



Veronica Fabiani

*on behalf of the
ATLAS collaboration*

SEARCH FOR DARK MATTER IN MONO-H(BB) FINAL STATES IN ATLAS

12th March 2019

La Thuile 2019 - Les Rencontres de
Physique de la Vallée d'Aoste

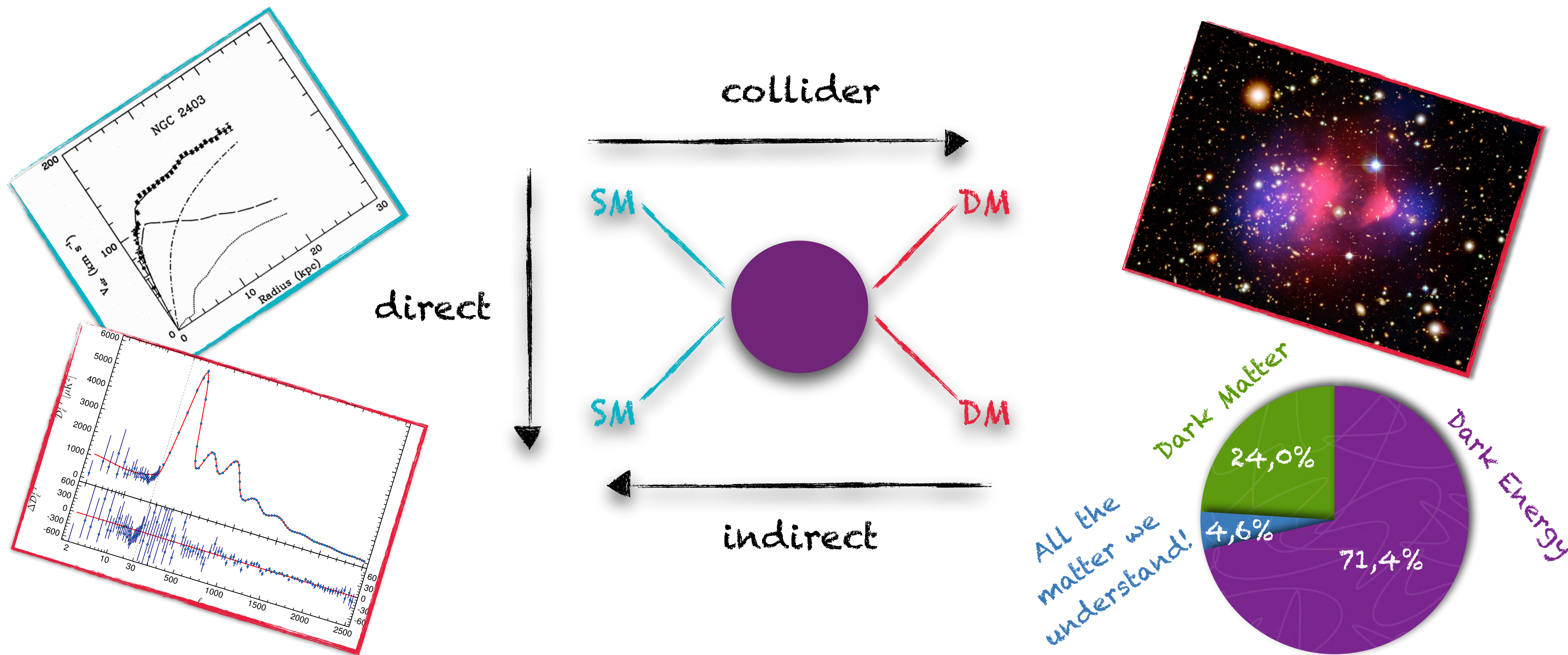


Radboud Universiteit



DARK MATTER SEARCHES

One of main open questions left by the Standard Model (SM) is about the nature of the Dark Matter (DM).

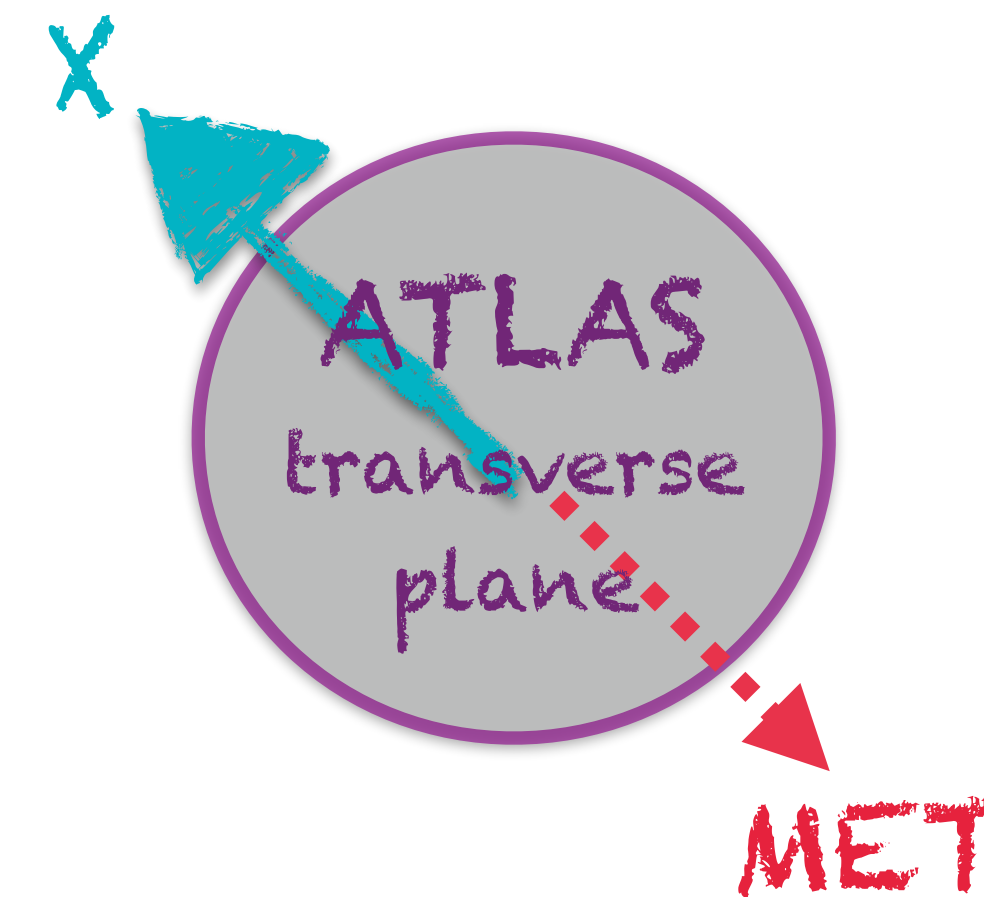
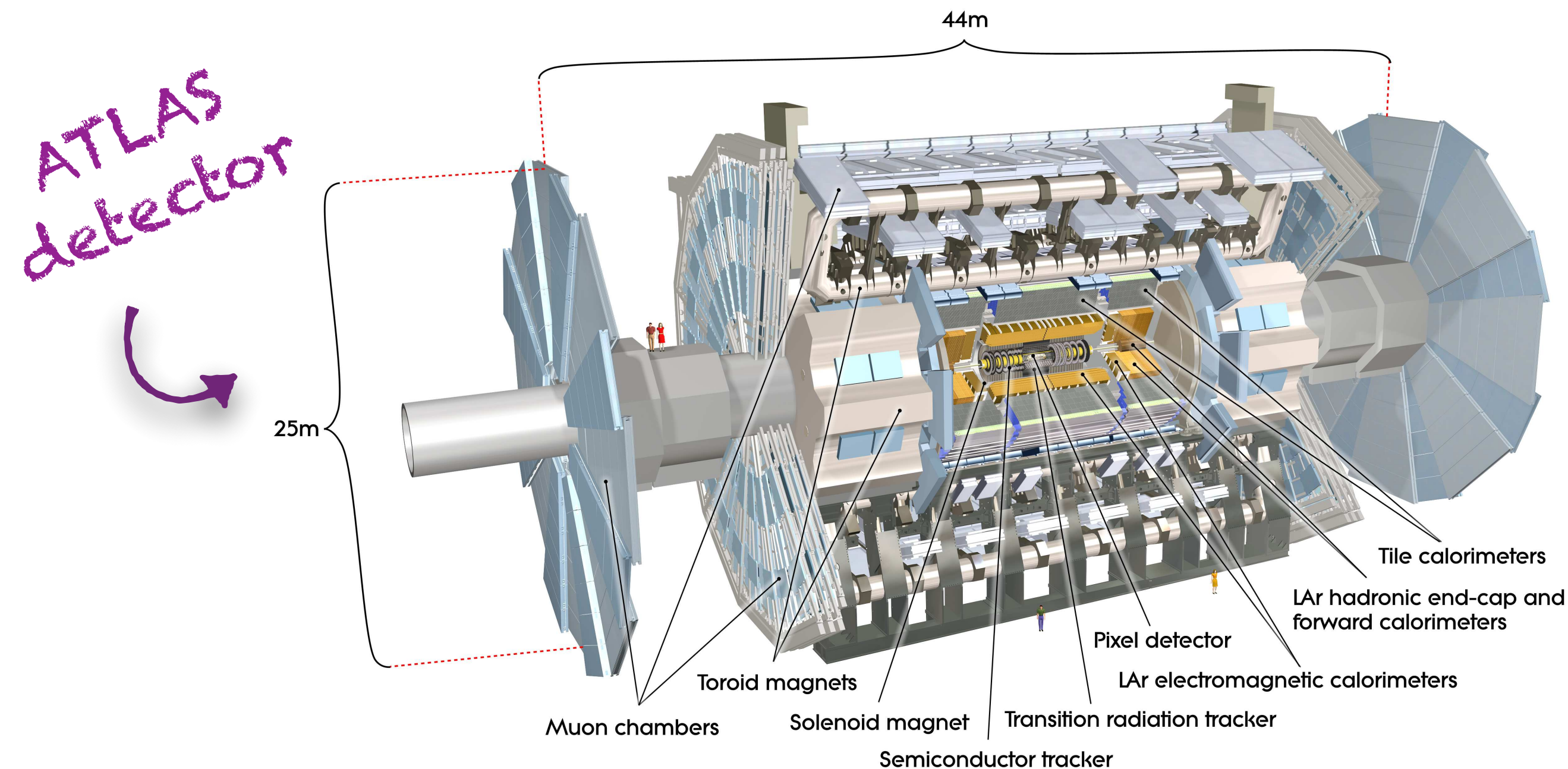


SEARCH FOR DM AT THE LHC: THE MONO-X STRATEGY

Mono-X search as a probe for DM signals:

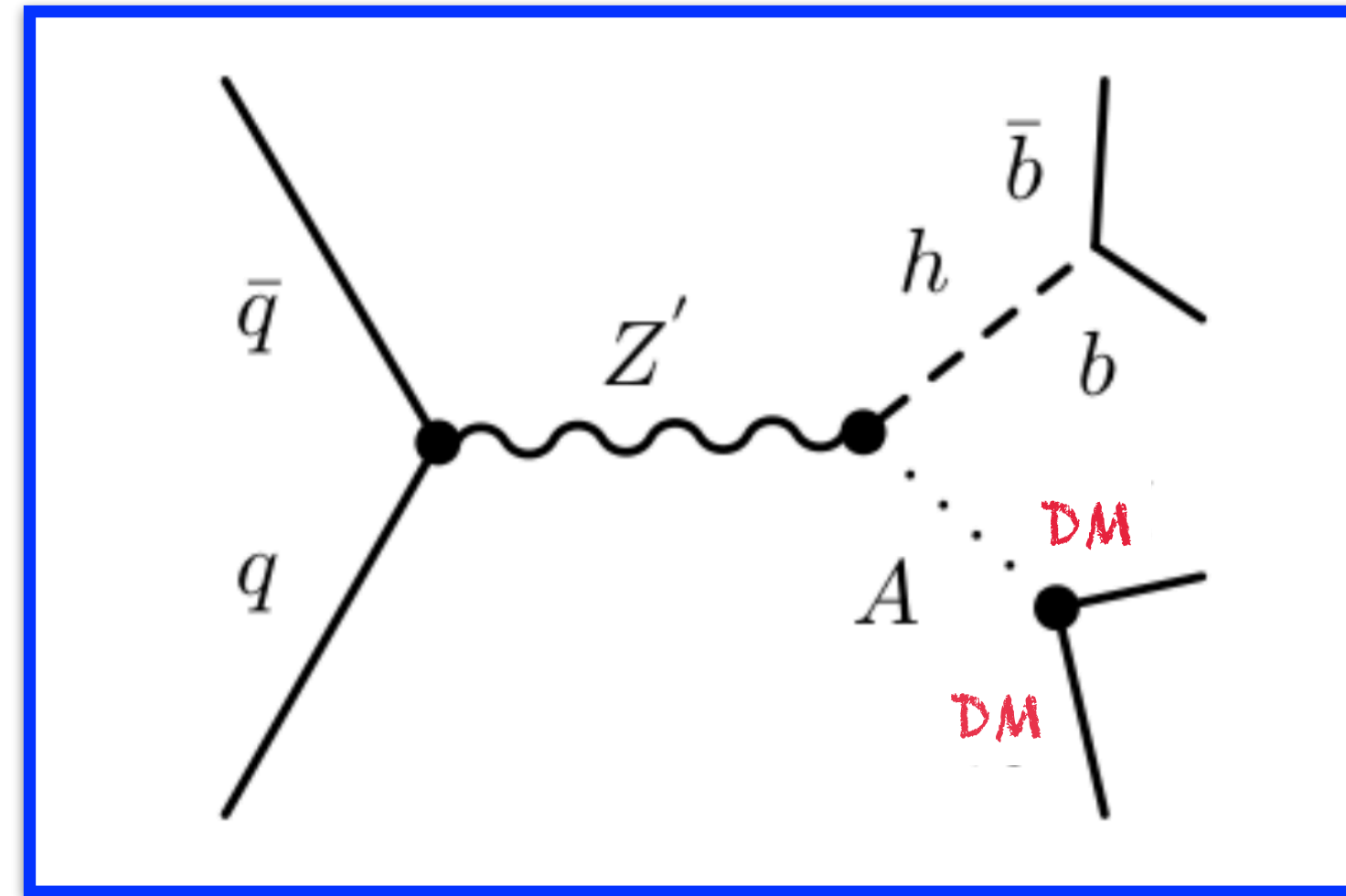
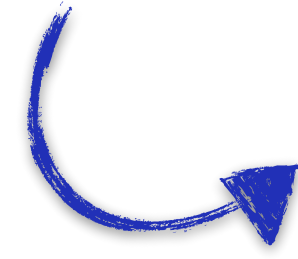
- * DM particles do not interact with the detector
- * large amount of missing transverse momentum (**MET**)
- * need an object **X** to trigger the event

Sensitive to many BSM theories:
Dark Matter, SUSY, Large Extra-Dimensions, Higgs invisible, Dark Energy, Long Lived Particles, ...



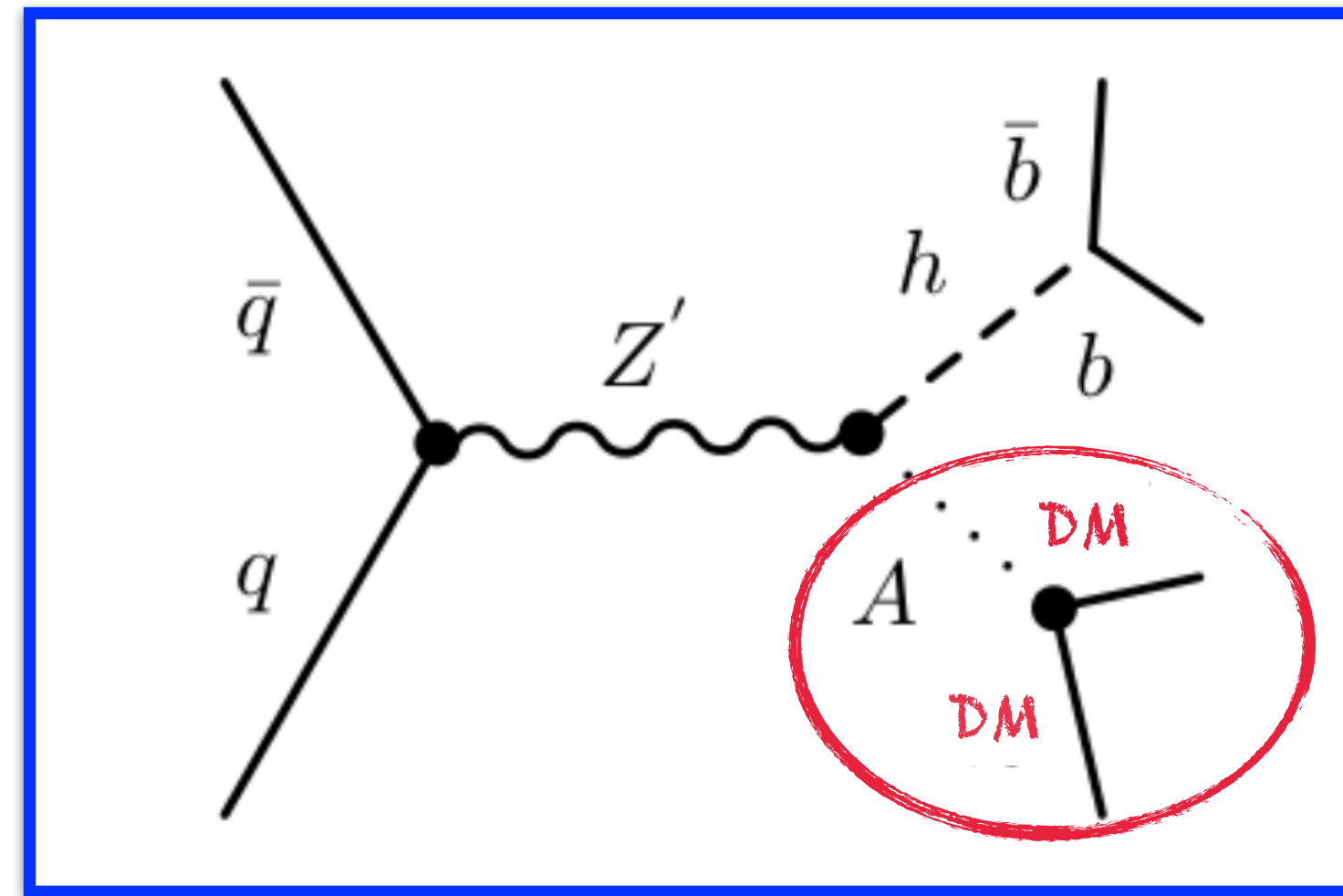
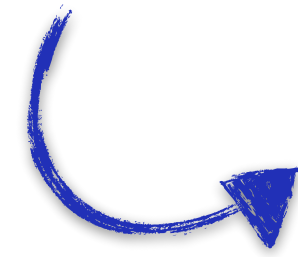
THE MONO-H(BB) CHANNEL

A Type-II two-Higgs-doublet model, which predicts a **new** mediator particle **Z'** (**Z' -2HDM**), is used as a benchmark.



THE MONO-H(BB) CHANNEL

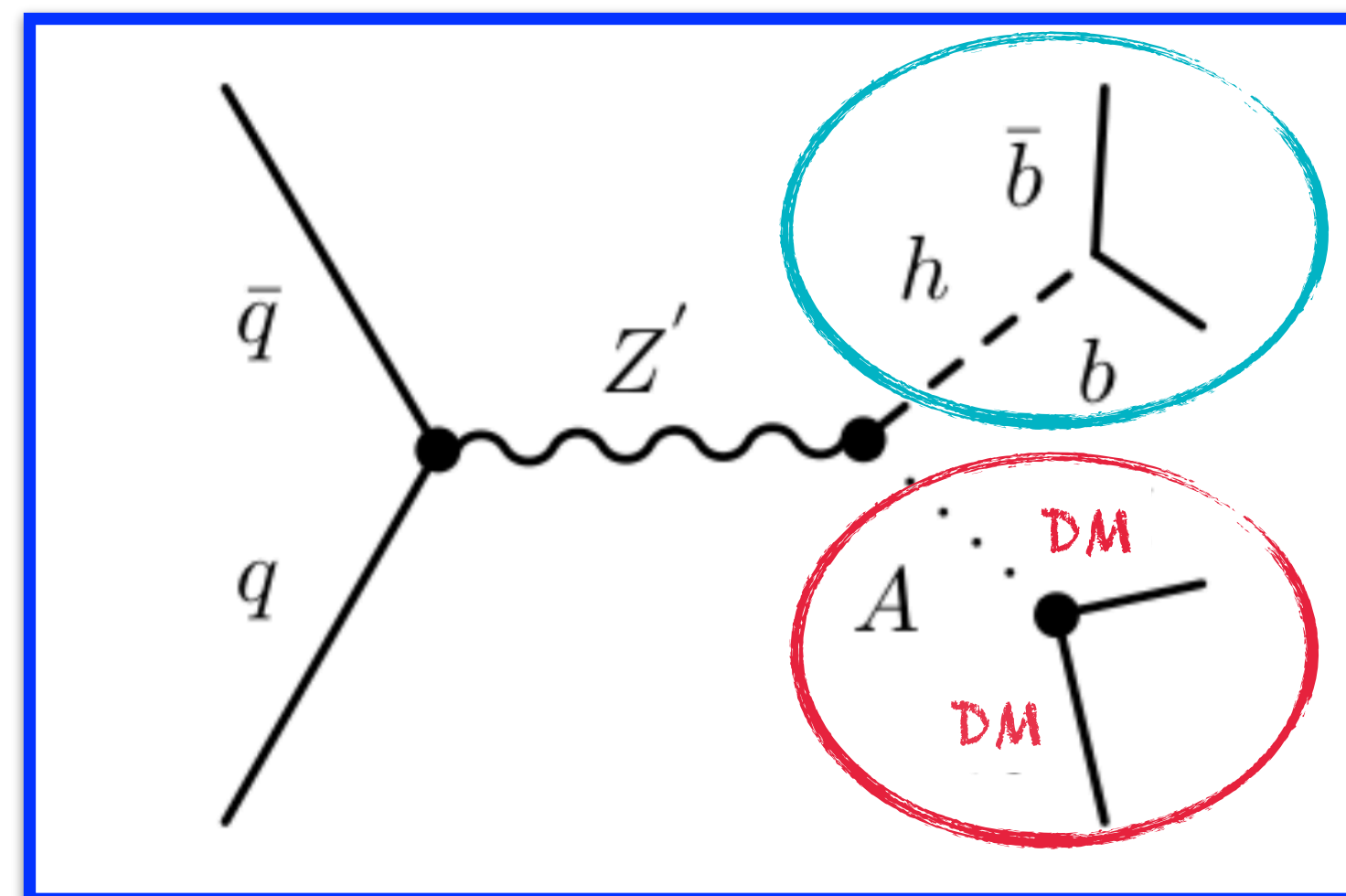
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$DM = MET$

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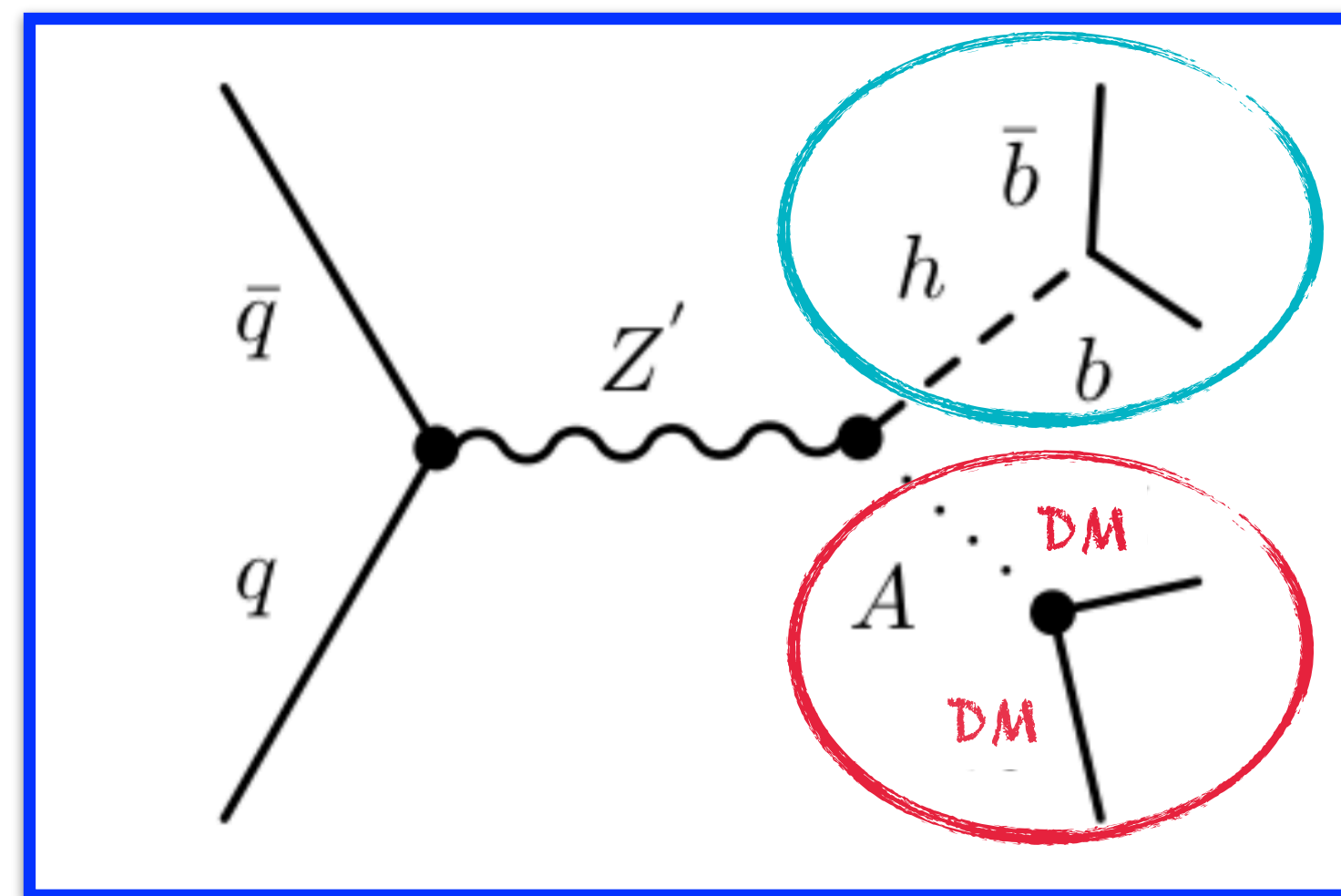
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$BR(H \rightarrow bb) \sim 57\%$
Observed last summer! 🎉
[arXiv:1808.08238](https://arxiv.org/abs/1808.08238)

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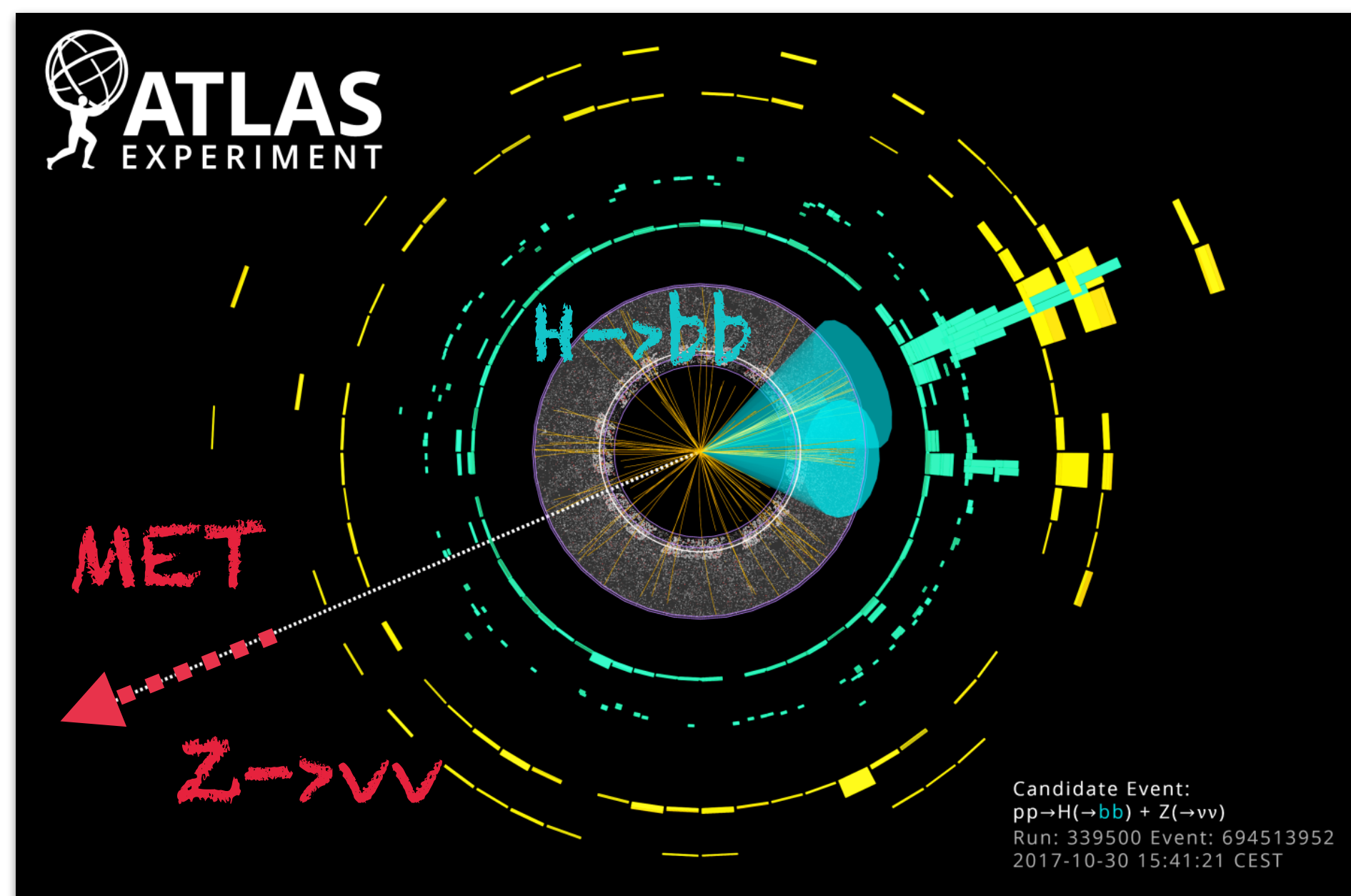
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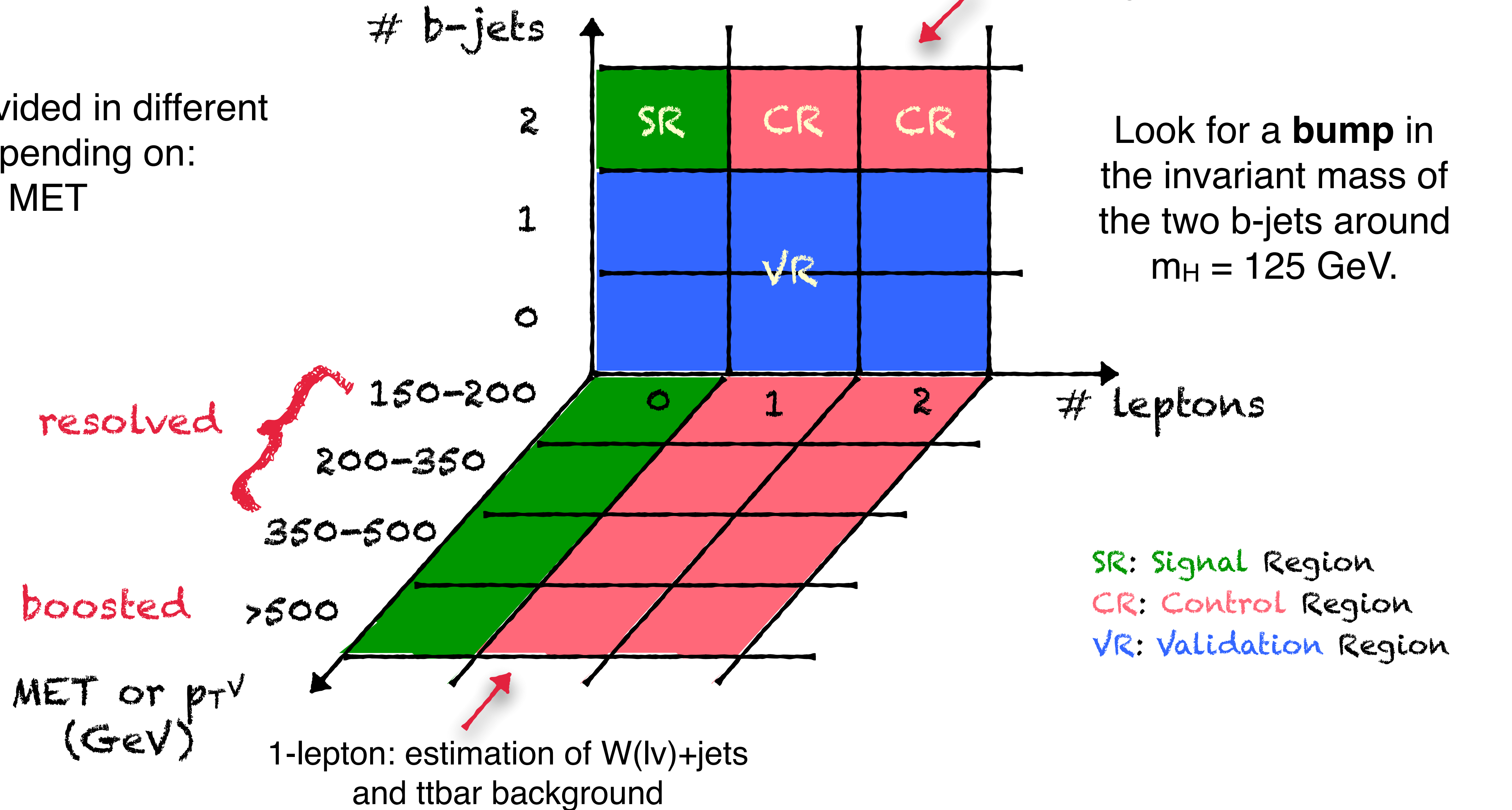
candidate Z(vv)H(bb) event:
irreducible background



THE MONO-HBB ANALYSIS

Events are divided in different categories depending on:

- amount of MET
- # leptons
- # b-jets

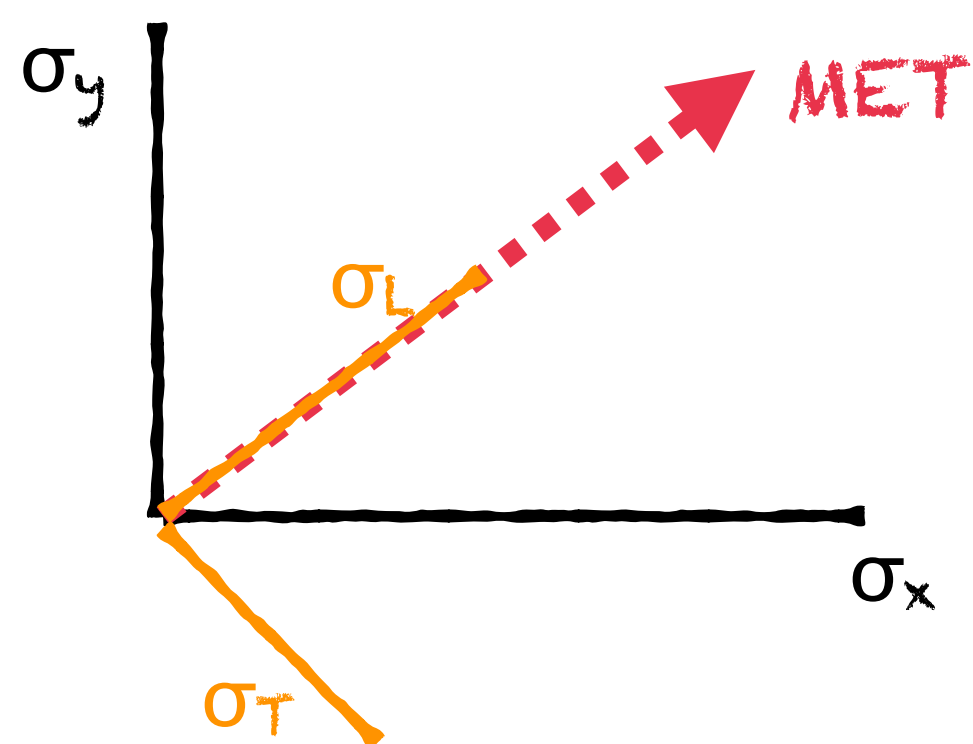


LOW MET CHALLENGE: QCD-BACKGROUND

Better distinction between events with *real* MET and events with *fake* MET, coming from mis-measured jets, thanks to the **object-based MET significance S**:

$$S = \frac{|\vec{E}_T^{\text{miss}}|^2}{\underbrace{\sigma_L^2}_{\text{total longitudinal variance}} (1 - \underbrace{\rho_{LT}^2}_{\text{correlation factor of longitudinal and transverse measurement}})}$$

ATLAS-CONF-2018-038



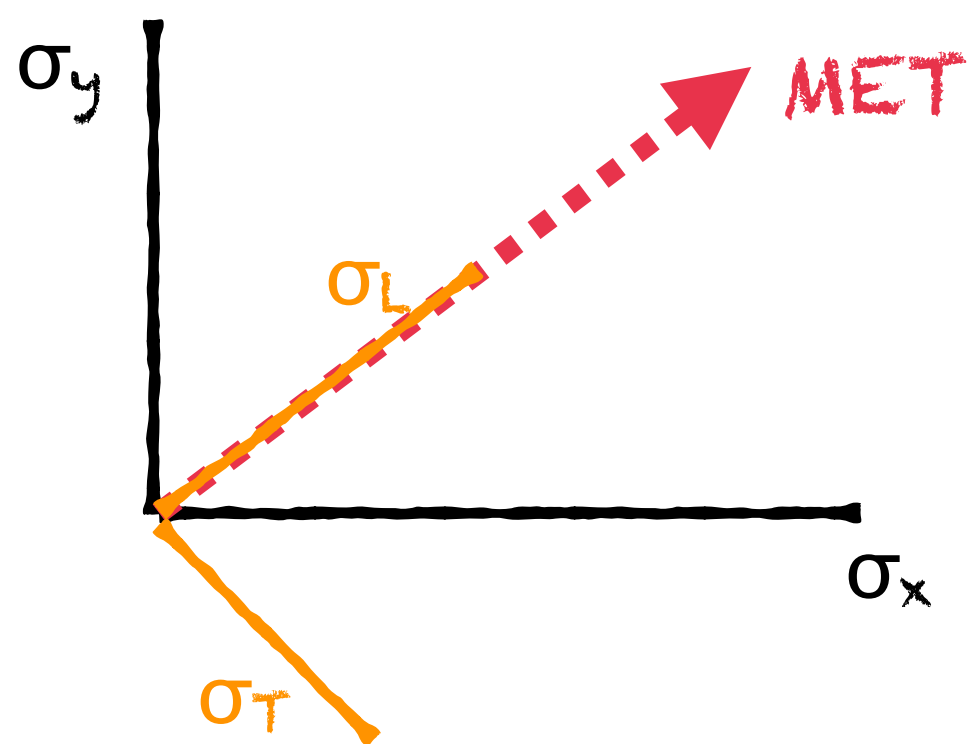
Expected resolutions and directional correlation of all objects entering in the MET reconstruction taken into account.

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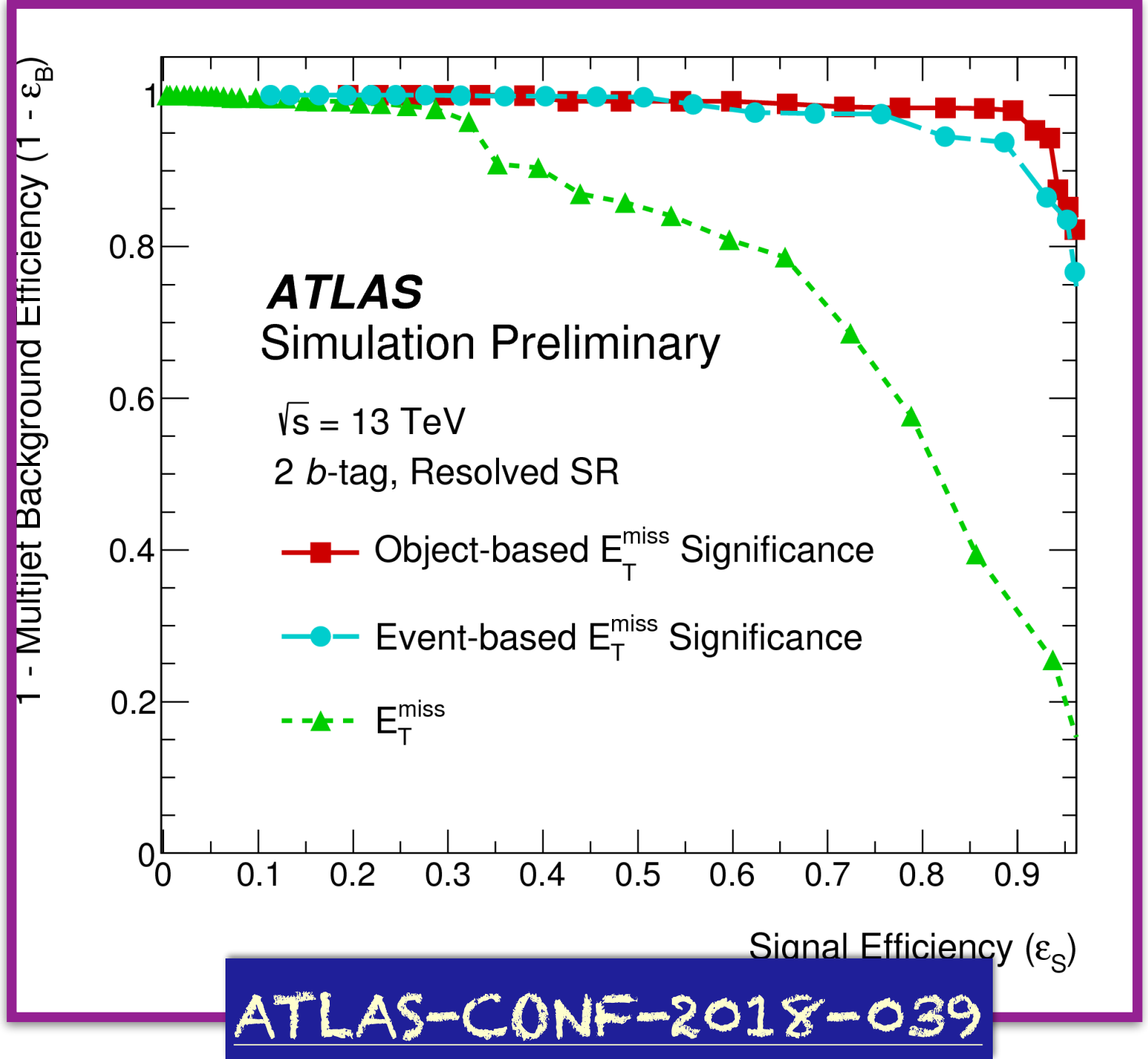
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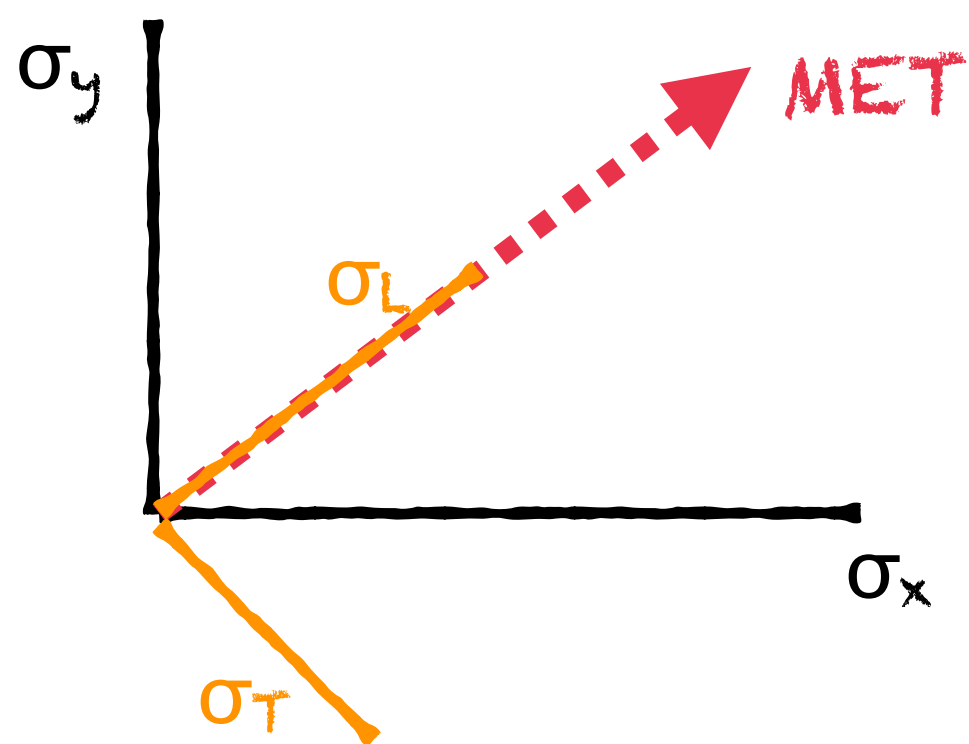
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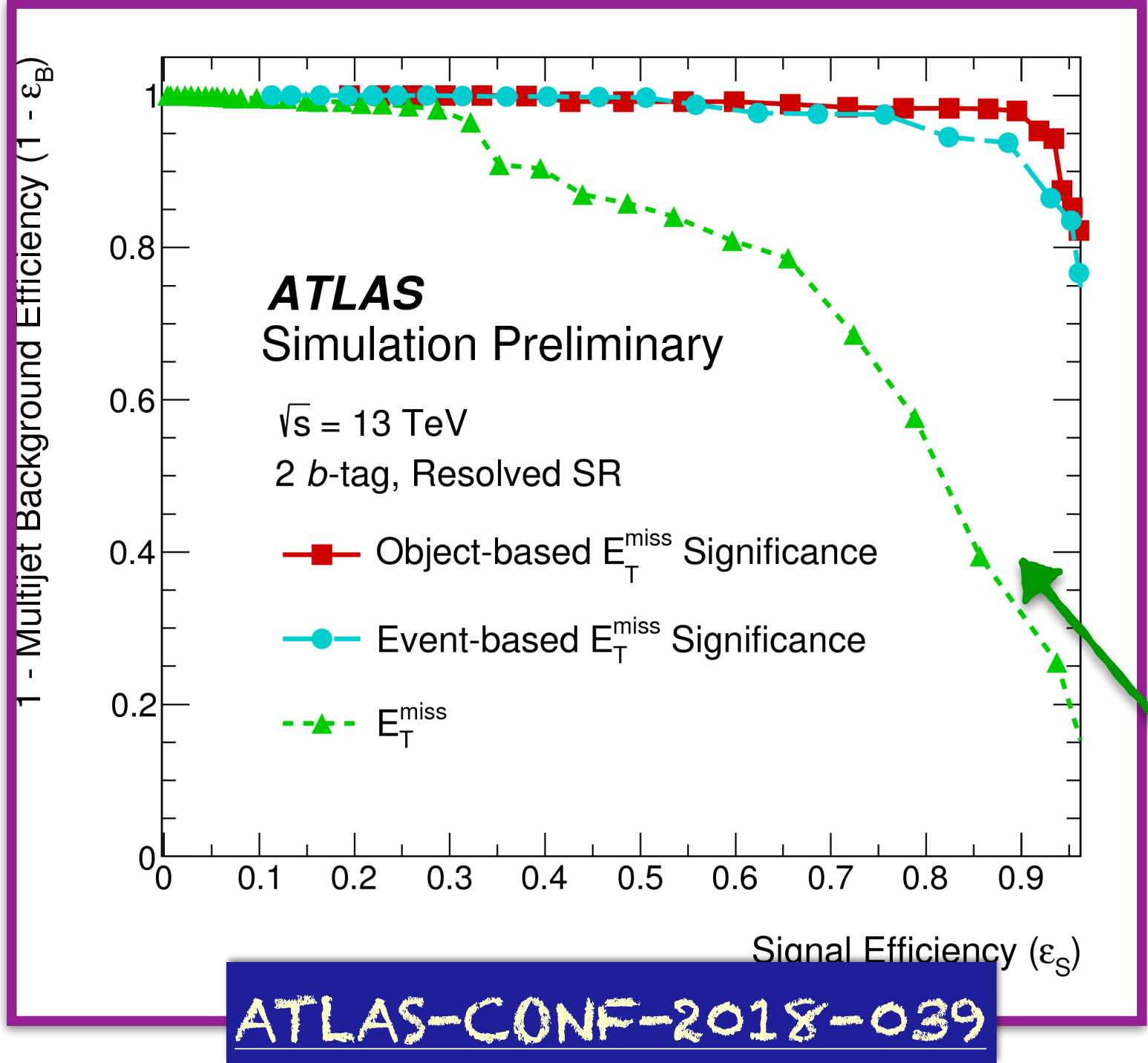
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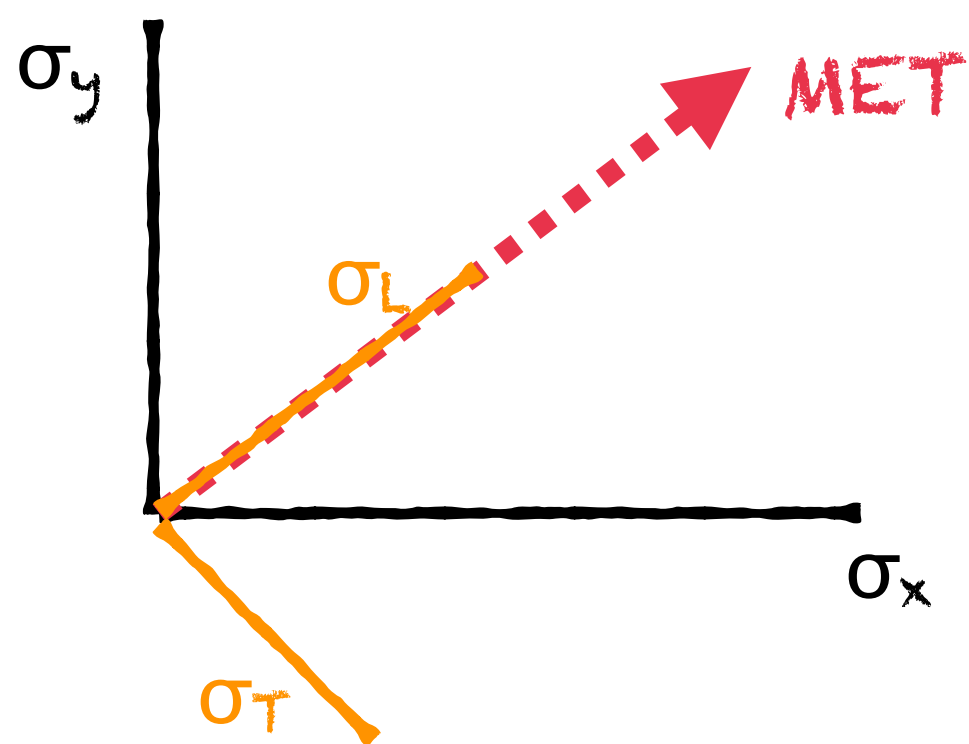


“standard”
anti-qcd cut

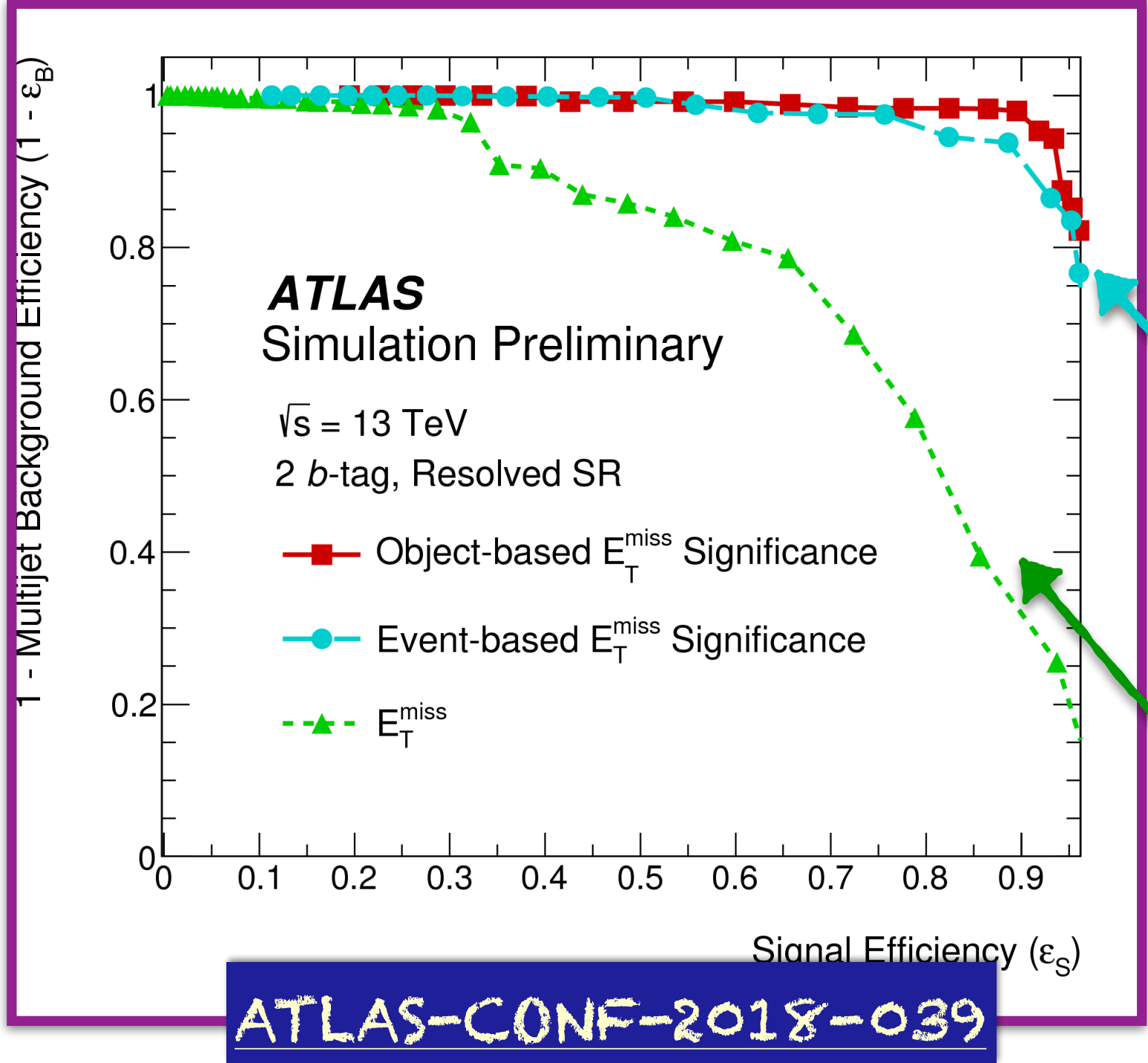
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Expected resolutions and directional correlation of all objects entering in the MET reconstruction taken into account.



ATLAS-CONF-2018-038

event-based
 $\frac{E_T^{\text{miss}}}{\sqrt{\sum E_T}}$
“standard”
anti-qcd cut

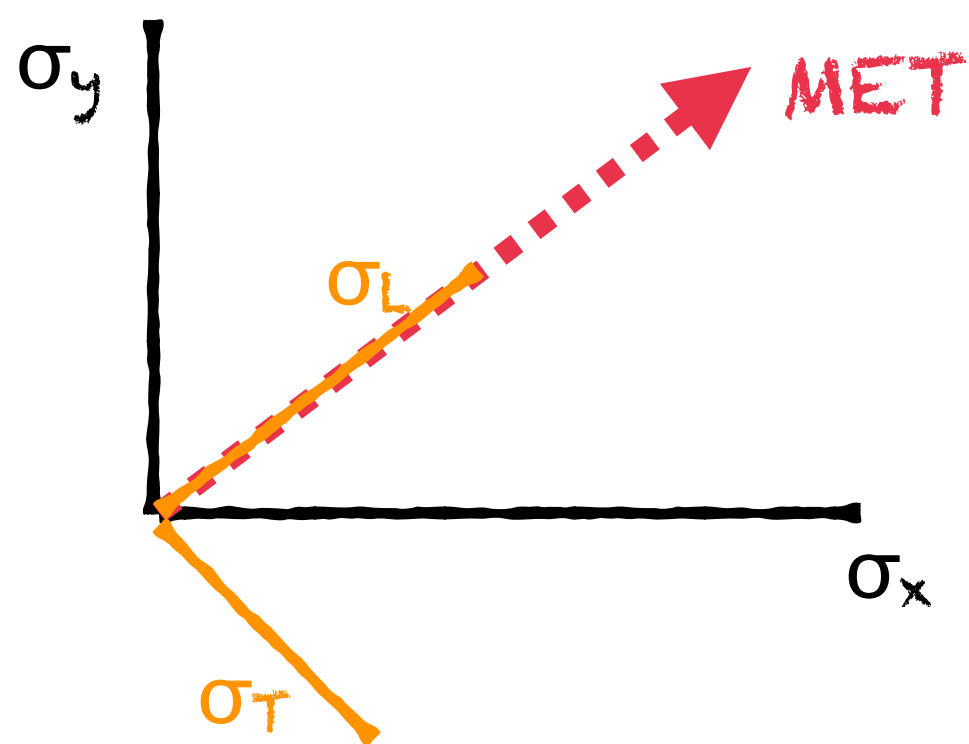
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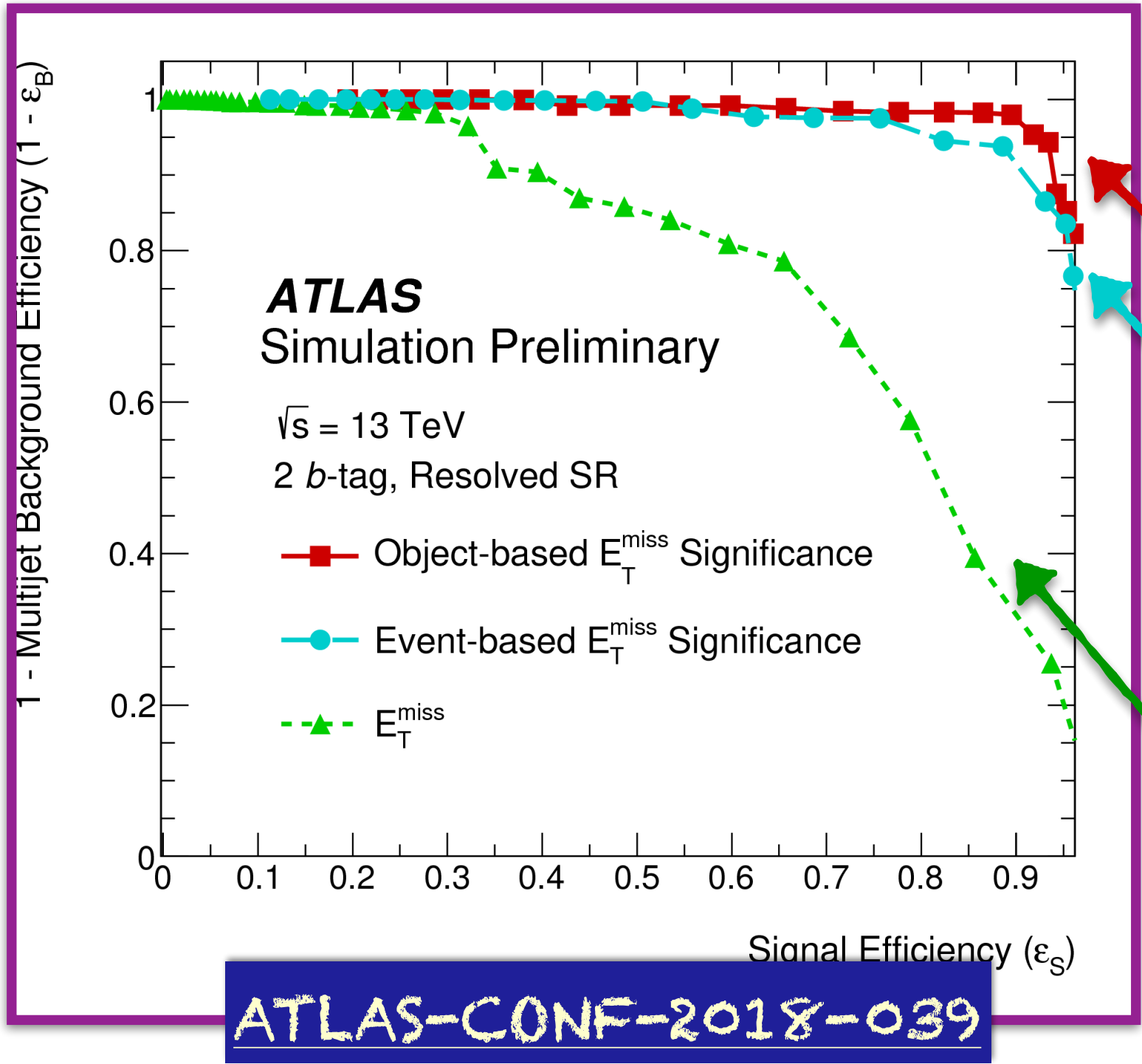
$$S = \frac{\left| \overrightarrow{E_T^{\text{miss}}} \right|^2}{\sigma_L^2 (1 - \rho_{LT}^2)}$$

total longitudinal variance

correlation factor of longitudinal and transverse measurement



Expected resolutions and directional correlation of all objects entering in the MET reconstruction taken into account.



object-based

event-based

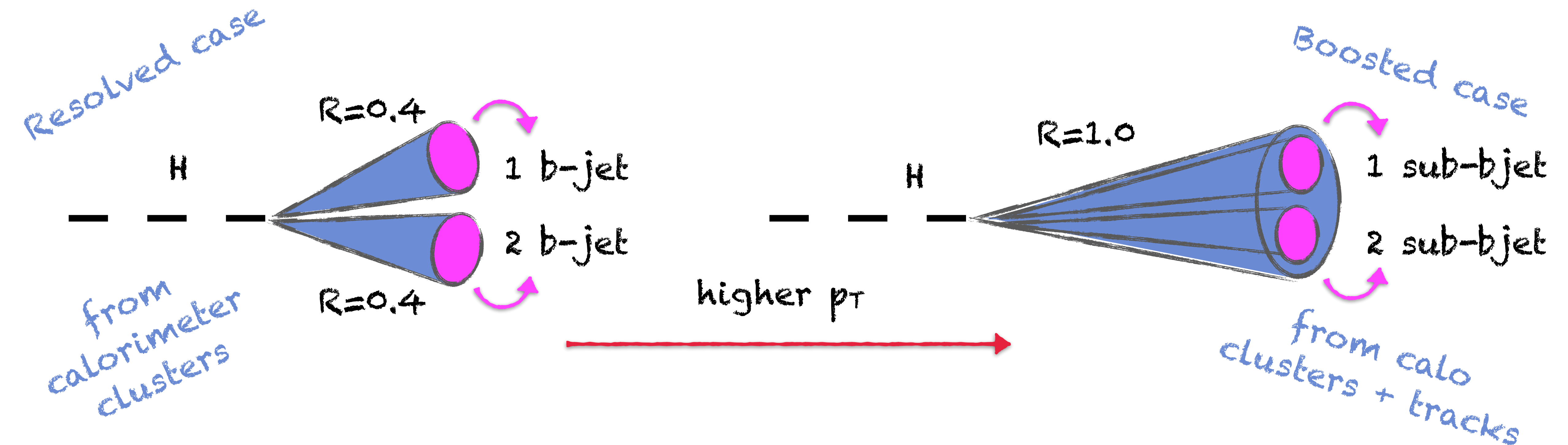
$\frac{E_T^{\text{miss}}}{\sqrt{\sum E_T}}$

“standard” anti-qcd cut

HIGH MET CHALLENGE: HOW TO IDENTIFY $H \rightarrow BB$

At high p_T , the **angular separation** between the two decay products decreases as $\sim 2m/p_T$.

For a Higgs boson ($m_H=125\text{GeV}$) with $p_T > 250\text{GeV}$, the two b-jets will be contained in a single **large-R jet** with $R < 1.0$.

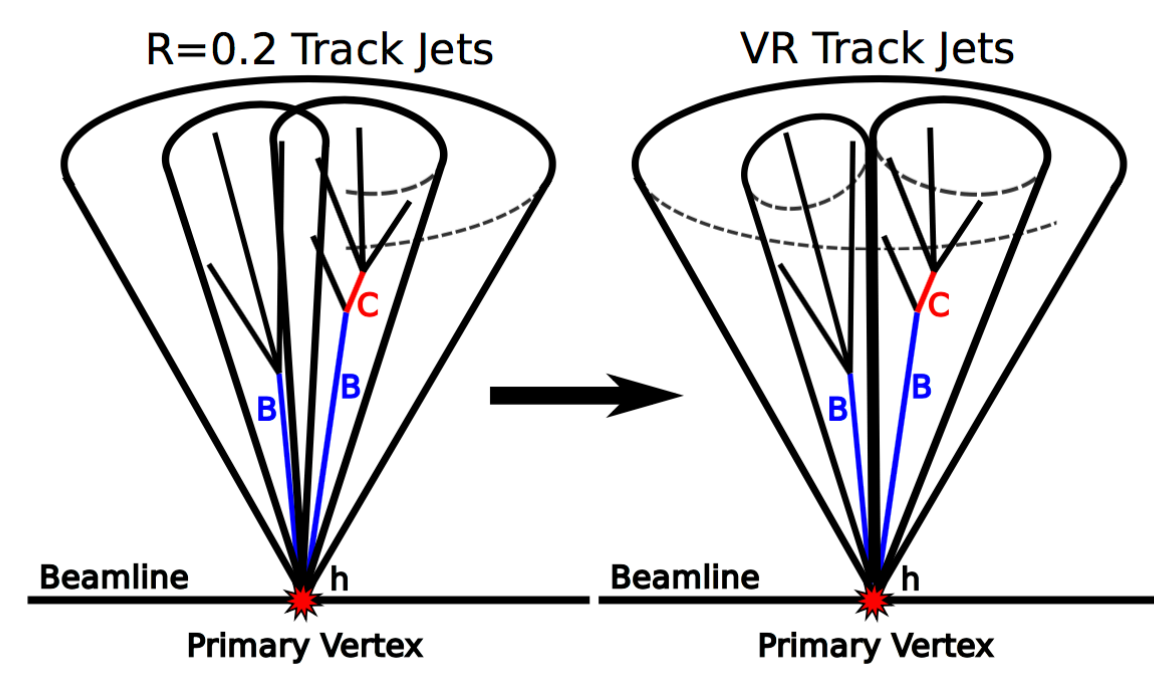


FROM FIXED-R TO VARIABLE-R TRACK JETS

ATL-PHYS-PUB-2017-010

At very high p_T , the two track jets tend to merge.

Solution: make the jet radius p_T dependent.

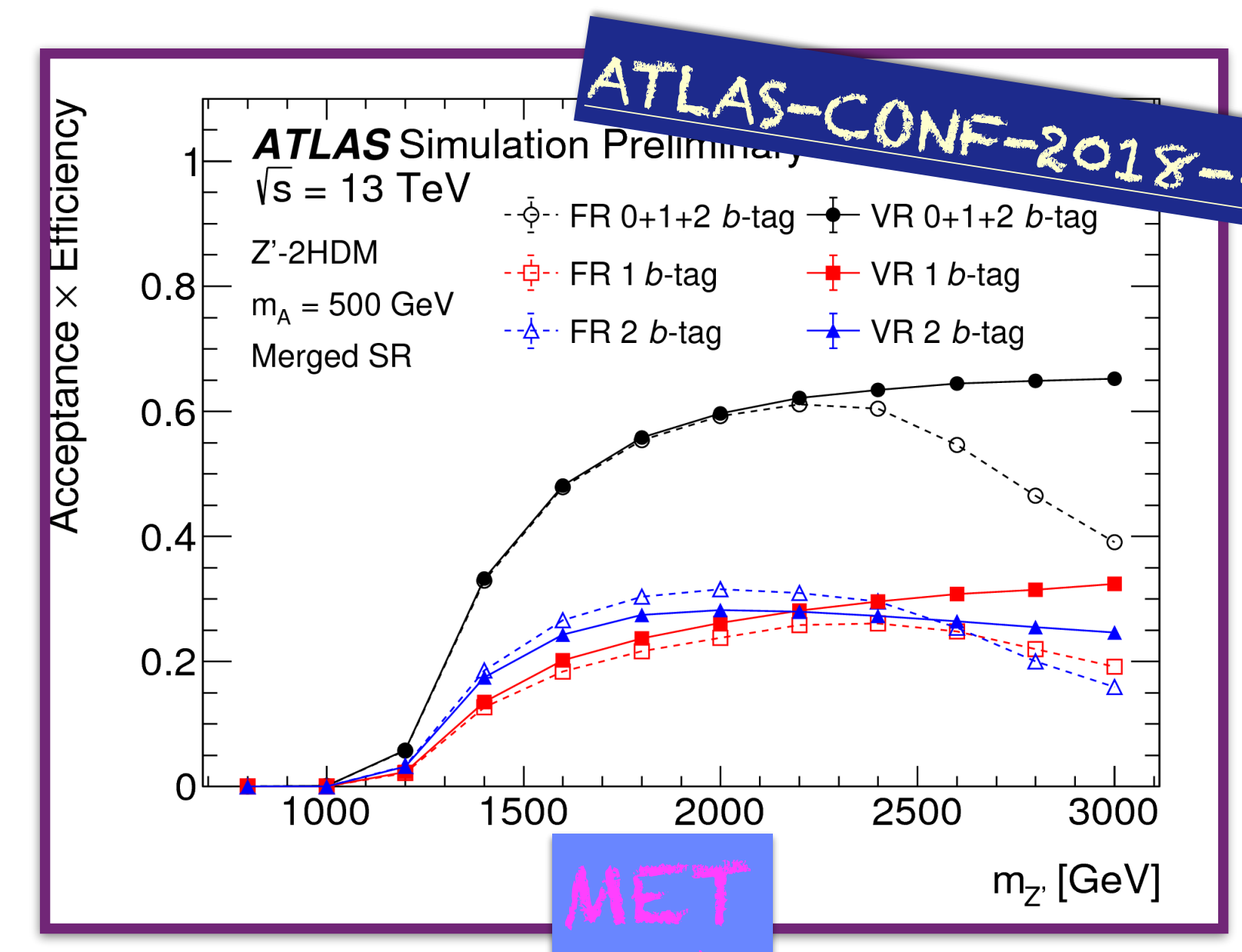
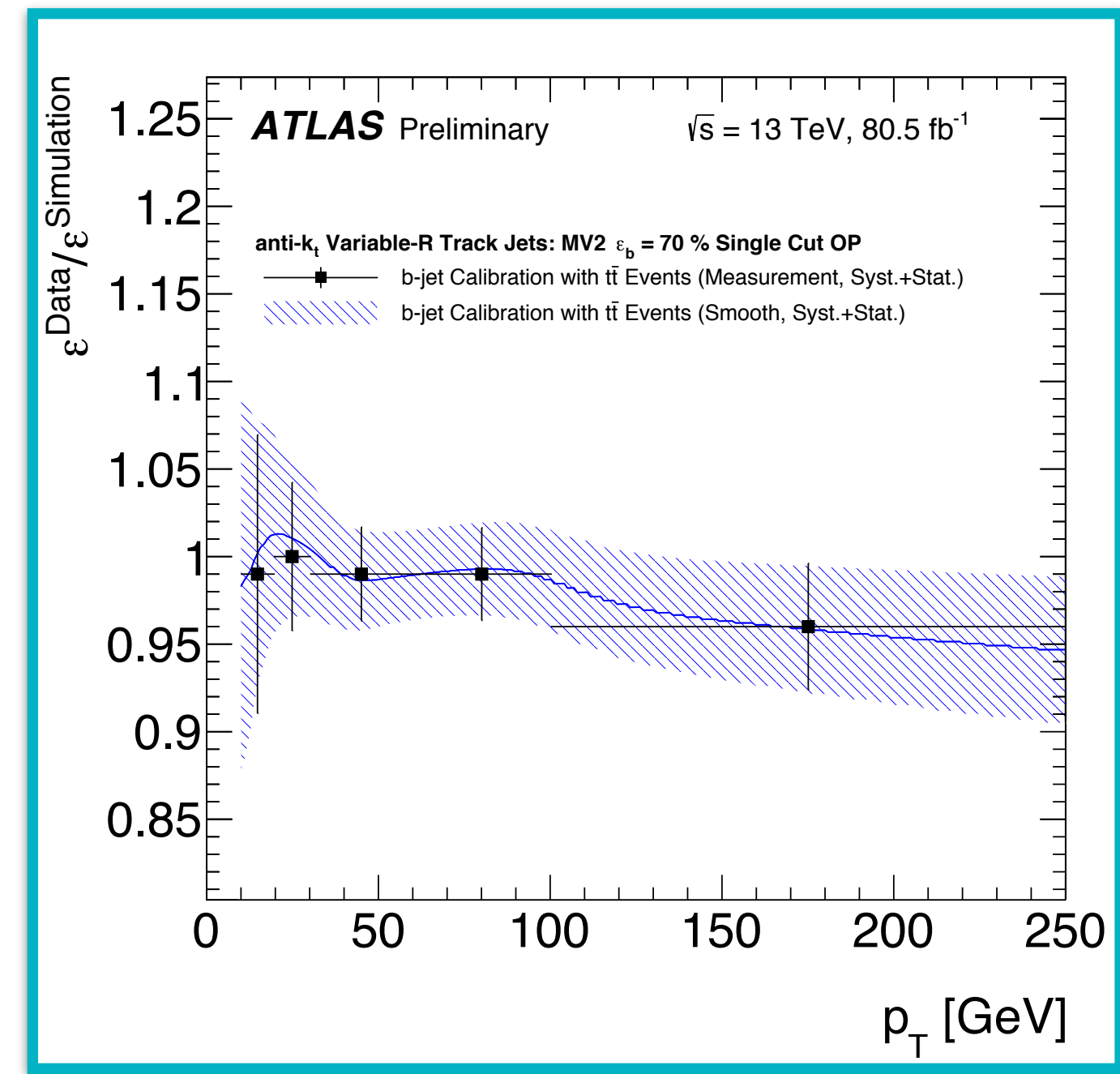
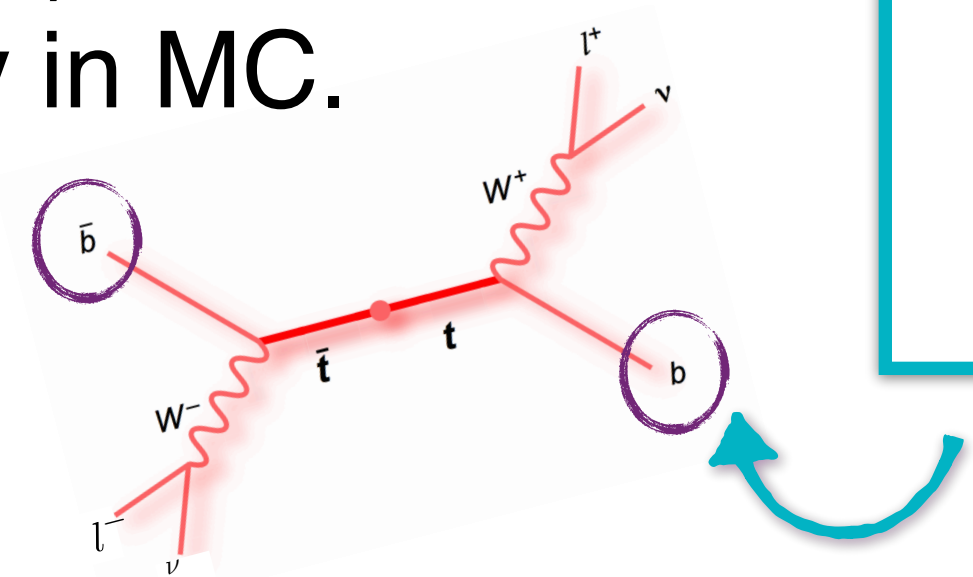


$$R \rightarrow R_{\text{eff}}(p_T) = \rho/p_T$$

$R_{\text{max}}=0.4$
 $R_{\text{min}}=0.02$
 $\rho=30\text{GeV}$

b-tagging
calibration

Extract the b-jet efficiency
in data from a clean sample
of b-jets ($t\bar{t}$ bar) and correct
the efficiency in MC.



Enhanced signal acceptance
above 2 TeV.

RESULTS

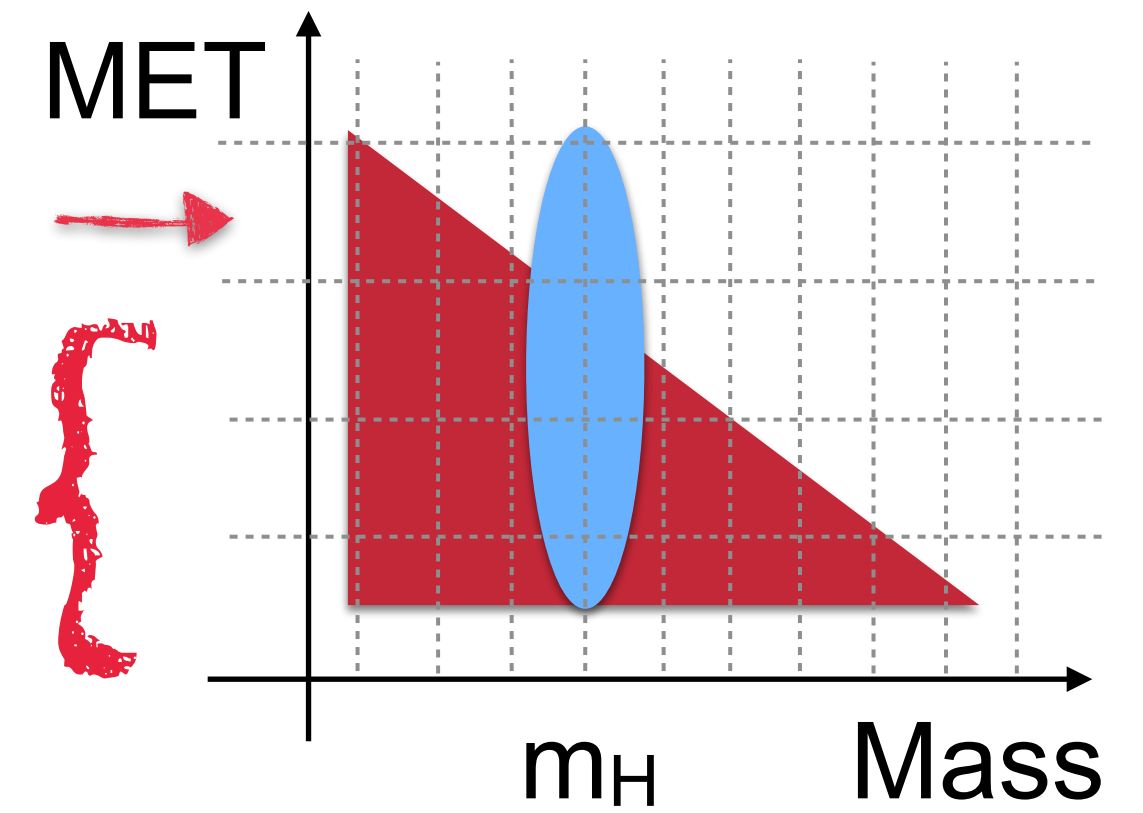
2015+16+17 data: 79.8 fb⁻¹

Performing a profile likelihood fit in all SRs and CRs:

- 0-lepton SR: m_{jj}/m_J final discriminant
- 1-lepton CR: muon charge as final discriminant
- 2-lepton CR: one single bin of m_{jj}/m_J

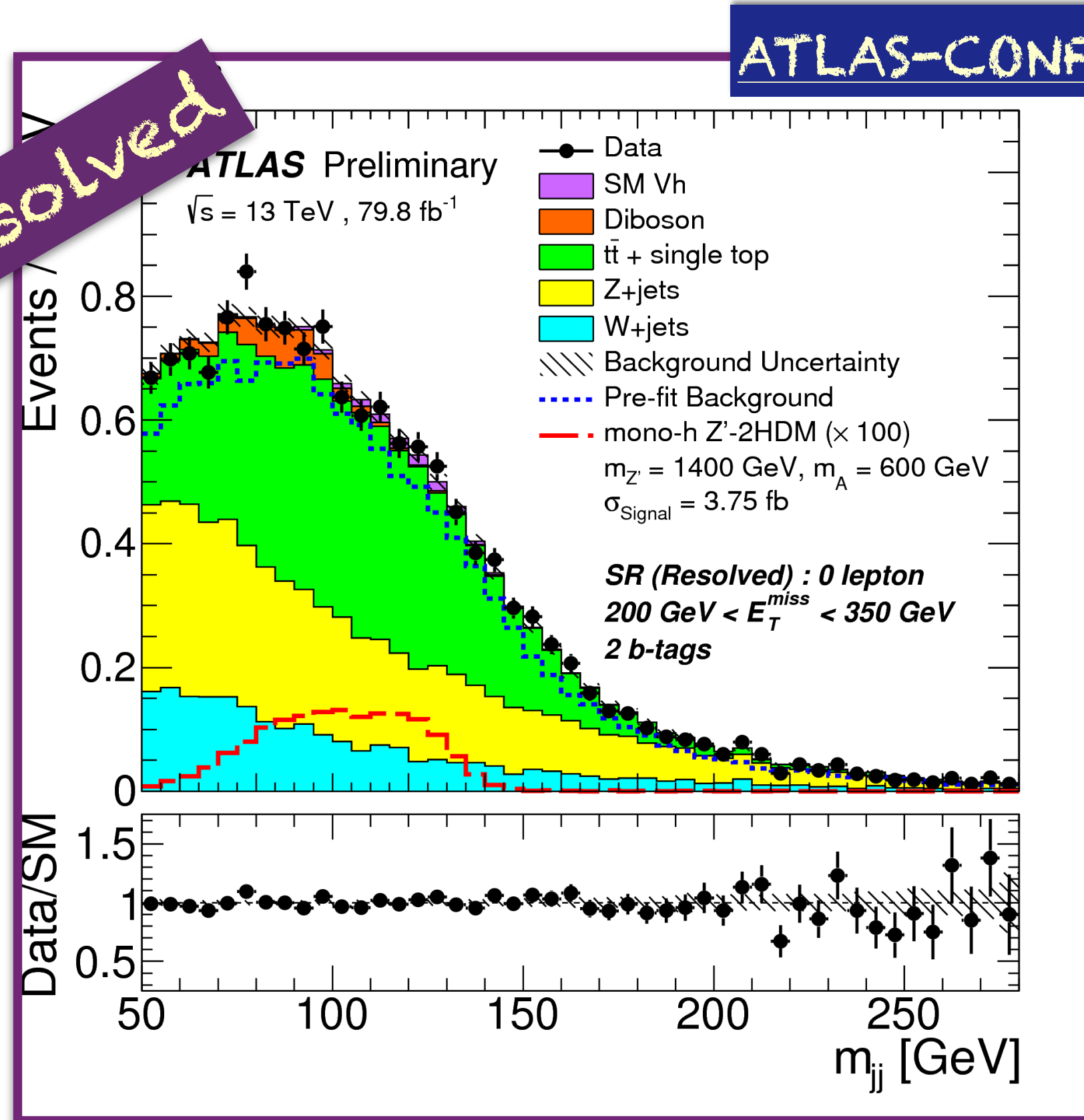
1 MET bin for boosted

3 MET bins for resolved

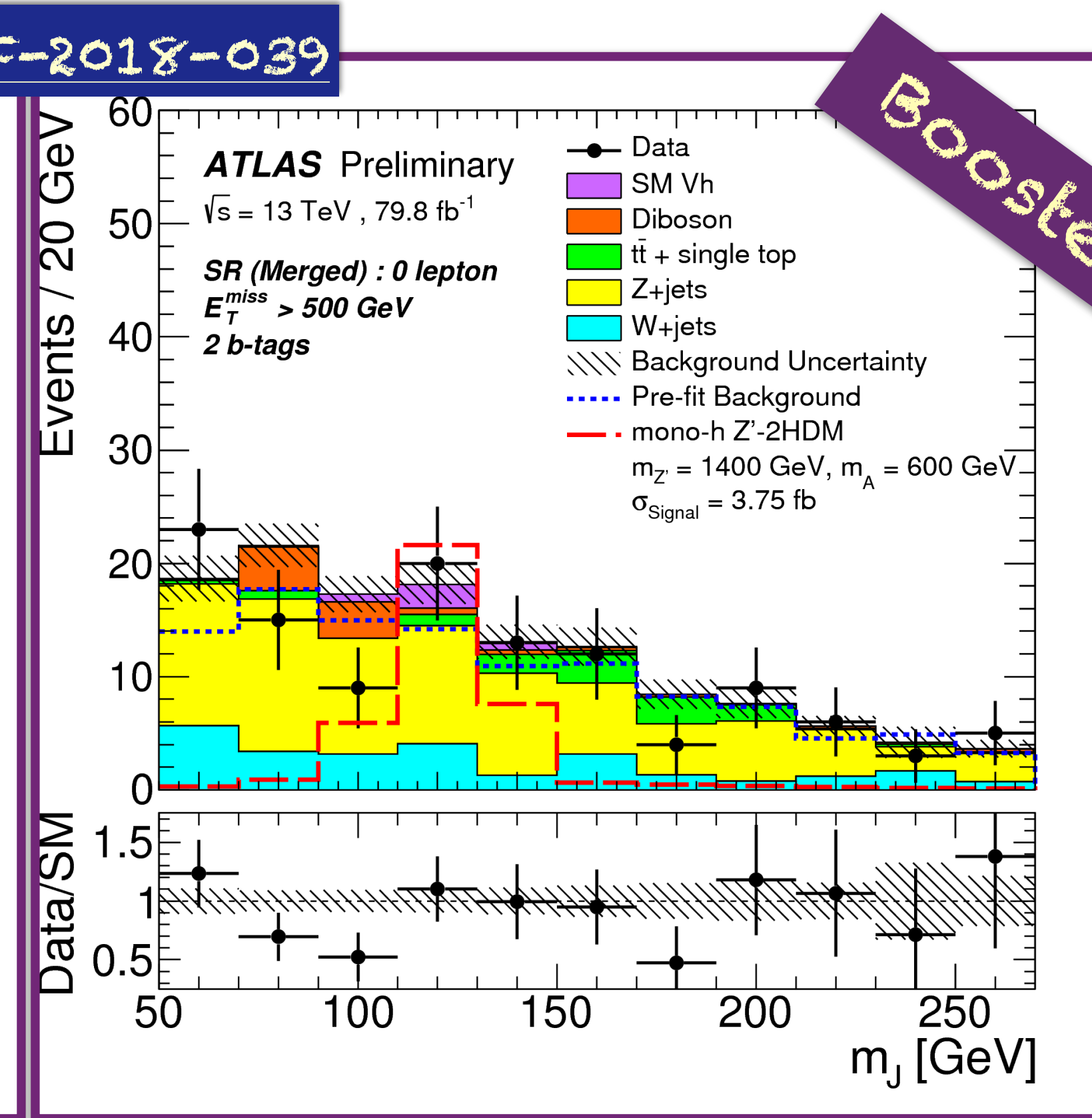


No excess observed over Standard Model prediction...

Resolved



Boosted

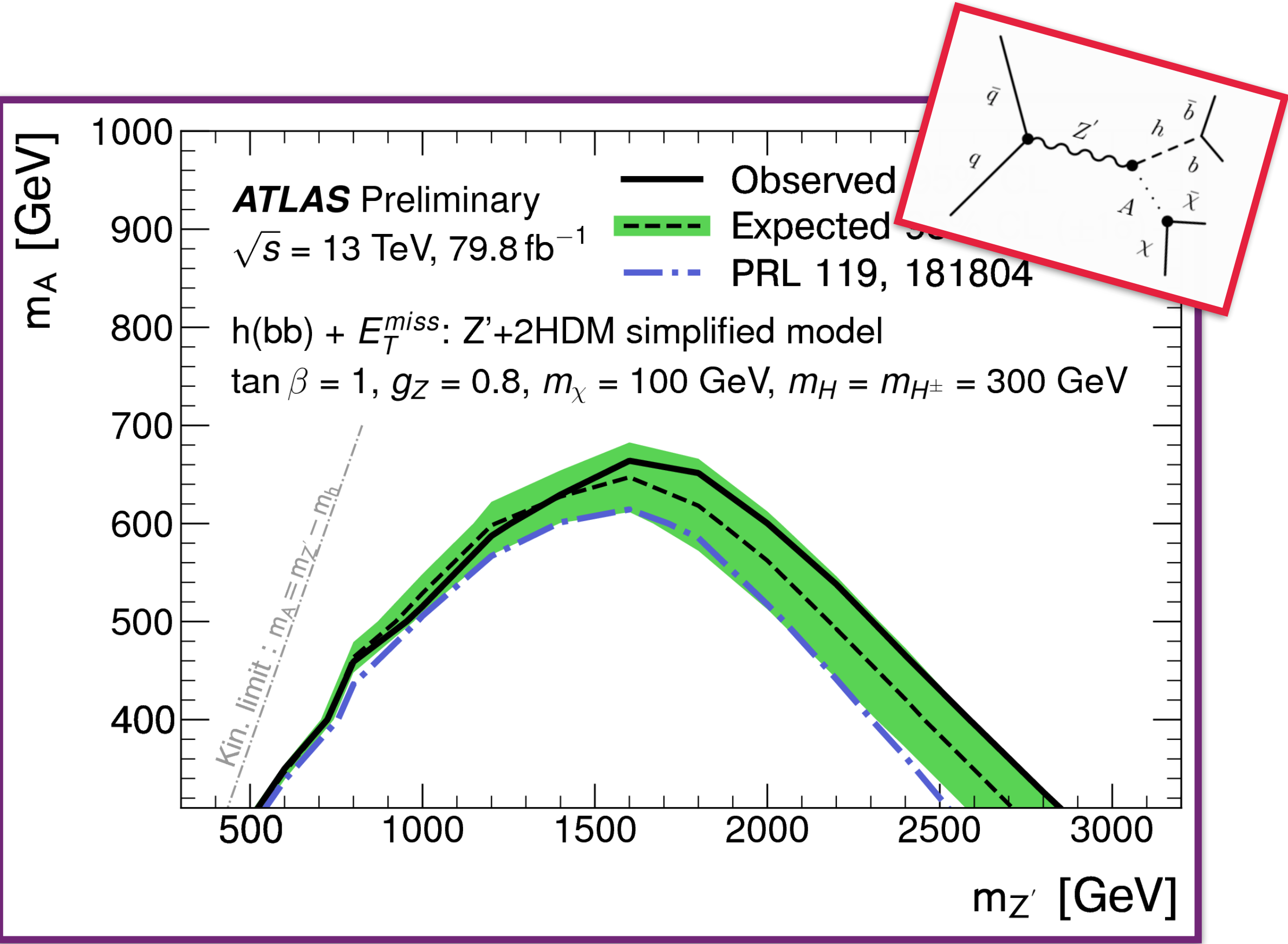


RESULTS

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ATLAS-CONF-2018-039

Z'-2HDM signal model used as a benchmark.

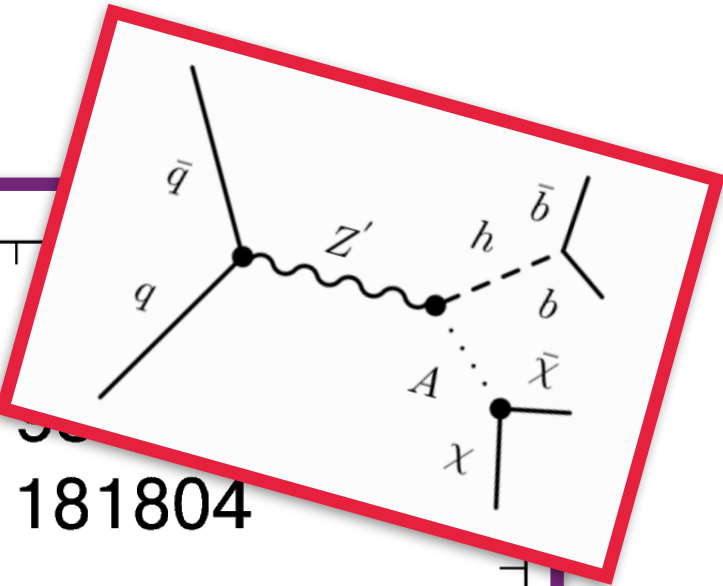
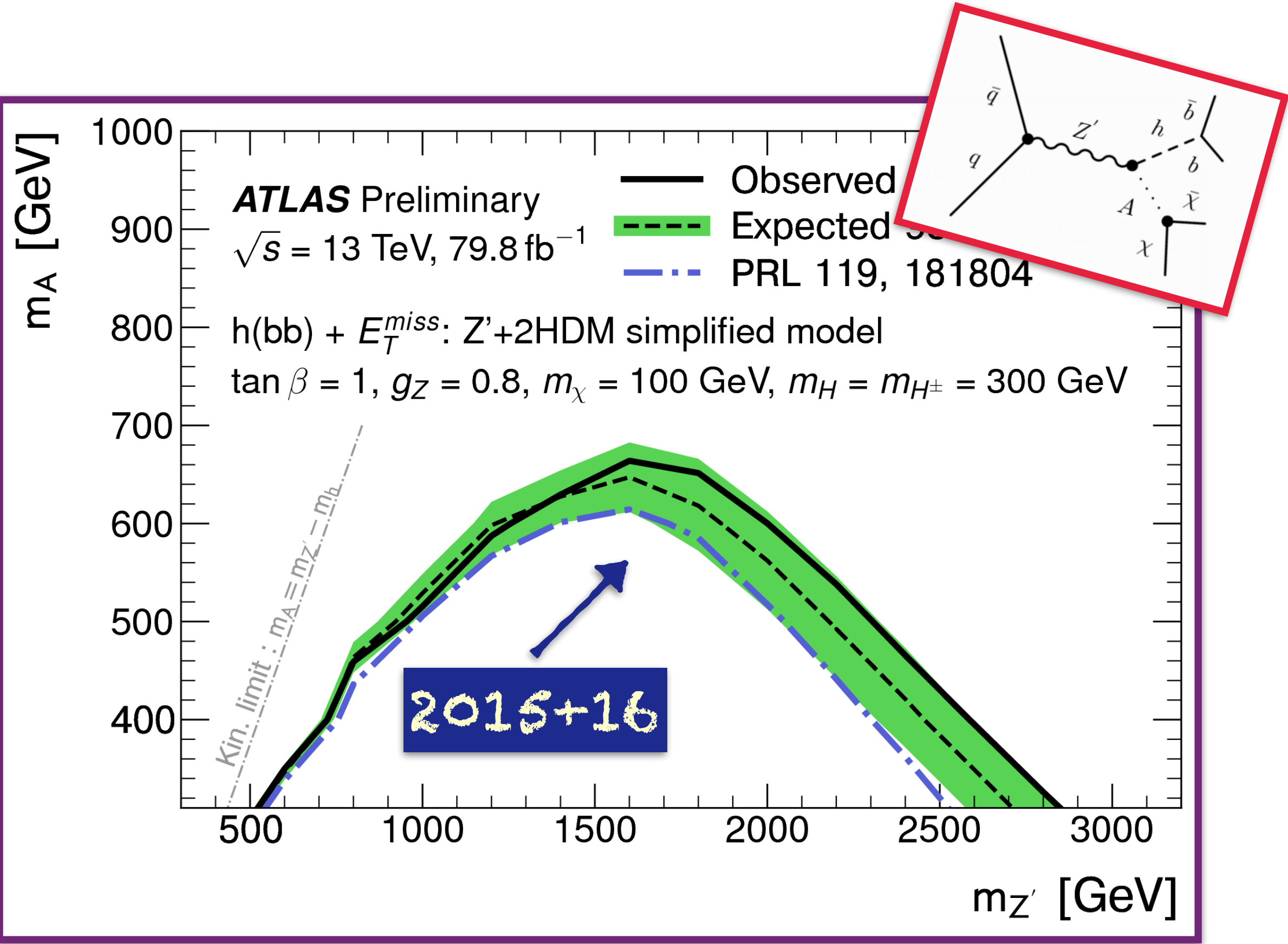


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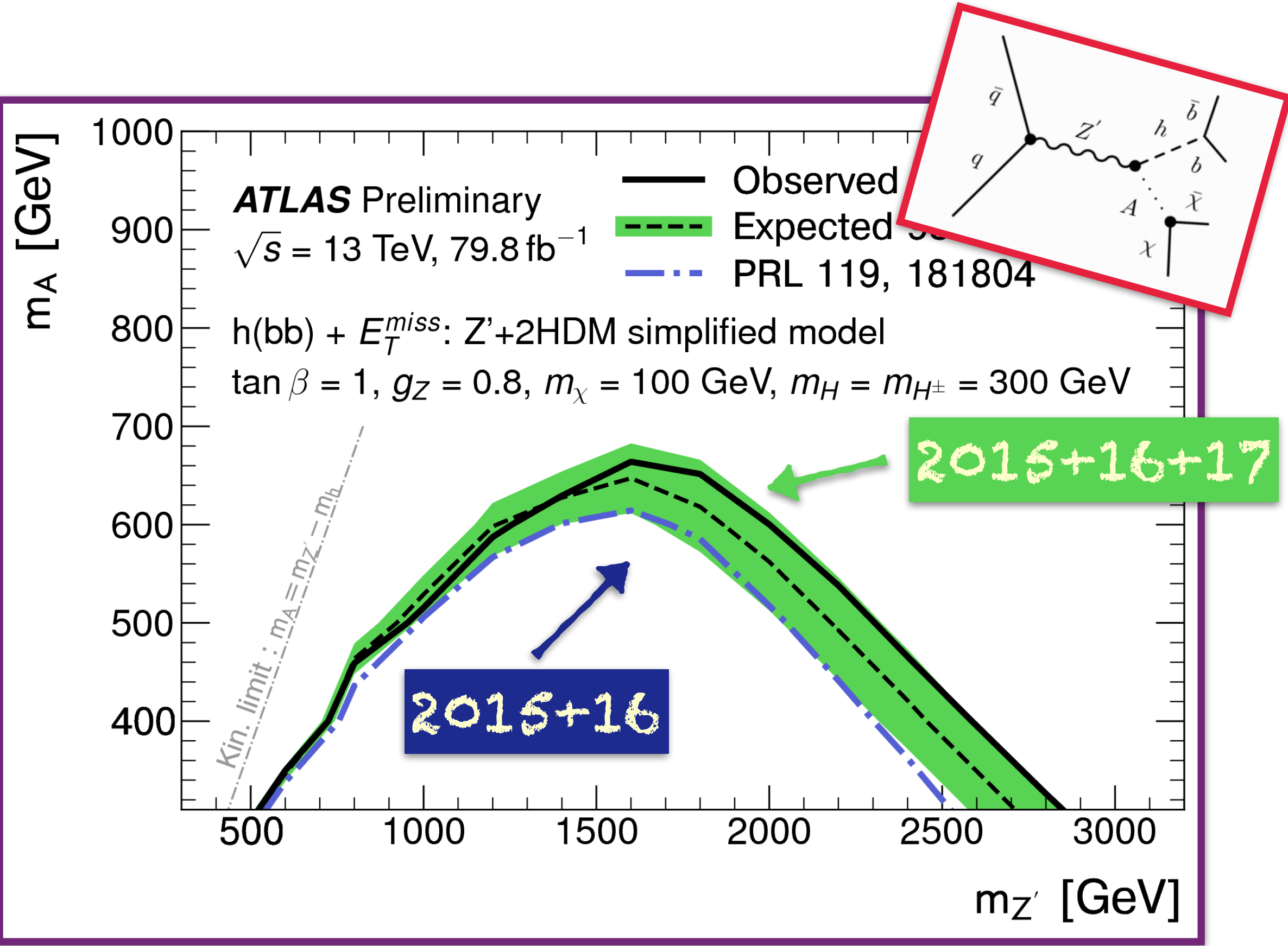


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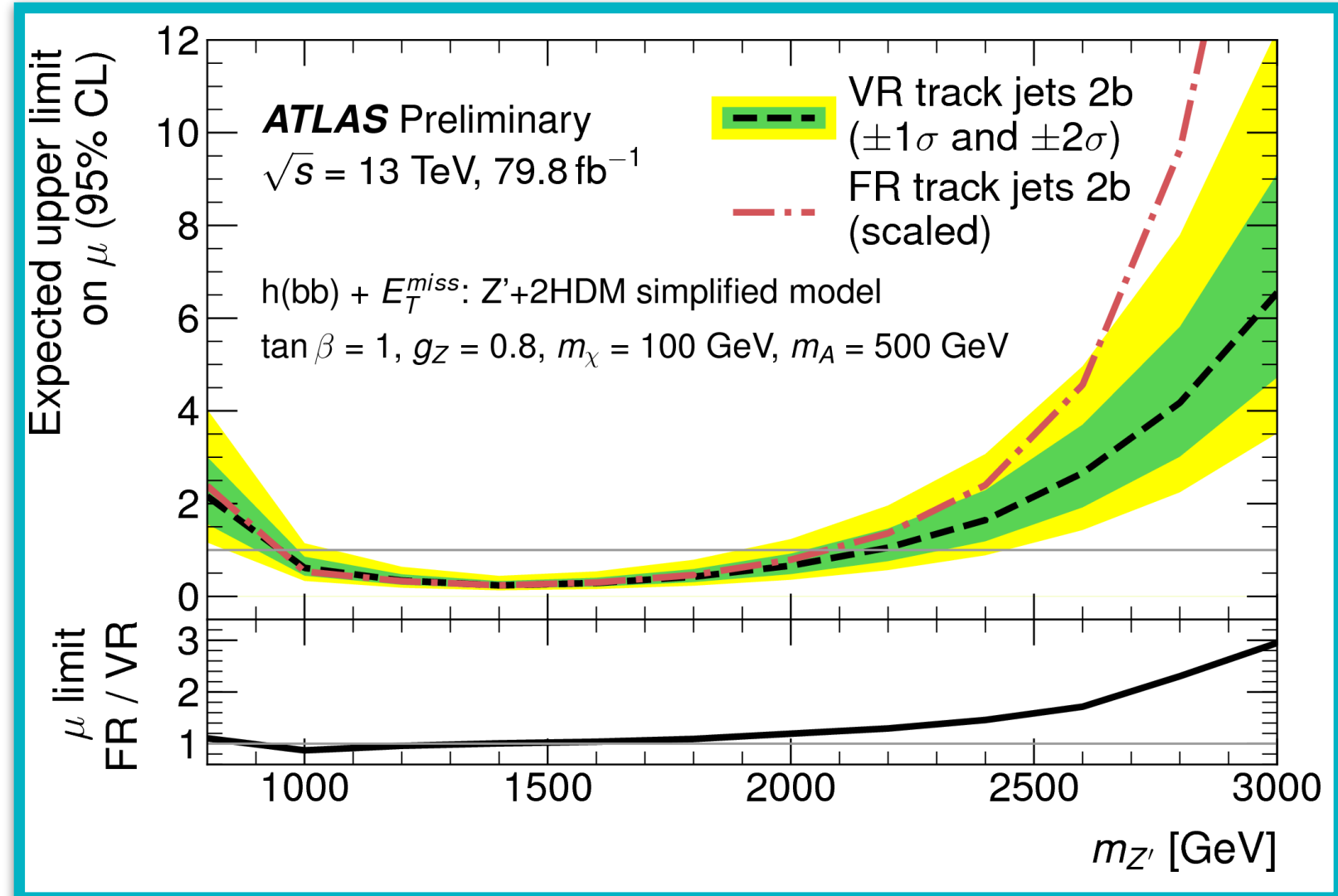
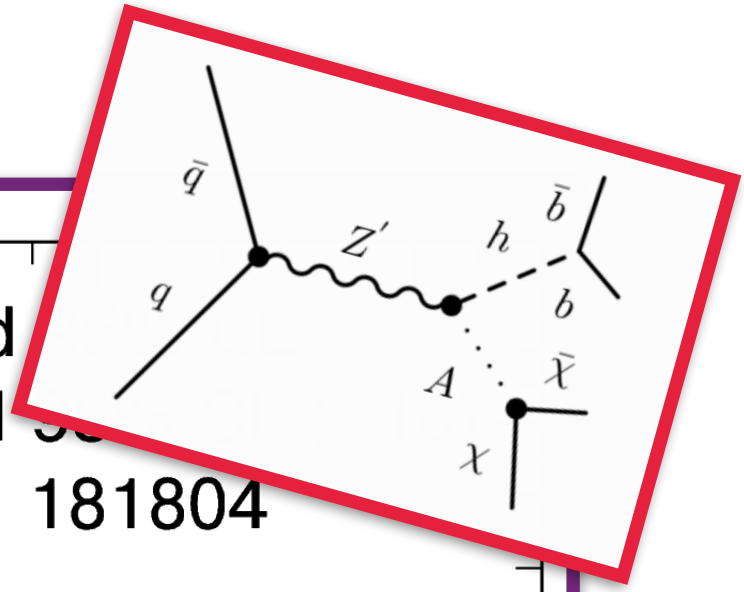
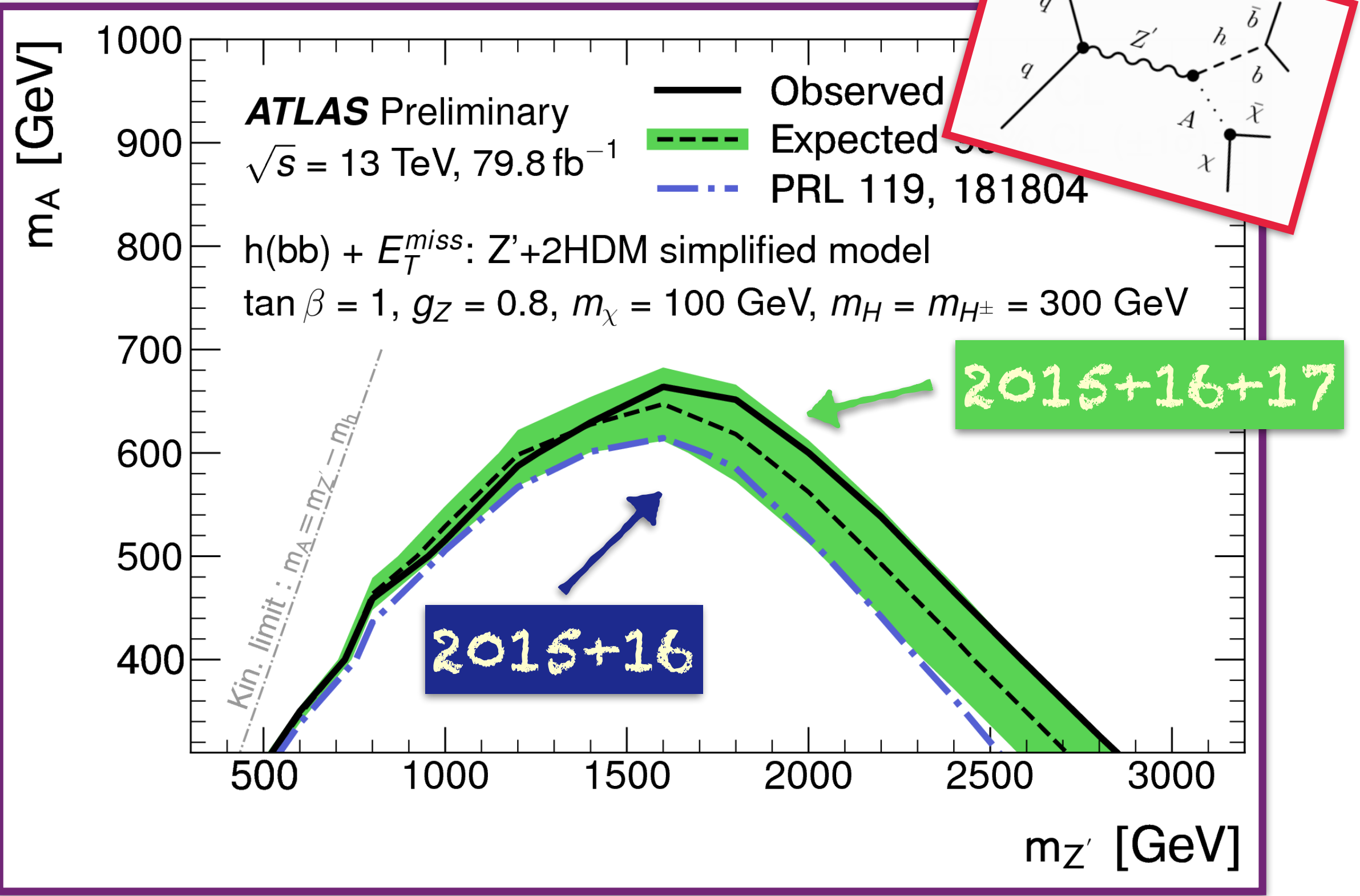


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Z'-2HDM signal model used as a benchmark.



Variable-R vs
Fixed-R jets
@ same
luminosity

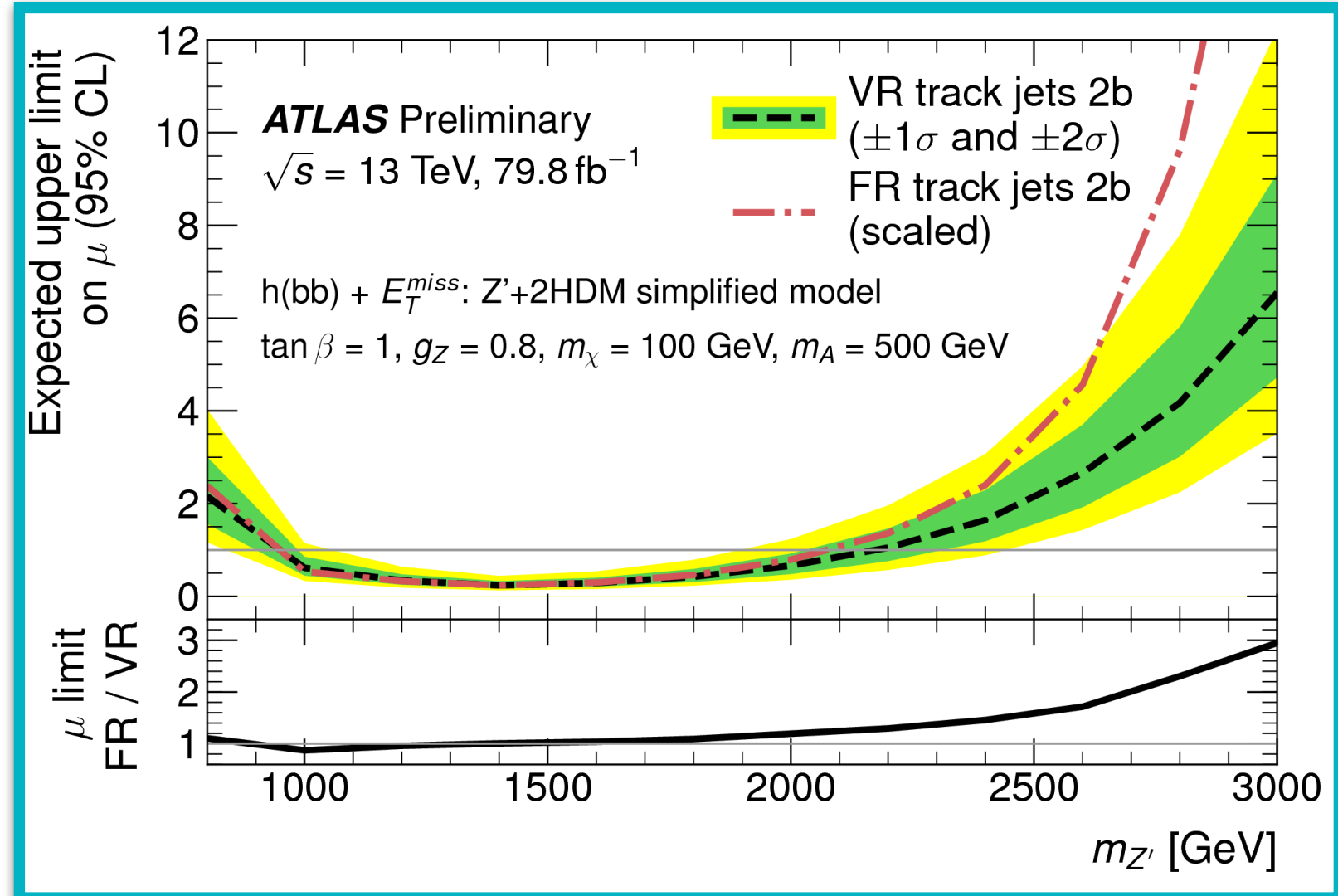
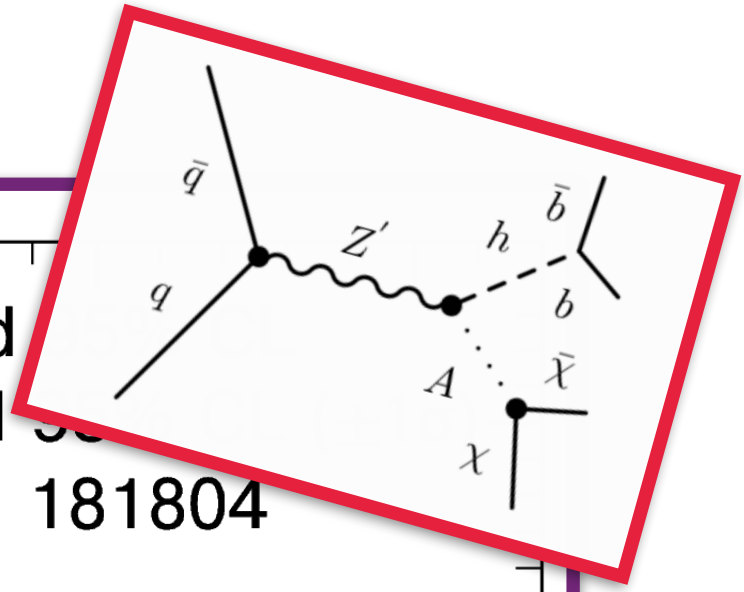
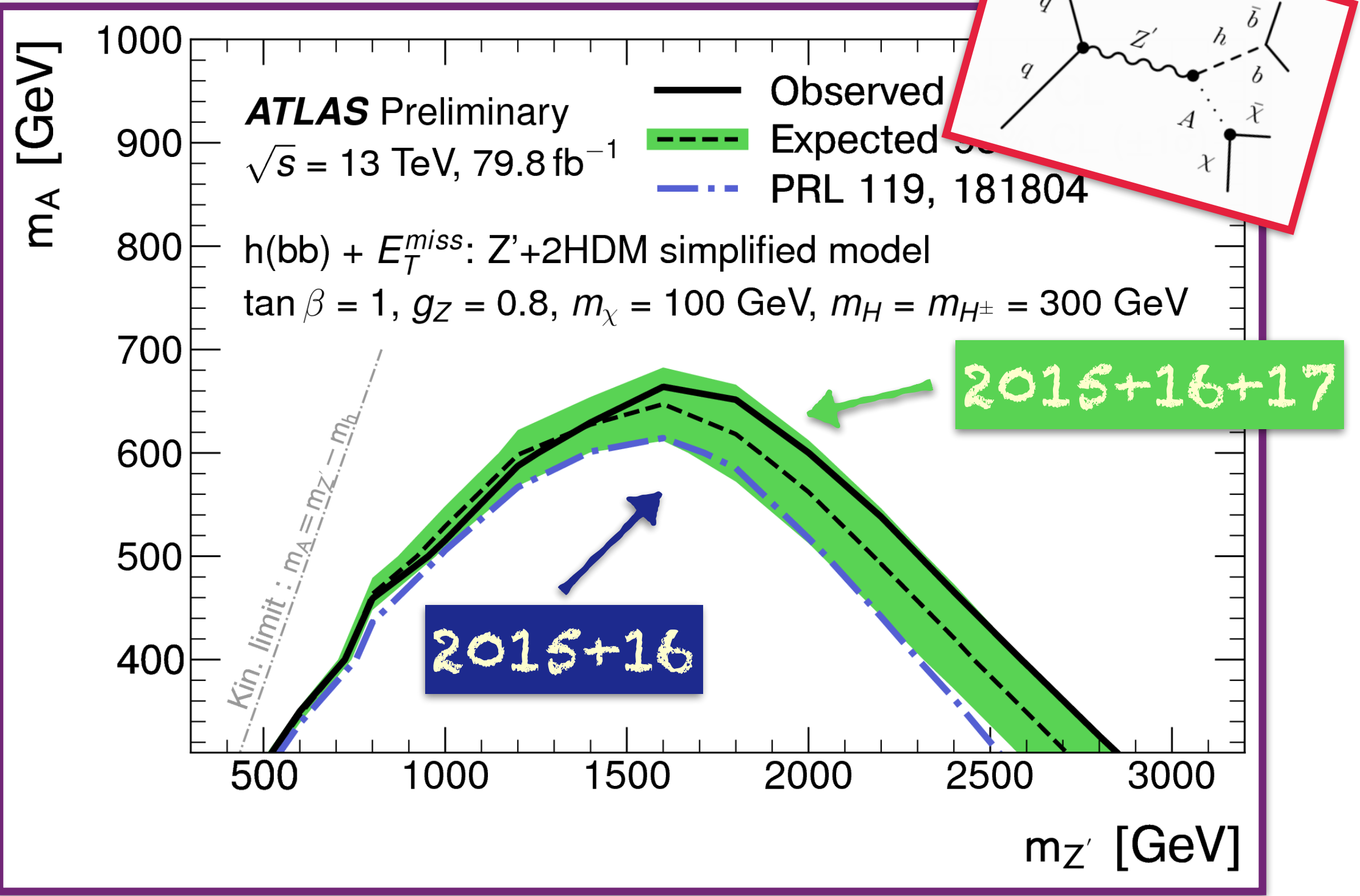
Improvement up to 200%
only due to the usage of
VR track jets!

RESULTS

2015+16+17 data: 79.8 fb⁻¹

ATLAS-CONF-2018-039

Z'-2HDM signal model used as a benchmark.



Variable-R vs Fixed-R jets @ same luminosity

Improvement up to 200% only due to the usage of VR track jets!

First ever usage of Variable-R track jets in ATLAS!

CONCLUSIONS

Mono-Hbb is currently one of the most competitive channels in the search for DM at the LHC.

- ✓ Improved sensitivity at high MET by doing b-tagging on Variable-R track jets.
- ✓ Substantial region of the phase space already excluded...
- ...But, with such a large amount of data, it's possible to explore also other regimes.
- Many ideas being discussed in view of full-Run2 results: new b-tagging techniques, new signal models, reduce impact of systematic uncertainties...

Thank you!

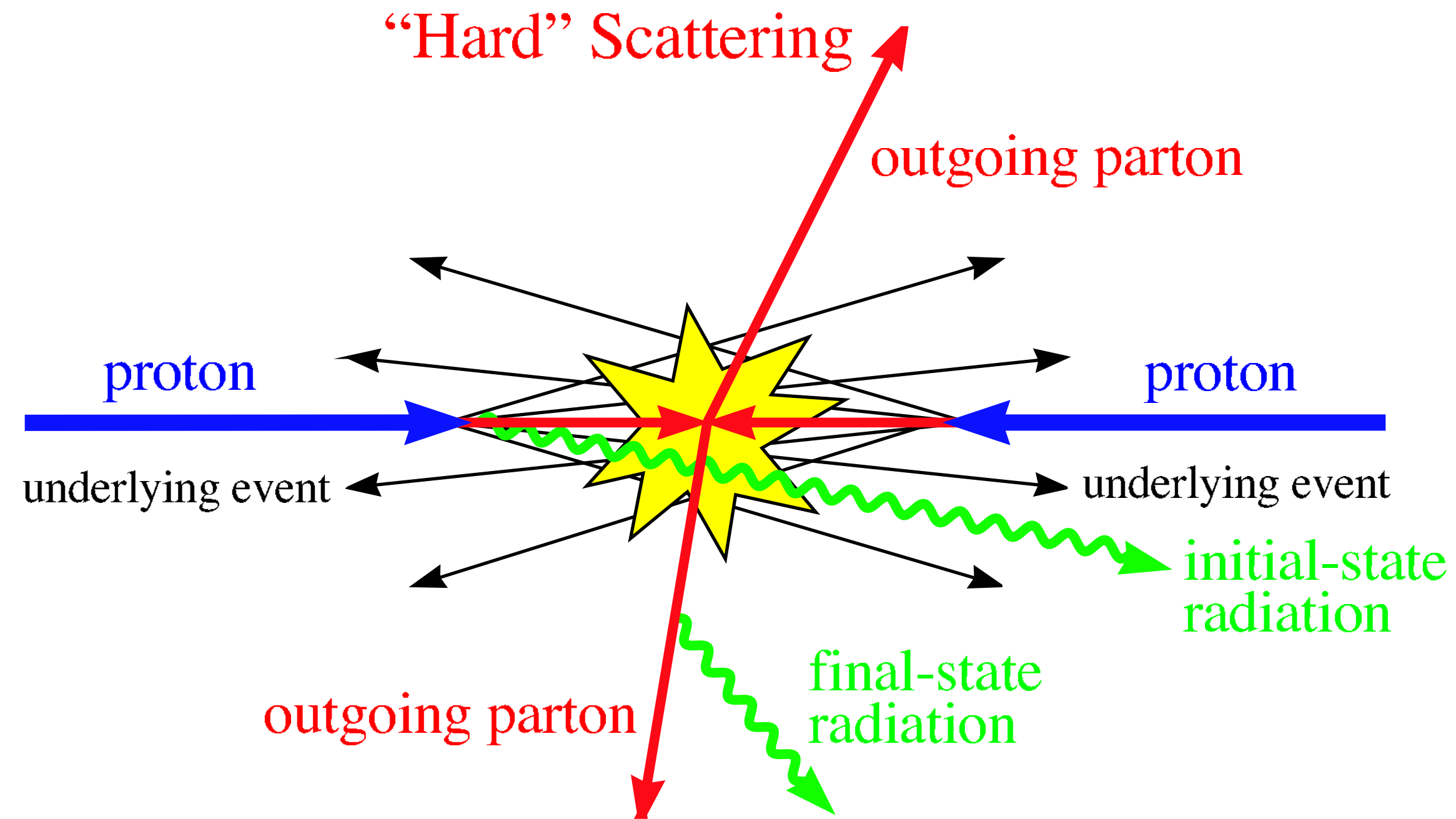


“It’s not dark matter, you’ve got the lens cap on.”



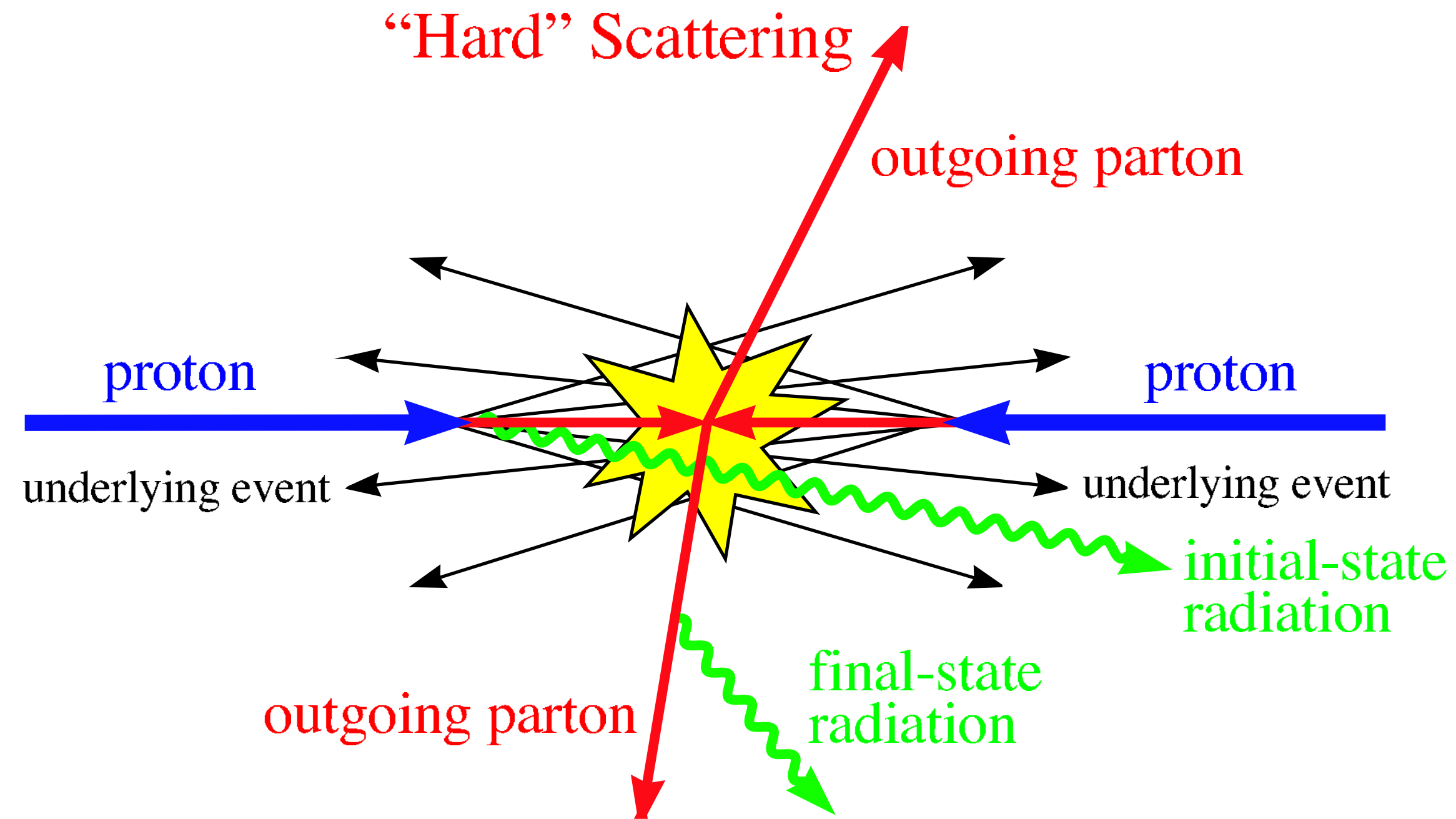
BACKUP SLIDES

SOMETHING ABOUT JETS



- Hard-Scattering from the initial state partons
- Showering from the interaction products
- In the hadronization process, partons re-combine and produce cones of particles (**jets**)

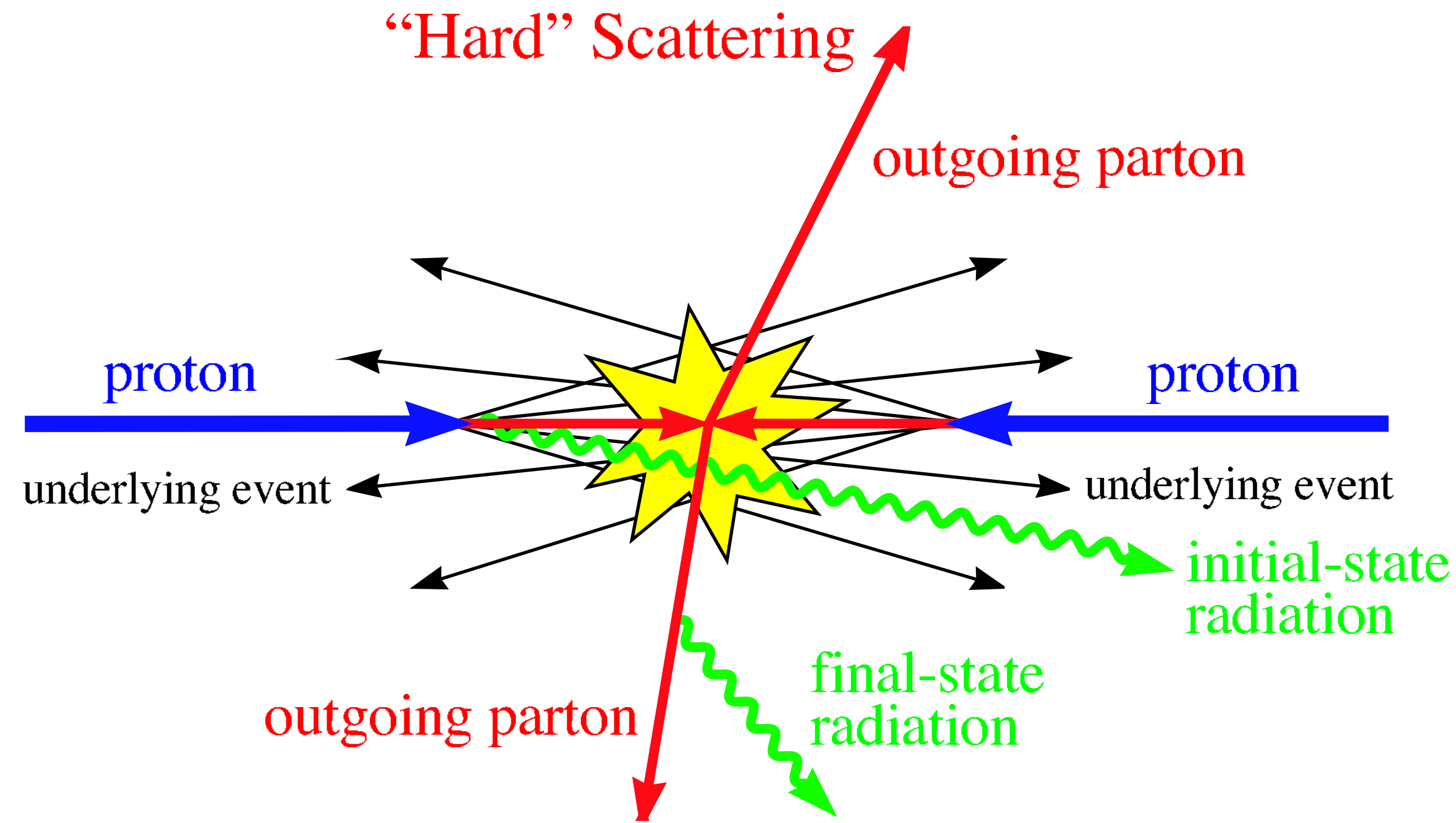
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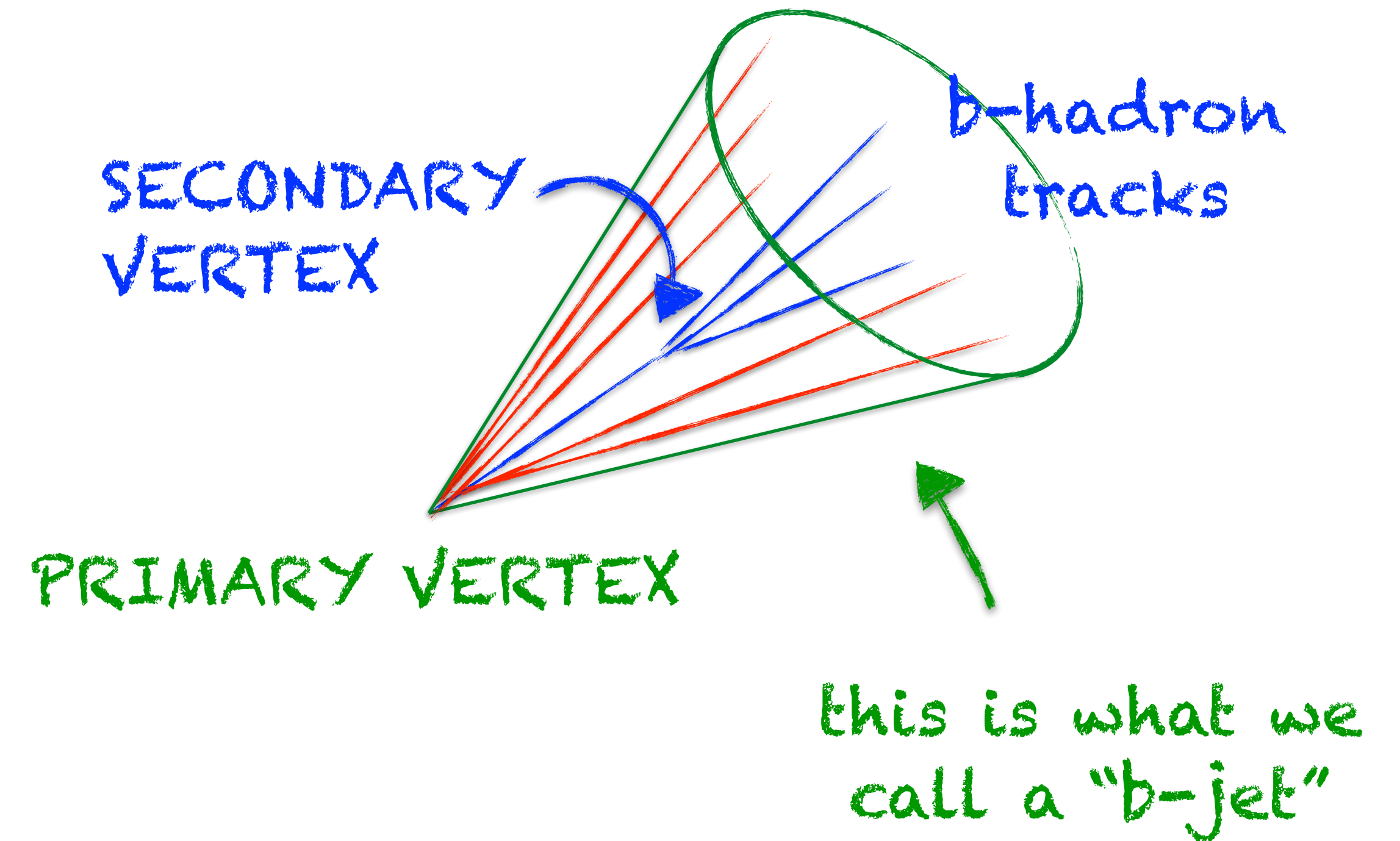
How do jets originating from b-quarks look?

- Hard-Scattering from the initial state partons
- Showering from the interaction products
- In the hadronization process, partons re-combine and produce cones of particles (**jets**)

SOMETHING ABOUT JETS

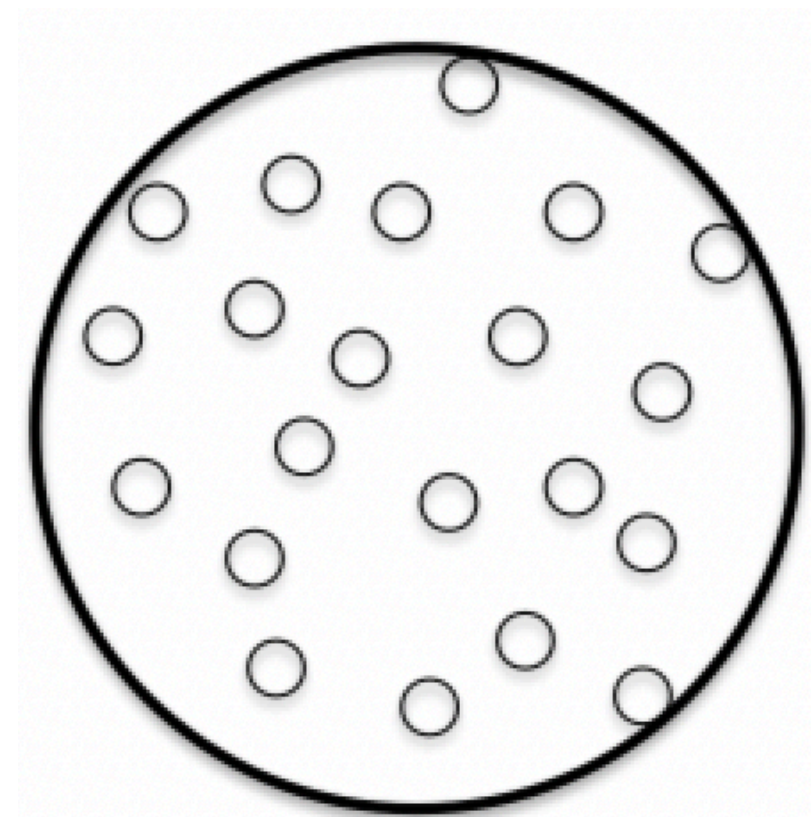


Hadrons originating from **b-quarks** have usually a longer lifetime and they can travel up to cm inside the detector before decaying. Very distinct signature.



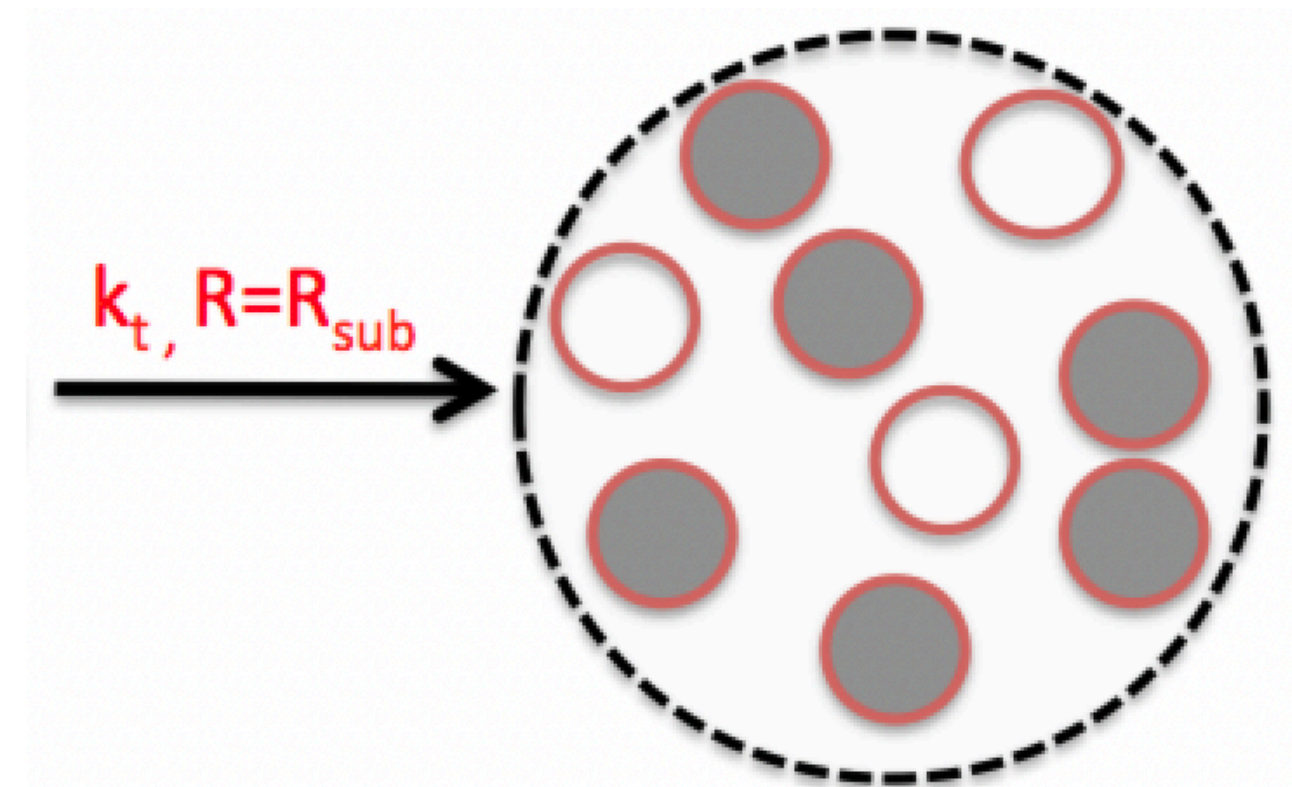
- Hard-Scattering from the initial state partons
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- In the hadronization process, partons re-combine and produce cones of particles (**jets**)

LARGE-R JET RECONSTRUCTION



Initial jet

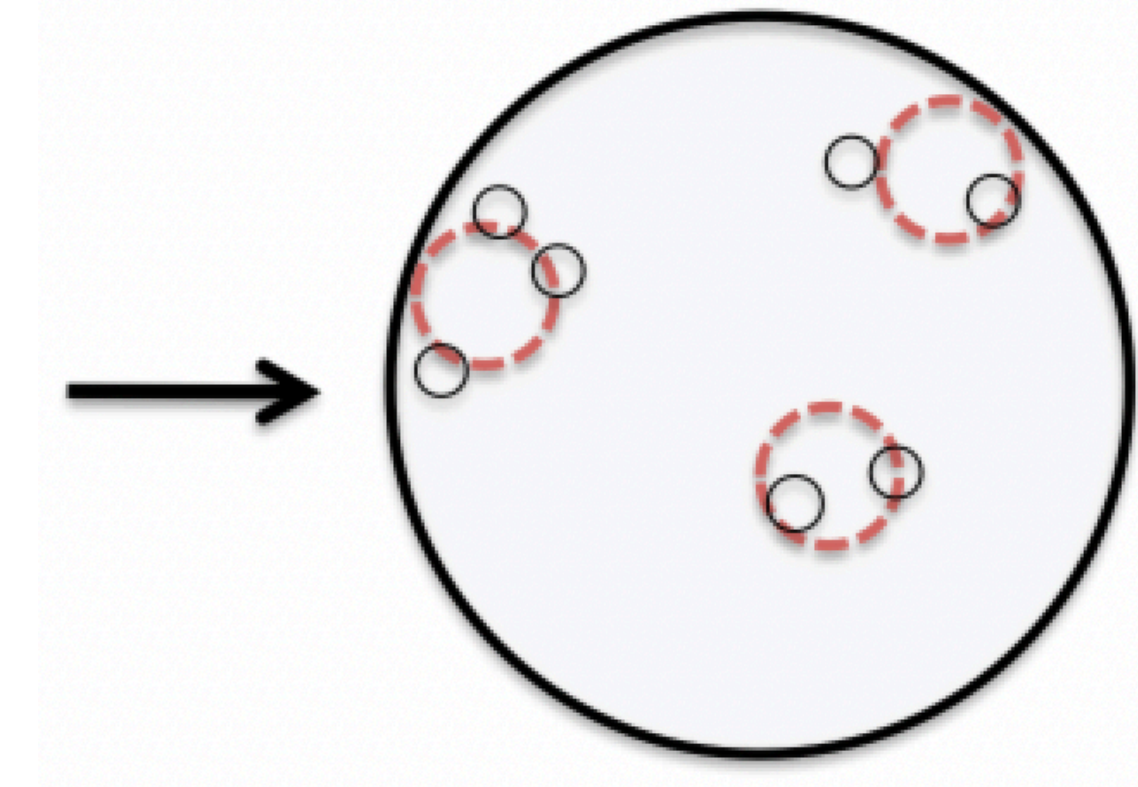
LARGE-R JET
ANTI- K_T $R=1.0$



$\text{red circle} = p_T^i / p_T^{\text{jet}} < f_{\text{cut}}$

SUBJETS

K_T $R_{\text{SUB}} = 0.2$, $F_{\text{CUT}} = 5\%$



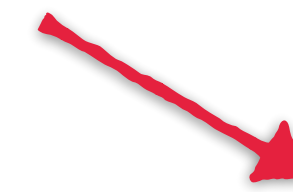
Trimmed jet

PU AND UE
REDUCTION

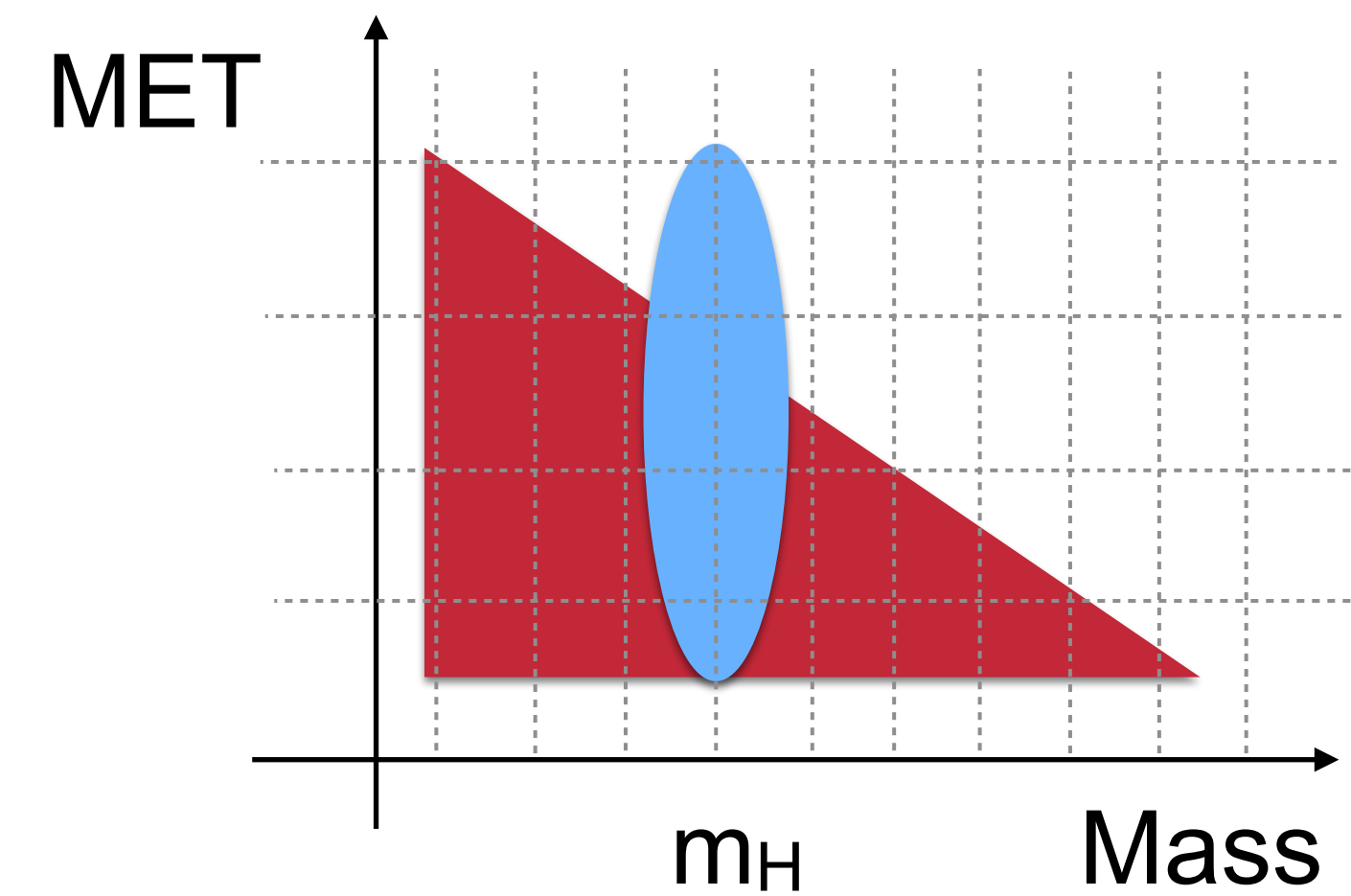
FITTING STRATEGY

Interpretation of final results done performing a profile likelihood fit in all SRs and CRs:

- 0-lepton SR: m_{jj}/m_J final discriminant 50-280 GeV
- 1-lepton CR: muon charge as final discriminant
- 2-lepton CR: one single bin of m_{jj}/m_J



x 4 MET bins:
 3 resolved (150-200, 200-350, 350-500)
 and 1 merged (>500)
2 b-tag only



Floating normalization parameters:

- W+HF (bb,bc,cc,bl)
- Z+HF (bb,bc,cc,bl)
- ttbar

Other background constrained by theory.

W+HF and Z+HF are decorrelated among different lepton regions (up to 20%).

Systematic uncertainties included as nuisance parameters (full list in backup).

$$\mathcal{L}(\mu, \theta) = \prod_{\text{SR bins: } i} \text{Pois}(n_i | \mu S_i(\theta) + B_i(\theta)) \prod_{\text{CR bins: } j} \text{Pois}(n_j | B_j(\theta)) \prod_{\text{Nuisance parameters: } k} \text{Gaus}(0 | \text{mean} = \theta_k, \sigma = 1)$$

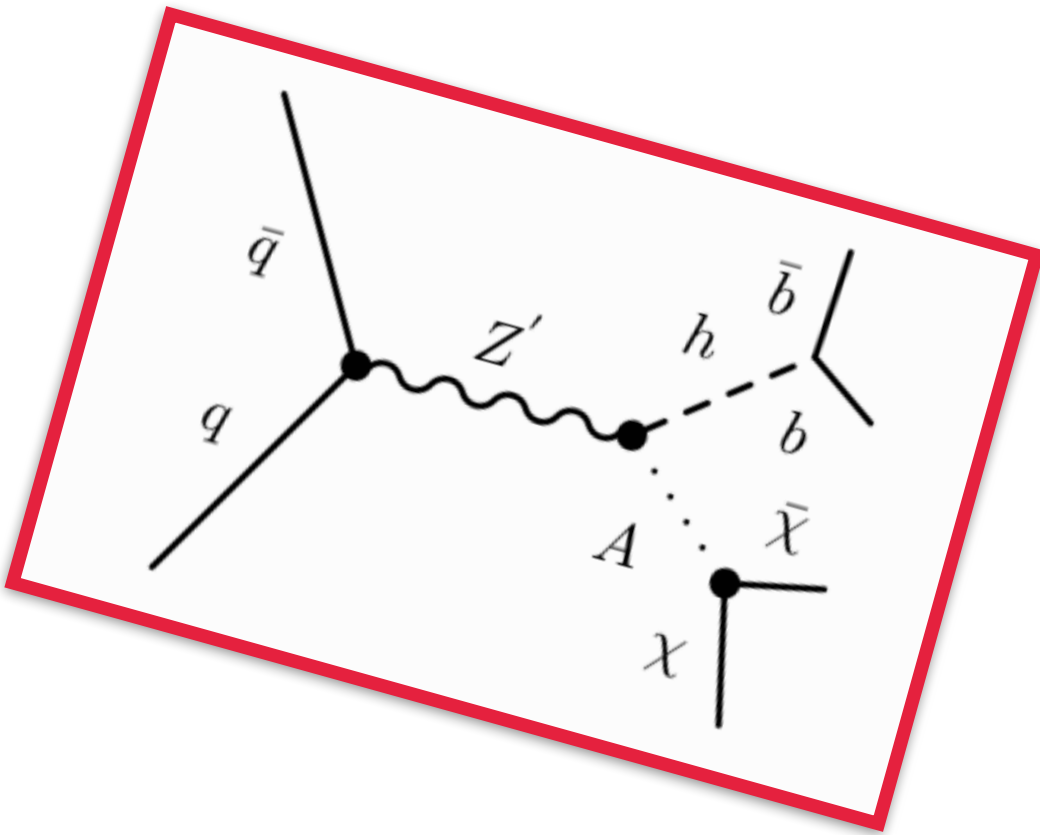
SYSTEMATICS BREAKDOWN

@79.8fb⁻¹

Impact of systematic uncertainties for different Z'-2HDM models (different masses hence different MET regimes).

Source of uncert.	In [MET]		
	(a)	(b)	(c)
<i>b</i> -tagging	4.0	8.0	10
V+jets modeling	3.5	6.0	5.0
Top modeling	3.7	4.8	4.5
MC statistics	1.8	5.4	4.9
SM $Vh(b\bar{b})$	0.8	3.2	2.1
Diboson modeling	0.8	1.5	1.1
Signal modeling	3.0	2.5	1.5
Luminosity	2.0	2.5	2.5
Small- <i>R</i> jets	1.4	3.0	2.0
Large- <i>R</i> jets	0.2	1.0	2.0
E_T^{miss}	1.2	1.7	1.1
Leptons	0.2	0.8	0.7
Total syst. uncert.	6.5	13	13
Statistical uncert.	2.3	20	22
Total uncertainty	7	24	25

- a) $(m_{Z'}, m_A) = (0.6\text{TeV}, 0.3\text{TeV})$
- b) $(m_{Z'}, m_A) = (1.4\text{TeV}, 0.6\text{TeV})$
- c) $(m_{Z'}, m_A) = (2.6\text{TeV}, 0.3\text{TeV})$



- *b*-tagging and V+jets/Top modelling are the dominant sources of systematic uncertainty
- the analysis is statistically limited at medium-high MET

SR EVENT SELECTION

Resolved	Merged
trigger	
lepton veto (SR) or selection (CRs)	
(modified) $E_T^{\text{miss}} > 150 \text{ GeV}$	
$\min \Delta\phi(E_T^{\text{miss}}, \text{jets}) > 20^\circ$	
$\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < 90^\circ$	
S > 16 (SR only)	—
0 ℓ SR: $E_T^{\text{miss}} < 500 \text{ GeV}$	0 ℓ SR: $E_T^{\text{miss}} > 500 \text{ GeV}$
1 μ -CR: $E_T^{\text{miss, no } \mu} < 500 \text{ GeV}$	1 μ -CR: $E_T^{\text{miss, no } \mu} > 500 \text{ GeV}$
2 ℓ -CR: $p_T^{\ell\ell} < 500 \text{ GeV}$	2 ℓ -CR: $p_T^{\ell\ell} > 500 \text{ GeV}$
N(central small- R jets) ≥ 2	N(central large- R jets) ≥ 1
$p_T^{\text{jet}_1} > 45 \parallel p_T^{\text{jet}_2} > 45$	—
$\sum_{i=1}^{2(3)} p_T^{\text{jet}_i} > 120 \text{ (150) GeV}$	—
$\Delta\phi(\text{jet}_1, \text{jet}_2) < 140^\circ$	—
$\Delta\phi(E_T^{\text{miss}}, h) > 120^\circ$	—
τ -veto	
additional b -jet veto	
H_T ratio	
$\Delta R(\text{jet}_1, \text{jet}_2) < 1.8$	$\frac{\Delta R(\text{VR}_1, \text{VR}_2)}{R_{\min}} > 1$
b -tag requirement on small- R jets	track-jets

SR EVENT SELECTION

Resolved	Merged
trigger	
lepton veto (SR) or selection (CRs)	
	(modified) $E_T^{\text{miss}} > 150 \text{ GeV}$
	$\min \Delta\phi(E_T^{\text{miss}}, \text{jets}) > 20^\circ$
	$\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < 90^\circ$
 $S > 16$ (SR only)	—
0 ℓ SR: $E_T^{\text{miss}} < 500 \text{ GeV}$	0 ℓ SR: $E_T^{\text{miss}} > 500 \text{ GeV}$
1 μ -CR: $E_T^{\text{miss, no } \mu} < 500 \text{ GeV}$	1 μ -CR: $E_T^{\text{miss, no } \mu} > 500 \text{ GeV}$
2 ℓ -CR: $p_T^{\ell\ell} < 500 \text{ GeV}$	2 ℓ -CR: $p_T^{\ell\ell} > 500 \text{ GeV}$
N(central small- R jets) ≥ 2	N(central large- R jets) ≥ 1
$p_T^{\text{jet}_1} > 45 \parallel p_T^{\text{jet}_2} > 45$	—
$\sum_{i=1}^{2(3)} p_T^{\text{jet}_i} > 120 \text{ (150) GeV}$	—
$\Delta\phi(\text{jet}_1, \text{jet}_2) < 140^\circ$	—
$\Delta\phi(E_T^{\text{miss}}, h) > 120^\circ$	—
τ -veto	
additional b -jet veto	
H_T ratio	
$\Delta R(\text{jet}_1, \text{jet}_2) < 1.8$	$\frac{\Delta R(\text{VR}_1, \text{VR}_2)}{R_{\min}} > 1$
b -tag requirement on small- R jets	track-jets

(standard) anti-qcd cuts

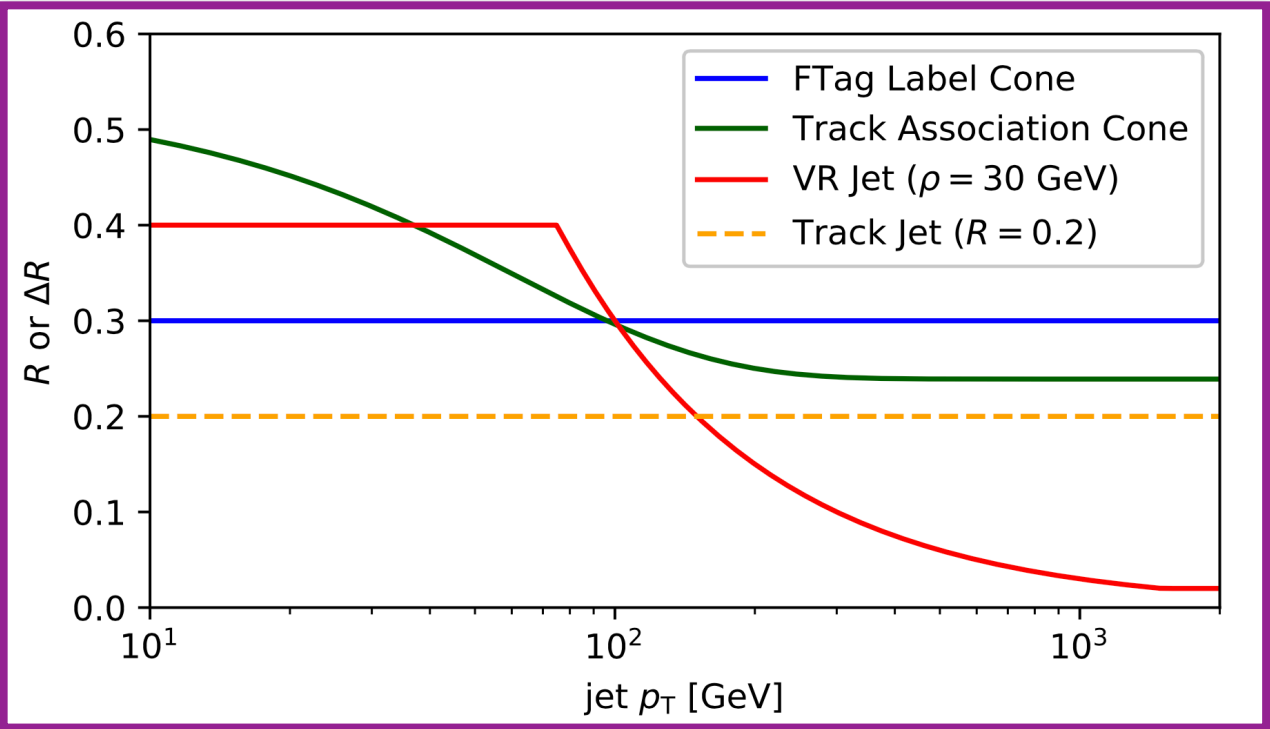
SR EVENT SELECTION

Resolved	Merged
trigger	
lepton veto (SR) or selection (CRs)	
(modified) $E_T^{\text{miss}} > 150 \text{ GeV}$	
$\min \Delta\phi(E_T^{\text{miss}}, \text{jets}) > 20^\circ$	
$\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < 90^\circ$	
new $S > 16$ (SR only)	—
0 ℓ SR: $E_T^{\text{miss}} < 500 \text{ GeV}$	0 ℓ SR: $E_T^{\text{miss}} > 500 \text{ GeV}$
1 μ -CR: $E_T^{\text{miss, no } \mu} < 500 \text{ GeV}$	1 μ -CR: $E_T^{\text{miss, no } \mu} > 500 \text{ GeV}$
2 ℓ -CR: $p_T^{\ell\ell} < 500 \text{ GeV}$	2 ℓ -CR: $p_T^{\ell\ell} > 500 \text{ GeV}$
N(central small- R jets) ≥ 2	N(central large- R jets) ≥ 1
$p_T^{\text{jet}_1} > 45 \parallel p_T^{\text{jet}_2} > 45$	—
$\sum_{i=1}^{2(3)} p_T^{\text{jet}_i} > 120 \text{ (150) GeV}$	—
$\Delta\phi(\text{jet}_1, \text{jet}_2) < 140^\circ$	—
$\Delta\phi(E_T^{\text{miss}}, h) > 120^\circ$	—
τ -veto	
additional b -jet veto	
H_T ratio	
$\Delta R(\text{jet}_1, \text{jet}_2) < 1.8$	$\frac{\Delta R(\text{VR}_1, \text{VR}_2)}{R_{\text{min}}} > 1$
b -tag requirement on small- R jets	VR track-jets new

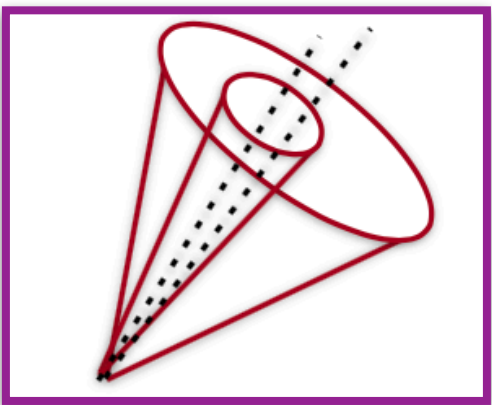
(standard) anti-qcd cuts

SR EVENT SELECTION

Resolved	Merged
trigger	
lepton veto (SR) or selection (CRs)	
(modified) $E_T^{\text{miss}} > 150 \text{ GeV}$	
$\min \Delta\phi(E_T^{\text{miss}}, \text{jets}) > 20^\circ$	
$\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < 90^\circ$	
new $S > 16$ (SR only)	—
0 ℓ SR: $E_T^{\text{miss}} < 500 \text{ GeV}$	0 ℓ SR: $E_T^{\text{miss}} > 500 \text{ GeV}$
1 μ -CR: $E_T^{\text{miss, no } \mu} < 500 \text{ GeV}$	1 μ -CR: $E_T^{\text{miss, no } \mu} > 500 \text{ GeV}$
2 ℓ -CR: $p_T^{\ell\ell} < 500 \text{ GeV}$	2 ℓ -CR: $p_T^{\ell\ell} > 500 \text{ GeV}$
$N(\text{central small-}R \text{ jets}) \geq 2$	$N(\text{central large-}R \text{ jets}) \geq 1$
$p_T^{\text{jet}_1} > 45 \parallel p_T^{\text{jet}_2} > 45$	—
$\sum_{i=1}^{2(3)} p_T^{\text{jet}_i} > 120 \text{ (150) GeV}$	—
$\Delta\phi(\text{jet}_1, \text{jet}_2) < 140^\circ$	—
$\Delta\phi(E_T^{\text{miss}}, h) > 120^\circ$	—
τ -veto	
additional b -jet veto	
H_T ratio	
$\Delta R(\text{jet}_1, \text{jet}_2) < 1.8$	new $\frac{\Delta R(\text{VR}_1, \text{VR}_2)}{R_{\min}} > 1$
b -tag requirement on small- R jets	new VR track-jets



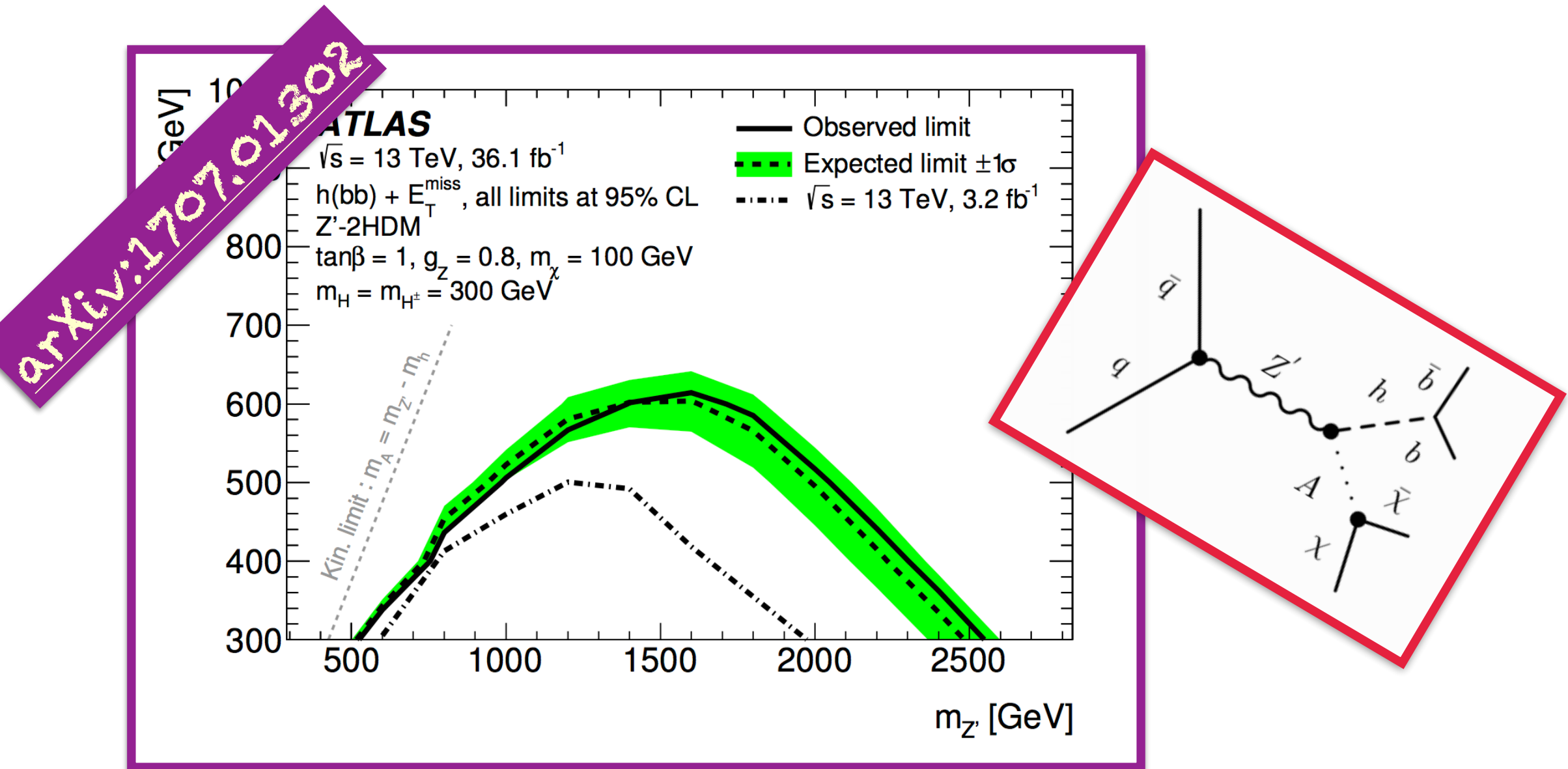
To reject events with collinear VR track jets, that can lead to ambiguous b-tagging



$\Delta R/R_{\min} < 1$

RESULTS @36fb⁻¹

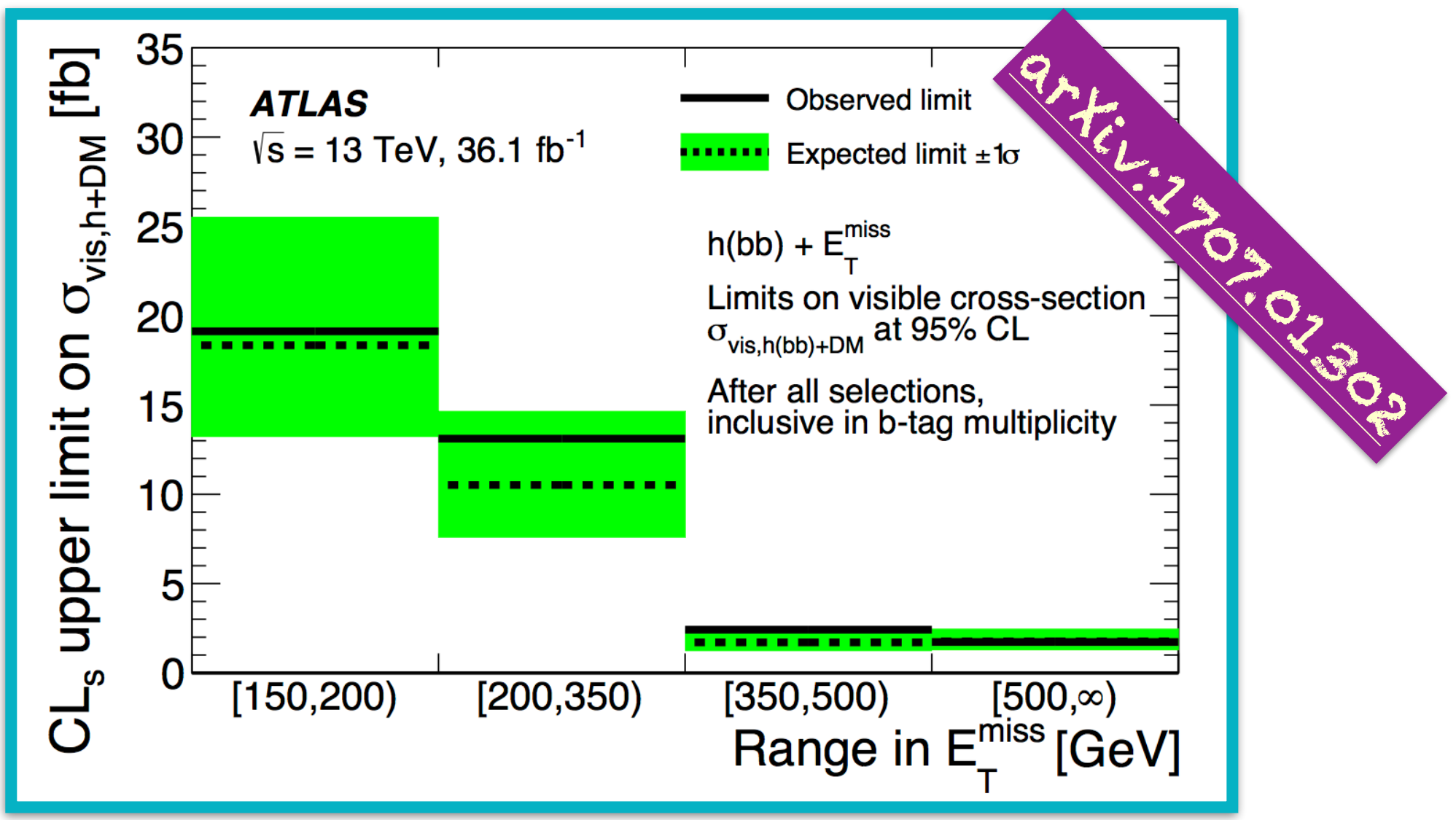
The results are interpreted as exclusion limits on **Z'-2HDM** models...



Fit one MET region at the time for SR, to minimise the dependance on a specific h+DM signal.

...and also as **less model-dependent** limits on:

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



OLD SYSTS BREAKDOWN TABLE @36fb-1

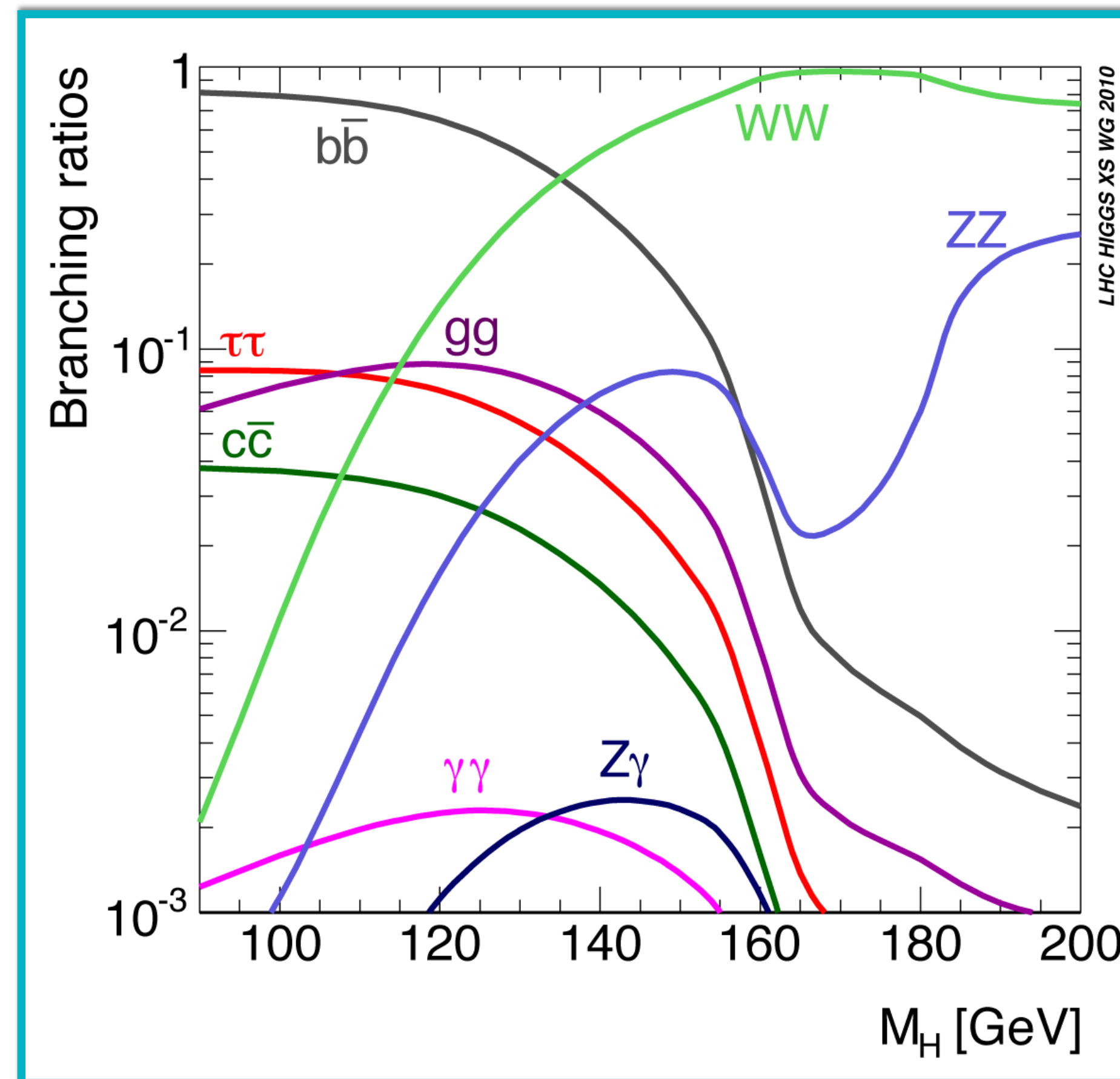
MC statistics dominant systematic uncertainty at high MET

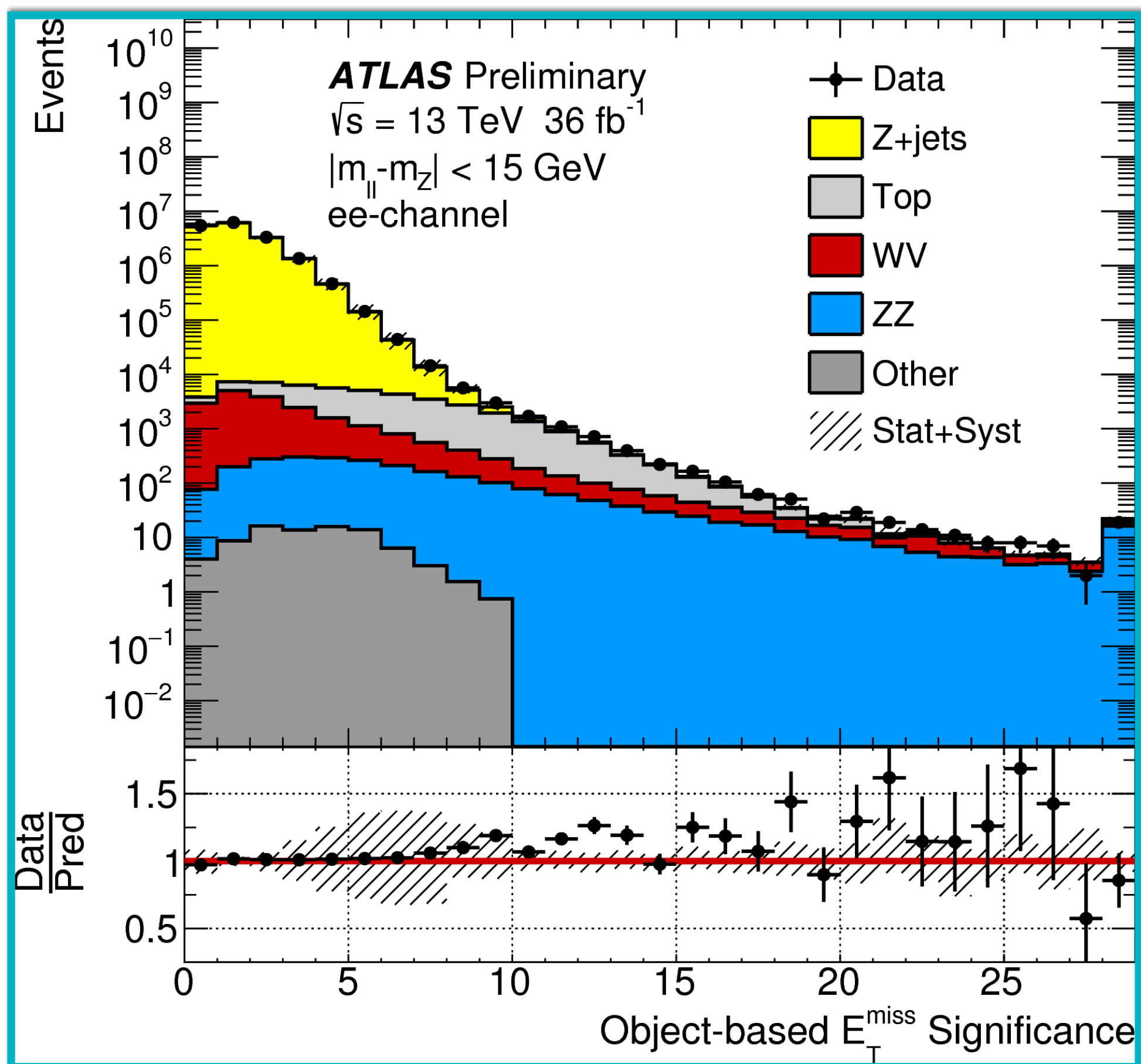
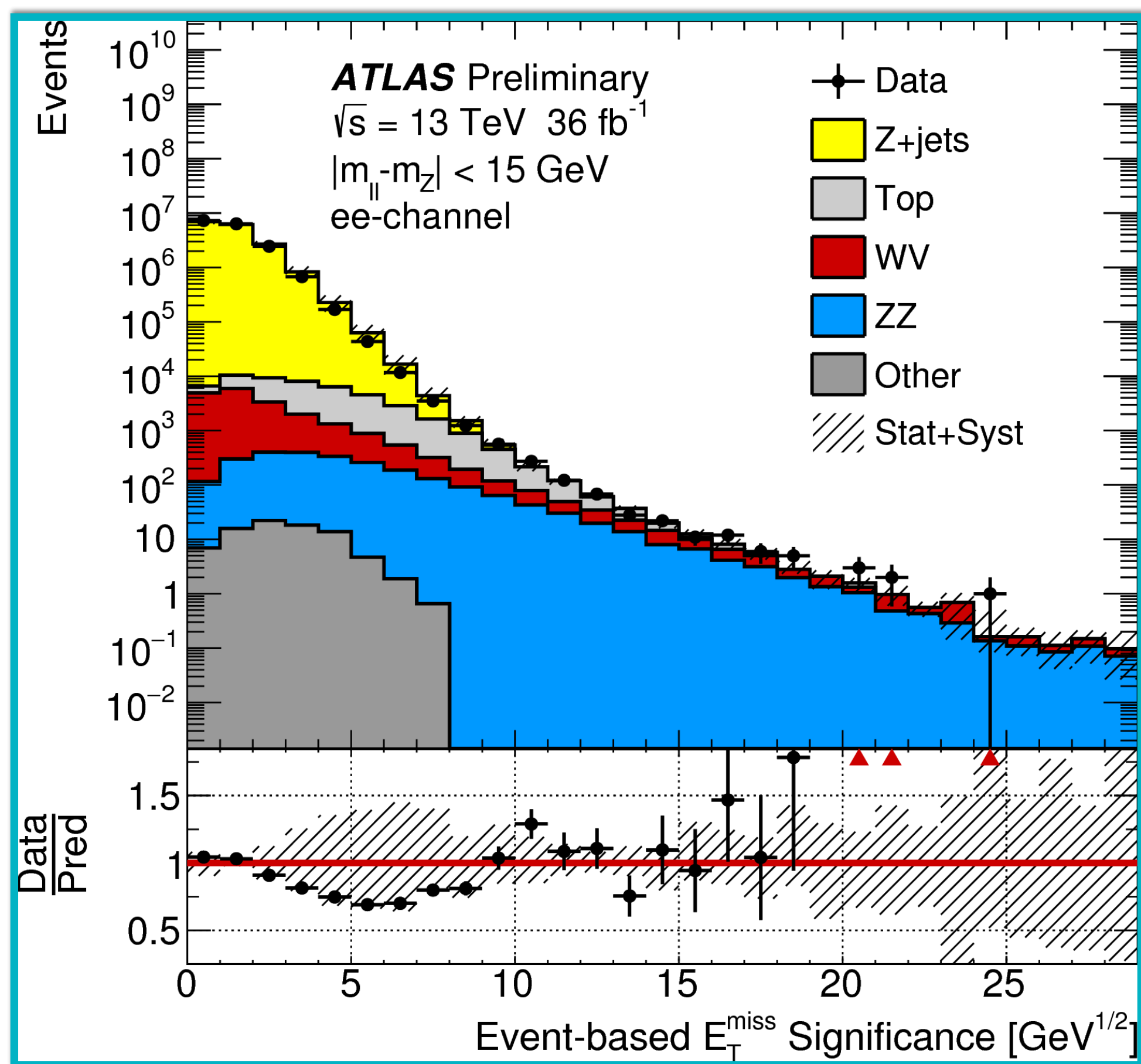
significant impact also from b-tagging and V+jets modeling

Source of uncert.	MET Impact [%]		
	(a)	(b)	(c)
V+jets modeling	5.0	5.7	8.2
$t\bar{t}$, single- t modeling	3.2	3.0	3.9
SM $Vh(b\bar{b})$ norm.	2.2	6.9	6.9
Signal modeling	3.9	2.9	2.1
MC statistics	4.9	11	22
Luminosity	3.2	4.5	5.4
b -tagging, track-jets	1.4	11	17
b -tagging, calo jets	5.0	3.4	4.7
Jets with $R = 0.4$	1.7	3.8	2.1
Jets with $R = 1.0$	<0.1	1.2	4.7
Total syst. uncert.	10	21	36
Statistical uncert.	6	38	62
Total uncert.	12	43	71

statistically limited at medium-high MET

HIGGS BRANCHING RATIO

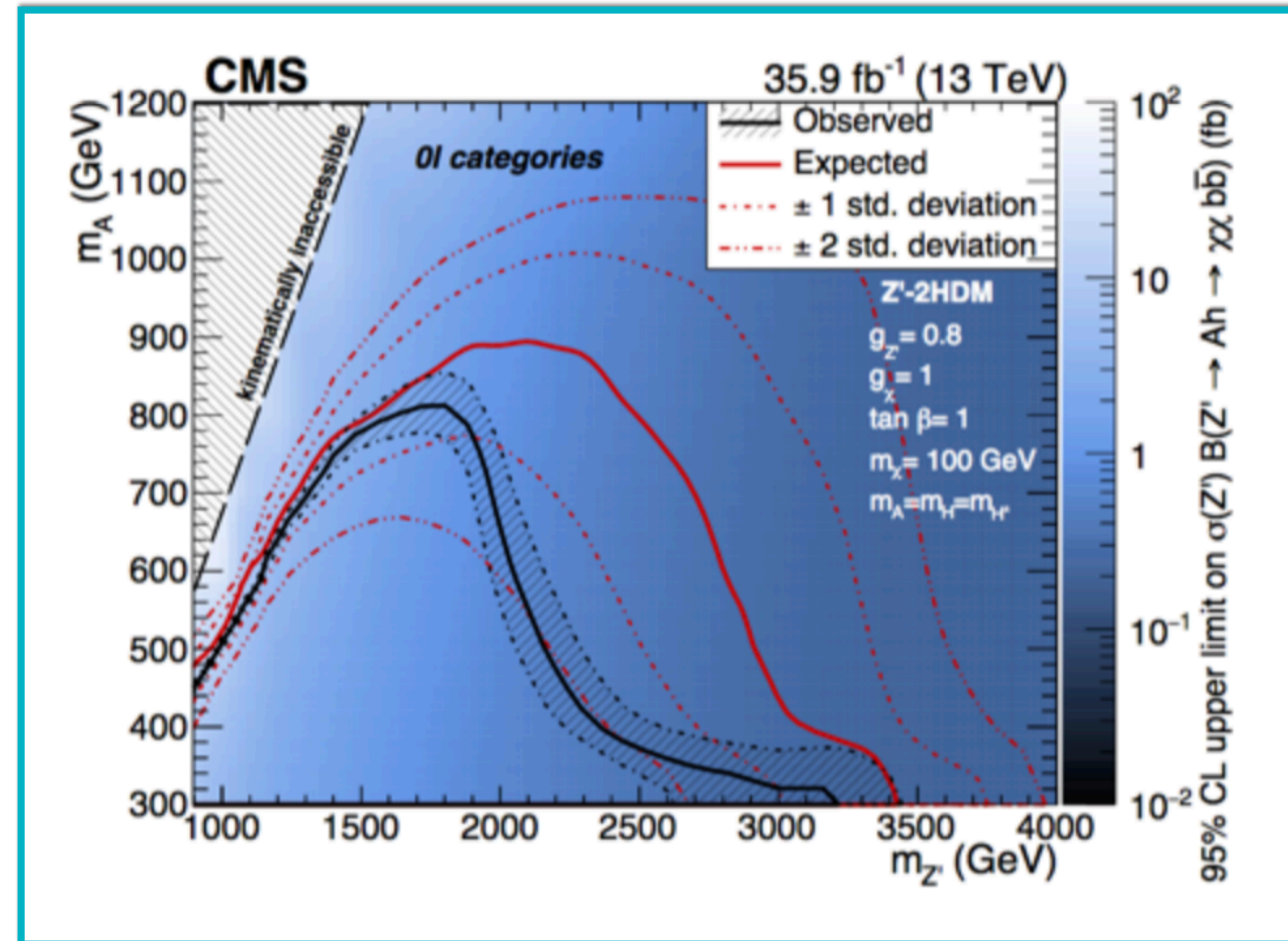




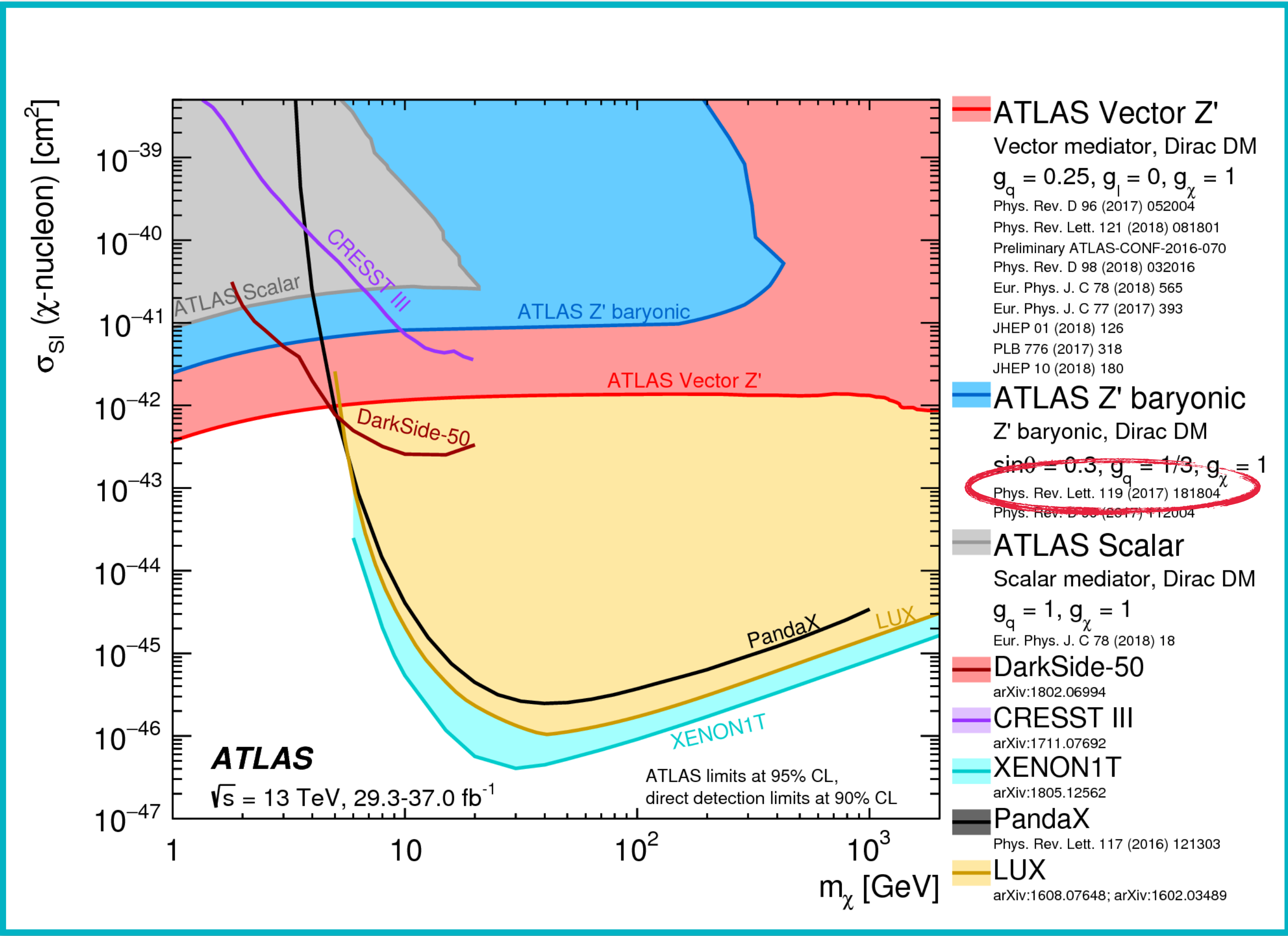
COMPARISON WITH CMS

Different parameter choice:

ATLAS $m_{H^{+-}}=m_H=300\text{GeV}$, CMS $m_A=m_{H^{+-}}=m_H$ (300-800GeV)



COMPARISON WITH DIRECT SEARCHES

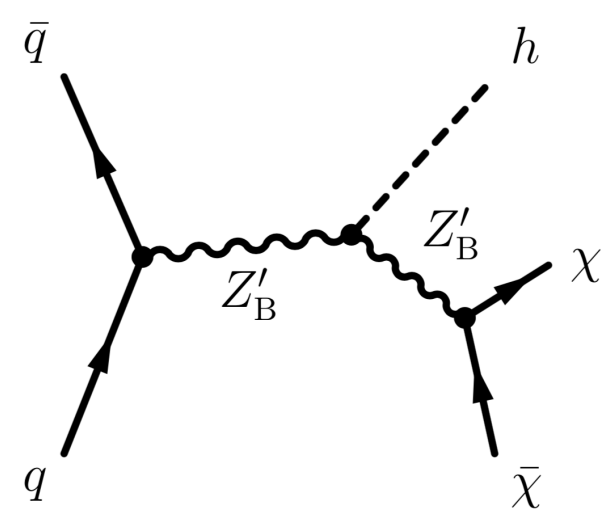


monoHbb result
@ 36/fb

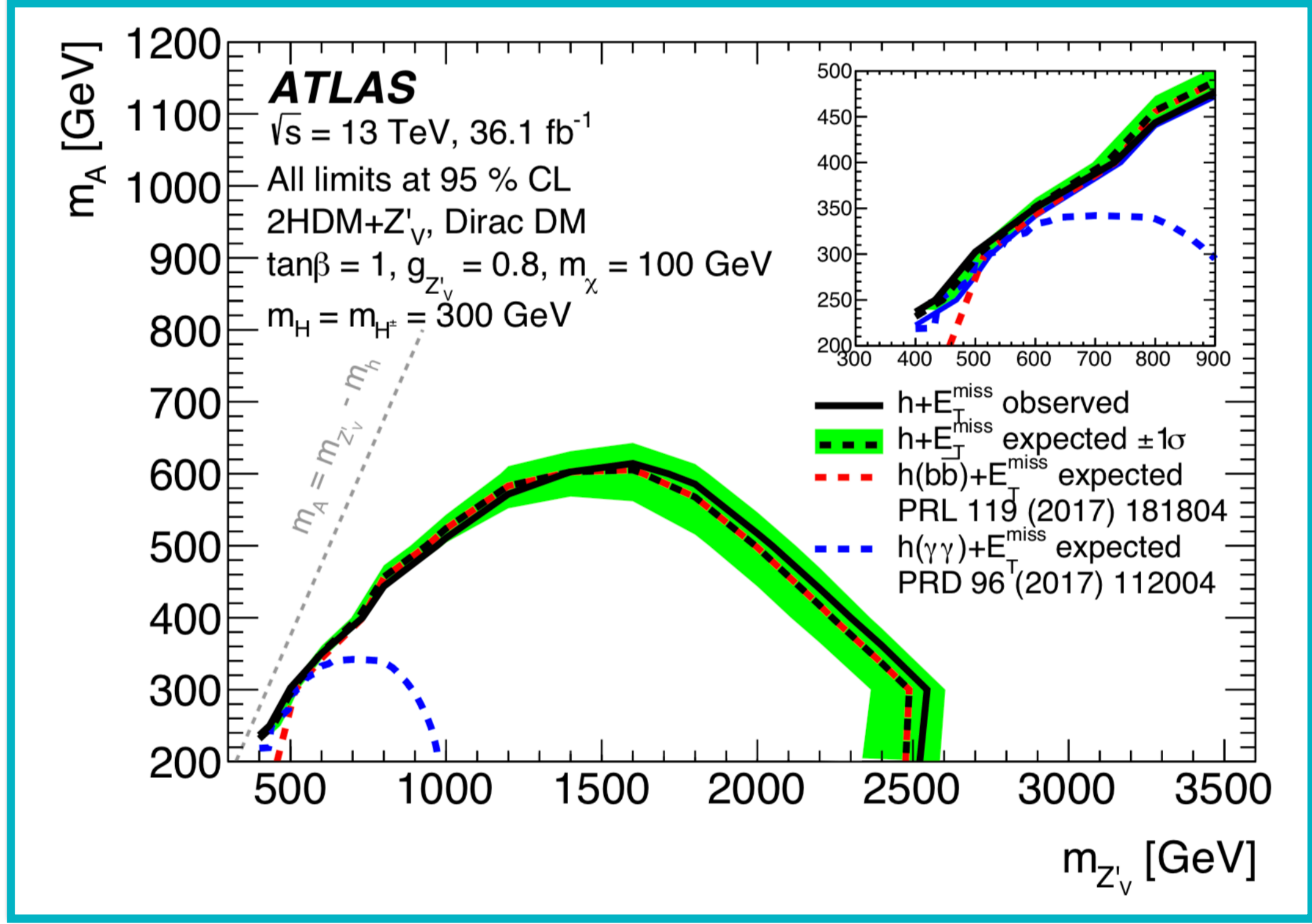
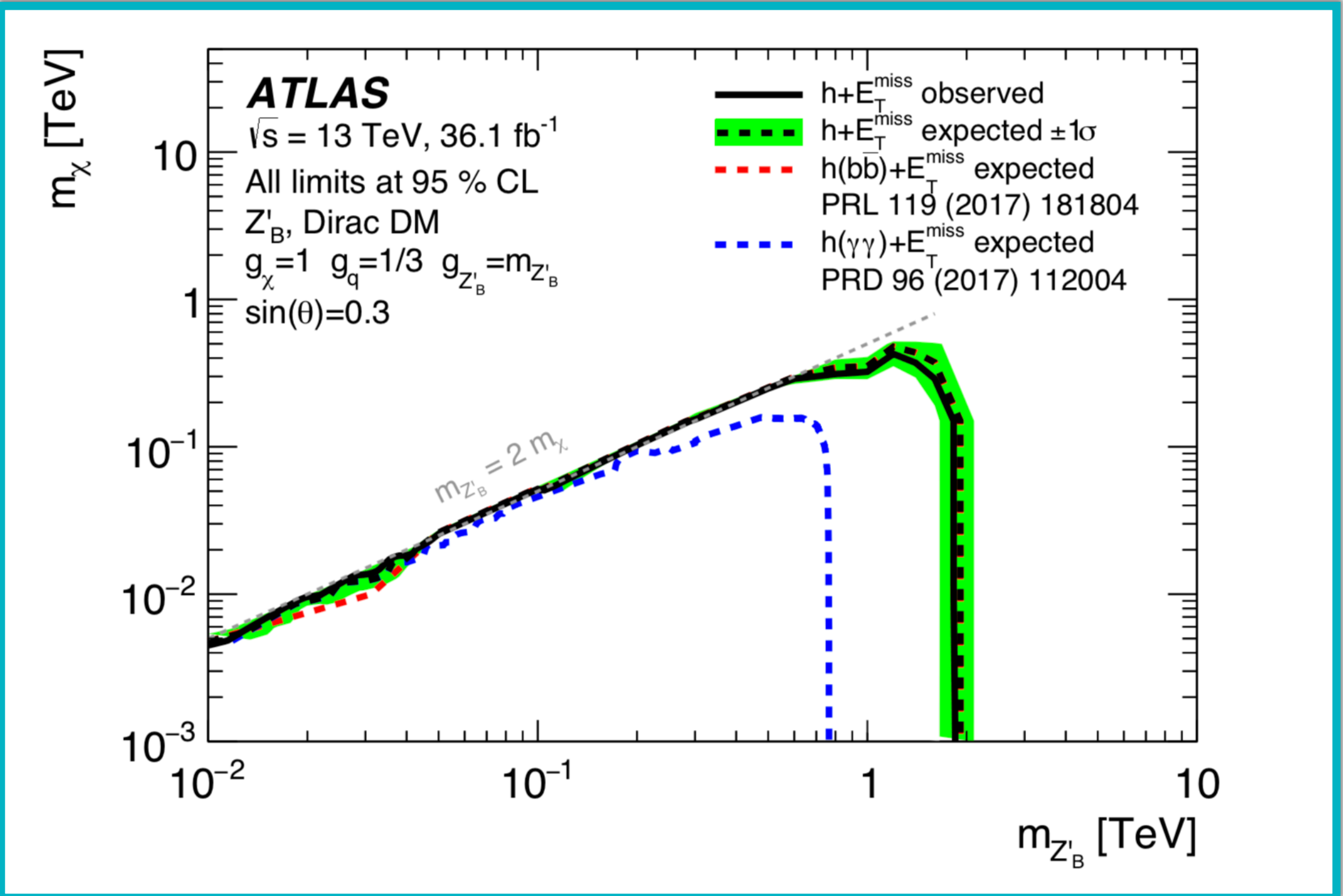
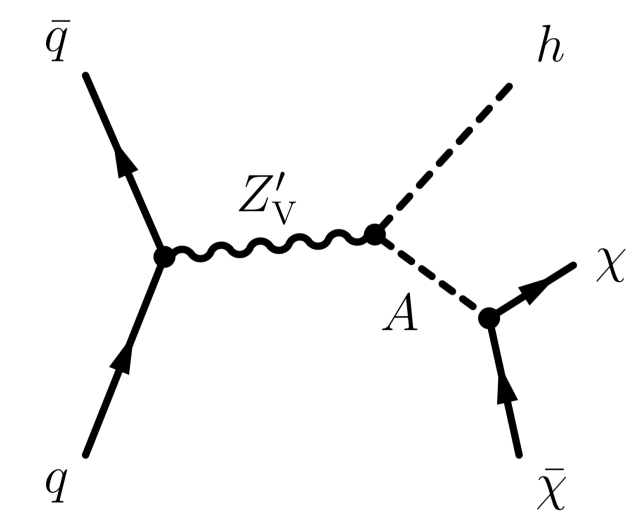
[arXiv:1903.01400](https://arxiv.org/abs/1903.01400)

COMPARISON WITH OTHER MONO-H SEARCHES

Z'_B Baryonic model



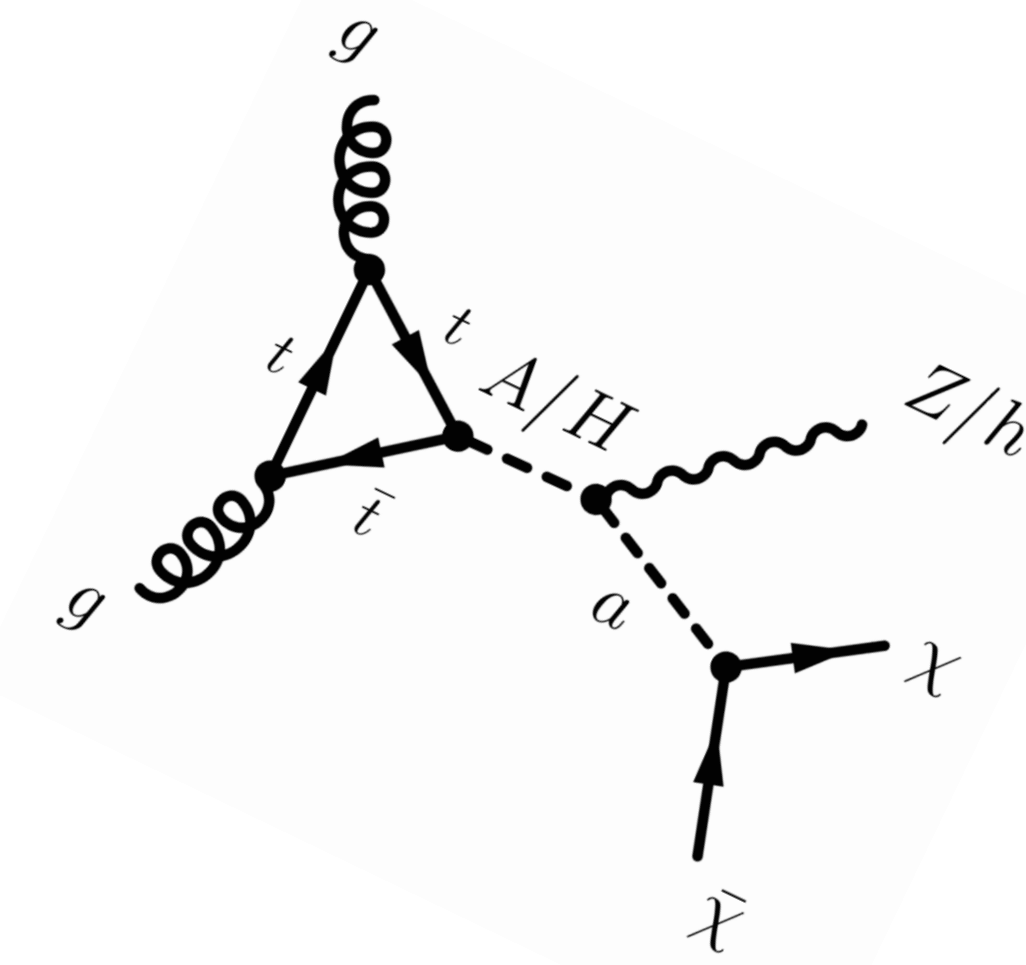
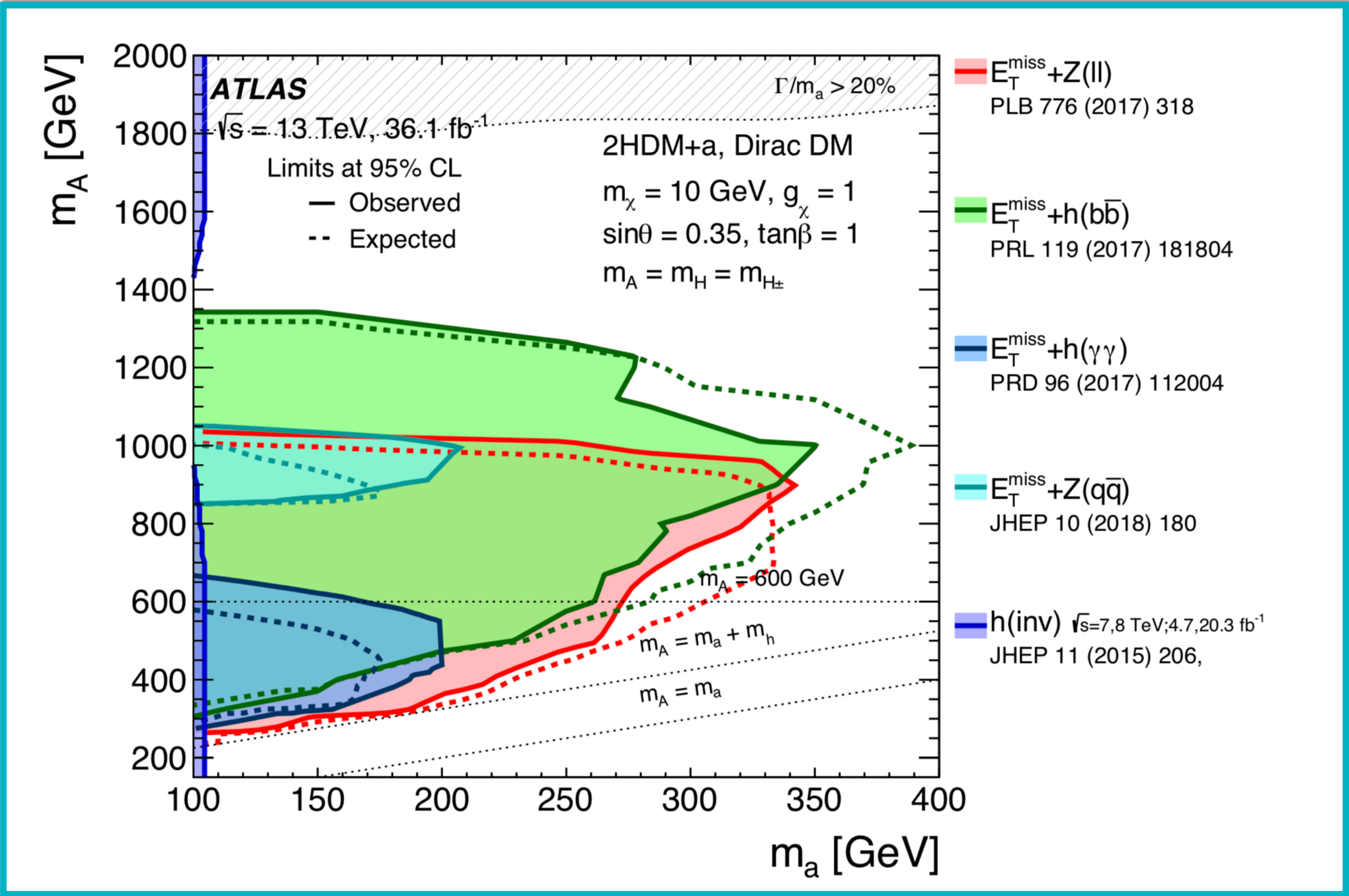
Z'_V -2HDM model



[arXiv:1903.01400](https://arxiv.org/abs/1903.01400)

COMPARISON WITH OTHER MONO-H SEARCHES

2HDM+a model



[arXiv:1903.01400](https://arxiv.org/abs/1903.01400)