

# HOW WE LOOK FOR DARK MATTER AT THE LHC

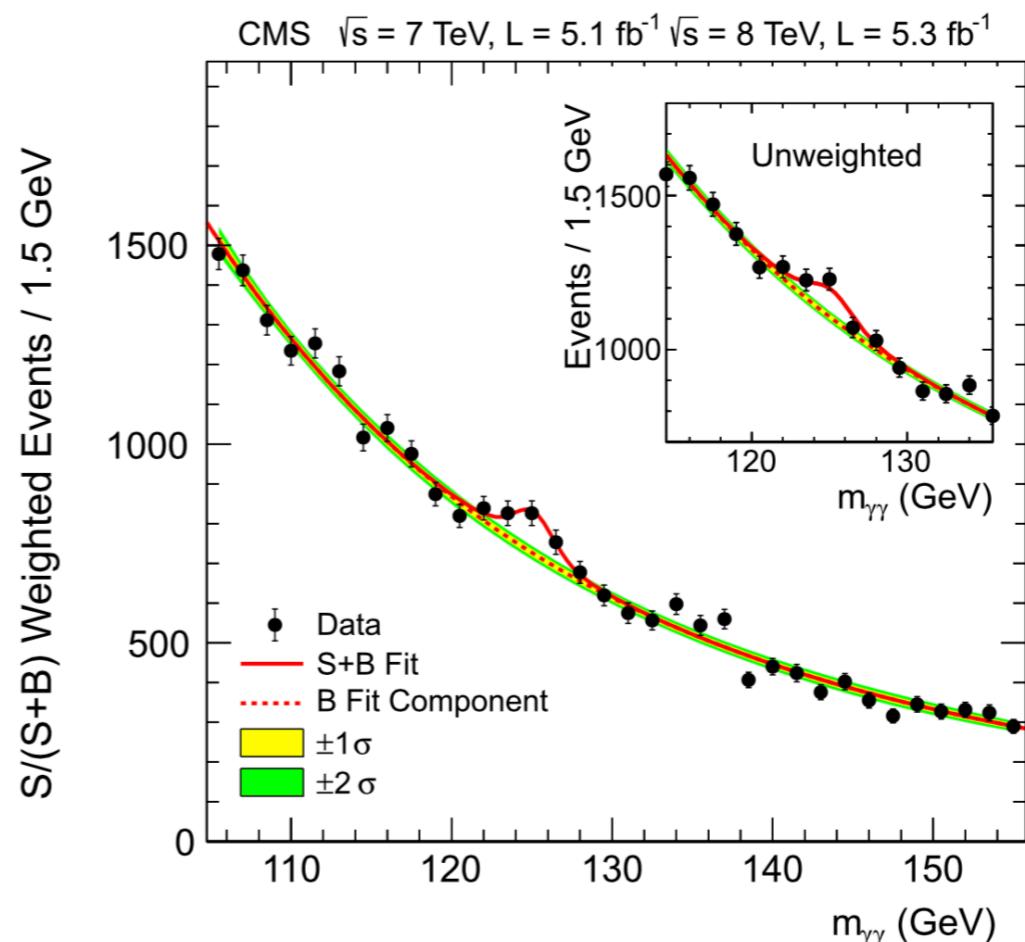
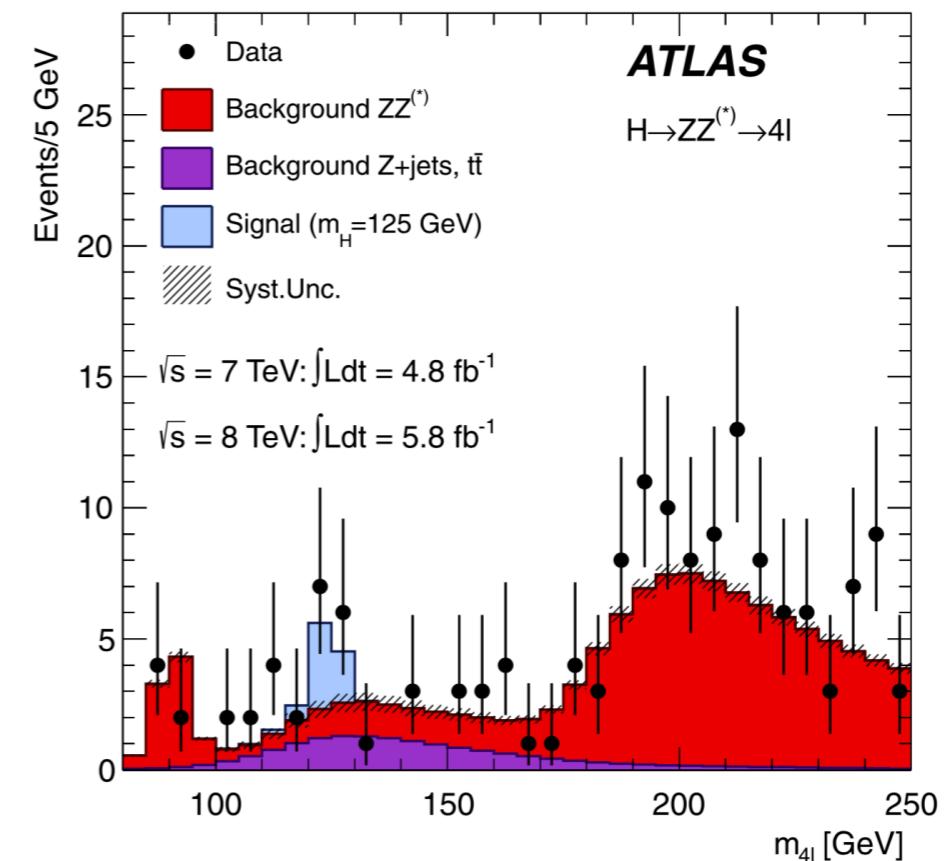
part II: gauge bosons and beyond

a talk on behalf of the ATLAS and CMS collaborations

## BORN ON THE FOURTH OF JULY (2012)

Phys.Lett. B716  
(2012) 1-29  
Phys.Lett. B716  
(2012) 30-61

- six years ago we discovered a new particle ( $H$ ) which behaves as the Higgs boson
  - spin-0, couplings compatible with Standard Model (SM) within  $\sim 30\%$  precision
- can it tell us something on new physics?
  - could easily show up with 1% / 0.1% deviations (loops)
  - per-se a motivation to run LHC until  $\sim 2038$
- could it be a portal to the invisible?
  - the (or, a) scalar boson mediating the standard sector and a dark sector

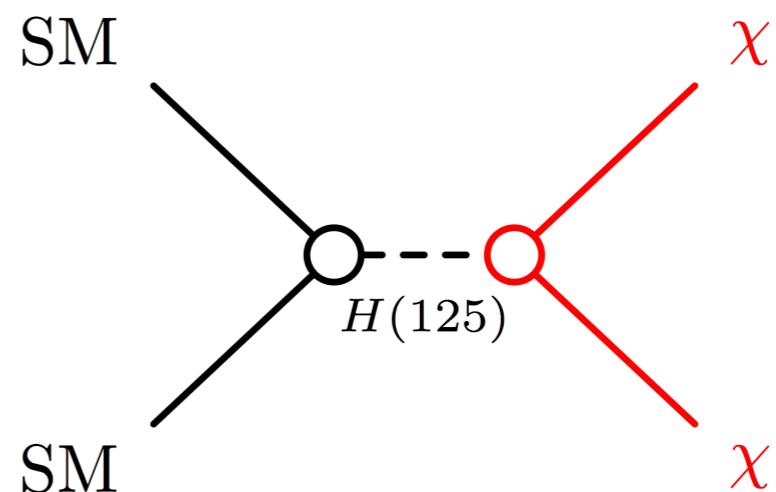


## HIGGS, A TOOL FOR WIMP DISCOVERY?

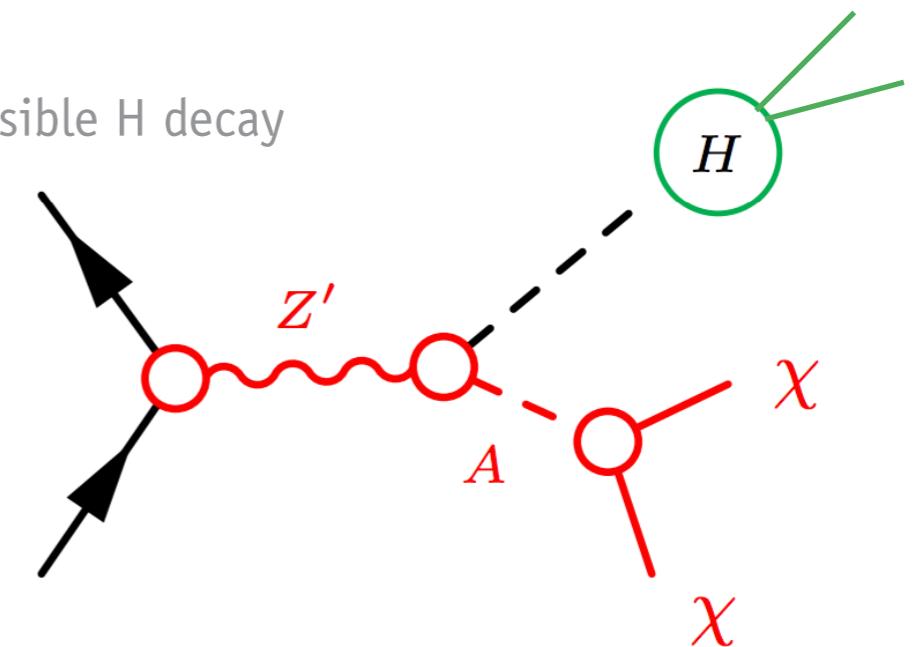
decay to heavier  
WIMPs would be  
kinematically  
prohibited

- a light WIMP ( $< \sim 62$  GeV) could couple directly to H: a new, invisible decay channel
  - compare to SM  $H \rightarrow ZZ^* \rightarrow vvvv$  ( $BR \sim 0.1\%$ )
- something you can do only at a collider...
  - spin-0 interaction may yield velocity-suppressed direct-detection cross-sections ( $J^P=0^-$ )
  - can access a plethora of final states to fully probe scenarios beyond the SM
    - ★ not necessarily limited to low-mass WIMPs
    - ★ e.g.: SUSY, Dark Sectors...
- also possible: indirect BR measurement from all other visible decay channels
- different experimental challenges for invisible or visible H decay

invisible H decay

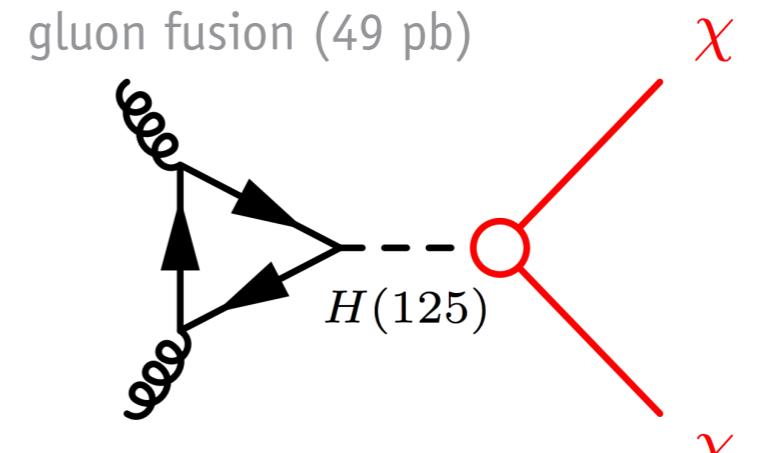
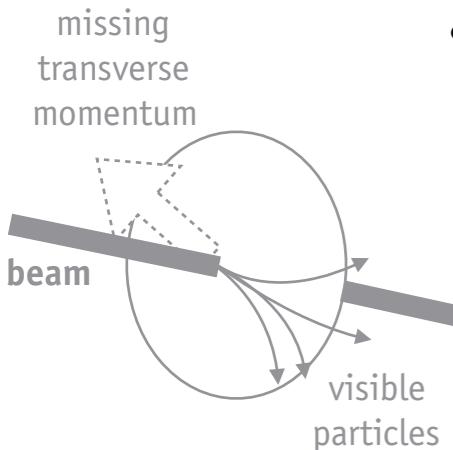


visible H decay

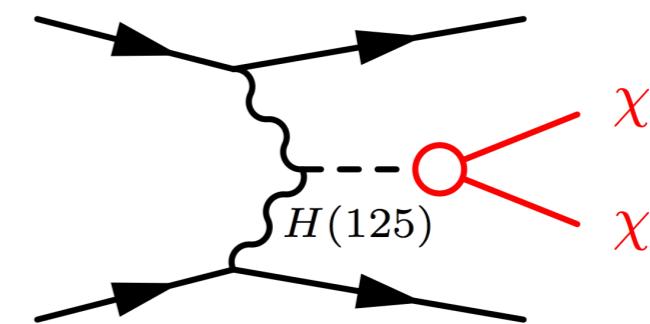


## H->INVISIBLE: CROSS-SECTION ISN'T THE FULL STORY

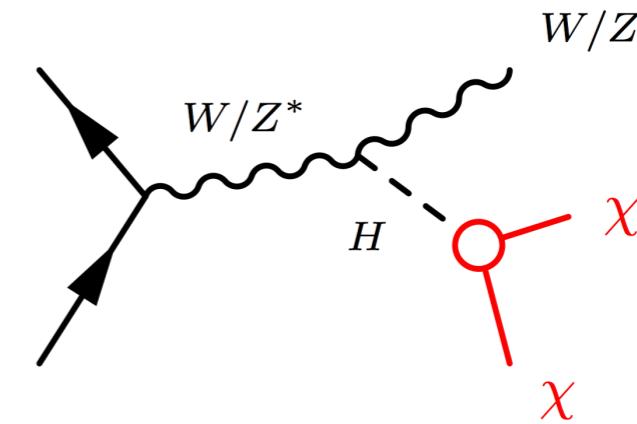
- vector-boson-fusion (VBF) is both the most challenging and most sensitive production mode
  - missing transverse momentum and forward jets
  - requires excellent calorimetry, extending to the highest-radiation region (close to proton beams)
- associated production comes next
  - missing transverse momentum and leptonic decay of W or Z
  - requires accurate particle reconstruction and identification
- ubiquitous player: missing transverse momentum
  - neutrinos are the obvious background



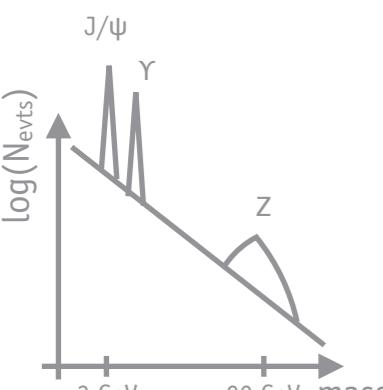
vector-boson fusion (3.8 pb)

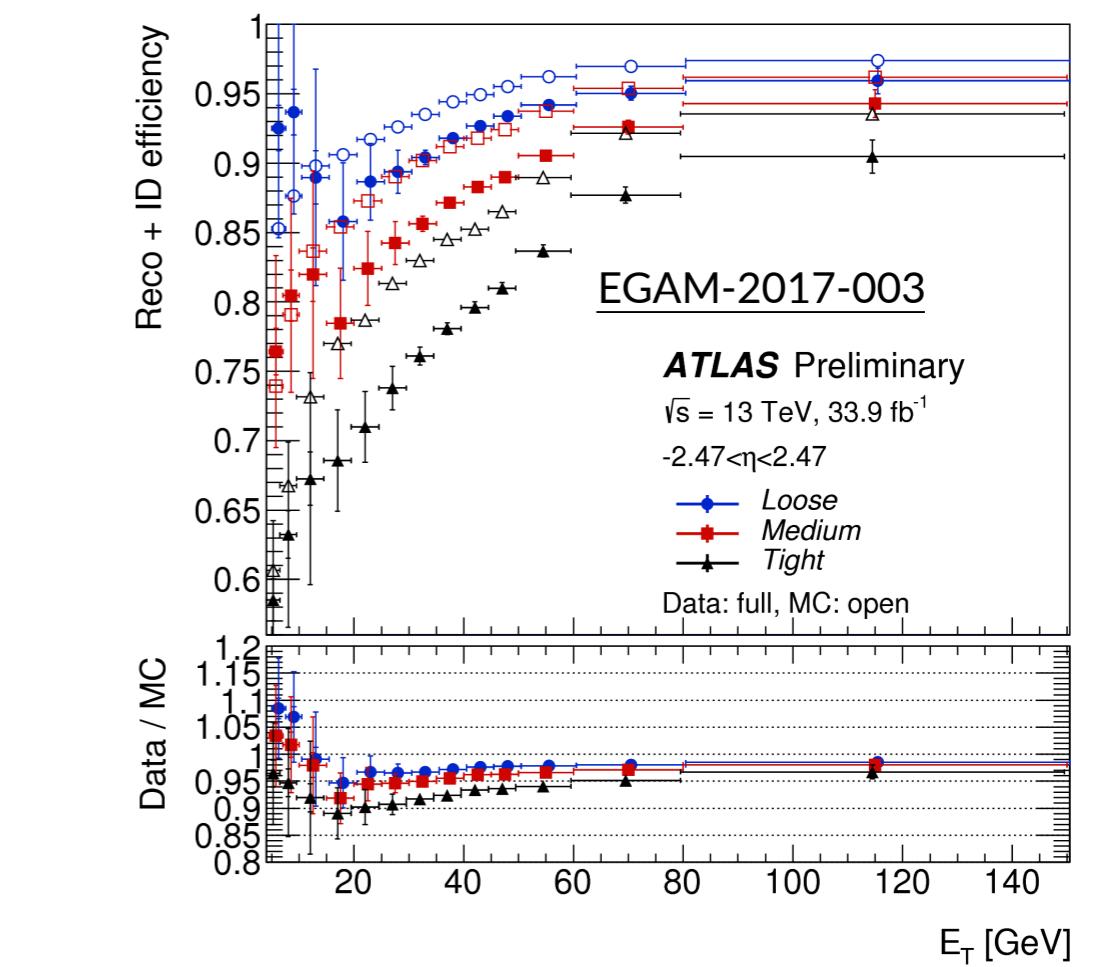
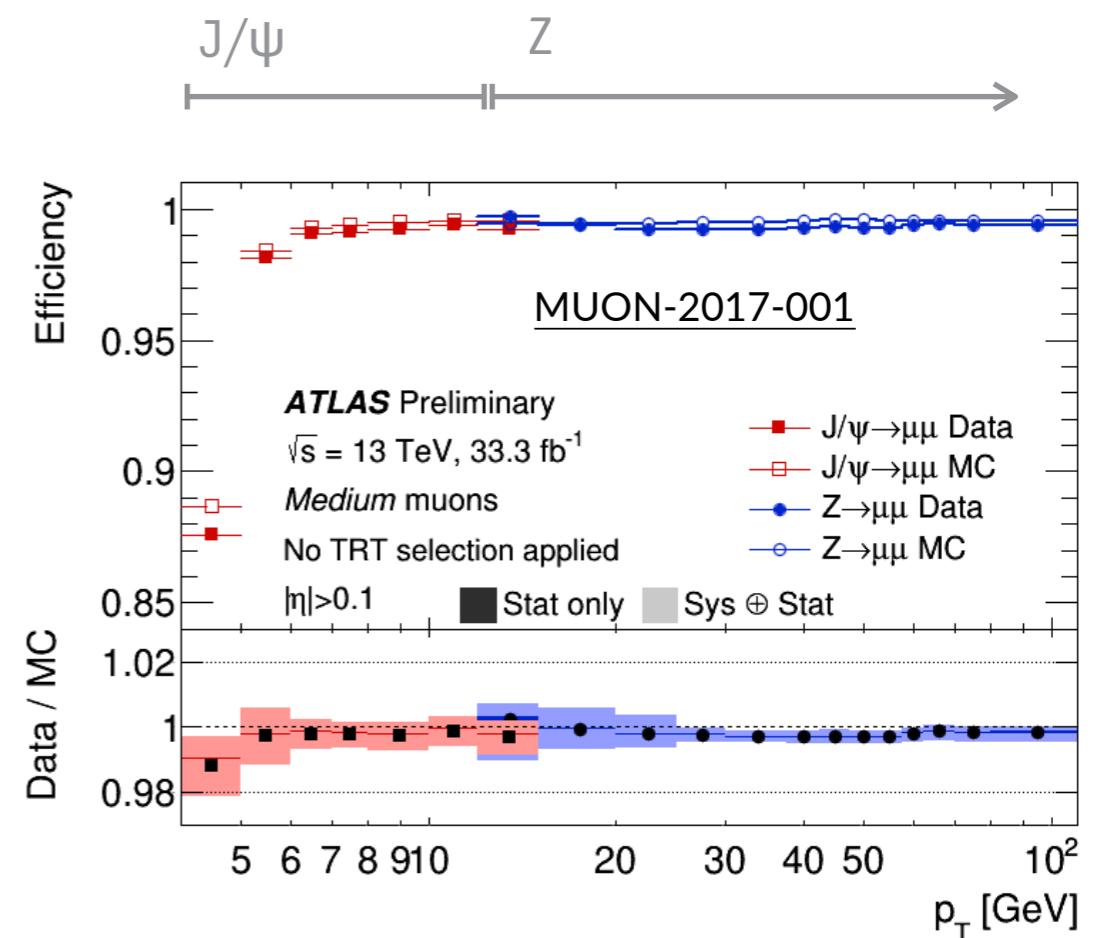


associated production (2.3 pb)



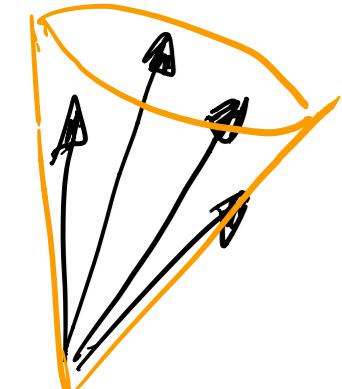
## THE INVISIBLE, THROUGH THE VISIBLE

- at hadron colliders, leptons are an invaluable resource
    - clean experimental signature
    - we use them to measure SM background processes
      - ★ e.g. W+jets, Z+jets
      - ★ WIMP searches use these measurements to infer the  $Z \rightarrow \nu\nu$  contamination!
  - ~1% precision achieved for electron/muon energy resolution
    - extremely precise tracking, calorimetric and muon systems
    - accurate calibration campaigns to correct Monte Carlo simulation (Geant4)
      - ★ use "standard candles"
- made Higgs discovery and measurements possible!
- 

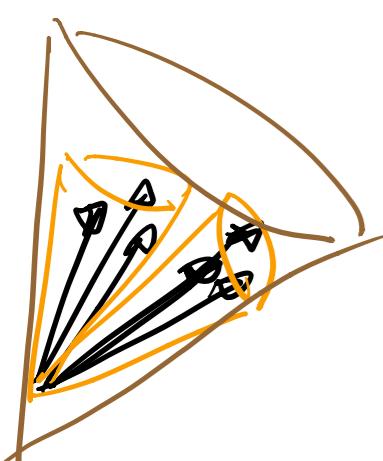


## JETS, OR THE TOUGH SIDE OF QUANTUM CROMODYNAMICS

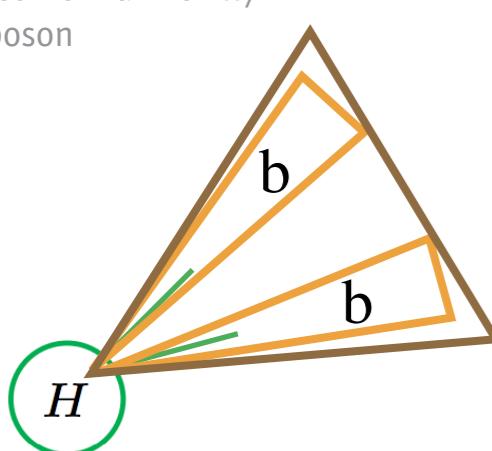
- ideally, a particle jet is a collection of particle 4-momenta ("constituents") originating from the hadronisation of a parton
  - a few infrared-safe algorithms used to distinguish substructure within the jet
    - ★ e.g. W or Z boson decays vs "background"
- experimental reality is harder
  - what's a "particle"?
    - ★ different strategies at ATLAS and CMS to determine which detector "hits" correspond to what kind of particle
  - event pile-up, the LHC stone guest



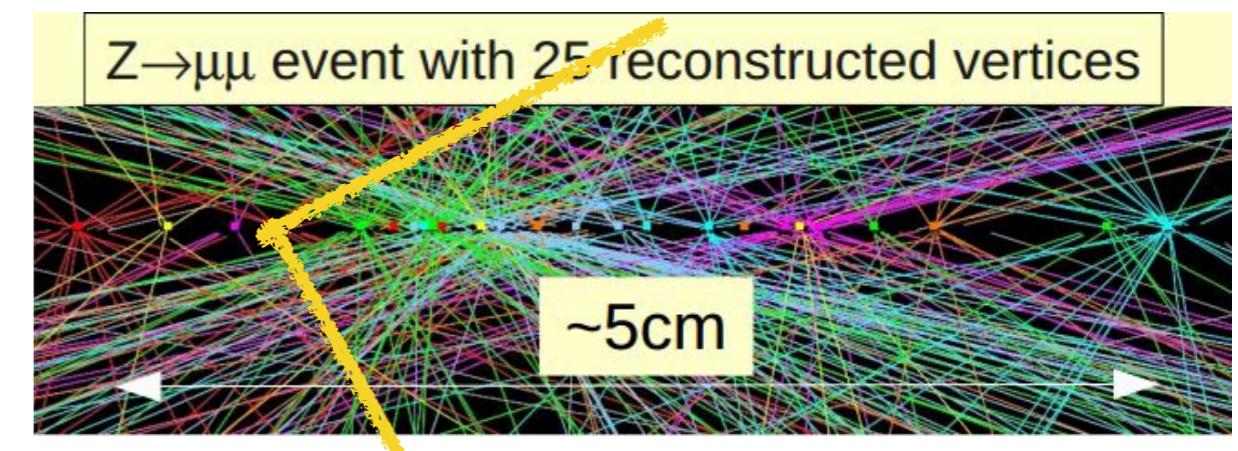
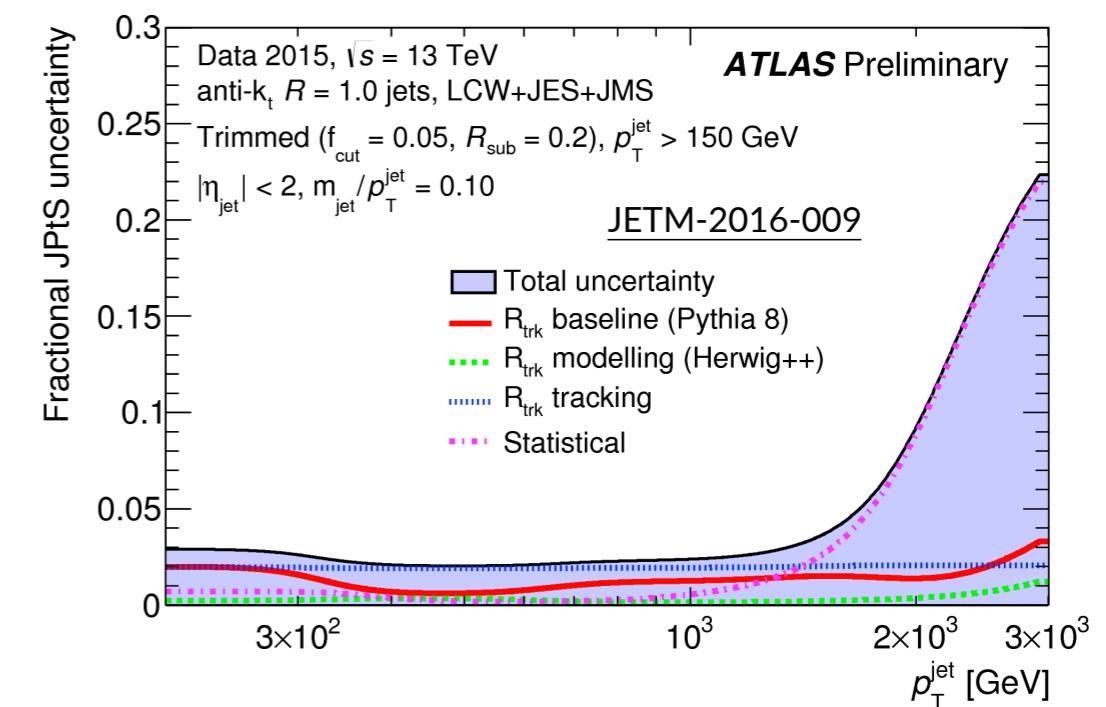
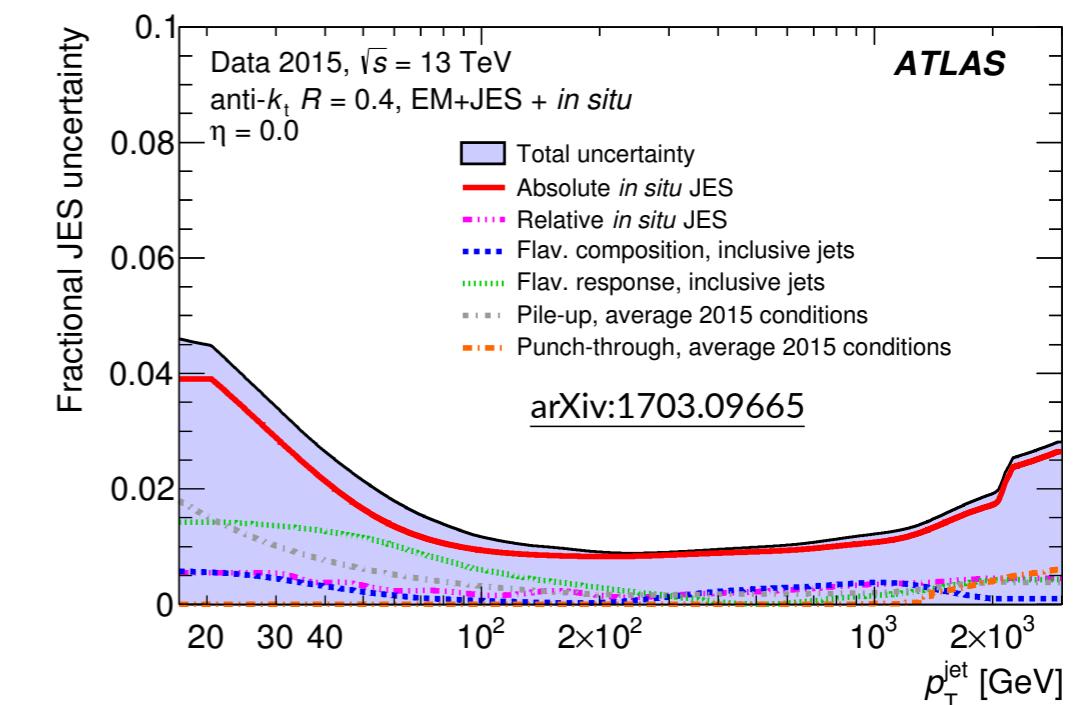
jet from a parton



jet from a H or W/Z boson

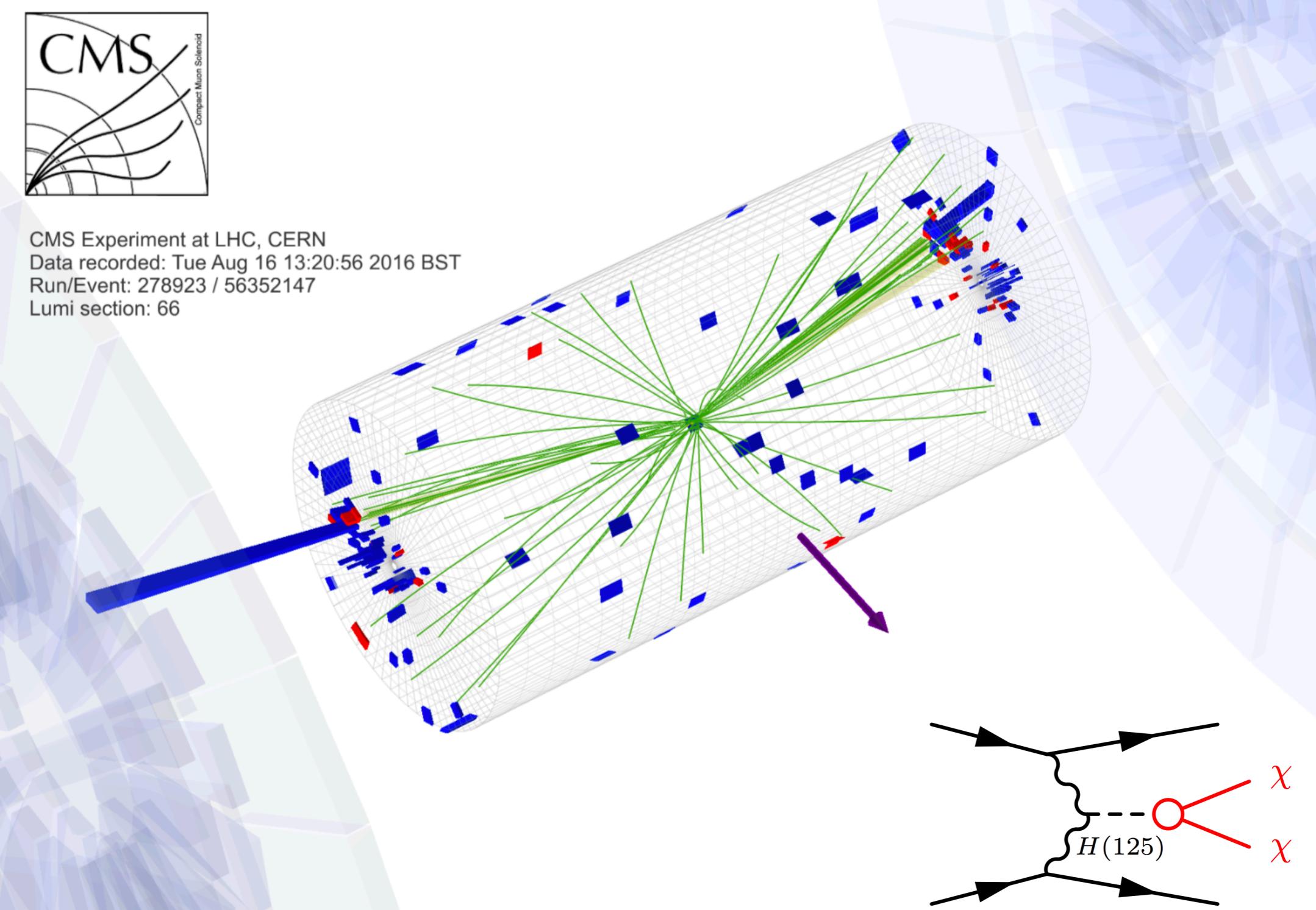


H



## HOW IT LOOKS: INVISIBLE HIGGS IN VECTOR BOSON FUSION

proton beam travels diagonally; green lines represent charged particle tracks, red (blue) histograms energy deposits in the electromagnetic (hadronic) calorimeter; an arrow indicates the missing transverse momentum direction



## INVISIBLE HIGGS IN VECTOR-BOSON FUSION

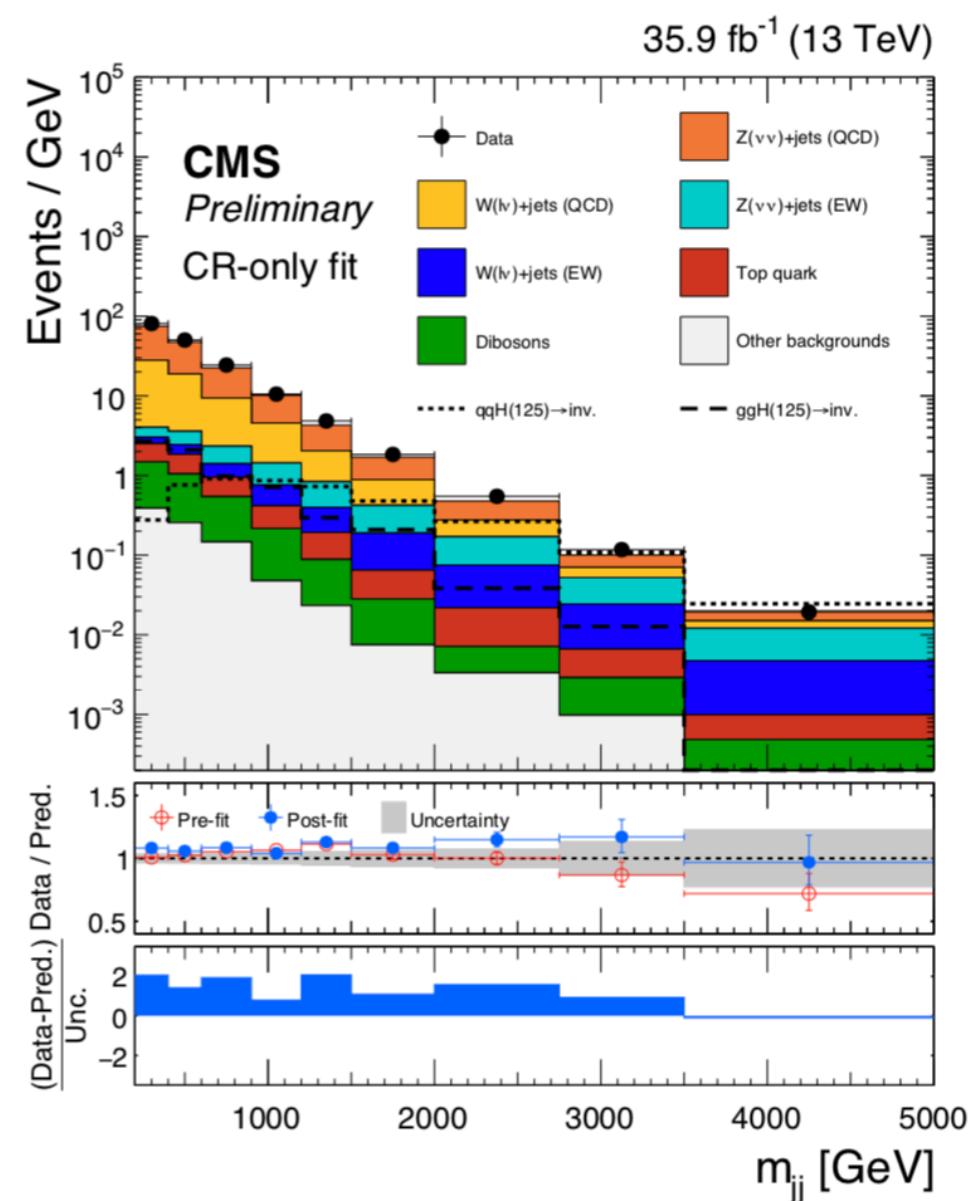
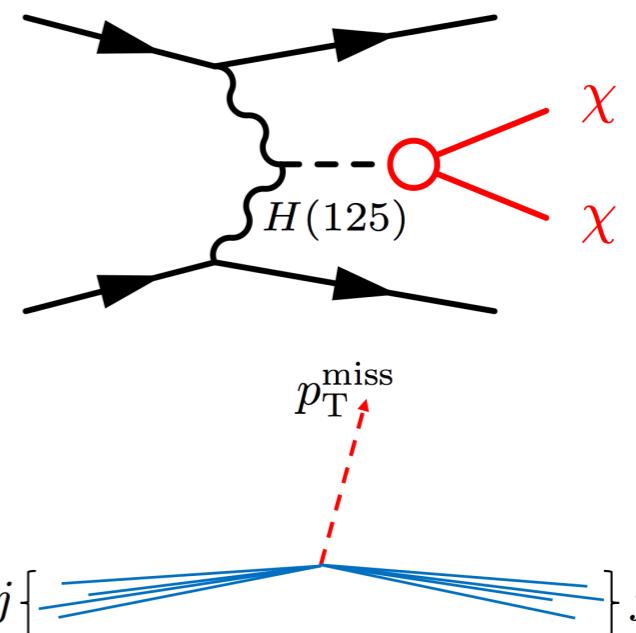
assuming  $H$  decays  
fully into invisible

- signal-to-background  $\sim 0.5$
- signature: two "forward", collimated jets recoil against large missing transverse momentum
  - veto events with leptons
- challenging!
  - trigger: "fake" missing transverse momentum can come from mis-measured jets
  - reconstruction: jet and lepton identification
- WIMPs would show up in tails of invariant mass distribution of the 2-jet system
  - more events than expected for  $H \rightarrow ZZ^* \rightarrow 4\nu$
  - main background is  $Z(vv) + \text{jets}$ , estimated measuring  $W$  and  $Z + \text{jet}$  processes in control regions with leptons

or from non-collision background (beam particles interact with LHC beam collimators, producing muons which travel horizontally and look like unbalanced jets...)

search sensitive to  $\text{BR}(H \rightarrow \text{inv}) \sim 0.20$

CMS-PAS-HIG-17-023  
JHEP 01 (2016) 172



## INVISIBLE HIGGS IN ASSOCIATED PRODUCTION

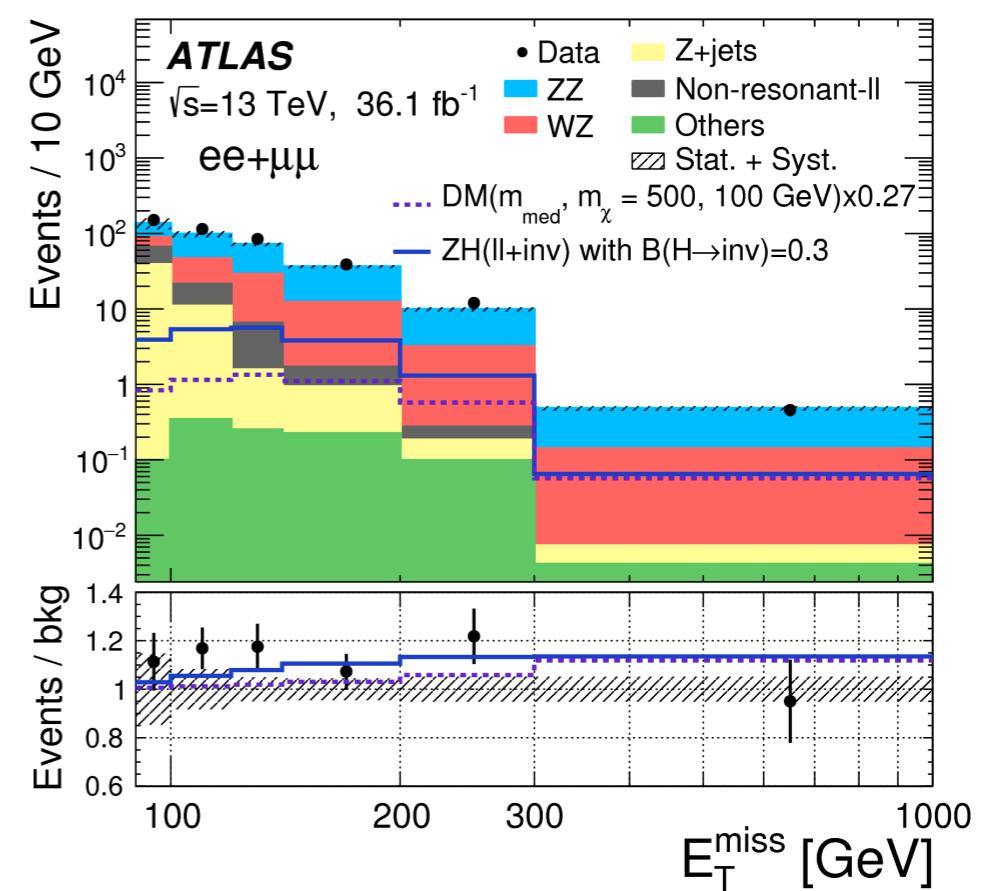
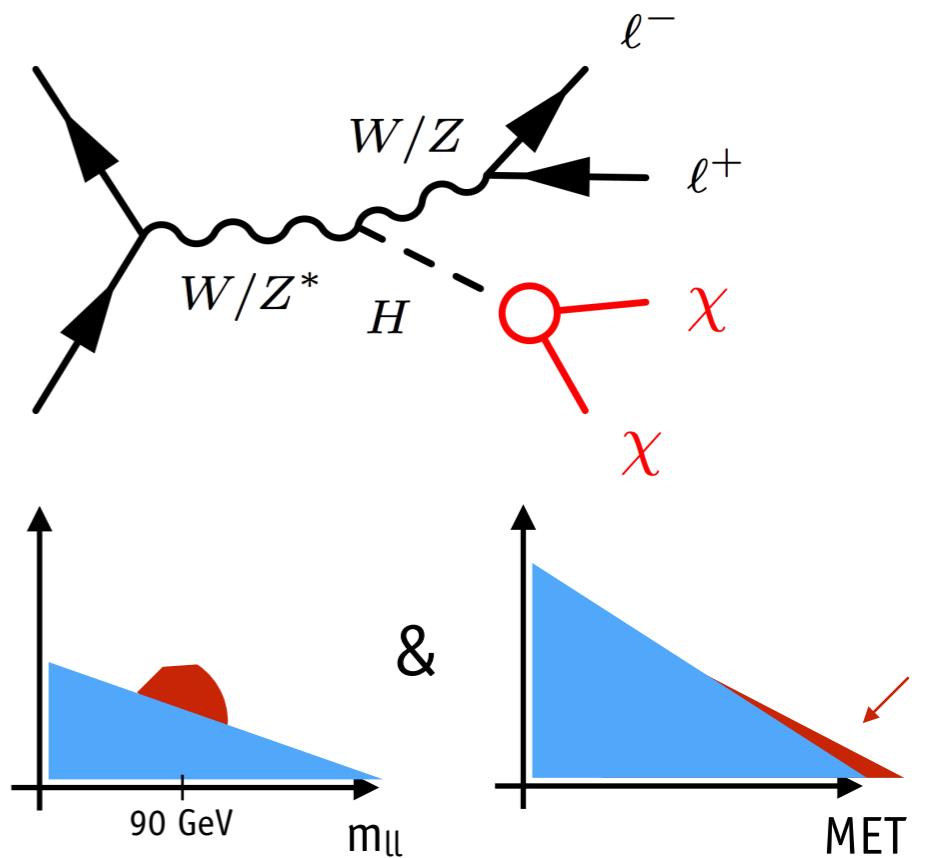
search sensitive to  
 $\text{BR}(H \rightarrow \text{inv}) \sim 0.20$

- look for large missing transverse momentum in events with a Z boson
  - clean, resonant signature in electron and muon channels
- a low-statistics channel
  - lepton trigger, based on fast calorimeters / gas detectors + charged particle tracker
  - crucial: background modelling in simulation ( $ZZ \rightarrow llvv$ )
- signal would show up in the missing transverse momentum tails
  - a typical feature of WIMP searches at ATLAS & CMS

with current LHC luminosity, can go as down as 24 GeV in electron/muon  $p_T$

dominant source of uncertainty, followed by lepton reconstruction

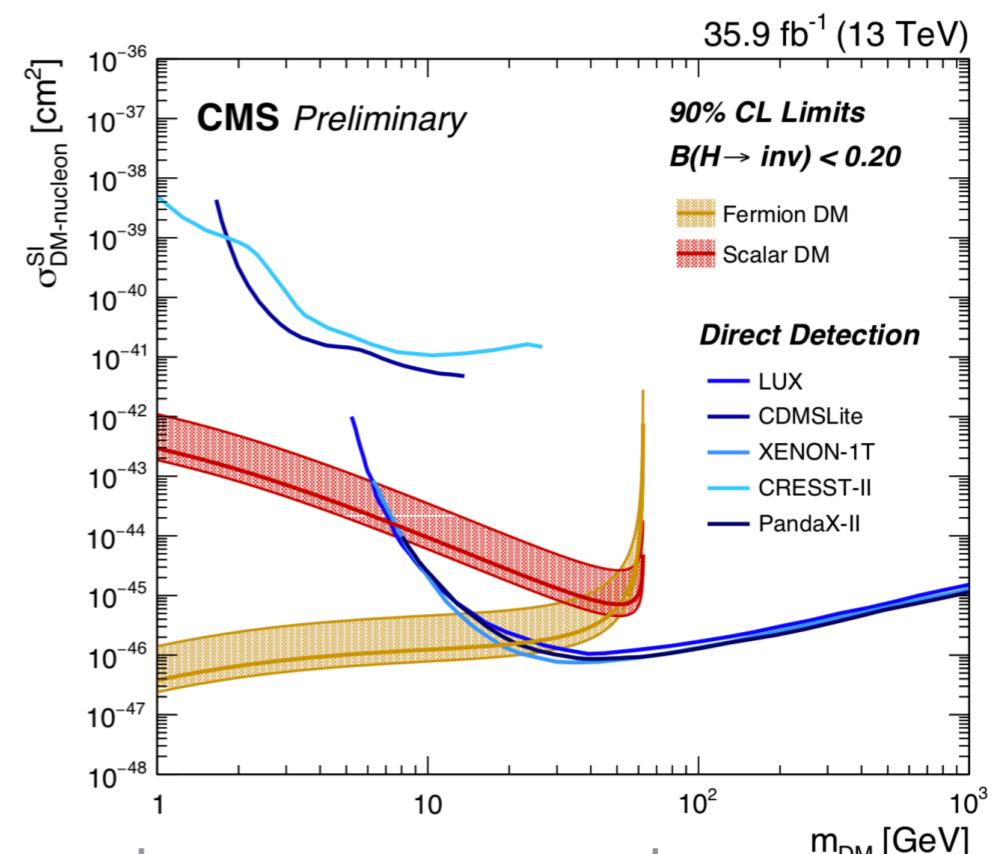
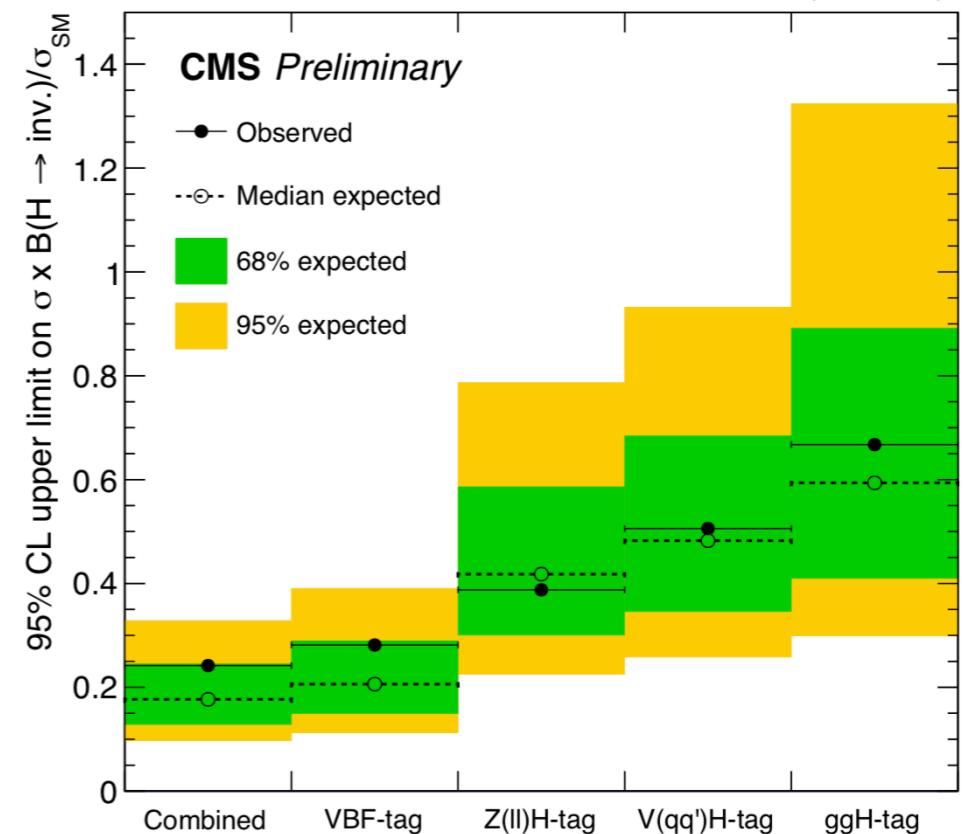
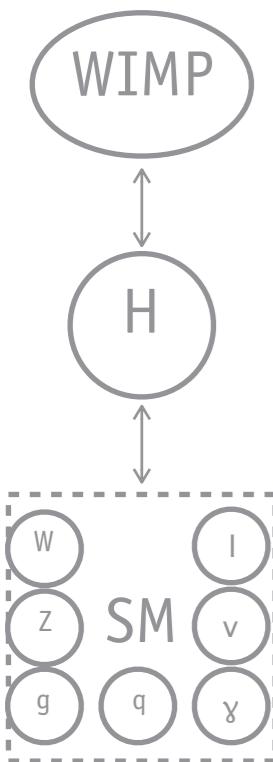
Phys.Lett. B776  
(2018) 318-337  
Eur. Phys. J. C 78  
(2018) 291



## INVISIBLE HIGGS RESULTS

ATLAS results are based on the 8 TeV dataset (2011-2012)

- best 95% CL limits come from VBF channel
  - ATLAS:  $\text{BR}(H \rightarrow \text{inv}) < 0.28$
  - CMS:  $\text{BR}(H \rightarrow \text{inv}) < 0.28$ ,  $< 0.24$  combining all channels
- competitive with direct detection when re-interpreted in scenarios with fermion or scalar DM
  - contribution to BR from 2WIMP channel proportional to portal coupling
    - ★ use the latter to compute WIMP-nucleon cross-sections



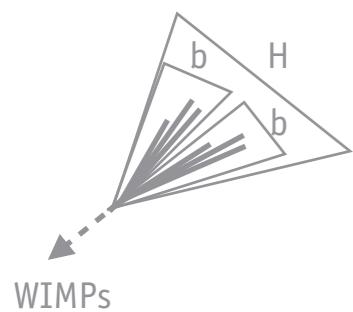
H can decay into WIMP pair

## THE INVISIBLE, THROUGH THE VISIBLE

Phys. Rev. Lett. 119,  
181804  
Phys. Rev. D 96,  
112004  
JHEP 10 (2017) 180

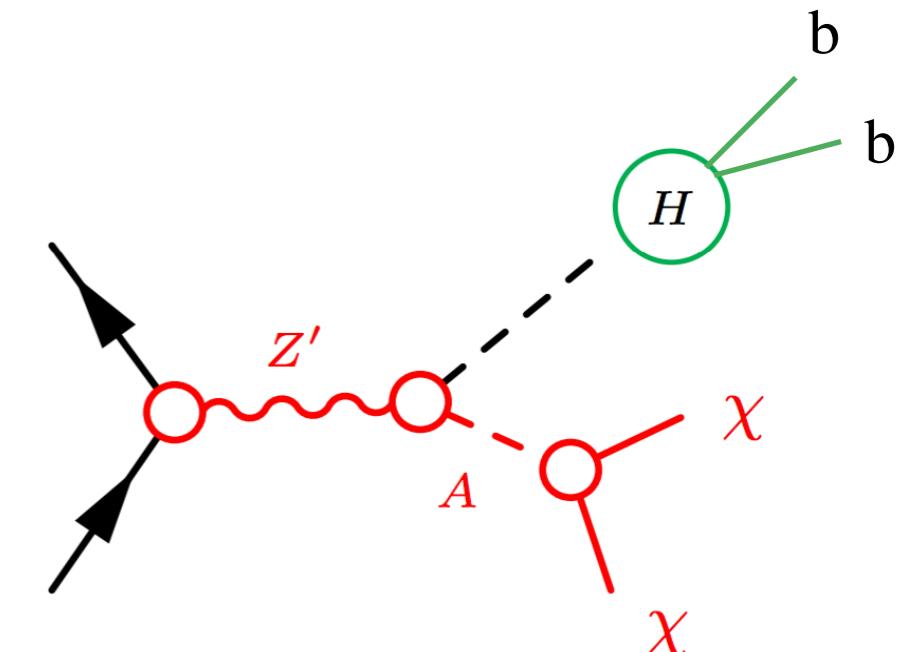
2HDM-like, e.g. JHEP  
06 (2014) 78

0(10x) better than  
 $H \rightarrow \gamma\gamma$

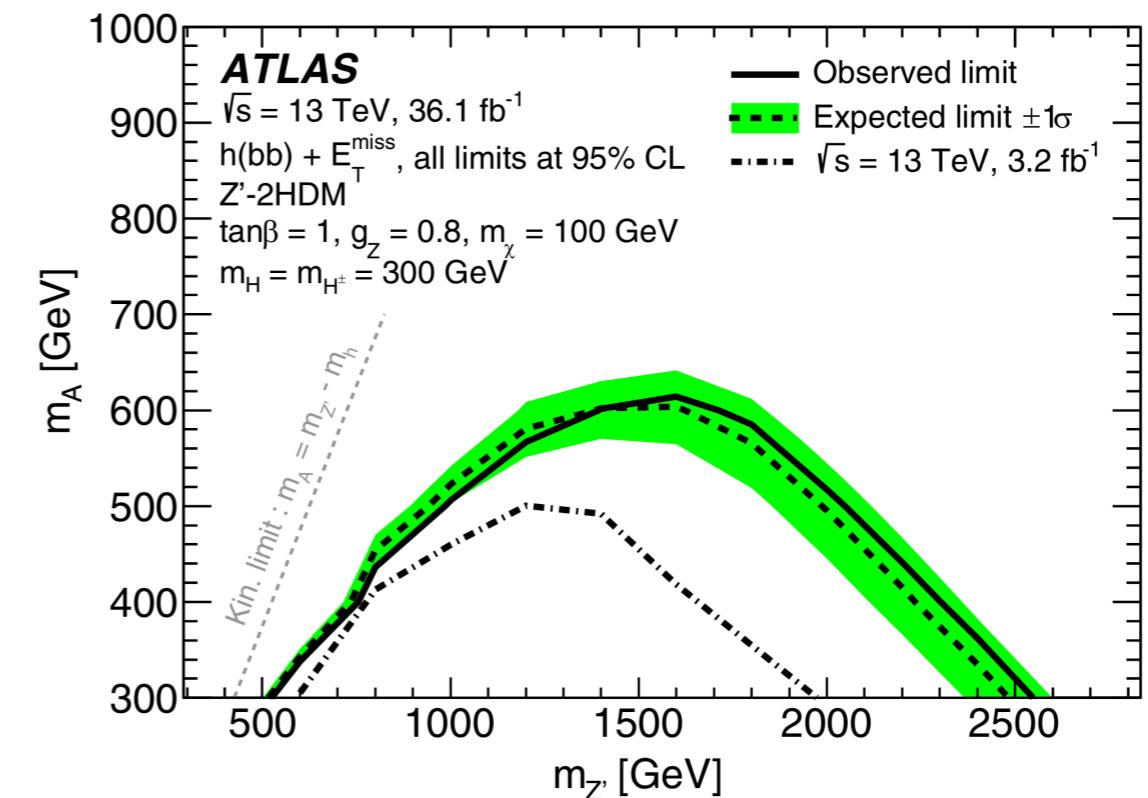


algorithms based on  
energy density ("2-  
prongness"); machine  
learning promising  
for exploiting low-  
level observables

- search for visible H decay and WIMPs
  - through heavier states  $Z'$  and  $A$ 
    - ★ a possible source of pseudoscalar interactions!
- $H \rightarrow bb$  most sensitive channel
  - BR~0.60, background from  $Z+jets$ ,  $W+jets$  and  $t\bar{t}$
  - select resonant di-jet mass and look at tails in missing transverse momentum distribution
- crucial: identify jet substructure
  - relies on calorimeter granularity + energy clustering techniques



$Z'$  and  $A$  mass exclusion contour for a 100 GeV WIMP



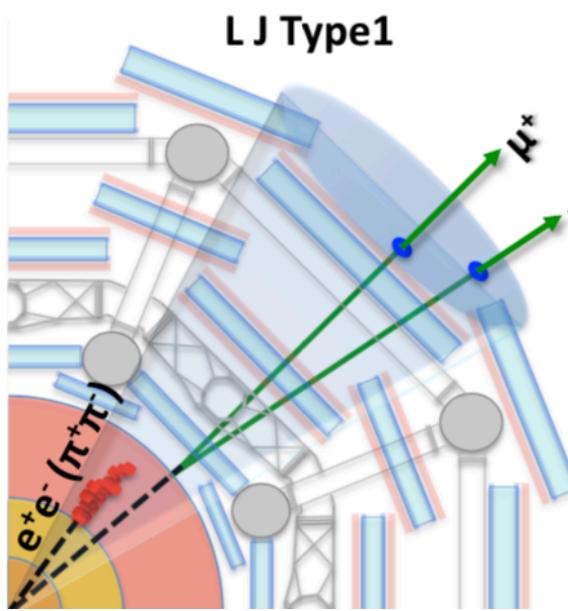
## A PORTAL TO A DARK SECTOR?

search performed also  
for heavier H-like  
states

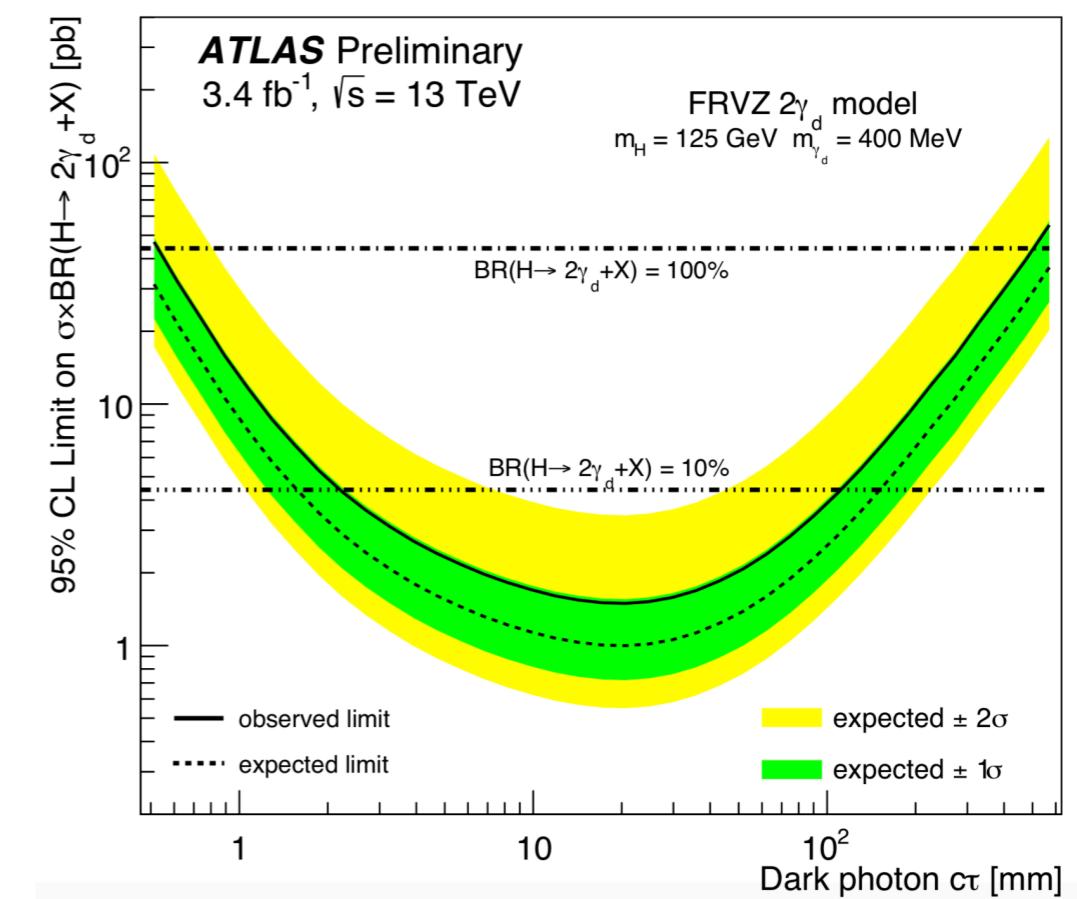
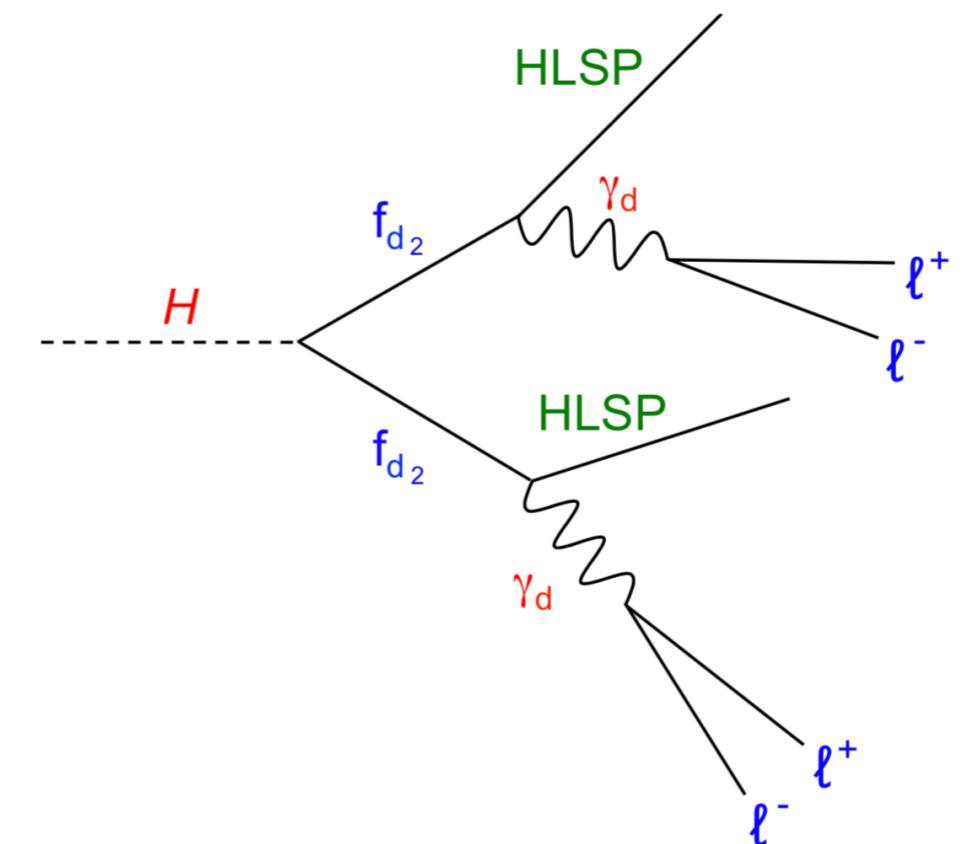
- what if H decays to unstable states from a hidden sector?
  - hidden, lightest stable particle could explain Dark Matter
- long-lived particles, which travel undetected for ~meters and then decay into visible particles
  - example: lepton jets starting in the calorimeters or in the muon spectrometer
- a challenge for current detectors

ATLAS-  
CONF-2016-042

dedicated trigger and tracking strategies are essential!



LJ Type1  
clever reconstruction  
techniques for such non-  
standard signatures



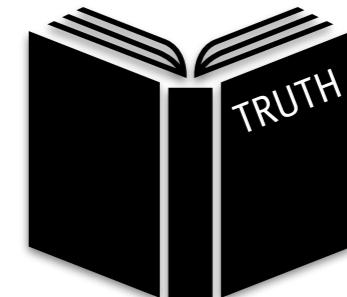
## AND MANY MORE!

experimental strategies try to cover all possible signatures, as predicted by effective, simplified and UV-complete models

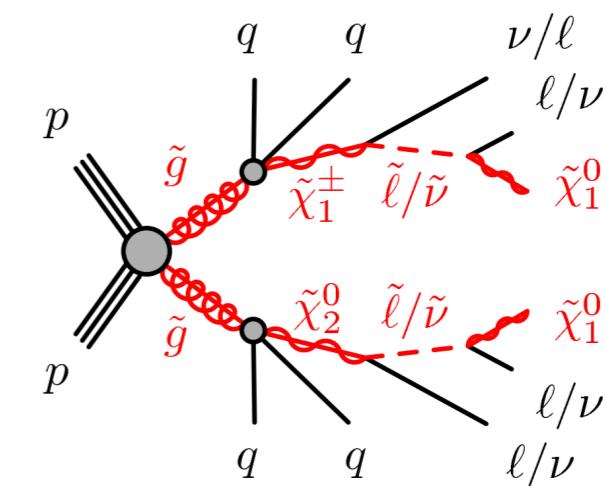
- H decays to WIMPs
- H produced with WIMPs
- H decays to metastable states which produce WIMPs
- metastable states decay to WIMPs
  - we need to test all these!



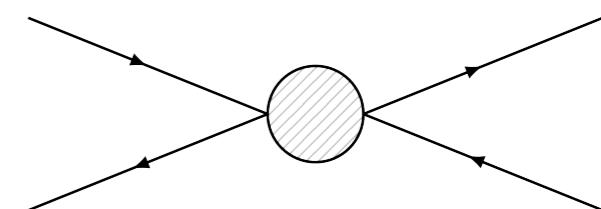
UV-  
complete  
theory



simplified  
model



effective  
field theory



# A PLETHORA OF SEARCHES...

## ATLAS SUSY Searches\* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Reference

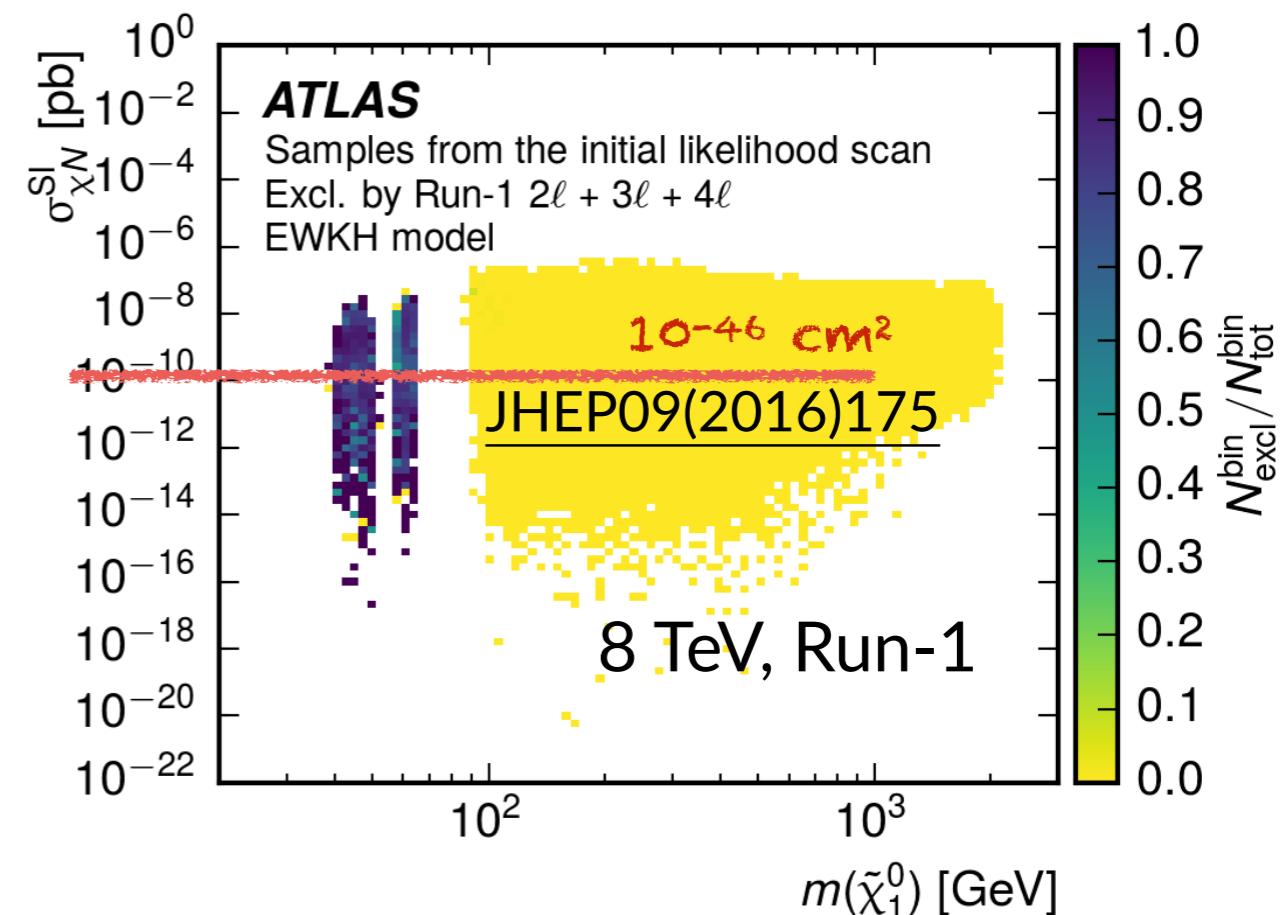
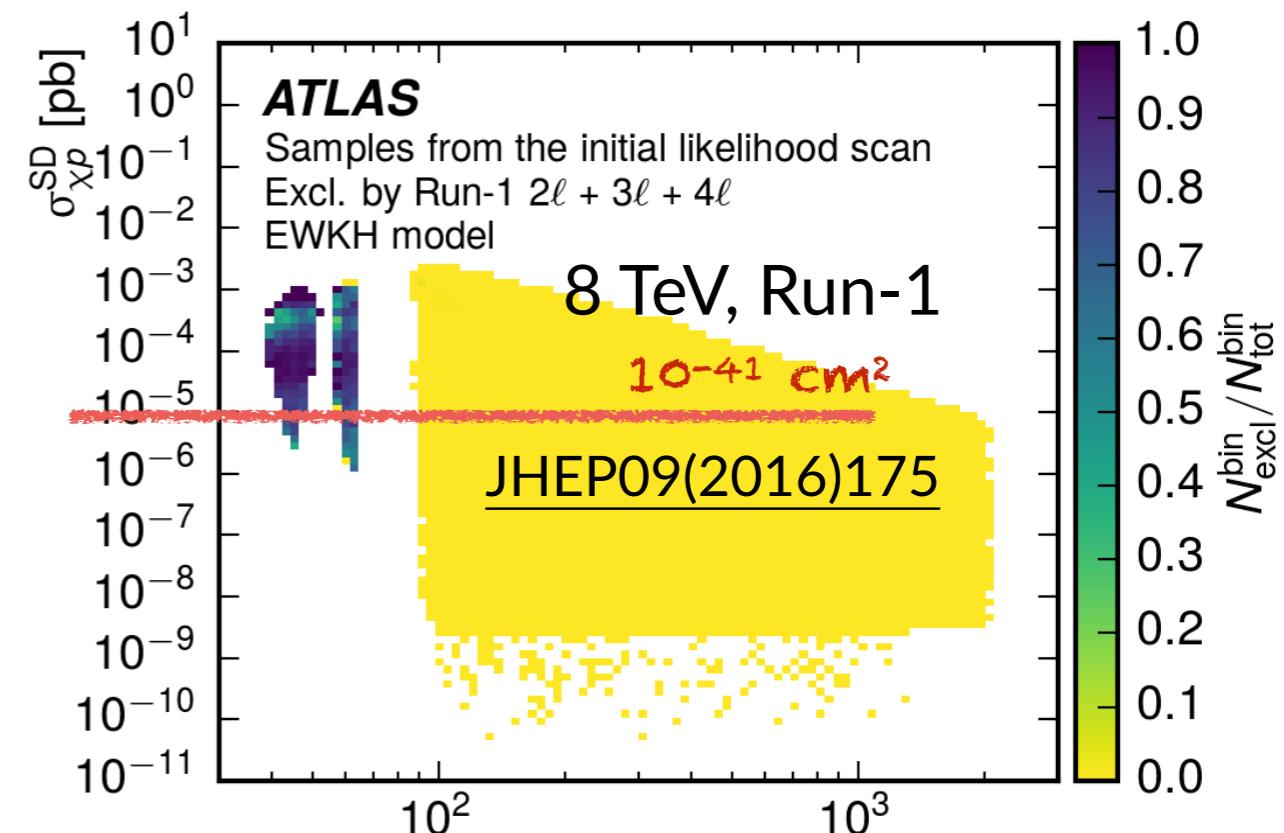
probing  
supersymmetry at the  
TeV scale...

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	<b>1.57 TeV</b>	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q}) = m(2^{\text{nd}} \text{ gen. } \tilde{q})$
	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$	<b>710 GeV</b>	$m(\tilde{q}) - m(\tilde{\chi}_1^0) < 5 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	<b>2.02 TeV</b>	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^\pm \rightarrow qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	<b>2.01 TeV</b>	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}^\pm) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{g}))$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$	<b>1.7 TeV</b>	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	$3 e, \mu$	4 jets	-	36.1	$\tilde{g}$	<b>1.87 TeV</b>	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	<b>1.8 TeV</b>	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	$\tilde{g}$	<b>2.0 TeV</b>	$c\tau(\text{NLSP}) < 0.1 \text{ mm}$
	GGM (bino NLSP)	$2\gamma$	-	Yes	36.1	$\tilde{g}$	<b>2.15 TeV</b>	$c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$
	GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes	36.1	$\tilde{g}$	<b>2.05 TeV</b>	$m(\tilde{\chi}_1^0) = 1700 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$
$3^{\text{rd}}$ gen. $\tilde{g}$ med.	Gravitino LSP	0	mono-jet	Yes	20.3	$\tilde{g}^{1/2} \text{ scale}$	<b>865 GeV</b>	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g}) = m(\tilde{q}) = 1.5 \text{ TeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow bb\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	<b>1.92 TeV</b>	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow tt\tilde{\chi}_1^0$	0-1 $e, \mu$	3 b	Yes	36.1	$\tilde{g}$	<b>1.97 TeV</b>	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$
$3^{\text{rd}}$ gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$	<b>950 GeV</b>	$m(\tilde{\chi}_1^0) < 420 \text{ GeV}$
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow t\tilde{\chi}_1^\pm$	2 $e, \mu$ (SS)	1 b	Yes	36.1	$\tilde{b}_1$	<b>275-700 GeV</b>	$m(\tilde{\chi}_1^\pm) < 200 \text{ GeV}, m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) + 100 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow b\tilde{\chi}_1^\pm$	0-2 $e, \mu$	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	<b>117-170 GeV</b>	$m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 55 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 $e, \mu$	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	<b>200-720 GeV</b>	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$	<b>90-198 GeV</b>	$m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	<b>90-430 GeV</b>	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ (Z)	1 b	Yes	36.1	$\tilde{t}_2$	<b>150-600 GeV</b>	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow \tilde{t}_1 + h$	1-2 $e, \mu$	4 b	Yes	36.1	$\tilde{t}_2$	<b>290-790 GeV</b>	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow \tilde{t}_1 + h$	1-2 $e, \mu$	4 b	Yes	36.1	$\tilde{t}_2$	<b>320-880 GeV</b>	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{\ell}_{\text{L,R}}\tilde{\ell}_{\text{L,R}}, \tilde{\ell}\rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	36.1	$\tilde{\ell}$	<b>90-500 GeV</b>	$m(\tilde{\chi}_1^0) = 0$
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm}\rightarrow \tilde{\ell}\nu(\tilde{\tau}\bar{\nu})$	2 $e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$	<b>750 GeV</b>	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm}\rightarrow \tilde{\tau}\nu(\tau\bar{\nu}), \tilde{\chi}_2^0\rightarrow \tilde{\tau}\tau(\bar{\nu}\nu)$	2 $\tau$	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$	<b>760 GeV</b>	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 \rightarrow \tilde{\ell}_L \nu_L \tilde{\ell}'_L (\bar{\nu}_L), \tilde{\ell}'_L \tilde{\ell}_L \ell' \bar{\nu}_L$	3 $e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	<b>1.13 TeV</b>	$m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 $e, \mu$	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	<b>580 GeV</b>	$m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell} \text{ decoupled}$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow bb/WW/\tau\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 b	Yes	20.3	$\tilde{\chi}_{1,2}^{\pm}$	<b>270 GeV</b>	$m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell} \text{ decoupled}$
	$\tilde{\chi}_2^0\tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R \ell$	4 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	<b>635 GeV</b>	$m(\tilde{\chi}_2^0) = m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0))$
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$	<b>115-370 GeV</b>	$c\tau < 1 \text{ mm}$
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 $\gamma$	-	Yes	36.1	$\tilde{W}$	<b>1.06 TeV</b>	$c\tau < 1 \text{ mm}$
	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$	<b>460 GeV</b>	$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^{\pm}) = 0.2 \text{ ns}$
	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	<b>495 GeV</b>	$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^{\pm}) < 15 \text{ ns}$
Long-lived particles	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	<b>850 GeV</b>	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	<b>1.58 TeV</b>	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, \tau > 10 \text{ ns}$
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	<b>1.57 TeV</b>	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, \tau(\tilde{g}) = 0.17 \text{ ns}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	$\tilde{g}$	<b>2.37 TeV</b>	$10 < \tan\beta < 50$
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 $\mu$	-	-	19.1	$\tilde{\chi}_1^0$	<b>537 GeV</b>	$1 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS model}$
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$	2 $\gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$	<b>440 GeV</b>	$7 < \tau(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow ee/\nu\mu/\mu\nu$	displ. $ee/\nu\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	<b>1.0 TeV</b>	$\text{BR}(\tilde{t}_1 \rightarrow be/\mu) > 20\%$
RPV	LFV $pp \rightarrow \tilde{\nu}_1 + X, \tilde{\nu}_1 \rightarrow e\mu/\tau\mu/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_1$	<b>1.9 TeV</b>	$\lambda'_{311} = 0.11, \lambda_{132}/\lambda_{133}/\lambda_{233} = 0.07$
	Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 b	Yes	20.3	$\tilde{g}, \tilde{g}$	<b>1.45 TeV</b>	$m(\tilde{q}) = m(\tilde{g}), c\tau_{LSP} < 1 \text{ mm}$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm}\rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\nu, e\nu\nu, \mu\nu\nu$	4 $e, \mu$	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$	<b>1.14 TeV</b>	$m(\tilde{\chi}_1^0) > 400 \text{ GeV}, \lambda_{12k} \neq 0 (k=1, 2)$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm}\rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	<b>450 GeV</b>	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda_{133} \neq 0$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	0	4-5 large- $R$ jets	-	36.1	$\tilde{g}$	<b>1.875 TeV</b>	$m(\tilde{\chi}_1^0) = 1075 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	1 $e, \mu$	8-10 jets					

## CORNERING SUPERSYMMETRY

example from Run-1:  
exclusion contour  
combining 8 TeV  
results of searches in  
final states with 2, 3  
and 4 leptons,  
together with direct-  
detection, relic  
density and flavour  
constraints

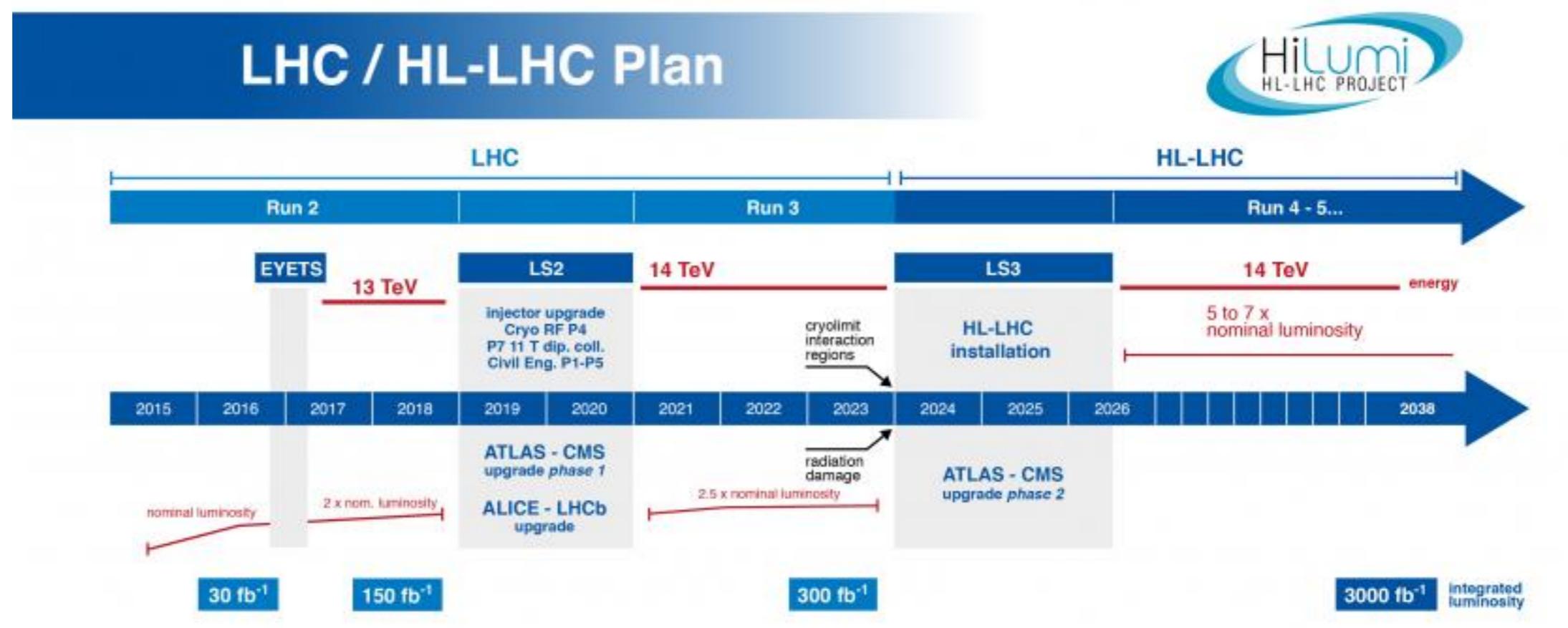
- searches for supersymmetric particles span parameter space often compatible with Dark Matter relic density
  - Run-1 results expressed in terms of fraction of allowed models which are also excluded
    - ★ yellow area: less than 10% of the explored phase space was excluded
- how to fill the missing space?
  - analyse all signatures with full dataset at 13 TeV
  - a significant improvement in mass reach would come from an increase in center-of-mass energy



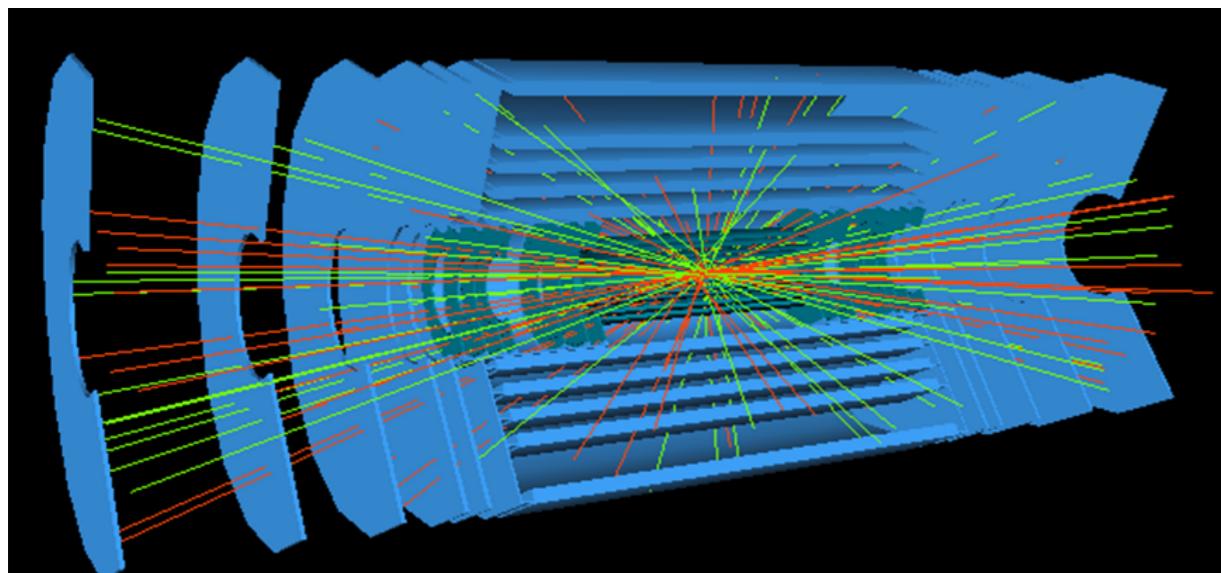
## HIGH LUMINOSITY, HIGH CHALLENGES

data taking  
programmed for the  
next 20 years:  
detector upgrades  
needed to cope with  
the higher  
instantaneous  
luminosity...

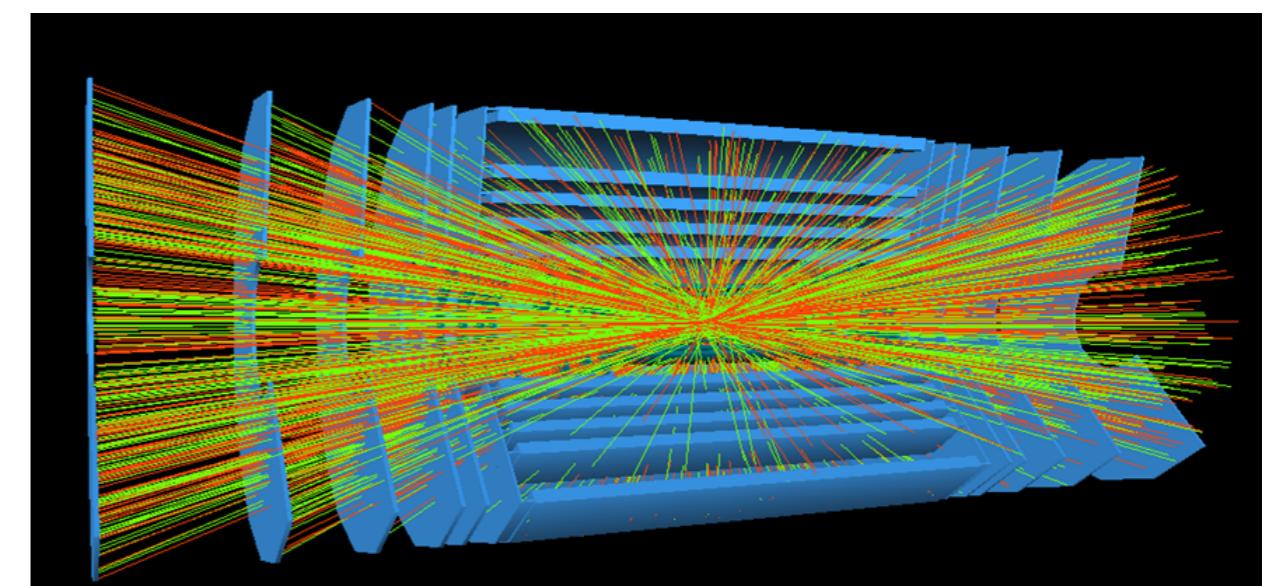
event pile-up is a  
major challenge!



23 pile-up vertices



230 pile-up vertices

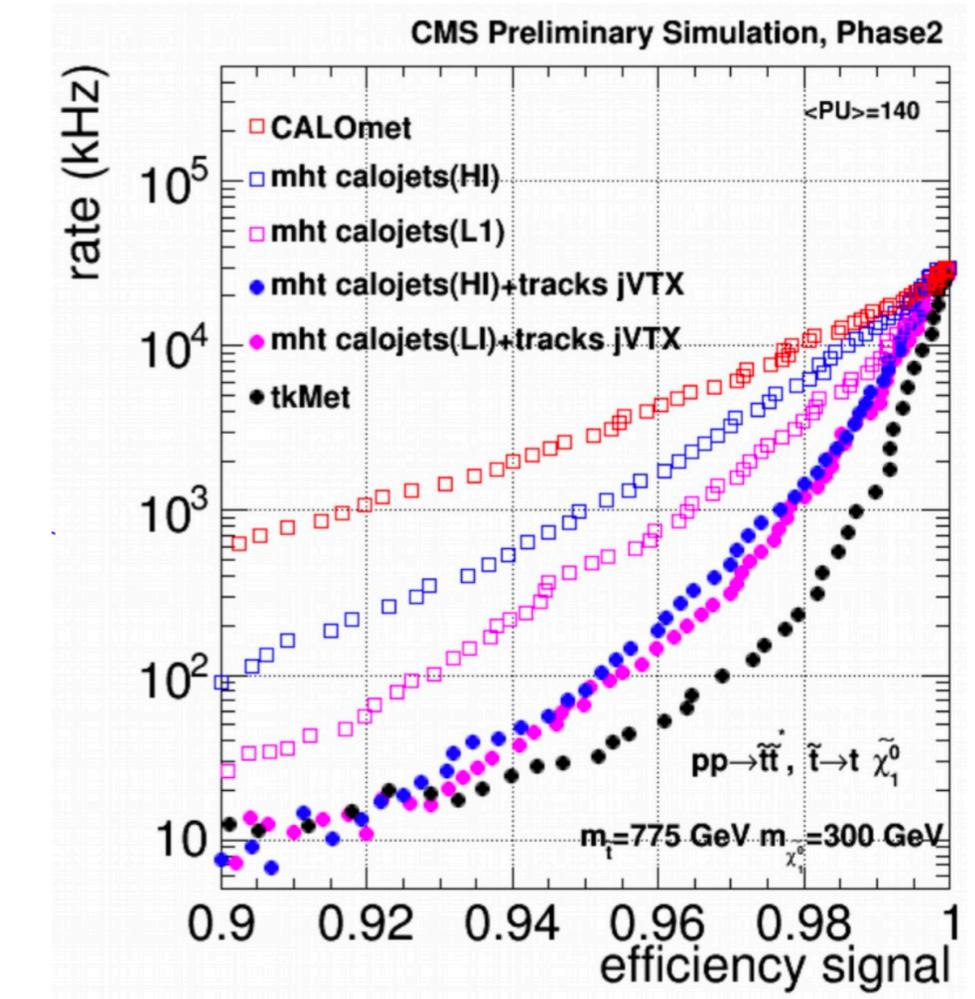
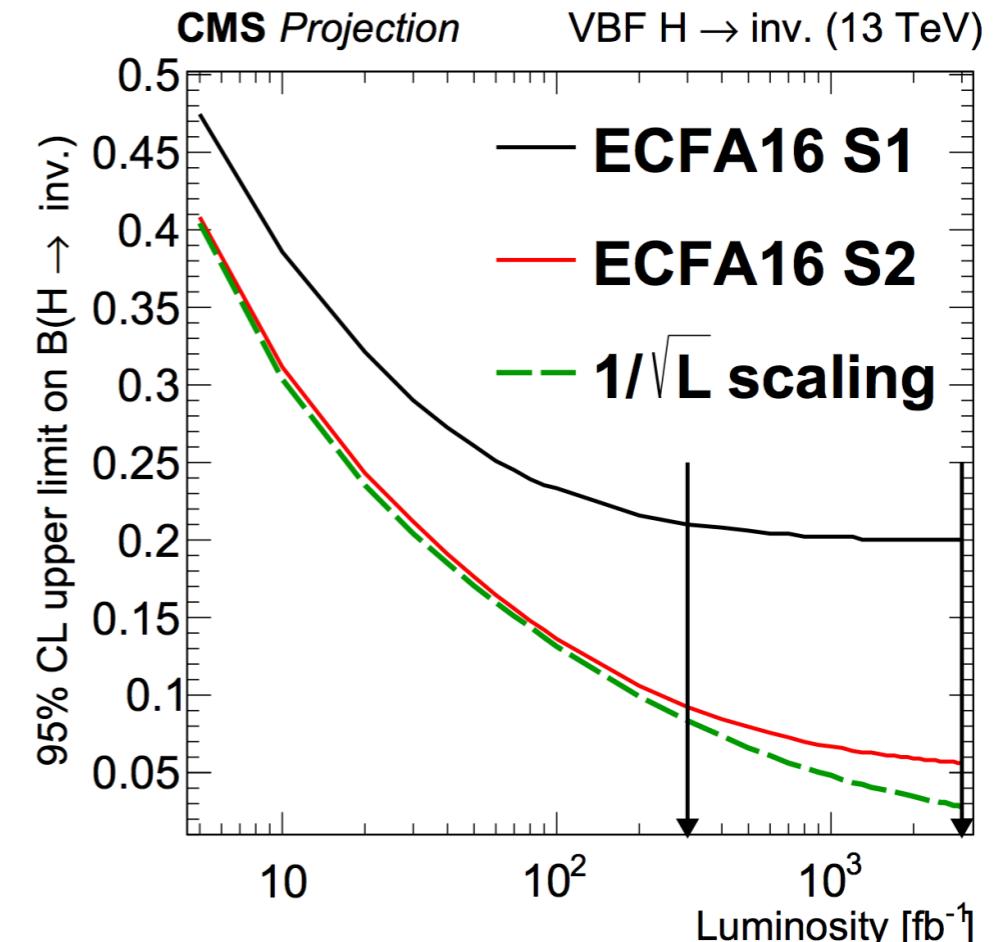
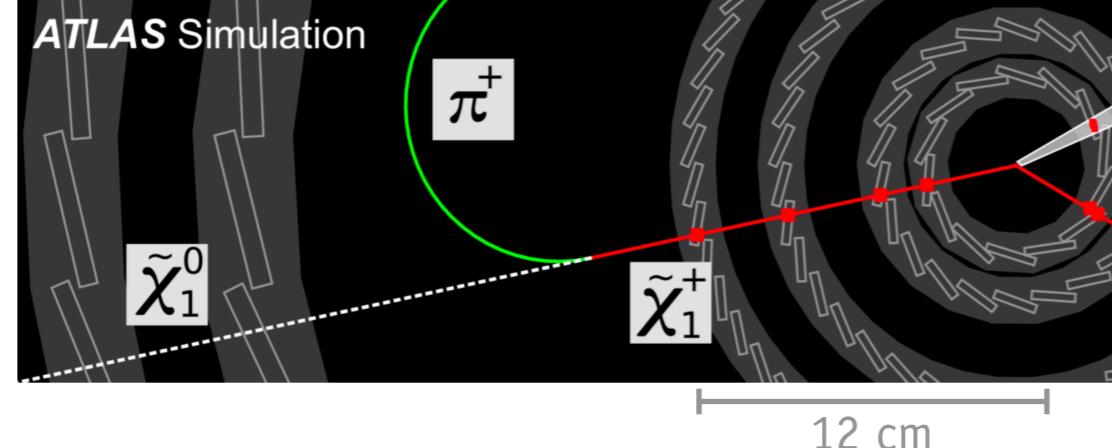


## A LOOK AT THE FUTURE

[CMS-PAS-FTR-16-002](#)

- invisible H decay searches limited by systematics within 2023
  - may reach  $\text{BR}(\text{H} \rightarrow \text{inv}) \sim 0.05$  by 2038
- R&D for pileup-robust detector upgrades
  - track information at early stages of missing transverse momentum trigger to reduce noise rate
- an opportunity for long-lived particles
  - new fast timing layers help to reconstruct displaced vertexes?

ATLAS: new trigger design integrates new silicon tracker (ITk)  
CMS: similar, could target 2-3 GeV tracks



## CONCLUSIONS

- LHC, a gateway to the invisible?
  - the Higgs boson discovery opens a new era for precision measurements and new-physics searches
- includes for example searches in final states with MET and b- or t-quarks (statistically limited)
- strong physics programme for H-related and spin-0 interactions
  - WIMP search complementary/unique with respect to direct detection
  - non-standard, challenging searches for long-lived states
- ATLAS and CMS are robust, multi-purpose detectors of the unknown
  - understanding the invisible needs mastering the visible



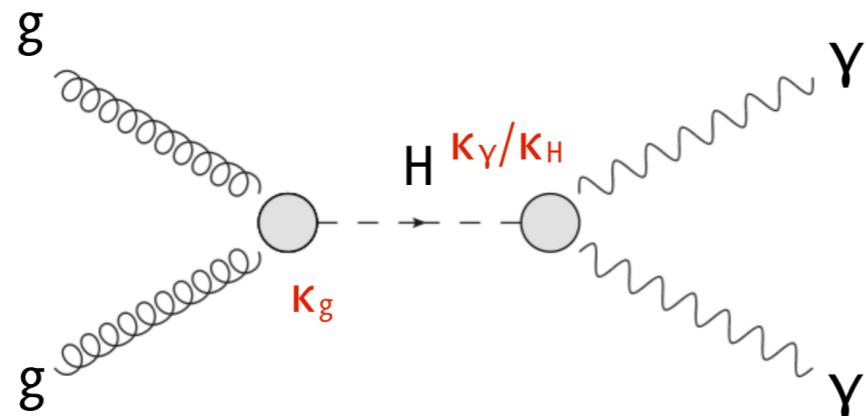
# Spares

## WHAT WE LEARNED FROM HIGGS COUPLINGS

[JHEP 08 \(2016\) 045](#)  
[JHEP 11 \(2015\) 206](#)

- constraints on invisible and undetected H branching ratios also come from coupling measurements
  - measure H event rates simultaneously in all channels and compare to SM expectation
- this approach lives in a simplified framework for probing deviations due to new physics
  - modify H lagrangian density with "coupling strength" factors (example below)

direct invisible searches provide leading sensitivity w.r.t. other channels (plot on the right)



$$(\sigma \times BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow \gamma\gamma) \cdot K_g^2 \cdot K_Y^2 / K_H^2$$

