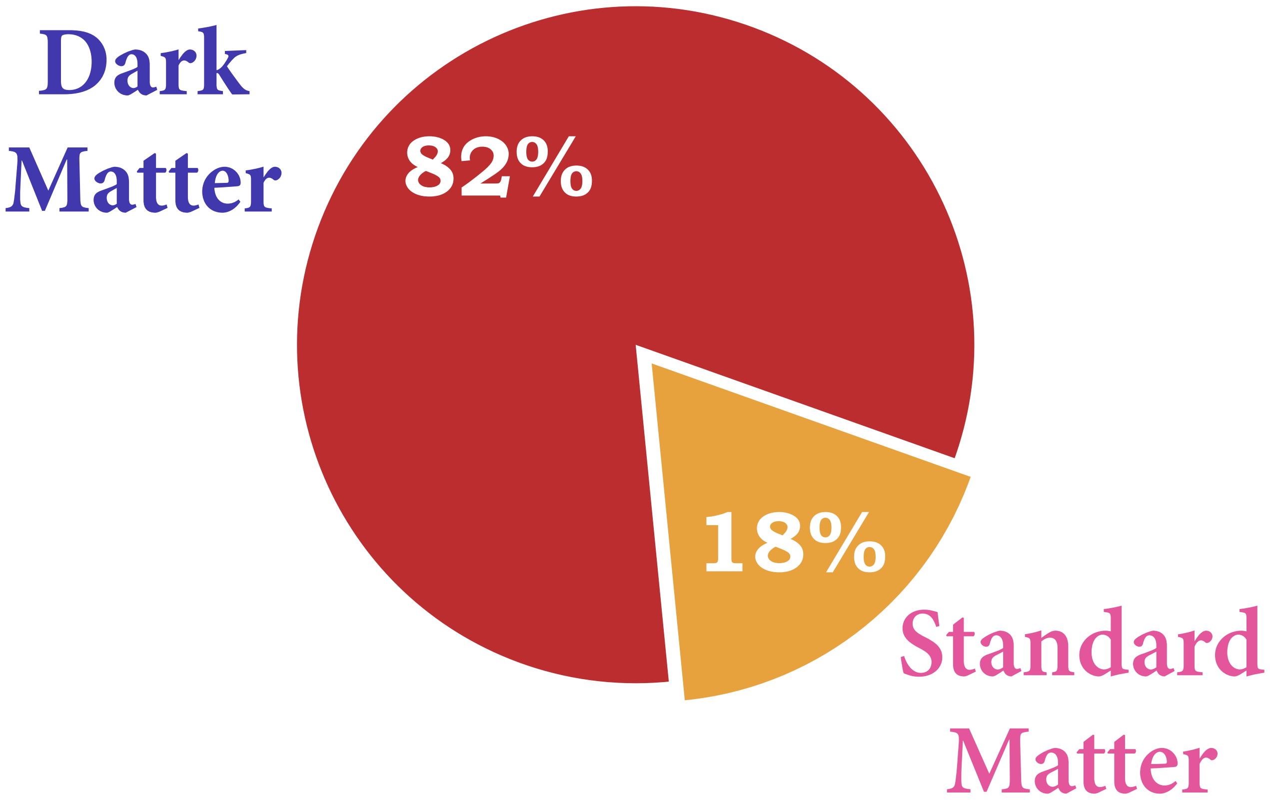
On top of Dark Matter

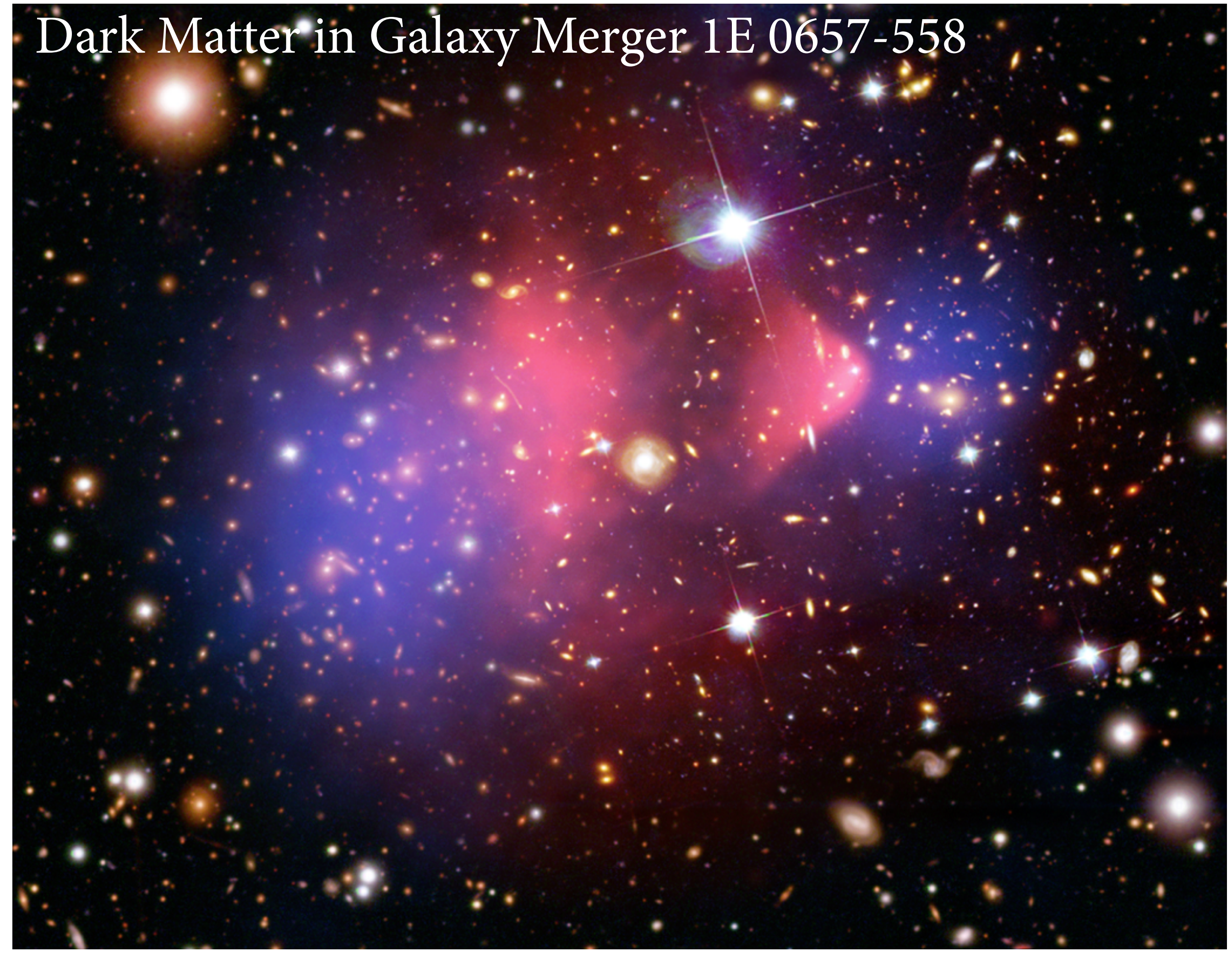
with the ATLAS detector at the LHC

Priscilla Pani
(CERN)
Roma, Feb '18

G. Bertone - Particle Dark Matter

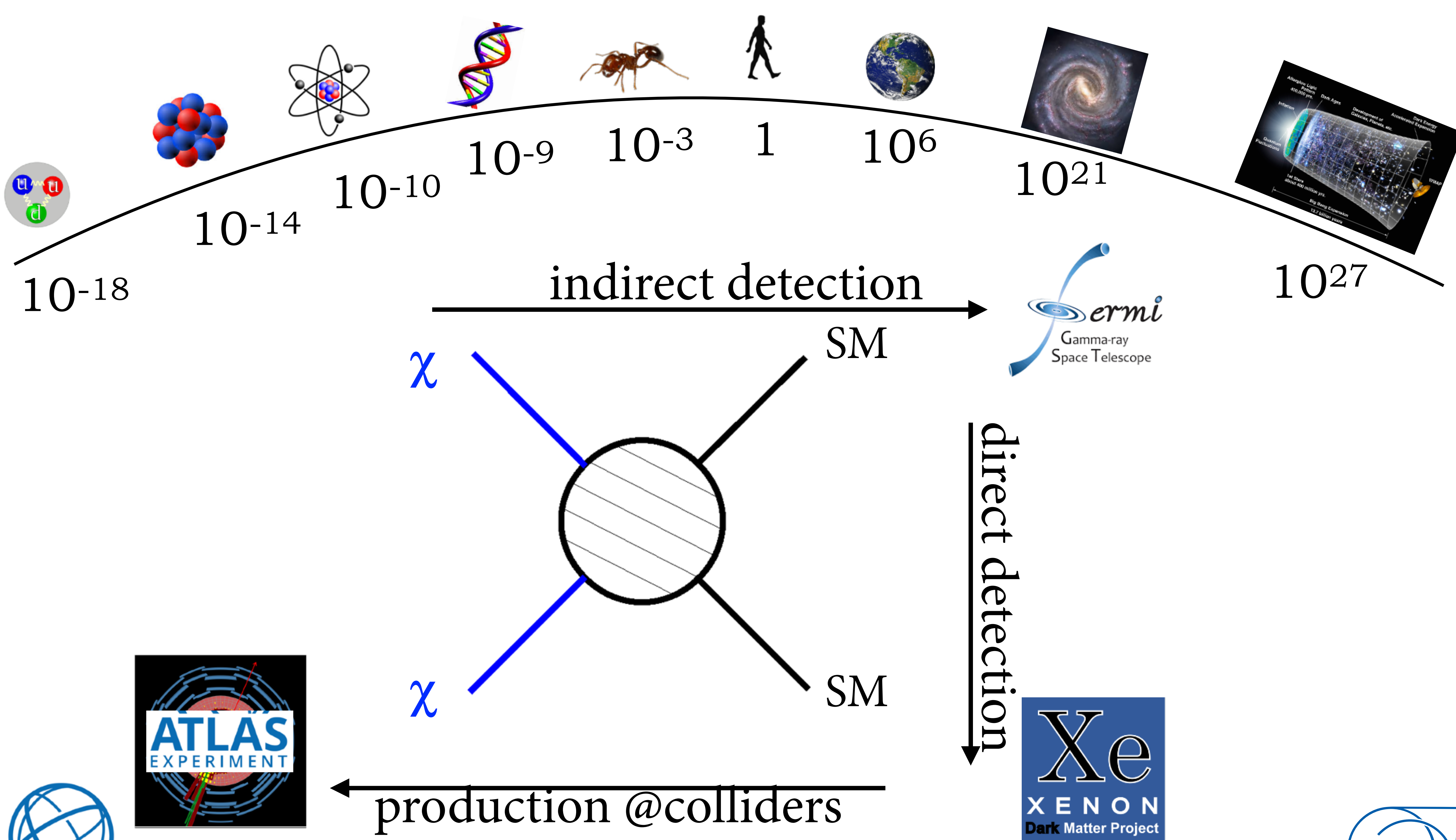
The Dark Matter mystery



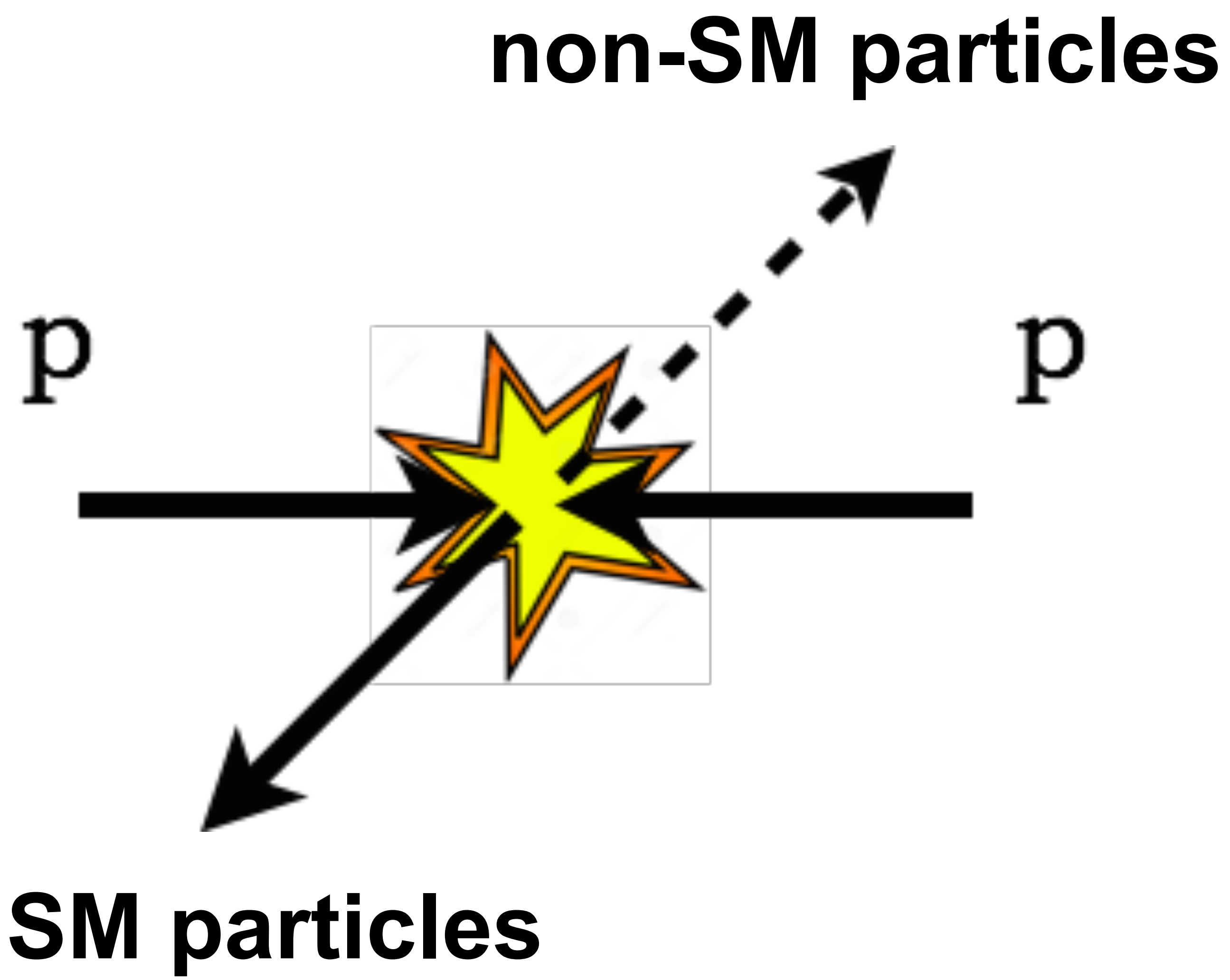


- ★ Electrically neutral
- ★ Observed via gravity, massive
- ★ Weakly interacting
- ★ Elementary particles created in the early universe

The Dark Matter quest



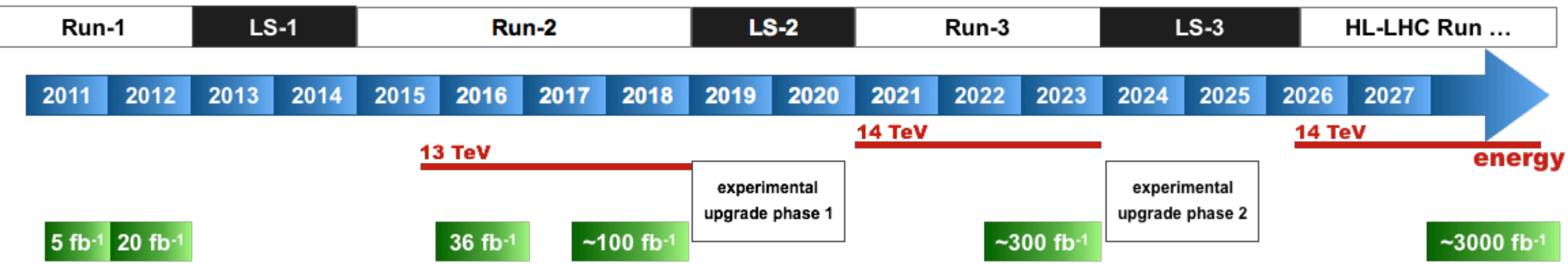
The collider ansatz

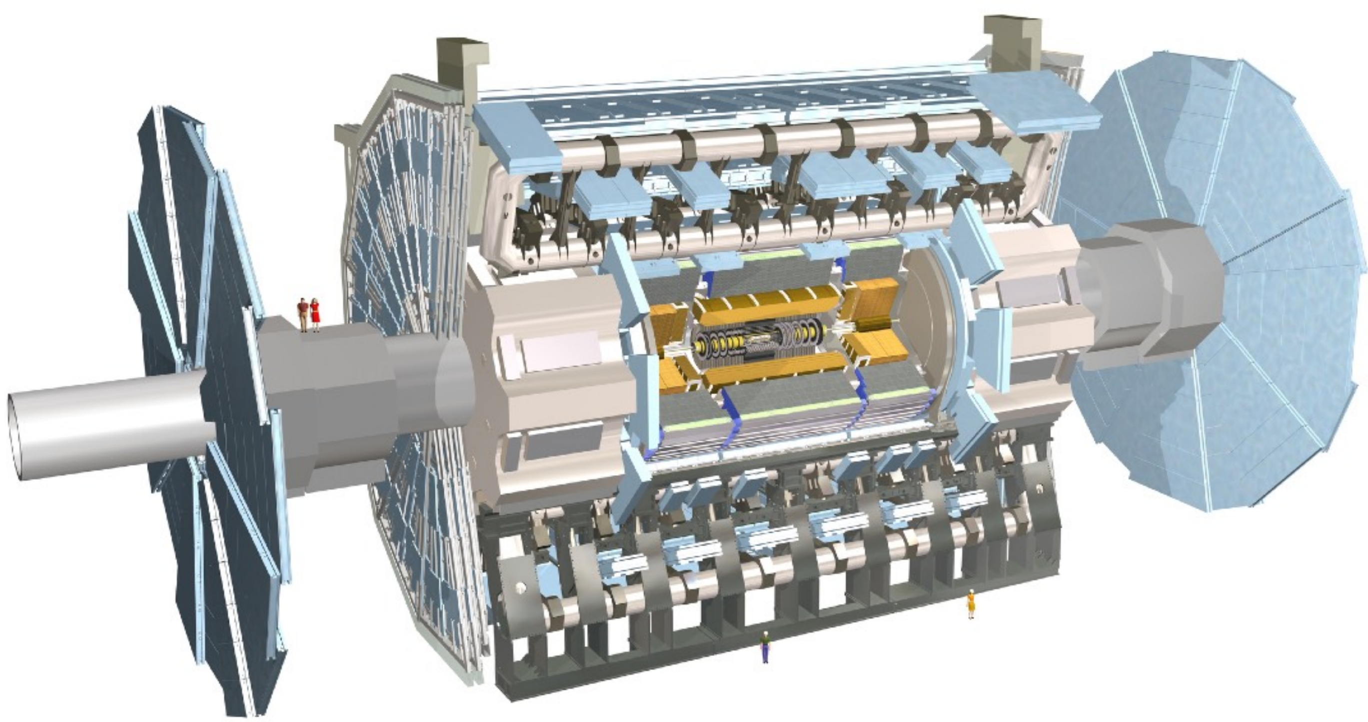


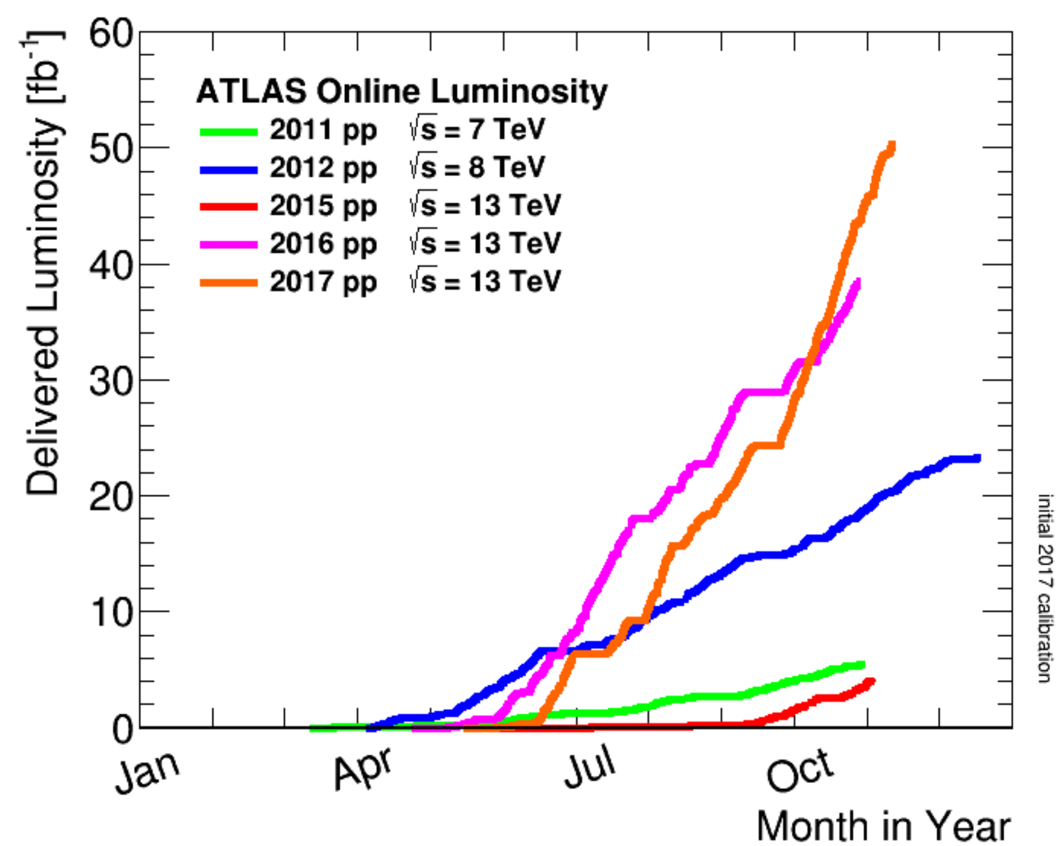
1. Production mechanism

2. Particles detection and identification

The ATLAS detector





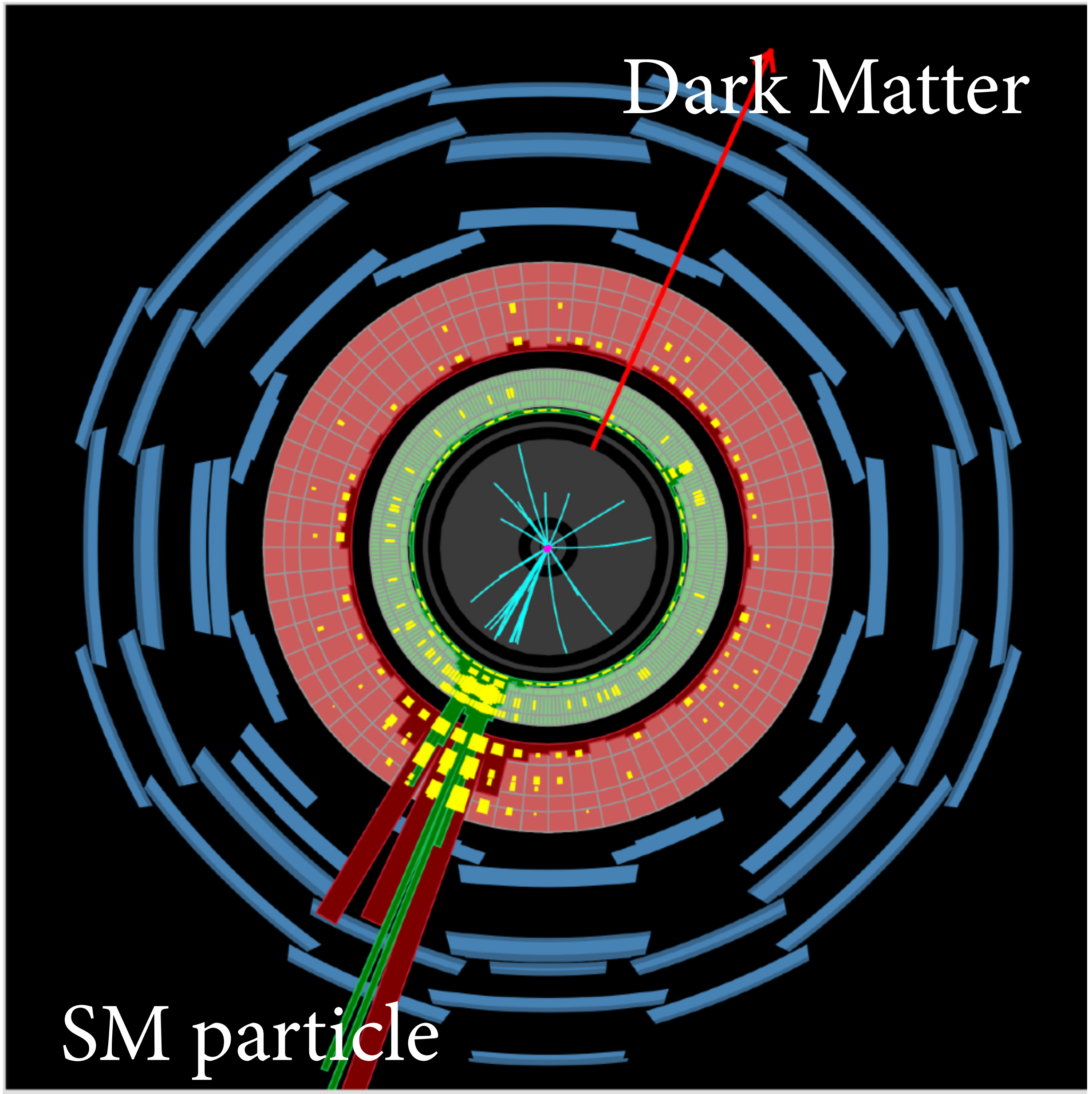


The ATLAS detector is one of the two general-purpose experiments that detects and records collisions produced at the LHC

Particles detection

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

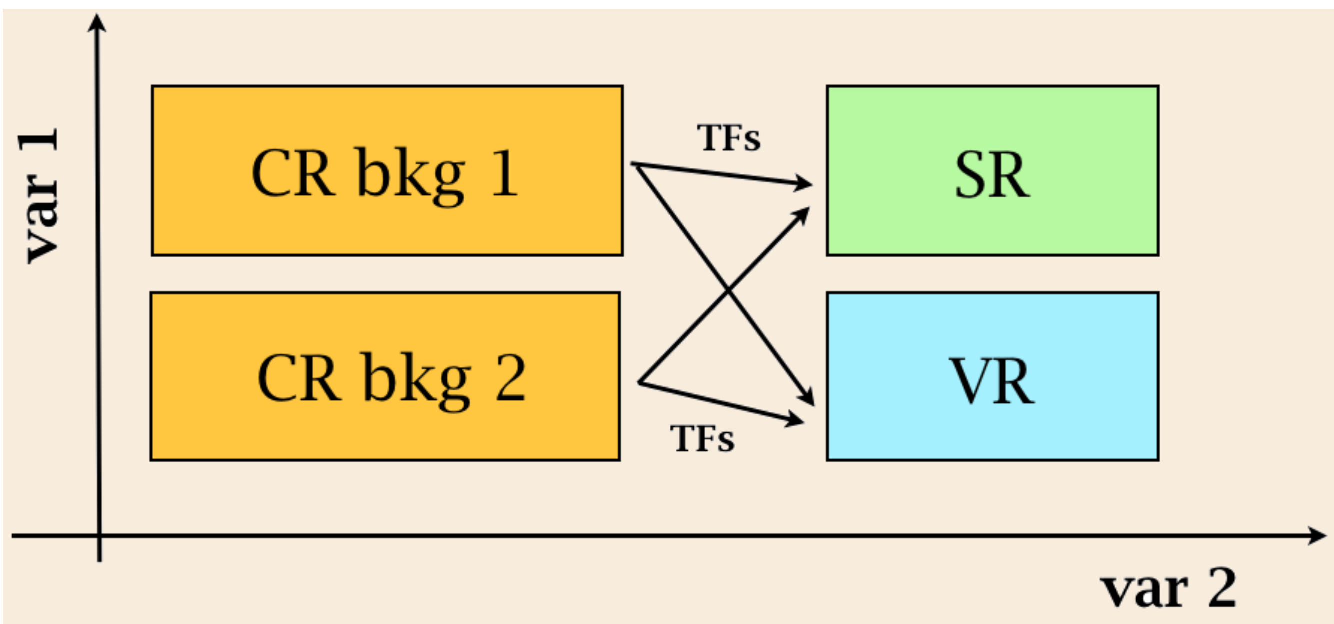
- Electrons
- Muons
- Photons
- jets
- b-jets/c-jets
- invisible particles

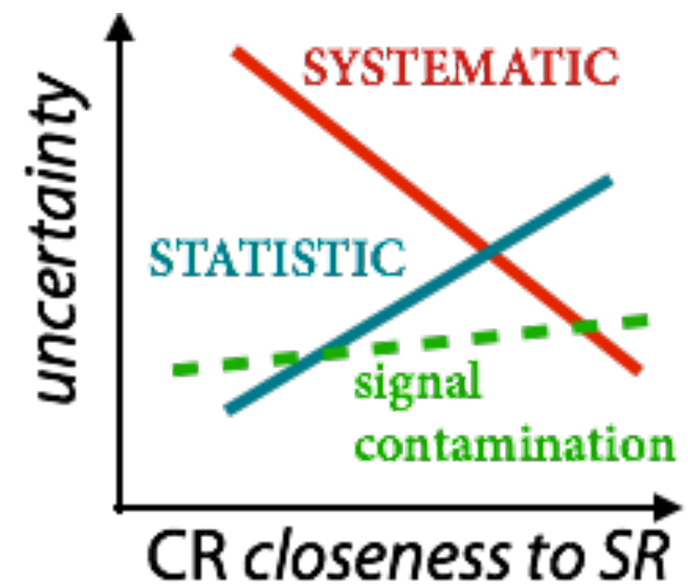


Experimental approach

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).



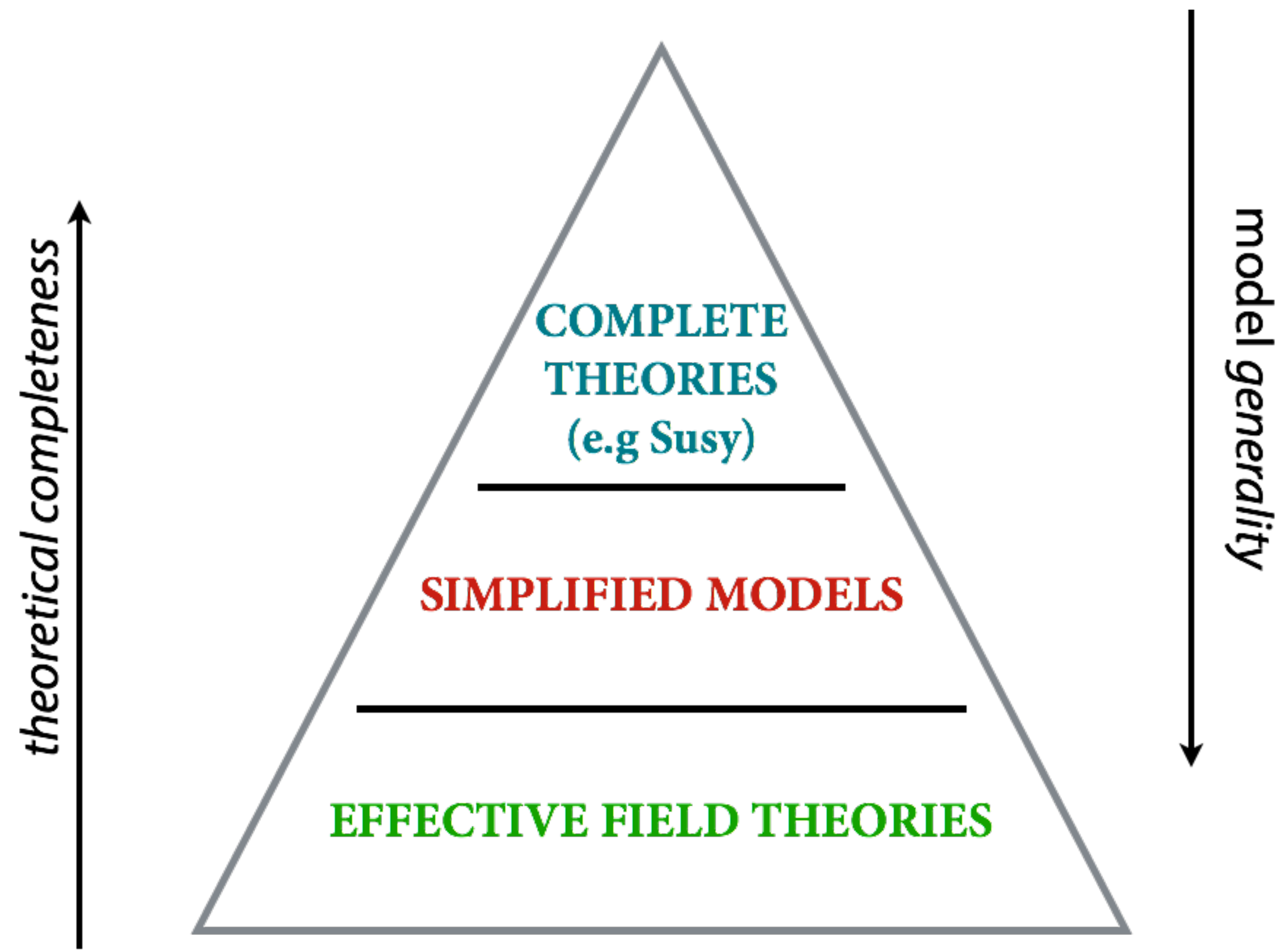


3) Validation of the TF in the Validation Region (VR)

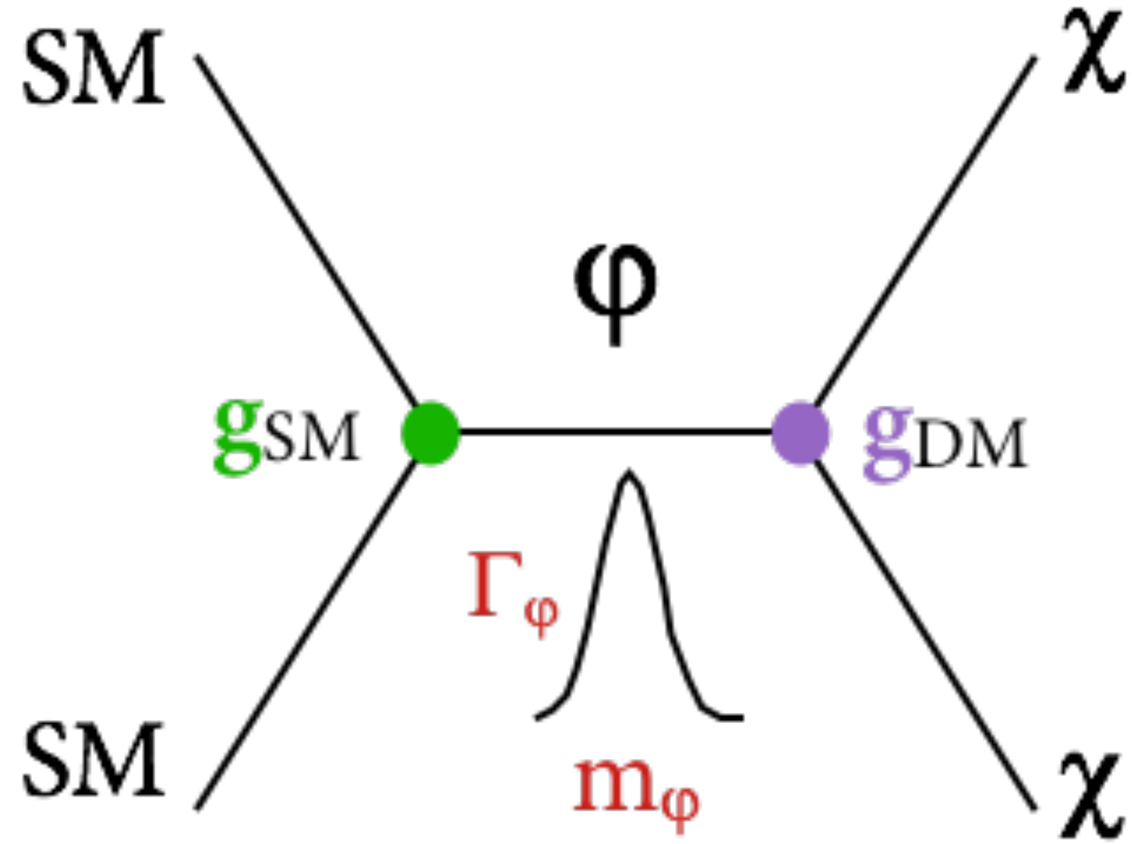
4) Unblinding ! check whether an excess is observed (p-value)

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

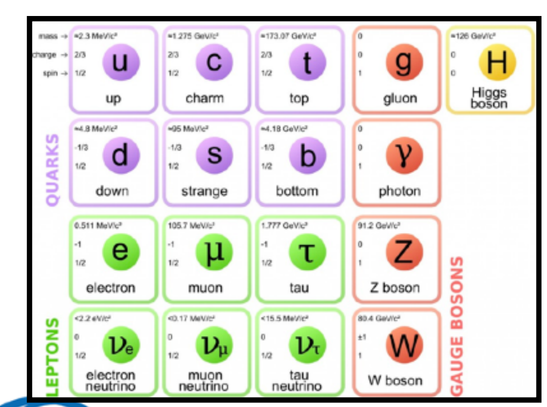
Theoretical framework



(Portal) simplified models



SM Sector



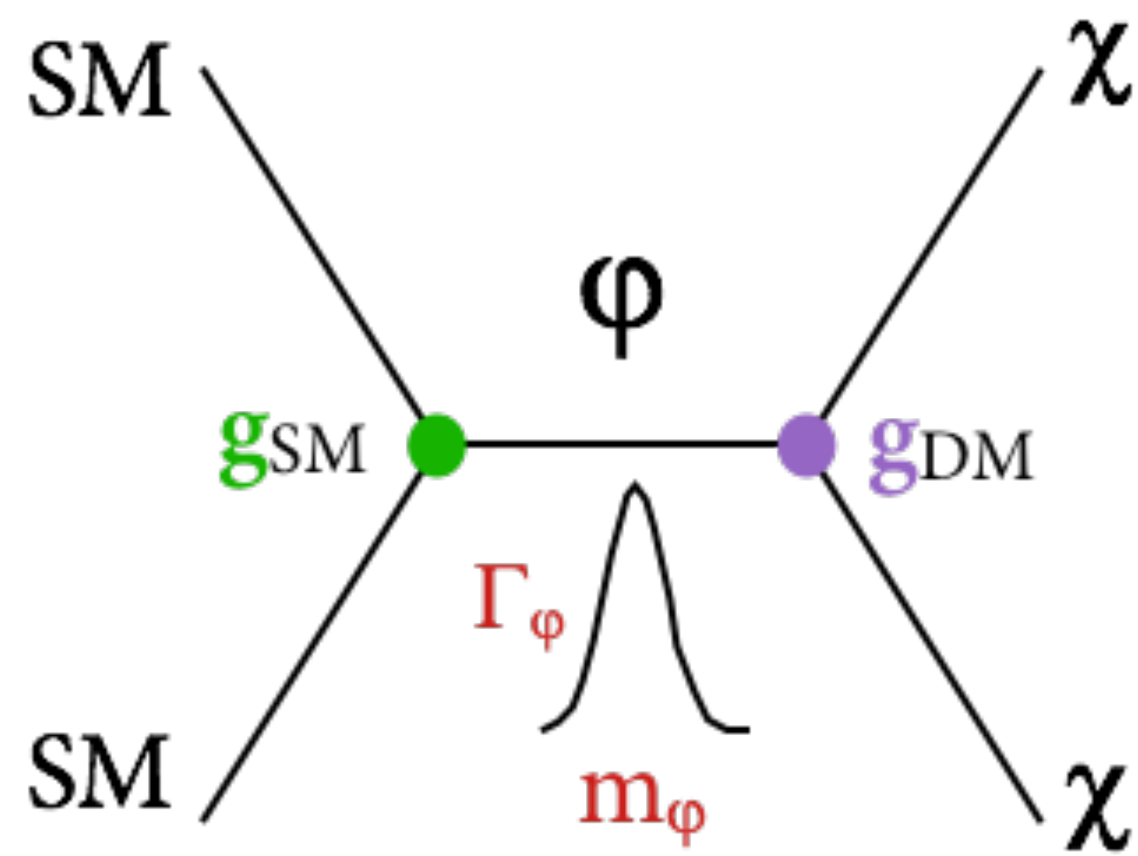
Dark Mediator

Dark Sector

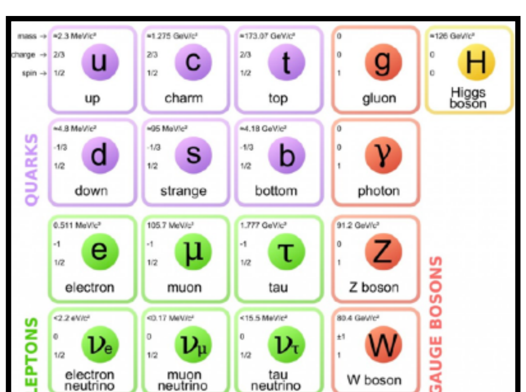
arXiv:1507.00966 (and ref. therein) + LPCC WG

(Portal) simplified models

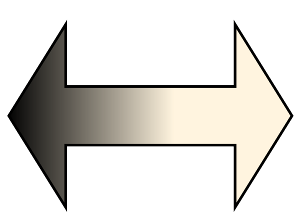
- ★ Reduce a complex model to a simple one with **DM + mediator**
- ★ **Few free parameters:** mφ, mχ, gSM, gDM, Γφ
- ★ Nature of mediator and DM can (also) be **systematically classified based on their spin**



SM SECTOR



DARK MEDIATOR

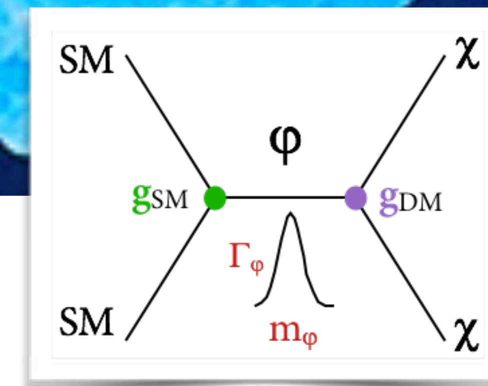


DARK SECTOR

- ★ **Very rich phenomenology:** E_T^{miss}+jet/g/V/H/bb/tt, resonance searches

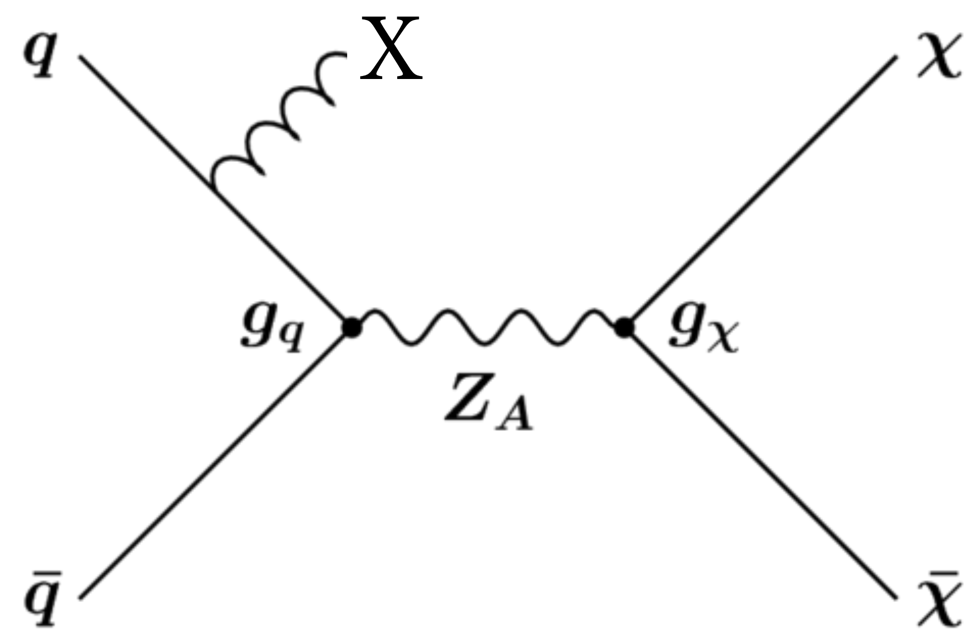
arXiv:1507.00966 (and ref. therein) + LPCC WG

Overview: E_T^{miss} + X (1)



Spin-1 mediators

E_T^{miss} + jet	EXOT-2016-27
E_T^{miss} + γ	arXiv:1704.03848
E_T^{miss} + W/Z	arXiv:1608.02372 arXiv:1708.09624
E_T^{miss} + H	arXiv:1706.03948 arXiv:1707.01302



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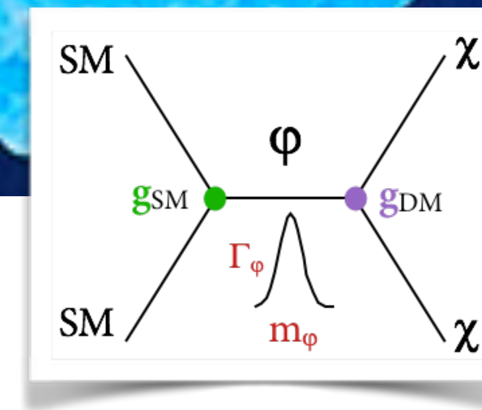

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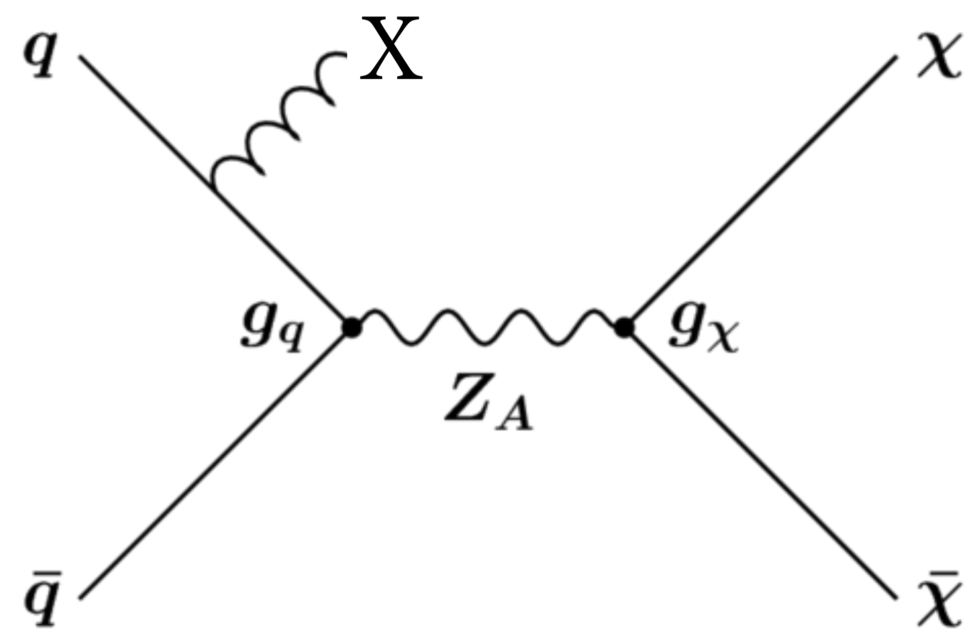
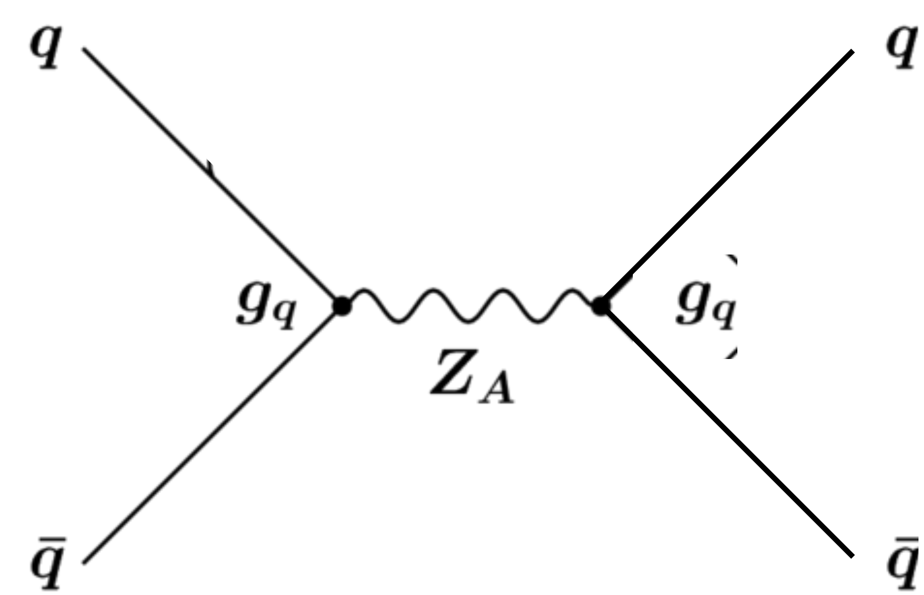
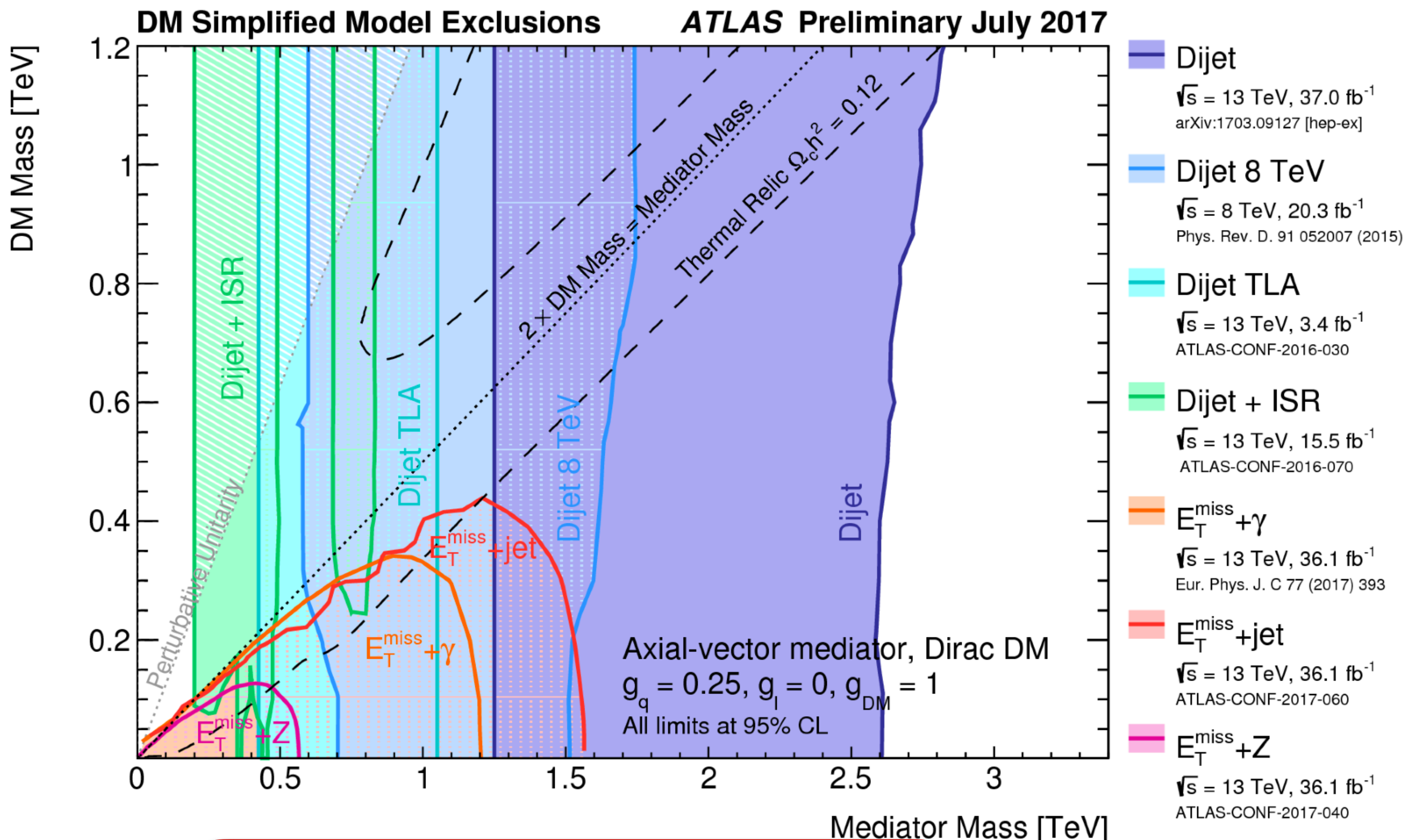


di-jets	arXiv:1703.09127 ATLAS-CONF-2016-030
di-bjets	arXiv:1603.08791



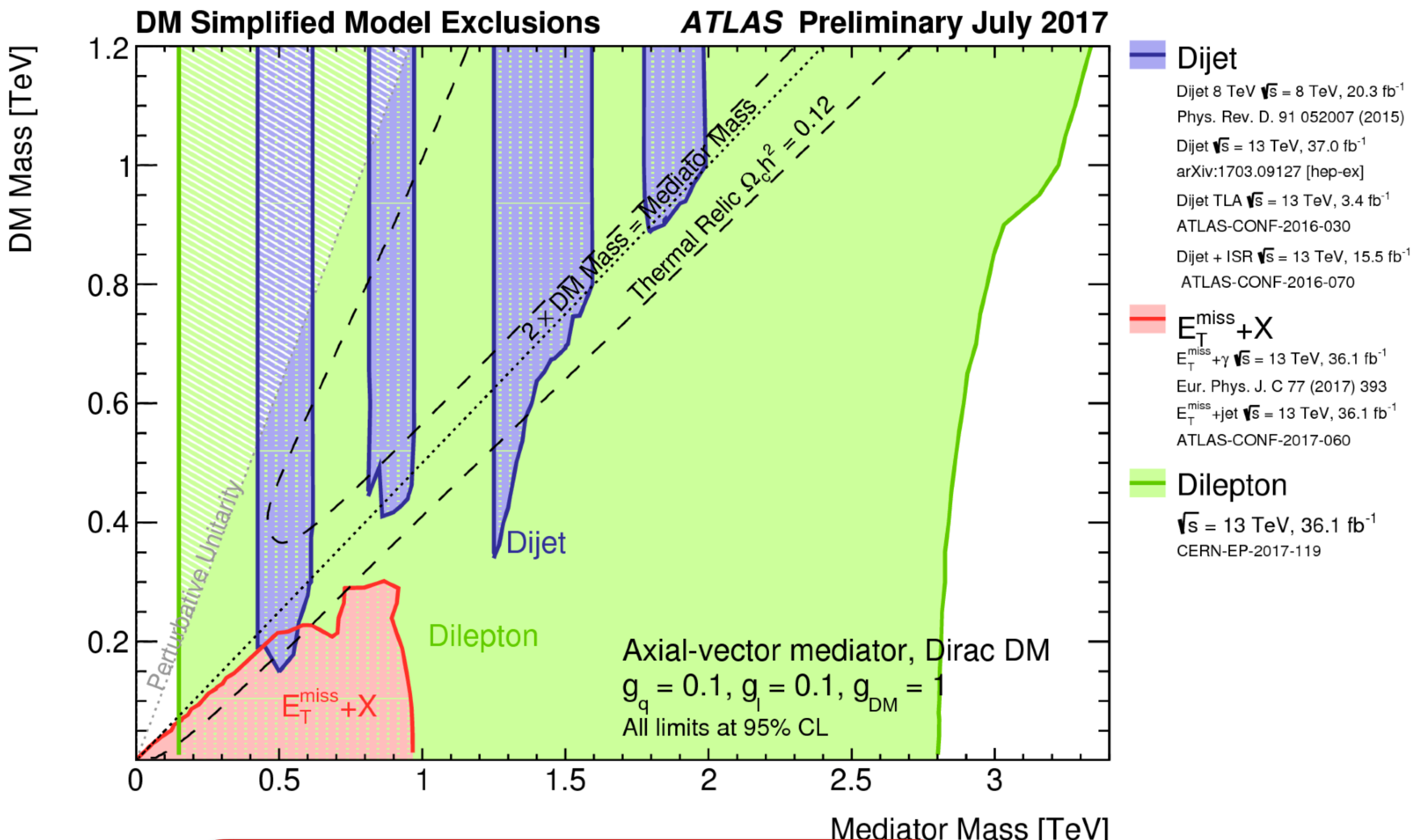
"bump hunt"

Spin-1 mediators in a nutshell



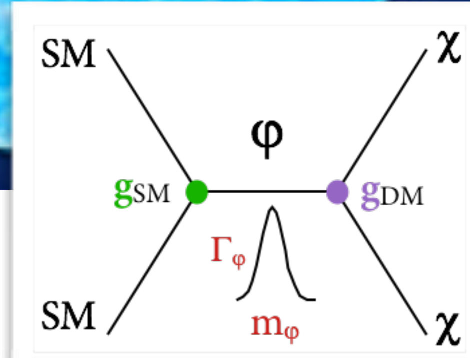
$$g_q = 0.25,\ g_{lep} = 0,\ g_{DM} = 1$$

Spin-1 mediators in a nutshell



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

Overview: E_T^{miss} + X (2)



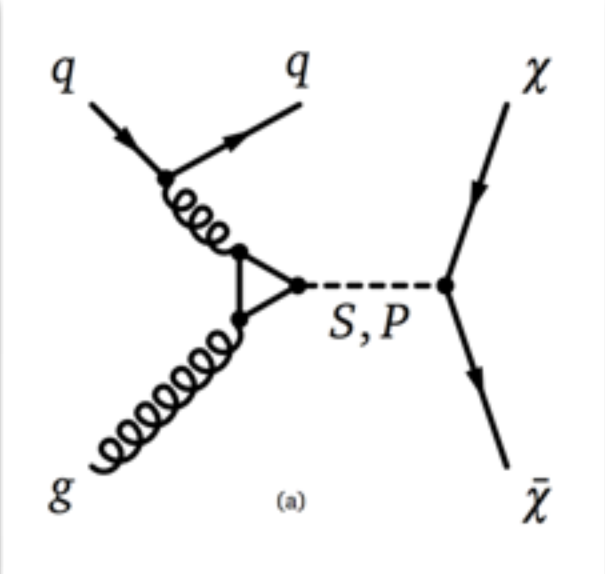
SPIN-0 MEDIATORS

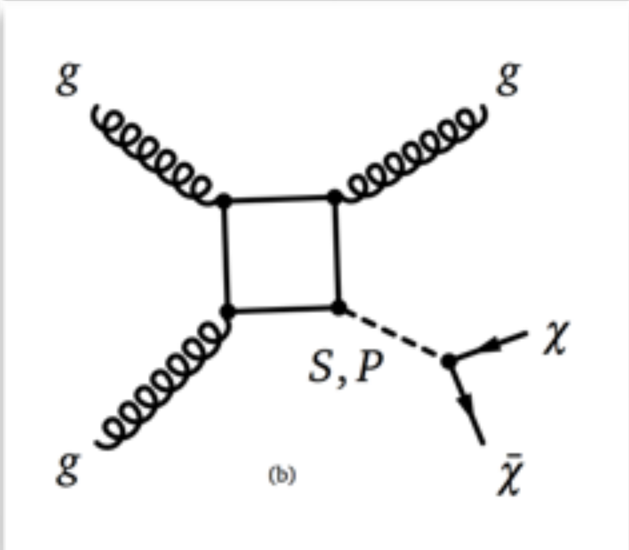
E_T^{miss} + jet	EXOT-2016-27
E_T^{miss} + γ	arXiv:1704.03848
E_T^{miss} + W/Z	arXiv:1608.02372 arXiv:1708.09624
E_T^{miss} + H	arXiv:1706.03948 arXiv:1707.01302

di-jets	arXiv:1703.09127 ATLAS-CONF-2016-030
di-bjets	arXiv:1603.08791

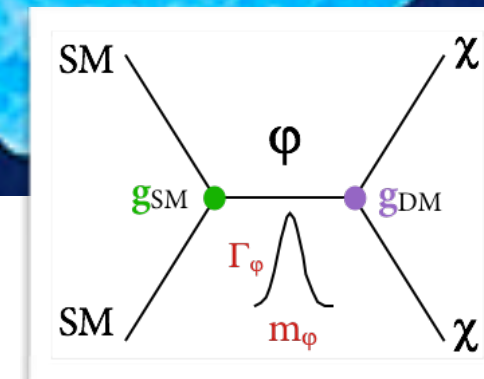
$$\mathcal{L} \sim \sum_f i g_v \frac{y_f}{\sqrt{2}} A \bar{f} \gamma^5 f$$

Needed to easily fulfil Flavour Constraints (MFV)





Overview: E_T^{miss} + X (2)



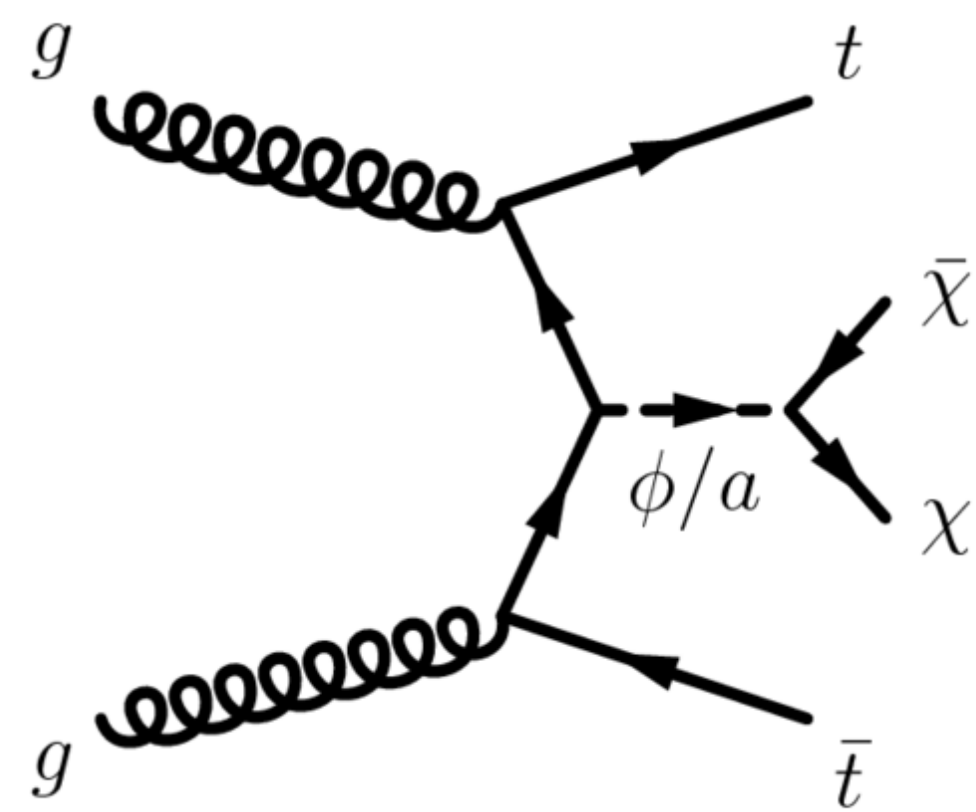
SPIN-0 MEDIATORS

E_T^{miss} + jet	EXOT-2016-27
E_T^{miss} + tt	arXiv:1710.11412 ATLAS-CONF-2017-037
E_T^{miss} + bb	arXiv:1710.11412

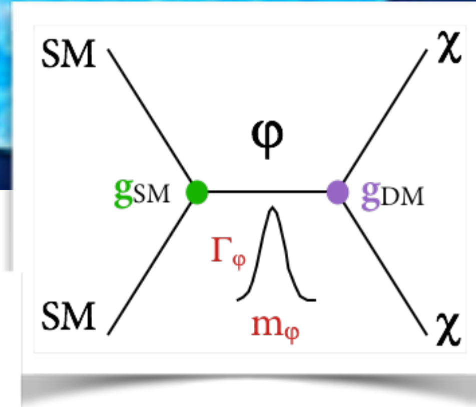
$$\mathcal{L} \sim \sum_f i g_v \frac{y_f}{\sqrt{2}} A \bar{f} \gamma^5 f$$

Needed to easily fulfil Flavour Constraints (MFV)

di-top	arXiv:1707.06025
di-bjets	arXiv:1603.08791
4-tops	coming soon

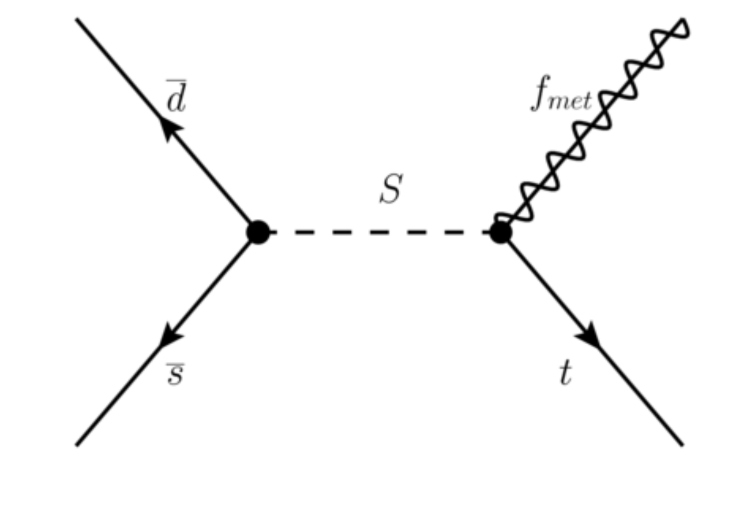


Overview: E_T^{miss} + X (3)



OTHER STUFF

mono-top	arXiv:1410.5404



+ Long Lived Particles sector

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

+ SUSY EW

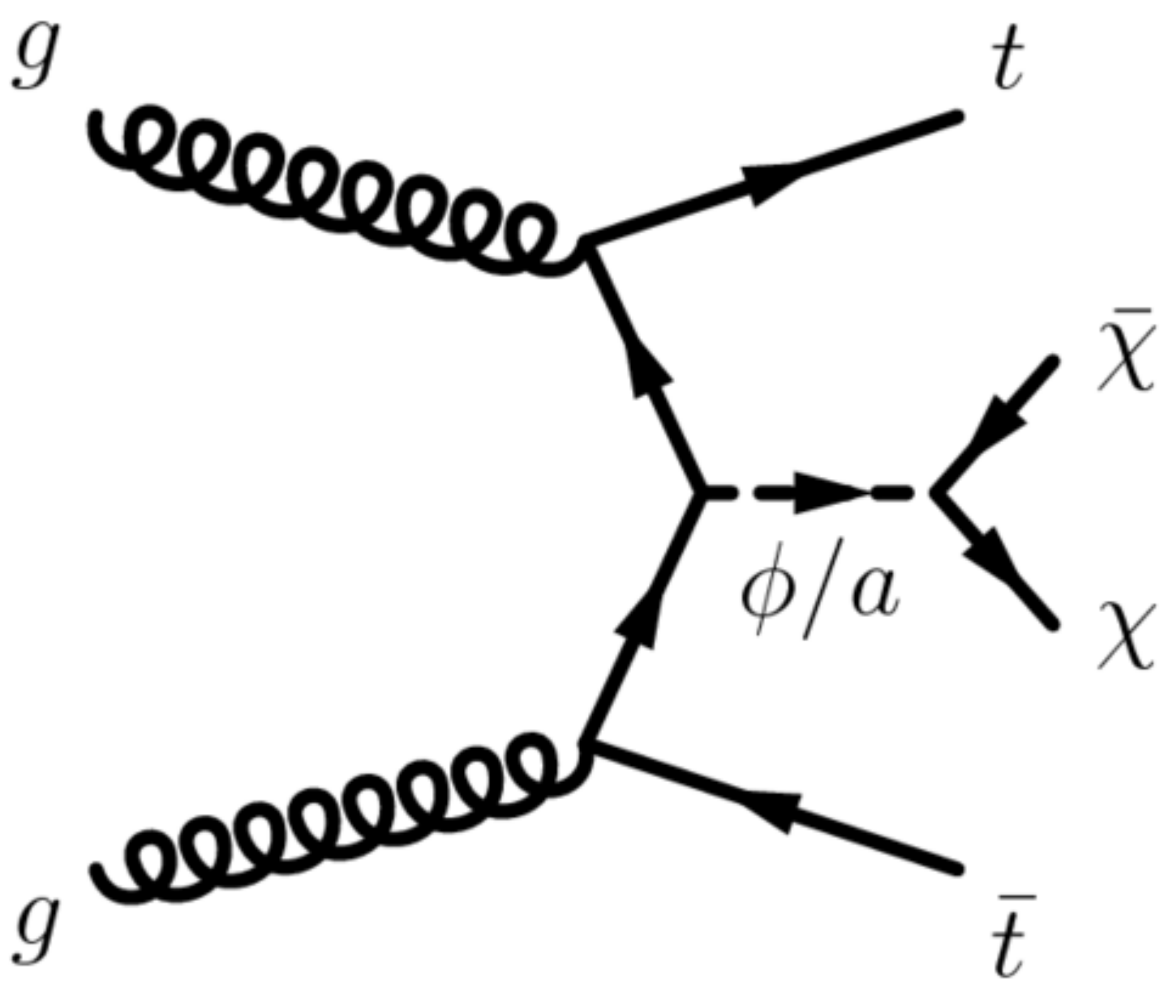
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

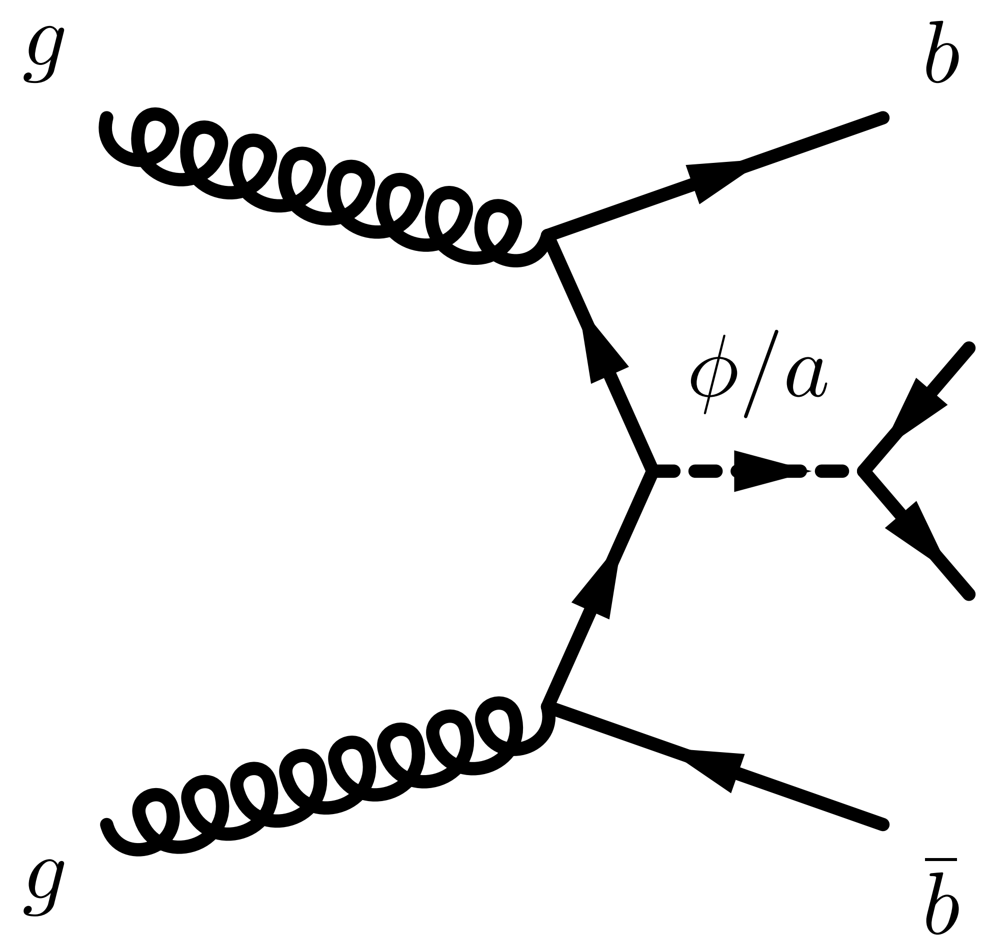
DM EWK interpretation	arXiv:1608.00872

+ even more exotics models

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**



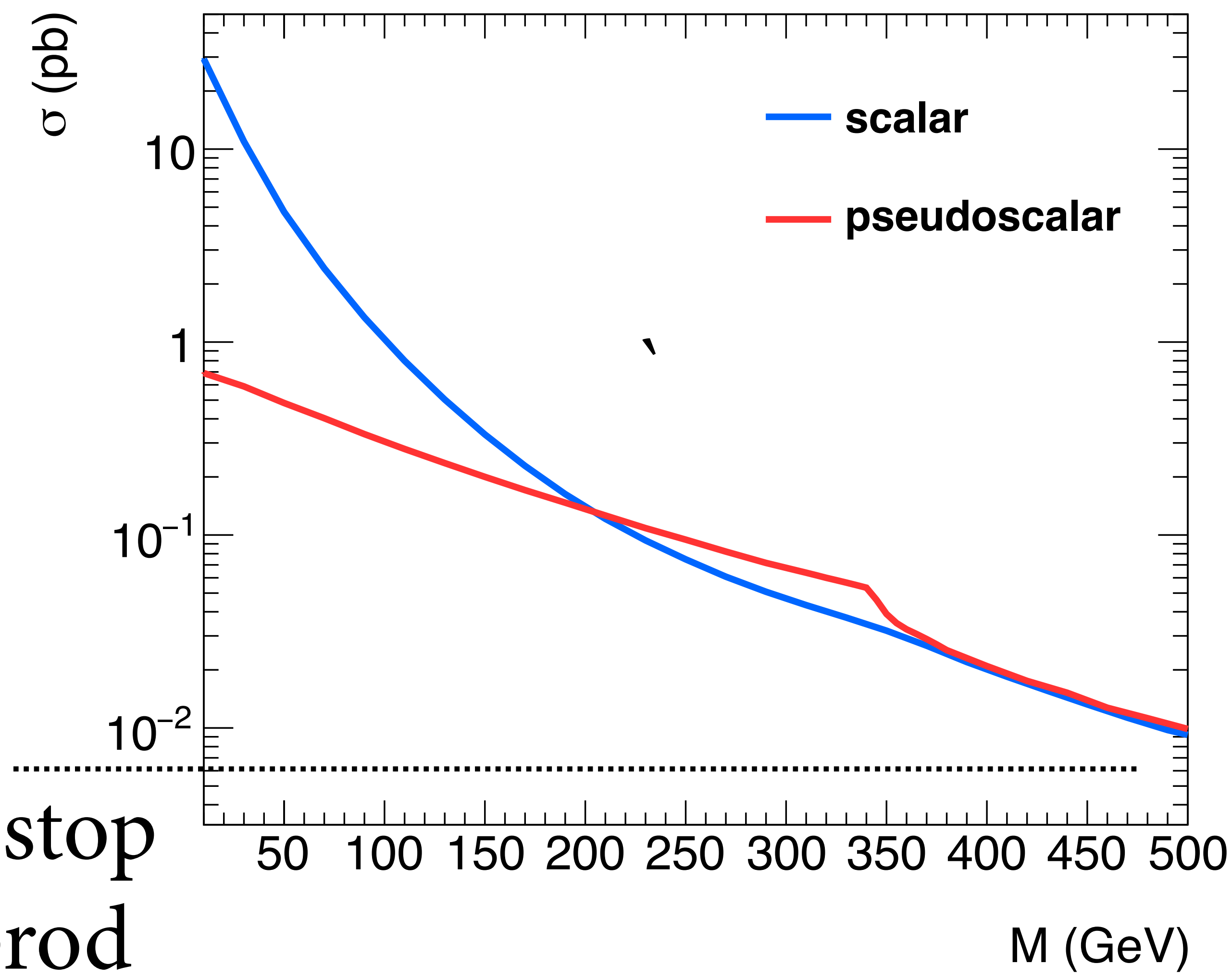


arXiv:1710.11412 and ATLAS-CONF-2017-037

Understanding the signal

830 pb

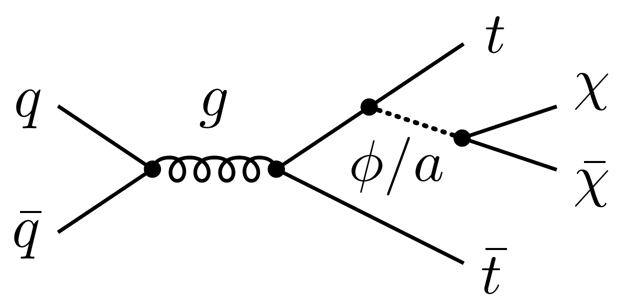
σ(ttbar)



1 TeV stop pair prod

[Haisch,PP,Polesello 2017]

Understanding the signal

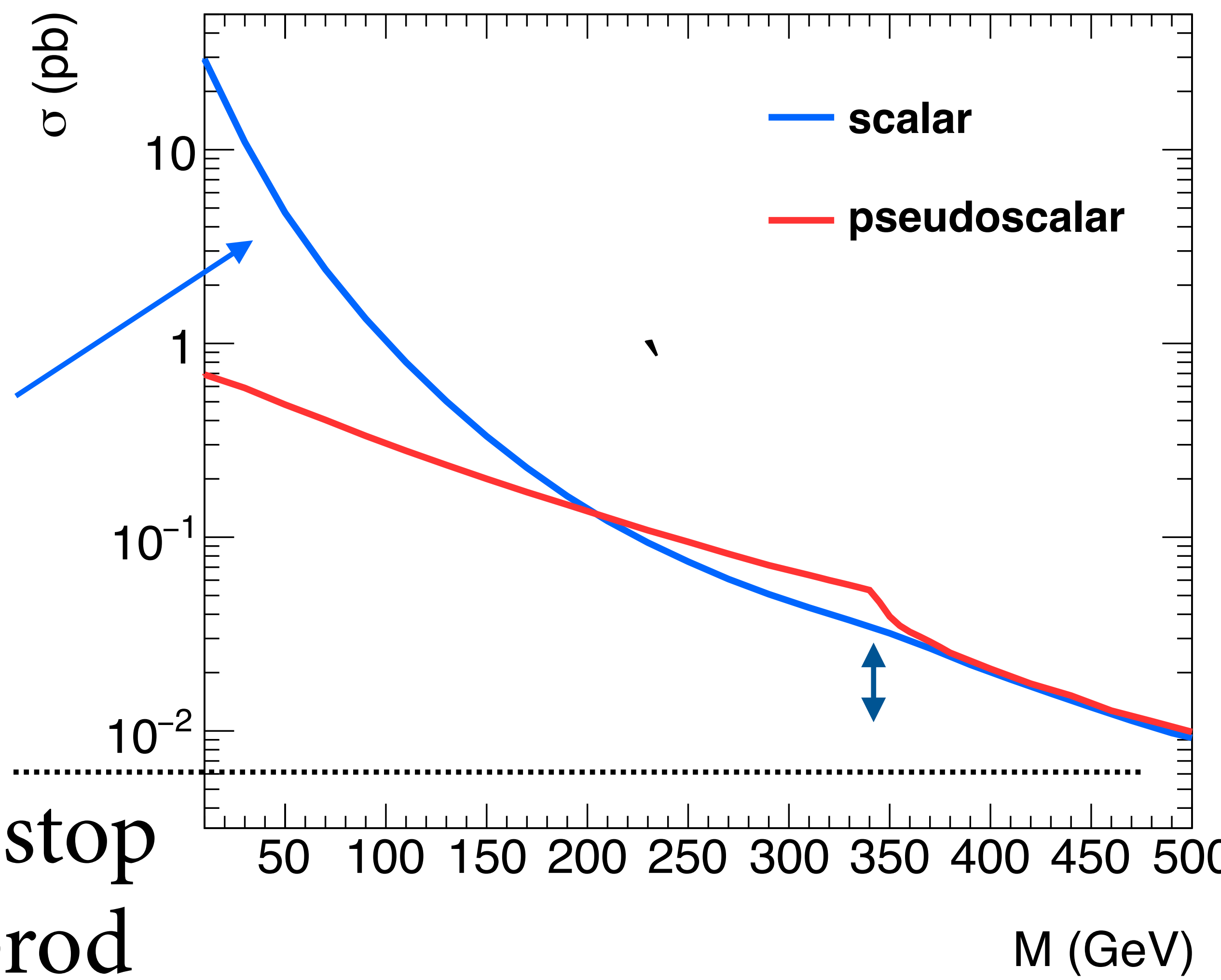


$f_{t\to\phi}(x) \sim 1/x$

soft-enhancement term

830 pb

σ(ttbar)



1 TeV stop pair prod

spin and color-averaged ME

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

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

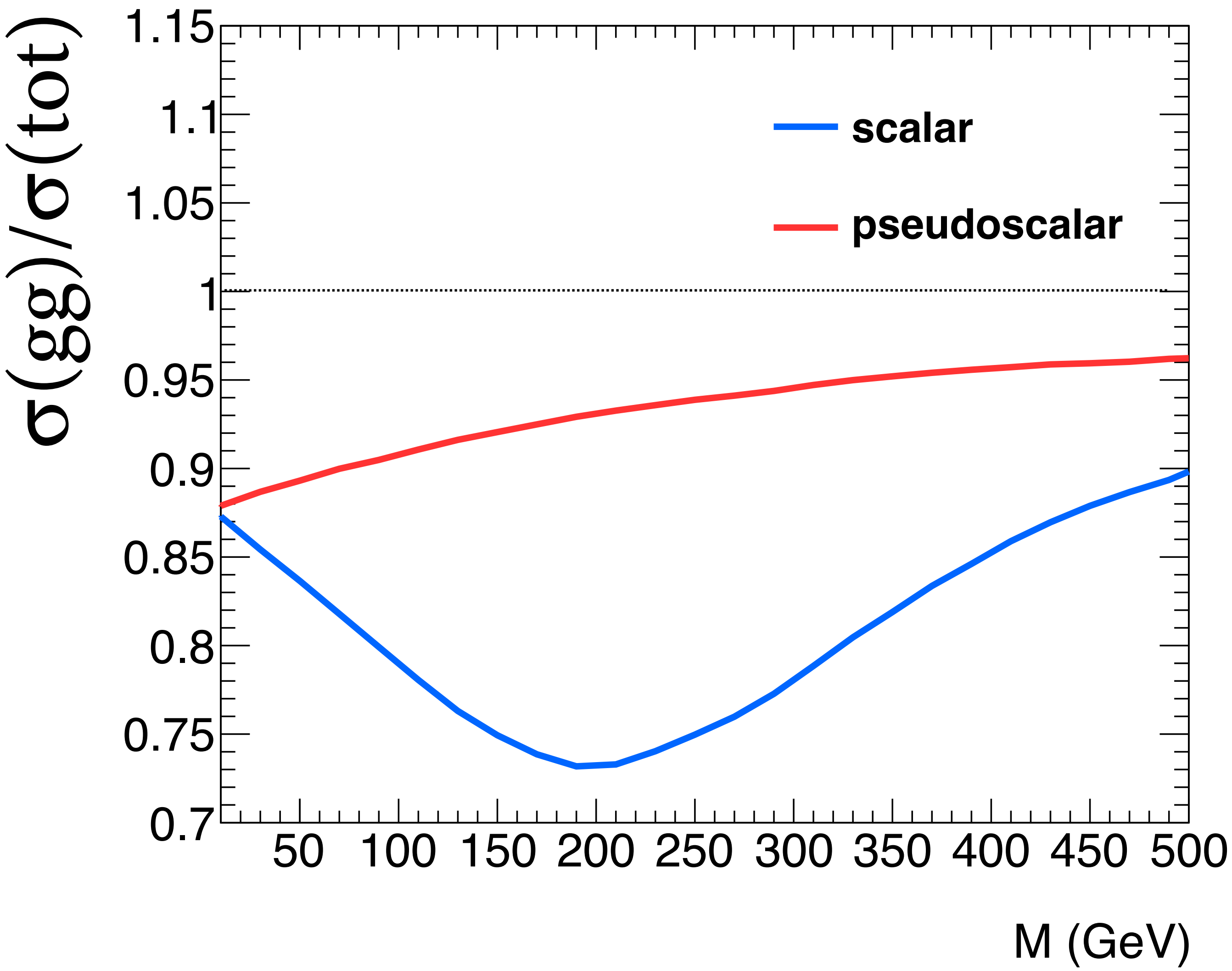
$$\beta = \sqrt{1 - 4m_t^2/s}$$

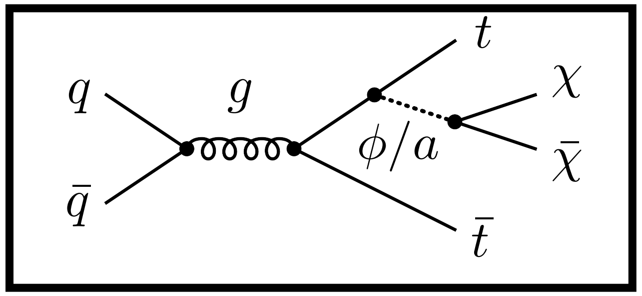
top-threshold suppression from

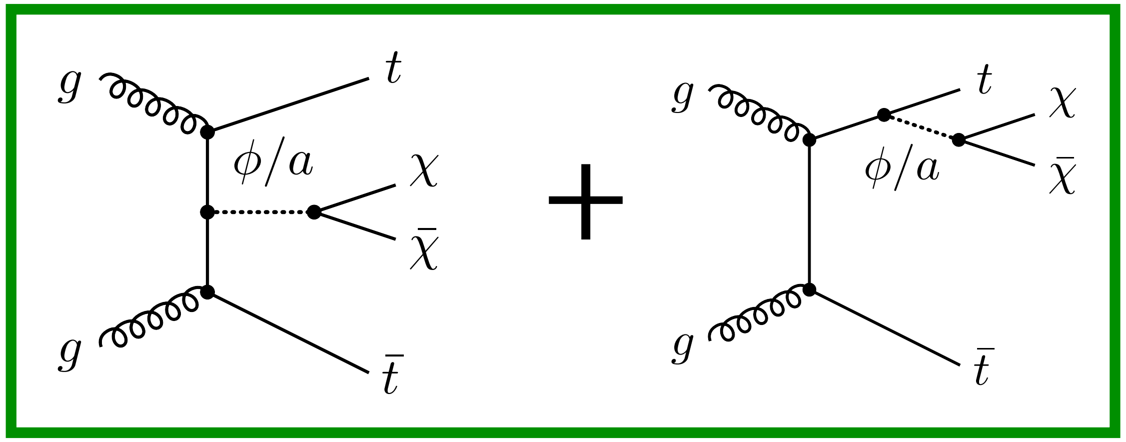
$$\phi/a \to t\bar{t}$$

[Haisch,PP,Polesello 2017]

Understanding the signal







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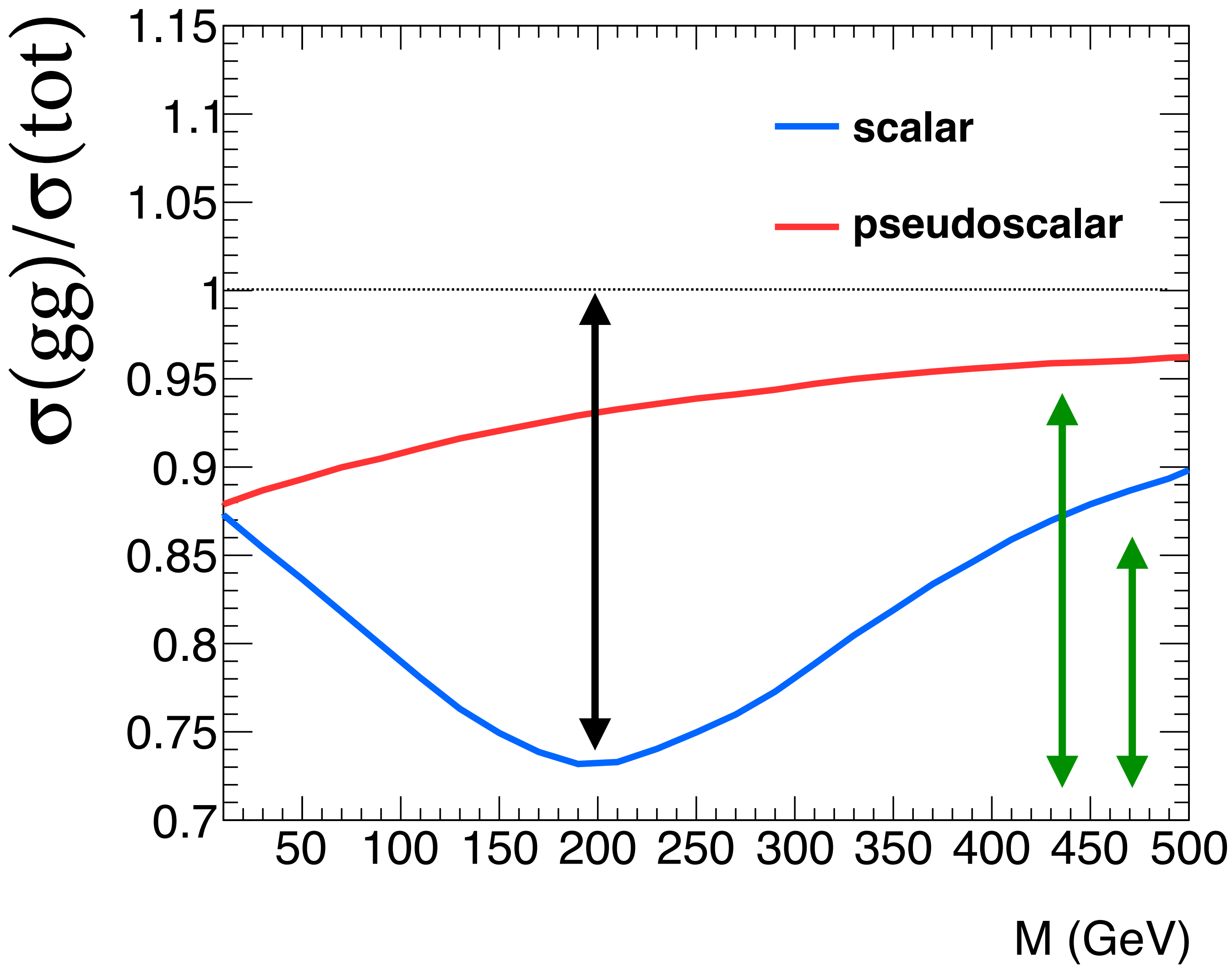
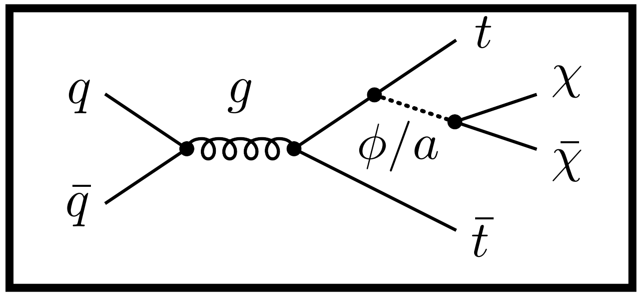
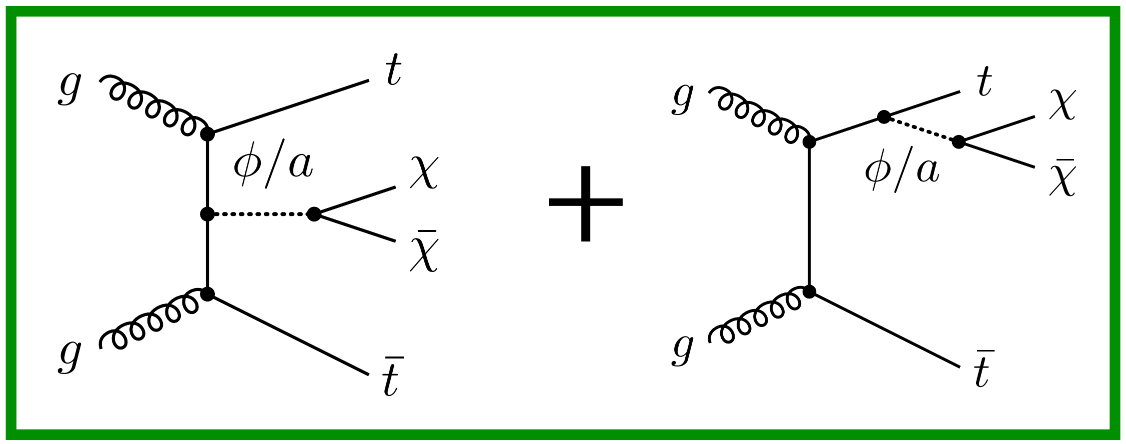
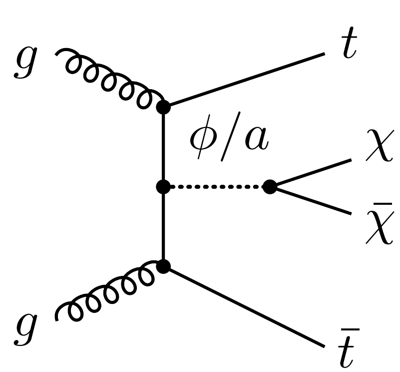
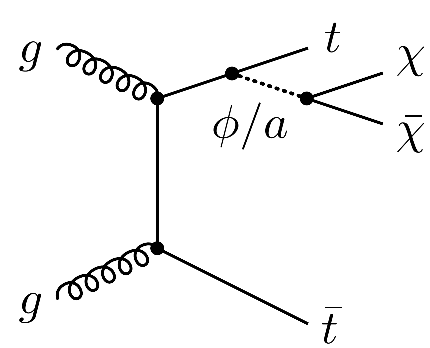






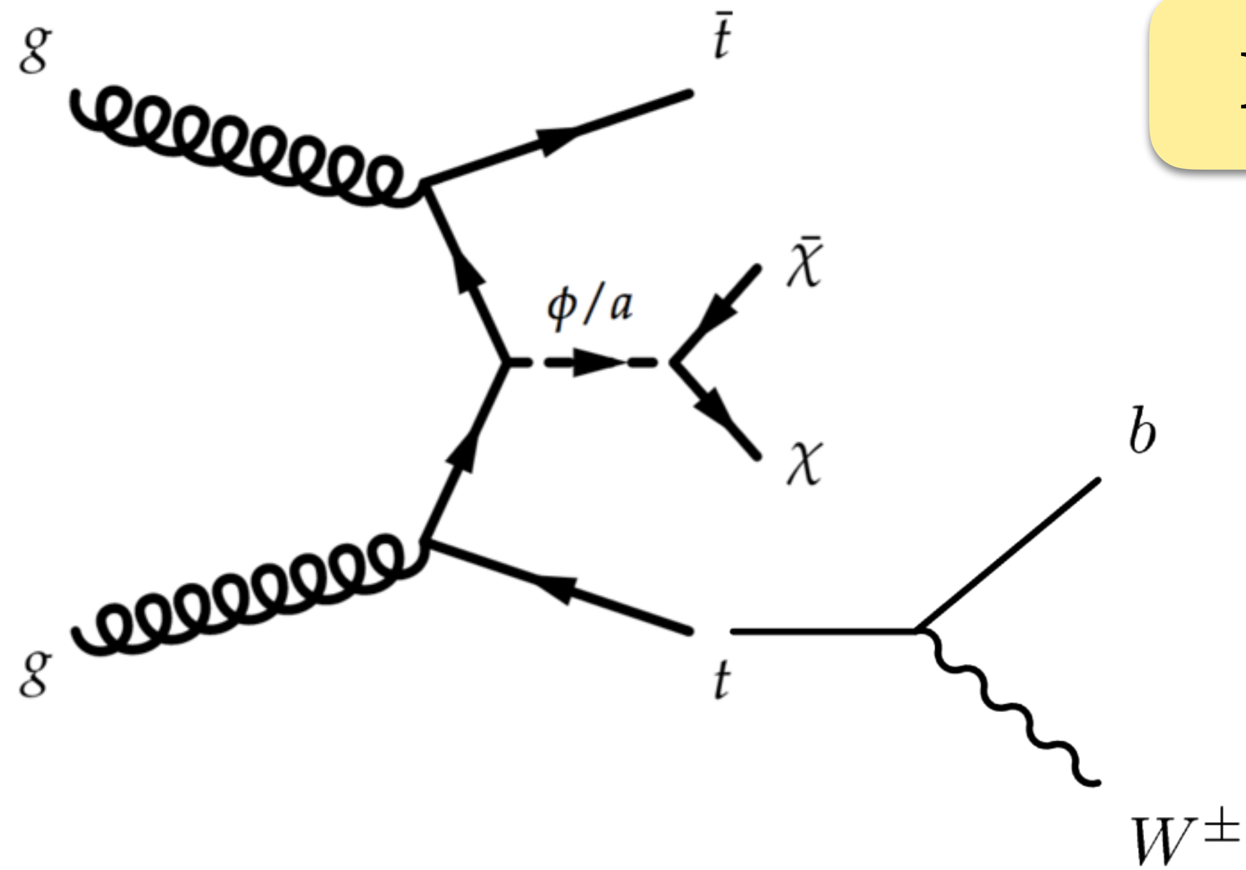


: dominant at high mass and low-mass a

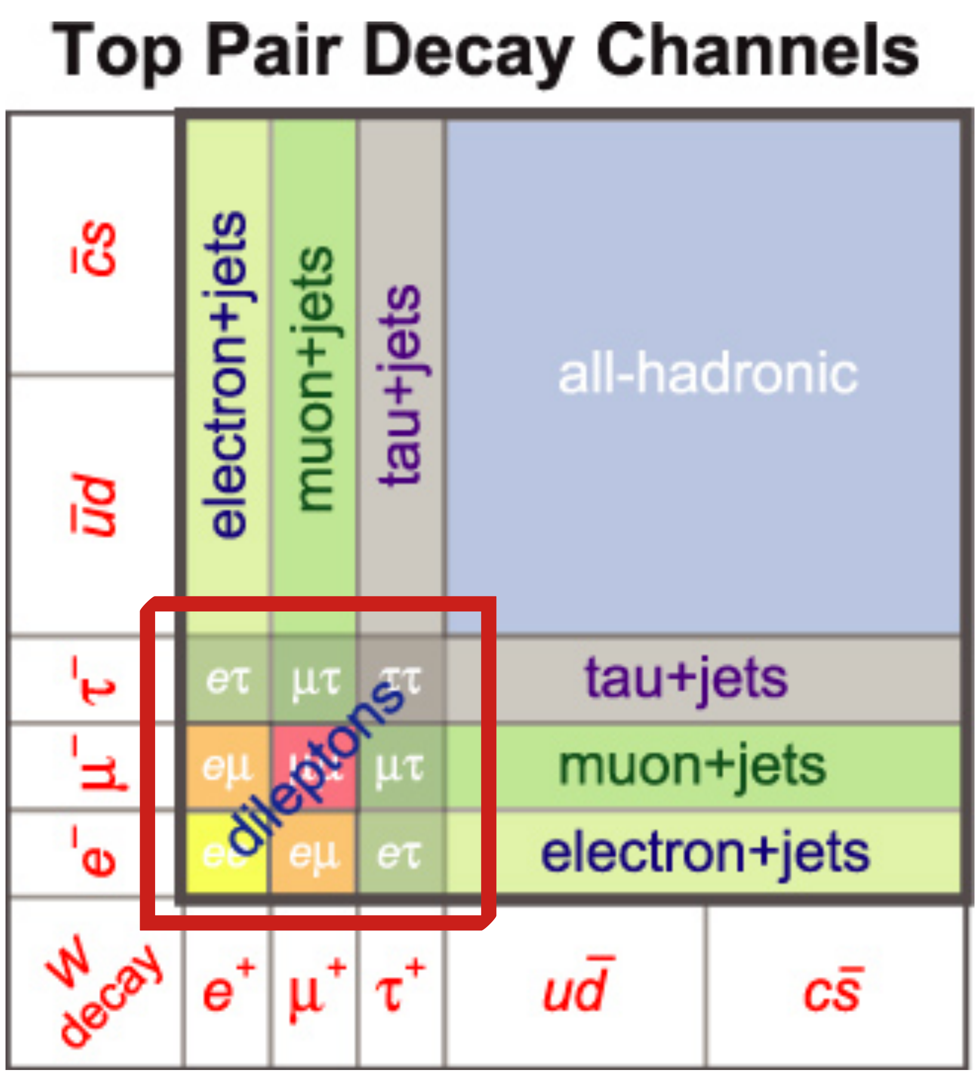


: dominant at low-mass φ

Understanding the channel



Missing Energy + 2 tops

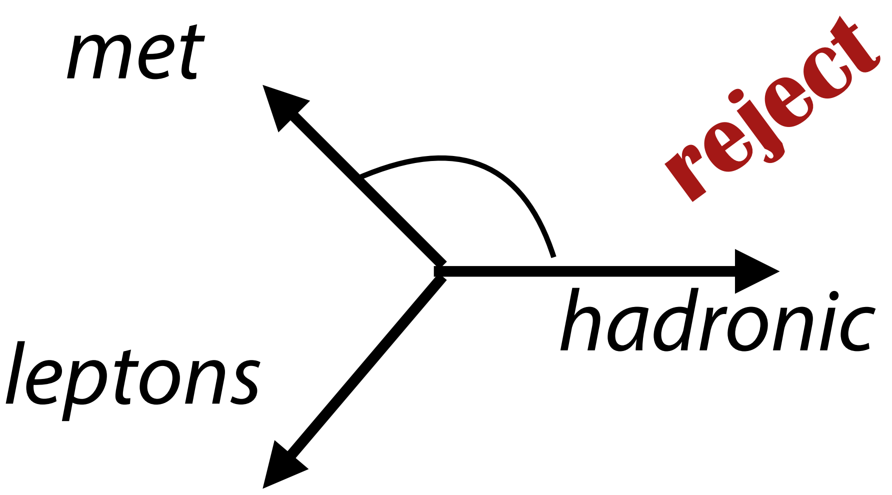


- ★ 2 leptons (e or μ)
- ★ very clean signature
- ★ low statistics

Understanding the background

★ Reducible backgrounds

- Z+jets
- VV
- fakes and non-prompt leptons



Understanding the background

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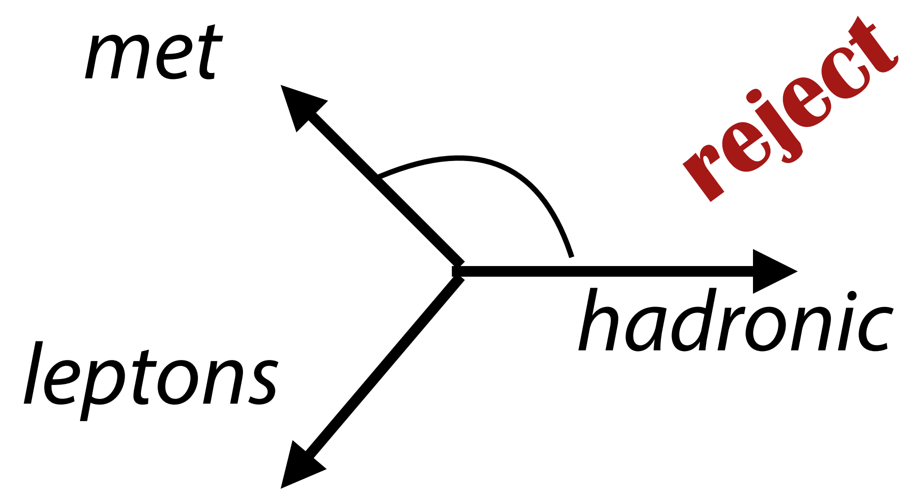


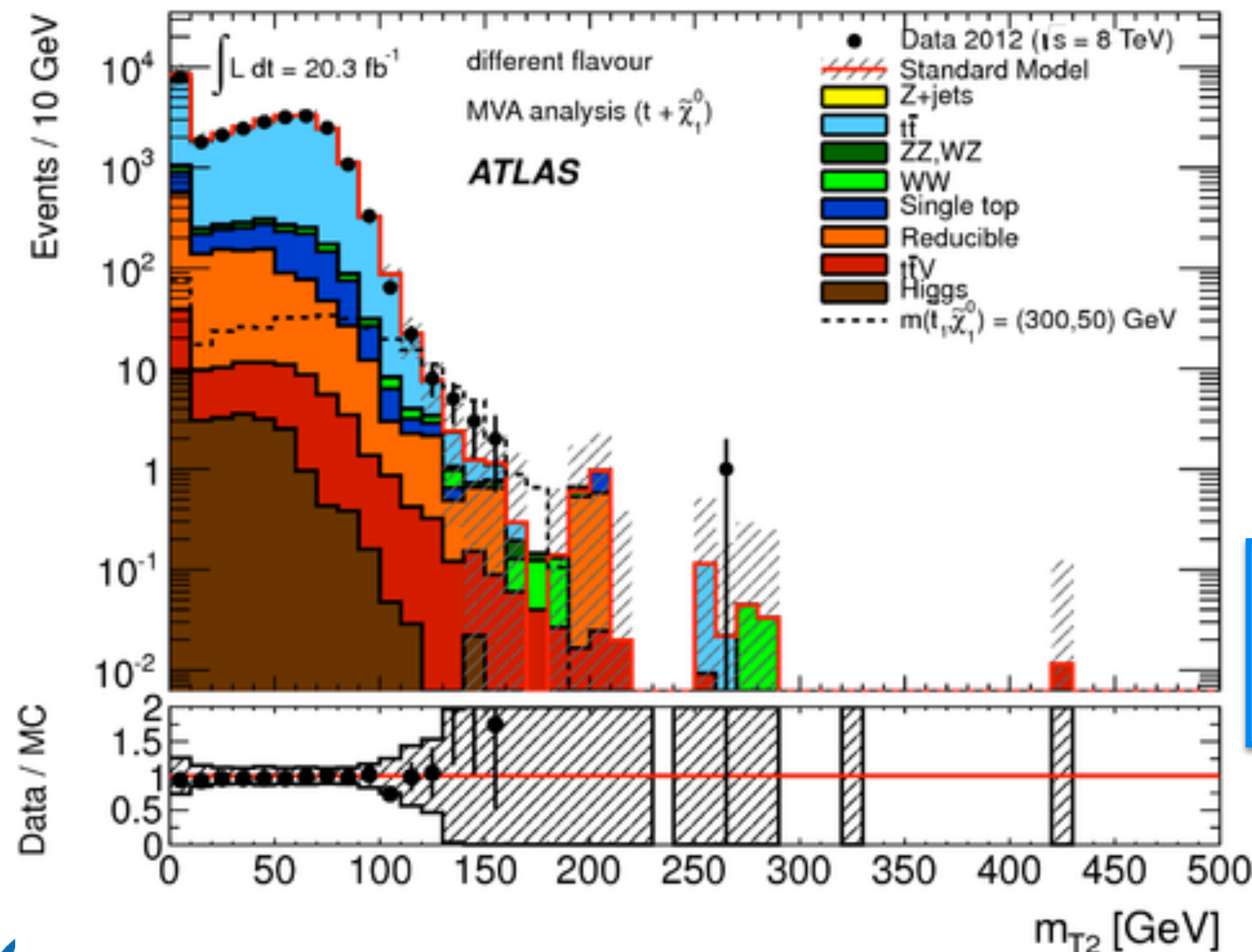
★ Irreducible/hard backgrounds

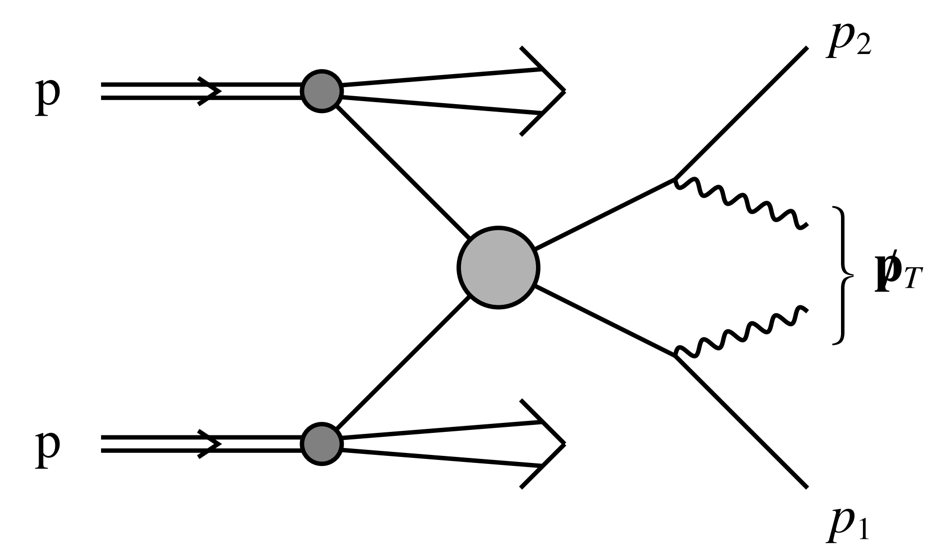
- top pairs
- tt+Z(νν)

Dedicated variables

Main signal selection

$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{q}_T) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{q}_T} \{\max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2}) \,]\},$$





$$\xi^+ = m_{T2}^{\ell\ell} + 0.2 \cdot E_T^{\text{miss}}$$

Background estimate

	SRt3
Observed	18
Total background (fit)	15.2 ± 4.3
$t\bar{t}$	4.5 ± 2.5
$t\bar{t}$+Z	4.4 ± 1.9
W+ jets	incl. in Fakes/NP
Wt	$0.33^{+0.53}_{-0.33}$
Z/γ^{*}+ jets	incl. in Others
VV	0.61 ± 0.25
Fakes/NP	2.7 ± 1.3
Others	2.69 ± 0.93
$t\bar{t}$ (pre-fit)	4.0
$t\bar{t}$+Z (pre-fit)	5.6
Z/γ^{*}+ jets (pre-fit)	-
Signal benchmarks	
$m(\phi, \chi) = (20, 1)$ GeV, $g = 1$	21.0 ± 2.3
$m(a, \chi) = (20, 1)$ GeV, $g = 1$	14.1 ± 1.6
$m(\phi, \chi) = (100, 1)$ GeV, $g = 1$	11.5 ± 1.5
$m(a, \chi) = (100, 1)$ GeV, $g = 1$	11.9 ± 1.5

Background estimate

	SRt3
Observed	18
Total background (fit)	15.2 ± 4.3
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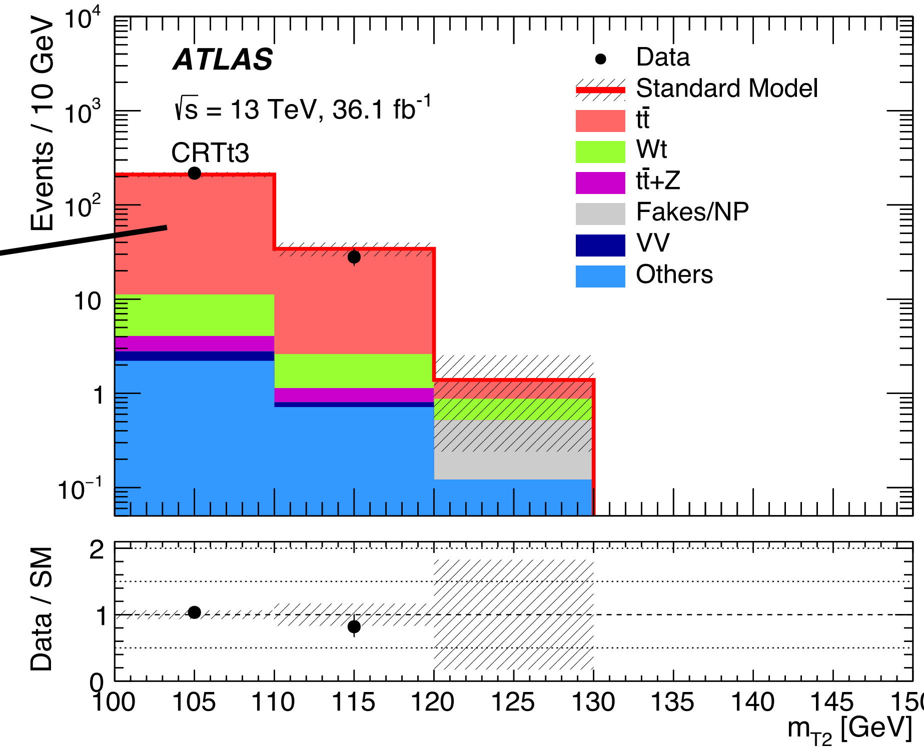
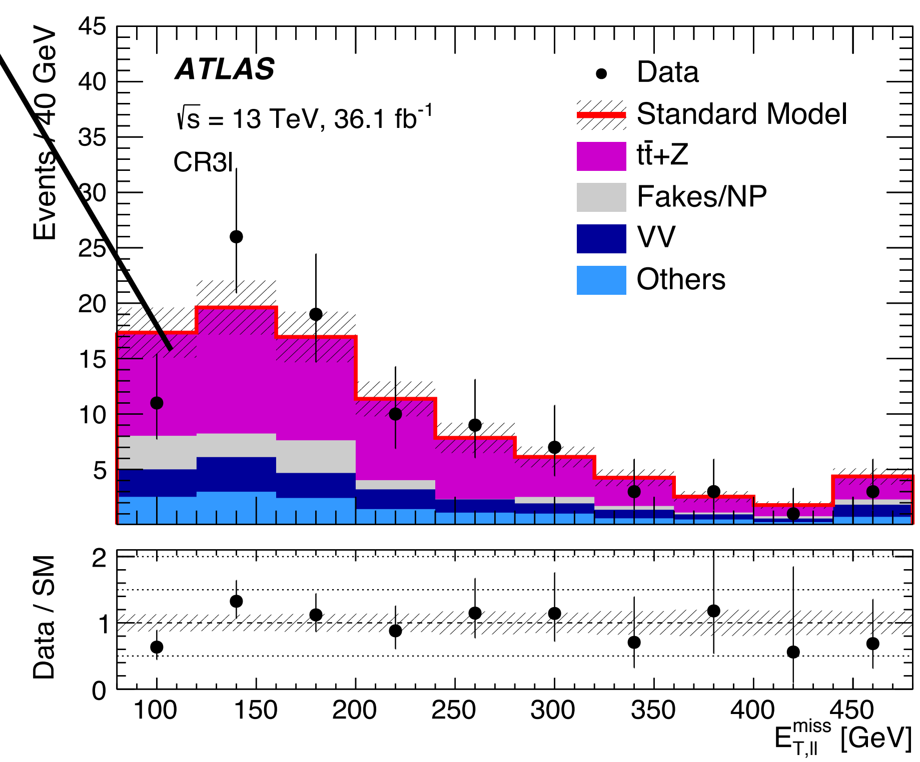
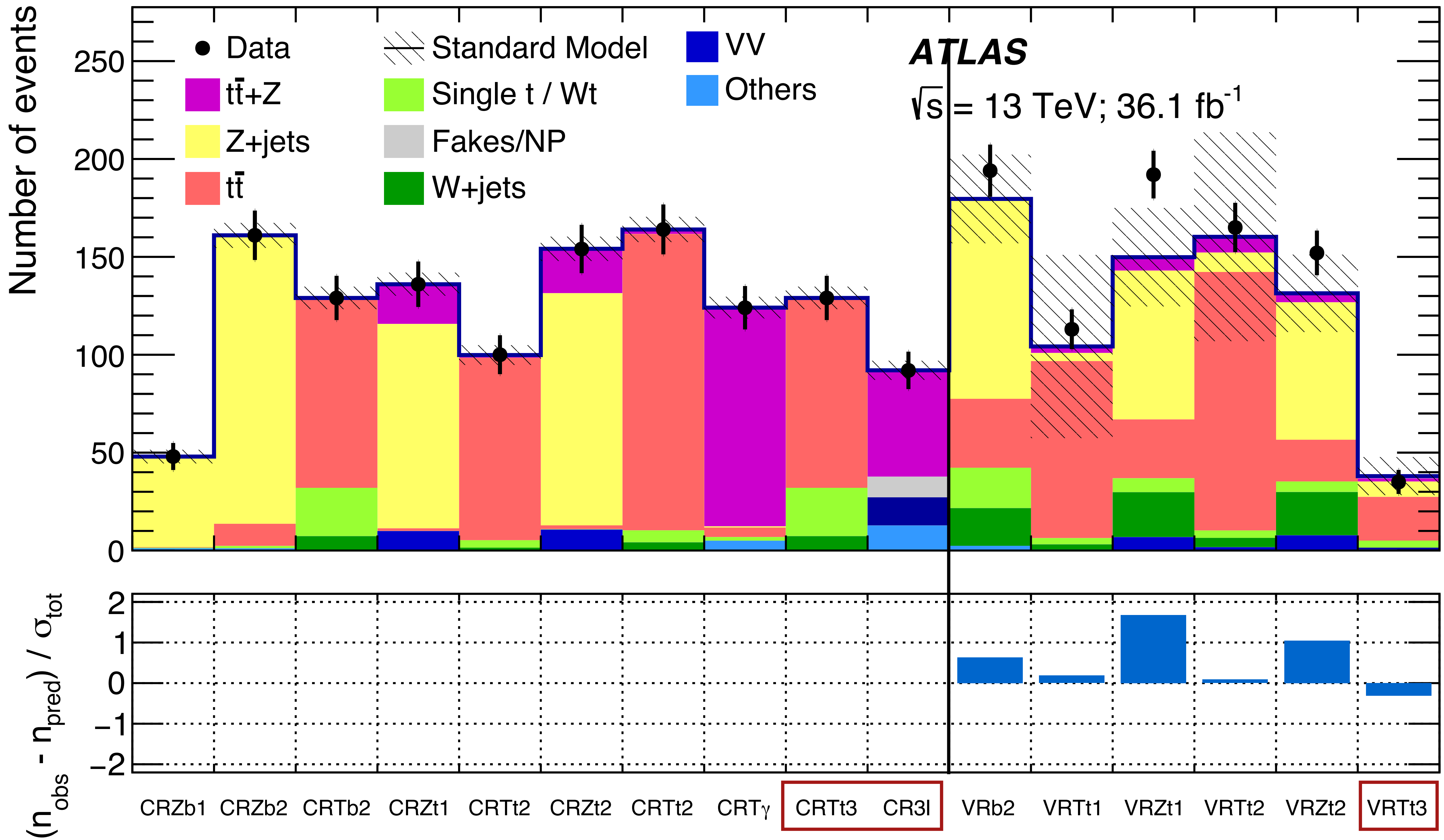
$t\bar{t}+Z$ (pre-fit)	5.6
$Z/\gamma^{*}+$ jets (pre-fit)	-
Signal benchmarks	
$m(\phi,\chi) = (20, 1)$ GeV, $g = 1$	21.0 ± 2.3
$m(a,\chi) = (20, 1)$ GeV, $g = 1$	14.1 ± 1.6
$m(\phi,\chi) = (100, 1)$ GeV, $g = 1$	11.5 ± 1.5
$m(a,\chi) = (100, 1)$ GeV, $g = 1$	11.9 ± 1.5





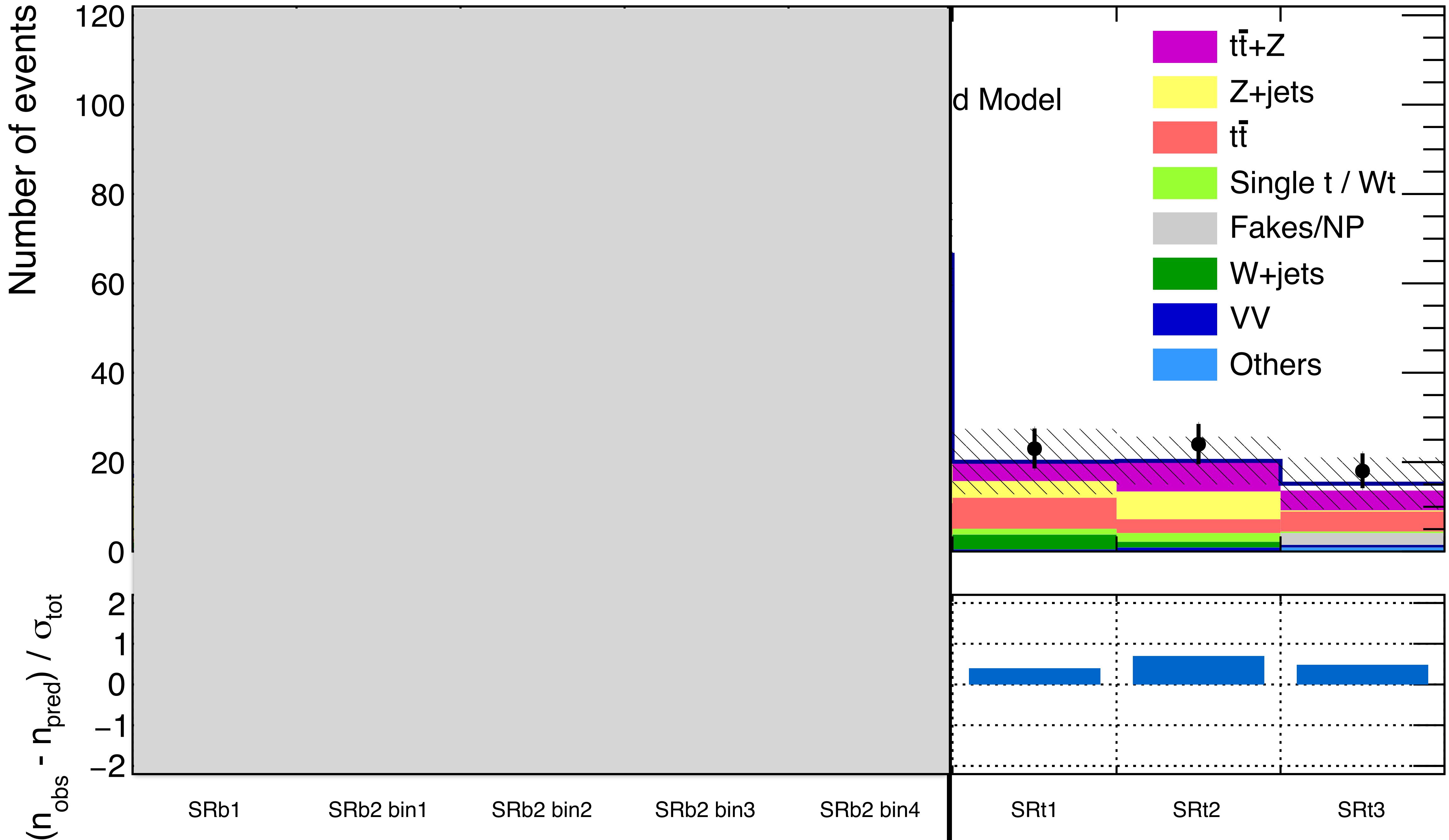
Validation of the backgrounds

Control regions | Validation regions



Results (all channels)

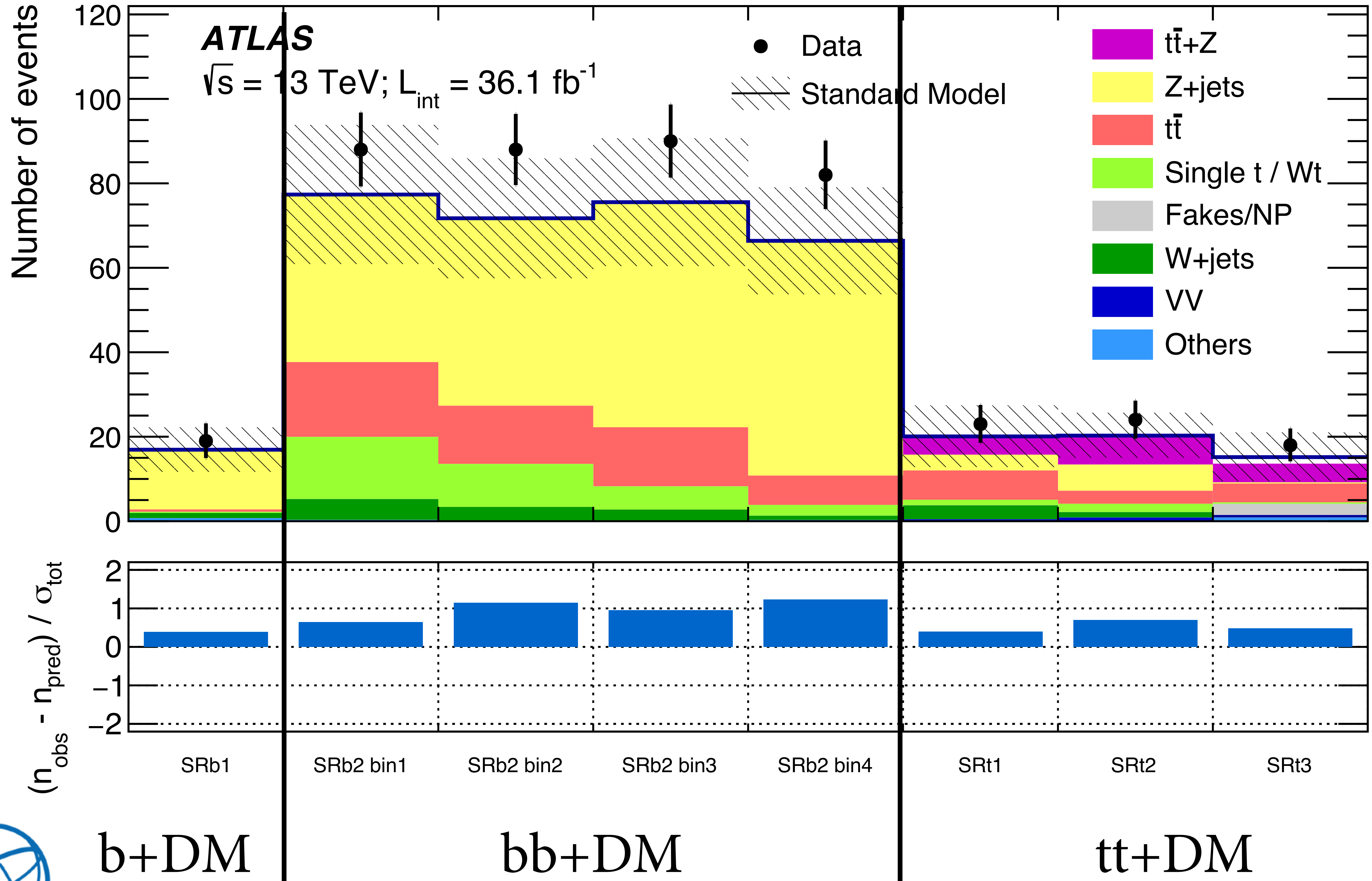
no excess found ...



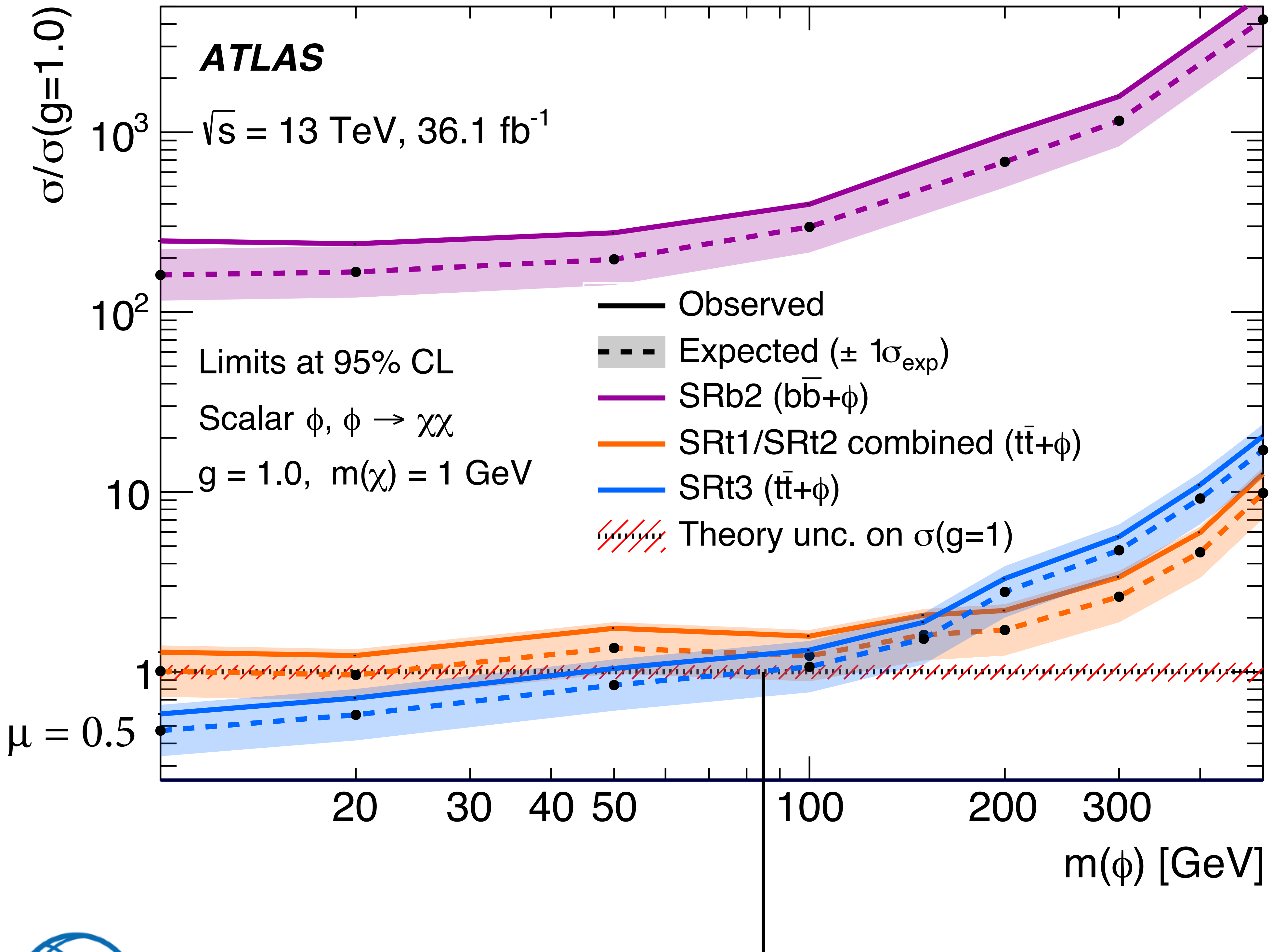
tt+DM

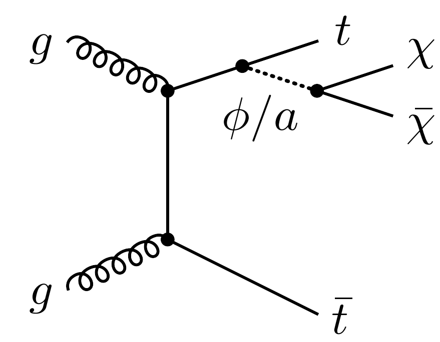
Results (all channels)

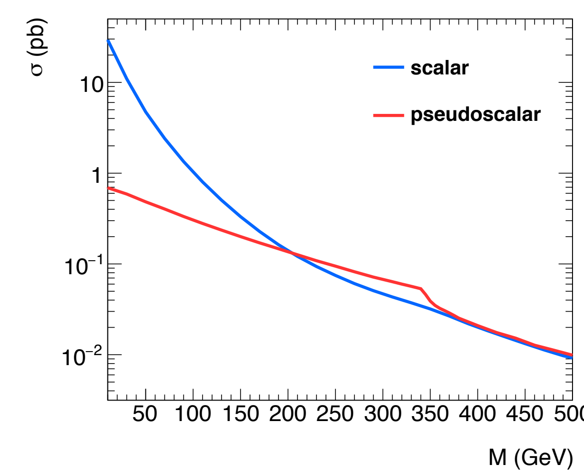
no excess found …



Interpretation of the results

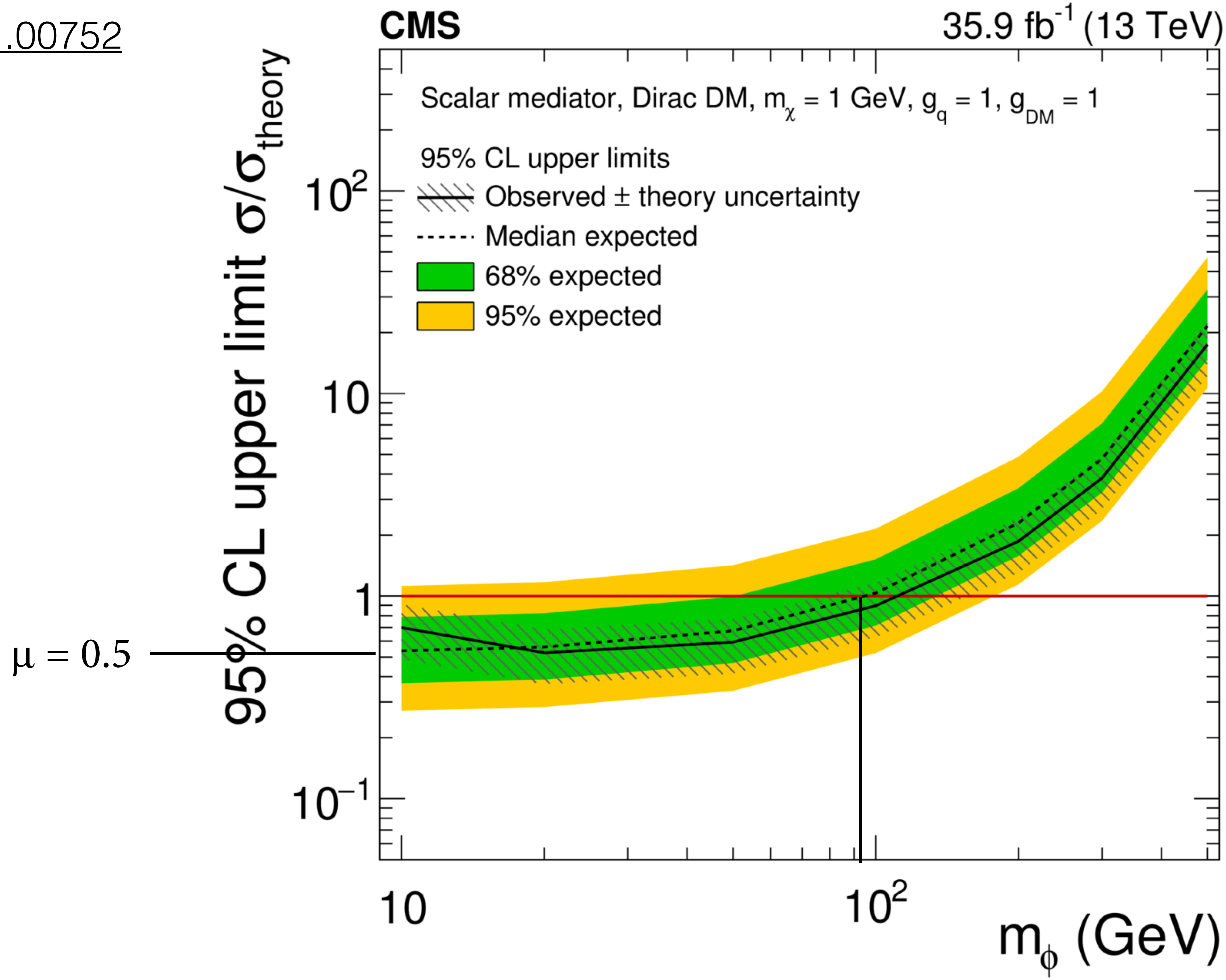




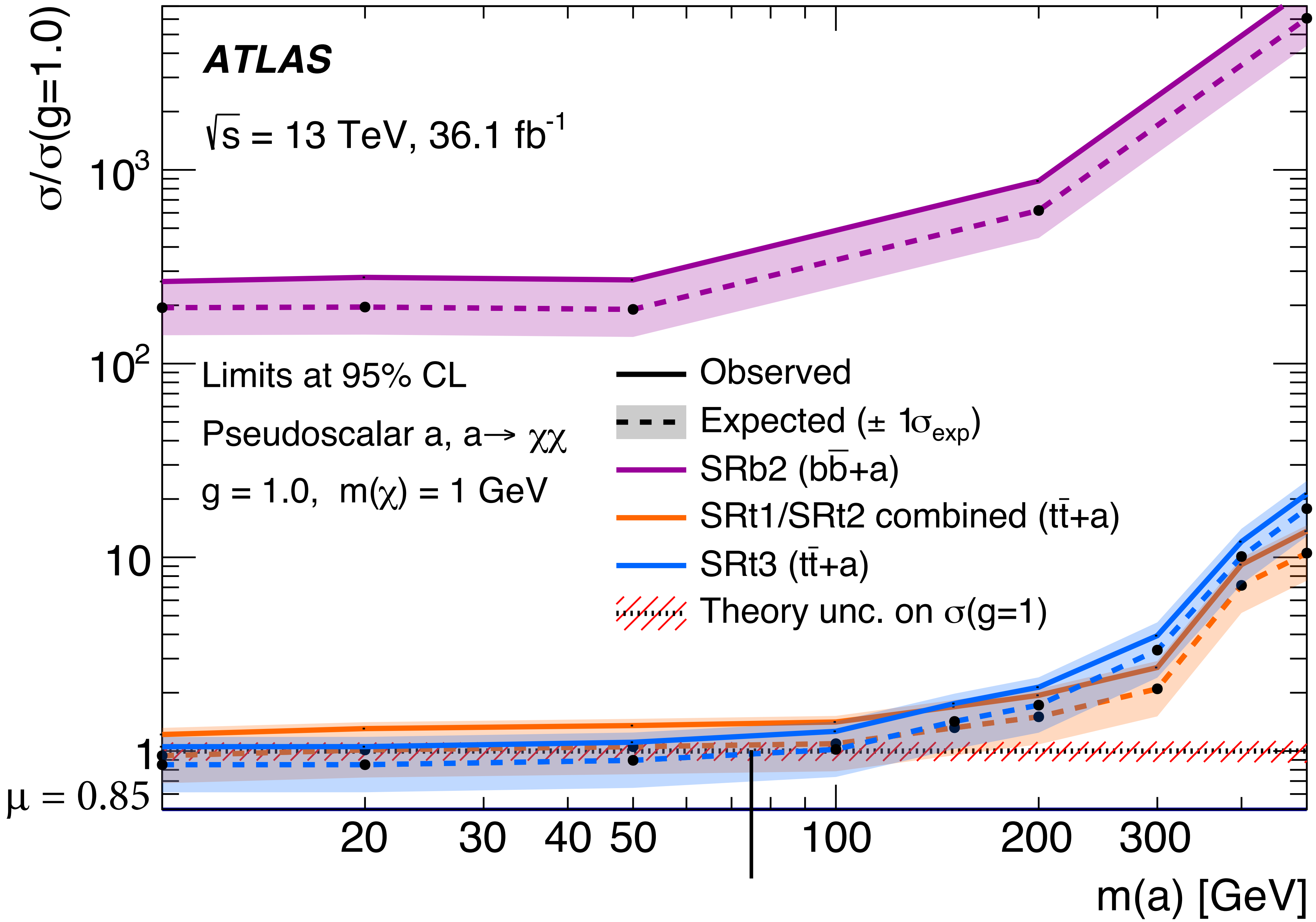


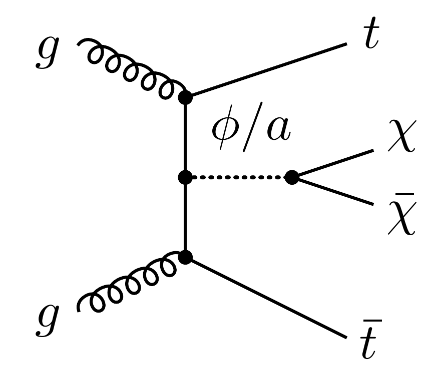
The other side of the ring

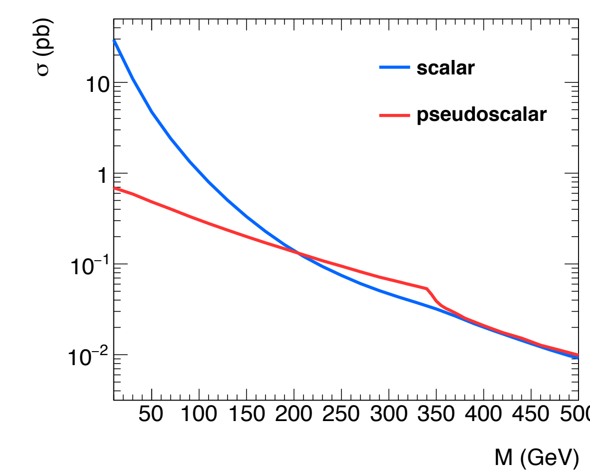
arXiv:1711.00752



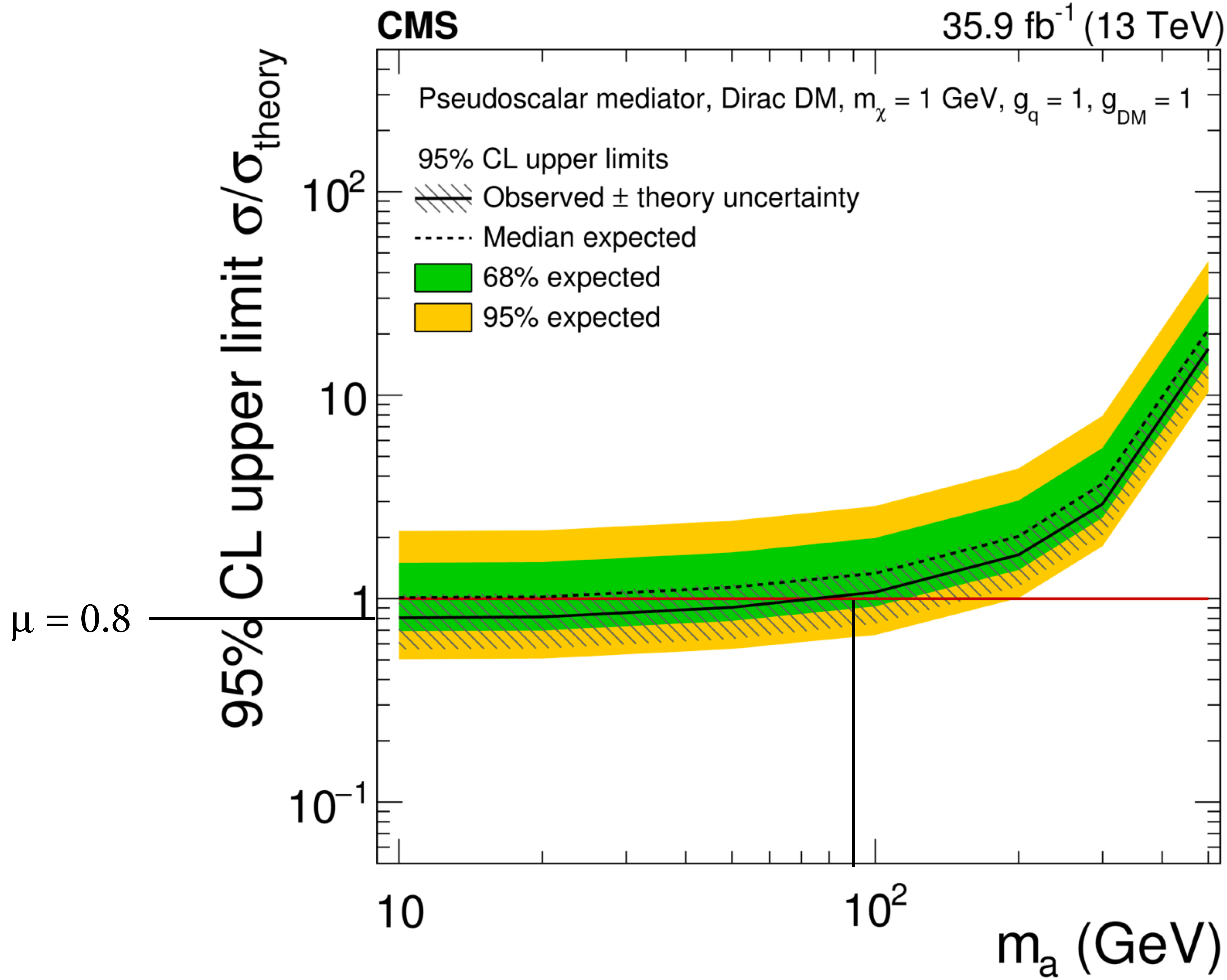
Interpretation of the results (2)



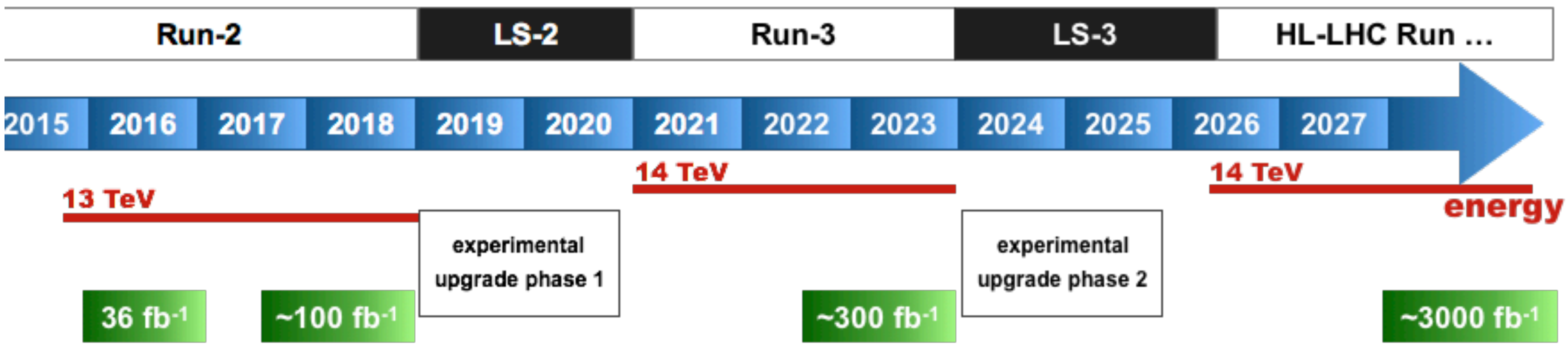




The other side of the ring (2)

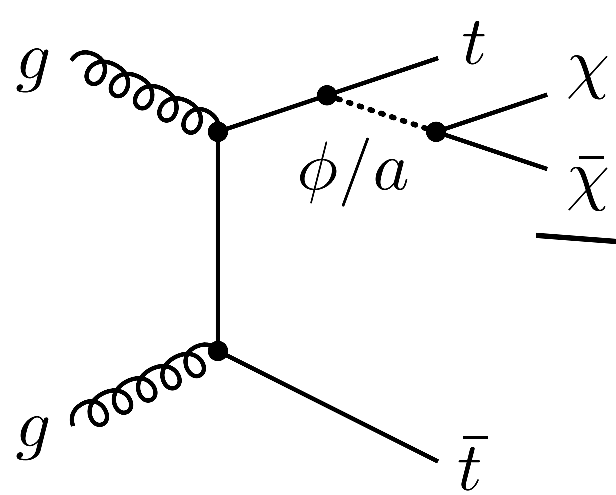


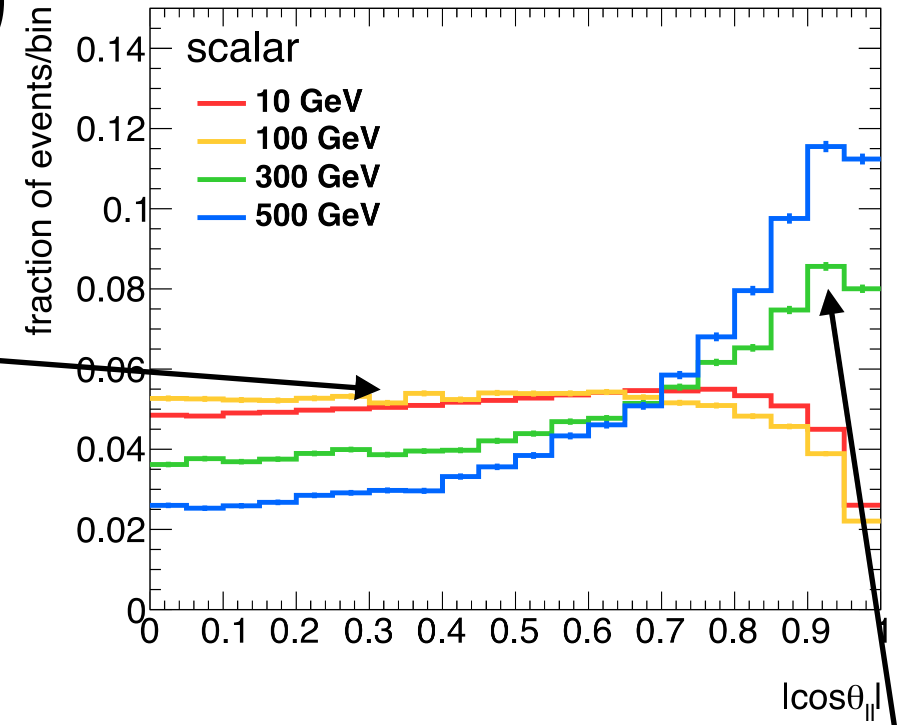
What next?

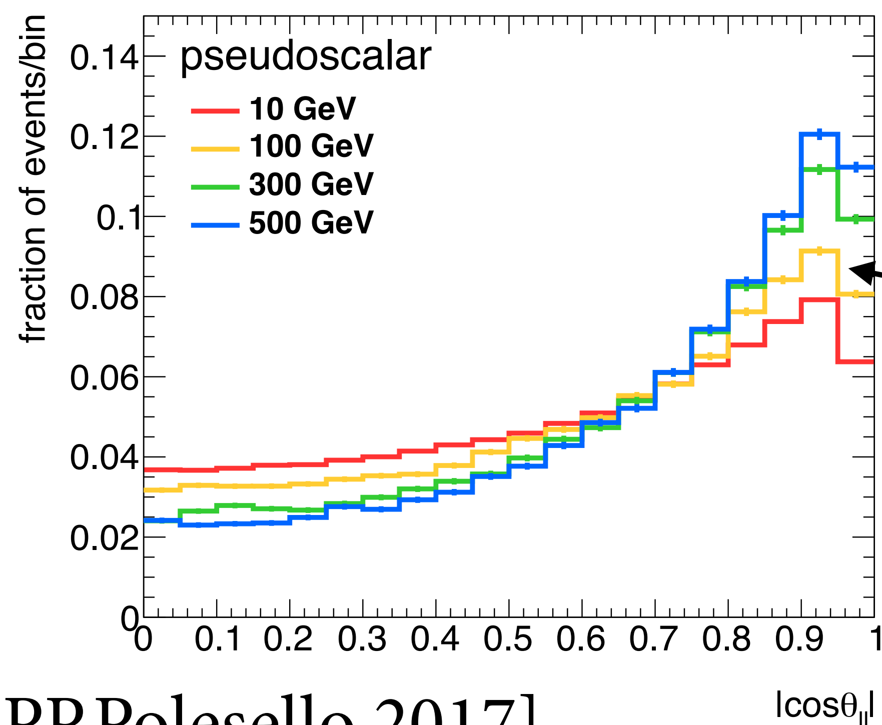

Run-2
LS-2
Run-3
LS-3
HL-LHC Run ...
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
13 TeV
14 TeV
14 TeV
energy
experimental upgrade phase 1
experimental upgrade phase 2
36 fb-1
~100 fb-1
~300 fb-1
~3000 fb-1

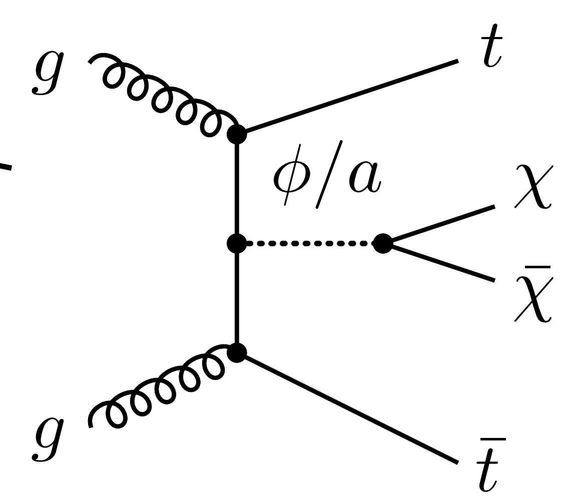
Future perspectives on the results

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



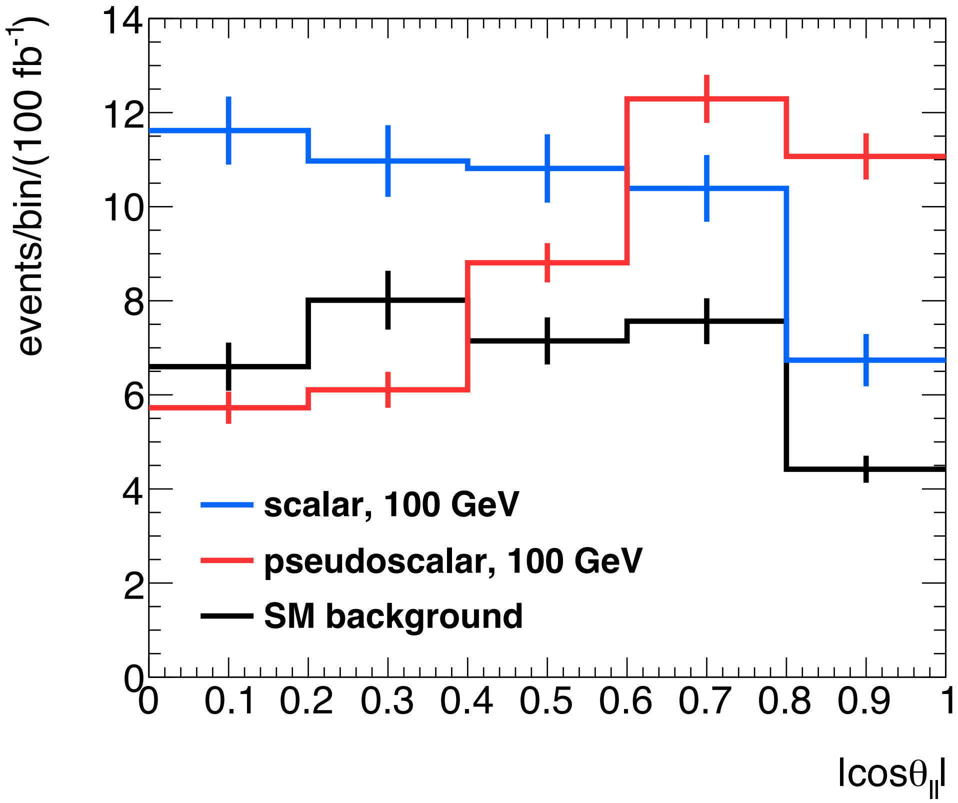






[Haisch,PP,Polesello 2017]

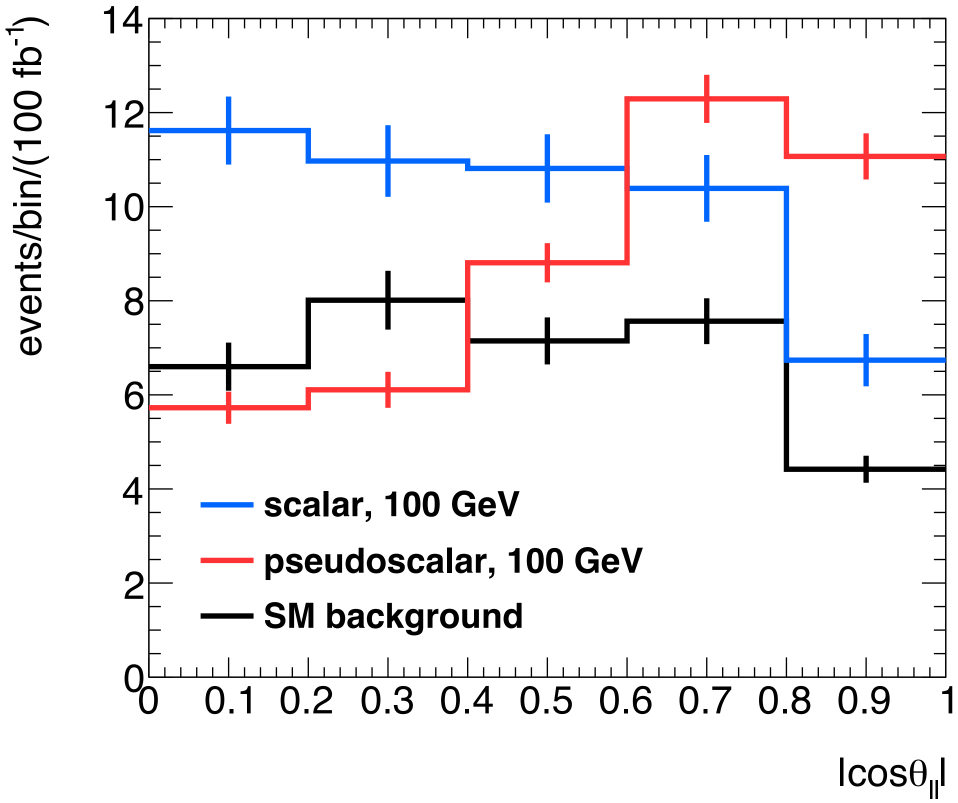
Run 3 and HL-LHC outlook

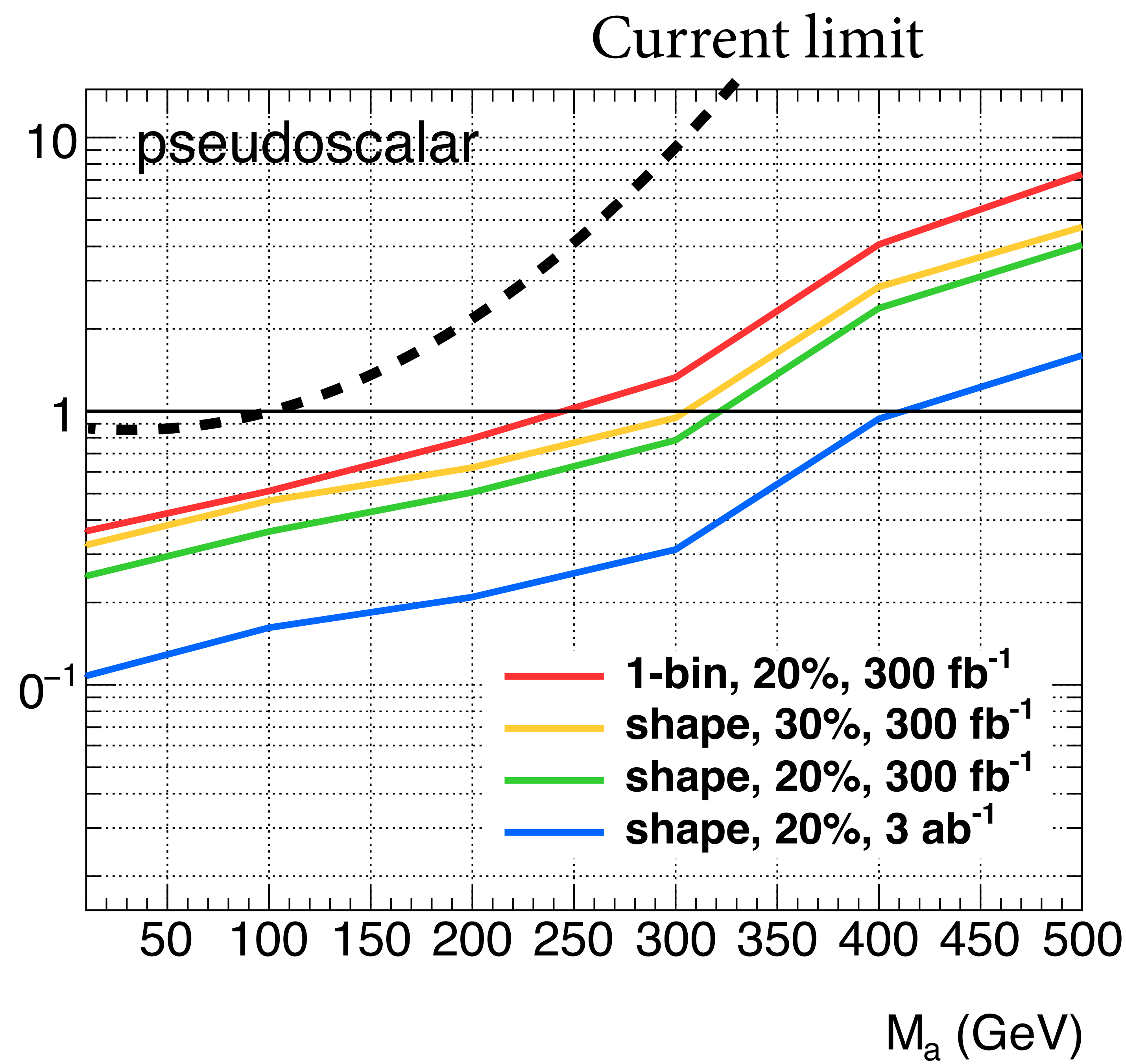


Multi-bin fit

[Haisch,PP,Polesello 2017]

Run 3 and HL-LHC outlook





Multi-bin fit

[Haisch,PP,Polesello 2017]

Can also exclude scalar hypothesis in favour of the pseudo scalar one

Considerations on the results

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

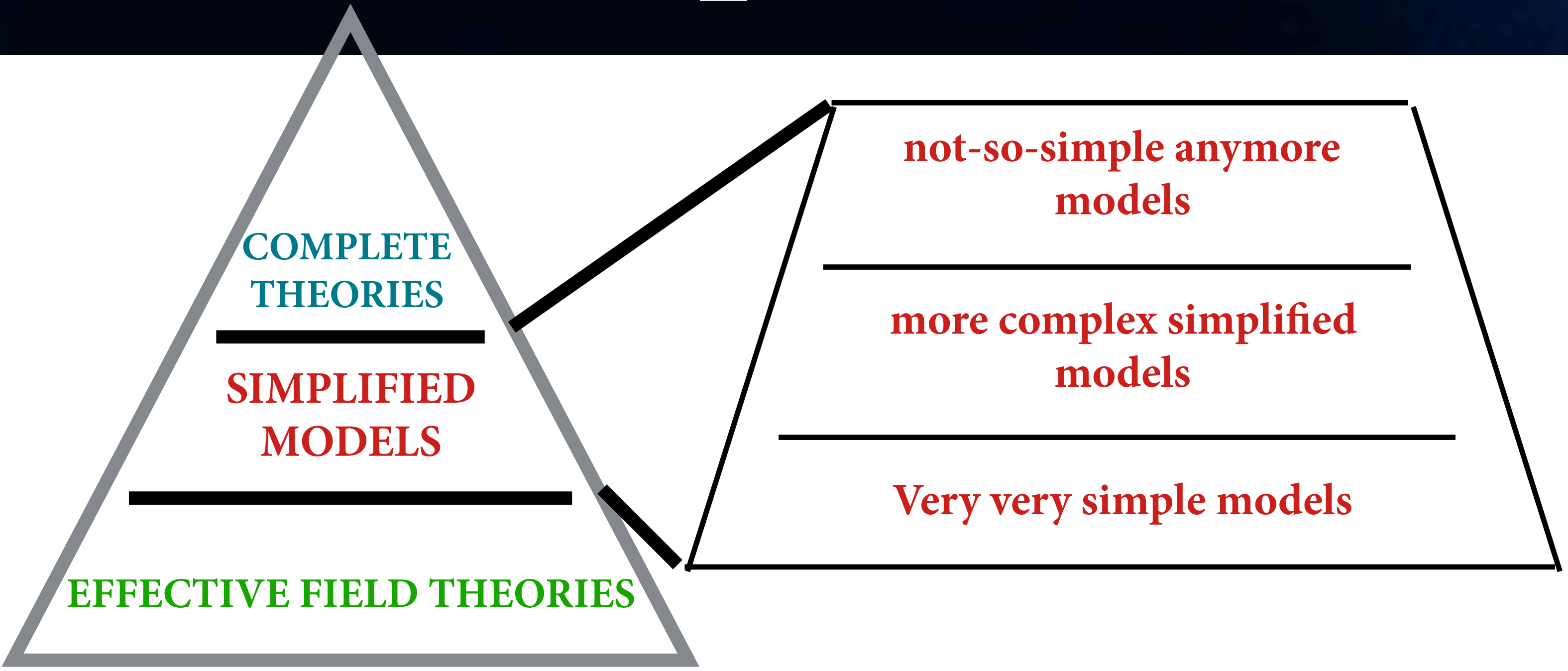
Towards the next level

new ideas

more realistic topologies

new signatures

Less simplified models



2HDM + pseudoscalar

arXiv:1701.07427

h - SM higgs

A, a - CP-odd heavy higgses

H - CP-even heavy higgs

$H^{\pm}$ - charged Higgs

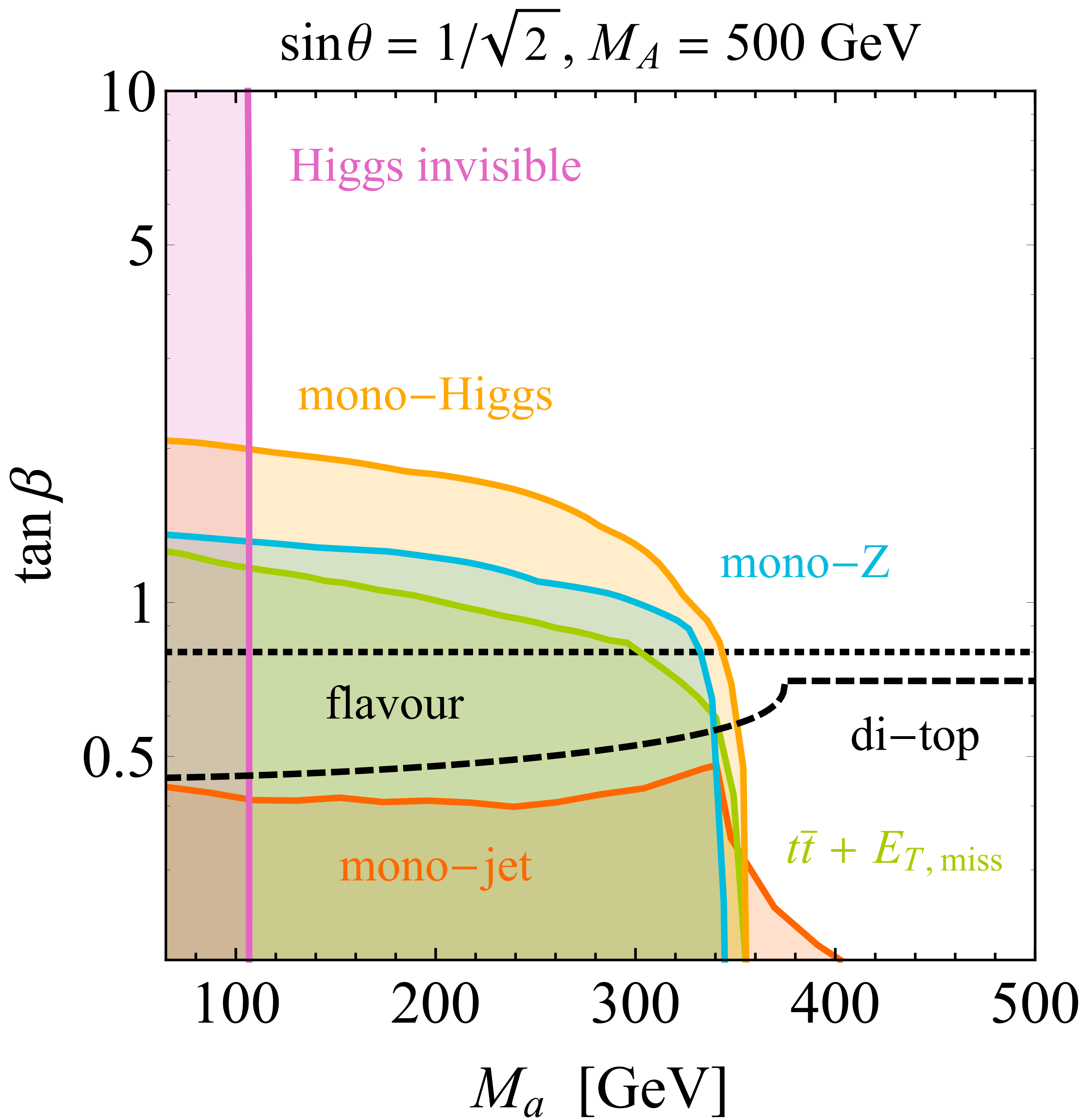
χ - DM candidate

7 parameters fixed by symmetry and EWK/Higgs measurements.

7 left free:

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

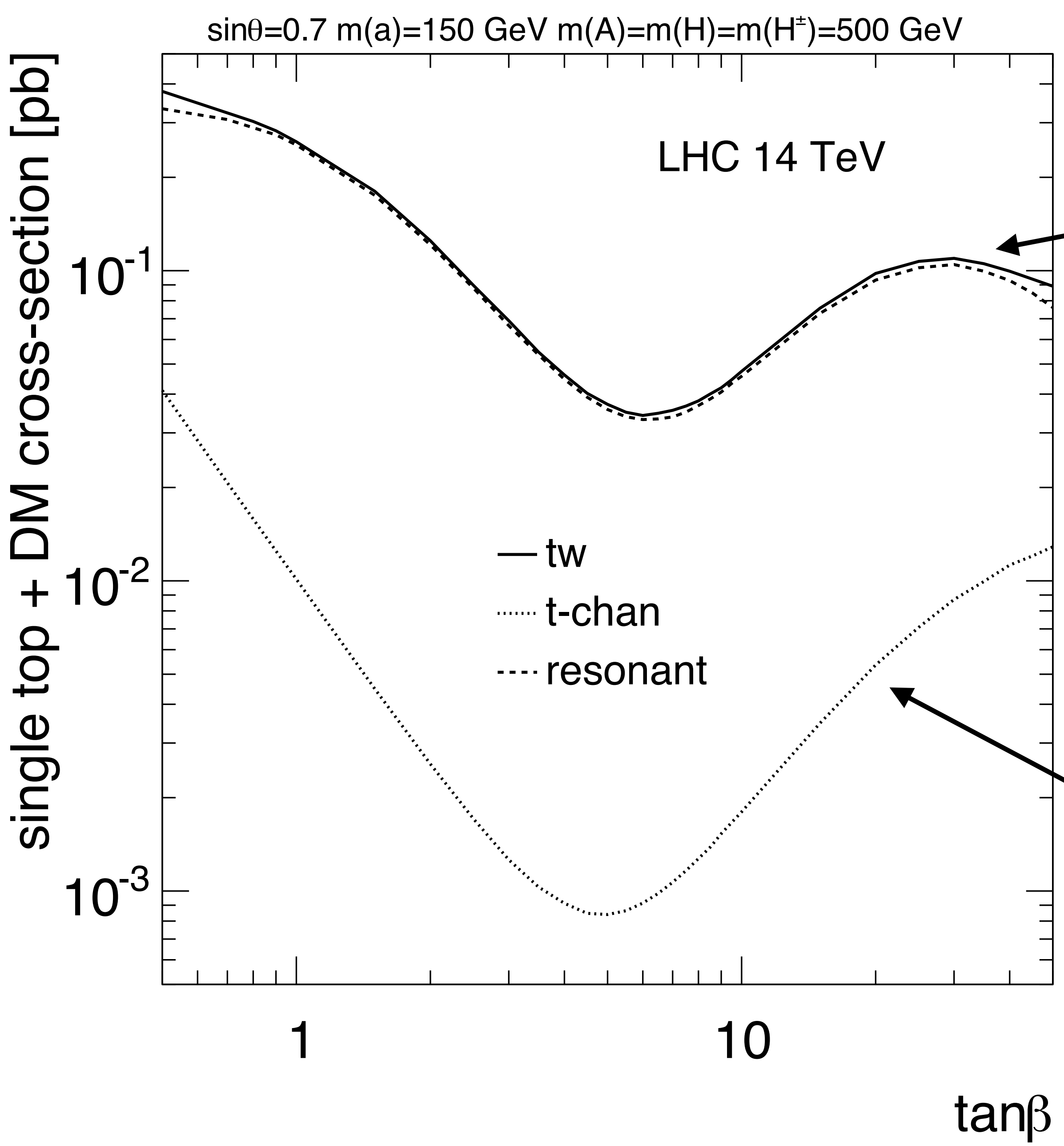
2HDM+a

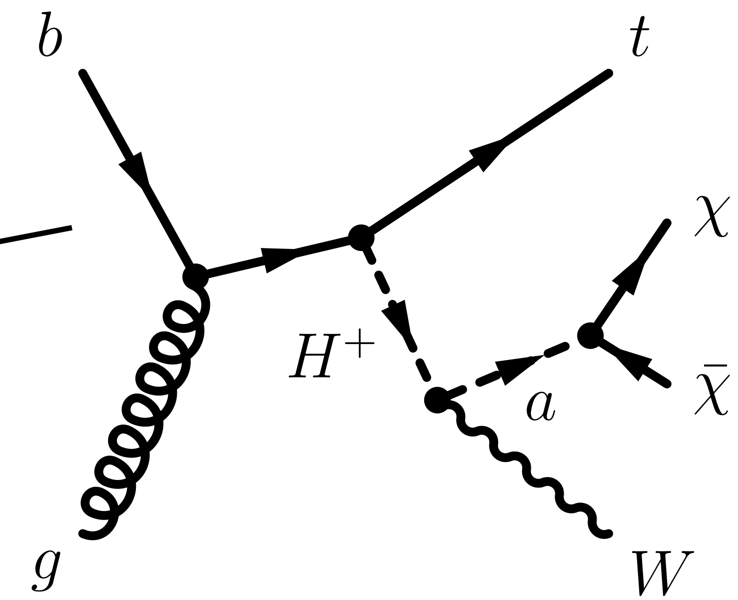


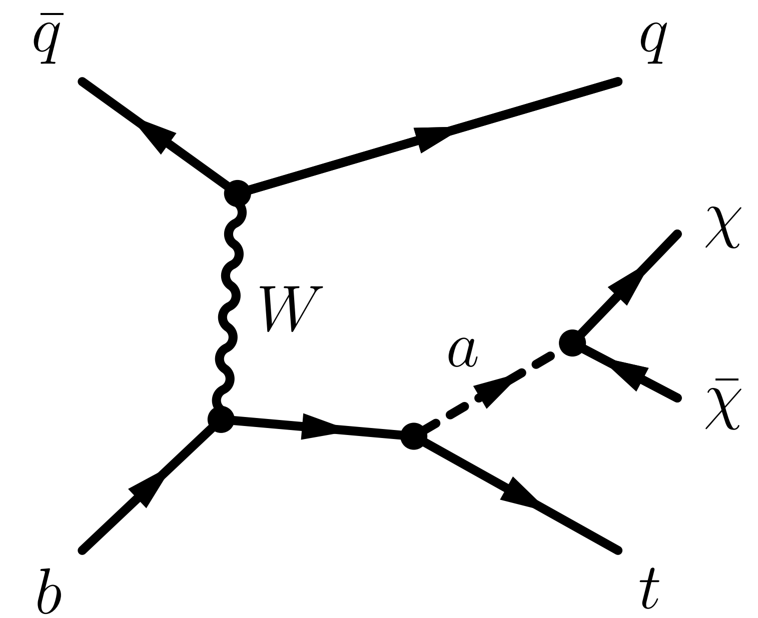
- ★ Phenomenology recast
- ★ Looking forward sensitivity evaluation from experiments

arXiv:1701.07427

New signatures

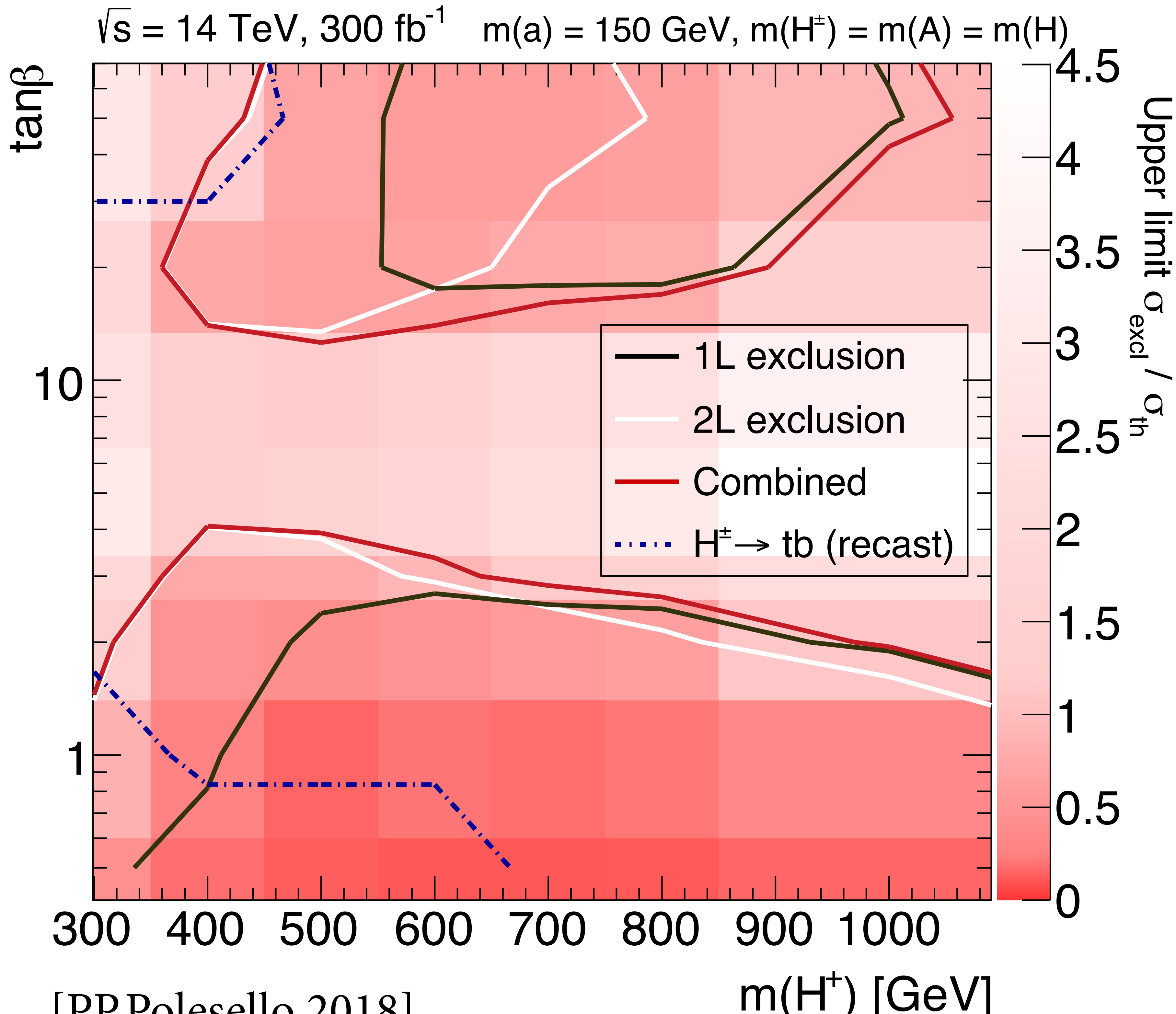






[PP,Polesello 2018]

Sensitivity forecast



[PP,Polesello 2018]

Conclusions

- The quest for Dark Matter is an extremely exciting field that can also be pursued at collider experiments
- Heavy quark final states allow to cover the search for spin-0 mediators and cover a broad range of parameter space
- More complex and realistic models are an important tool to uncover new signatures to be pursued in future analyses.

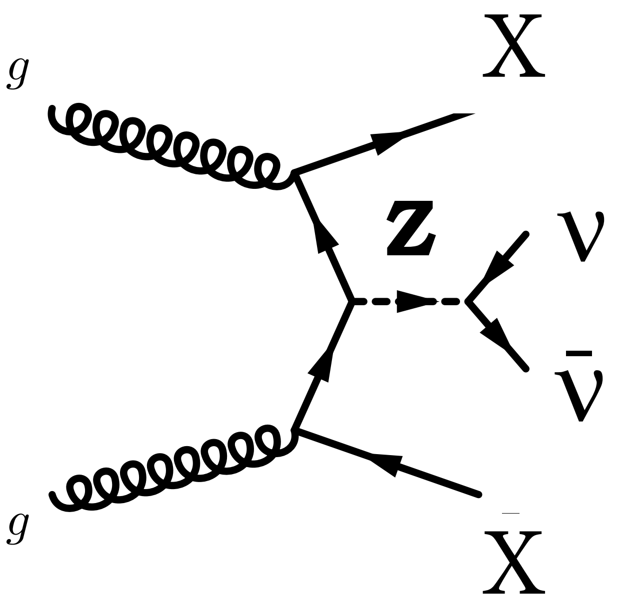
The End

Thanks for your ~~attention~~ patience

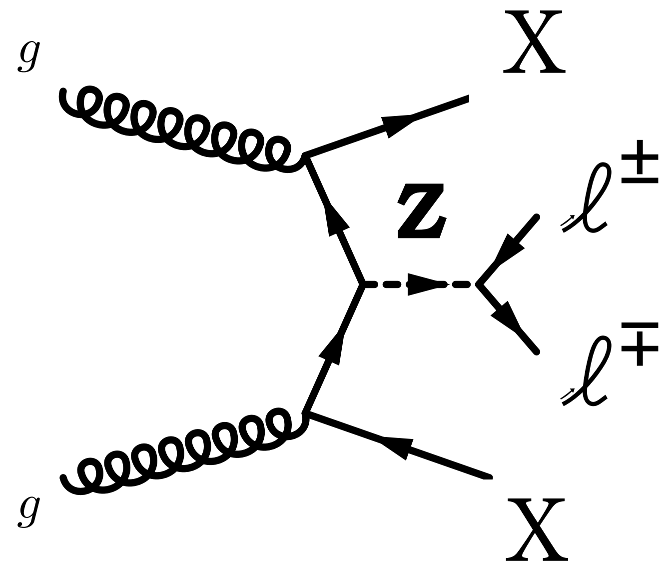
Any question ?

Backup

The Z(νν) background

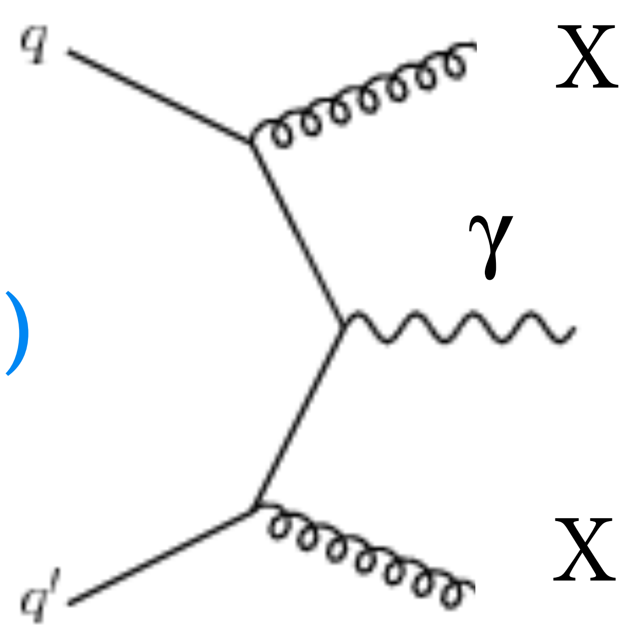


1)



- lower BR / stat ✗
- good control of lepton-related syst. ✓
- can select b-jets CR ✓

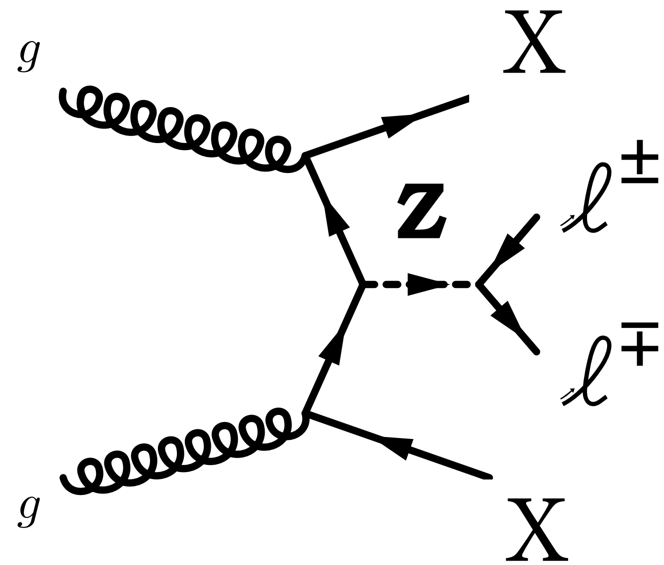
2)



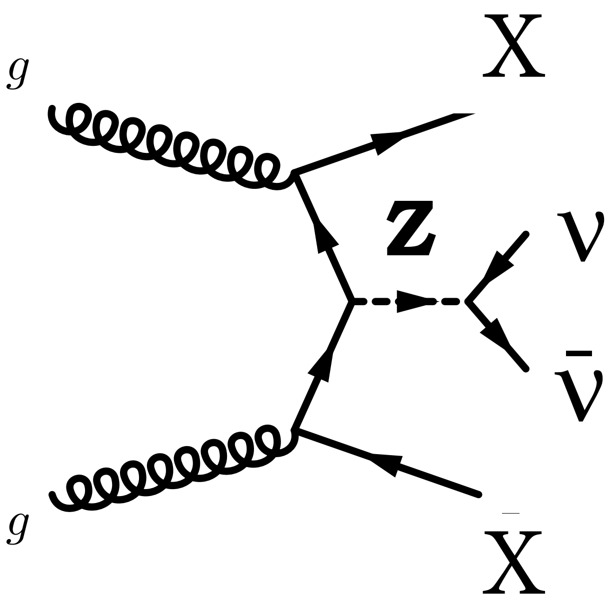
- higher xsec / stat ✓
- good proxy only if pT(Z) >> M(Z)
- higher extrapolation uncertainties ✗

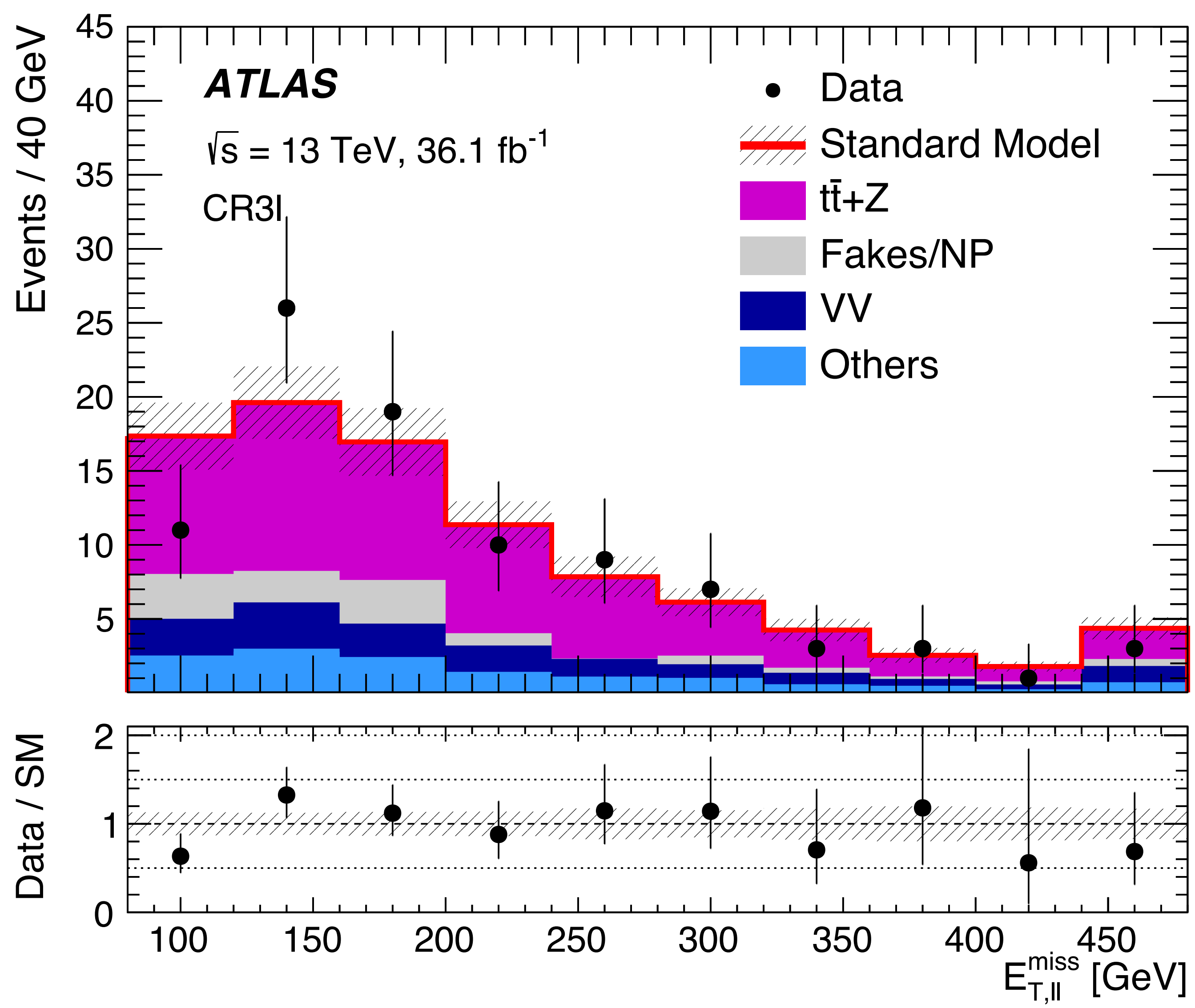
The Z(νν) background

1)

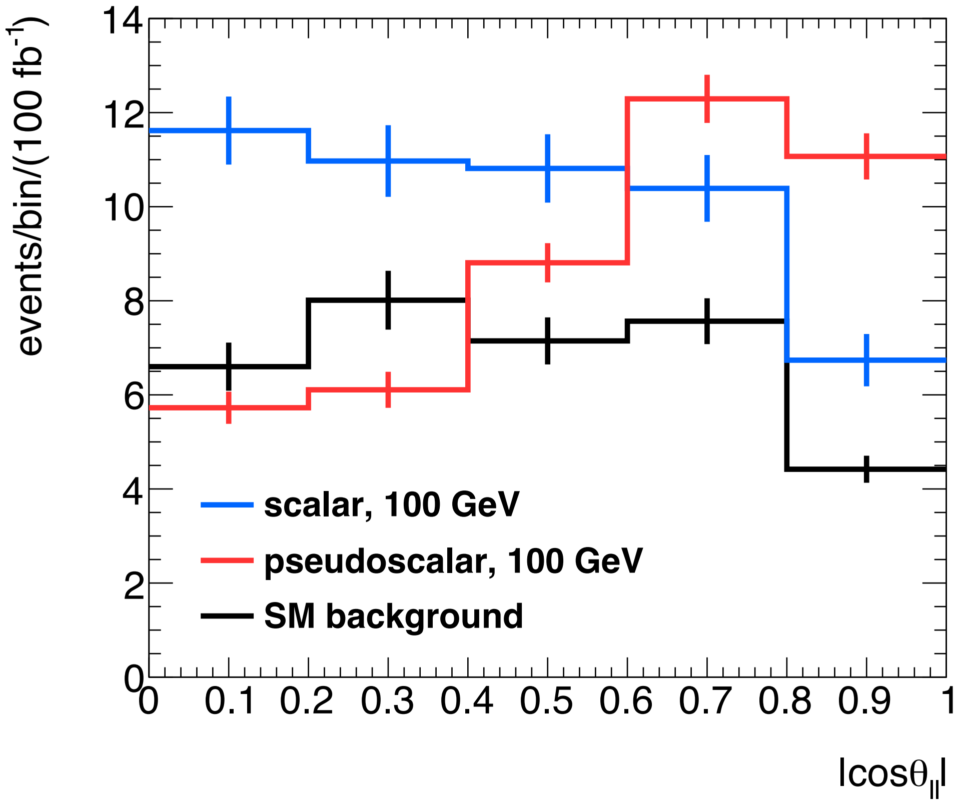


- ★ lower BR / stat ✘
- ★ good control of lepton-related syst. ✓
- ★ can select b-jets CR ✓

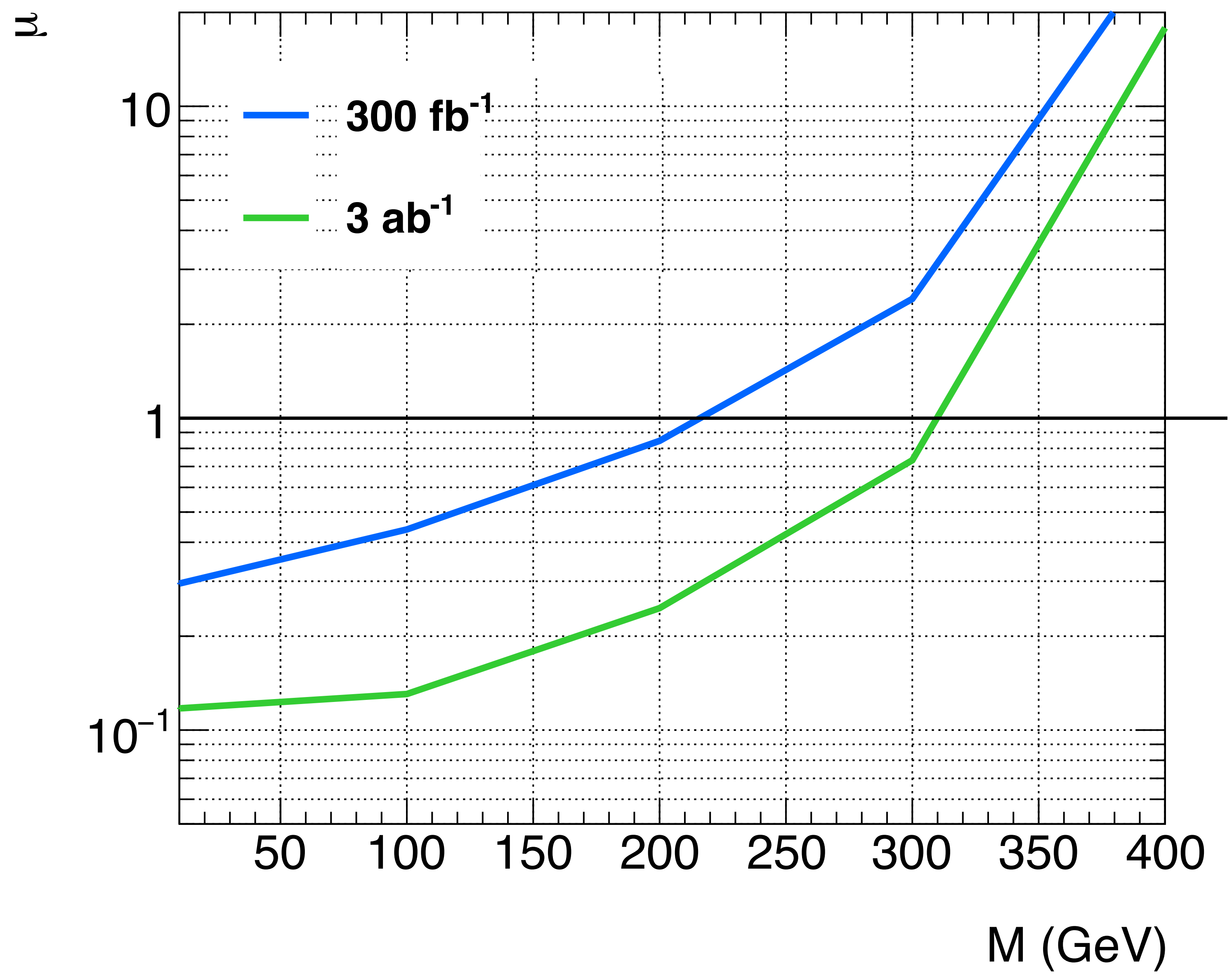




Run 3 and HL-LHC outlook



Exclude scalar hypothesis in favour of the pseudo scalar one

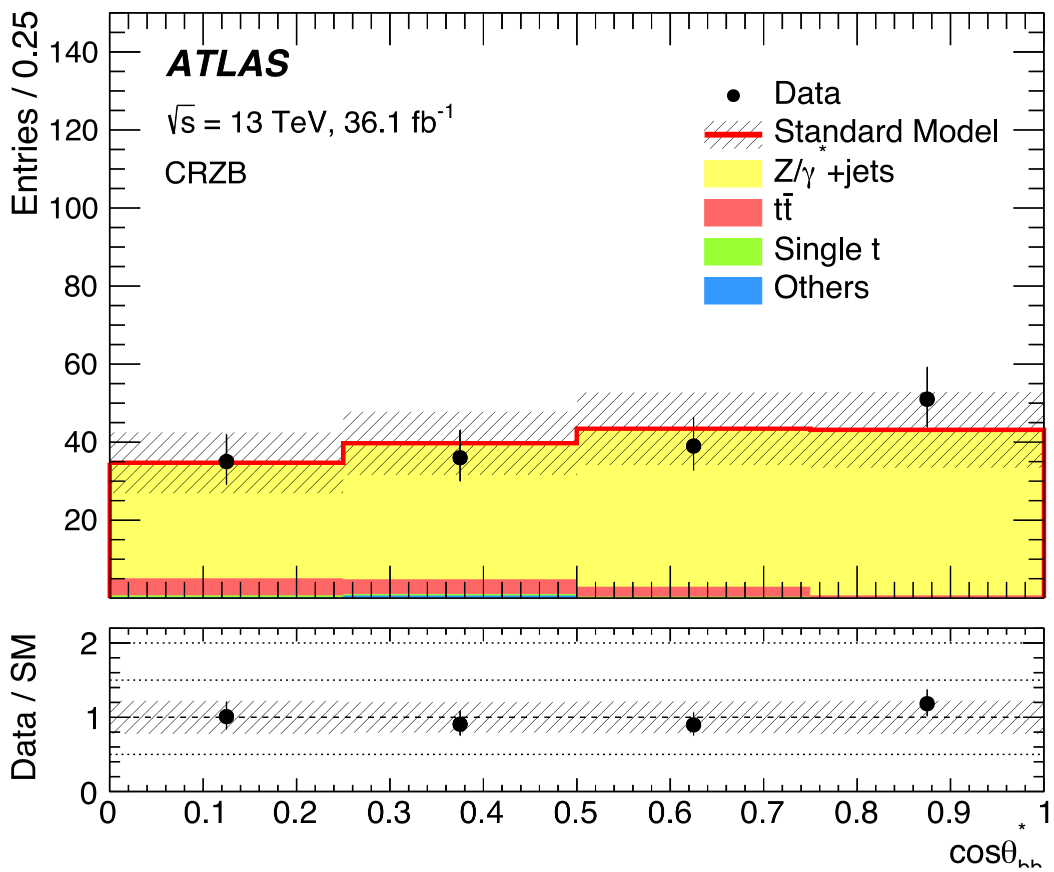


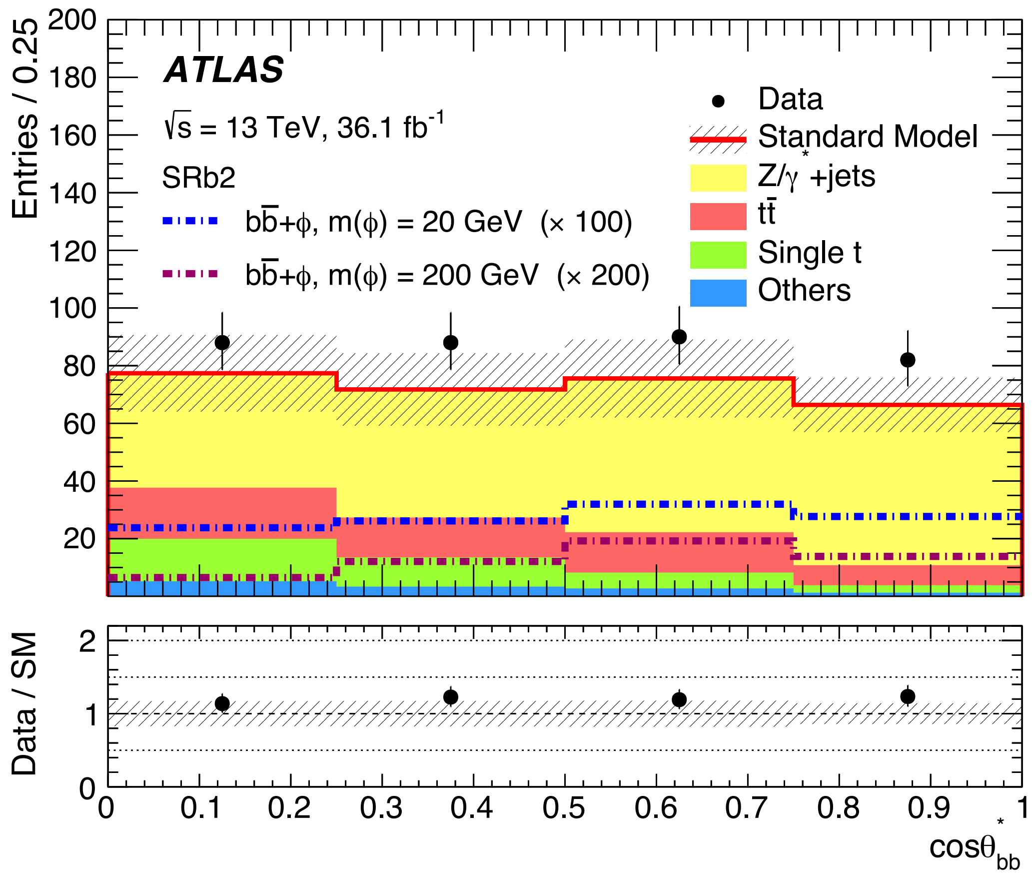
Multi-bin fit

[Haisch,PP,Polesello 2017]

SRb2 details

	SRb2 [%]
Total systematic uncertainty	15–18
Z theoretical uncertainties	7.9–12
$t\bar{t}+Z$ theoretical uncertainties	<1
$t\bar{t}$ theoretical uncertainties	2.7–9.8
MC statistical uncertainties	4.8–6.4
Z fitted normalisation	12–19
$t\bar{t}+Z$ fitted normalisation	-
$t\bar{t}$ fitted normalisation	1.9–4.2
Fake or non-prompt leptons	-
Pile-up	<1–1.4
Jet energy resolution	1.3–6.9
Jet energy scale	5.0–10
E_T^{miss} soft term	4.3–6.3
b-tagging	2.4–6.9





Total systematic uncertainties

	SRb1 [%]	SRb2 [%]	SRt1 [%]	SRt2 [%]	SRt3 [%]
Total systematic uncertainty	18	15–18	29	14	28
Z theoretical uncertainties	5.7	7.9–12	5.0	2.1	<1
$t\bar{t}+Z$ theoretical uncertainties	<1	<1	3.3	5.3	8.4
$t\bar{t}$ theoretical uncertainties	<1	2.7–9.8	17	5.7	11
MC statistical uncertainties	6.4	4.8–6.4	15	5.9	18
Z fitted normalisation	13	12–19	2.3	3.4	-
$t\bar{t}+Z$ fitted normalisation	-	-	2.2	3.5	7.1
$t\bar{t}$ fitted normalisation	-	1.9–4.2	3.9	1.4	2.0
Fake or non-prompt leptons	-	-	-	-	7.9
Pile-up	3.8	<1–1.4	6.8	5.5	<1
Jet energy resolution	1.5	1.3–6.9	7.0	<1	<1
Jet energy scale	7.7	5.0–10	5.0	2.8	8.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term	<1	4.3–6.3	2.0	<1	12
b-tagging	<1	2.4–6.9	8.6	3.1	<1

SR yields

	SRb1	SRb2-bin1	SRb2-bin2	SRb2-bin3	SRb2-bin4
Observed	19	88	88	90	82
Total background (fit)	16.9 ± 3.3	77 ± 13	72 ± 11	76 ± 13	66.4 ± 9.1
Z/γ^{*}+ jets	14.2 ± 3.1	39.7 ± 6.3	44.4 ± 6.6	53.3 ± 9.9	55.6 ± 8.6
$t\bar{t}$	$0.58^{+0.60}_{-0.58}$	17.8 ± 6.5	13.8 ± 5.5	14.0 ± 4.7	7.0 ± 2.9
Single top quark	$0.25^{+0.42}_{-0.25}$	14.7 ± 5.8	10.2 ± 3.7	5.5 ± 3.1	2.6 ± 1.7
Others	2.0 ± 1.1	5.2 ± 3.4	$3.4^{+1.7}_{-1.6}$	2.7 ± 1.1	1.3 ± 1.0
Z/γ^{*}+ jets (pre-fit)	12.1	30.6	34.2	41.1	42.8
$t\bar{t}$ (pre-fit)	-	27.1	21.1	21.4	10.6
Signal benchmarks					
$m(\phi, \chi) = (20, 1)$ GeV, $g = 1$		0.238 ± 0.085	0.262 ± 0.079	0.320 ± 0.082	0.277 ± 0.080
$m(a, \chi) = (20, 1)$ GeV, $g = 1$		0.256 ± 0.065	0.199 ± 0.060	0.308 ± 0.085	0.267 ± 0.067
$m(\phi_b, \chi) = (1000, 35)$ GeV	18.6 ± 3.8				

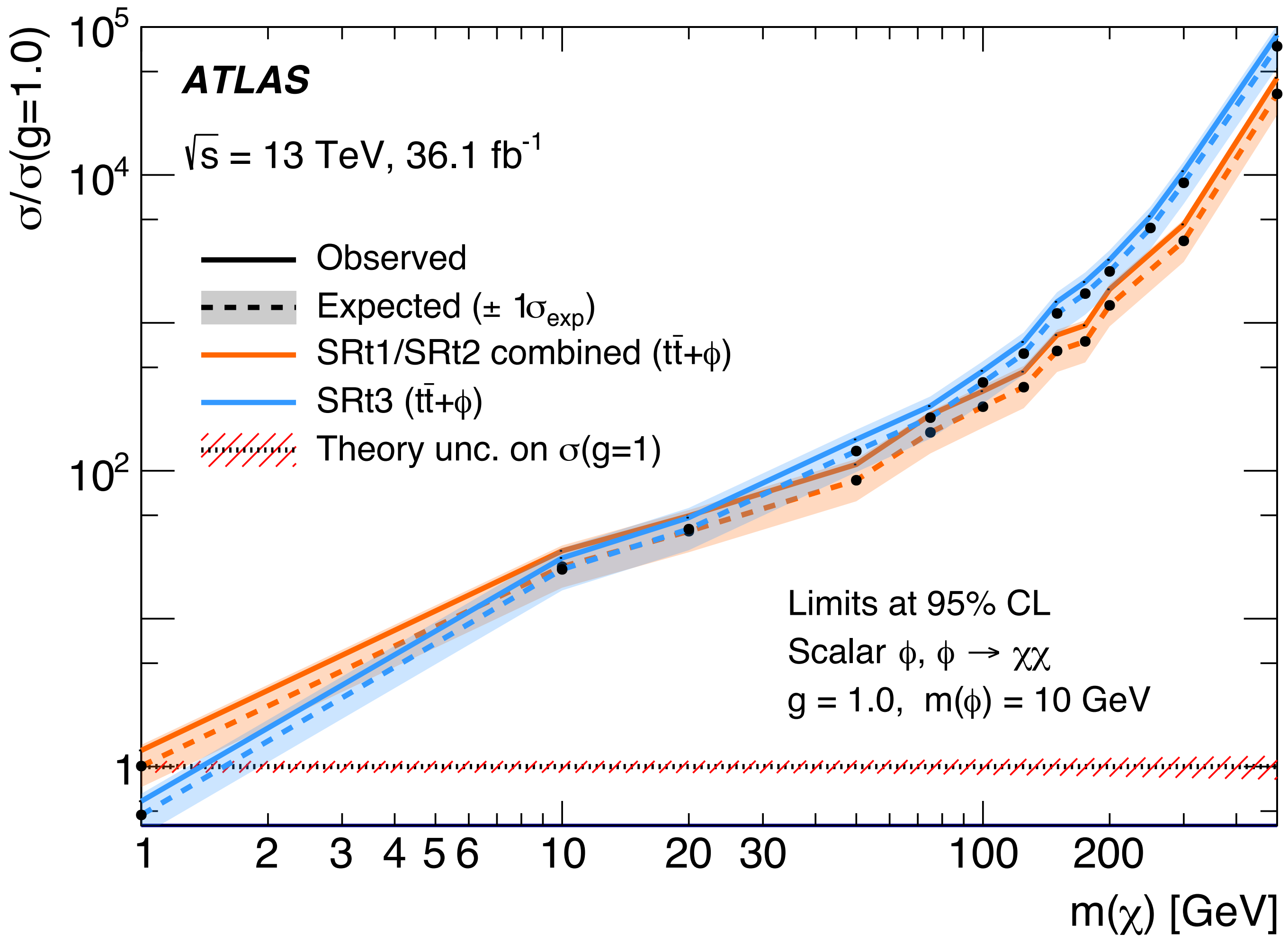
SR yields

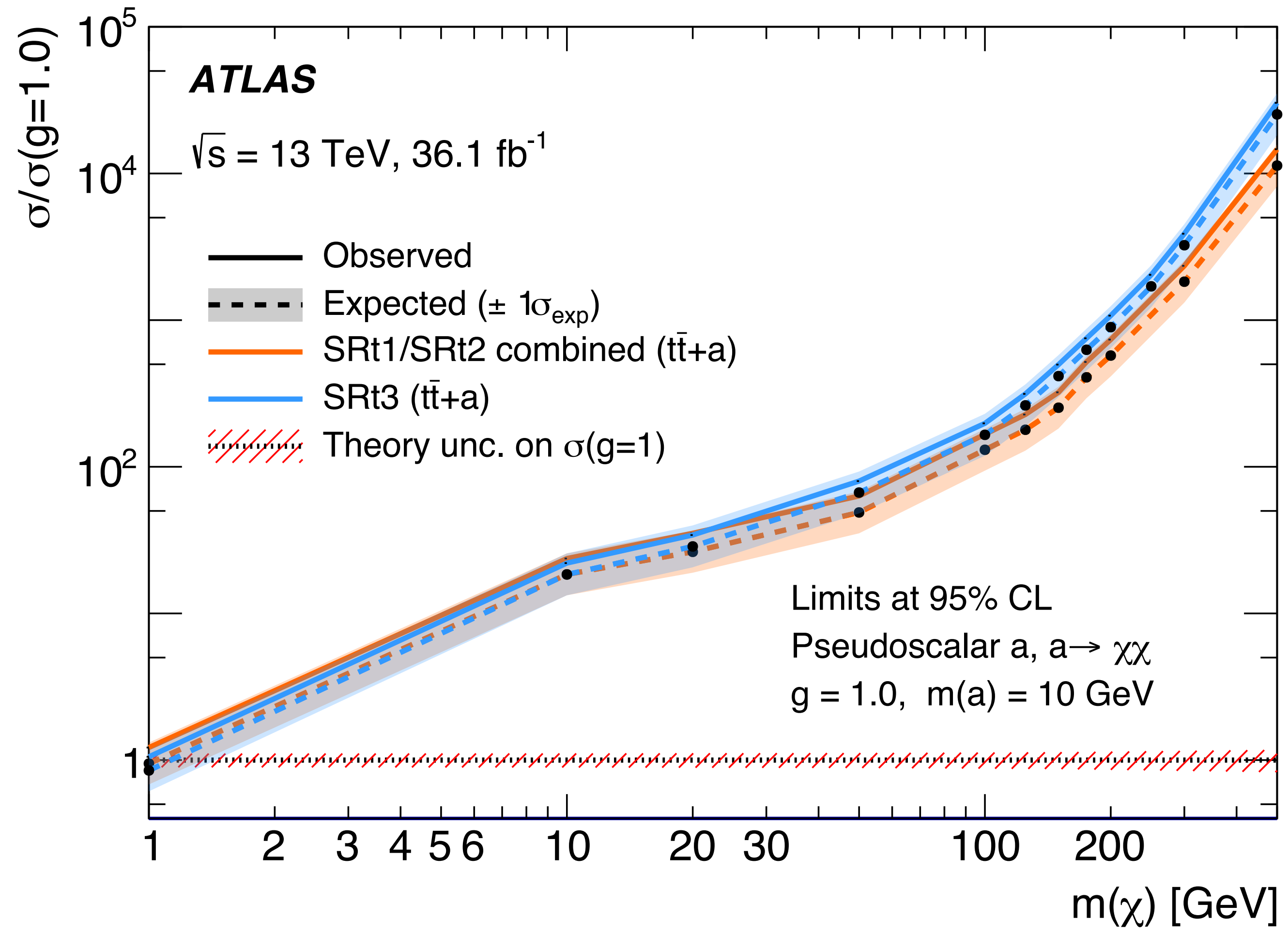
	SRt1	SRt2	SRt3
Observed	23	24	18
Total background (fit)	20.5 ± 5.8	20.4 ± 2.9	15.2 ± 4.3
$t\bar{t}$	7.0 ± 3.9	3.1 ± 1.3	4.5 ± 2.5
$t\bar{t}$+Z	4.3 ± 1.1	6.9 ± 1.4	4.4 ± 1.9
W+ jets	3.3 ± 2.6	1.28 ± 0.50	incl. in Fakes/NP
Wt	incl. in Others	incl. in Others	$0.33^{+0.53}_{-0.33}$
Z/γ^{*}+ jets	3.7 ± 1.4	6.2 ± 1.1	incl. in Others
VV	incl. in Others	incl. in Others	0.61 ± 0.25
Fakes/NP	-	-	2.7 ± 1.3
Others	2.2 ± 1.2	3.00 ± 1.6	2.69 ± 0.93
$t\bar{t}$ (pre-fit)	6.1	2.8	4.0
$t\bar{t}$+Z (pre-fit)	3.53	5.6	5.6
Z/γ^{*}+ jets (pre-fit)	3.2	5.72	-
Signal benchmarks			
$m(\phi, \chi)$ = (20, 1) GeV, g = 1	9.3 ± 1.6	12.8 ± 1.9	21.0 ± 2.3
$m(a, \chi)$ = (20, 1) GeV, g = 1	7.6 ± 1.5	12.1 ± 1.8	14.1 ± 1.6
$m(\phi, \chi)$ = (100, 1) GeV, g = 1	6.5 ± 1.3	10.1 ± 1.5	11.5 ± 1.5
$m(a, \chi)$ = (100, 1) GeV, g = 1	6.2 ± 1.2	11.5 ± 2.0	11.9 ± 1.5

Model independent limits

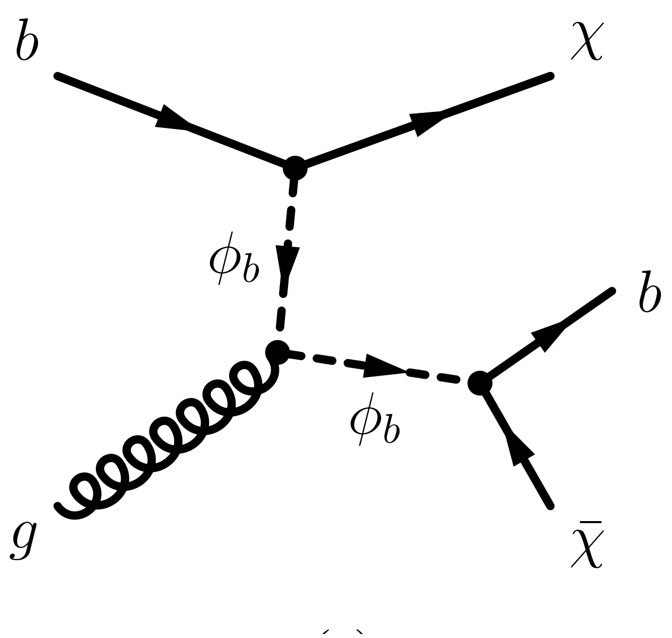
Signal channel	$\langle \epsilon \mathcal{A} \sigma \rangle_{95}^{\text{obs}}$[fb]	S_{95}^{obs}	S_{95}^{exp}	$p(s = 0)$ (Z)
SRb1	0.37	13.4	12^{+5}_{-1}	0.33 (0.43)
SRb2 bin-1	1.10	39.6	33^{+12}_{-8}	0.22 (0.76)
SRb2 bin-2	1.17	42.1	31^{+10}_{-8}	0.11 (1.21)
SRb2 bin-3	1.21	43.7	33^{+11}_{-8}	0.16 (1.00)
SRb2 bin-4	1.10	39.8	26^{+11}_{-7}	0.10 (1.26)
SRt1	0.51	18.4	16^{+5}_{-4}	0.33 (0.44)
SRt2	0.44	15.7	12^{+5}_{-3}	0.24 (0.70)
SRt3	0.44	15.9	13^{+5}_{-2}	0.33 (0.45)

Off-shell interpretation

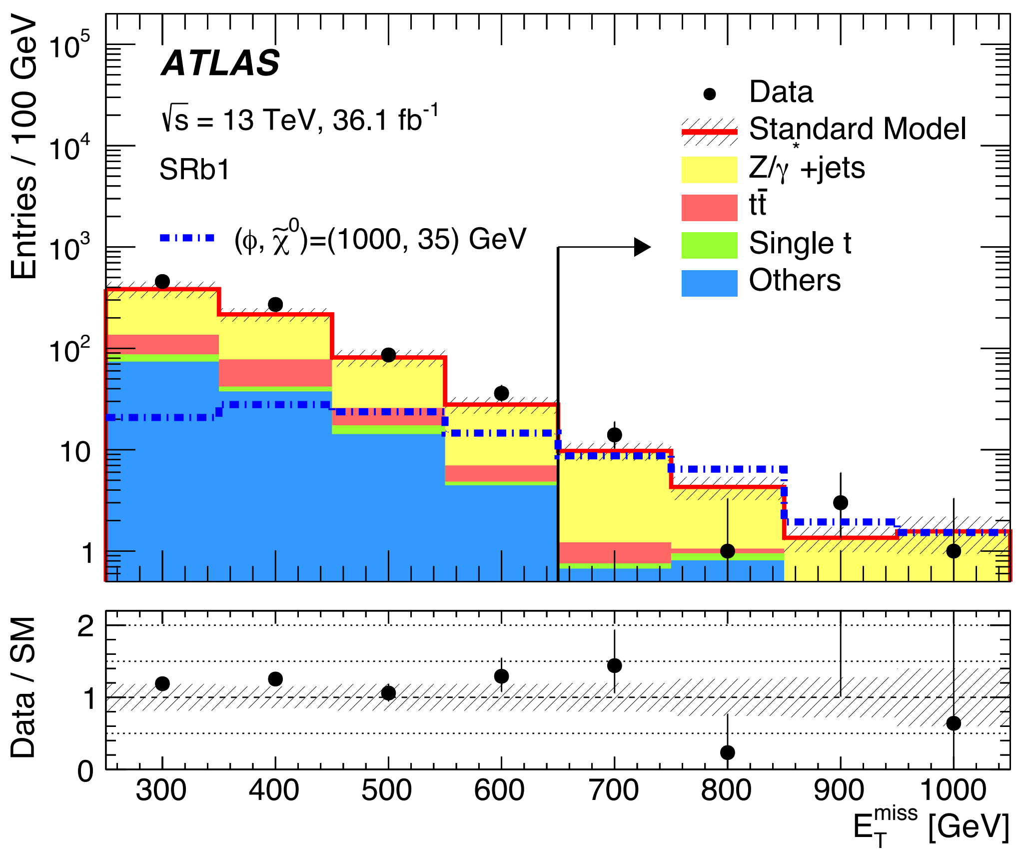




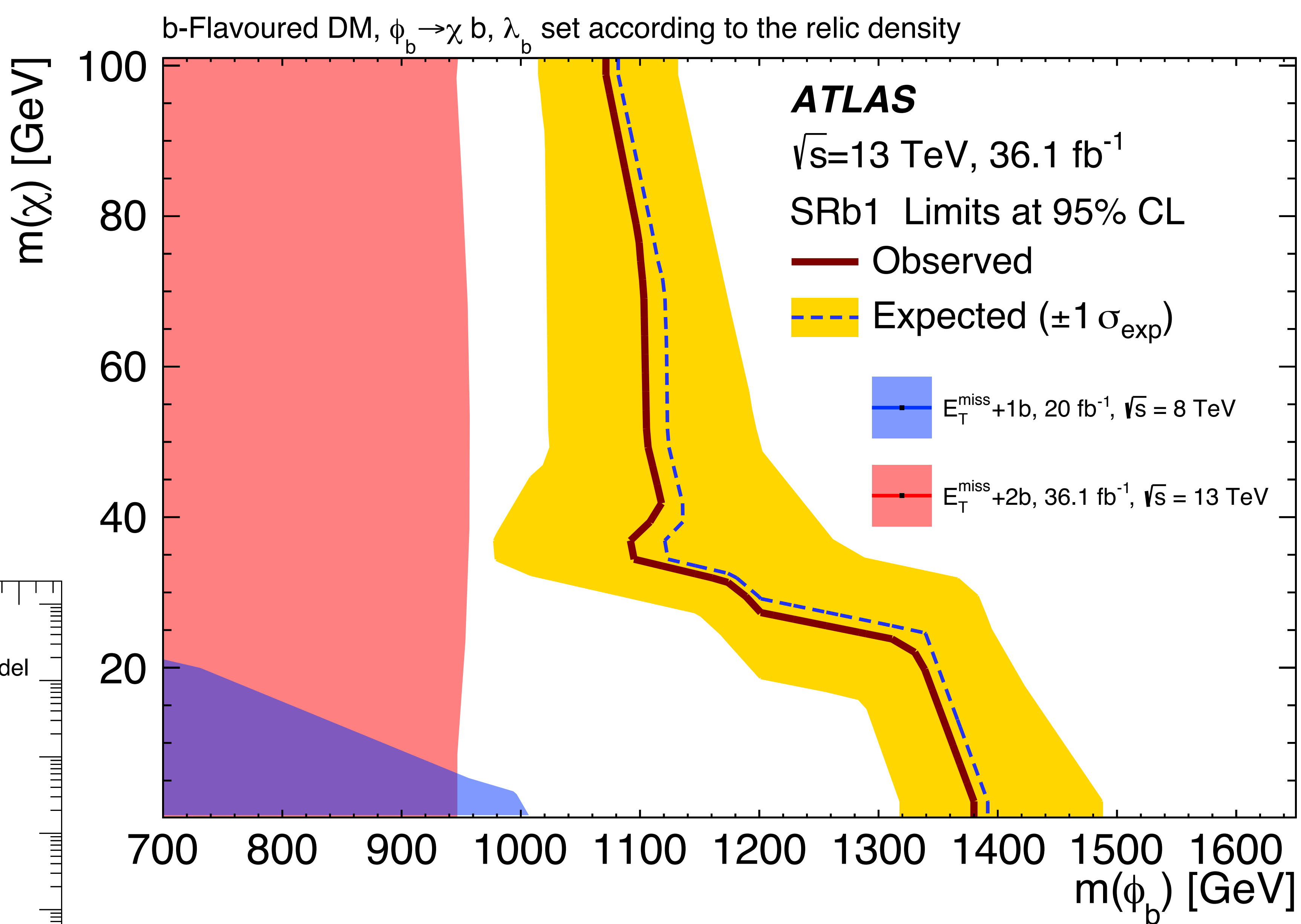
SRb1 - bFDM



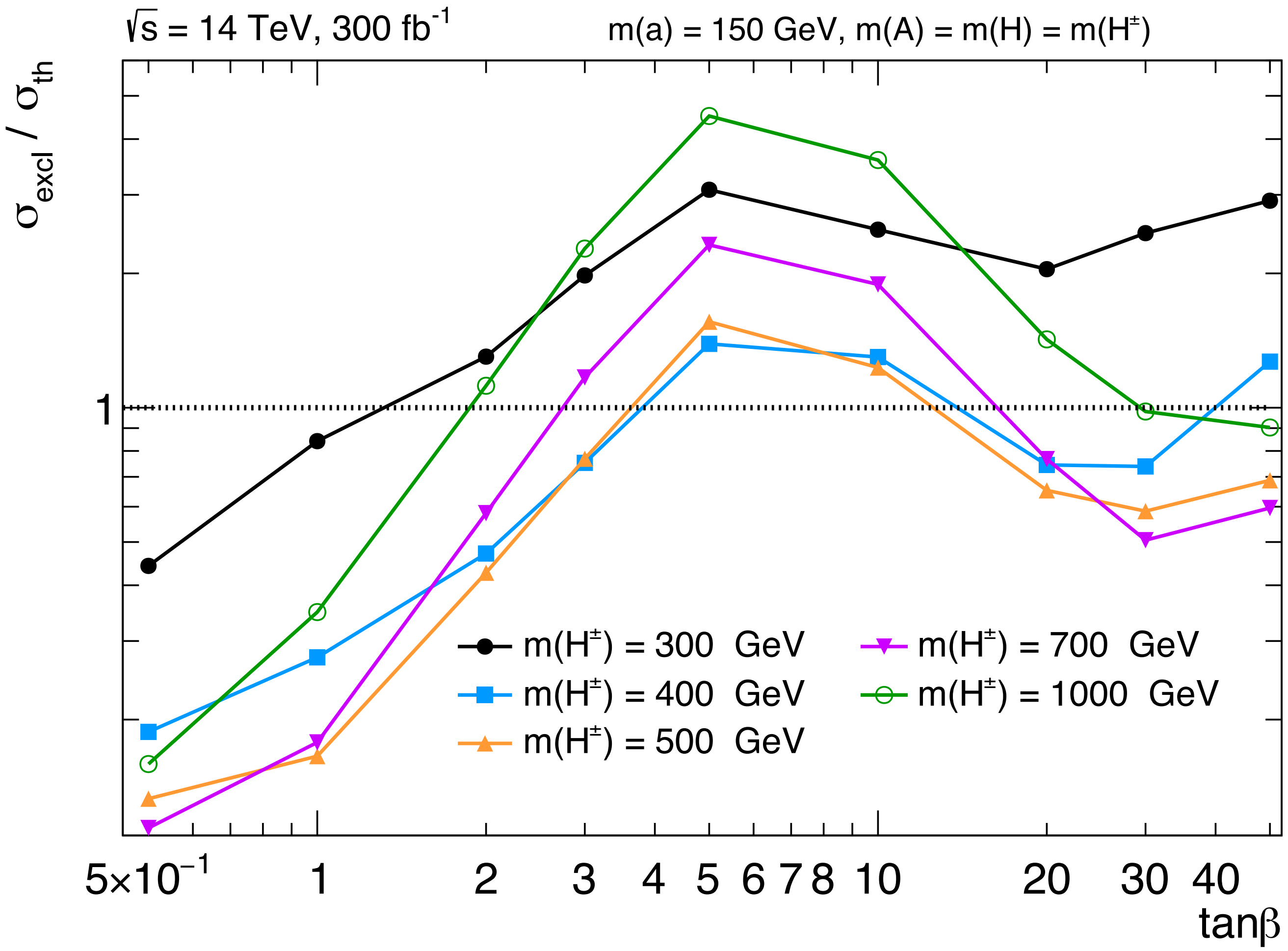
b
χ
ϕ_b
b
ϕ_b
g
$\bar{\chi}$

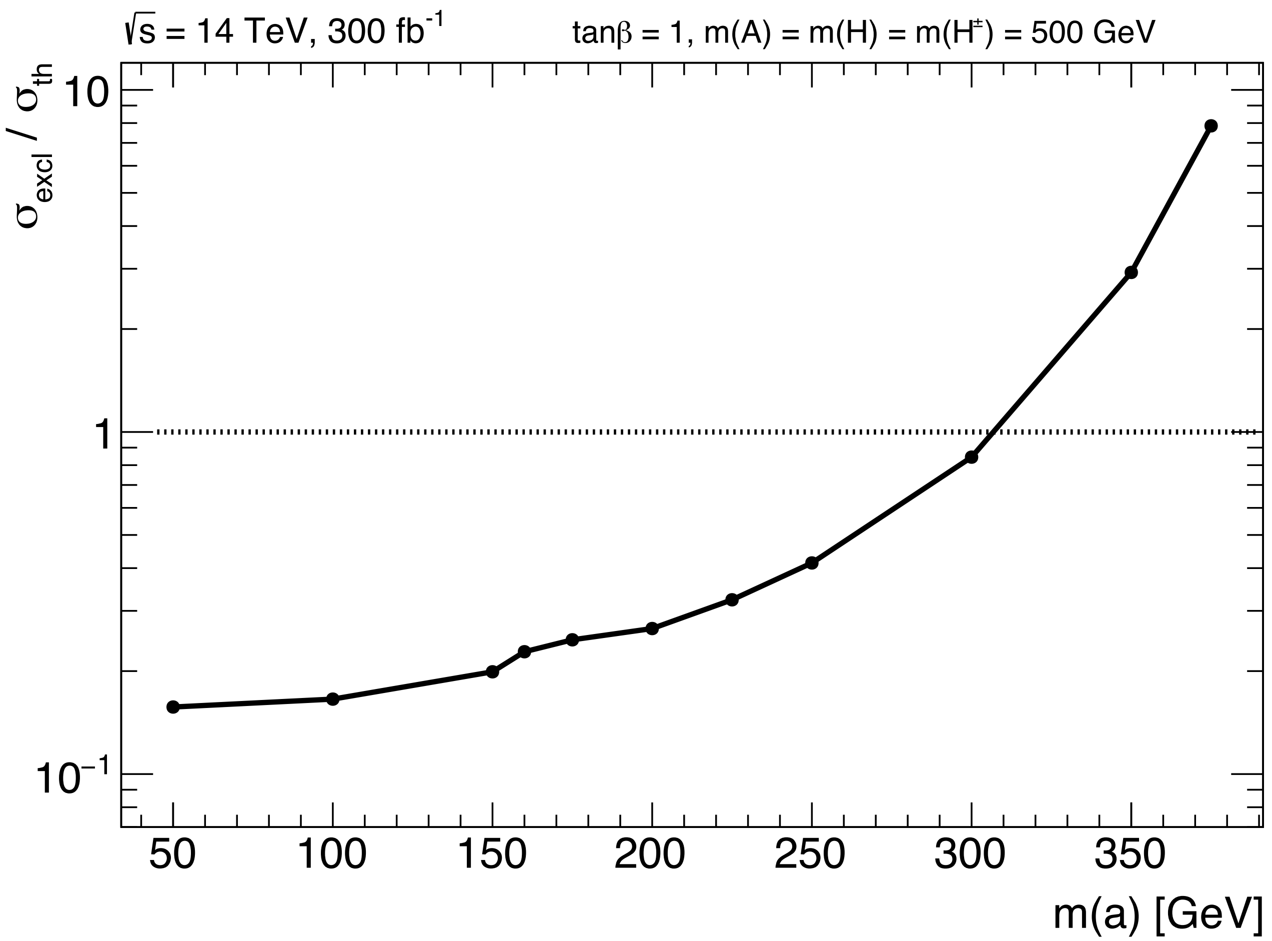


ATLAS
√s = 13 TeV, 36.1 fb-1
SRb1
(φ, $\tilde{\chi}^0$)=(1000, 35) GeV
Data
Standard Model
Z/γ* +jets
$t\bar{t}$
Single t
Others
Entries / 100 GeV
Data / SM
E_T^{miss} [GeV]



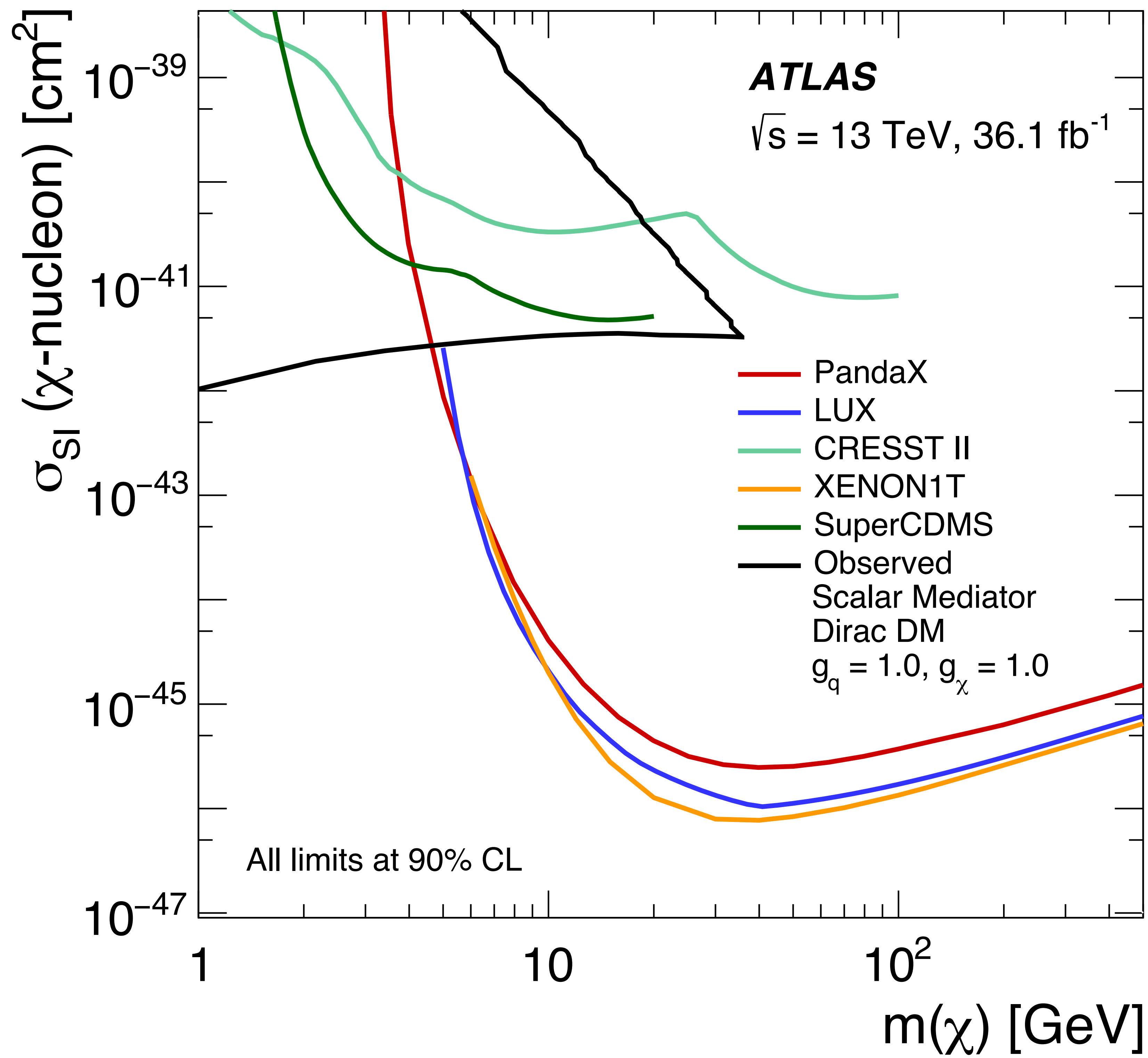
b-Flavoured DM, $\phi_b \rightarrow \chi$ b, λ_b set according to the relic density
ATLAS
√s=13 TeV, 36.1 fb-1
SRb1 Limits at 95% CL
Observed
Expected (±1 σ_{exp})
E_T^{miss}+1b, 20 fb-1, √s = 8 TeV
E_T^{miss}+2b, 36.1 fb-1, √s = 13 TeV
m(χ) [GeV]
m(ϕ_b) [GeV]


√s = 14 TeV, 300 fb-1
m(a) = 150 GeV, m(A) = m(H) = m(H±)
σexcl / σth
m(H±) = 300 GeV
m(H±) = 400 GeV
m(H±) = 500 GeV
m(H±) = 700 GeV
m(H±) = 1000 GeV
tanβ

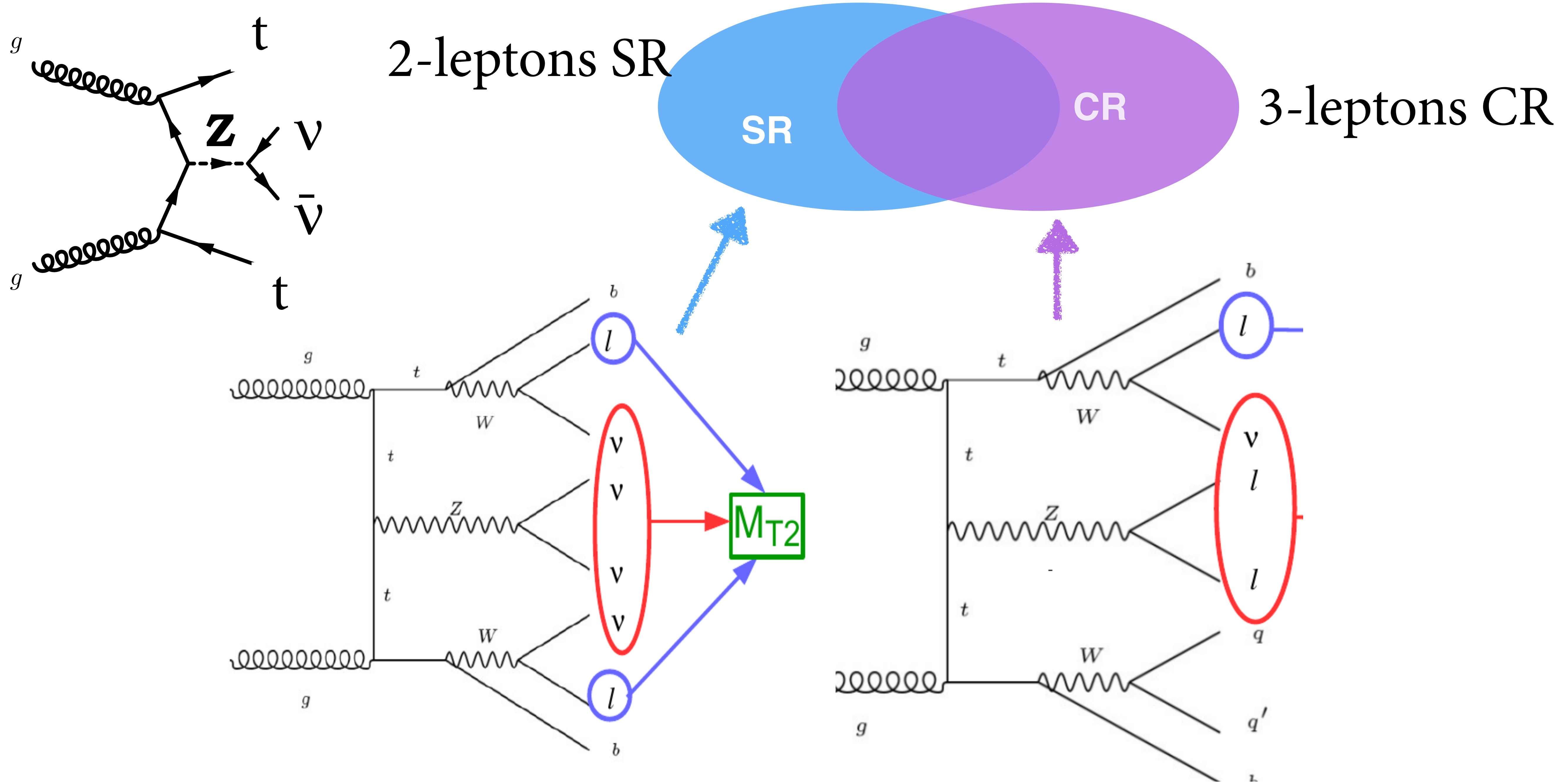

√s = 14 TeV, 300 fb-1
tanβ = 1, m(A) = m(H) = m(H±) = 500 GeV
σexcl / σth
m(a) [GeV]

(b)

The infamous plot



The Z(νν) estimate (details)



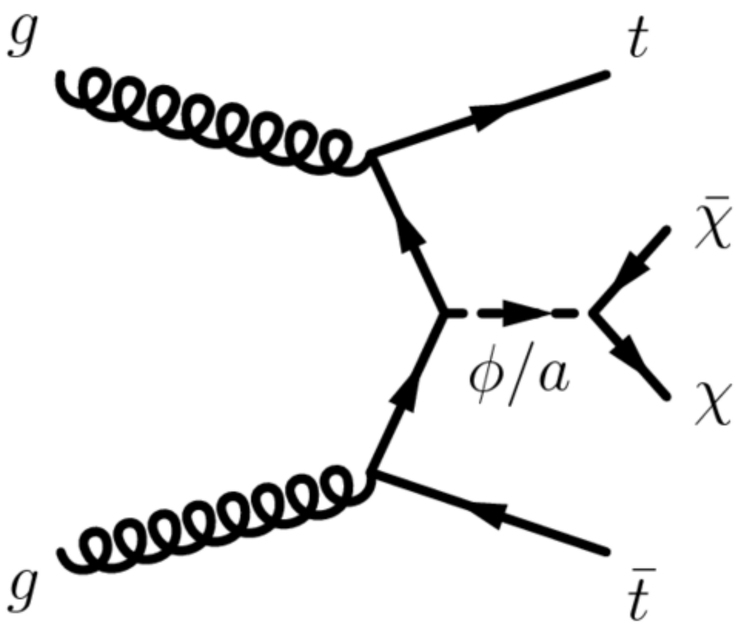
2 Leptons	3 Leptons
MT2	MT_{corr}
EtMiss	$Etmiss_{corr}$

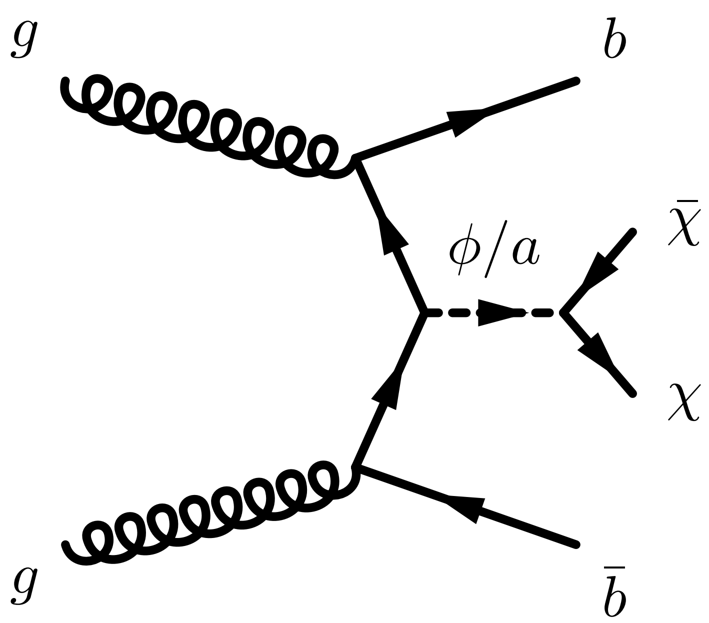
(*) 4-leptons CR would be ideal but too low statistics

Exploring the dark sector with heavy quarks

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

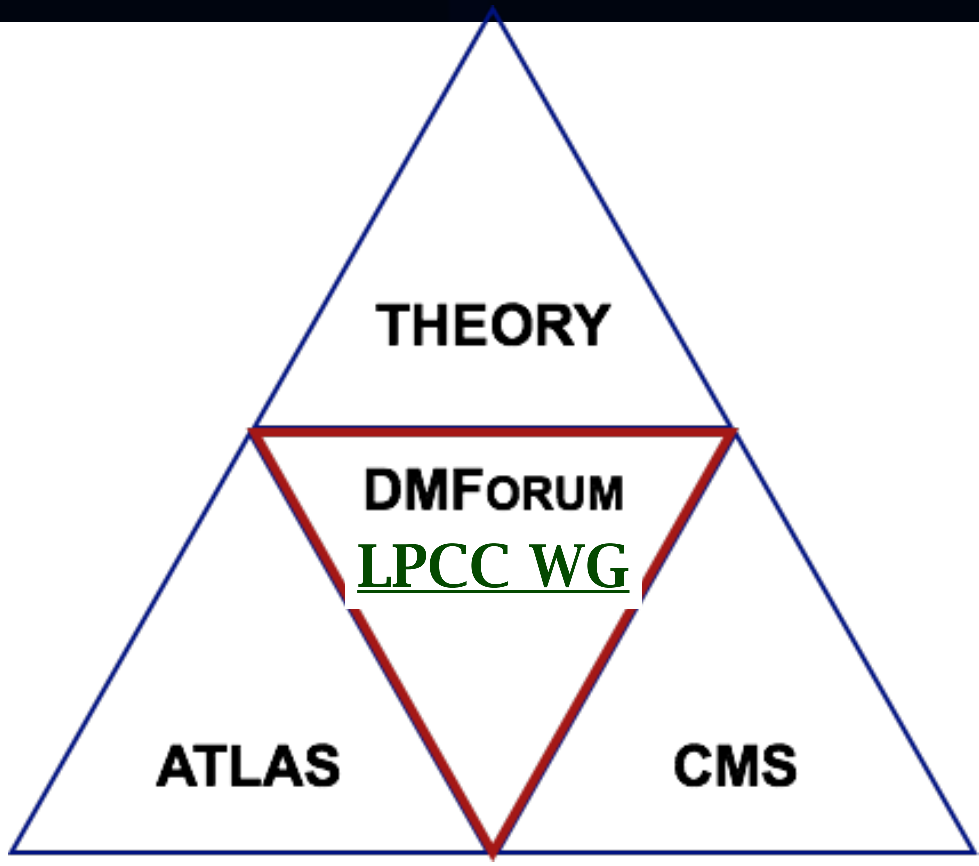
→ **Enhanced cross-section for tops and bottoms**





- ★ 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

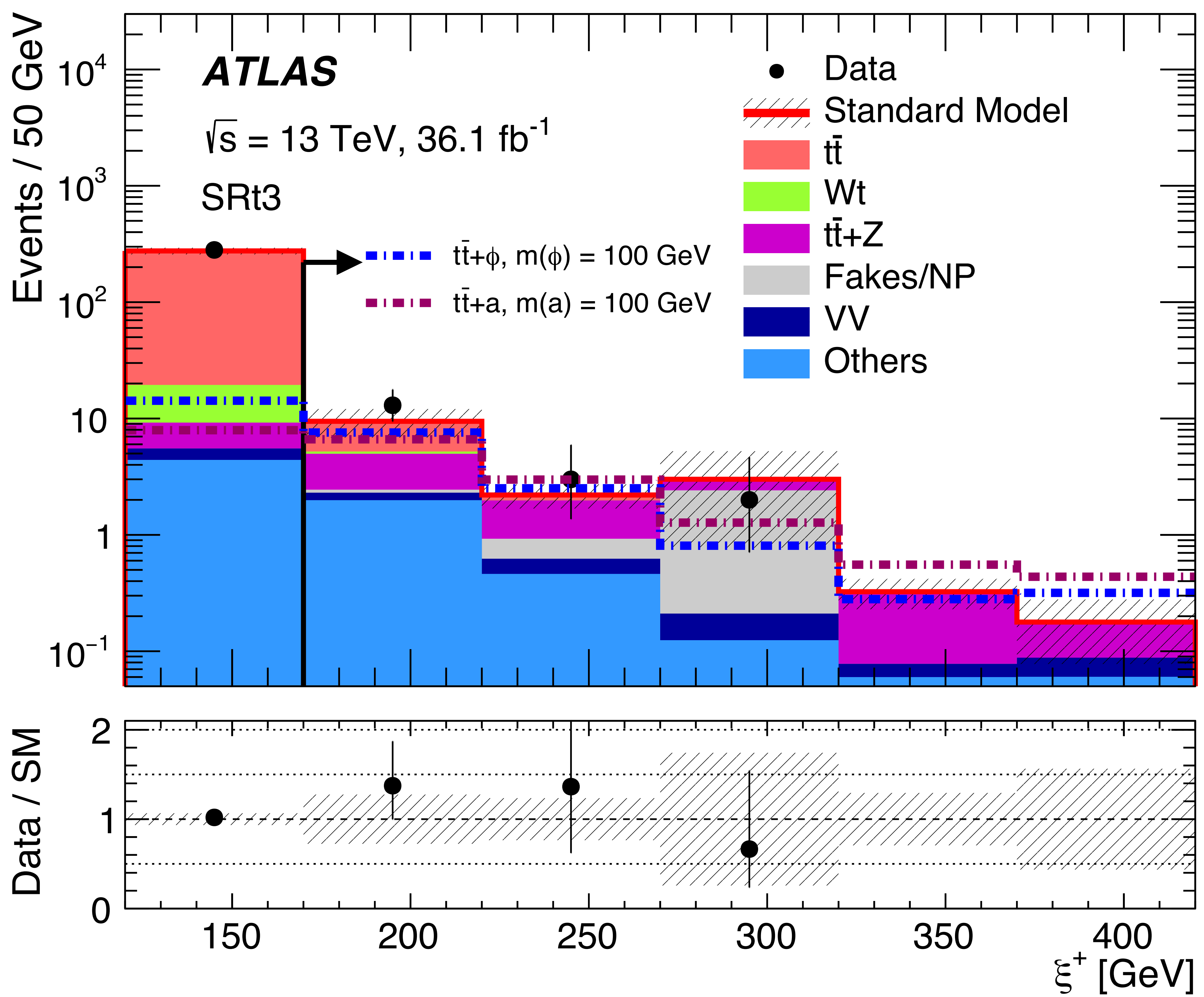
★ Simplified Models are the Run II paradigm:

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

ATLAS EXPERIMENT

CERN

Results (1)



ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SRt3
Data
Standard Model
$t\bar{t}$
Wt
$t\bar{t}$+Z
Fakes/NP
VV
Others
$t\bar{t}+\phi$, m(ϕ) = 100 GeV
$t\bar{t}$+a, m(a) = 100 GeV
Events / 50 GeV
Data / SM
ξ^{+} [GeV]