Higgs and New Physics at ATLAS and CMS

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Introduction & Outline

- After the discovery of the H(125) particle in 2012 compatible with the Standard Model Higgs boson, ATLAS and CMS have greatly intensified the search program for signs of physics beyond the SM
  - exploiting the increase in energy and data from LHC Run-2
  - engaging the problem from several sides: Higgs precision measurements, search for additional Higgs bosons, direct search for new particles not necessarily related to the Higgs ...
- In this summary talk, selected results on:
  - H(125) properties
  - BSM Higgs searches
  - Other New Physics searches

NOTE: impossible to cover everything here. A full and daily updated list of results from collider experiments, with details on each analysis, available here:

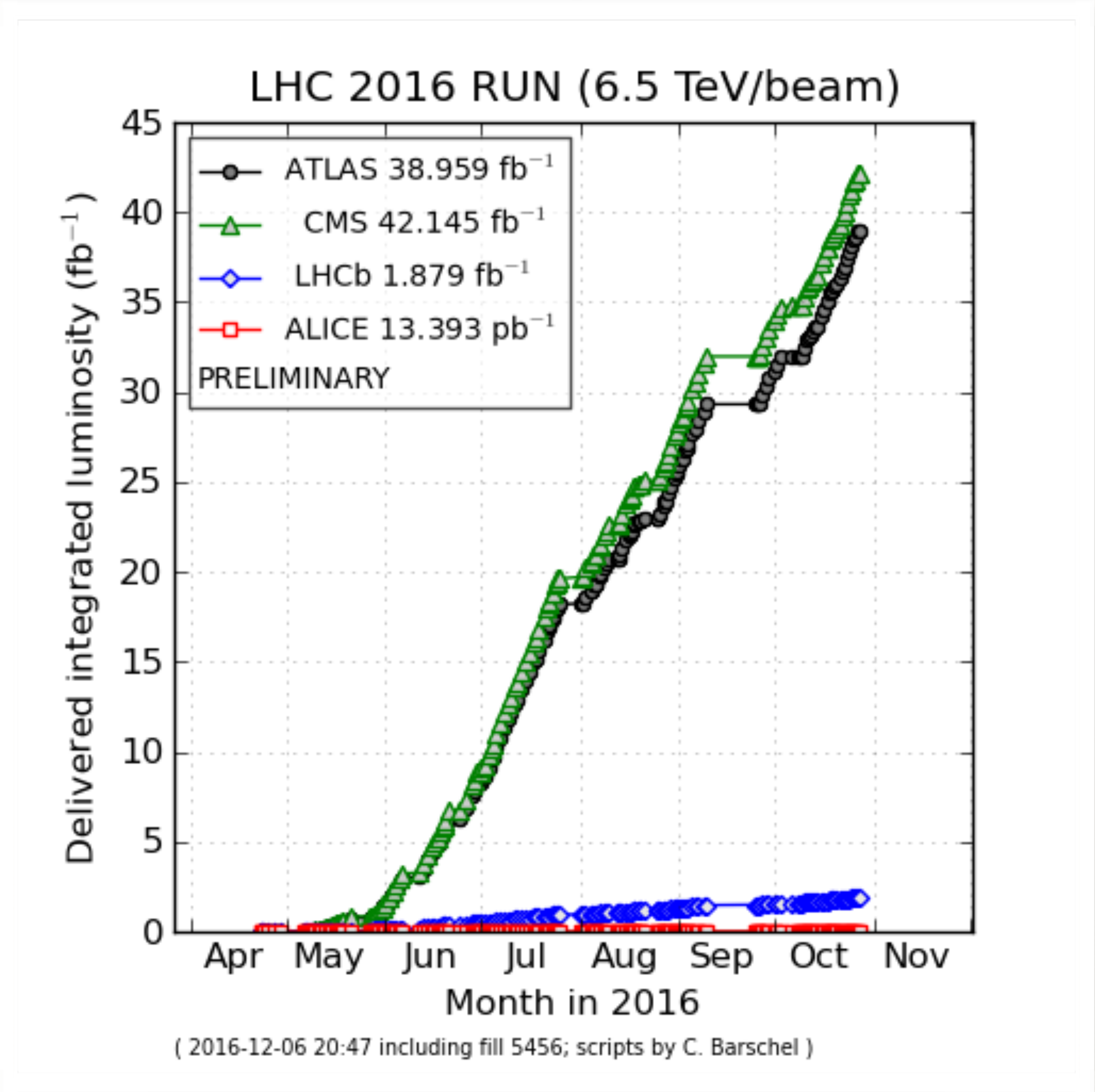
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

http://cms.web.cern.ch/org/cms-papers-and-results

LHC

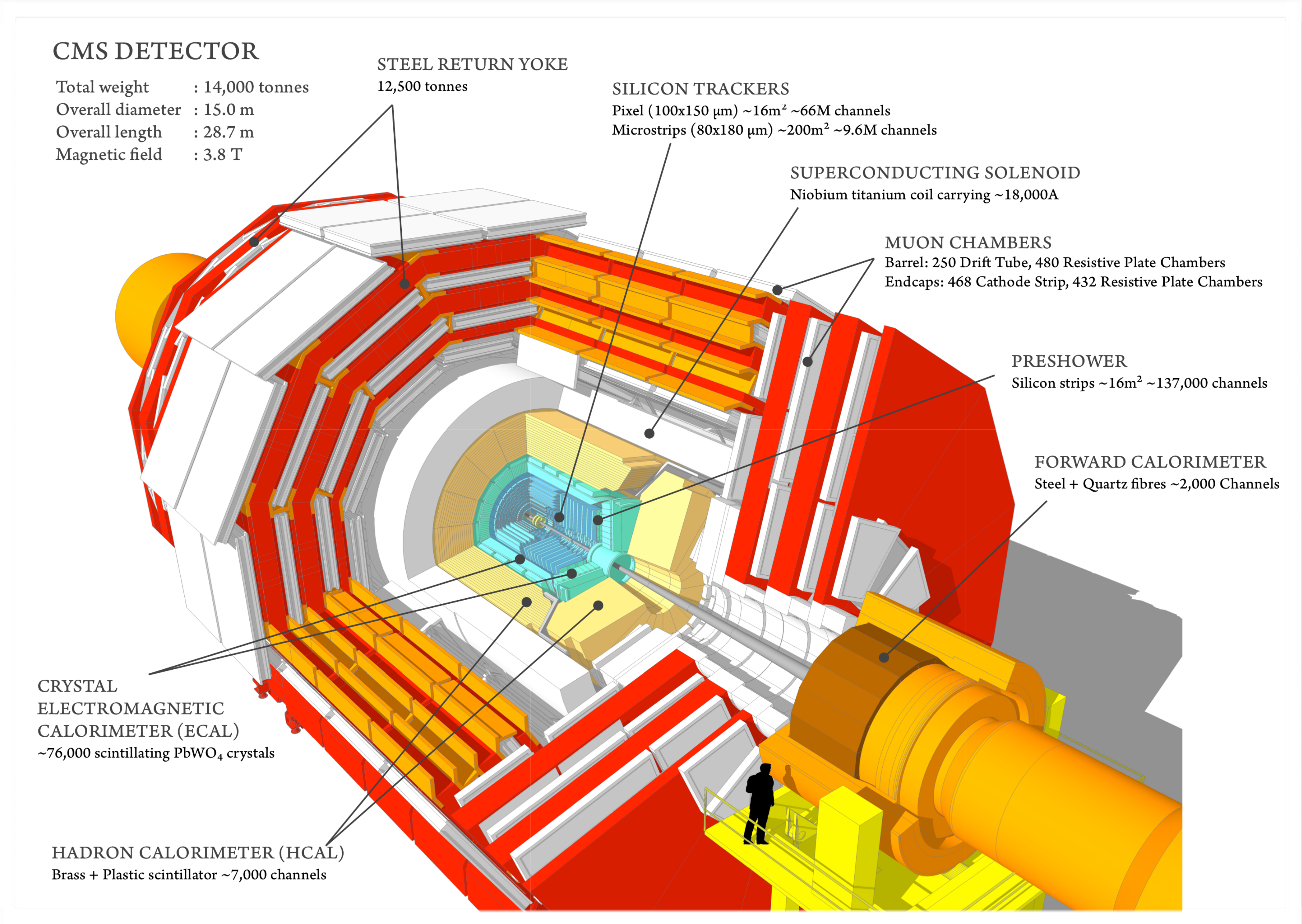
Superlative performance in Run-2:

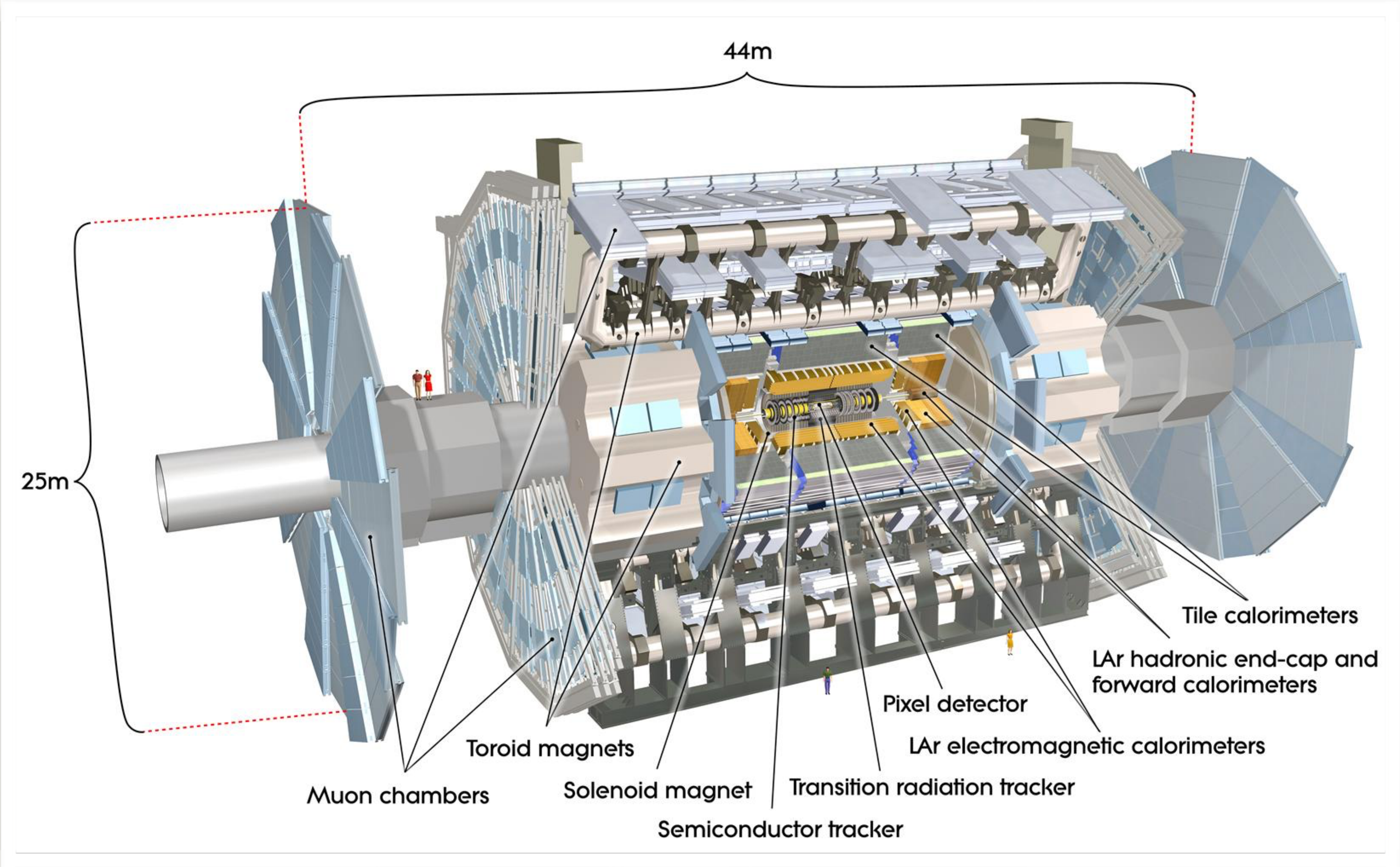
- peak L > 1.4×10^{34} $cm^{-2}s^{-1}$ (exceeds design)
- $\int L \sim 4$ (2015) + 40 (2016) fb^{-1}



Results presented here based on a subset of the total data: ~3-15 fb^{-1}

The Experimental Tools





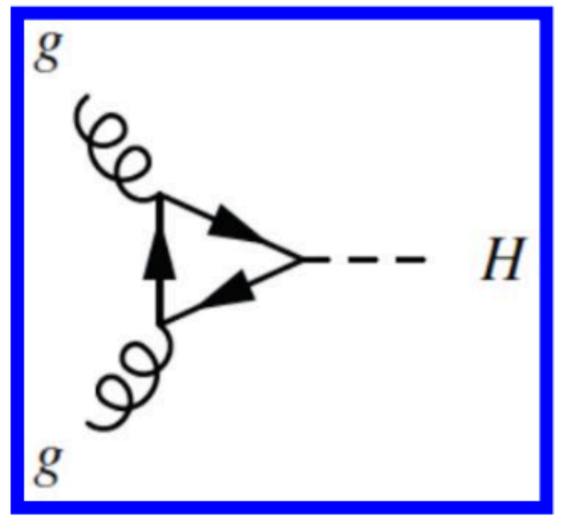
ATLAS and CMS similar in many respects but also with complementary features for particle detection

CMS: excellent reconstruction of secondary vertices in the inner tracker, fast response and excellent energy and time resolution of ECAL

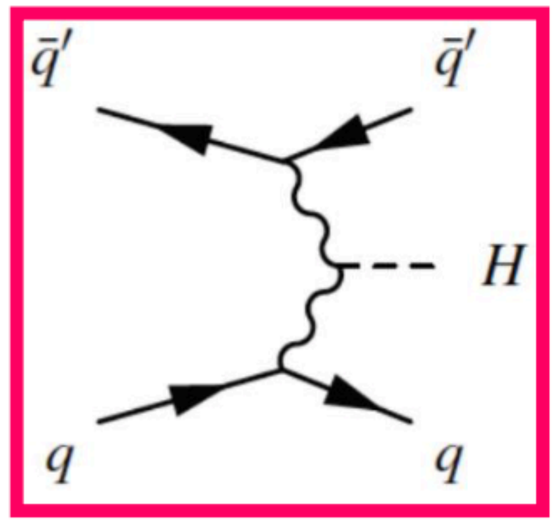
ATLAS: segmented ECAL/HCAL, air core and standalone tracking in a large muon system

Higgs(125) Production & Decays

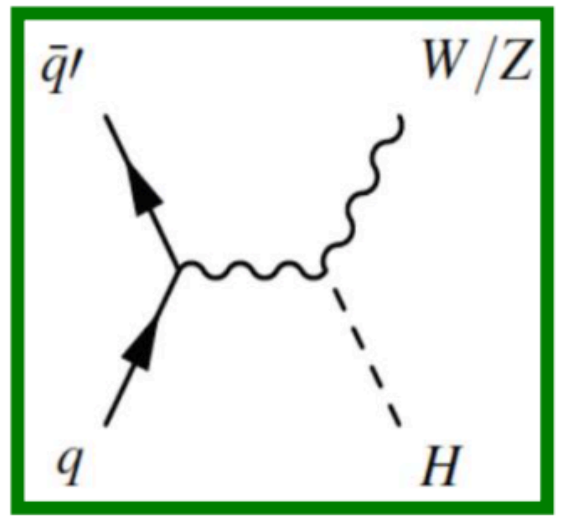
H(125) Production



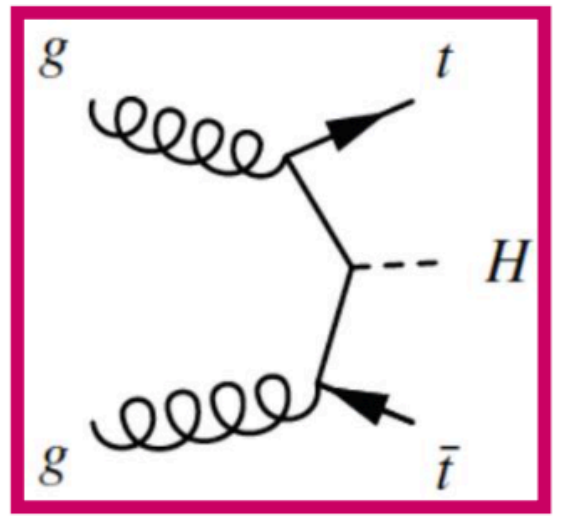
Gluon-Gluon Fusion
87.4%



Vector Boson Fusion
7.1%

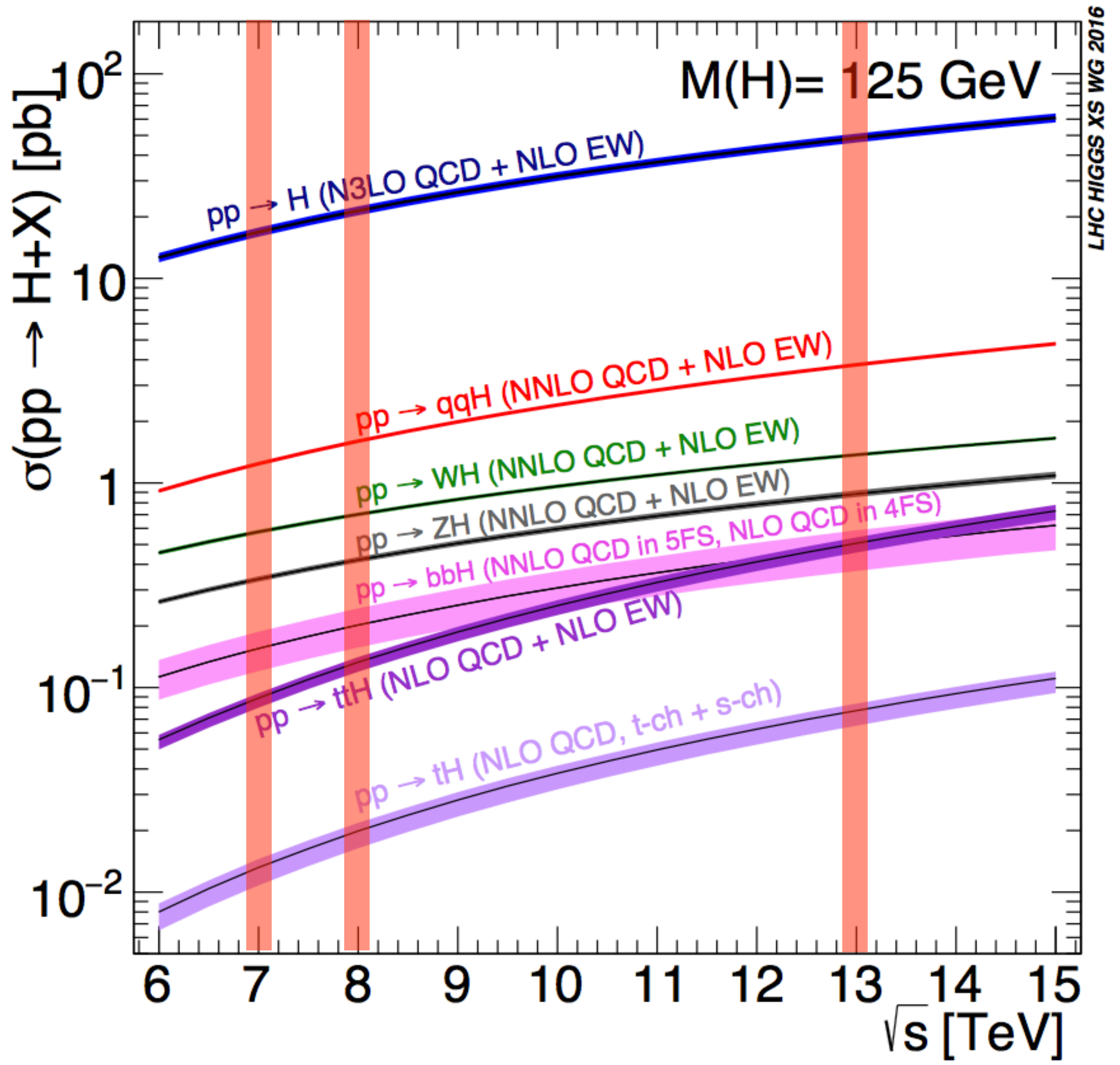


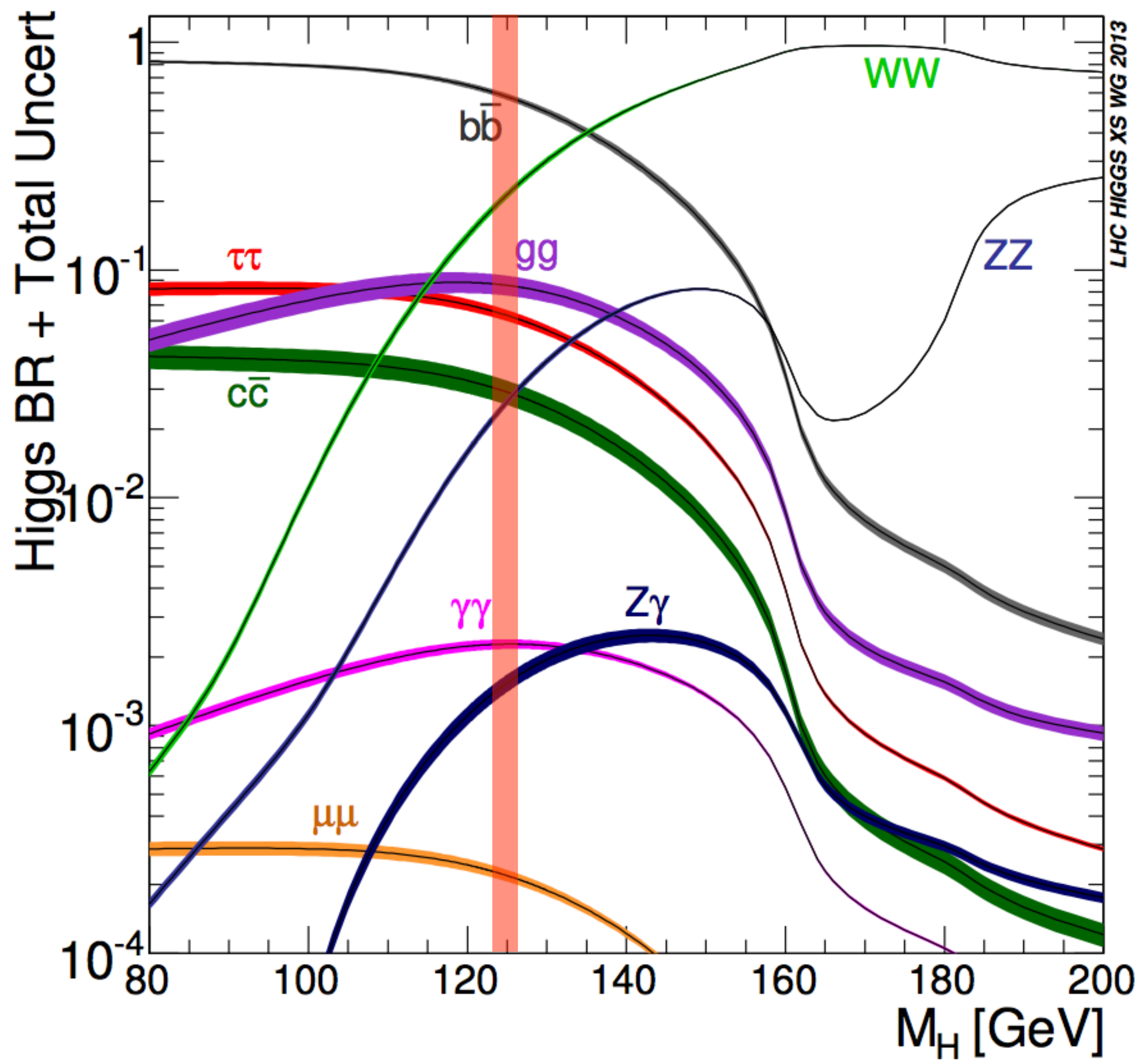
W/ZH (Higgs-strahlung)
4.9%



Top Fusion ($t\bar{t}H$)
0.6 %

H(125) Branching Fractions



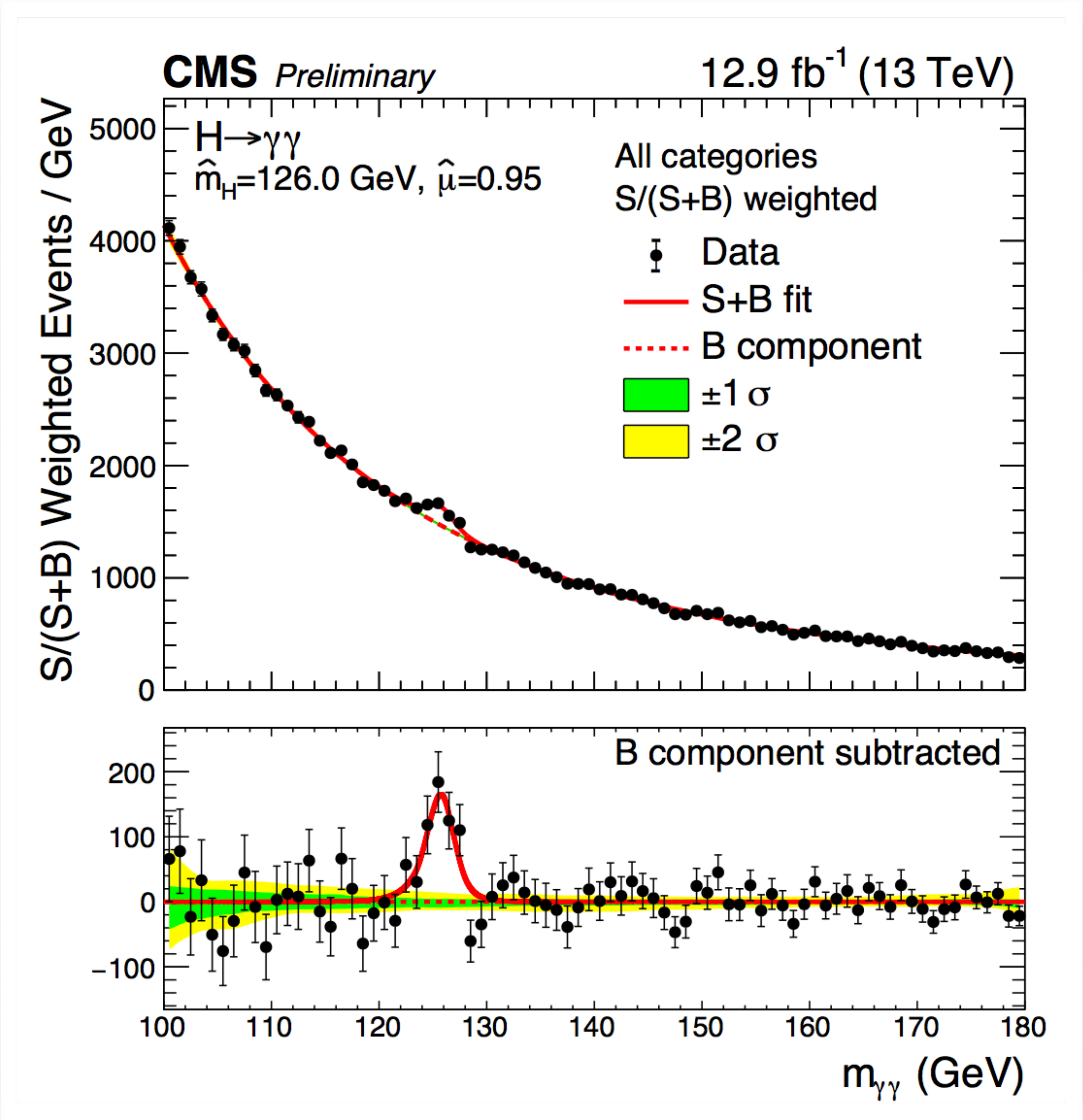


- production cross section > x2 moving from 8 to 13 TeV (~x4 for ttH)
- 125 GeV Higgs allows to probe higgs decays in multiple final states

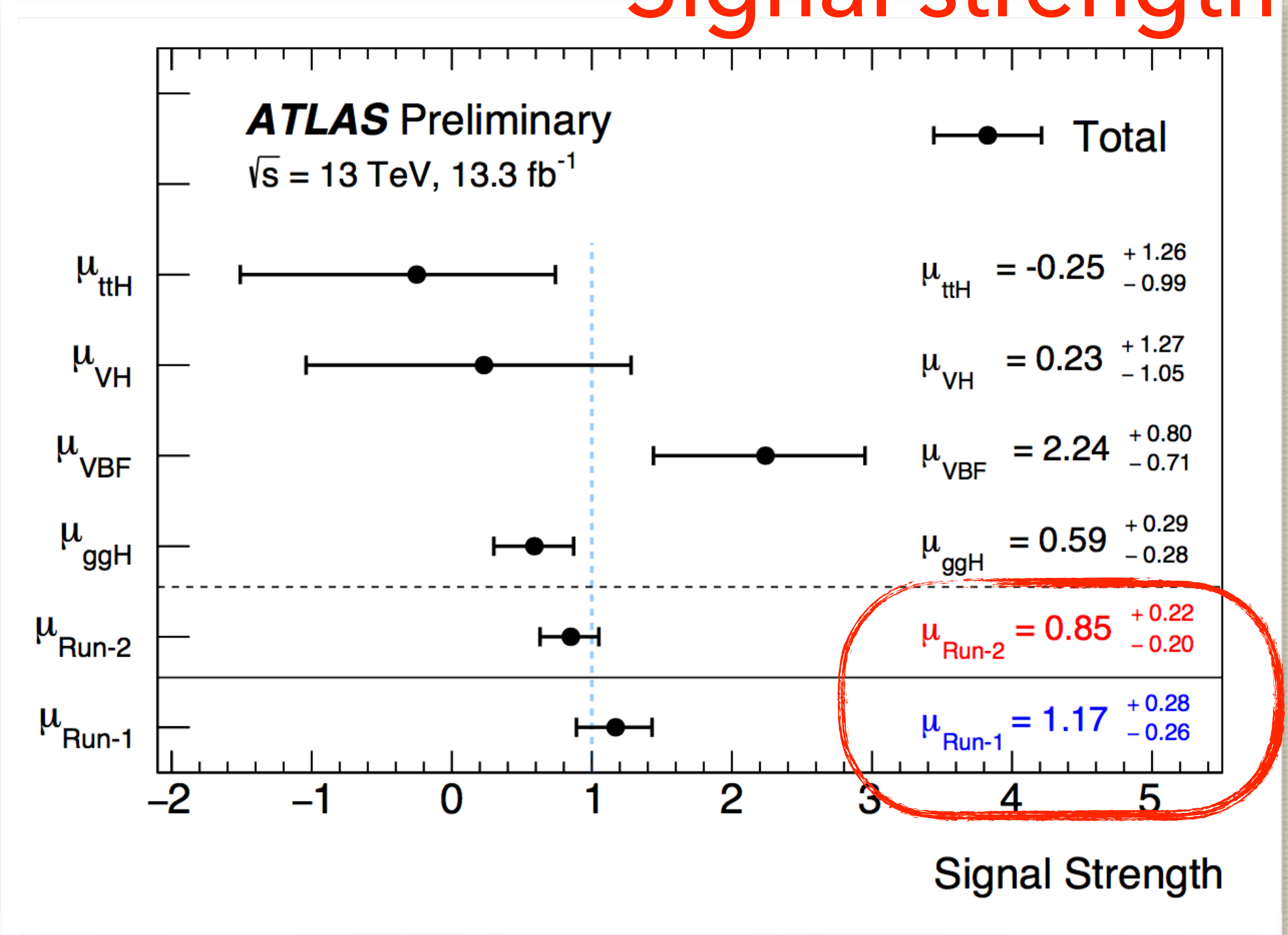
H(125)→γγ

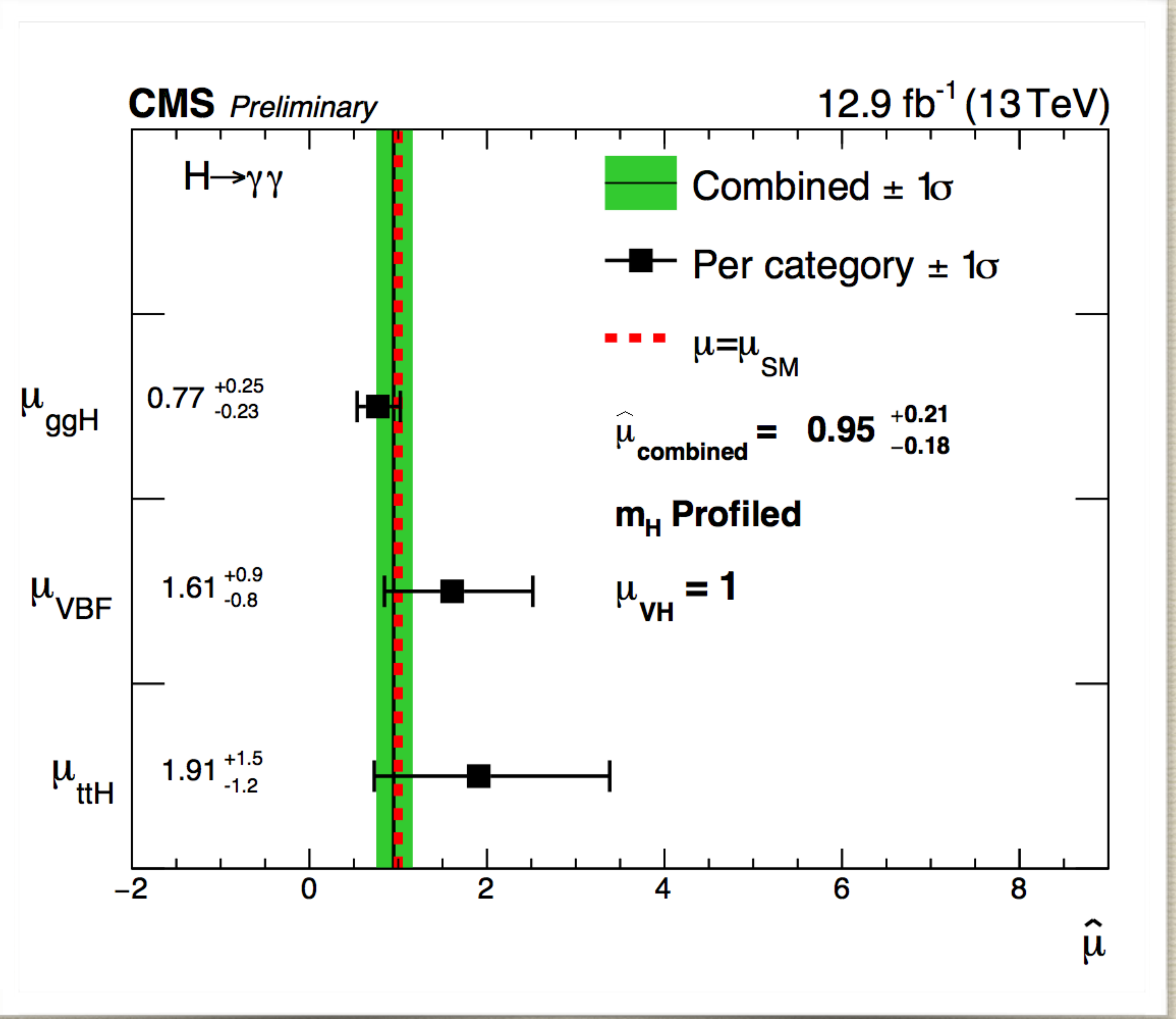
CMS-PAS-HIG-16-020

ATLAS-CONF-2016-067



Signal strength

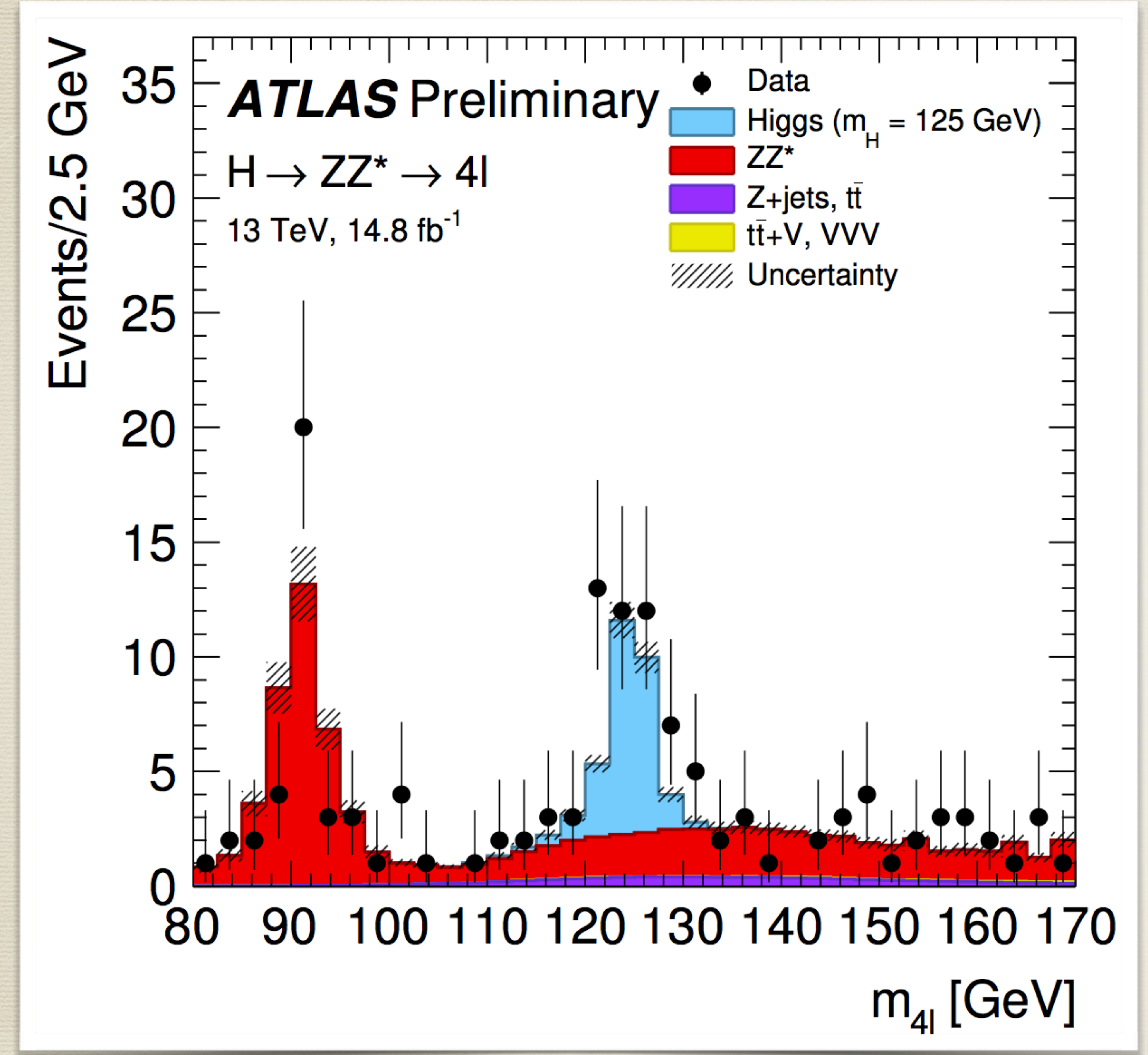




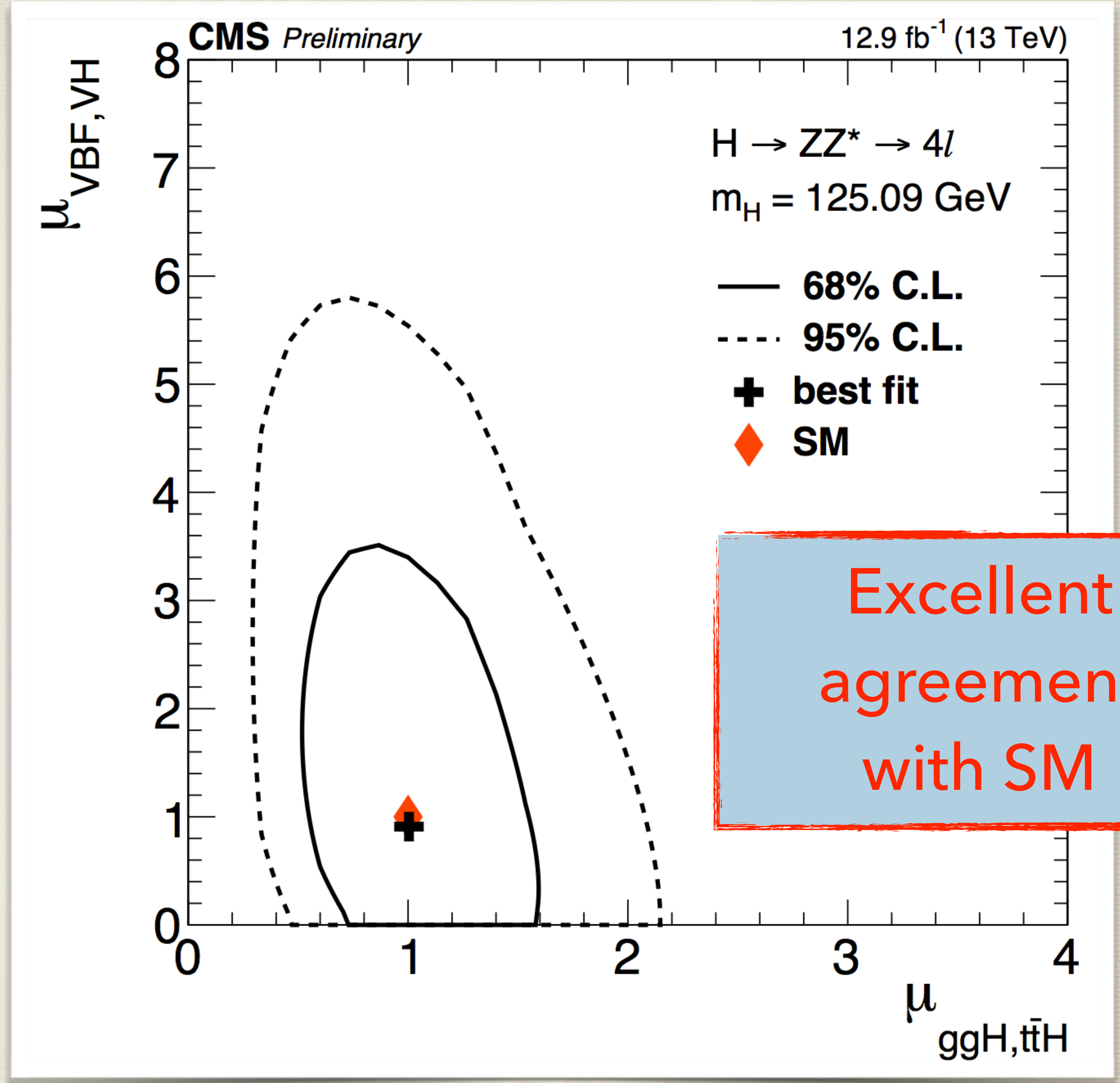
- narrow mass peak over a large smoothly falling background from γγ, γ-jet and jet-jet
- background modelled on data
- sensitivity maximised using event categorisation: S/B, expected mass resolution, jets/leptons and MET to target different production mechanisms

H(125)→ ZZ*→4l

CMS-PAS-HIG-16-033
ATLAS-CONF-2016-079



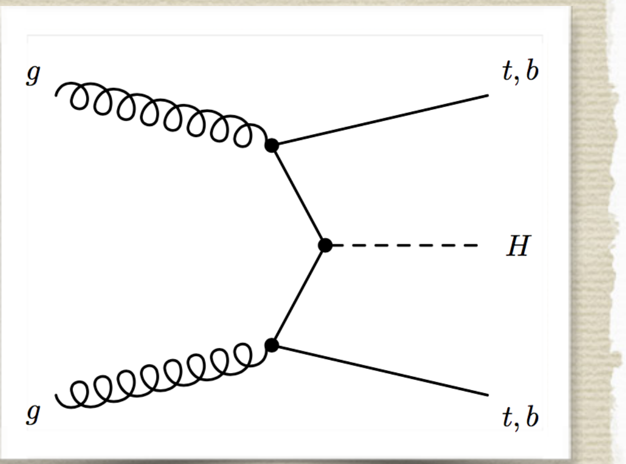
Signal strengths



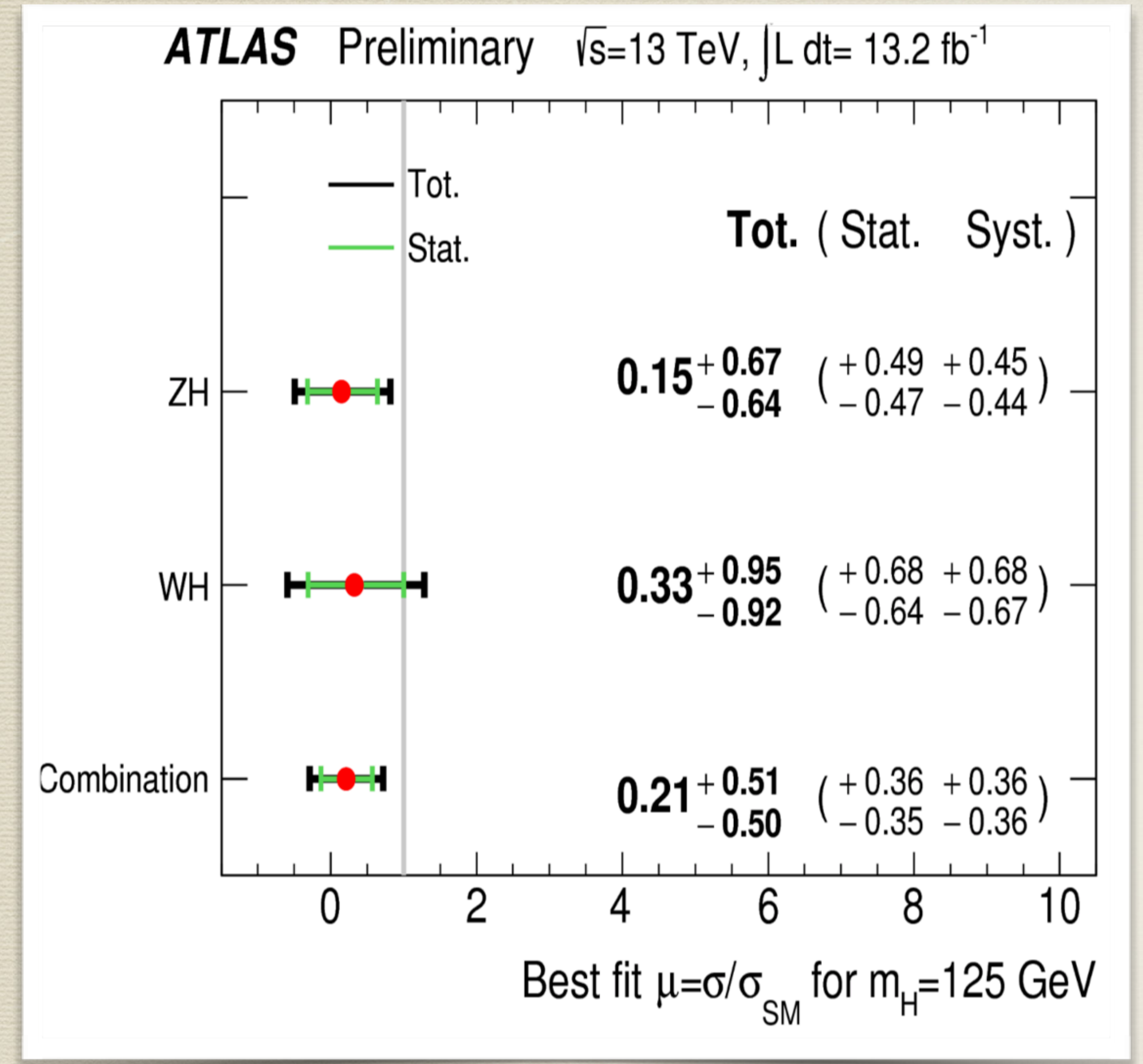
Excellent agreement with SM

- high resolution mass peak with large S/B counterbalance low event yield
- sensitivity maximised using matrix-element based discriminants to reduce non-resonant ZZ*→4l background
- event categorisation applied to different production modes

H(125)→bb & ttH(125)

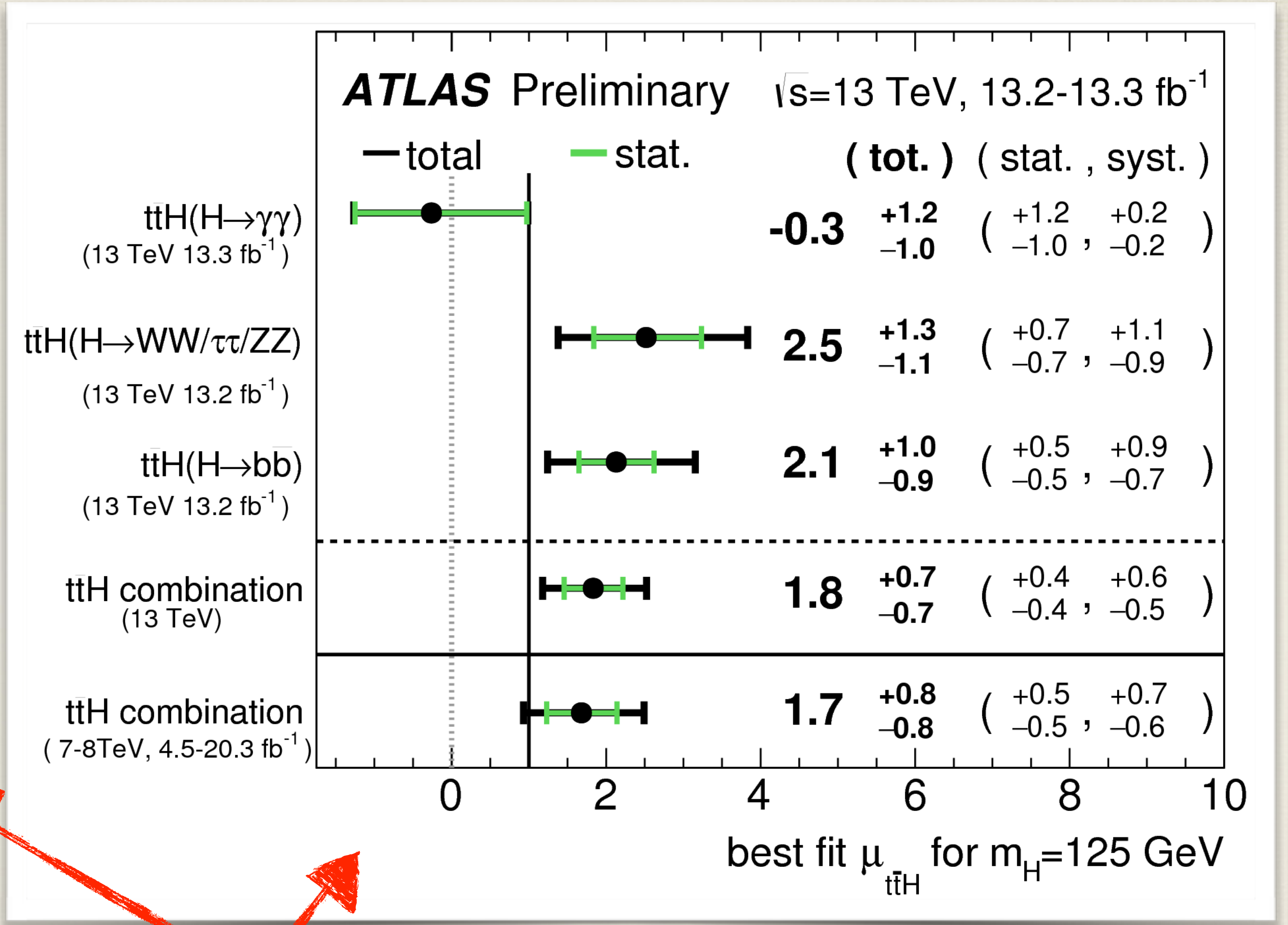


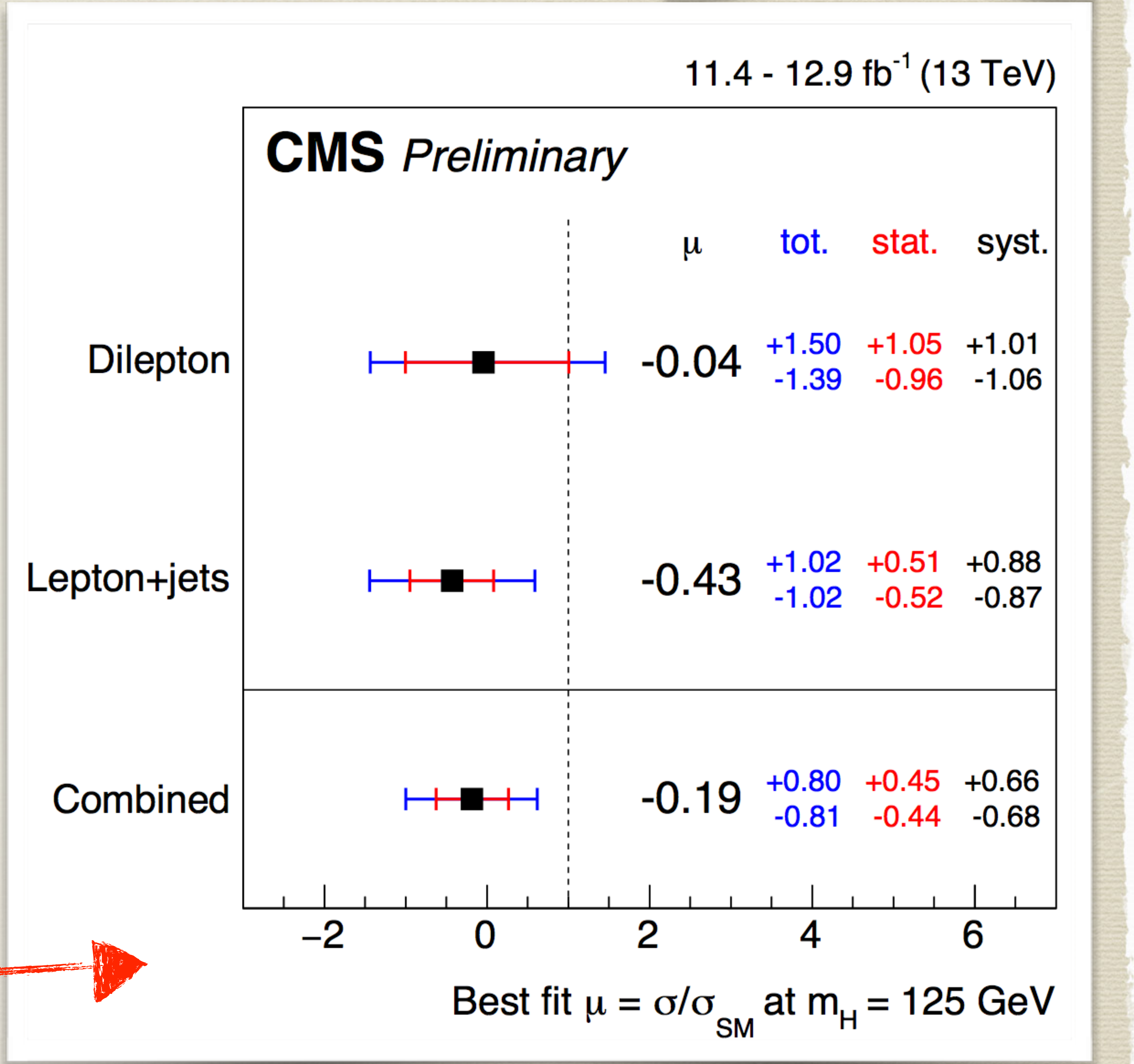
pp→VH→Vbb



ttH

- direct probe of top Yukawa coupling
- Run-1 results above SM with large uncertainties





results start to be limited by systematic uncertainties!

CMS ttH (H→bb)

CMS Run 1+2 VBF H→bb
$\mu=1.3^{+1.2}_{-1.1}$ $\mu < 3.4$ (2.2) @ 95 CL

CMS ttH (H→WW/ZZ/ττ) 2015+2016
best fit $\mu=2.0^{+0.8}_{-0.7}$ $\mu < 3.4$ ($1.3^{+0.6}_{-0.4}$) @ 95 CL

ATLAS-CONF-2016-091
CMS-PAS-HIG-16-003

CMS-PAS-HIG-16-022
CMS-PAS-HIG-16-038
ATLAS-CONF-2016-068

H(125) Mass & Width

CMS-PAS-HIG-16-033
PRL 114 (2015) 191803

- Best mass measurement still from ATLAS+CMS Run-1 from combination of $H \to \gamma\gamma$ and $ZZ^* \to 4l$

$m_H = 125.09 \pm 0.24\ (\pm 0.21 \pm 0.11)$ GeV

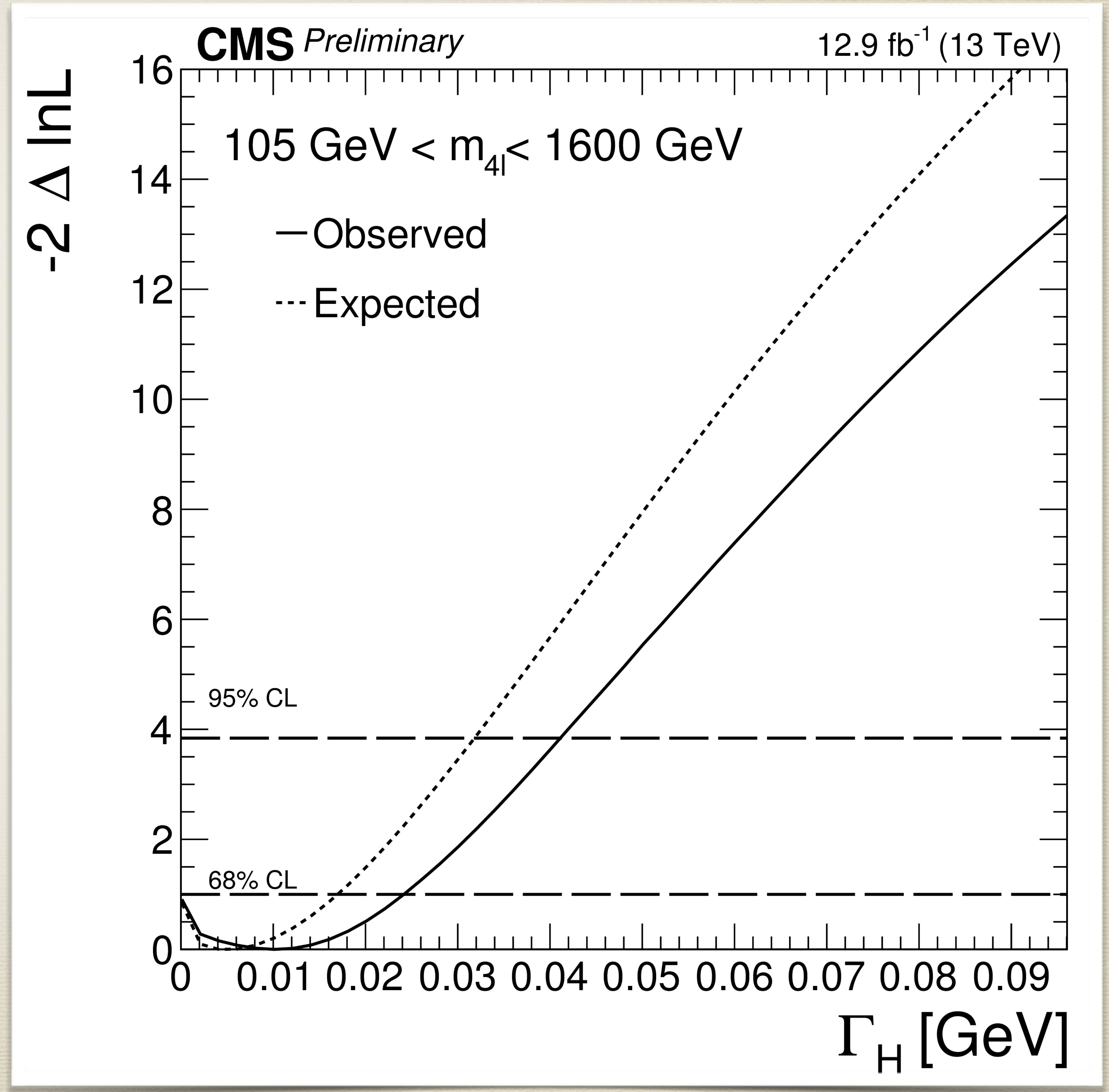
0.2% total uncertainty

- Width: impossible to directly probe SM Higgs width (~4 MeV @ 125 GeV)
- indirect constraint (with assumptions) by studying interference effects at high $ZZ^* \to 4l$ mass

CMS@13 TeV via interference on-shell/off-shell:
$\Gamma_H < 41$ MeV @95% CL

indirect Run-1 ATLAS/CMS : $\Gamma_H <\sim 20\text{-}30$ MeV @95% CL

direct constraints: O(1 GeV)

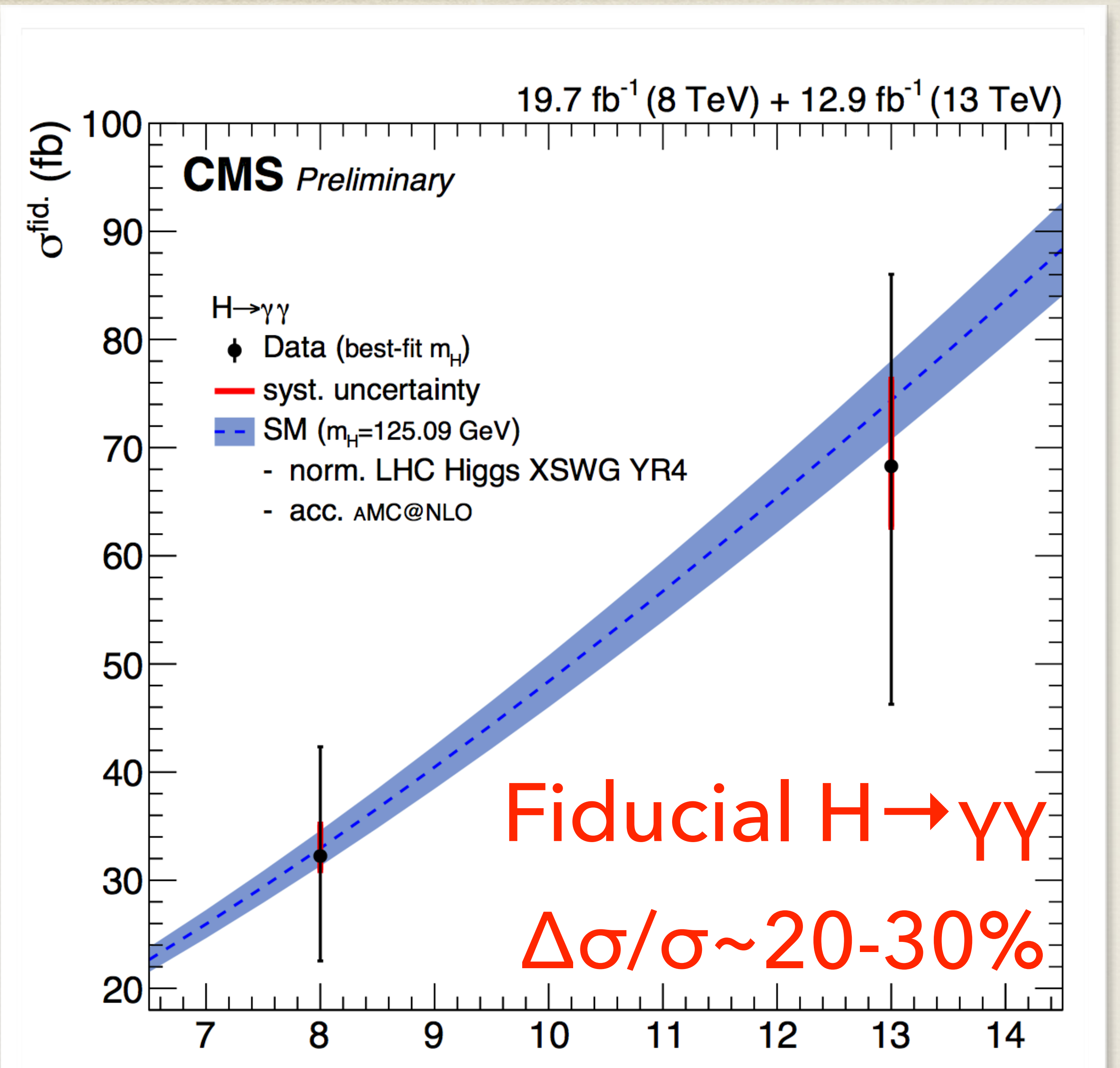


H(125) Cross sections

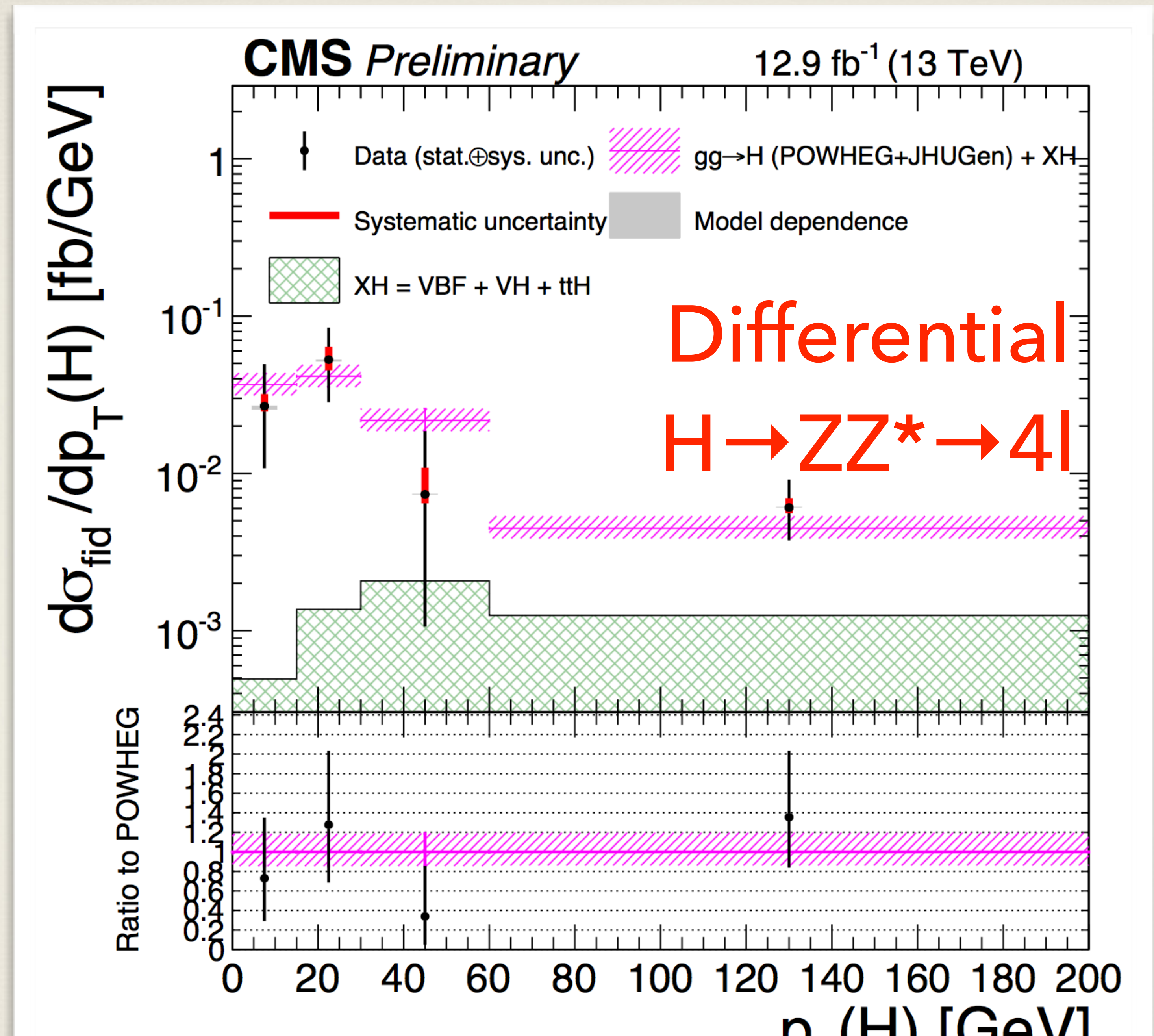
- sensitive to kinematics of production, decay mechanism, detector acceptance, ...
- selection on p_T, η, categorisation modified to reduce model-dependence

$$\sigma_{tot} = \frac{N - N_B}{A \times BR \times L_{int} \times C}$$

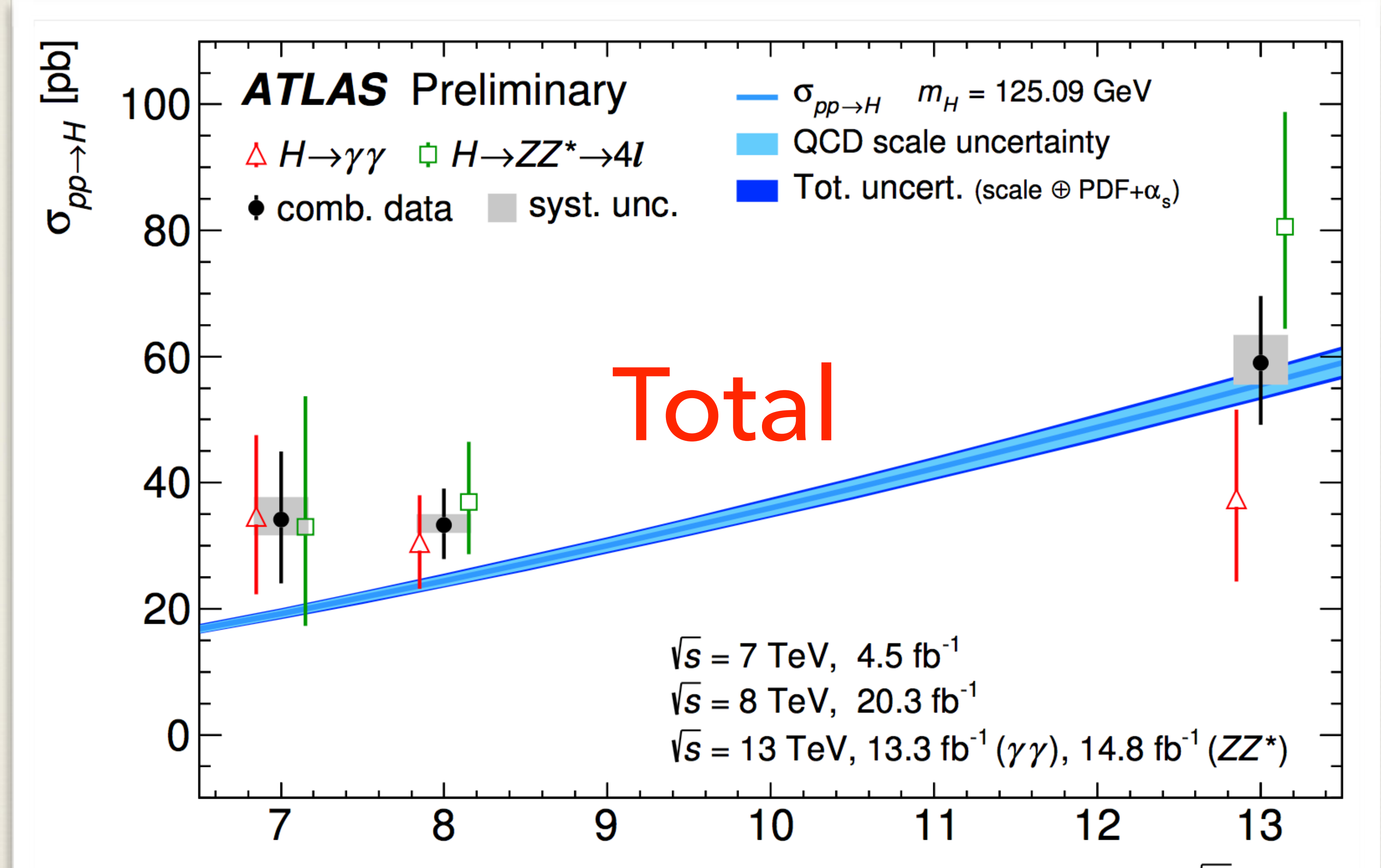
$$\sigma_{fid} = \frac{N - N_B}{L_{int} \times C}$$



CMS-PAS-HIG-16-020



CMS-PAS-HIG-16-033



ATLAS-CONF-2016-081

σ Fiducial (fb)	H→γγ	H→ZZ*→4l
ATLAS SM prediction	$43.2 \pm 14.9(\text{stat}) \pm 4.9(\text{syst})$ $62.8^{+3.4}_{-4.4}$ (N^3LO+XH)	$4.54^{+1.02}_{-0.90}$ $3.07^{+0.21}_{-0.25}$
CMS SM prediction	$69^{+16}_{-22}(\text{stat})^{+8}_{-6}(\text{syst})$ 73.8 ± 3.8	$2.29^{+0.74}_{-0.64}(\text{stat})^{+0.30}_{-0.23}(\text{syst})$ 2.53 ± 0.13

- combination from extrapolation to inclusive Higgs production cross-section
- N^3LO QCD predictions now available for inclusive ggF cross-section

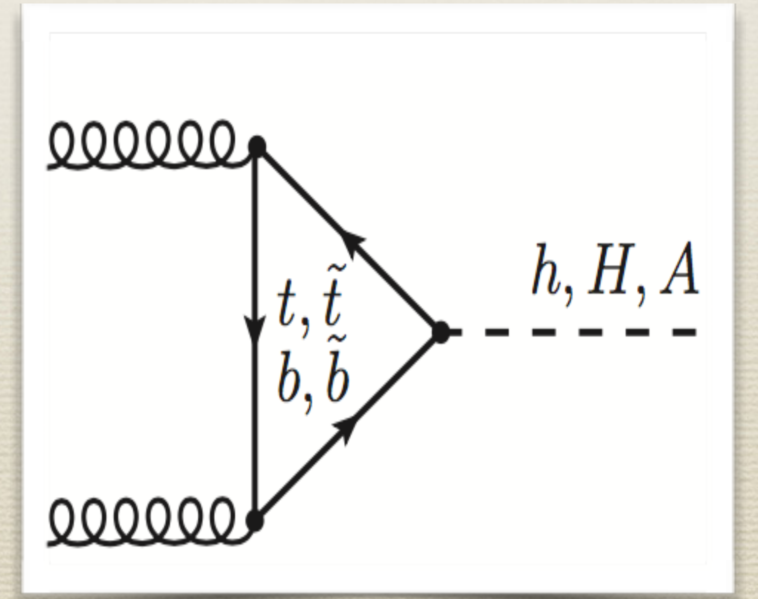
BSM Higgs Searches

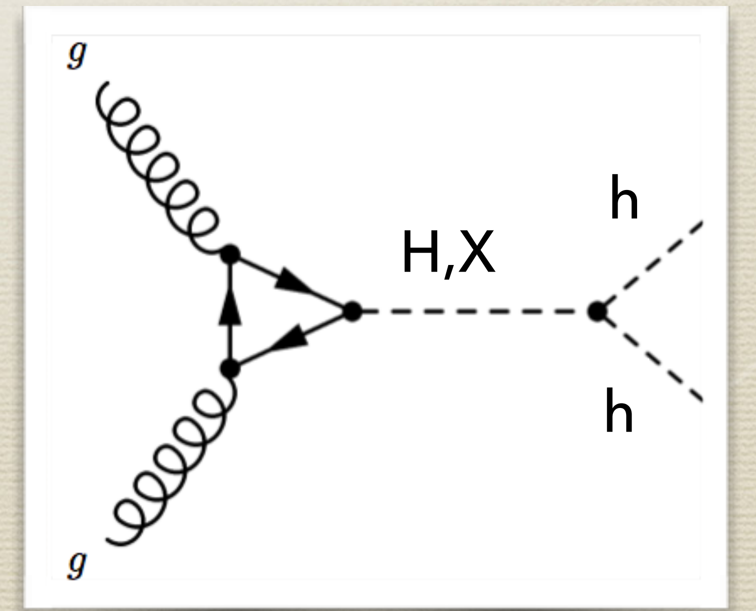
- if spontaneous symmetry breaking is the mechanism by which particles acquire mass, then is crucial to understand the structure of the Higgs sector: minimal as in the SM, or extended as predicted in several BSM models?

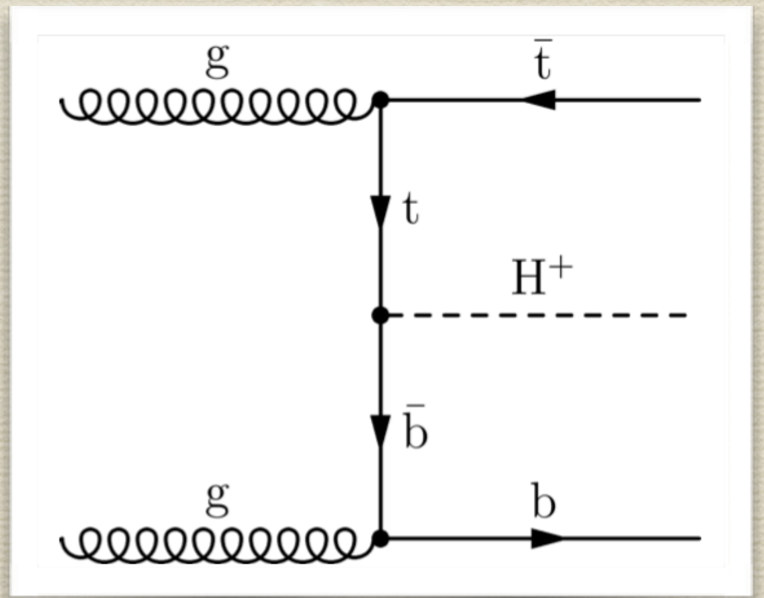
- among the NP models, Two Higgs Doublets Models (2HDM) have taken the role of standard benchmark scenarios in the searches carried on in ATLAS and CMS:
  - 5 scalar Higgs bosons: **h, H, A, H^+, H^-**
  - 6 main parameters: **m_h, m_H, m_A, $m_{H^\pm}$, tanβ** and the mixing angle between h and H: **α**

- common scenarios:
  - Type-I 2HDM: all fermions couple only to one doublet
  - Type-II 2HDM (ex. MSSM): up-type q couple to one doublet, down-type q and charged lepton to the other
    - in MSSM (type II) spectrum governed (at tree-level) by only 2 parameters m_A and tanβ
    - beyond tree-level: common scenarios used as benchmarks: m_h^{mod+} and hMSSM

- Search channels:
  - neutrals: H/A→bb,ττ,μμ, di-bosons, X→HH
  - charged: $H^\pm$→τν, tb, cb, cs





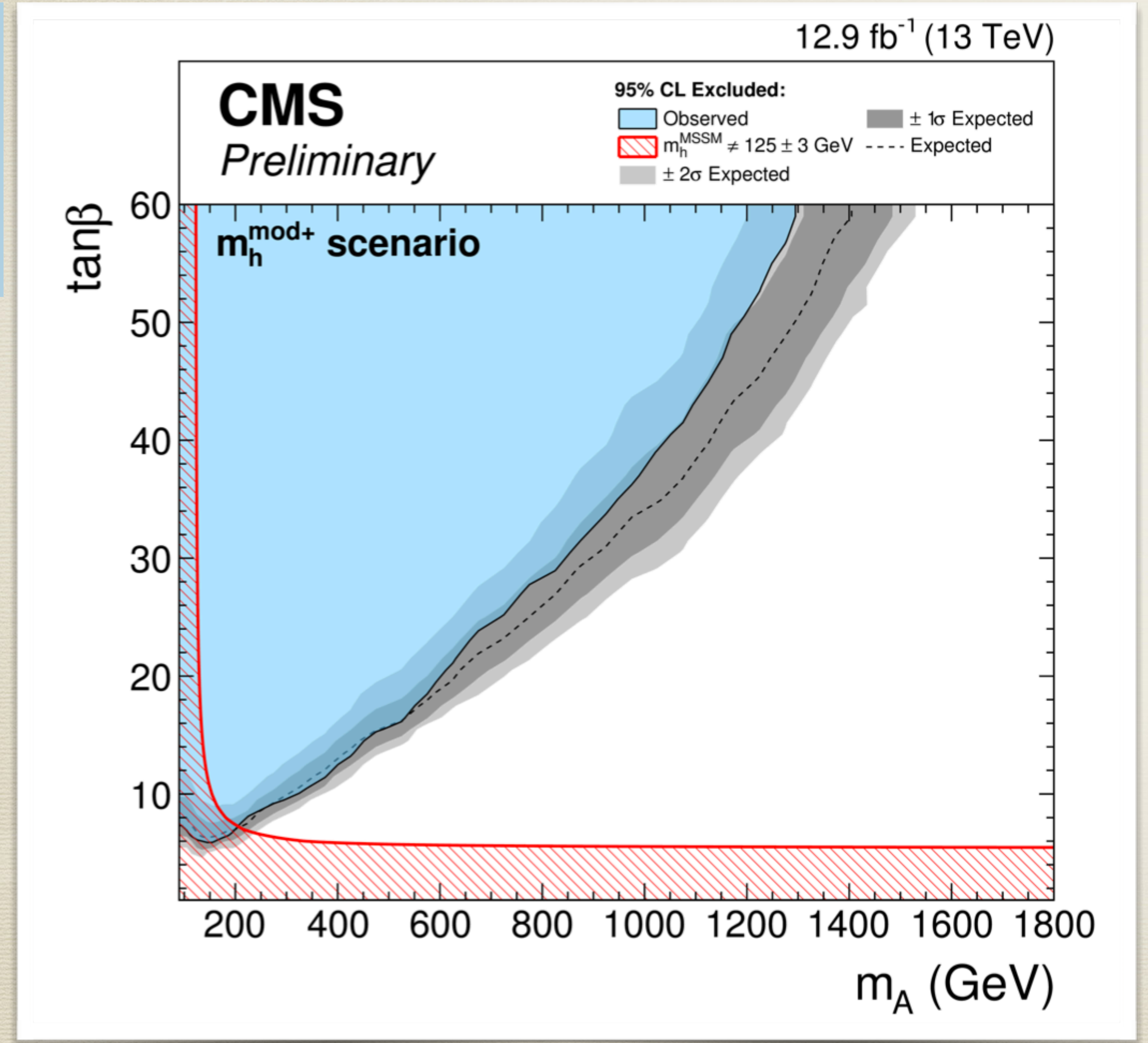


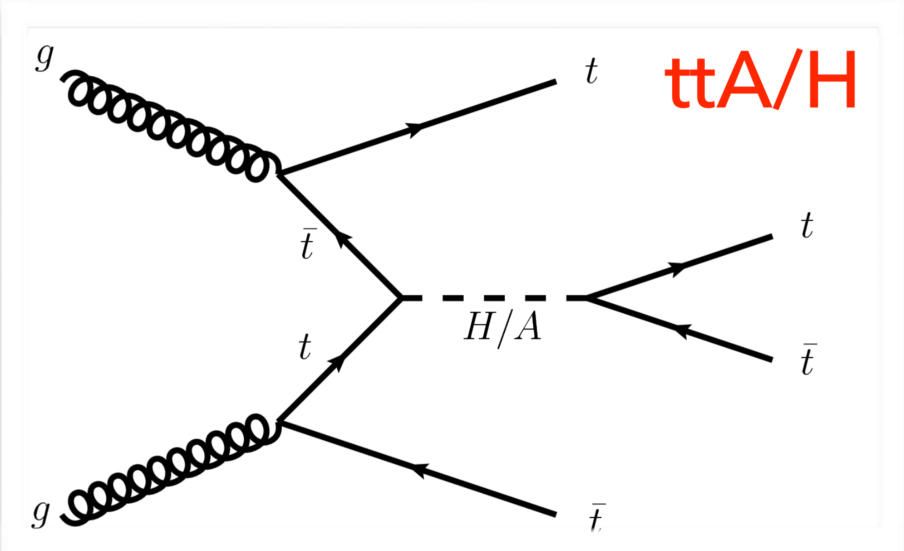
Neutral BSM Higgs Searches: decays to fermions

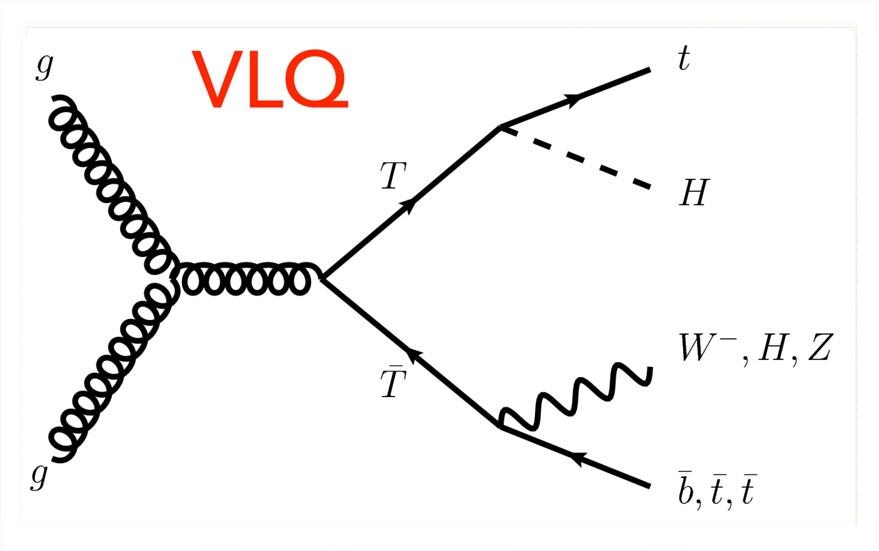
- searched in several final states: ττ, μμ, bb, tt
  - ττ: dominant for large values of tanβ
  - tt: dominant in the alignment limit for low tanβ when $m_{H/A} > m_t$

broad search for NP in tt final states with additional HF jets: covering a variety of BSM models

A/H→ττ

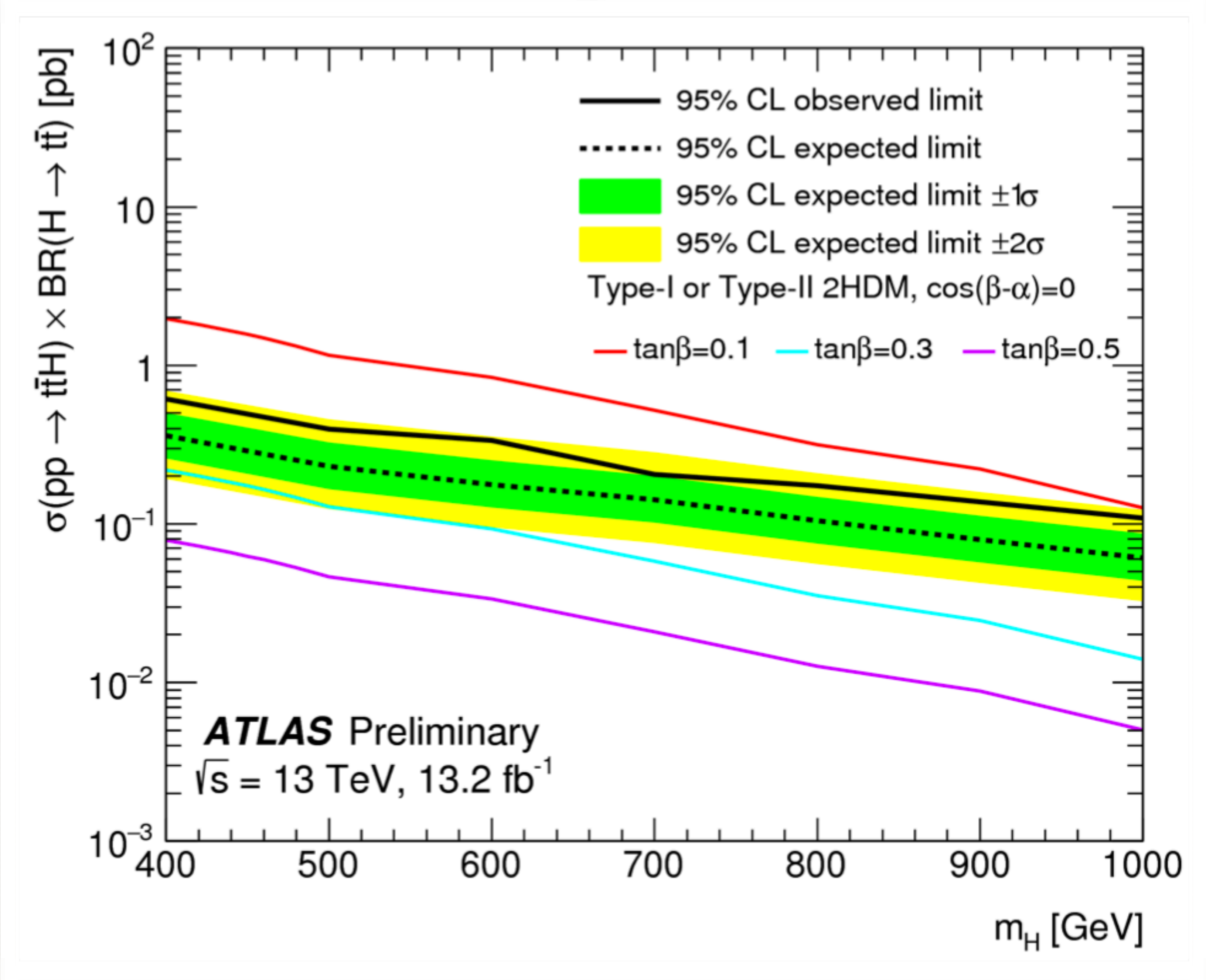






...

ttA/H→tttt



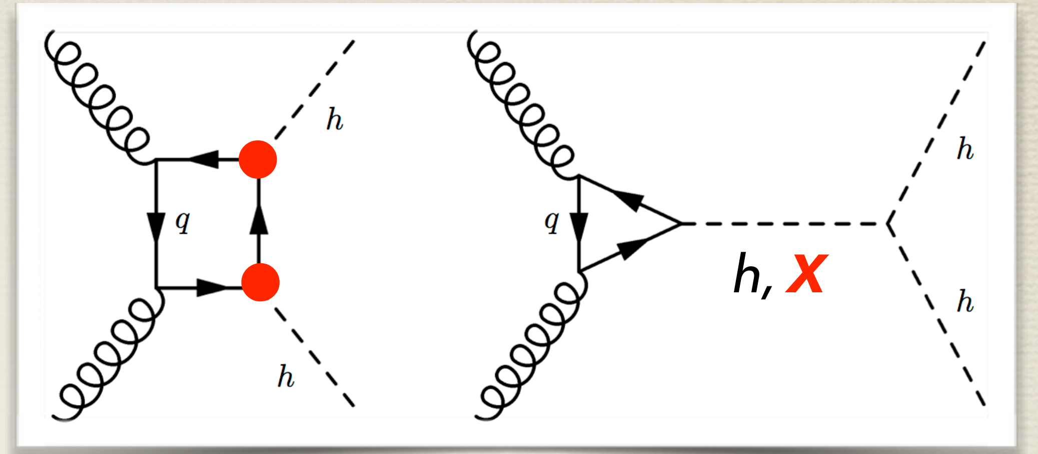
Sensitivity to exclude MSSM Higgs up to 1.4 TeV

CMS-PAS-HIG-16-037

ATLAS-CONF-2016-104

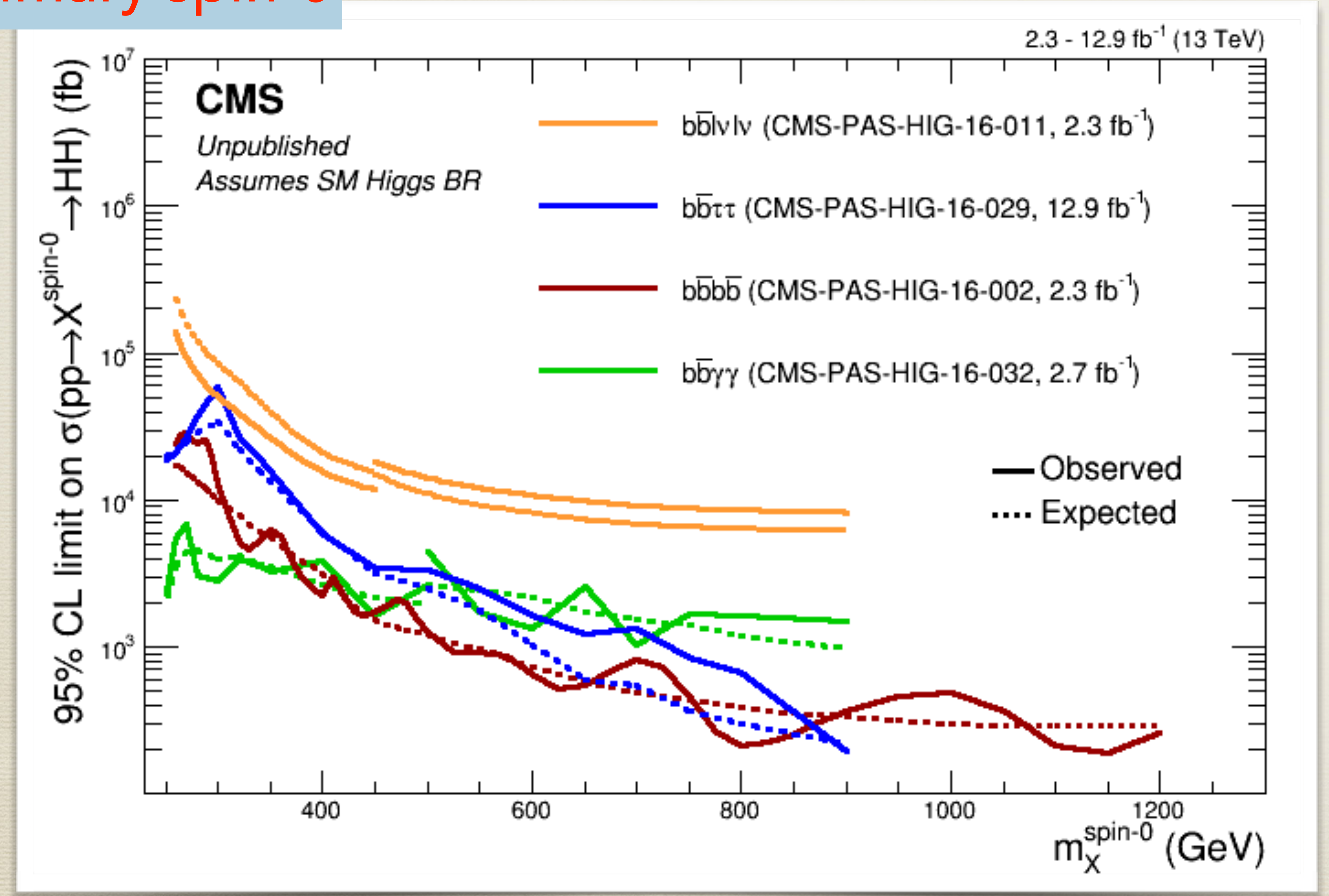
Neutral BSM Higgs Searches: decays to bosons

- pp→H/X→hh:
  - SM: hh production cross-section orders of magnitude below experimental sensitivity due to destructive interference
  - BSM: di-higgs production can be enhanced via modified coupling constants or new resonances
    - search decay modes: bbbb, bbWW, bbττ, bbγγ, WWγγ

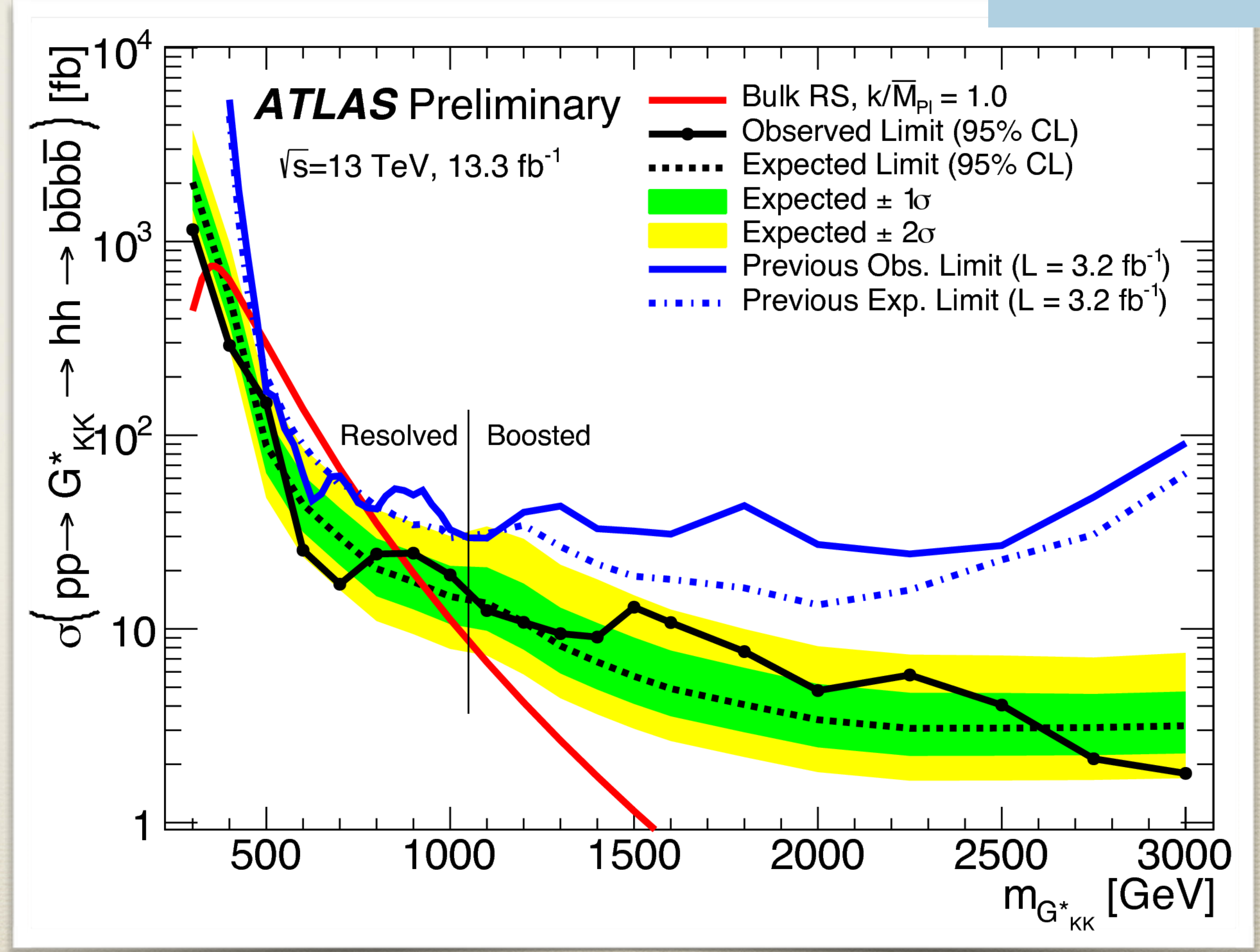


CMS summary spin-0

CMS-PAS-HIG-16-011
CMS-PAS-HIG-16-029
CMS-PAS-HIG-16-002
CMS-PAS-HIG-16-032



ATLAS 4b



spin-0 Radion (Λ_R=1 TeV): excluded up to 750 GeV

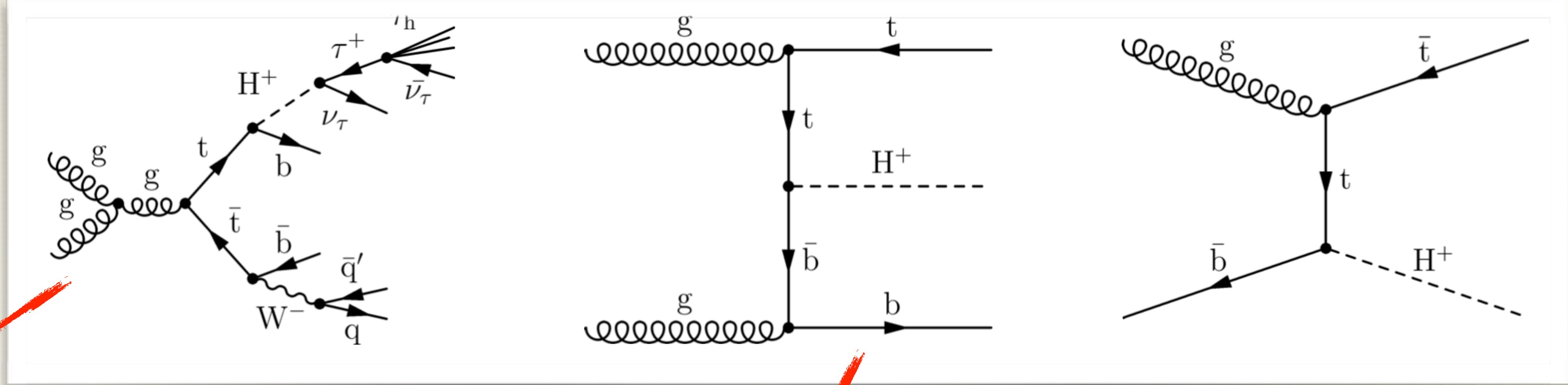
spin-2 RS1 Graviton (k/M_{Pl}=0.1, kL=35): excluded up to 850 GeV

Interpretation in the RS model

ATLAS-CONF-2016-049

Charged BSM Higgs Searches

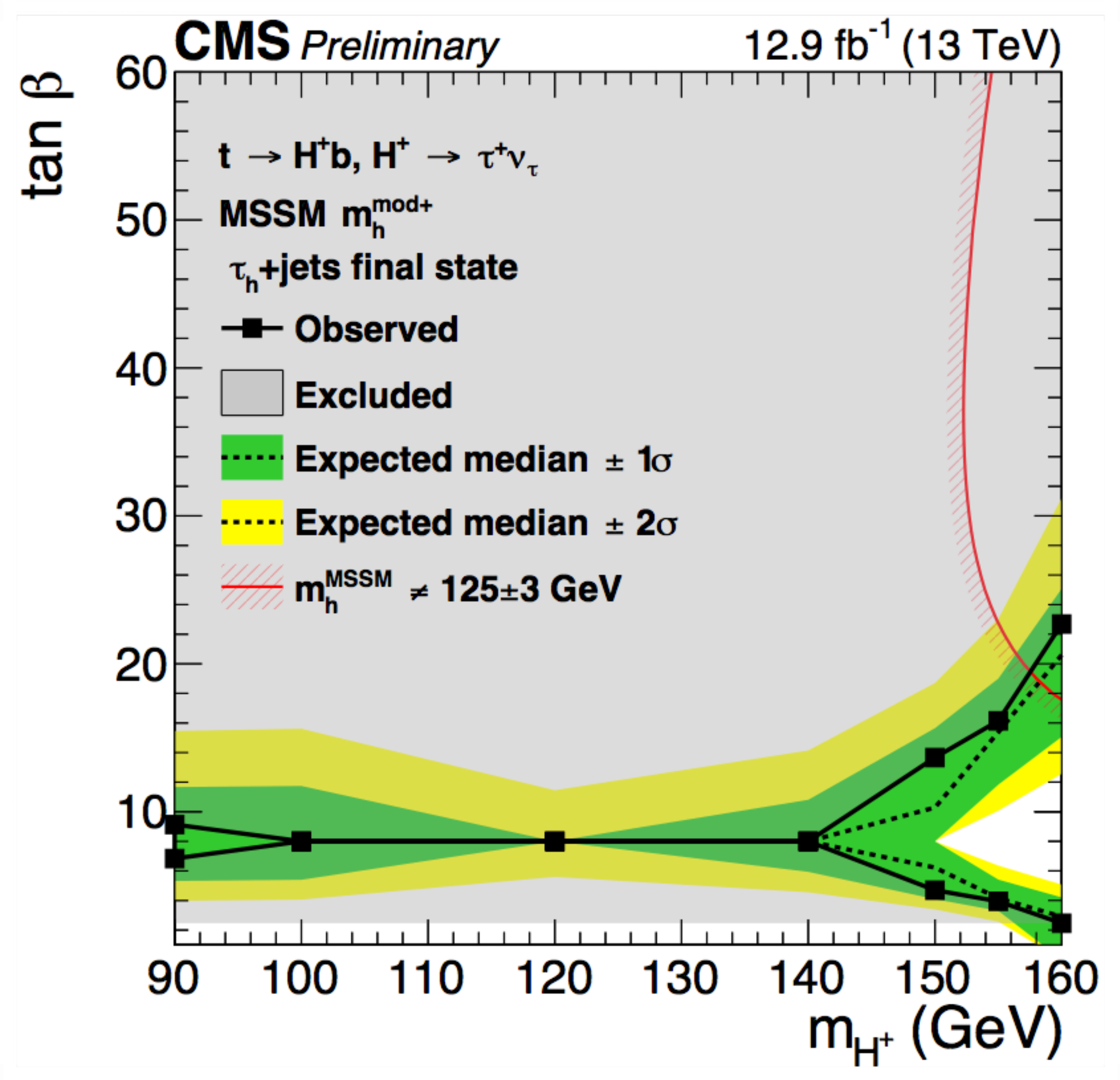
- in 2HDM charged Higgs can decay into τν, tb, cb, cs depending on the parameter of the model
  - in Type-II 2HDM:
    - dominant decay tb, but τν always sizeable O(15%)
    - for $m_{H+} \lesssim 200$ GeV dominant decay is into τν
  - light H± ($m_{H\pm} < m_t$): dominant production t→bH±
  - heavy H± ($m_{H\pm} > m_t$): dominant production tH±



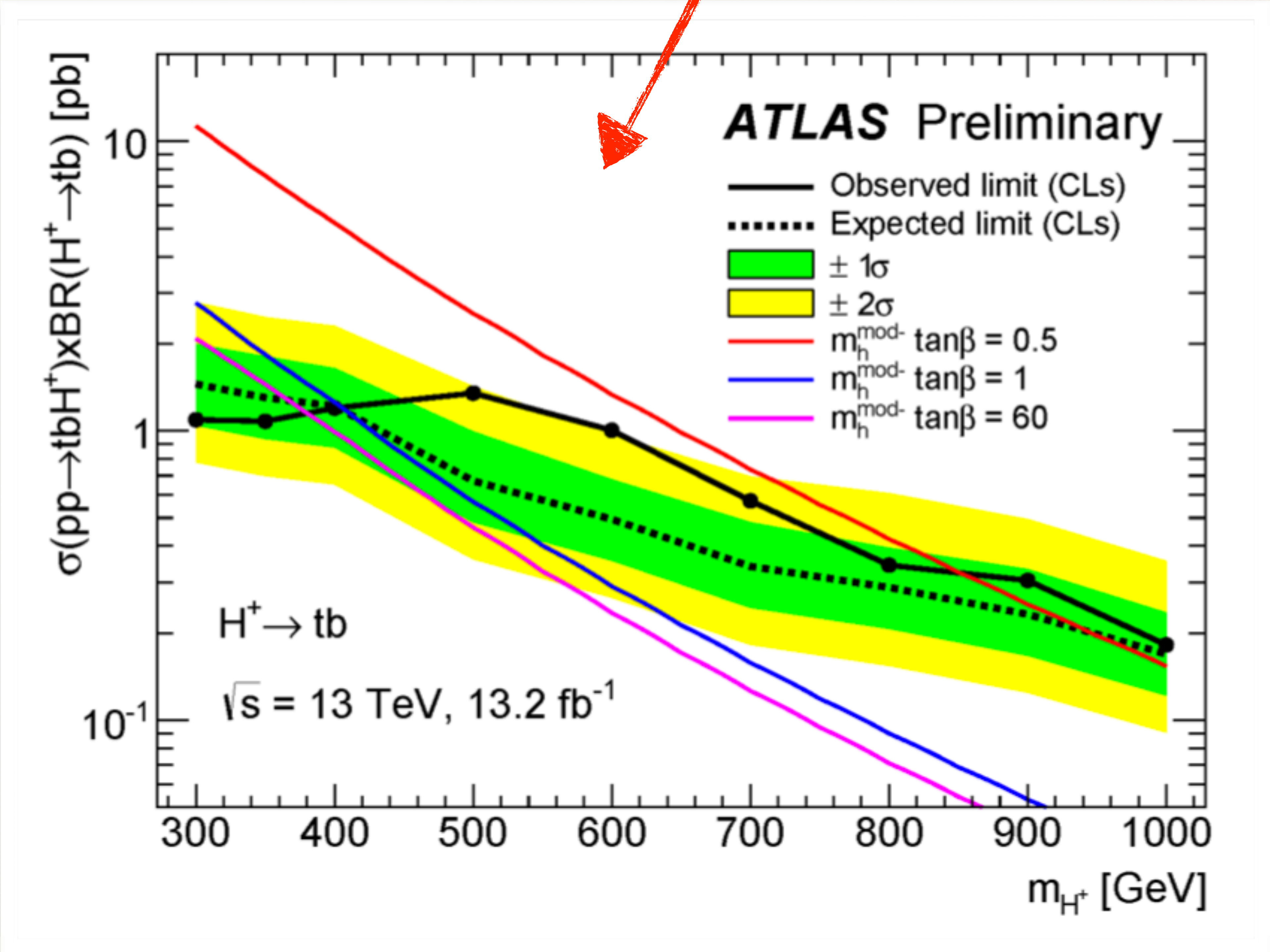
CMS-PAS-HIG-16-031

JHEP 11 (2015) 018

CMS t→bH±, H±→τν



ATLAS tbH±, H±→tb



ATLAS-CONF-2016-088

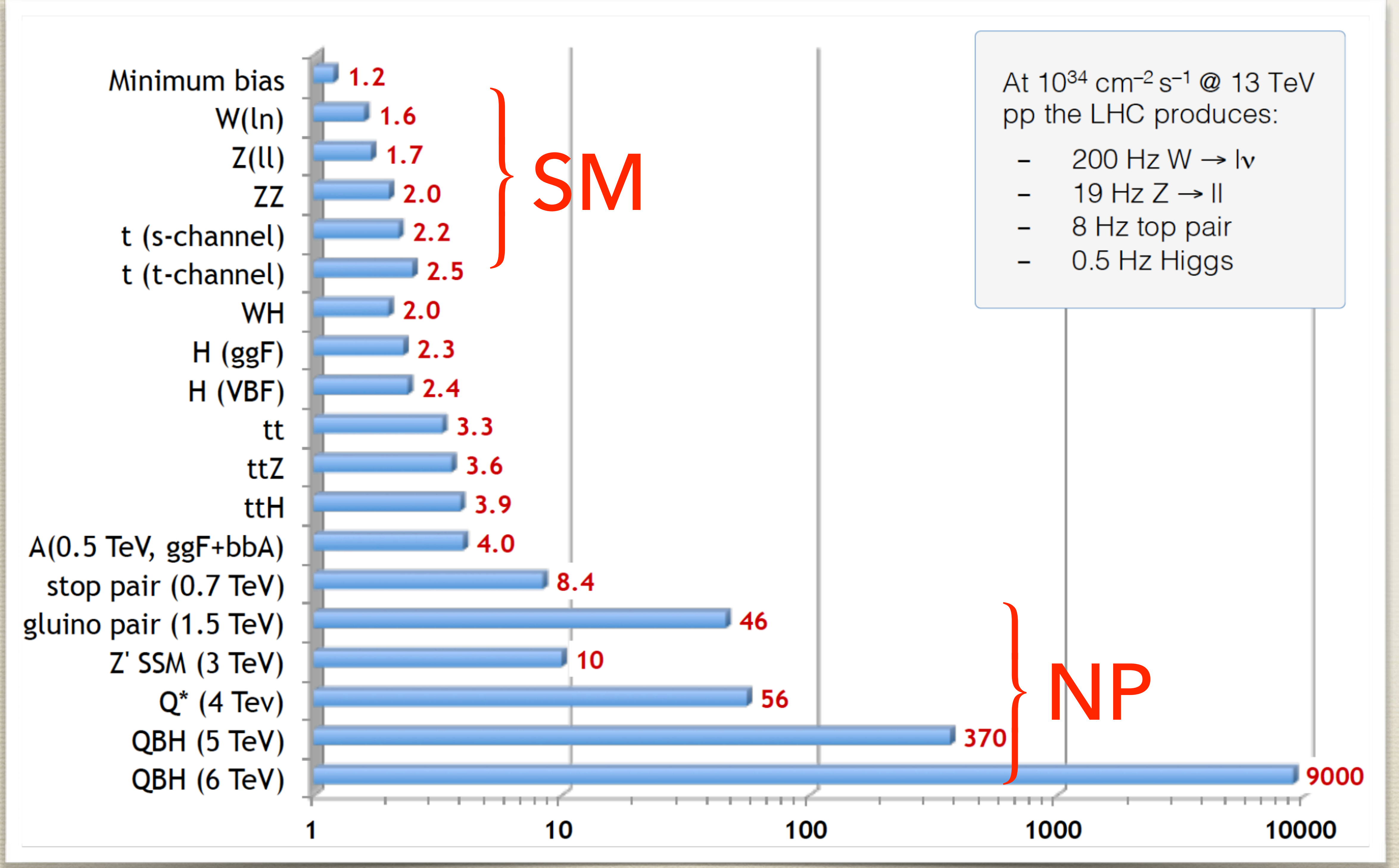
ATLAS-CONF-2016-089

constraints on parameter space of several MSSM scenarios

SUSY & Exotic Searches

- the new energy frontier and the higher luminosity of the Run-2 of LHC provide ideal conditions for direct searches of new particles pushing the boundary of the regions explored in Run-1

- LHC Run-2 is expected to deliver O(150) fb^{-1} by end of 2018, however with the increase in energy from 8 to 13 TeV already with a fraction of the data accumulated in 2015 and 2016 searches sensitivity surpasses the Run-1 reach



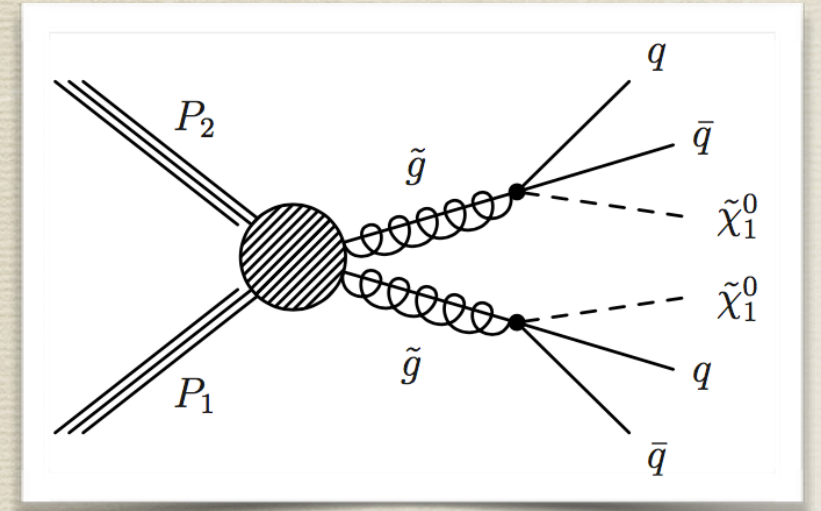
x-sections scaling factors
8 to 13 TeV

only a small selected set of analyses shown here to give a general view of the broad landscape of searches performed in ATLAS and CMS …

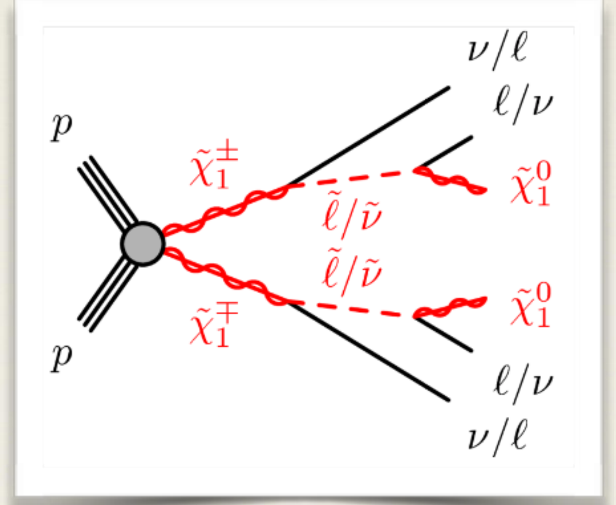
SUSY Searches

CMS-PAS-SUS-16-015
ATLAS-CONF-2016-096

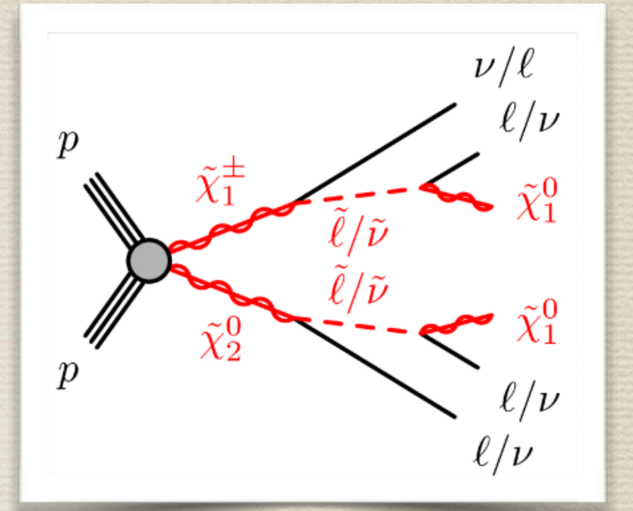
- huge number of analyses performed or onging in ATLAS and CMS, two representative ones shown here:
- strong SUSY production in events with large hadronic activity and 0-leptons: sensitive to gluino/squark production
- electroweak SUSY production in events with multi-leptons: sensitive on EWKino production

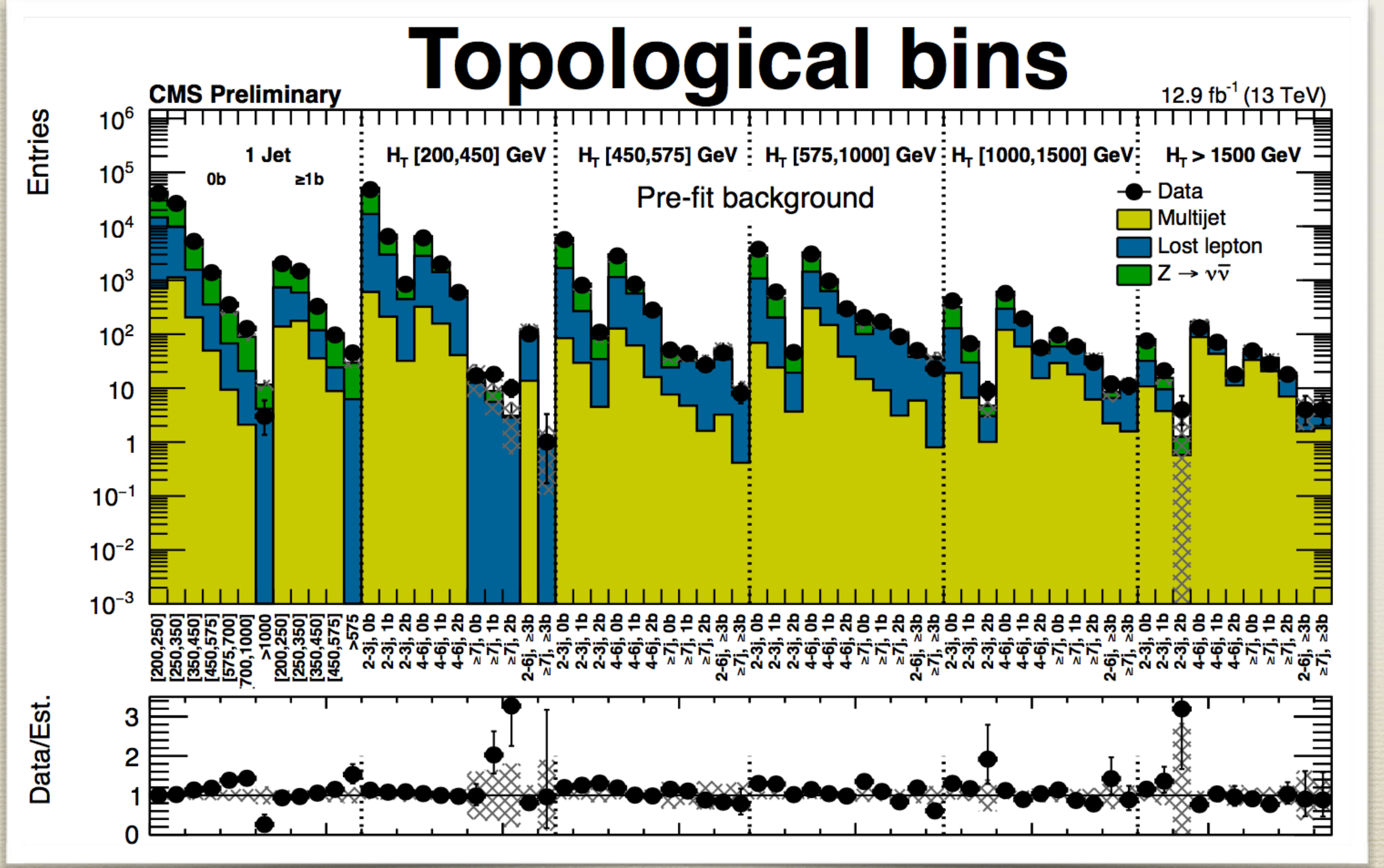


- looks at events with large hadronic activity, MET and no leptons
- categorize in topological bins
- in each bin signal region based on stranverse mass M_{T2}

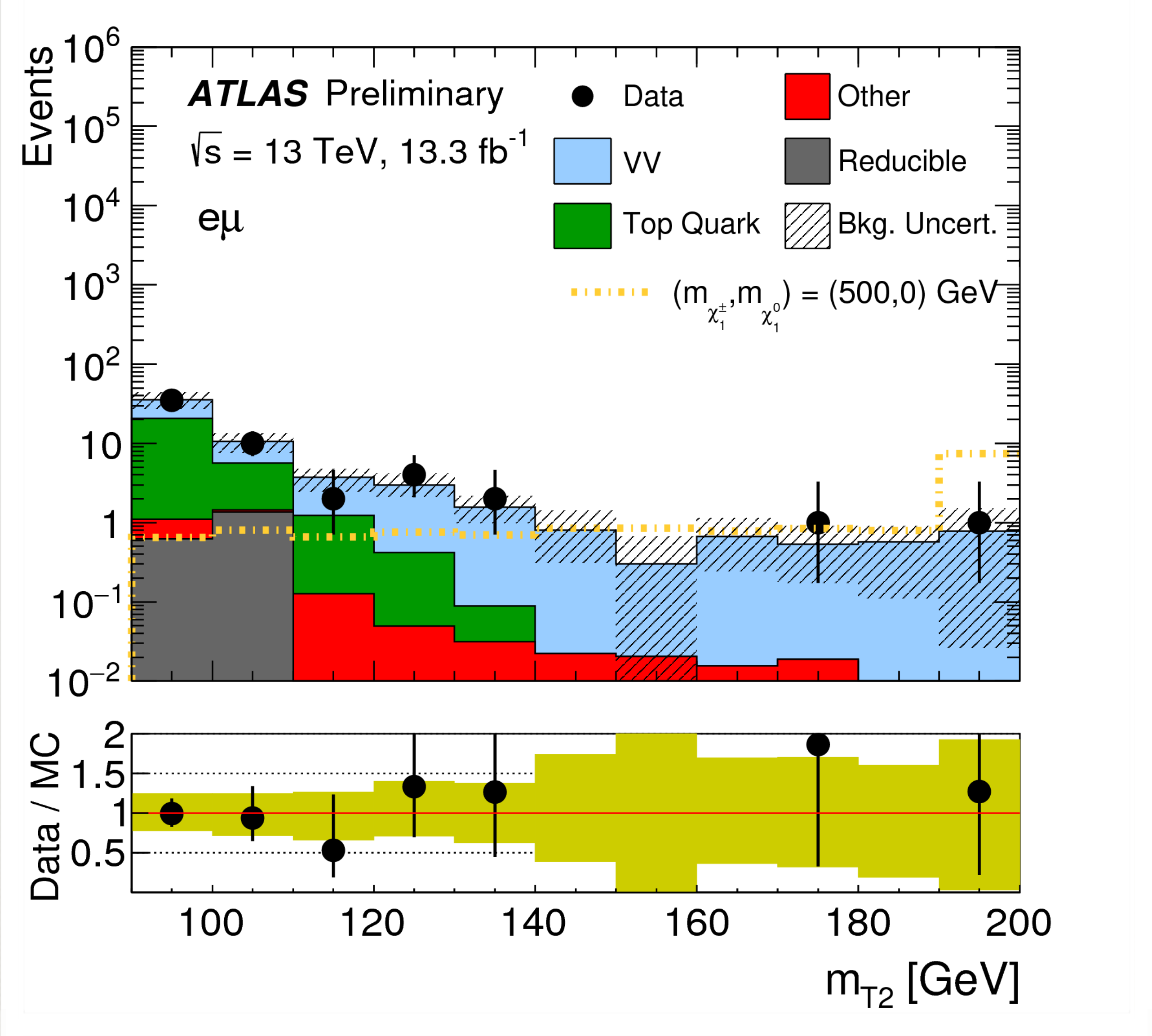


- events with 2 or 3 leptons + MET and no jets
- selections based on M_{T2}, MET, p_T …

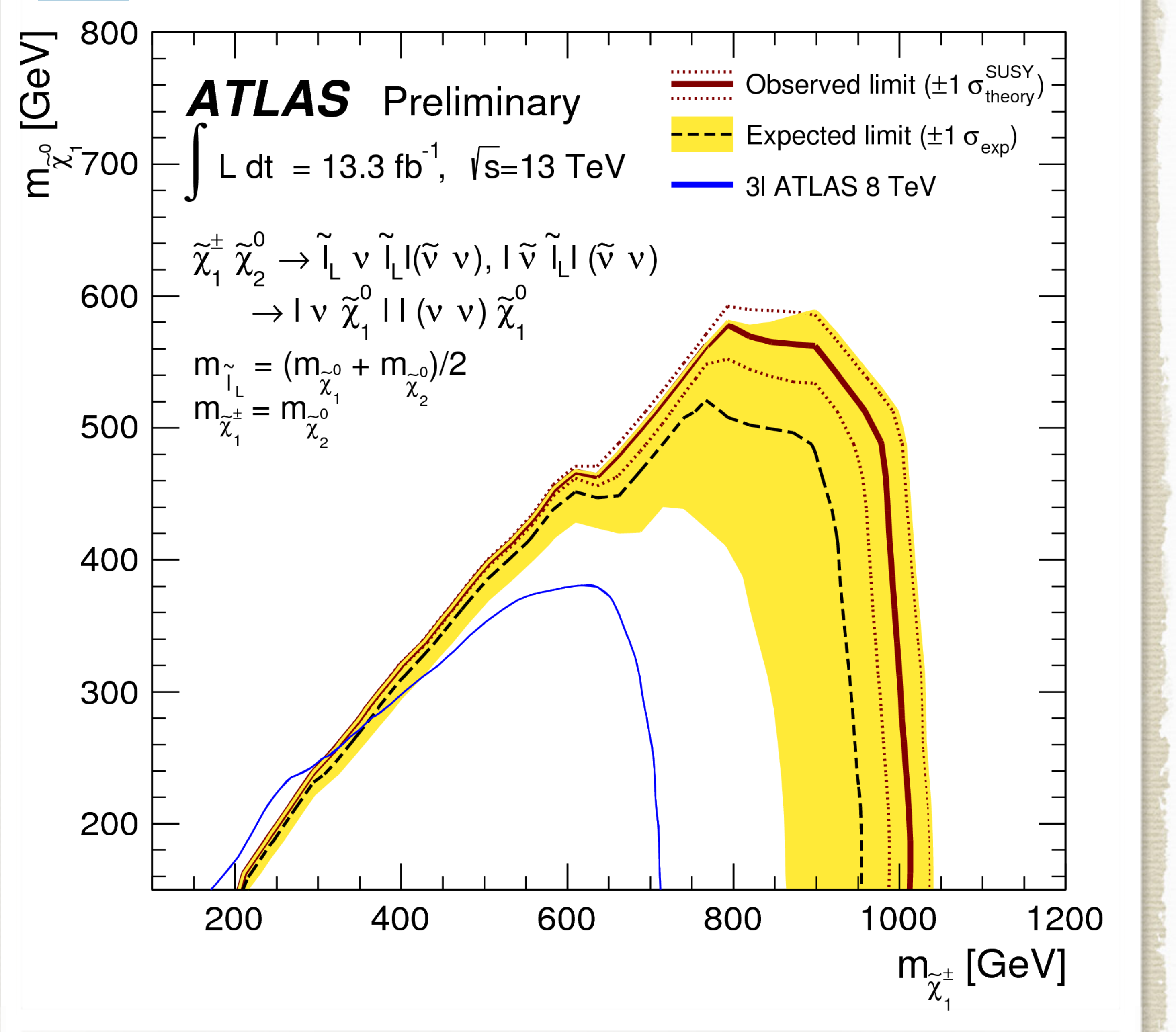




2L

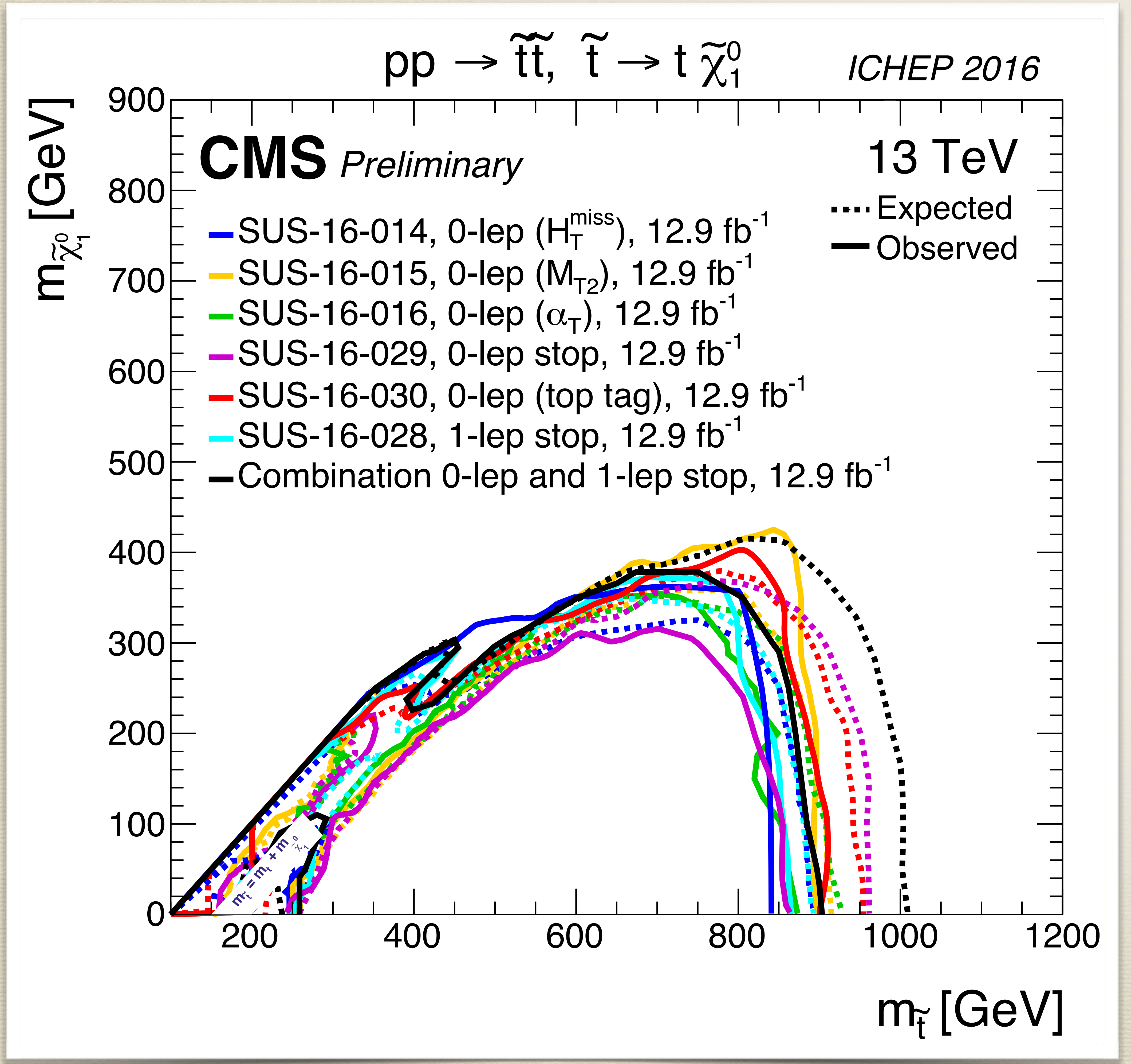


3L

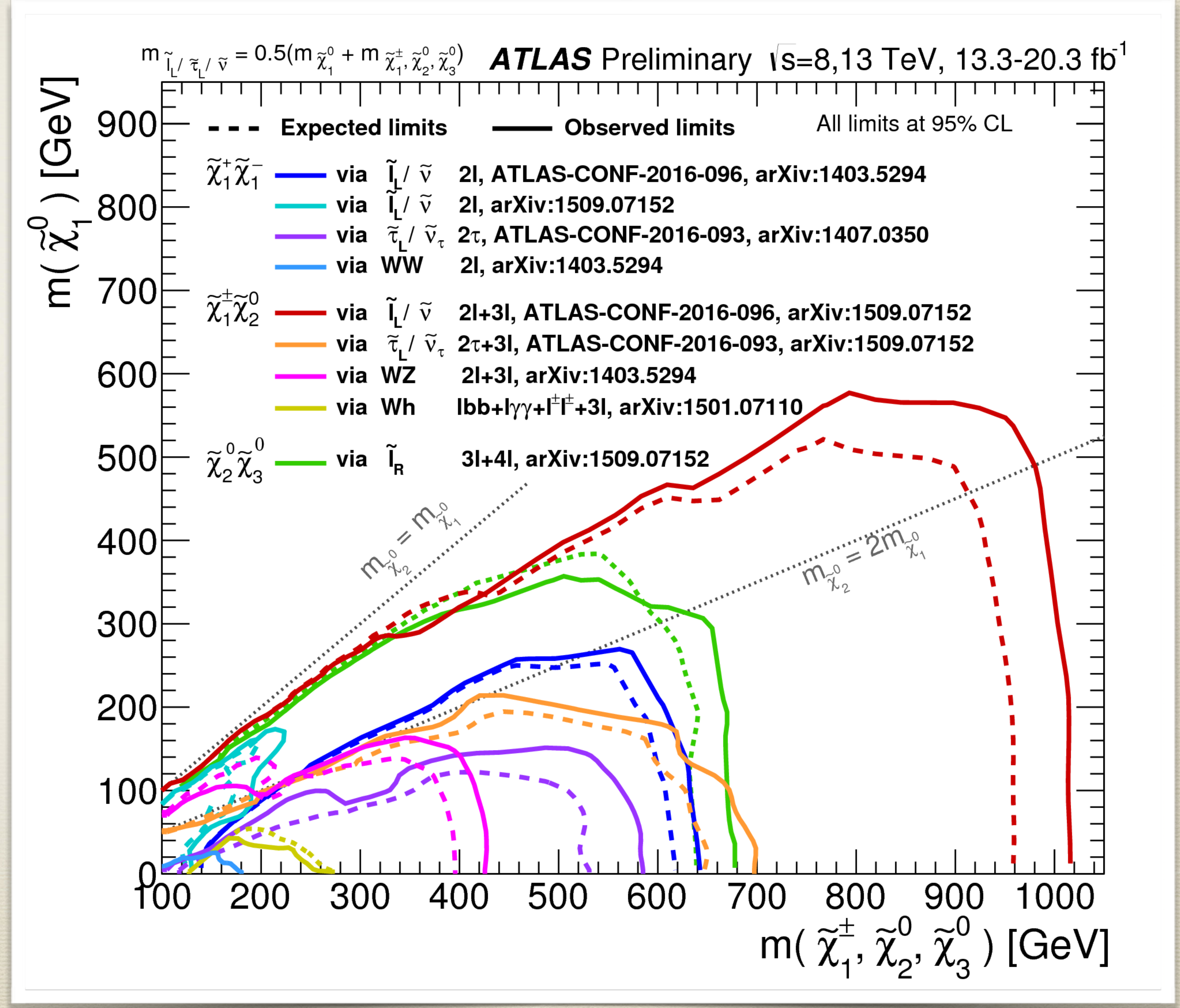


SUSY Searches

Stop summary

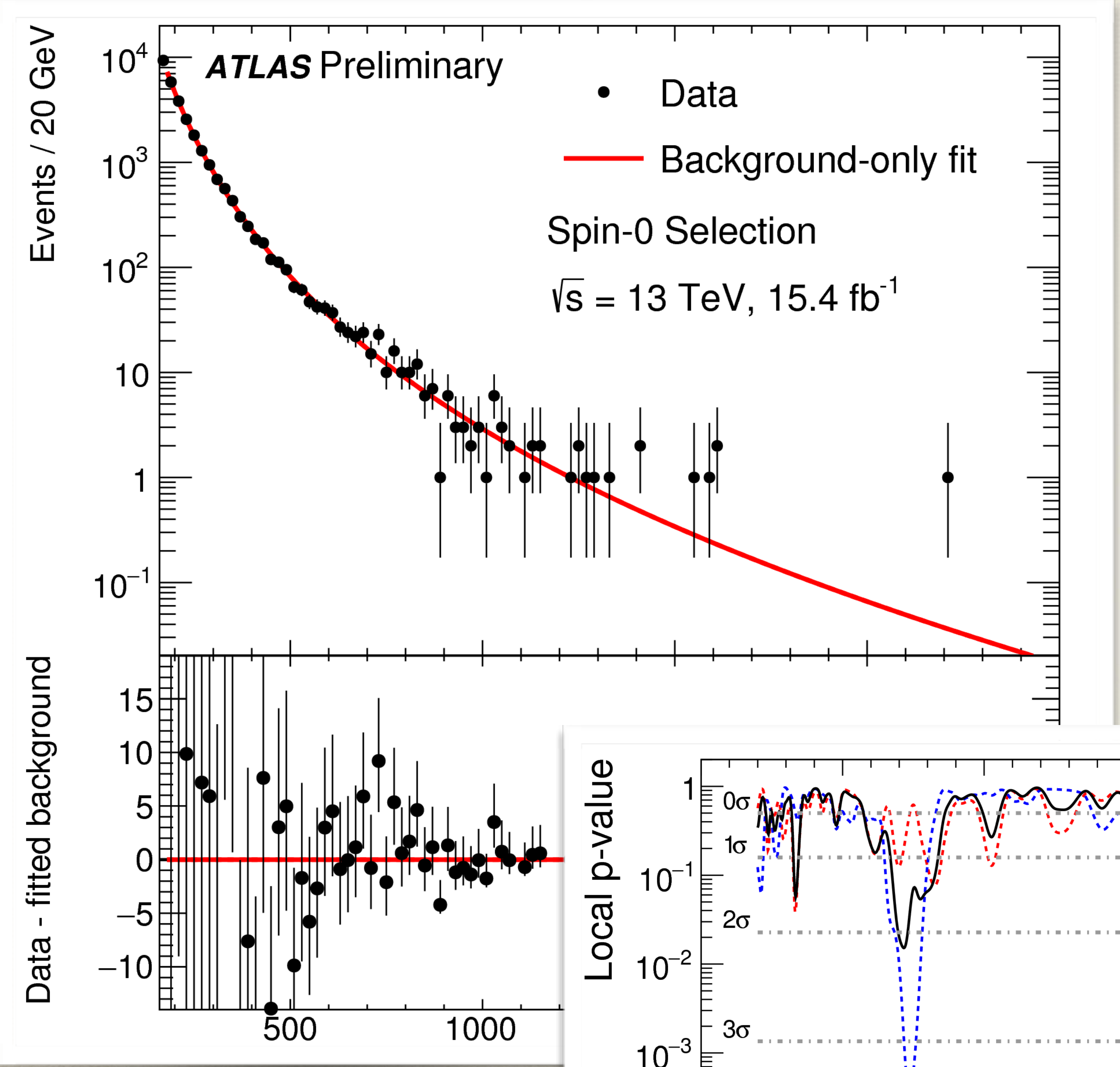


Electroweakino Limits

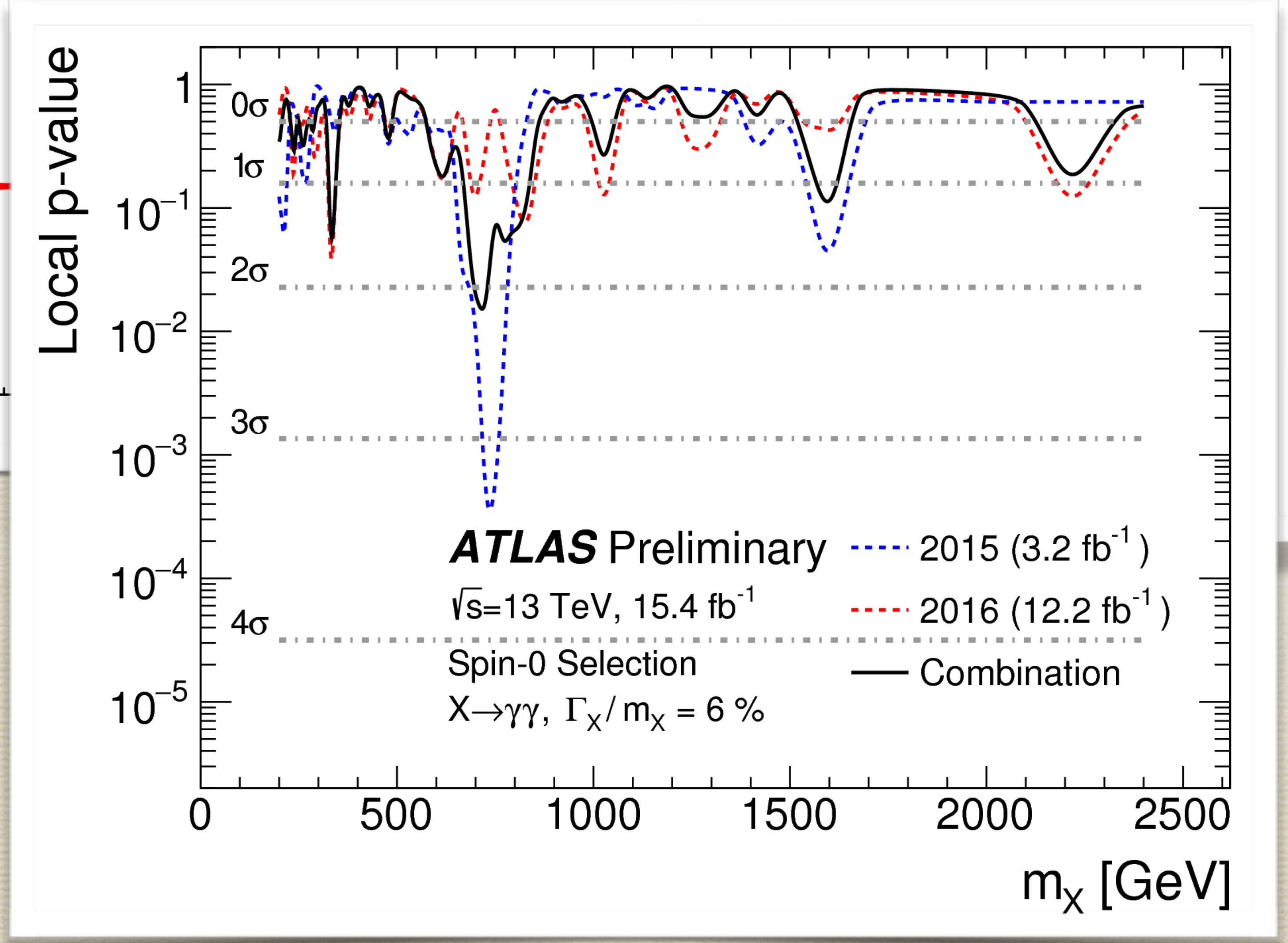


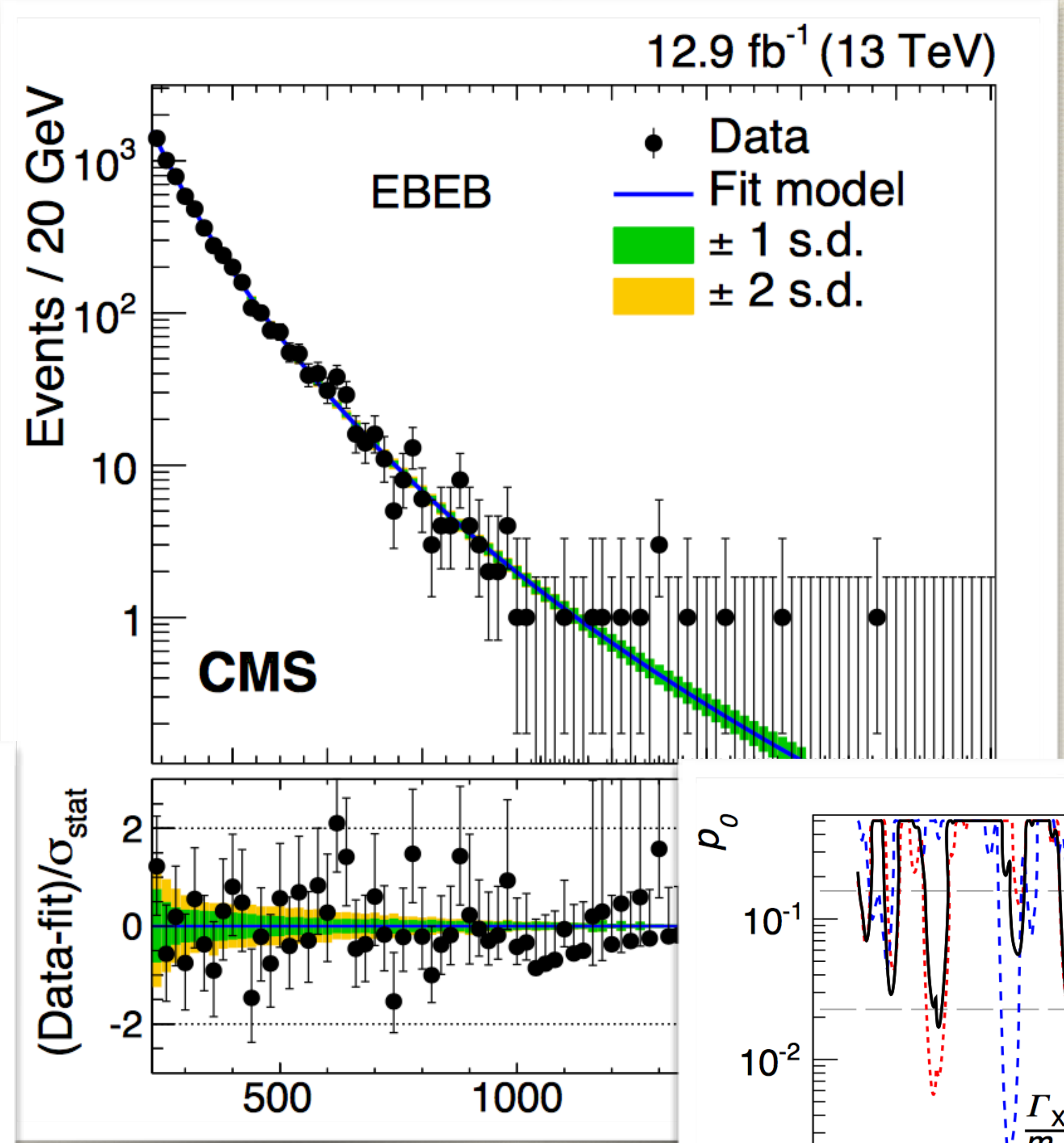
Di-boson resonances: di-photons

- well known excess at ~750 GeV observed in 2015 data at 13 TeV not confirmed in 2016 data …

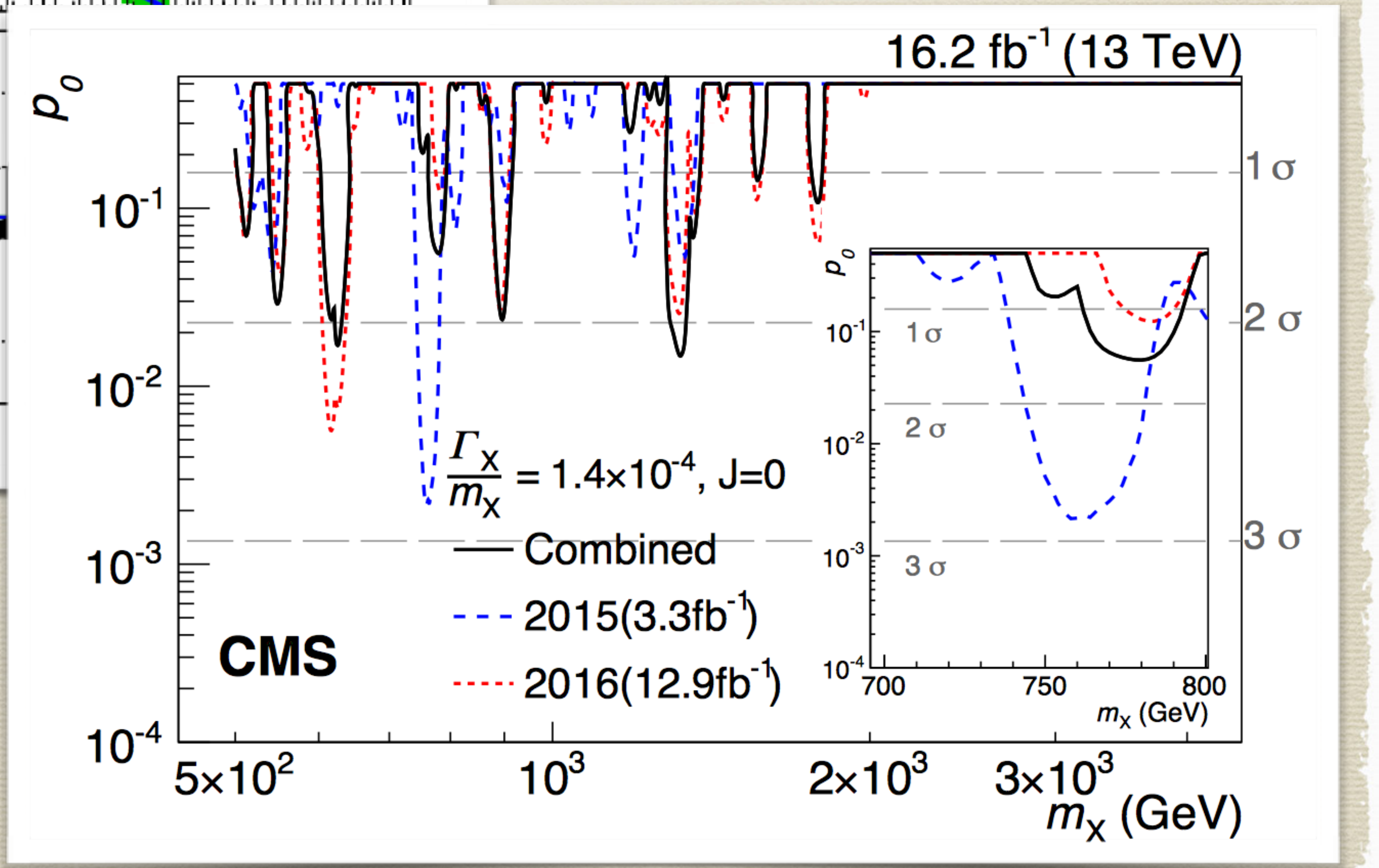


$M_{\gamma\gamma}$ [GeV]





$M_{\gamma\gamma}$ [GeV]



ATLAS-CONF-2016-059
arXiv:1609.02507

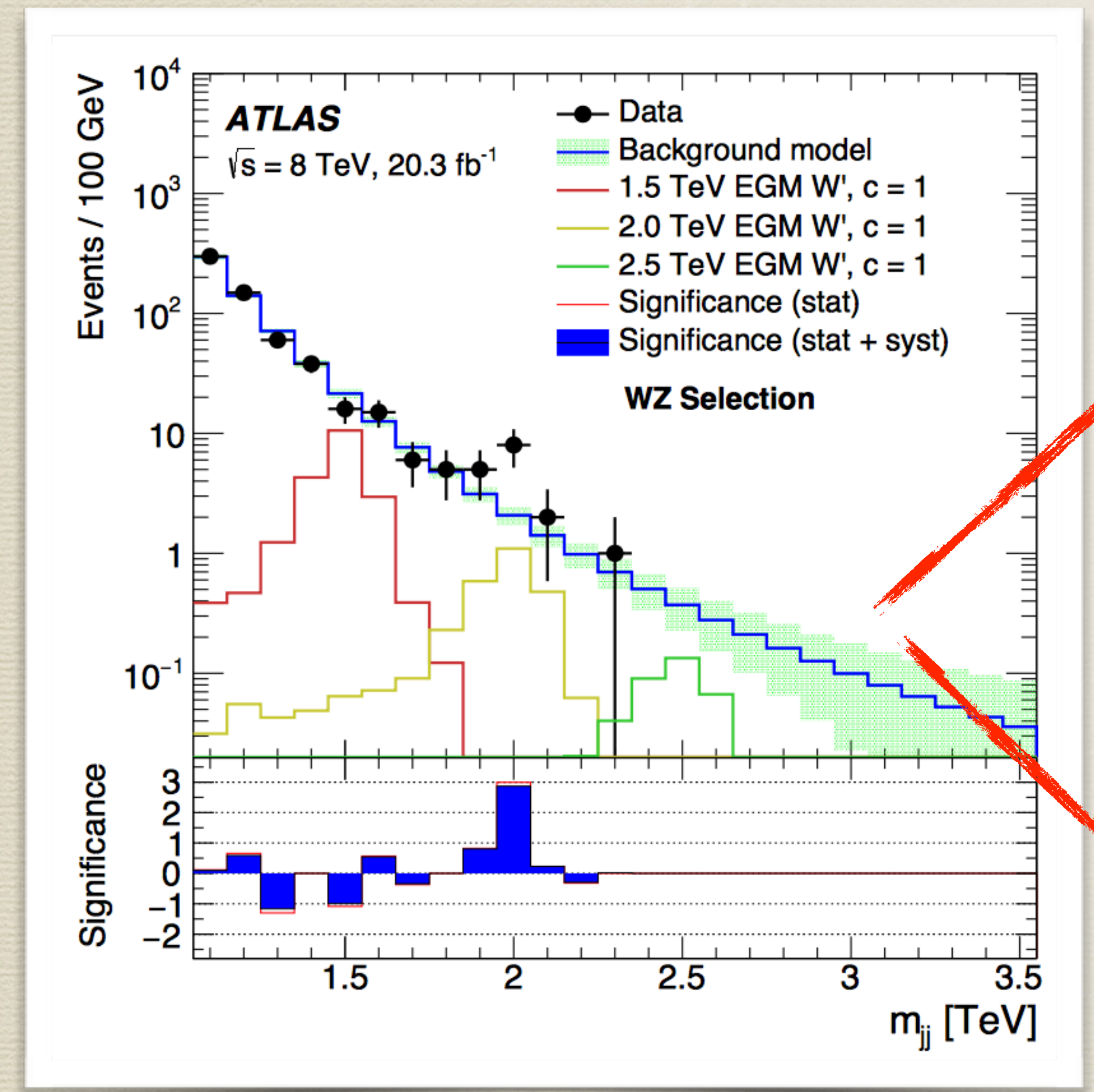
- 2015+2016 @750 GeV:
  - ATLAS: ~2.3σ / <1σ (global)
  - CMS: ~0.8σ (local)

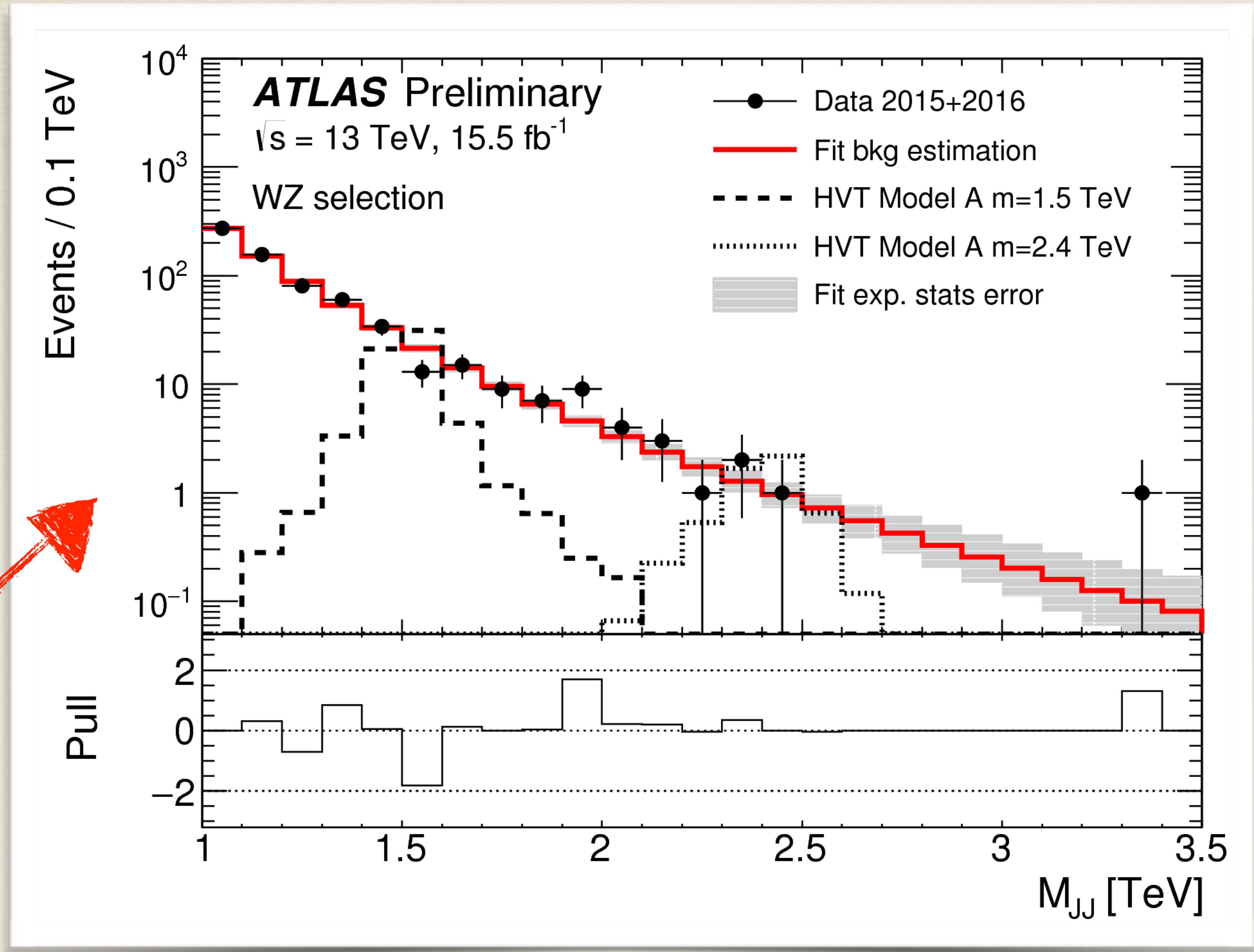
Di-boson resonances

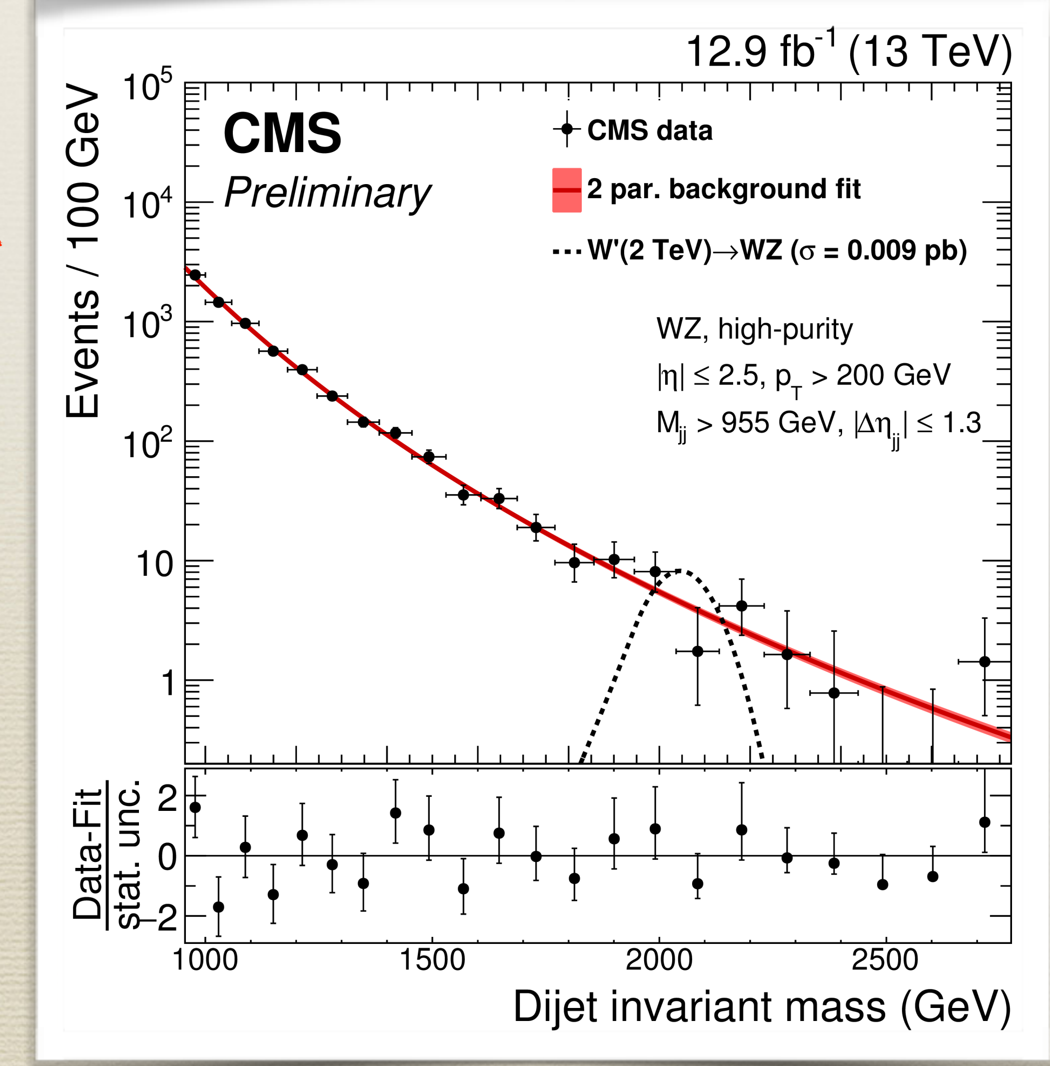
VV/VH searches
interpretation in HVT A and B models

- ATLAS 8 TeV 3.4σ (2.5σ) excess in hadronic WZ/ZZ/WW at ~ 2 TeV mass also not confirmed in 13 TeV data …

8 TeV

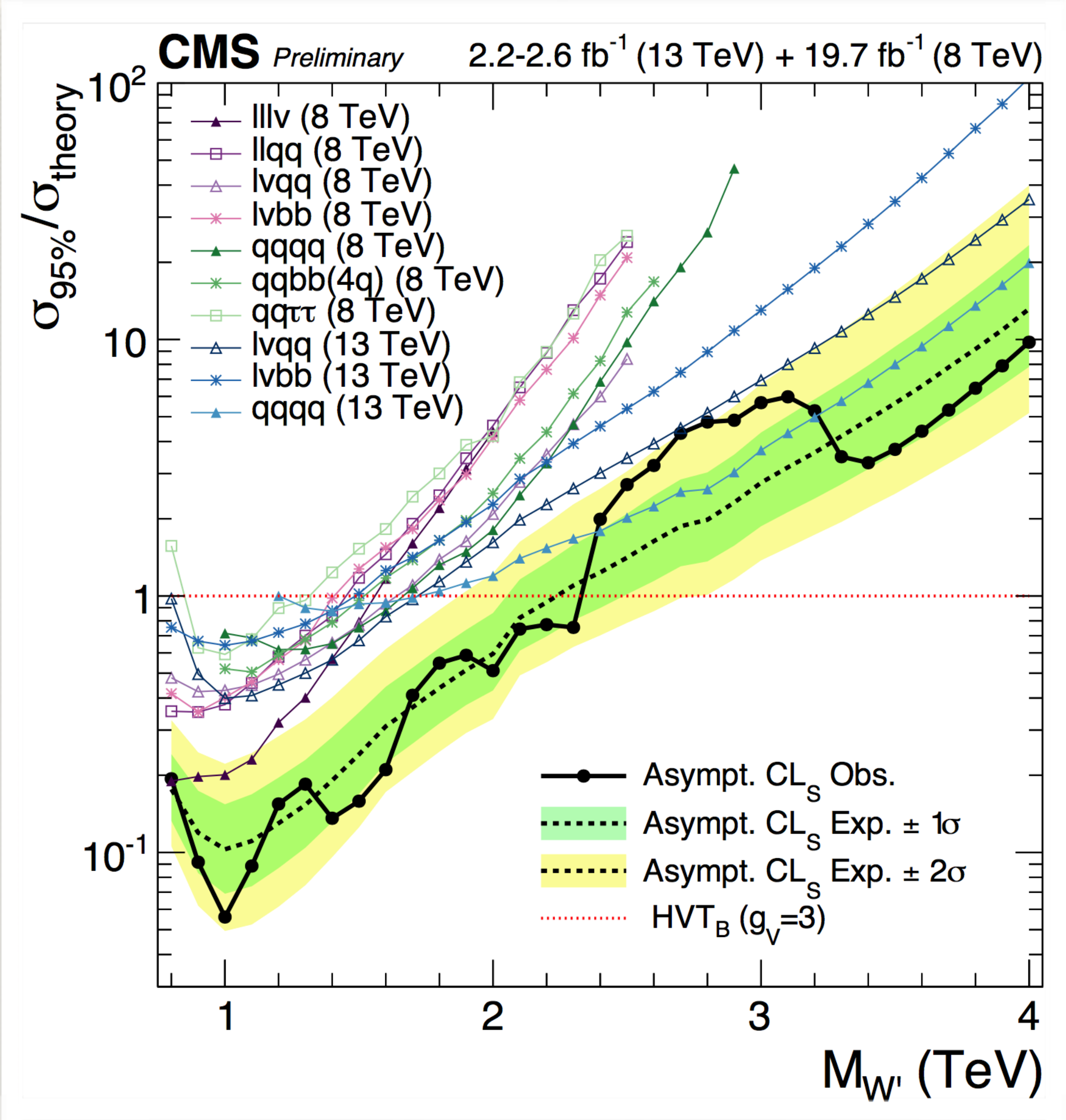




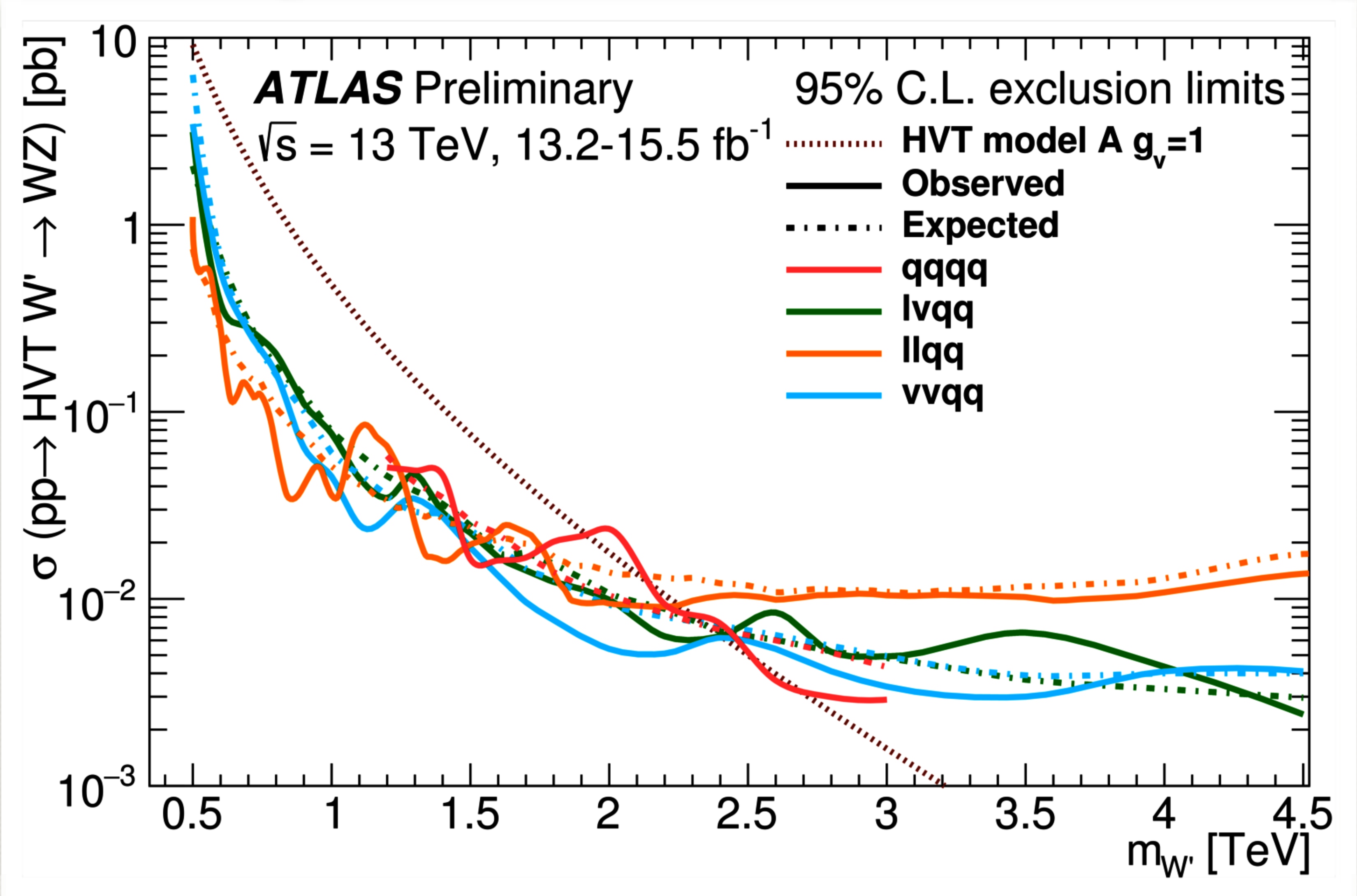


2015
+
2016

CMS-PAS-B2G-16-007



HVT excluded
up to ~2.4 TeV



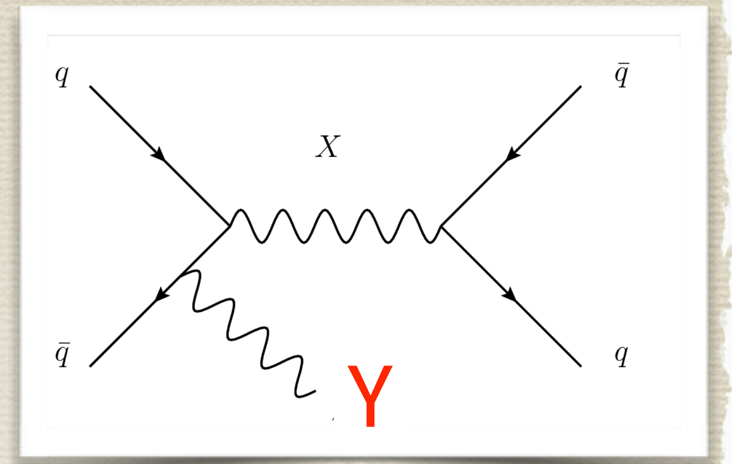
JHEP 12 (2015) 055
ATLAS-CONF-2016-055
CMS-PAS-B2G-16-021

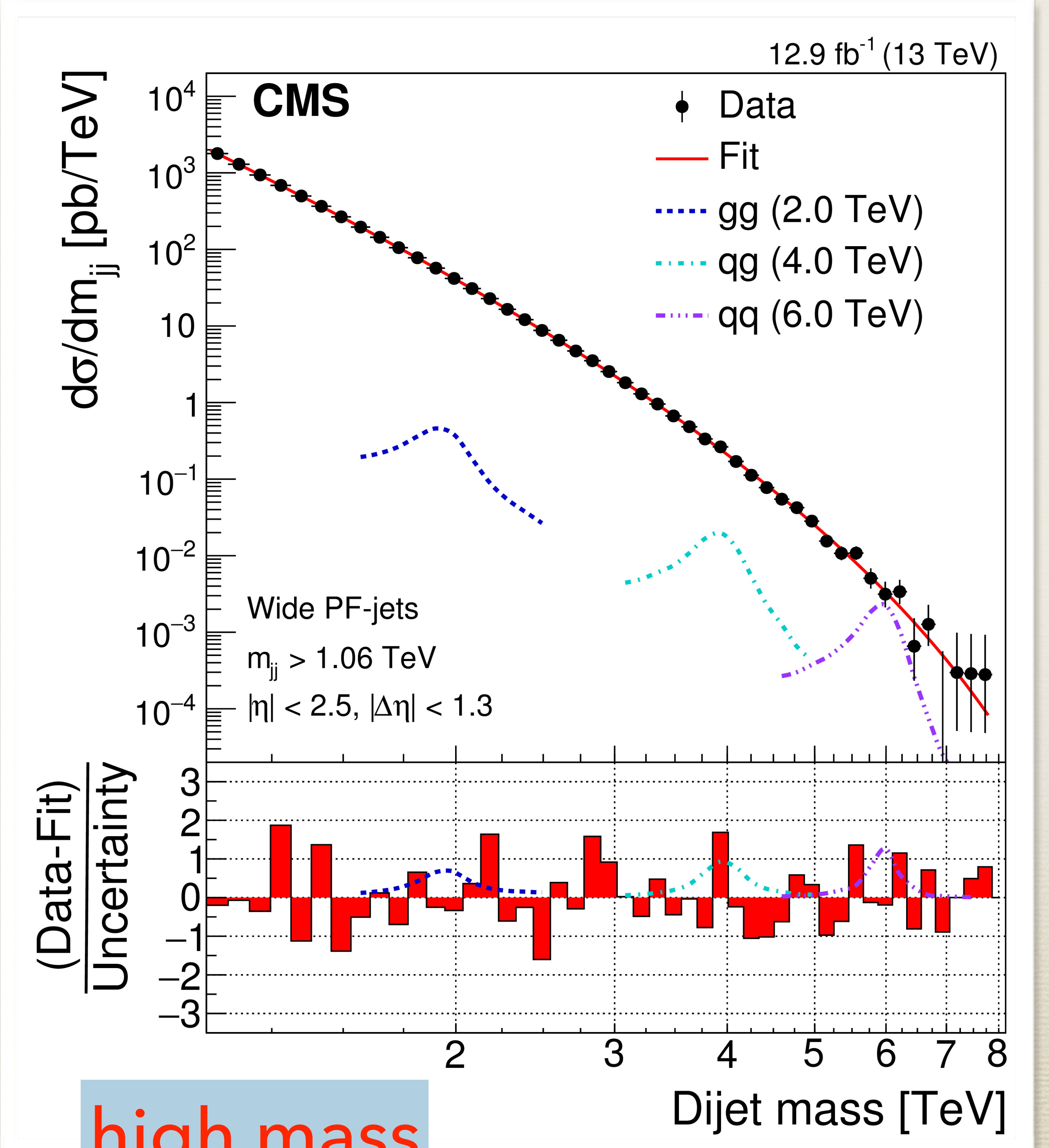
ATLAS-CONF-2016-055
ATLAS-CONF-2016-062
ATLAS-CONF-2016-082

Di-jet resonances

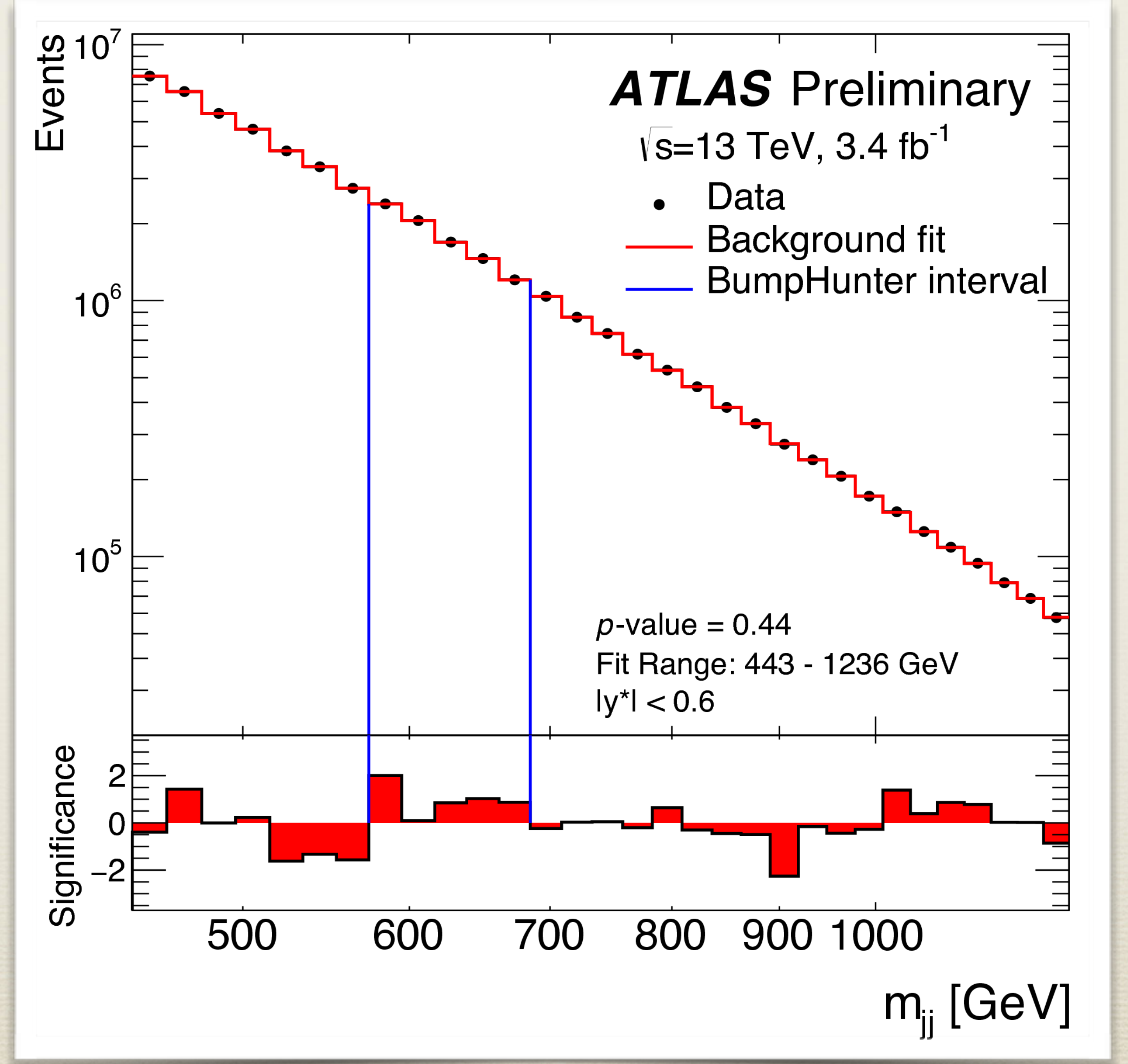
arXiv:1611.03568
ATLAS-CONF-16-030
ATLAS-CONF-16-070

- Check the di-jet invariant mass distribution against expectations from QCD
  - jj resonances predicted in several NP models (excited quarks, strong gravity, contact interactions …)
  - search for "bumps" in m_{jj}, describing QCD shape via a smooth functional form
  - probed jets with transverse momenta up to multi-TeV

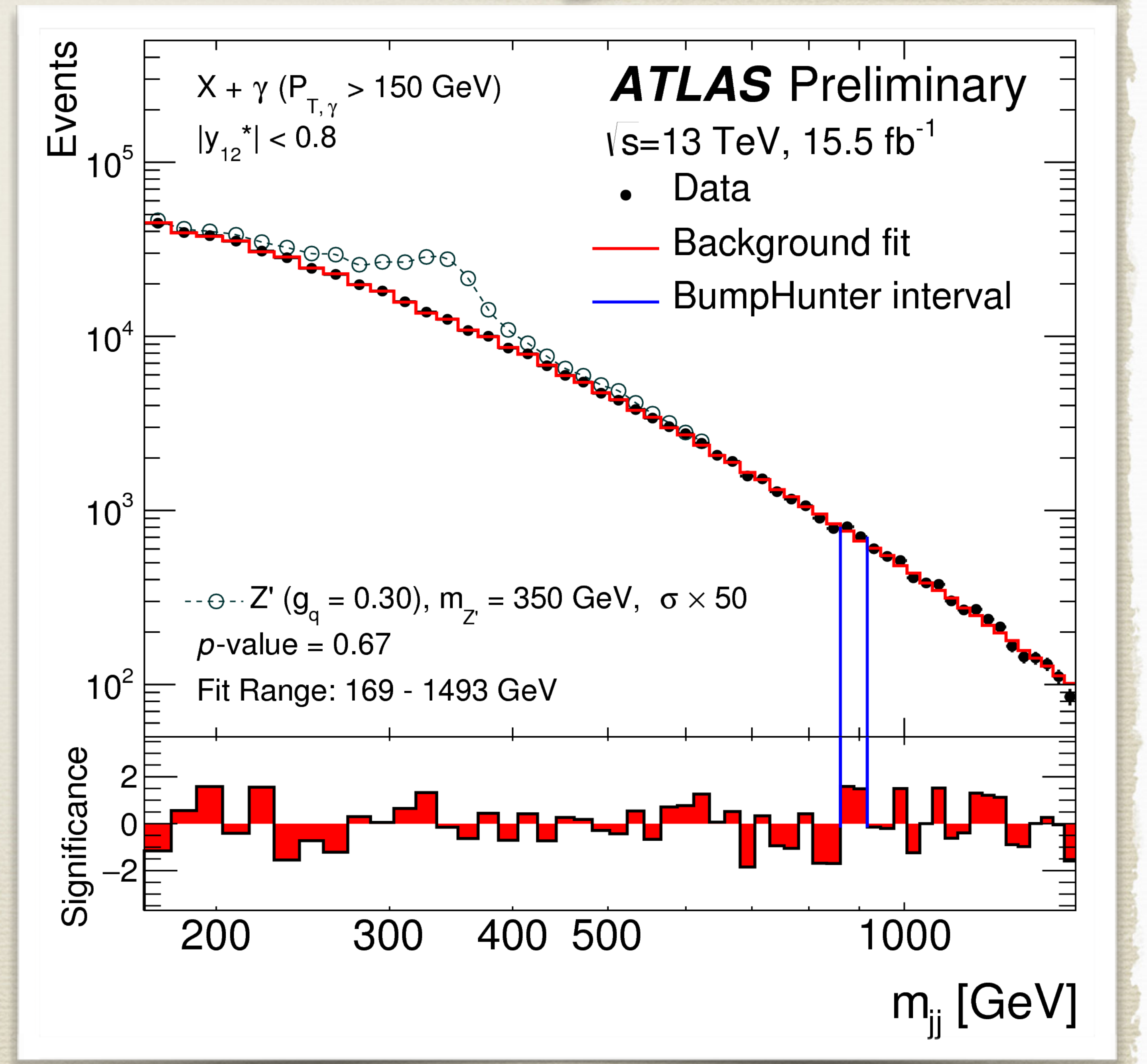




high mass

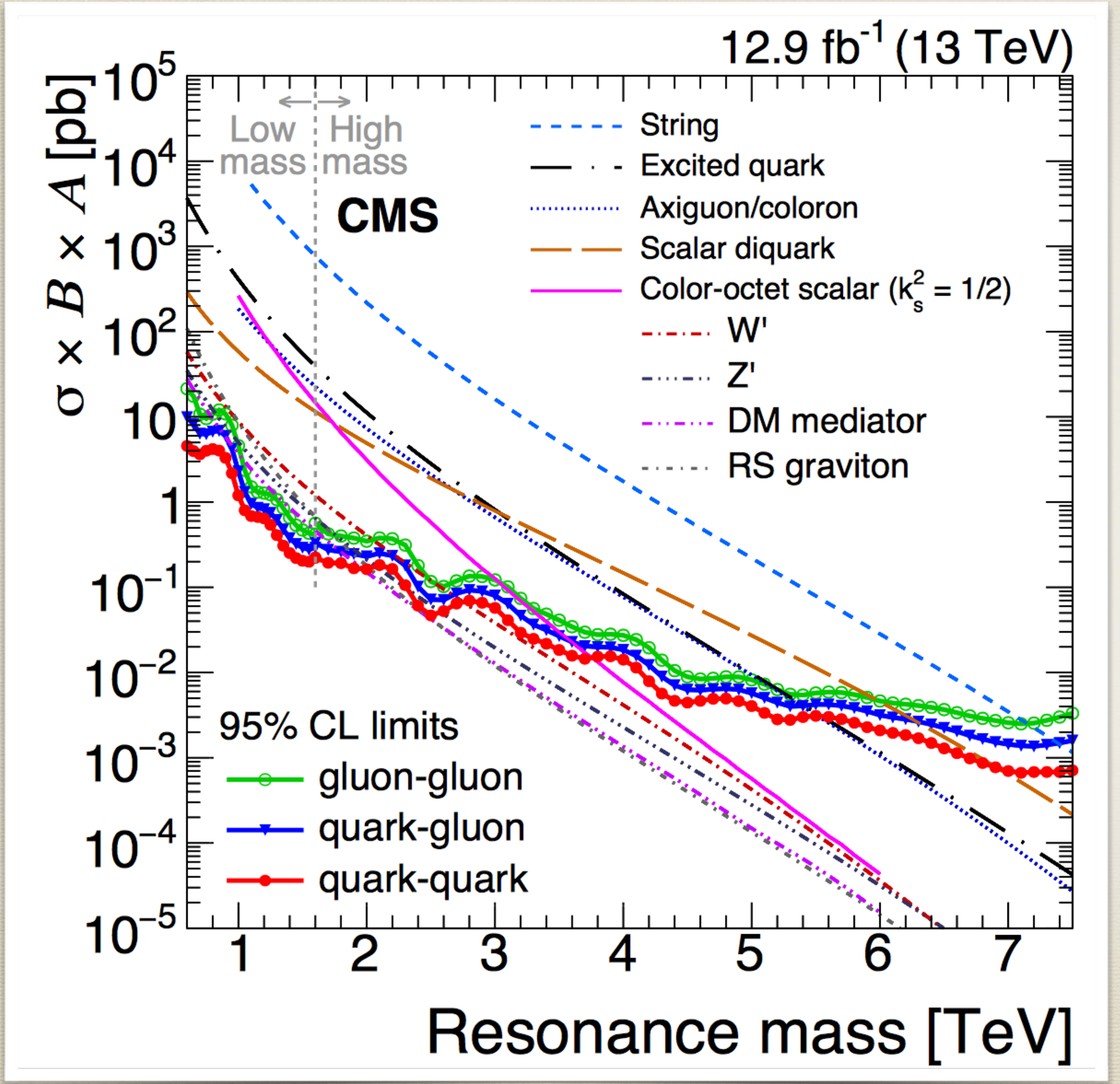


lower mass: trigger level analysis



even lower mass: jj+ISR

Di-jet resonances summary



Model	Final state	Limit [TeV] Obs.	Exp.
String	qg	7.4	7.4
Scalar diquark	qq	6.9	6.8
Axigluon/coloron	$q\bar{q}$	5.5	5.6
Excited quark	qg	5.4	5.4
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.0	3.3
W′	$q\bar{q}$	2.7	3.1
Z′	$q\bar{q}$	2.1*	2.3
DM mediator ($m_{DM} = 1$GeV)	$q\bar{q}$	2.0	2.0
RS graviton	$q\bar{q}$, gg	1.9	1.8

arXiv:1611.03568

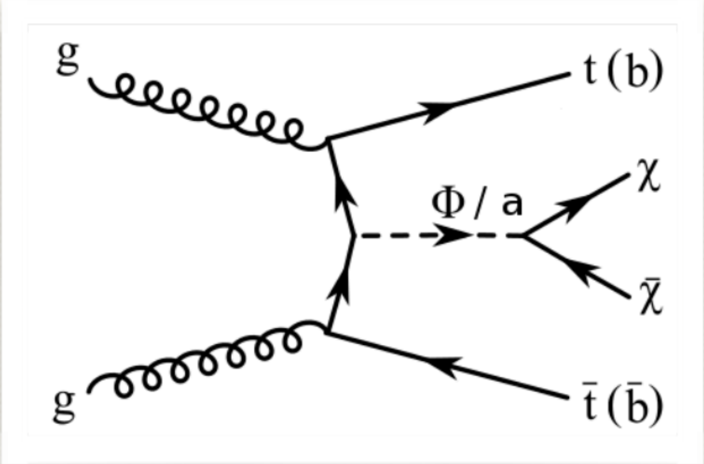
Dark Matter

PRD 94 032005 (2016)
CMS-PAS-EXO-16-005

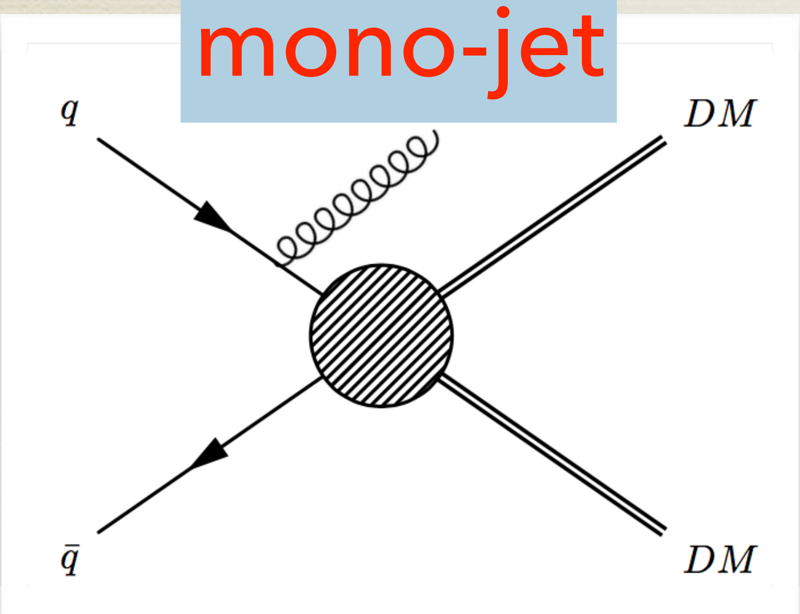
- ATLAS and CMS program competitive and complementary with direct searches for WIMPs
- several search strategies:
  I. look for the initial state radiation to tag DM pair production: mono-X (X=jet, γ, V, t/b, H)
  II. associated production of DM with other particles: ex. tt+DM
  III. look at DM mediators in di-jets events
  IV. constrain DM from invisible Higgs decays into WIMPs

tt+DM

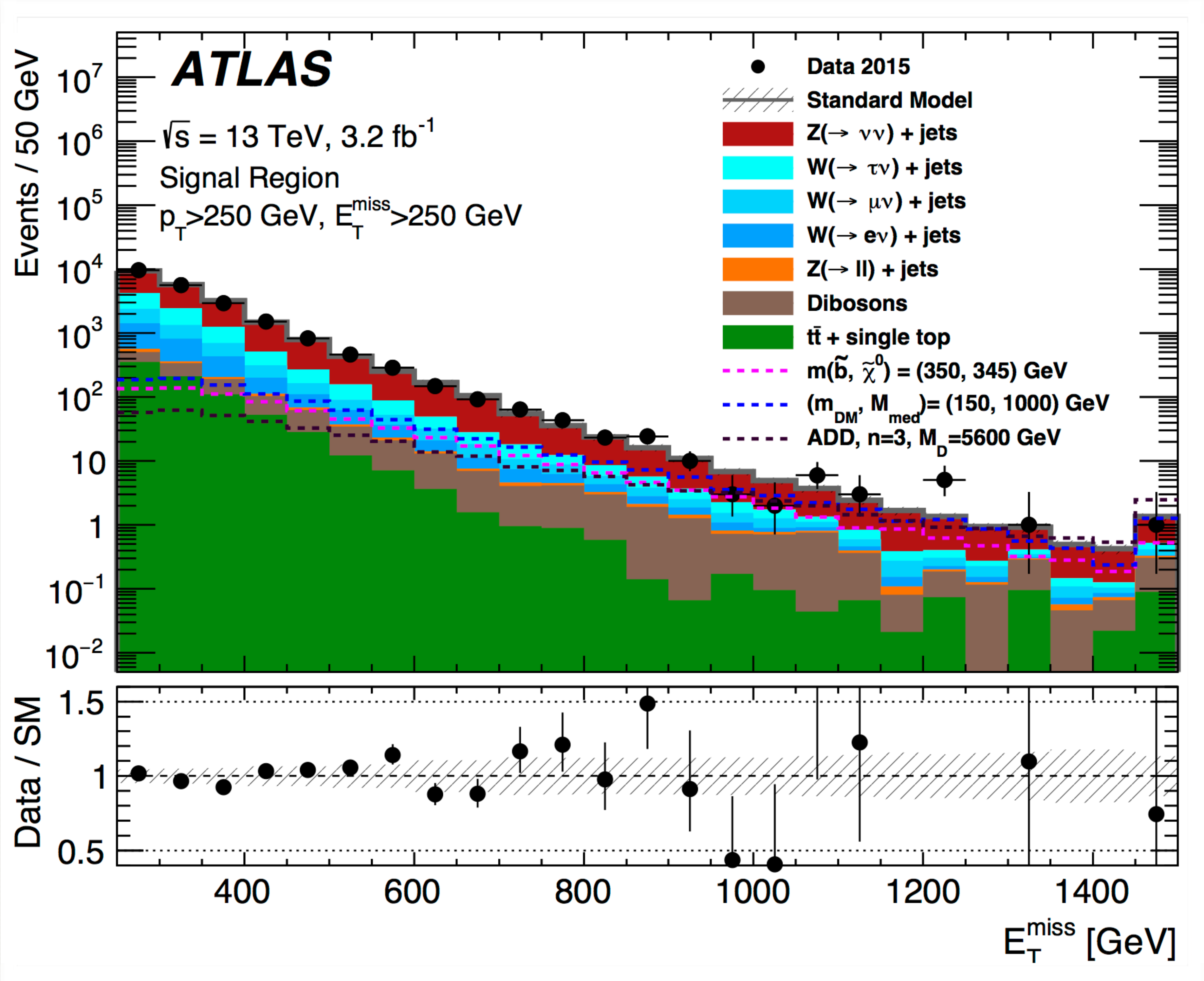
- most sensitive channel for scalar mediator DM

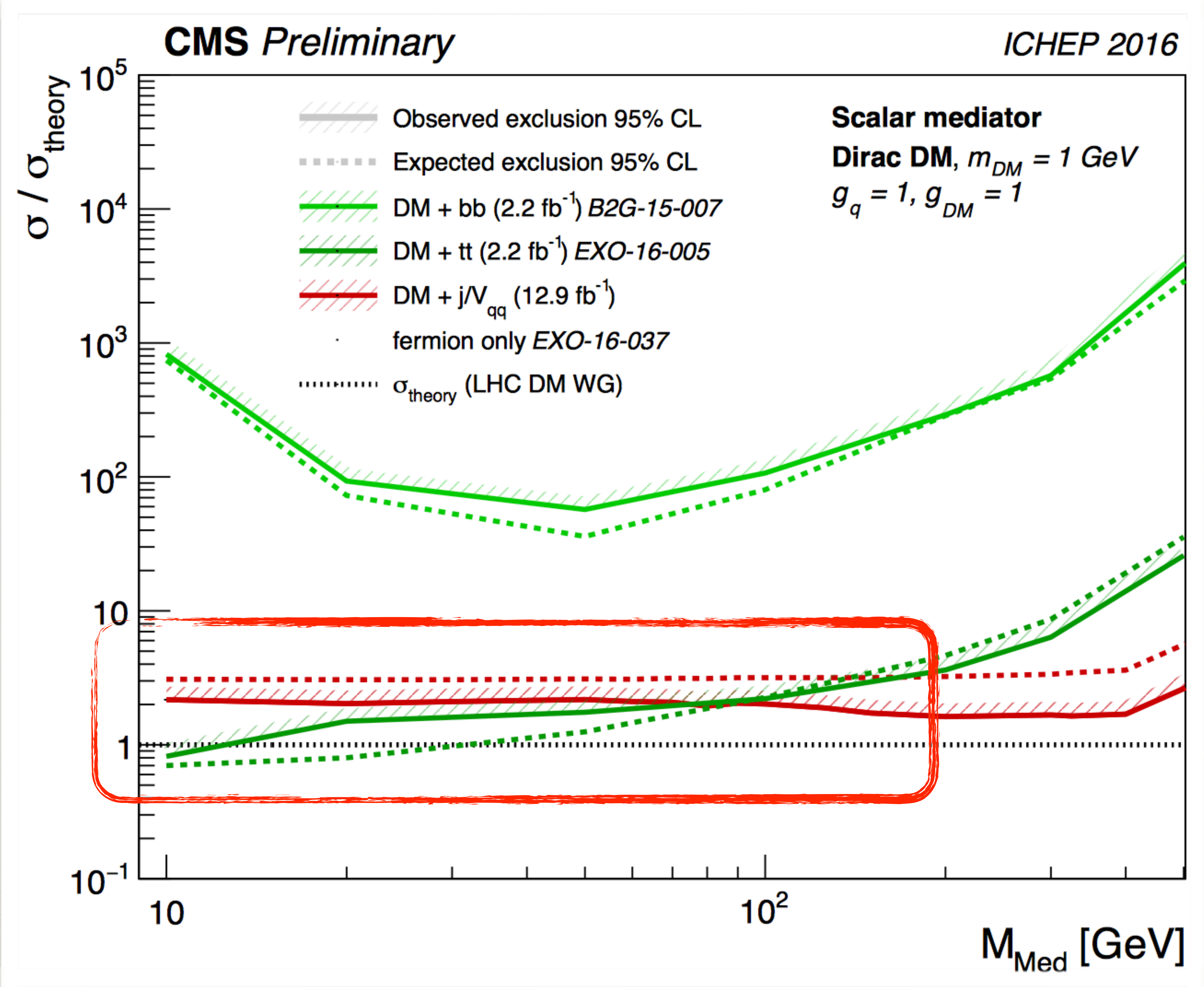


mono-jet



- $\alpha_s \gg \alpha \rightarrow$ large signal yield
- most sensitive channel for vector mediator DM
- look at jets recoiling against DM system

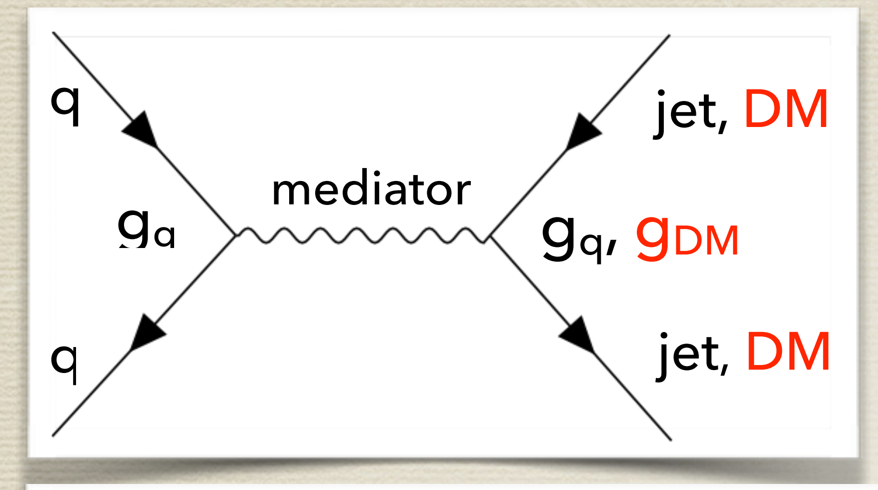




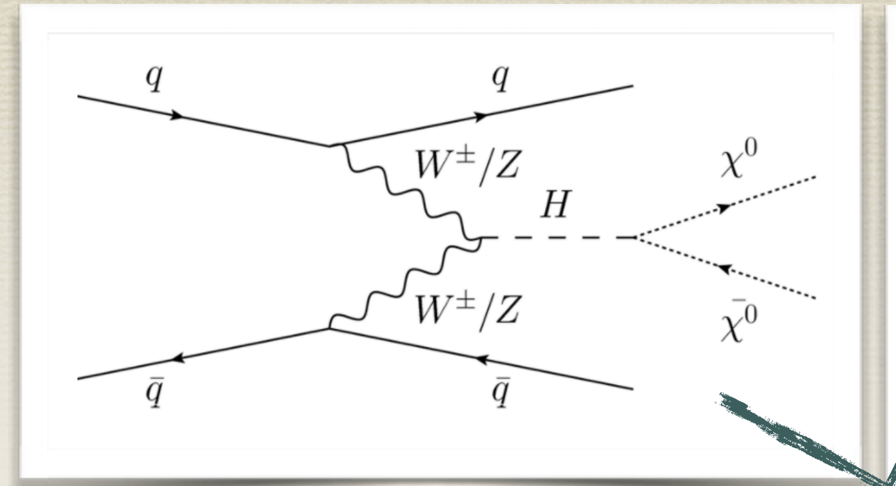
Dark Matter

Interpretation of H→inv searches in the context of the Higgs Portal model
B(H→inv) → Γ^{inv} → couplings → cross-section DM-Nucleon

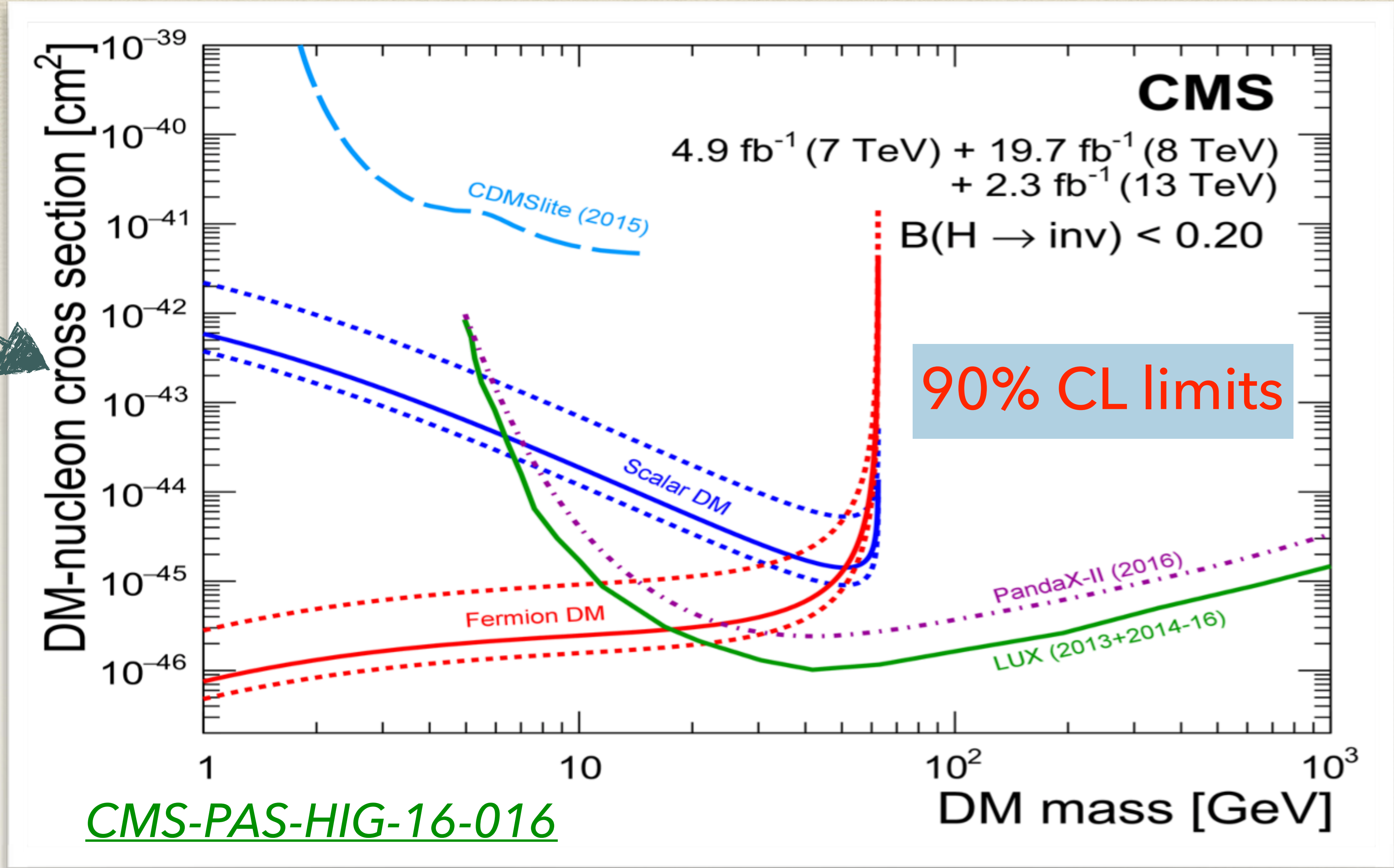
di-jet - if the DM mediator couple to quarks in addition to mono-jet signal it will also contribute to di-jet

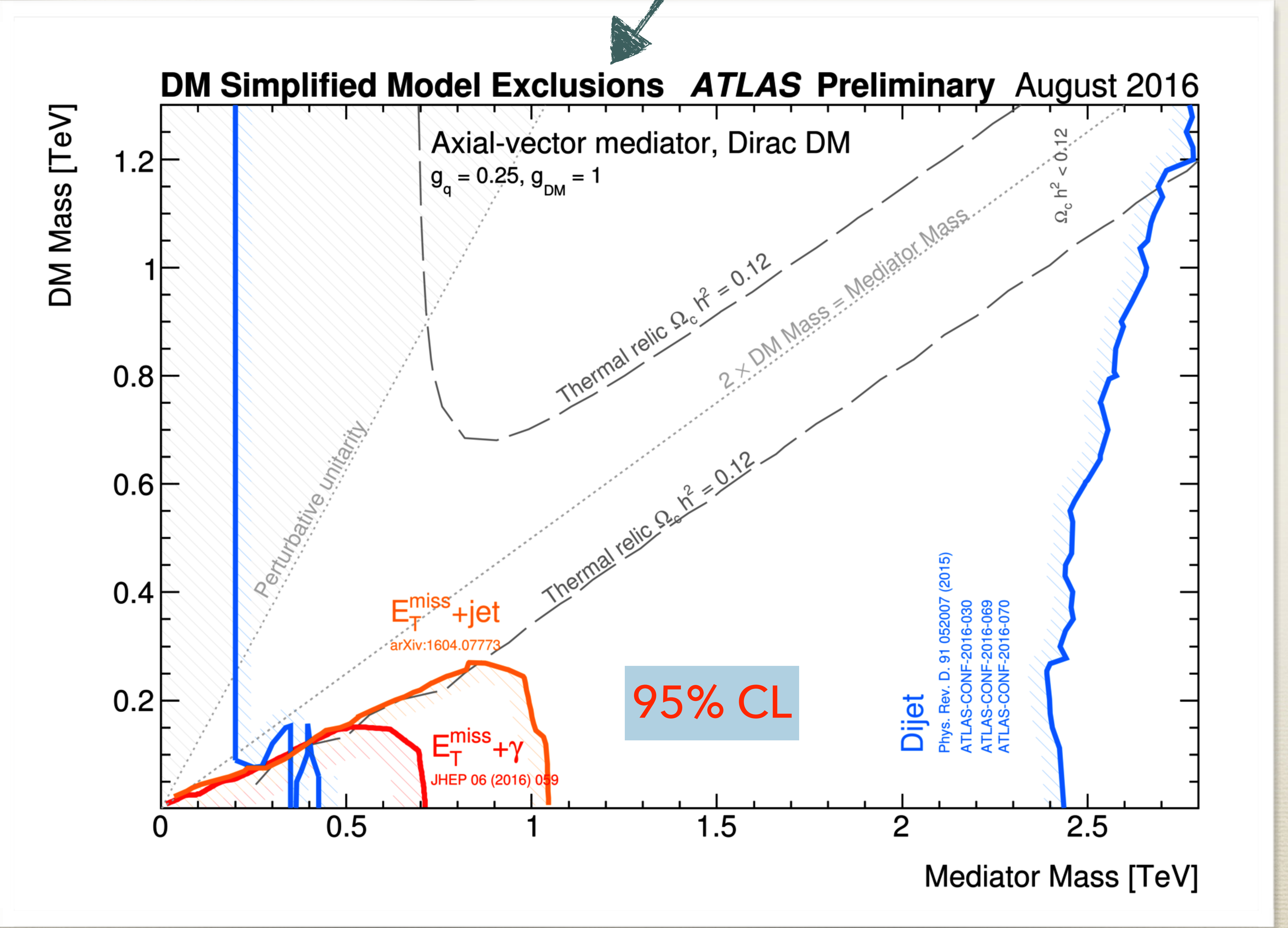


bounds on DM-mediator mass plane from mono-jet/γ and di-jet searches (g_q=0.25, g_{DM}=1)



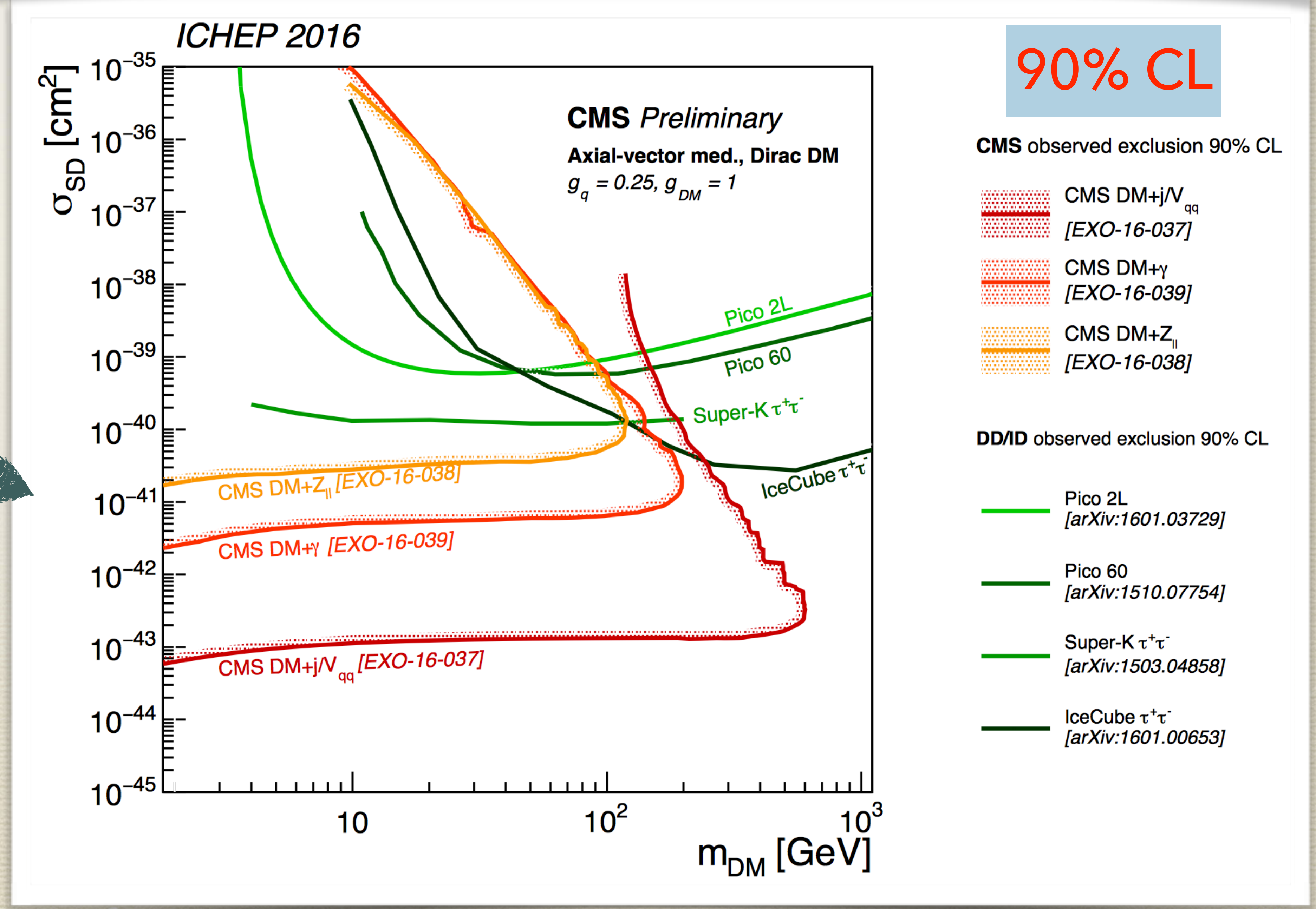
H→inv





complementarity to direct DM searches

IMPORTANT: all interpretations highly dependent on assumptions



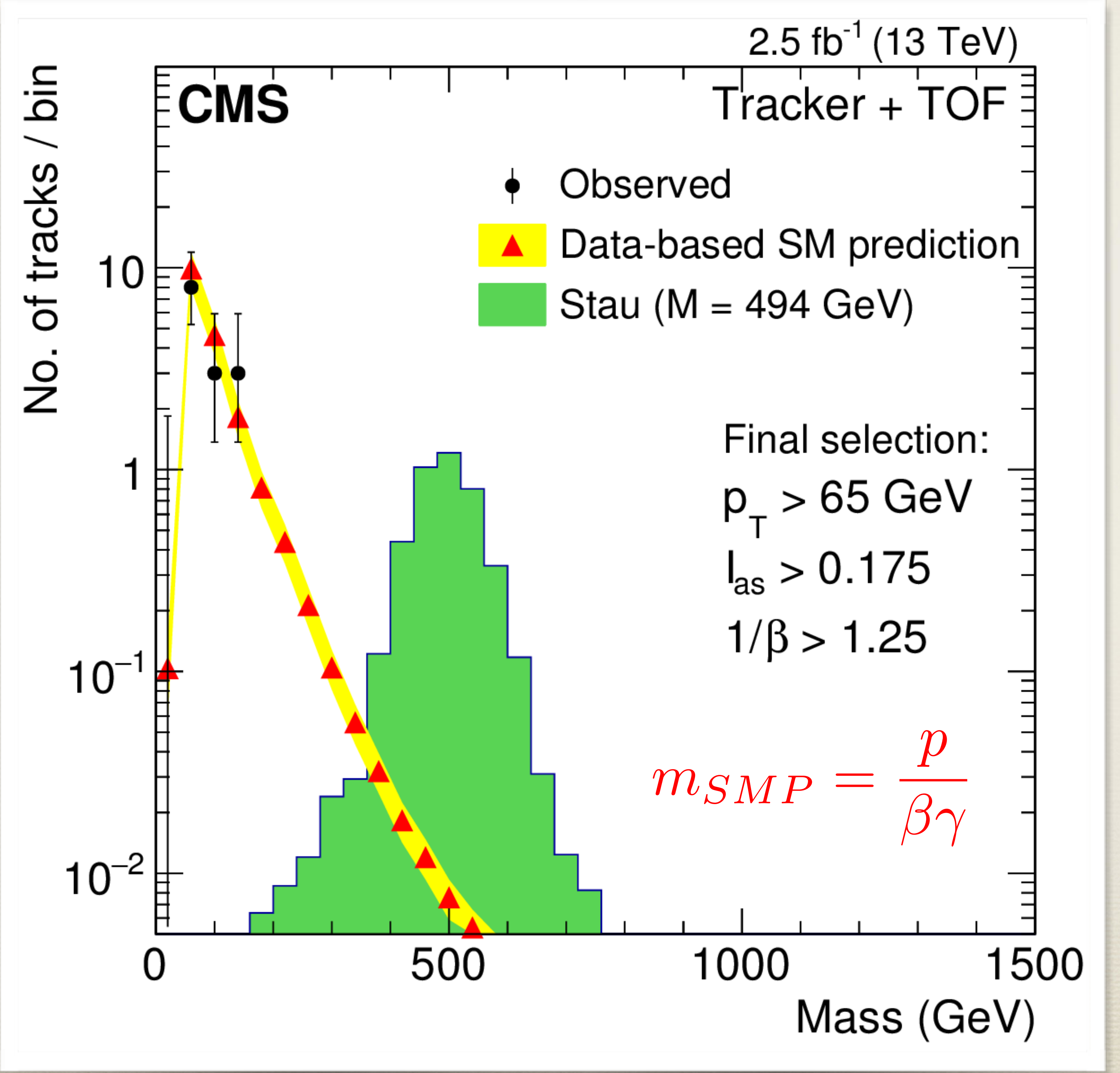
spin-independent

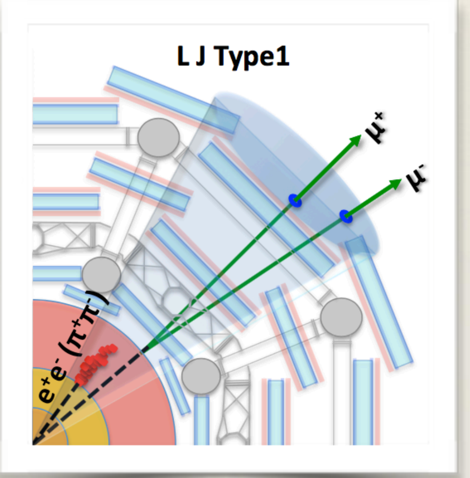
spin-dependent

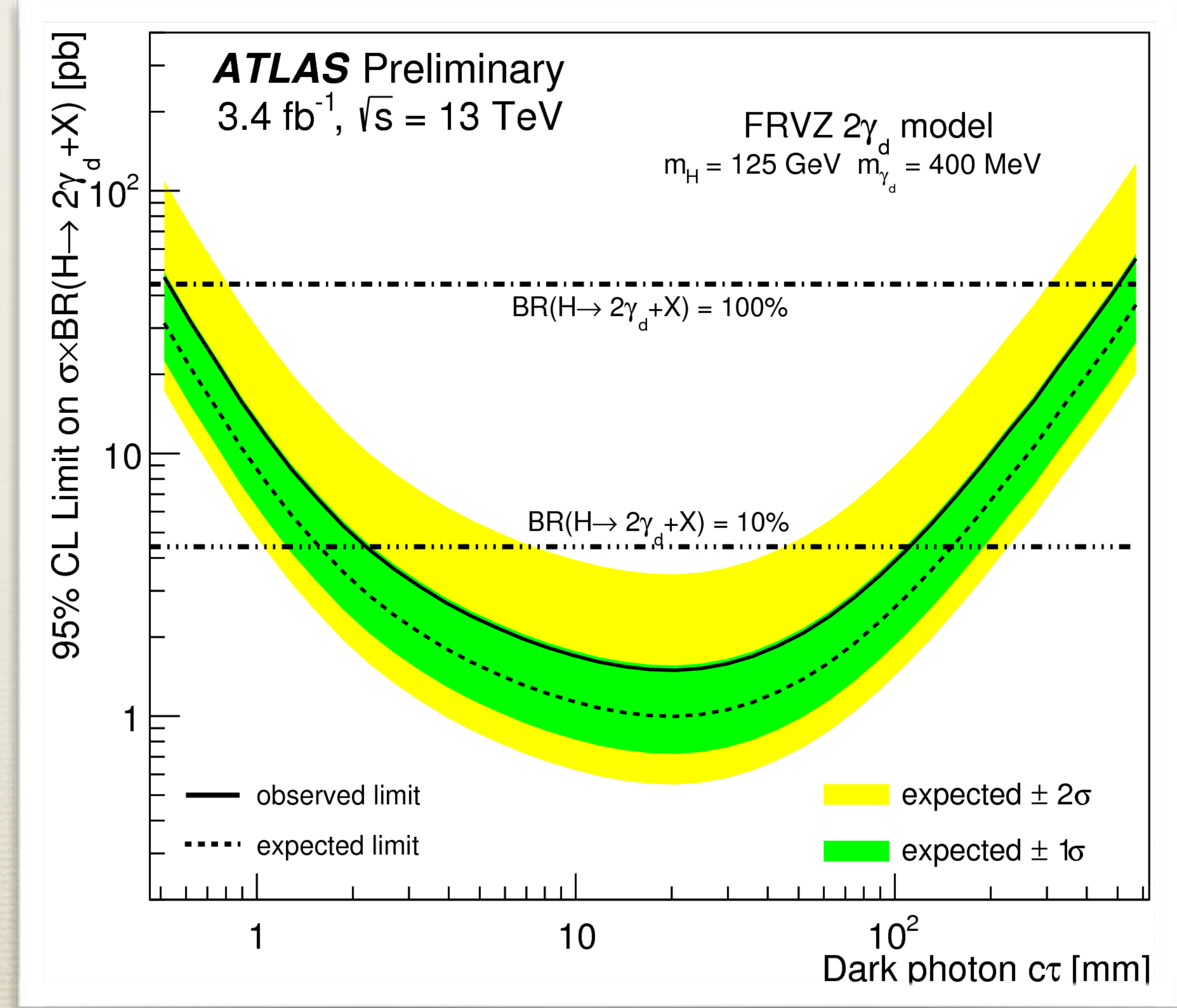
Unconventional Searches: LLP

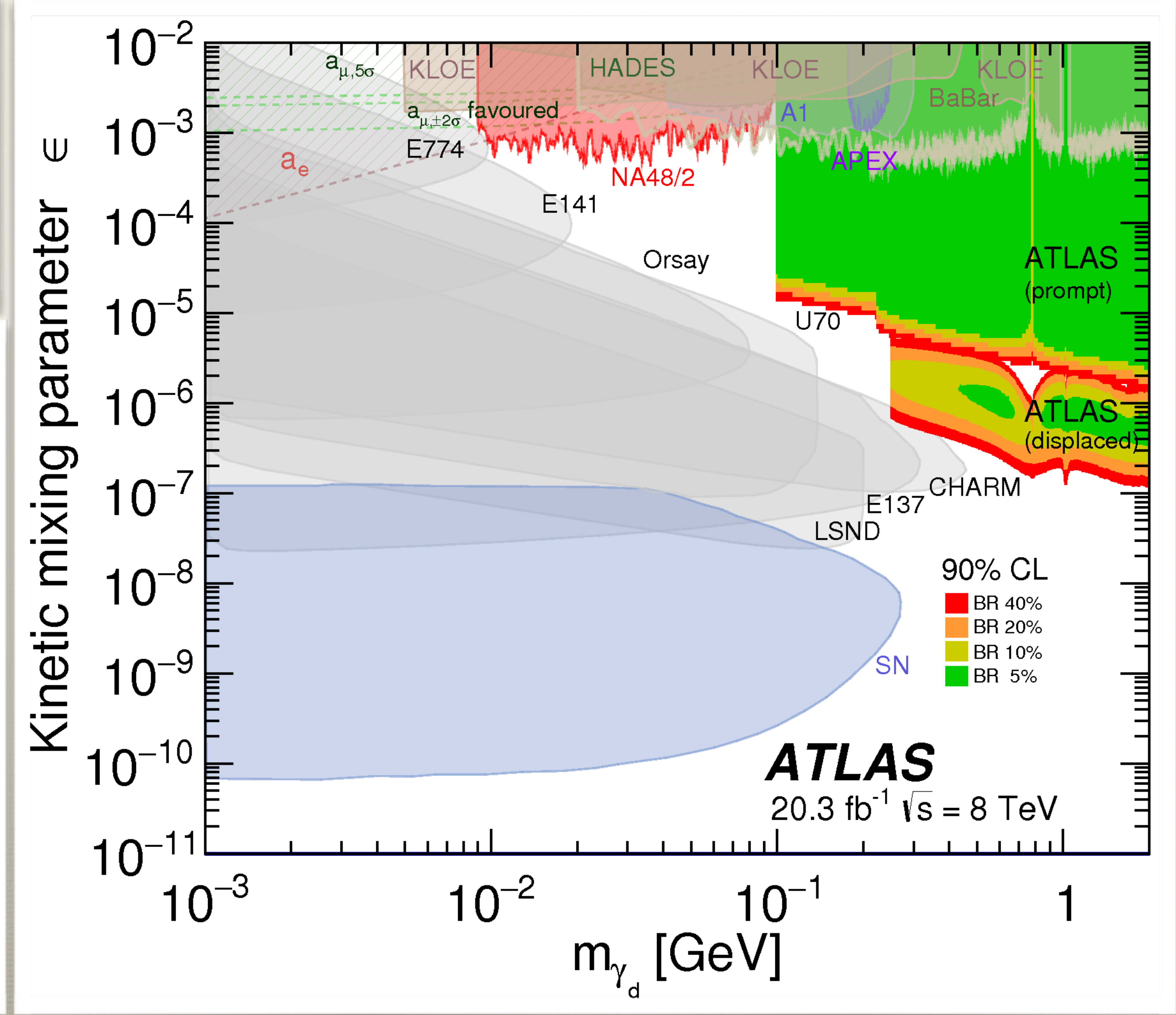
arXiv:1609.08382
ATLAS-CONF-2016-042

- long-lived particles and unusual topologies offers a means for new physics to escape the strict limits placed by prompt searches and at the same time a great potential for discovery
  - two examples of such searches:
    - Heavy Stable Charged Particles predicted in Split-SUSY and GMSB models: large dE/dx and low β (long TOF)
    - LeptonJets (collimated jets of leptons and hadrons) predicted by Dark Sector/Hidden Sector models









limits set on long-lived gluinos (~1.5-1.8 TeV), scalar tops (~ 1 TeV) and taus (~0.5 TeV)

interpreted in the context of Vector portal models

Summary

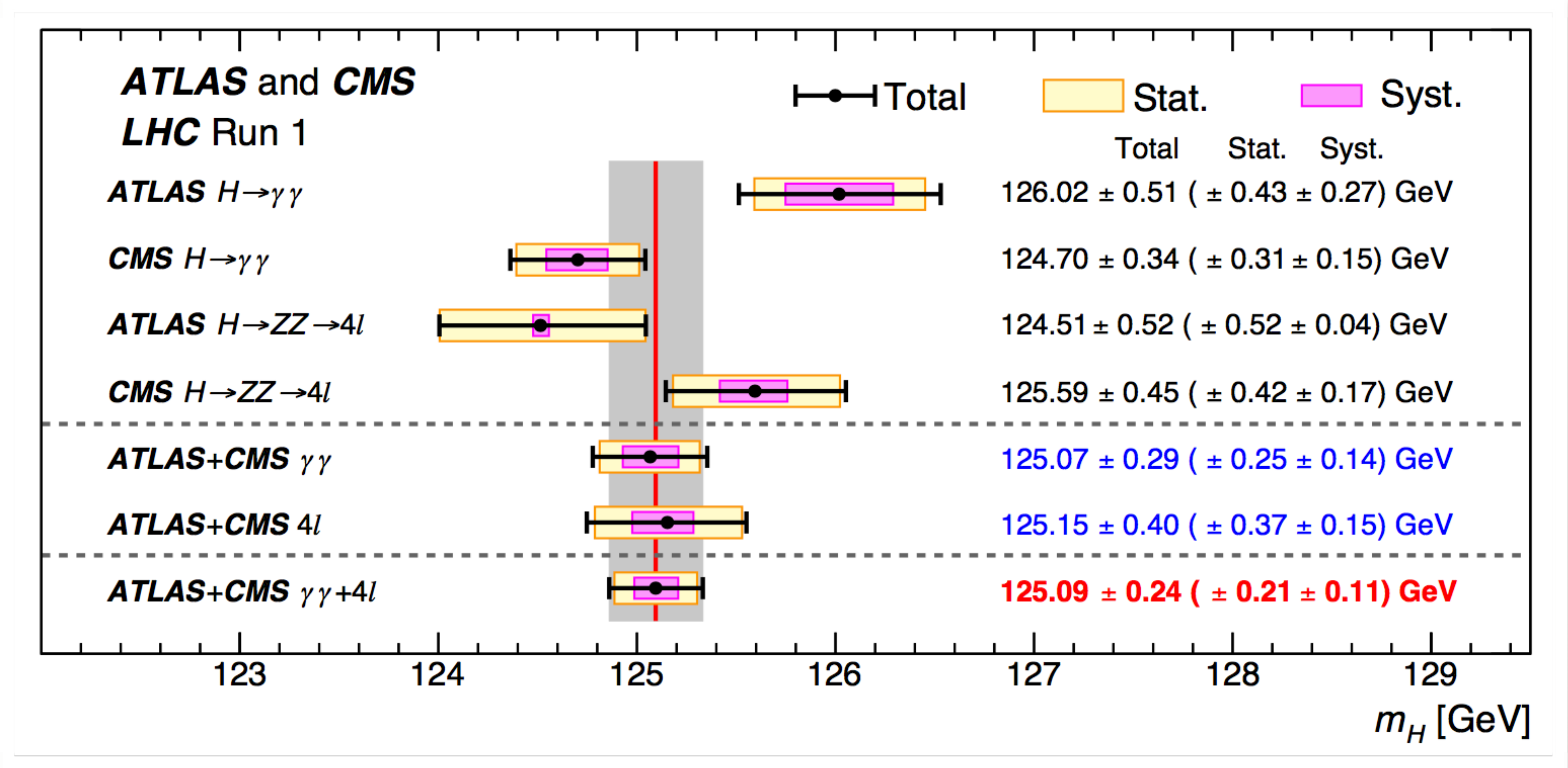
- Comprensive set of precision measurements in the Higgs sector and searches for new physics effects from ATLAS and CMS at 13 TeV
  - few results shown today but many more available …
  - expanded exploration of NP models and our knowledge of nature of fundamental interactions

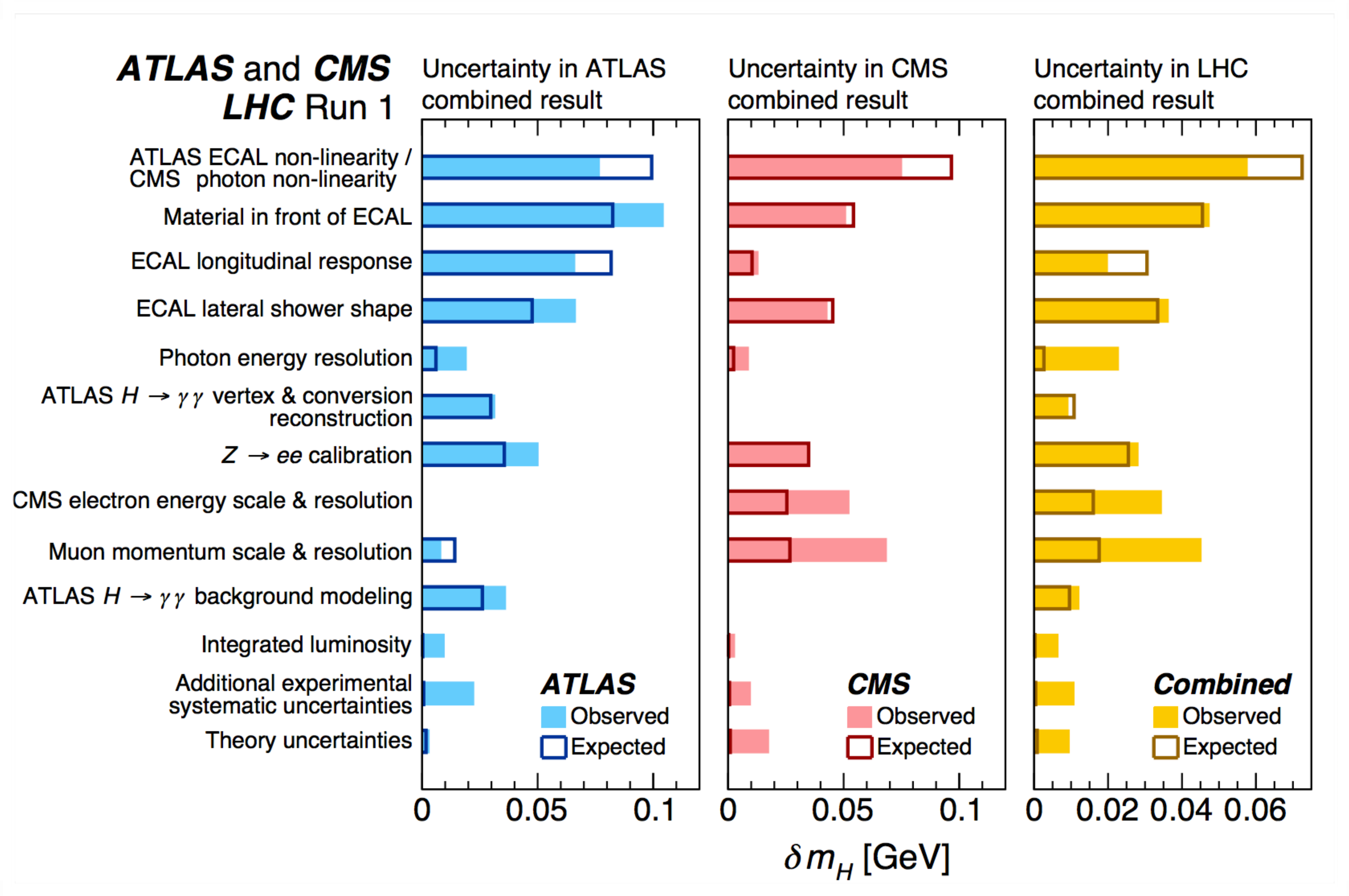
- No evidence of new particles or significant anomalies up to now, but …
  - ~2/3 of the available 2016 data still under analysis and much more to come by the end of Run-2 and beyond
  - many regions still unexplored and substantial space available for surprises & discoveries!

Additional Slides

H(125) Mass

- best mass measurement from ATLAS+CMS Run-1 combination of H→γγ and ZZ*→4l
- dominant sources of systematic uncertainty from calibrations, energy scale & resolution





$m_H = 125.09 \pm 0.24\ (\pm 0.21 \pm 0.11)$ GeV

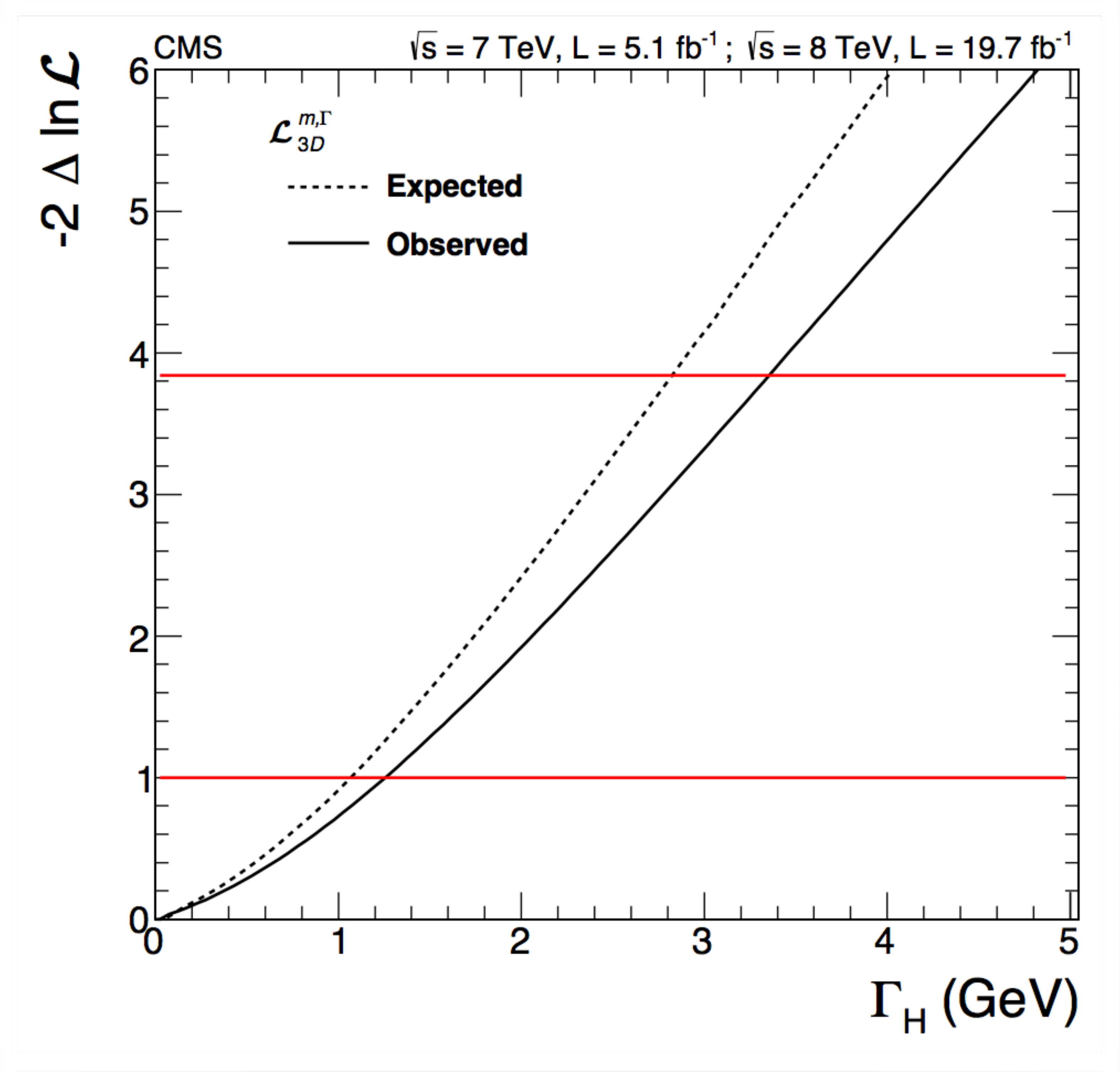
0.2% total uncertainty

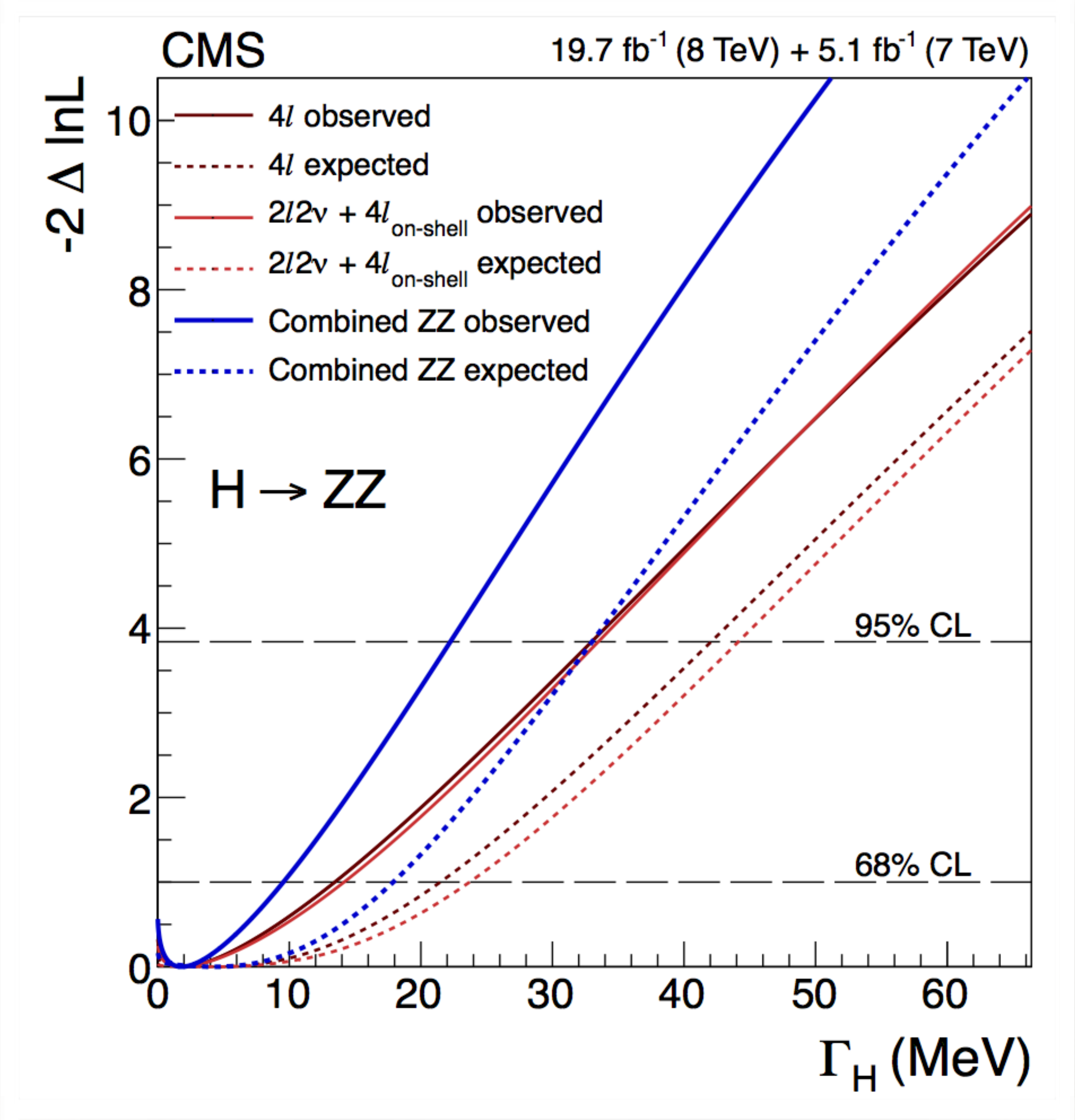
PRL 14 (2015) 191803

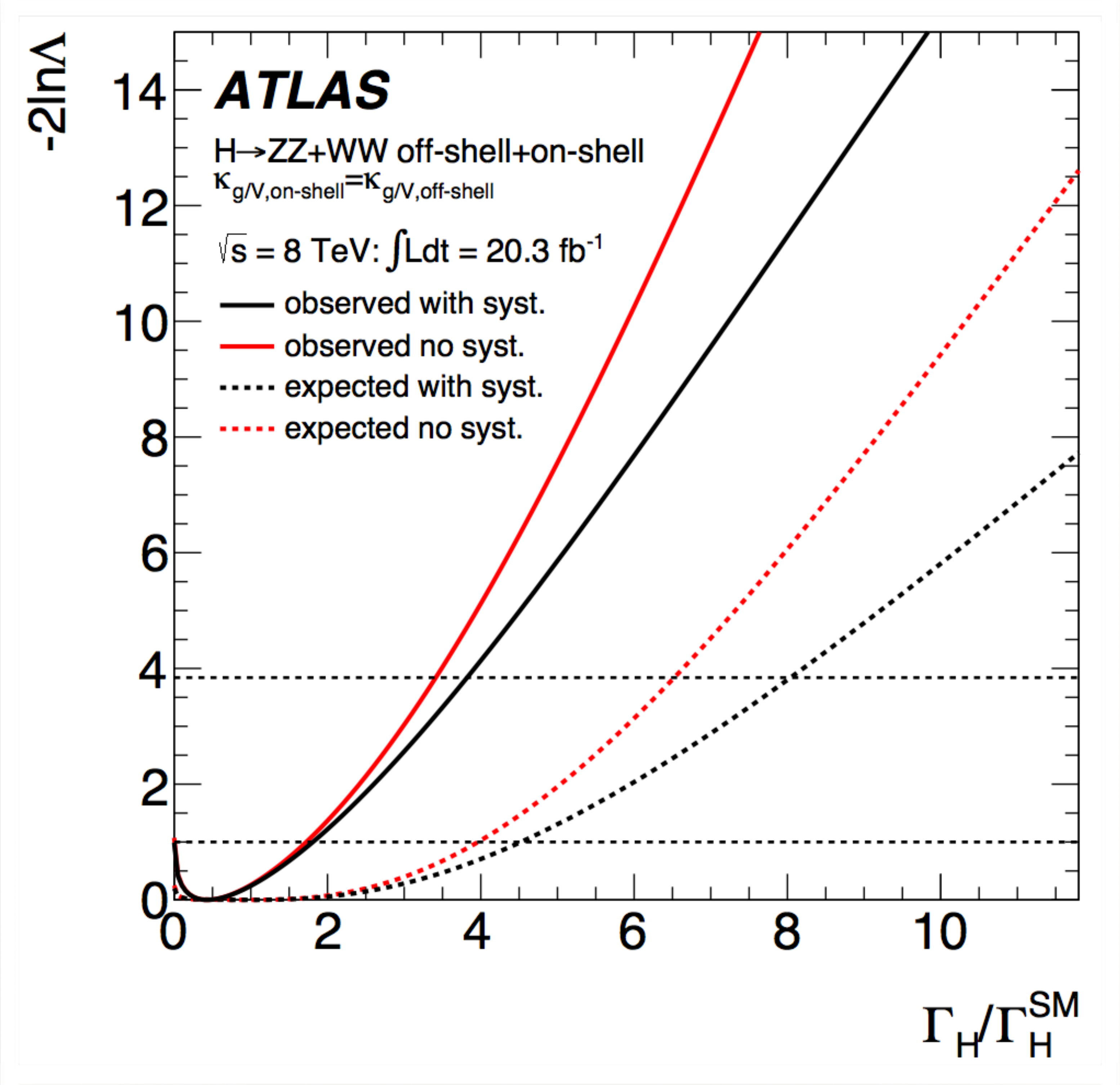
H(125) Width

Phys.Rev.D 89 (2014) 092007
Phys.Lett. B 736 (2014) 64
Eur.Phys.J. C (2015) 75: 335

- experimental resolution not enough to directly probe SM Higgs width (~4 MeV @ 125 GeV)
- indirect constraint at level of few 10's of MeV obtained by studying interference effects at high ZZ*→4l mass
  - several assumptions implied: couplings independent of energy scale, size of neglected higher order corrections for loop-induced gg→VV background







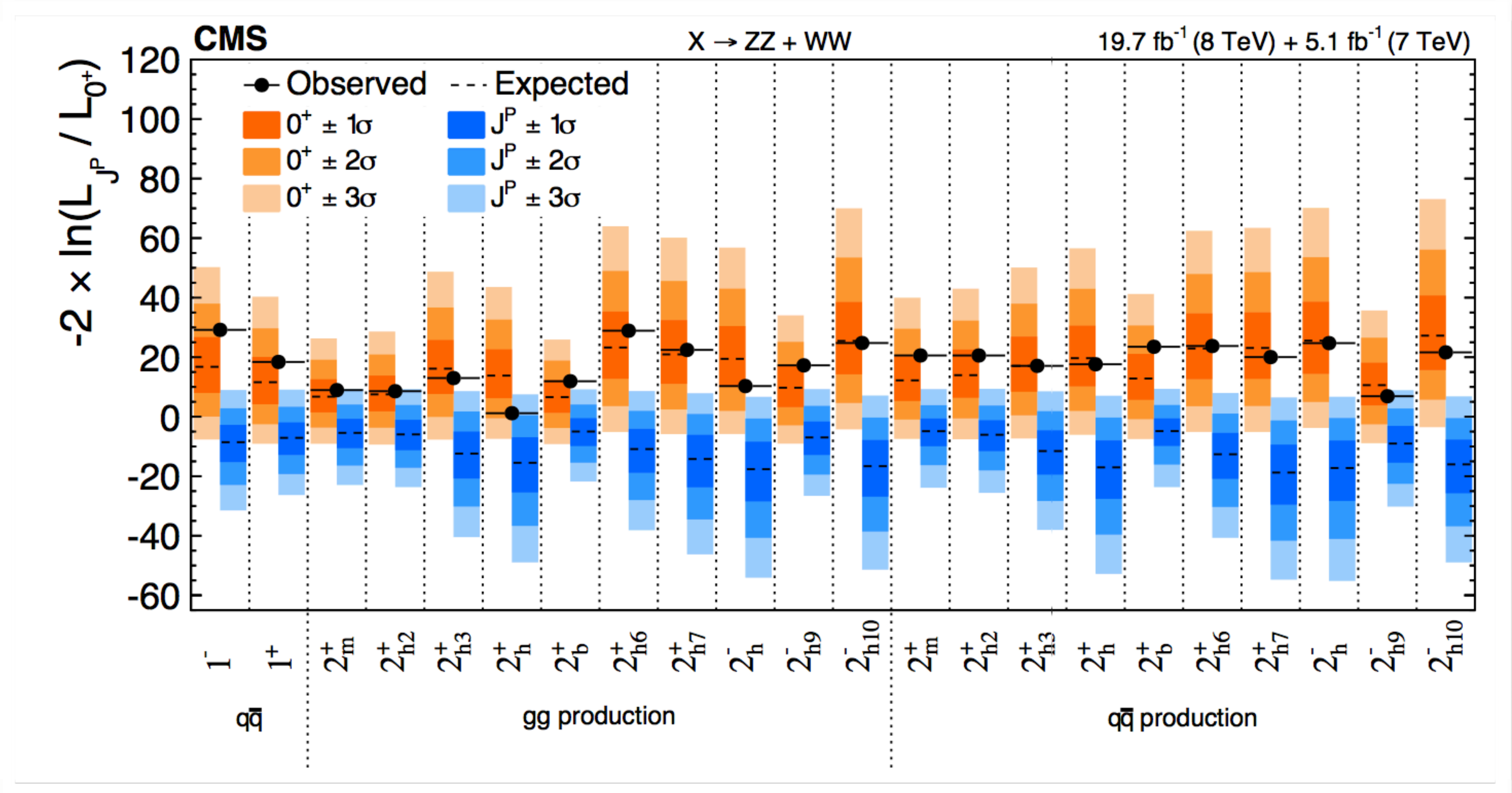
direct : Γ_H<~3 GeV @95% CL

indirect : Γ_H<~20-40 MeV @95% CL

Spin-parity & coupling combination

JHEP 08 (2016) 045

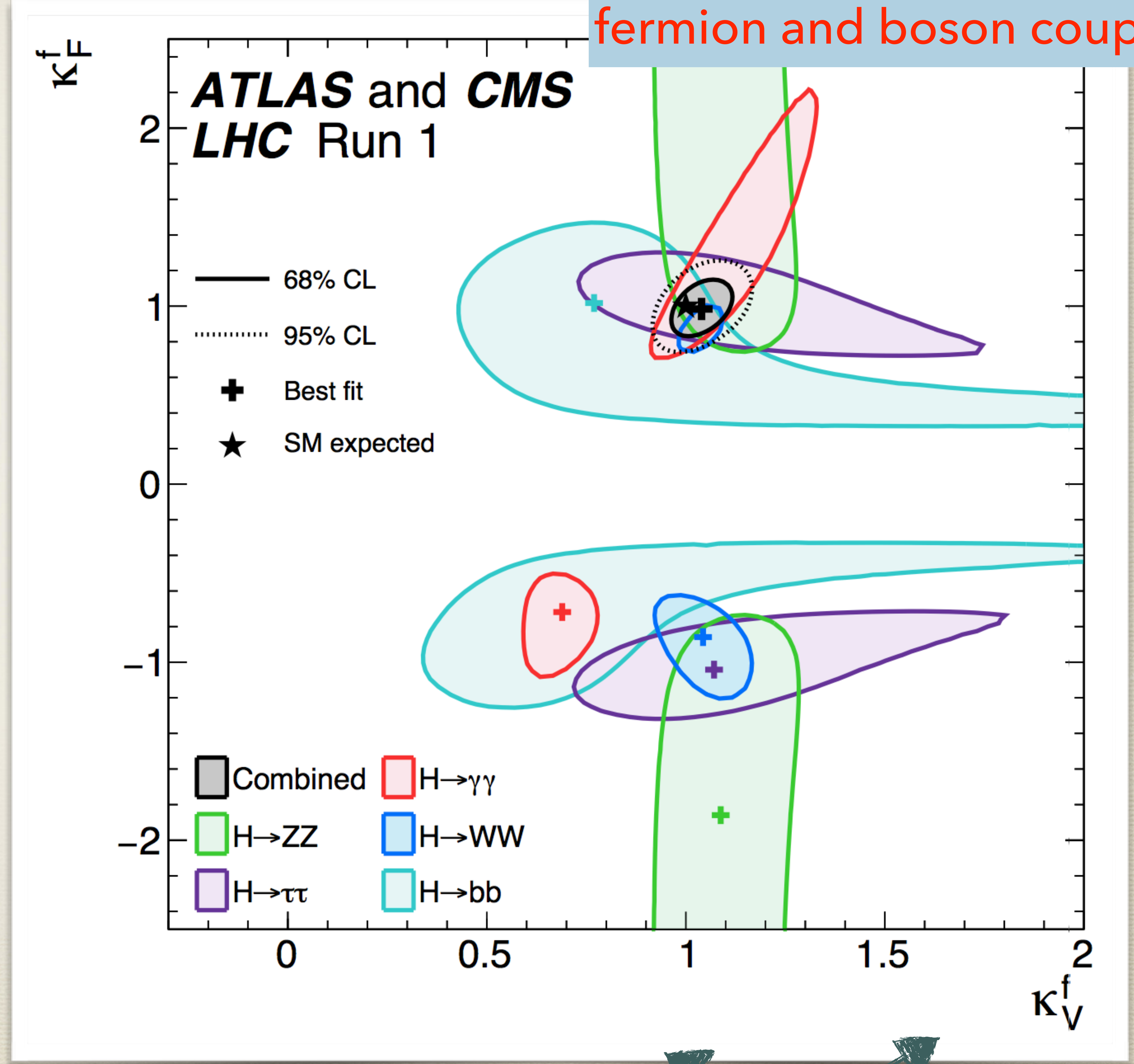
- **Spin-Parity:**
  - angular and mass distributions in ZZ*, WW* and γγ decays sensitive to spin-parity of the Higgs
  - test different spin-parity hypothesis against SM 0^+



wide range of J^P variations strongly excluded

- **Run-1 combination of ATLAS and CMS still provides best available constraint on couplings**

fermion and boson couplings



coupling modifiers $k_j^2 = \frac{\sigma_j}{\sigma_j^{SM}}$

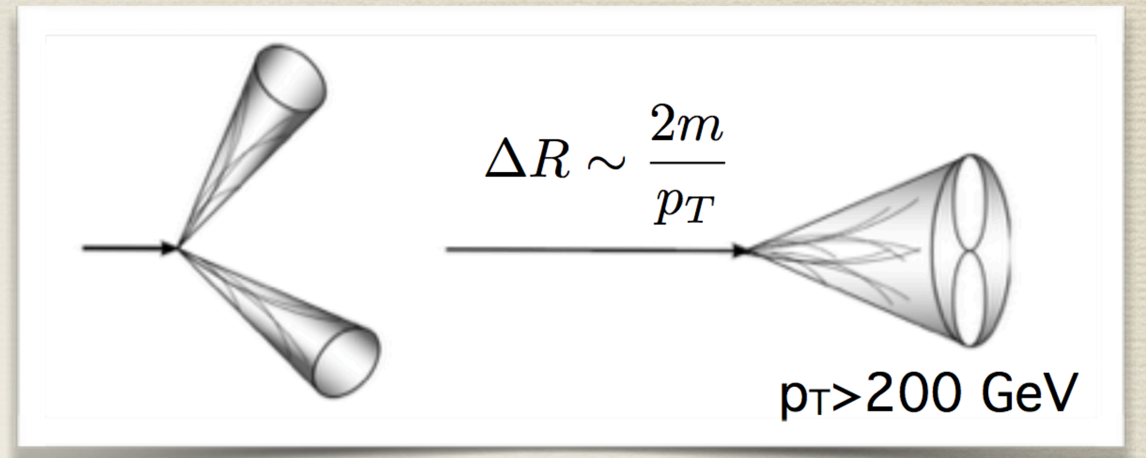
Eur.Phys.J. C75 (2015) 476

PRD 92 (2015) 012004

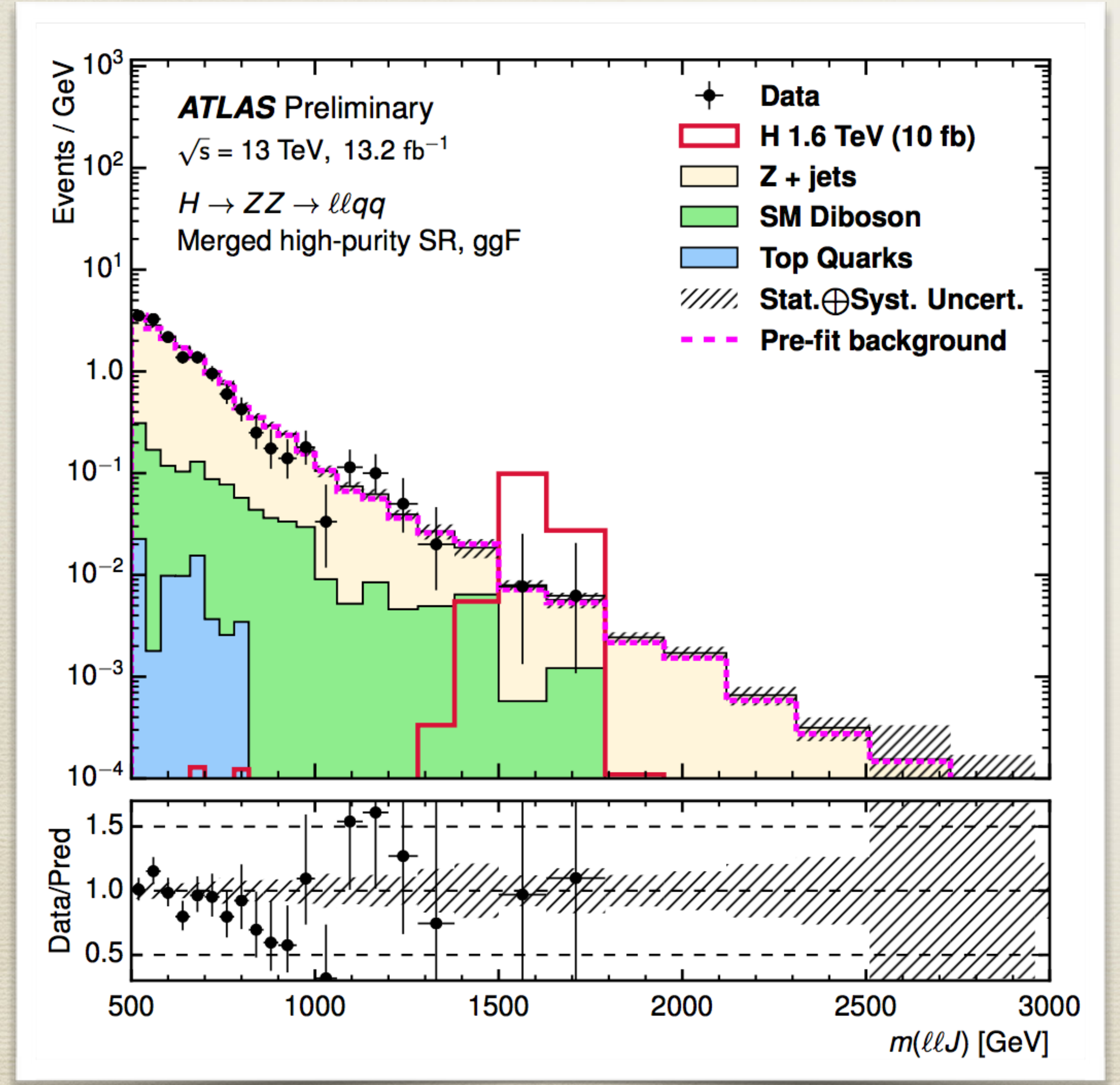
Run-2 analyses ongoing …

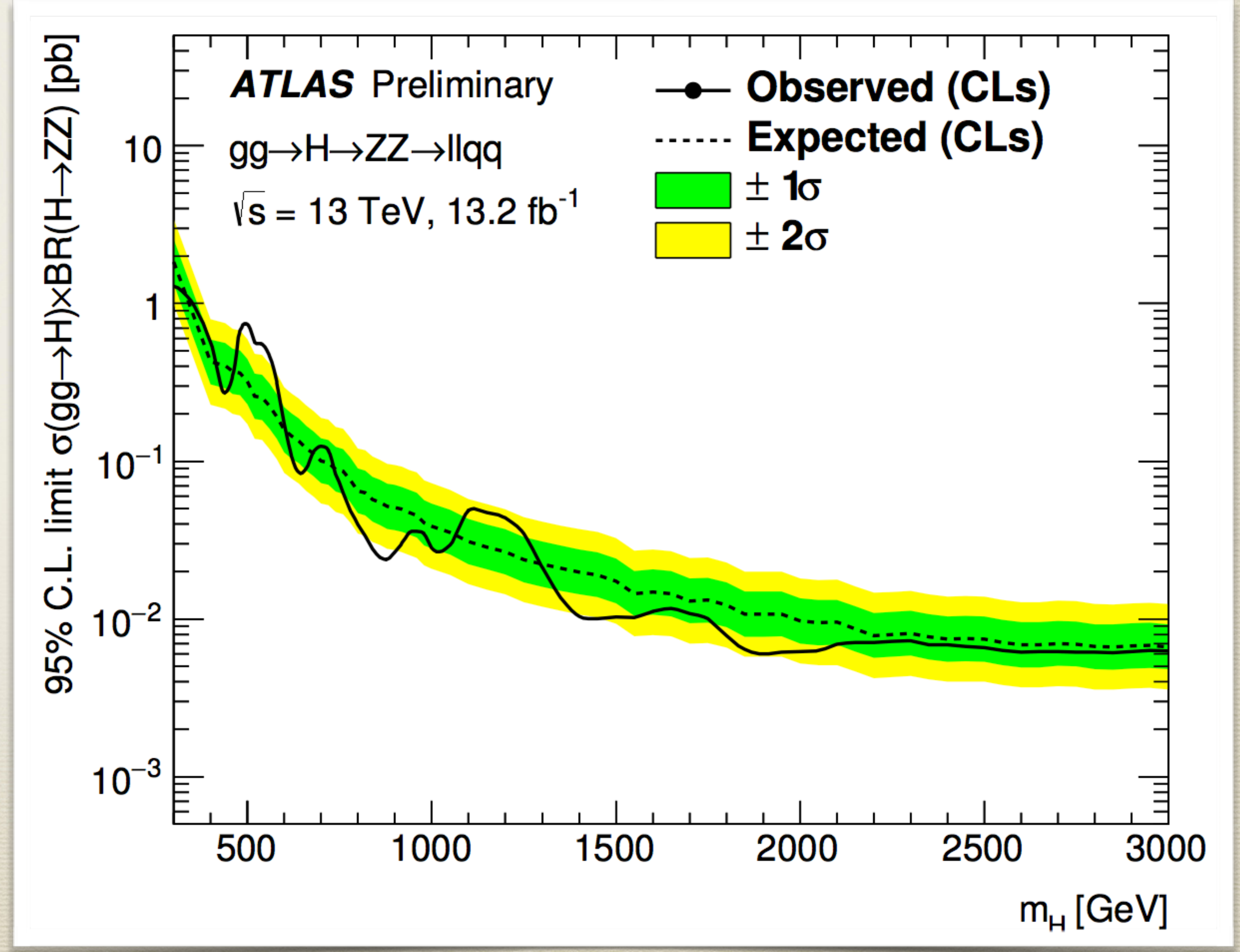
Neutral BSM Higgs Searches: decays to bosons

- analysed several final states and p_T regimes: ZH, HH, ZZ, WW, … non-boosted, boosted …
- **H→ZZ→llqq:** boosted boson tagging when $m_H \gg m_Z$
  - collimated qq from Z decay → reconstructed as a single fat-jet
  - m(jet) consistent with Z mass
  - merged (llJ) and resolved (llJJ) categories to maximise sensitivity



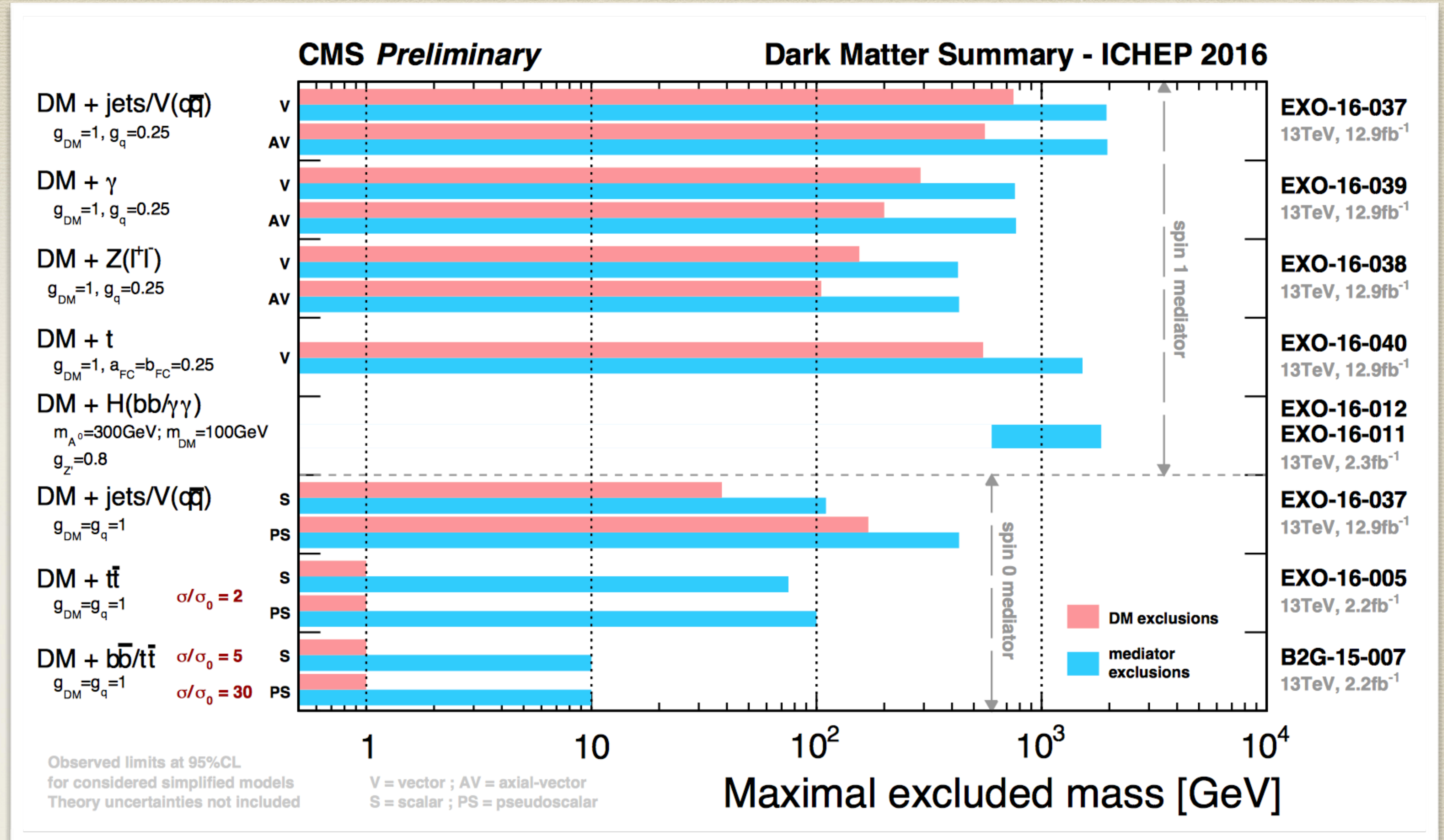
ATLAS-CONF-2016-082

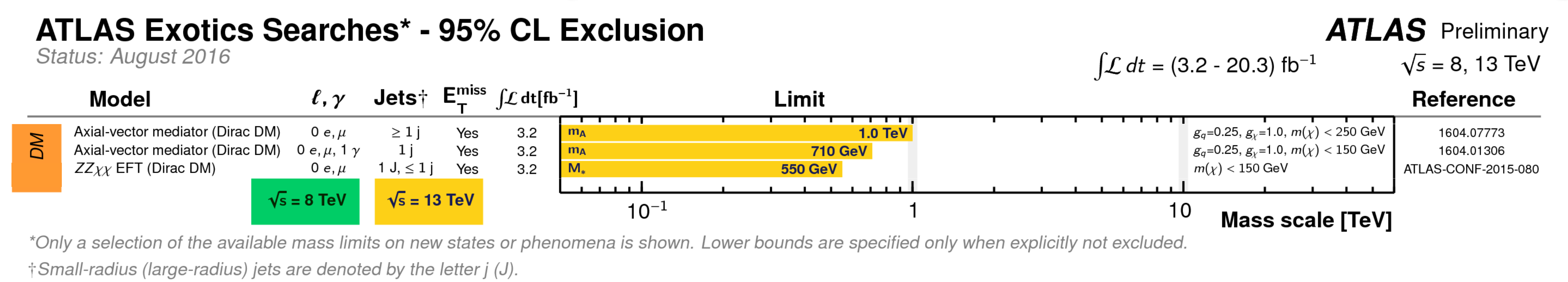




data in agreement with background expectations

DM SUMMARY


CMS Preliminary
Dark Matter Summary - ICHEP 2016
DM + jets/V(qq̄)
g_DM=1, g_q=0.25
DM + γ
g_DM=1, g_q=0.25
DM + Z(l+l-)
g_DM=1, g_q=0.25
DM + t
g_DM=1, a_FC=b_FC=0.25
DM + H(bb/γγ)
m_A0=300GeV; m_DM=100GeV
g_Z'=0.8
DM + jets/V(qq̄)
g_DM=g_q=1
DM + tt̄
g_DM=g_q=1
σ/σ_0 = 2
DM + bb̄/tt̄
g_DM=g_q=1
σ/σ_0 = 5
σ/σ_0 = 30
V
AV
S
PS
spin 1 mediator
spin 0 mediator
DM exclusions
mediator exclusions
EXO-16-037
13TeV, 12.9fb-1
EXO-16-039
13TeV, 12.9fb-1
EXO-16-038
13TeV, 12.9fb-1
EXO-16-040
13TeV, 12.9fb-1
EXO-16-012
EXO-16-011
13TeV, 2.3fb-1
EXO-16-037
13TeV, 12.9fb-1
EXO-16-005
13TeV, 2.2fb-1
B2G-15-007
13TeV, 2.2fb-1
1
10
10^2
10^3
10^4
Maximal excluded mass [GeV]
Observed limits at 95%CL
for considered simplified models
Theory uncertainties not included
V = vector ; AV = axial-vector
S = scalar ; PS = pseudoscalar


ATLAS Exotics Searches* - 95% CL Exclusion
Status: August 2016
ATLAS Preliminary
∫L dt = (3.2 - 20.3) fb^-1
√s = 8, 13 TeV
Model
ℓ, γ
Jets†
E_T^miss
∫L dt[fb^-1]
Limit
Reference
DM
Axial-vector mediator (Dirac DM) | 0 e, μ | ≥ 1 j | Yes | 3.2 | m_A 1.0 TeV | g_q=0.25, g_χ=1.0, m(χ) < 250 GeV | 1604.07773
Axial-vector mediator (Dirac DM) | 0 e, μ, 1 γ | 1 j | Yes | 3.2 | m_A 710 GeV | g_q=0.25, g_χ=1.0, m(χ) < 150 GeV | 1604.01306
ZZχχ EFT (Dirac DM) | 0 e, μ | 1 J, ≤ 1 j | Yes | 3.2 | M_* 550 GeV | m(χ) < 150 GeV | ATLAS-CONF-2015-080
√s = 8 TeV
√s = 13 TeV
10^-1
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.
†Small-radius (large-radius) jets are denoted by the letter j (J).

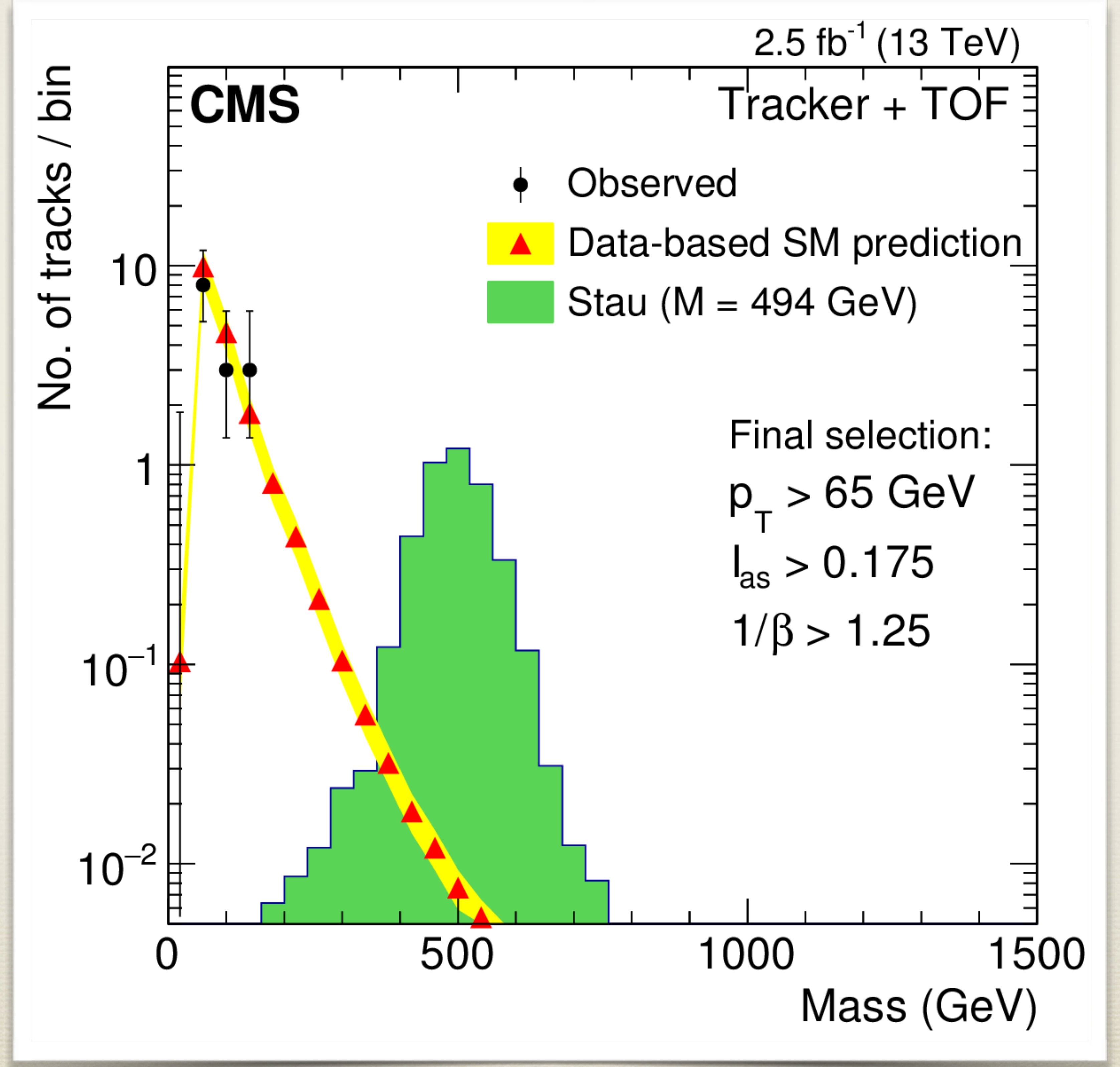
HEAVY SLOW/STABLE CHARGED PARTICLES

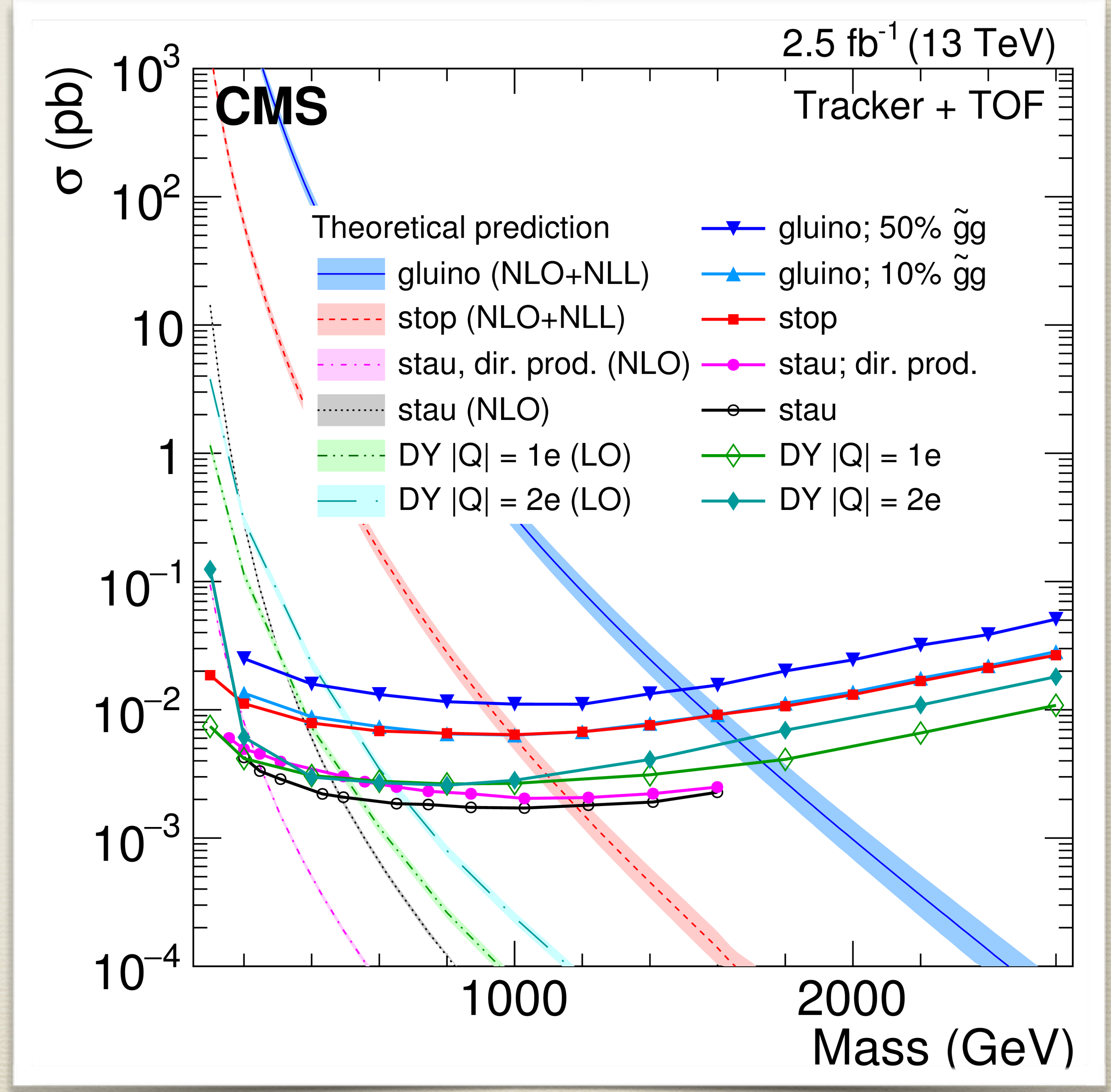
- Split-SUSY, GMSB models predict existence of HSCP, with anomalous dE/dx and low β (long TOF)
- CMS 13 TeV search:
  - **tracker-only analysis:** requires tracks to be reconstructed only in the silicon detector with anomalous dE/dx
  - **tracker+TOF analysis:** tracks reconstructed both in the silicon and muon system, exploiting dE/dx + TOF measurements

$$m_{SMP} = \frac{p}{\beta\gamma}$$

p ← measured in the inner tracker

$\beta\gamma$ ← β measured from TOF in the MS and/or dE/dx





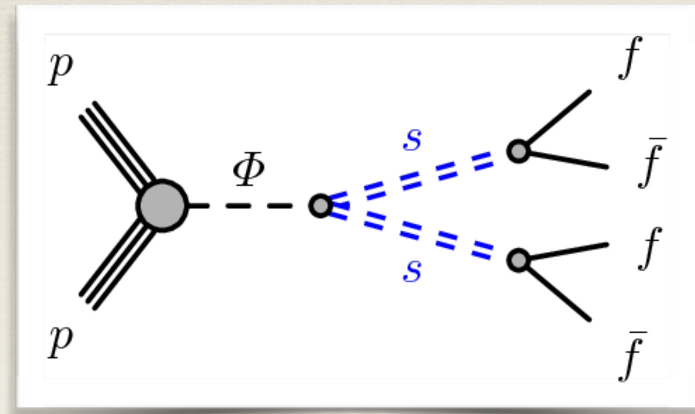
limits set on long-lived gluinos (~1.5-1.8 TeV), scalar tops (~ 1 TeV) and taus (~0.5 TeV)

arXiv:1609.08382

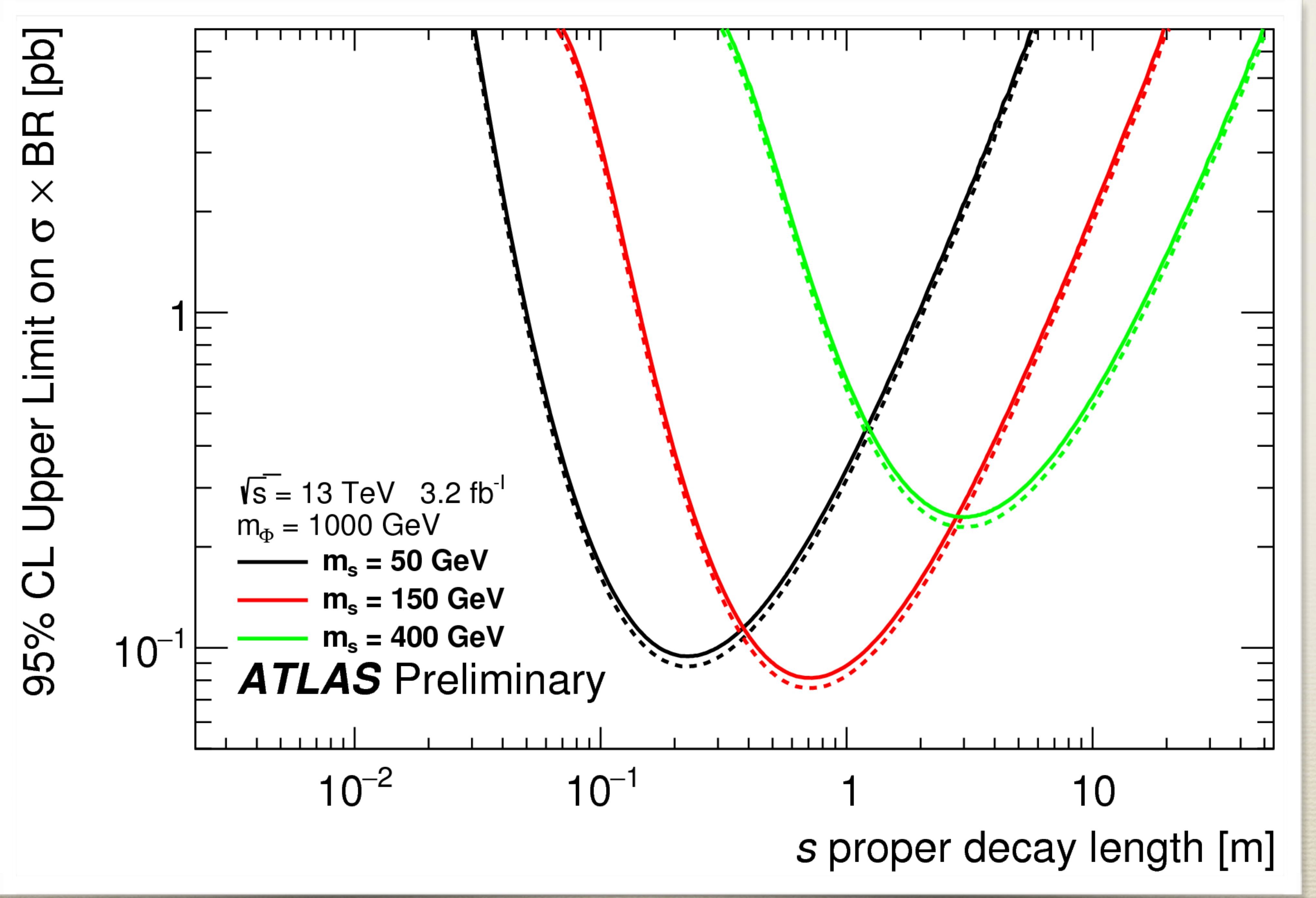
Hidden/Dark Sectors

- search for Hidden Valley displaced decays in jets:

- displaced jets produced from heavy higgs scalar decays to a pair of neutral LLPs scalars which in turn decays in fermions (typically b-quarks)



- specialised calorimeter trigger to select decays into the hadron calorimeter
- requires jets with anomalous Had/EM energy ratio
- main background: SM multijet events, estimated with data driven methods

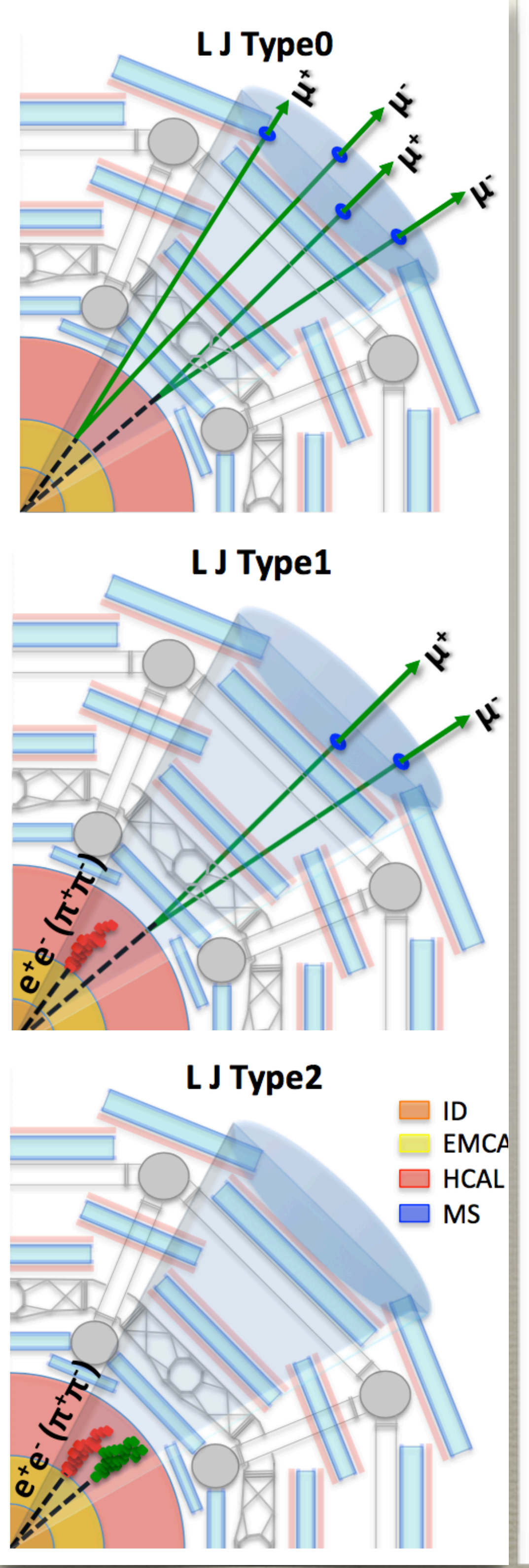


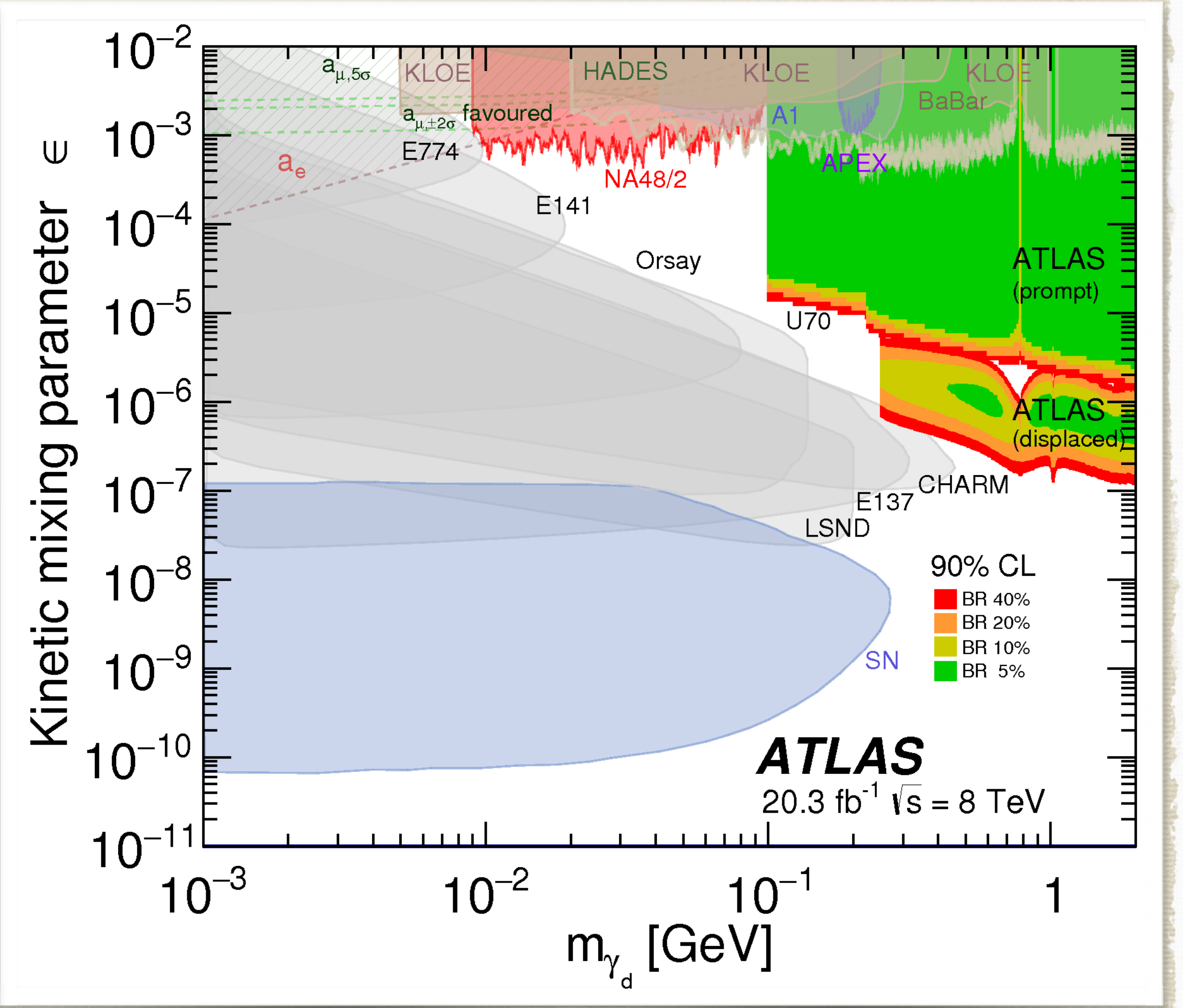
ATLAS-CONF-2016-103

ATLAS-CONF-2016-042

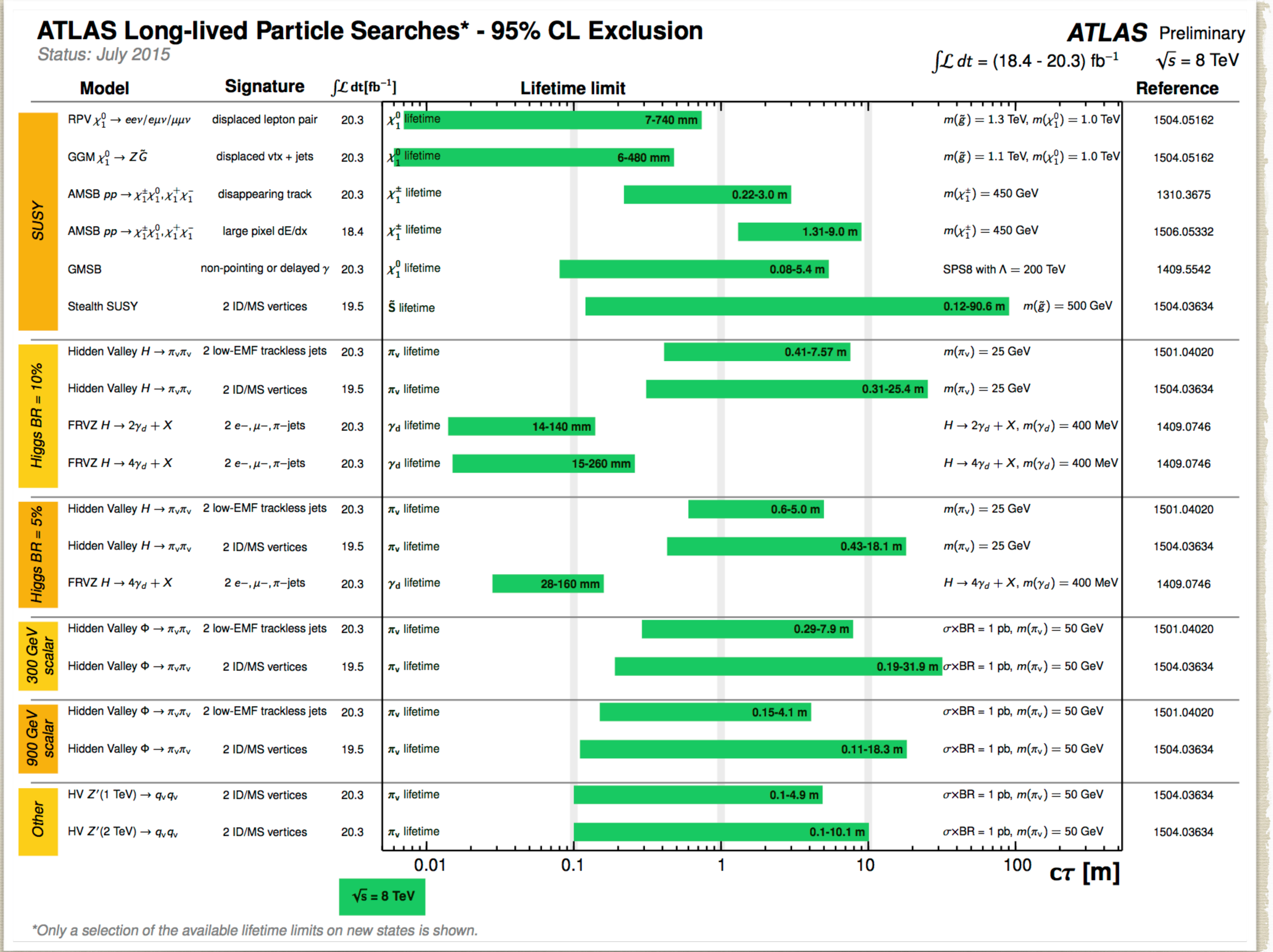
- search for lepton-jets (collimated jets of leptons (or hadrons)):

- 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

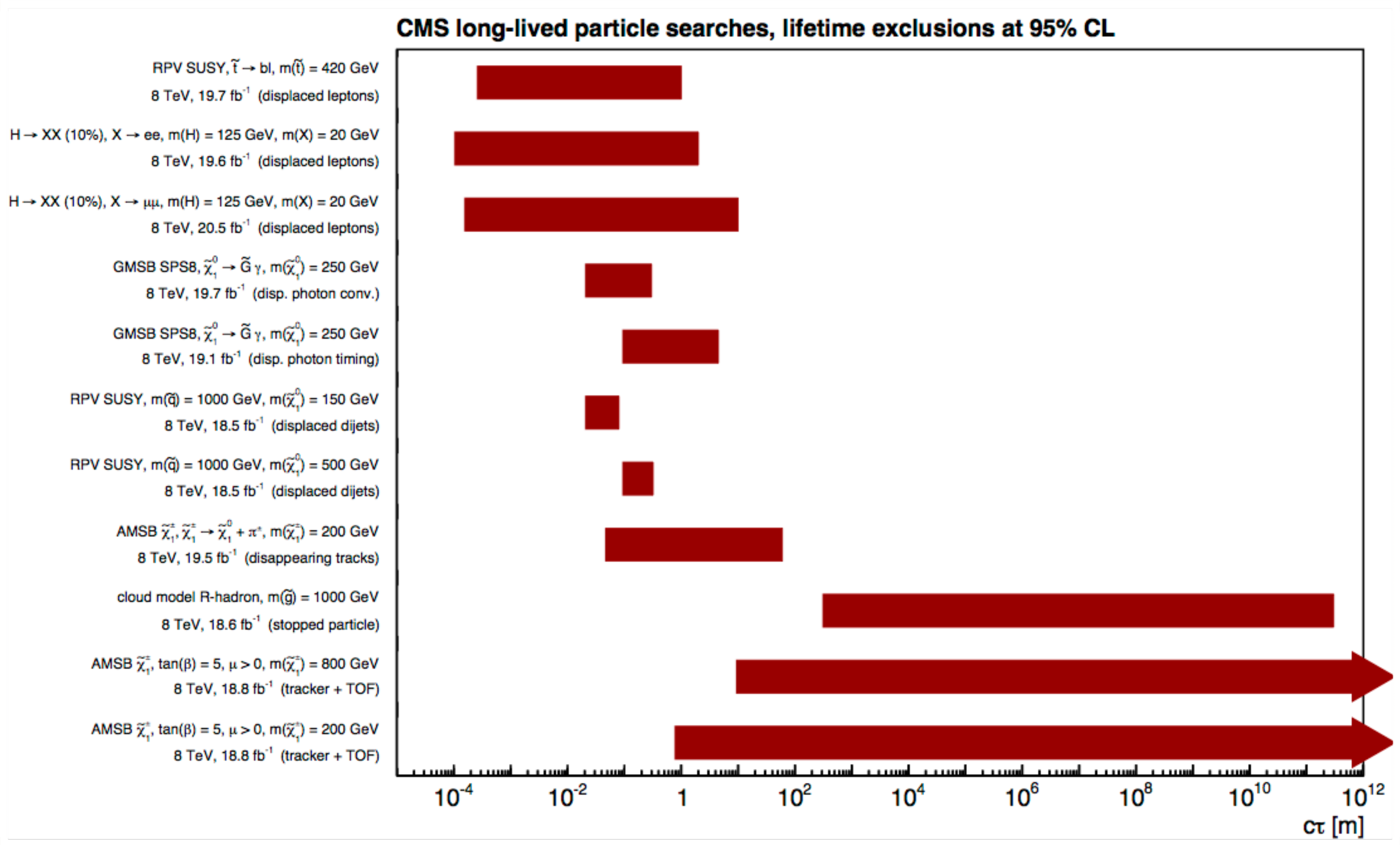




ATLAS LLP SUMMARY



CMS LLP SUMMARY

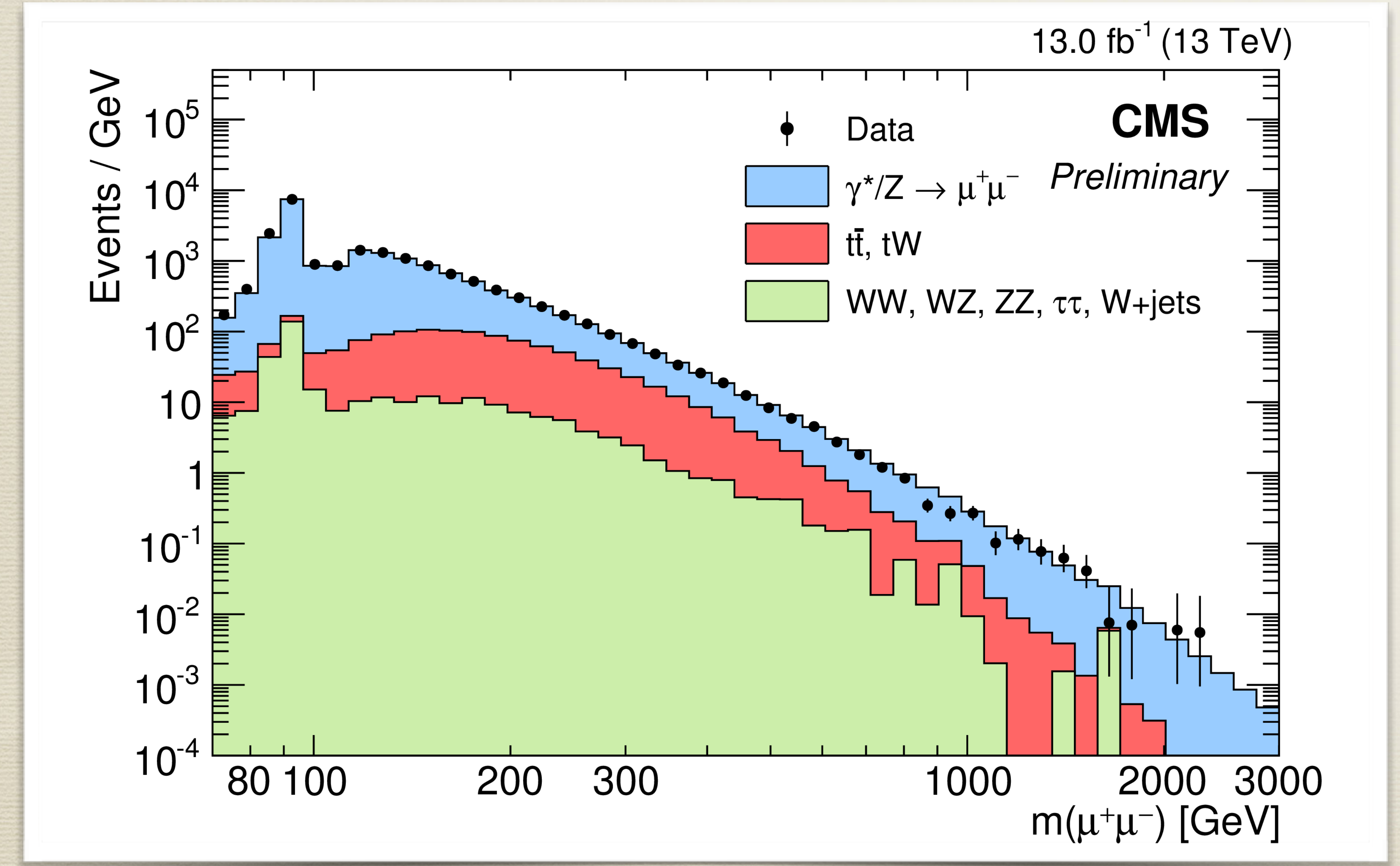


Di-lepton resonances

ATLAS-CONF-2016-061
CMS-PAS-EXO-16-031

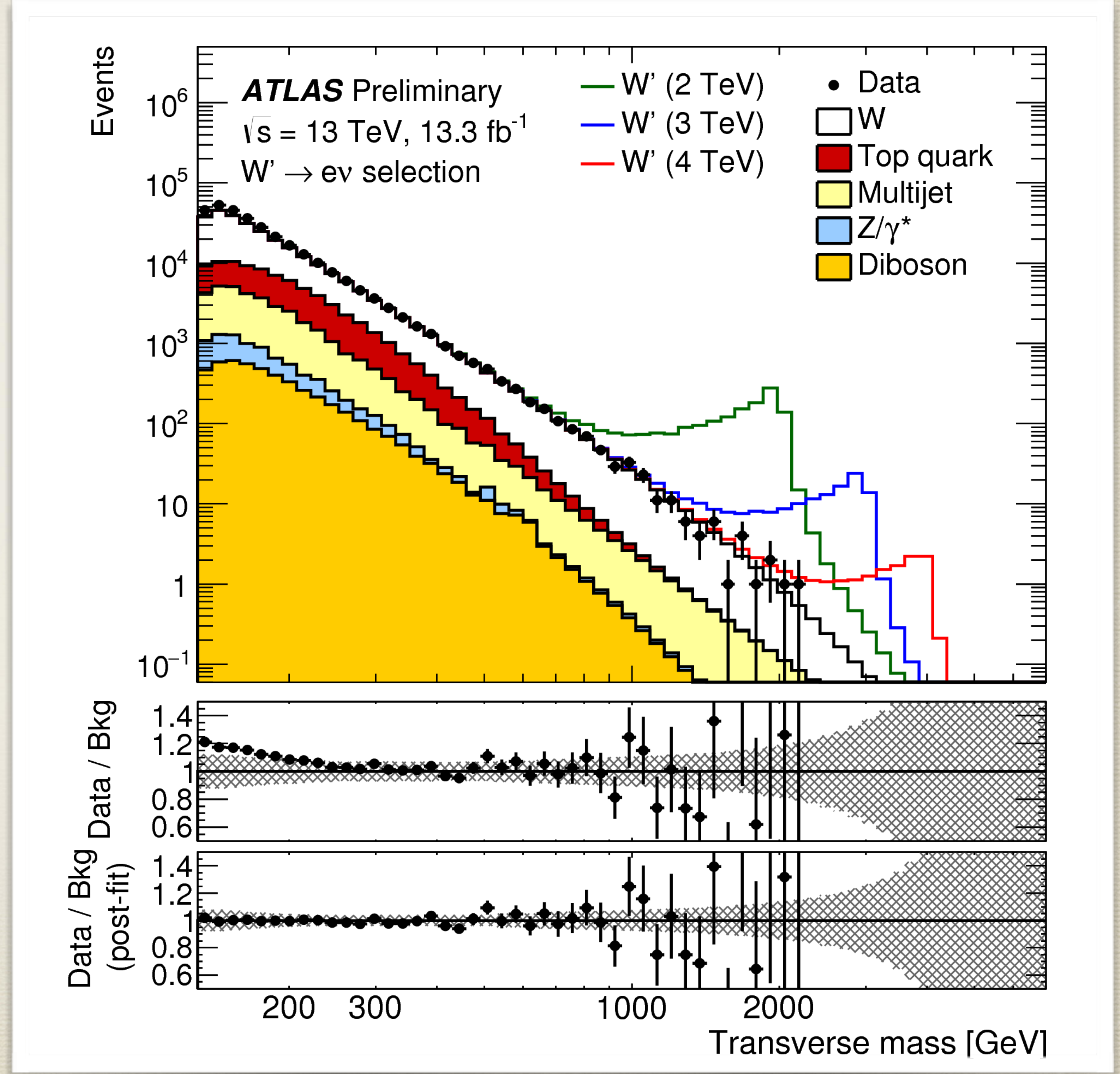
- present in the particle spectrum of many extensions of the Standard Model:
  - new gauge bosons: sequential SM, GUT-inspired theories E6, SO(10)
  - Randall-Sundrum Kaluza-Klein gravitons, Little/Littlest Higgs heavy gauge bosons, narrow techni-hadrons, ED, ...

- di-lepton and lepton+MET spectrum: a very clean place to look
- experimental signature: bumps or Jacobian peaks in the invariant mass distributions



LL

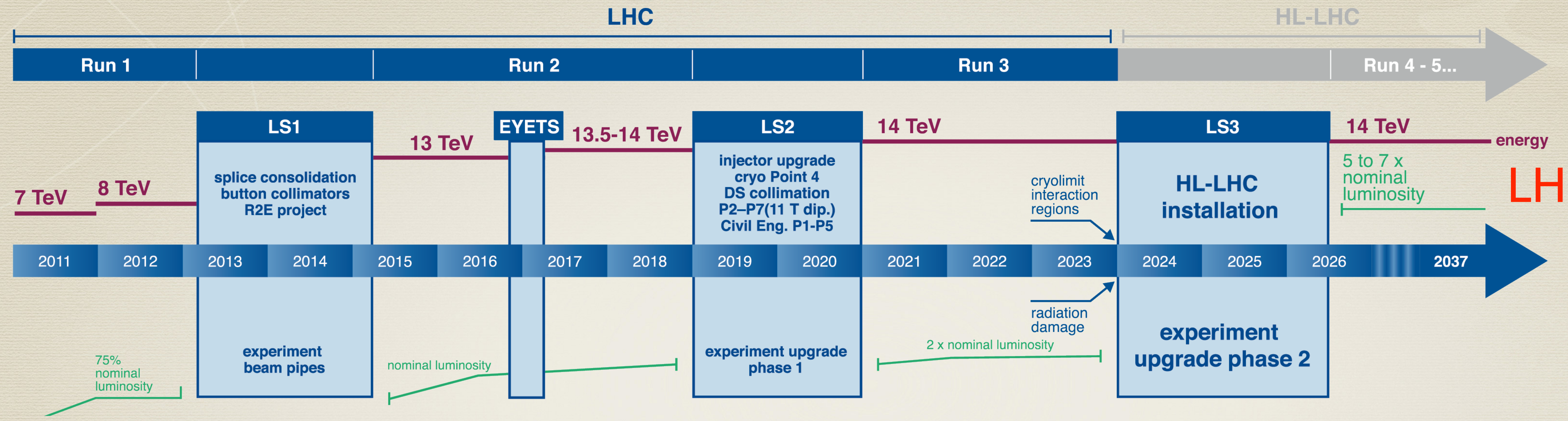
L+MET



- Experimental challenges: detector resolution and efficiency at very high momentum (with almost no control samples)

$$m_T = \sqrt{2 p_T^l E_T^{miss} (1 - \cos\phi_{l\nu})}$$

Future Perspectives



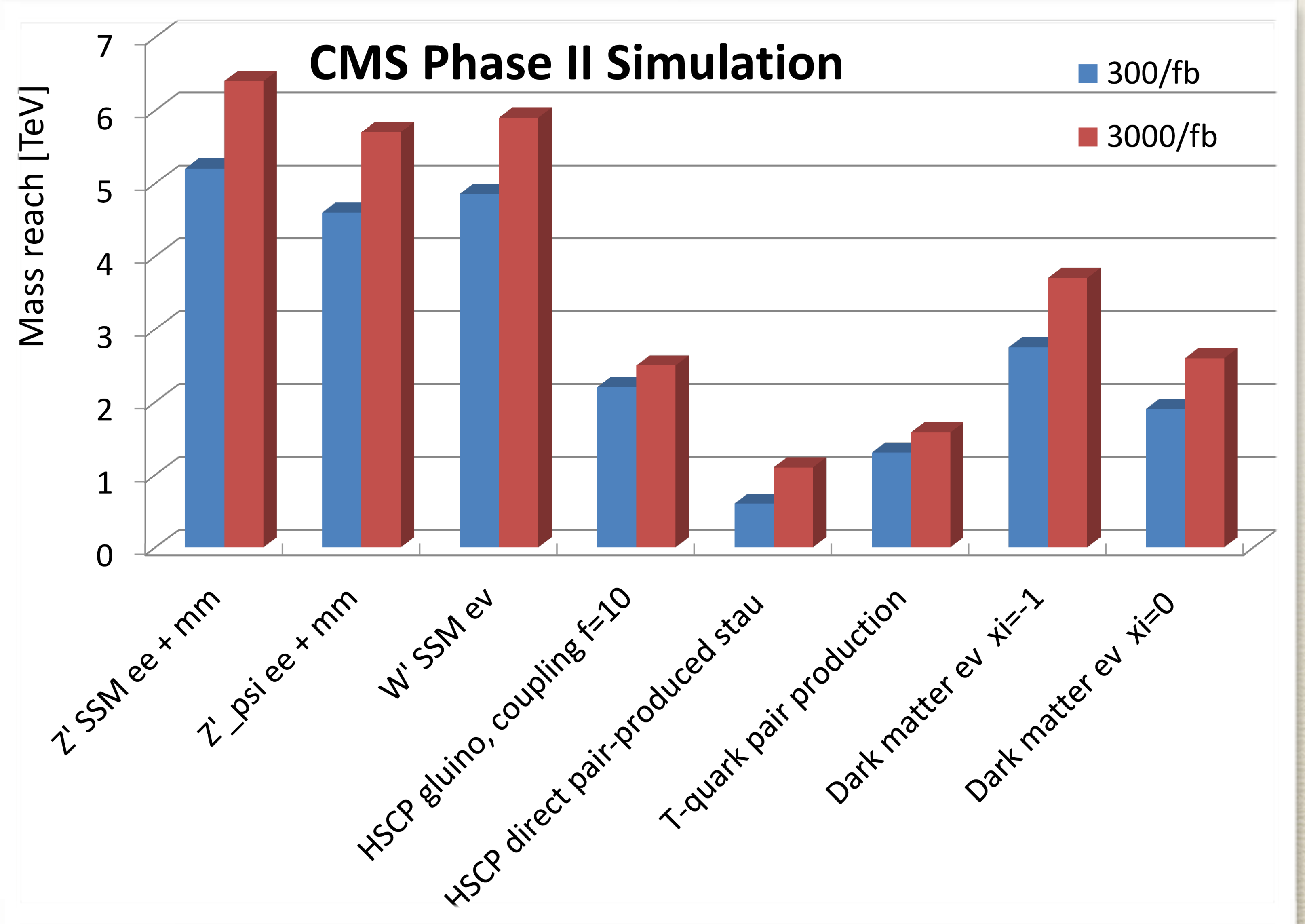
LHC/HL-LHC plan

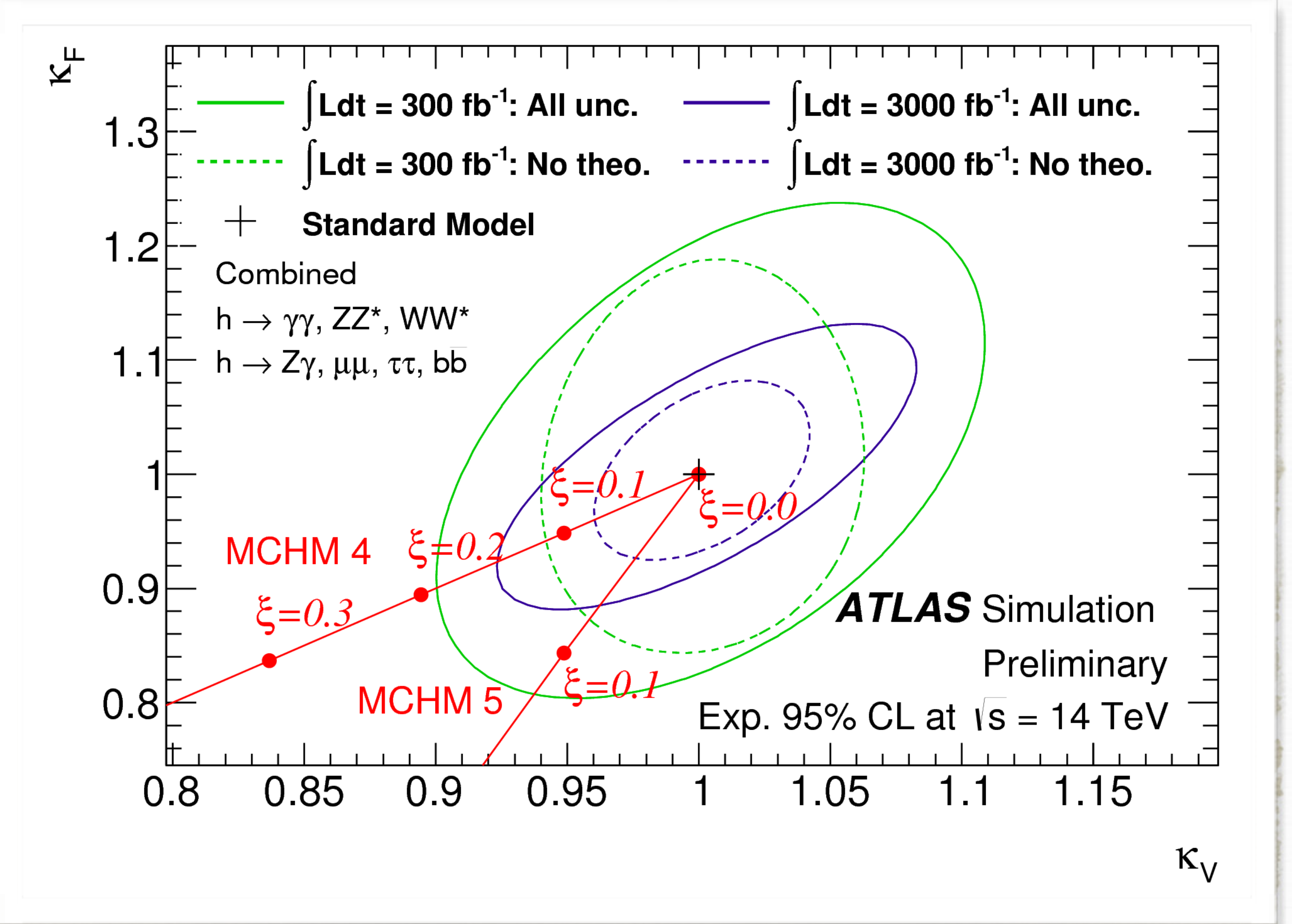
Run 1
7-8 TeV, 0.7×10^{34} ($\mu\approx20$), 25 fb^{-1}

Run 2
13-14 TeV, 1.6×10^{34} ($\mu\approx43$), 150 fb^{-1}

Run 3
14 TeV, $2\text{-}3\times10^{34}$ ($\mu\approx50\text{-}80$), 350 fb^{-1}

Run 4
14 TeV, $5\text{-}7\times10^{34}$ ($\mu\approx140\text{-}200$), 3000 fb^{-1}





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