ATLAS EXPERIMENT

ATLAS RESULTS OVERVIEW (w/ FOCUS ON DM)

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DARKWIN 02.07.2019 - Natal, Brazil

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INTRODUCTION & OUTLINE

- After the discovery of the Higgs in 2012 ATLAS has greatly intensified the search program for signs of physics beyond the SM and in particular for Dark Matter
  - exploiting the increase in data statistics from LHC Run 2
  - engaging the problem from several sides: indirect searches from precision measurements, direct search for DM particles or DM mediators, searches for non-WIMP DM ...
- In this summary selected results on:
  - highlights on most recent ATLAS results: precision measurements, top, Higgs, searches
  - review of the status of the searches for signals from Dark Matter
  - future prospects

NOTE: impossible to cover in detail everything here. A full updated list of results from ATLAS available in: *https://twiki.cern.ch/twiki/bin/view/AtlasPublic*

LHC RUN 2

The Large Hadron Collider is a multipurpose and flexible machine

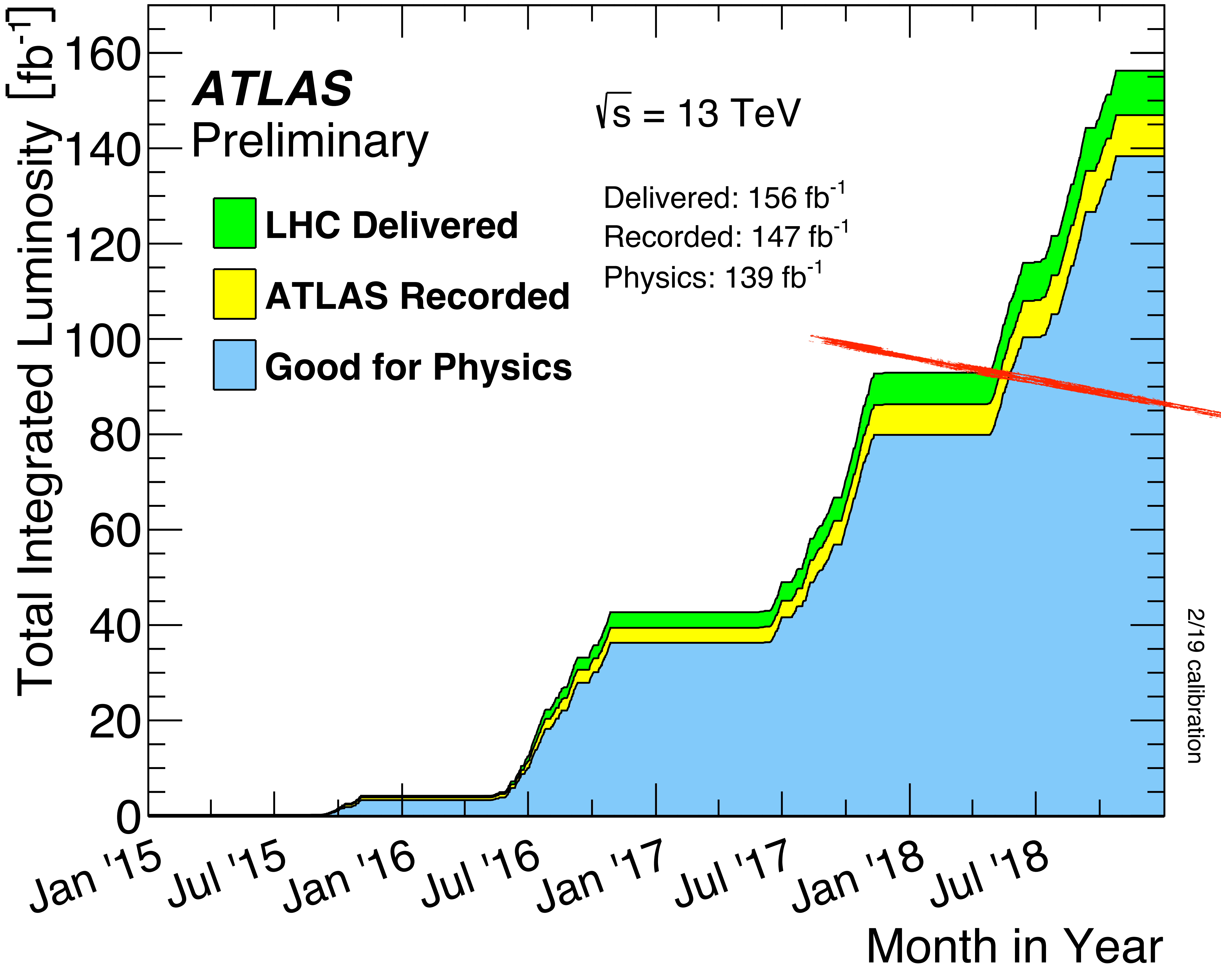
Run 2 (2015-2018):

- 156 fb^{-1} of proton-proton interactions delivered at $\sqrt{s}$ = 13 TeV
- Heavy Ions (2.3 nb^{-1} @ 5 TeV Pb-Pb, p-Pb, Xe-Xe), low-pileup p-p, p-p for diffractive physics

ATLAS DATA IN RUN 2

ATLAS-CONF-2019-021

excellent data taking (94%) and data quality (95%) efficiencies



Yields at 13 TeV w/ 139 fb^{-1}

Higgs	~7.7 10^6
Top	~300 10^6
$Z \to ll$	~300 10^6
$W \to l\nu$	~3 10^9

PRECISION TESTS OF THE SM

- TOP, EW/ QCD
- FLAVOUR PHYSICS

EWSB

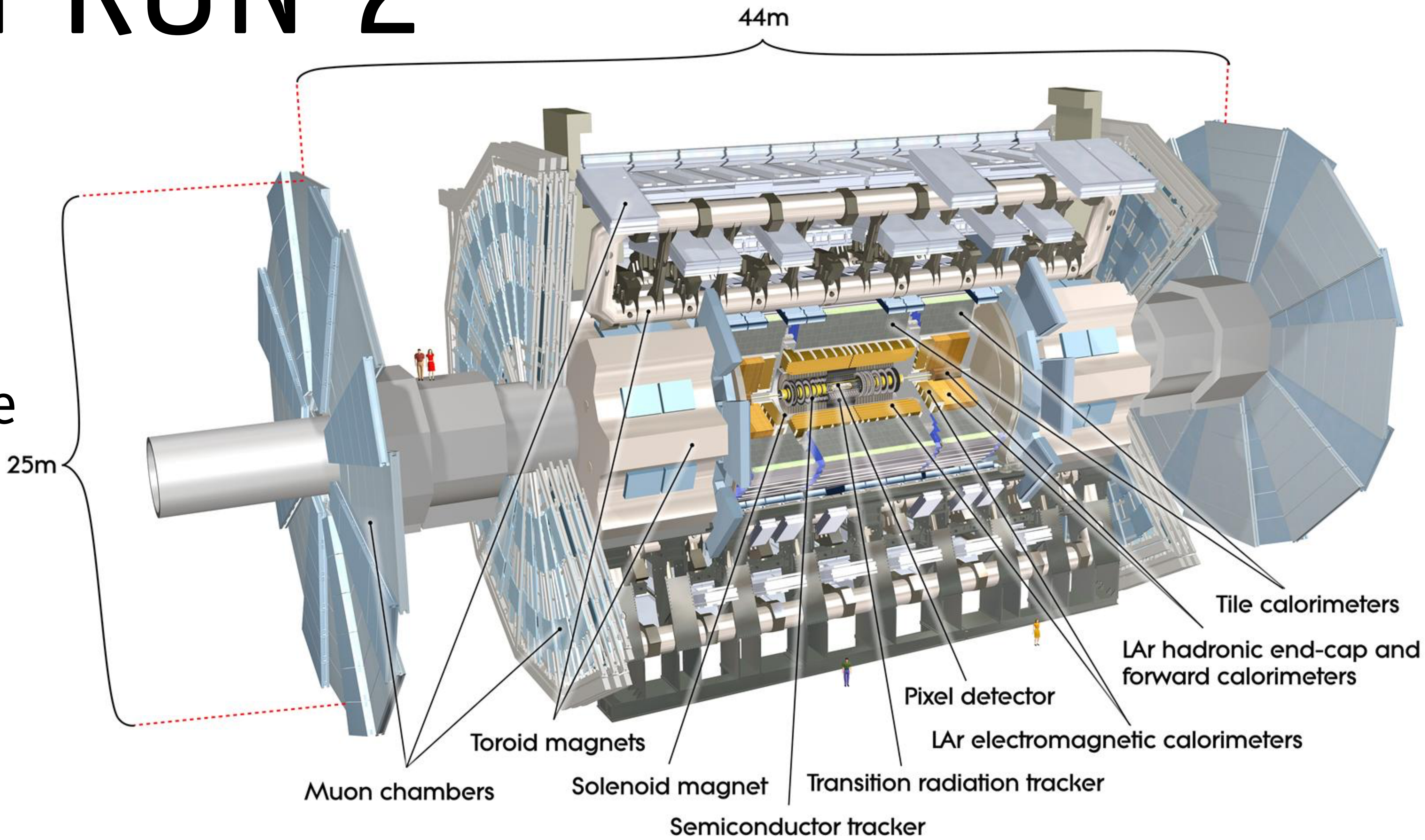
- YUKAWA COUPLINGS
- VH INTERACTIONS
- HIGGS POTENTIAL

BSM

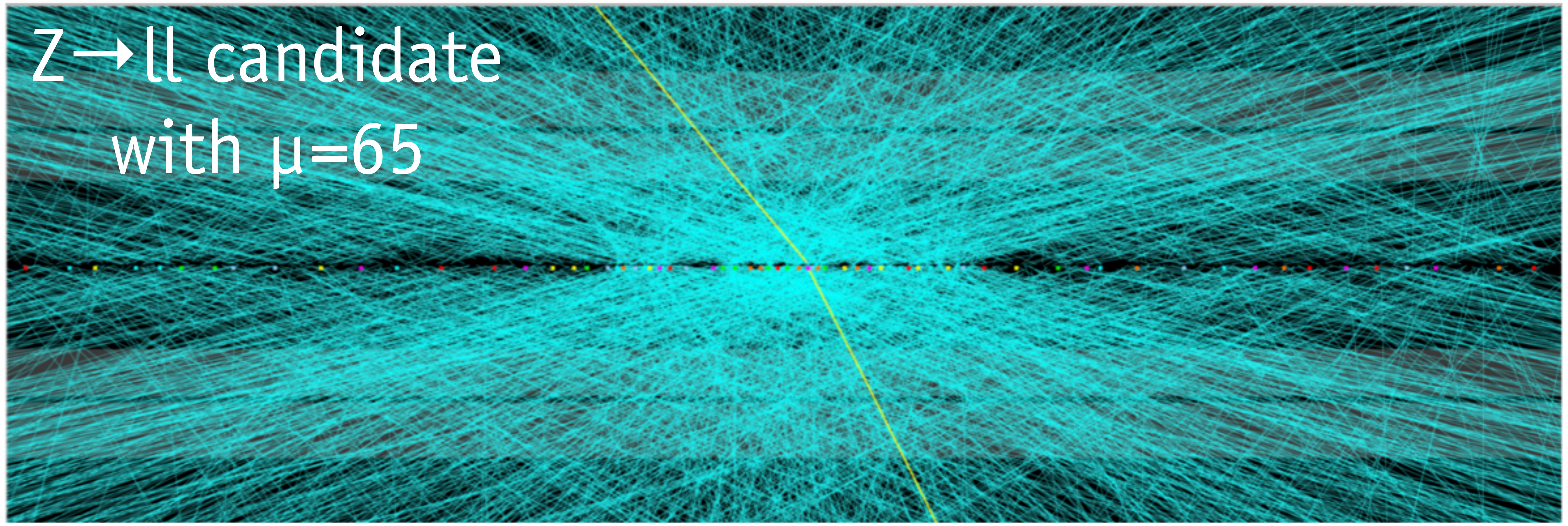
- DIRECT&INDIRECT SEARCHES
- SUSY, ED, HV, …
- DARK MATTER

ATLAS DETECTOR IN RUN 2

- improved physics capabilities
- achieved excellent reconstruction performance up to very large pileup values (x3 above design)



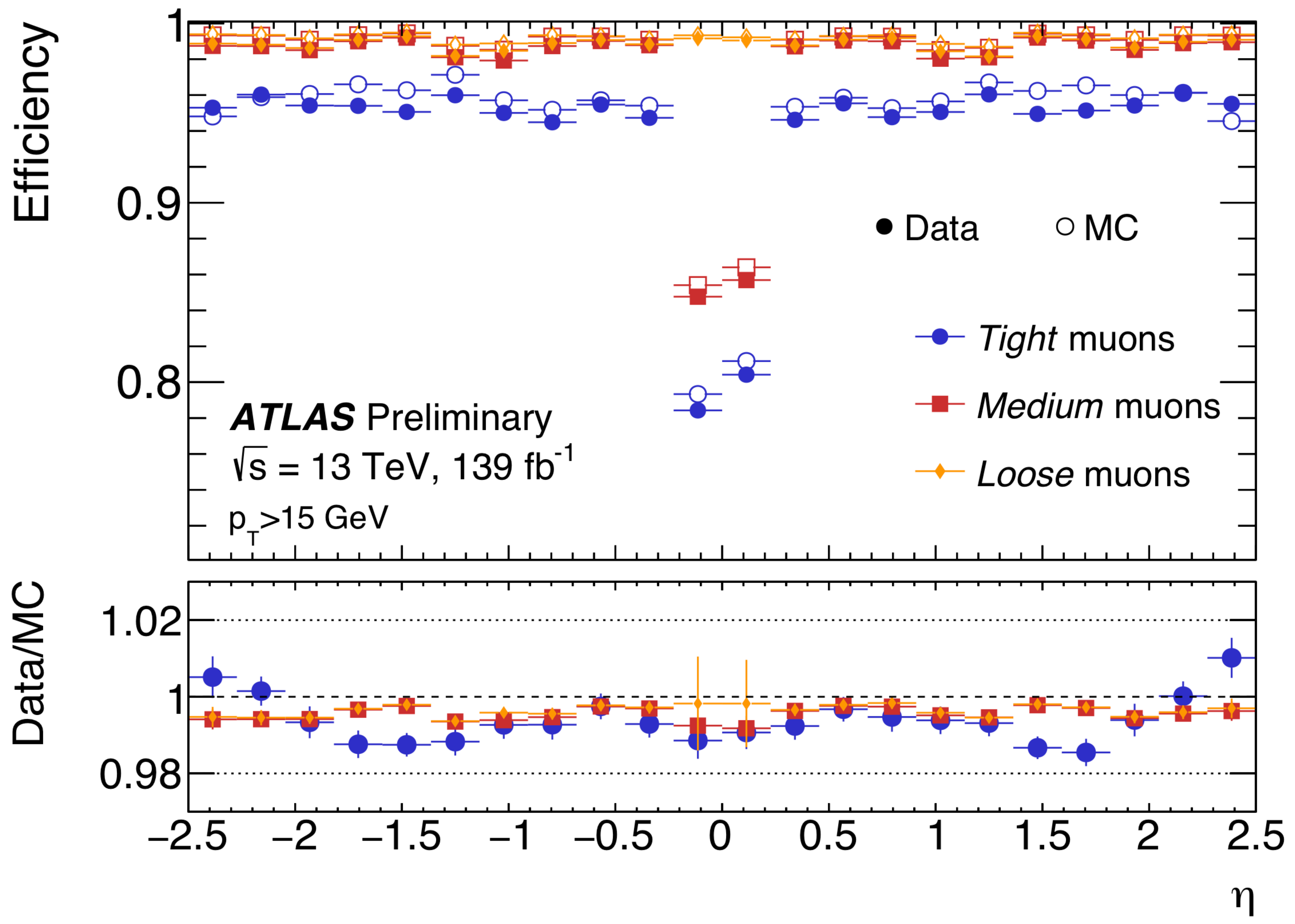
- widespread use of machine learning techniques for particle reconstruction & identification
- dedicated algorithms/calibrations for specific physics cases (low-p_T leptons, hadronic taus, b-tagging, boosted hadronic objects, ...)

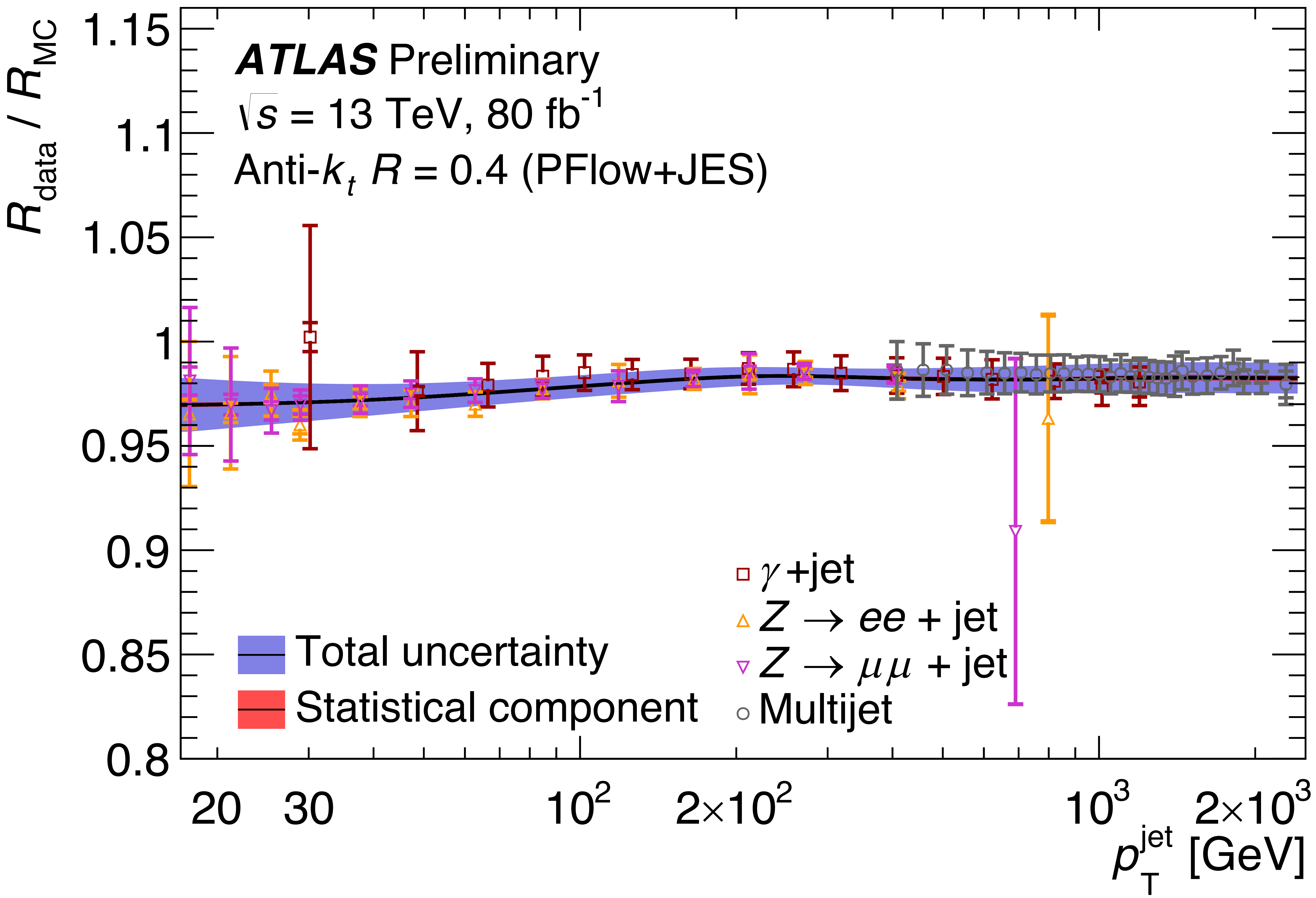


RECONSTRUCTION PERFORMANCE

ATLAS-MUON-2019-03
JETM-2018-006

already reached sub-percent precisions in a large p_T range for jet, b-tagging and lepton reconstruction. Additional improvements expected soon





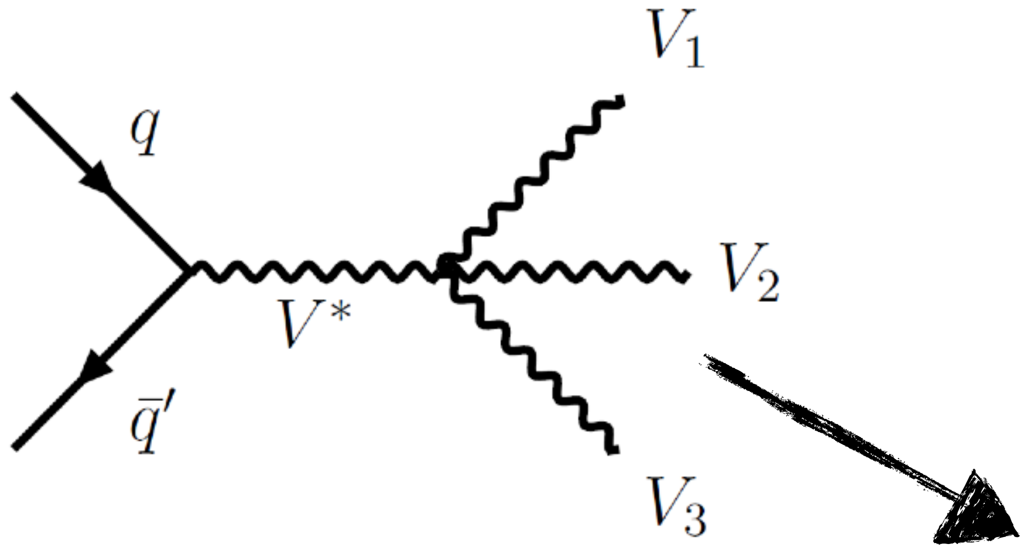
data-driven calibrations for muon efficiency and energy calibration of standard particle flow jets

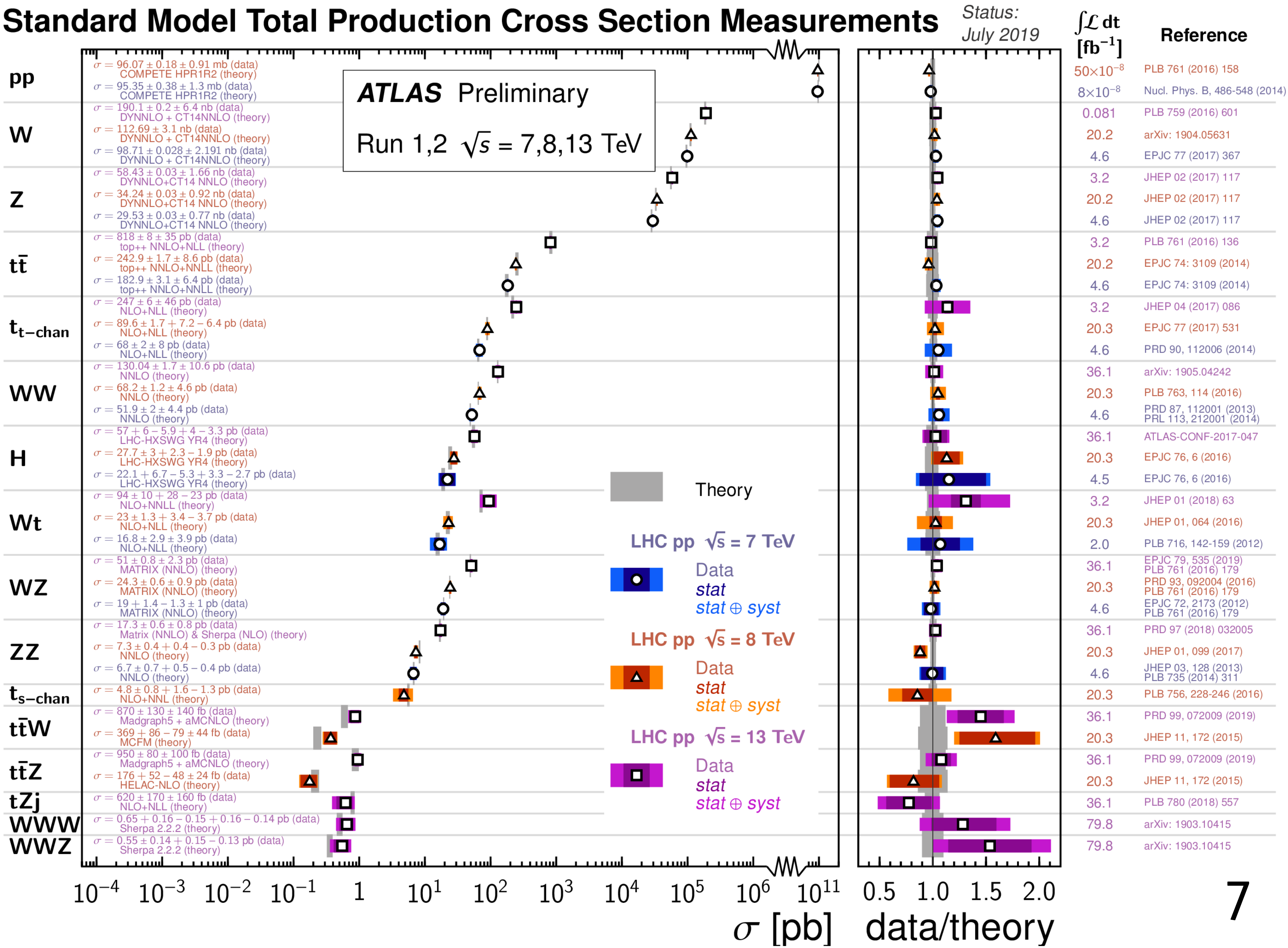
SM STATUS

Harvest of ATLAS cross section measurements confirms the predictive power of the SM

almost all theoretical calculations now at NNLO

evidence for weak 3-boson production



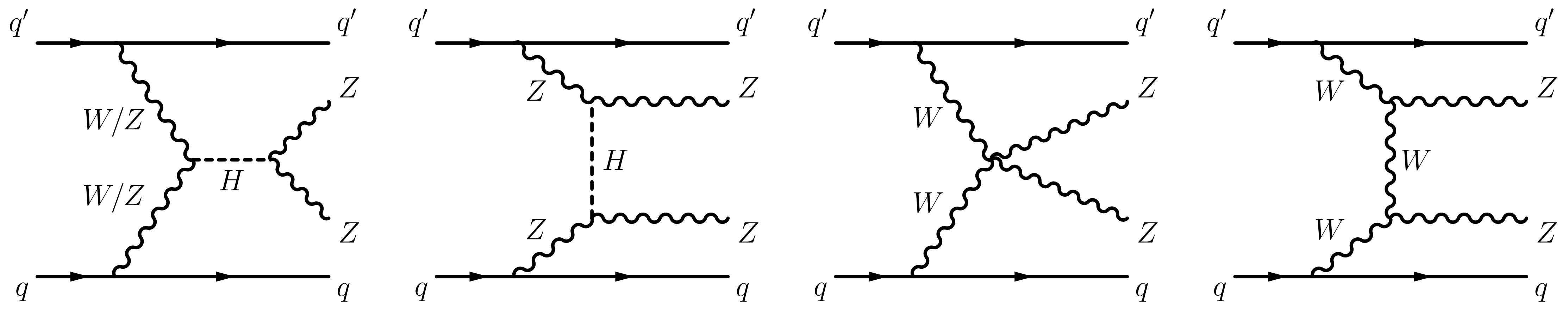


arXiv:1903.10415

OBSERVATION OF VECTOR BOSON SCATTERING

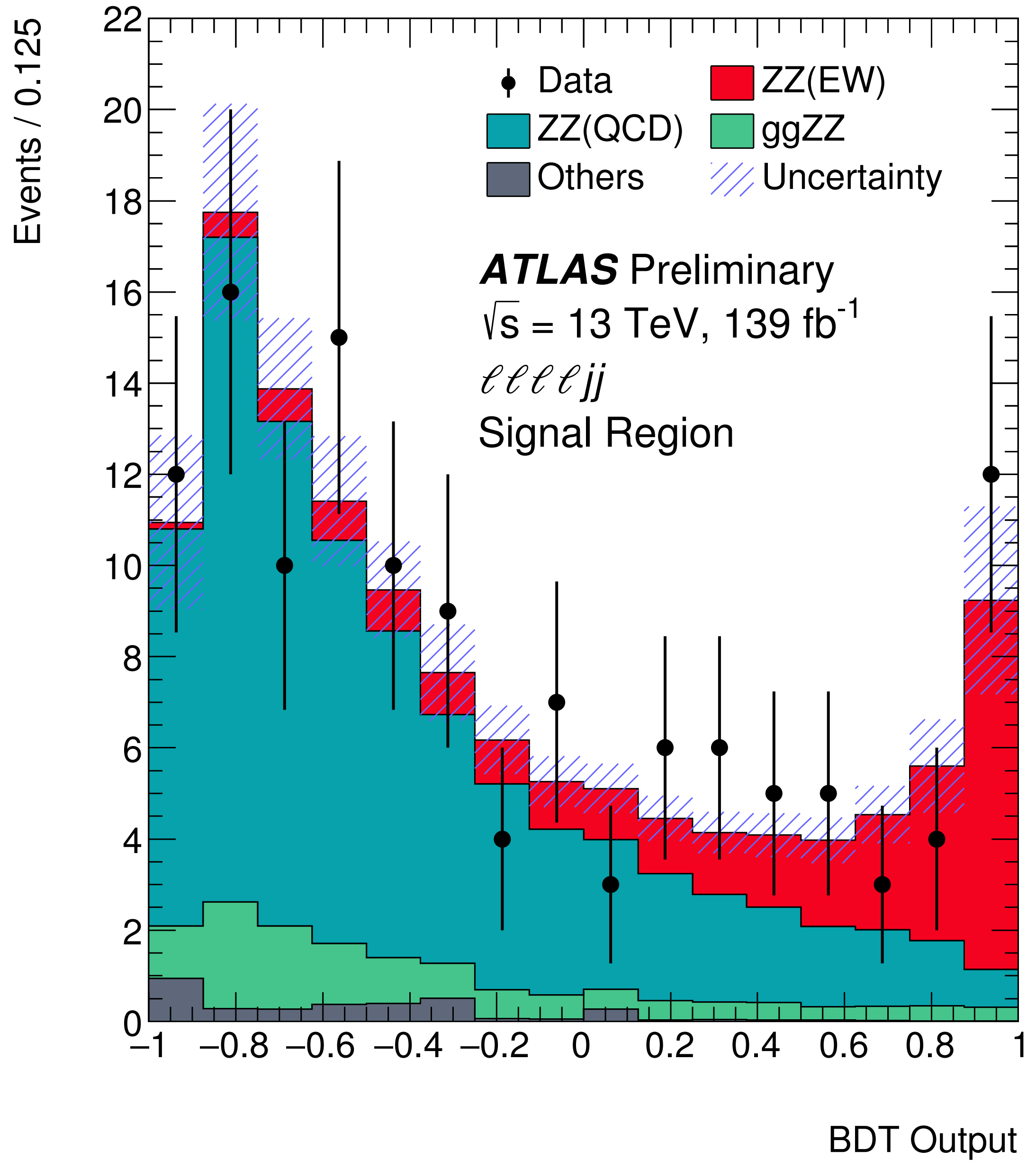
extends SM x-section tests over 14 orders of magnitude

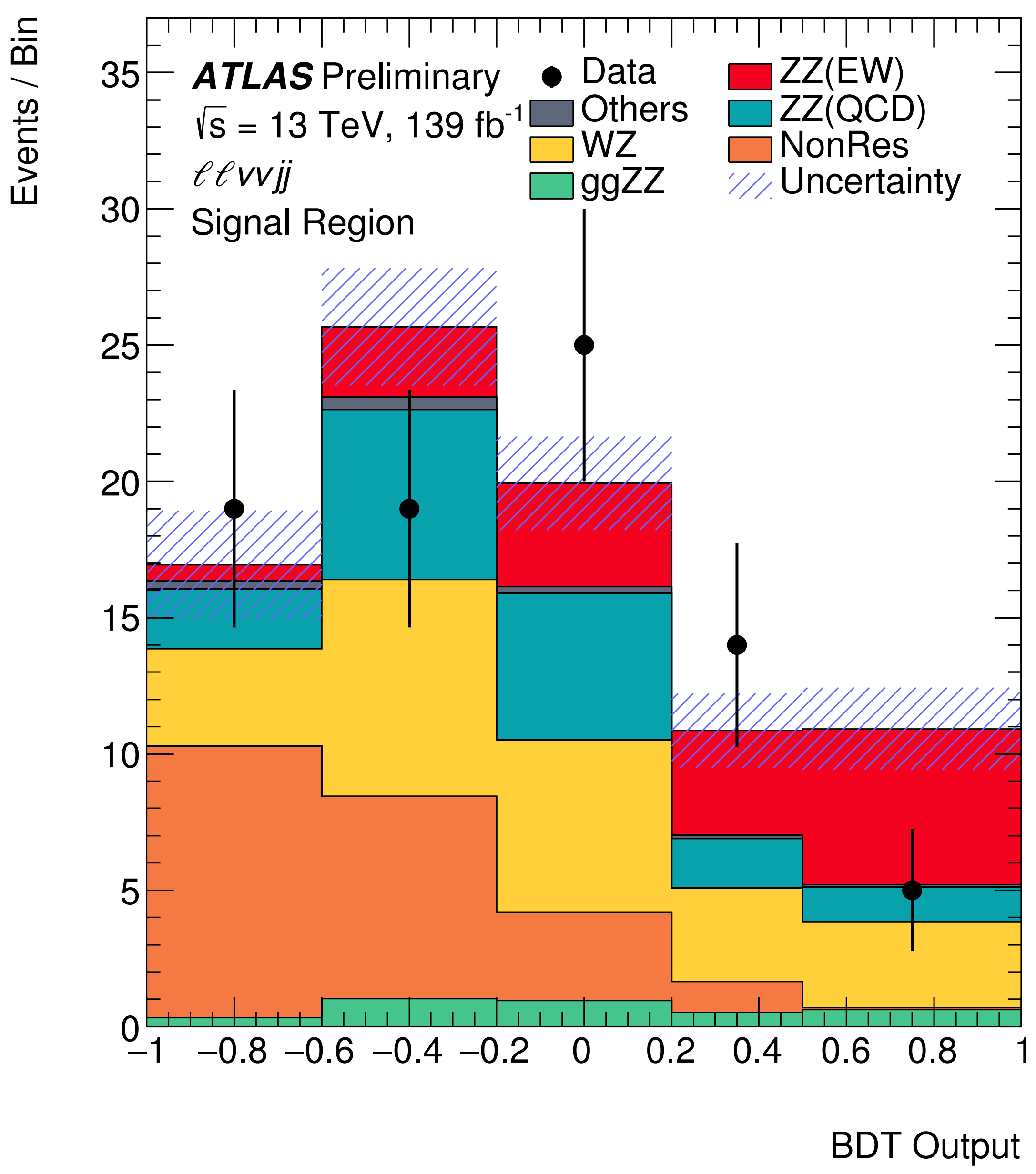
ZZjj: very rare (σ<fb) but clean modes using Z decays to charged leptons; exploit multivariate analysis to separate EW signal from strong interaction background



σ(fid) = 0.82 ± 0.21 fb (SM: 0.61 ± 0.03 fb)

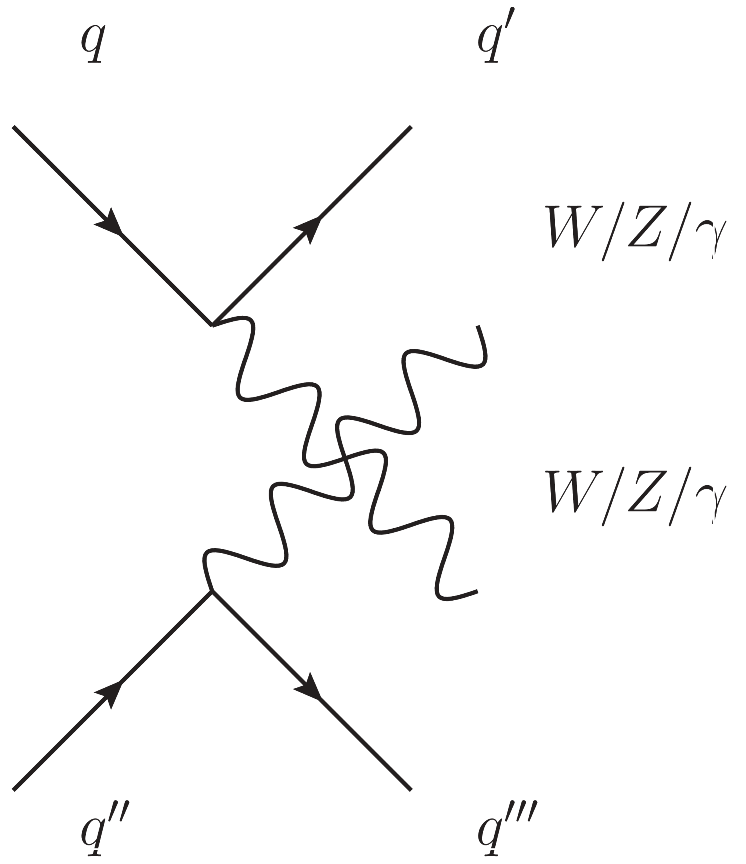
significance 5.5σ: first observation of ZZjj VBS

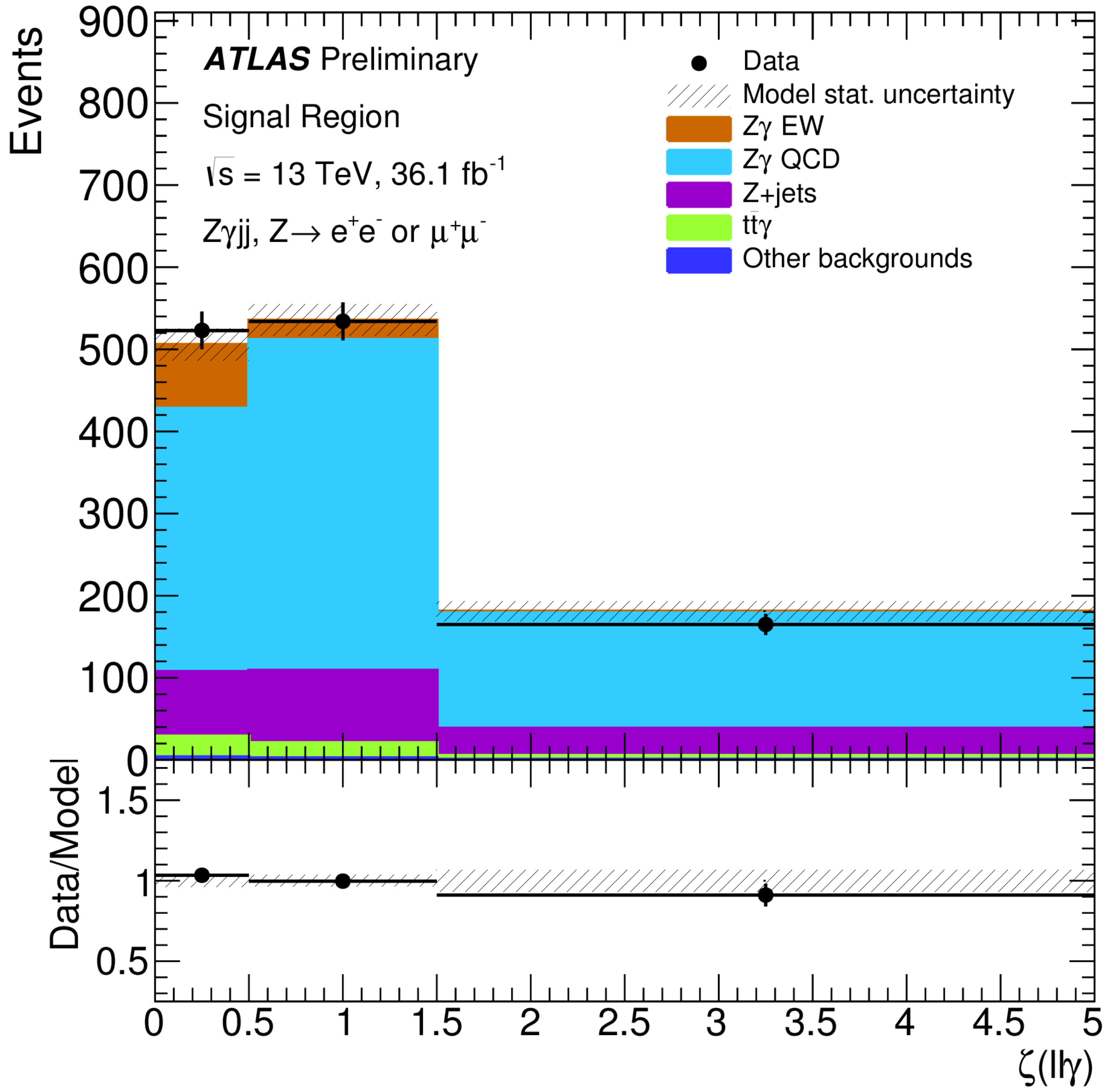




Zγjj electroweak production:

- sensitive to SM quartic gauge coupling diagram
- 4.1σ significance observed (3.8σ expected)





ATLAS-CONF-2019-033; ATLAS-CONF-2019-039

TOP PRECISION PHYSICS

NEW PRECISION TOTAL X-SECTION MEASUREMENT ATLAS-CONF-2019-041

$$\sigma_{t\bar{t}} = 826 \pm 20\,\text{pb}$$

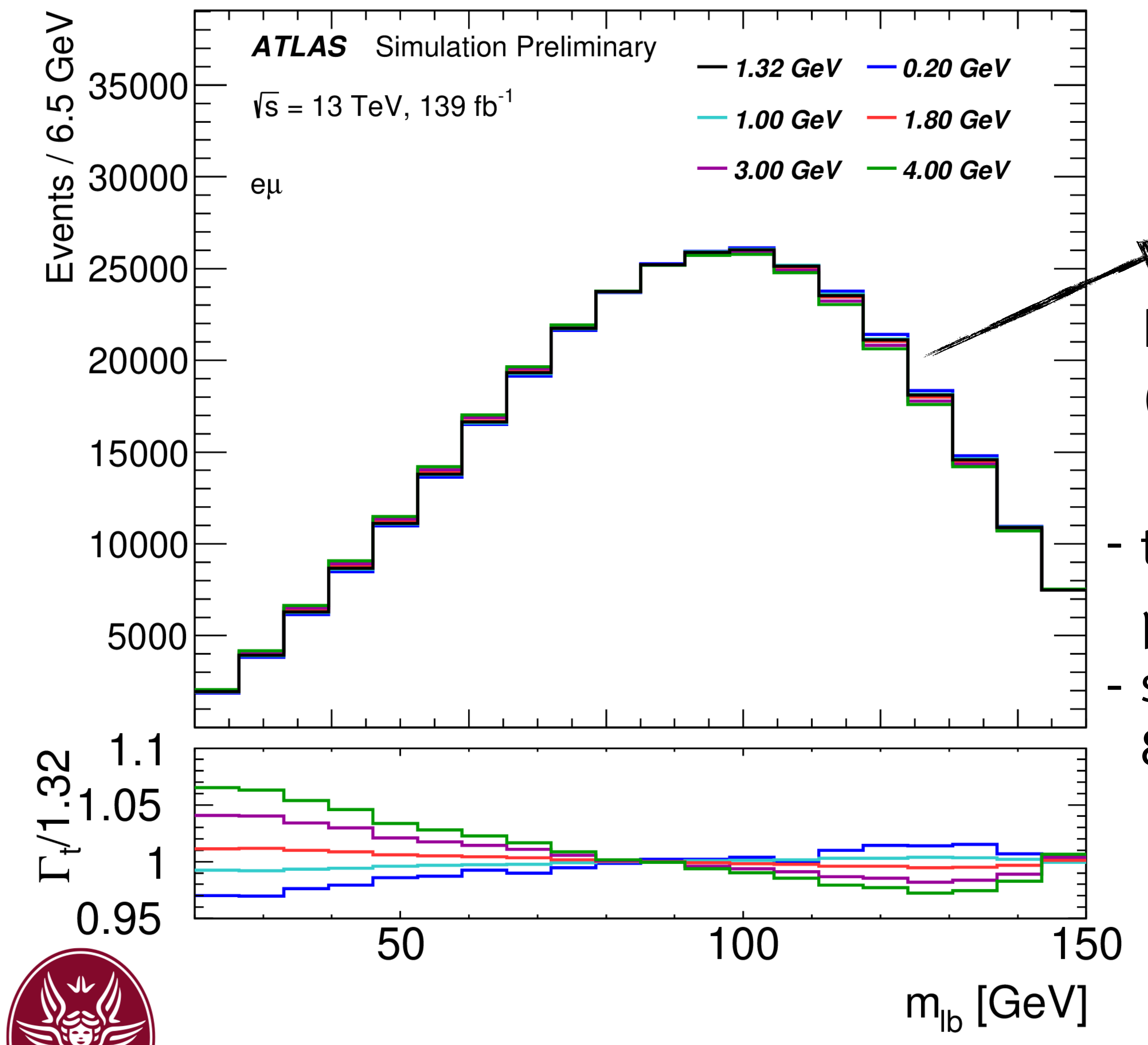
$$\sigma(\text{NNLO}) = 832 \pm 45\,\text{pb}$$

2.4% uncertainty due to state of the art reconstruction performances for e/μ

CHARGE ASYMMETRY MEASUREMENT ATLAS-CONF-2019-026

- resolved and boosted top-quark decays in lepton+jets events
- asymmetry at LHC from higher order QCD effects from qqbar and qg initial states

TOP QUARK DECAY WIDTH WITH FULL LHC RUN 2 DATASET

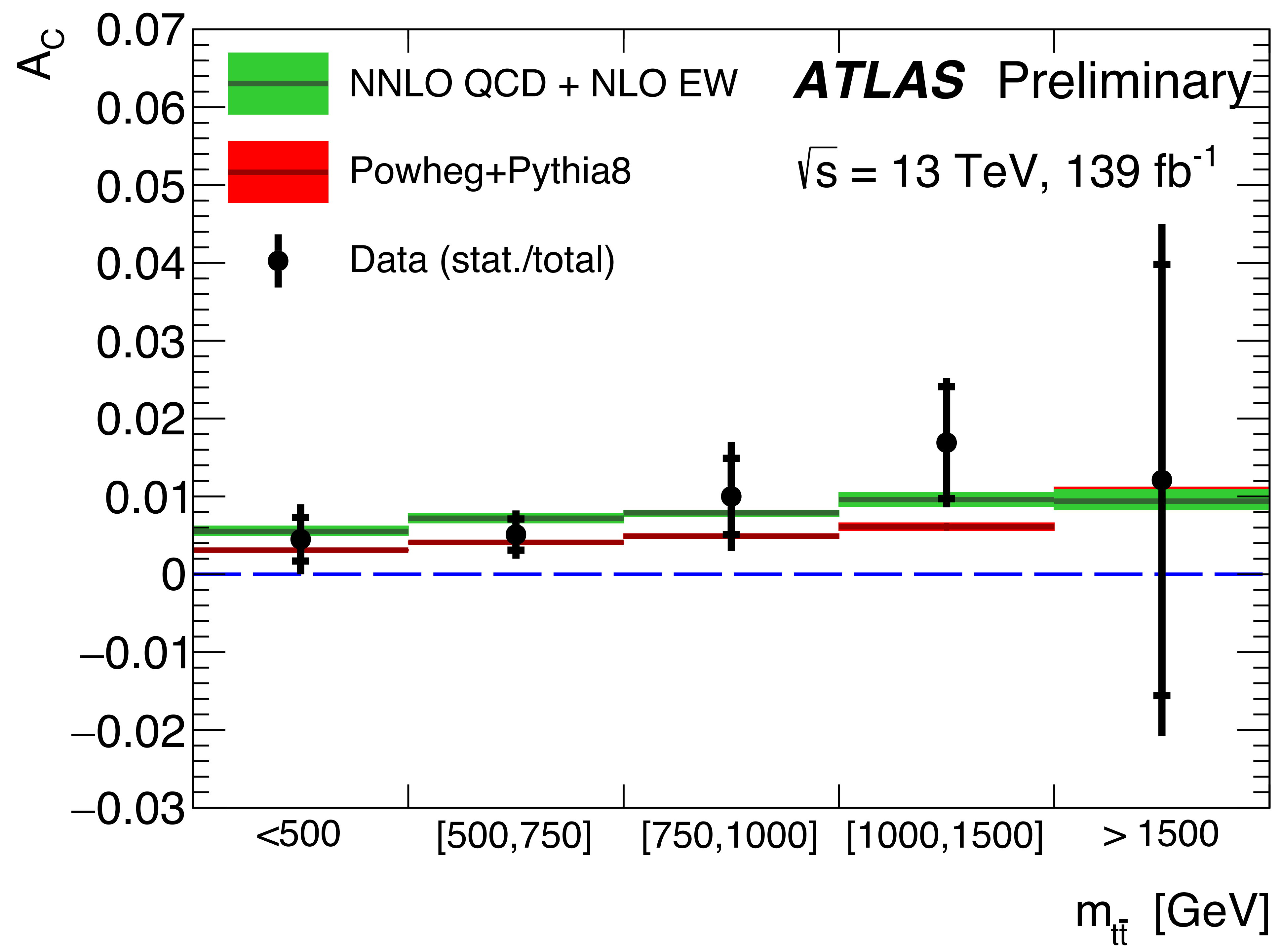


$$\Gamma_t = 1.94^{+0.52}_{-0.49}\,\text{GeV}$$

NNLO prediction 1.322 GeV (uncertainty ~ 1%)

- template fit of m_{lb} (leptons paired the closest b-jet)
- significant improvement from 8 TeV results

ATLAS-CONF-2019-038



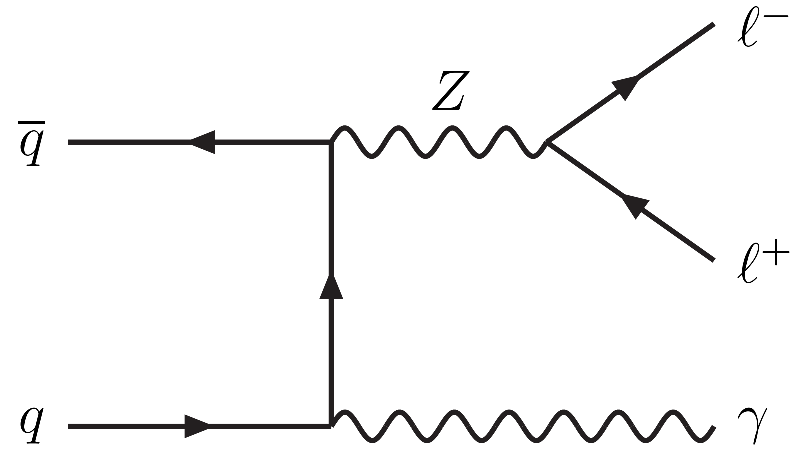
$$A_C^{t\bar{t}} = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} = 0.0060 \pm 0.0011_{\text{stat}} \pm 0.0010_{\text{sys}}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

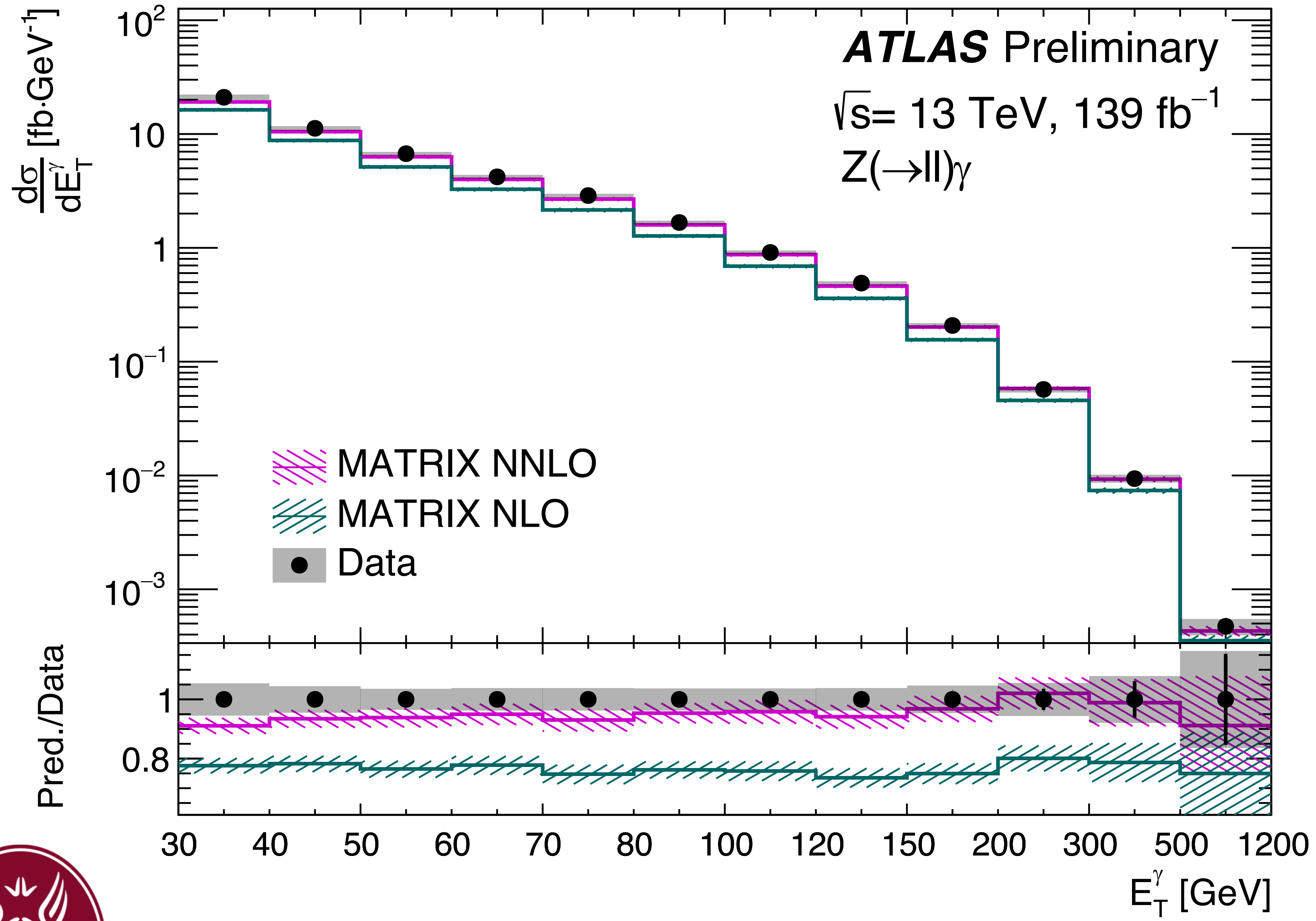
$A_c \neq 0$ at 4σ level

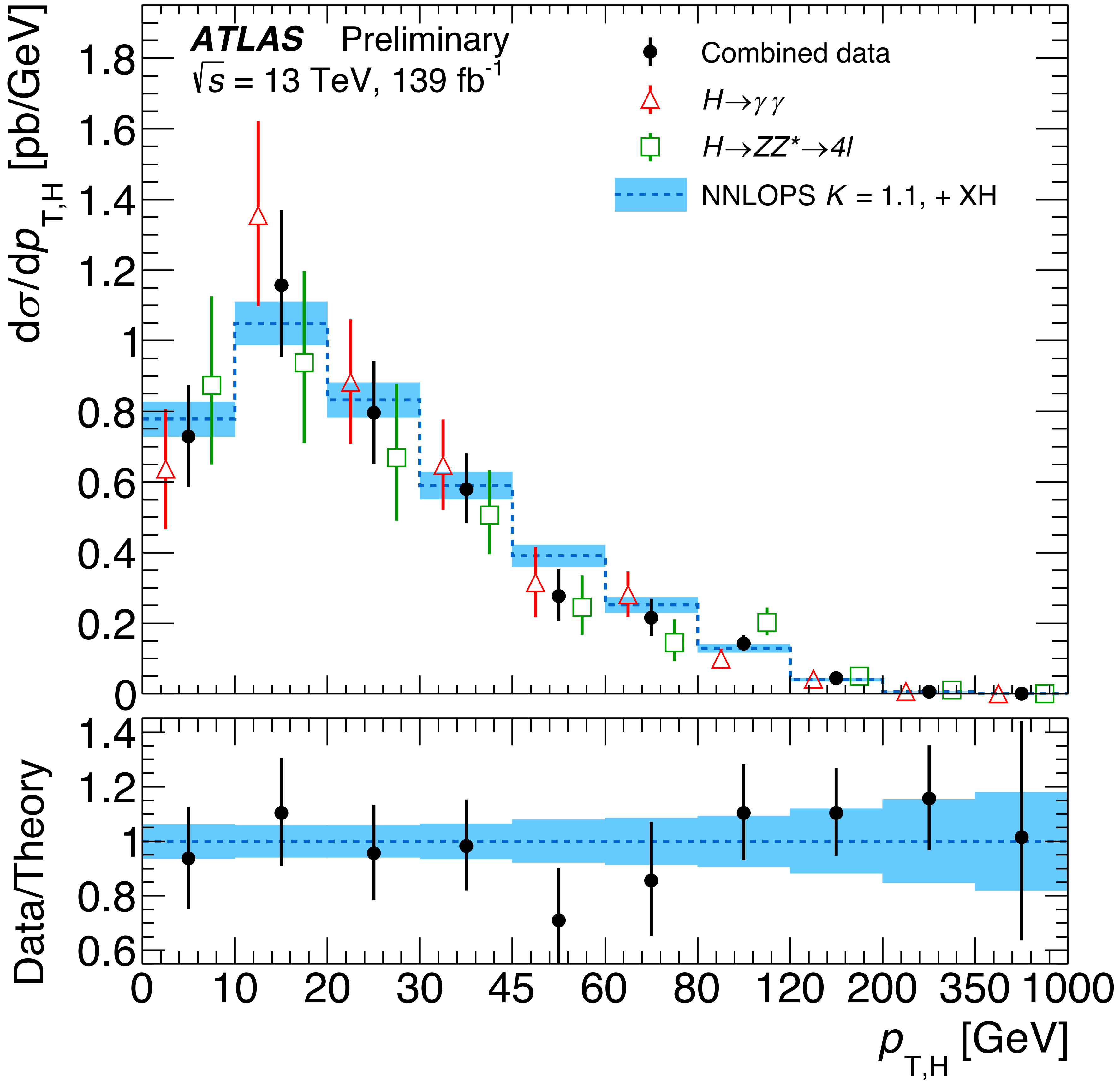
EXPLORING DIFFERENTIAL X-SECTIONS

high-precision measurement of differential Zγ diboson cross sections, probing EW gauge structure of SM and tests QCD



Zγ





HIGGS

Higgs differential cross section measurements: H→γγ and H→ZZ*→4l

- well described by POWHEG NNLO+PS up to 1 TeV
- constrain EFT parameters and charm Yukawa coupling → NP effects

ATLAS-CONF-2019-034

ATLAS-CONF-2019-032

PROBING NP WITH HIGH PRECISION HIGGS MEASUREMENTS

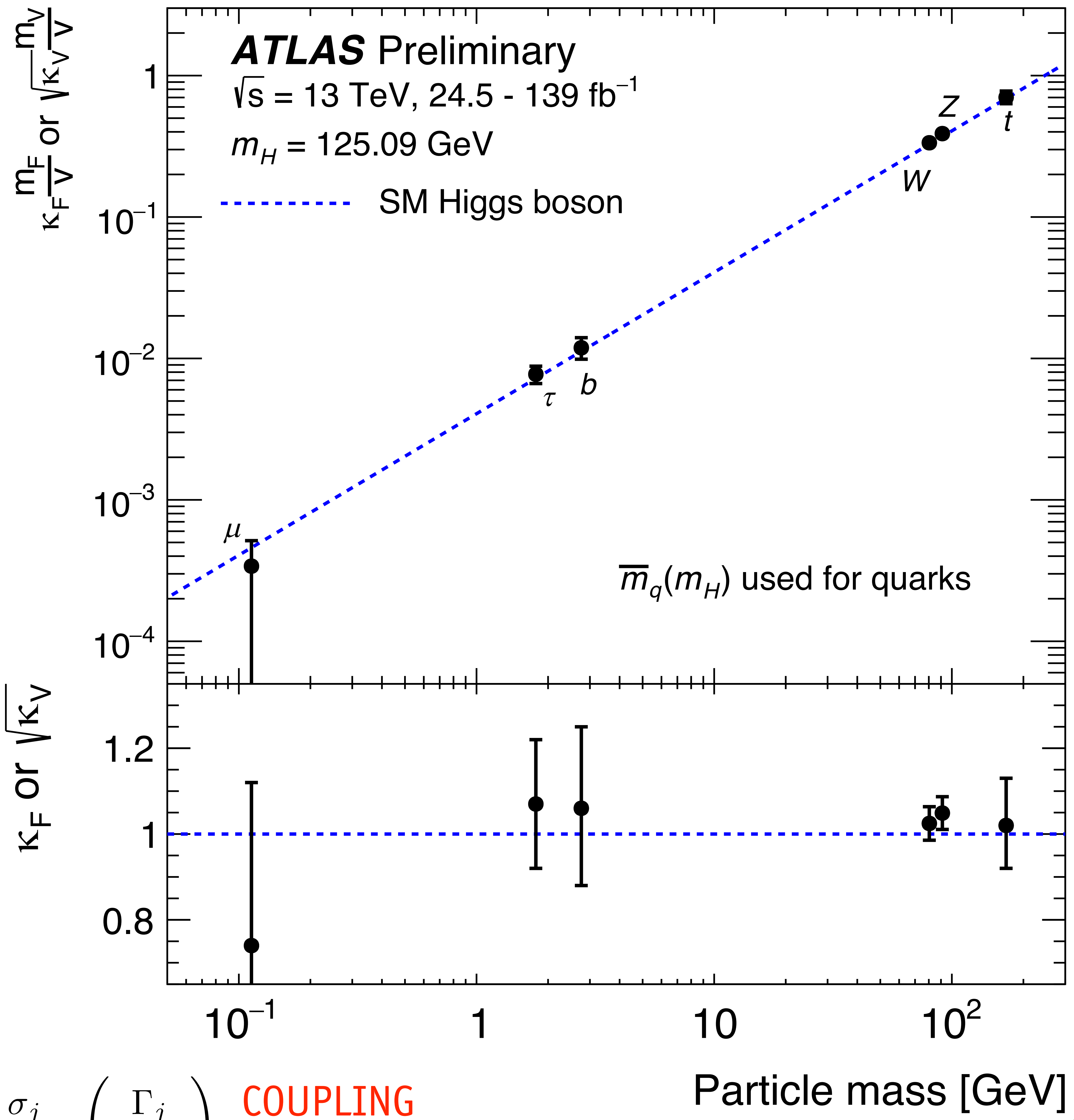
higgs sector directly connected with most important open questions of the SM: naturalness, vacuum stability & energy, flavour

a broad experimental programme that will extend till the end of HL-LHC …

major progresses in the last year:

- observation of H→bb decay
- observation of ttH and VH productions

all major production and higgs decay modes now observed
Higgs couplings measured at 10-20% precision

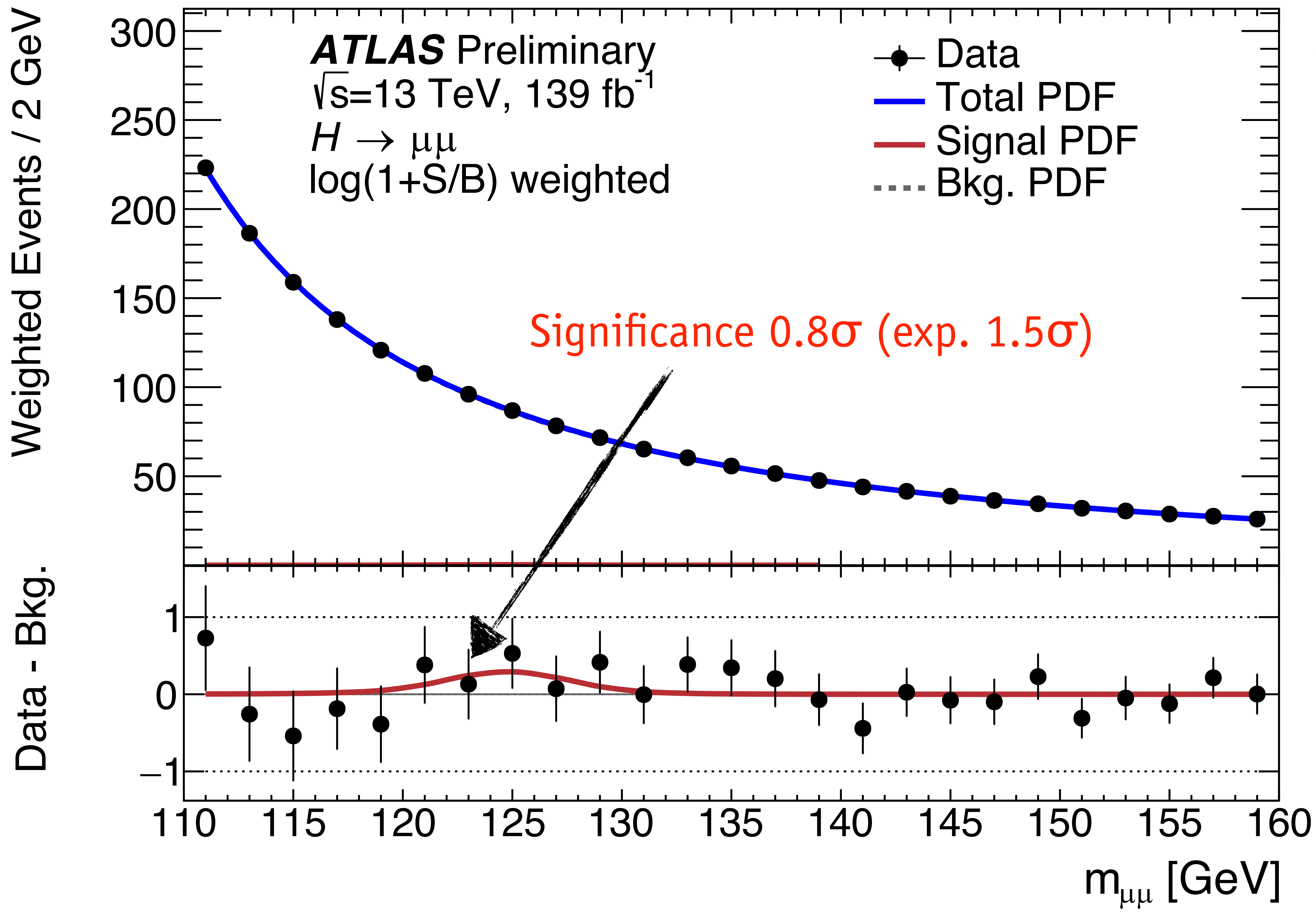


ATLAS-CONF-2019-005
ATLAS-CONF-2019-028

$$k_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \left(\frac{\Gamma_j}{\Gamma_j^{SM}}\right)$$ COUPLING MODIFIERS

PROBING NP WITH HIGH PRECISION HIGGS MEASUREMENTS

next frontier: test higgs interactions with lighter generation fermions



ATLAS-CONF-2019-028

$H \to \mu\mu$: challenging due to huge $pp \to Z/\gamma^* \to \mu\mu$ background
using categories (jet multiplicity) + MVA discriminants

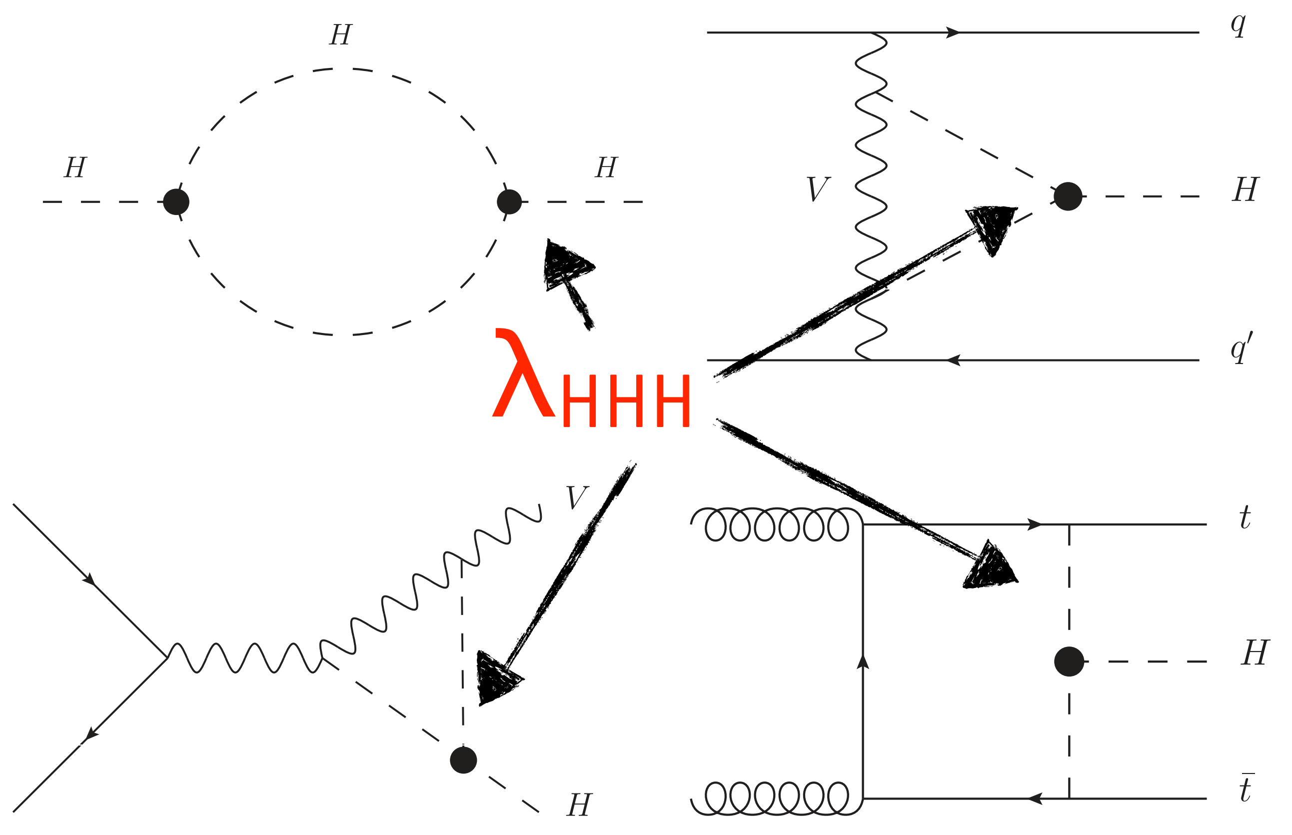
$$\frac{\sigma(\text{obs})}{\sigma(\text{SM})} = 0.5 \pm 0.7 \; (< 1.7 \,@\, 95\,\%\,\text{CL})$$

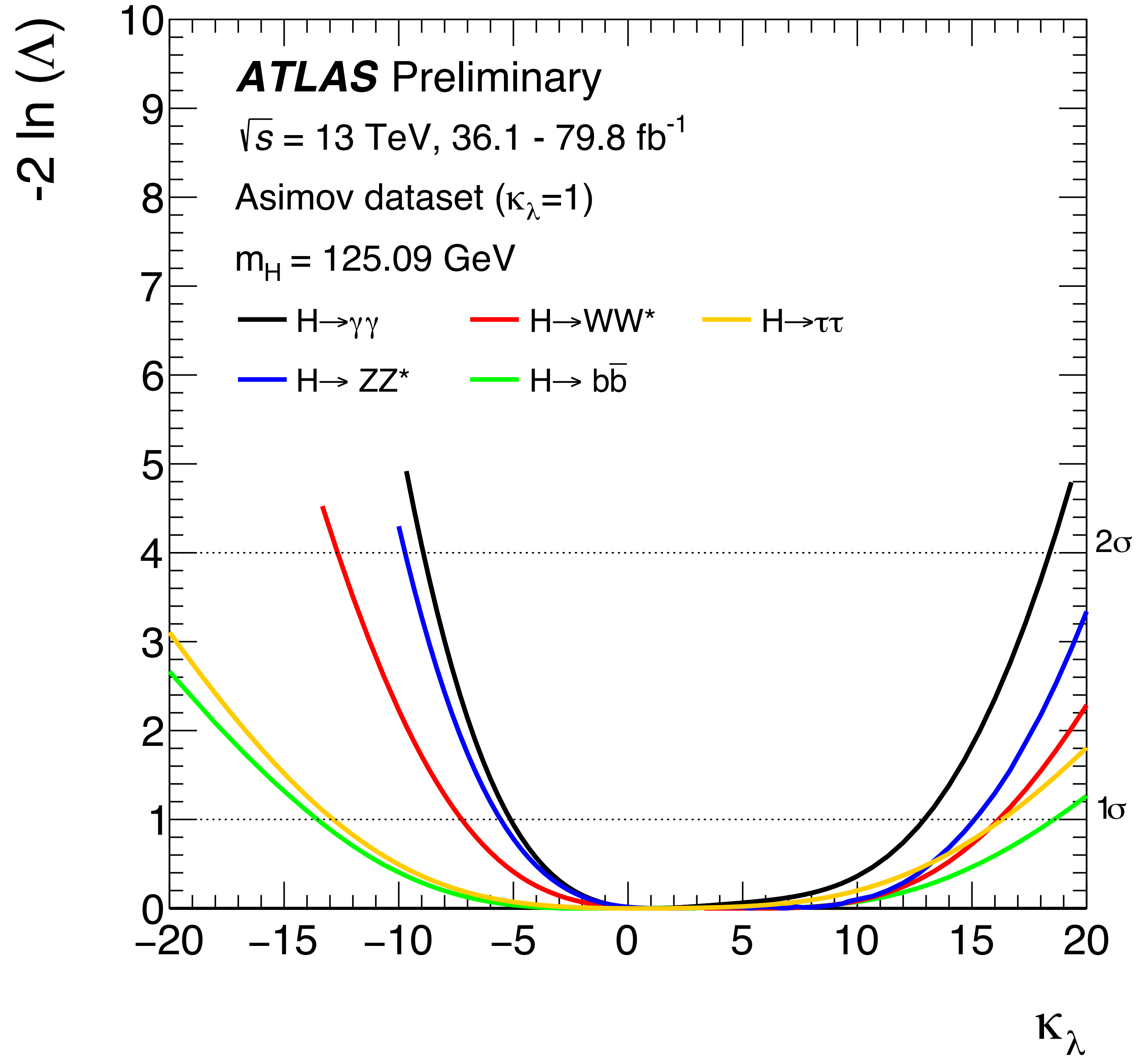
50% improvement wrt previous analysis (80 fb^{-1})

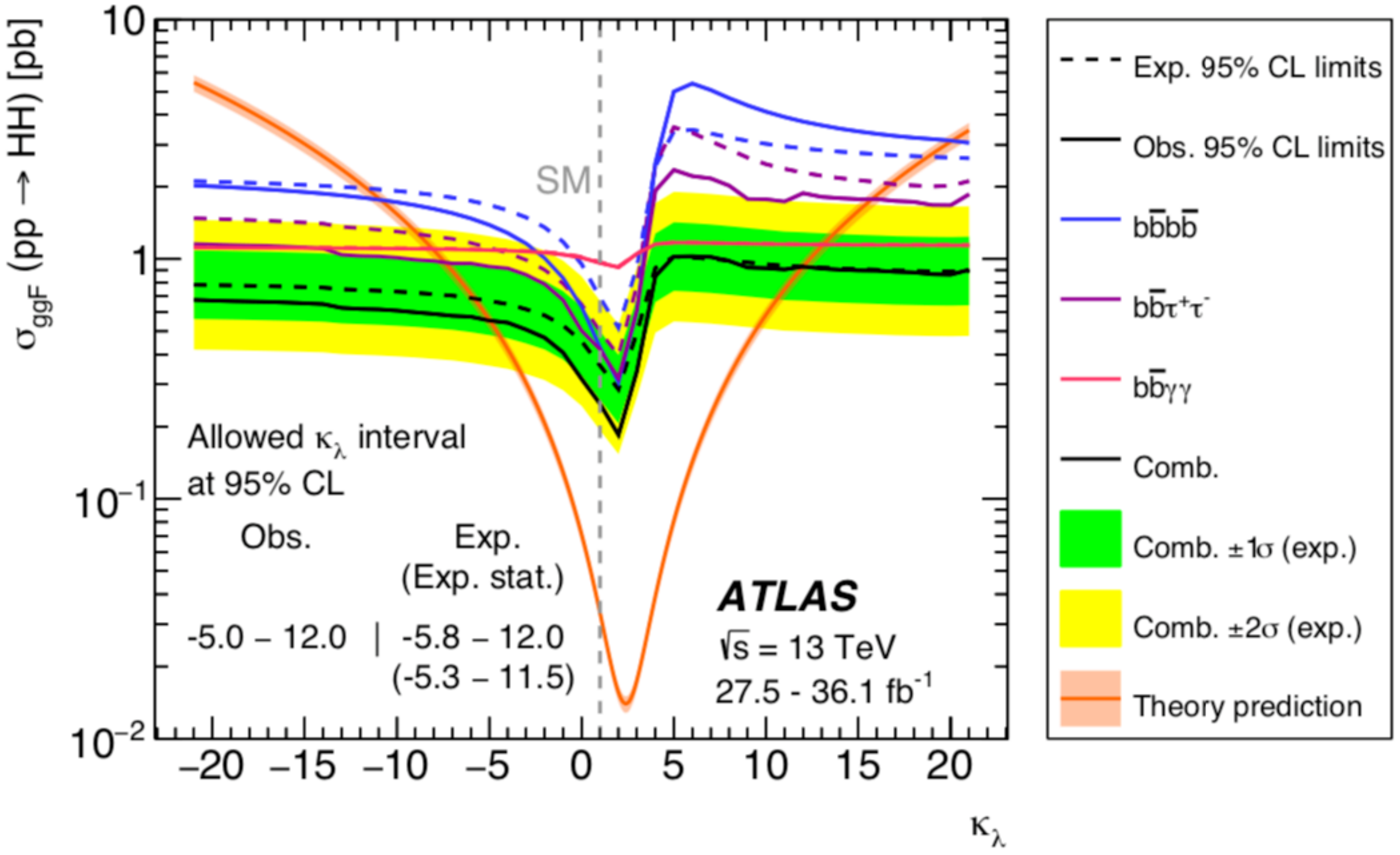
HIGGS SELF INTERACTIONS

SELF-COUPLINGS

DI-HIGGS PRODUCTION

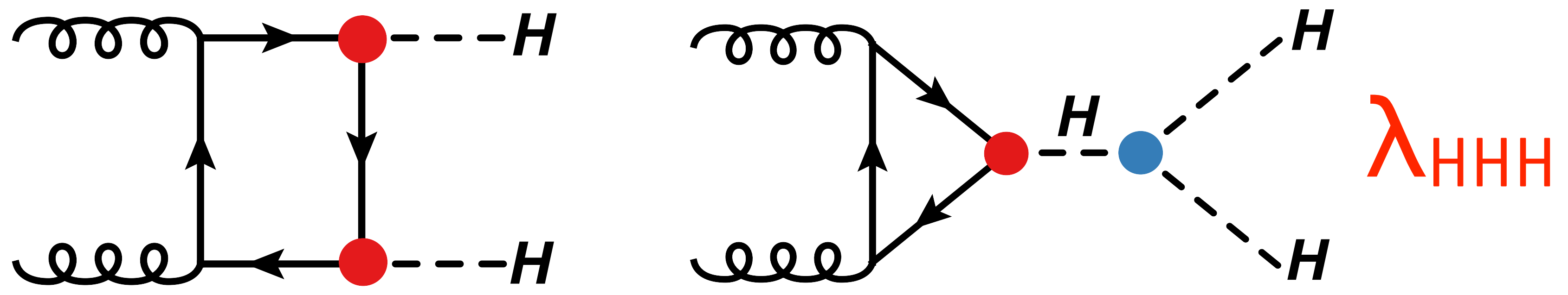






global fit of λ_{HHH} in NLO corrections to combined Higgs STXS measurements, assuming no other new physics present

$$-3.2 < k_\lambda = \frac{\lambda_{HHH}(\text{obs})}{\lambda_{HHH}(\text{SM})} < 11.9$$



No observation yet …

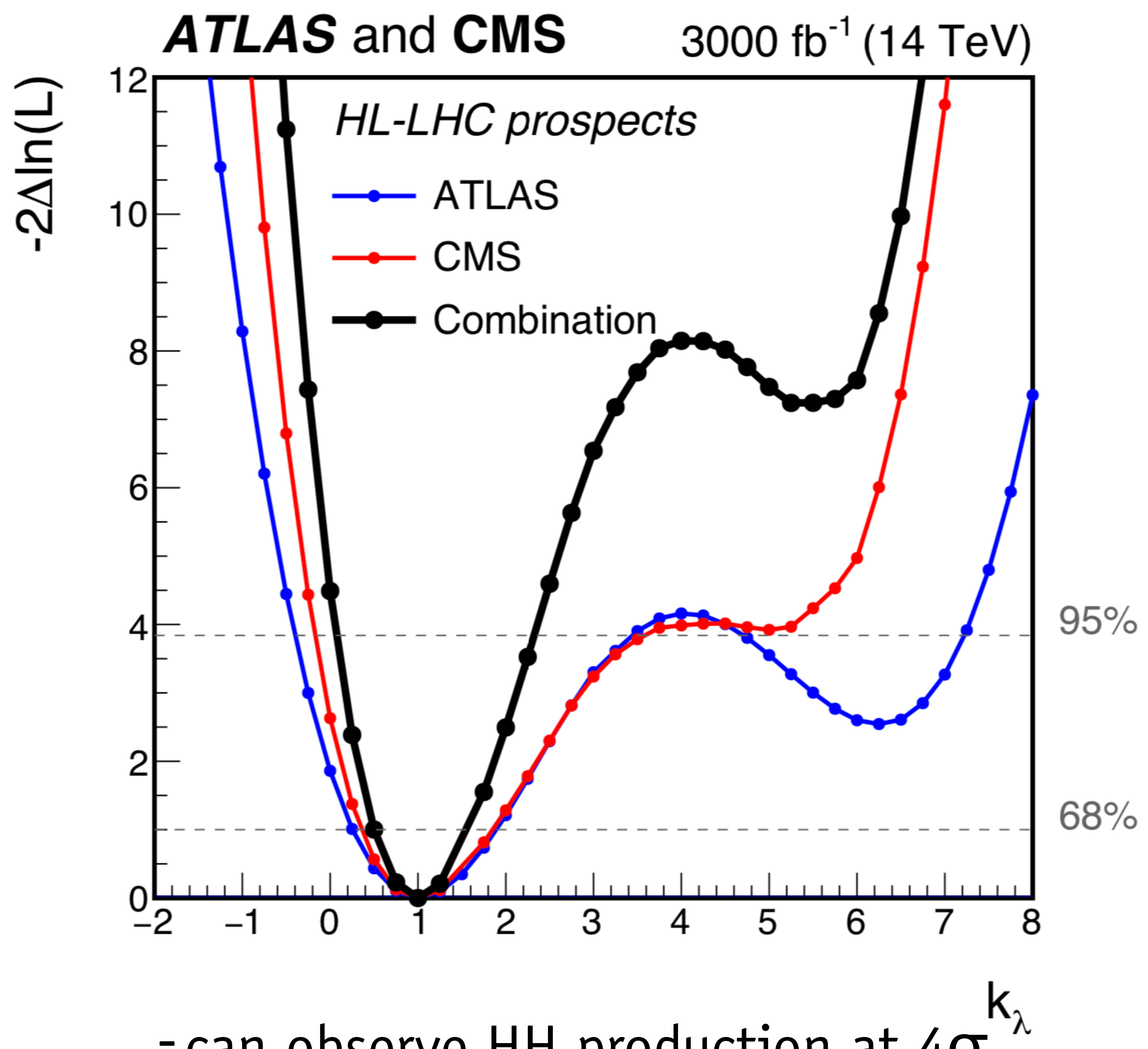
$-5.0 < k_\lambda < 12.0$ @95% CL

ATLAS-PHYS-PUB-2019-009

arXiv:1906.02025 [hep-ex]

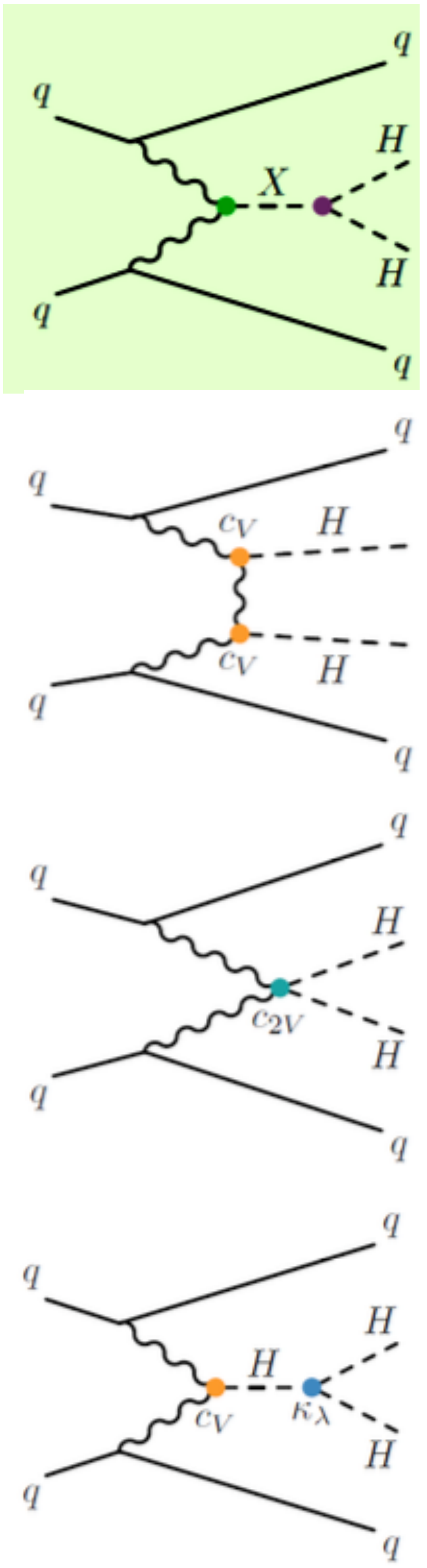
HIGGS SELF INTERACTIONS & NP

kλ @ HL-LHC

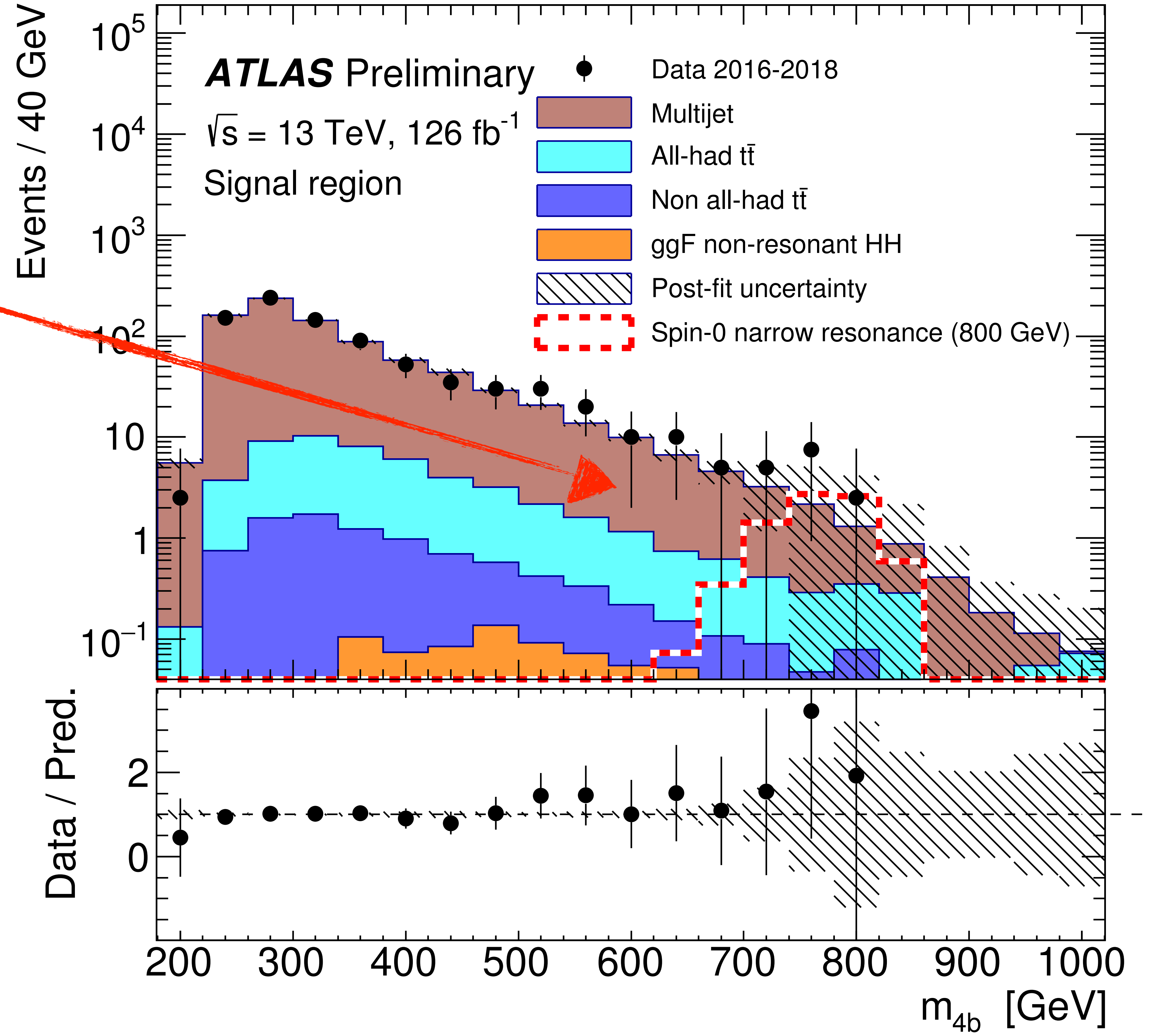


- can observe HH production at 4σ
- can measure kλ with 50% uncertainty

PROBE XHH VERTEX



BSM resonant contributions



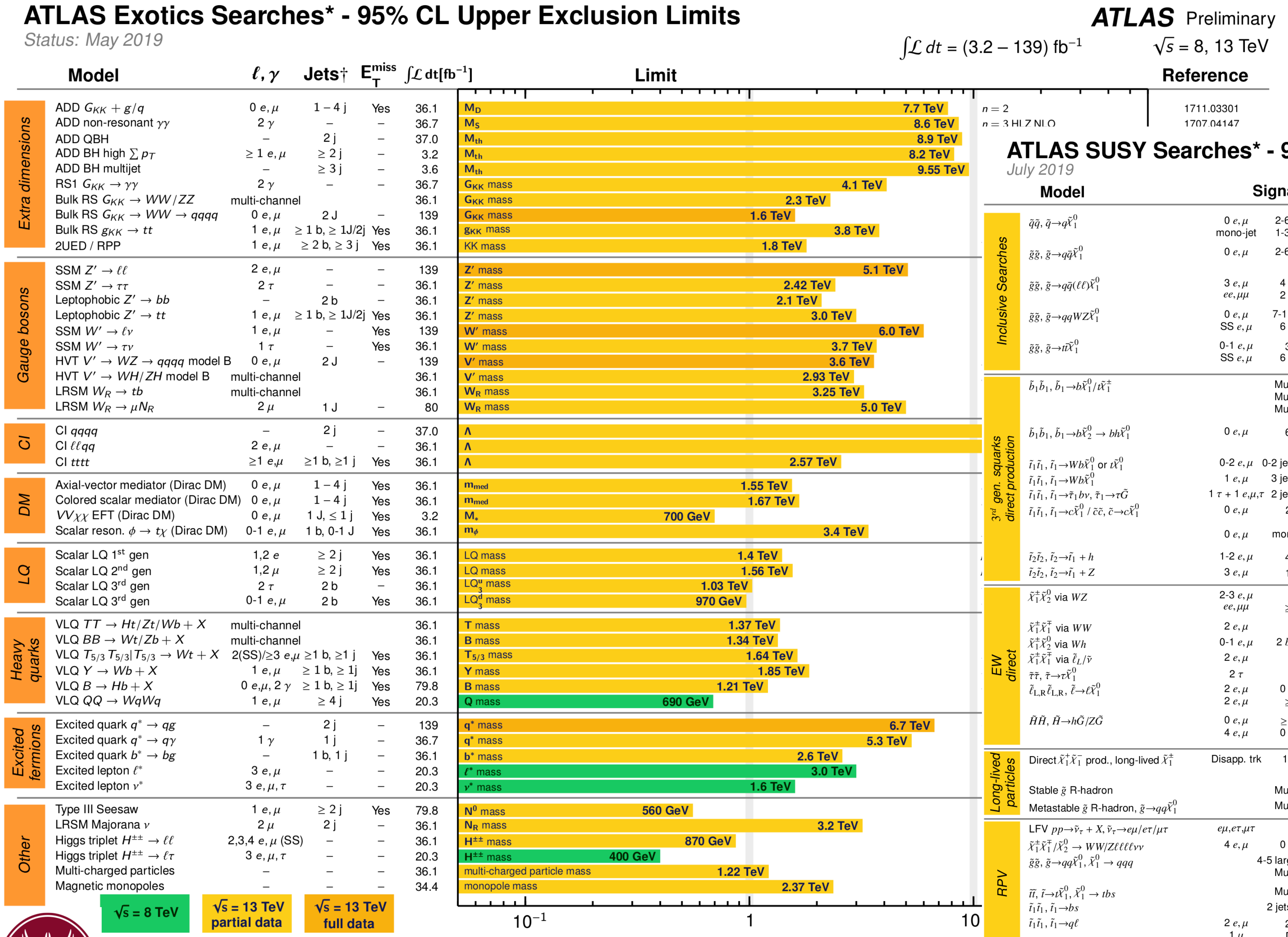
- search for HH production in 4b channel
- data-driven backgrounds using m_{bb} sidebands

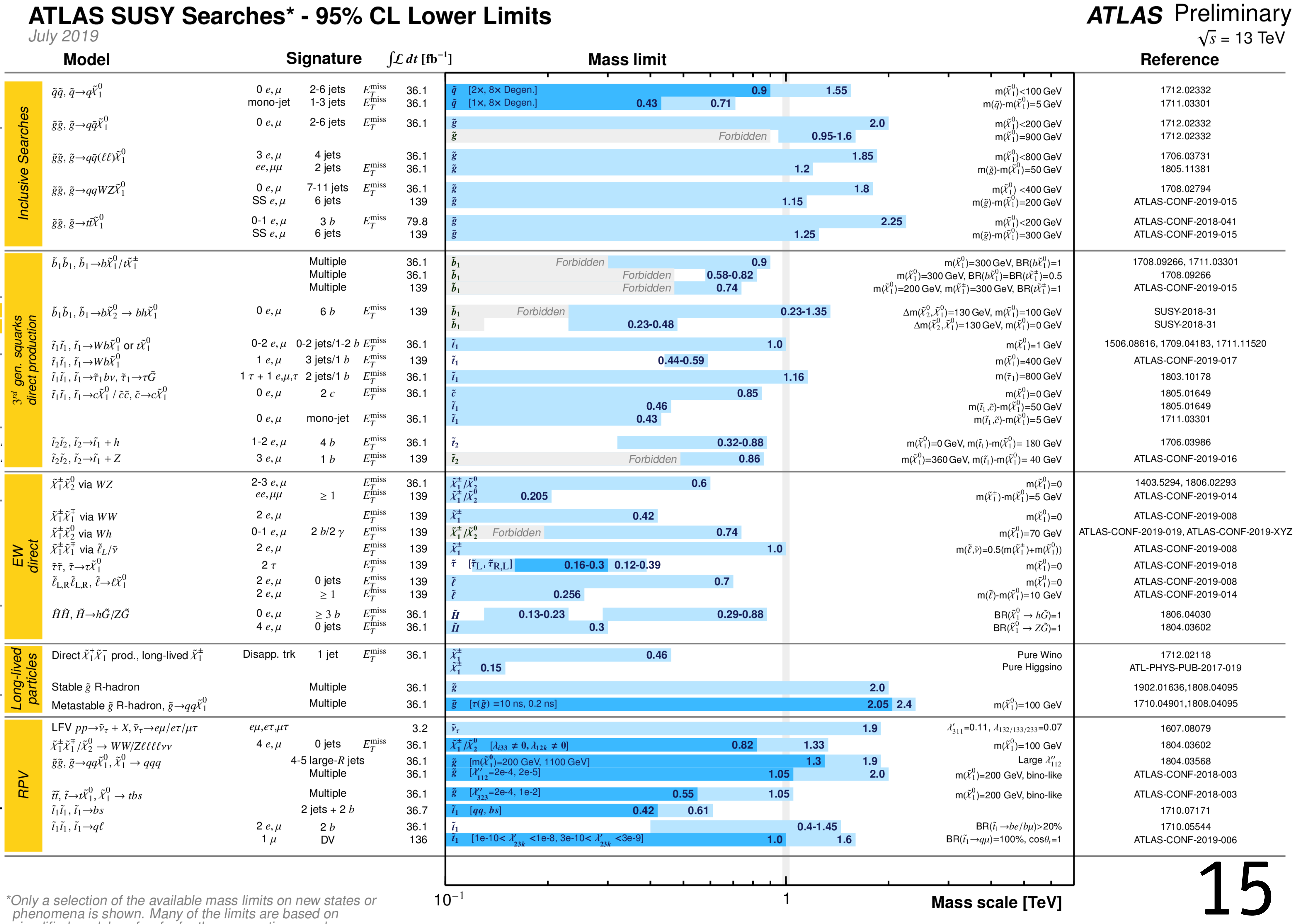
arXiv:1902.00134 [hep-ph]

ATLAS-CONF-2019-030

ATLAS NEW PHYSICS SEARCHES SUMMARY

both signature-based and model-targeted searches probed masses in the 1-10 TeV range



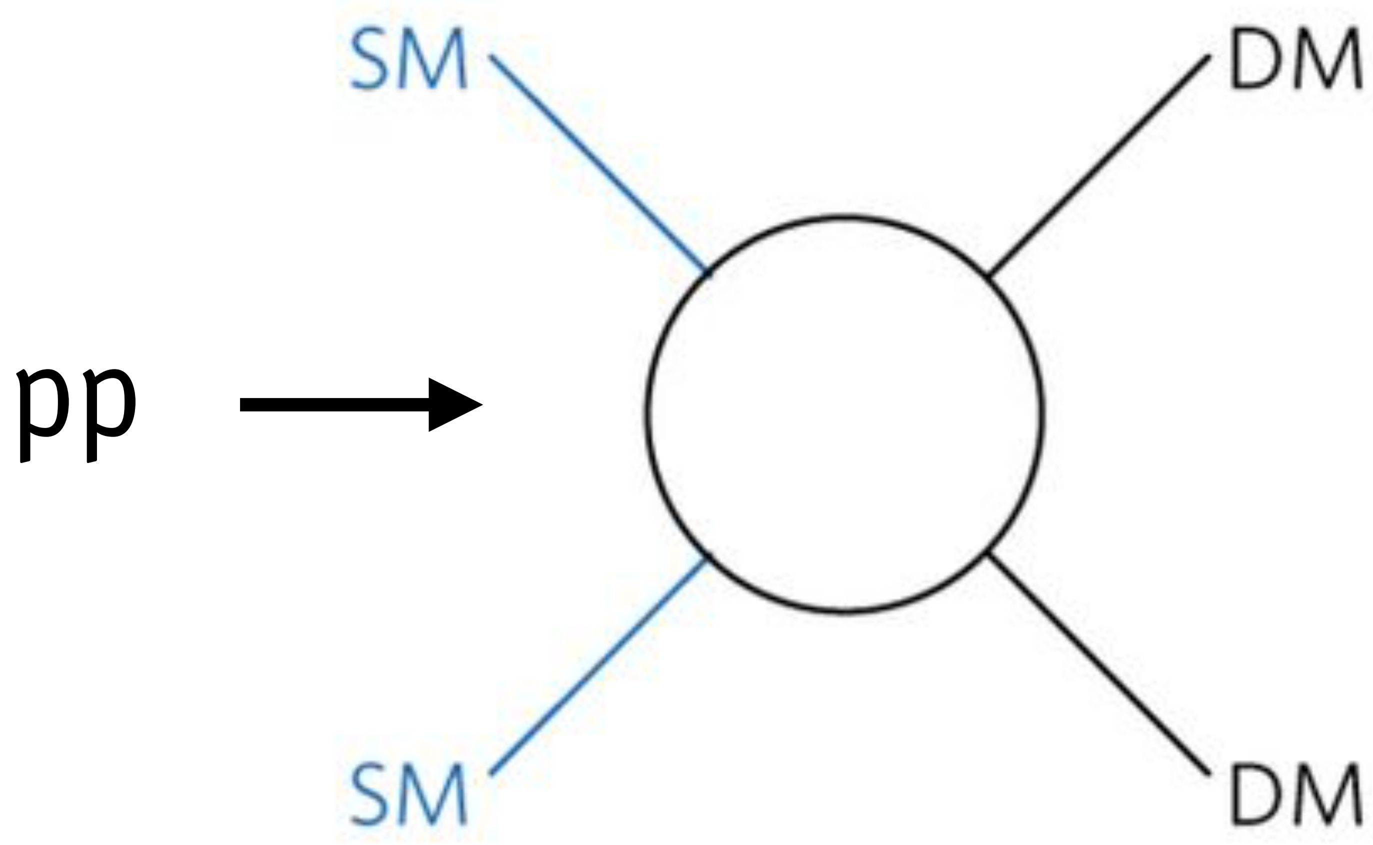


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

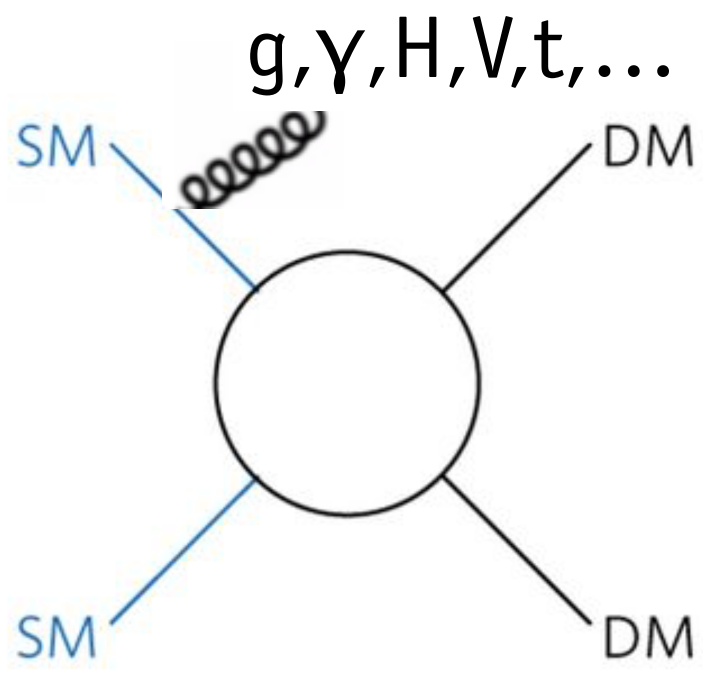
DIRECT SEARCHES FOR DM@LHC

DM LHC/COLLIDERS PARADIGM

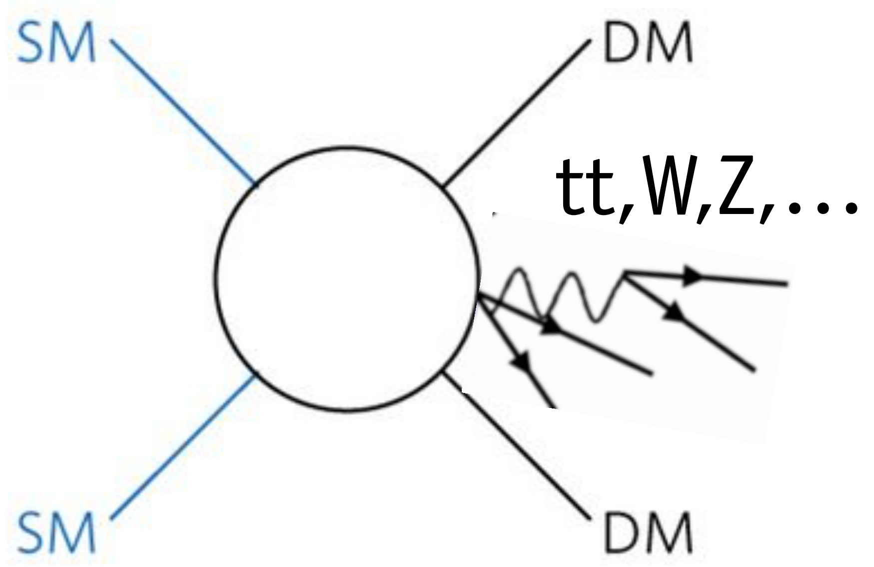
if in some way DM particles interact with ordinary particles LHC can in principle produce them



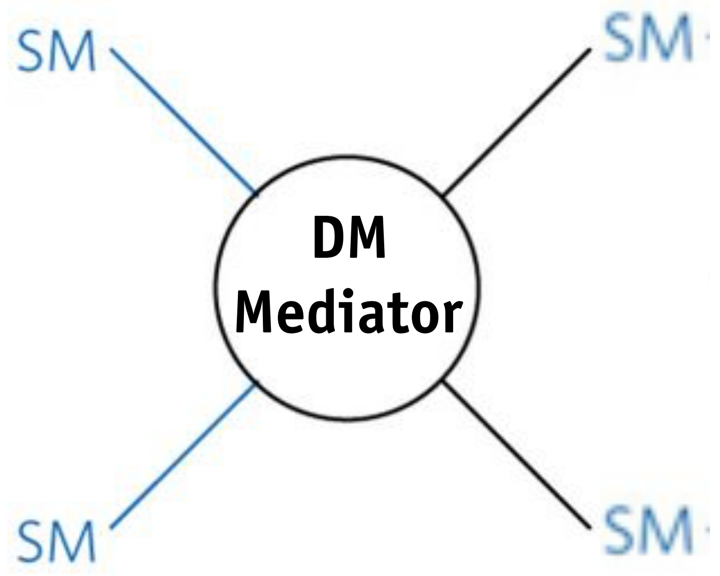
at LHC we need something visibile to detect invisibile things …



MONO-X SEARCHES

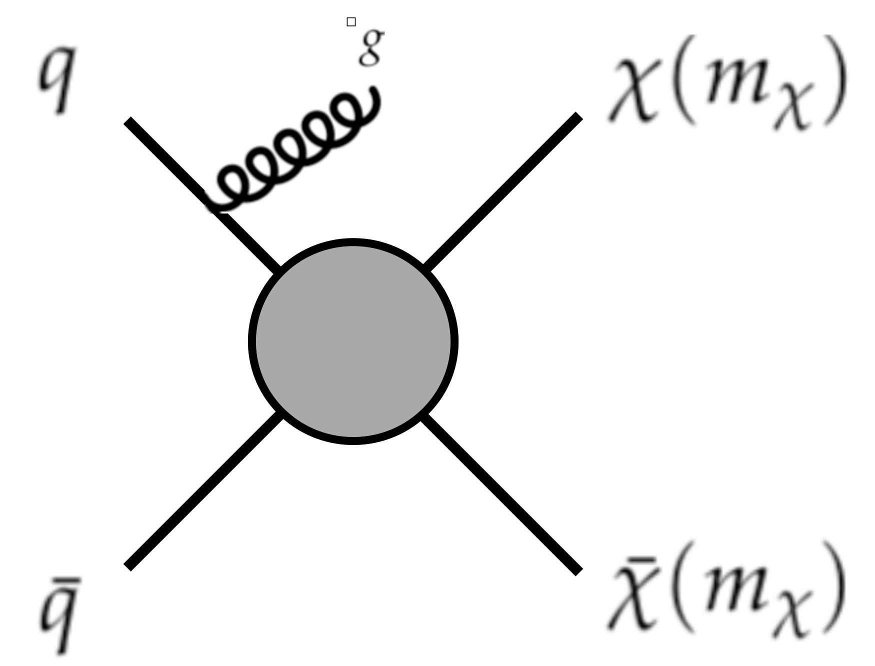


ASSOCIATE PRODUCTION OF DM WITH SM PARTICLES



DM MEDIATOR SEARCHES

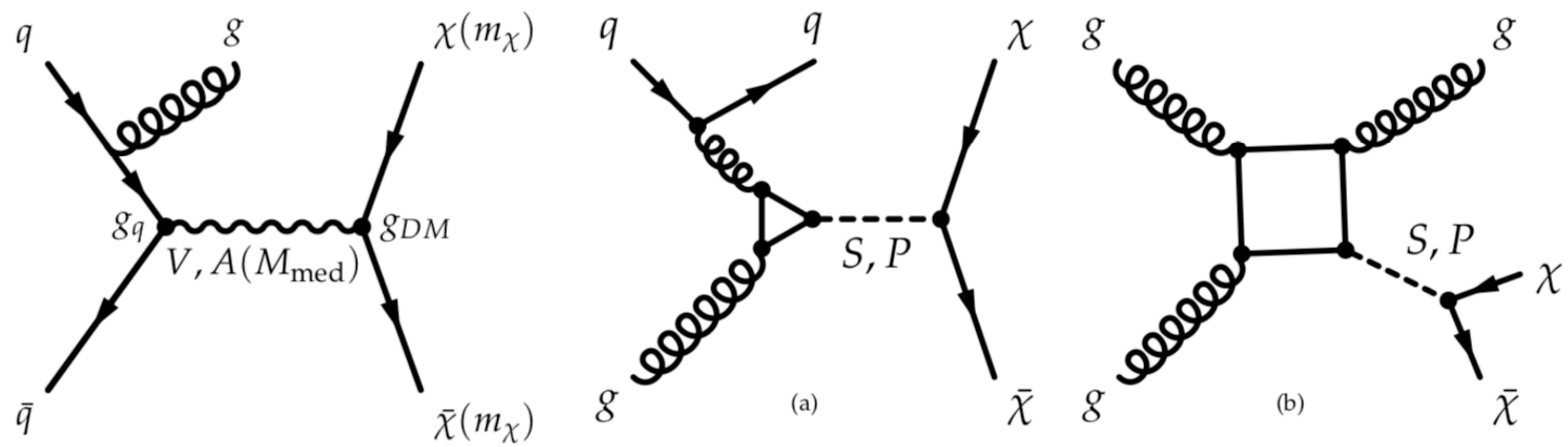
DM BENCHMARKS



EFFECTIVE FIELD THEORIES

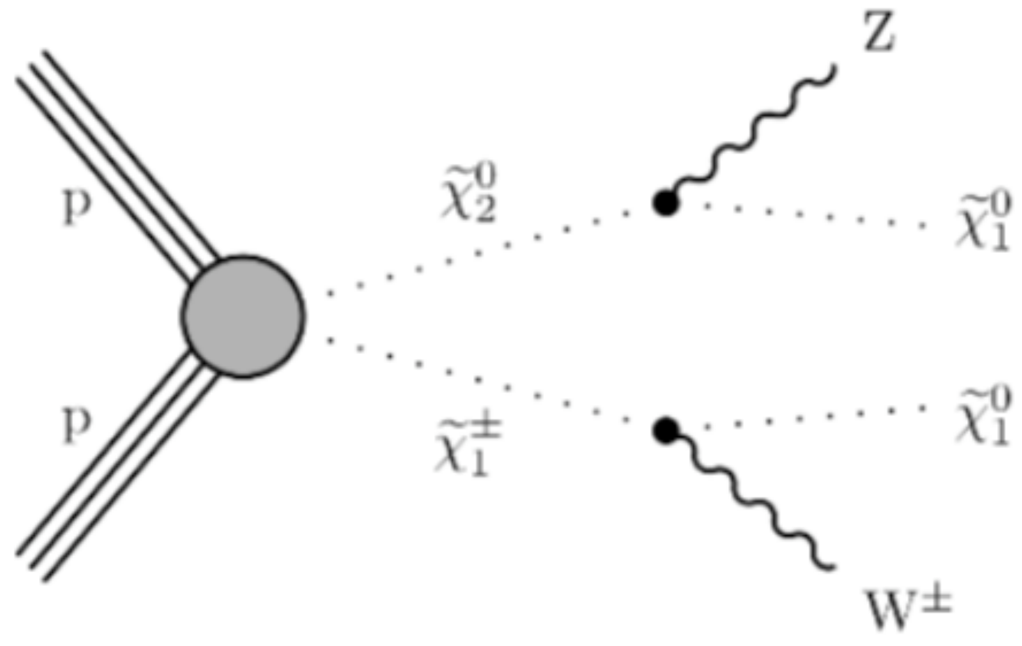
valid as long as we can integrate out higher-scale physics (mediator)

SIMPLIFIED MODELS



able to capture common aspects of different models
depends on few parameters
easy to compare with direct detection experiments

MODEL COMPLEXITY



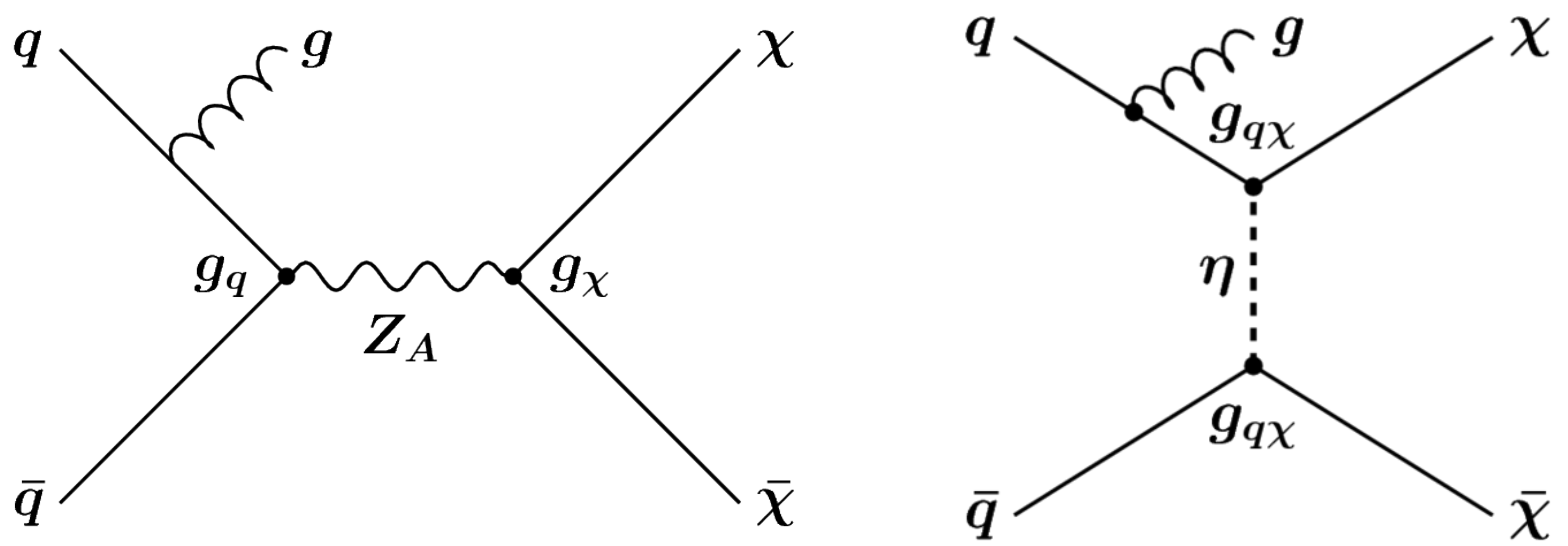
COMPLETE THEORIES

UV-complete models (ex. SUSY)
results more sensitive to specific models but also more model dependent

MONO-X SEARCHES

Search strategy:

- look at ISR objects recoiling against DM system (MET)
  - $\alpha_s \gg \alpha$ → larger signal yield in case of mono-Jet
  - most sensitive channel for vector mediator DM

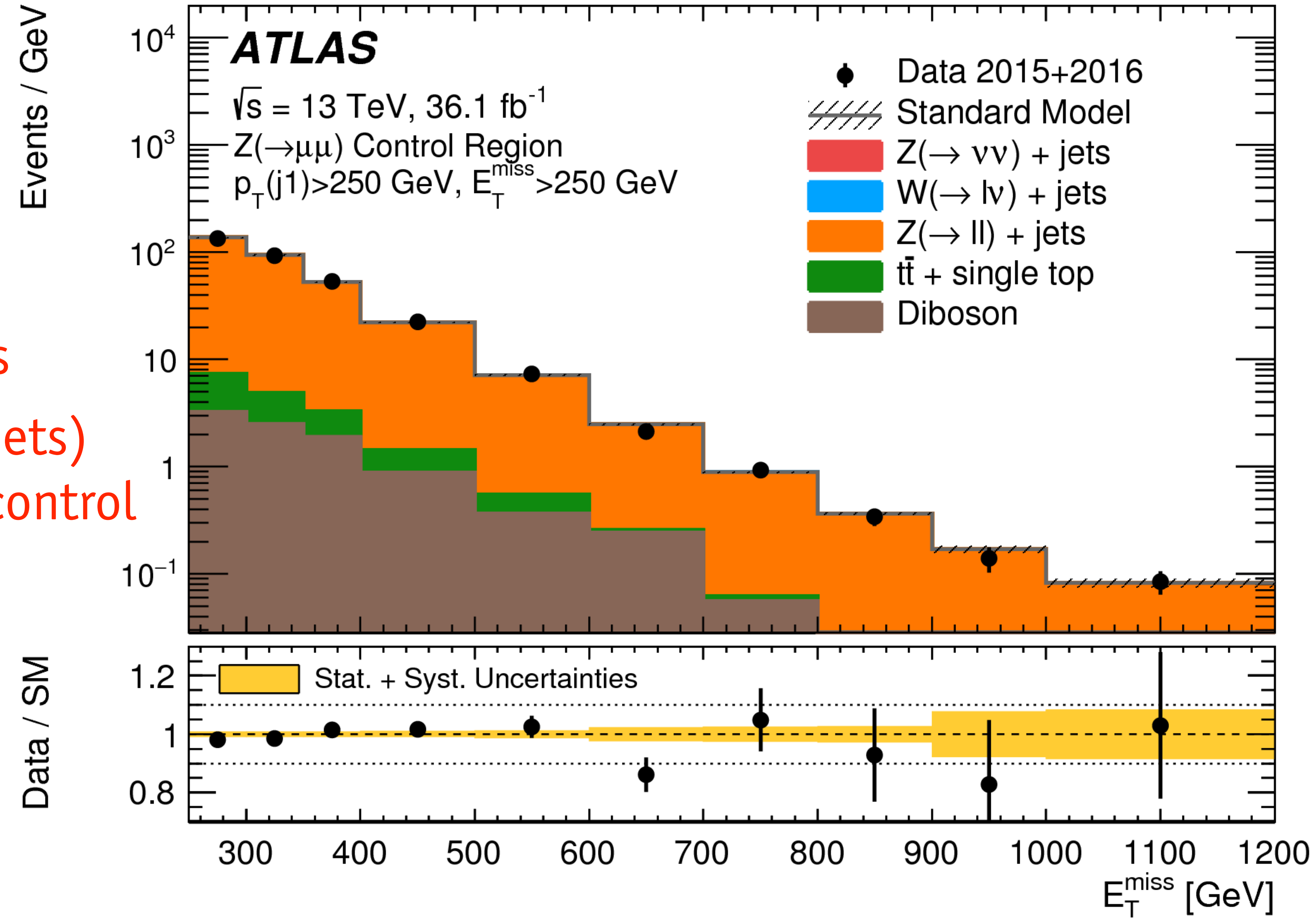


Benchmark models:

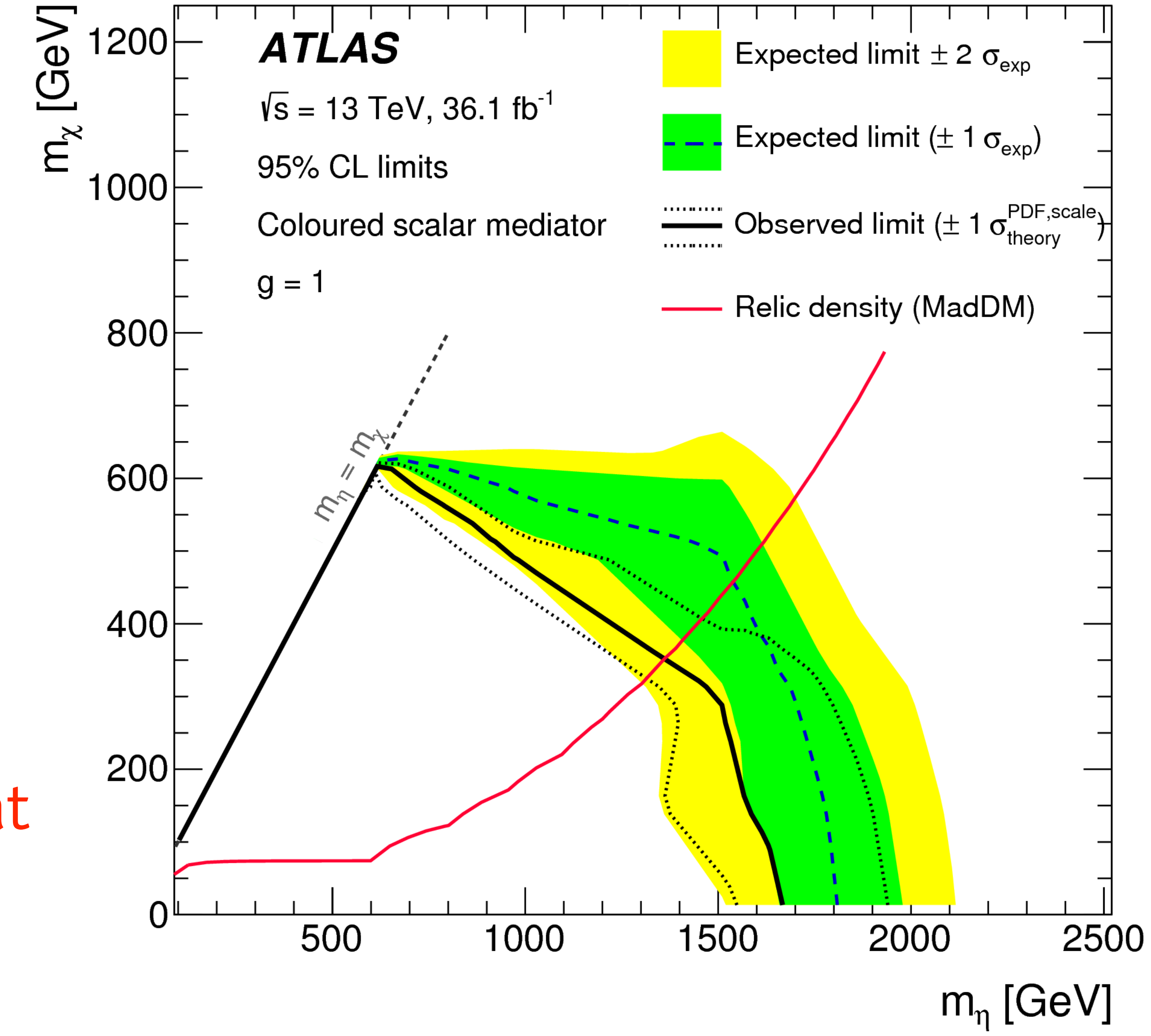
- s-channel exchange of spin-1 mediator with axial-vector (vector) couplings
- t-channel scalar coloured mediator, spin 0
- sensitive to many other BSM scenarios

JHEP 01 (2018) 126

data-driven backgrounds ((W/Z→l/νν)+jets) from orthogonal control regions



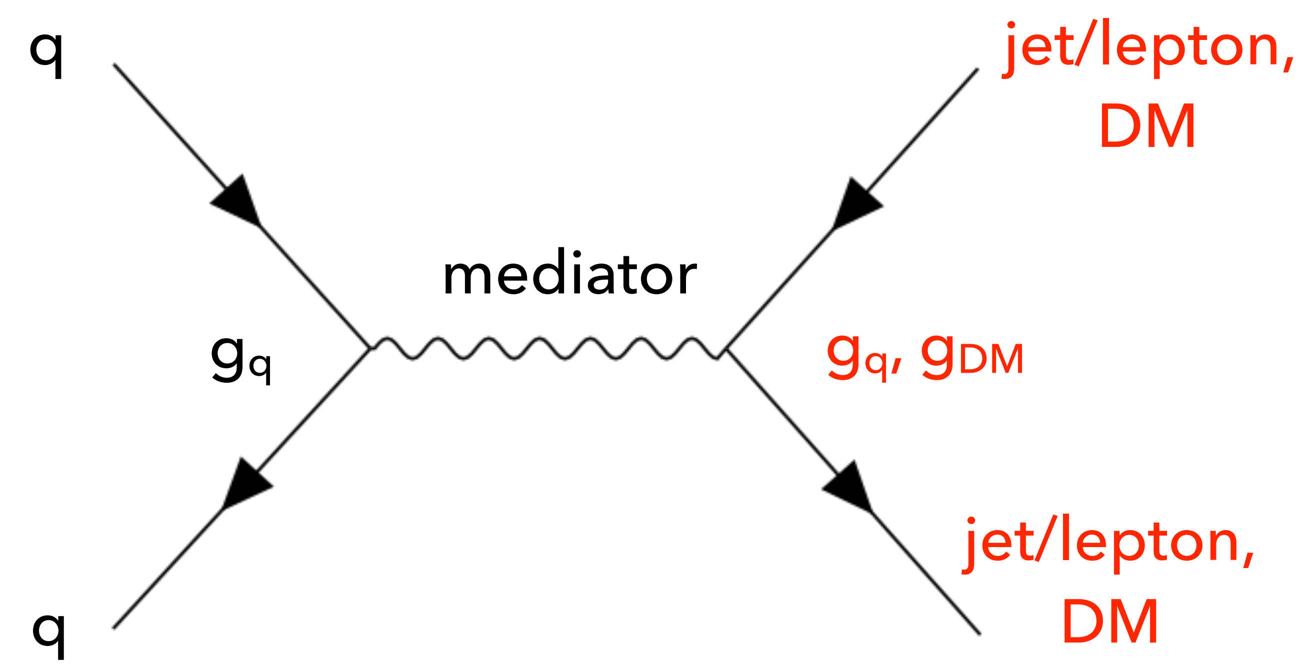
t-channel result: mediator masses up to about 1.67 TeV excluded at 95%CL for light DM



RESONANCES (DIJET/DILEPTON) SEARCHES

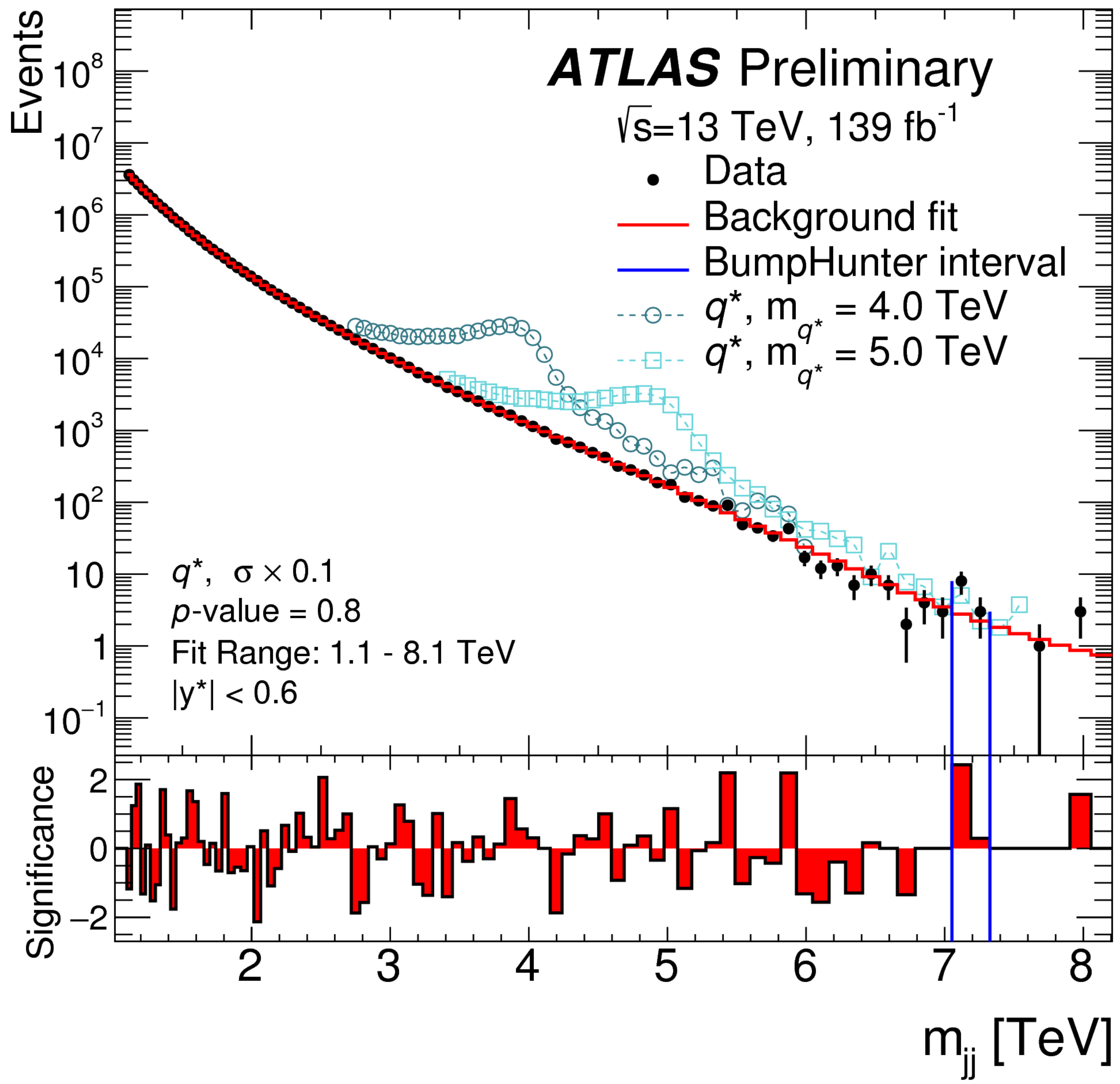
if the DM mediator couple to quarks or leptons in addition to mono-X signals it will also affect di-jet /di-lepton spectra

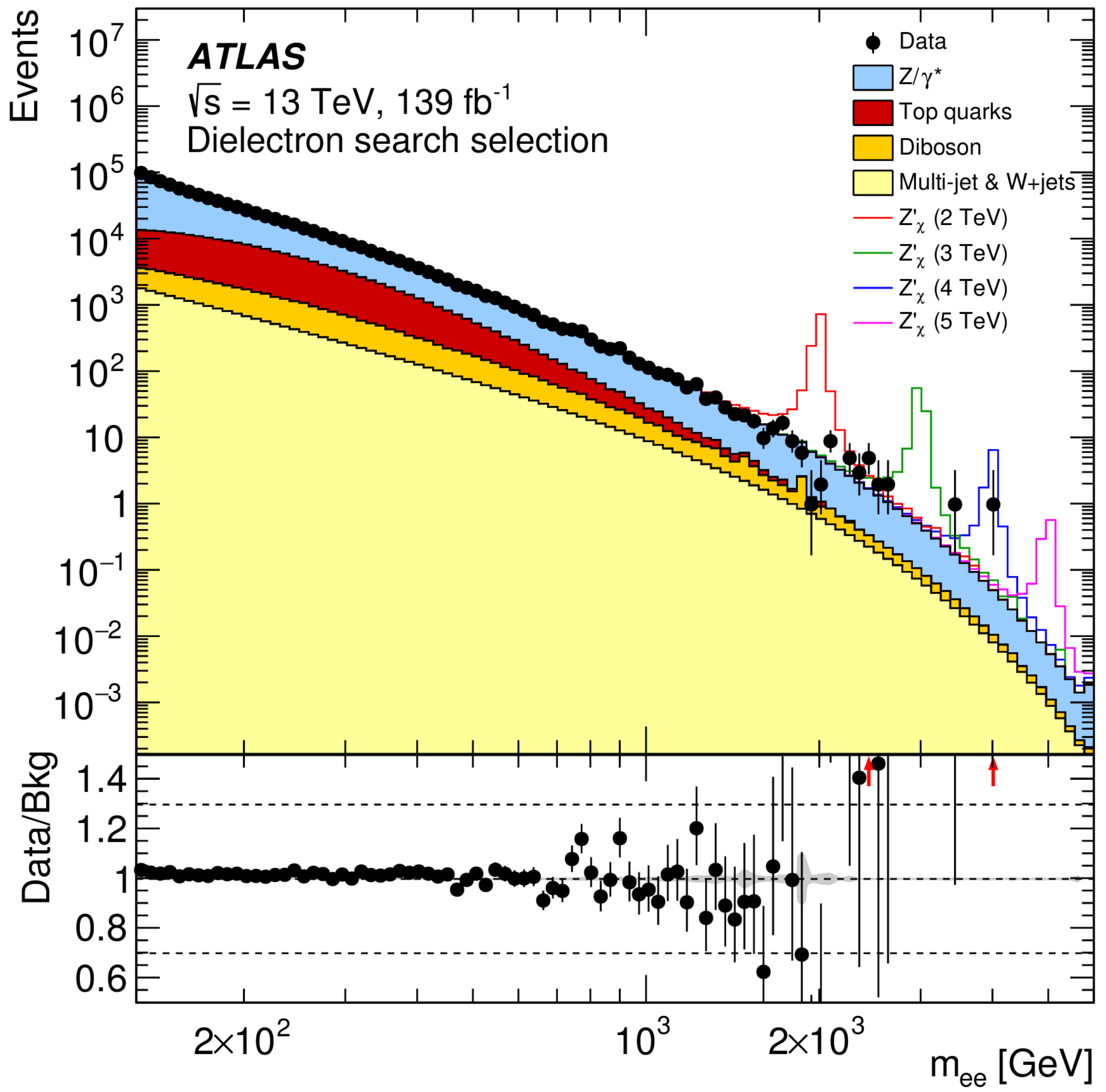
- check the di-jet / di-lepton invariant mass distributions against expectations from SM processes
- search for "bumps" in the m_{jj}/m_{ll}, describing background shapes with smooth functional forms
- probed jets and leptons with transverse momenta up to multi-TeV



di-jet

ATLAS-CONF-2019-007





di-electrons

Phys. Lett. B 796 (2019) 68

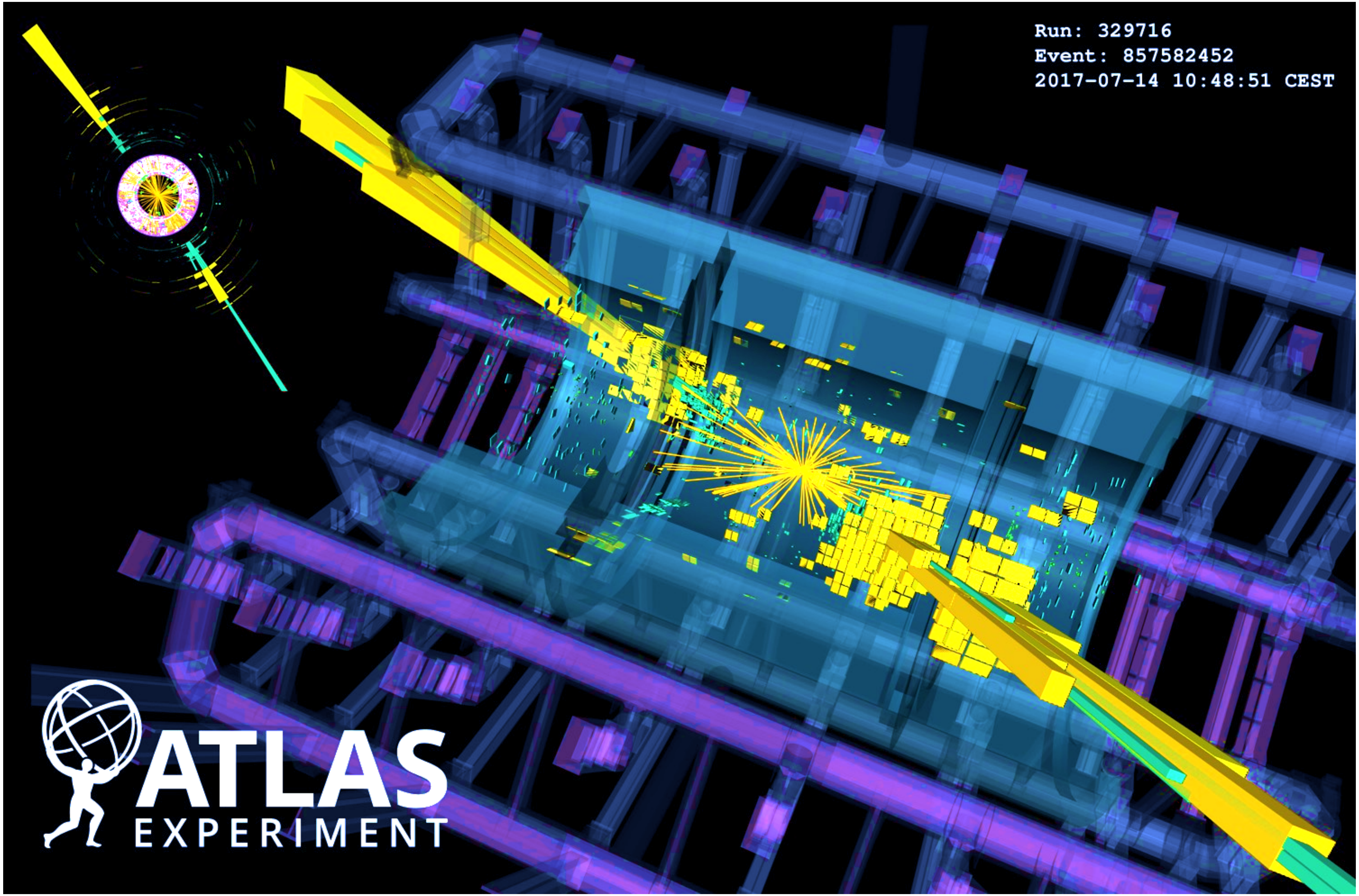
A DI-JET EVENTS SEEN IN ATLAS

Run 2 2017

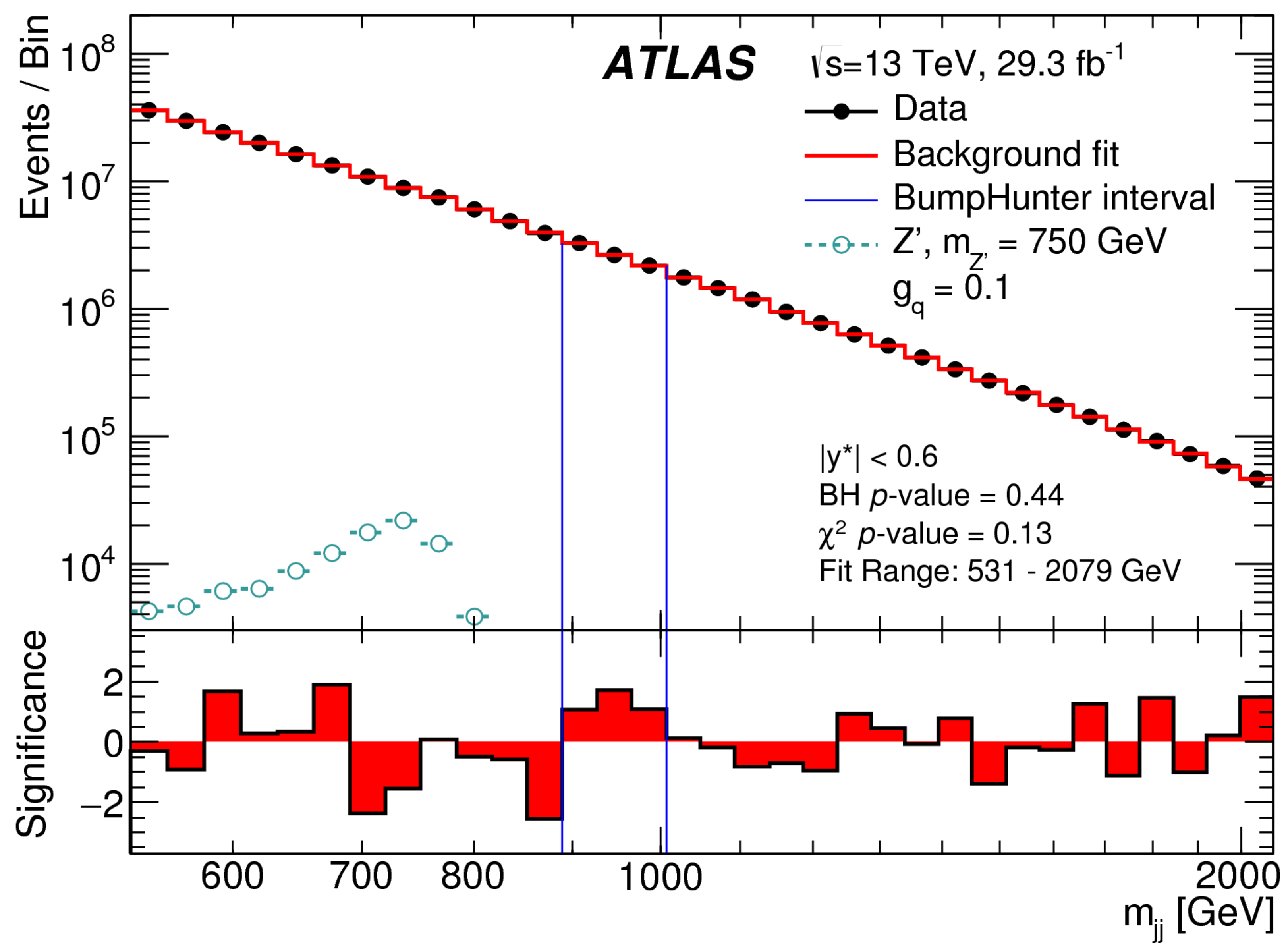
$\sqrt{s}$ = 13 TeV

m_{jj} = 9.3 TeV

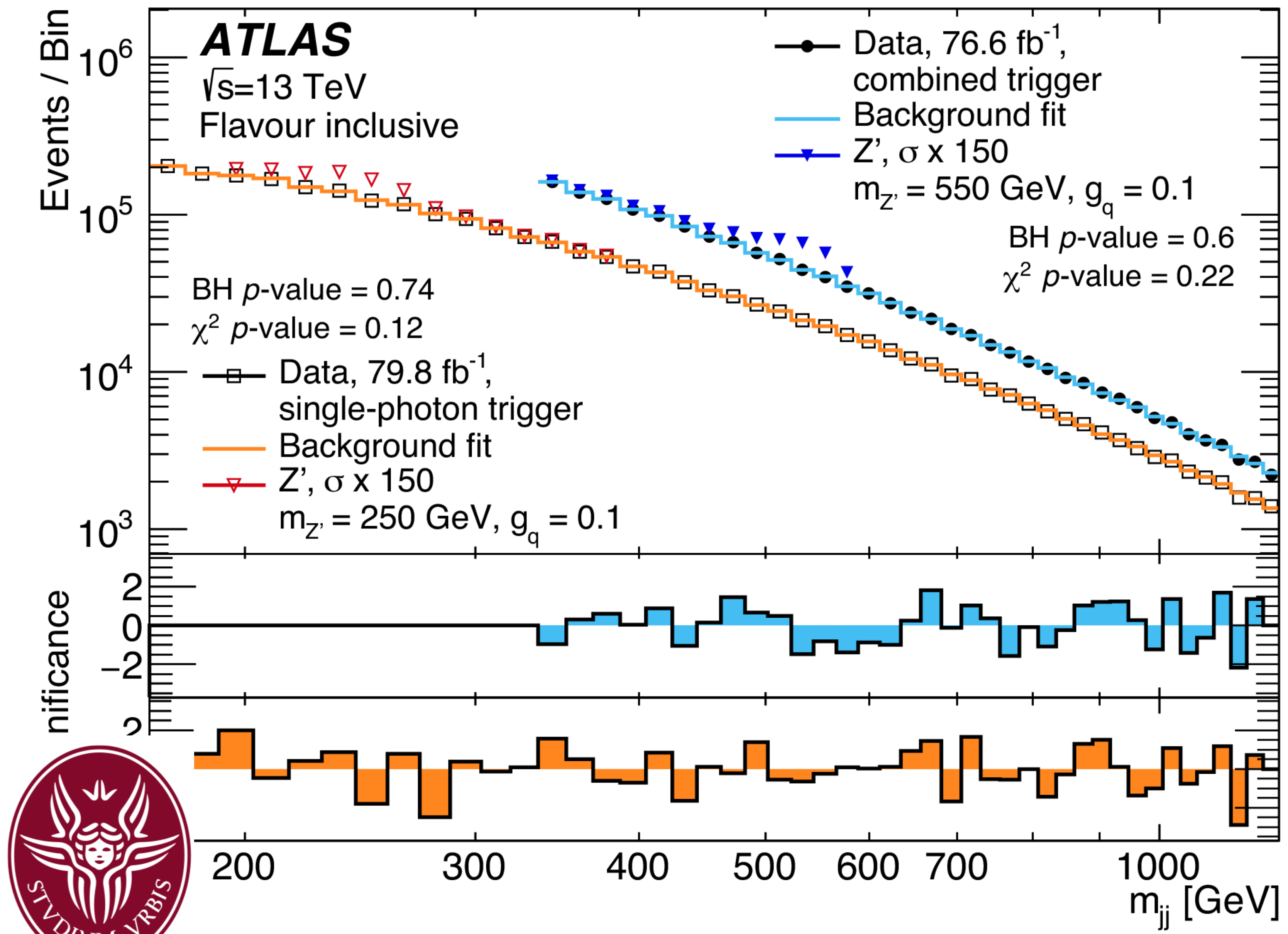
jet p_T 2.9 TeV

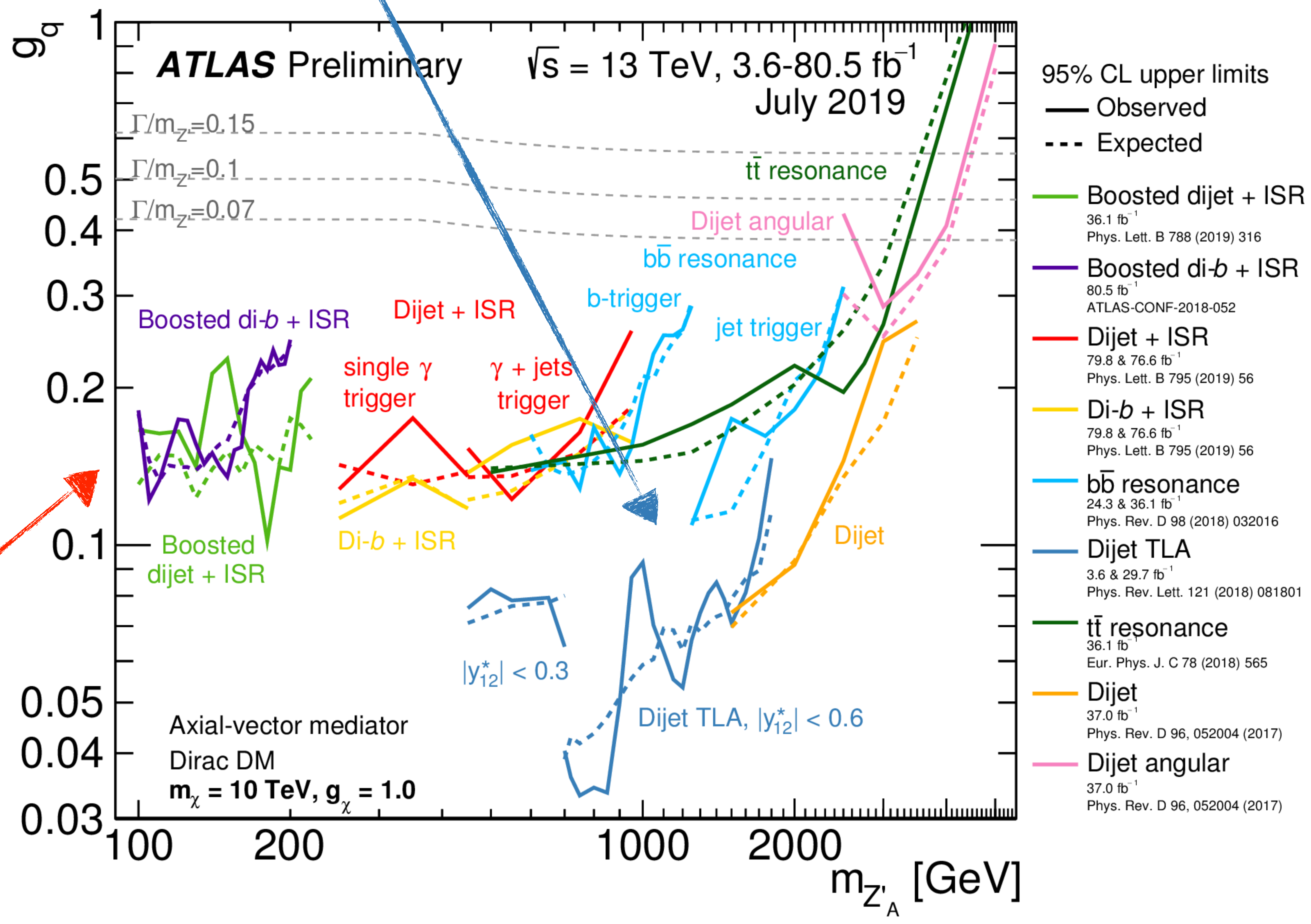


RESONANCES (DIJET/DILEPTON) SEARCHES



LOWER MASS: TRIGGER LEVEL ANALYSIS





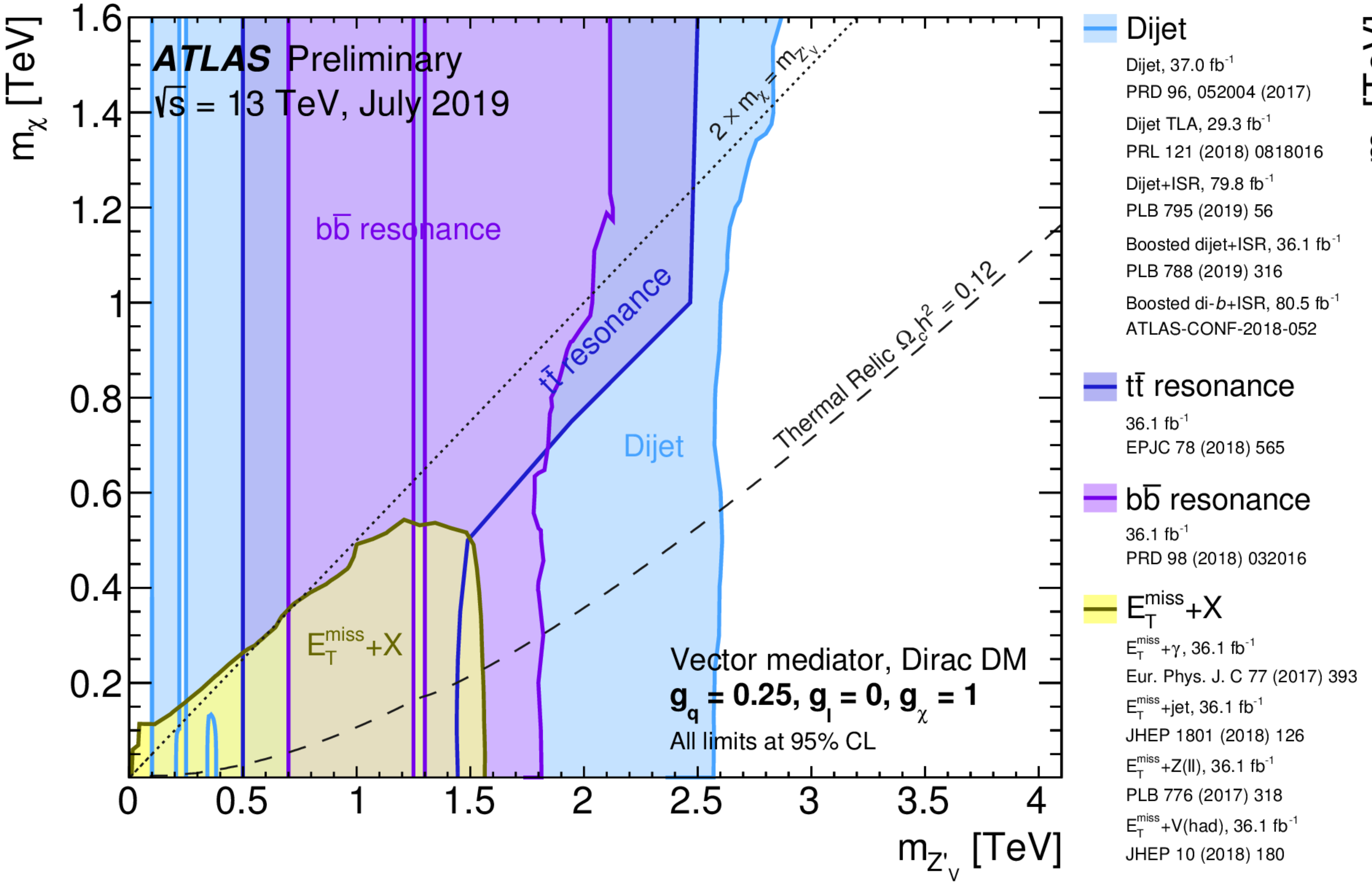
EVEN LOWER MASS: JJ+ISR

Phys. Rev. Lett. 121 (2018) 081801; *Phys. Lett. B 795 (2019) 56*

COMBINATION

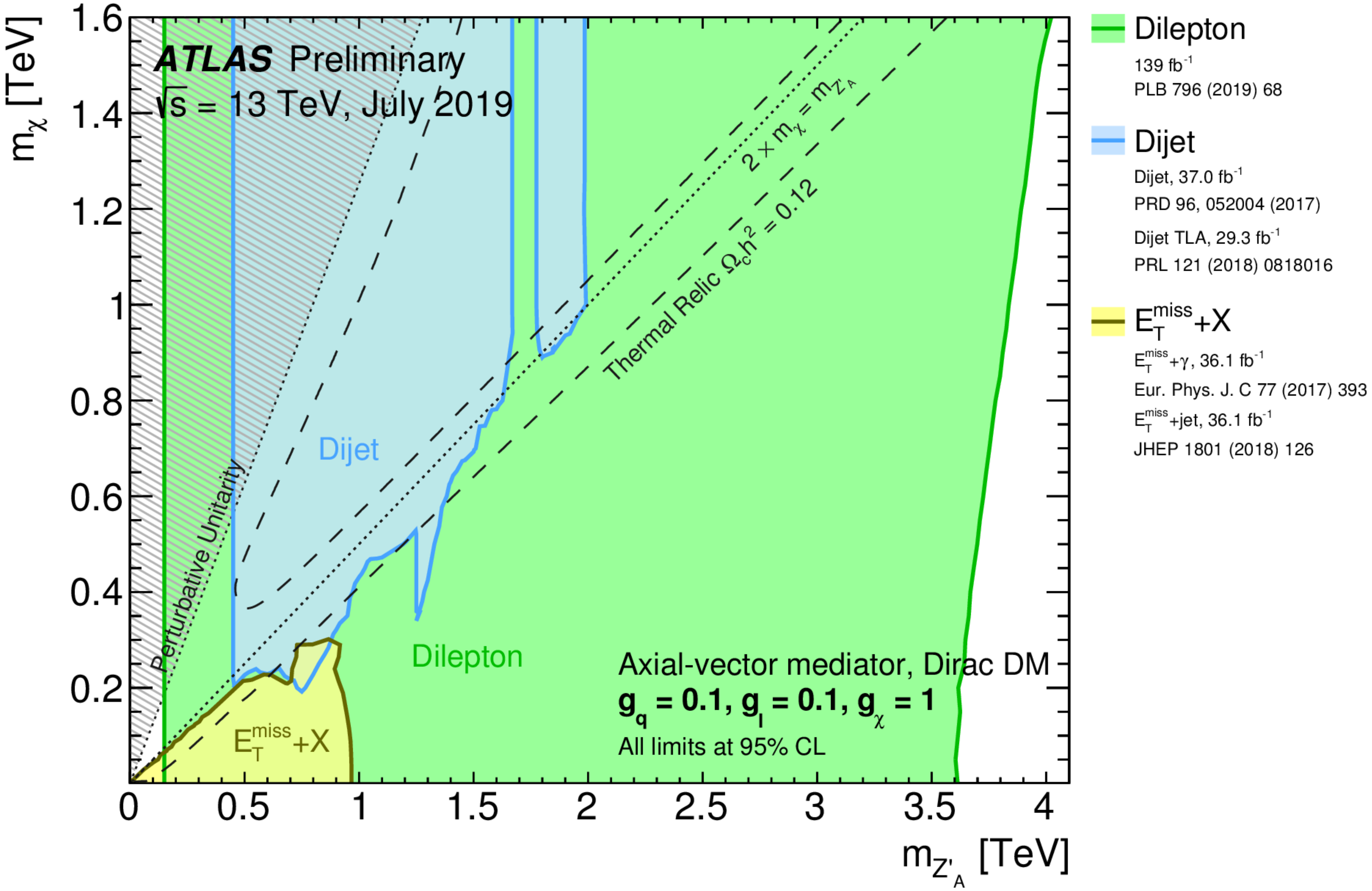
bounds on DM-mediator mass plane from mono-X and di-jet searches

VECTOR MEDIATOR



Vector Mediator (g_q=0.25,g_l=0,g_{DM}=1)

AXIAL-VECTOR MEDIATOR

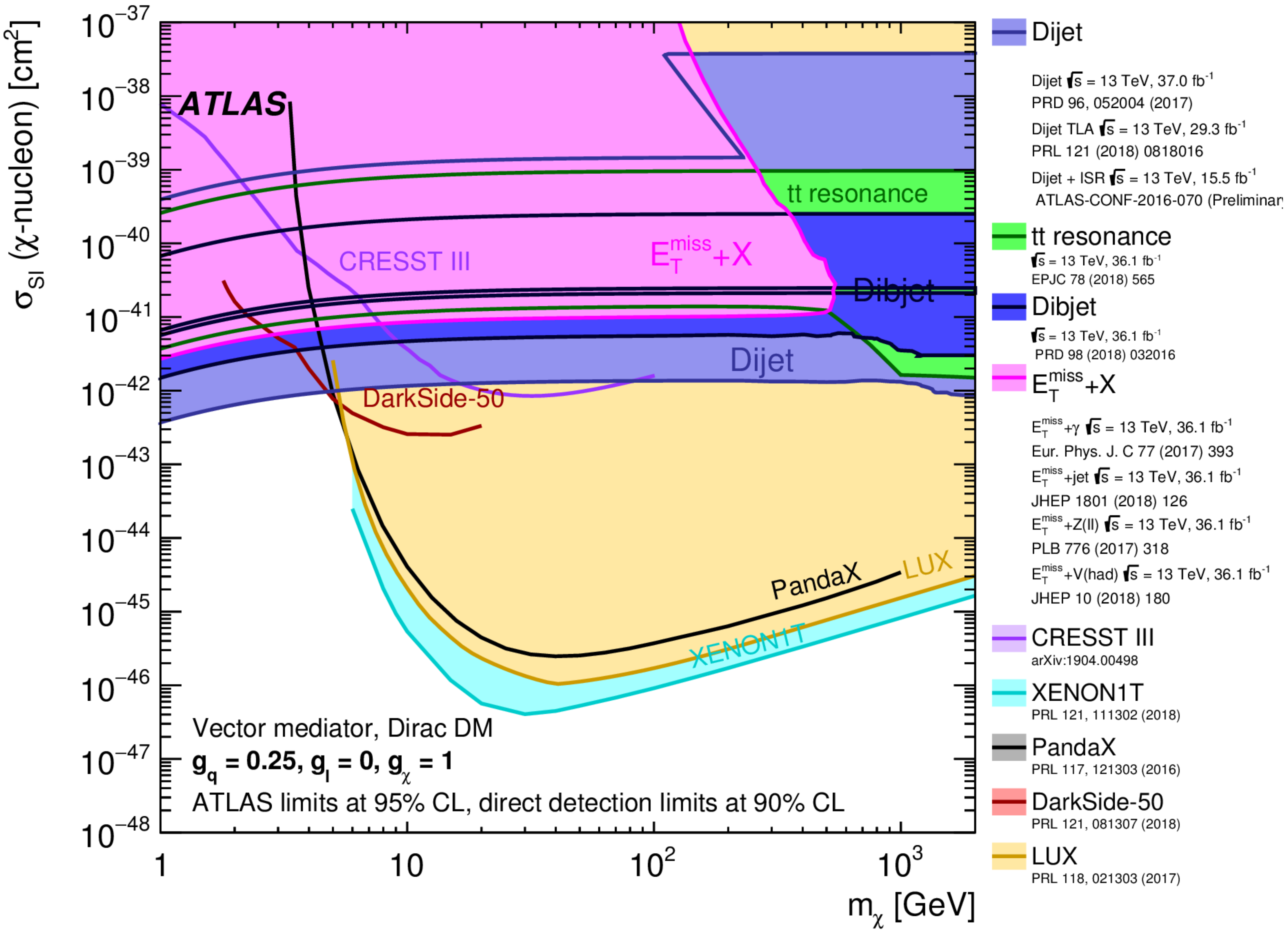


Axial-Vector Mediator (g_q=0.1,g_l=0.1,g_{DM}=1)

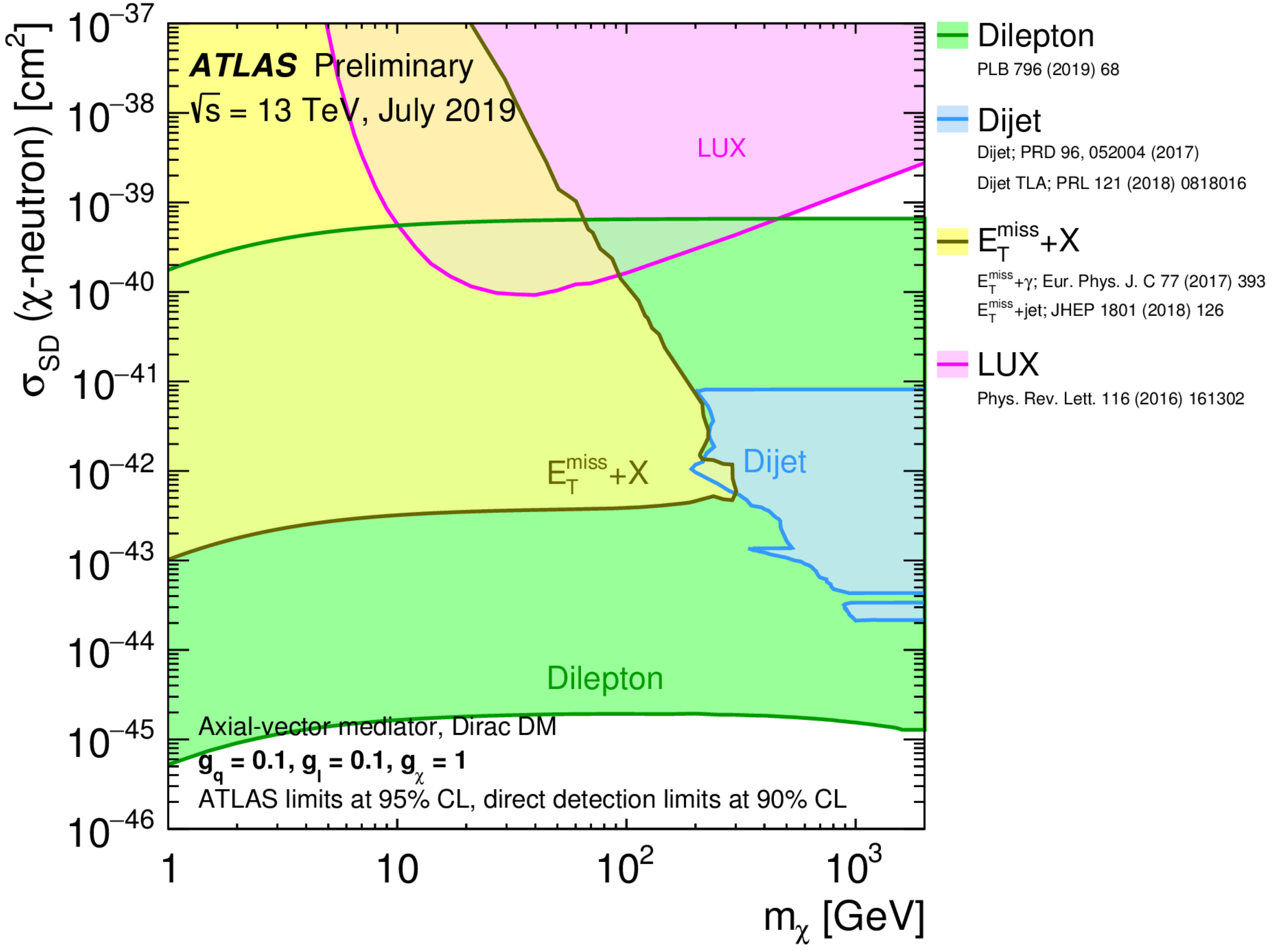
IMPORTANT: ALL INTERPRETATIONS HIGHLY DEPENDENT ON ASSUMPTIONS!

COMPLEMENTARITY WITH DIRECT SEARCHES

VECTOR MEDIATOR

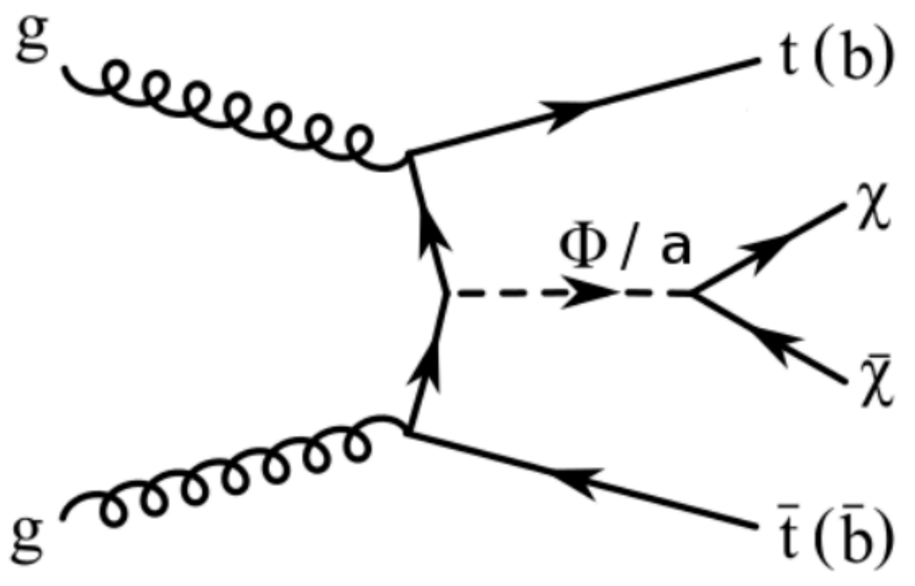


AXIAL-VECTOR MEDIATOR



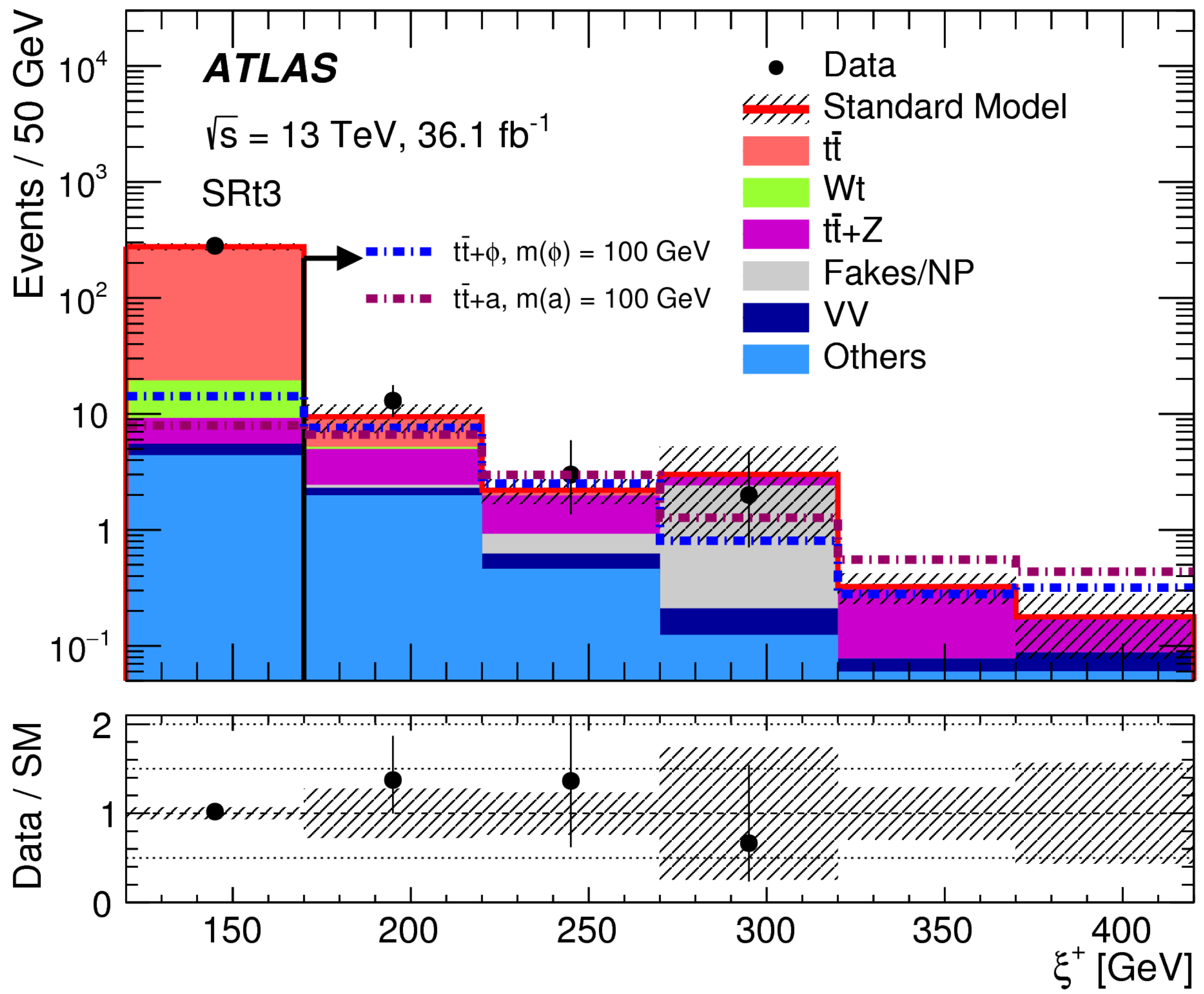
ATLAS (95% CL) limits converted in spin independent or spin dependent χ-nucleon cross-sections

SCALAR MEDIATOR PROBES: DM + HF

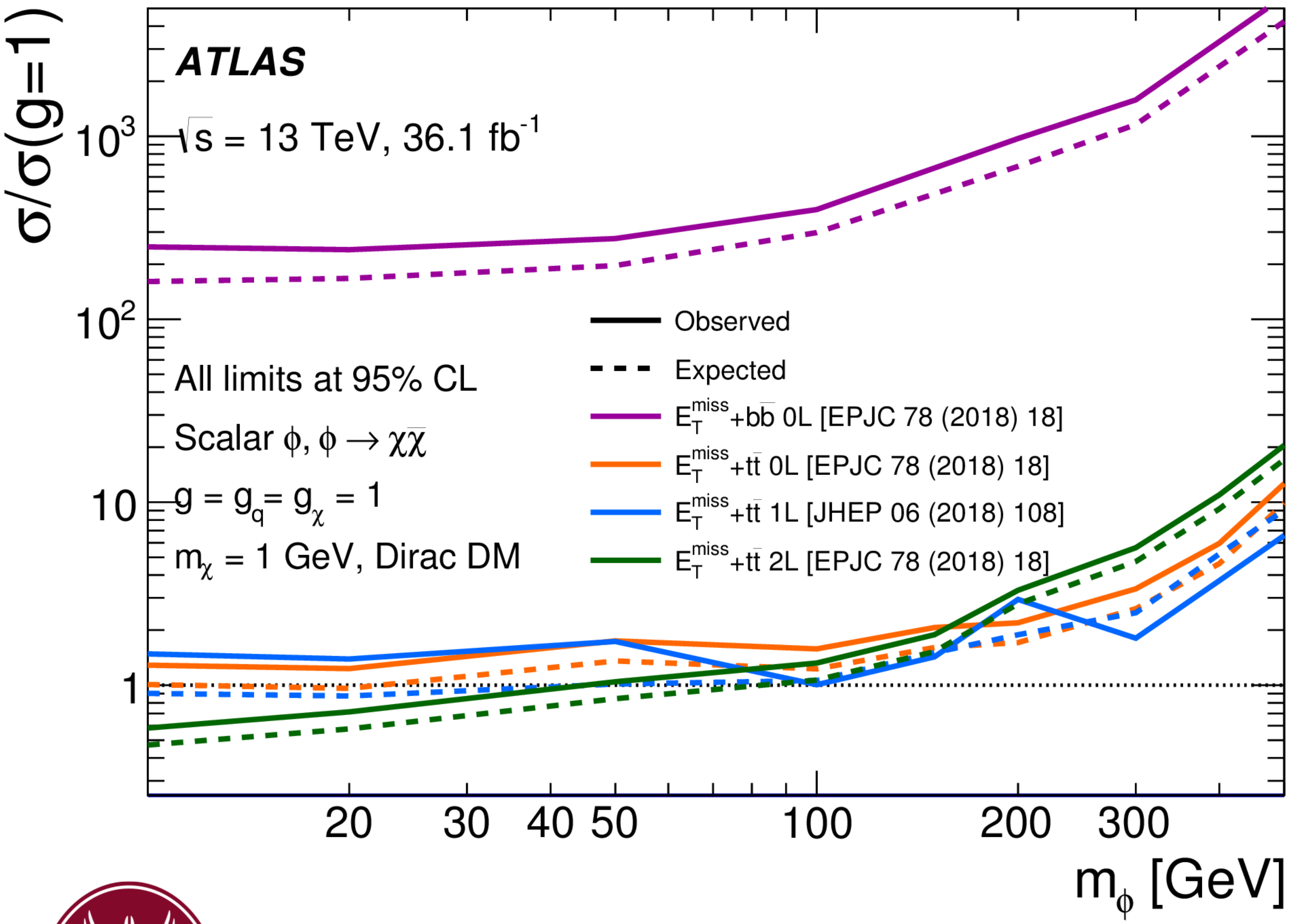


most sensitive channel for spin 0, scalar or pseudo-scalar, color neutral mediator

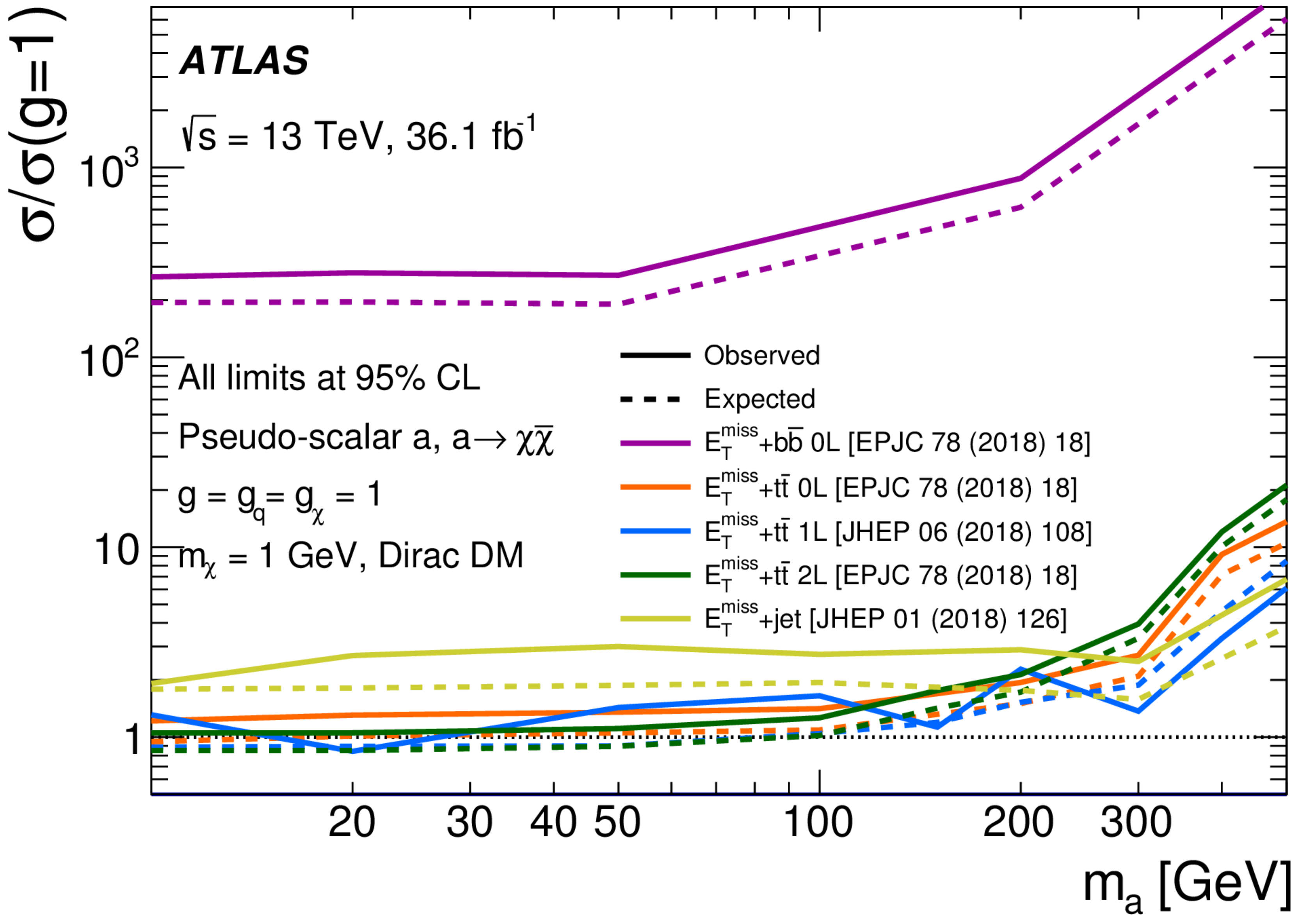
- looks for final states with top and bottom enhanced by Yukawa coupling between DM and SM sectors
- 0, 1 and 2-leptons final states
- final discriminant variables: stranverse-mass and MET



SCALAR



PSEUDO-SCALAR

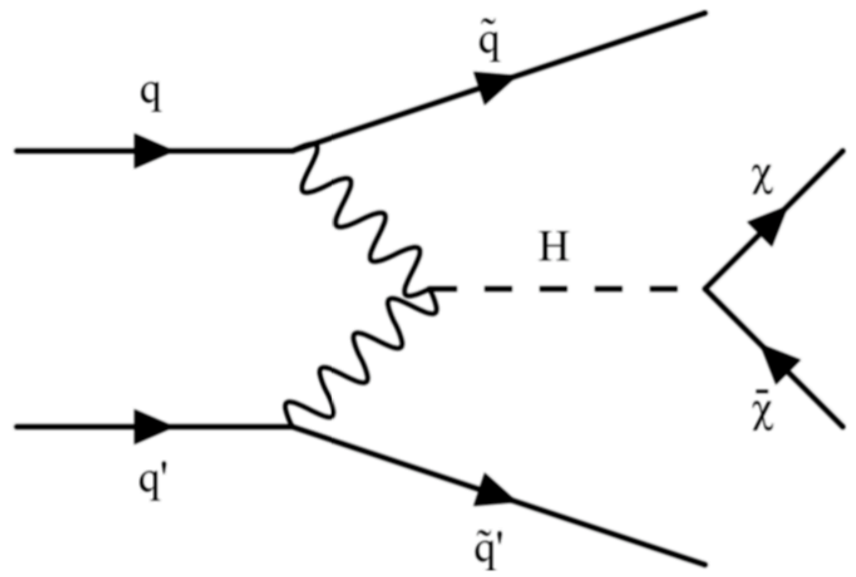


- excluded mediator mass up to 45 GeV (scalar) and 15-25 GeV (pseudo-scalar)
- results do not depend on the DM mass, as long as the DM is on-shell

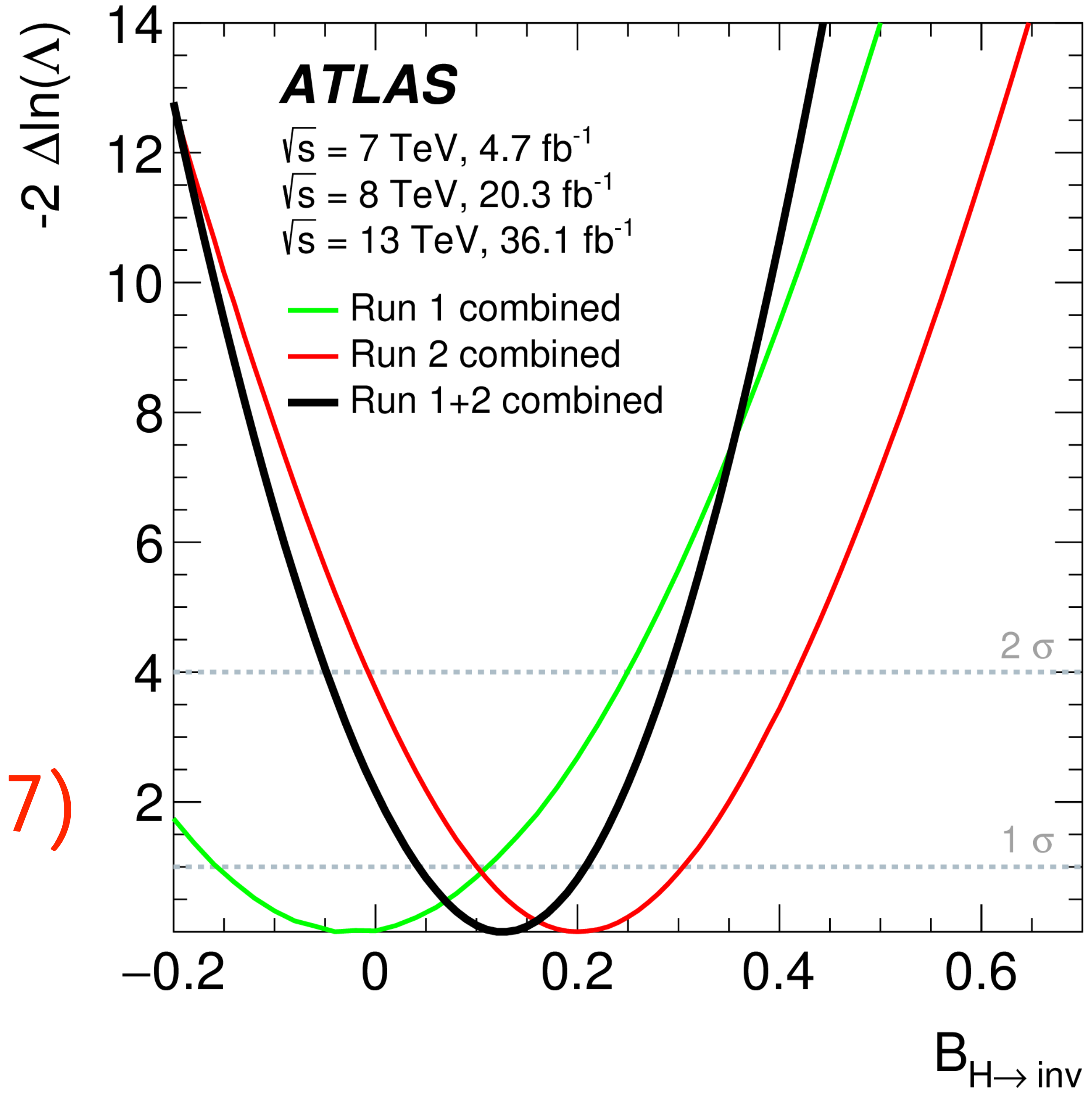
Eur. Phys. J. C 78 (2018) 18
JHEP 05 (2019) 142

DM THROUGH H→ INVISIBLE

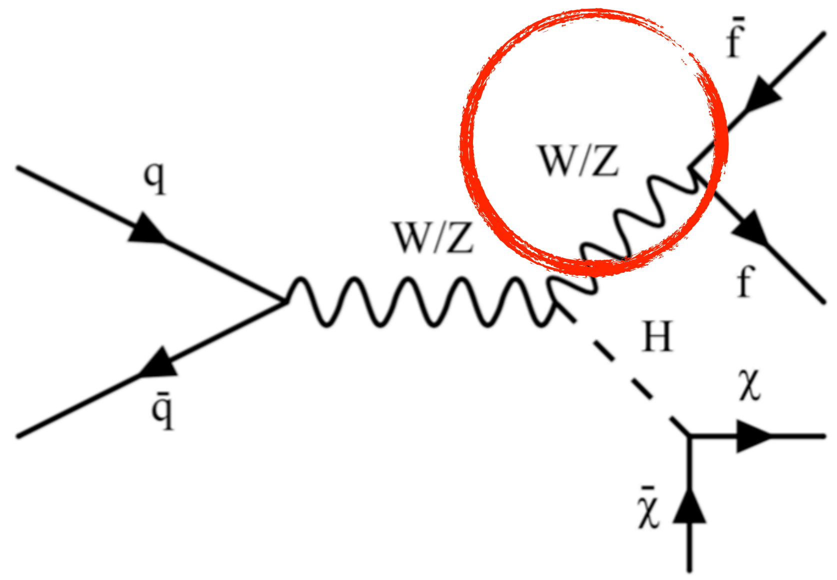
- Search for Higgs decaying into WIMPs
  - connection with Dark Matter (or general hidden sectors) via Higgs or scalar portals
  - SM $B(H \to ZZ \to 4\nu) \sim 0.12\%$
  - most sensitive channel at LHC: VBF

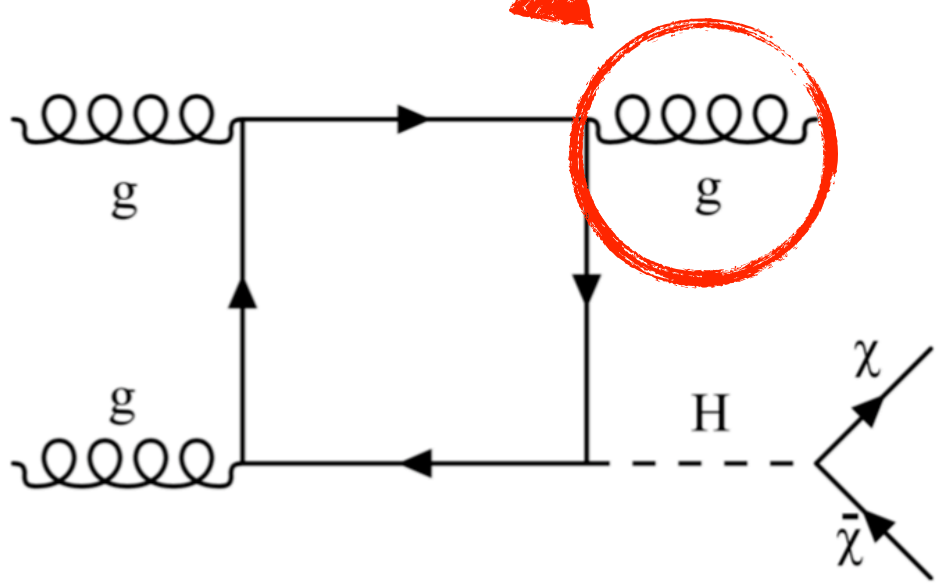


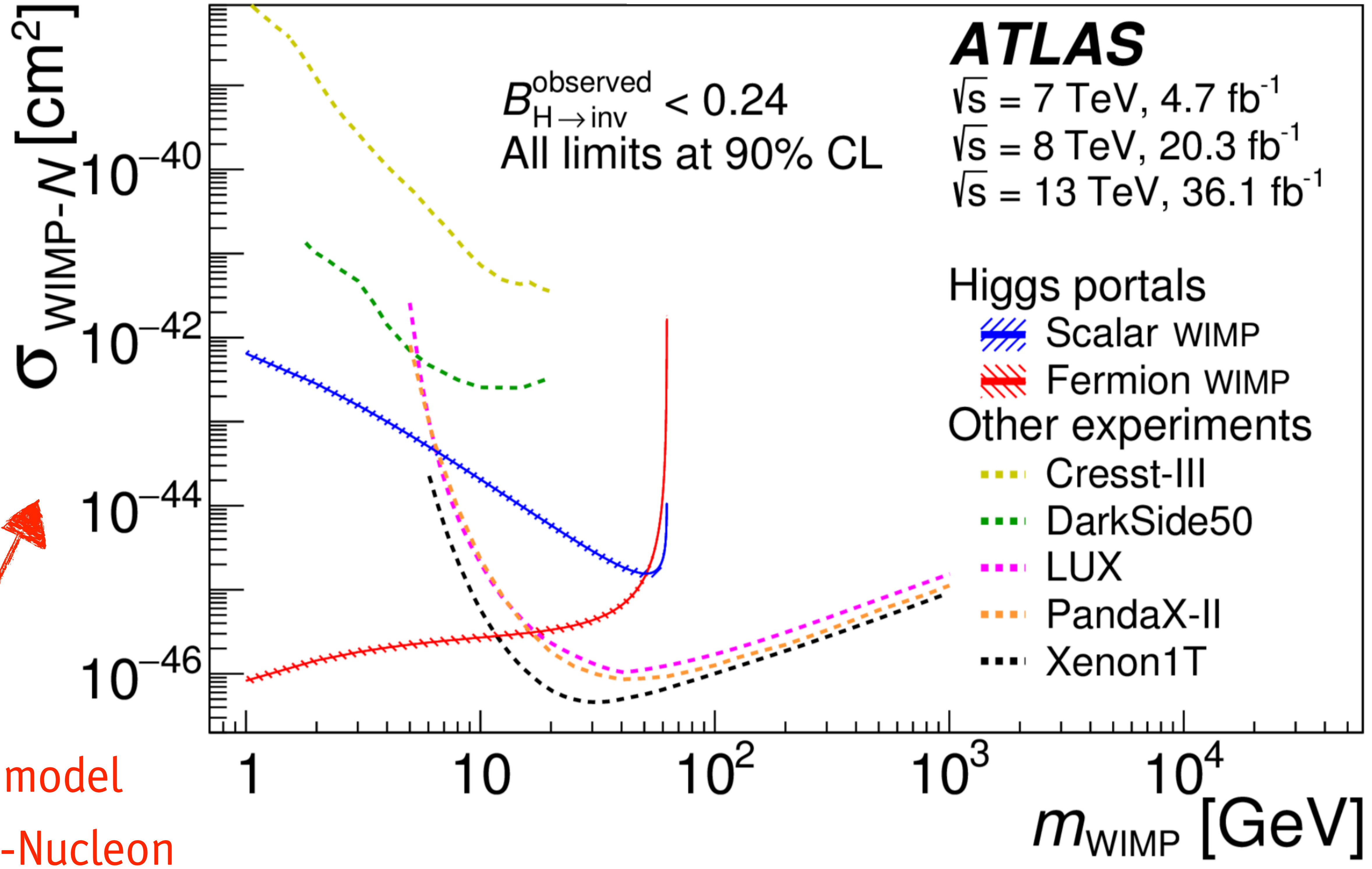
$B(H \to inv) < 0.26\ (0.17)$ @95% CL



VH and ggF exp. signature:
MET measured from recoiling V or Jet







Interpretation in the context of the Higgs Portal model

$B(H \to inv) \to \Gamma^{inv} \to$ couplings $\to$ cross-section DM-Nucleon

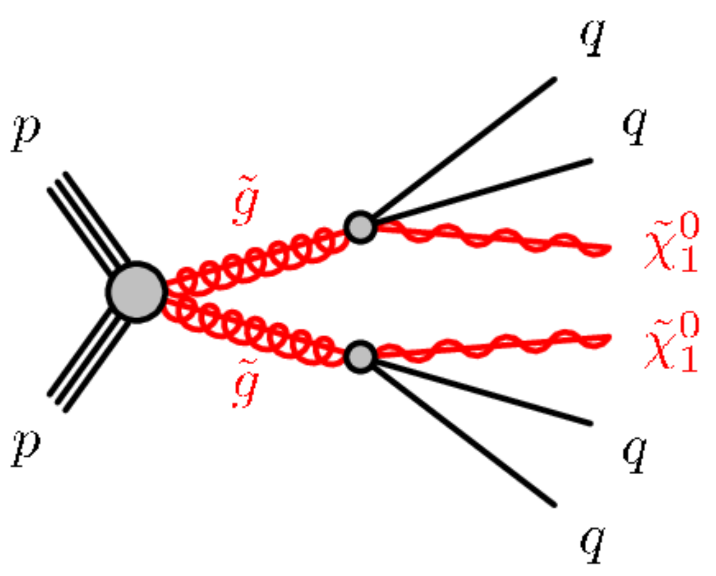
Phys. Rev. Lett. 122, 231801 (2019)

SUSY SEARCHES

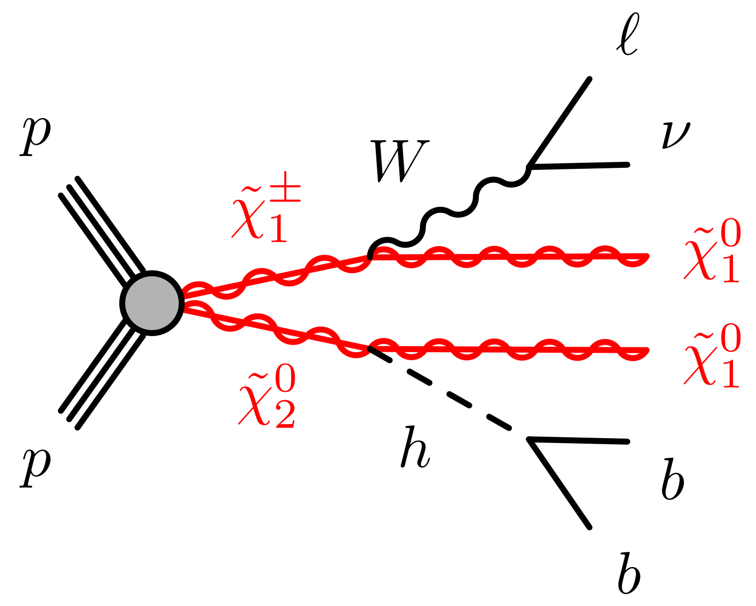
ATLAS-CONF-2019-040
ATLAS-CONF-2019-008
ATLAS-CONF-2019-031

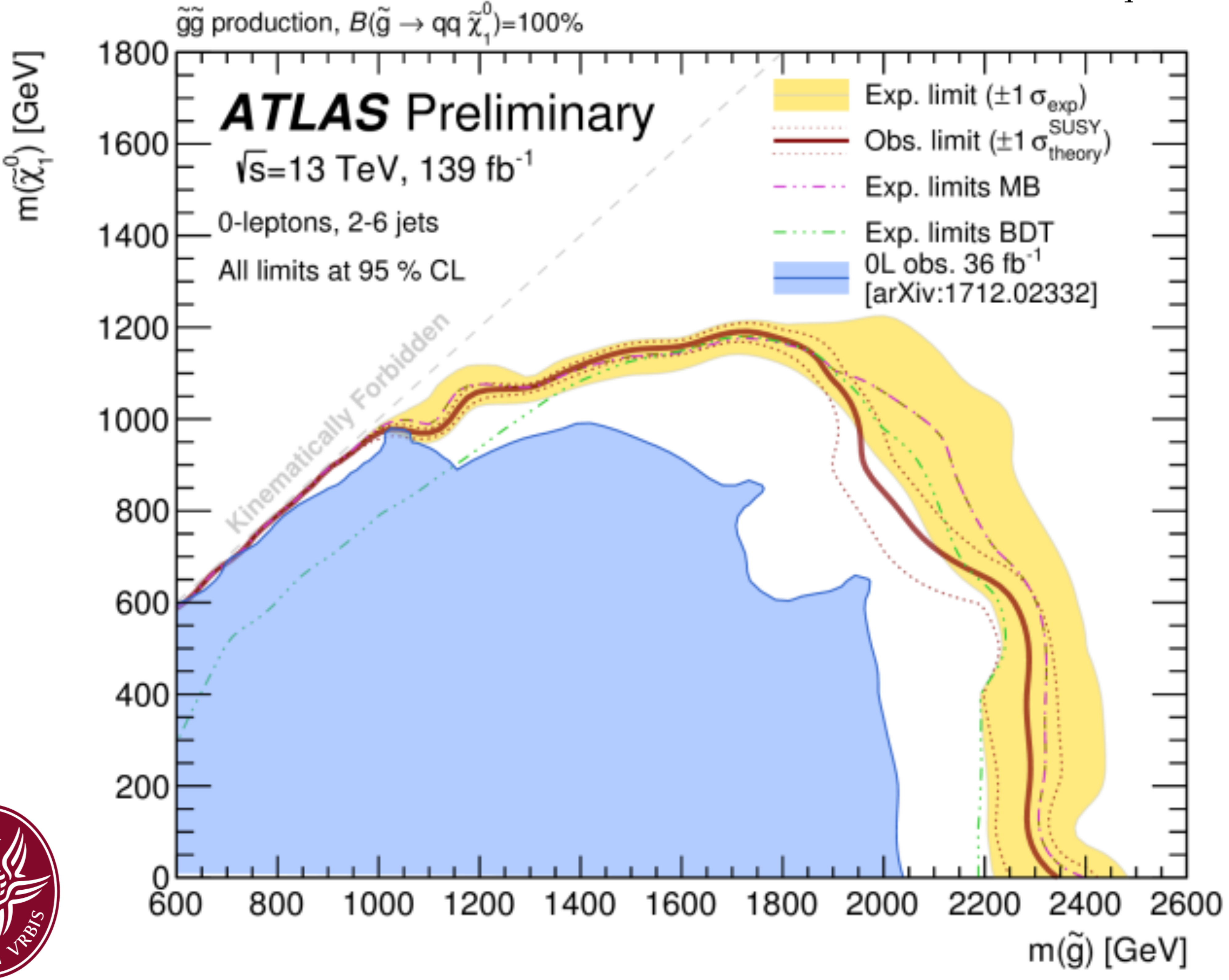
- a large number of analyses performed or onging in ATLAS, looking at very diverse signatures, two representative ones shown here:
- strong SUSY production in events with large hadronic activity and 0-leptons: sensitive to gluino/squark production
- electroweak SUSY production in events with multi-leptons: sensitive on EWKino production

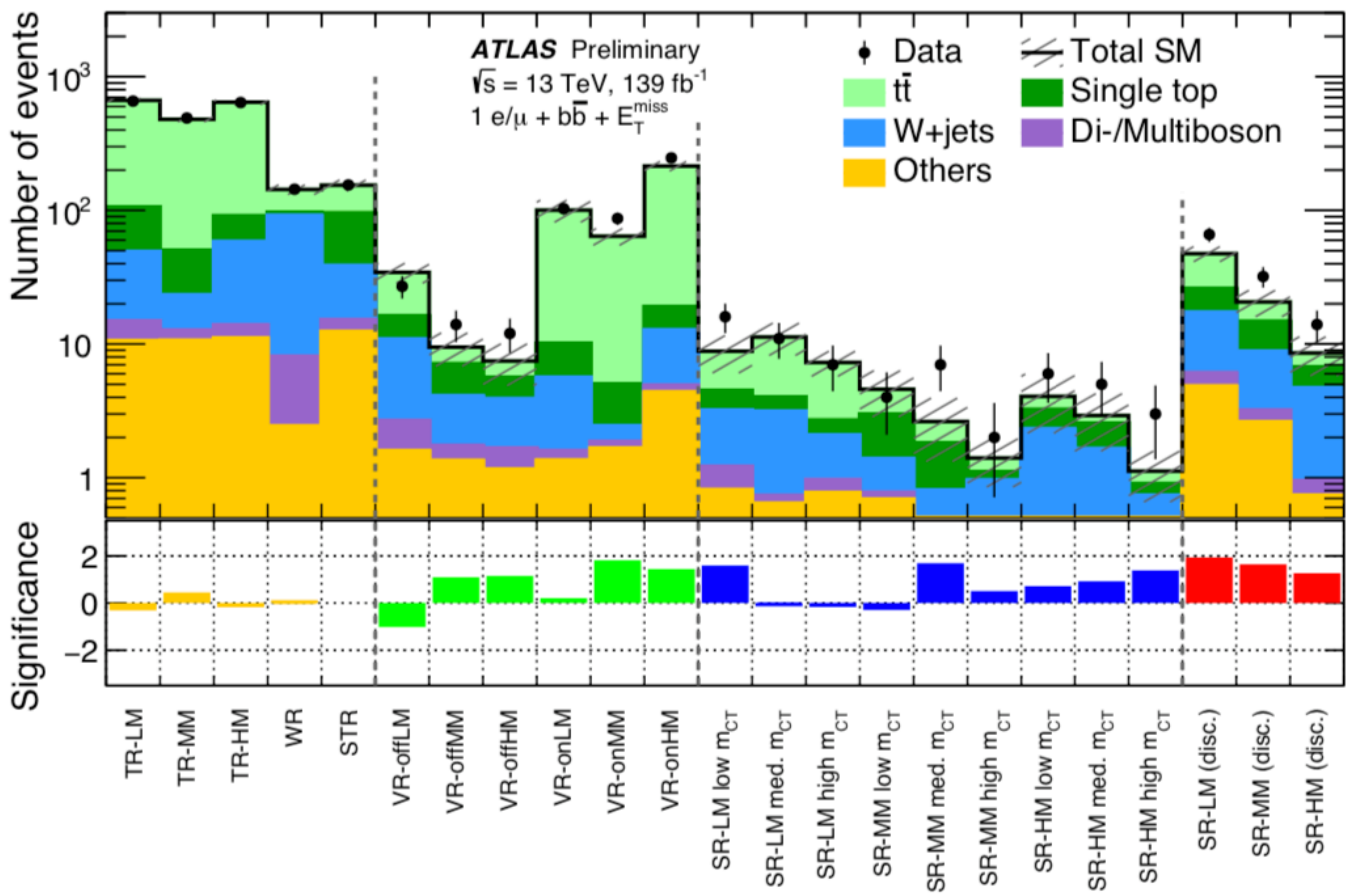
- looks at events with large hadronic activity, MET and no leptons
- cut-based and MVA approaches



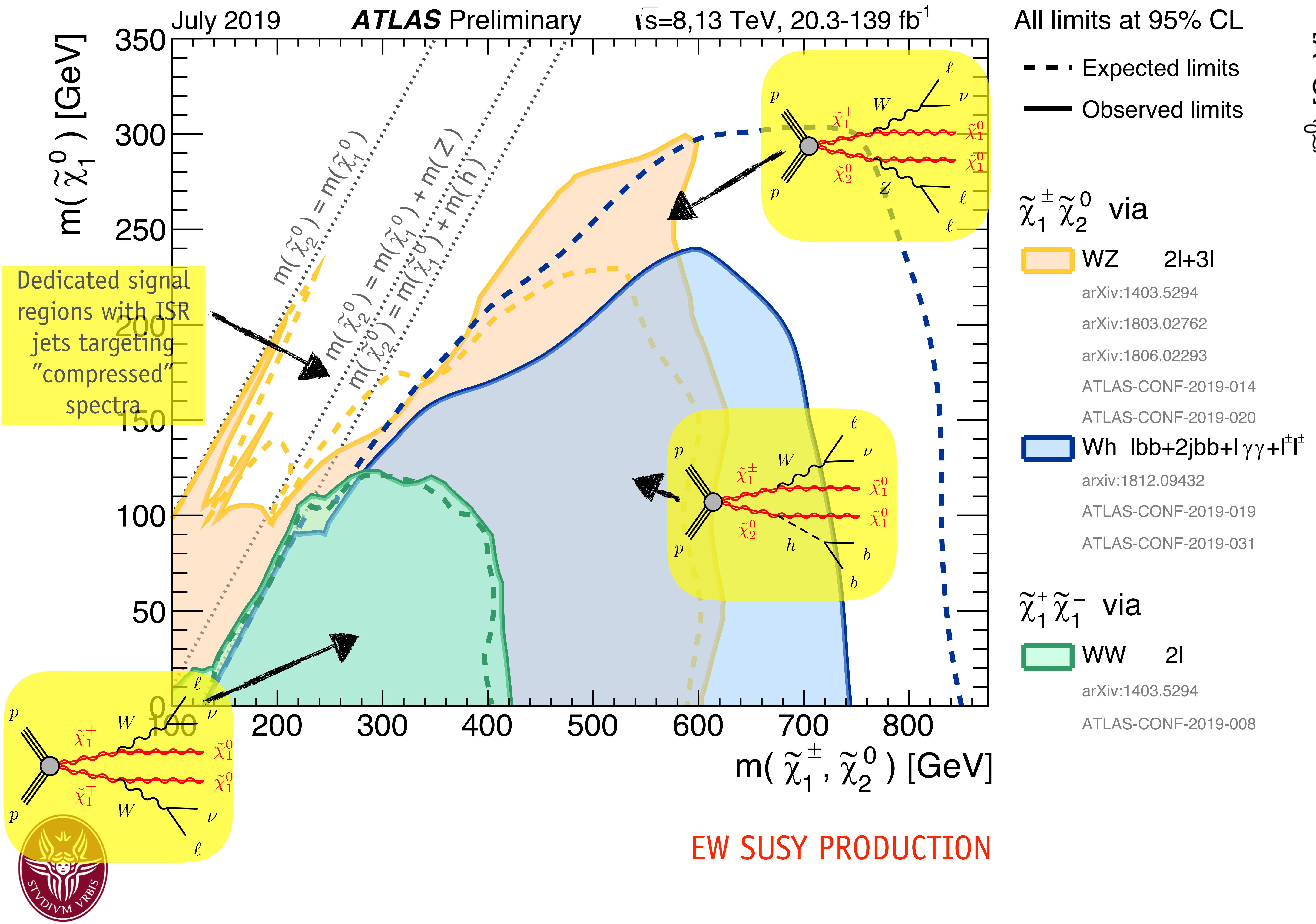
- dominate if squark/gluinos are very heavy
- events with 1 lepton + jets, 2 or more leptons and no jets + MET
- discrimination based on based on stranverse and contransverse masses: M_{T2}, M_{CT}
- dedicated signal regions with ISR jets targeting ”compressed” spectra



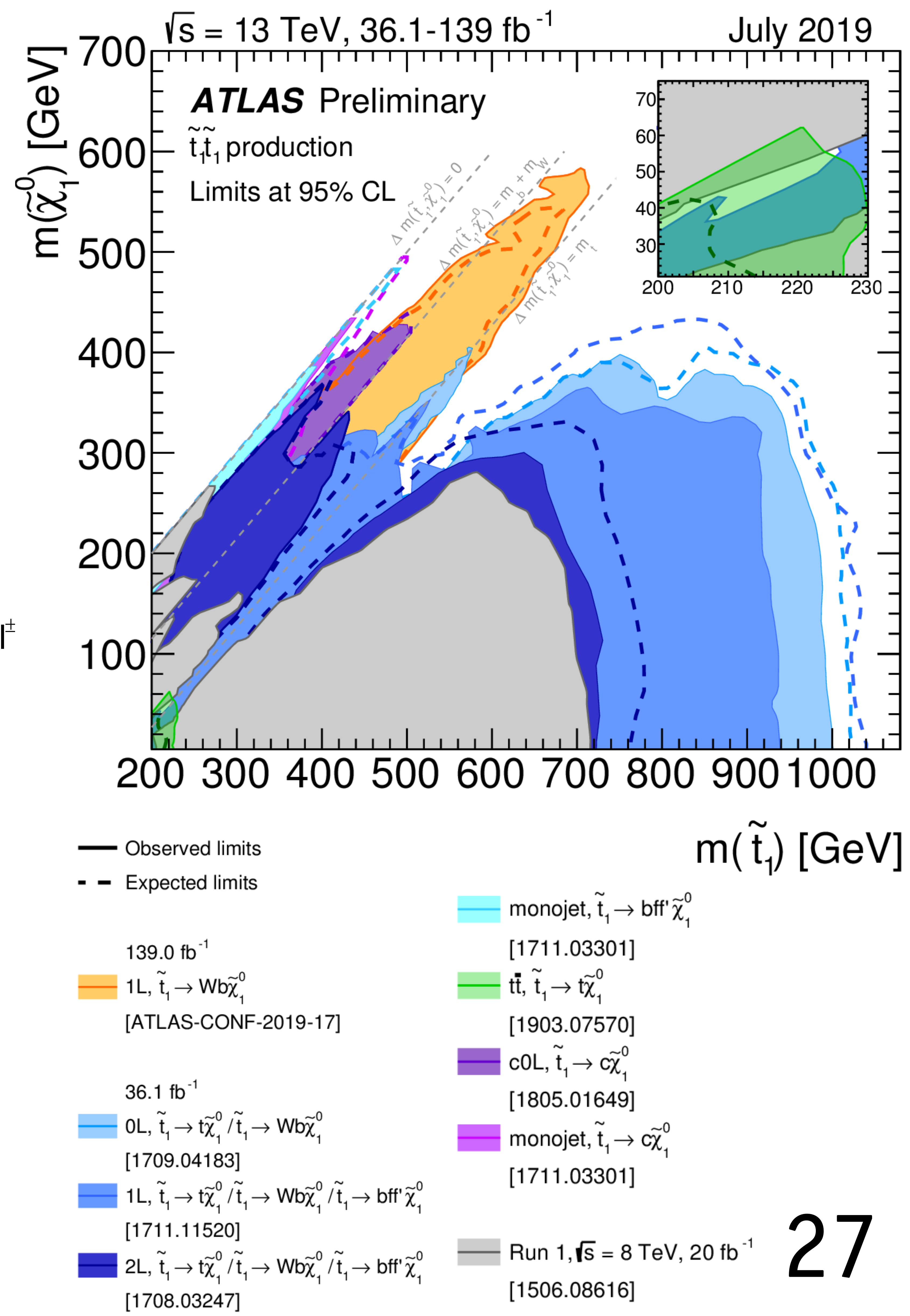




SUSY SEARCHES



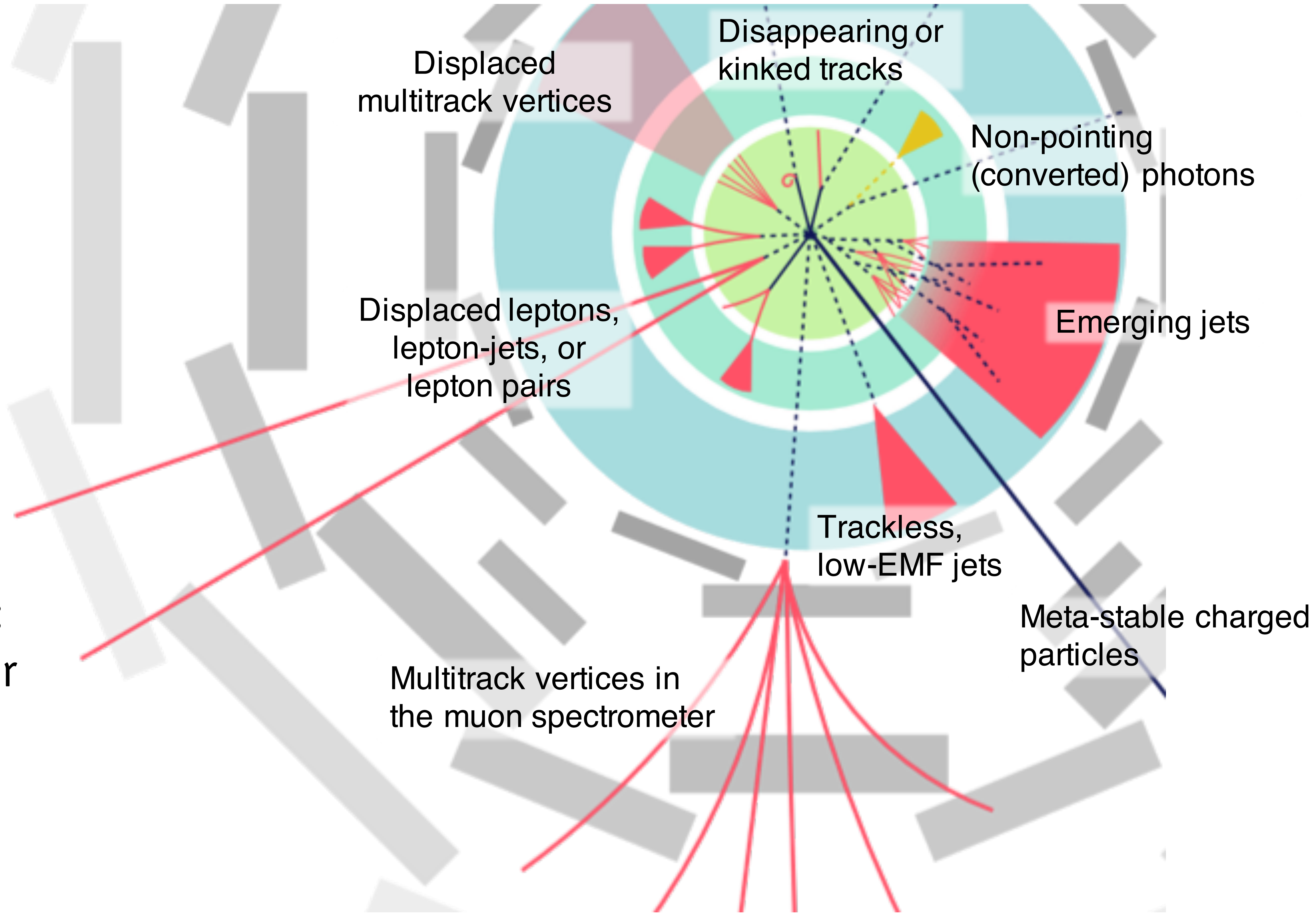
STRONG STOP PRODUCTION



LIGHT DM SEARCHES THROUGH UNCONVENTIONAL SIGNATURES

unconventional signatures expected in many NP models that can provide viable solutions for DM:

- small phase space (ex. mass degeneracy in compressed SUSY models)
- weak couplings, energy barriers, etc. (ex. dark/ hidden sectors)



a diverse set of signatures analysed in ATLAS: most of them requiring special triggers and/or dedicated reconstruction and non-standard analyses …

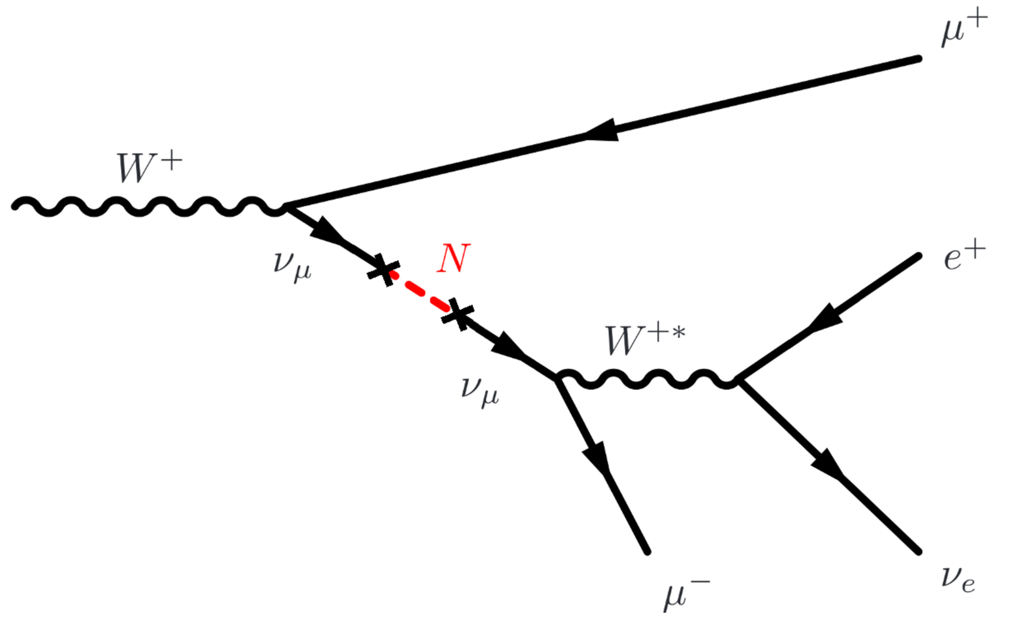
here just two examples of such searches …

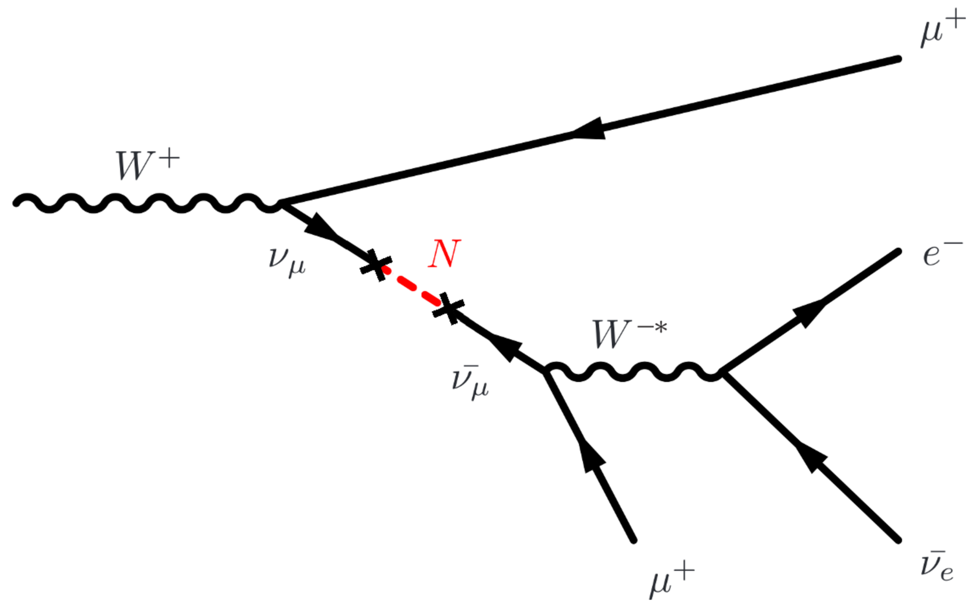
SEARCH FOR LONG-LIVED NEUTRAL PARTICLES

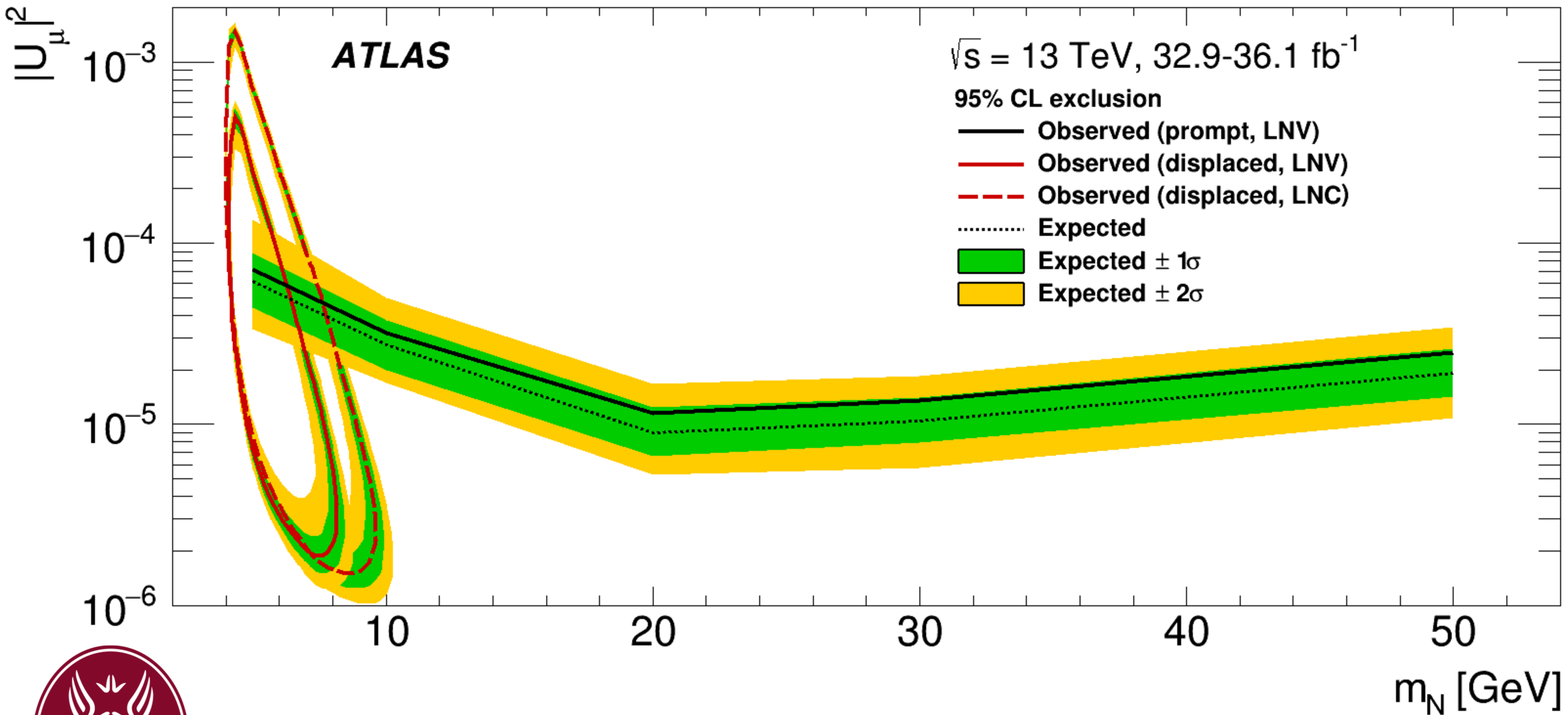
HEAVY NEUTRAL LEPTONS

right-handed Majorana neutrinos give rise to type-I see-saw mechanism and provide DM candidates

- looks for lepton number conserved / violated decays with prompt / displaced leptons

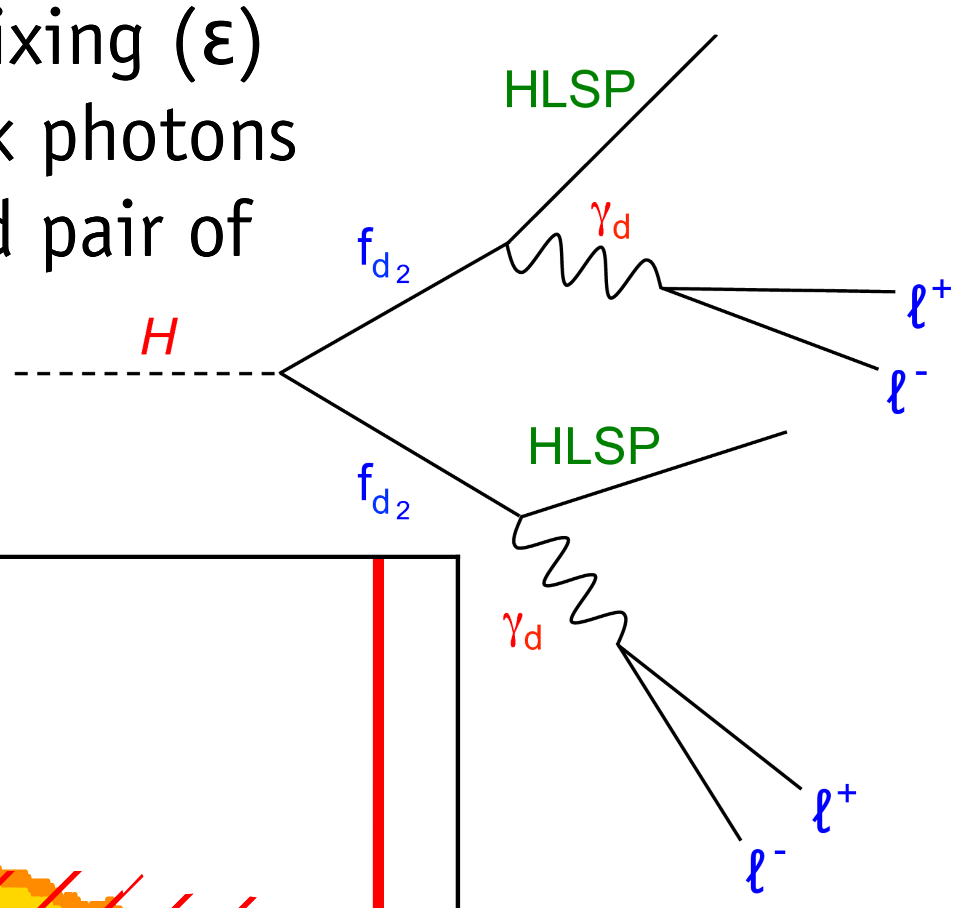


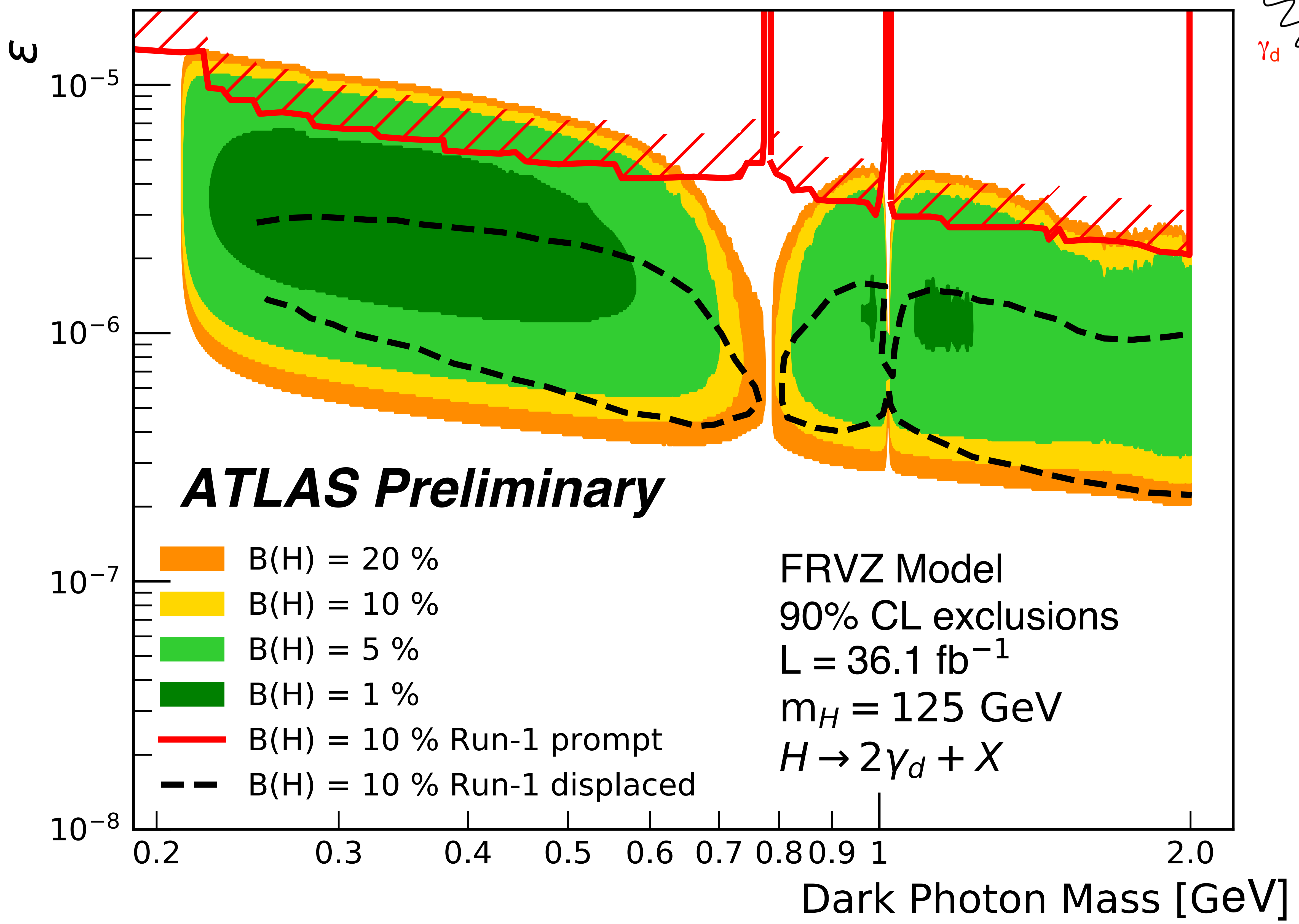




LIGHT DARK PHOTONS

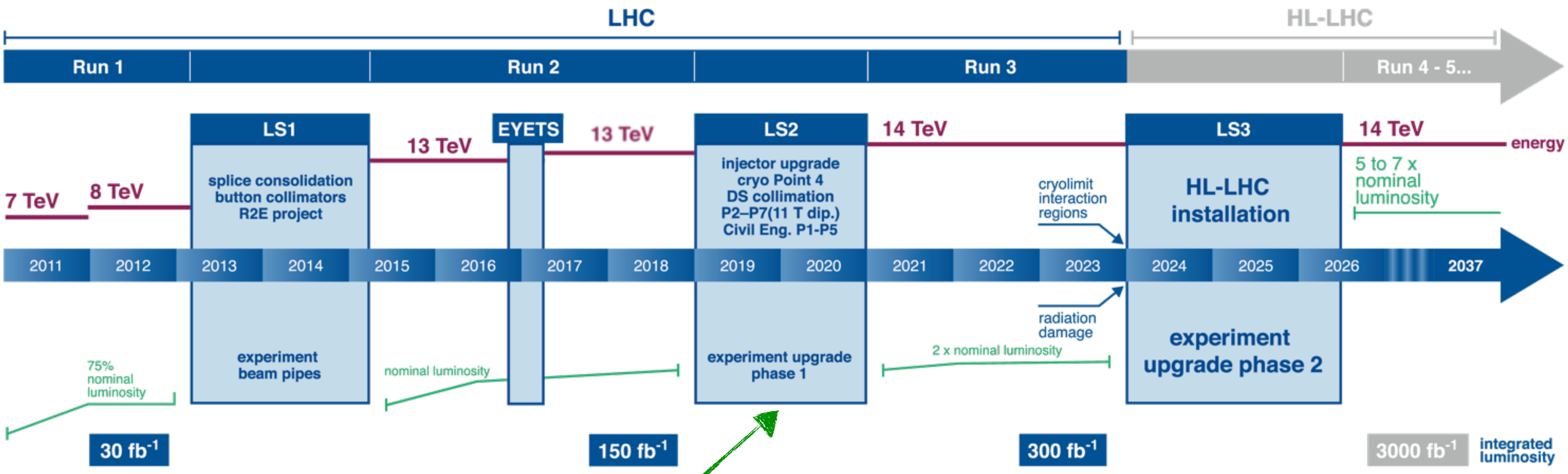
- expected in many extensions of the SM with hidden sectors
- connection to the hidden sector through kinetic mixing (ε)
- SM-dark-sector strength determines lifetime of dark photons
- predict low mass dark photons decays to collimated pair of electrons/muons/hadrons





arXiv:1905.09787 [hep-ex]; ATLAS-EXOT-2017-28

PROSPECTS



NEXT STEPS:

NOW: LS2 PHASE → COMPLETE PHASE I UPGRADES

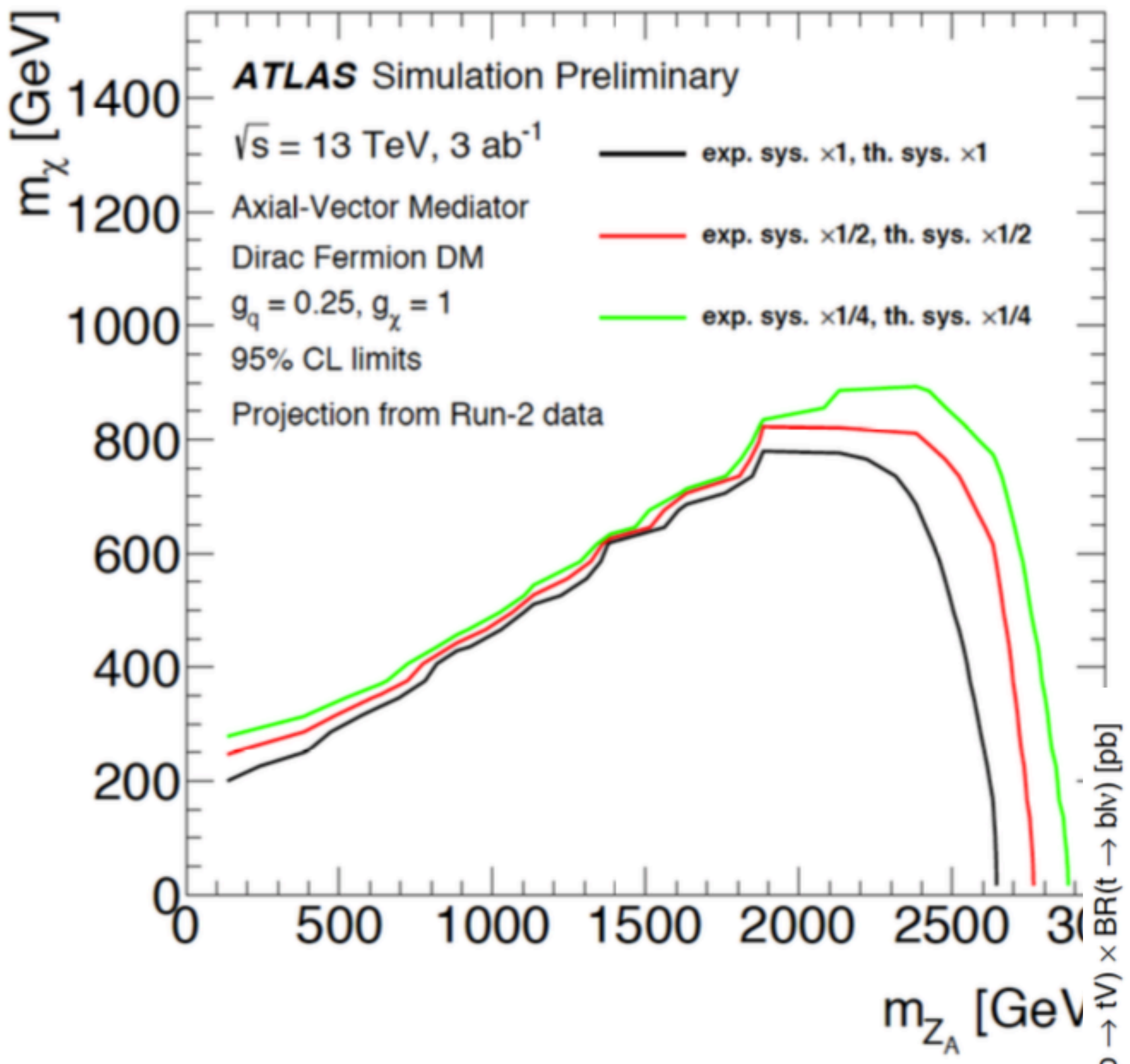
~2021: RUN 3 → EXPECTED ~300 FB^{-1} @ 14 TEV

~2024: LS3 PHASE → INSTALL PHASE II UPGRADES

~2027: RUN 4 (HL-LHC) → x10 DATA STATISTICS OF PHASE I

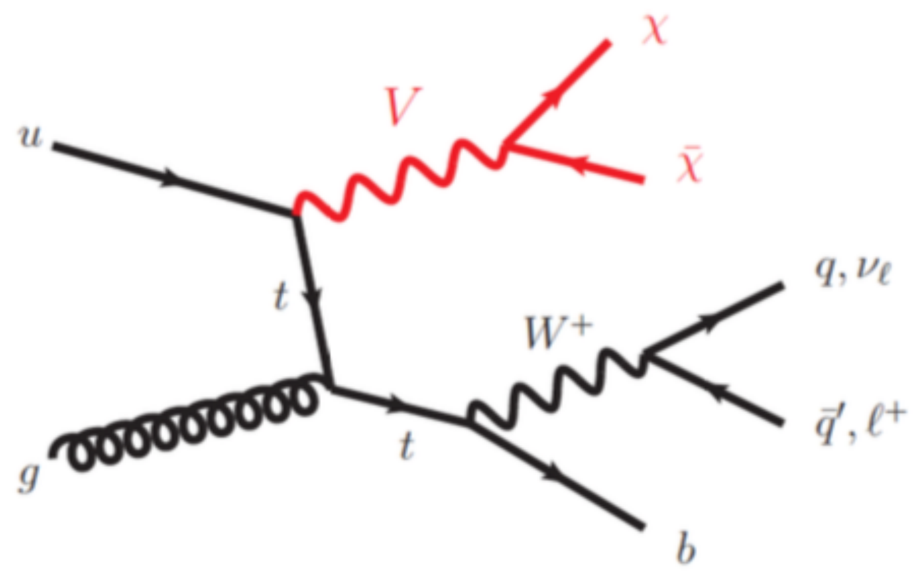
DIRECT DM SEARCHES

MONO JET

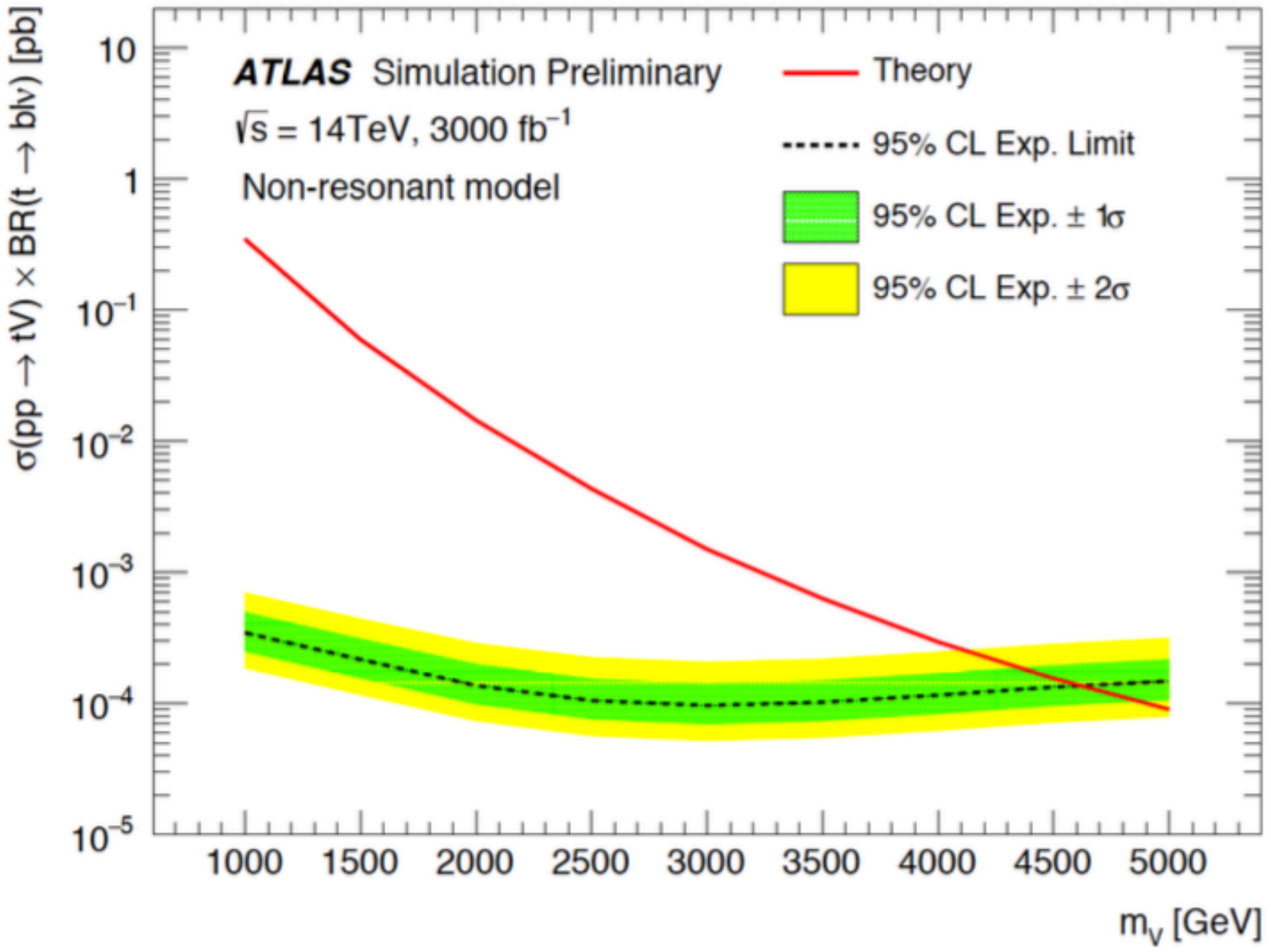


axial-vector mediator probed up to 2.7 TeV

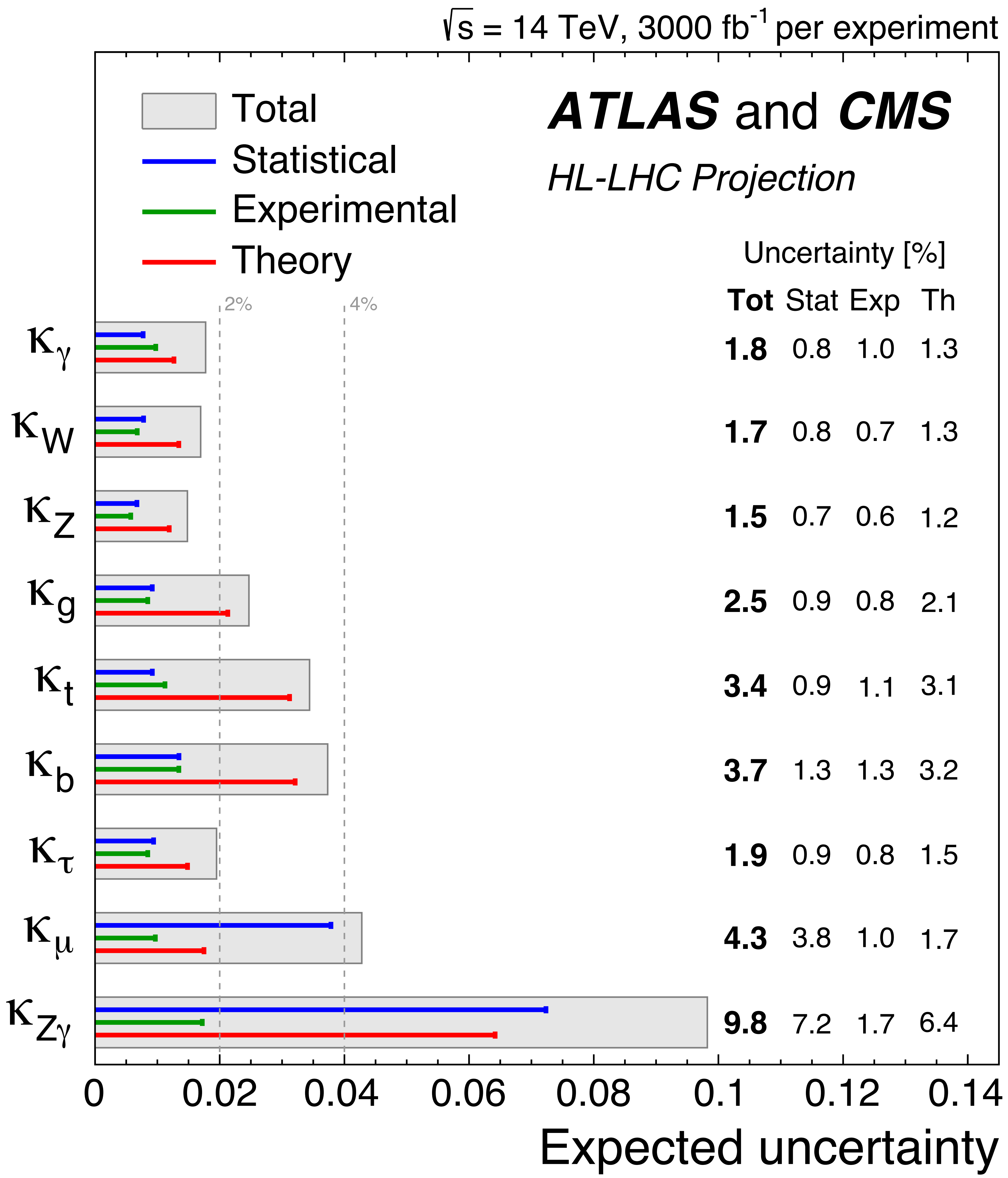
MONO-TOP



vector mediator up to 4.5 TeV



HIGGS COUPLINGS



HL-LHC: is a Higgs factory for precision Higgs coupling measurements

ATL-PHYS-PUB-2018-043
ATL-PHYS-PUB-2018-024

OUTLOOK

- An impressive set of precision measurements and searches for new physics effects from ATLAS in Run 2
  - analysis of the full dataset in full swing with already many results based on 2018 data
  - expand the exploration of possible physics BSM and our knowledge of nature of fundamental interactions

- No evidence of Dark Matter from multiple searches up to now, but ...
  - powerful constraints set on a variety of different benchmarks
  - extension to searches beyond WIMP simplified models (less simplified and complete models, dark sectors, ...)
  - Run 2 data still under analysis and much more to come in Run 3 and HL-LHC (300, 3000 fb^{-1}), with many regions still unexplored and substantial space available for surprises & discoveries!

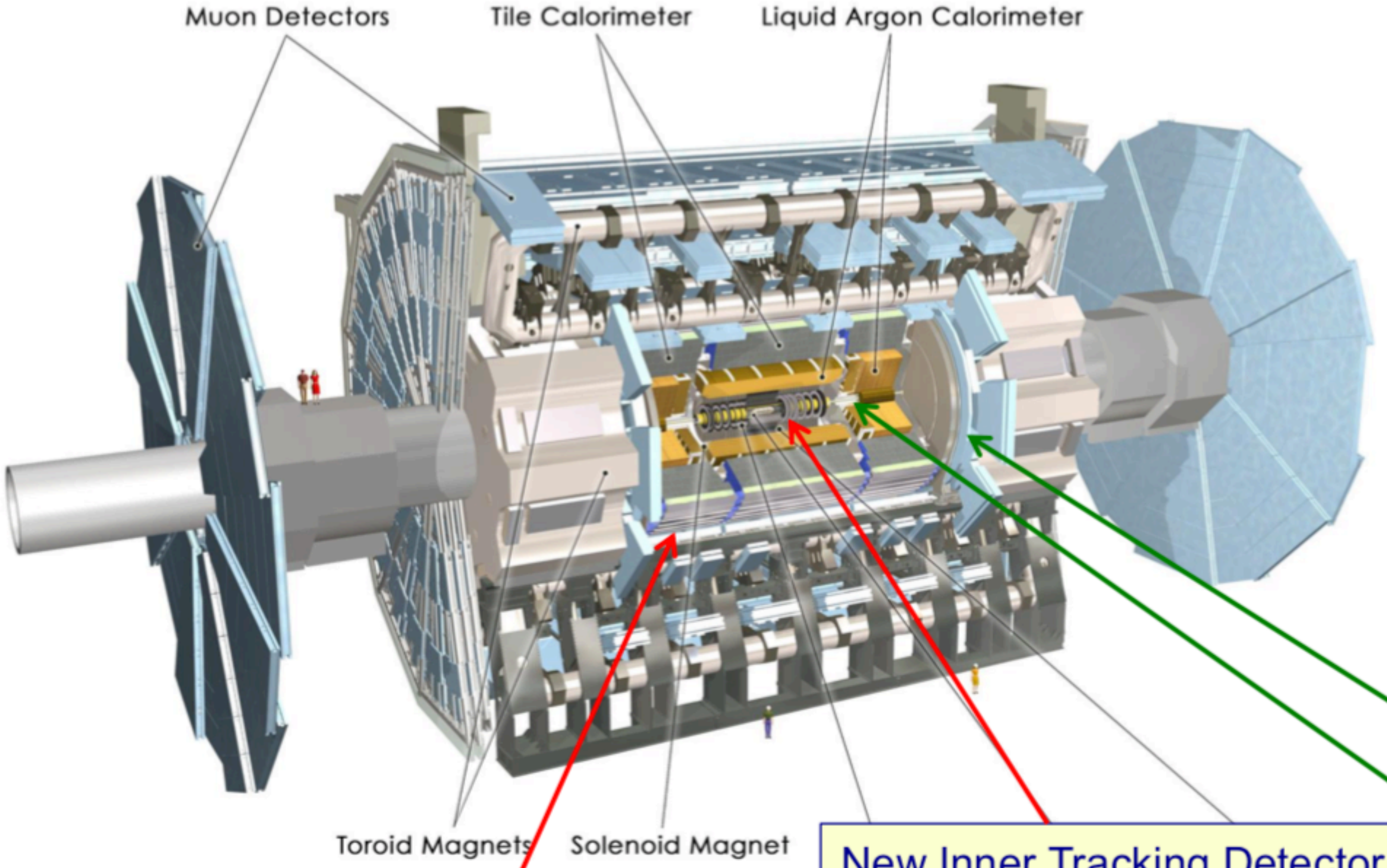
ADDITIONAL MATERIAL

ATLAS UPGRADES

PHASE II (HL-LHC) UPGRADE

PHASE I (RUN 3) UPGRADE

- new LAr calorimeter electronics
  - finer segmentation available @L1
  - improves L1 calo trigger
- new inner end-caps muon system (New Small Wheel)
  - reduce trigger rate from fake muons
  - preserve resolution/efficiency @ HL-LHC
- trigger/DAQ
  - enhanced jet-rejectons/pile-up subtraction
  - improved muons trigger information
  - fast inner detector tracking



Upgraded Trigger and Data Acquisition System:

- L0: 1 MHz
- Improved High-Level Trigger

Electronics Upgrade :

- LAr Calorimeter
- Tile Calorimeter
- Muon system

New Inner Tracking Detector (all silicon tracker, up to $|\eta|$ =4)

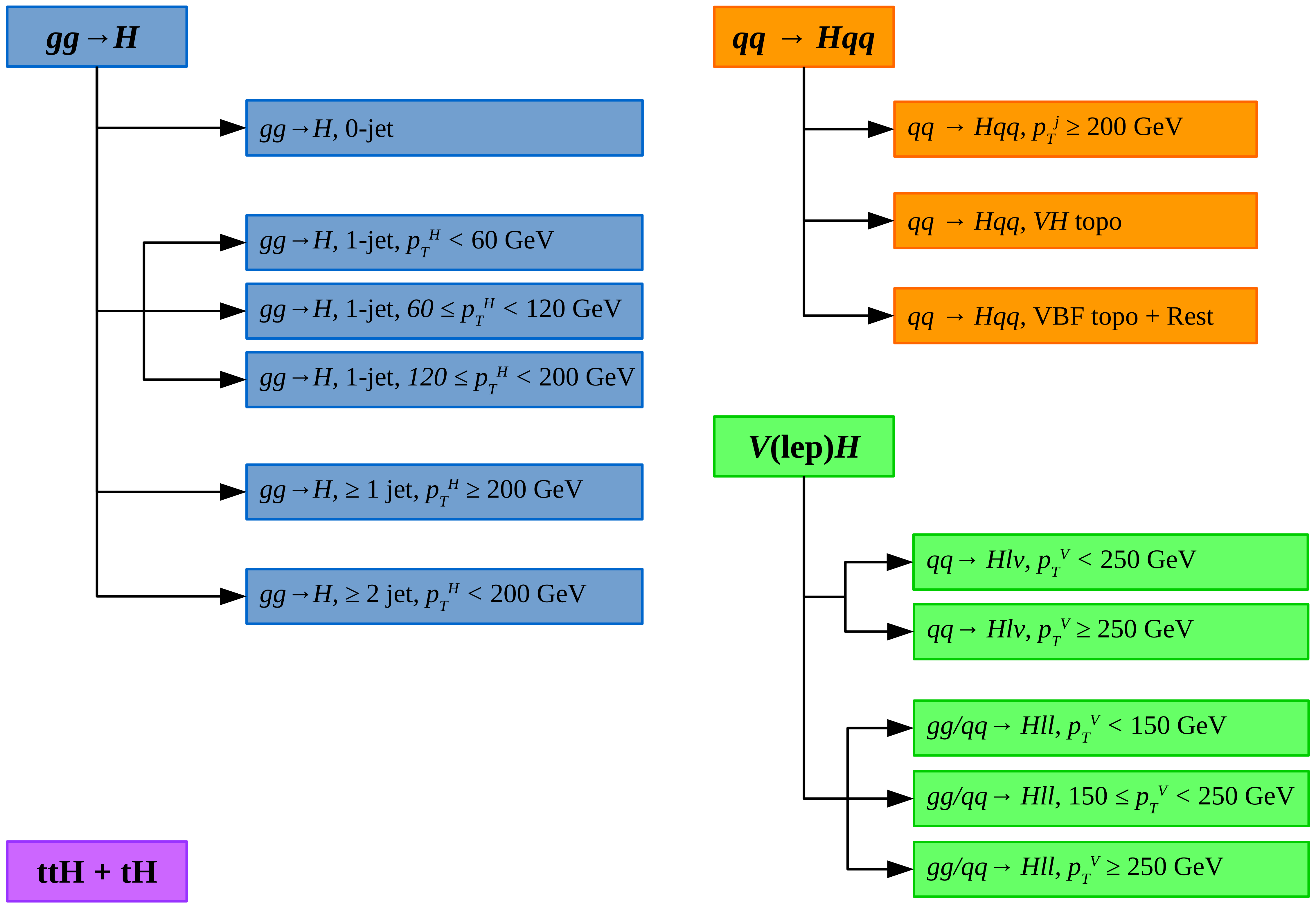
New muon chambers in the inner barrel region

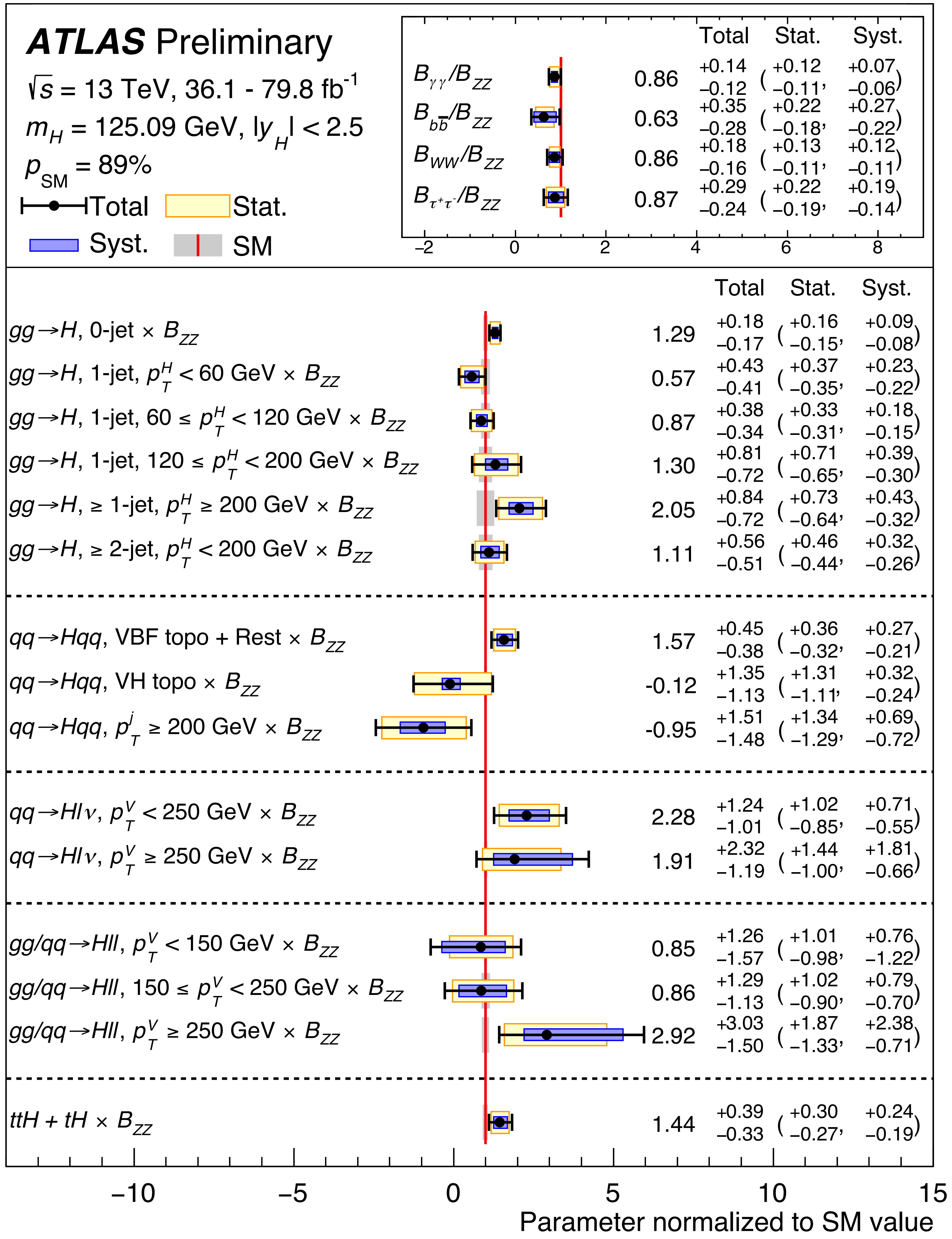
Options:
- High granularity timing detector (forward region)
- High-η muon tagger

COMBINED MEASUREMENT OF SIMPLIFIED TEMPLATE CROSS SECTIONS (STXS)

STXS allow to combine different channels in well defined phase space regions* with reduced theory input

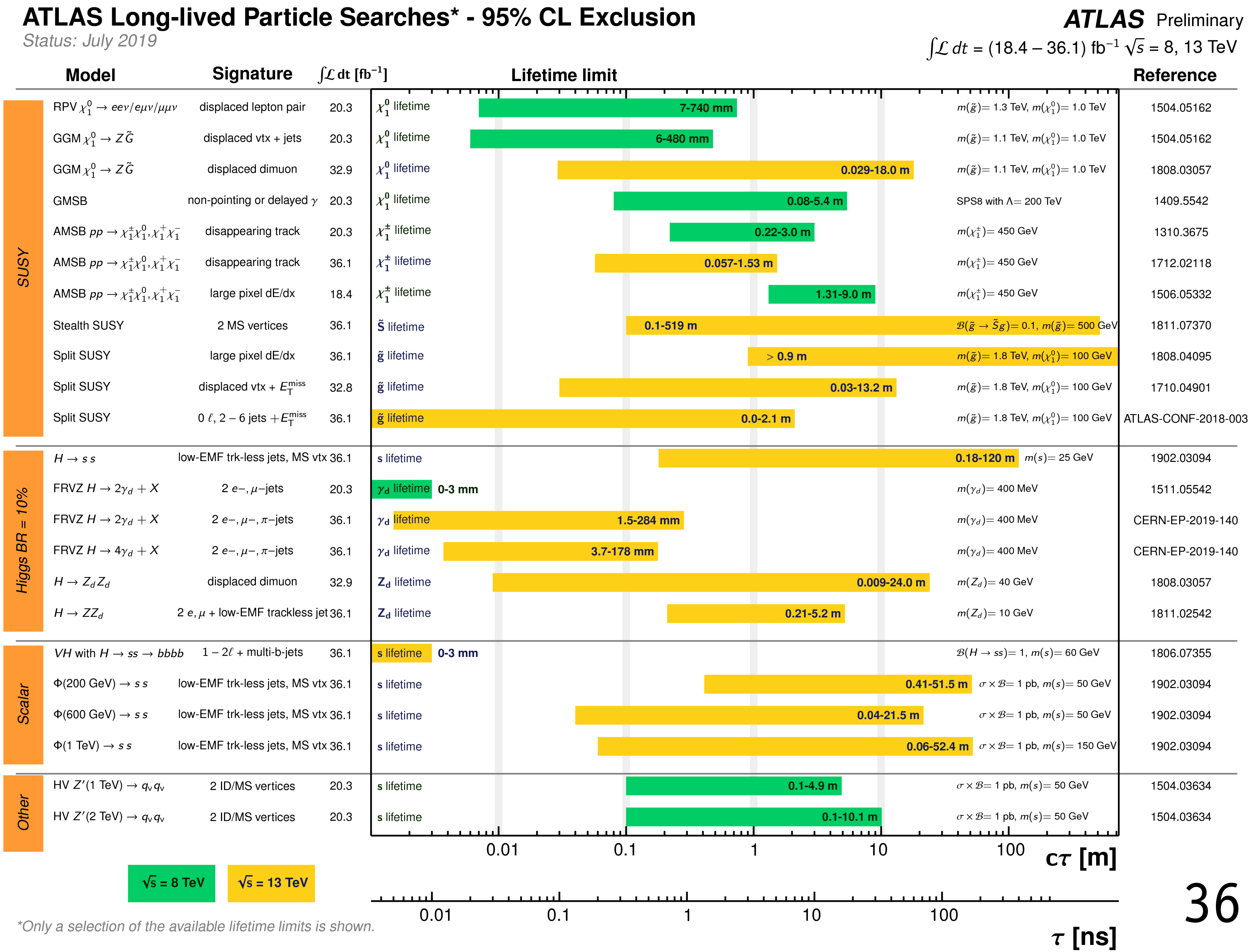
*incl. regions sensitive to new physics (such as high p_T) that might not manifest itself in total cross-section





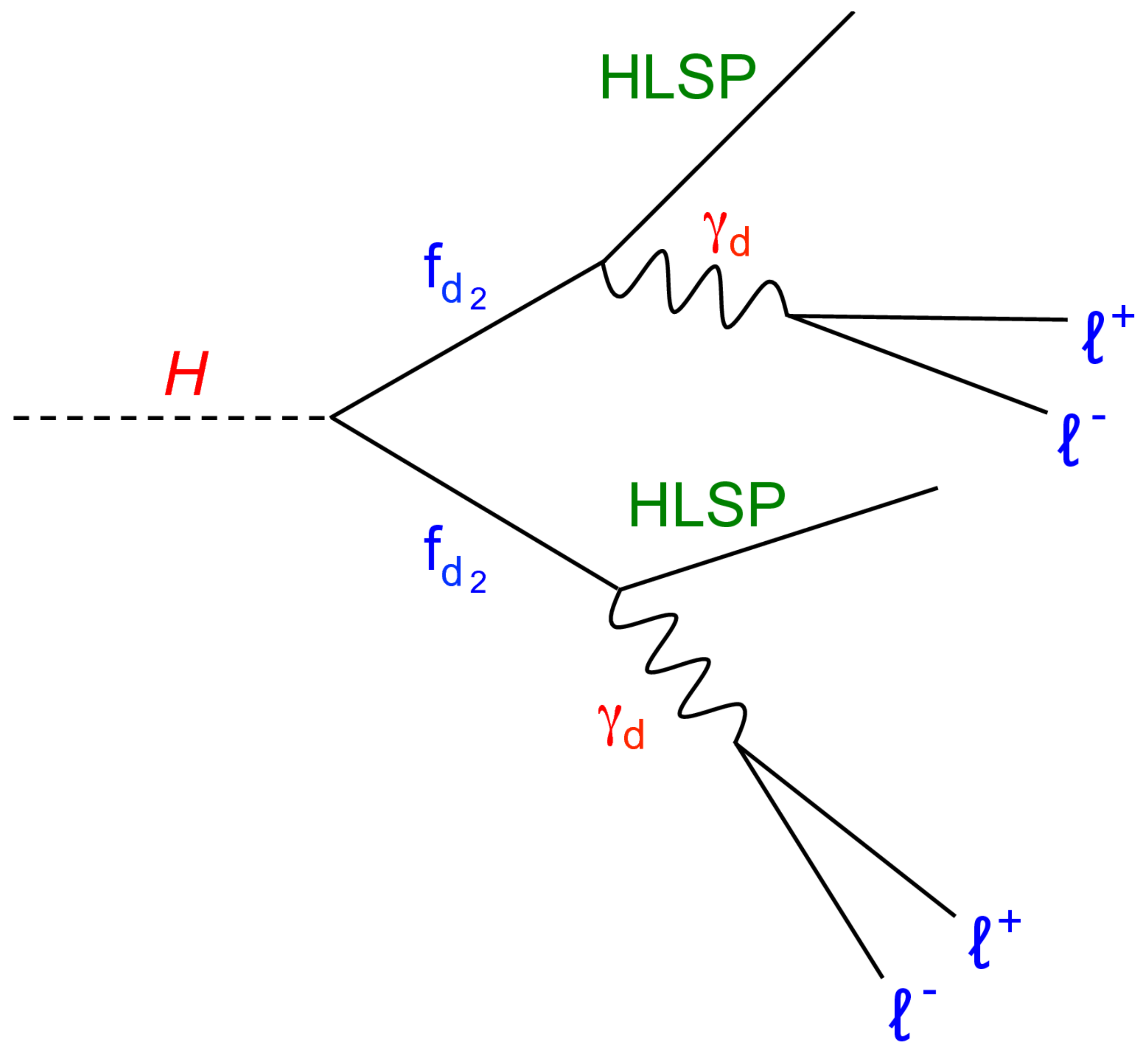
ATLAS LLP SEARCHES SUMMARY

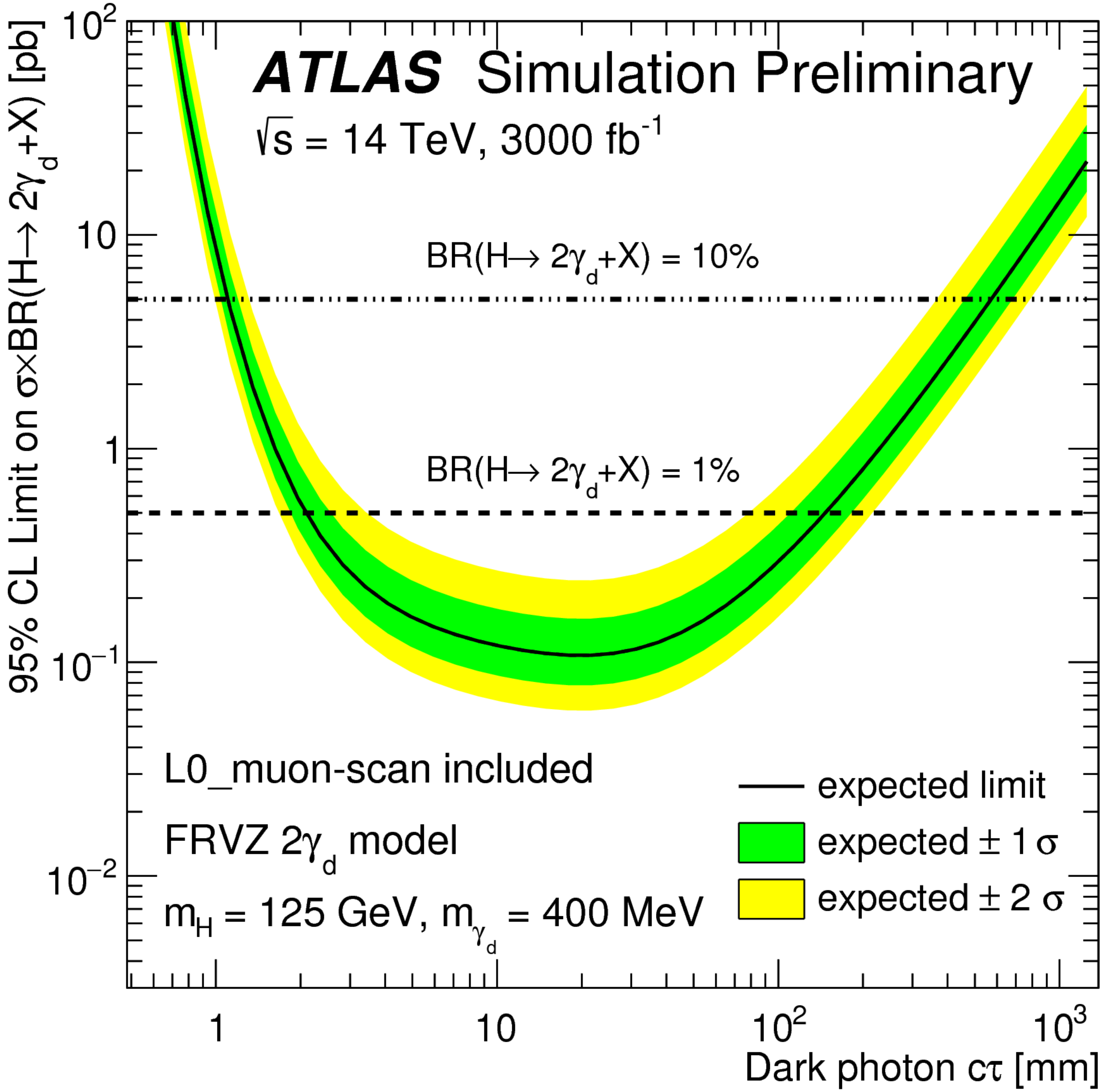
study of LLPs is a new and very promising direction in the interests of the LHC community



DARK-SECTORS PROSPECTS

DISPLACED DARK-PHOTONS

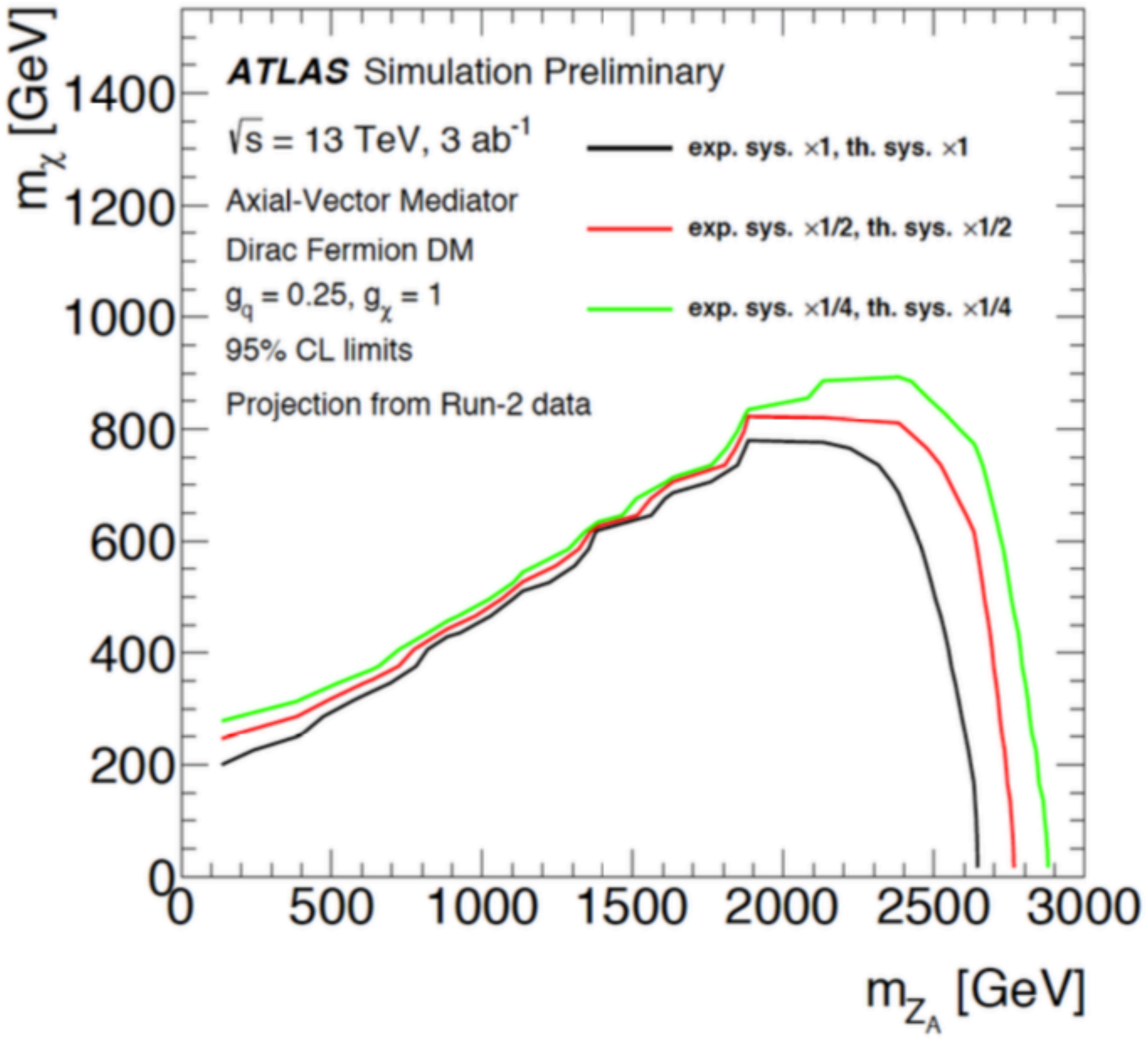




ATL-PHYS-PUB-2019-002

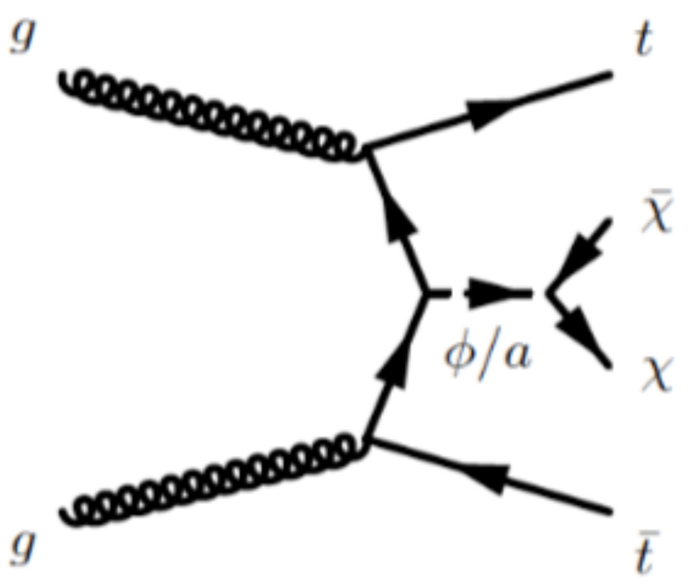
DIRECT DM SEARCHES

MONO JET



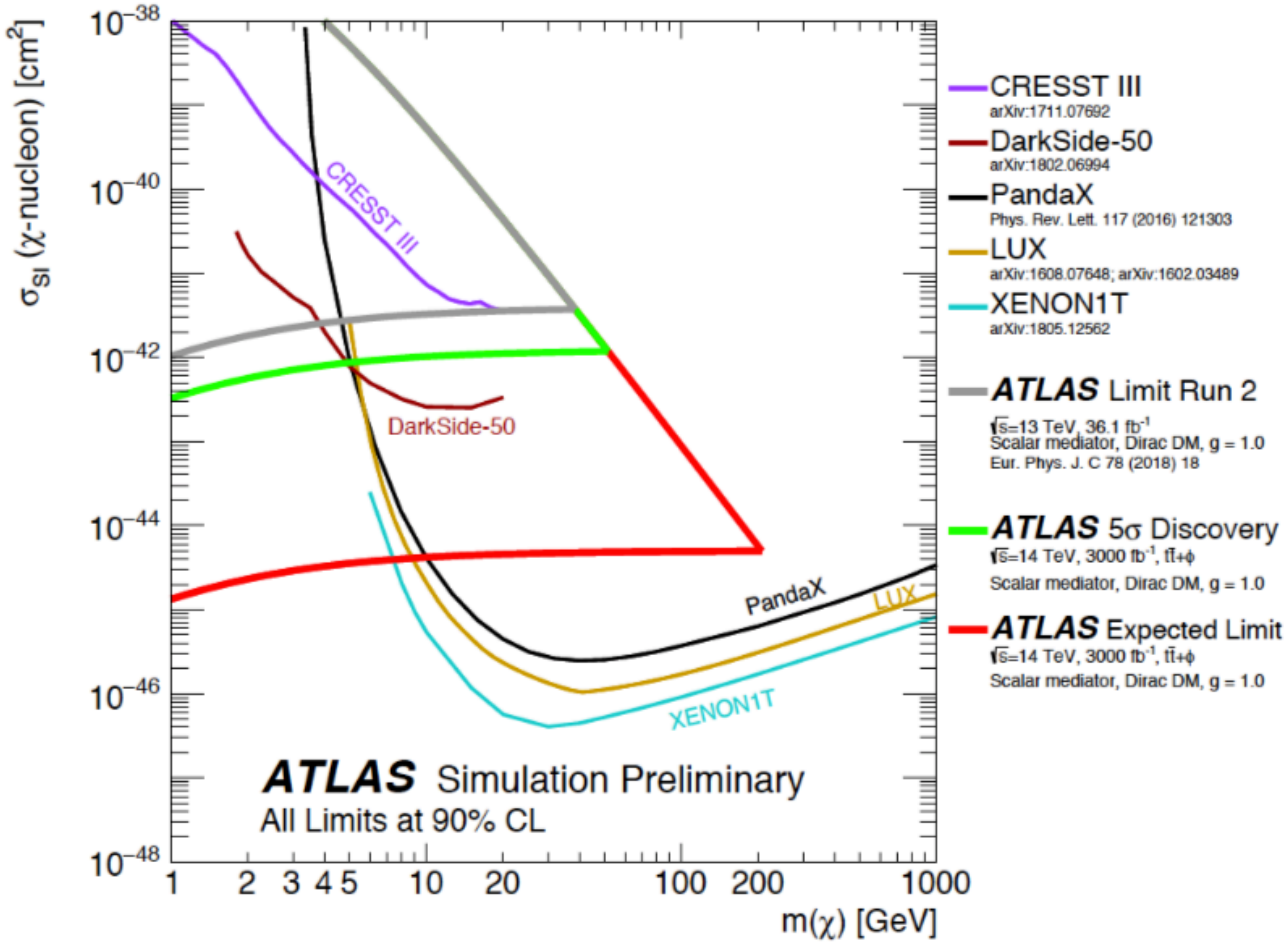
axial-vector mediator probed up to 2.7 TeV

DM + HEAVY QUARKS

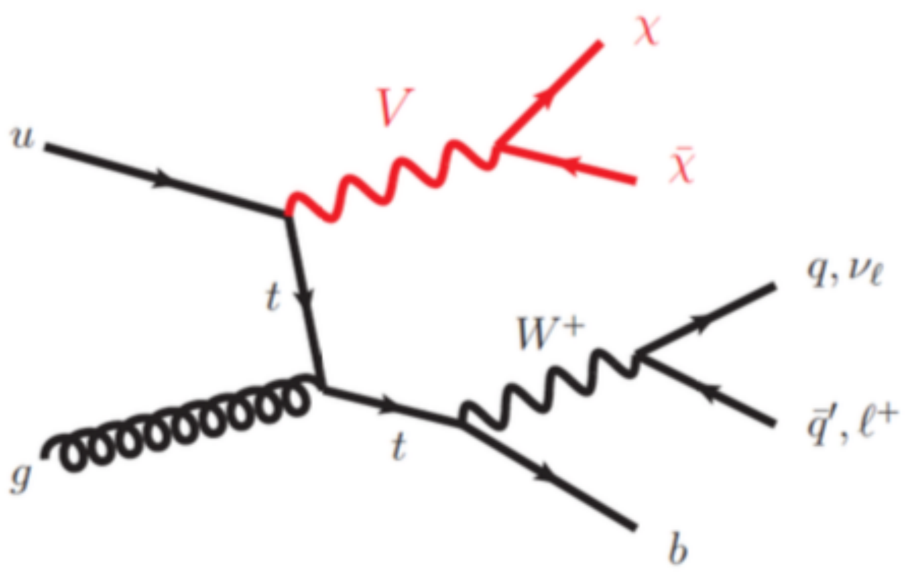


(a) DM+$t\bar{t}$

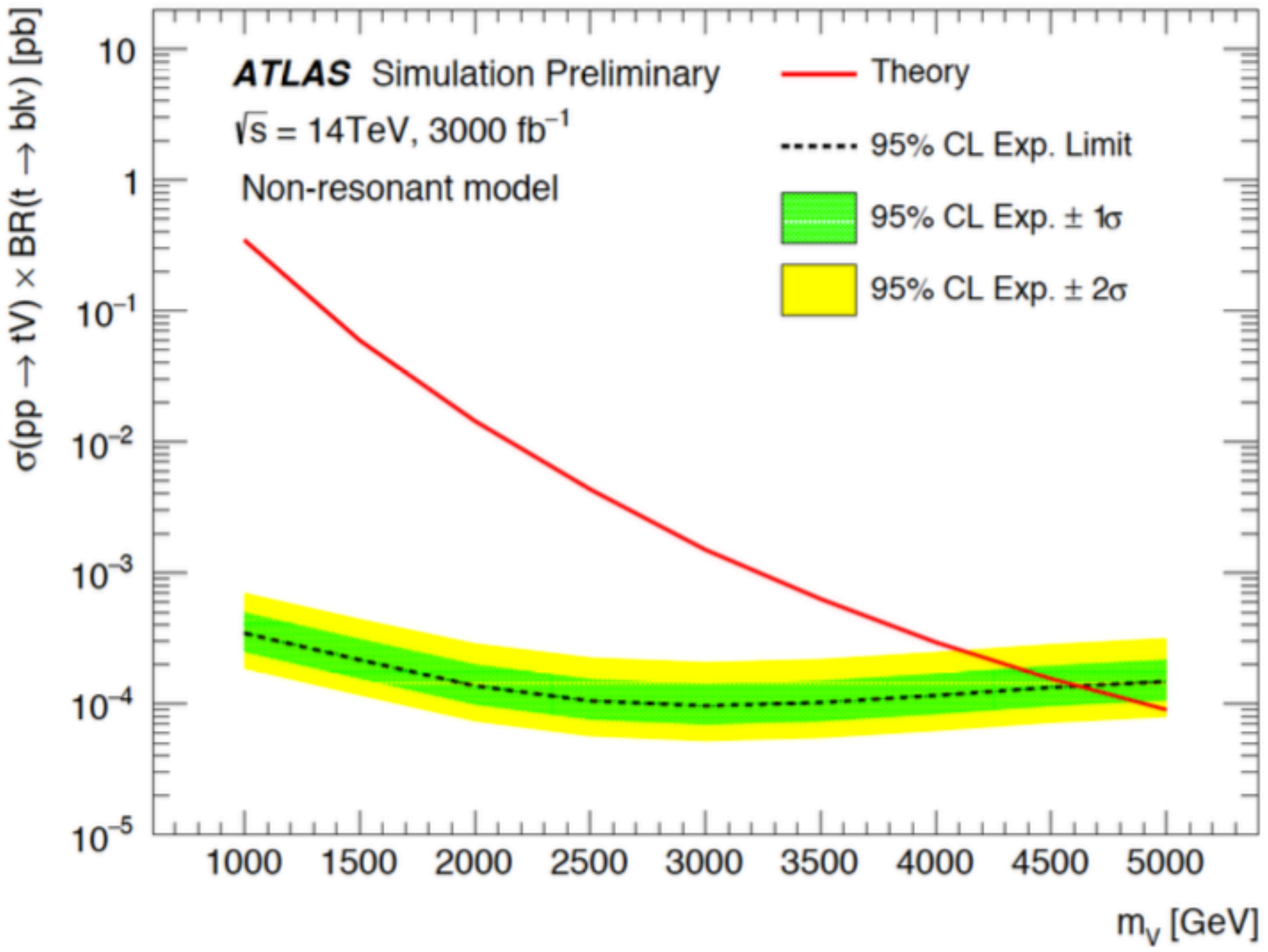
scalar mediator up to ~0.5 TeV



MONO-TOP



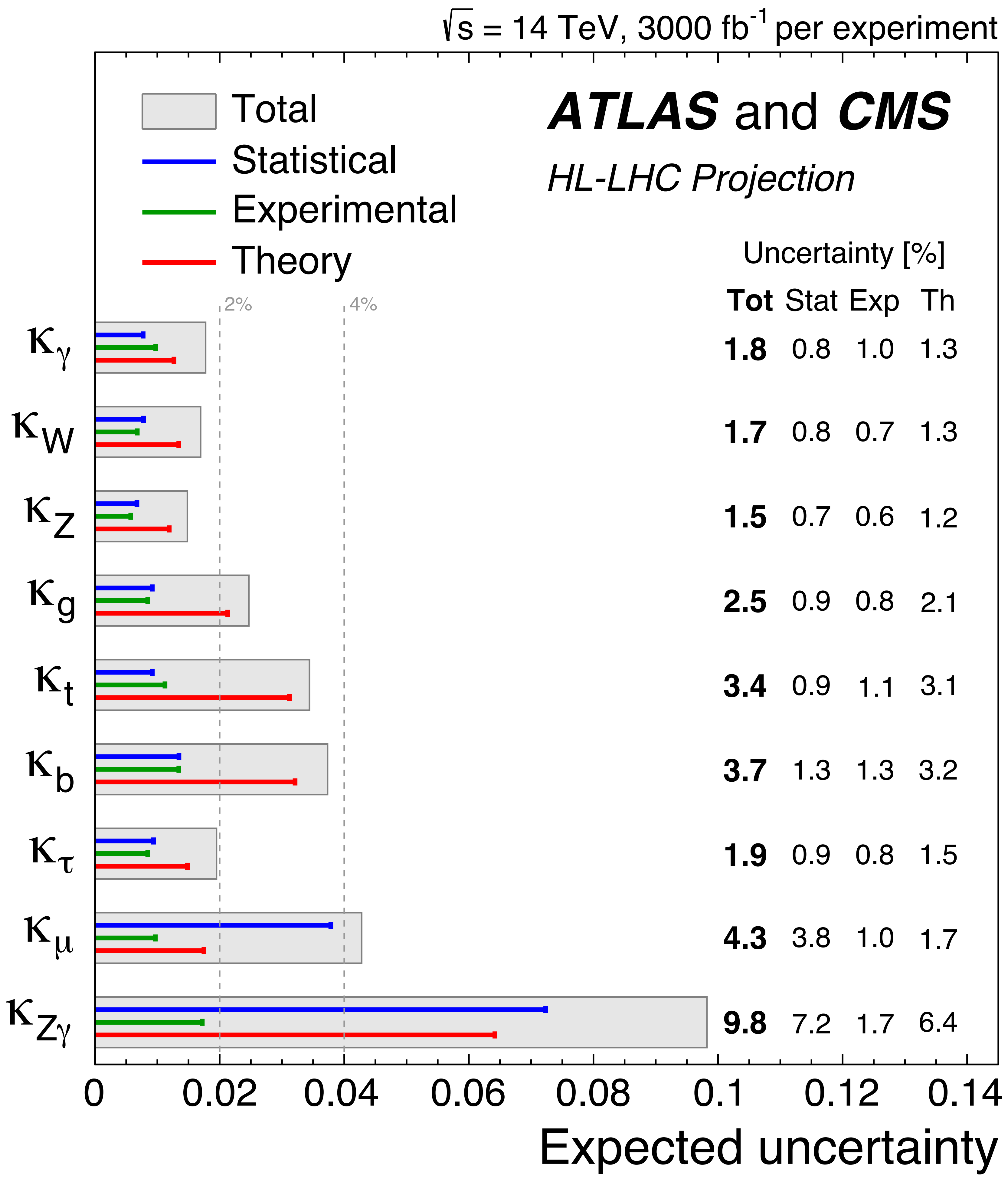
vector mediator up to 4.5 TeV



ATL-PHYS-PUB-2018-043; ATL-PHYS-PUB-2018-038
ATL-PHYS-PUB-2018-036; ATL-PHYS-PUB-2018-024

HIGGS / SUSY PROSPECTS

HIGGS COUPLINGS

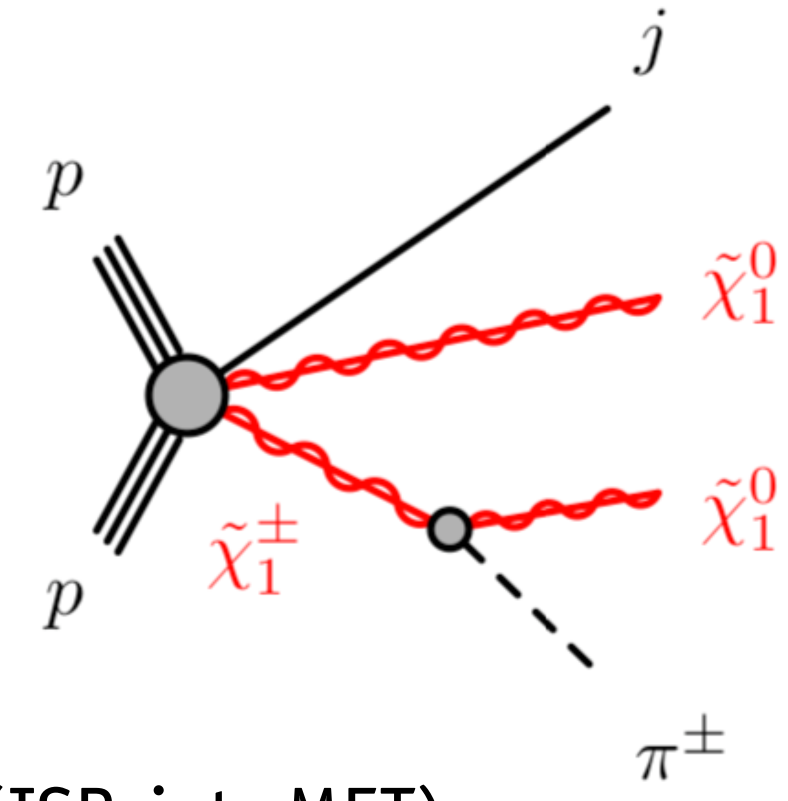


HL-LHC: is a Higgs factory for precision Higgs coupling measurements

DISAPPEARING TRACKS

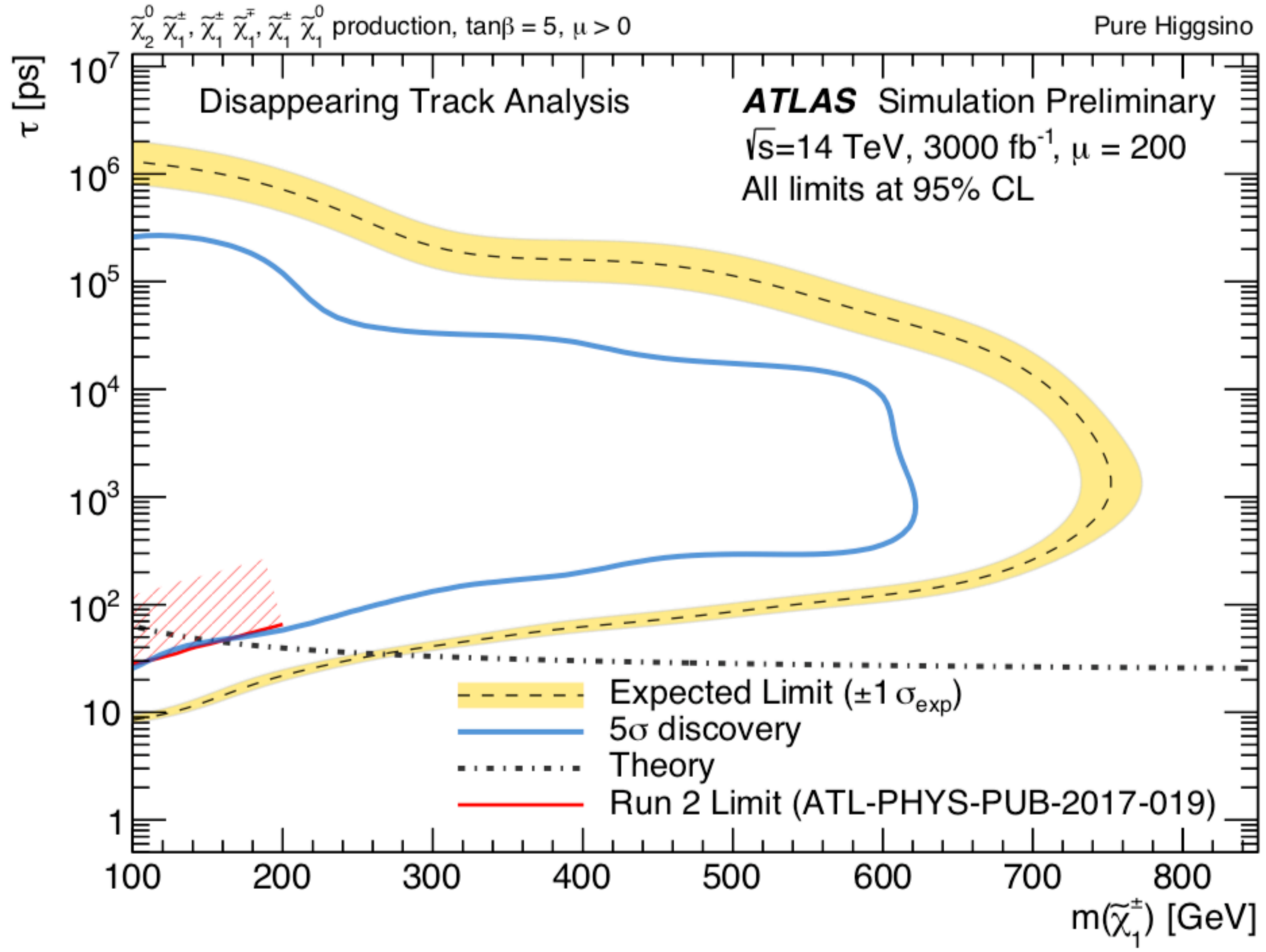
lightest chargino nearly degenerate with lightest neutralino, resulting in long chargino lifetimes)

striking experimental signature:



with charged pion too soft to be reconstructed (~100 MeV) that leads to chargino that "disappear"

- dedicated track reconstruction & triggers (ISR-jet, MET)



ATL-PHYS-PUB-2018-031