Search for Dark Matter in mono-H(bb) final states

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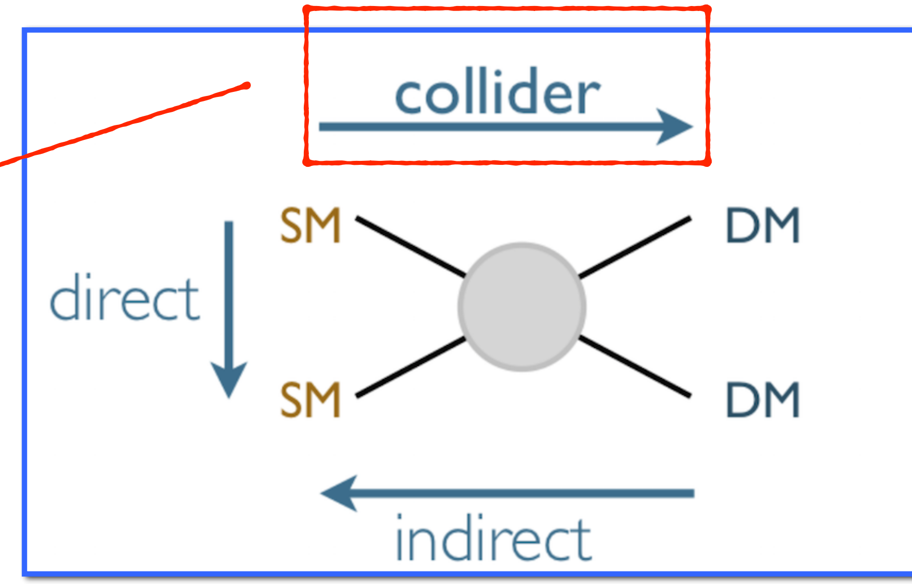
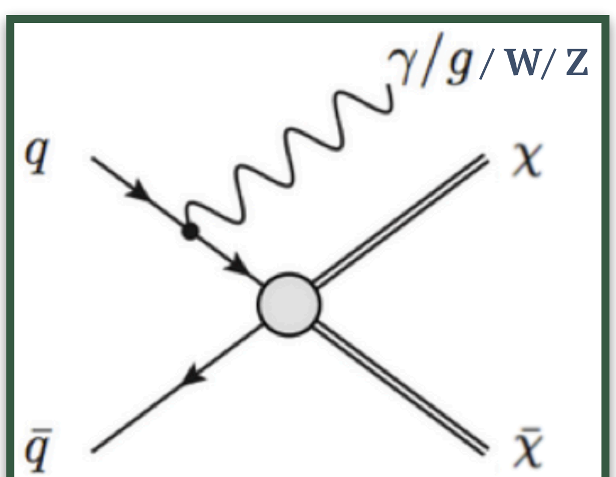
The mono-X strategy

Mono-X search as a probe for DM signals:

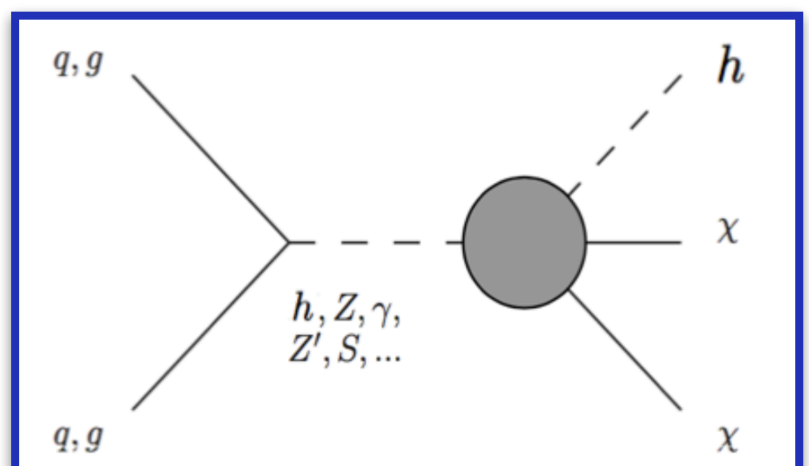
- DM particles do not interact with the detector
  - large amount of missing transverse momentum (**MET**)
- need an object **X** to trigger the event



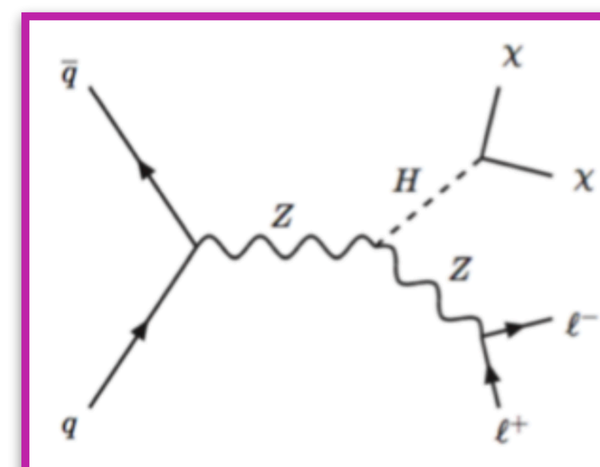
mono-γ,
mono-jet,
mono-V



mono-Higgs



Higgs->invisible



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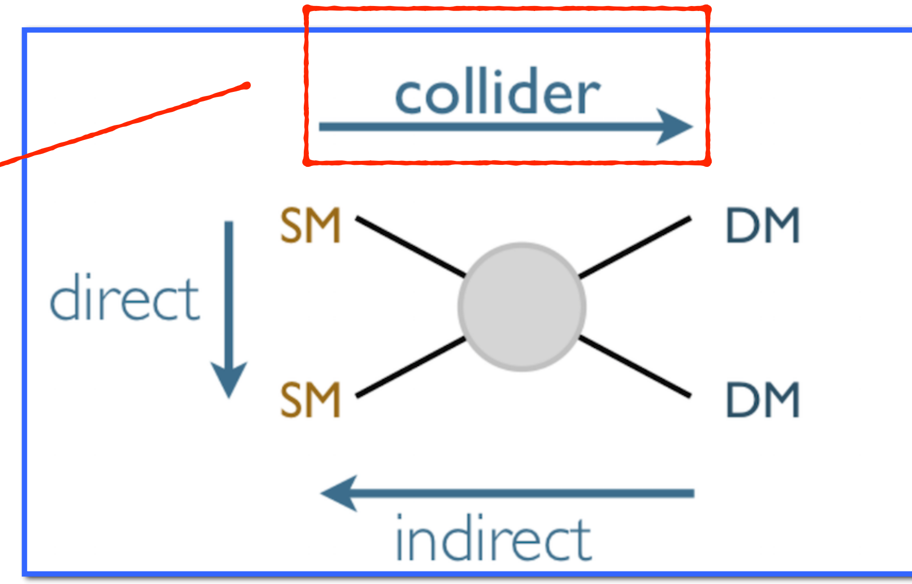

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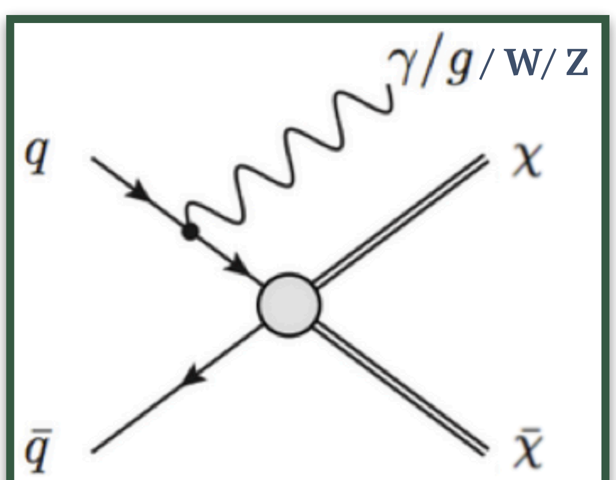
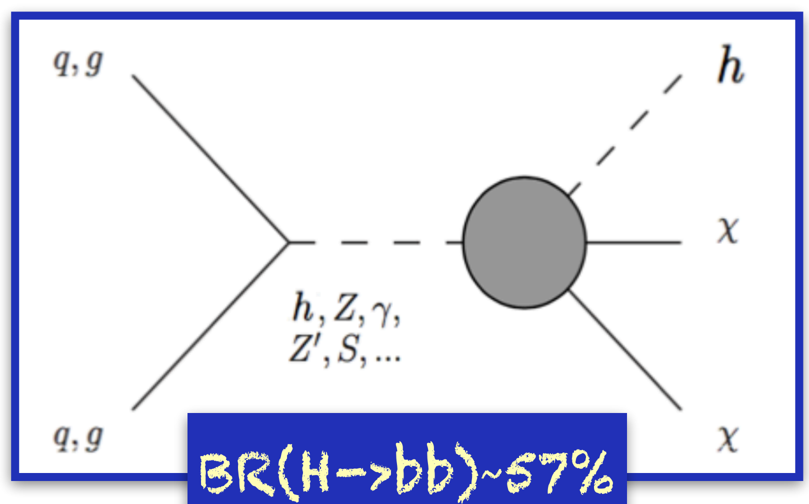
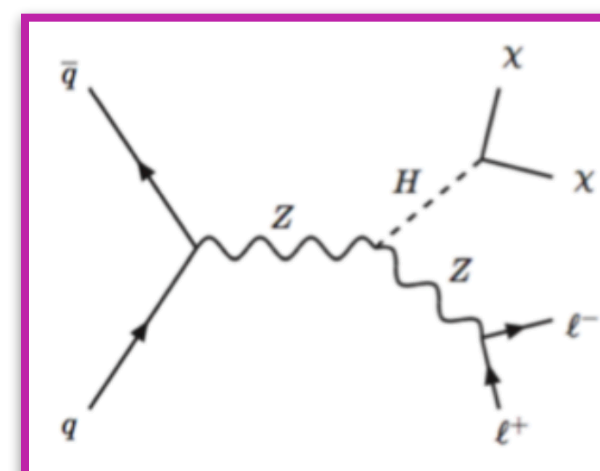


mono-Higgs



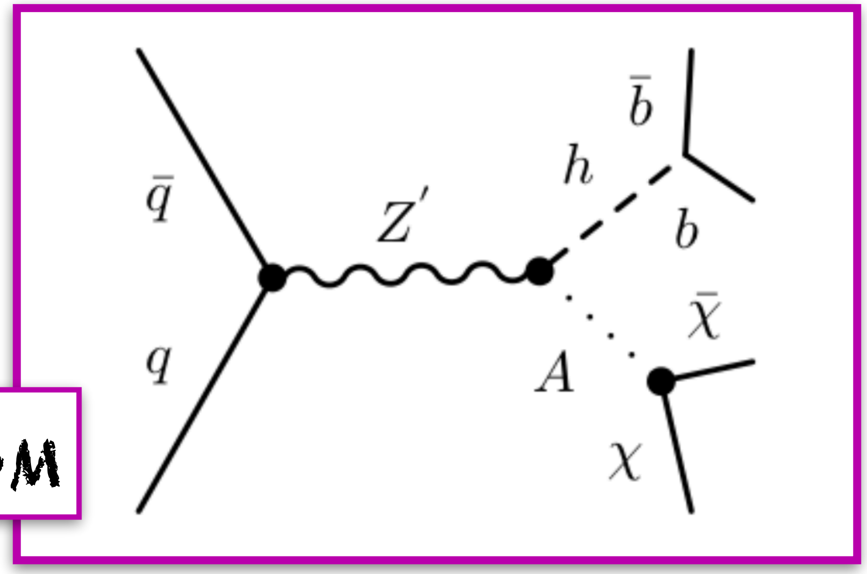
mono-H(bb)

Higgs->invisible



The mono-Hbb analysis

The production mechanism can be directly probed (complementary to other DM searches).



Z′-2HDM

→ Look for a bump in the m_{bb} distribution.

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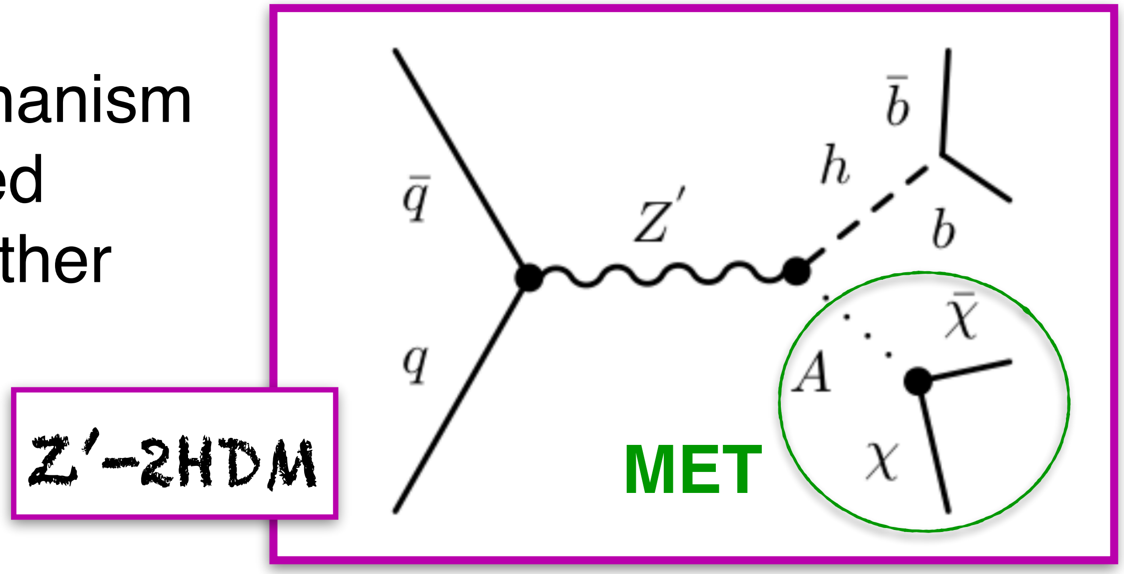

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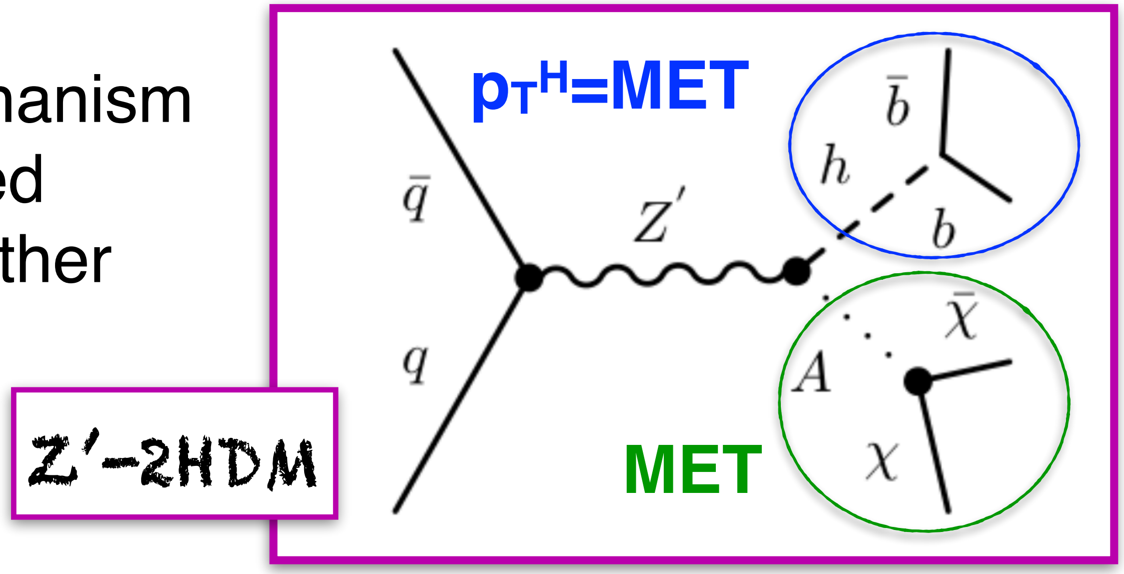

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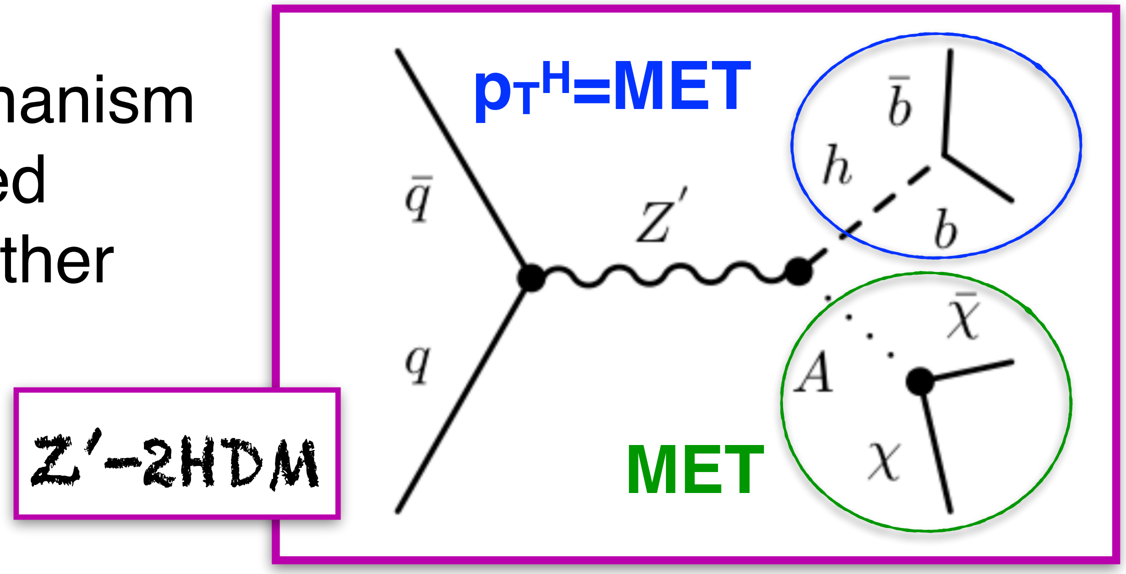

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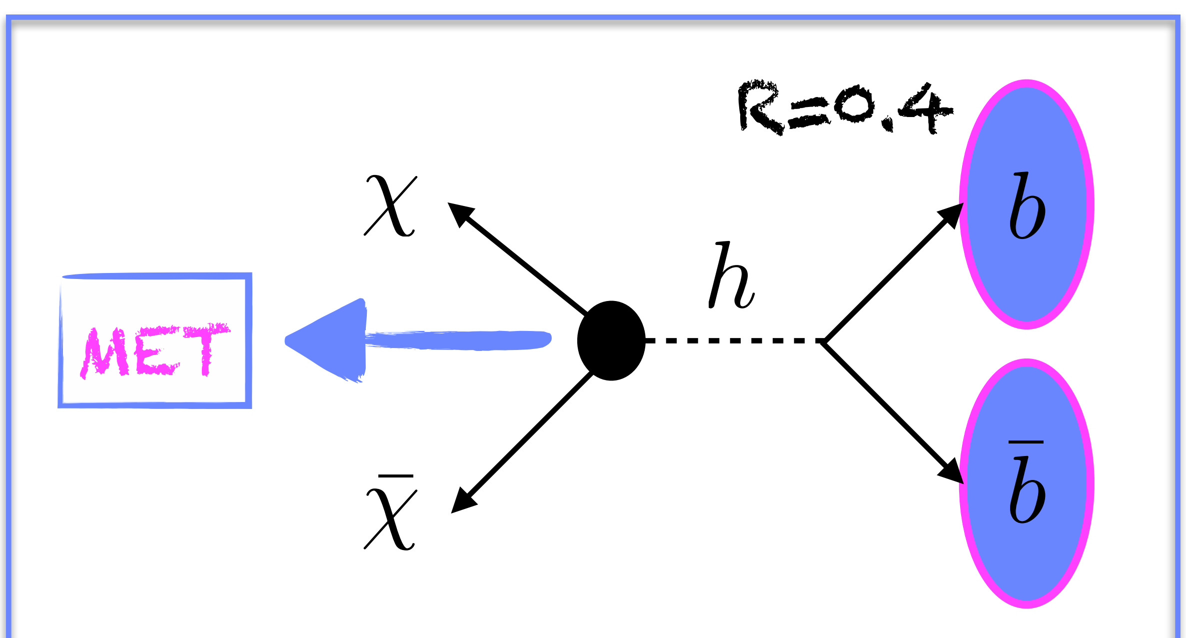
Low p_T of the Higgs boson

Resolved: MET≤500GeV



b-tagging on central small-R calo jets

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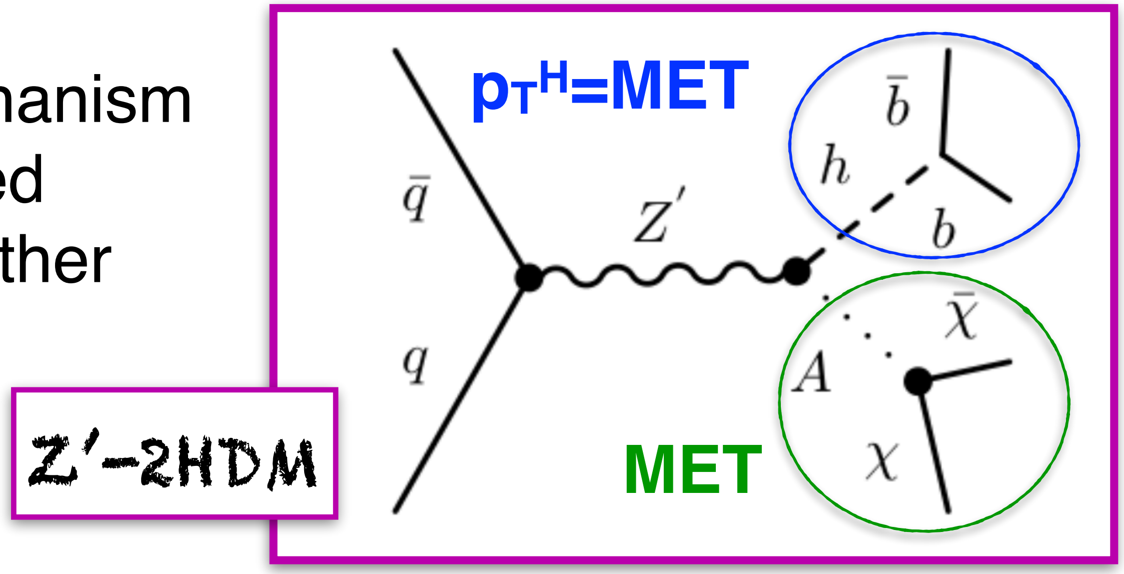

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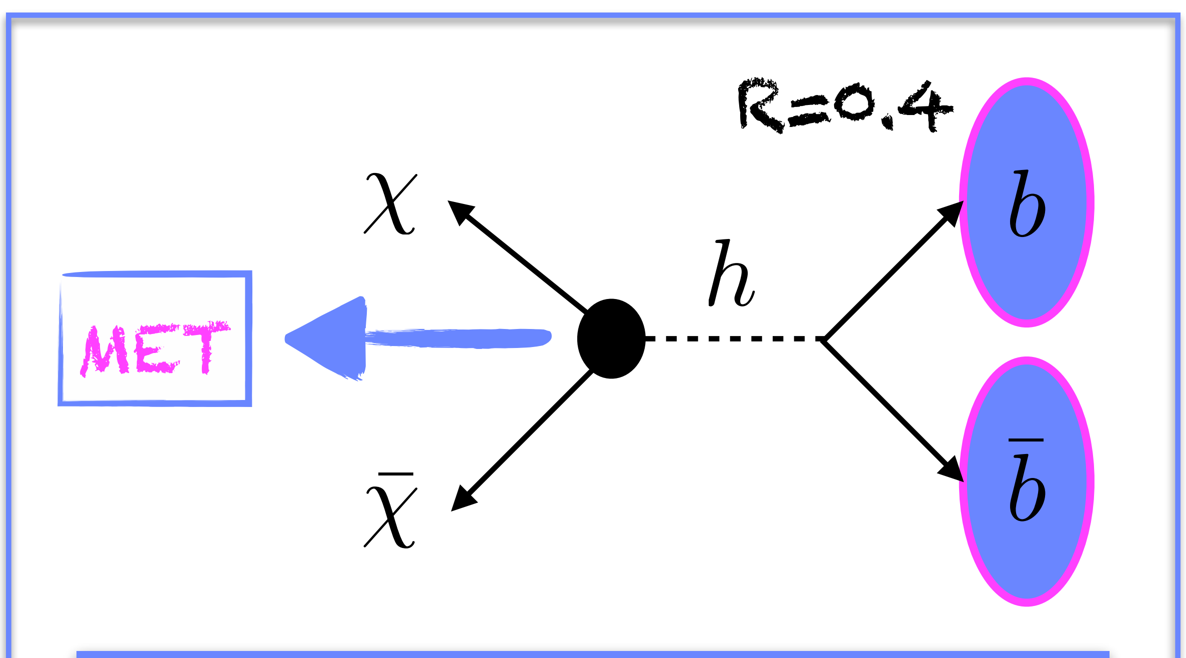
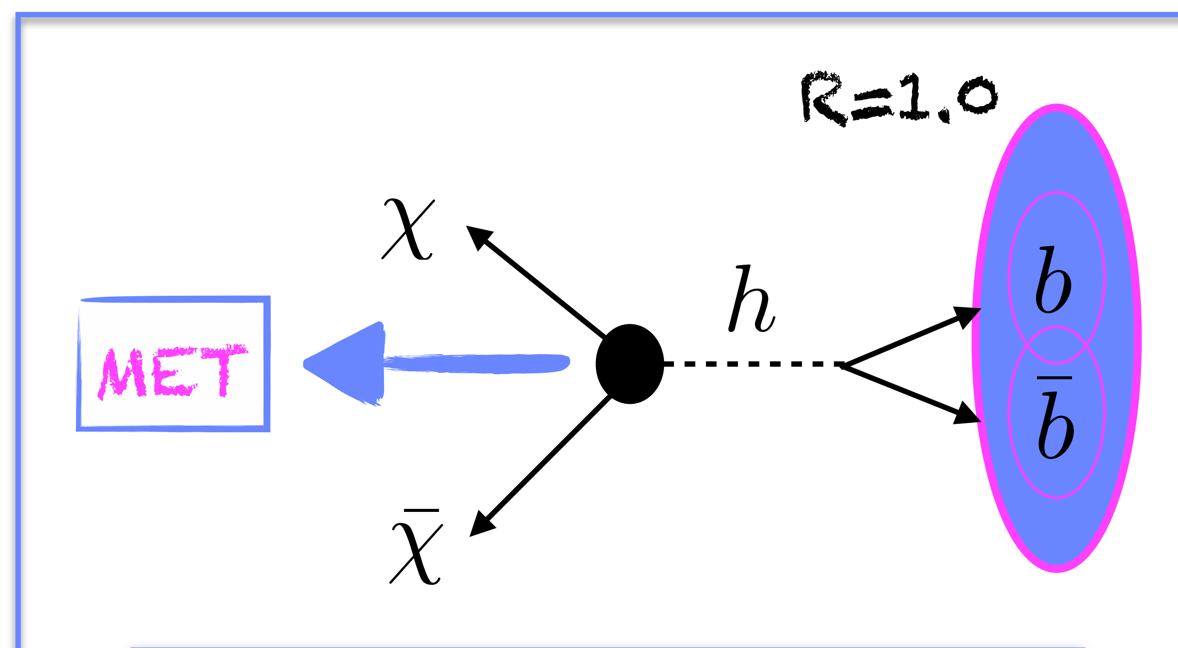


b-tagging on central small-R calo jets

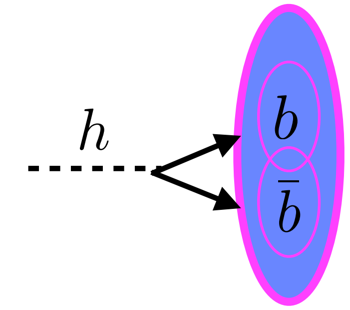
High p_T of the Higgs boson

Boosted: MET>500GeV



b-tagging on leading two track jets

Boosted topology



Angular separation between the two decay products of a high p_T particle with mass m

$$\Delta R \simeq \frac{1}{\sqrt{z(1-z)}}\frac{\mathrm{m}}{\mathrm{p_T}}$$

$\mathrm{p_T} >> m$

fraction of transverse momentum carried by the single decay product

For an Higgs boson with p_T>250GeV, the two b-jets will be contained in a single **large-R jet** with R<1.0.

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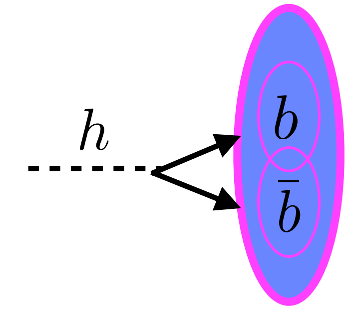

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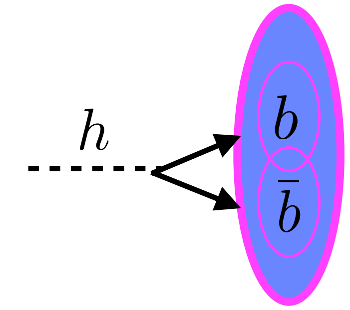
How do we reconstruct a large-R jet?

Boosted topology



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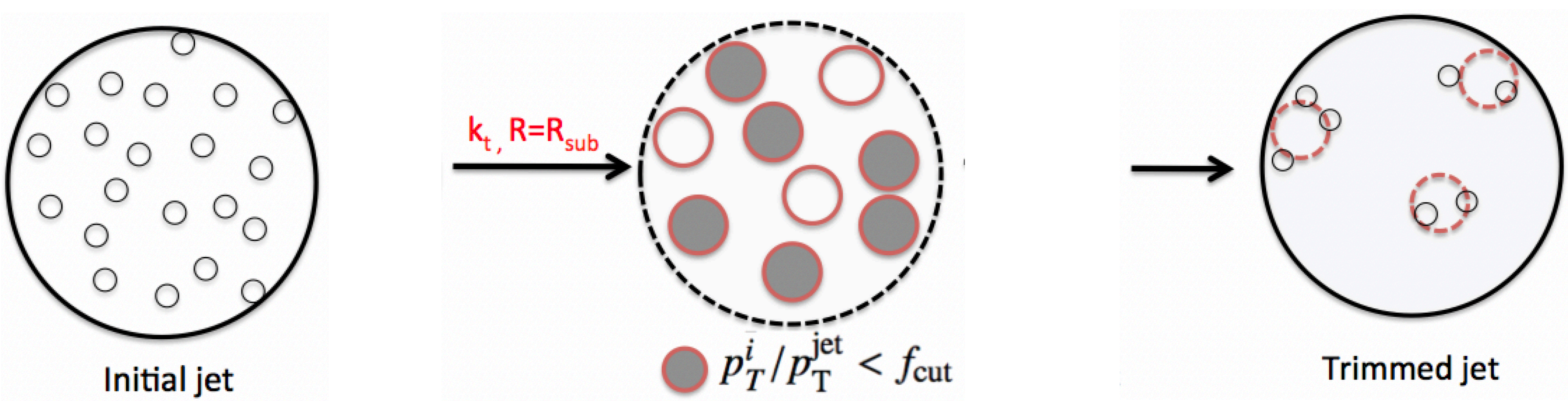
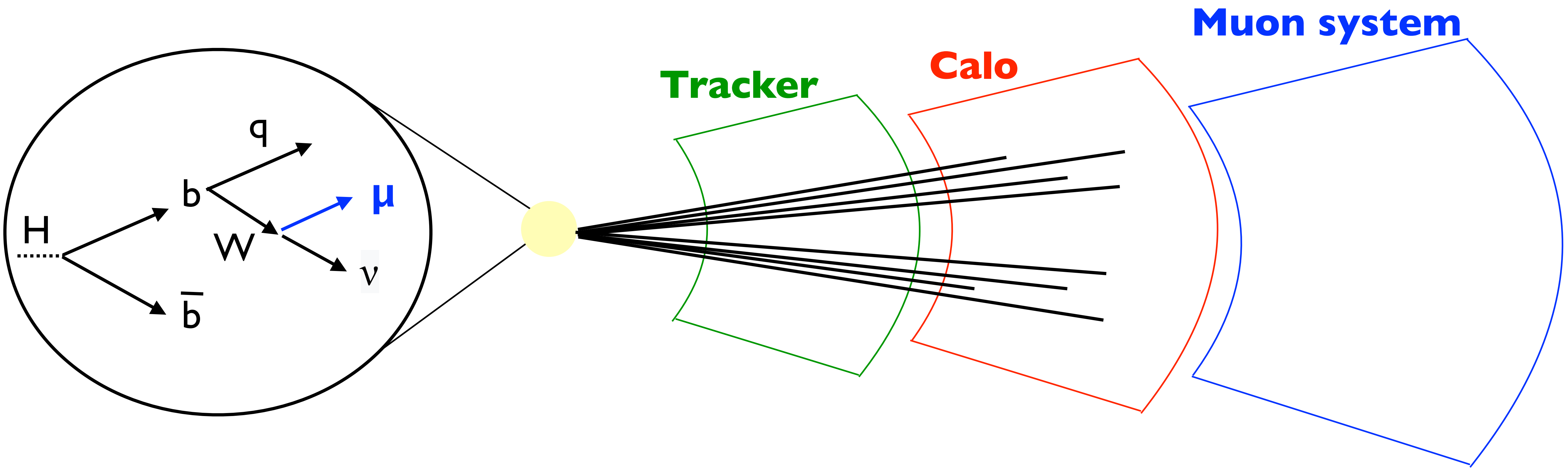


large-R jet
anti-k_T R=1.0

subjets
k_T R_{sub}= 0.2, f_{cut} = 5%

PU and UE reduction

Boosted H->bb tagging



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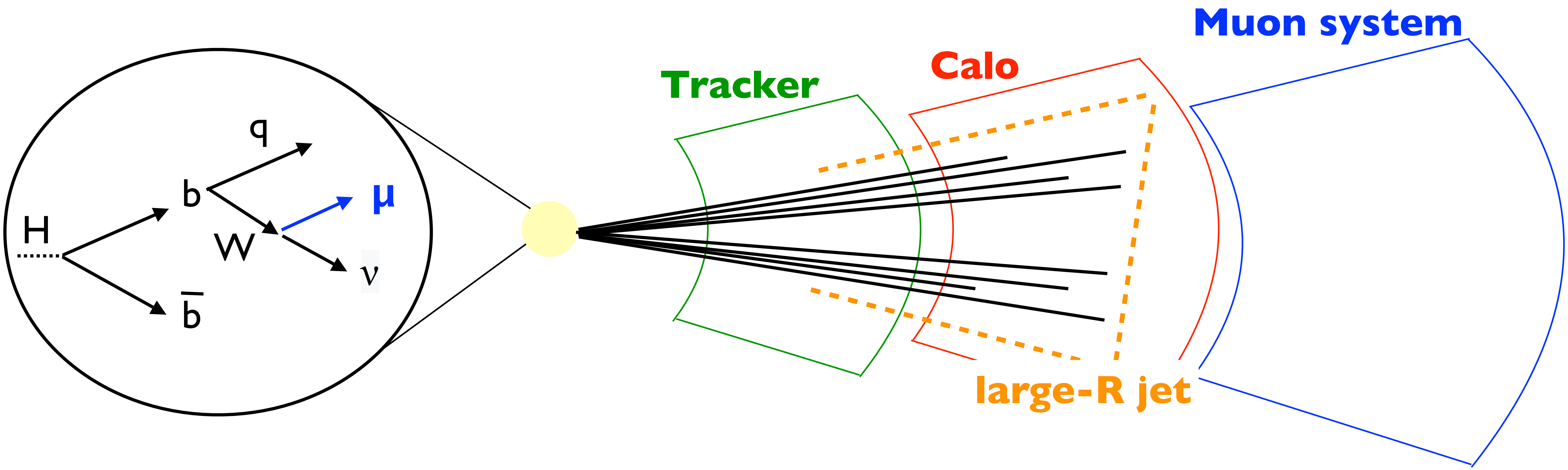
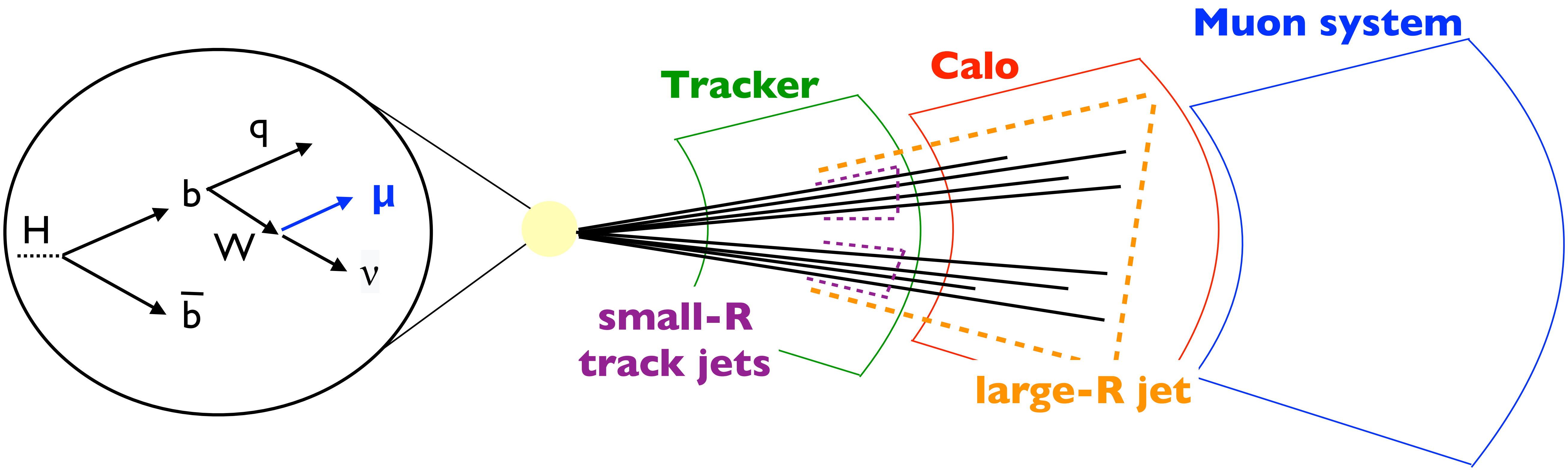


- **large-R jets**:
  - R=1.0 trimmed jets, p_T > 200 GeV

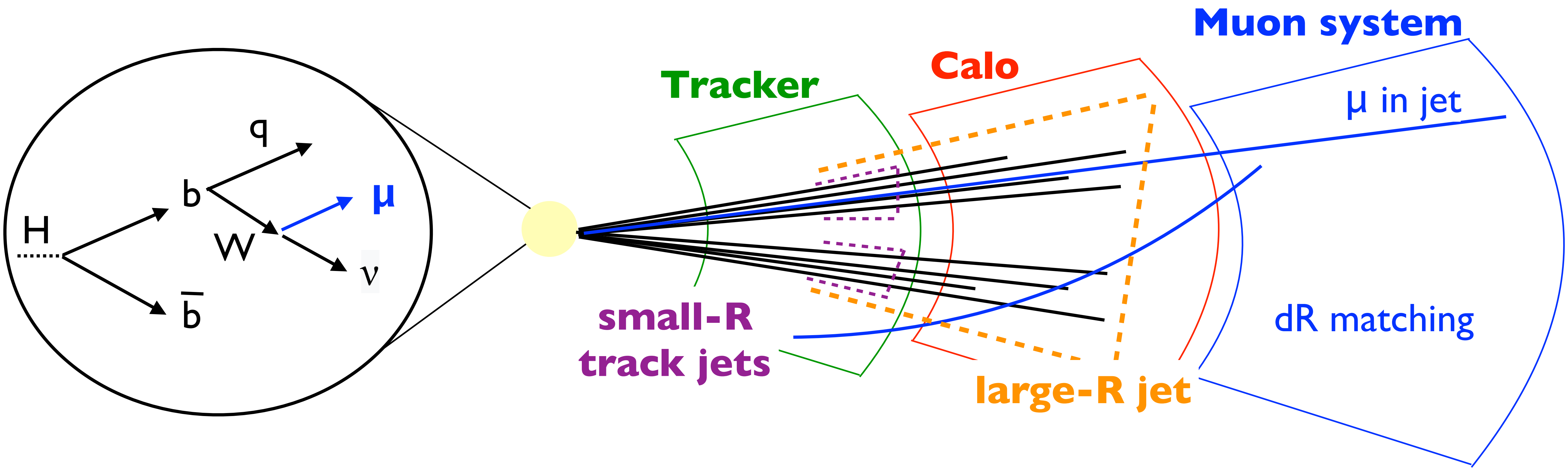
Boosted H->bb tagging



- large-R jets:
  - R=1.0 trimmed jets, $p_T > 200$ GeV

- track jets:
  - R=0.2, $p_T > 10$ GeV. **b-tagging done on track jets**.

Boosted H->bb tagging

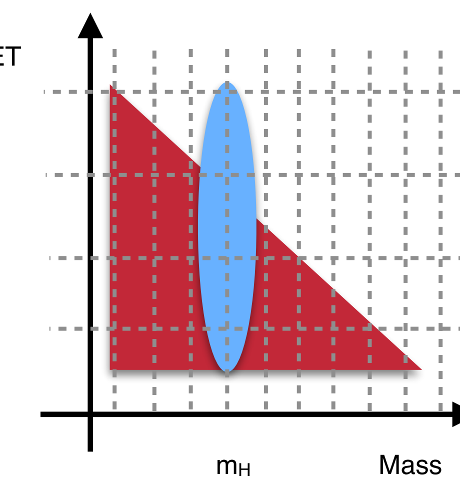


- **large-R jets**:
  - R=1.0 trimmed jets, p_T > 200 GeV
- **track jets**:
  - R=0.2, p_T > 10 GeV. **b-tagging done on track jets**.
- **muon in jet correction**:
  - add the μ four momentum to the one of the large-R jet if dR(b-tagged track jet, μ)<0.2

The mono-Hbb analysis strategy

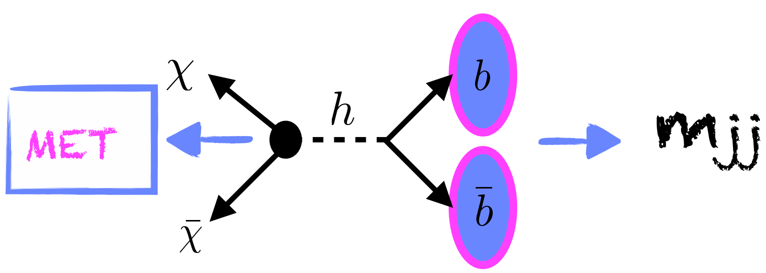
Divide events depending on:

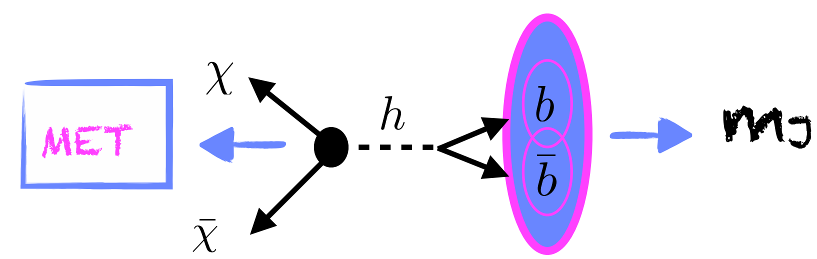
- lepton multiplicity: 0 lepton (SR), 1 and 2 lepton (CRs)
- b-tag multiplicity: 1,2 b-tags
- MET: 4 bins (3 for resolved and 1 for merged regime)
- **final discriminant: m_{jj}/m_J**

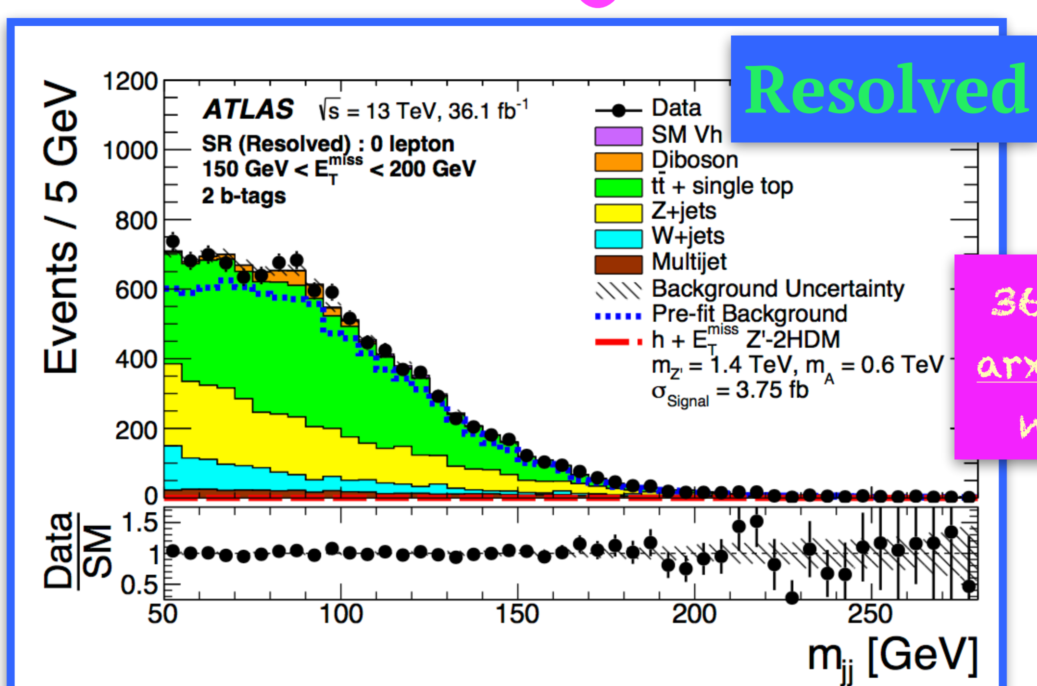


↓

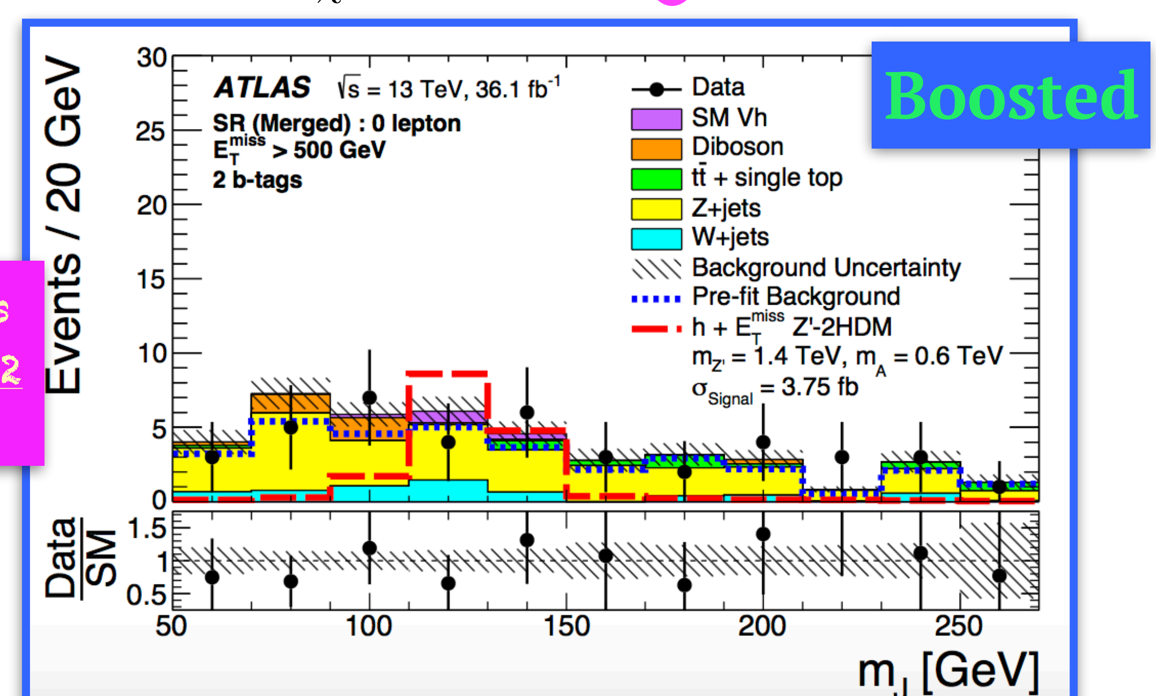
24 regions fitted simultaneously





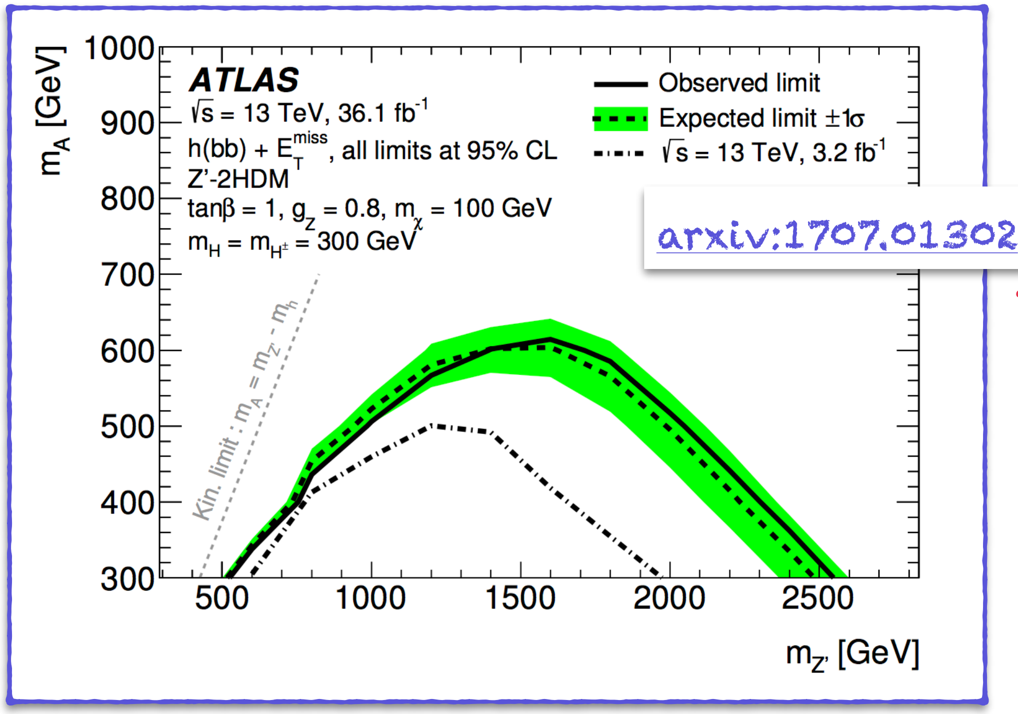


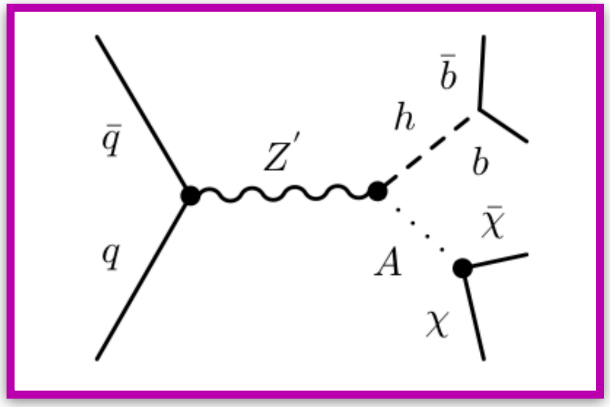
36.1fb⁻¹ results
arxiv:1707.01302
now in PRL!



The mono-Hbb results @ 36.1fb-1

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

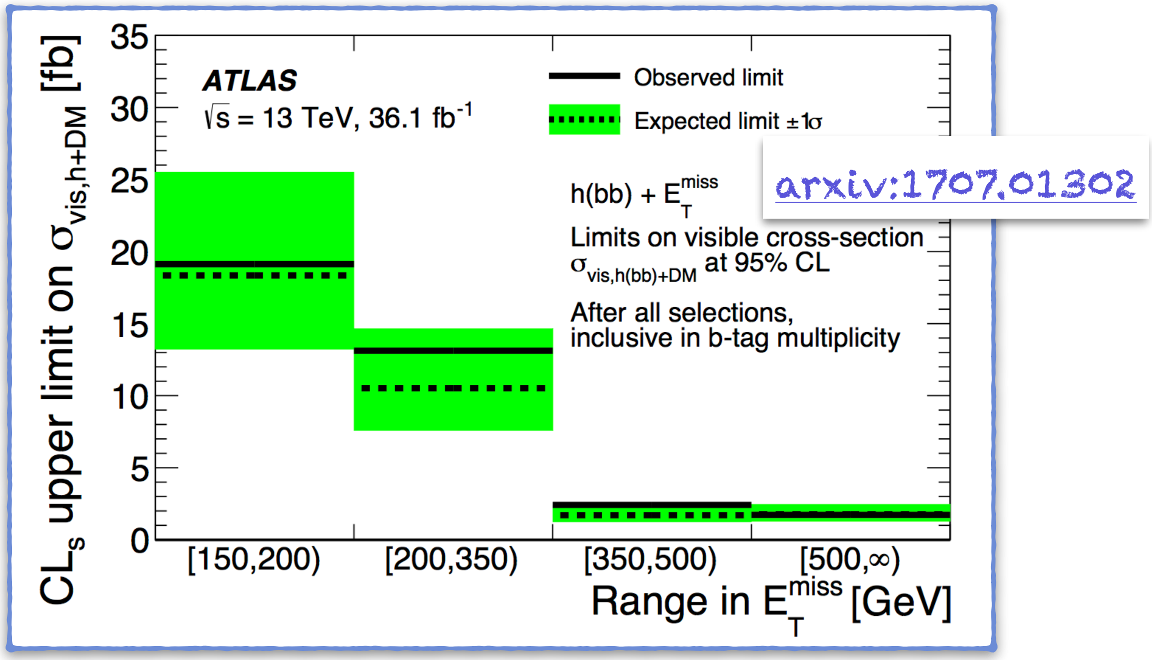




…and also as **less model-dependent** limits on:

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

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



So far so good...what's next?

The mono-Hbb analysis is aiming now for a public result in early 2018 with full dataset 2015+2016+**2017**:

- improvements expected by the usage of Variable Radius track jets (for b-tagging) and MET significance

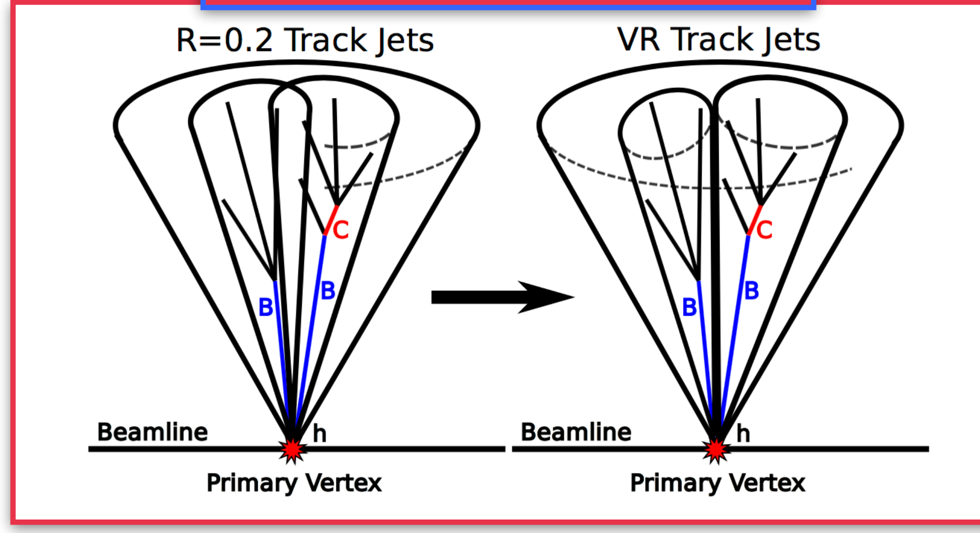
Variable Radius track jets

arXiv:0903.0392

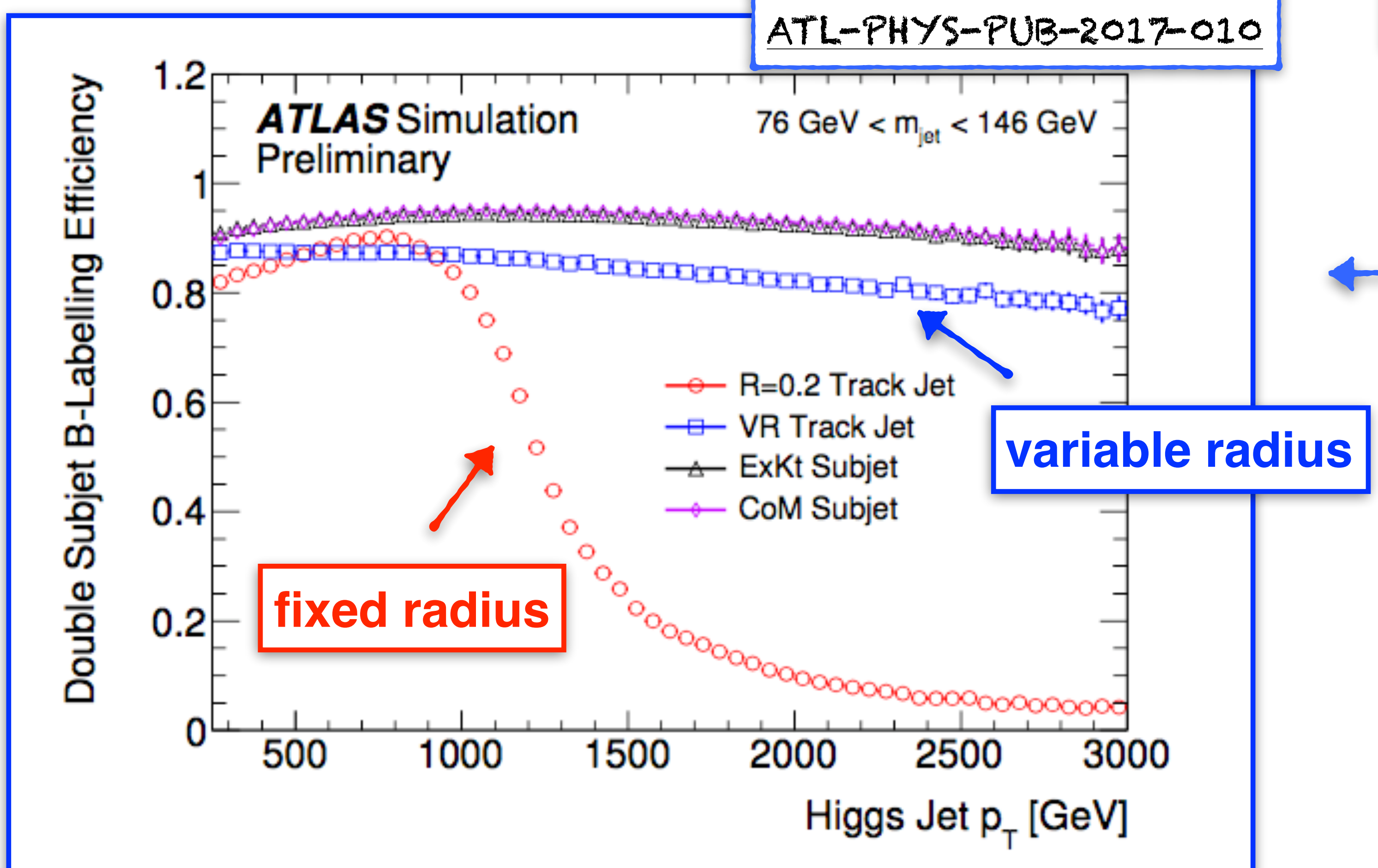
At very high p_T, the two track jets tend to merge. This leads to a worse background (ttbar,qcd) rejection for fixed radius track jets.

Solution: adjust the radius on varying of the track jet p_T.

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



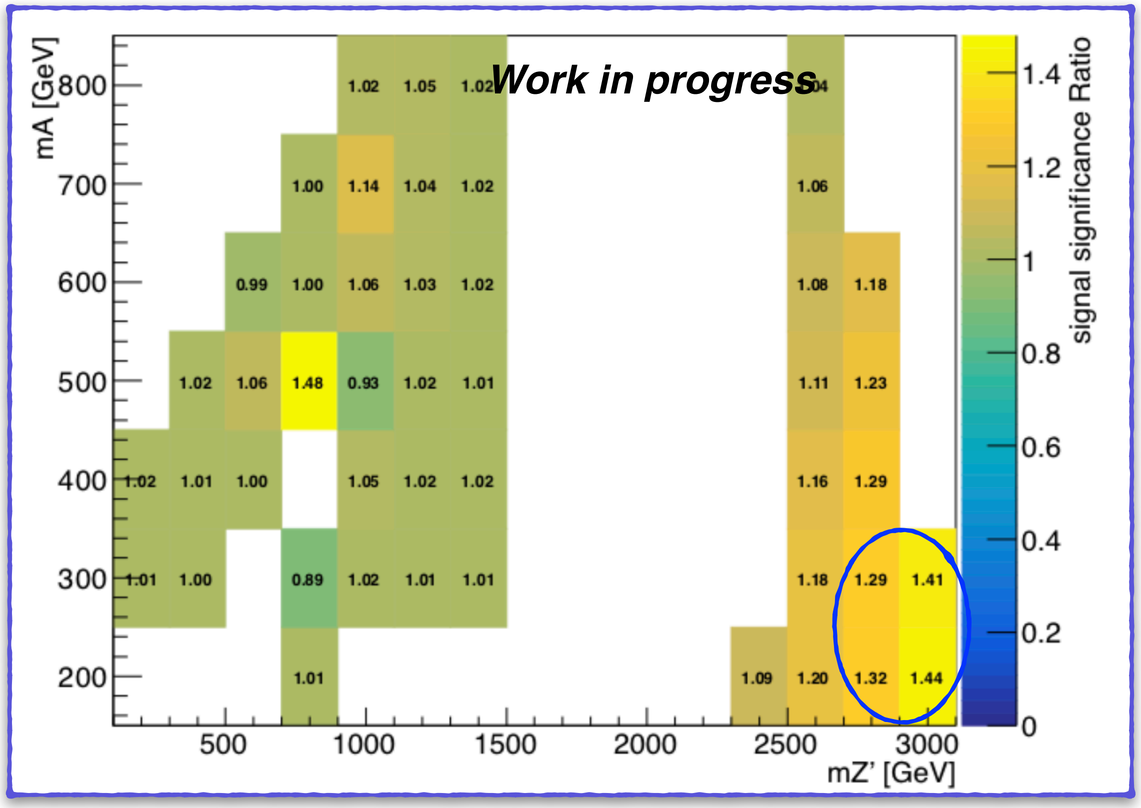
ATL-PHYS-PUB-2017-010



Efficiency for a Higgs jet to have its two leading subjets matched to truth b-hadrons as a function of Higgs jet p_T.

Higgs jet: large-R jet matched to two truth b-hadrons and one truth Higgs boson.

Variable Radius track jets

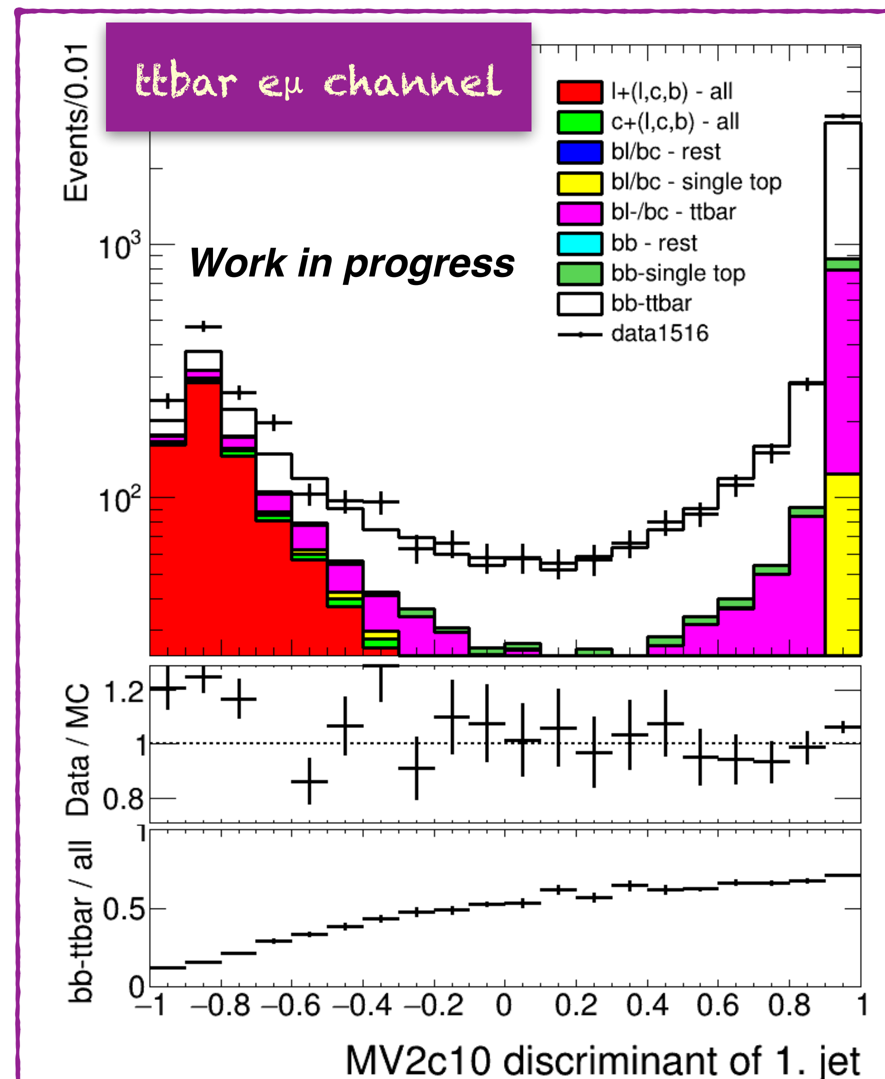


- improved acceptance in 2-tag boosted region
- improved signal significance at high $m_{Z'}$, expected gains up to 40%

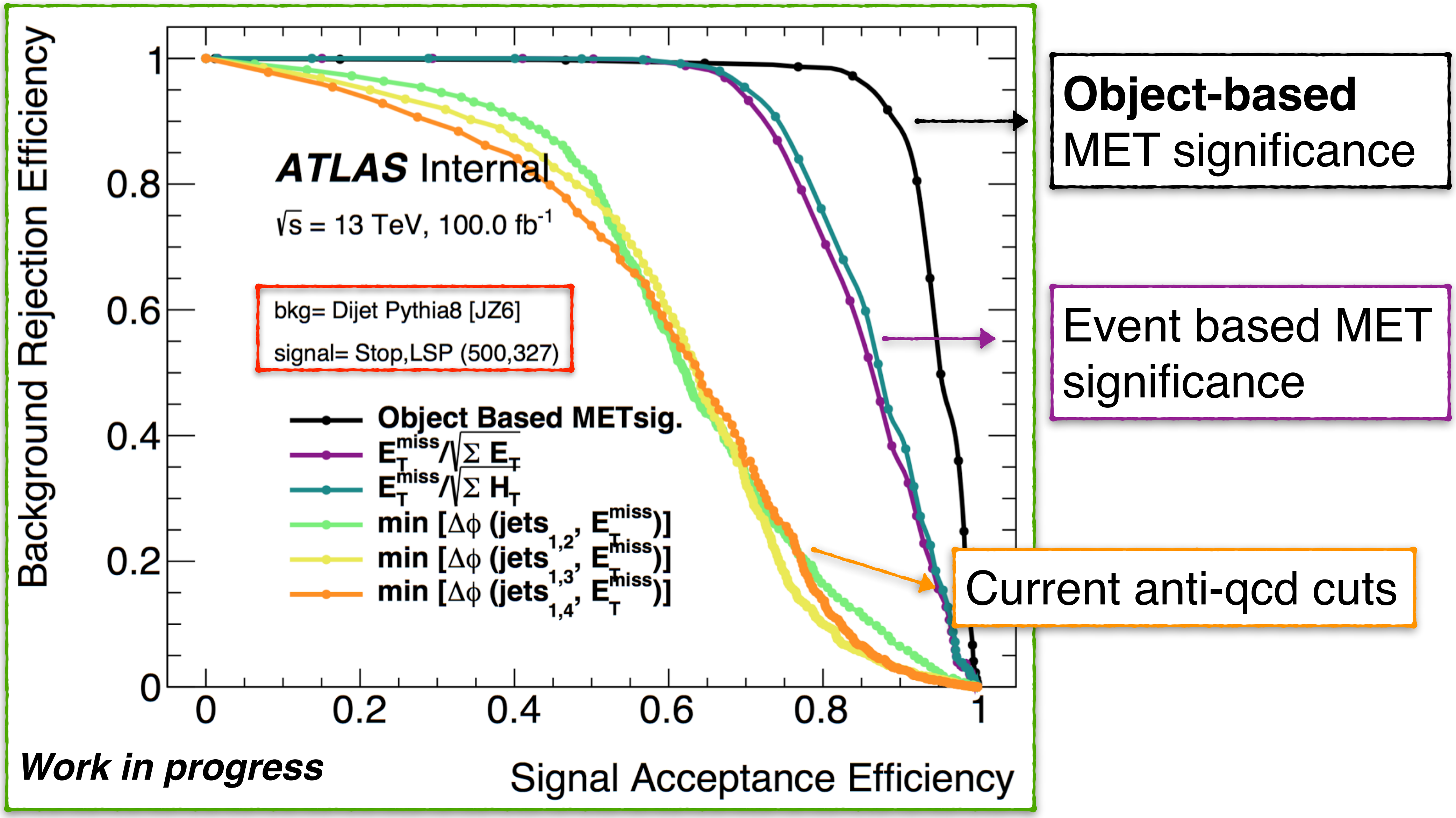
The b-tagging working points and efficiencies are derived from simulation.

Ongoing effort in the *calibration* to measure the b-tag efficiency and mistag rate in data.

First data/MC comparison



MET significance

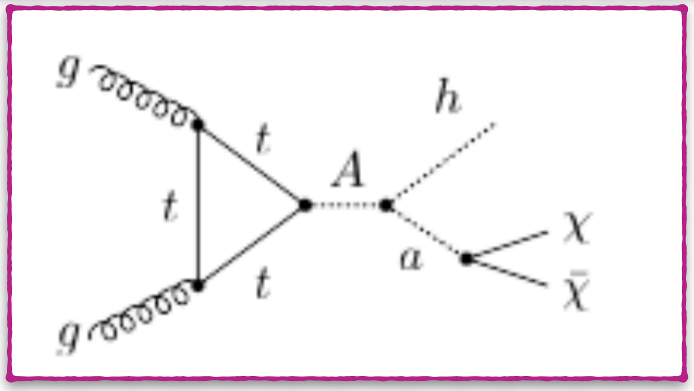


- A new object-based definition of the MET significance gives so far the best discrimination
- Currently checking the performance

Reinterpretations

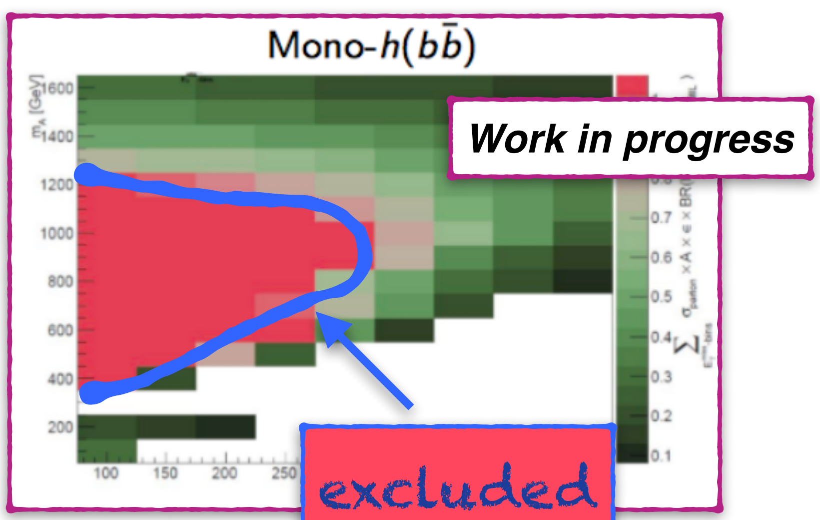
Many BSM signals share the same final state. Need of a reinterpretation!

Study of a new signal model: **scalar mediator model a+2HDM.**



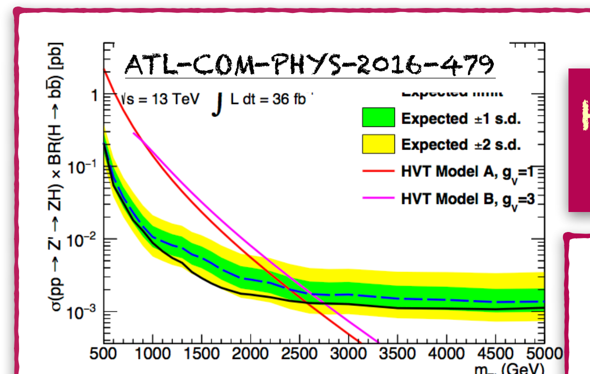
Compare the parton level cross section wrt the model independent limit, bin by bin, to estimate the sensitivity.

$$\sum_{\mathrm{E_T^{miss}\,bins}} \sigma_{\mathrm{parton}} \times A \times \varepsilon \times BR(h \to b\bar{b})/\sigma_{\mathrm{MIL}}$$



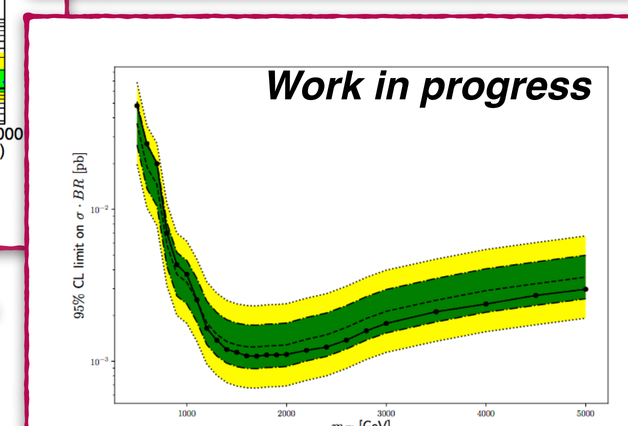
Study of **any** possible signal model with same final state.

Capture of the analysis with the **RECAST** framework.



Original Analysis

Heavy Vector Triple model
Z'->ZH->vvbb

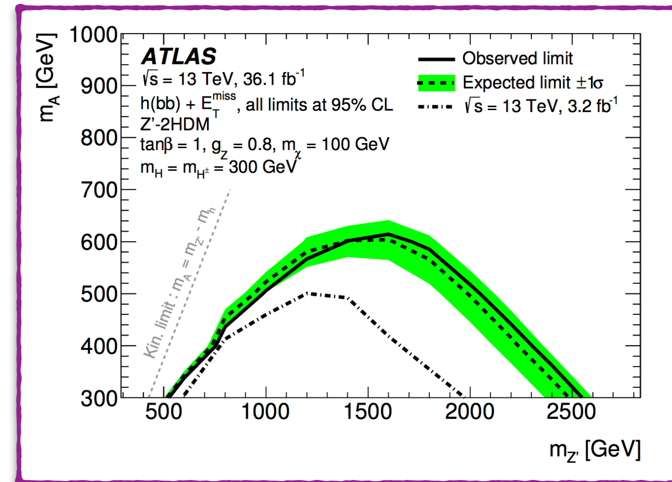


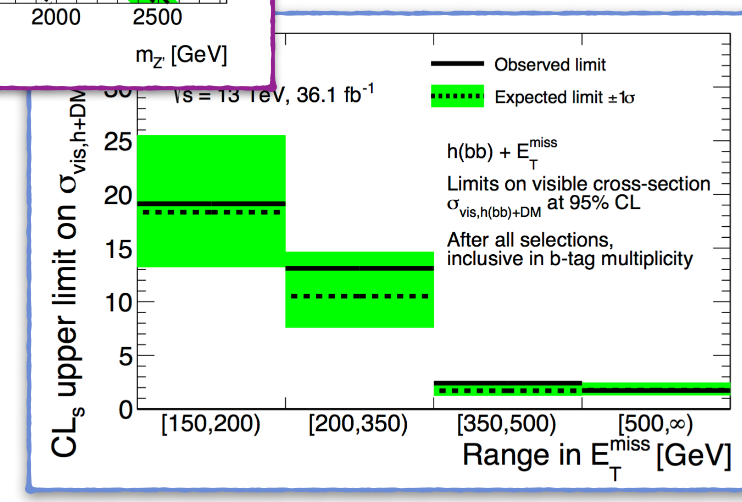
Mono-H(bb) RECAST

Planned to be used also for **Dark Higgs** and **a+2HDM** model.

Conclusions

- The mono-X search is one of most interesting ways to look for DM at the LHC
- Mono-Hbb results for 36.1fb^{-1} with full 2015+2016 dataset published in **PRL**
  - no DM signals *(yet)*
  - exclusion limits on Z’-2HDM model and less model dependent limits
- Aiming now for a publication in early 2018 including also **2017** data
  - expected improvements:
    - VR track jets
    - MET significance





STAY TUNED!

Thanks for your attention!

BACKUP SLIDES

Challenges faced during last iteration of the analysis

problematic at high p_T...we should use a better V+jets slicing

MET

Source of uncert.	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

- large systematic
- difficulties in the fit configuration

large impact due to extrapolation at high p_T. Might be solved with a dedicated calibration using dijet(bb) events.

statistically limited at medium-high MET

Mono-H(bb) event selection

Main backgrounds: Z(vv)+jets (30-60%), W(lv)+jets (10-25%) and ttbar (15-50%).

0-lep SR | 1-μ CR | 2-lep CR

<table>
<tr><th>Region</th><th>SR</th><th>1μ-CR</th><th>2ℓ-CR</th></tr>
<tr><td>Trigger</td><td>E_T^{miss}</td><td>E_T^{miss}</td><td>Single lepton</td></tr>
<tr><td>Leptons</td><td>No e or μ</td><td>Exactly one μ</td><td>Exactly two e or μ
83 GeV $< m_{ee} <$ 99 GeV
71 GeV $< m_{\mu^\pm\mu^\mp} <$ 106 GeV</td></tr>
<tr><td rowspan="2">Resolved</td><td>$E_T^{miss} \in [150, 500)$ GeV
$p_T^{miss,trk} > 30$ GeV (1 b-tag only)
$\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{j}\right)\right] > \pi/9$
$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss,trk}\right) < \pi/2$
–</td><td>$p_T(\mu, E_T^{miss}) \in [150, 500)$ GeV
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–</td><td>$p_T(\ell, \ell) \in [150, 500)$ GeV
–
–
–
$E_T^{miss} \times \left(\sum_{jets,leptons} p_T\right)^{-1/2} < 3.5\ \mathrm{GeV}^{1/2}$</td></tr>
<tr><td colspan="3">Number of central small-R jets ≥ 2
Leading Higgs candidate small-R jet $p_T > 45$ GeV
$H_{T,2j} > 120$ GeV for 2 jets, $H_{T,3j} > 150$ GeV for > 2 jets
$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_{T,h}\right) > 2\pi/3$
Veto on τ-leptons
$\Delta R\left(\vec{p}_h^{j_1}, \vec{p}_h^{j_2}\right) < 1.8$
Veto on events with > 2 b-tags
Sum of p_T of two Higgs candidate jets and leading extra jet $> 0.63 \times H_{T,all\,jets}$
b-tagging : one or two small-R calorimeter jets
Final discriminant = Dijet mass</td></tr>
<tr><td rowspan="2">Merged</td><td>$E_T^{miss} \geq 500$ GeV
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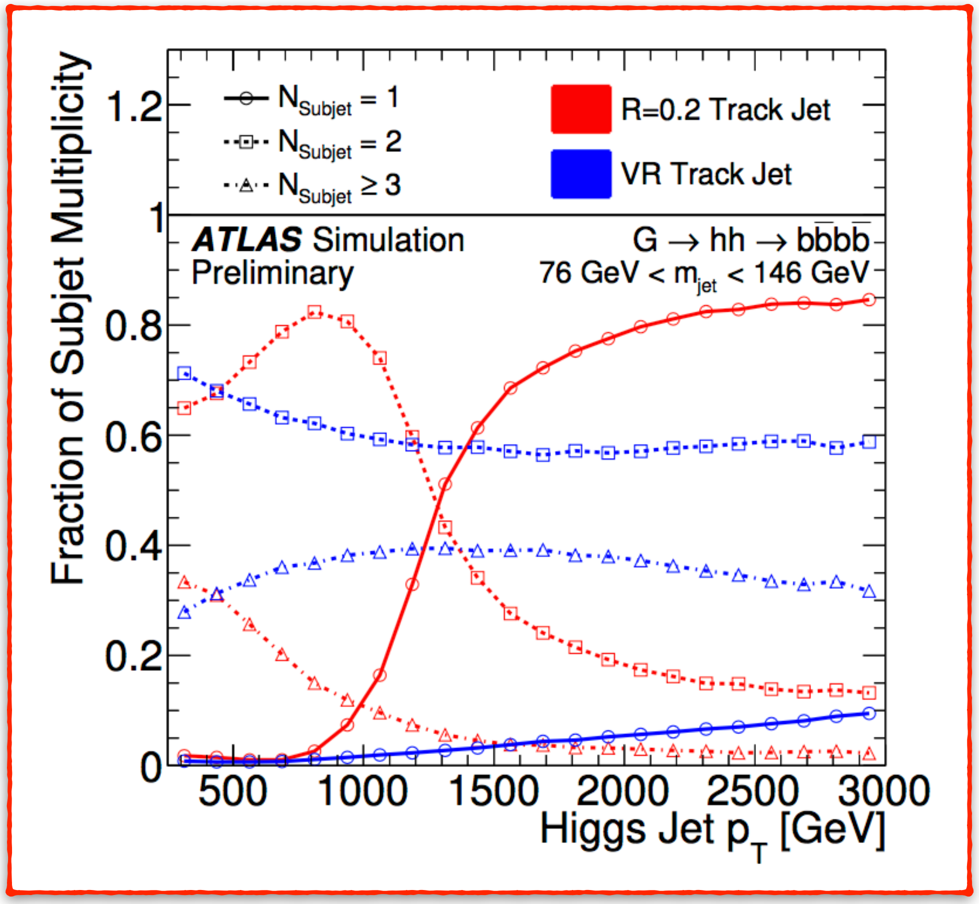
–
–
–</td></tr>
<tr><td colspan="3">Number of large-R jets ≥ 1
Veto on τ-lepton not associated to large-R jet
Veto on b-jets not associated to large-R jet
H_T-ratio selection (<0.57)
b-tagging : one or two ID track jets matched to large-R jet
Final discriminant = Large-R jet mass</td></tr>
</table>

anti-qcd cuts

- 0-lepton SR
- 1-μ CR -> W+jets and ttbar
- 2-leptons CR -> Z+jets
- data-driven estimation of the multijet background (template fit method)

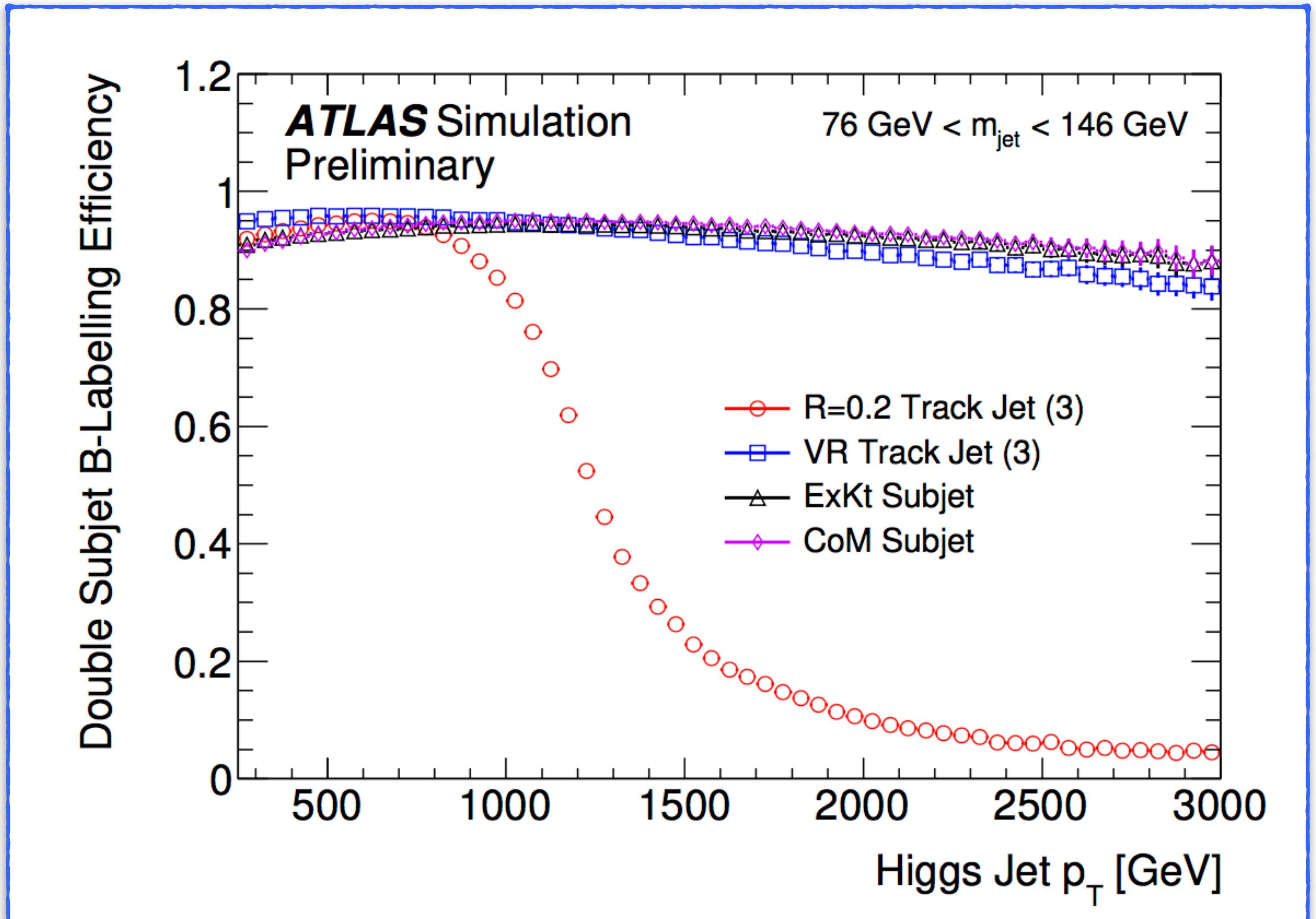
new optimised cuts:
- ttbar (and single-top, W(lv)+jets) background heavily reduced
- negligible signal loss

VR track jets efficiency

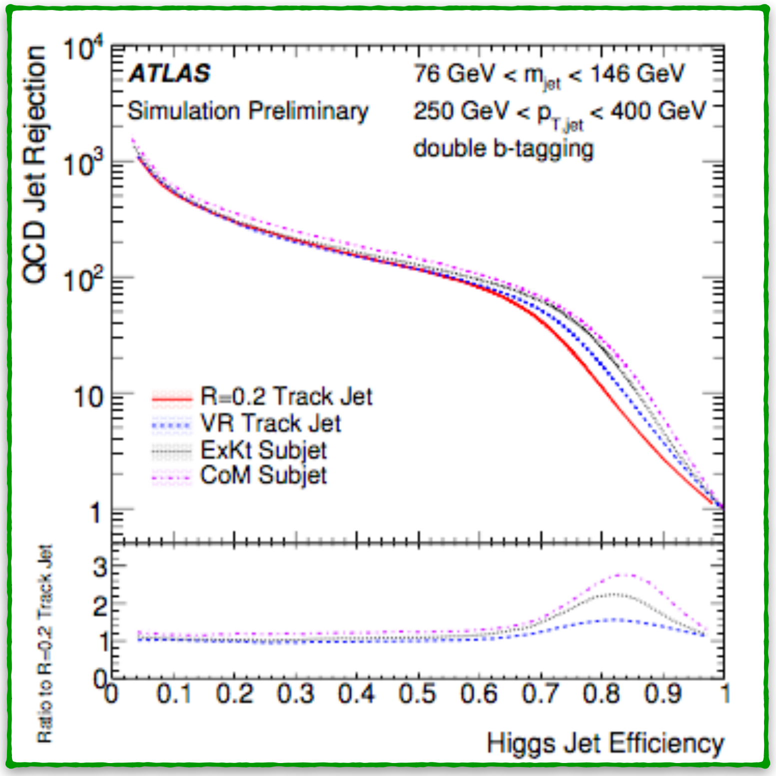


A large fraction of large-R jets (~30-40%) contains three VR track jets instead of two.
Therefore considering only the two leading VR track jets might lead to an inefficiency.

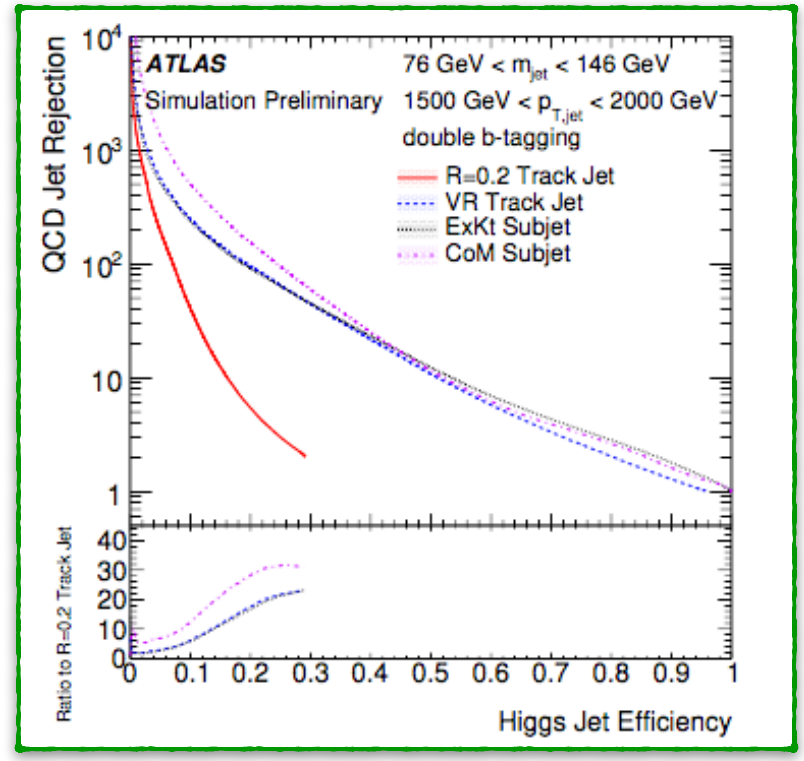
Efficiency for a Higgs jet to have two of the leading **three** associated subjets matched to truth *b*- hadrons vs Higgs jet p_T .

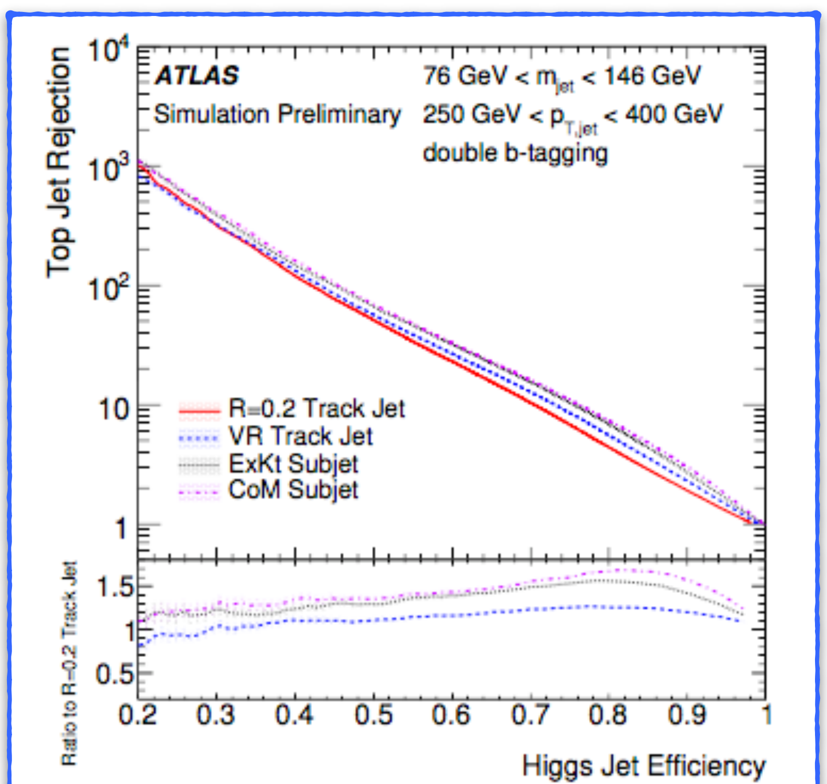


VR track jets background rejection

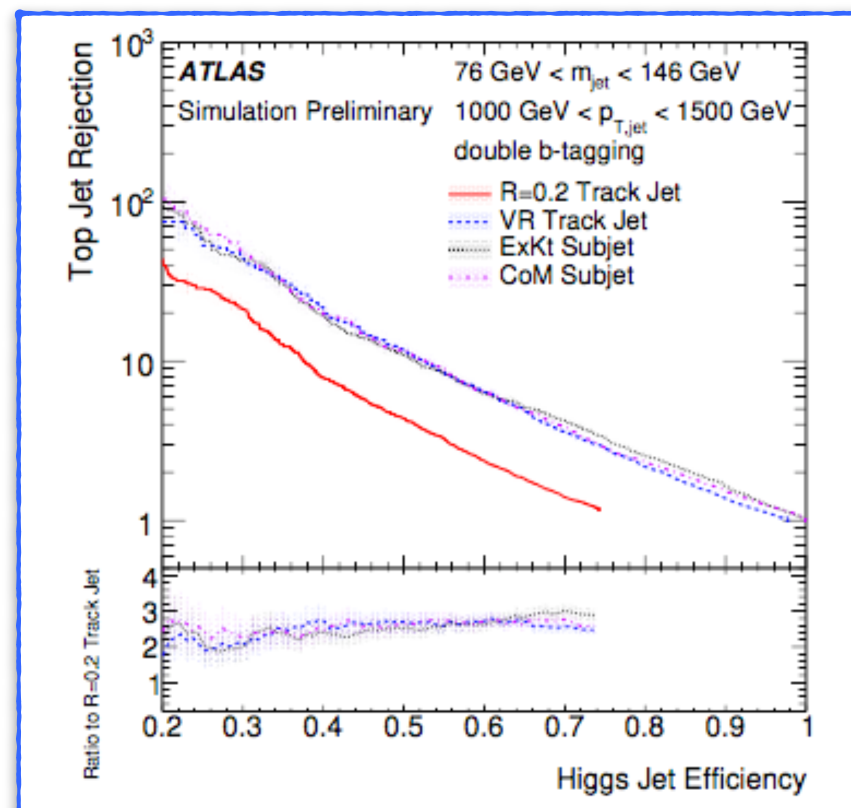


p_T > 1.5 TeV



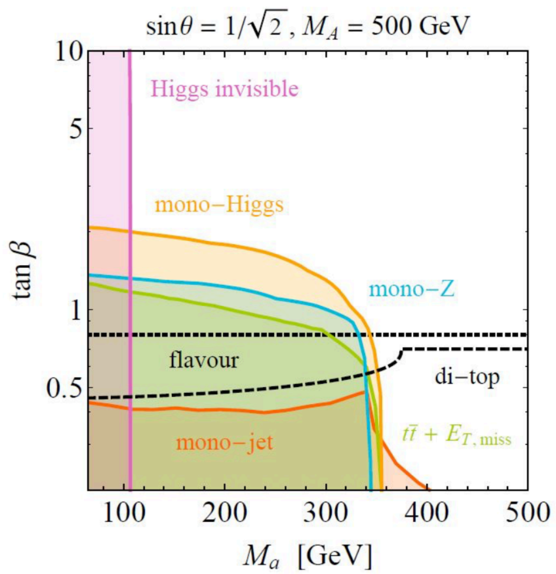


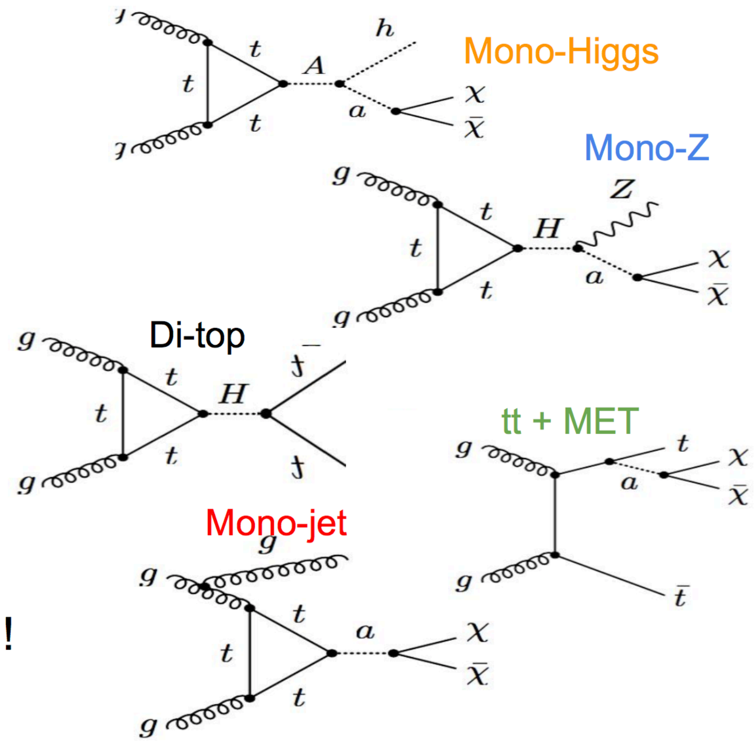
p_T > 1.5 TeV



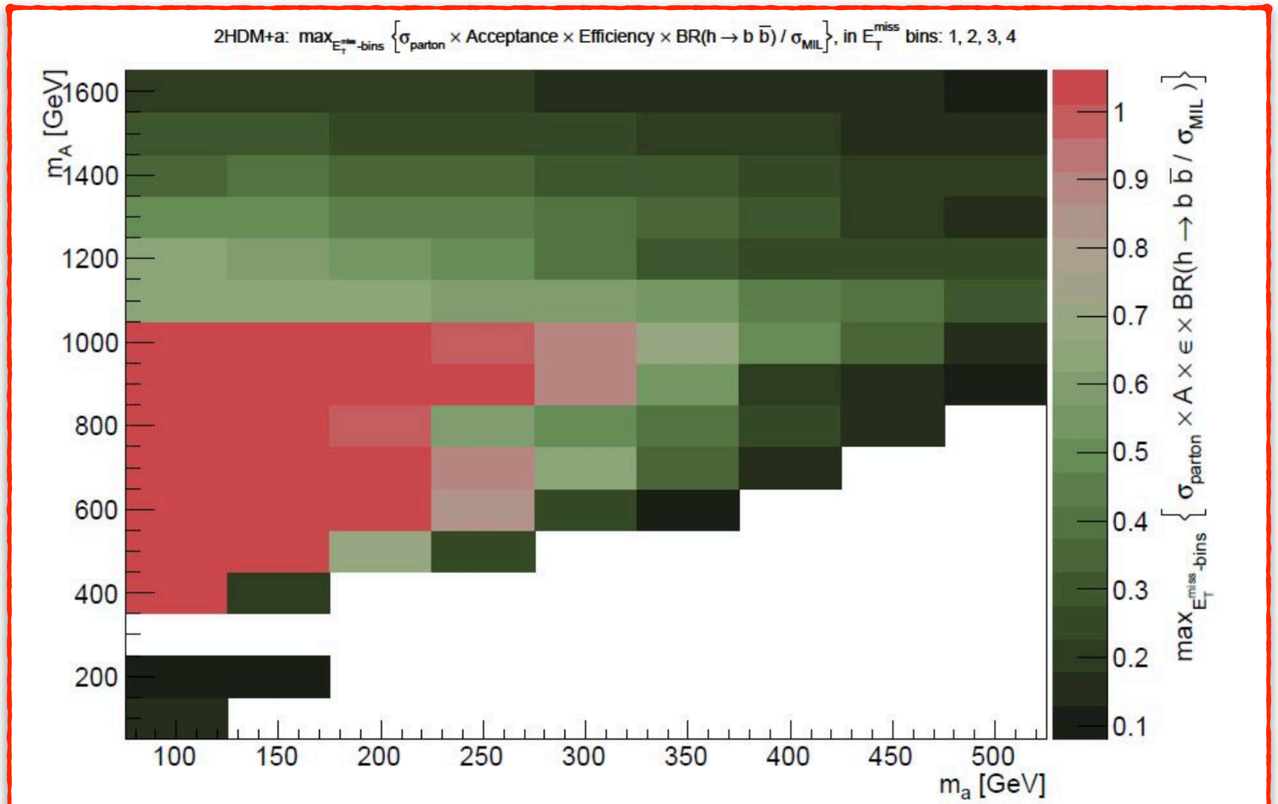
Scalar mediator model

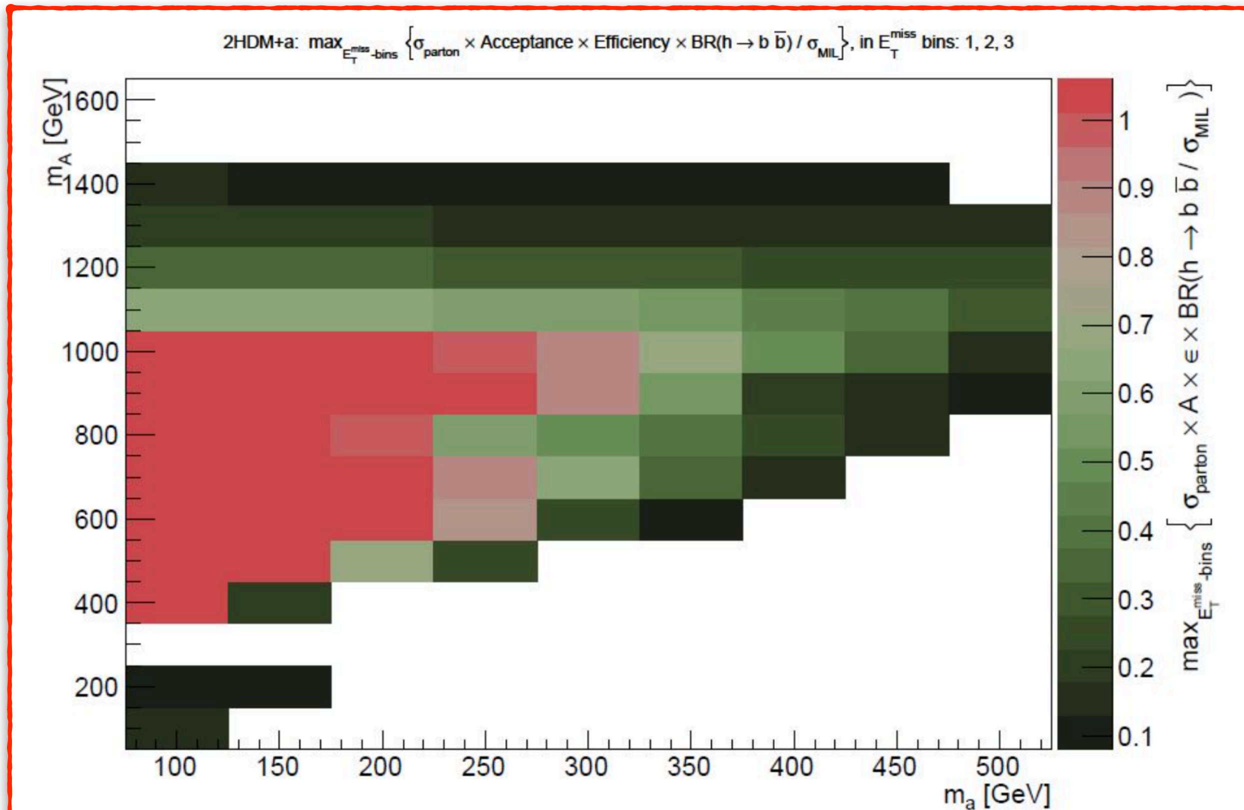
2HDM+a: Diverse palette of signatures





The interplay is experimentally exciting!

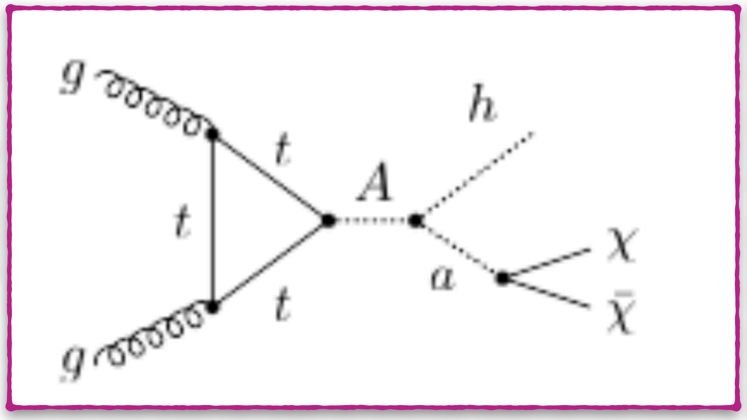


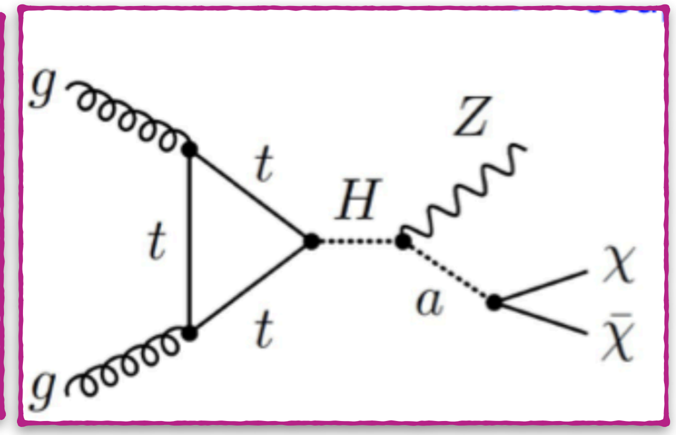


Scalar mediator model

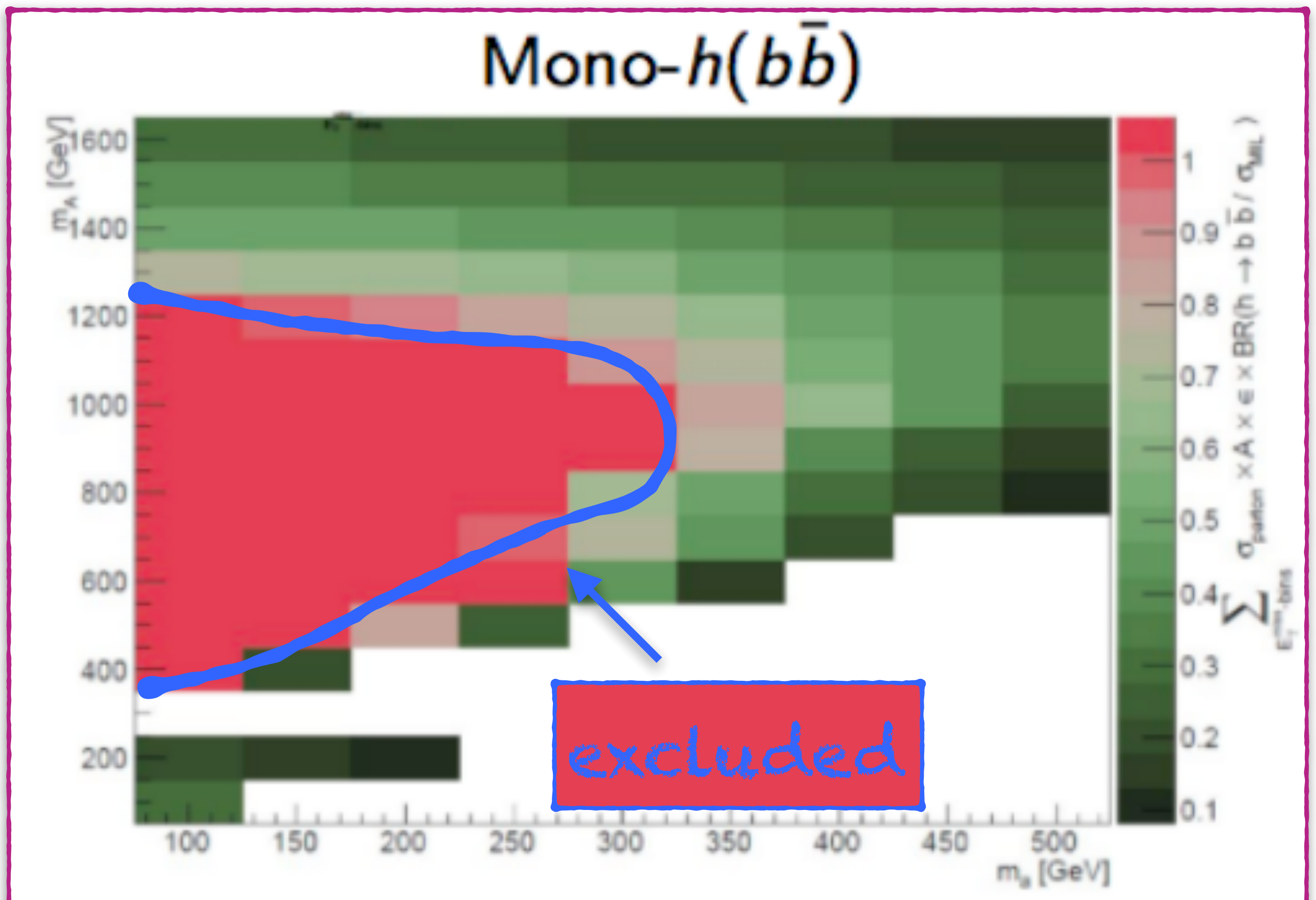
Use MIL to derive a first guess on the sensitivity with respect to other signal models, as **a+2HDM**.

arXiv:1701.07427





AND MANY OTHER MONO-X SIGNATURES!



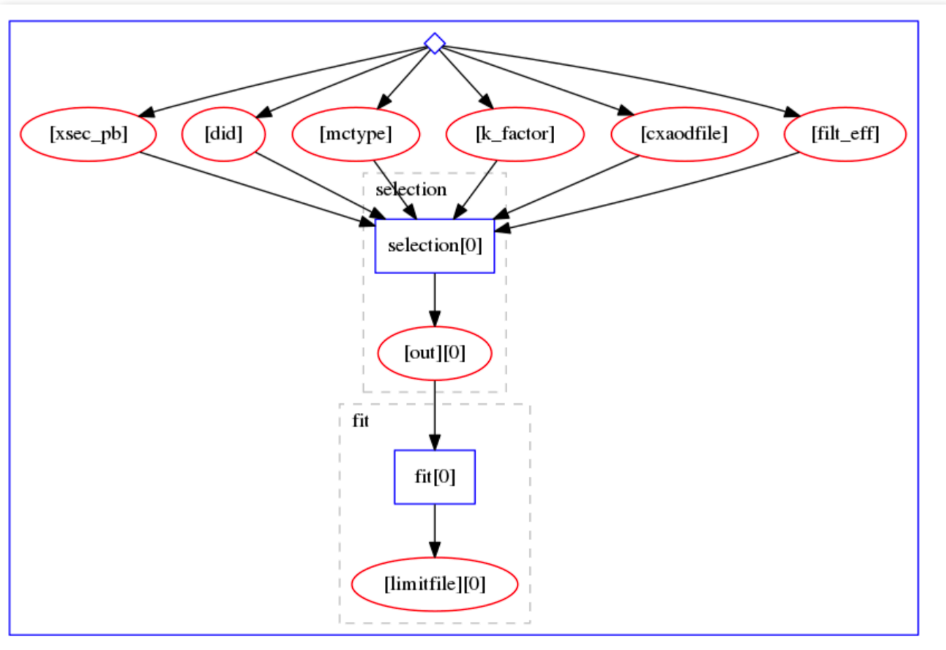
You can simulate the cross section at parton level and compare withe MIL bin by bin.

$$\sum_{E_T^{miss}\,\mathrm{bins}} \sigma_{\mathrm{parton}} \times A \times \varepsilon \times BR(h \to b\bar{b})/\sigma_{\mathrm{MIL}}$$

New MC requested, planned to be used by both mono-H(bb) and mono-V(had), as well as many other JET+DM searches.

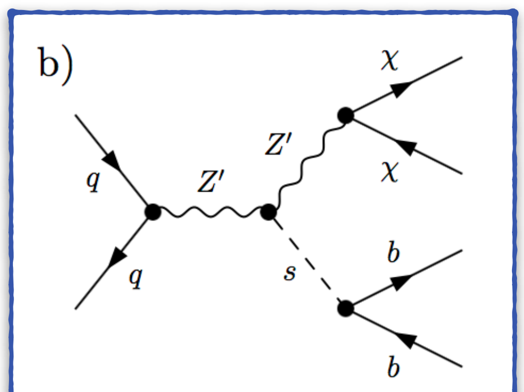
RECAST!

arXiv:1010.2506



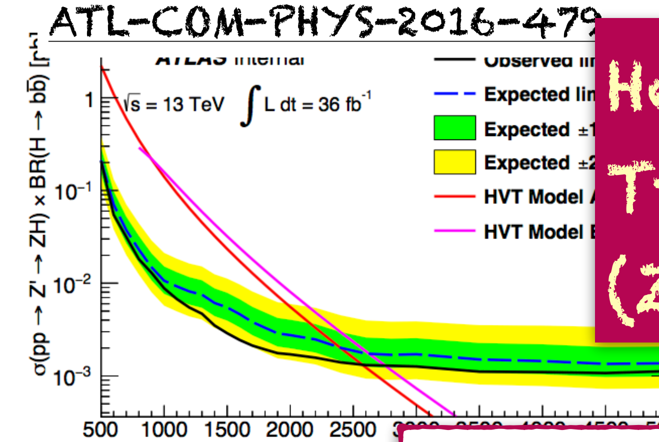
No assumption on how the analysis code is running. Does not require additional estimates of background rates or systematic uncertainties.
Capture of the code (for mono-Hbb, CxAODReader/WSMaker) and data (bkg and data histograms used as input for the fit). Syst uncert. taken into account as done in CxAODReader. Full RECAST (capturing also the CxAODMaker and derivation code) is possible.

arXiv:1701.08780



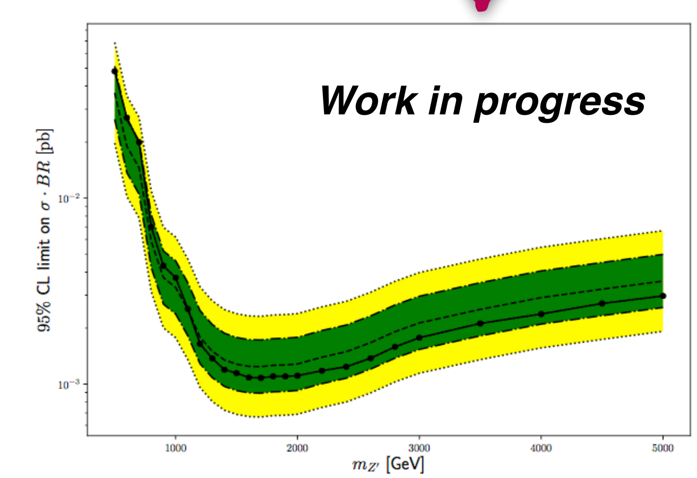
Proposal of a new **Dark Higgs** model.
Full recast for this model.
Ongoing study.

ATL-COM-PHYS-2016-479



Original An

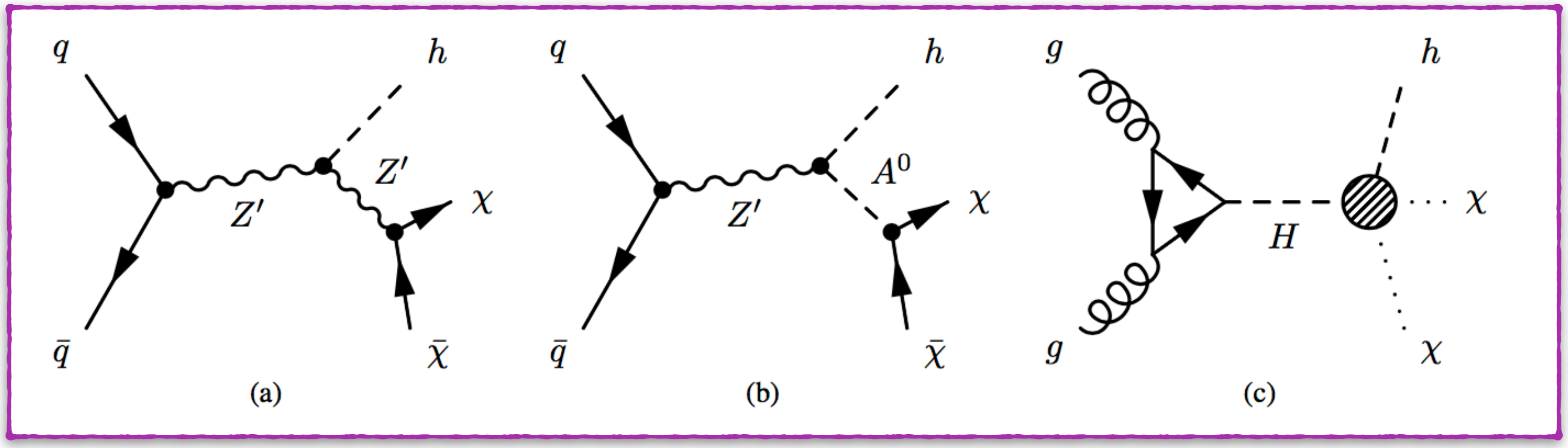
Heavy Vector Triple model (ZH resonance)



Mono-H(bb) RECAST

Mono-H(bb) is already using RECAST (vector mediator model,a+2HDM, Dark Higgs..).
Mono-V(had) will do the same, as soon as the analysis is finalized.

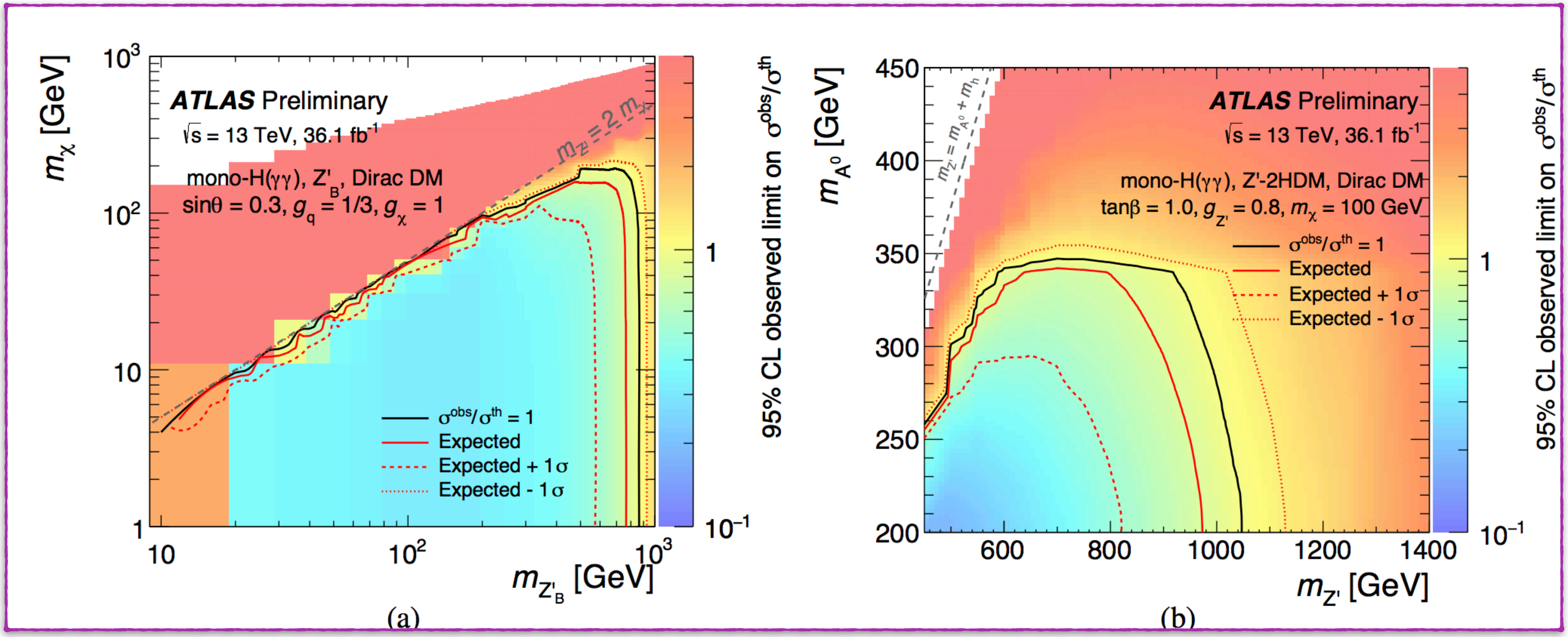
mono-H(bb) vs mono-H(γγ)



more signal models considered:

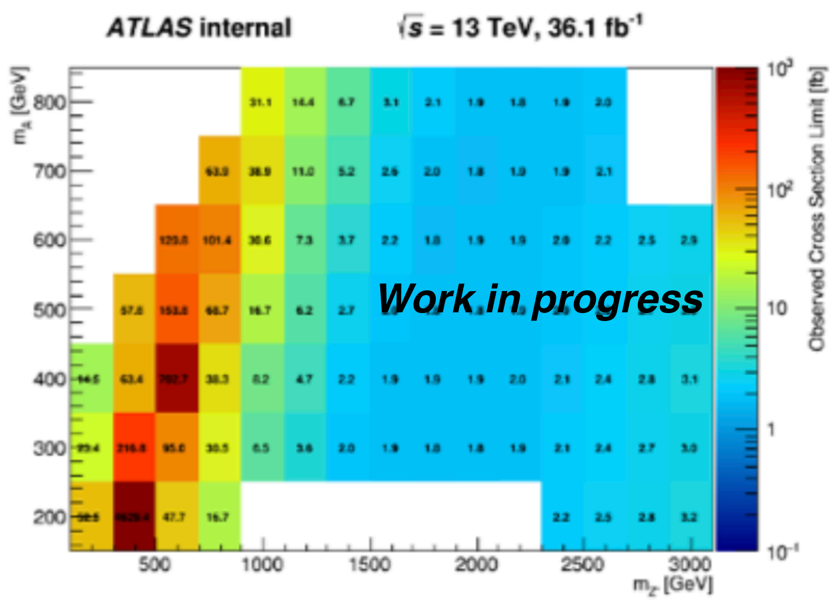
(a) Baryonic model

(c) Heavy scalar model

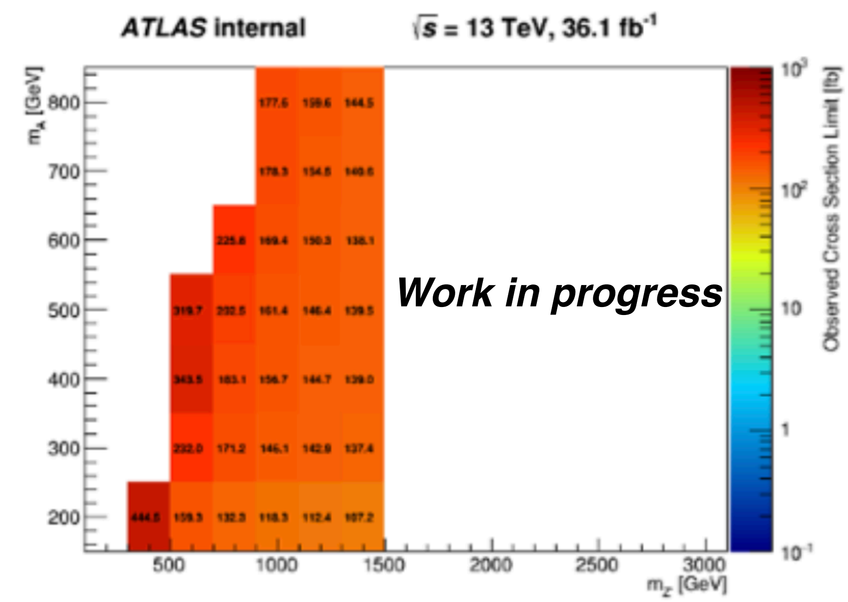


mono-H(bb) vs mono-H(γγ)

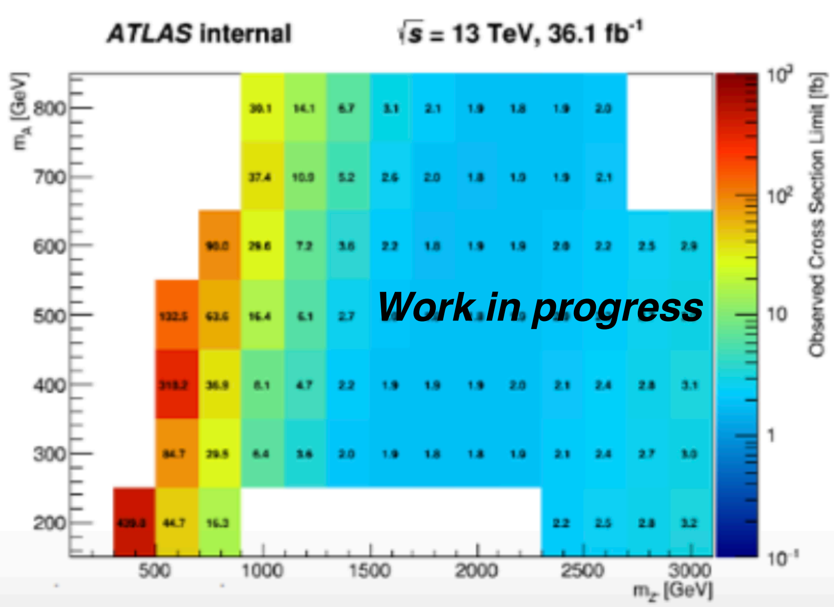
monoH→$b\bar{b}$



monoH→$\gamma\gamma$



Combination



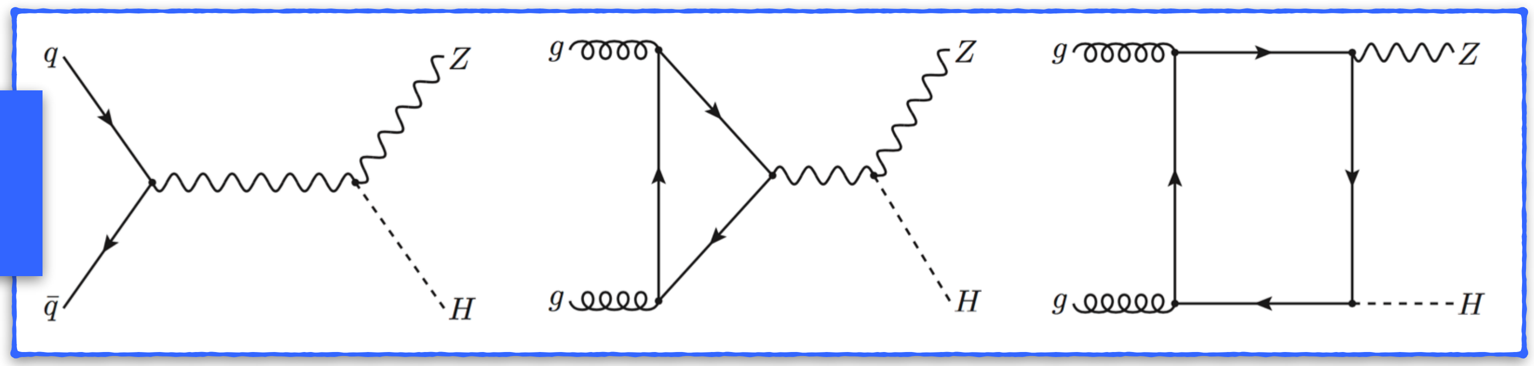
- monoH→$\gamma\gamma$ is important for low $m_{Z'}$ (low $E_{\mathrm{T}}^{\mathrm{miss}}$) scenarios, and less important for high $m_{Z'}$ (high $E_{\mathrm{T}}^{\mathrm{miss}}$) scenarios

H->invisible interpretations

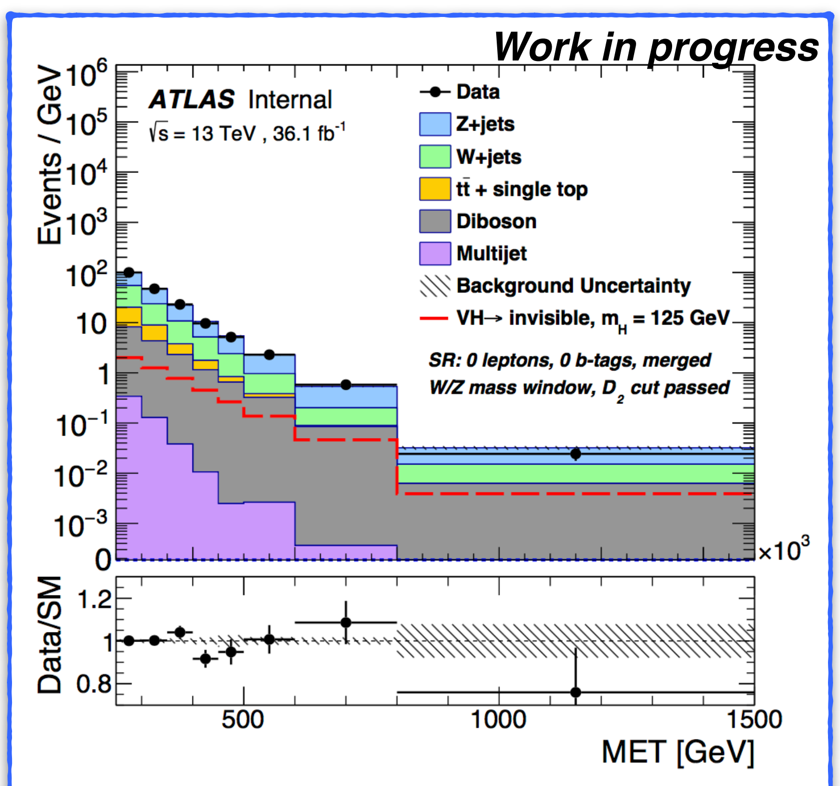
Some extensions of the SM allow for invisible decays of the Higgs bosons (DM, LLP).
In the SM, it's possible only in the Z(vv)Z(vv) channel (BR~0.1%).
A measurement of a large BR would indicate the presence of physics BSM.

Search for Higgs->invisible through the VH production, W/Z decaying hadronically.

mono-V(had) signature



Same analysis strategy as mono-V(had) applied to do such interpretation.



	Significance	Limit on BR($H \to$ invisible)
Expected	2.31	0.80
Observed	0.41	0.95

The observed significance for H->inv is measured to be 0.41, indicating the no excess beyond SM expectations is observed.

more on MET significance

Current MET Significance in ATLAS: Event based

$$S = \frac{\text{Met}}{\sqrt{\text{Ht}}}$$

$$S = \frac{\text{Met}}{\sqrt{\text{Sumet}}}$$

- Proxis for the MET resolution
- Event based quantities
- Do not take into account directional correlations

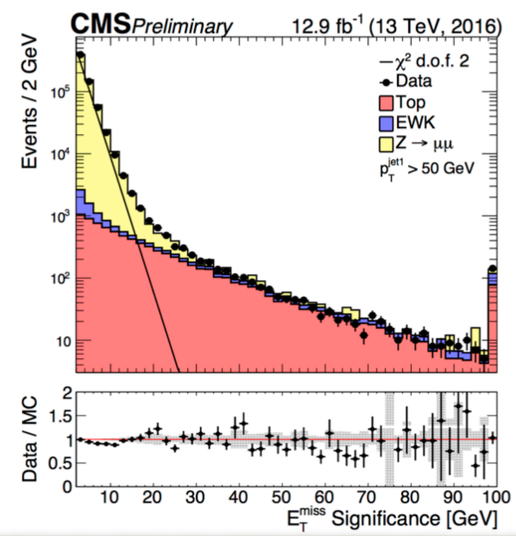
Object based Met Significance Definition

- ◇ Based on the expected resolutions for all objects that enter the MET reconstruction
- ◇ Event by event calculated

Met Significance corresponds to a χ^2variable:

$$S^2 = \left(\sum_i \overrightarrow{E_{T_i}}\right)^{\dagger} \left(\sum_i V_i\right)^{-1} \left(\sum_i \overrightarrow{E_{T_i}}\right)$$

Covariance Matrix for each object



2

VHBB FEEDBACK ON OBJECT BASED MET SIGNIFICANCE

ROC curve

- Signal: ZH→ννbb
- Background: Dijet

Object based met significance shows good behavior compare to some of the variables already used as anti-QCD cuts.

- ◇ Performs better than the event based Met significances.

↓

Good discrimination between signal from QCD