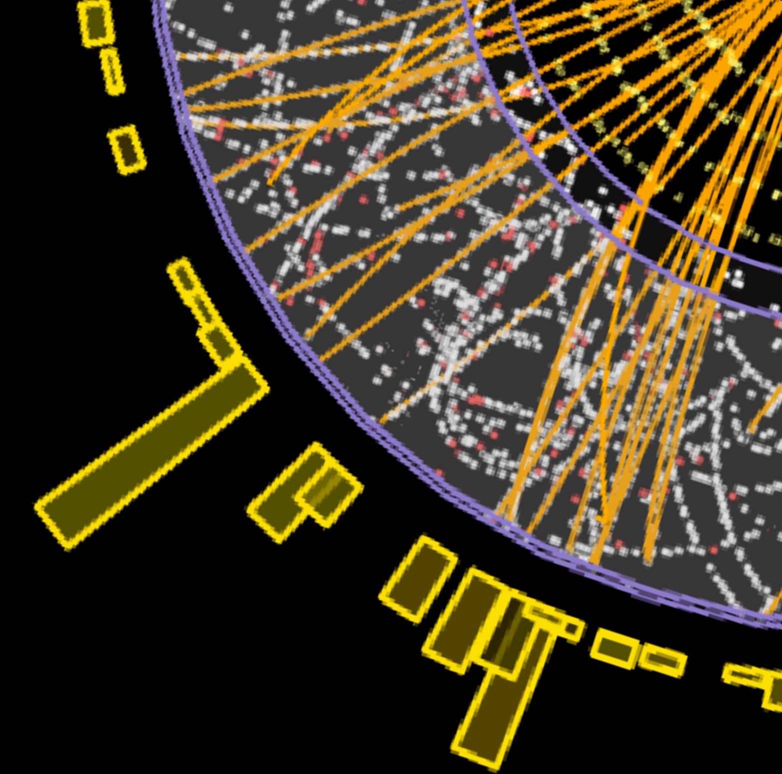
Valerio Ippolito
INFN Sezione di Roma



HOW WE LOOK FOR DARK MATTER AT THE LHC

part II: gauge bosons and beyond

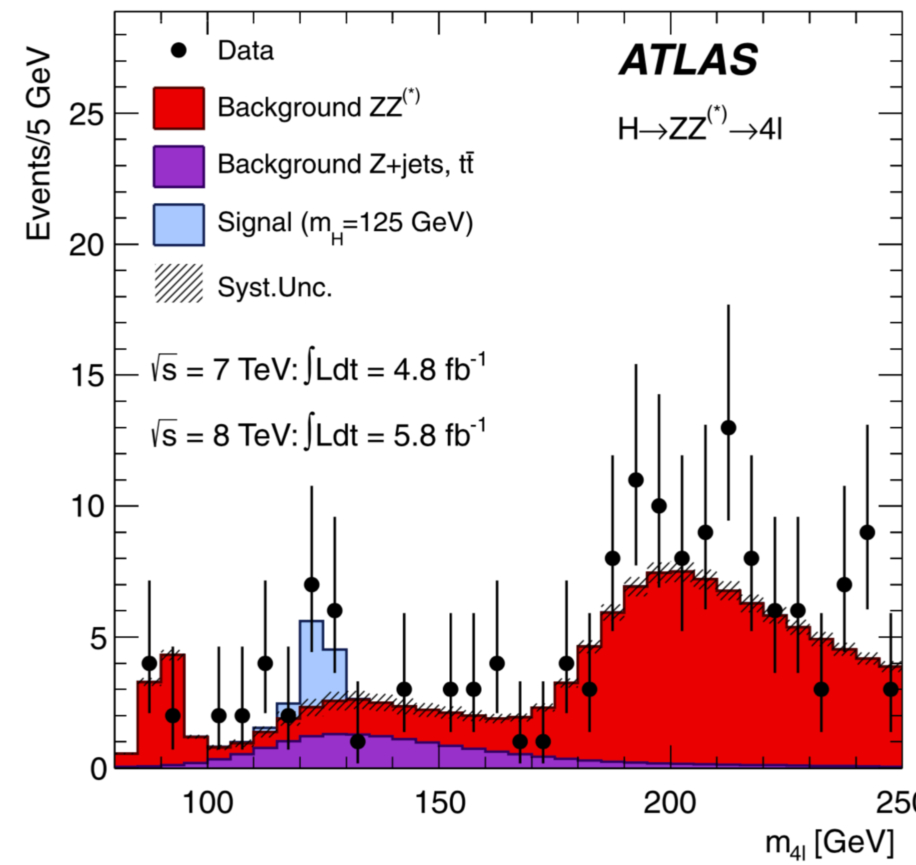
a talk on behalf of the ATLAS and CMS collaborations

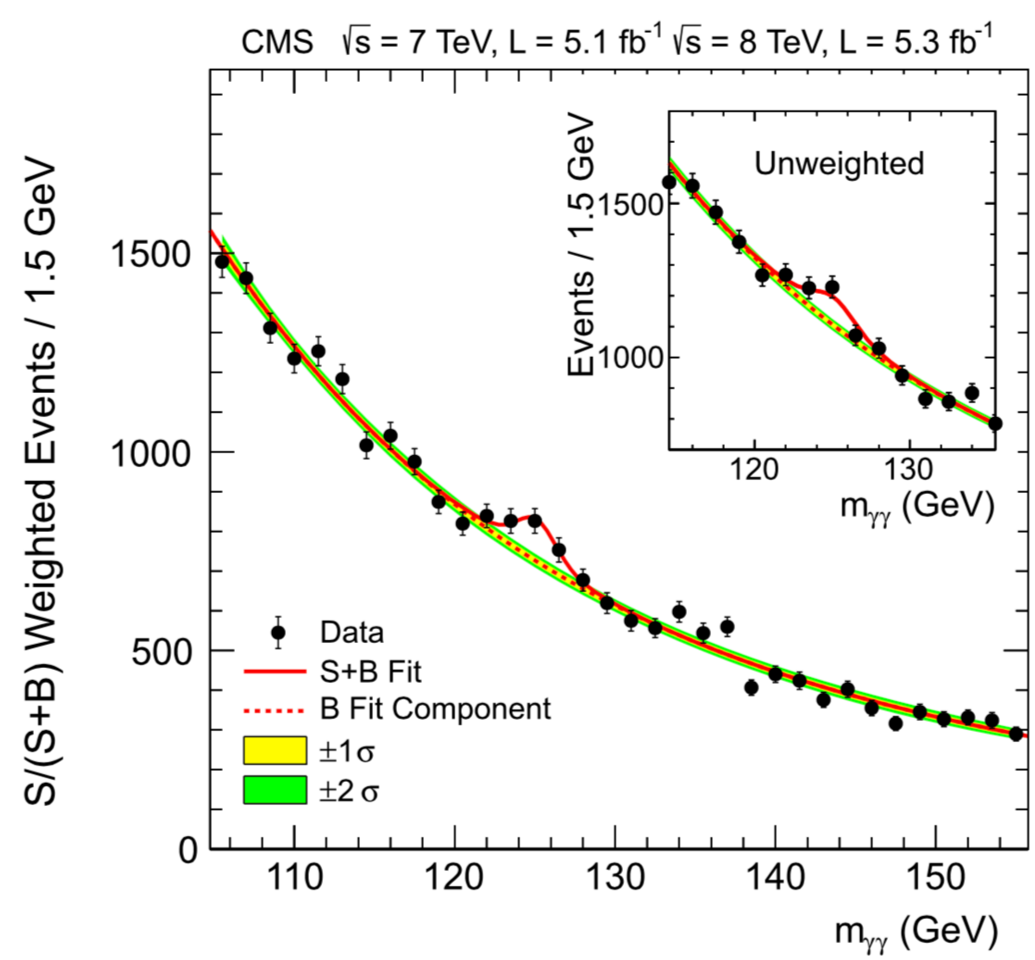
INFN
Istituto Nazionale di Fisica Nucleare

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 ~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 ~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 (< ~62 GeV) could couple directly to H: a new, invisible decay channel
  - compare to SM H->ZZ*->νννν (BR ~ 0.1%)
- something you can do only at a collider...

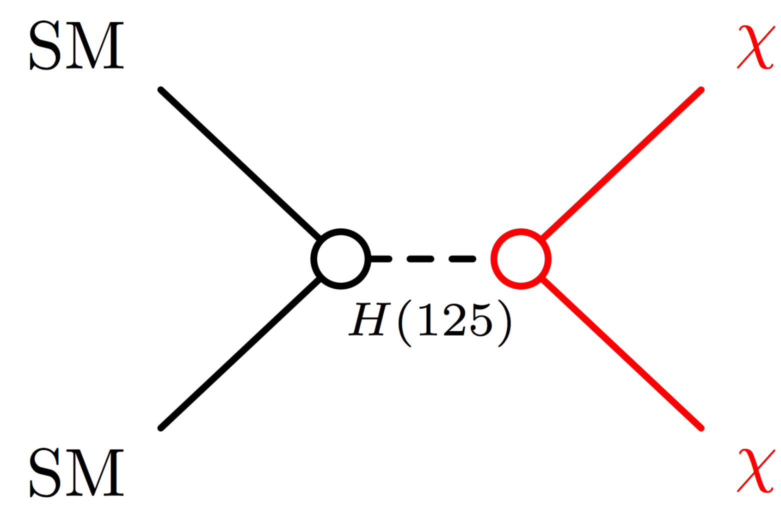
for example, in two-Higgs-doublet-model scenarios

  - 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...

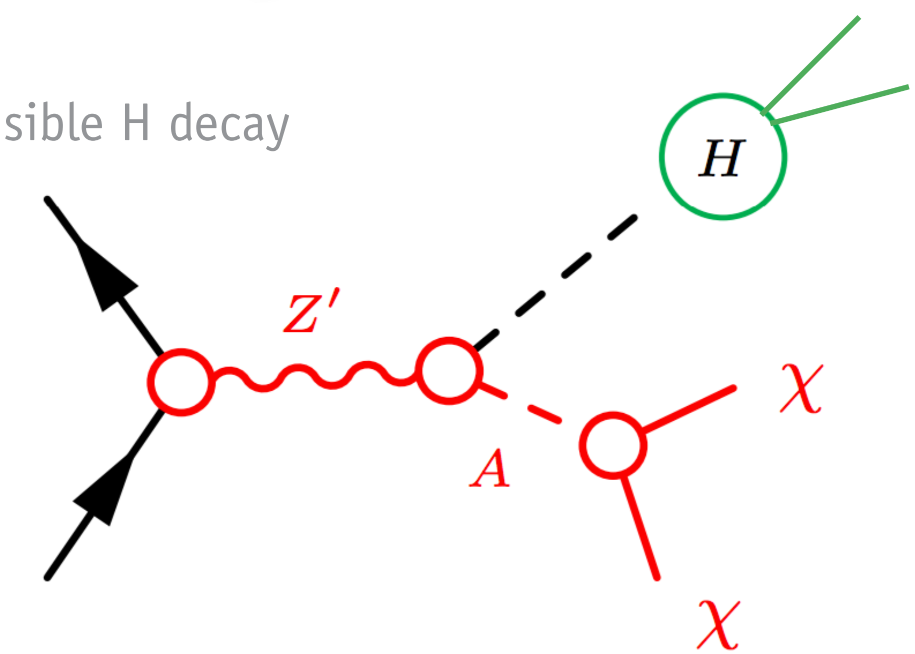
also possible: indirect BR measurement from all other visible decay channels

- different experimental challenges for invisible or visible H decay

invisible H decay



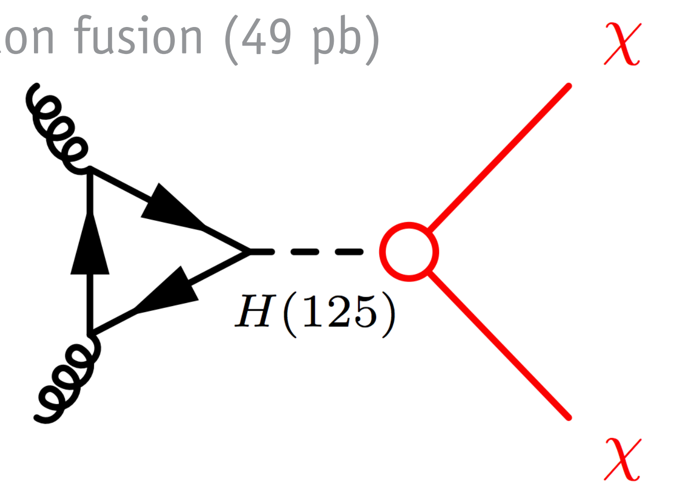
visible H decay



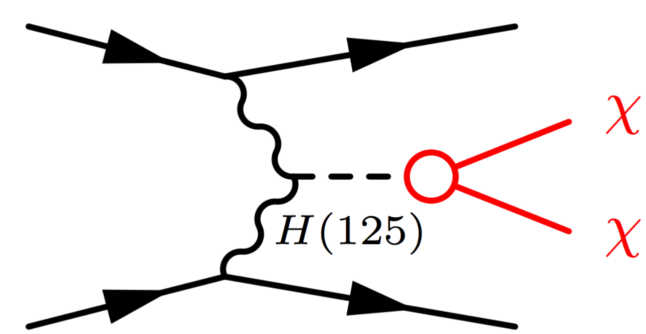
H->INVISIBLE: CROSS-SECTION ISN'T THE FULL STORY

- vector-boson-fusion (VBF) is the 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

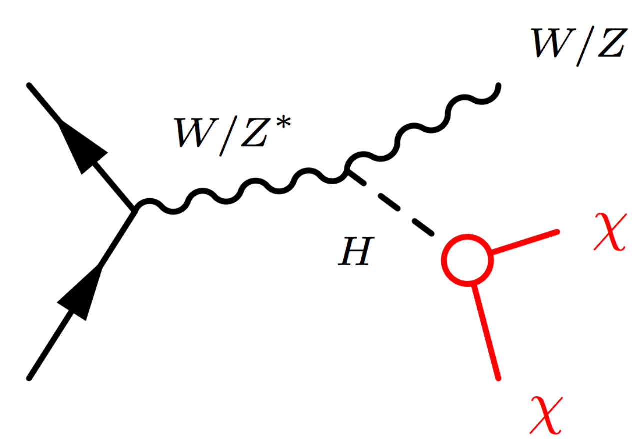
gluon fusion (49 pb)

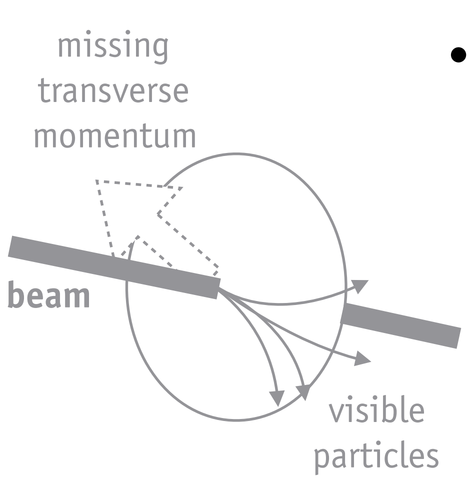


vector-boson fusion (3.8 pb)



associated production (2.3 pb)

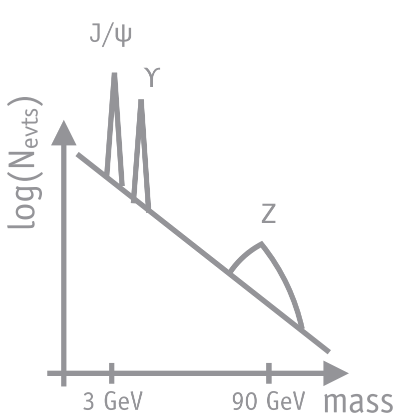


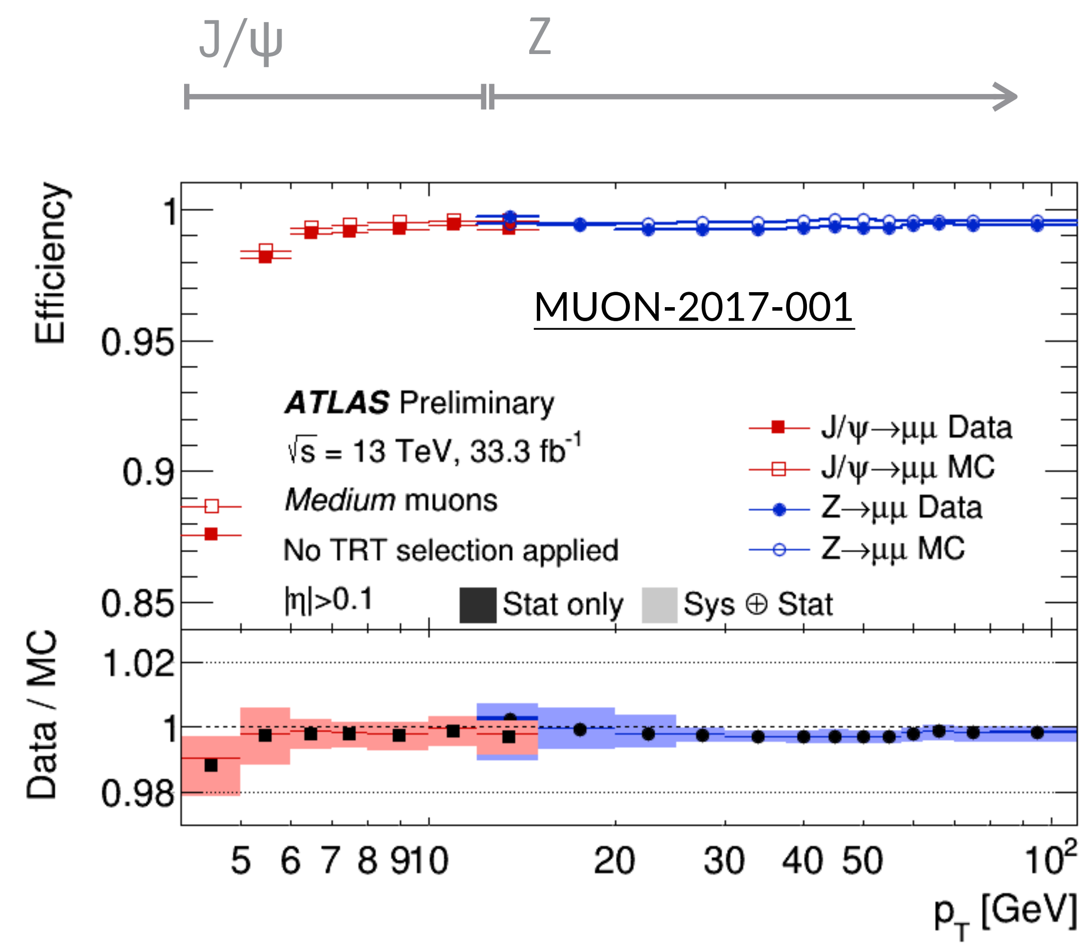


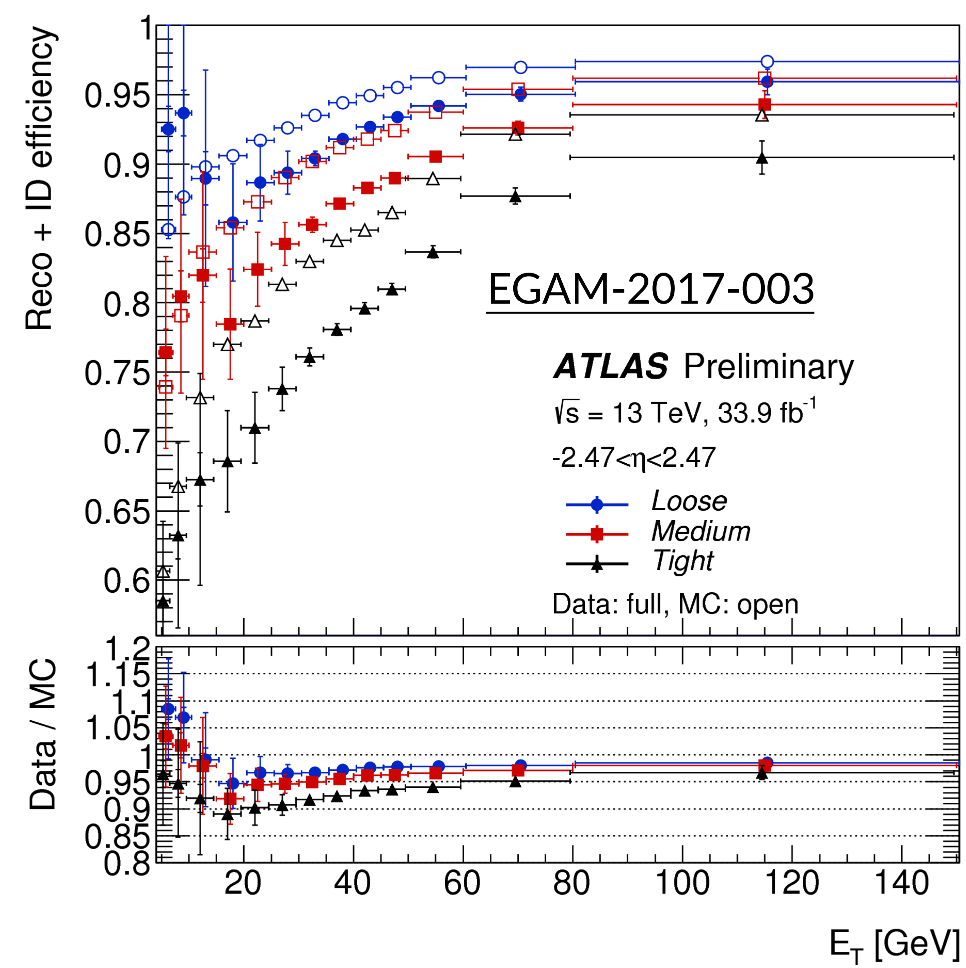
THE INVISIBLE, THROUGH THE VISIBLE

- 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->νν 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"

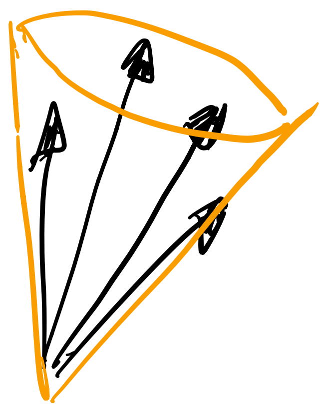
made Higgs discovery and measurements possible!



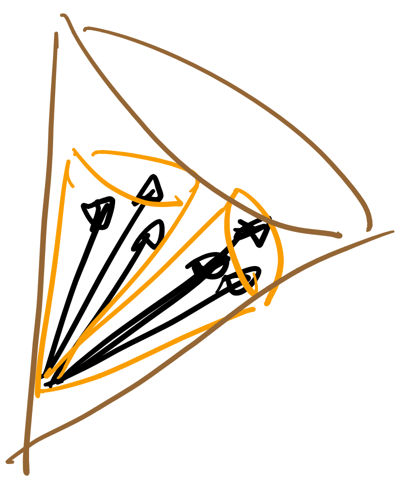




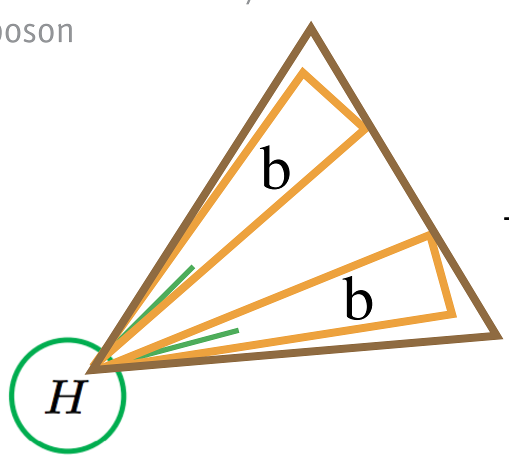
JETS, OR THE TOUGH SIDE OF QUANTUM CROMODYNAMICS



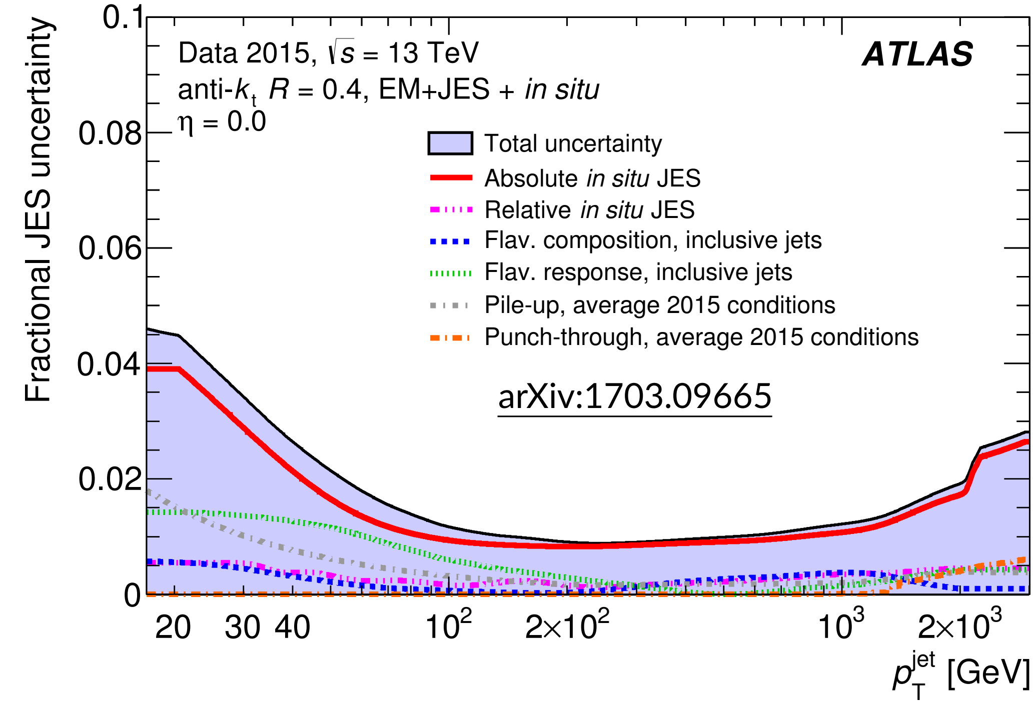
jet from a parton

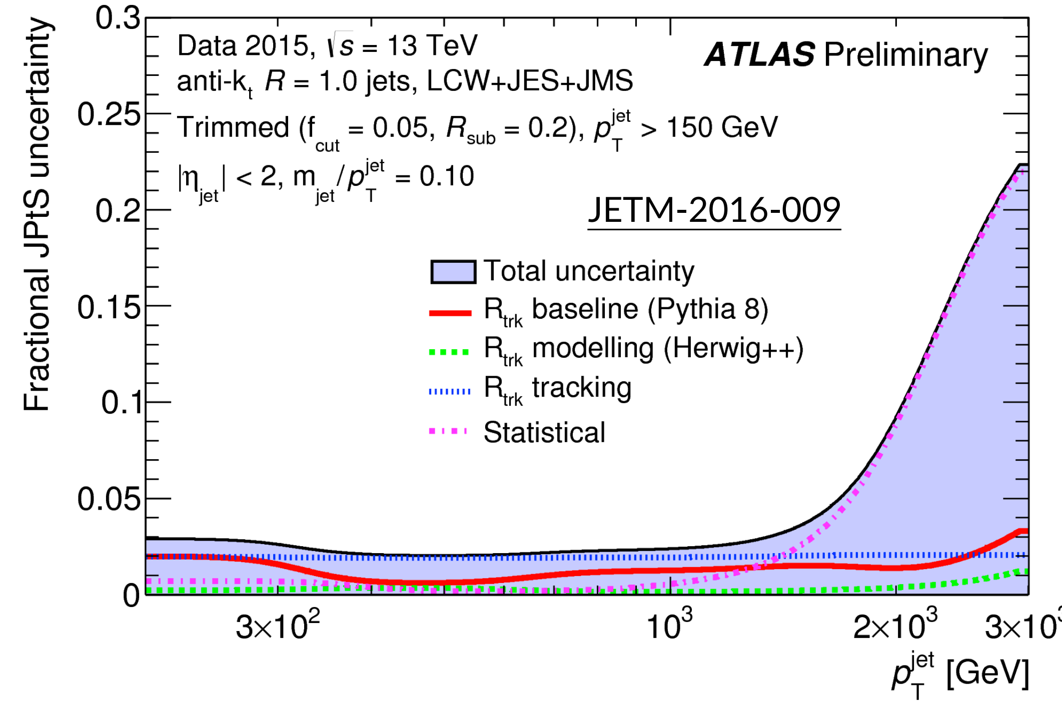


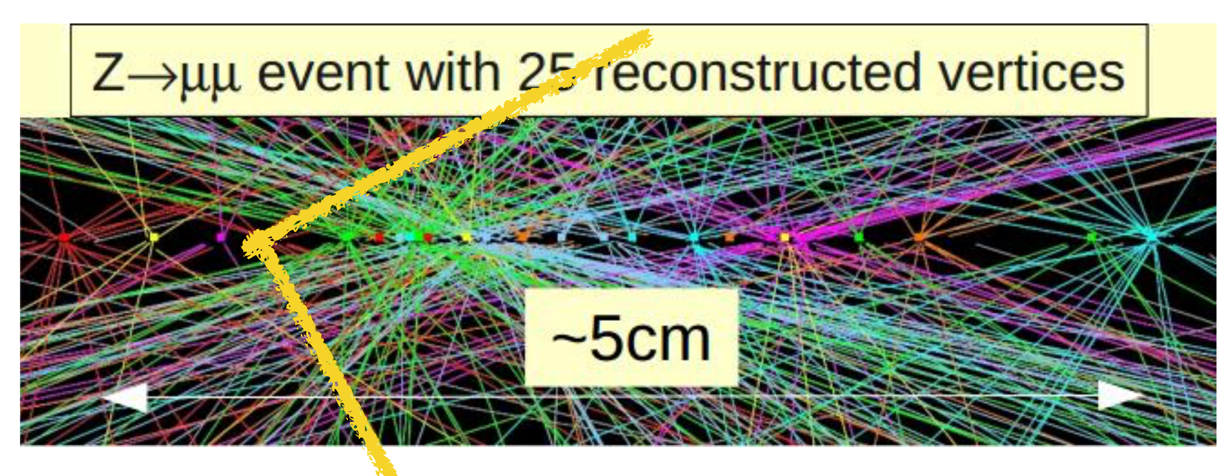
jet from a H or W/Z boson



- 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

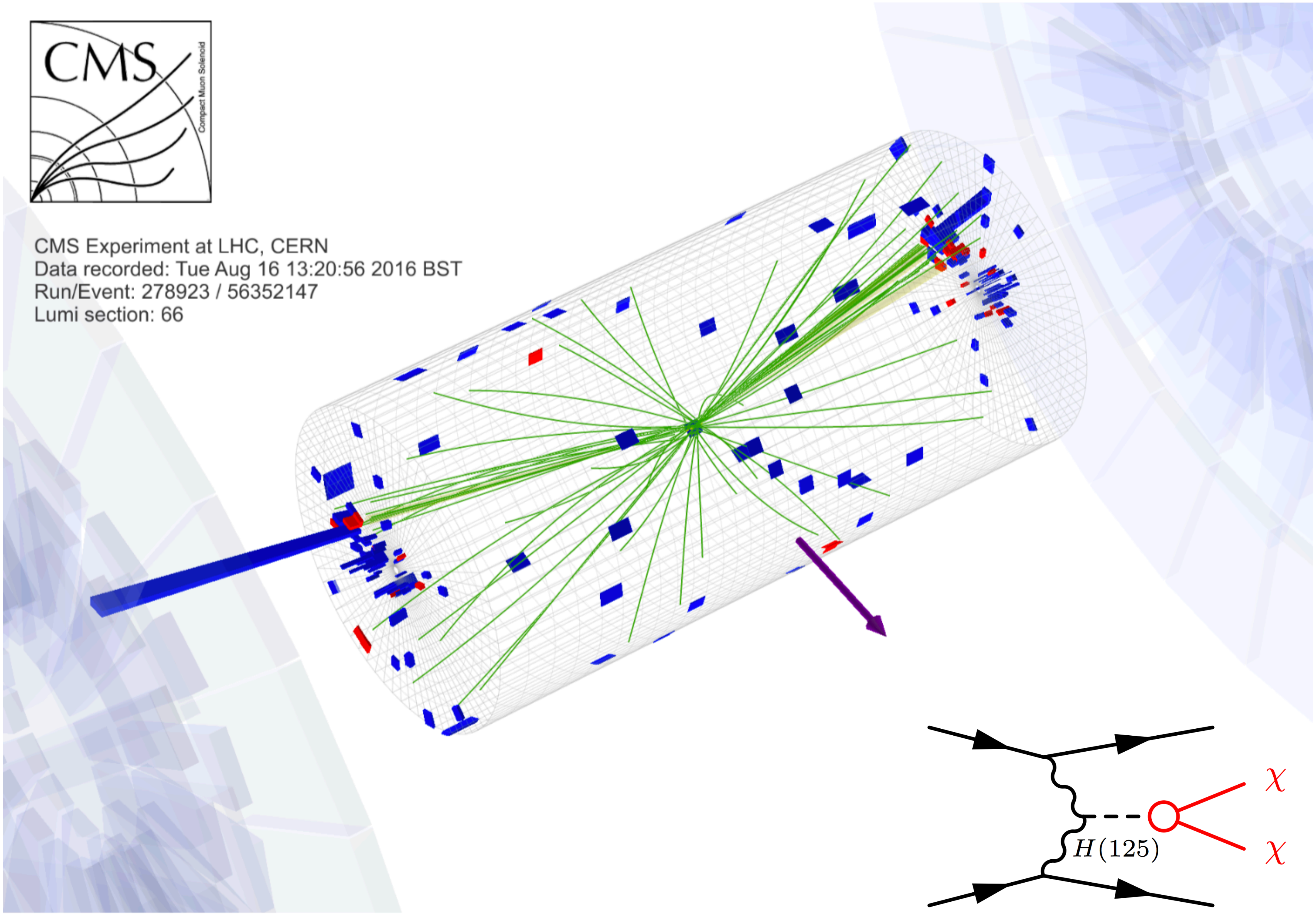




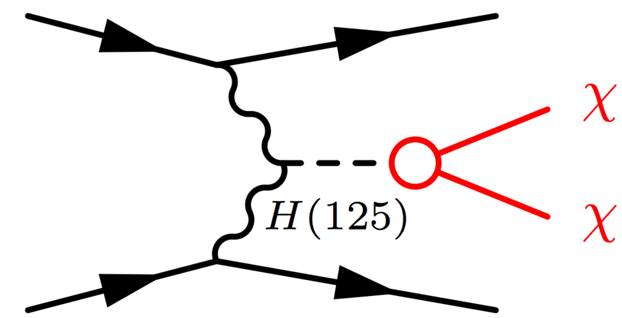


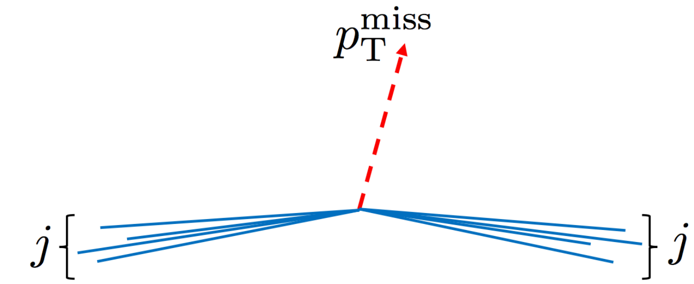
HOW IT LOOKS: INVISIBLE HIGGS IN VECTOR BOSON FUSION

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

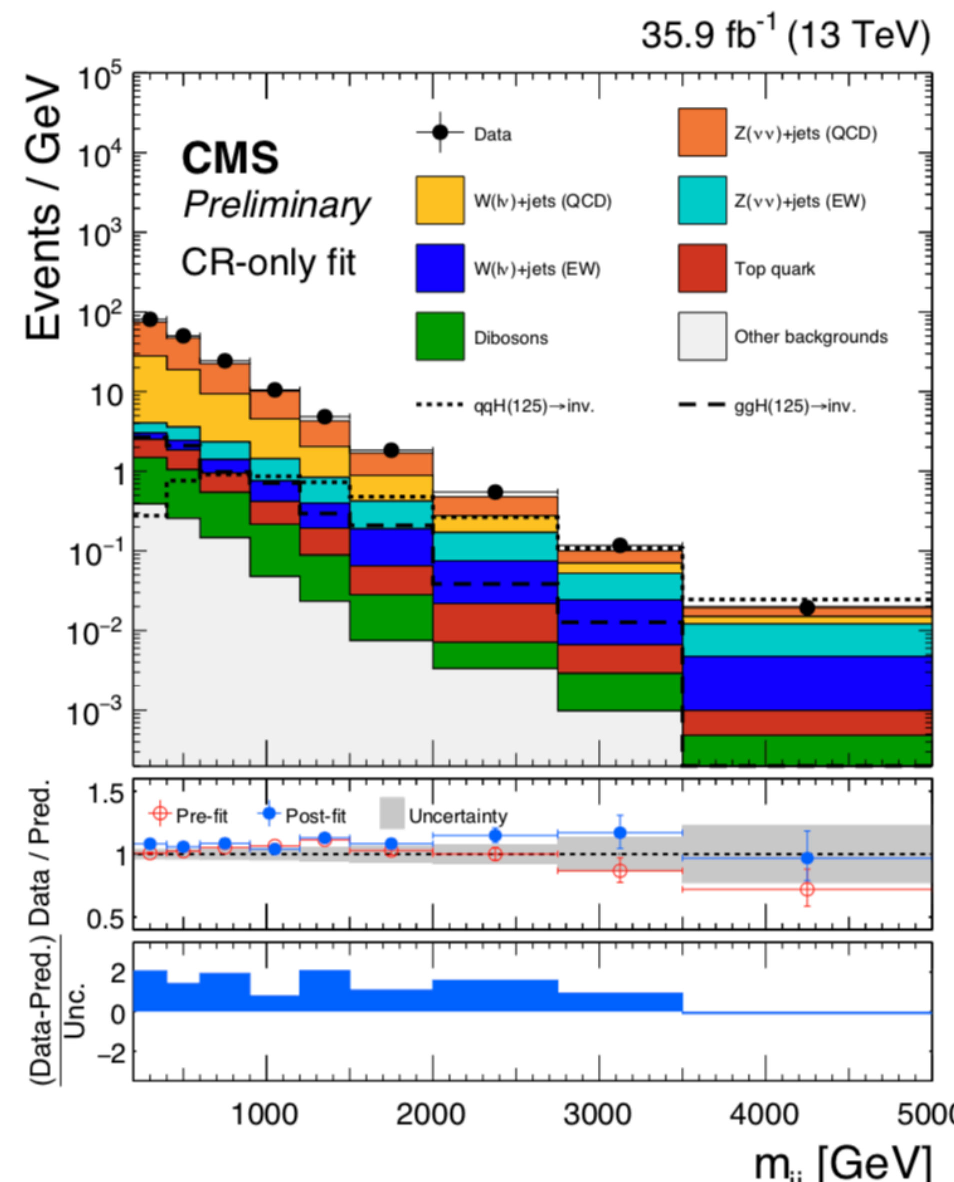
- signal-to-background ~ 0.5
- signature: two "forward", collimated jets recoil against large missing transverse momentum
  - veto events with leptons
- challenging!
  - trigger: "fake" missing transverse momentum can come from mis-measured jets
  - reconstruction: jet and lepton identification

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

- WIMPs would show up in tails of invariant mass distribution of the 2-jet system
  - more events than expected for $H \to ZZ^* \to 4\nu$
  - main background is Z(νν)+jets, estimated measuring W and Z+jet processes in control regions with leptons

search sensitive to BR(H→inv) ~ 0.20

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



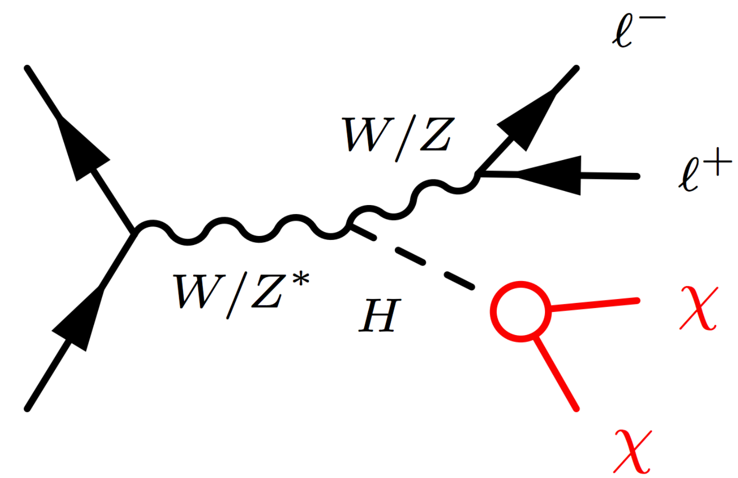
INVISIBLE HIGGS IN ASSOCIATED PRODUCTION

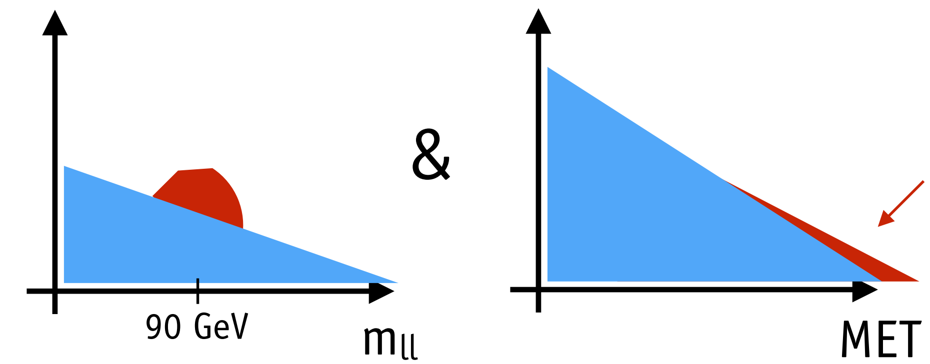
search sensitive to BR(H→inv) ~ 0.20

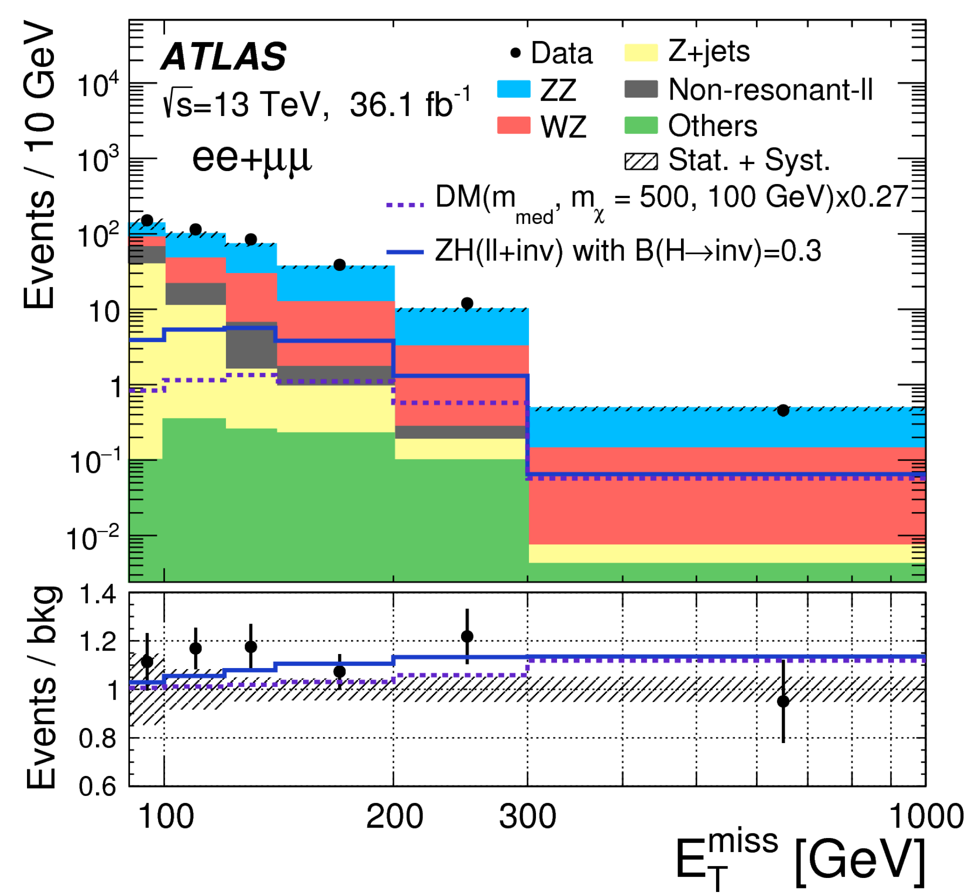
- look for large missing transverse momentum in events with a Z boson
  - clean, resonant signature in electron and muon channels
- a low-statistics channel
  - lepton trigger, based on fast calorimeters / gas detectors + charged particle tracker
  - crucial: background modelling in simulation (ZZ→llνν)
- 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





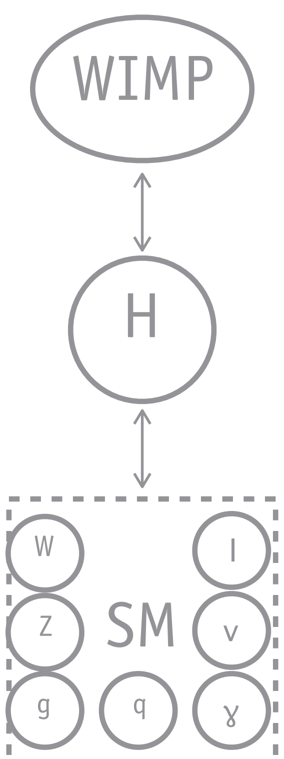


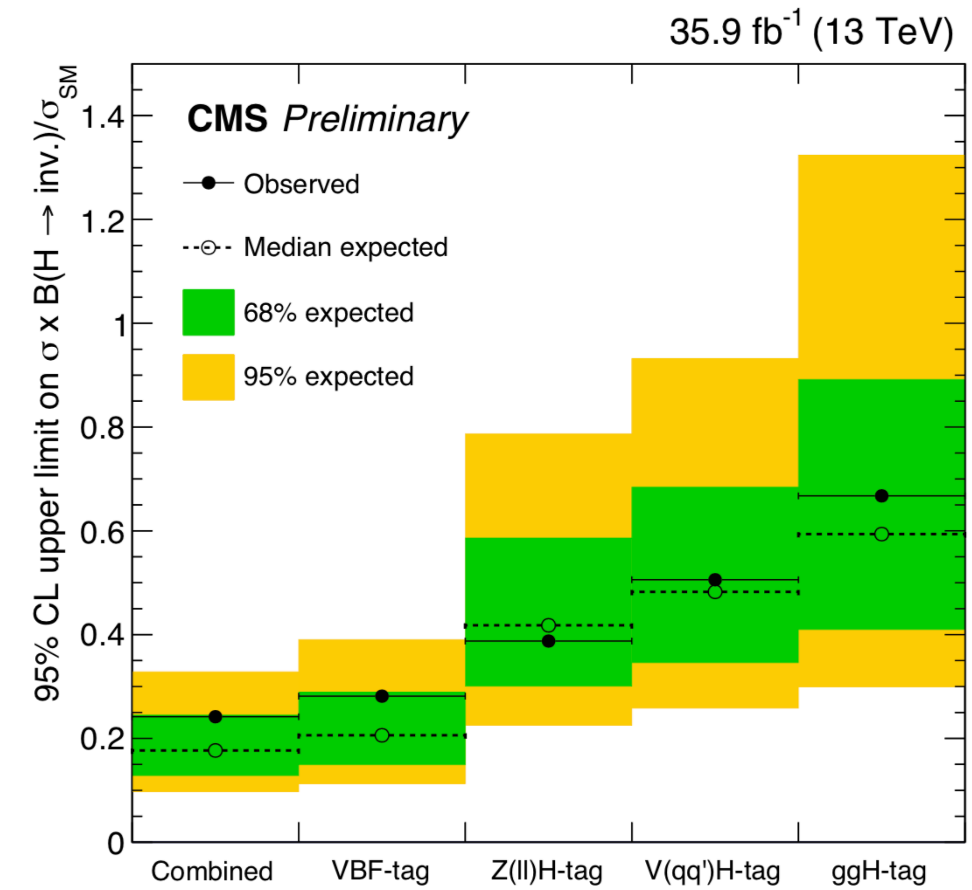
Phys.Lett. B776 (2018) 318-337
Eur. Phys. J. C 78 (2018) 291

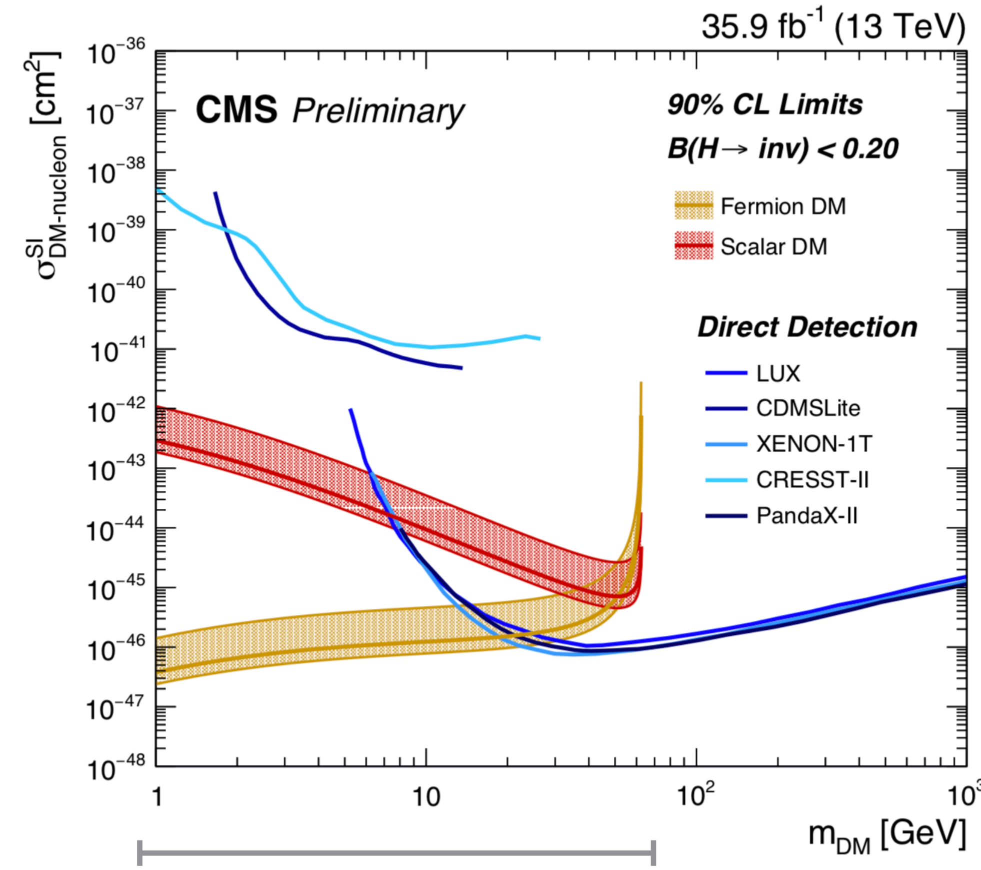
INVISIBLE HIGGS RESULTS

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

- best 95% CL limits come from VBF channel
  - ATLAS: BR(H→inv) < 0.28
  - CMS: BR(H→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

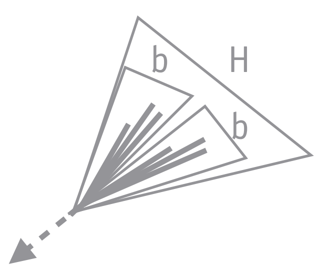
Phys. Rev. Lett. 119, 181804
Phys. Rev. D 96, 112004
JHEP 10 (2017) 180

- search for visible H decay and WIMPs
  - through heavier states Z' and A
    - ⋆ a possible source of pseudoscalar interactions!

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

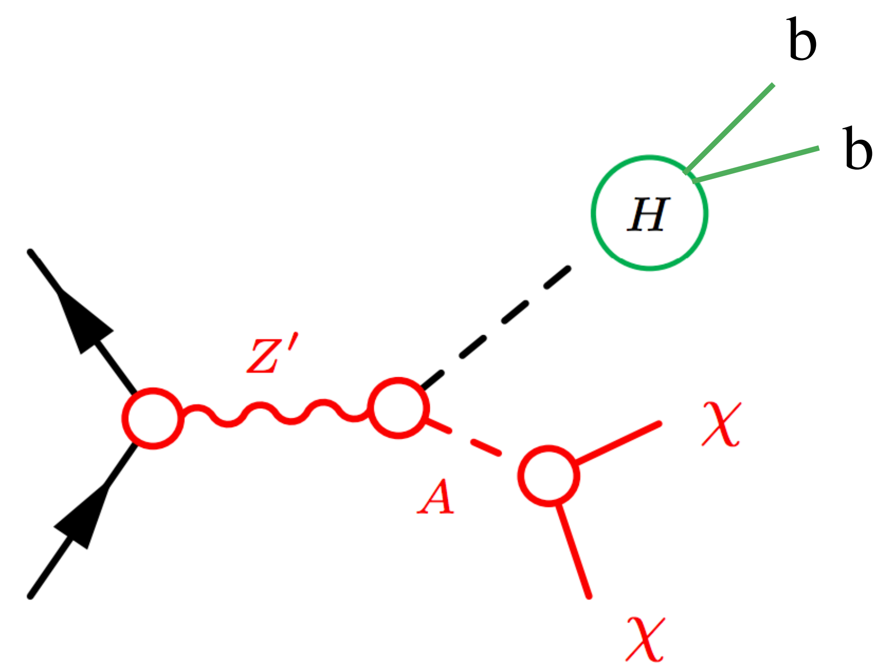
O(10x) better than $H \to \gamma\gamma$

- $H \to bb$ most sensitive channel
  - BR~0.60, background from Z+jets, W+jets and ttbar
  - select resonant di-jet mass and look at tails in missing transverse momentum distribution

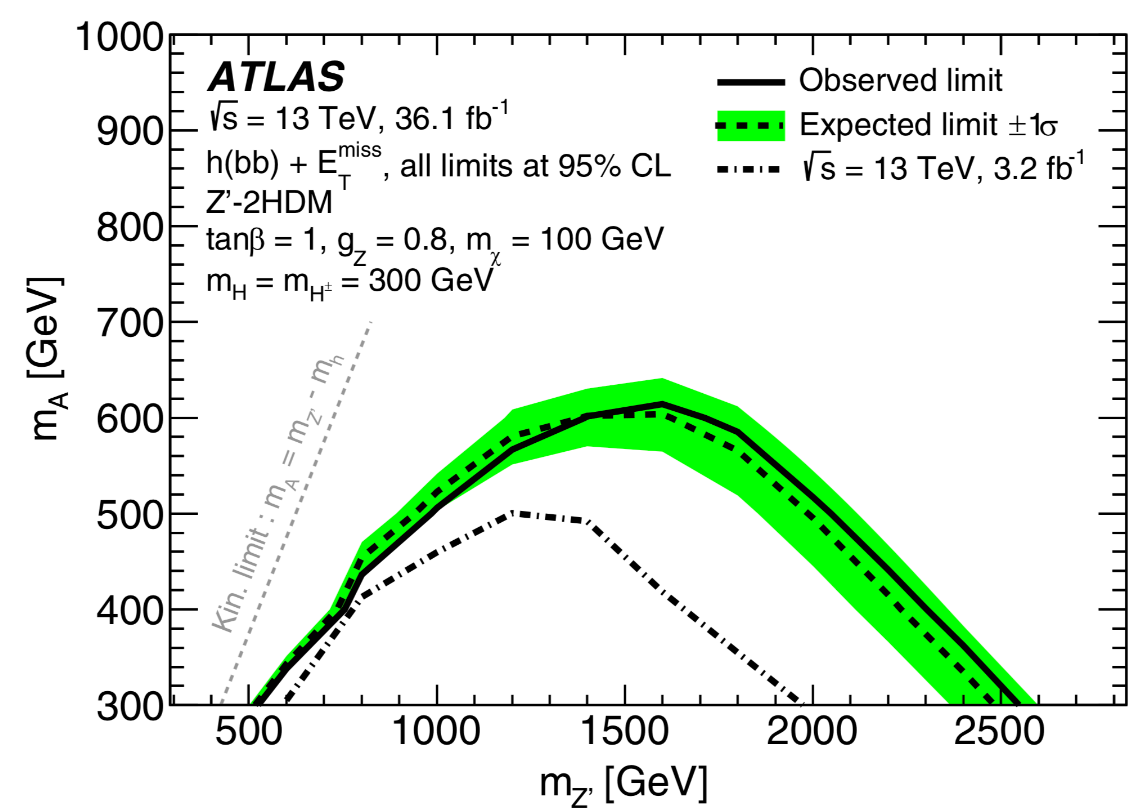


algorithms based on energy density ("2-prongness"); machine learning promising for exploiting low-level observables

- 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

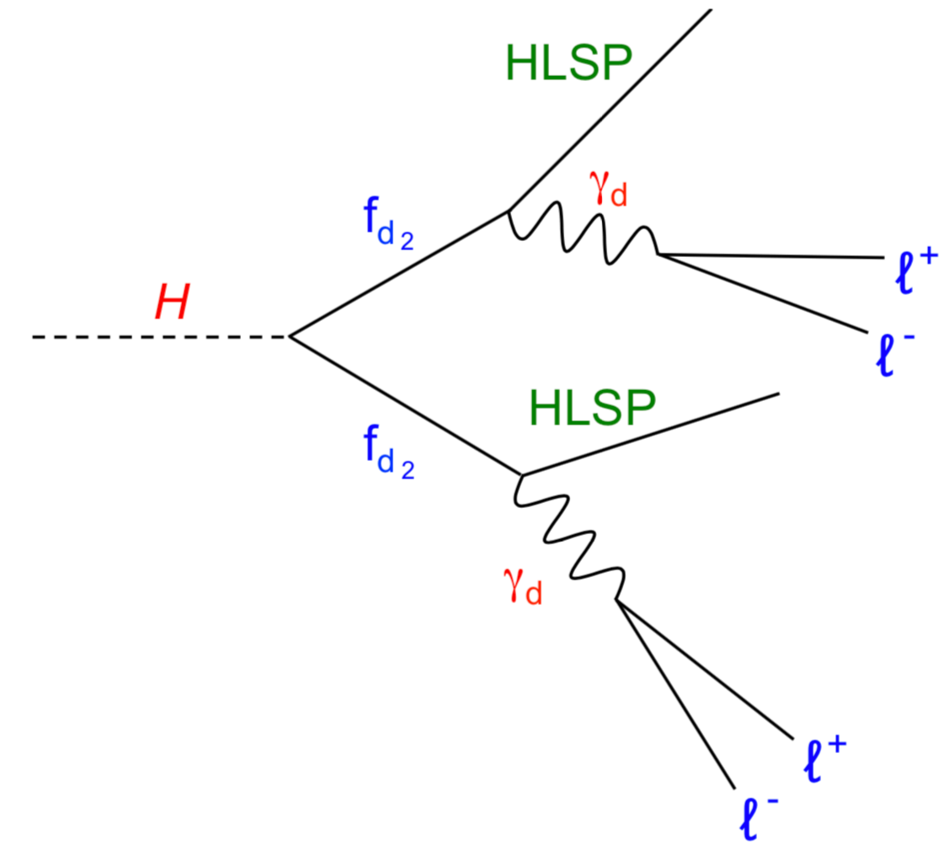
- what if H decays to unstable states from a hidden sector?
  - hidden, lightest stable particle could explain Dark Matter

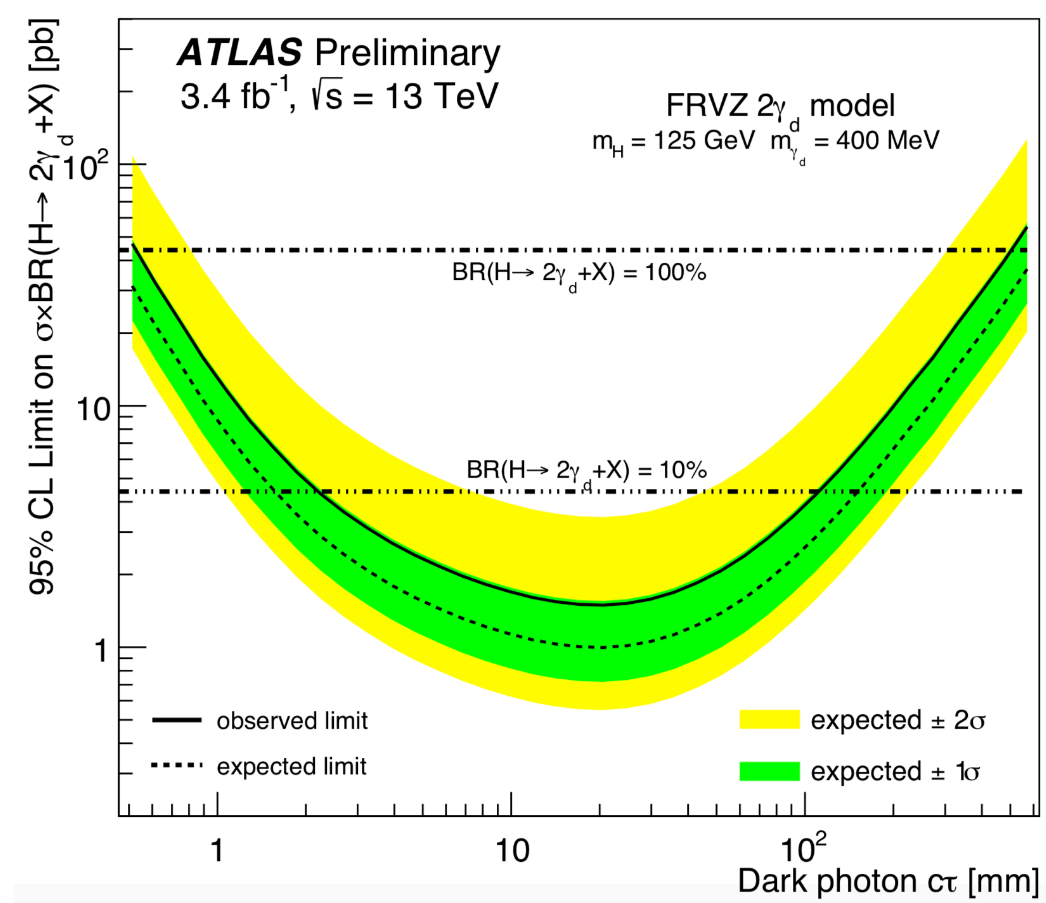
ATLAS-CONF-2016-042

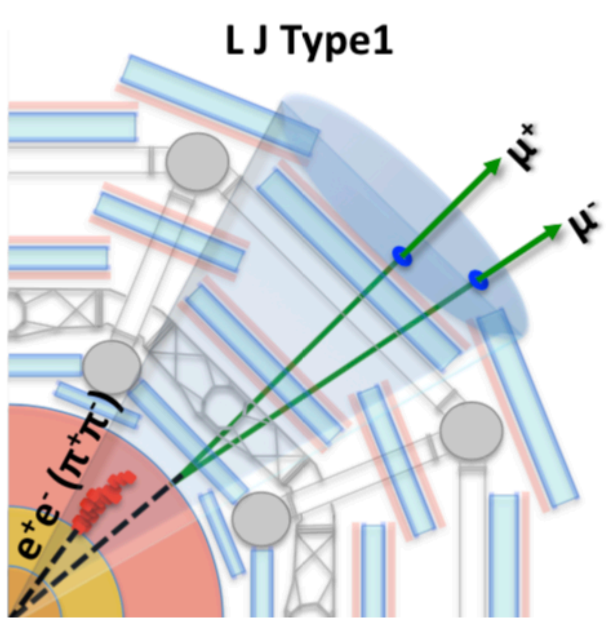
- long-lived particles, which travel undetected for ~meters and then decay into visible particles

dedicated trigger and tracking strategies are essential!

  - example: lepton jets starting in the calorimeters or in the muon spectrometer
- a challenge for current detectors
  - clever reconstruction techniques for such non-standard signatures





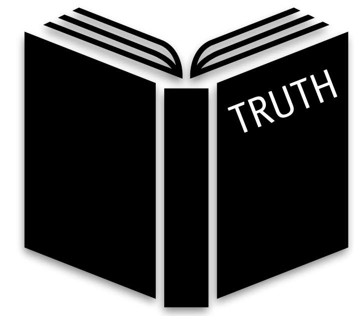


AND MANY MORE!

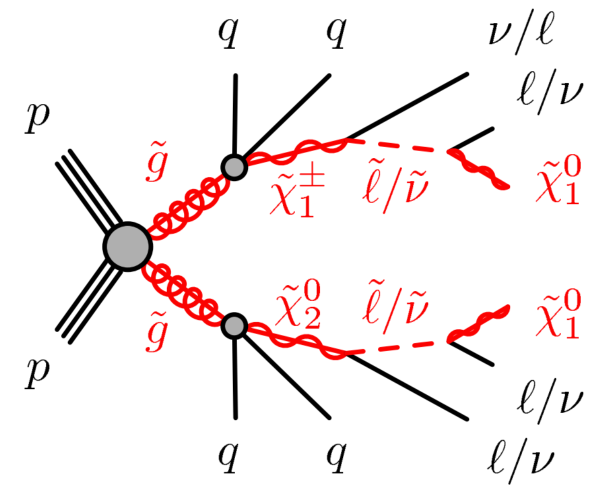
experimental strategies try to cover all possible signatures, as predicted by effective, simplified and UV-complete models

- 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!

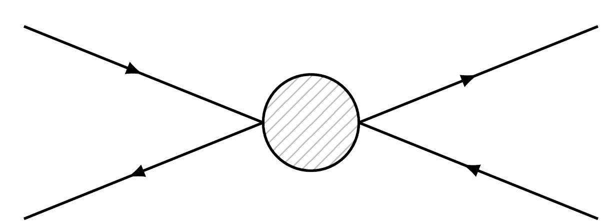
UV-complete theory



simplified model

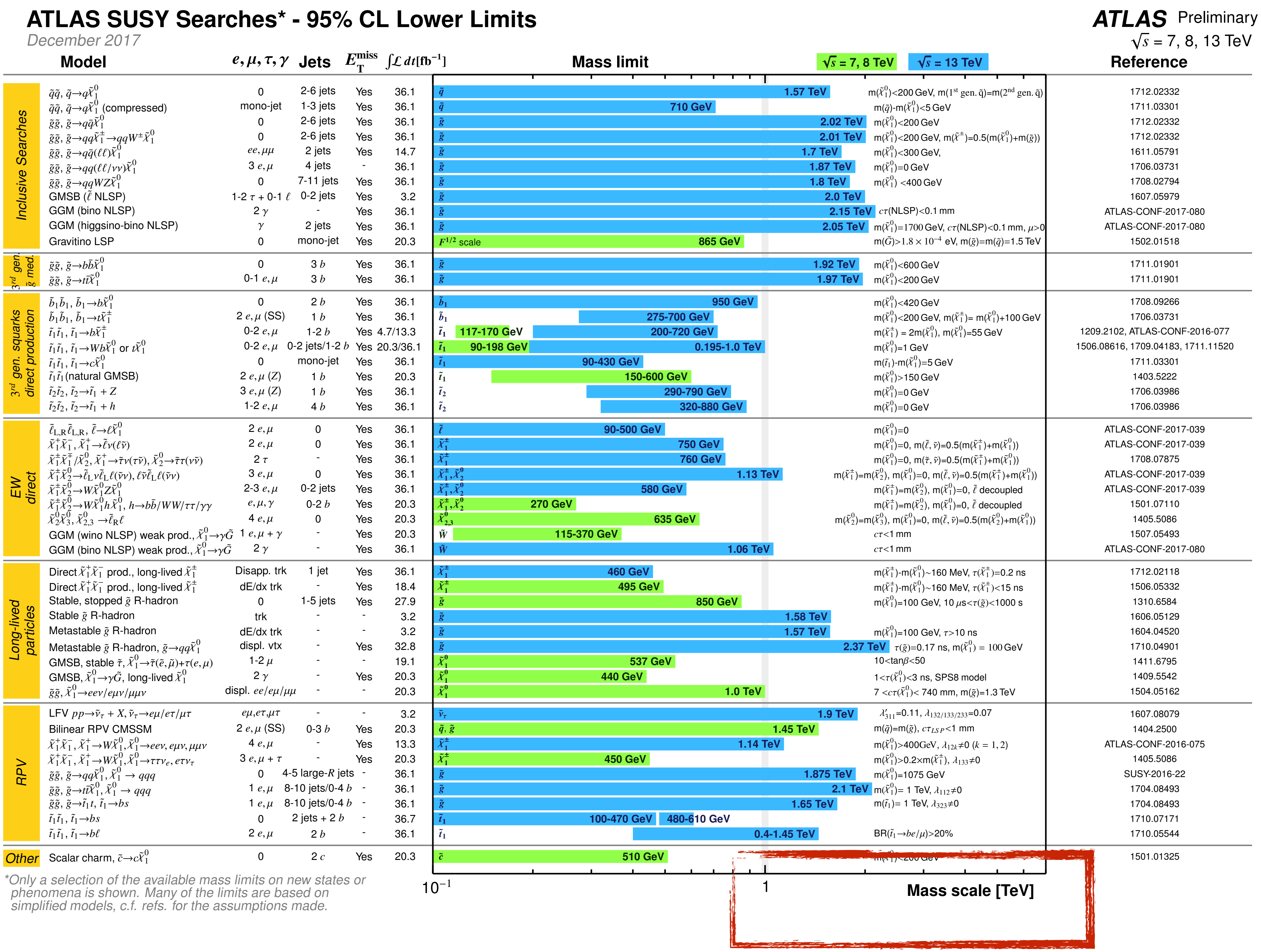


effective field theory



A PLETHORA OF SEARCHES...

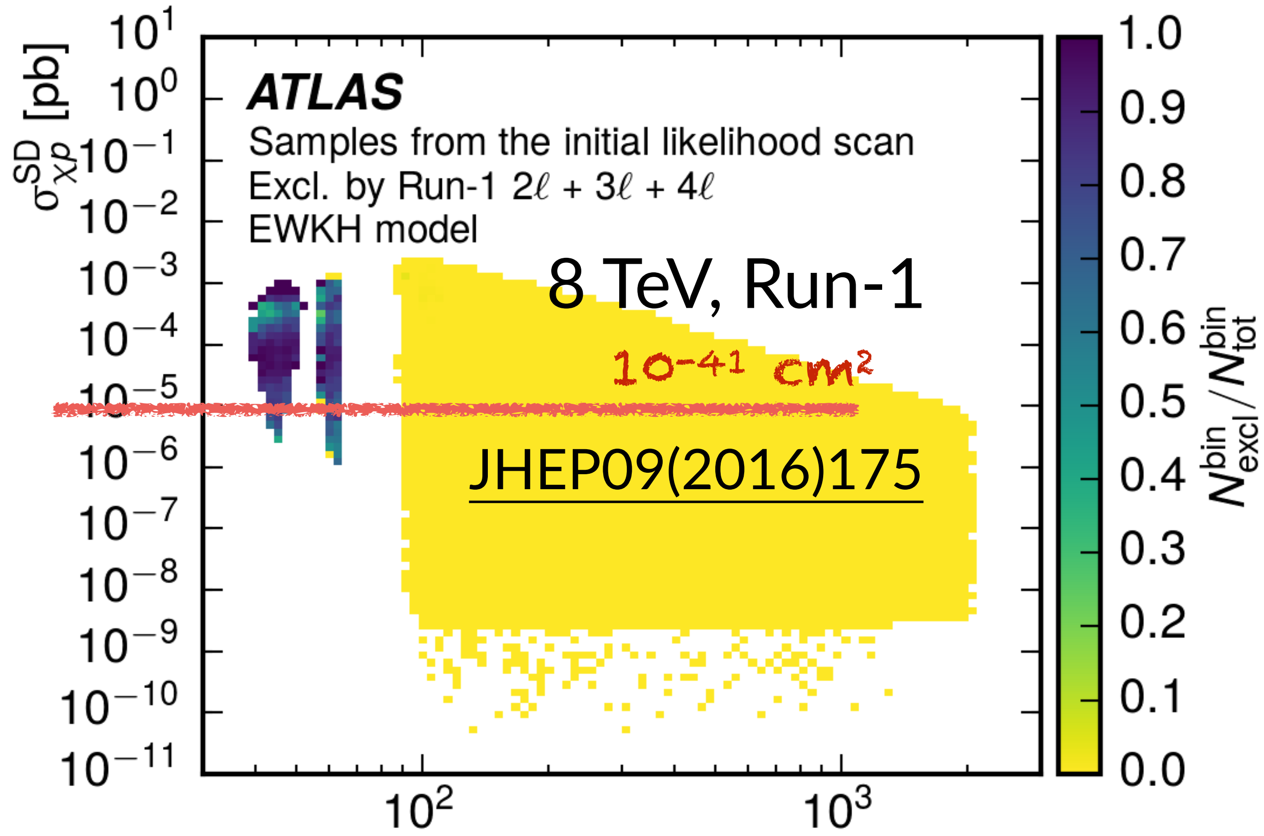
probing supersymmetry at the TeV scale...

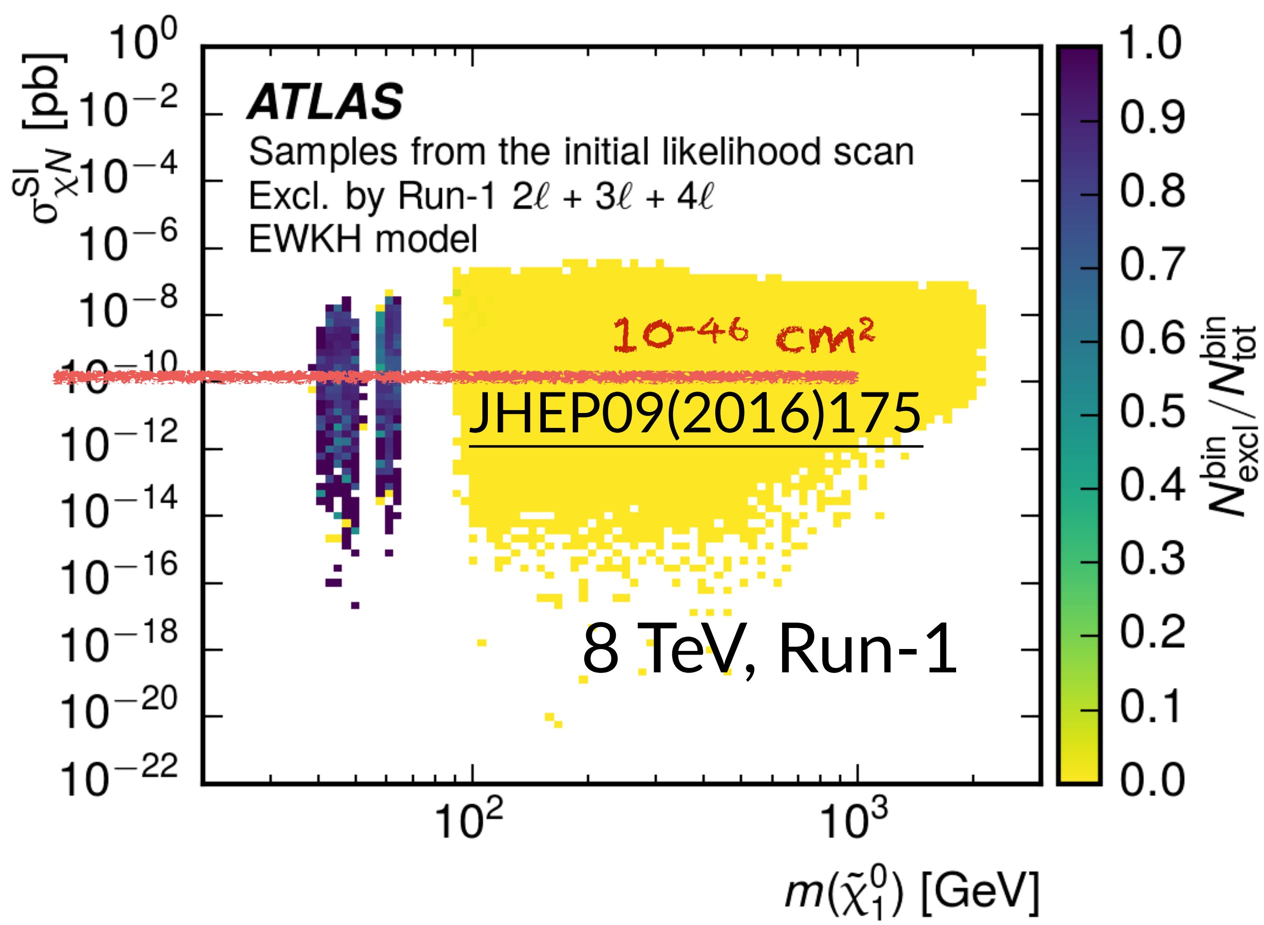


CORNERING SUPERSYMMETRY

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

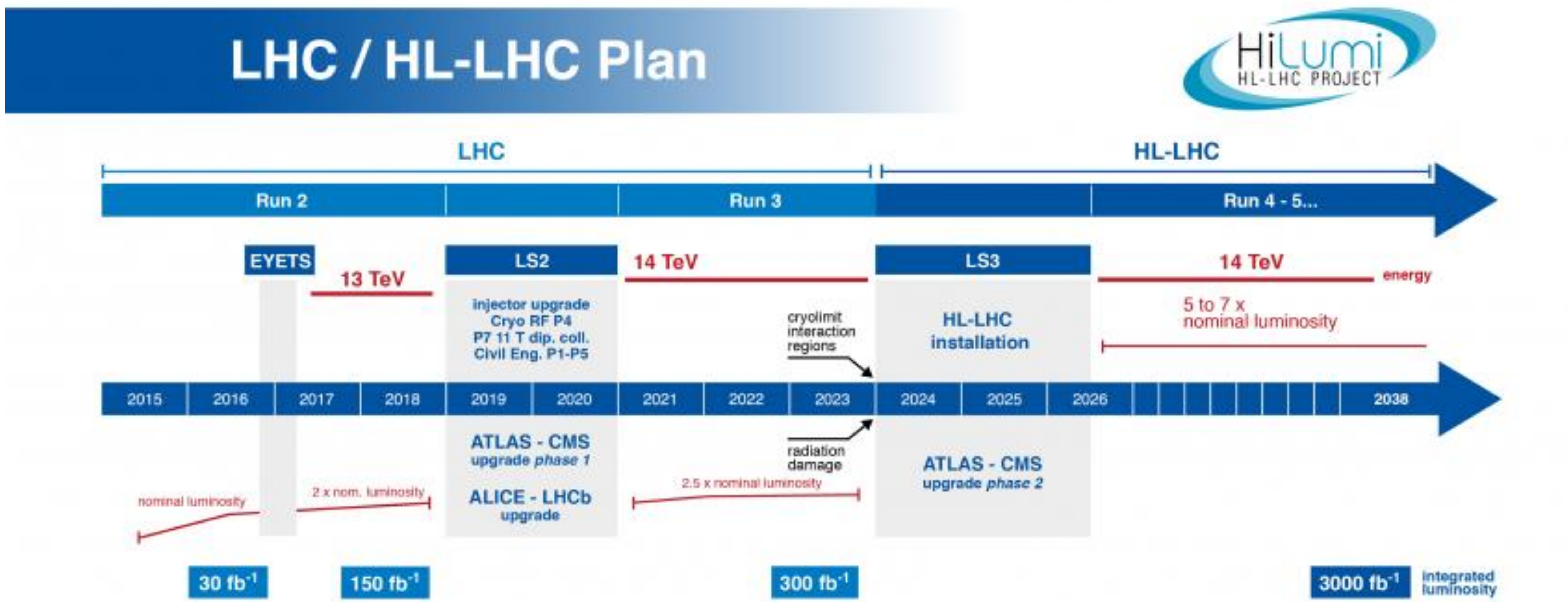
- searches for supersymmetric particles span parameter space often compatible with Dark Matter relic density
  - Run-1 results expressed in terms of fraction of allowed models which are also excluded
    - yellow area: less than 10% of the explored phase space was excluded
- how to fill the missing space?
  - 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





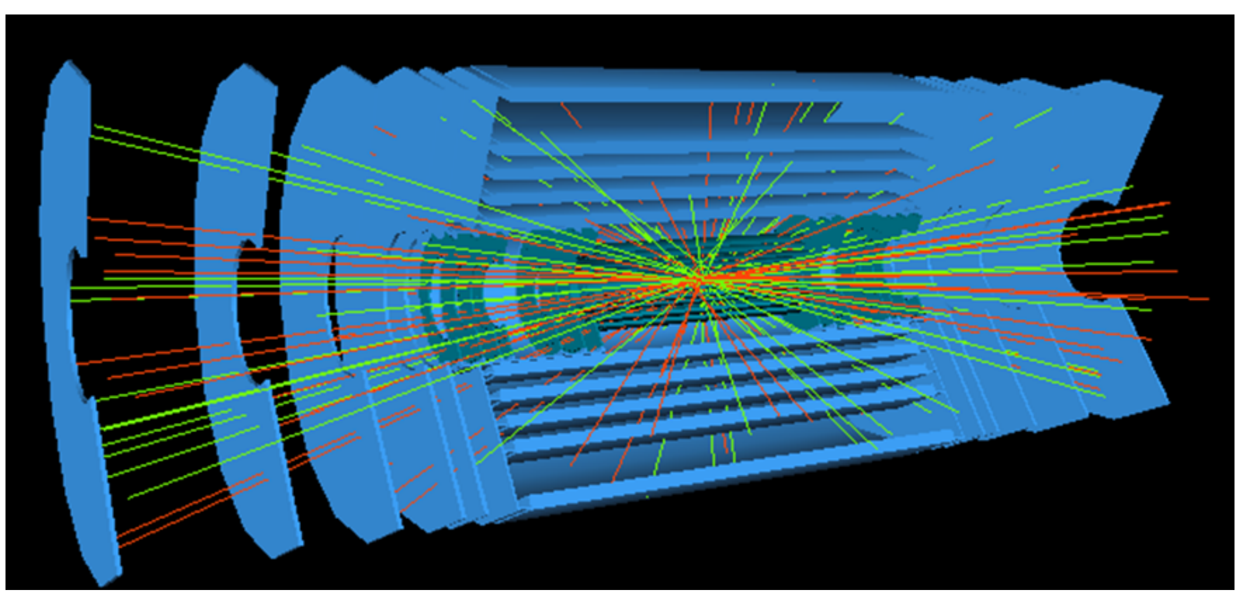
HIGH LUMINOSITY, HIGH CHALLENGES

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

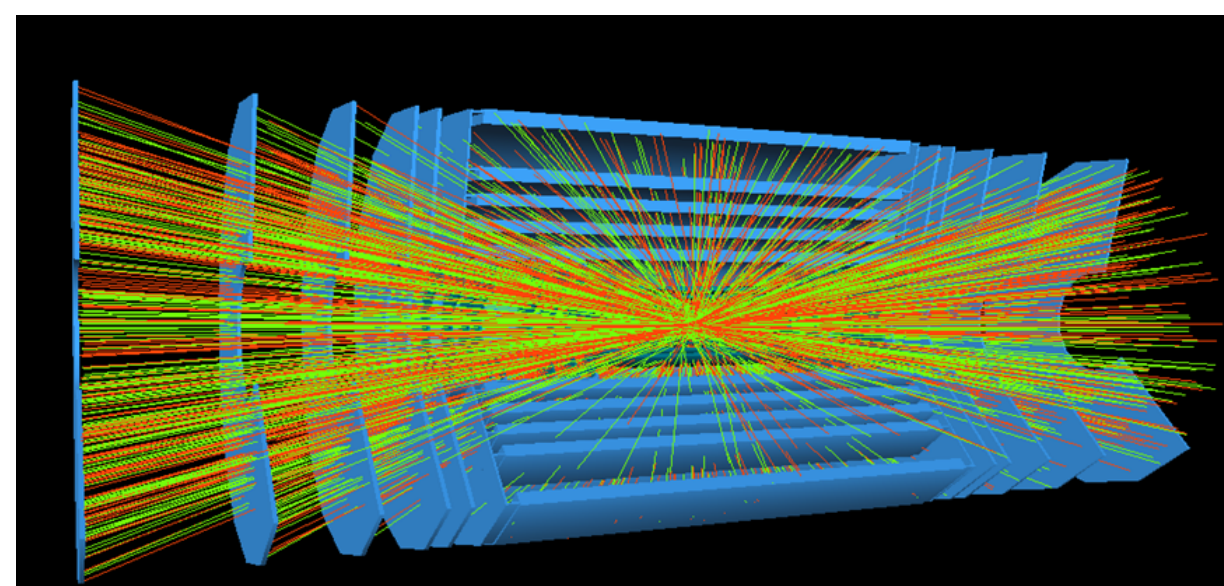


event pile-up is a major challenge!

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 BR(H→inv) ~ 0.05 by 2038

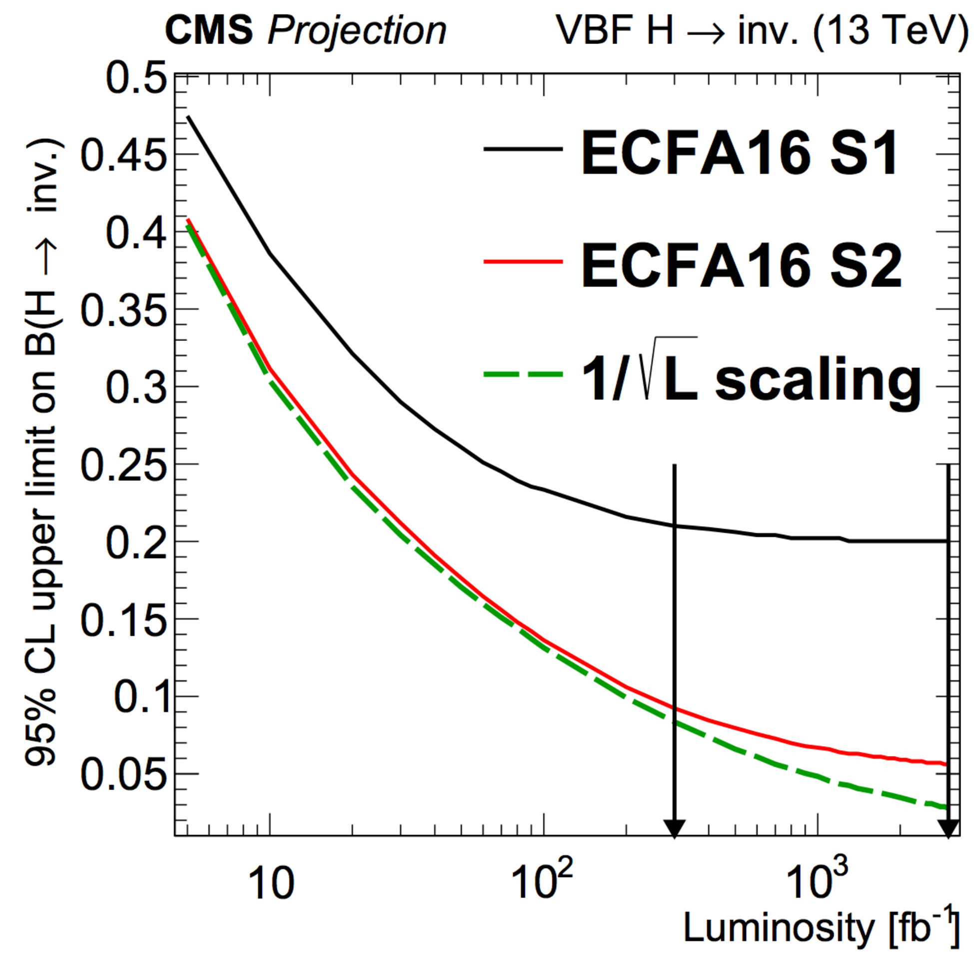
CMS-TDR-014

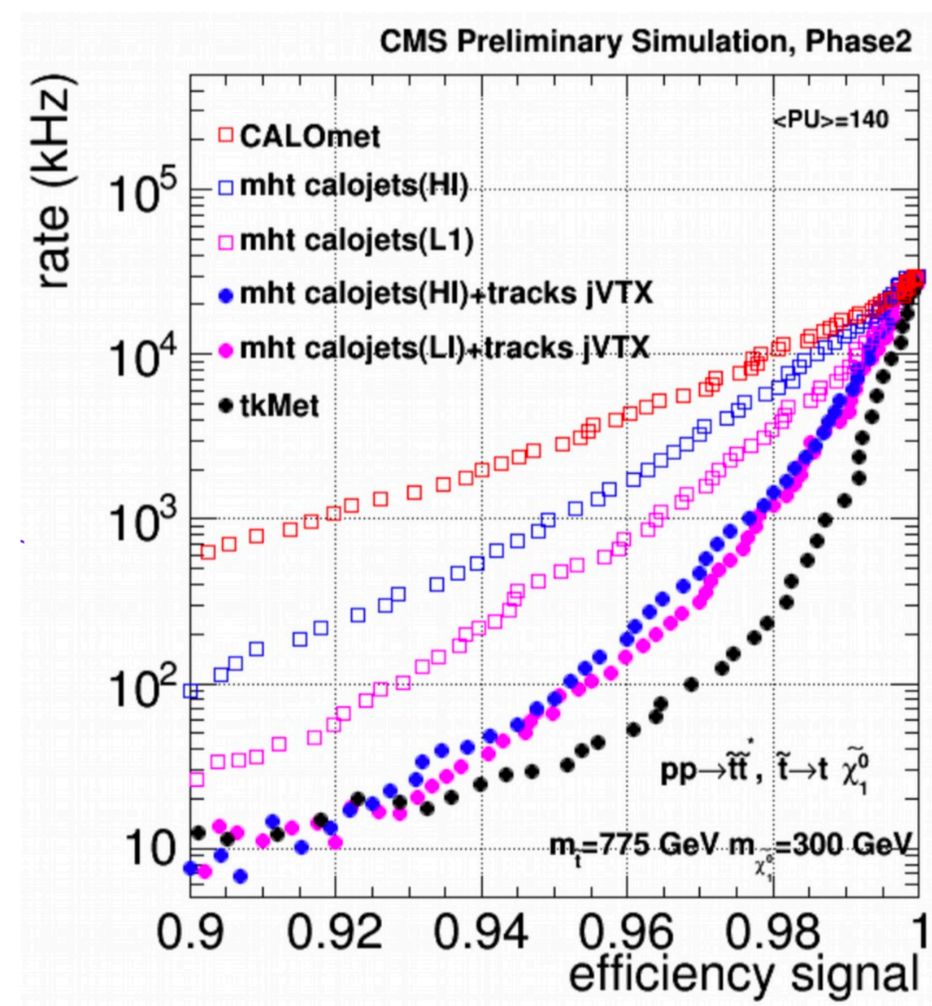
- R&D for pileup-robust detector upgrades
  - track information at early stages of missing transverse momentum trigger to reduce noise rate

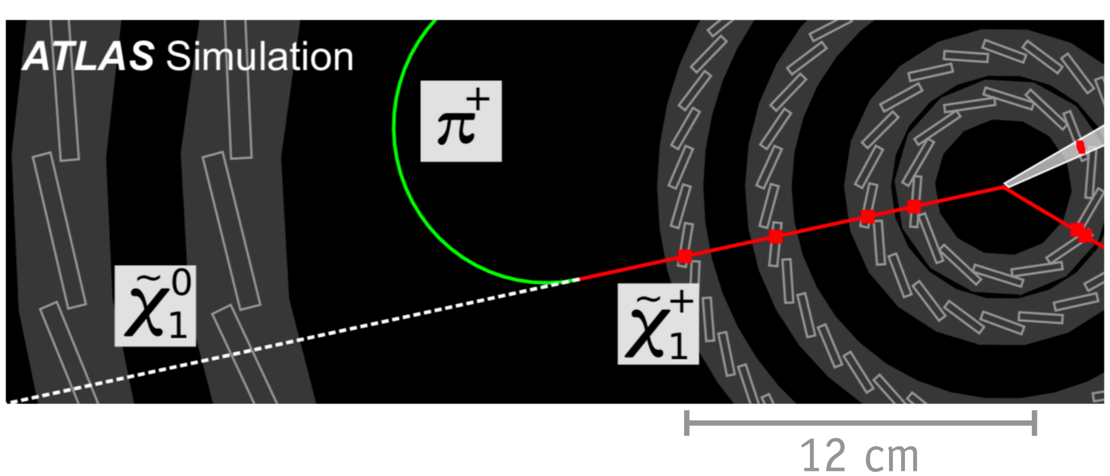
ATLAS: new trigger design integrates new silicon tracker (ITk)
CMS: similar, could target 2-3 GeV tracks

- an opportunity for long-lived particles
  - new fast timing layers help to reconstruct displaced vertexes?

high-granularity detectors to replace/enhance calorimetry in the forward region and improve pile-up rejection





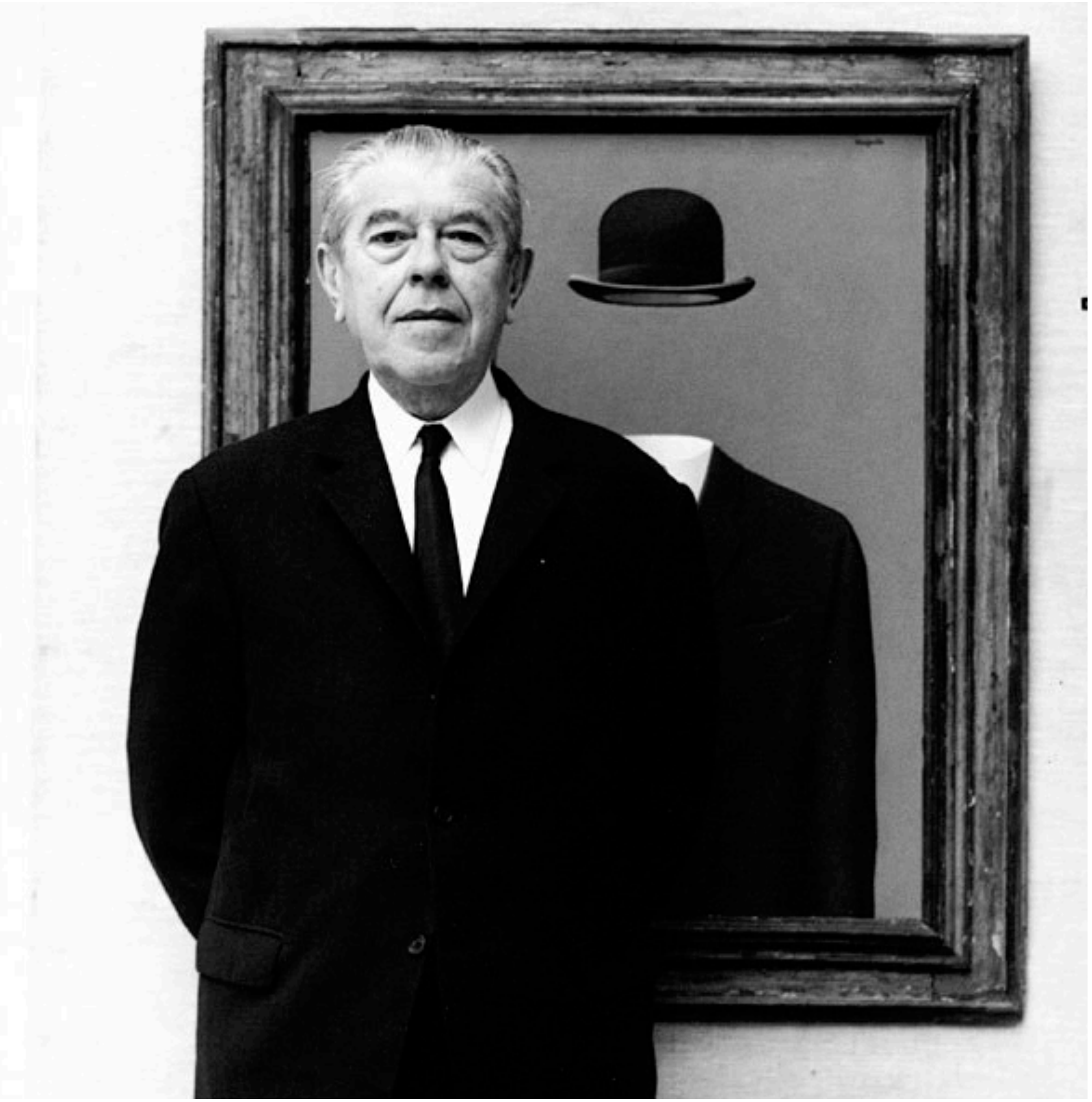


CONCLUSIONS

- 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



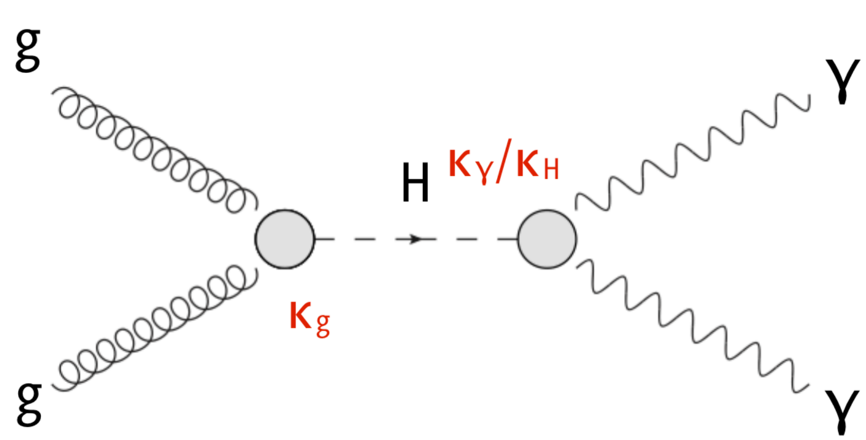
Spares

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)



$$(\sigma\times BR)(gg\to H\to\gamma\gamma) = \sigma_{SM}(gg\to H)\cdot BR_{SM}(H\to\gamma\gamma)\cdot \boldsymbol{\kappa_g^2\cdot\kappa_\gamma^2/\kappa_H^2}$$