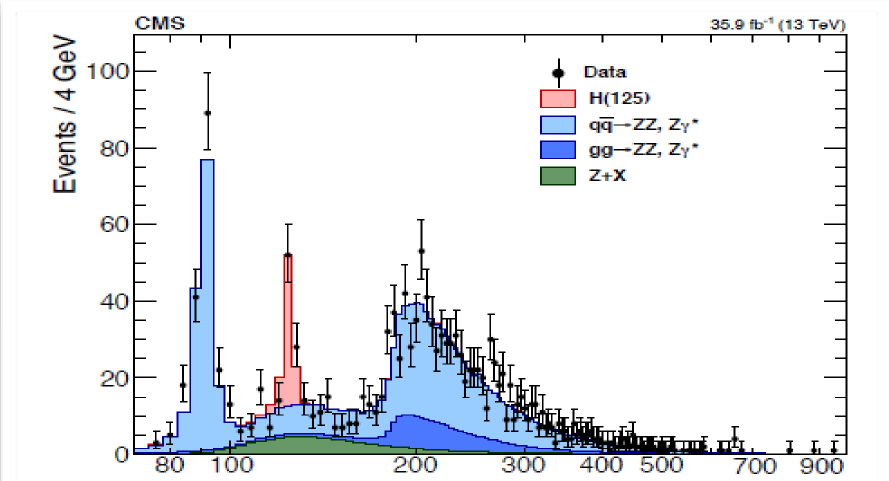
Interference between A and C : $(A+C)^2 = A^2 + C^2 + 2AC$

tiny ← → *accessible*

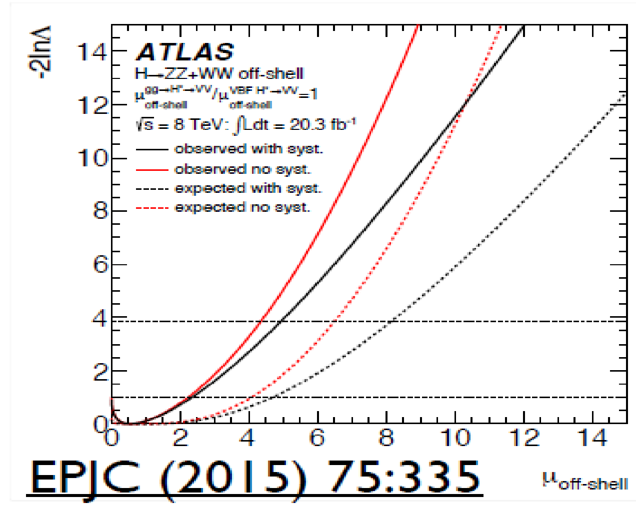
Higgs boson decay width

Total width

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

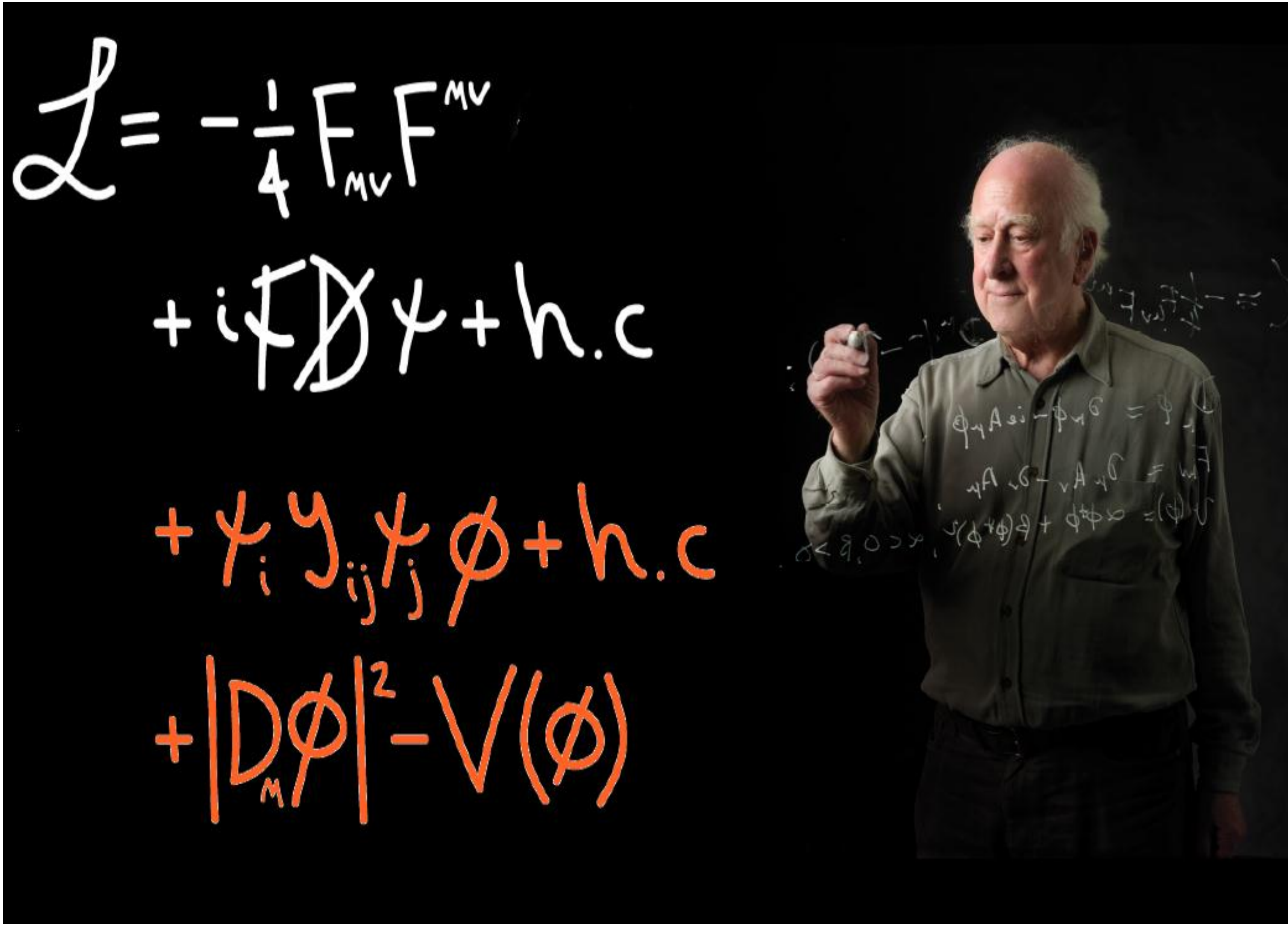


accepted by JHEP



EPJC (2015) 75:335

*N. Kauer and G. Passarino, JHEP (2012) 2012: 116
*F. Caola and K. Melnikov,PRD88 (2013) 054024


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c$
$+ \psi_i y_{ij} \psi_j \phi + h.c$
$+ |D_\mu \phi|^2 - V(\phi)$

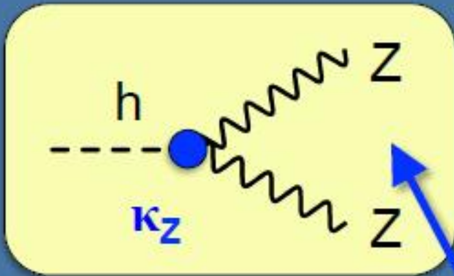
Couplings: kappa-framework

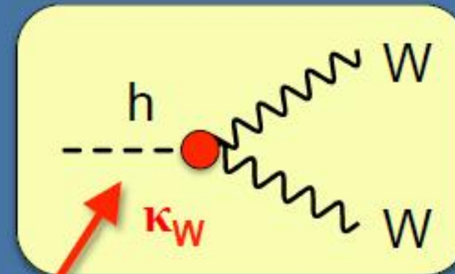
Scale factor for each (fundamental) coupling:

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

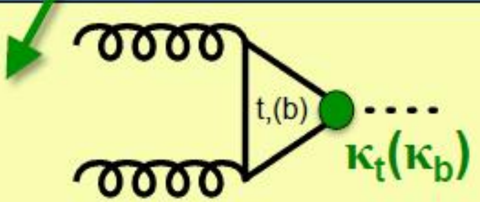
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v}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

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

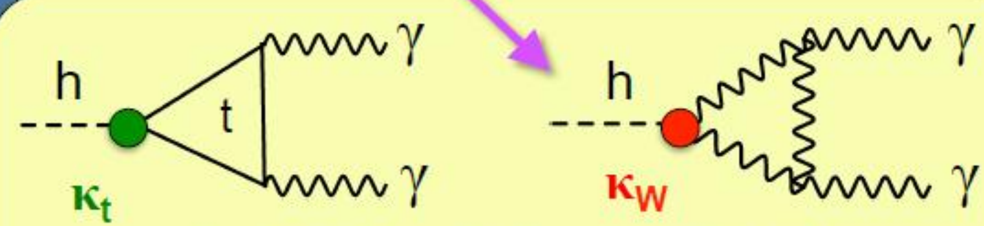




$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v}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



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



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

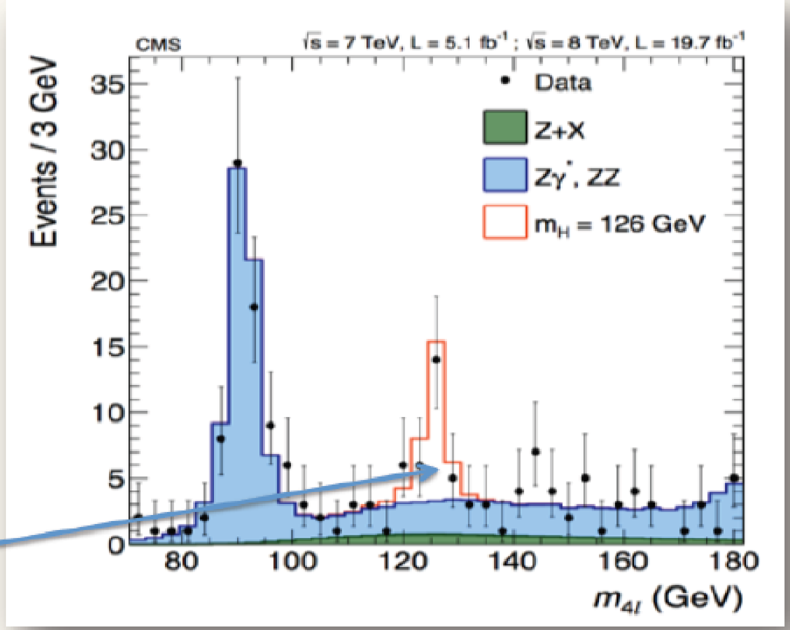
What do we measure?

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



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

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

μ^{ZZ}(@125.5 GeV) = 1.44 $^{+0.40}_{-0.35}$ 6.6σ (4.4 exp) ATLAS

μ^{ZZ}(@125.6 GeV) = 0.93 $^{+0.26+0.13}_{-0.23-0.09}$ 6.8σ (6.7 exp) CMS

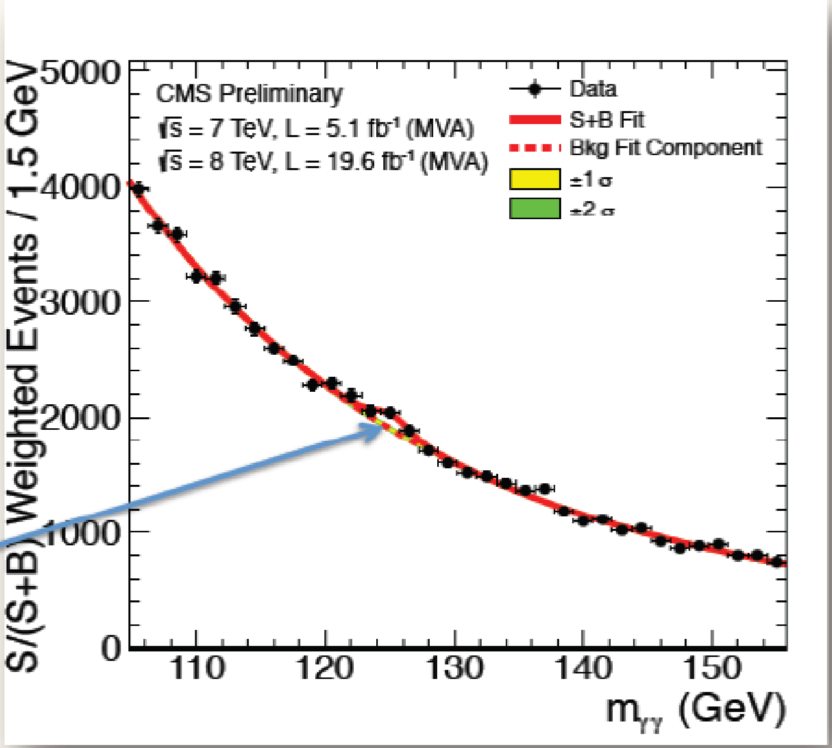
What do we measure?

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

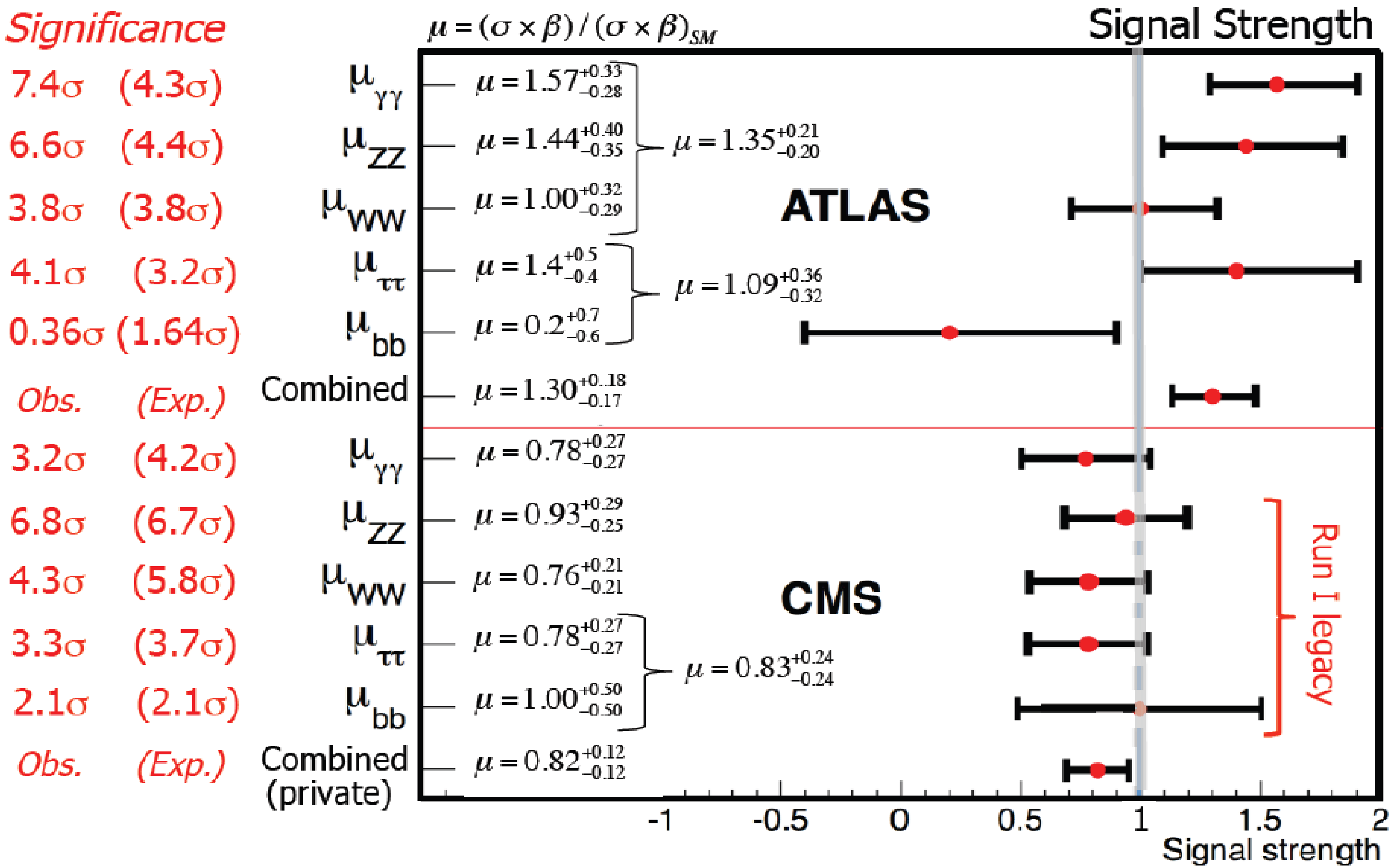
The analysis is using discriminators (usually reconstructed mass related) to increase S/B



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

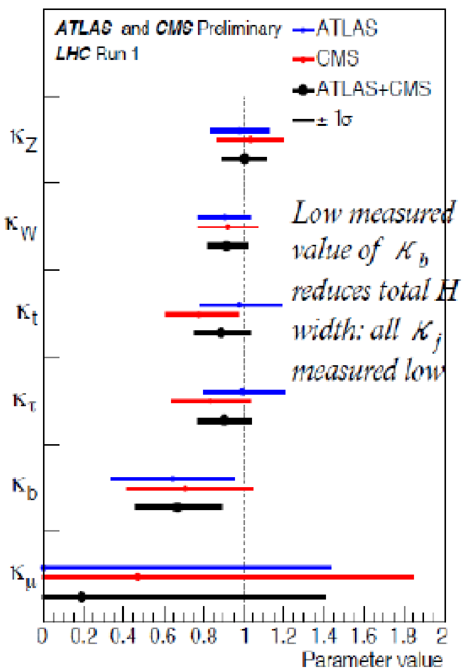
$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

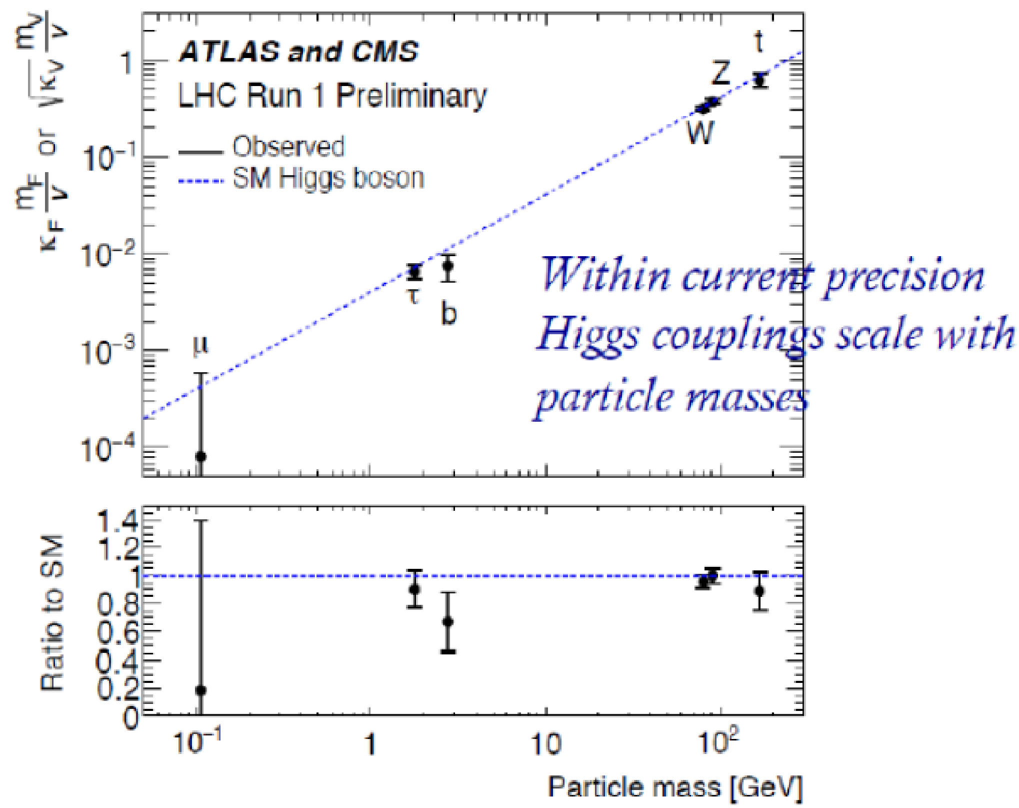
Higgs boson decay channels



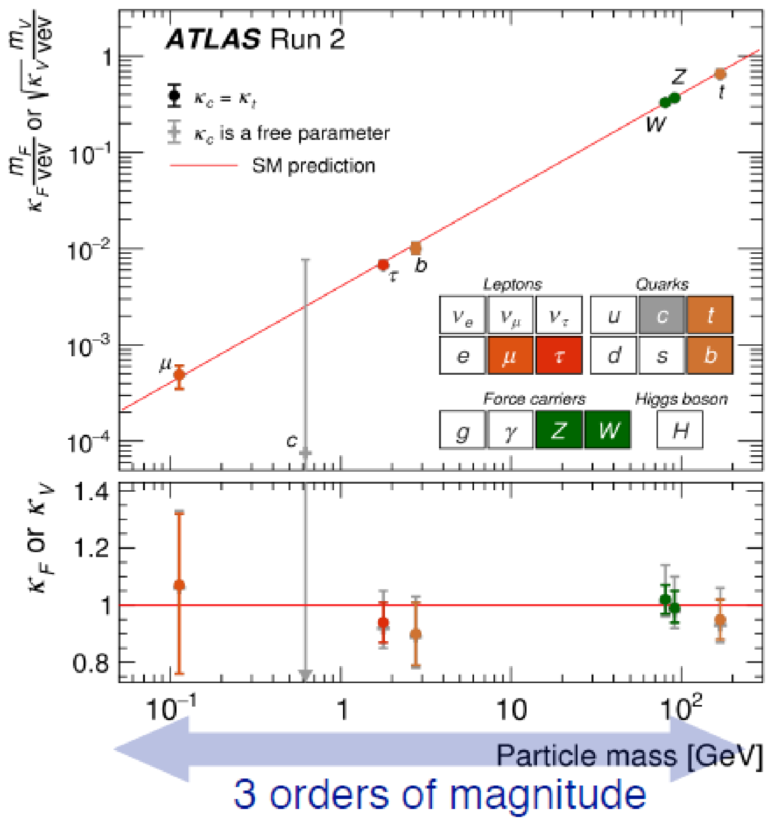
Constrains on three-level Higgs couplings

- 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 > 5σ
- Couplings to gauge bosons and 3rd gen. charged fermions observed, evidence for H→Zγ
- Couplings to 2nd gen. charged fermions: evidence for H→μμ; first constraints on H→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

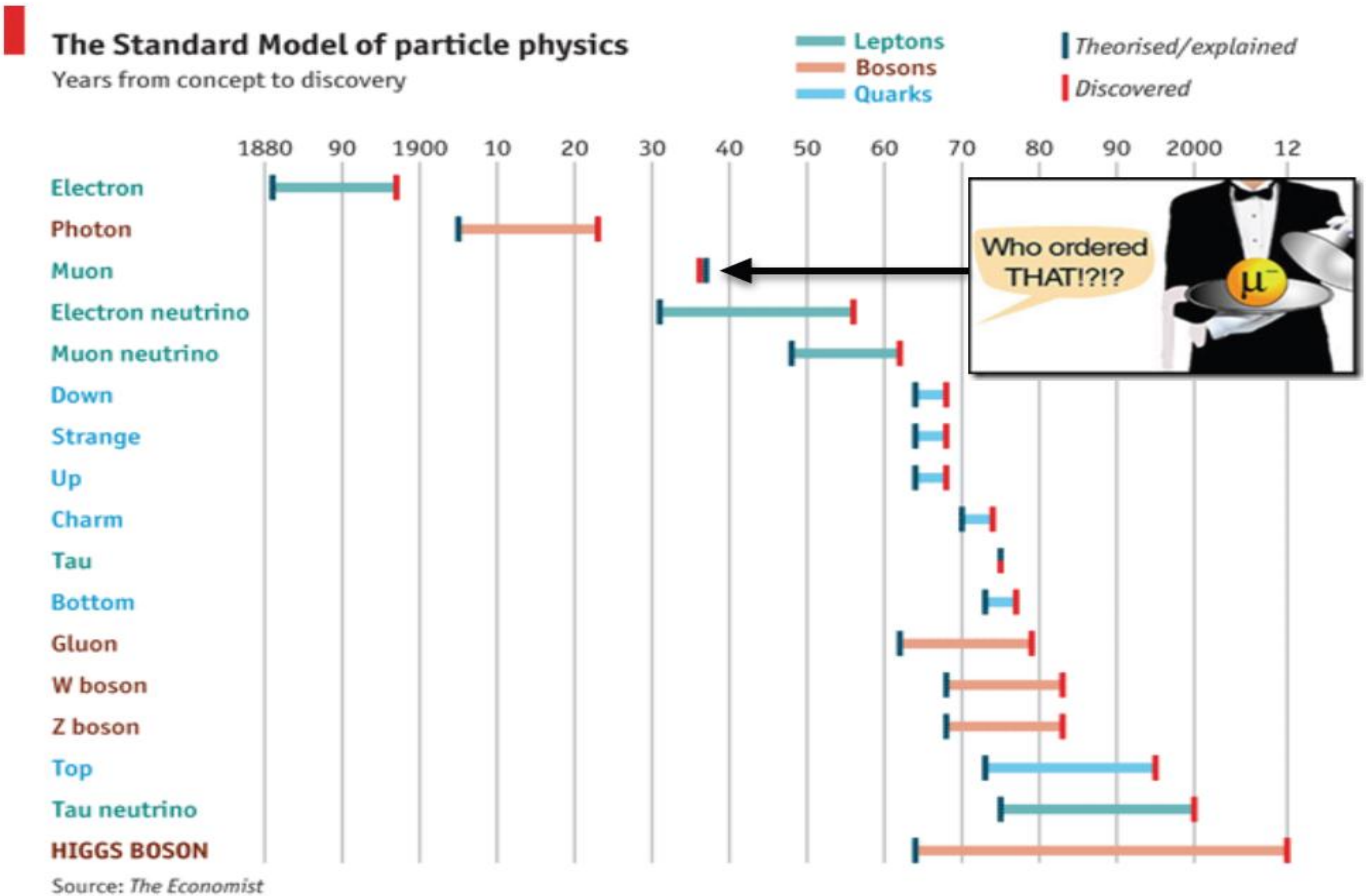
	$H\to\gamma\gamma$	$H\to ZZ^*$	$H\to WW^*$	$H\to\tau\tau$	$H\to b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 ℓ + 2 τ_{had} $t\bar{t}H$ multilepton 2 opposite-sign ℓ + 1 τ_{had} $t\bar{t}H$ multilepton 2 same-sign ℓ (categories 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 $H\to ZZ^*\to 4\ell$) $t\bar{t}H$ leptonic, $H\to ZZ^*\to 4\ell$ $t\bar{t}H$ hadronic, $H\to ZZ^*\to 4\ell$			$t\bar{t}H$ 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, $p_T^{\ell+E_T^{\text{miss}}} \geq 150$ GeV VH 1 ℓ, $p_T^{\ell+E_T^{\text{miss}}} < 150$ GeV VH E_T^{miss}, $E_T^{\text{miss}} \geq 150$ GeV VH E_T^{miss}, $E_T^{\text{miss}} < 150$ GeV VH+VBF $p_T^{j1} \geq 200$ GeV VH hadronic (2 categories)	VH leptonic 0-jet, $p_T^{4\ell} \geq 100$ GeV 2-jet, $m_{jj} < 120$ GeV			2 ℓ, $75 \leq p_T^V < 150$ GeV, $N_{\text{jets}} = 2$ 2 ℓ, $75 \leq p_T^V < 150$ GeV, $N_{\text{jets}} \geq 3$ 2 ℓ, $p_T^V \geq 150$ GeV, $N_{\text{jets}} = 2$ 2 ℓ, $p_T^V \geq 150$ GeV, $N_{\text{jets}} \geq 3$ 1 ℓ $p_T^V \geq 150$ GeV, $N_{\text{jets}} = 2$ 1 ℓ $p_T^V \geq 150$ GeV, $N_{\text{jets}} = 3$ 0 ℓ, $p_T^V \geq 150$ GeV, $N_{\text{jets}} = 2$ 0 ℓ, $p_T^V \geq 150$ GeV, $N_{\text{jets}} = 3$
VBF	VBF, $p_T^{\gamma\gamma jj} \geq 25$ GeV (2 categories) VBF, $p_T^{\gamma\gamma jj} < 25$ GeV (2 categories)	2-jet VBF, $p_T^{j1} \geq 200$ GeV 2-jet VBF, $p_T^{j1} < 200$ GeV	2-jet VBF	VBF $p_T^{\tau\tau} > 140$ 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, $p_T^{\gamma\gamma} \geq 200$ GeV 2-jet, 120 GeV $\leq p_T^{\gamma\gamma}$¡200 GeV 2-jet, 60 GeV $\leq p_T^{\gamma\gamma}$¡120 GeV 2-jet, $p_T^{\gamma\gamma} < 60$ GeV 1-jet, $p_T^{\gamma\gamma} \geq 200$ GeV 1-jet, 120 GeV $\leq p_T^{\gamma\gamma}$¡200 GeV 1-jet, 60 GeV $\leq p_T^{\gamma\gamma}$¡120 GeV 1-jet, $p_T^{\gamma\gamma} < 60$ GeV 0-jet (2 categories)	1-jet, $p_T^{4\ell} \geq 120$ GeV 1-jet, 60 GeV$\leq p_T^{4\ell}$¡120 GeV 1-jet, $p_T^{4\ell} < 60$ GeV 0-jet, $p_T^{4\ell} < 100$ GeV	1-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell 2} < 20$ GeV 1-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell 2} \geq 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell 2} < 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell 2} \geq 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell 2} < 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_T^{\ell 2} \geq 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell 2} < 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_T^{\ell 2} \geq 20$ GeV	Boosted, $p_T^{\tau\tau} > 140$ GeV Boosted, $p_T^{\tau\tau} \leq 140$ GeV	

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

Searches for New Physics

- Supersymmetry
- Exotic models
- Dark Matter
- Unconventional signatures

Uncharted discoveries?



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 then anti-matter?

How do neutrinos get mass?

Are there more forces?

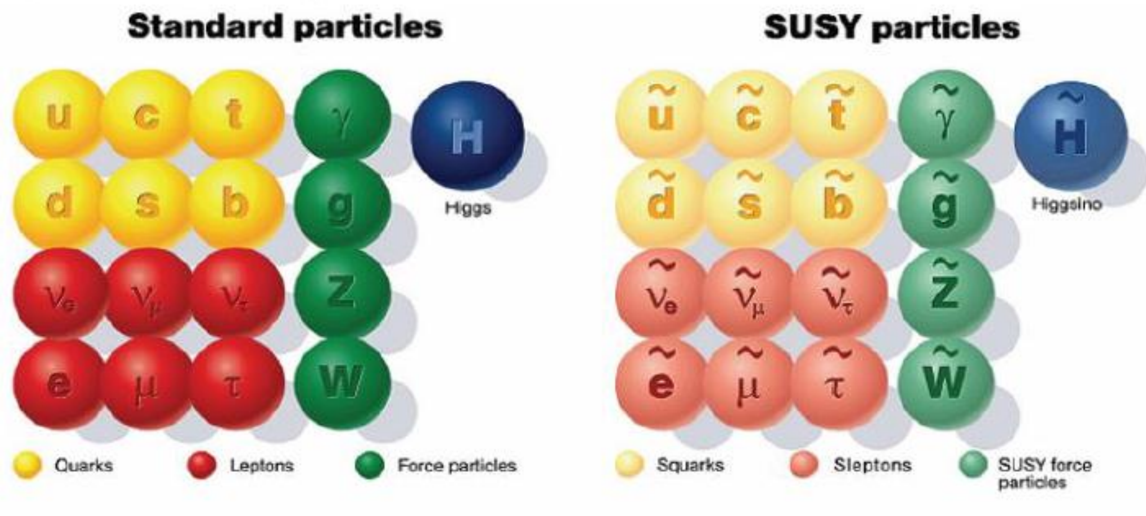
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

… and as many possible answers to probe!

- Super-symmetry?



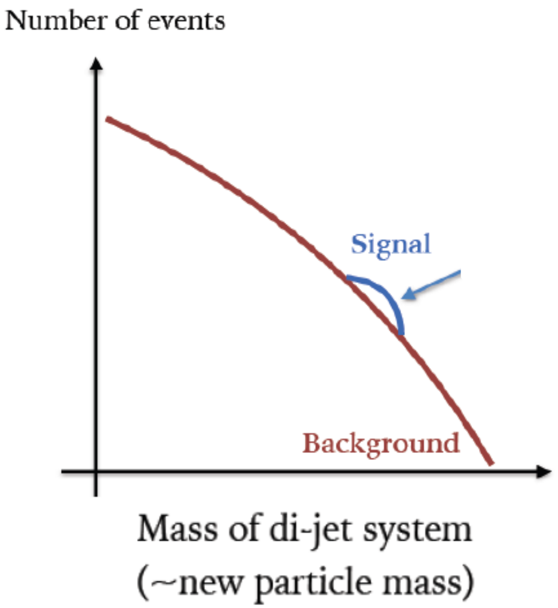
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

Any new theory need to agree with the SM!

How would new phenomena manifest itself?

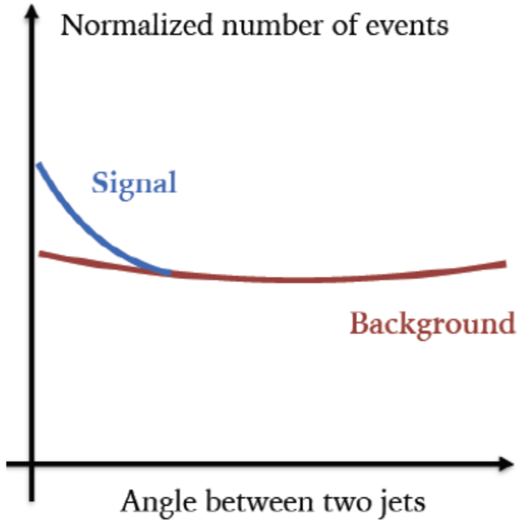
New particles:

resonant excess (bump) over Standard Model background



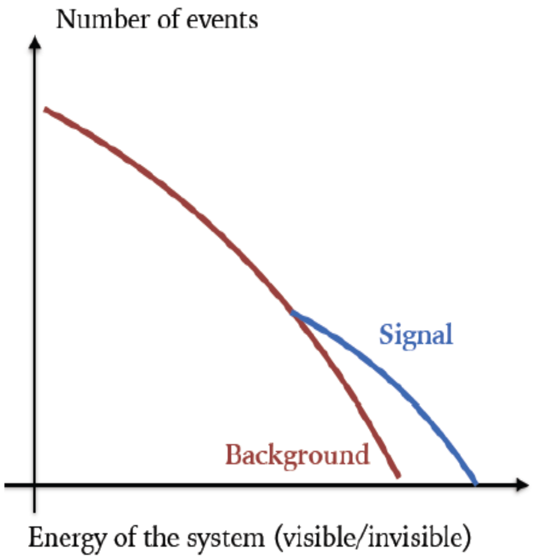
New interactions:

more central production (~Rutherford experiment)

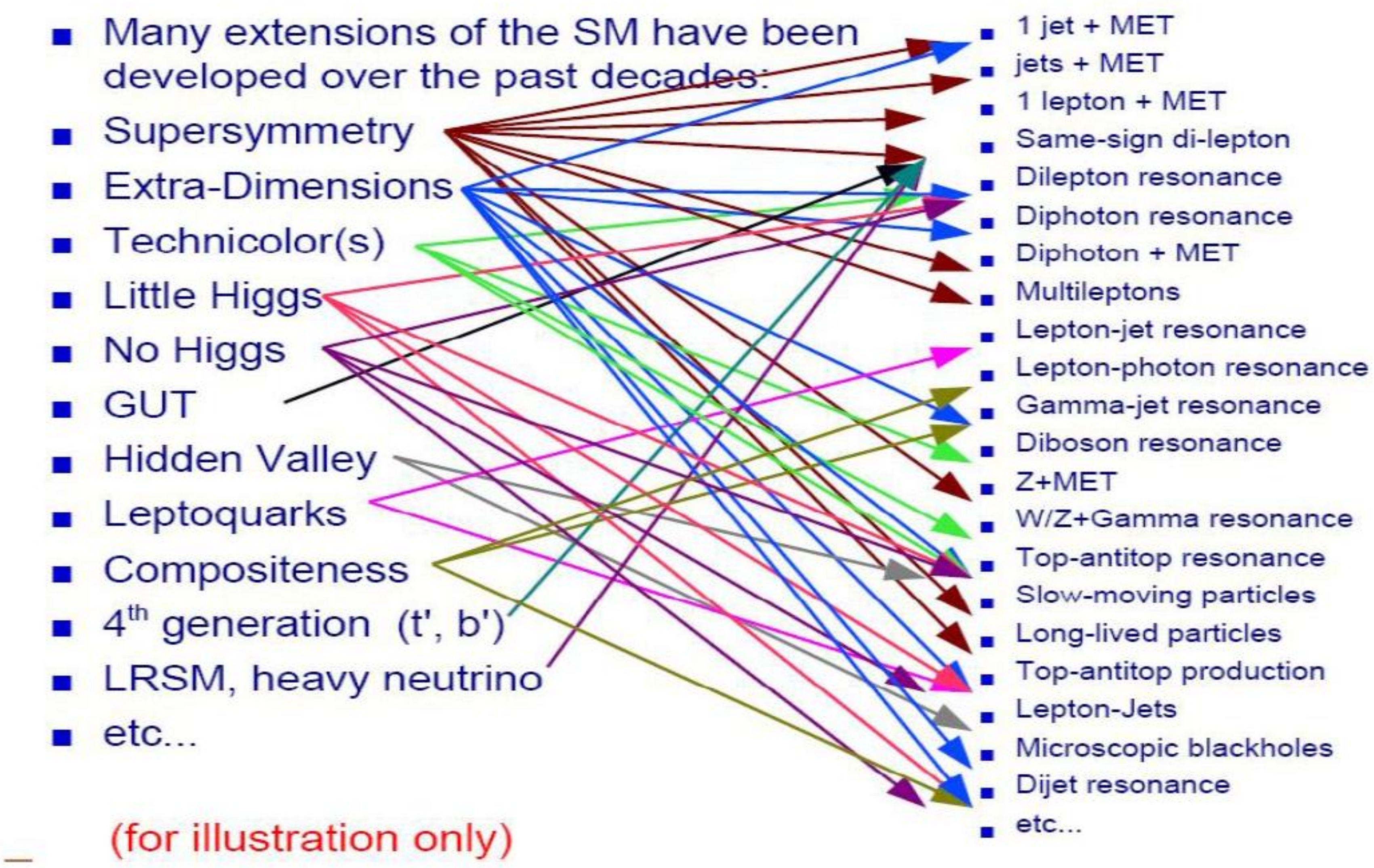


New particles and states:

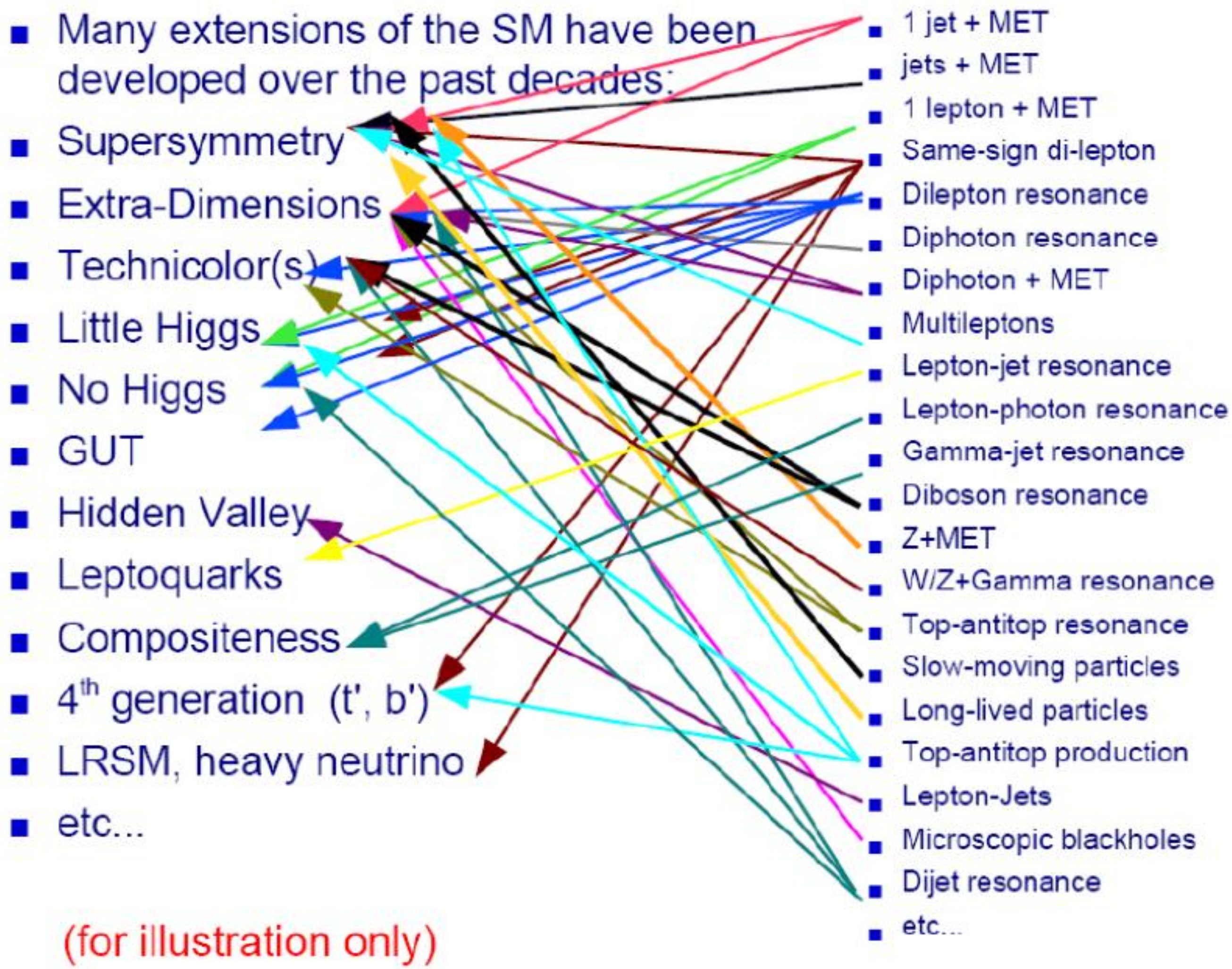
larger multiplicity of objects at high masses



Long list of models and signatures



Long list of models and signatures



A complex 2D problem

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

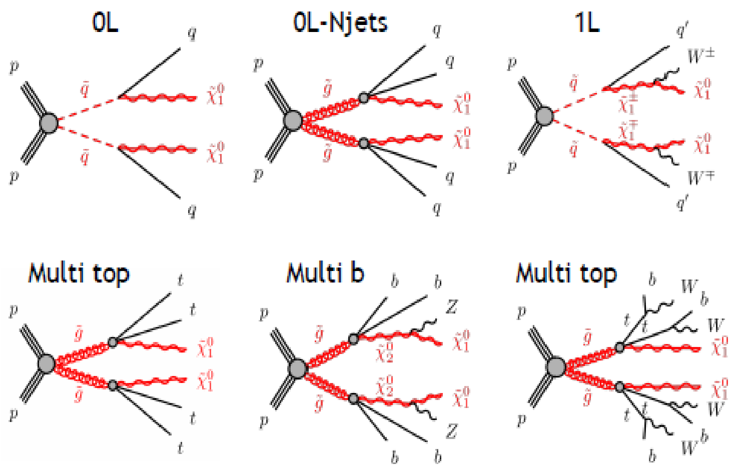
→ Practical

→ Less model-dependent

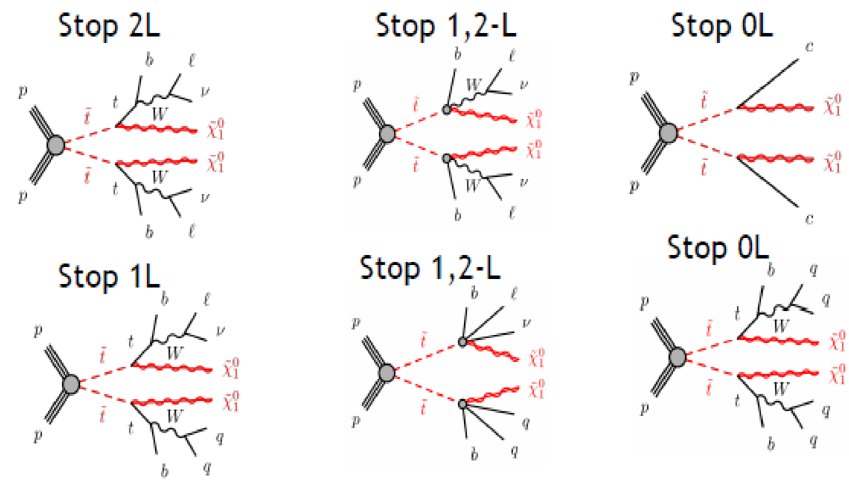
→ Important to cover every possible signature

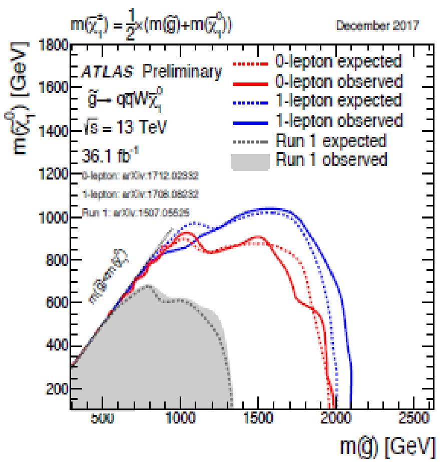
Strongly produced SUSY searches

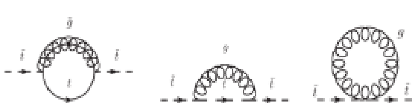
Squarks and gluinos



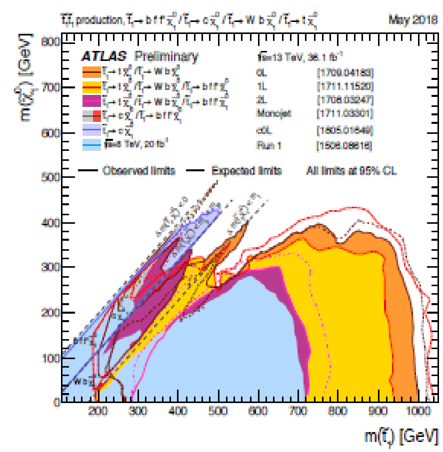
Stop







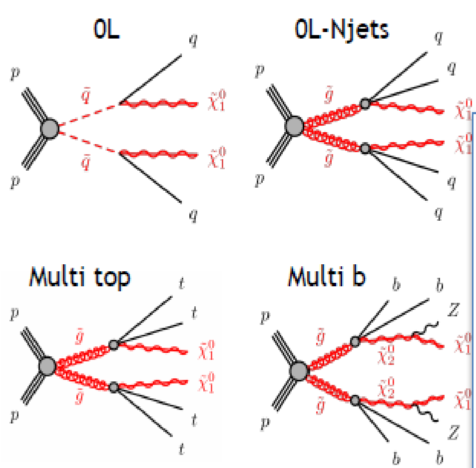
Stop also a scalar requires light gluinos to be light enough: for gluinos > 1.8 TeV ~tuning of Factor of 30



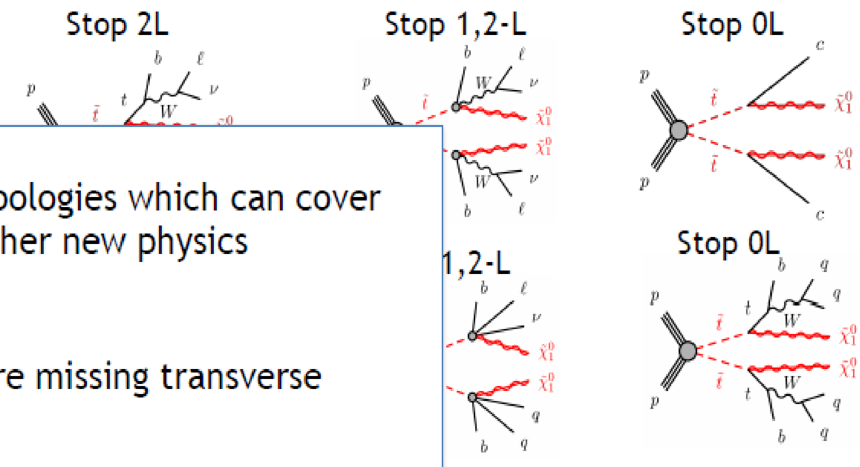
Not so natural SUSY: Stops > 800 GeV ~Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

Strongly produced SUSY searches

Squarks and gluinos

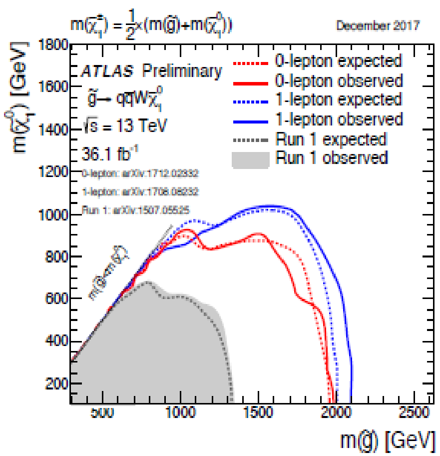


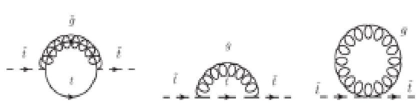
Stop



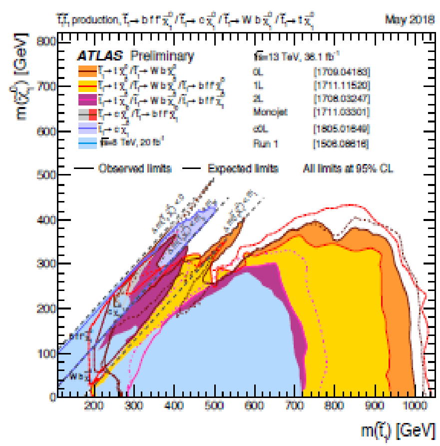
Large number of topologies which can cover different SUSY or other new physics scenarios

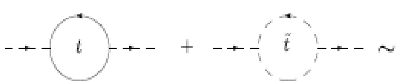
All signatures feature missing transverse energy!





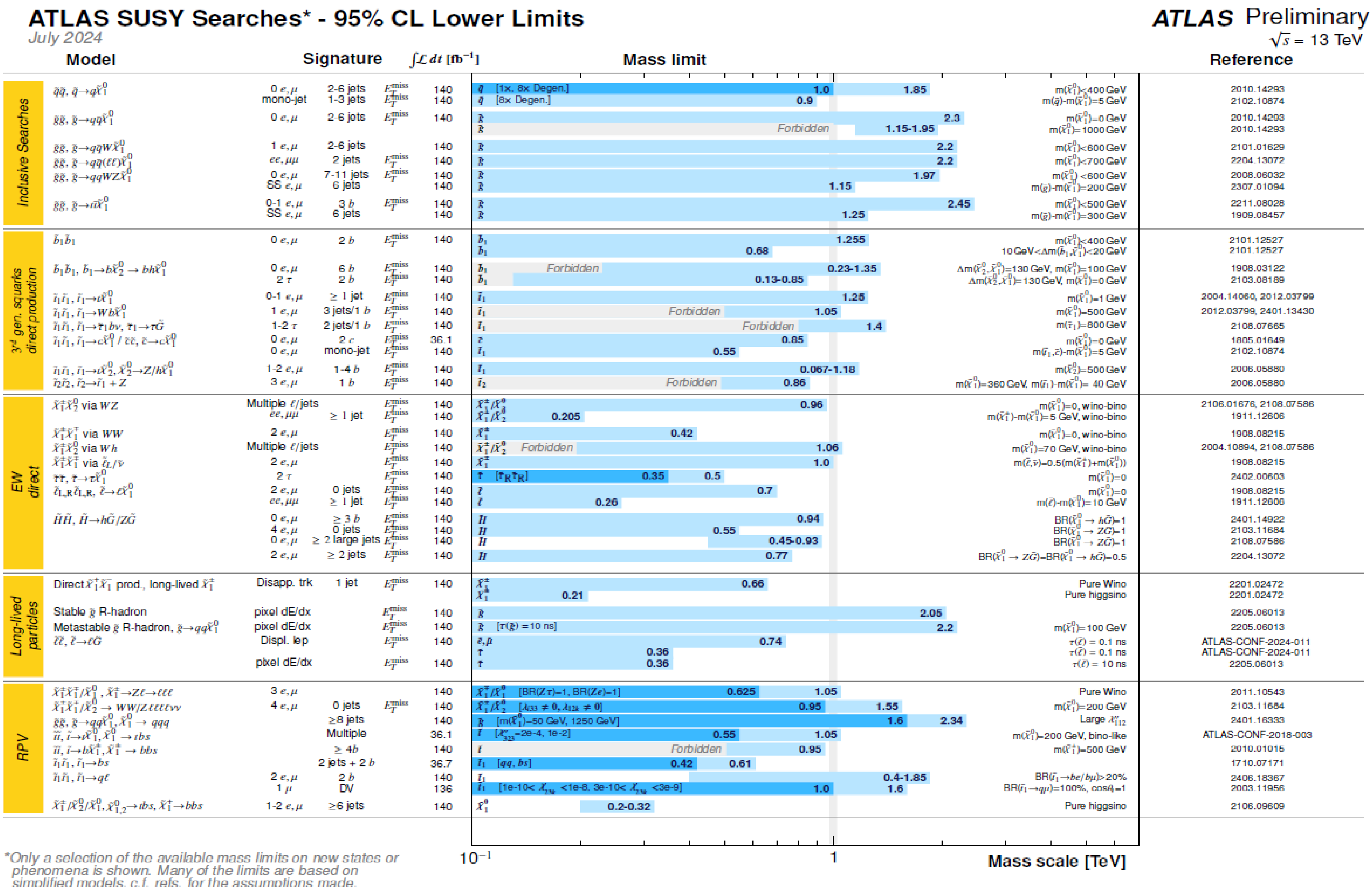
Stop also a scalar requires light gluinos to be light enough: for gluinos > 1.8 TeV ~tuning of Factor of 30





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

SUSY Searches Overview (2024)

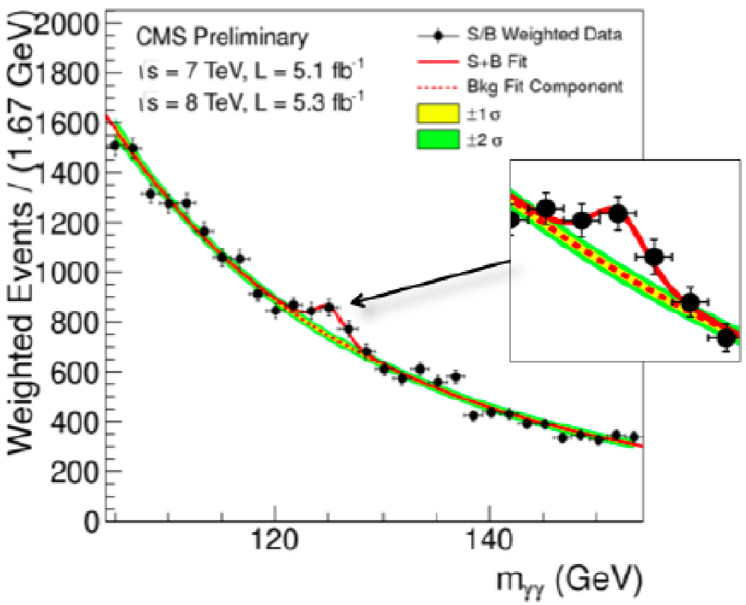


What characterizes Exotics Searches

No precise model to guide us

Standard Model:

Predicted Higgs boson

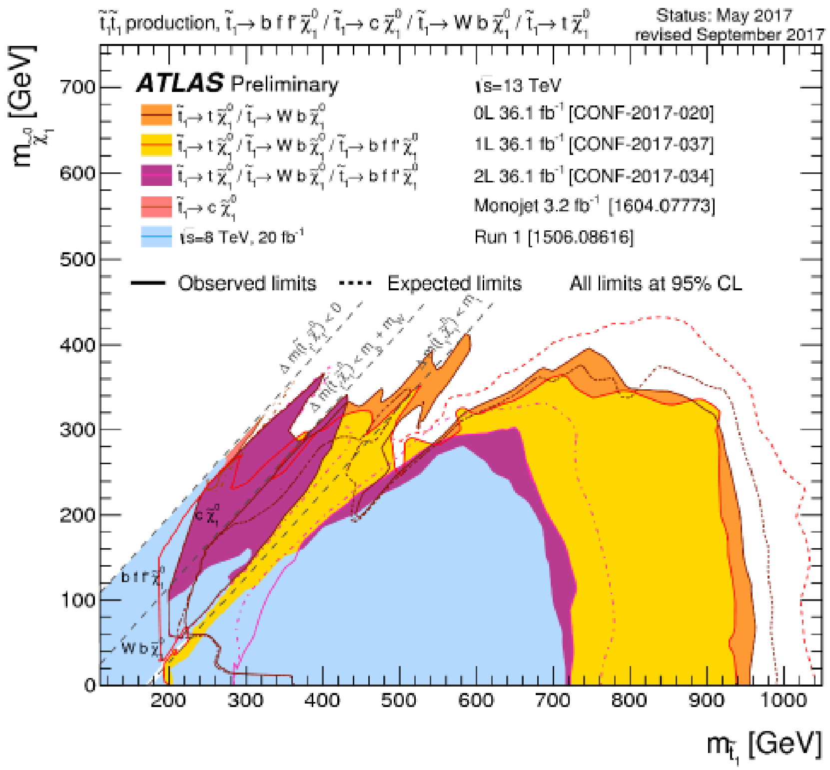


[Phys. Lett. B 716 (2012) 1-29](#)

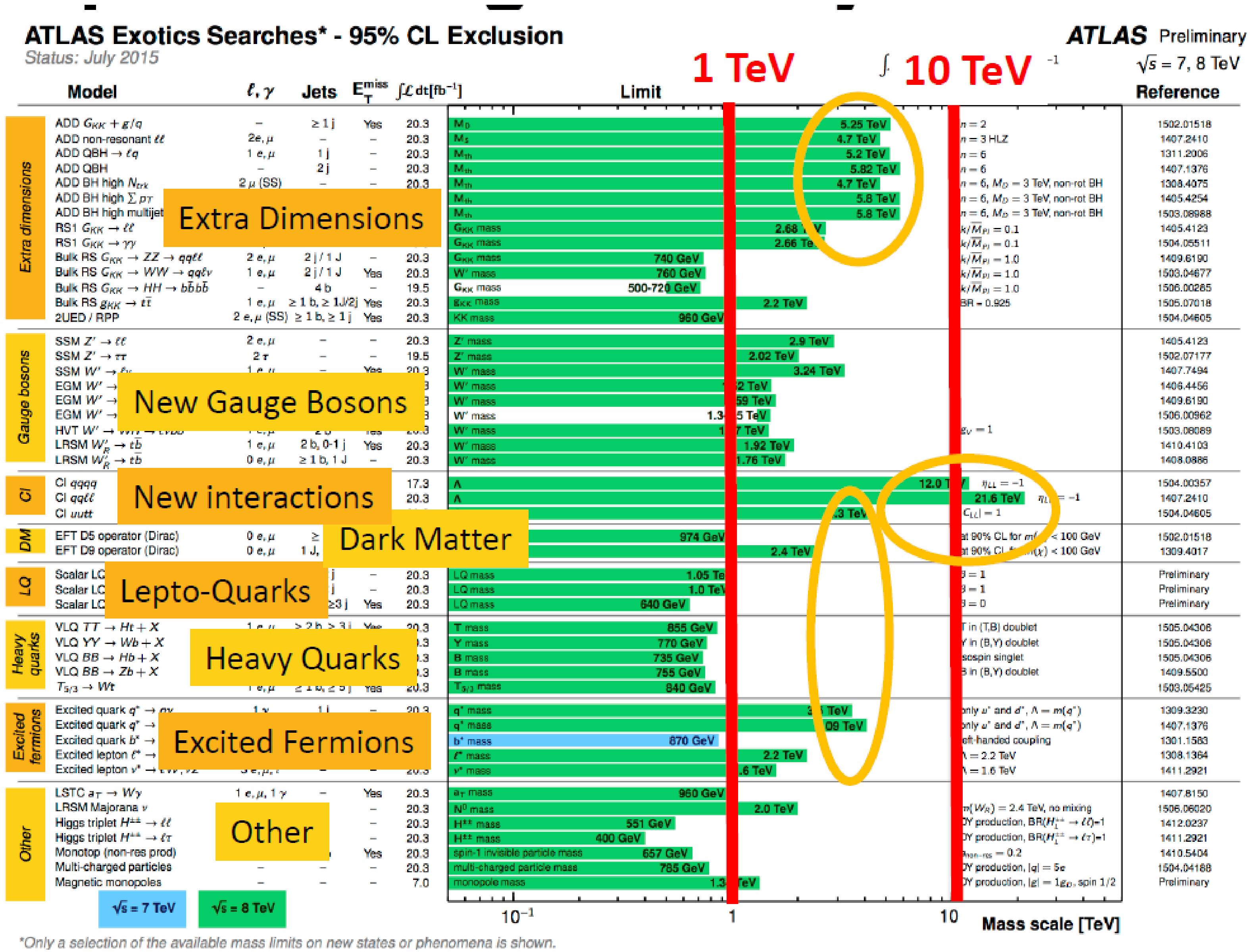
[Phys. Lett. B 716 (2012) 30-61](#)

No unified parameter phase space

Supersymmetry Searches:



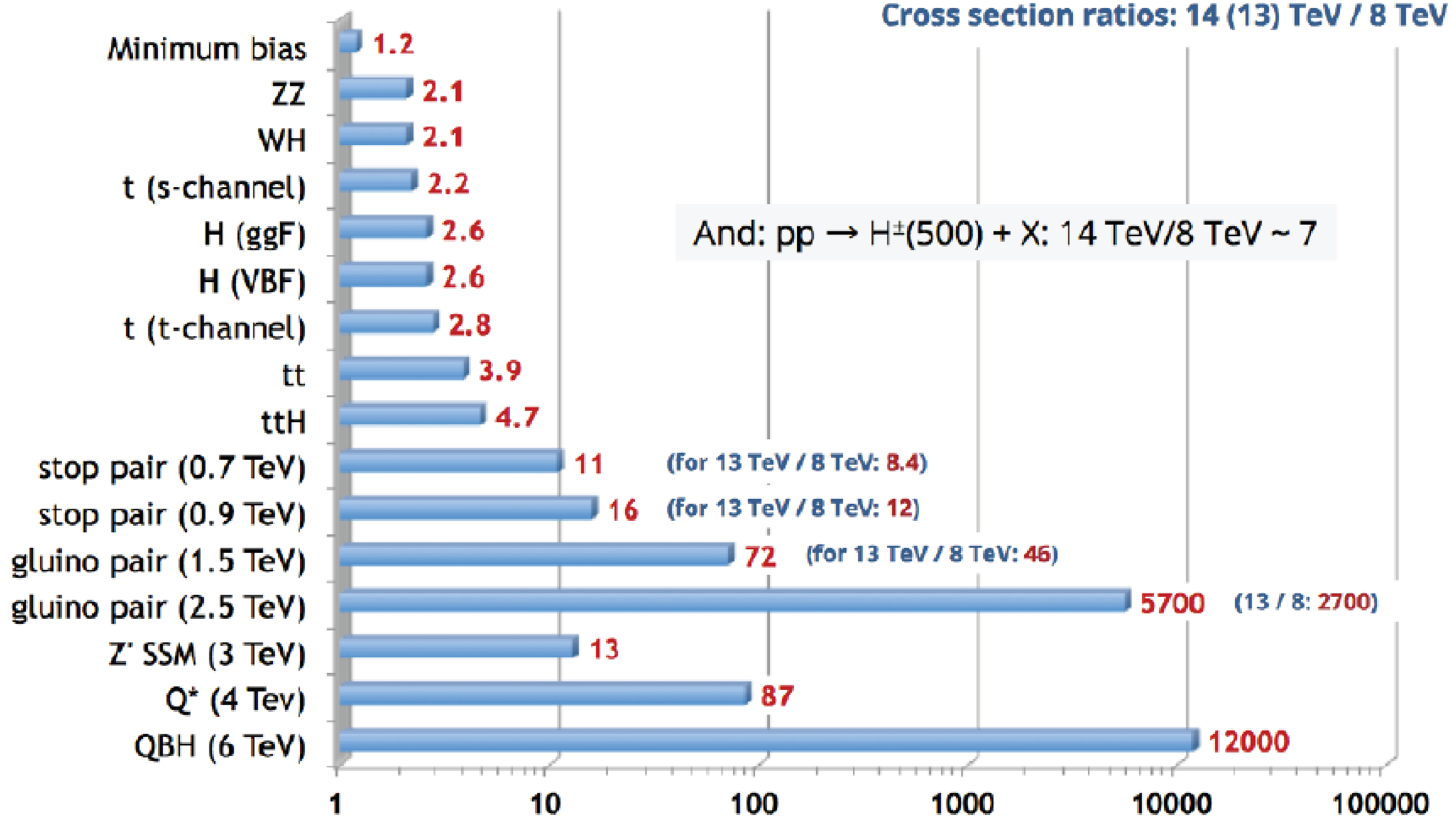
Exploration range of LHC by mid 2015



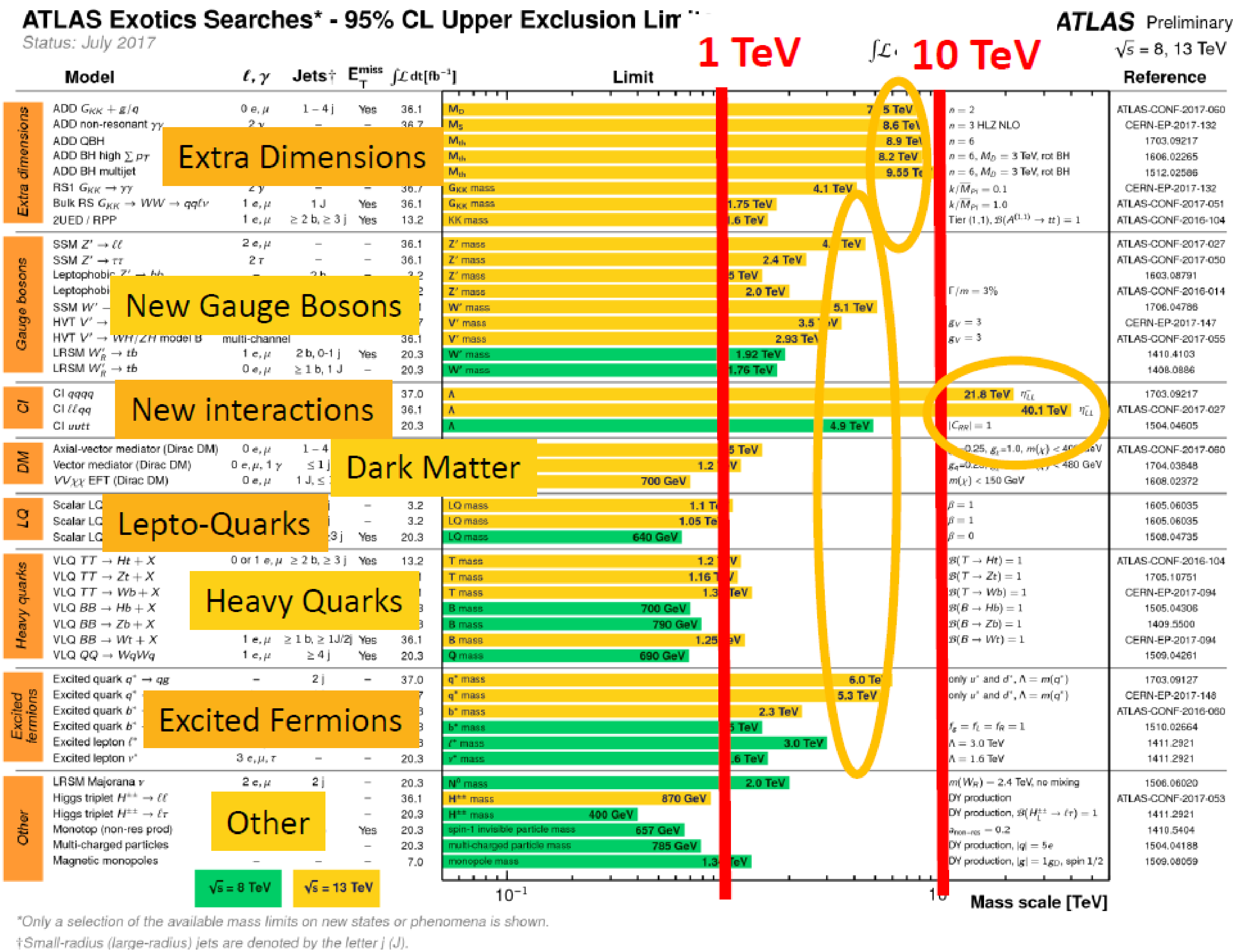
LHC Run II

Hugely increased potential for discovery of heavy particles at 13 TeV

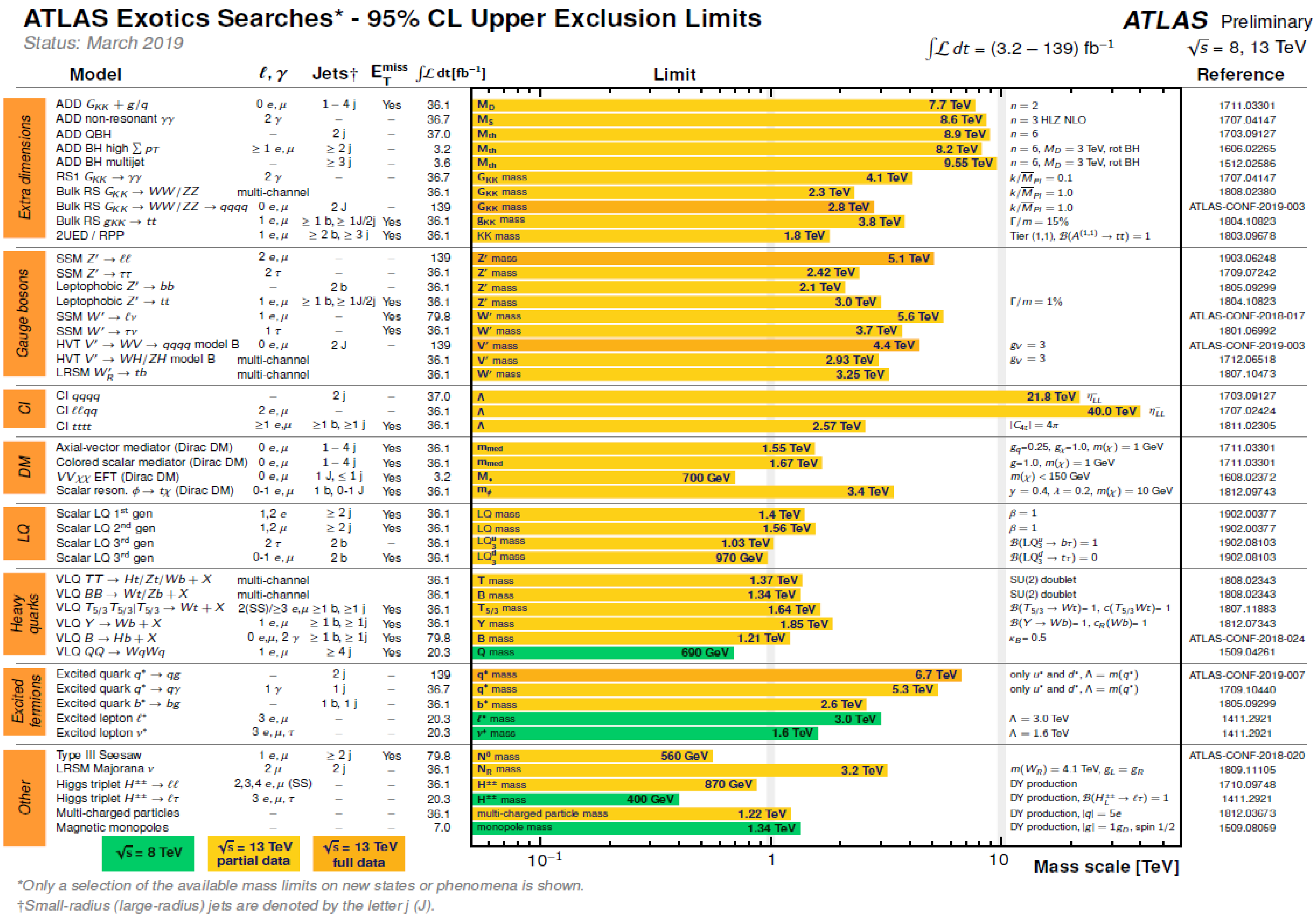
Perfect occasion for young motivated physicists: join the search!



Exploration range of LHC by mid 2017



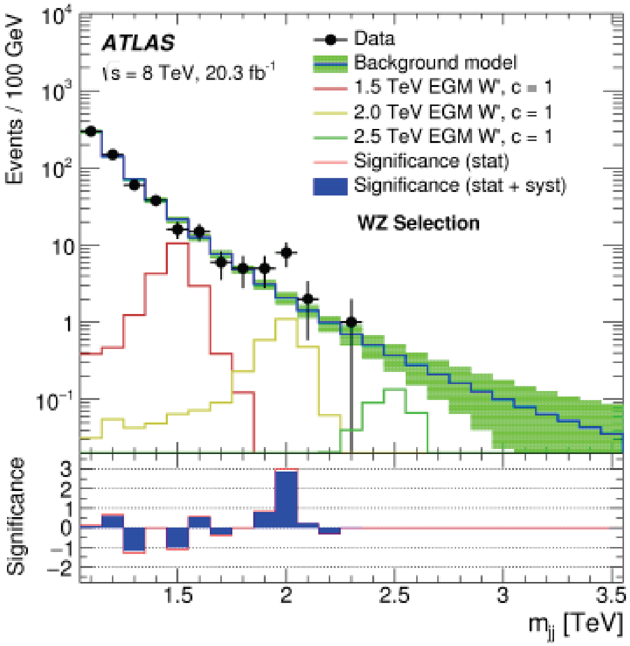
Exploration range of LHC by mid 2019



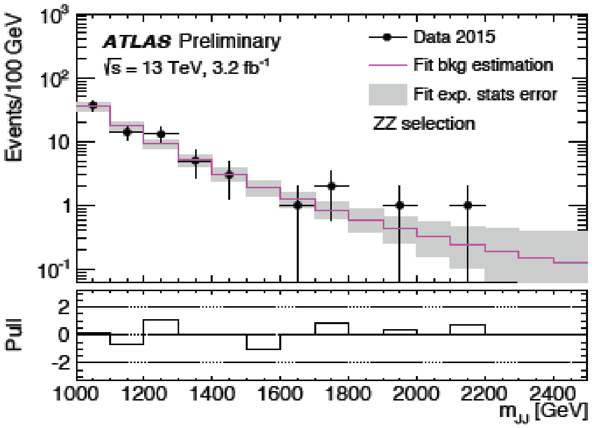
Fully hadronic Diboson Searches

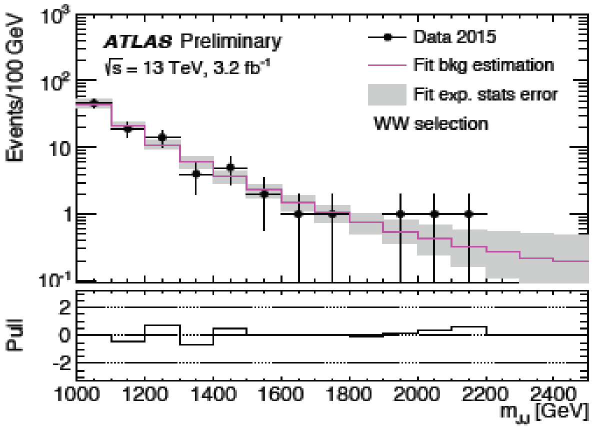
ATLAS-CONF-2015-073

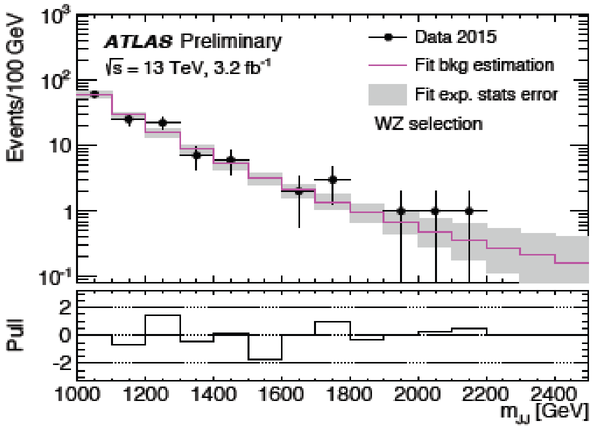
Run-1



- **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



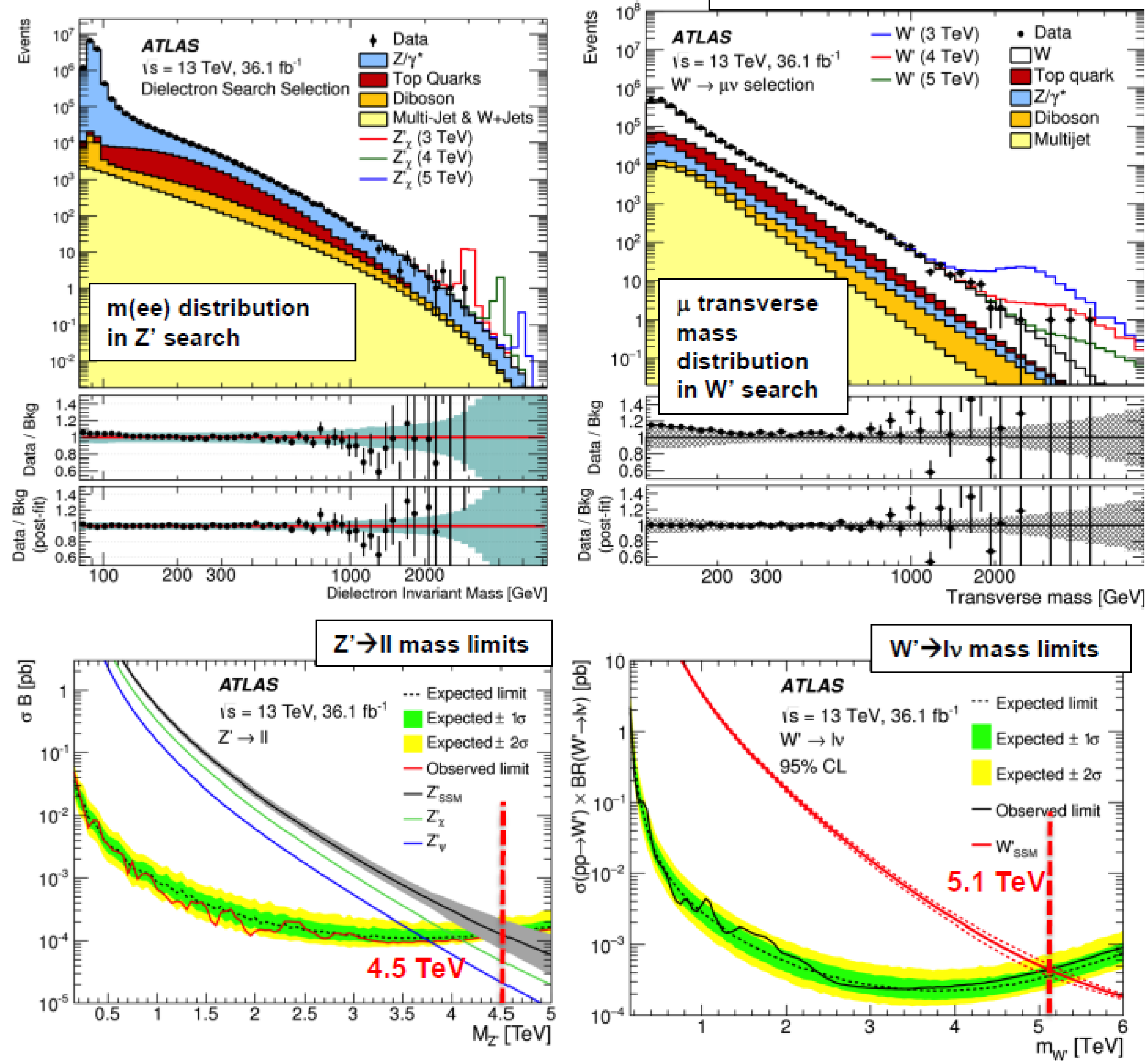




Resonance Searches (Dilepton, Lepton+ETmiss)

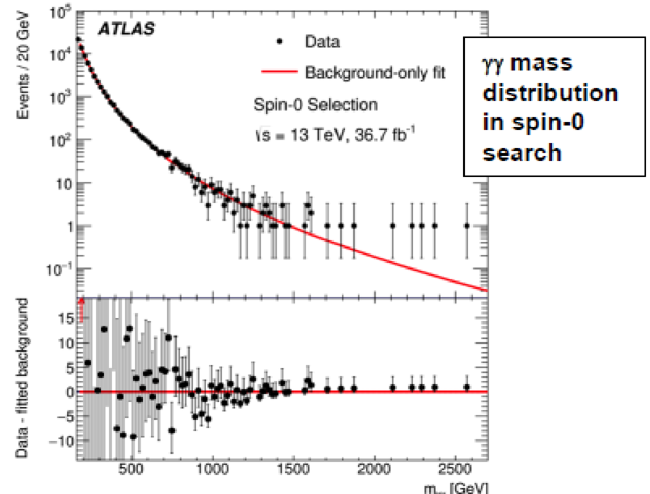
- Searches for new resonances decaying to lepton pairs (e.g. Z') or lepton+E_T^{miss} (e.g. W')
- Signature is peak in invariant mass distribution (dilepton) or tranverse mass distributions (lepton+E_T^{miss})
- No significant excess over SM expectation
- 95% CL exclusion limits extracted in various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

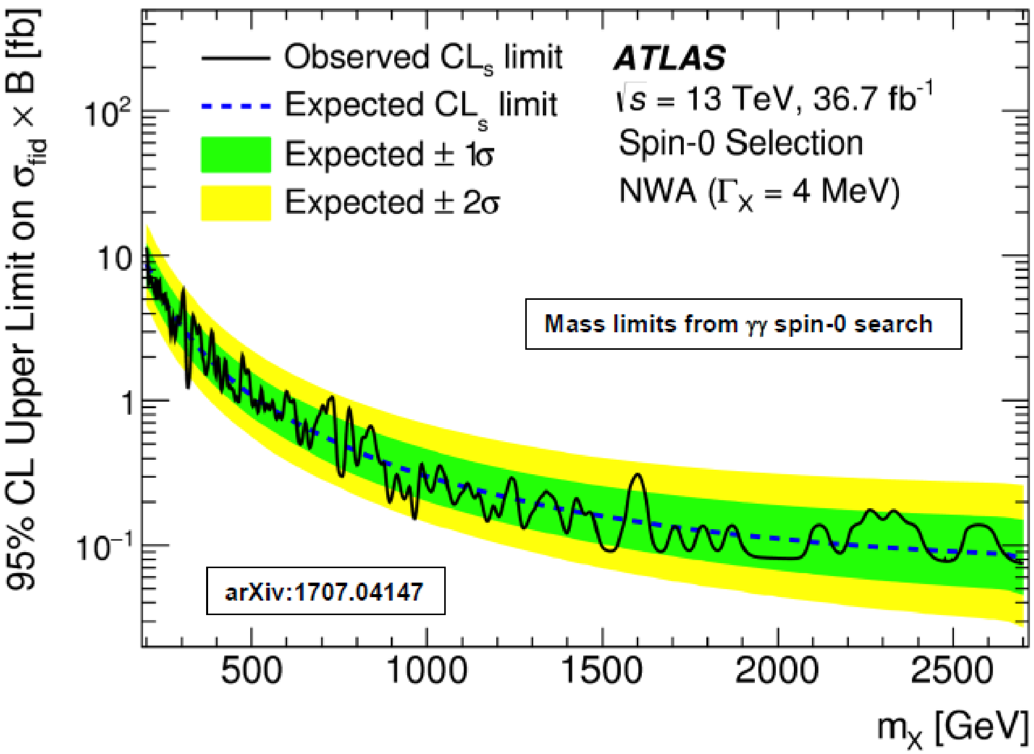
arXiv:1707.02424, arXiv:1706.04786

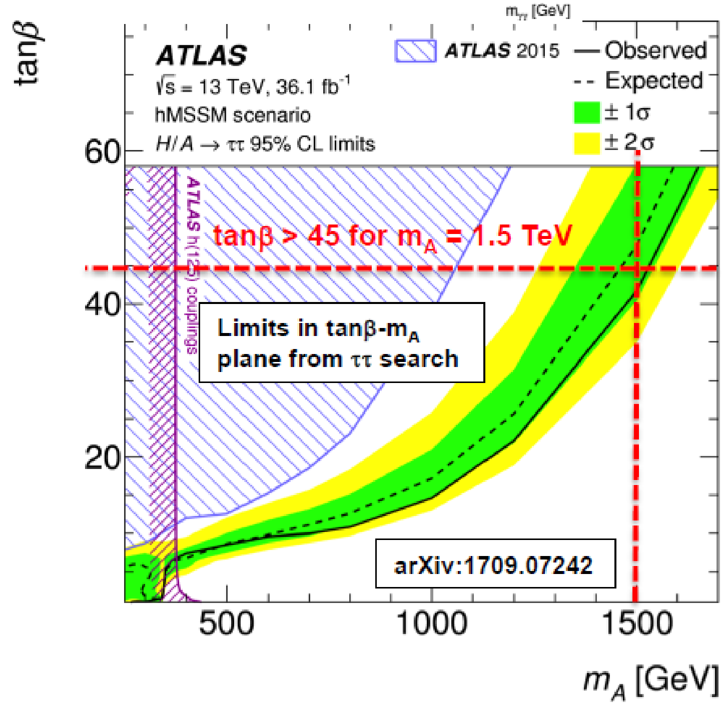


Resonance Searches (γγ, ττ)

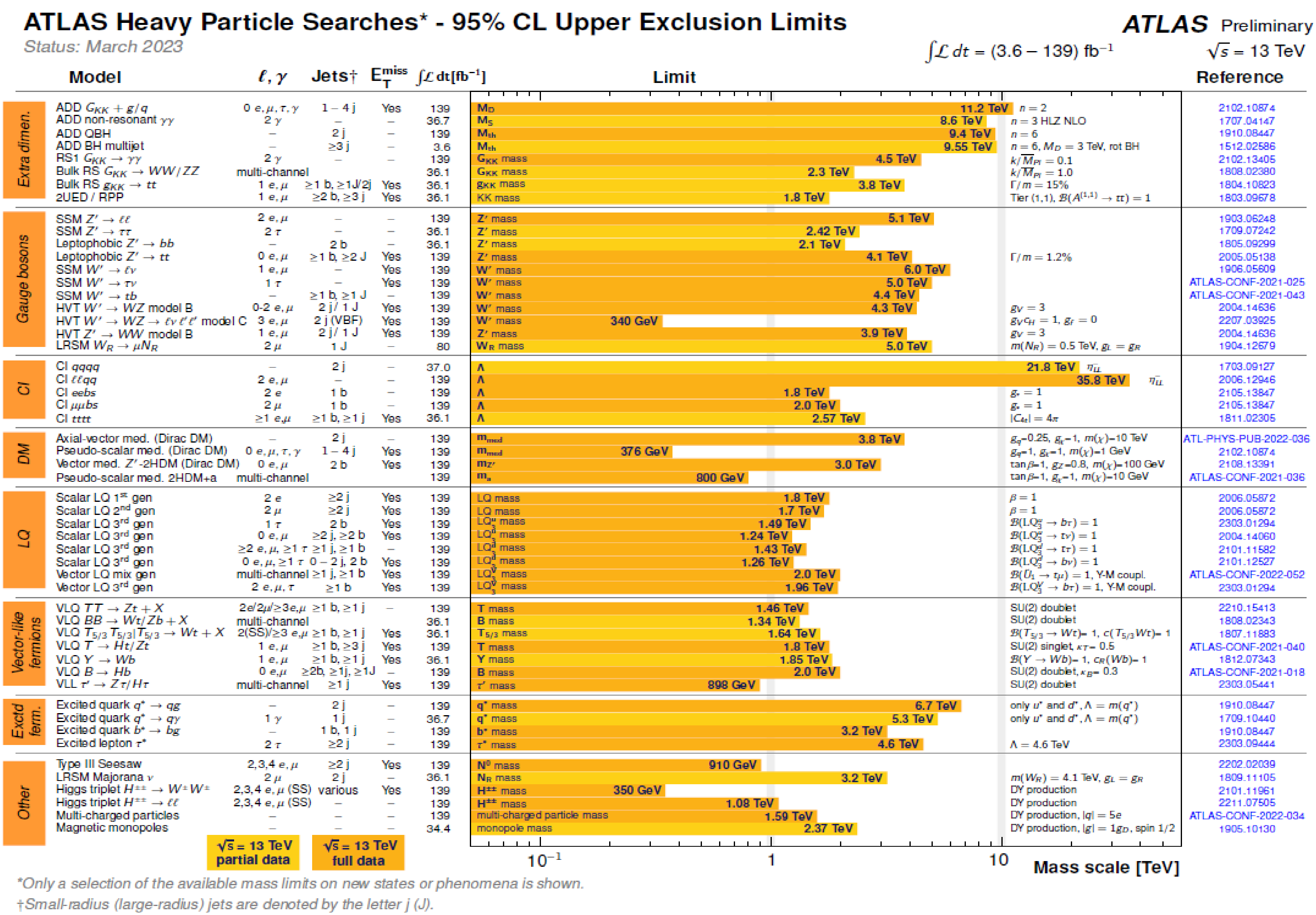
- Diboson resonance searches also sensitive to new heavy scalars, e.g. Higgs bosons.
- Searches also conducted with γγ and ττ final states
- γγ search also targets spin-2 (graviton) production with a dedicated selection
- ττ searches sensitive to SUSY Higgs (H/A) models
- No significant excesses over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



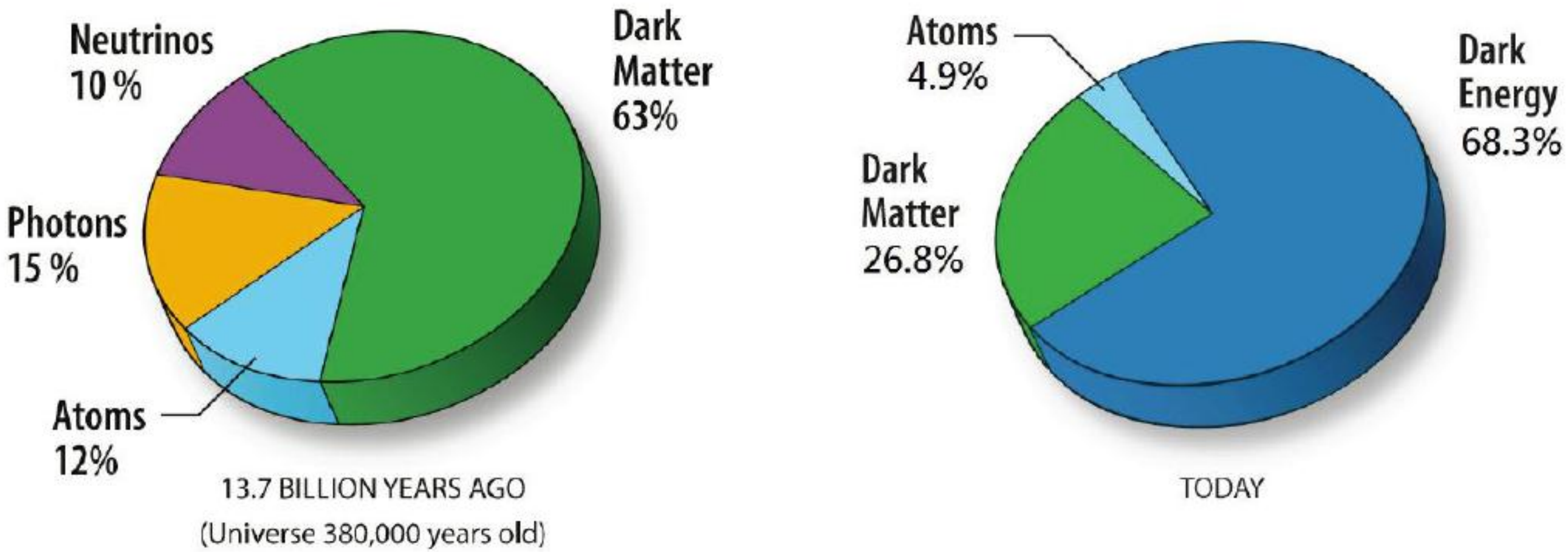




Exploration range of LHC: March 2023



What do we know about Dark Matter

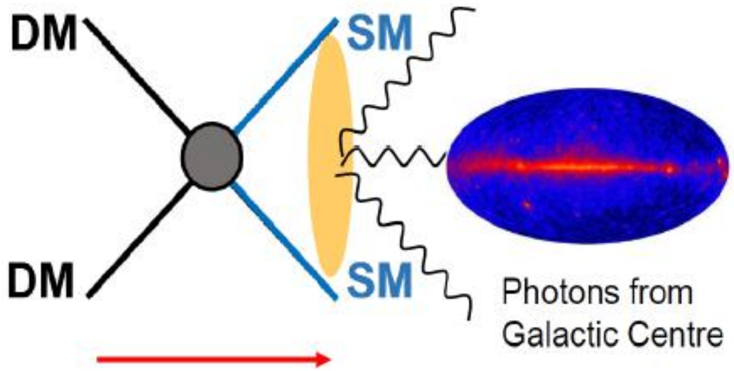


Strong astrophysical evidence for the existence of dark matter

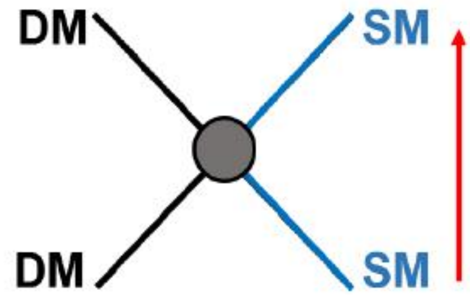
What do we know about Dark Matter

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

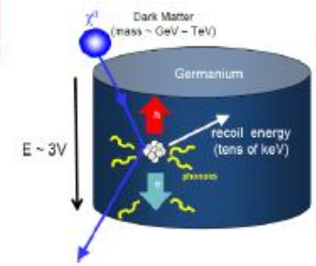
Experimental detection of Dark Matter



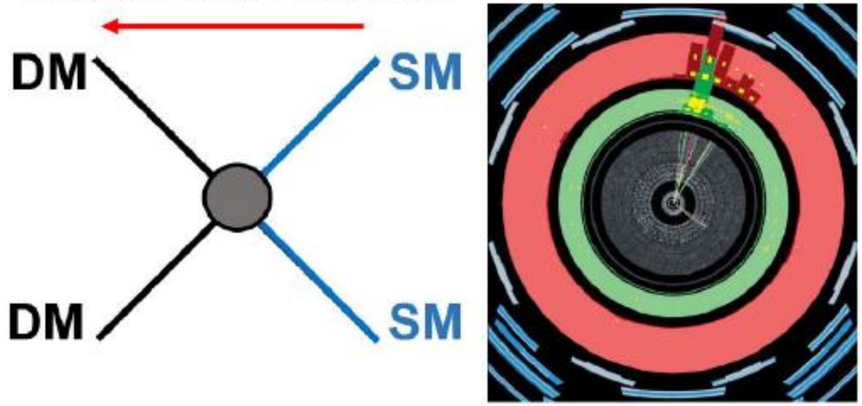
"break it": indirect detection



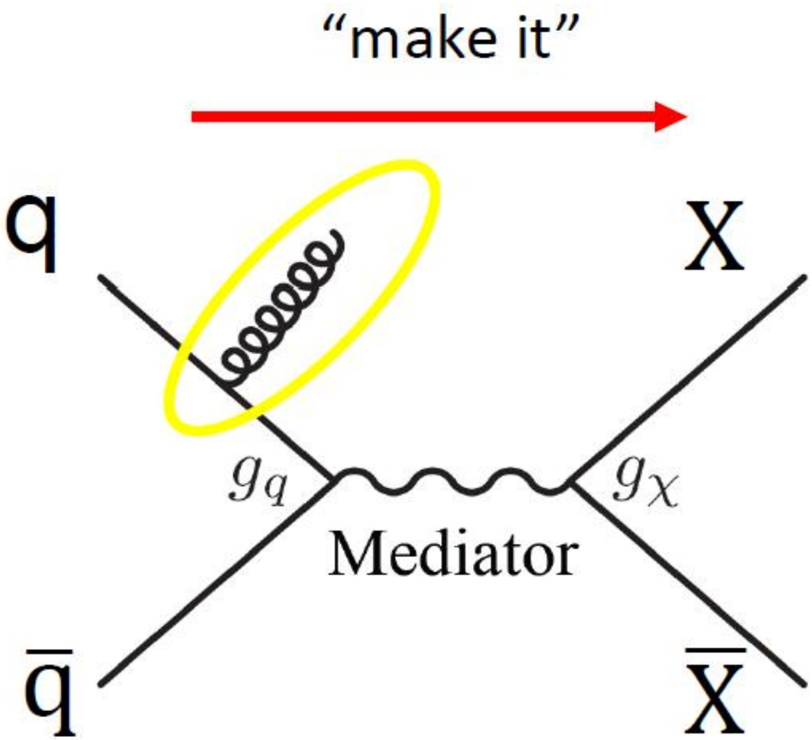
"shake it"
direct detection



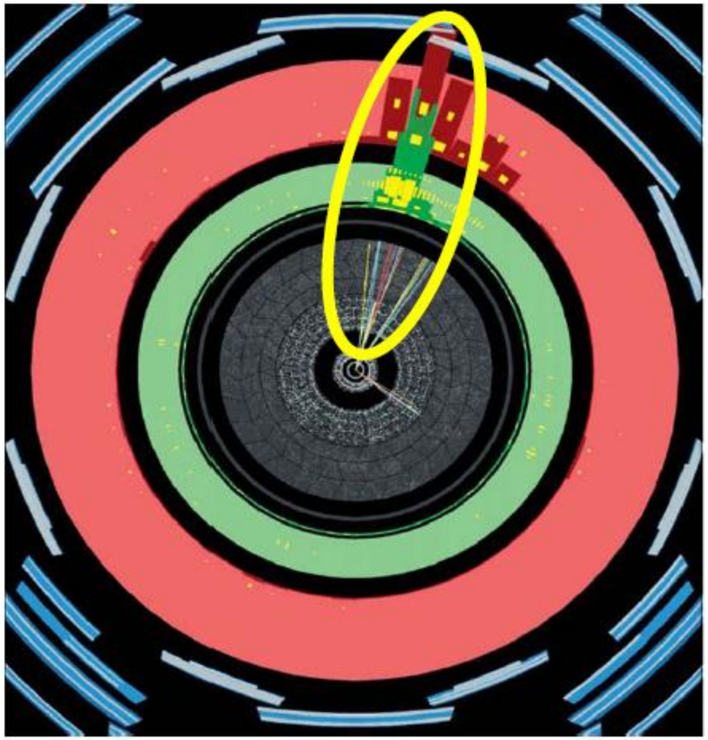
"make it": Collider Production



Dark Matter serches at Colliders

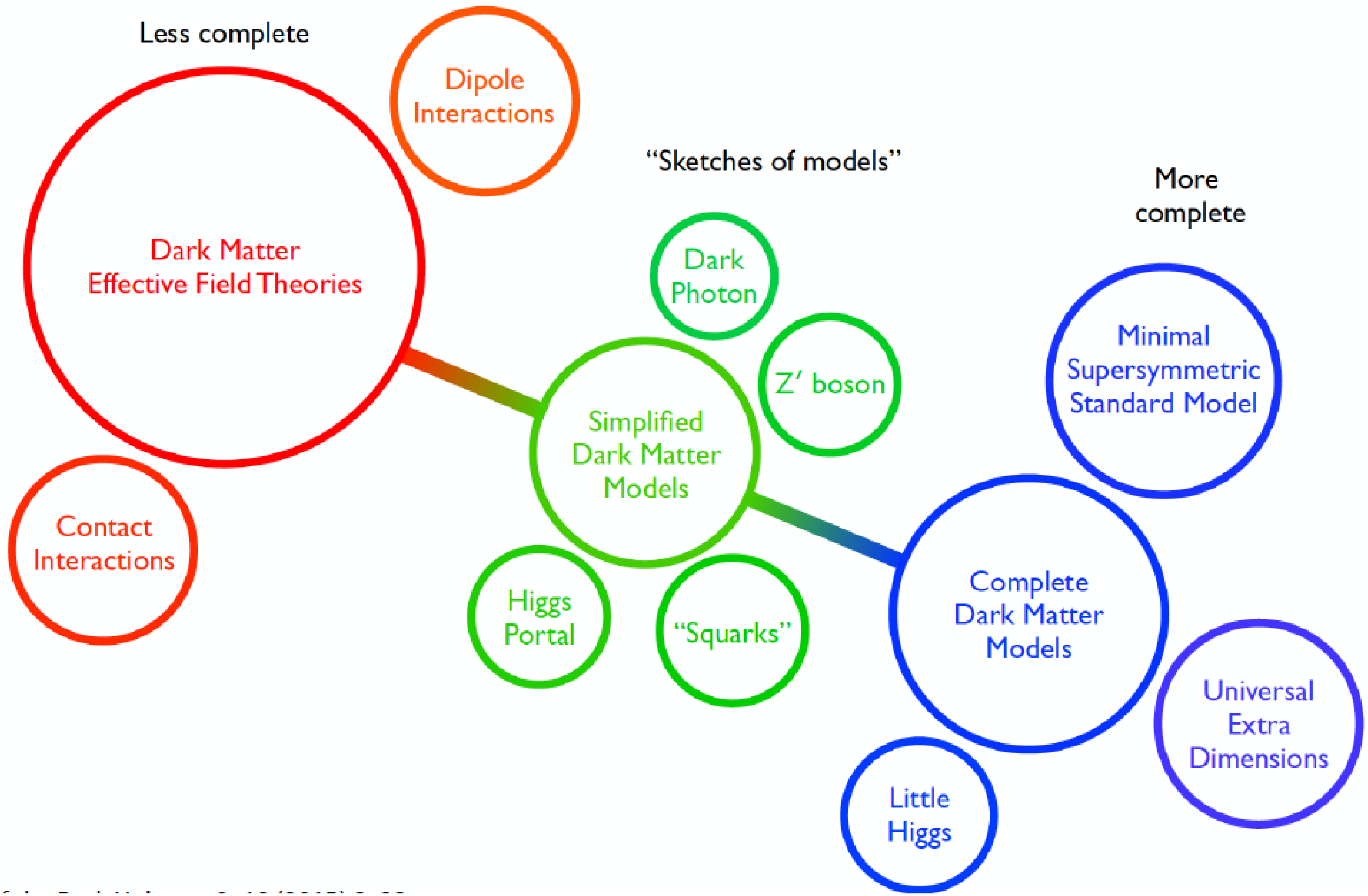


g_q and g_χ coupling strengths

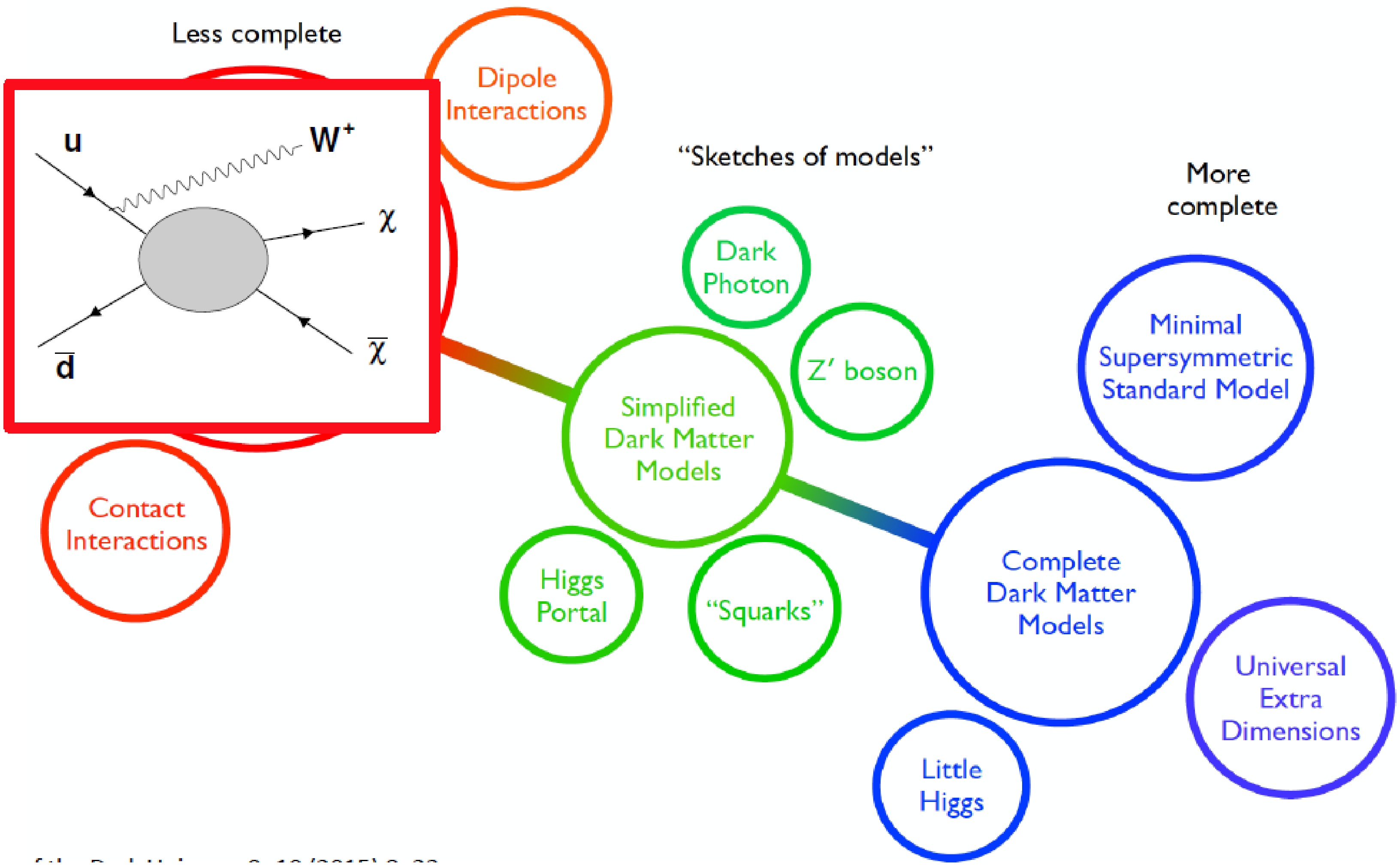


Empty detector + something

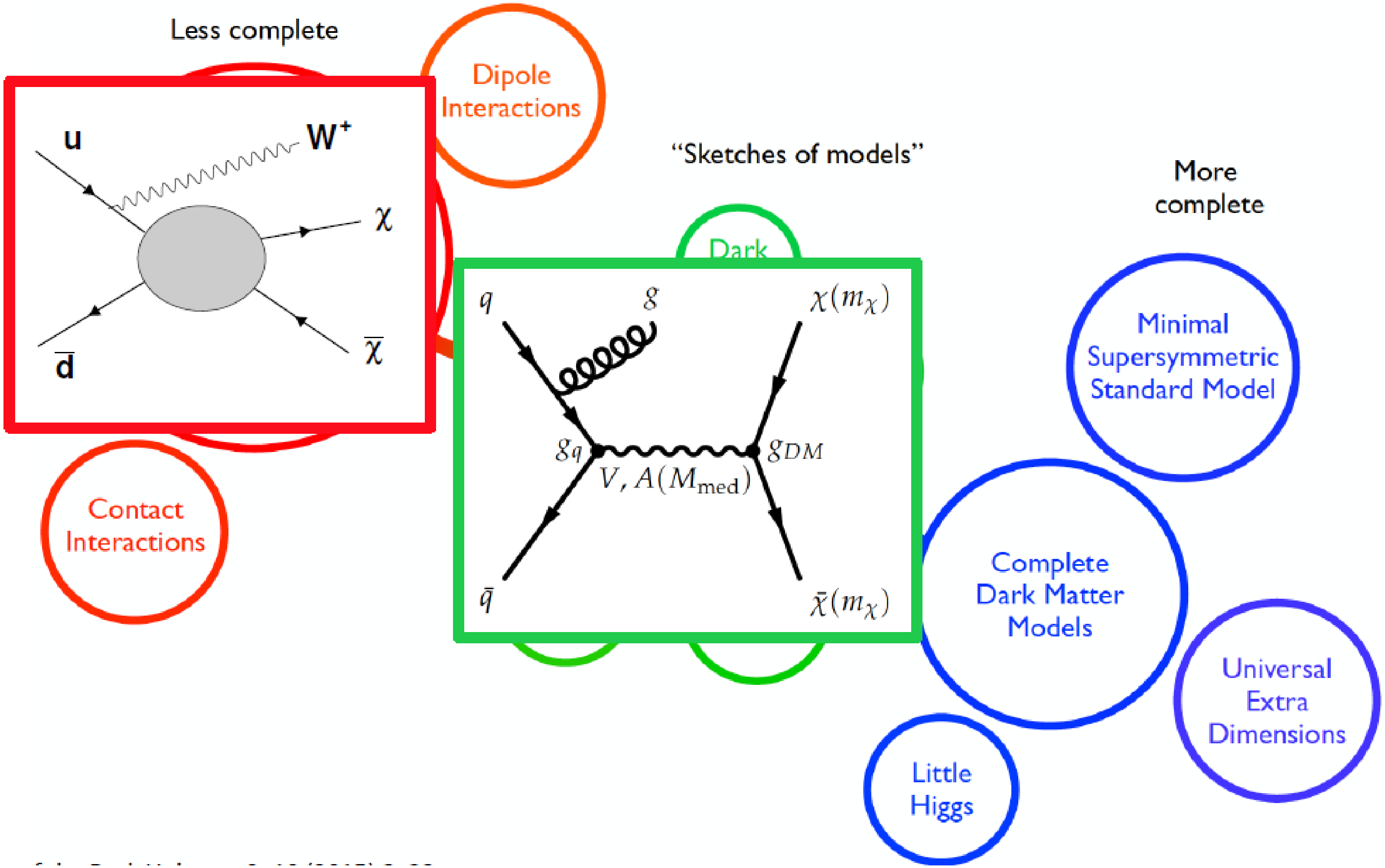
Dark Matter theory space



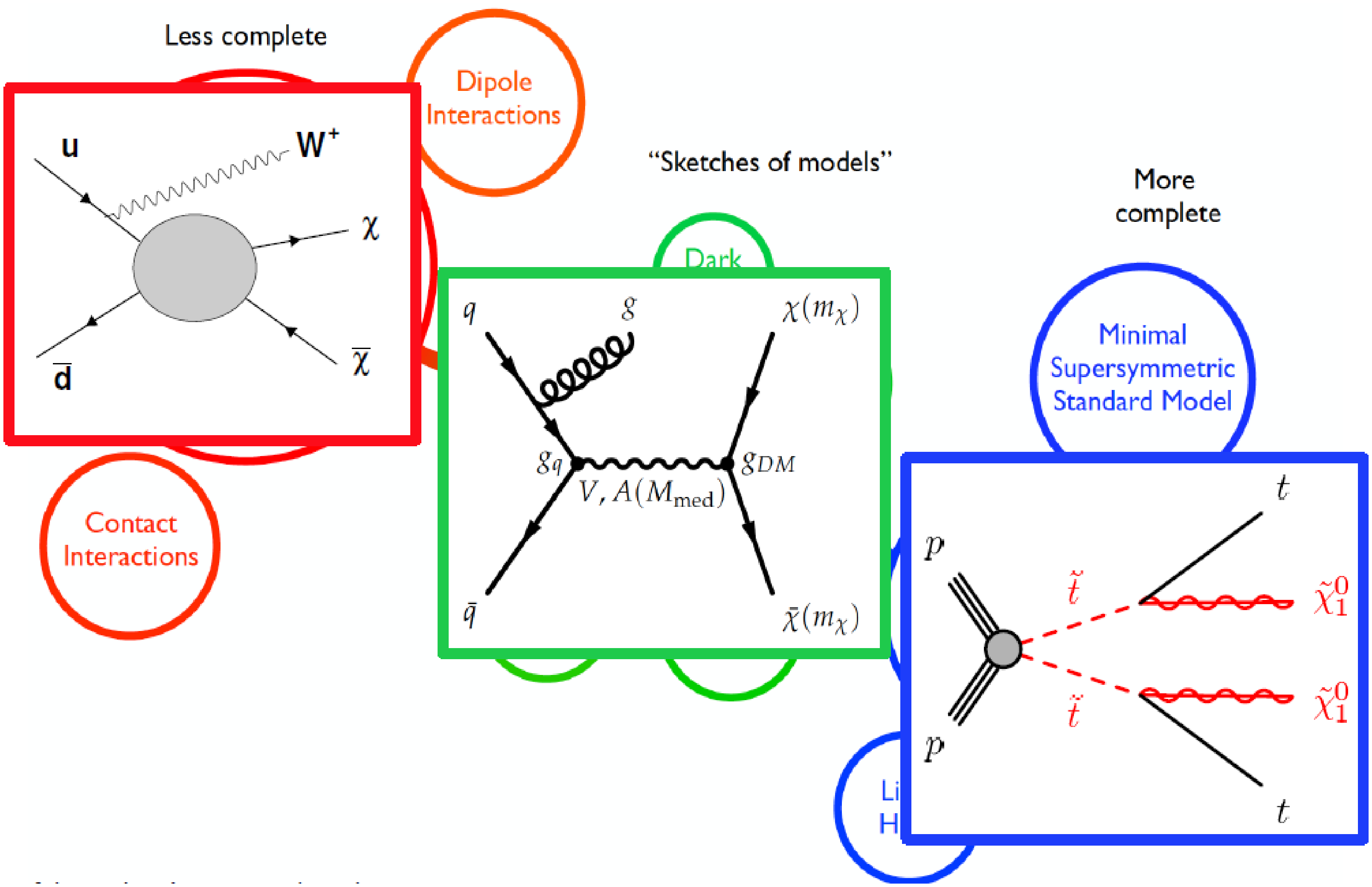
Dark Matter theory space



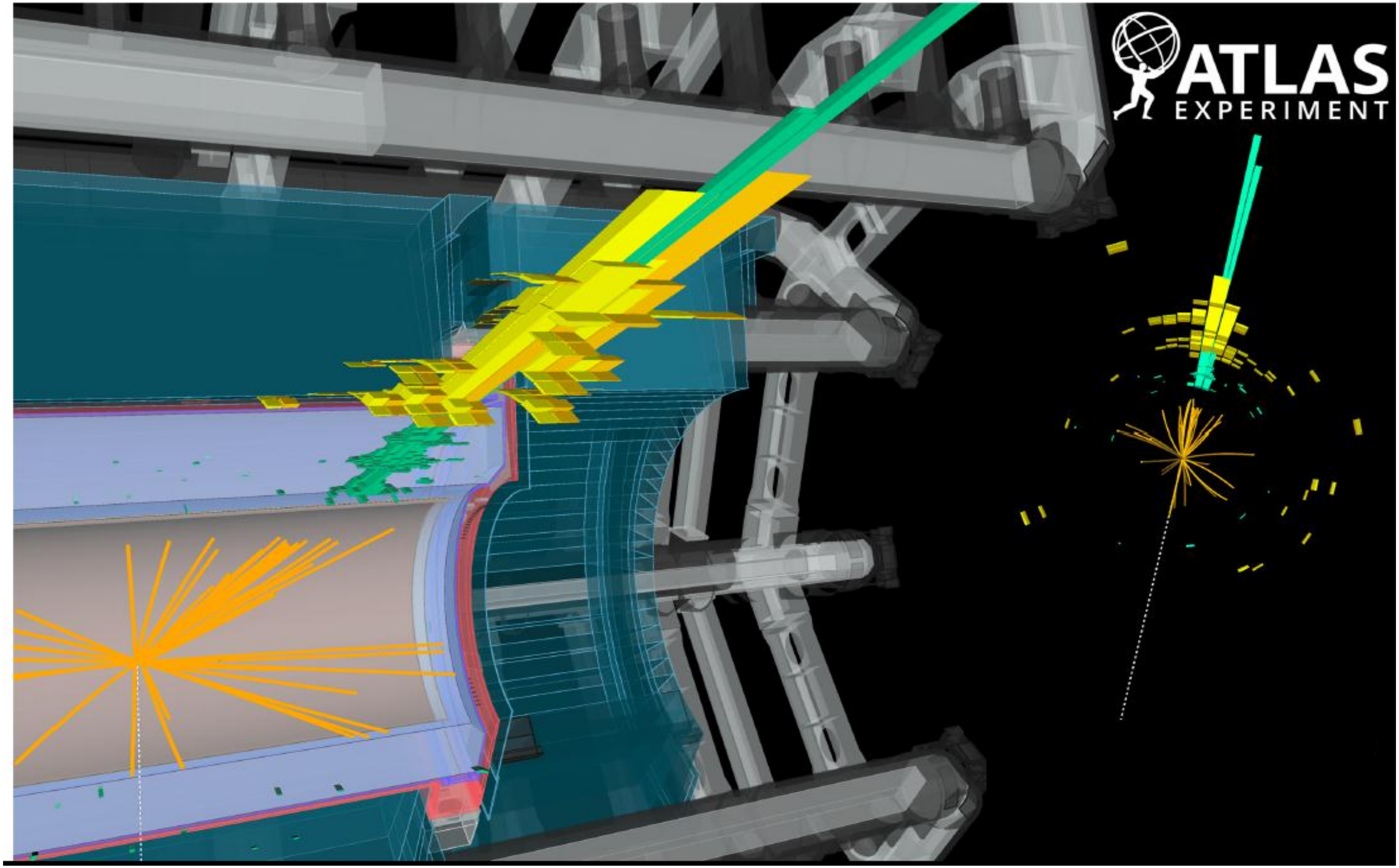
Dark Matter theory space



Dark Matter theory space

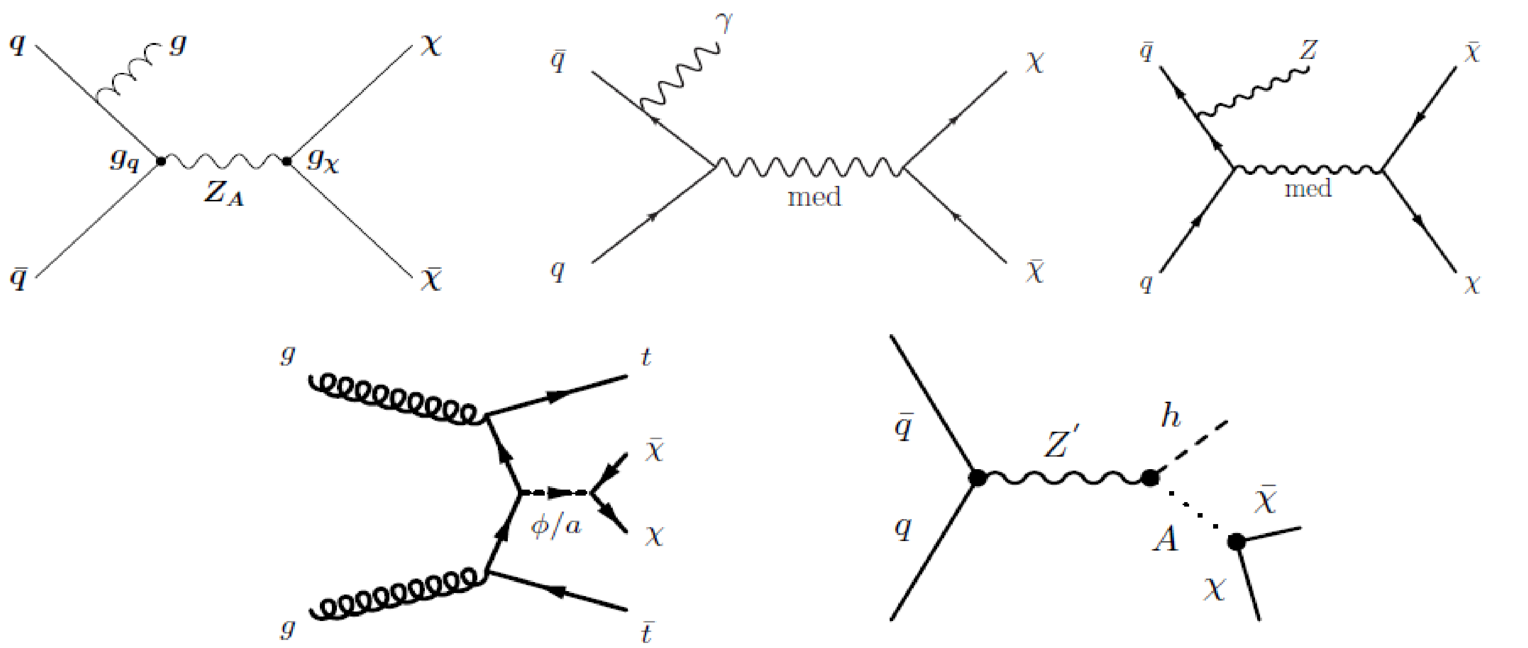


Searches for DM with (E_T^{miss} +X) Signatures



(E_T^{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 = SM particles that tag the event, $X = \text{jet}, \gamma, V, t, b, h \ldots$

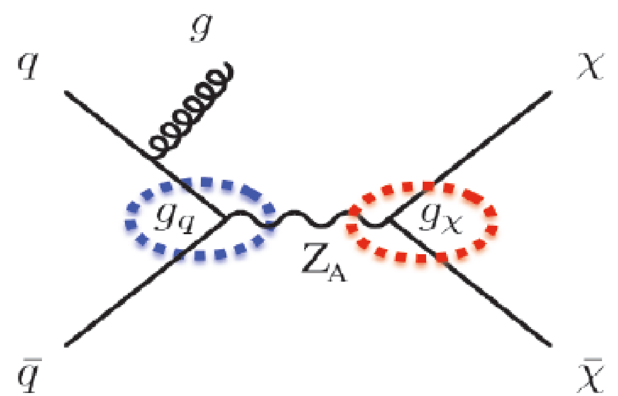


Mediators: vector, axial-vector, scalar, pseudoscalar
Parameters: $m_{\text{med}}, m_\chi, g_q, g_\chi$

Simplified Model

Simplified Model

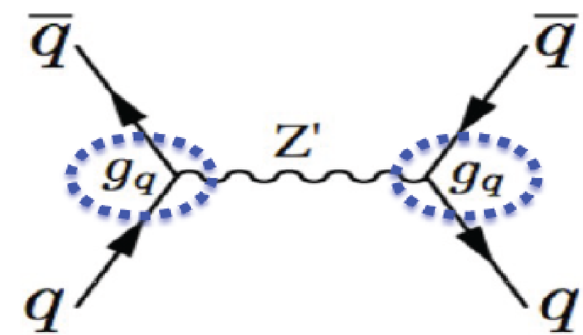
$SM \rightarrow mediator \rightarrow DM$



→Mono-X signature

E_T^{miss}+ jet, W/Z/H, γ, ...

$SM \rightarrow mediator \rightarrow SM$

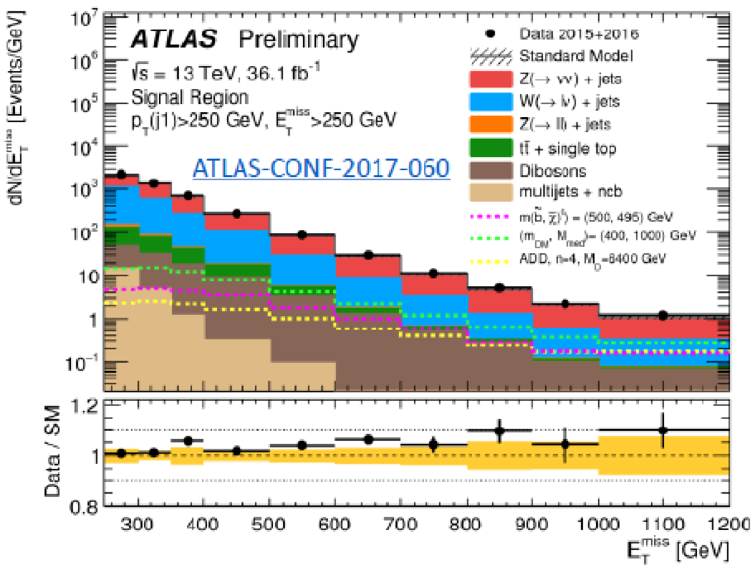


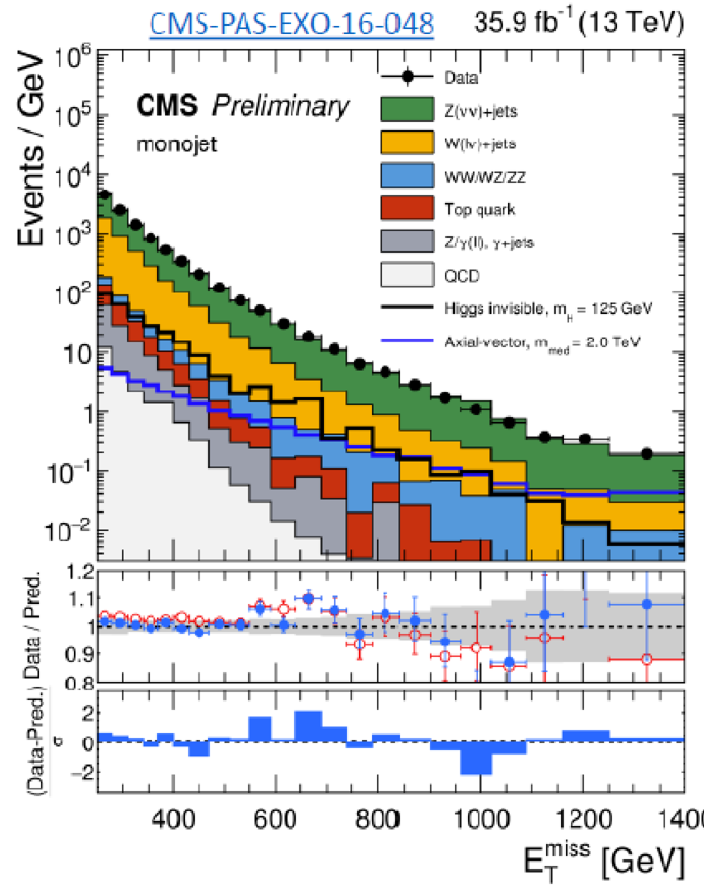
→resonant production

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	∝ mass		∝ charge	

Mono-jet





ATLAS

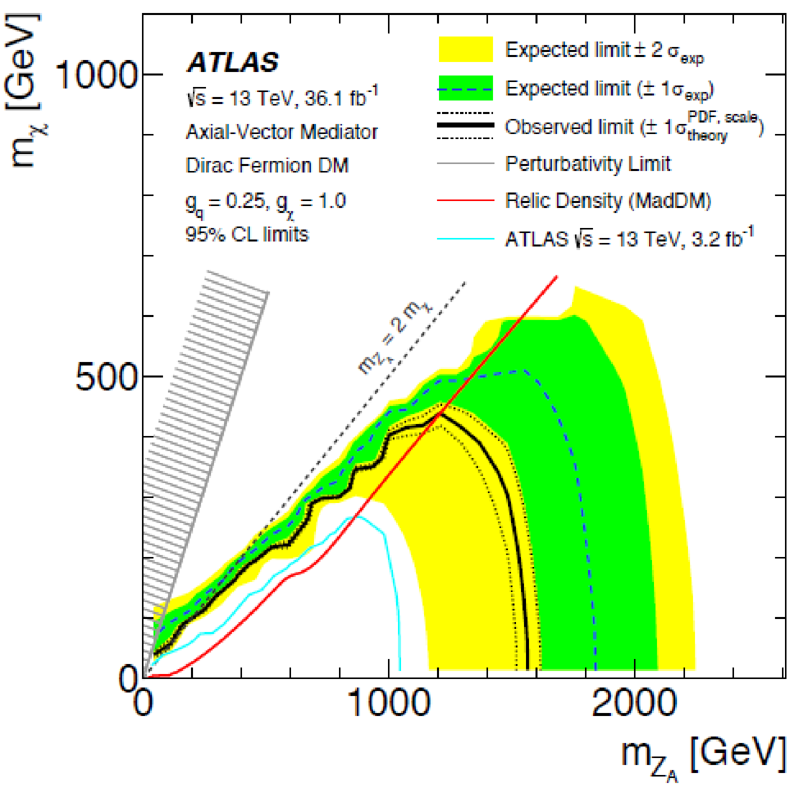
- $E_T^{miss} > 250$ GeV, $\Delta\varphi(\text{jet}, p_T^{miss}) > 0.4$
- Jet $p_T > 250$ GeV, $|\eta| < 2.4$
- $N_{jets} \leq 4$

CMS

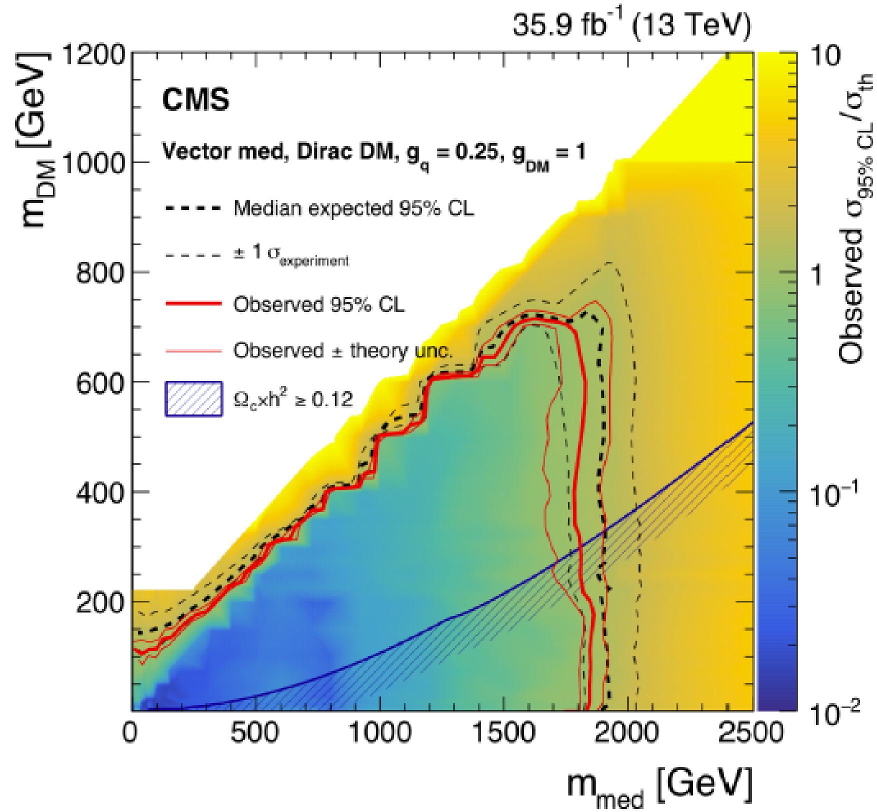
- $E_T^{miss} > 250$ GeV
- Jet $p_T > 100$ GeV, $|\eta| < 2.5$

Mono-X searches

Axial-Vector Mediator



Vector Mediator

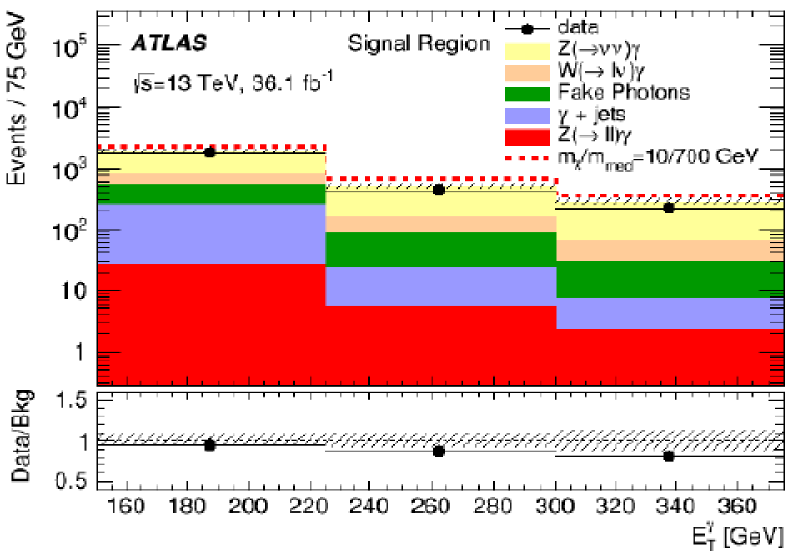


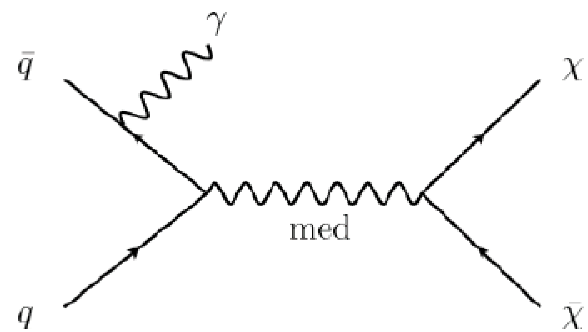
For couplings $g_q = 0.25,\ g_\chi = 1.0$, axial-vector and vector mediators excluded up to 1.8 TeV (1.55 TeV) by CMS (ATLAS) for $m_\chi \sim 1$ GeV.

JHEP 01 (2018) 126
arXiv:1712.02345

Mono-X searches

Mono-photon



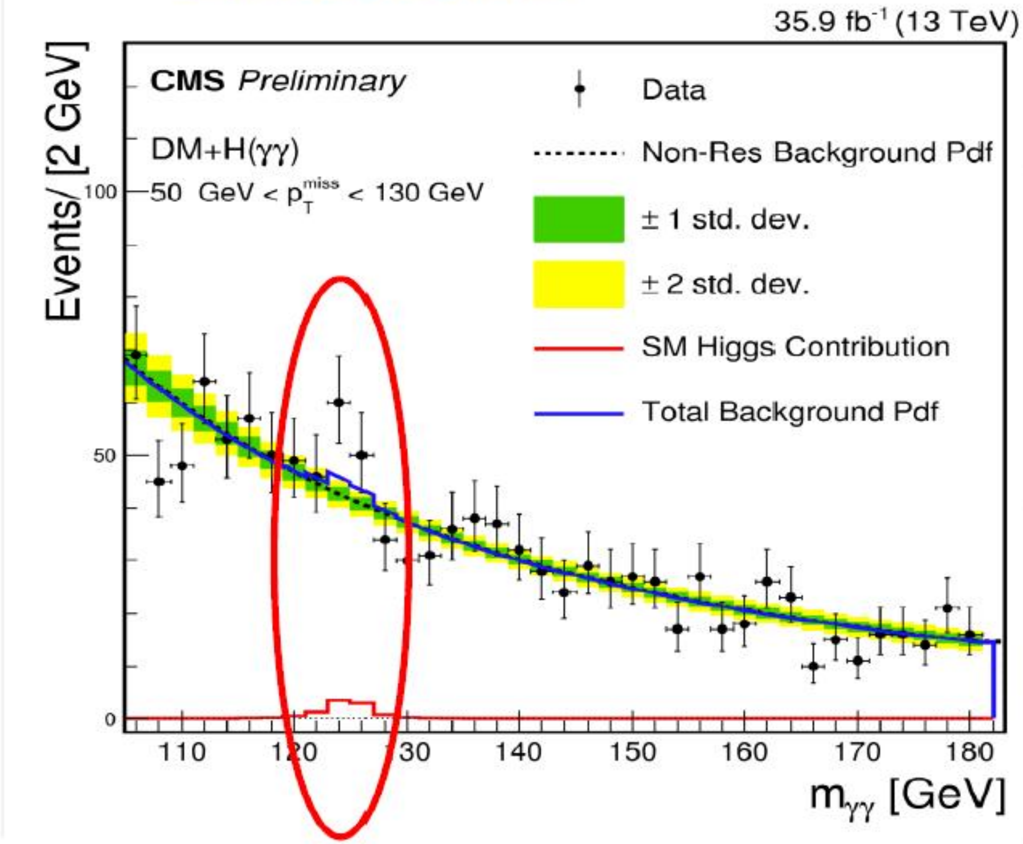


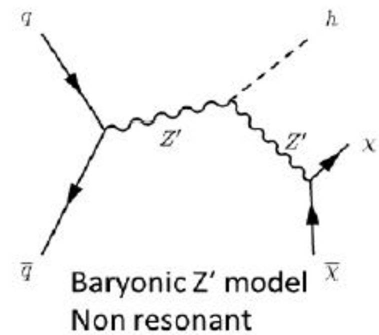
- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{miss}/\sqrt{\sum E_T} > 8.5\ \mathrm{GeV}^{1/2}$
- $\Delta\varphi(\mathrm{photon}, E_T^{miss}) > 0.4$
- $N_{jets}(p_T > 30\ \mathrm{GeV}, |\eta| < 4.5) \leq 1$

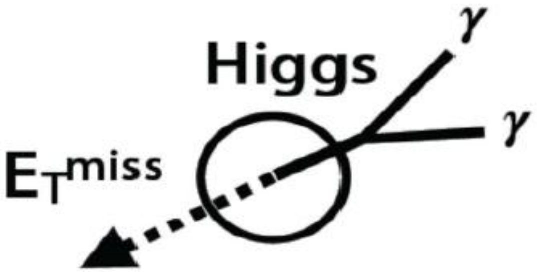
Mono-X searches

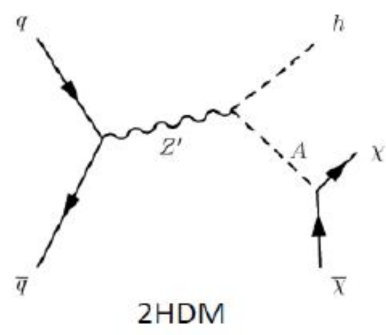
Mono-Higgs

CMS-PAS-EXO-16-054

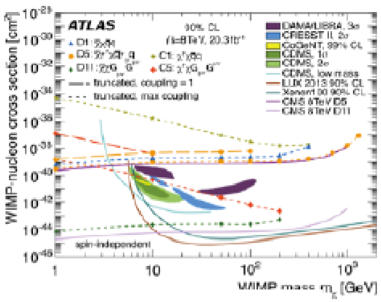




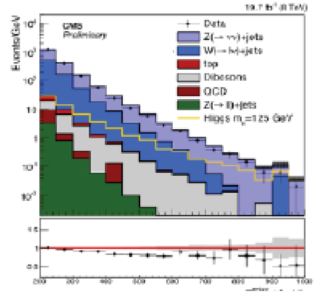




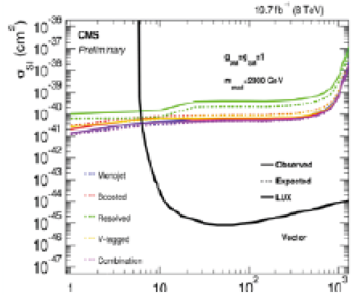
Plenty of mono-signatures



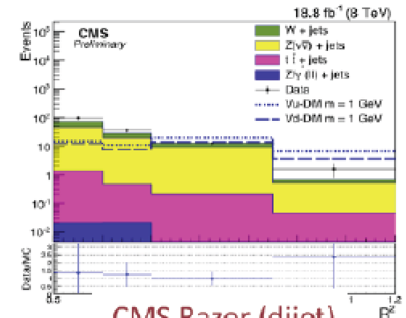
ATLAS Monojet
EPJC (2015) 75:299



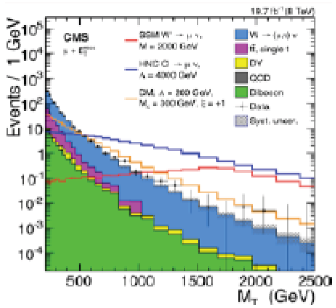
CMS j/V (mono/dijet)
PAS-EXO-12-055



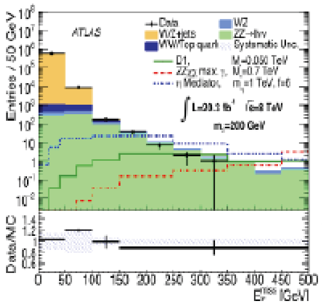
CMS j/V (mono/dijet)
PAS-EXO-12-055



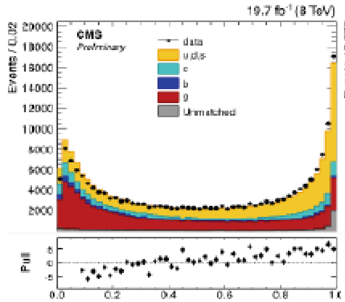
CMS Razor (dijet)
PAS-EXO-14-004



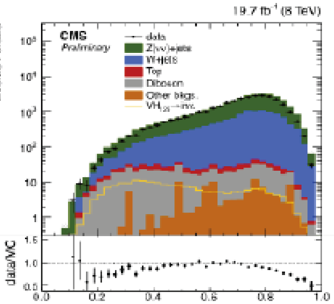
CMS, ATLAS MonoW
PRD 91, 092005, JHEP 09 (2014) 037 (2015)



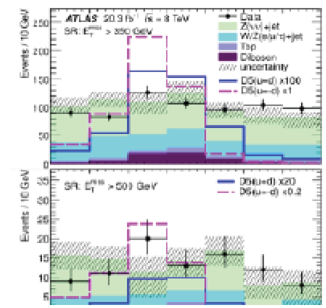
CMS, ATLAS MonoZ
EXO-12-054, PRD 90, 012004 (2014)



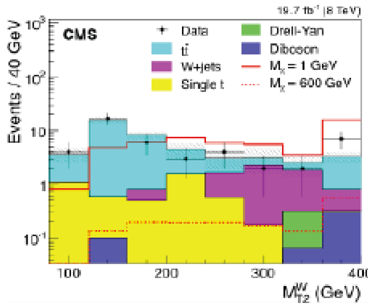
CMS MonoV (resolved)
PAS-EXO-12-005, PAS-JME-14-002



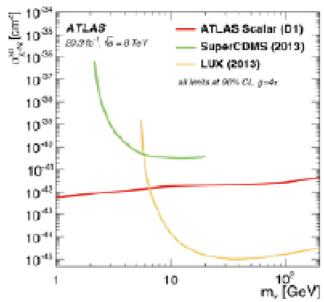
CMS MonoV (boosted)
EXO-12-005/JME-14-002



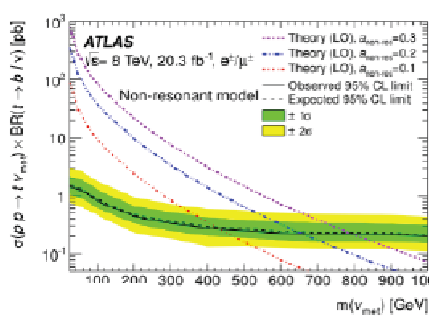
ATLAS MonoV (boosted)
ATLAS, PRL 112, 041802 (2014)



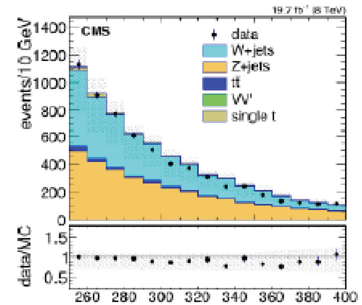
CMS TopPairs
CMS, JHEP 06 (2015) 121



ATLAS TopPairs
ATLAS, EPJC (2015) 75:92

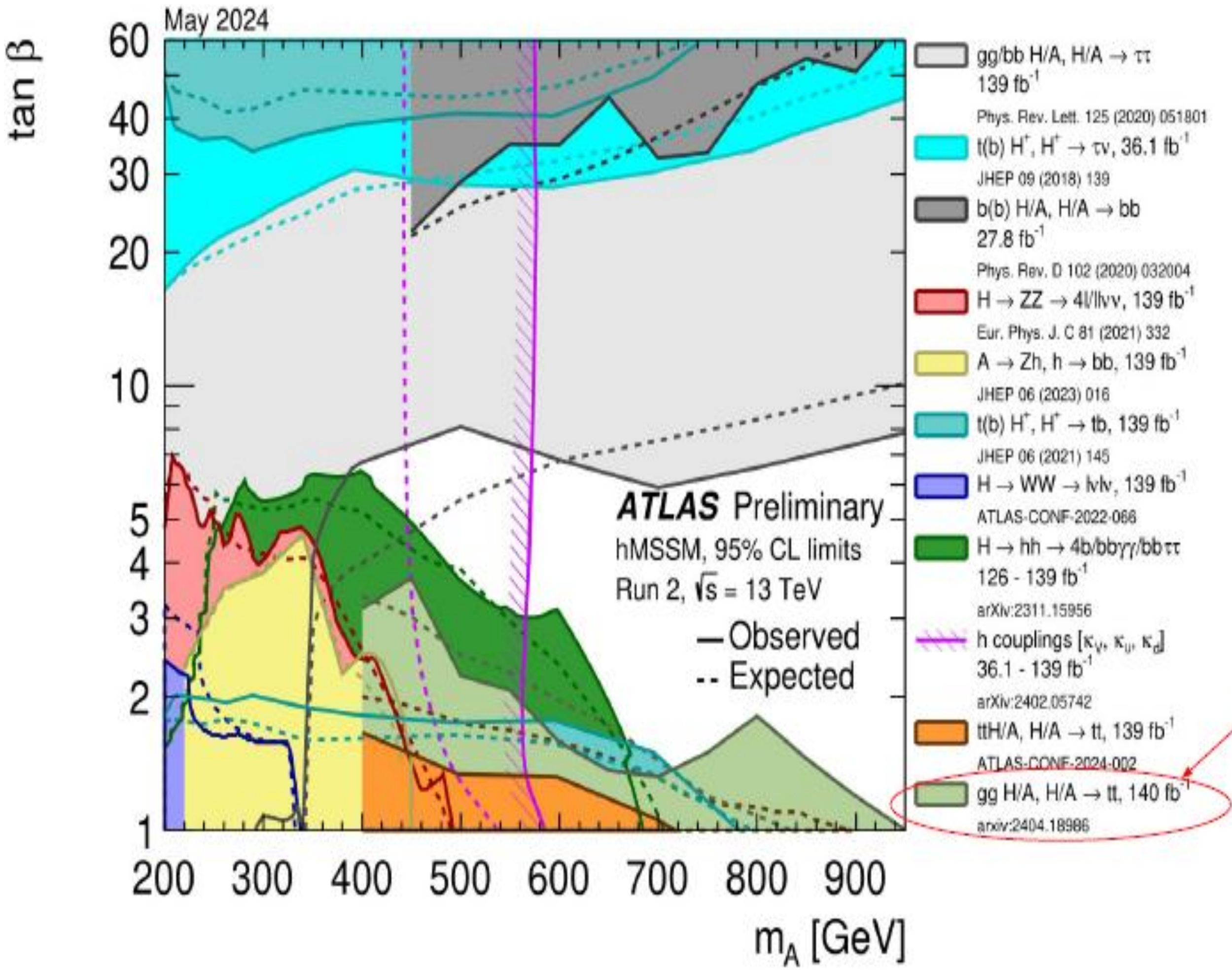


CMS MonoTop
CMS, PRL 114 (2015) 101801



ATLAS MonoTop
ATLAS, JHEP 11 (2014) 118

Heavy Higgs summary plot

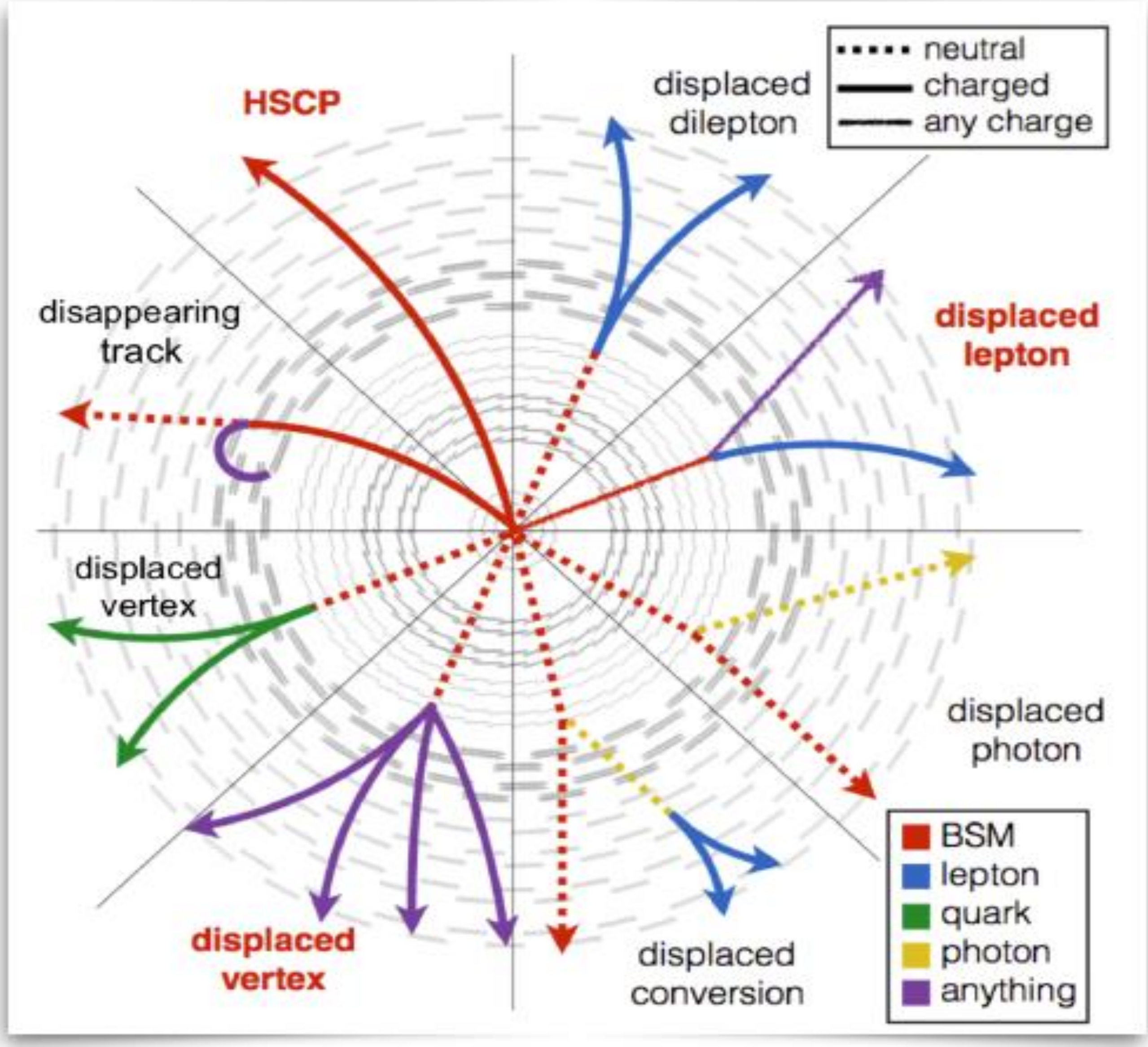


Excluded regions of $[m_A, \tan\beta]$ plane excluded in the hMSSM via direct searches for heavy Higgs bosons

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

ATL-COM-PHYS-2024-195

Unconventional signatures

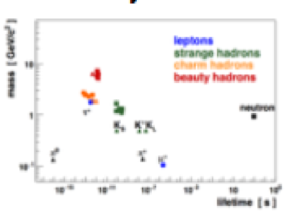


Unconventional signatures: challenges

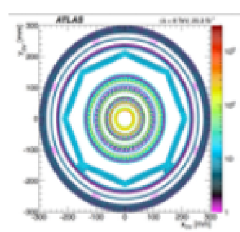
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger 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

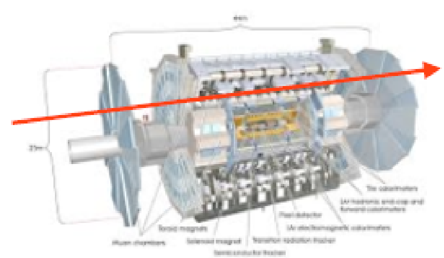
weak decays of heavy flavour



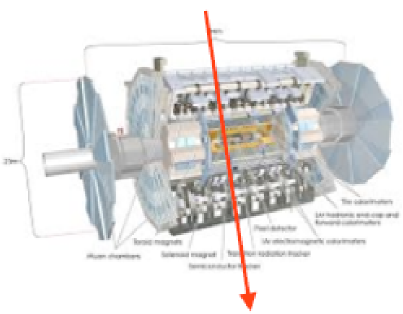
material interactions



beam halo muons



cosmic muons



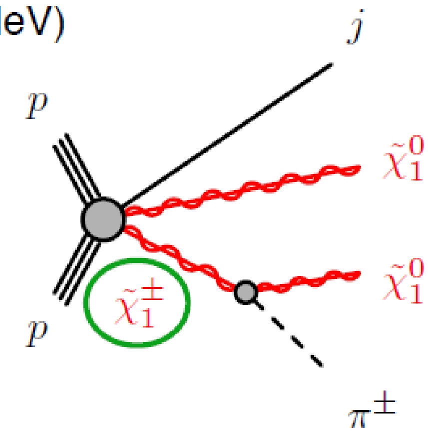
- Systematic uncertainties: can't use standard recommendations for object reconstruction nor trigger

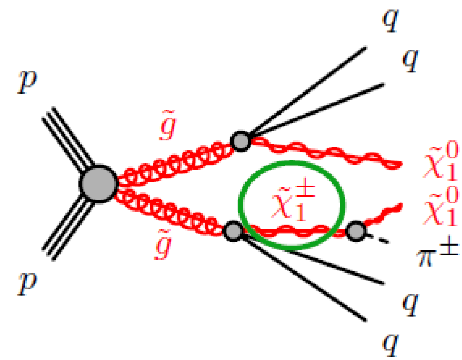
Unconventional signatures: disapearing tracks

LLP

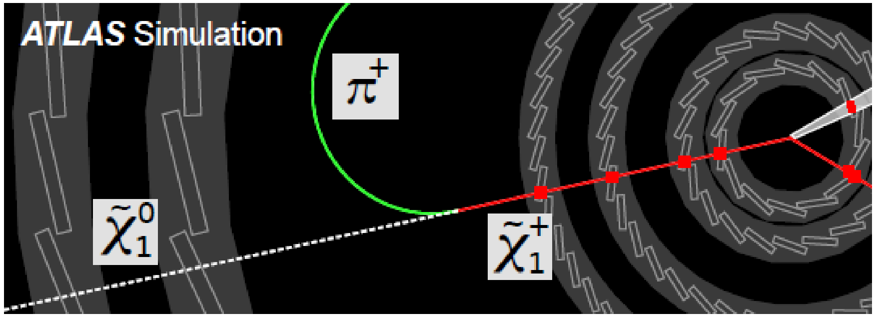
- Search for disappearing track + MET + jets
- Signature: Chargino track "disappears" when it decays, into MET
  - Low momentum pion track (~0.1 GeV) is hard to reconstruct
  - Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks

- Benchmark model: AMSB model with almost degenerate neutralino and chargino $\Delta m \sim O(100\ \text{MeV})$

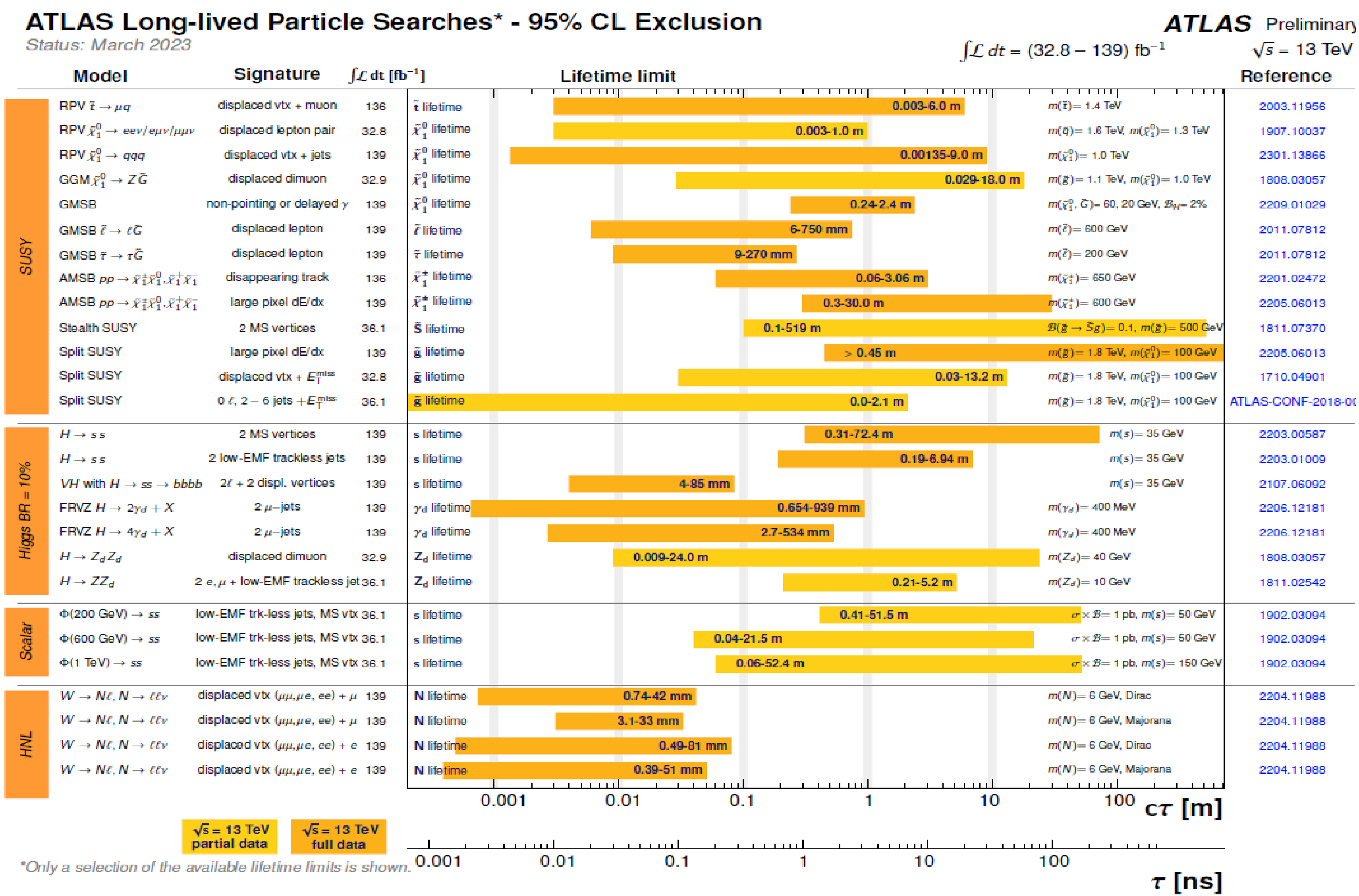




- Search sensitive to LLP lifetime of 10ps to 10 ns



Long -lived particle searches : March 2023



HL-LHC is coming and it's huge