

ATLAS RESULTS OVERVIEW

(w/ FOCUS ON DM)

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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



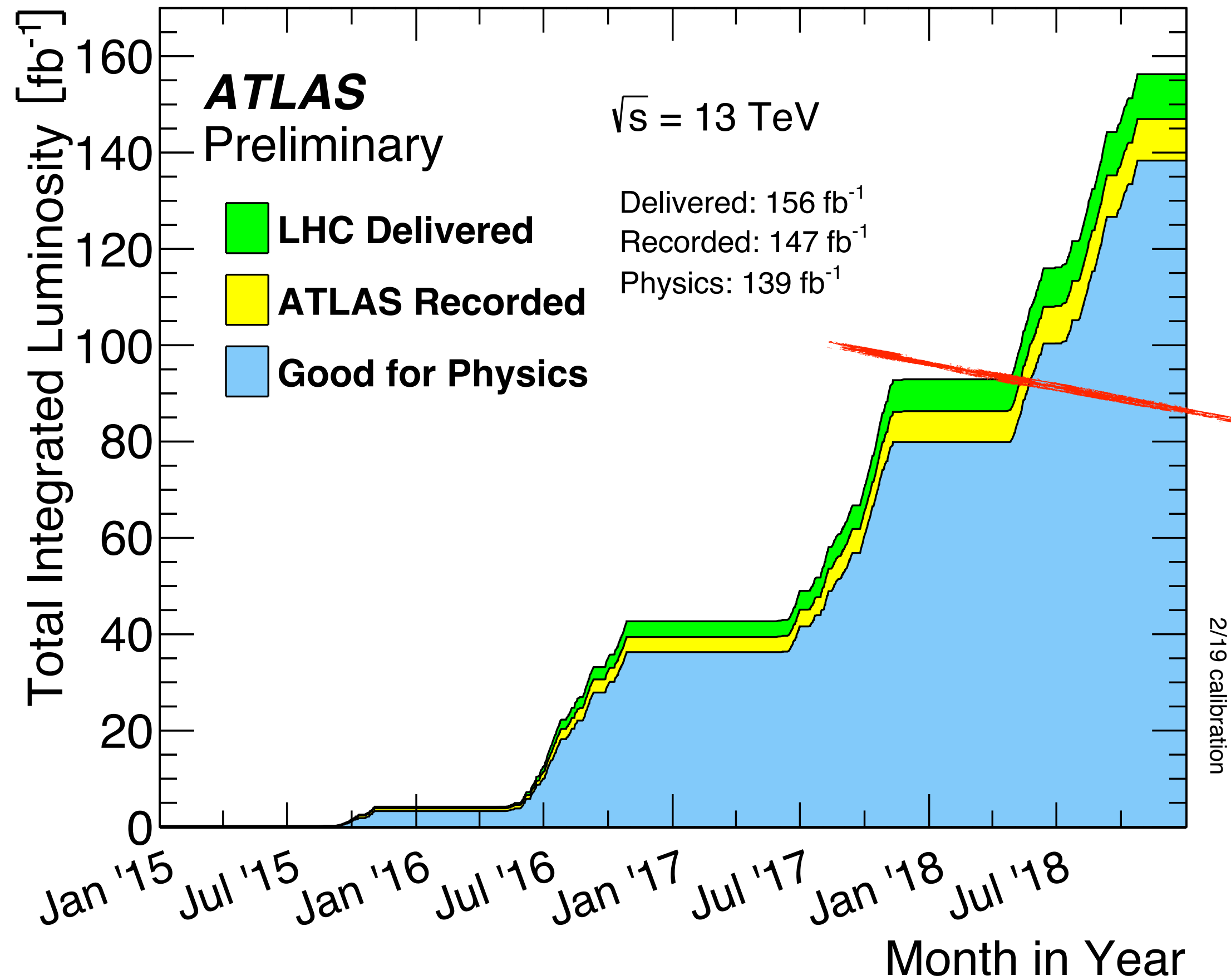
The Large Hadron Collider is a multipurpose and flexible machine
Run 2 (2015-2018):

- 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

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



Yields at 13 TeV
w/ 139 fb⁻¹

Higgs	$\sim 7.7 \cdot 10^6$
Top	$\sim 300 \cdot 10^6$
Z → ll	$\sim 300 \cdot 10^6$
W → lv	$\sim 3 \cdot 10^9$

PRECISION TESTS OF THE SM

- TOP, EW/ QCD
- FLAVOUR PHYSICS

EWSB

- YUKAWA COUPLINGS
- VH INTERACTIONS
- HIGGS POTENTIAL

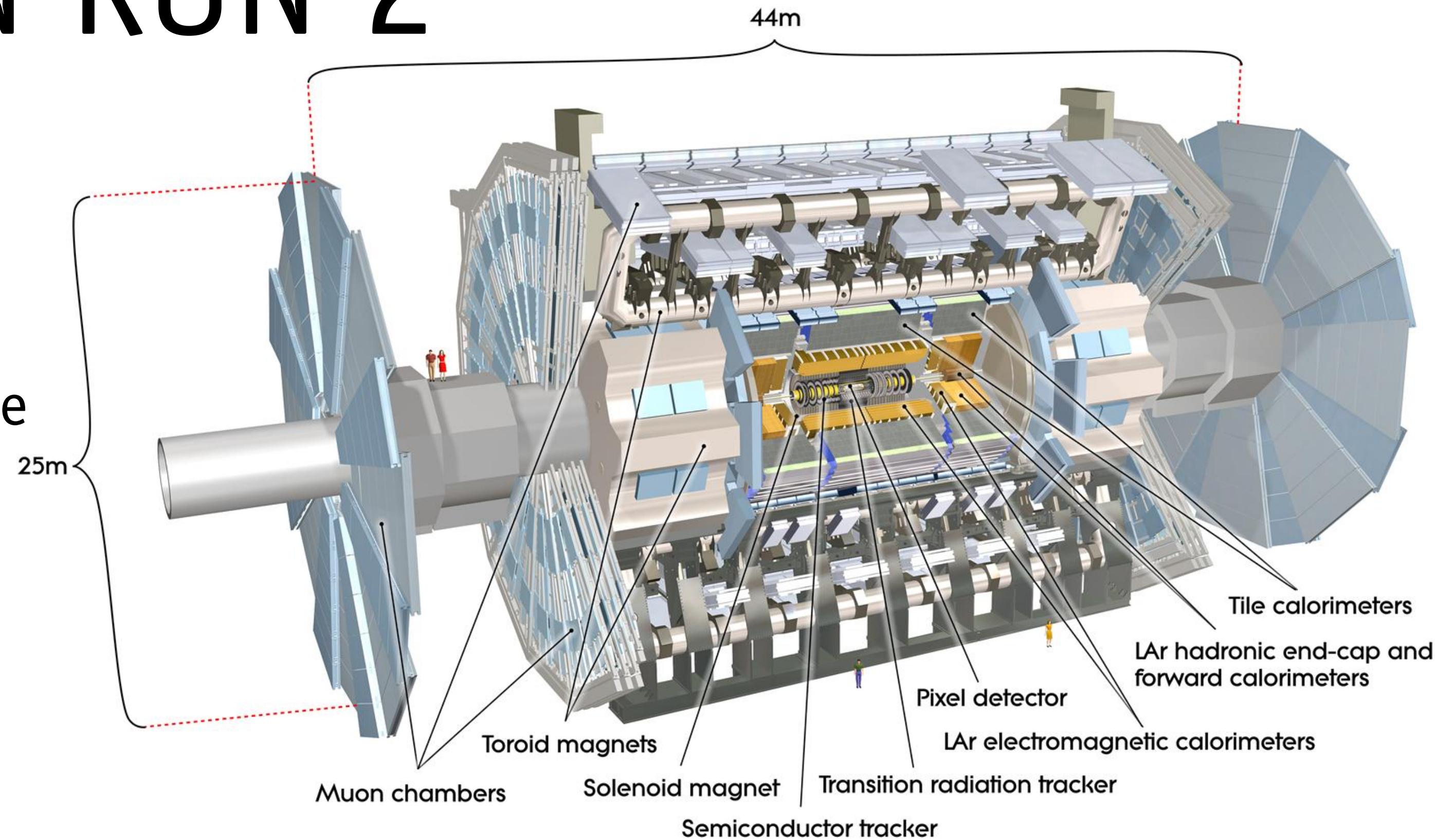
BSM

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

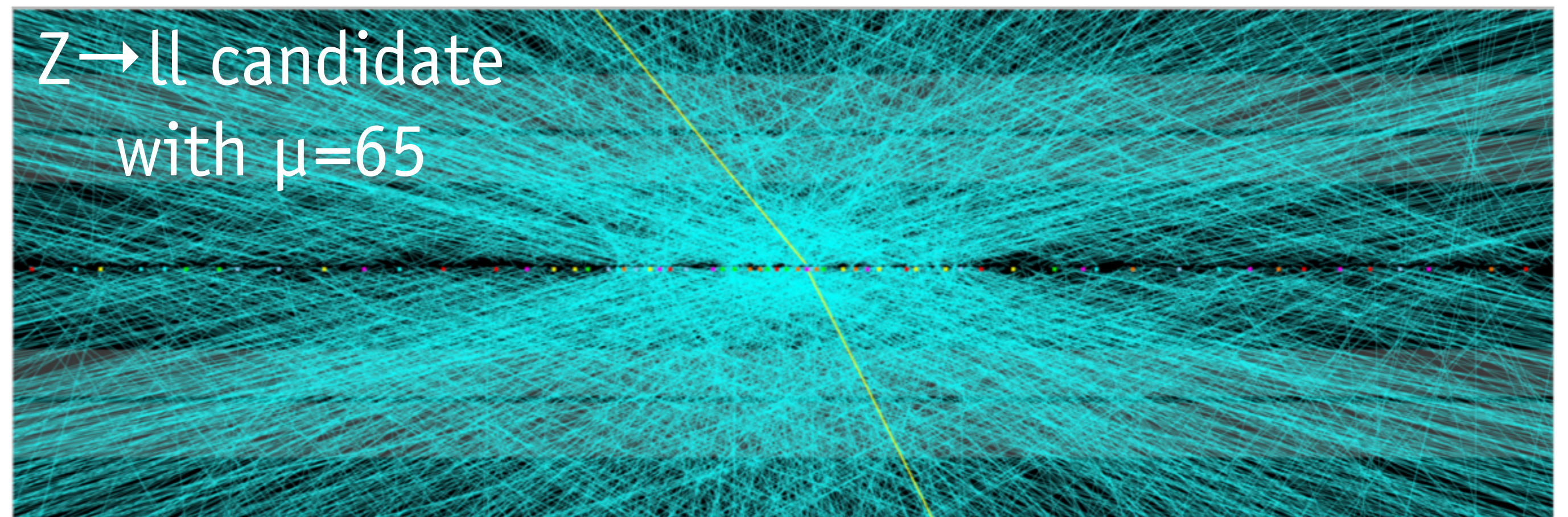


ATLAS DETECTOR IN RUN 2

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

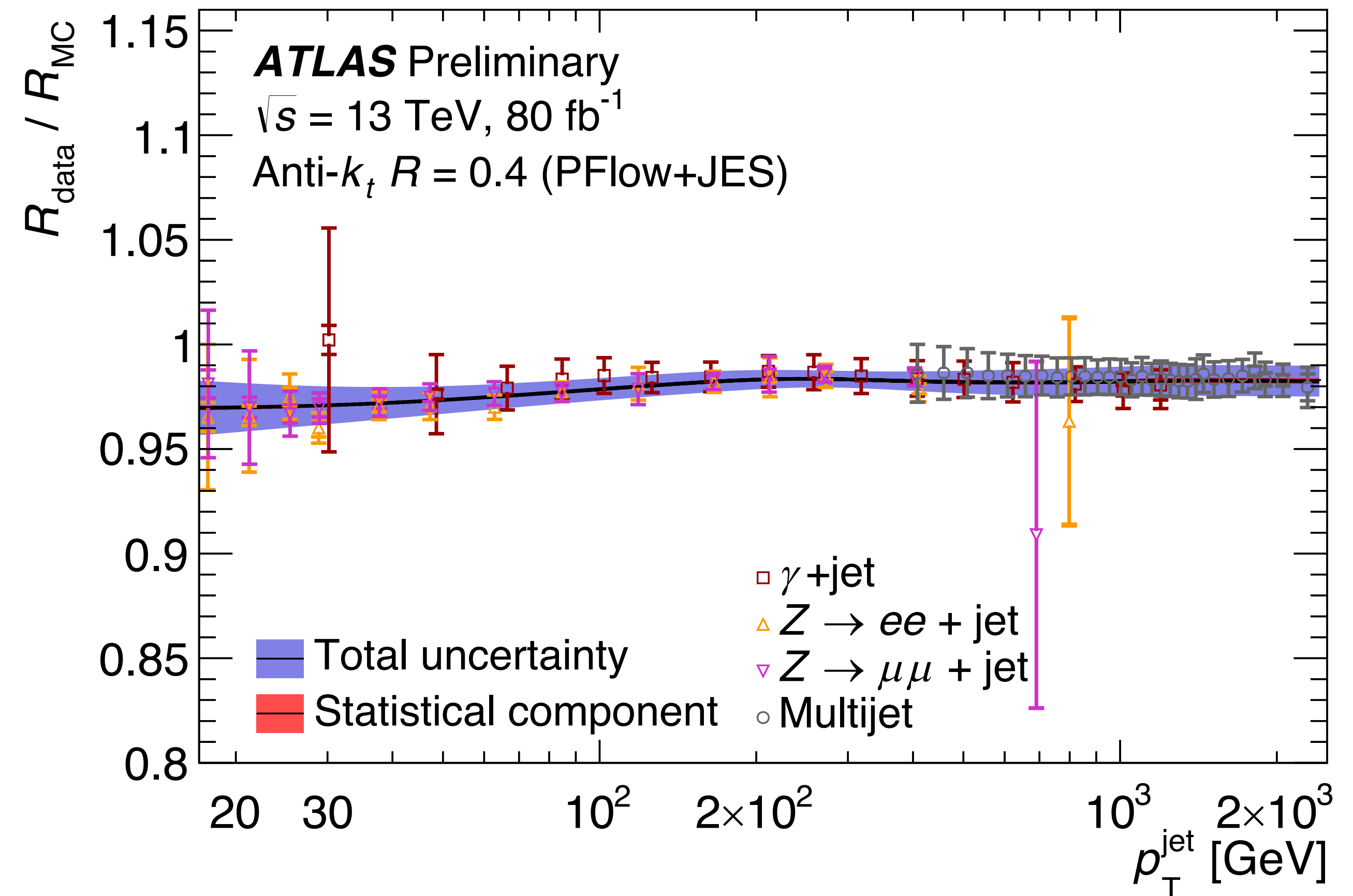
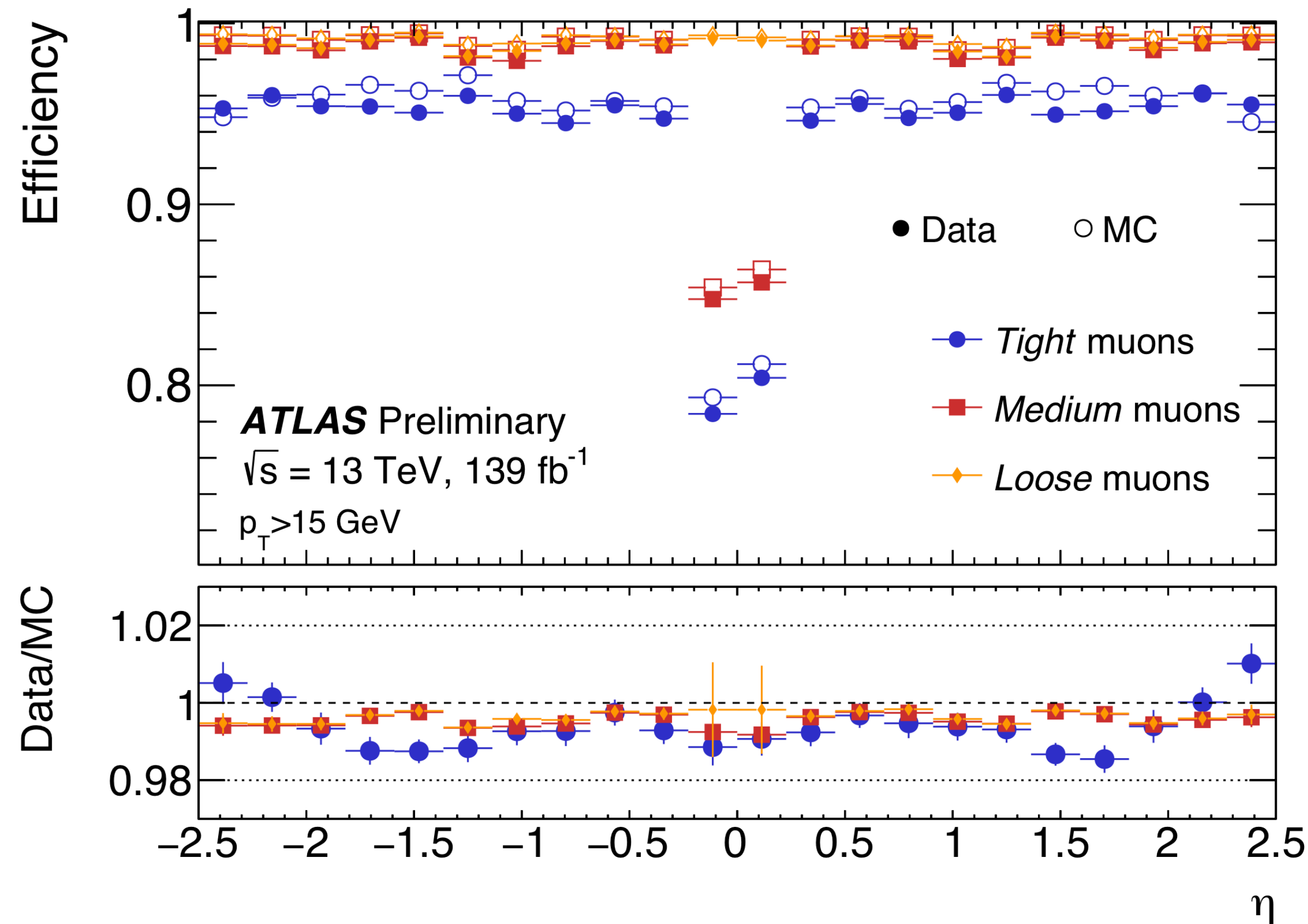


- widespread use of machine learning techniques for particle reconstruction & identification
- dedicated algorithms/calibrations for specific physics cases (low- p_T leptons, hadronic taus, b-tagging, boosted hadronic objects, ...)



RECONSTRUCTION PERFORMANCE

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



SM STATUS

Standard Model Total Production Cross Section Measurements

Status:
July 2019

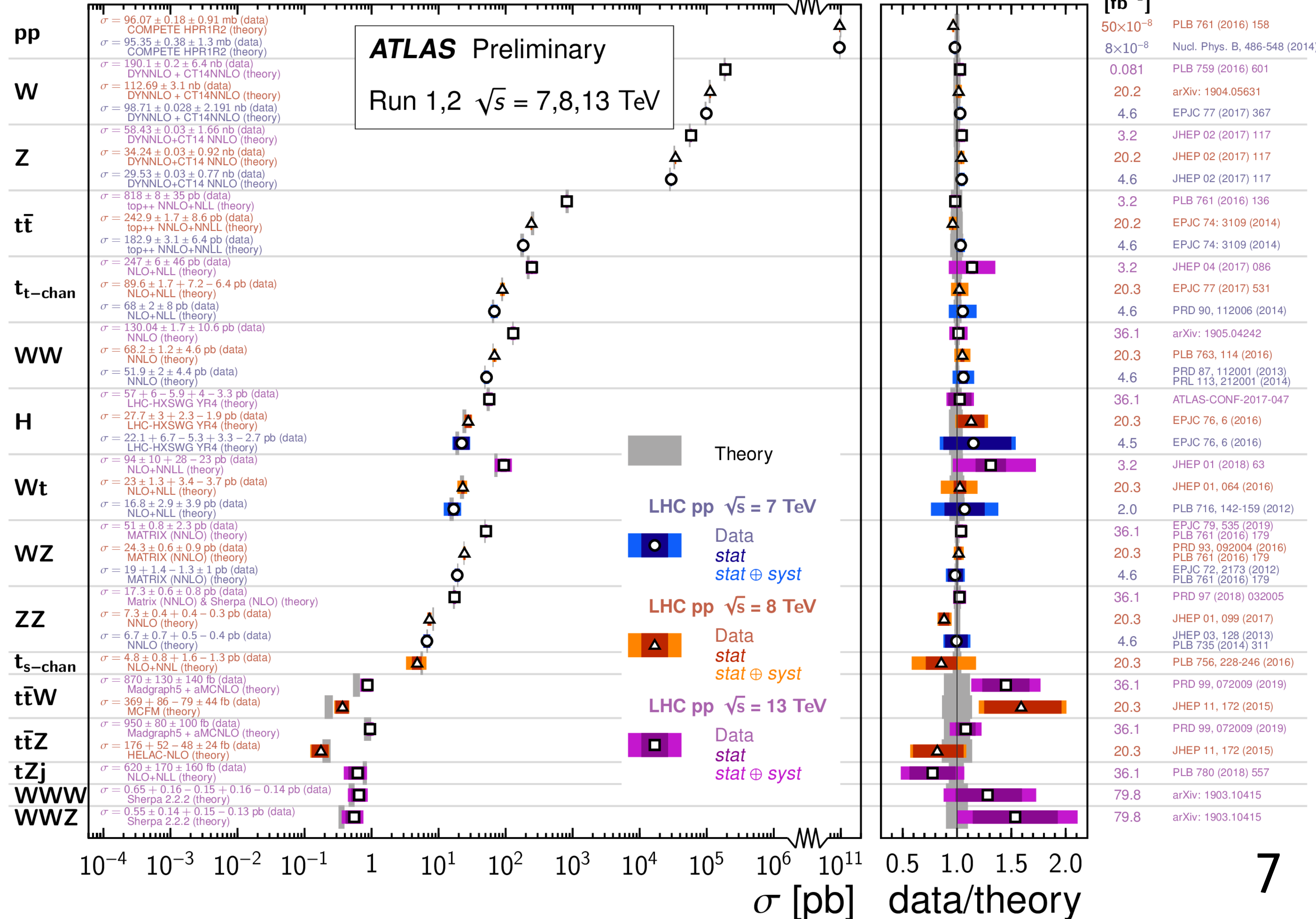
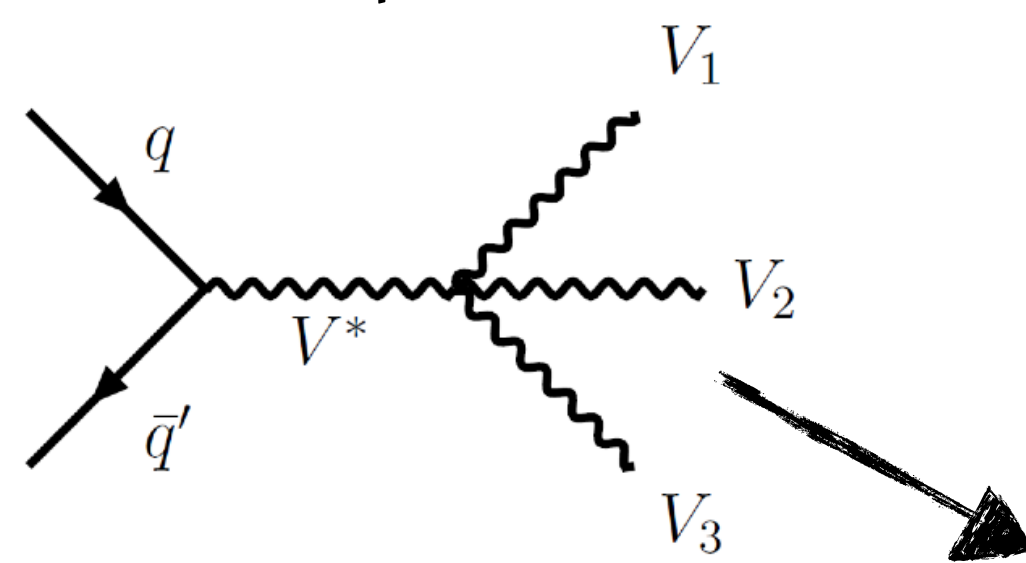
$\int \mathcal{L} dt$
[fb⁻¹]

Reference

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

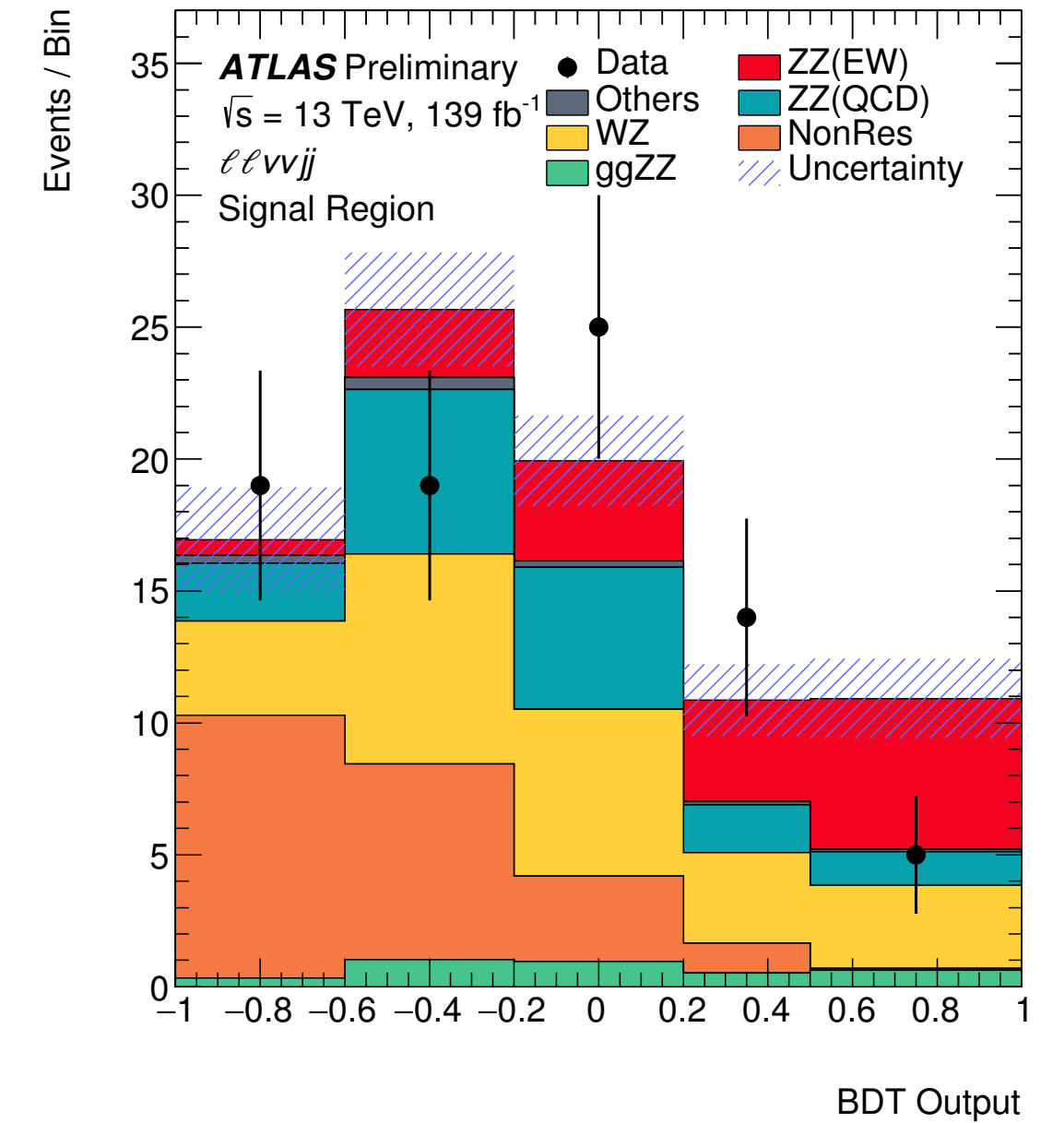
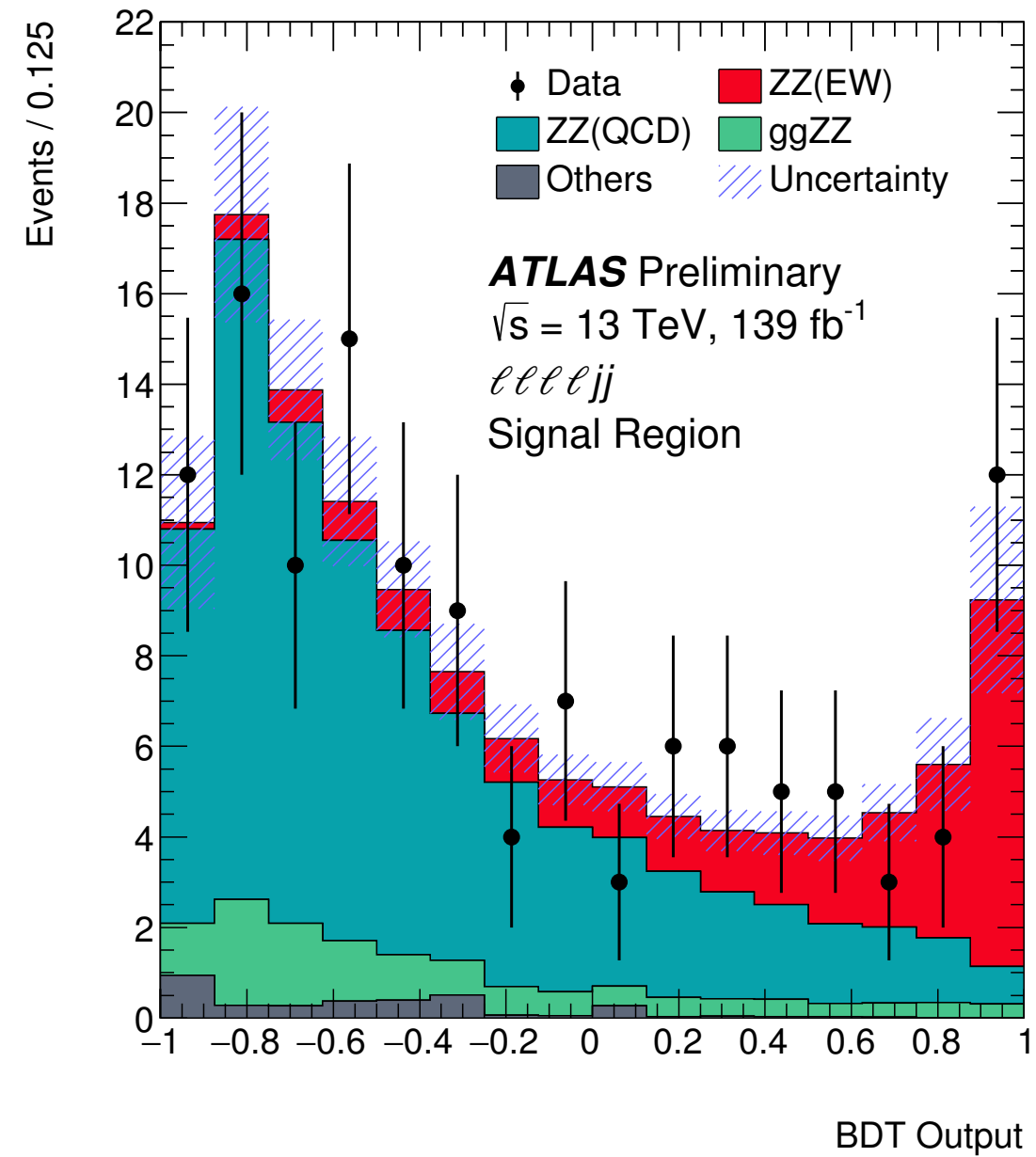
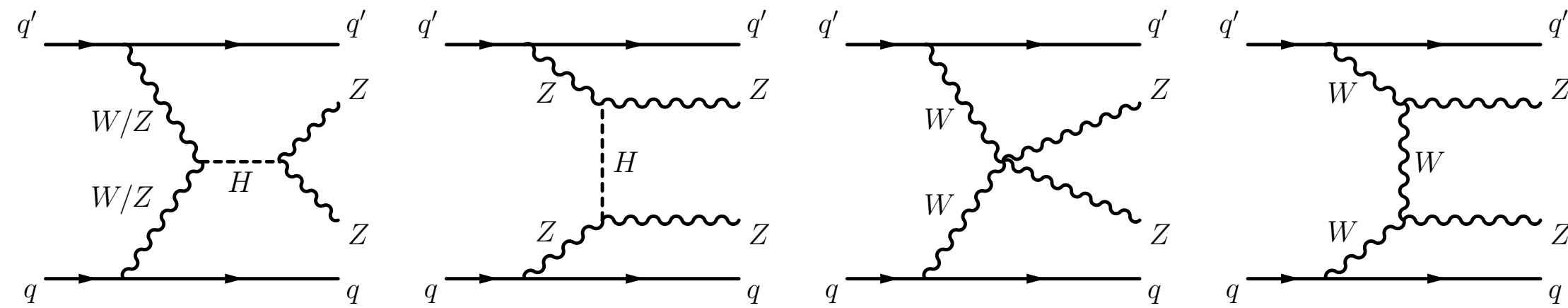


arXiv:1903.10415

OBSERVATION OF VECTOR BOSON SCATTERING

extends SM x-section tests over 14 orders of magnitude

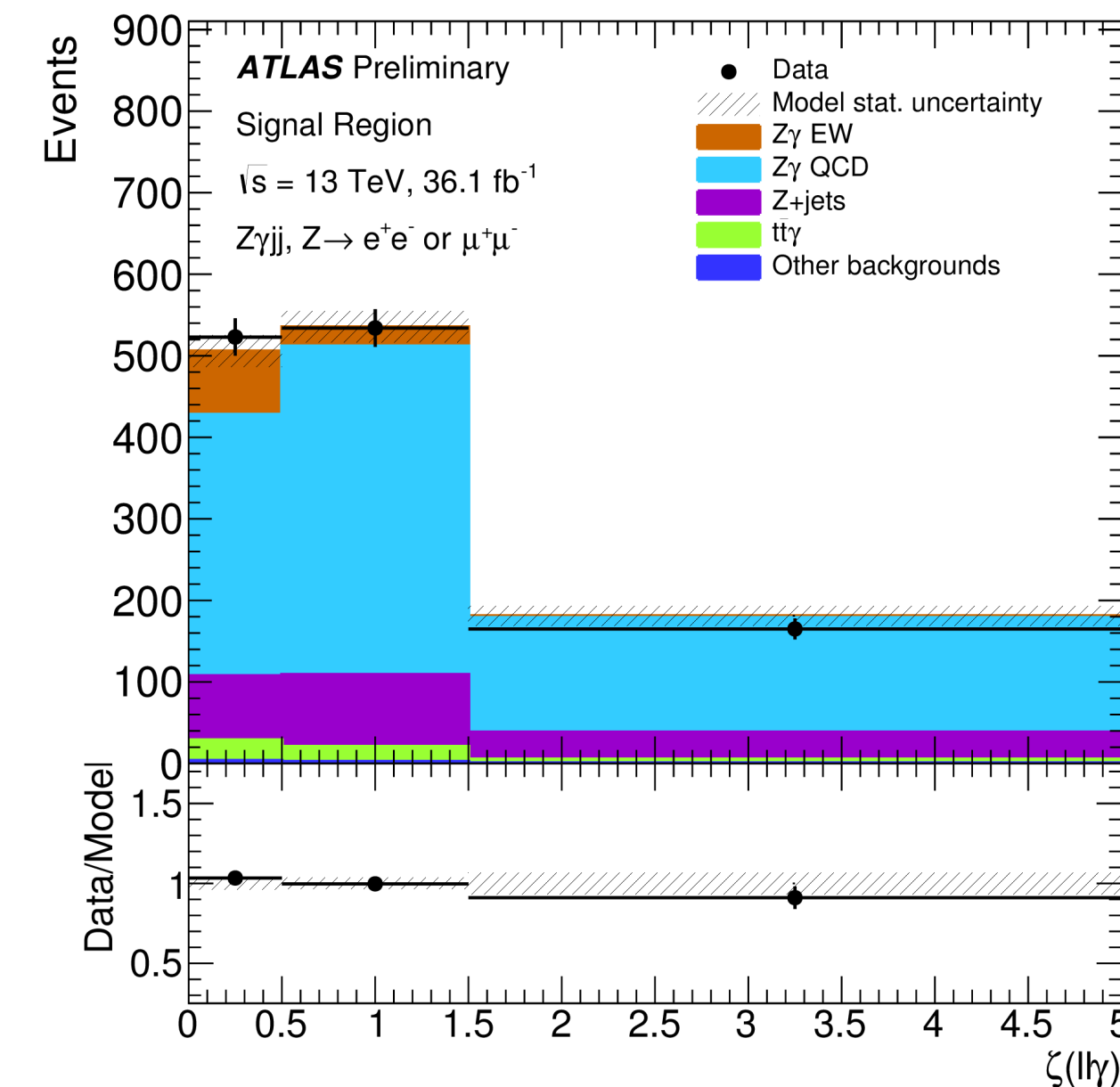
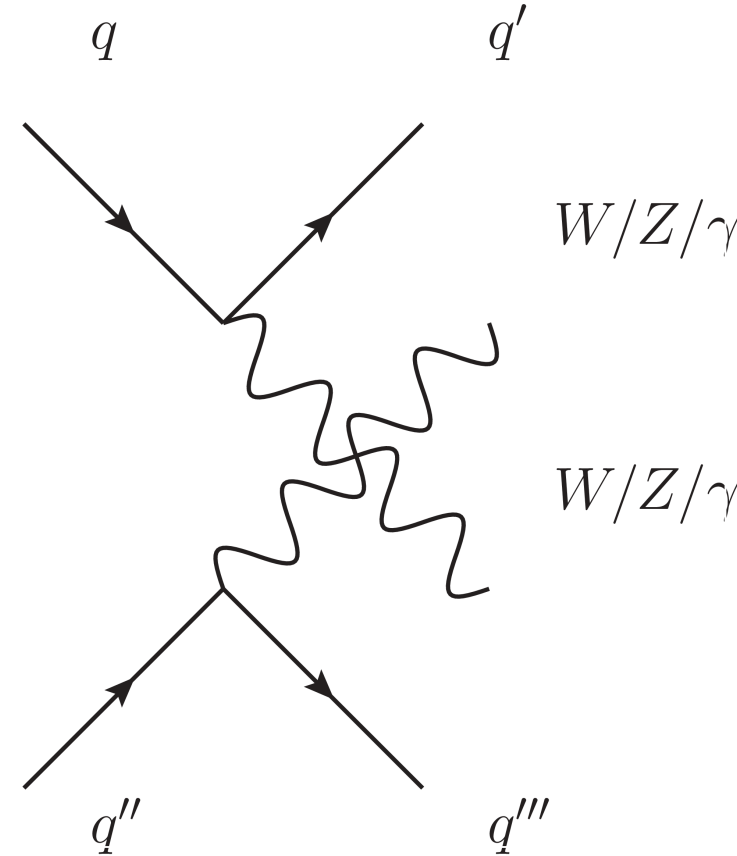
ZZjj: very rare ($\sigma < \text{fb}$) but clean modes using Z decays to charged leptons; exploit multivariate analysis to separate EW signal from strong interaction background



$\sigma(\text{fid}) = 0.82 \pm 0.21 \text{ fb}$ (SM: $0.61 \pm 0.03 \text{ fb}$)
 significance 5.5σ : first observation of ZZjj VBS

Z γ jj electroweak production:

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



TOP PRECISION PHYSICS

NEW PRECISION TOTAL X-SECTION MEASUREMENT

[ATLAS-CONF-2019-041](#)

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

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

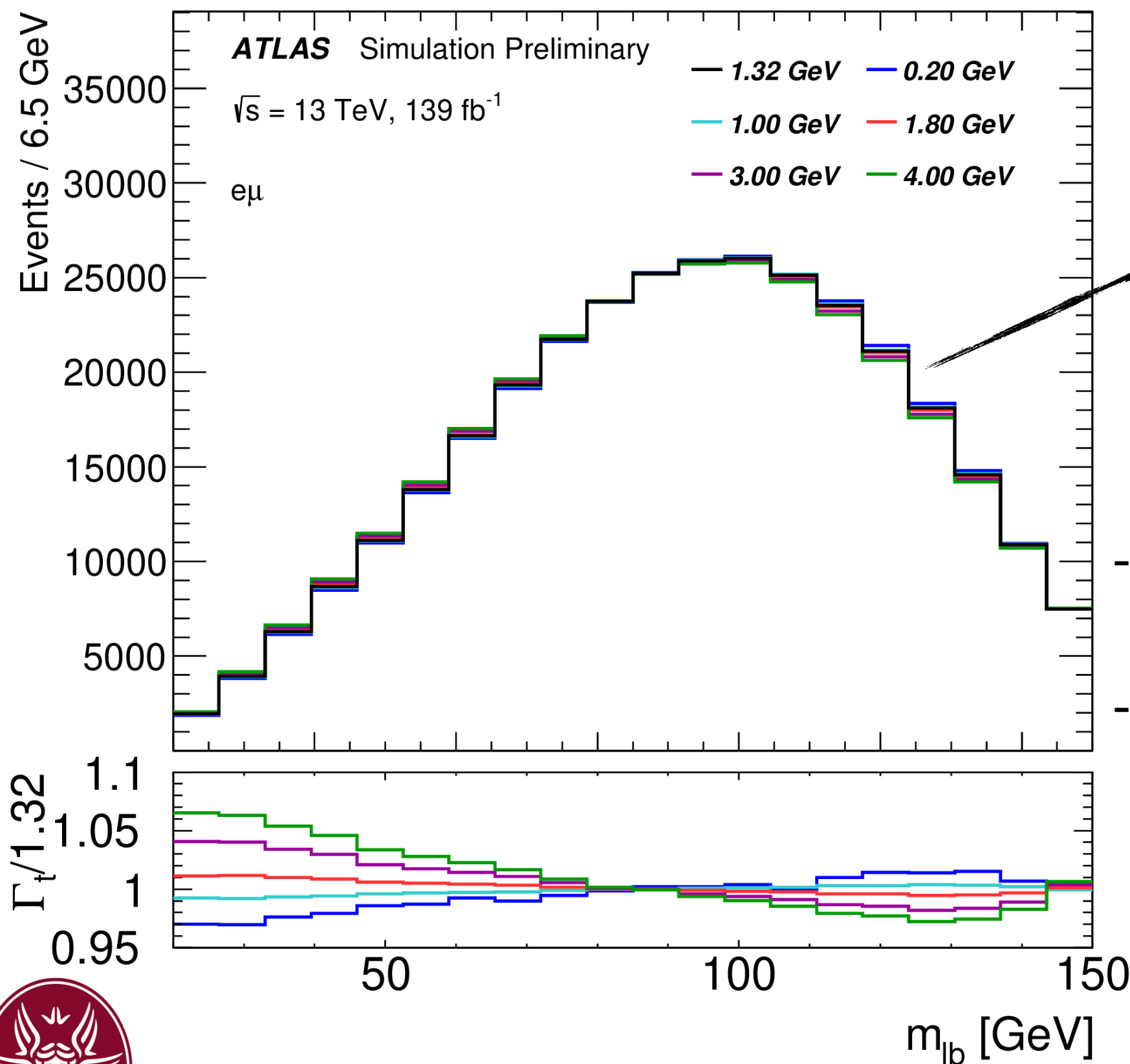
$$\sigma(\text{NNLO}) = 832 \pm 45 \text{ pb}$$

CHARGE ASYMMETRY MEASUREMENT

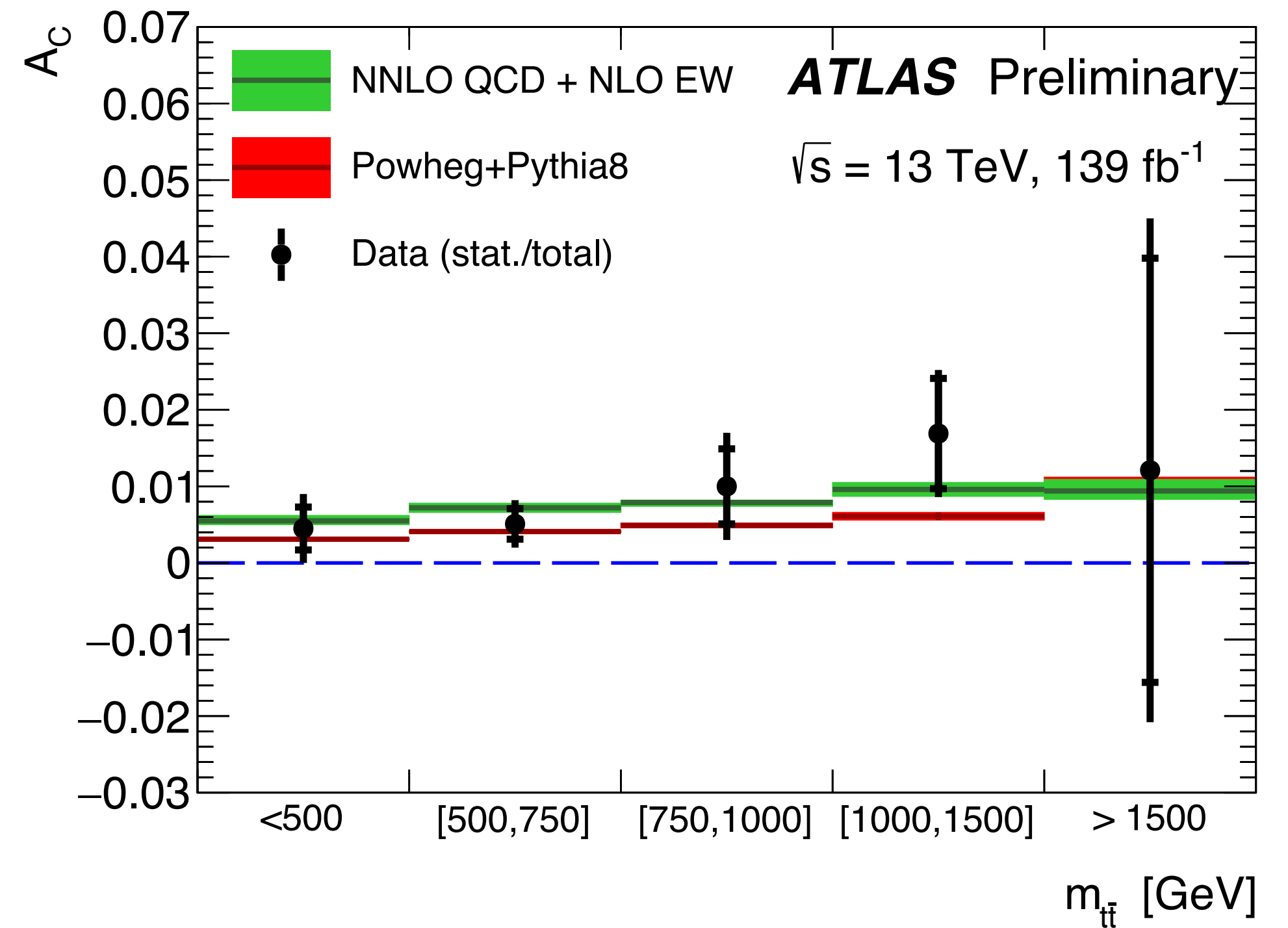
[ATLAS-CONF-2019-026](#)

- 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



[ATLAS-CONF-2019-038](#)



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

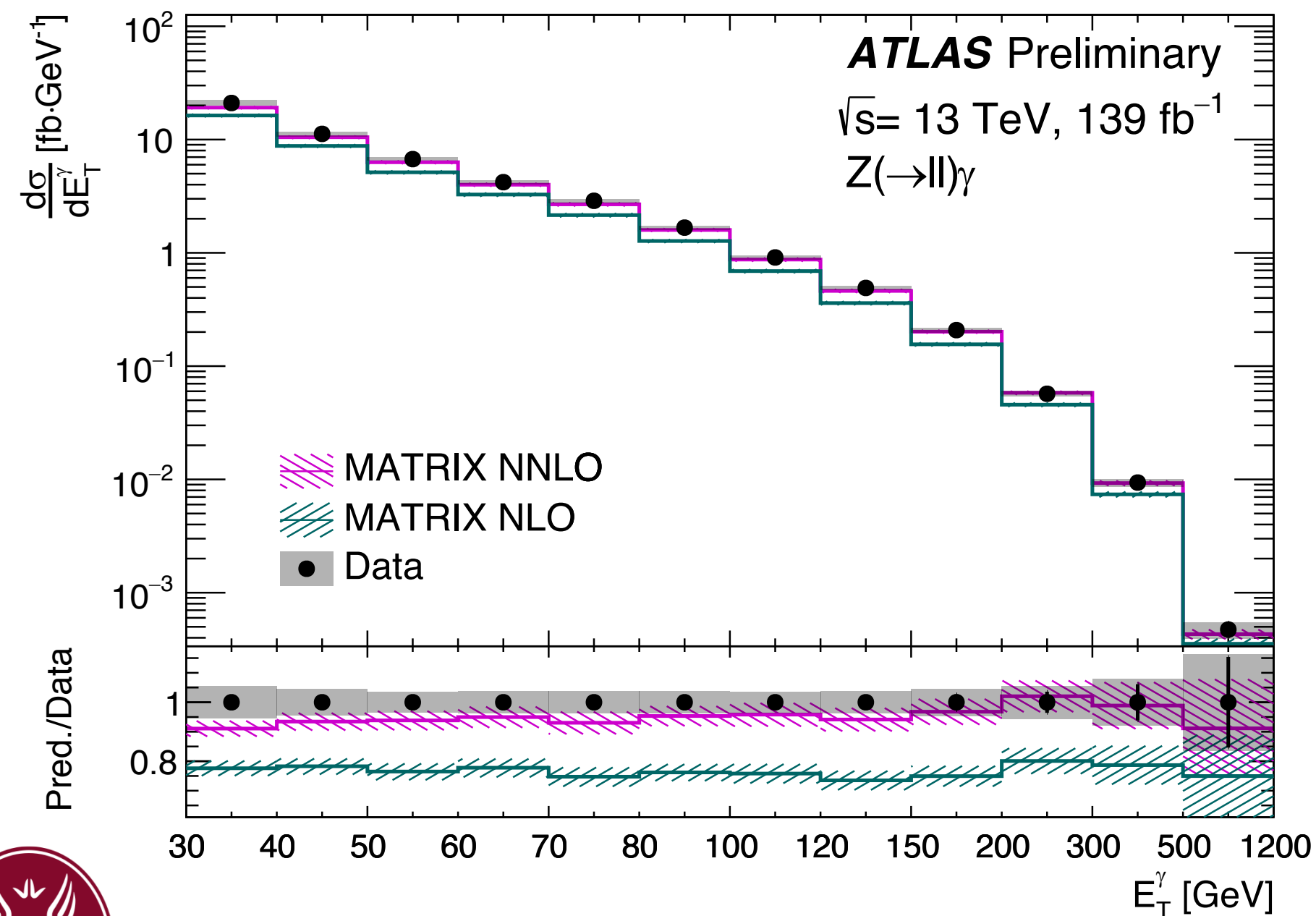
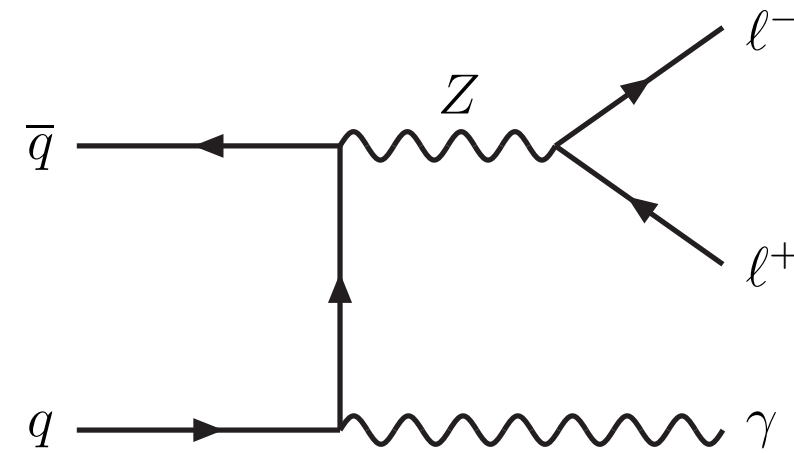
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

$A_C \neq 0$ at 4σ level

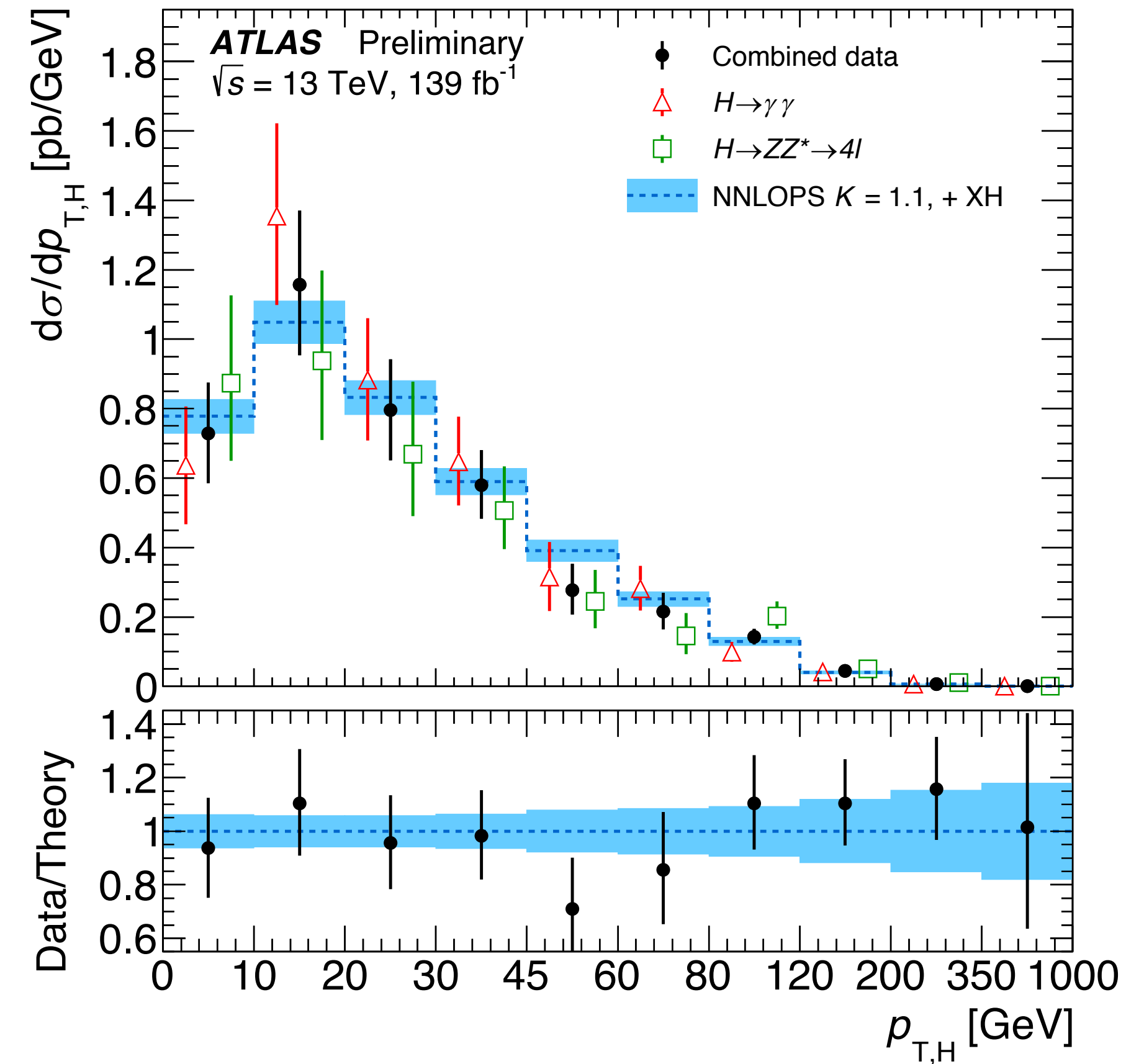


EXPLORING DIFFERENTIAL X-SECTIONS

high-precision measurement of differential $Z\gamma$ diboson cross sections, probing EW gauge structure of SM and tests QCD



Z γ



HIGGS

Higgs differential cross section measurements: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$
 - well described by POWHEG NNLO+PS up to 1 TeV
 - constrain EFT parameters and charm Yukawa coupling \rightarrow NP effects



PROBING NP WITH HIGH PRECISION HIGGS MEASUREMENTS

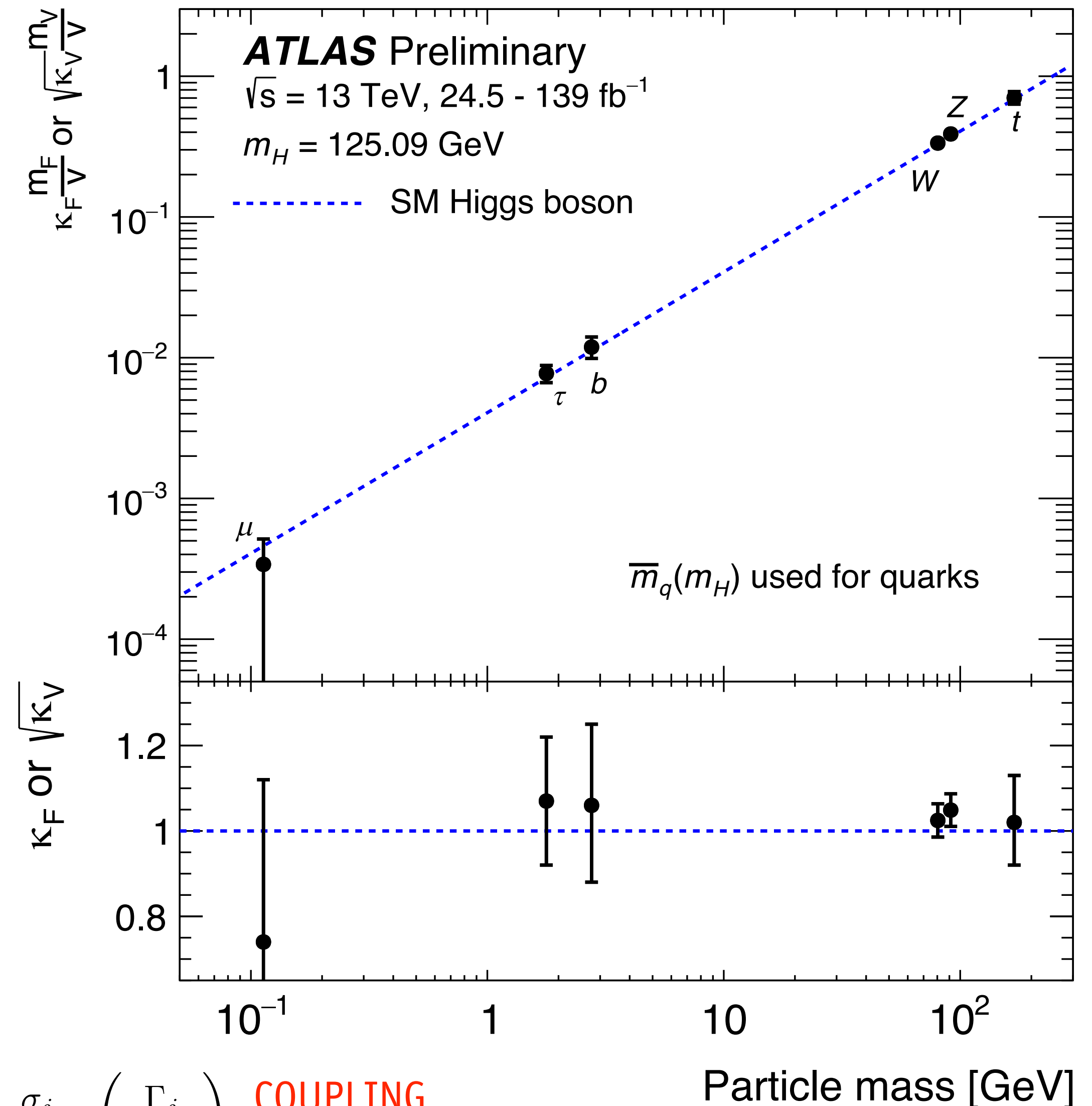
higgs sector directly connected with most important open questions of the SM: naturalness, vacuum stability & energy, flavour

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

major progresses in the last year:

- observation of $H \rightarrow bb$ decay
- observation of ttH and VH productions

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

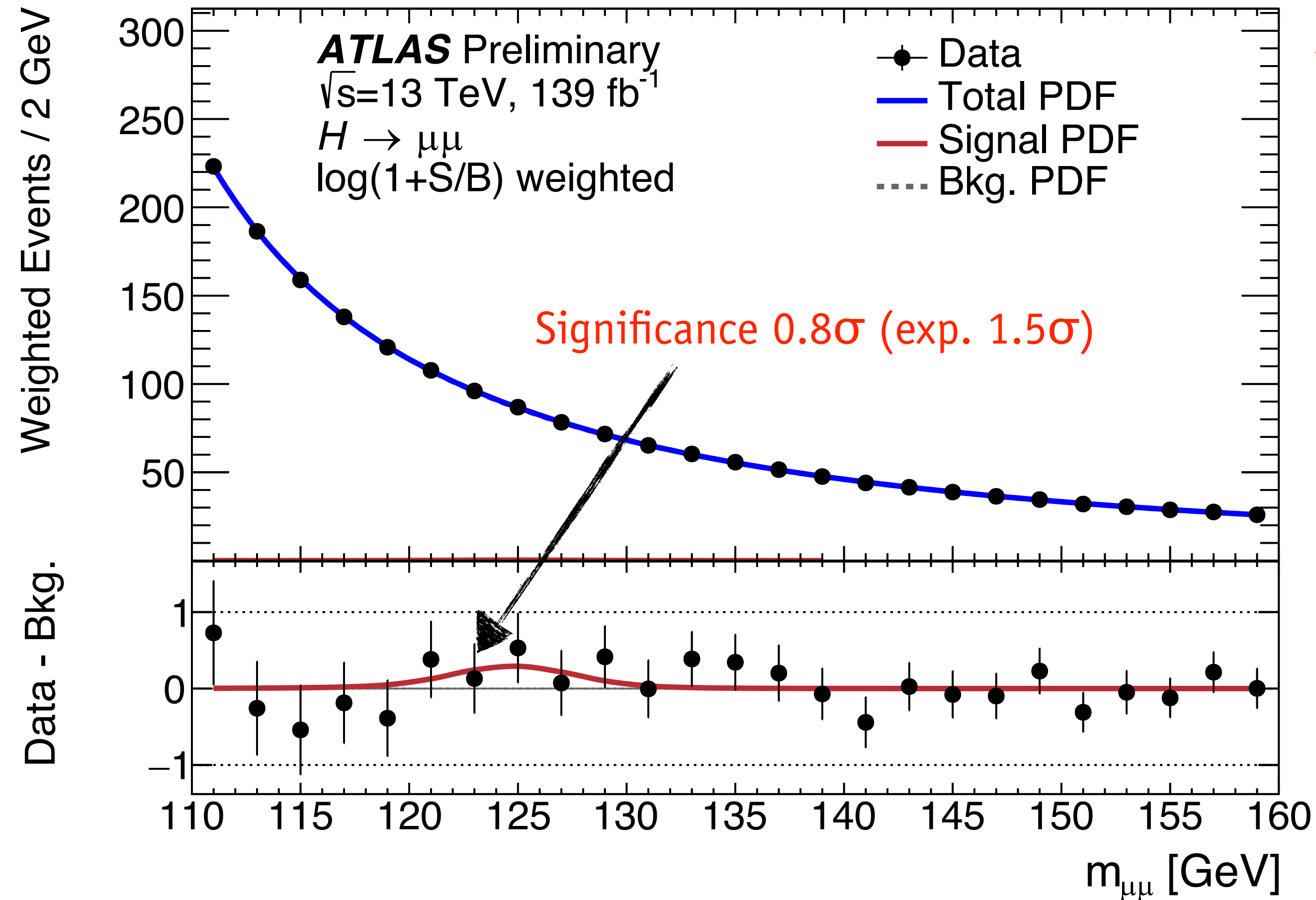


$$k_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \left(\frac{\Gamma_j}{\Gamma_j^{SM}} \right) \text{ COUPLING MODIFIERS}$$



PROBING NP WITH HIGH PRECISION HIGGS MEASUREMENTS

next frontier: test higgs interactions with lighter generation fermions



[ATLAS-CONF-2019-028](#)

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

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

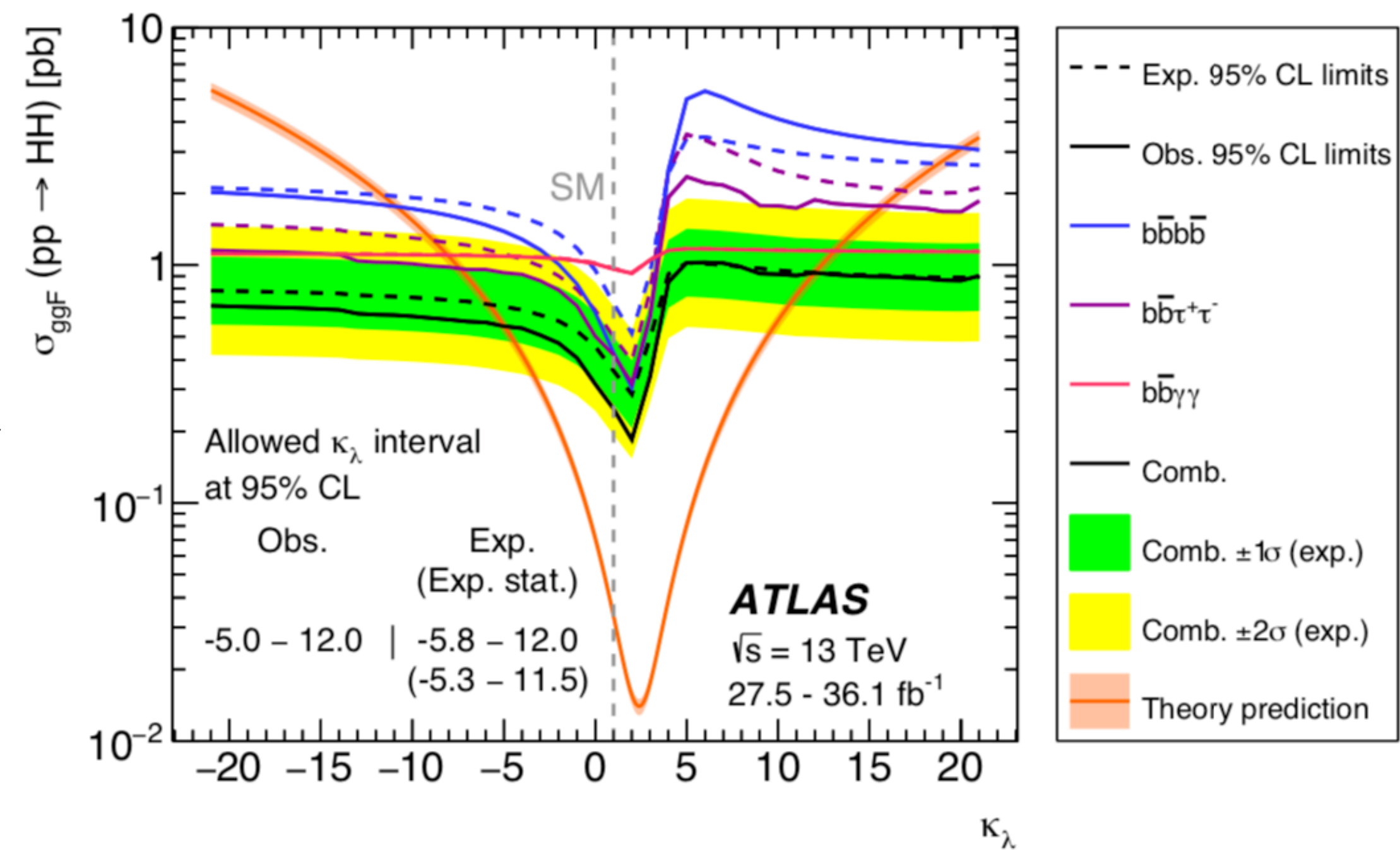
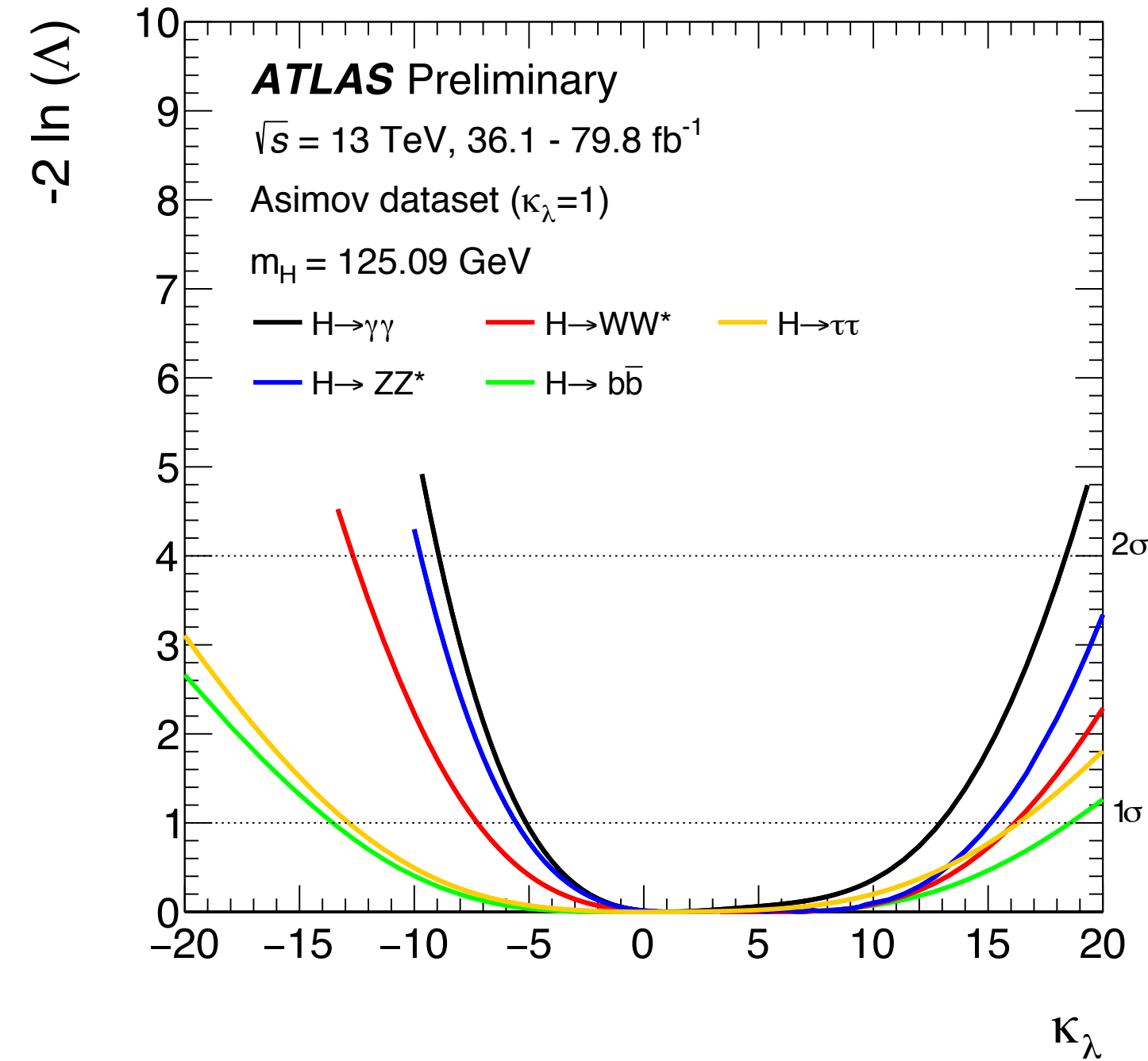
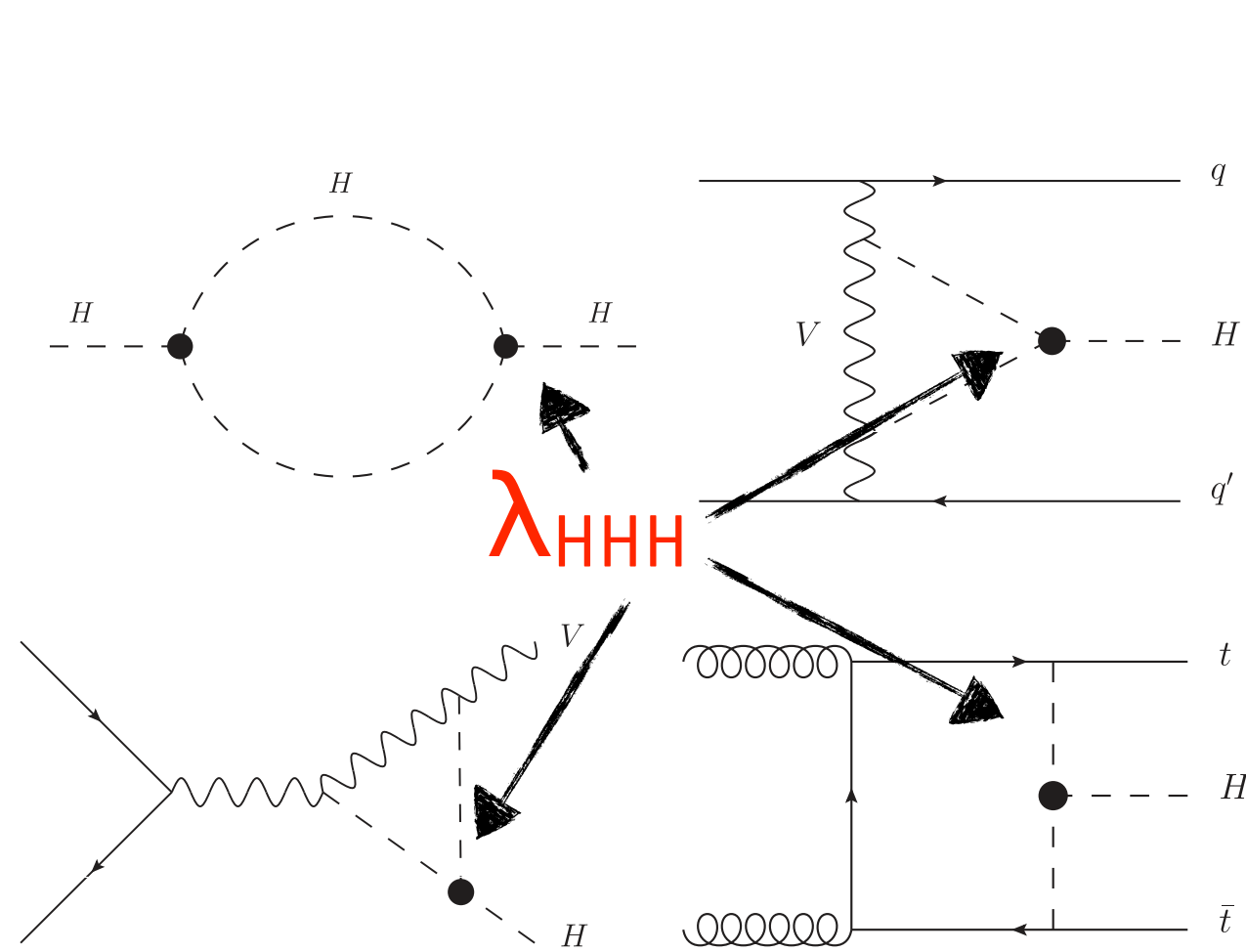
50% improvement wrt previous analysis (80 fb $^{-1}$)



HIGGS SELF INTERACTIONS

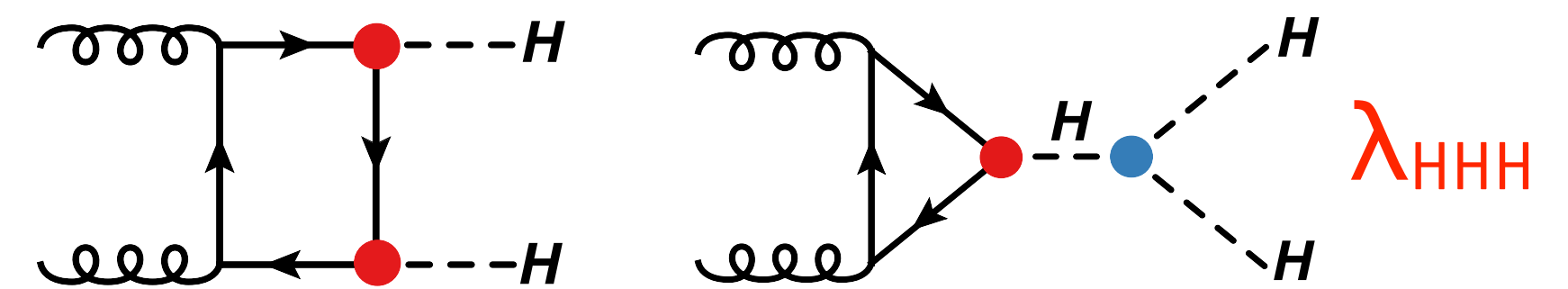
SELF-COUPPLINGS

DI-HIGGS PRODUCTION



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

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

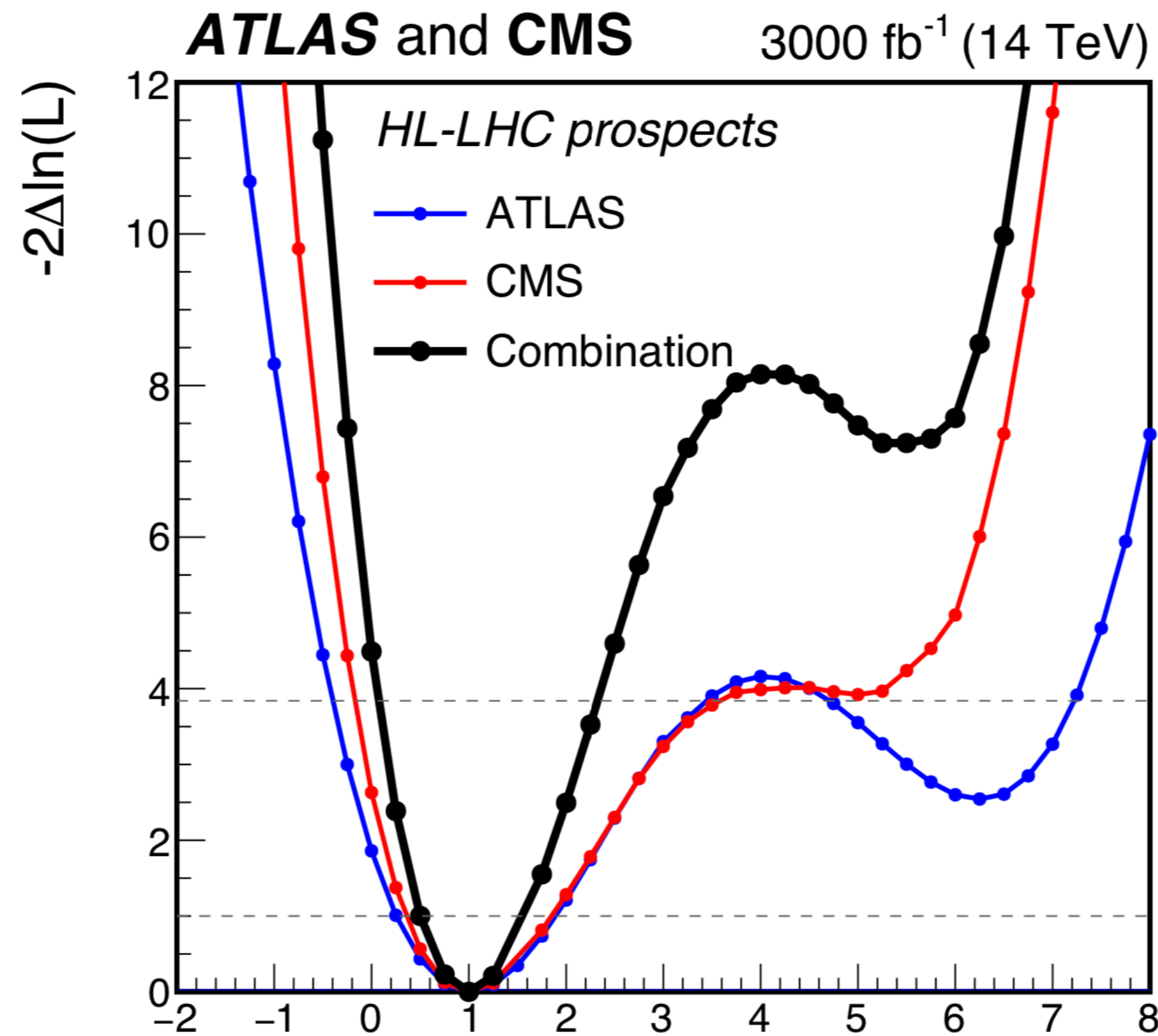


No observation yet ...
 $-5.0 < k_\lambda < 12.0$ @95% CL



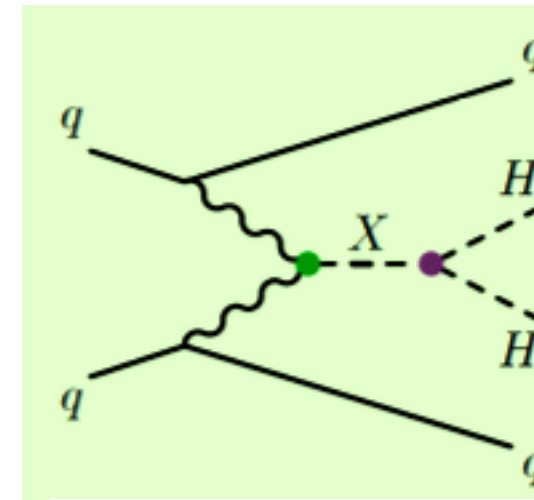
HIGGS SELF INTERACTIONS & NP

k_λ @ HL-LHC

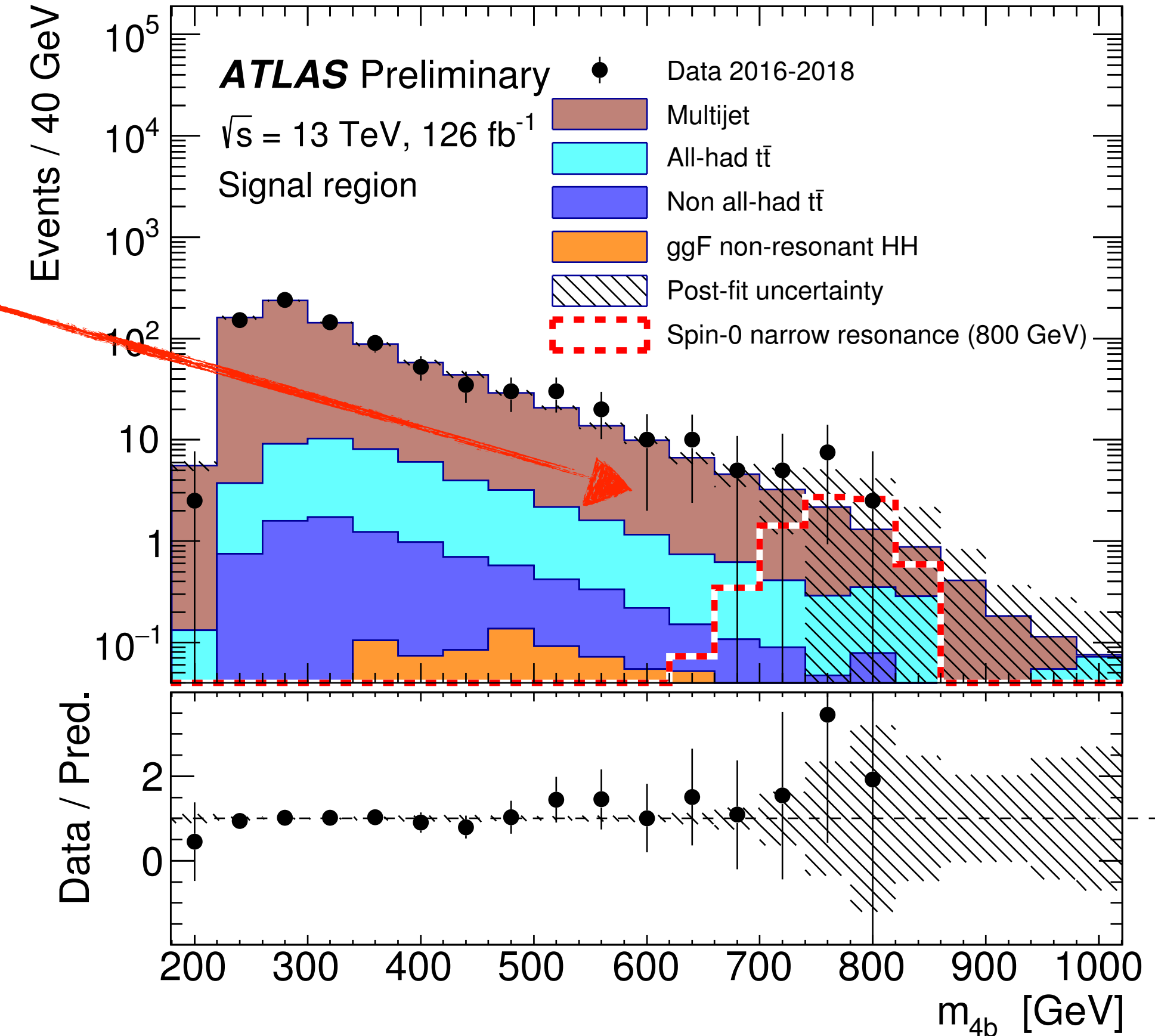
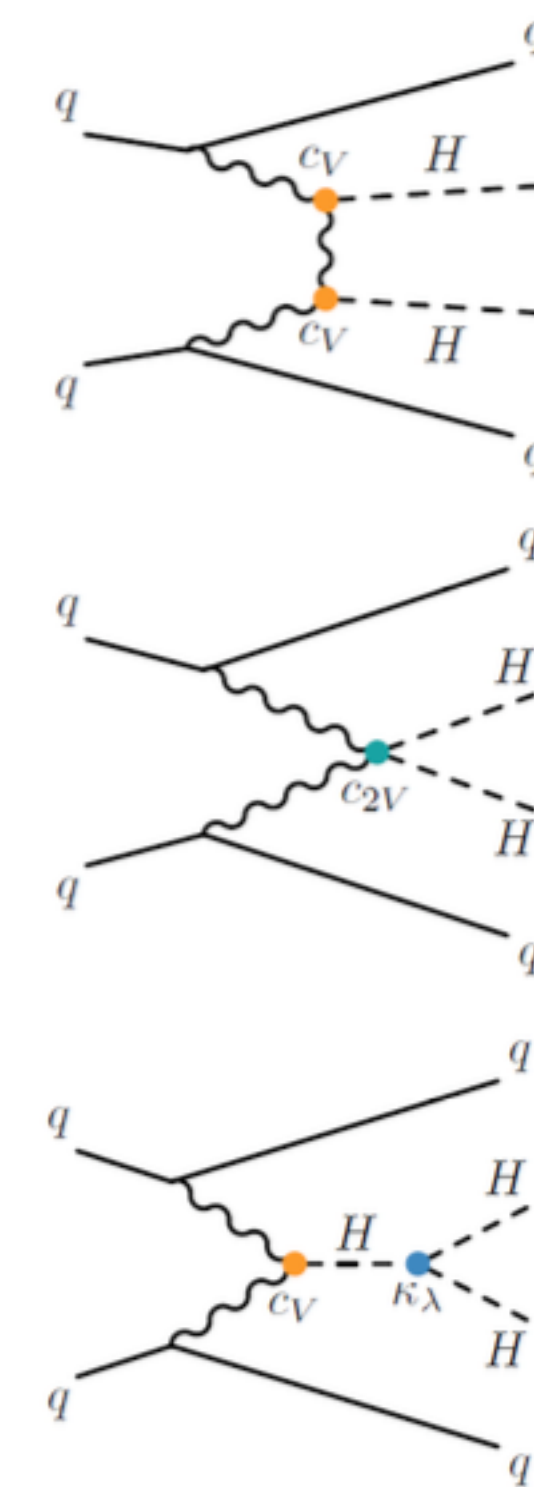


- can observe HH production at $4\sigma^{k_\lambda}$
- can measure k_λ with 50% uncertainty

PROBE XHH VERTEX



BSM resonant contributions



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



ATLAS NEW PHYSICS SEARCHES SUMMARY

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

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit
Extra dimensions					
ADD $G_{KK} + g/q$	$0 e, \mu$	1-4 j	Yes	36.1	M_D 7.7 TeV
ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_S 8.6 TeV
ADD QBH	-	2 j	-	37.0	M_{th} 8.9 TeV
ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{th} 8.2 TeV
ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{th} 9.55 TeV
RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	36.7	G_{KK} mass 4.1 TeV
Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV
Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\bar{q}\bar{q}$	$0 e, \mu$	2 J	-	139	G_{KK} mass 1.6 TeV
Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	g_{KK} mass 3.8 TeV
2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV
Gauge bosons					
SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV
SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV
Leptophobic $Z' \rightarrow bb$	-	2 b	-	36.1	Z' mass 2.1 TeV
Leptophobic $Z' \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	Z' mass 3.0 TeV
SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV
SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	36.1	W' mass 3.7 TeV
HVT $V' \rightarrow WZ \rightarrow qq\bar{q}\bar{q}$ model B	$0 e, \mu$	2 J	-	139	V' mass 3.6 TeV
HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV
LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	W_R mass 3.25 TeV
LRSM $W_R \rightarrow \mu N_R$	2μ	1 J	-	80	W_R mass 5.0 TeV
CI					
CI $qqqq$	-	2 j	-	37.0	Λ
CI $\ell\ell qq$	$2 e, \mu$	-	-	36.1	Λ
CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV
DM					
Axial-vector mediator (Dirac DM)	$0 e, \mu$	1-4 j	Yes	36.1	m_{med} 1.55 TeV
Colored scalar mediator (Dirac DM)	$0 e, \mu$	1-4 j	Yes	36.1	m_{med} 1.67 TeV
$VV\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	1 J, $\leq 1 j$	Yes	3.2	M_* 700 GeV
Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	$0-1 e, \mu$	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV
LQ					
Scalar LQ 1 st gen	$1, 2 e$	$\geq 2 j$	Yes	36.1	LQ mass 1.4 TeV
Scalar LQ 2 nd gen	$1, 2 \mu$	$\geq 2 j$	Yes	36.1	LQ mass 1.56 TeV
Scalar LQ 3 rd gen	2τ	2 b	-	36.1	LQ ₃ mass 1.03 TeV
Scalar LQ 3 rd gen	$0-1 e, \mu$	2 b	Yes	36.1	LQ ₃ mass 970 GeV
Heavy quarks					
VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV
VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV
VLQ $T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	
VLQ $Y \rightarrow Wb + X$	$1 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	
VLQ $B \rightarrow Hb + X$	$0 e, \mu, 2 \gamma \geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	
VLQ $QQ \rightarrow WqWq$	$1 e, \mu \geq 4 j$	Yes	20.3	Q mass 690 GeV	
Excited fermions					
Excited quark $q^* \rightarrow qg$	-	2 j	-	139	q^* mass 6.7 TeV
Excited quark $q^* \rightarrow q\gamma$	1γ	1 j	-	36.7	q^* mass 5.3 TeV
Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	36.1	b^* mass 2.6 TeV
Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	ℓ^* mass 3.0 TeV
Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV
Other					
Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	N^0 mass 560 GeV
LRSM Majorana ν	2μ	2 j	-	36.1	N_R mass 3.2 TeV
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV
Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV

ATLAS SUSY Searches* - 95% CL Lower Limits
 July 2019

ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}$

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches				
$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	$0 e, \mu$ mono-jet	2-6 jets E_T^{miss}	36.1 0.9 1.55	$m(\tilde{q}) < 100 \text{ GeV}$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	$0 e, \mu$	2-6 jets E_T^{miss}	36.1 0.43 0.71 2.0	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$3 e, \mu$	4 jets E_T^{miss}	36.1 1.2 1.85	$m(\tilde{g}) < 800 \text{ GeV}$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	$0 e, \mu$	7-11 jets E_T^{miss}	36.1 1.15 1.8	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	$0-1 e, \mu$	3 b E_T^{miss}	79.8 1.25 2.25	$m(\tilde{g}) < 200 \text{ GeV}$
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0/\tilde{\chi}_1^\pm$	Multiple	Multiple	36.1 0.9	$m(\tilde{b}_1) = 300 \text{ GeV}, \text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 1$
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b\tilde{b}\tilde{\chi}_1^0$	Multiple	Multiple	36.1 0.58-0.82	$m(\tilde{b}_1) = 300 \text{ GeV}, \text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_2^0) = 0.5$
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^\pm \rightarrow b\tilde{b}\tilde{\chi}_1^0$	Multiple	Multiple	139 0.74	$m(\tilde{b}_1) = 200 \text{ GeV}, m(\tilde{\chi}_2^\pm) = 300 \text{ GeV}, \text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_2^\pm) = 1$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{t}_1\tilde{t}_1$	$0-2 e, \mu$	0-2 jets/1-2 b E_T^{miss}	36.1 1.0	$\Delta m(\tilde{t}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{t}_1^0) = 100 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^\pm$	$1 e, \mu$	3 jets/1 b E_T^{miss}	139 0.44-0.59	$\Delta m(\tilde{t}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{t}_1^0) = 0 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 b\nu, \tilde{t}_1 \rightarrow \tau\tilde{G}$	$1 \tau + 1 e, \mu, \tau$	2 jets/1 b E_T^{miss}	36.1 1.16	$m(\tilde{t}_1) = 400 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0/\tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	$0 e, \mu$	2 c E_T^{miss}	36.1 0.85	$m(\tilde{t}_1) = 800 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^\pm/\tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^\pm$	$0 e, \mu$	2 c E_T^{miss}	36.1 0.46 0.85	$m(\tilde{t}_1) = 0 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{\chi}_1^\pm) = 180 \text{ GeV}$
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	$1-2 e, \mu$	4 b E_T^{miss}	36.1 0.32-0.88	$m(\tilde{t}_2) = 360 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40 \text{ GeV}$
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	$3 e, \mu$	1 b E_T^{miss}	139 0.86	
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	$2-3 e, \mu$	≥ 1 E_T^{miss}	36.1 0.6	$m(\tilde{\chi}_1^\pm) = 0$
$\tilde{\chi}_1^\pm\tilde{\chi}_2^\pm$ via WW	$2 e, \mu$	≥ 1 E_T^{miss}	139 0.205	$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$0-1 e, \mu$	2 b/2 γ E_T^{miss}	139 0.42	$m(\tilde{\chi}_1^\pm) = 0$
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ via $\tilde{t}_L/\tilde{\nu}$	$2 e, \mu$	2 b/2 γ E_T^{miss}	139 0.74	$m(\tilde{\chi}_1^\pm) = 70 \text{ GeV}$
$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2τ	E_T^{miss}	139 1.0	$m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$
$\tilde{\tau}_L\tilde{\tau}_L, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	$2 e, \mu$	0 jets E_T^{miss}	139 0.16-0.3 0.12-0.39	$m(\tilde{\tau}_L) = 0$
$\tilde{\tau}_L\tilde{\tau}_L, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^\pm$	$2 e, \mu$	≥ 1 E_T^{miss}	139 0.7	$m(\tilde{\tau}_L) = 0$
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	$0 e, \mu$	$\geq 3 b$ E_T^{miss}	36.1 0.13-0.23 0.29-0.88	$\text{BR}(\tilde{H} \rightarrow h\tilde{G}) = 1$
Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet E_T^{miss}	36.1 0.46	$\text{BR}(\tilde{\chi}_1^\pm \rightarrow q\mu) = 1$
Stable \tilde{g} R-hadron	Multiple	Multiple	36.1 2.0	Pure Wino
Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple	Multiple	36.1 2.05 2.4	Pure Higgsino
LFBV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, e\tau, \mu\tau$	0 jets E_T^{miss}	3.2 1.9	$\lambda_{311} = 0.11, \lambda_{132}/\lambda_{133}/\lambda_{233} = 0.07$
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell/\nu\nu$	$4 e, \mu$	0 jets E_T^{miss}	36.1 0.82 1.33	$m(\tilde{\chi}_1^\pm) = 100 \text{ GeV}$
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	4-5 large-R jets	Multiple	36.1 1.05 1.3 1.9	Large λ'_{12}
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	Multiple	Multiple	36.1 1.05 2.0	$m(\tilde{t}_1) = 200 \text{ GeV}$, bino-like
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	Multiple	36.1 0.55 1.05	$m(\tilde{t}_1) = 200 \text{ GeV}$, bino-like
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	$2 e, \mu$	2 b	36.1 0.42 0.61	$\text{BR}(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$
	1μ	DV	136 0.4-1.45 1.6	$\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta = 1$

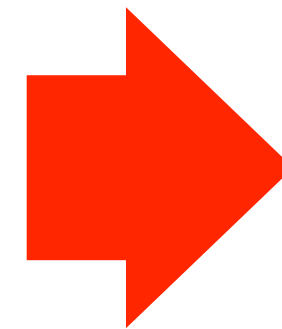
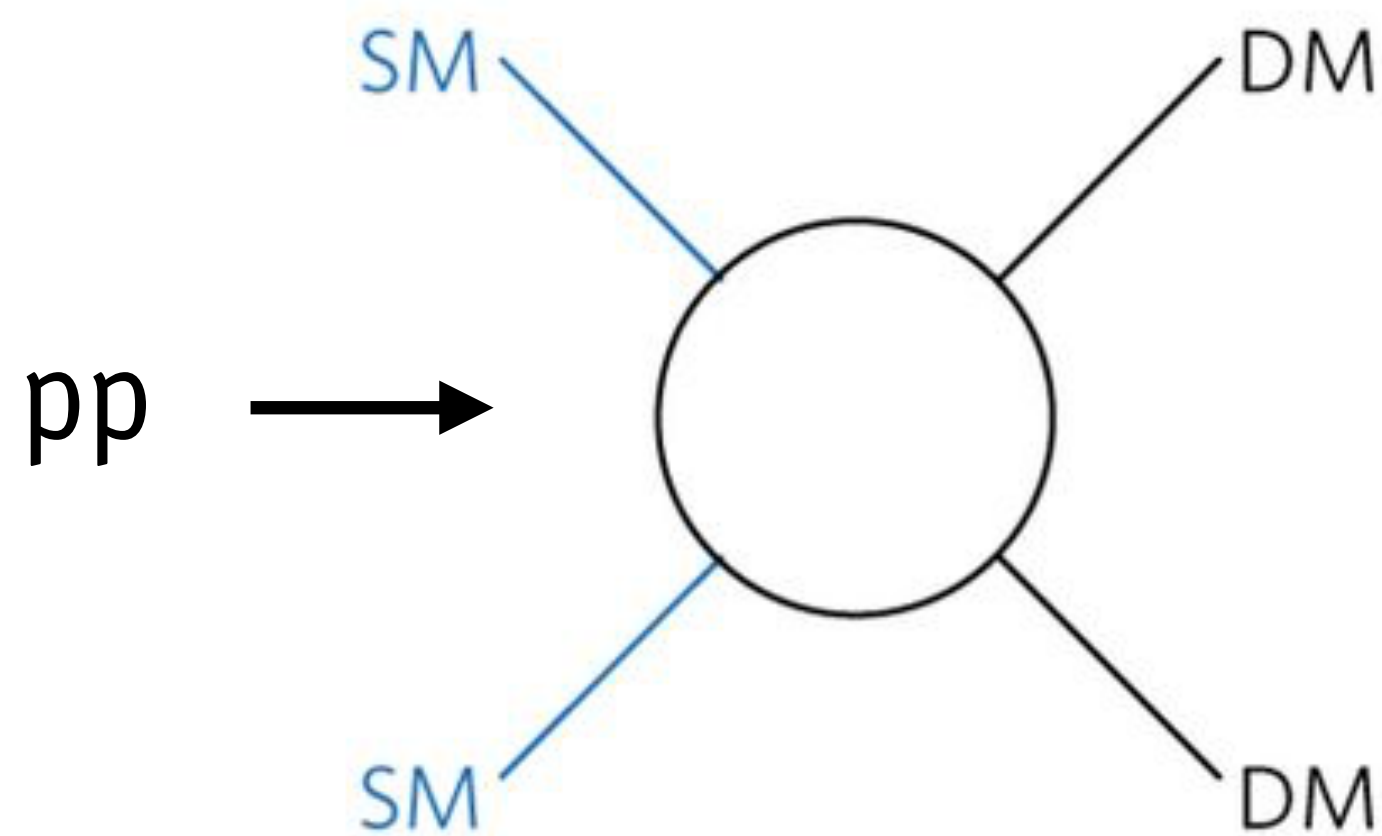
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



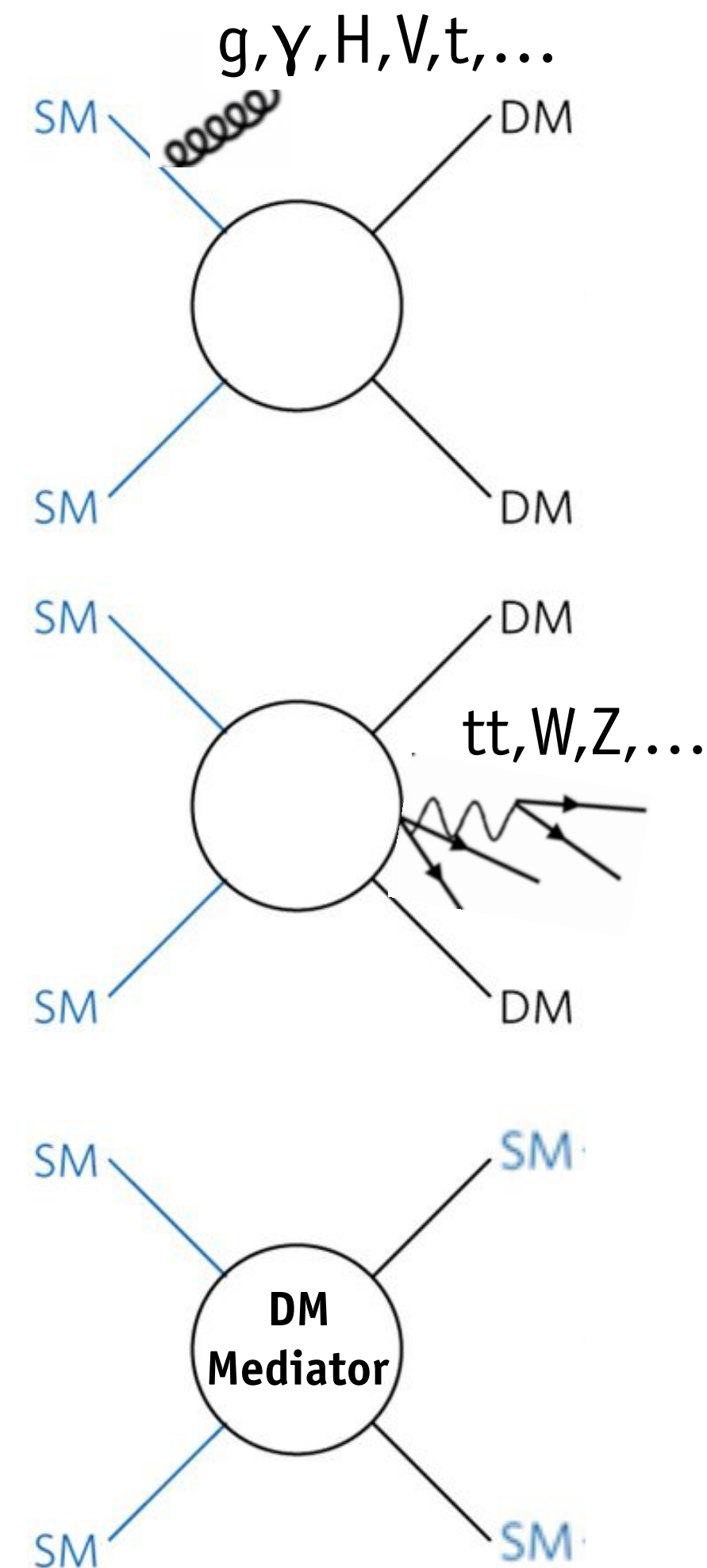
DIRECT SEARCHES FOR DM@LHC

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 visible to detect invisible things ...



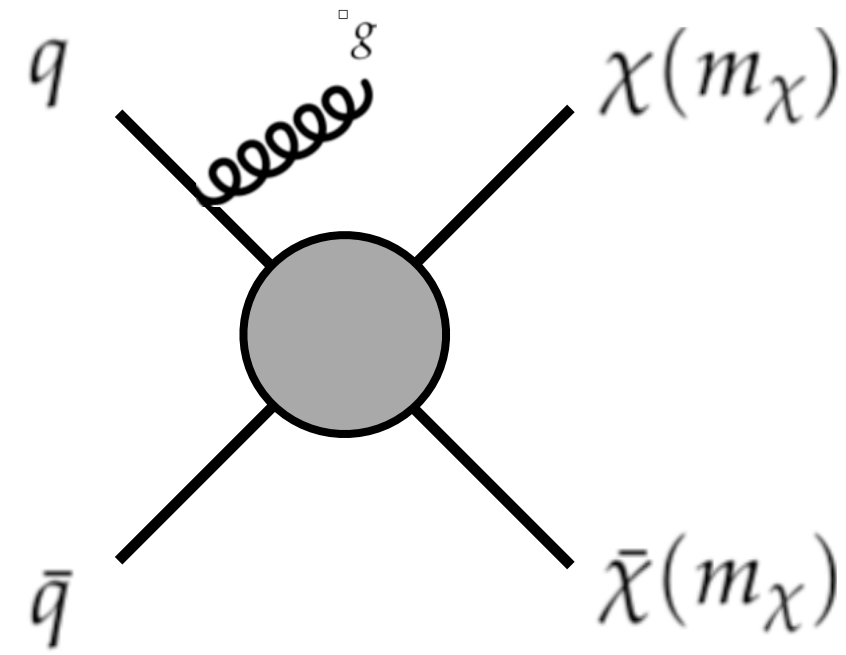
MONO-X SEARCHES

ASSOCIATE PRODUCTION OF DM WITH SM PARTICLES

DM MEDIATOR SEARCHES



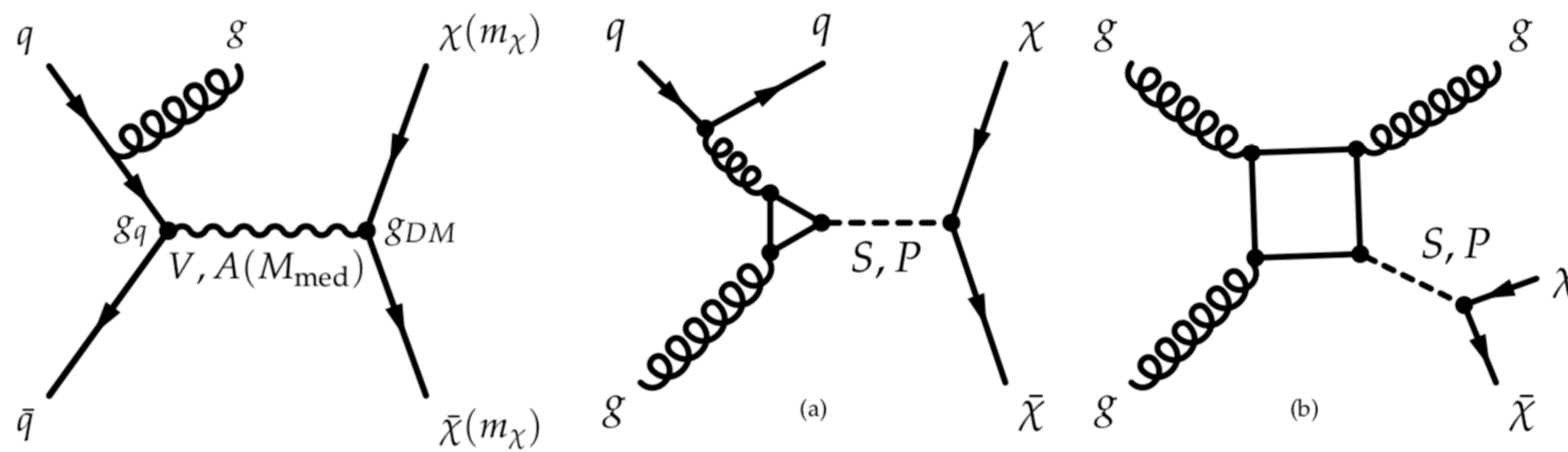
DM BENCHMARKS



EFFECTIVE FIELD THEORIES

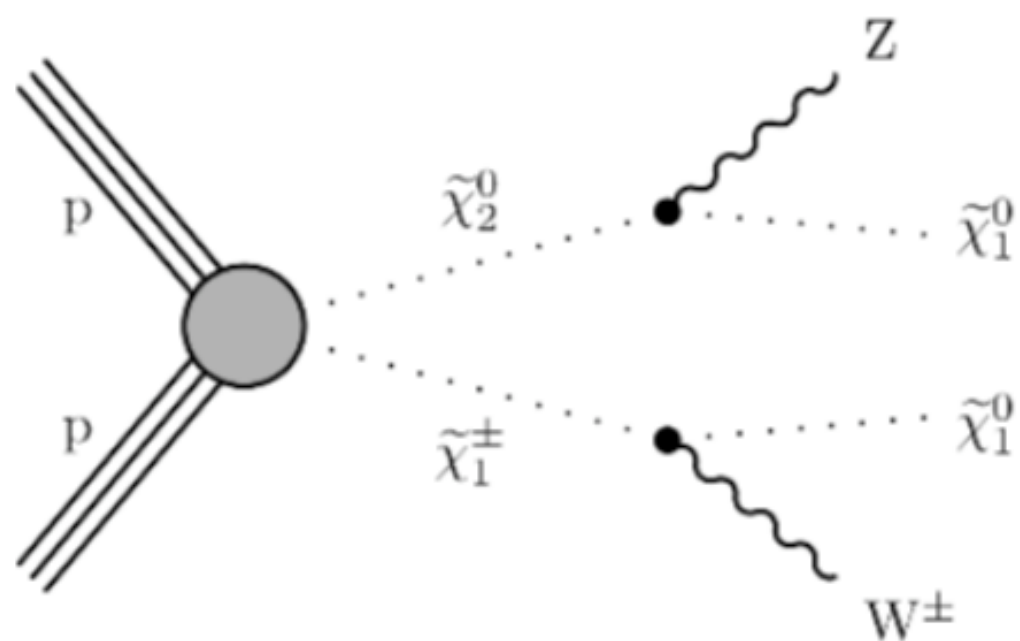
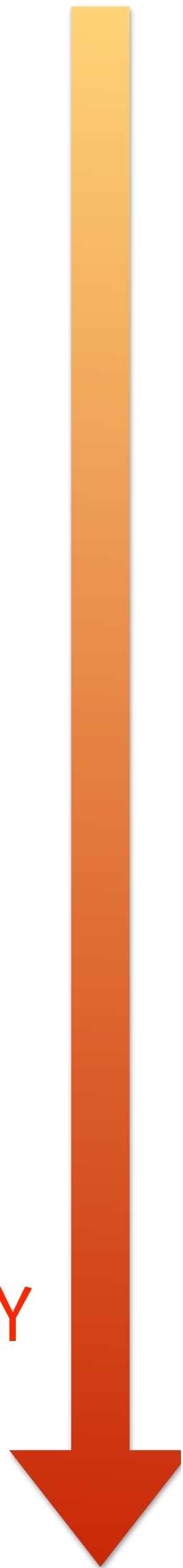
valid as long as we can integrate out higher-scale physics (mediator)

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

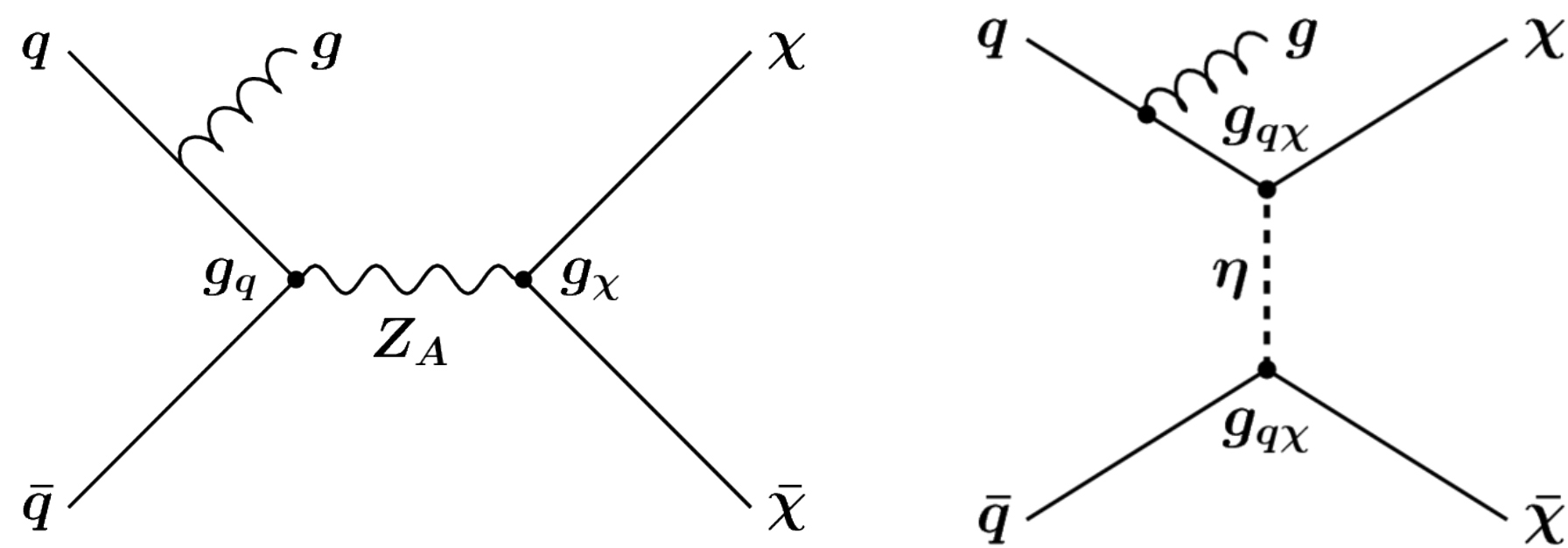
UV-complete models (ex. SUSY) results more sensitive to specific models but also more model dependent



MONO-X SEARCHES

Search strategy:

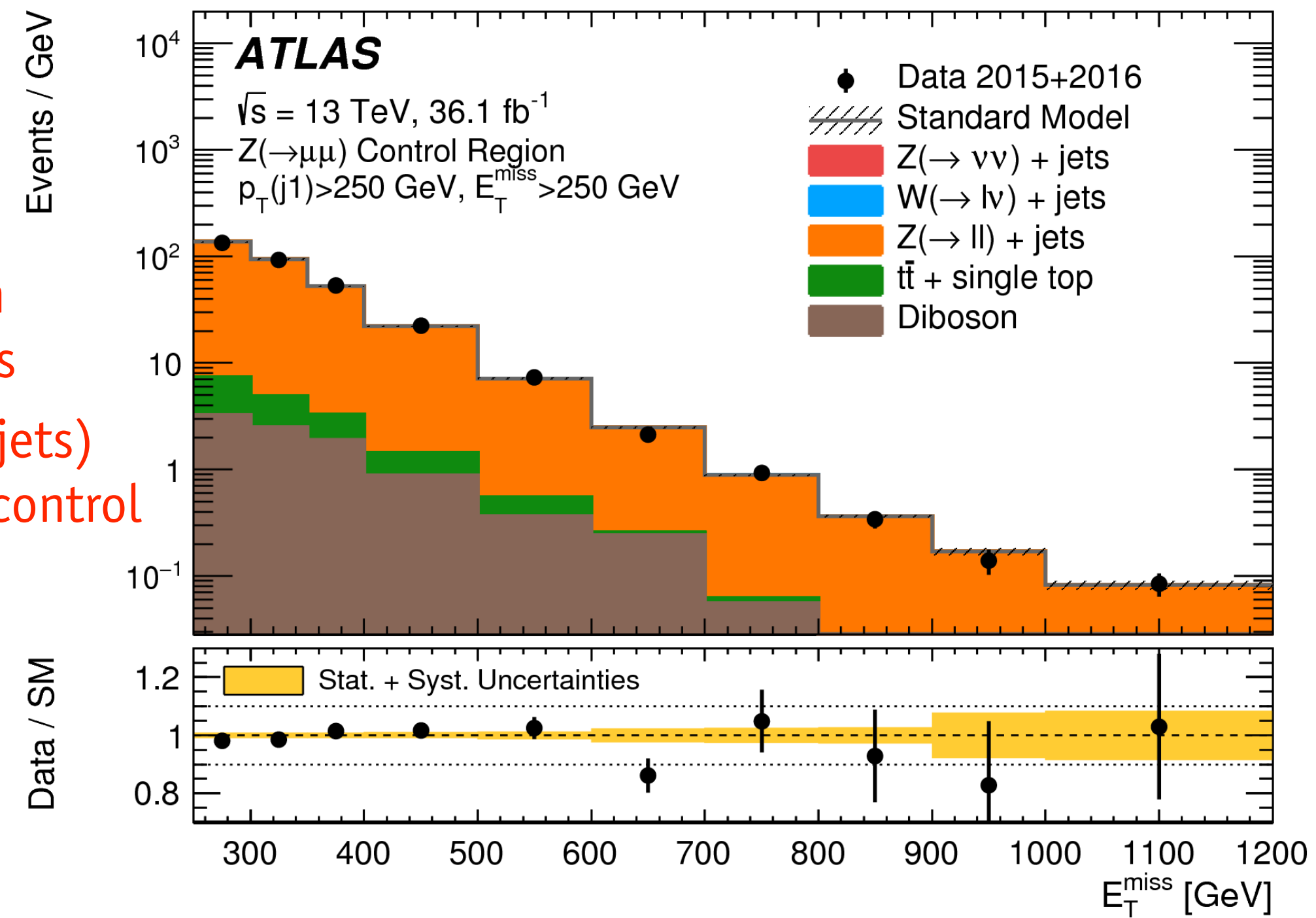
- look at ISR objects recoiling against DM system (MET)
- $\alpha_s \gg \alpha \rightarrow$ larger signal yield in case of mono-Jet
- most sensitive channel for vector mediator DM



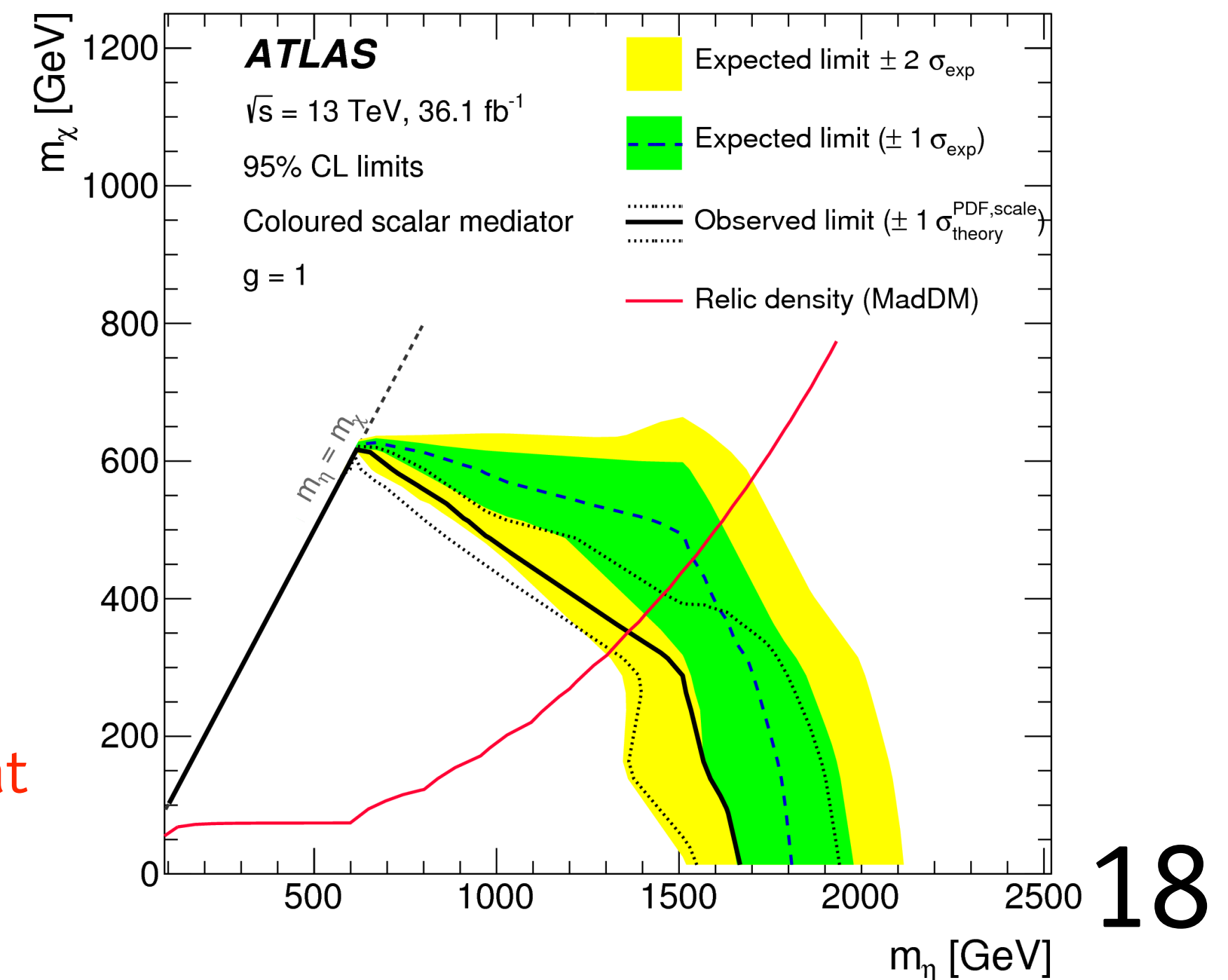
Benchmark models:

- 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

data-driven
backgrounds
((W/Z \rightarrow l/vv)+jets)
from orthogonal control
regions



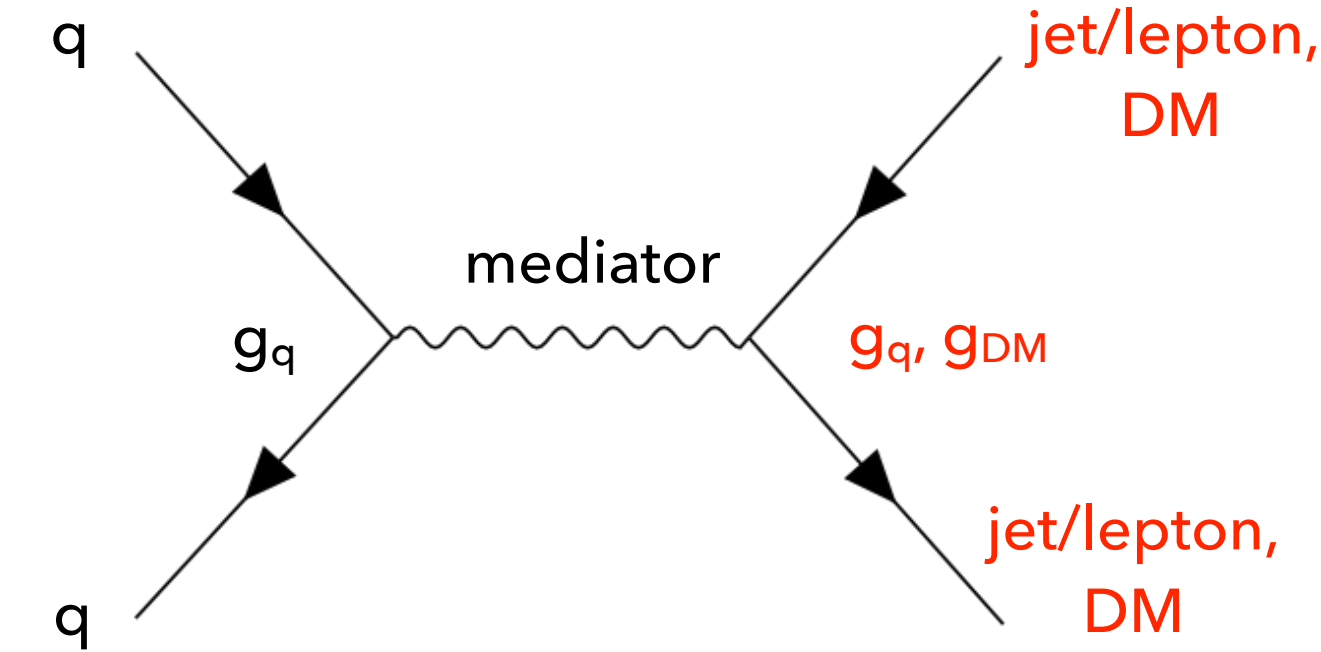
t-channel result:
mediator masses up to
about 1.67 TeV excluded at
95%CL for light DM



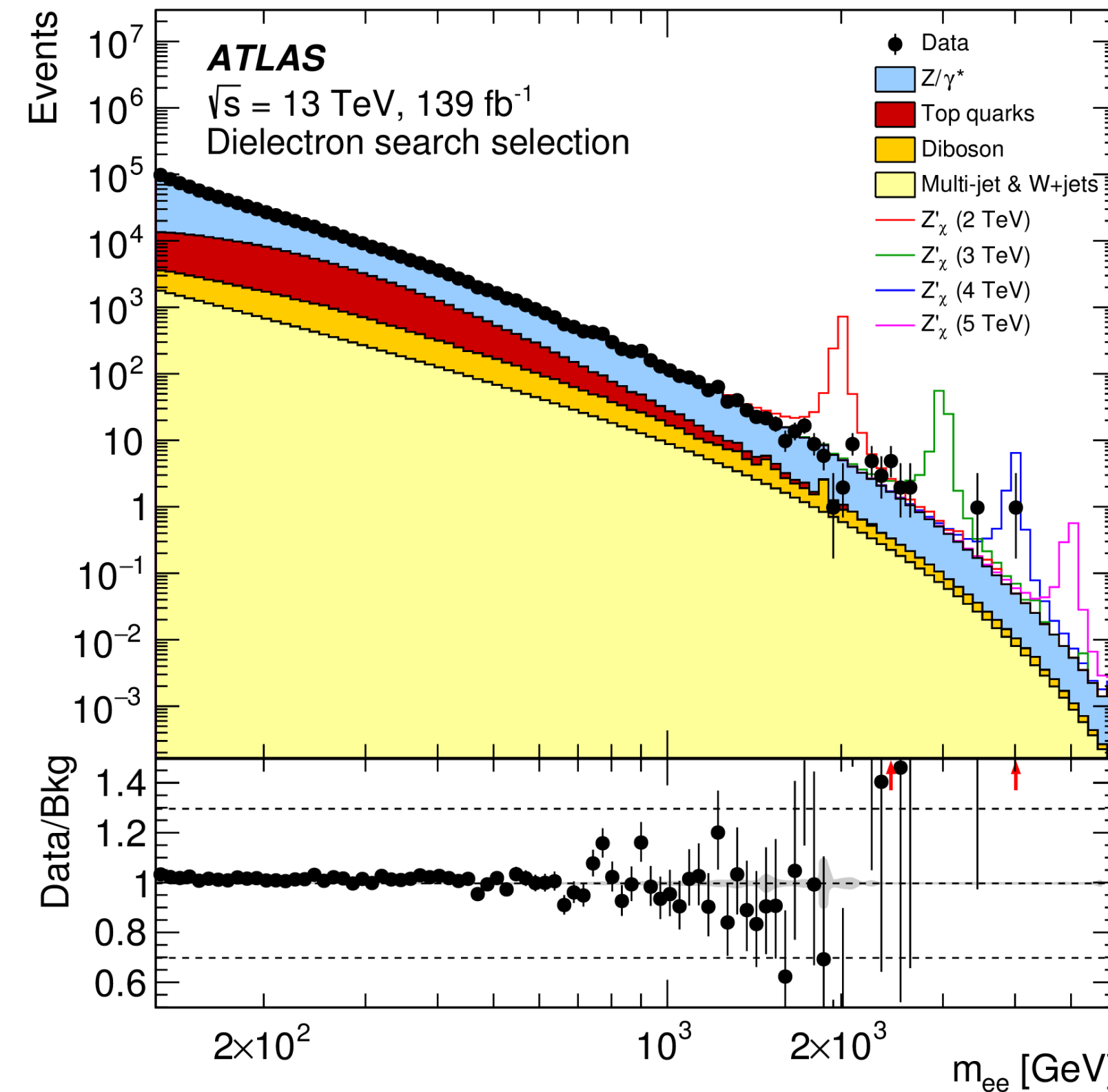
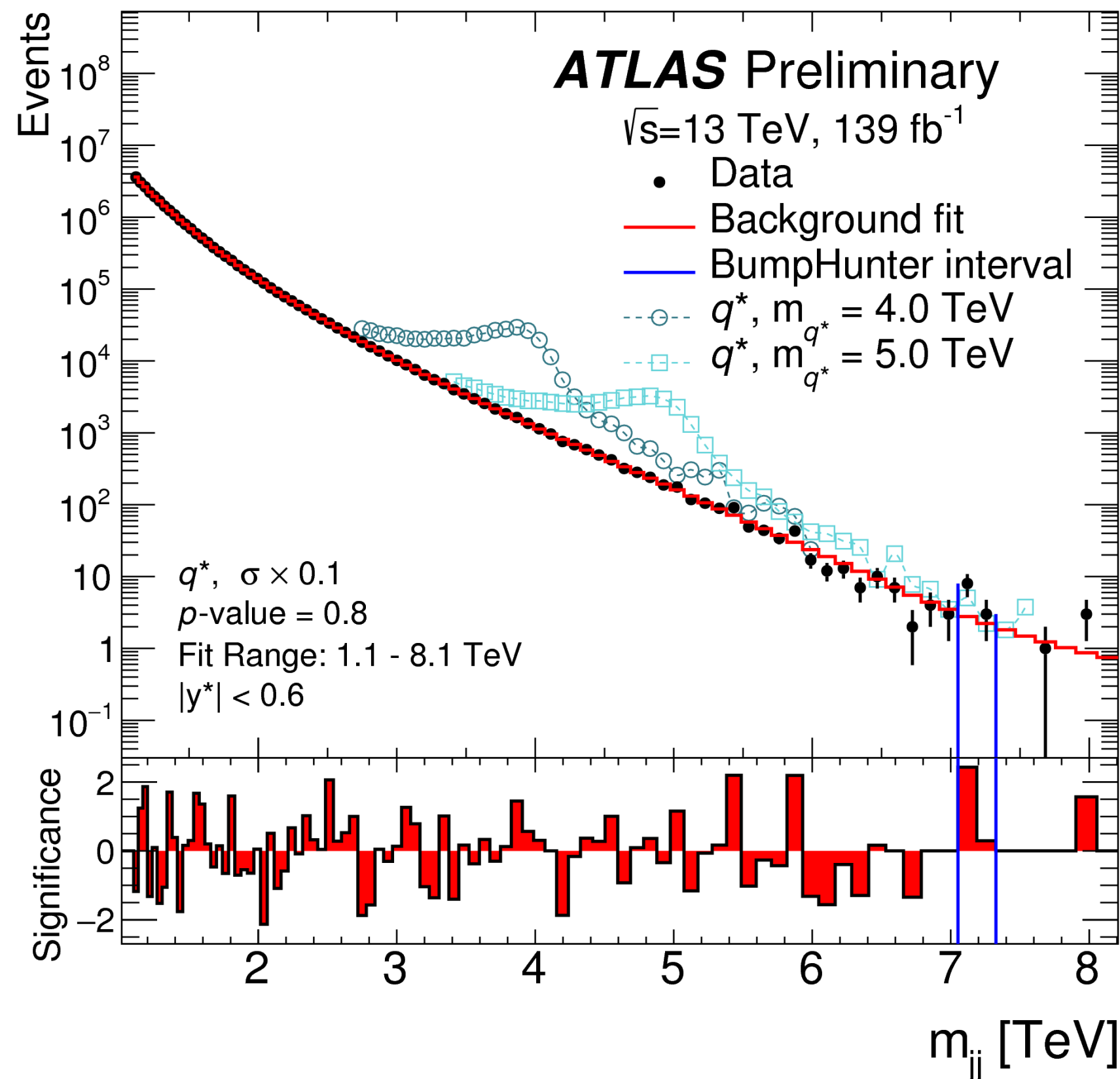
RESONANCES (DIJET/DILEPTON) SEARCHES

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



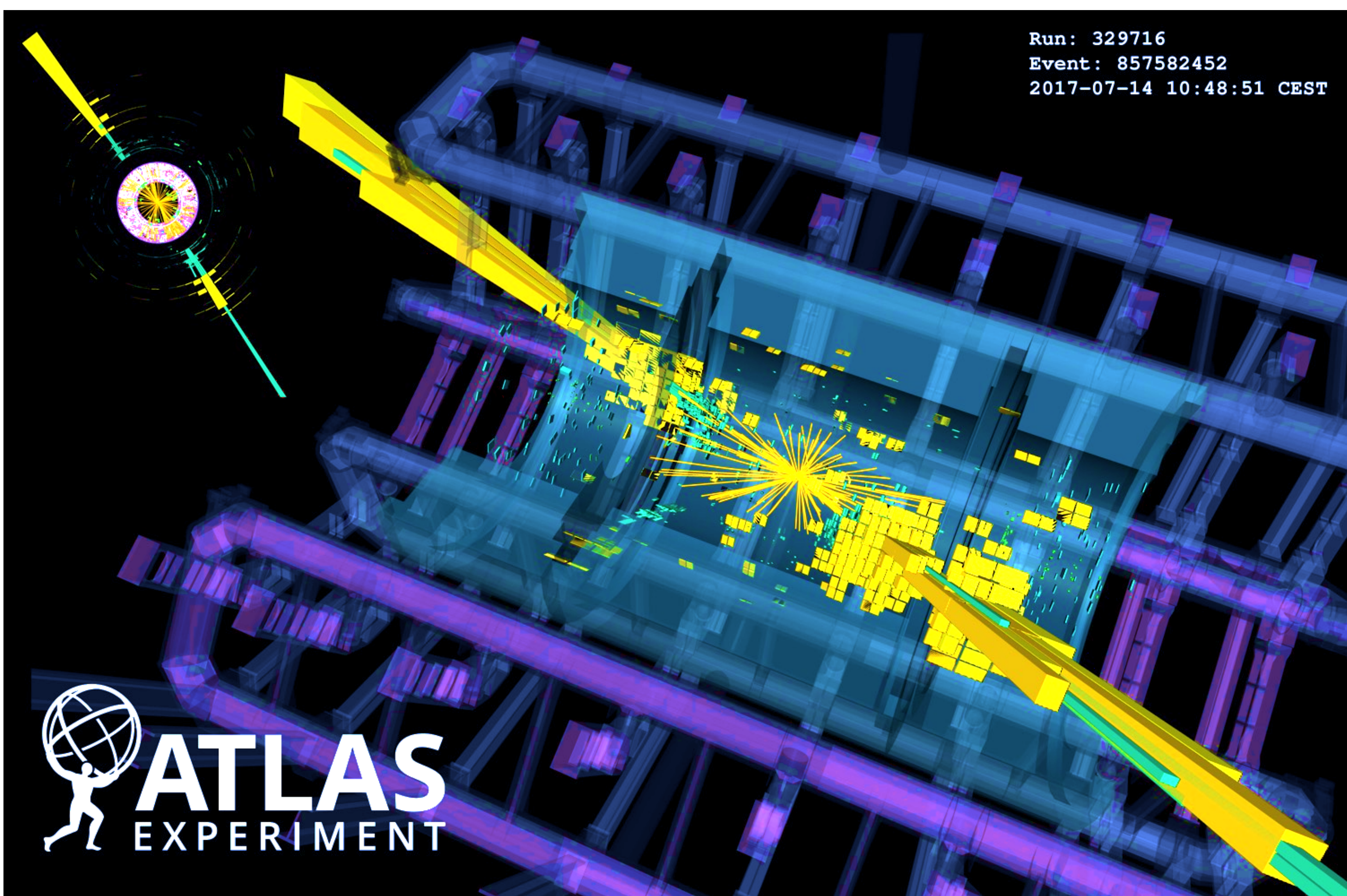
di-electrons




A DI-JET EVENTS SEEN IN ATLAS

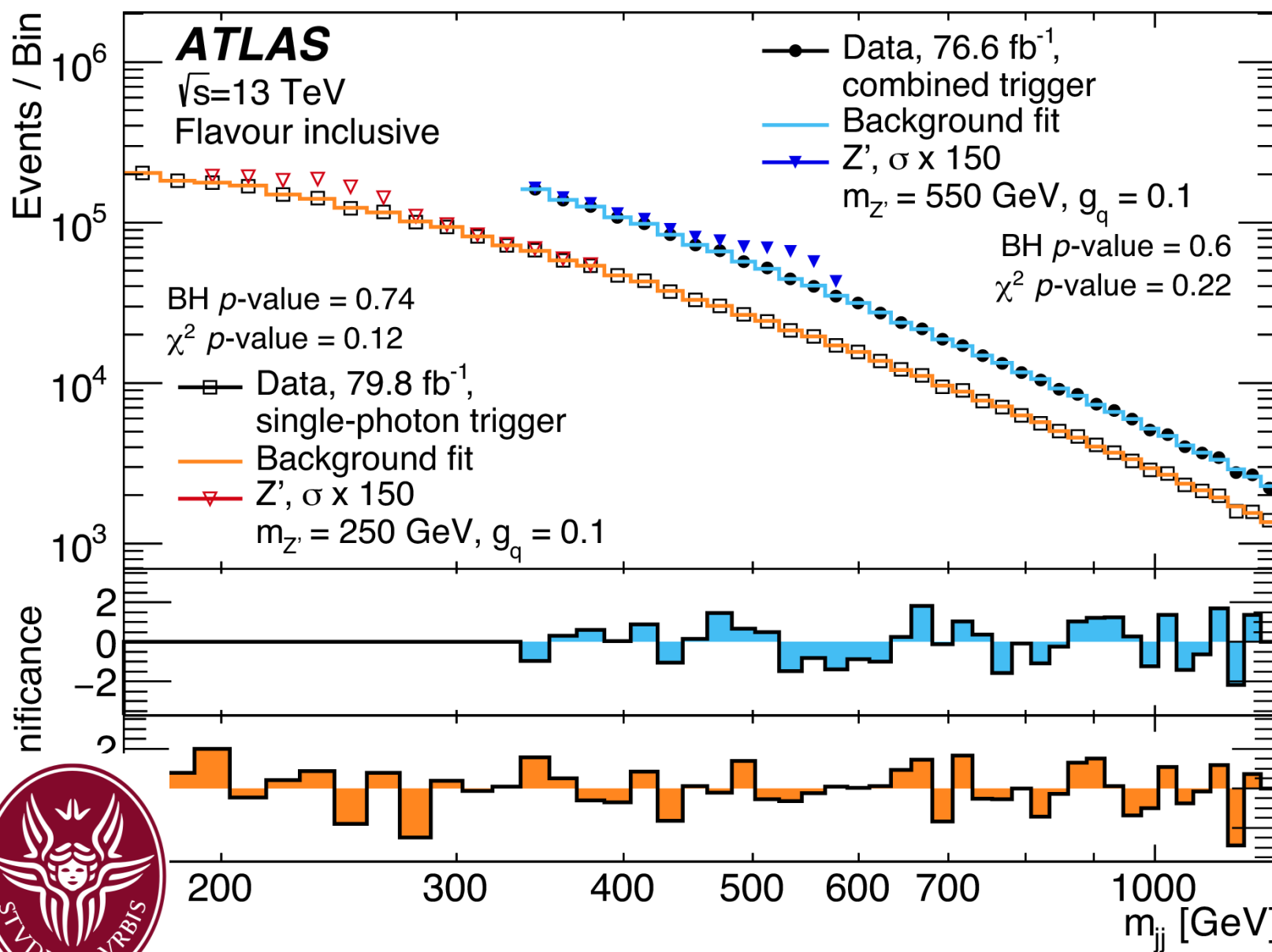
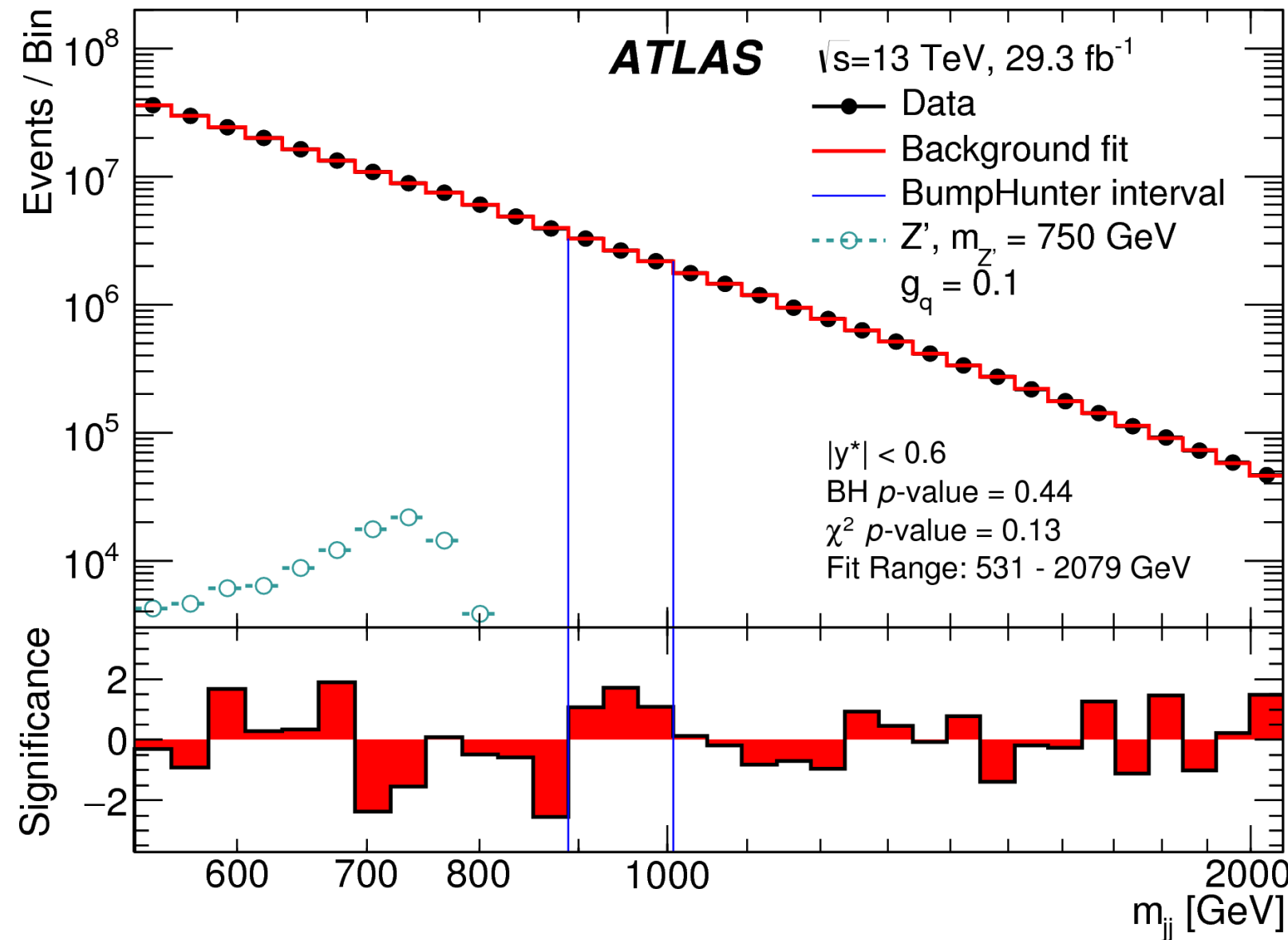
Run: 329716
Event: 857582452
2017-07-14 10:48:51 CEST

Run 2 2017
 $\sqrt{s} = 13 \text{ TeV}$
 $m_{jj} = 9.3 \text{ TeV}$
jet p_T 2.9 TeV

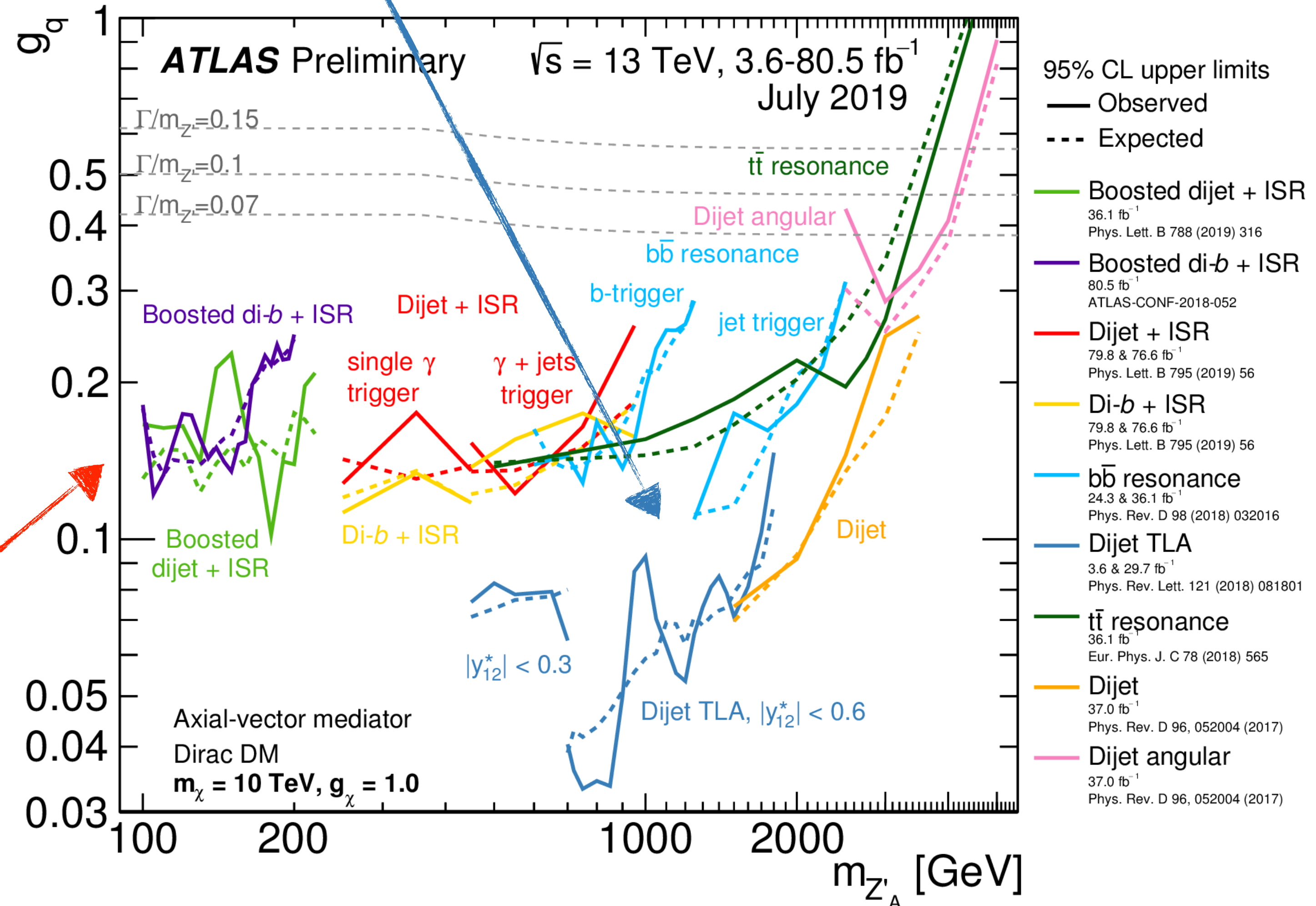


 **ATLAS**
EXPERIMENT

RESONANCES (DIJET/DILEPTON) SEARCHES



LOWER MASS: TRIGGER LEVEL ANALYSIS



EVEN LOWER MASS: JJ+ISR

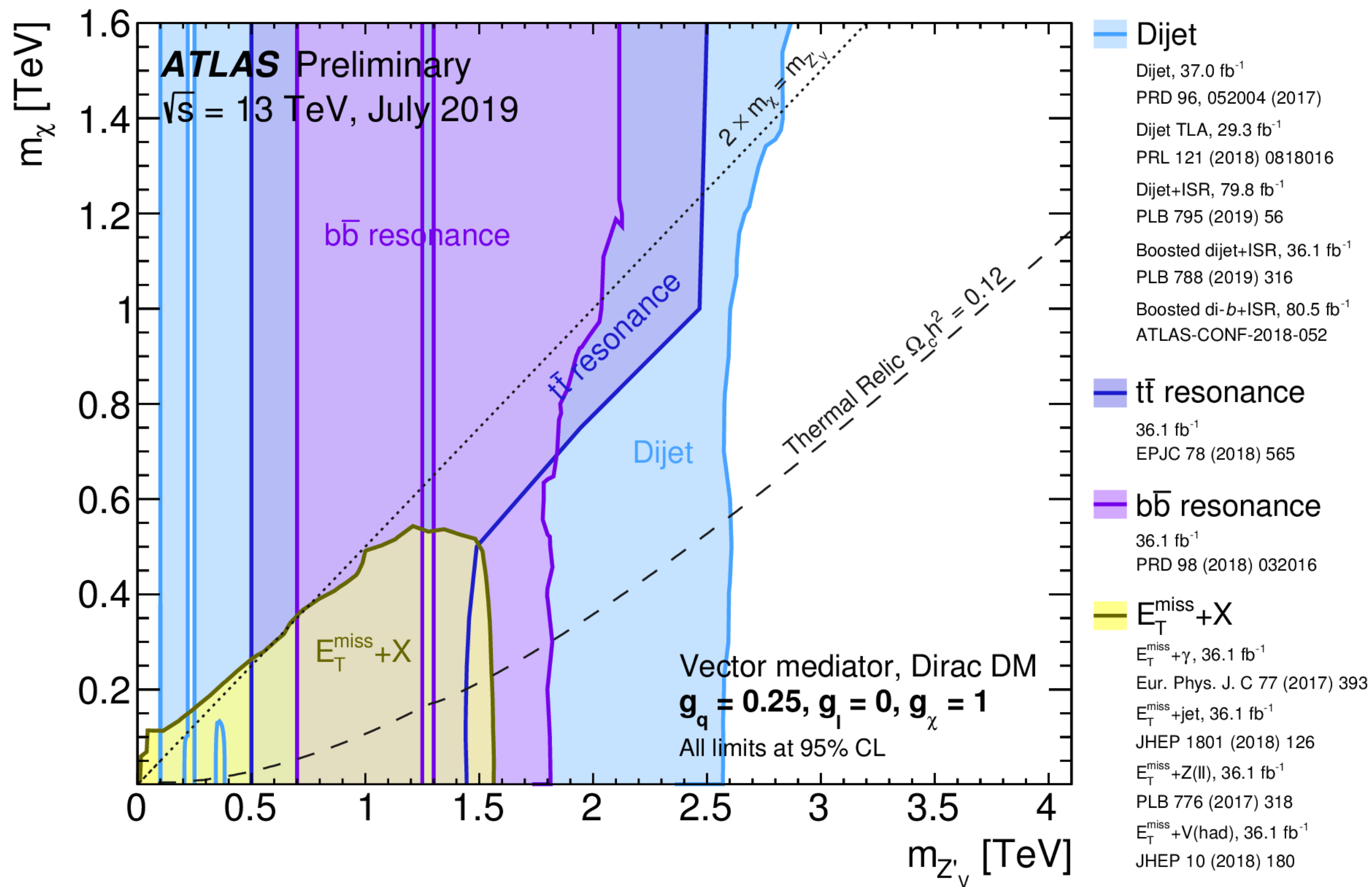
Phys. Rev. Lett. 121 (2018) 081801; Phys. Lett. B 795 (2019) 56



COMBINATION

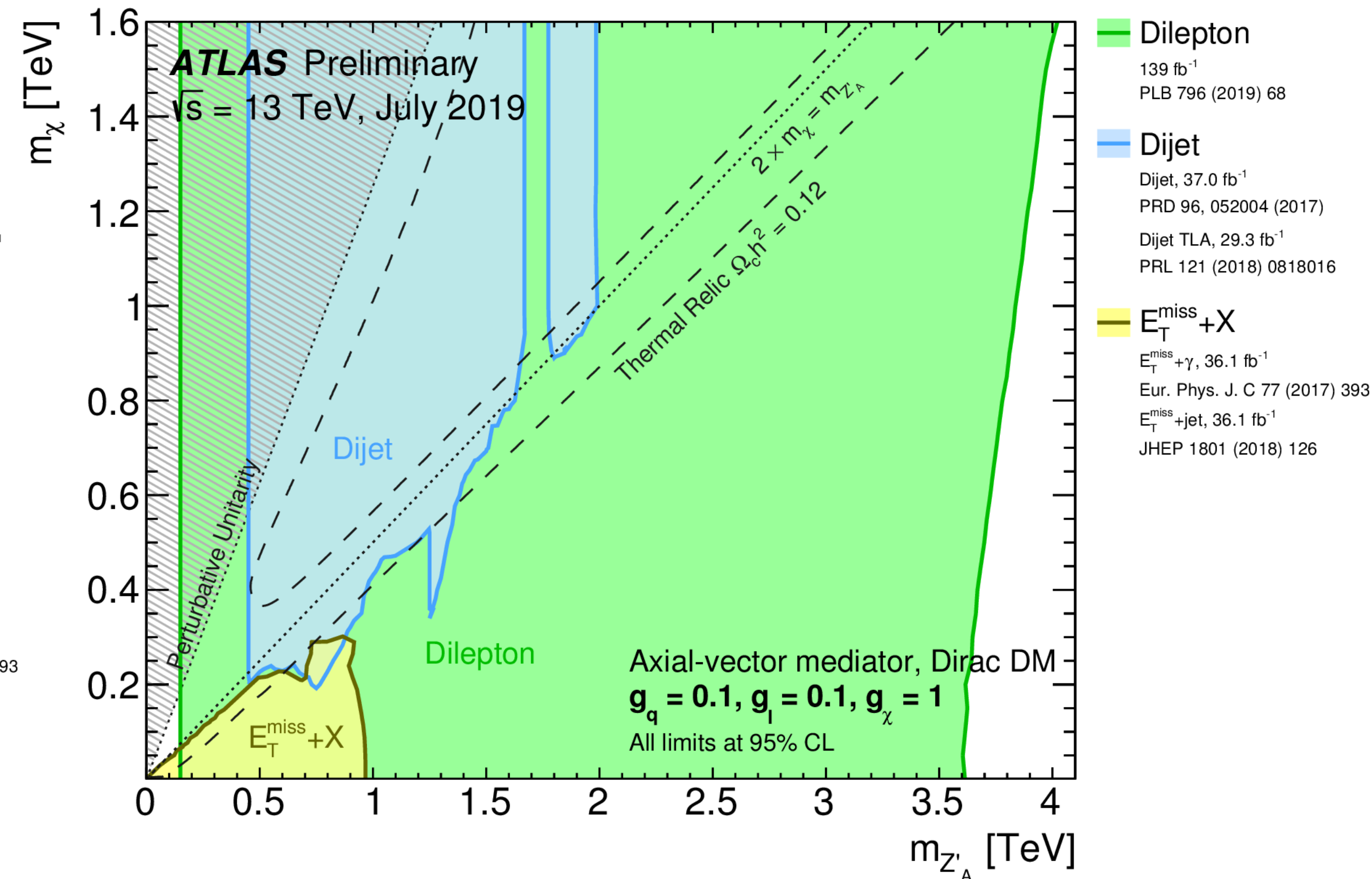
bounds on DM-mediator mass plane from mono-X and di-jet searches

VECTOR MEDIATOR



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

AXIAL-VECTOR MEDIATOR



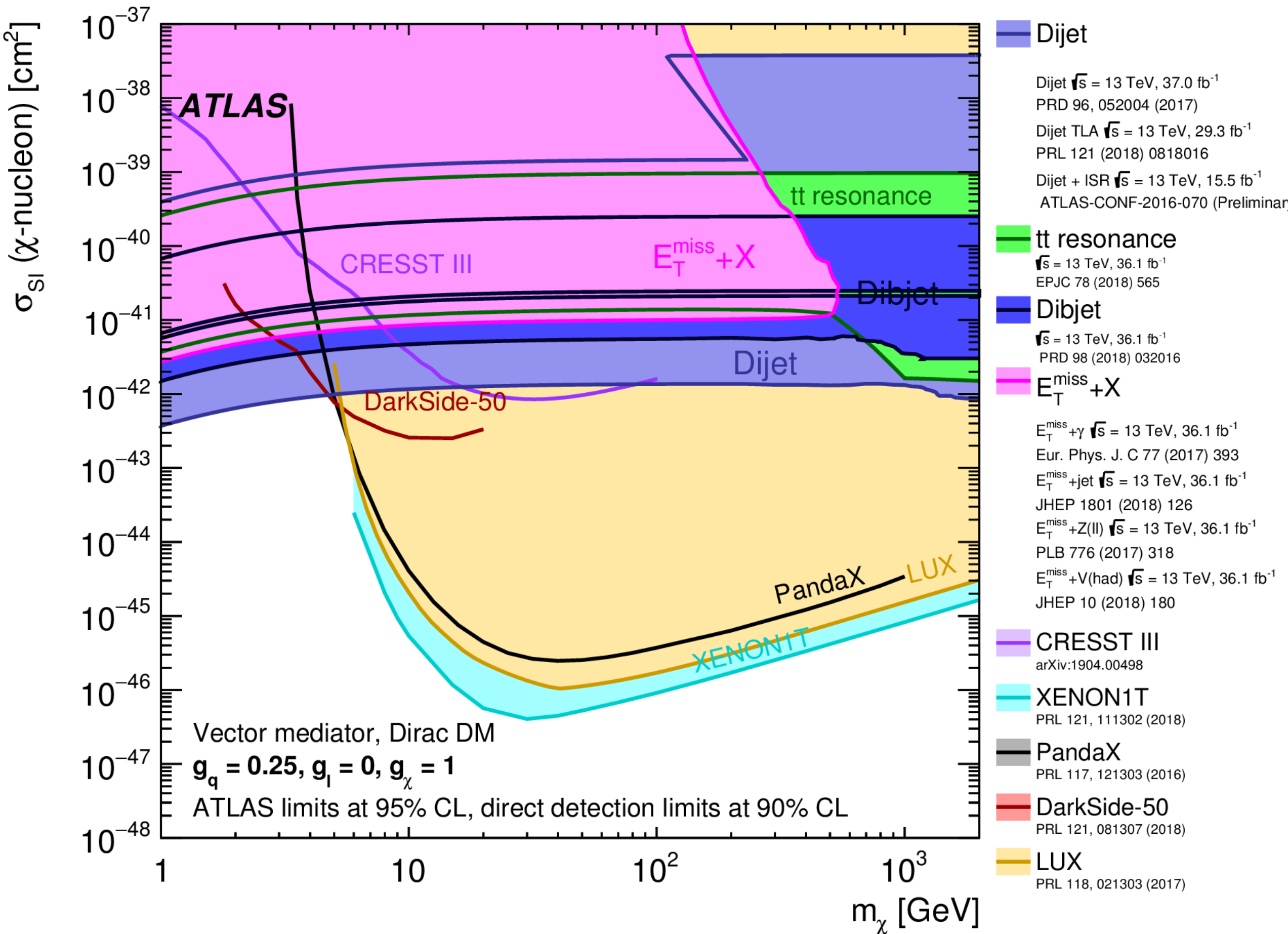
Axial-Vector Mediator ($g_q=0.1, g_l=0.1, g_{DM}=1$)



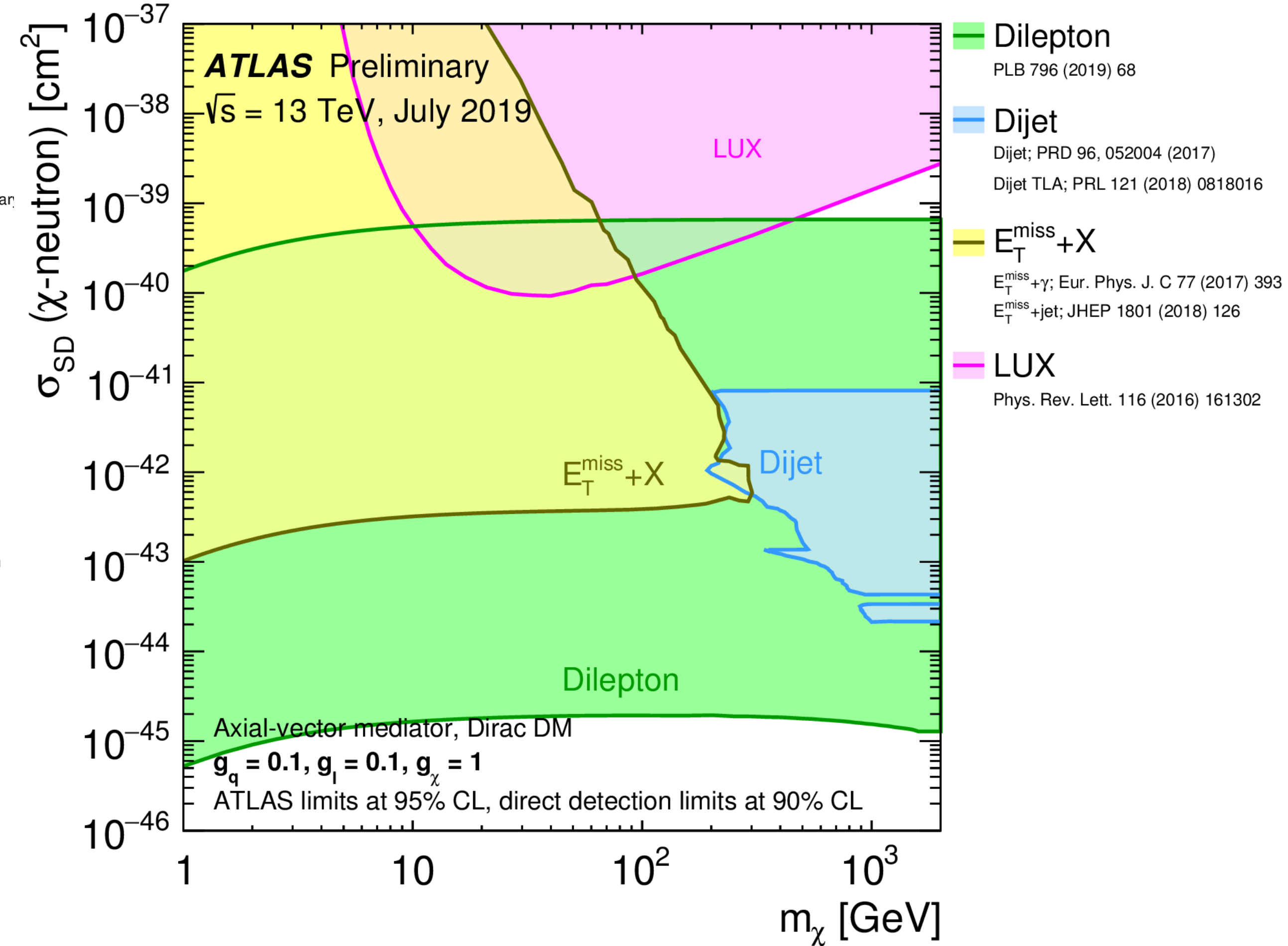
IMPORTANT: ALL INTERPRETATIONS HIGHLY DEPENDENT ON ASSUMPTIONS!

COMPLEMENTARITY WITH DIRECT SEARCHES

VECTOR MEDIATOR

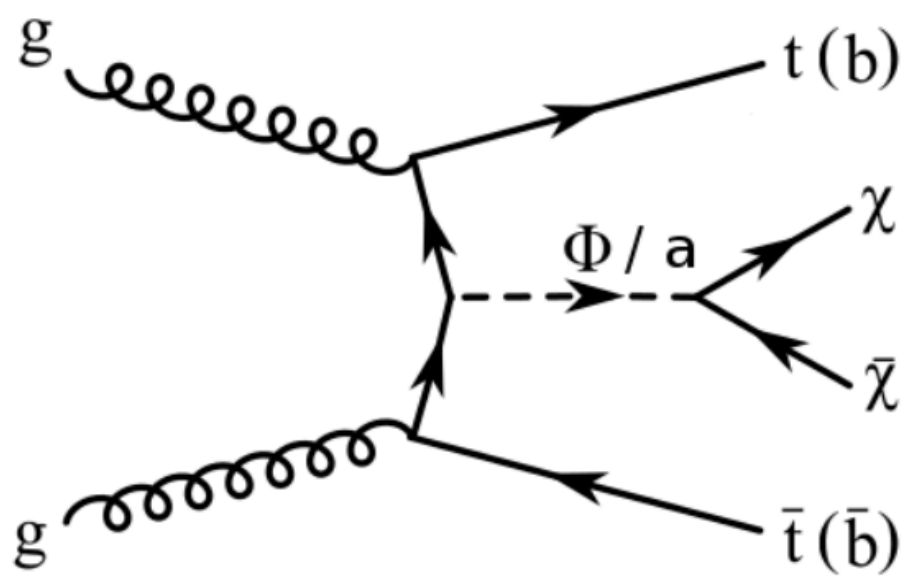


AXIAL-VECTOR MEDIATOR



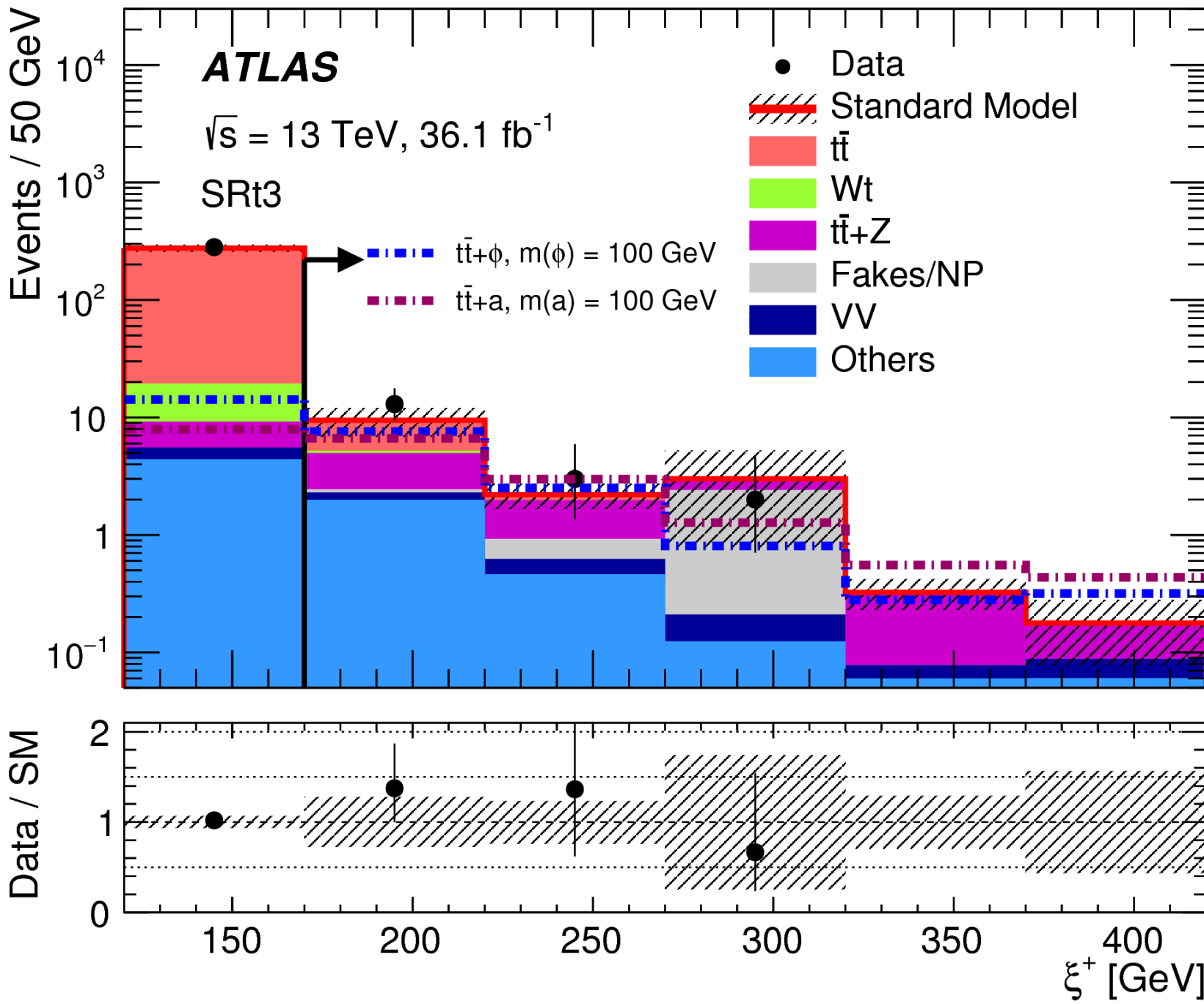
ATLAS (95% CL) limits converted in spin independent or spin dependent χ -nucleon cross-sections

SCALAR MEDIATOR PROBES: DM + HF

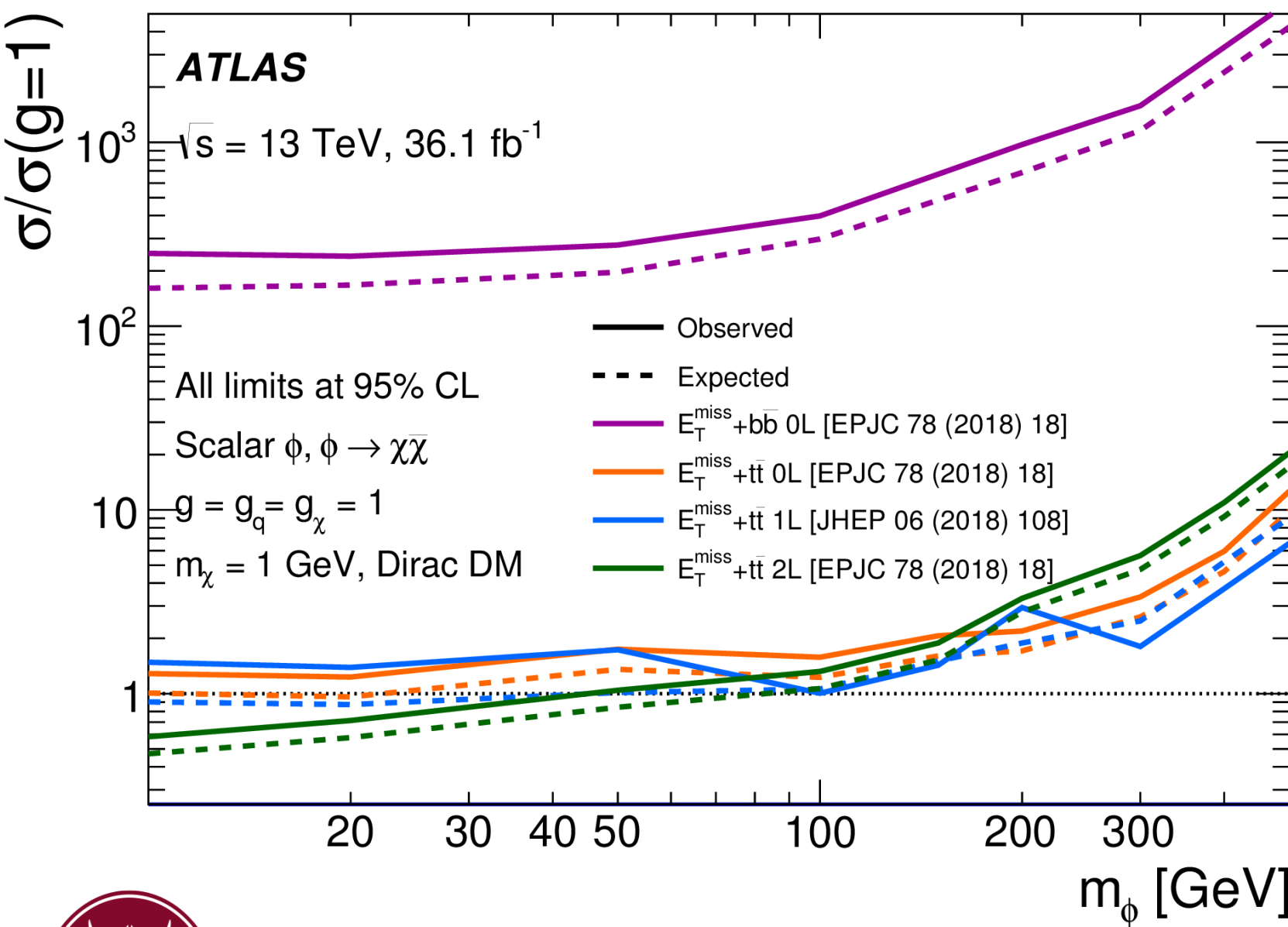


most sensitive channel for spin 0, scalar or pseudo-scalar, color neutral mediator

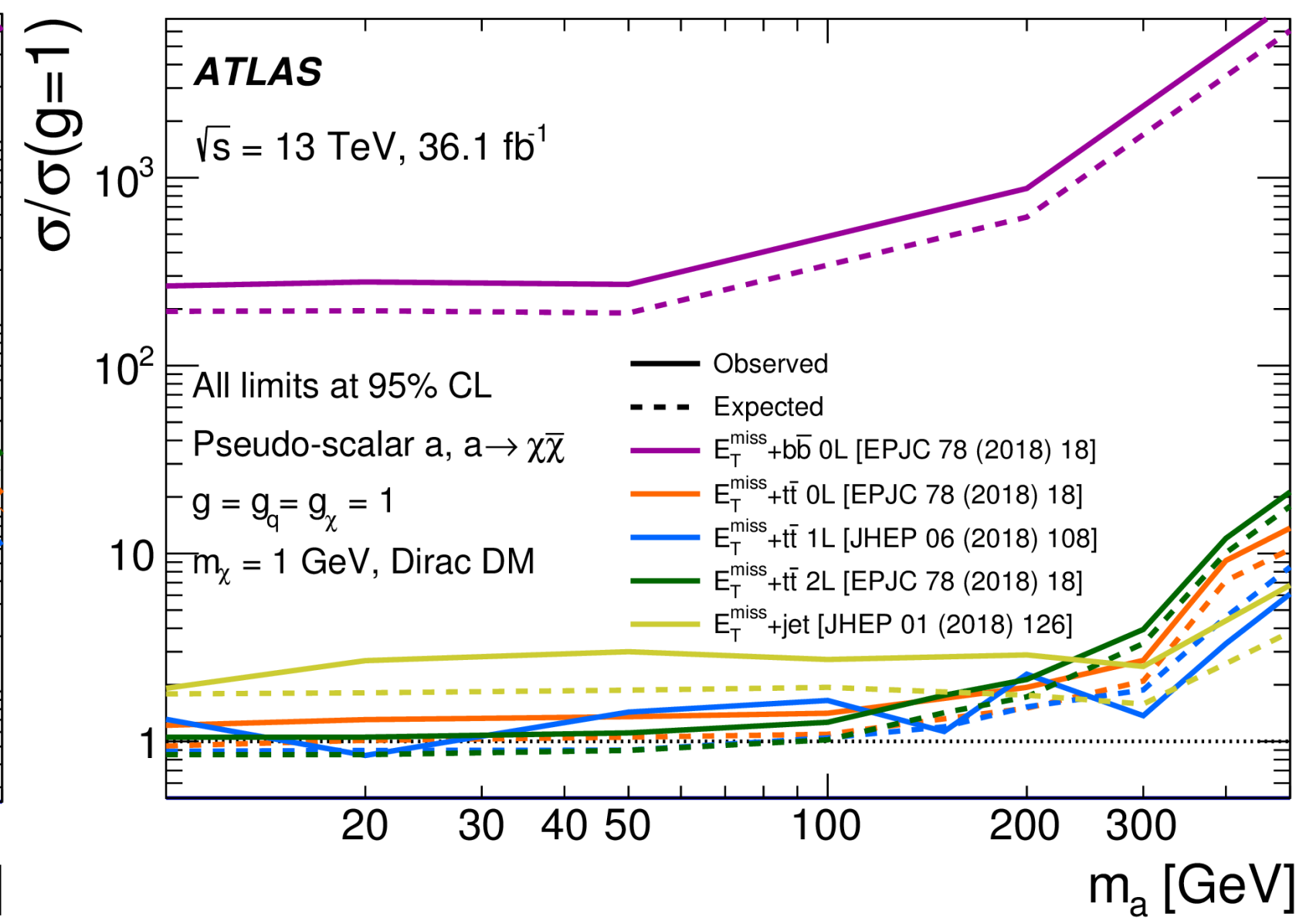
- looks for final states with top and bottom enhanced by Yukawa coupling between DM and SM sectors
- 0, 1 and 2-leptons final states
- final discriminant variables: stranverse-mass and MET



SCALAR



PSEUDO-SCALAR

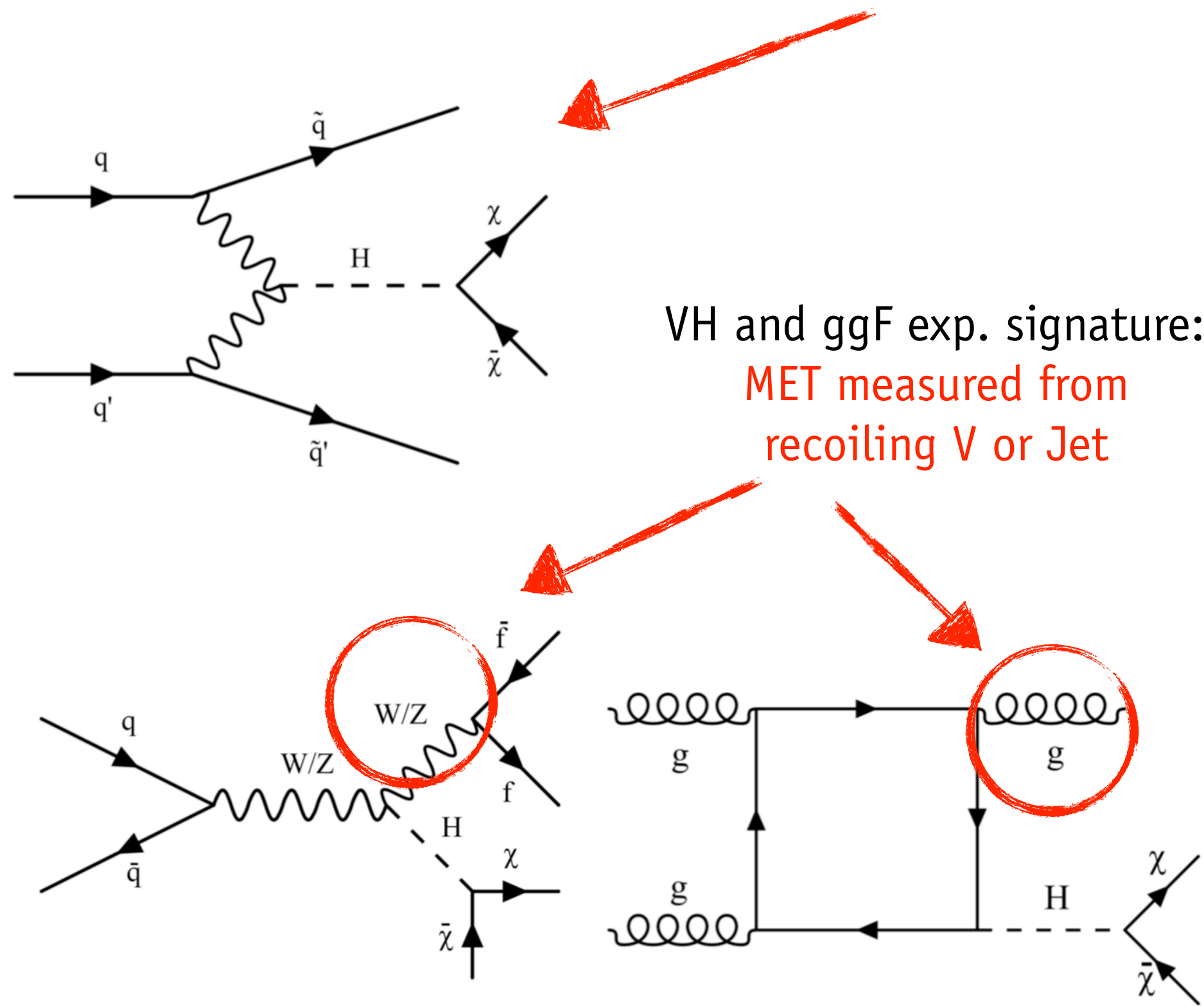


- excluded mediator mass up to 45 GeV (scalar) and 15-25 GeV (pseudo-scalar)
- results do not depend on the DM mass, as long as the DM is on-shell

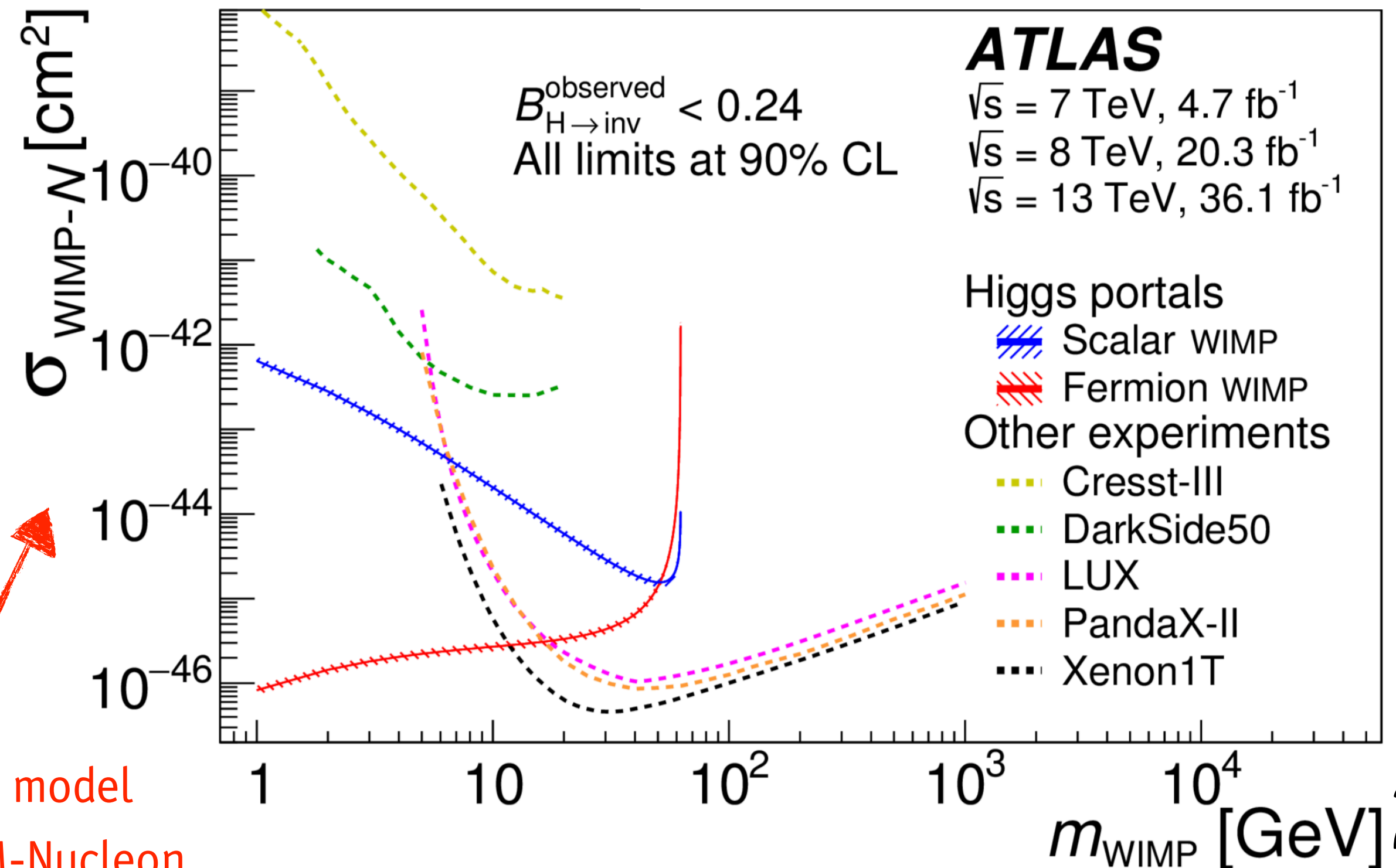
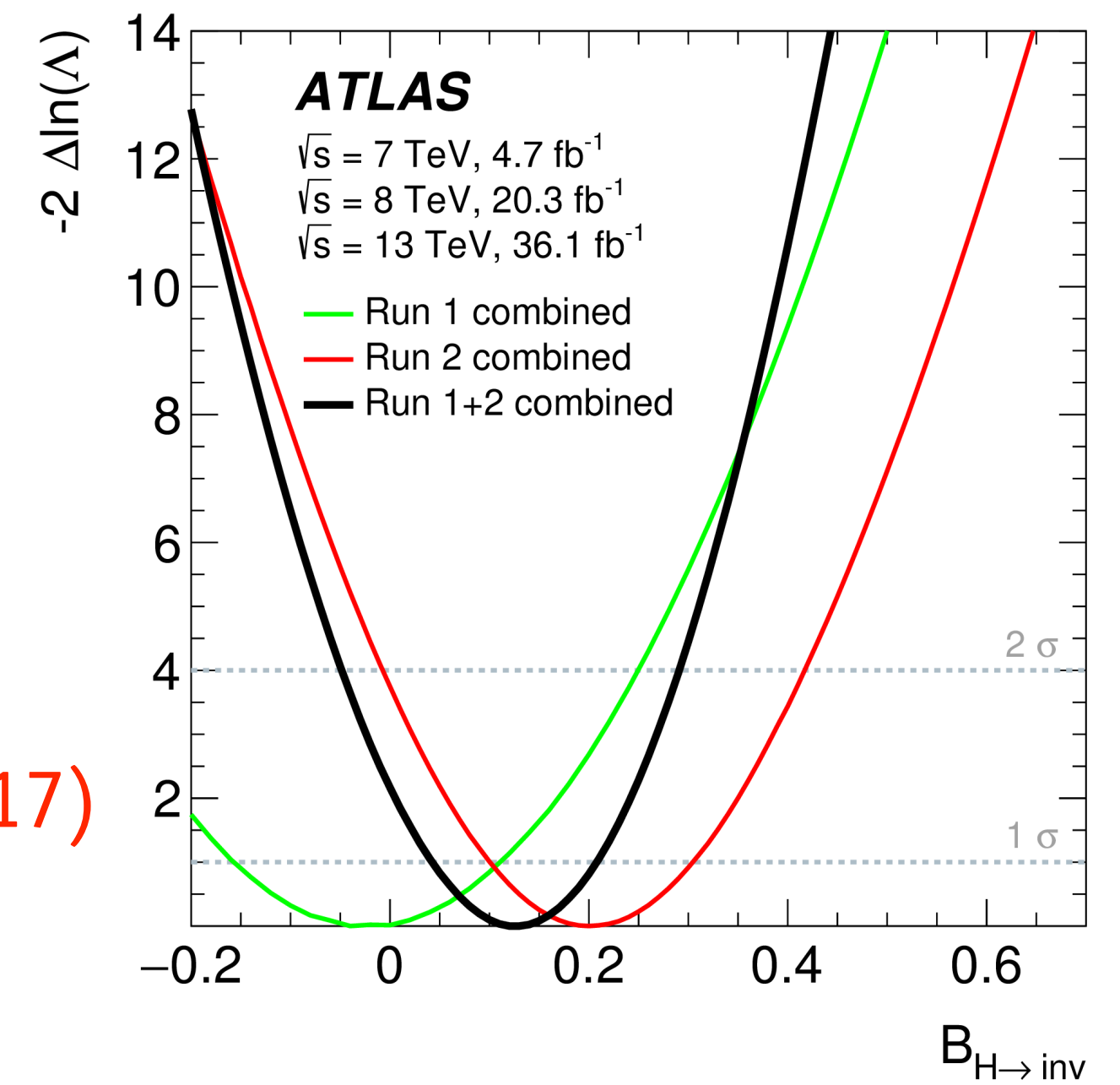


DM THROUGH $H \rightarrow$ INVISIBLE

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



$B(H \rightarrow \text{inv}) < 0.26$ (0.17)
@95% CL



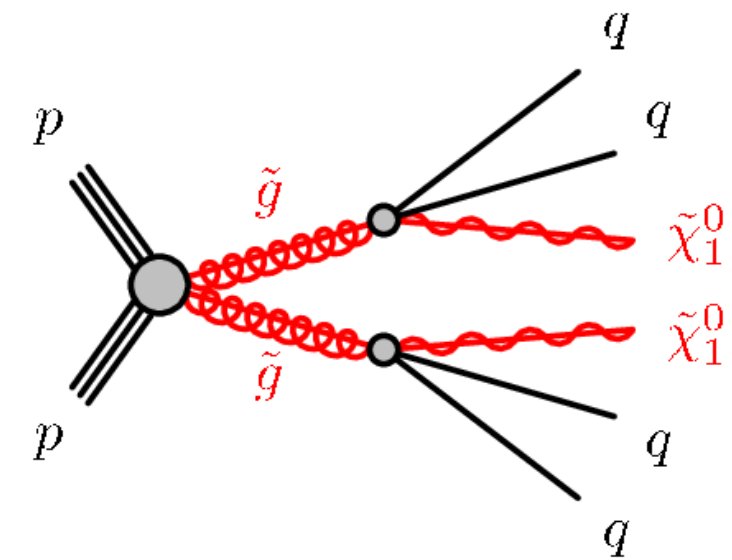
Interpretation in the context of the Higgs Portal model
 $B(H \rightarrow \text{inv}) \rightarrow \Gamma_{\text{inv}} \rightarrow \text{couplings} \rightarrow \text{cross-section DM-Nucleon}$



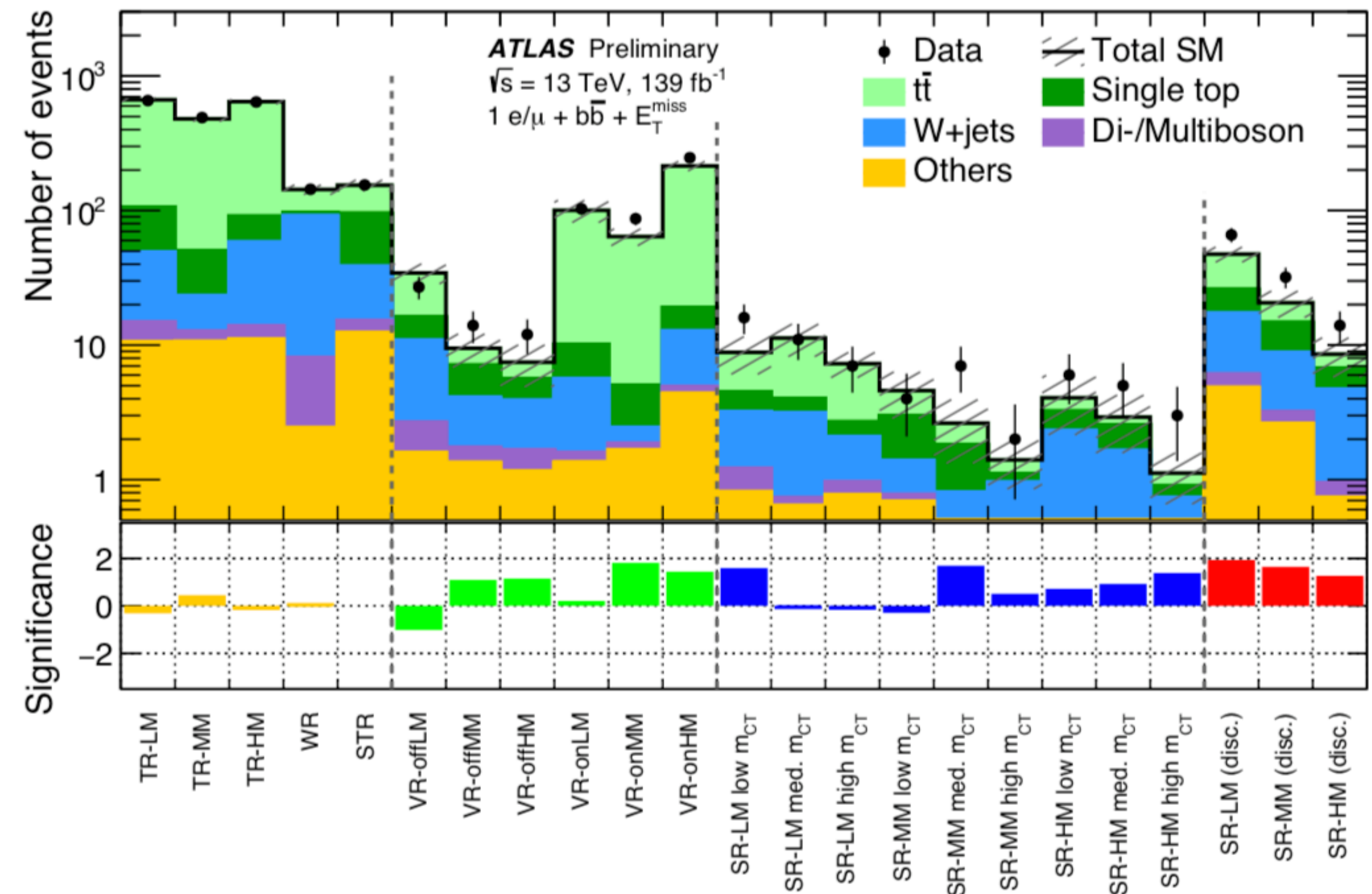
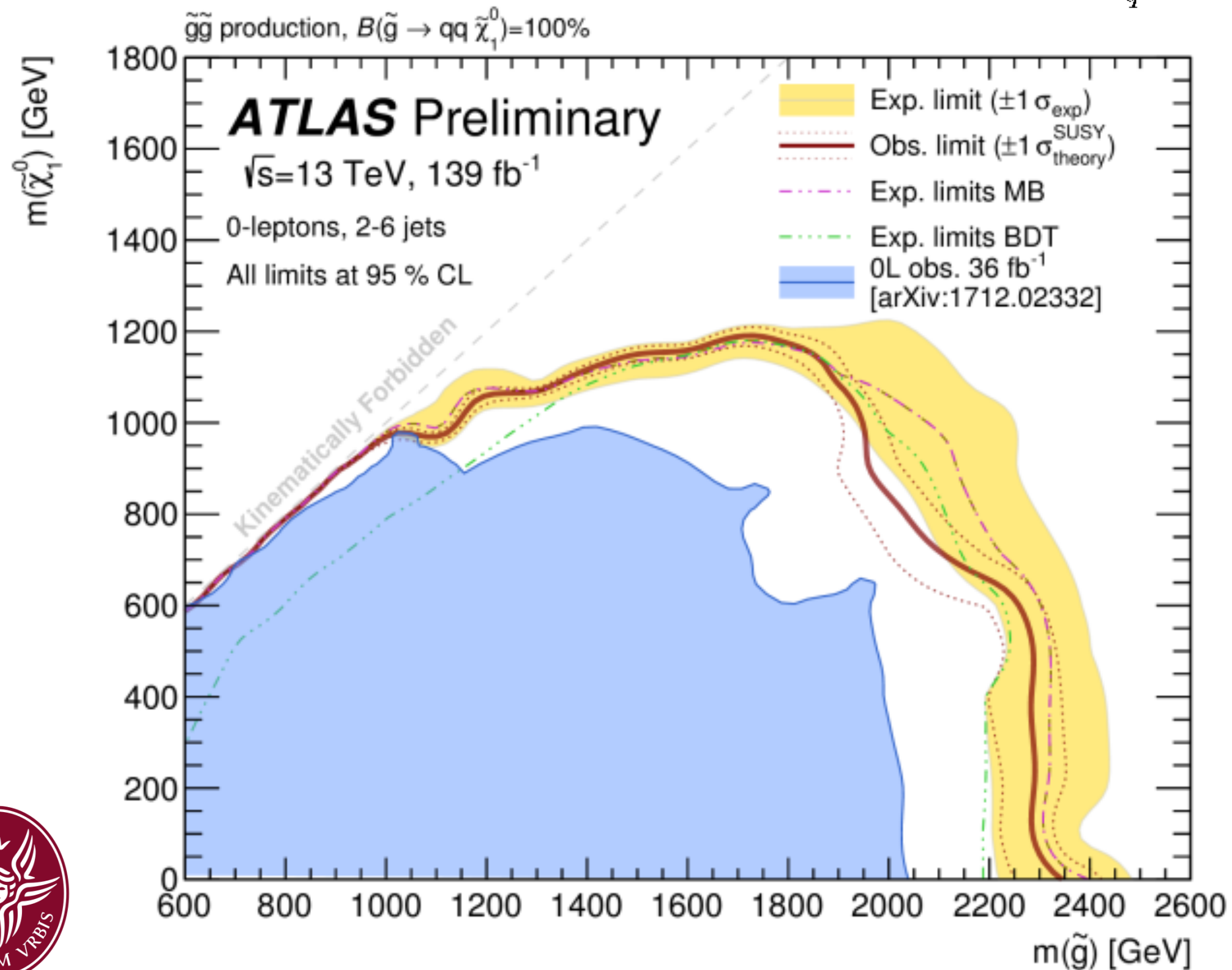
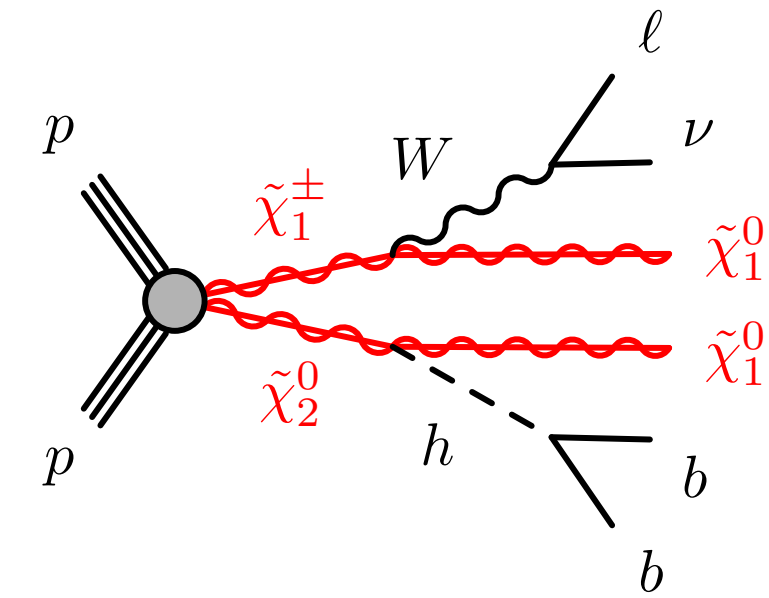
SUSY SEARCHES

- a large number of analyses performed or ongoing 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

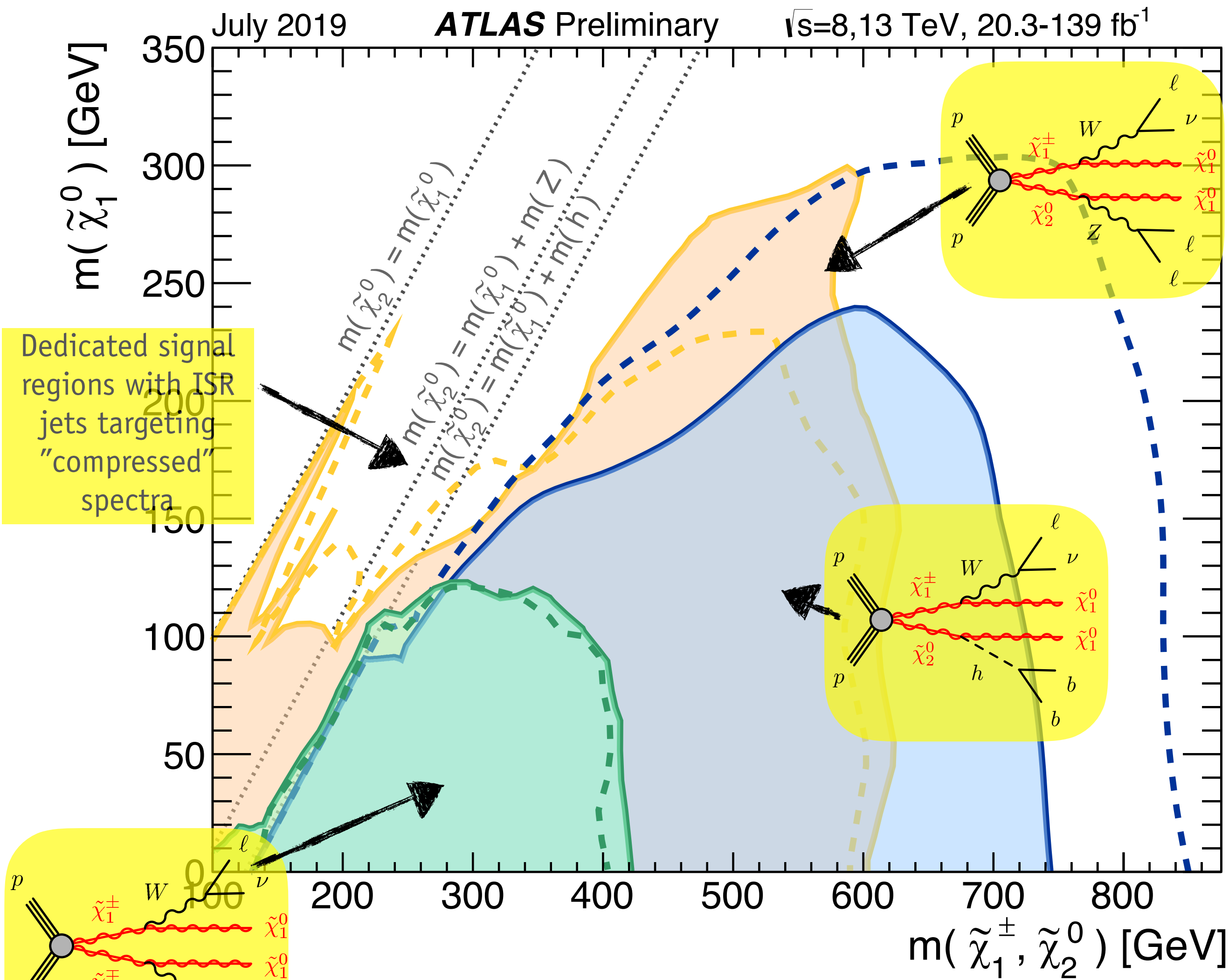


- dominate if squark/gluinos are very heavy
- events with 1 lepton + jets, 2 or more leptons and no jets + MET
- discrimination based on based on stranverse and contranverse masses: M_{T2} , M_{CT}
- dedicated signal regions with ISR jets targeting "compressed" spectra



SUSY SEARCHES

STRONG STOP PRODUCTION



EW SUSY PRODUCTION

All limits at 95% CL

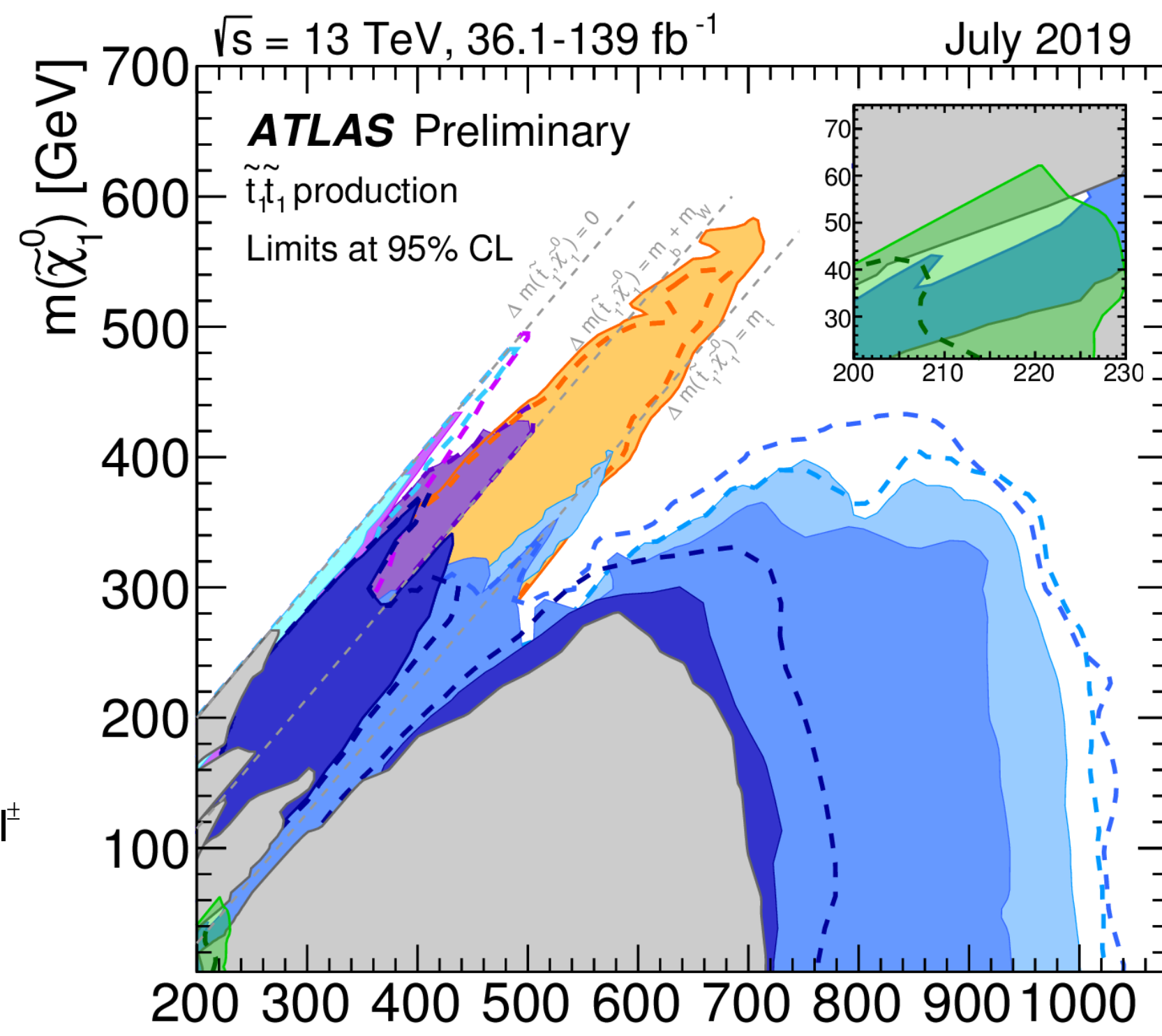
- - - Expected limits
- Observed limits

$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via

- WZ** 2l+3l
 arXiv:1403.5294
 arXiv:1803.02762
 arXiv:1806.02293
 ATLAS-CONF-2019-014
 ATLAS-CONF-2019-020
- Wh lbb+2jbb+l $\gamma\gamma$ +l Γ^\pm**
 arxiv:1812.09432
 ATLAS-CONF-2019-019
 ATLAS-CONF-2019-031

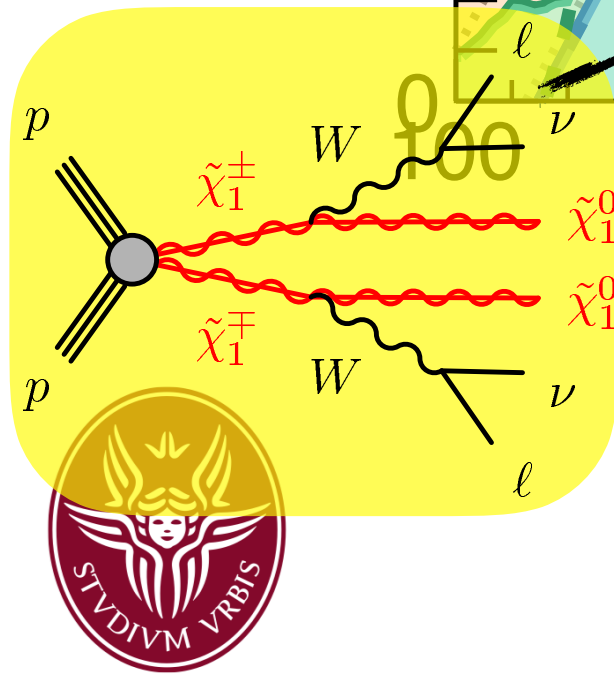
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$ via

- WW** 2l
 arXiv:1403.5294
 ATLAS-CONF-2019-008



— Observed limits
- - - Expected limits

- 139.0 fb^{-1}
- 1L, $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$
[ATLAS-CONF-2019-17]
- 36.1 fb^{-1}
- 0L, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$
[1709.04183]
- 1L, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b\tilde{t}\tilde{\chi}_1^0$
[1711.11520]
- 2L, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b\tilde{t}\tilde{\chi}_1^0$
[1708.03247]
- monojet, $\tilde{t}_1 \rightarrow b\tilde{t}\tilde{\chi}_1^0$
[1711.03301]
- $\tilde{t}\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$
[1903.07570]
- c0L, $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$
[1805.01649]
- monojet, $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$
[1711.03301]
- Run 1, $\sqrt{s} = 8 \text{ TeV}, 20 \text{ fb}^{-1}$
[1506.08616]

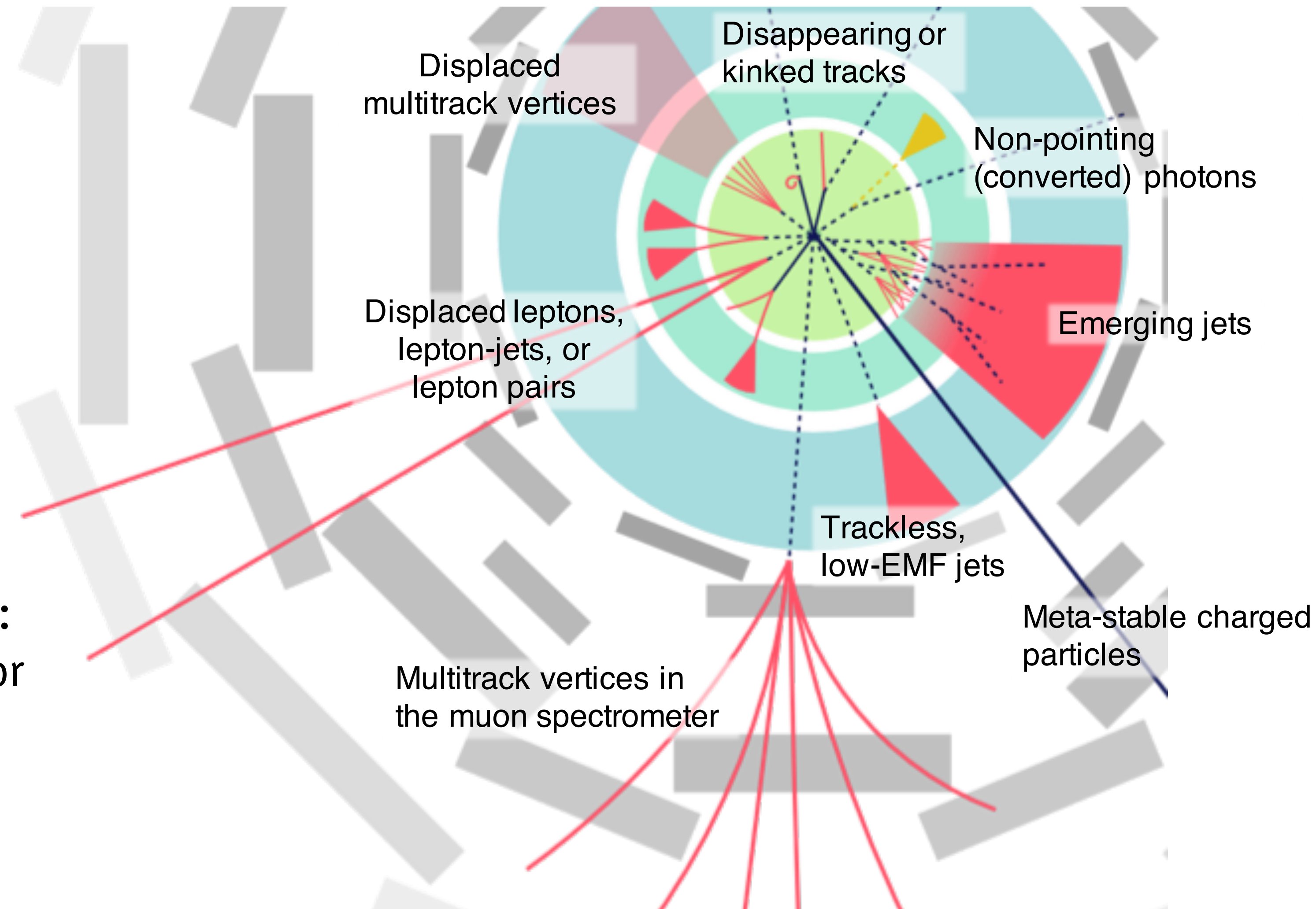


LIGHT DM SEARCHES THROUGH UNCONVENTIONAL SIGNATURES

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 ...

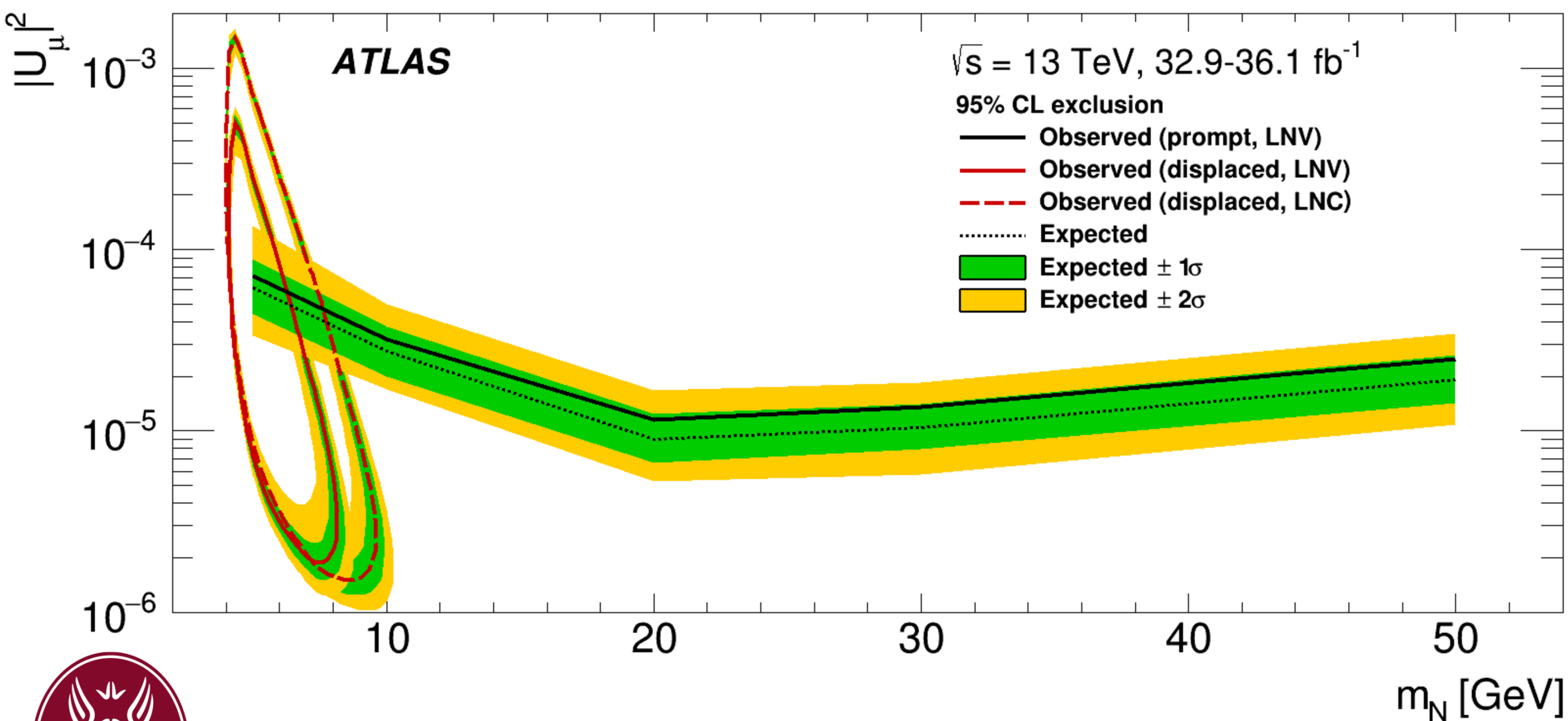
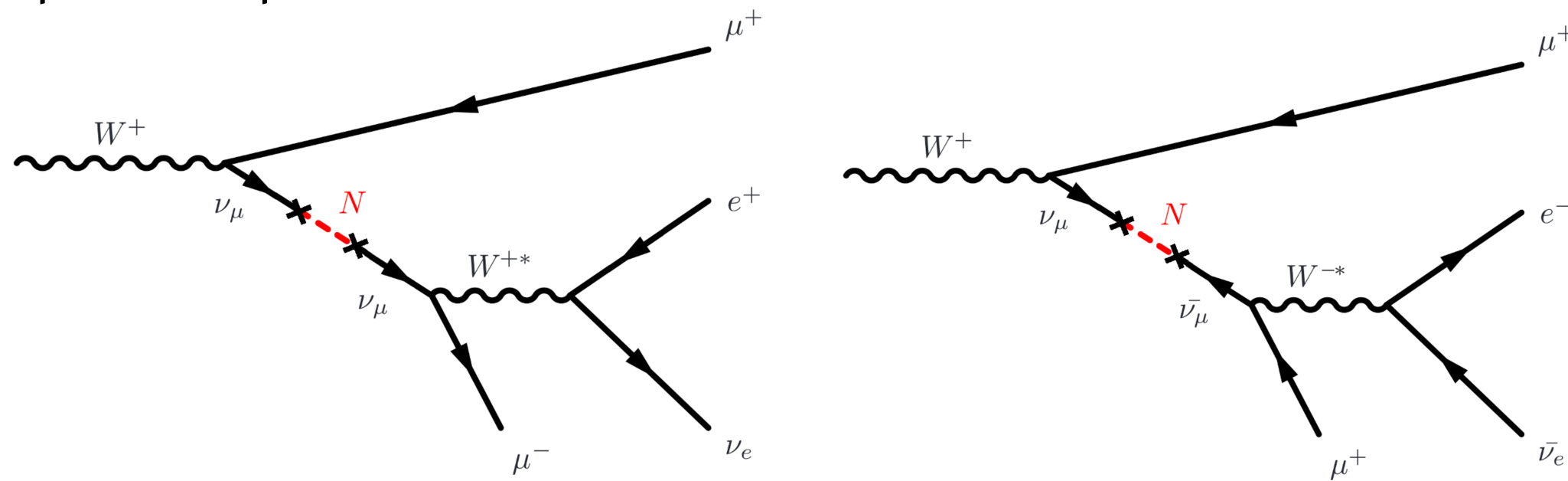


SEARCH FOR LONG-LIVED NEUTRAL PARTICLES

HEAVY NEUTRAL LEPTONS

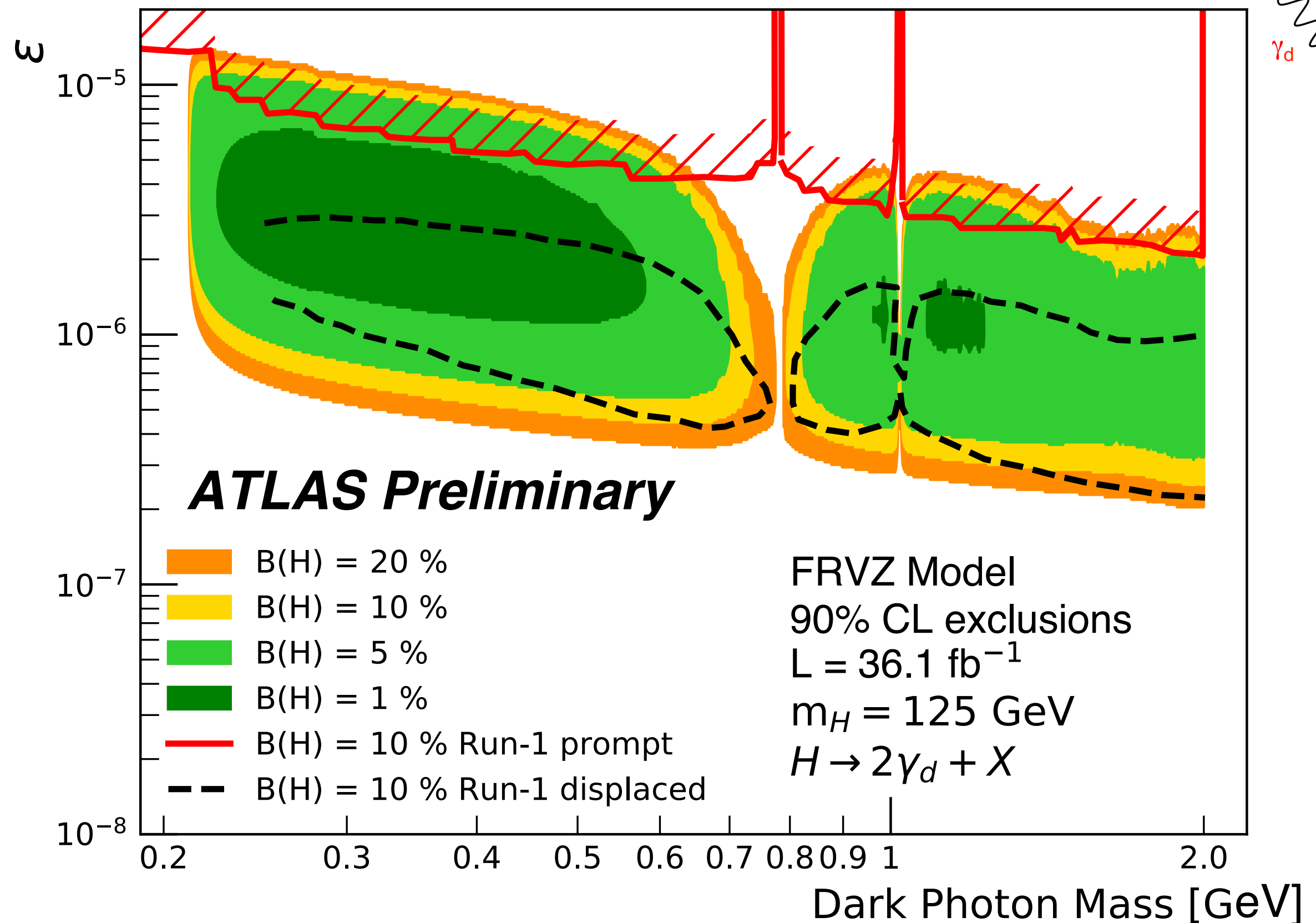
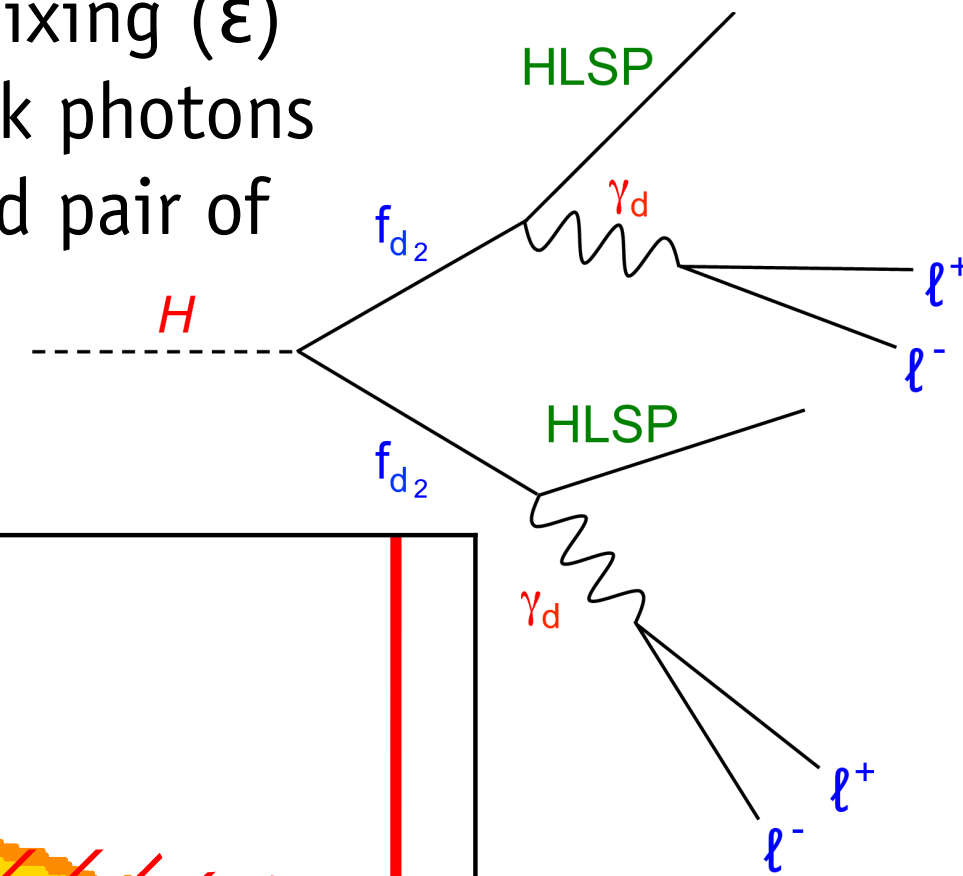
right-handed Majorana neutrinos give rise to type-I see-saw mechanism and provide DM candidates

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

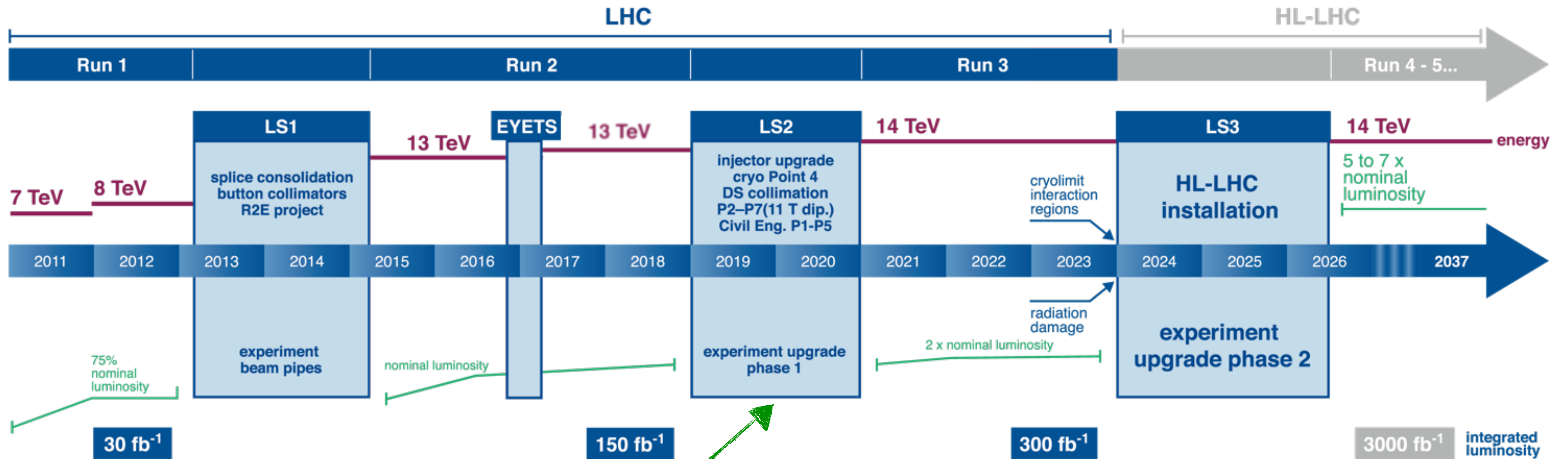


LIGHT DARK PHOTONS

- 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



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

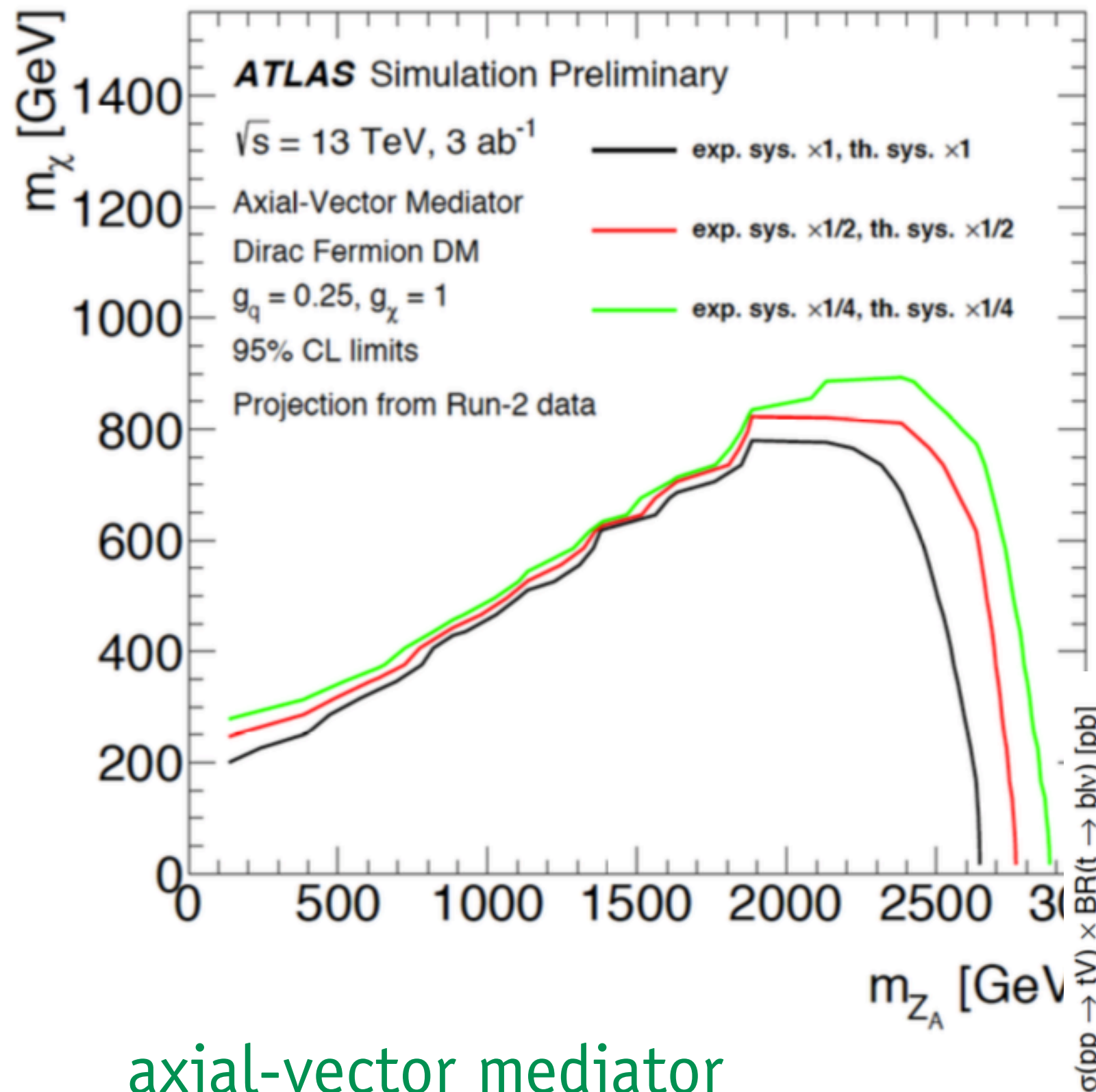


DIRECT DM SEARCHES

HIGGS COUPLINGS

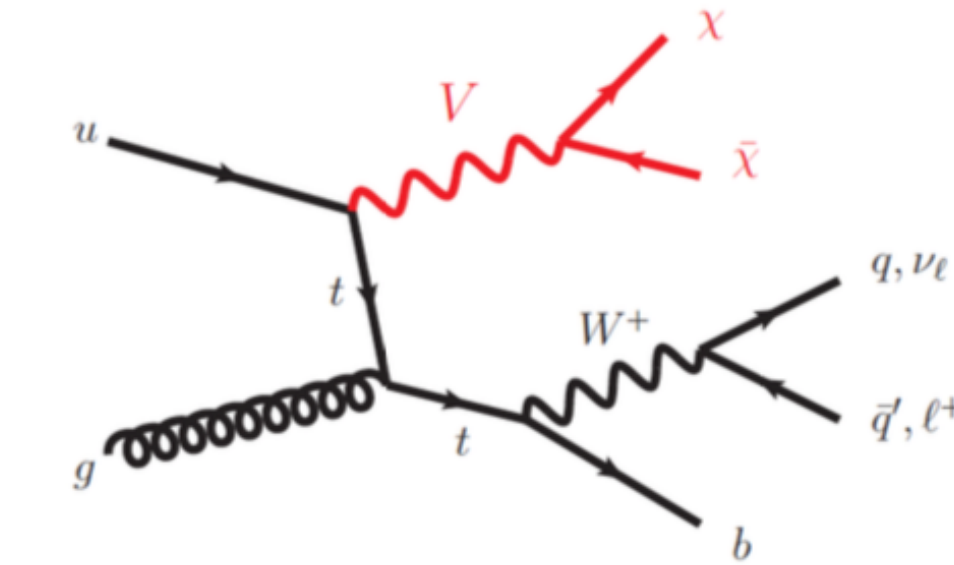
$\sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1}$ per experiment

MONO JET

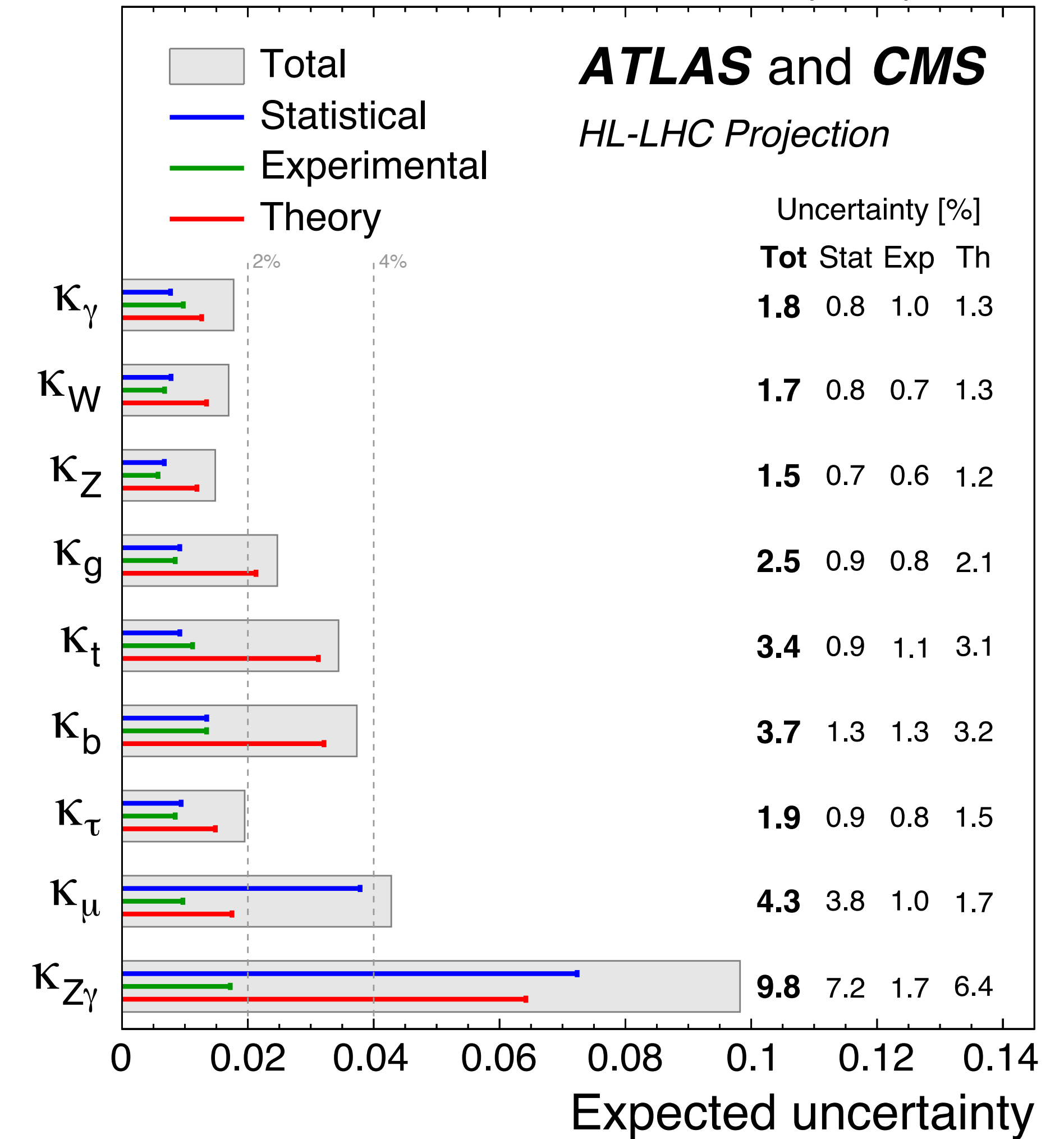
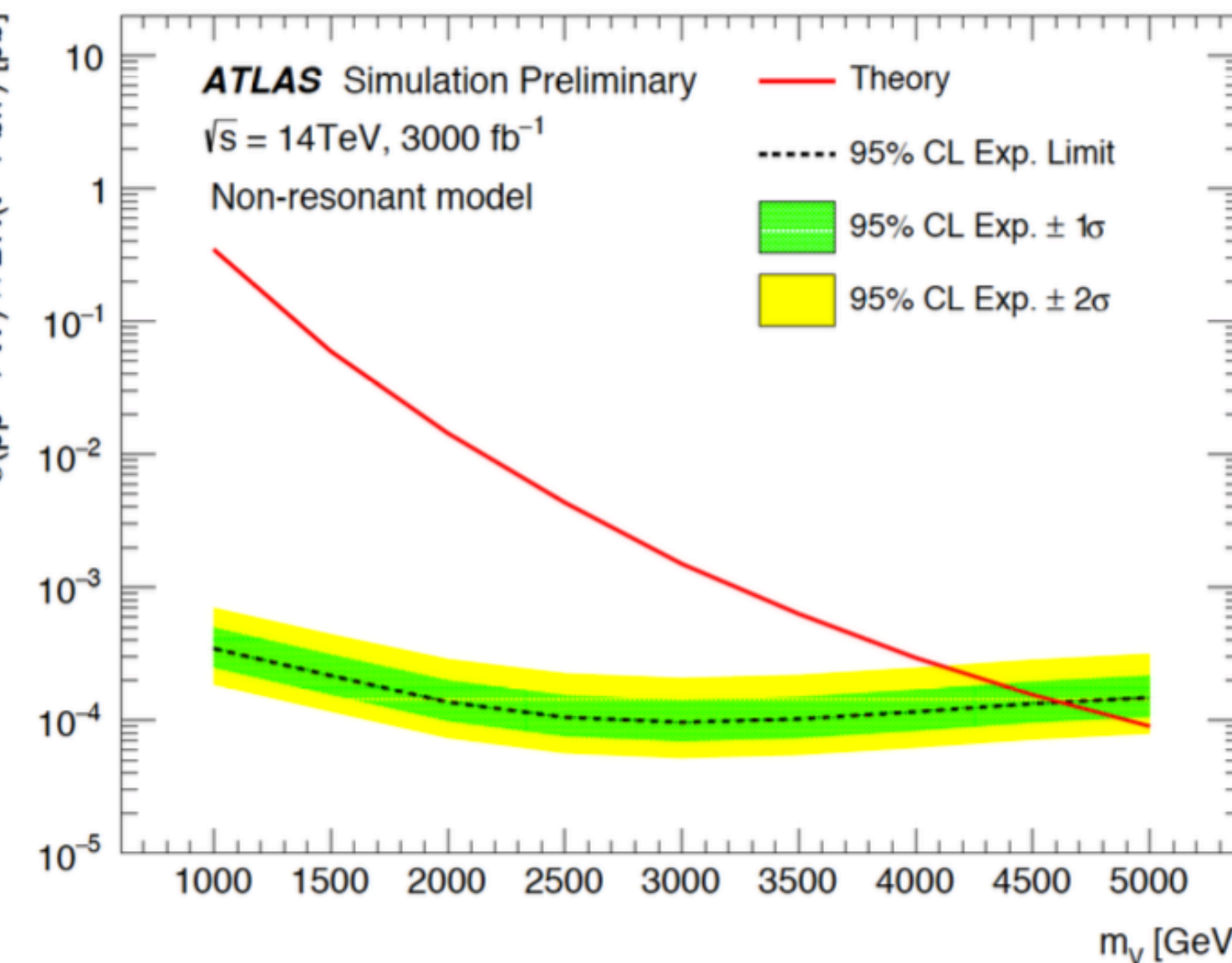


axial-vector mediator probed up to 2.7 TeV

MONO-TOP



vector mediator up to 4.5 TeV



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

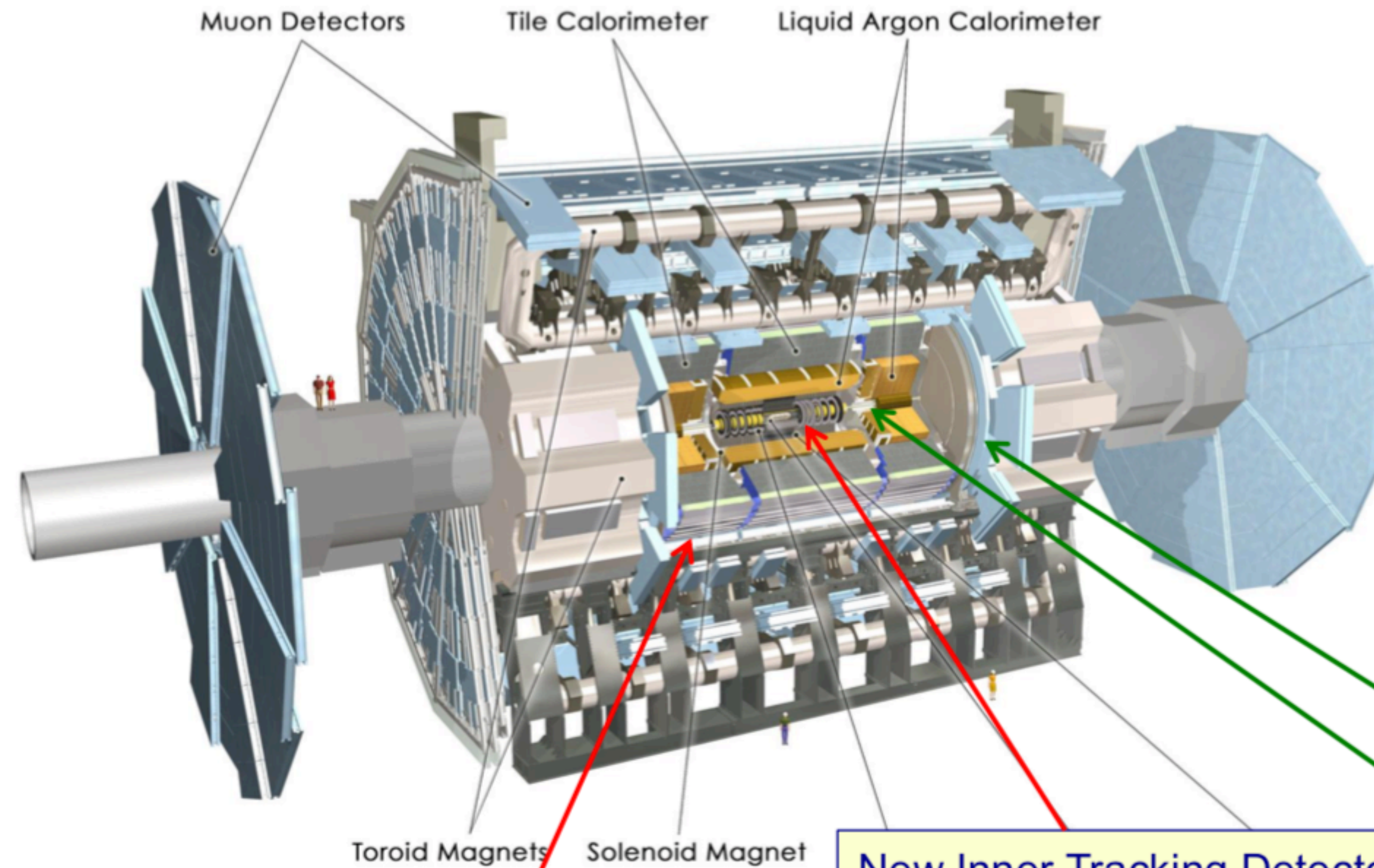


ATLAS UPGRADES

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:

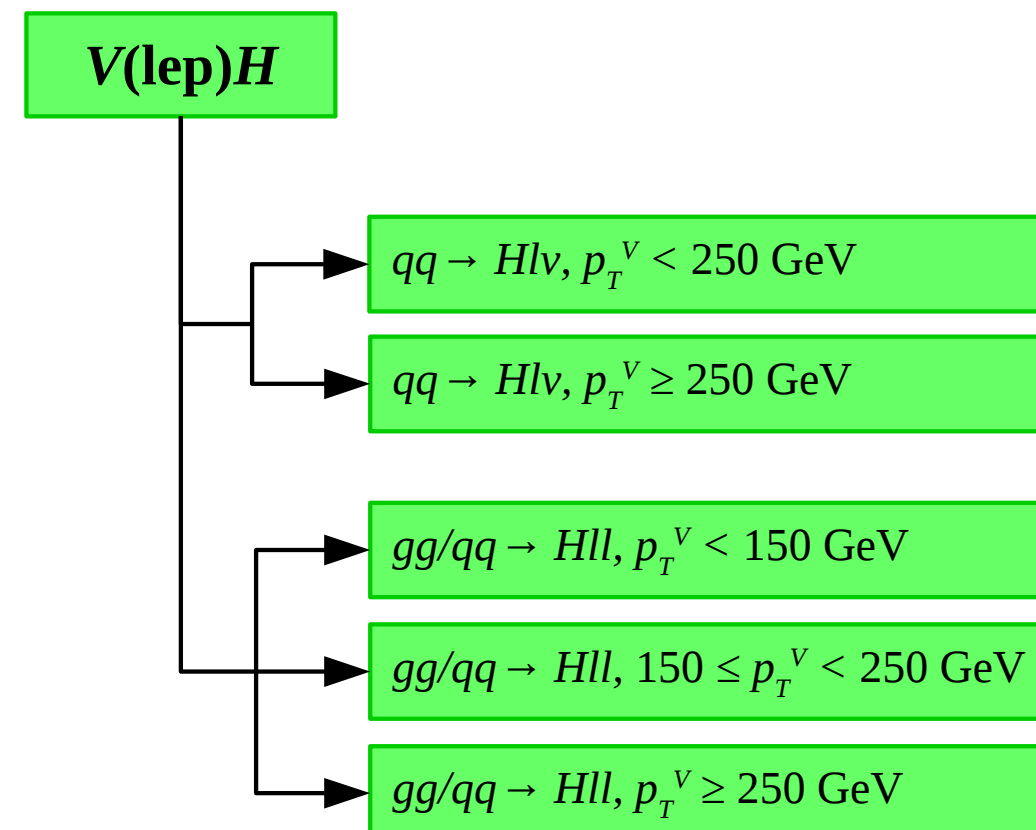
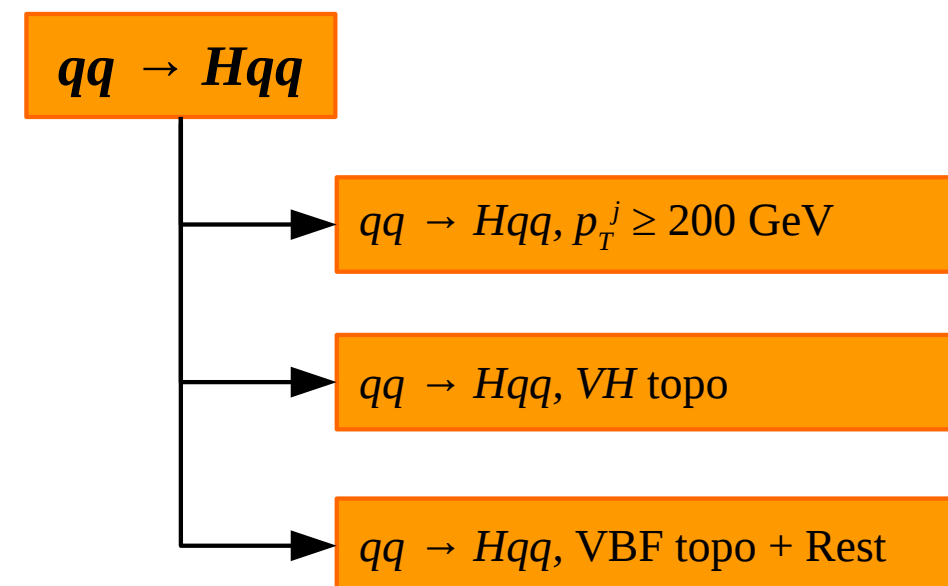
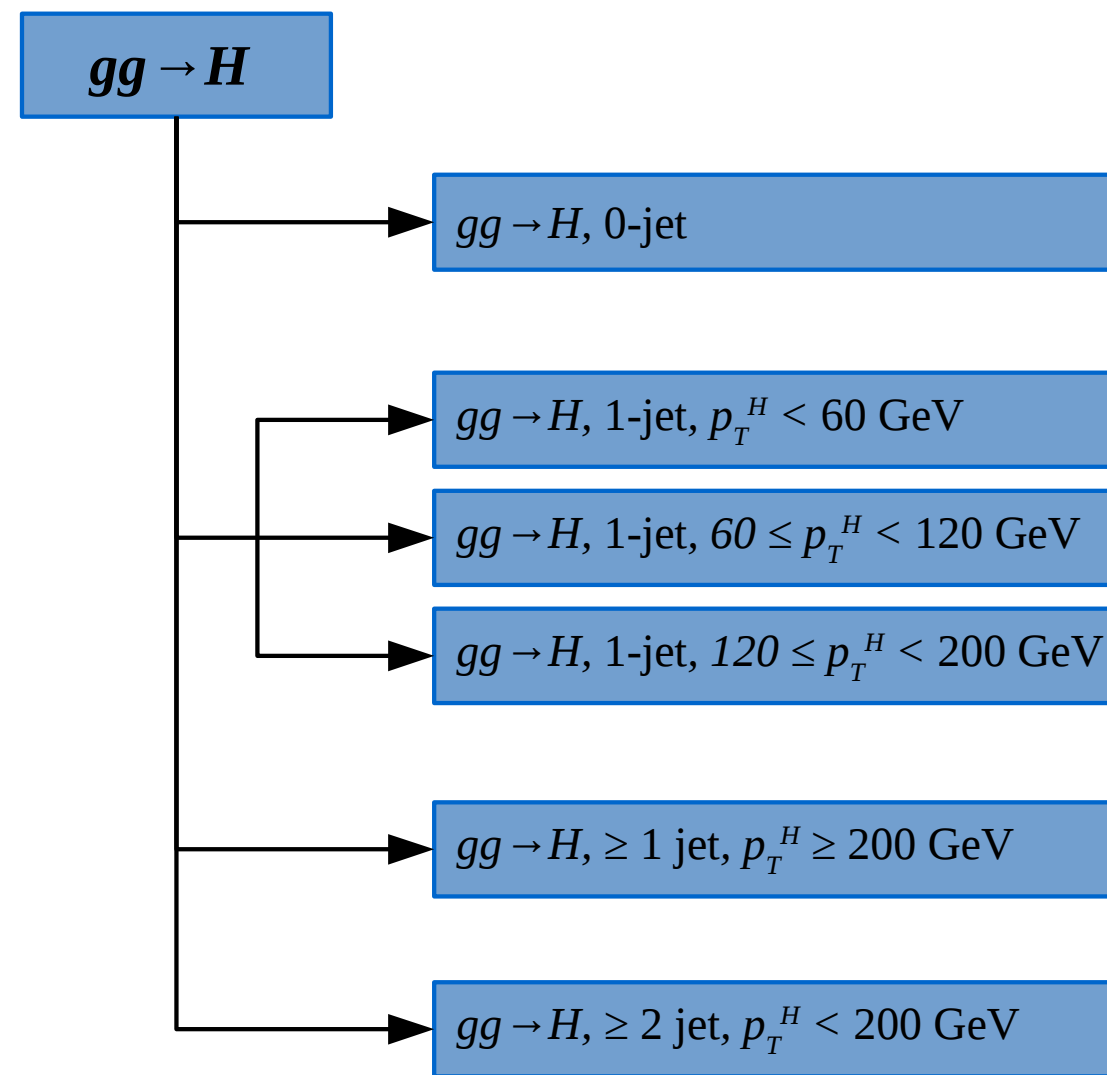
- High granularity timing detector (forward region)
- High- η muon tagger



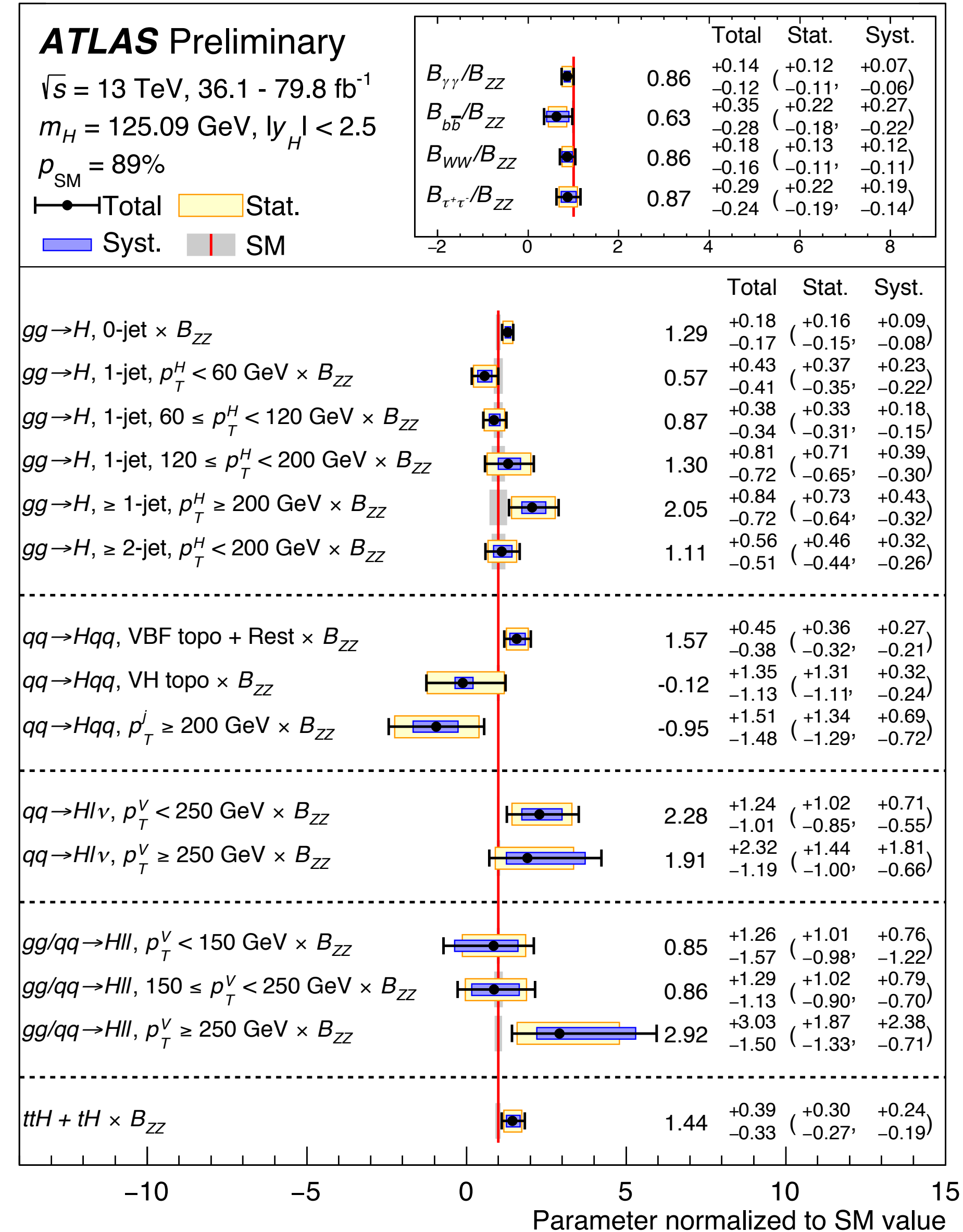
COMBINED MEASUREMENT OF SIMPLIFIED TEMPLATE CROSS SECTIONS (STXS)

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



ttH + tH



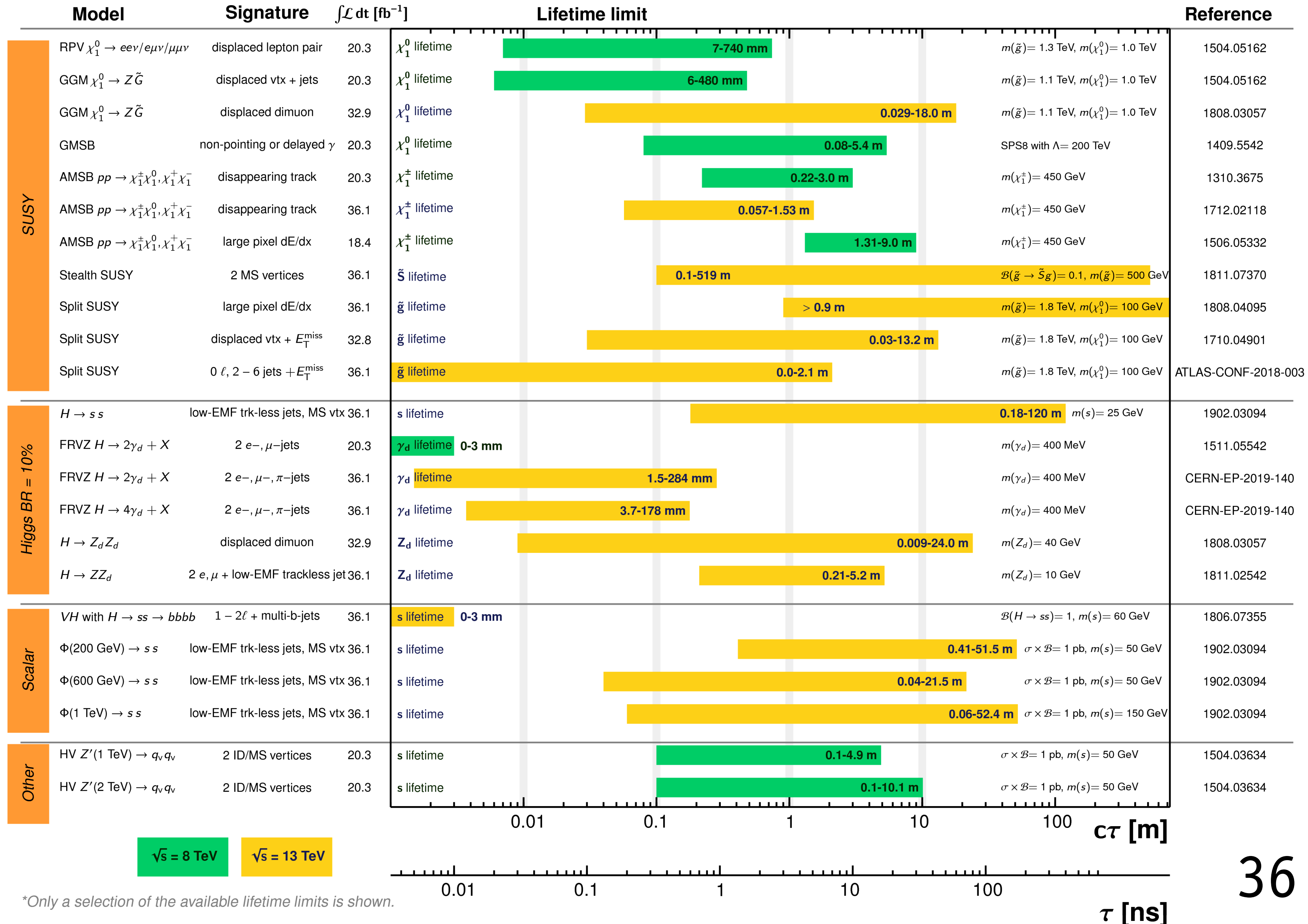
ATLAS LLP SEARCHES SUMMARY

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2019

ATLAS Preliminary

$$\int \mathcal{L} dt = (18.4 - 36.1) \text{ fb}^{-1} \sqrt{s} = 8, 13 \text{ TeV}$$

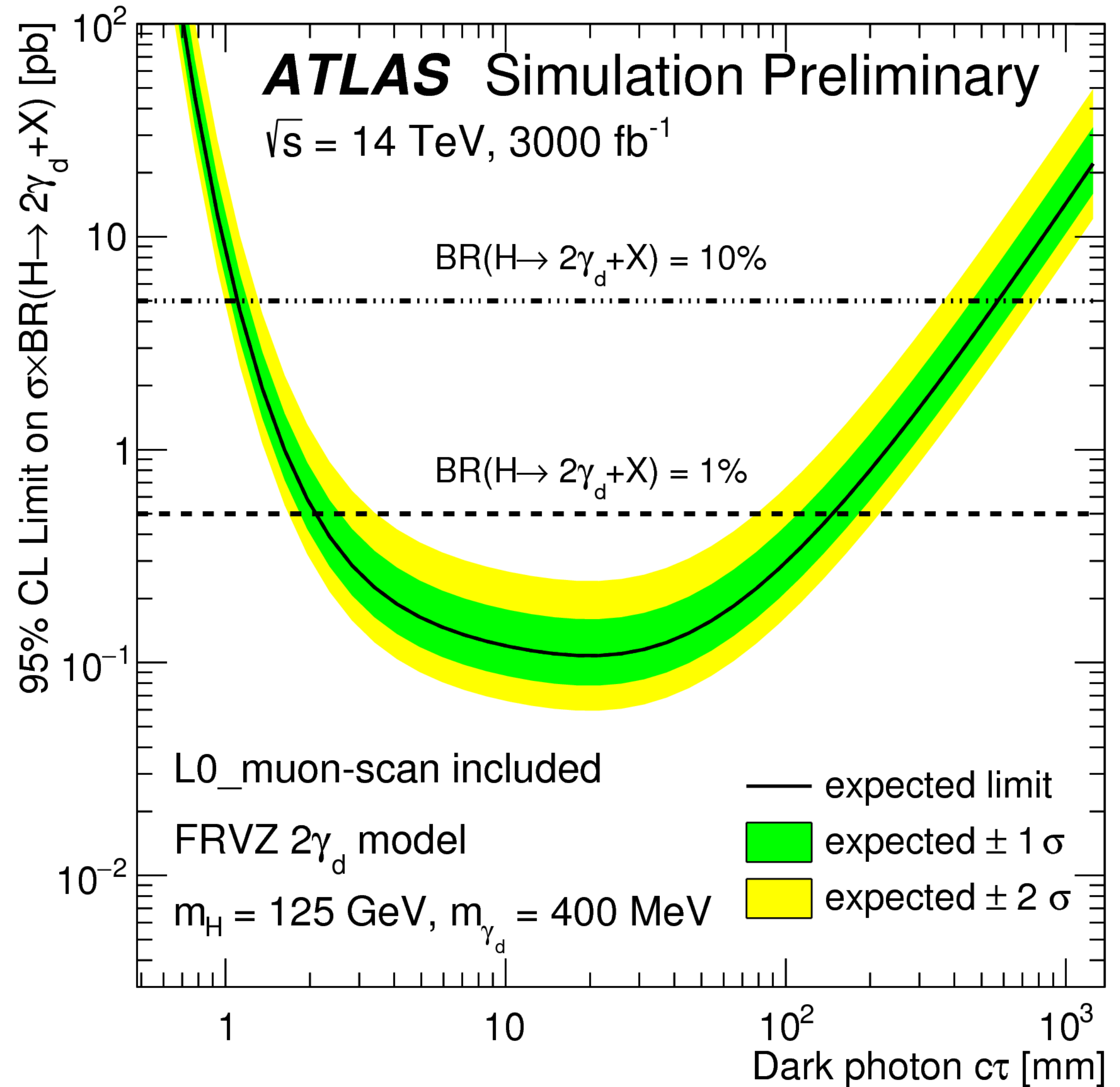
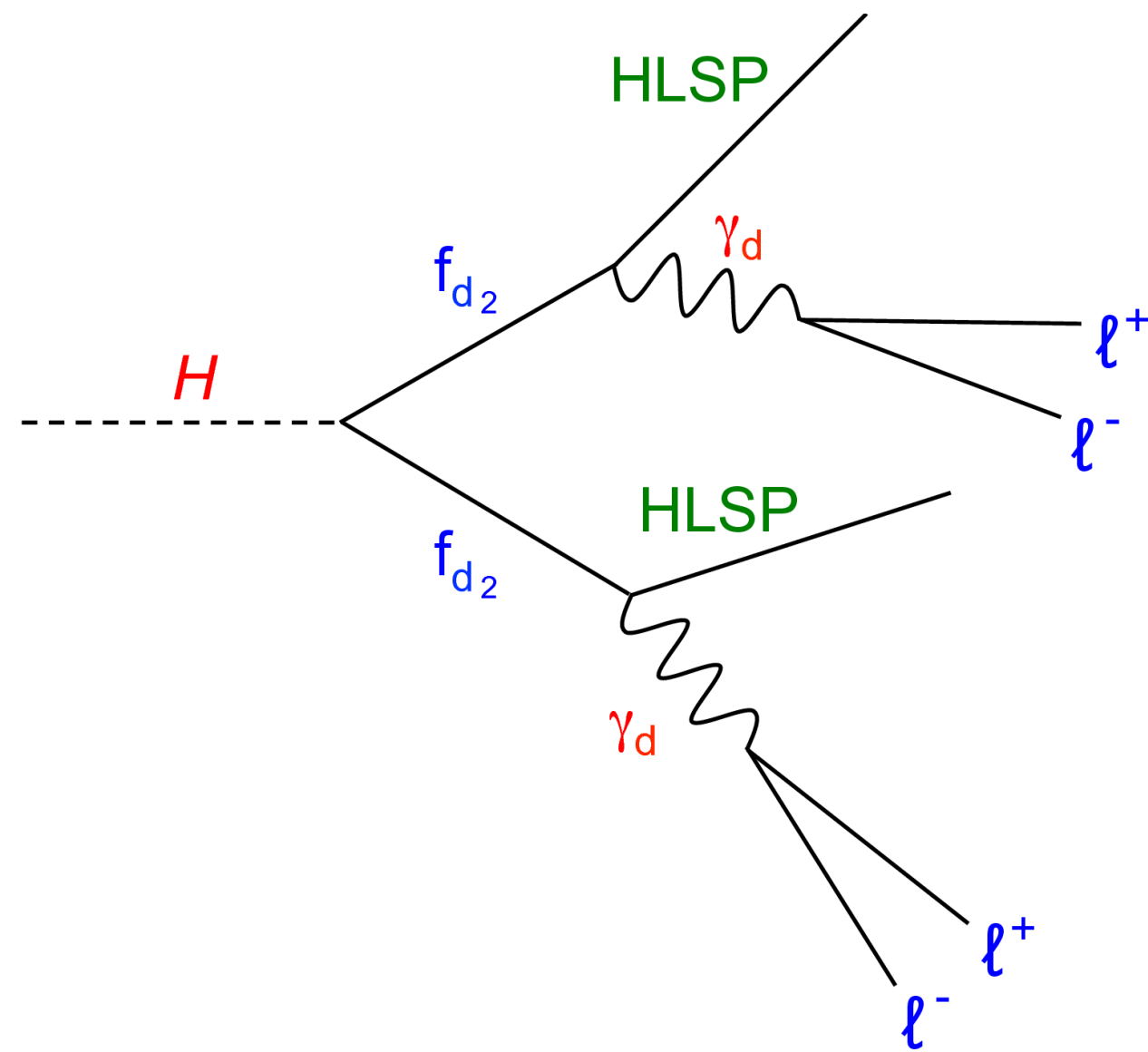


study of LLPs is a new and very promising direction in the interests of the LHC community



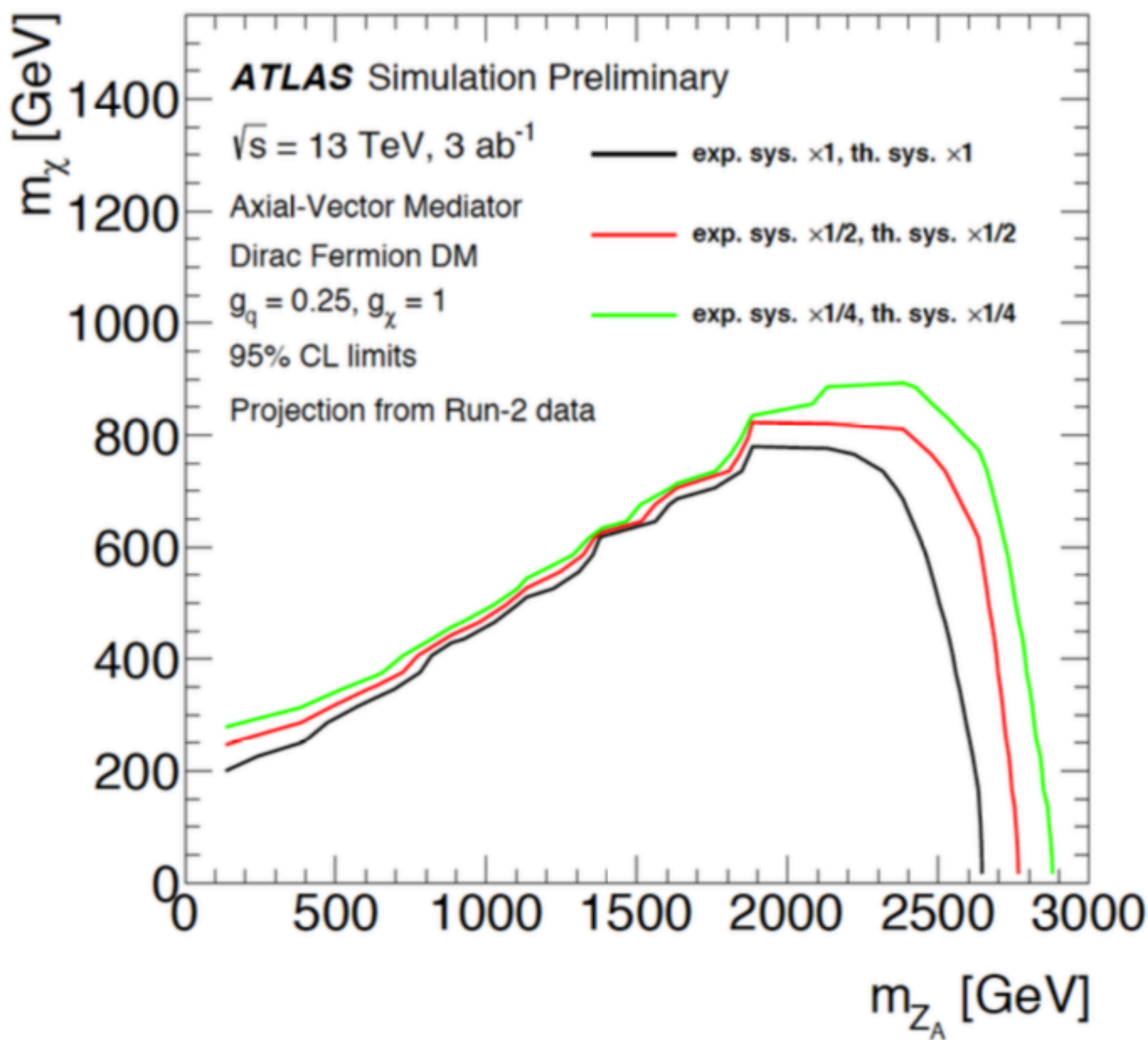
DARK-SECTORS PROSPECTS

DISPLACED DARK-PHOTONS



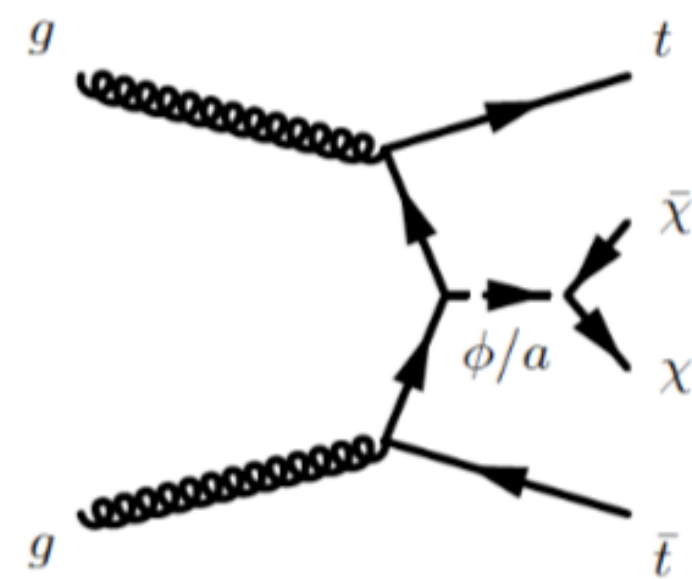
DIRECT DM SEARCHES

MONO JET



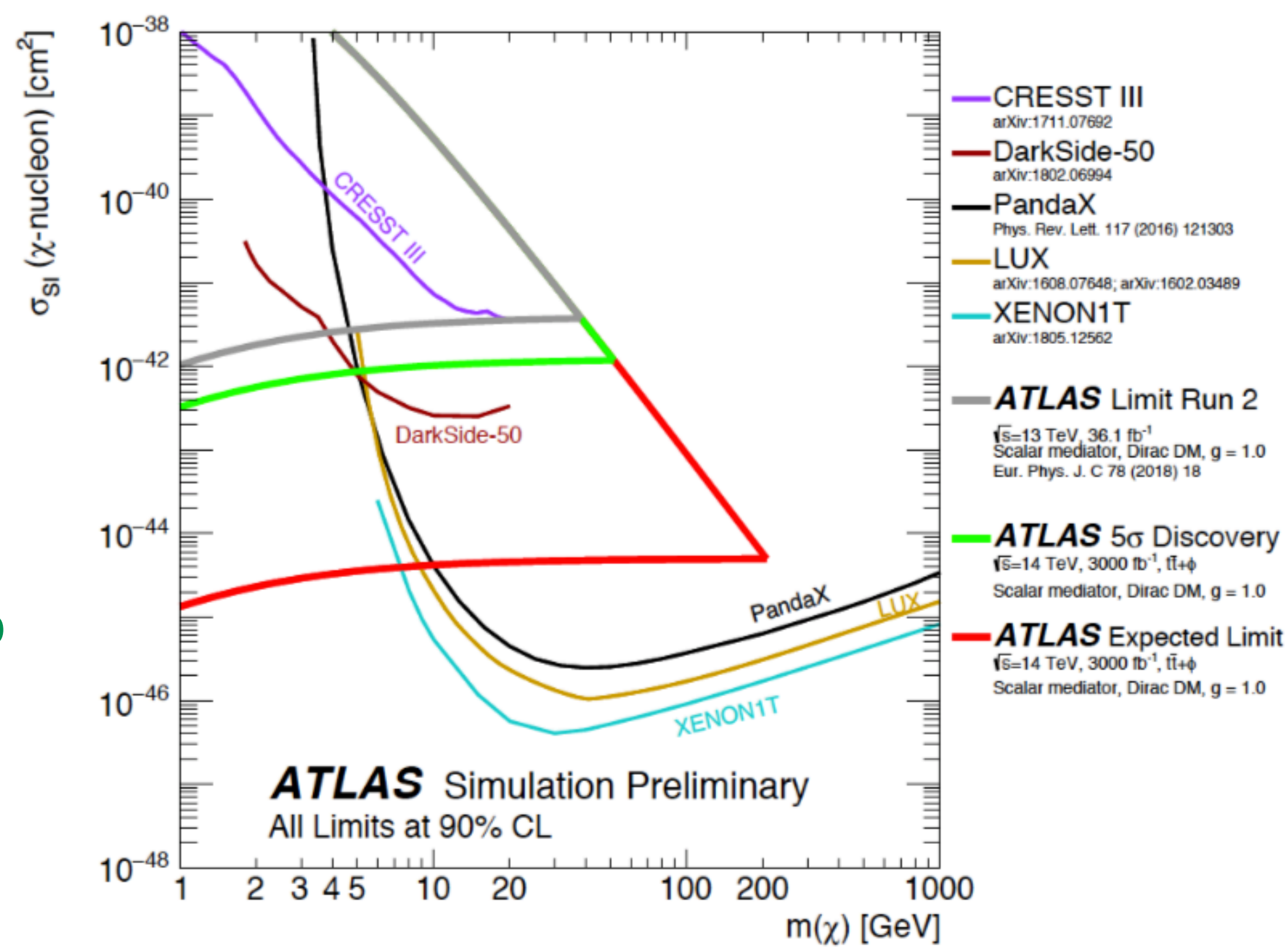
axial-vector mediator probed up to 2.7 TeV

DM + HEAVY QUARKS

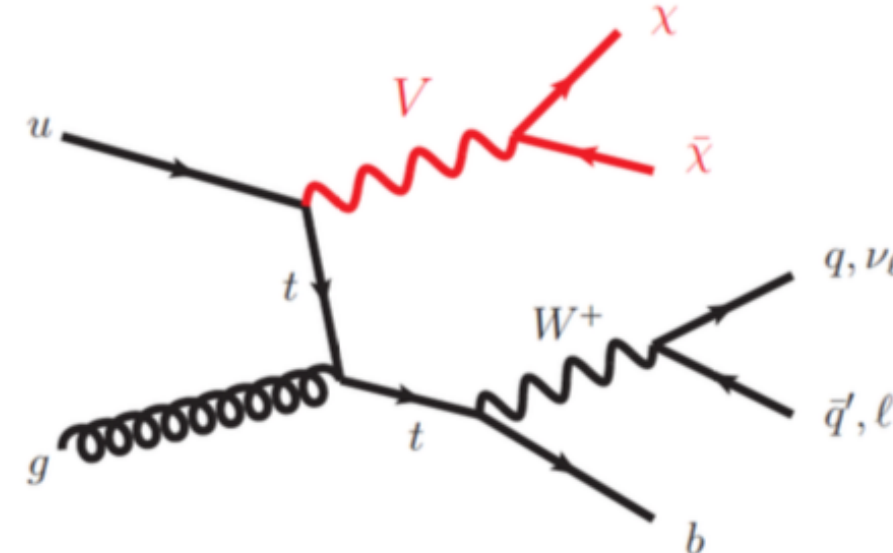


(a) DM+t \bar{t}

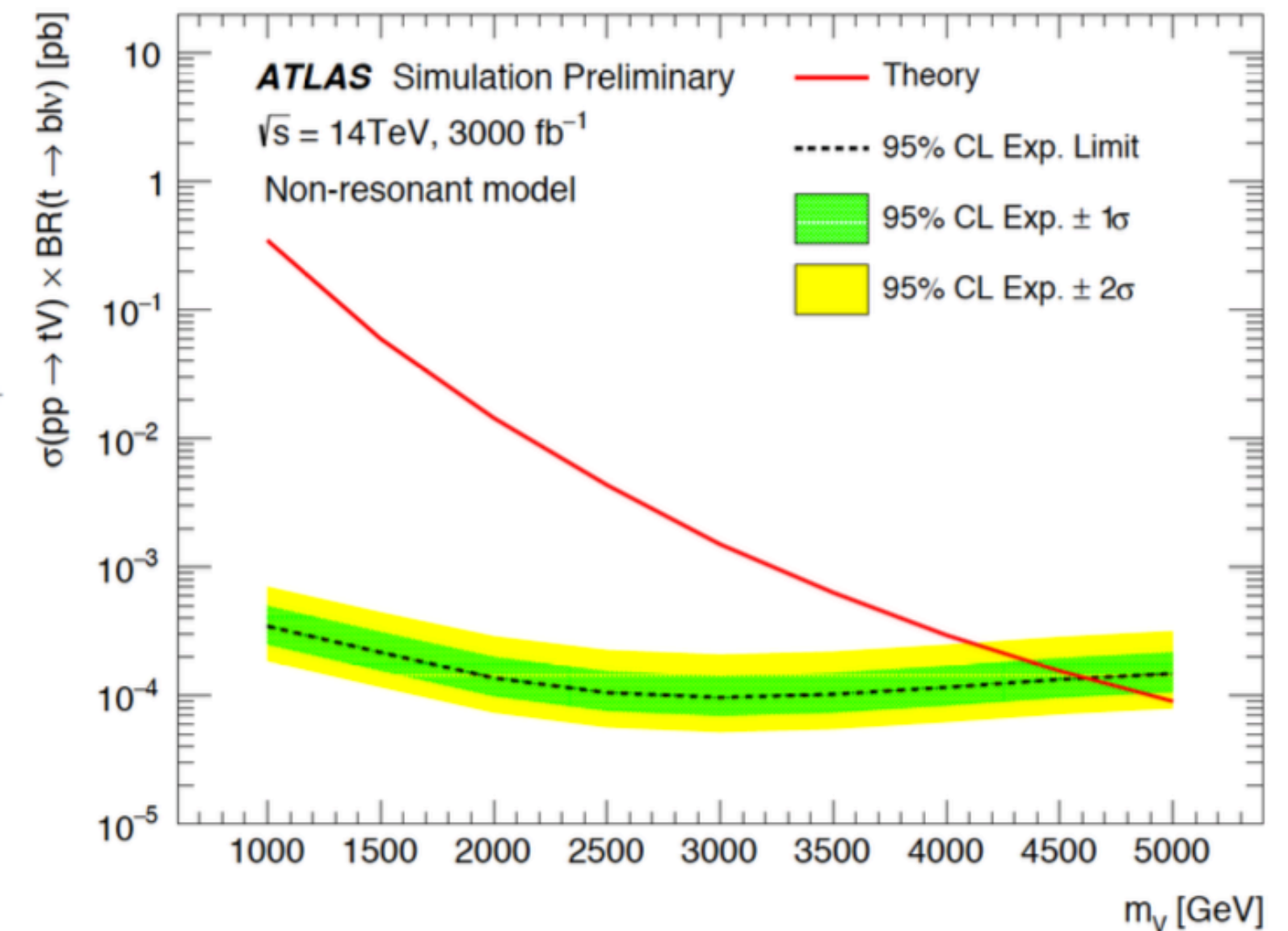
scalar mediator up to ~0.5 TeV



MONO-TOP



vector mediator up to 4.5 TeV



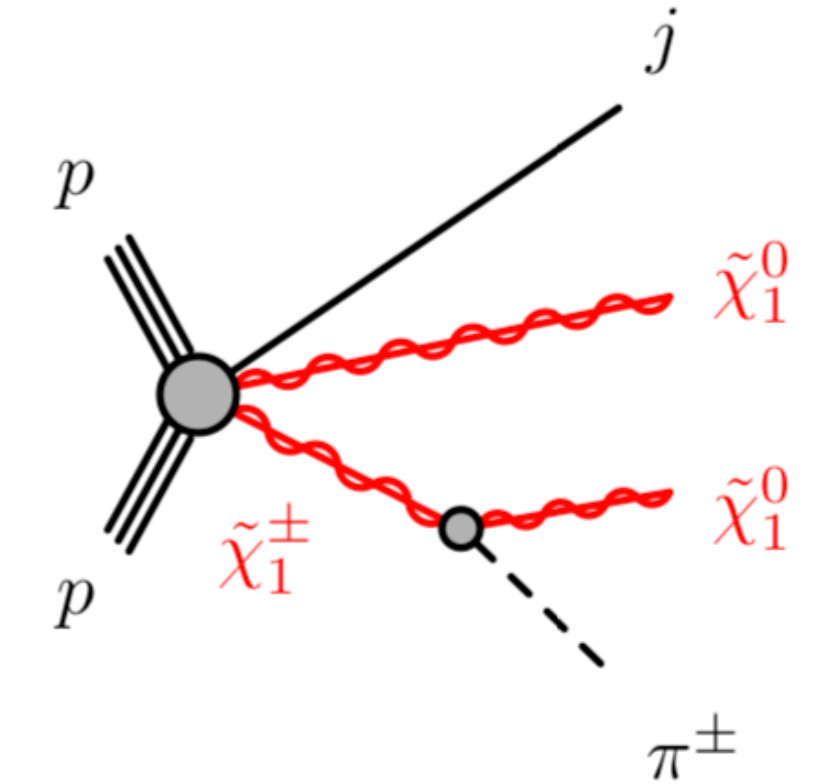
[ATL-PHYS-PUB-2018-043](#); [ATL-PHYS-PUB-2018-038](#)
[ATL-PHYS-PUB-2018-036](#); [ATL-PHYS-PUB-2018-024](#)

HIGGS / SUSY PROSPECTS

DISAPPEARING TRACKS

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

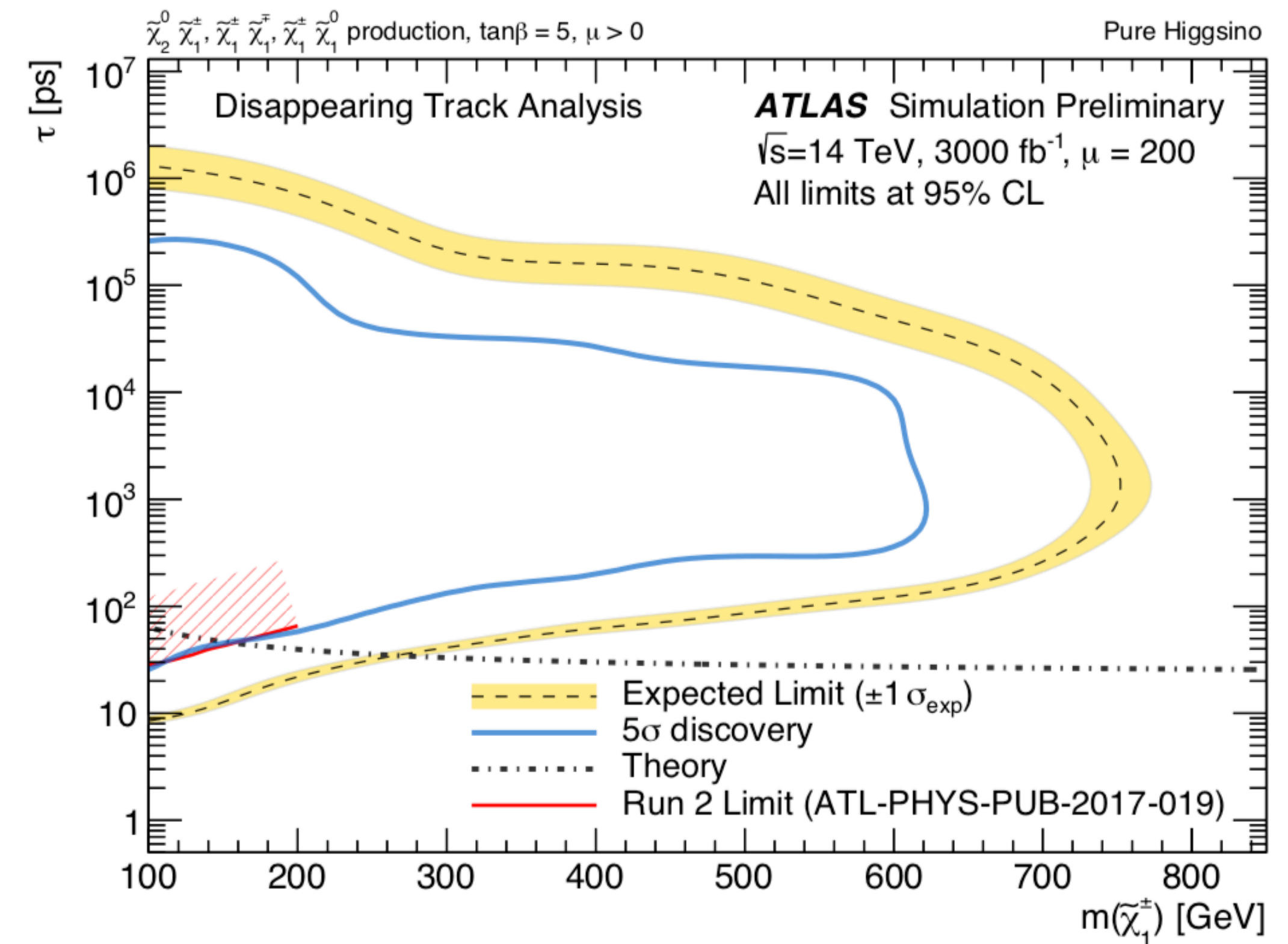
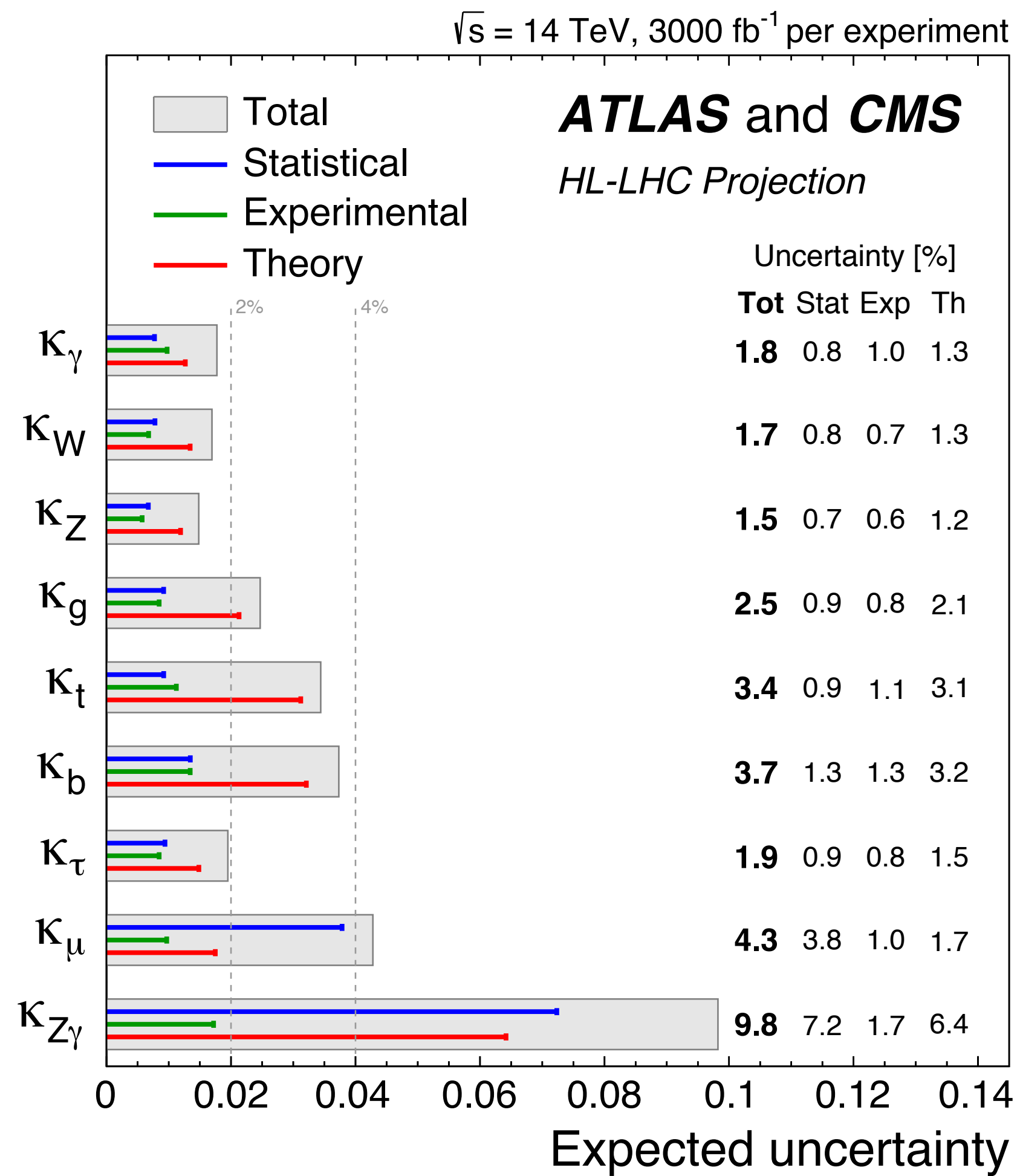
striking experimental signature:



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

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

HIGGS COUPLINGS



ATL-PHYS-PUB-2018-031



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