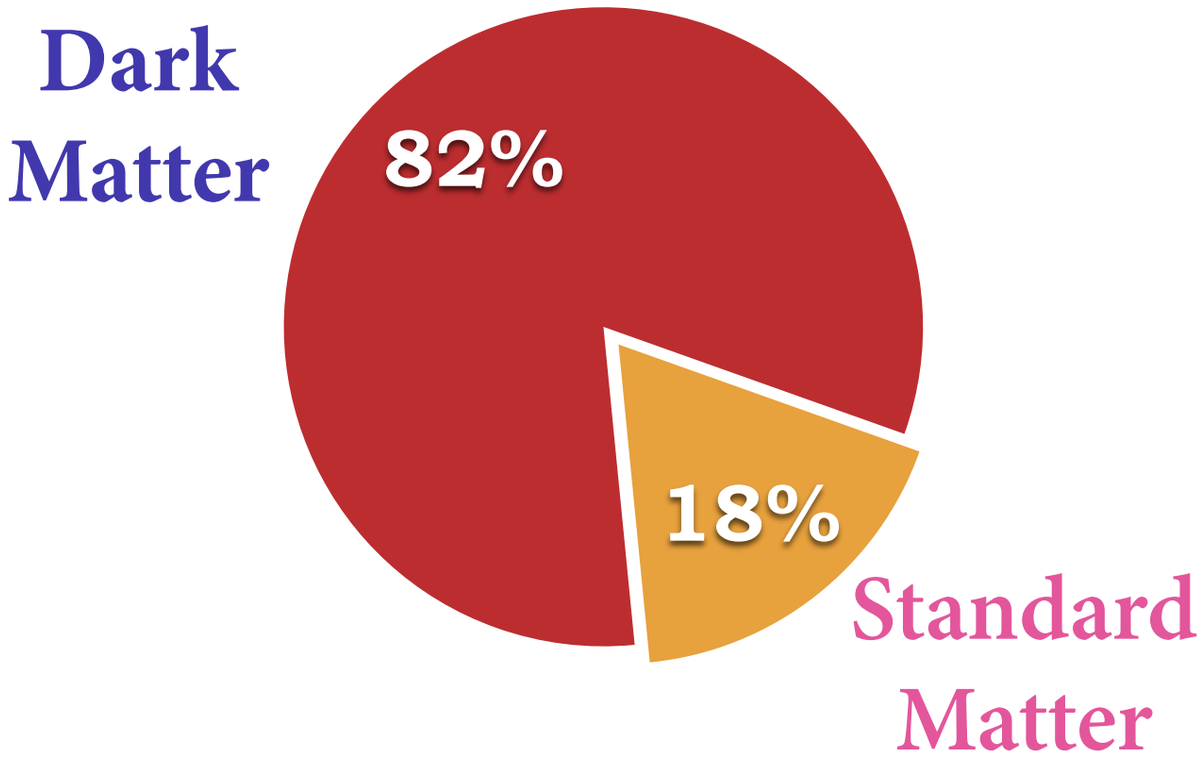
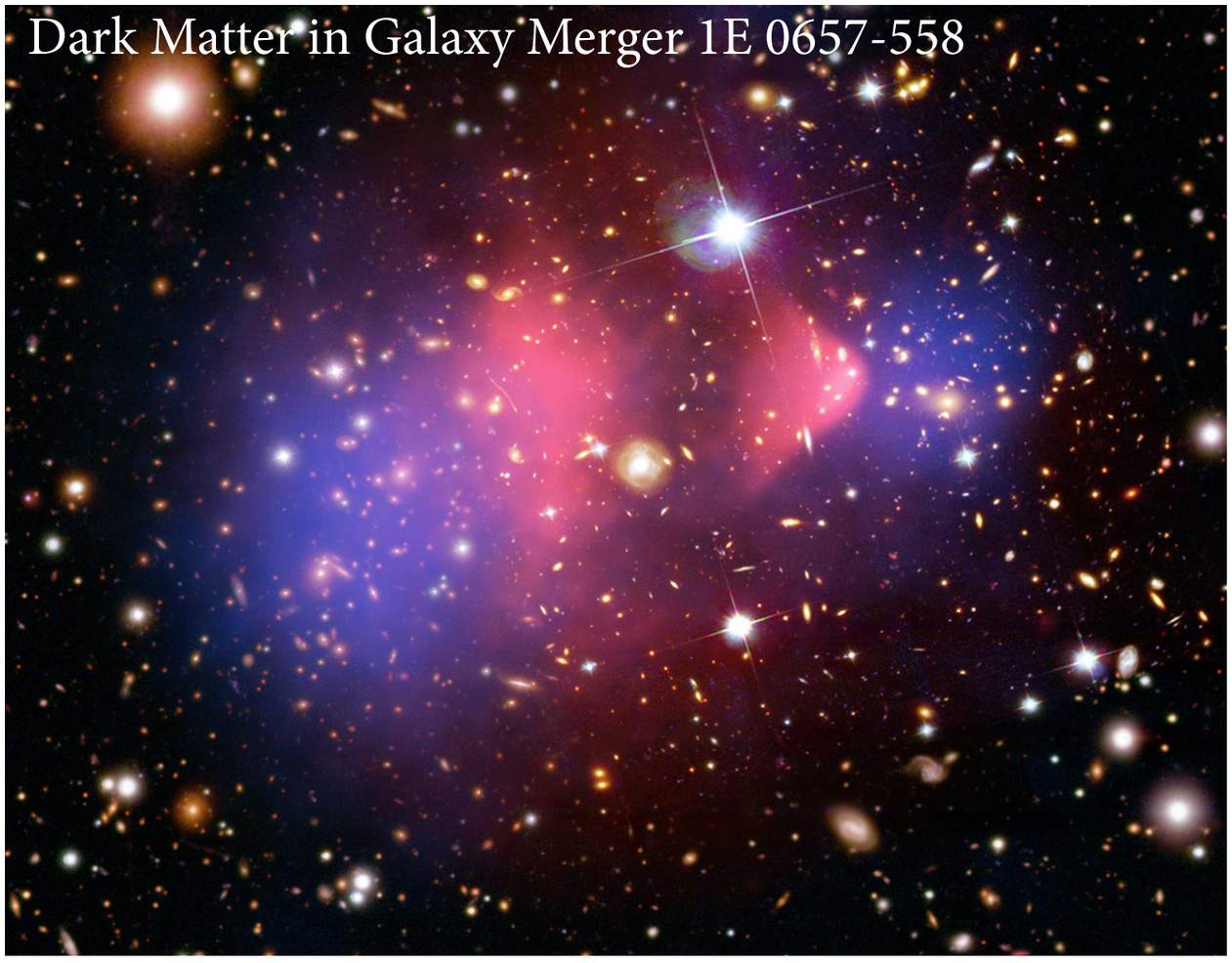
# Dark matter searches at ATLAS & CMS.

**Priscilla Pani**
(DESY)


HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

# The Dark Matter mystery

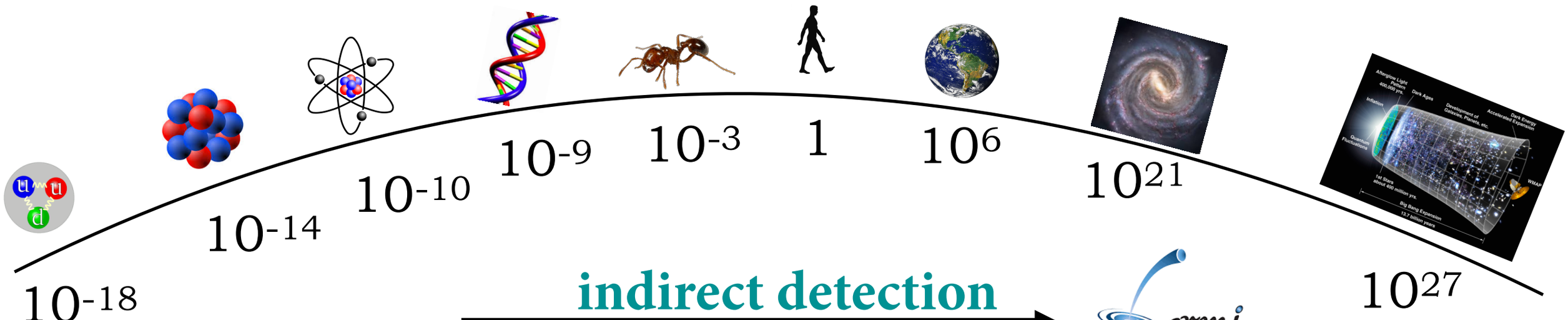



- Electrically neutral
- Observed via gravity, massive
- Weakly interacting
- Elementary particles created in the early universe

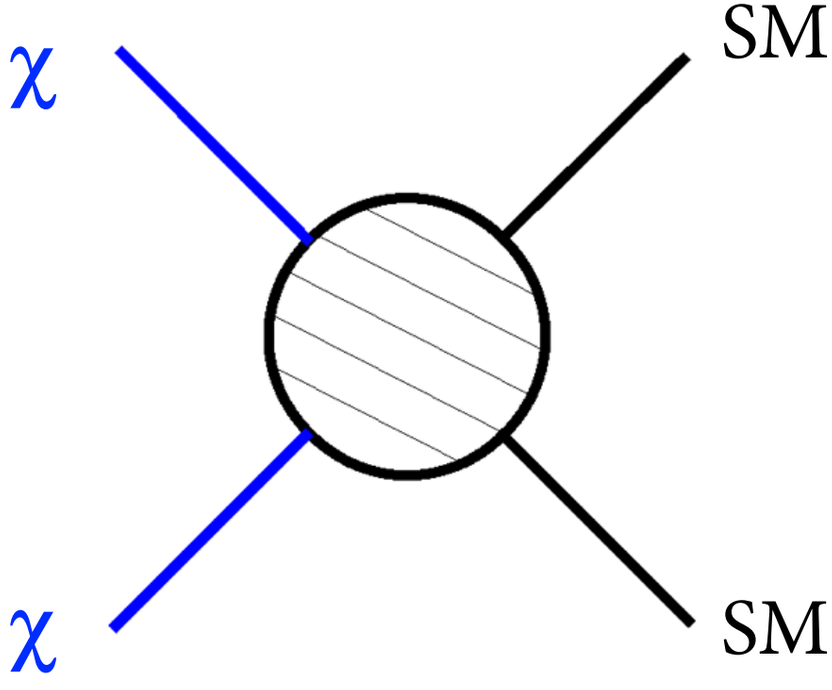
# The Dark Matter quest

universe scales in meters




indirect detection

Fermi Gamma-ray Space Telescope




direct detection

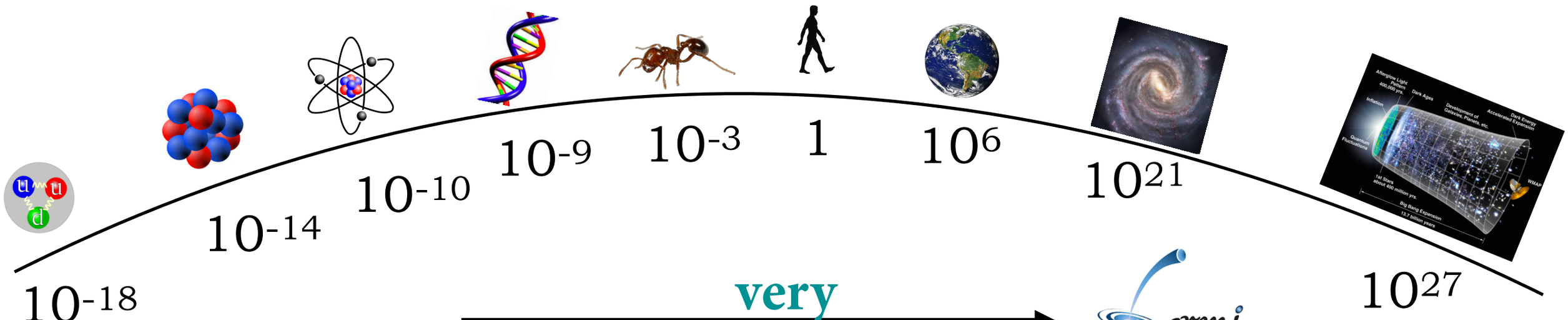
XENON Dark Matter Project

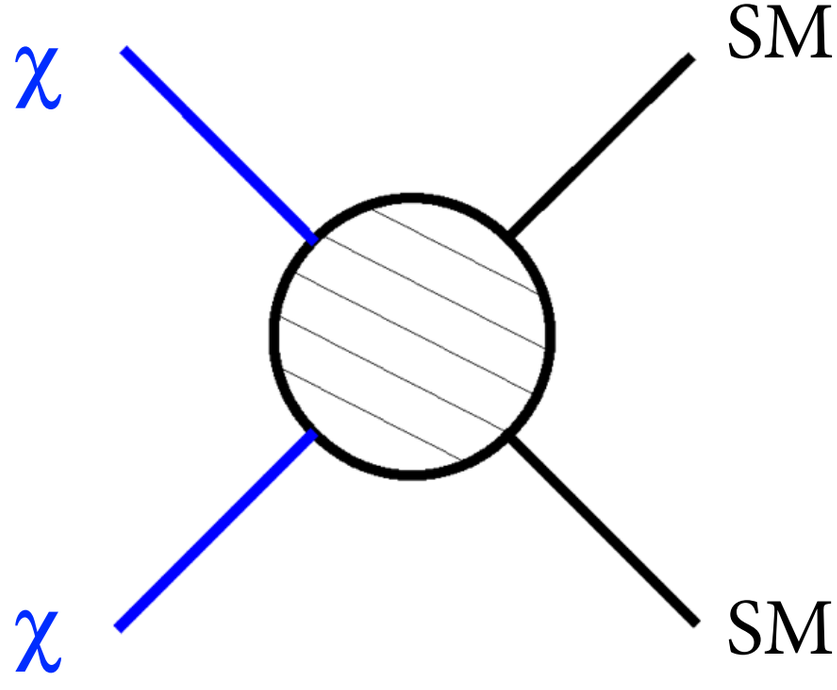
ATLAS EXPERIMENT

production @colliders

# The Dark Matter quest

universe scales in meters

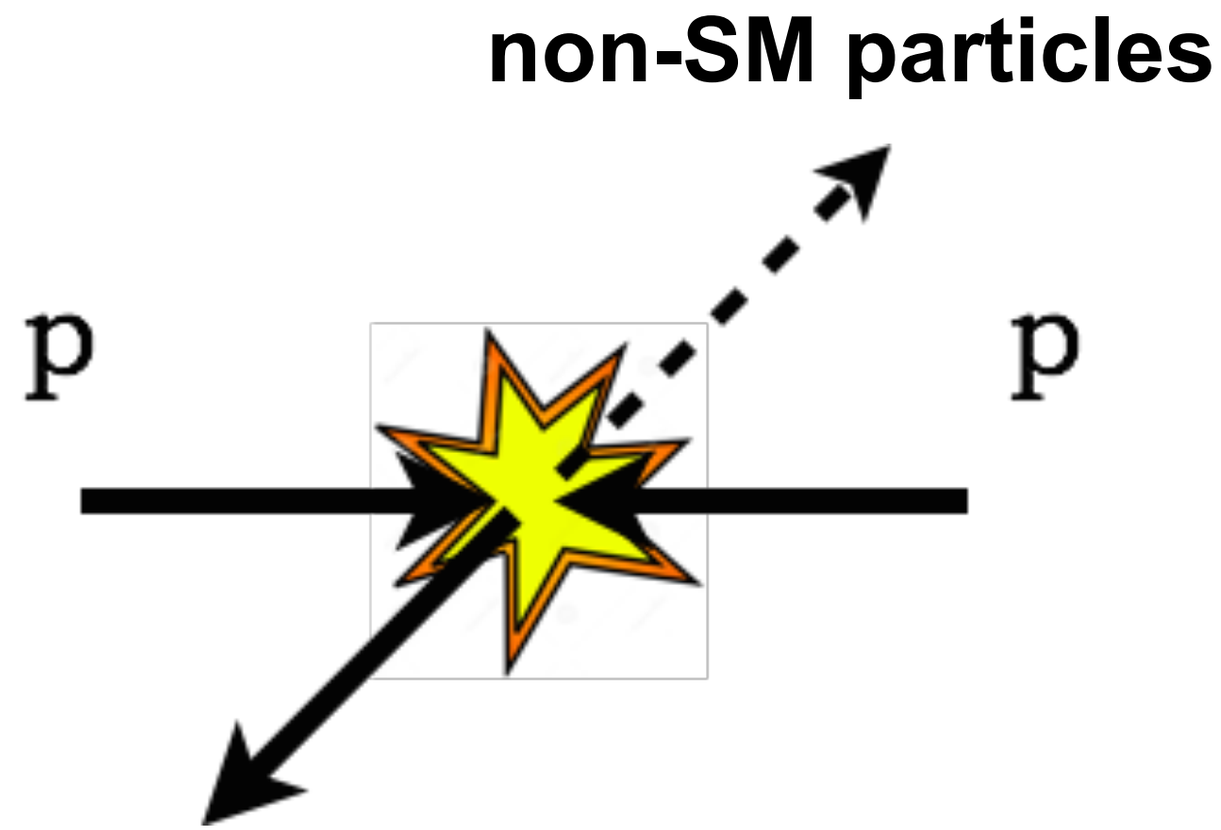



different

assumptions

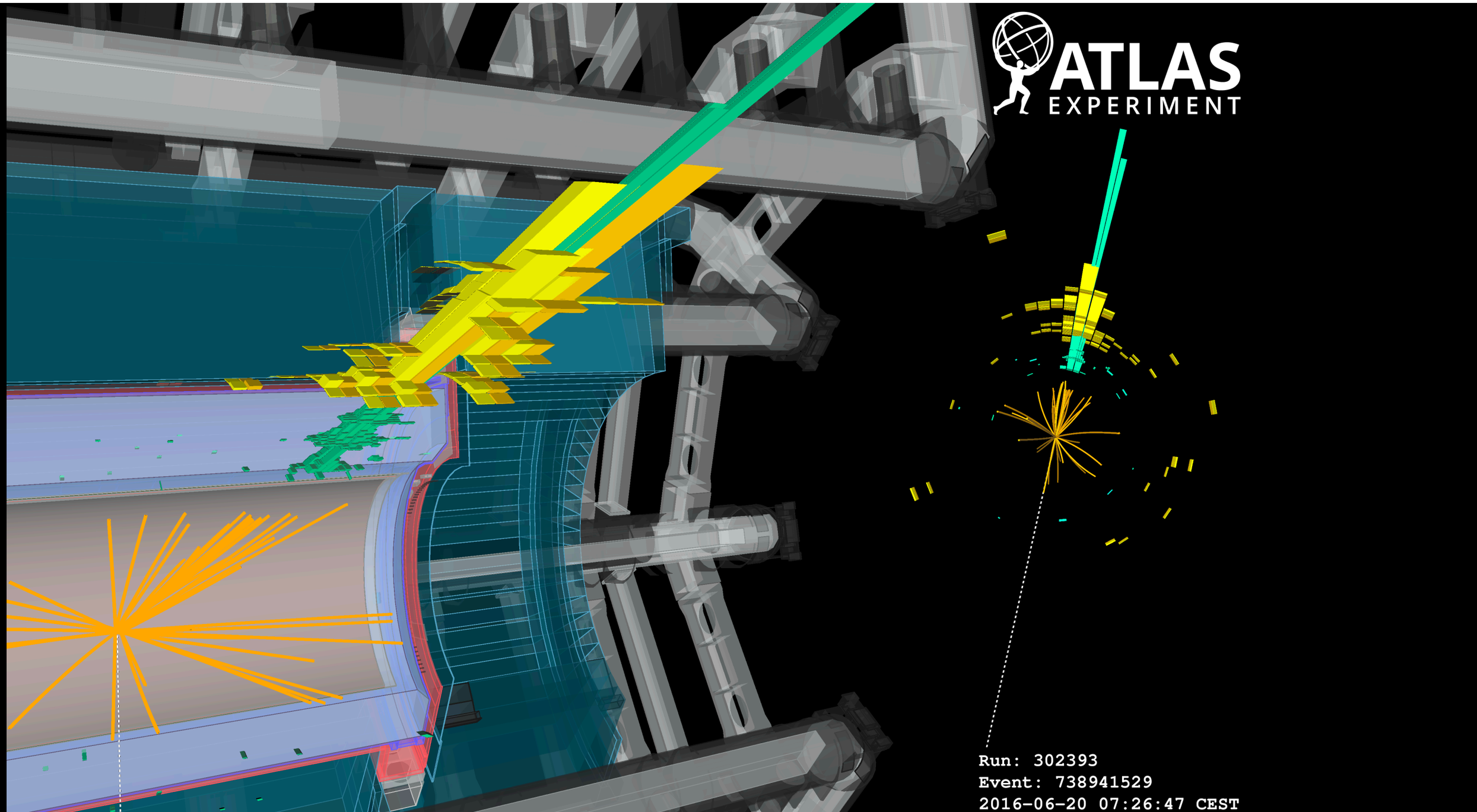
# The collider ansatz



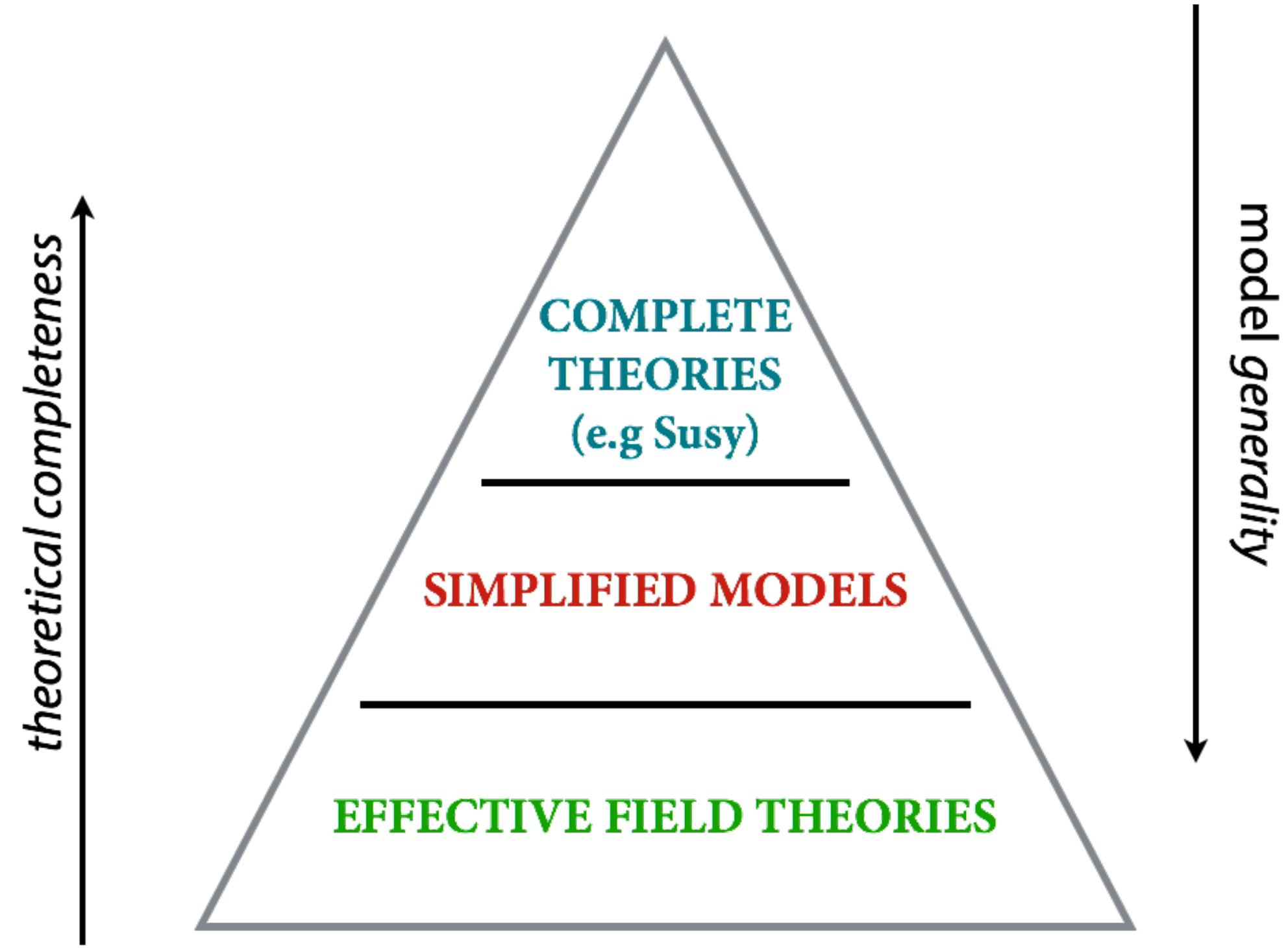

1. Production mechanism / theoretical framework

2. Particles detection and identification

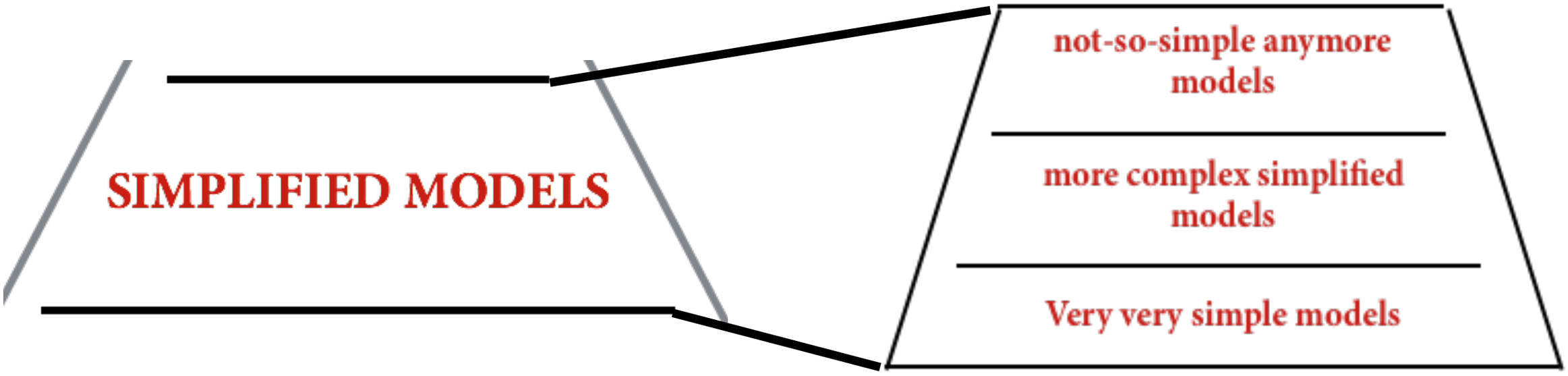
# 1. Production mechanism



# Theoretical framework



# Theoretical framework



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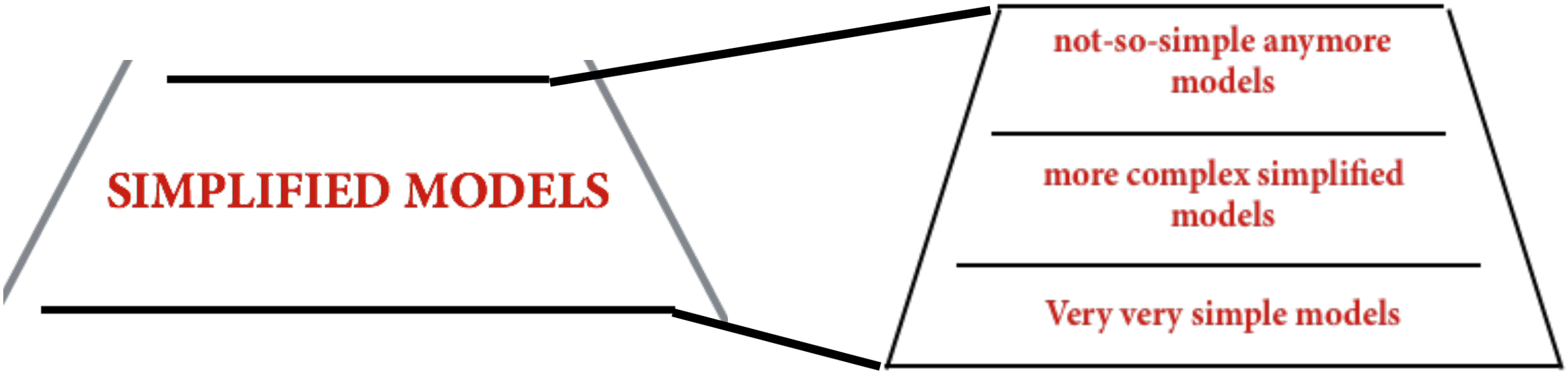
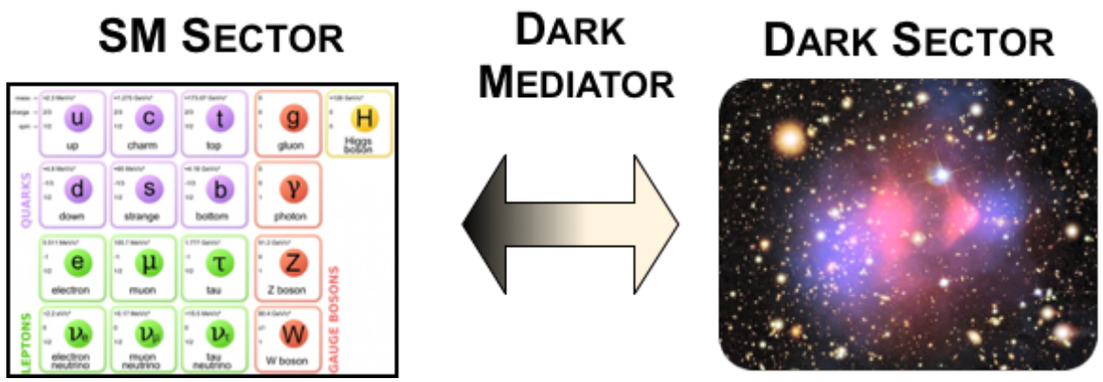
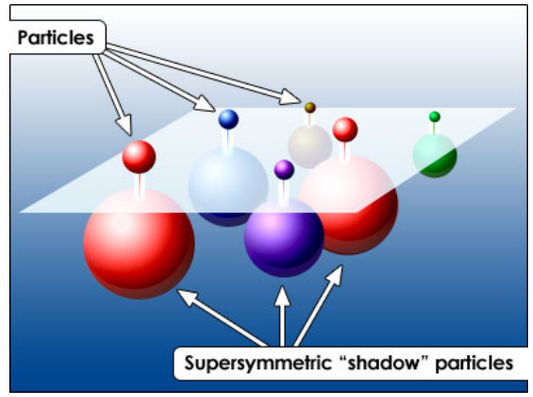



*"Mediator-based DM models"*

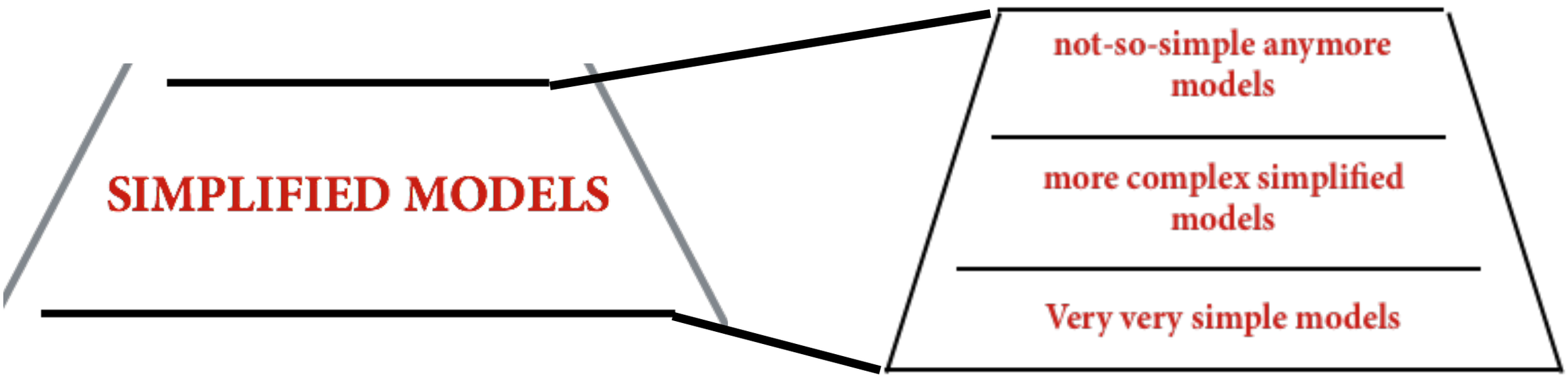



*"SUSY simplified models"*




*+ "Higgs Portal DM models" + axions*

# Theoretical framework

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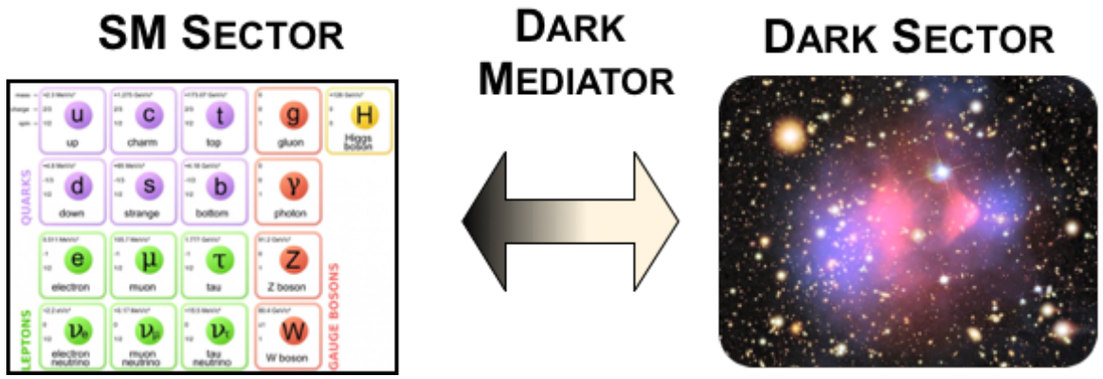
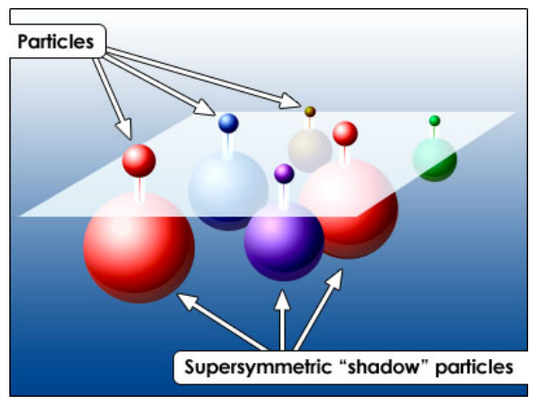



**not covered further**

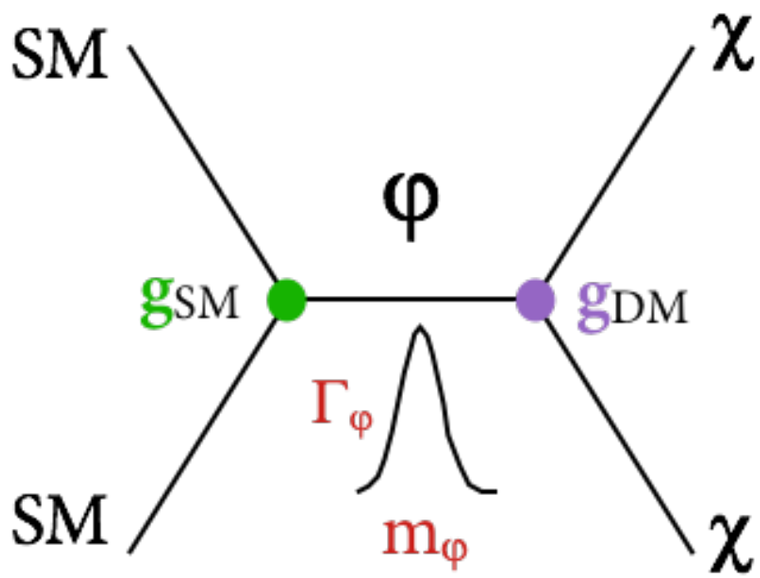
*"SUSY simplified models"*




*+ "Higgs Portal DM models" + axions*

# 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

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

**Selected results on spin-0 and spin-1 mediators in the following**

# Mediator simplified models

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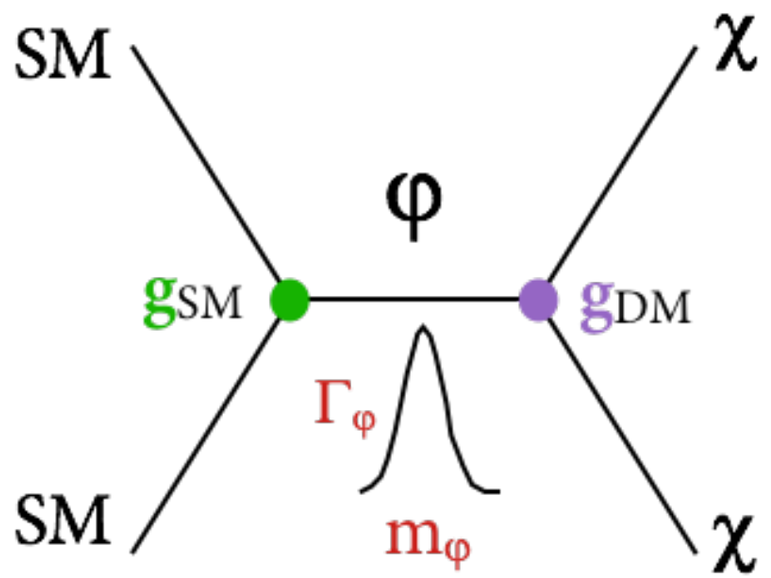


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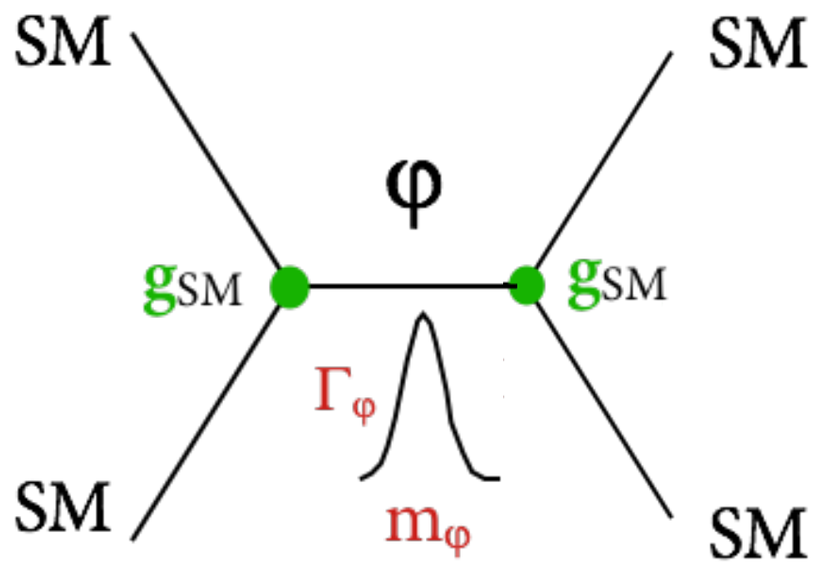
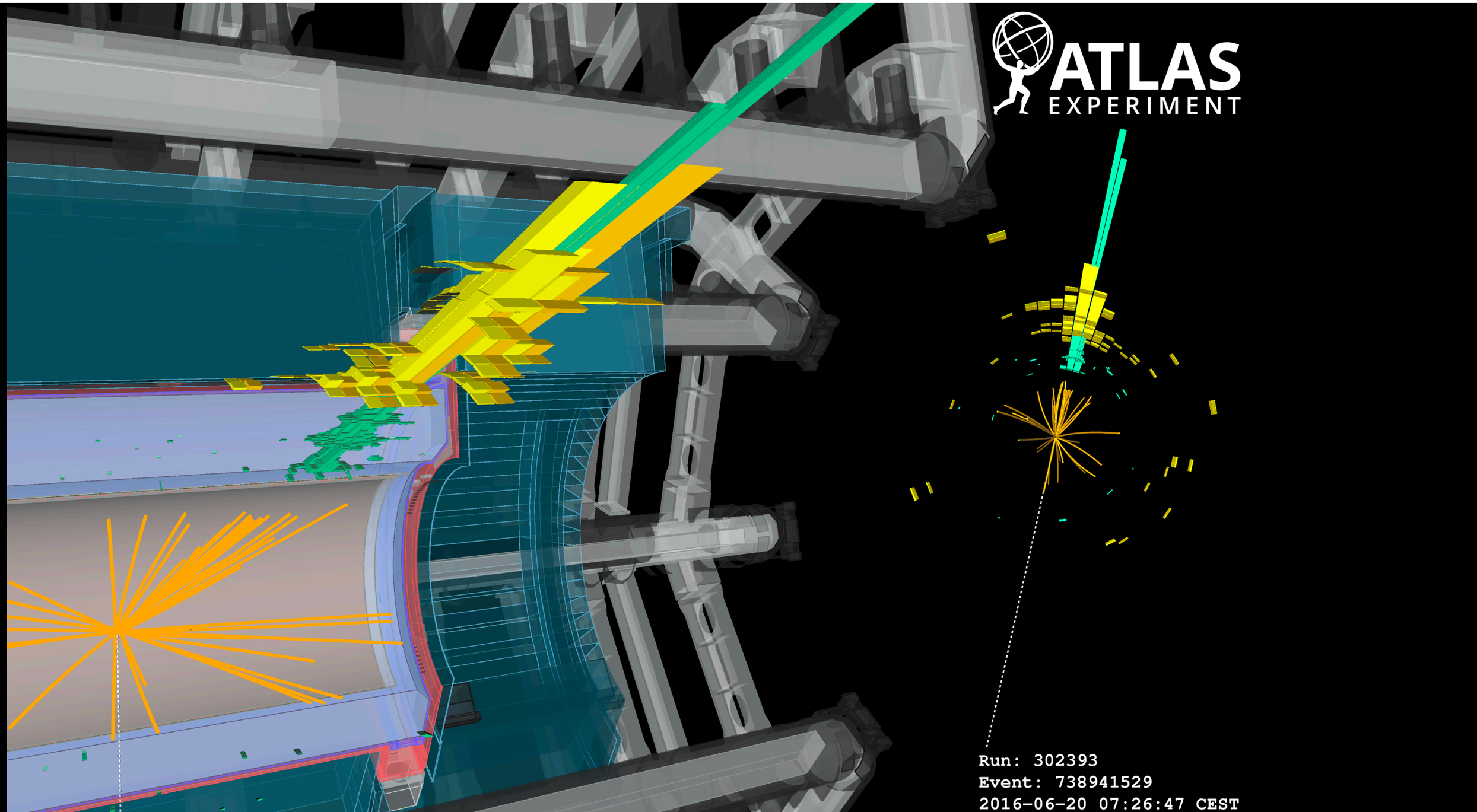


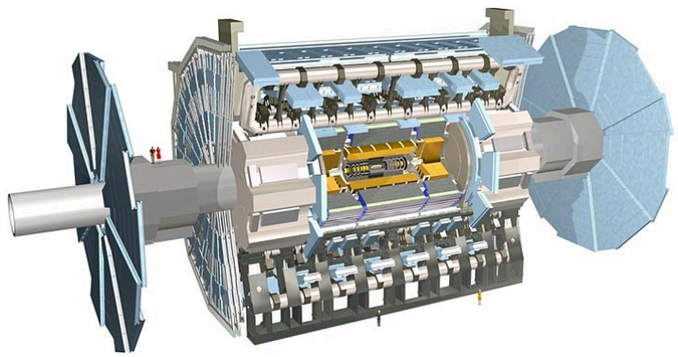

Resonance

**Selected results on spin-0 and spin-1 mediators in the following**

# 2. Detection and identification

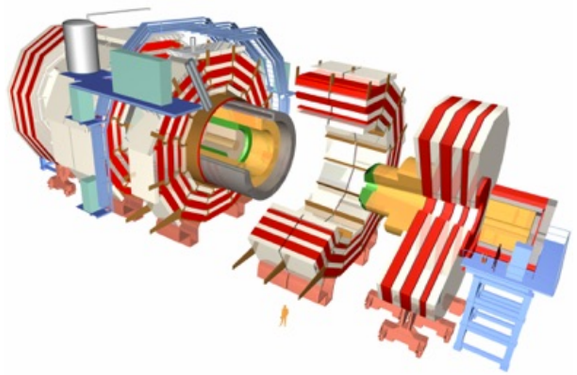


# Summary of DM Collider experiments



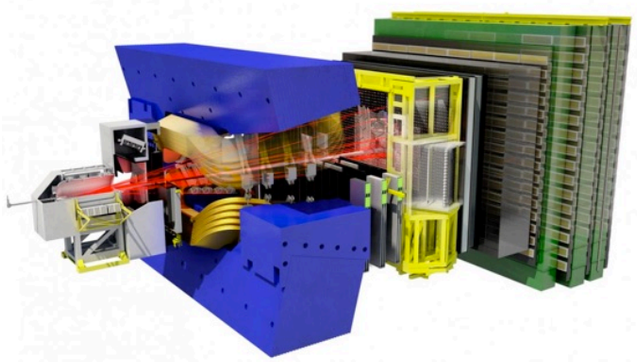
ATLAS EXPERIMENT

| | |
|---|---|
| Focus | Mediator-models & SUSY |
| DM Results | Public Page |
| Overview : | DM Summary Paper |



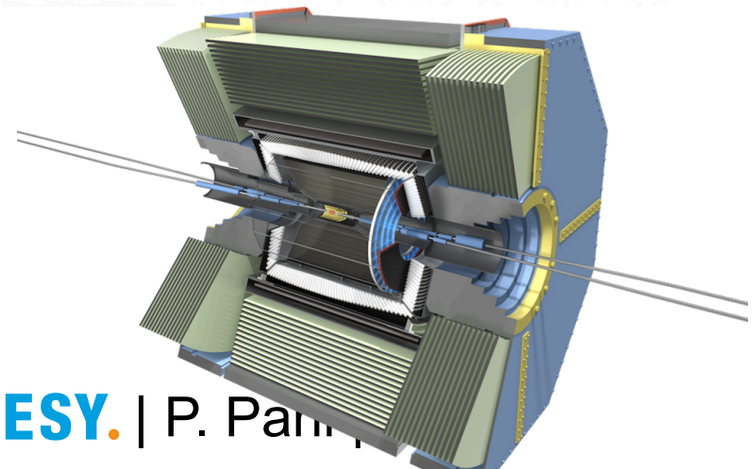
CMS

| | |
|---|---|
| Focus | Mediator-models & SUSY |
| DM Results | EXOTICA, B2G |
| Overview (2018): | DM summary plots |



LHCb

| | |
|---|---|
| Focus | B-mesons, loops, resonance |
| DM Results | Public page |



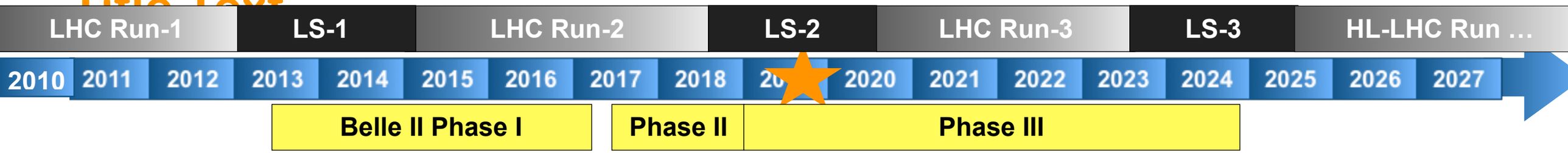
Belle II

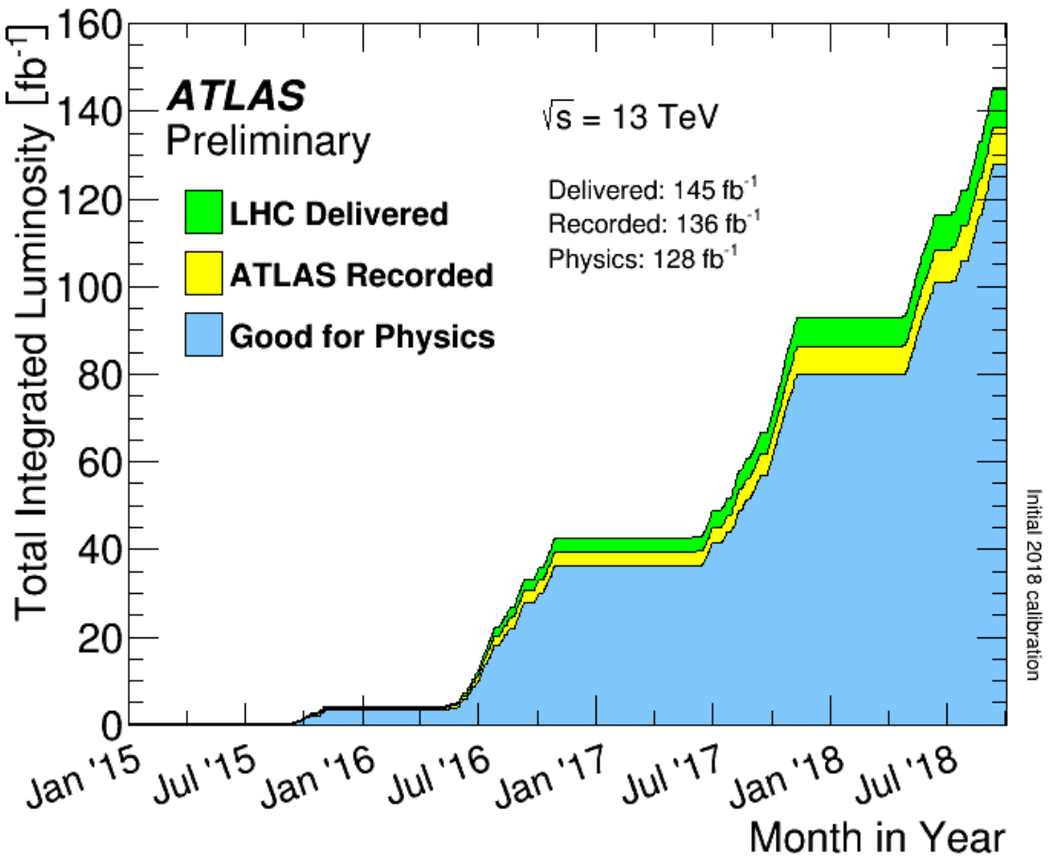
| | |
|---|---|
| Focus | B-mesons, dark sector |
| DM Results | DMPuzzle2018, BelleII Book |

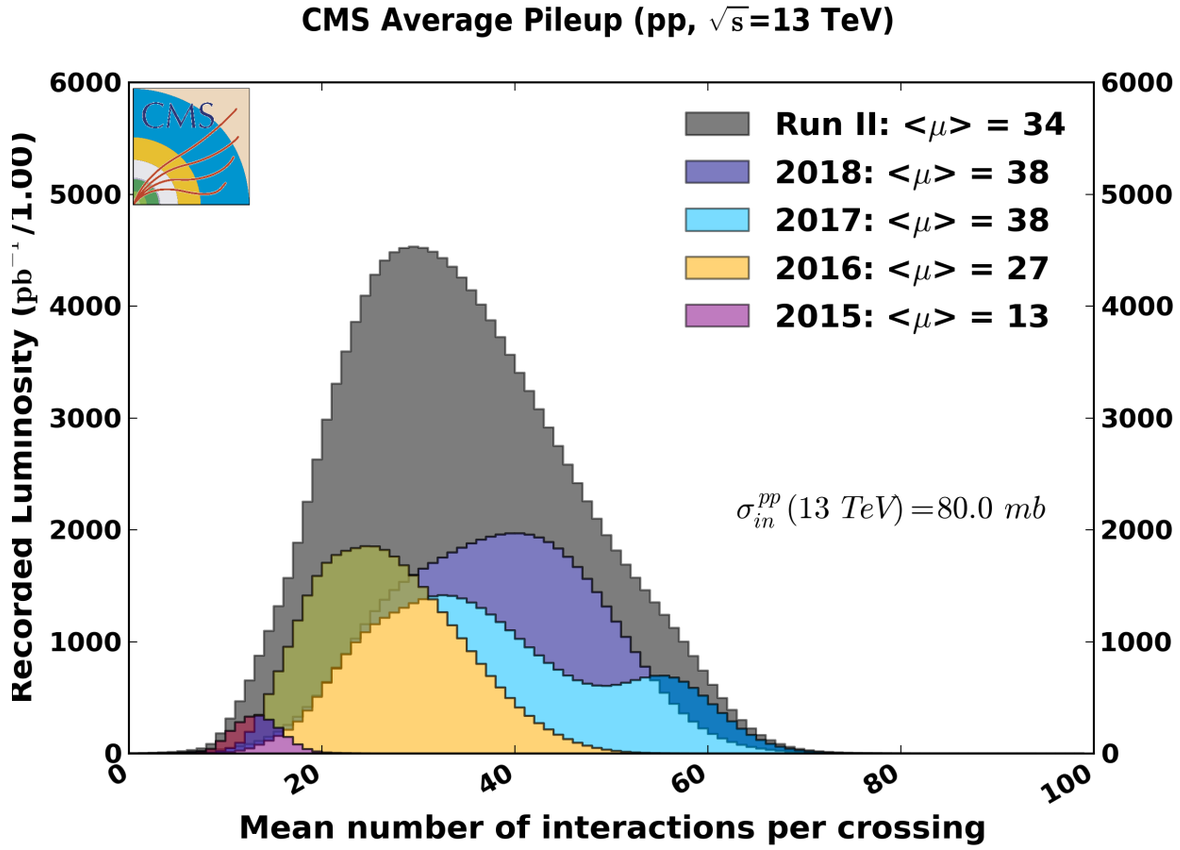
# Timelines and datasets

Title Text

you are here



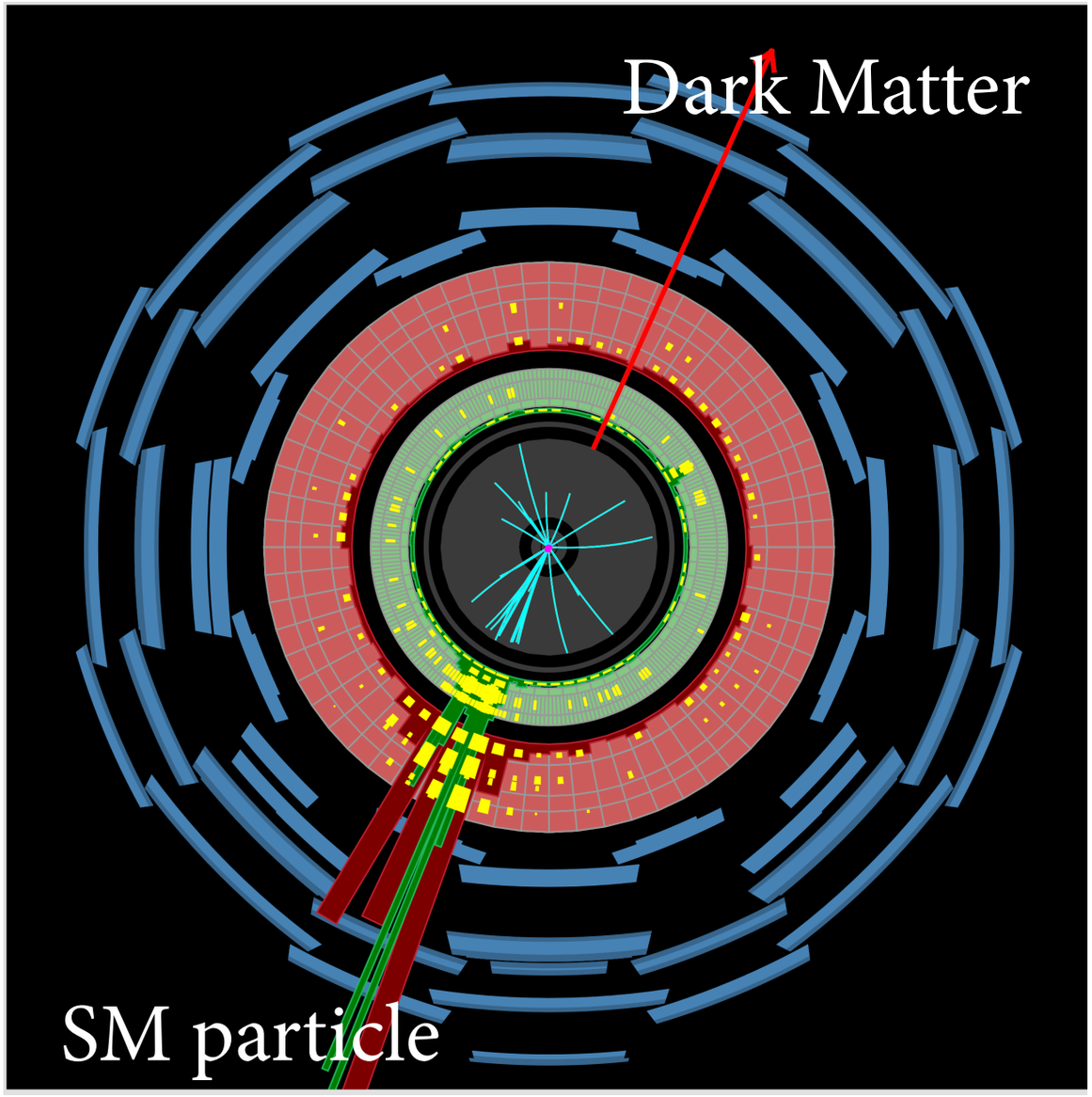



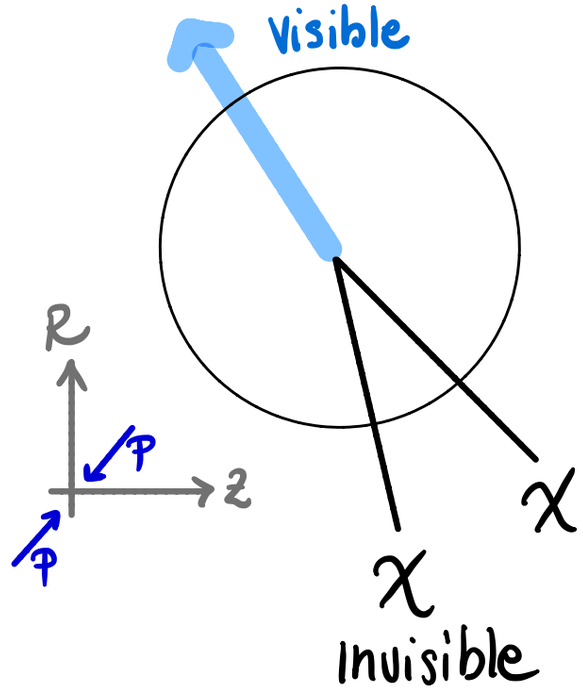



# Particles detection

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

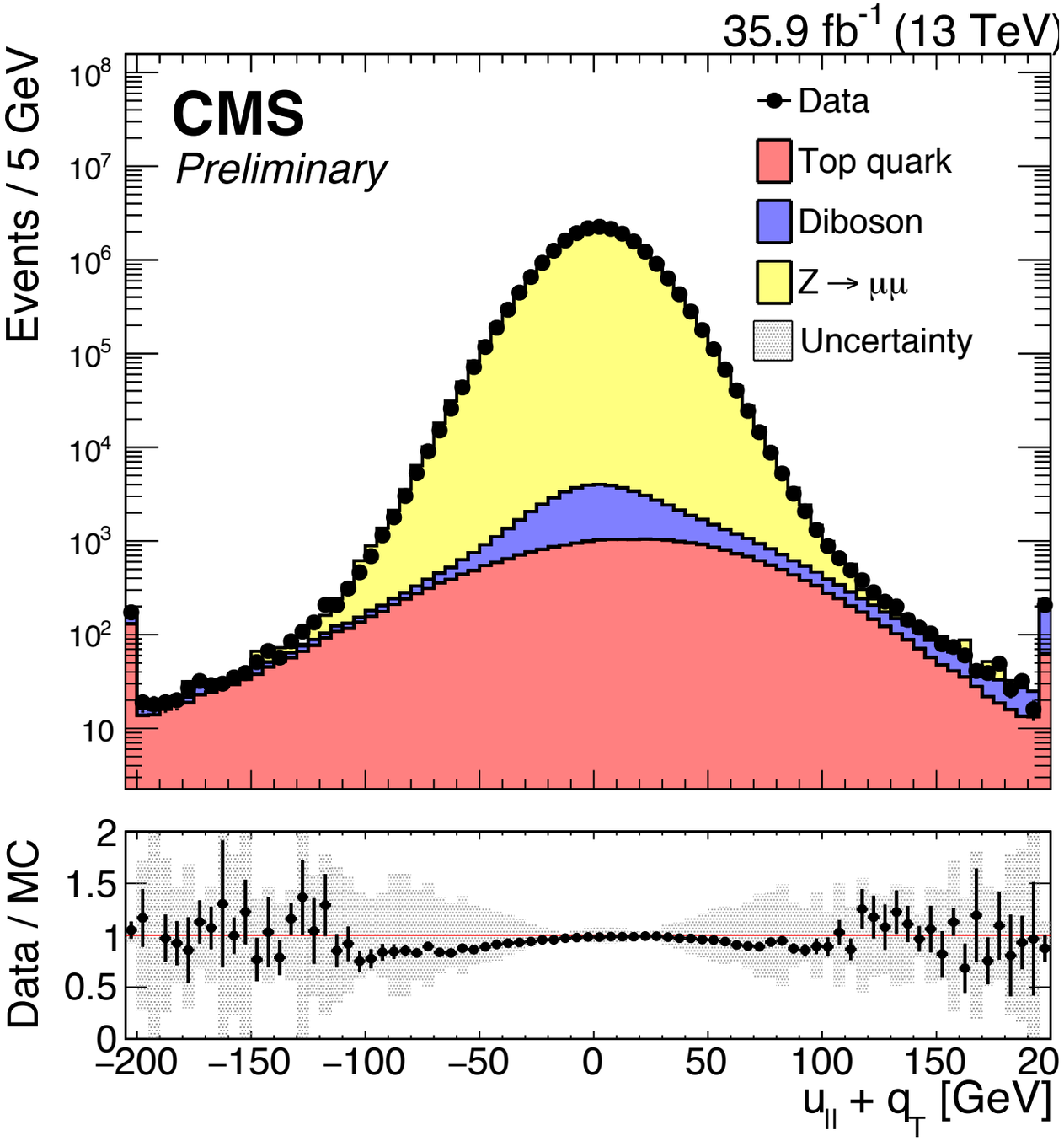
- Electrons
- Muons
- Photons
- jets
- b-jets/c-jets
- invisible particles

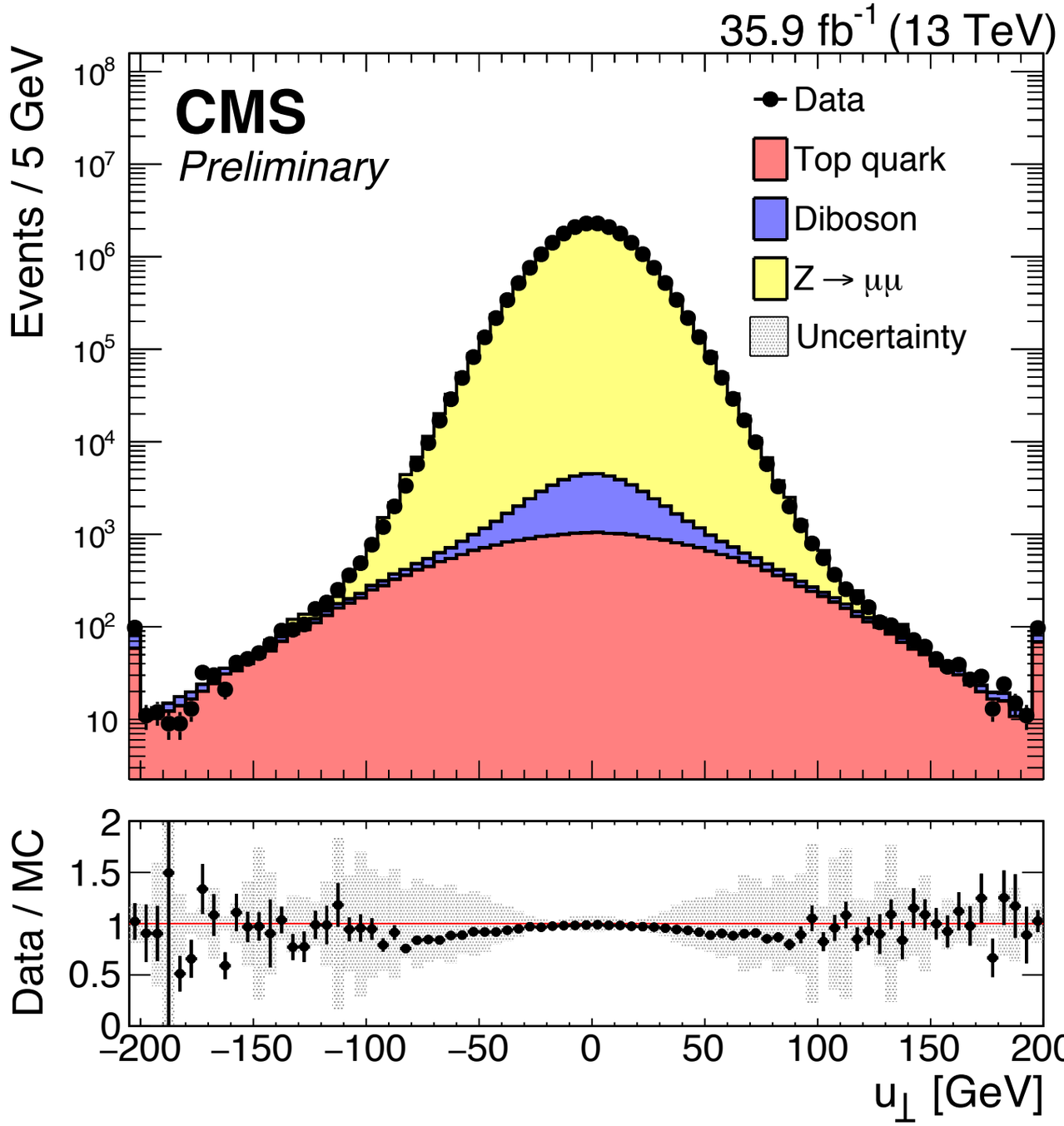



C. Doglioni TeVPa2018

# Missing Energy performance

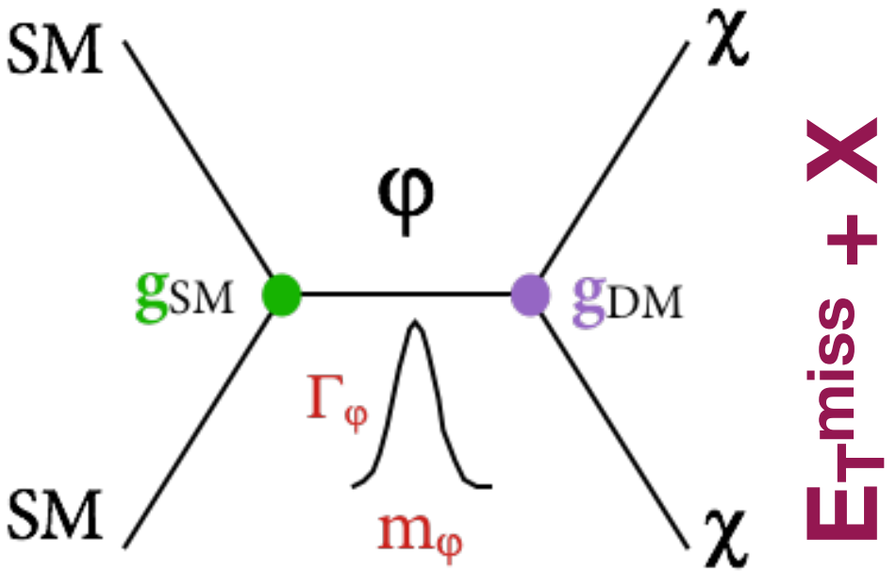


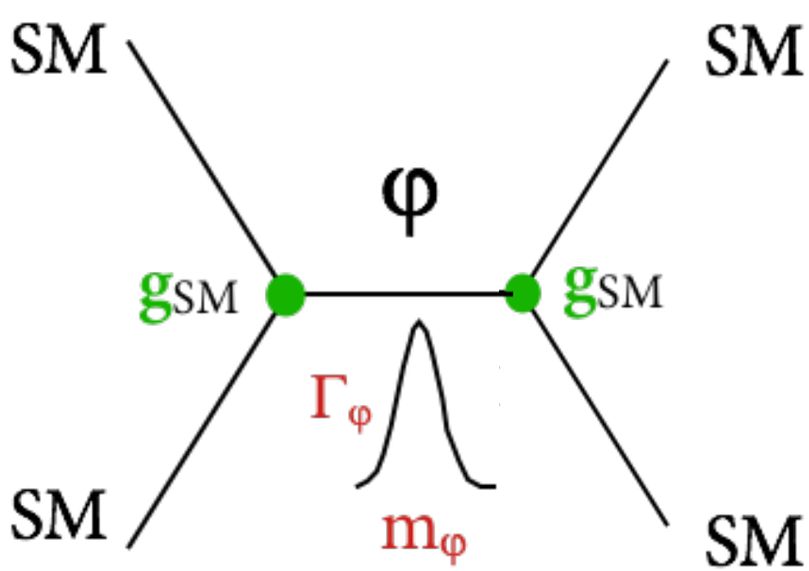

CMS-PAS-JME-17-001

# Mediator simplified models

## Reminder




× + $E_T^{miss}$ +

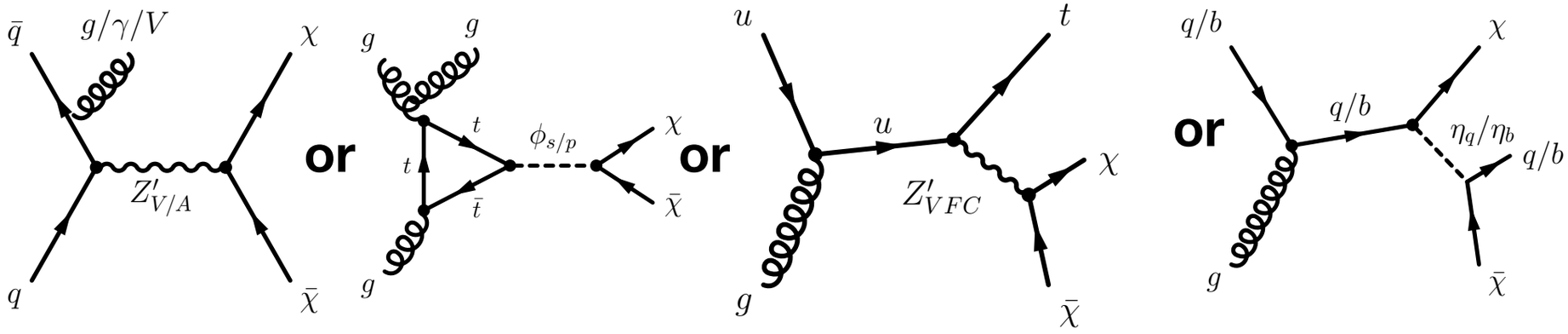


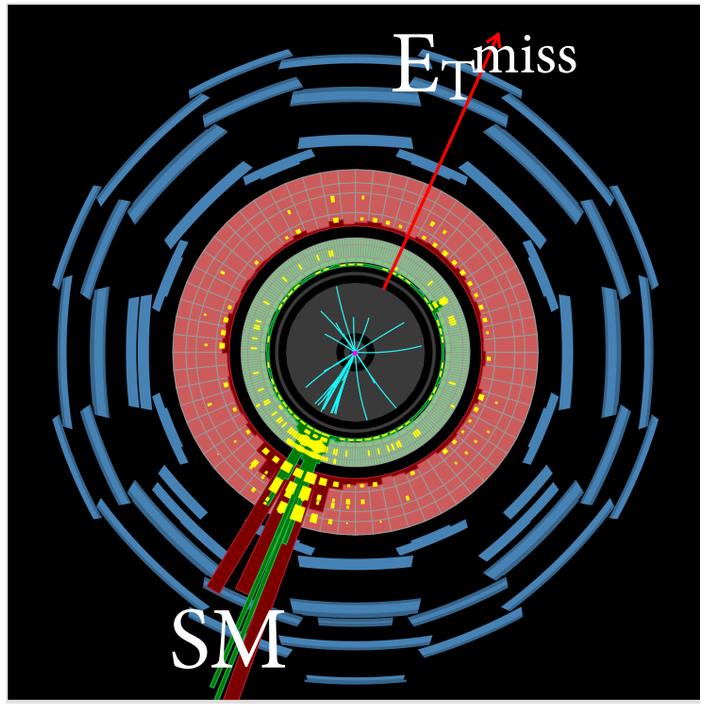

Resonance

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

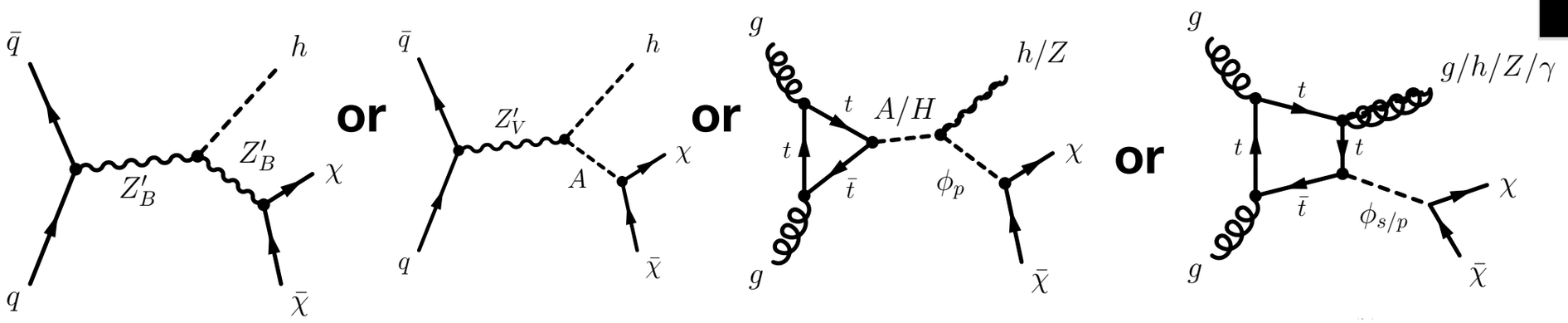
# Techniques 1 - $E_T^{miss}$ + X

## jet/b-jet/single-t/$\gamma$/V+ $E_T^{miss}$



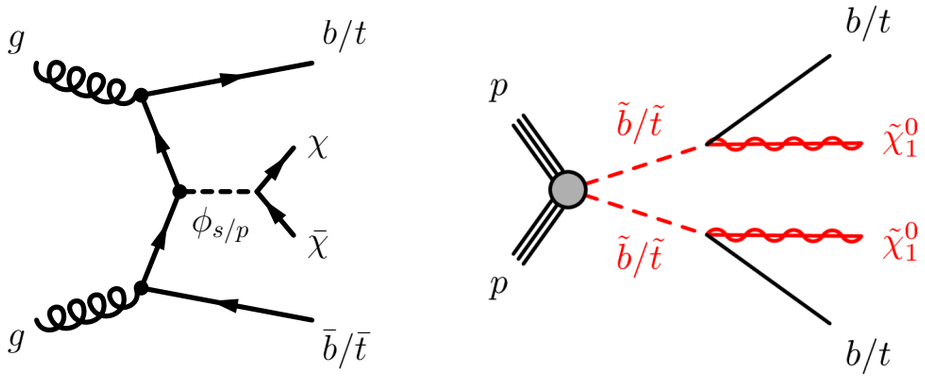




## h/Z + $E_T^{miss}$ ⟶ h(bb/$\gamma\gamma$) Strahlung/decay

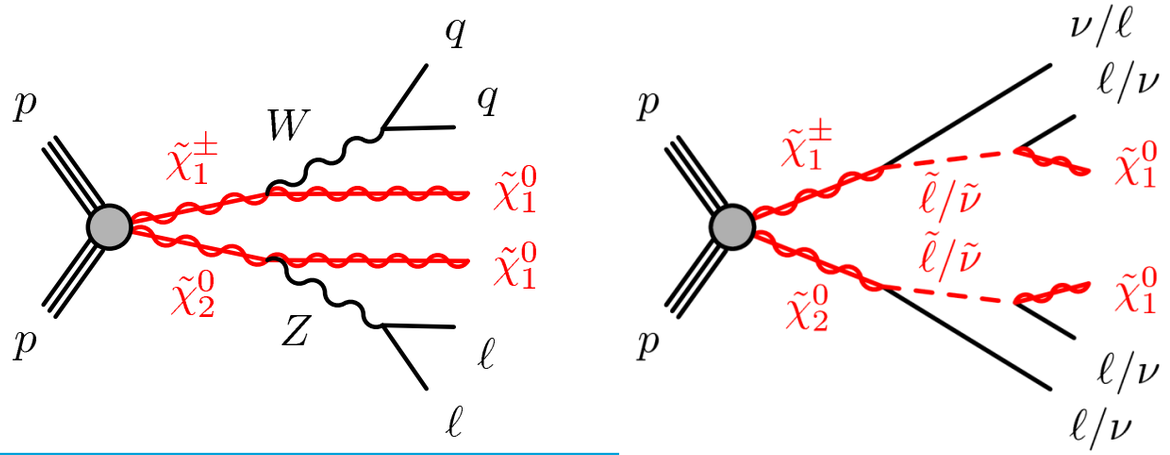



or ...

## tt / bb + $E_T^{miss}$




## 2L/2LSS/3L + $E_T^{miss}$

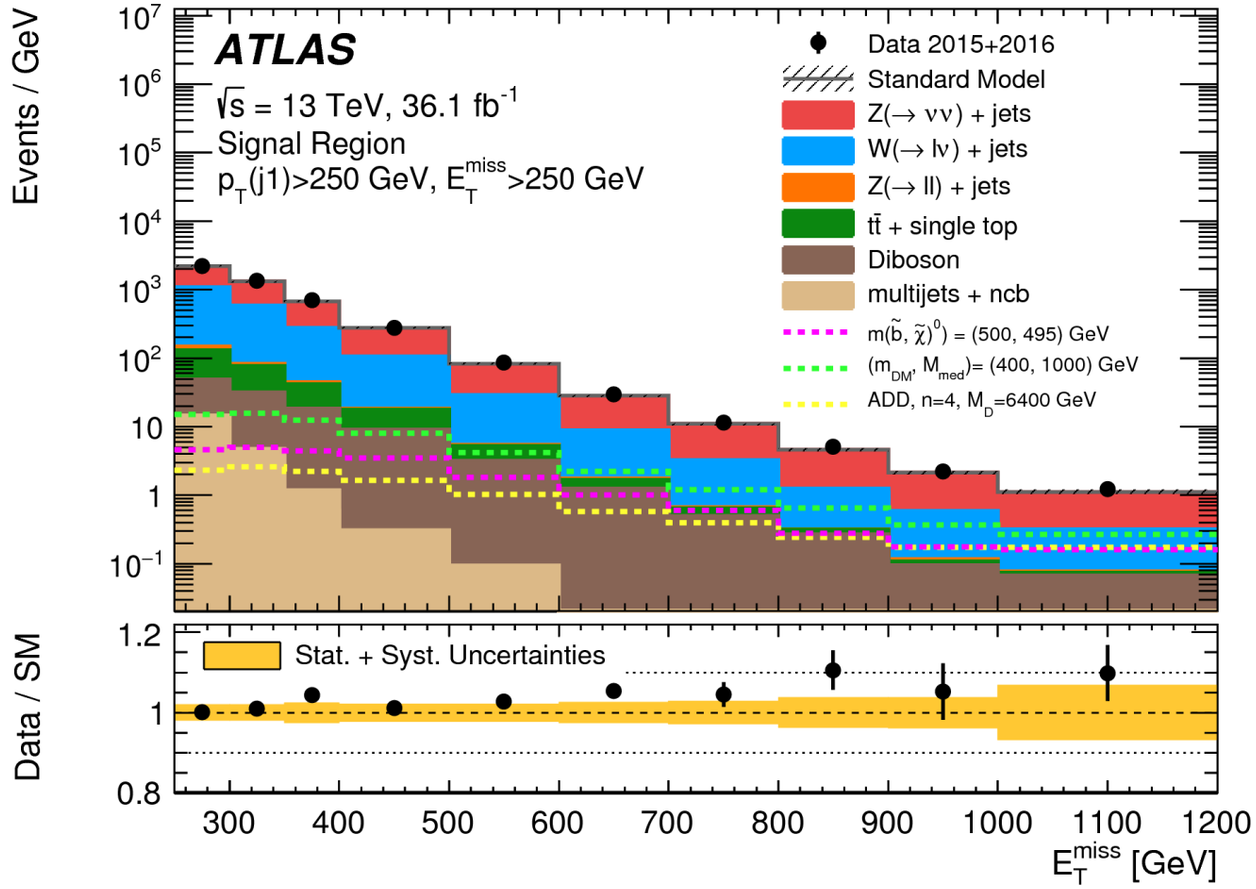


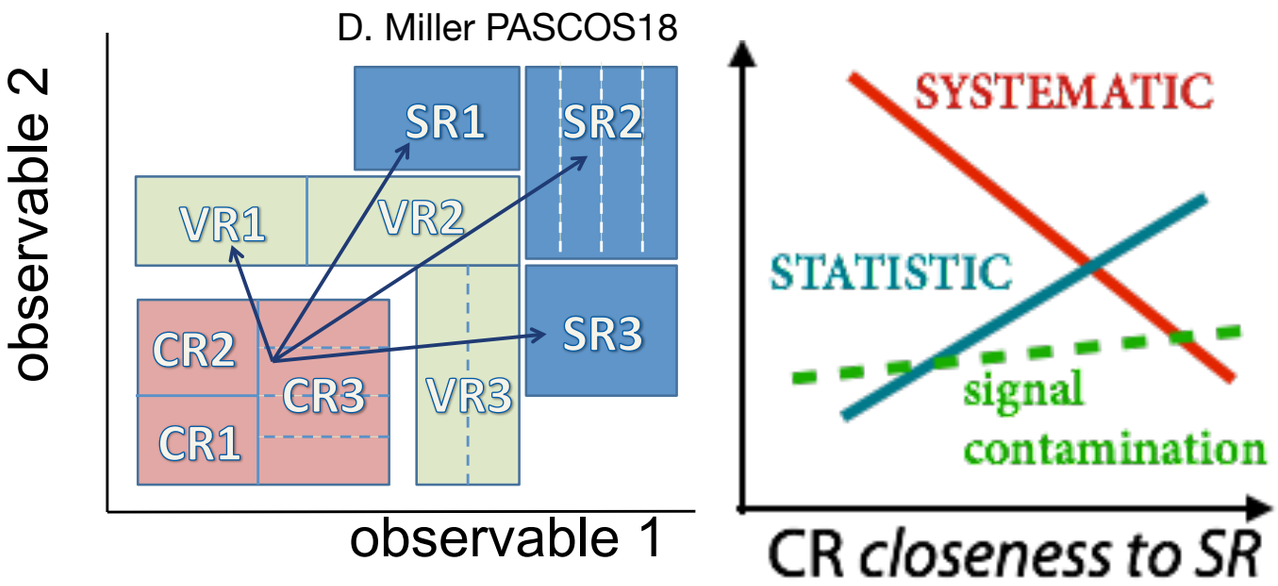
# $E_T^{miss}$ + X commonalities

1) Definition of a set of Signal enriched Regions (SR)

2) Definition of a set of Control Regions (CR) to derive a data-driven normalisation of MC with transfer factors (TF).

3) Validation of the TF in the Validation Region (VR)

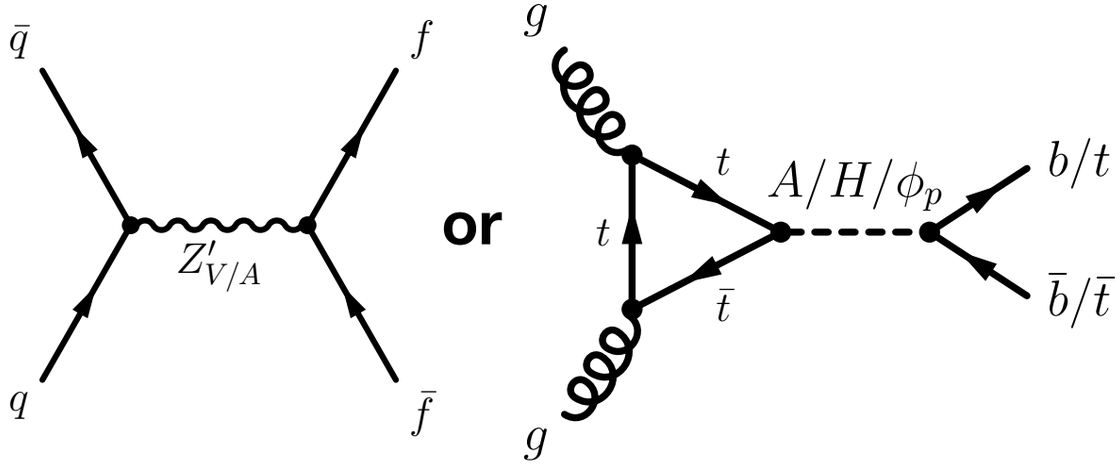


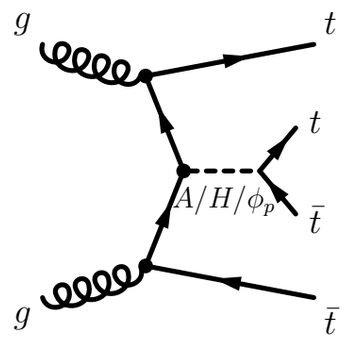

4) Unblinding ! check whether an excess is observed (p-value)

5) If no excess is found the results are interpreted in terms of limits on selected models.

# Techniques 2 - resonances

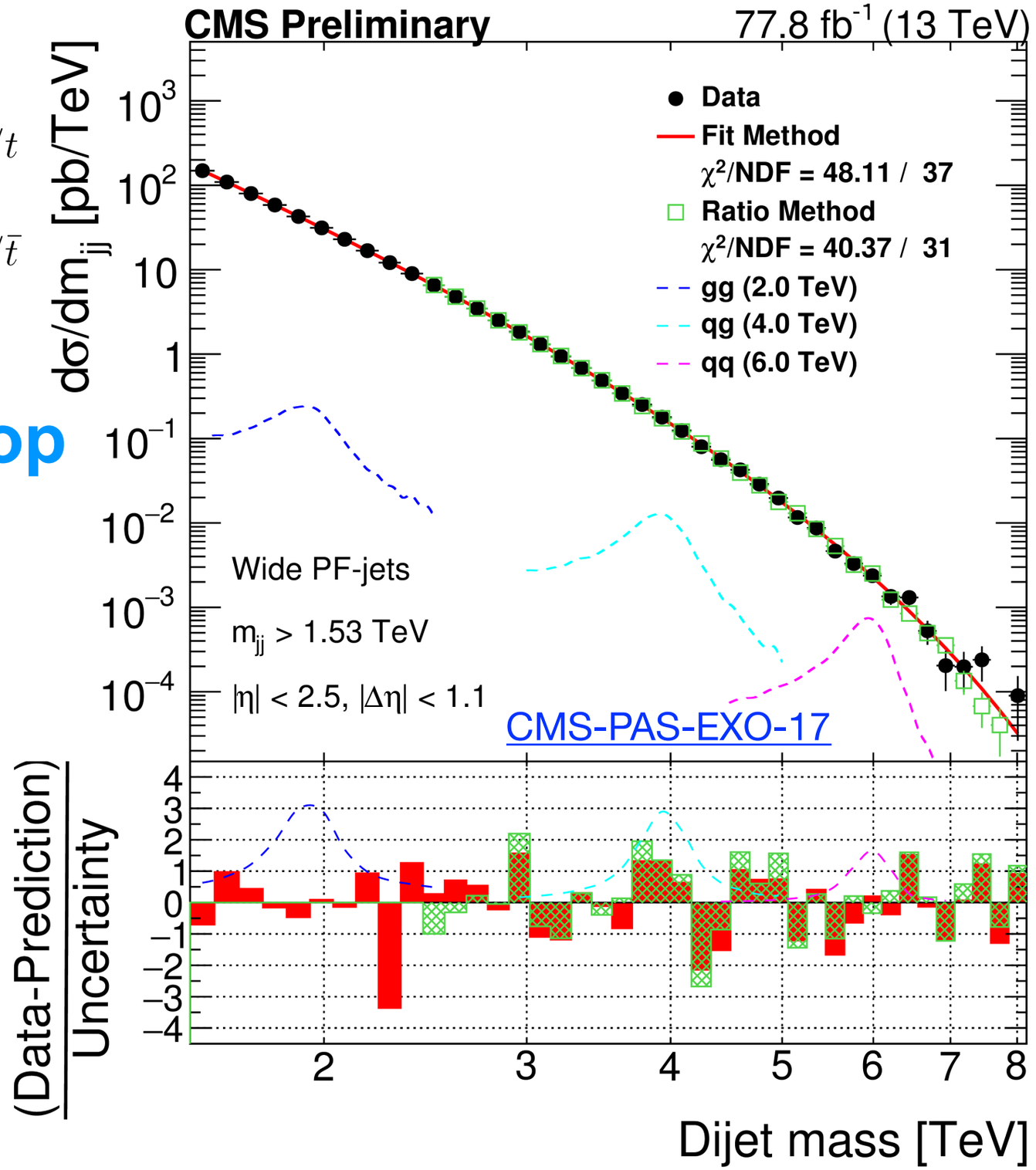



## di-jet/di-lepton/di-bjet/di-top

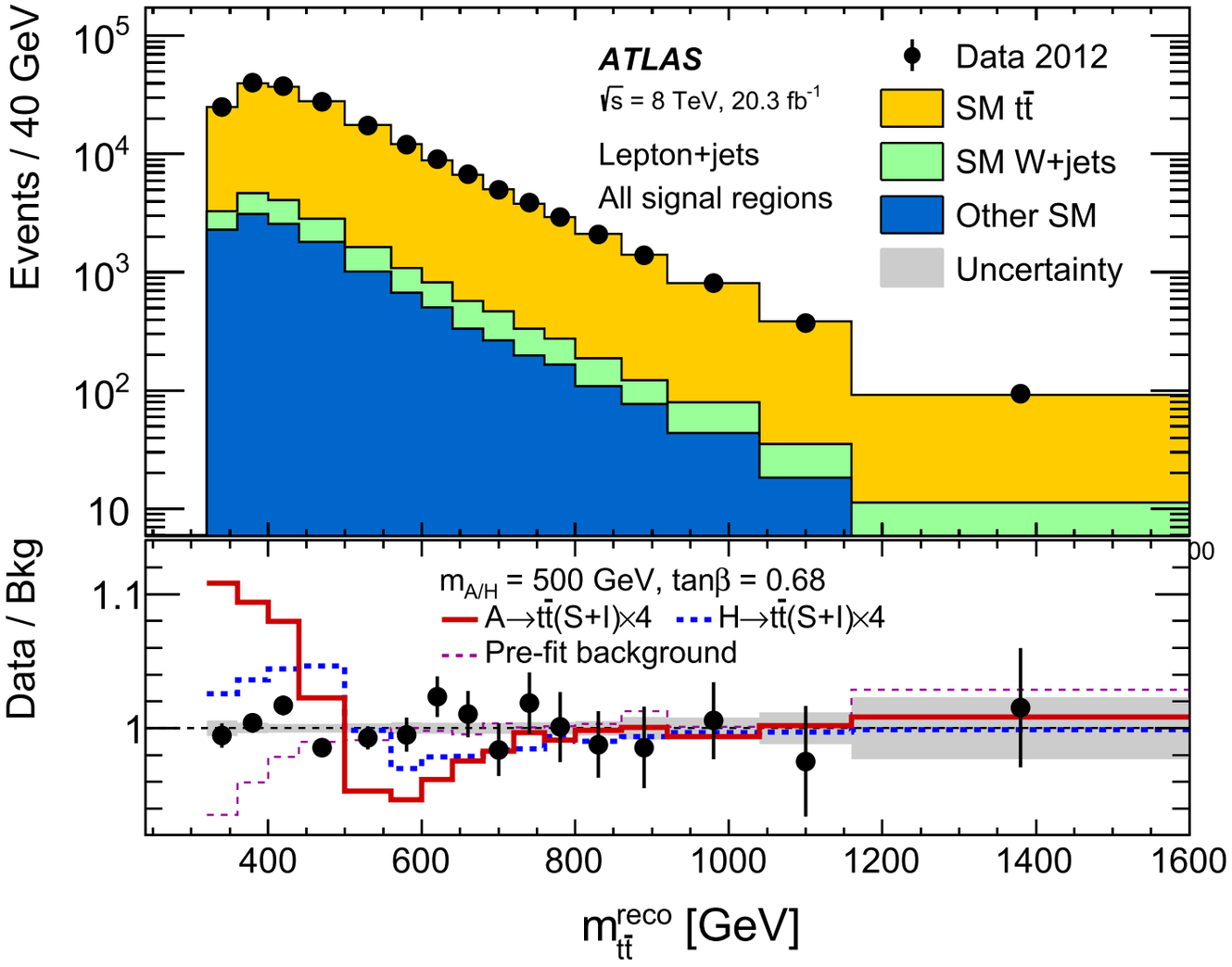


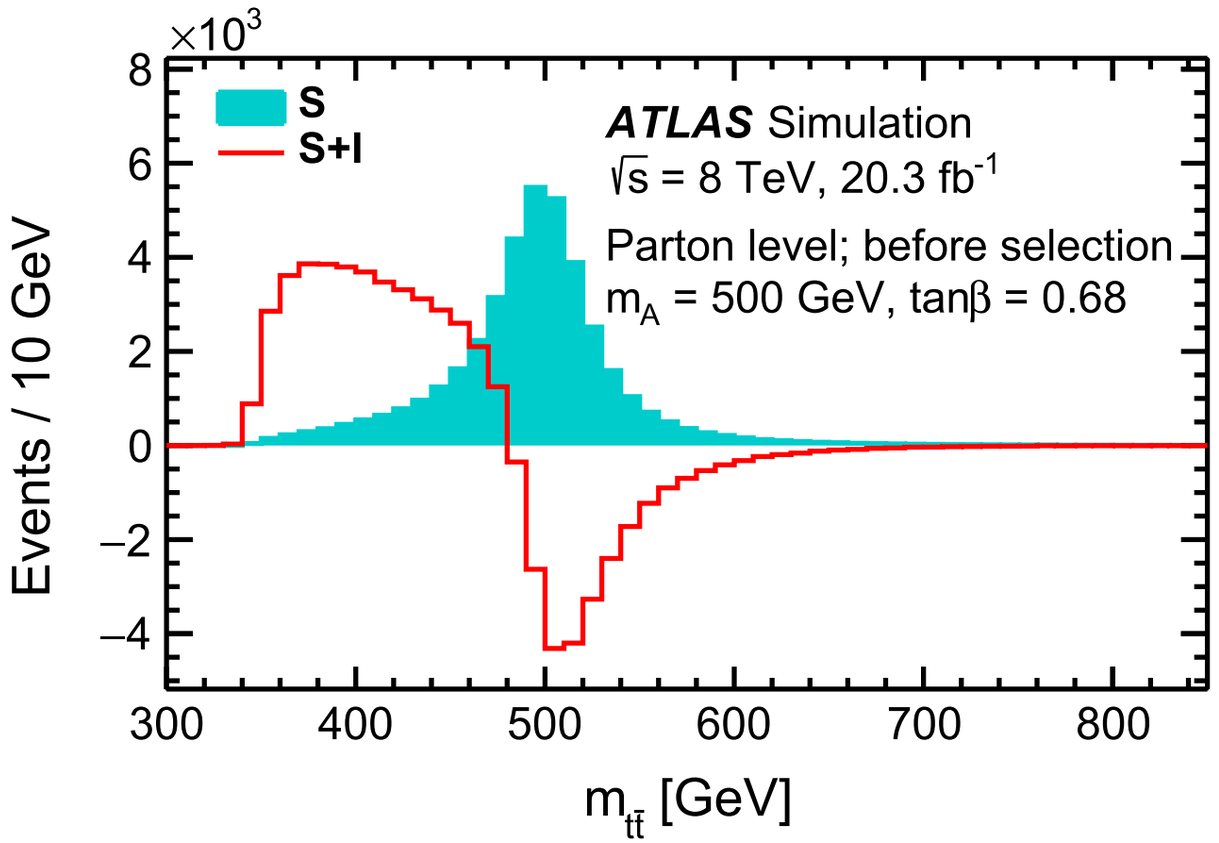

## 4tops

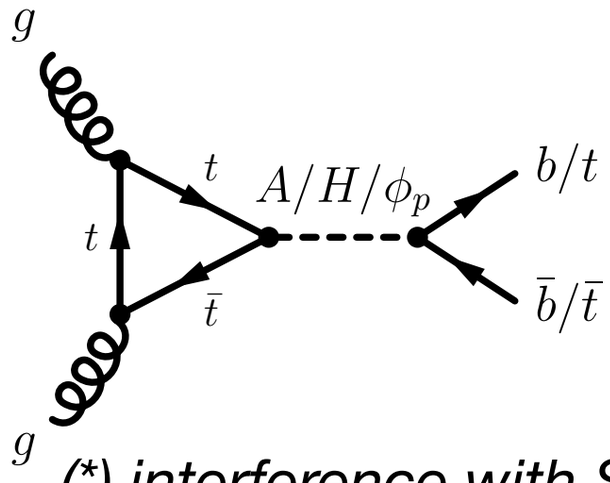
- ★ Low-mass determined by trigger (TLA/di-jet+ISR have the lowest mass sensitivity)
- ★ Sensitive to the mediator width



# A special case …



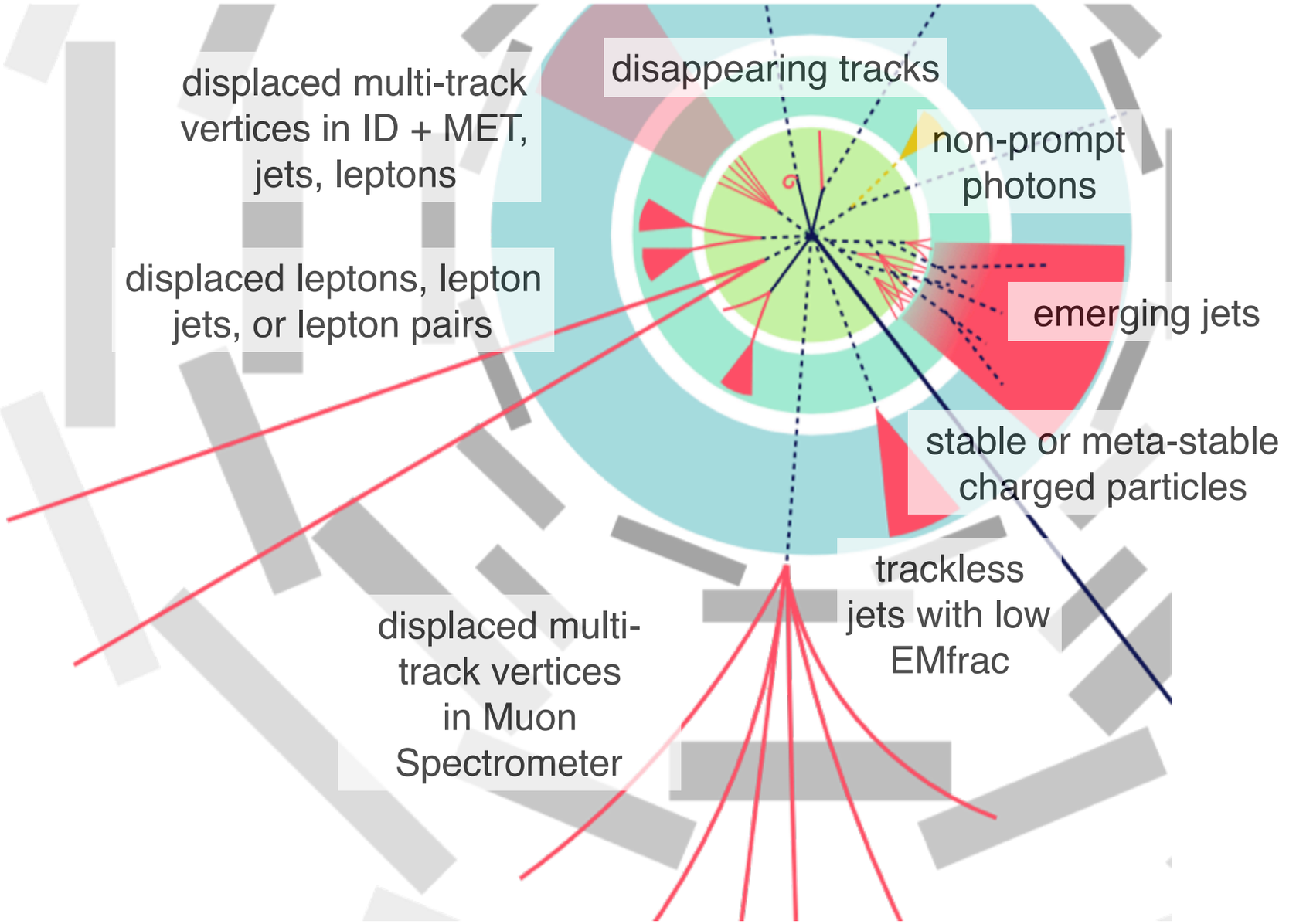




arXiv:1707.06025

*(*) interference with SM tt to be considered (e.g.1707.06025)*

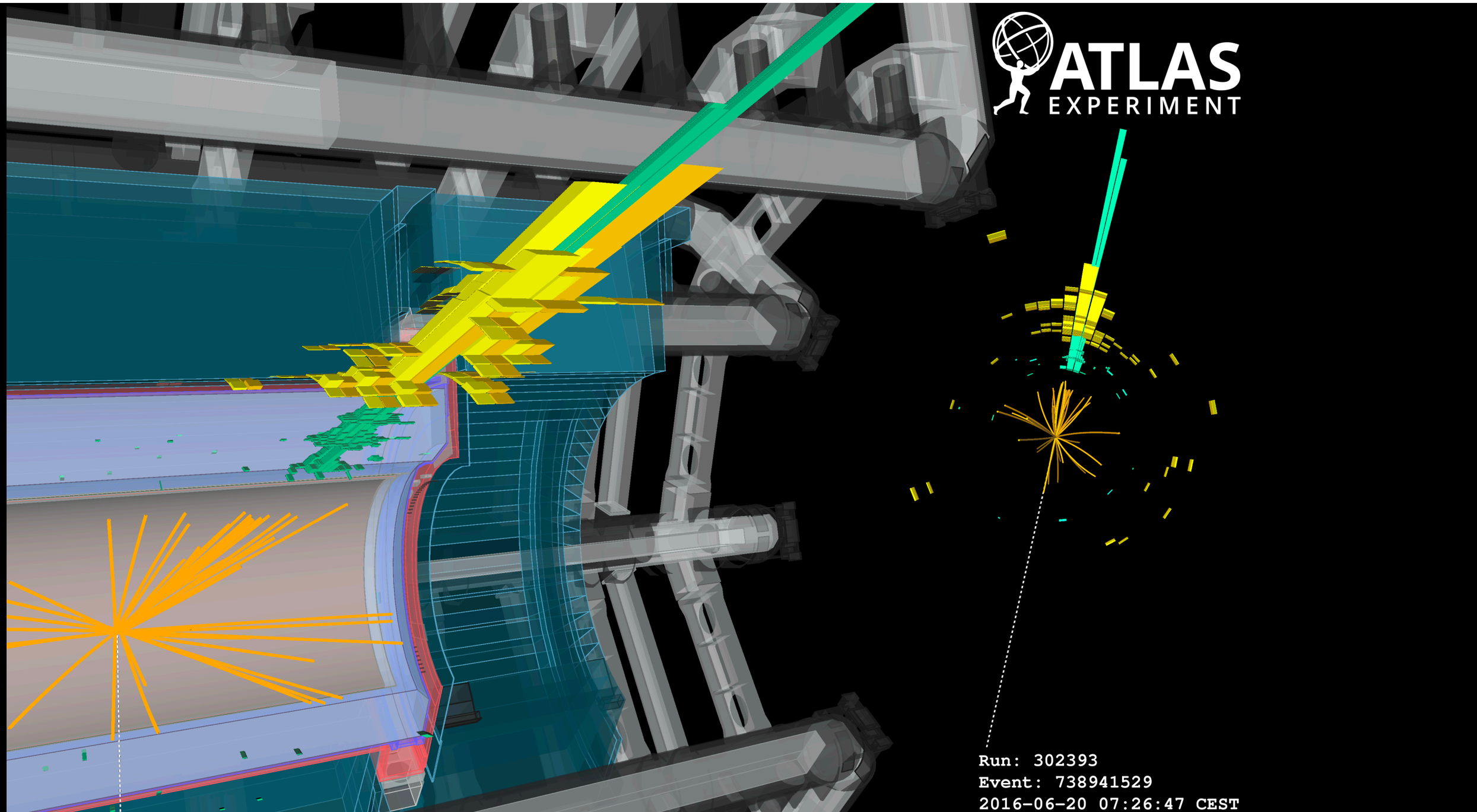
# Techniques 3 - Long Lived Particles

- 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**

# 3. Highlights for simplified models



# Spin-1 mediators - masses

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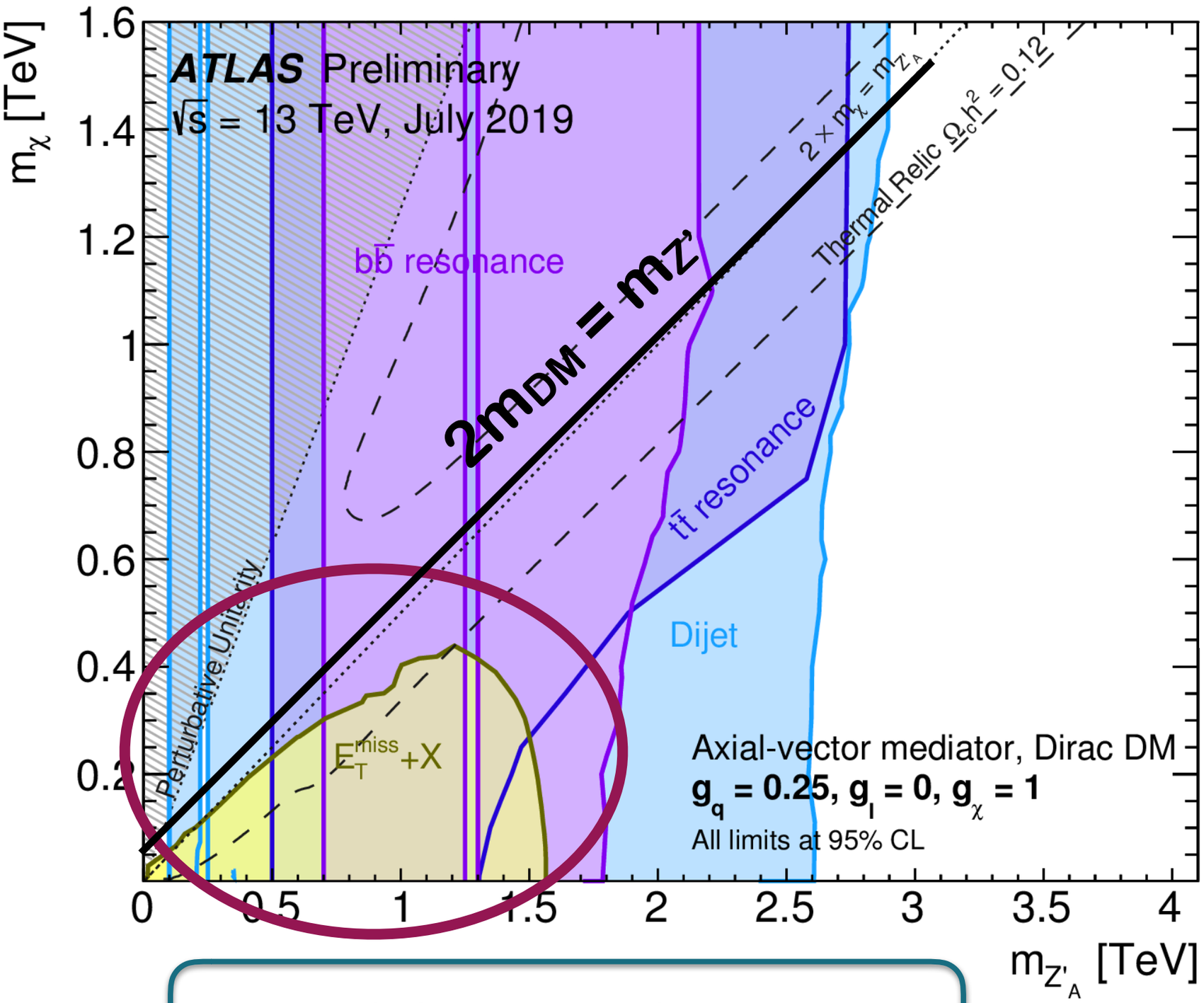
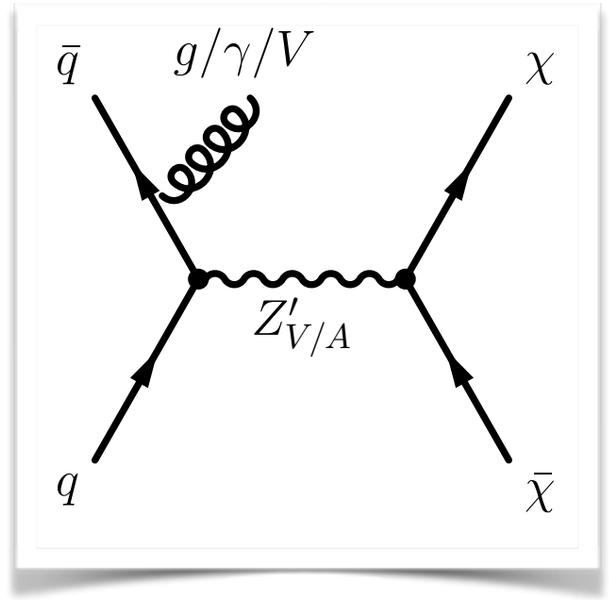
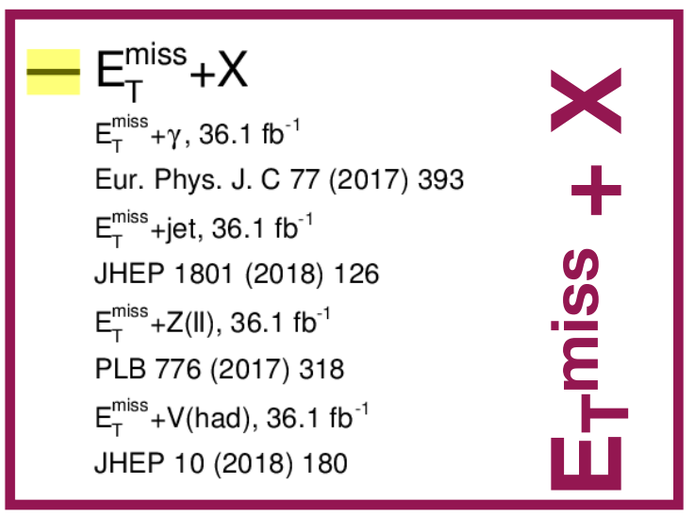


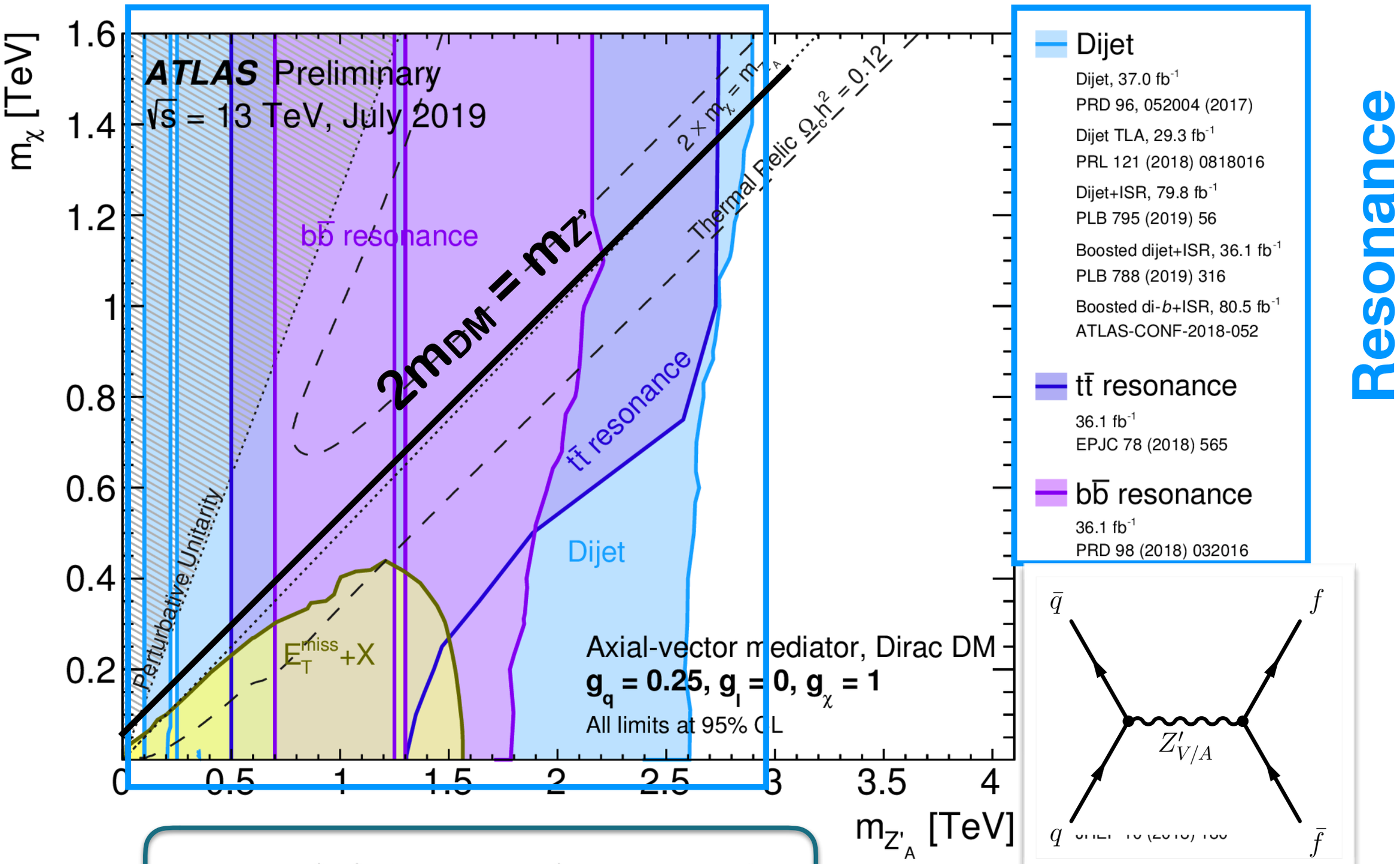




$$g_q = 0.25, g_{lep} = 0, g_{DM} = 1$$

**Axial-vector mediator**

# Spin-1 mediators - masses



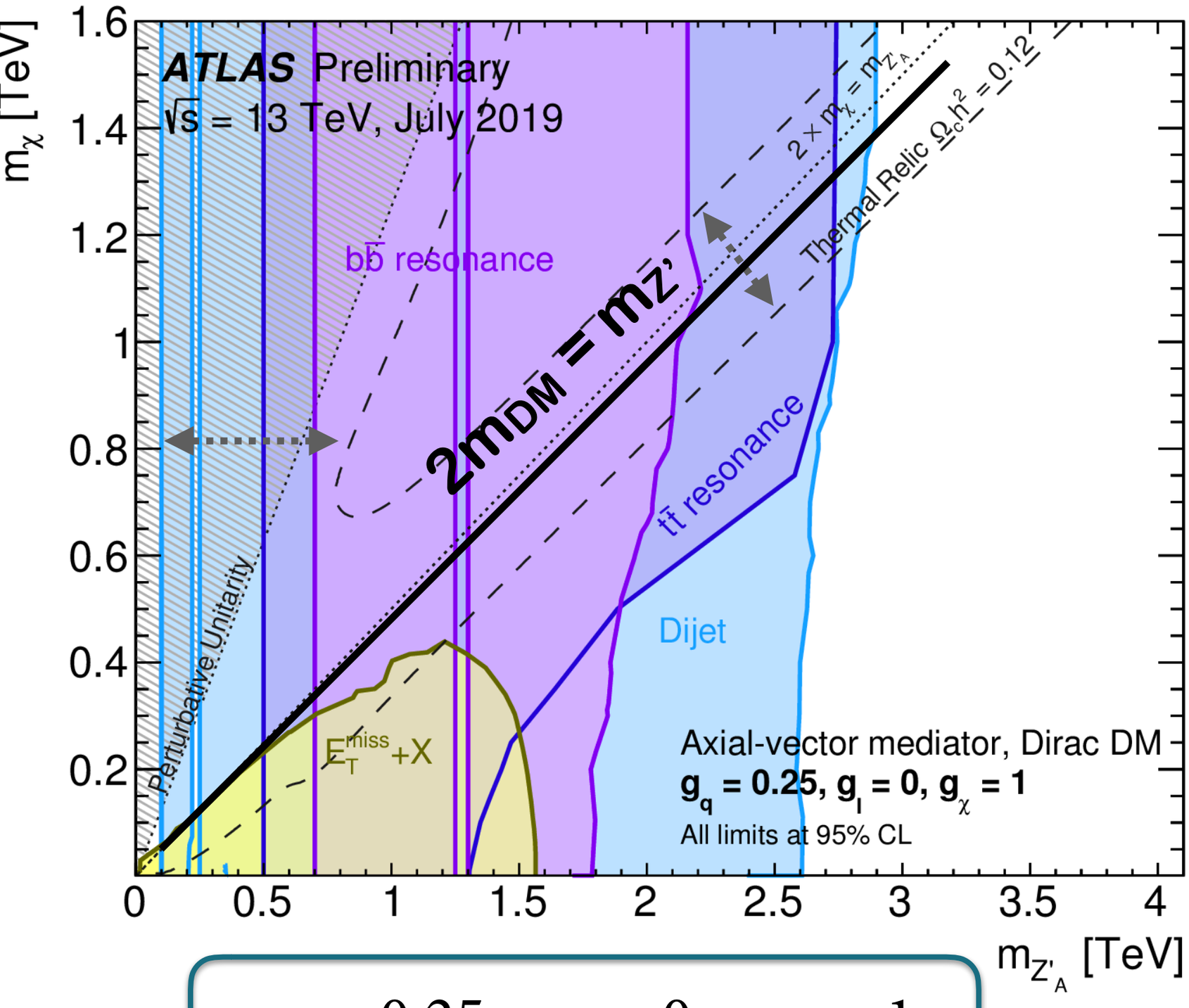

Resonance




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

## Axial-vector mediator

# Spin-1: features explained




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

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

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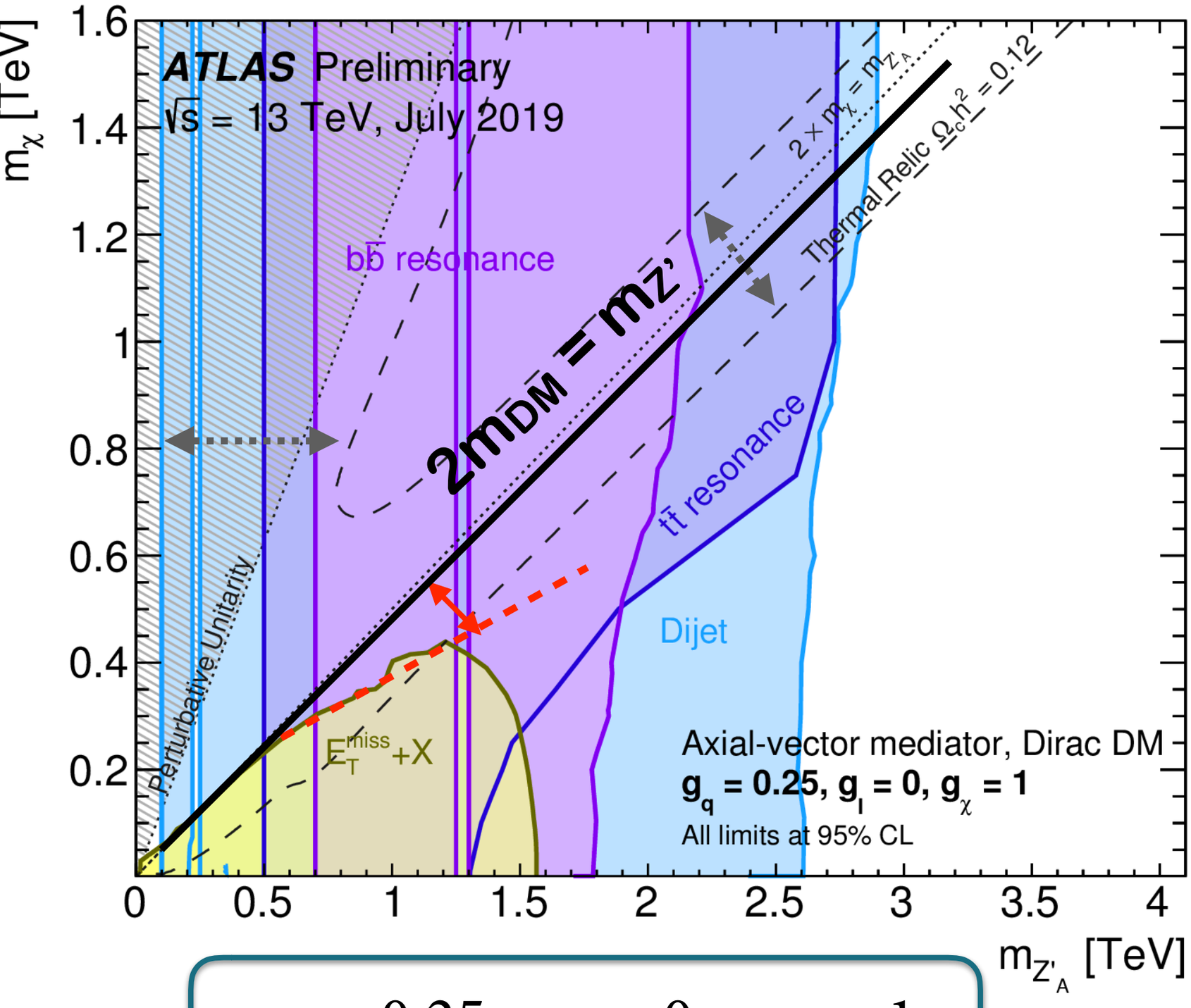


Loss of sensitivity due to mediator width effects

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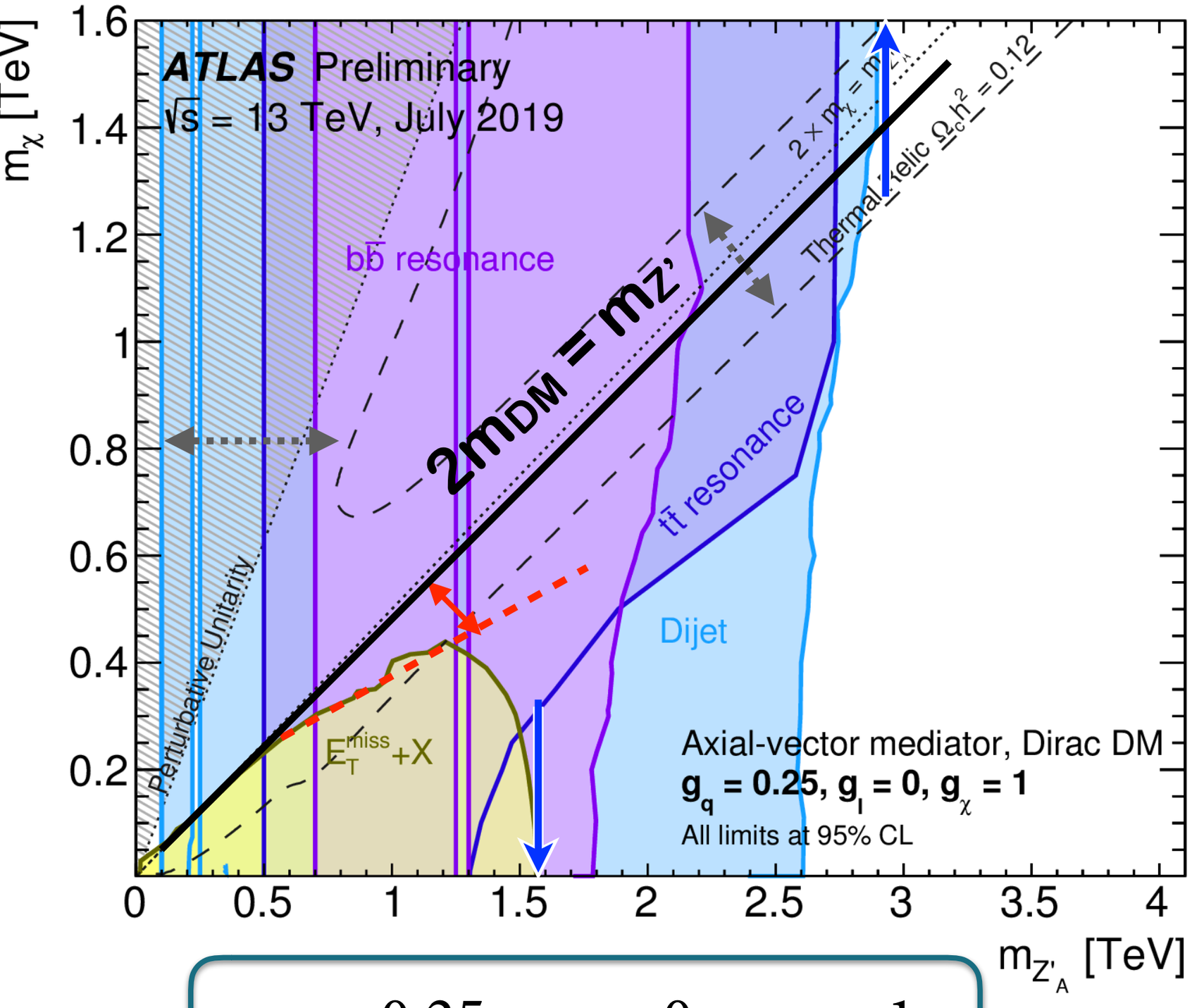


Loss of sensitivity due to mediator width effects

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

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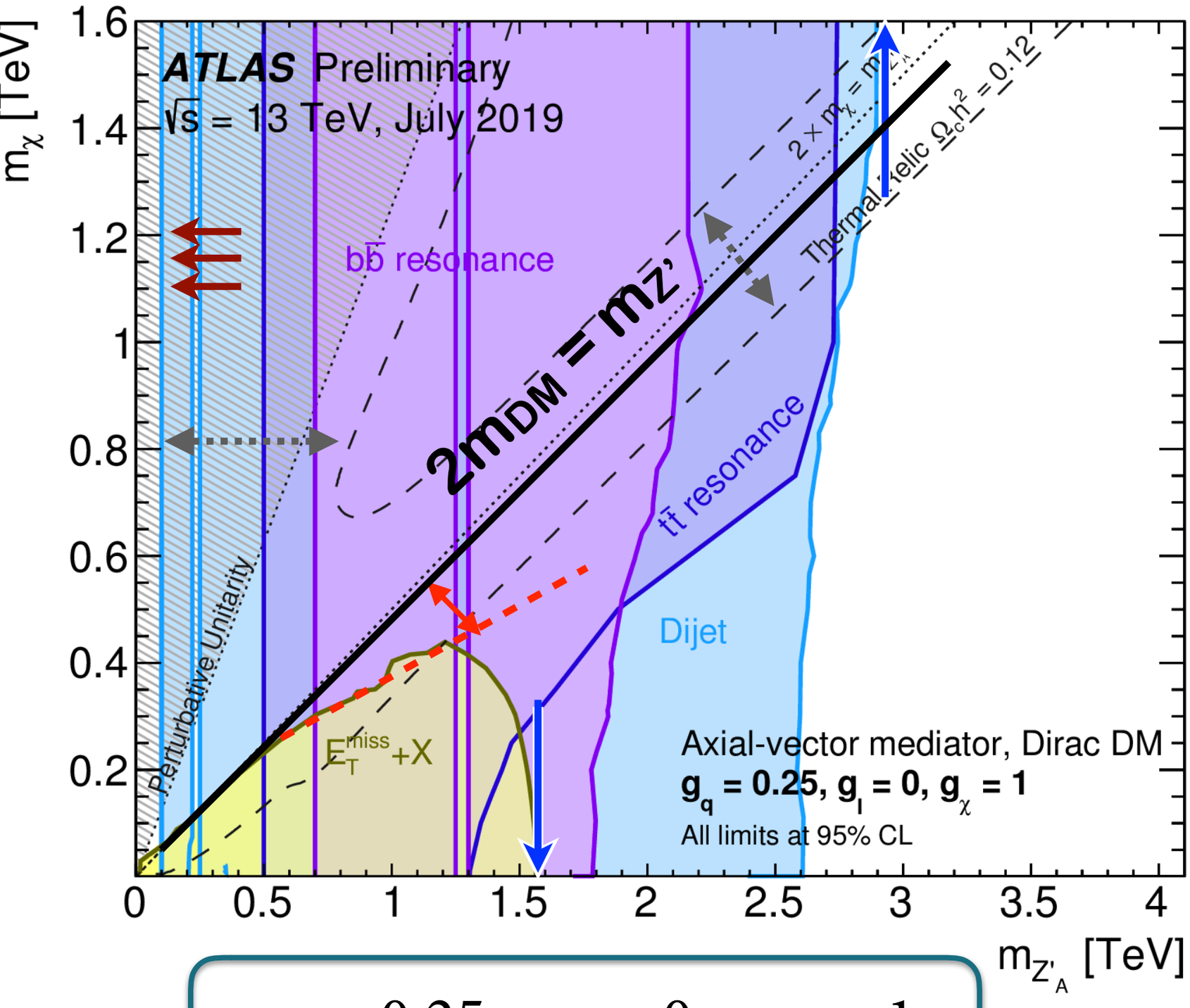


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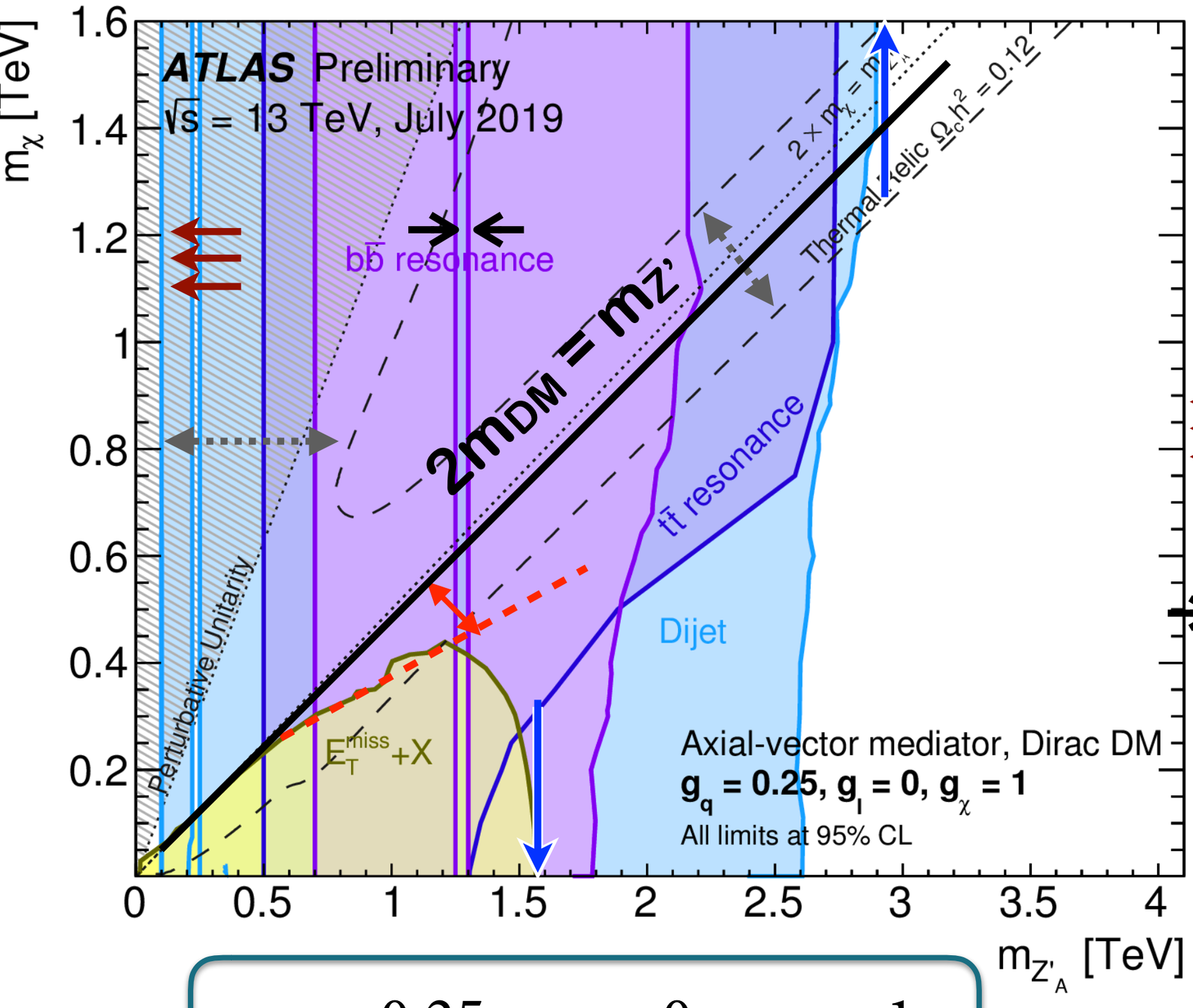


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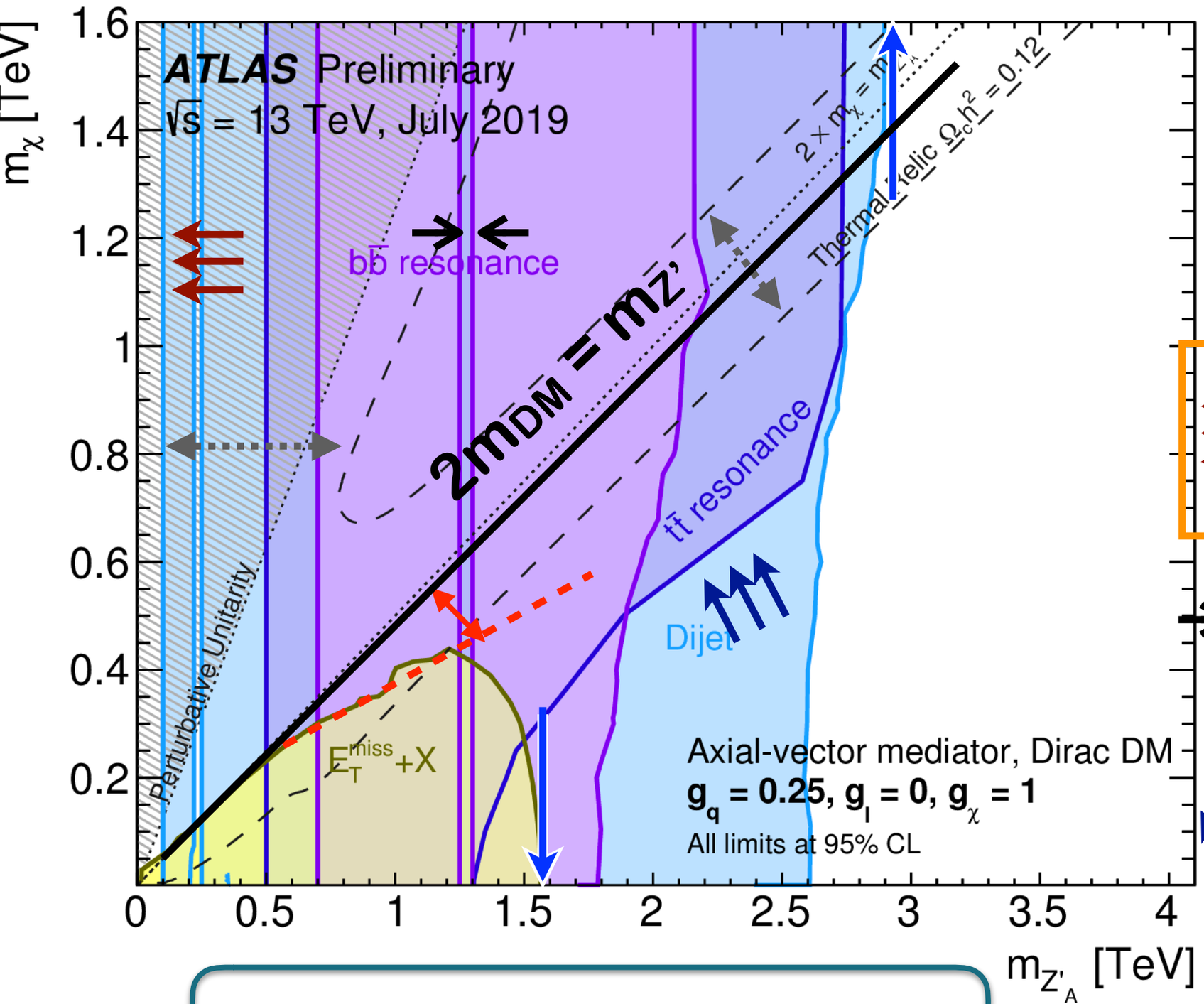


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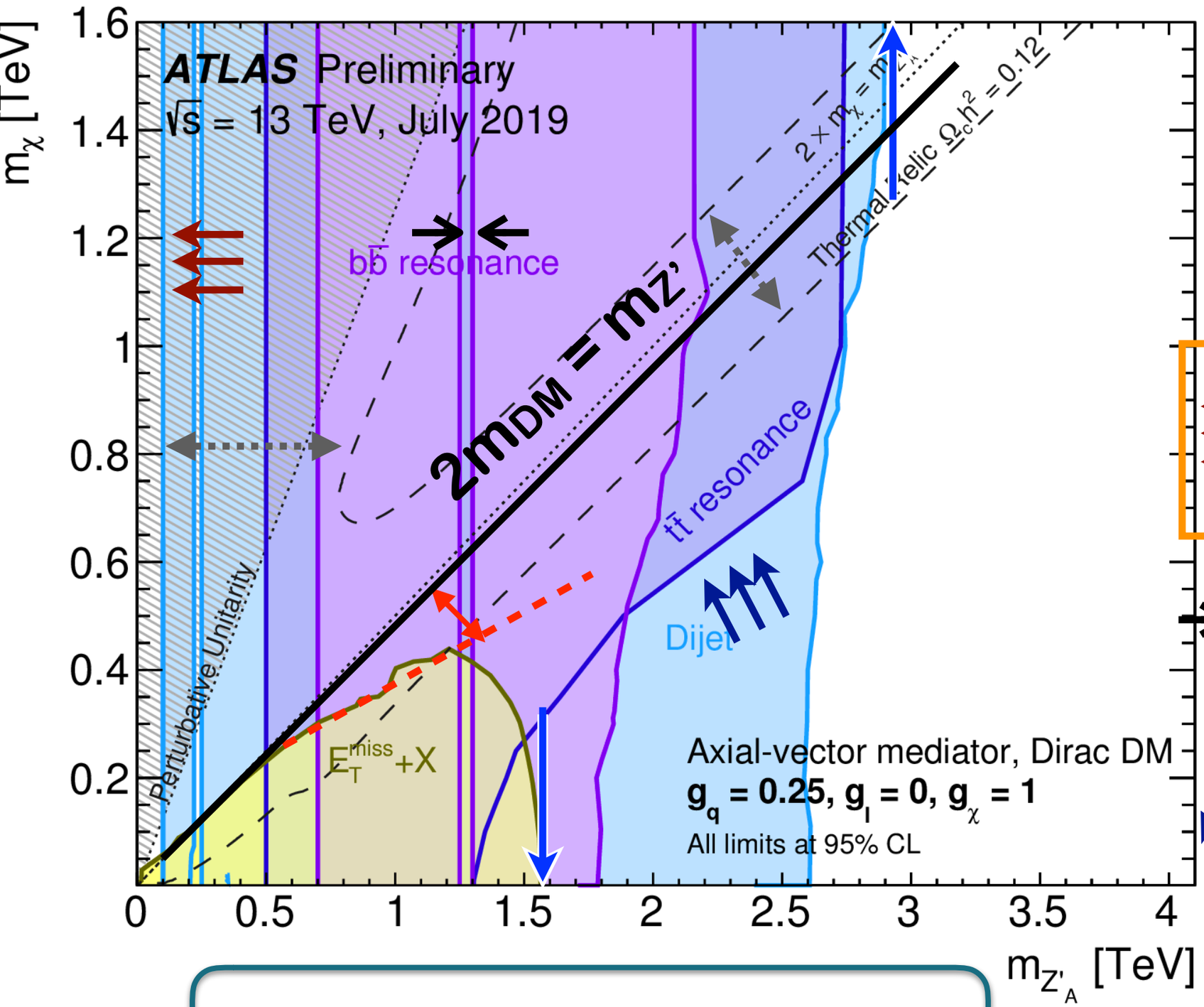


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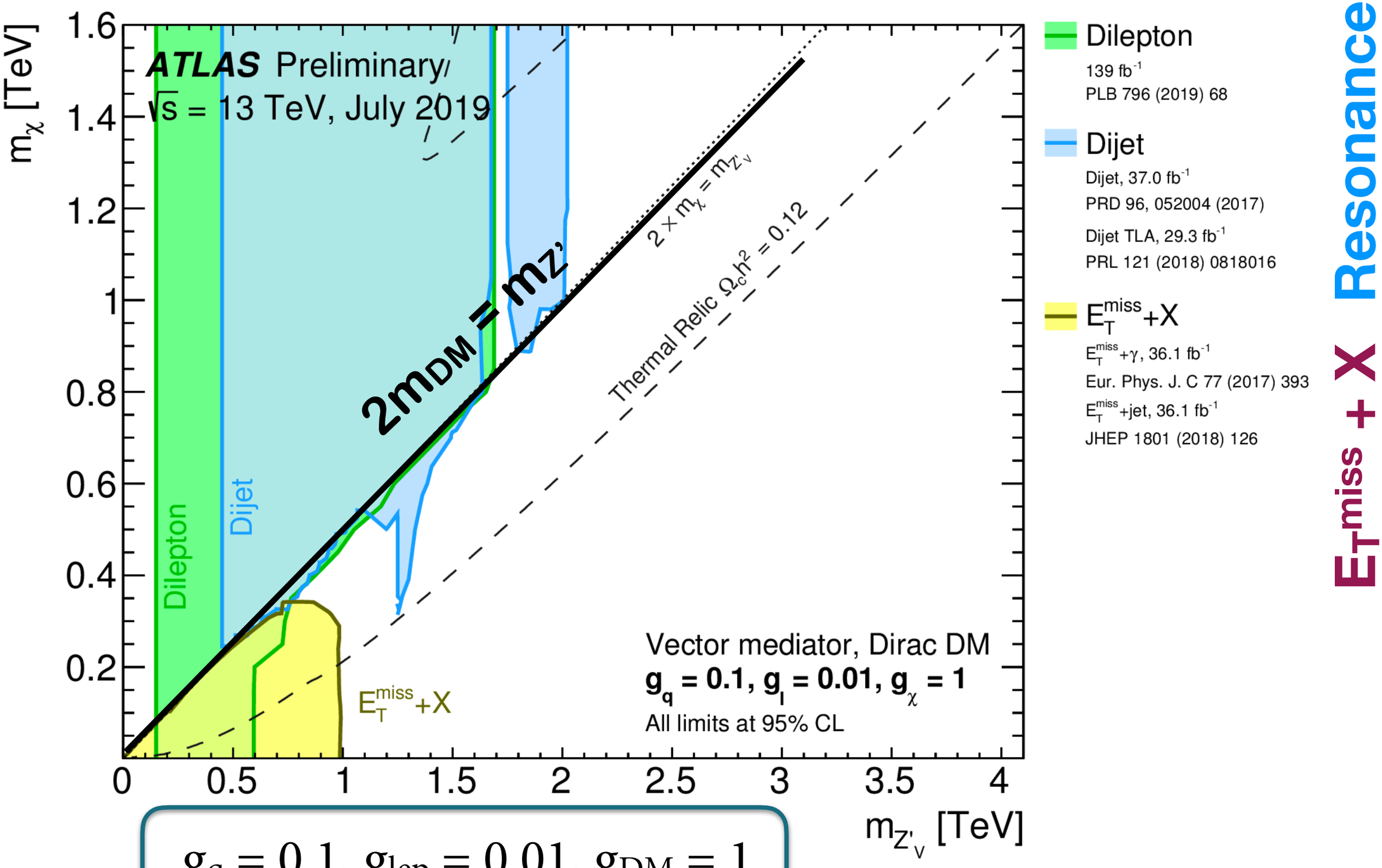
# Spin-1 leptophilic case




**Resonance + X**

**$E_T^{miss}$**

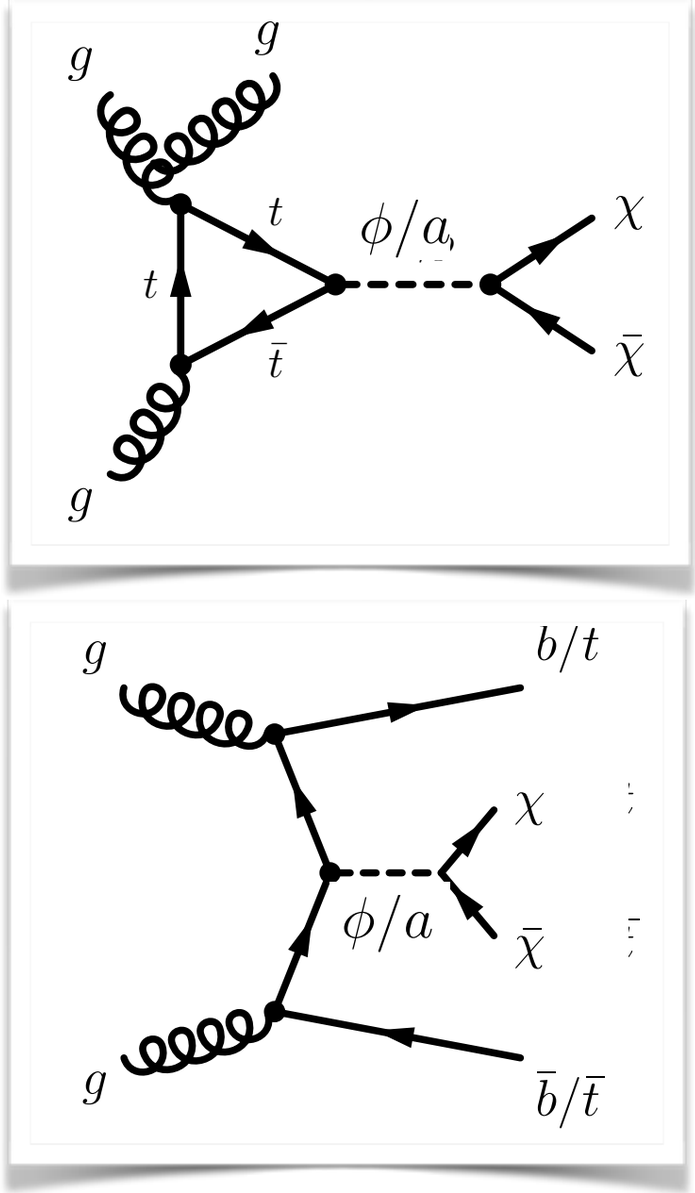
$$g_q = 0.1, g_{lep} = 0.01, g_{DM} = 1$$

**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)**




CMS Public Page

# Spin-0 mediators

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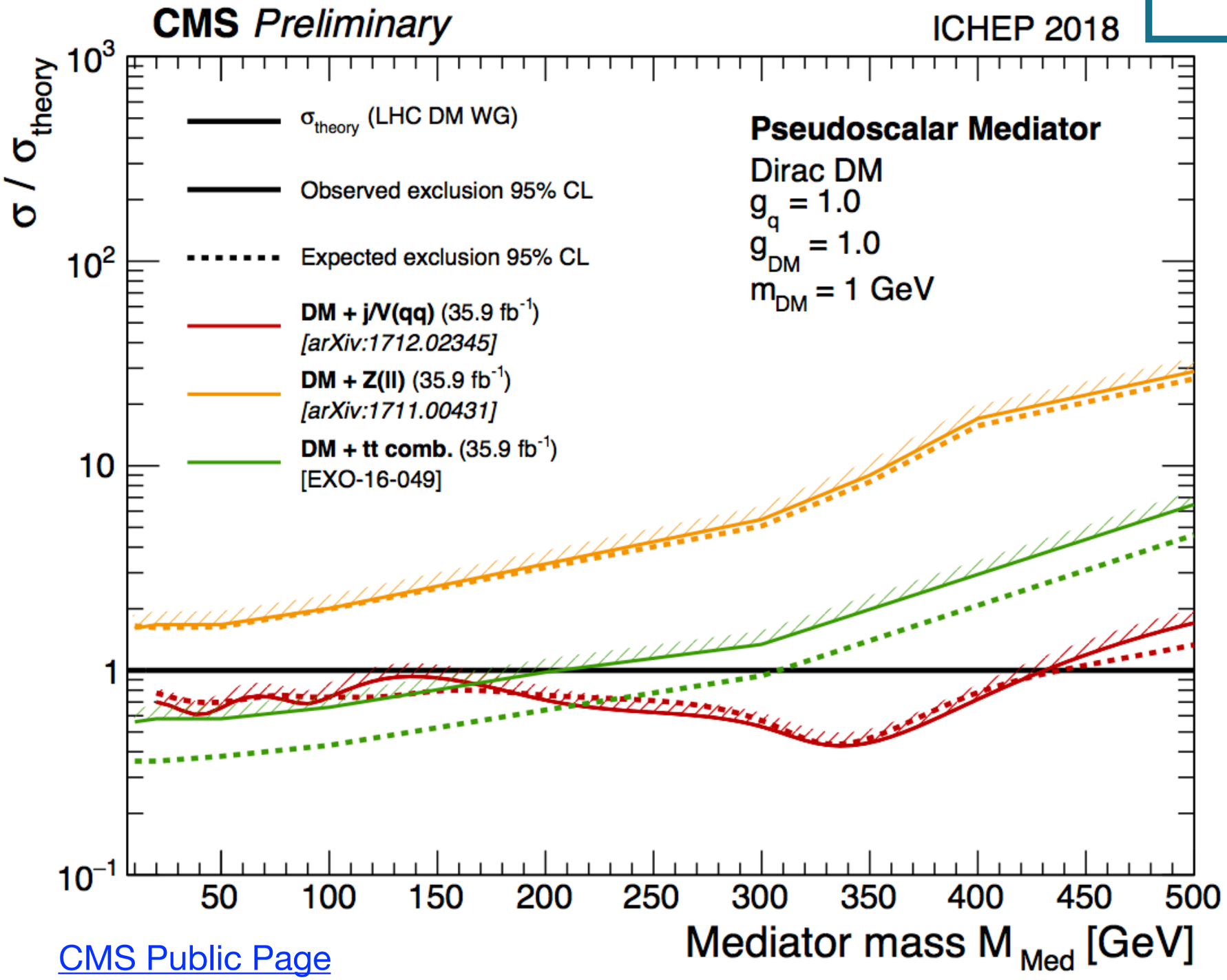
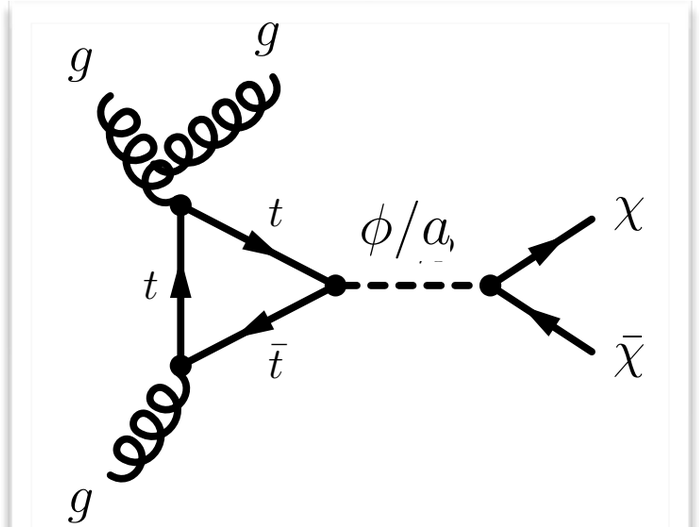
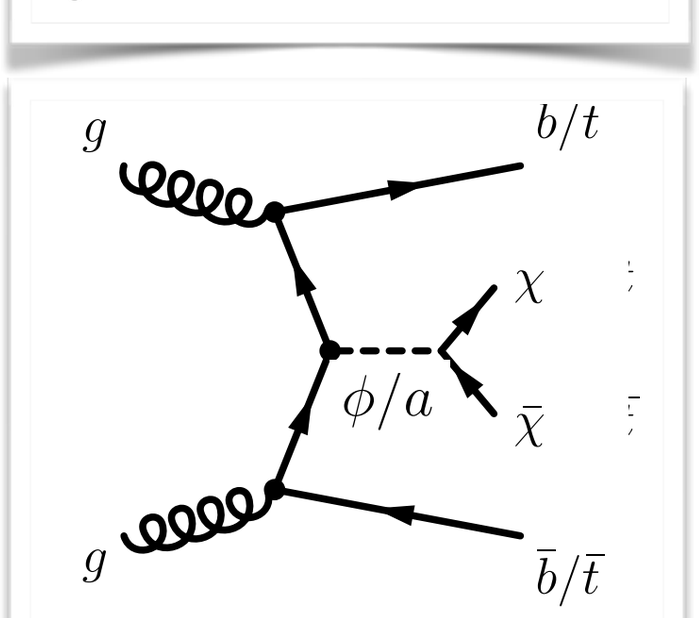


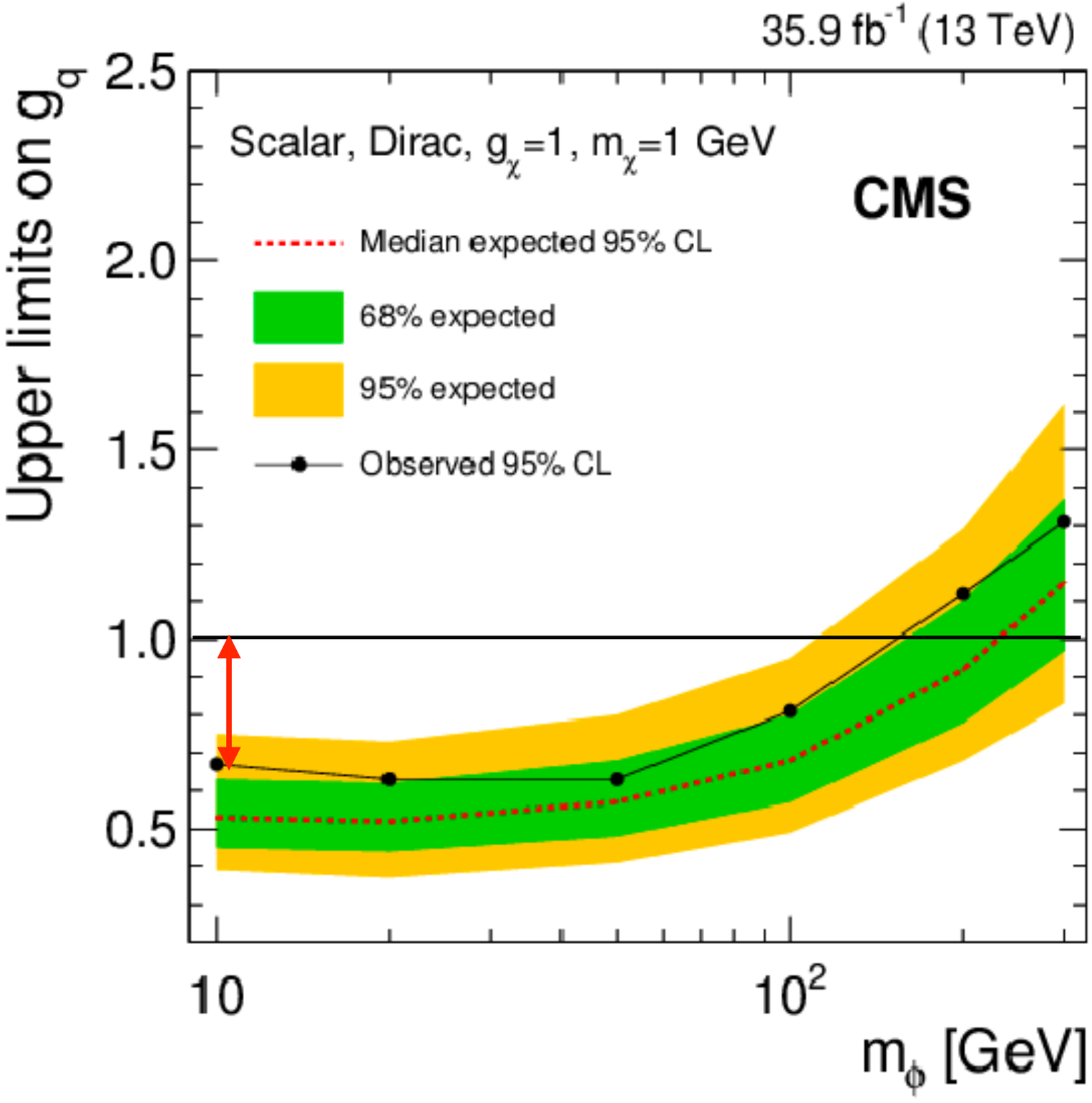



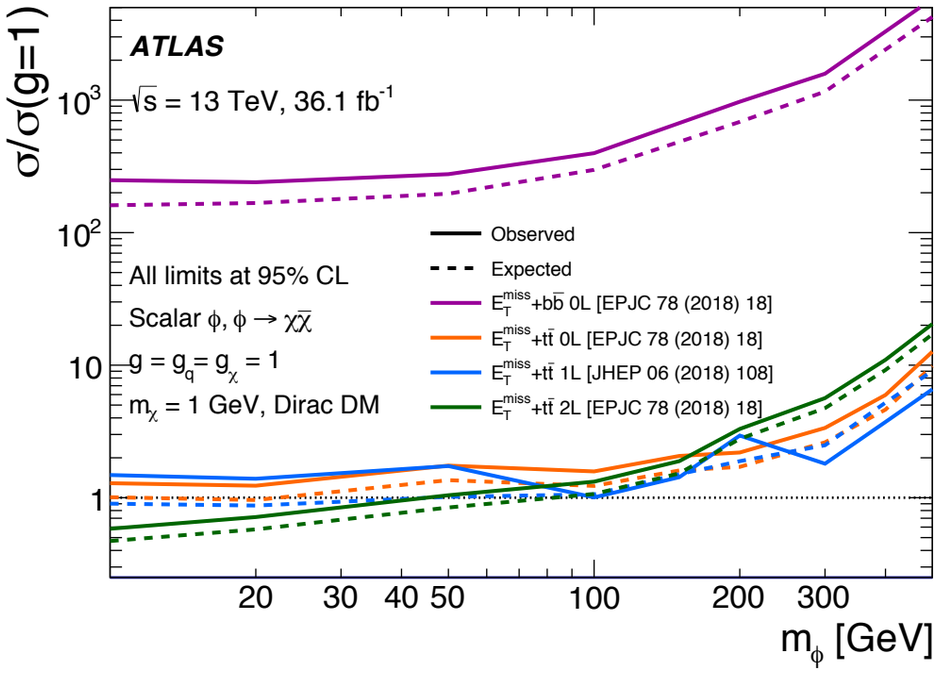




CMS Public Page

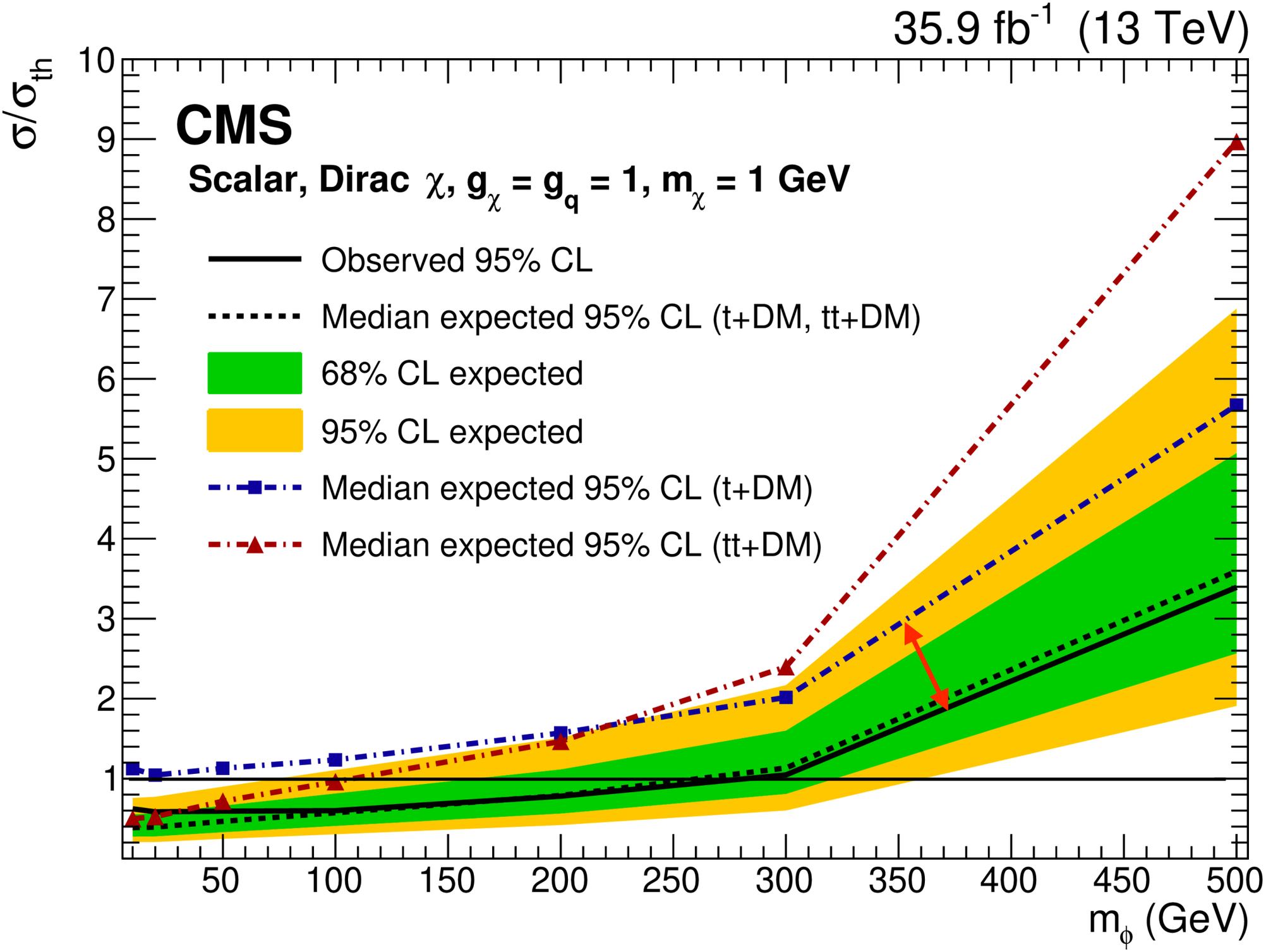
# CMS grand combination

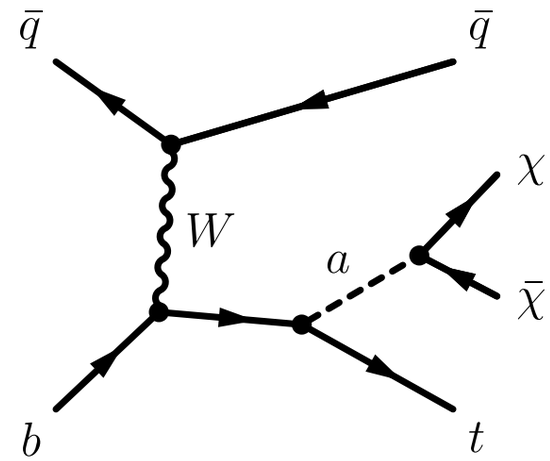
arXiv:1807.06522

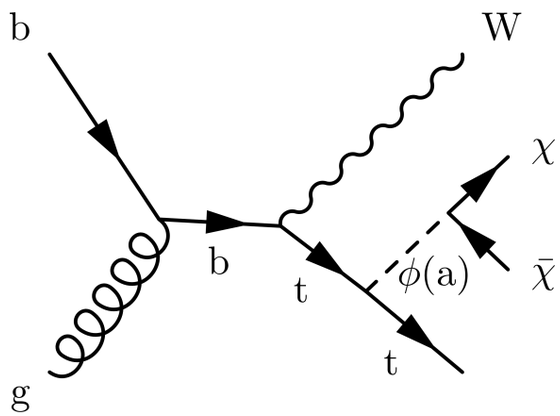


# Spin-0 with single top



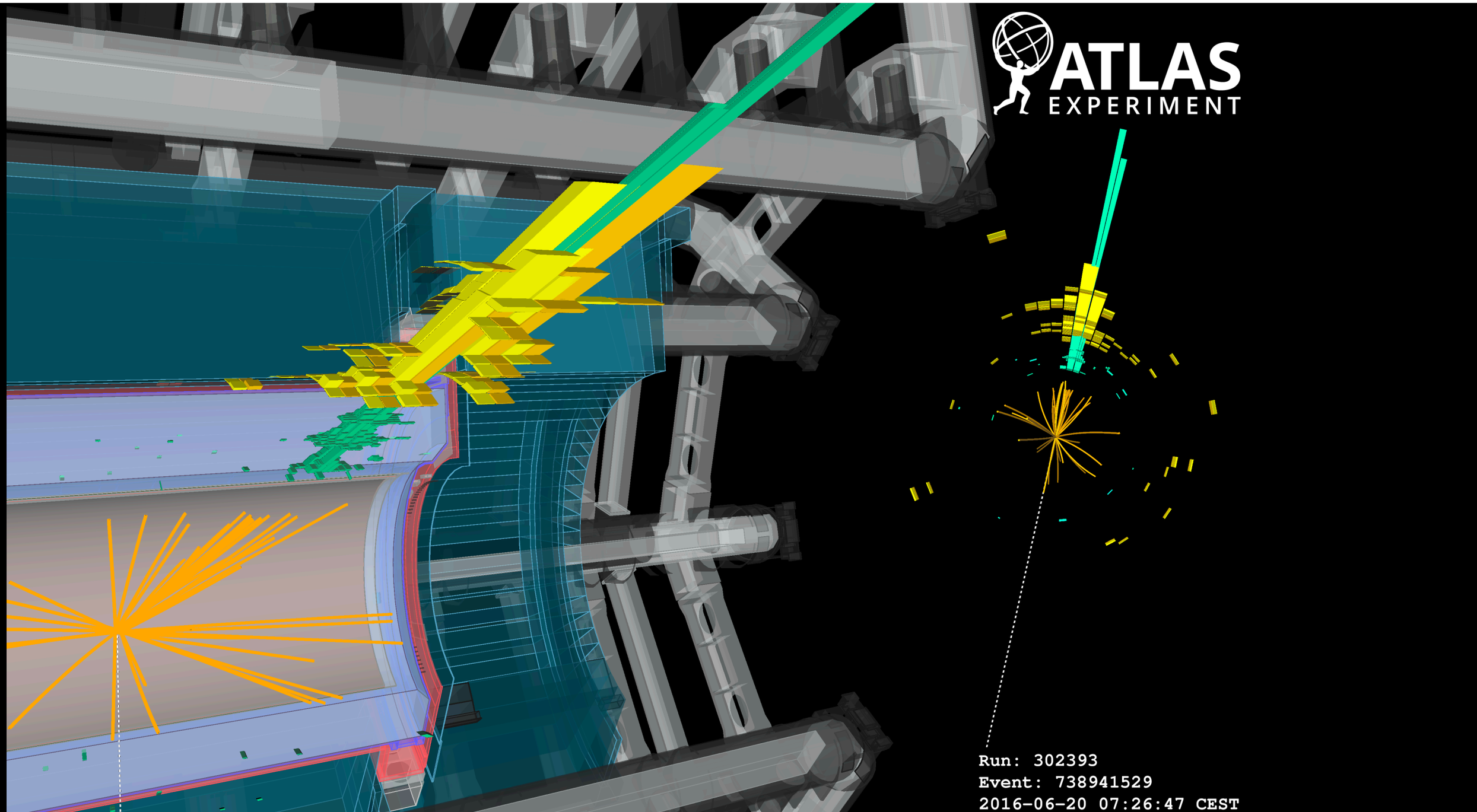



# Considerations on the results

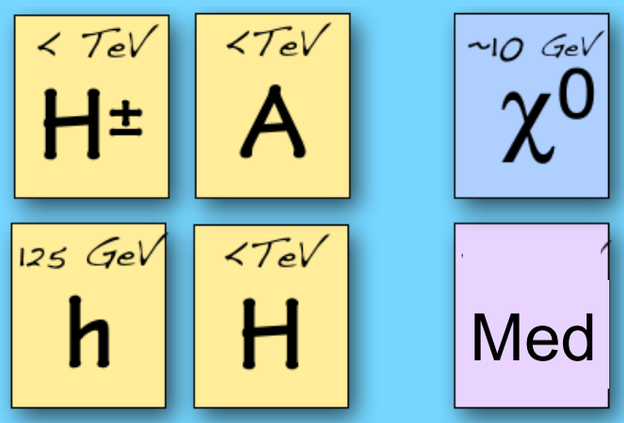
- ★ Simplified models are good phenomenology proxies.
- ★ Simplified models are simplified models.
- ★ Simplified models are not full and complete theories, which might have more complex topologies.
- ★ All exclusions need to be taken with a grain of salt.

# 4. highlights for less simplified models: 2HDMs

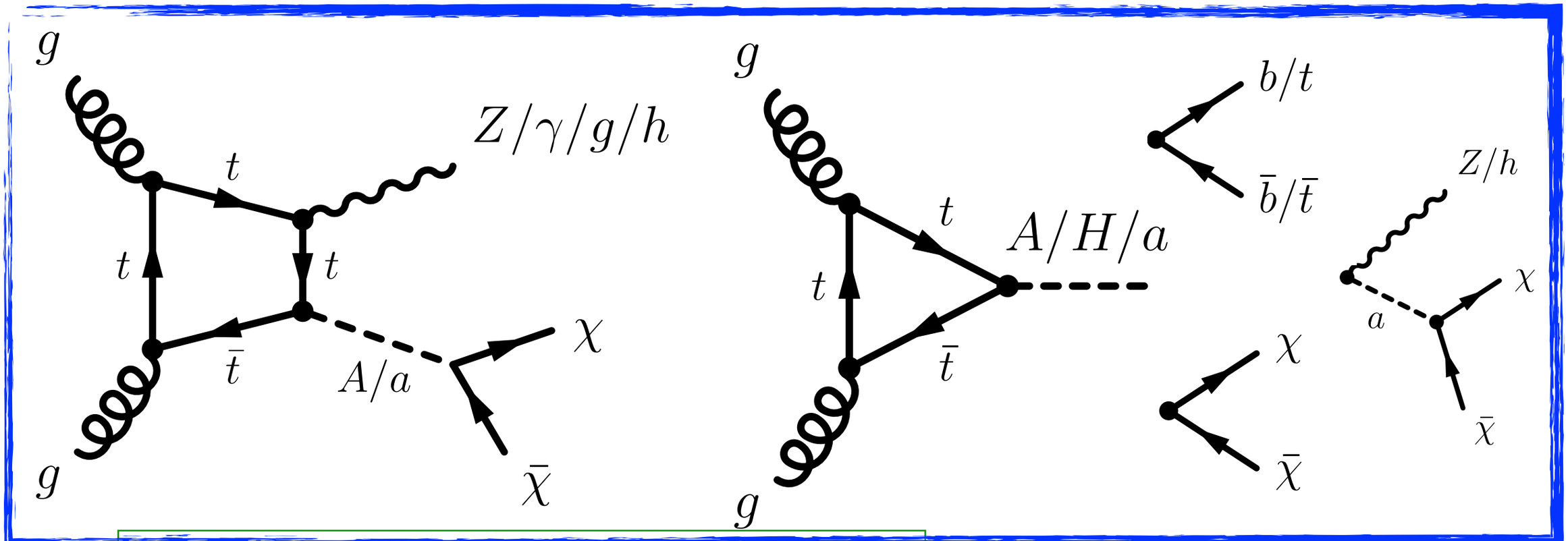


# 2HDM-based models

**2HDM DM models**



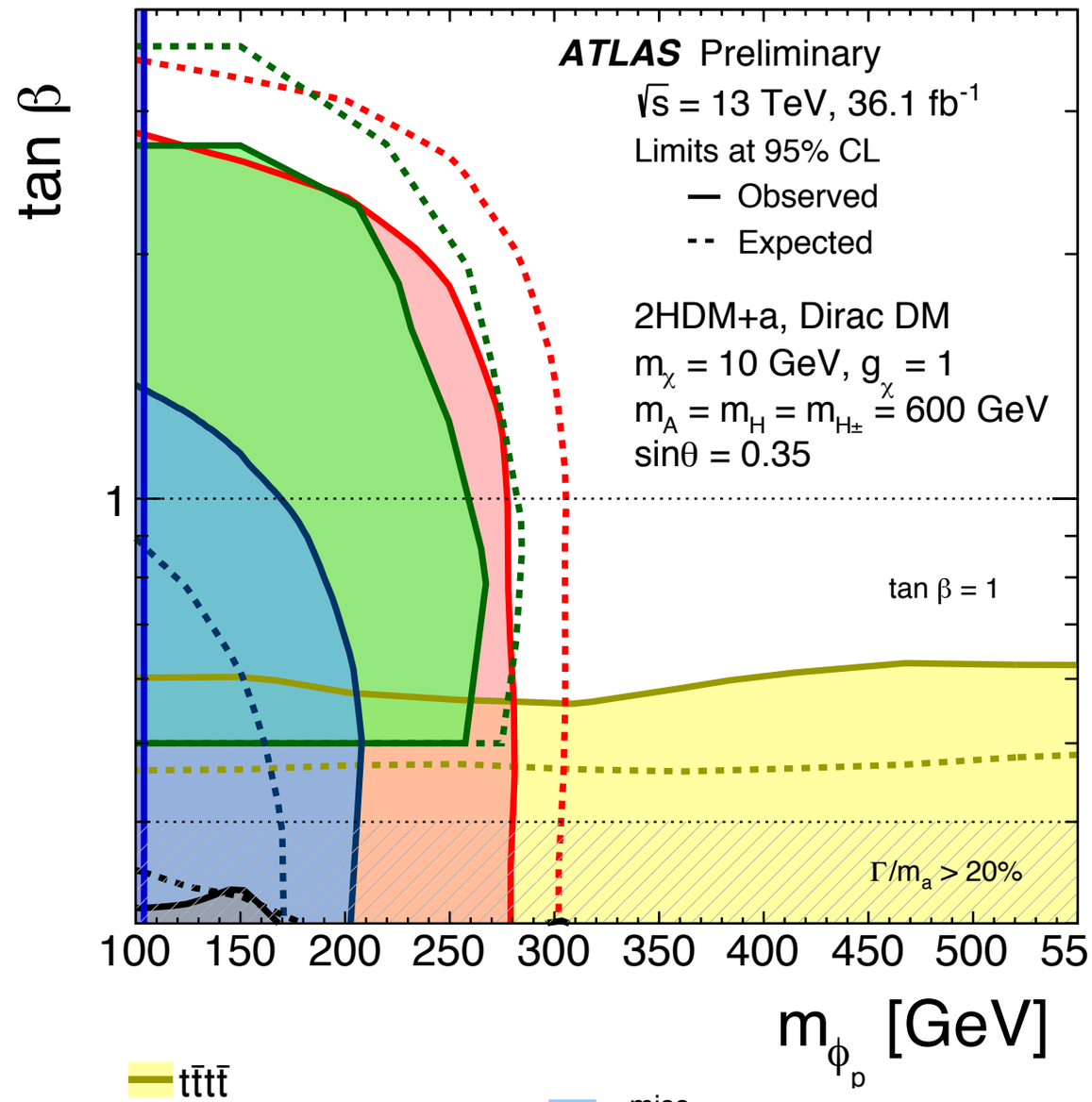

★ **Richer phenomenology:**
Higgs bosons productions and decays, mixing, many final states.




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

# 2HDM+pseudoscalar models

JHEP 05 (2019) 142




$t\bar{t}t\bar{t}$
JHEP 09 (2017) 088

$E_T^{miss}$+h($\gamma\gamma$)
PRD 96 (2017) 112004

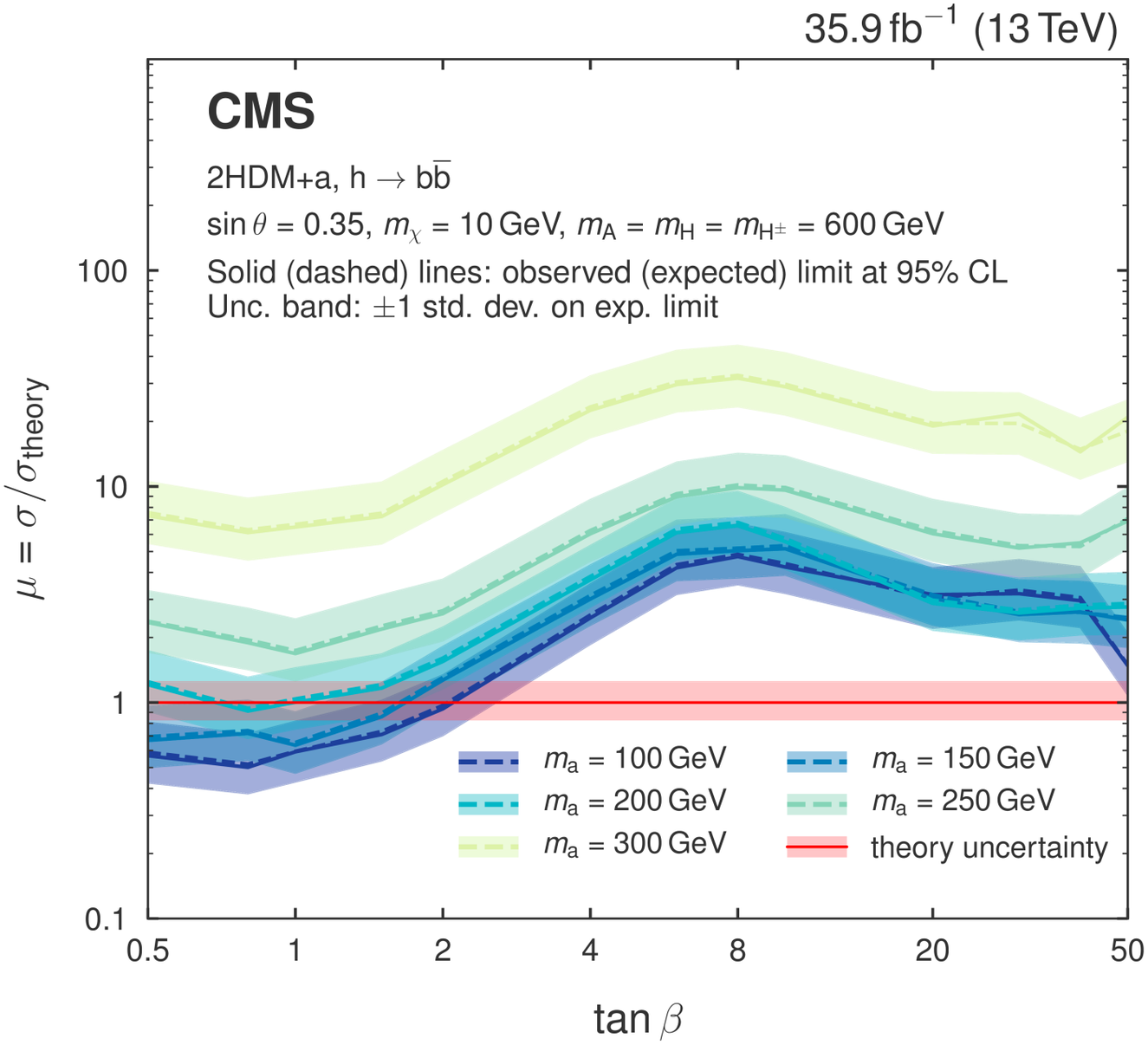
$E_T^{miss}$+Z(ll)
PLB 776 (2017) 318

$E_T^{miss}$+$t\bar{t}$
EPJC 78 (2018) 18
JHEP 06 (2018) 108

$E_T^{miss}$+h($b\bar{b}$)
PRL 119 (2017) 181804

h(inv)
JHEP 06 (2018) 108

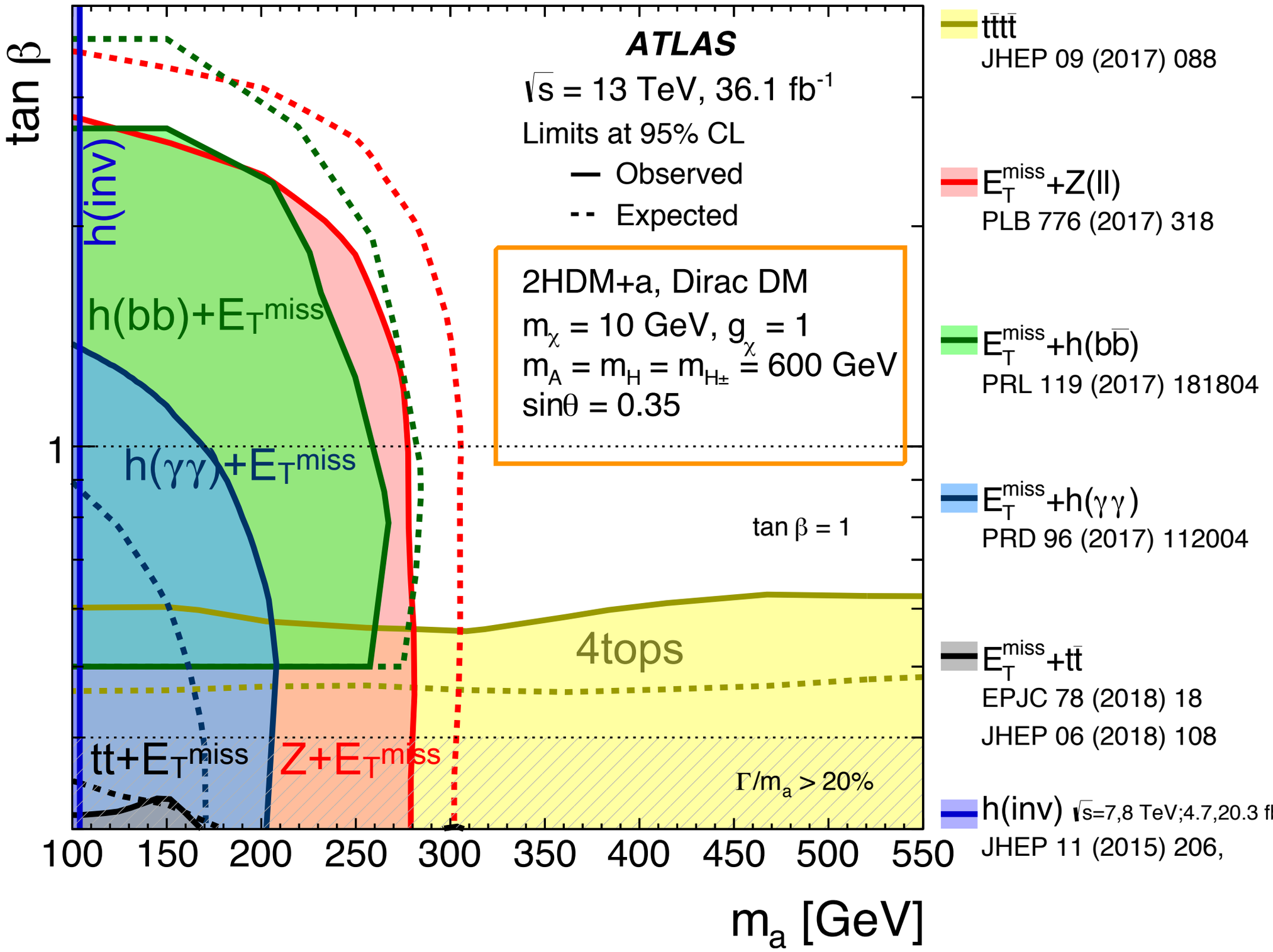
Eur. Phys. J. C 79 (2019) 280




$m_a$ = 100 GeV
$m_a$ = 150 GeV
$m_a$ = 200 GeV
$m_a$ = 250 GeV
$m_a$ = 300 GeV

# Results (I)

JHEP 05 (2019) 142



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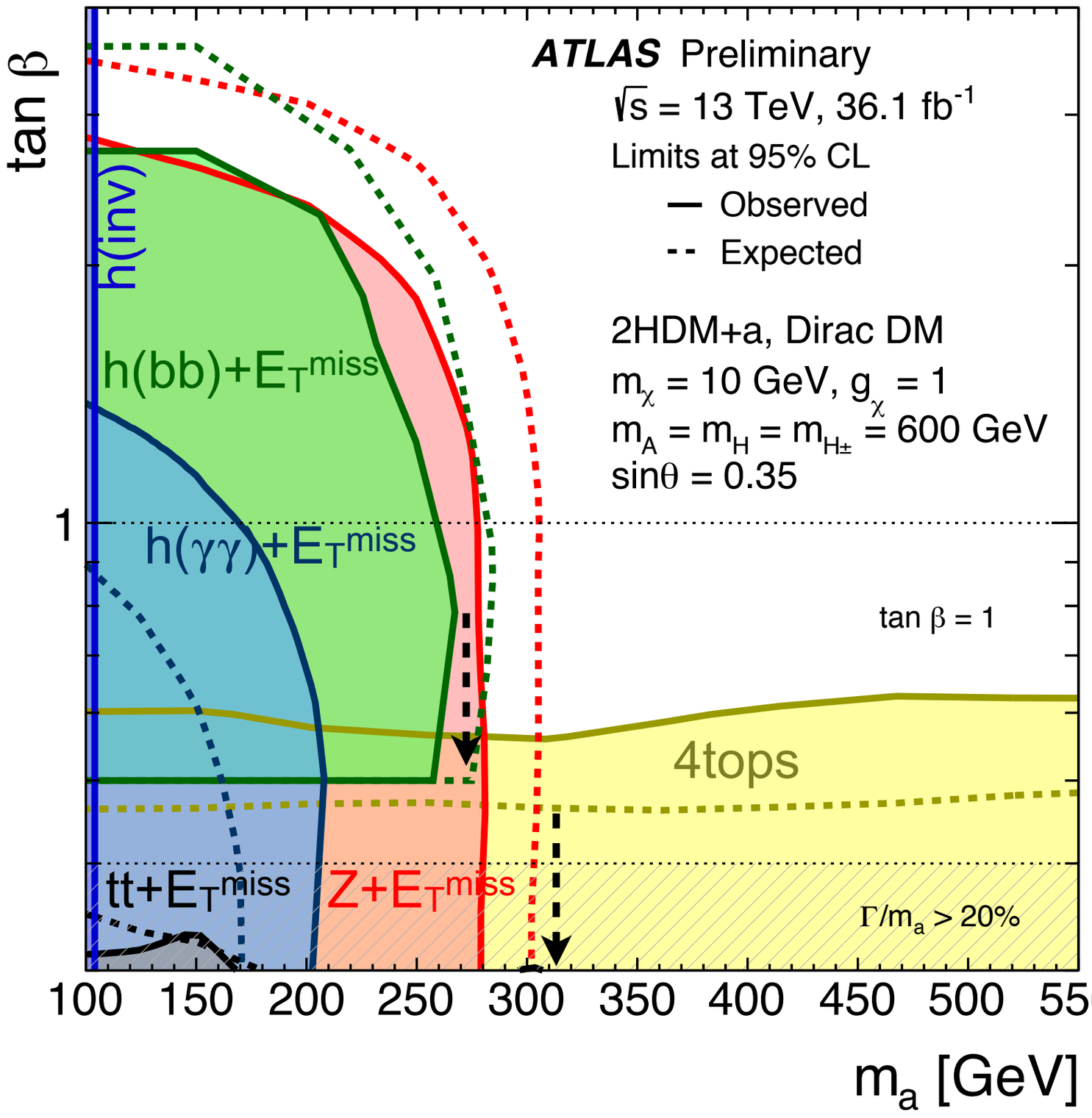


Mass reach driven by BR(A➡aZ) and BR(H➡ah) and mass threshold

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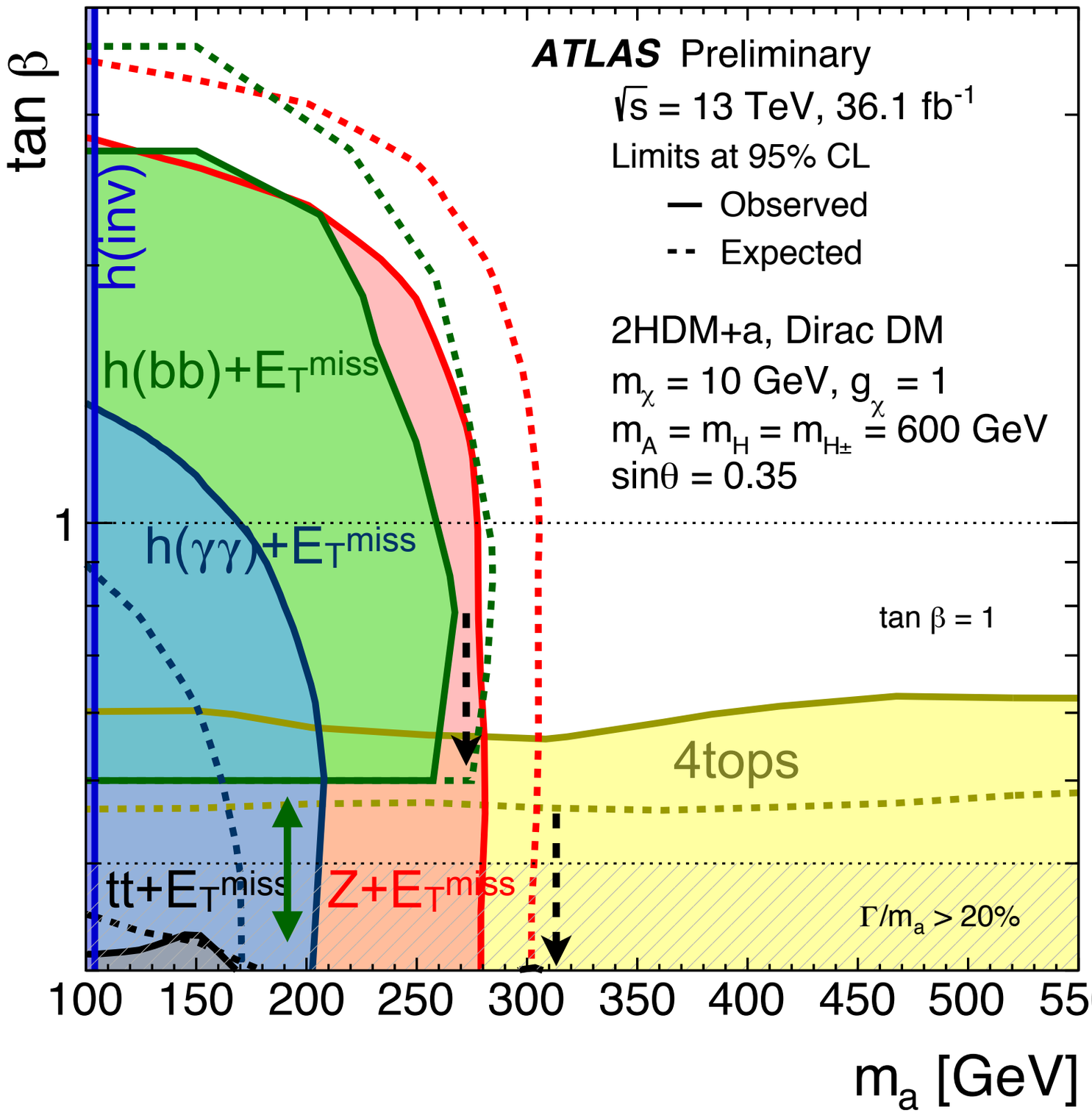


Mass reach driven by BR(A➡aZ) and BR(H➡ah) and mass threshold

Plotting effect due to missing samples

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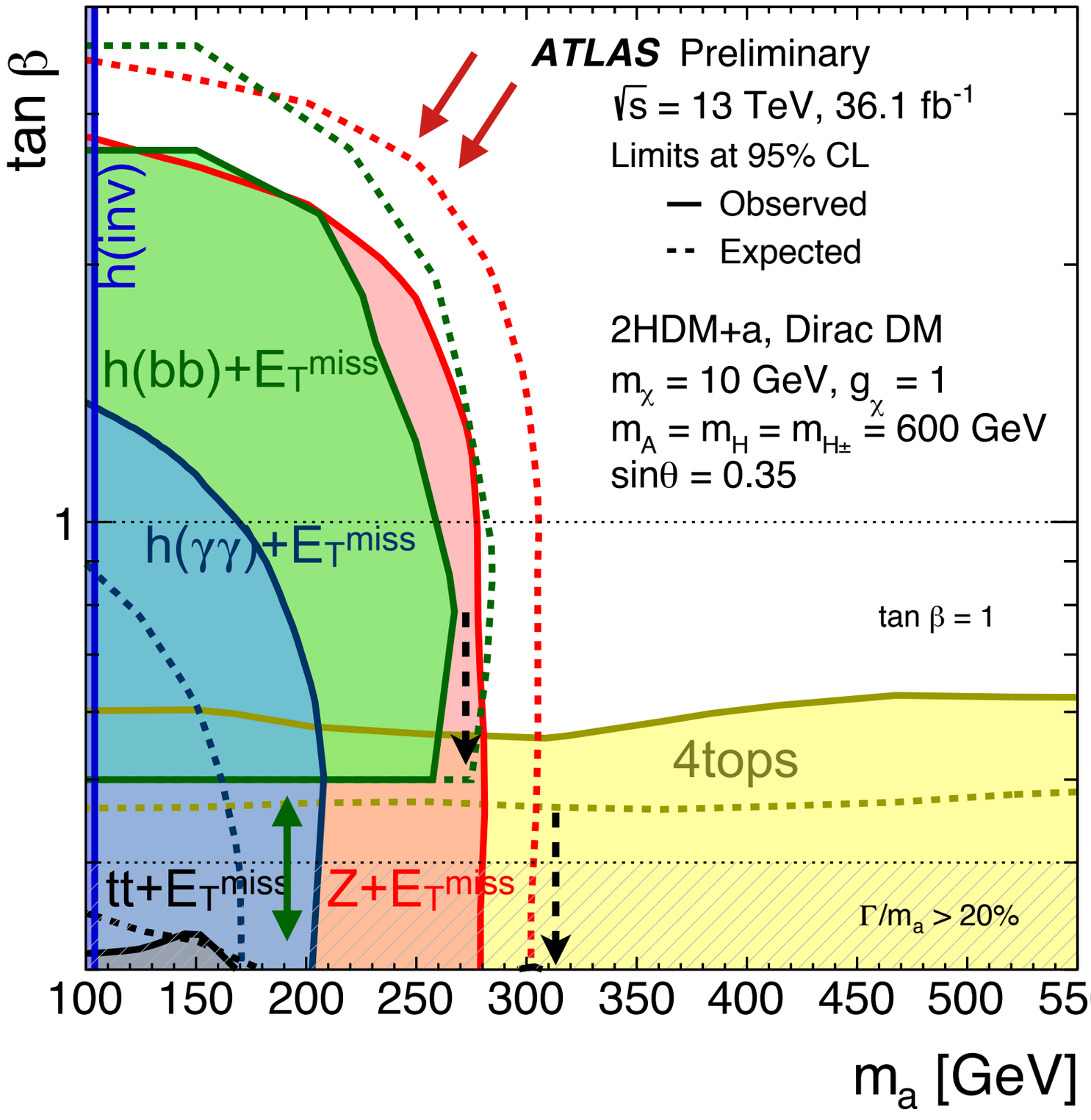


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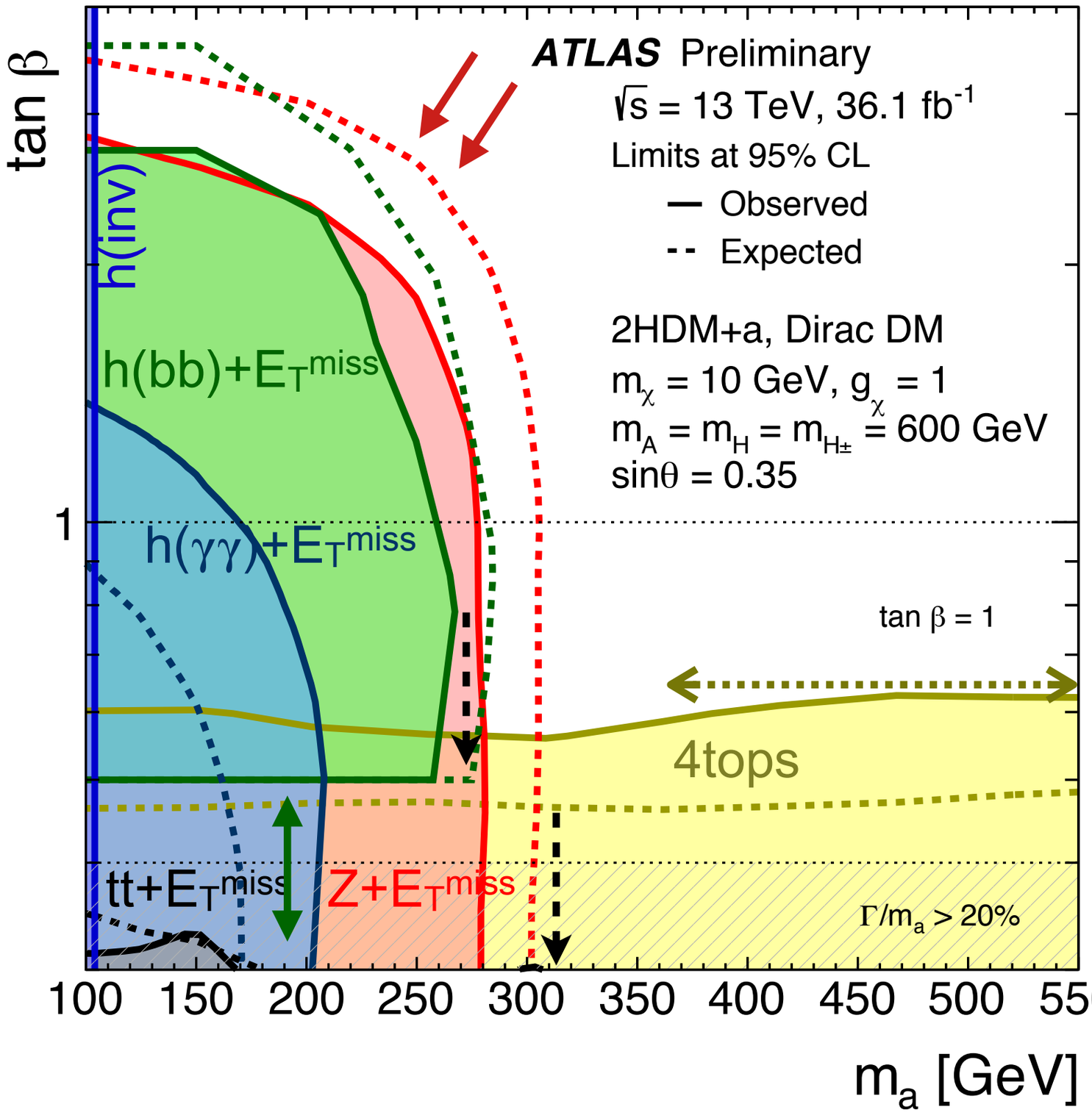


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Sensitivity dominated by ttA/ H(tt) ⇒ independent on m(a)

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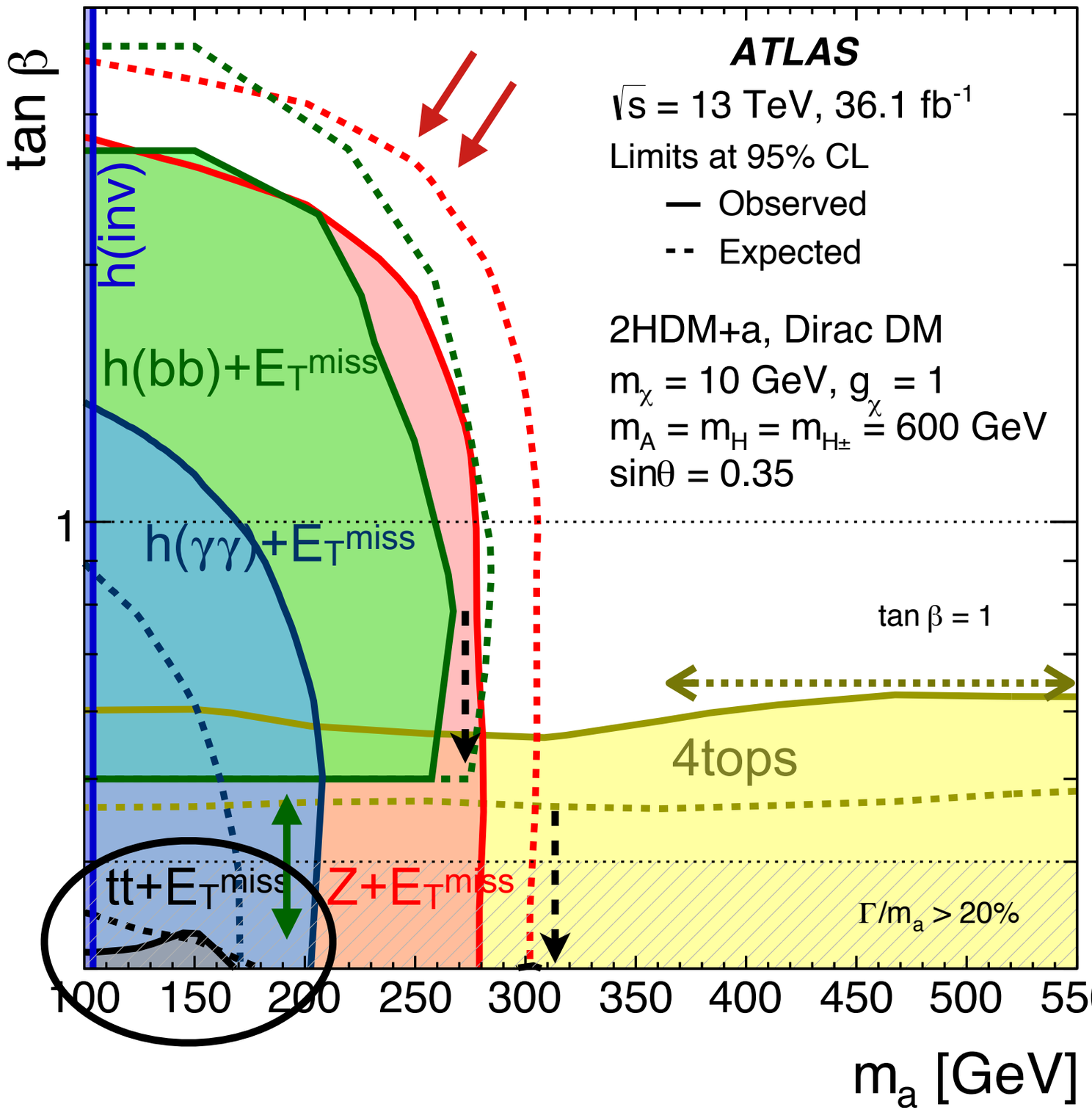


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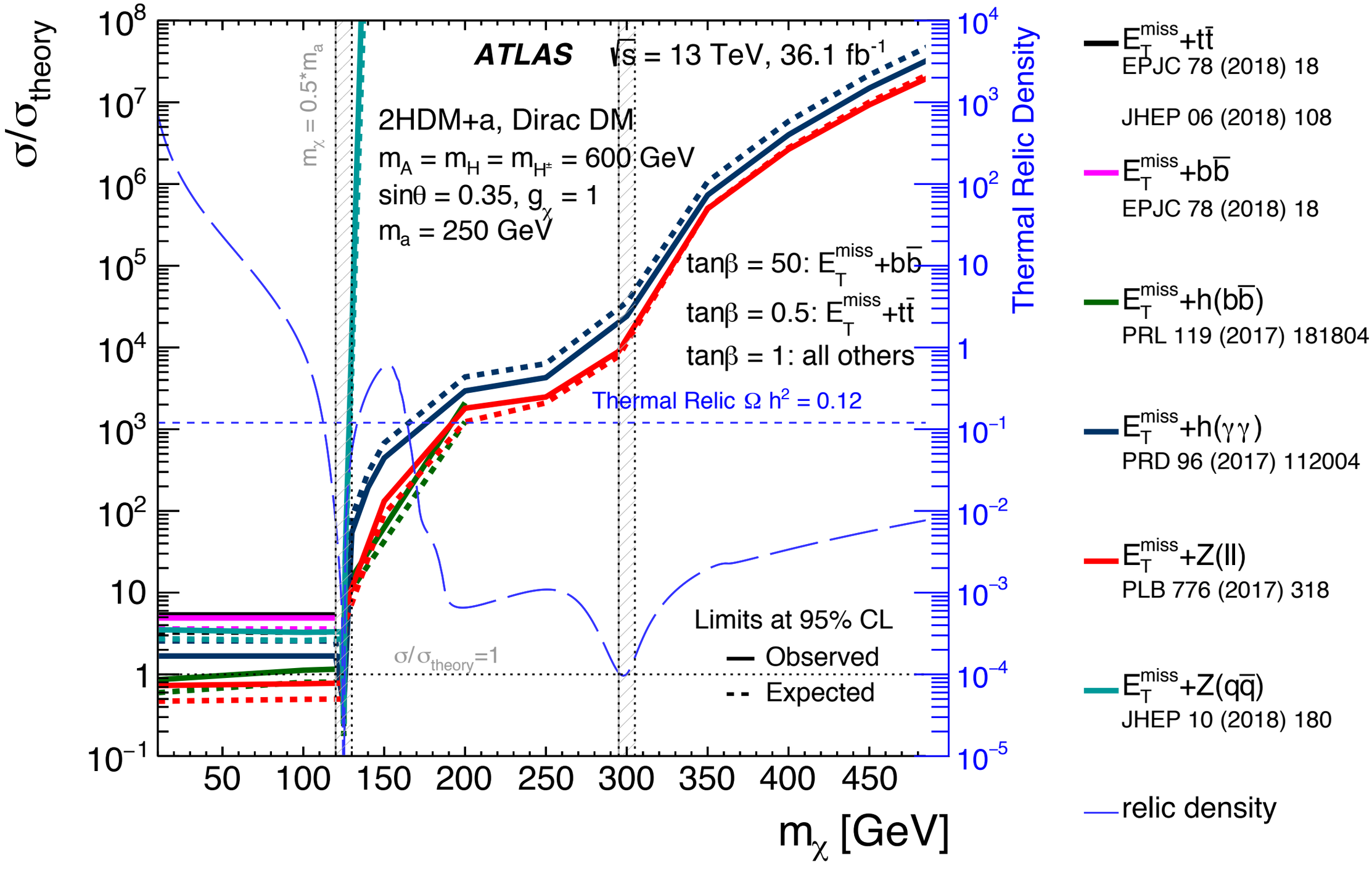
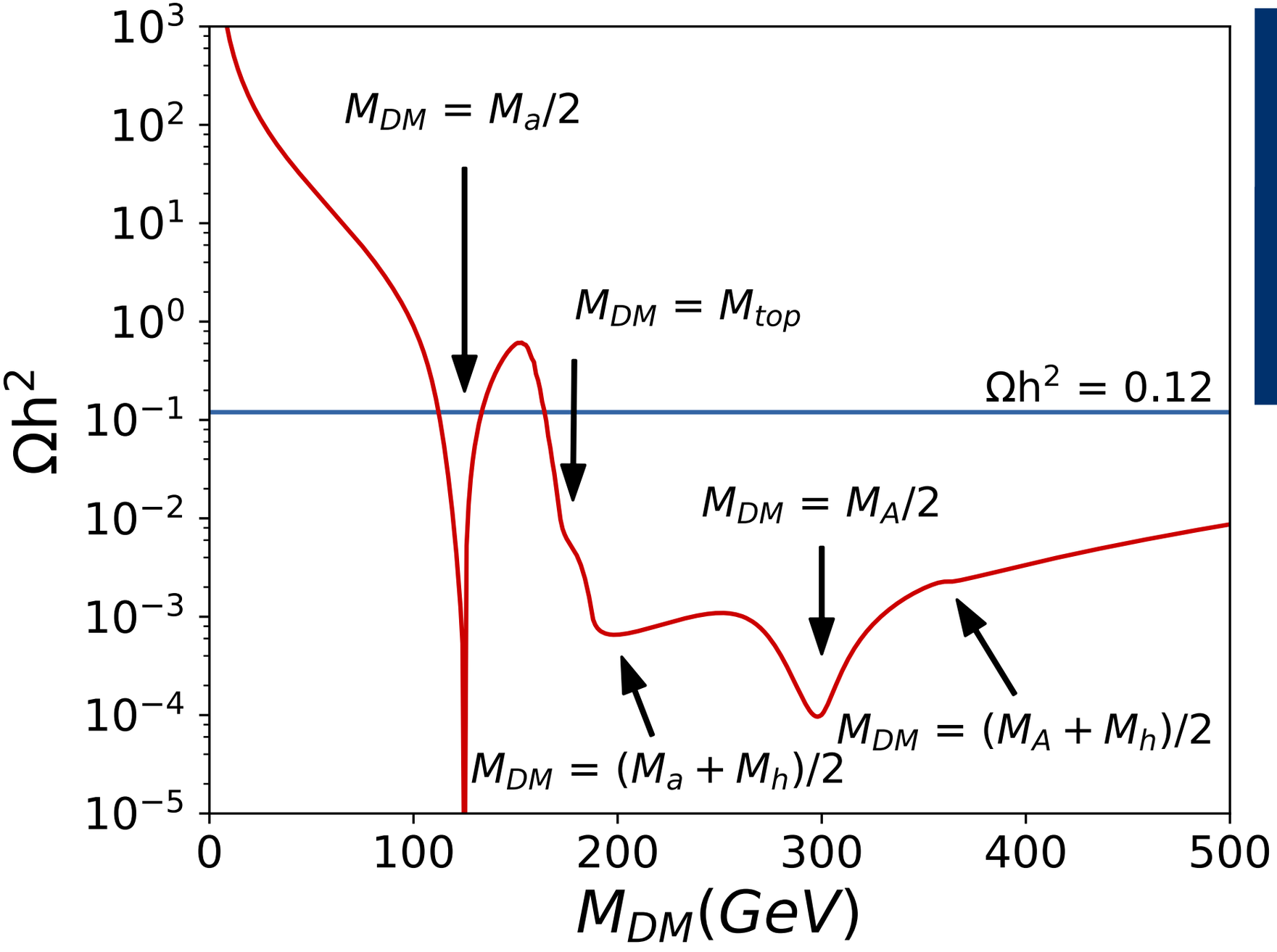
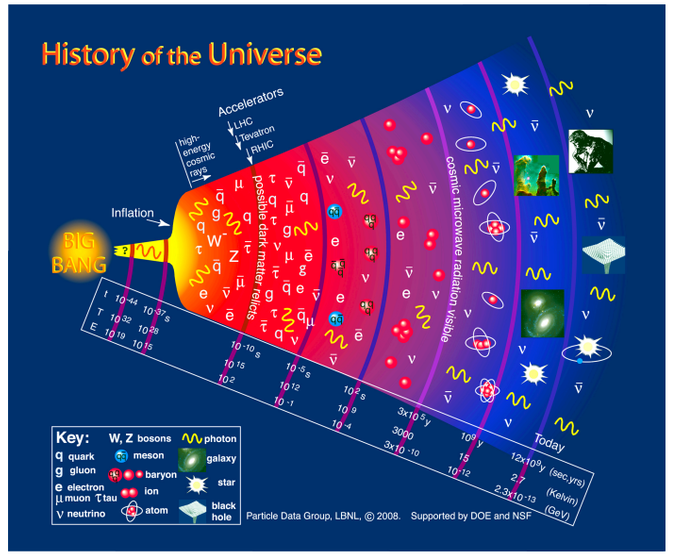
Limited by the choice of sinθ

# Relic density perspective



# Understanding the relic prediction



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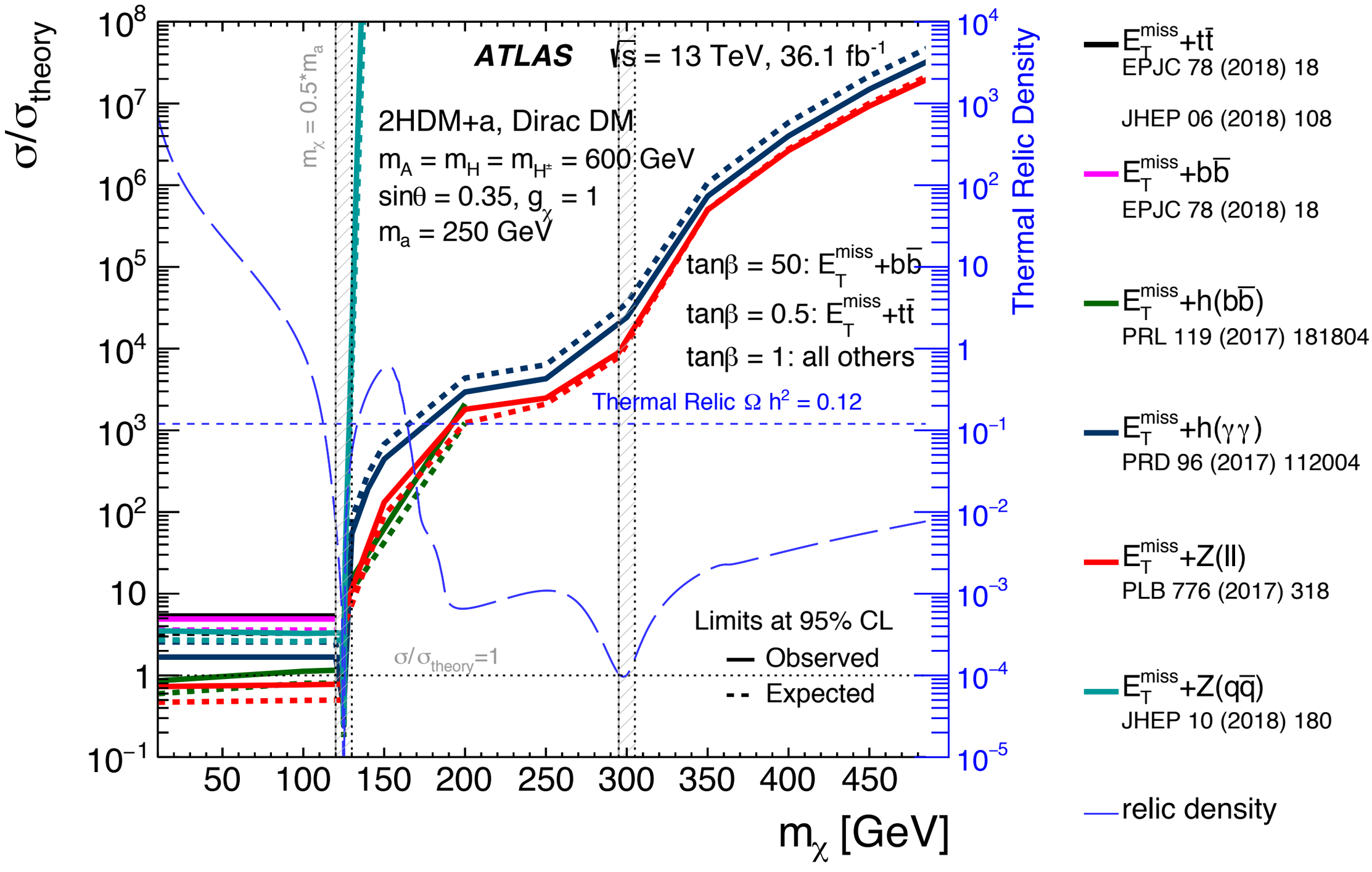


# Further considerations

## where to from here?

★ Many results with the full Run-2 datasets still in preparation but we can already plan ahead: leave no stone unturned!

★ HL-LHC Yellow Report shows many projection on searches evolution in the next data-taking periods, reaching higher higher DM & mediator masses

★ LPCC DMWG working on establishing additional "less simplified" frameworks

My personal take:
1) NEW TRIGGERS 2) NEW SIGNATURES

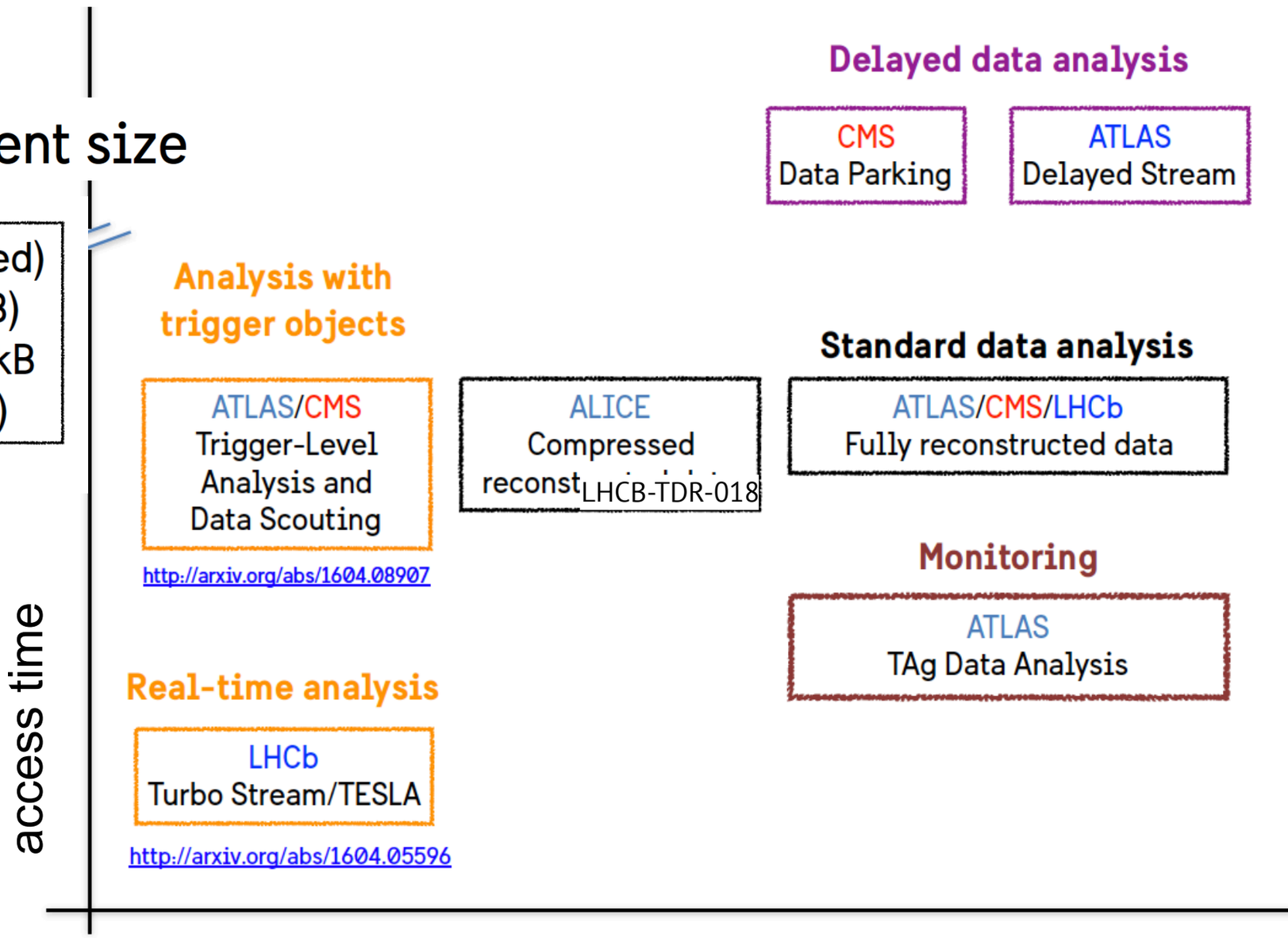
# Recording more/better data

**Limited by:**
fast **read-out** of o(100M) detector channels
**computing** resources (reconstruction)
disk **storage** (saving for further processing)
everyone else's favourite **physics** channel

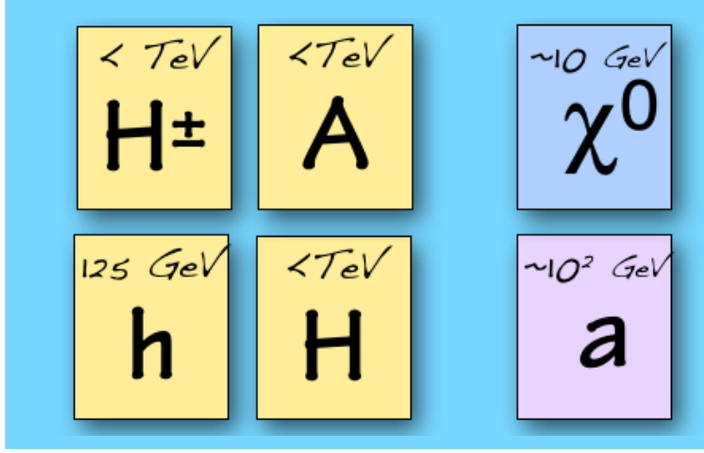
**Bandwidth** = Event rate **x** Event size

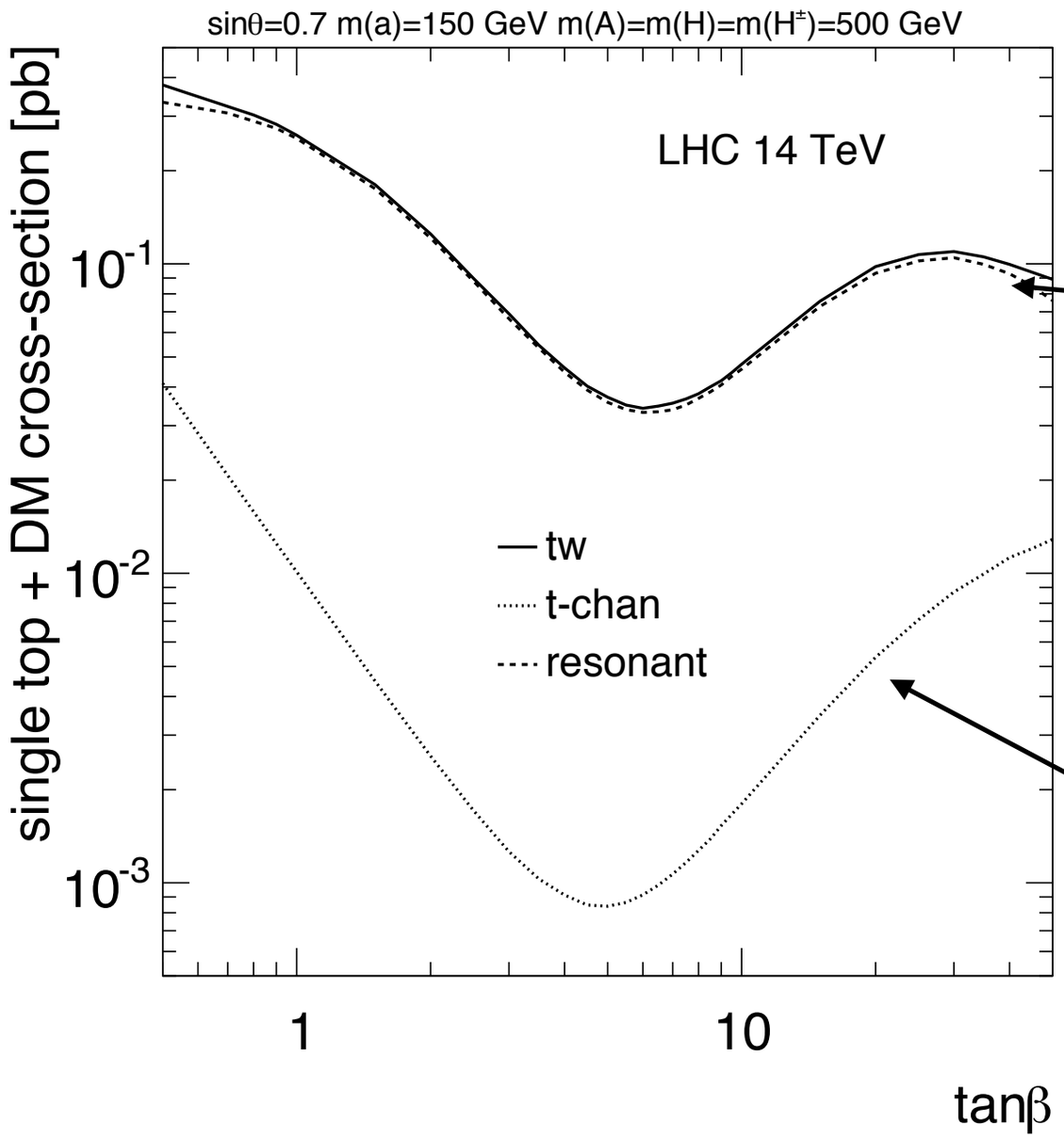
| **LHC**: 40 MHz | (Reconstructed) |
|---|---|
| ATLAS: 1 kHz | ATLAS: o(MB) |
| LHCb: 12.5 kHz | LHCb: ~100 kB |
| CMS: 1 kHz | CMS: o(MB) |

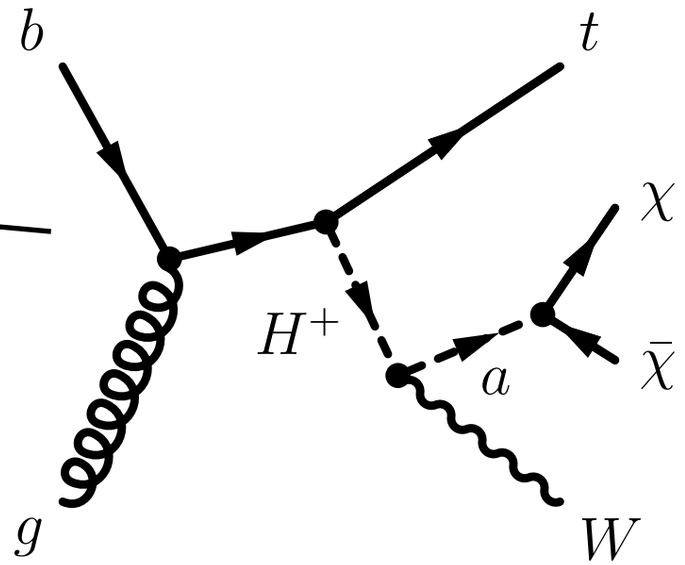
We need more of this !

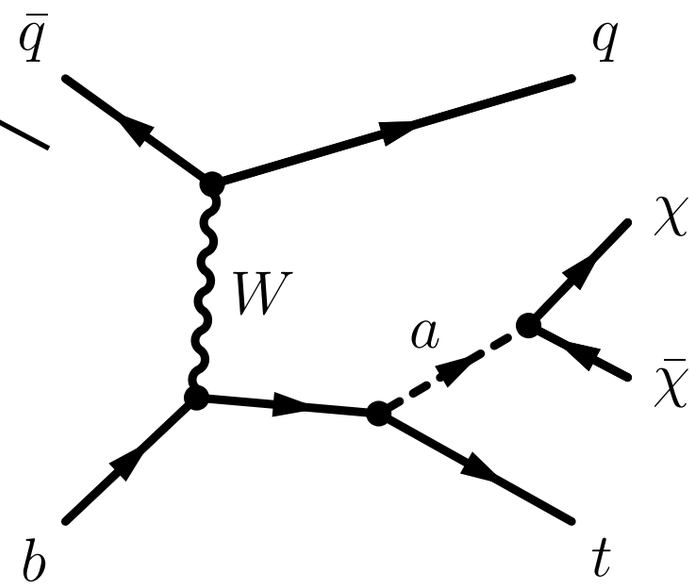


# New signatures



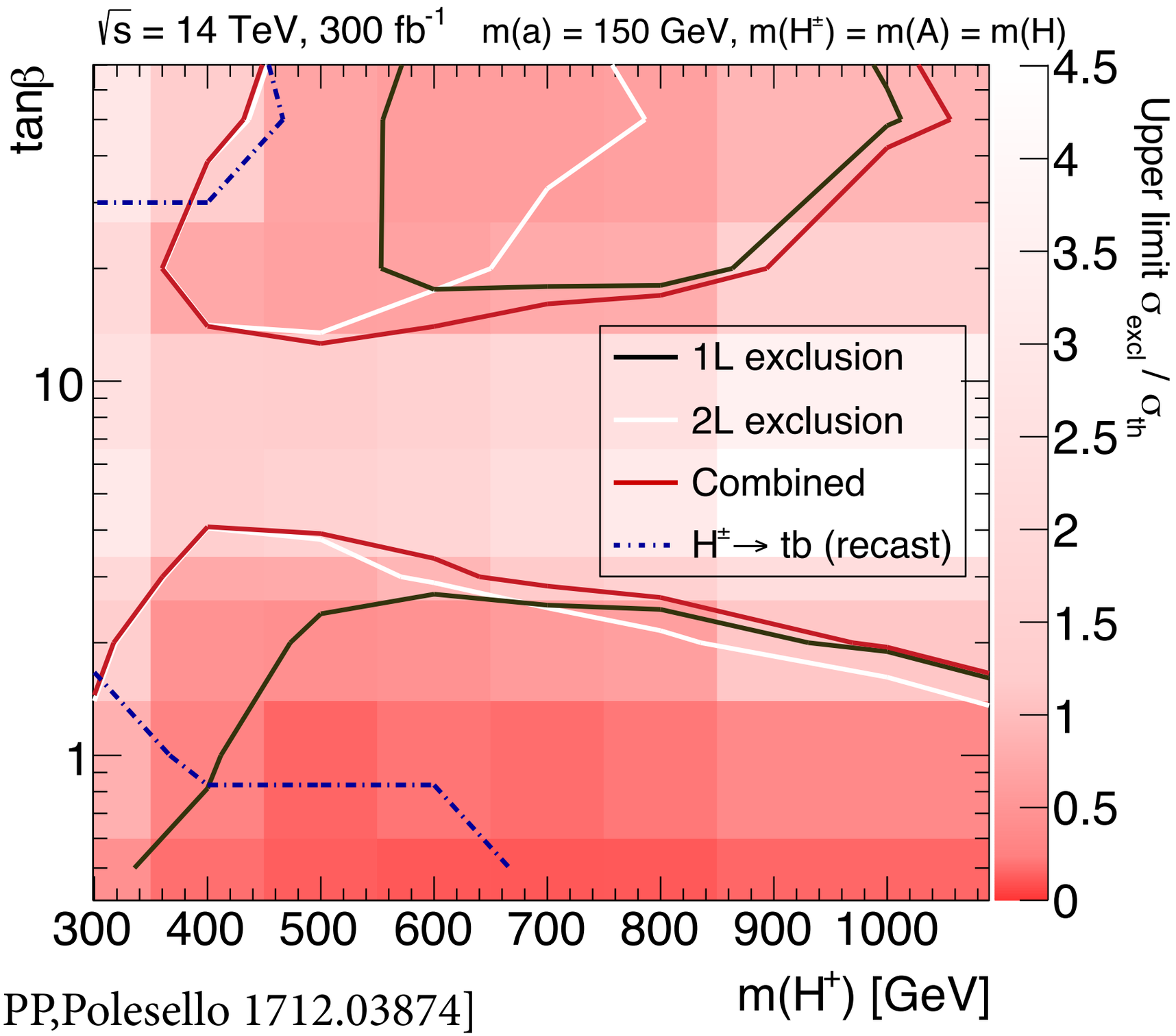



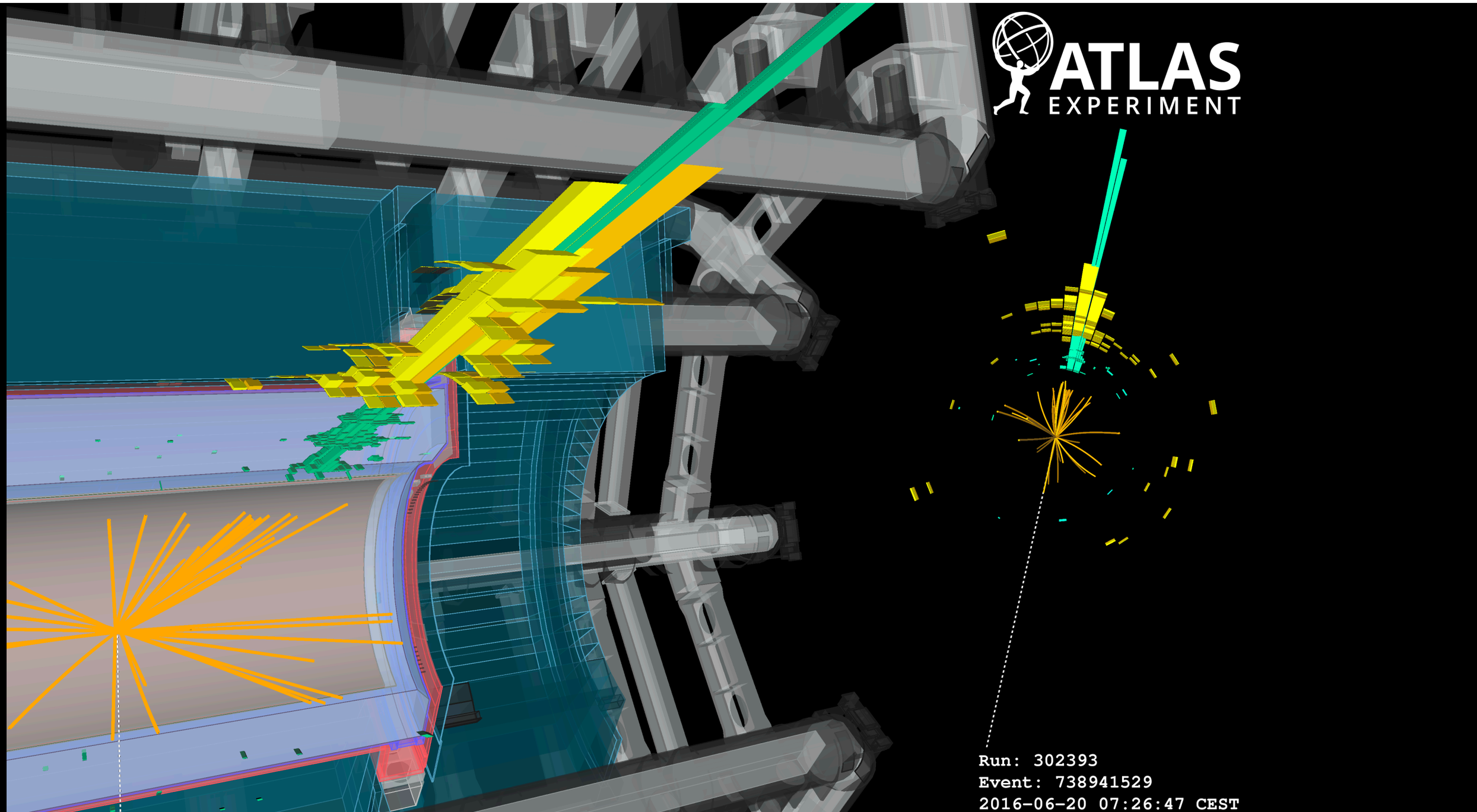

[PP,Polesello 1712.03874]

# Sensitivity forecast




[PP,Polesello 1712.03874]

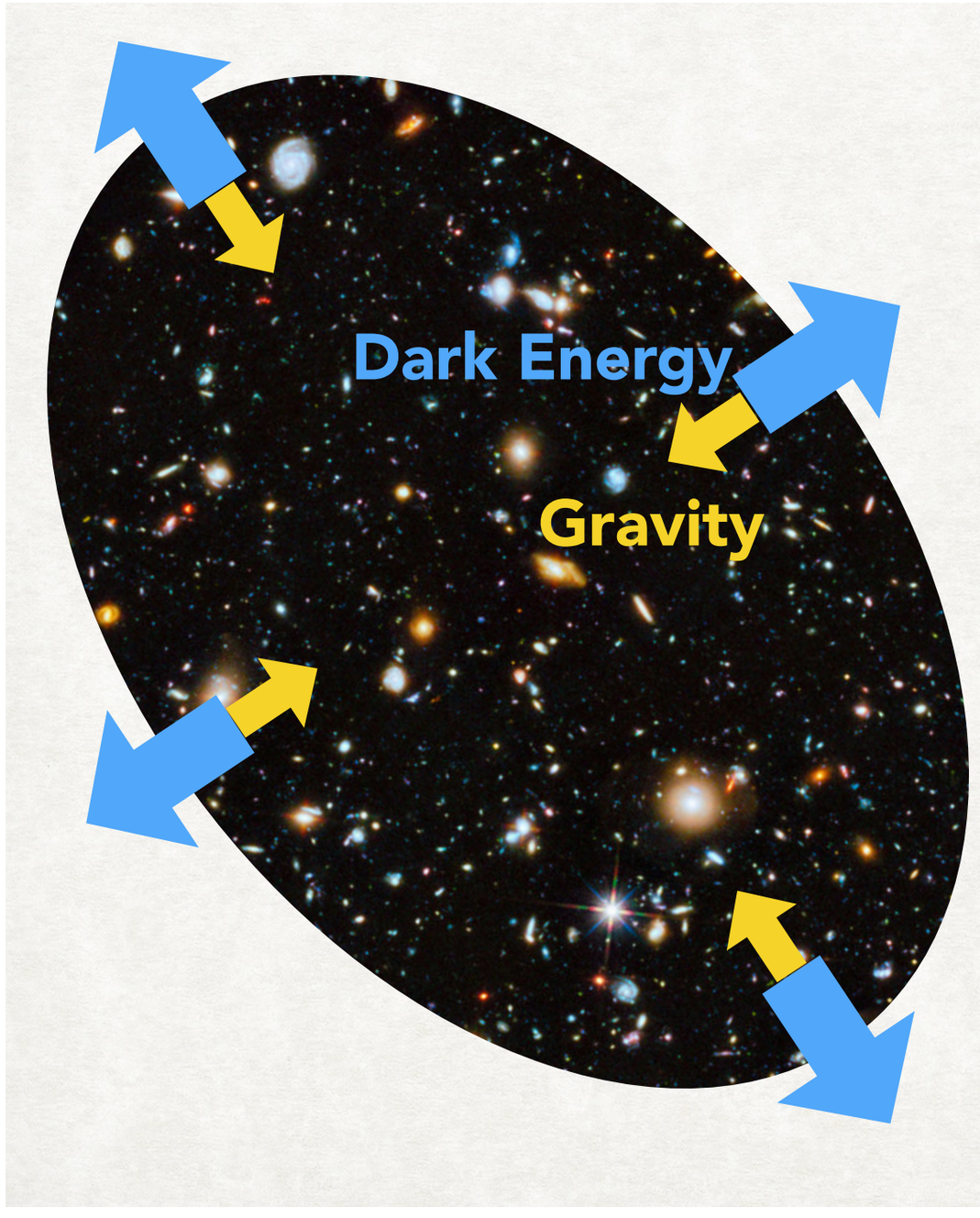
# Bonus: Dark Energy



# 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**

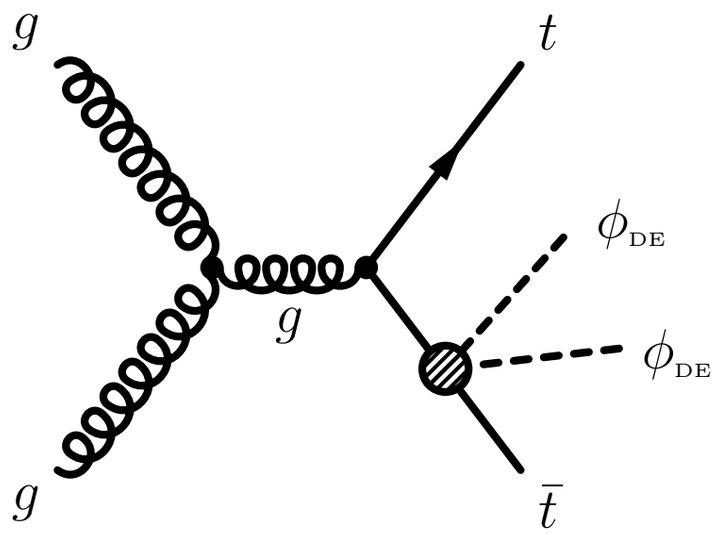


# Horndeski EFT model

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

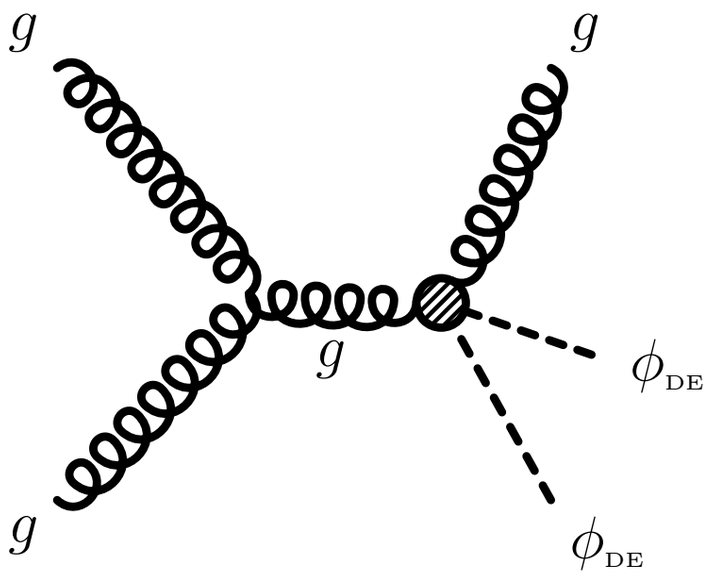
1 scalar field $\phi_{\rm DE}$ coupled to gravity

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




➡ tops + $E_T^{miss}$

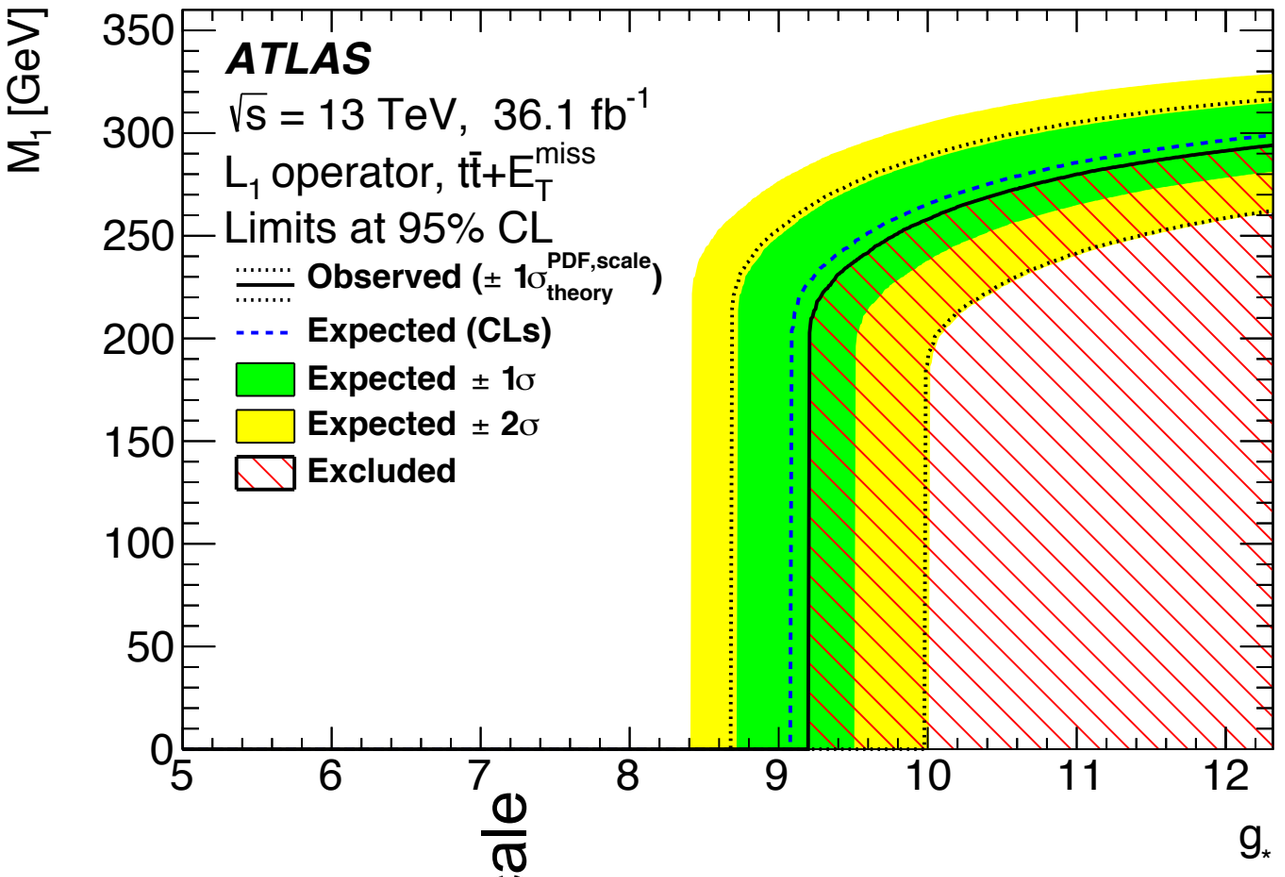
$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M_2^4} T^{\mu\nu},$$



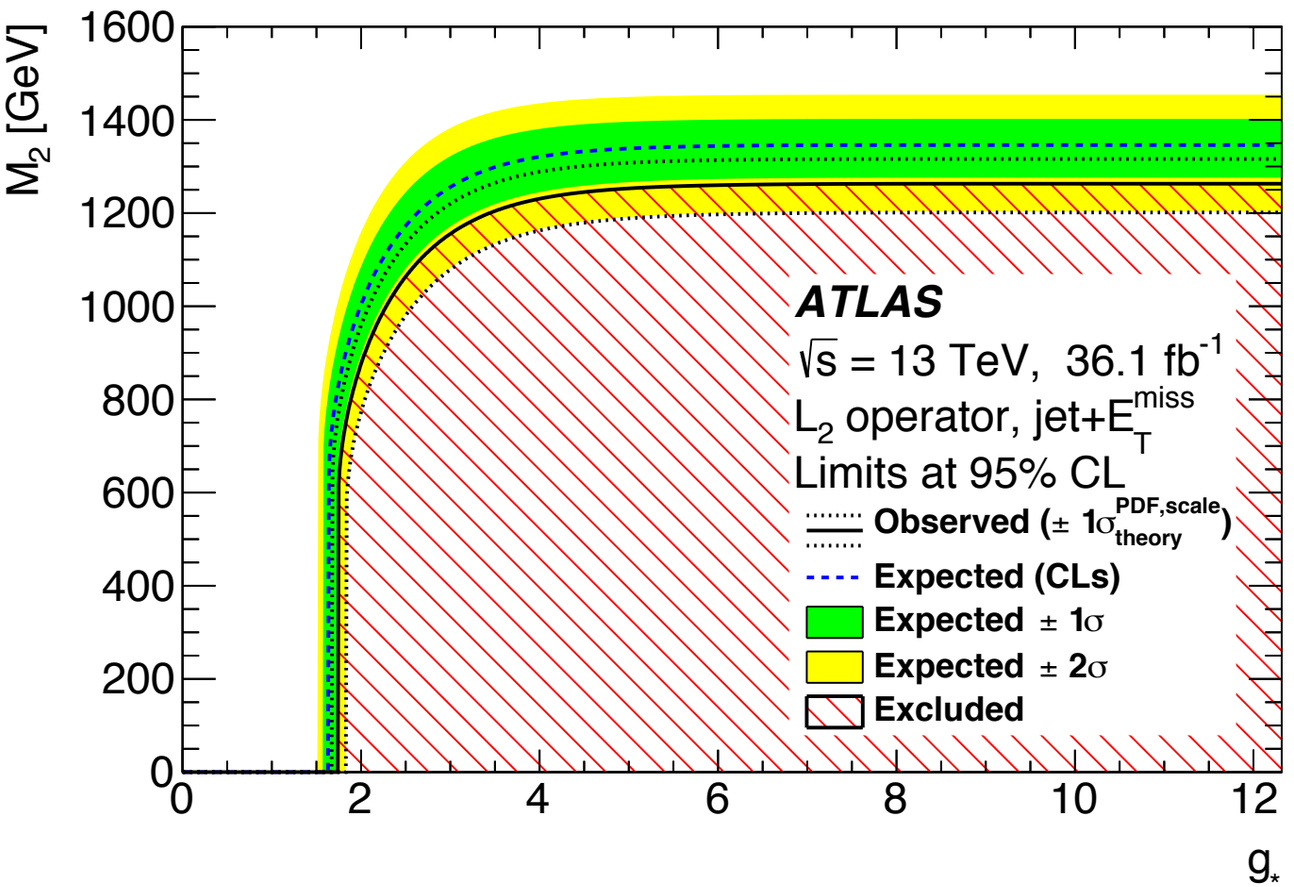

➡ jet + $E_T^{miss}$

# Results

## tops + $E_T^{miss}$




## jet + $E_T^{miss}$



# Conclusion - Cheat sheet

## DM-mediator searches

| Signature | Dataset | Reference |
|---|---|---|
| Di-lepton resonance | 139 $fb^{-1}$ | 1903.06248 |
| Di-jet, Di-jet + ISR, | 139 $fb^{-1}$ | 1901.10917, ATLAS-CONF-2019-007, 1808.03124 |
| Di-bjet | 80 $fb^{-1}$ | ATLAS-CONF-2018-052 |
| Di-jet + leptons | 80 $fb^{-1}$ | ATLAS-CONF-2018-015 |
| Dijet + photons | 36 $fb^{-1}$ | 1905.10331 |
| Etmiss + Higgs | 36 $fb^{-1}$ | 1908.01713 |
| Etmiss + t/ttbar | 36 $fb^{-1}$ | 1901.01553 |
| Etmiss + jet | 36 $fb^{-1}$ | 1712.02345 |
| H invisible | 36 $fb^{-1}$ | Phys. Rev. Lett. 122 (2019) 231801 |
| ATLAS DM summary | 36 $fb^{-1}$ | JHEP 05 (2019) 142 |

# Thanks for your attention!

**Contact**

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www.desy.de

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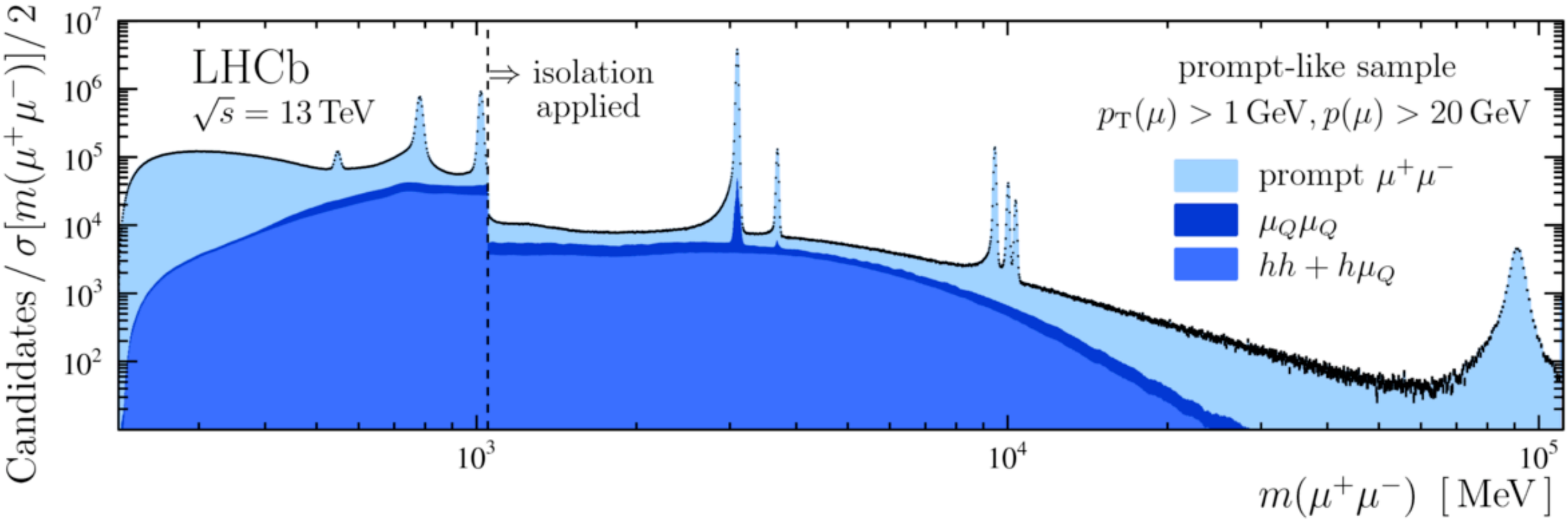
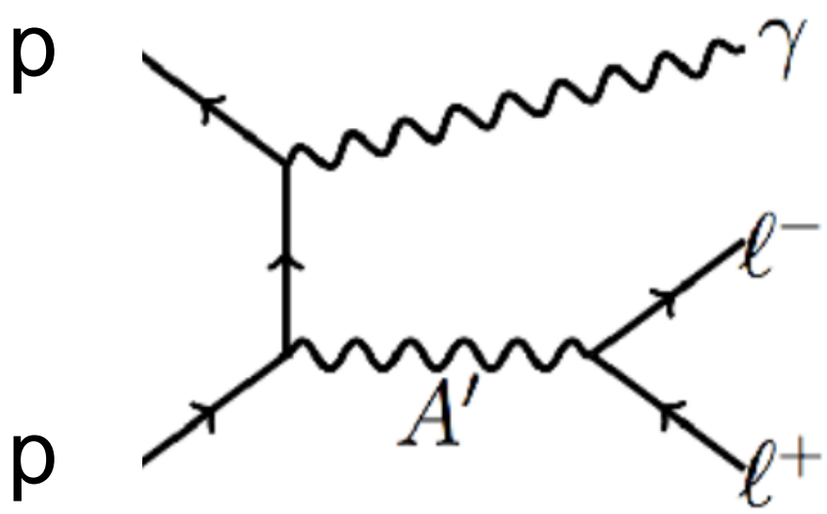
ATLAS Group Campus Zeuthen
priscilla.pani@desy.de

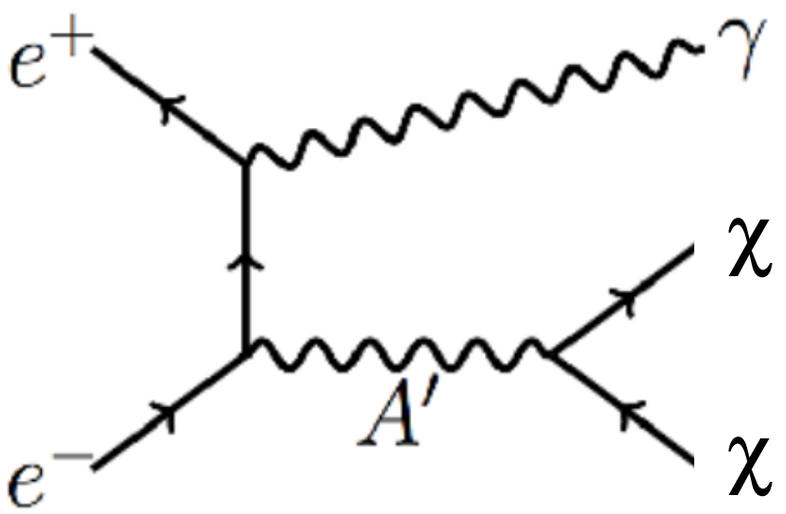
https://atlas.desy.de/external_grants/priscilla_pani_yig/

# Backup

# A word on Dark Photons

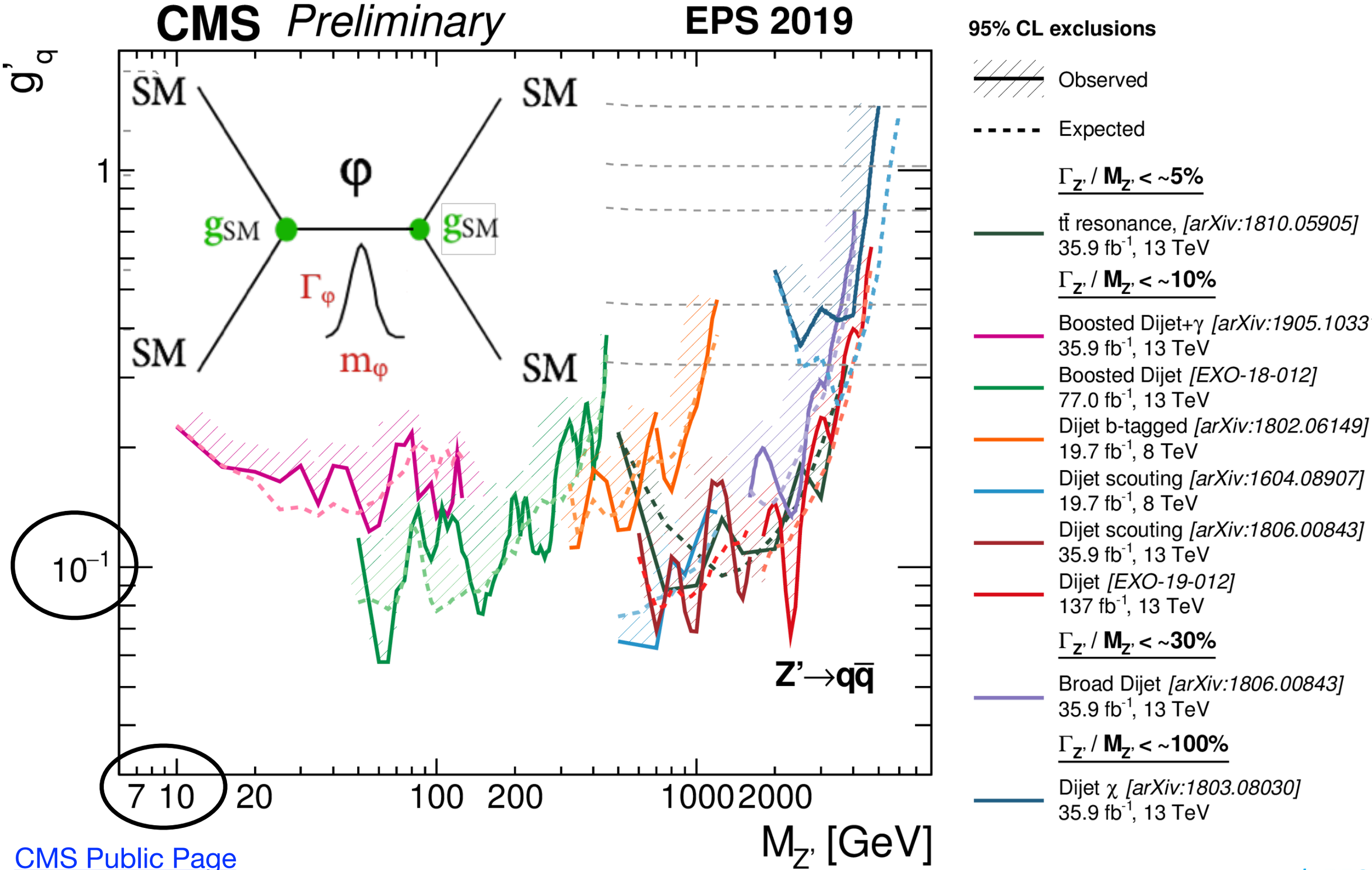


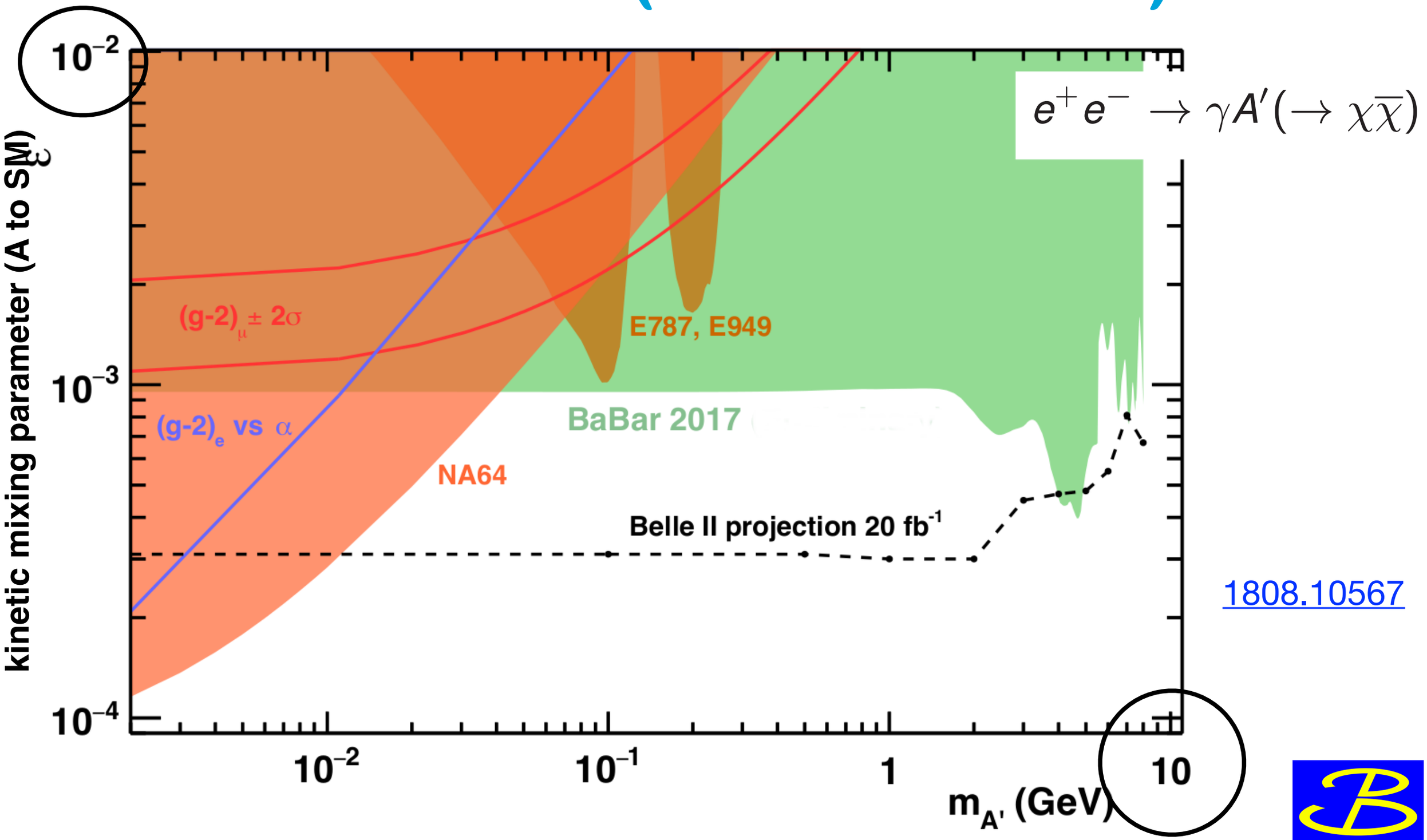

See more details on Thursday's parallel session (DM15)

# Vector mediators (couplings)




CMS Public Page

# Dark Photons (low masses)




1808.10567

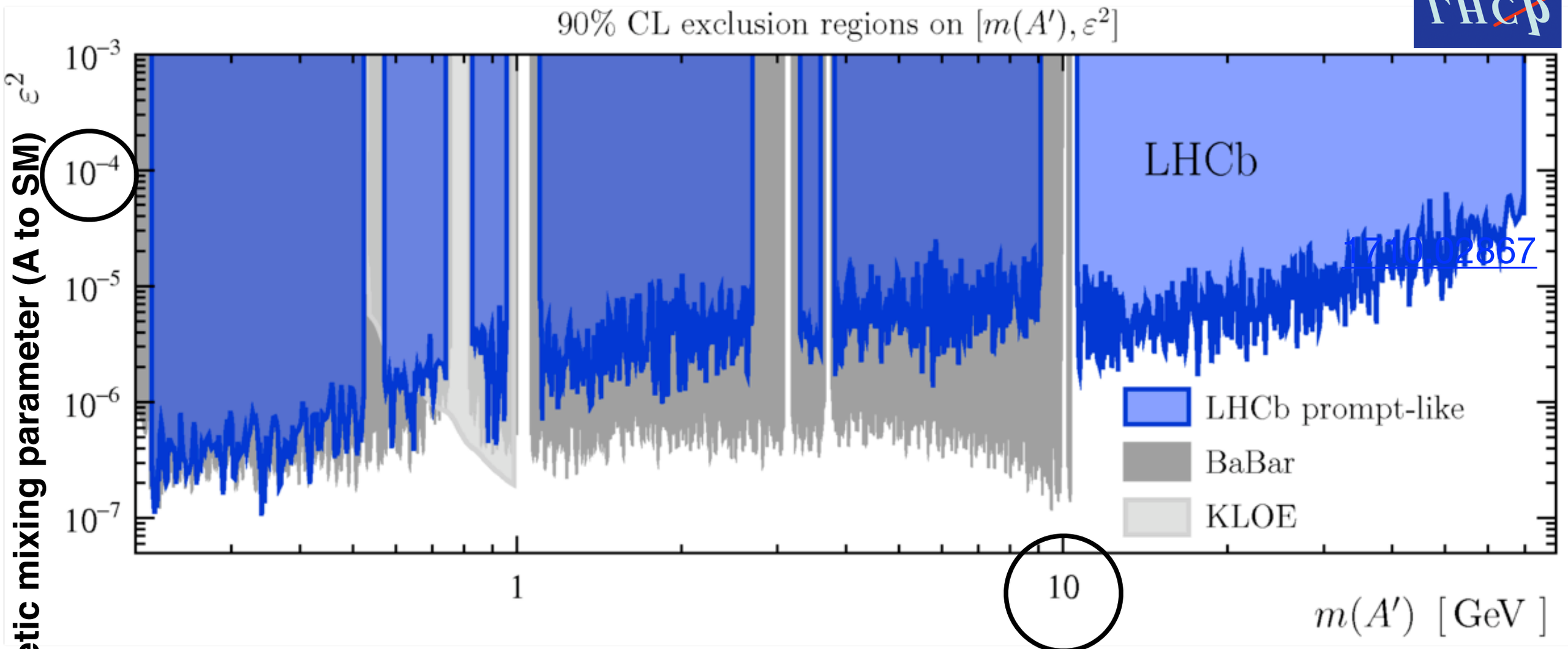
Belle II

See more details on Thursday's parallel session (DM15)



DESY.

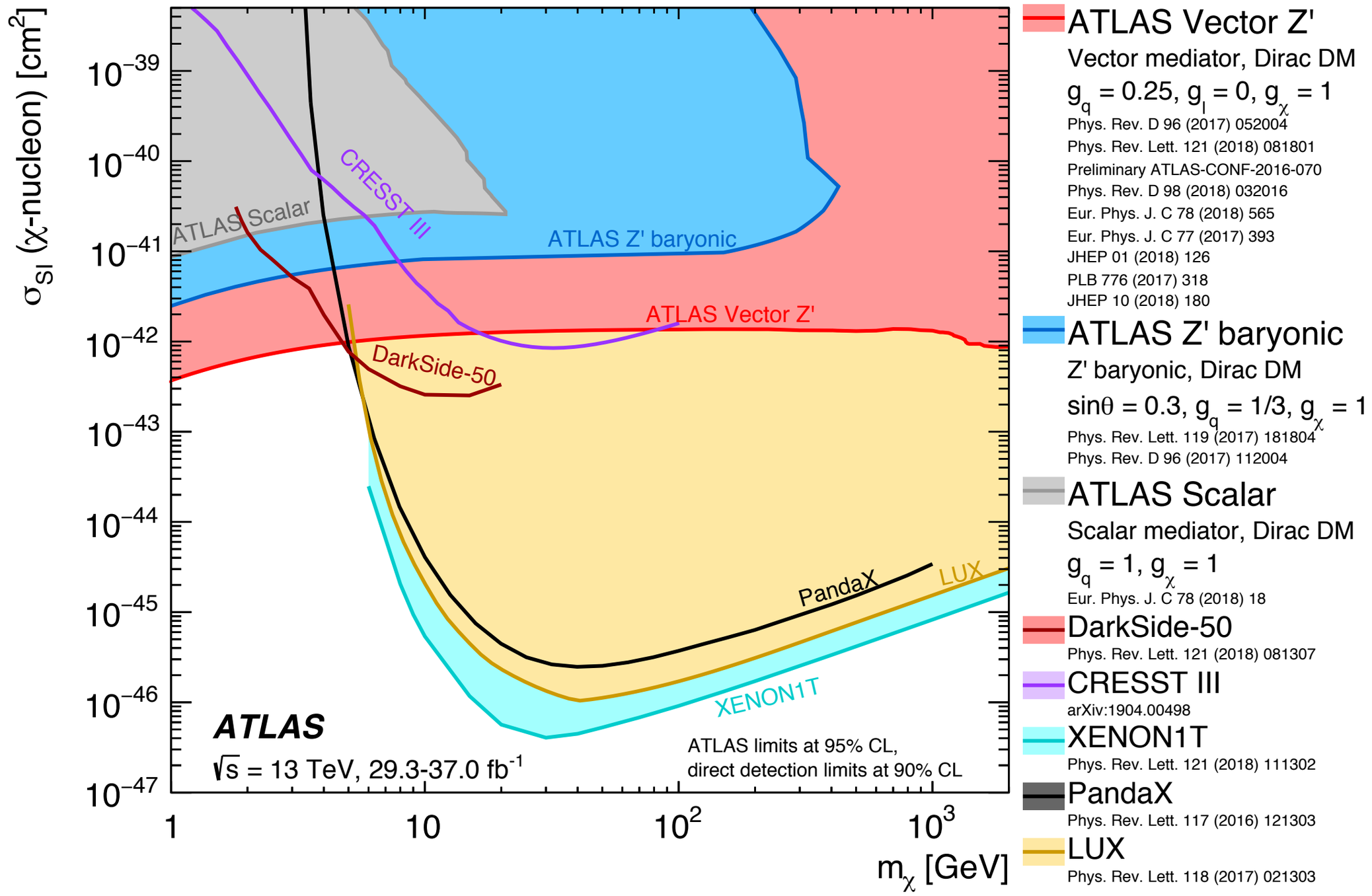
# Dark Photons (low masses)




Not covered further, see T. Ferber's talk for details

# Comparing to direct detection

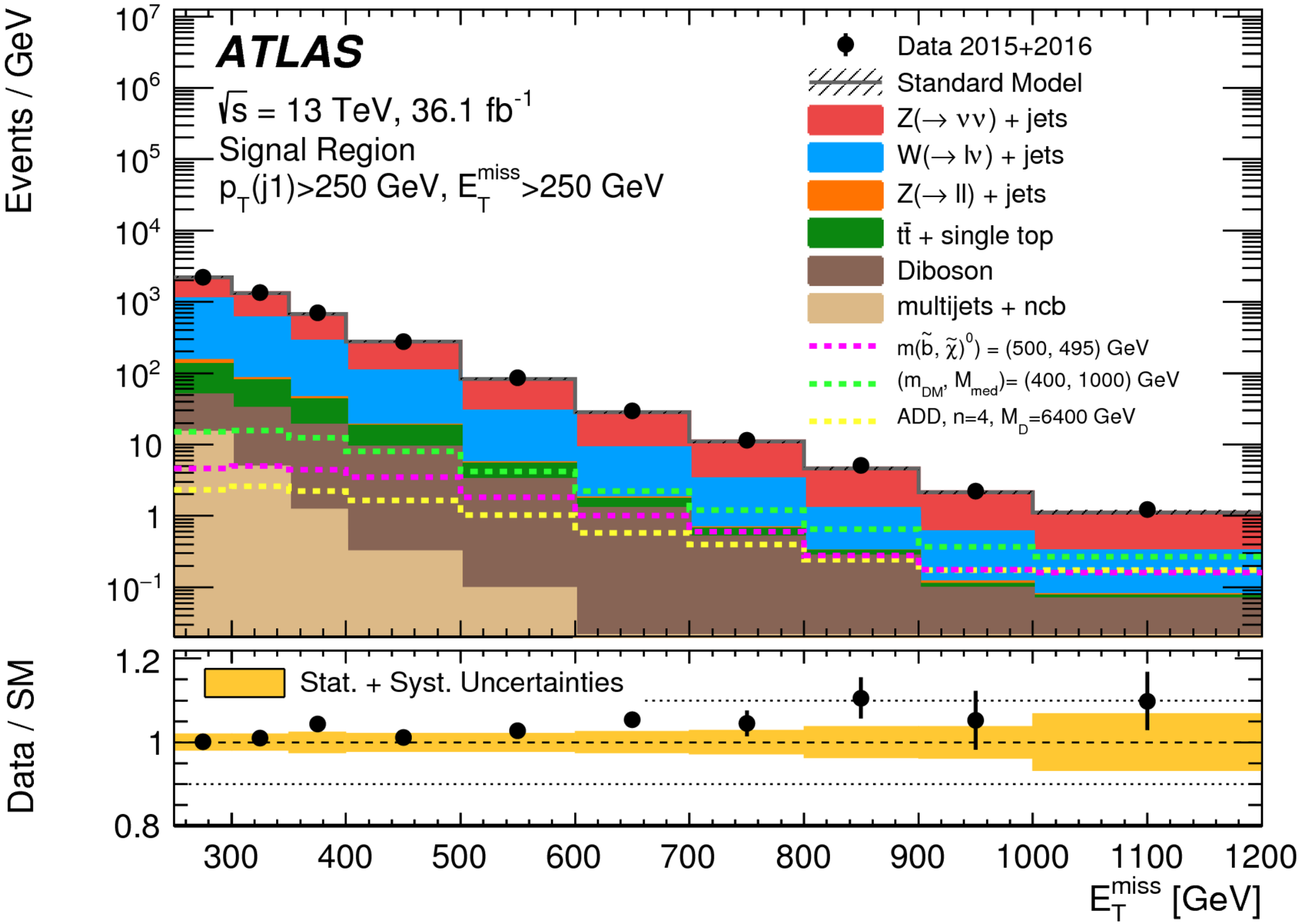
## "The plot"



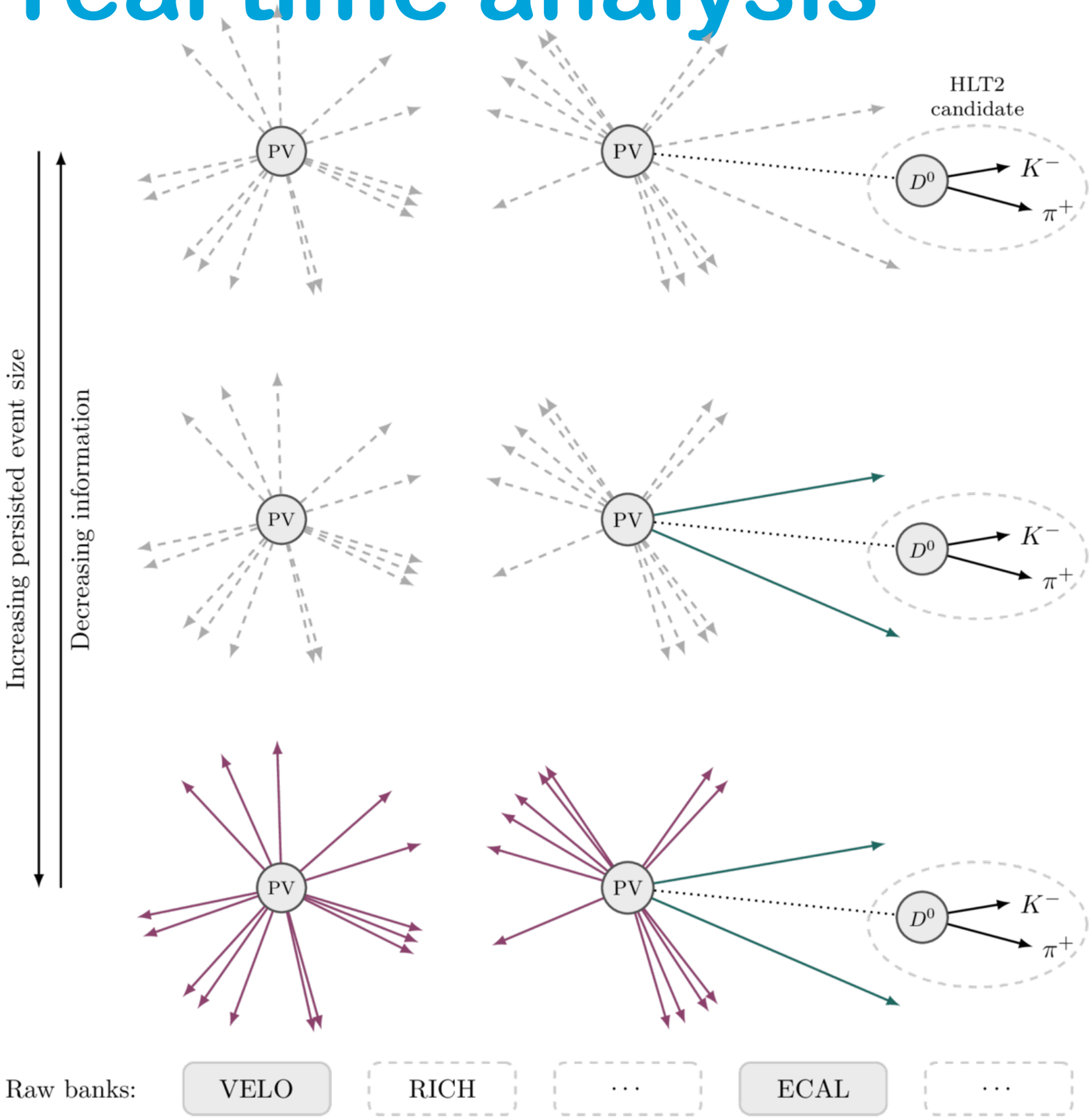

JHEP 05 (2019) 142

Details and limitations of the conversion in arXiv:1603.04156

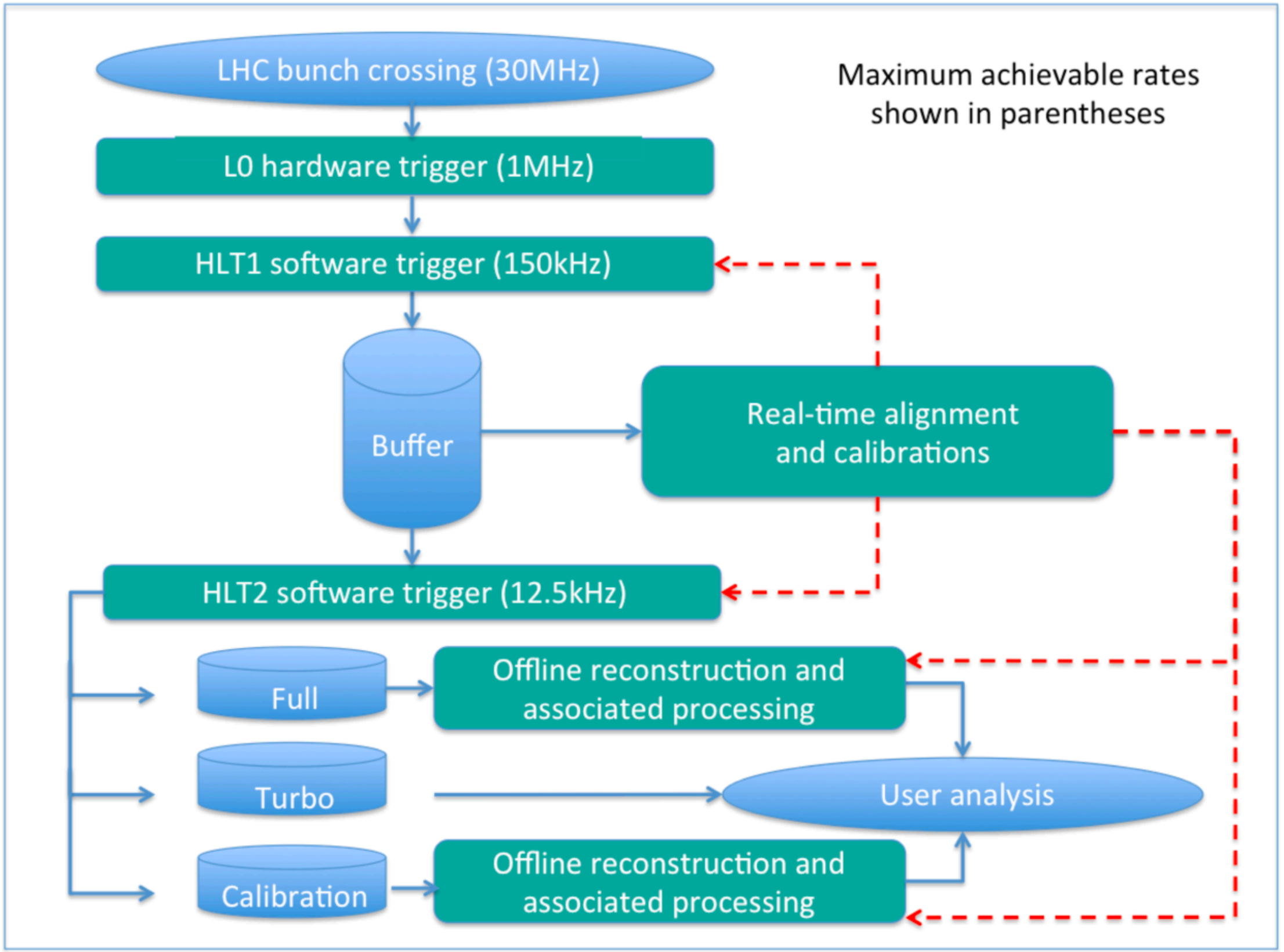
# mono-jet SR


ATLAS
√s = 13 TeV, 36.1 fb-1
Signal Region
pT(j1)>250 GeV, ETmiss>250 GeV
Data 2015+2016
Standard Model
Z(→ νν) + jets
W(→ lν) + jets
Z(→ ll) + jets
tt̄ + single top
Diboson
multijets + ncb
m(b̃, χ̃)0) = (500, 495) GeV
(mDM, Mmed)= (400, 1000) GeV
ADD, n=4, MD=6400 GeV
Events / GeV
Stat. + Syst. Uncertainties
Data / SM
ETmiss [GeV]

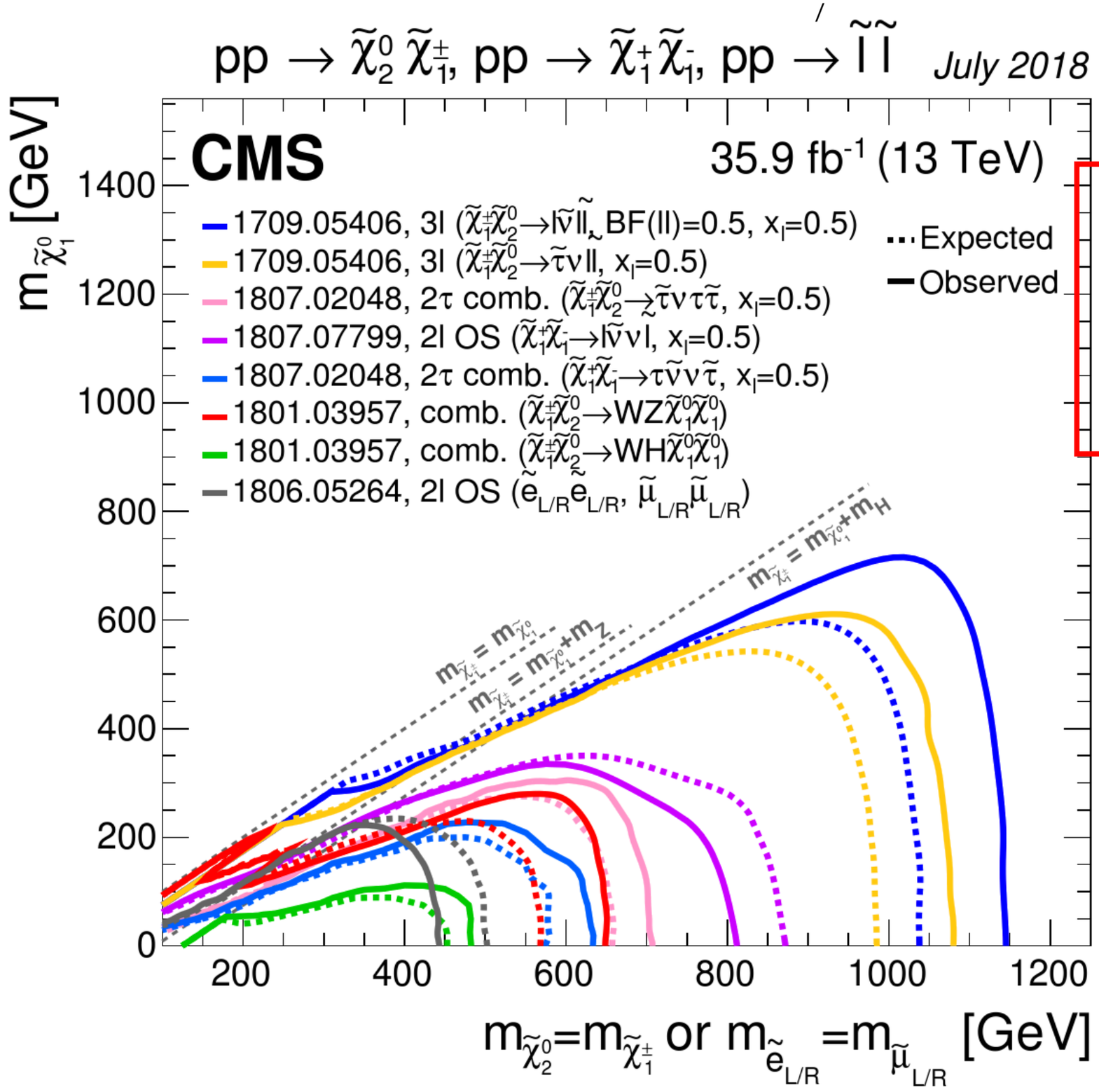
# LHC real time analysis

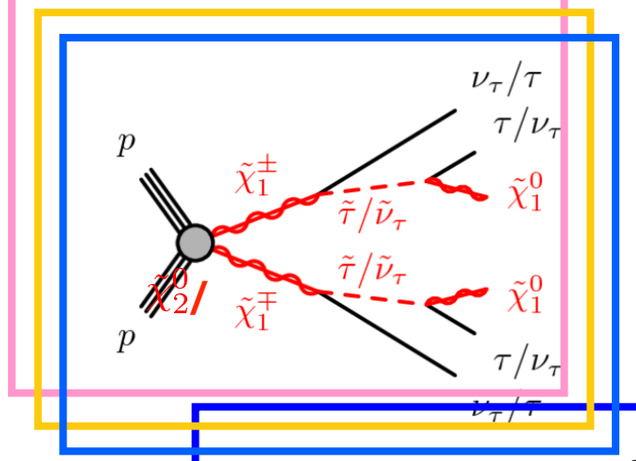


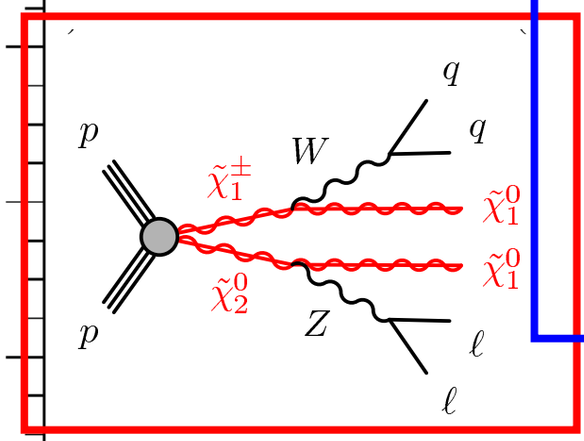
# LHCb real time model

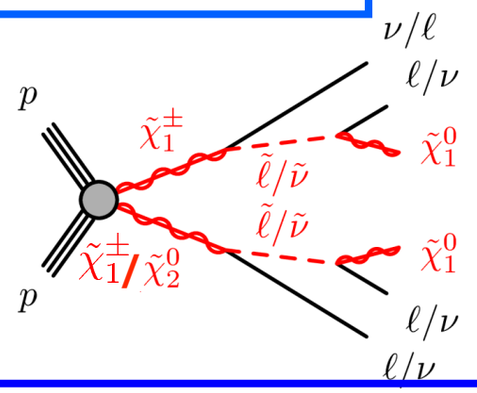


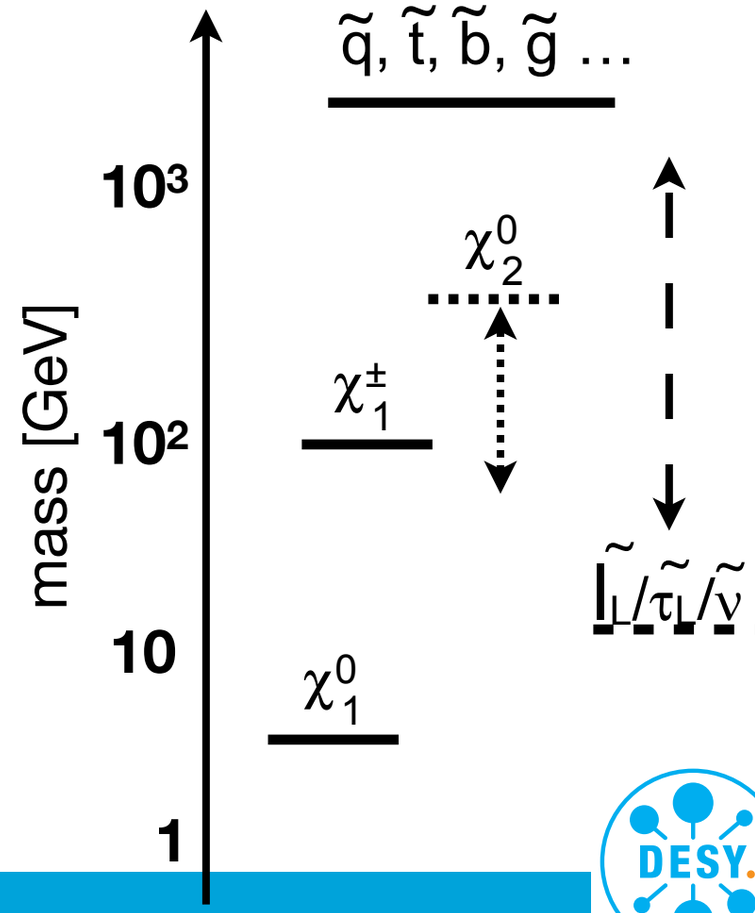
# SUSY: Electroweak



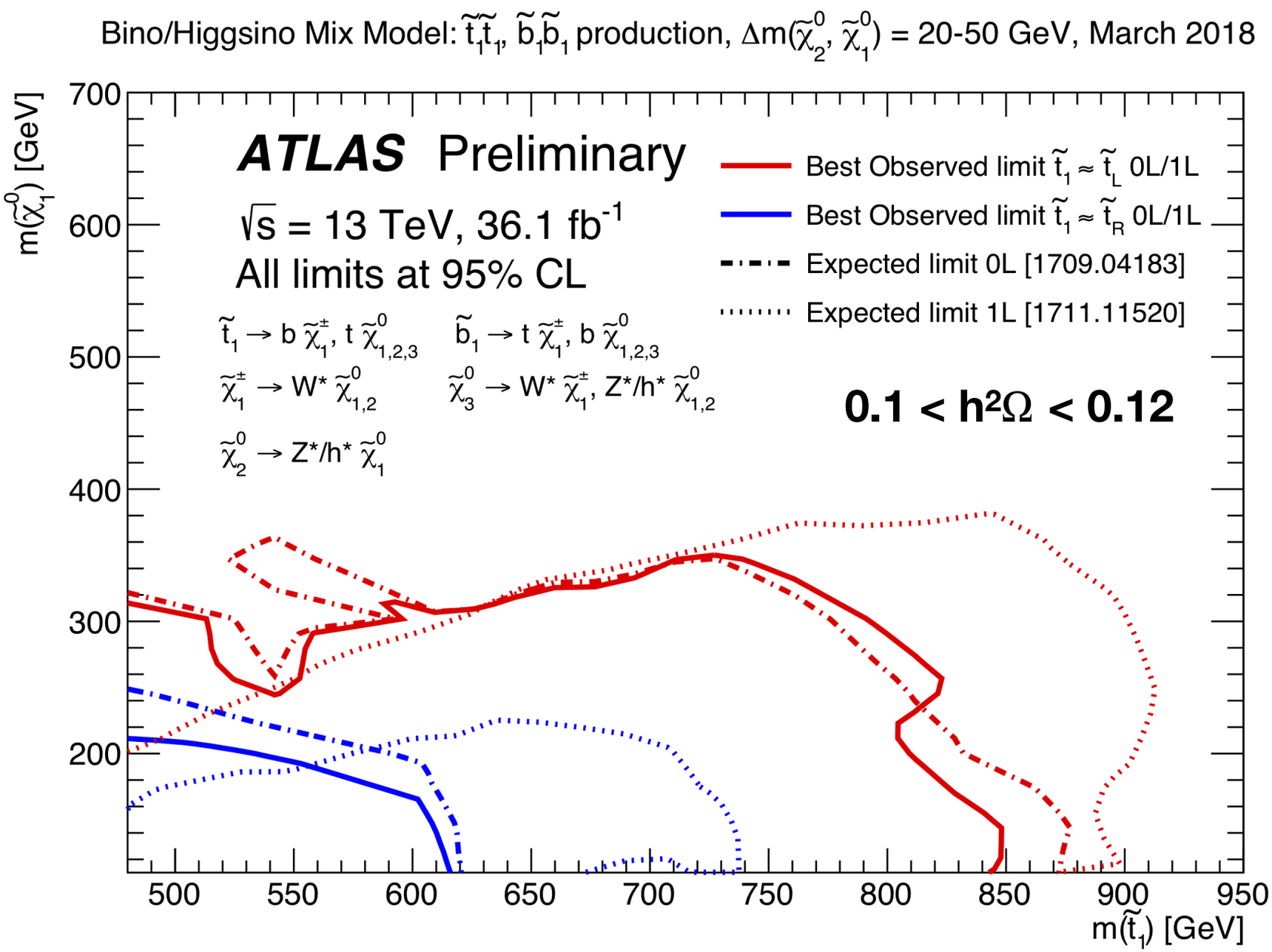



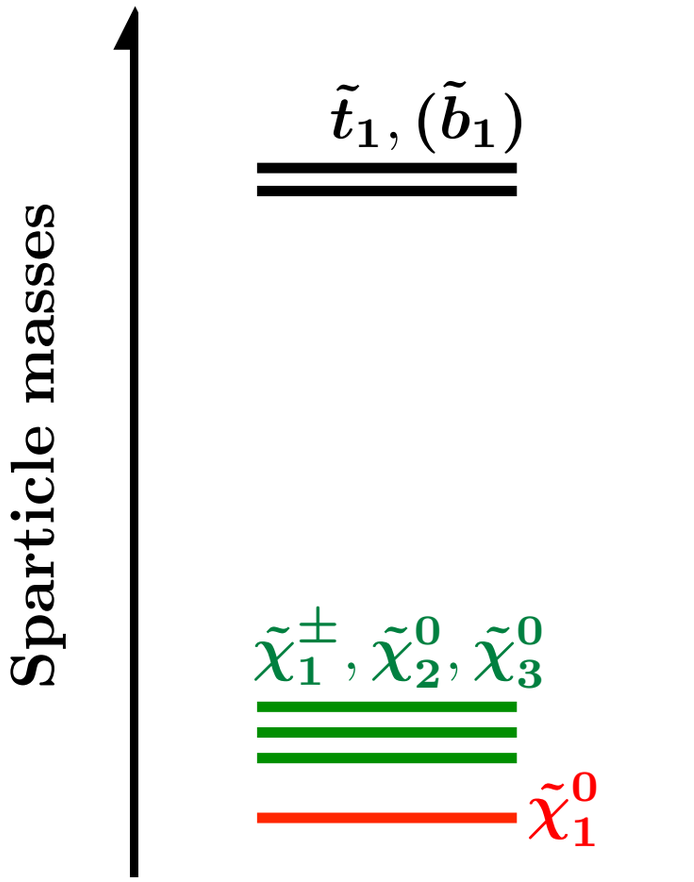



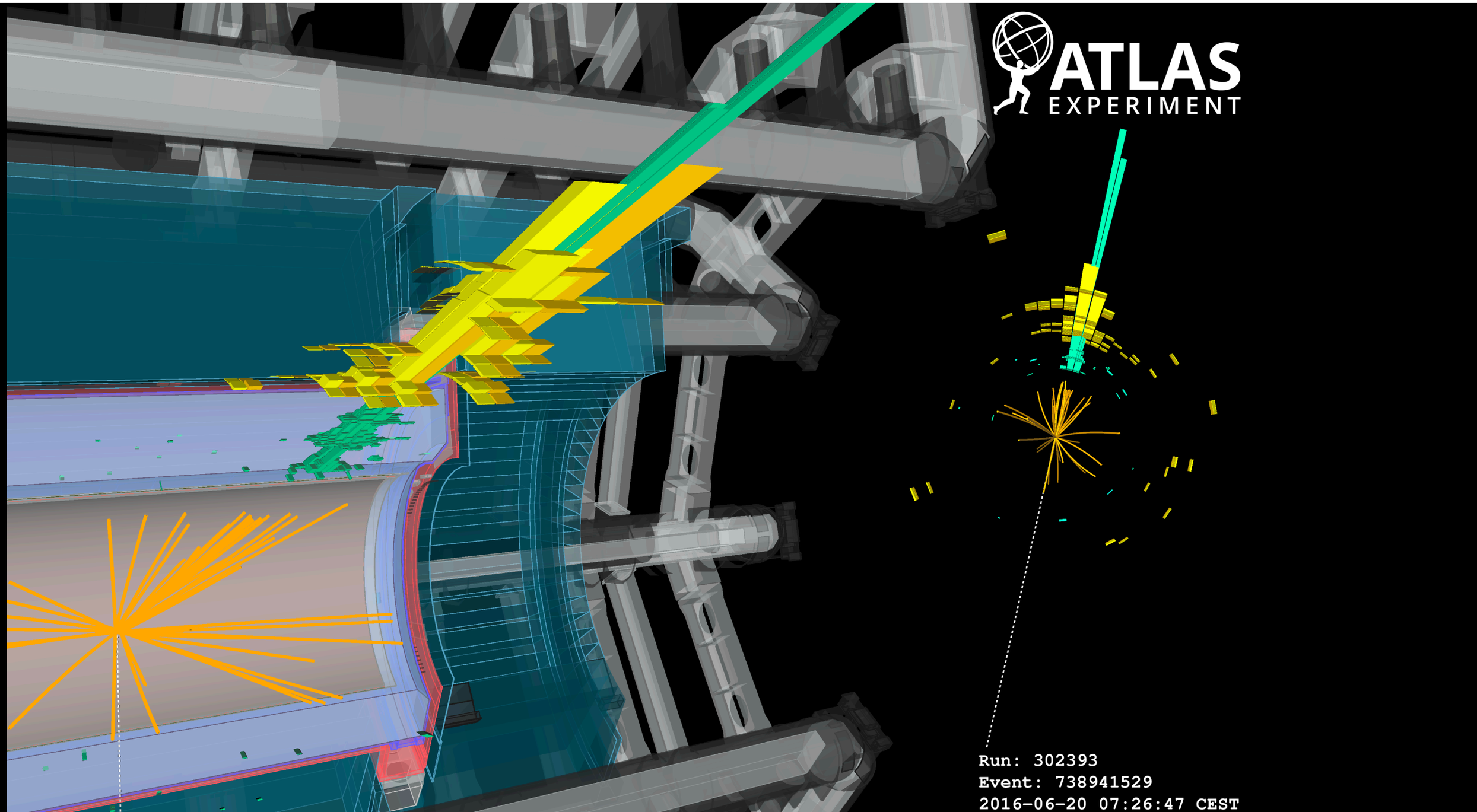
# SUSY: 3rd generation & DM




d) Bino/Higgsino mix

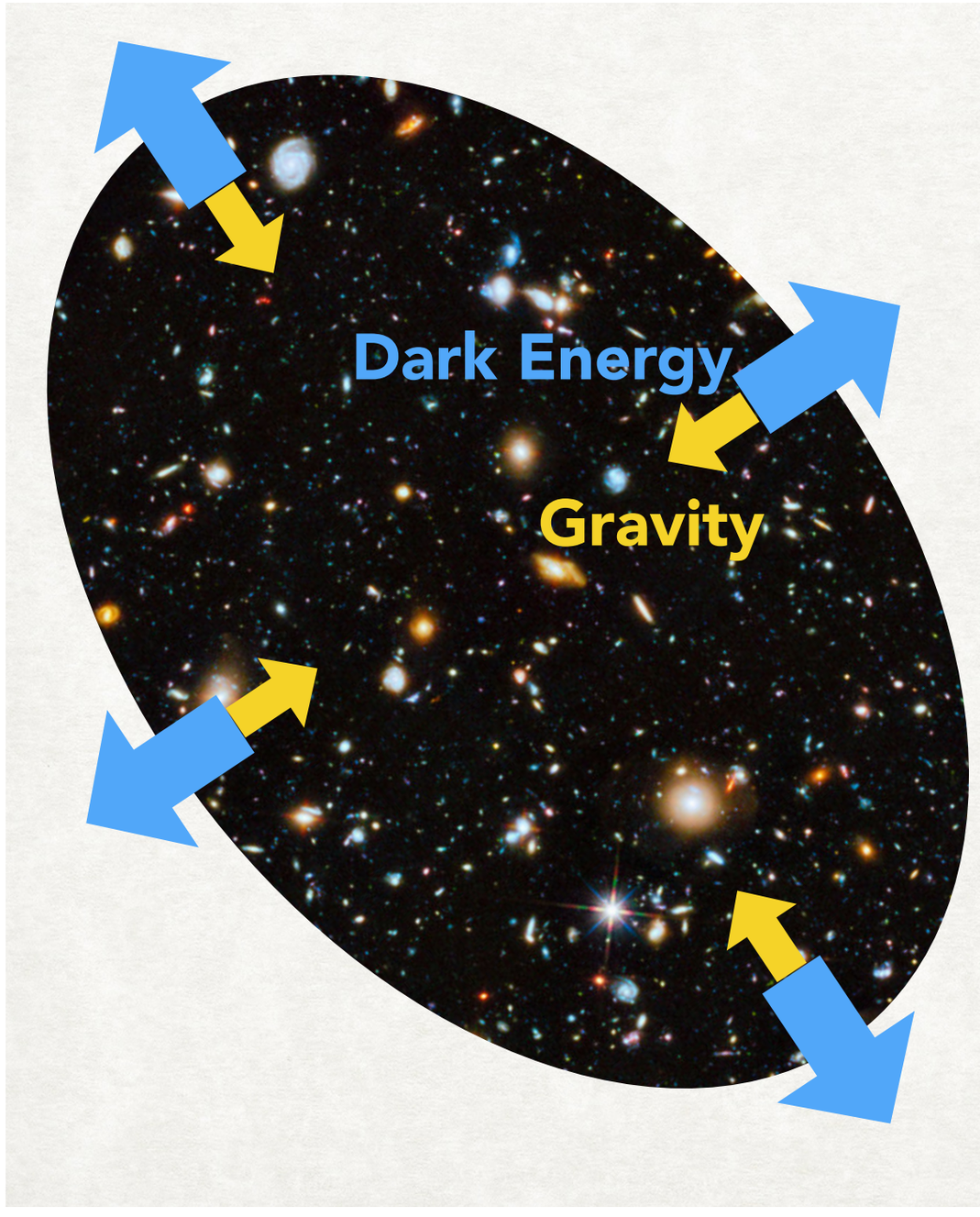
# Bonus: Dark Energy



# 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**

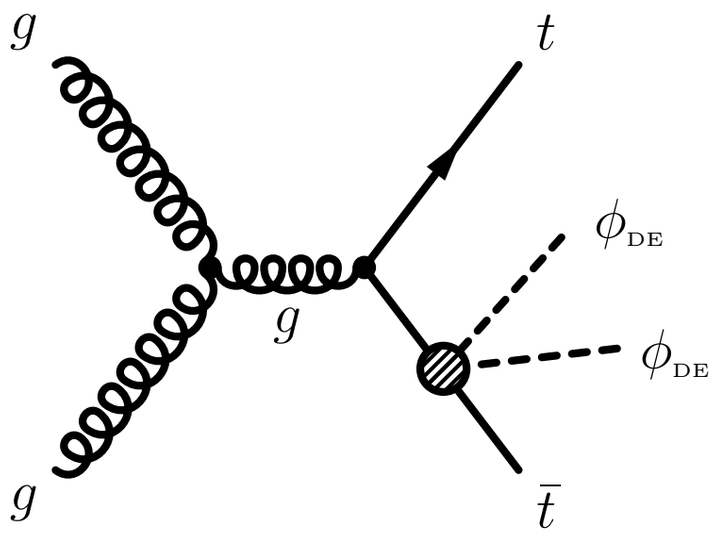


# Horndeski EFT model

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

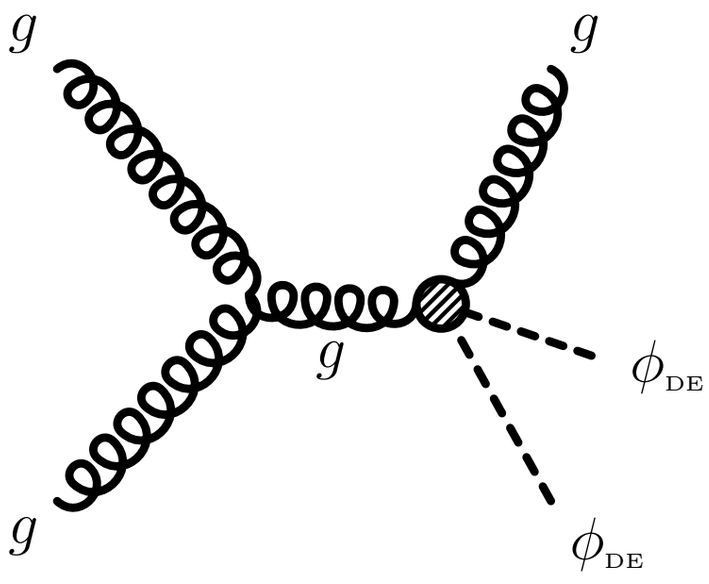
1 scalar field $\phi_{\rm DE}$ coupled to gravity

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




➡ tops + $E_T^{miss}$

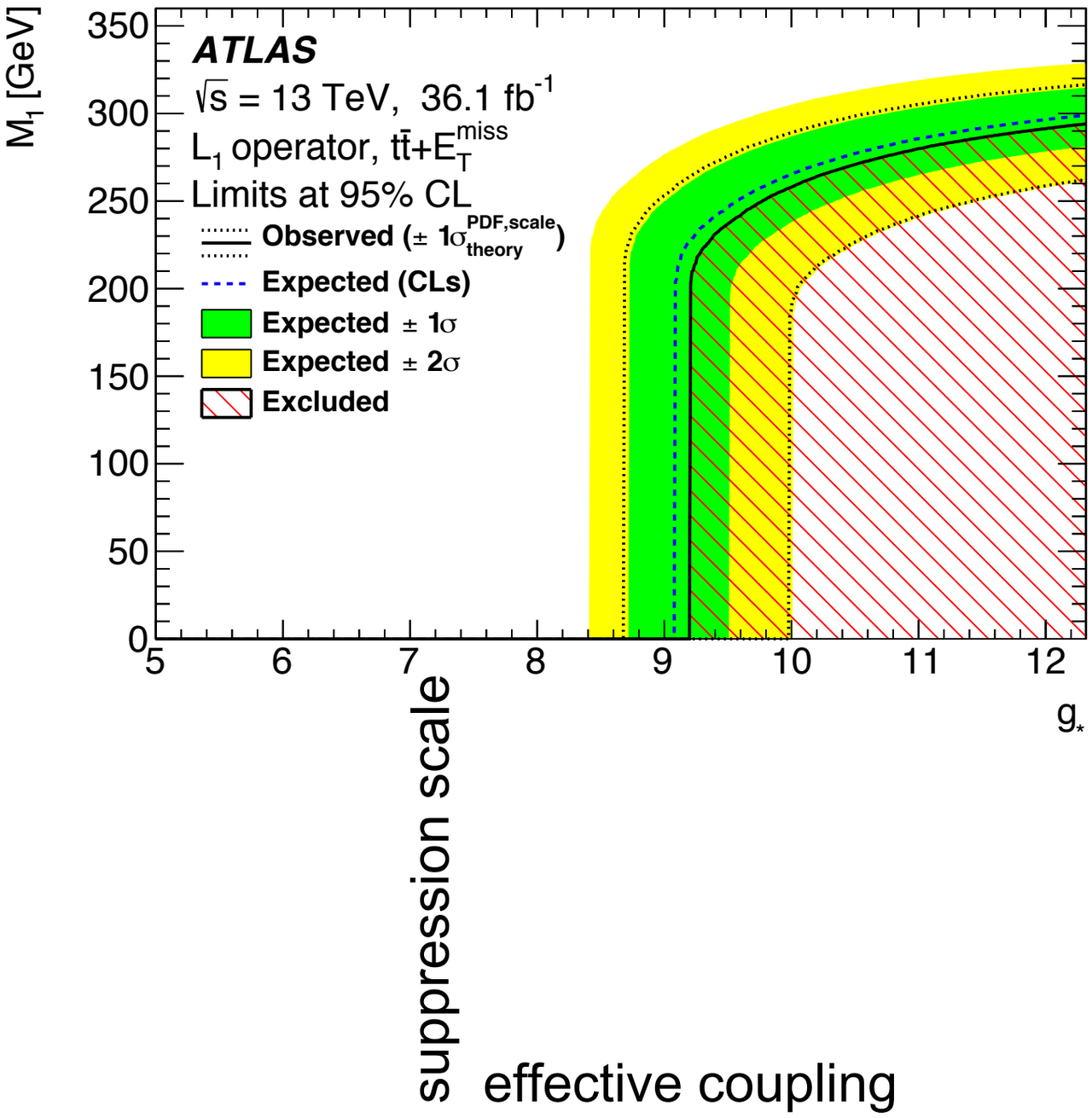
$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M_2^4} T^{\mu\nu},$$



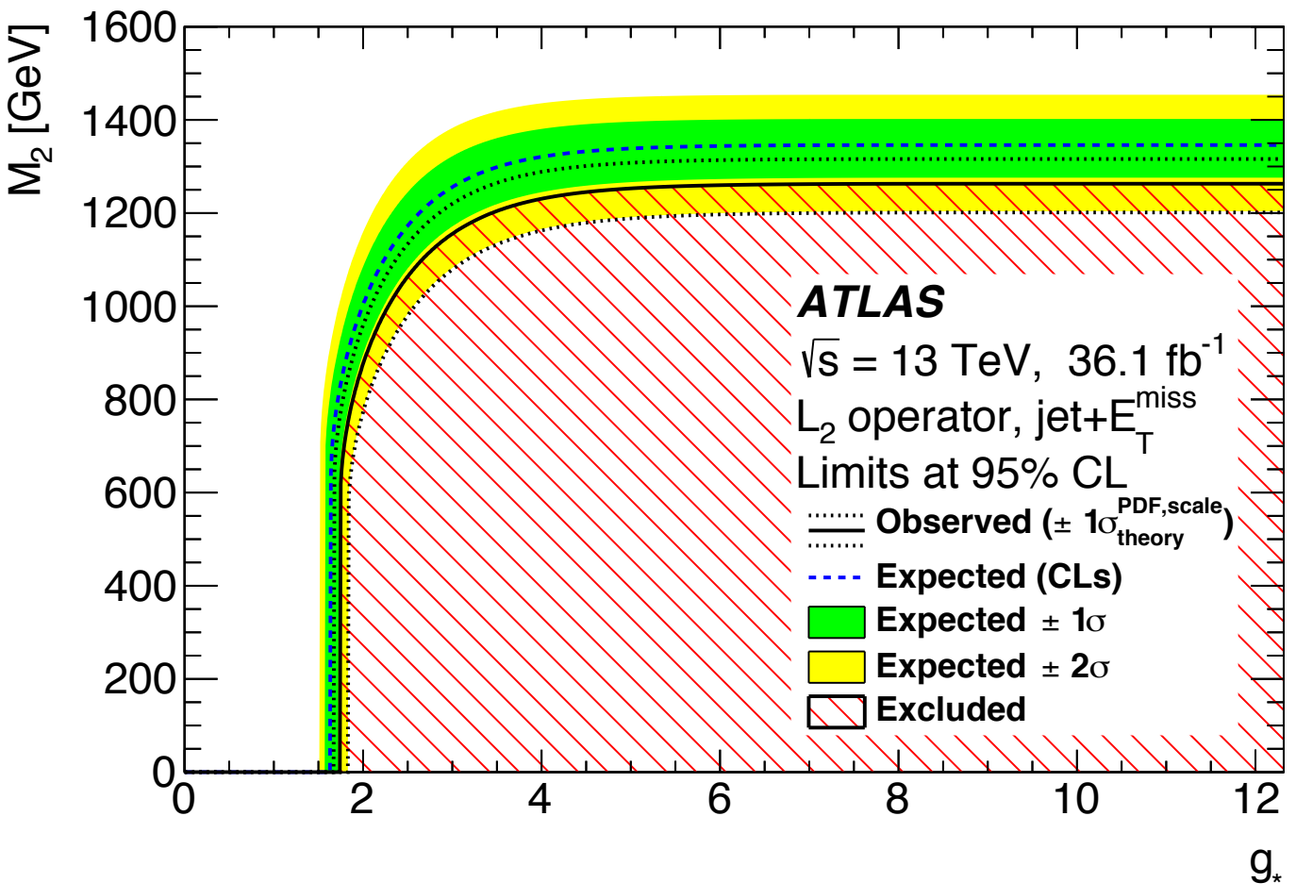

➡ jet + $E_T^{miss}$

# Results

## tops + $E_T^{miss}$

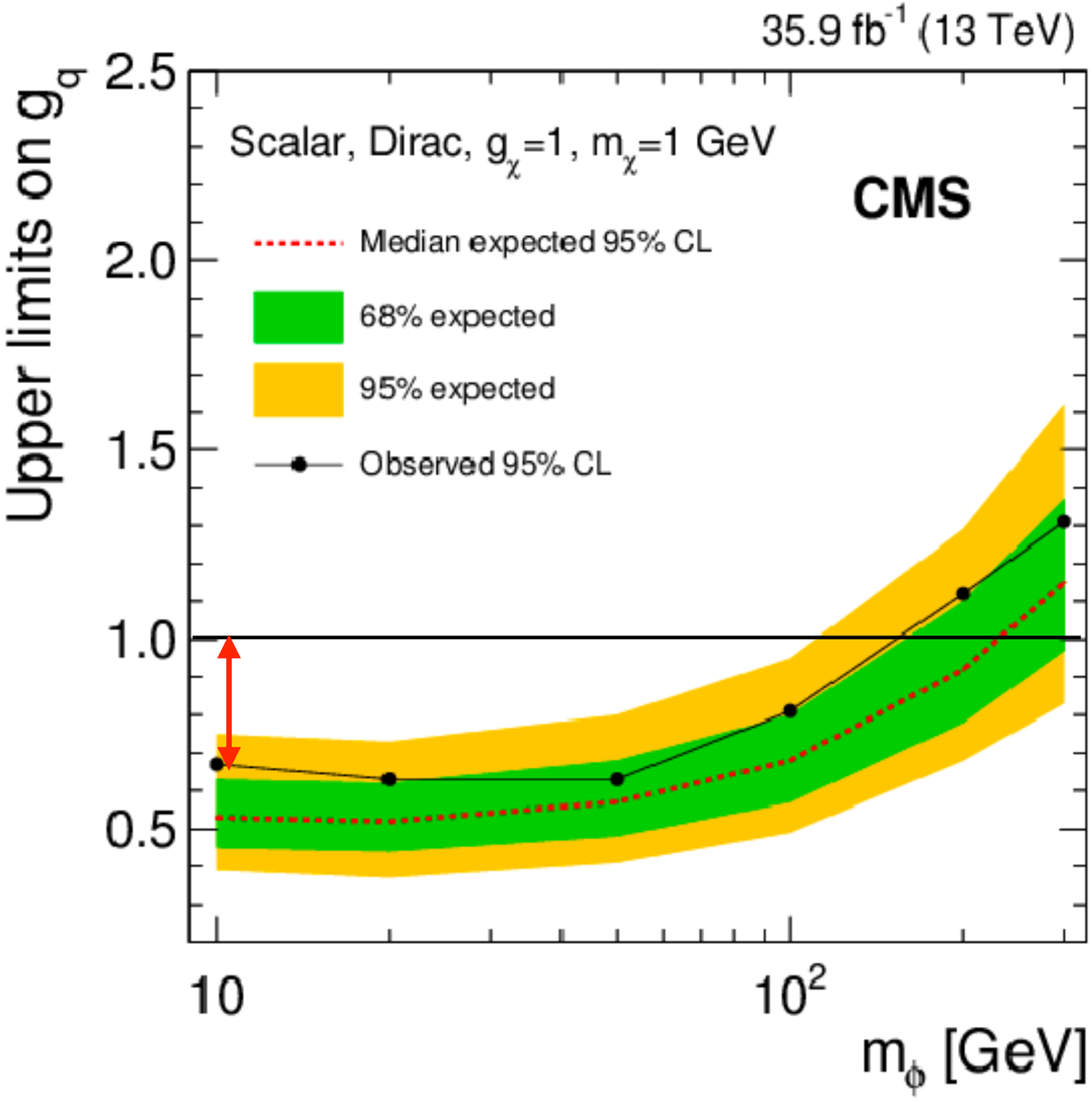


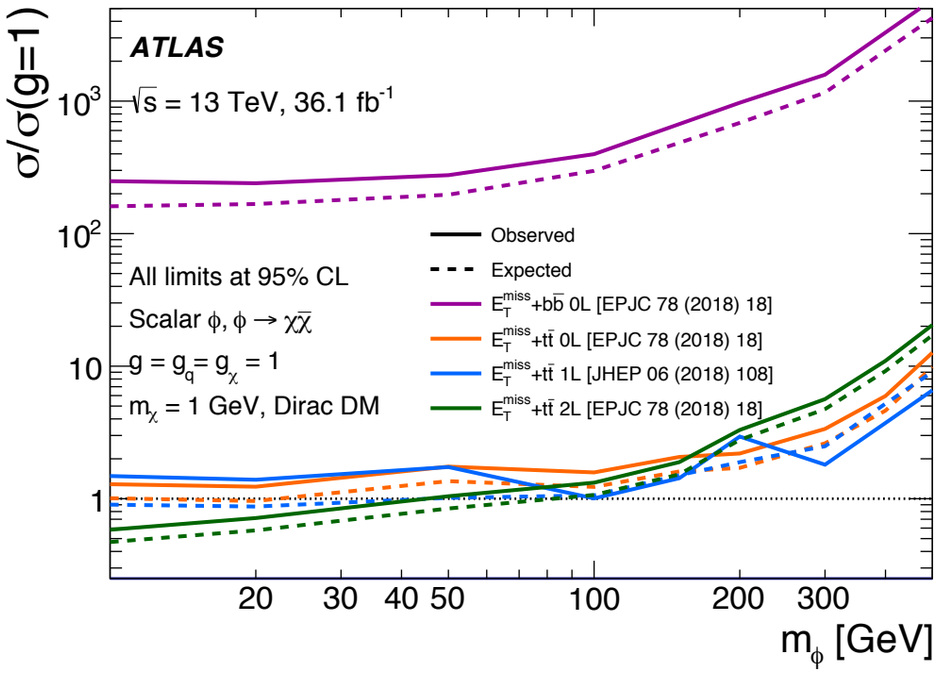

## jet + $E_T^{miss}$



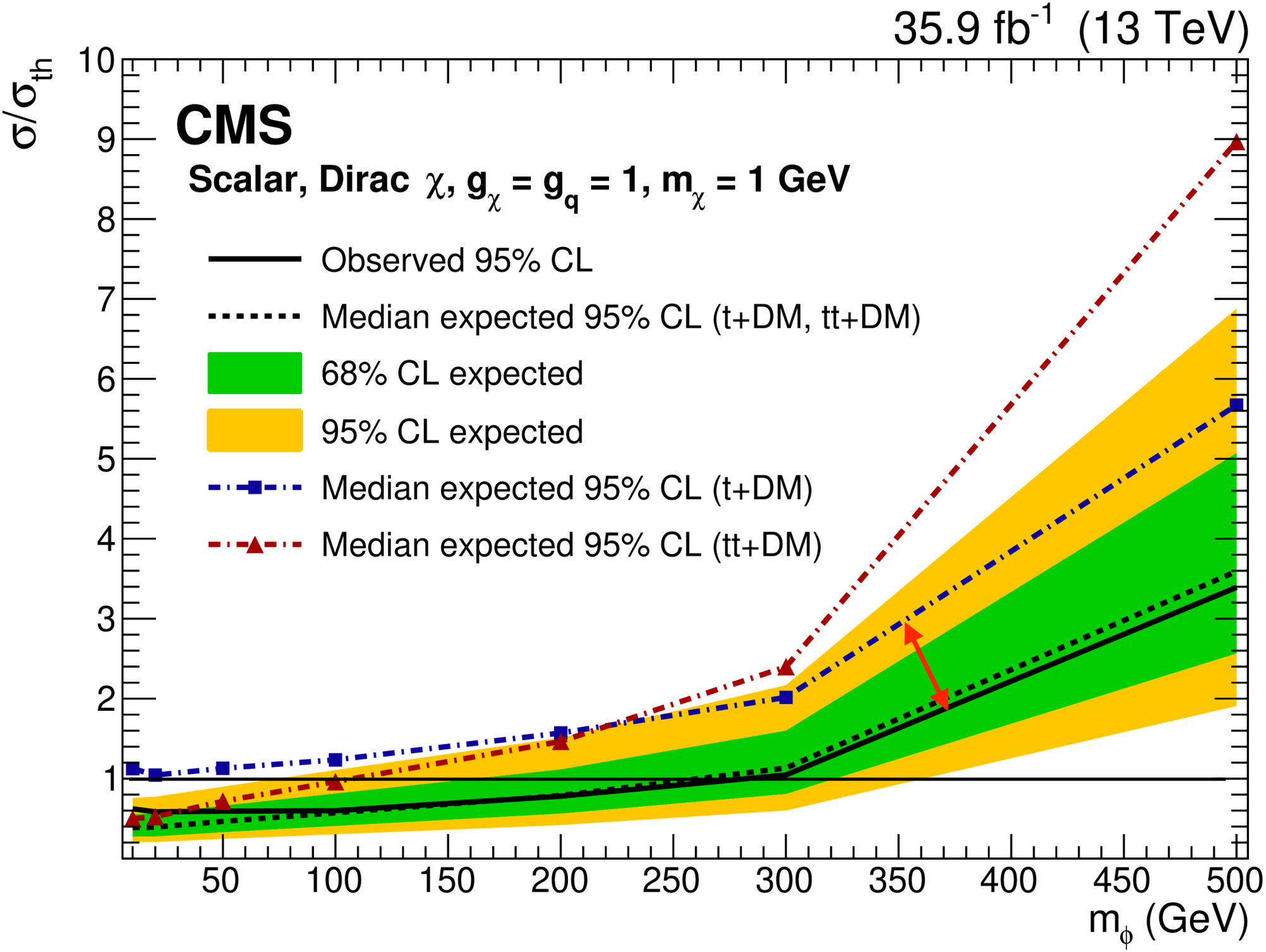
# CMS grand combination

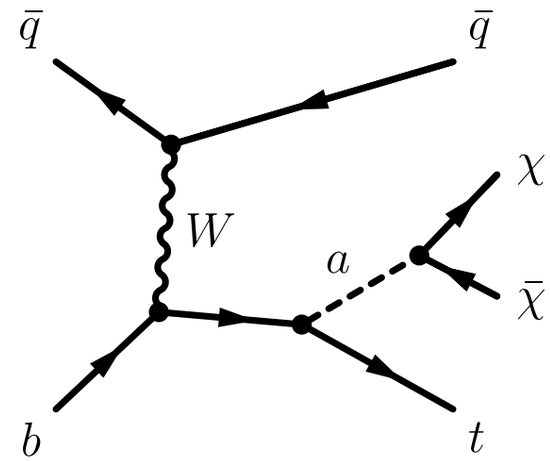
arXiv:1807.06522

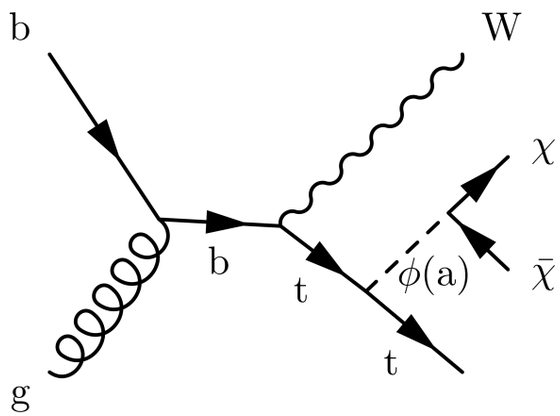


# Spin-0 with single top

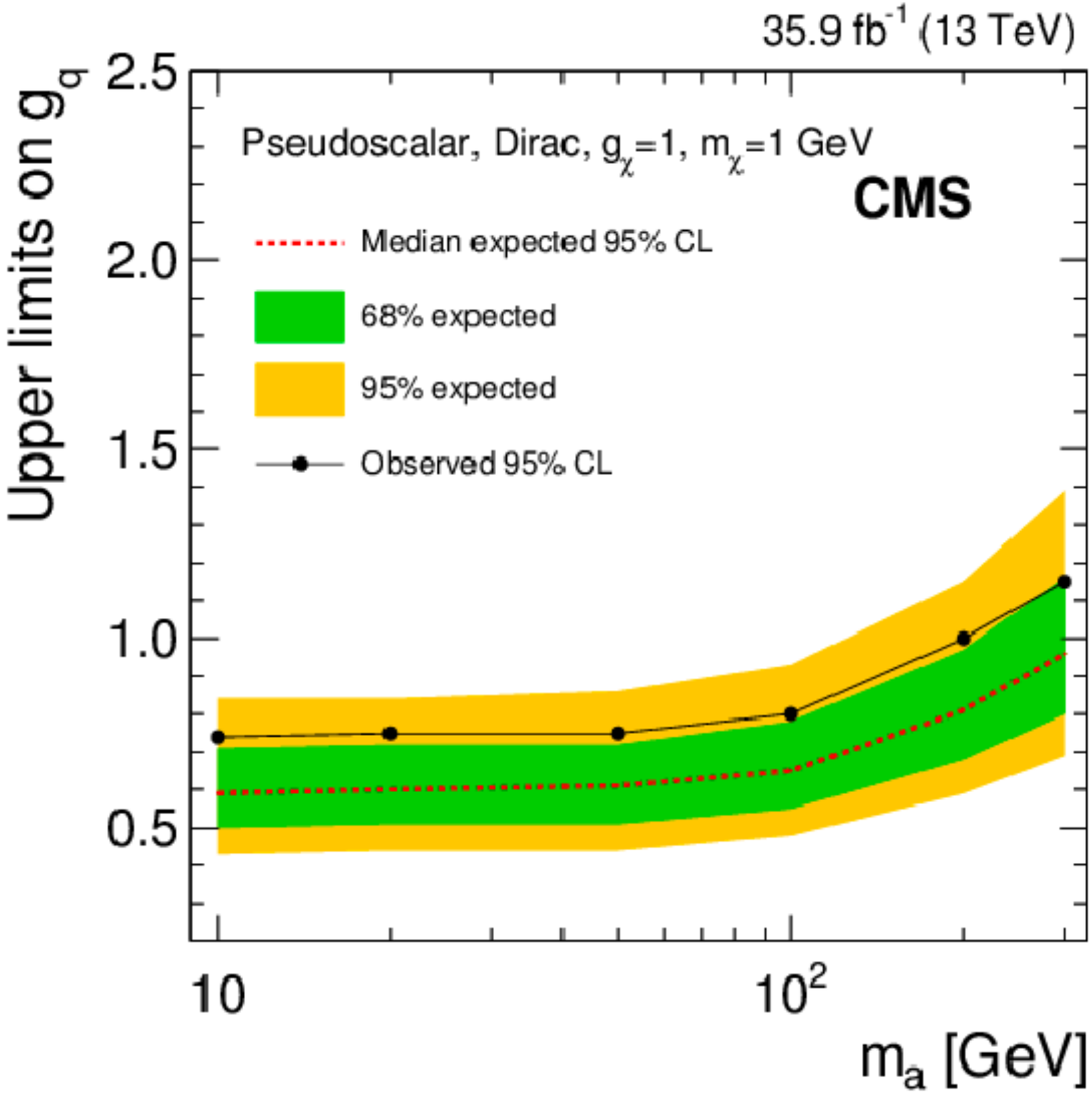


# CMS combination Pseudo

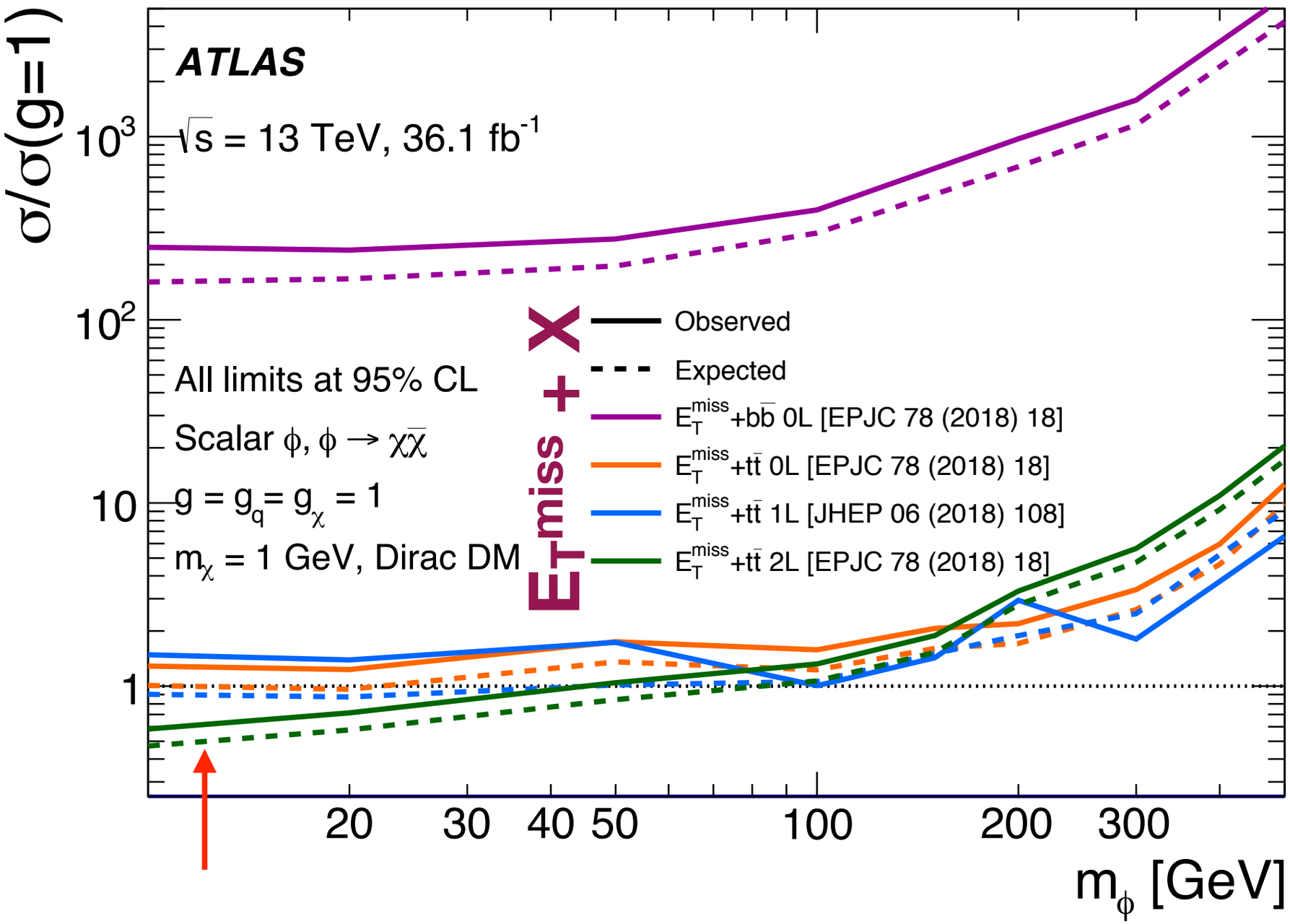
arXiv:1807.06522

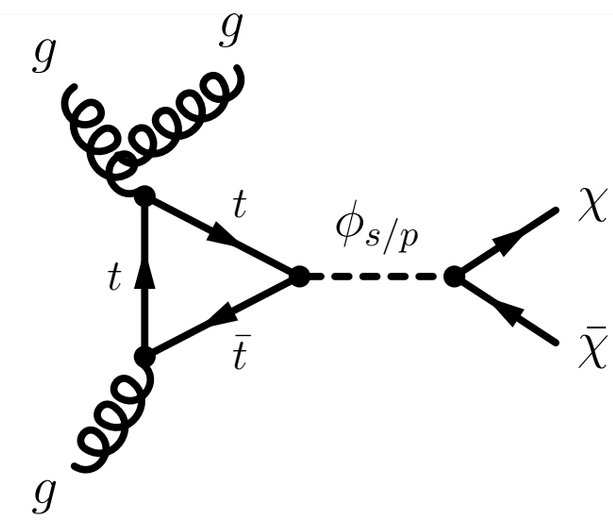


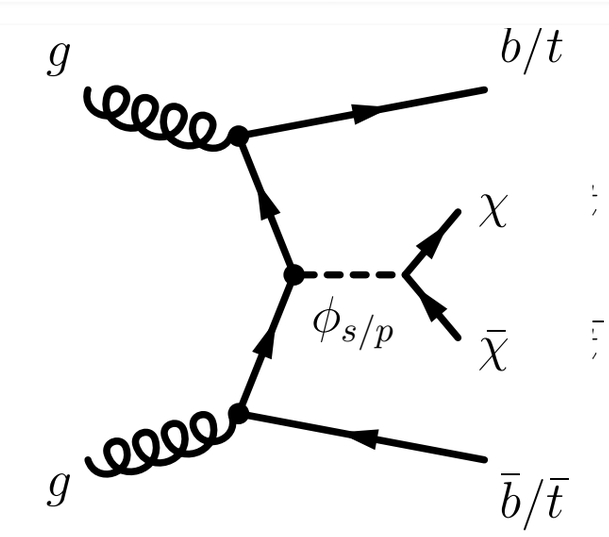
# Spin-0 mediators

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

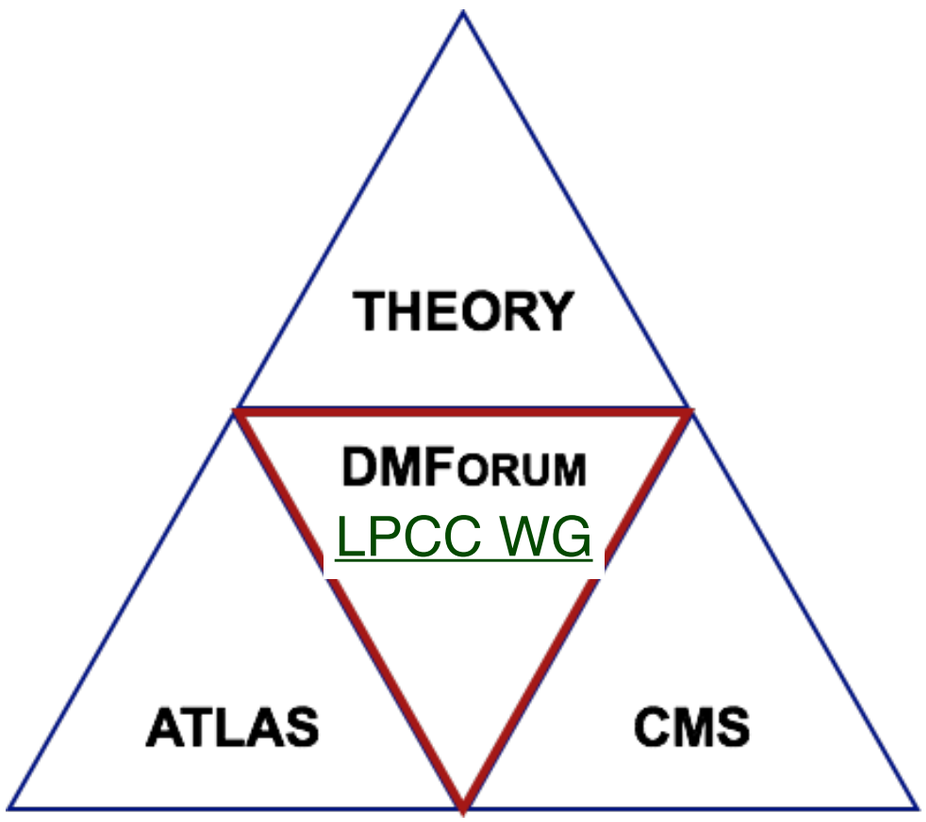
**Needed to easily fulfil Flavour Constraints (MFV)**



# An inter-community achievement




**Simplified Models for Dark Matter Searches at the LHC**

Jalal Abdallah, Henrique Araujo, Alexandre Arbey, Adi Ashkenazi, Alexander Belyaev, Joshua Berger, Celine Boehm,

Phys. Dark Univ. 9-10 (2015) 8-23

**Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum**

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, ~~Barbara Alvarez Gonzalez, Jeremy~~

arXiv:1507.00966

**Recommendations on presenting LHC searches for missing transverse energy signals using simplified $s$-channel models of dark matter**

Antonio Boveia, Oliver Buchmueller, Giorgio Busoni, Francesco D'Eramo, Albert De Roeck, Andrea De Simone, Caterina

arXiv:1603.04156

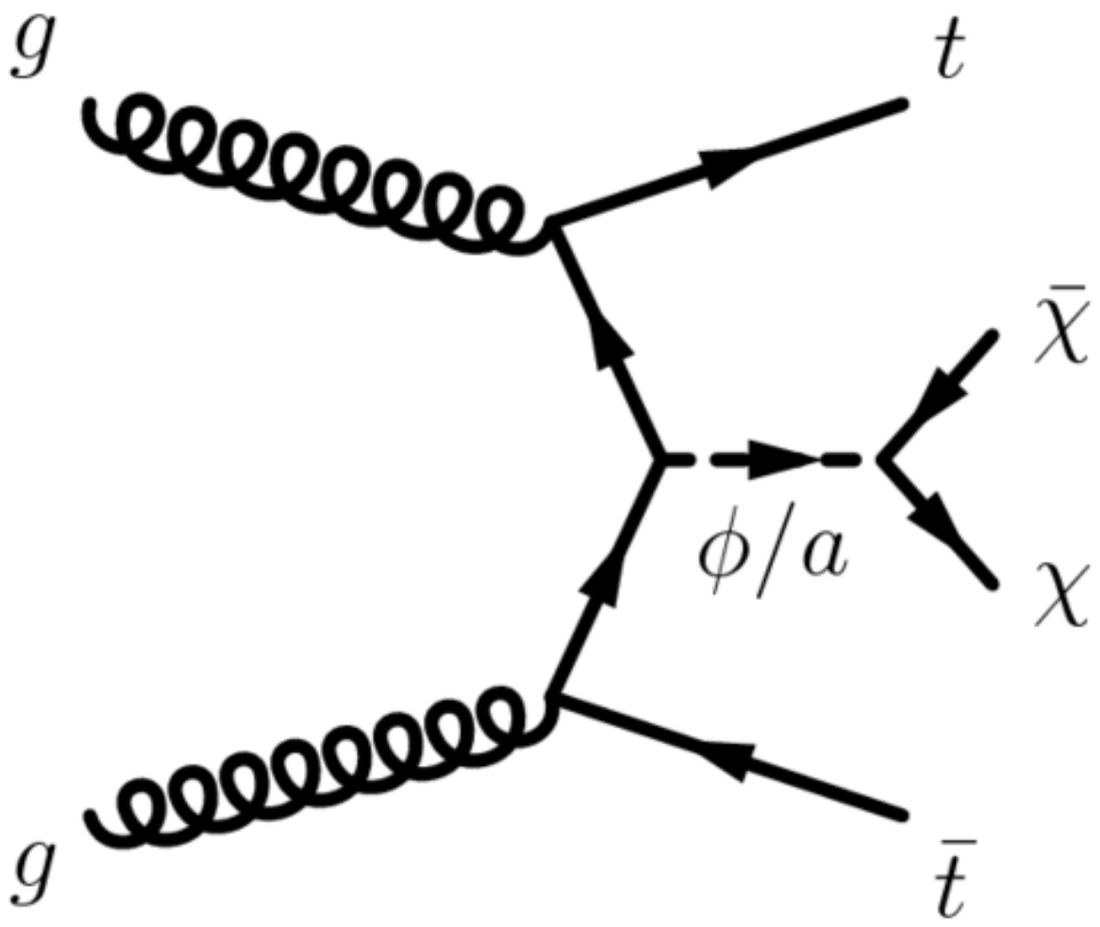
★Simplified Models are the Run II paradigm:

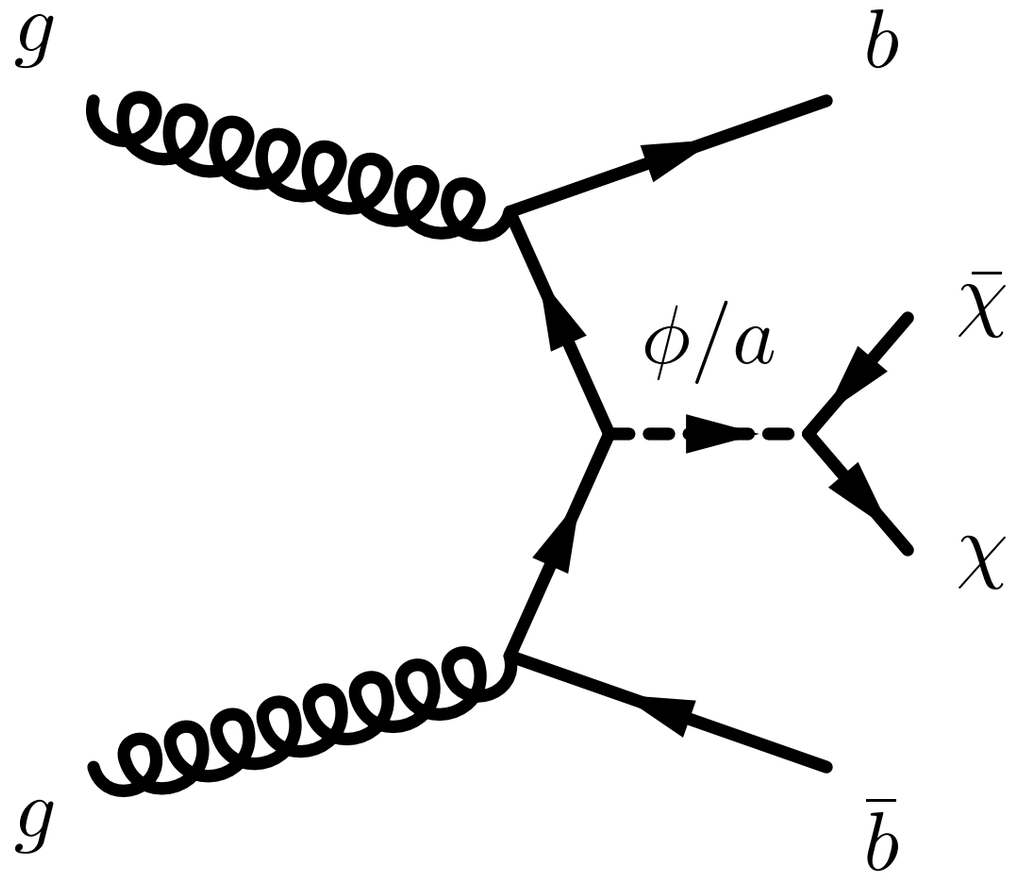
- theoretically self consistent
- minimal and motivated assumptions
- good phenomenology proxies

# Exploring the dark sector with heavy quarks

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

→ Enhanced cross-section for tops and bottoms

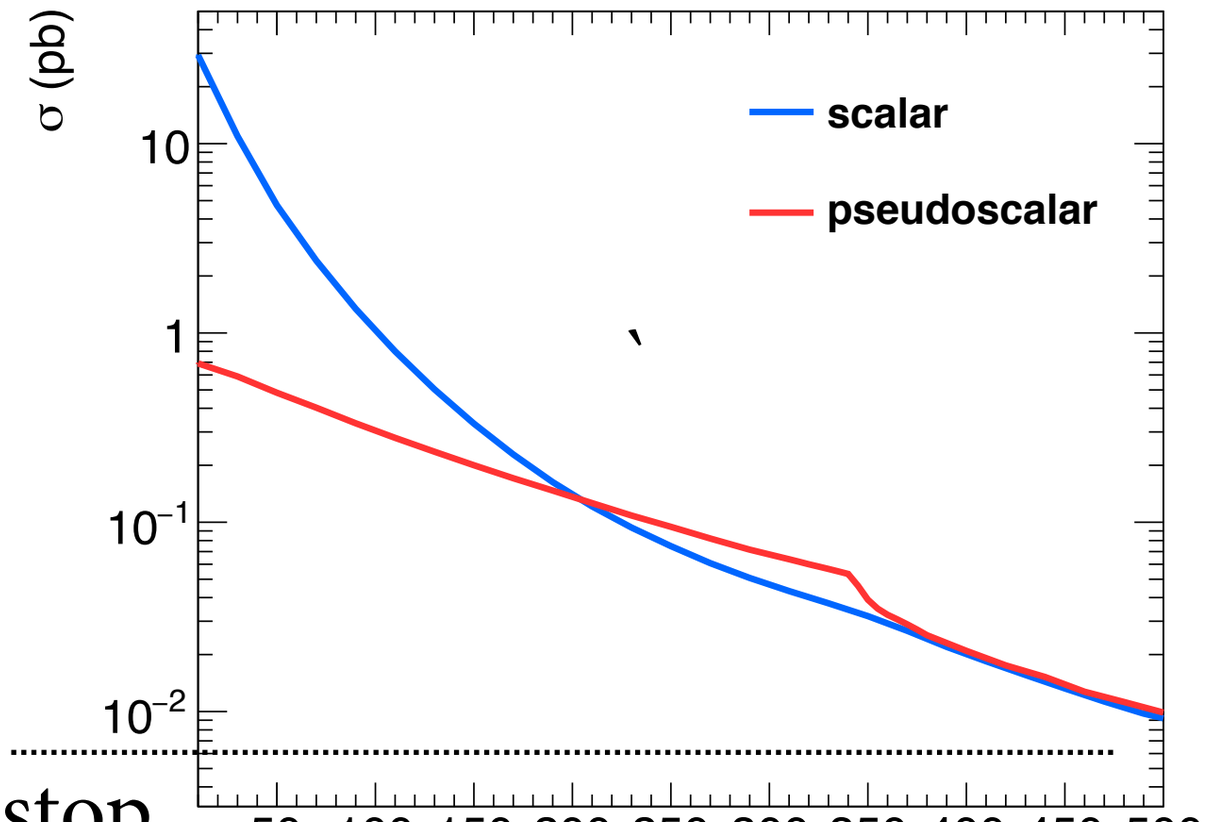



arXiv:1710.11412 and ATLAS-CONF-2017-037

# Understanding the signal

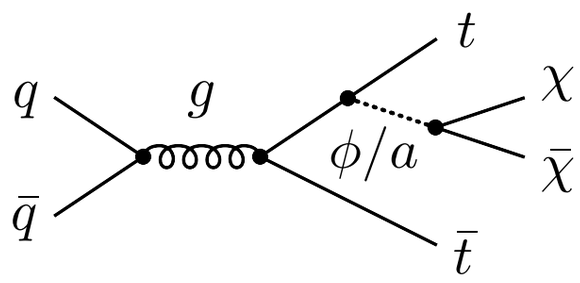
830 pb ..... σ(ttbar)




1 TeV stop pair prod

[Haisch,PP,Polesello 2017]

# Understanding the signal

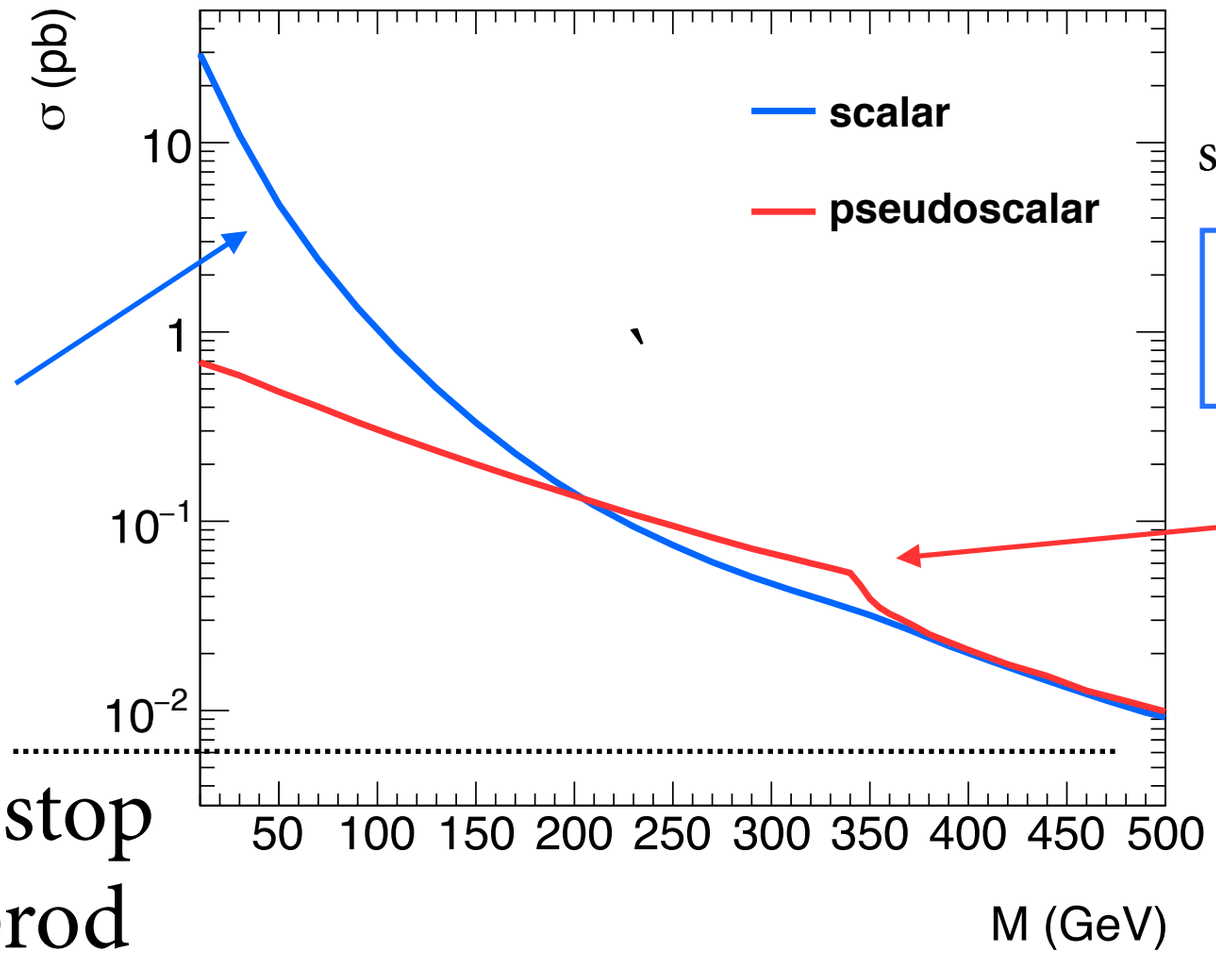



$f_{t\to\phi}(x) \sim 1/x$

soft-enhancement term

830 pb

σ(ttbar)




1 TeV stop pair prod

spin and color-averaged ME

$$\overline{\sum} |\mathcal{M}(t\bar{t} \to \phi)|^2 = \frac{g_t^2 s}{12} \beta^2$$

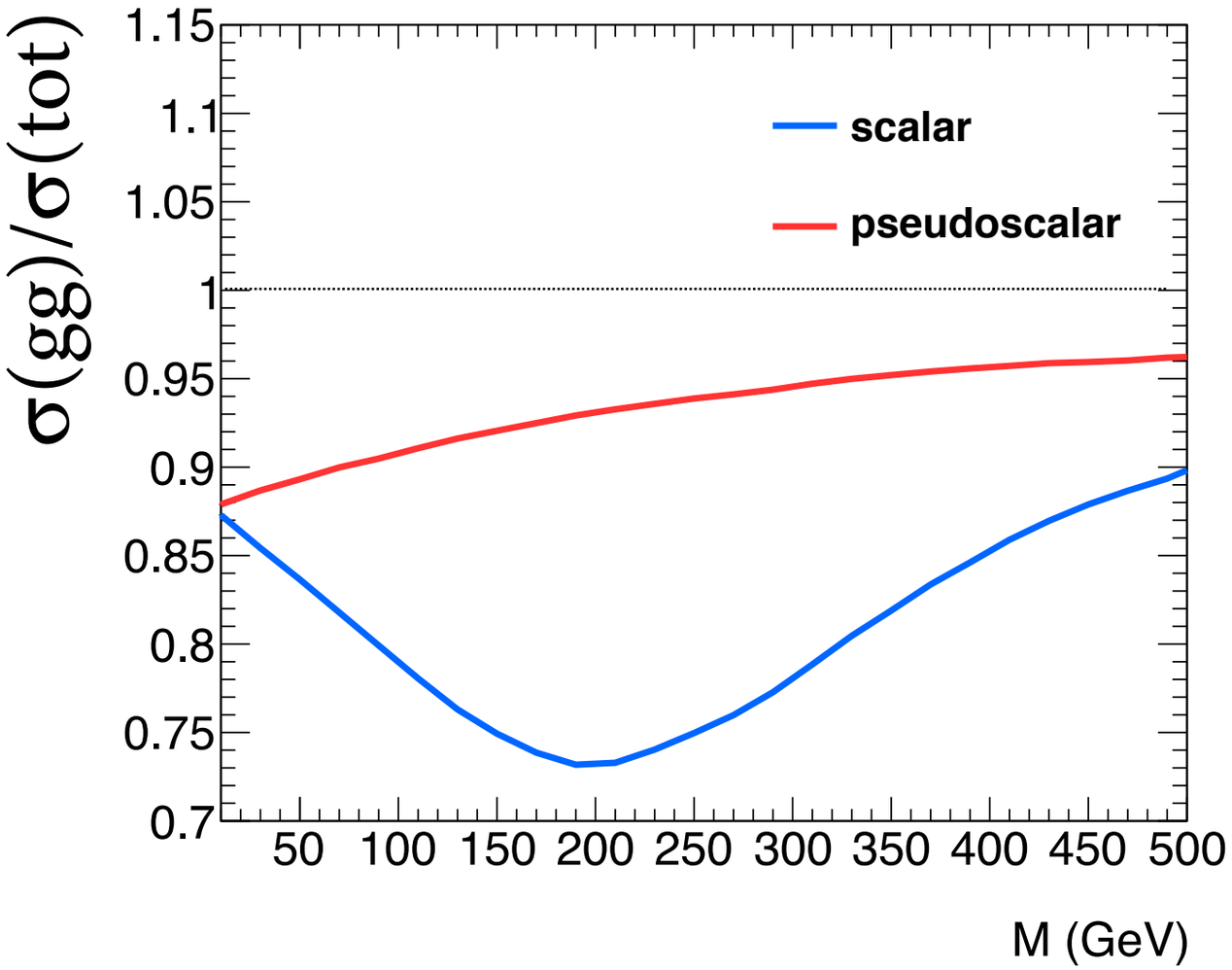
$$\beta = \sqrt{1 - 4m_t^2/s}$$

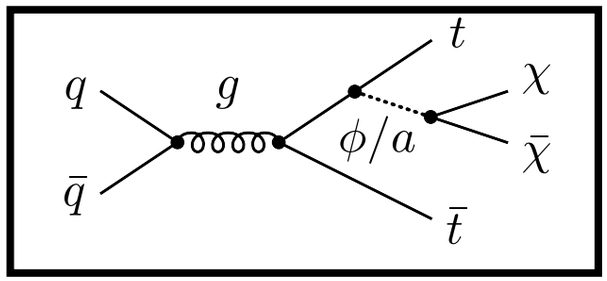
top-threshold suppression

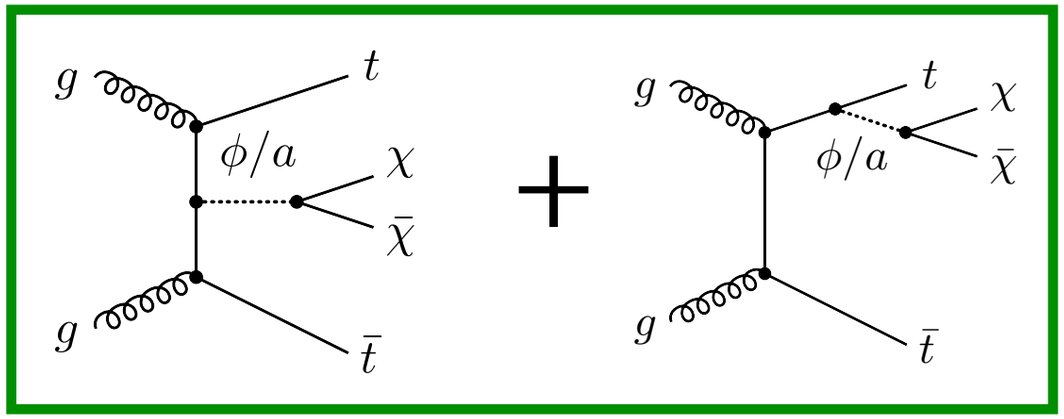
$\phi/a \to t\bar{t}$

[Haisch,PP,Polesello 2017]

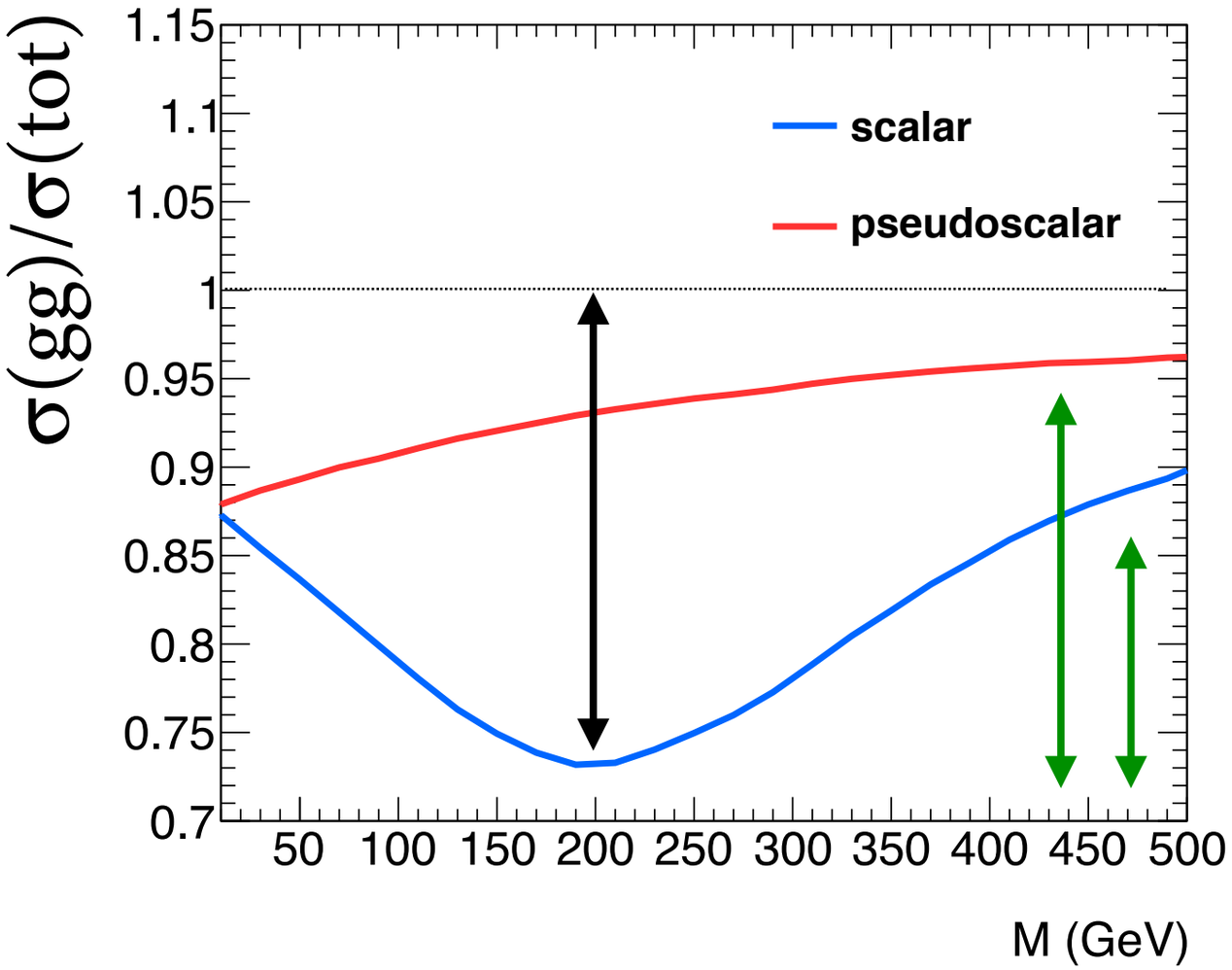
# Understanding the signal

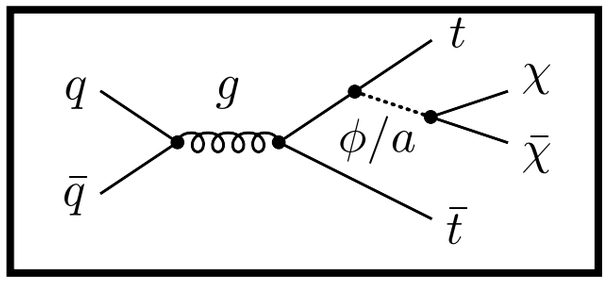


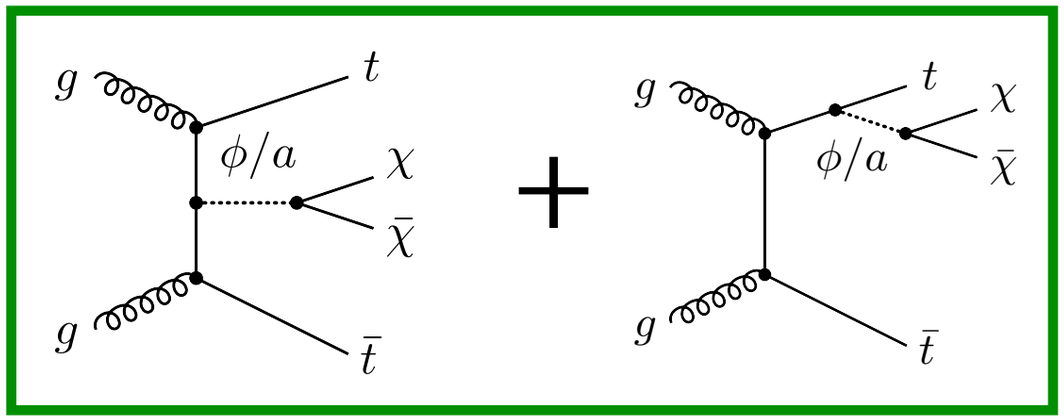



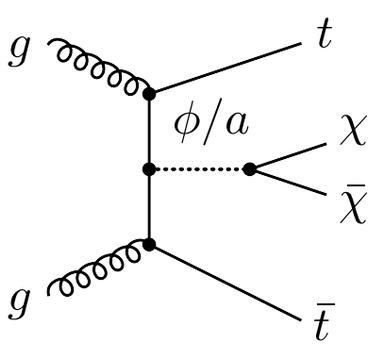



# Understanding the signal

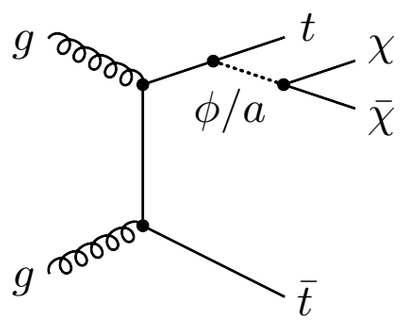


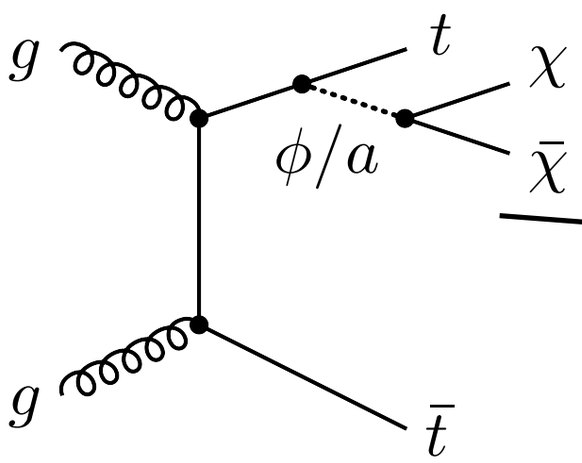

: dominant at high mass and low-mass a

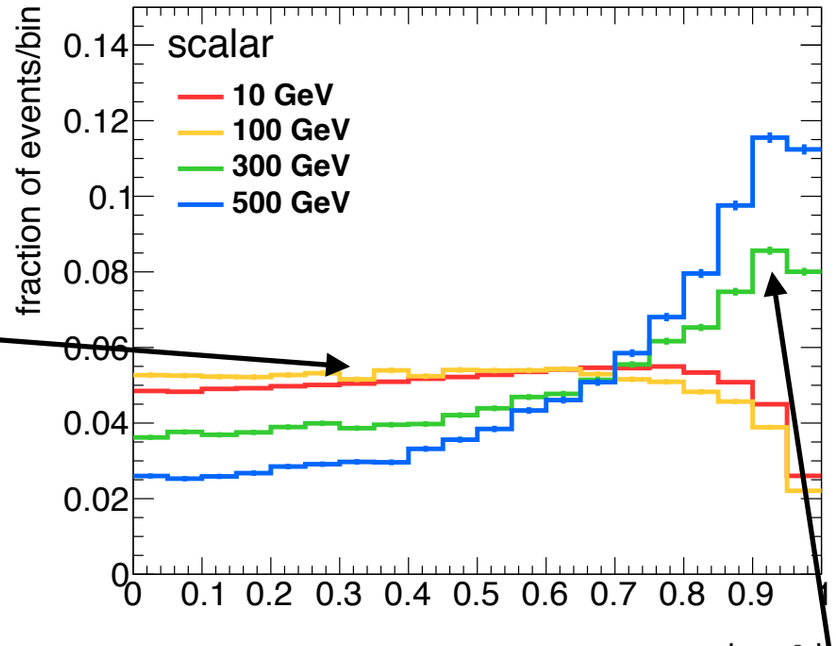


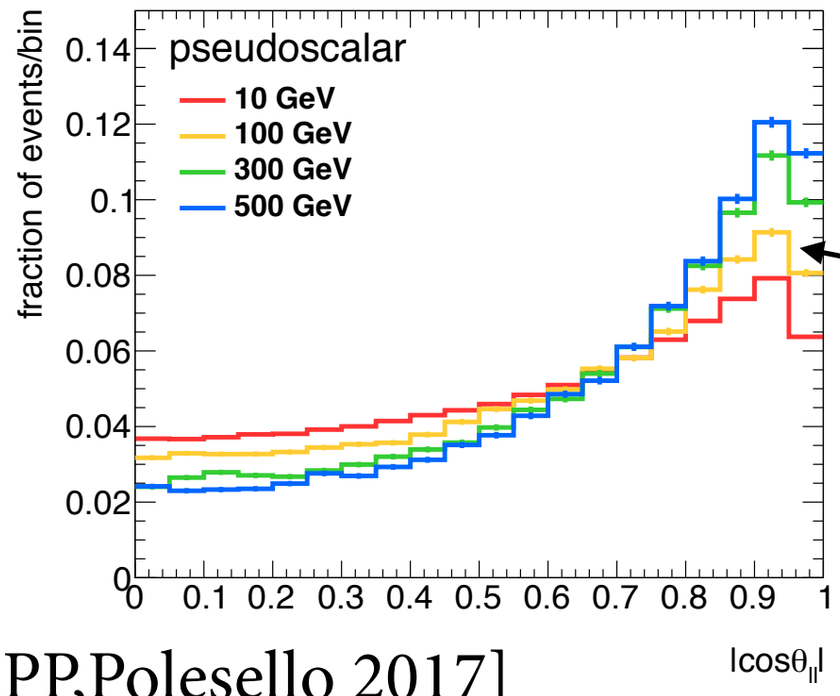

: dominant at low-mass φ

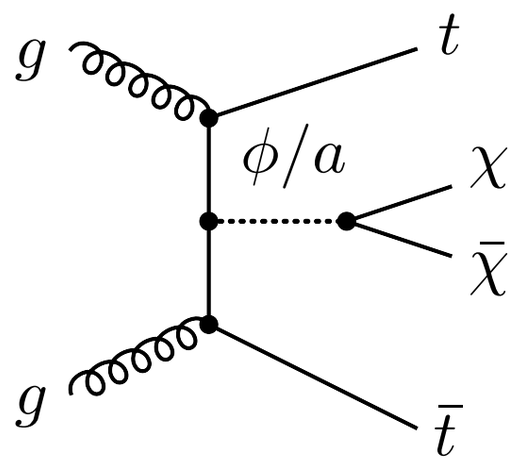
# Future perspectives on the results

$$\cos\theta_{t\bar{t}} \equiv \tanh\left(\Delta\eta_{t\bar{t}}/2\right)$$



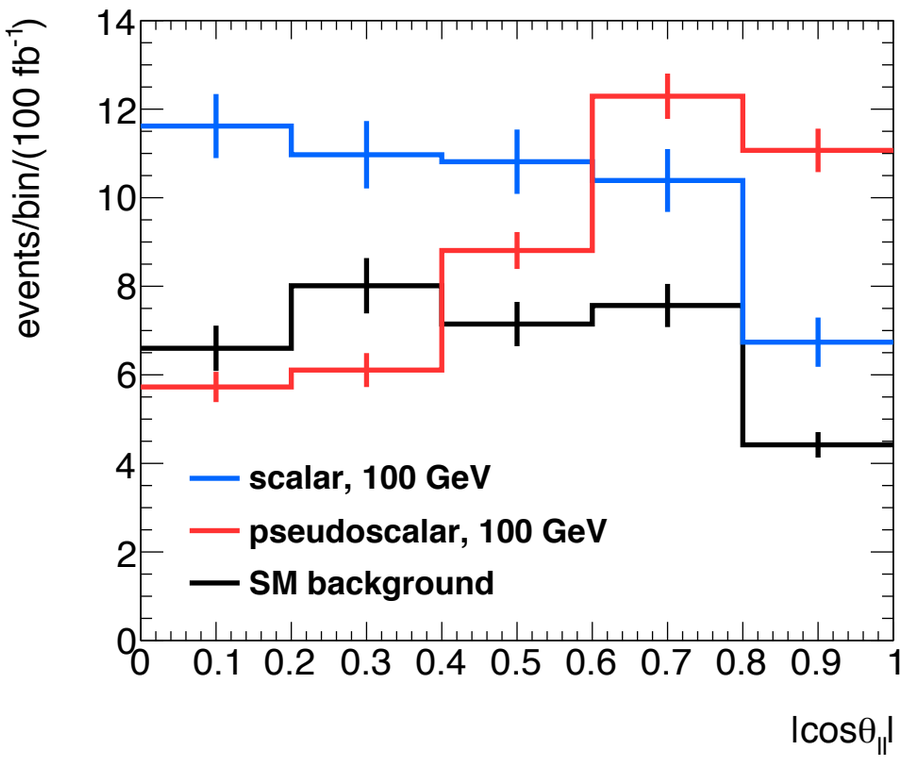




[Haisch,PP,Polesello 2017]

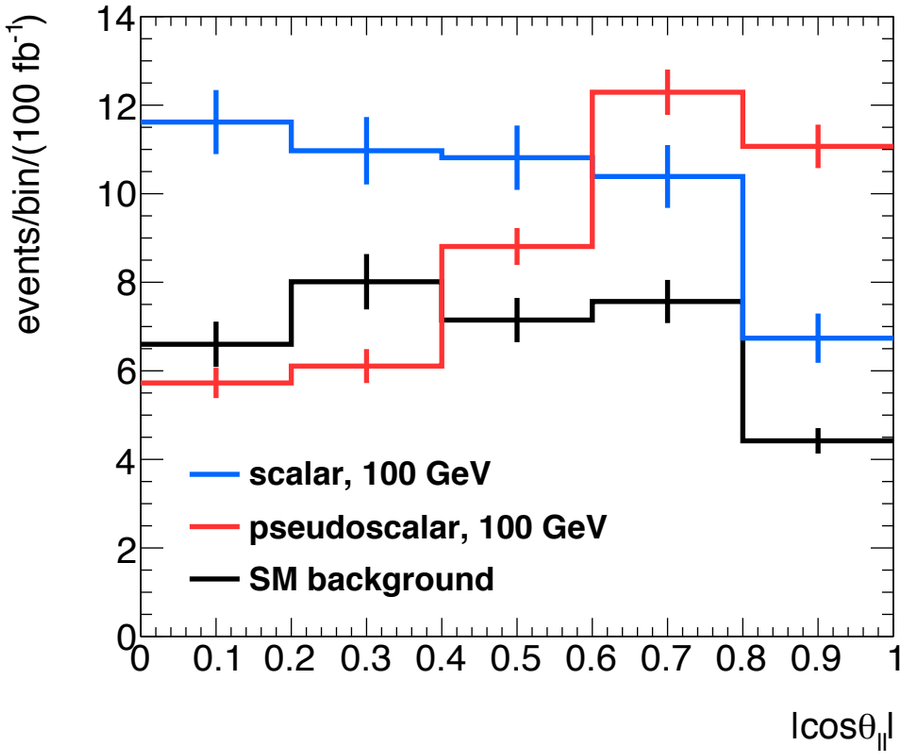
# Run 3 and HL-LHC outlook



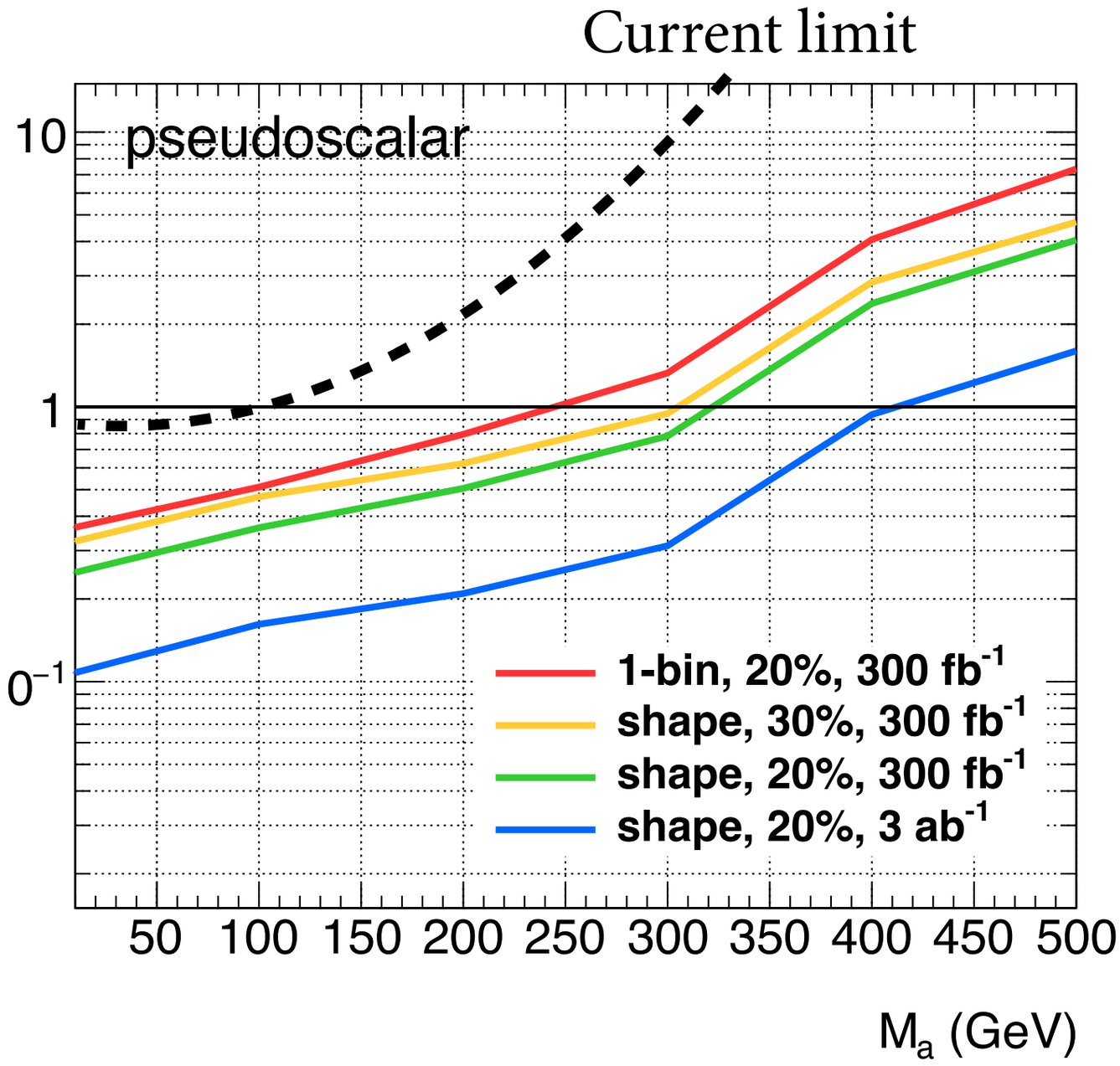

Multi-bin fit

[Haisch,PP,Polesello 2017]

# Run 3 and HL-LHC outlook

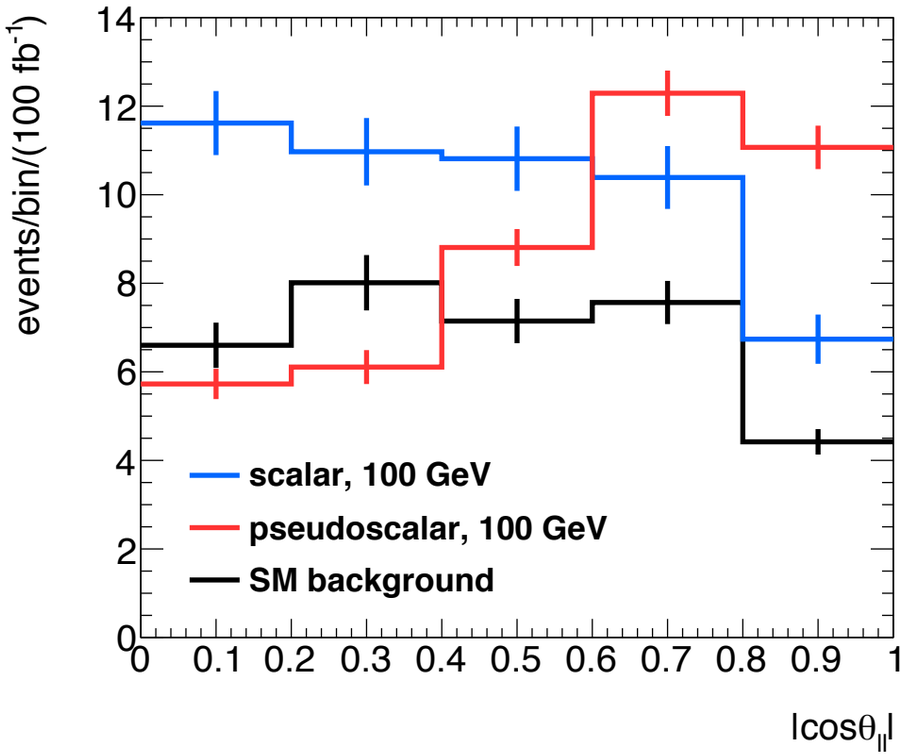



Multi-bin fit




[Haisch,PP,Polesello 2017]

# Run 3 and HL-LHC outlook




Multi-bin fit




[Haisch,PP,Polesello 2017]