Dark matter searches at colliders.

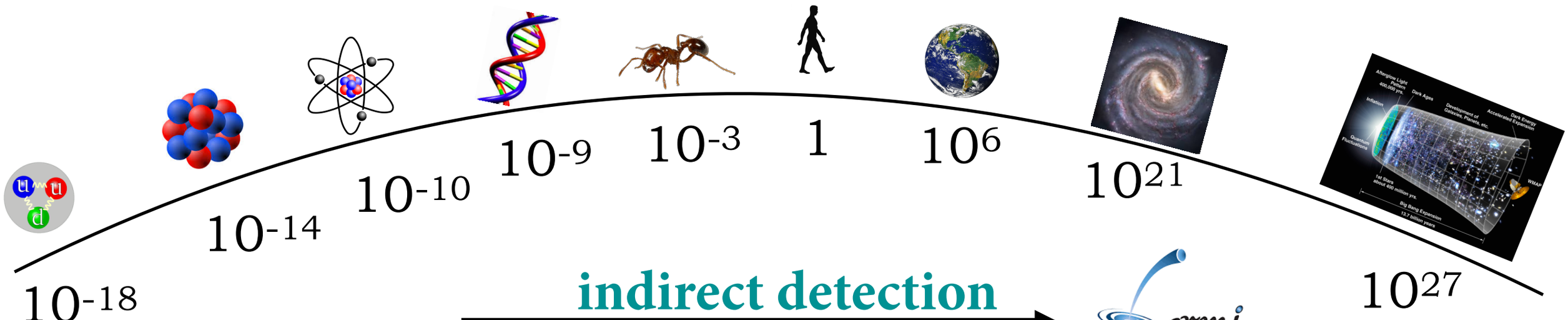
Priscilla Pani
on behalf of ATLAS, CMS & LHCb

Dark Matter searches in the 2020 - Tokyo
11-13 November 2019

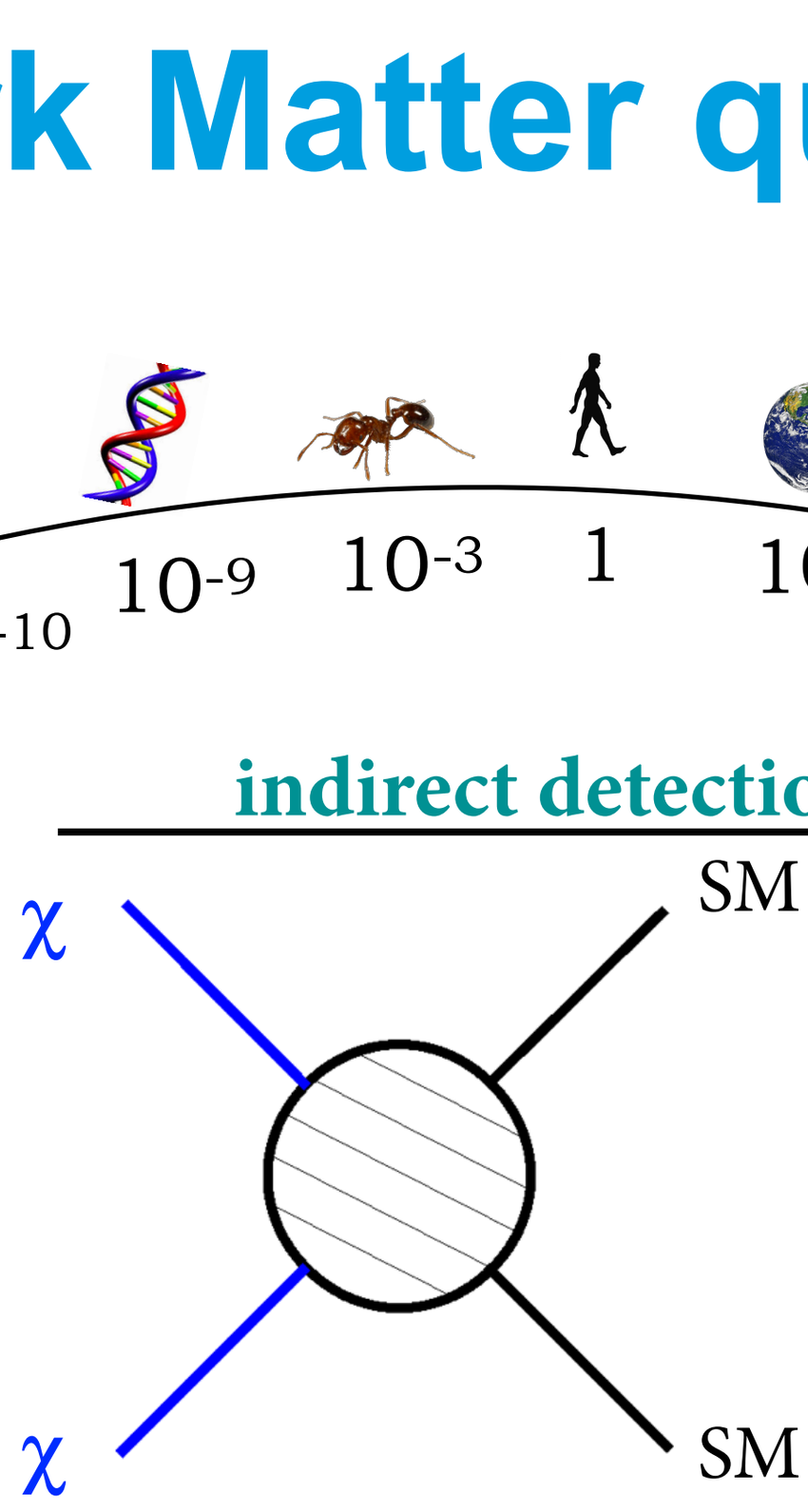
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

The Dark Matter quest

universe scales in meters



indirect detection

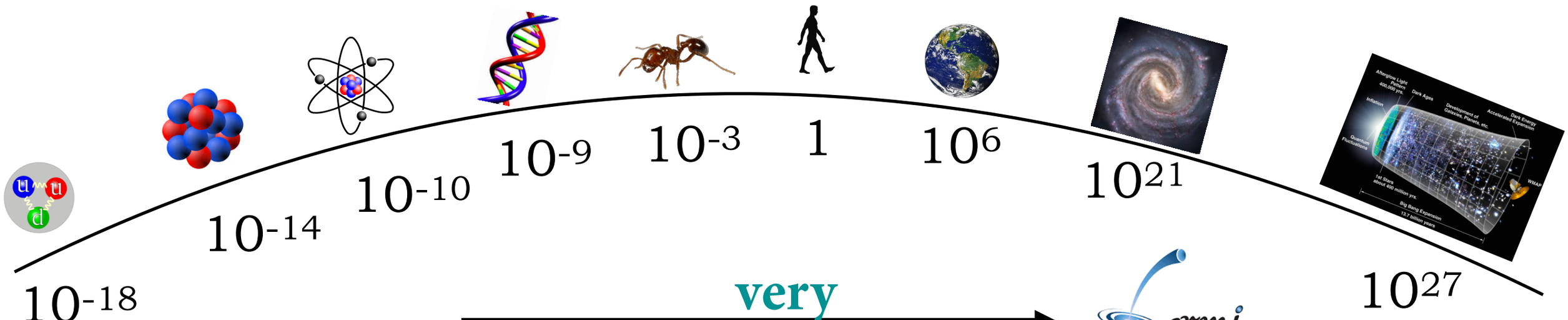


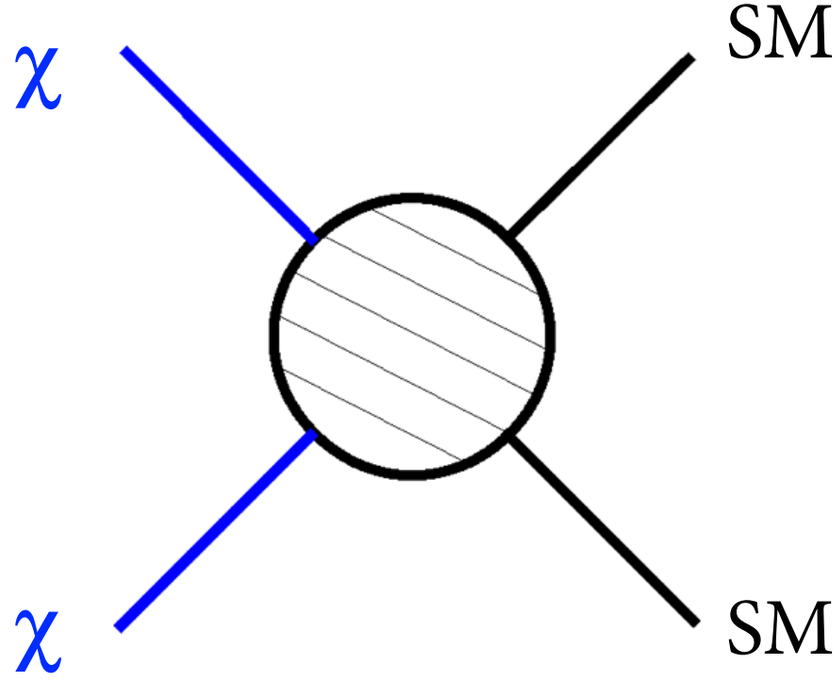
production @colliders

direct detection

The Dark Matter quest

universe scales in meters

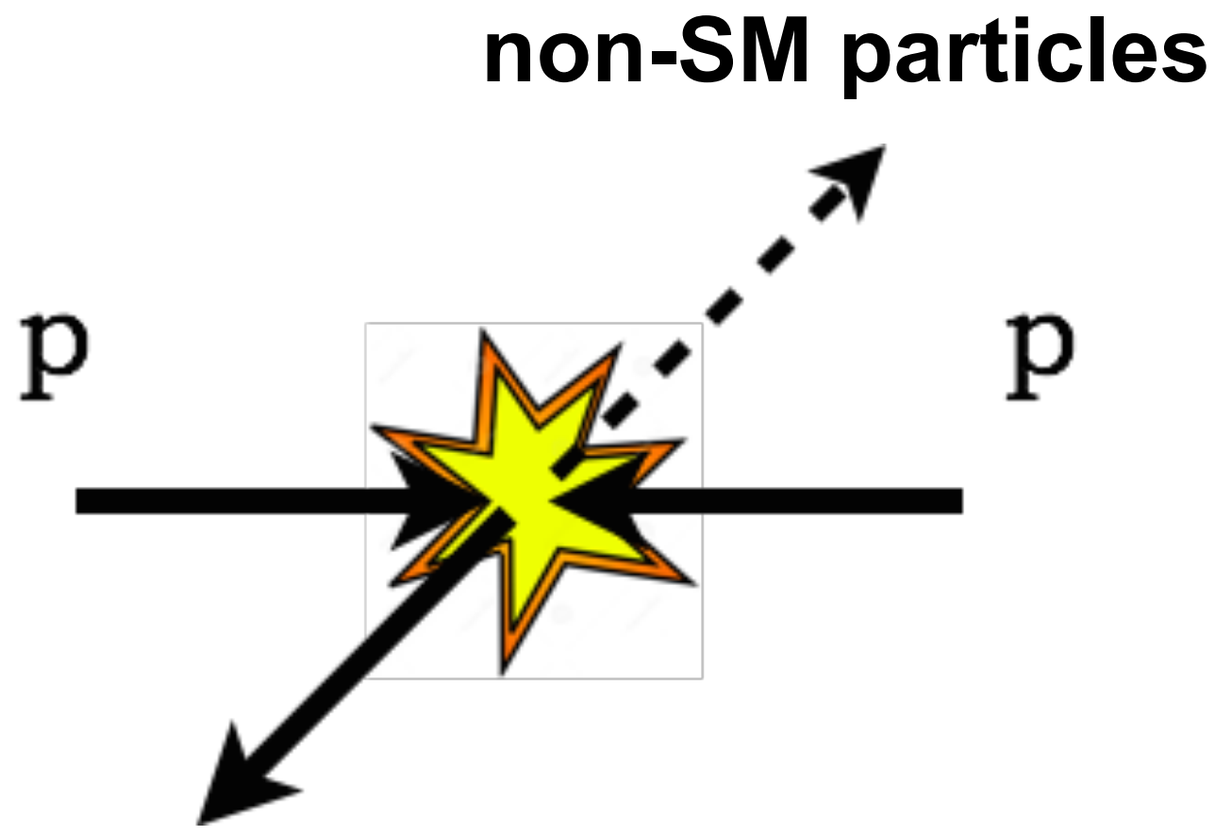




different

assumptions

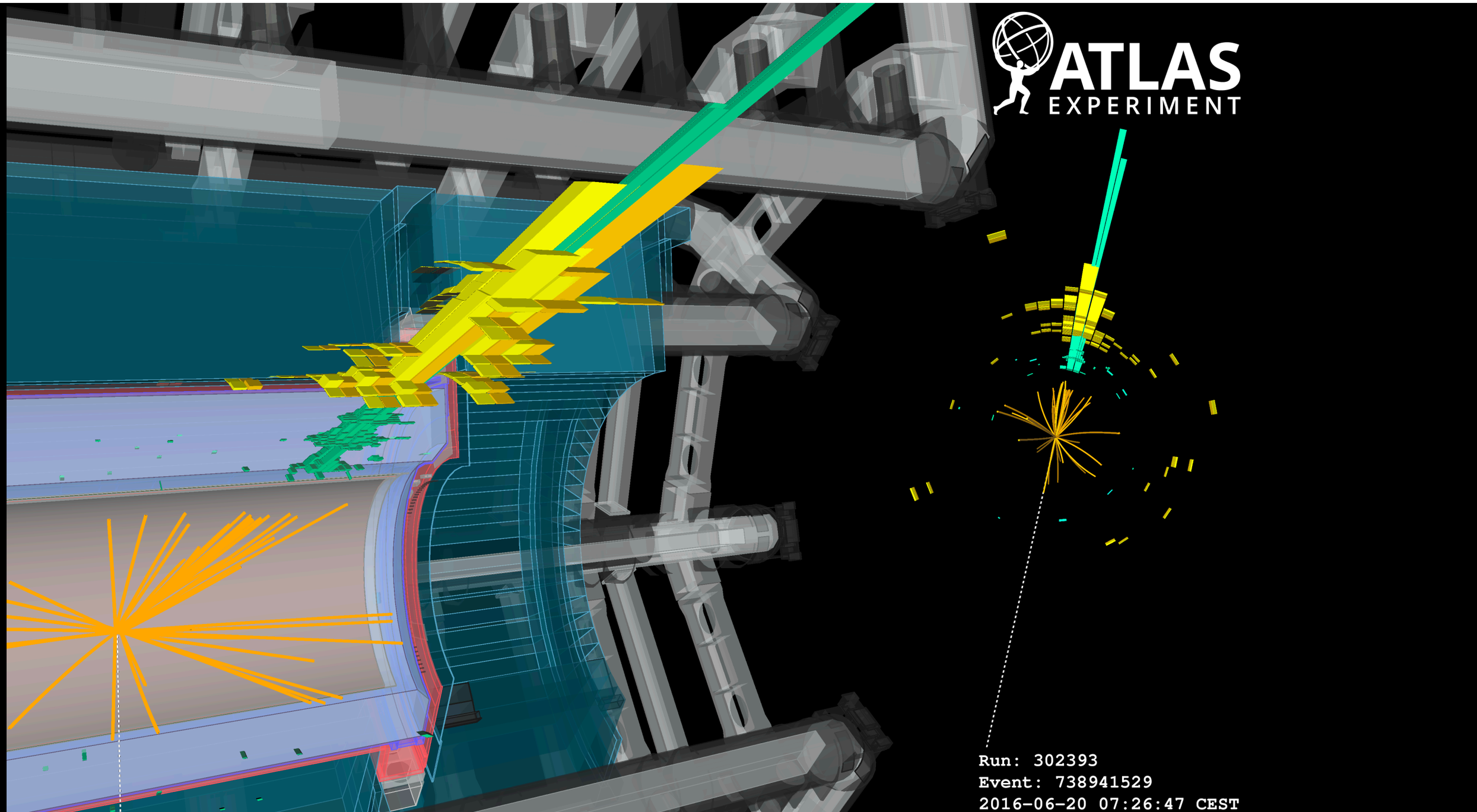
The collider ansatz



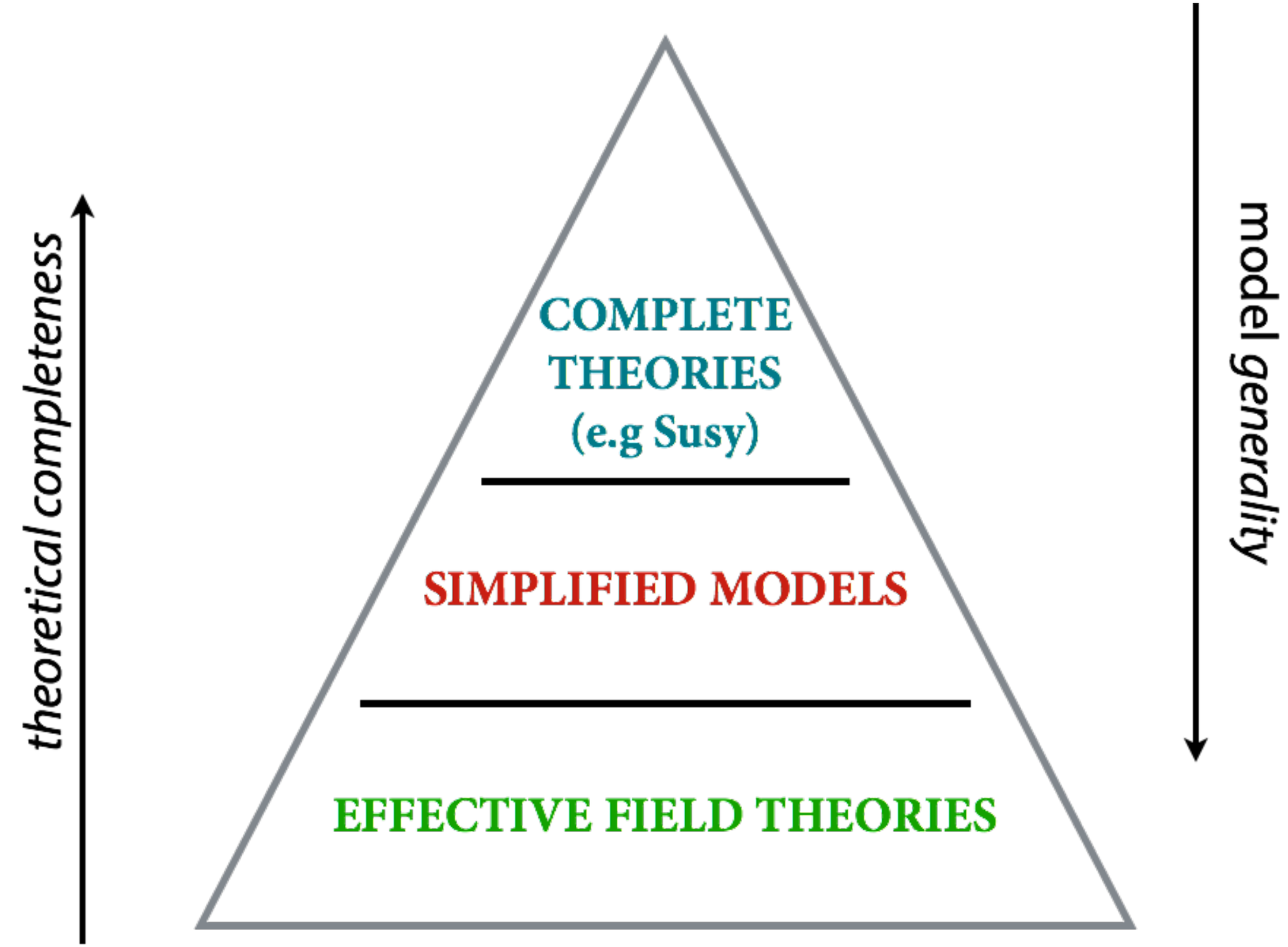
1. Production mechanism / theoretical framework

2. Particles detection and identification

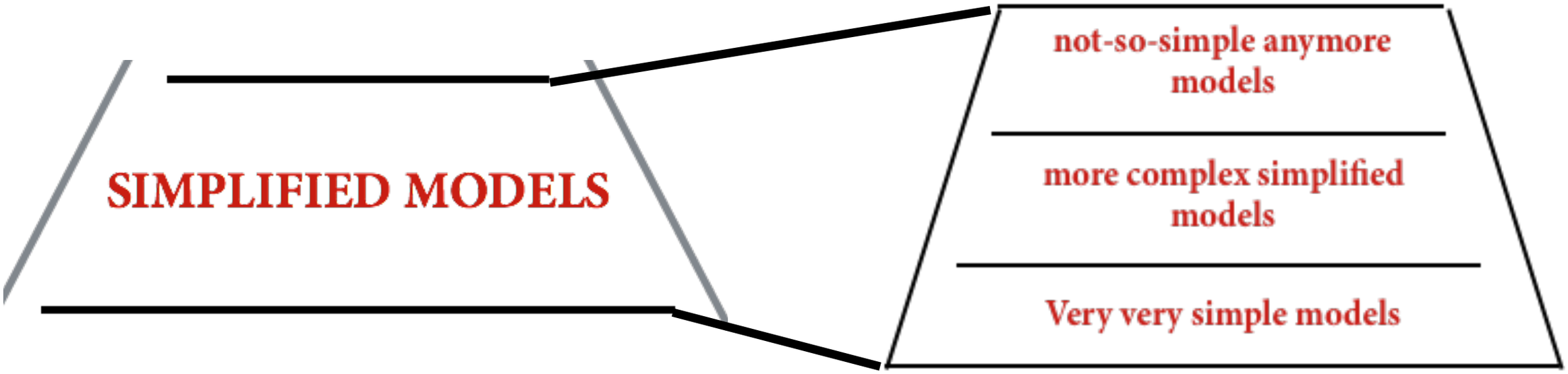
1. Production mechanism



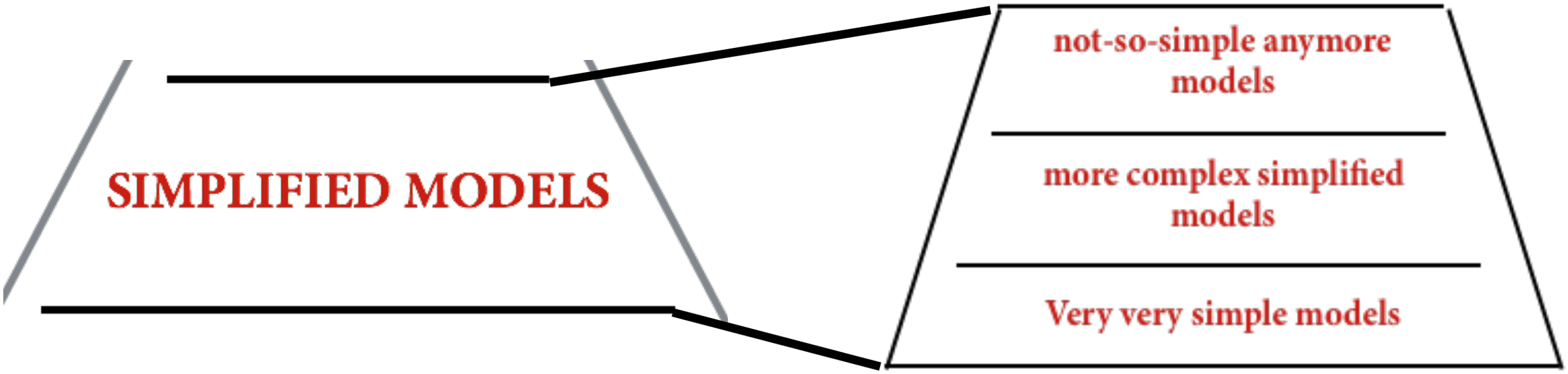
Theoretical framework



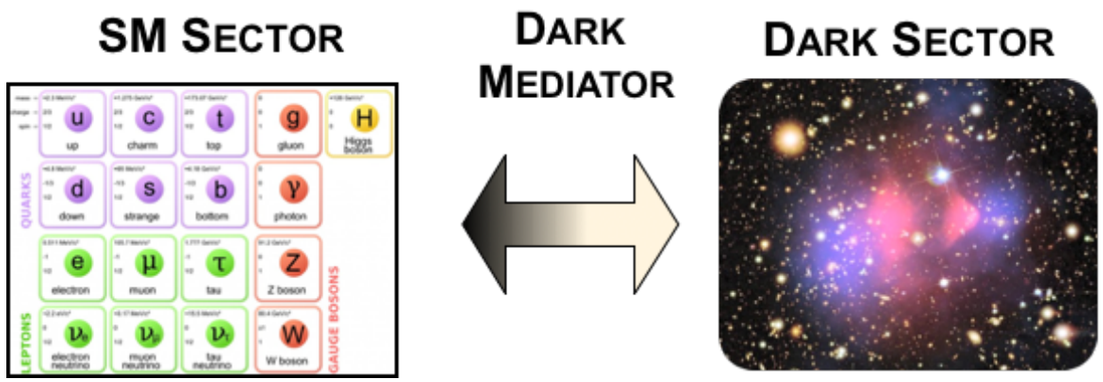
Theoretical framework



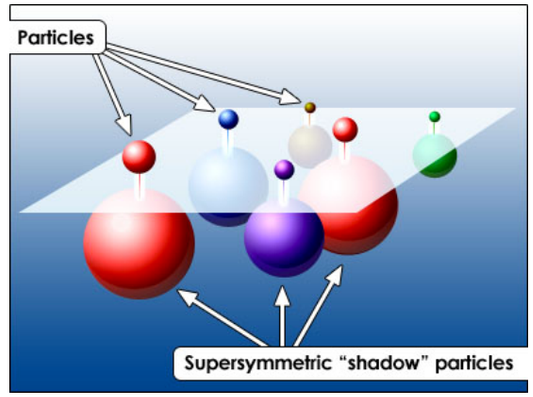
Theoretical framework



"Mediator-based DM models"

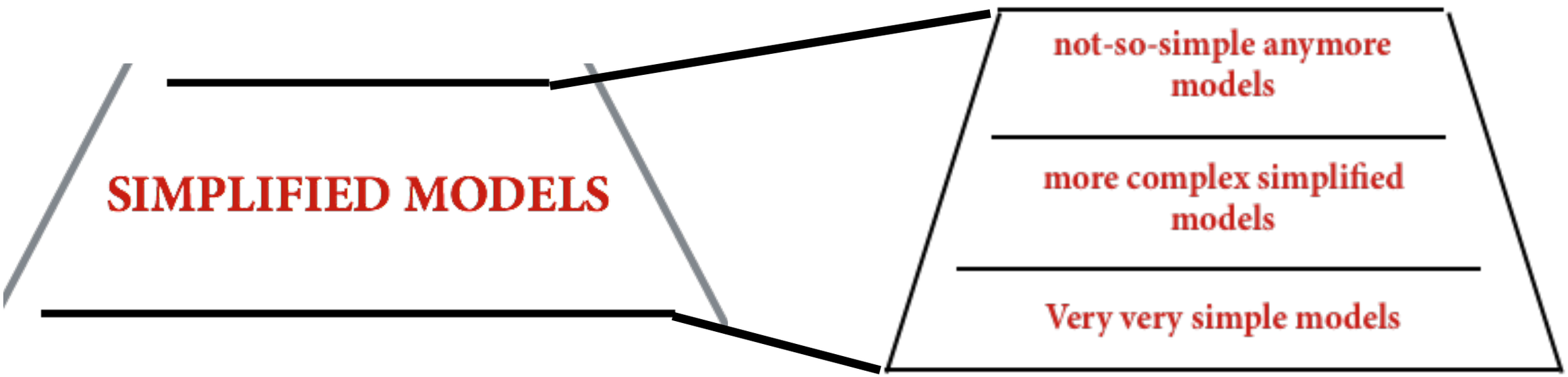


"SUSY simplified models"

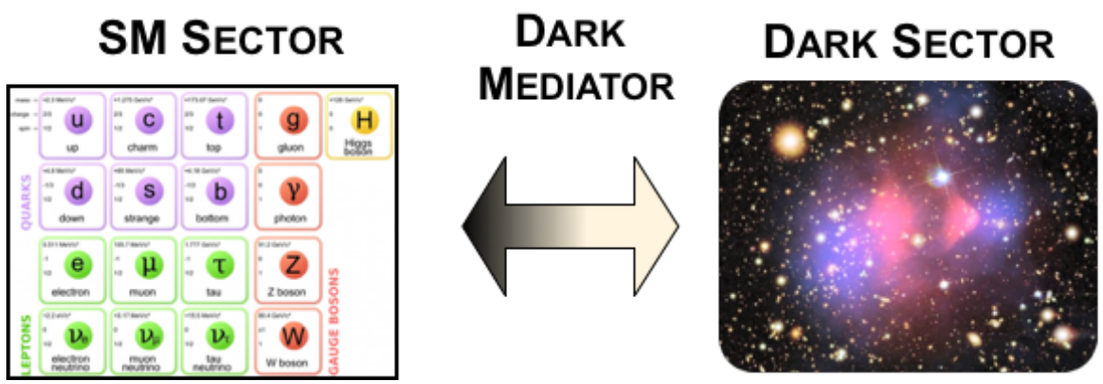


+ "Higgs Portal DM models" + axions

Theoretical framework

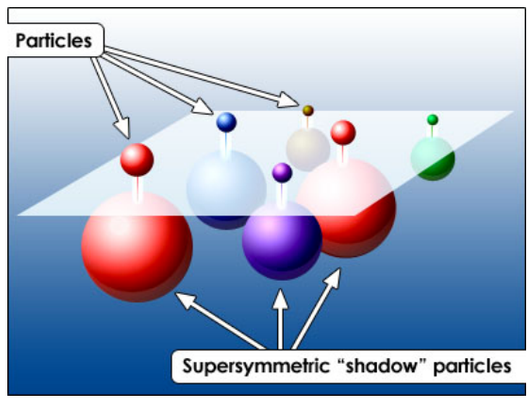


"Mediator-based DM models"



Koji Terashi's talk

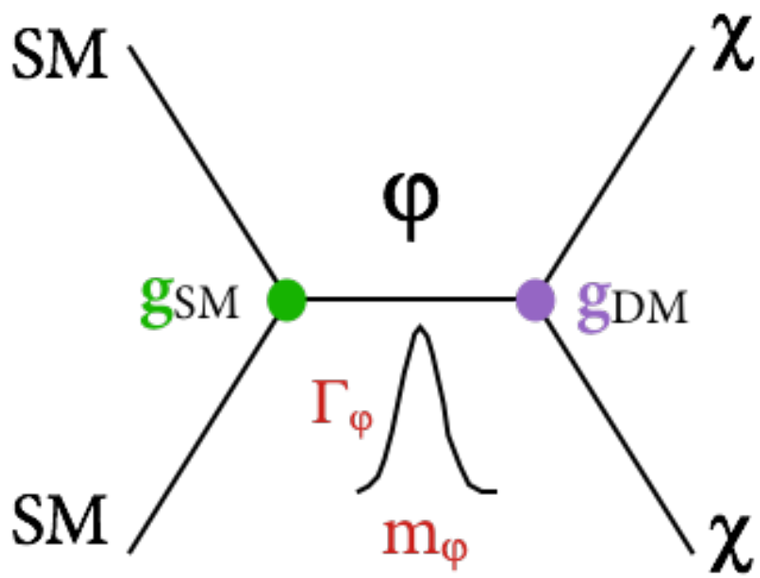
"SUSY simplified models"



+ "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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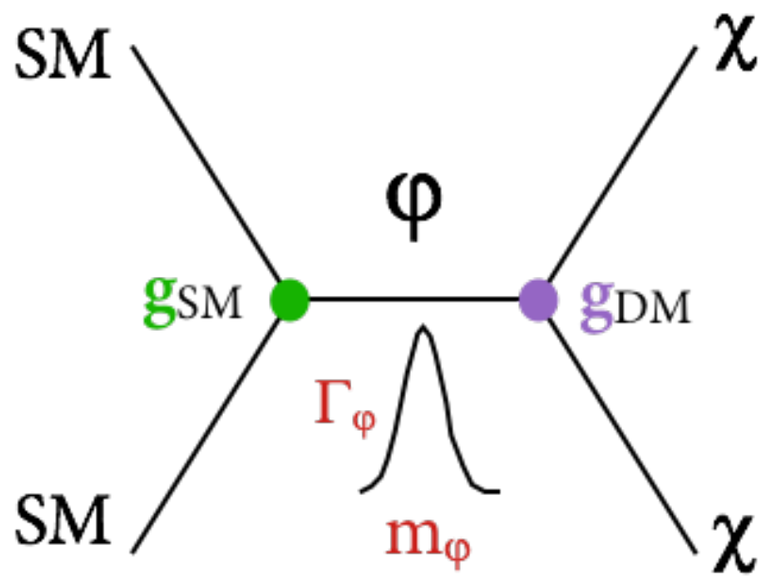
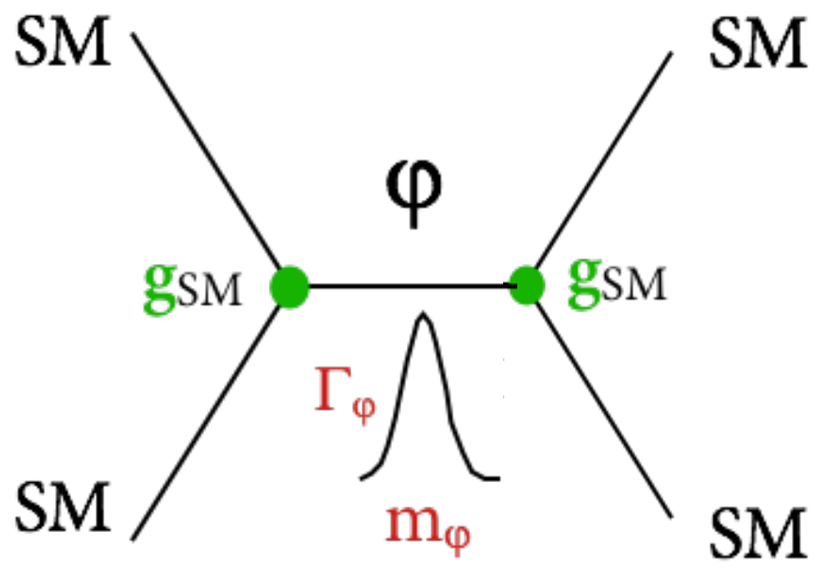


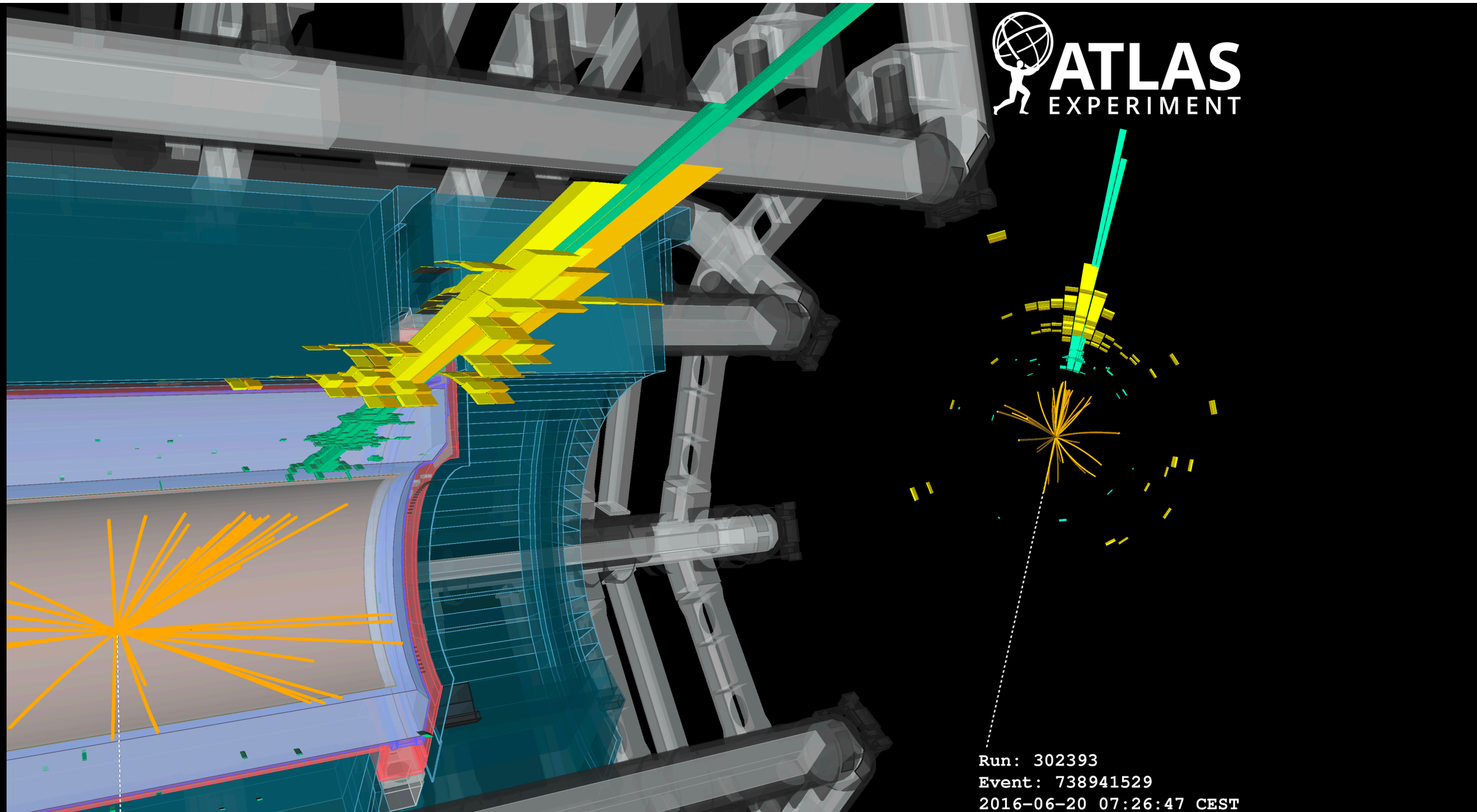
E_T^{miss} + X



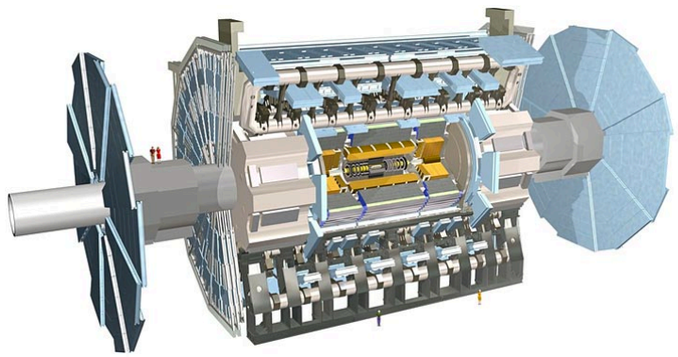
Resonance

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

2. Detection and identification

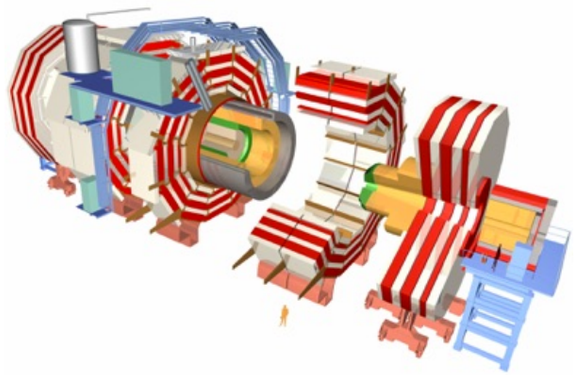


DM Collider experiments



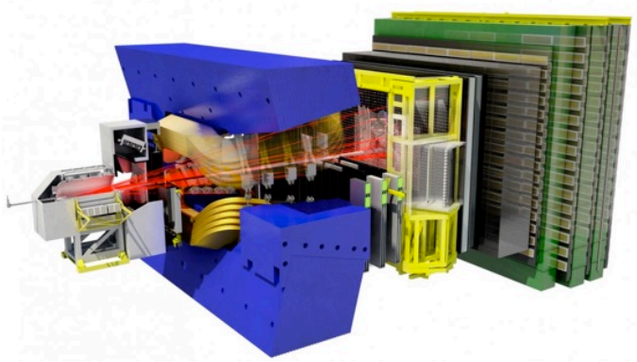
ATLAS EXPERIMENT

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



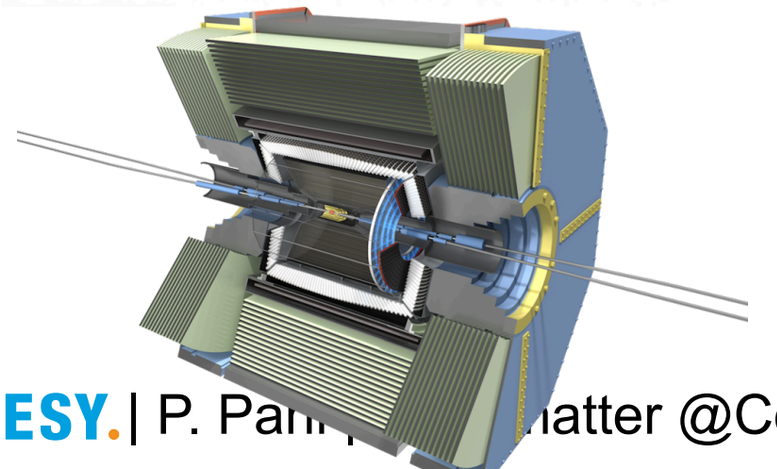
CMS

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

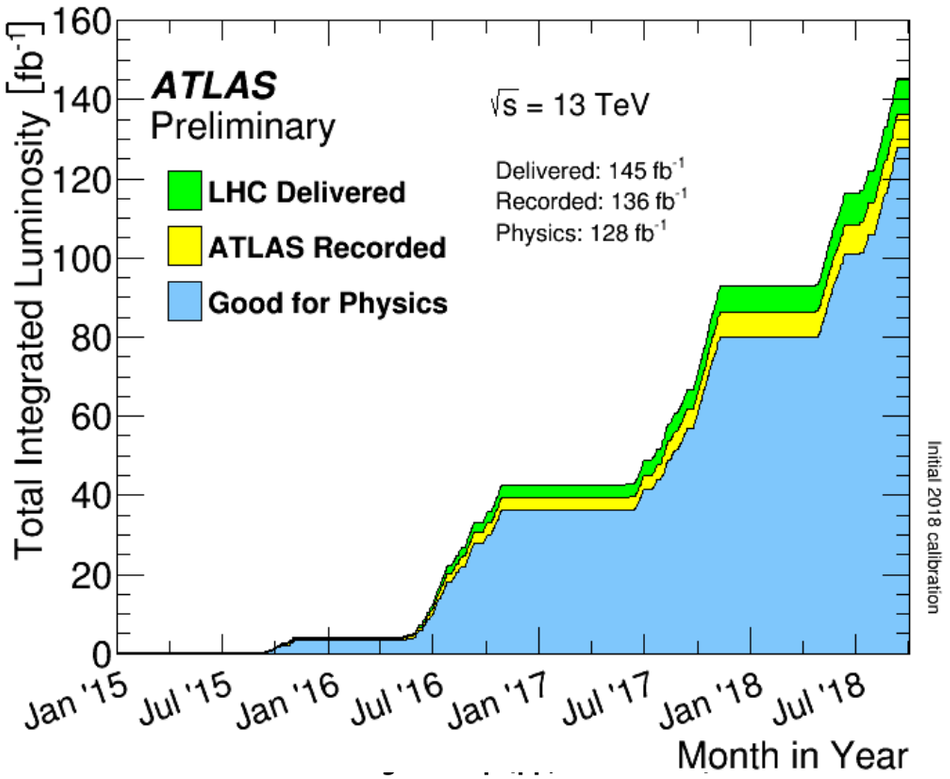
Timelines and datasets

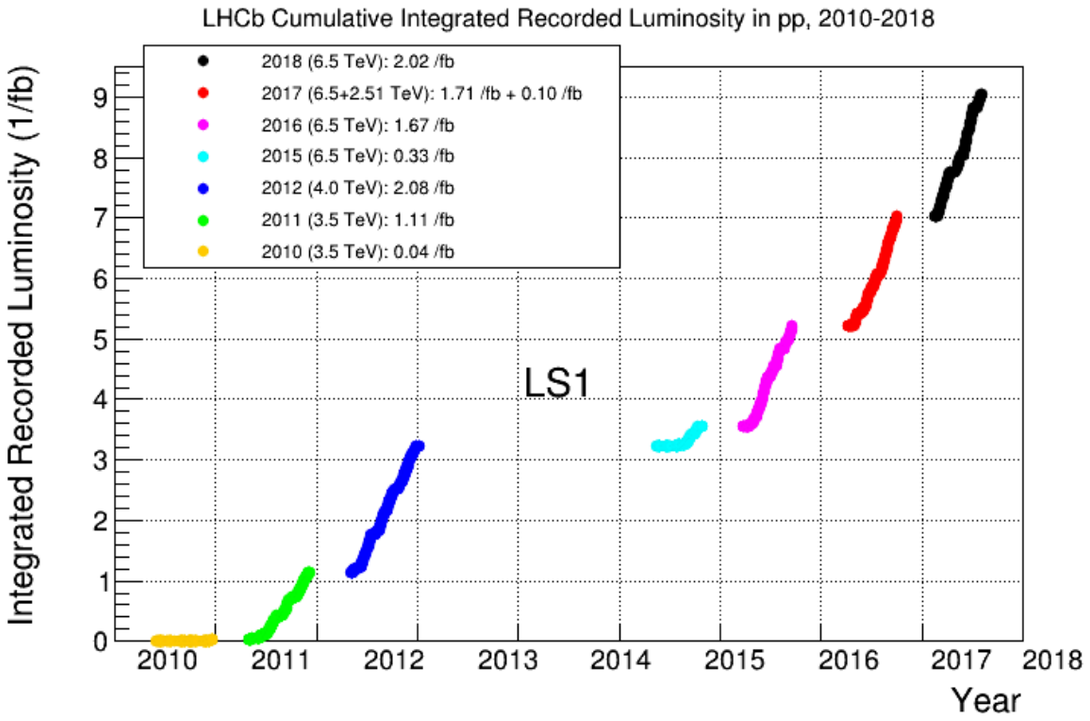
you are here

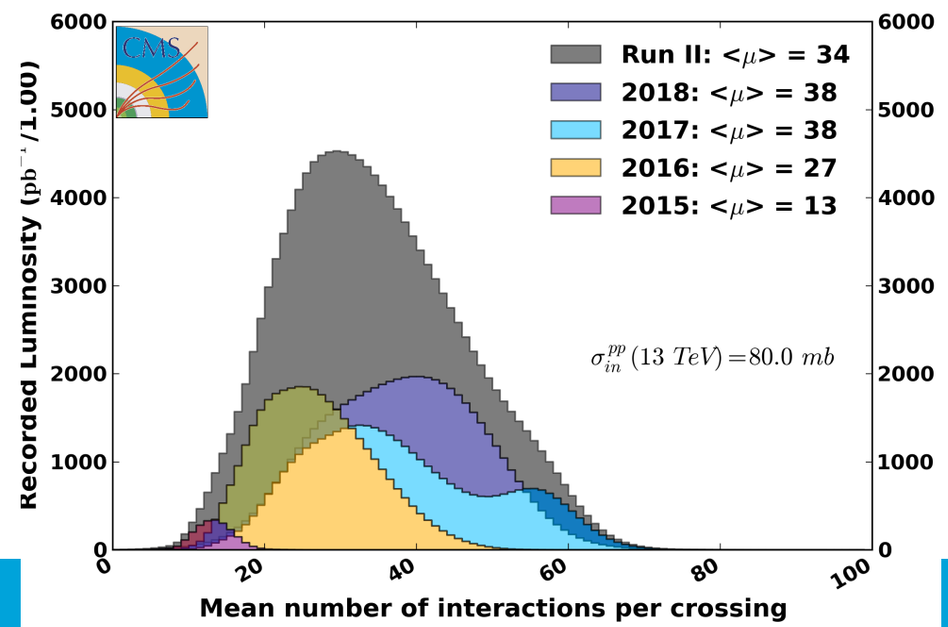
LHC Run-1 | LS-1 | LHC Run-2 | LS-2 | LHC Run-3 | LS-3 | HL-LHC Run …

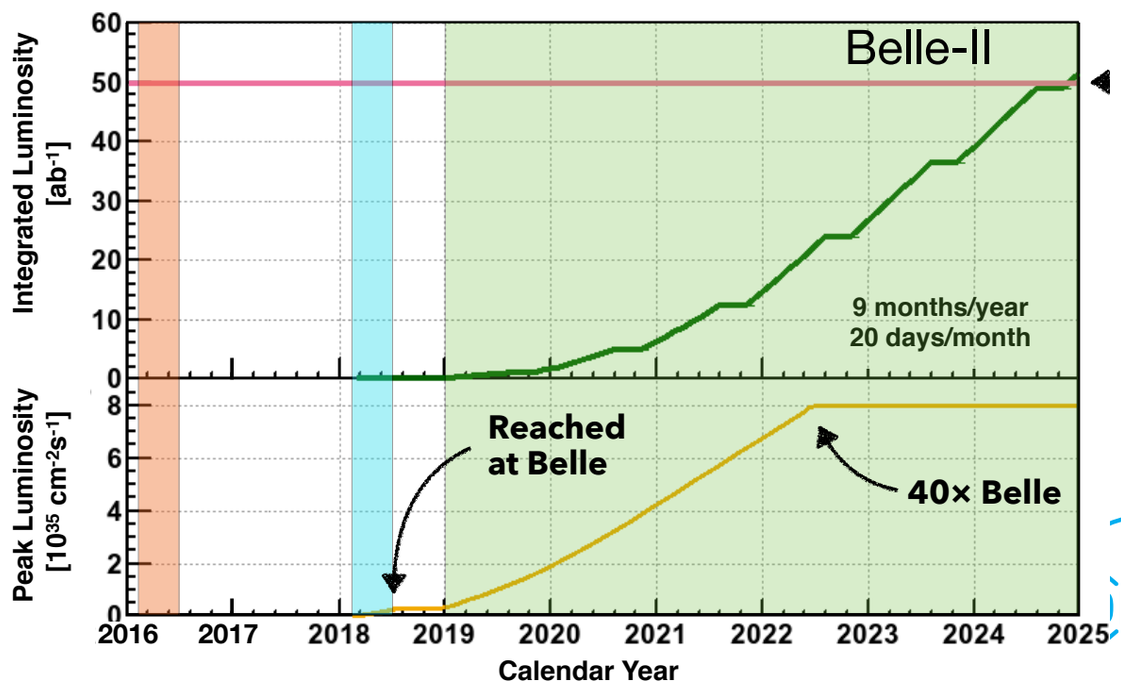
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

Belle II Phase I | Phase II | Phase III





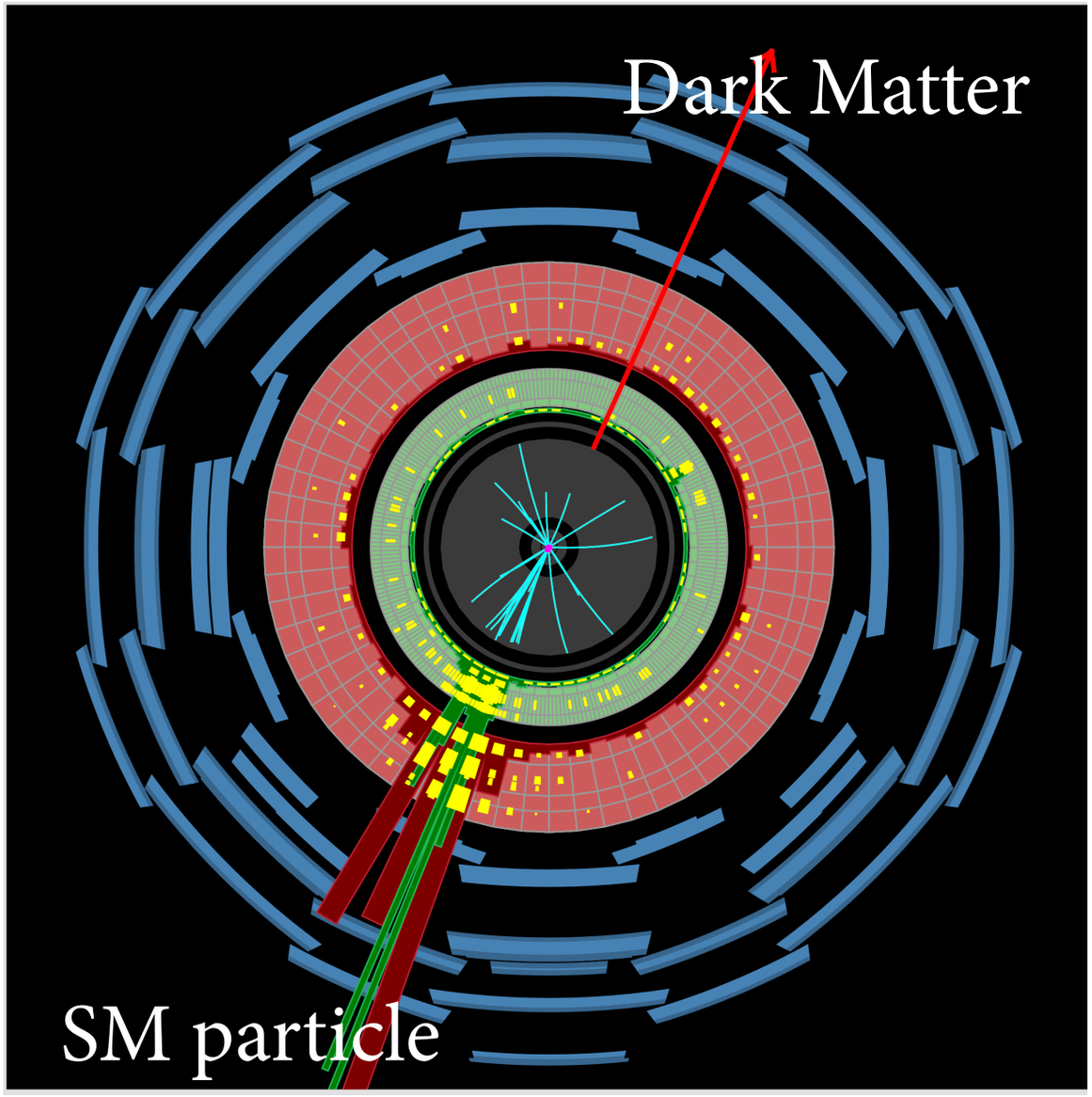


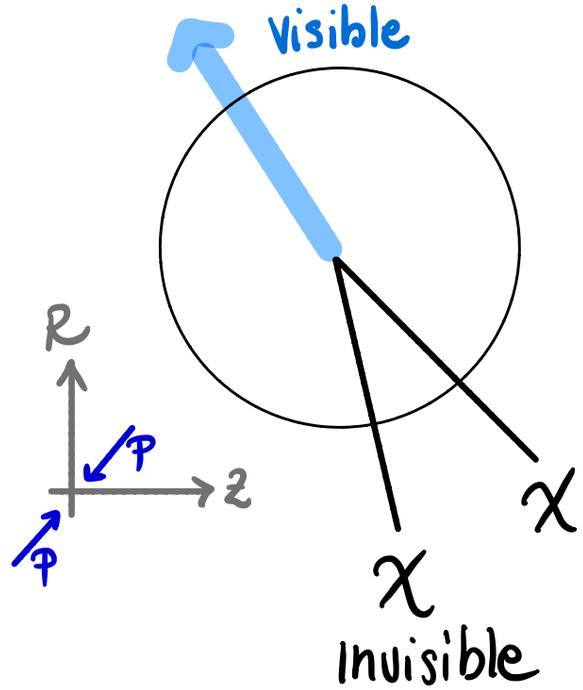


Particles detection

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

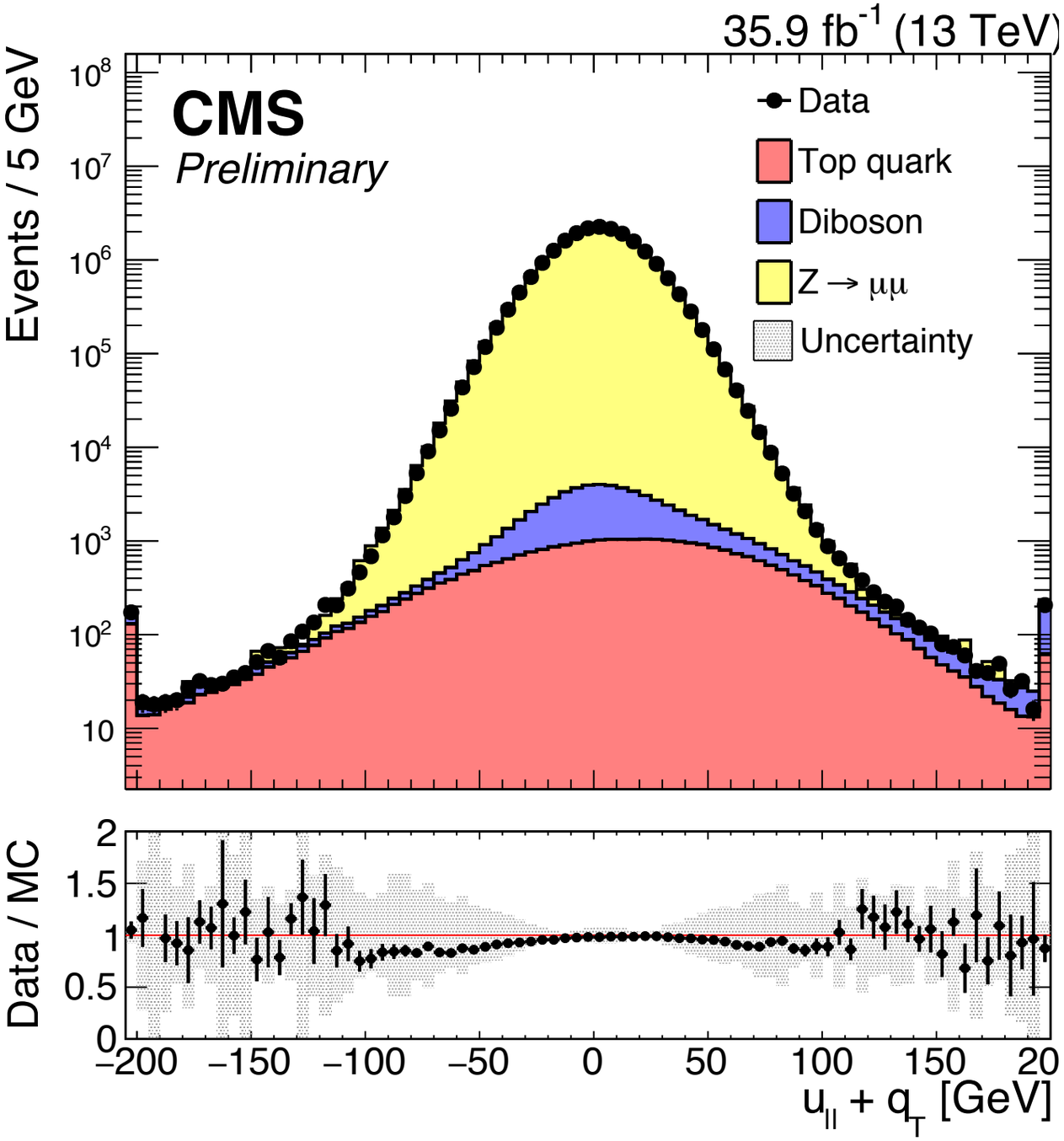
- Electrons
- Muons
- Photons
- jets
- b-jets/c-jets
- invisible particles

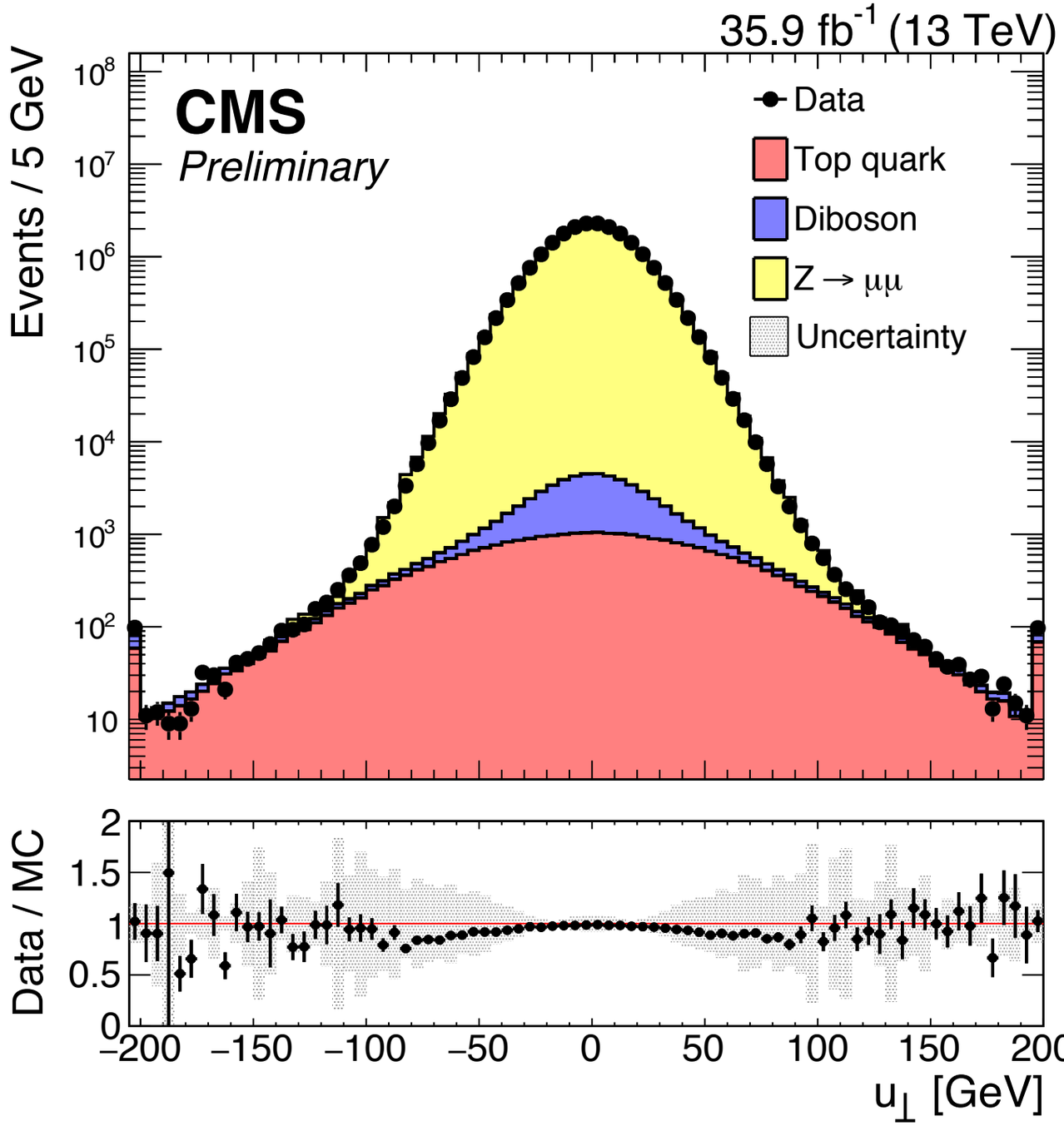




C. Doglioni TeVPa2018

Missing Energy performance

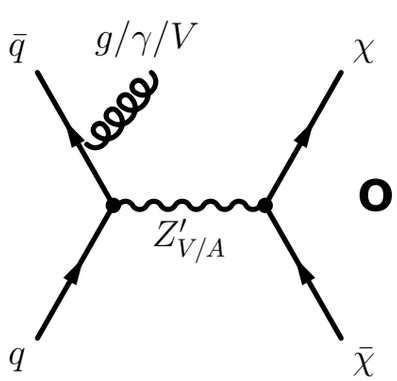




CMS-PAS-JME-17-001

Techniques 1 - E_T^{miss} + X

jet/b-jet/single-t/γ/V+ E_T^{miss}



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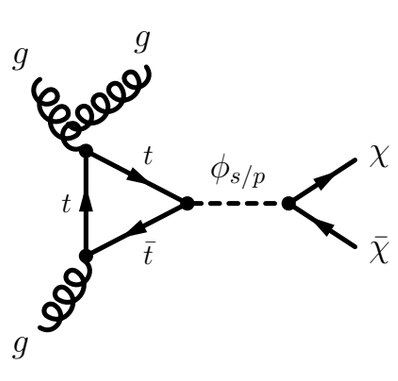

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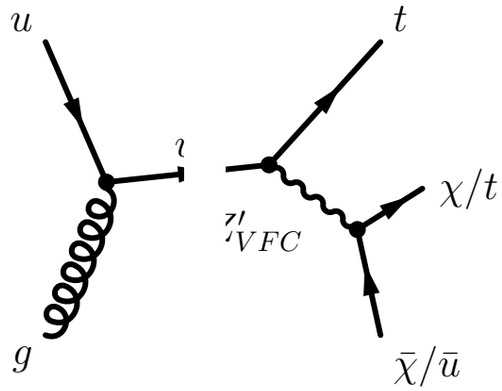
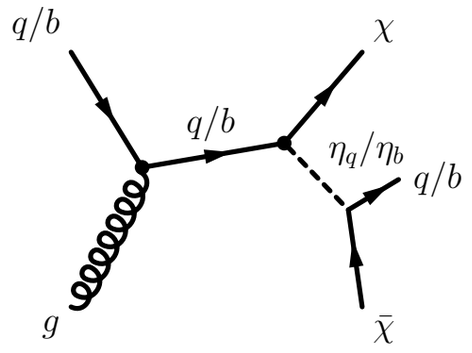
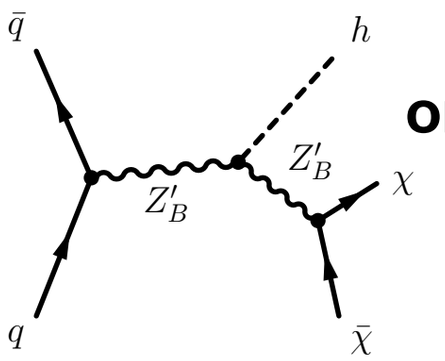


or



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



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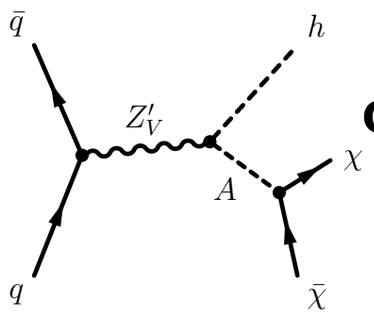

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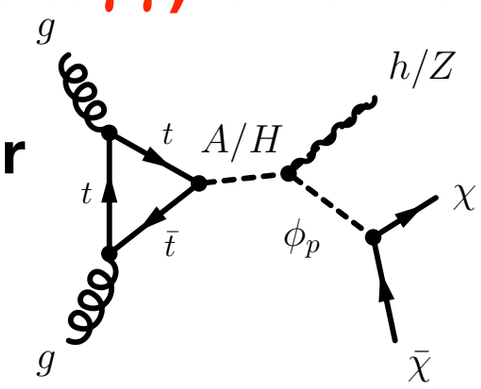

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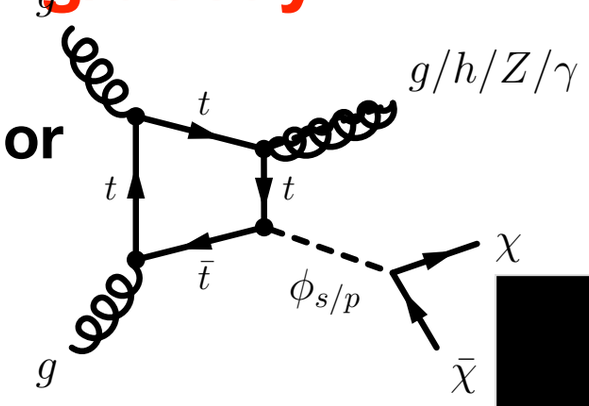
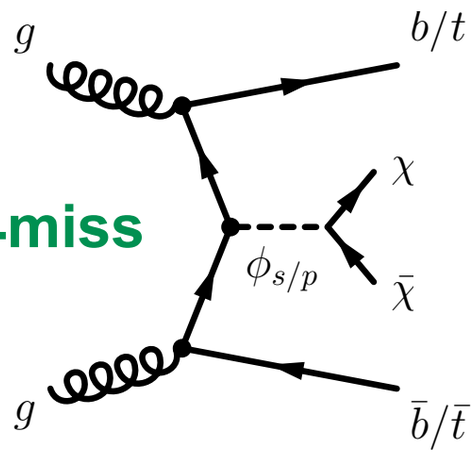
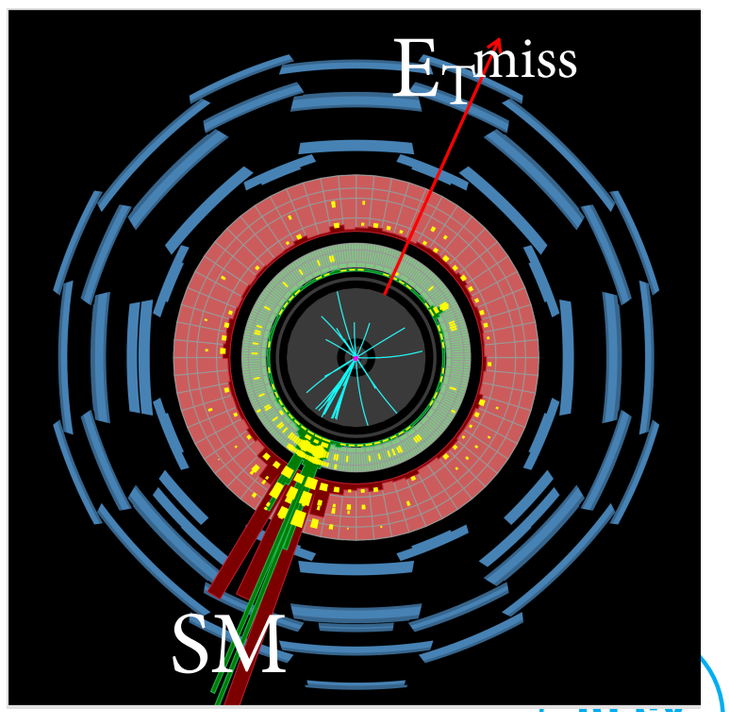


tt / bb + E_T^{miss}



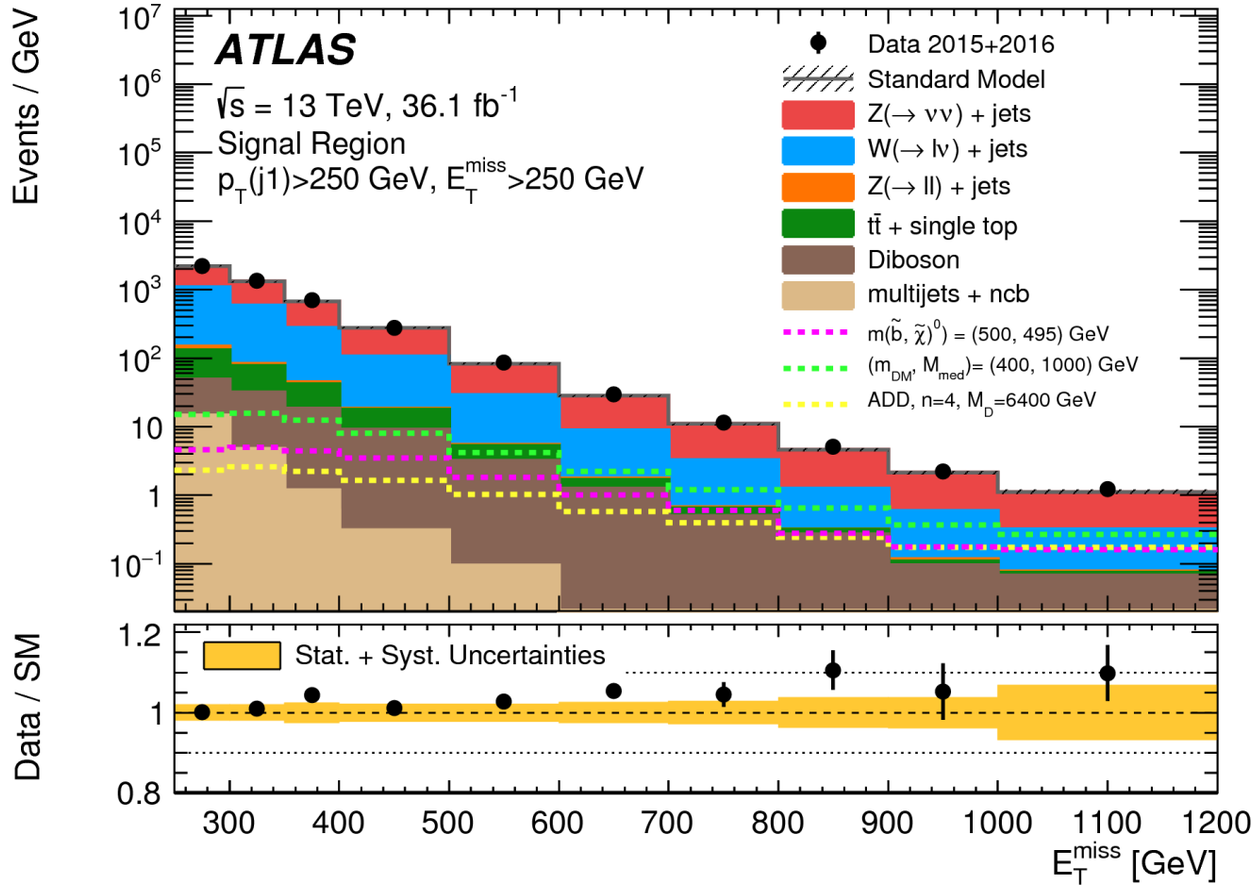


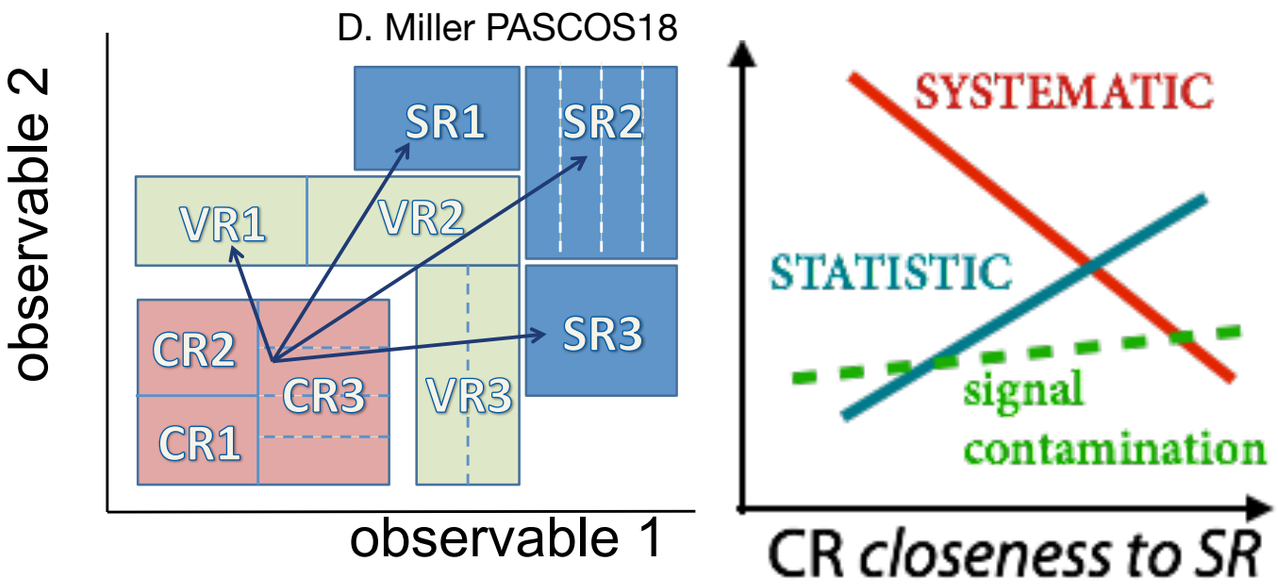
E_T^{miss} + X commonalities

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)

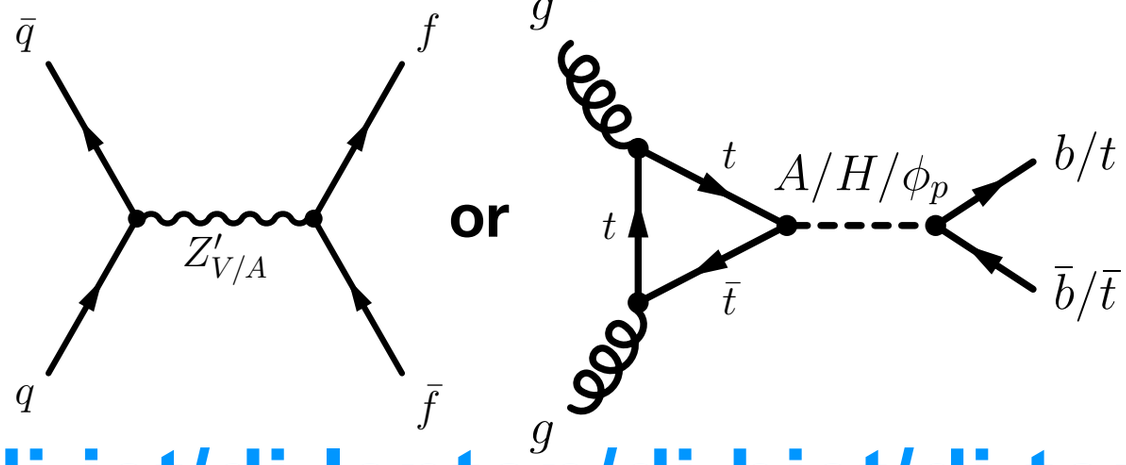




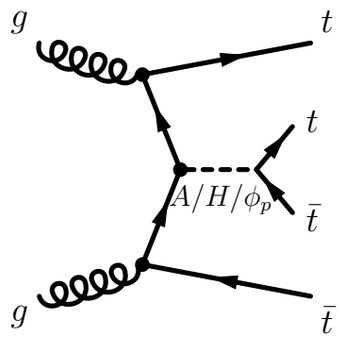
4) Unblinding ! check whether an excess is observed (p-value)

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

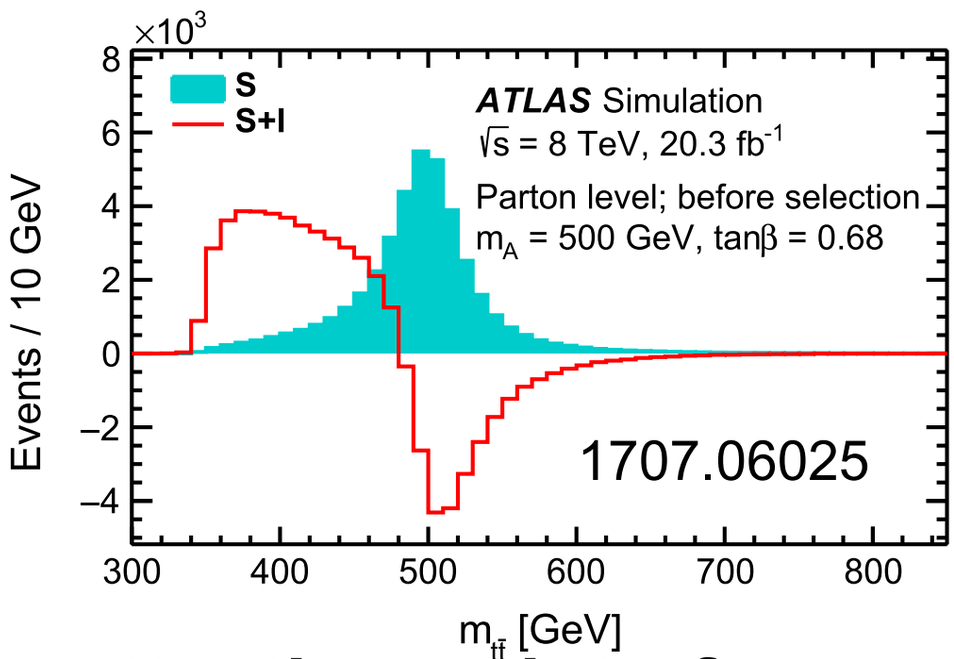
Techniques 2 - resonances



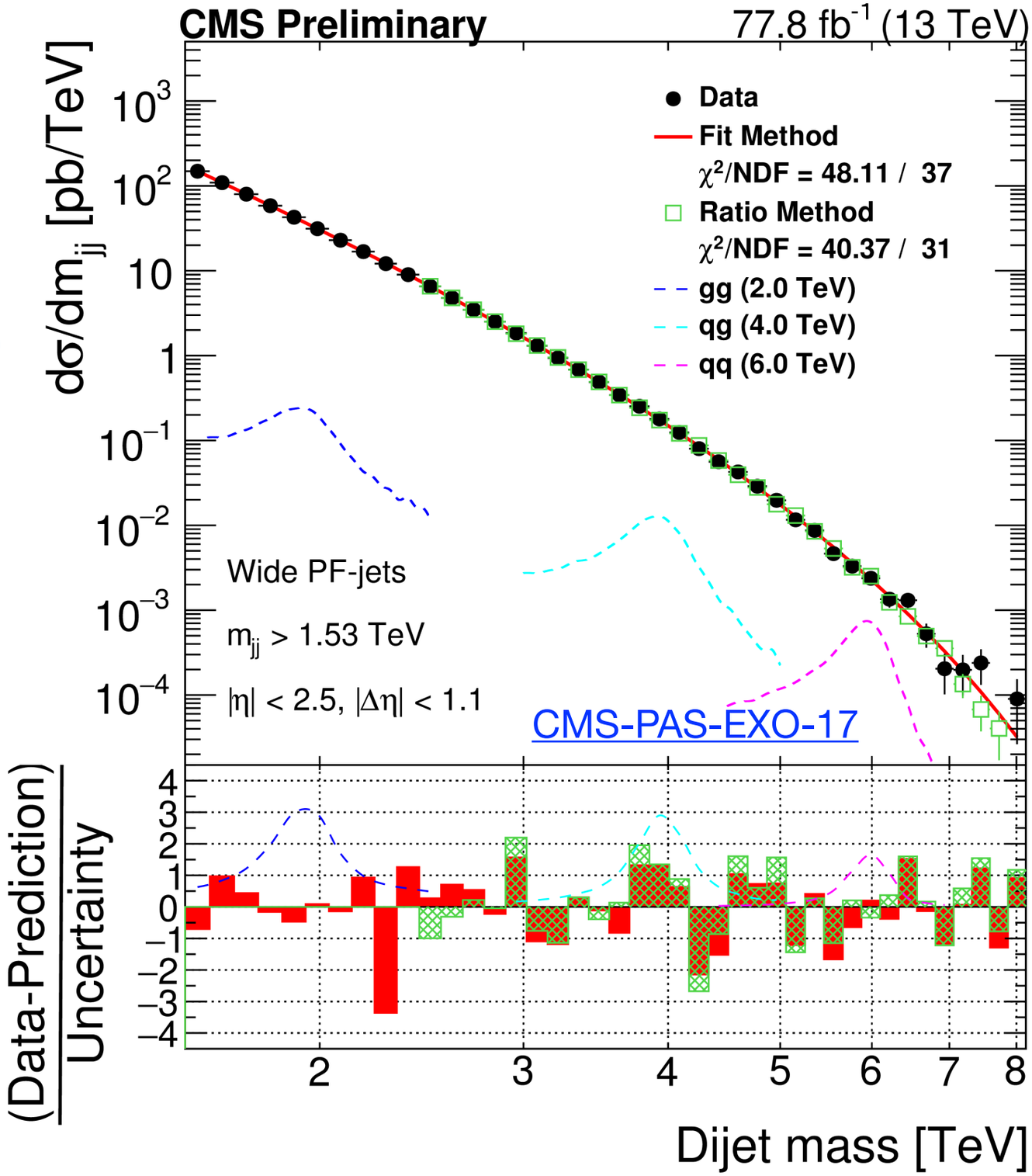
di-jet/di-lepton/di-bjet/di-top



4tops

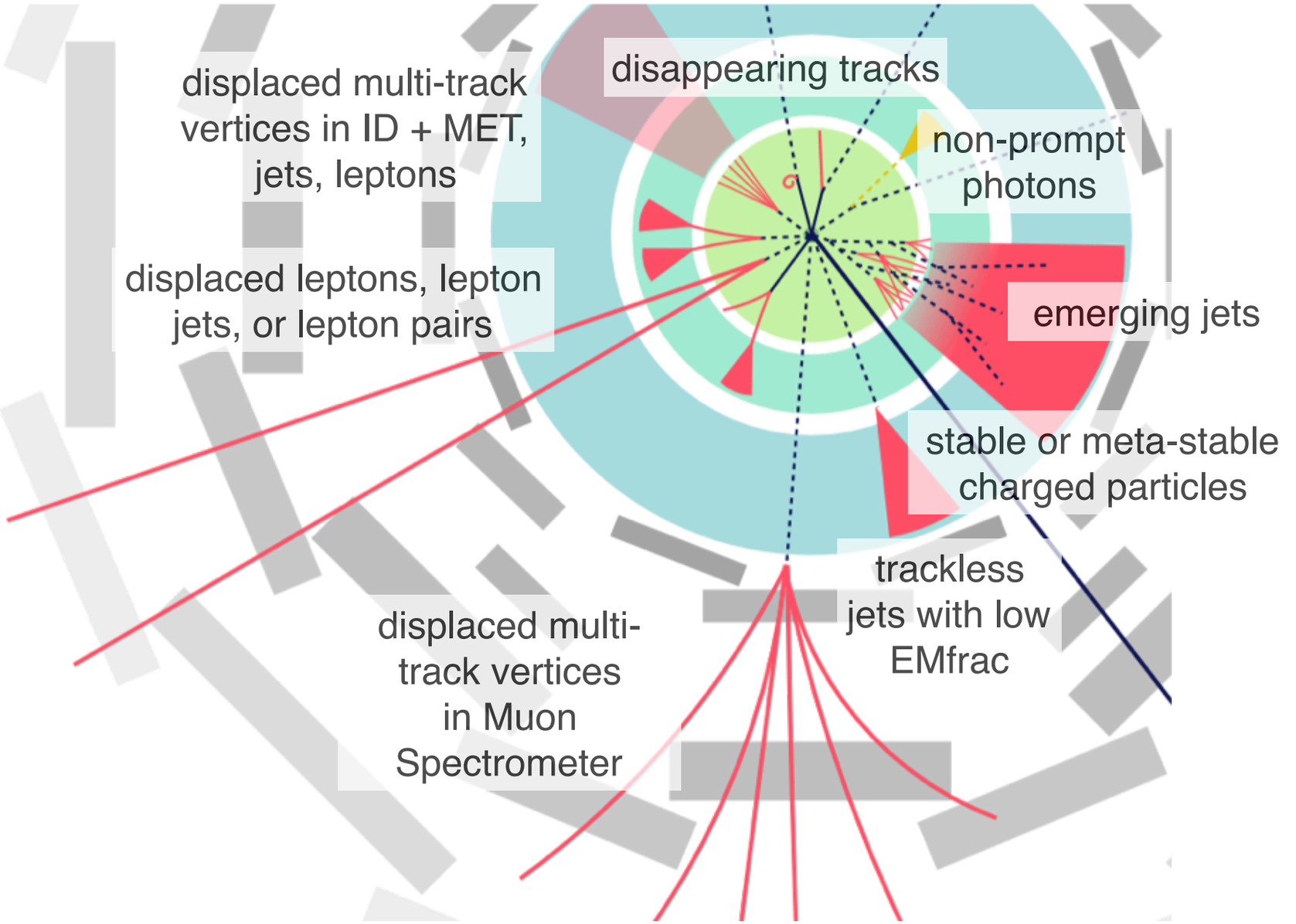


… attention to interference!



Techniques 3 - Long Lived Particles

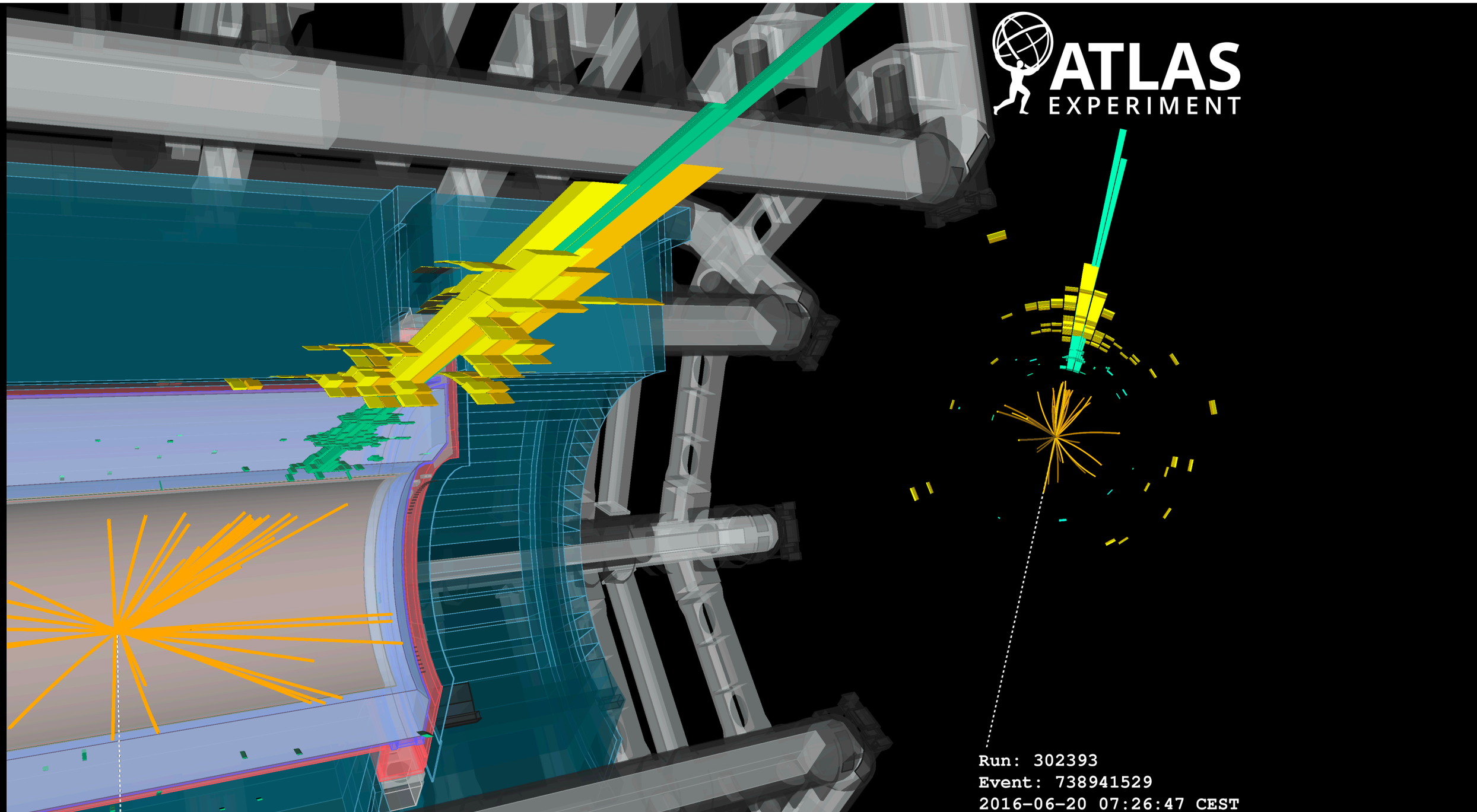
- macroscopic decay length models
- hidden DM
- weak-scale hidden sectors
- SUSY LLPs
- ….



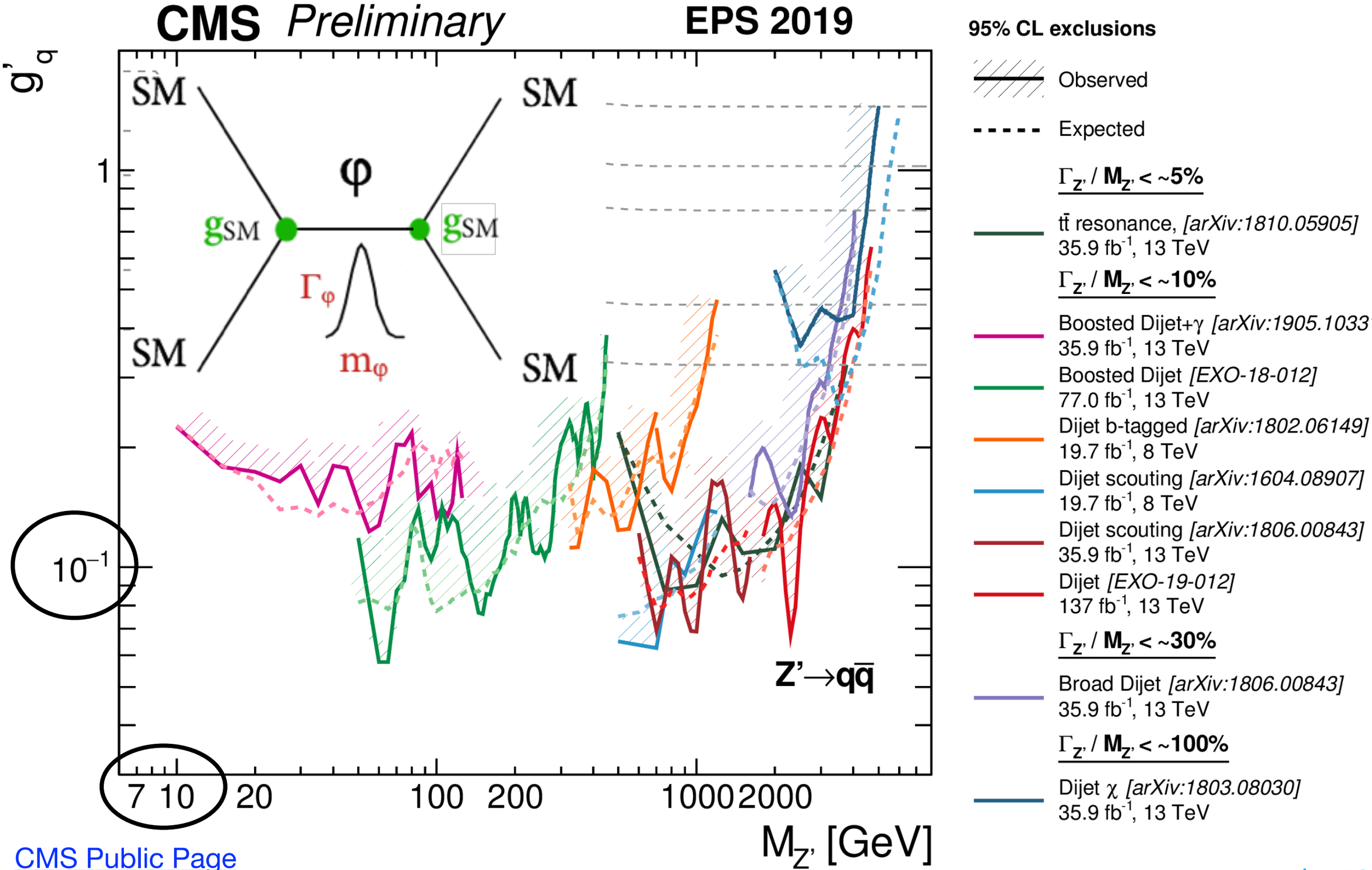
Well established in SUSY, less interpretation in other DM models.

See Ryu Sawada's talk

3. Highlights for simplified models

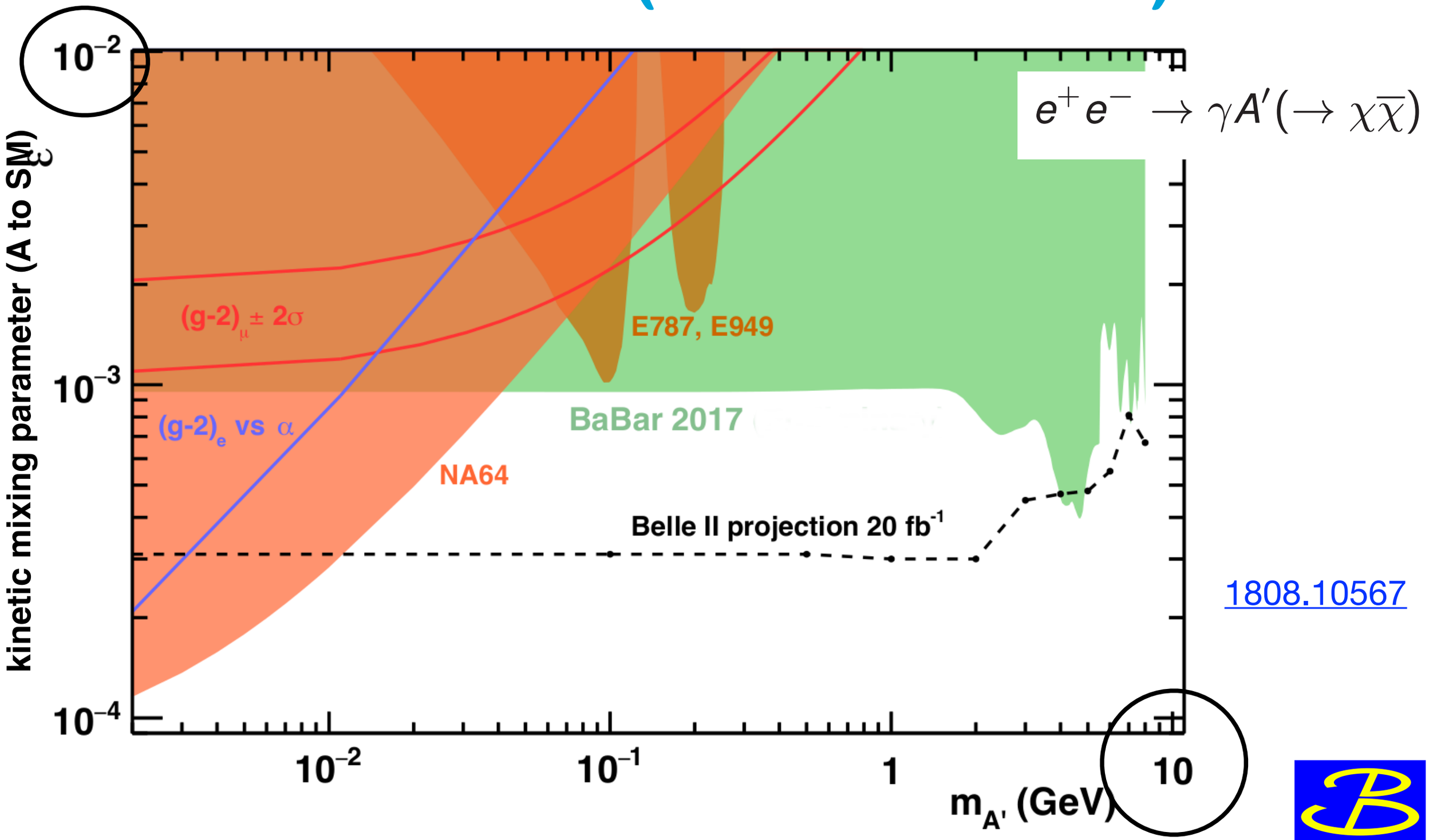


Vector mediators (couplings)



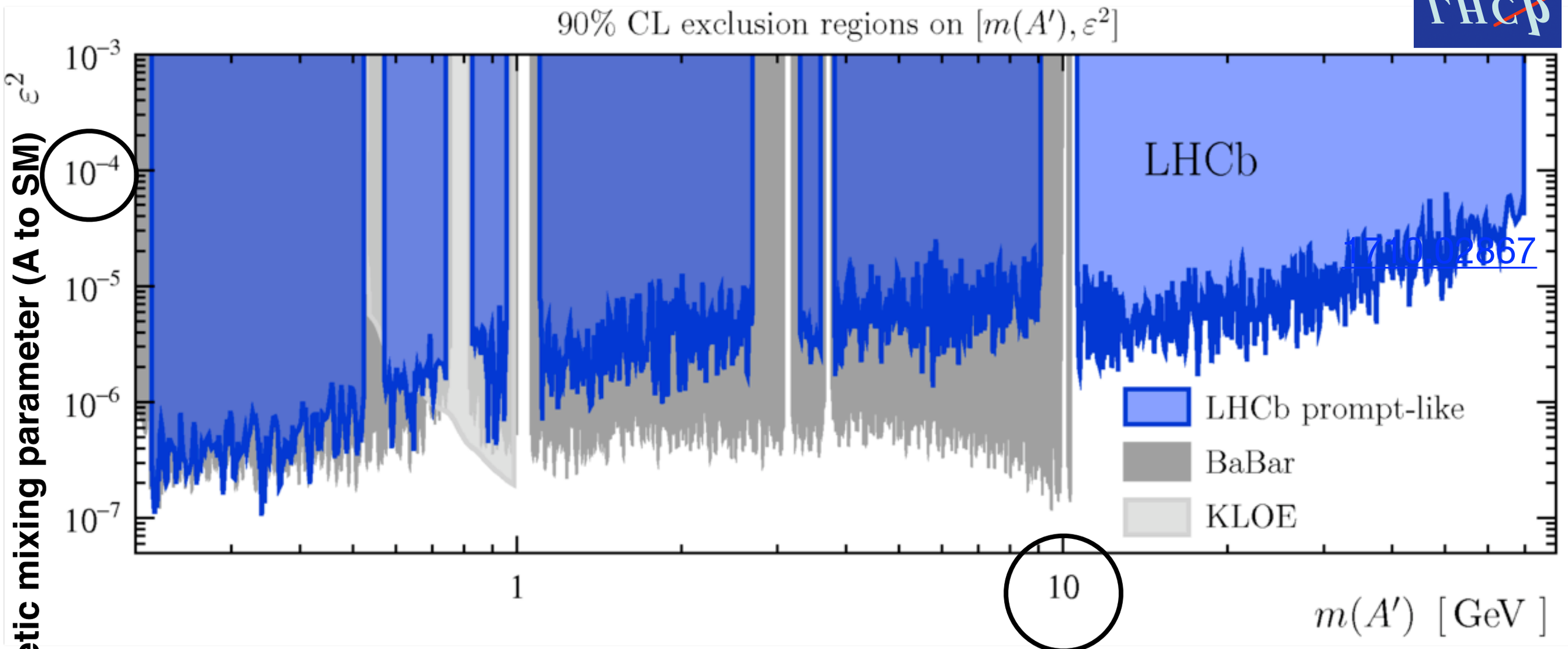
CMS Public Page

Dark Photons (low masses)



1808.10567

Dark Photons (low masses)



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

Spin-1 mediators - masses

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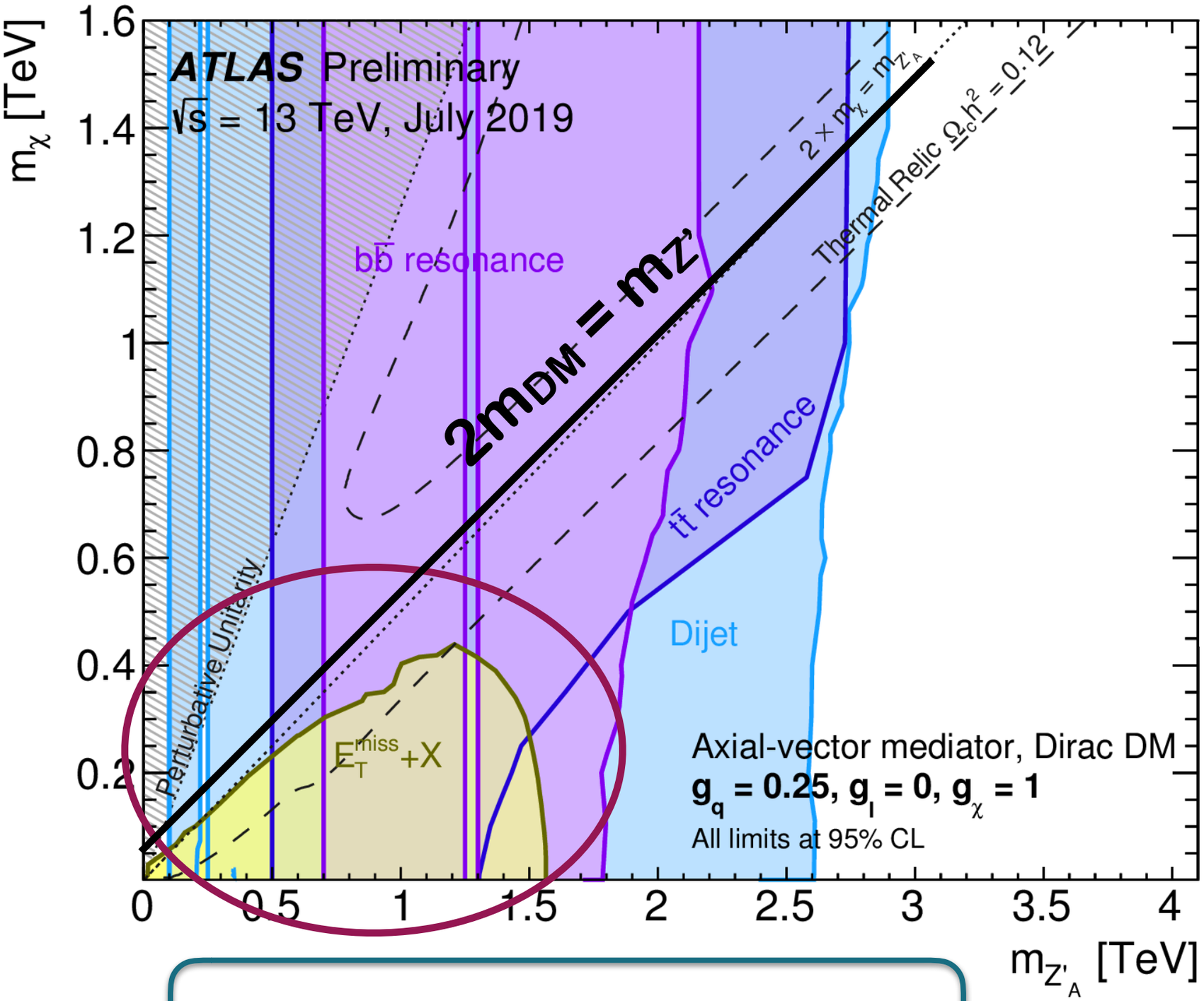
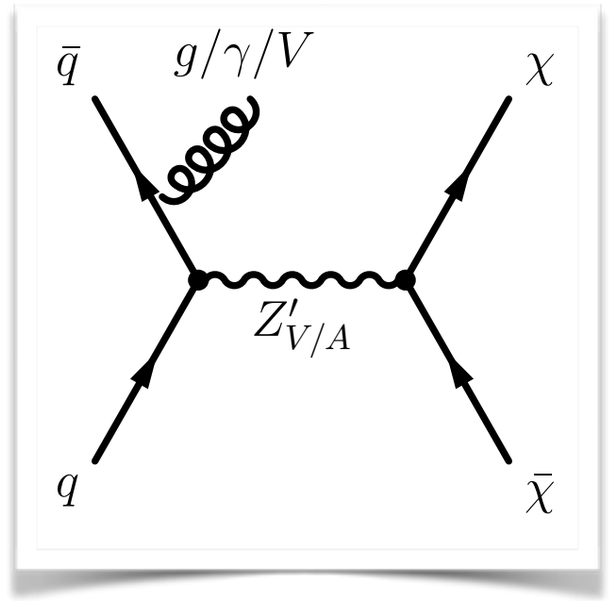
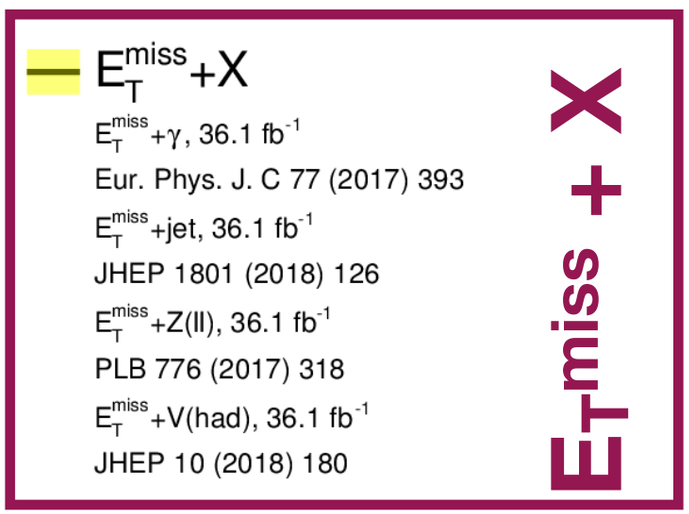


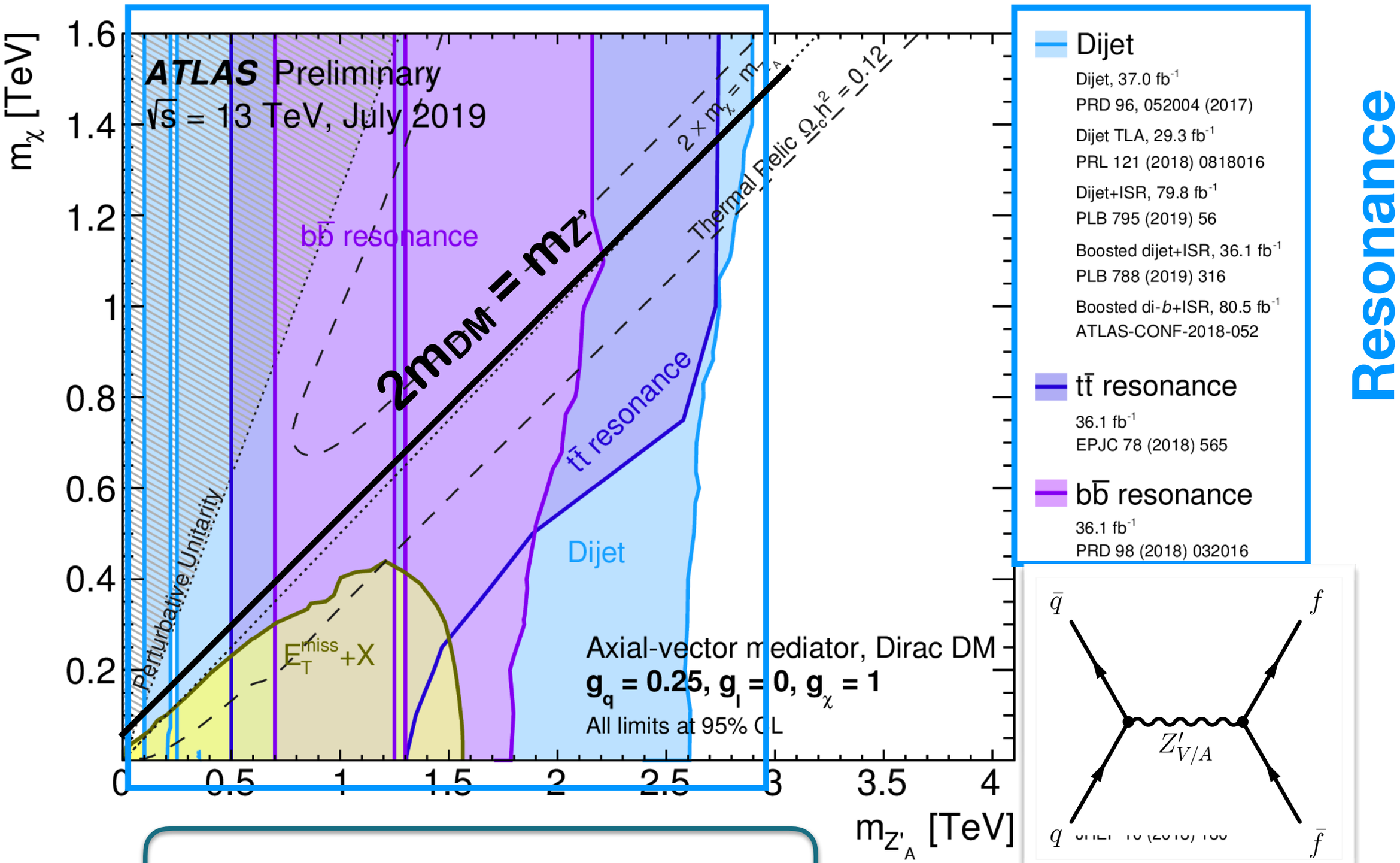




$$g_q = 0.25, g_{lep} = 0, g_{DM} = 1$$

Axial-vector mediator

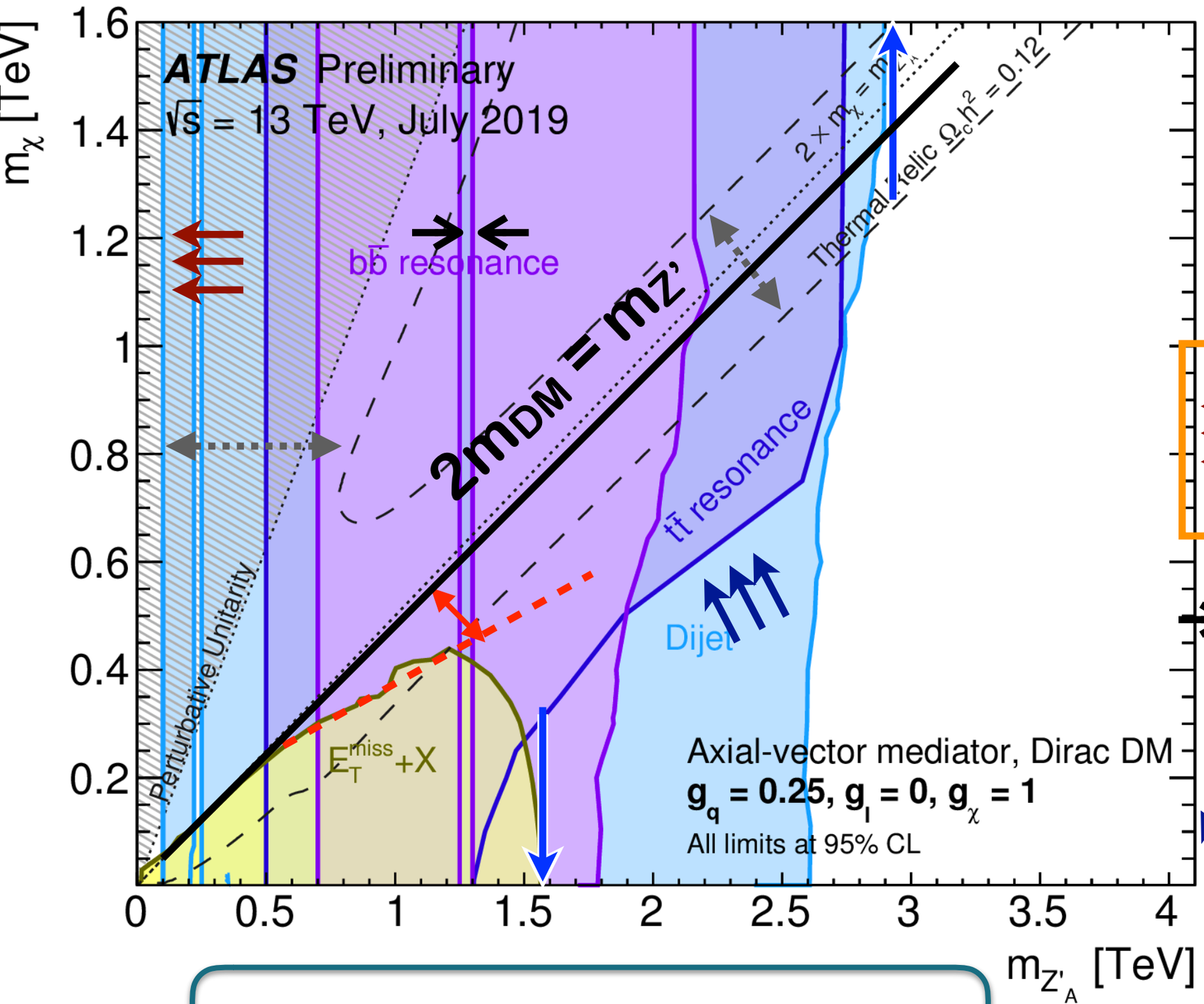
Spin-1 mediators - masses



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

Axial-vector mediator

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

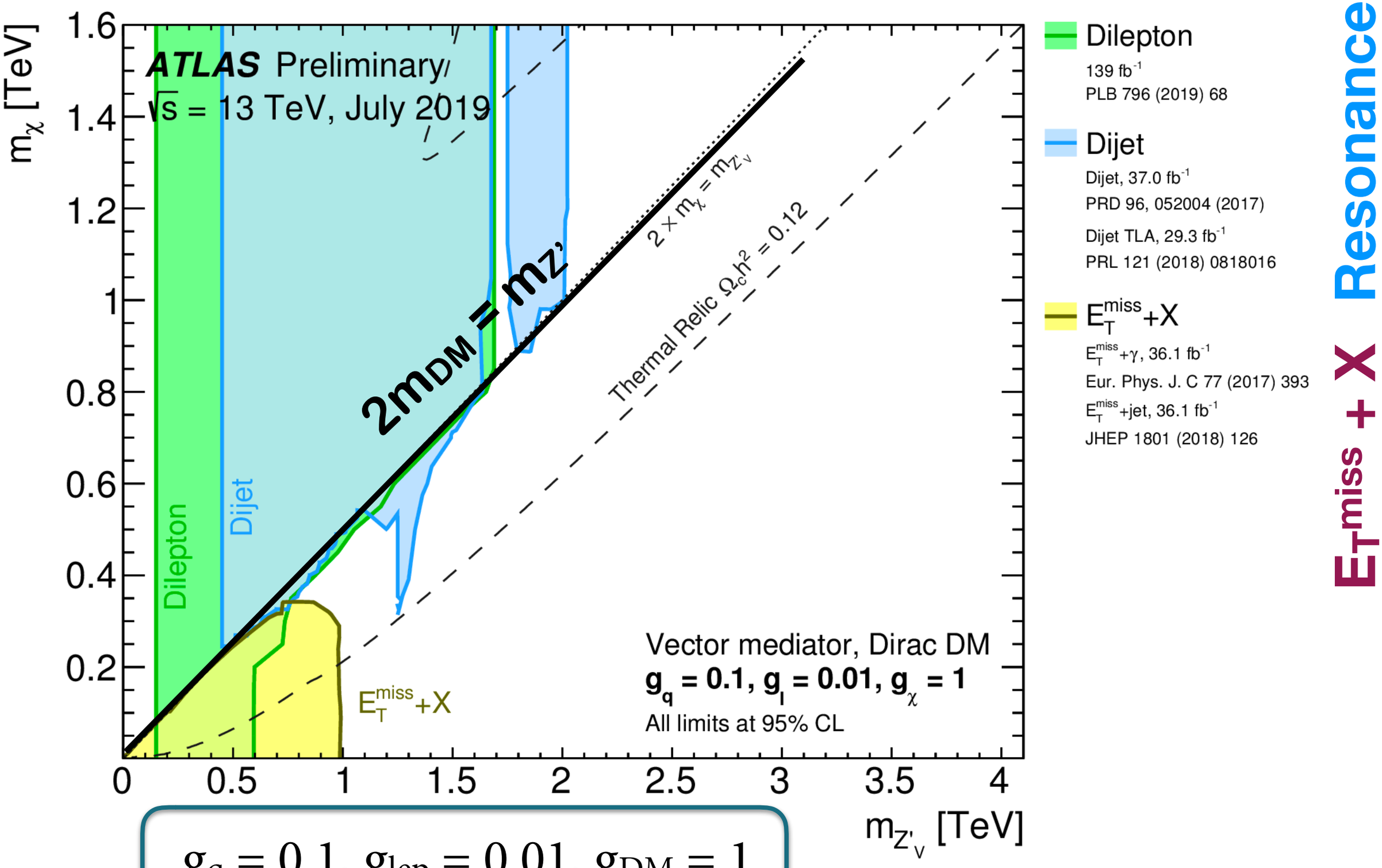
Change of trigger strategy & analysis width sensitivity

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

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

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

Spin-1 leptophilic case



E_T^{miss} + X Resonance

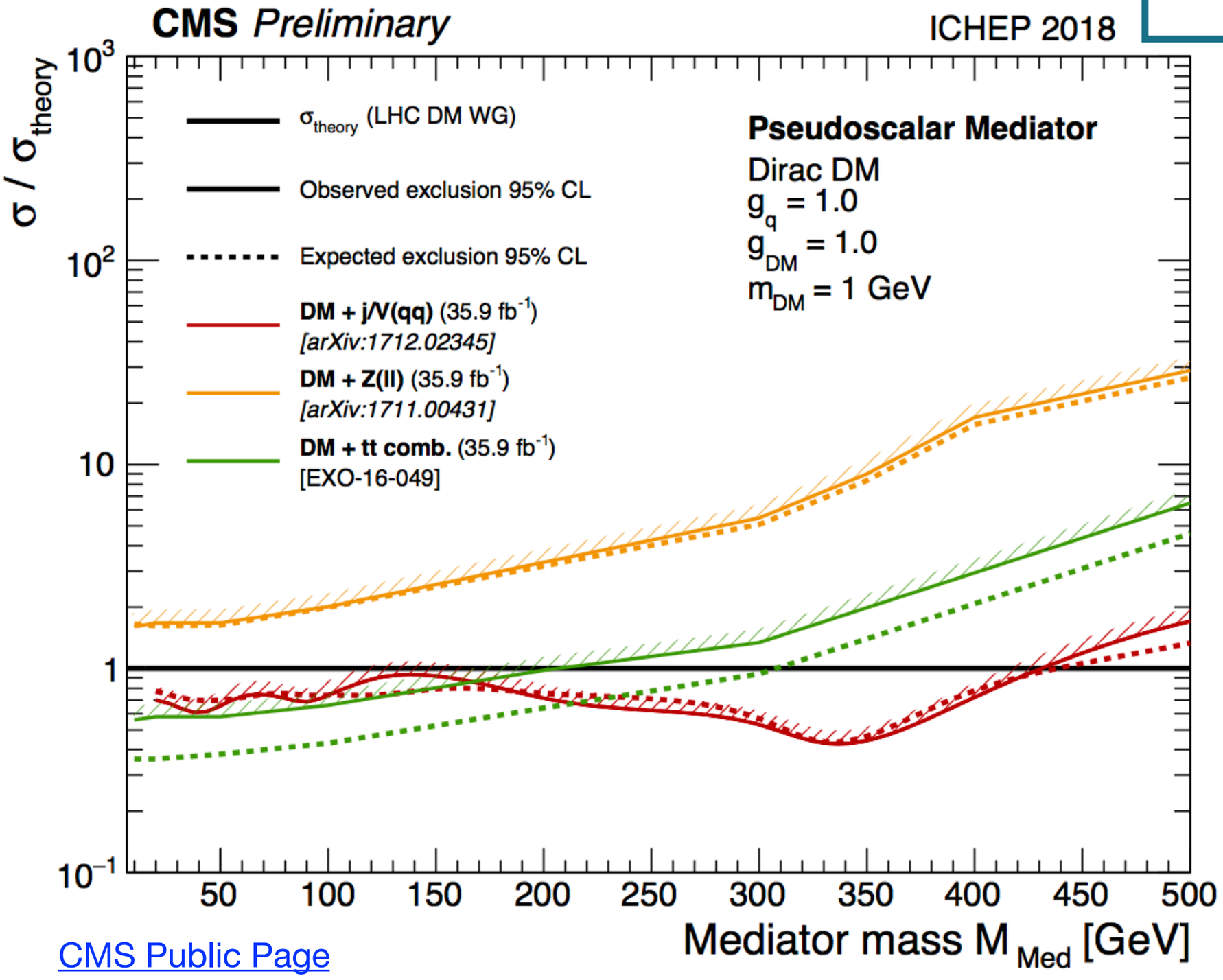
$$g_q = 0.1, g_{lep} = 0.01, g_{DM} = 1$$

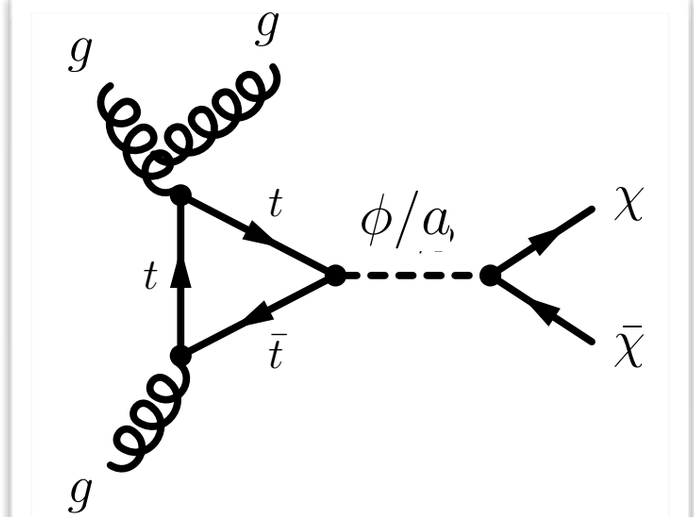
Vector mediator

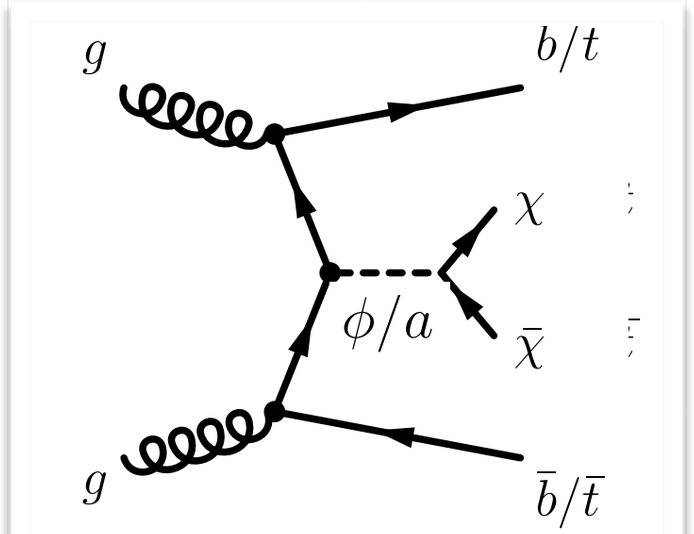
Spin-0 mediators

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

Needed to easily fulfil Flavour Constraints (MFV)



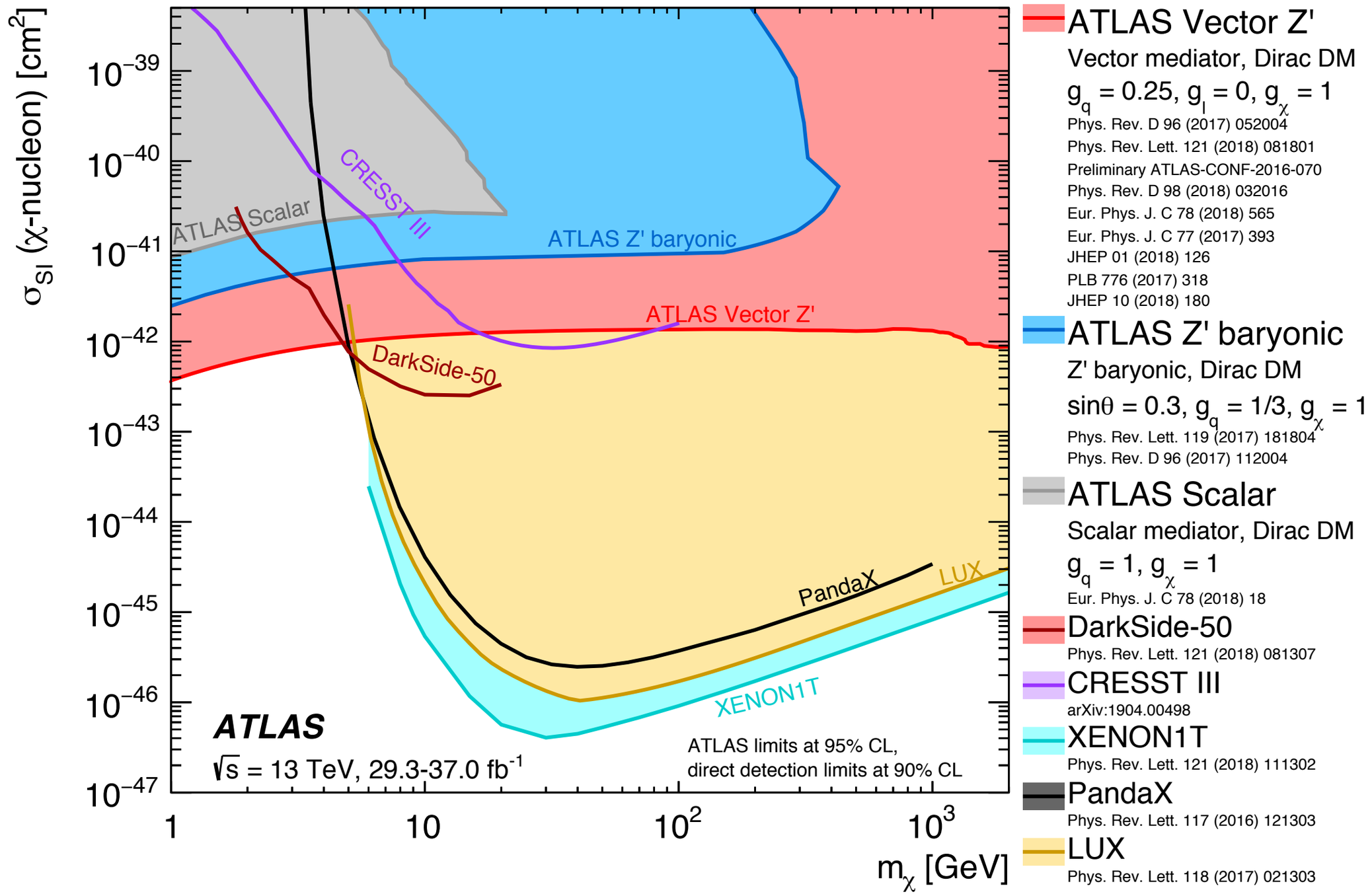




CMS Public Page

Comparing to direct detection

"The plot"



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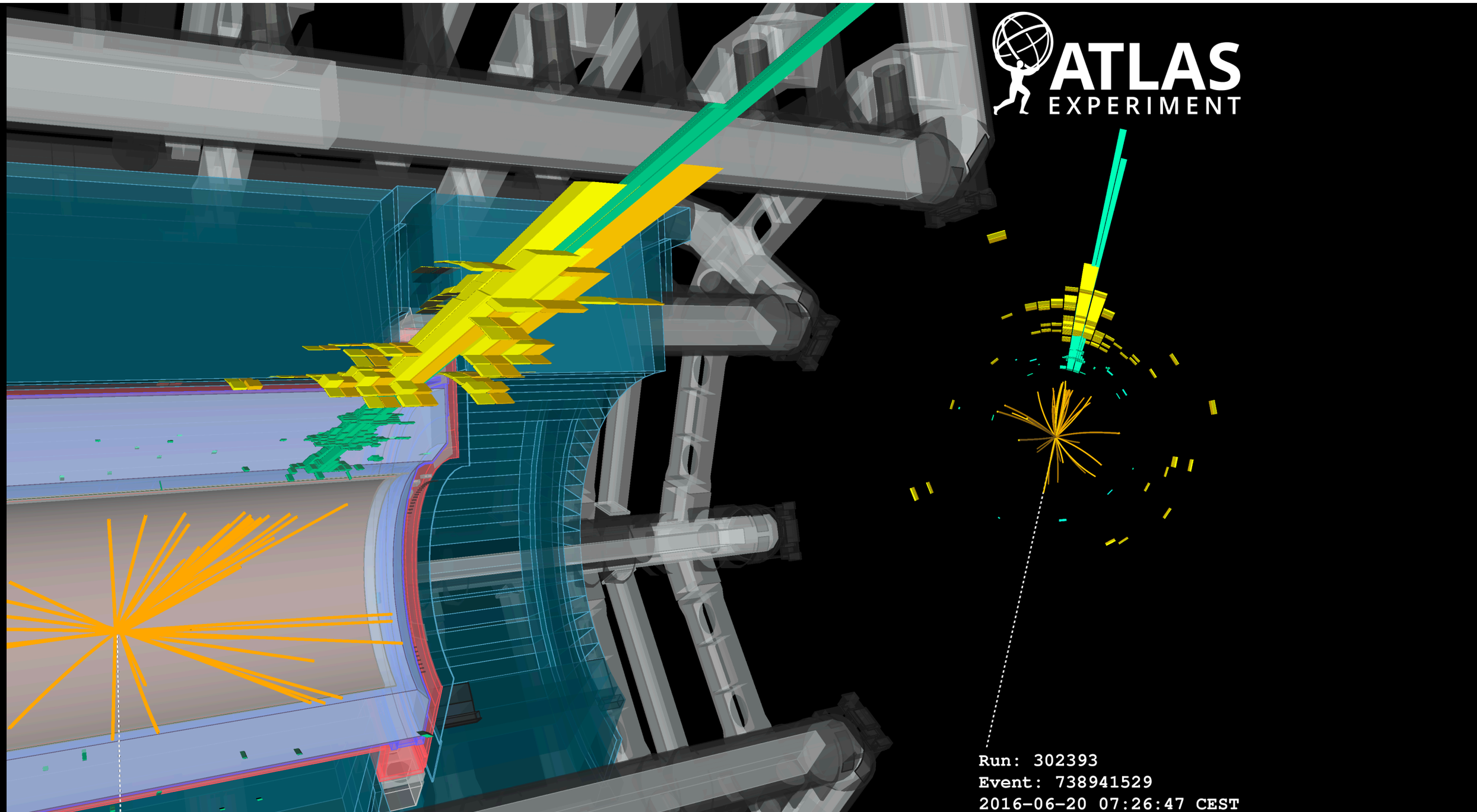
Details and limitations of the conversion in arXiv:1603.04156

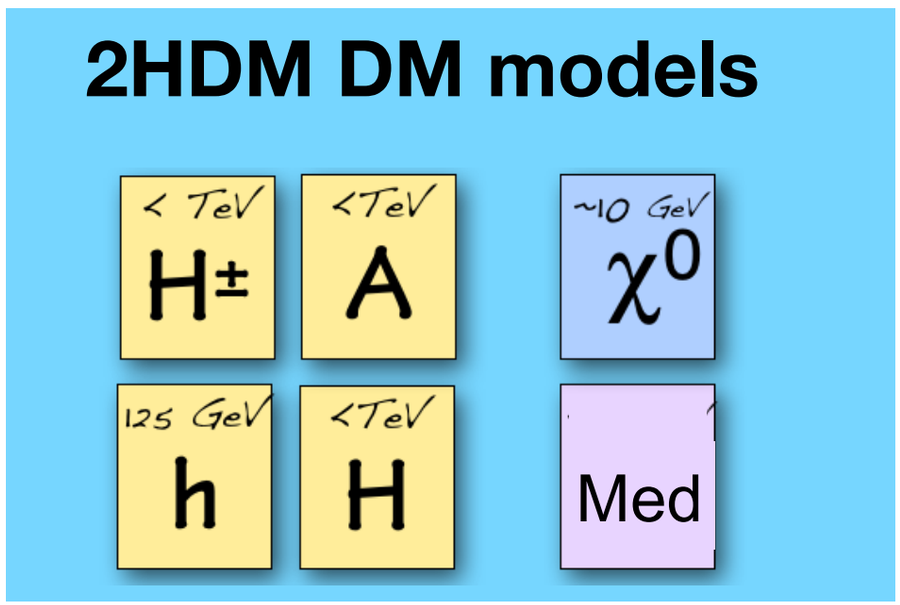
Considerations on the results

- ★ 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.

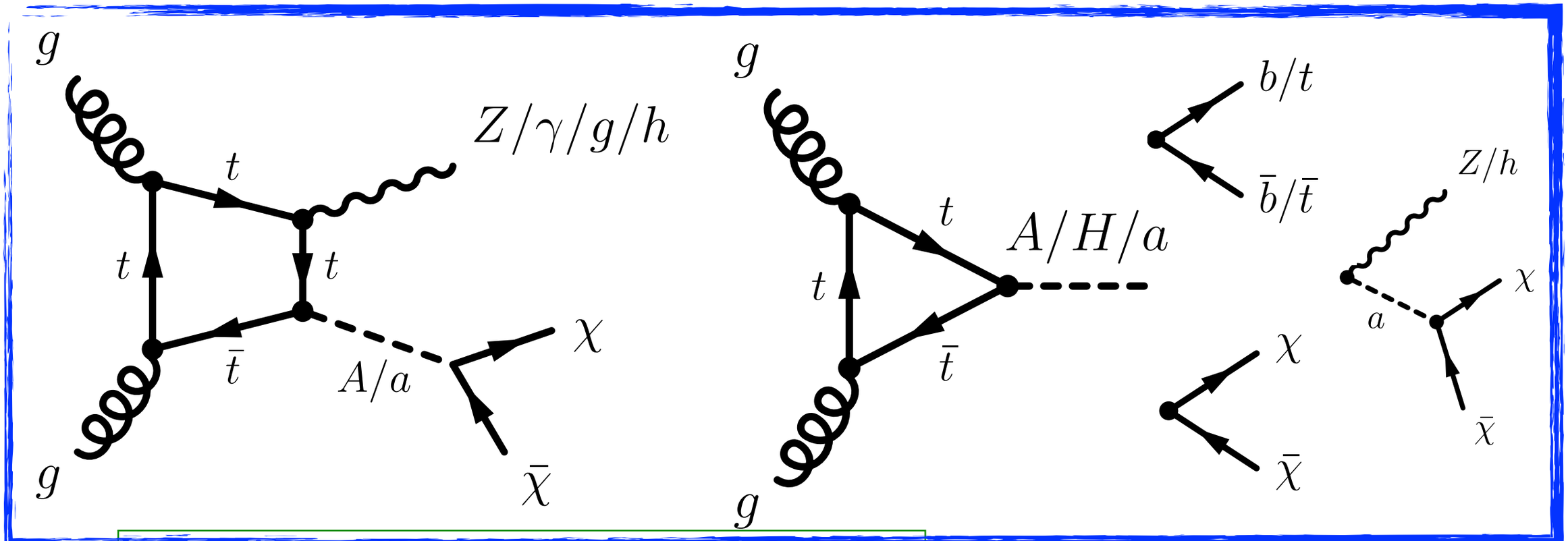
4. highlights for less simplified models: 2HDMs



2HDM-based models



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



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

2HDM+pseudoscalar models

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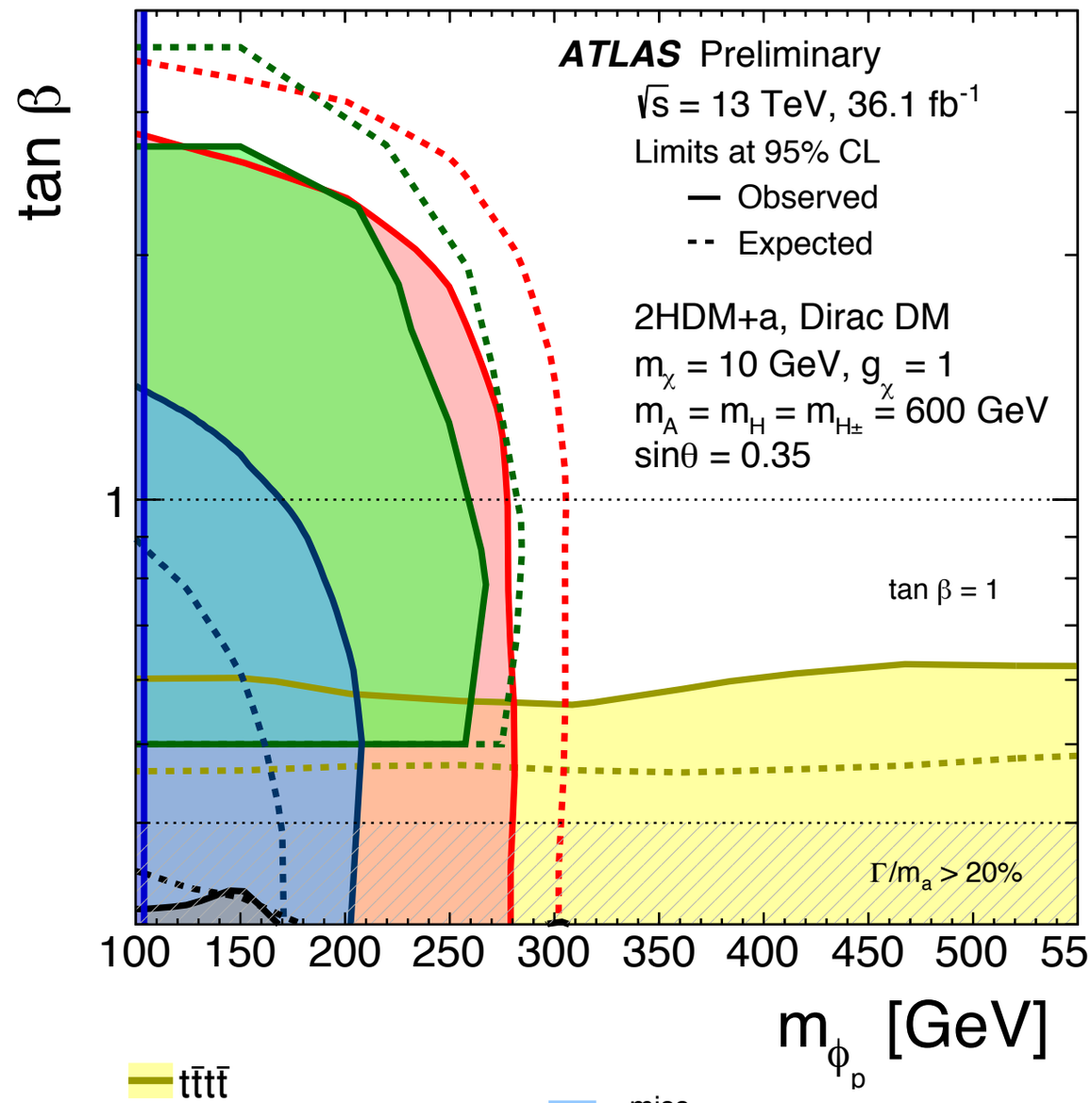


$t\bar{t}t\bar{t}$
JHEP 09 (2017) 088

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

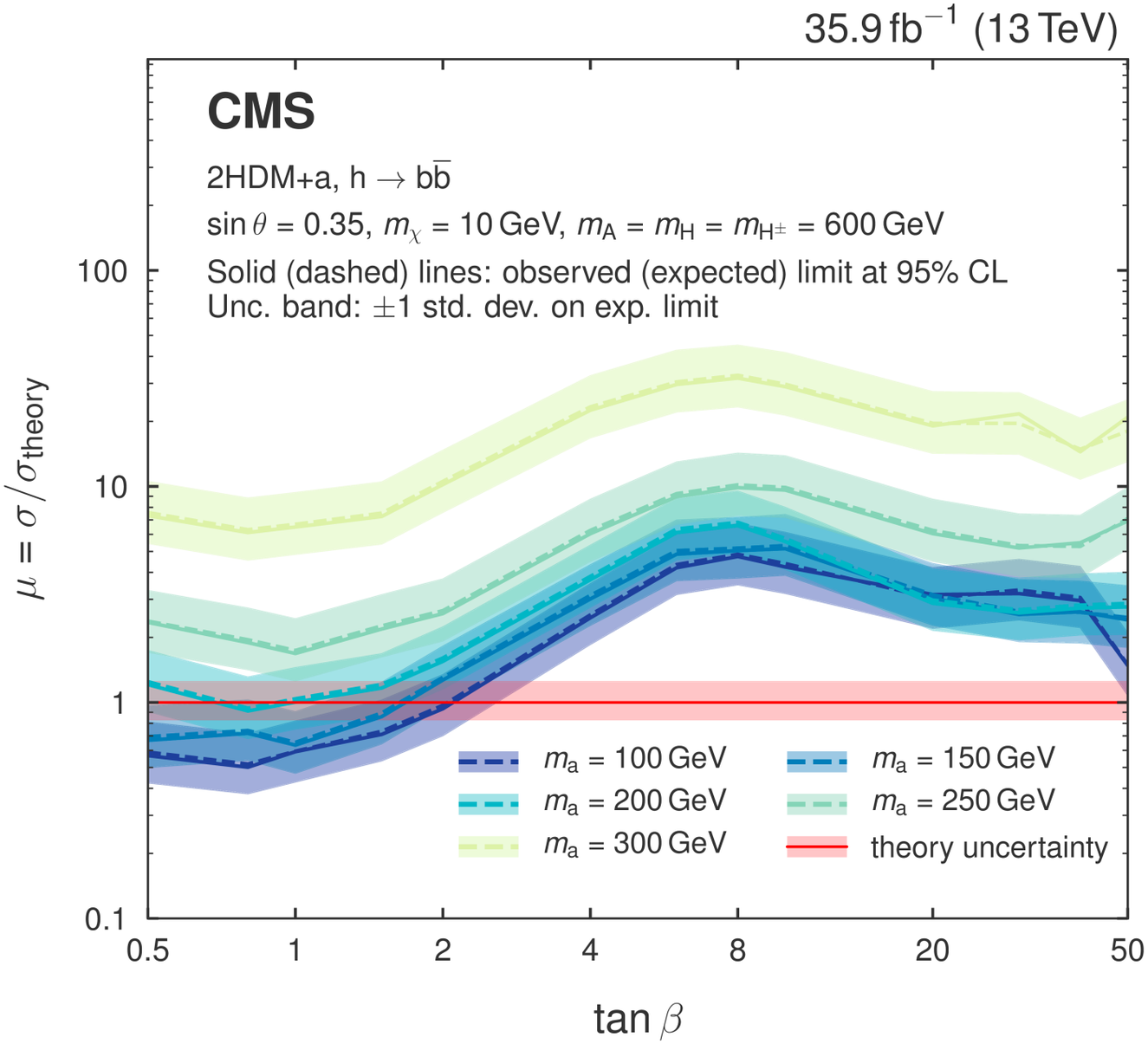
E_T^{miss}+Z(ll)
PLB 776 (2017) 318

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

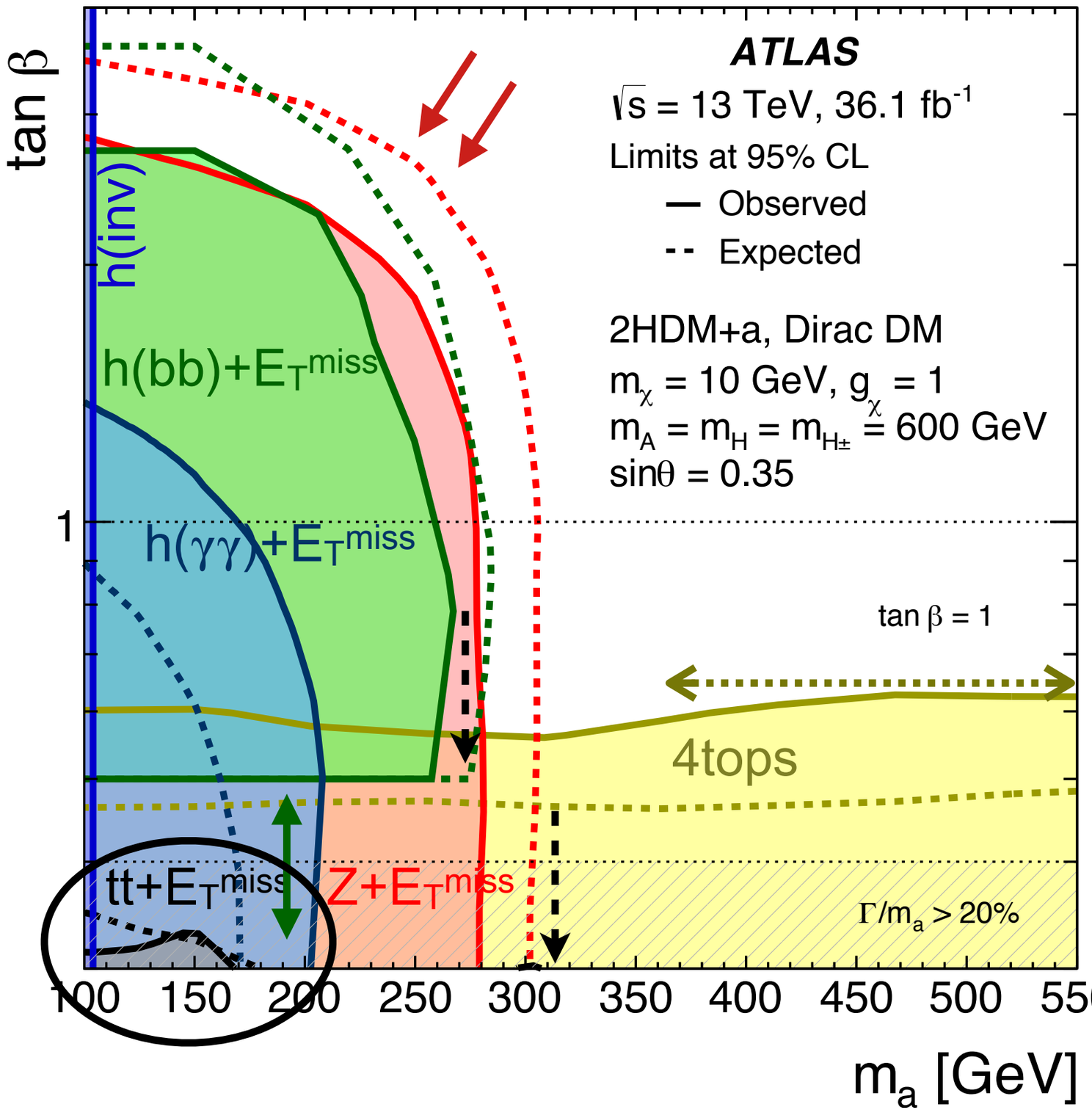
E_T^{miss}+h($b\bar{b}$)
PRL 119 (2017) 181804

h(inv)
JHEP 06 (2018) 108

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



Results (I)



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

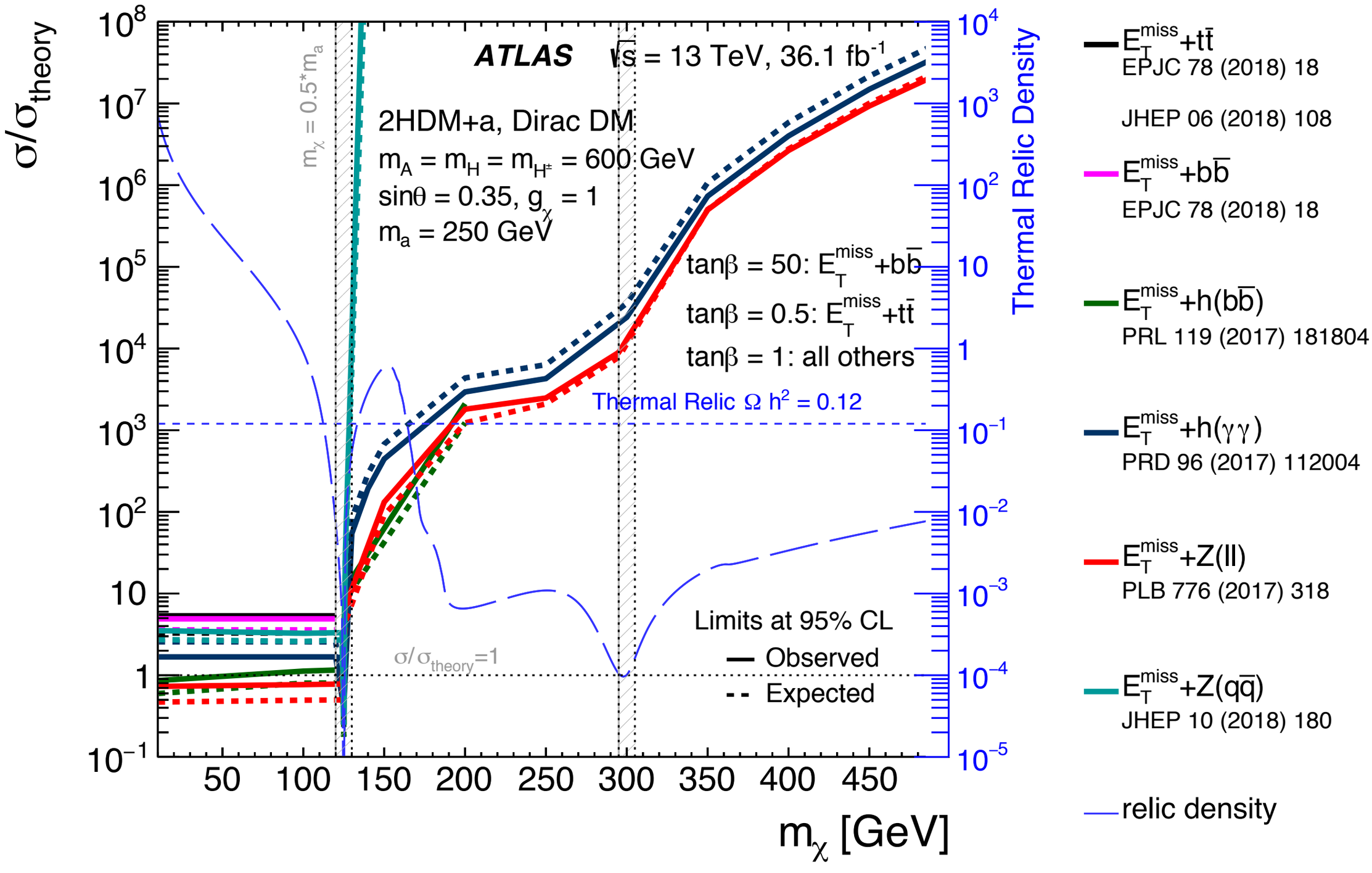
Plotting effect due to missing samples

Loss of sensitivity due to missing bb-initiated production

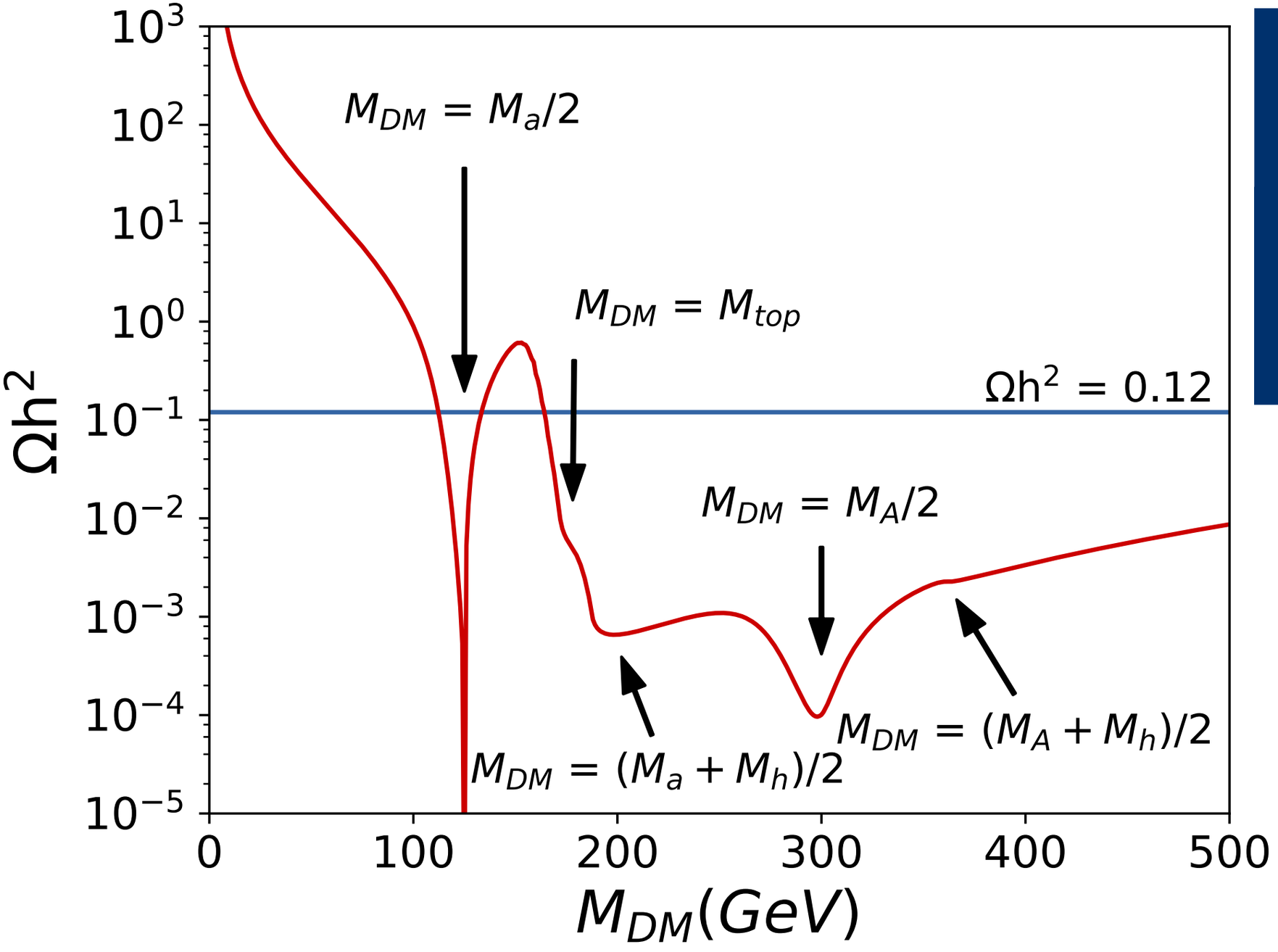
Sensitivity dominated by ttA/ H(tt) ⇒ independent on m(a)

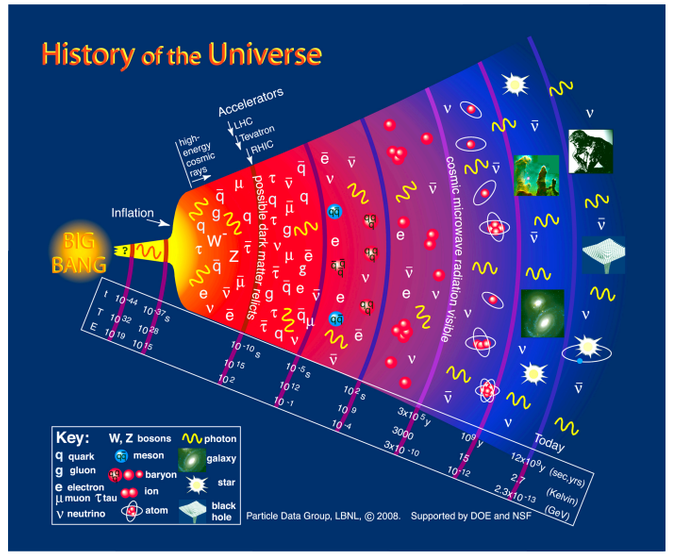
Limited by the choice of sinθ

Relic density perspective

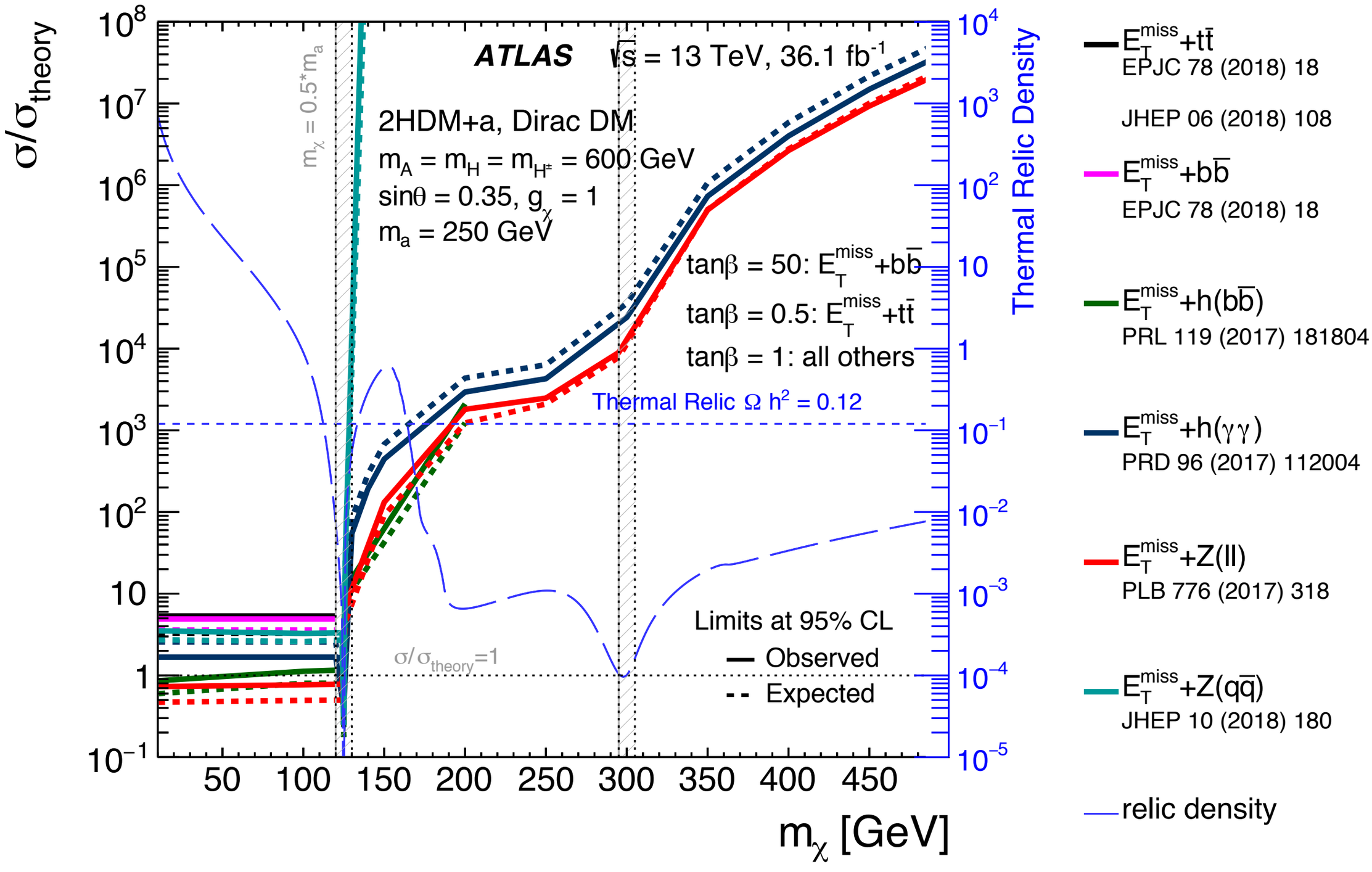


Understanding the relic prediction





Relic density perspective



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

Further considerations

where to from here?

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

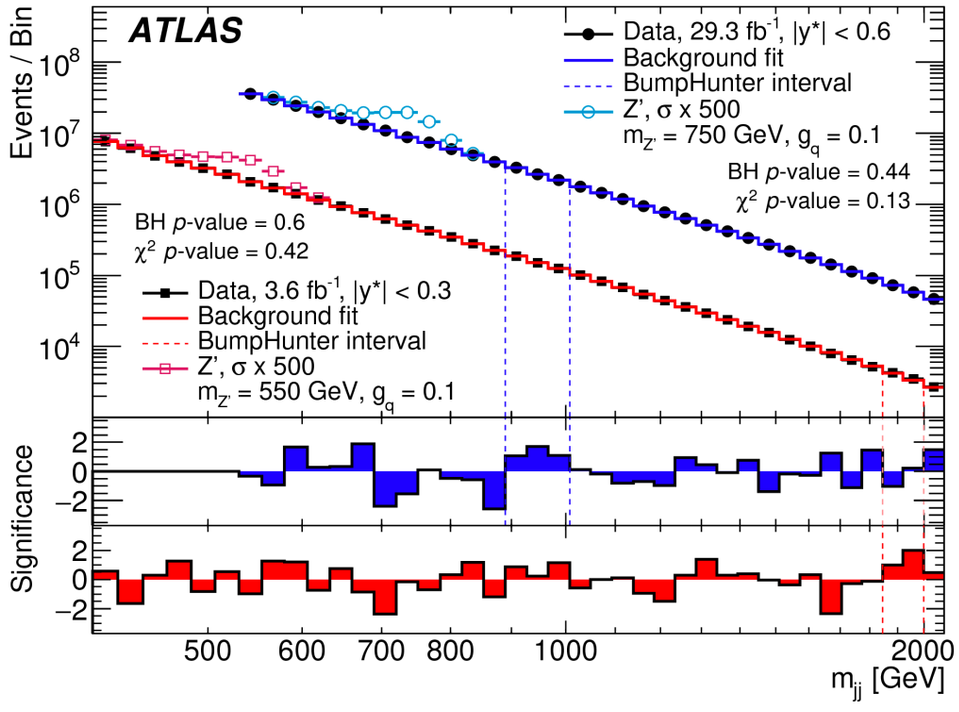
See also Ryu's Sawada's talk

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)



access time

Delayed data analysis

CMS Data Parking | ATLAS Delayed Stream

Analysis with trigger objects

ATLAS/CMS Trigger-Level Analysis and Data Scouting
http://arxiv.org/abs/1604.08907

ALICE Compressed reconstructed data

Standard data analysis

ATLAS/CMS/LHCb Fully reconstructed data

Monitoring

ATLAS TAg Data Analysis

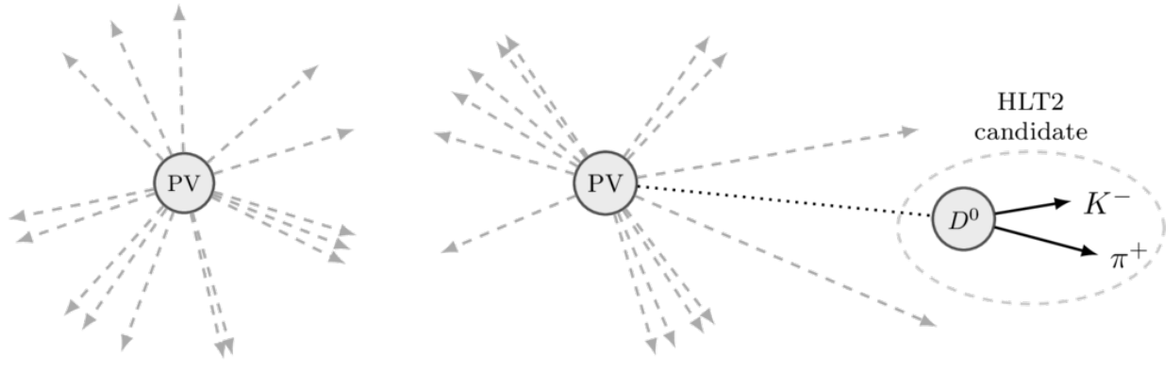
Real-time analysis

LHCb Turbo Stream/TESLA
http://arxiv.org/abs/1604.05596

LHCB-TDR-018

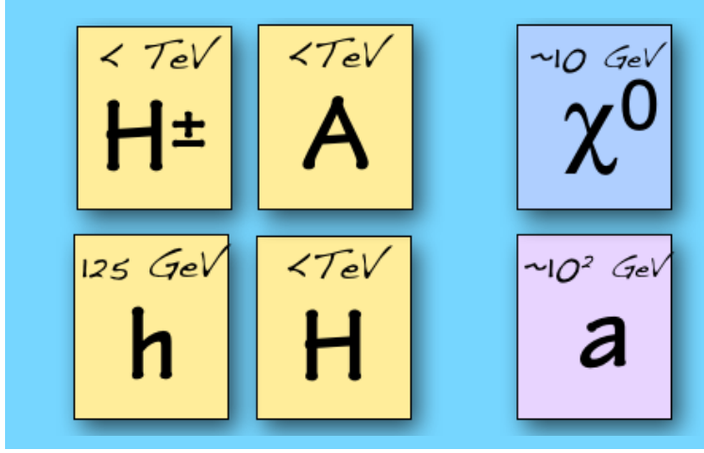
Data complexity/size

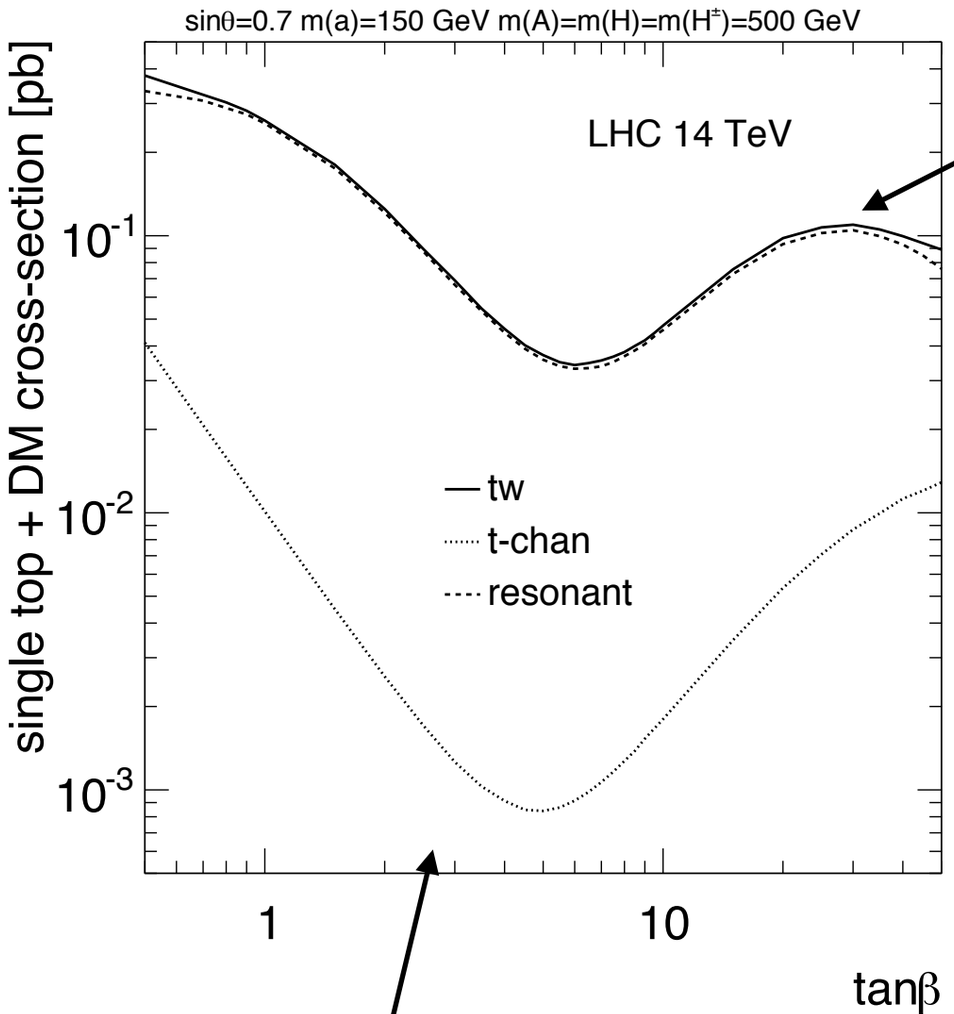
LHCb Turbo stream

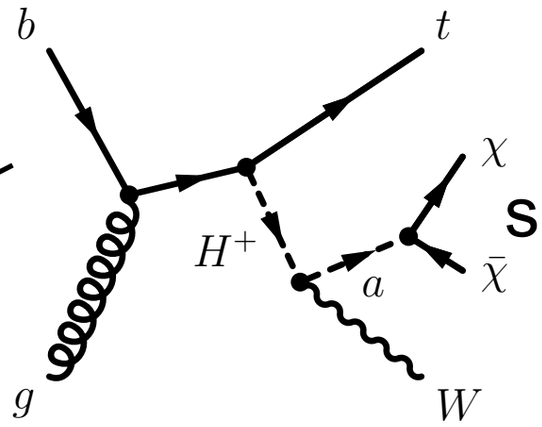


model already used in dark photon analysis

Trying new signatures

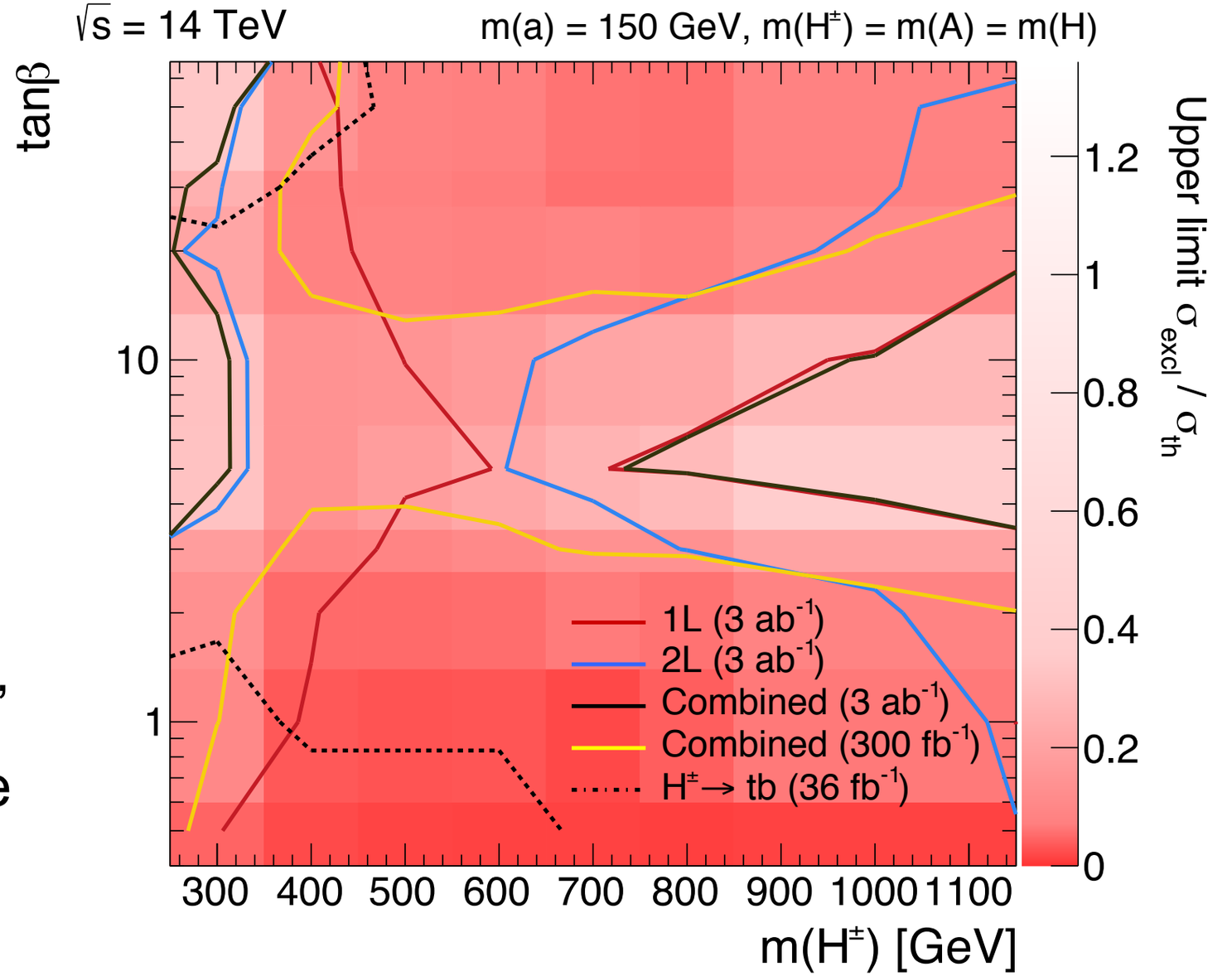


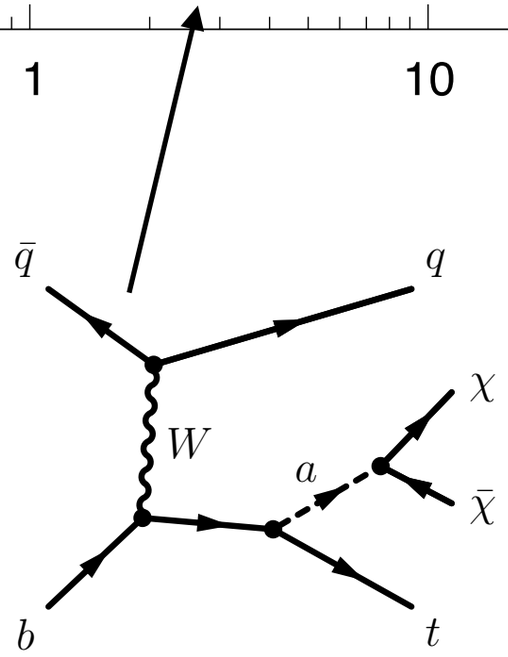




'new' signalture

[PP,Polesello 1712.03874]





'classical' signalture

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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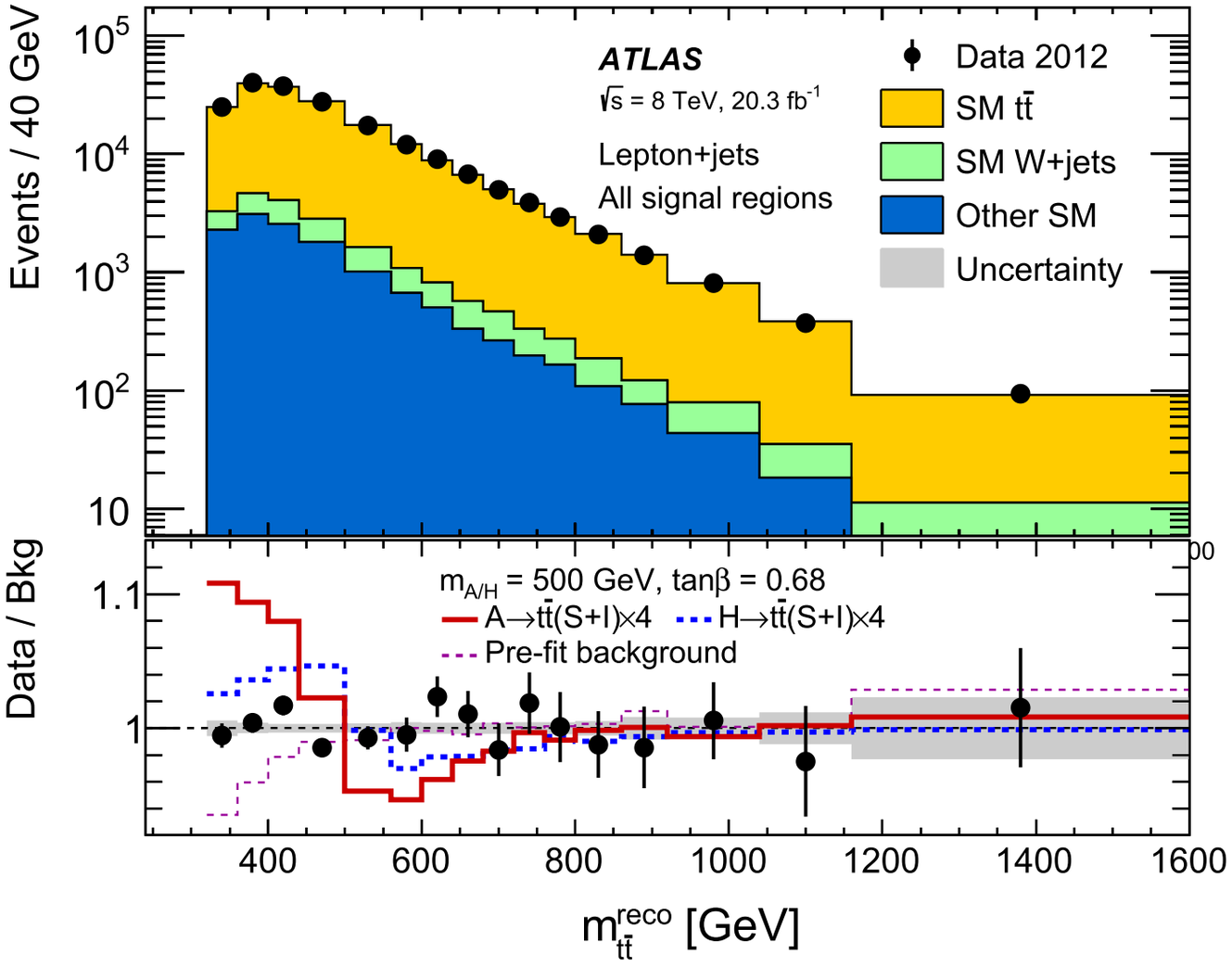
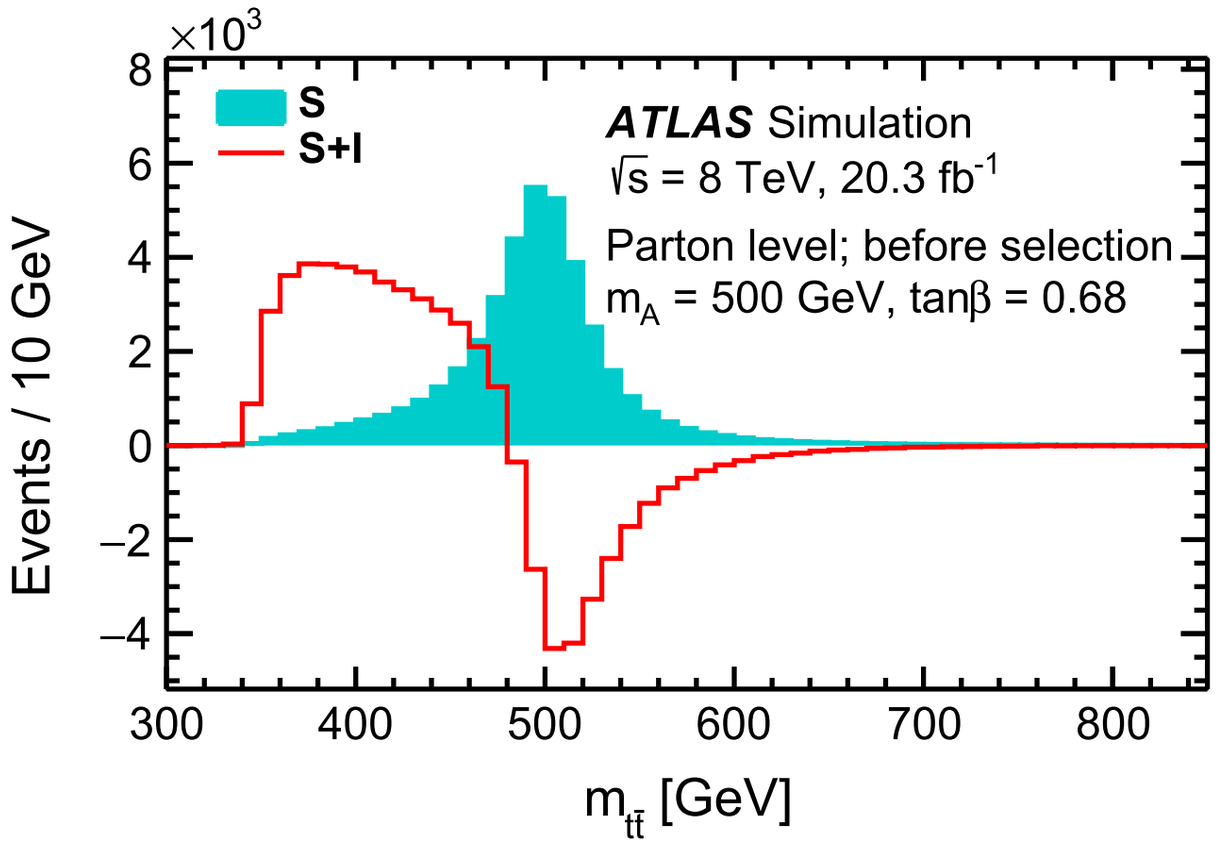
ATLAS Group Campus Zeuthen
priscilla.pani@desy.de

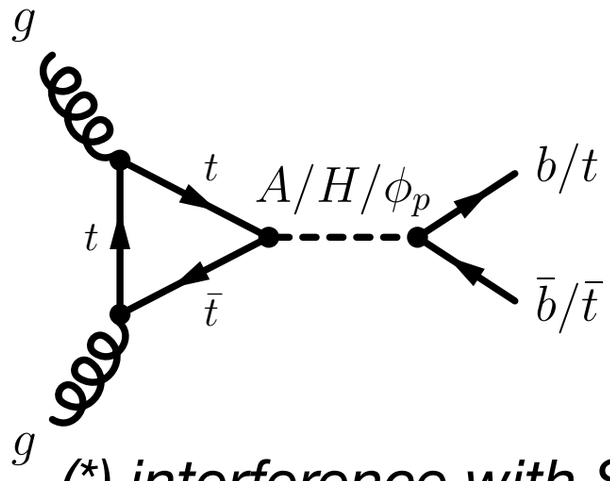
https://atlas.desy.de/external_grants/priscilla_pani_yig/

Backup

A special case …



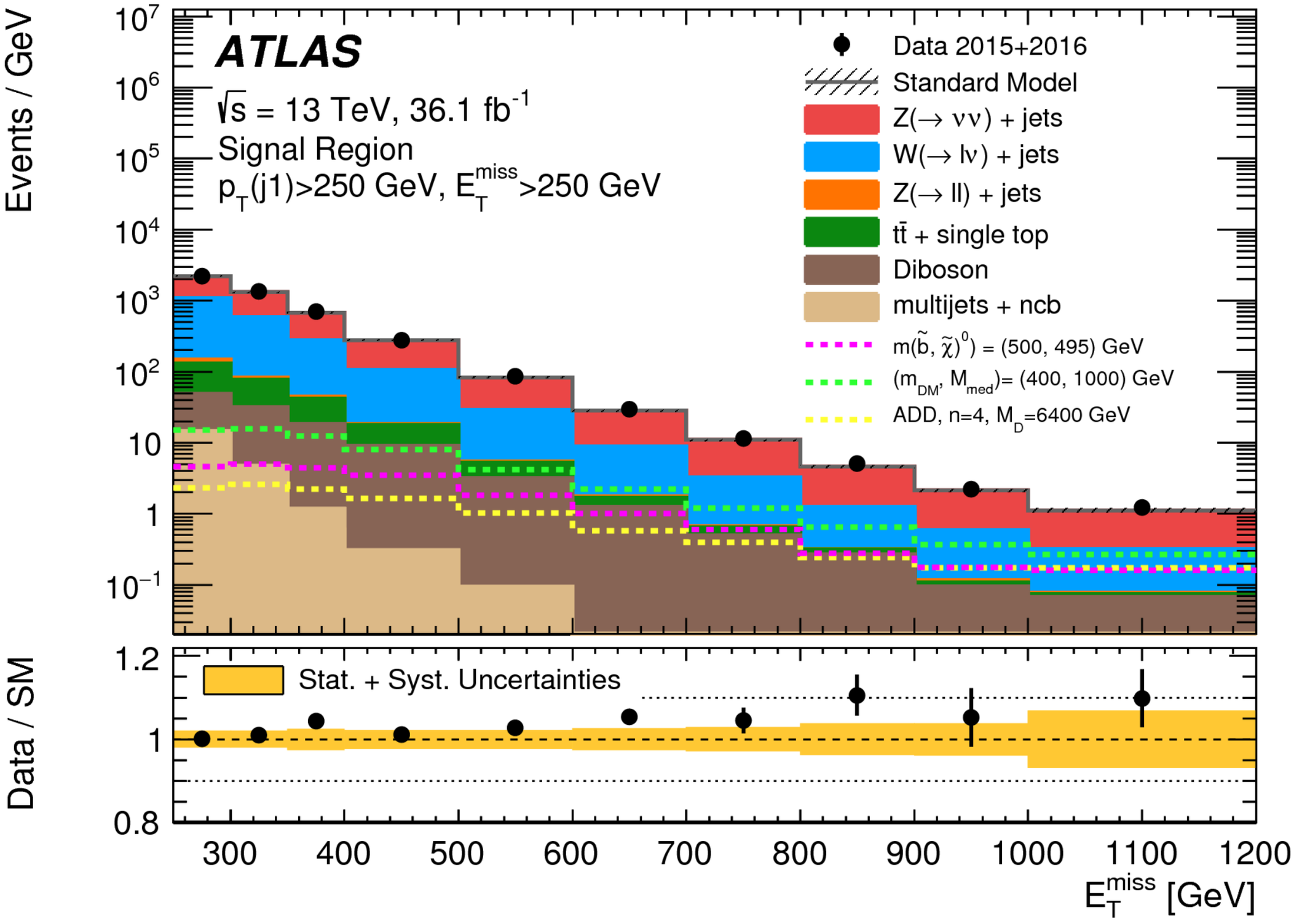




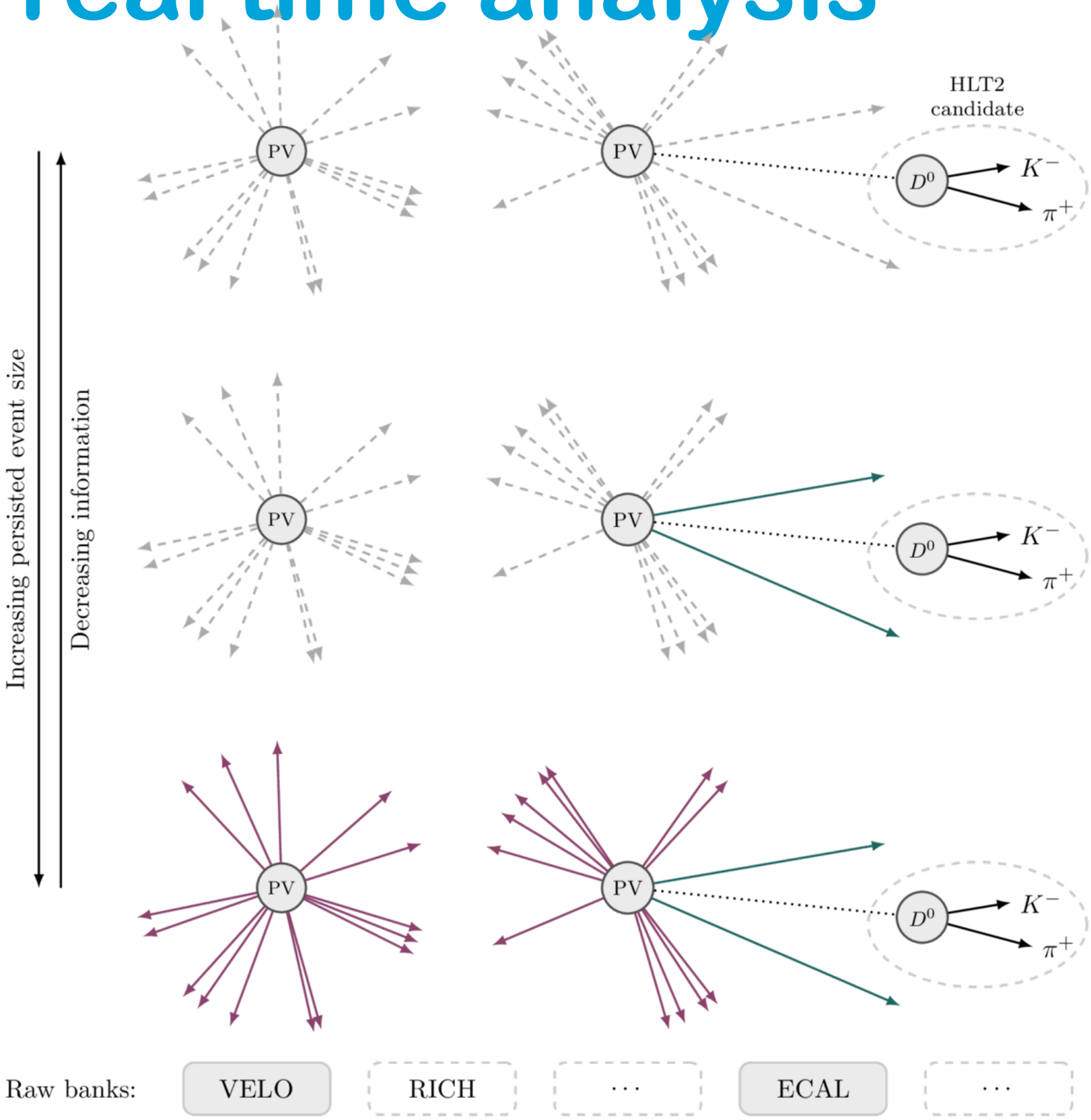
arXiv:1707.06025

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

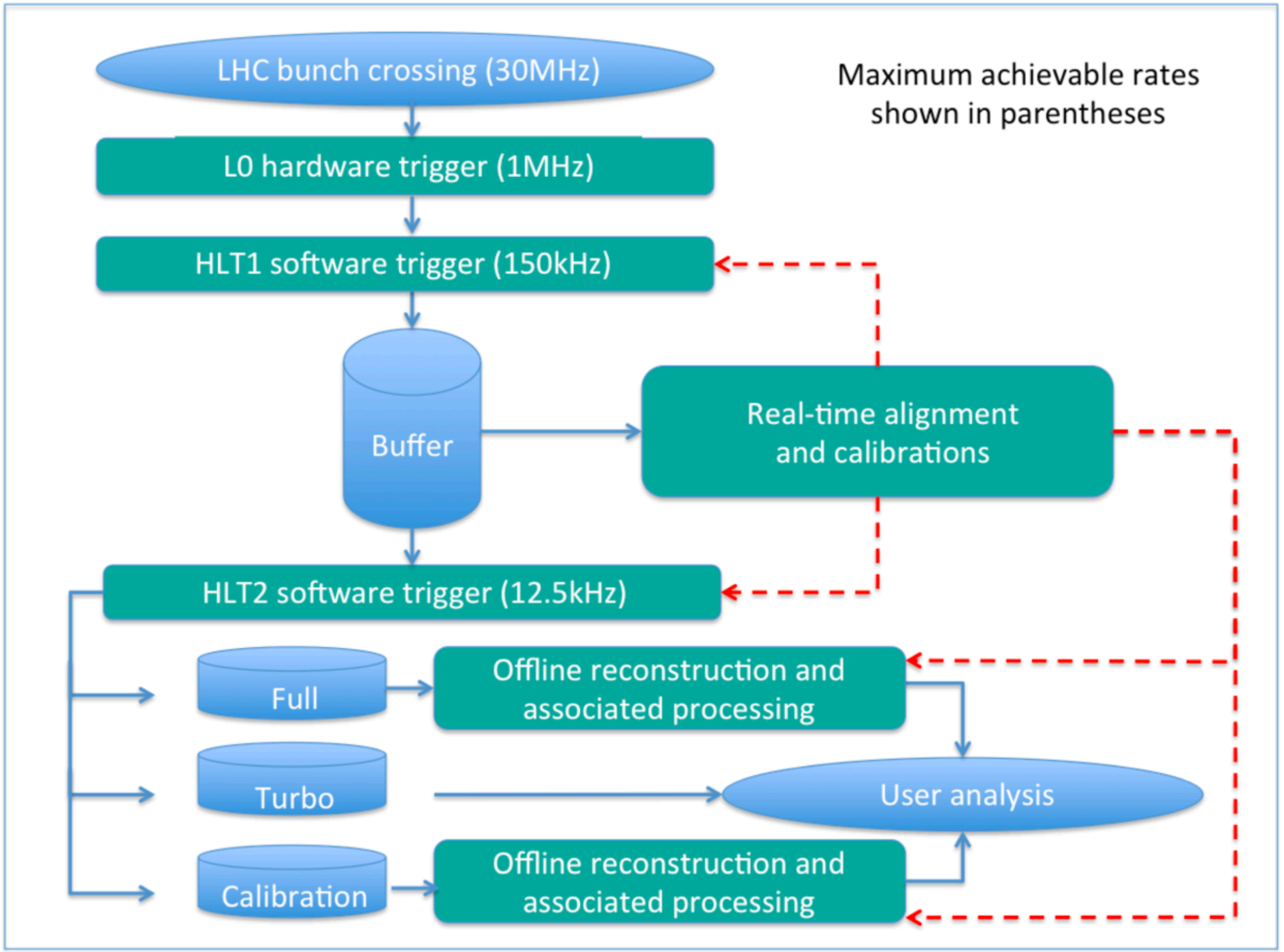
mono-jet SR


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]

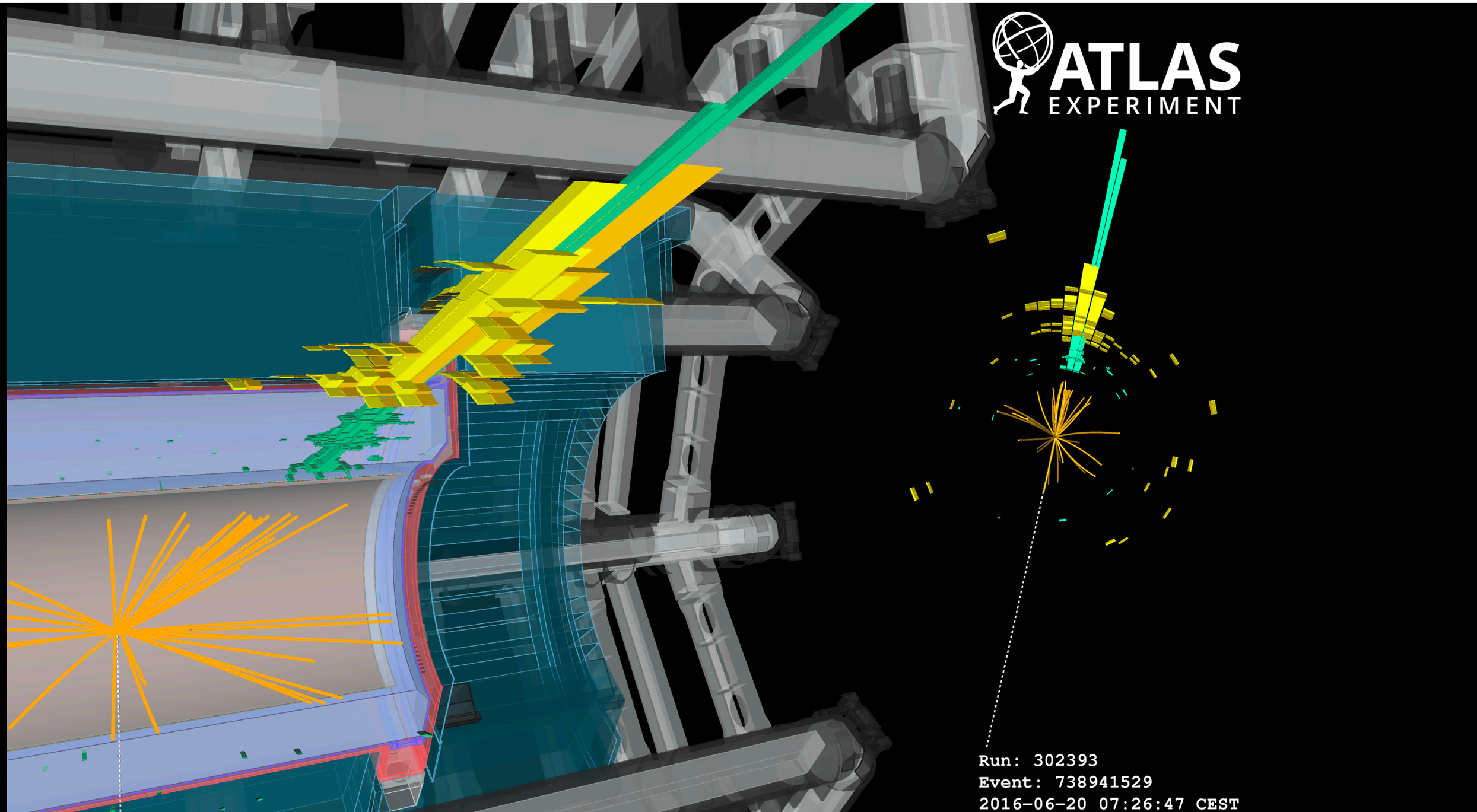
LHC real time analysis



LHCb real time model



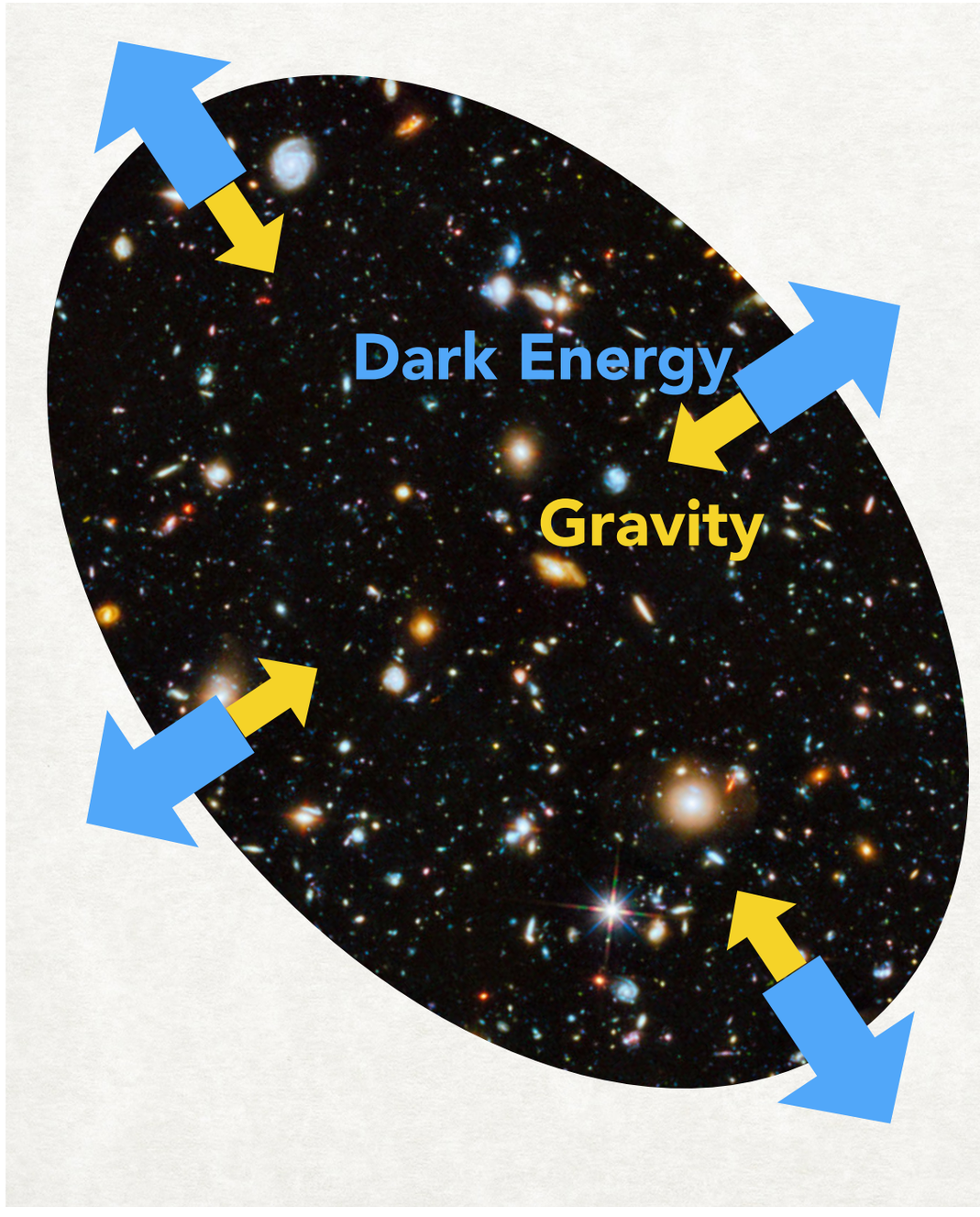
Bonus: Dark Energy



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**

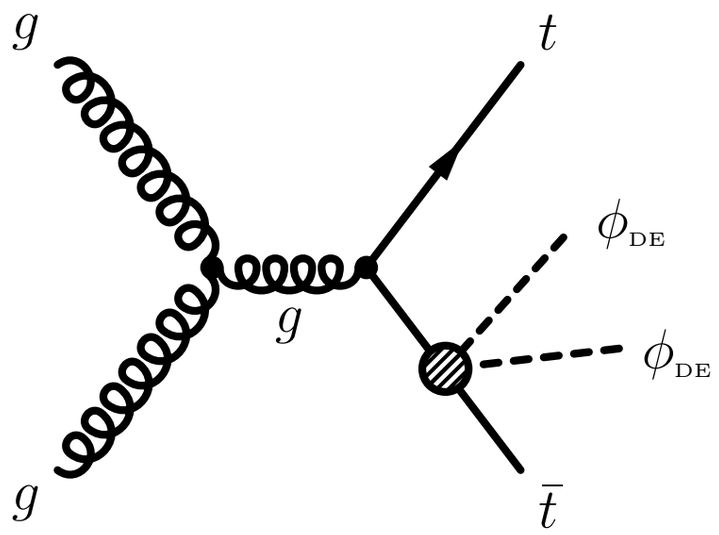


Horndeski EFT model

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

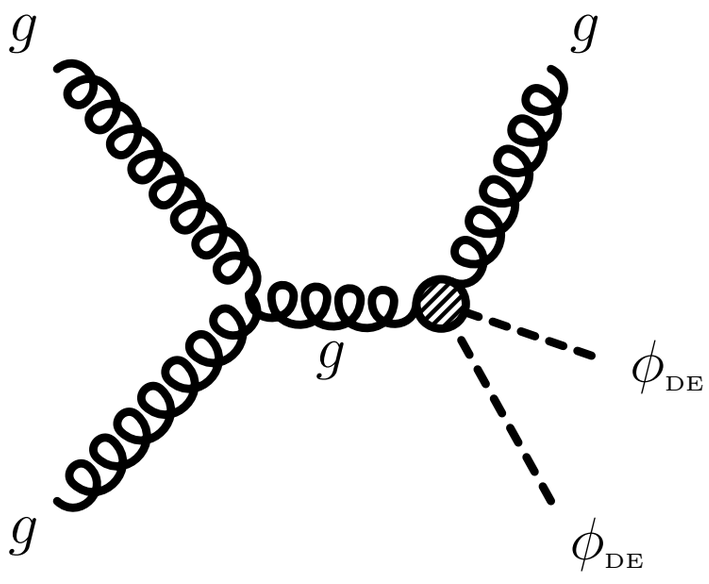
1 scalar field $\phi_{\rm DE}$ coupled to gravity

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



➡ tops + E_T^{miss}

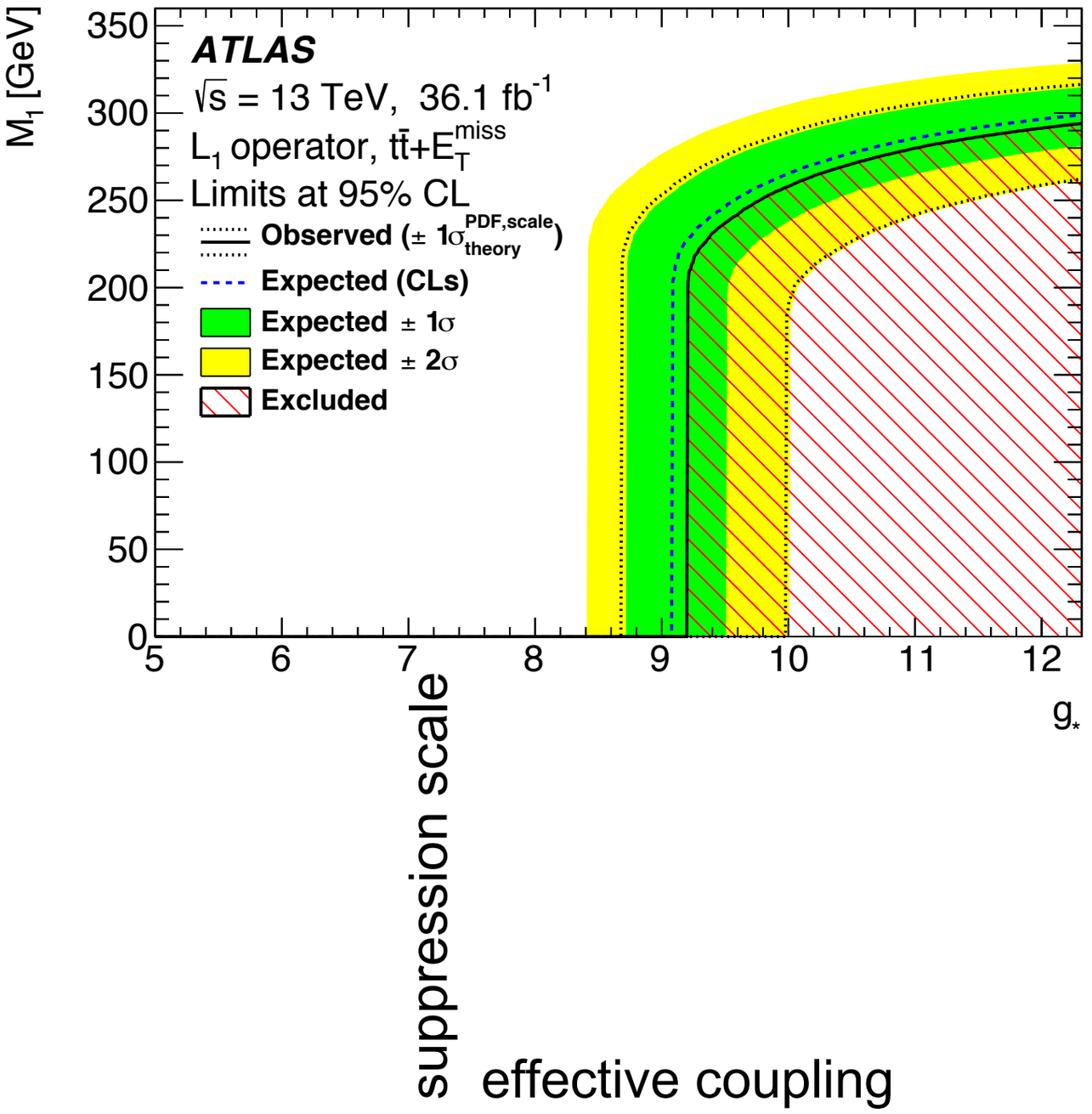
$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M_2^4} T^{\mu\nu},$$



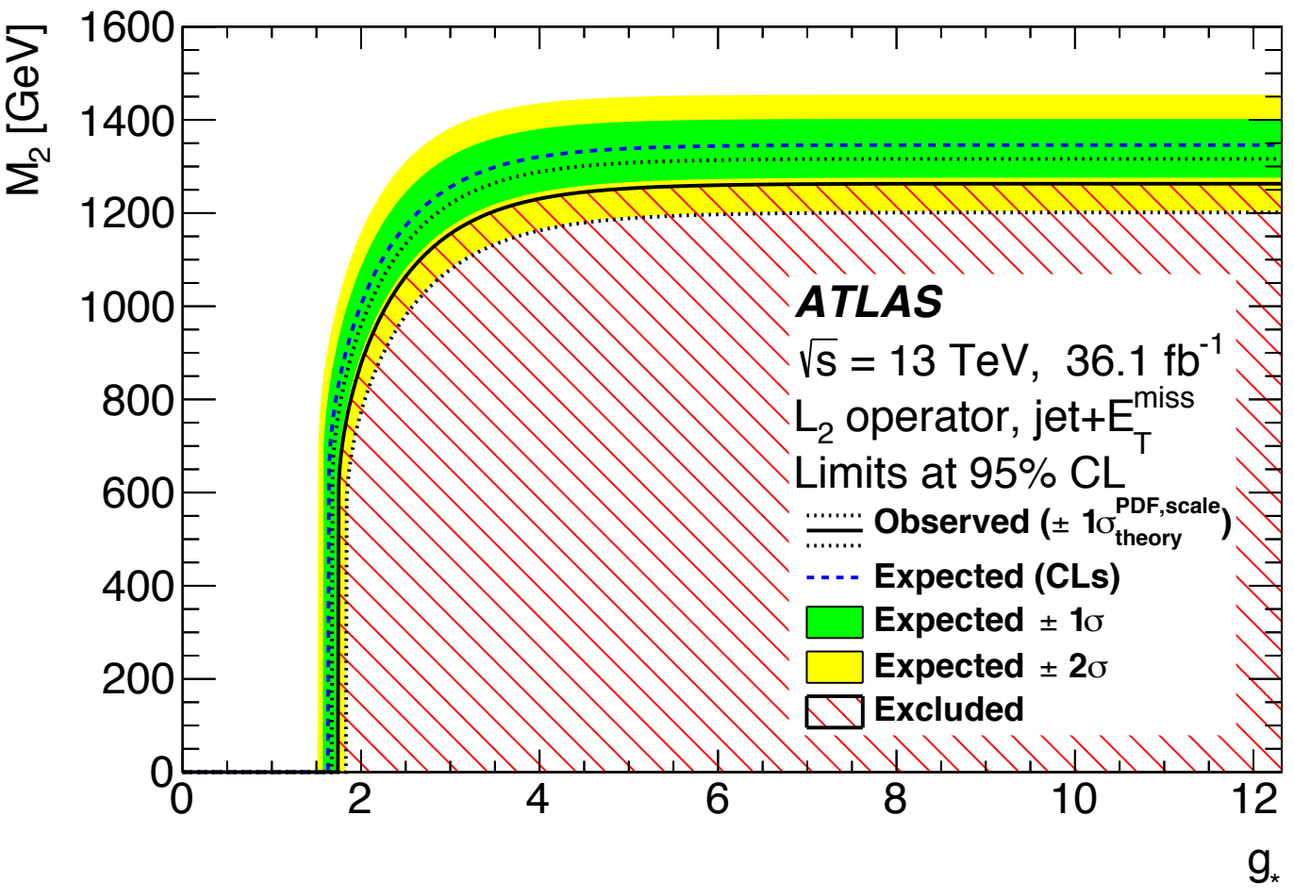
➡ jet + E_T^{miss}

Results

tops + E_T^{miss}

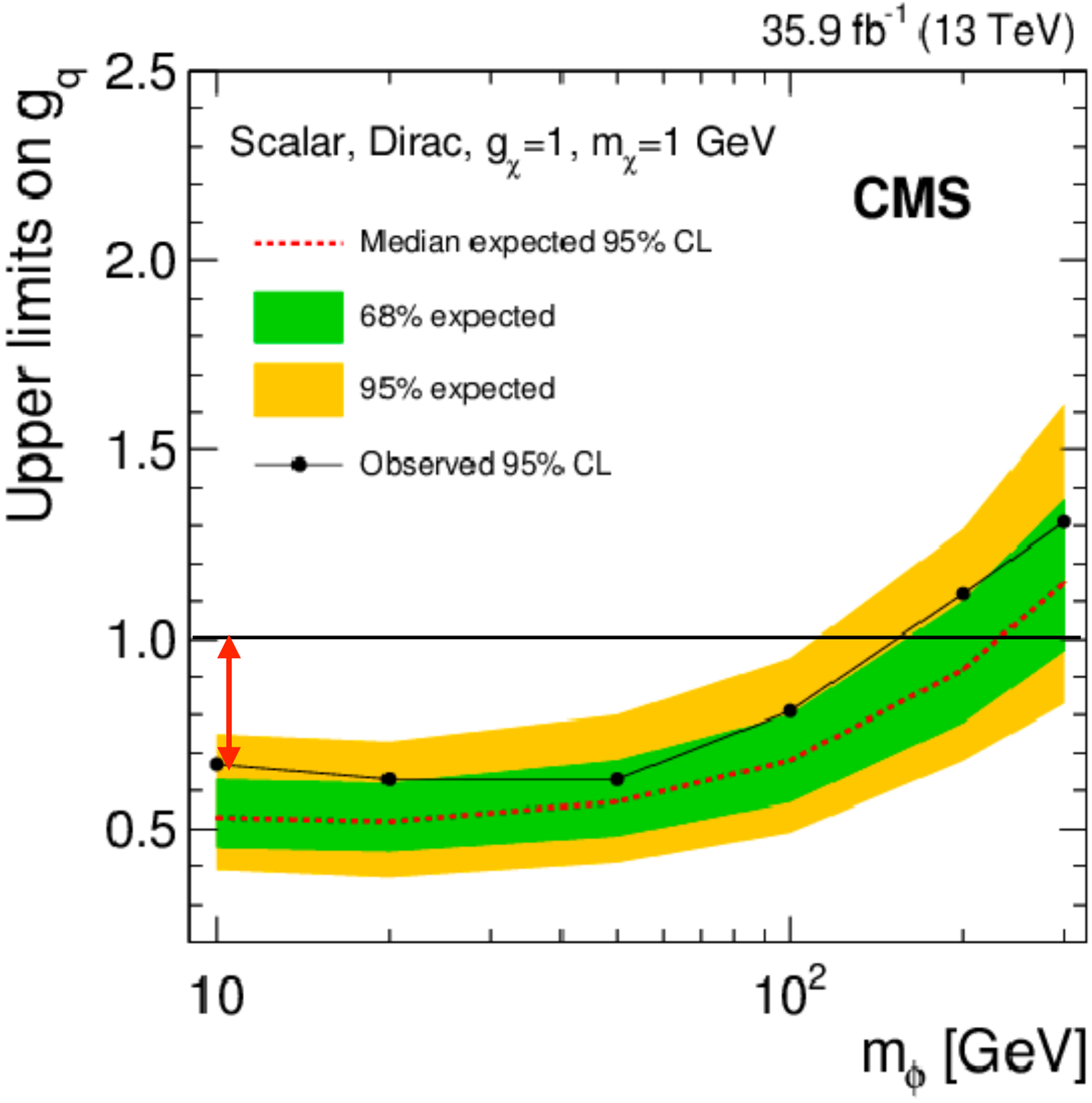


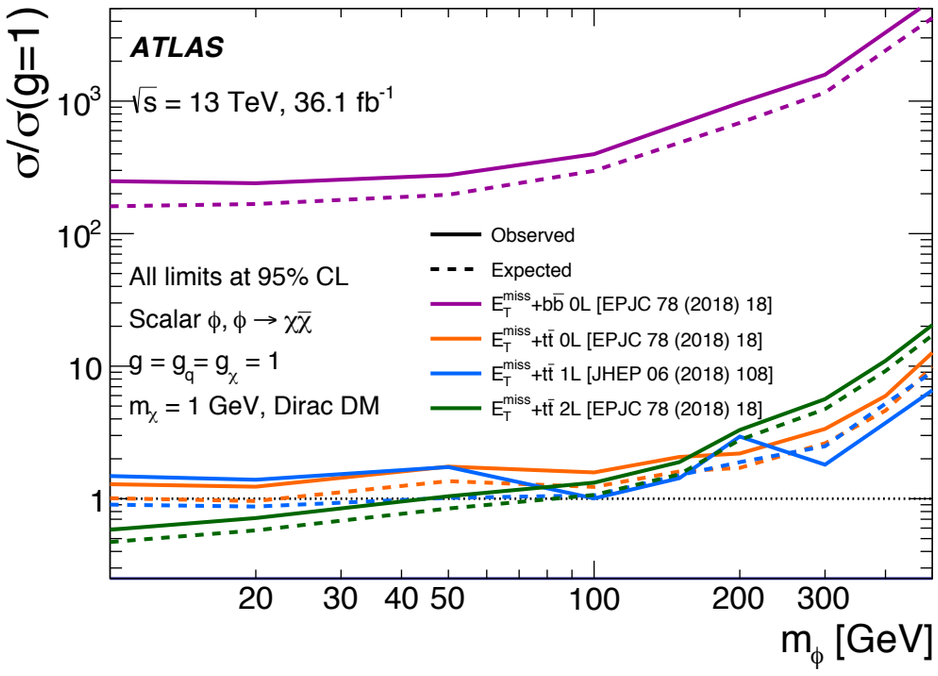
jet + E_T^{miss}



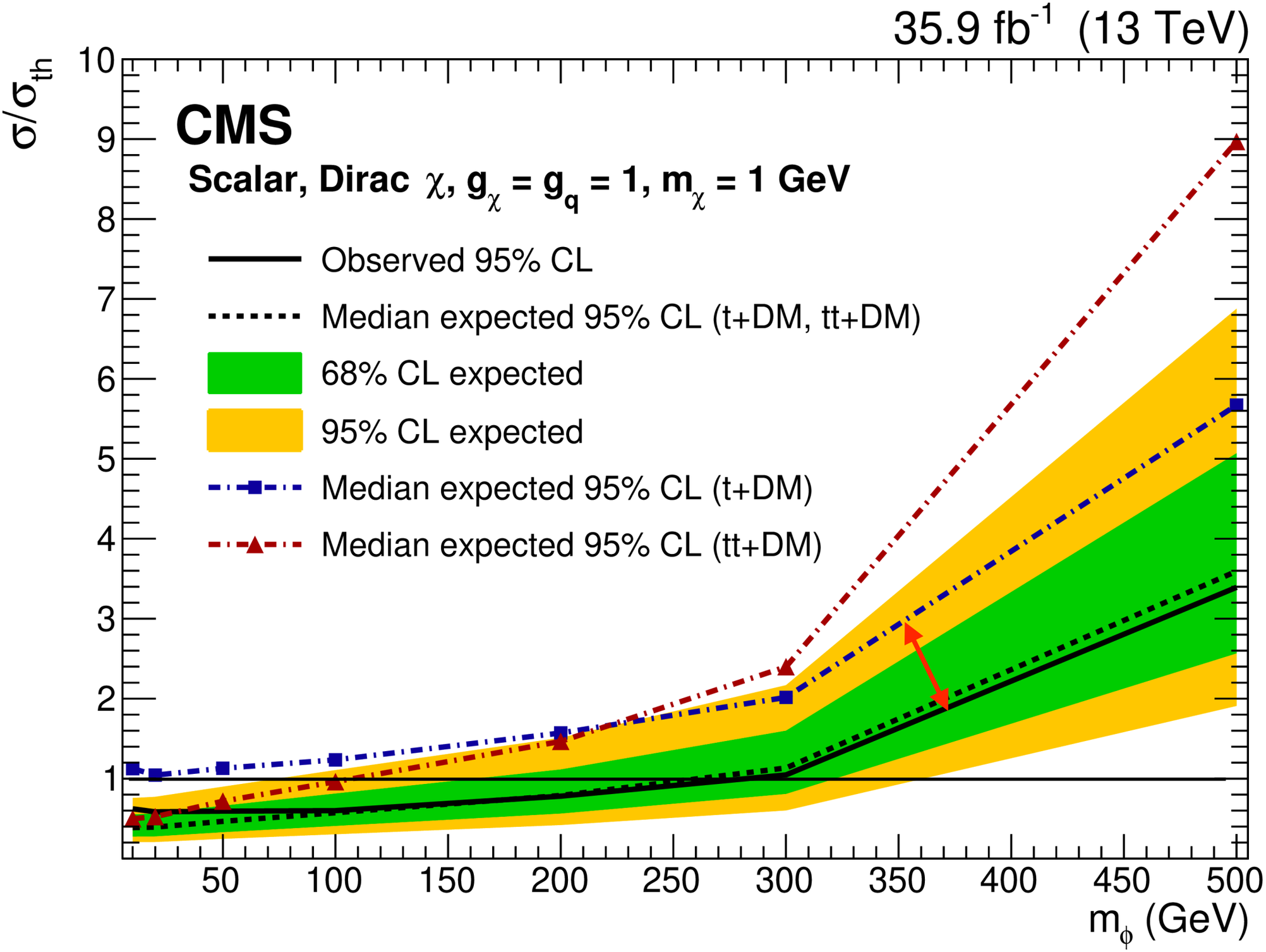
CMS grand combination

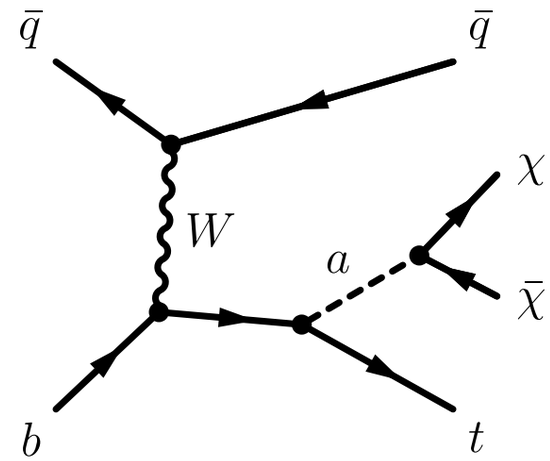
arXiv:1807.06522

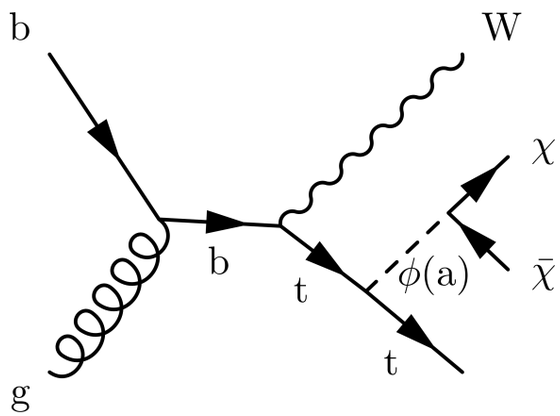




Spin-0 with single top

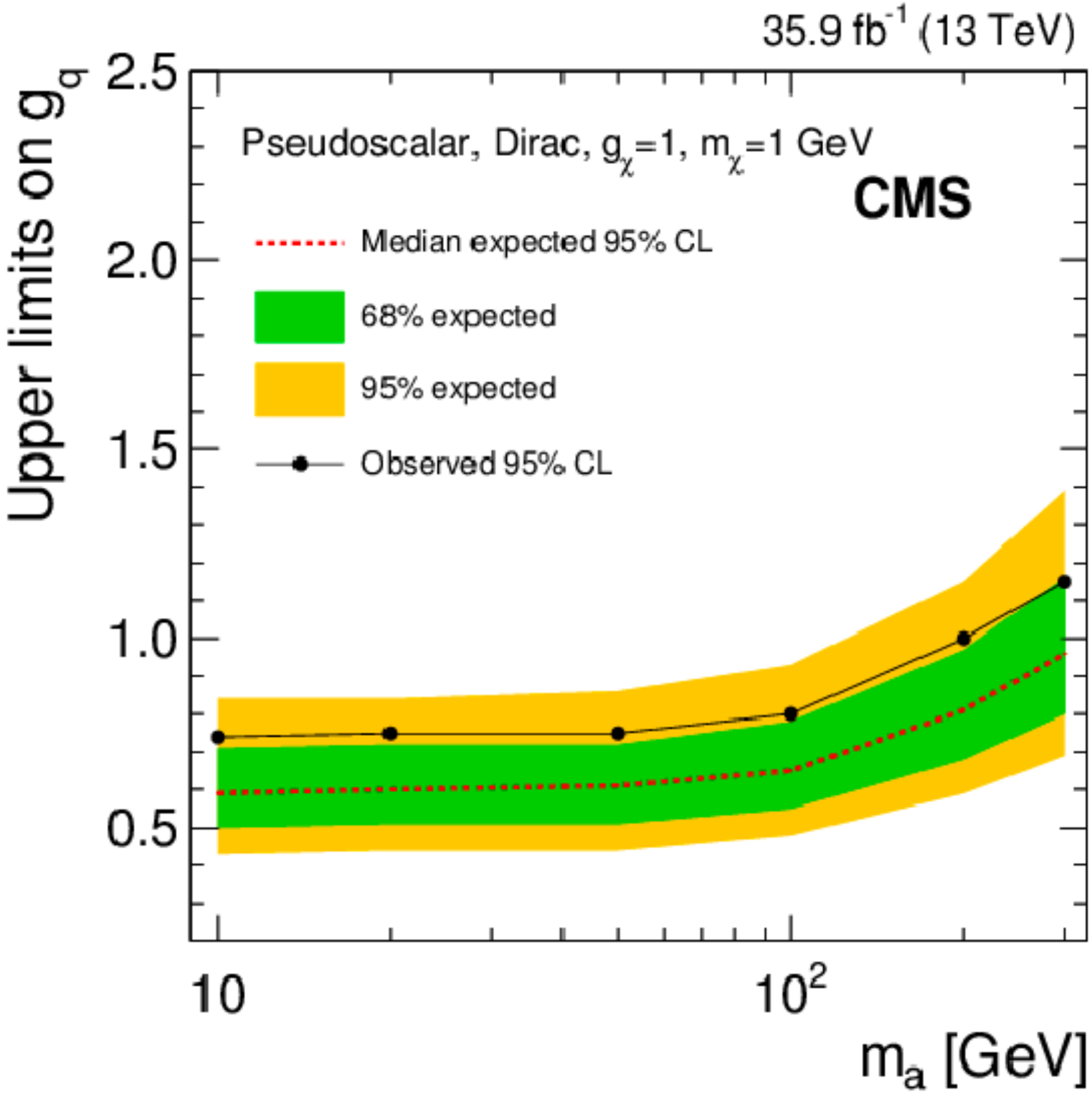






CMS combination Pseudo

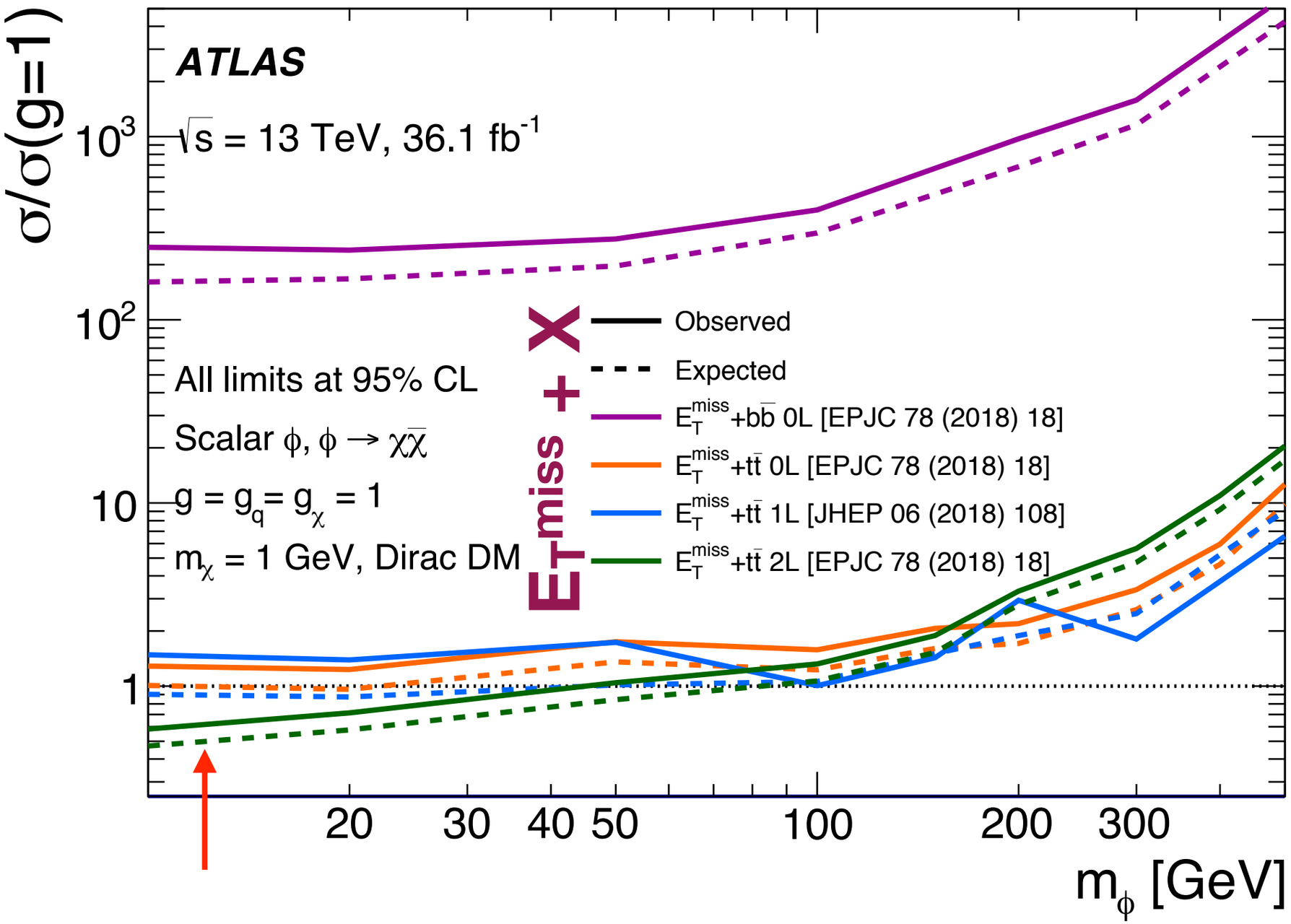
arXiv:1807.06522

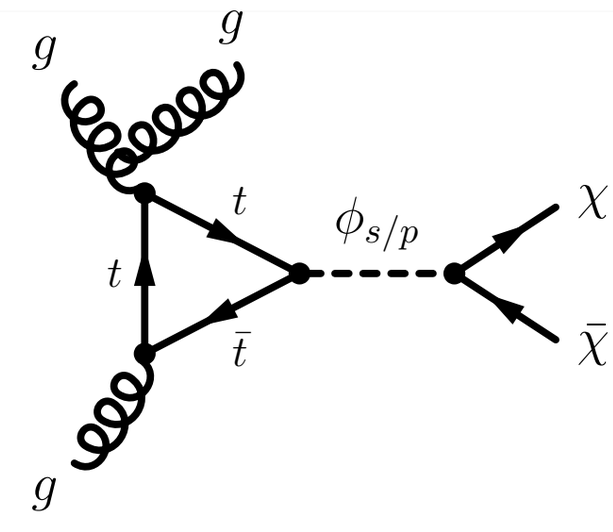


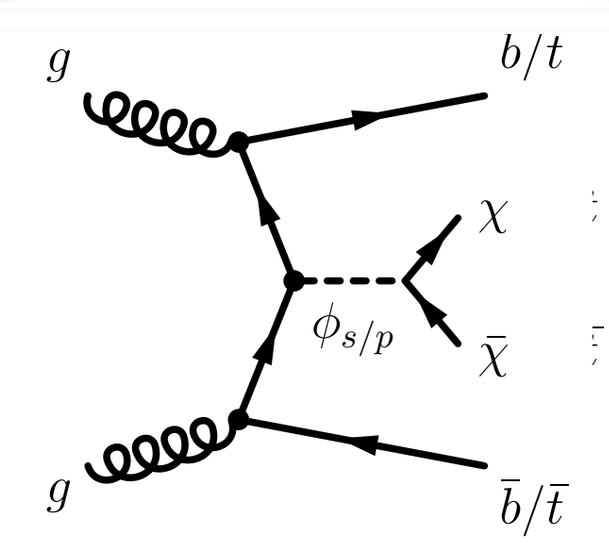
Spin-0 mediators

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

Needed to easily fulfil Flavour Constraints (MFV)



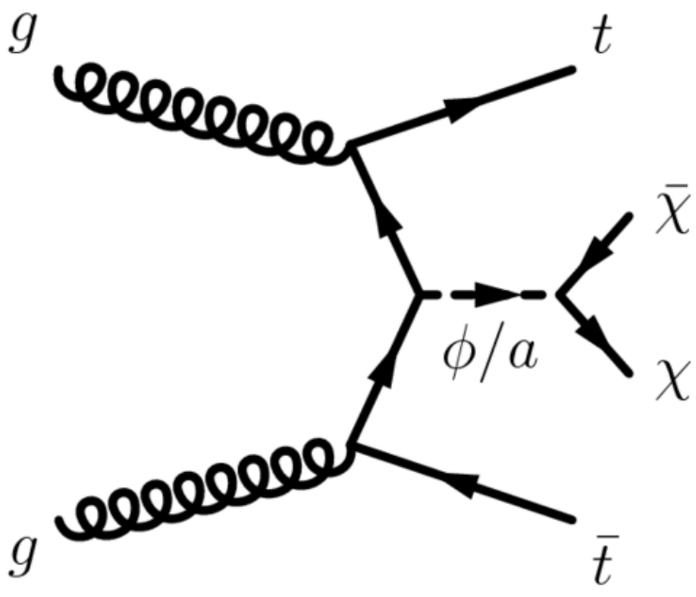


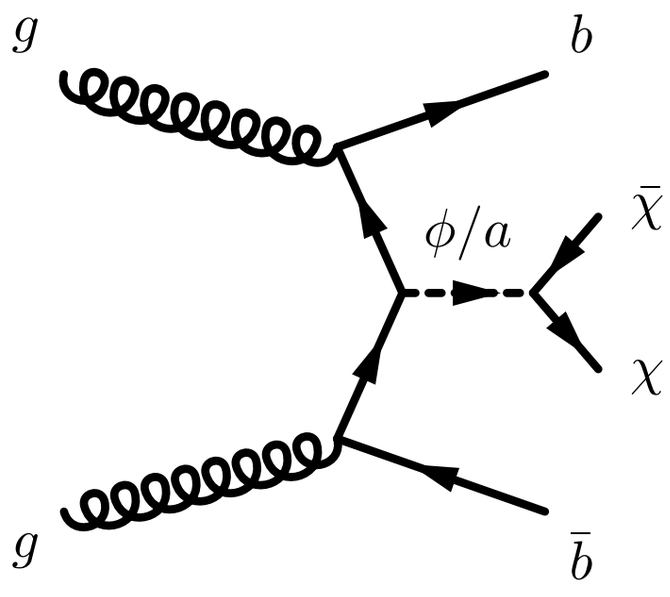


Exploring the dark sector with heavy quarks

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

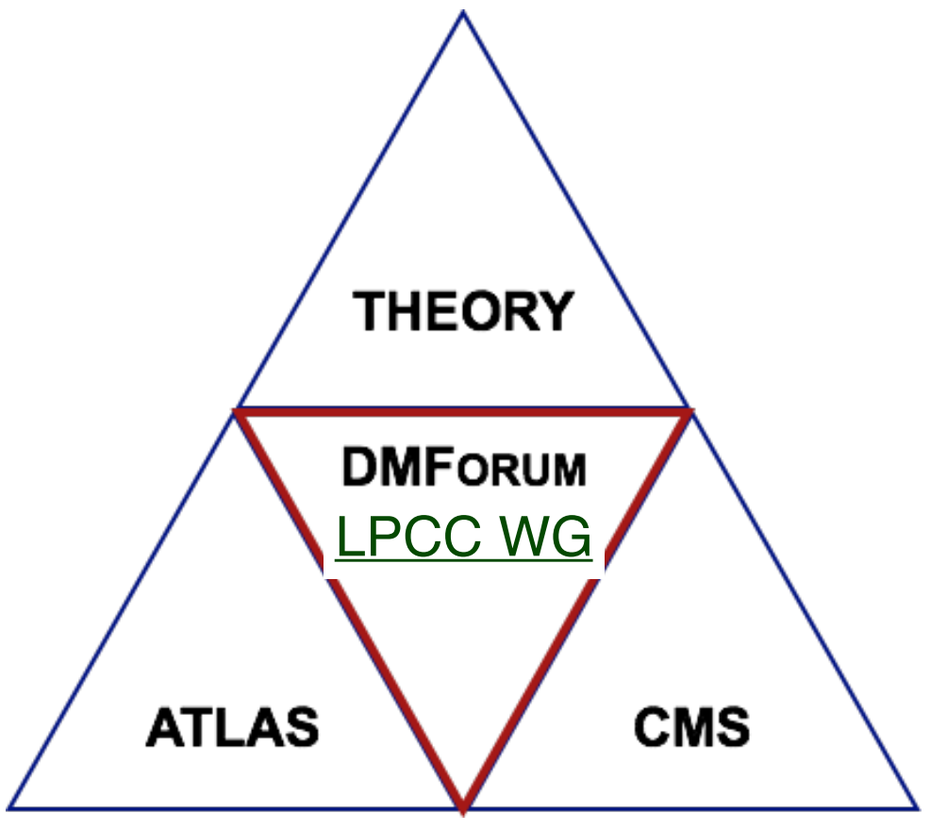
→ Enhanced cross-section for tops and bottoms





- ★ Scalar mediator(s) in Lagrangian violate flavour precision measurements
- ★ Simple Solution: Yukawa-type couplings (as in SM)
- ★ Additional parameter (tanβ) regulates b-quarks enhancement
- ★ b-quark enhanced couplings motivated by the Galactic Center Excess interpretation

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

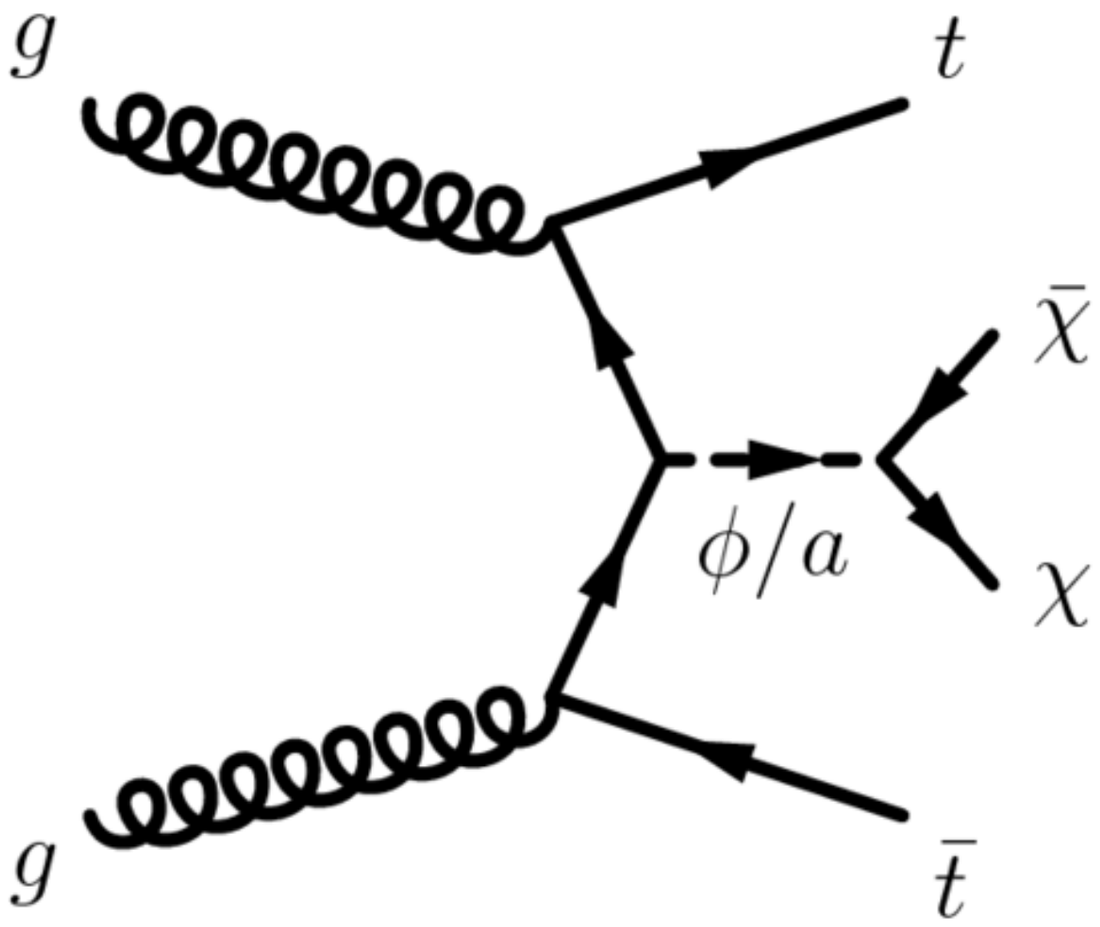
★Simplified Models are the Run II paradigm:

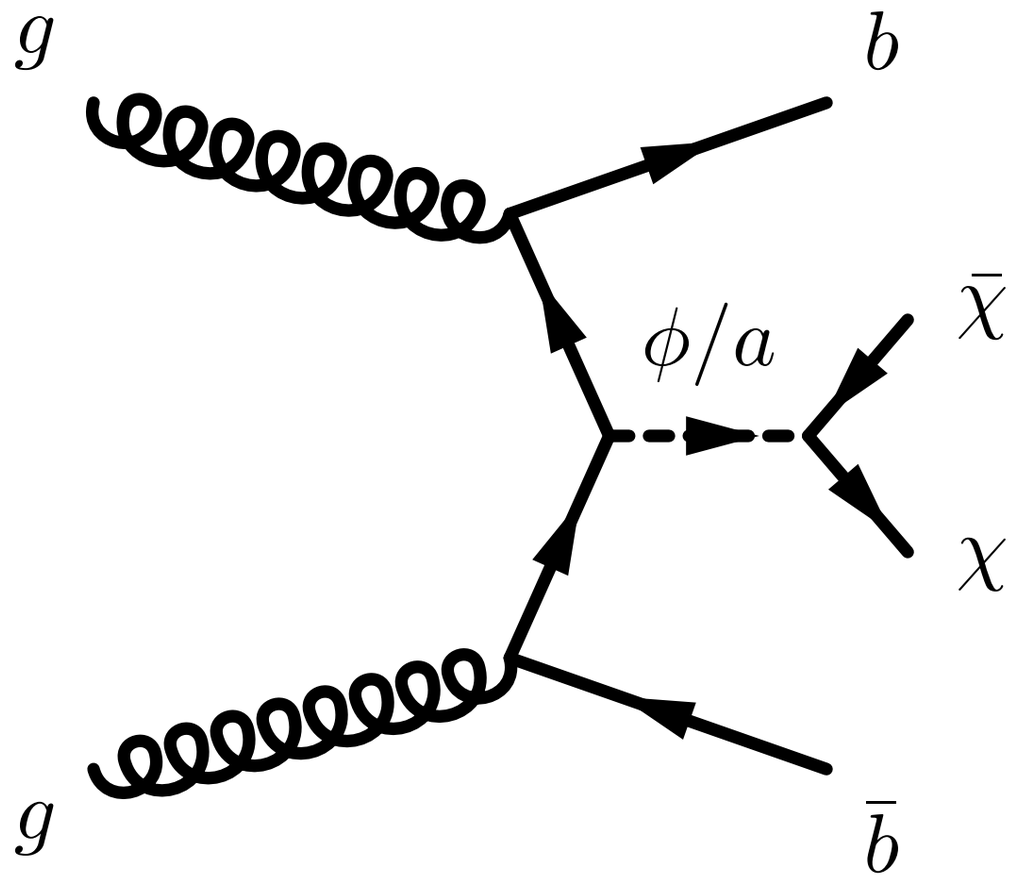
- theoretically self consistent
- minimal and motivated assumptions
- good phenomenology proxies

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

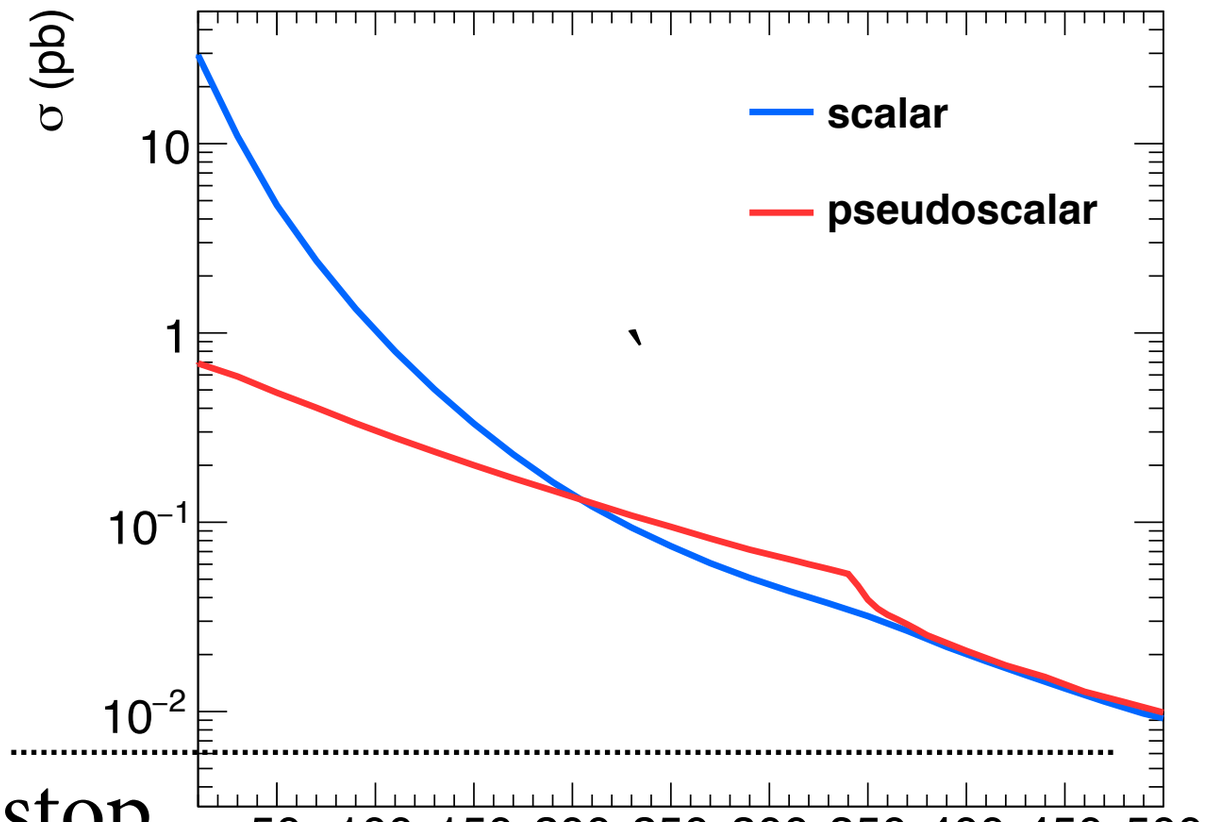




arXiv:1710.11412 and ATLAS-CONF-2017-037

Understanding the signal

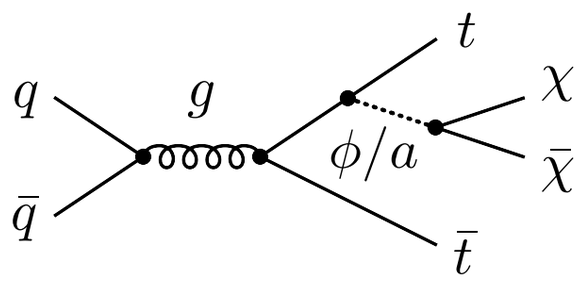
830 pb ..... σ(ttbar)



1 TeV stop pair prod

[Haisch,PP,Polesello 2017]

Understanding the signal

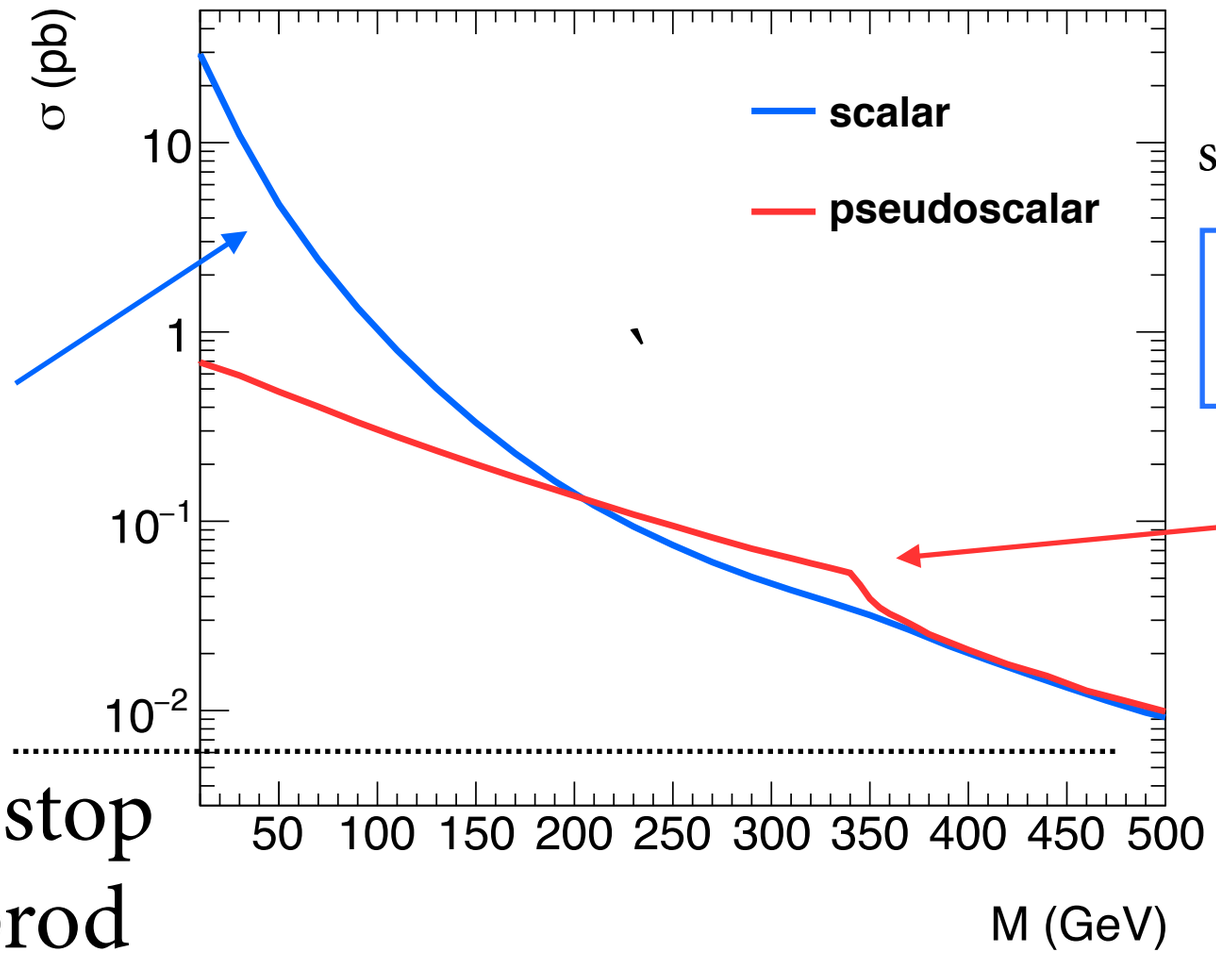


$f_{t\to\phi}(x) \sim 1/x$

soft-enhancement term

830 pb

σ(ttbar)



1 TeV stop pair prod

spin and color-averaged ME

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

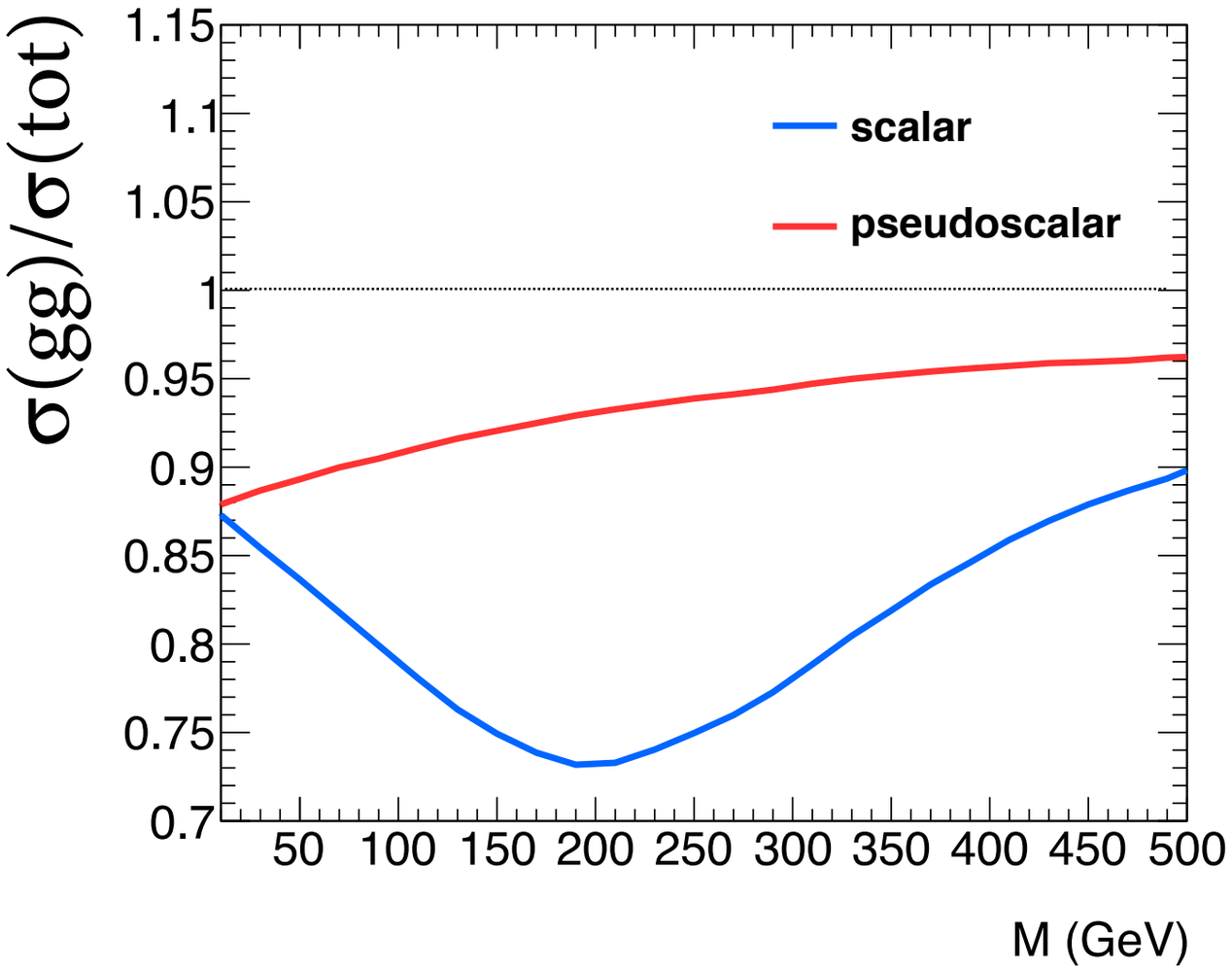
$$\beta = \sqrt{1 - 4m_t^2/s}$$

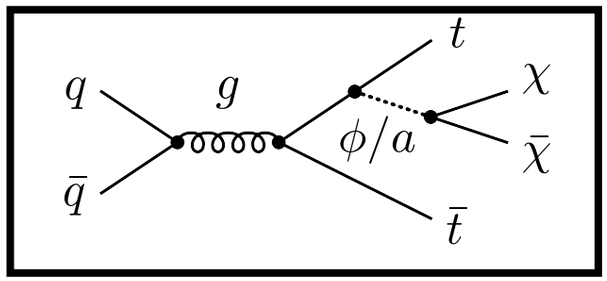
top-threshold suppression

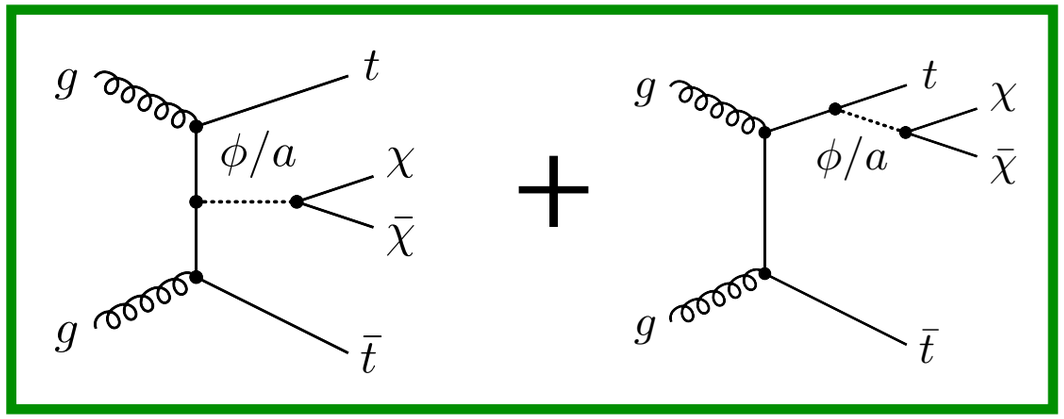
$\phi/a \to t\bar{t}$

[Haisch,PP,Polesello 2017]

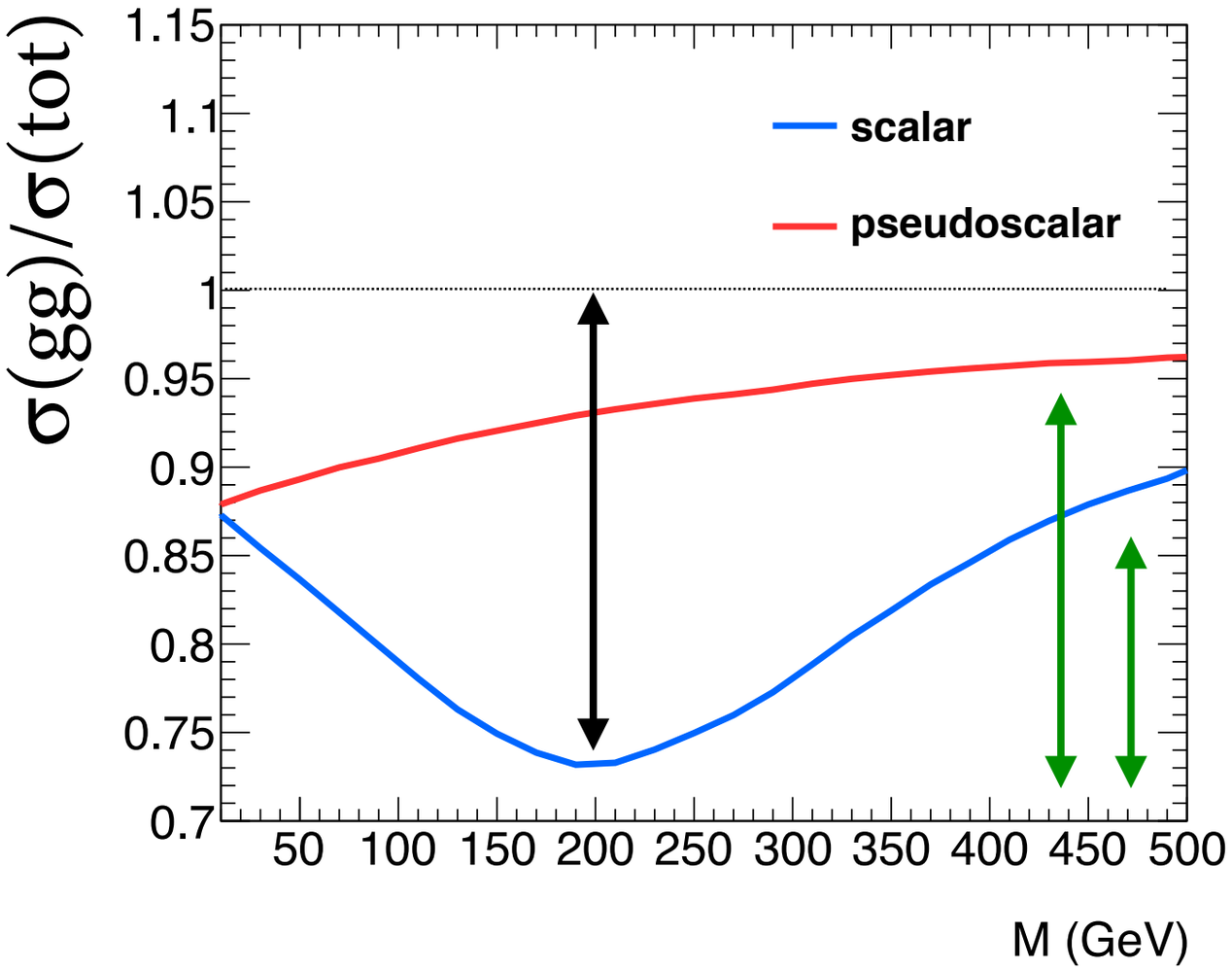
Understanding the signal

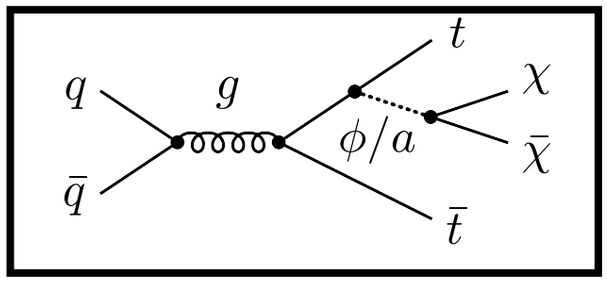


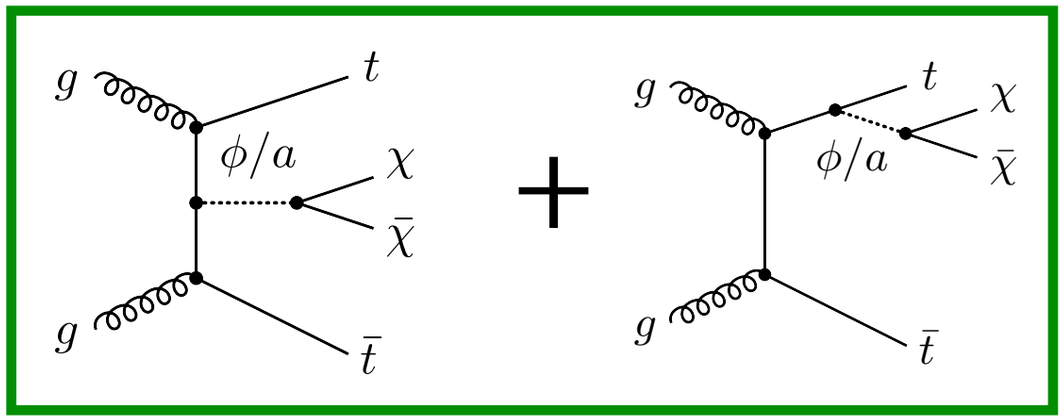


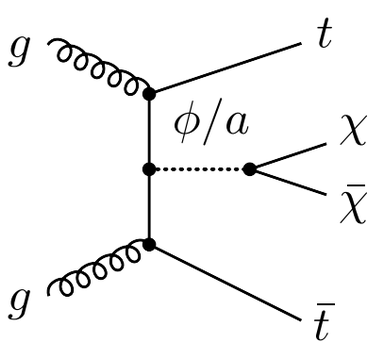


Understanding the signal

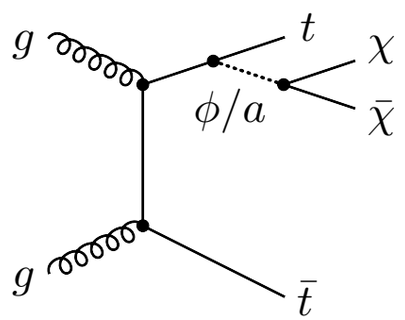








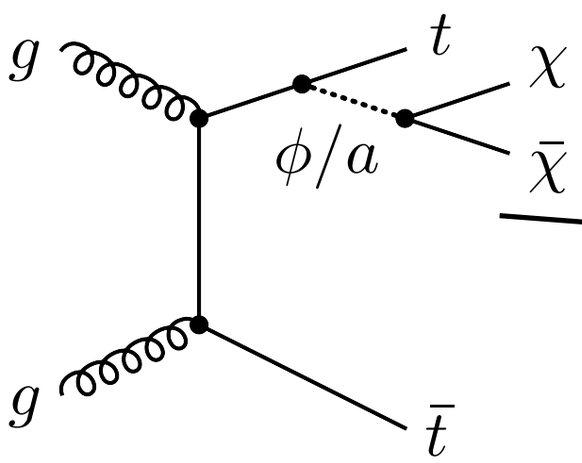
: dominant at high mass and low-mass a

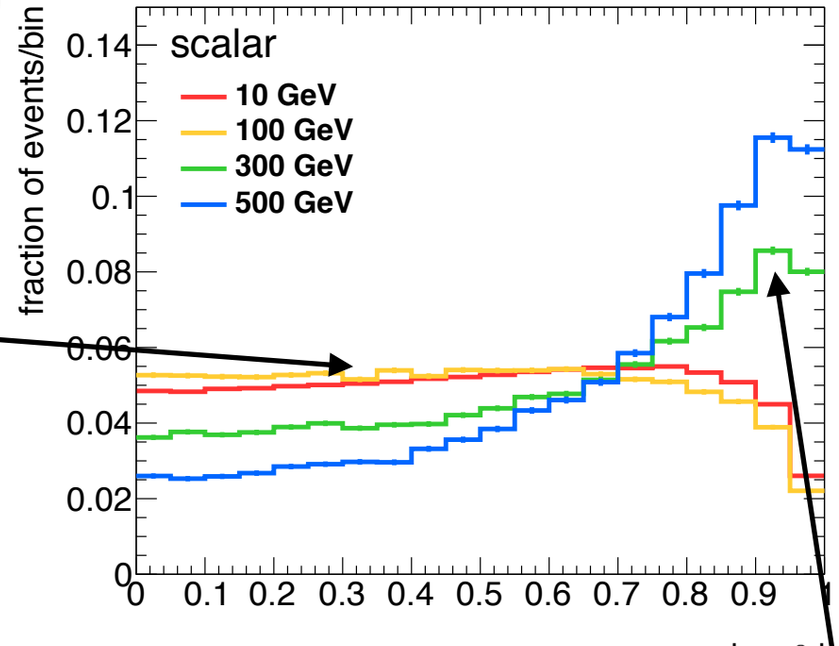


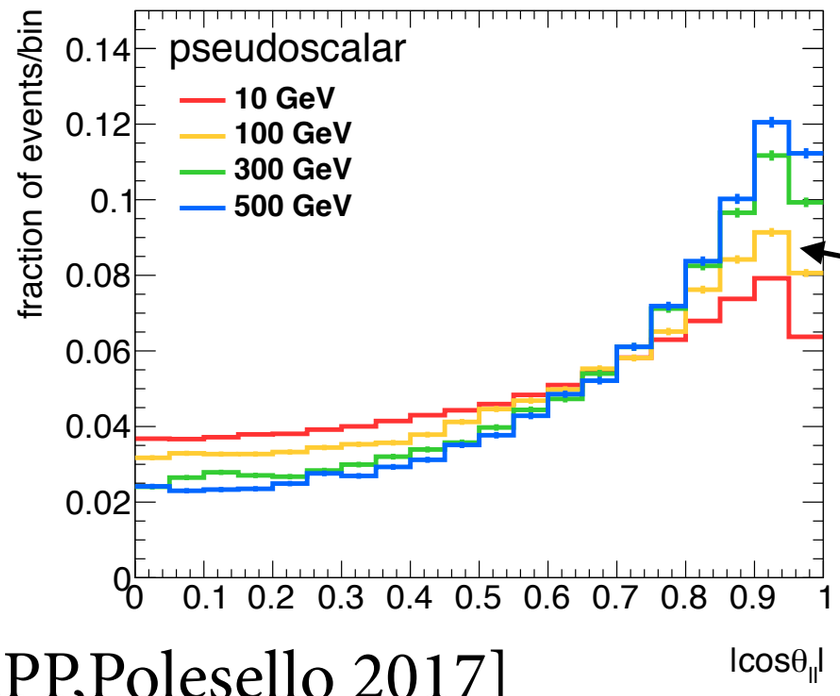
: dominant at low-mass φ

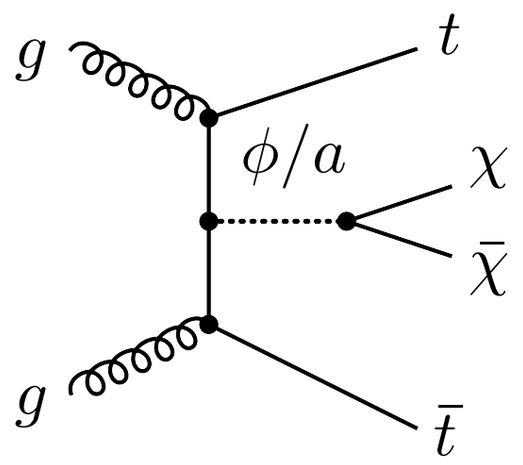
Future perspectives on the results

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



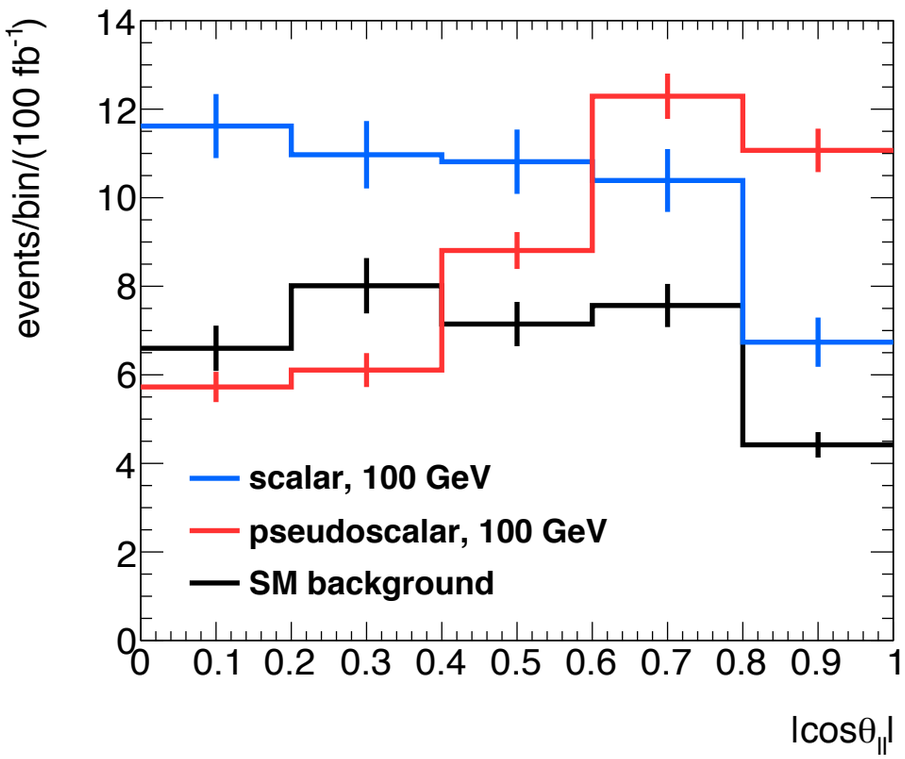






[Haisch,PP,Polesello 2017]

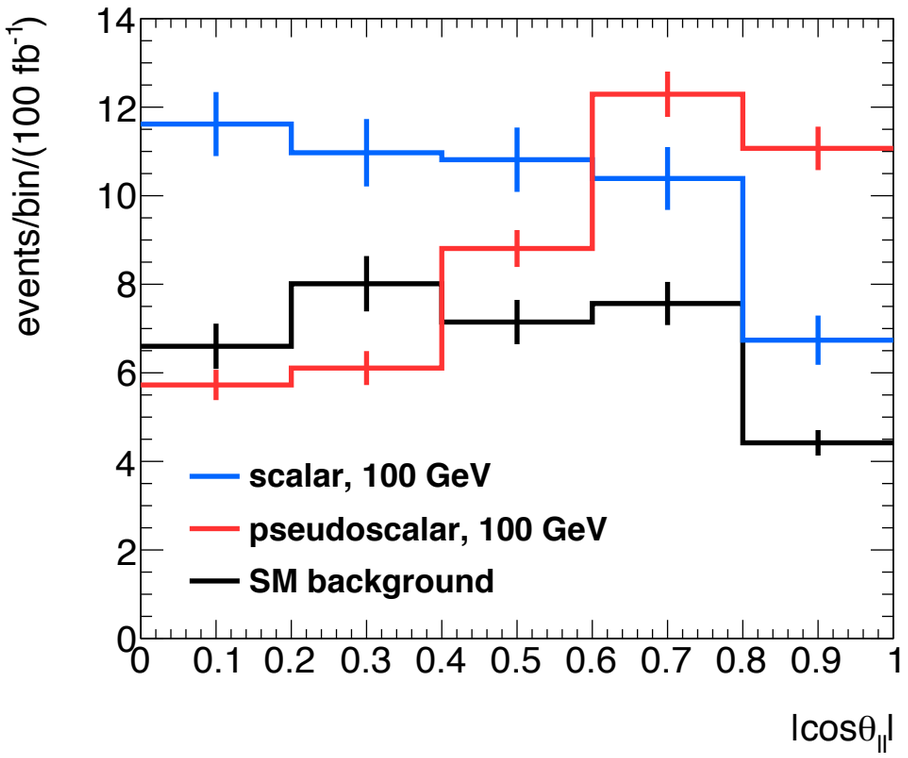
Run 3 and HL-LHC outlook



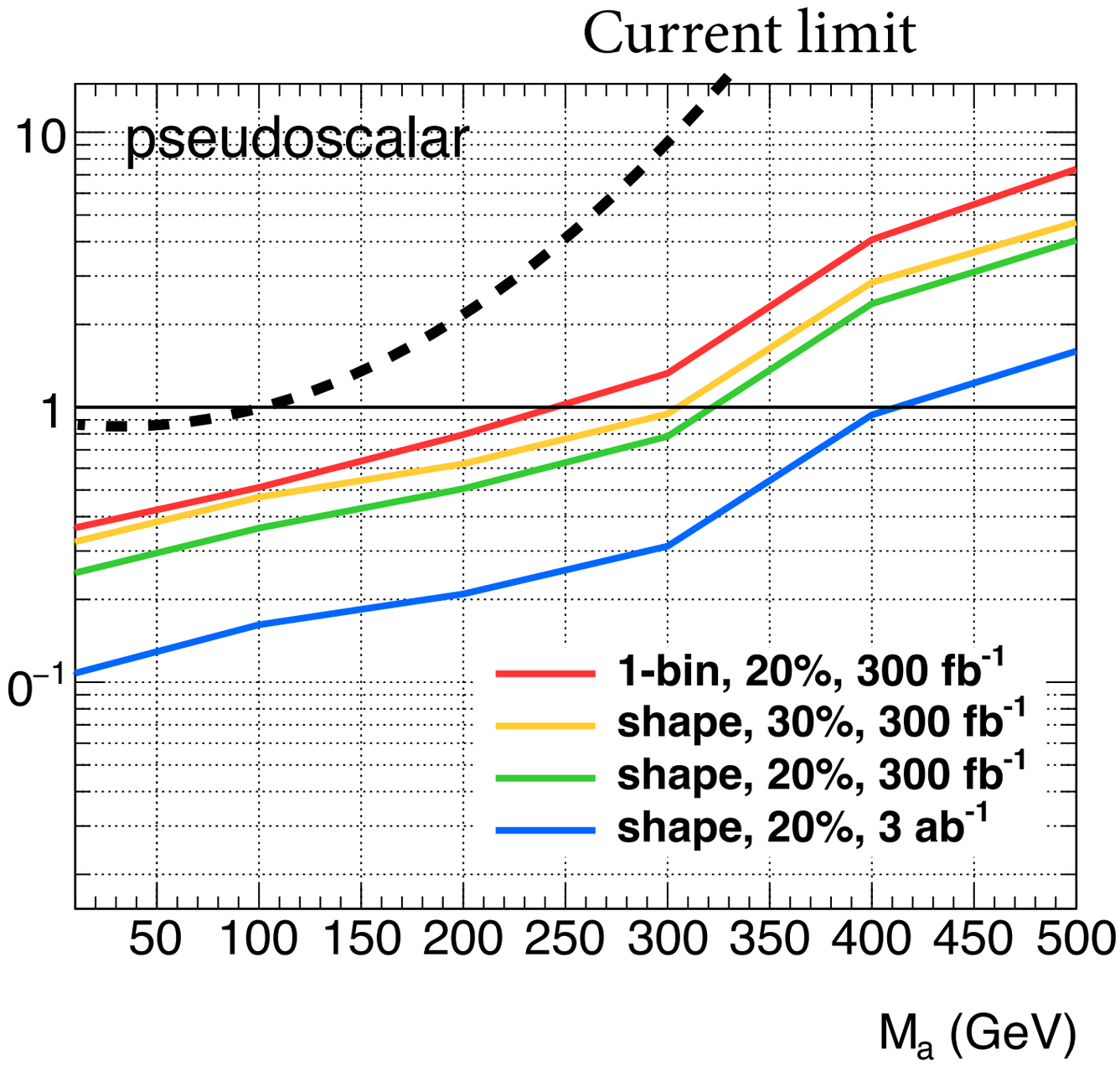
Multi-bin fit

[Haisch,PP,Polesello 2017]

Run 3 and HL-LHC outlook

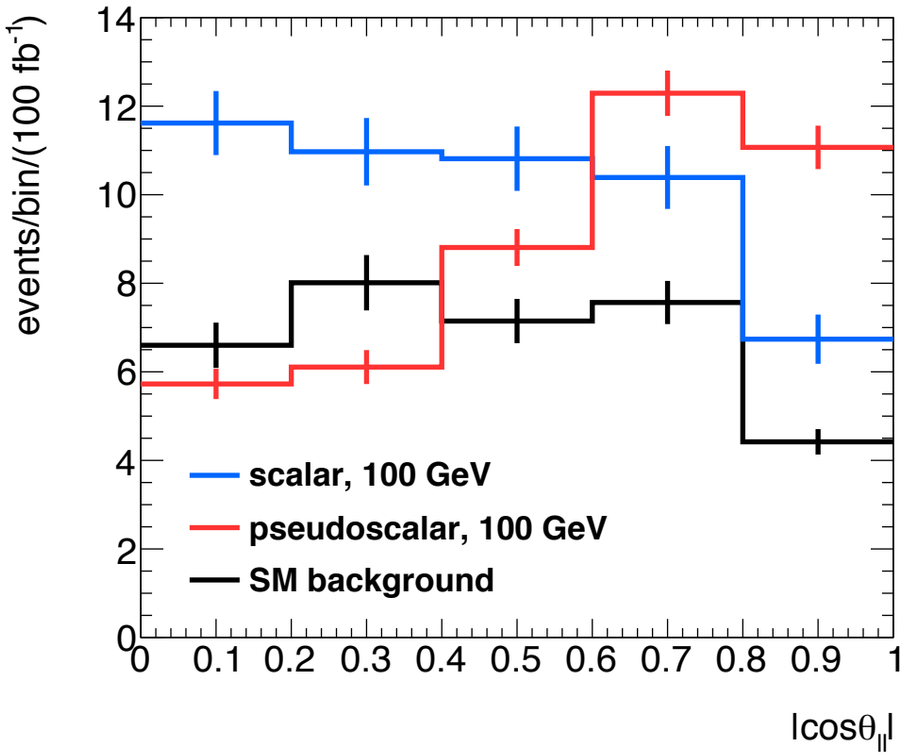


Multi-bin fit



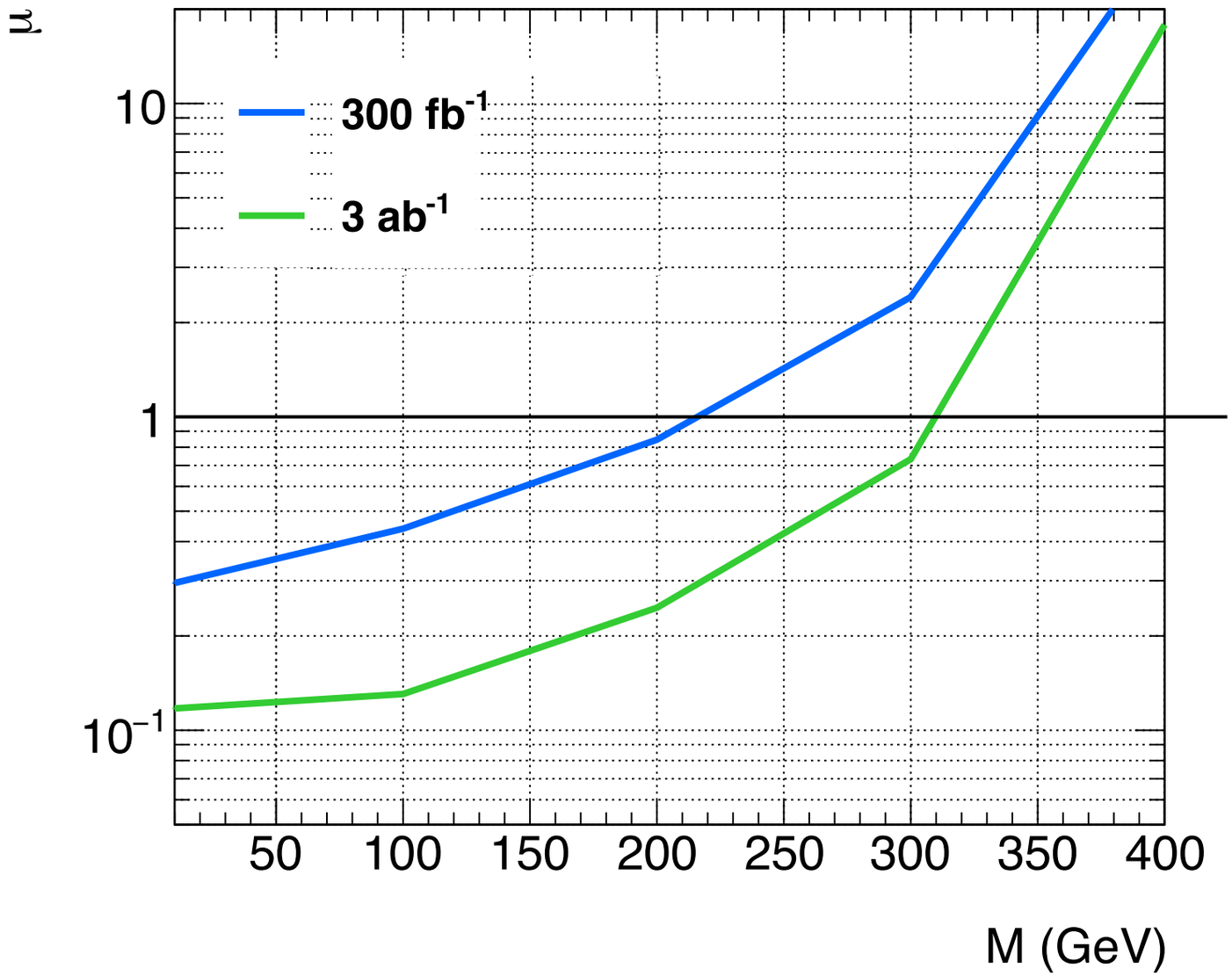
[Haisch,PP,Polesello 2017]

Run 3 and HL-LHC outlook



Multi-bin fit

Exclude scalar hypothesis in favour of the pseudo scalar one



[Haisch,PP,Polesello 2017]