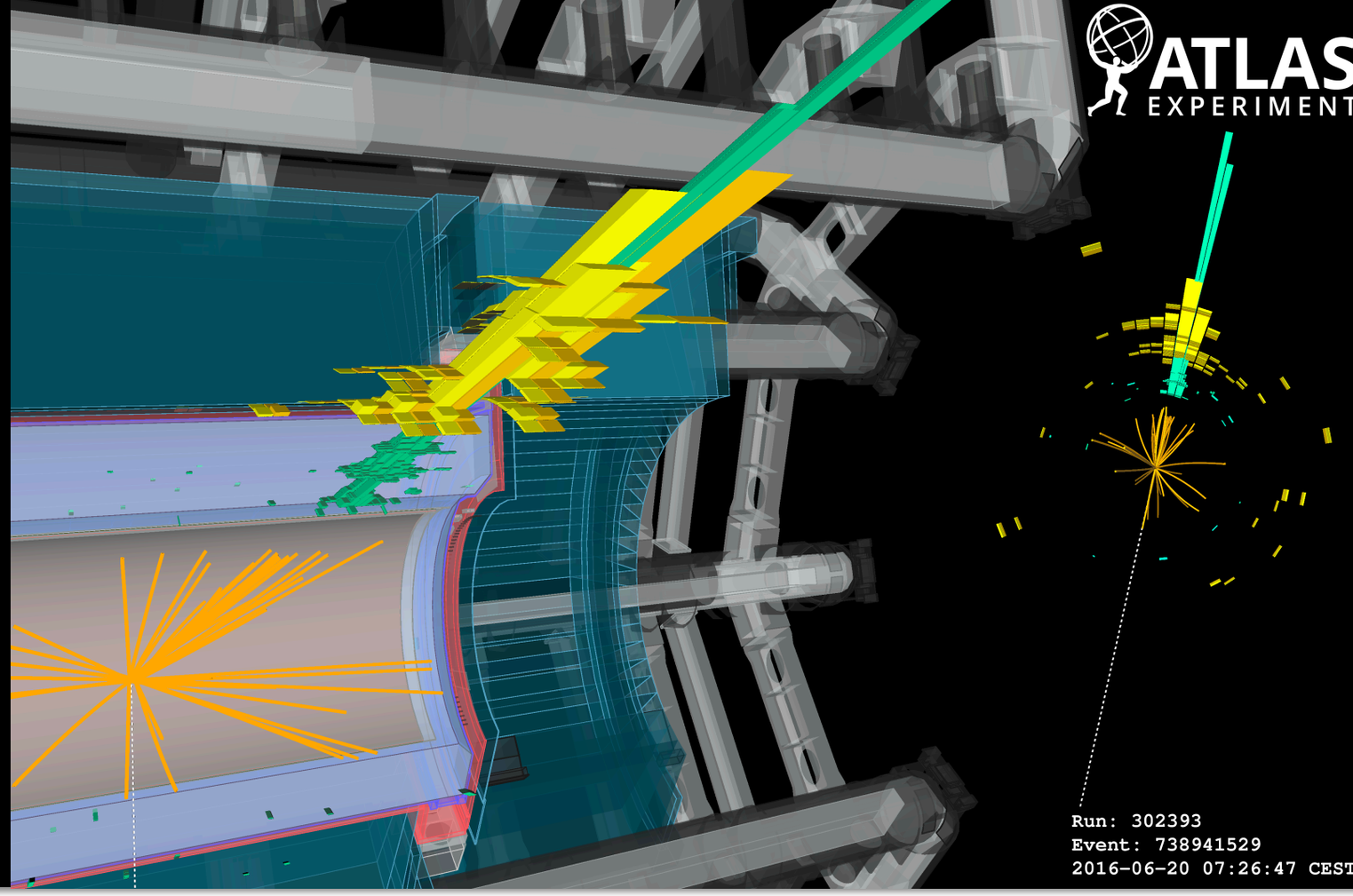
Dark Matter & Dark Energy with the early Run-2 LHC dataset



Priscilla Pani (DESY-Zeuthen)

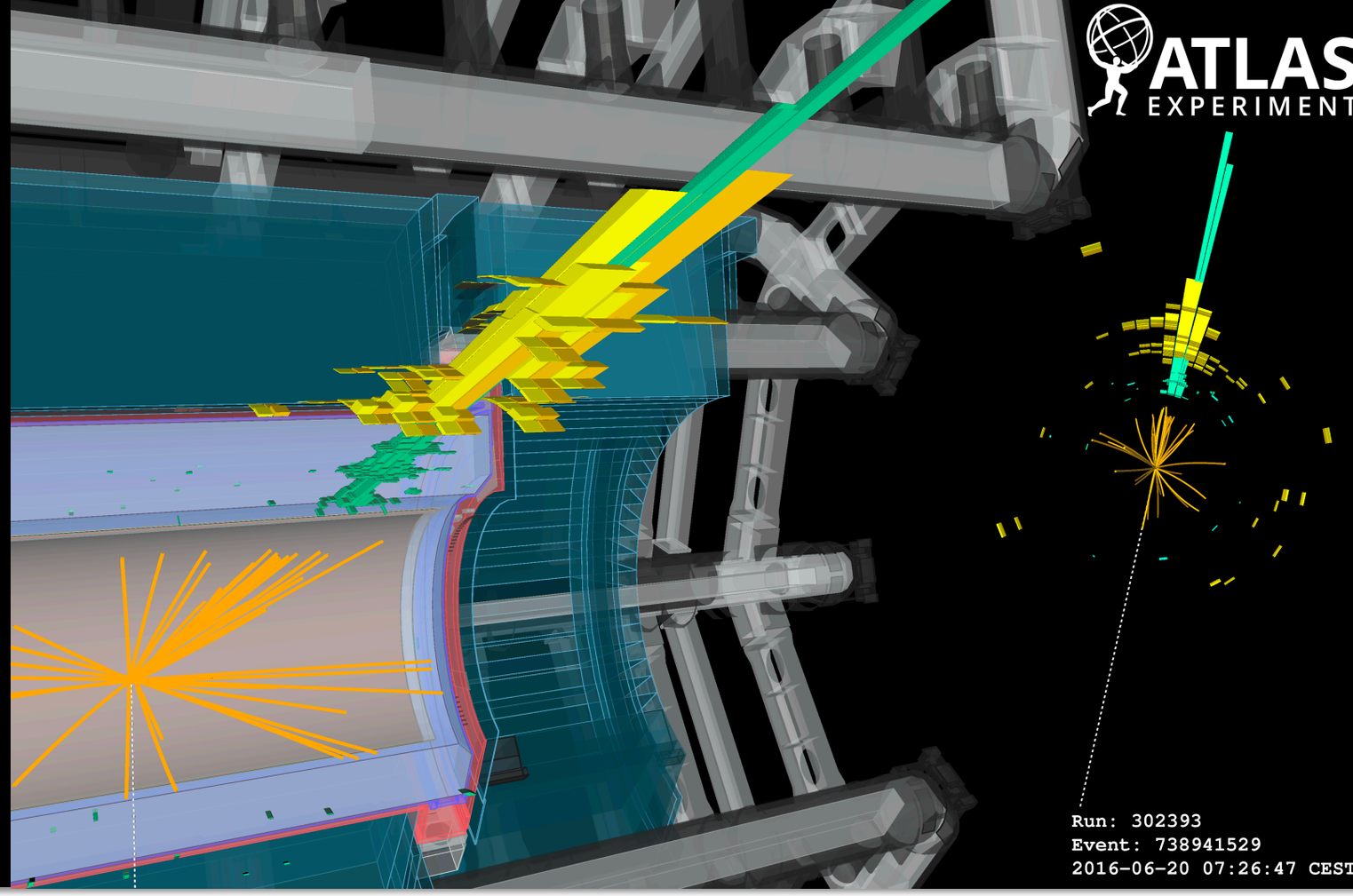
Colloquium 13/03/2019

SLi.do
#B464

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY.

Summary of the recent ATLAS results arXiv:1903.01400 & personal thoughts



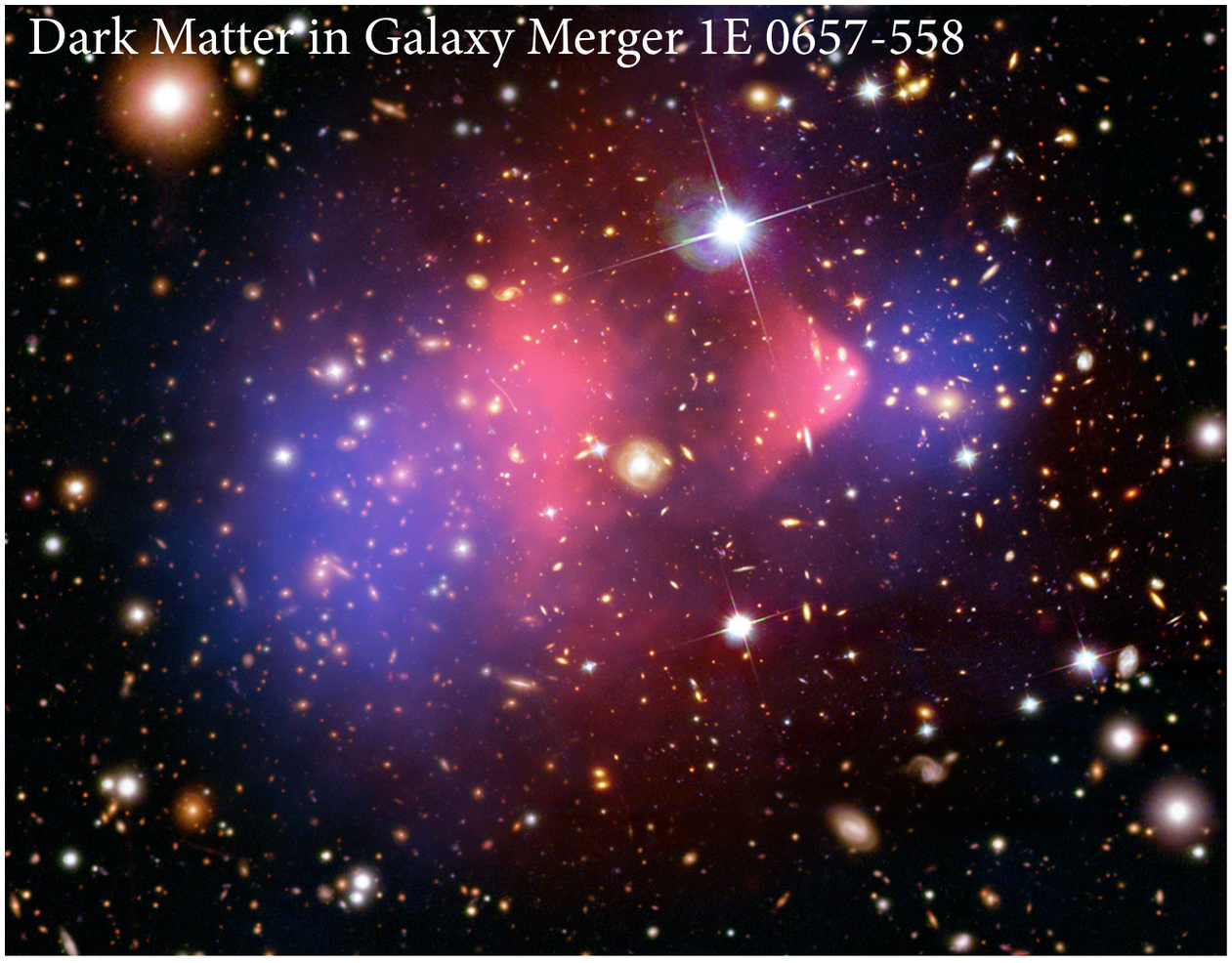
Priscilla Pani (DESY-Zeuthen)

Colloquium 13/03/2019

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY.

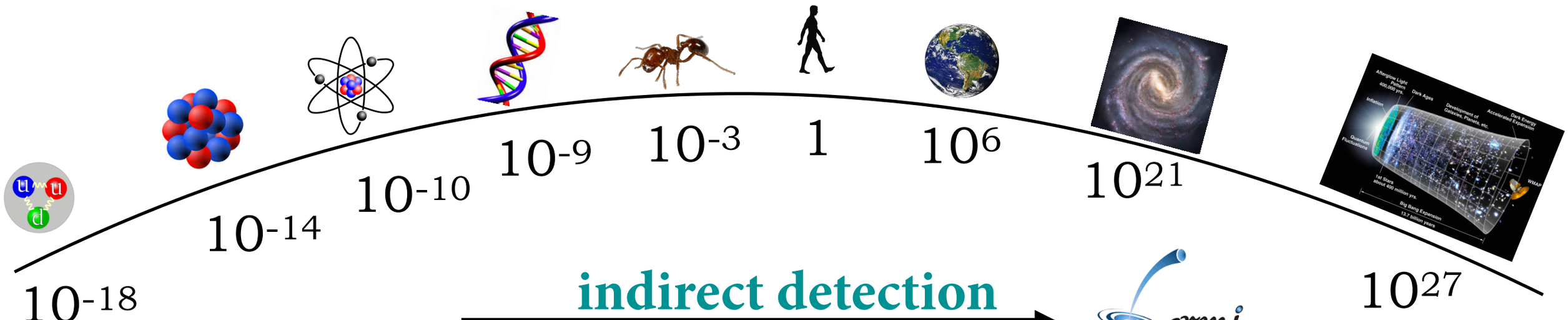
The Dark Matter mystery



- Electrically neutral
- Observed via gravity, massive
- Weakly interacting
- Elementary particles created in the early universe

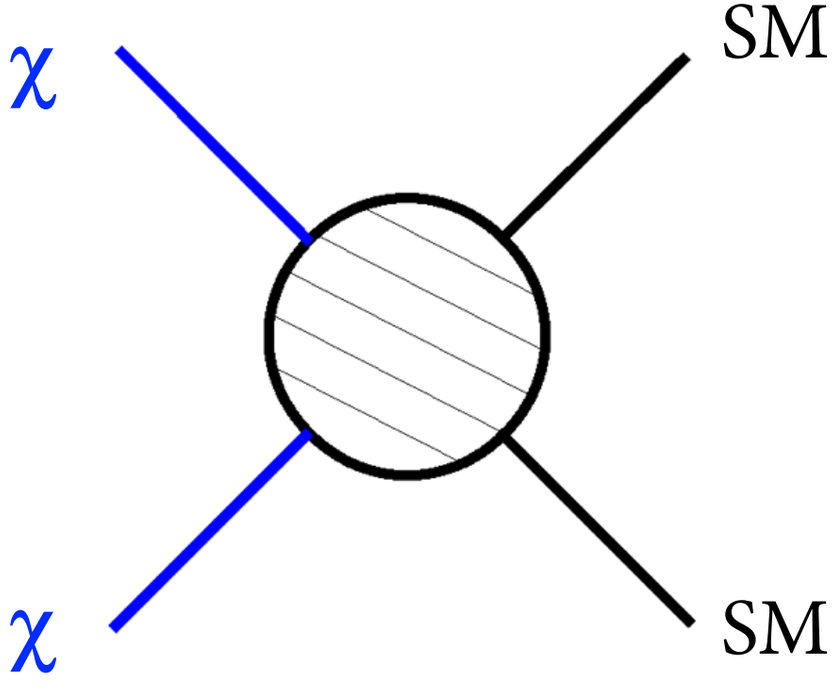
The Dark Matter quest

universe scales in meters



indirect detection

Fermi Gamma-ray Space Telescope



direct detection

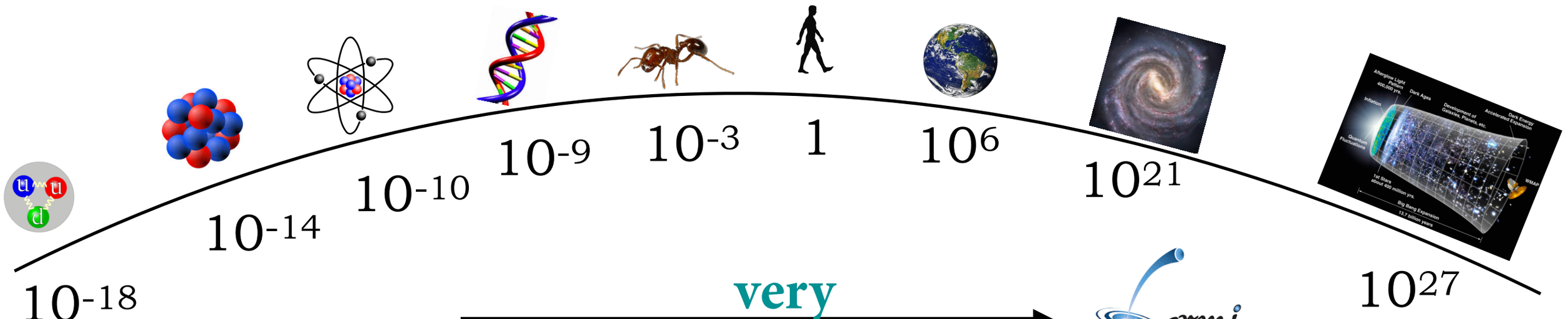
XENON Dark Matter Project

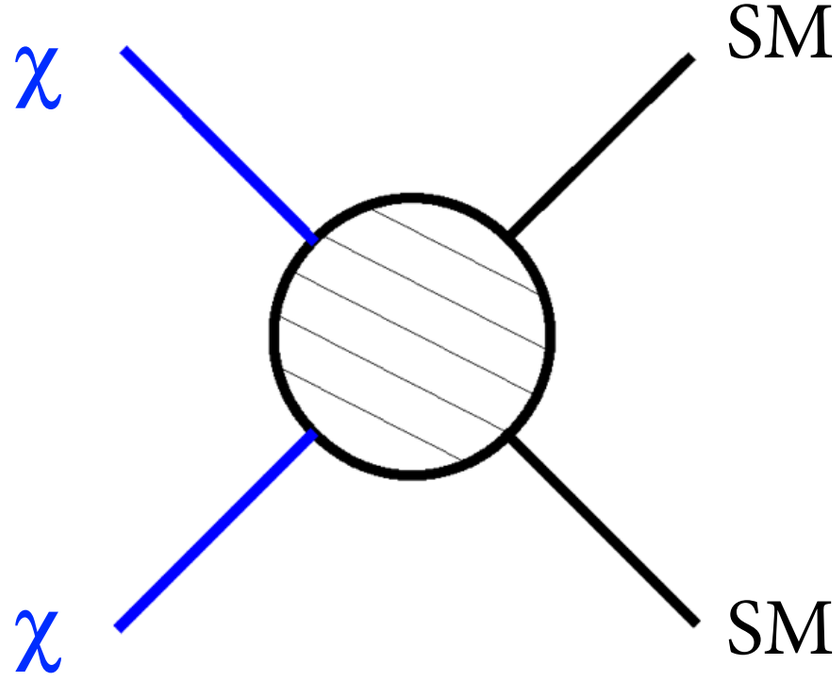
ATLAS EXPERIMENT

production @colliders

The Dark Matter quest

universe scales in meters

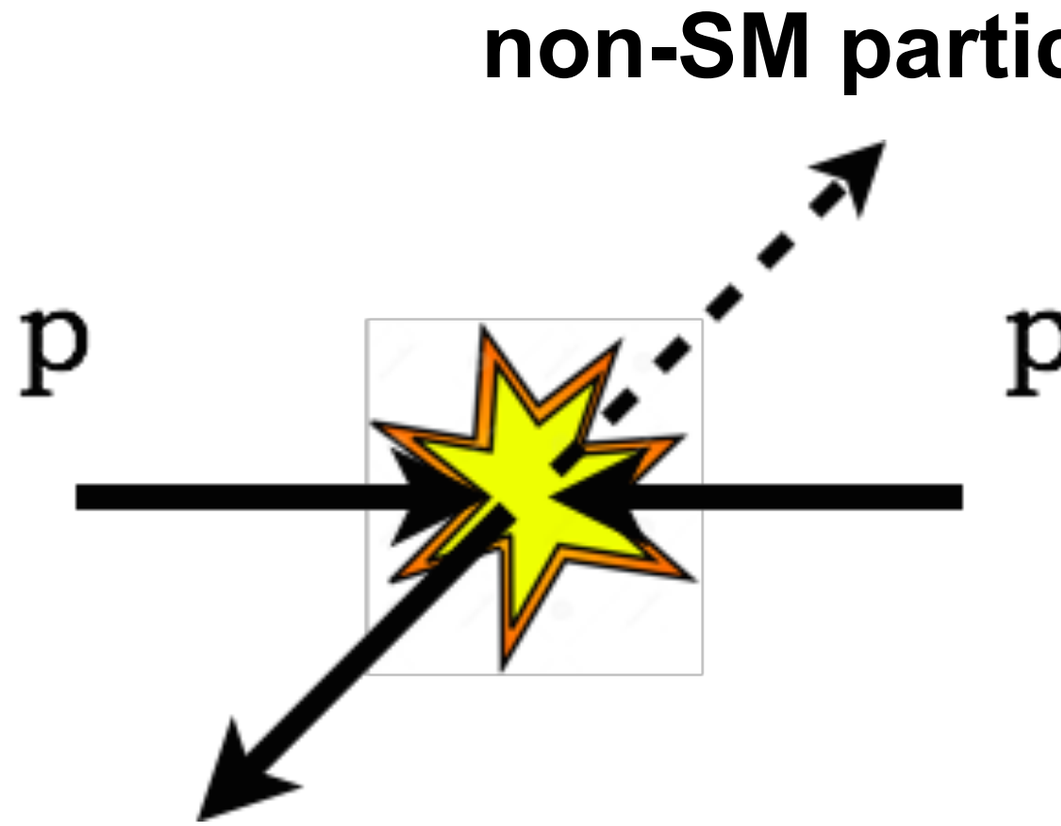




different

assumptions

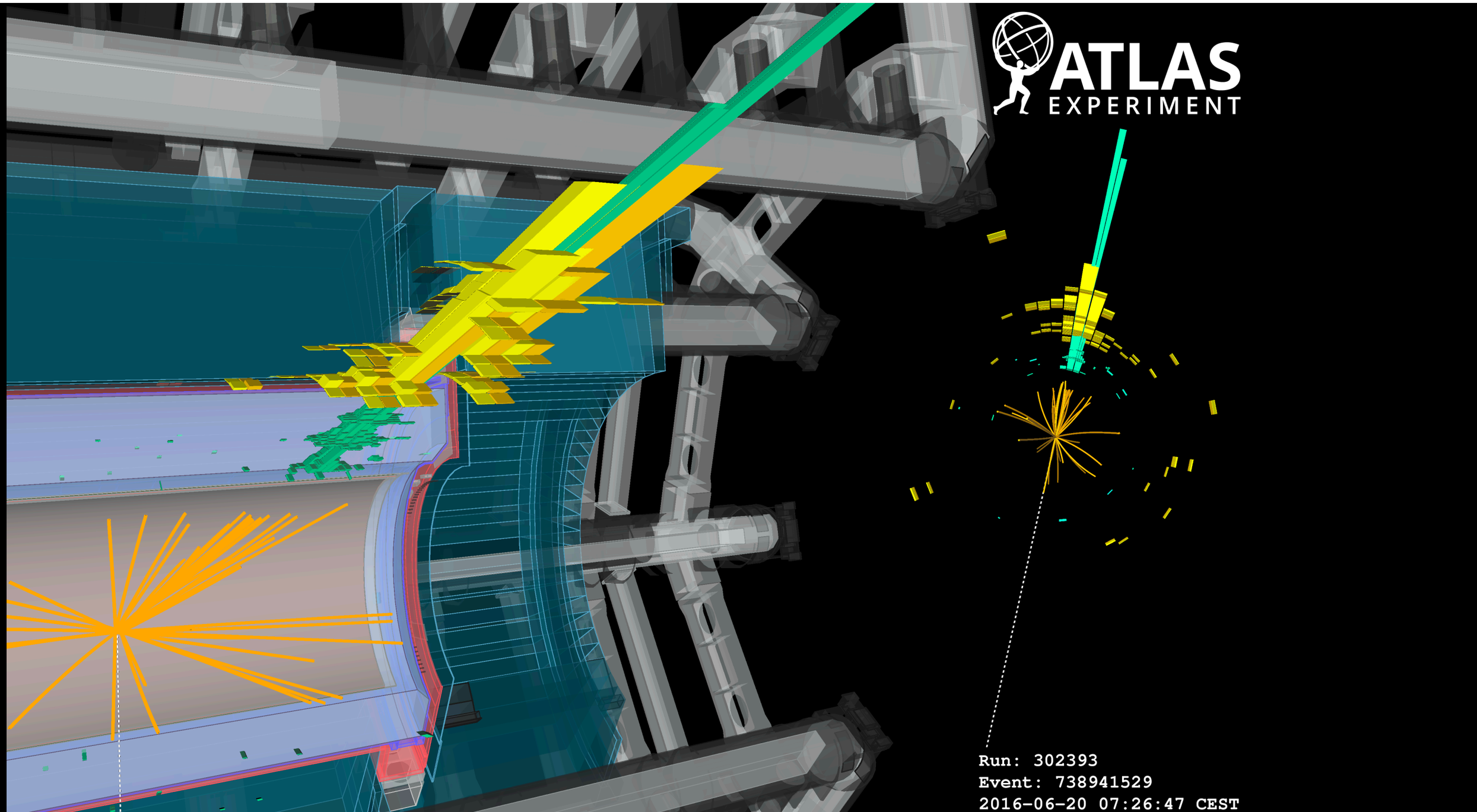
The collider ansatz



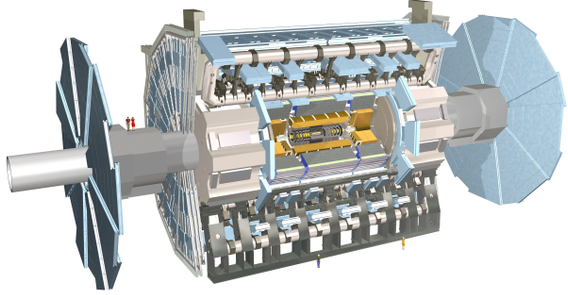
1. Production mechanism

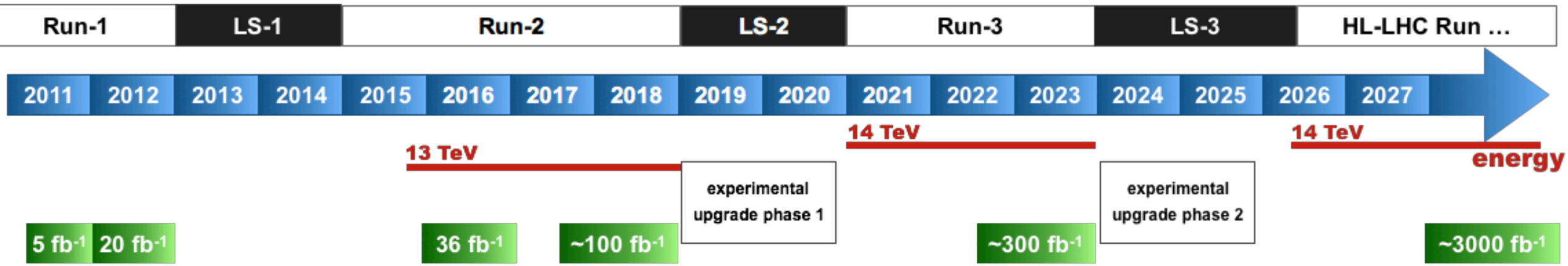
2. Particles detection and identification

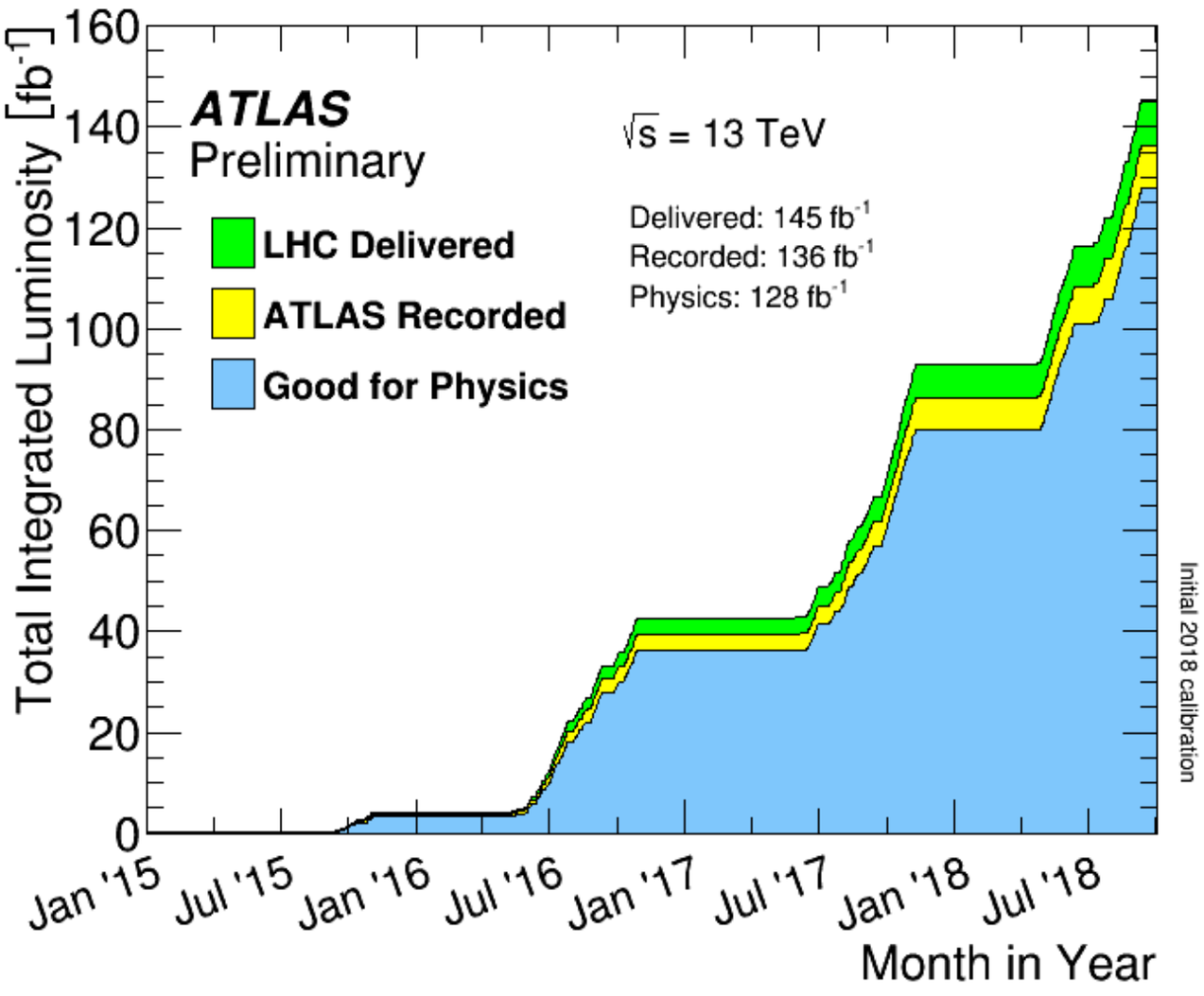
2. Particle identification



The ATLAS detector

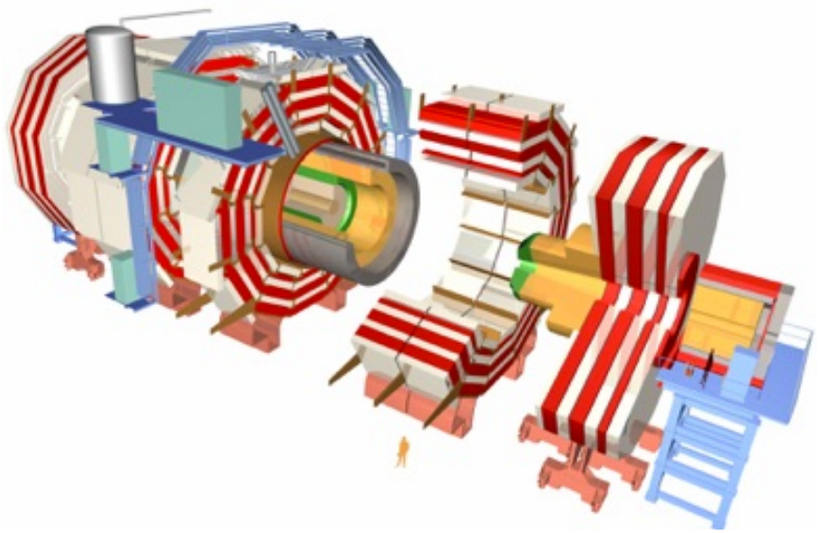




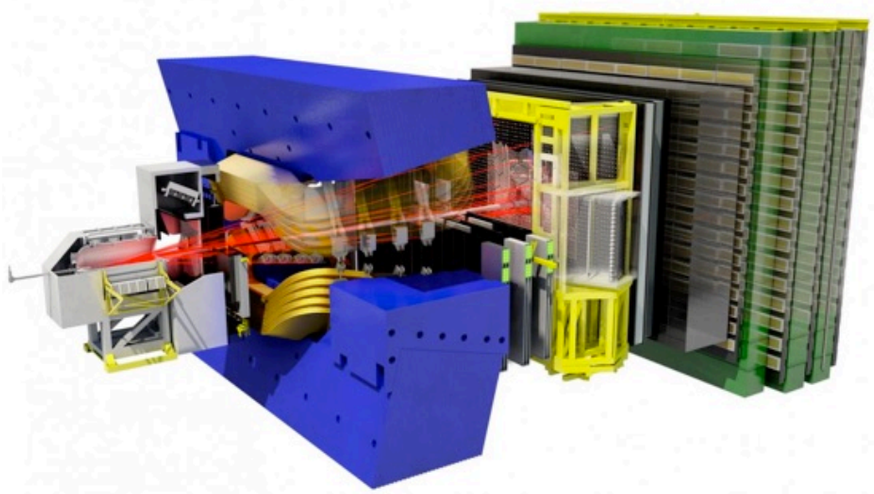


The results presented here focus on 2015+2016 data for a total of 36ifb

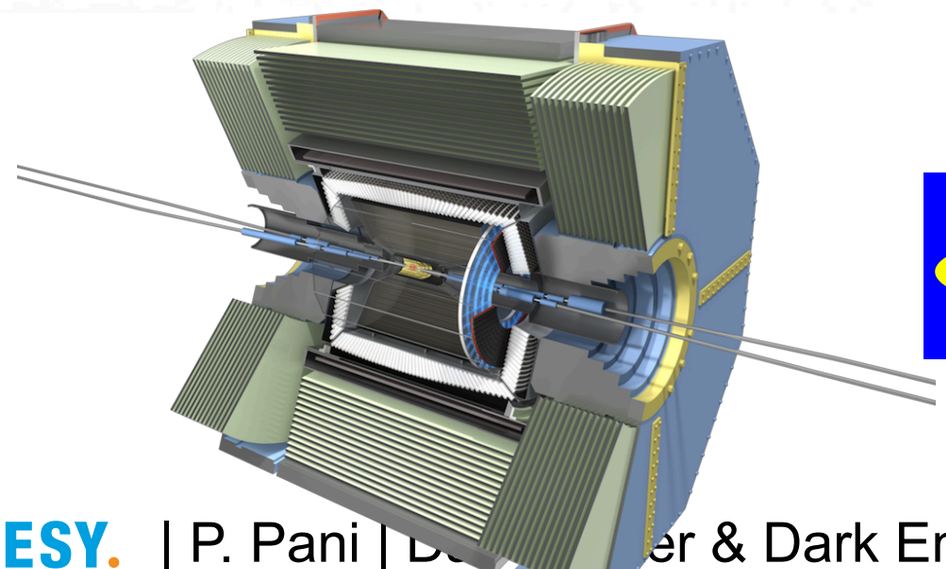
Other collider experiments



Focus	Mediator-models & SUSY
DM Results	EXOTICA, B2G
Overview (2017):	DM summary plots
Latest updates:	



Focus	B-mesons, loops, resonance
DM Results	Public page
Latest updates:	DM@LHC 2018

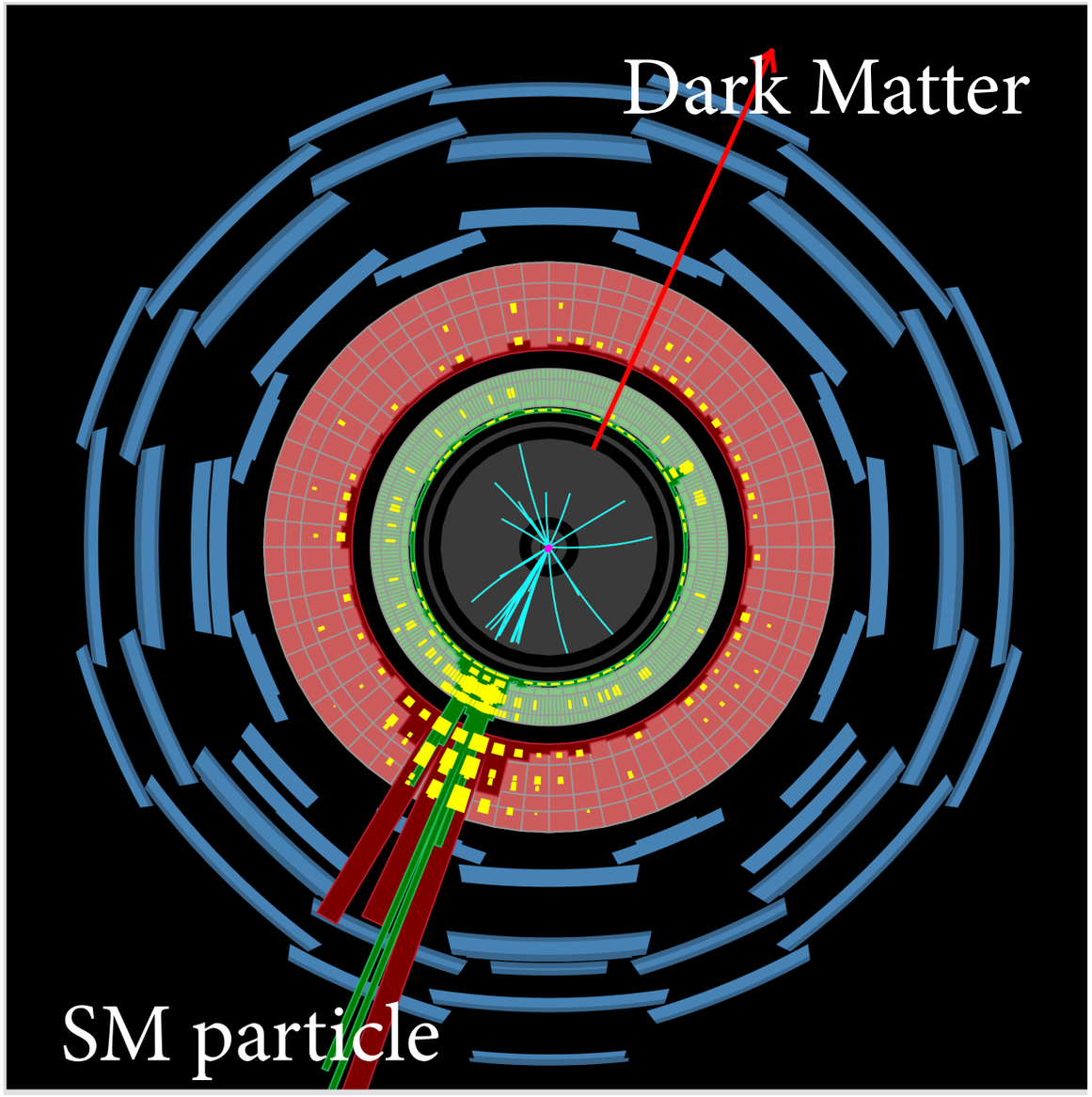


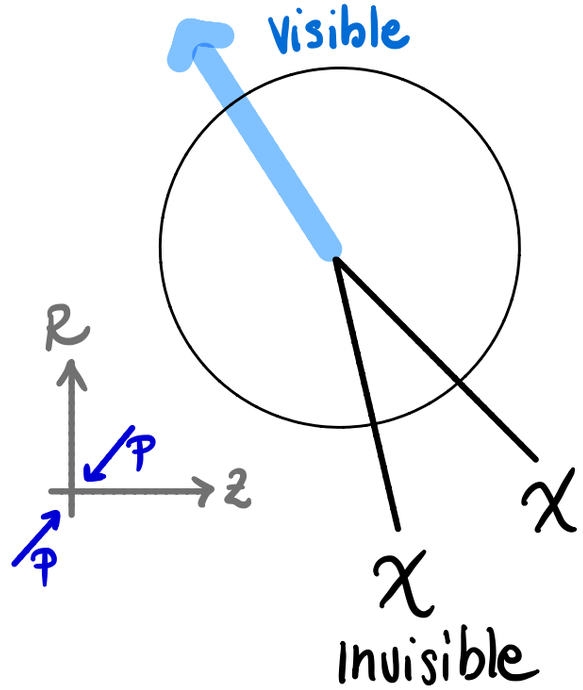
Focus	B-mesons, dark sector
DM Results	DMPuzzle2018, BelleII Book
Latest updates:	LaThuille2019

Particles detection

Particles produced in the collision are detected as analogue signals by the ATLAS sub-detectors, digitised, recorded and reconstructed *offline* as *particle-objects*.

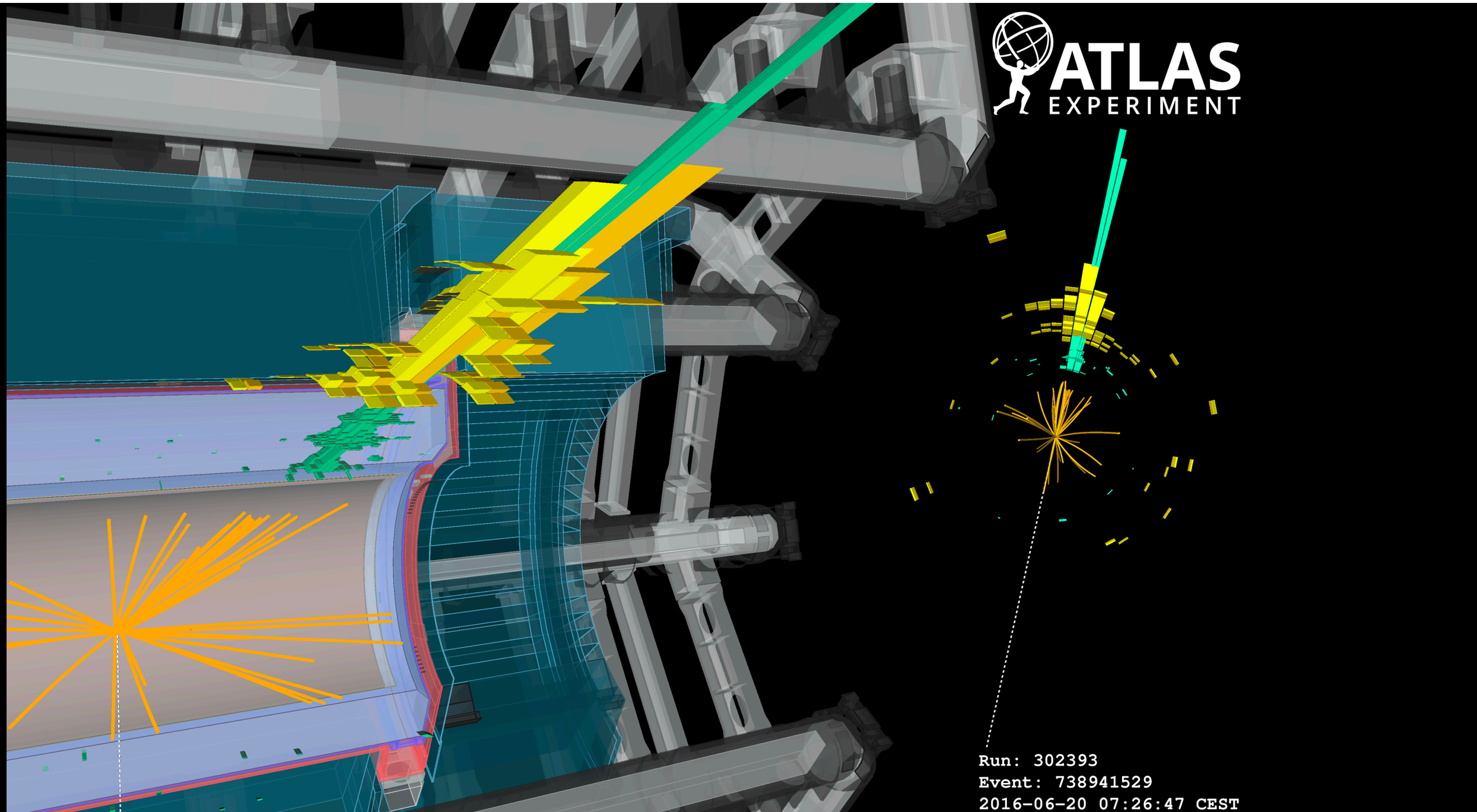
- Electrons
- Muons
- Photons
- jets
- b-jets/c-jets
- invisible particles





C. Doglioni TeVPa2018

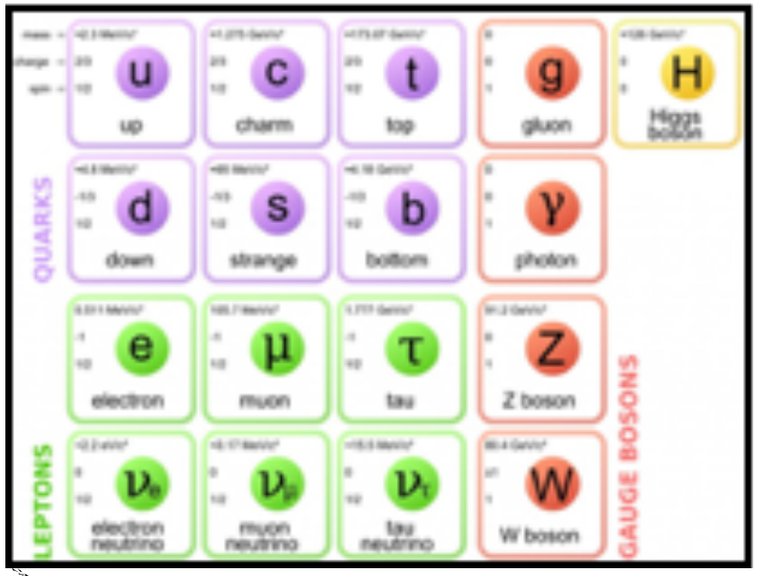
1. Production mechanism



Theoretical framework

"Mediator-based DM simplified models"

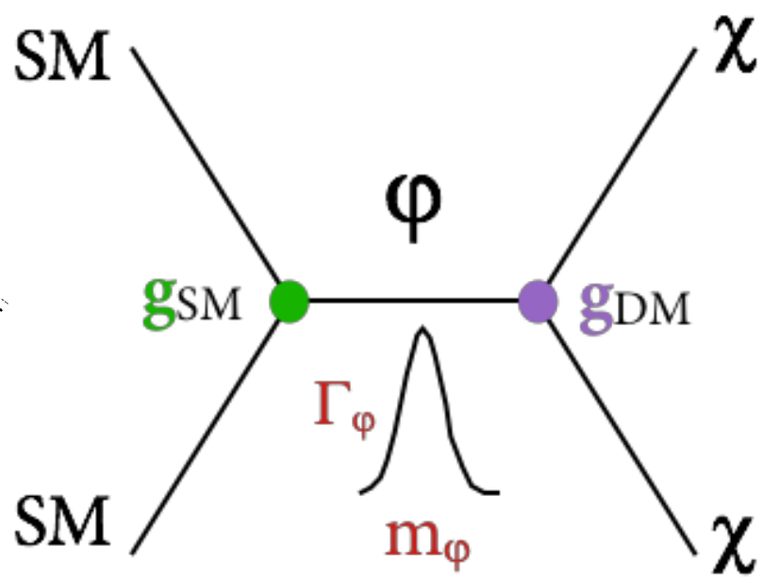
SM SECTOR



DARK MEDIATOR

DARK SECTOR

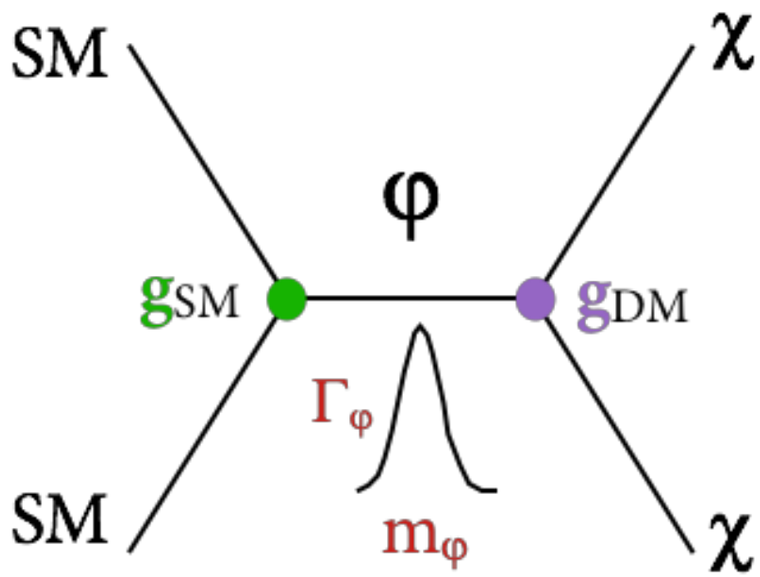
1 mediator



1 DM particle

Mediator simplified models

- ★ Reduce a complex model to a simple one with **DM + mediator**
- ★ **Few free parameters:** mφ, mχ, gSM, gDM, Γφ
- ★ Nature of mediator and DM can (also) be **systematically classified based on their spin and CP**

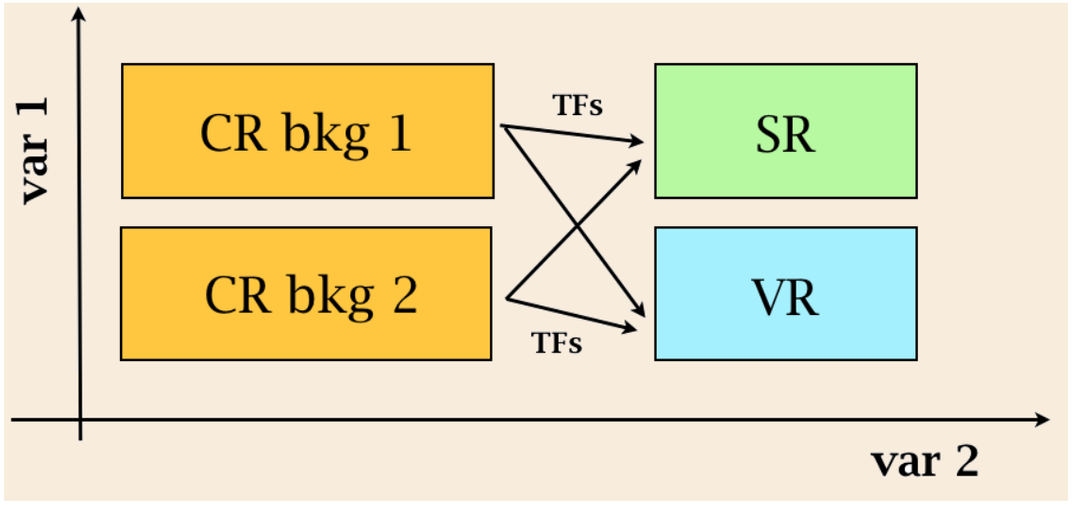


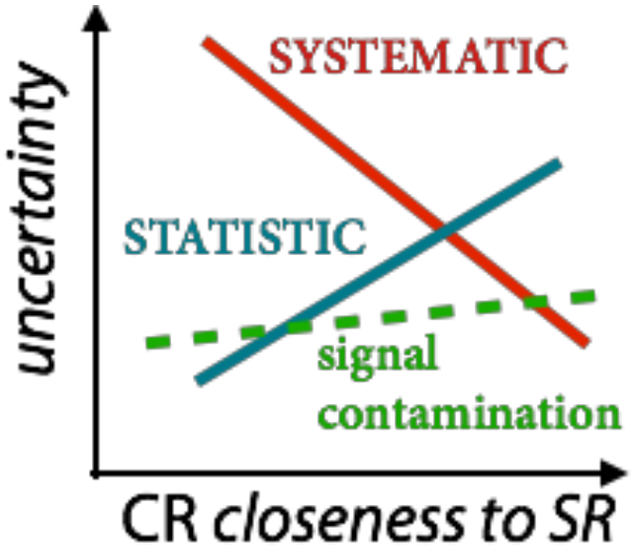
E_T^{miss} + X

arXiv:1507.00966 (and ref. therein) + LPCC WG

E_T^{miss}+X experimental approach

- Definition of a set of Signal enriched Regions (SR)
- Definition of a set of Control Regions (CR) to derive a data-driven normalisation of MC with transfer factors (TF).
  - ✓ Needs precise theory prediction for shapes arxiv:1705.04664

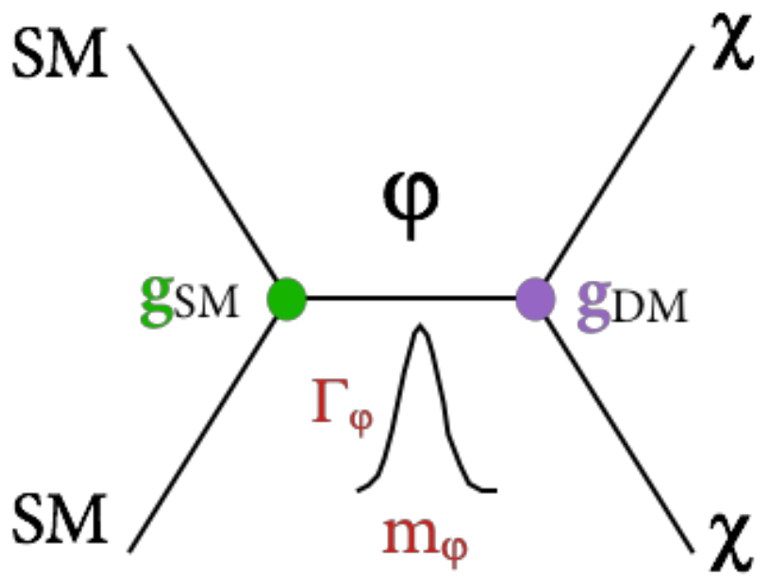




- Validation of the TF in the Validation Region (VR)
- Unblinding ! check whether an excess is observed (p-value)
- Interpretation in terms of limits on selected models.

Mediator simplified models

- ★ Reduce a complex model to a simple one with **DM + mediator**
- ★ **Few free parameters:** mφ, mχ, gSM, gDM, Γφ
- ★ Nature of mediator and DM can (also) be **systematically classified based on their spin and CP**



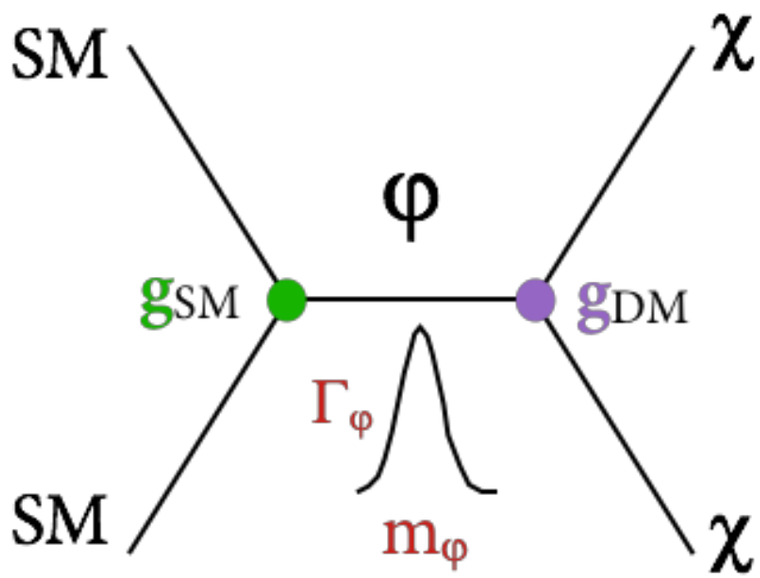
E_T^{miss} + X

- E_T^{miss} + jet
- E_T^{miss} + photon
- E_T^{miss} + Z/W
- E_T^{miss} + heavy quarks

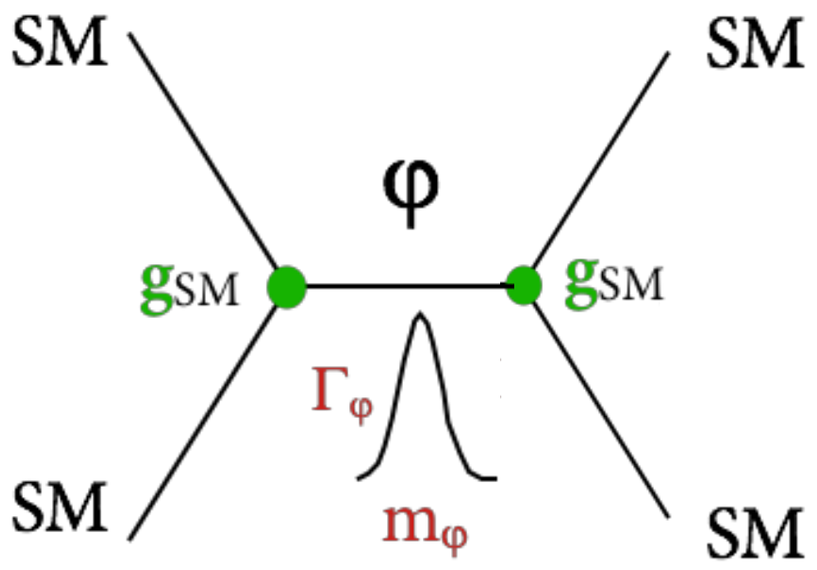
arXiv:1507.00966 (and ref. therein) + LPCC WG

Mediator simplified models

- ★ Reduce a complex model to a simple one with **DM + mediator**
- ★ **Few free parameters:** mφ, mχ, gSM, gDM, Γφ
- ★ Nature of mediator and DM can (also) be **systematically classified based on their spin and CP**
- ★ **Very rich phenomenology**



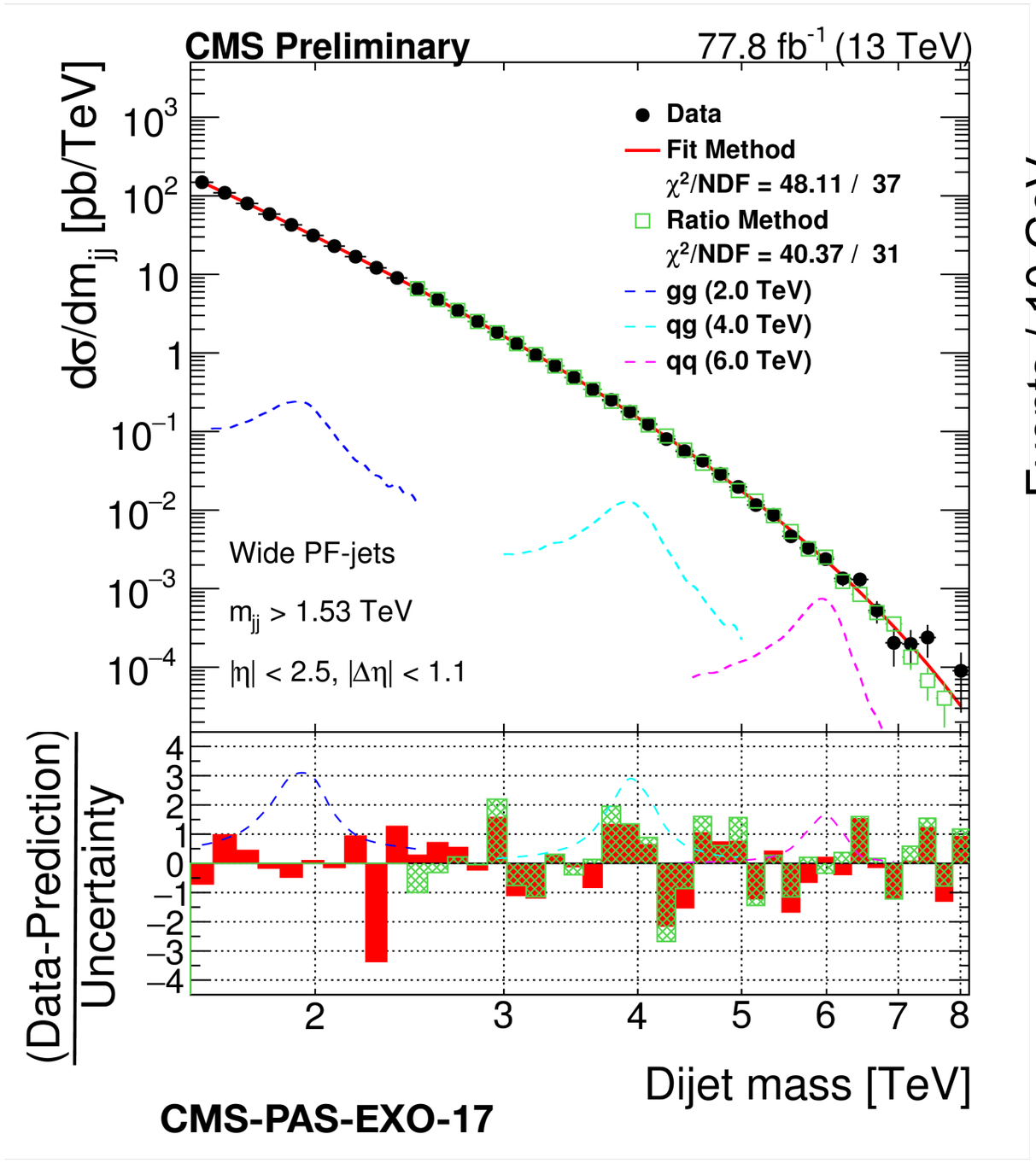
E_T^{miss} + X

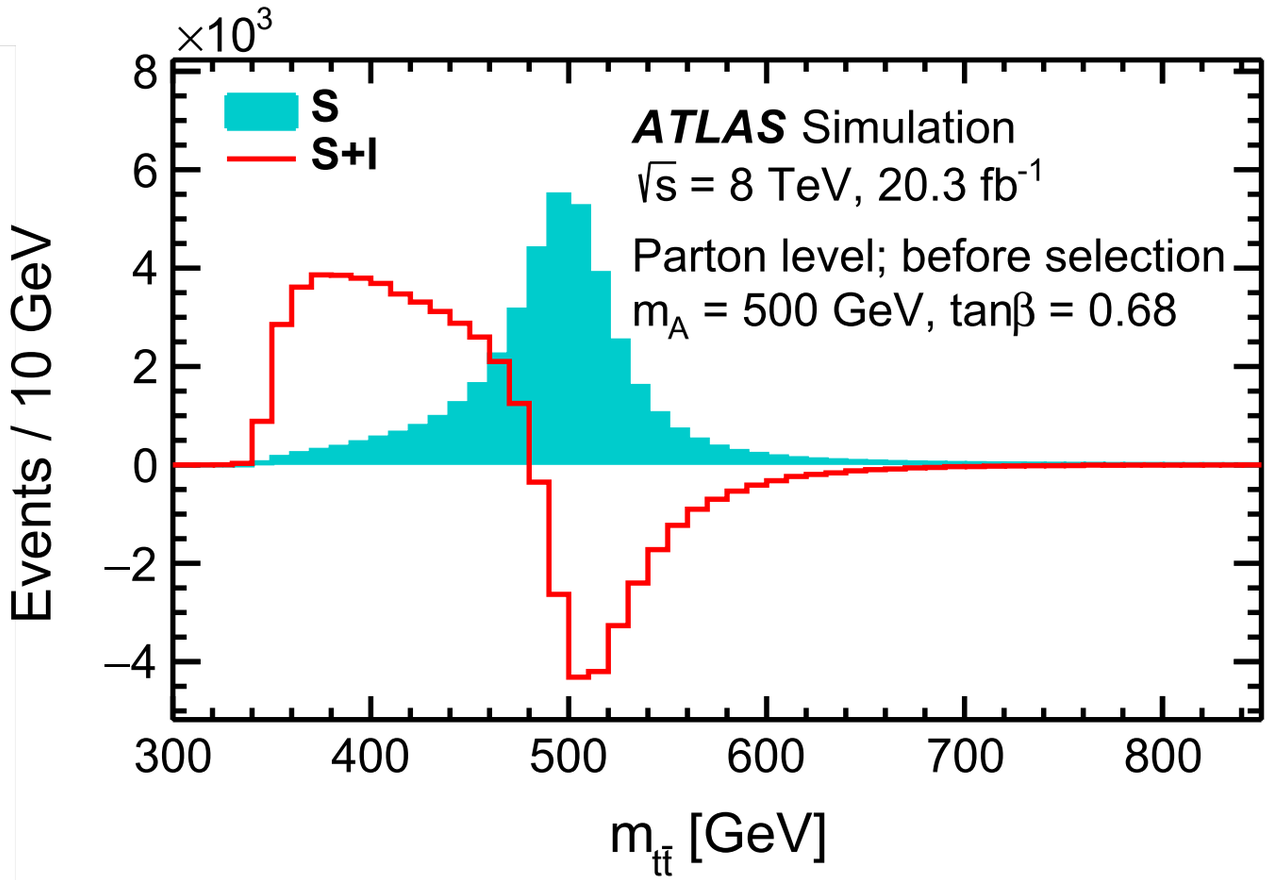


Resonance

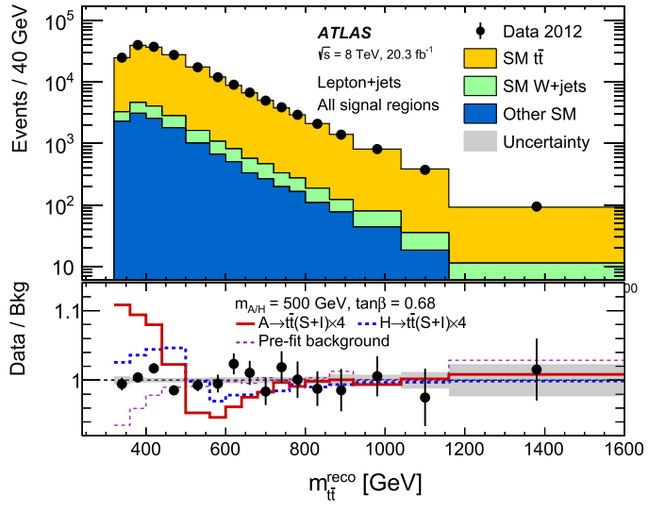
- jet-jet
- bjet-bjet
- lep-lep
- top-top

Resonances experimental approach



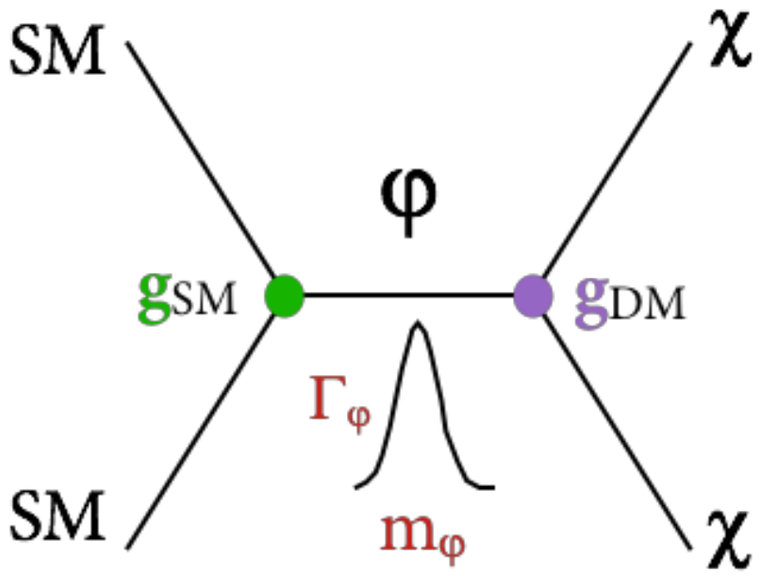


arXiv:1707.06025

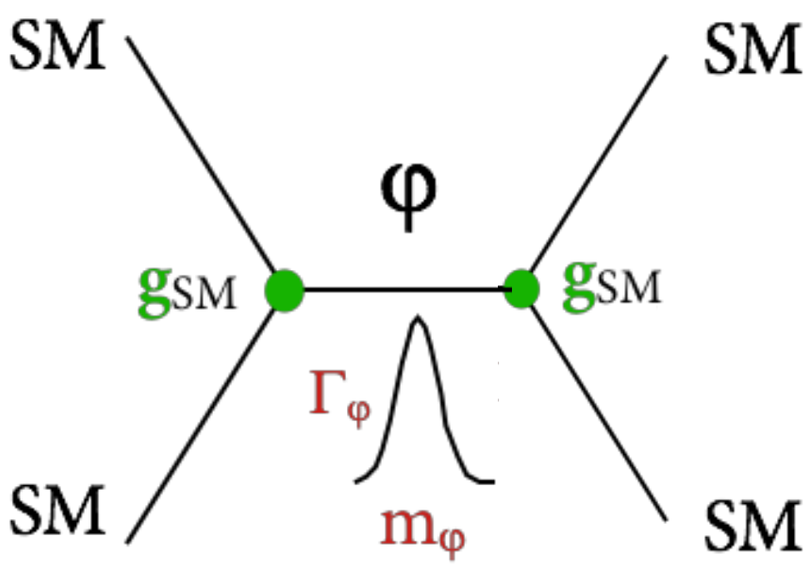


Mediator simplified models

E_T^{miss} + X



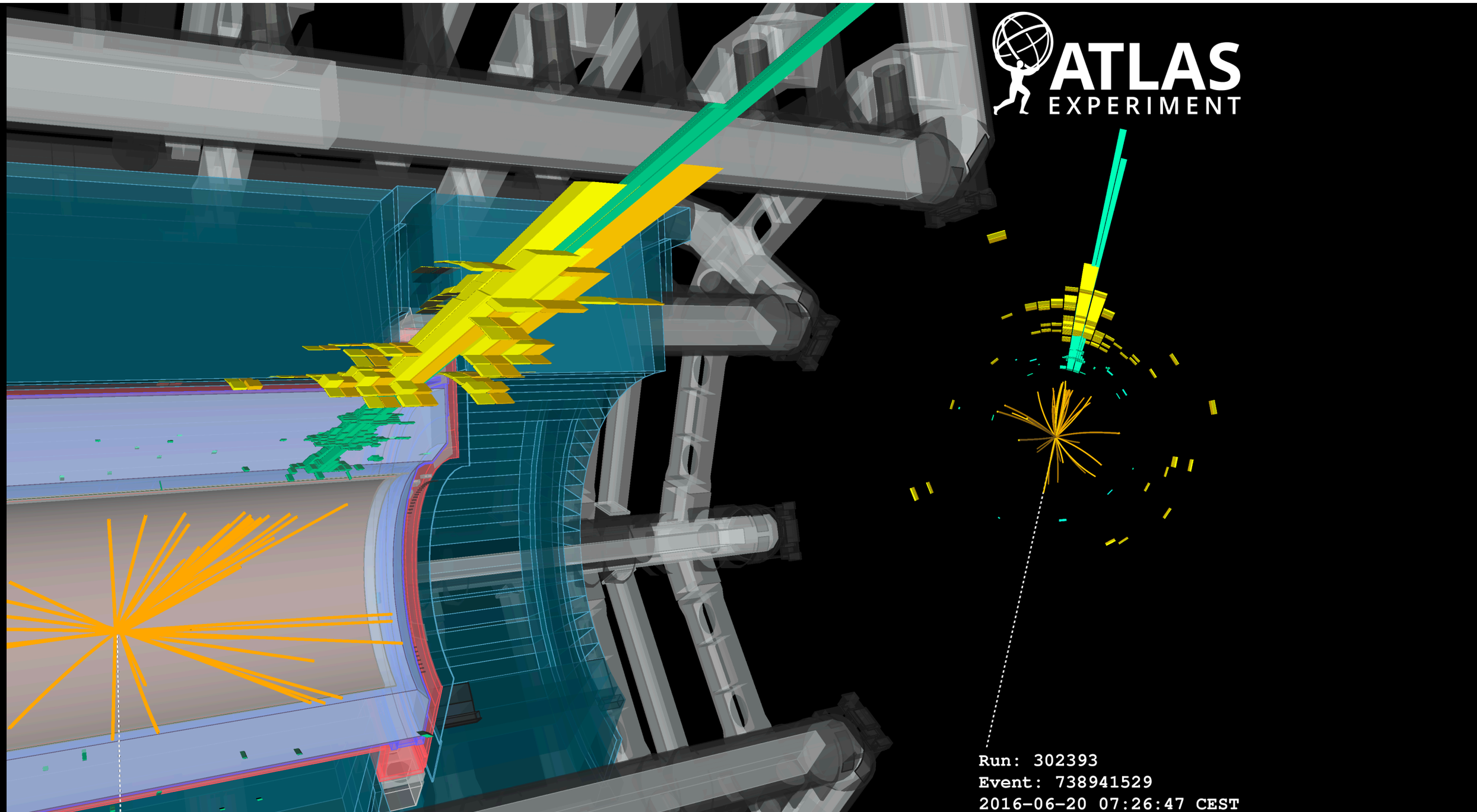
Resonance



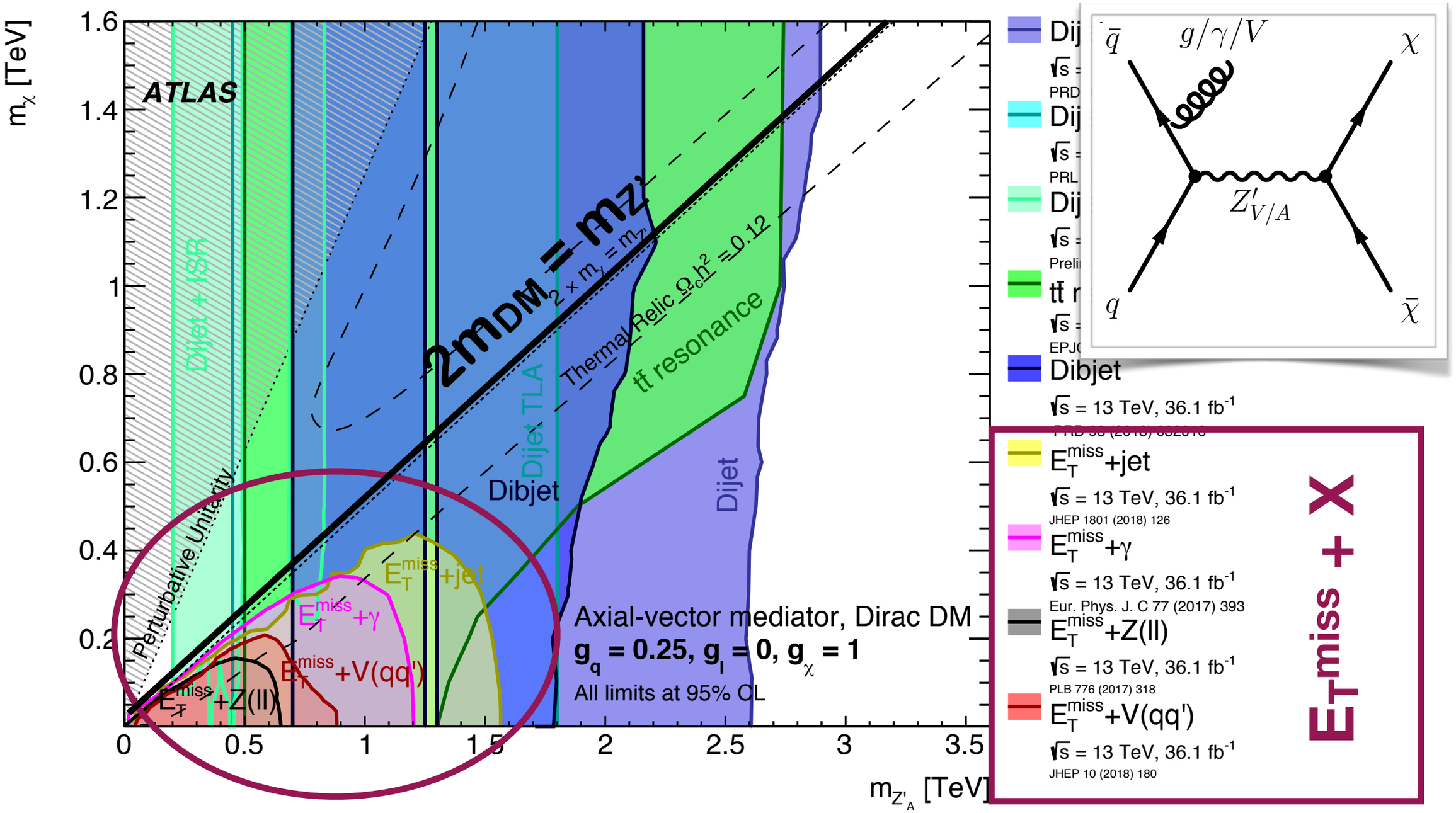
		Spin 1	Spin 0
Short description	Acronym	Symbol	J^P
Vector/axial-vector mediator	V/AV	$Z'_{\mathrm{V}}/Z'_{\mathrm{A}}$	$1^{\mp}$
Vector baryon-number-charged mediator	VBC	Z'_{B}	1^{-}
Vector flavour-changing mediator	VFC	Z'_{VFC}	1^{-}
Scalar/pseudo-scalar mediator	S/PS	ϕ/a	$0^{\pm}$
Scalar colour-charged mediator	$\mathrm{SCC}_{q/b/t}$	$\eta_{q/b/t}$	0^{+}

Table 1: arXiv:1903.01400

3. Results for simplified models



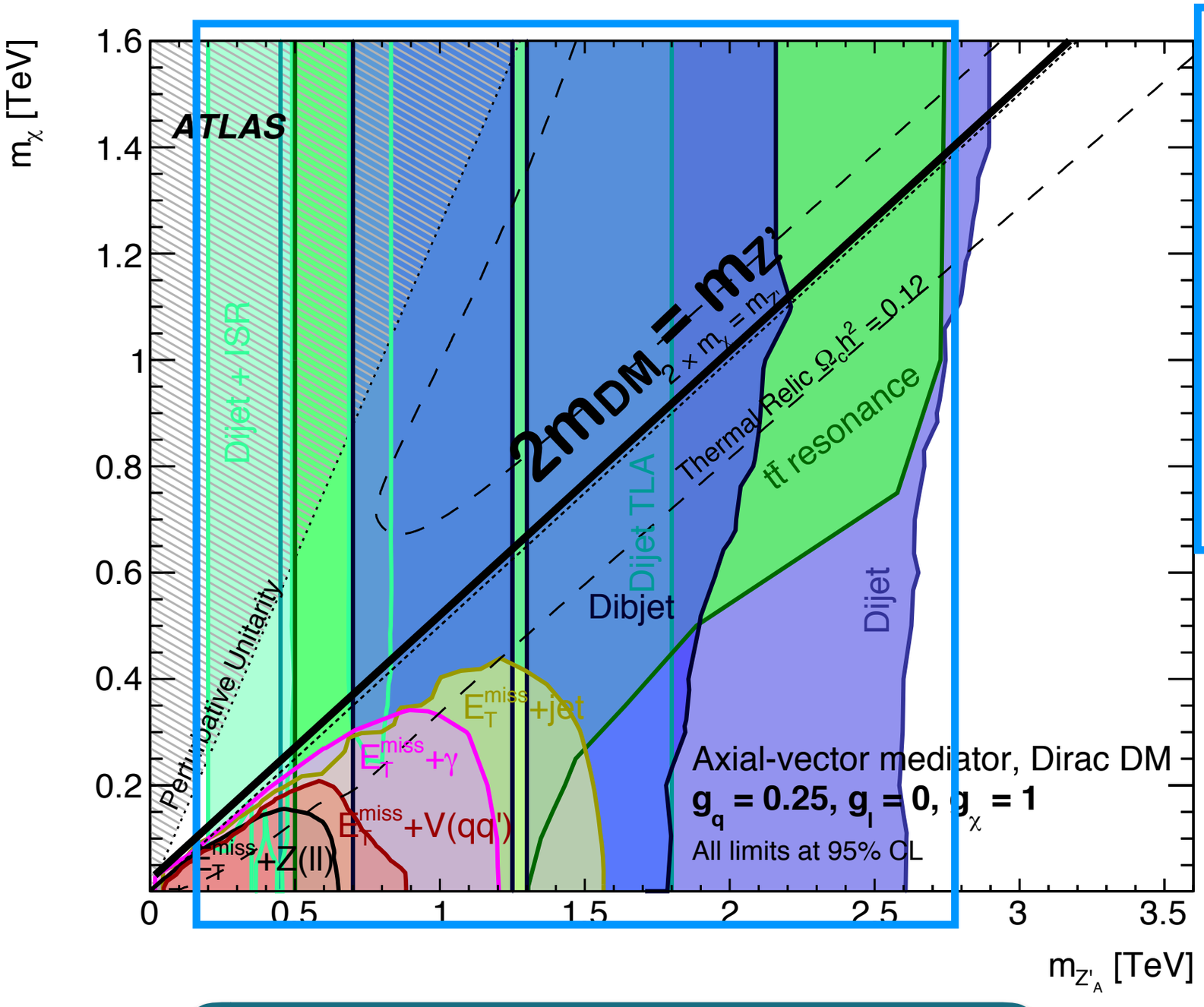
Spin-1 mediators

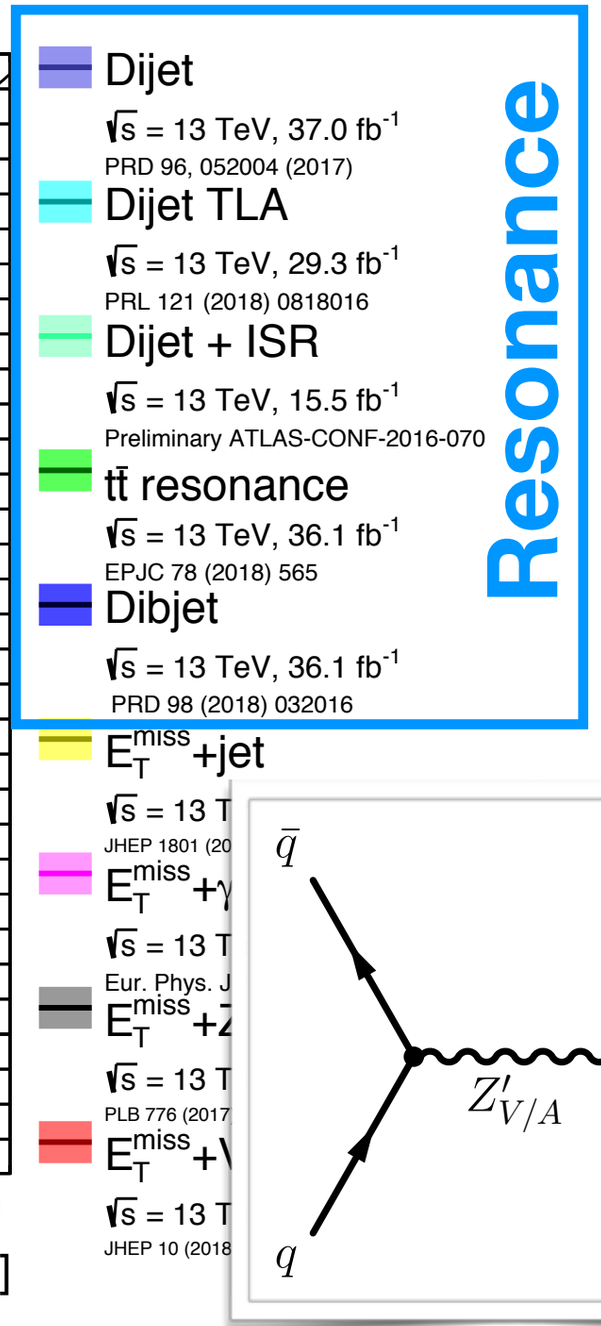


$$g_q = 0.25, g_{lep} = 0, g_{DM} = 1$$

Axial-vector mediator

Spin-1 mediators



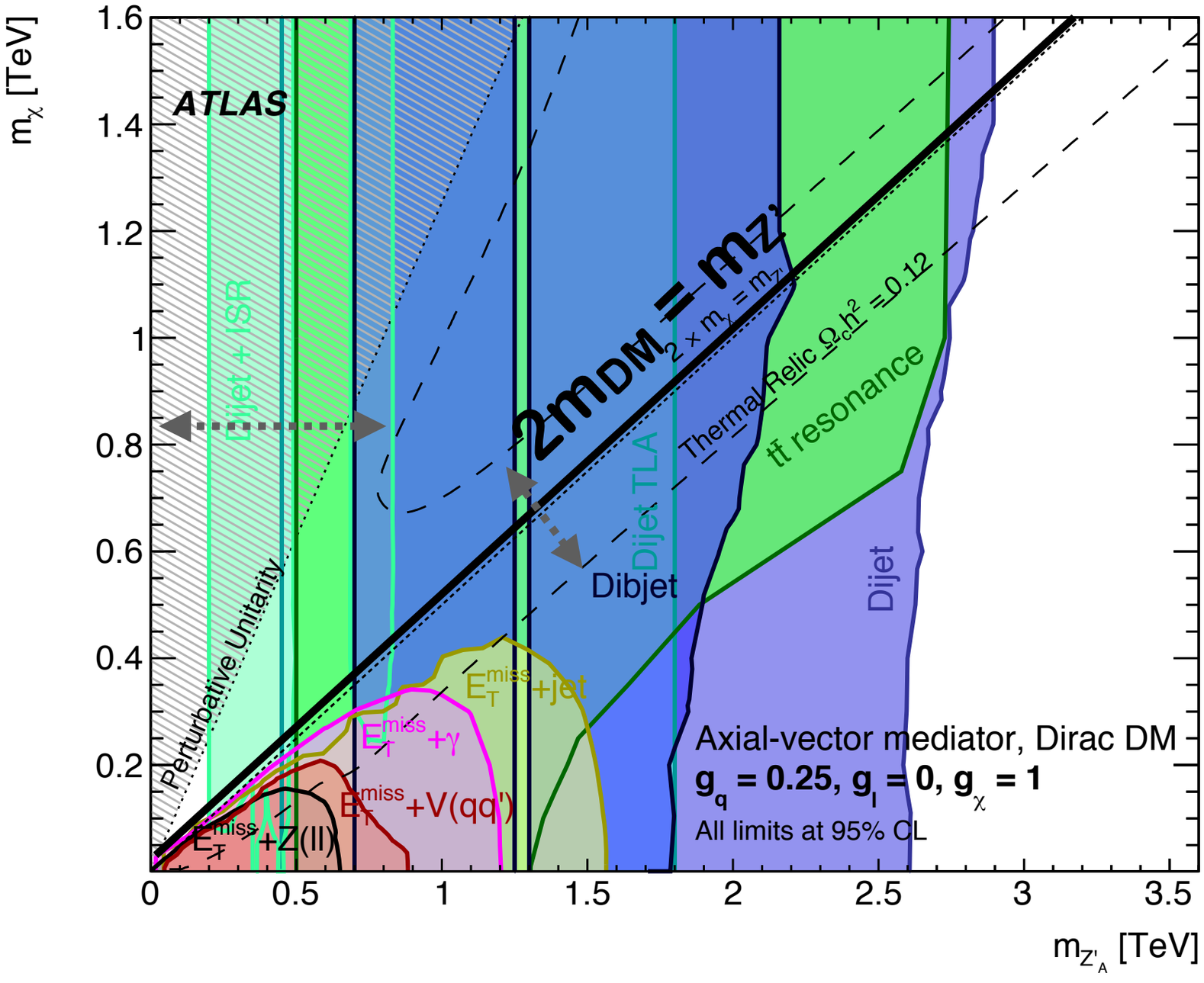


derived from gaussian model-independent limits

$$g_q = 0.25,\ g_{lep} = 0,\ g_{DM} = 1$$

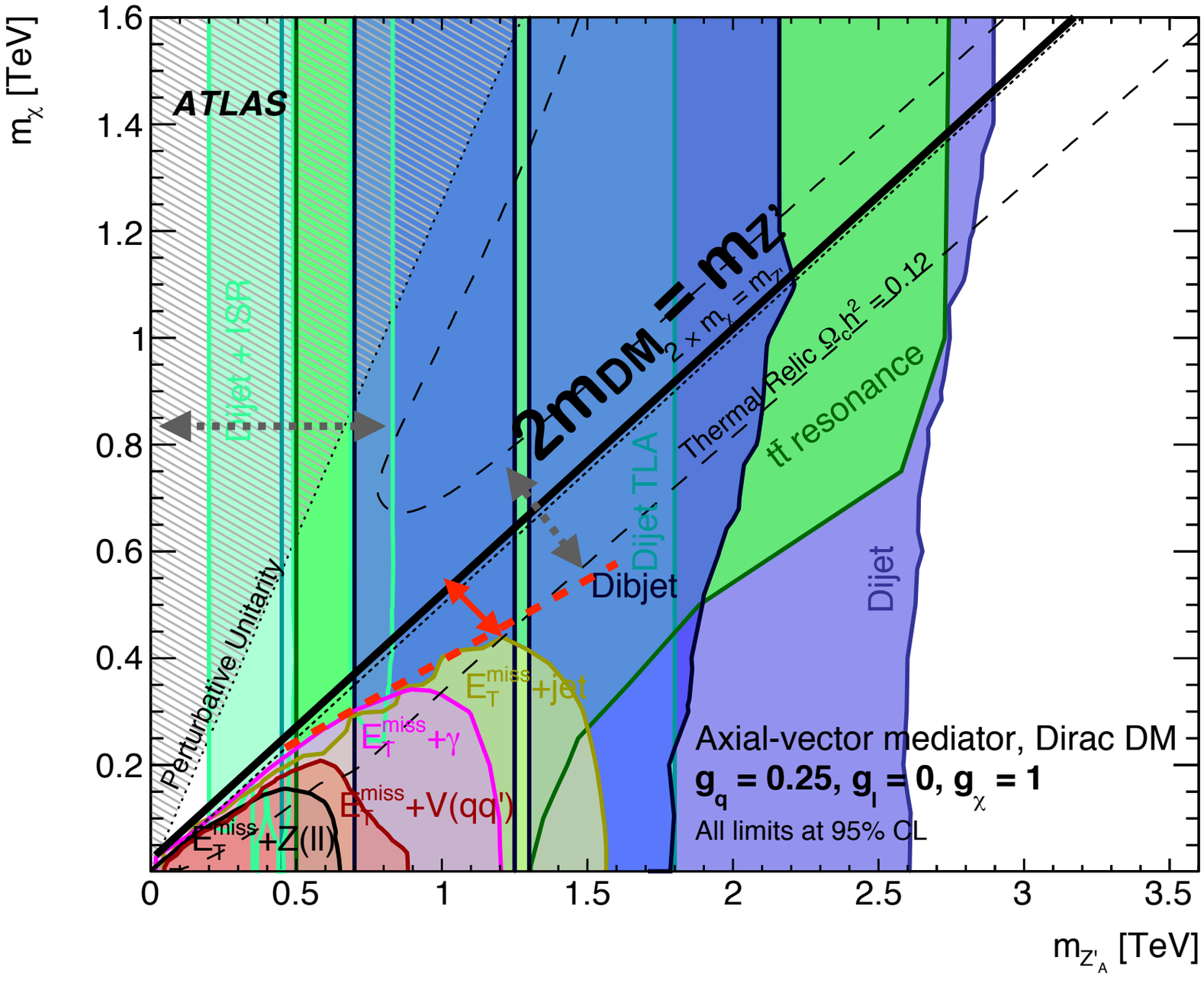
Axial-vector mediator

Spin-1: features explained



Model's predicted relic density depleted with respect to 0.12 thermal relic

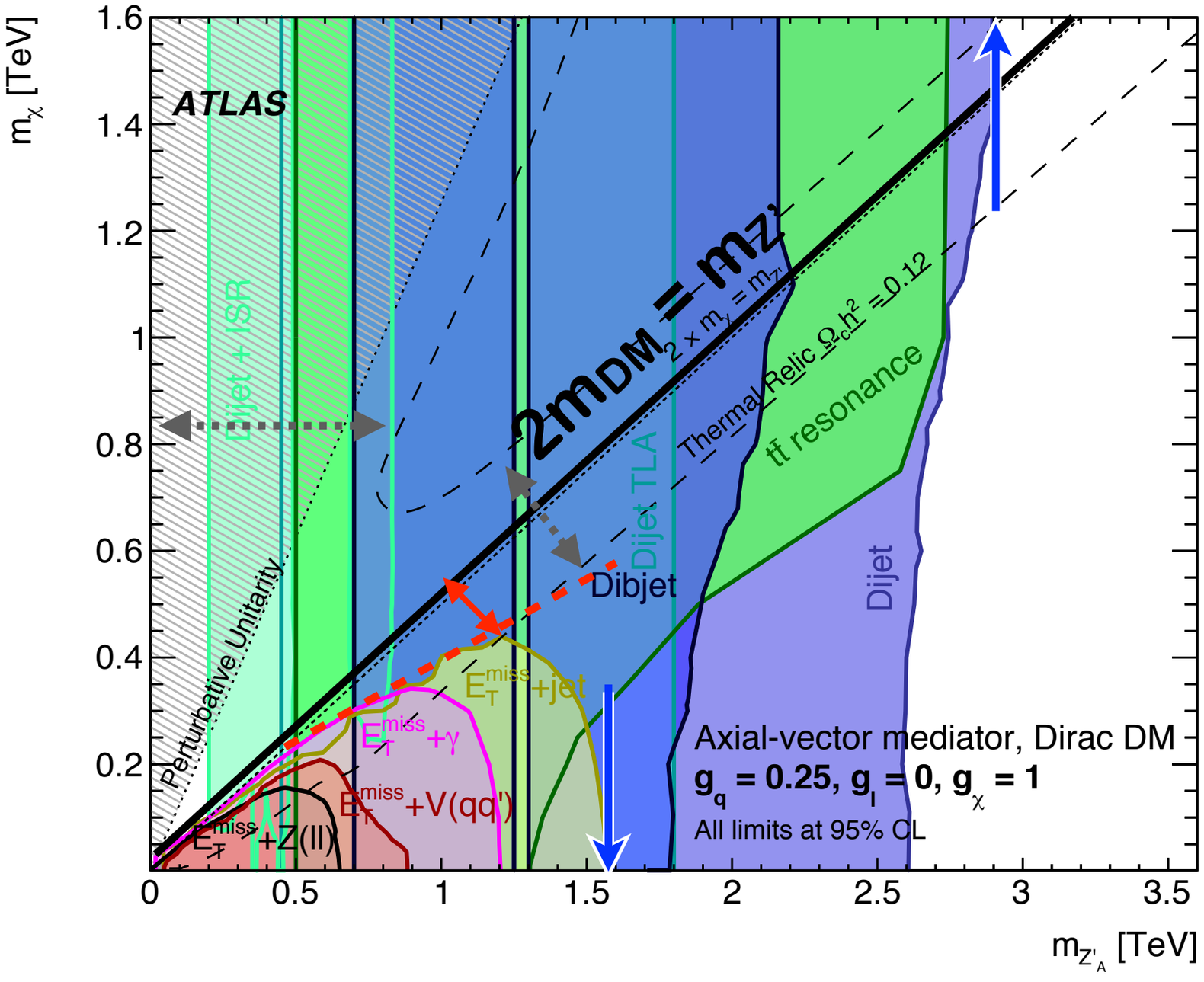
Spin-1: features explained



Loss of sensitivity due to mediator width effects

Model's predicted relic density depleted with respect to 0.12 thermal relic

Spin-1: features explained

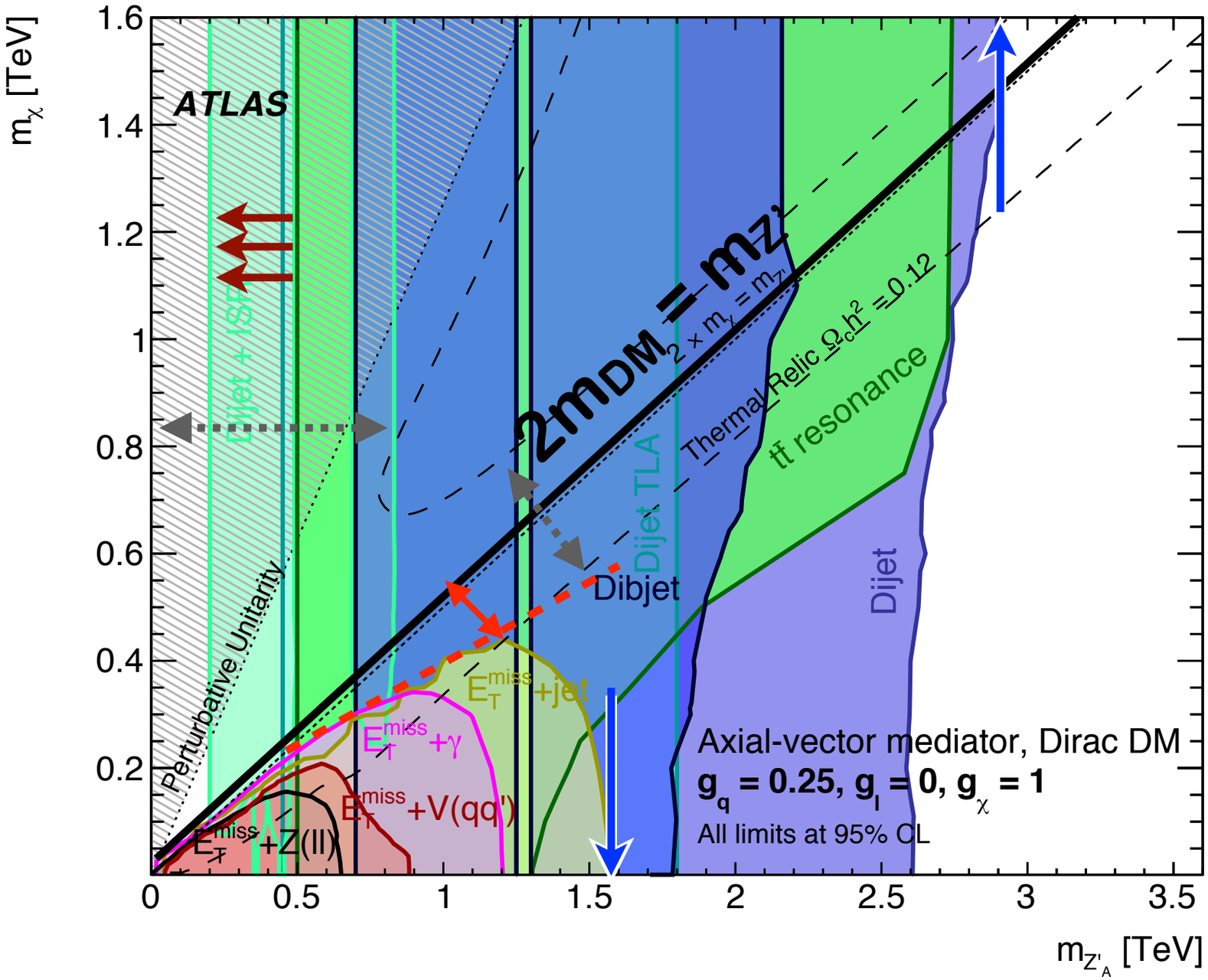


Loss of sensitivity due to mediator width effects

Highest mass reach, driven by E_T^{miss}/m_{jj} tails & statistics (jet+ E_T^{miss}/dijet)

Model's predicted relic density depleted with respect to 0.12 thermal relic

Spin-1: features explained



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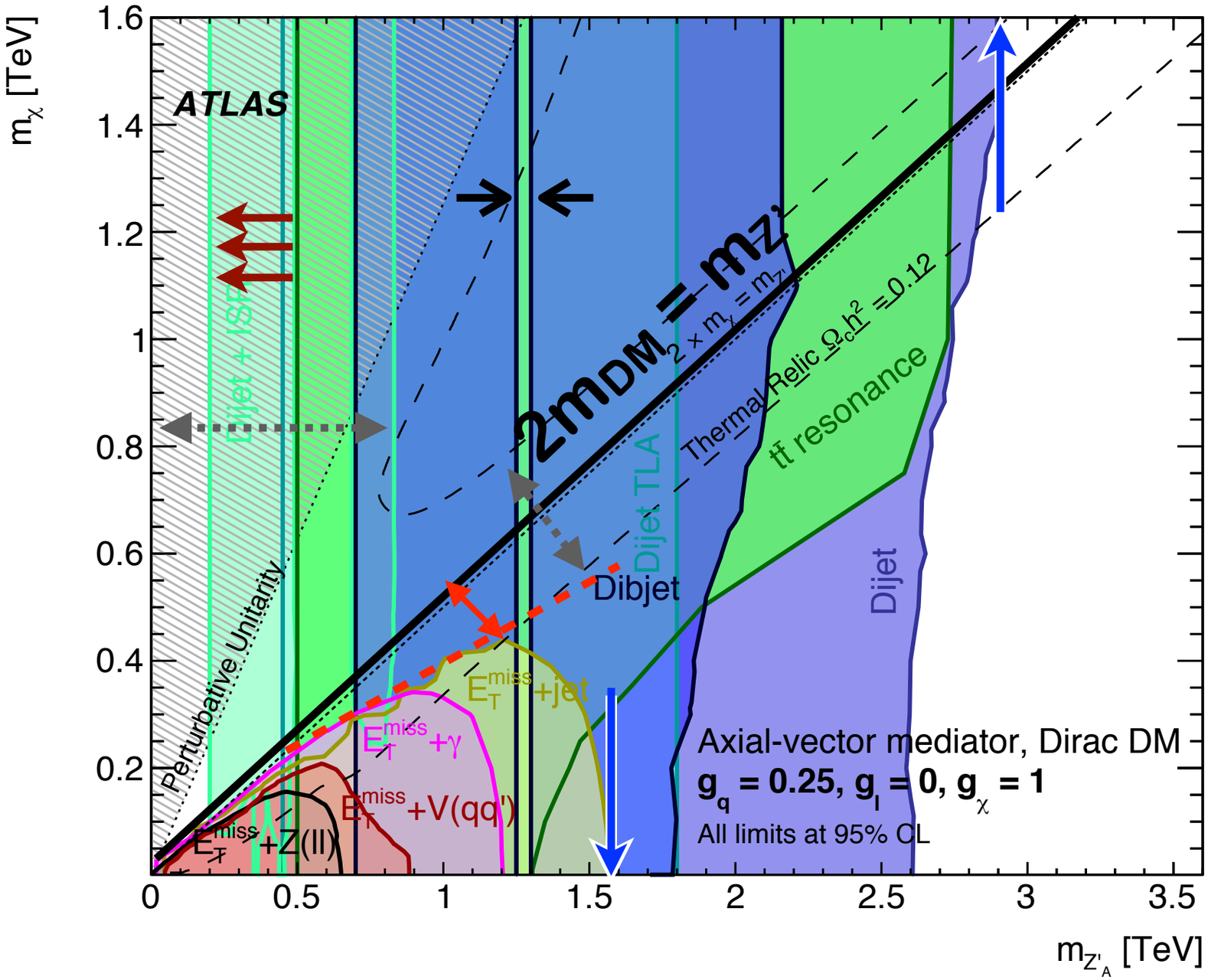
Highest mass reach, driven by E_T^{miss}/m_{jj} tails & statistics (jet+ E_T^{miss}/dijet)

Jet trigger thresholds limiting low-mass reach

Model's predicted relic density depleted with respect to 0.12 thermal relic

Spin-1: features explained



Loss of sensitivity due to mediator width effects

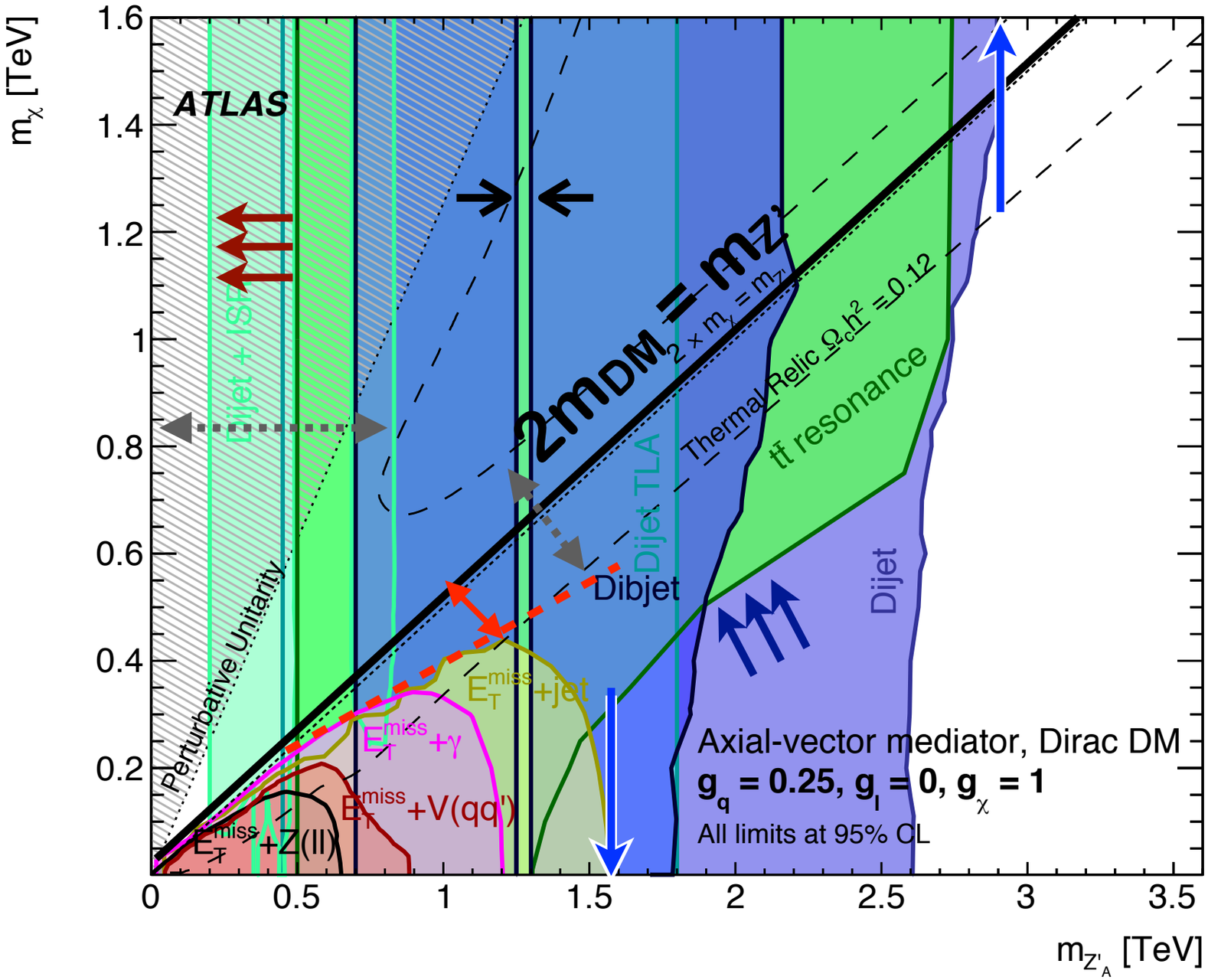
Highest mass reach, driven by E_T^{miss}/m_{jj} tails & statistics (jet+ E_T^{miss}/dijet)

Jet trigger thresholds limiting low-mass reach

Change of trigger strategy & analysis width sensitivity

Model's predicted relic density depleted with respect to 0.12 thermal relic

Spin-1: features explained



Loss of sensitivity due to mediator width effects

Highest mass reach, driven by E_T^{miss}/m_{jj} tails & statistics (jet+ E_T^{miss}/dijet)

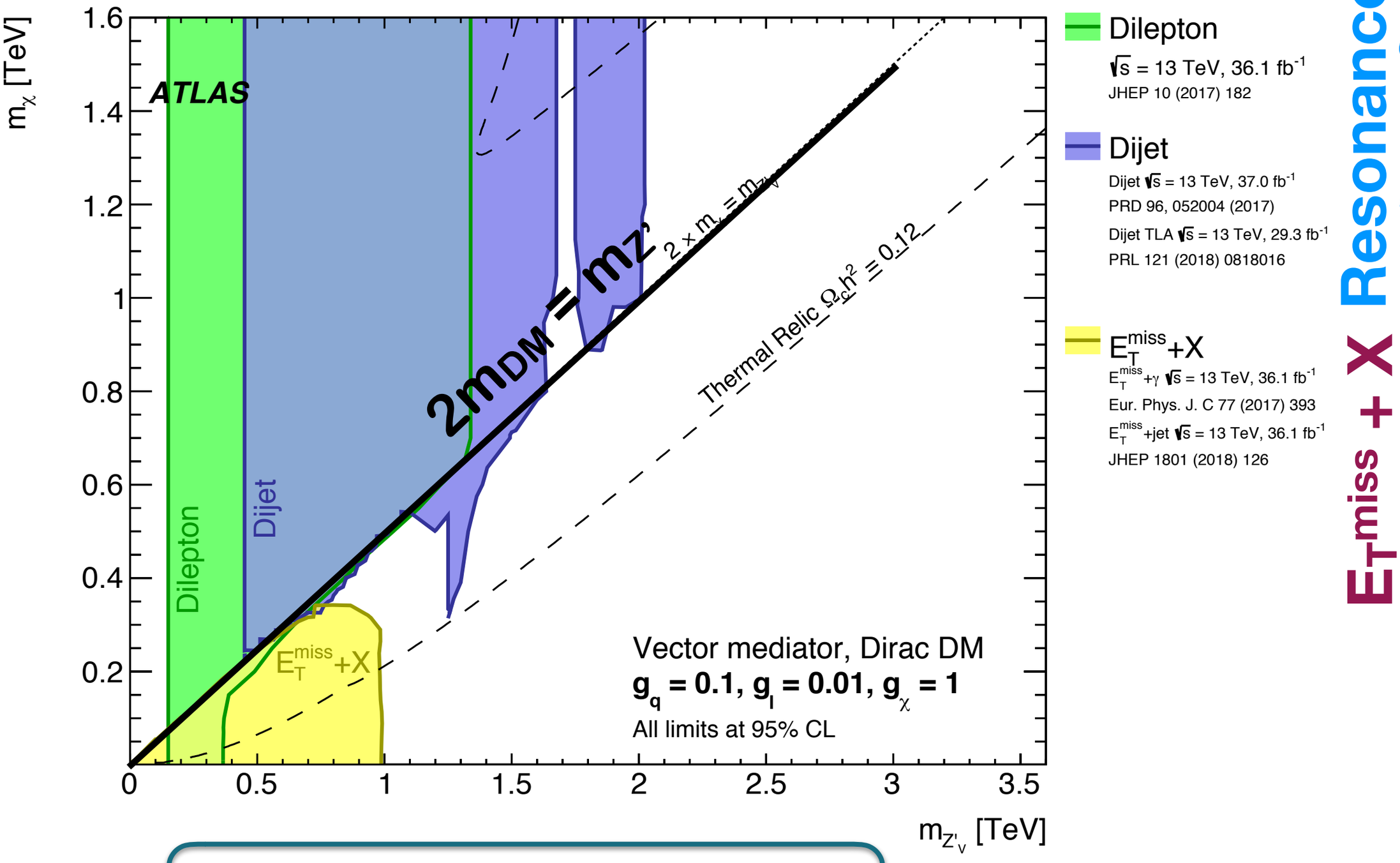
Jet trigger thresholds limiting low-mass reach

Change of trigger strategy & analysis width sensitivity

Increase of BR(Z'➡χχ) ⇒ loss of sensitivity for Z'➡tt

Model's predicted relic density depleted with respect to 0.12 thermal relic

Spin-1 leptophilic case



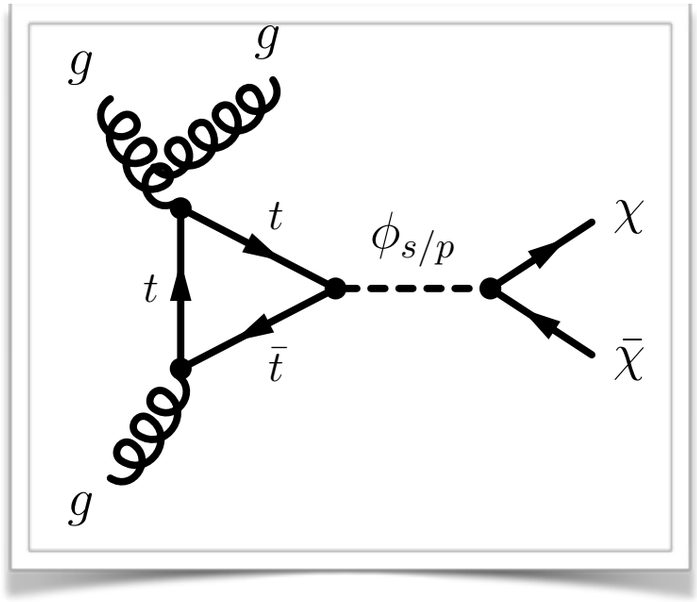
$$g_q = 0.1,\ g_{lep} = 0.01,\ g_{DM} = 1$$

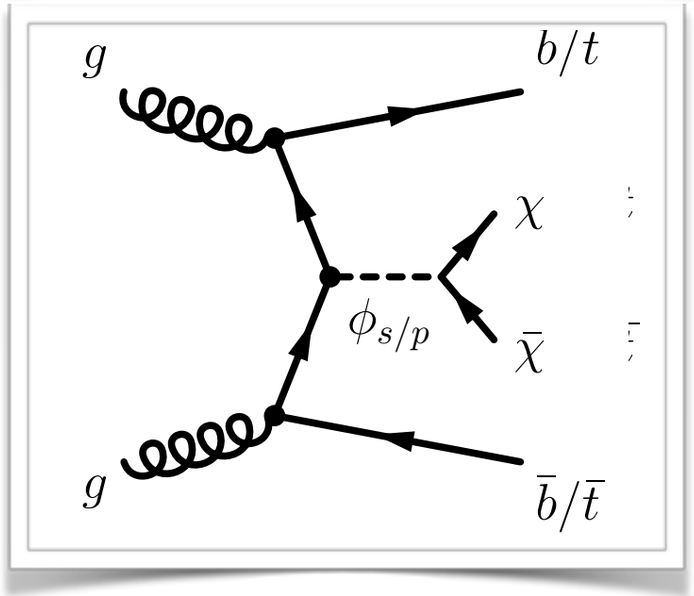
Vector mediator

Spin-0 mediators

$$\mathcal{L} \sim \sum_f i g_v \frac{y_f}{\sqrt{2}} A \bar{f} \gamma^5 f$$

Needed to easily fulfil Flavour Constraints (MFV)





Spin-0 mediators

$$\mathcal{L} \sim \sum_f i g_v \frac{y_f}{\sqrt{2}} A \bar{f} \gamma^5 f$$

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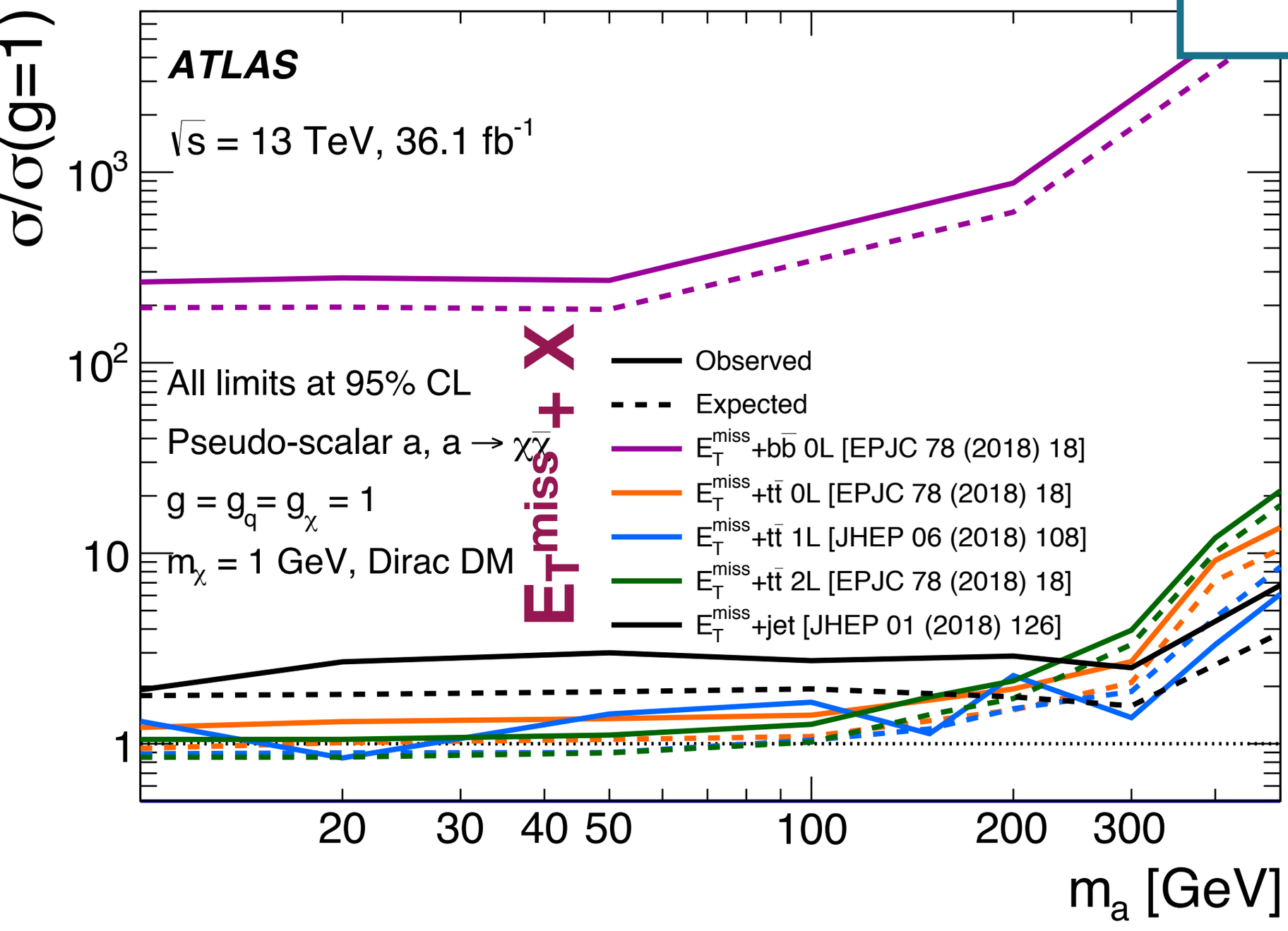
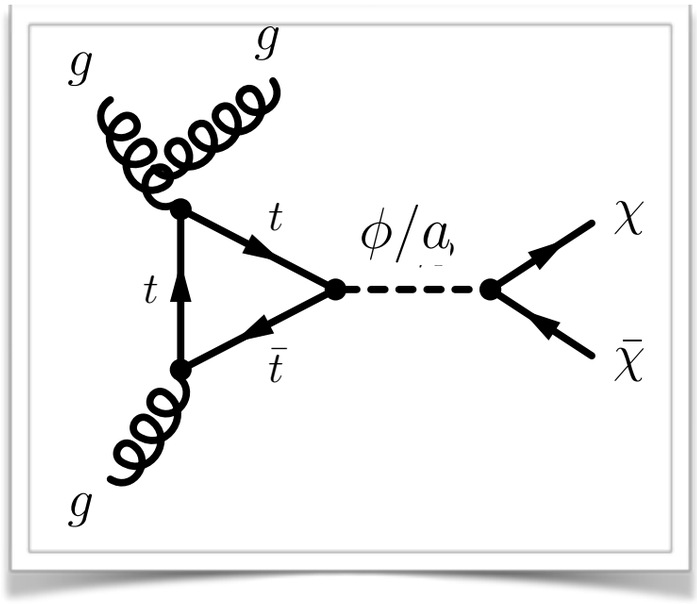
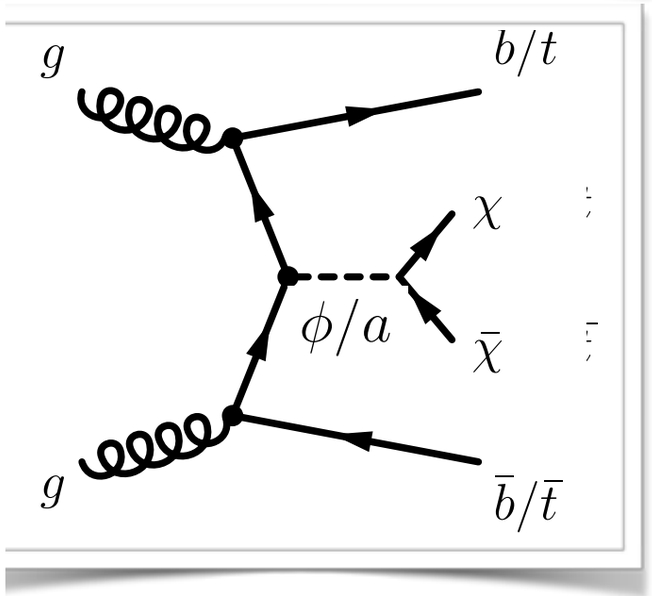
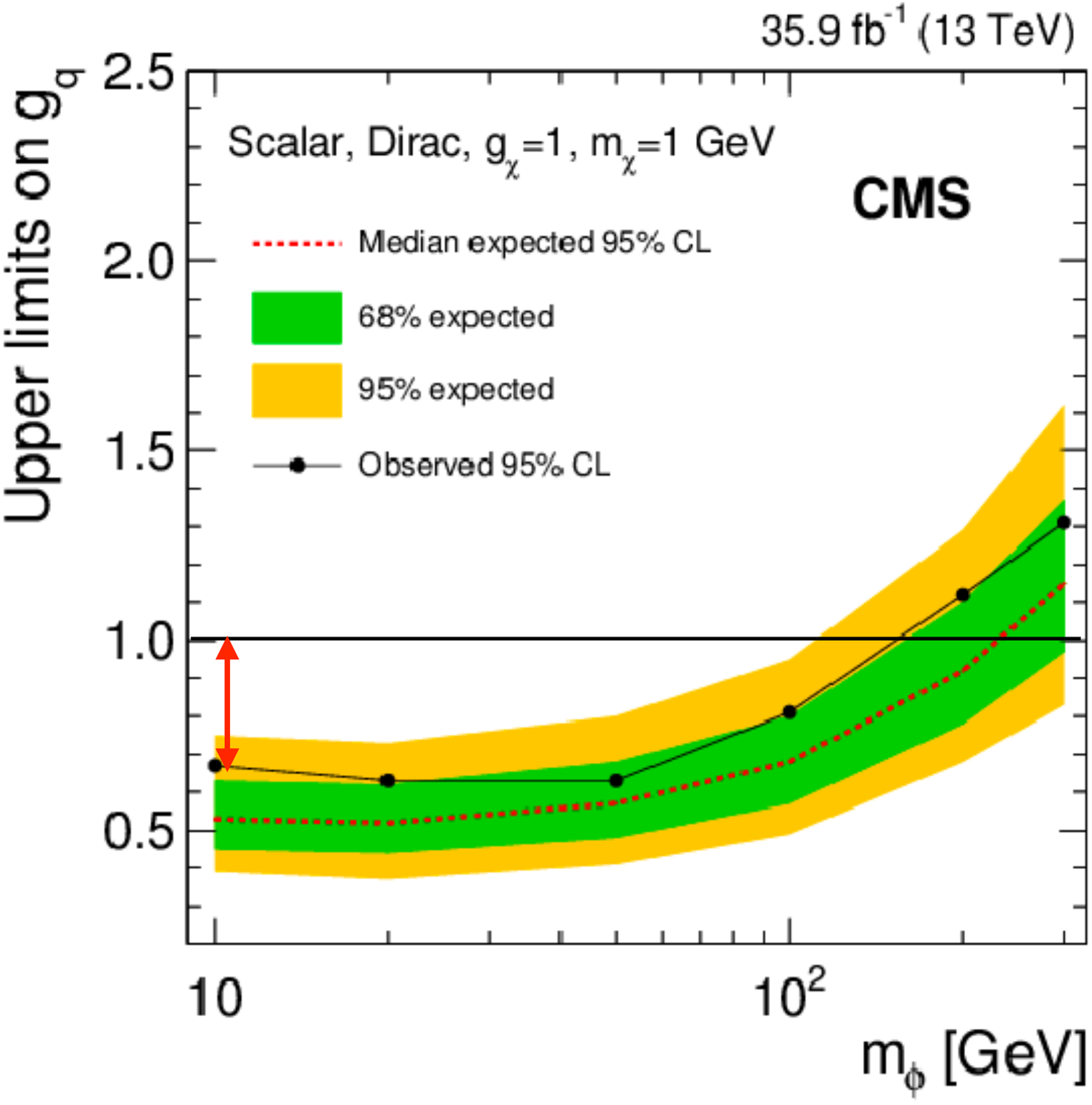


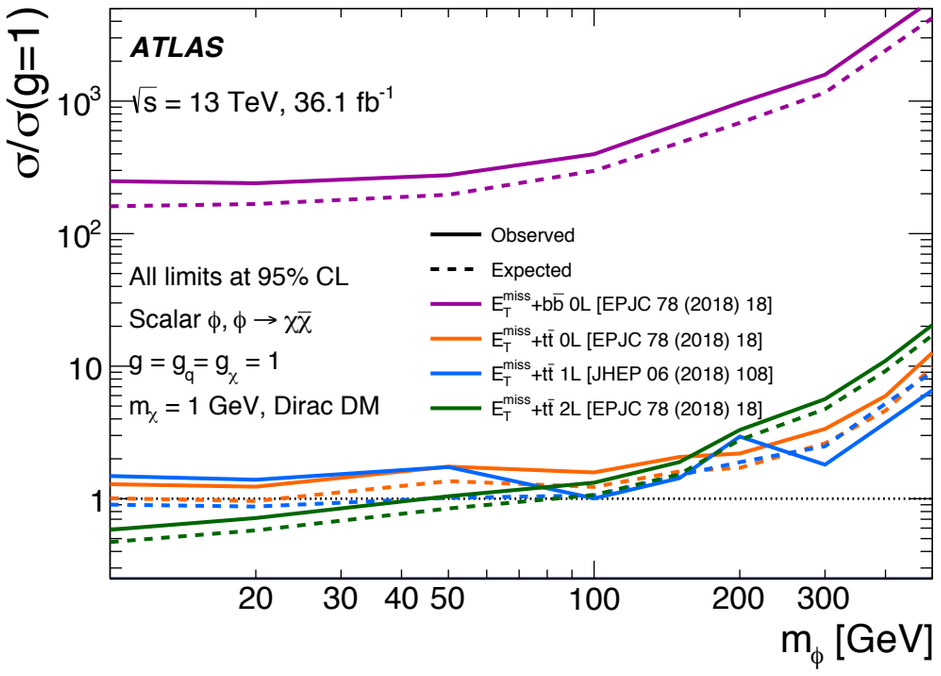




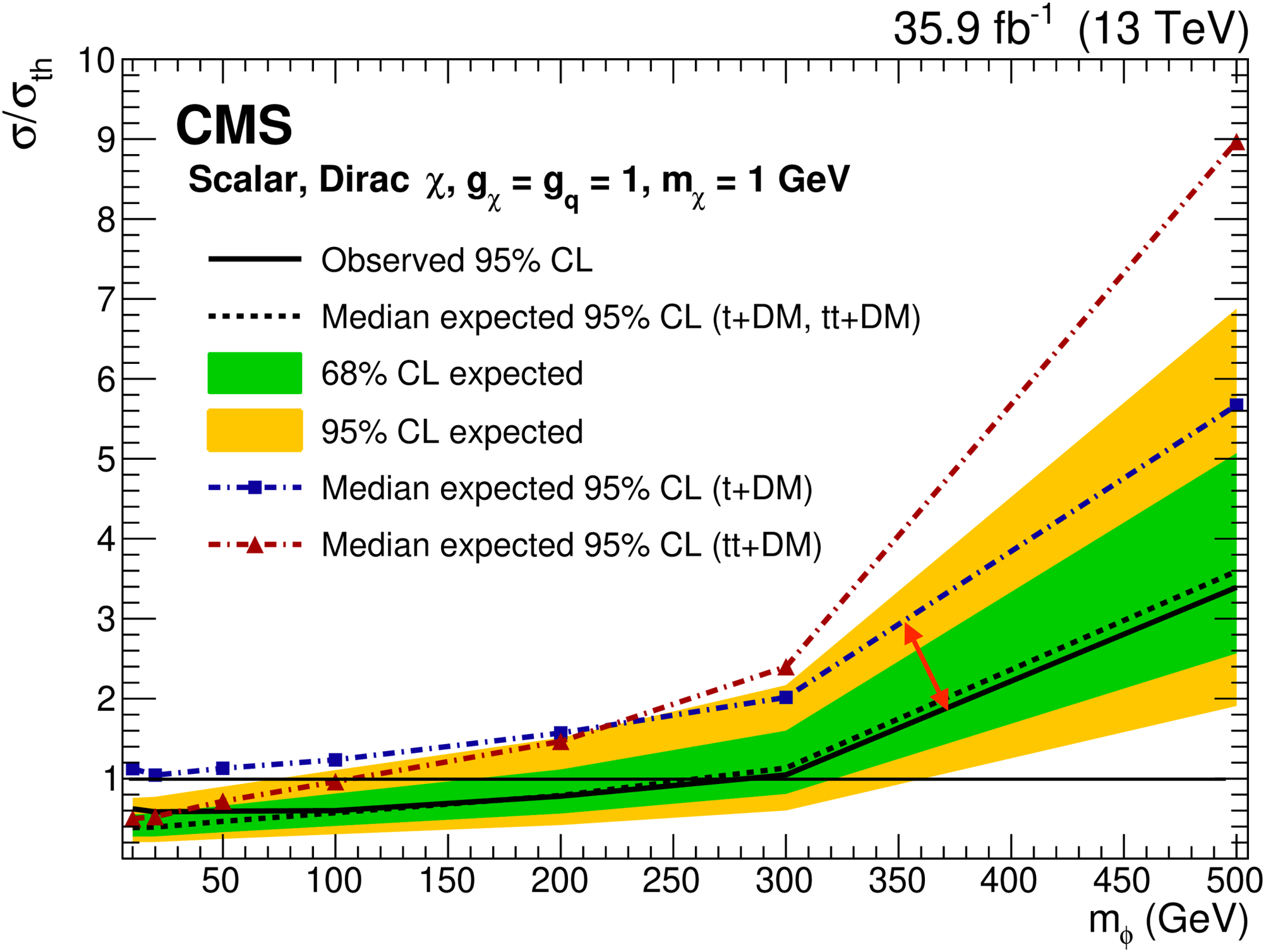
CMS grand combination

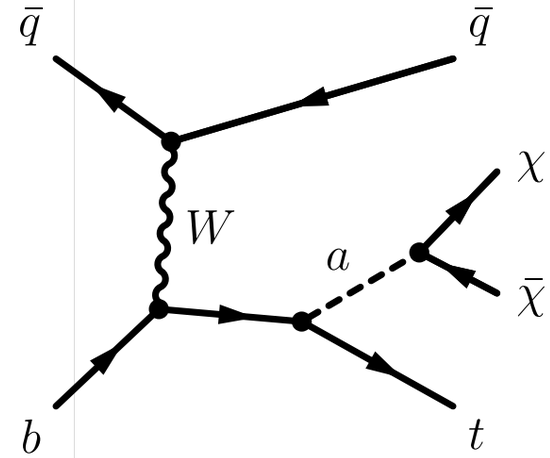
arXiv:1807.06522

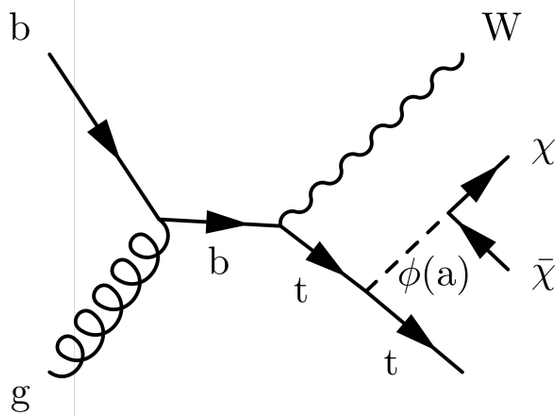




Spin-0 with single top







Considerations on the results

- ★ Simplified models are **good phenomenology proxies.**
- ★ Simplified models are simplified models.
- ★ Simplified models are not full and complete theories, which might have **more complex topologies.**
- ★ **All exclusions need to be taken with a grain of salt.**

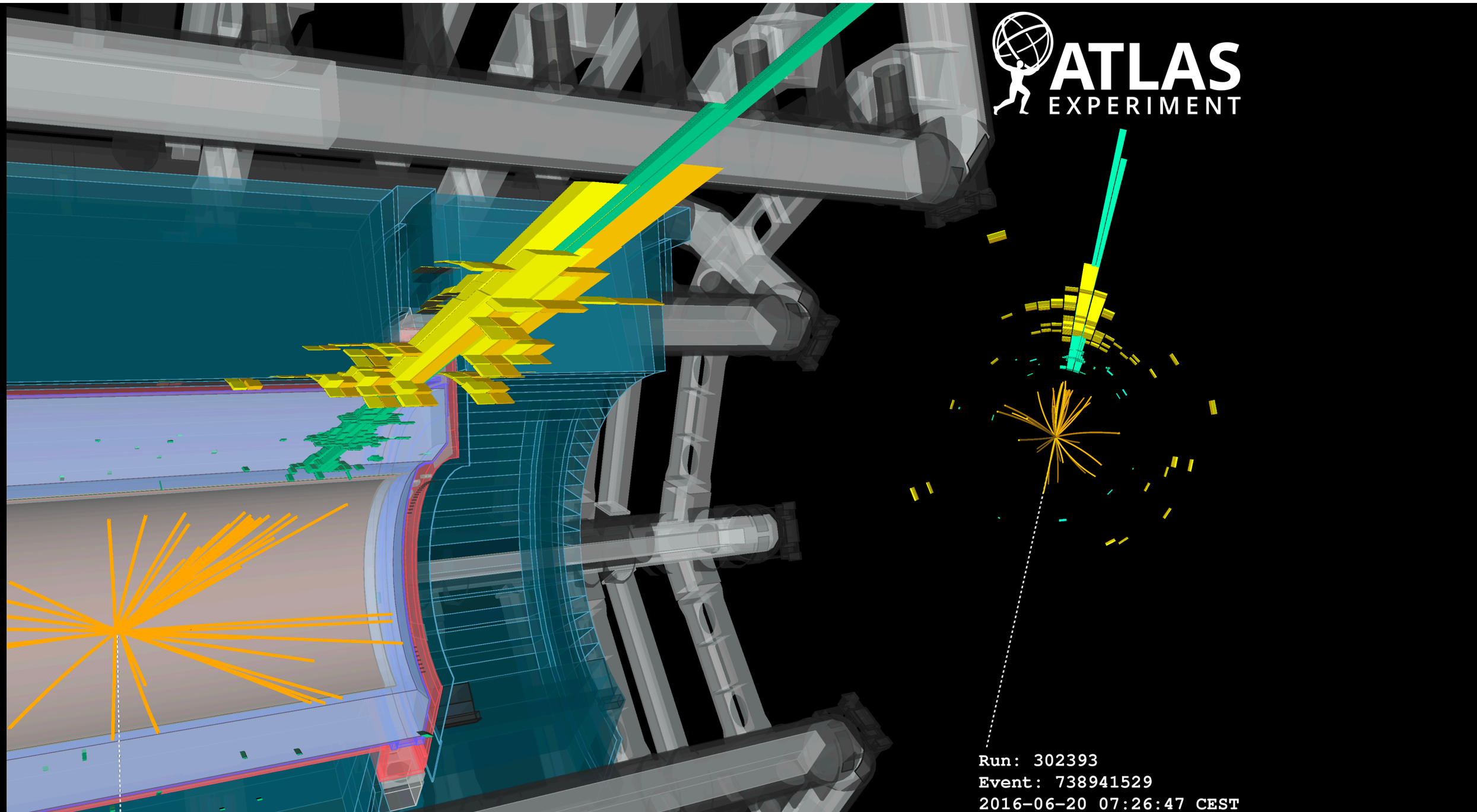
Towards the next level

new ideas

more realistic topologies

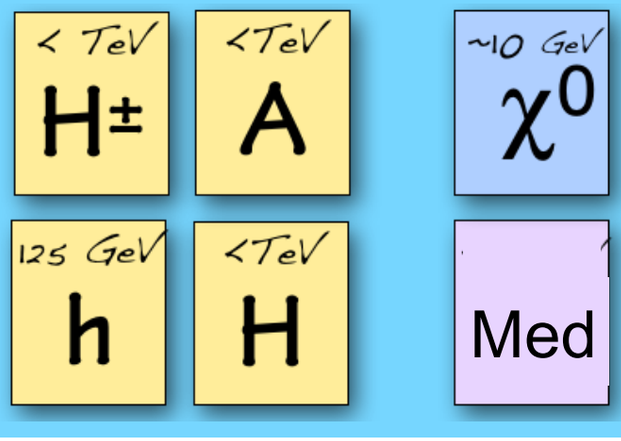
new signatures

4. less simplified models: 2HDMs



2HDM-based models

2HDM DM models



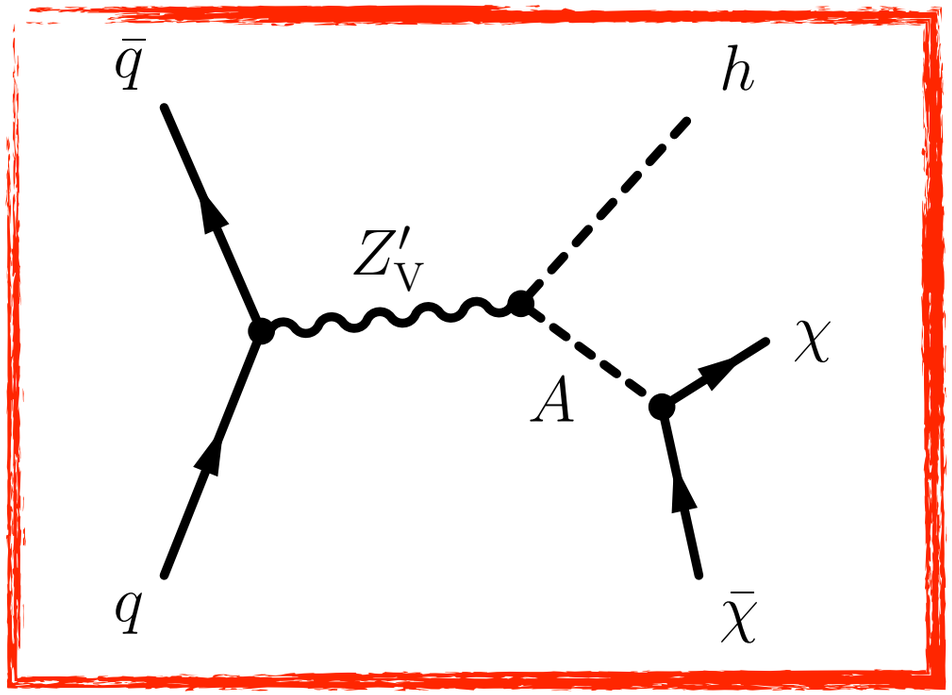
- jet-jet
- bjet-bjet
- top-top
- 4 tops

- E_T^{miss} + jet
- E_T^{miss} + photon
- E_T^{miss} + Z/W
- E_T^{miss} + higgs
- E_T^{miss} + heavy quarks

★ **Richer phenomenology:**
Higgs bosons productions and decays, mixing, many final states.

arxiv:1810.09420 (and ref. therein) + LPCC WG

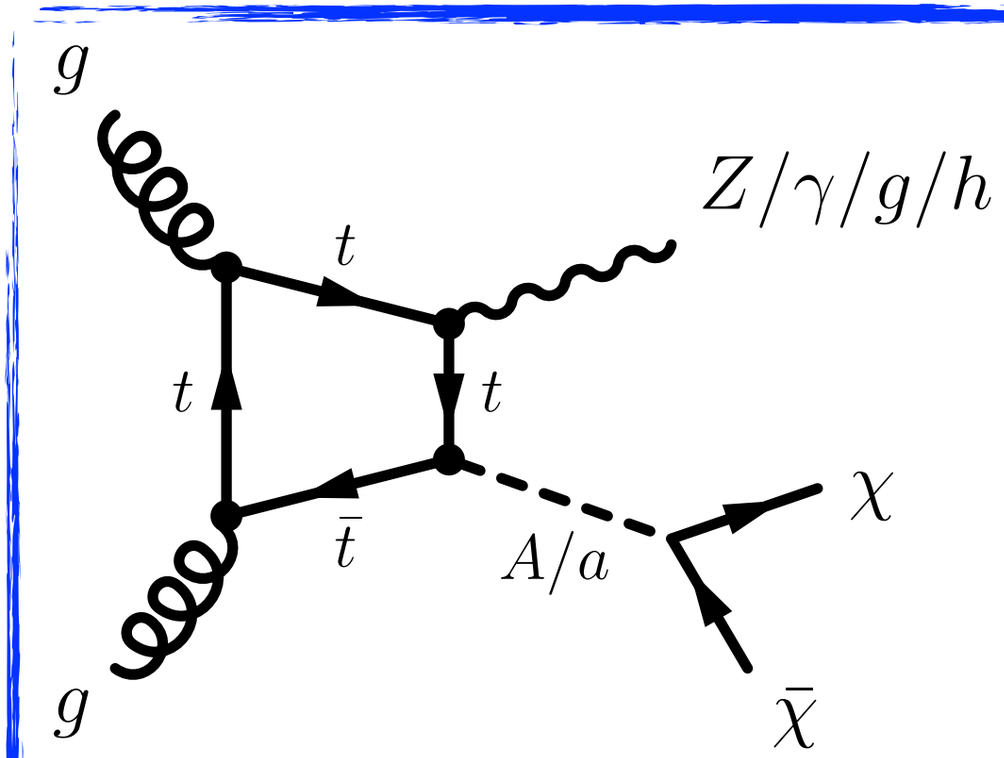
2HDM-based models

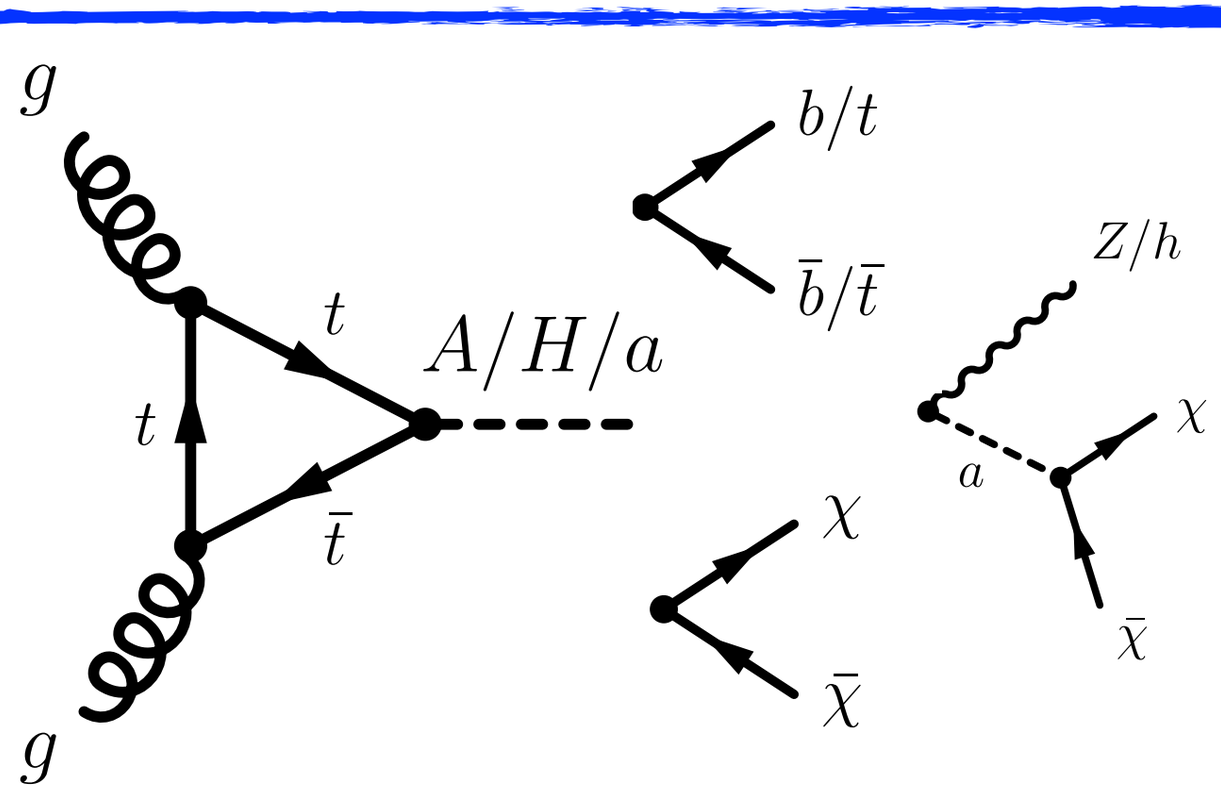


Spin 1

Spin 0

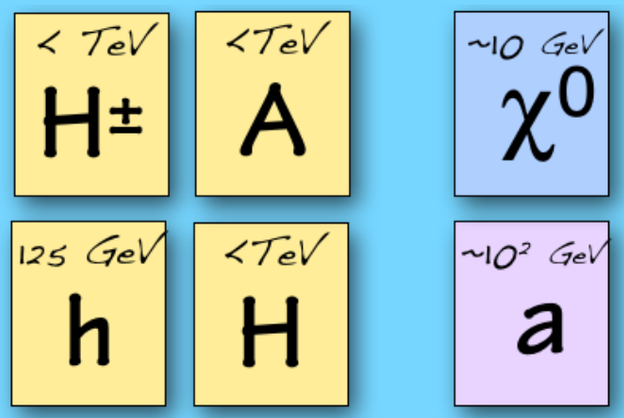
Short description	Acronym	Symbol	J^P
Two-Higgs-doublet plus vector mediator	2HDM+Z'_{V}	Z'_{V}	1^-
Two-Higgs-doublet plus pseudo-scalar mediator	2HDM+a	a	0^-





2HDM+a

2HDM+a models



h - SM higgs

A, a - CP-odd heavy scalars

H - CP-even heavy higgs

H± - charged Higgs

χ - DM candidate

7 parameters fixed by symmetry and EWK/Higgs measurements.

7 left free:

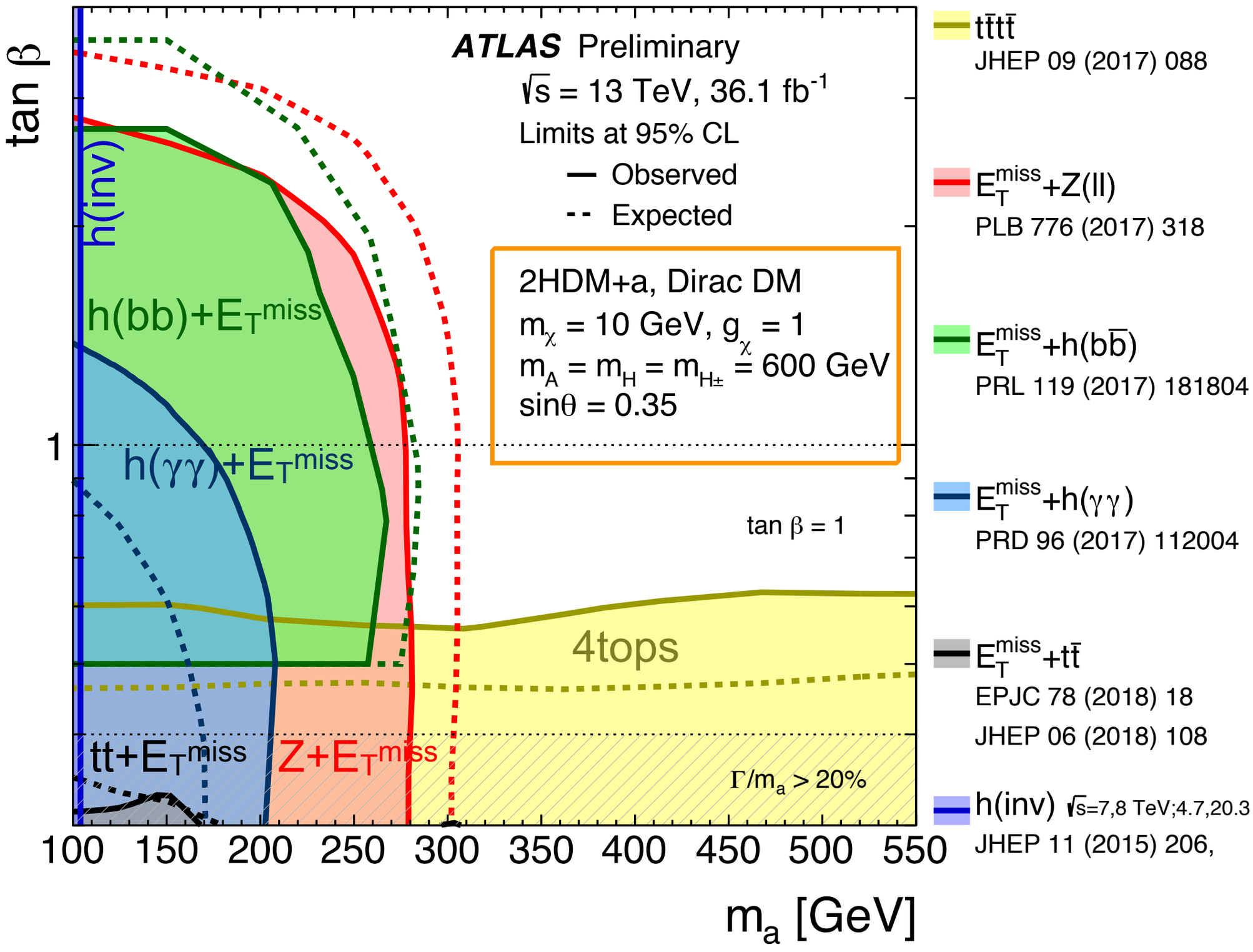
- **masses**
- A/a mixing angle **sinθ**
- Higgses VEV ratio **tanβ**

(DM coupling set to 1)

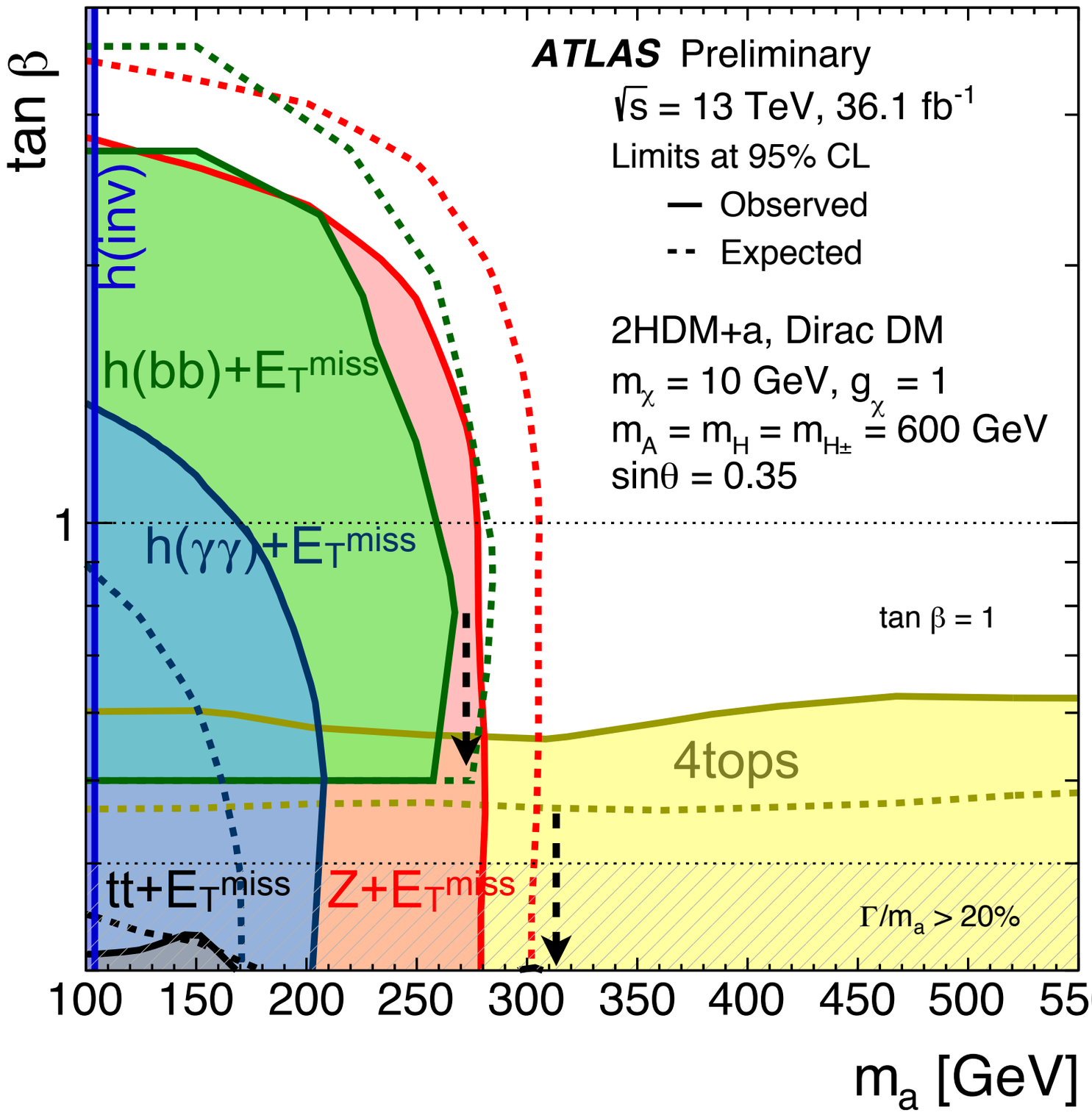
★ **Richer phenomenology:** Higgs bosons productions and decays, mixing, many final states.

arxiv:1810.09420 (and ref. therein) + LPCC WG

Results (I)

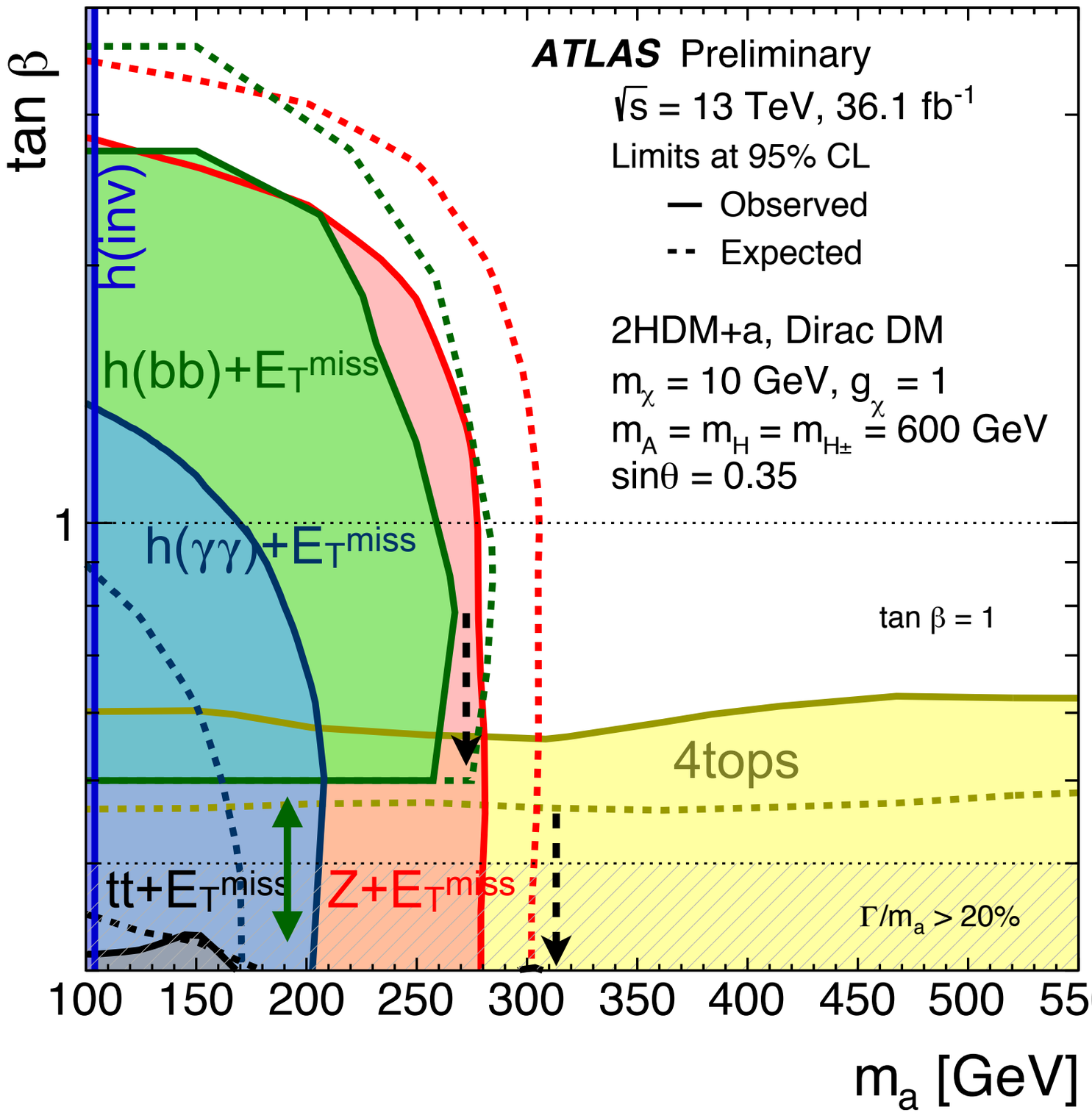

ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
Limits at 95% CL
Observed
Expected
2HDM+a, Dirac DM
mχ = 10 GeV, gχ = 1
mA = mH = mH± = 600 GeV
sinθ = 0.35
tan β = 1
tan β
h(inv)
h(bb)+ETmiss
h(γγ)+ETmiss
4tops
tt+ETmiss
Z+ETmiss
Γ/ma > 20%
1
100 150 200 250 300 350 400 450 500 550
ma [GeV]
tttt̄
JHEP 09 (2017) 088
ETmiss+Z(ll)
PLB 776 (2017) 318
ETmiss+h(bb̄)
PRL 119 (2017) 181804
ETmiss+h(γγ)
PRD 96 (2017) 112004
ETmiss+tt̄
EPJC 78 (2018) 18
JHEP 06 (2018) 108
h(inv) √s=7,8 TeV;4.7,20.3 fb-1
JHEP 11 (2015) 206,

Results (I)



Mass reach driven by BR(A➡aZ) and BR(H➡ah) and mass threshold

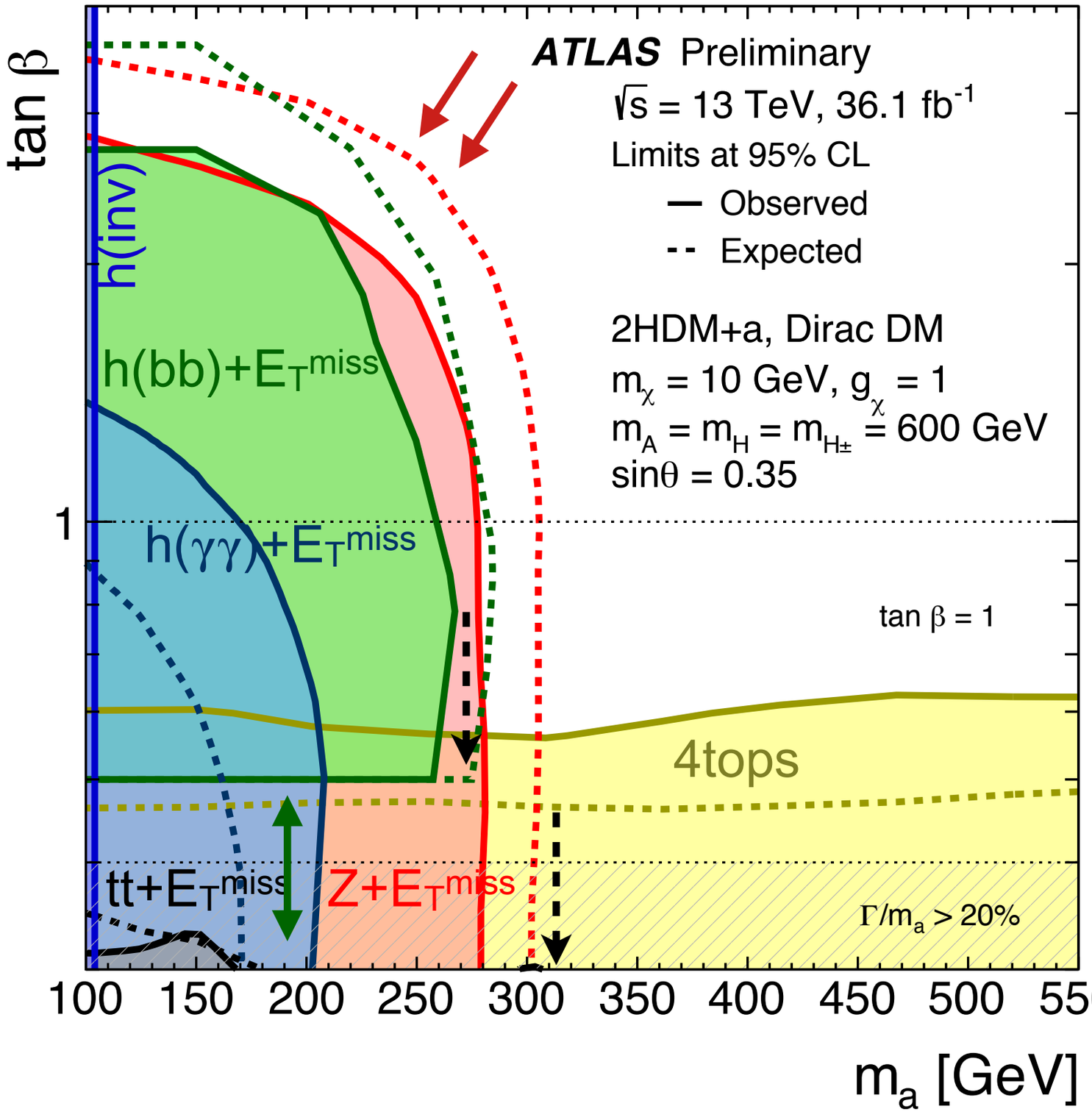
Results (I)



Mass reach driven by BR(A➡aZ) and BR(H➡ah) and mass threshold

Plotting effect due to missing samples

Results (I)

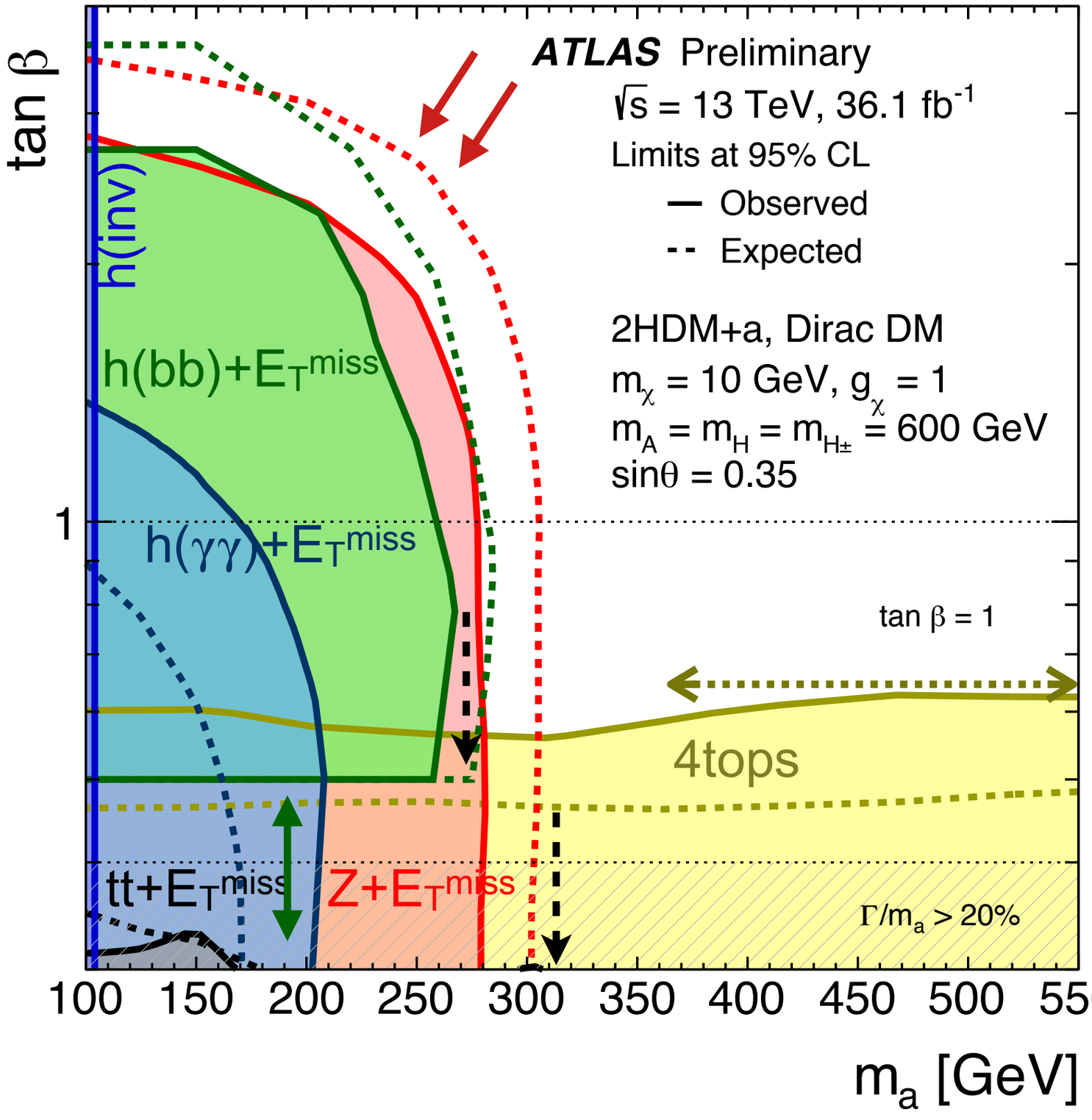


Mass reach driven by BR(A➡aZ) and BR(H➡ah) and mass threshold

Plotting effect due to missing samples

Loss of sensitivity due to missing bb-initiated production

Results (I)



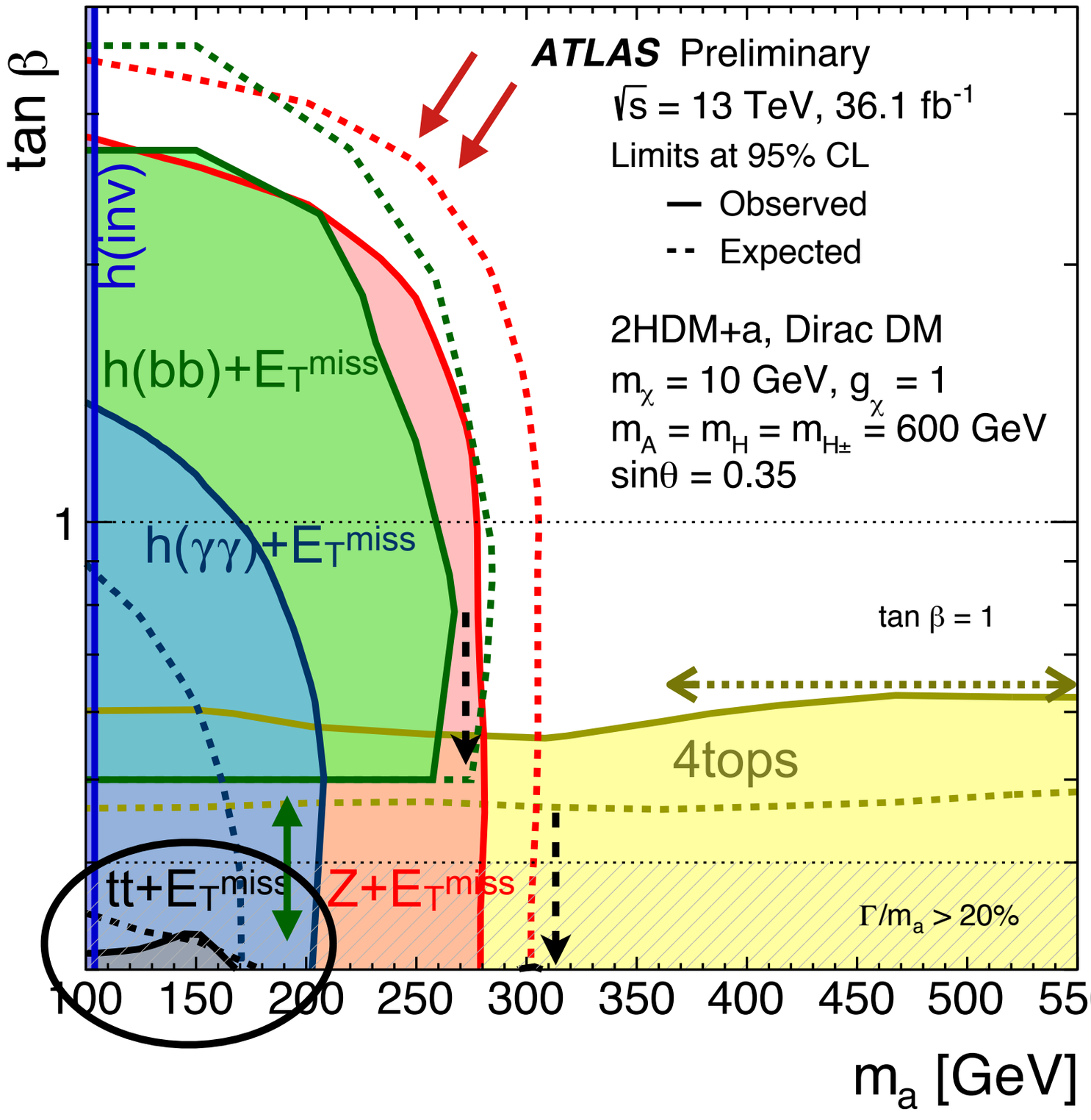
Mass reach driven by BR(A➡aZ) and BR(H➡ah) and mass threshold

Plotting effect due to missing samples

Loss of sensitivity due to missing bb-initiated production

Sensitivity dominated by ttA/ H(tt) ⇒ independent on m(a)

Results (I)



Mass reach driven by BR(A➡aZ) and BR(H➡ah) and mass threshold

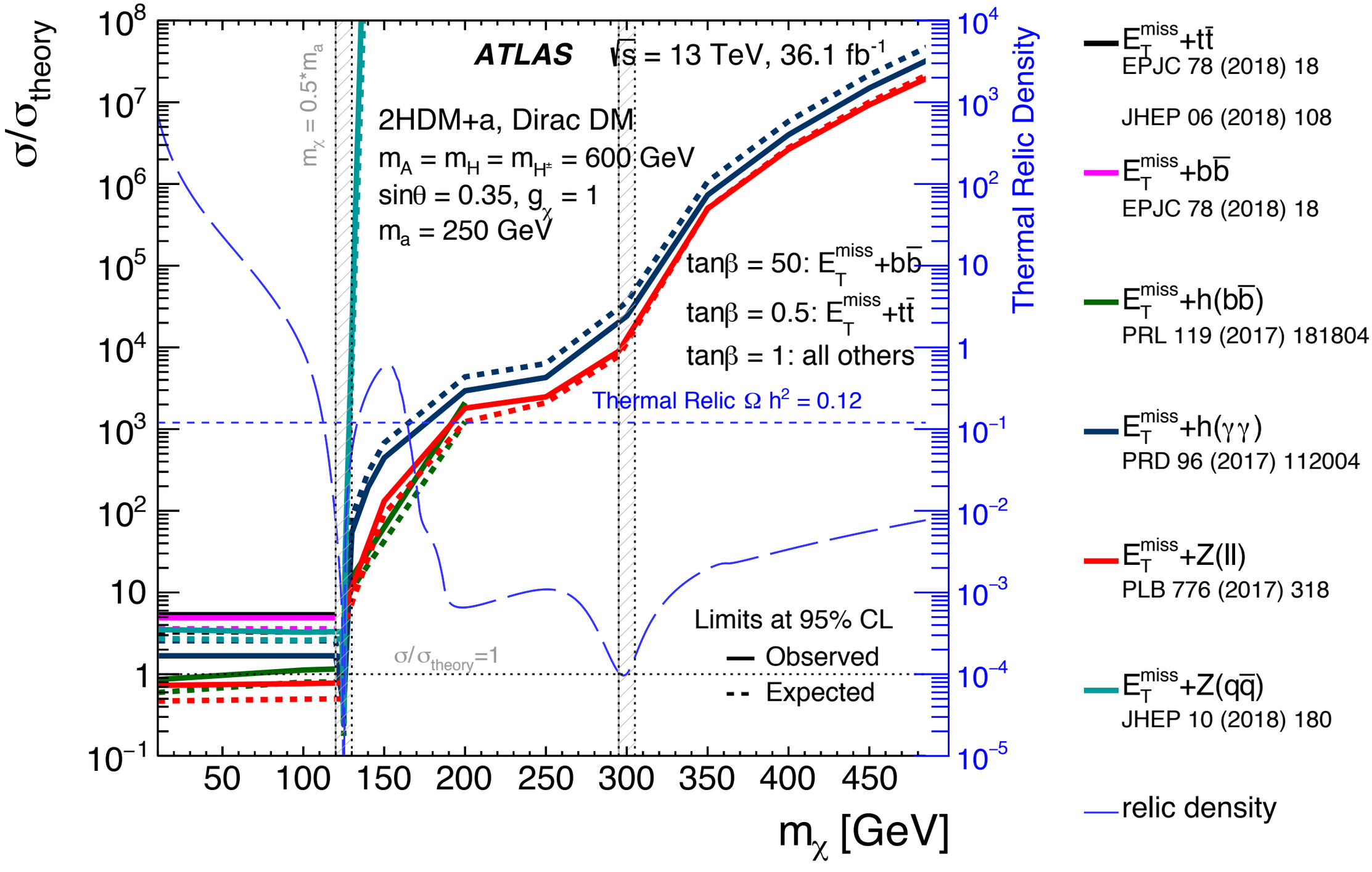
Plotting effect due to missing samples

Loss of sensitivity due to missing bb-initiated production

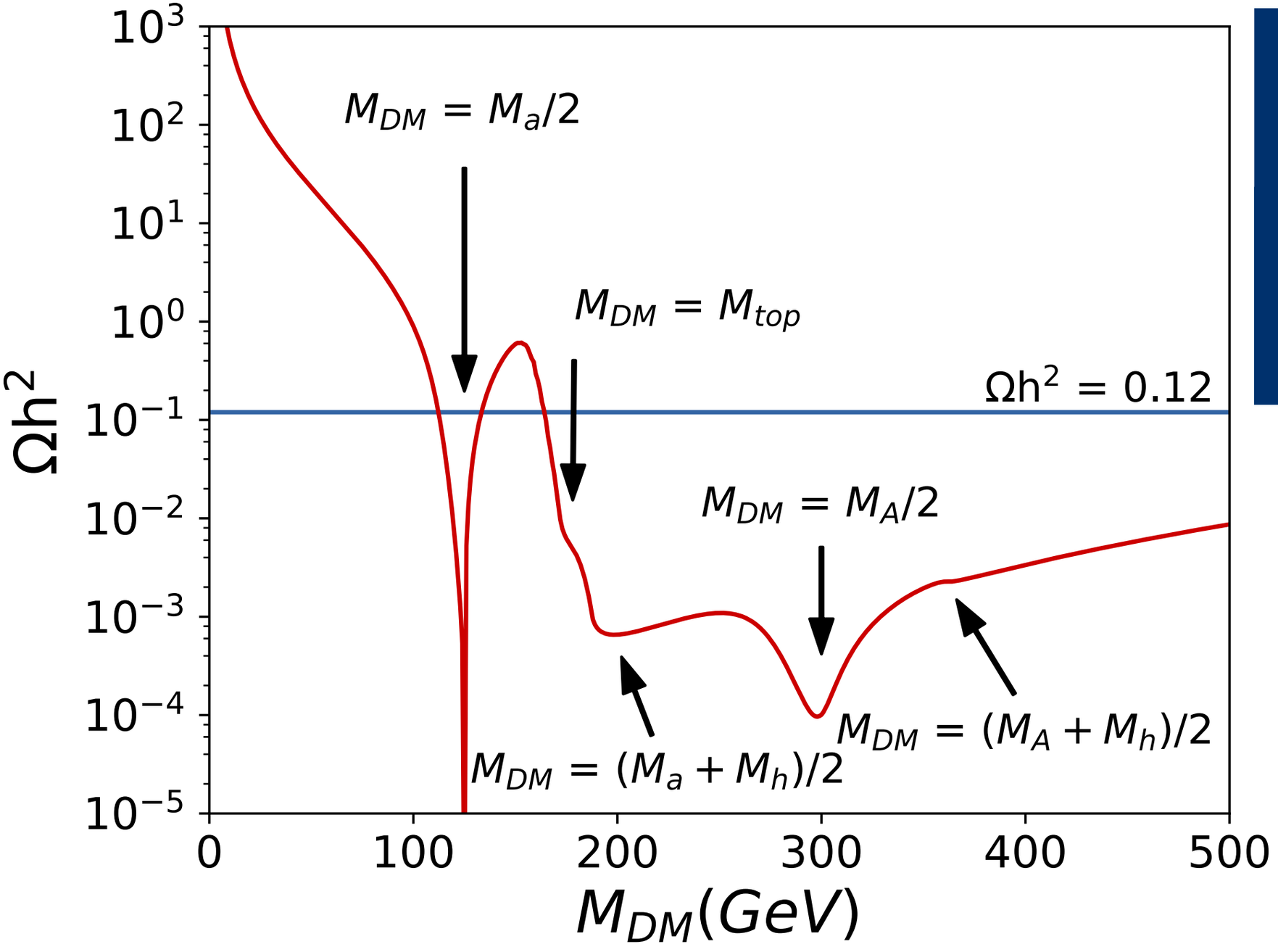
Sensitivity dominated by ttA/ H(tt) ⇒ independent on m(a)

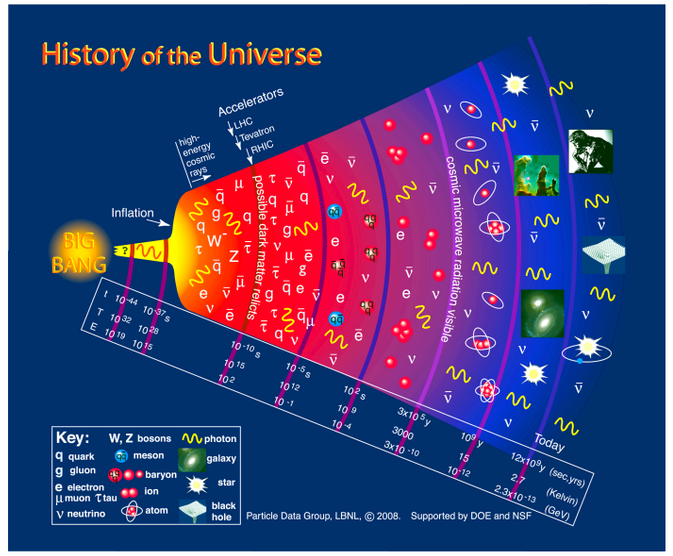
Limited by the choice of sinθ

Relic density perspective

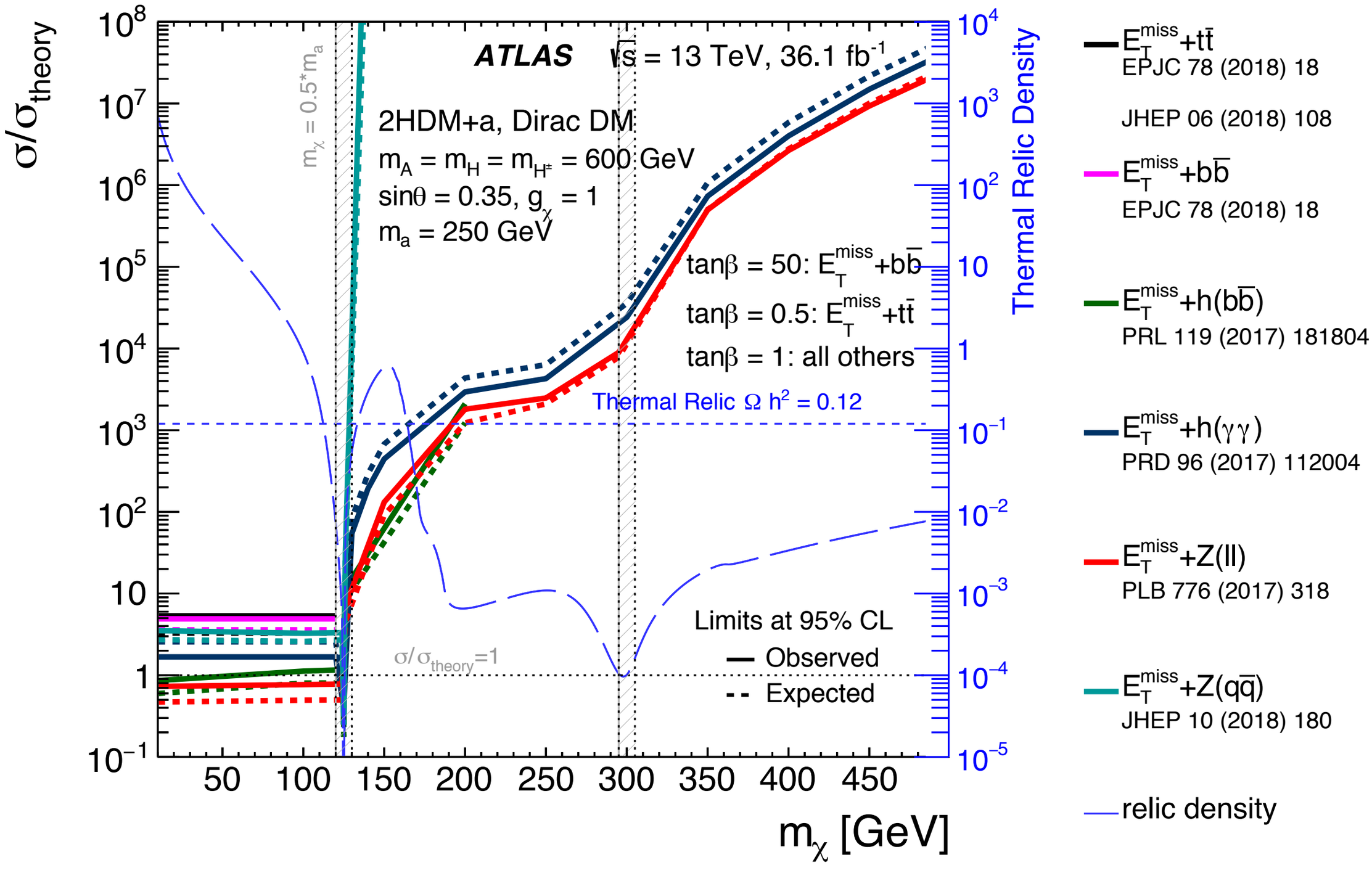


Understanding the relic prediction

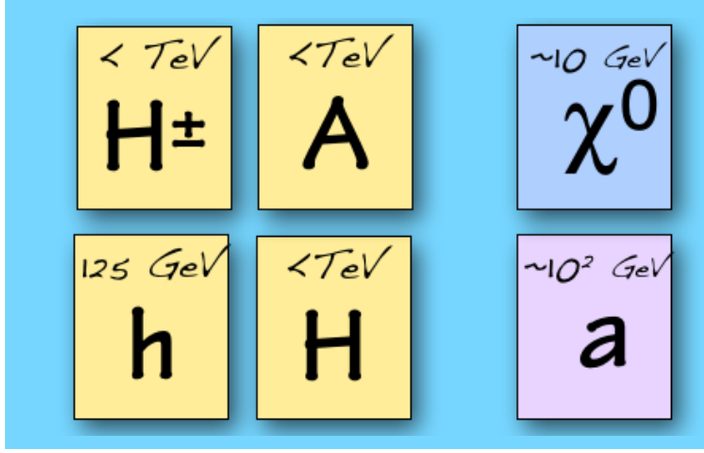


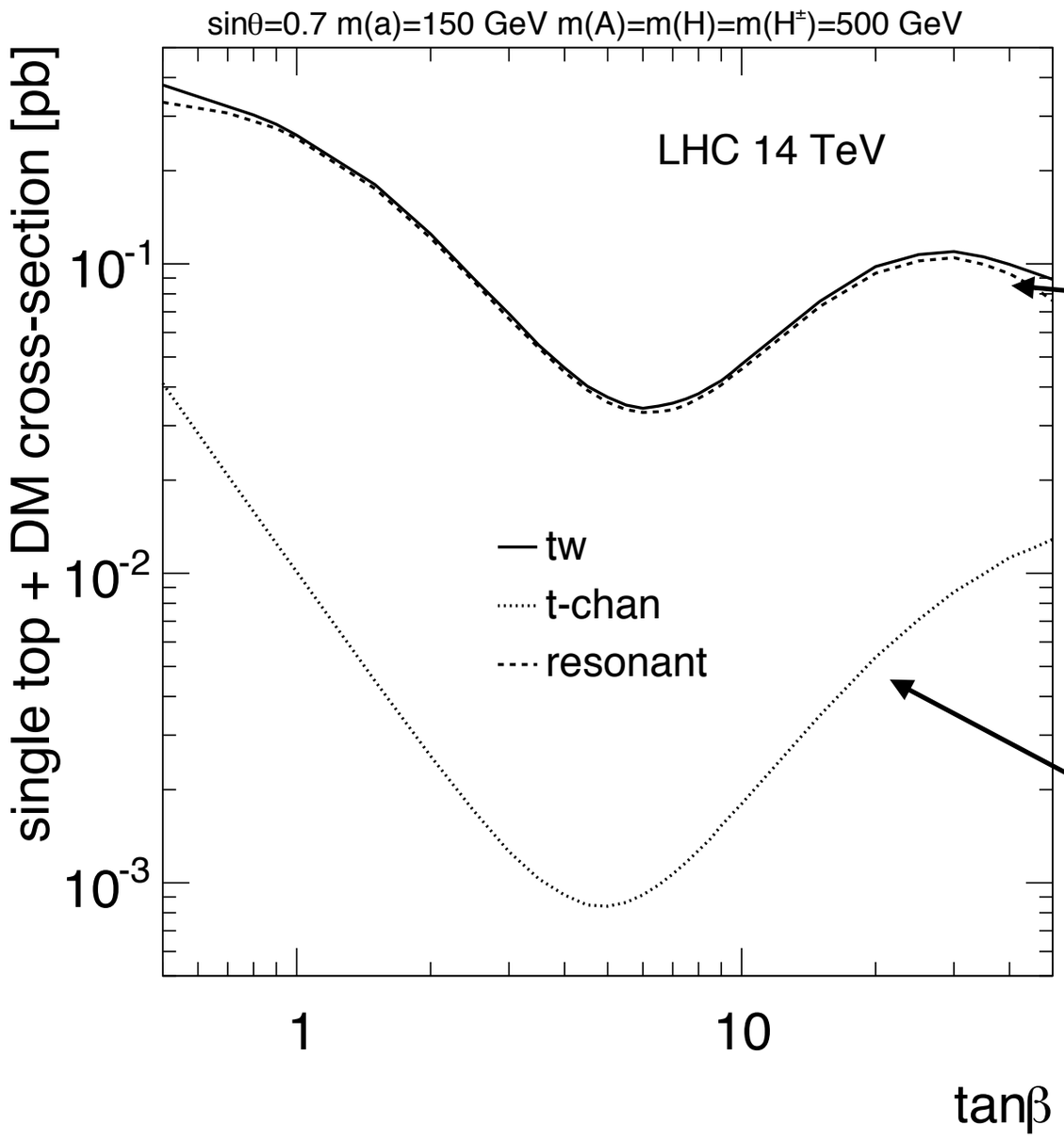


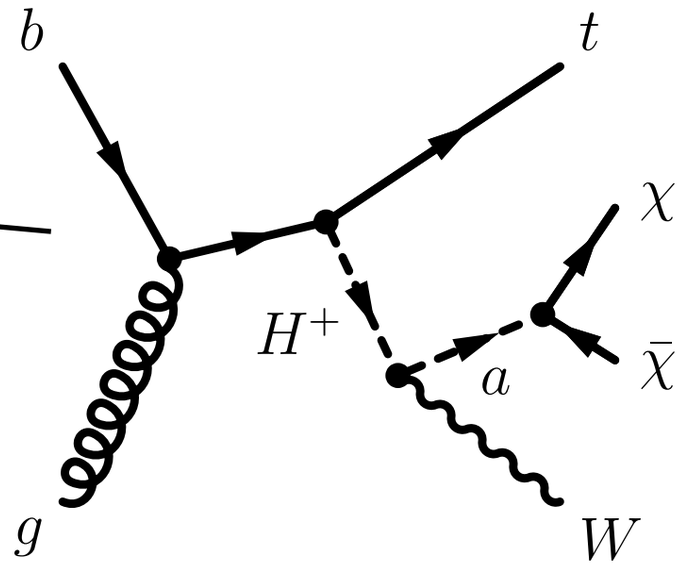
Relic density perspective

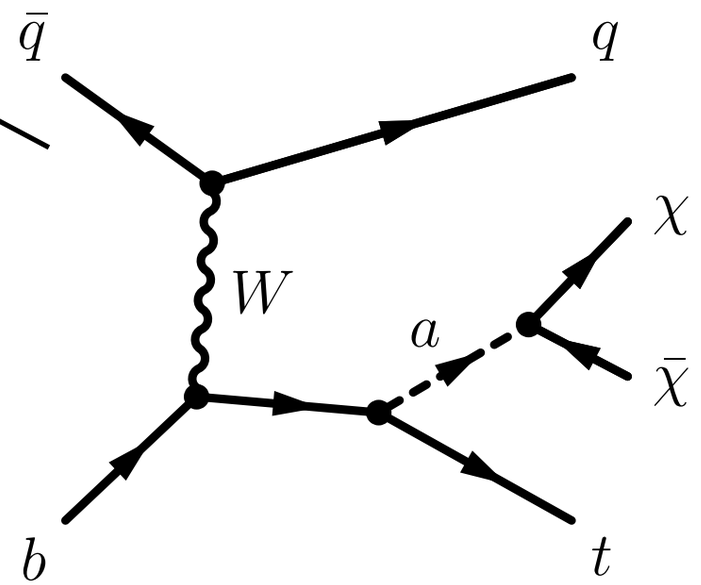


New signatures



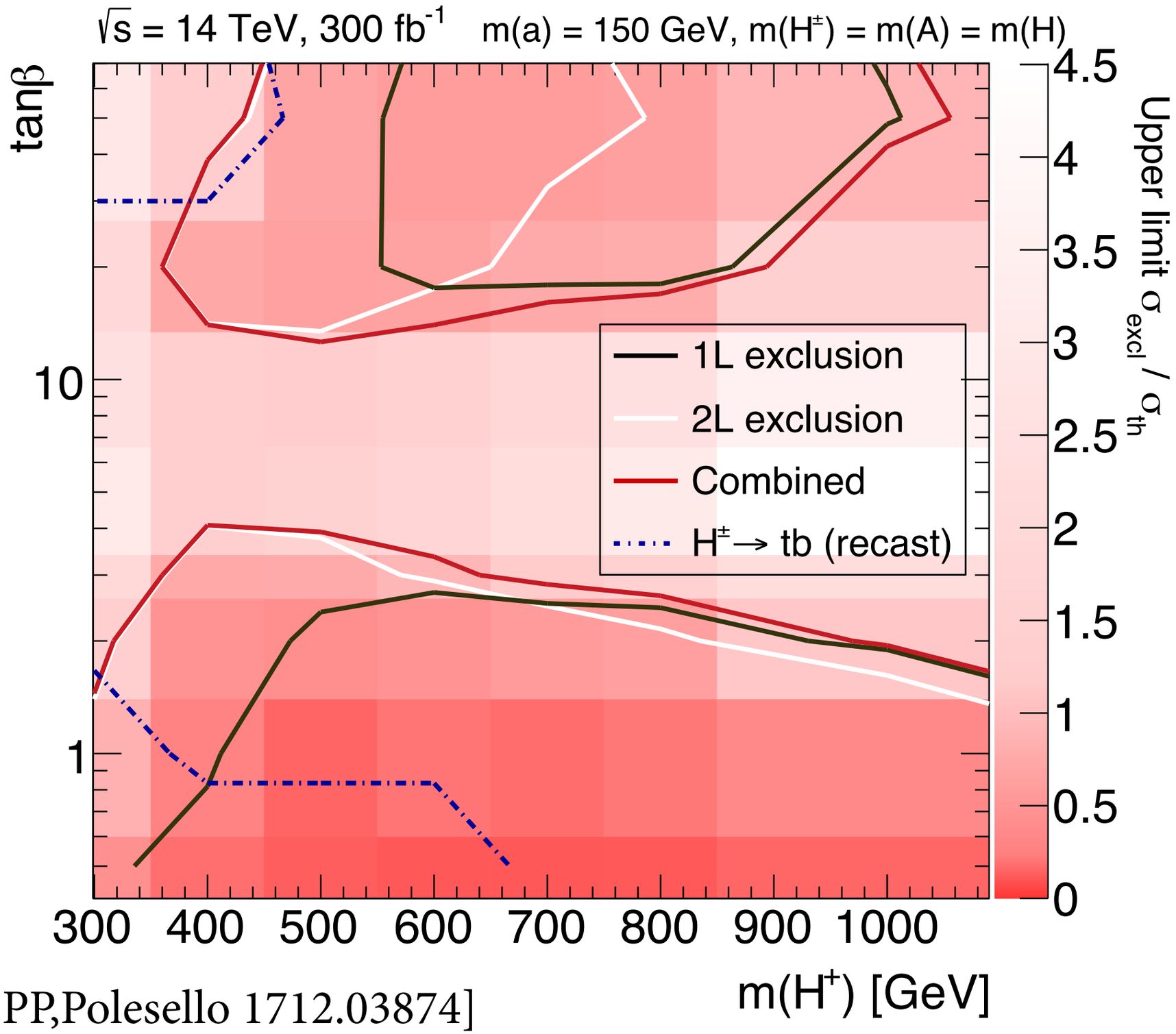






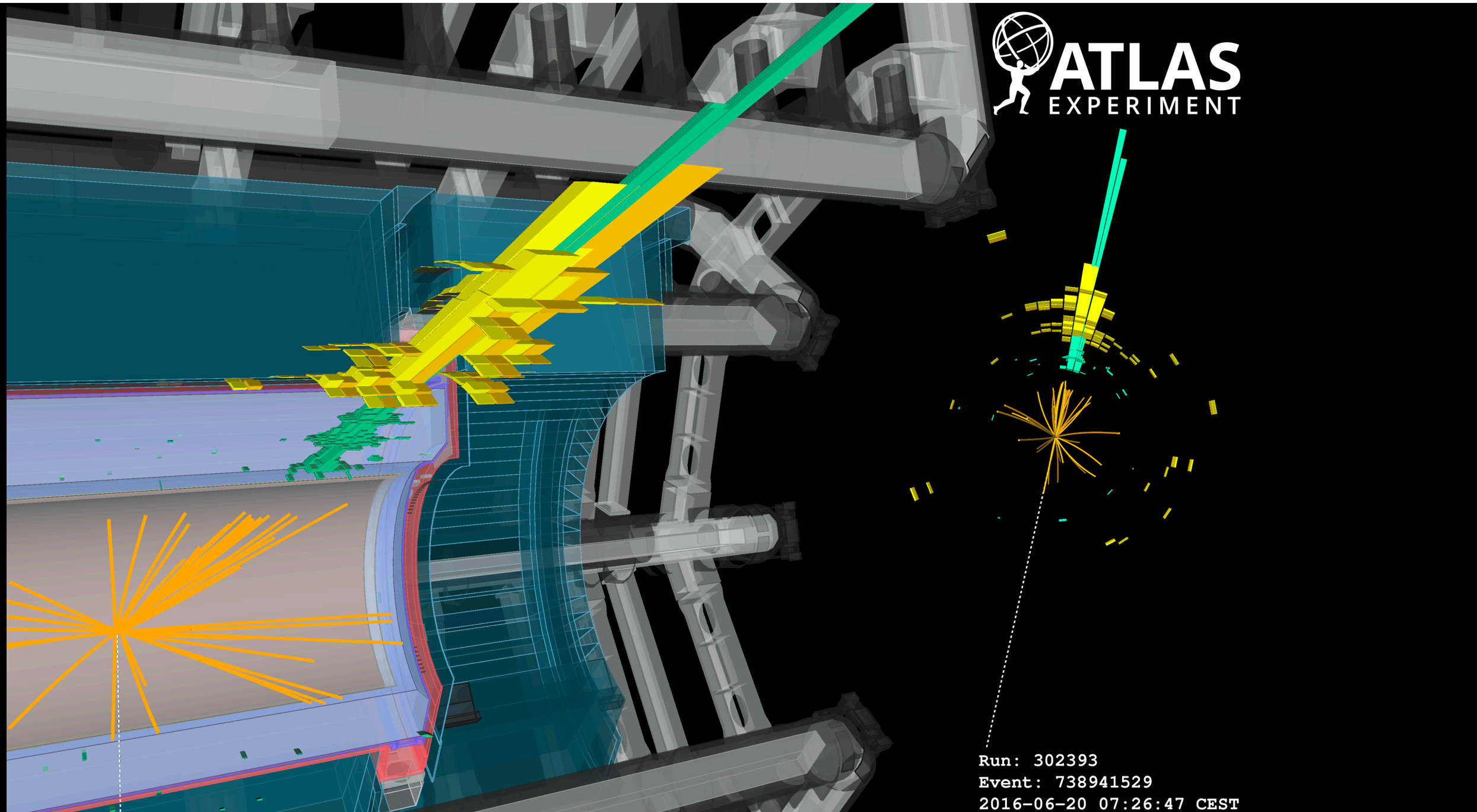
[PP,Polesello 1712.03874]

Sensitivity forecast



[PP,Polesello 1712.03874]

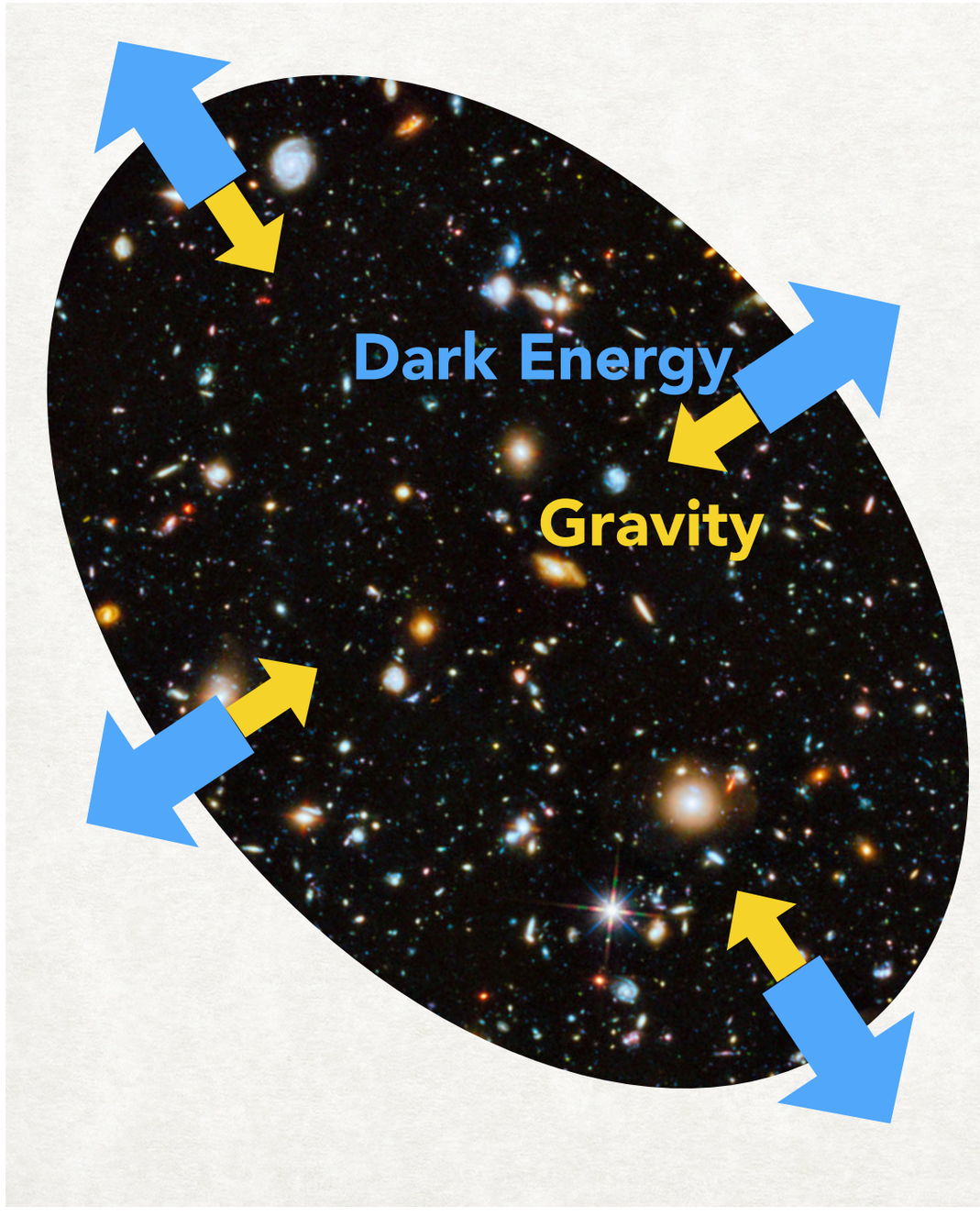
Bonus: Dark Energy



Dark Energy

- ★ Dark Energy = universe accelerated expansion
- ★ Big **unanswered question** in cosmology and particle physics
  - new particle or modified gravity?
  - constant or dynamic?
  - interacting or not?
  - microscopic nature?

★ **no leading candidate theory**

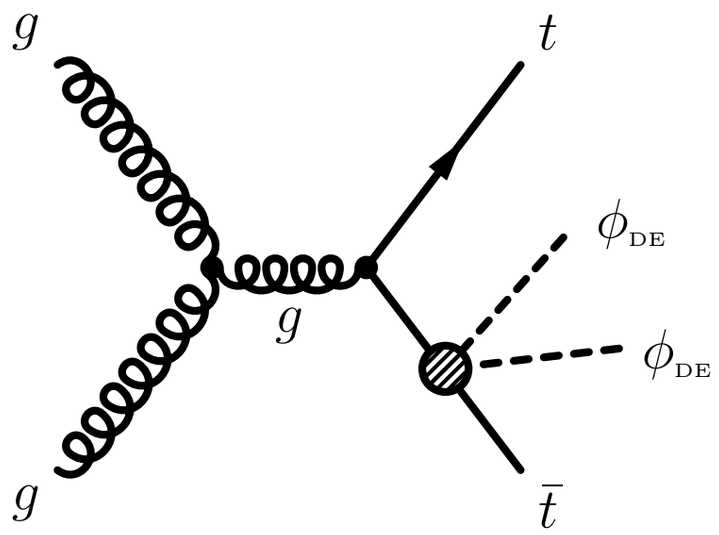


Horndeski EFT model

$$\mathcal{L}_{\rm SM} + \sum_{i=1}^{9} \frac{c_i}{M_i^{(d-4)}} \mathcal{O}_i^{(d)},$$

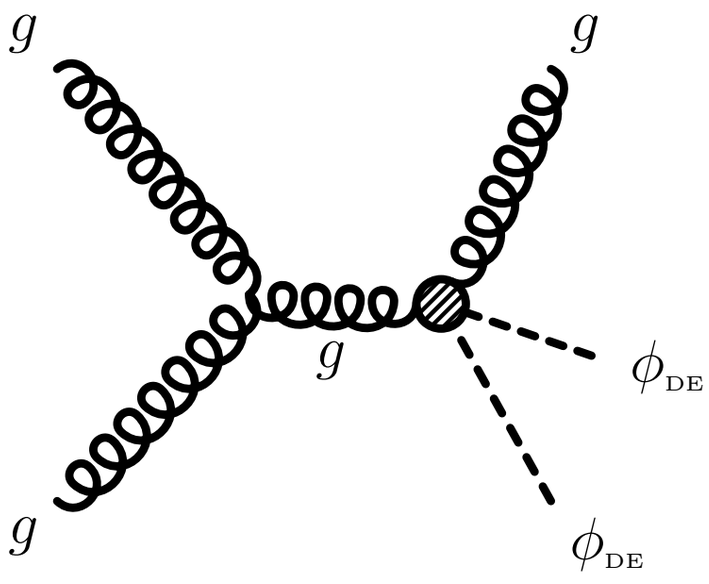
1 scalar field $\phi_{\rm DE}$ coupled to gravity

$$\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M_1^4} T^\nu_\nu$$



➡ tops + E_T^{miss}

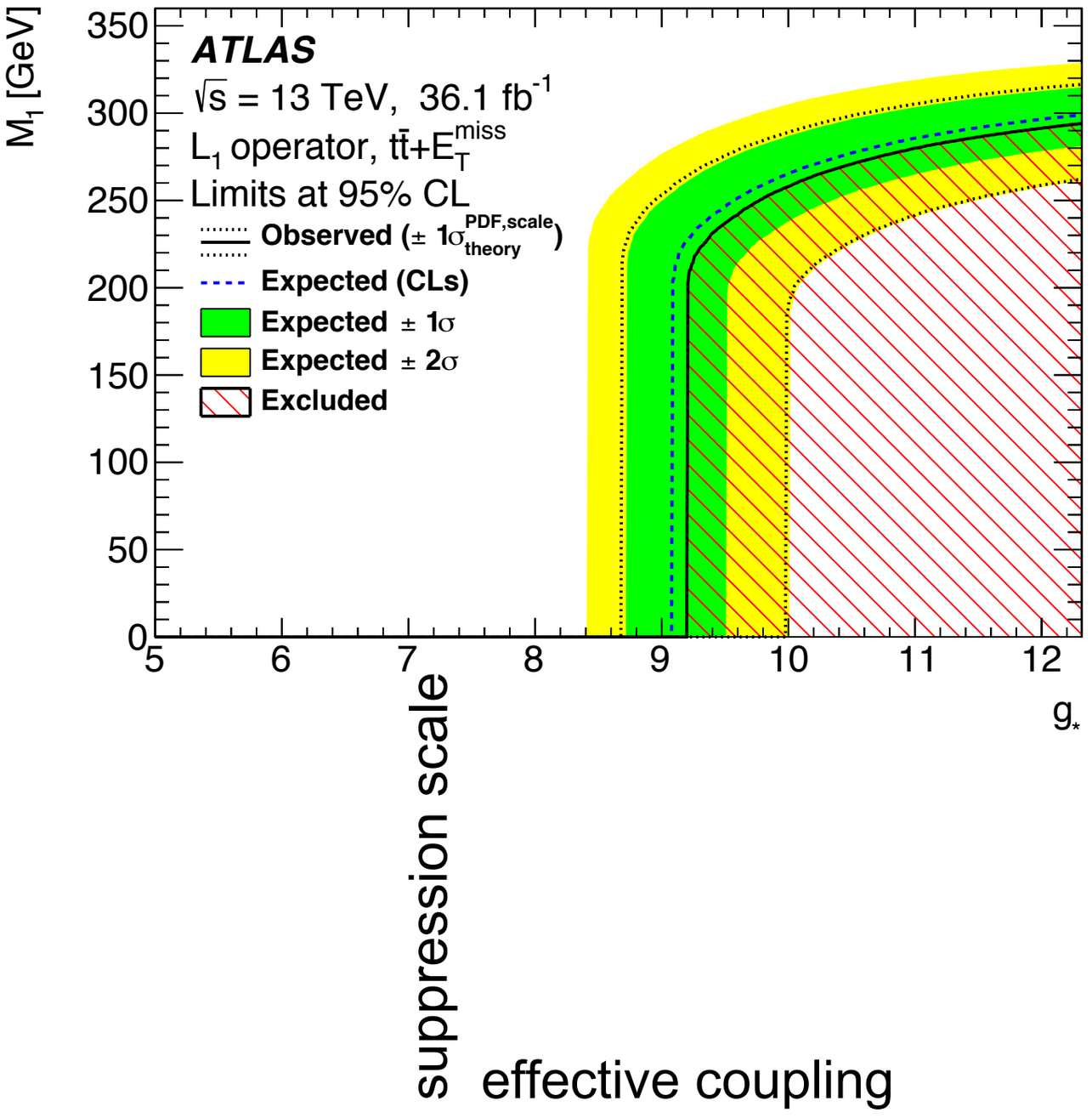
$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M_2^4} T^{\mu\nu},$$



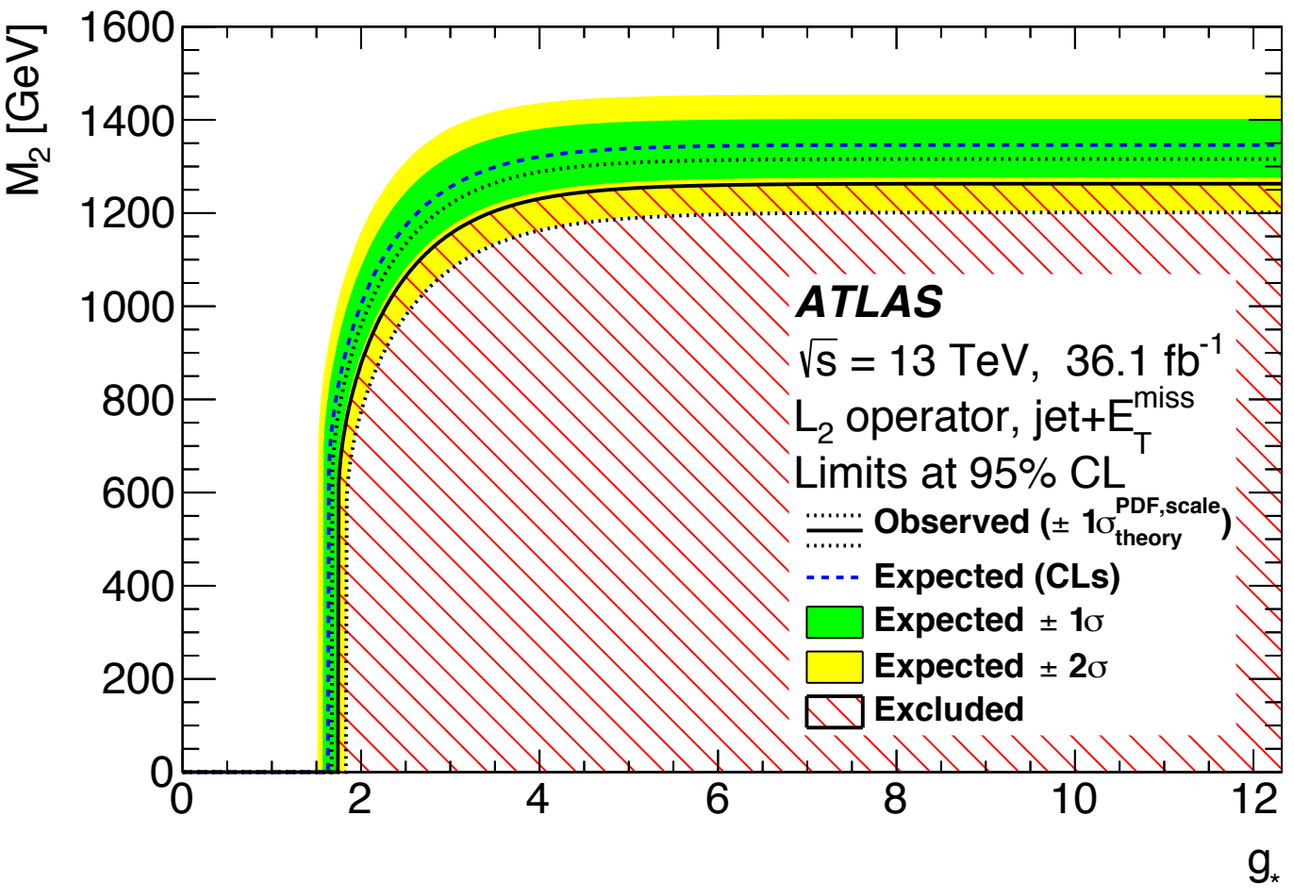
➡ jet + E_T^{miss}

Results

tops + E_T^{miss}



jet + E_T^{miss}



Perspectives

- Dark Matter is an exciting topic also for colliders!
- Quite a few results with full Run-2 dataset already available:

ATLAS

Dilepton Resonance Search NEW	ATLAS-CONF-2019-001	26-FEB-19	13	139 fb^{-1}
Combination h(125)h(125)	ATLAS-CONF-2018-043	04-SEP-18	13	36.1 fb^{-1}
MET + H search with H to bb	ATLAS-CONF-2018-039	25-JUL-18	13	80 fb^{-1}
Dijet resonance search in events with leptons	ATLAS-CONF-2018-015	29-MAY-18	13	80 fb^{-1}

CMS

Searches for dijet resonances	EXO17026	PAS EXO-17-026	78 fb^{-1}
Search for high mass resonances in dielectron final state	EXO18006	PAS EXO-18-006	41 fb^{-1}

Thanks for your attention!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

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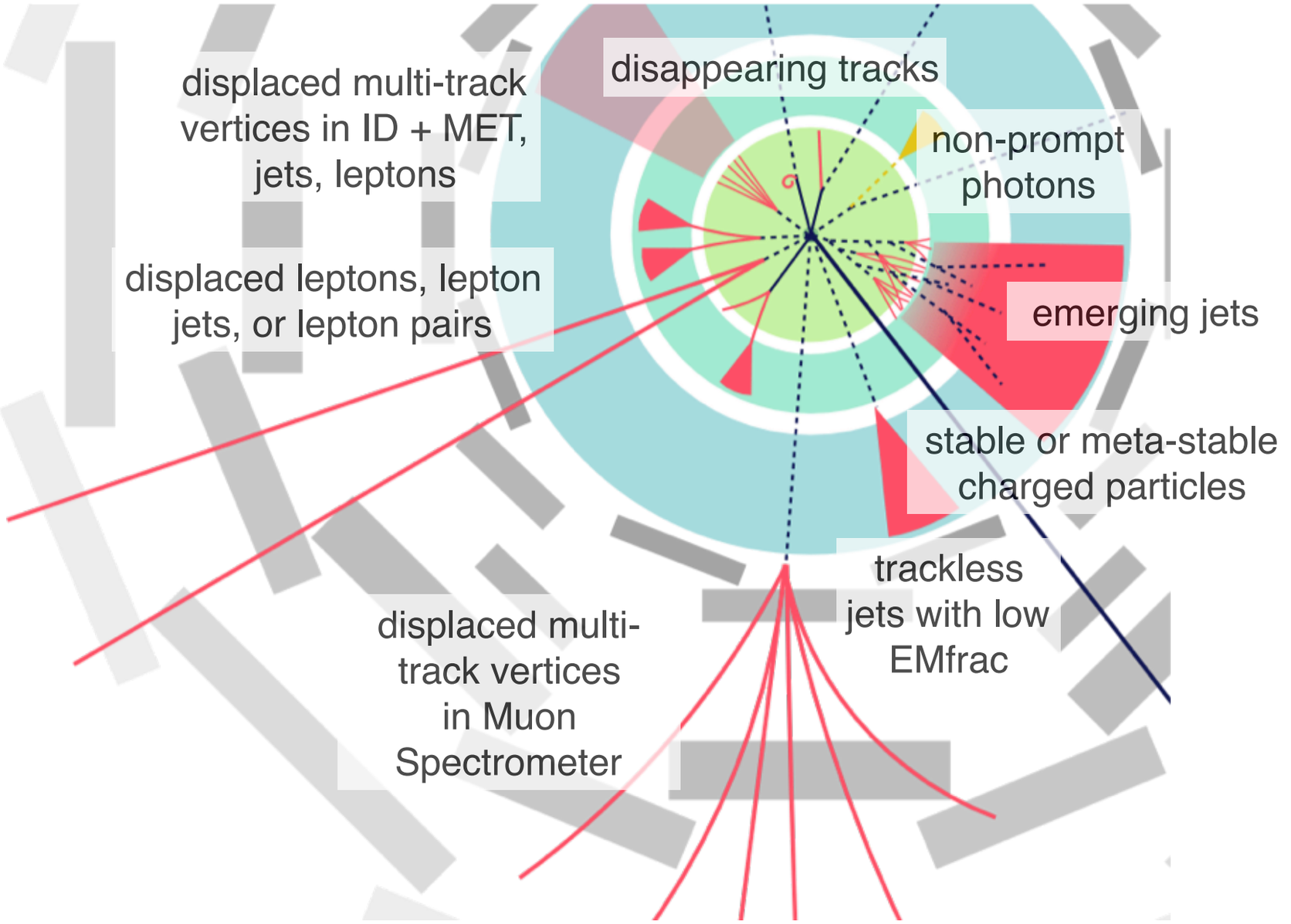
https://atlas.desy.de/external_grants/priscilla_pani_yig/

Backup

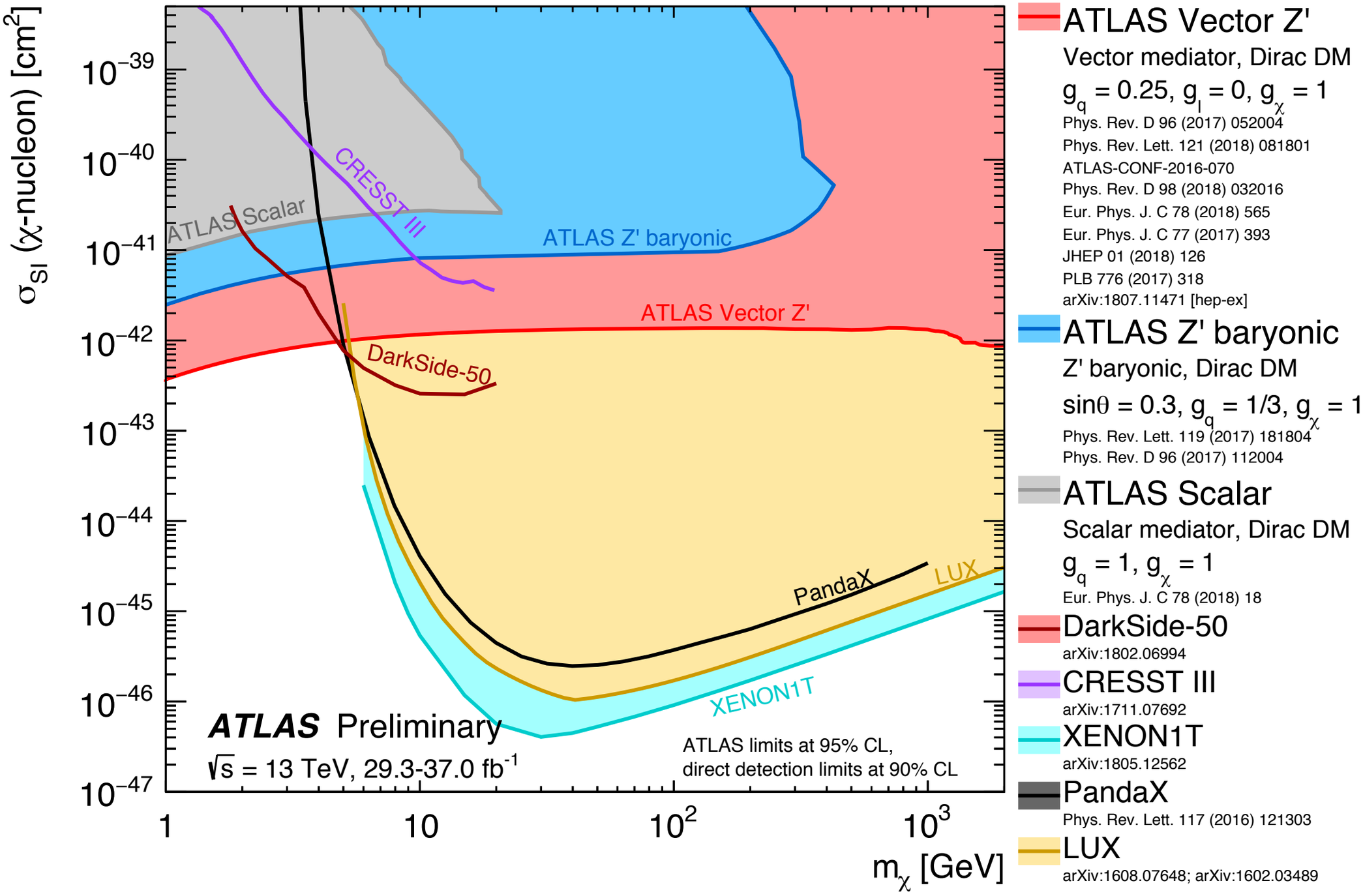
Long lived particles

- macroscopic decay length models
- hidden DM
- weak-scale hidden sectors
- SUSY LLPs
- ….



Well established in SUSY, less interpretation in other DM models.
Not covered further here

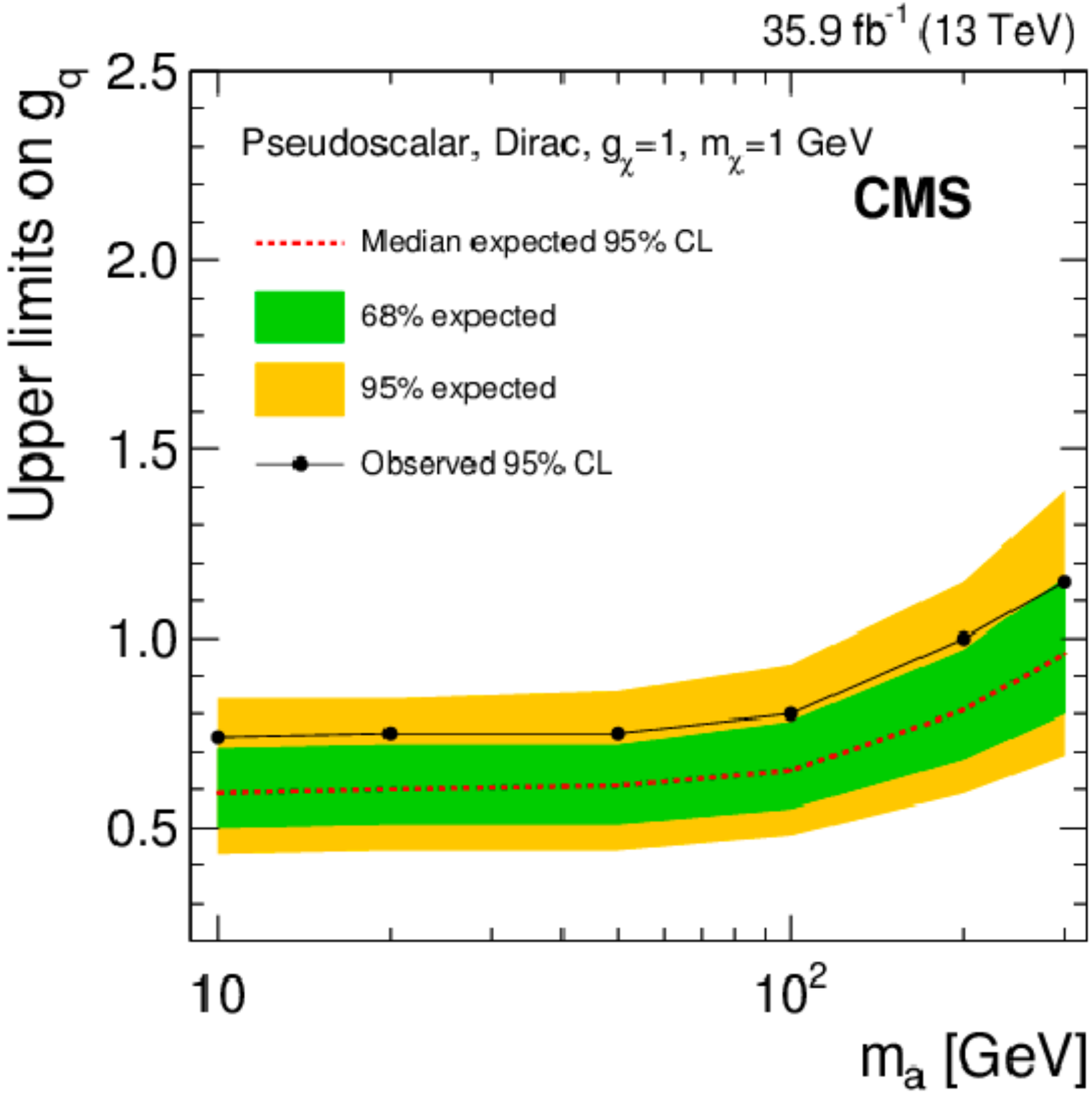
DD Comparison



Details and limitations of the conversion in arXiv:1603.04156

CMS combination Pseudo

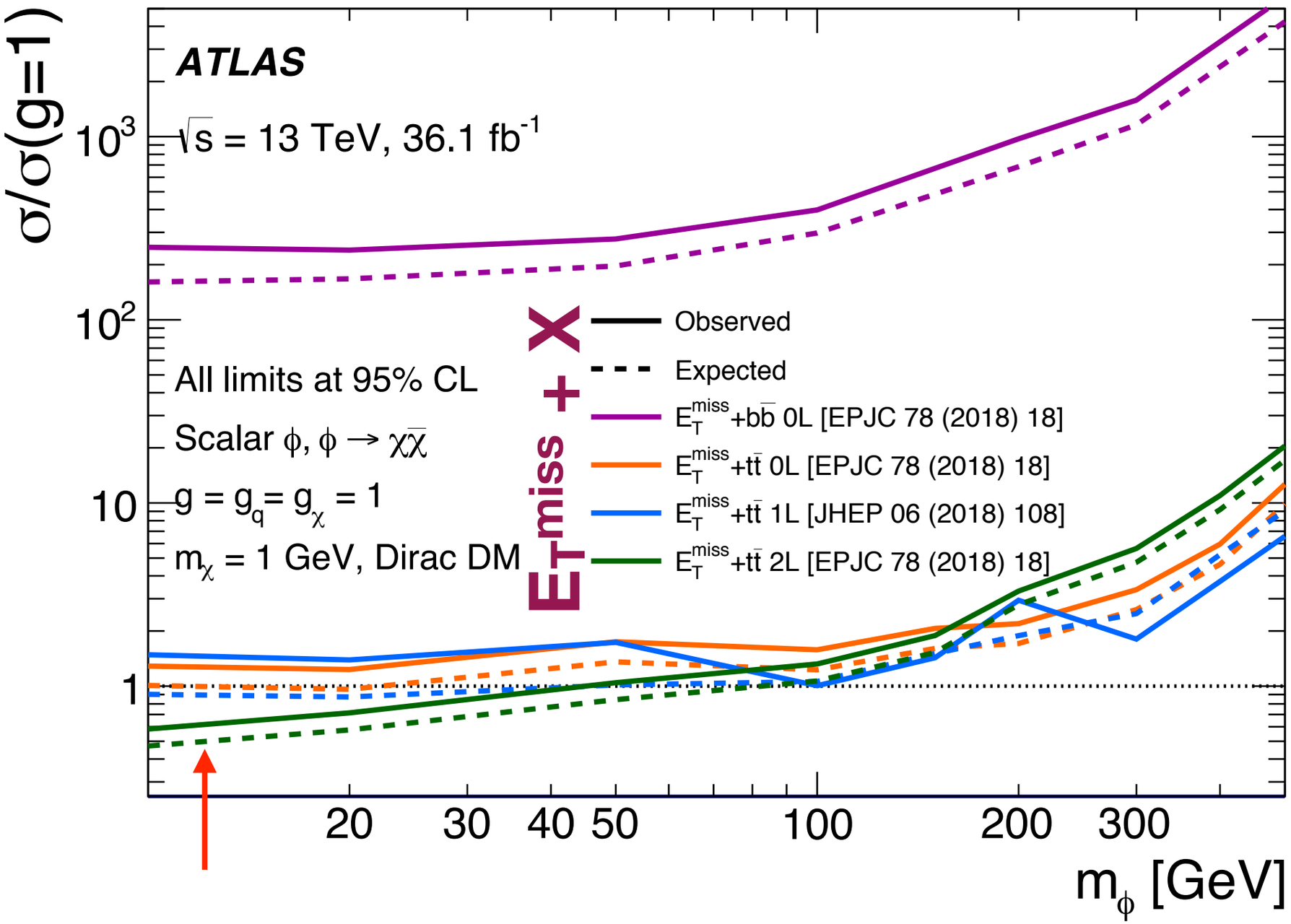
arXiv:1807.06522

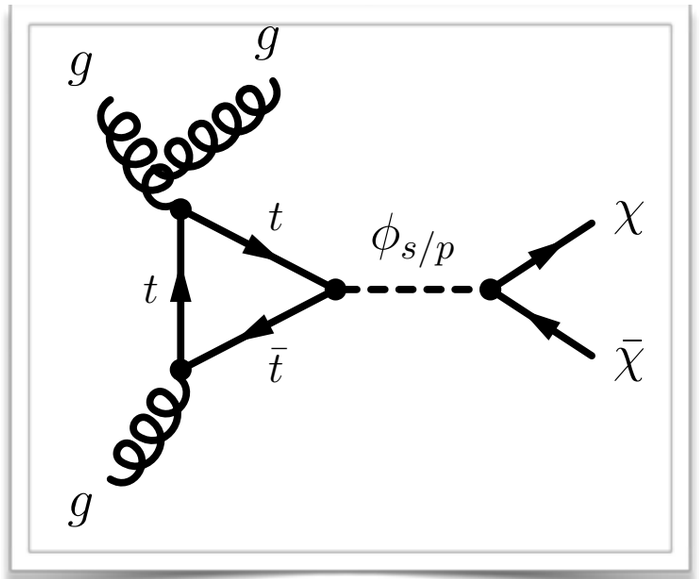


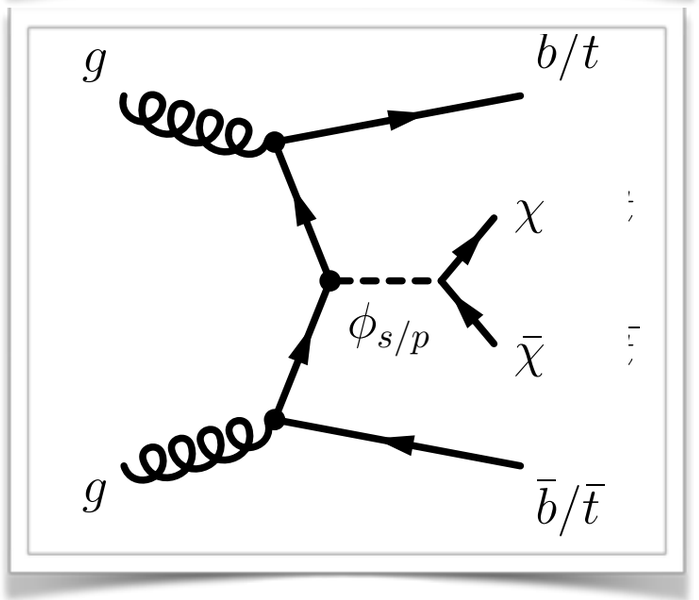
Spin-0 mediators

$$\mathcal{L} \sim \sum_f i g_v \frac{y_f}{\sqrt{2}} A \bar{f} \gamma^5 f$$

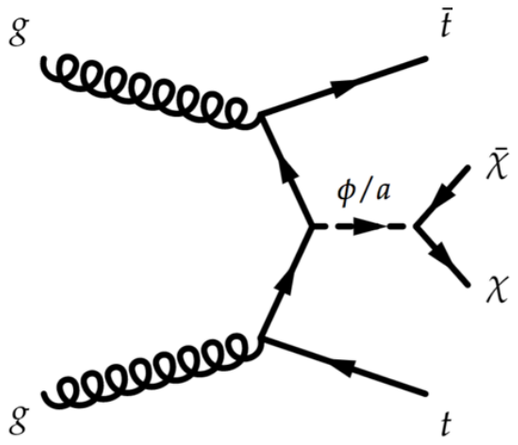
Needed to easily fulfil Flavour Constraints (MFV)







The tt2l channel for DM



➡$W^{\pm}\to\ell^{\pm}\nu$

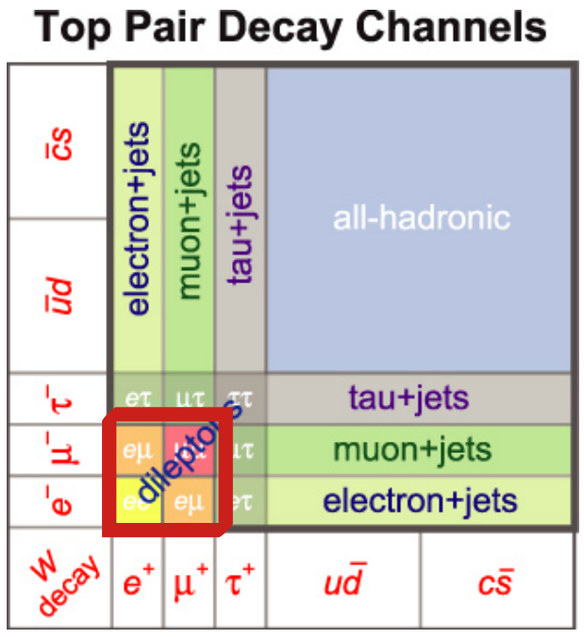
+ extra E_T^{miss}

➡$W^{\pm}\to\ell^{\pm}\nu$

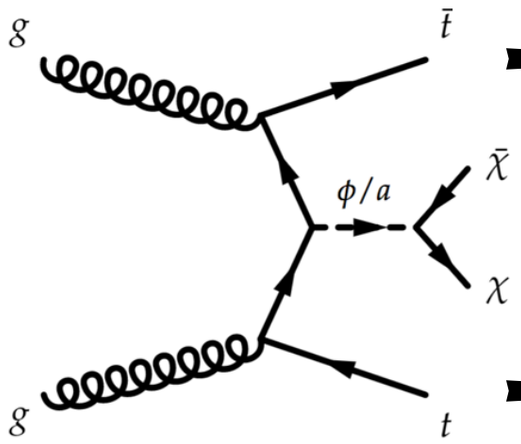
★2 leptons (e or μ)

★clean signature

★**low statistics due to branching ratio ~4%**



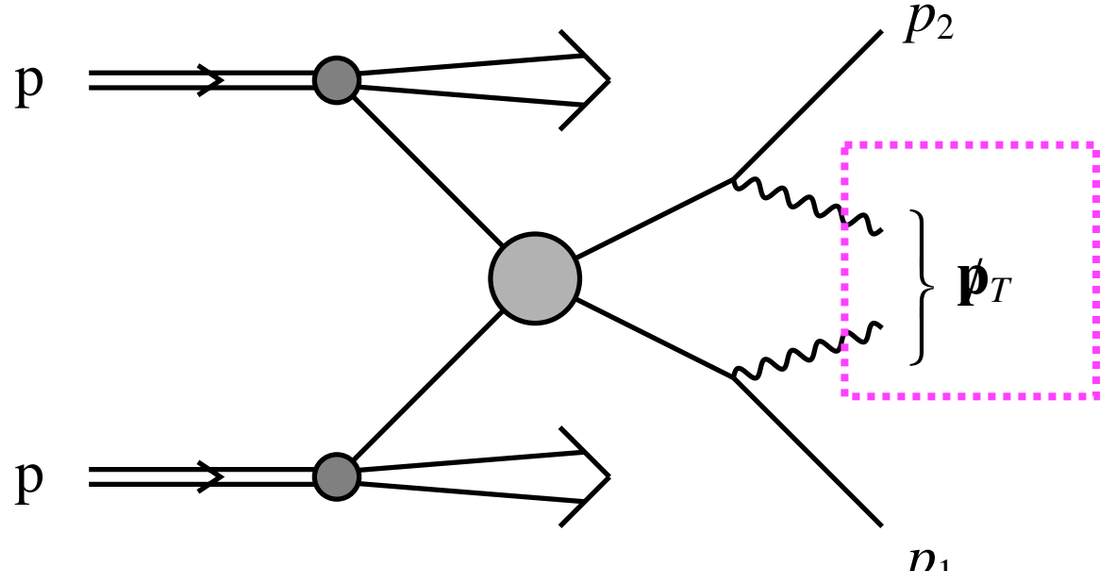
The tt2l channel for DM

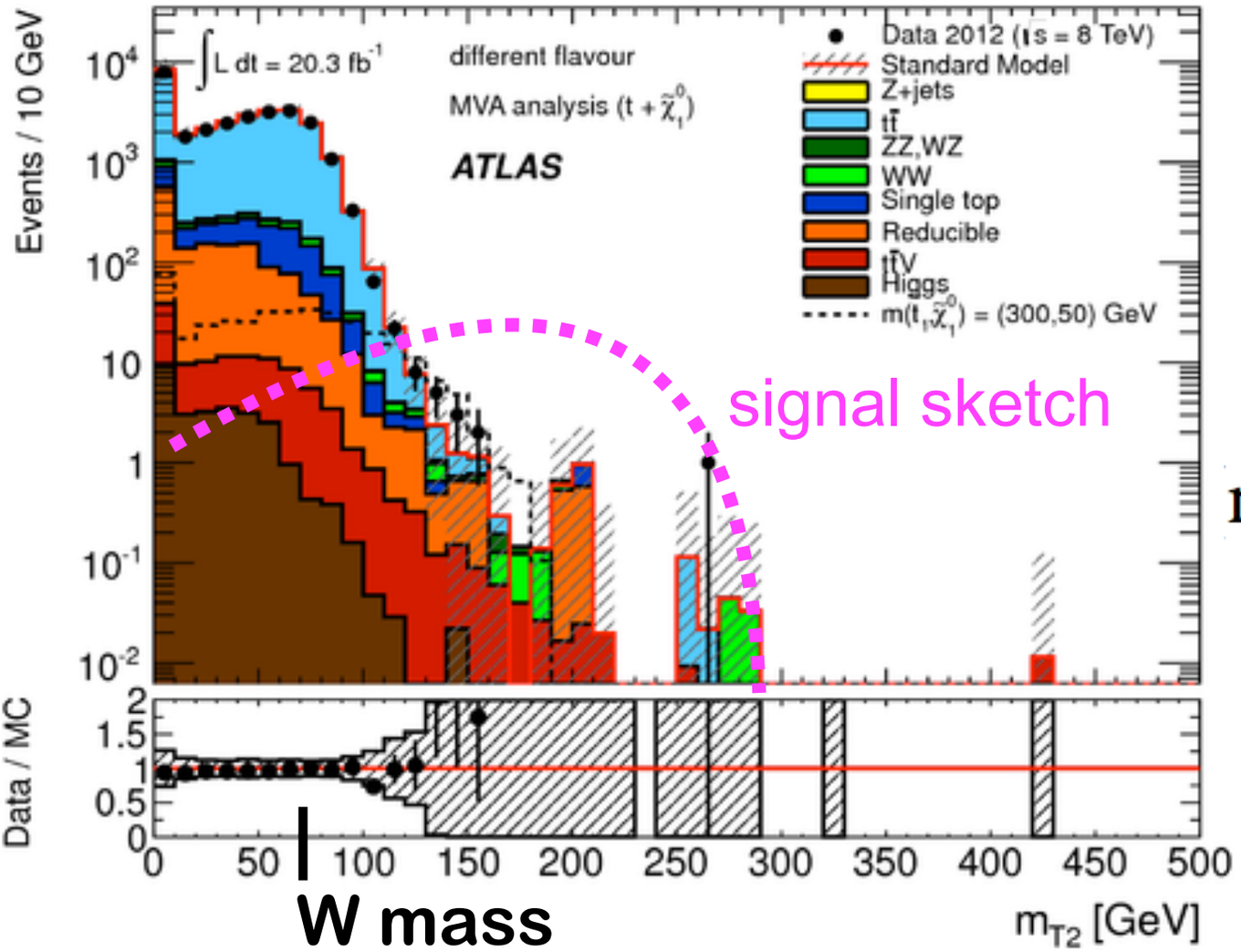


→bW±→bℓ±ν

+ extra E_T^{miss}

→bW±→bℓ±ν





$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{q}_T) =$$

$$= \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{q}_T} \{$$

$$\max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2}) \,]$$

$$\}$$

arXiv: hep-ph/030422
arXiv: hep-ph/9906349