Searches for Dark Matter with the ATLAS detector at the LHC

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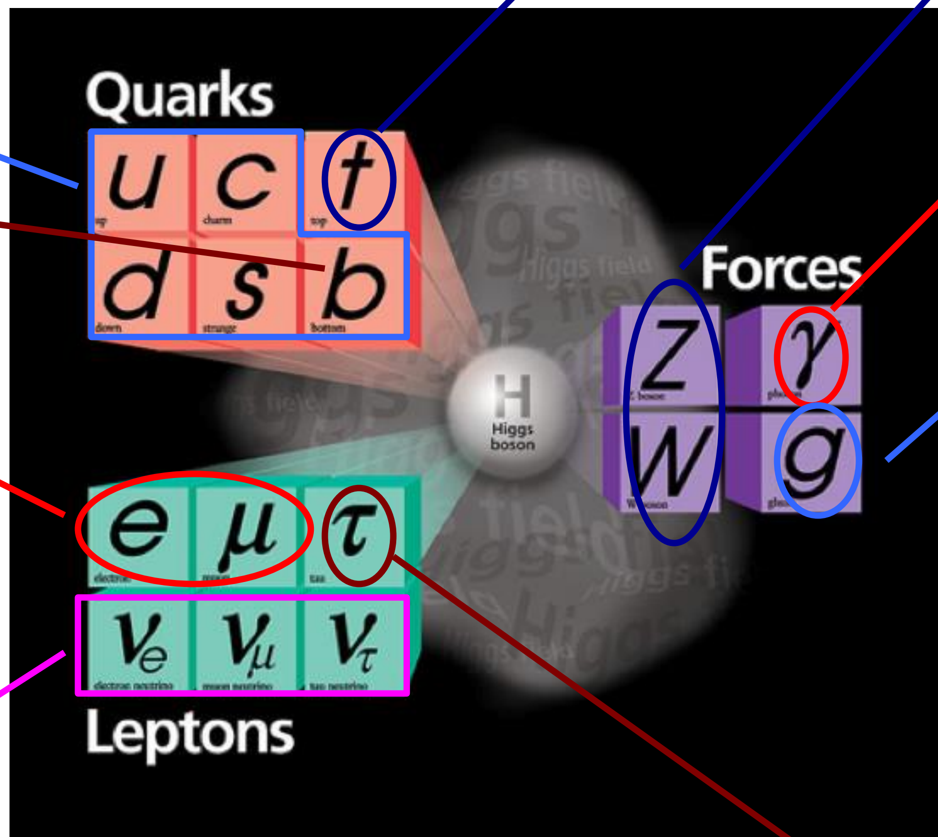
Elementary Particles of the Standard Model

Unstable: t → bW

Unstable: identify via decay products

Hadronisation → Jets

b jets: dedicated identification techniques



Stable!

Hadronisation → Jets

((quasi-)stable hadrons: $\pi^{\pm}$, $K^{\pm}$, K^0_L, p, n)

Stable!
(μ not really, but as seen by a detector)

No interaction with detector
→ Missing (transverse) energy/momentum

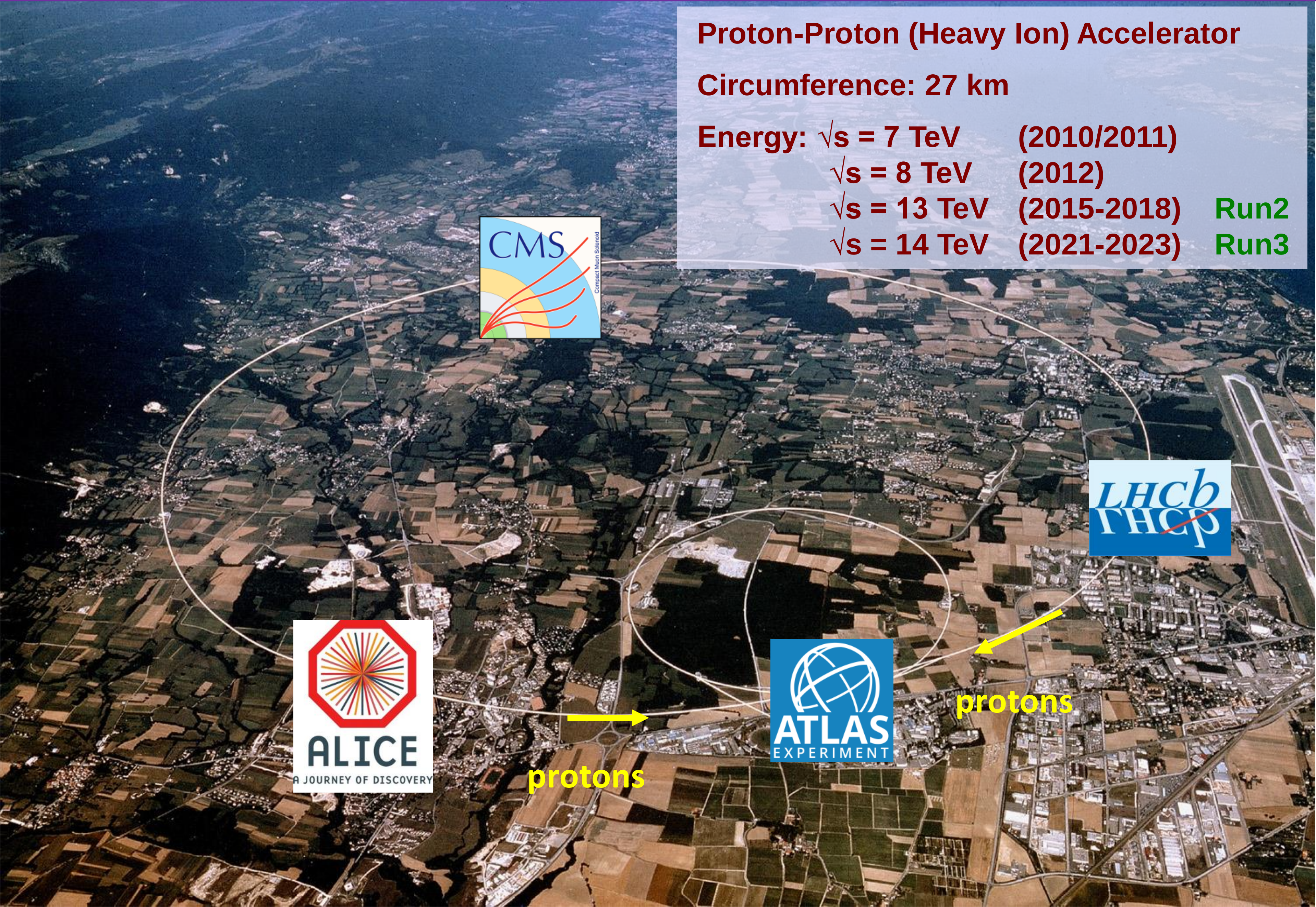
Unstable: identify via decay products

The Large Hadron Collider: LHC

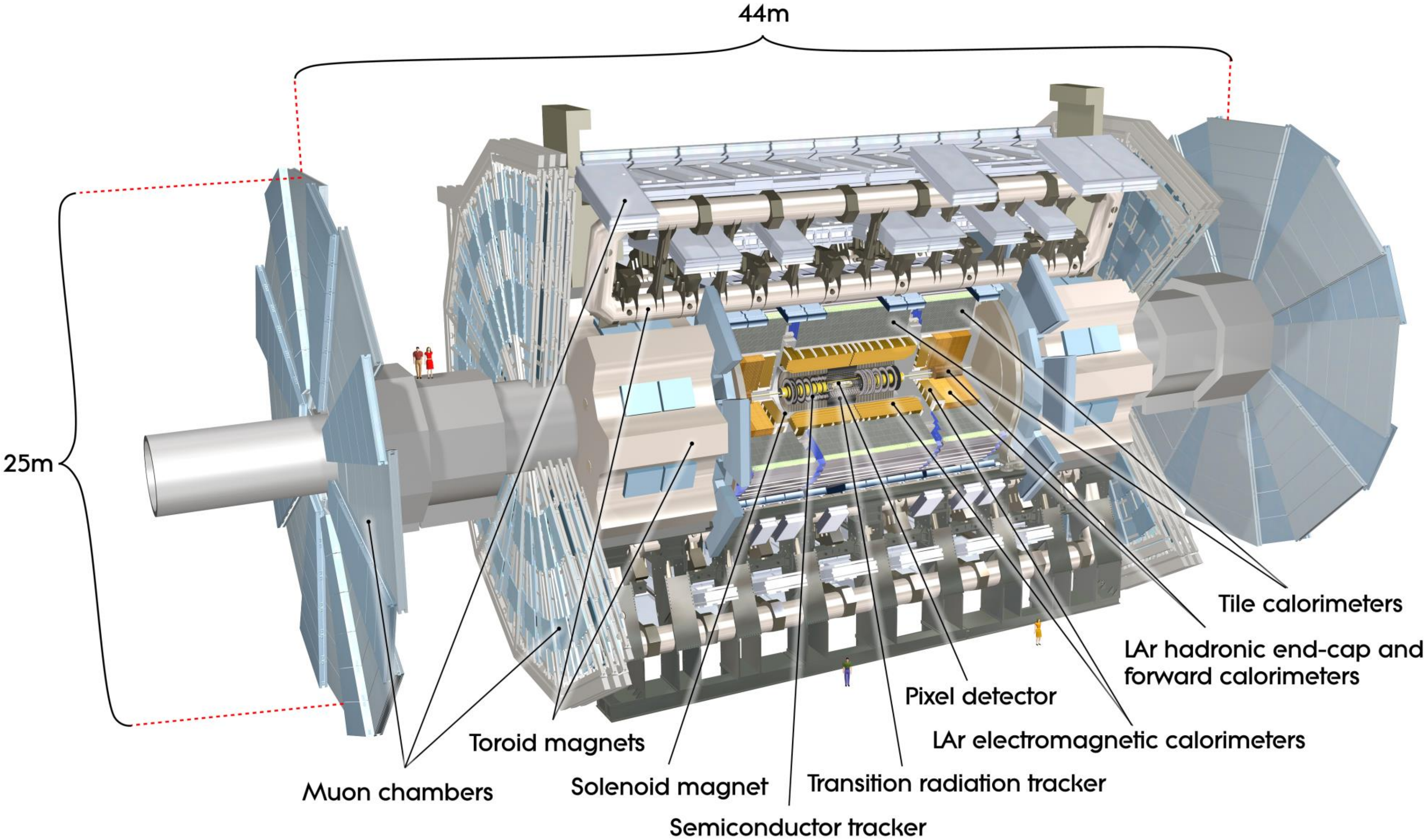
Proton-Proton (Heavy Ion) Accelerator

Circumference: 27 km

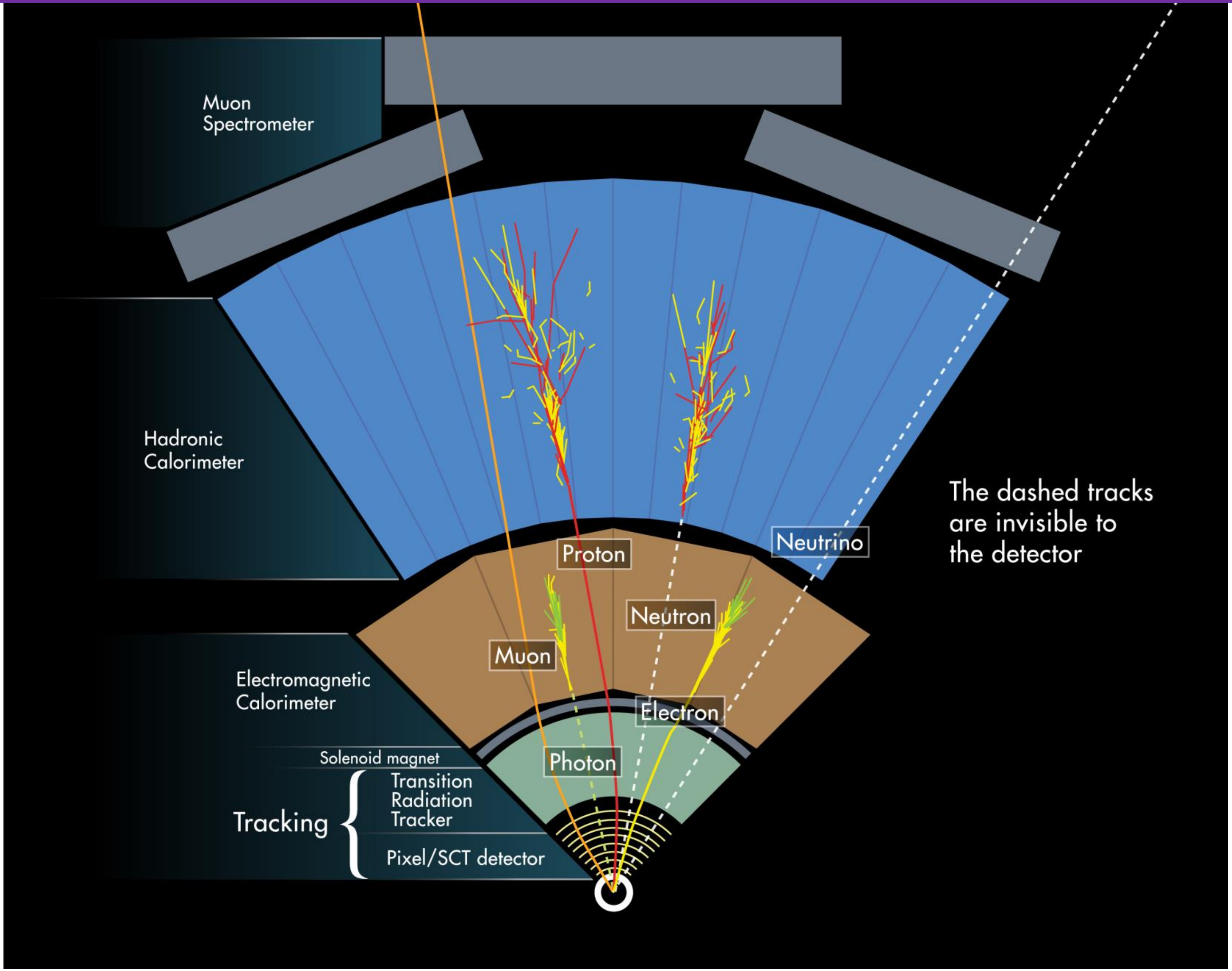
Energy:	**$\sqrt{s}$ = 7 TeV**	**(2010/2011)**	
	$\sqrt{s}$ = 8 TeV	**(2012)**	
	$\sqrt{s}$ = 13 TeV	**(2015-2018)**	**Run2**
	$\sqrt{s}$ = 14 TeV	**(2021-2023)**	**Run3**

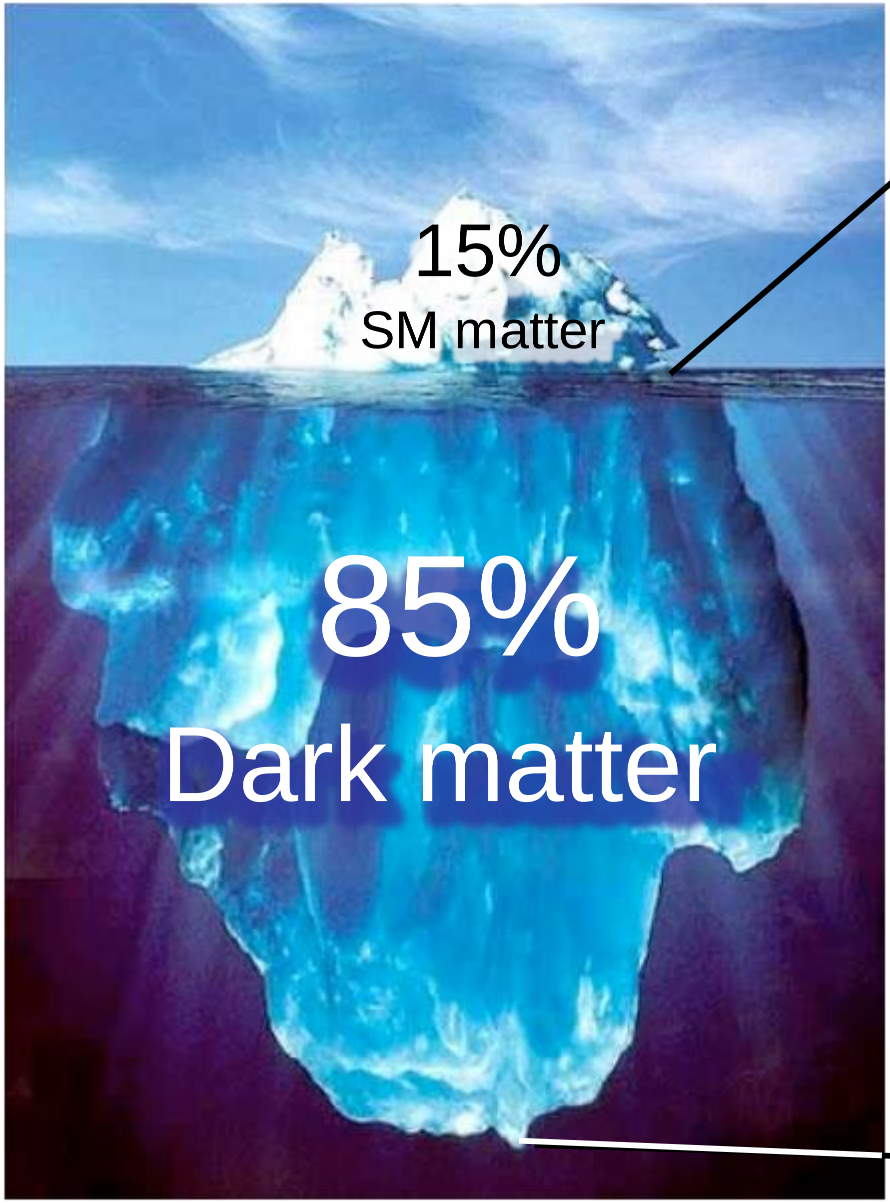


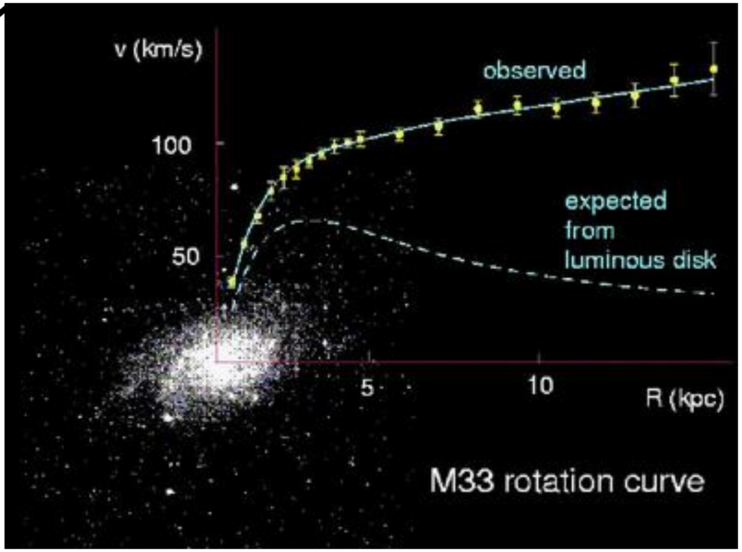
The ATLAS detector

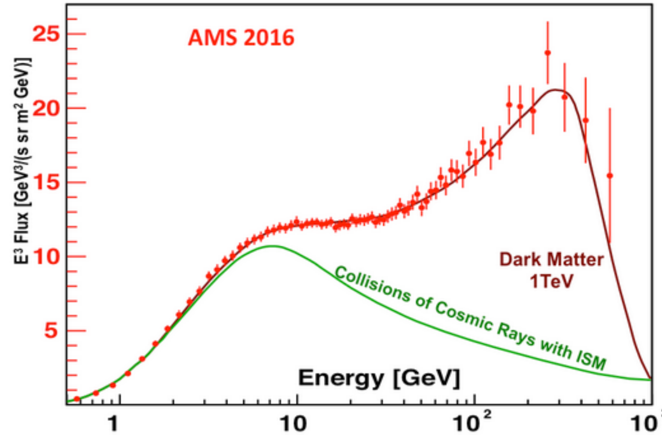


The ATLAS detector: Particle Identification

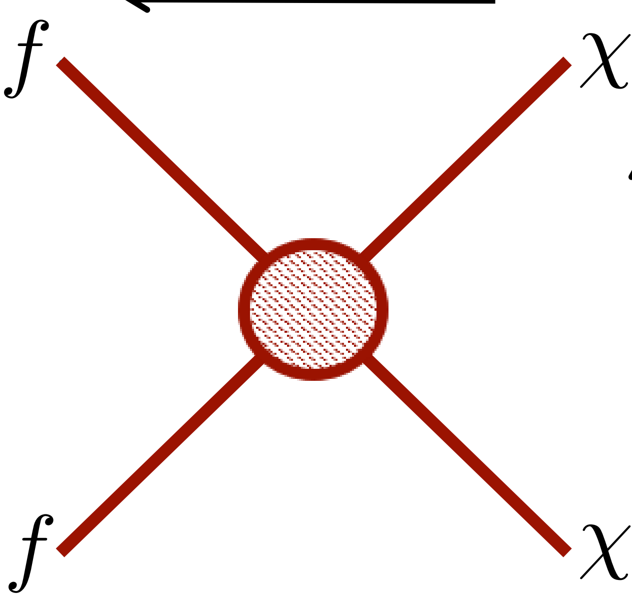



15%
SM matter
85%
Dark matter

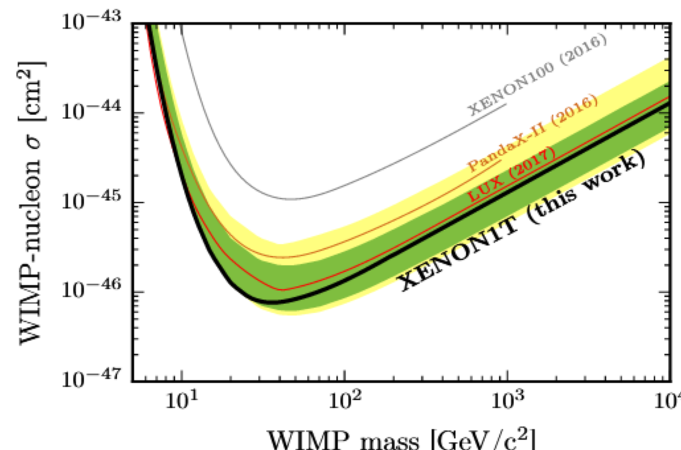

v (km/s)
observed
100
50
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve



Indirect detection

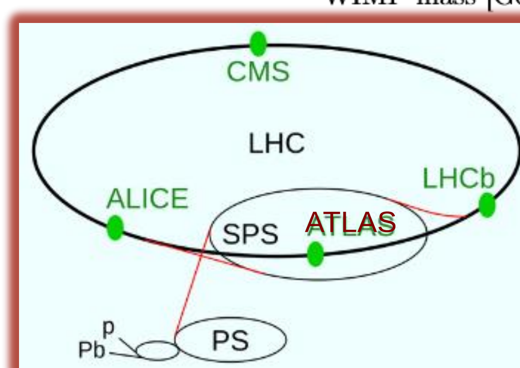


Direct detection

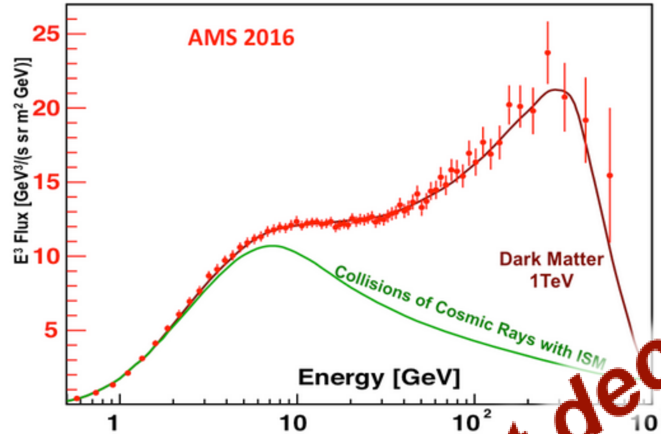


Collider production

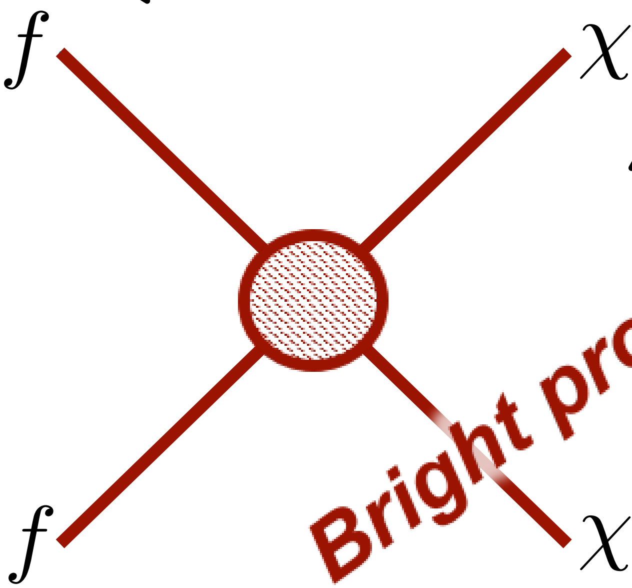
← *This presentation*



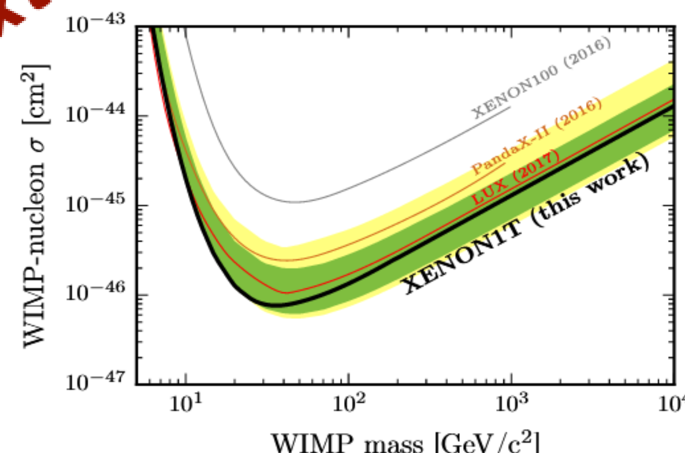
DARK MATTER DETECTION



Indirect detection



Direct detection



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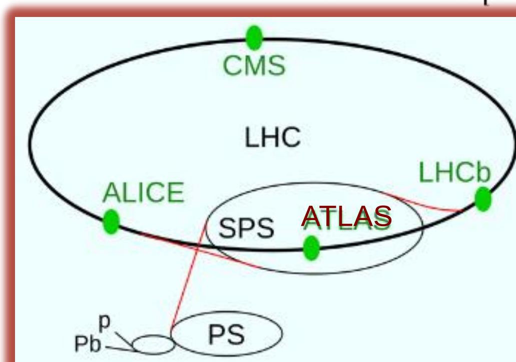
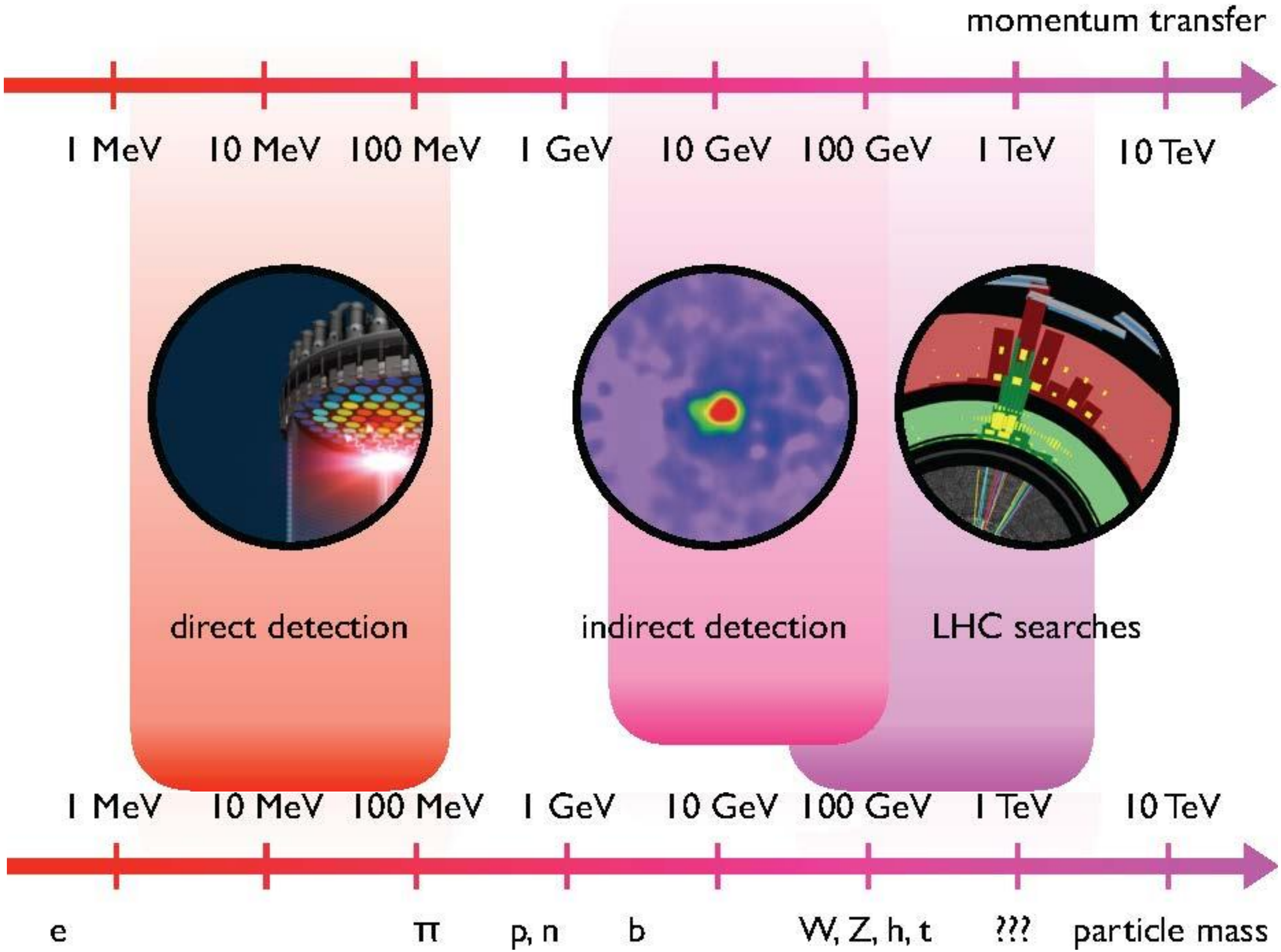
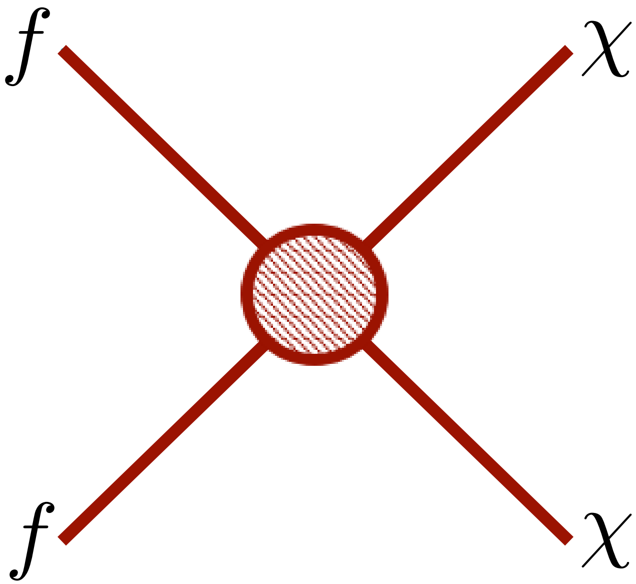
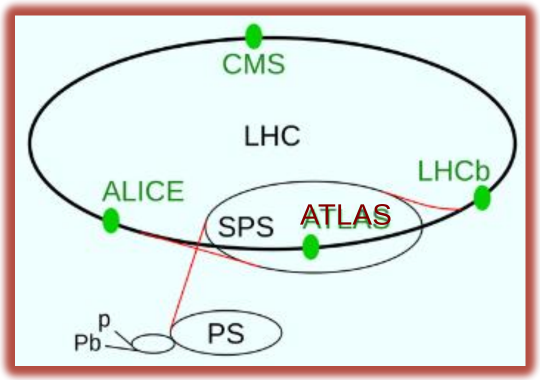


Bright prospects for next decade(s)!

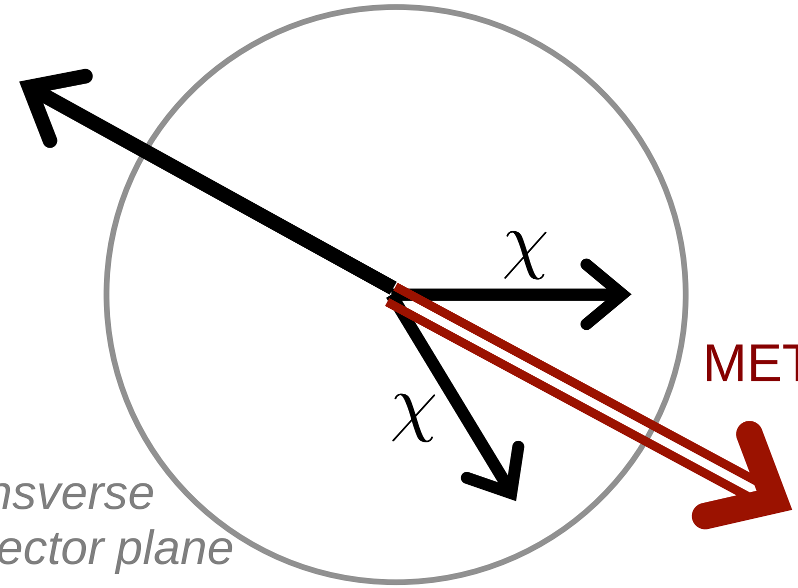

momentum transfer
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
direct detection
indirect detection
LHC searches
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
e
π
p, n
b
W, Z, h, t
???
particle mass



Collider production
(controlled experi-
mental environment!)

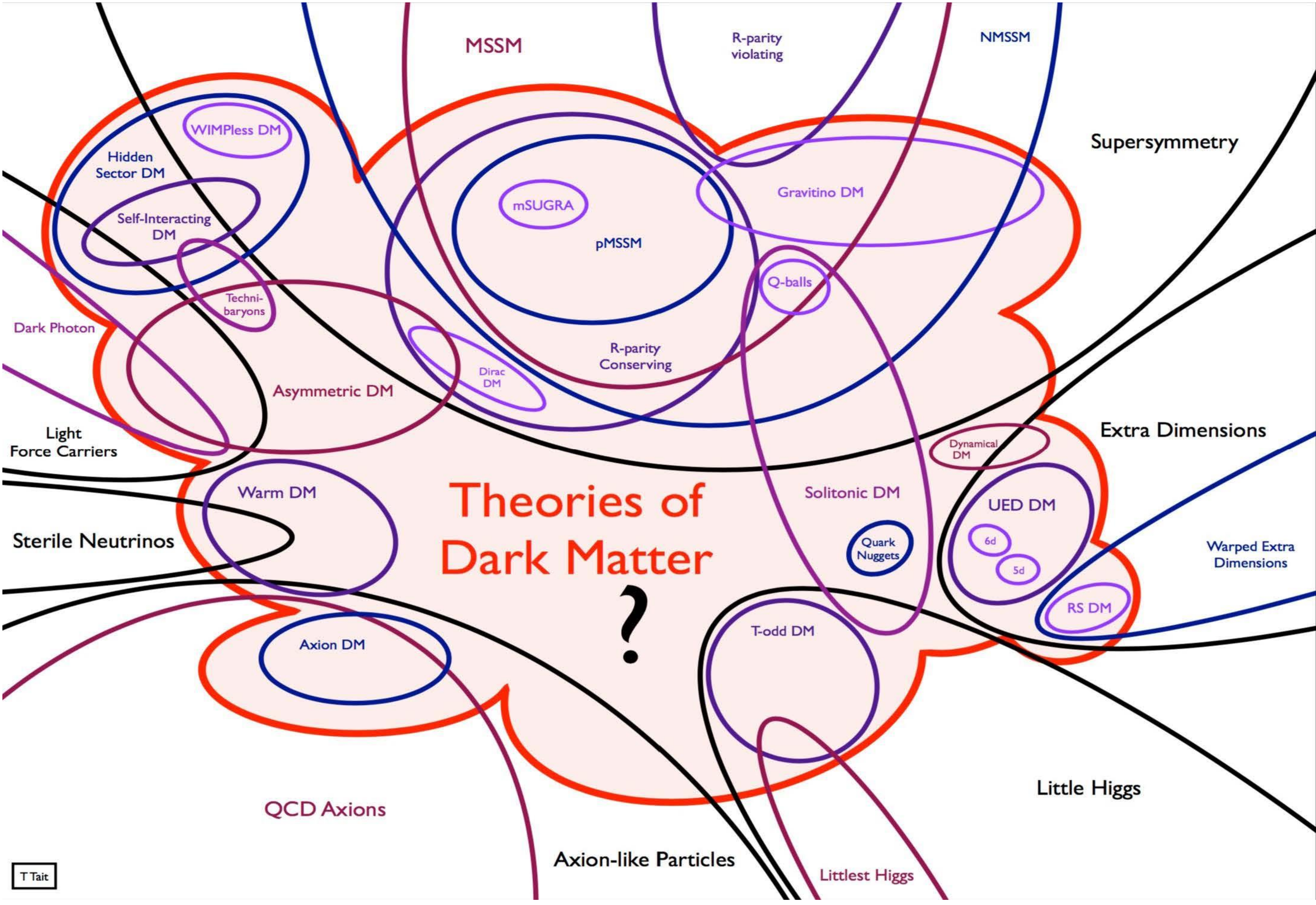


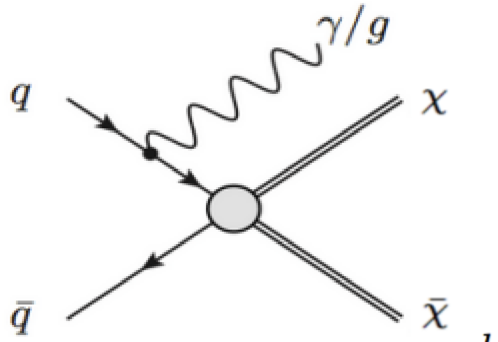
Generic signature:
SM particles, e.g., jet(s), Higgs boson, etc

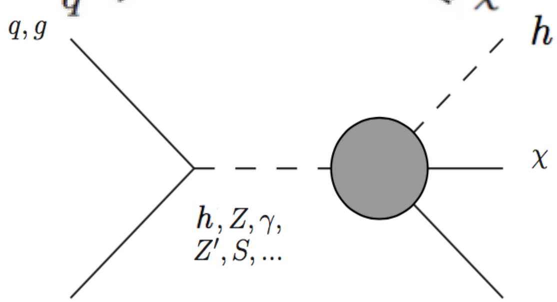


[1] *MET: missing transverse momentum*

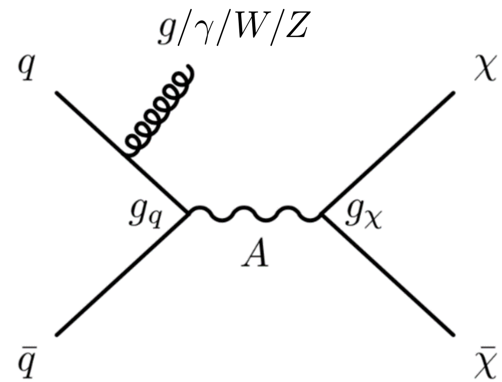
DARK MATTER MODELS







DMF recommendations
arXiv:1507.00966



V/AV mediator model
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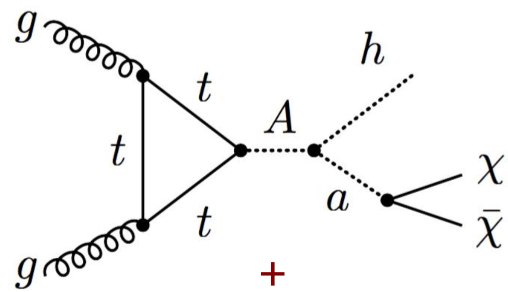


\+
many other signatures

2HDM+a model
JHEP 05 (2017) 138
arXiv:1507.00966

Supersymmetry

White Papers of [LHC DM WG/DMF]

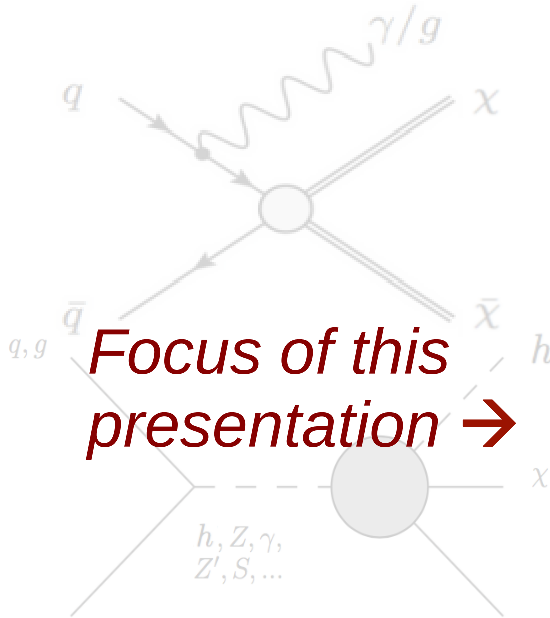
1) Effective field theory

2) Simplified models

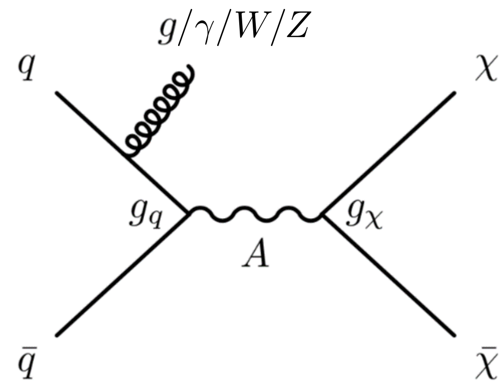
3) Simplified, consistent, & UV-complete models

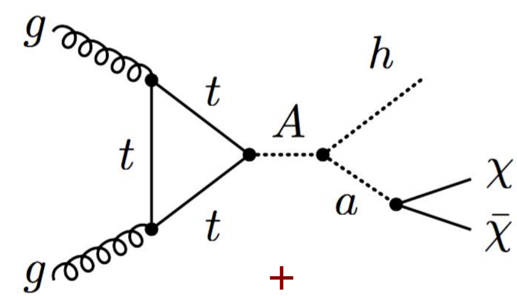
4) complete models

Richer kinematics + phenomenology



Focus of this presentation →





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many other signatures

Supersymmetry

DMF recommendations
arXiv:1507.00966

V/AV mediator model
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JHEP 05 (2017) 138
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White Papers of
[LHC DM WG/DMF](LHC DM WG/DMF)

1) Effective field theory

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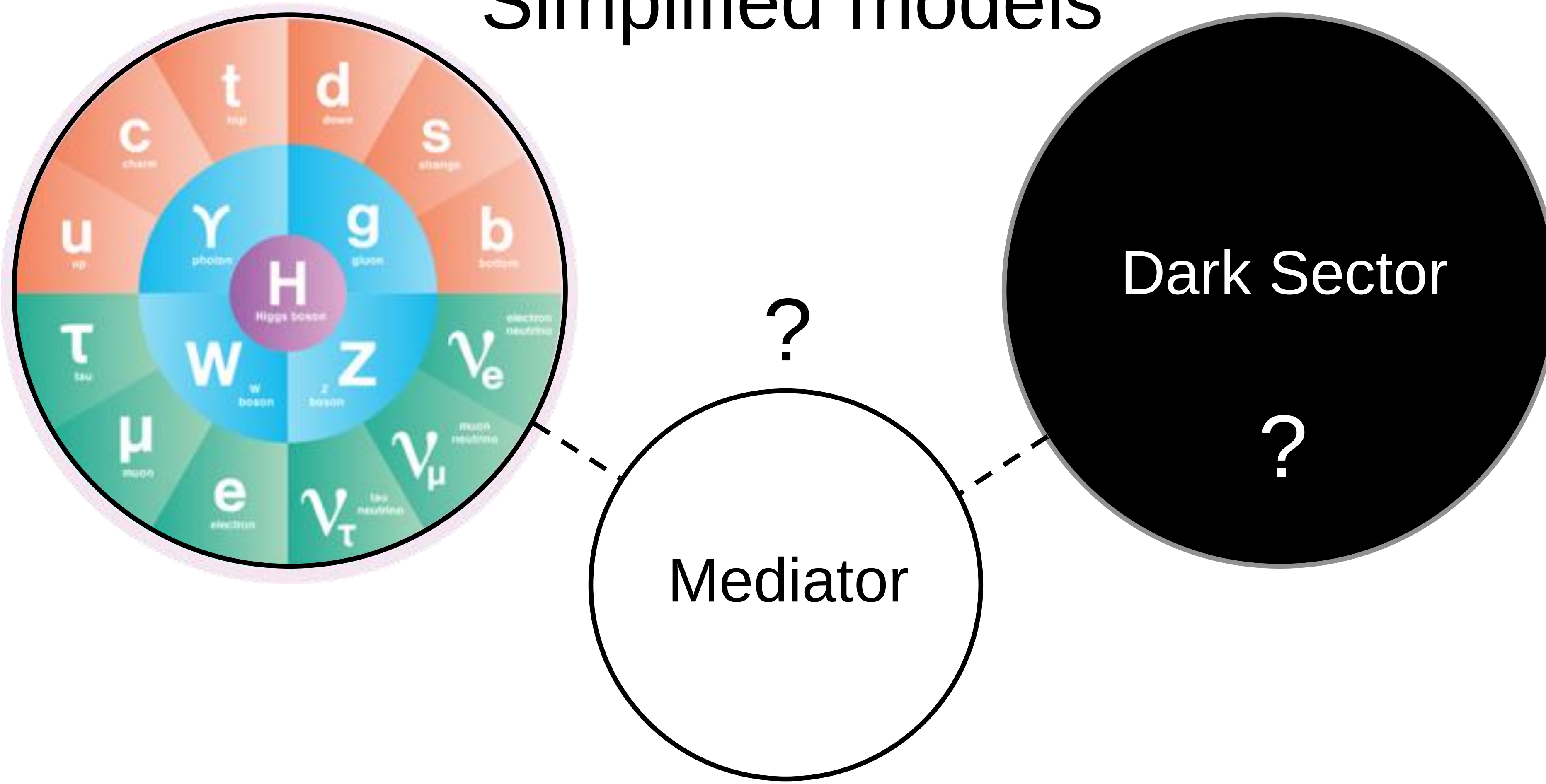
Richer kinematics + phenomenology

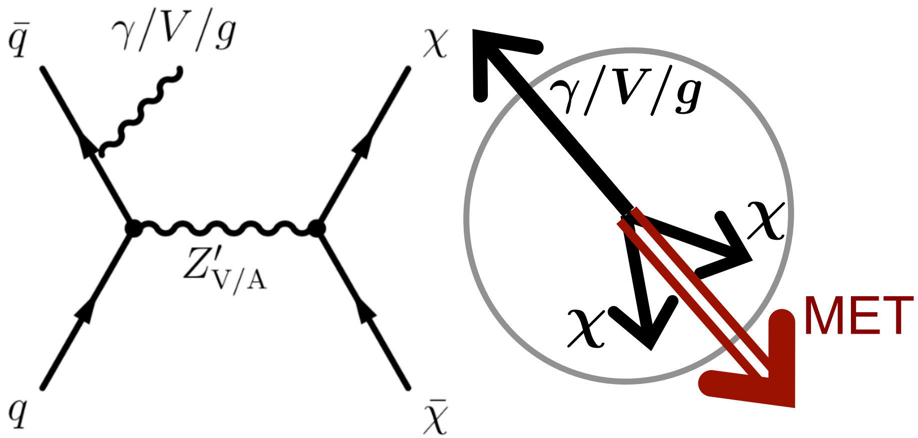
Simplified models



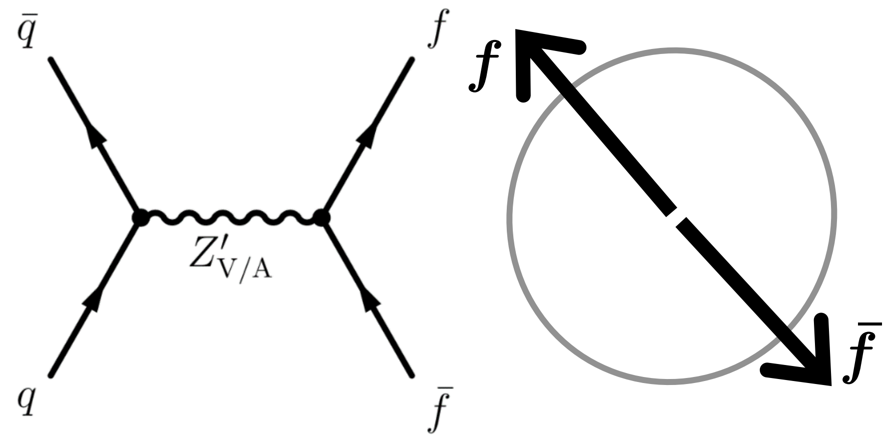
Motivation: 1) Mediator that couples to SM and to Dark Sector particles
2) Generic signatures that are present in complete models

- Motivation:
  - Simplified model with generic signatures
  - s-channel mediator: interplay between signatures

X+MET



Resonances



- Work horse model:
  - Assume vector (V) or axial vector (AV) mediator ($Z'_{V/A}$)
    - Easy to calculate for $m_{Z'}$ > 200 GeV
  - LHC Dark Matter WG: coherence across ATLAS & CMS
    - *arXiv:1507.00966 (DMF report)*
    - *arXiv:1603.04156, arXiv:1703.05703 (White Papers of LHC DM WG)*

- X+MET searches:
  - Mono-jet 36 fb^{-1}, JHEP 01 (2018) 126
  - Mono-photon 36 fb^{-1}, EPJC 77 (2017) 393
  - Mono-Z(ll) 36 fb^{-1}, PLB 776 (2017) 318
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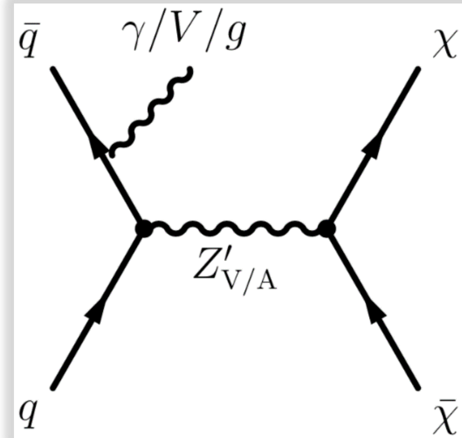

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  - Dijet Trigger-Level Analysis 29 fb^{-1}, PRL 121 (2018) 081801
  - Boosted dijet+ISR 36 fb^{-1}, PLB 788 (2019) 316
  - Boosted di-b-jet+ISR 81 fb^{-1}, ATLAS-CONF-2018-052
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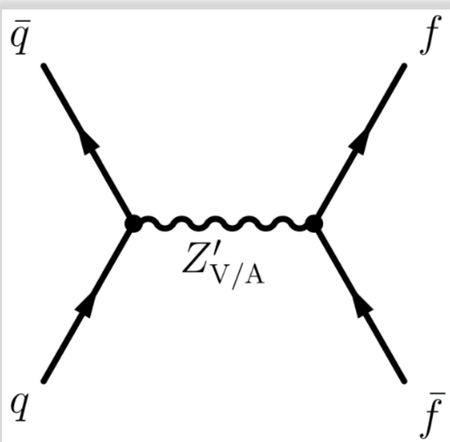
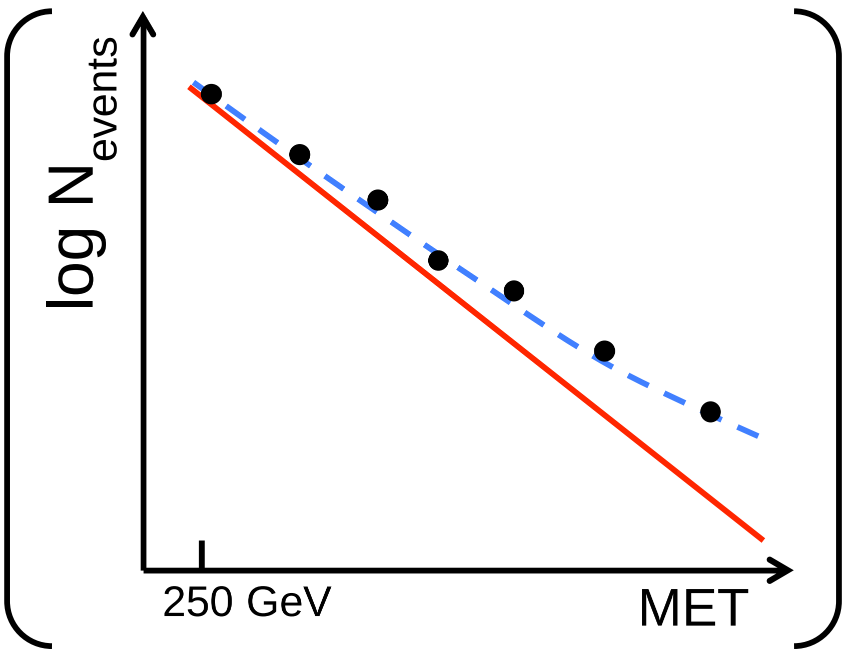
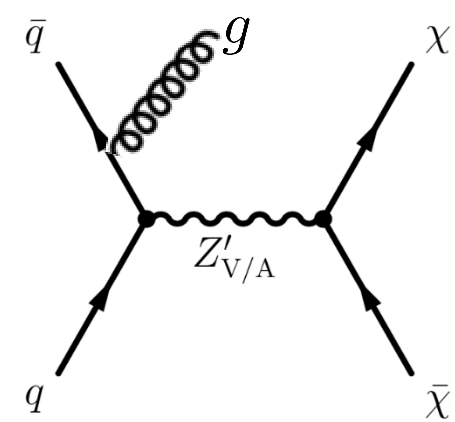
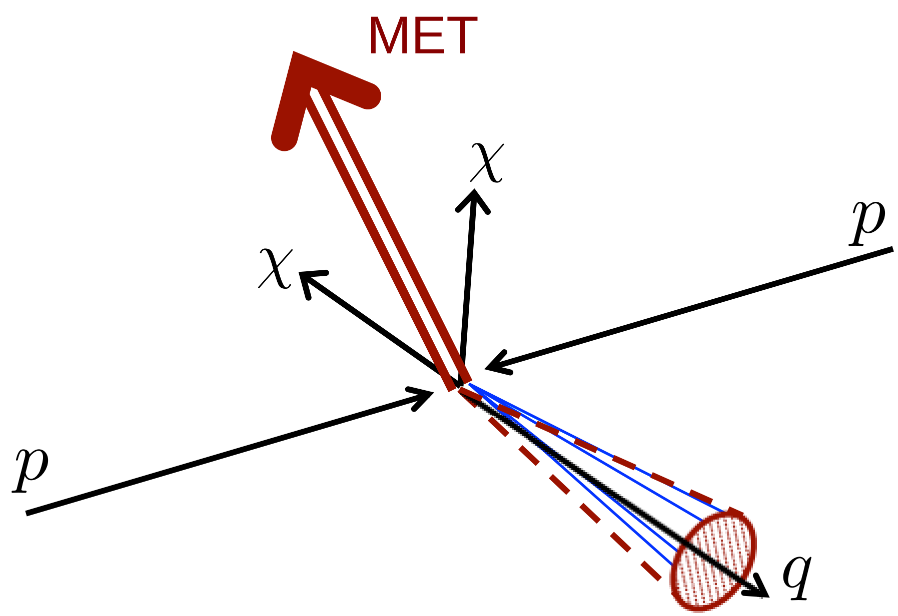


All 2015+2016 (36 fb^{-1}) results in DM summary arXiv:1903.01400

- Analysis strategy:
  - Require MET > 250 GeV
  - Require jet with p_T > 250 GeV
  - Inclusive selection: up to 3 extra jets
  - Look for excess at high MET:







Shape fit: 10 bins in MET

JHEP 01 (2019) 126

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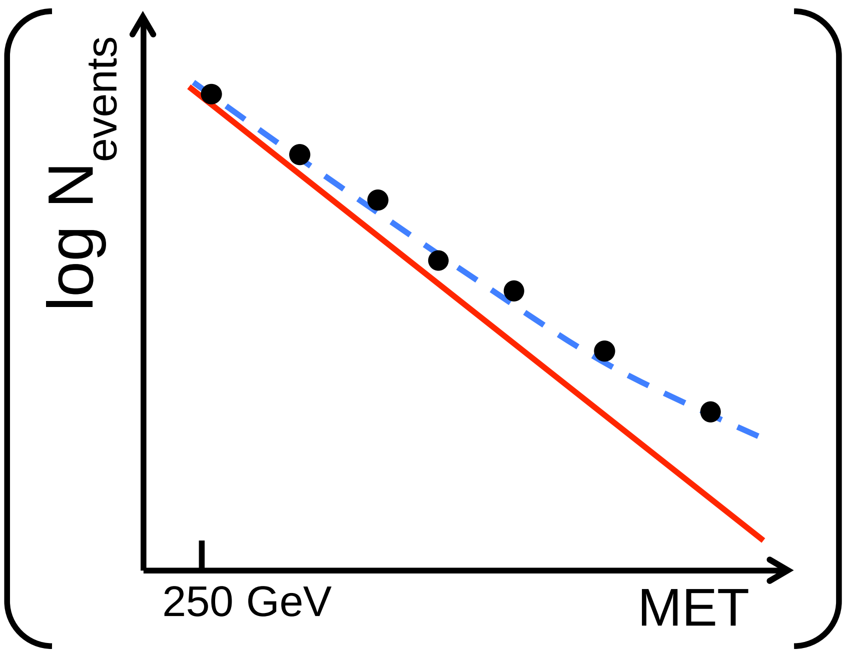

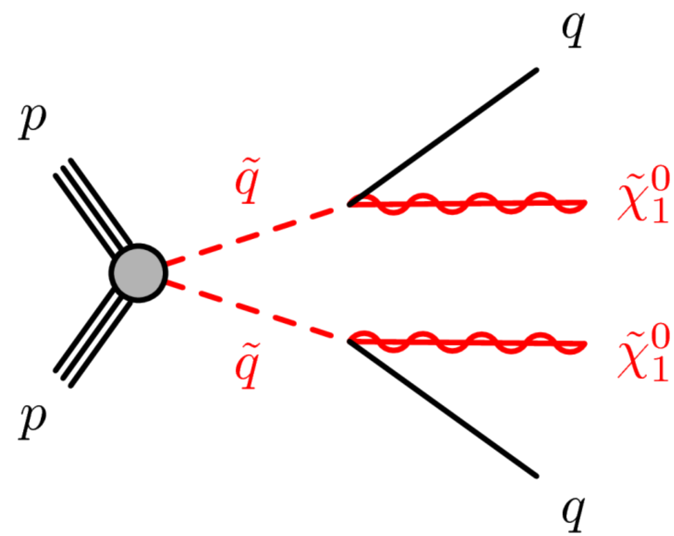

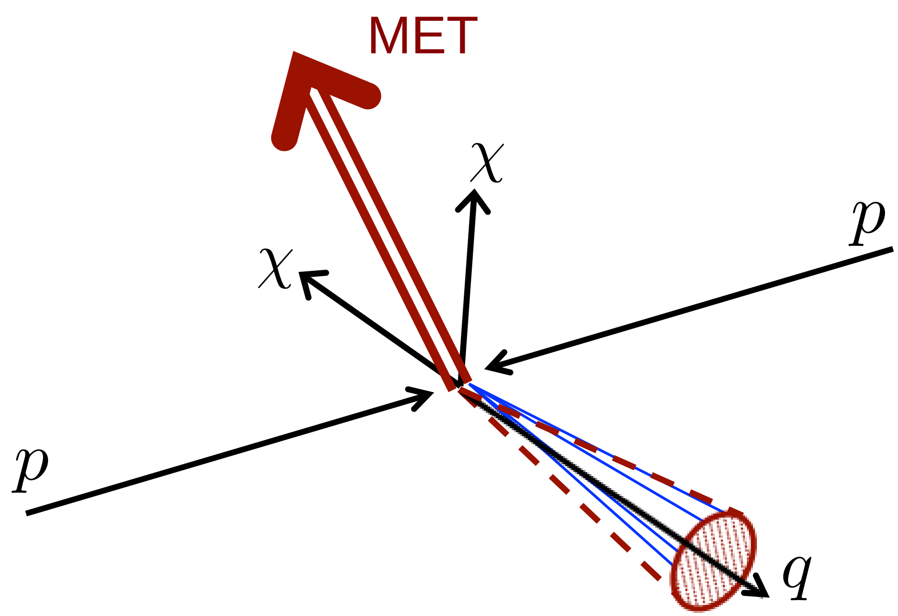

Shape fit: 10 bins in MET

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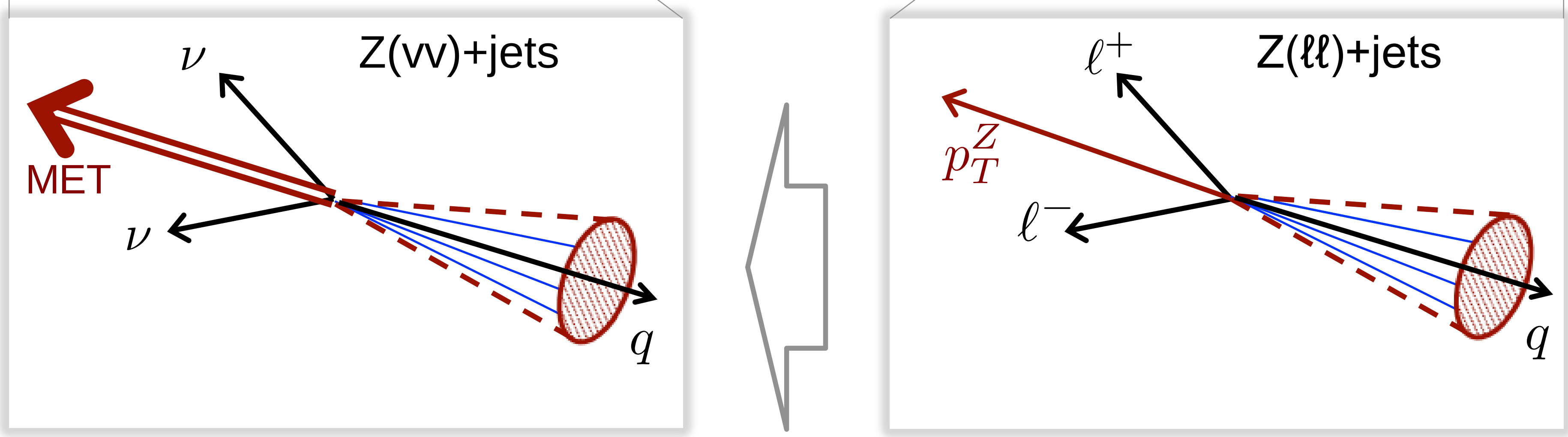
JHEP 01 (2019) 126

- Backgrounds:
  - SM Z(νν)+jets (dominant), W+jets, Diboson, tt + rest
- Strategy:
  - Constrain major backgrounds:

0 lepton signal region	1 lepton control region	2 lepton control region
Signal	Constrain W(ℓν)+jets and Z(νν)+jets	Constrain Z(νν)+jets using Z(ℓℓ)+jets



JHEP 01 (2019) 126

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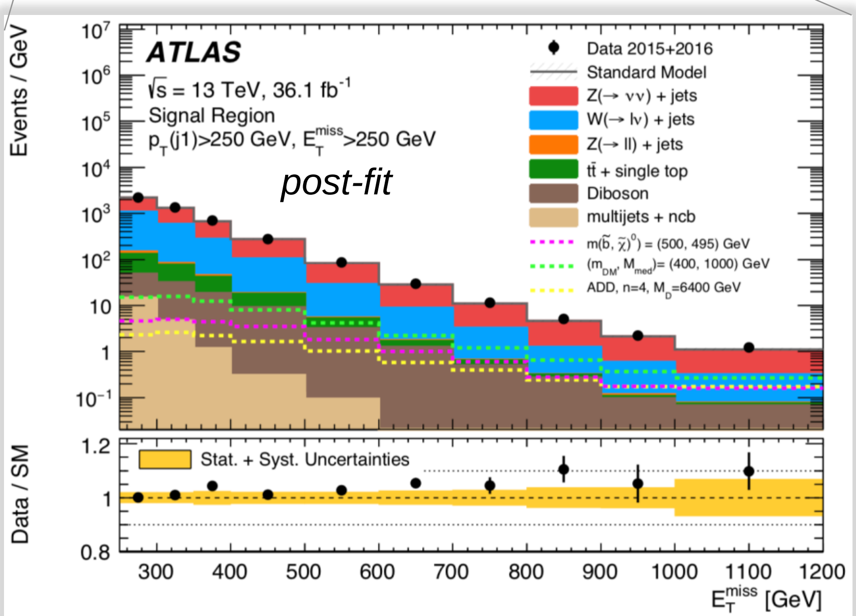

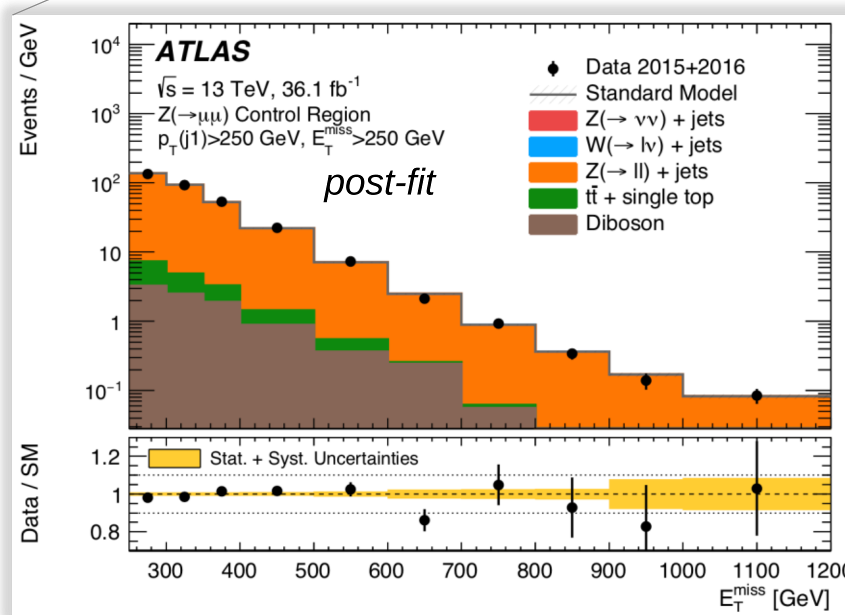

JHEP 01 (2019) 126

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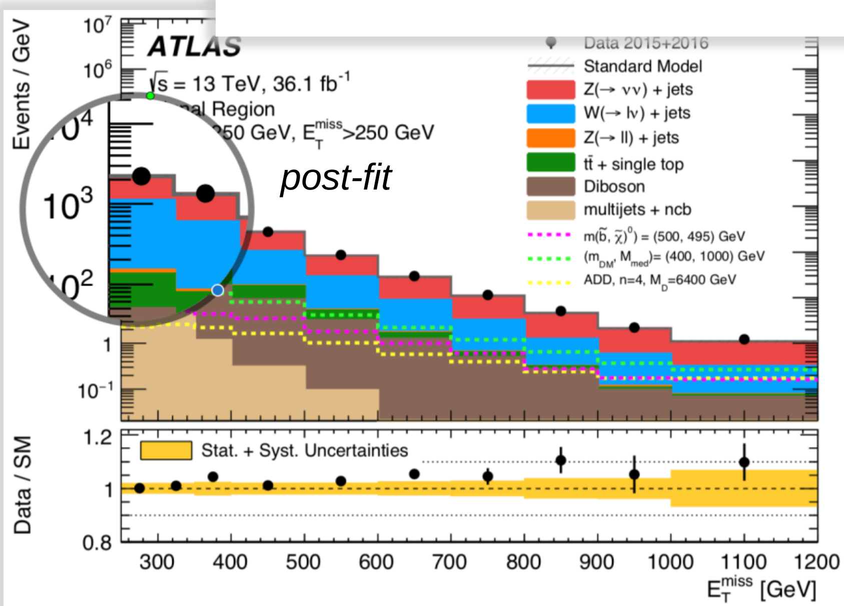
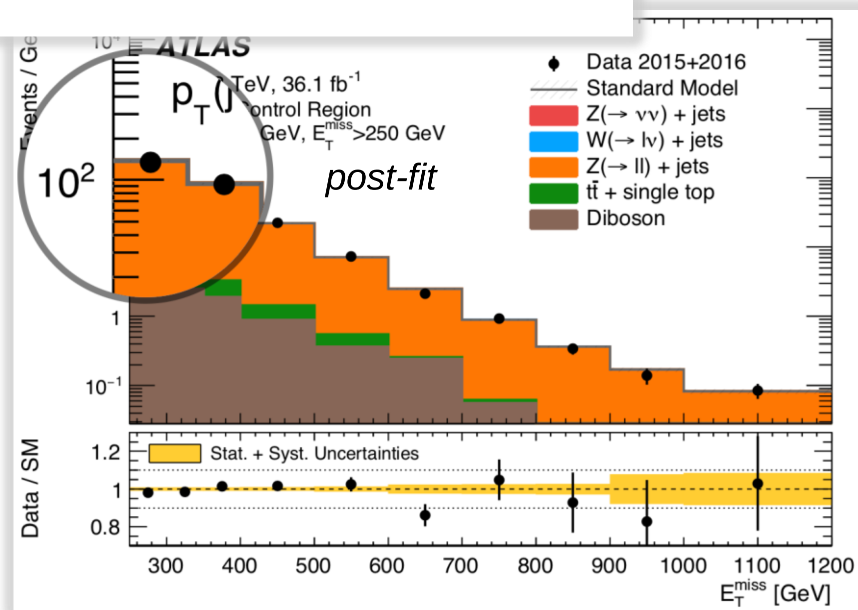
Challenge: $BR(Z \to \nu\nu) \approx 20\%$ $BR(Z \to \mu\mu) \approx 3\%$





JHEP 01 (2019) 126

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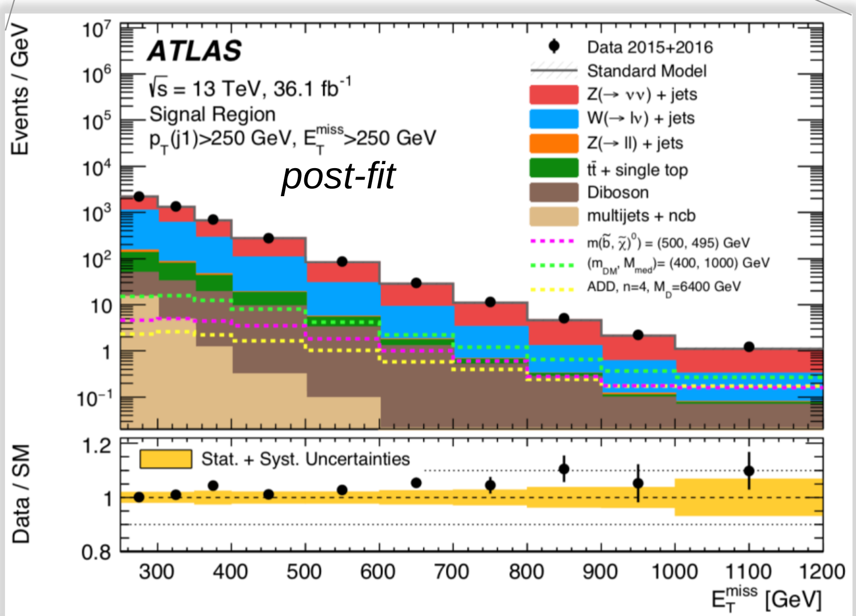
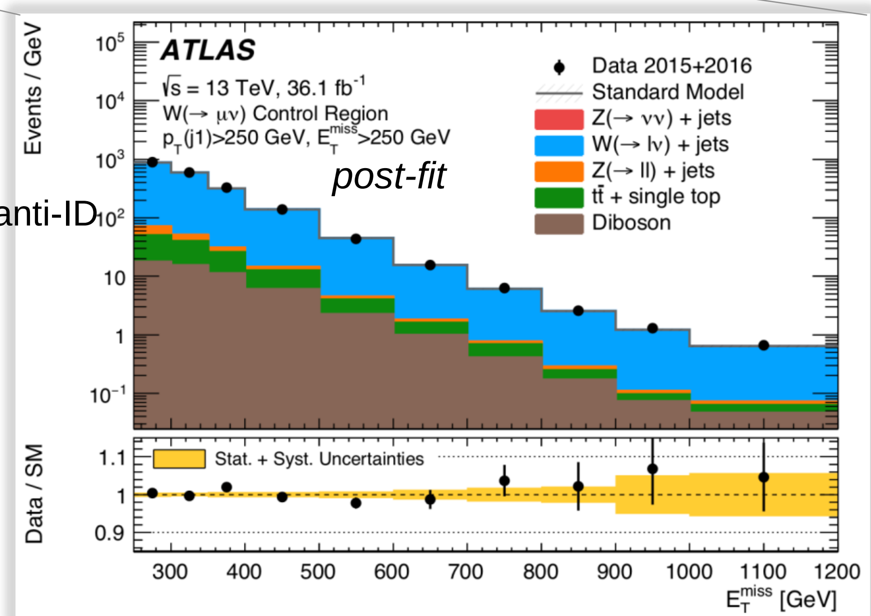
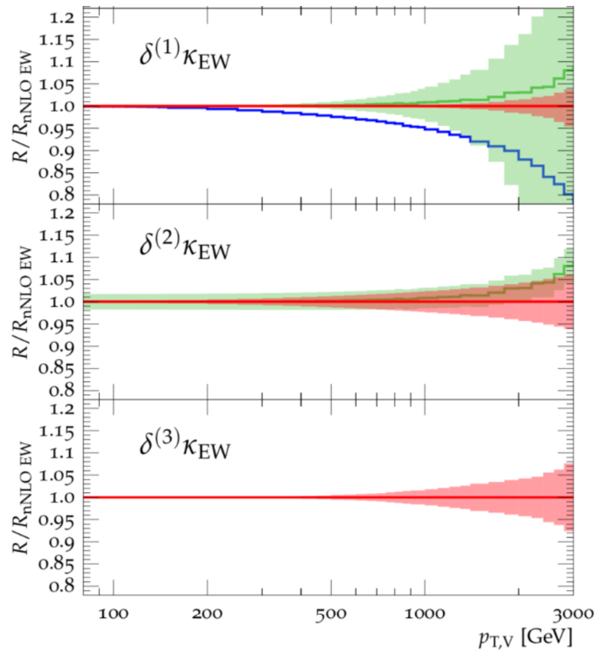


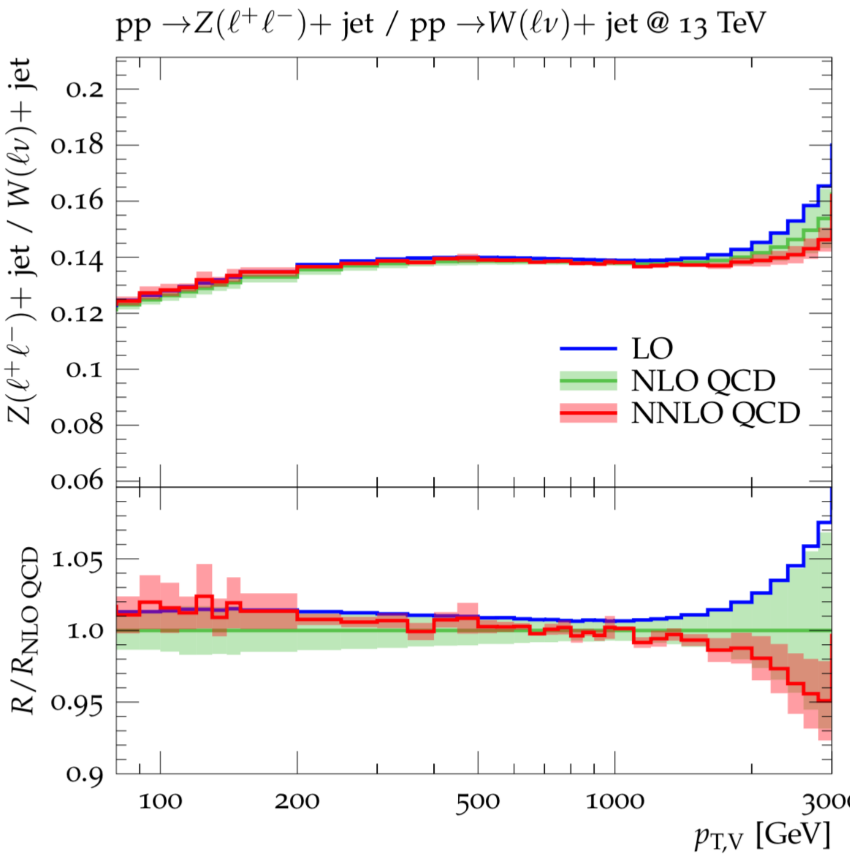
$\times \varepsilon_{\text{anti-ID}}$



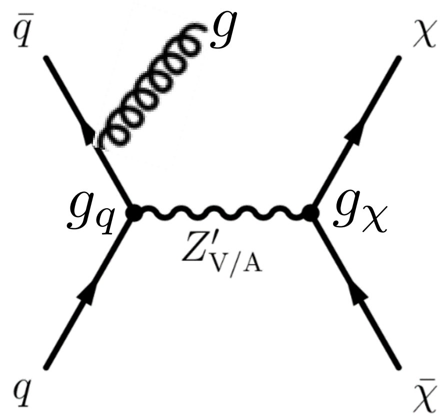
EPJC 77 (2019) 929
CERN-LPCC-2017-002
(LHC DM WG report)

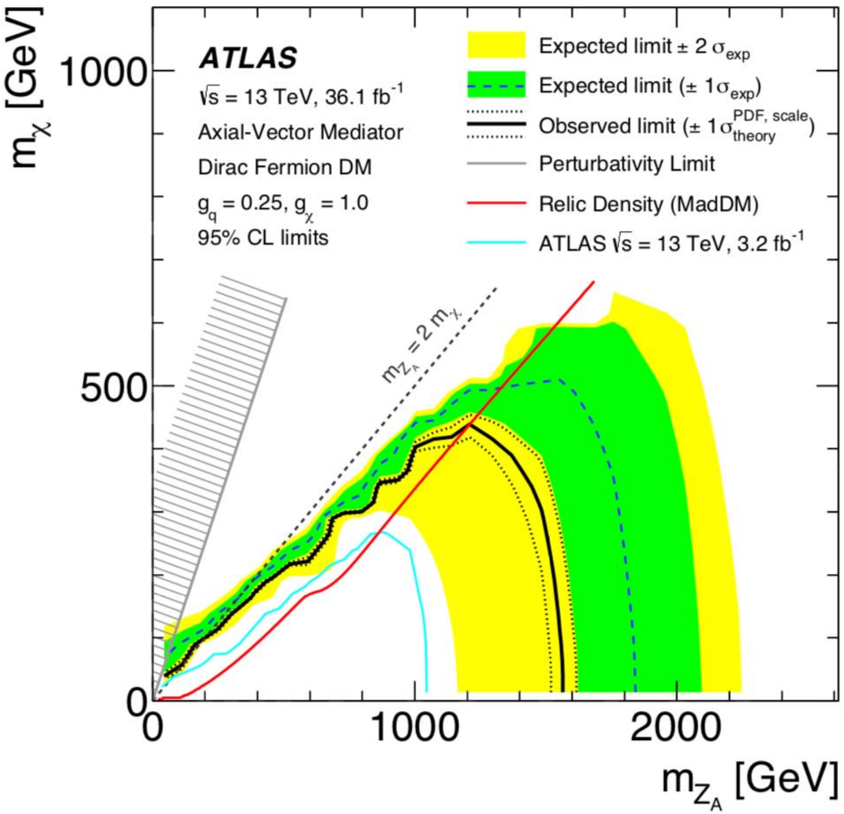
- Ansatz:
  - Constrain Z(νν)+jets using W+jets!
  - Benefit: $BR(W \rightarrow \mu\nu) \approx\ 10\% \mid \times\ 2\ (e\nu)$
- Challenge:
  - Z+jets and W+jets related, but different!
- Solution:
  - Calculate Z+jets vs W+jets difference at NNLO(α_S)+NNLL(α_S), NLO(α_{EW})

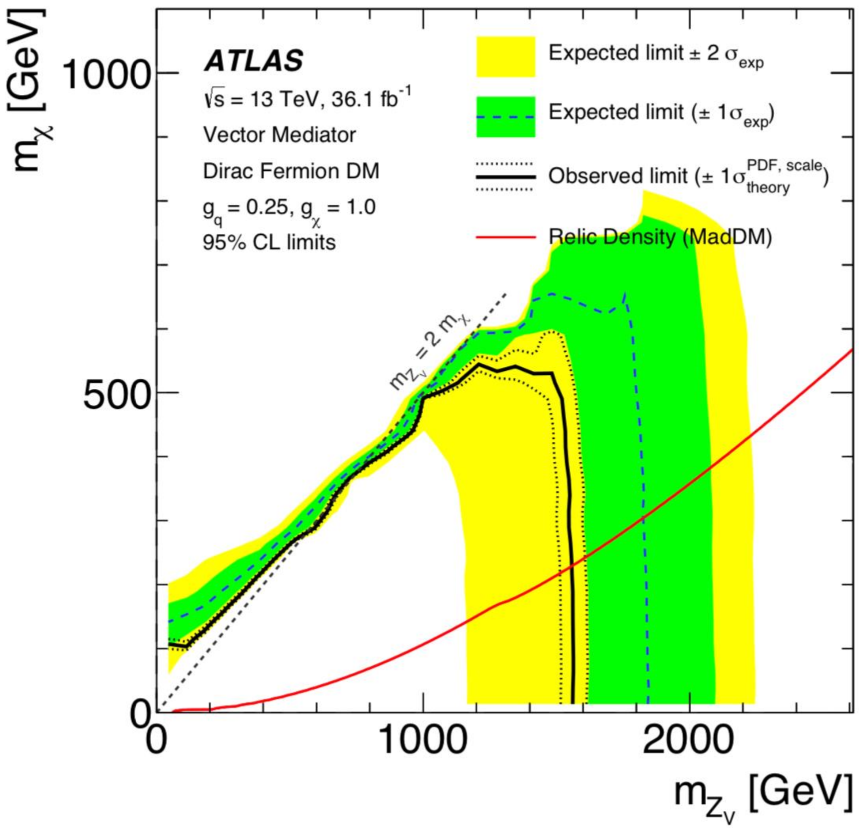




- Results:







JHEP 01 (2019) 126

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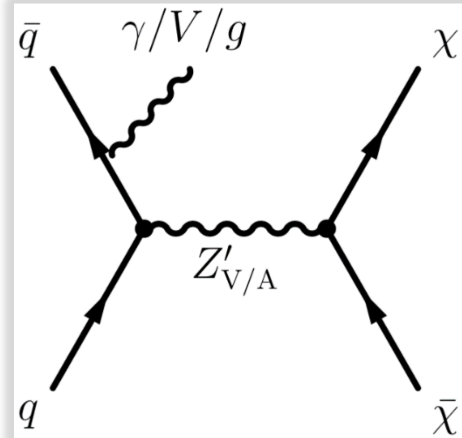

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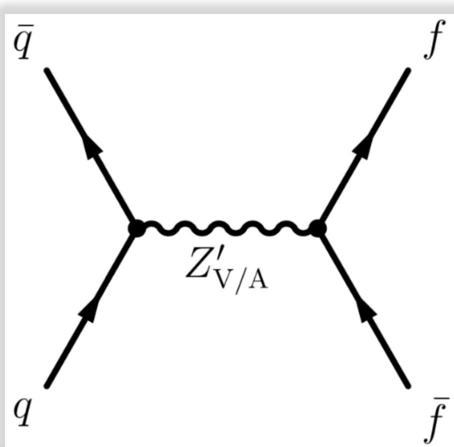
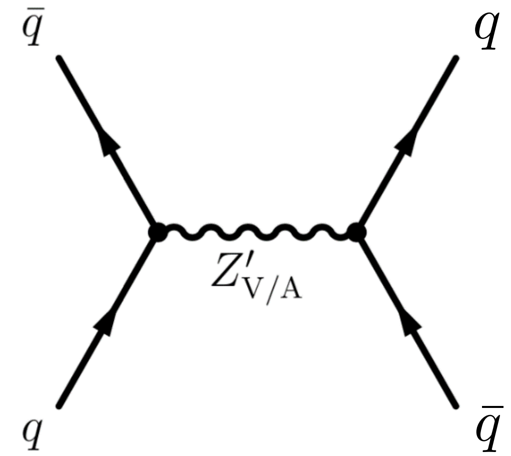


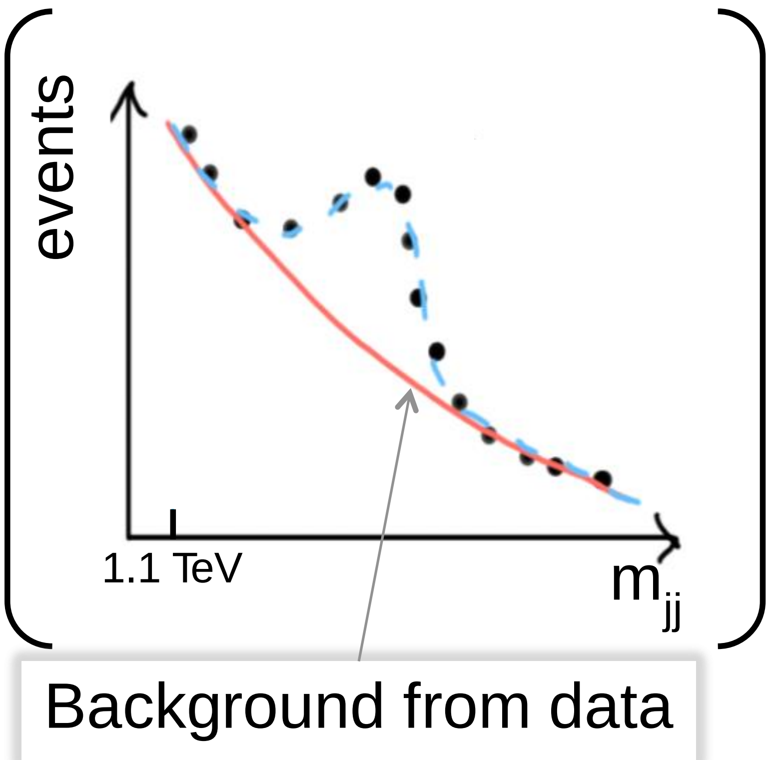
All 2015+2016 (36 fb^{-1}) results in DM summary arXiv:1903.01400

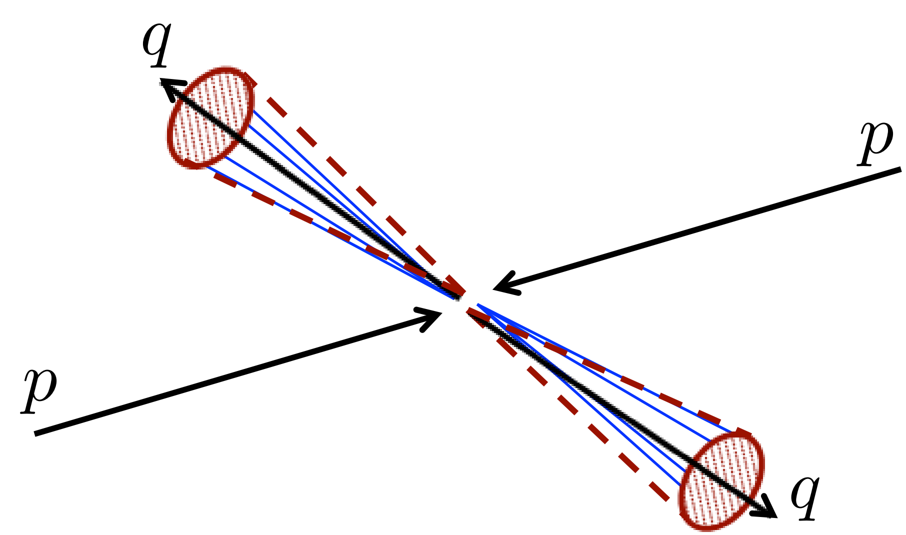
- Analysis strategy:
  - Require ≥2 of jets with p_T > 150 GeV
  - Reduce SM *t*-channel dijets:

$$|y^*| = \frac{1}{2}|y_1 - y_2| < 0.6$$

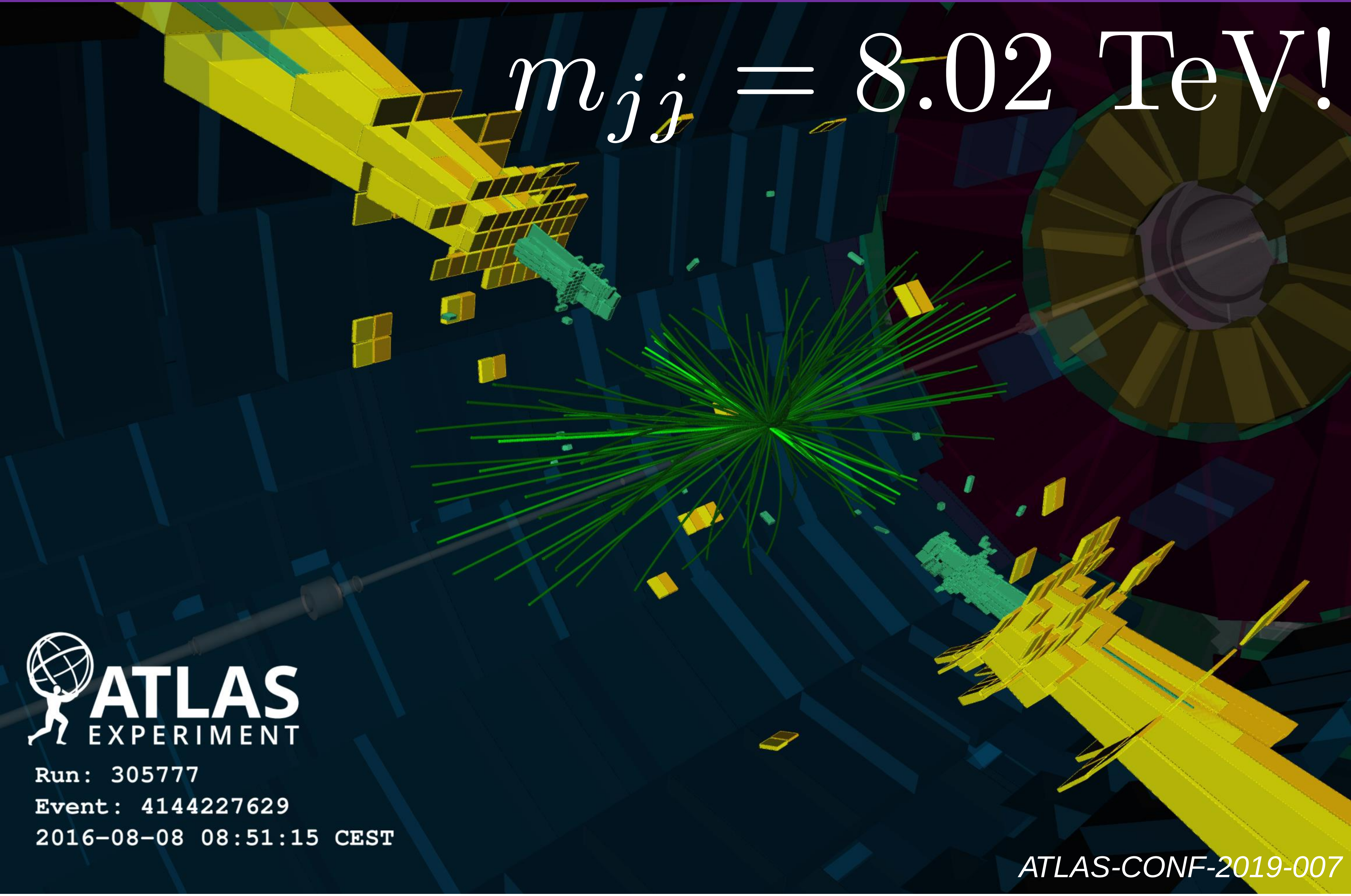
  - M_{jj} > 1.1 TeV
  - Look for excess in m_{jj} distribution:



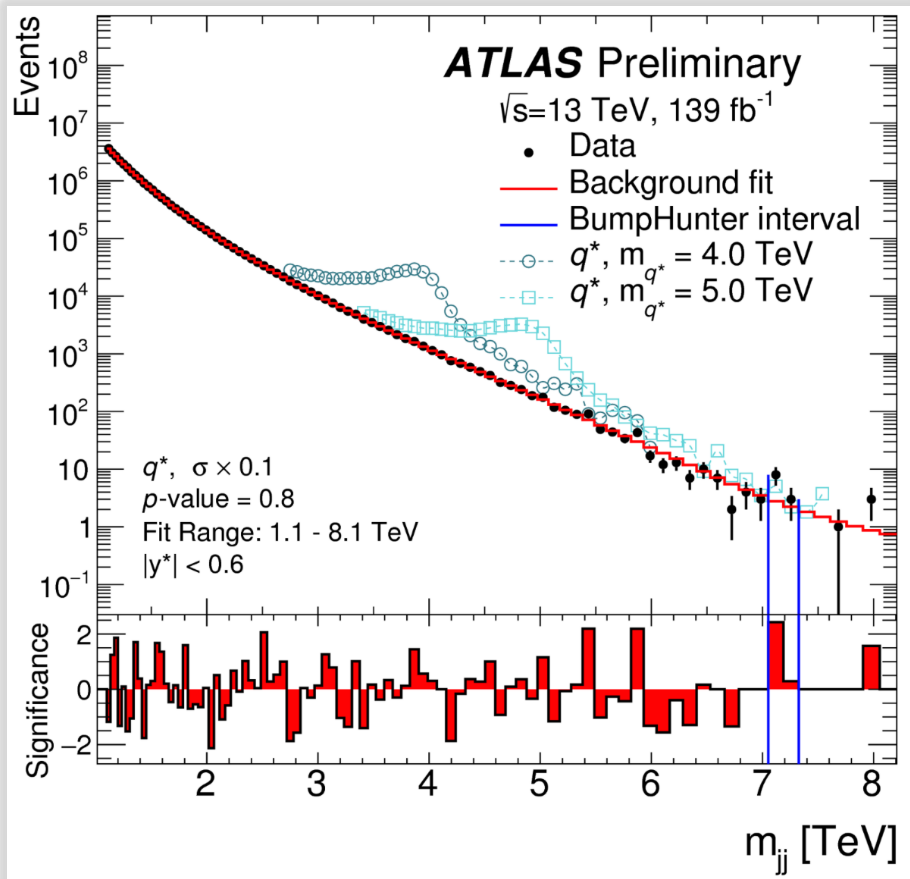


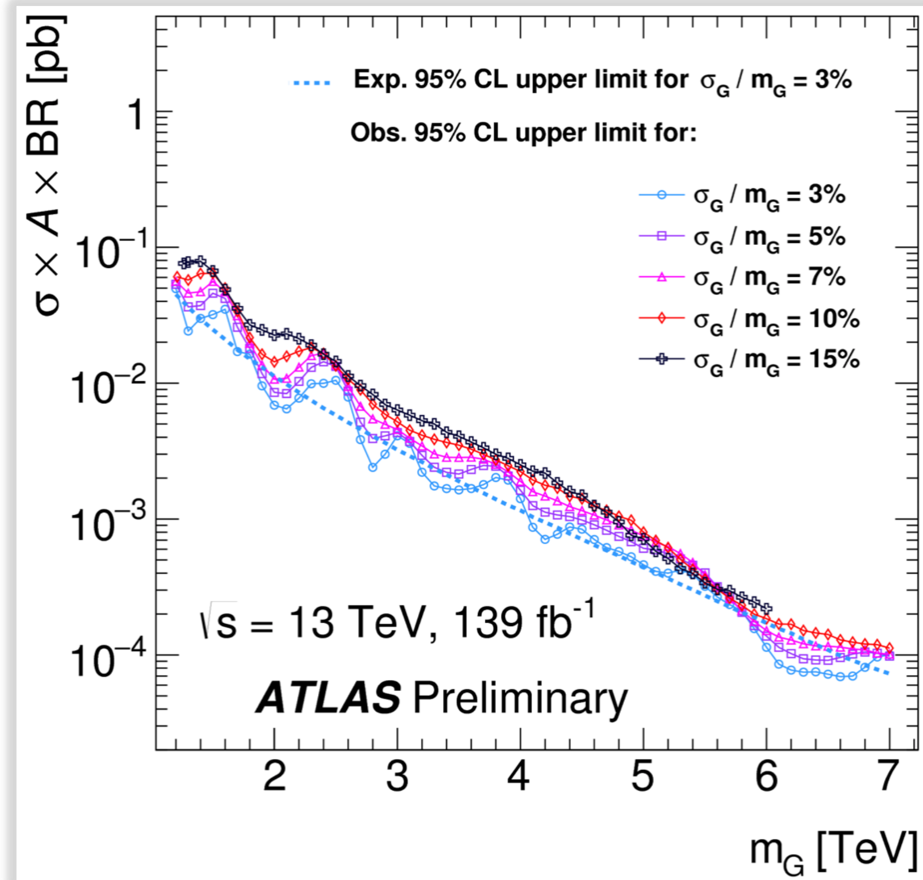


ATLAS-CONF-2019-007


$m_{jj} = 8.02$ TeV!
ATLAS
EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST
ATLAS-CONF-2019-007

- Results:



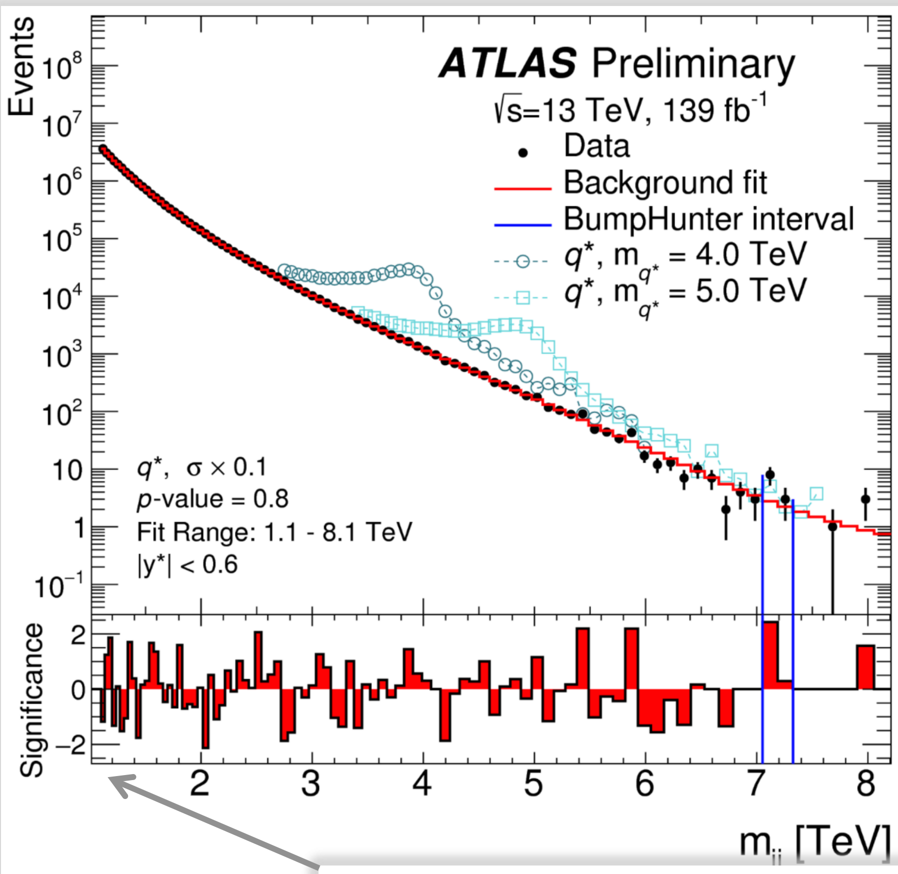


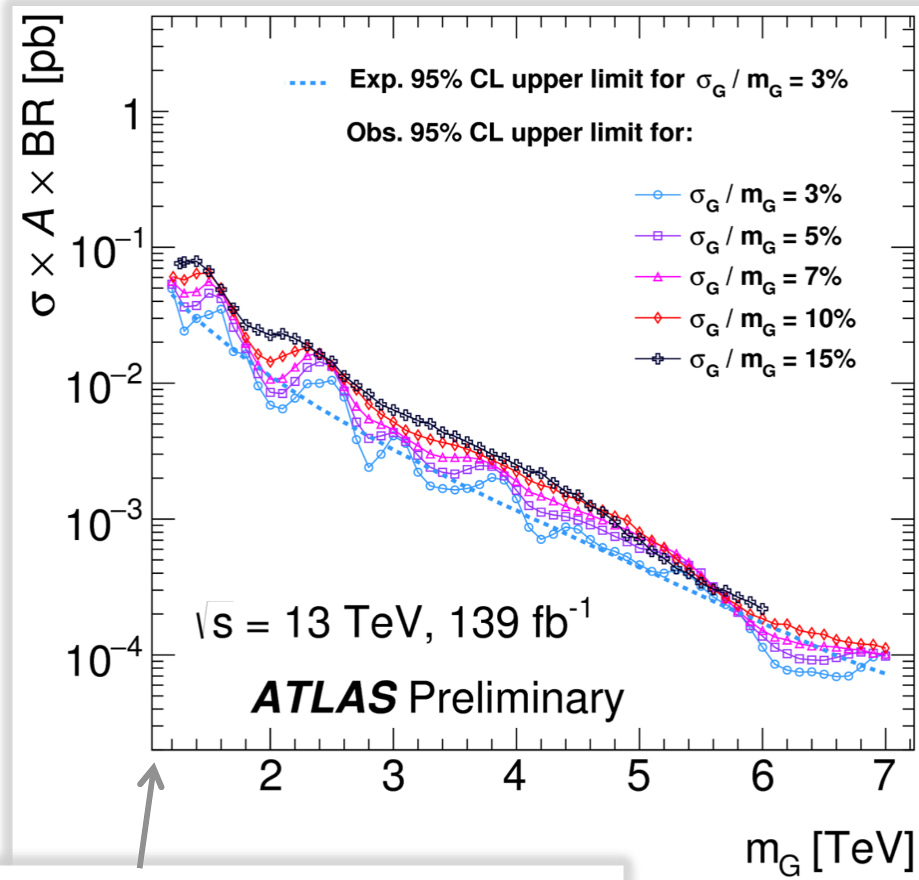
$$f(x) = p_1 (1-x)^{p_2} x^{p_3 + p_4 \ln x + p_5 (\ln x)^2}$$

$x \equiv m_{jj}/\sqrt{s}$ Nominally: $p_5 = 0$

ATLAS-CONF-2019-007

- Results:





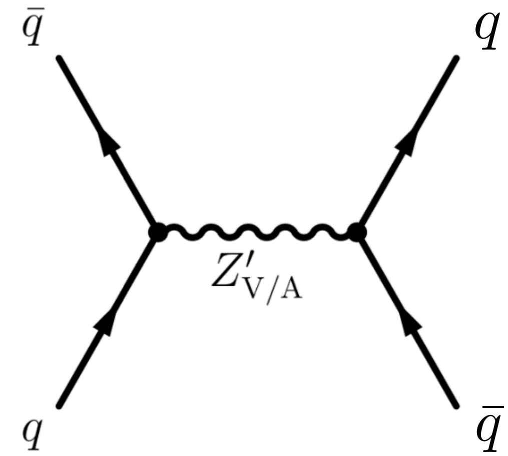
Challenge: trigger limitations below $m_{jj} < 1$ TeV!

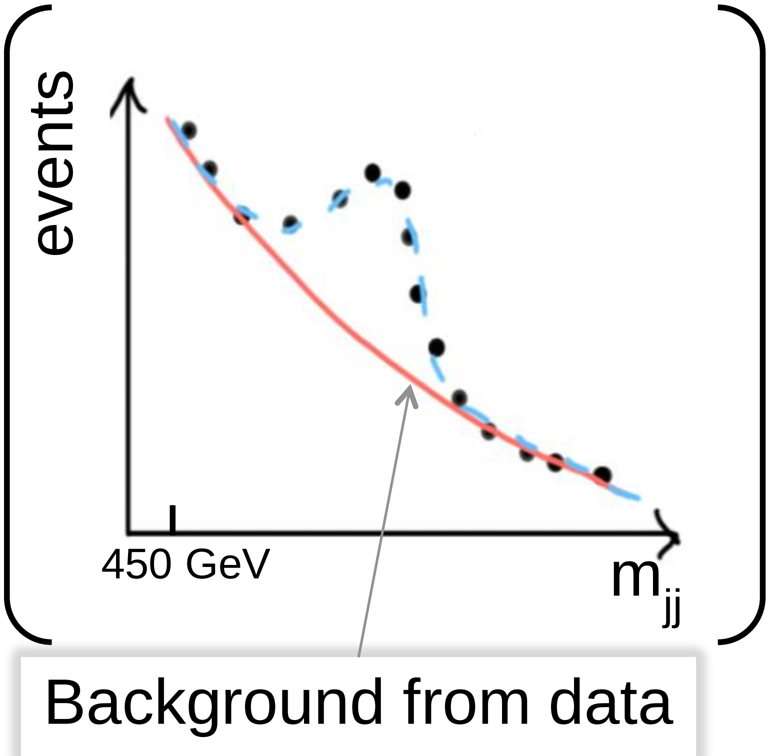
$f(x) = p_1 (1$ …

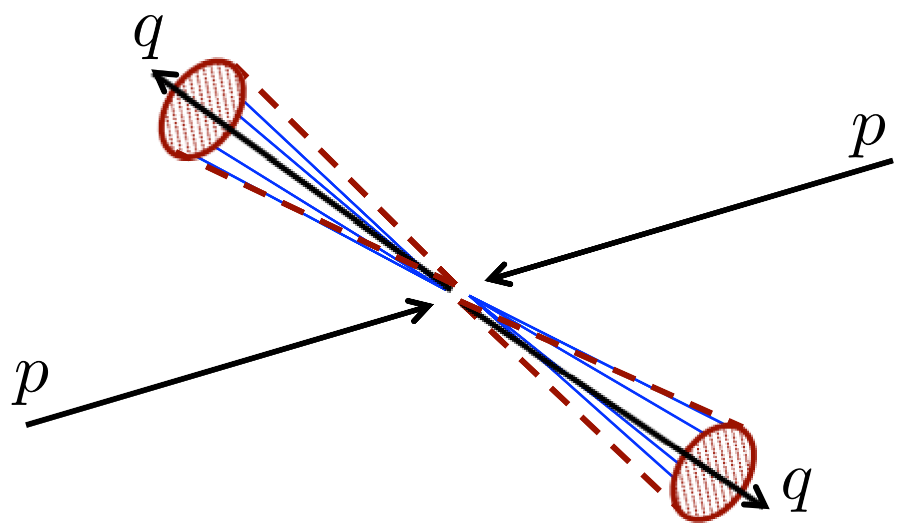
$x \equiv m_{jj}/\sqrt{s}$ Nominally: $p_5 = 0$

ATLAS-CONF-2019-007

- Analysis strategy:
  - Jets reconstructed by high-level trigger
  - Require ≥2 of jets with $p_T \gtrsim 220$ GeV
    $|y^*| = \frac{1}{2}|y_1 - y_2| < 0.6$ (also 0.3)
  - $M_{jj} > 450$ GeV
  - Look for excess in m_{jj} distribution:



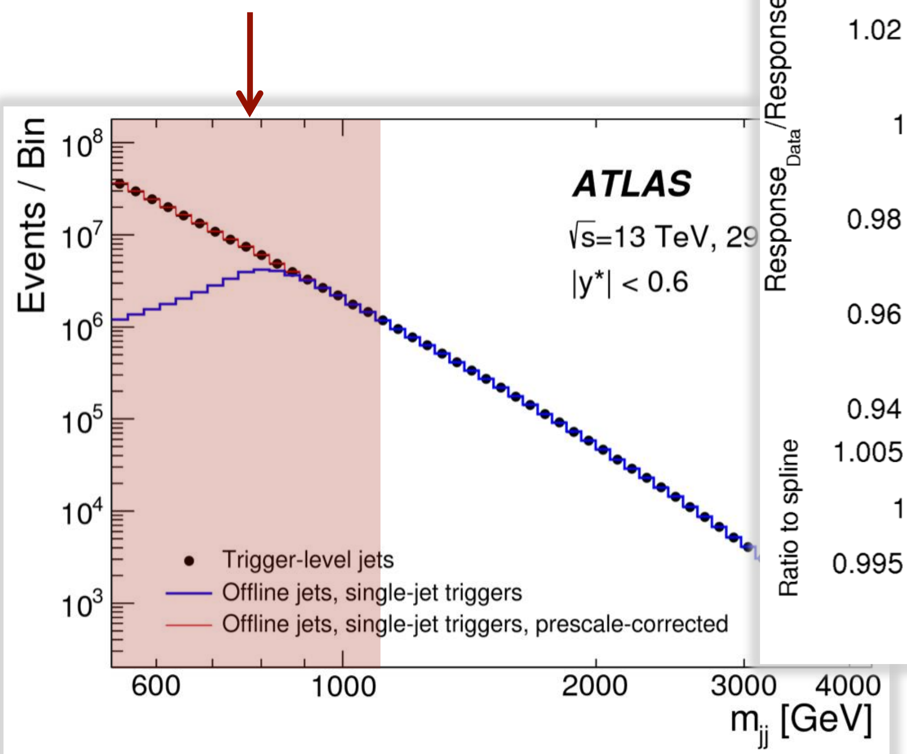


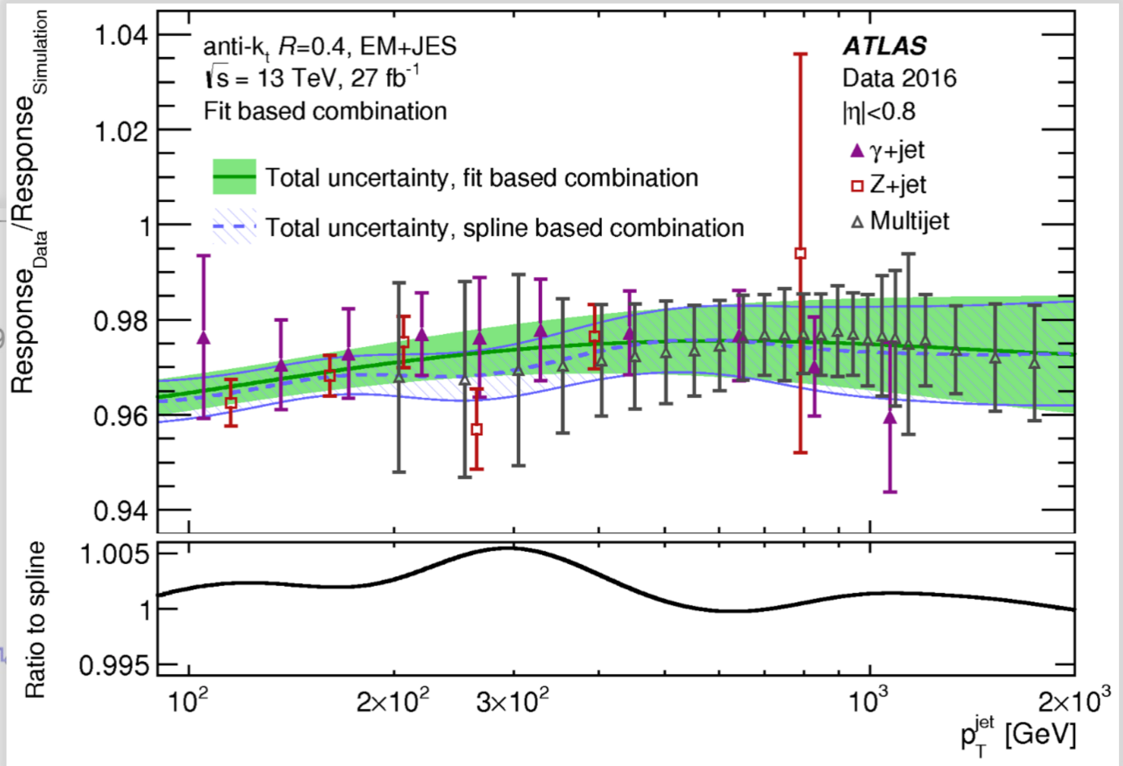


PRL 121 (2018) 081801

- Ansatz:
  - Reconstruct jets using High Level Trigger
  - Storage: one 4-vector per jet → larger bandwidth!
- Challenge:
  - Calibration of jets in High Level Trigger:

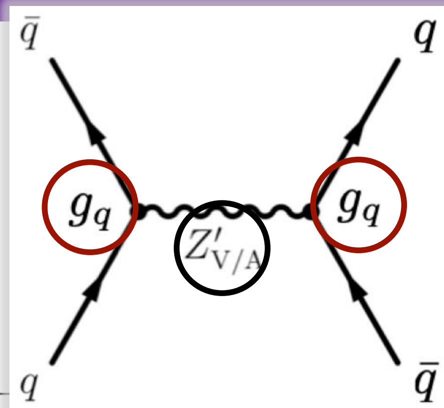
Trigger level analysis

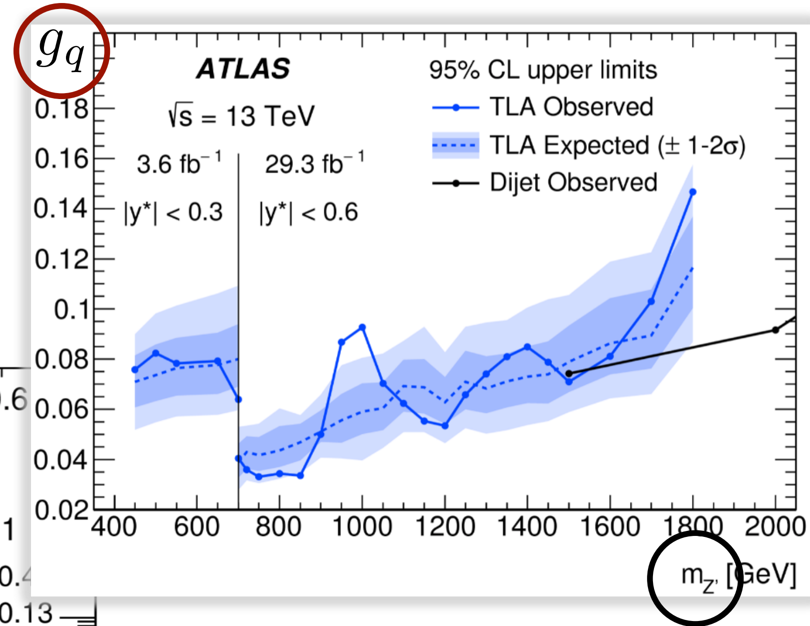


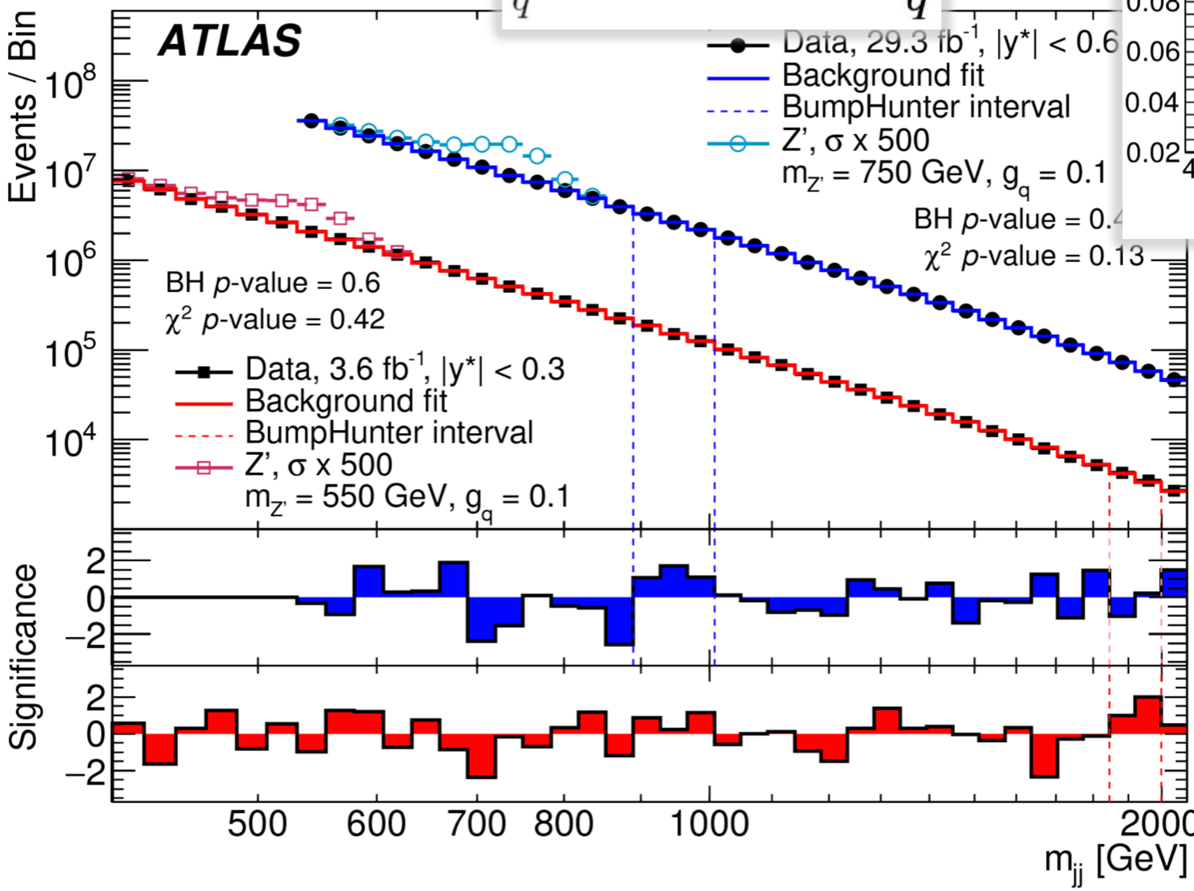


PRL 121 (2018) 081801

- Results:

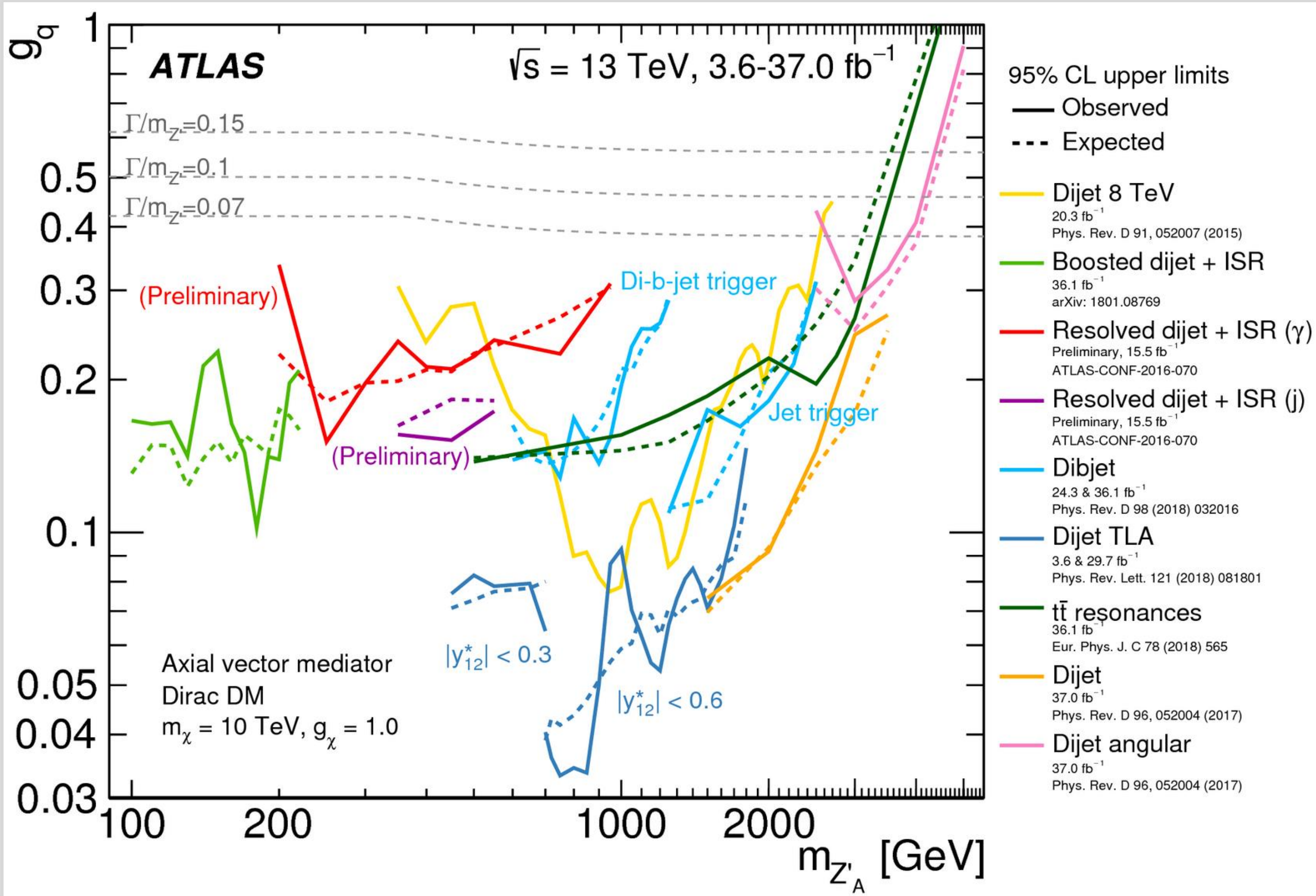






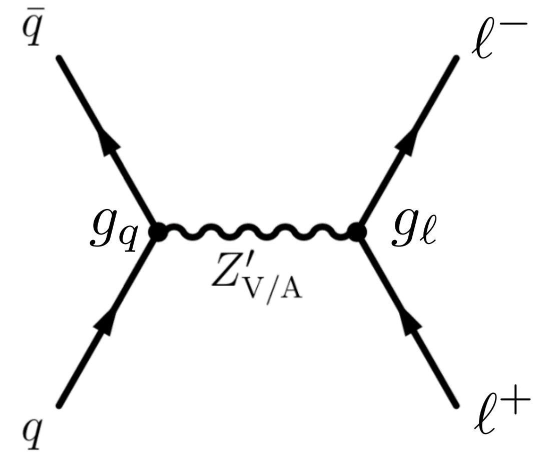
PRL 121 (2018) 081801

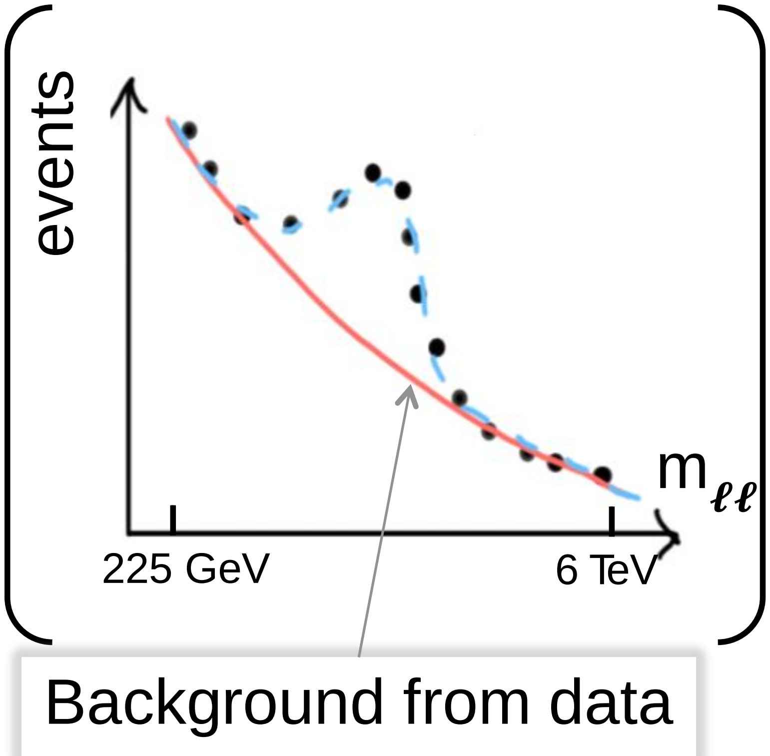
- Overview plot from the Dark Matter Summary Paper:
  - using 2015+2016 data only – expect improvements!

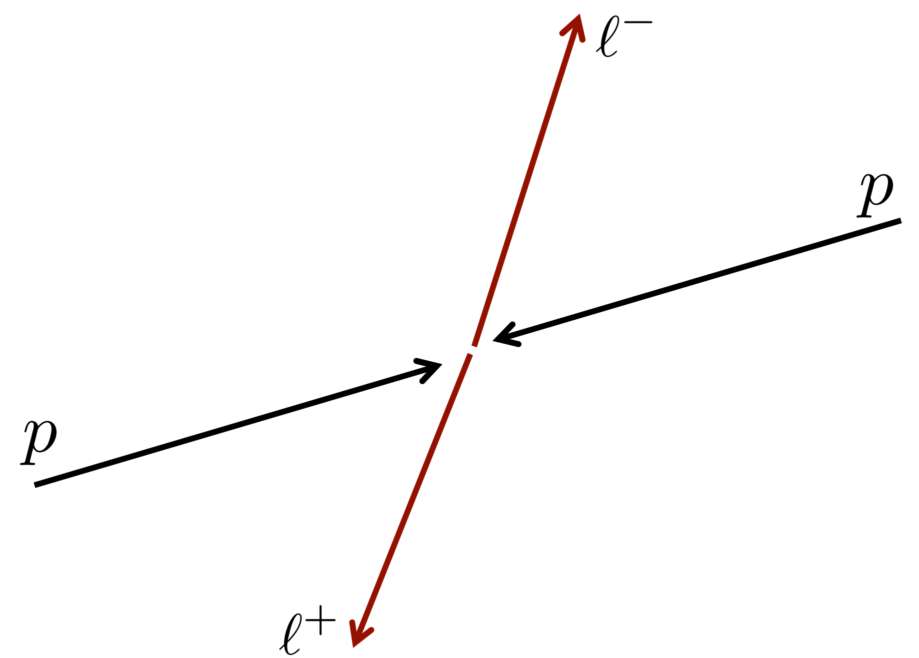


acc'd by JHEP, arXiv:1903.01400

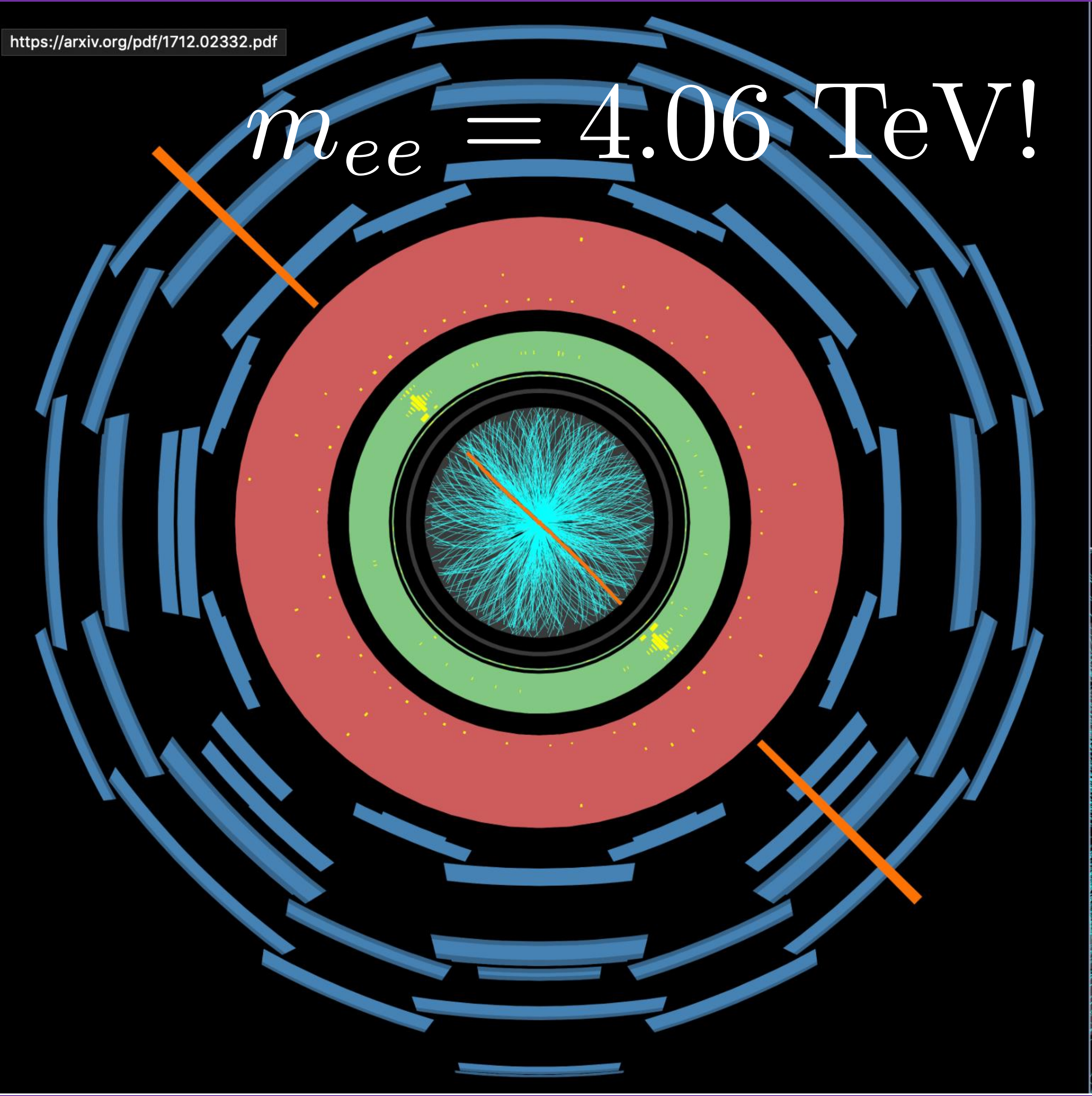
- Analysis strategy:
  - Require ee or $\mu\mu$ pair with $p_T \gtrsim 220$ GeV
  - $m_{\ell\ell} > 225$ GeV
  - Look for excess in $m_{\ell\ell}$ distribution:



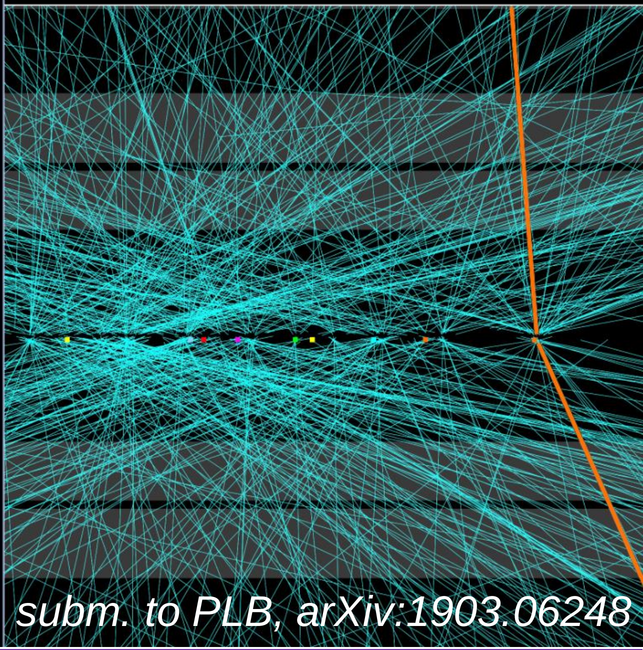




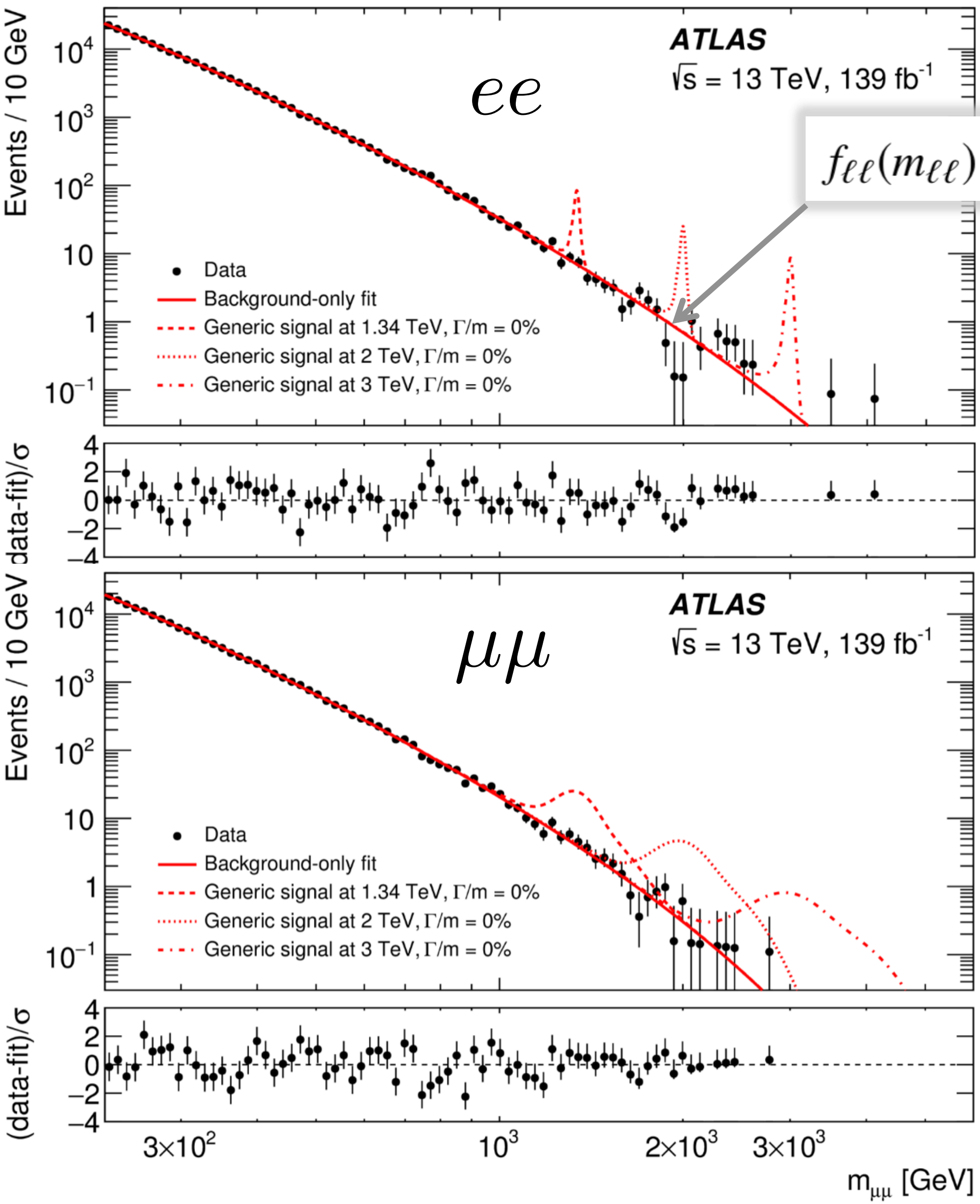
subm. to PLB, arXiv:1903.06248


https://arxiv.org/pdf/1712.02332.pdf
$m_{ee} = 4.06$ TeV!


ATLAS
EXPERIMENT
Run Number: 336852, Event Number: 1440436043
Date: 2017-09-29 11:44:35 CEST


subm. to PLB, arXiv:1903.06248

DILEPTON RESONANCES: RESULTS

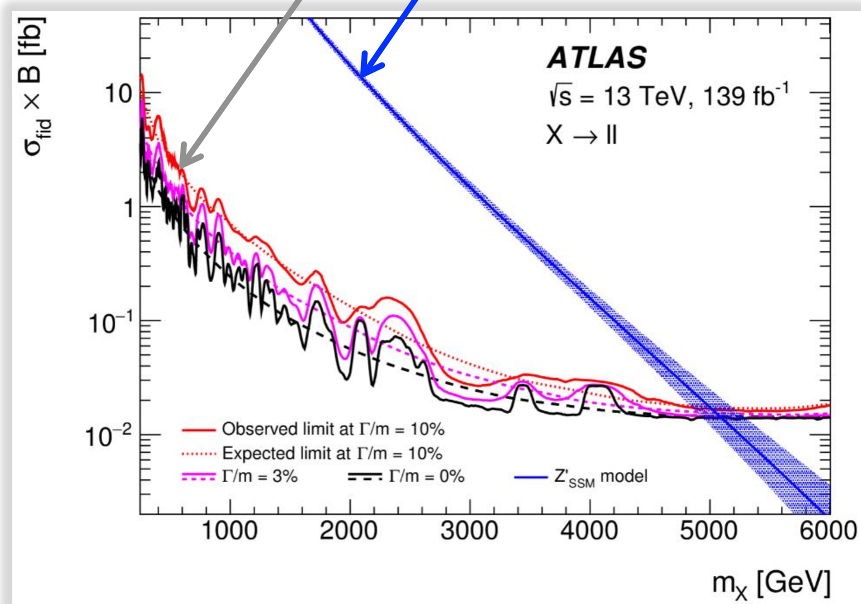


Background parametrisation:

$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i},$$

Generic resonance limits for Breit-Wigner ⊗ resolution

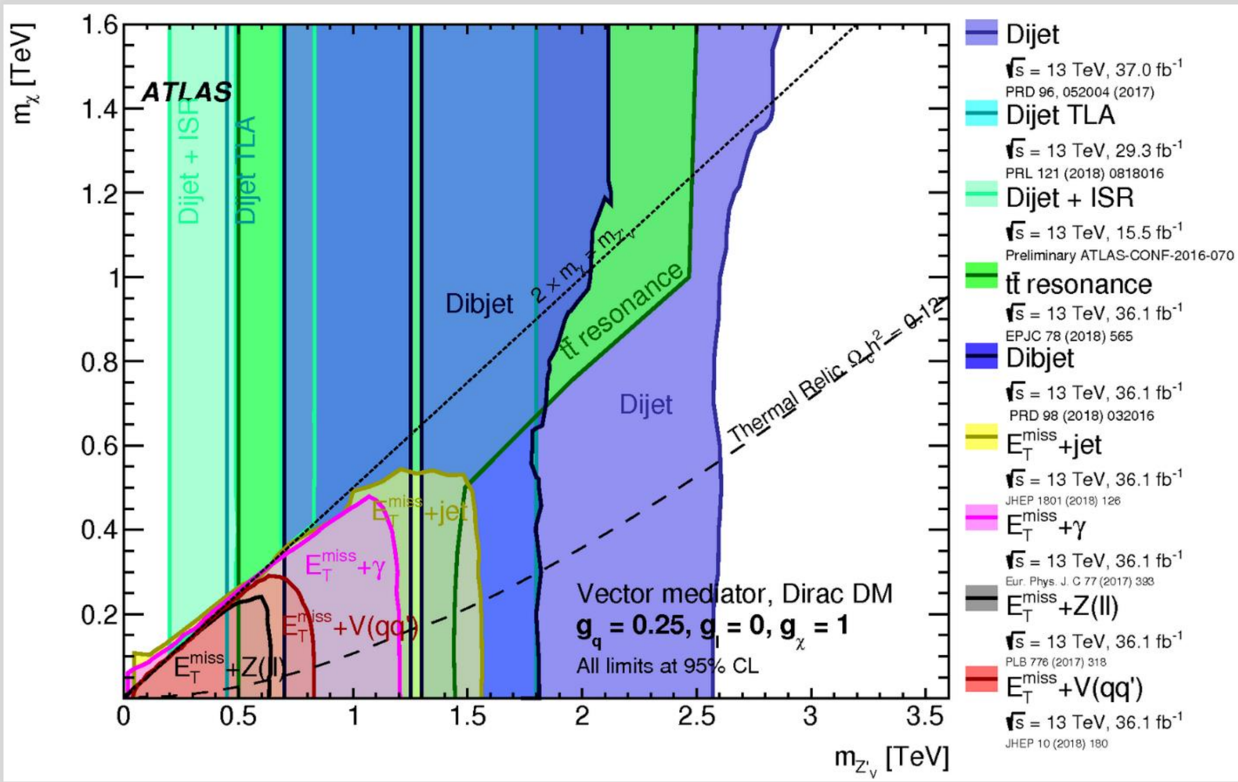
Z'_{SSM} $(\Gamma/m = 3.0\%)$

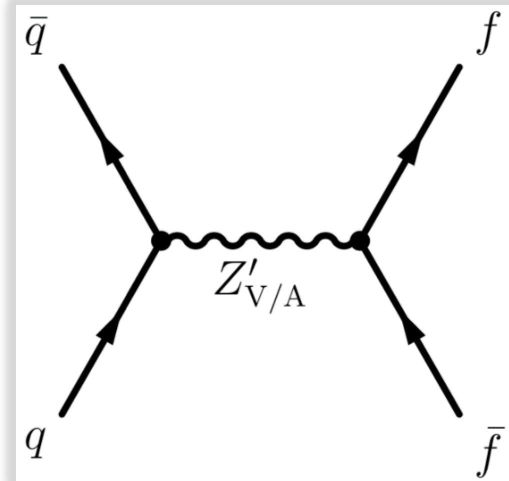


subm. to PLB, arXiv:1903.06248

Dark Matter V/AV model: COMBINATION

- Objective: summarise DM searches using 2015+2016 data:





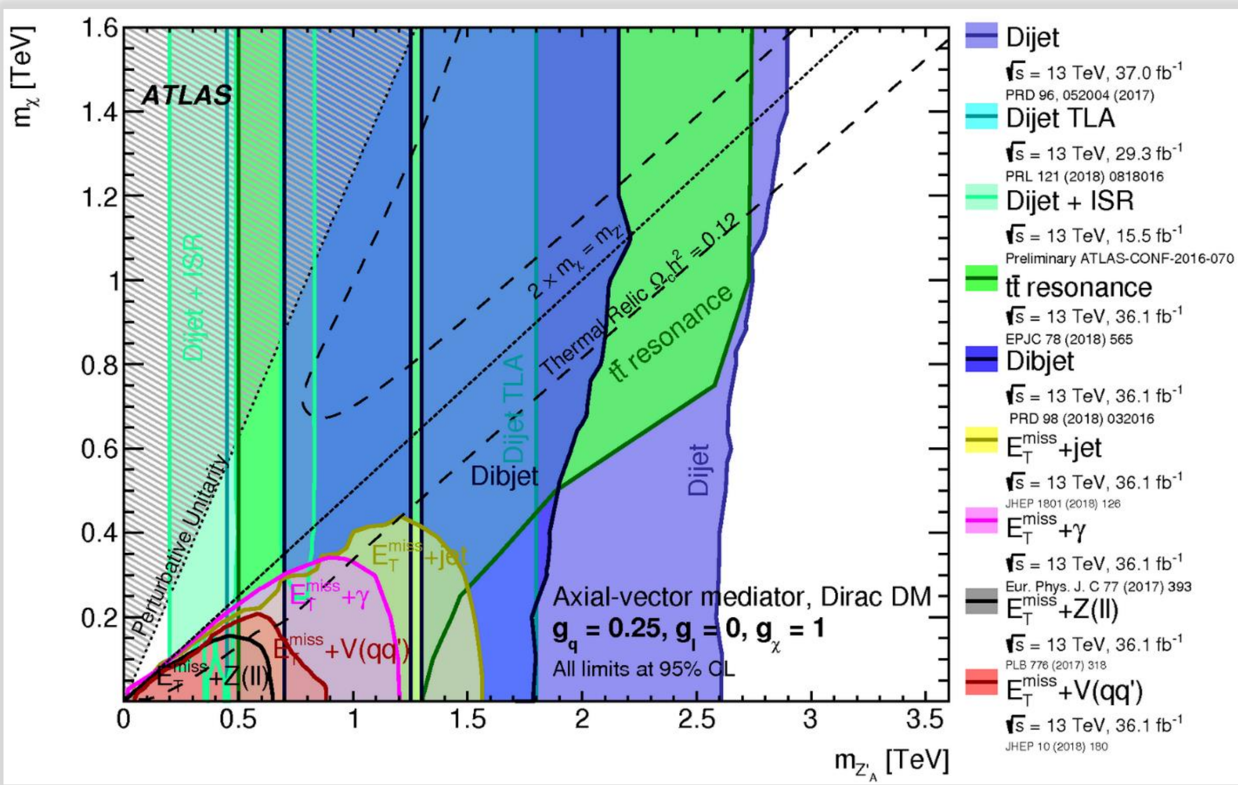
arXiv:1703.05703

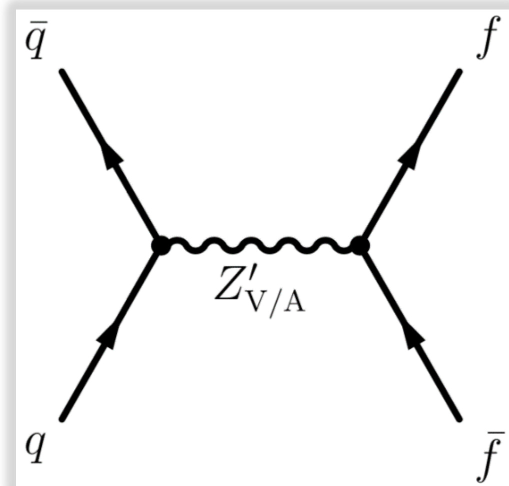
LHC DM WG recommendation:
Explore complementarity between X+MET & resonance searches
→ 4 representative scenarios!

Coupl.	V1	V2	A1	A2
g_q	0.25	0.1	0.25	0.1
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1

JHEP, arXiv:1903.01400

- Objective: summarise DM searches using 2015+2016 data:





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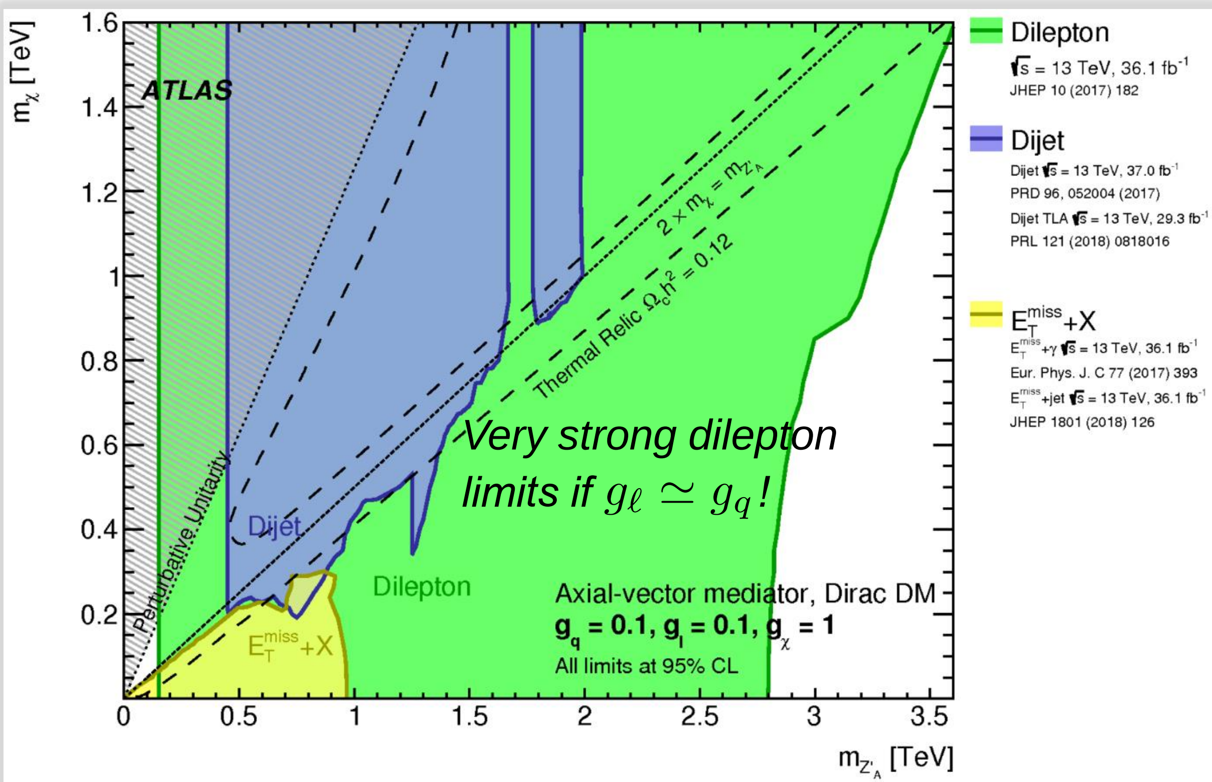

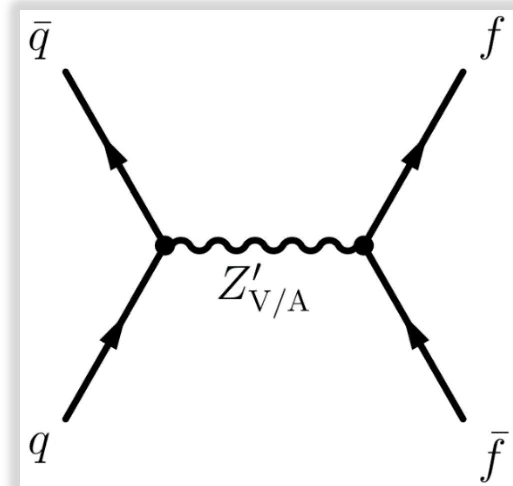

arXiv:1703.05703

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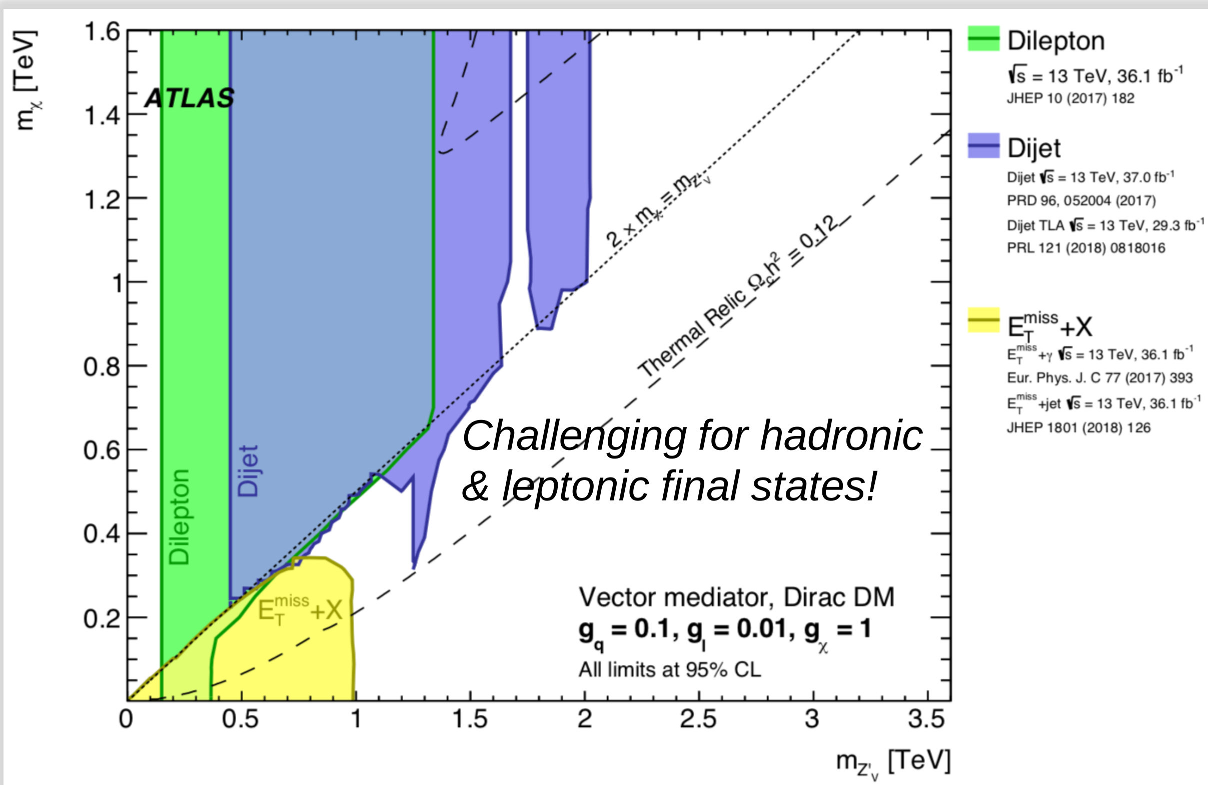
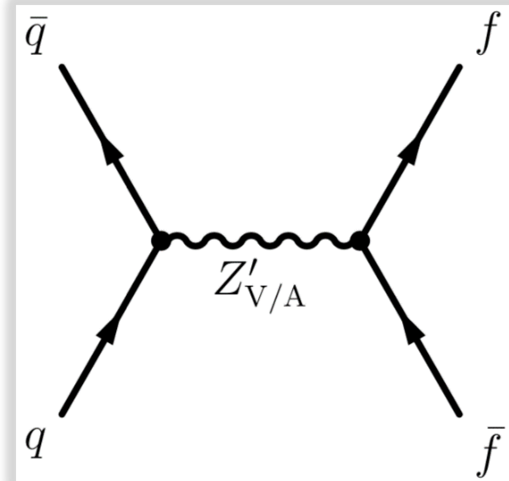
JHEP, arXiv:1903.01400

DARK MATTER SUMMARY PAPER: OVERVIEW

- Objective: summarise DM searches using 2015+2016 data:





arXiv:1703.05703

LHC DM WG recommendation:
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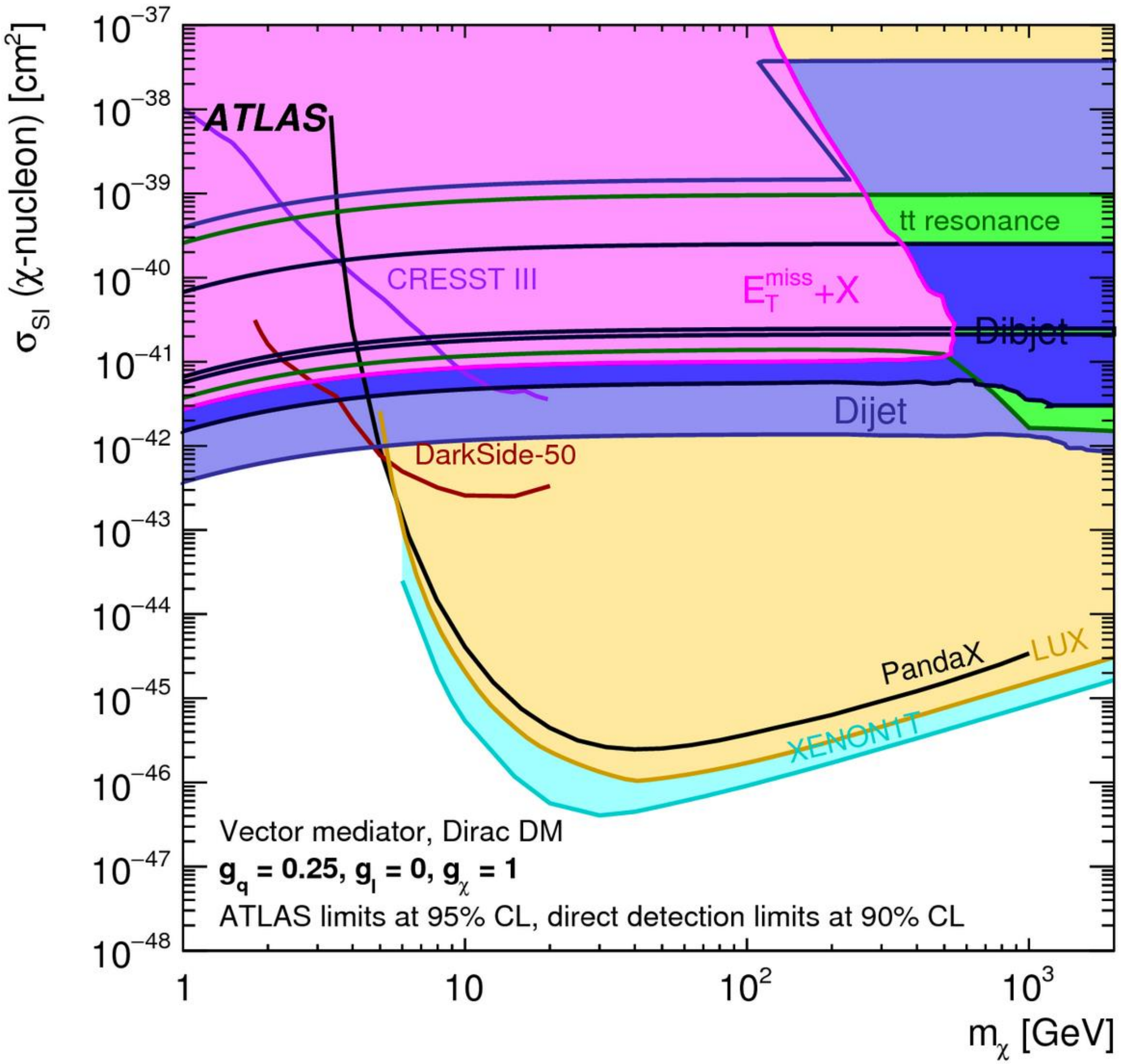
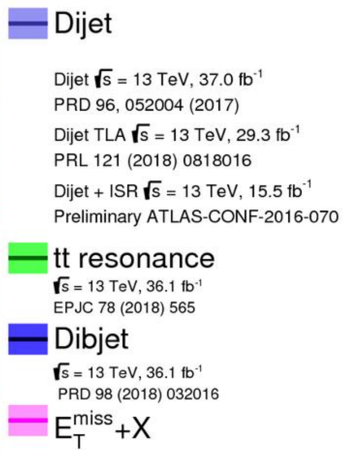
JHEP, arXiv:1903.01400

- Complementarity of ATLAS results and direct detection expertiments





arXiv:1703.05703

Coupl.	V1	V2	A1	A2
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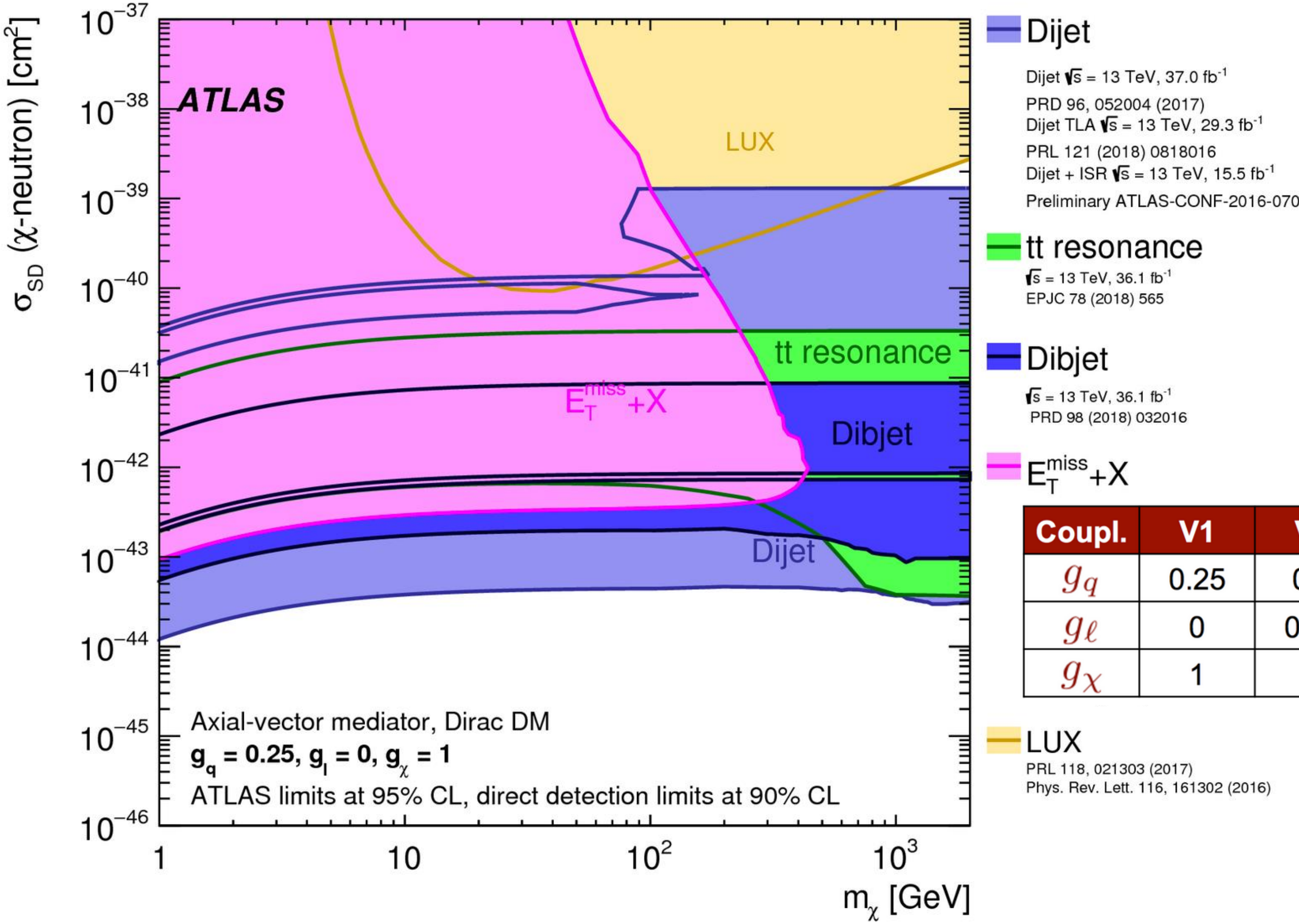
JHEP, arXiv:1903.01400

- Complementarity of ATLAS results and direct detection exptertiments



arXiv:1703.05703

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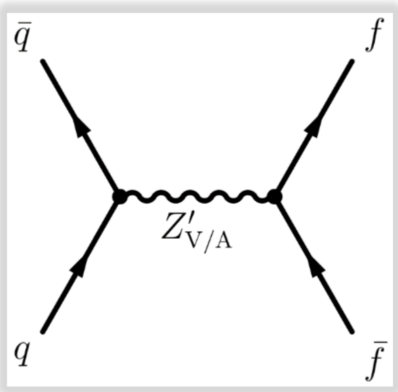
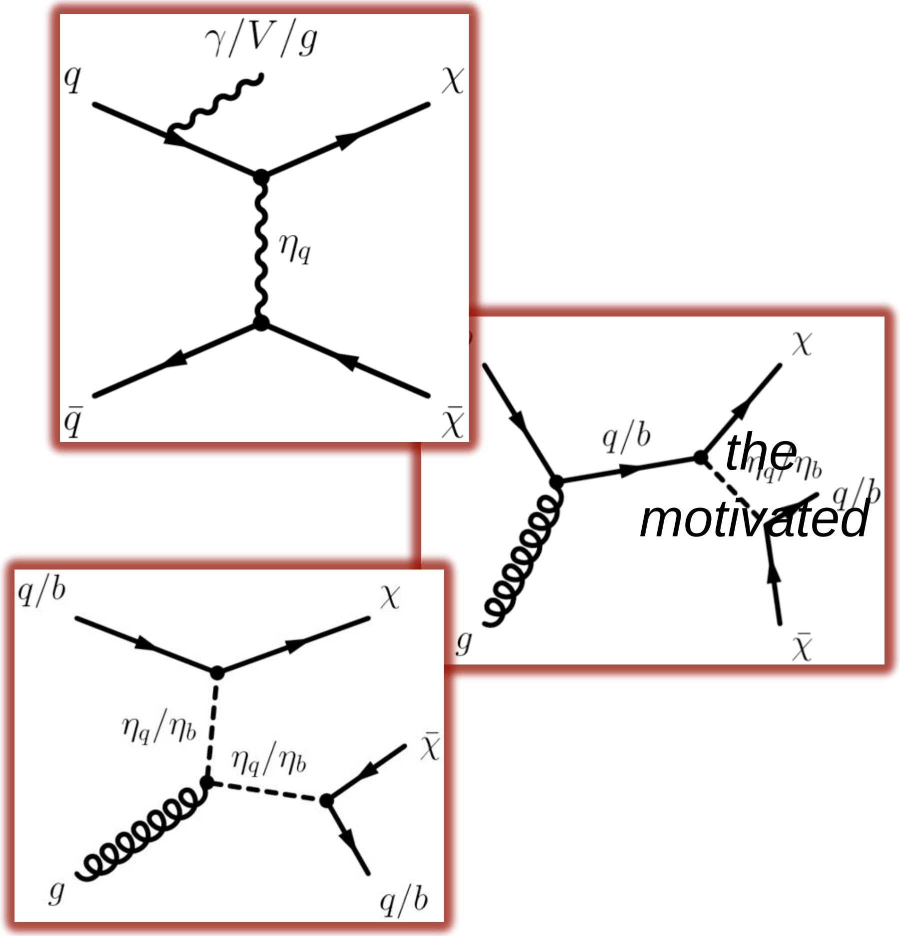
g_ℓ	0	0.01	0	0.1
g_χ	1	1	1	1

JHEP, arXiv:1903.01400

- Interpretations shown focus on s-channel mediator case:



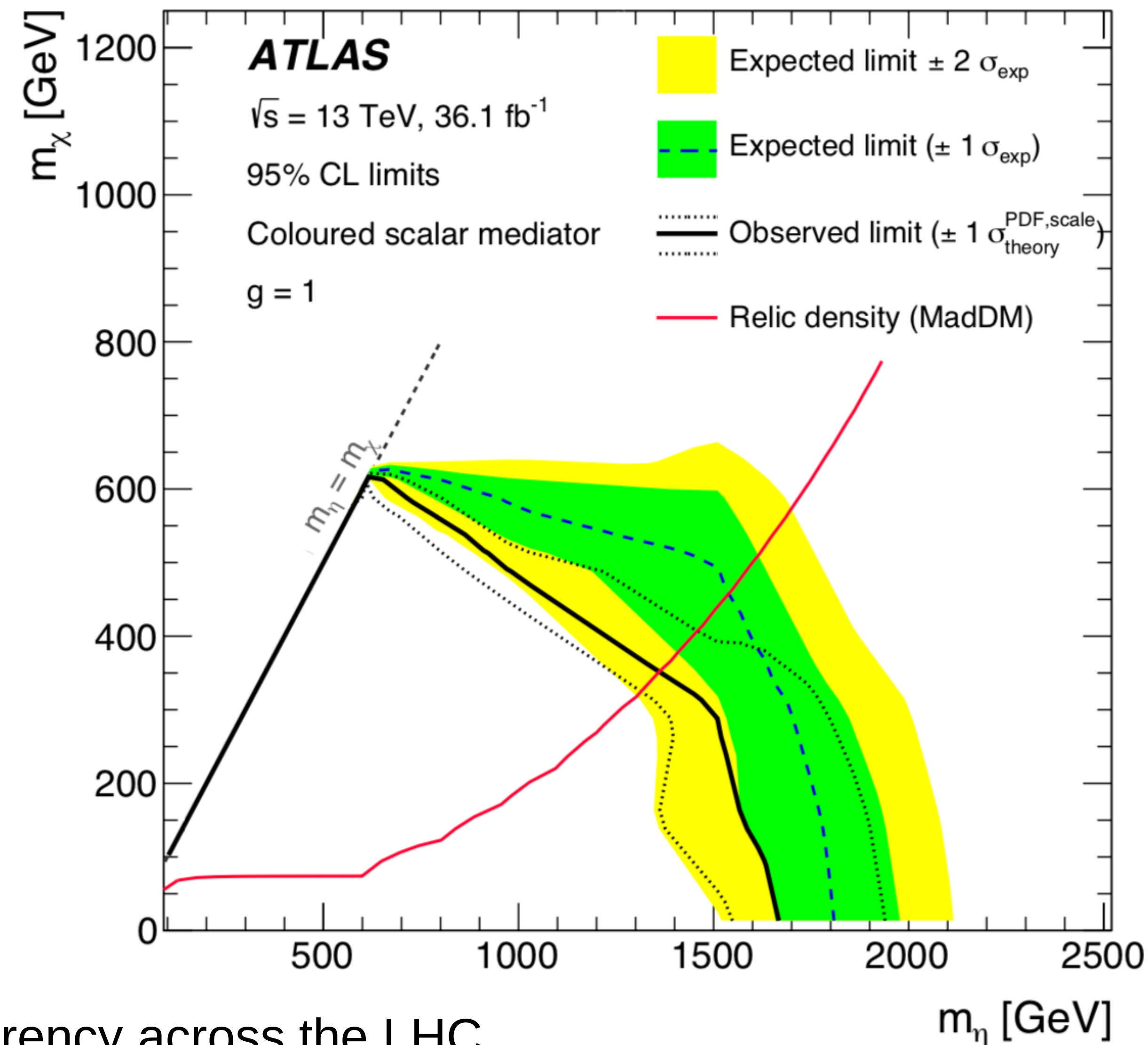
- What if…
  - Nature thought differently?
    - E.g. t-channel mediators?
      - *t-channel mediators to dark sector are equally motivated as s-channel*



Dramatic difference, → no resonances!

- Results:

JHEP 01 (2019) 126



But: no coherency across the LHC...

LPCC: LHC Physics Centre at CERN

Welcome | About | LHC working groups | LHC publications | Events | Newsletter | HL/HE-LHC Workshop

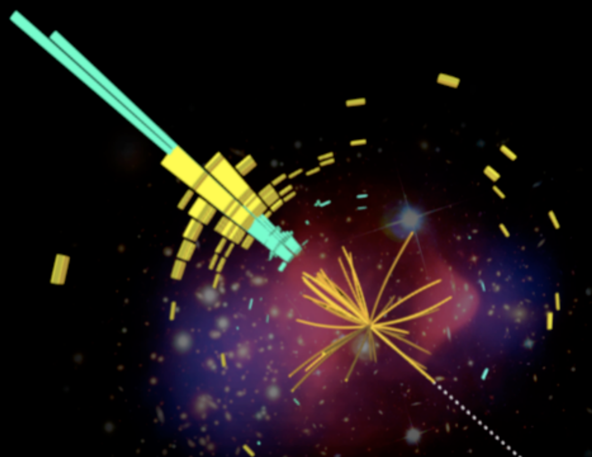
LHC DM WG: WG on Dark Matter Searches at the LHC

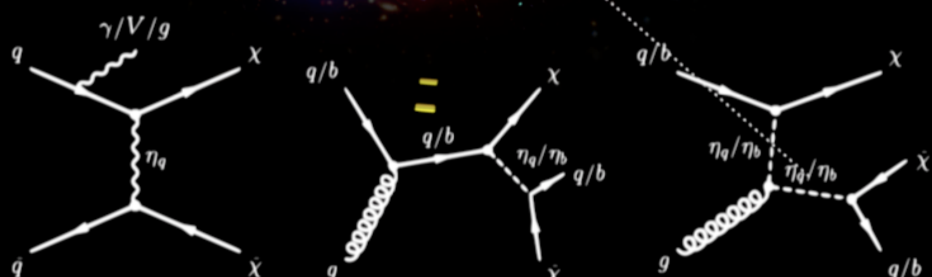
- Role:
  - Provide open, collaborative, and friendly environment for:
    - Discuss new Dark Matter signatures
    - Devise future searches for Dark Matter
    - Provide recommendations for interpretation of Dark Matter searches
  - Your ideas very welcome:
    - E.g. t-channel mediators, dark photon models, you name it!
      - Suggestions for future topics you would like to tackle very welcome!
  - Facilitate exchange of ideas through meetings etc:
    - http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors

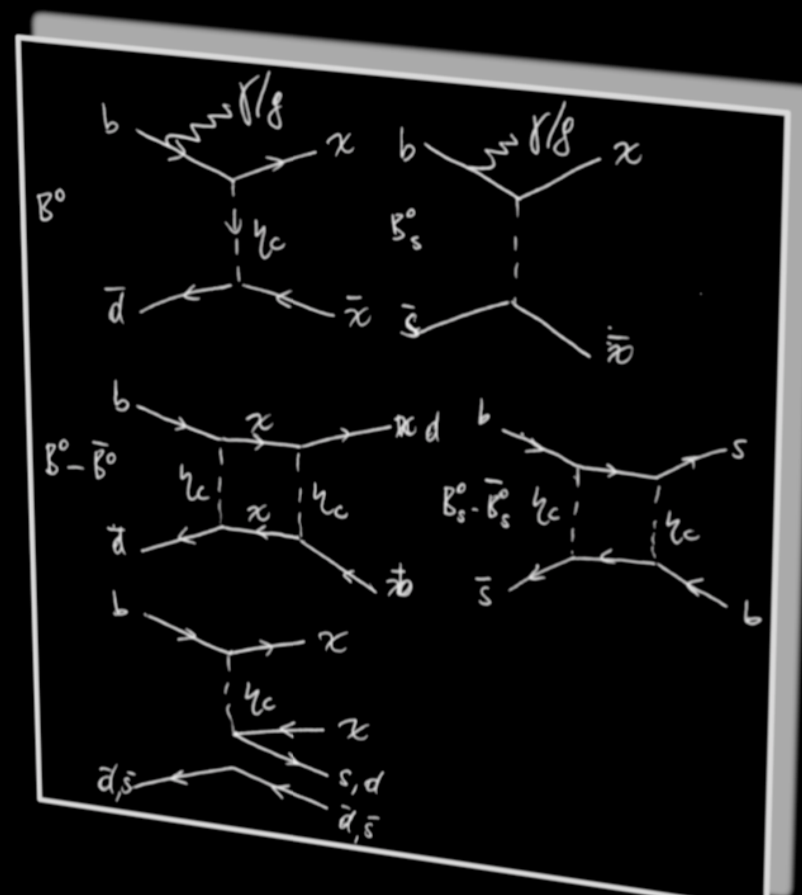
Dark Matter Models with *t*-Channel Mediators | @LHC & B-Factories

26 April 2019 • 13:00-18:00 • CERN 40-S2-C01 (Salle Curie) • Vidyo

& Going Beyond?







Consolidating Existing Work

Experimental + Theory Workshop

https://indico.cern.ch/e/tChannelDM

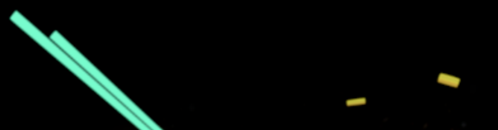
LHC Dark Matter Working Group

Organisers: Oleg Brandt • Ulrich Haisch • Philipp Harris • Christian Ohm • Tim Tait • Xabier Cid Vidal

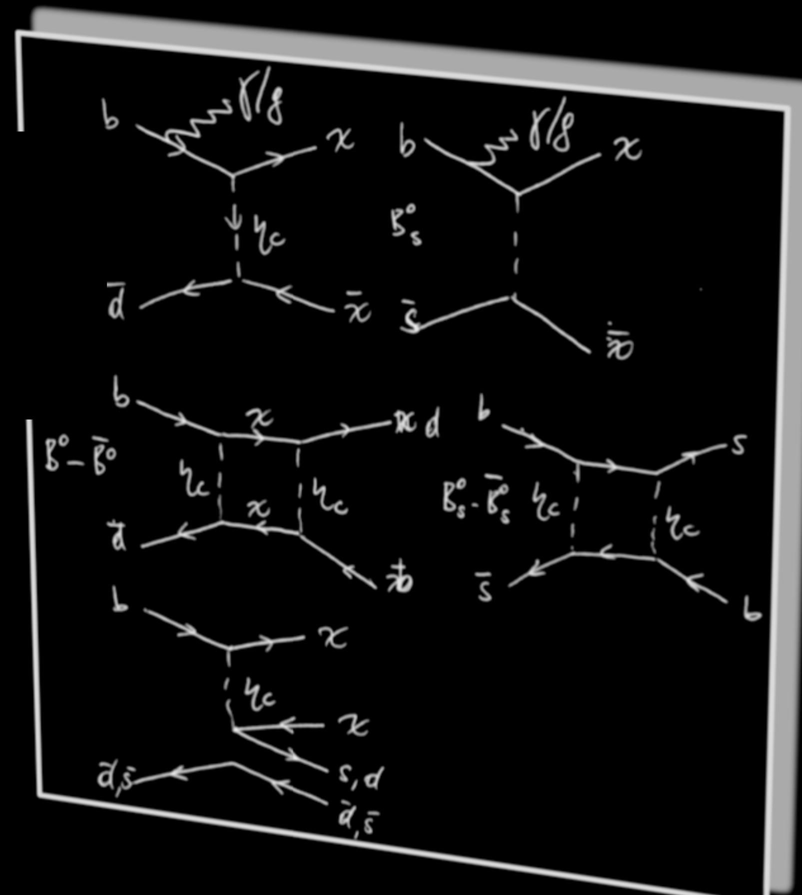
DARK MATTER MODELS WITH *t*-CHANNEL MEDIATORS | @LHC & B-FACTORIES

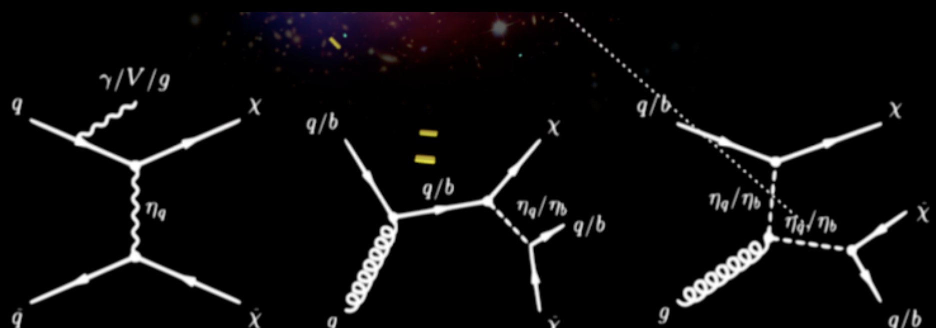
26 April 2019 • 13:00-18:00 • CERN 40-S2-C01 (Salle Curie) • Vidyo

& GOING BEYOND?



Work towards White Paper started!
Expressions of interest being collected in document linked from workshop page
https://indico.cern.ch/event/806526/





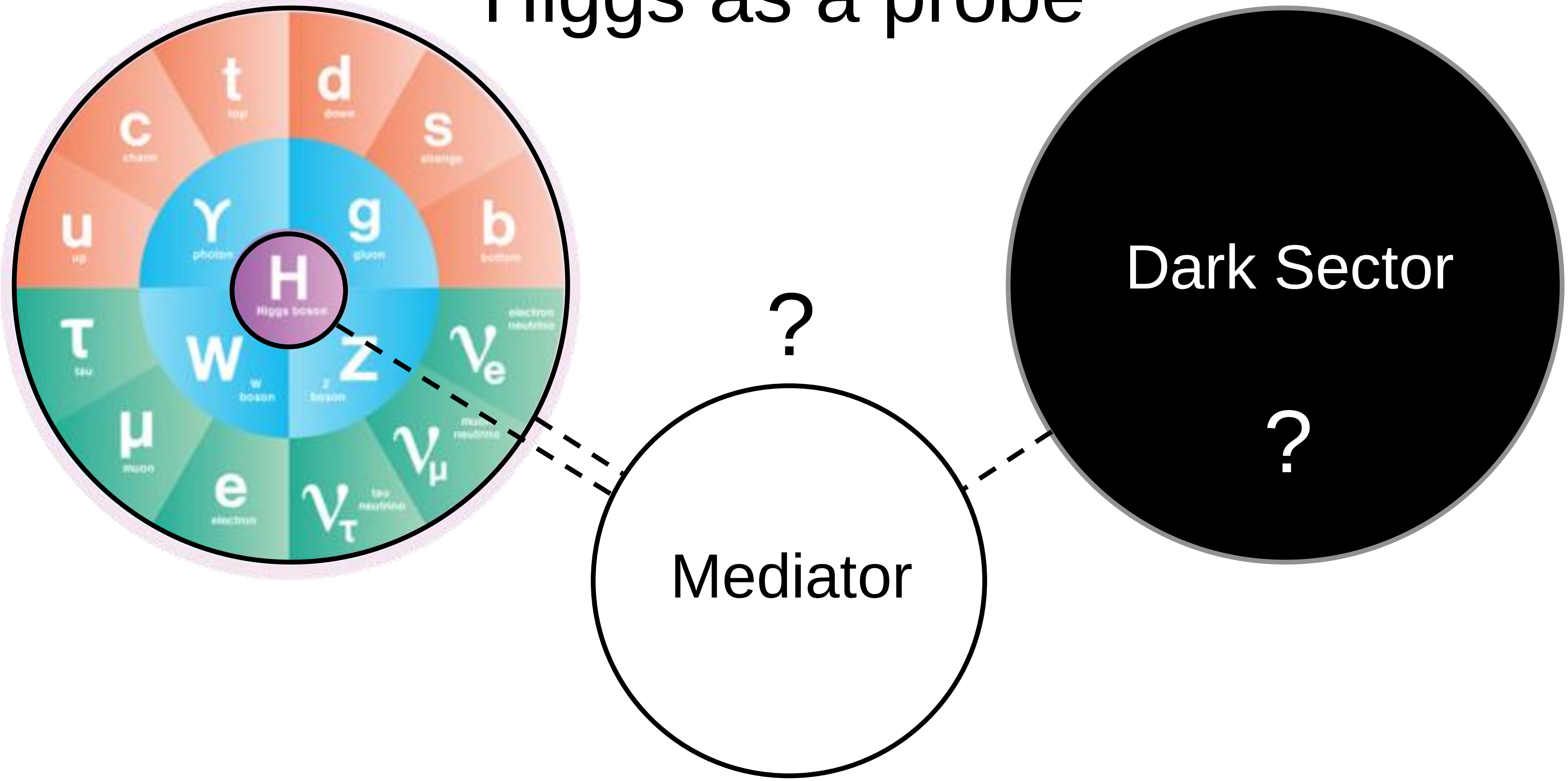
CONSOLIDATING EXISTING WORK

EXPERIMENTAL + THEORY WORKSHOP
https://indico.cern.ch/e/tChannelDM

LHC DARK MATTER WORKING GROUP

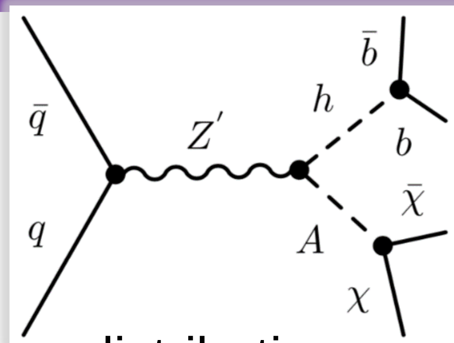
ORGANISERS: OLEG BRANDT • ULRICH HAISCH • PHILIPP HARRIS • CHRISTIAN OHM • TIM TAIT • XABIER CID VIDAL

Higgs as a probe

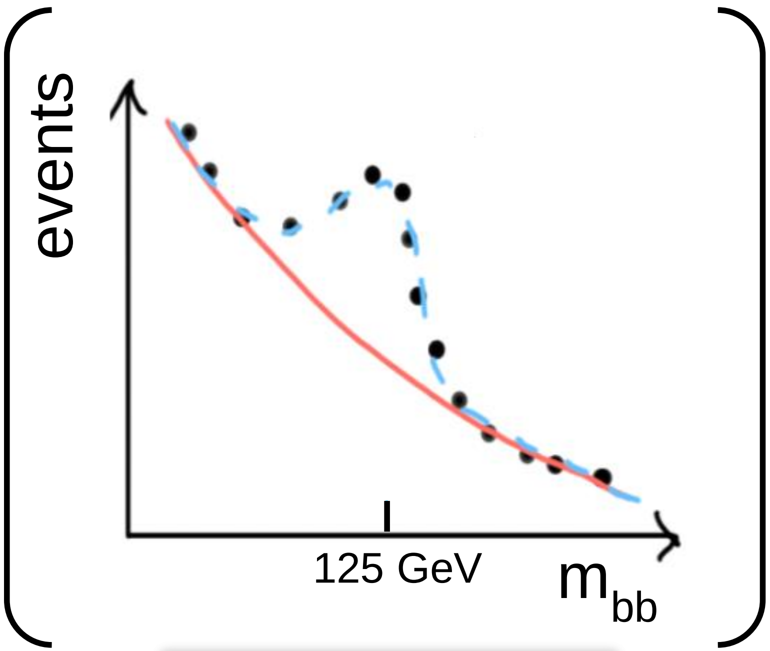


Motivation: 1) Mediator that couples to Higgs, SM and Dark Sector
typically: Higgs sector extension, 2HDM
2) Higgs coupling to new particles (hierarchy problem)

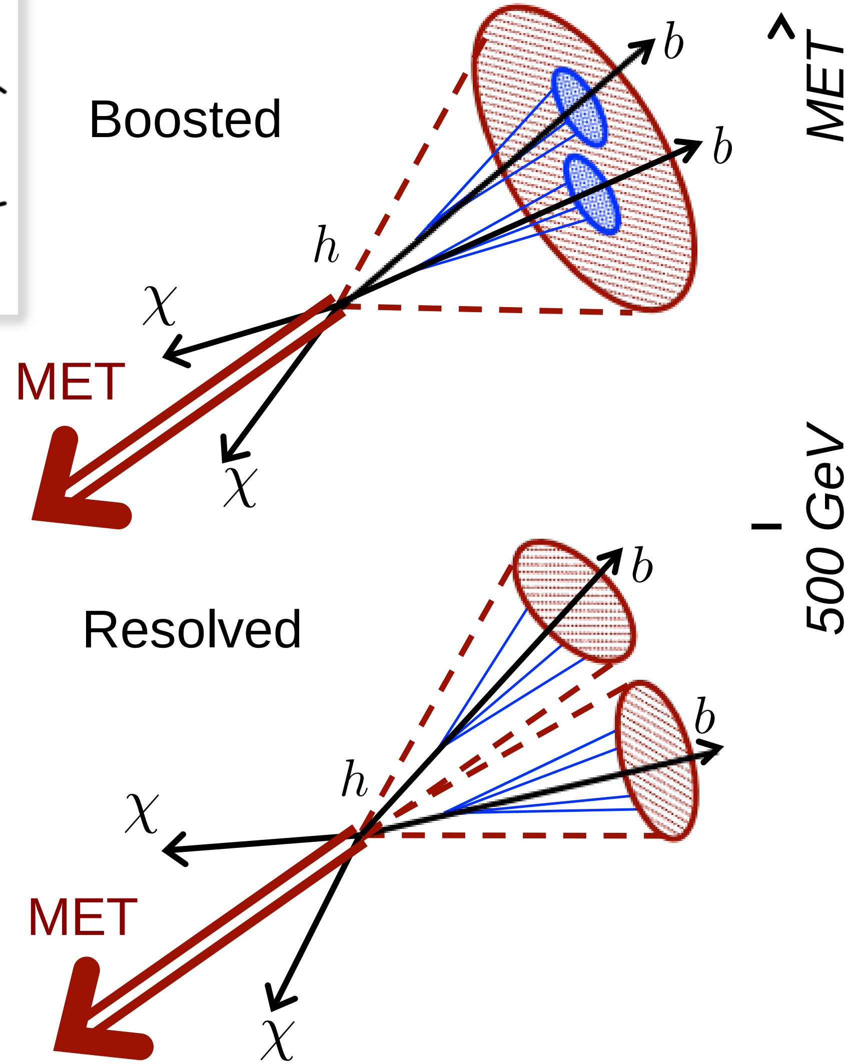
- Signal proxy:
  - Z'+2HDM model →



- Analysis strategy:
  - Require MET
  - Look for excess in m_{bb} distribution:

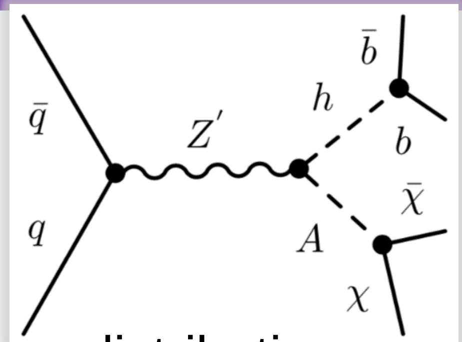


× (1, 2 b-tags)
× 4 MET bins

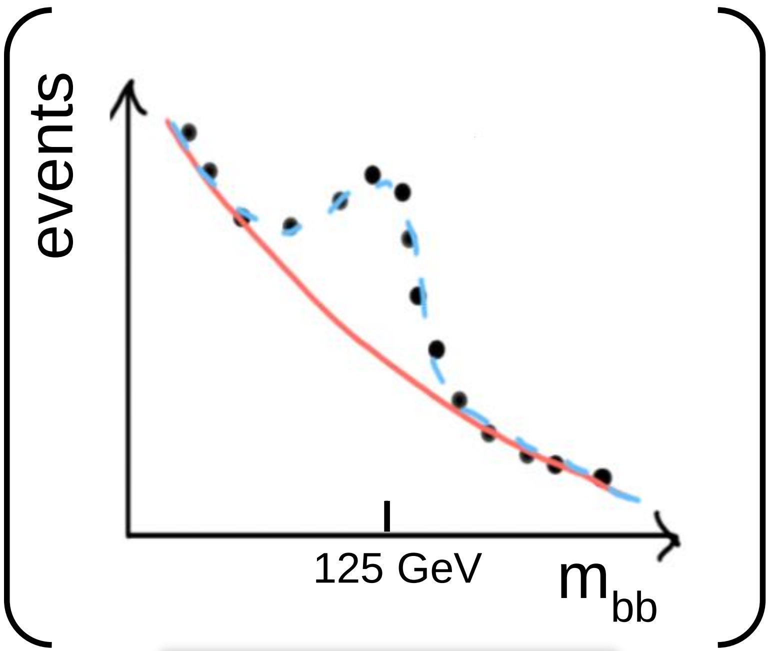


ATLAS-CONF-2018-039

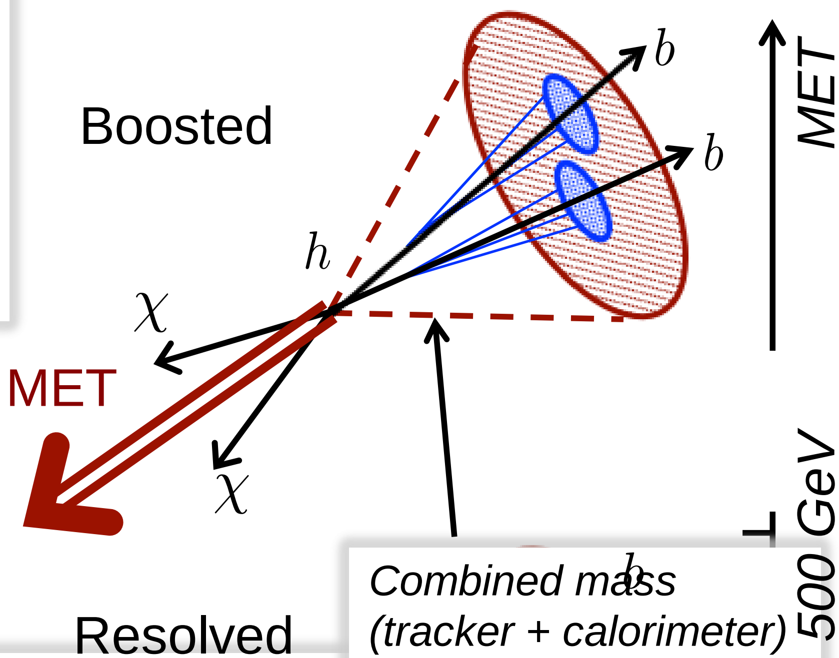
- Signal proxy:
  - Z'+2HDM model →



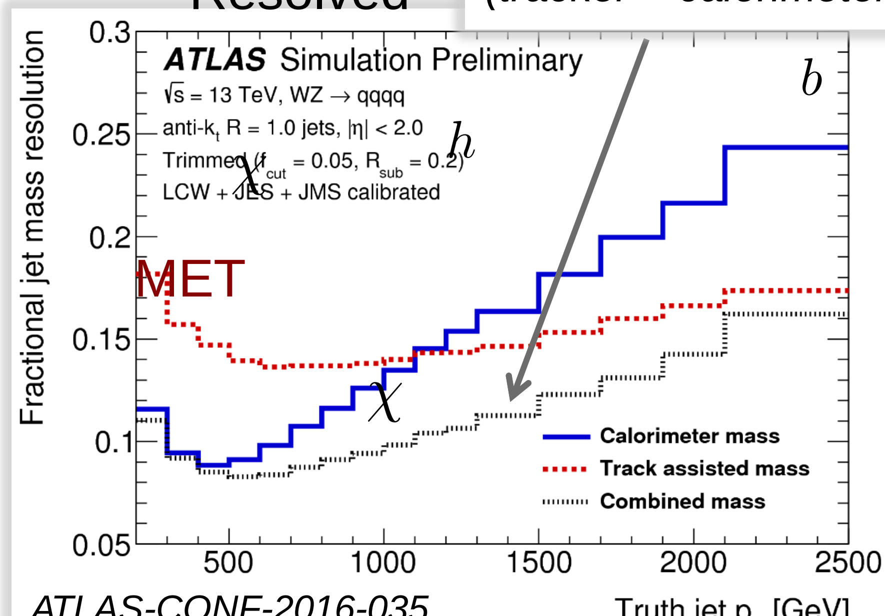
- Analysis strategy:
  - Require MET
  - Look for excess in m_{bb} distribution:



× (1, 2 b-tags)
× 4 MET bins



Combined mass (tracker + calorimeter)



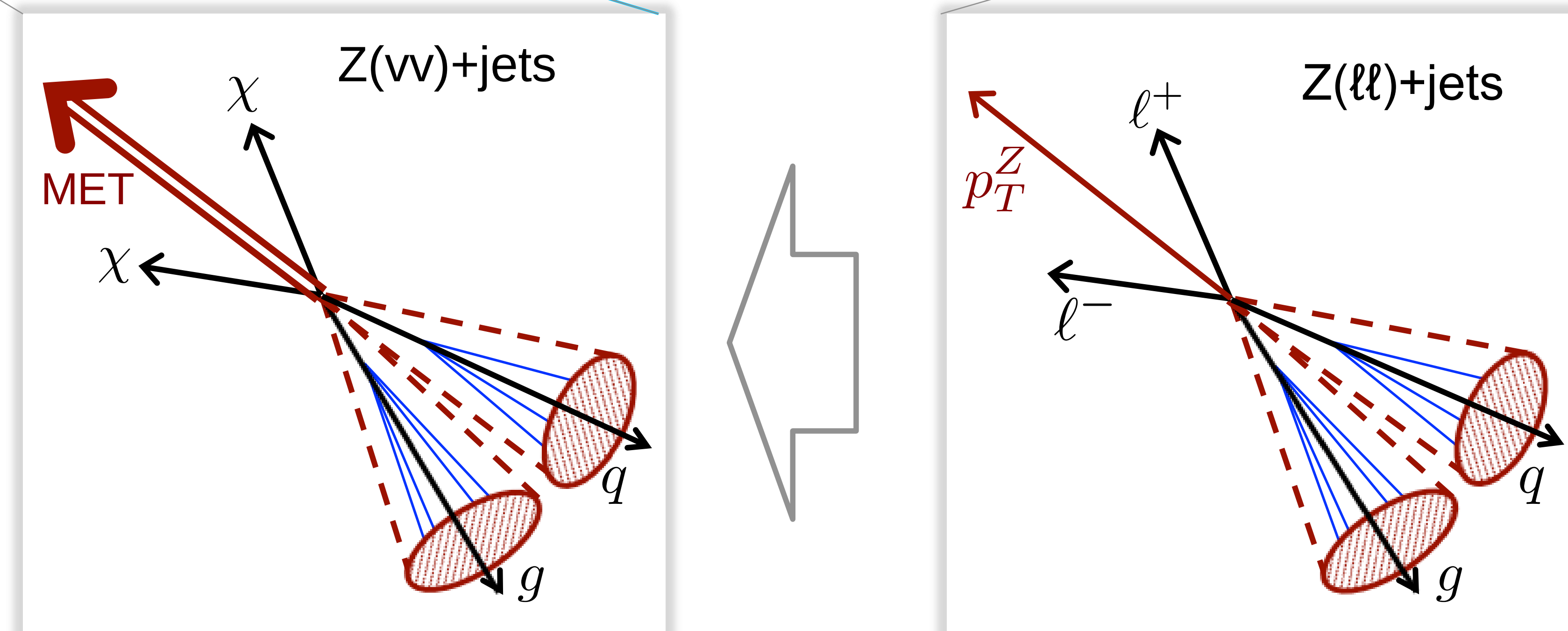
ATLAS-CONF-2016-035

ATLAS-CONF-2018-039

ATLAS-CONF-2018-039

- Backgrounds:
  - SM Z(νν)h(bb), resonant
  - Z(νν)+jets, W+jets, tt, +rest
- Strategy:

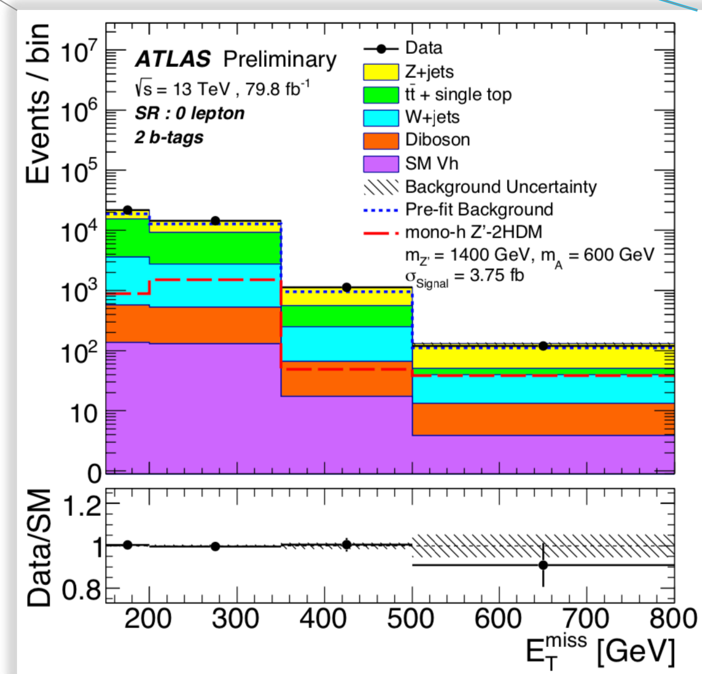
0 lepton signal region	1 lepton control region	2 lepton control region
Signal + m_{bb} sidebands	Constrain tt and W+jets	Constrain Z(νν)+jets using Z(ℓℓ)+jets

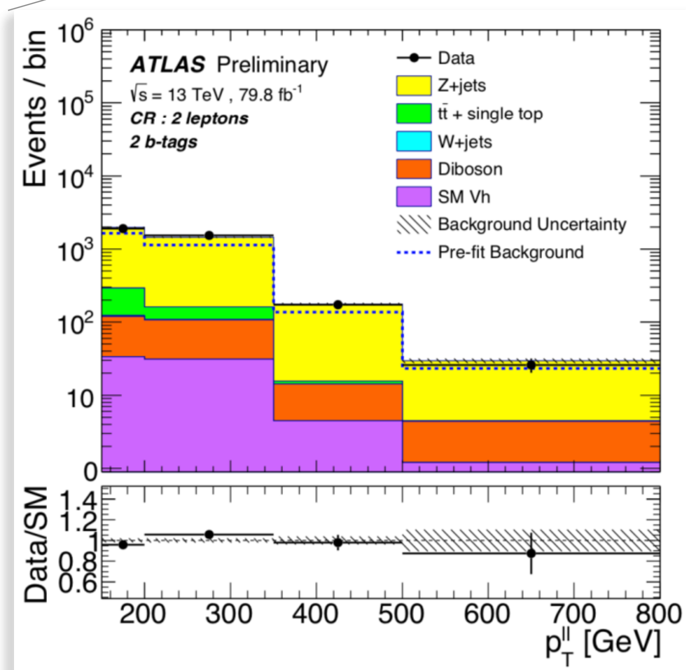


ATLAS-CONF-2018-039

- Backgrounds:
  - SM Z(νν)h(bb), resonant
  - Z(νν)+jets, W+jets, tt, +rest
- Strategy:

0 lepton signal region	1 lepton control region	2 lepton control region
Signal + m_{bb} sidebands	Constrain tt and W+jets	Constrain Z(νν)+jets using Z(ℓℓ)+jets

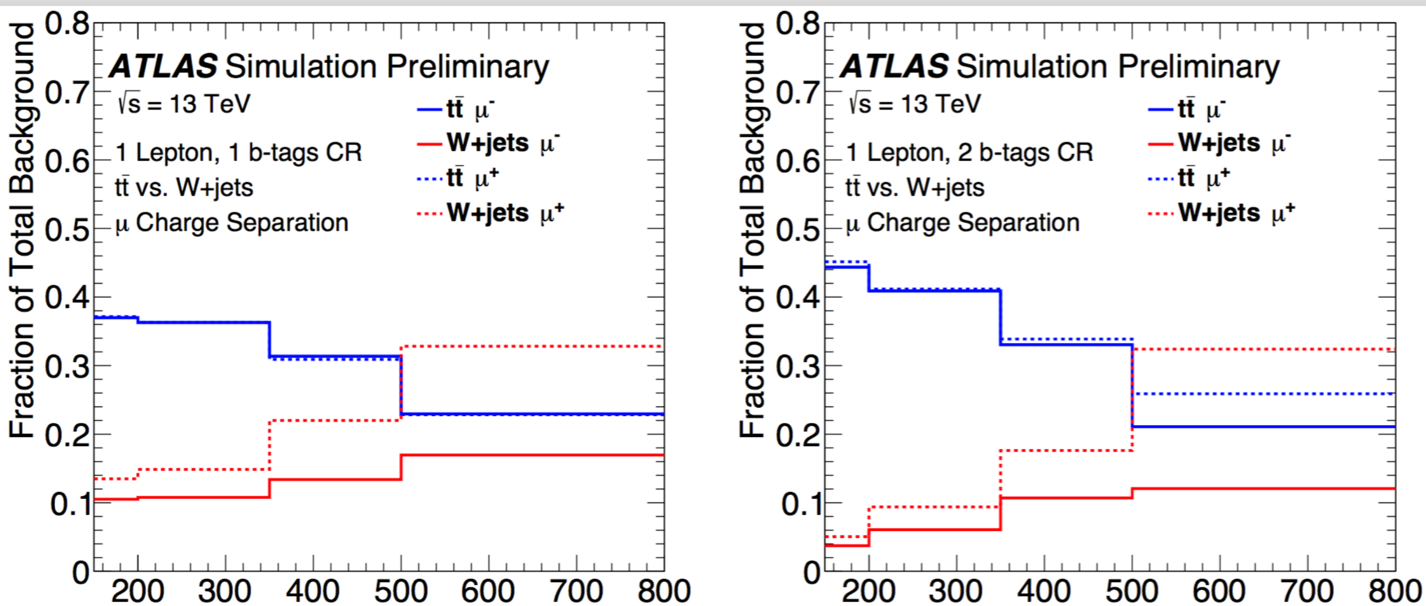




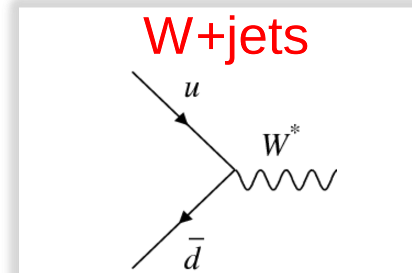
ATLAS-CONF-2018-039

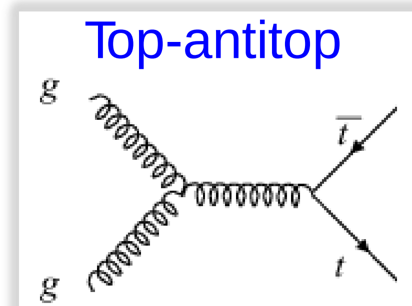
- Backgrounds:
  - SM Z(νν)h(bb), resonant
  - Z(νν)+jets, W+jets, tt, +rest
- Strategy:

0 lepton signal region	1 lepton control region	2 lepton control region
Signal + m_{bb} sidebands	Constrain tt and W+jets	Constrain Z(νν)+jets using Z(ℓℓ)+jets

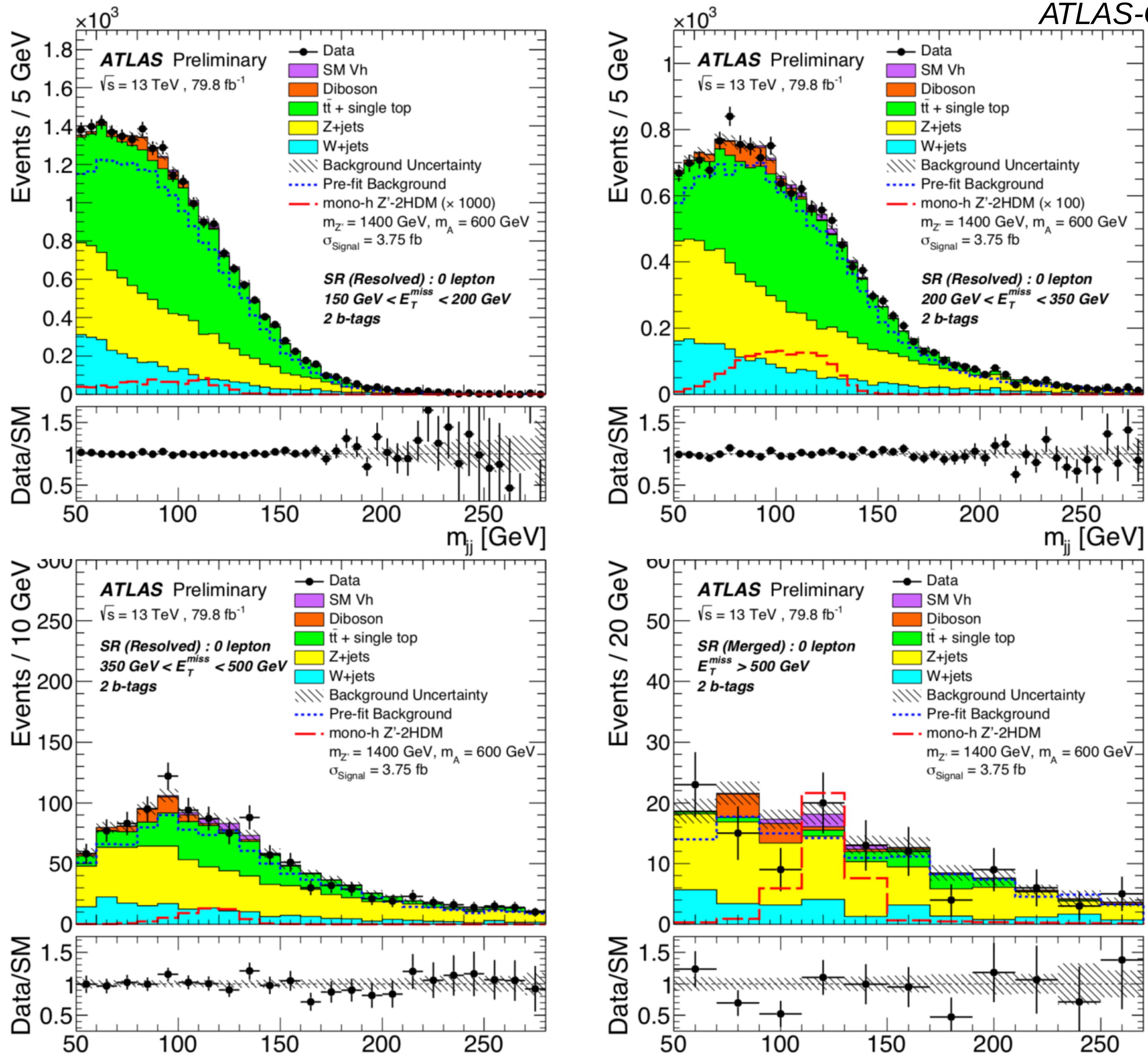


PRL 119 (2017) 181804



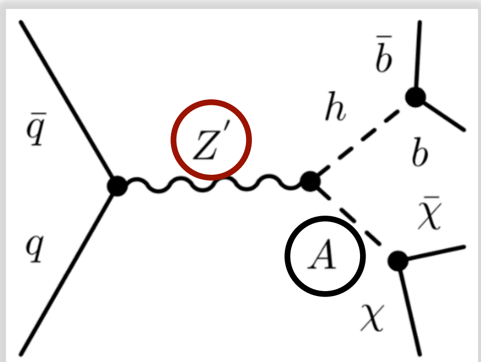


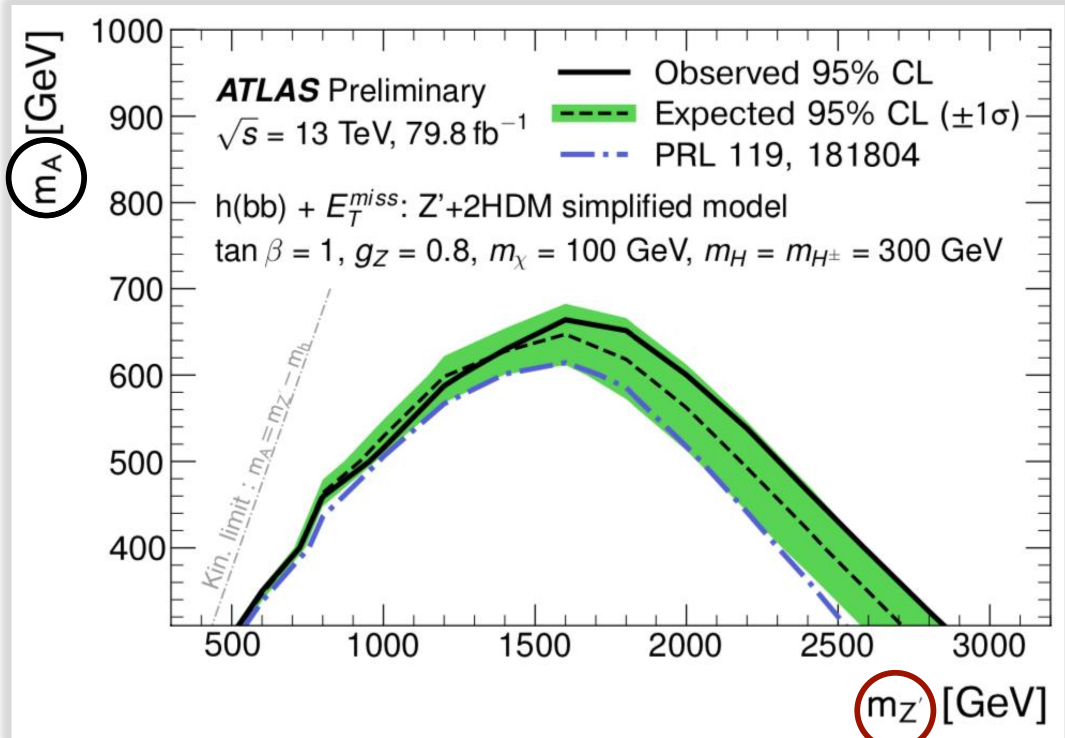
ATLAS-CONF-2018-039



ATLAS-CONF-2018-039

- Interpretation:
  - Z'+2HDM model



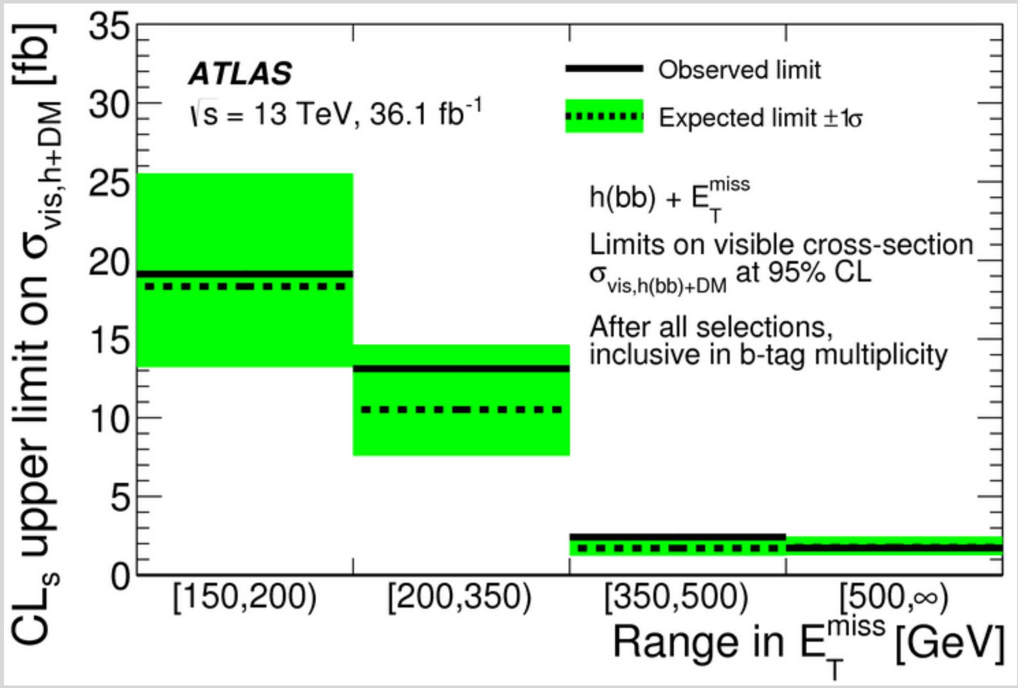


- Alternative new models?
  - → provide generic limits on Higgs + DM production!

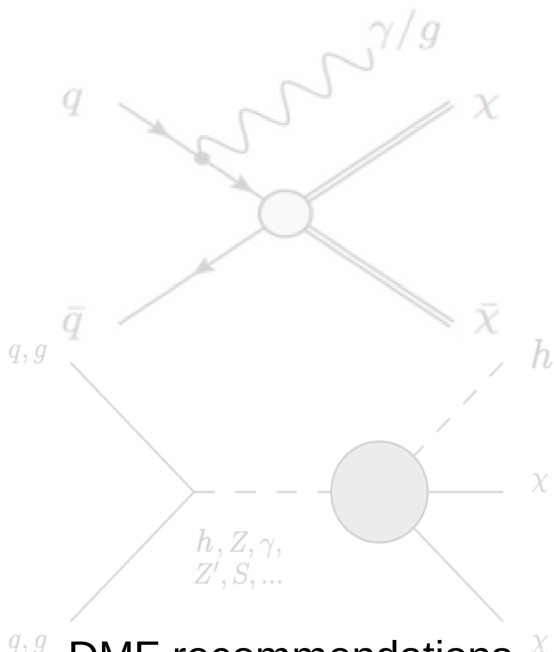
PRL 119 (2017) 181804

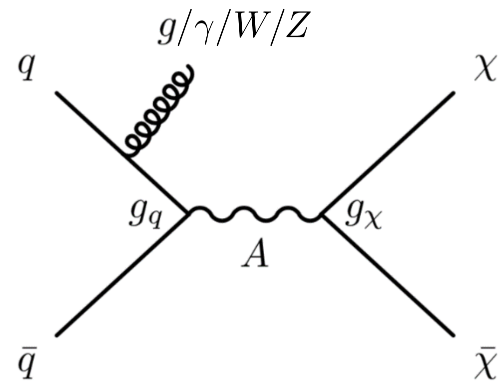
- Generic limits on h+DM
  - Assume SM-like Higgs boson ($m_h \approx 125$ GeV, BR(h→bb) ≈ 58%)
  - Assume back-to-back topology of Higgs and MET
- Set limits on visible cross section:

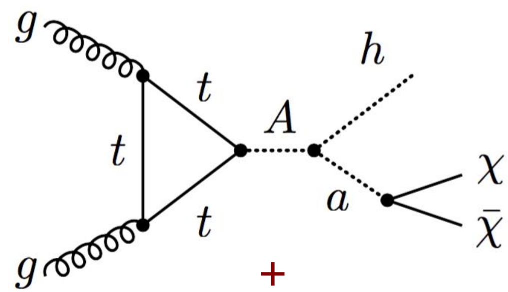
$$\sigma_{\text{vis},h+\text{DM}} \equiv \sigma_{h+\text{DM}} \times BR(h \to b\bar{b}) \times \mathcal{A} \times \varepsilon$$



- Can translate limits on $\sigma_{\text{vis},h+\text{DM}}$ to parton level $\sigma_{h+\text{DM}}$ using $\mathcal{A} \times \varepsilon$
  - Easy to check exclusion of a new model! → next slides







\+ *many other signatures*

V/AV mediator model
arXiv:1507.00966

2HDM+a model
JHEP 05 (2017) 138
arXiv:1507.00966

Supersymmetry
→ Tuesday session
Tommaso et al.

DMF recommendations
arXiv:1507.00966

White Papers of
[LHC DM WG/DMF](LHC DM WG/DMF)

1) Effective field theory

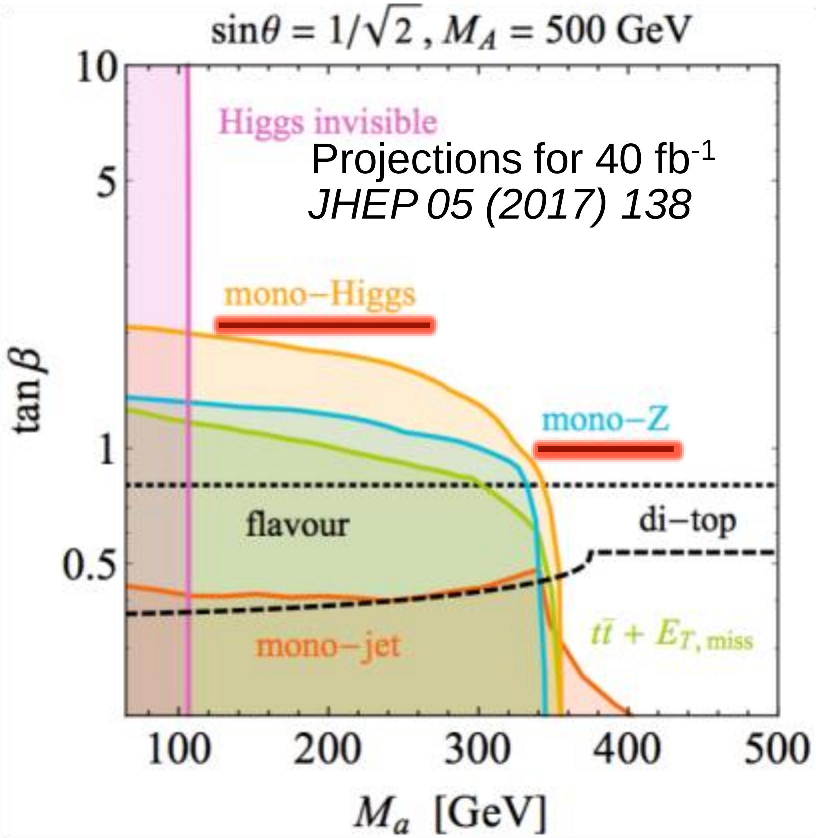
2) Simplified models

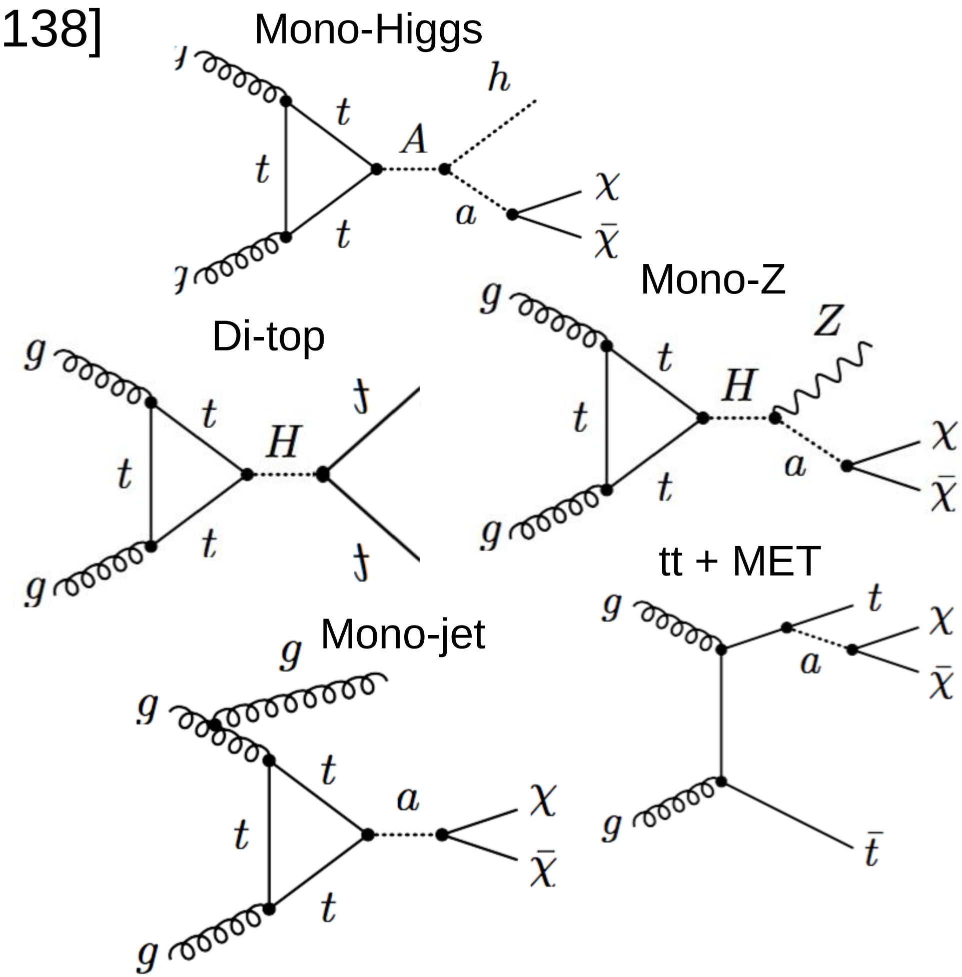
3) Simplified, consistent, & UV-complete models

4) complete models

Richer kinematics + phenomenology

- Future benchmark for DM searches @ LHC:
  - 2HDM+a model [JHEP 05 (2017) 138]
    - Simplified, but UV-complete
- Diverse palette of signatures
  - Experimentally exciting interplay!





+ other signatures

- Pseudoscalar DM mediator
  - Weak constraint from direct detection experiments
    - No tree-level coupling
- 2HDM (II) extension of Higgs sector
  - Well motivated
  - Avoid Higgs constraints in alignment limit
  - Avoid issues of pure pseudoscalar models
- Predictiveness:
  - Minimal particle content for a complete theory
  - Simple enough to parametrise on simple grids
- Diverse palette of signatures
  - Confront, combine complementary channels
  - Mono-Z, mono-h play special role

Particle content:
- CP even: h, H
- CP odd: A, a
- Charged: $H^{\pm}$
- Dirac DM: χ

A, a mixed: sinθ

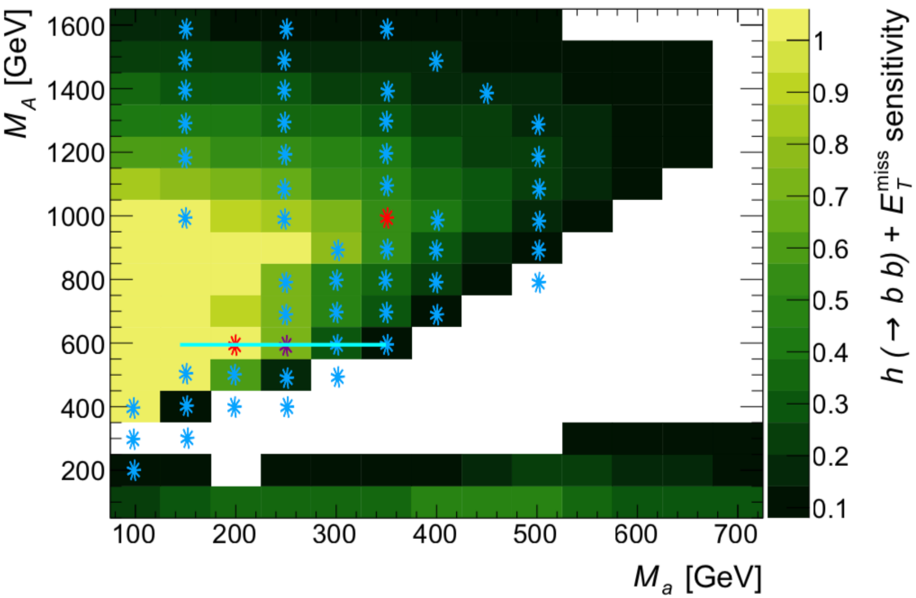
a_0 (before mixing) couples to χ

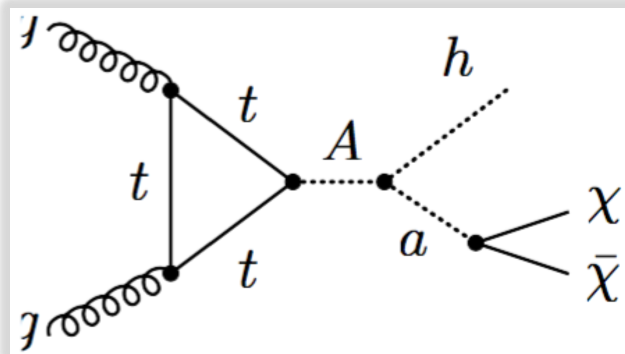
Simplified scalar models from LHC DM WG exist (arXiv:1603.04156) that map directly to 2HDM for some final states, e.g. monojet, tt+H

- Identify relevant regions of parameter space (see spares)
  - Diverse experimental signatures
  - Phenomenology-inspired
- Identify "interesting" regions:
  - NOT clearly excluded
  - NOT clearly beyond reach
- Define MC request

Use generic limits derived in h+DM analysis!

Estimate from generic limits



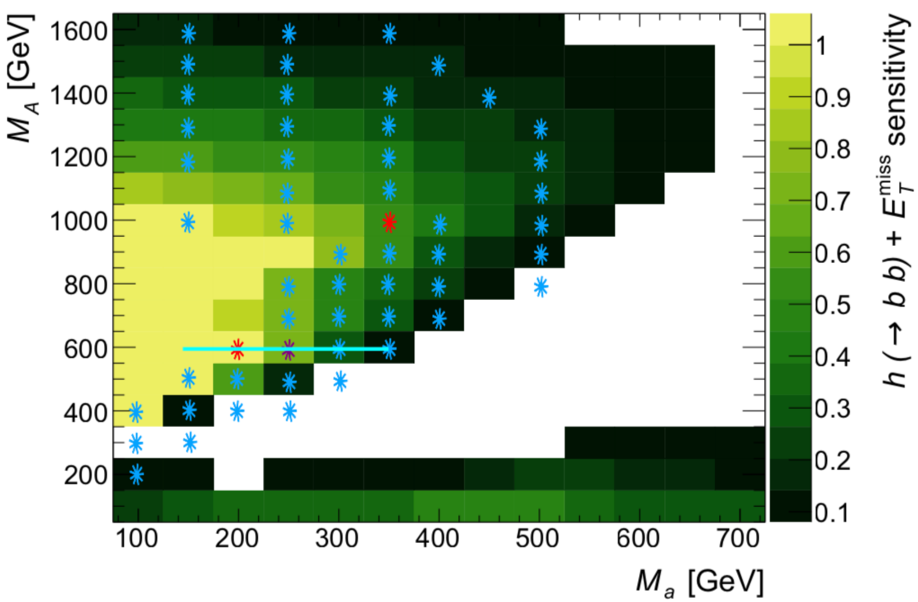


- Identify relevant regions of parameter space (previous slides)
  - Diverse experimental signatures
  - Phenomenology-inspired
- Identify "interesting" regions:
  - NOT clearly excluded
  - NOT clearly beyond reach

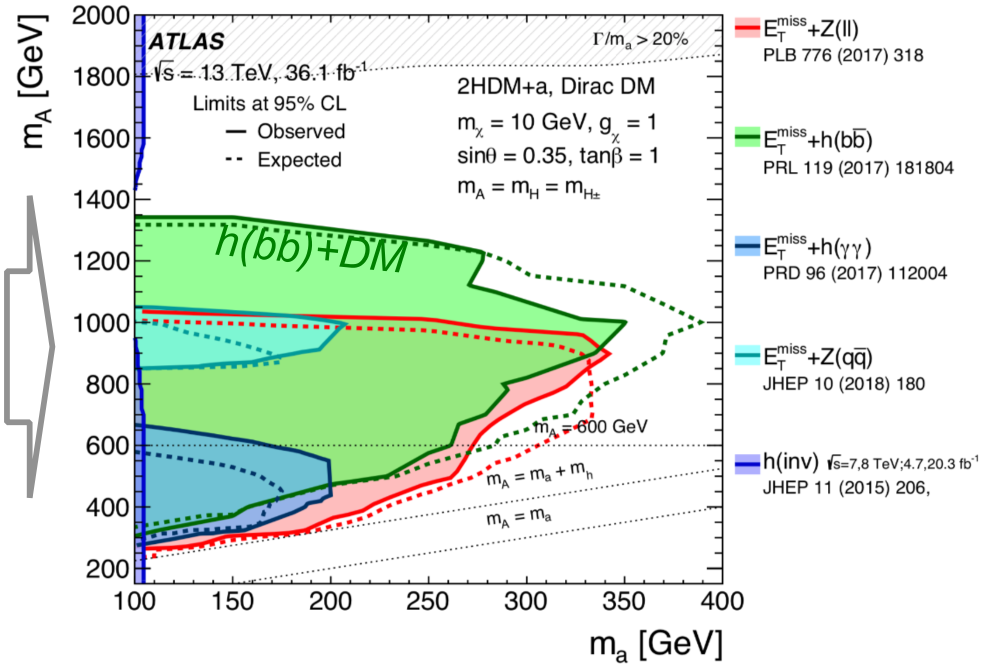
Use generic limits derived in h+DM analysis!

- Define MC request

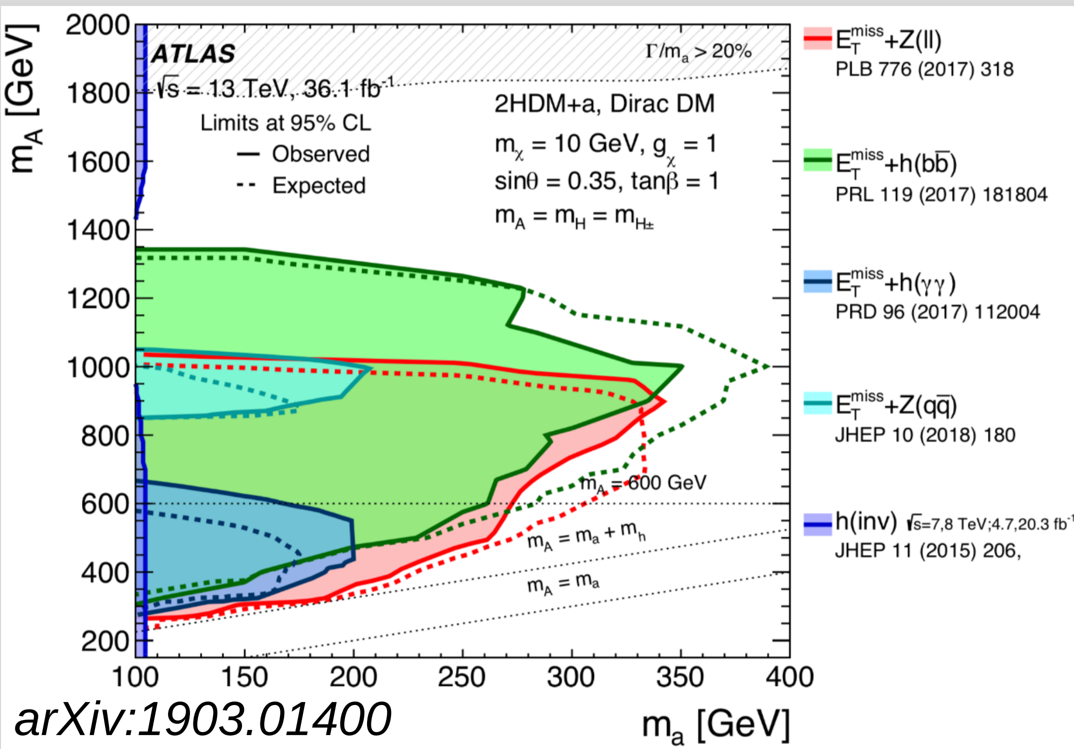
Estimate from generic limits

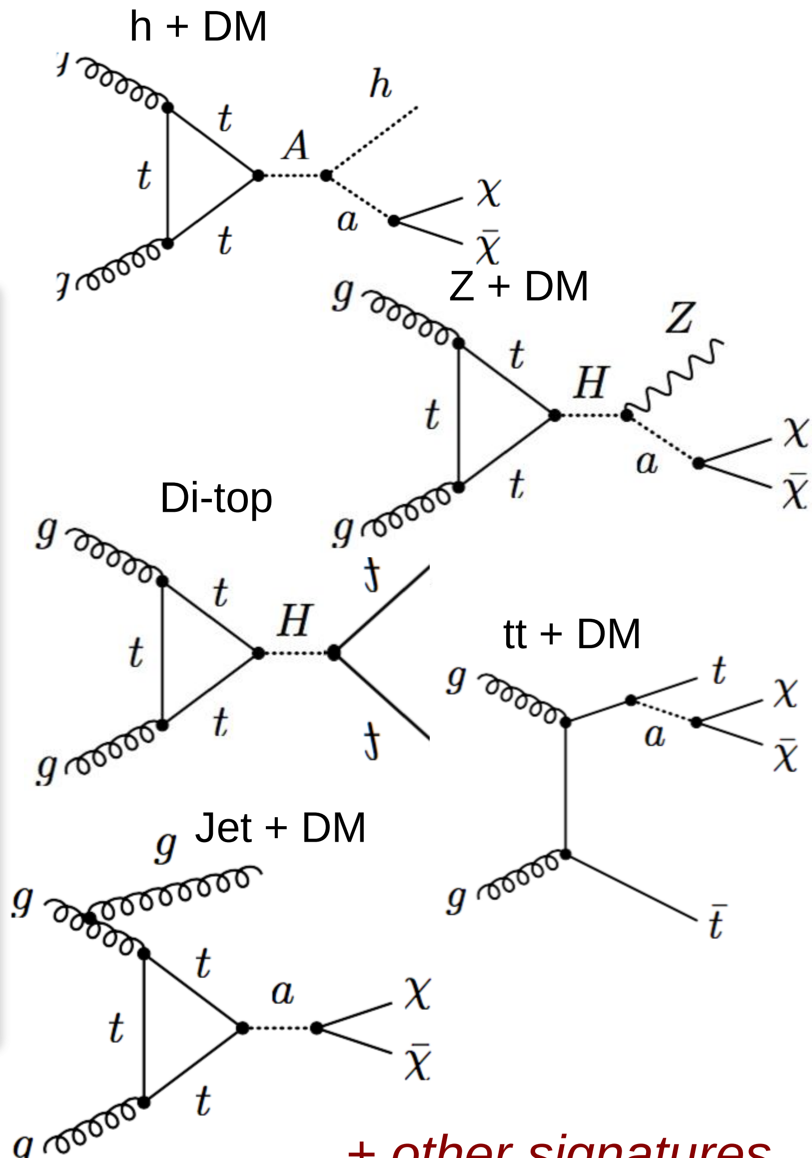


Limits with full analysis (4+ months):



- Overlay of results in different channels:

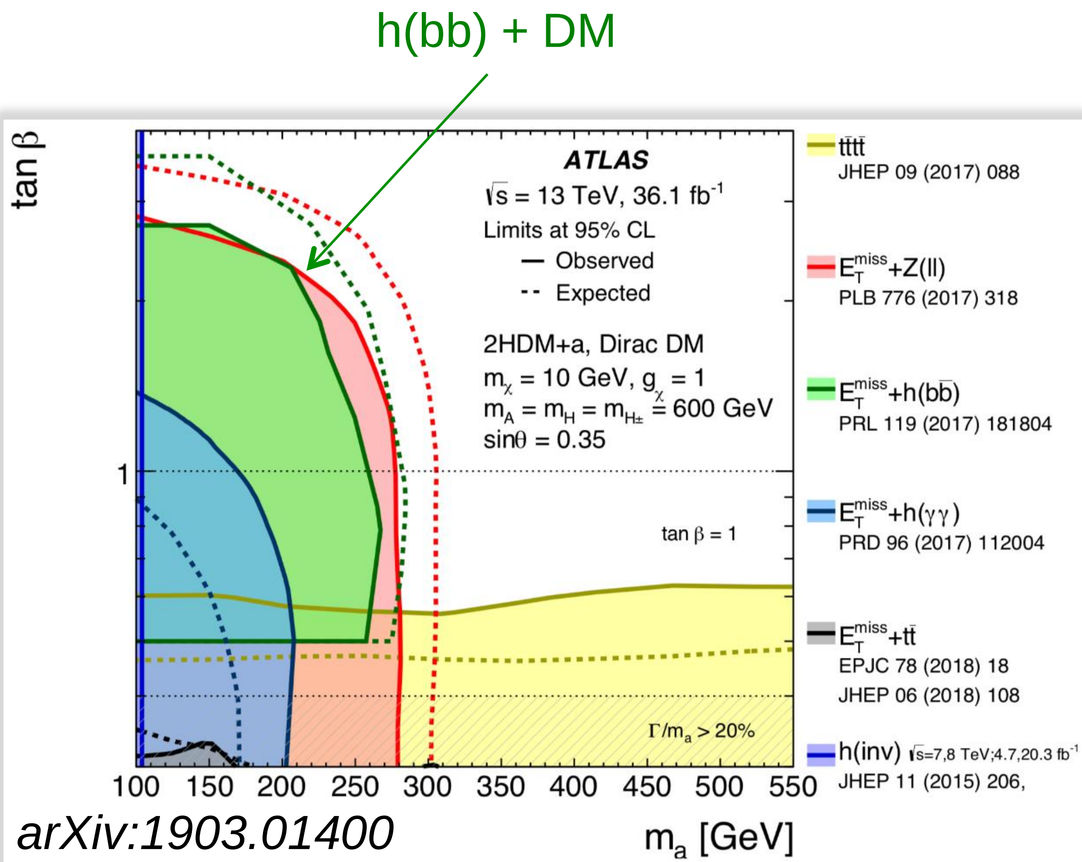


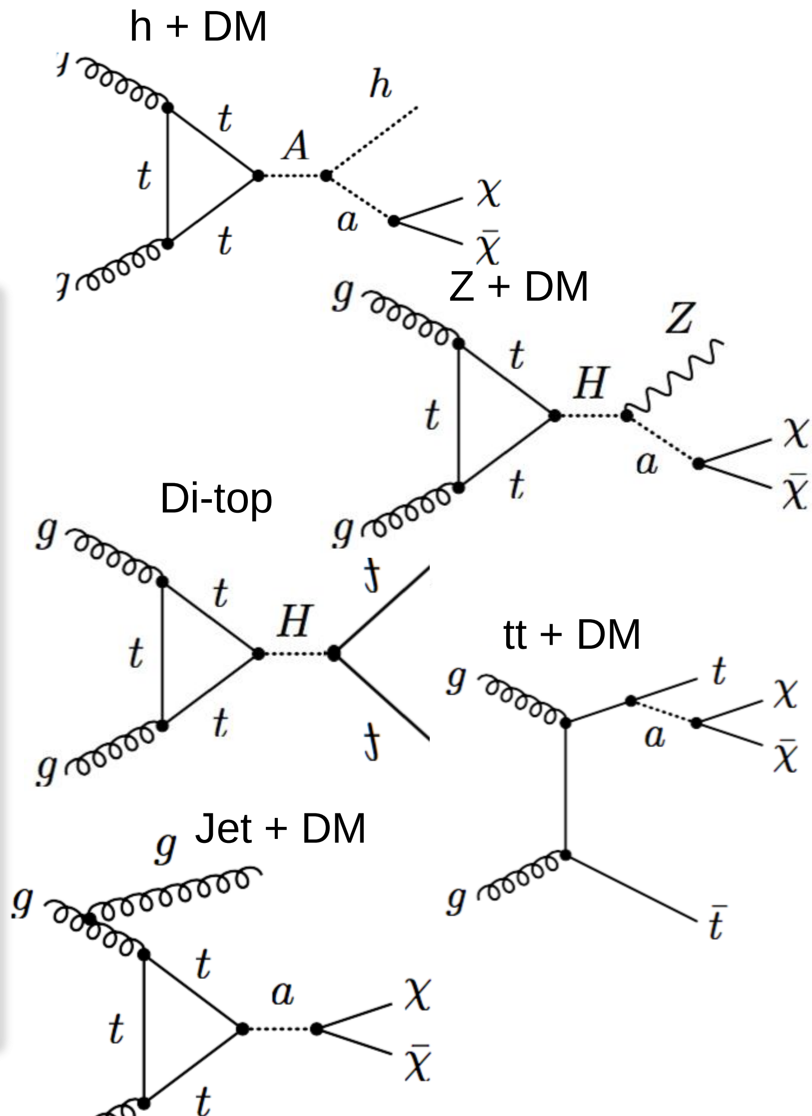


+ other signatures

2HDM+a: Results in all channels (ATLAS)

- Overlay of results in different channels:

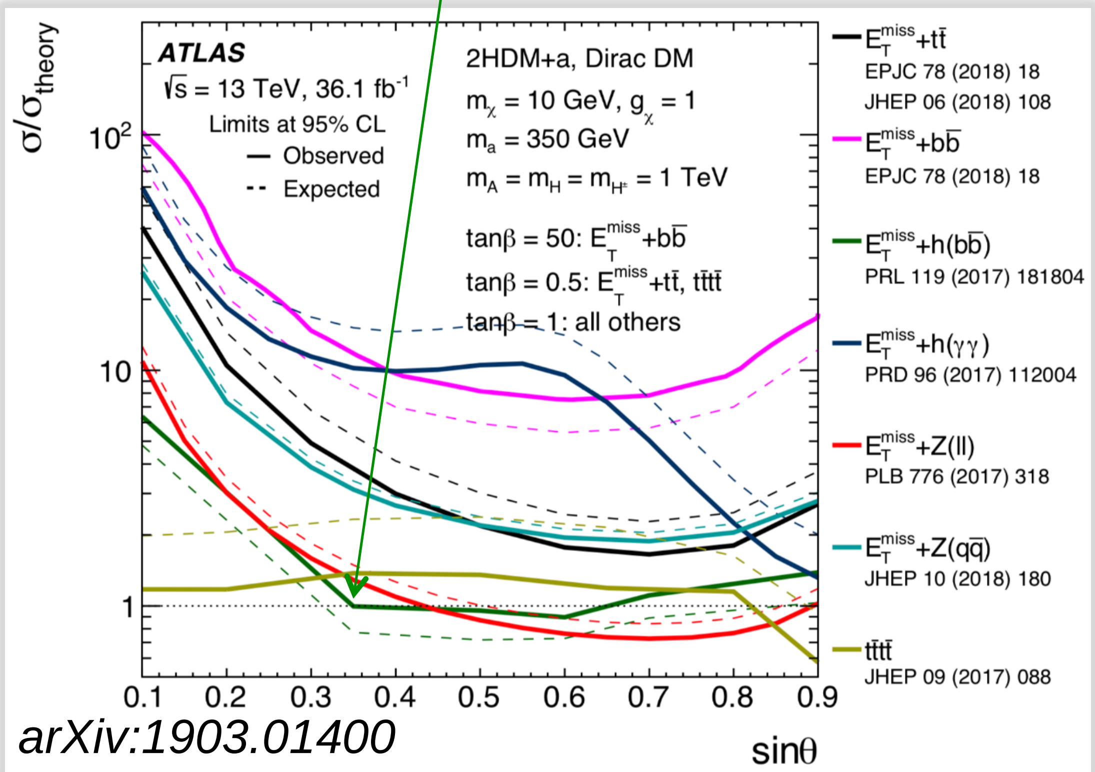




+ other signatures

- Overlay of results in different channels:

h(bb) + DM



arXiv:1903.01400

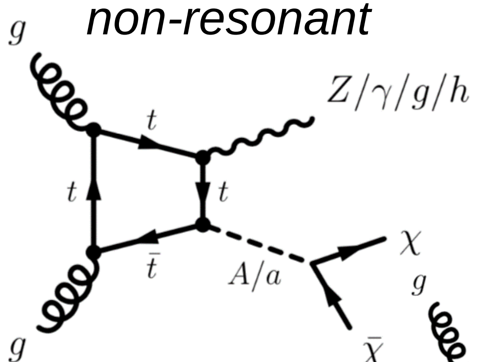
- Important parameter sin$\boldsymbol{\theta}$ (mixing angle A_0 / a_0):
  - Balance of signatures with and w/o MET:

$$\Gamma(A \to ah) \propto \sin\theta\cos\theta$$

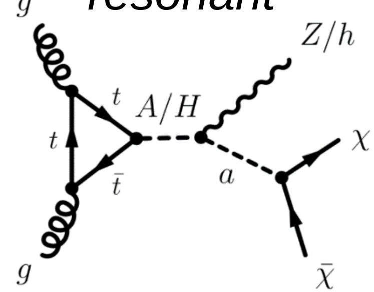
  - Balance of (non-) resonant

$$\Gamma(a \to \chi\chi) \propto \cos^2\theta$$
$$\Gamma(a \to ff) \propto \sin^2\theta$$

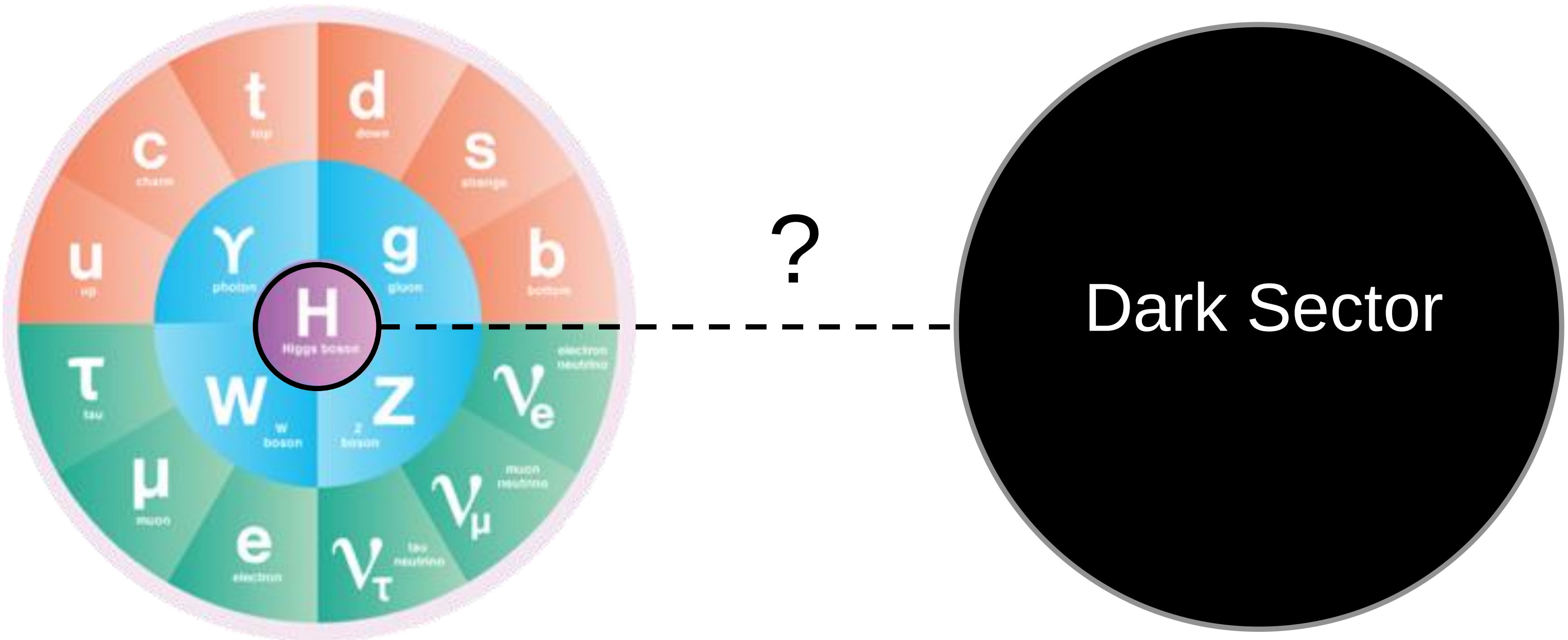
non-resonant



resonant



Higgs-portal models

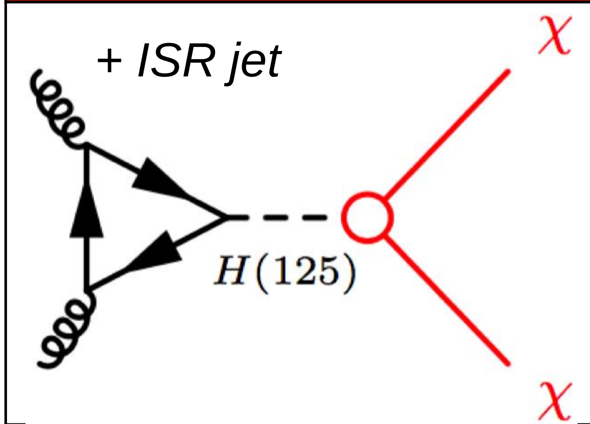
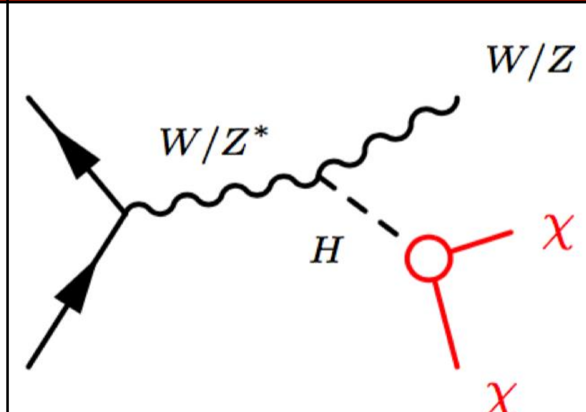
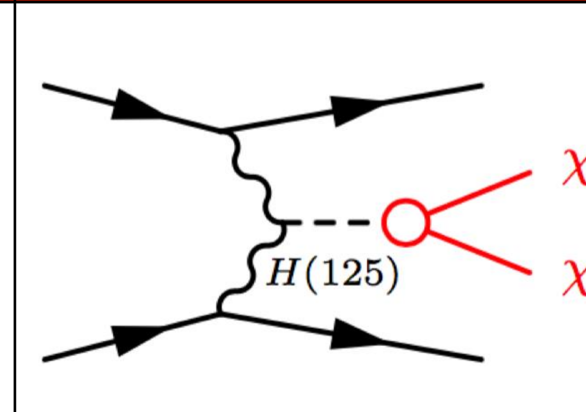


Motivation: 1) Higgs Yukawa coupling to massive Dark Sector particles
→ appealing fundamental interaction!
2) Higgs coupling to new particles (hierarchy problem)

- Motivation:
  - Higgs couples to massive particles
  - Dark Matter particles massive…
  - $H \to \chi\chi$ possible if $M_\chi \leq M_H$

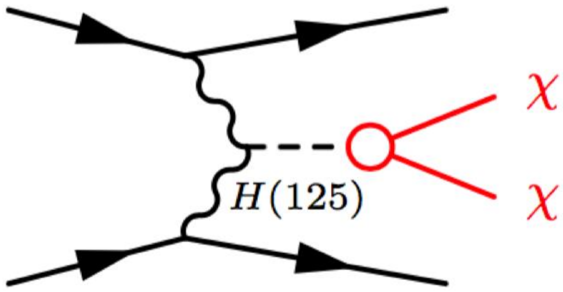
[1] *JHEP 10 (2018) 180*
[2] *PLB 776 (2017) 318*
[3] *PLB 04 (2019) 024* New
[4] *arXiv:1904.05105 acc'd by PRL* New

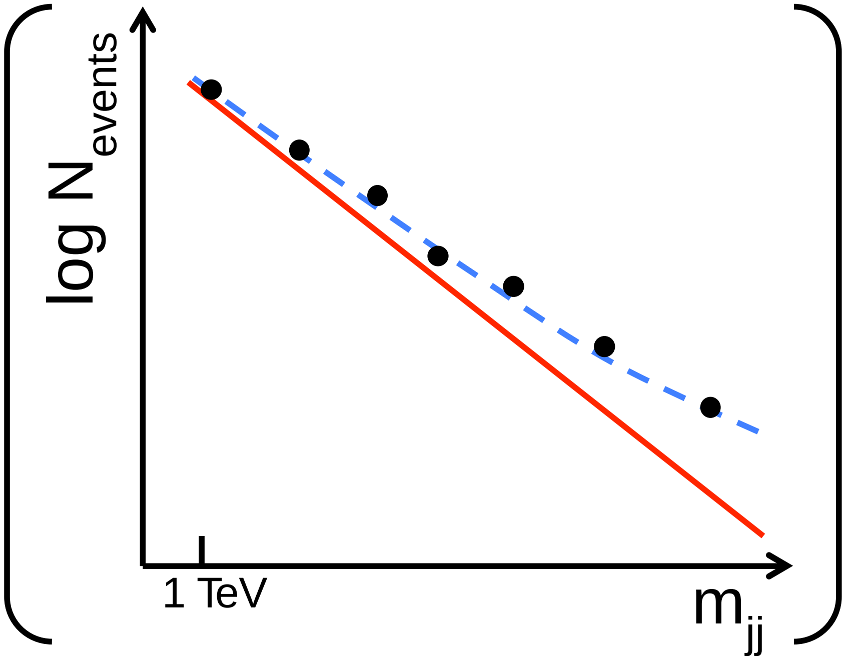
- Competitive – Higgs production as tag:

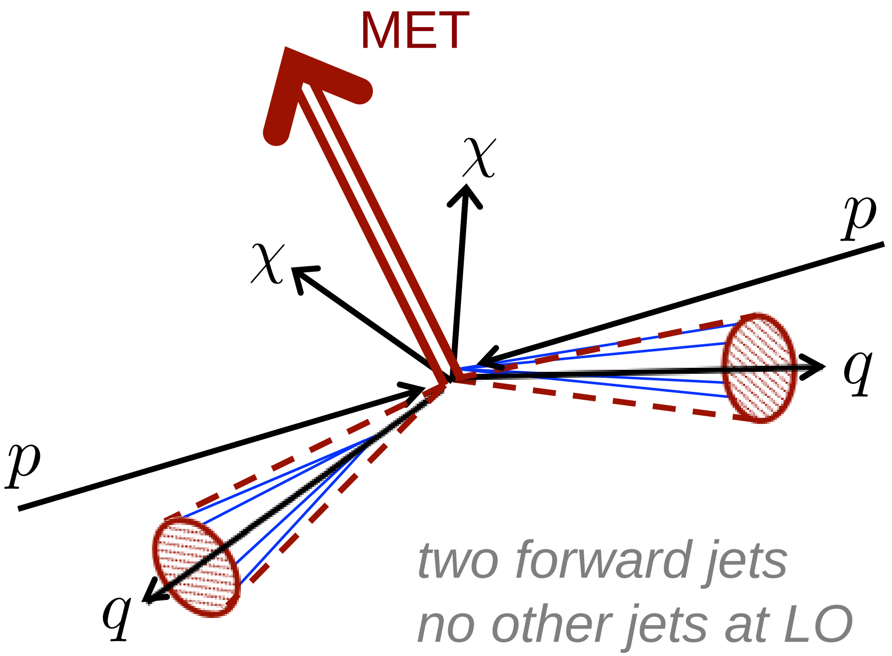
ggF H [49 pb]	VH [2.3 pb]	VBF H [3.8 pb]
		
ggF+V(had)H(inv): 0.83 (0.58) [1] Z(ℓℓ)H(inv): 0.67 (0.39) [2]	Combo [4]	0.37 (0.28) [3]

New!

- Analysis strategy:
  - Require MET > 180 GeV
  - Require high $|\Delta\eta_{jj}| > 4.8$
  - No 3rd jet with p_T > 25 GeV
  - Look for excess at high m_{jj}:







Shape fit: 3 bins in m_{jj} > 1 TeV

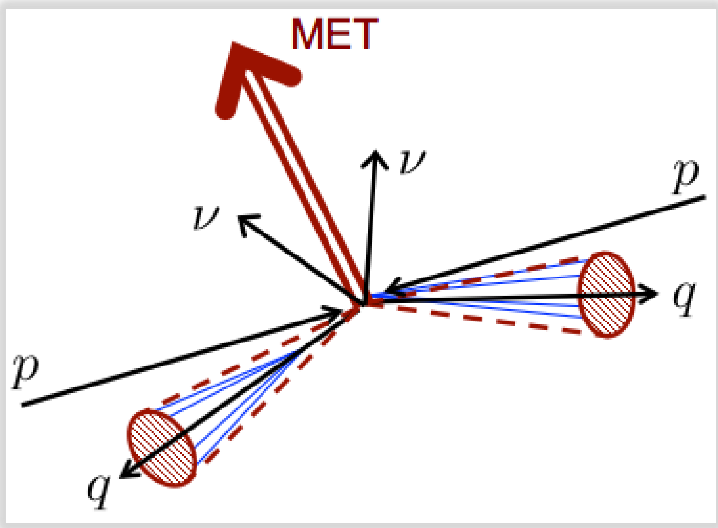
PLB 04 (2019) 024

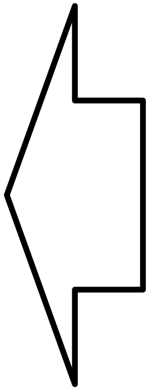
VBF Higgs → invisible: constrain backgrounds

- Constrain Z(νν)+jets, W+jets in signal region (SR) using control regions (CR):

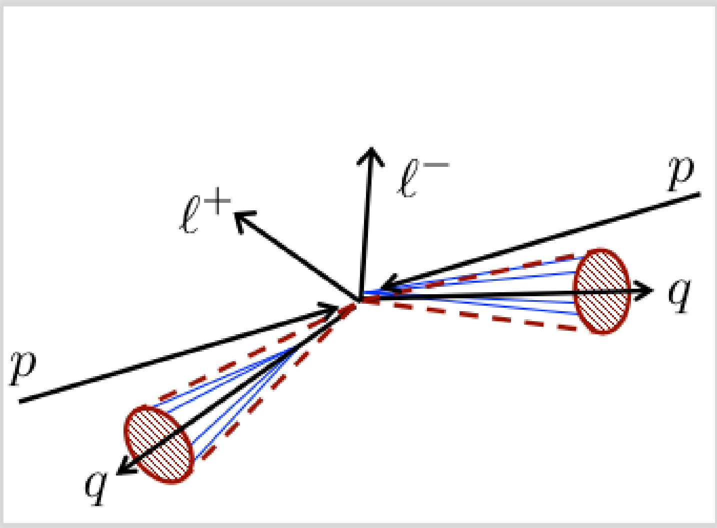
0 lepton SR	1 lepton CR	2 lepton CR
Signal + constrain Z(νν)+jets etc. at low mjj	Constrain W+jets	Constrain Z(νν)+jets using Z(ℓℓ)+jets

Z(νν)+jets





Z(ℓℓ)+jets



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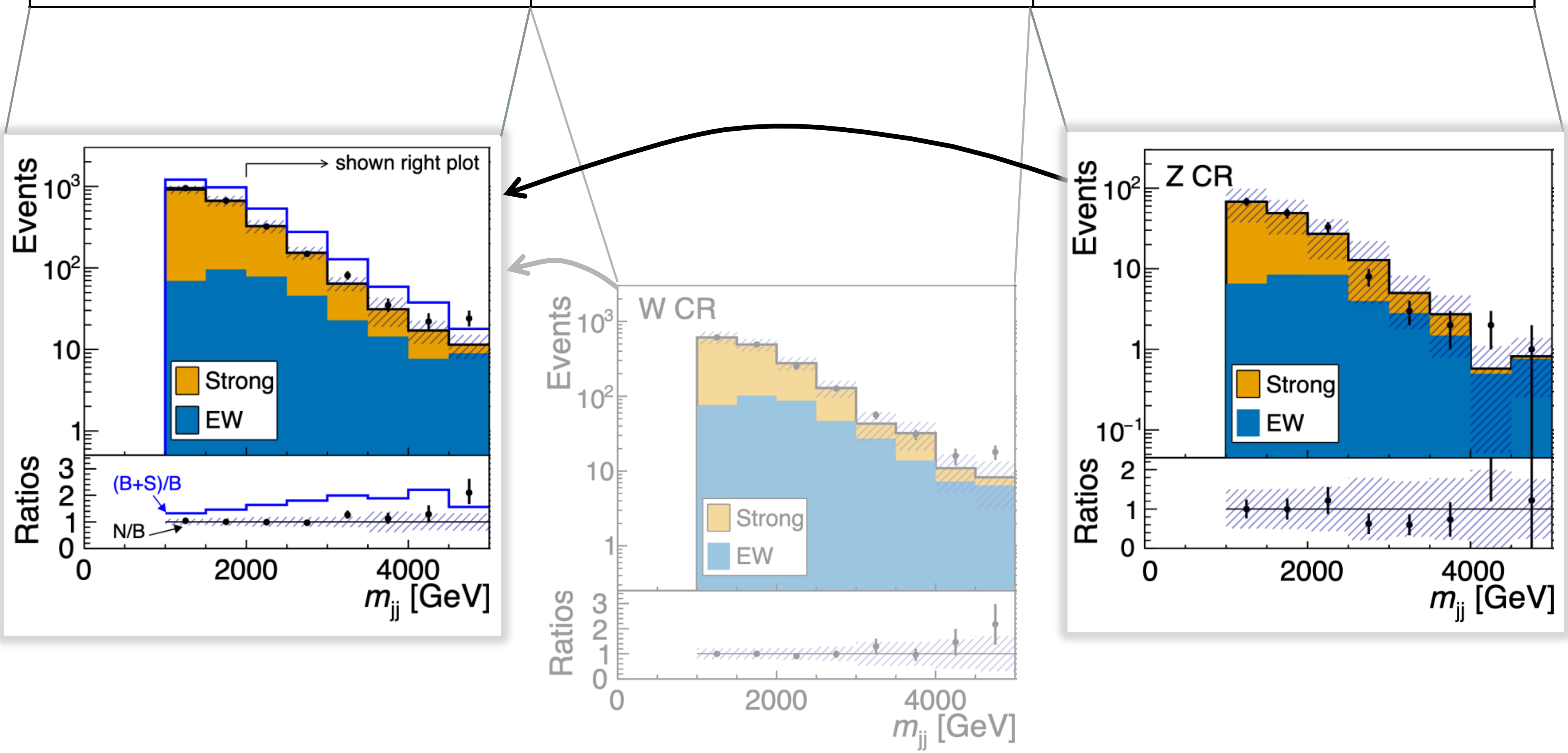
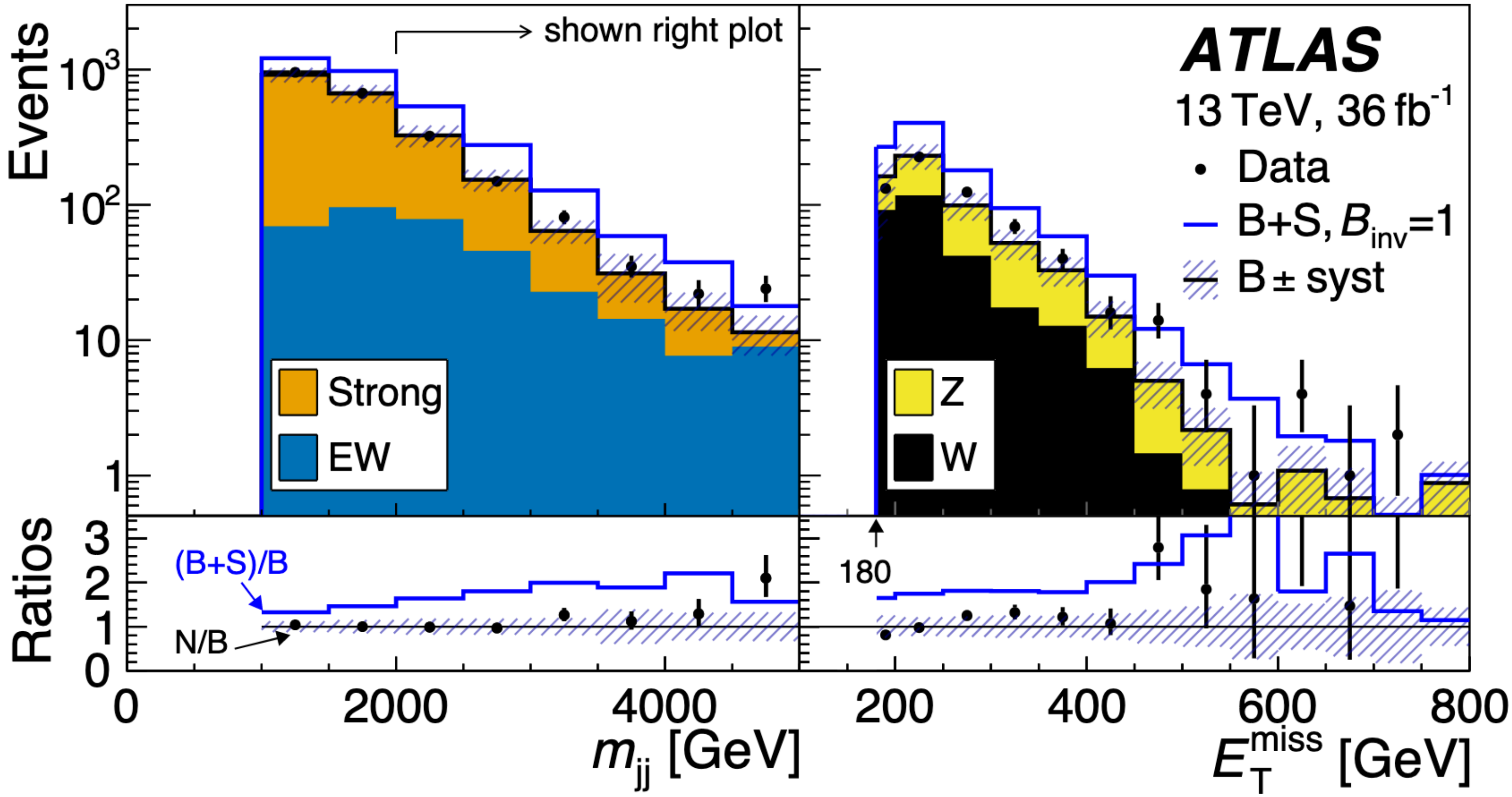
Signal + constrain Z(νν)+jets etc. at low mjj	Constrain W+jets	Constrain Z(νν)+jets using Z(ℓℓ)+jets

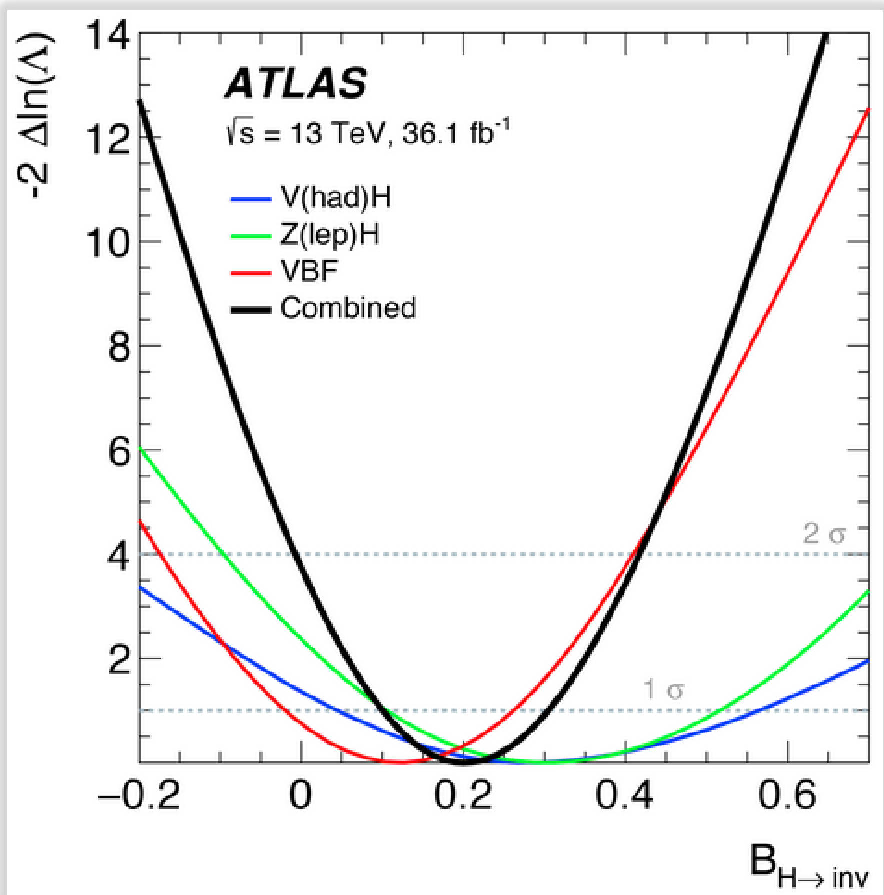


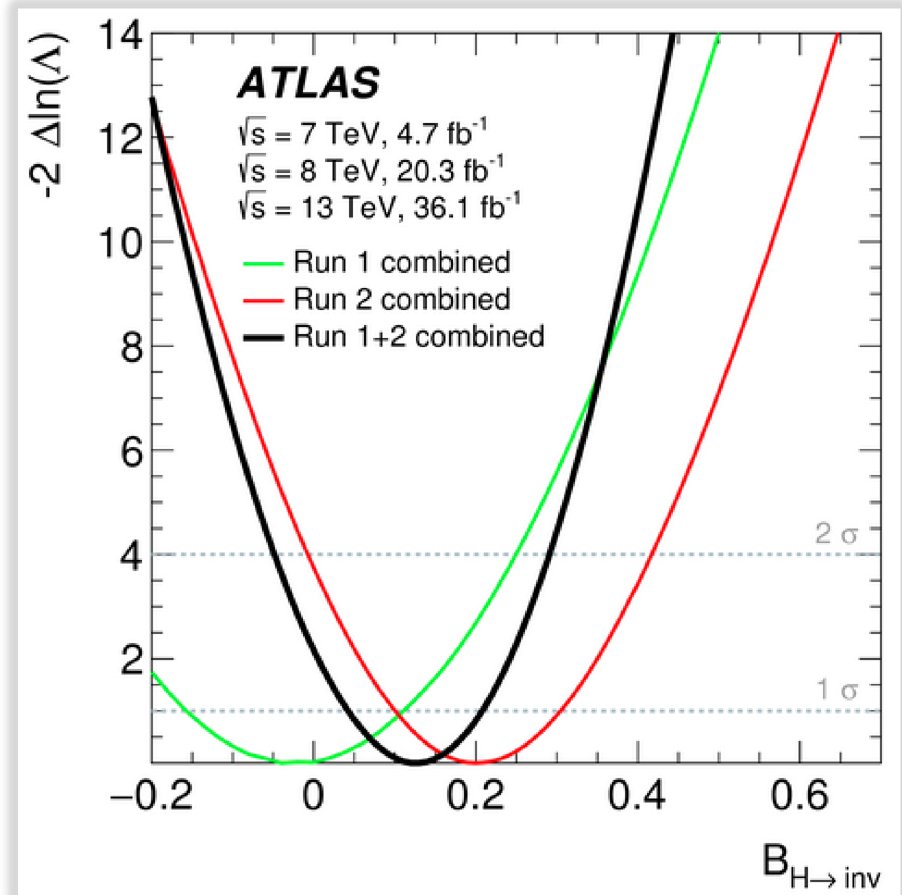
- Results:



$$BR(h \to \text{inv.}) < 0.37\ (0.28^{+0.11}_{0.08})$$

- Results:

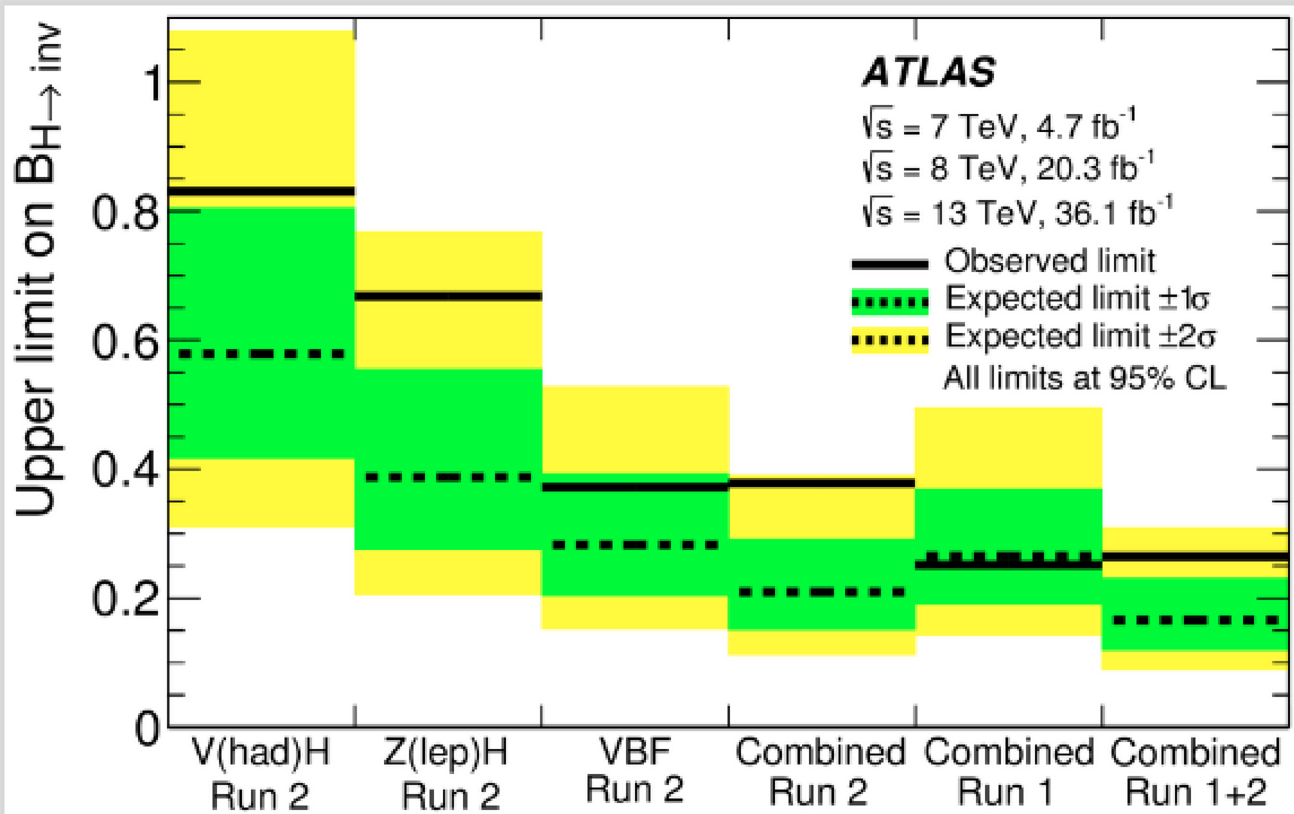




arXiv:1904.05105

H→INVISIBLE COMBO: RESULTS

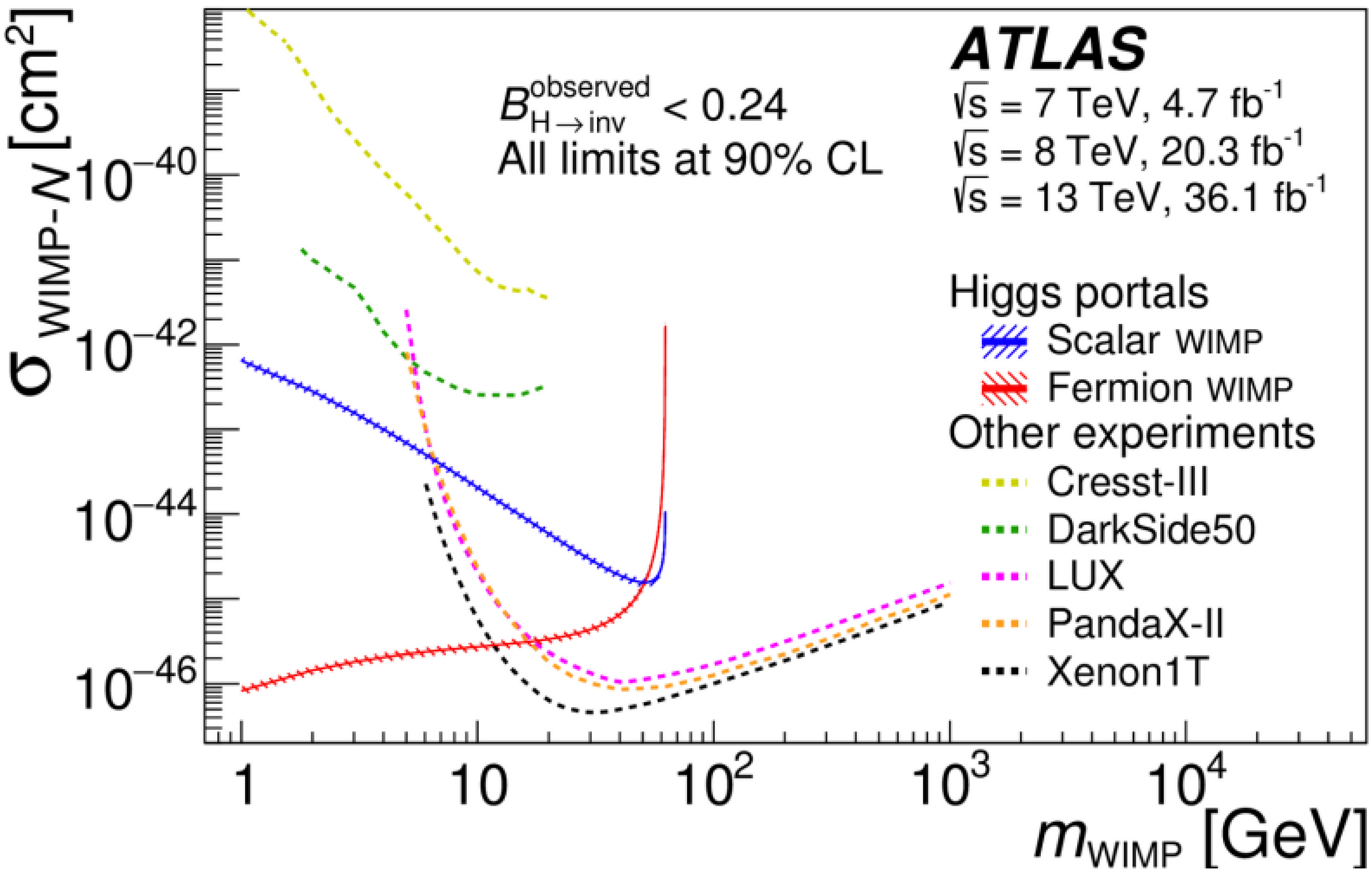
- Results:



$$\mathcal{B}_{H\to\mathrm{inv}} < \mathbf{0.26}\ (\mathbf{0.17}^{+\mathbf{0.07}}_{\mathbf{0.05}})$$

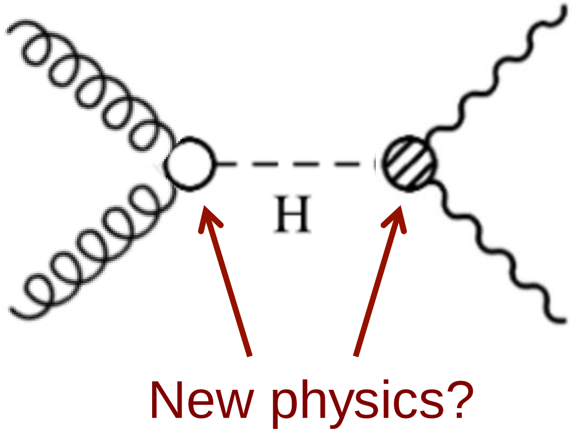
arXiv:1904.05105

- Results:



arXiv:1904.05105

- Motivation:
  - New physics may affect Higgs production and visible decays



- Ansatz:
  - Combined fit with visible Higgs decay channels in $\boldsymbol{\kappa}$ framework [1]:

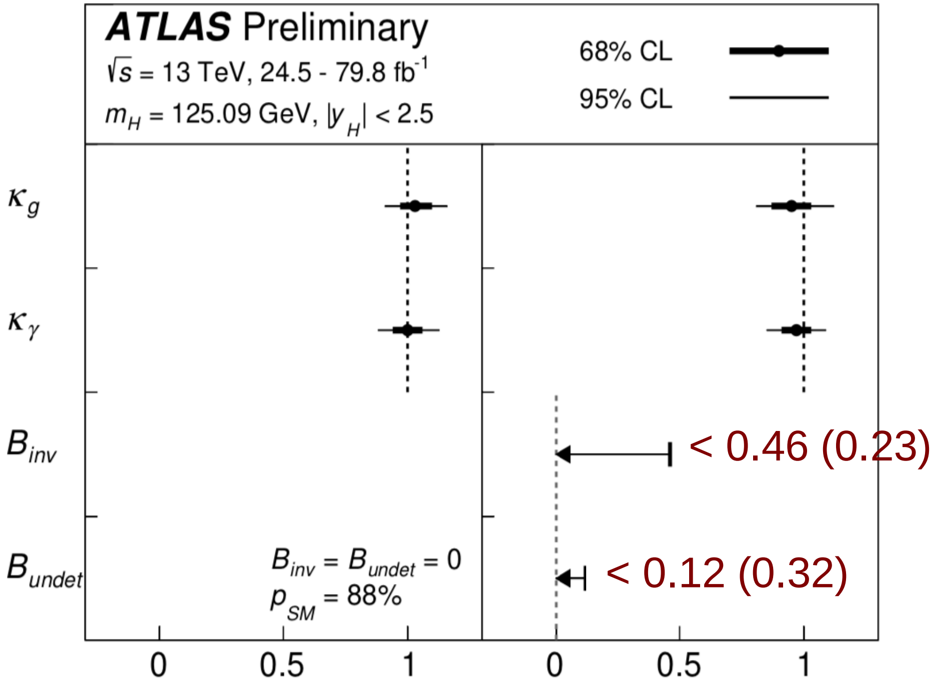
$$\sigma_i \times \mathrm{B}_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H} \quad \text{with} \quad \kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

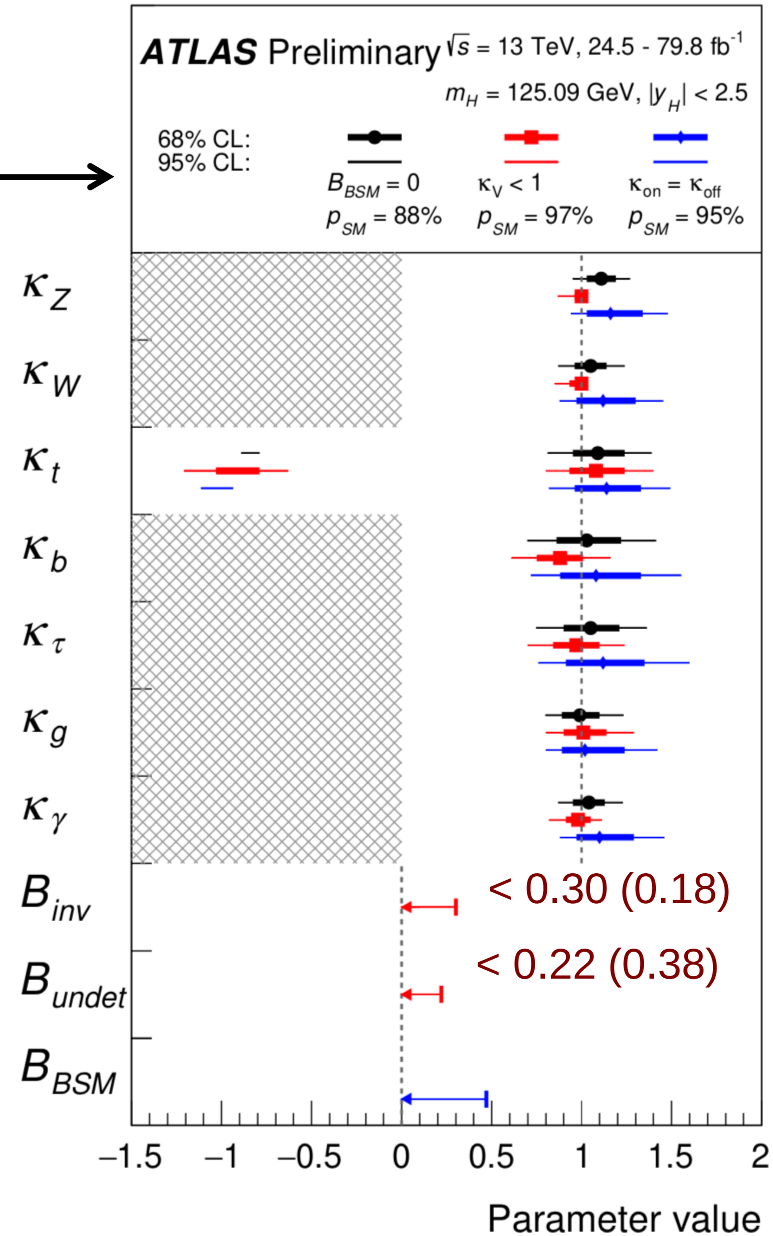
$$\Gamma_H(\boldsymbol{\kappa}, \mathrm{B_{inv}}, \mathrm{B_{undet}}) = \frac{\kappa_H^2(\boldsymbol{\kappa})}{(1 - \mathrm{B_{inv}} - \mathrm{B_{undet}})} \Gamma_H^{\mathrm{SM}}$$

ATLAS-CONF-2019-005

[1] YR 3 1307.1347 [hep-ph]

- Results: (including Run 2 invisible searches)
  - Maximum granularity for κ_{SM} →
  - Free κ_γ and κ_g:

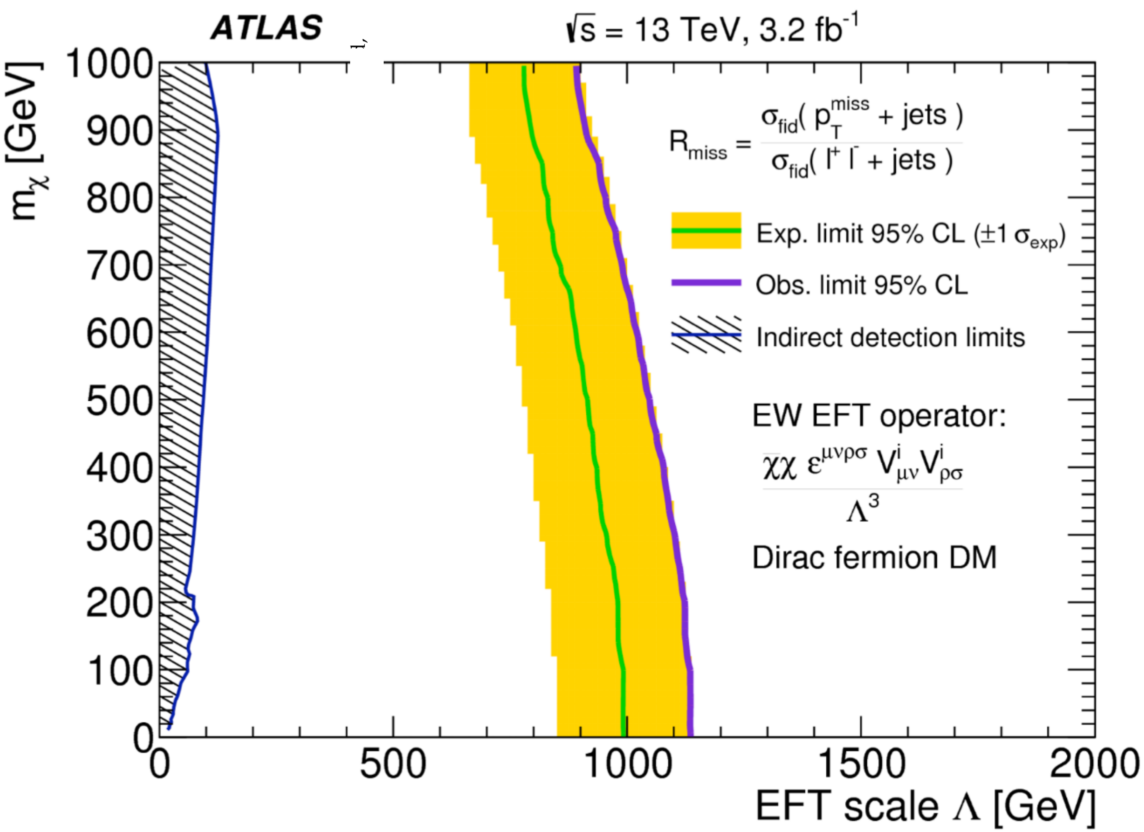


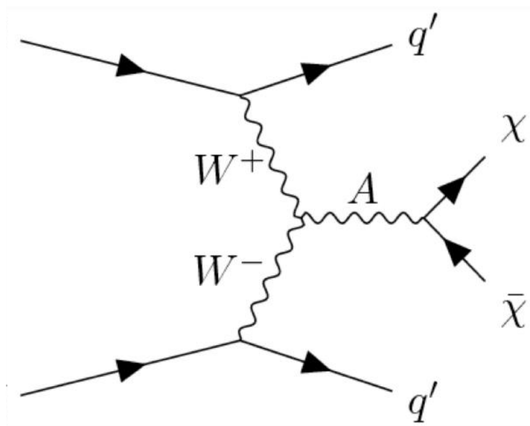


ATLAS-CONF-2019-005

EPJC 77 (2017) 11, 765; arXiv:1707.03263

Exclusion contours (@ 95% CL) for Dirac-fermion dark matter produced via contact interaction with two electroweak bosons with a dimension-seven EFT operator

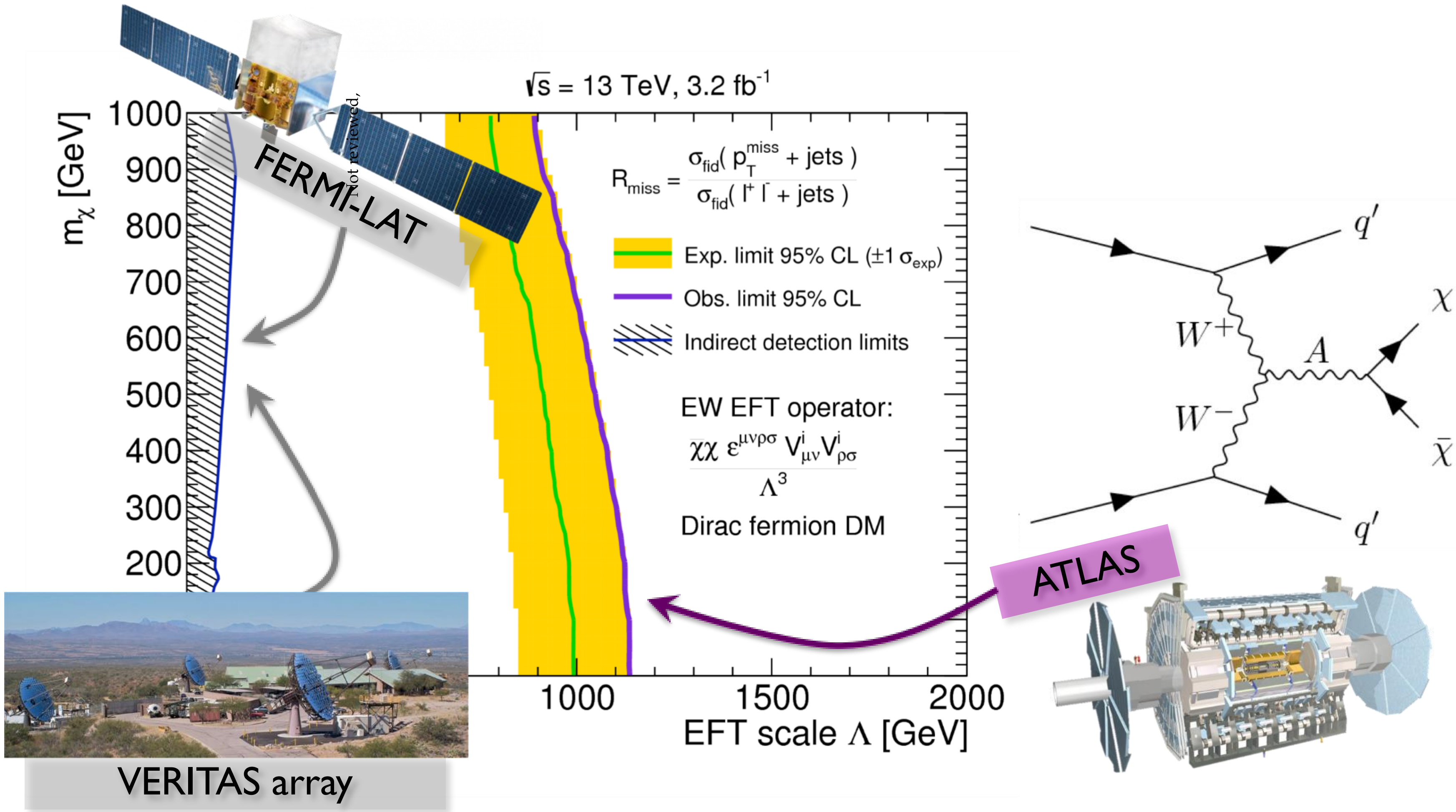




Most stringent constraints to-date on such interactions!

EPJC 77 (2017) 11, 765; arXiv:1707.03263

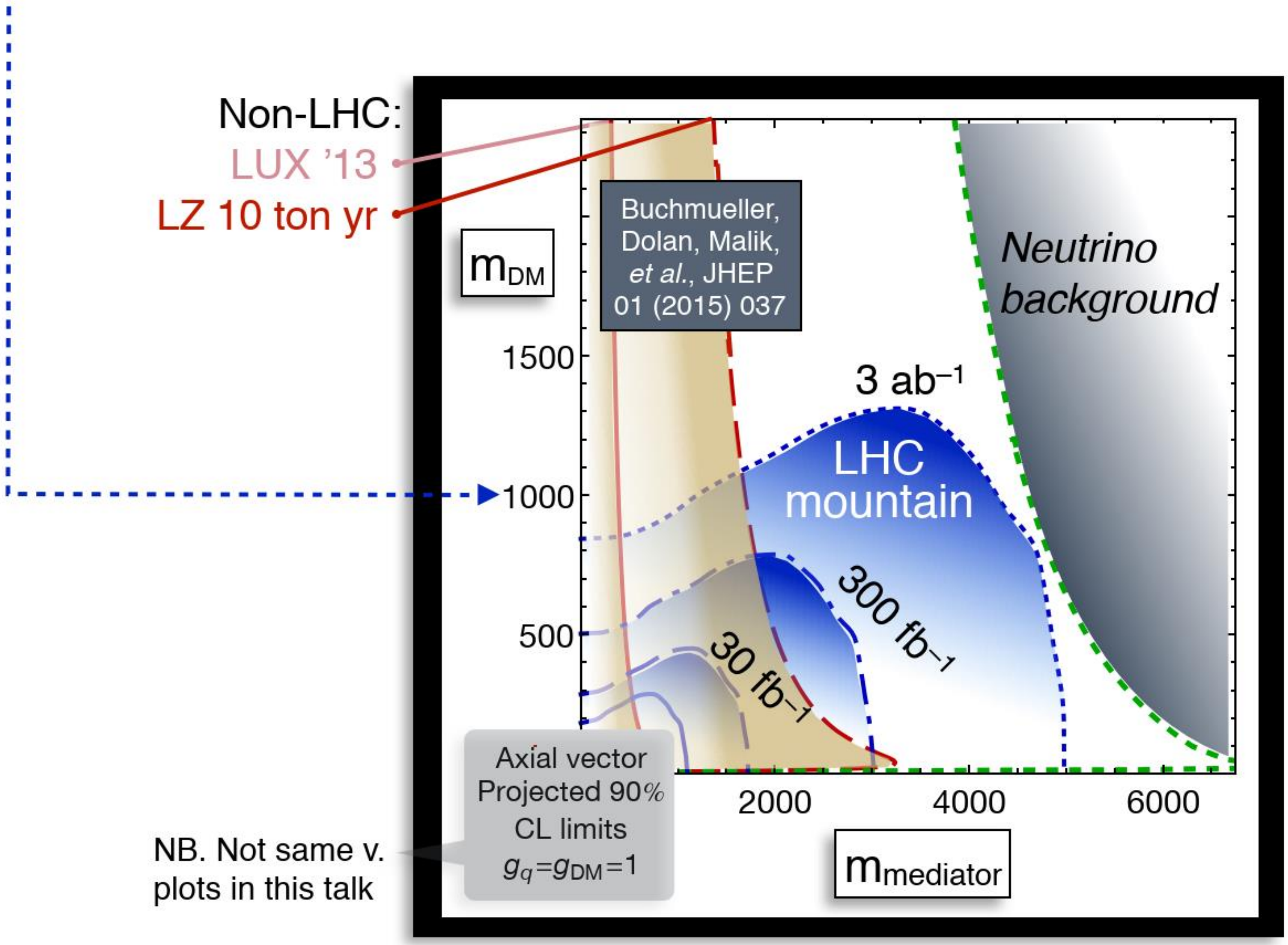
Exclusion contours (at 95 % CL) for Dirac-fermion dark matter produced via a contact interaction with two electroweak bosons with a dimension-seven EFT operator.



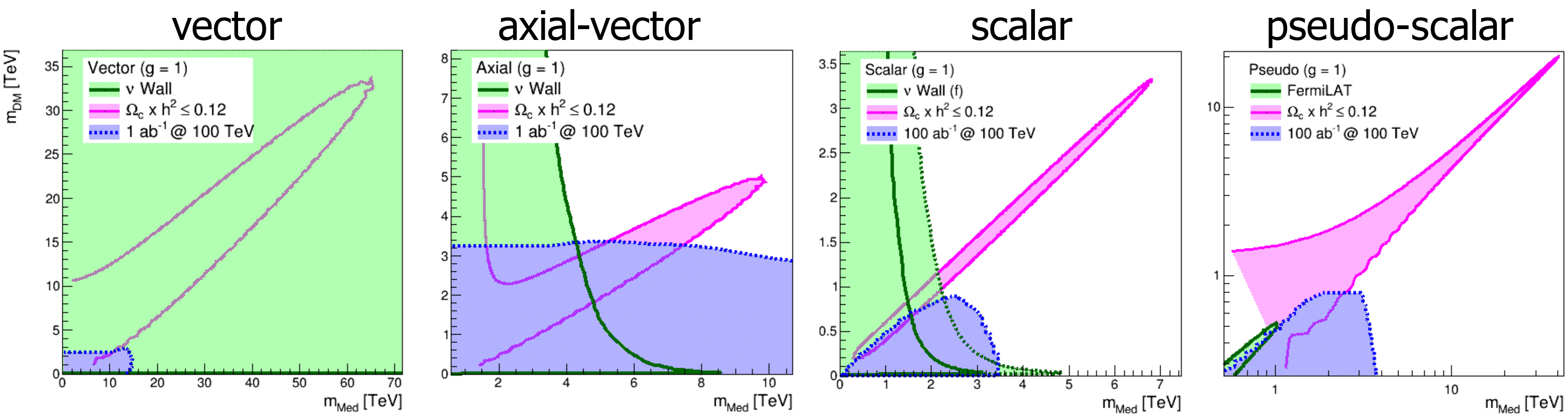
Most stringent constraints to-date on such interactions!

The future of DM searches at the LHC

m_{DM} reach TeV at HL-LHC



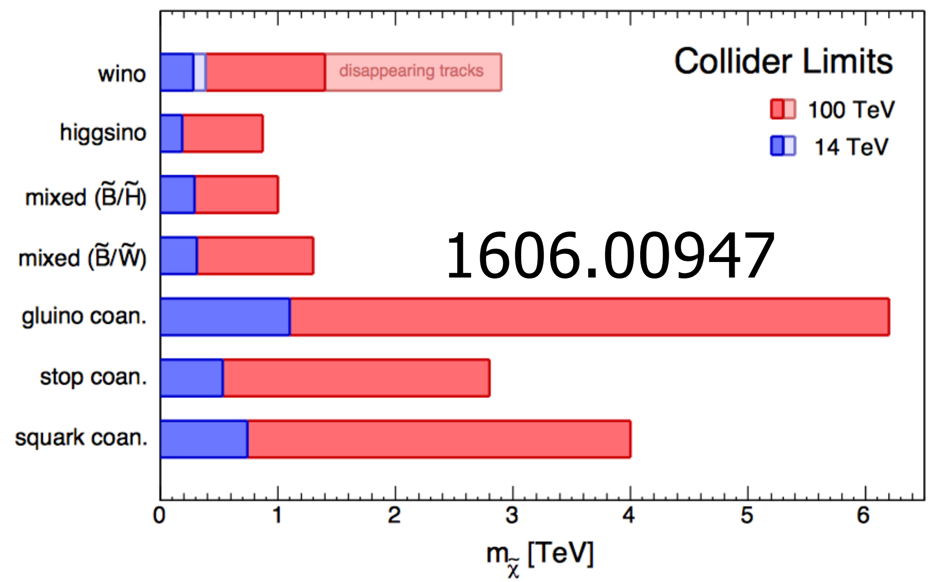
Beyond the LHC



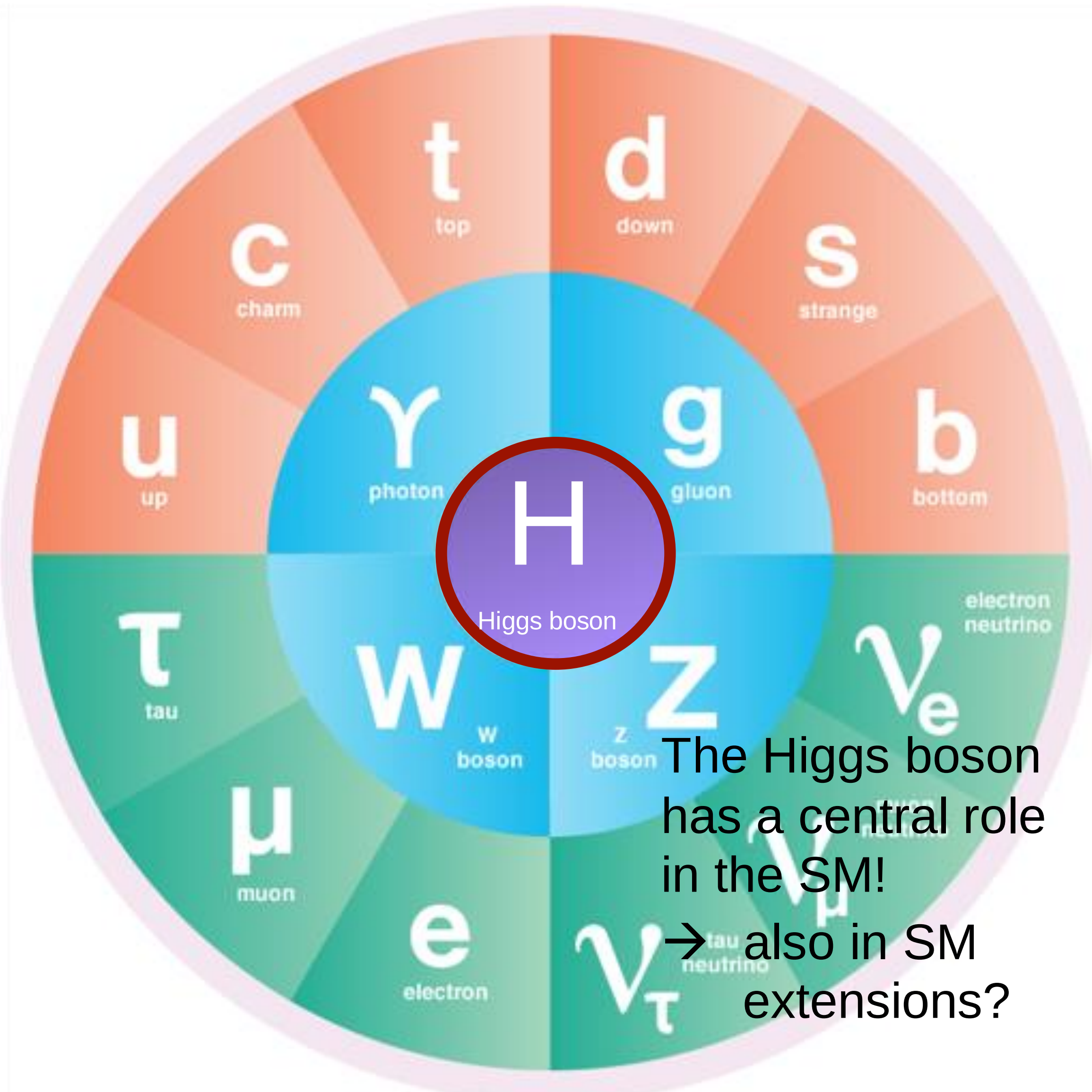
green: xsec ⇐ neutrino bkg
blue: 1000 fb⁻¹ @ 100 TeV
red: compatible with measured relic density

(for some choice of the couplings)

a higher-energy circular collider may push sensitivity to the TeV scale



- Bottom line:
  - Dark Matter a fact, but particle nature not clear
  - Higgs boson at the centre of SM + extensions
- Turn every stone:
  - Consider simplified models with generic signatures
  - s-channel mediator addressed, t-channel targeted
  - Generic limits: useful and powerful tool
- Higgs as a probe:
  - Direct probe of interaction with DM, Co-dominant in 2HDM+a model
- Higgs → invisible decays:
  - Probe Yukawa-like couplings of Higgs to DM
  - Combination: $\mathcal{B}_{H\to\mathrm{inv}} < 0.26 \ (0.17^{+0.07}_{0.05})$
  - Single-digit precision with 140 fb^{-1} (full Run 2)
- Exploring the nature of Dark Sector: Possible hints at the LHC
  - Dark photons, charged DM
- Exciting times ahead:
  - One order of magnitude more data at HL-LHC!



The Higgs boson has a central role in the SM!
→ also in SM extensions?

N.B.: ignoring gravitational interaction

- SM is beautiful:
  - Locally gauge invariant quantum field theory
  - Underlying symmetry:

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

- BUT it is massless!
  - QED: simple mass term

$$\Delta\mathcal{L} = \frac{1}{2} m_A^2 A_\mu A^\mu$$

  - breaks gauge invariance

$$A_\mu \to A_\mu - \frac{1}{e}\partial_\mu \alpha$$

- Solution:
  - Mass term via Yukawa coupling to Higgs field:

$$\Delta\mathcal{L} = y_e \, \bar{e}_R \, (\phi^+, \phi^0) \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

  - If $\langle \phi^0 \rangle = v \neq 0$:

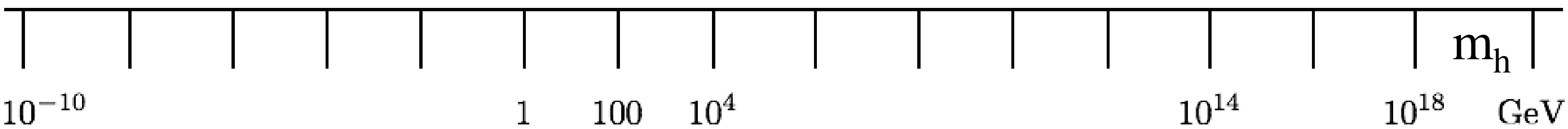
$$\Rightarrow m_e = y_e v$$

HIGGS: A WINDOW TO NEW PHYSICS

- Naturalness problem:
  - m_h = 125 GeV seems unnaturally small

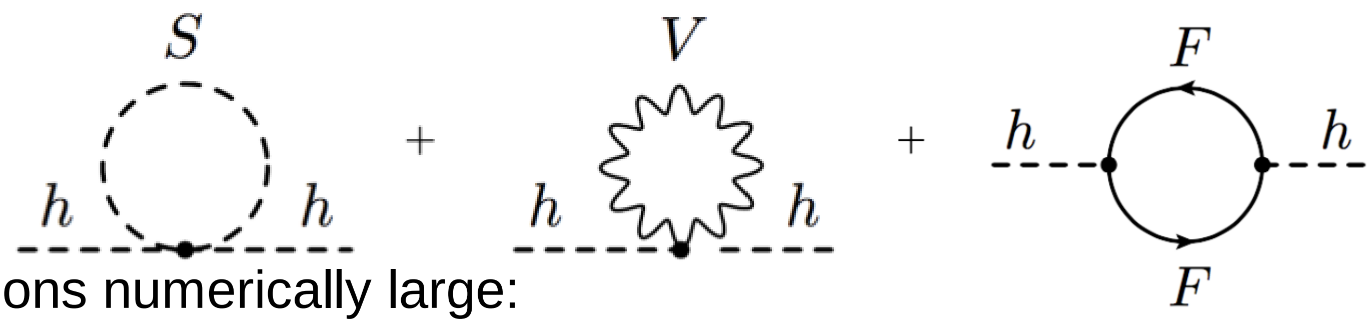
$m_p > m_n$

$m_n - m_p >$ nuclear binding energy



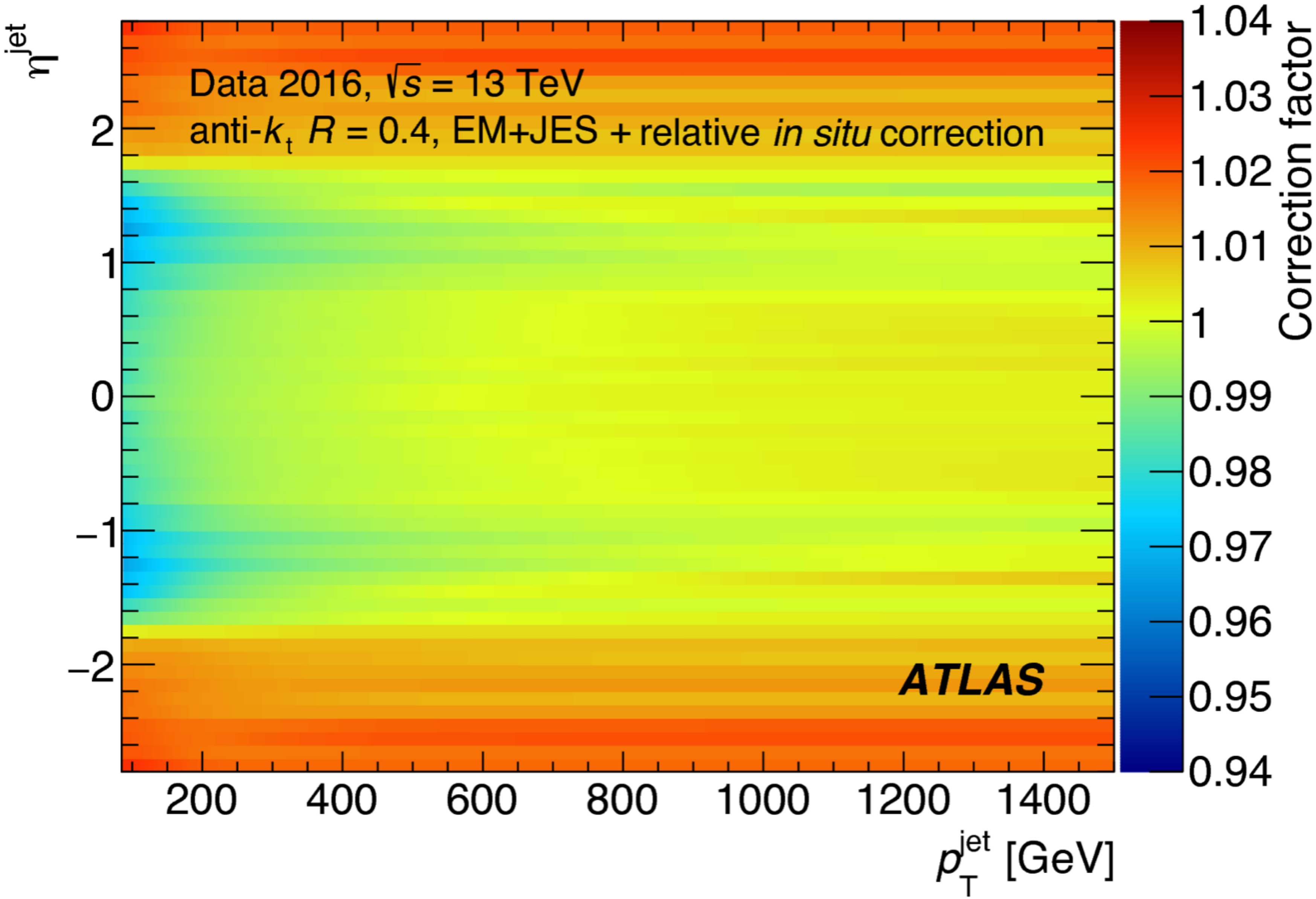
- Loop corrections to m_h from all particle types:

$\delta\mu_h^2 \propto$

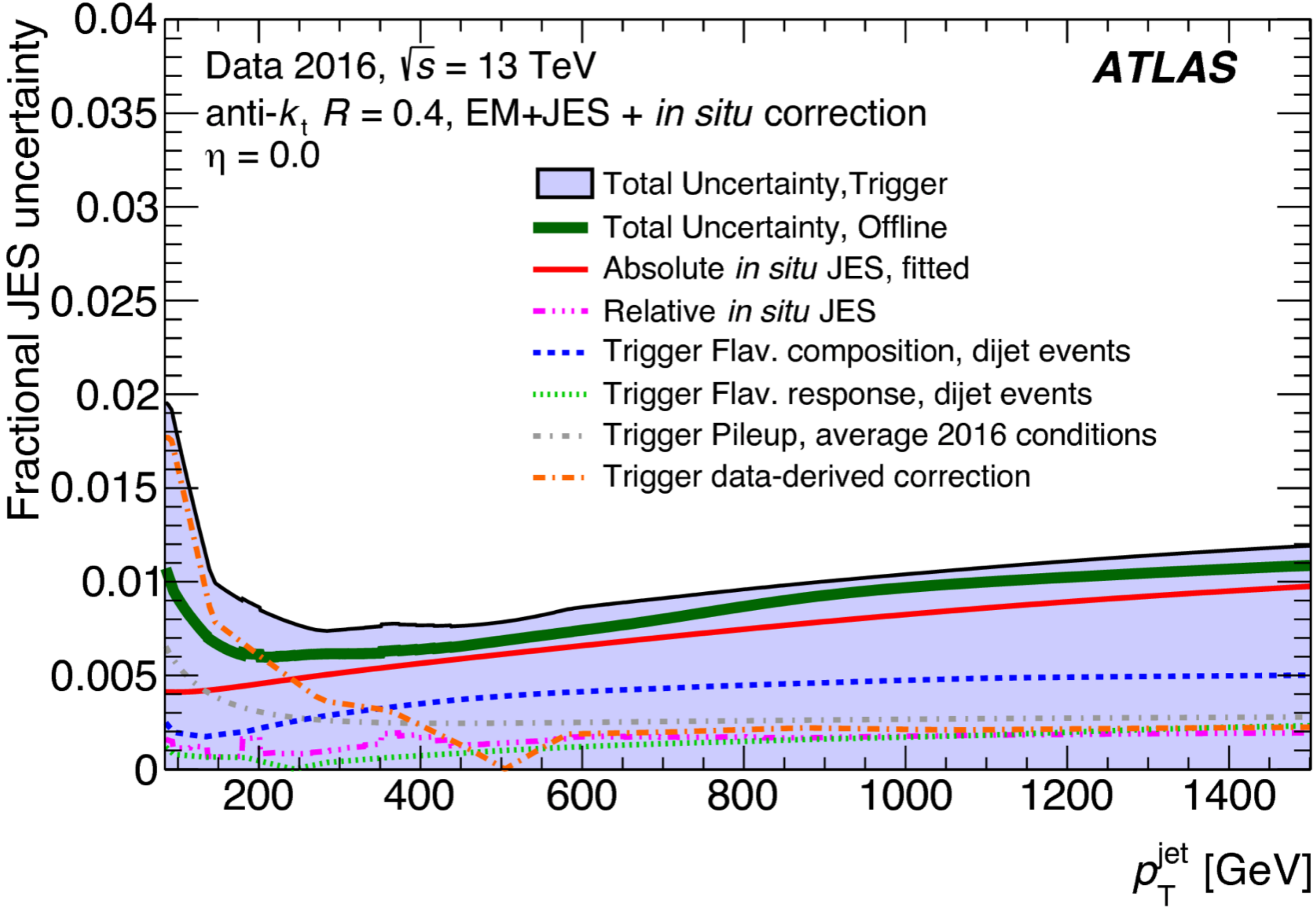


  - Corrections numerically large:
    - Fine-tuning at ≈ 1% level to get m_h “right” already for **Λ** = 5 TeV
    - **Λ** = 5 TeV ≪ $\mathbf{\Lambda}_{\text{Planck}}$!
- If New Physics to make m_h more natural:
  - → Corrections to m_h from New Physics
    - → New Physics likely to couple to Higgs!

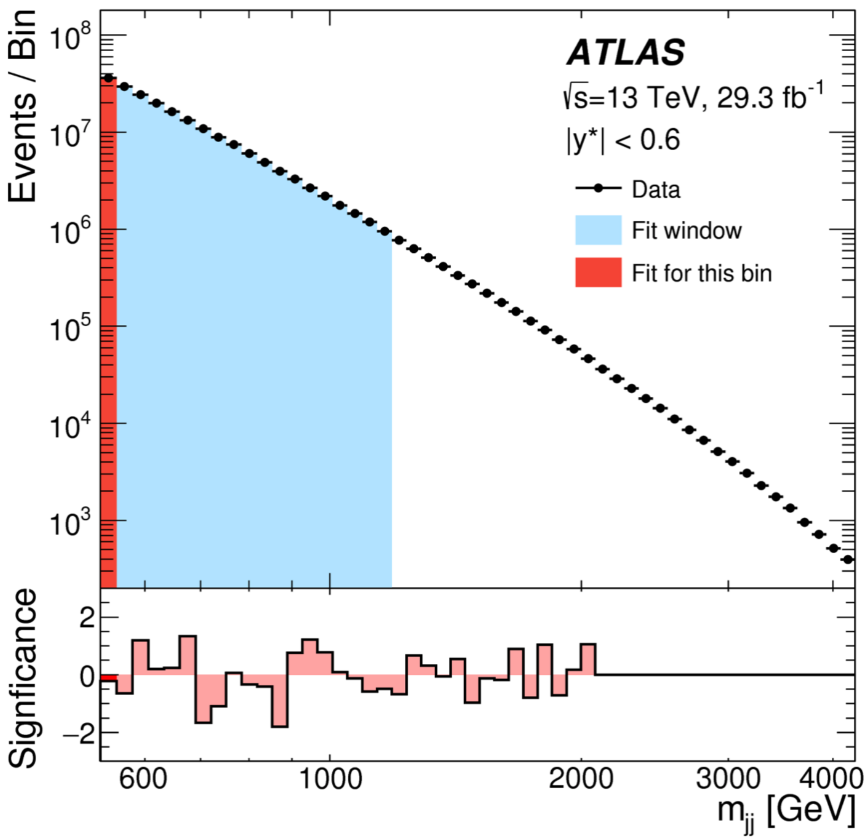
TLA DIJETS

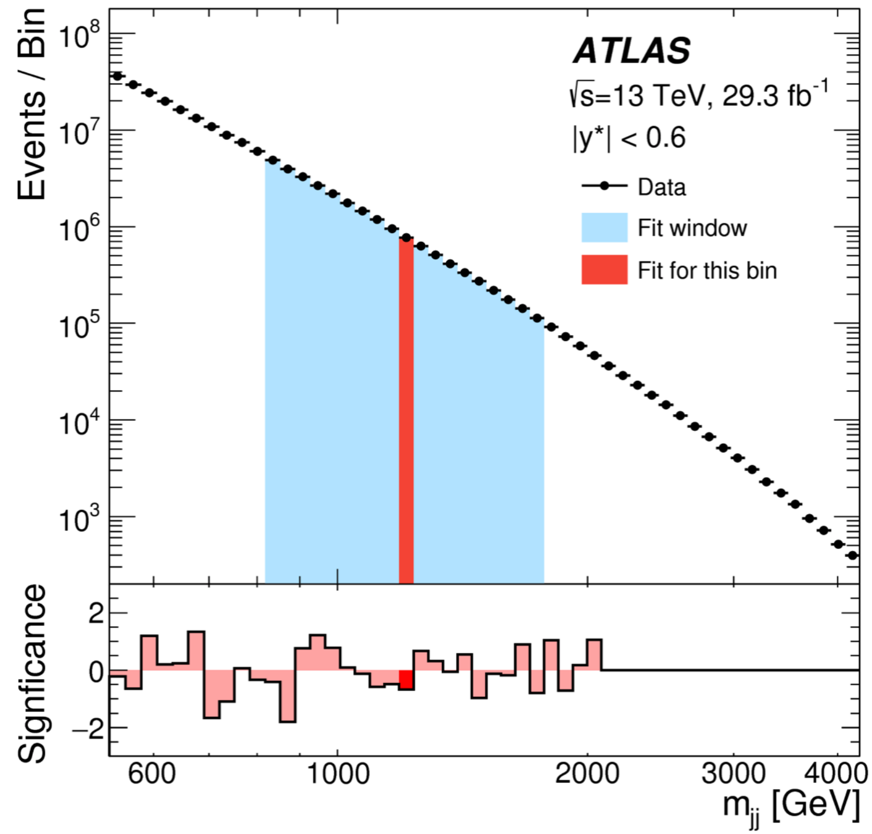


Data 2016, $\sqrt{s}$ = 13 TeV
anti-k_t R = 0.4, EM+JES + relative *in situ* correction
ATLAS
η^{jet}
2
1
0
−1
−2
200
400
600
800
1000
1200
1400
p_T^{jet} [GeV]
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
Correction factor



Data 2016, √s = 13 TeV
anti-k_t R = 0.4, EM+JES + in situ correction
η = 0.0
ATLAS
Total Uncertainty,Trigger
Total Uncertainty, Offline
Absolute in situ JES, fitted
Relative in situ JES
Trigger Flav. composition, dijet events
Trigger Flav. response, dijet events
Trigger Pileup, average 2016 conditions
Trigger data-derived correction
Fractional JES uncertainty
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
200
400
600
800
1000
1200
1400
p_T^jet [GeV]


ATLAS
√s=13 TeV, 29.3 fb-1
|y*| < 0.6
Data
Fit window
Fit for this bin
Events / Bin
Signficance
m_jj [GeV]
600
1000
2000
3000
4000


ATLAS
√s=13 TeV, 29.3 fb-1
|y*| < 0.6
Data
Fit window
Fit for this bin
Events / Bin
Signficance
m_jj [GeV]
600
1000
2000
3000
4000

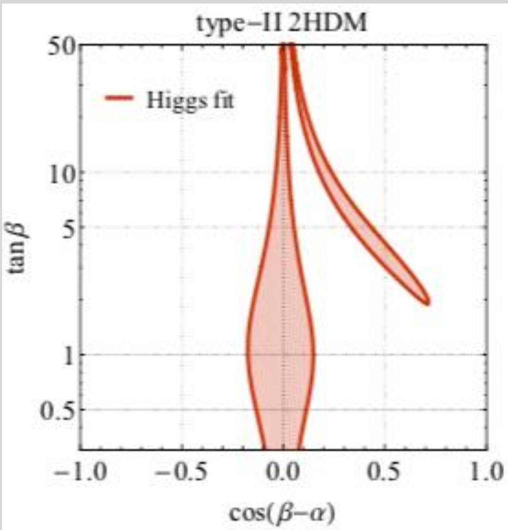
CERN-LPCC-2018-02

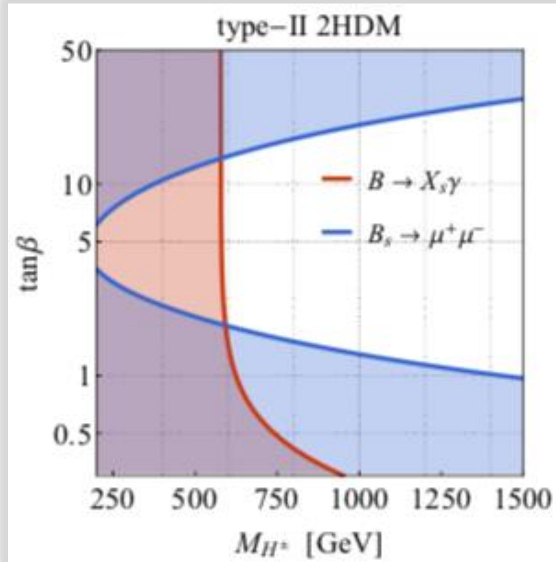
LHC Dark Matter Working Group: Next-generation spin-0 dark matter models

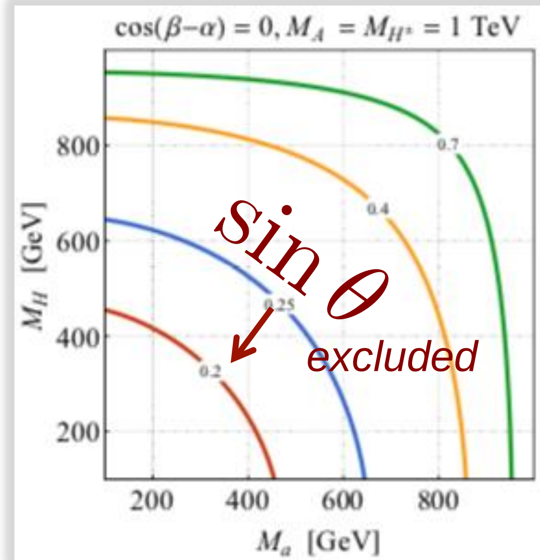
arXiv:1810.09420v2 [hep-ex]

Abstract. Dark matter (DM) simplified models are by now commonly used by the ATLAS and CMS Collaborations to interpret searches for missing transverse energy (E_T^{miss}). The coherent use of these models sharpened the LHC DM search program, especially in the presentation of its results and their comparison to DM direct-detection (DD) and indirect-detection (ID) experiments. However, the community has been aware of the limitations of the DM simplified models, in particular the lack of theoretical consistency of some of them and their restricted phenomenology leading to the relevance of only a small subset of E_T^{miss} signatures. This document from the LHC Dark Matter Working Group identifies an example of a next-generation DM model, called 2HDM+a, that provides the simplest theoretically consistent extension of the DM pseudoscalar simplified model. A comprehensive study of the phenomenology of the 2HDM+a model is presented, including a discussion of the rich and intricate pattern of mono-X signatures and the relevance of other DM as well as non-DM experiments. Based on our discussions, a set of recommended scans are proposed to explore the parameter space of the 2HDM+a model through LHC searches. The exclusion limits obtained from the proposed scans can be consistently compared to the constraints on the 2HDM+a model that derive from DD, ID and the DM relic density.

2HDM+α: PARAMETERS



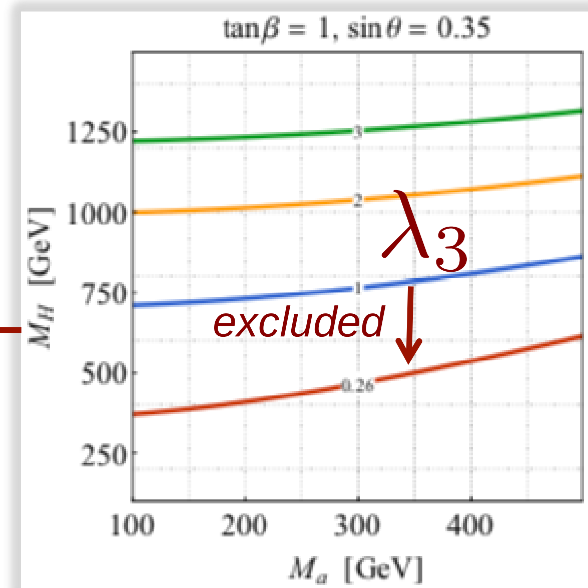




$$M_H = M_A = M_{H\pm}\,, \quad m_\chi = 10\,\text{GeV}\,,$$
$$\cos(\beta-\alpha) = 0\,, \quad \tan\beta = 1\,, \quad \sin\theta = 0.35\,,$$
$$y_\chi = 1\,, \quad \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3\,.$$

Convenience

Resonant enhancement



- ~~Executive~~ Experimental summary on model pheno:
  - 14 parameters to start with
    - 7 parameters fixed:
      - symmetry, EW-precision measurements, Higgs properties,...
    - 7 "free" parameters:

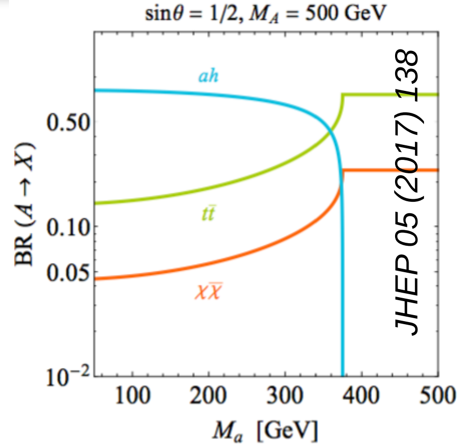
More details in talk by Johanna Gramling
https://indico.cern.ch/event/665524/sessions/260090/

- *4 affect MET shape:*
  - m_a
  - m_A
  - m_H
  - $\sin(\theta)$

  (m_a, m_A, m_H: *kinematics & channels*; $\sin(\theta)$: ← *couplings*)
- 3 only affect total cross-section:
  - $\tan(\beta)$ [1]
  - m_χ [2]
  - y_χ ← *DM Yukawa*

- A/a mixing angle sin$\boldsymbol{\theta}$ important, e.g.:

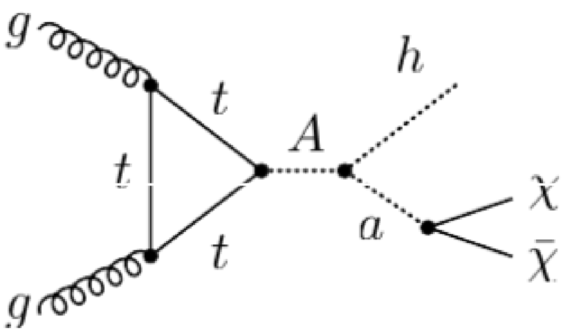
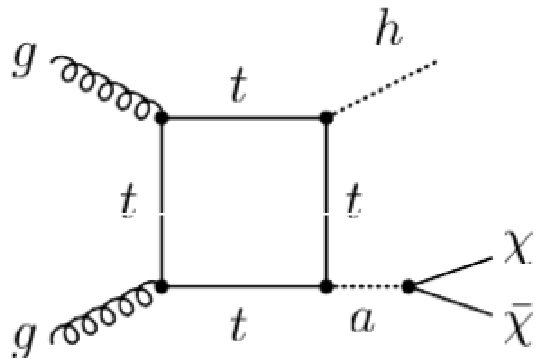
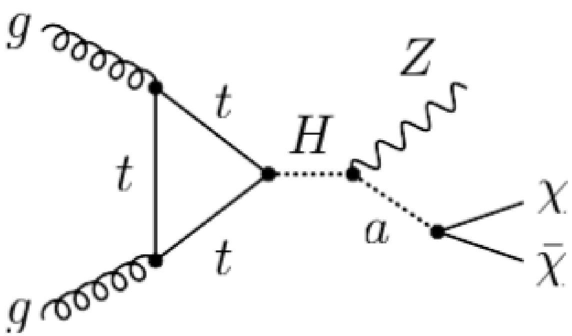
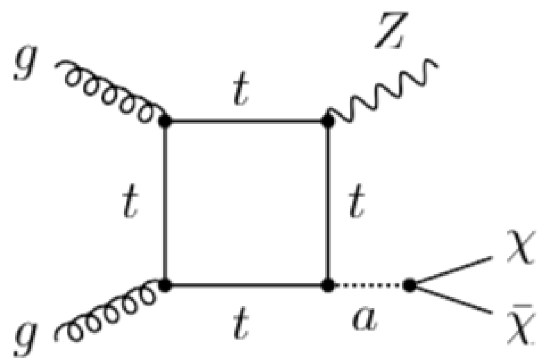
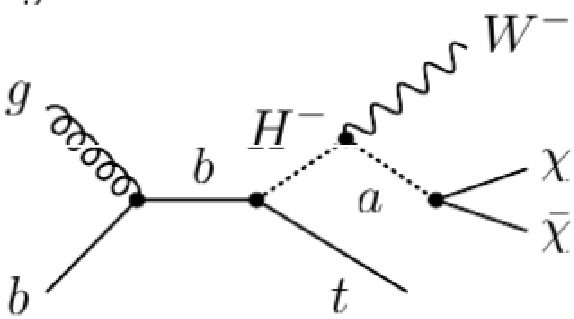
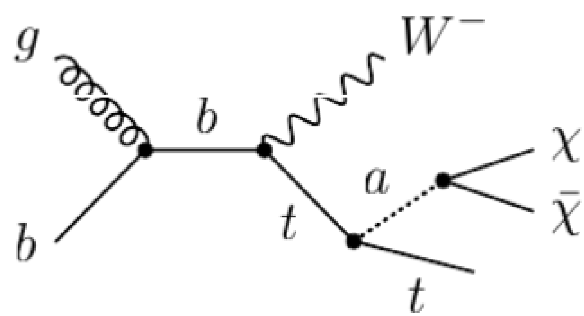
$$\Gamma(A \to \chi\chi) \propto \sin^2\theta \qquad \Gamma(a \to \chi\chi) \propto \cos^2\theta$$
$$\Gamma(A \to ff) \propto \cos^2\theta \qquad \Gamma(a \to ff) \propto \sin^2\theta$$
$$\Gamma(A \to ah) \propto \sin\theta\cos\theta$$



JHEP 05 (2017) 138

[1] can change shapes if u/d-type couplings process-relevant
[2] statement true if decay mediator on-shell

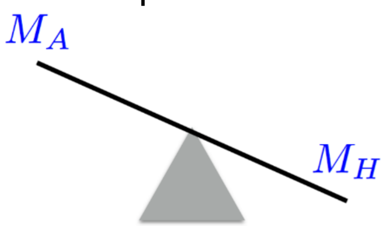
2HDM+a: (NON-) RESONANT SIGNATURES

Resonant		Non-Resonant
	h + DM	
	Z + DM	
	Wt + DM	

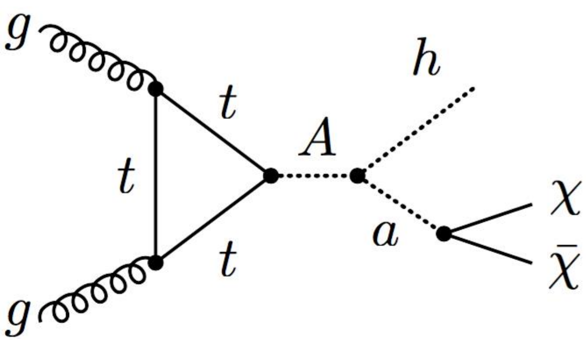
+ many other signatures

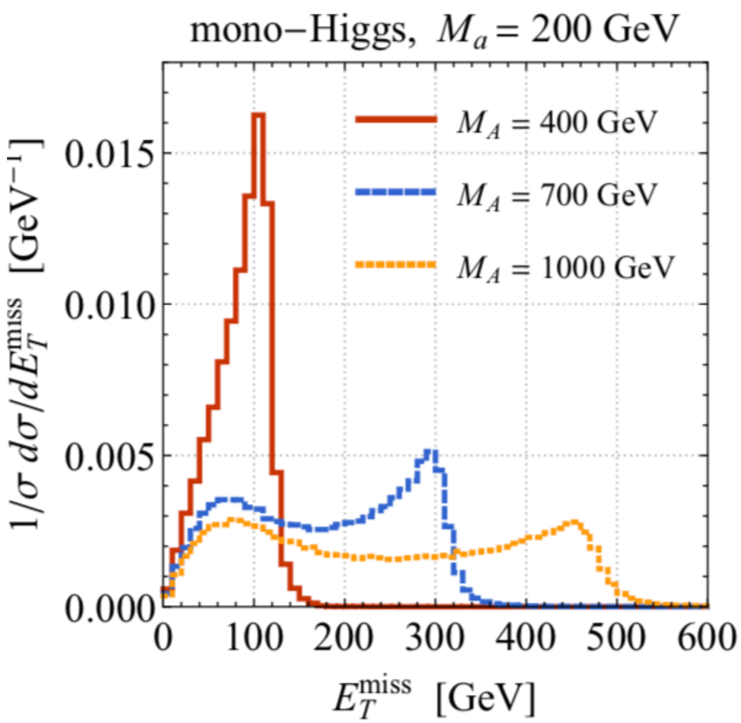
2HDM+a: h + DM

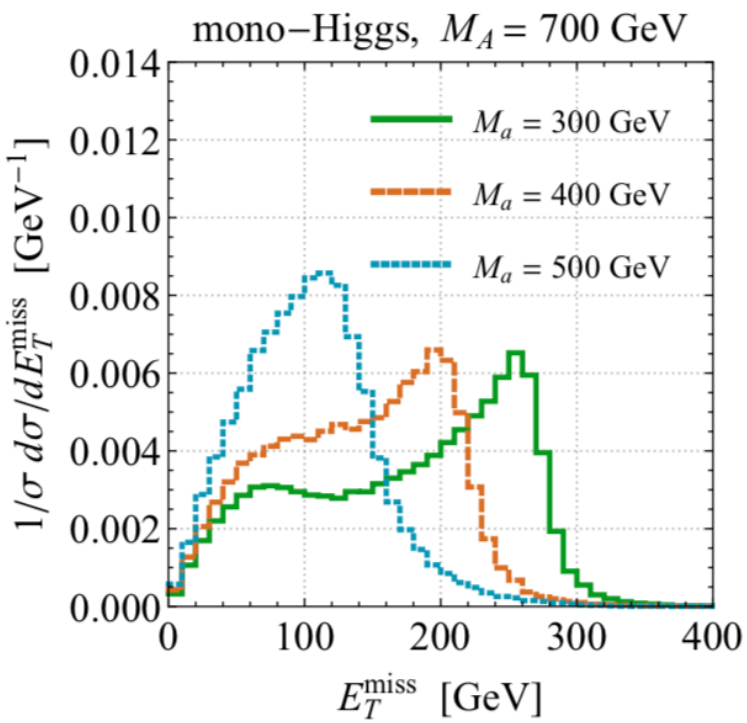
- General:
  - Can be resonantly enhanced
    - → driving sensitivity for 2HDM+a
  - h + E_T^{miss} dominant over Z + E_T^{miss} if



$$\Rightarrow M_H = M_{H^\pm} = M_A$$

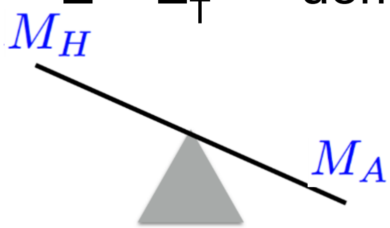




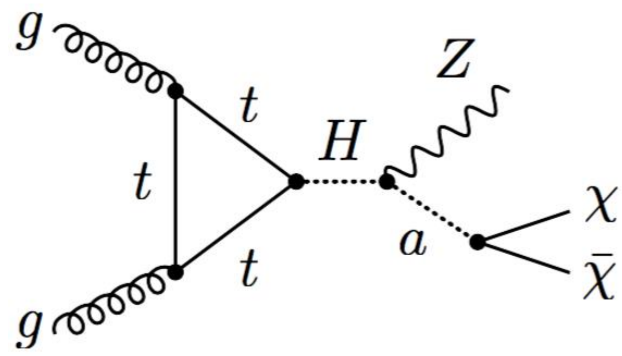


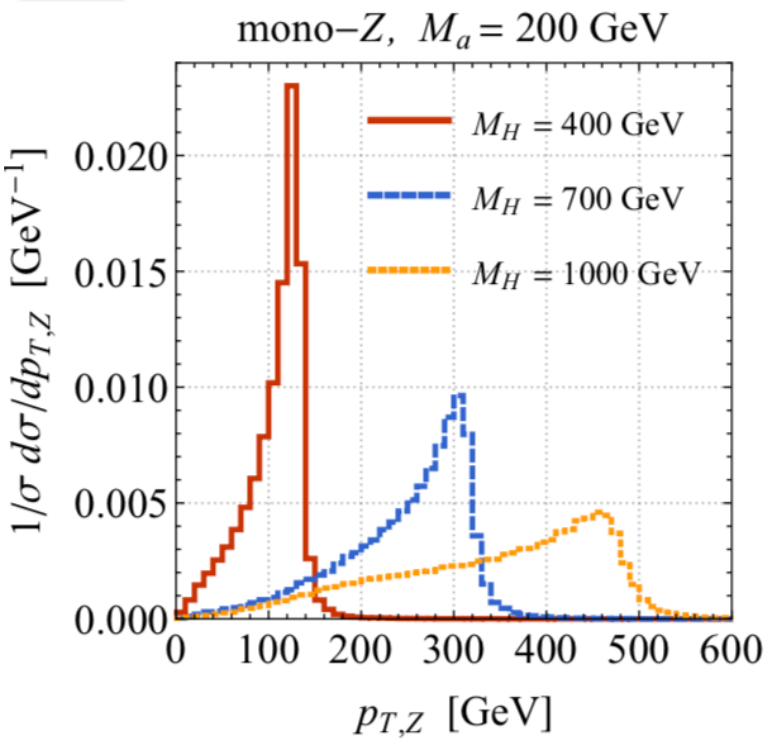
2HDM+a: Z + DM

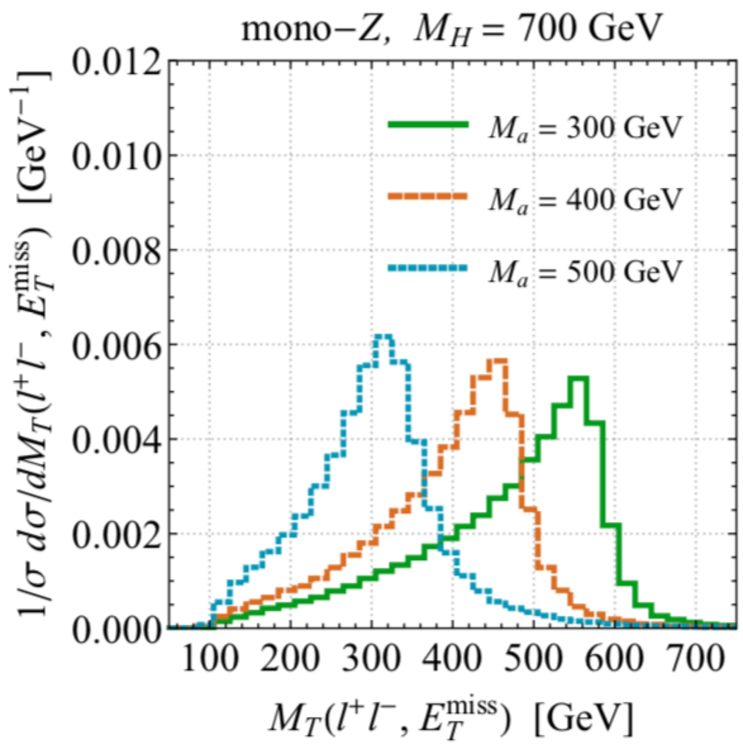
- General:
  - Can be resonantly enhanced
    - → driving sensitivity for 2HDM+a
  - Z + E_T^{miss} dominant over h + E_T^{miss} if



$$\Rightarrow M_H = M_{H^\pm} = M_A$$



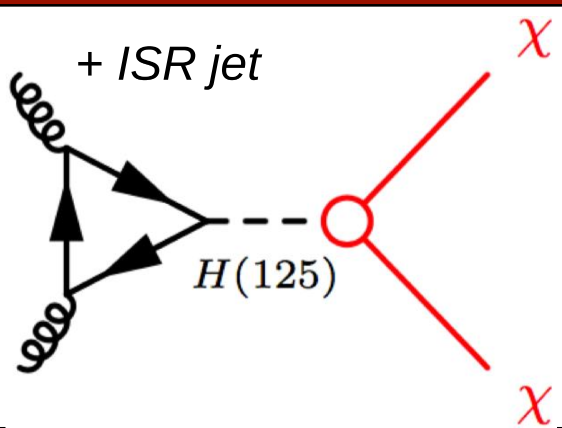
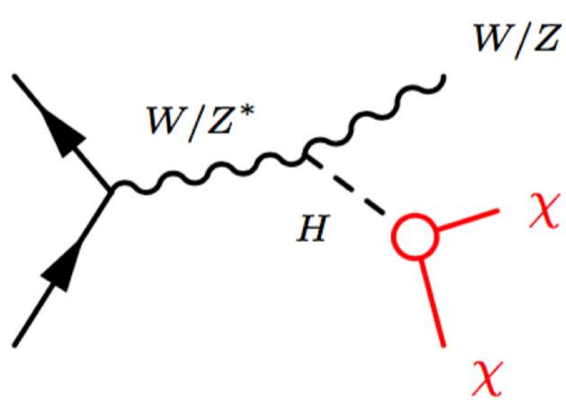
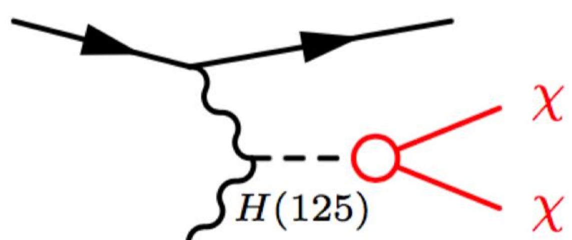




- Motivation:
  - Higgs couples to massive particles
  - Dark Matter particles massive…
  - $H \to \chi\chi$ possible if $M_\chi \leq M_H$
- Competitive – Higgs production as tag:

[1] *JHEP 10 (2018) 180*
[2] *PLB 776 (2017) 318*
[3] *arXiv:1809.06682*
[4] *arXiv:1904.05105*
[5] *PRD 97 (2018) 092005*
[6] *EPJC 78 (2018) 291*
[7] *arXiv:1809.05937*

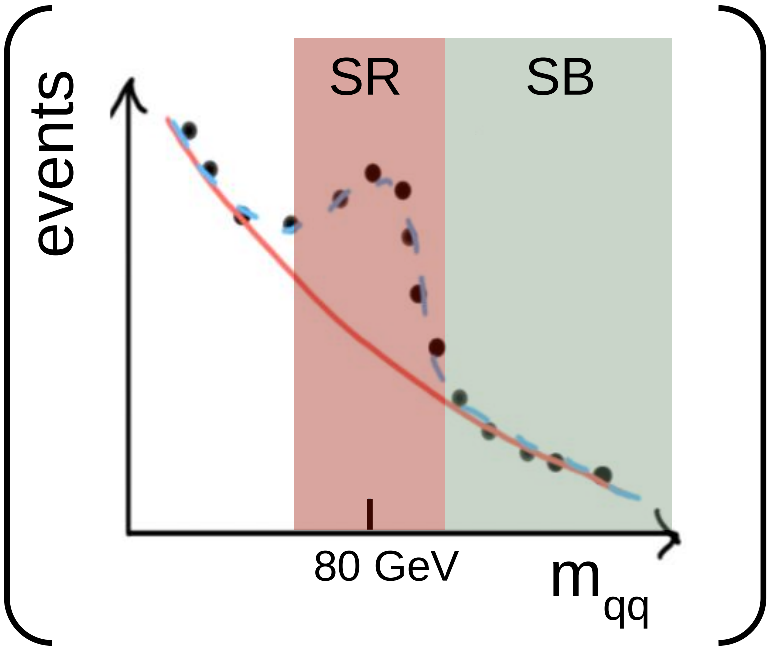
New → [3], [4], [7]

	ggF H [49 pb]	VH [2.3 pb]	VBF H [3.8 pb]
			
ATLAS	ggF+V(had)H(inv): 0.83 (0.58) [1] Z(ℓℓ)H(inv): 0.67 (0.39) [2]	Combo [4]	0.37 (0.28) [3]
CMS	ggF+V(had)H(inv): 0.53 (0.40) [5] Z(ℓℓ)H(inv): 0.40 (0.42) [6]	Combo [7]	0.33 (0.25) [7]

Feynman diagrams: Christian Ohm

VH Higgs → invisible: strategy

- Analysis strategy:
  - Require MET
  - Look for excess in m_{qq} distribution:



× ~10 MET bins
× (0,1, 2 b-tags)
× ~merged/resolved

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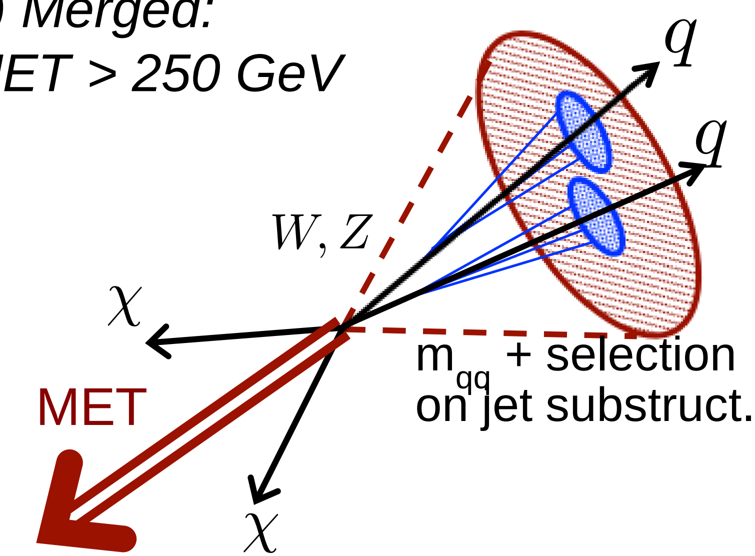
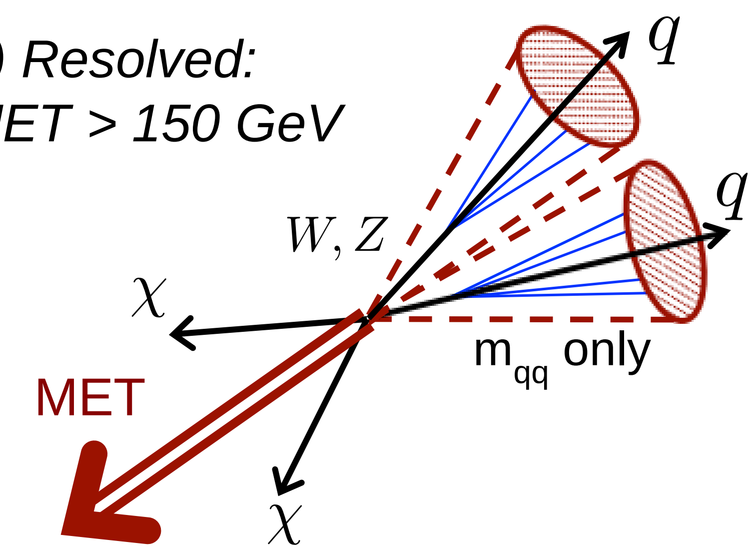
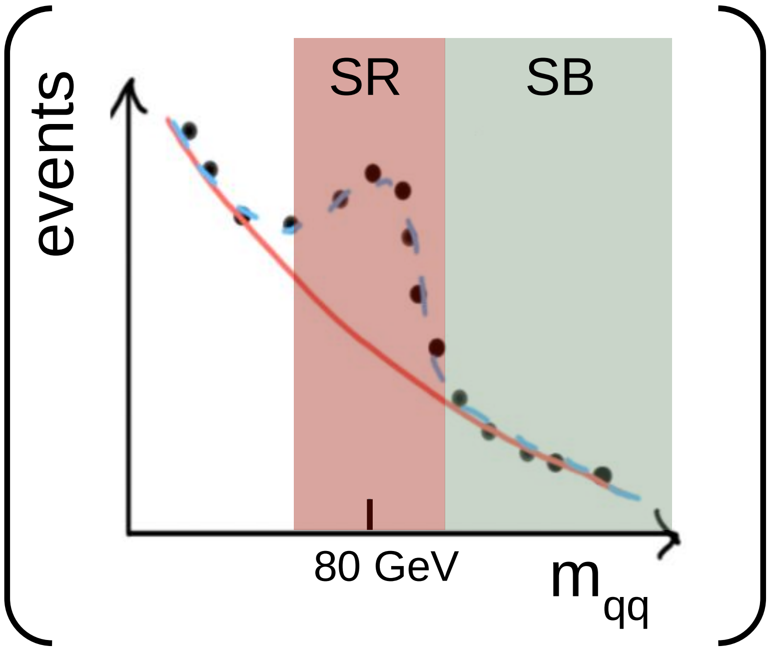




- Analysis strategy:
  - Require MET
  - Look for excess in m_{qq} distribution:



× ~10 MET bins
× (0,1, 2 b-tags)
× ~merged/resolved

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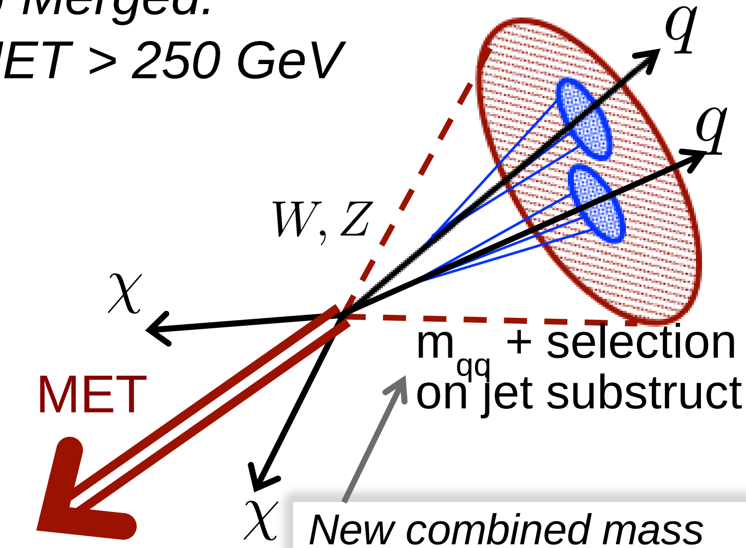
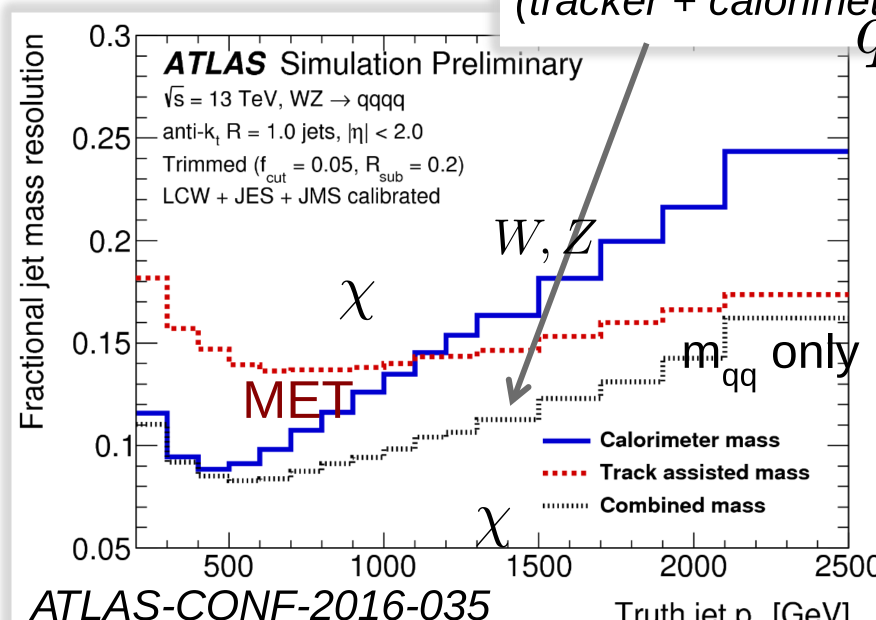
1) Merged:
MET > 250 GeV

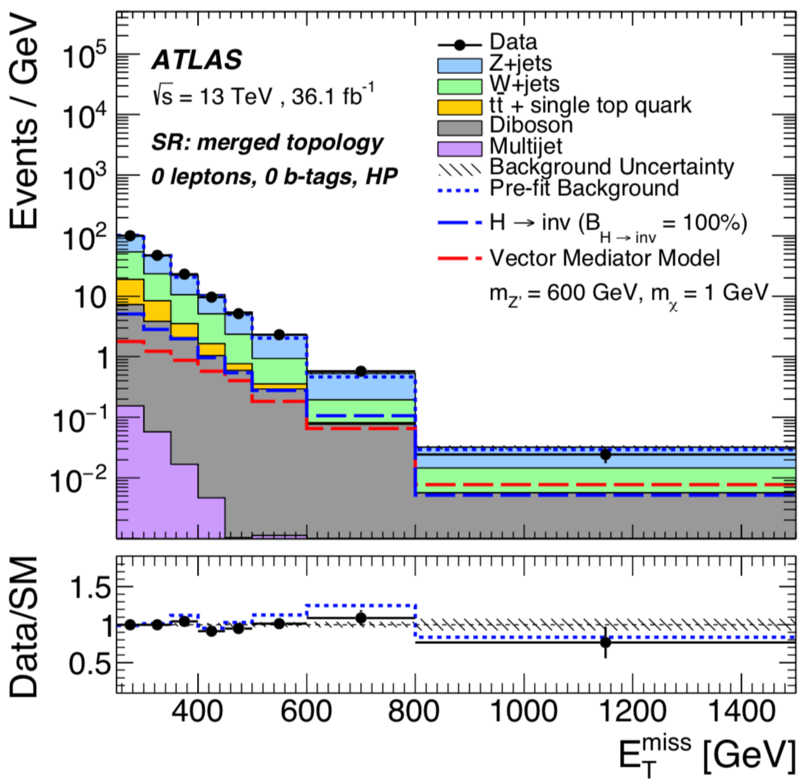


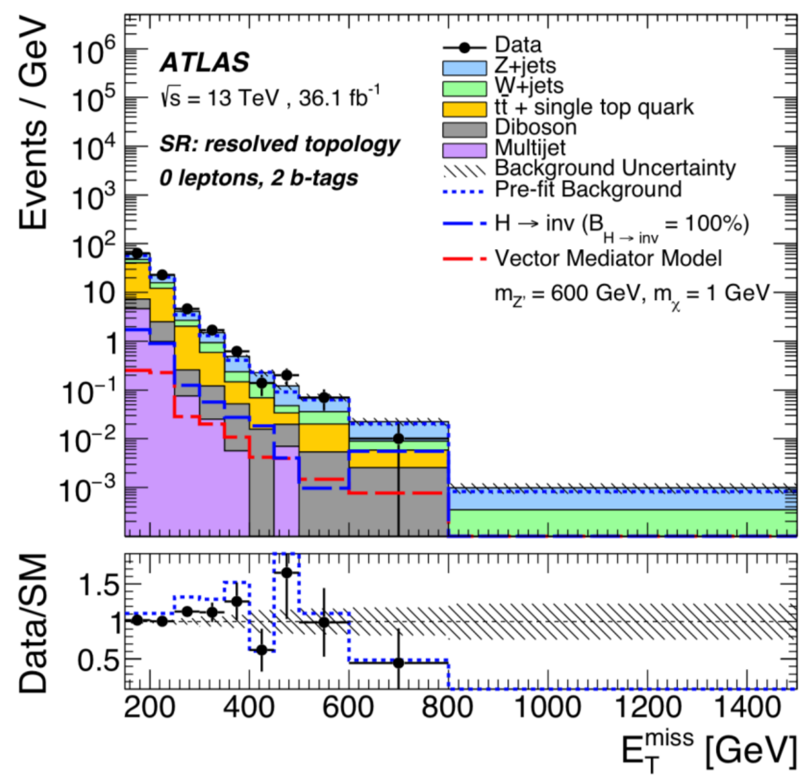
New combined mass (tracker + calorimeter)



ATLAS-CONF-2016-035

- Constrain Z(νν)+jets, W+jets in signal region using control regions
  - Similar to VBF Higgs → invisible
- Representative signal region (SR) plots:





- Higgs → invisible interpretation:

$$BR(h \rightarrow \mathbf{inv.}) < \mathbf{0.83}\ (\mathbf{0.58}^{+\mathbf{0.23}}_{\mathbf{0.16}})$$

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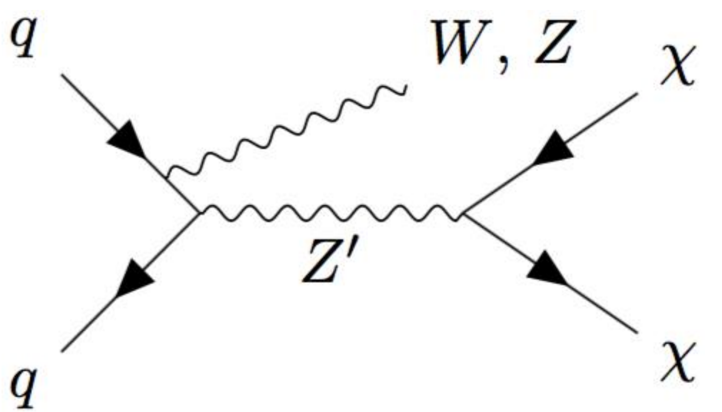
V + MET: RESULTS

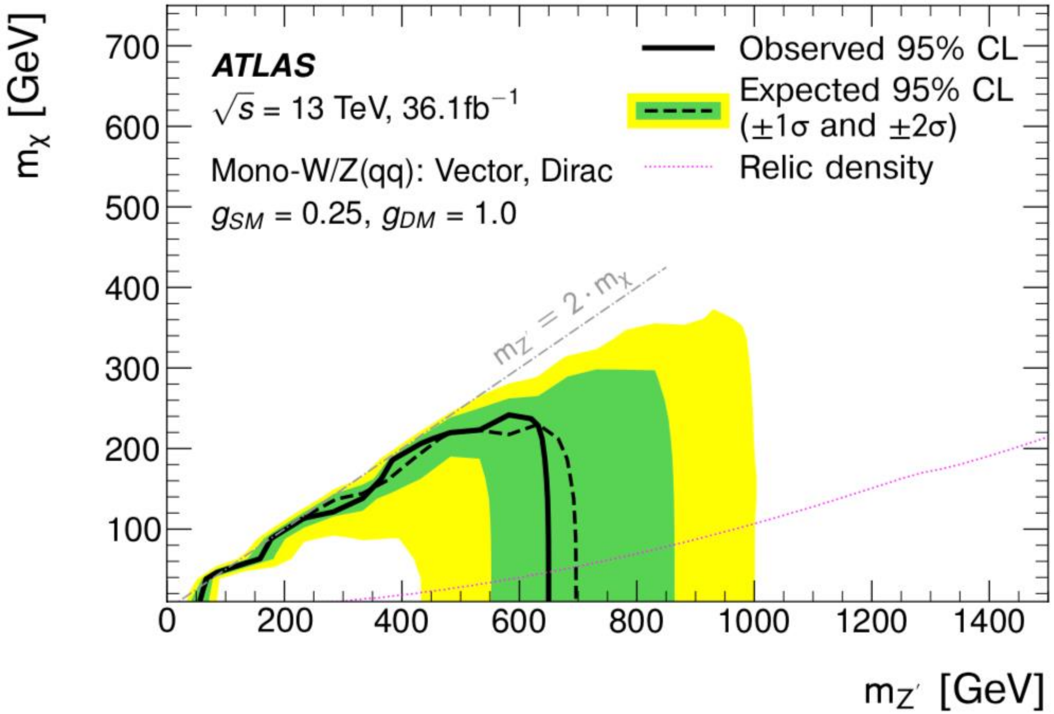


s-channel (V/AV) mediator model

arXiv:1507.00966

(White Paper of

LHC DM WG/DMF)



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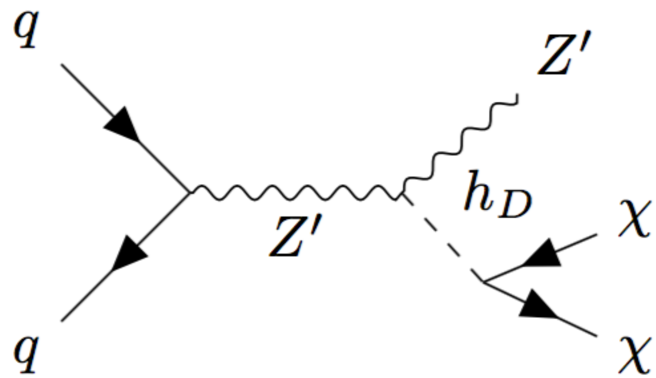
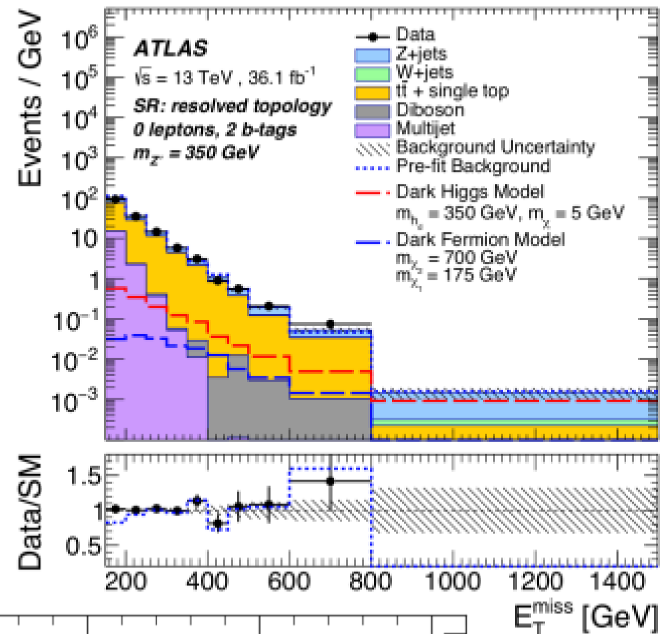
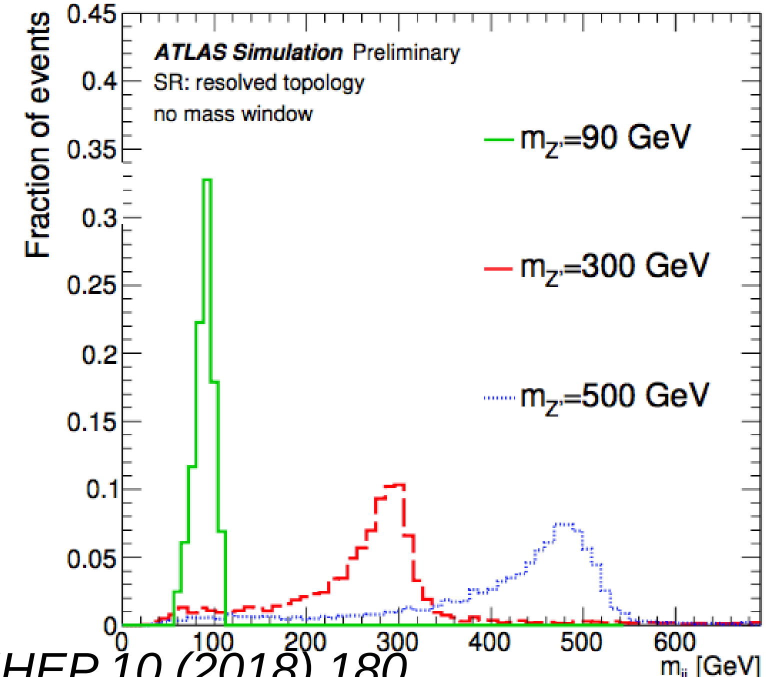
V + MET: RESULTS

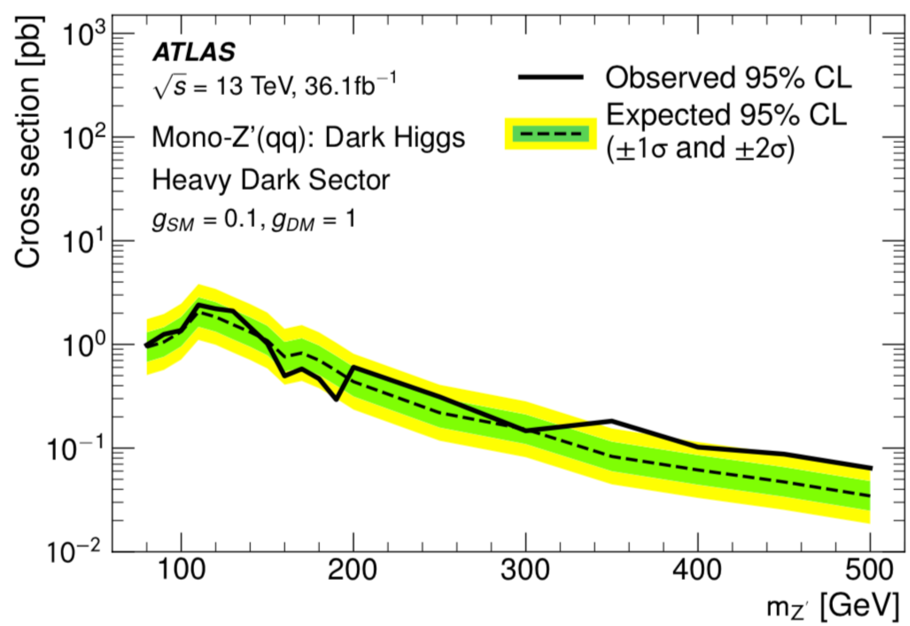
- Strategy: change the mass hypothesis in V+MET
  - For $m_{Z'} \geq 100$ GeV only resolved regime

First search for Z'+DM!









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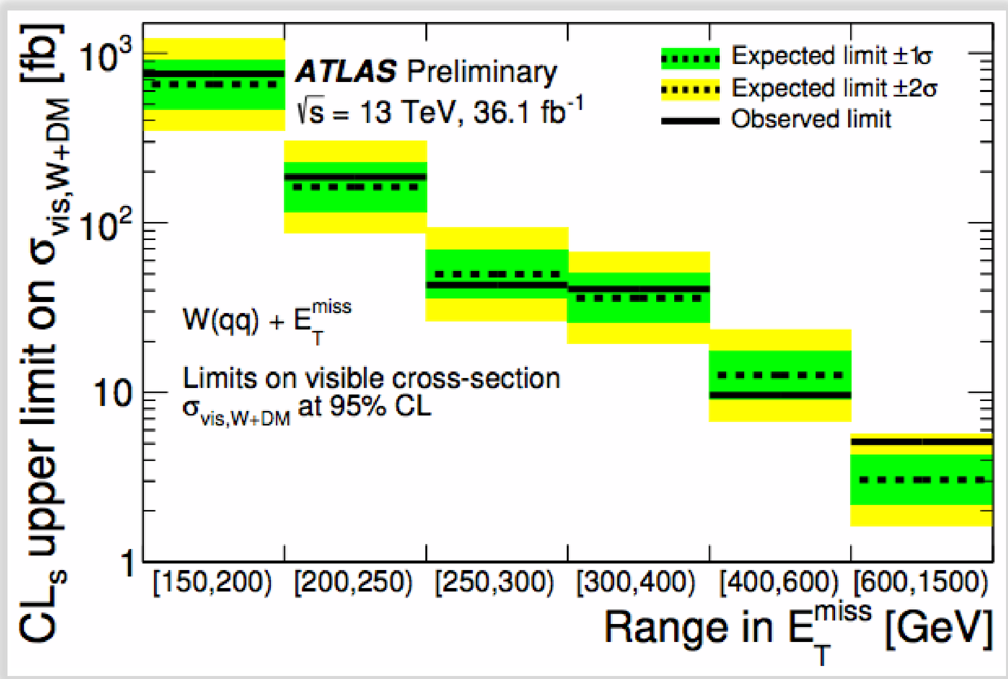
- Generic limits on W/Z + DM production:

$$\sigma_{\text{vis, W+DM}}(E_T^{\text{miss}}) \equiv \sigma_{W+\text{DM}}(E_T^{\text{miss}}) \times \mathcal{B}_{W\to q'q} \times (A \times \varepsilon)(E_T^{\text{miss}})$$

Provided in paper → limits on partonic $\boldsymbol{\sigma}_{W/Z+\text{DM}}$



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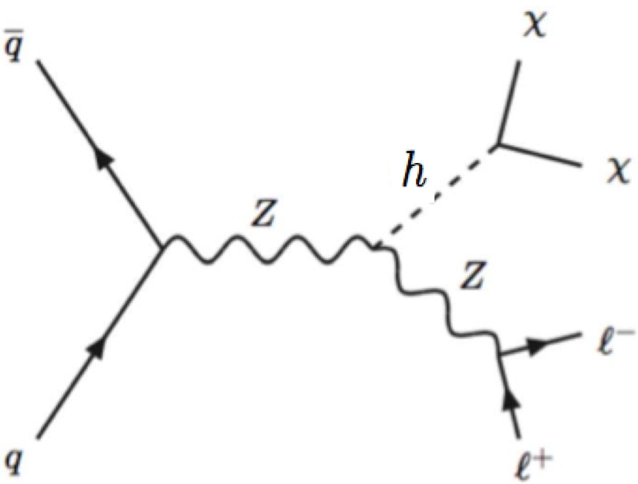
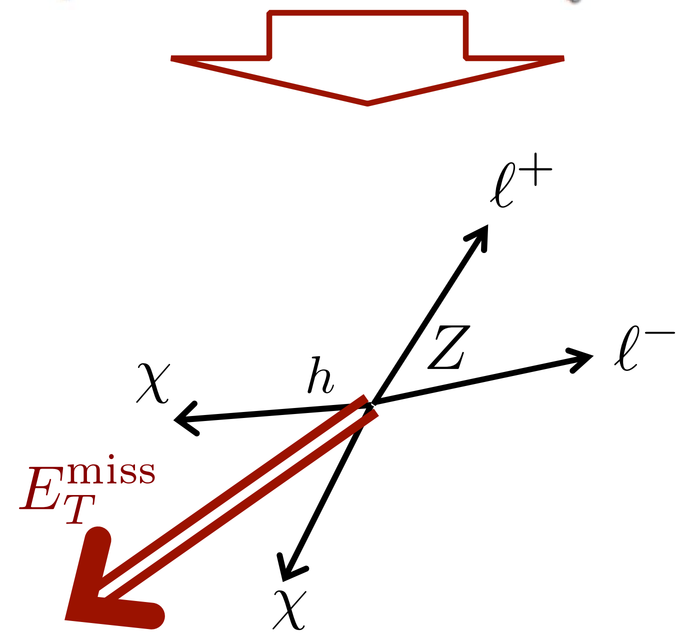
Z(ℓℓ)h(INVISIBLE) [1]

- Analysis strategy:
  - Require Z(ℓℓ) candidate
  - Look for excess in E_T^{miss} distribution:

× (ee, $\mu\mu$)

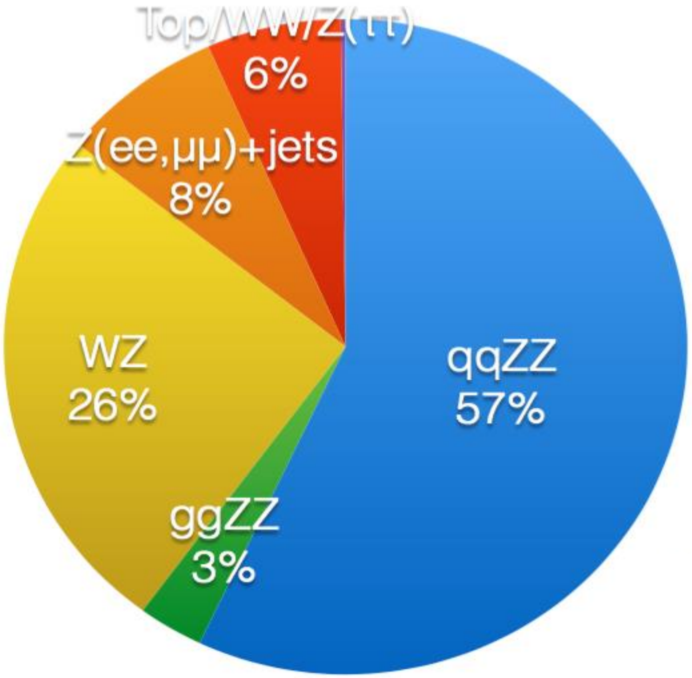




ATLAS-CONF-2016-056

Z(ℓℓ)h(INVISIBLE)

- Backgrounds:
  - Irreducible (dominant):
    - Z(ℓℓ)Z(→νν) [60%]
  - Reducible:
    - WZ(ℓℓ) [25%]
    - Z(ℓℓ)+jets [10%]
    - Rest [10%]



- Overview of signal regions and control regions:

2 lepton signal region	3 lepton control region	2 lepton control region
Signal	Constrain WZ(ℓℓ), Propagate using lepton inefficiency scale factor	Constrain Z(ℓℓ)+jets, Estimate E_T^{miss} rate from jet p_T mis-measurements

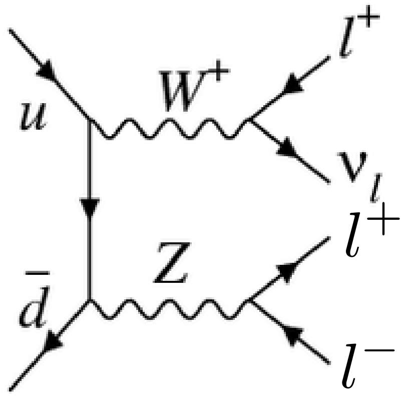
Z($\ell\ell$)h(INVISIBLE)

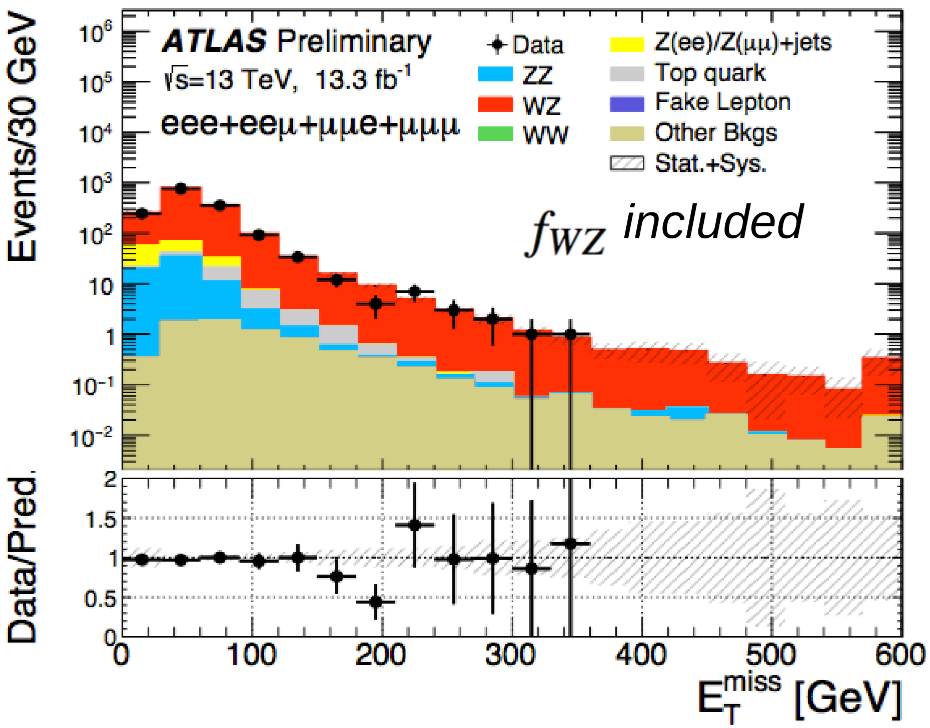
- Estimate WZ($\ell\ell$) in 3 lepton control region:

ATLAS-CONF-2016-056

$$N_{WZ}^{SR} = N_{WZ,\,MC}^{SR} \times f_{WZ}$$

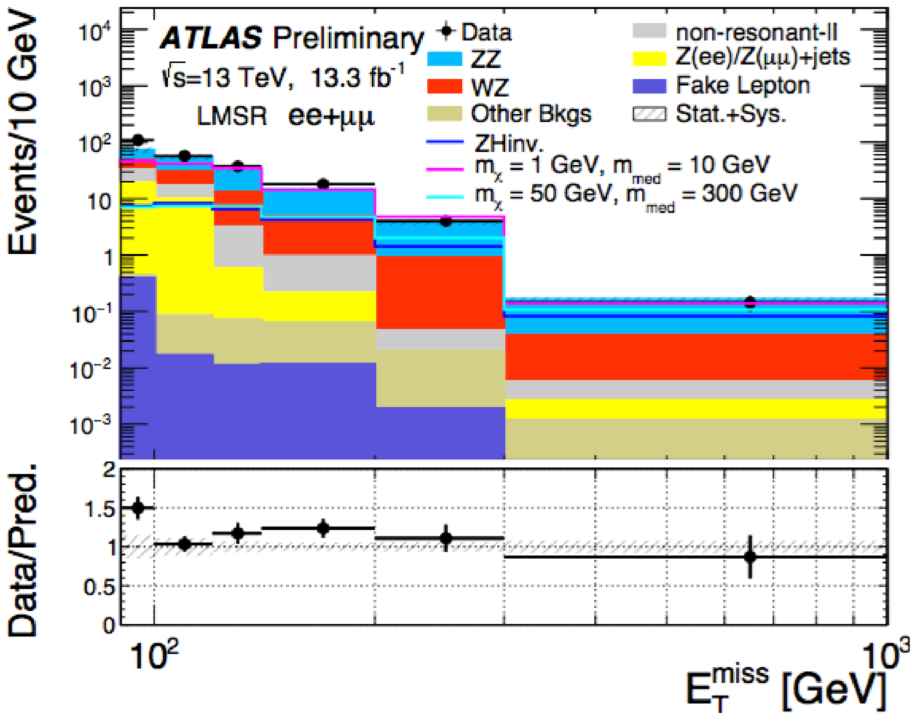
$$f_{WZ} = 1.25 \pm 0.04(\text{stat}) \pm 0.05(\text{syst})$$

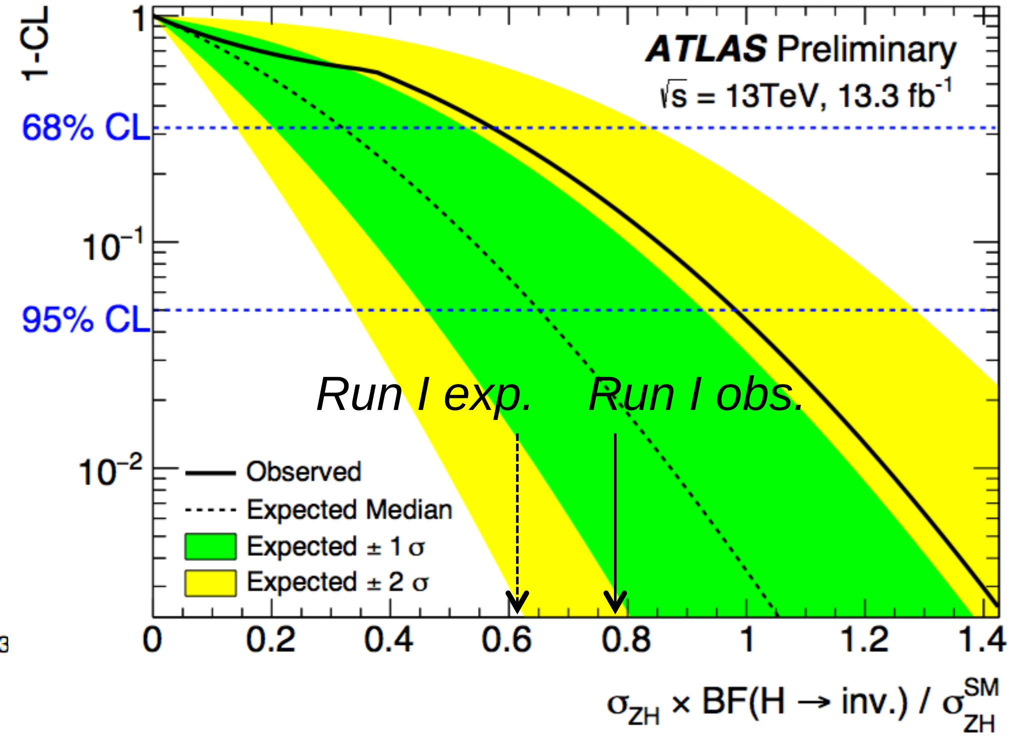




- Trigger:
  - Easy (single leptons, ε=98%)
- Selection:
  - Z mass window, no b-jets
  - topological requirements: Zh back-to-back, $|\Delta\phi(\vec{E}_T^{\text{miss}}, \text{jets})|$
- Challenge:
  - MET resolution

Z(ℓℓ)h(INVISIBLE): RESULTS





ATLAS Run I, all channels combined:
BR(h→inv) = 0.25 obs. (0.27 exp.) [1]

CMS Run I+2015 data, all channels combined:
BR(h→inv) = 0.24 obs. (0.23 exp.) [2]

[1] *JHEP11(2015)206*

[2] *JHEP 02 (2017) 135*

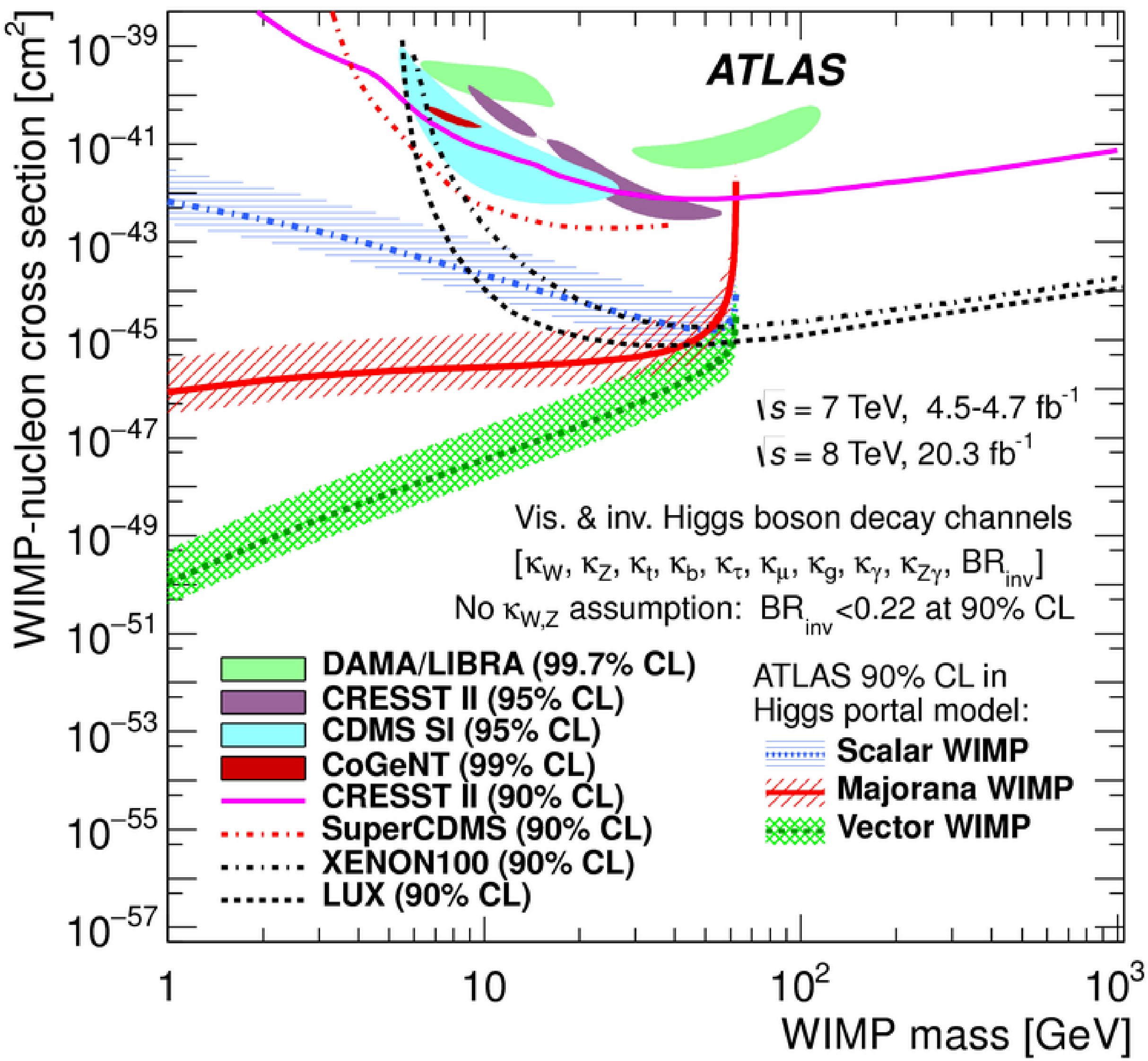
Z(ℓℓ)h(INVISIBLE): RESULTS

- Interpretation:
  - Stringent limits for

$$M_{\mathrm{WIMP}} \lesssim \frac{M_h}{2}$$

  - Complementary to direct detection experiments

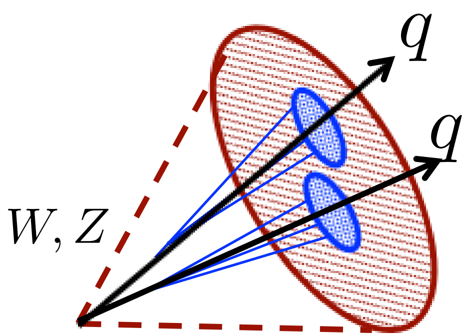
JHEP11(2015)206



H→INVISIBLE OUTLOOK (RUN 2, 140 FB^{-1})

- Improvement strategies #1 (VBF):
  - Re-optimise VBF selections in view of experimental uncertainties:
    - Jet energy scale + resolution, lepton ID, etc.
  - Lower MET threshold → dedicated VBF trigger!
  - More V+jets (QCD) MC simulations (leading systematic uncert.)
  - Improved theory predictions for V+jets

- Improvement strategies #2 (ZH, not shown):
  - Z(ll)Z(vv) background estimation
  - Lower MET threshold



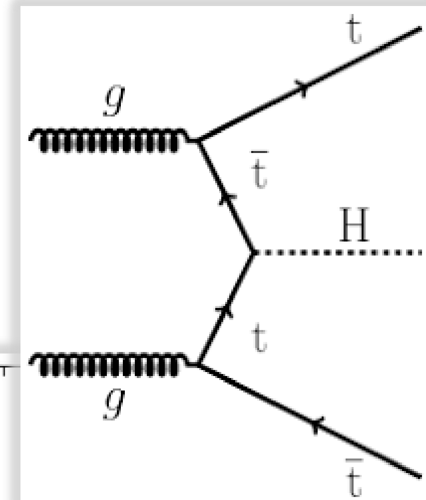
- Improvement strategies #3 (VH):
  - Benefit from improved V+jets theory for jet+MET
  - Further improve W → qq identification:
    - Include tracking information (better jet substructure resolution)
    - Design custom multivariate discriminant for boosted W → qq

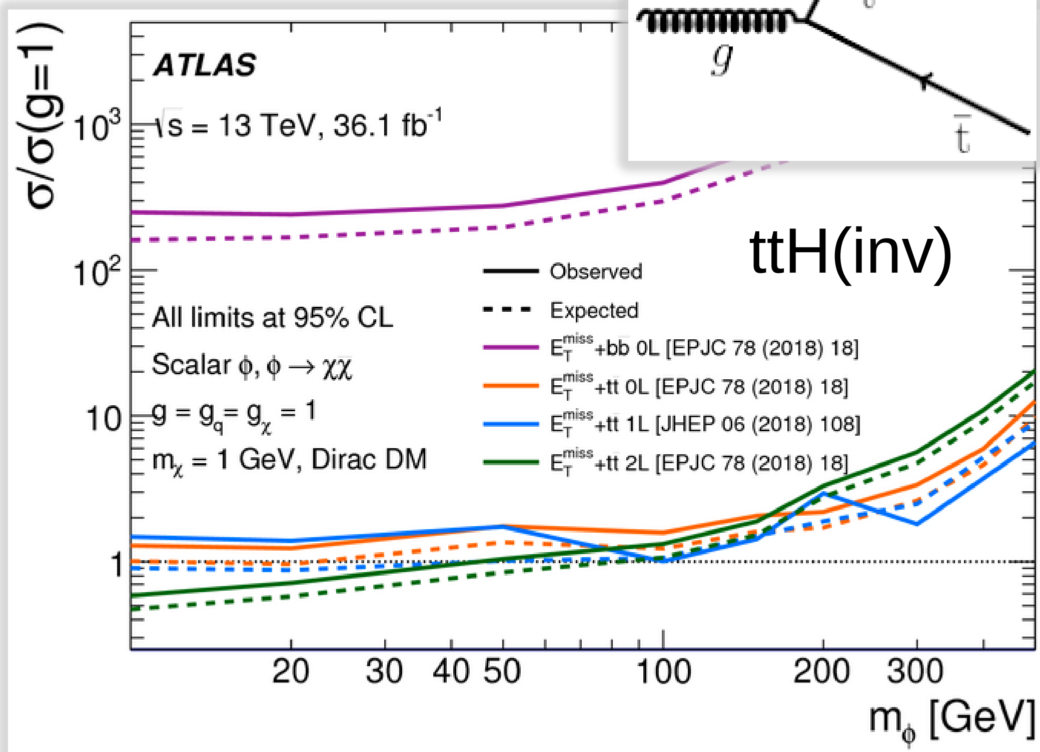
H→INVISIBLE OUTLOOK (RUN 2, 140 FB^{-1})

- Improvement for Run 2 combination (technical):
  - Orthogonality by construction
  - Design analyses with future combo in mind
  - More coherent treatment of systematic uncertainties
- Improvement for Run 2 combination (more channels):
  - VBF H(inv)
  - Z(ll)H(inv)
  - V(qq)H(inv)
  - ttH(inv)
  - ggF H(inv)

Aim for single-digit expected limit on $B_{H\to inv}$!

Evidence for $B_{H\to inv}$!= 0 possible if same central value





- Orthogonality checks
  - < 1% overlap (use sensitivity-ranked orthogonal selections in the future!)
- Input checks:
  - Individual analyses represented correctly
- Correlation scheme:
  - Detector uncertainties straightforward (exception: jet uncertainties)

Source	name	VBF	ZH	VH
Luminosity	Lumi	(✓)	✓	✓
Muon trigger	MUON_EFF_TrigStatUncertainty	✓	✓	–
Muon trigger	MUON_EFF_TrigSystUncertainty	✓	✓	–
Muon isolation	MUON_ISO_STAT	✓	✓	–
Muon isolation	MUON_ISO_SYS	✓	✓	✓
Muon reconstruction	MUON_EFF_STAT	✓	✓	✓
Muon reconstruction	MUON_EFF_SYS	✓	✓	✓

...

  - Theory uncertainties “tricky”
    - Lots of talking to analysers + deciphering nuisance parameter names
- Combination with Run 1 results → more detective work

arXiv:1904.05105

VBF Higgs → invisible: Systematic uncertainties

Source	$\mathcal{B}_{\text{inv}}$ improve. [%] using all m_{jj} bins		Yields, α changes (%) in $1<m_{jj}<1.5$ TeV				
	Δ	visual	S	B^Z_{SR}	B^Z_{CR}	α_Z	α_W
Experimental (†)							
Jet energy scale	10		12	7	8	8	6
Jet energy resol.	2		2	0	1	1	4
$E_{\text{T}}^{\text{miss}}$ soft term	1		2	2	2	2	2
Lepton id., veto	2		-	-	-	-	4
Pileup distrib.	1		3	1	2	3	1
Luminosity	0		2	2	2	-	-
Theoretical (‡)							
Resum. scale	1		-	2	3	0	2
Renorm., fact.	2		-	20	19	1	2
CKKW matching	4		-	2	3	1	5
PDF	0		1	1	2	1	1
3^{rd} jet veto	2		7	-	-	-	-
Statistical							
MC sample (★)	12		4	5	9	10	9
Data sample	21		6	5	12	12	6
Combined							
All † sources	17						
All ‡ sources	10						
Combine †, ‡	28						
Combine †, ‡, ★	42						