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

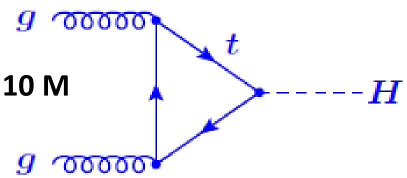
Discovery of the Higgs boson

- Measurements: mass, spin, couplings

The Higgs Boson at the LHC

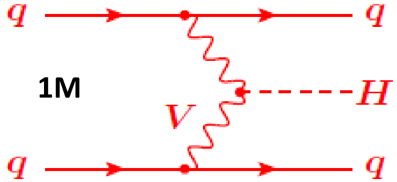
#Higgs produced at 13 TeV (2015-2017)

Production



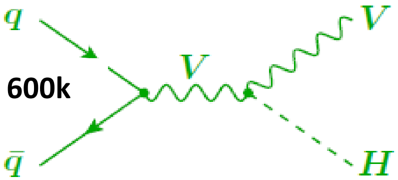
10 M

Main production channel



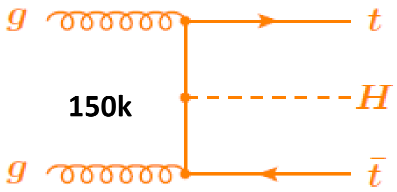
1M

2 forward jets, little central hadronic activity



600k

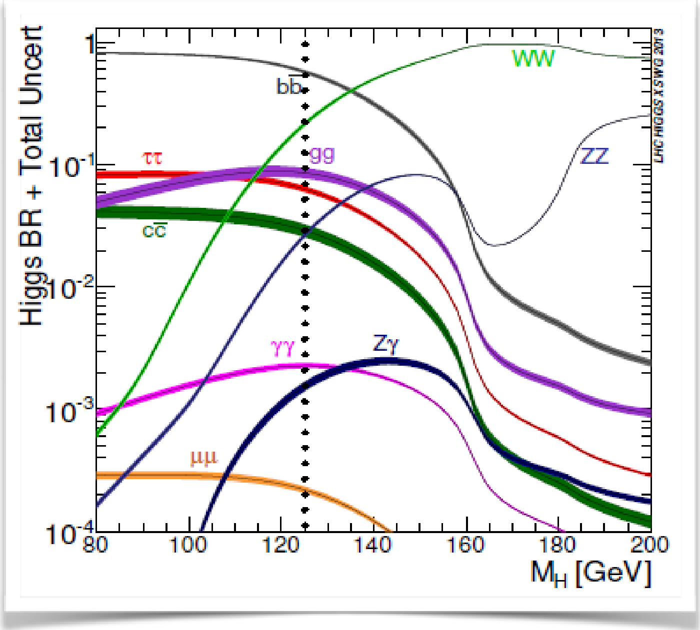
Tag W and Z decays



150k

Tag 2 top quarks

Decays



5 main channels at the LHC

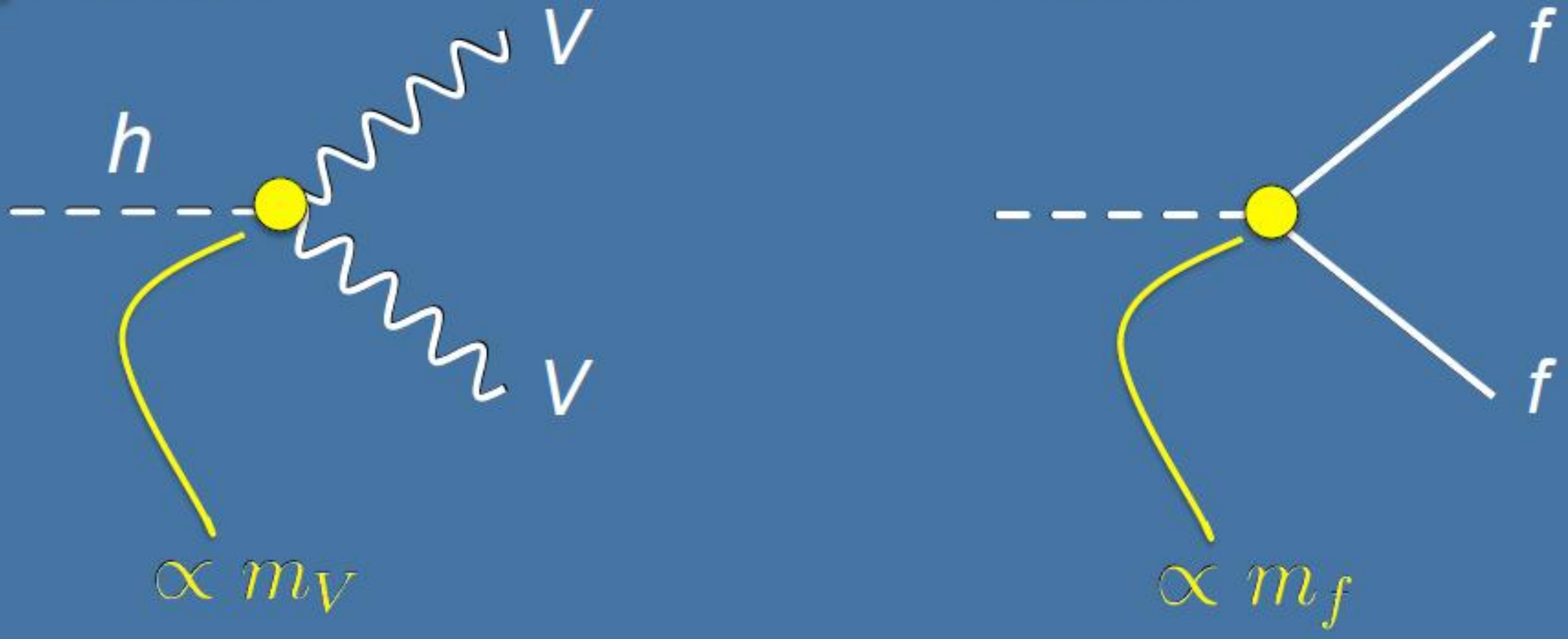
Decay branching fractions for m_H = 125 GeV

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

Higgs boson couplings

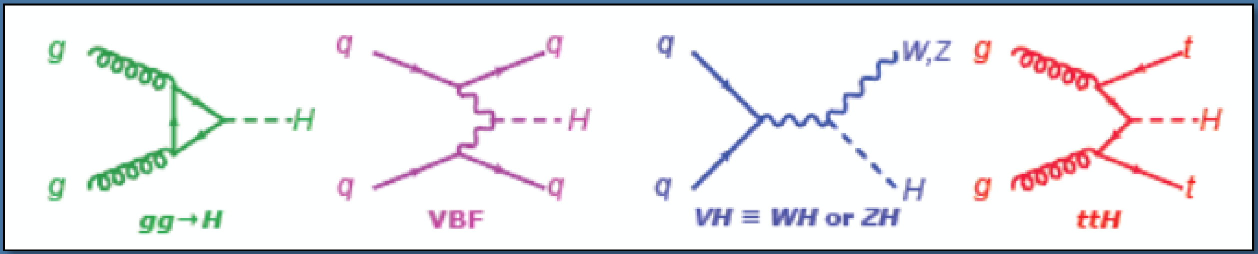
Gauge bosons

Fermions



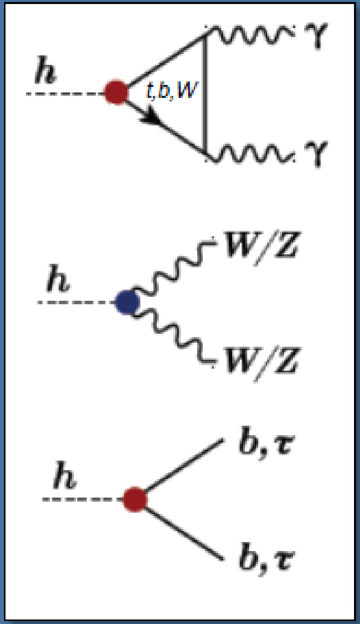
Higgs boson properties are fixed in the Standard Model (m_h)

Higgs boson phenomenology



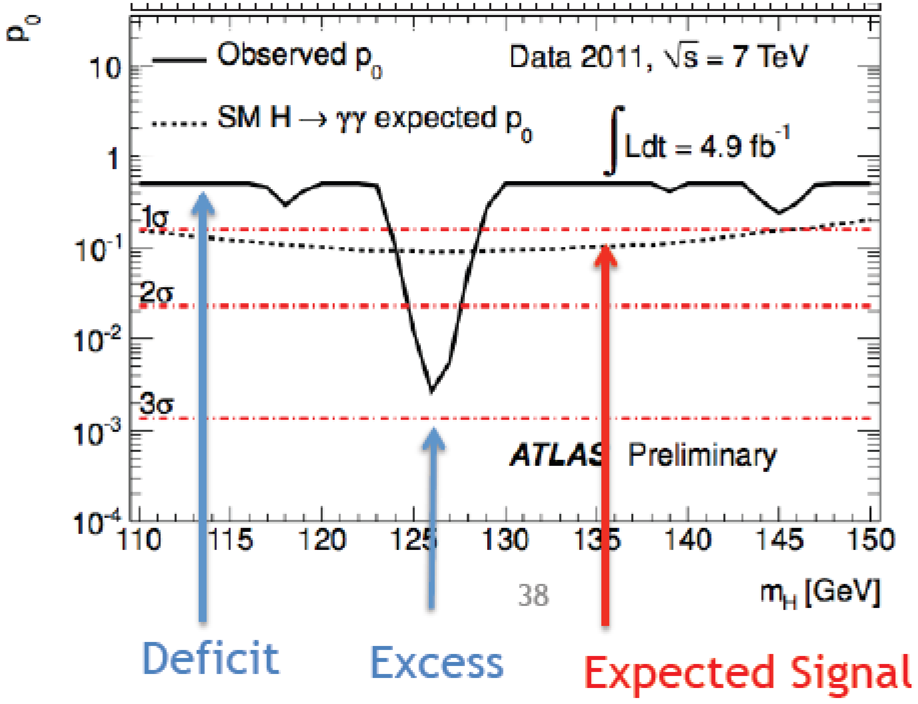
‘production & decay matrix’

sensitivity to different Higgs properties

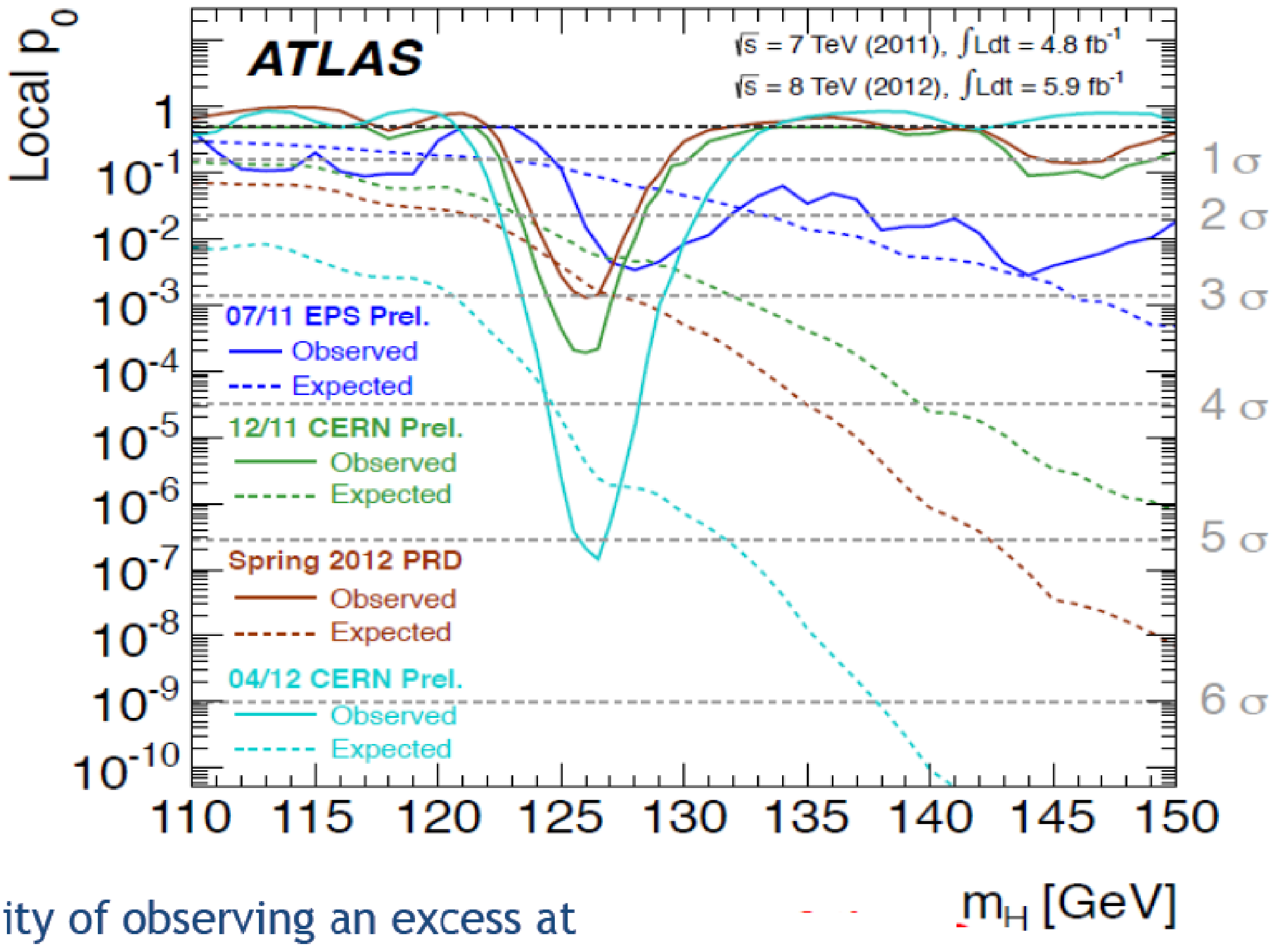


Local p_0

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.



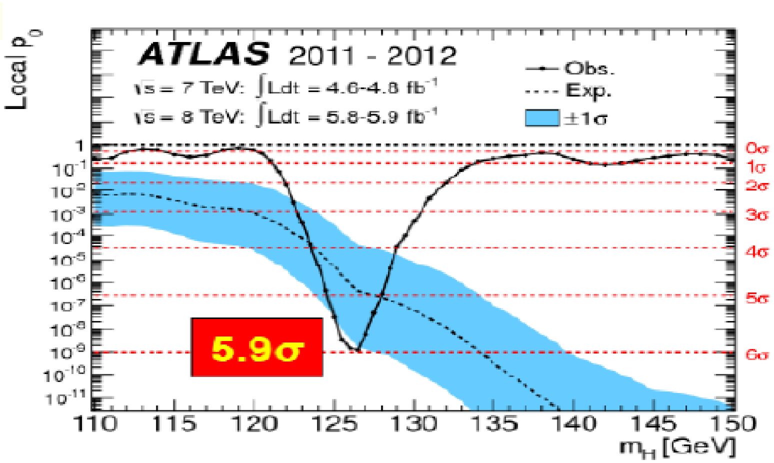
Birth of a particle



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

Higgs-like particle – 4 July 2012

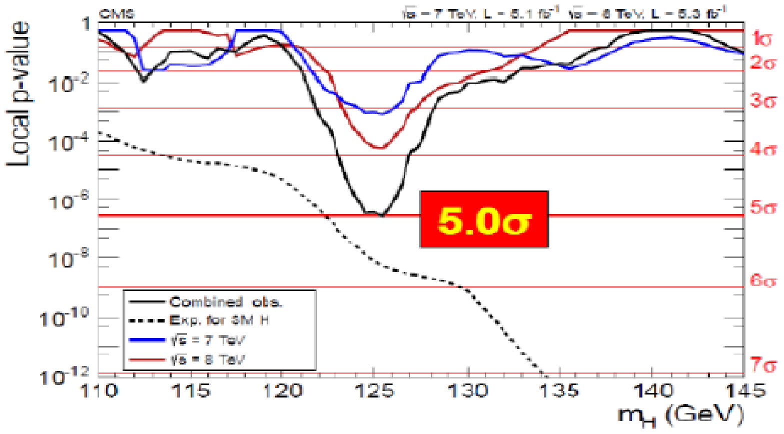
- We are living in a privileged moment in the history of High Energy Physics: **first fundamental scalar**
- The discovery came at half of the design energy, much more severe pile-up and one-third of integrated luminosity than was originally judged as



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)



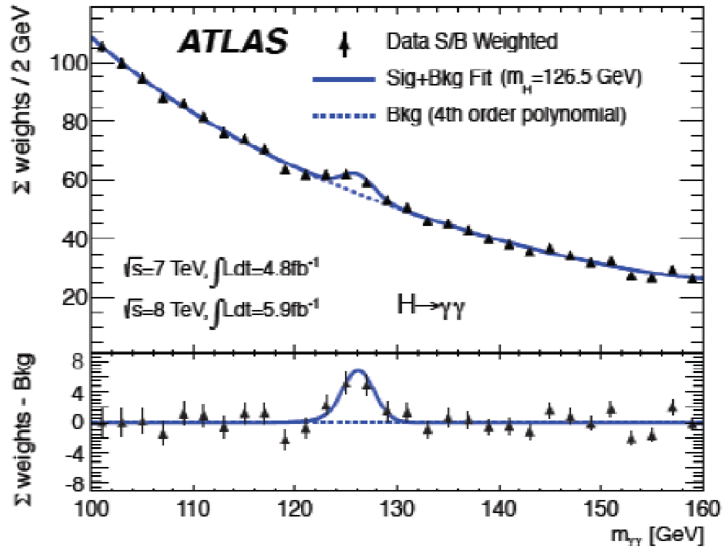
CMS PLB 716 (2012) 30-61, *Sept 17 (2012)*

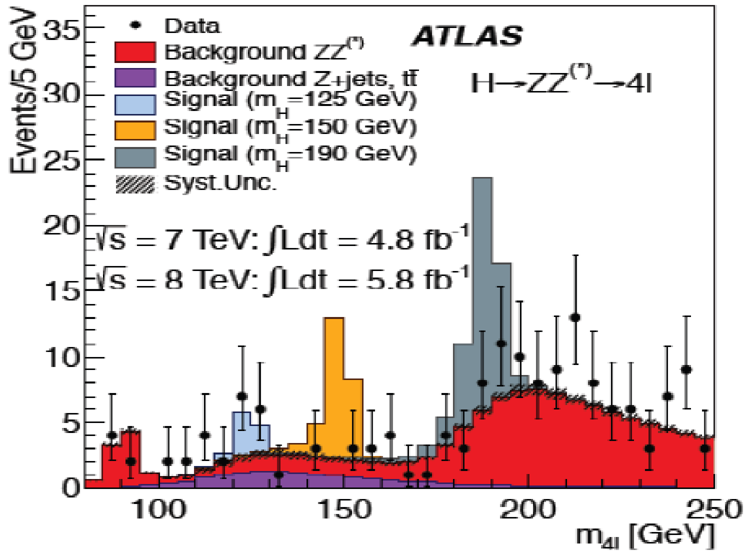
Largest local excess:
5.0σ at m_H= 125.5 GeV

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

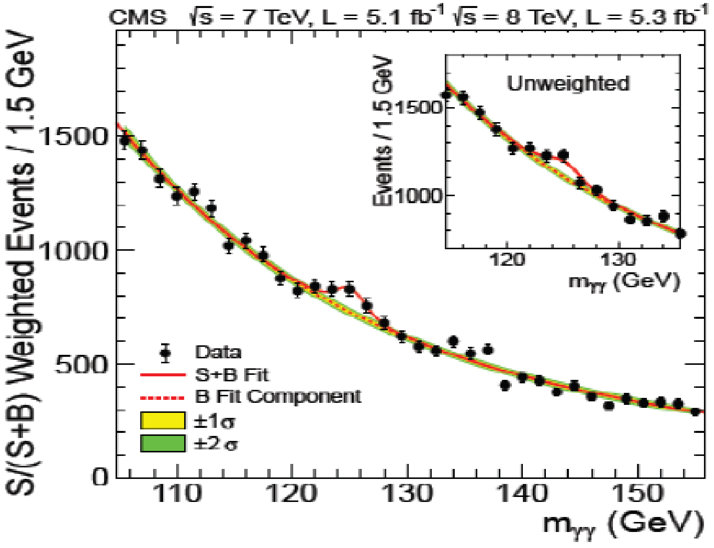
Higgs-like particle – 4 July 2012

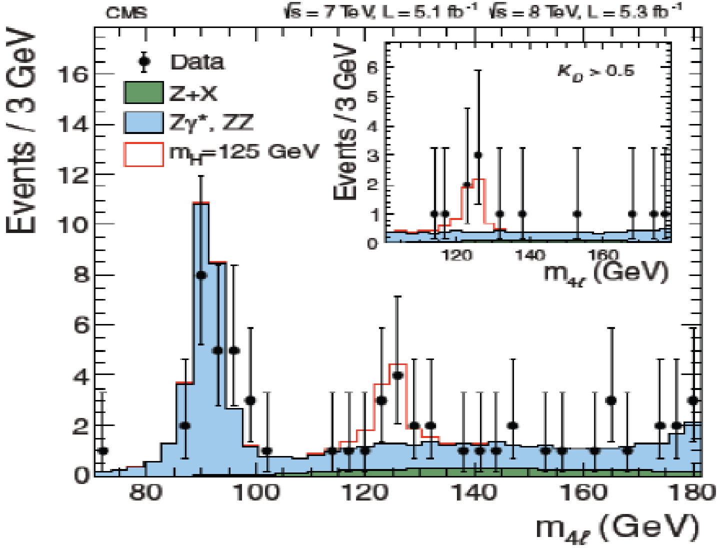
Phys.Lett. B716 (2012) 1-29



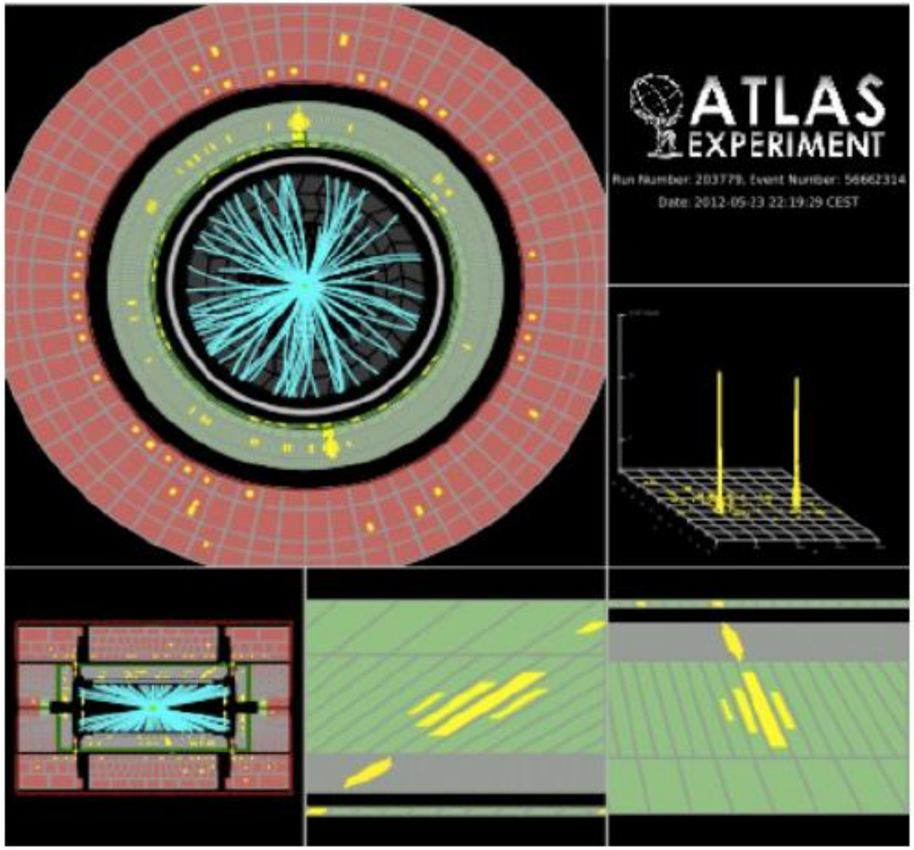


Phys.Lett. B716 (2012) 30-61





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

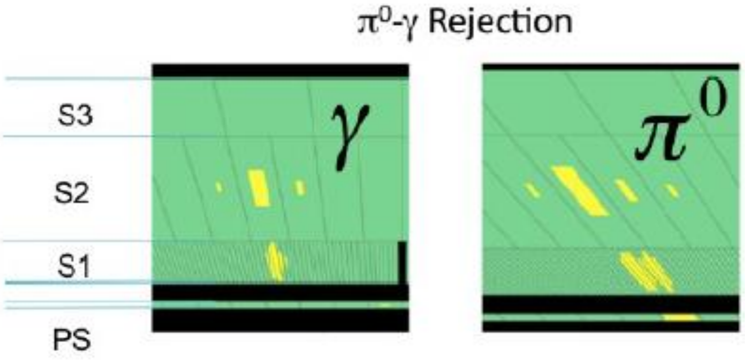
☐ Good energy calibration

☐ 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



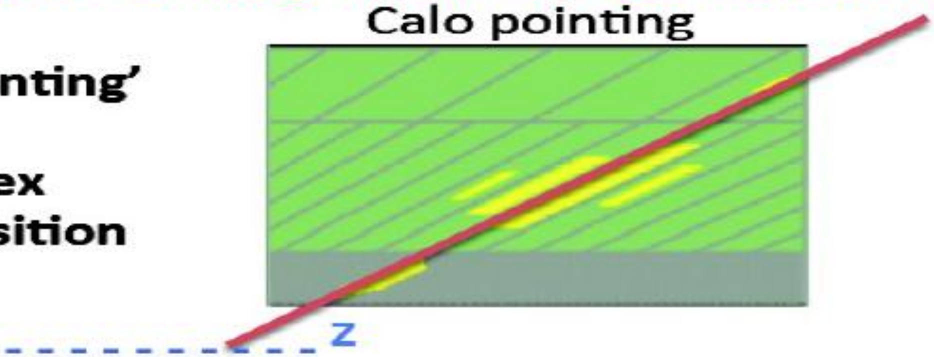
- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

Vertex Reconstruction

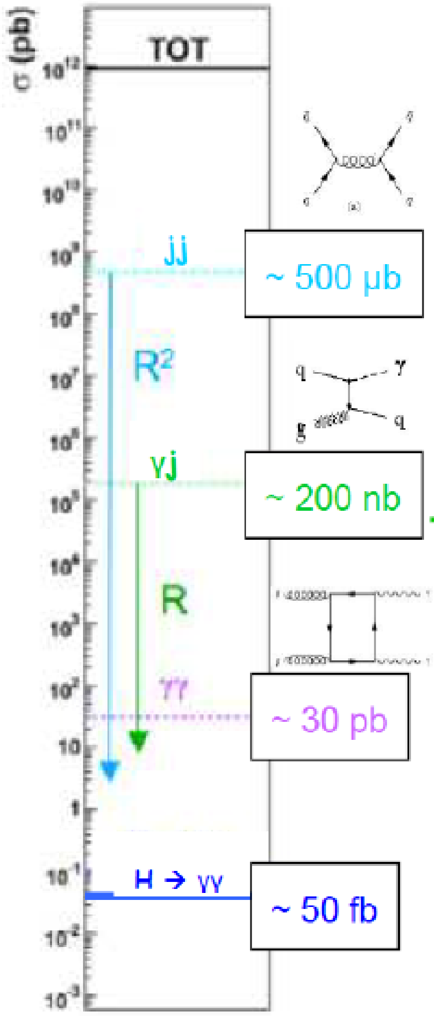
$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$$

☐ Vertex reconstructed through likelihood combination

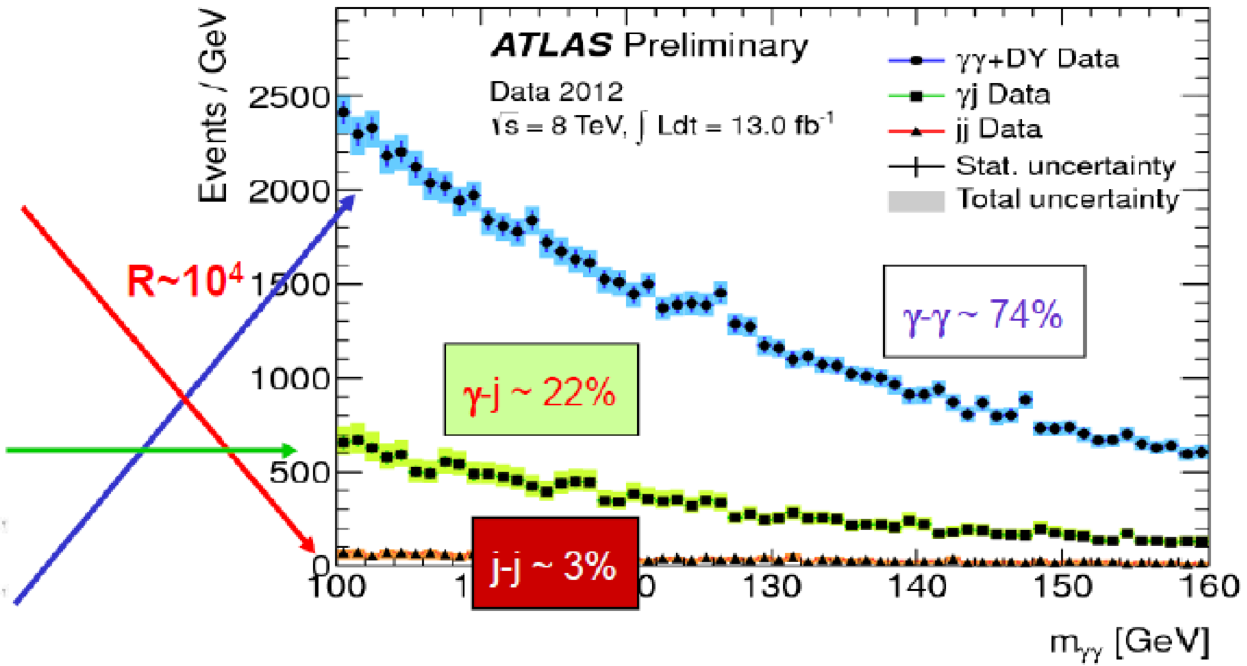
- Calorimeter ‘pointing’
- Σ tracks pT^2
- Conversion vertex
- Mean vertex position



H->γγ: background rejection



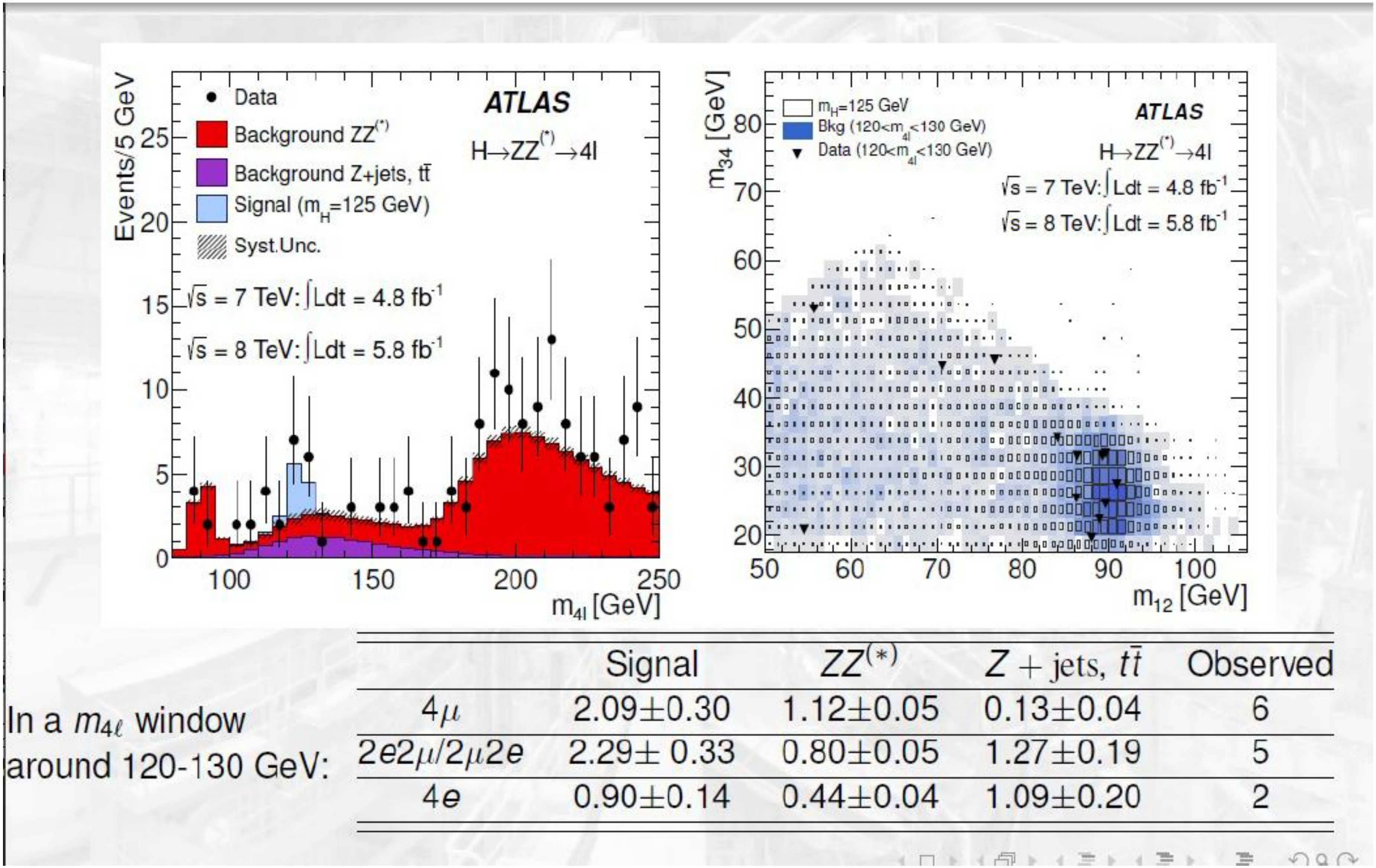
Data-driven background decomposition



➔ 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%)

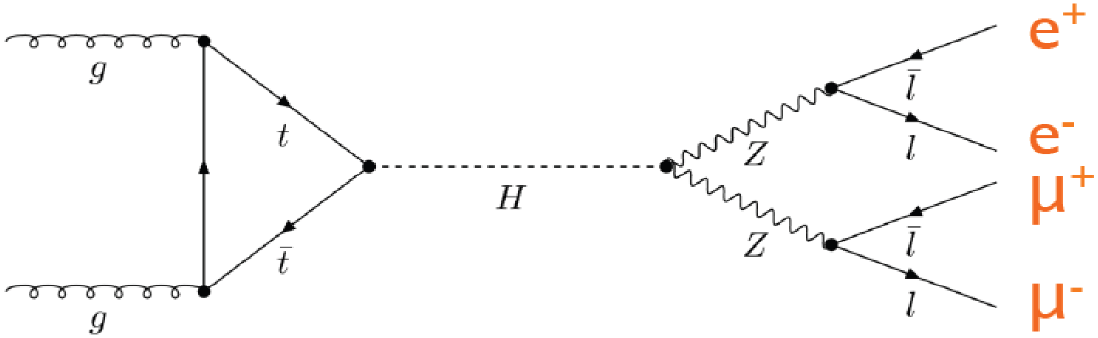
The golden channel: H->ZZ, Z->ll



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

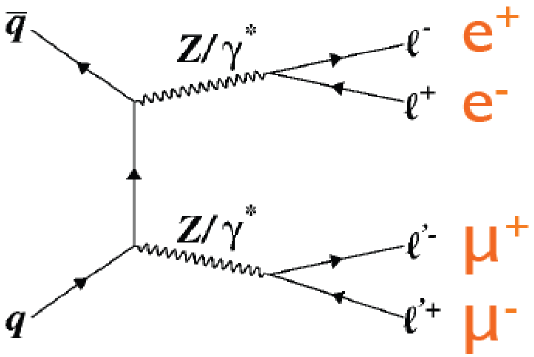
	Signal	$ZZ^{(*)}$	$Z+\text{jets}, t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

Signal and background



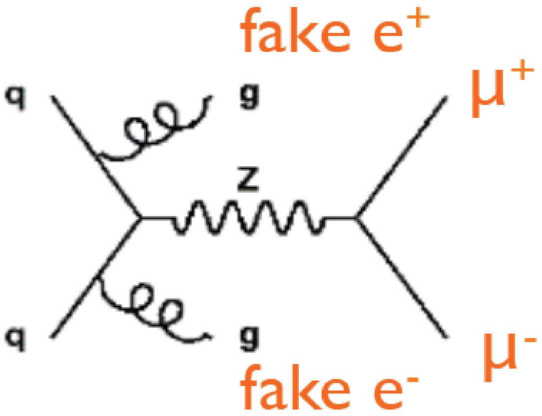
Irreducible background

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



Reducible background

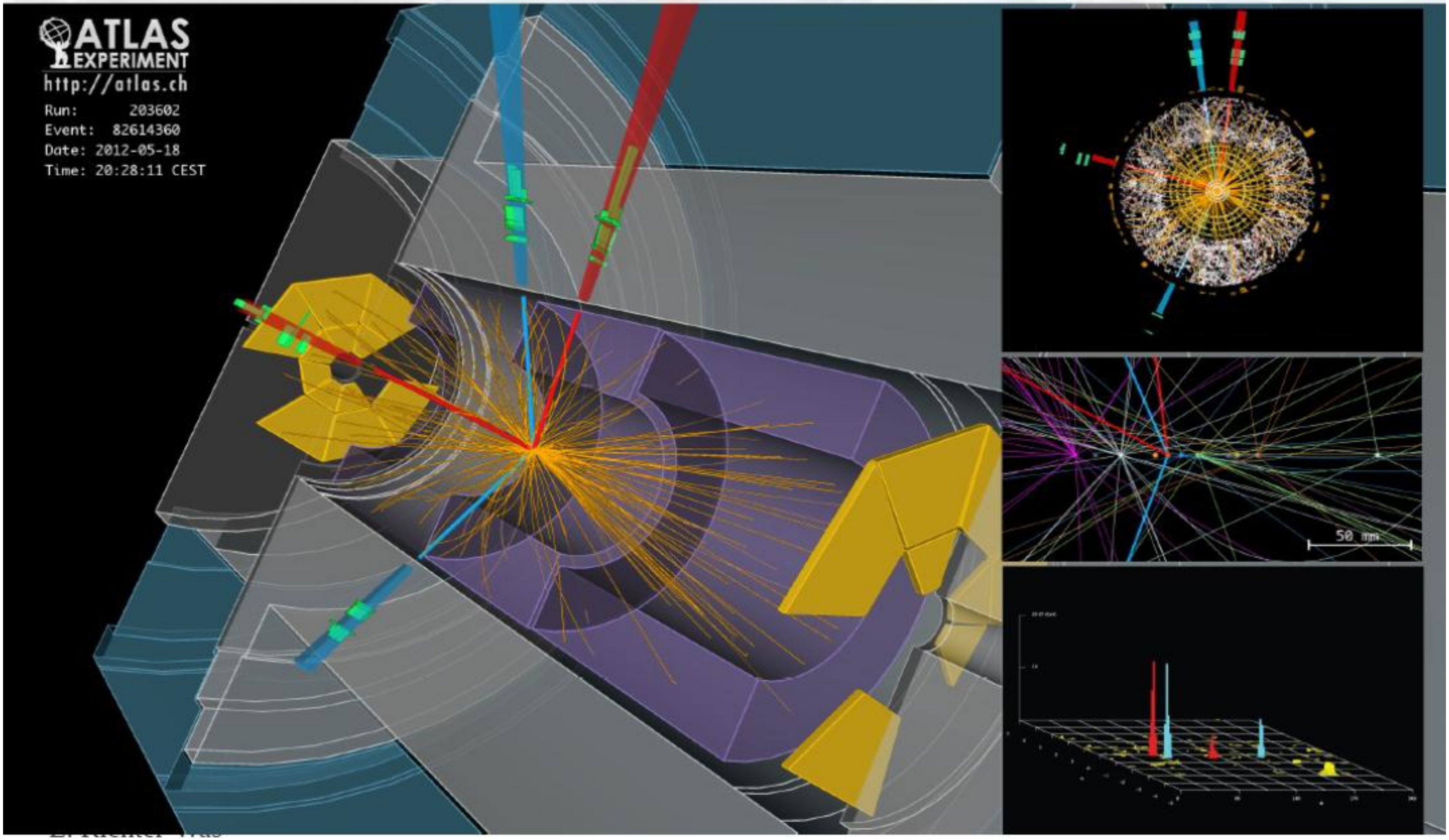
The final state looks like the same, but some f the particle fakes what you are looking for



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

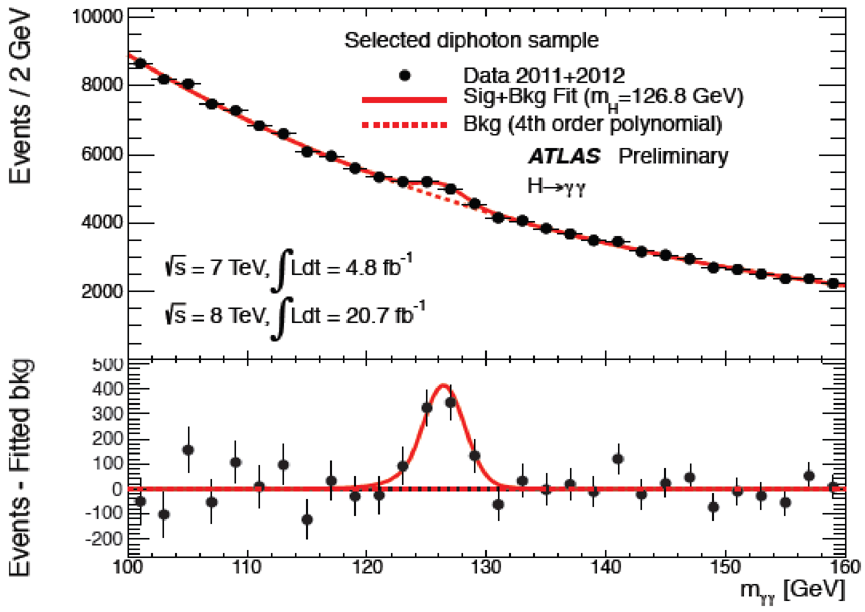
e_1: $P_T = 24.9$ GeV, $\eta = -0.33$, $\phi = 1.98$ e_2: $P_T = 53.9$ GeV, $\eta = -0.40$, $\phi = 1.69$

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



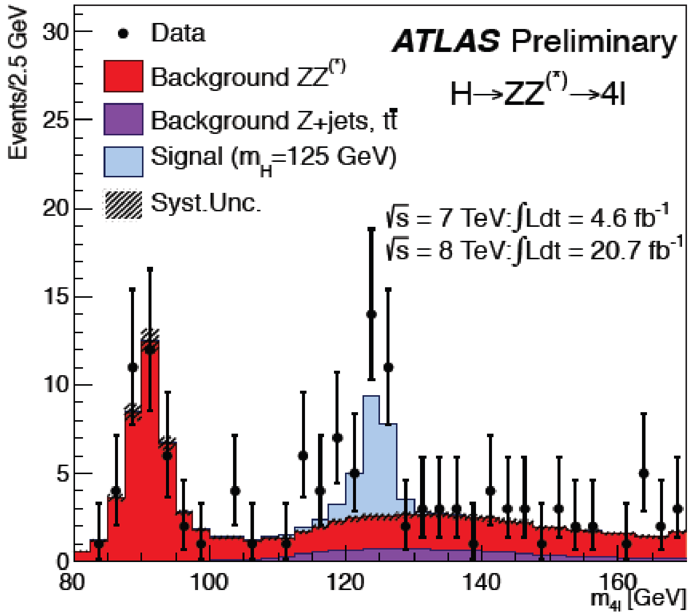
Higgs like signal with 7 TeV and 8 TeV data

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)

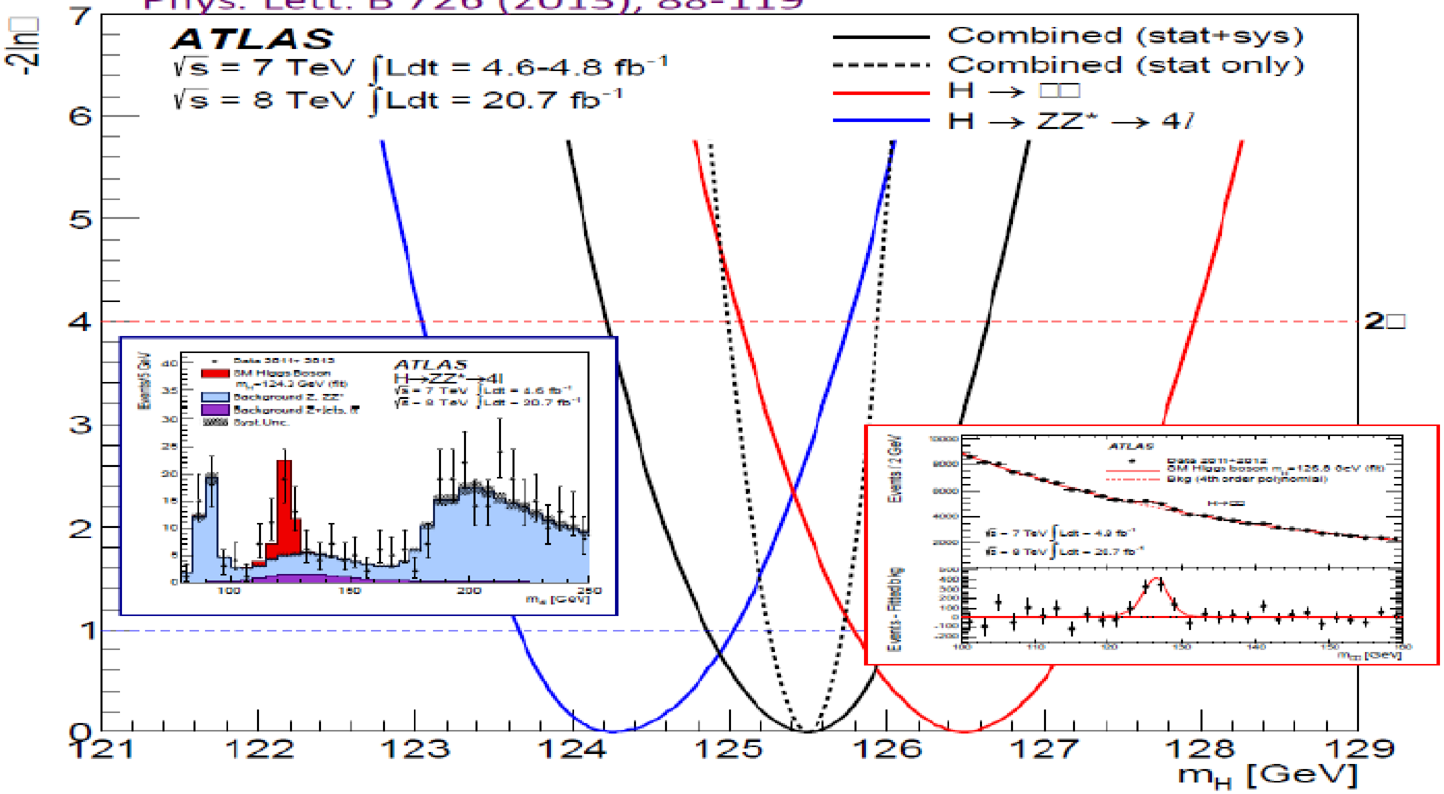
H→4l



- 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

Phys. Lett. B 726 (2013), 88-119

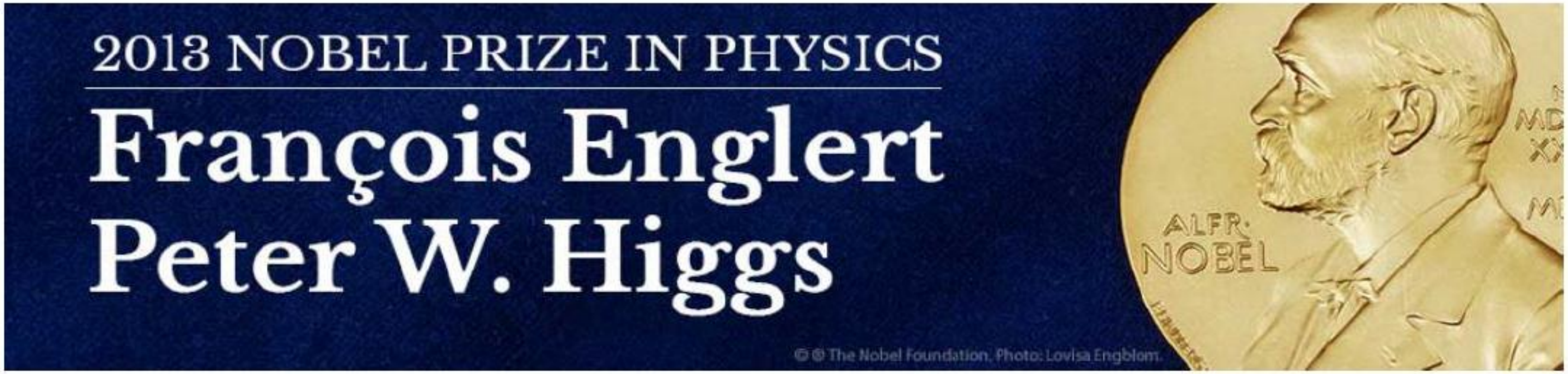


4ℓ: $M_H = 124.3 \pm 0.6_{stat} \pm 0.4_{sys}$ GeV

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

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

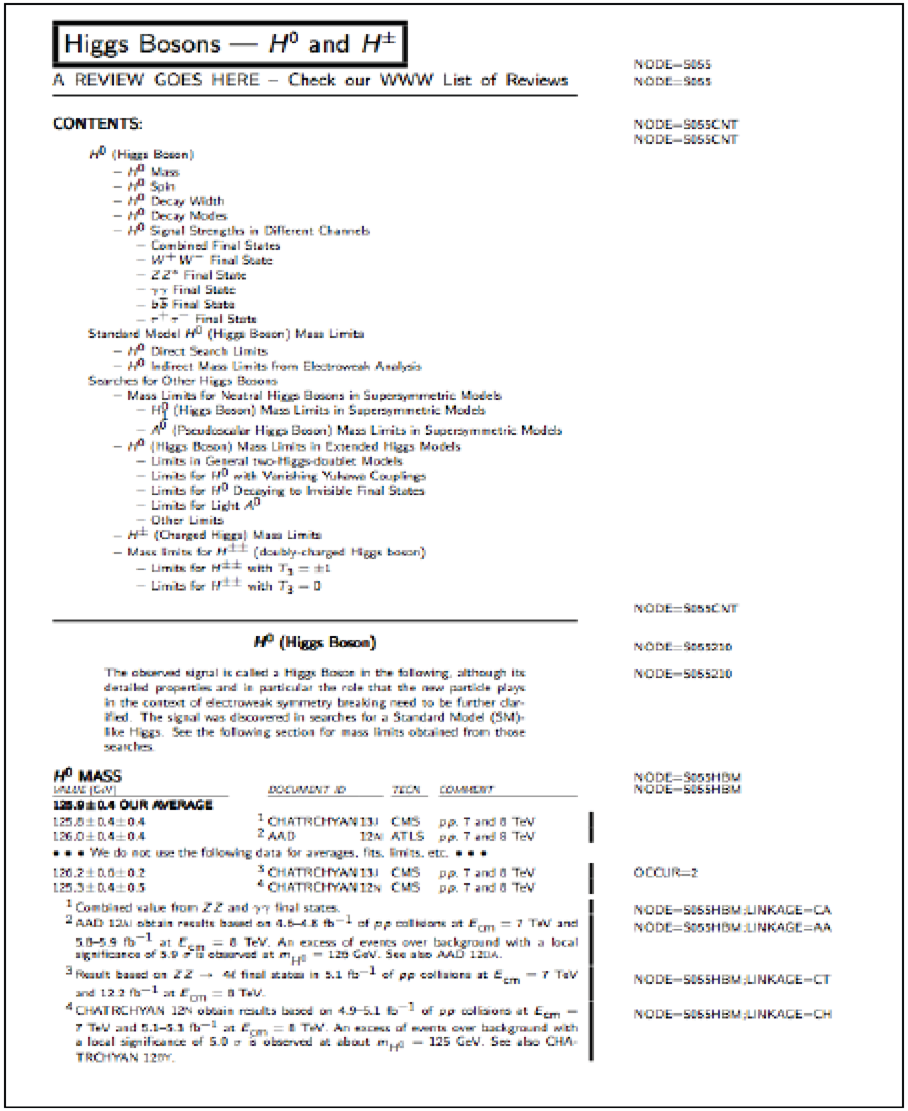
8 October 2013

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



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

- 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
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    - 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 $T_3 = \pm1$
    - Limits for $H^{\pm\pm}$ with $T_3 = 0$

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
125.3±0.4±0.5	[4] CHATRCHYAN	12N	CMS	pp, 7 and 8 TeV

OCCUR=2

[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 $E_{\rm cm}$ = 7 TeV and 5.8–5.9 fb^{-1} at $E_{\rm cm}$ = 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 $ZZ \rightarrow 4\ell$ final states in 5.1 fb^{-1} of pp collisions at $E_{\rm cm}$ = 7 TeV and 12.2 fb^{-1} at $E_{\rm cm}$ = 8 TeV.

NODE=S055HBM;LINKAGE=CT

[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at $E_{\rm cm}$ = 7 TeV and 5.1–5.3 fb^{-1} at $E_{\rm cm}$ = 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.

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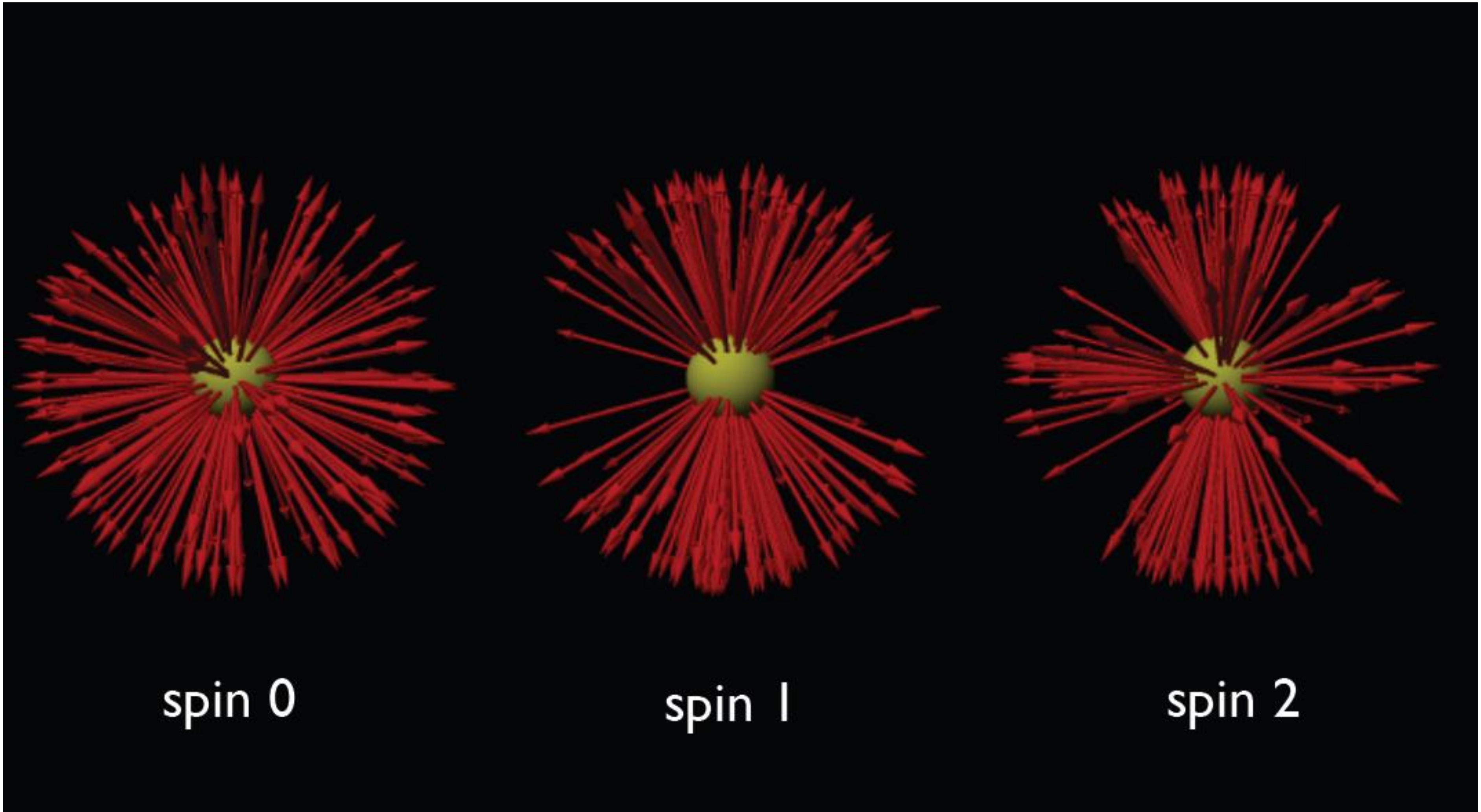
2013

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

$$H^0$$

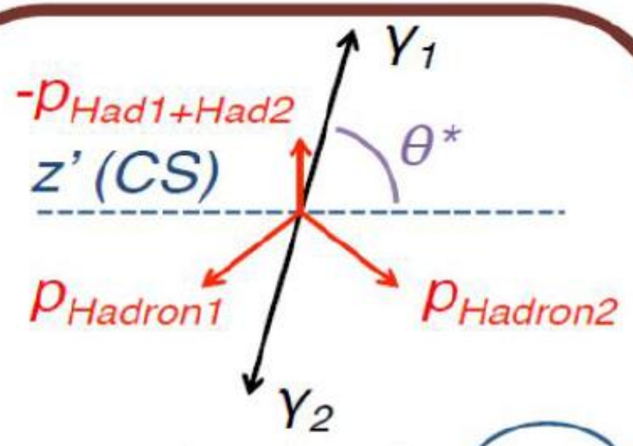
How we can recognize spin?



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



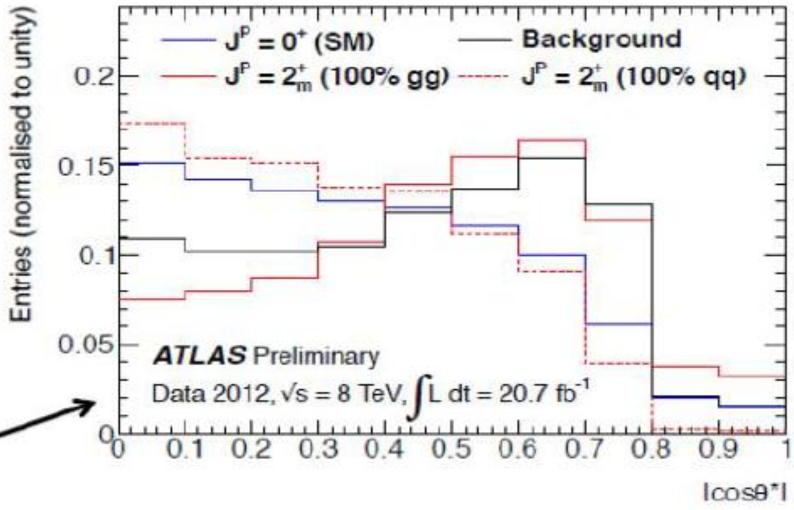
$$\left|\cos\theta^*_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\frac{2p_T^{\gamma1}p_T^{\gamma2}}{m_{\gamma\gamma}^2}$$

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

qq→2^+ very similar to SM *gg*→0^+

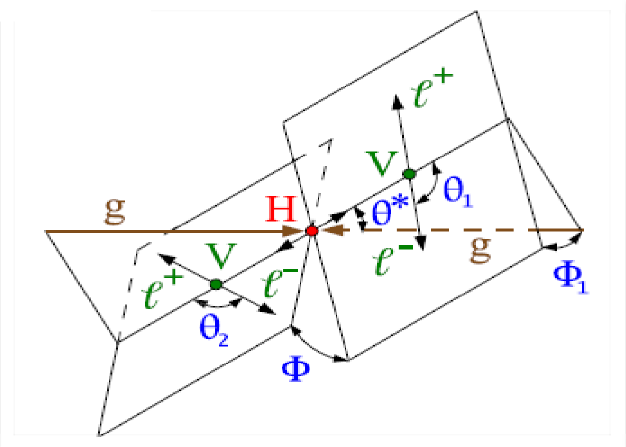
Collins-Soper frame used to get reference axis z' for cos(θ*)

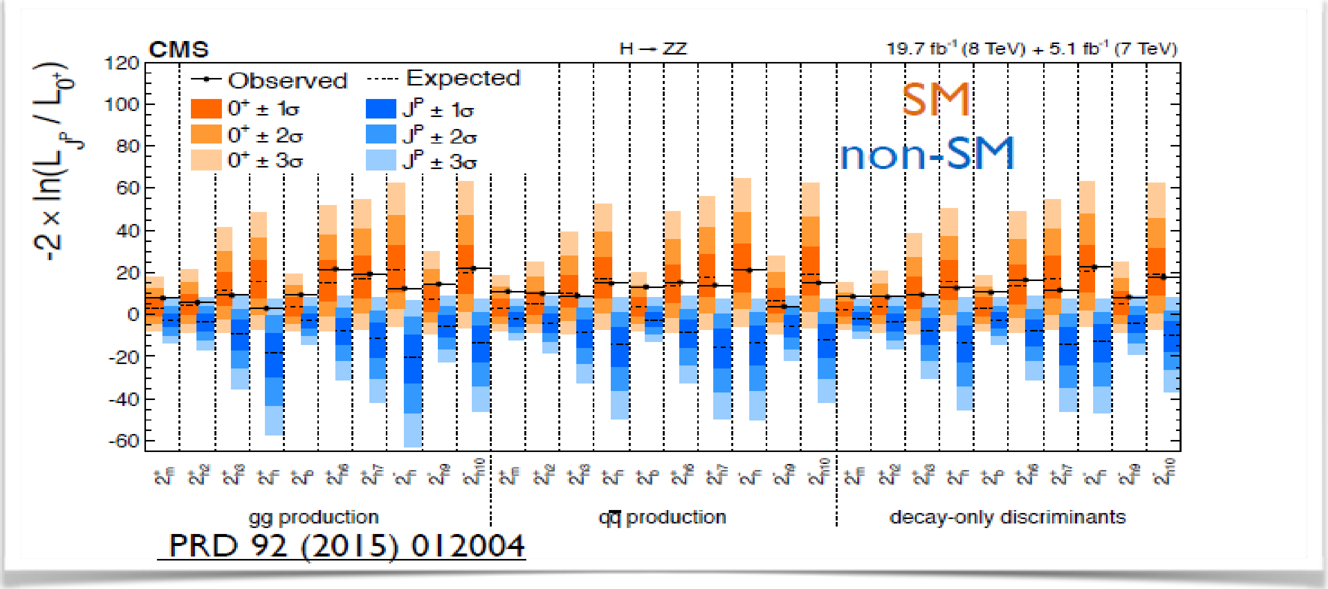
- z-axis bisects angle between the momenta of colliding hadrons
- Minimizes impact of ISR
- Better 0^+ / 2^+ discrimination



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

$m_h = 125$ GeV → $\Gamma_h = 4.07$ MeV

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

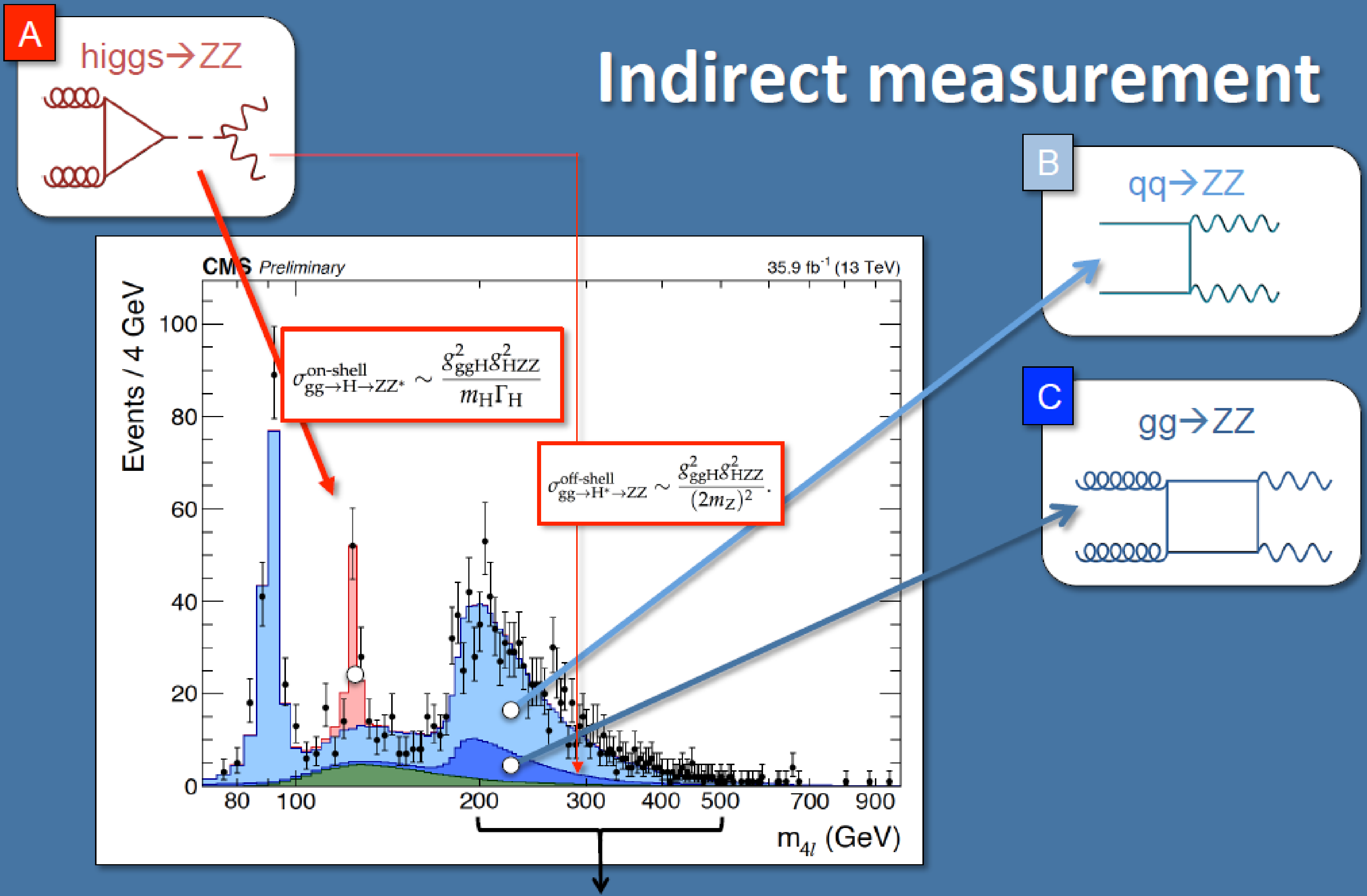
A deviation would imply a decay to non-SM particles

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



$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}.$$

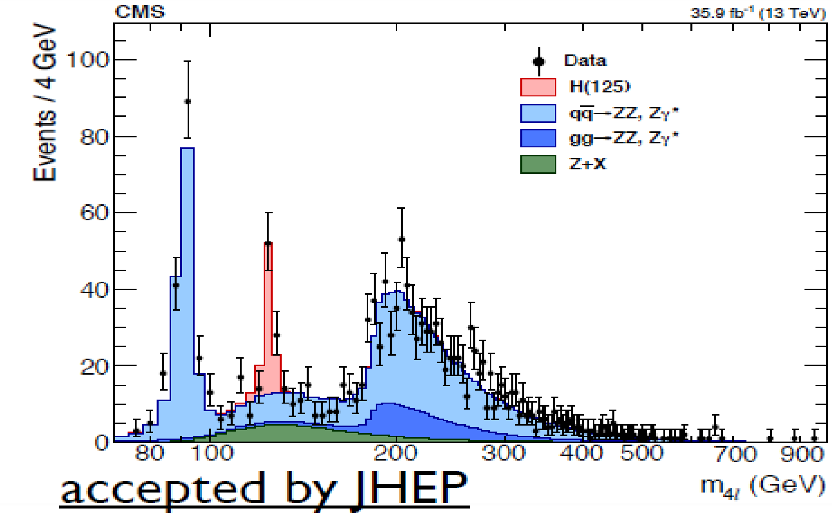
Interference between A and C : $(A+C)^2 = A^2 + C^2 + 2AC$

tiny ← → ***accessible***

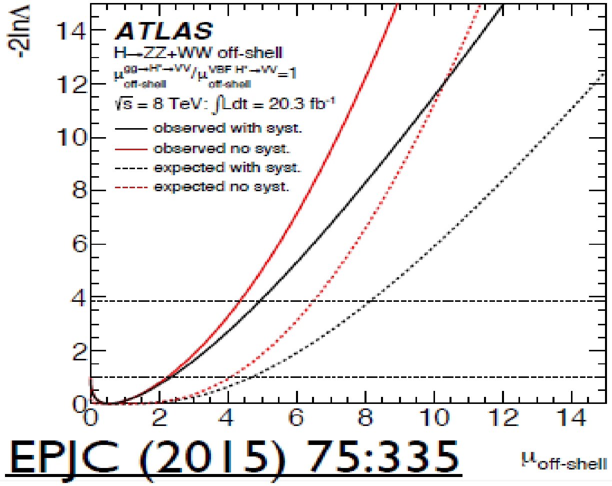
Higgs boson decay width

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

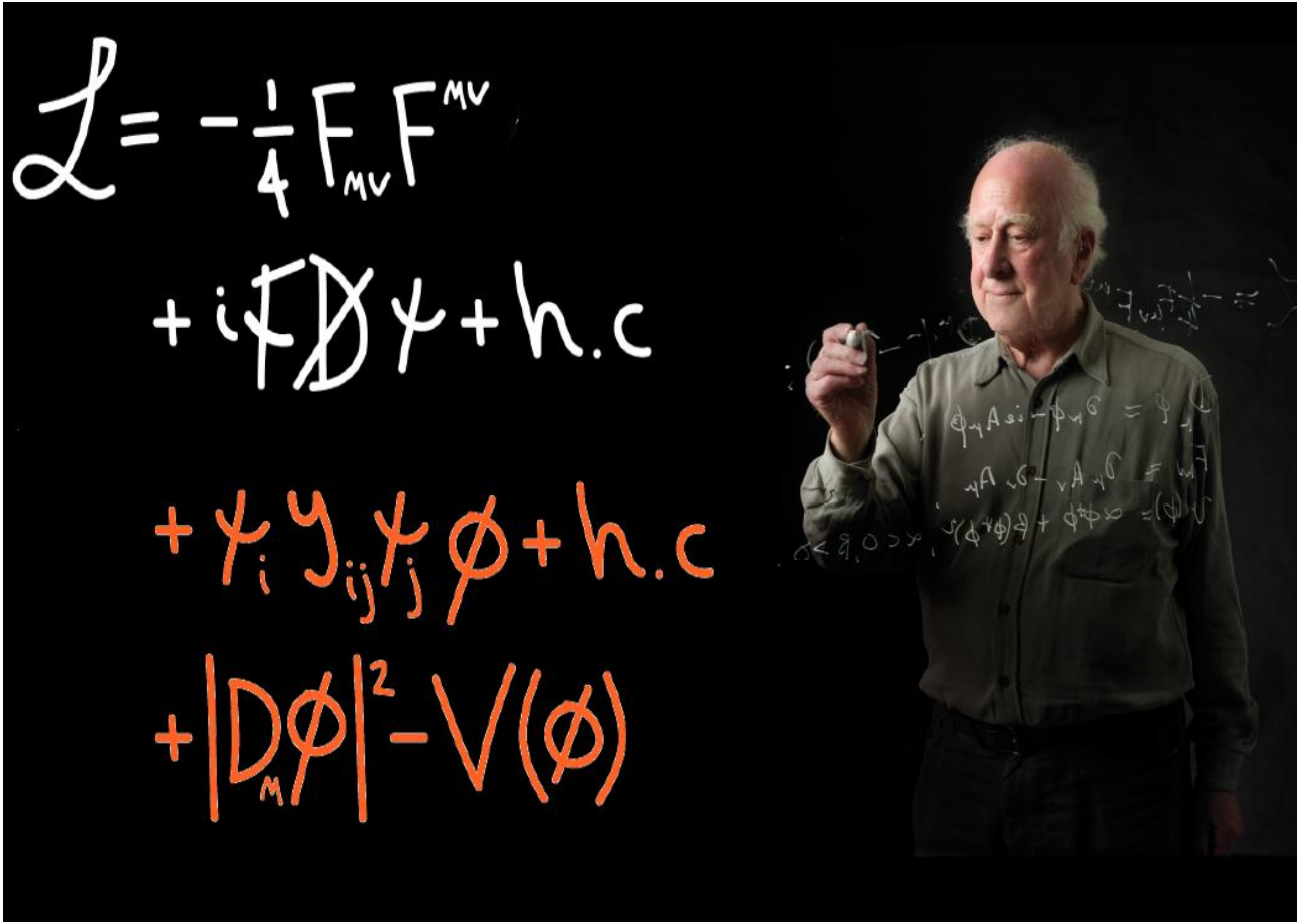


accepted by JHEP



EPJC (2015) 75:335

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



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

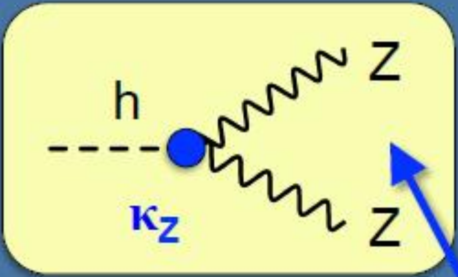
Couplings: kappa-framework

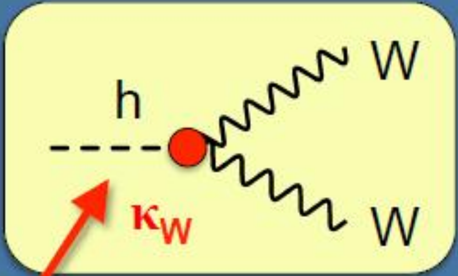
Scale factor for each (fundamental) coupling:

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

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

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

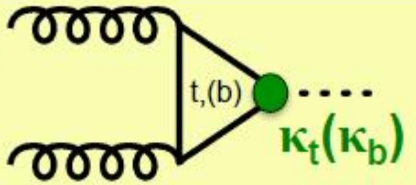




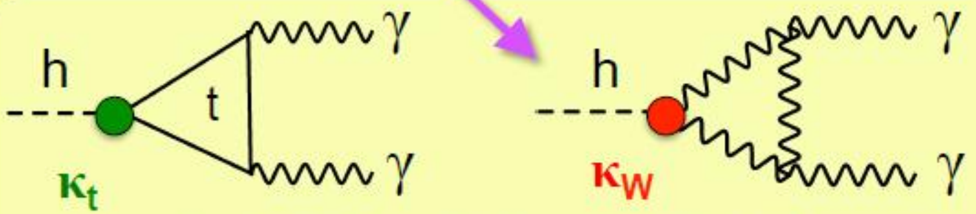
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$

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

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



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



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

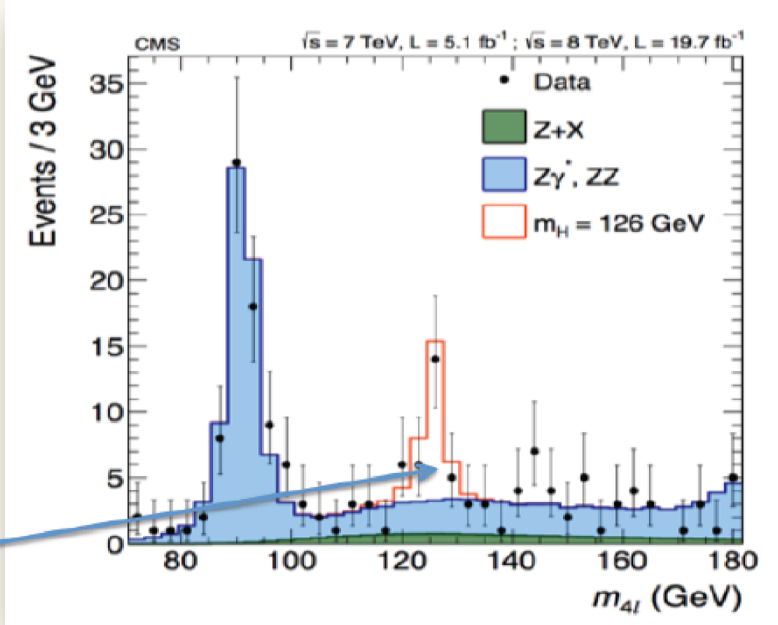
What do we measure?

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



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

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

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

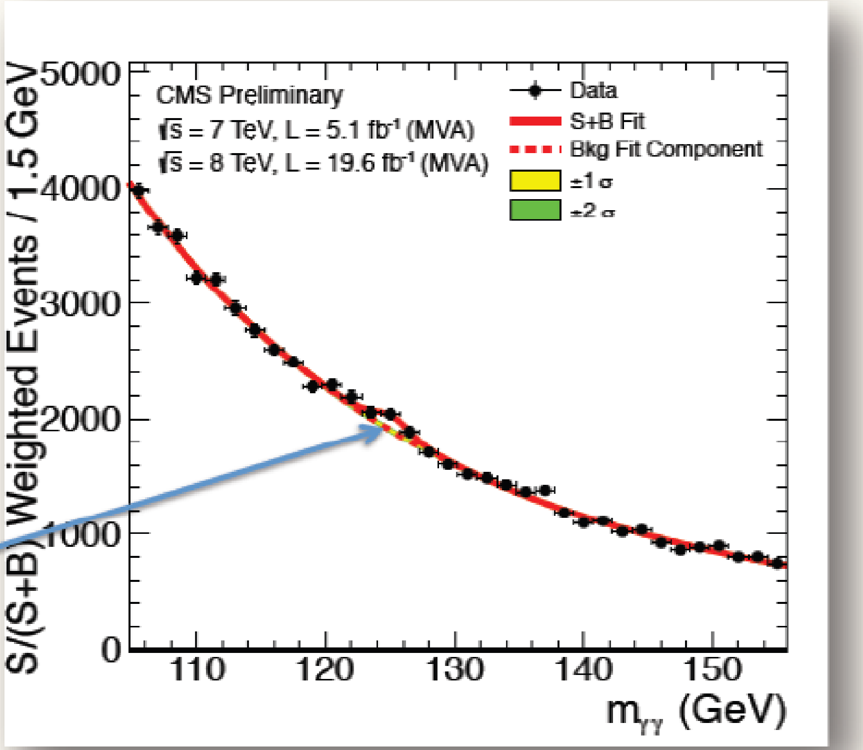
What do we measure?

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



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

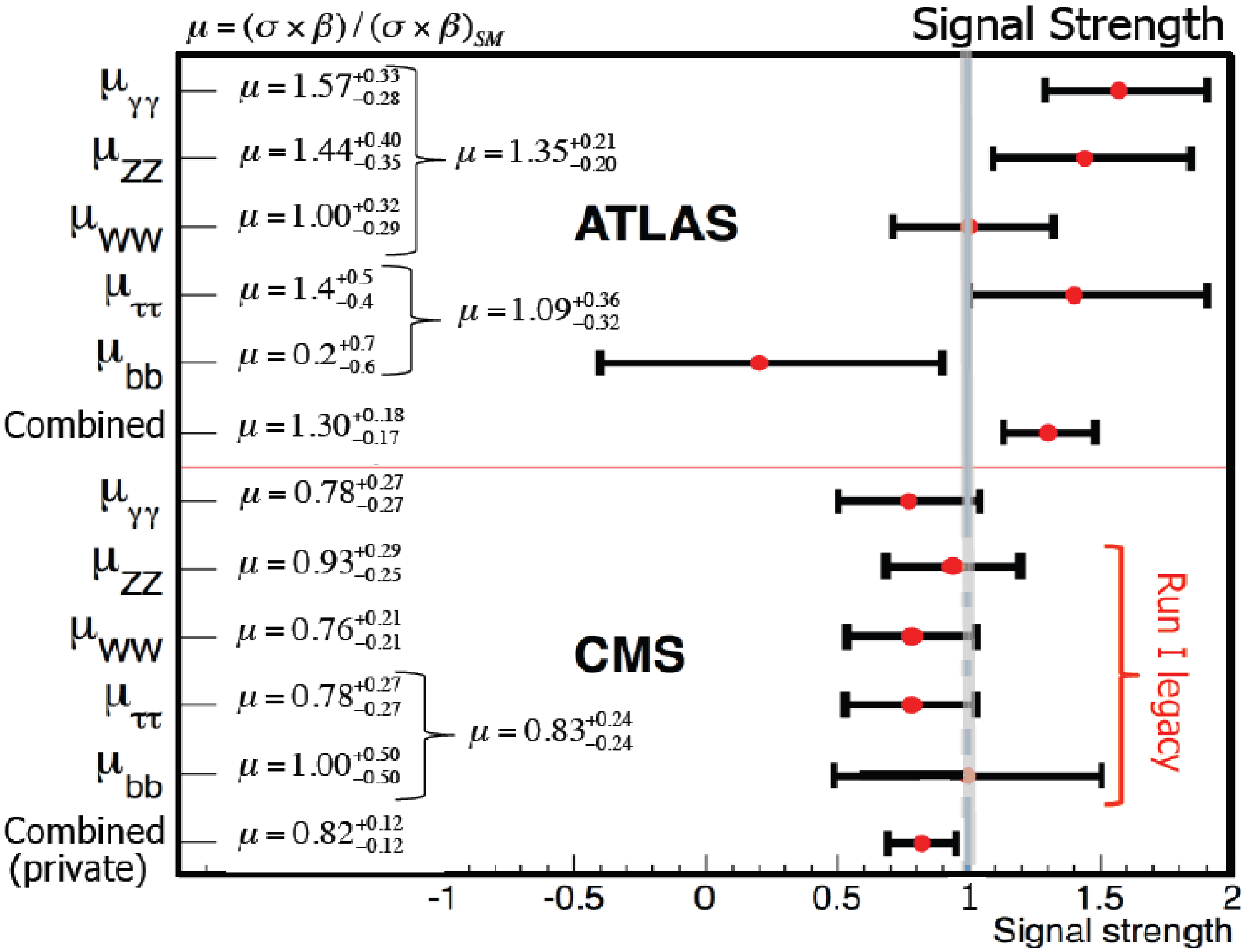
$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

Higgs boson decay channels

Significance

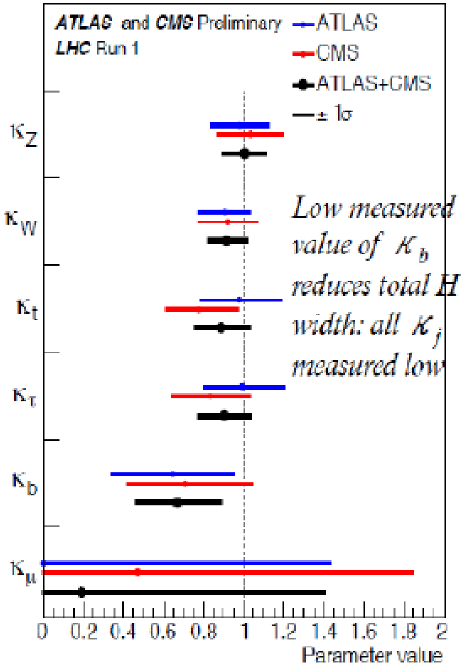
7.4σ	(4.3σ)
6.6σ	(4.4σ)
3.8σ	(3.8σ)
4.1σ	(3.2σ)
0.36σ	(1.64σ)
Obs.	*(Exp.)*

3.2σ	(4.2σ)
6.8σ	(6.7σ)
4.3σ	(5.8σ)
3.3σ	(3.7σ)
2.1σ	(2.1σ)
Obs.	*(Exp.)*

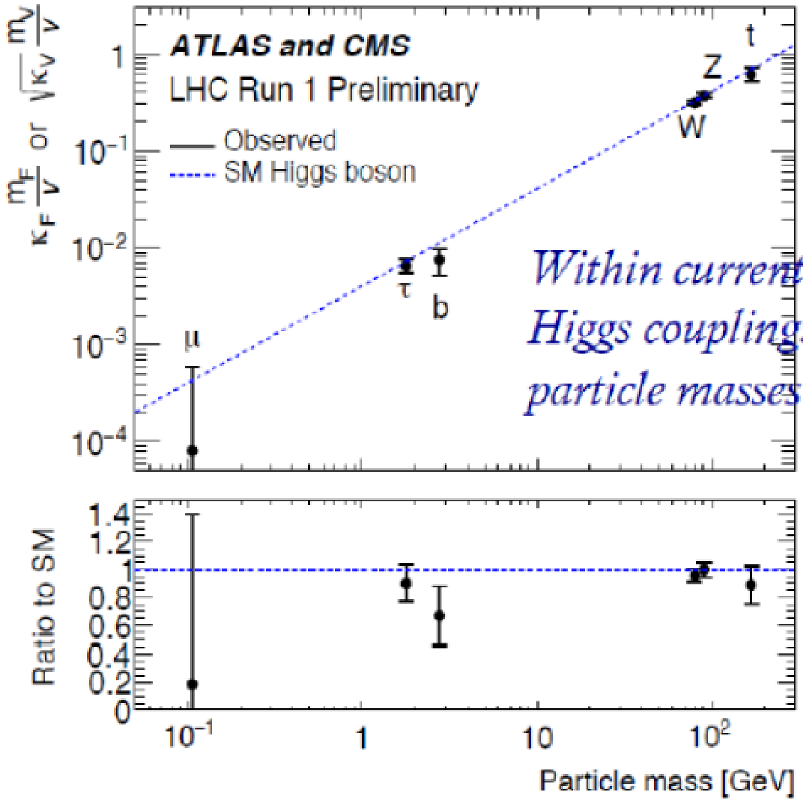


Constrains on three-level Higgs couplings

- 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

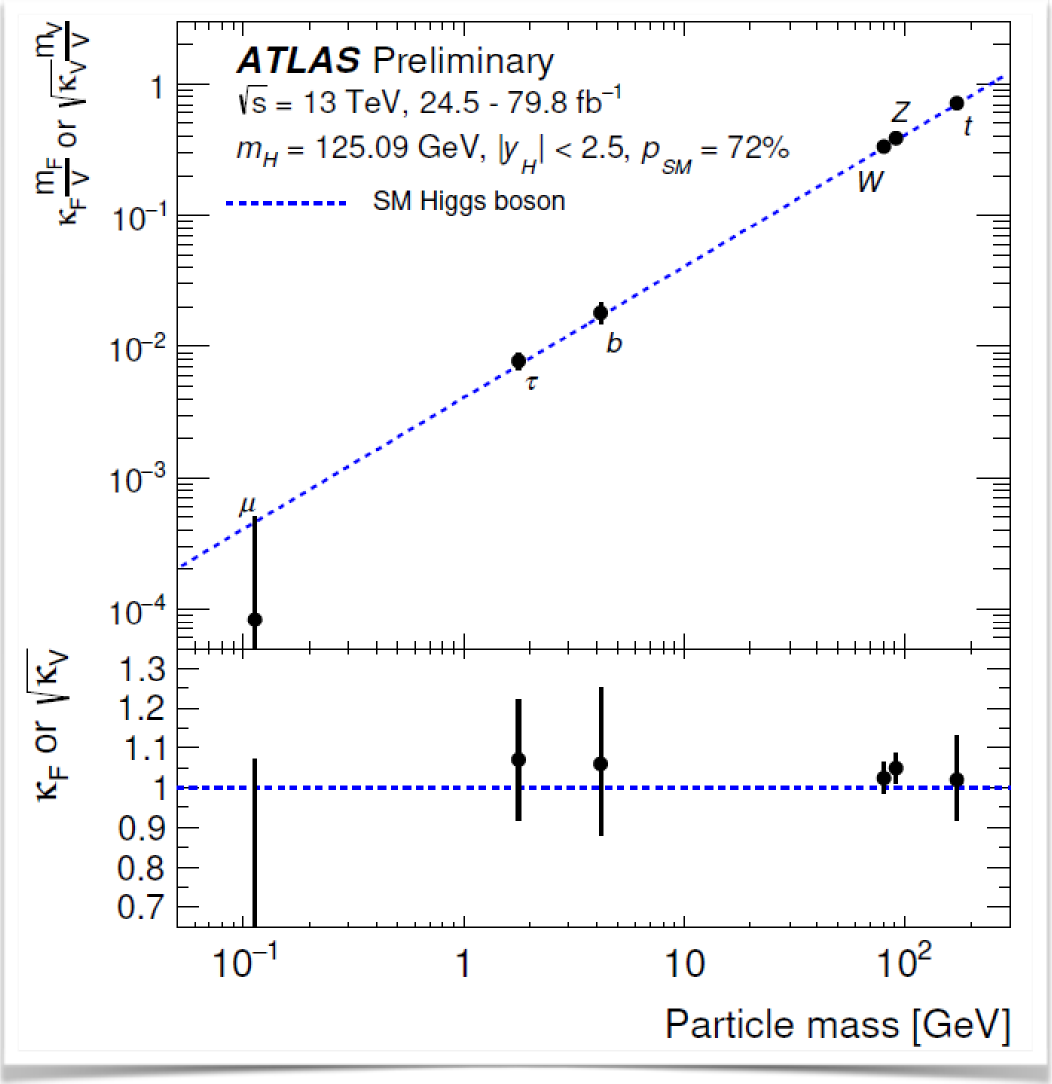


Low measured value of κ_b reduces total H width: all κ_j measured low



Within current precision Higgs couplings scale with particle masses

Couplings vs mass (2019)

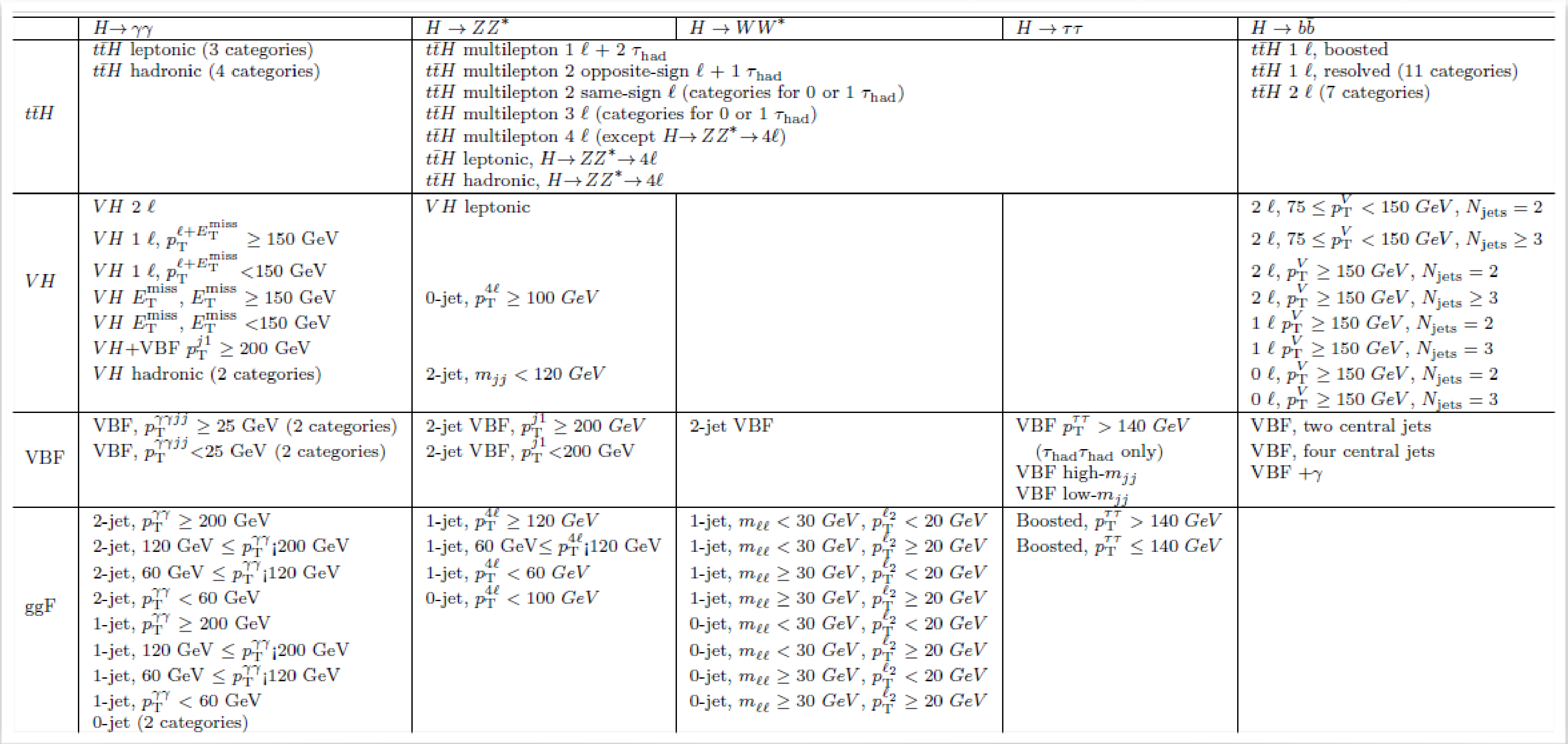


Interpret the results in the κ framework as a function of the particle mass assuming no BSM contributions to the total width

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{\mathrm{SM}}}$$

ATLAS-CONF-2019-005

ATLAS combination



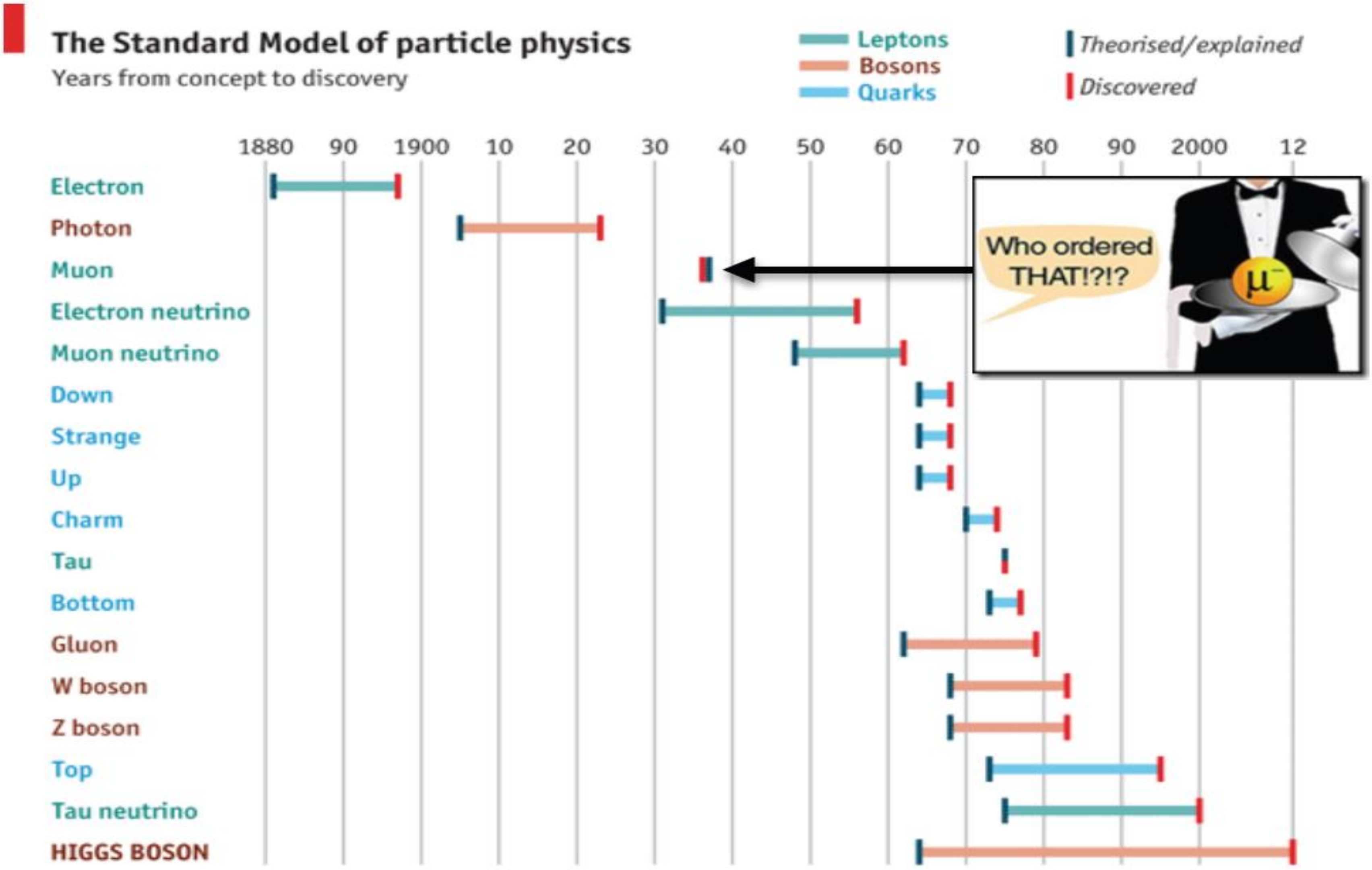
	$H\rightarrow\gamma\gamma$	$H\rightarrow ZZ^*$	$H\rightarrow WW^*$	$H\rightarrow\tau\tau$	$H\rightarrow b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 ℓ + 2 τ_{had} $t\bar{t}H$ multilepton 2 opposite-sign ℓ + 1 τ_{had} $t\bar{t}H$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

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

Searches for New Physics

- Supersymmetry
- Exotic models
- Dark Matter
- Unconventional signatures

Uncharted discoveries?



The Standard Model of particle physics

Years from concept to discovery

Source: *The Economist*

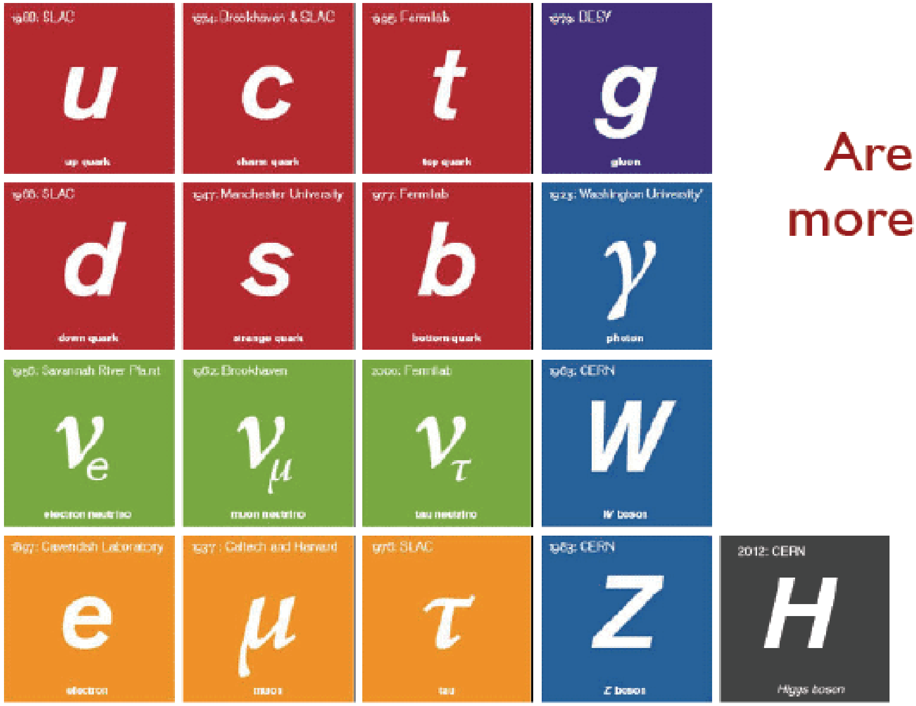
Many unanswered questions …

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

Why is the top quark so heavy?

Why there's more matter then anti-matter?

How do neutrinos get mass?



Are there more forces?

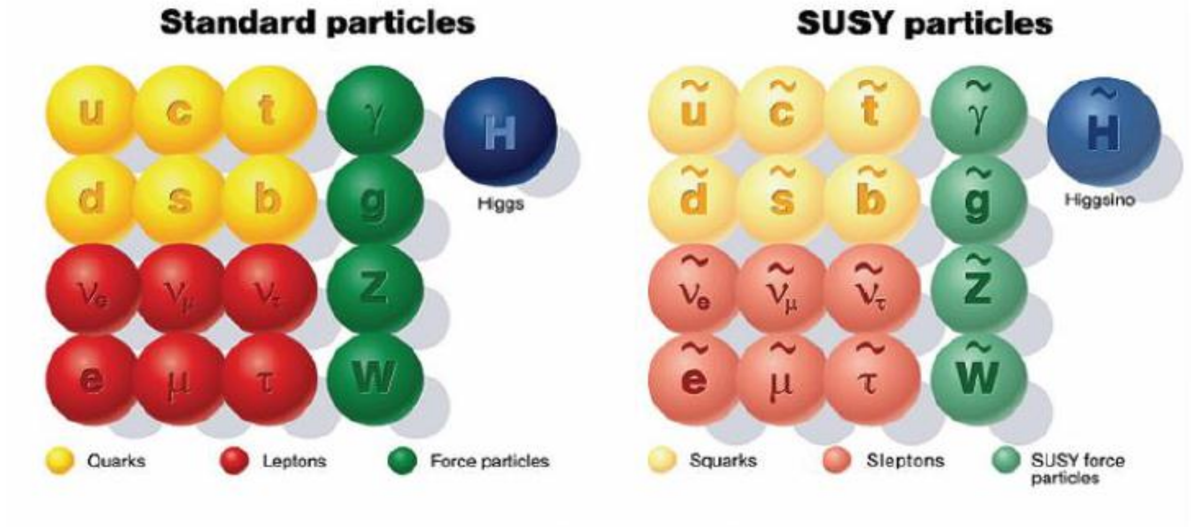
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

… and as many possible answers to probe!

- Super-symmetry?



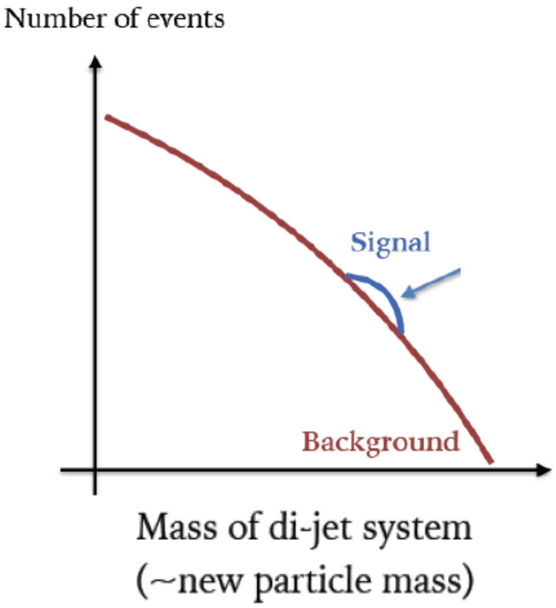
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

Any new theory need to agree with the SM!

How would new phenomena manifest itself?

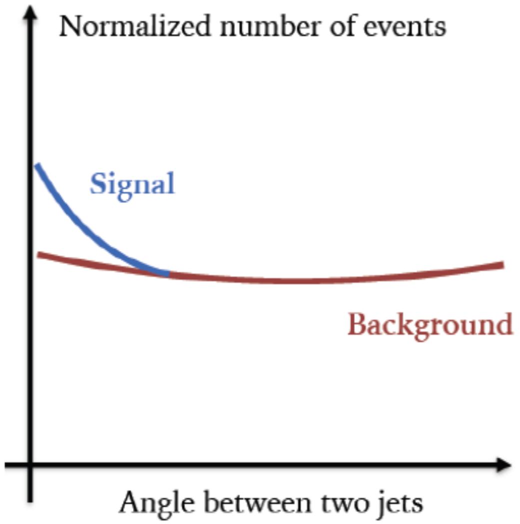
New particles:

resonant excess (bump) over Standard Model background



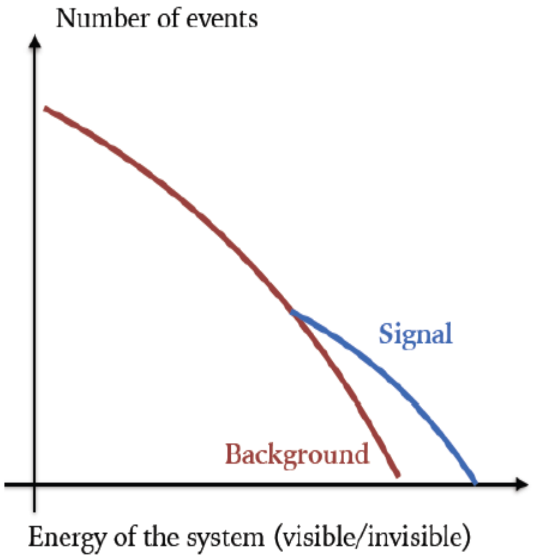
New interactions:

more central production (~Rutherford experiment)

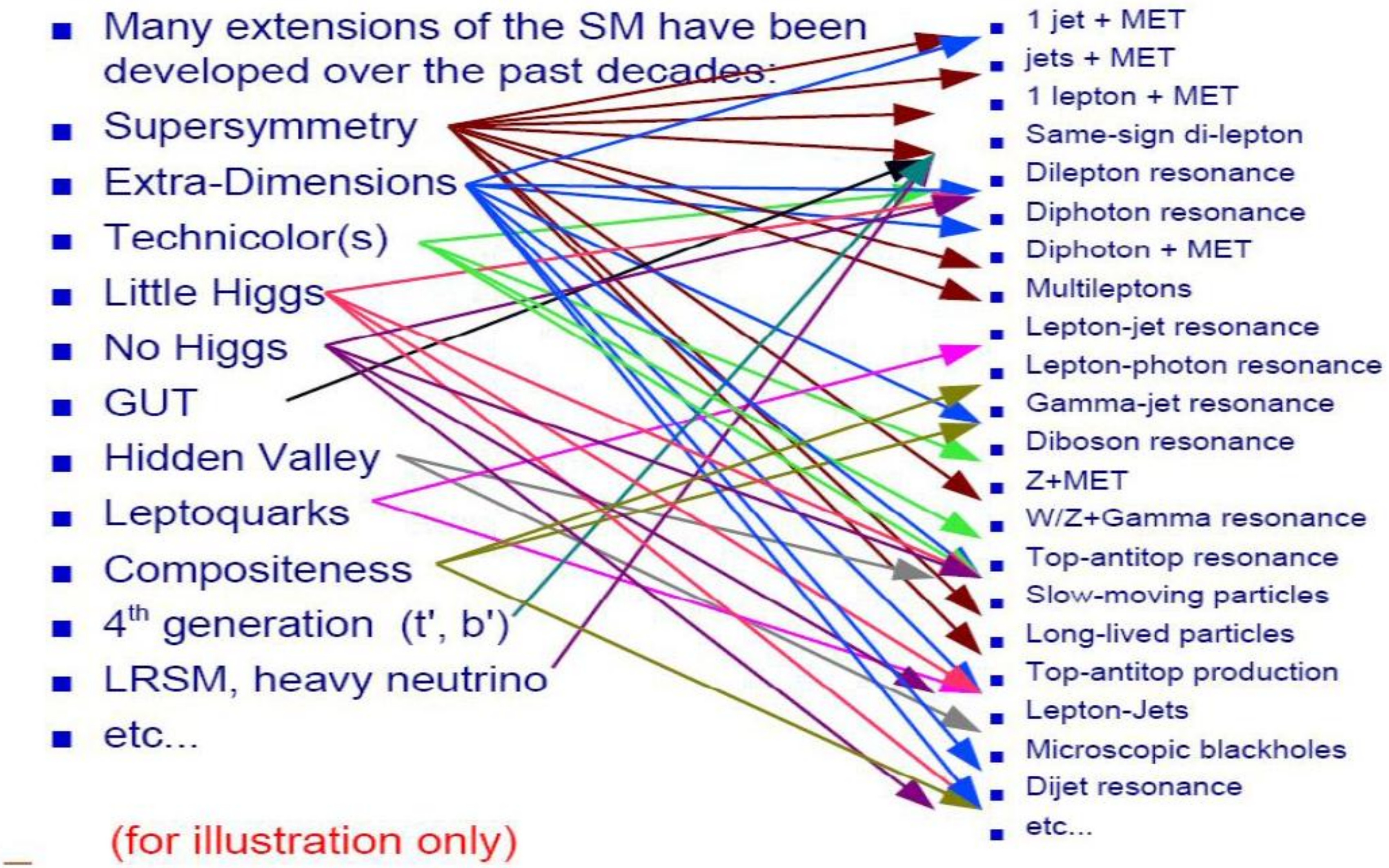


New particles and states:

larger multiplicity of objects at high masses



Long list of models and signatures

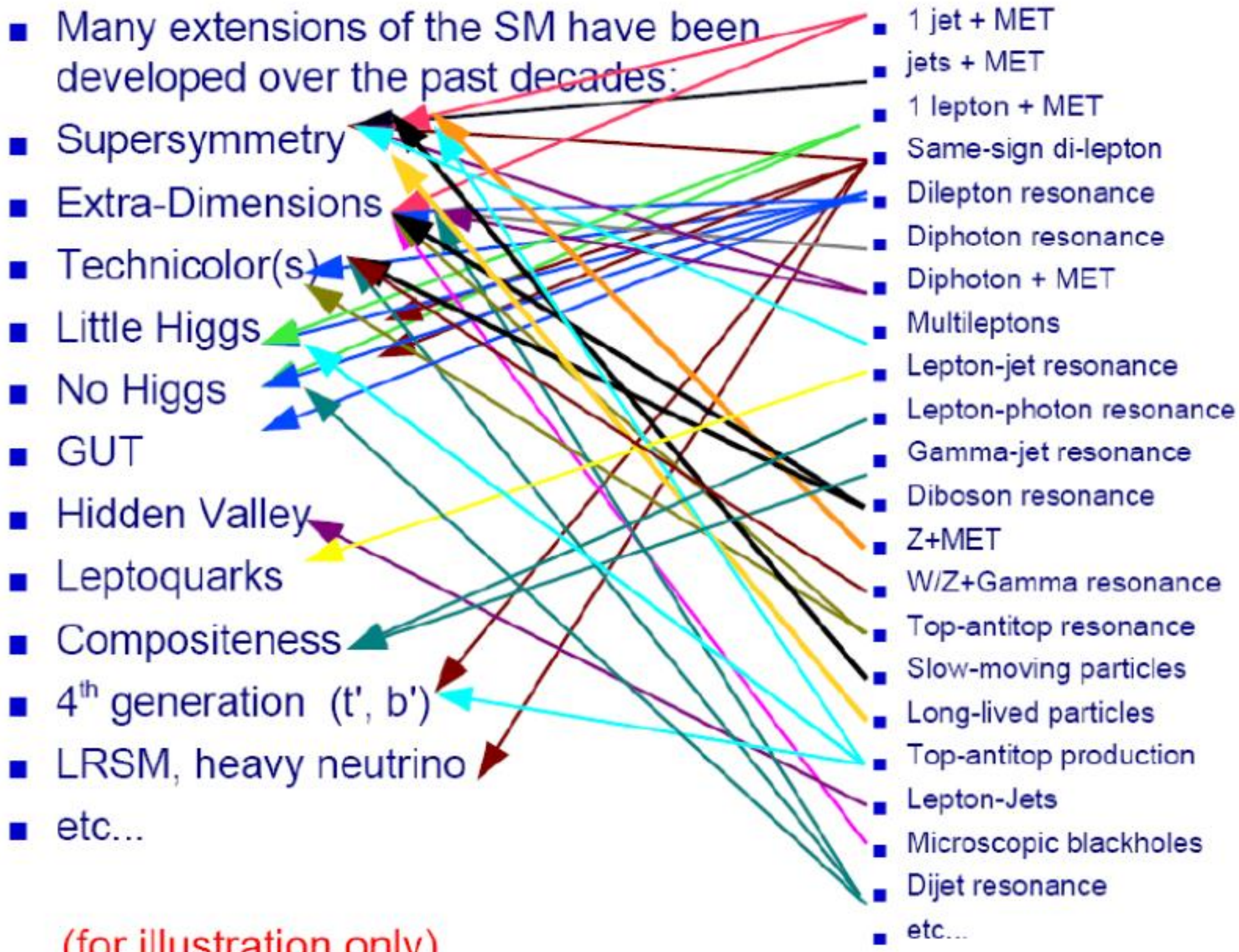


- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4^{th} generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

Long list of models and signatures



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- etc...

A complex 2D problem

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

→ Practical

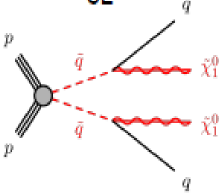
→ Less model-dependent

→ Important to cover every possible signature

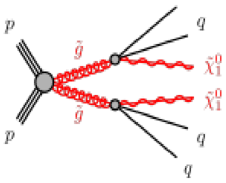
Strongly produced SUSY searches

Squarks and gluinos

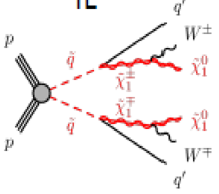
0L



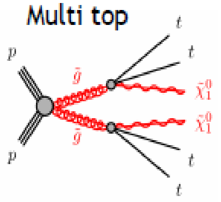
0L-Njets



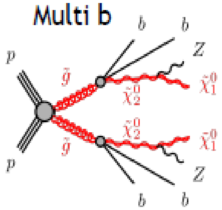
1L



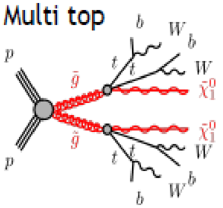
Multi top



Multi b

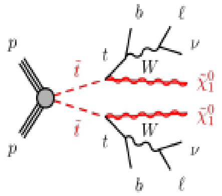


Multi top

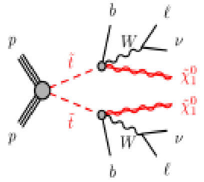


Stop

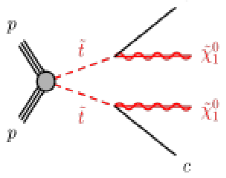
Stop 2L



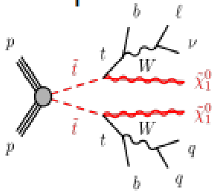
Stop 1,2-L



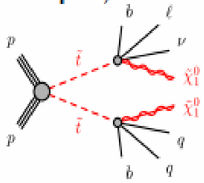
Stop 0L



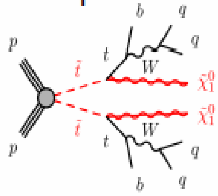
Stop 1L

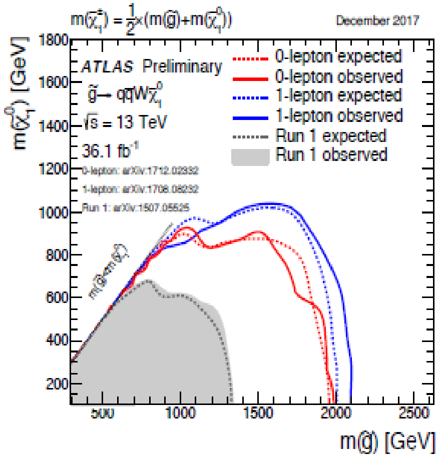


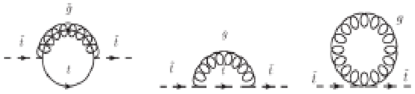
Stop 1,2-L



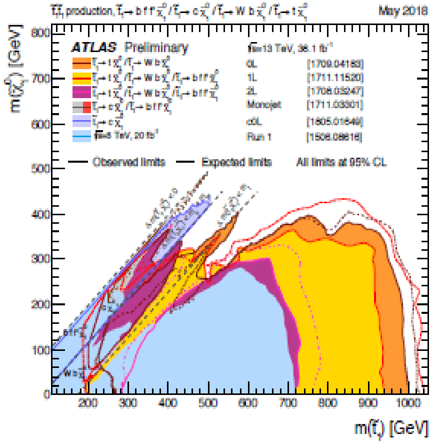
Stop 0L

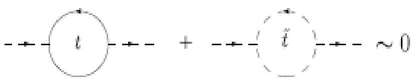






Stop also a scalar requires light gluinos to be light enough: for gluinos > 1.8 TeV ~tuning of Factor of 30



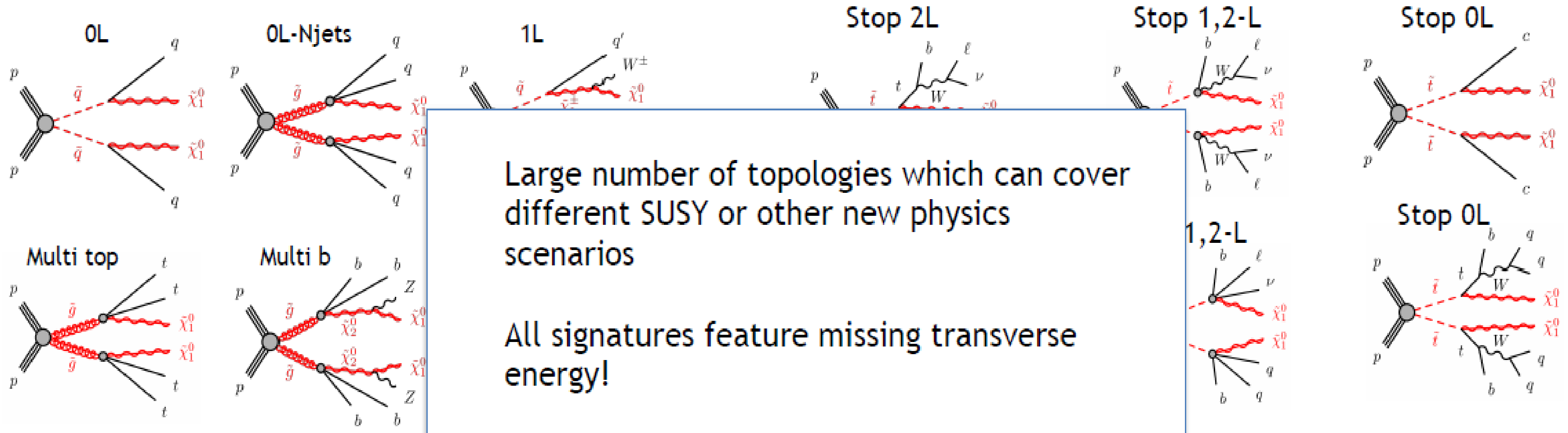


Not so natural SUSY: Stops > 800 GeV ~Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

Strongly produced SUSY searches

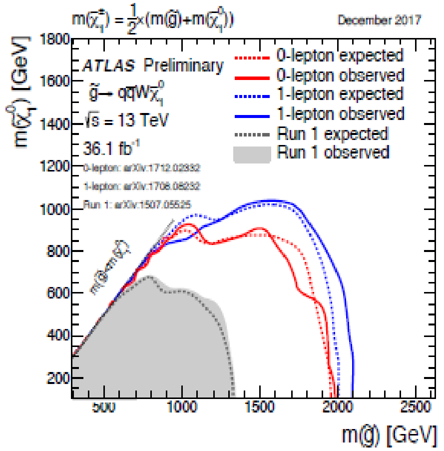
Squarks and gluinos

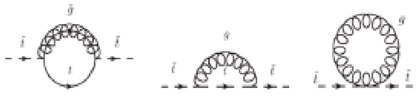
Stop



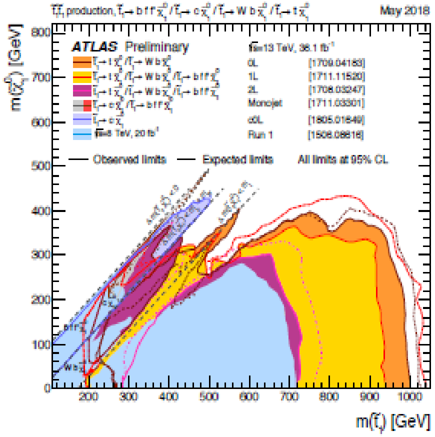
Large number of topologies which can cover different SUSY or other new physics scenarios

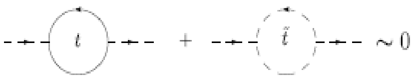
All signatures feature missing transverse energy!





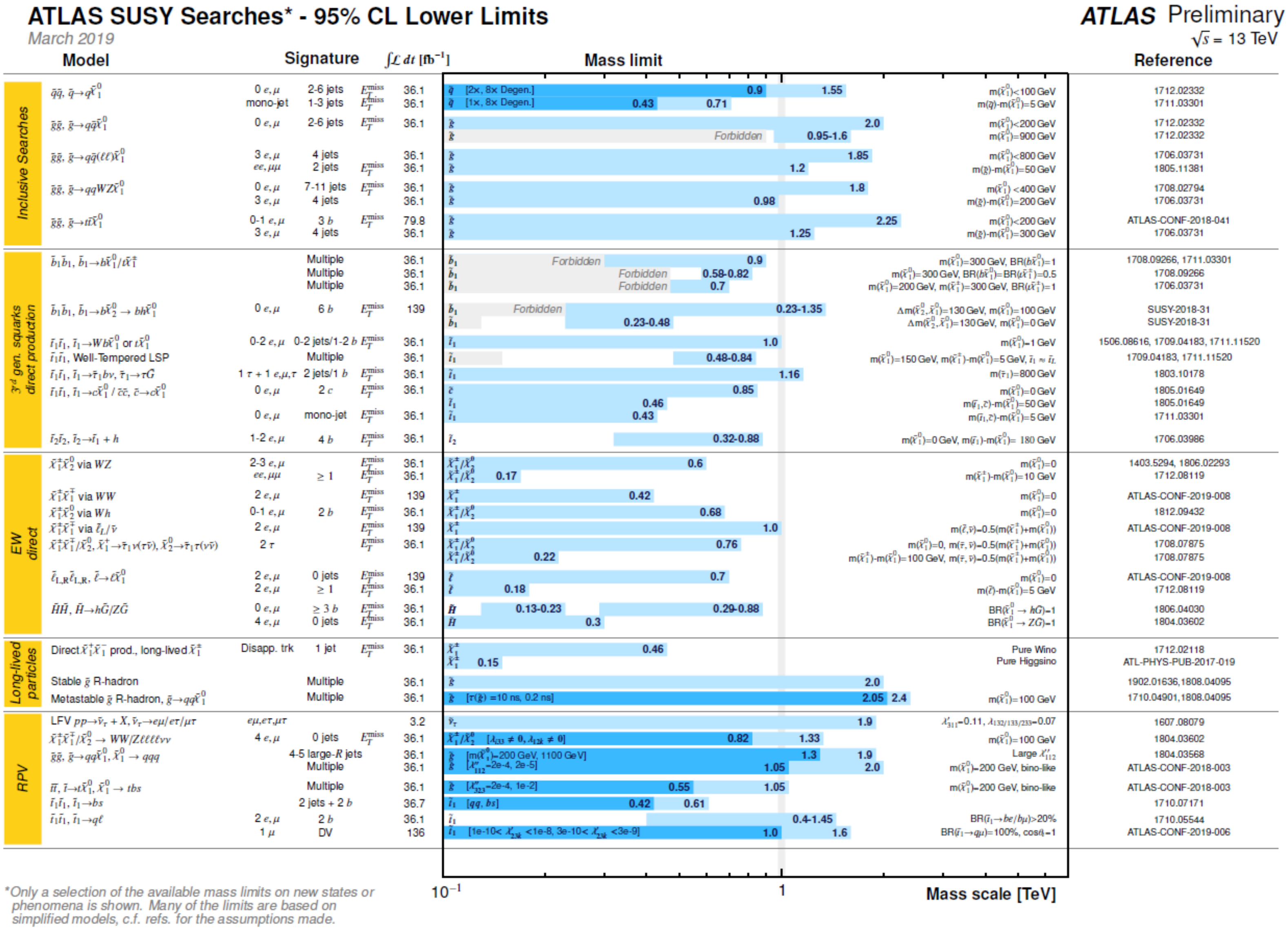
Stop also a scalar requires light gluinos to be light enough: for gluinos > 1.8 TeV ~tuning of Factor of 30





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 (2019)



ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[2x, 8x Degen.] 0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[1x, 8x Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$	Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets		36.1	$\tilde{g}$	0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		3 e,μ	4 jets		36.1	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	SUSY-2018-31
						$\tilde{b}_1$	0.23-0.48	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$	0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$	0.42	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.68	m($\tilde{\chi}_1^0$)=0	1812.09432
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}_1\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}_1\tau(\nu\tilde{\nu})$	2 τ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	$E_T^{\rm miss}$	36.1	$\tilde{\ell}$	0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$	[τ($\tilde{g}$) =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	[$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$	[m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$	[λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$	[λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

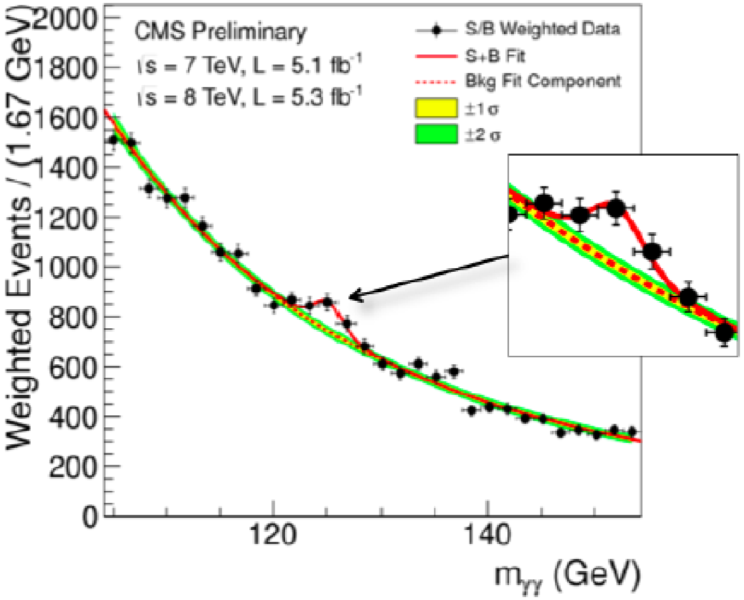
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

What characterizes Exotics Searches

No precise model to guide us

Standard Model:

Predicted Higgs boson

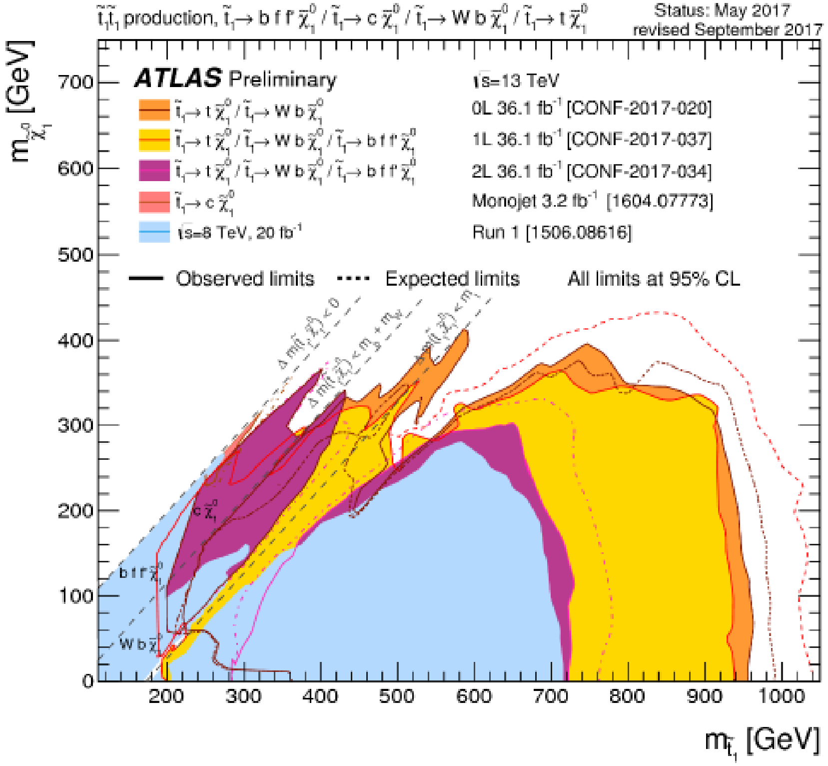


[*Phys. Lett. B 716 (2012) 1-29*]()

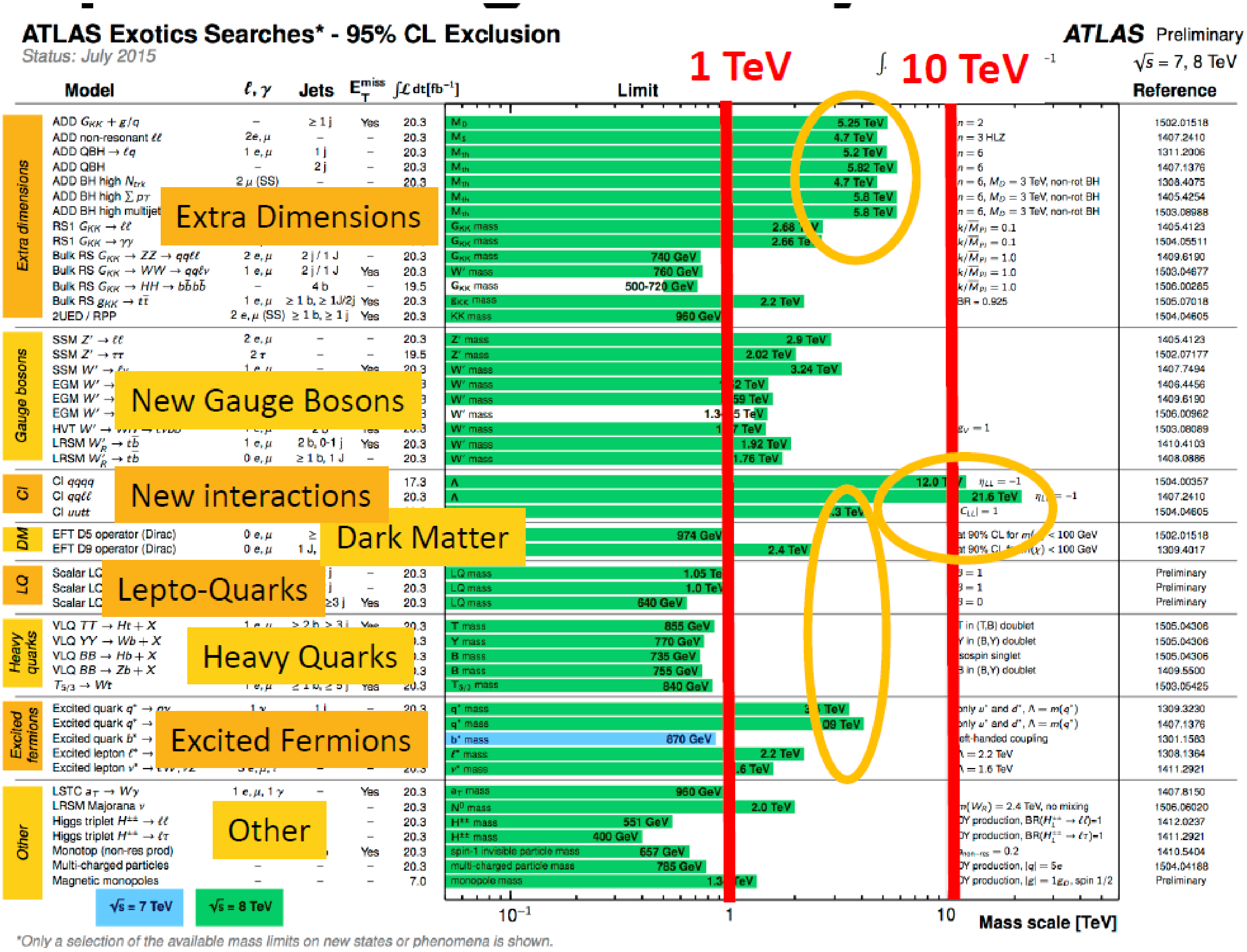
[*Phys. Lett. B 716 (2012) 30-61*]()

No unified parameter phase space

Supersymmetry Searches:



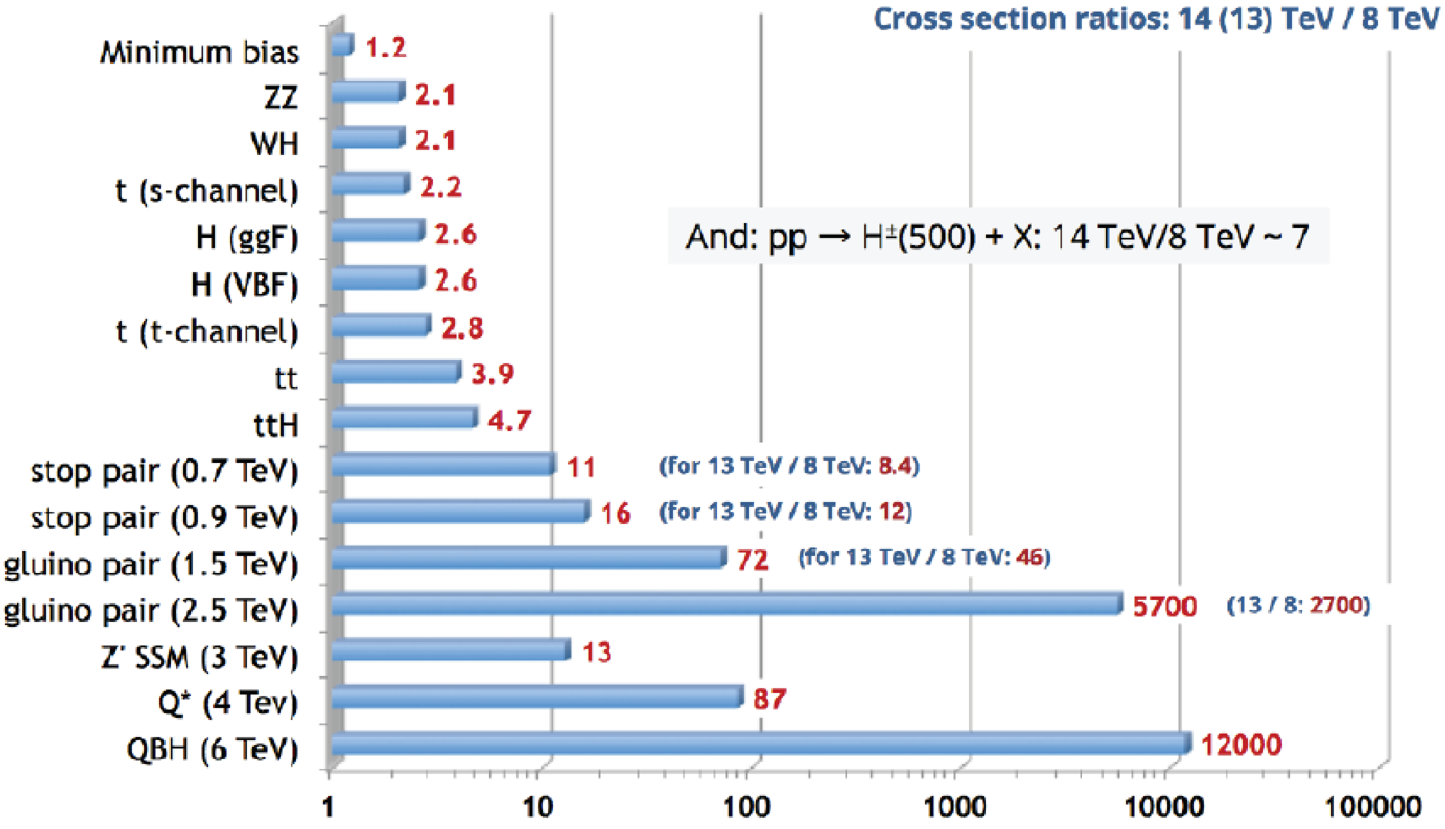
Exploration range of LHC by mid 2015



LHC Run II

Hugely increased potential for discovery of heavy particles at 13 TeV

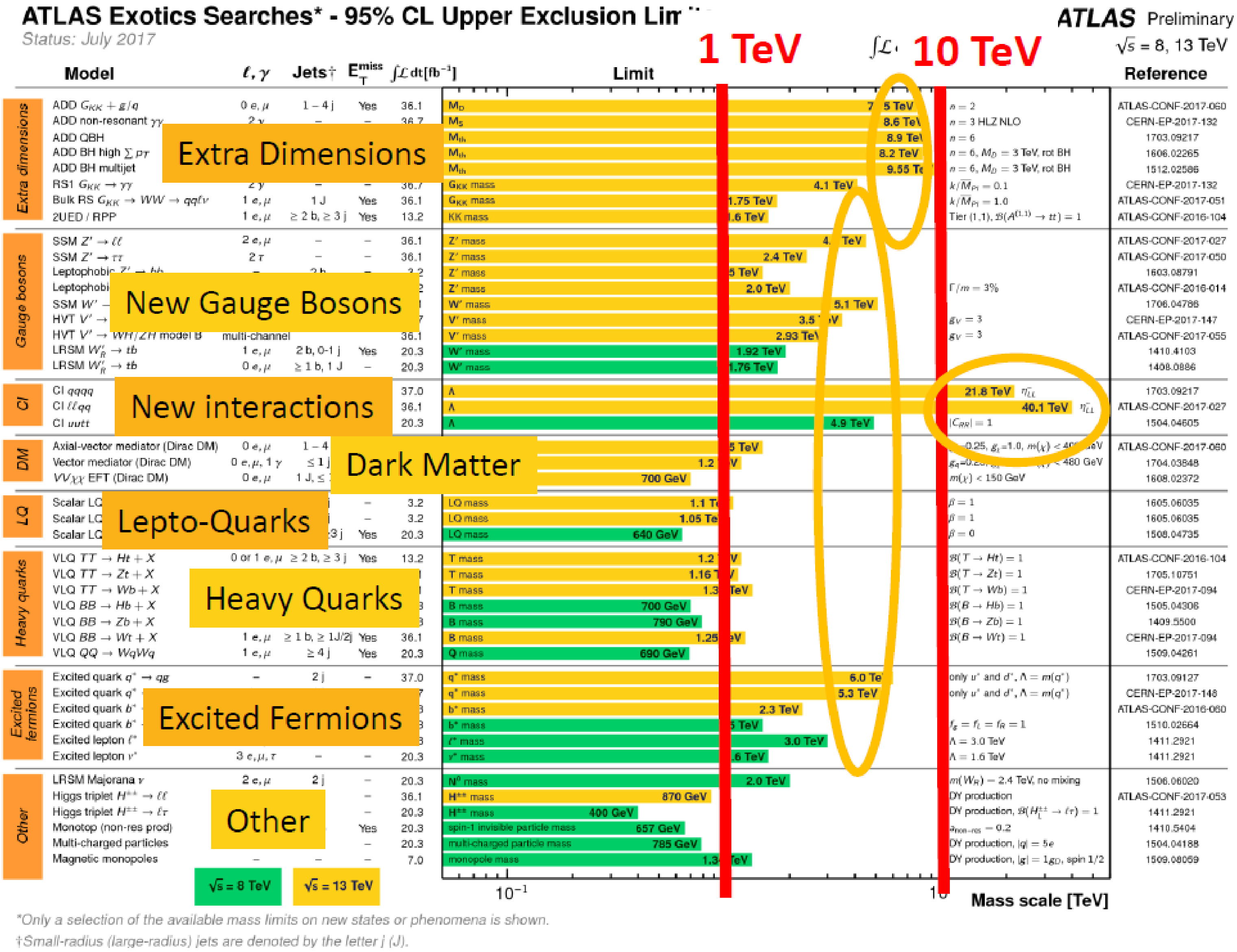
Perfect occasion for young motivated physicists: join the search!



Cross section ratios: 14 (13) TeV / 8 TeV

And: pp → H±(500) + X: 14 TeV/8 TeV ~ 7

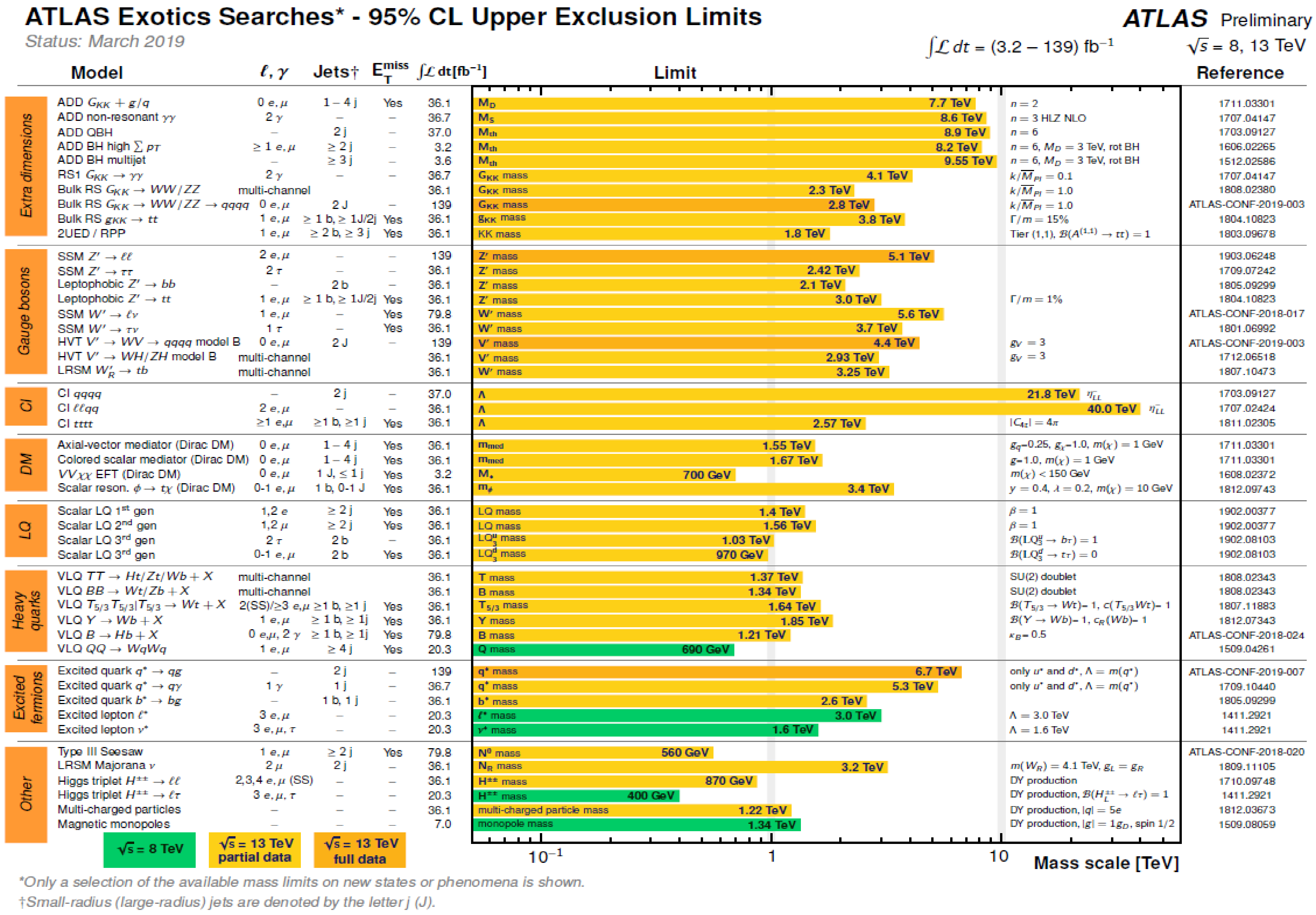
Exploration range of LHC by mid 2017



*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

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

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

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW/ZZ \to qqqq$	0 e, μ	2 J	–	139	G_{KK} mass	2.8 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass	5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass	3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass	4.4 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass	3.25 TeV		1807.10473
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ	40.0 TeV	η_{LL}^-	1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ	3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass	1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass	1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass	1.03 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass	970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass	1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass	1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	7.0	monopole mass	1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

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

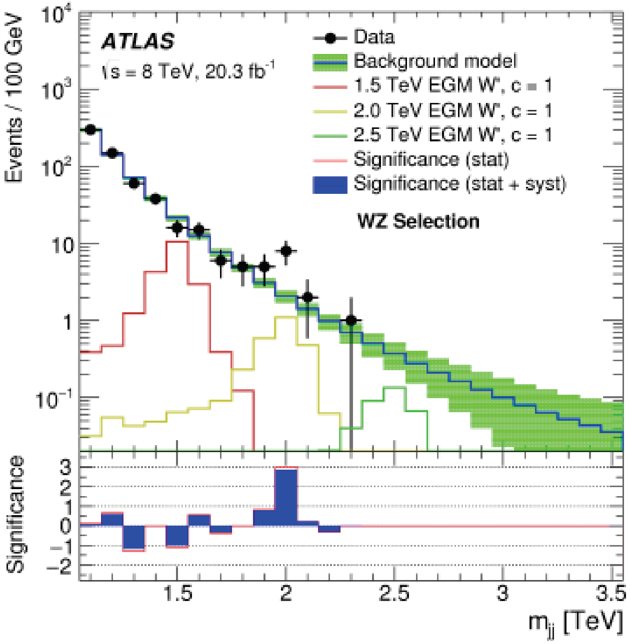
†Small-radius (large-radius) jets are denoted by the letter j (J).

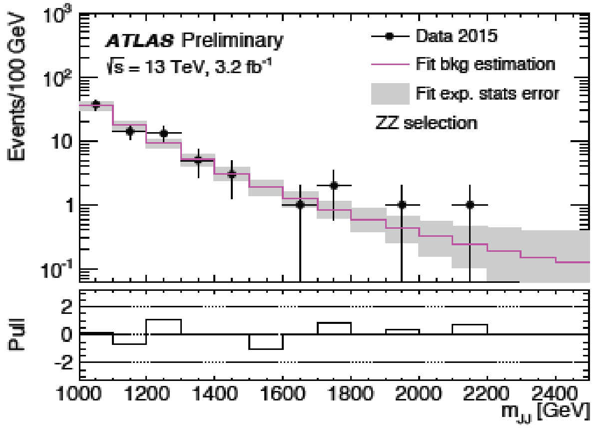
Fully hadronic Diboson Searches

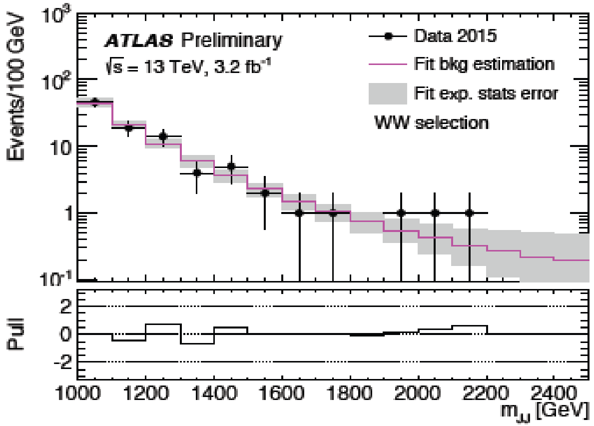
ATLAS-CONF-2015-073

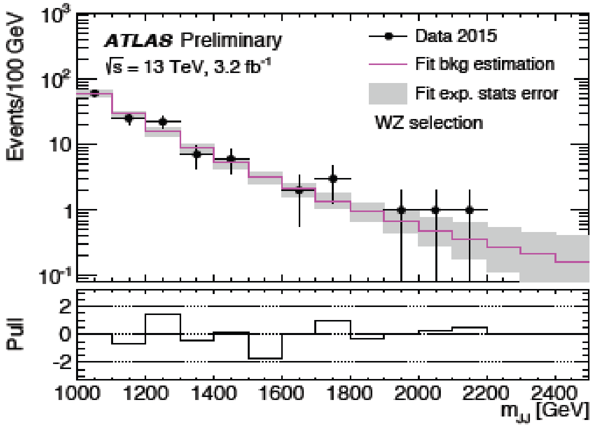
- **Modest excess at Run-1: 3.4σ** local / **2.5σ global**
- **Analysis very similar to Run 1**, with functional fit of the background
- **No significant excess is observed**
  however sensitivity not high enough for conclusive probe of the Run 1 excess

Run-1





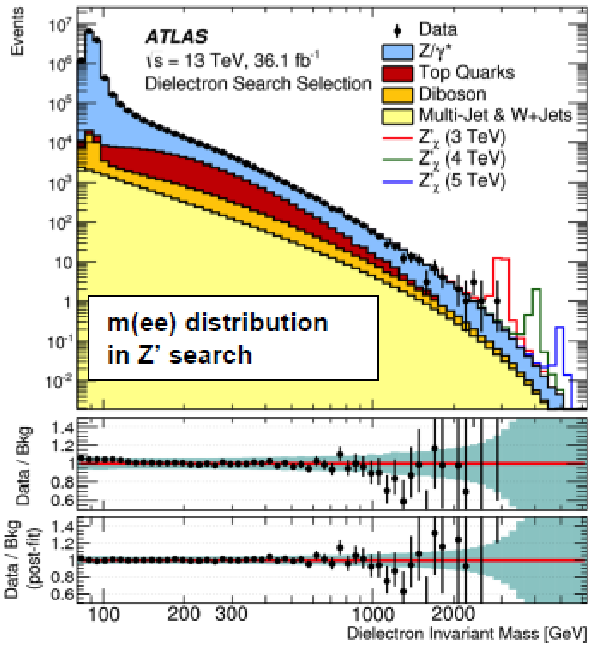




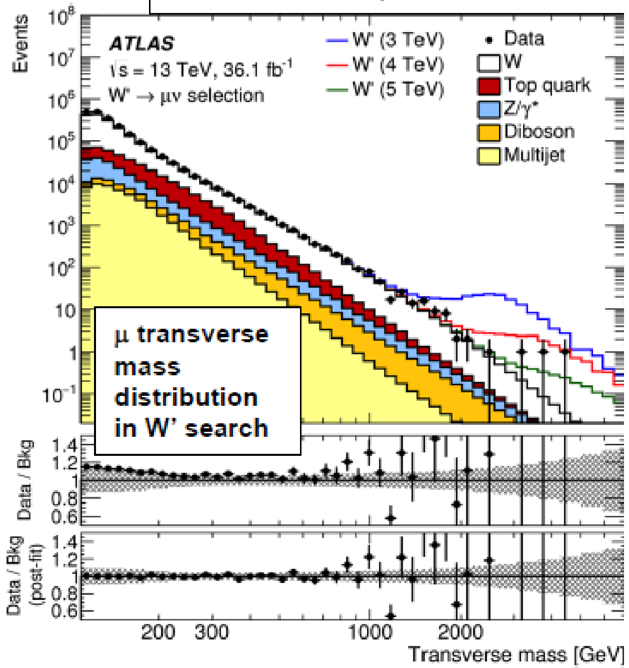
Resonance Searches (Dilepton, Lepton+ETmiss)

- 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 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

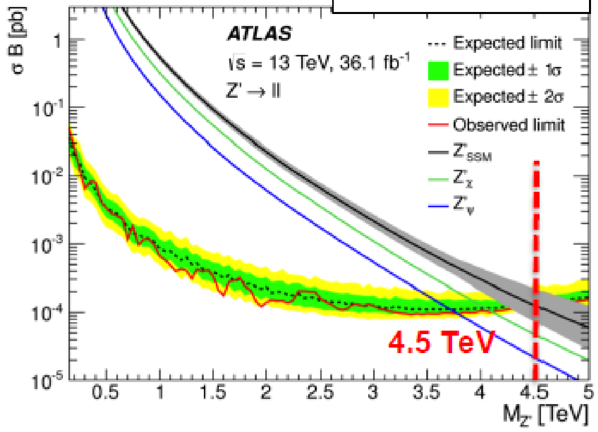


m(ee) distribution in Z' search



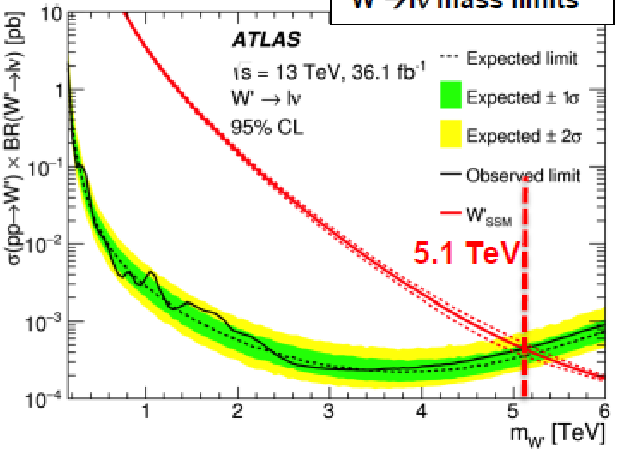
μ transverse mass distribution in W' search

Z'→ll mass limits



4.5 TeV

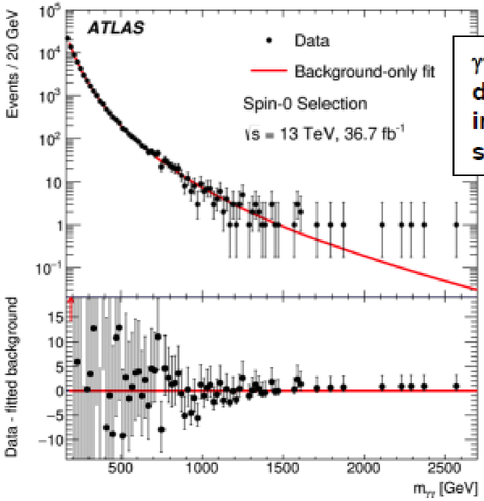
W'→lν mass limits



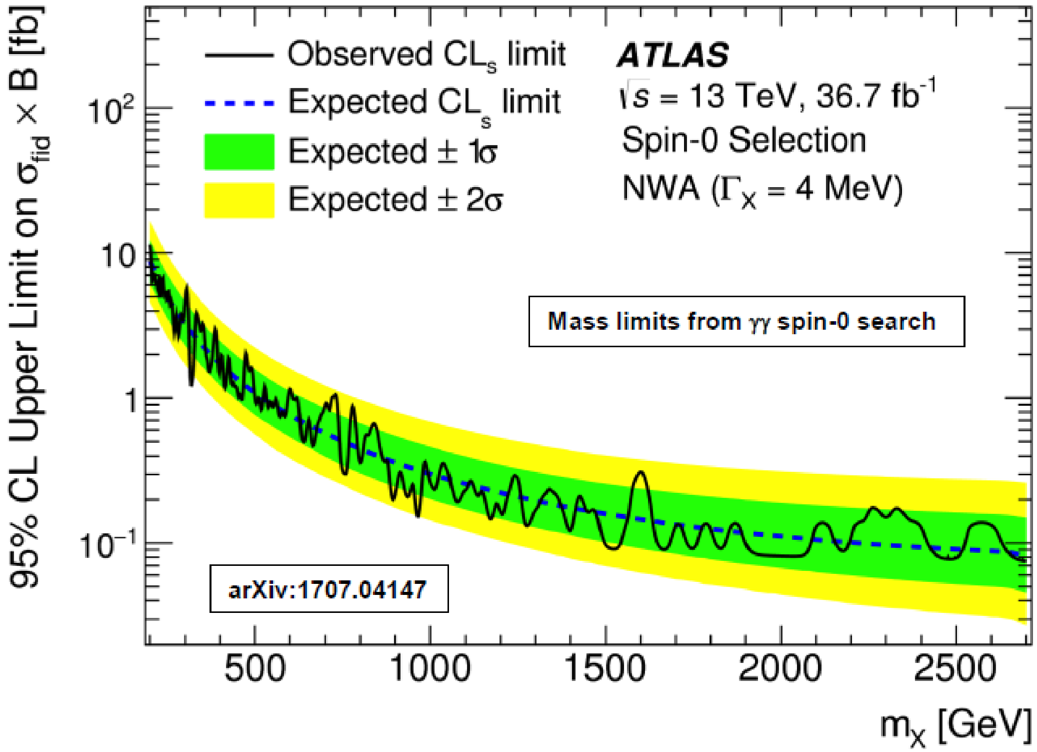
5.1 TeV

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

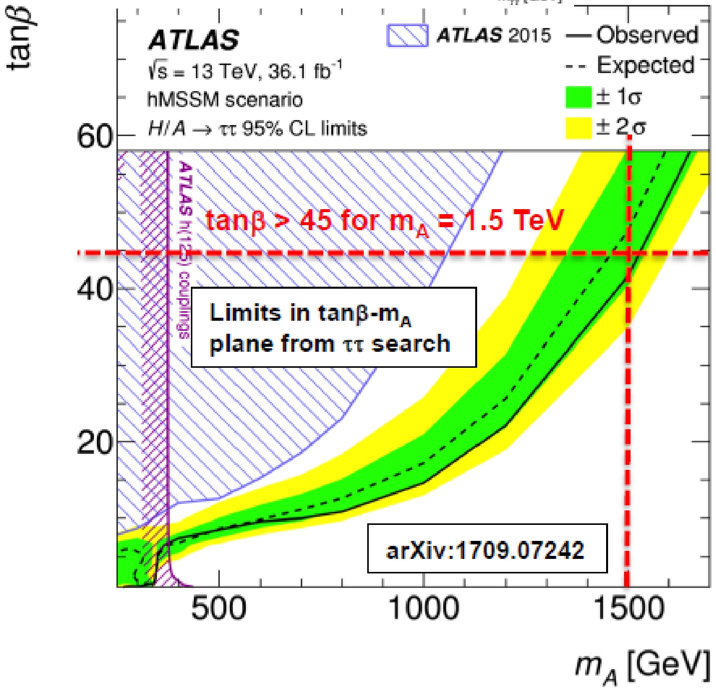


$\gamma\gamma$ mass distribution in spin-0 search



Mass limits from $\gamma\gamma$ spin-0 search

arXiv:1707.04147

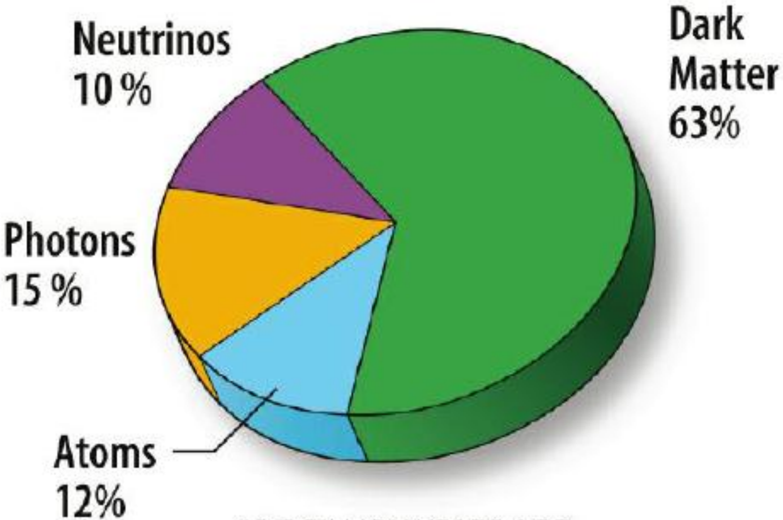


tanβ > 45 for m_A = 1.5 TeV

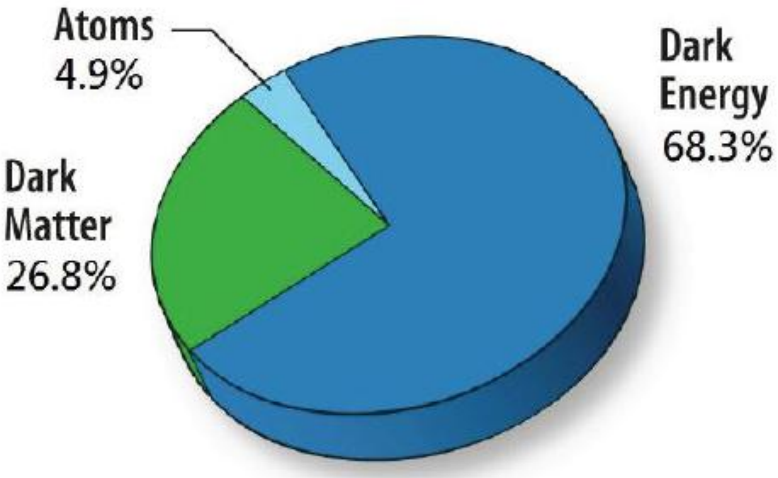
Limits in tanβ-m_A plane from $\tau\tau$ search

arXiv:1709.07242

What do we know about Dark Matter



13.7 BILLION YEARS AGO
(Universe 380,000 years old)



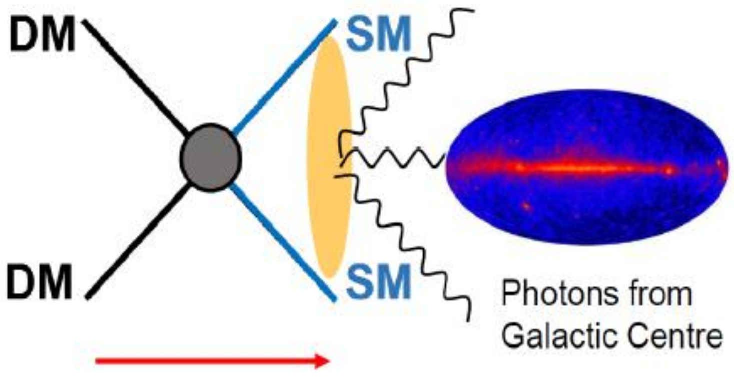
TODAY

Strong astrophysical evidence for the existence of dark matter

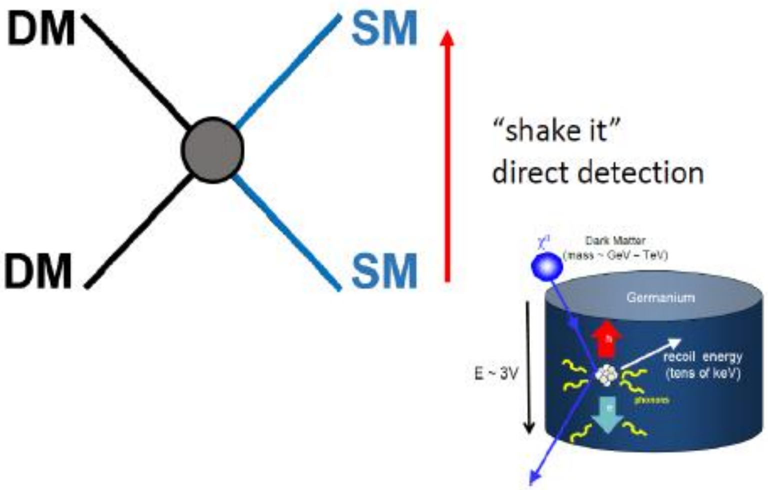
What do we know about Dark Matter

- 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

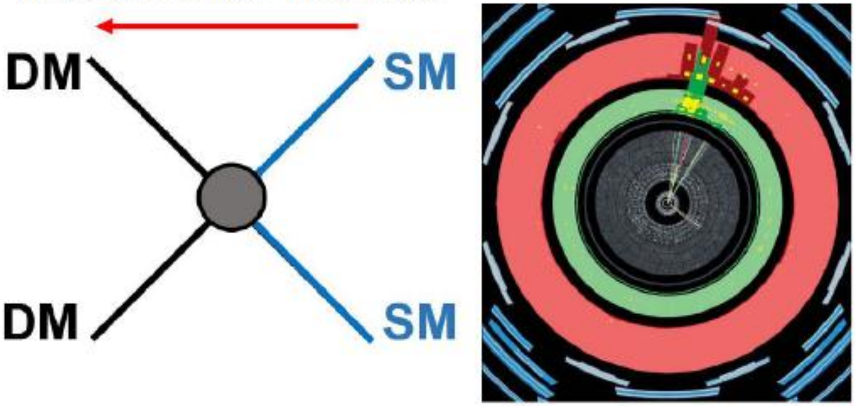


"break it": indirect detection

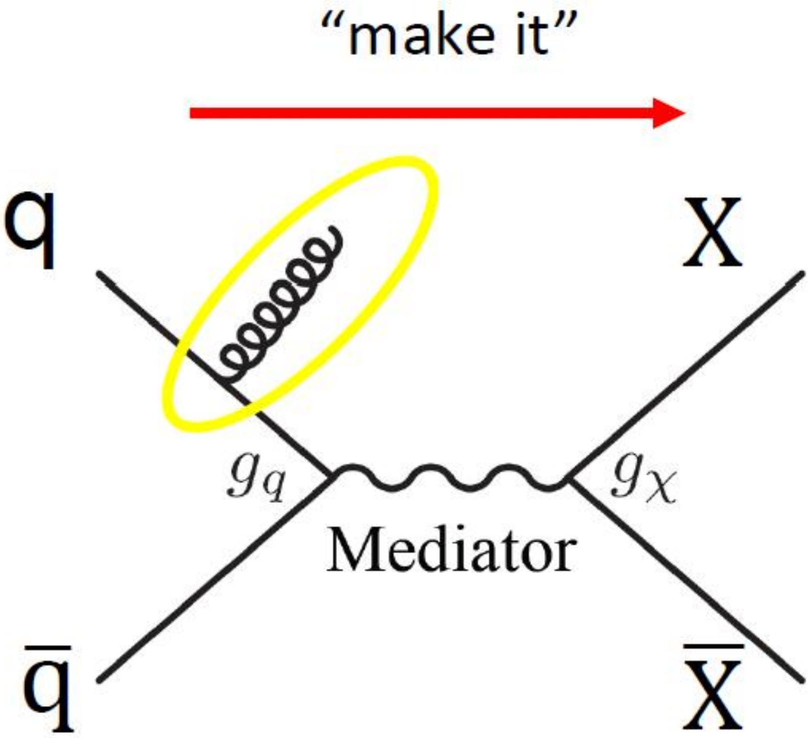


"shake it"
direct detection

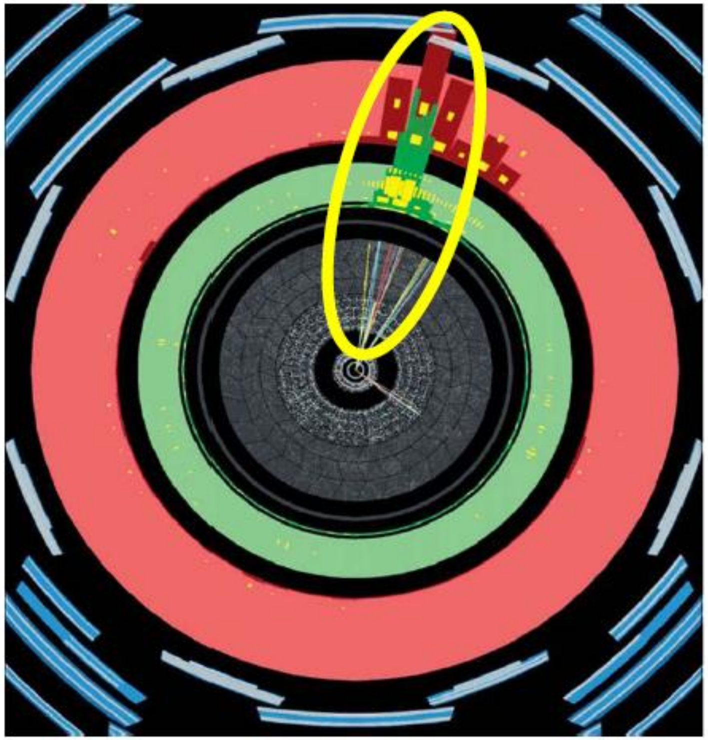
"make it": Collider Production



Dark Matter serches at Colliders

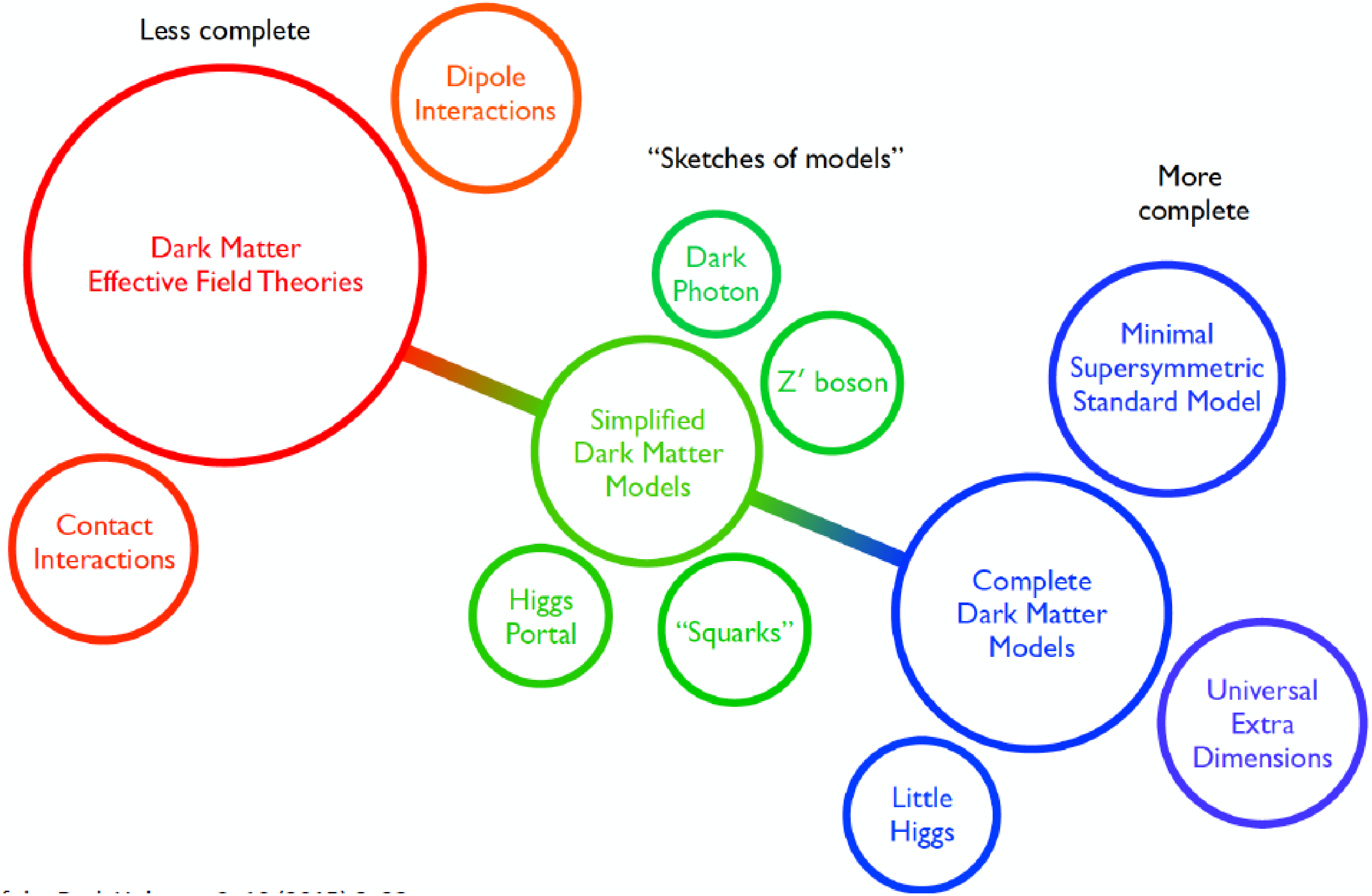


g_q and g_χ coupling strengths



Empty detector + something

Dark Matter theory space



Less complete

Dipole
Interactions

Dark Matter
Effective Field Theories

Contact
Interactions

"Sketches of models"

Dark
Photon

Z′ boson

Simplified
Dark Matter
Models

Higgs
Portal

"Squarks"

More
complete

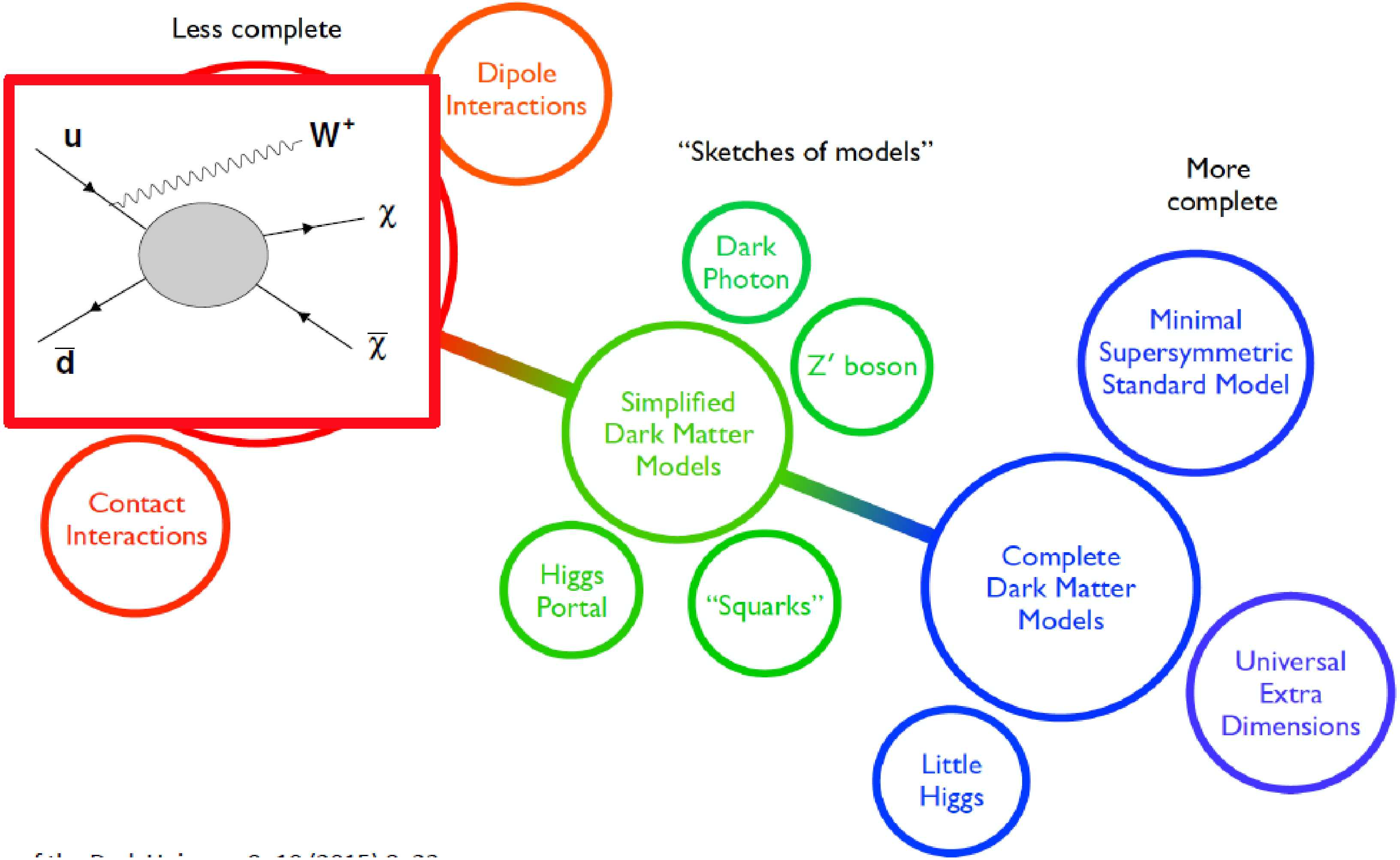
Minimal
Supersymmetric
Standard Model

Complete
Dark Matter
Models

Universal
Extra
Dimensions

Little
Higgs

Dark Matter theory space



Less complete

Dipole Interactions

Contact Interactions

"Sketches of models"

Dark Photon

Z′ boson

Simplified Dark Matter Models

Higgs Portal

"Squarks"

More complete

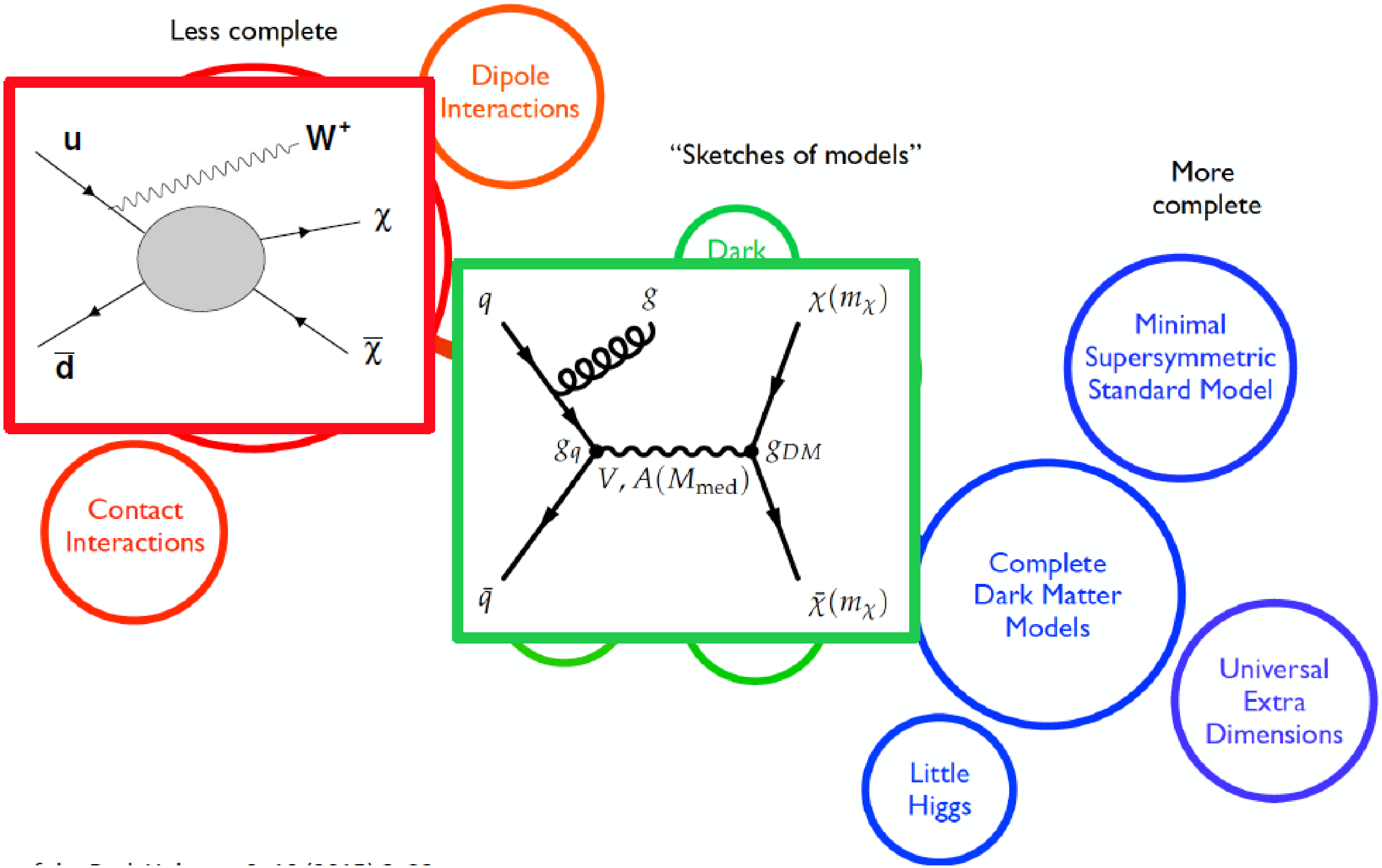
Minimal Supersymmetric Standard Model

Complete Dark Matter Models

Universal Extra Dimensions

Little Higgs

Dark Matter theory space



Less complete

Dipole Interactions

Contact Interactions

"Sketches of models"

Dark

More complete

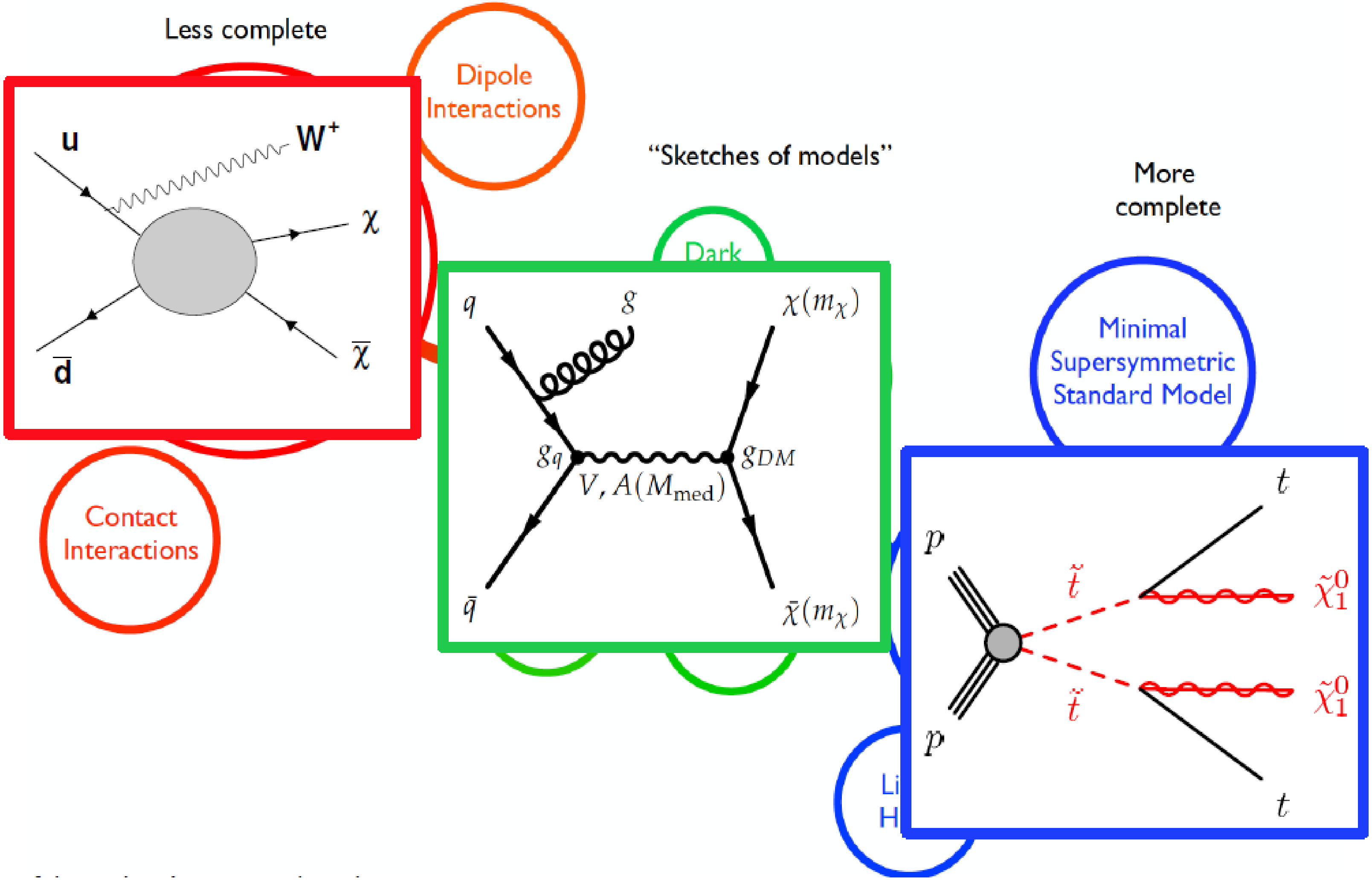
Minimal Supersymmetric Standard Model

Complete Dark Matter Models

Universal Extra Dimensions

Little Higgs

Dark Matter theory space



Less complete

Dipole Interactions

Contact Interactions

"Sketches of models"

Dark

More complete

Minimal Supersymmetric Standard Model

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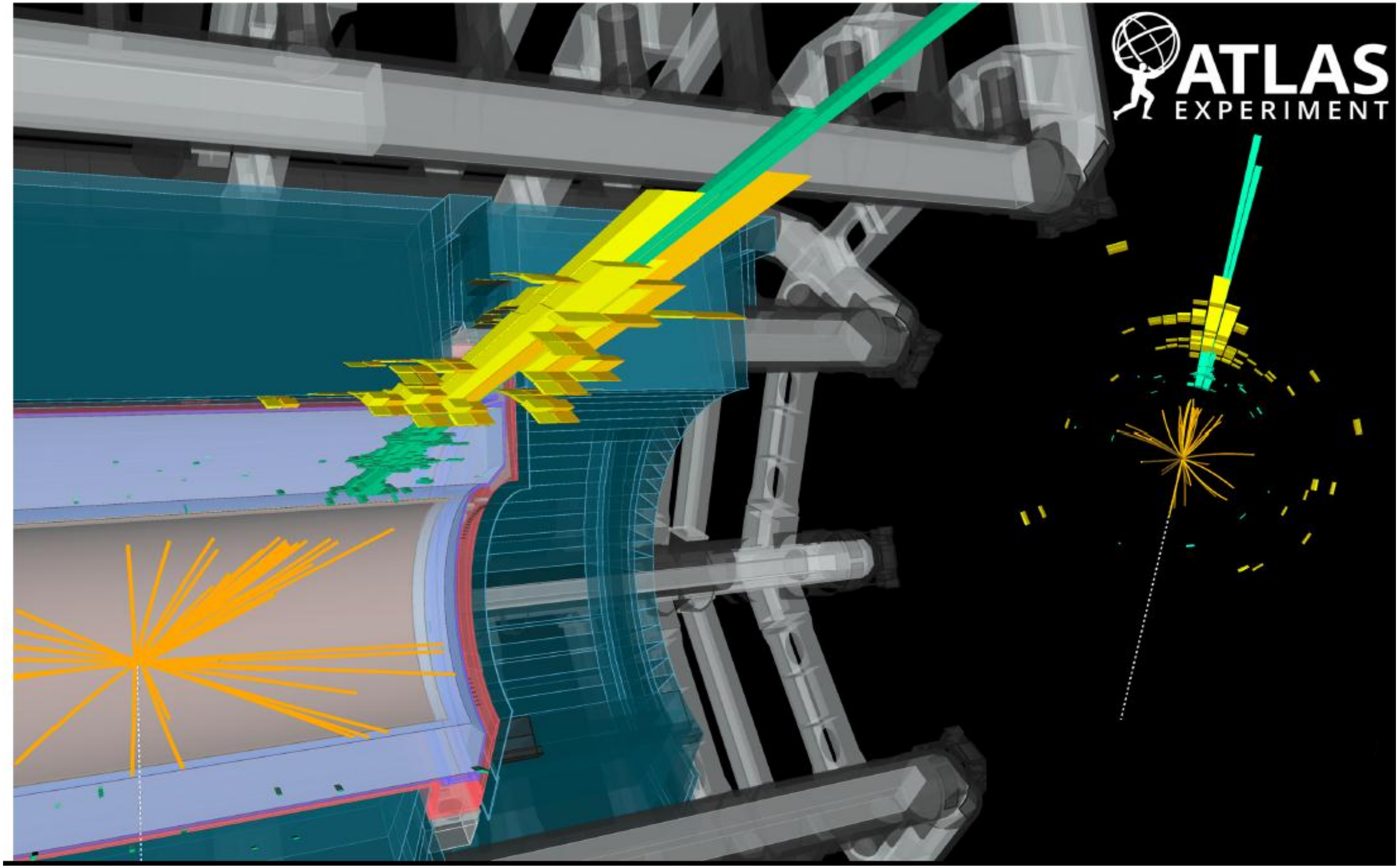
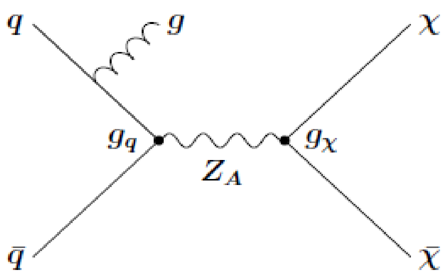
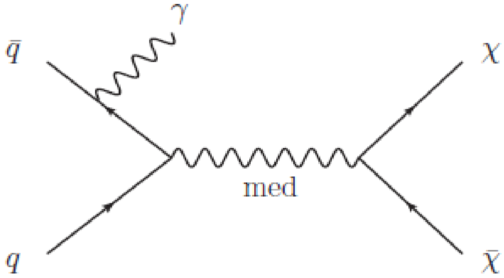
Searches for DM with (E_T^{miss} +X) Signatures

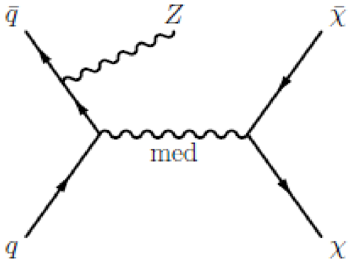


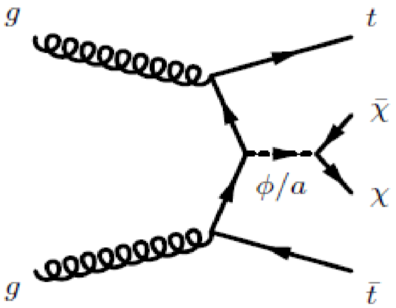
(E_T^{miss} +X) or Mono-X Signatures

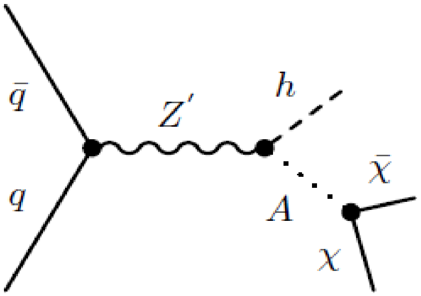
SM-DM mediator decays to DM pairs $\chi\bar{\chi}$ when $M_{\rm med}/2 > m_\chi$.
DM escapes detection $\Rightarrow$ $E_T^{\rm miss} + X$ signature where
X = SM particles that tag the event, $X = {\rm jet}, \gamma, V, t, b, h \ldots$





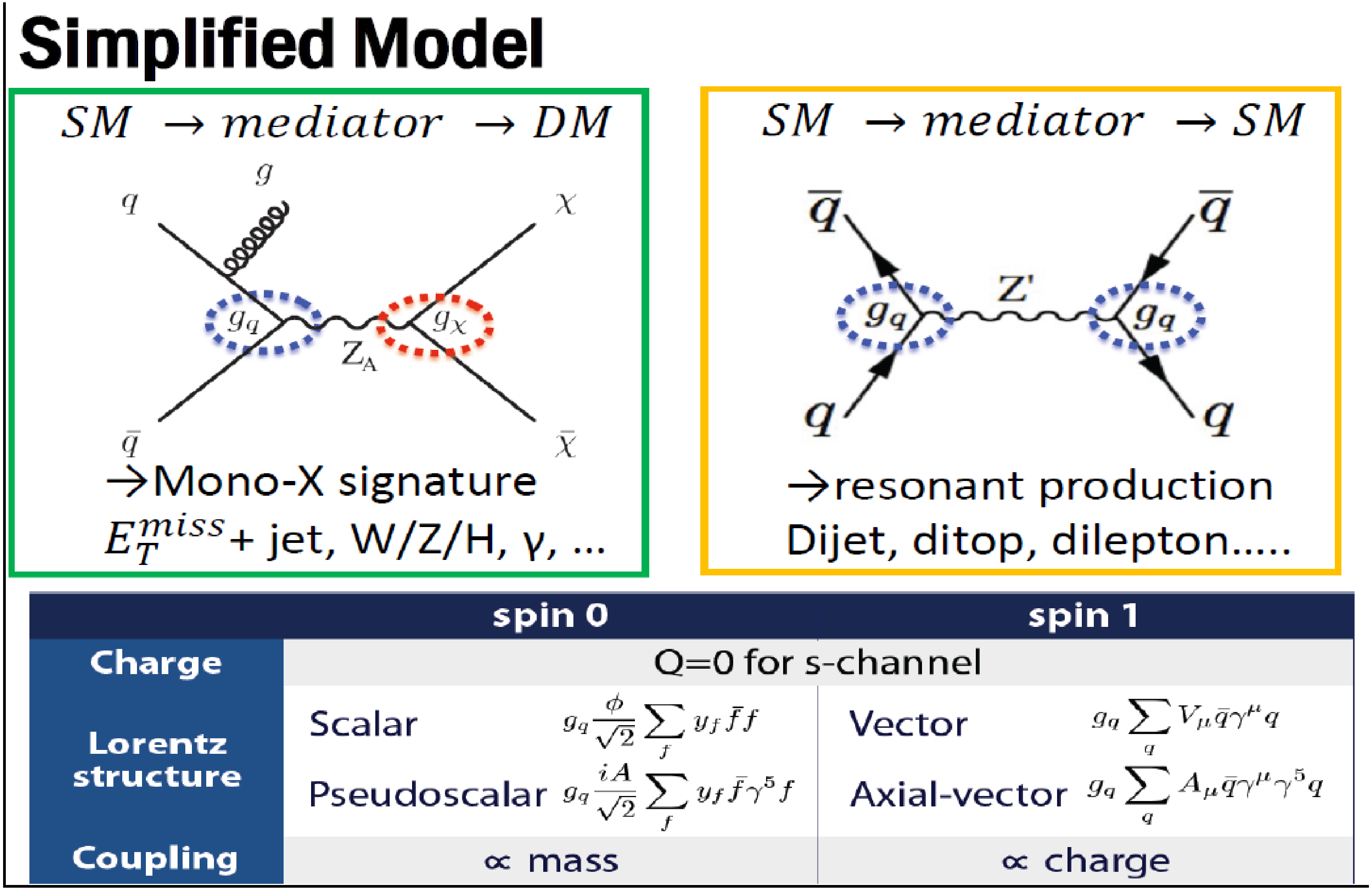






Mediators: vector, axial-vector, scalar, pseudoscalar
Parameters: $m_{\rm med}, m_\chi, g_q, g_\chi$

Simplified Model



Simplified Model

$SM \rightarrow mediator \rightarrow DM$

→Mono-X signature

E_T^{miss} + jet, W/Z/H, γ, ...

$SM \rightarrow mediator \rightarrow SM$

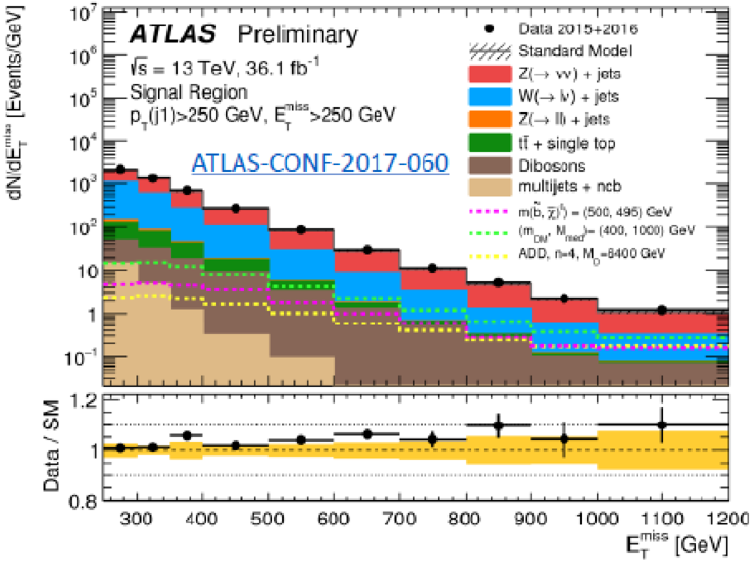
→resonant production

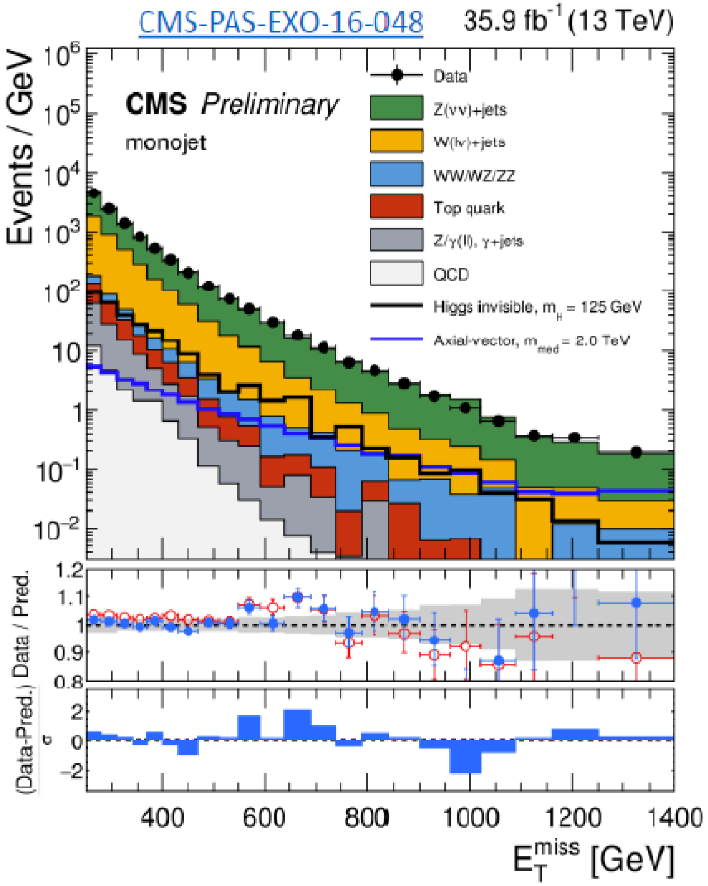
Dijet, ditop, dilepton.....

	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-X searches

Mono-jet





ATLAS

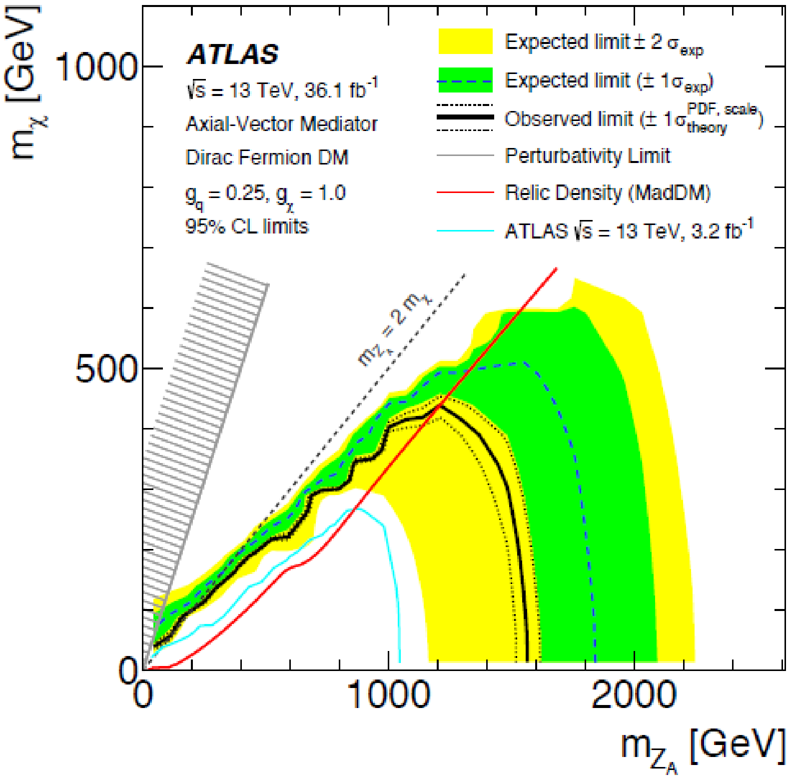
- $E_T^{miss} > 250$ GeV, $\Delta\varphi(\text{jet}, p_T^{miss}) > 0.4$
- Jet $p_T > 250$ GeV, $|\eta| < 2.4$
- $N_{jets} \leq 4$

CMS

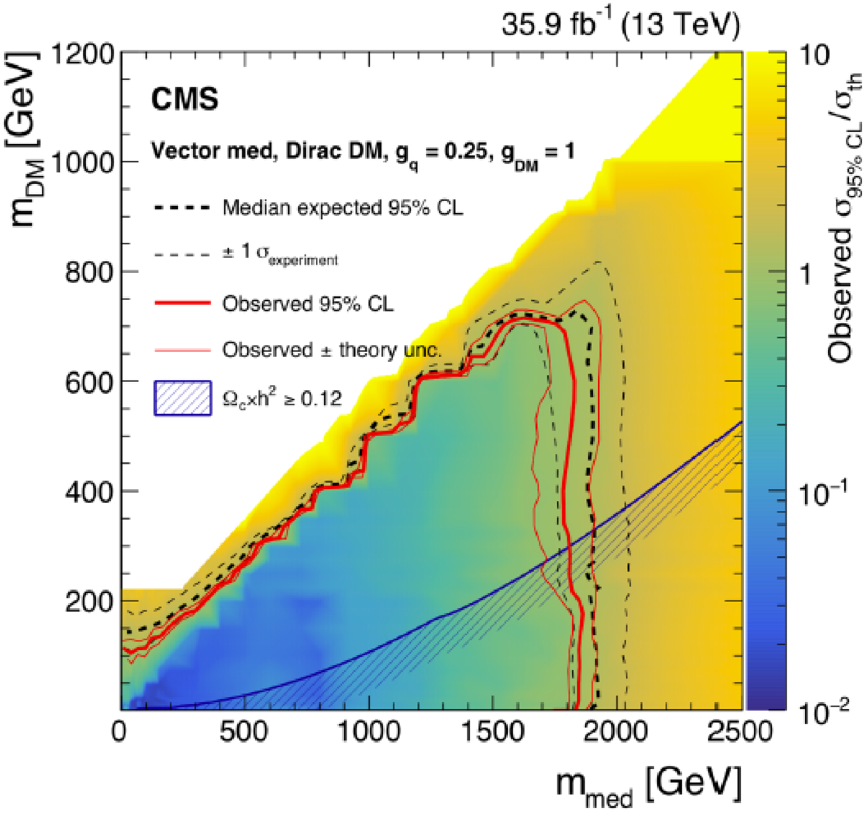
- $E_T^{miss} > 250$ GeV
- Jet $p_T > 100$ GeV, $|\eta| < 2.5$

Mono-X searches

Axial-Vector Mediator



Vector Mediator

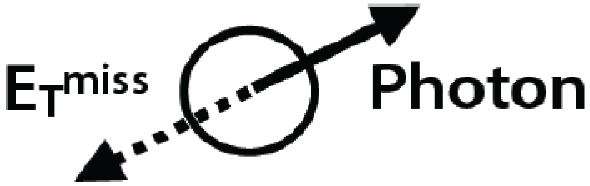


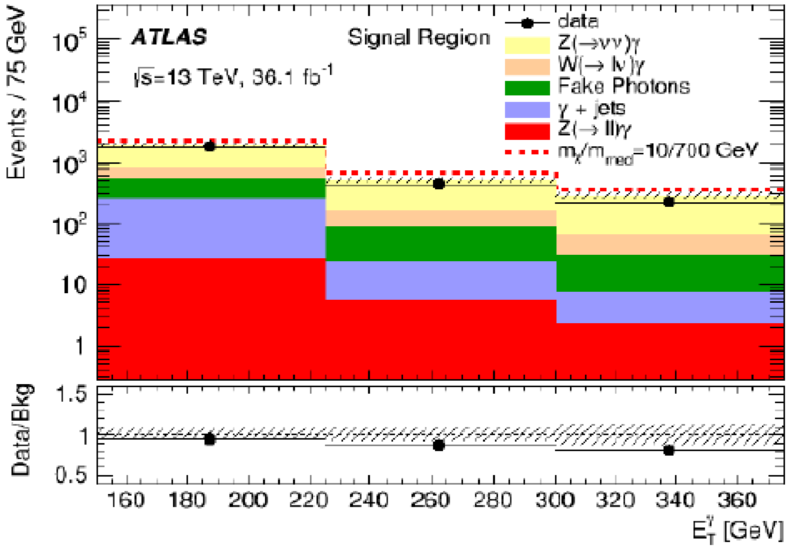
For couplings $g_q = 0.25,\ g_\chi = 1.0$, axial-vector and vector mediators excluded up to 1.8 TeV (1.55 TeV) by CMS (ATLAS) for $m_\chi \sim 1$ GeV.

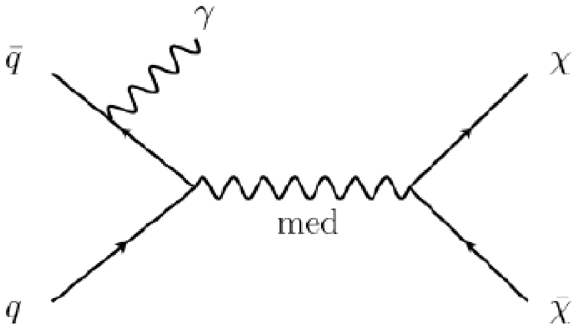
JHEP 01 (2018) 126
arXiv:1712.02345

Mono-X searches

Mono-photon





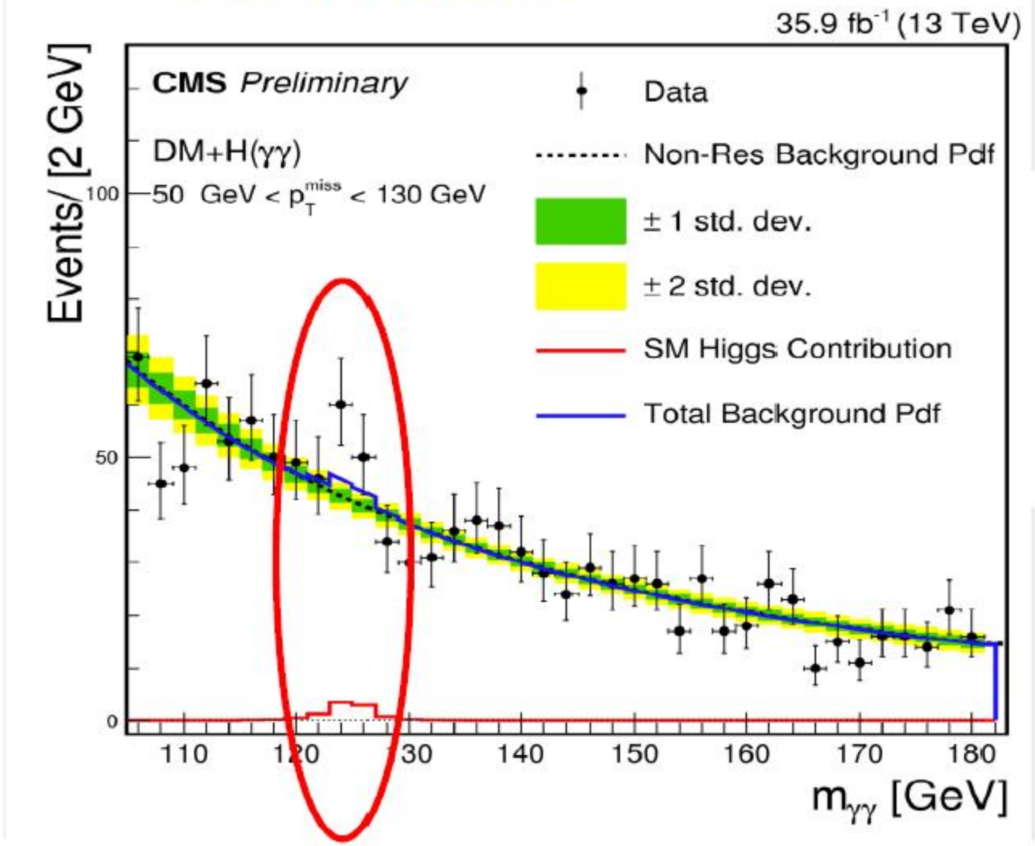


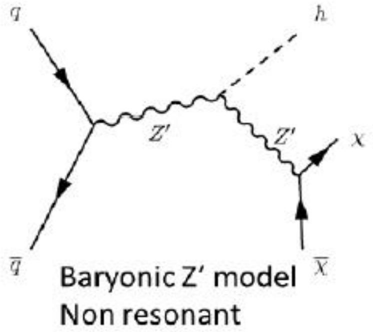
- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{miss}/\sqrt{\sum E_T} > 8.5\ \mathrm{GeV}^{1/2}$
- $\Delta\varphi(\mathrm{photon}, E_T^{miss}) > 0.4$
- $N_{jets}(p_T > 30\ \mathrm{GeV}, |\eta| < 4.5) \leq 1$

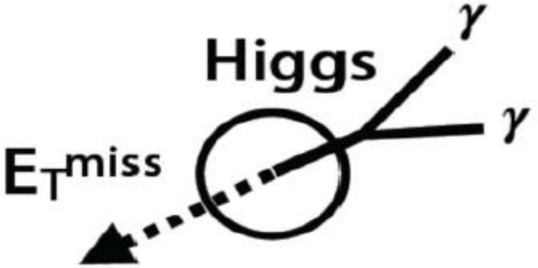
Mono-X searches

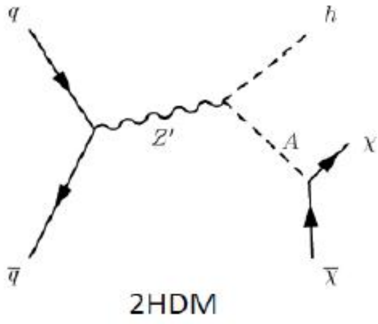
Mono-Higgs

CMS-PAS-EXO-16-054

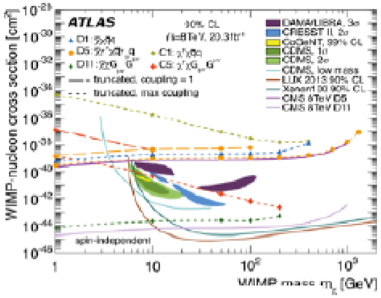






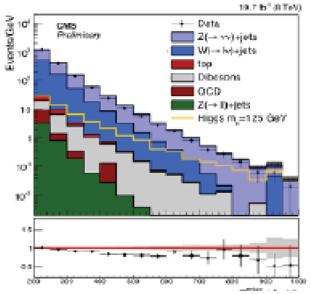


Plenty of mono-signatures



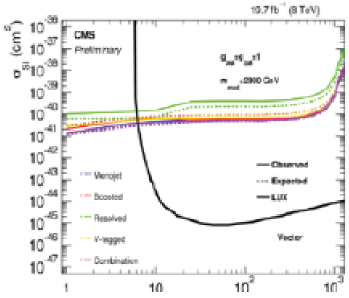
ATLAS Monojet

EPJC (2015) 75:299



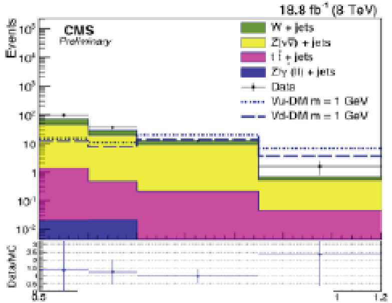
CMS j/V (mono/dijet)

PAS-EXO-12-055



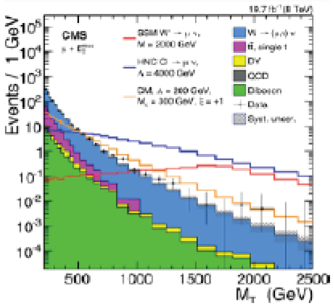
CMS j/V (mono/dijet)

PAS-EXO-12-055



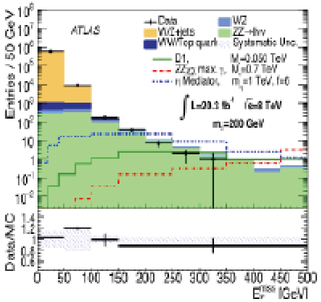
CMS Razor (dijet)

PAS-EXO-14-004



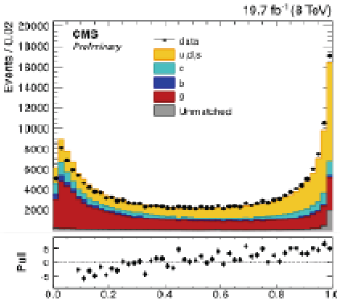
CMS, ATLAS MonoW

PRD 91, 092005, JHEP 09 (2014) 037 (2015)



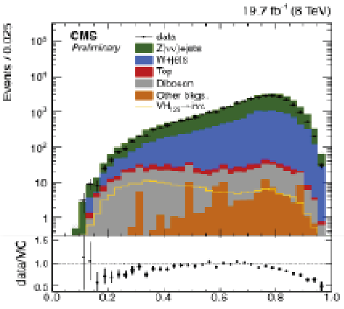
CMS, ATLAS MonoZ

EXO-12-054, PRD 90, 012004 (2014)



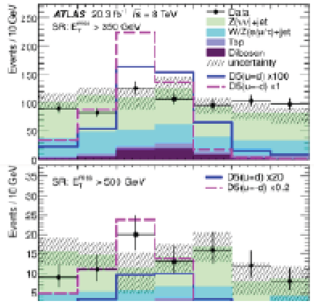
CMS MonoV (resolved)

PAS-EXO-12-005, PAS-JME-14-002



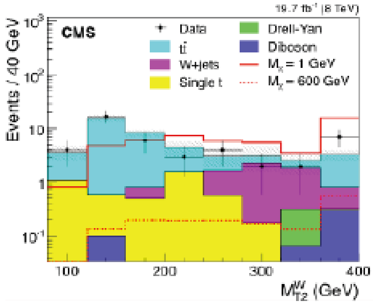
CMS MonoV (boosted)

EXO-12-005/JME-14-002



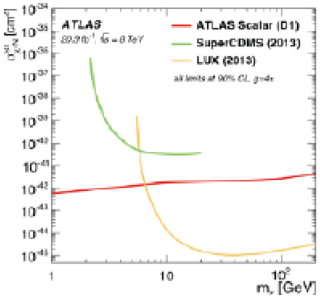
ATLAS MonoV (boosted)

ATLAS, PRL 112, 041802 (2014)



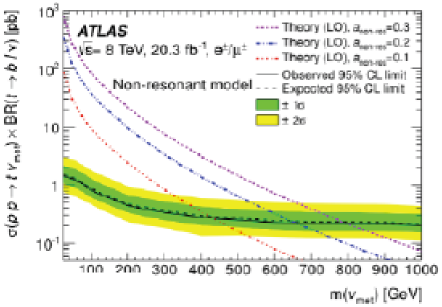
CMS TopPairs

CMS, JHEP 06 (2015) 121



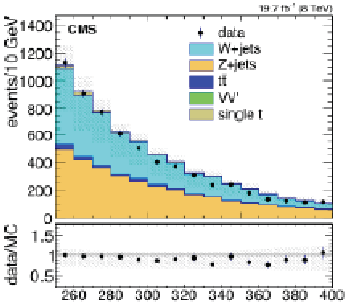
ATLAS TopPairs

ATLAS, EPJC (2015) 75:92



CMS MonoTop

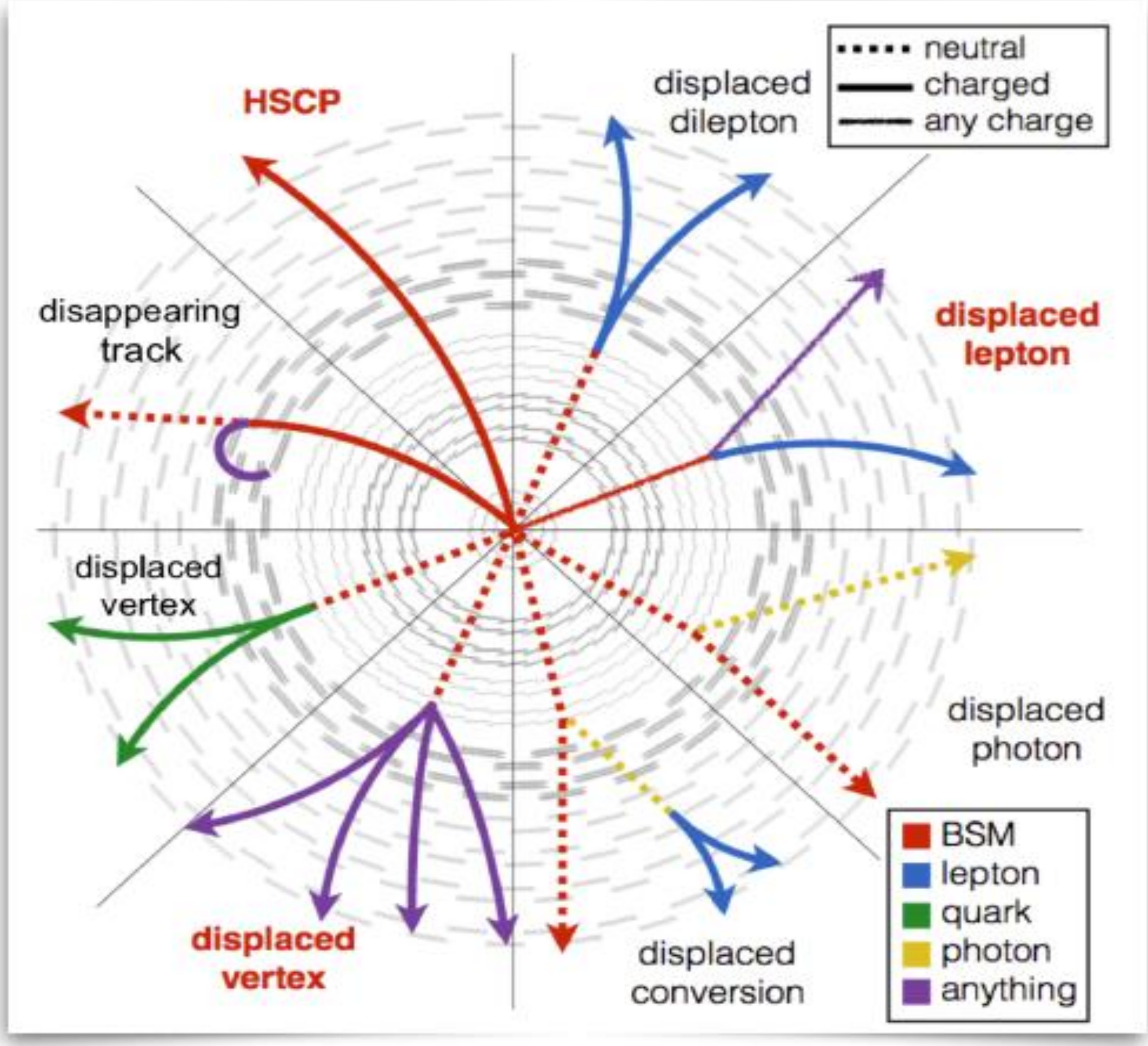
CMS, PRL 114 (2015) 101801



ATLAS MonoTop

ATLAS, JHEP 11 (2014) 118

Unconventional signatures

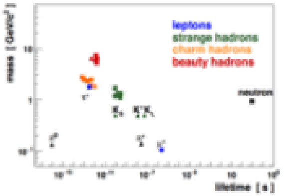


Unconventional signatures: challenges

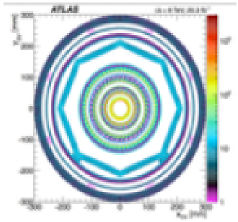
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
  - First step in every search for LLPs: make sure that interesting events are saved!
    1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger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

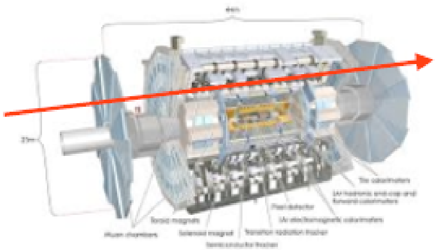
weak decays of heavy flavour



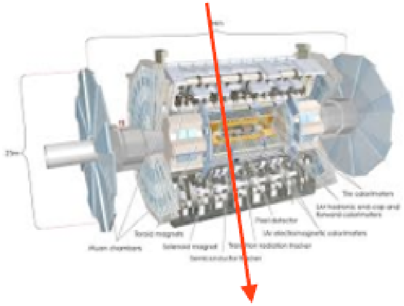
material interactions



beam halo muons



cosmic muons



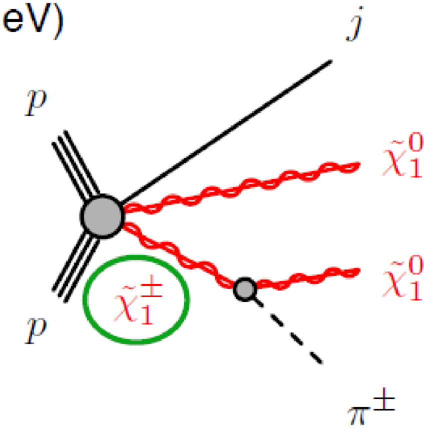
- Systematic uncertainties: can't use standard recommendations for object reconstruction nor trigger

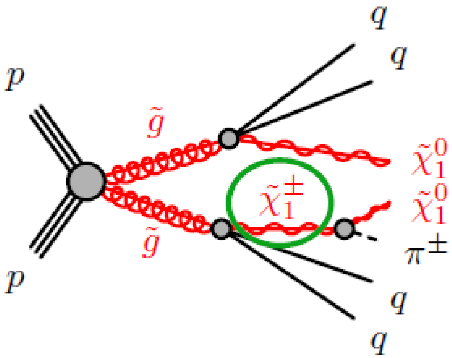
Unconventional signatures: disapearing tracks

LLP

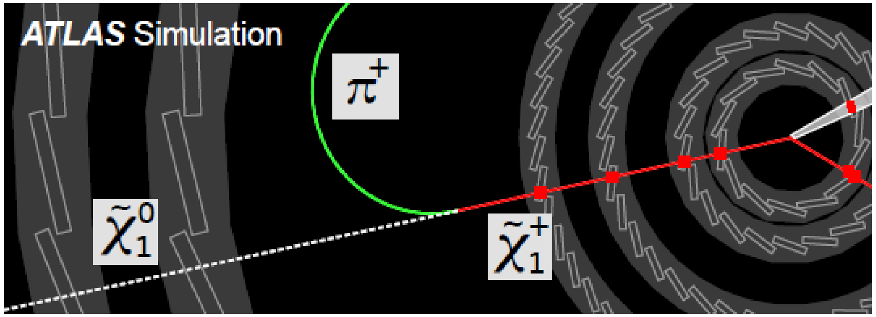
- Search for disappearing track + MET + jets
- Signature: Chargino track “disappears” when it decays, into MET
  - Low momentum pion track (~0.1 GeV) is hard to reconstruct
  - Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks

- Benchmark model: AMSB model with almost degenerate neutralino and chargino Δm ~ O(100 MeV)





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

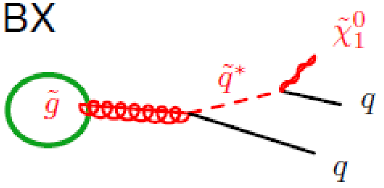


Unconventional signatures: stopped particles

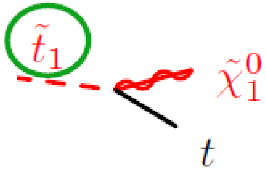
- Search for stopped LLPs decaying during non-collision bunch crossings (BX)

- Signature: LLPs come to rest in the detector and decays after the current BX
  - most likely to stop in the densest detector materials:
    - Calorimeters (ECAL, HCAL):

      a) Split SUSY: two-body and three-body decays of a gluino



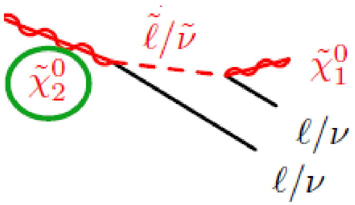
      b) top squark decay



    - Steel yoke in the muon system:

      a) three-body decay of the gluino (g → $qq\chi_2$, χ_2 → $\mu\ \mu\ \chi_1$)

      b) MCHAMPs, with charge |Q| = 2e decays into two same-sign muons (MCHAMP → $\mu^{\pm}\mu^{\pm}$)



- Search sensitive to wide range of LLP lifetime: 10^{-5} to 10^{6} s

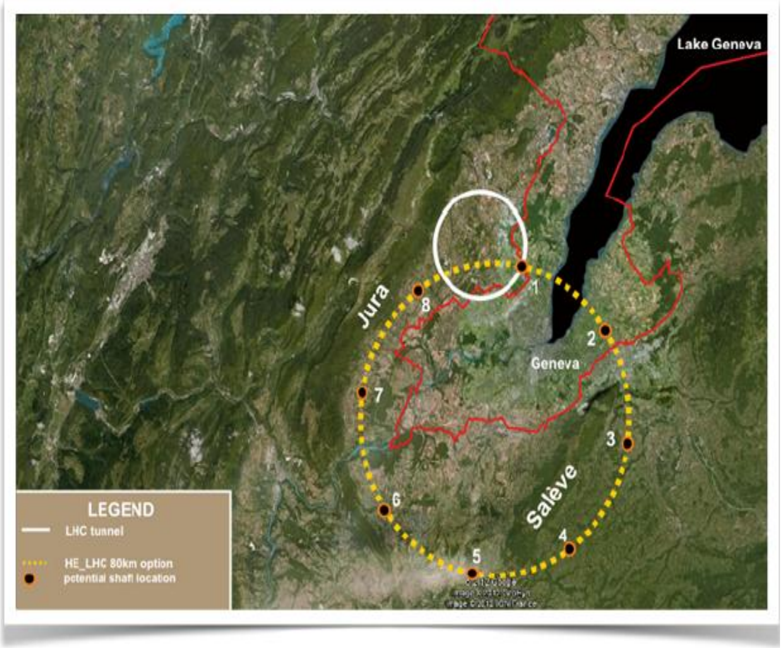
Summary (Exotic Searches)

- 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
  - $m_{DM} < O(10\ \text{GeV})$

Glimpse at Future Hadron Colliders

The candidate machines in a tiny nutshell

Project	HL-LHC	HE-LHC	FCC-hh	SppC
Location	CERN	CERN	CERN	China TBD
Circ.	27 km	27 km	100 km	55 - 100 km
COM energy	14 (15?) TeV	27 TeV	100 TeV	70 -140 TeV
Luminosity	3 ab-1	15 ab-1	20-30 ab-1	TBD
PU	up to 200	up to 800	up to 1000	TBS
Bunch sp.	25 ns	25 ns	25 ns	25 ns
Field	8T	16T	16T	20T
When?	Until 2037	After 2037?	After 2037	TBS



Much much more in Lecture by R. Corsini

Detector, Trigger DAQ, Reconstruction challenges

Two challenges: higher PU (1000) higher pT

Answer: granularity and resolution

Decay products of a Z at 10 TeV are separated by $\Delta R = 0.01$

A b at 5 TeV can travel 50cm and a tau 10 cm