



中央研究院  
ACADEMIA SINICA

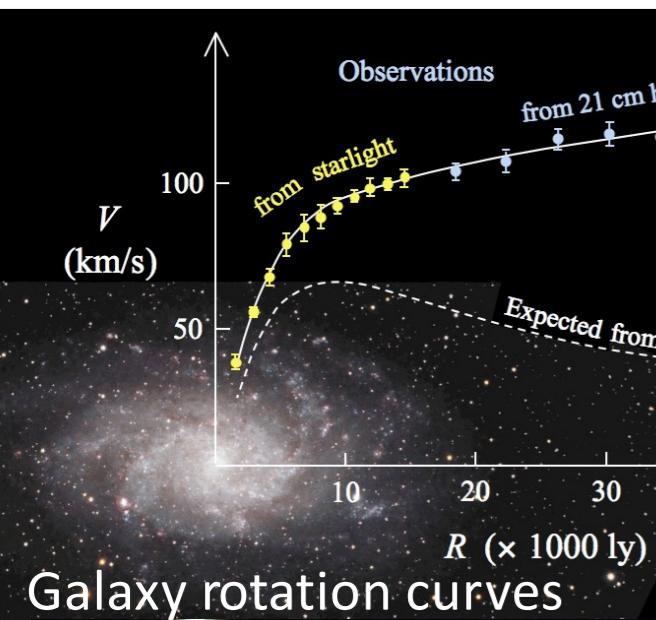


# Searches for Dark Matter at the LHC and future prospects

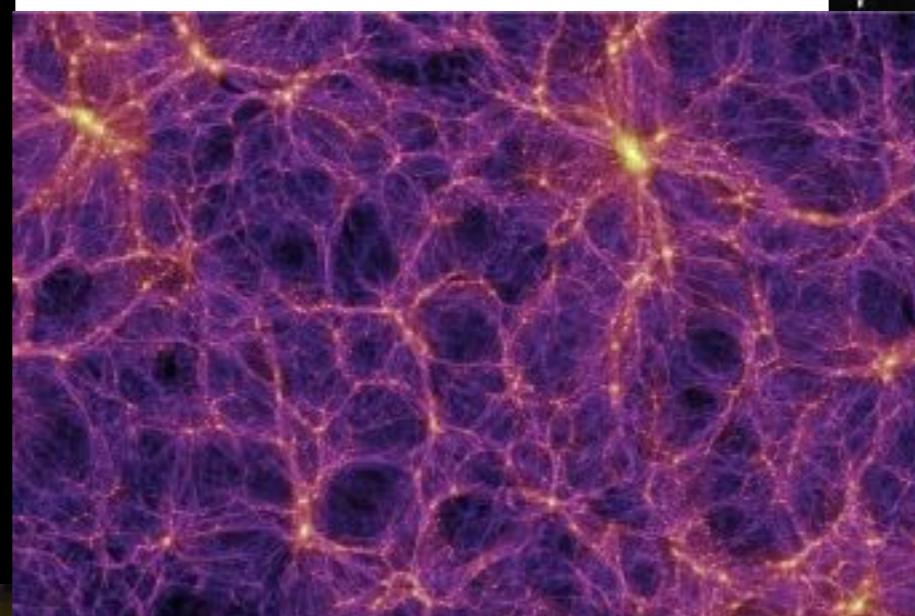
Rachid Mazini  
Academia Sinica, Taiwan

High Energy Physics Worshop  
Tanger, Morocco  
27-28 October 2017

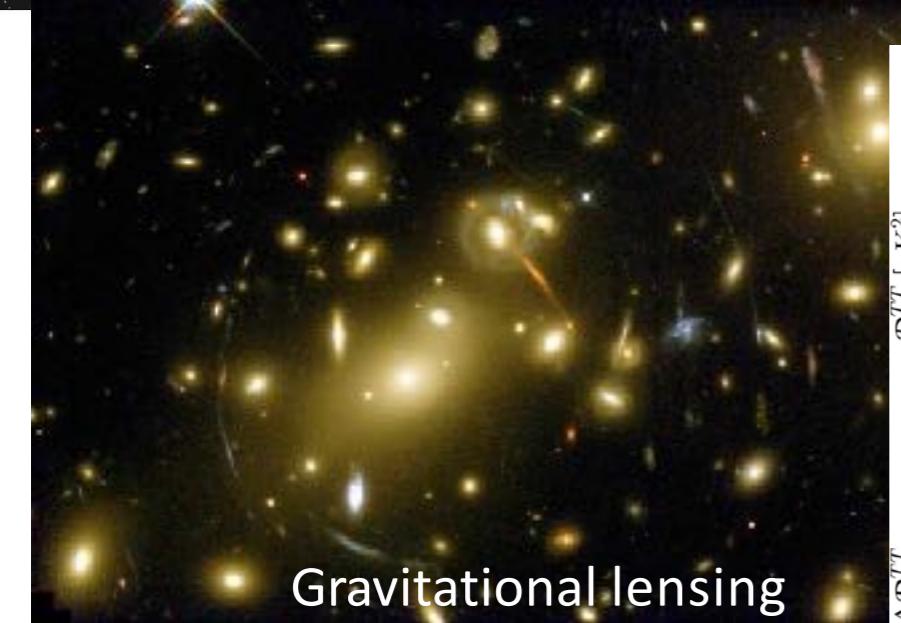
# Dark Matter?



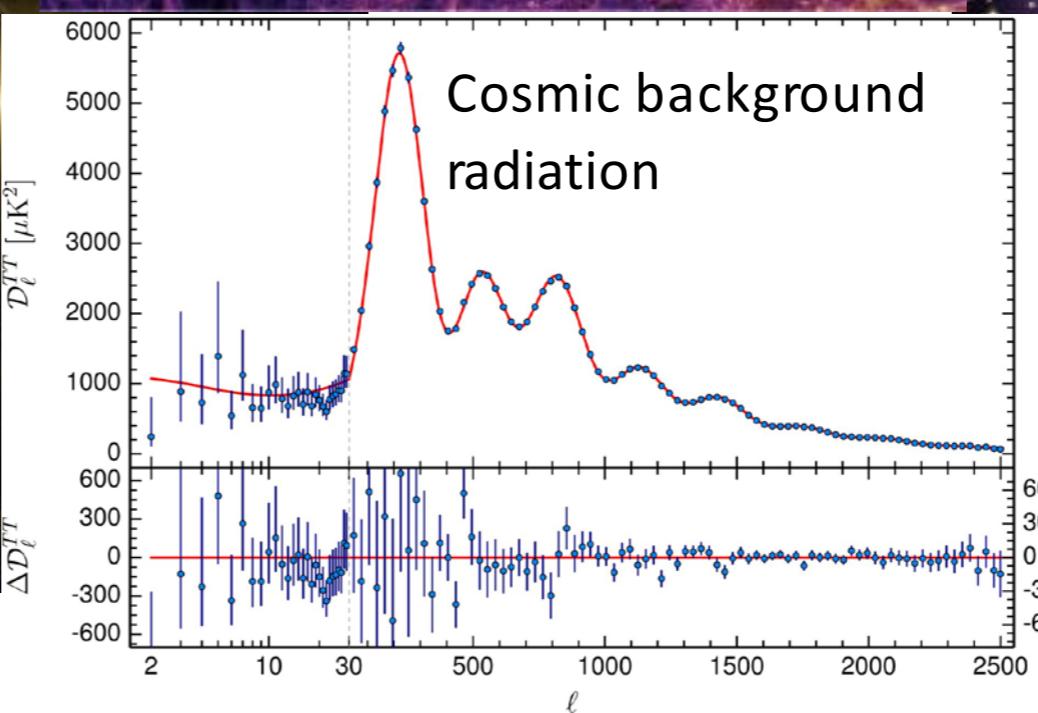
Galaxy rotation curves



Dwarf galaxies



Gravitational lensing

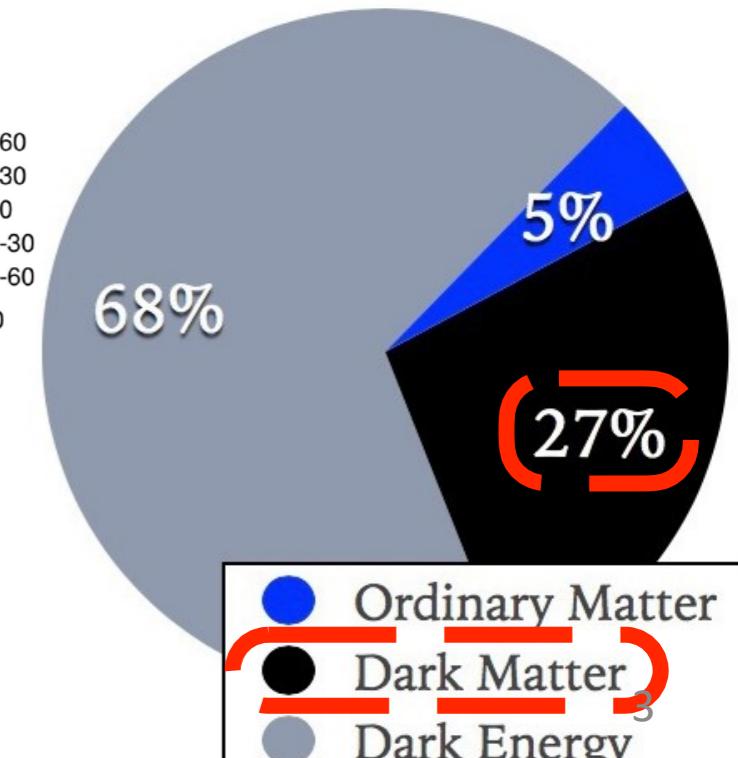
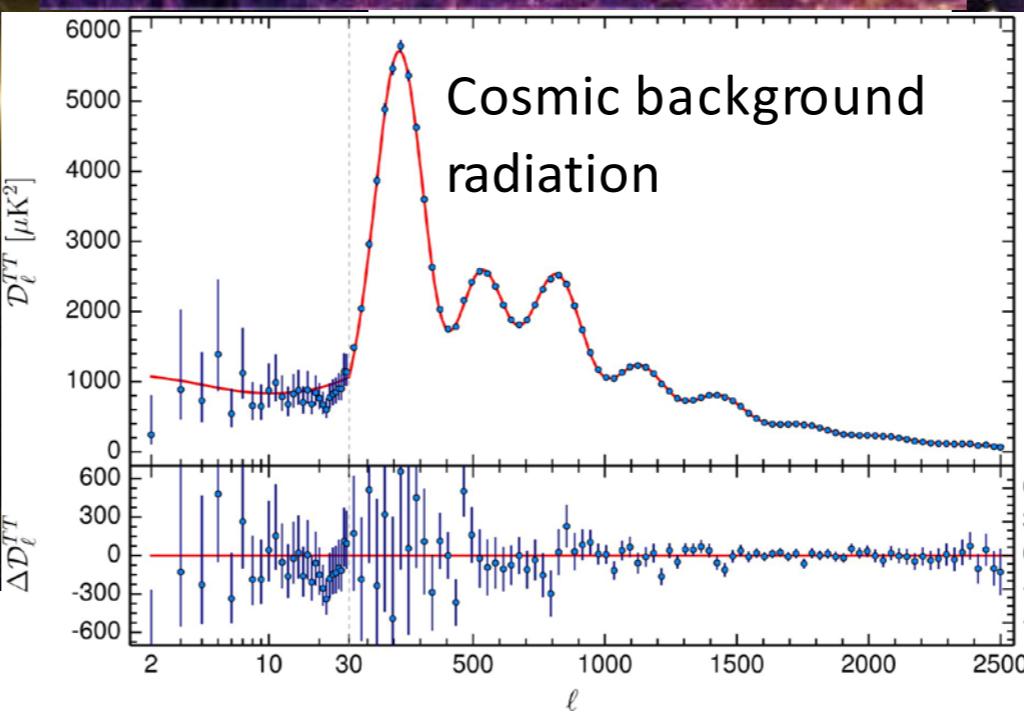
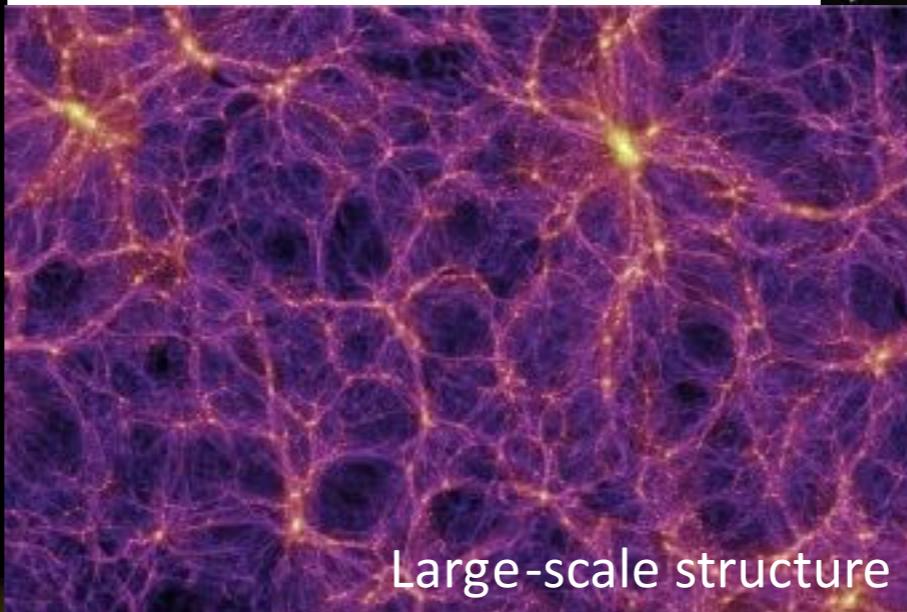
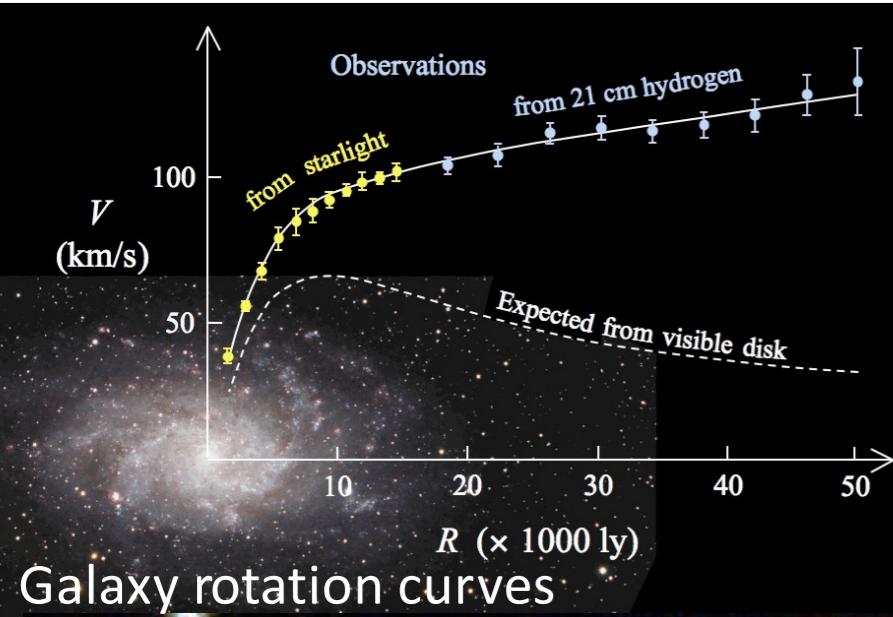


Cosmic background radiation



Bullet clusters

# Dark Matter?



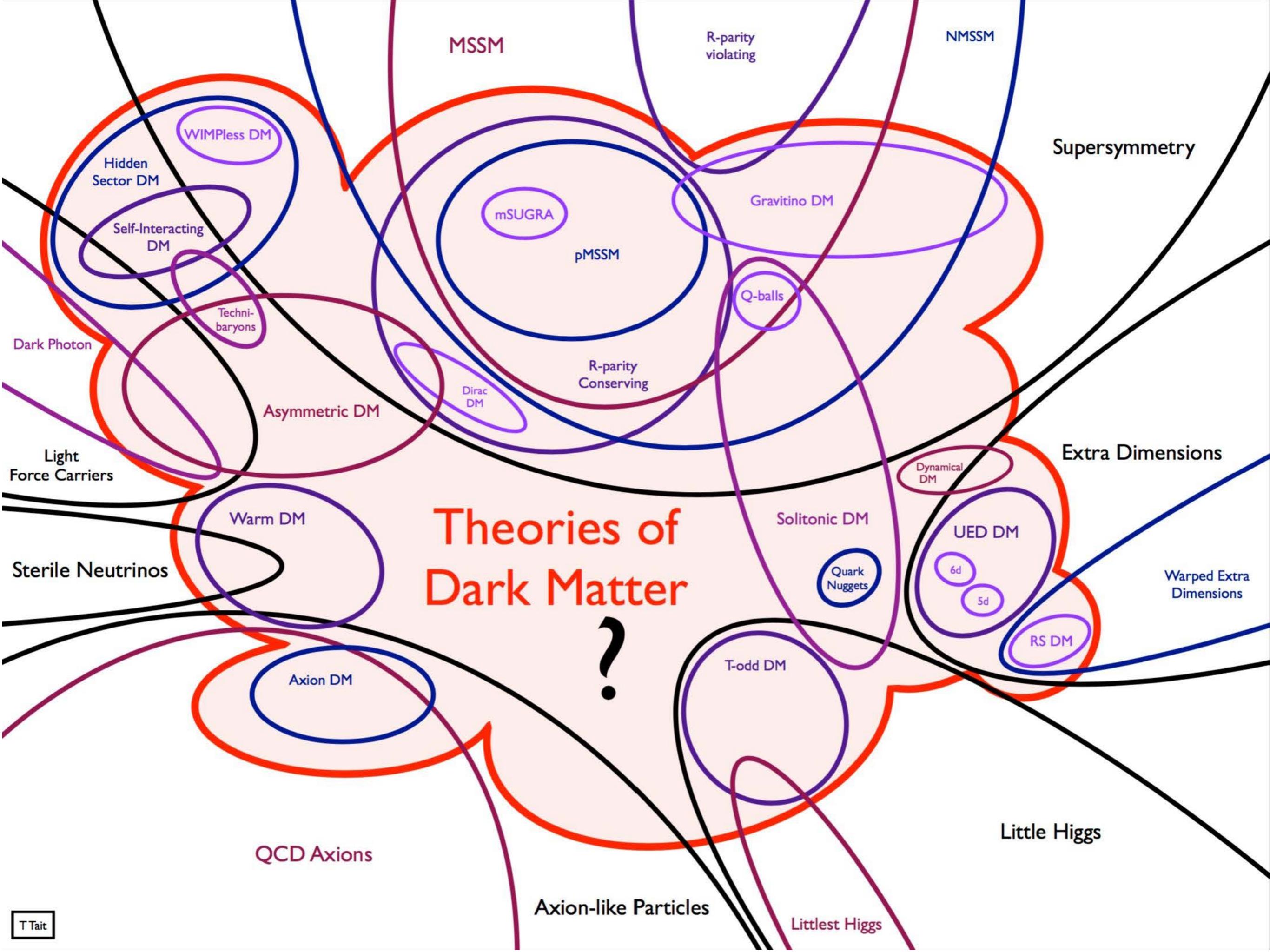
Abundant evidence for the presence of dark sector

No corresponding entity in the Standard Model

→ Dark Matter

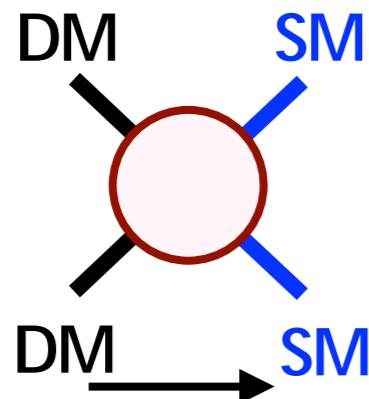
# Theories of Dark Matter

?

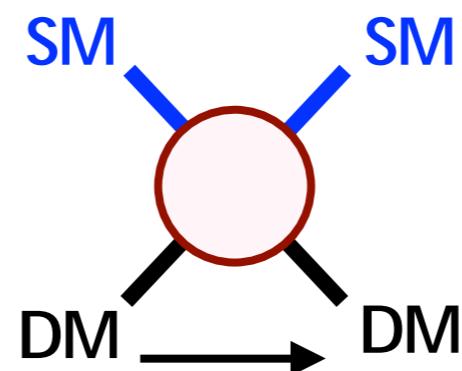
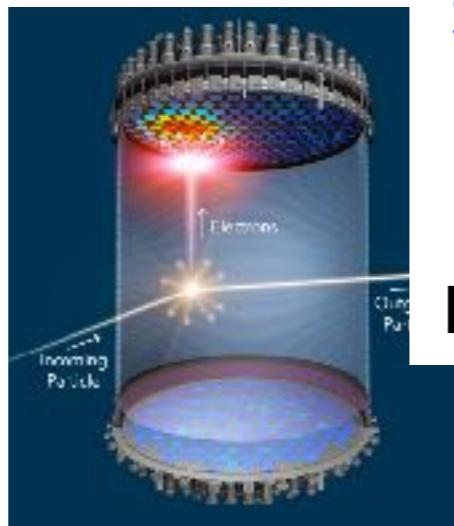


# Experimental Probes

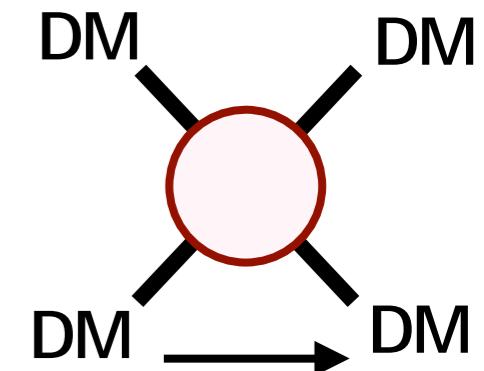
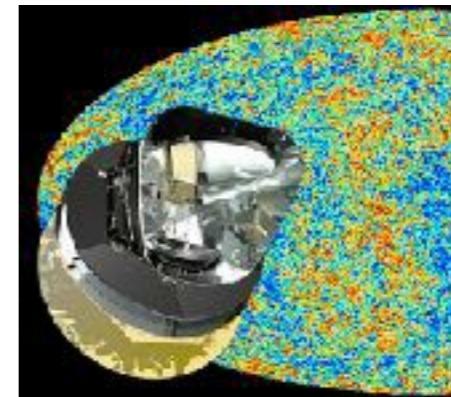
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Indirect detection

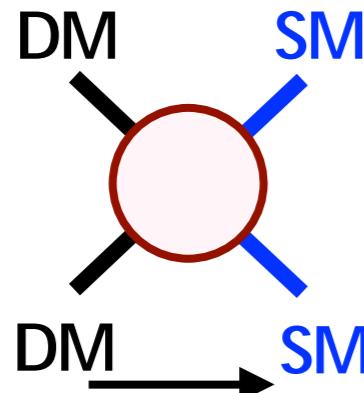


Direct detection

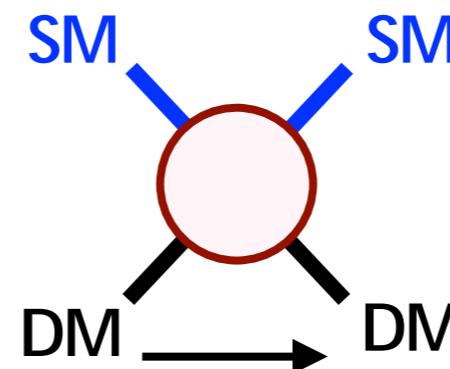
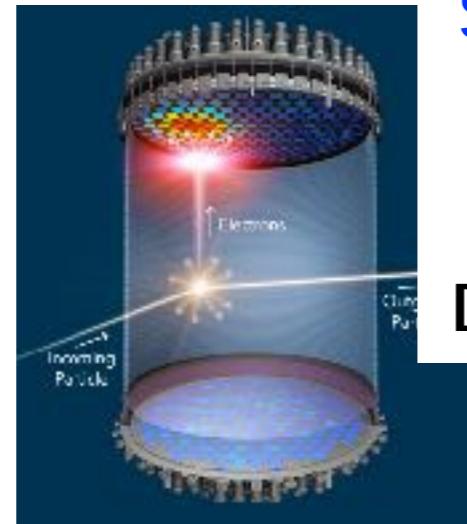


Astrophysical probes

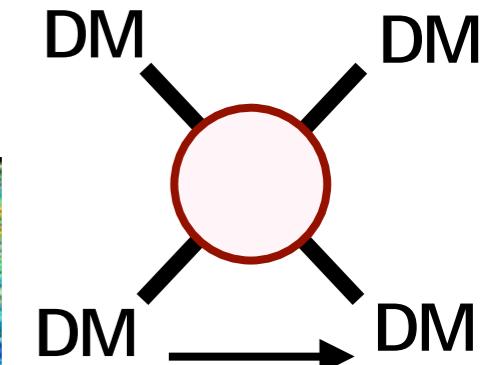
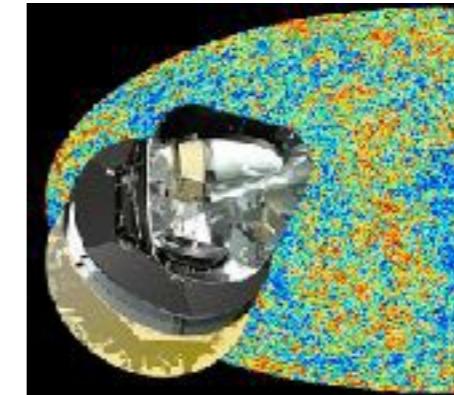
# Experimental Probes



Indirect detection

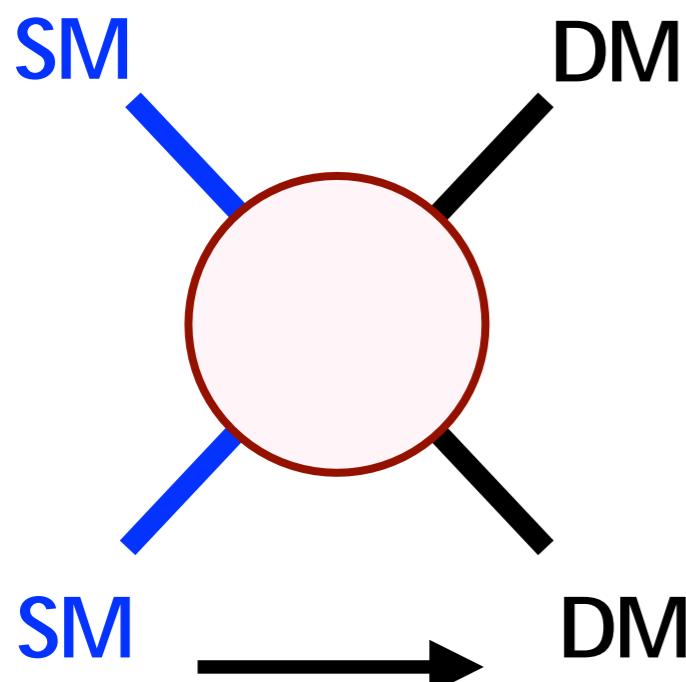


Direct detection



Astrophysical probes

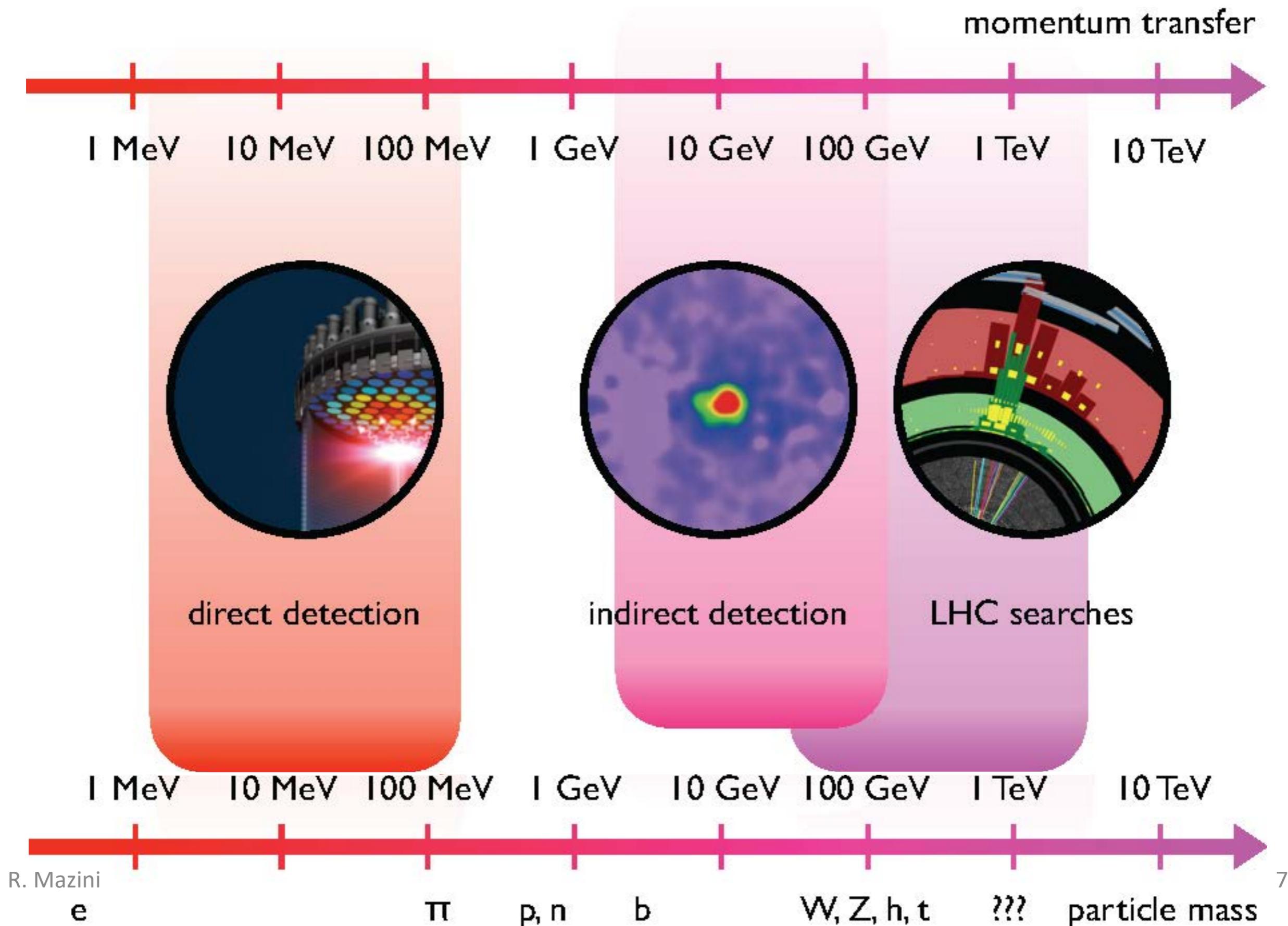
→ Collider searches for Dark Matter?



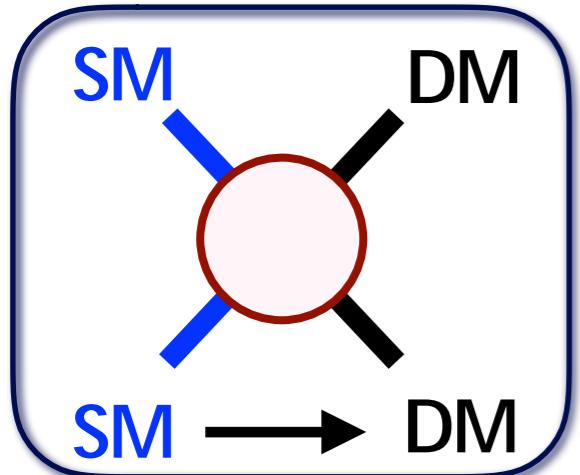
What can we do at LHC?

- ▶ Direct search for WIMP & mediator particles
- ▶ WIMP search in cascade decays
  - E.g., Neutralino in SUSY, Kaluza-Klein photon in UED
- ▶ Hidden (dark) sector search

# DM scale: experimental reach



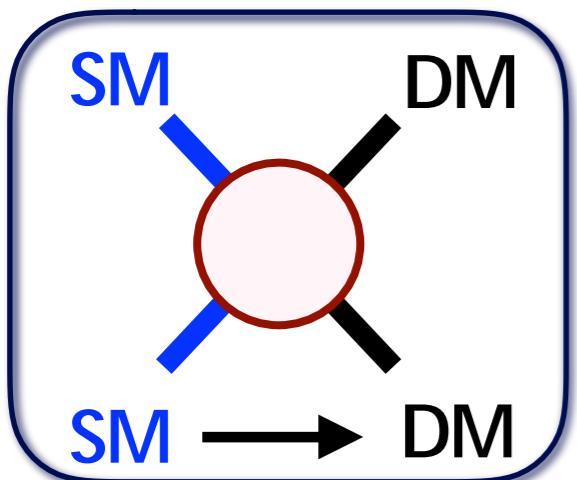
# DM at Collider



Key aspects:

- Less-model dependent formulation of DM processes
- Comparison with DD/ID experiments

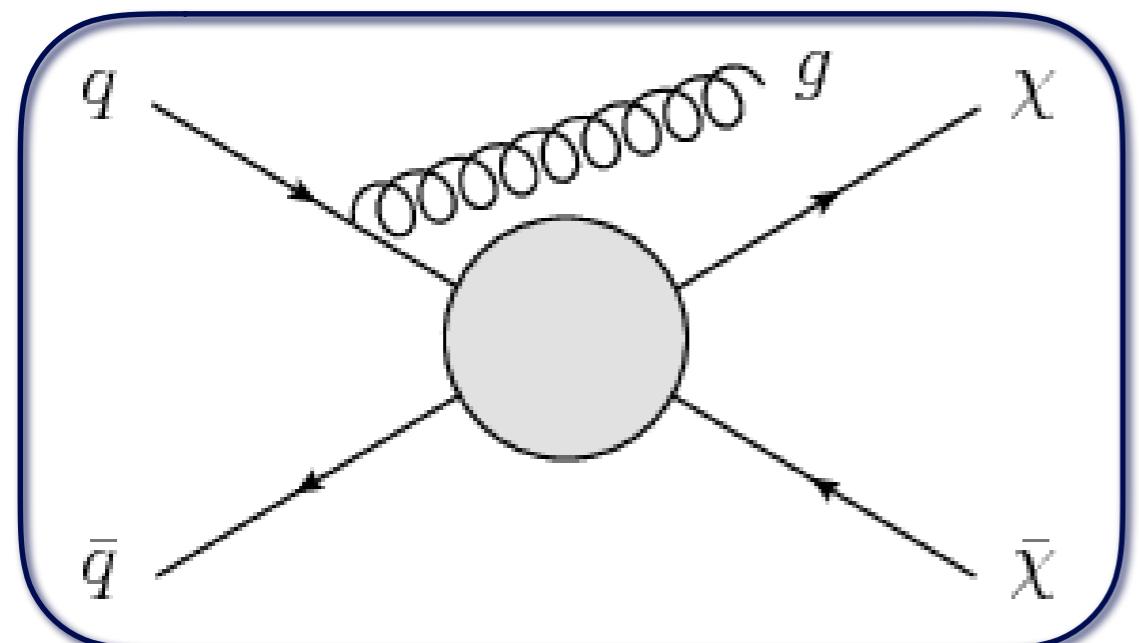
# DM at Collider : EFT



Key aspects:

- Less-model dependent formulation of DM processes
- Comparison with DD/ID experiments

Contact interaction operators  
in *Effective Field Theory*

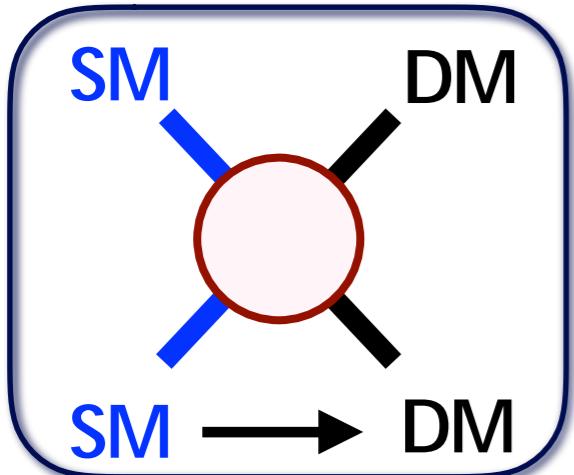


EFT invalid at large momentum transfer  $Q_{\text{tr}}^2 \sim M^*$

→ Problematic at Run 2 (13 TeV)

- Described in terms of Lorentz structure,  $m$ , cut-off scale
- Model-independent DD comparison
- Used in LHC Run 1

# DM at Collider : Simplified Model

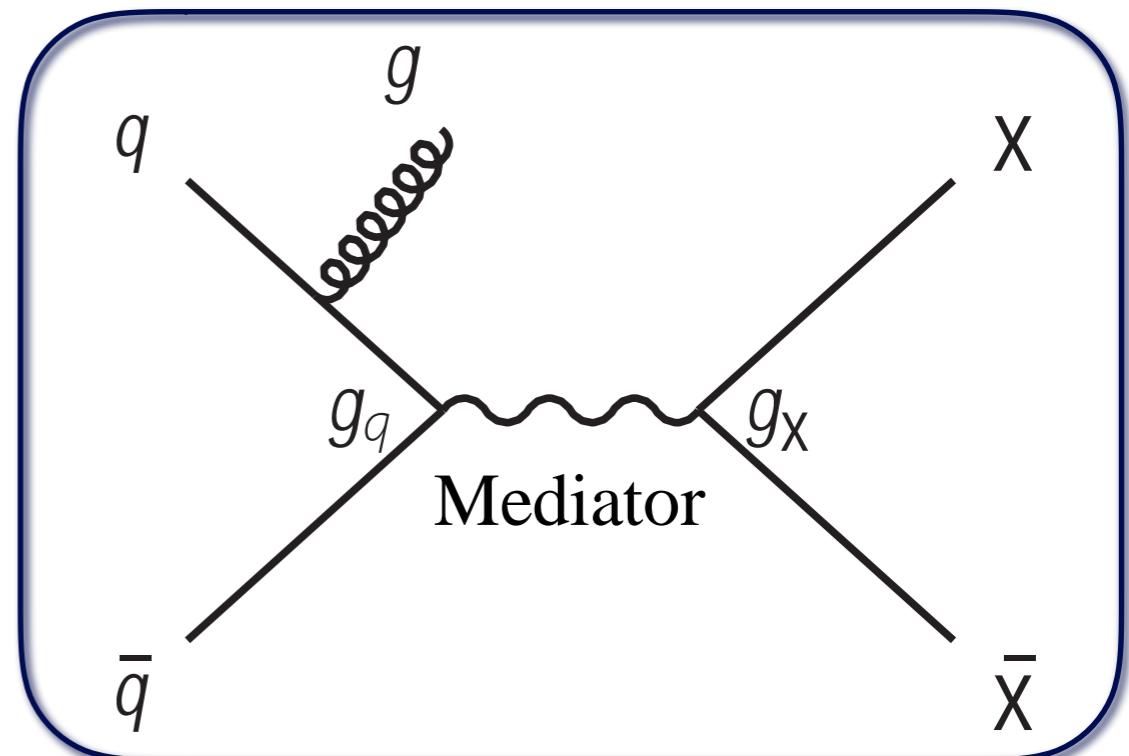
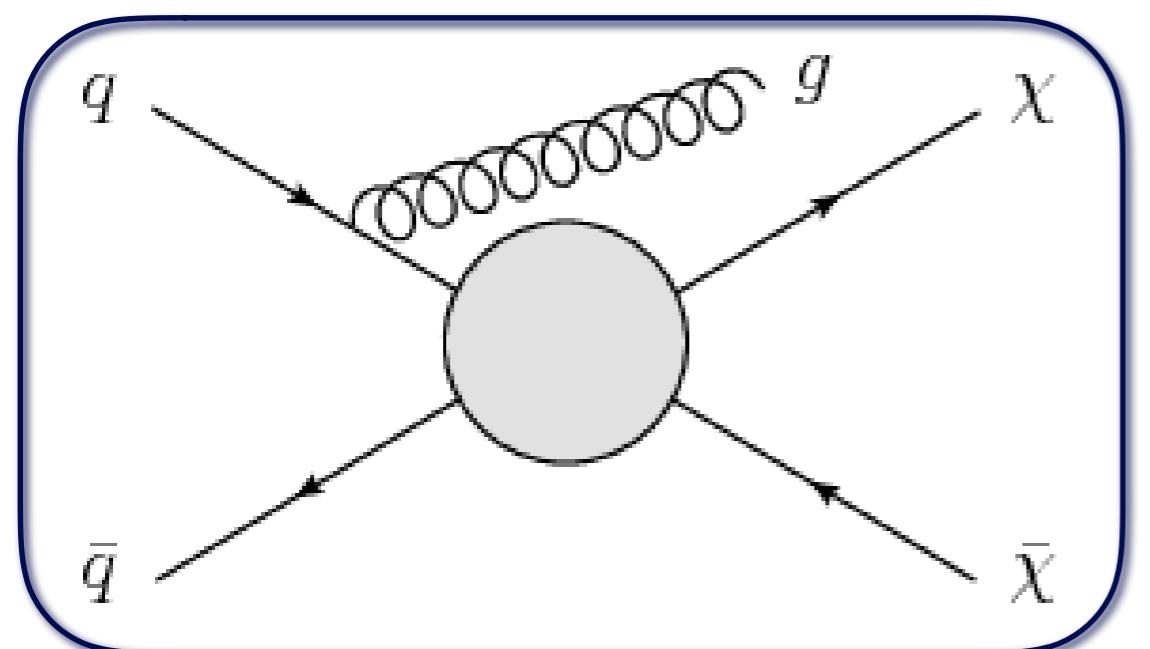


Key aspects:

- Less-model dependent formulation of DM processes
- Comparison with DD/ID experiments

***Simplified Models*** with only relevant couplings/particles

Contact interaction operators  
in ***Effective Field Theory***

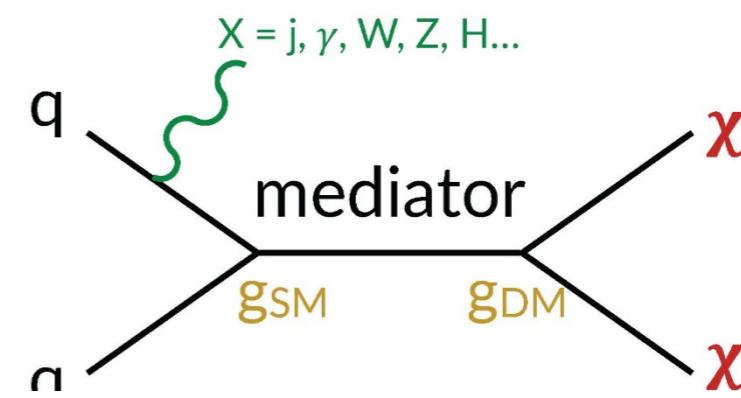
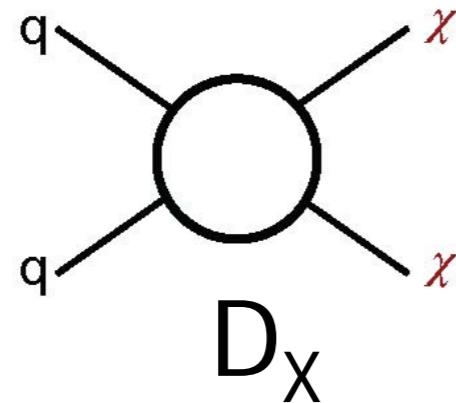


- Described in terms of Lorentz structure,  $m$ , cut-off scale
- Model-independent DD comparison
- Used in LHC Run 1

- Described in terms of Lorentz structure,  $m$ ,  $m_{med}$ ,  $g$  and  $g_q$
- More complicated DD/ID comparison
- Used in LHC Run II

# EFT vs Simplified models

*(a personal summary)*



# How/Does/Can EFT work at the LHC

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	$m_q/M_*^3$
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/M_*^3$
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	$im_q/M_*^3$
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	$m_q/M_*^3$
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	$i/M_*^2$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

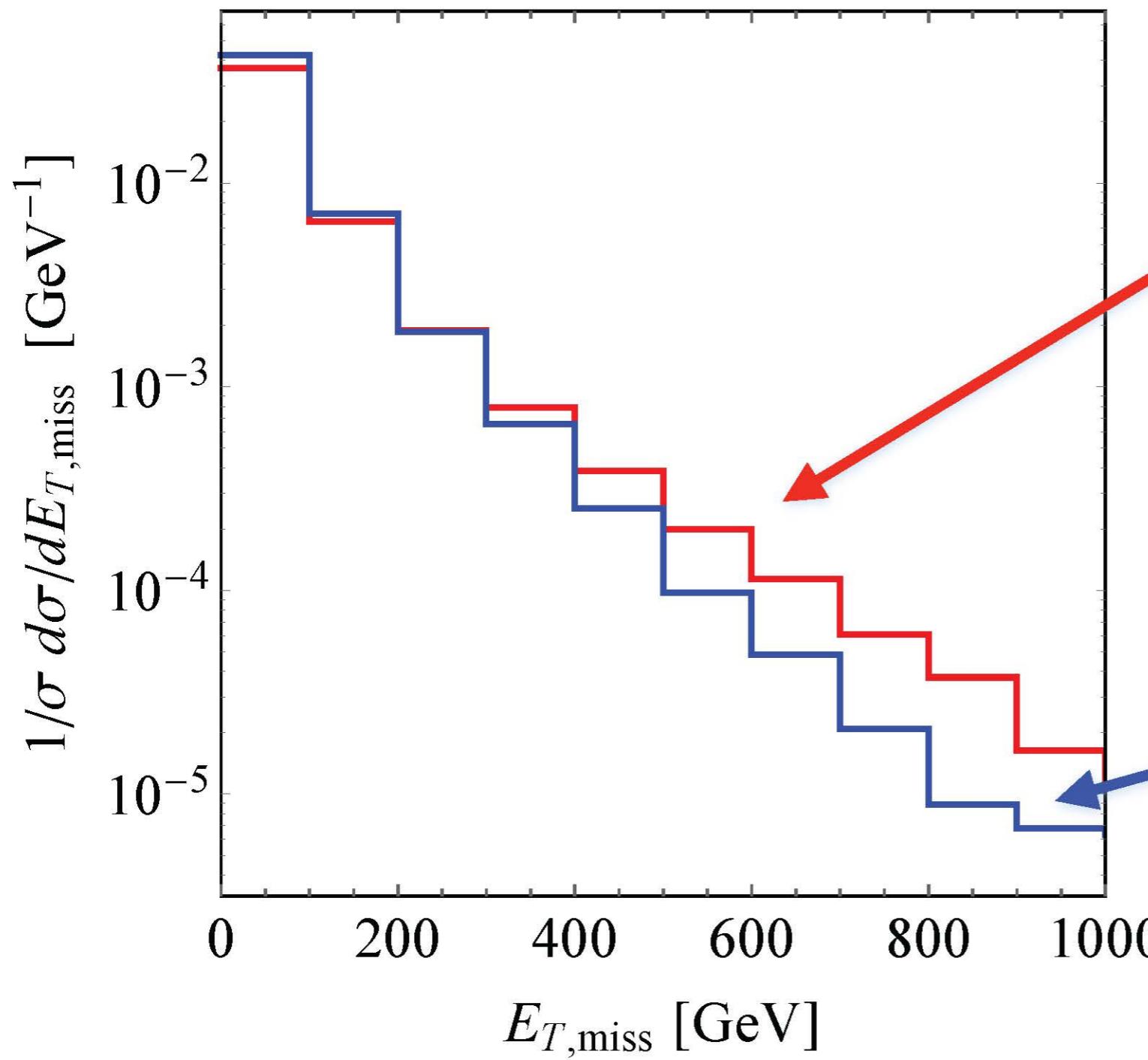
**One way to check:**

- (i) Pick one operator
- (ii) Construct simplified model that leads to operator in heavy mediator limit
- (iii) Calculate  $E_{T,\text{miss}}$  & other distributions in both EFT & simplified model
- (iv) If shapes of distributions are similar, can use EFT as proxy for simplified model, otherwise not

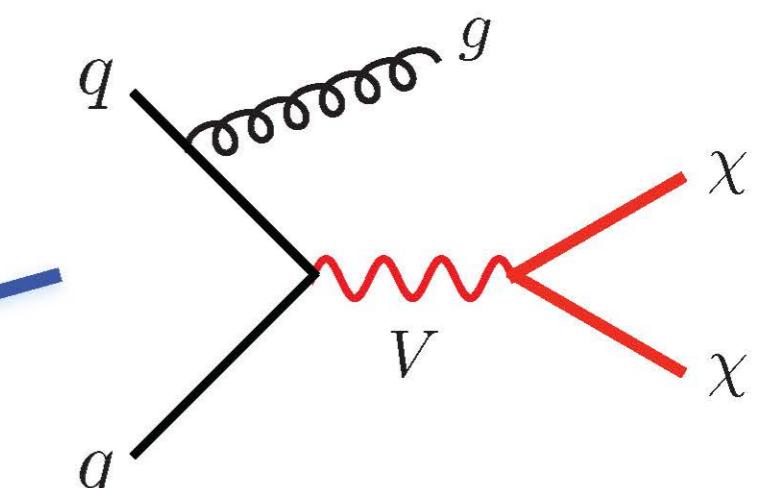
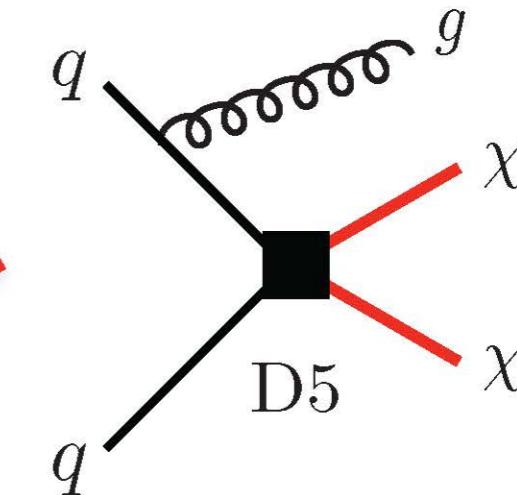
[Zhang et al., 0912.4511; Beltran et al., 1002.4137;  
Goodman et al., 1005.1286, 1008.1783, 1009.0008;  
Bai et al., 1005.3797; Rajaraman et al., 1108.1196;  
Fox et al., 1109.4398; ...]

# EFT vs Simplified Models

$M_V = 500 \text{ GeV}, \Gamma_V = 10 \text{ GeV}$

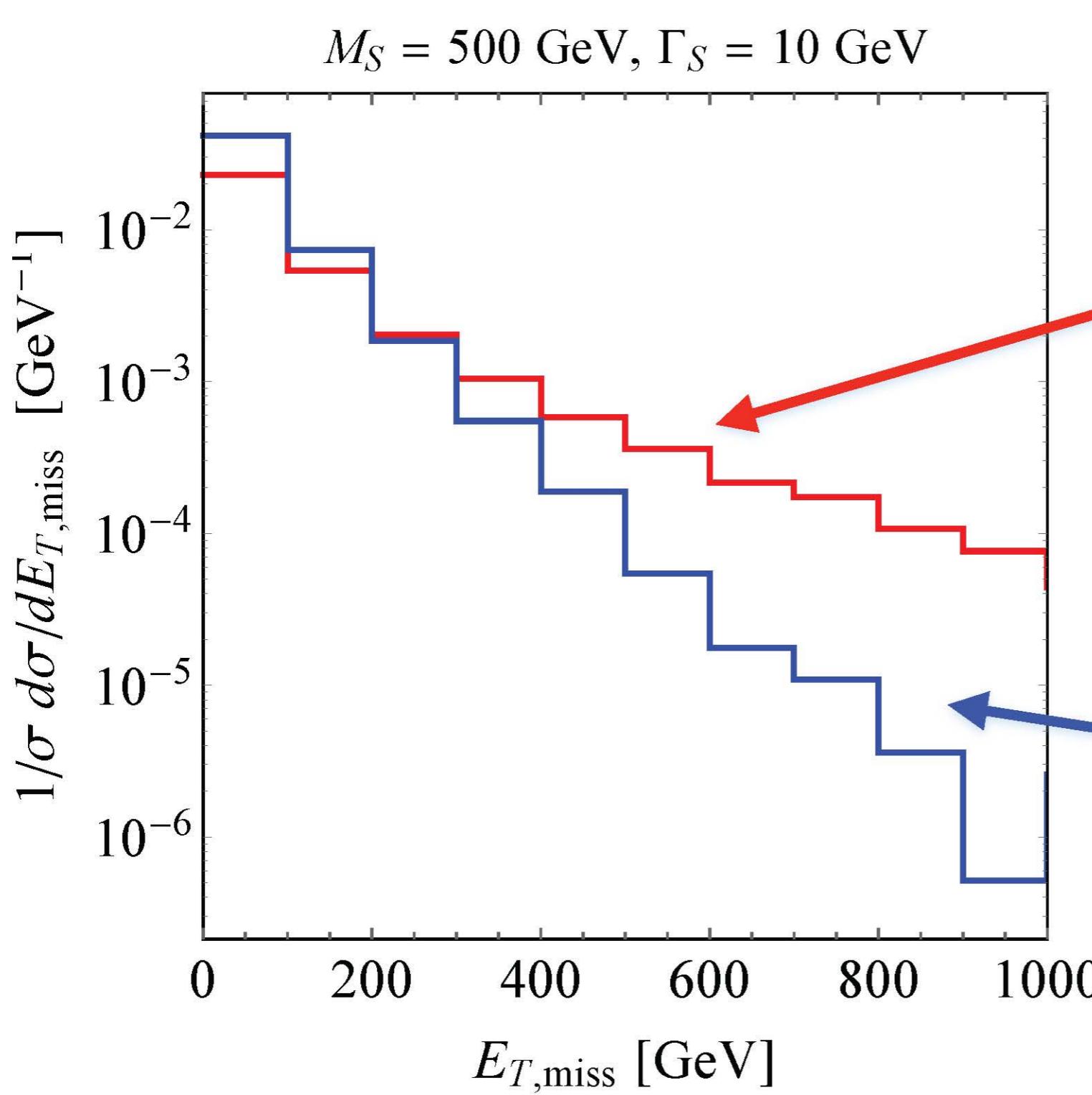


Vector operator

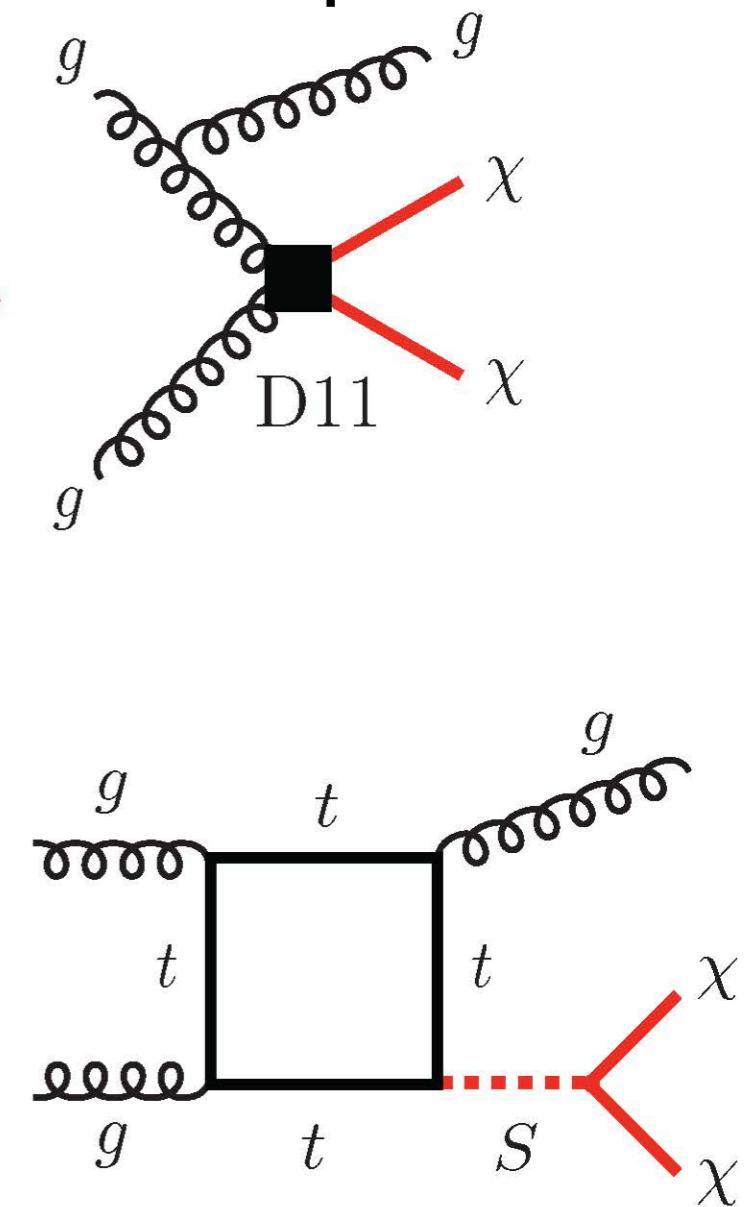


Spin-1 simplified  
model

# EFT vs Simplified Models



Gluonic operator



Spin-0 simplified  
model

# EFT vs Simplified models: The verdict

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- EFT often fails to correctly describe kinematical distributions of weakly-coupled simplified models with weak- or TeV-scale mediators. This flaw prompted ATLAS & CMS to move from EFT to simplified models when interpret ET, miss searches in LHC Run II
- But in case of strongly-coupled DM candidates — composite fermions, pseudo-Nambu-Goldstone bosons, Goldstini, ... — EFT appropriate & sometimes even necessary to describe most important interactions at LHC. ([Bruggisser, Riva & Urbano, 1607.02474](#) & [1607.02475](#) for EFT discussion of strongly-coupled DM)
- We should keep in mind that Simplified models are minimal extensions of EFT that besides DM typically contain a single mediator. SM- & DM-mediator couplings are treated as free parameters & mechanism that provides mass to mediator & DM is unspecified
- To UV complete simplified models (as in SM), more structure is needed to them & question is whether this will change their phenomenology

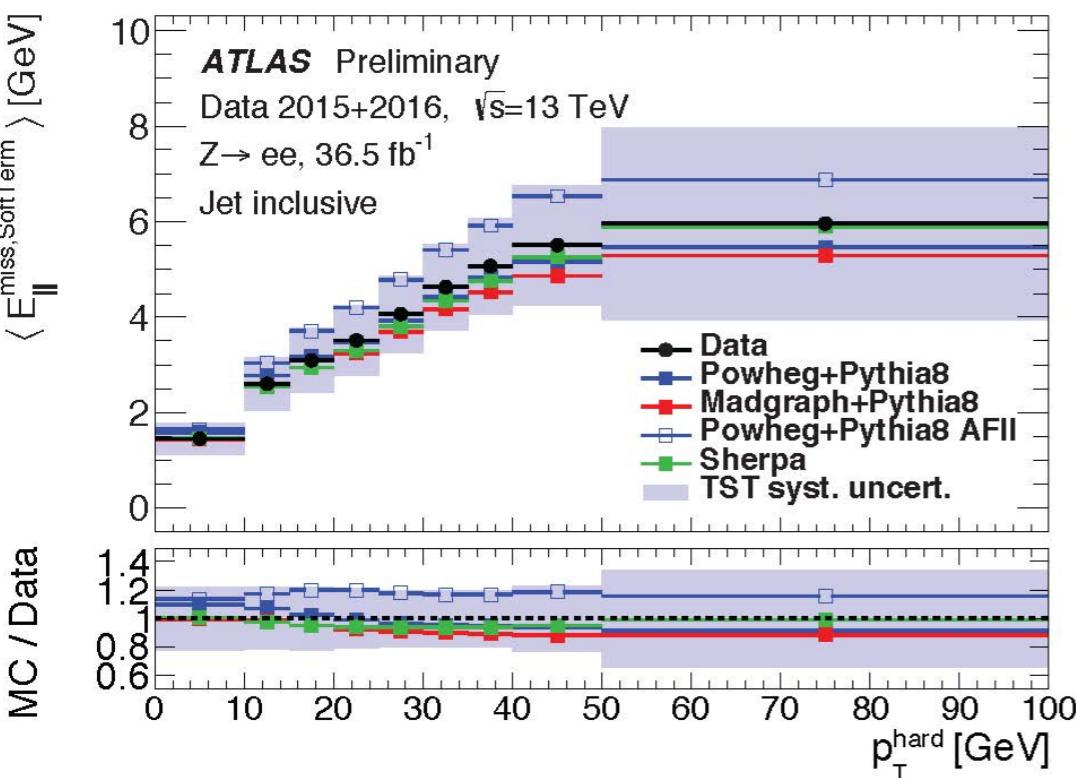
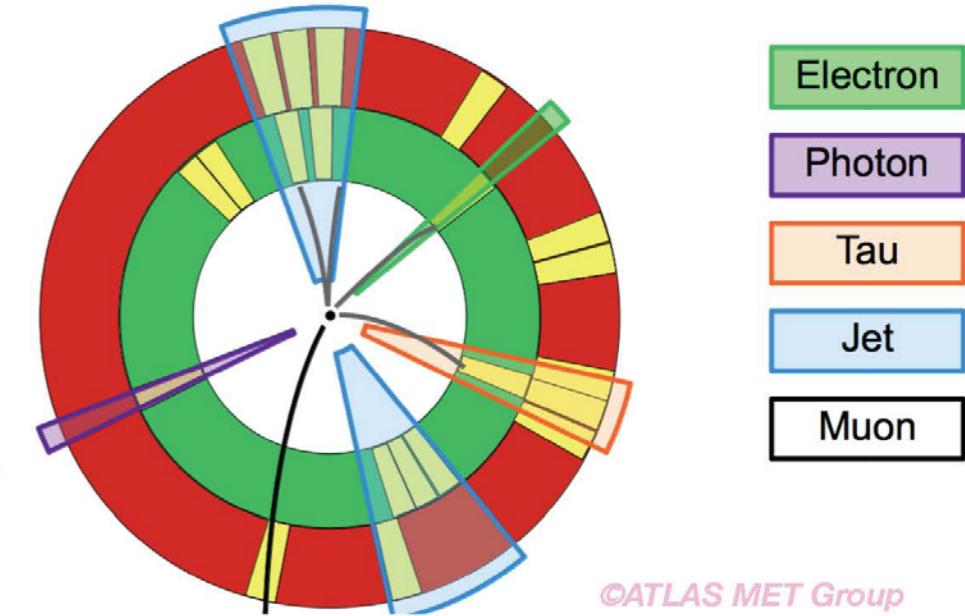
# **Some experimental issues in DM searches**

# Tools for DM searches / I

- Missing transverse momentum ( $E_T^{\text{miss}}$ ) is the  $p_T$  imbalance of reconstructed physics objects.

$$E_{x(y)}^{\text{miss}} = -p_{x(y)}^e - p_{x(y)}^\gamma - p_{x(y)}^{\tau_{\text{had,vis}}} - p_{x(y)}^{\text{jets}} - p_{x(y)}^\mu - p_{x(y)}^{\text{soft}}$$

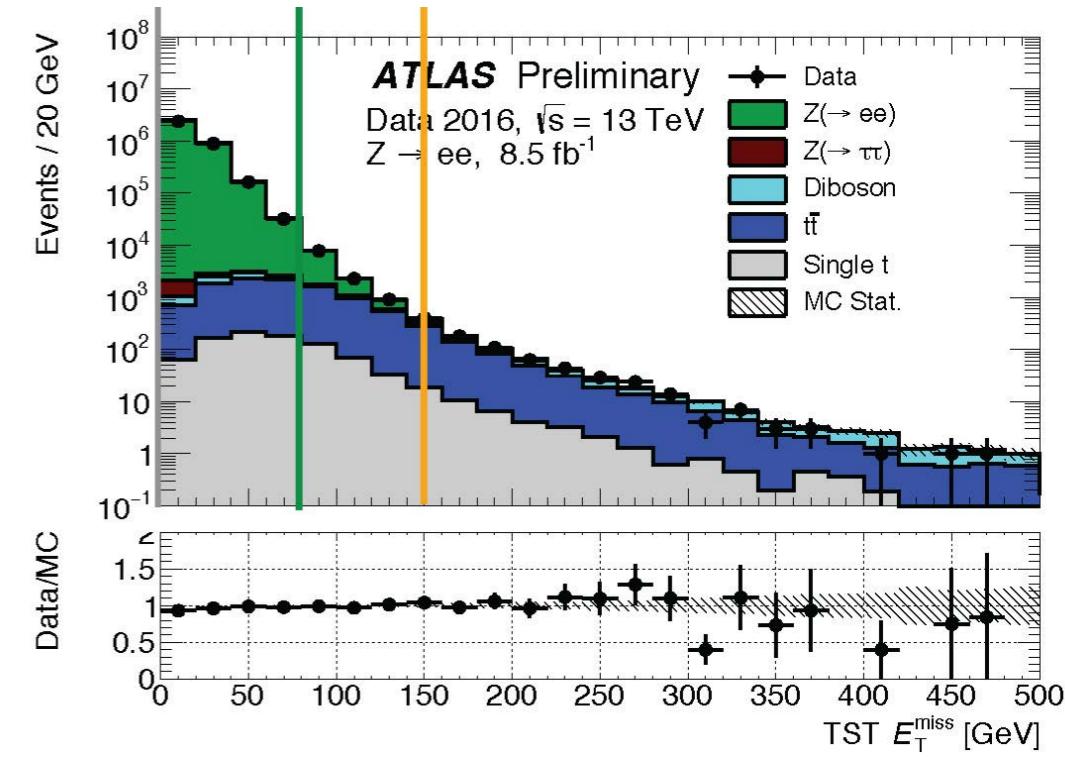
- It is **indirect measurement of weakly interacting particle (neutrinos, dark matter) momenta**, so very important for dark matter searches.



**CST  $E_T^{\text{miss}}$ :** Algorithm using Calorimeter Soft Term

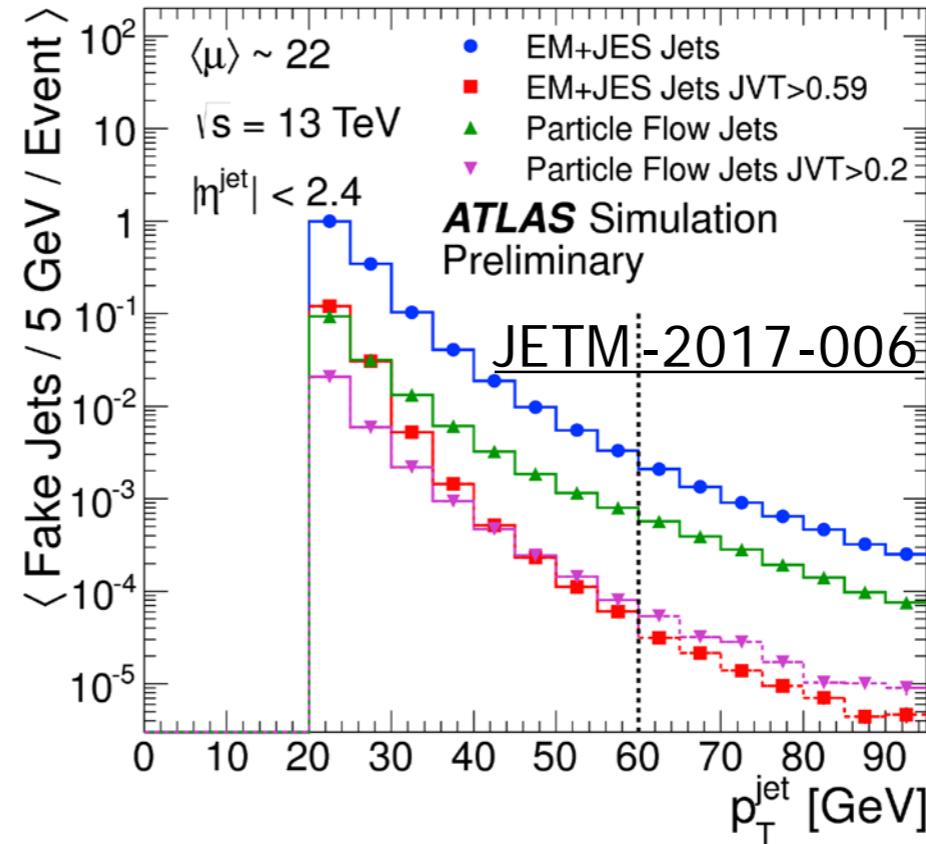
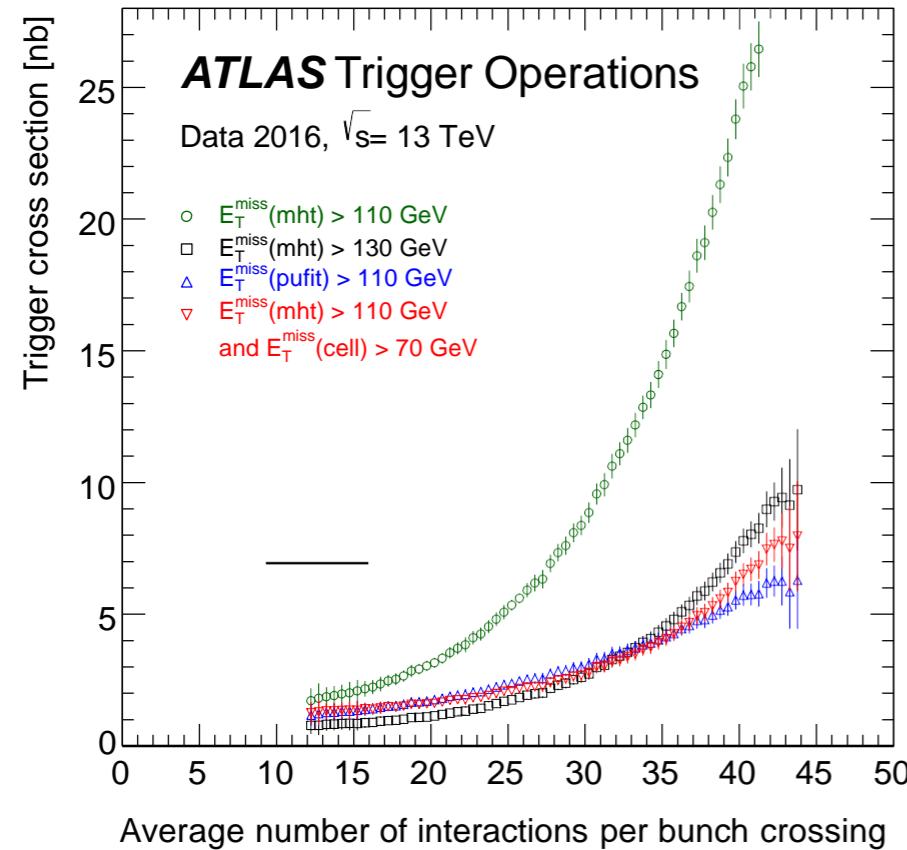
**TST  $E_T^{\text{miss}}$ :** Algorithm using Track Soft Term

**Track  $E_T^{\text{miss}}$ :** Purely reconstructed from tracks



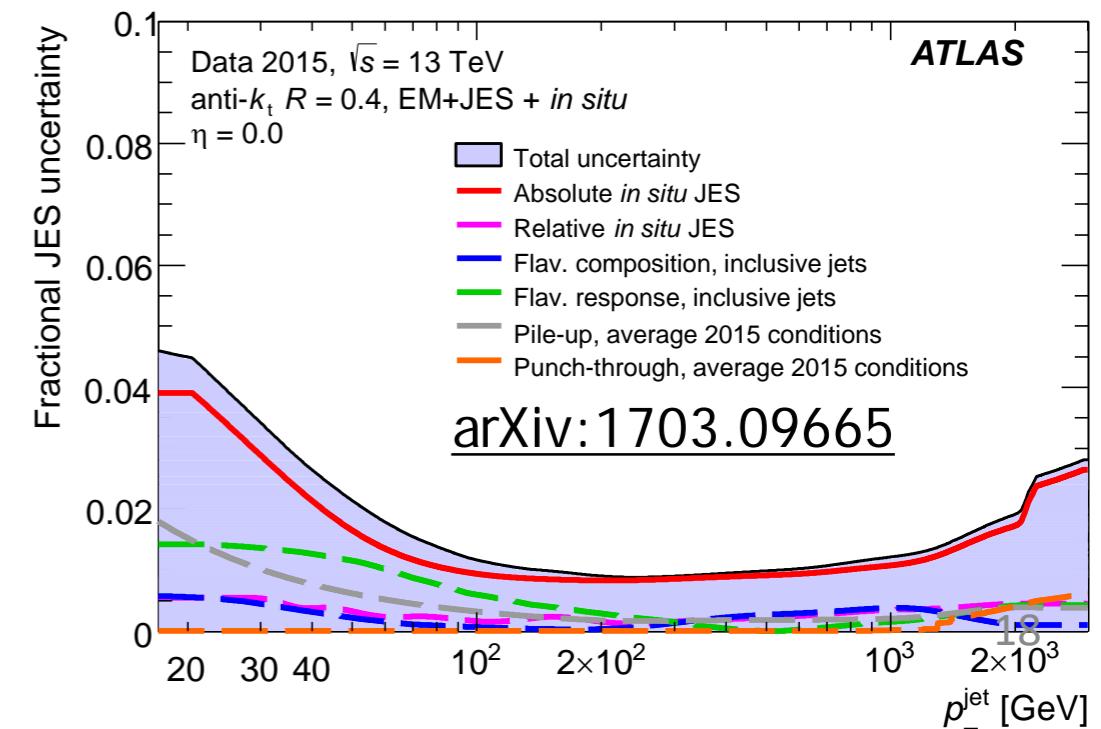
# Tools of DM searches / II

robust MET & jet reco/calibration techniques at all momenta



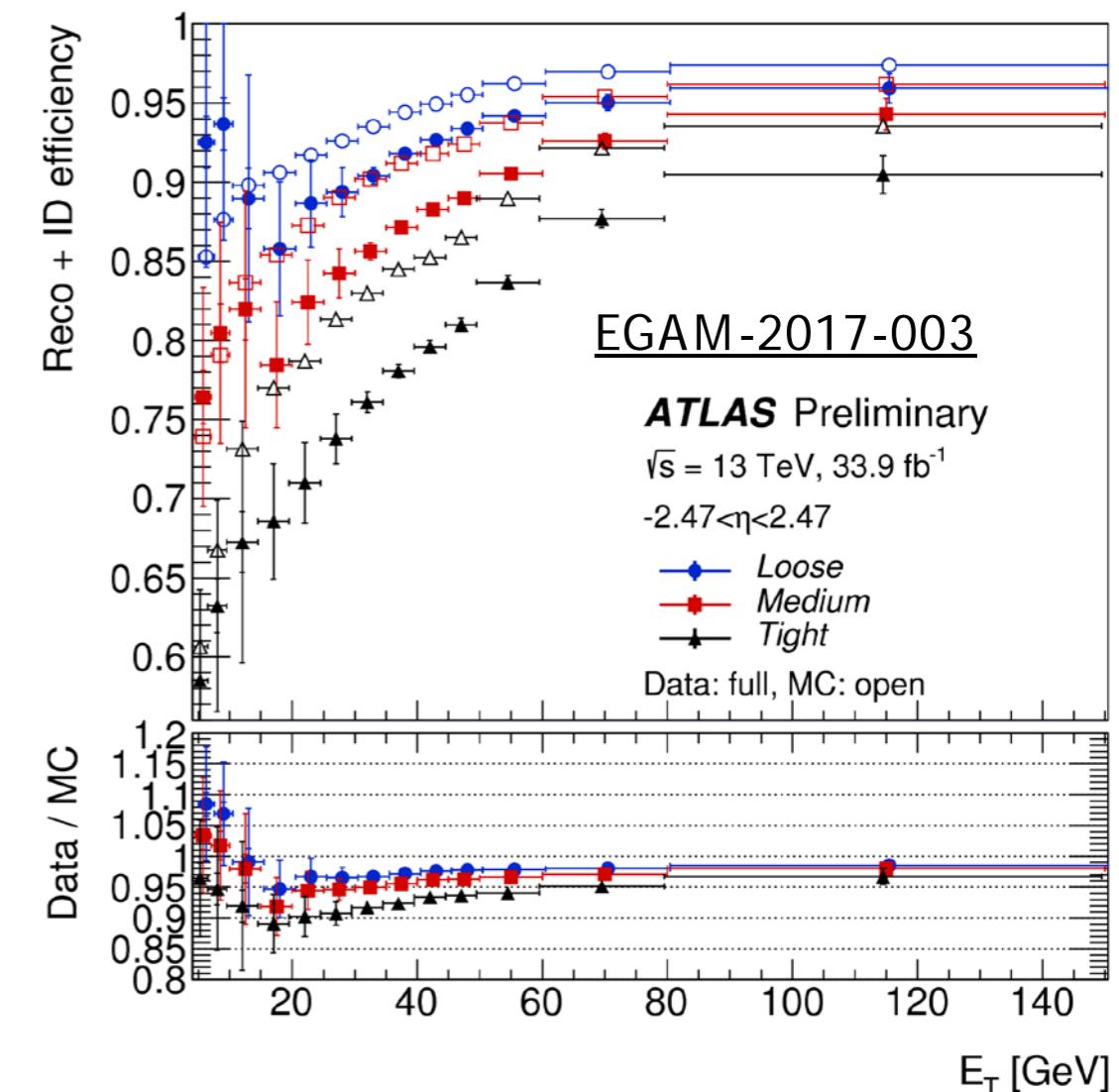
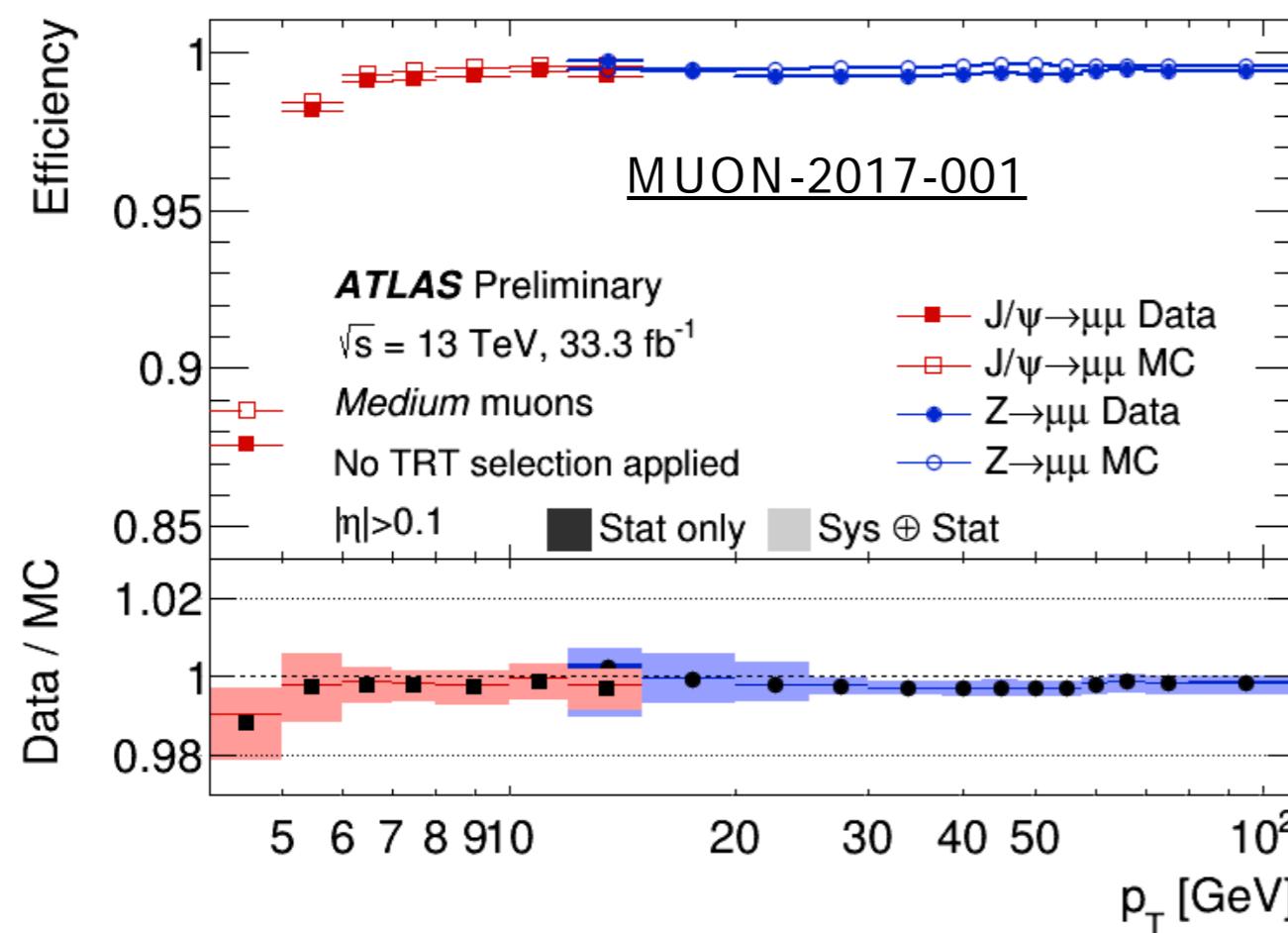
- pile-up is a limitation to MET trigger performance: need sophisticated algorithms to retain sensitivity for our signals (e.g. spin-0 interactions)
- understanding of calorimeter response paramount for accurate JES uncertainty

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# Tools of DM searches/ III

excellent lepton reconstruction performance



- crucial to exploit W/Z physics at the TeV scale
- you need to trust leptons reco/ID uncertainty to be able to constrain SM backgrounds from the data (notably  $Z\nu\nu + \text{jets!}$ )

# Data Scouting ("TLA") @ ATLAS

problem: limited trigger rate -> high pT threshold for single jet triggers

- 100 kHz @ L1 ->  $p_T(\text{single jet}) > \sim 400 \text{ GeV}$

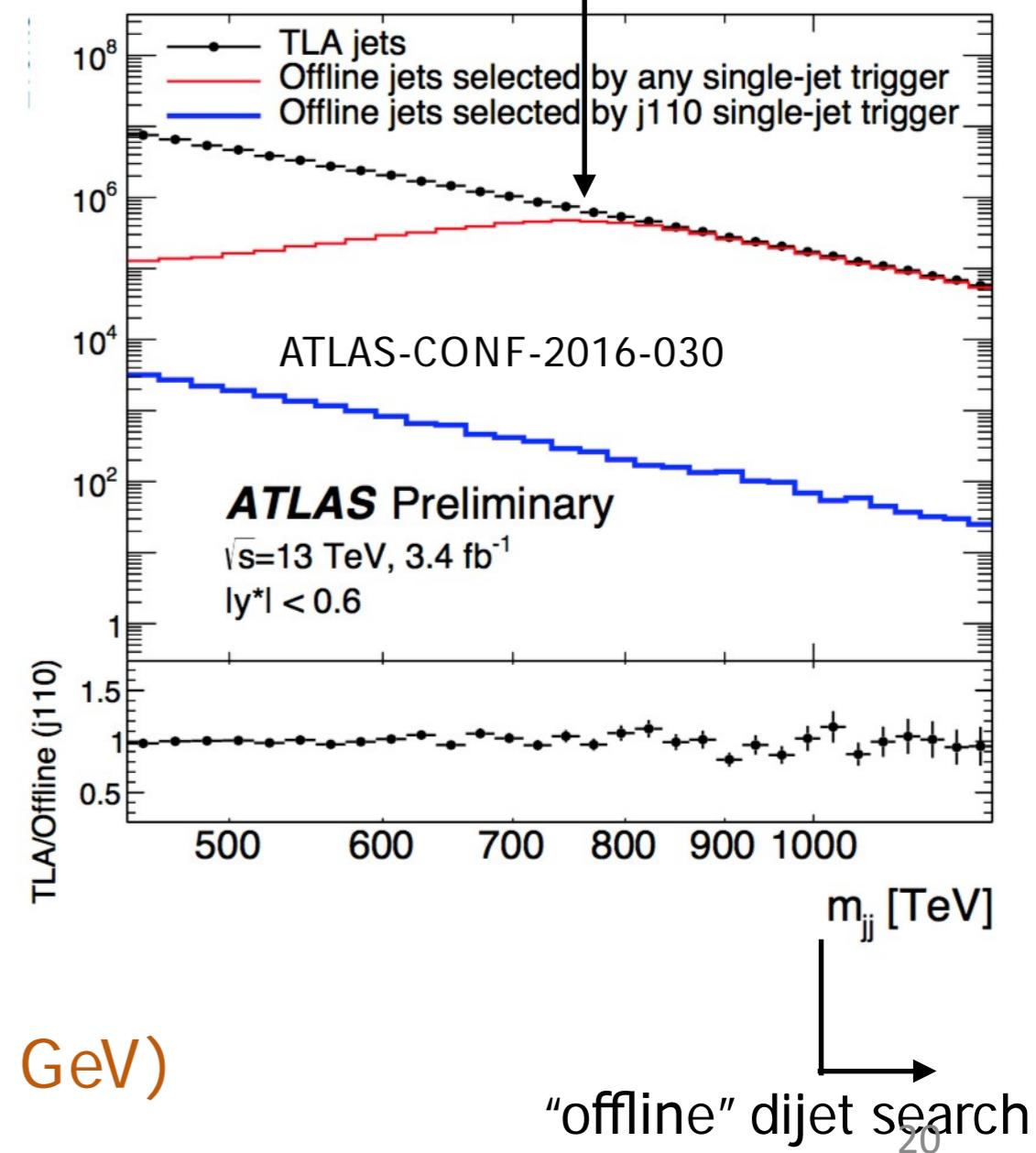
first unprescaled single jet trigger at  $p_T > 400 \text{ GeV}$

solution: store only minimal jet information

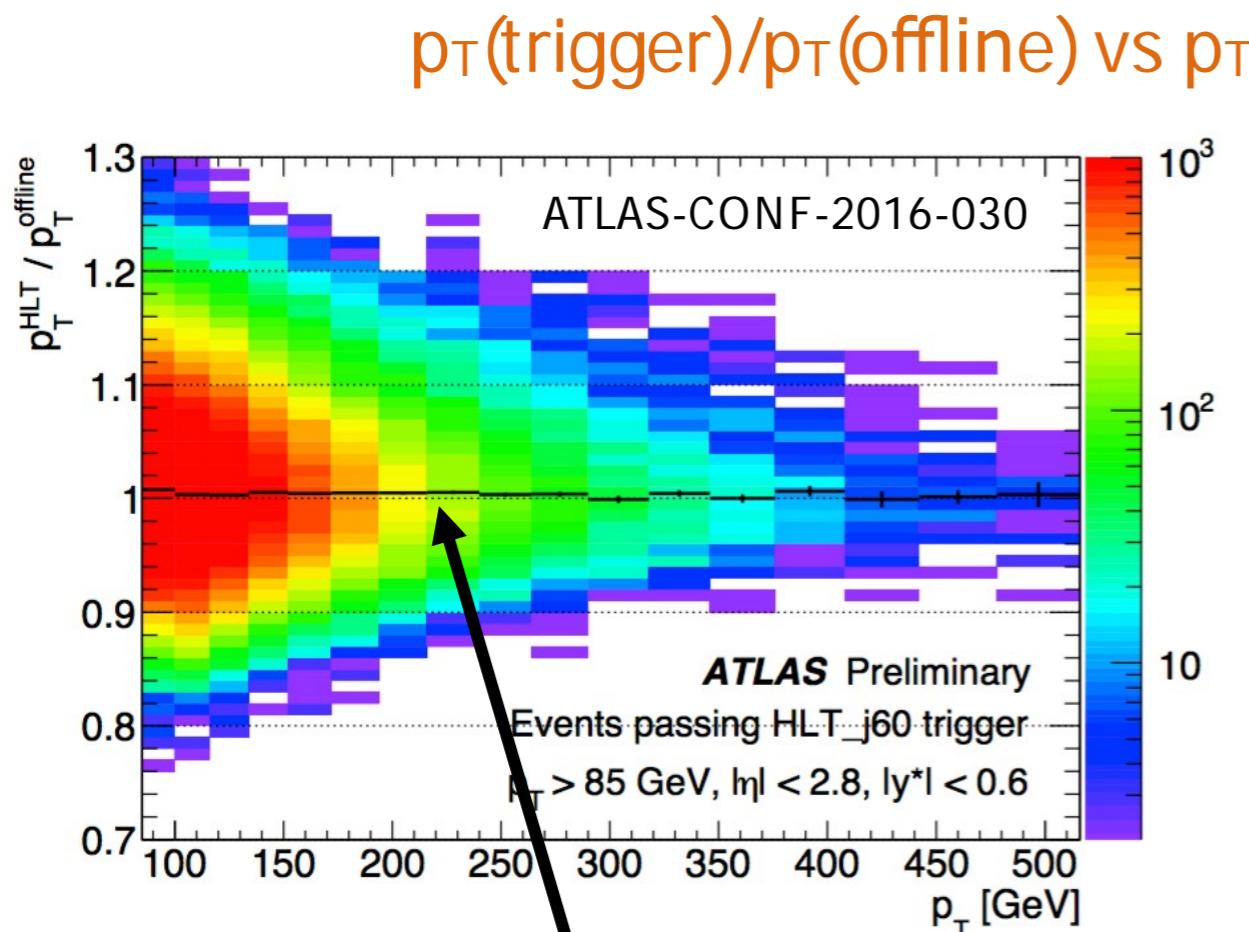
- start with 75 GeV L1 trigger (+2 kHz; EM scale)
- save all HLT jets above 4 GeV (~5% of total event size)
- calibrate them using offline jets
  - no tracking info -> 3.5-5% systematics (mostly due to flavour uncertainty)

dijet search using trigger-level jets

- $p_T 1 > 185 \text{ GeV}, p_T 2 > 85 \text{ GeV}$
- $|y^*| < 0.3$  (for  $m_{jj} < 550 \text{ GeV}$ ) or  $< 0.6$  ( $m_{jj} > 550 \text{ GeV}$ )

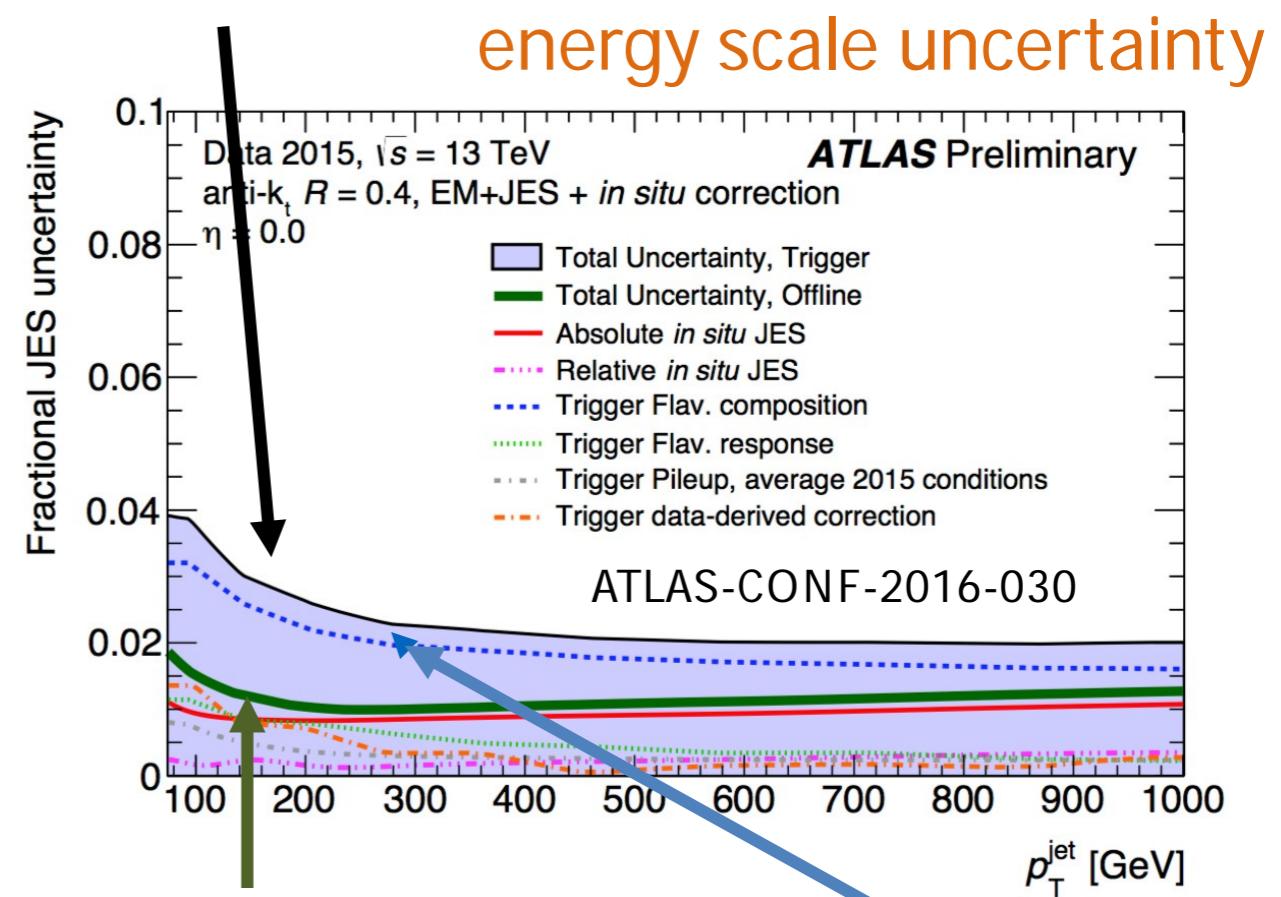


# Trigger-level Jets vs Offline Jets



trigger/offline pT  
response within ~1%

trigger jet  
total



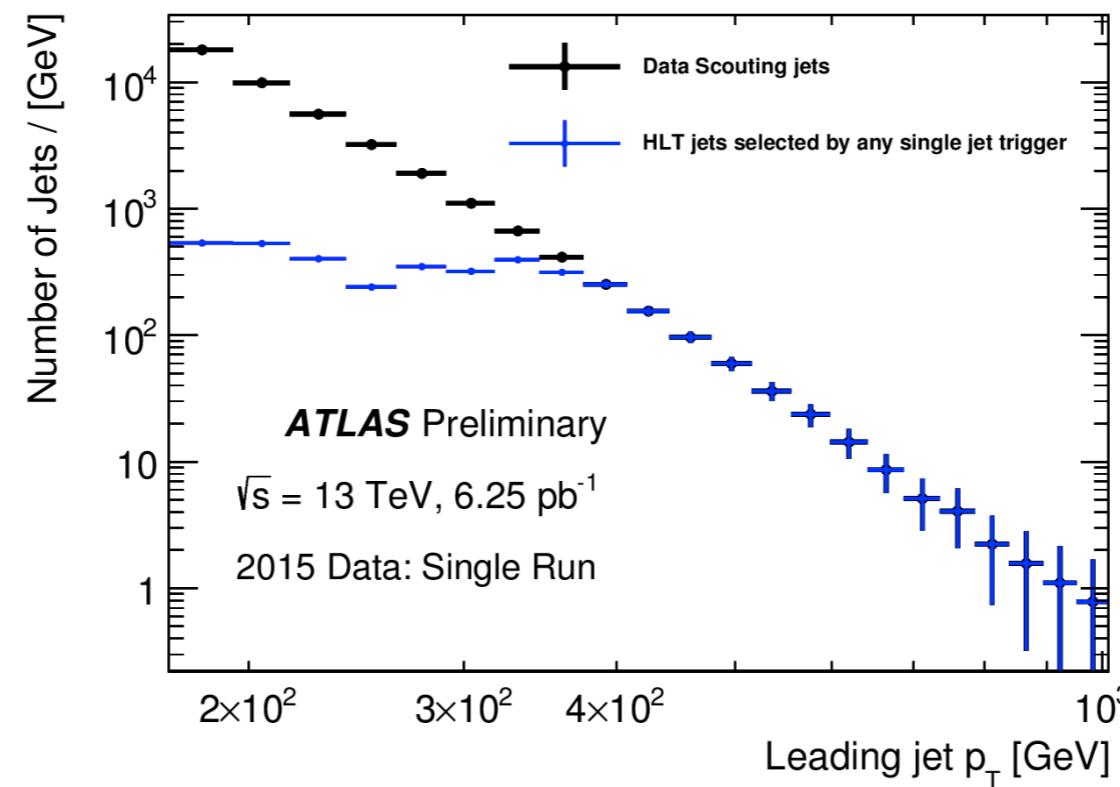
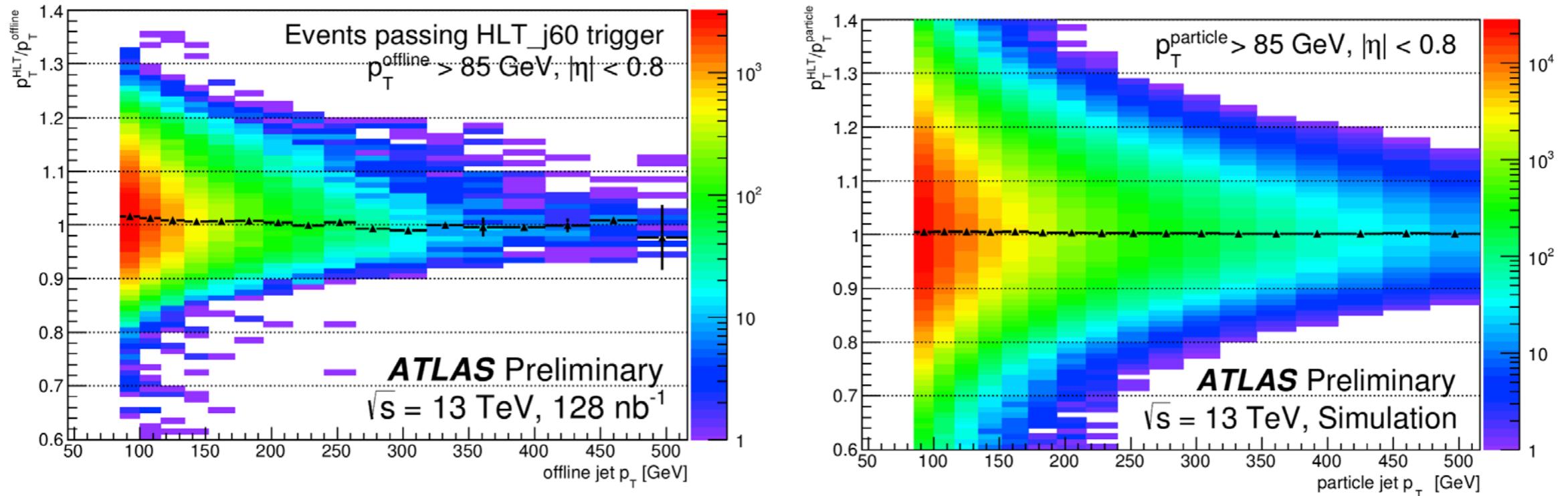
offline jet  
total

flavour  
composiYon  
(q vs g)

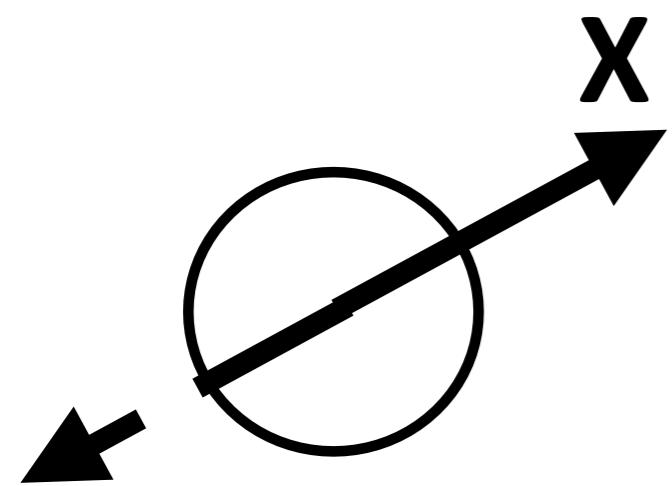
Trigger level tracking/vertexing of great importance

# TLA jets

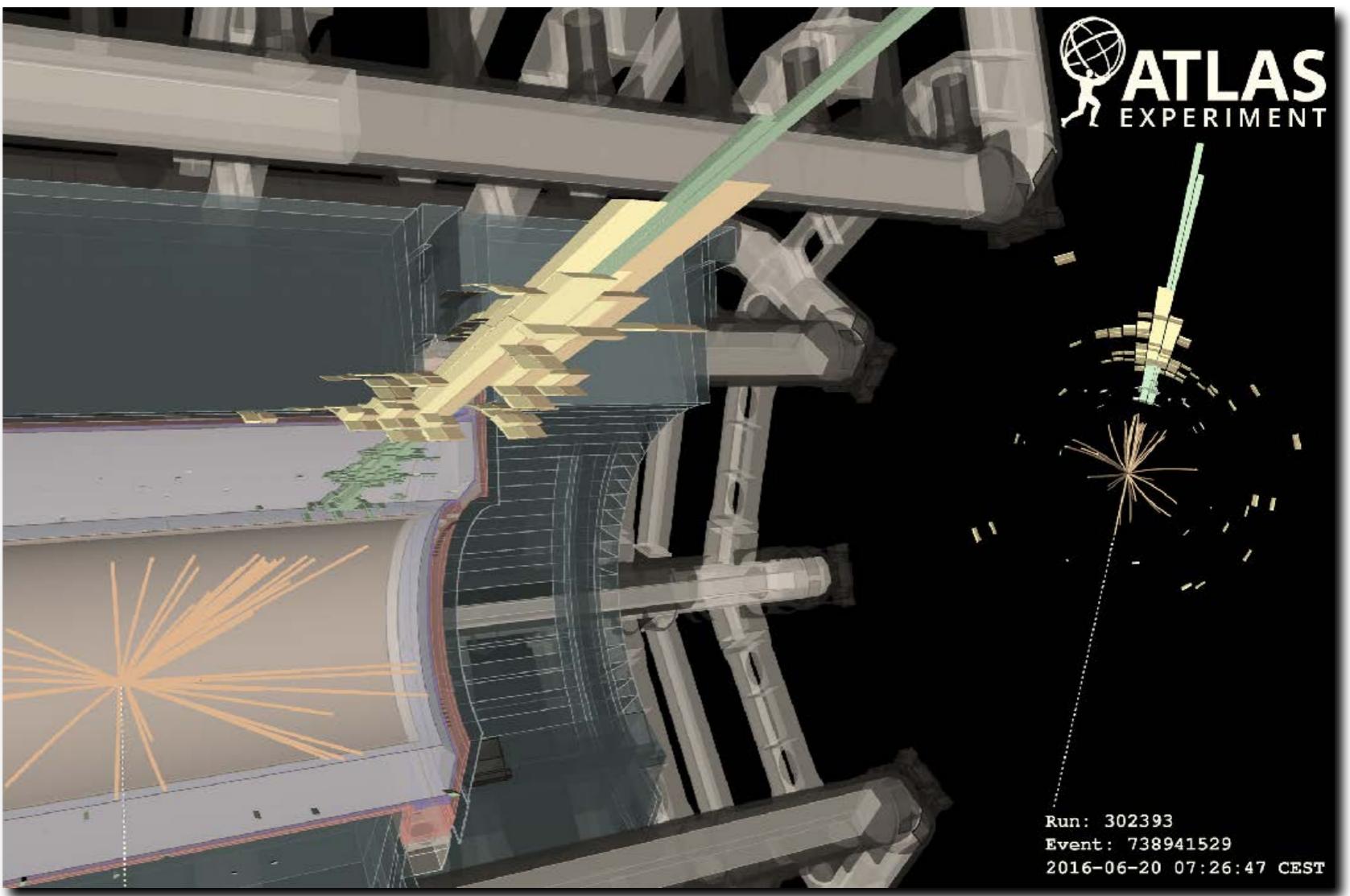
**ATL-COM-DAQ-2016-012**

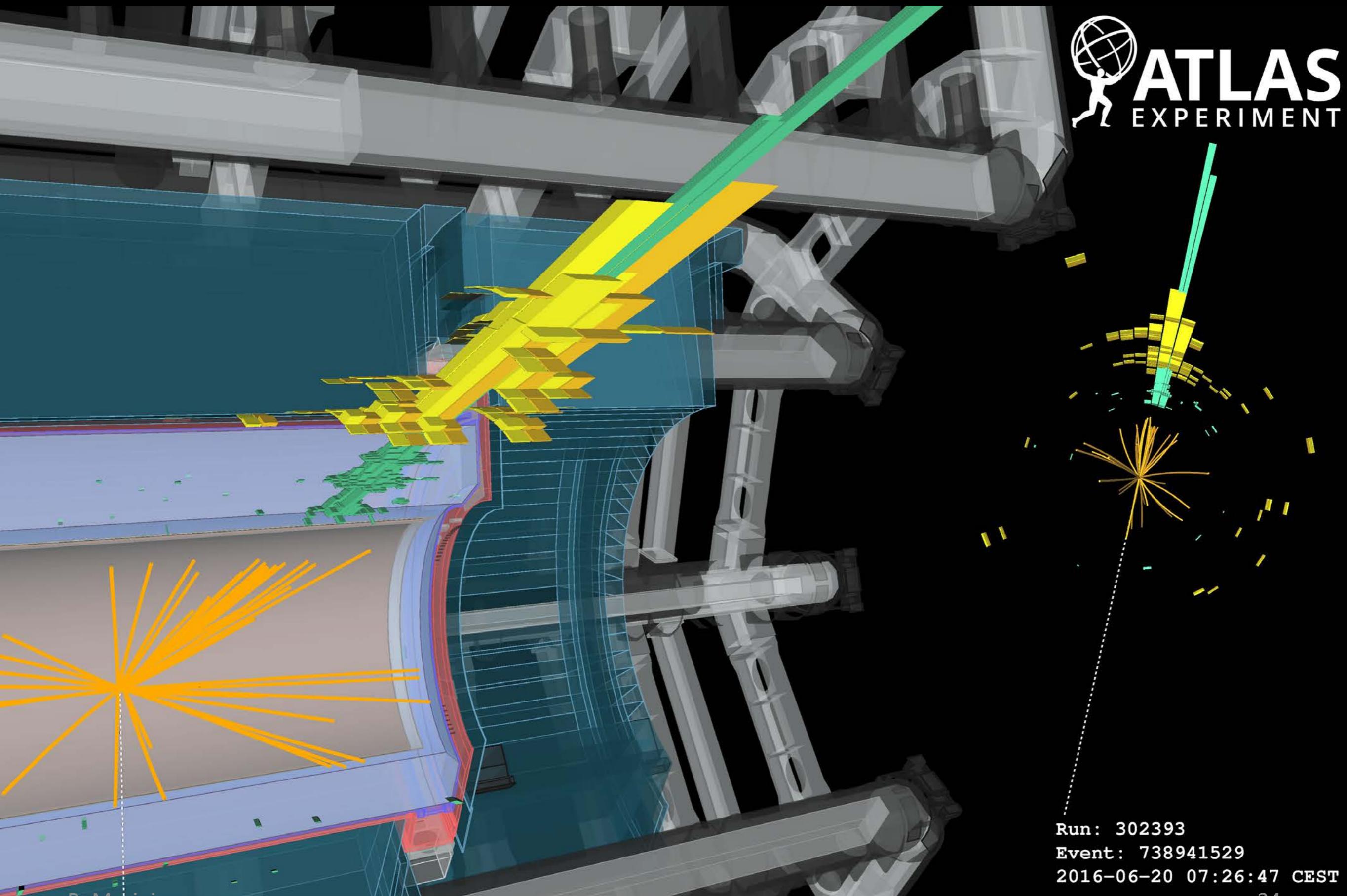


# Mono-X Searches



$E_T^{\text{miss}}$





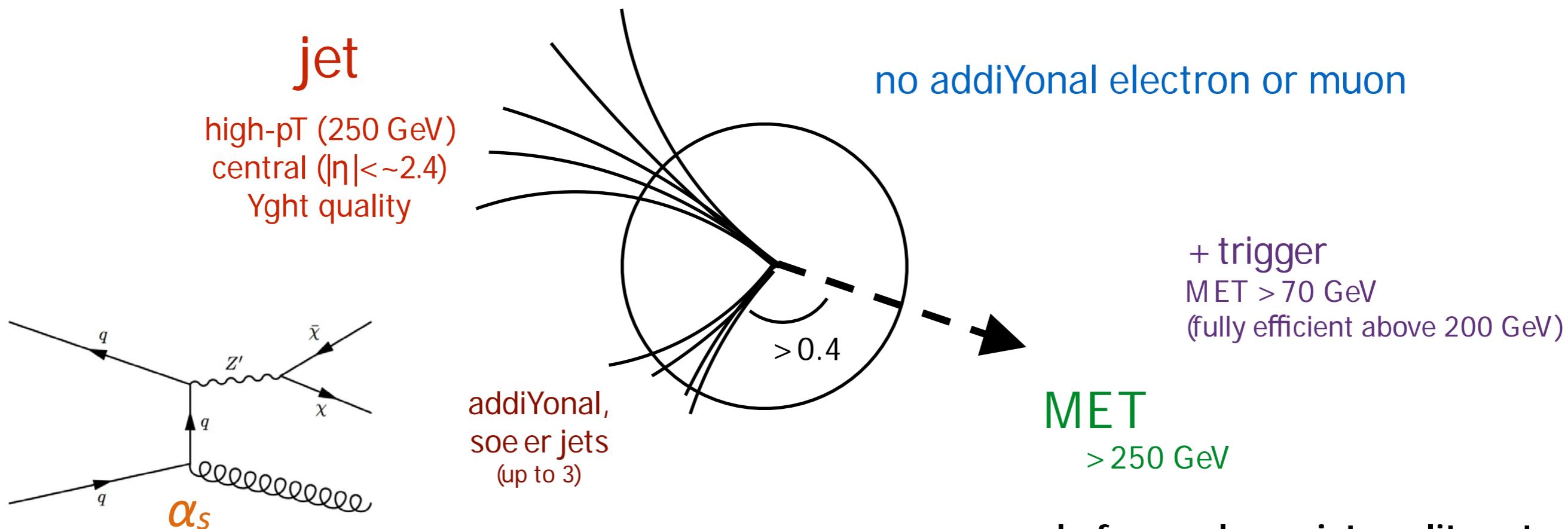
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Event: 738941529  
2016-06-20 07:26:47 CEST

24

# Mono-jet

**ATLAS-CONF-2017-060**

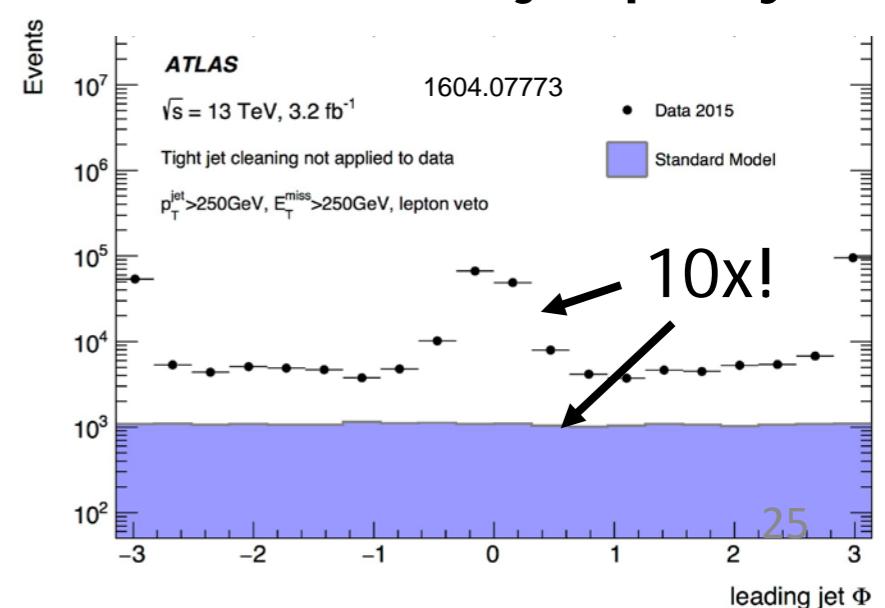
*best channel if tagging object comes from ISR! (pay only  $\alpha_s$ )*



same signature as

- $Z(vv) + \text{jets}$ ,  $W(\tau[qq']v) + \text{jets} \dots$ 
    - normalisation from simultaneous fit to  $p_T(W/Z)$  distributions in lepton control regions
    - use calorimeter segmentation to reject beam & instrumental background

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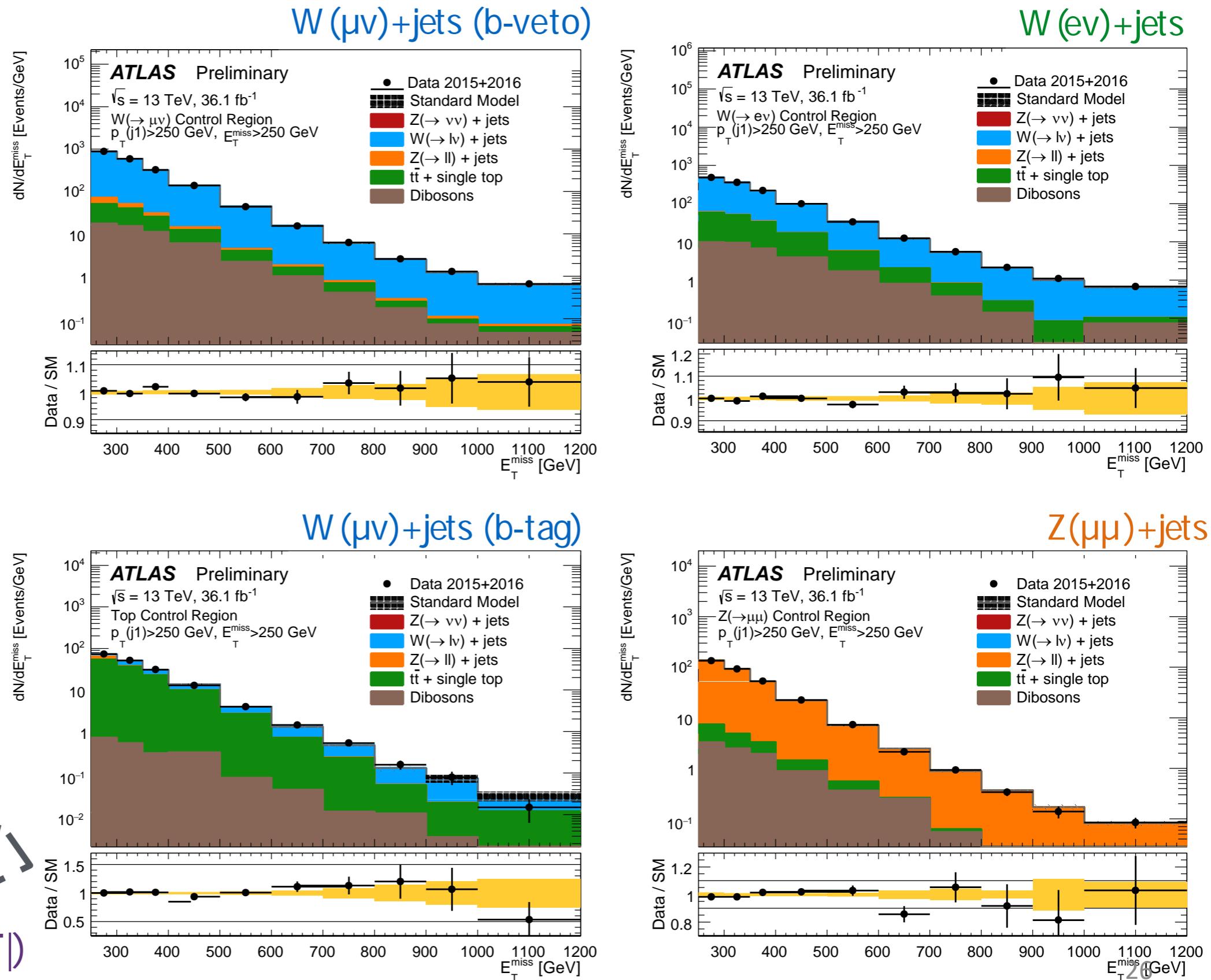
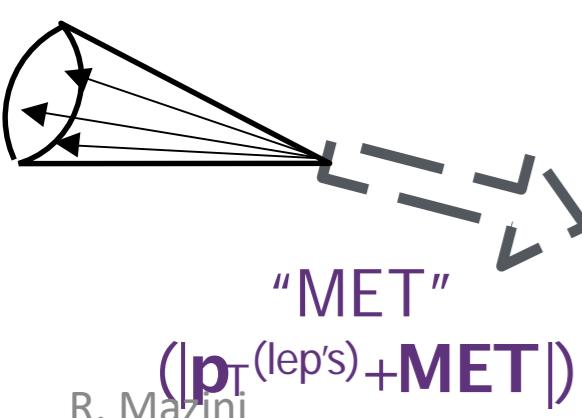
# Mono-jet: Control Regions

*results of CR-only fit*

fit parameters:

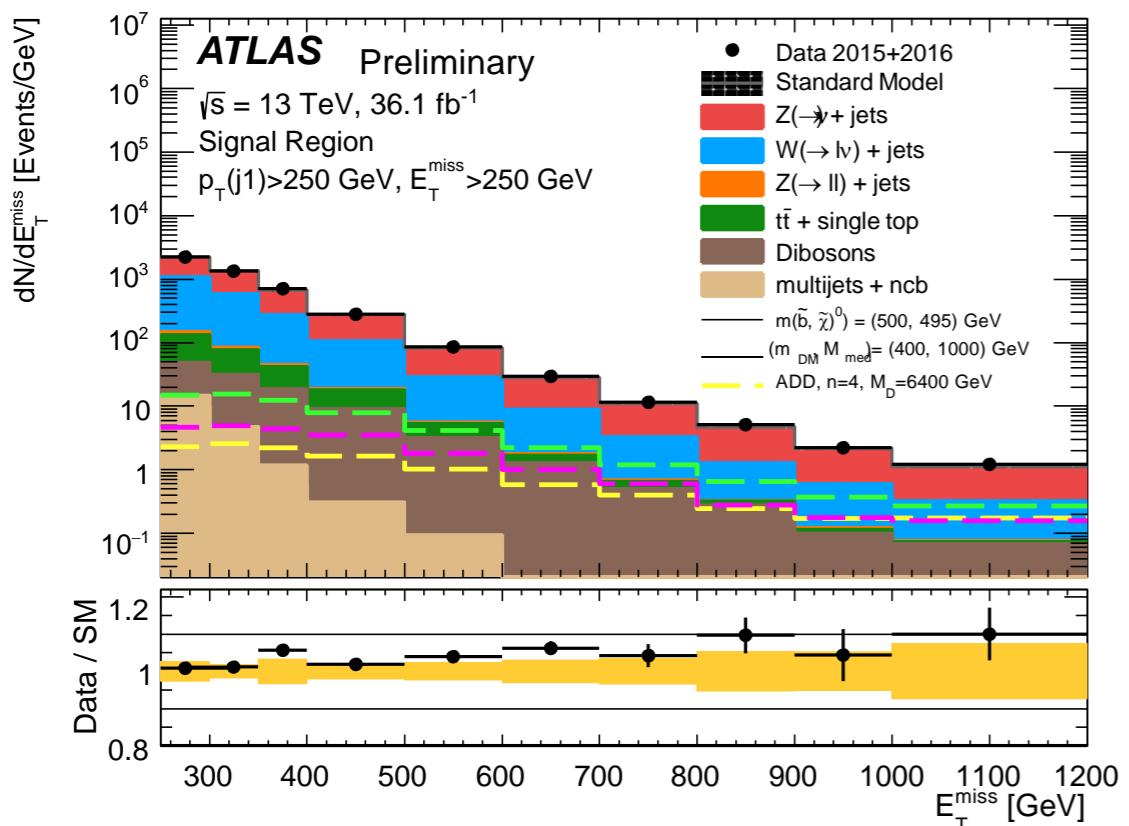
- W/Z  
normalisation  
(common also  
to Z(vv)+jets)
- a<sup>bar</sup>/single-t  
normalisation
- shape  
uncertainty

jet



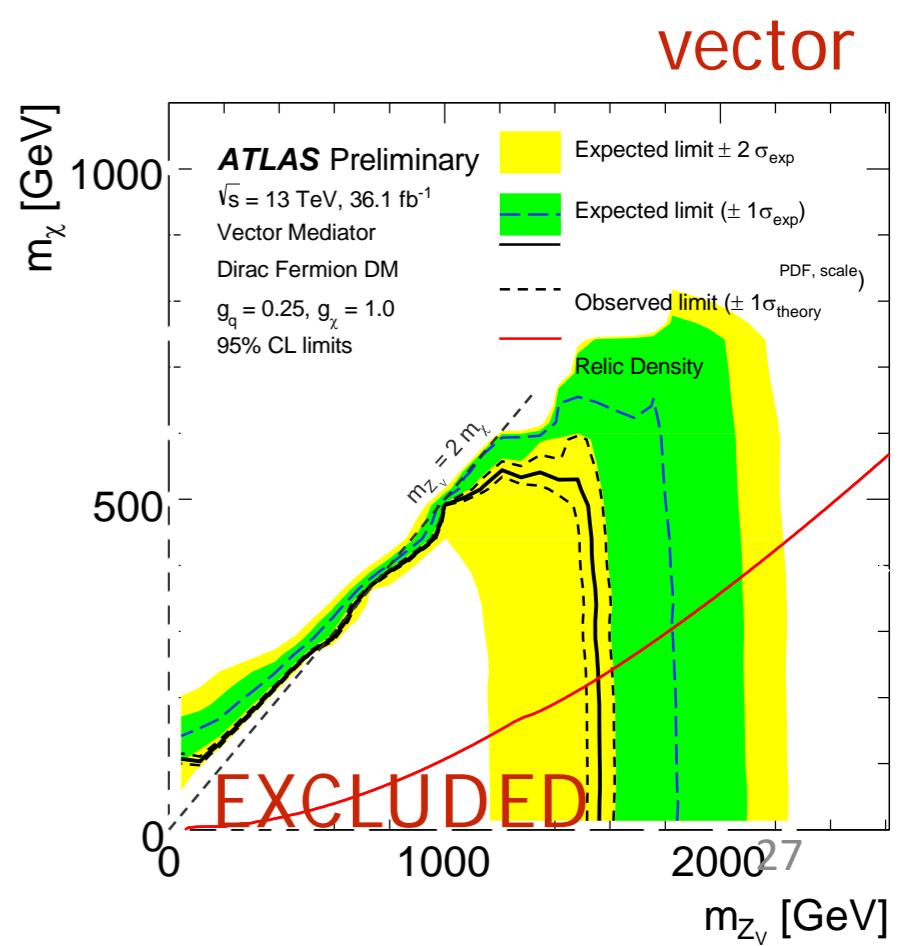
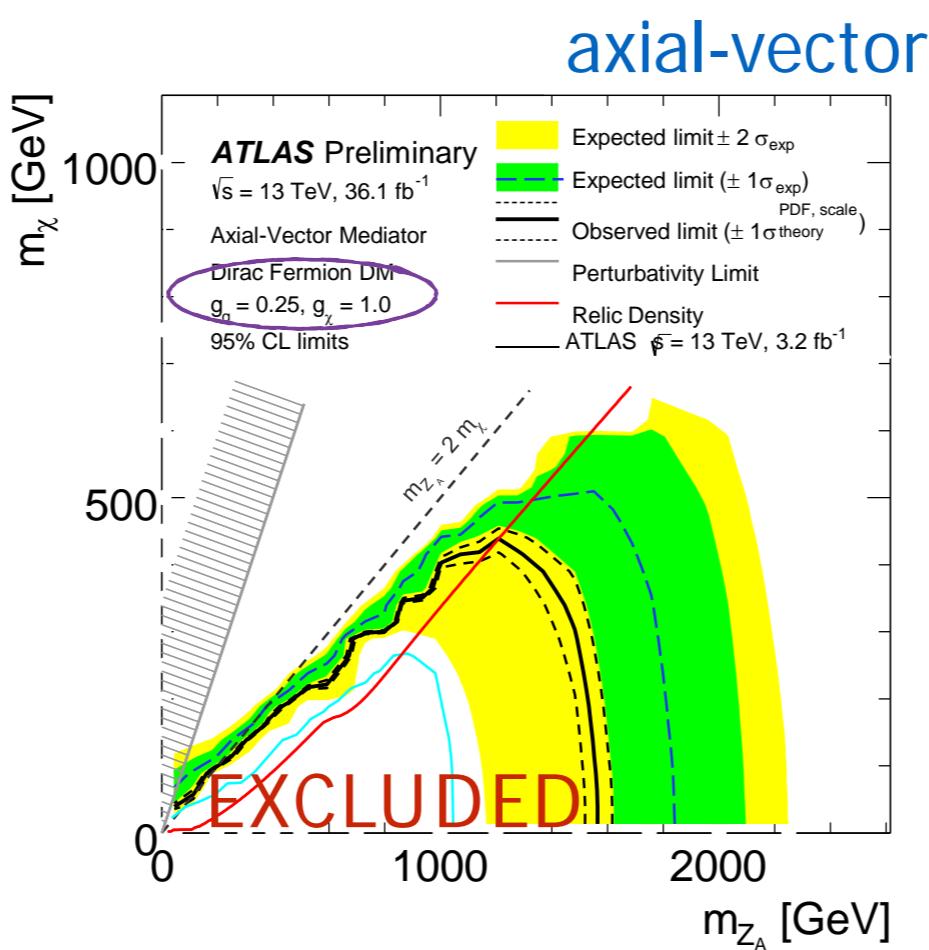
# Mono-jet: Results

*results of CR+SR fit*



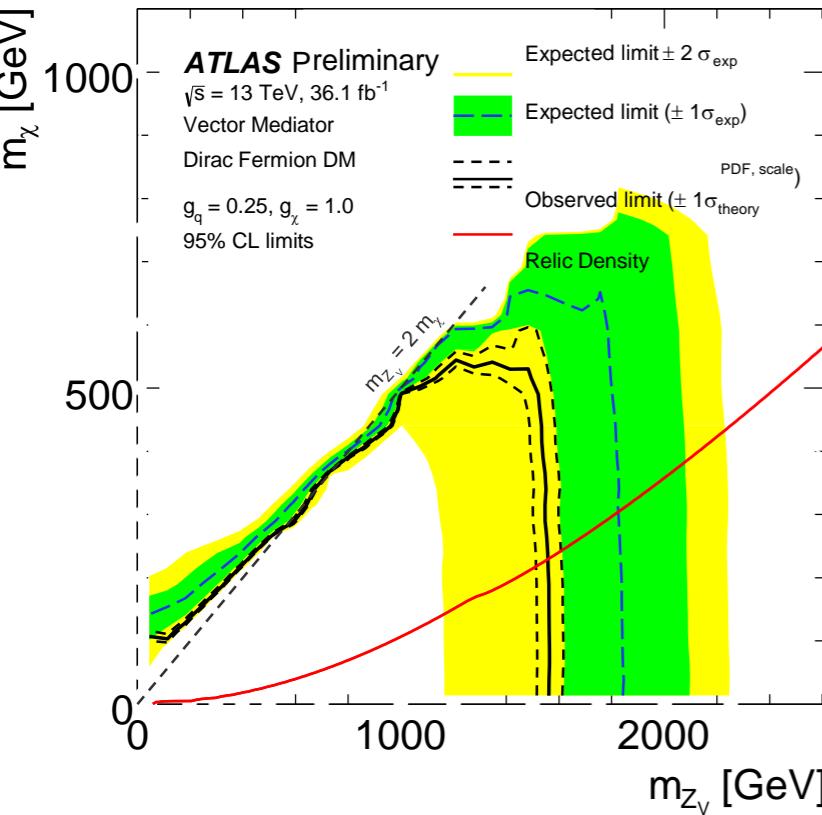
- W/Z modelled at NLO QCD & EW
  - Sherpa [NLO(LO) for 1,2(3,4) partons]  $\oplus$  theory reweighYng based on  $p_T(W/Z)$  [[arXiv:1705.04664](#)]
- 2-5% uncertainty on SR background
  - theo: 0.7-1% for the W(lv)/Z(ll)->Z(vv) extrapolation
  - exp: electron/muon efficiency, jet energy scale/reso
- probing s-channel ( $J^P=0^-, 1^+, 1^-$ ) DM -SM interactions
  - pseudoscalar: cannot yet exclude model with  $g=1$

discovery potential depends on assumed interaction and couplings!

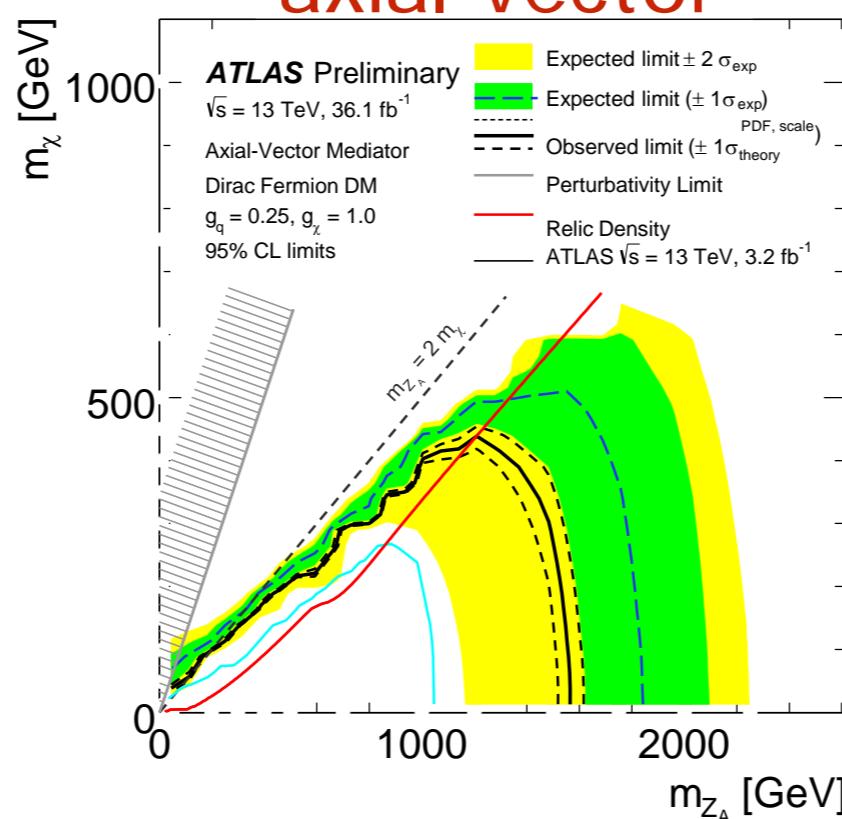


# Mono-jet: results

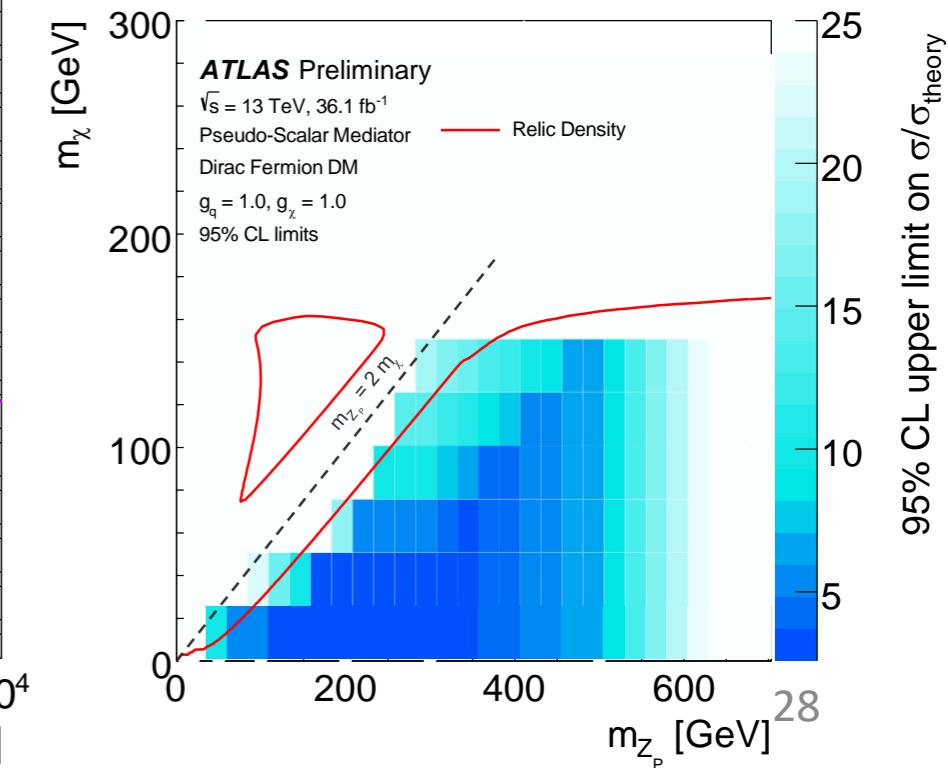
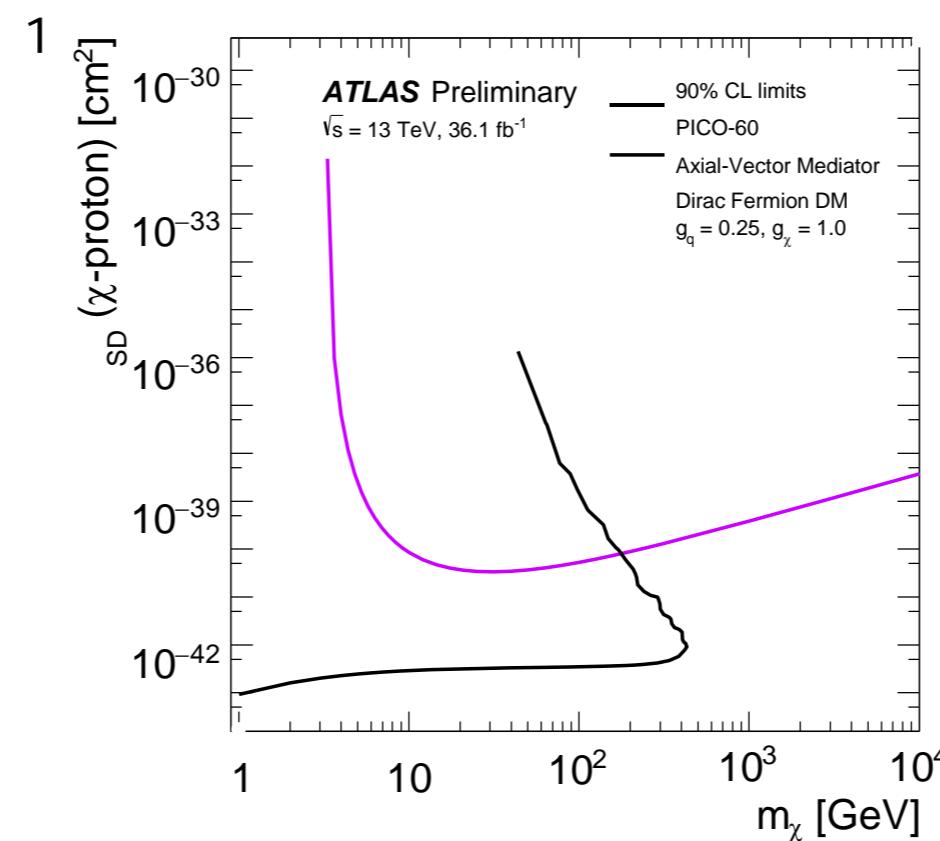
vector



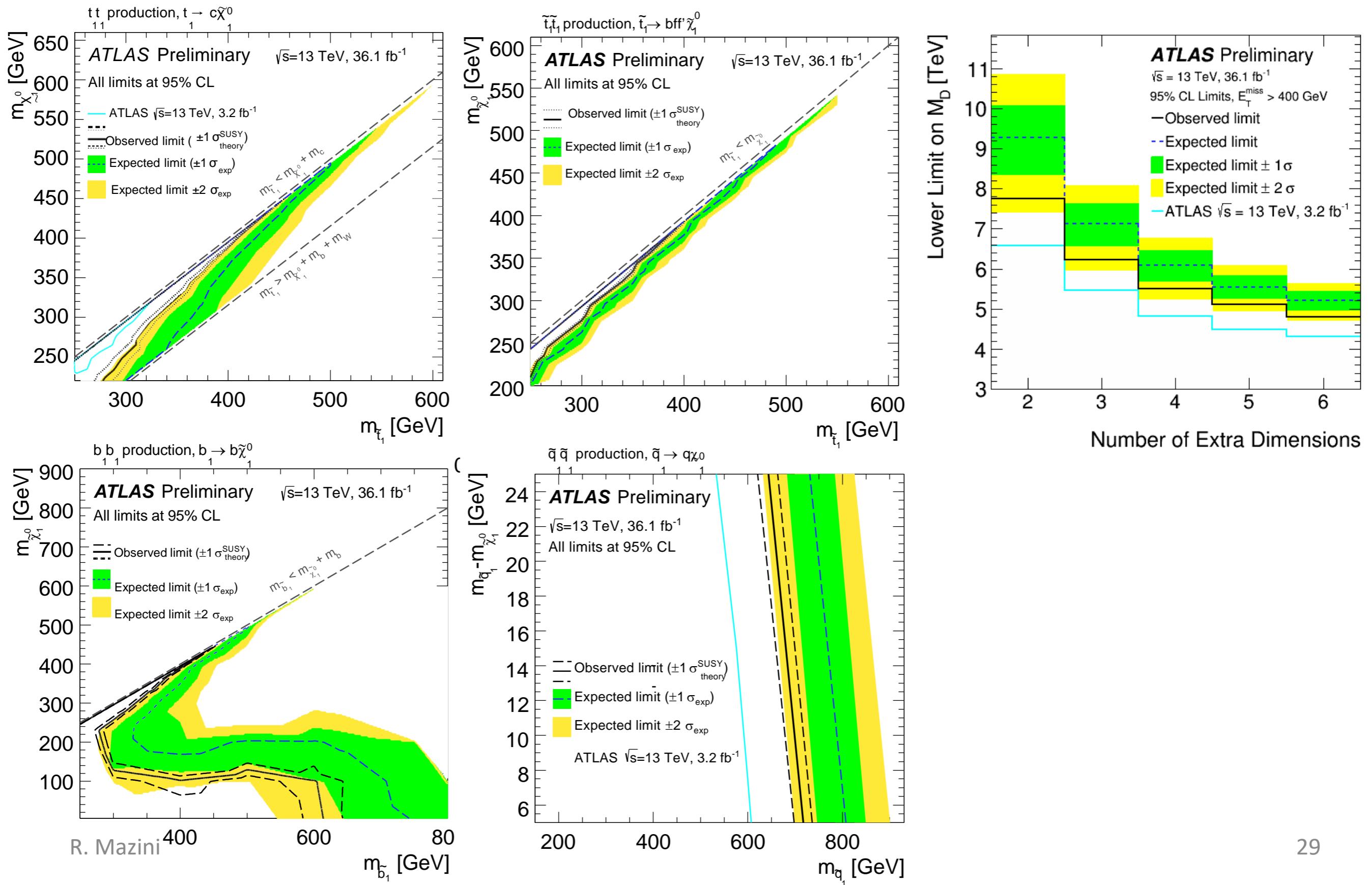
axial-vector



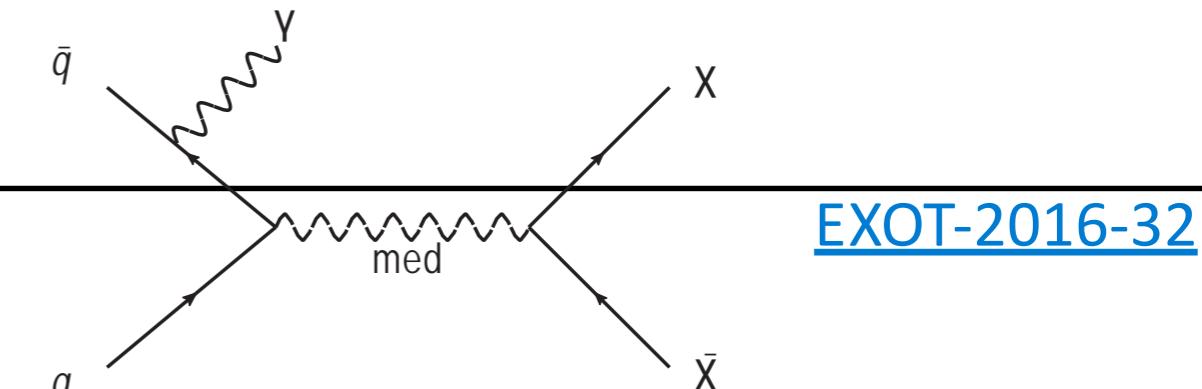
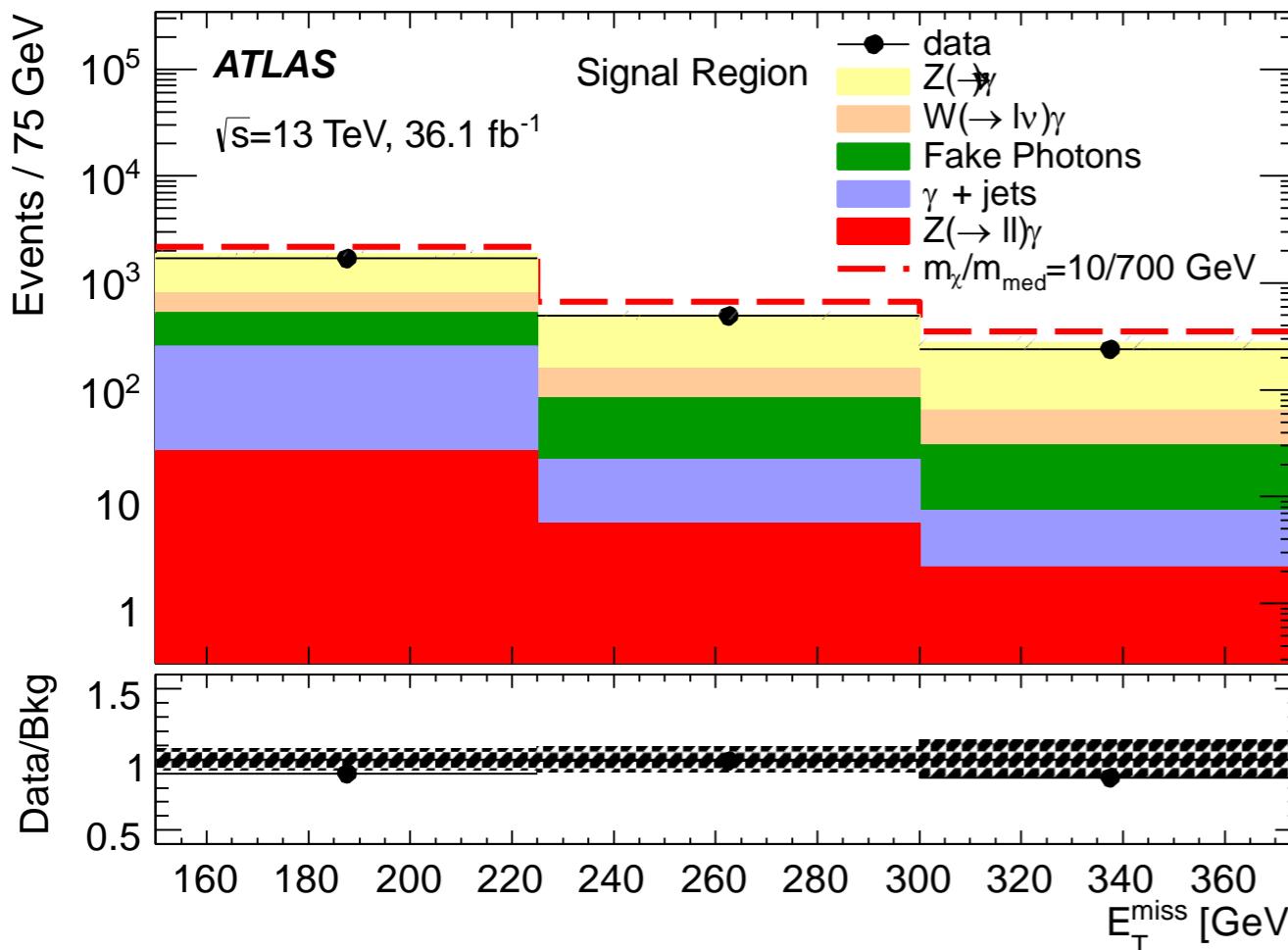
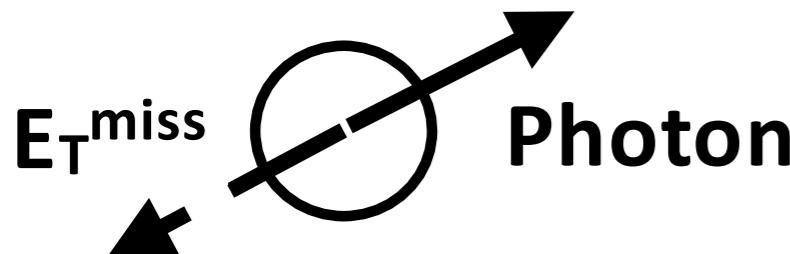
pseudo-scalar



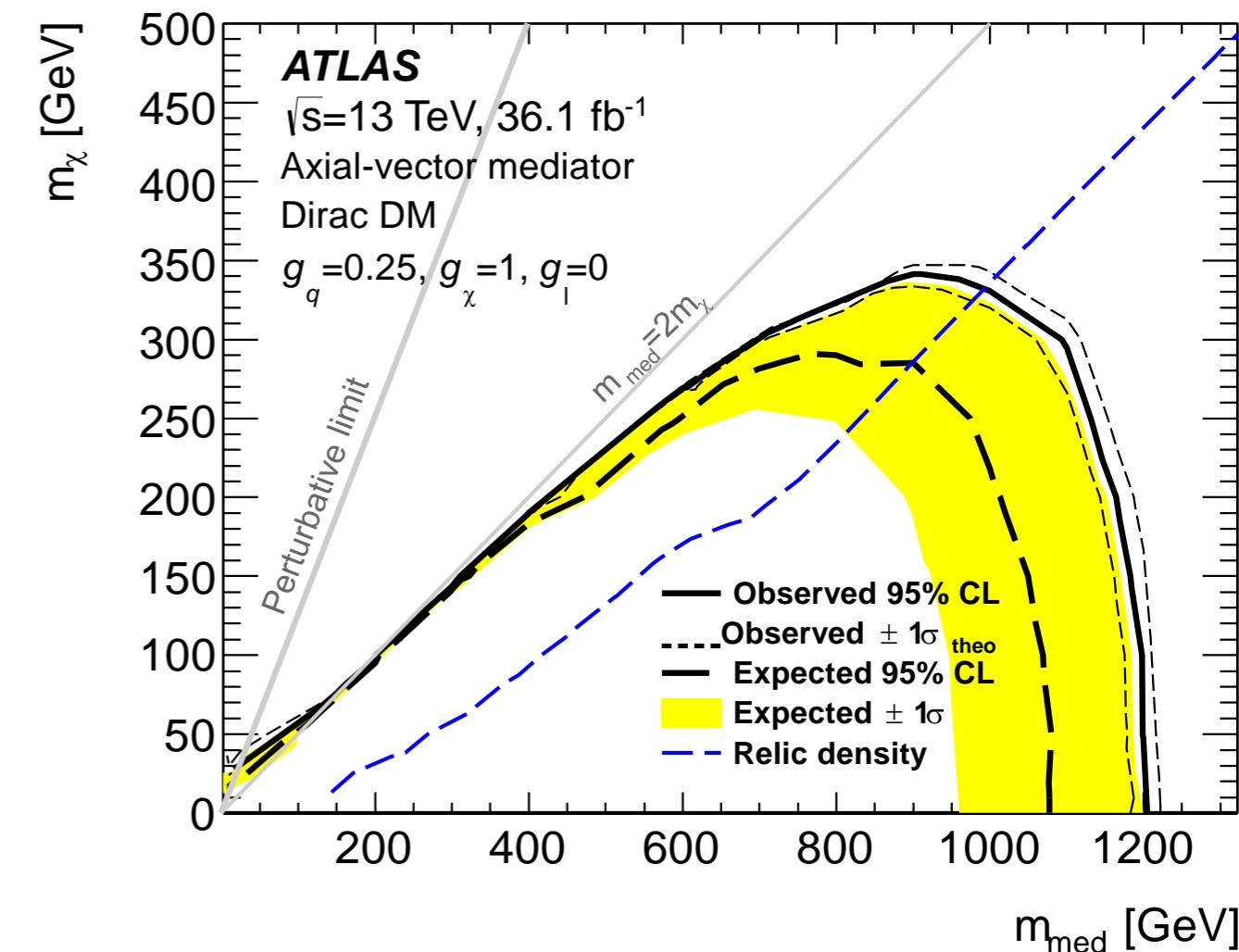
# Interpretation beyond DM simplified models



# Mono-photon



## Axial-vector mediator

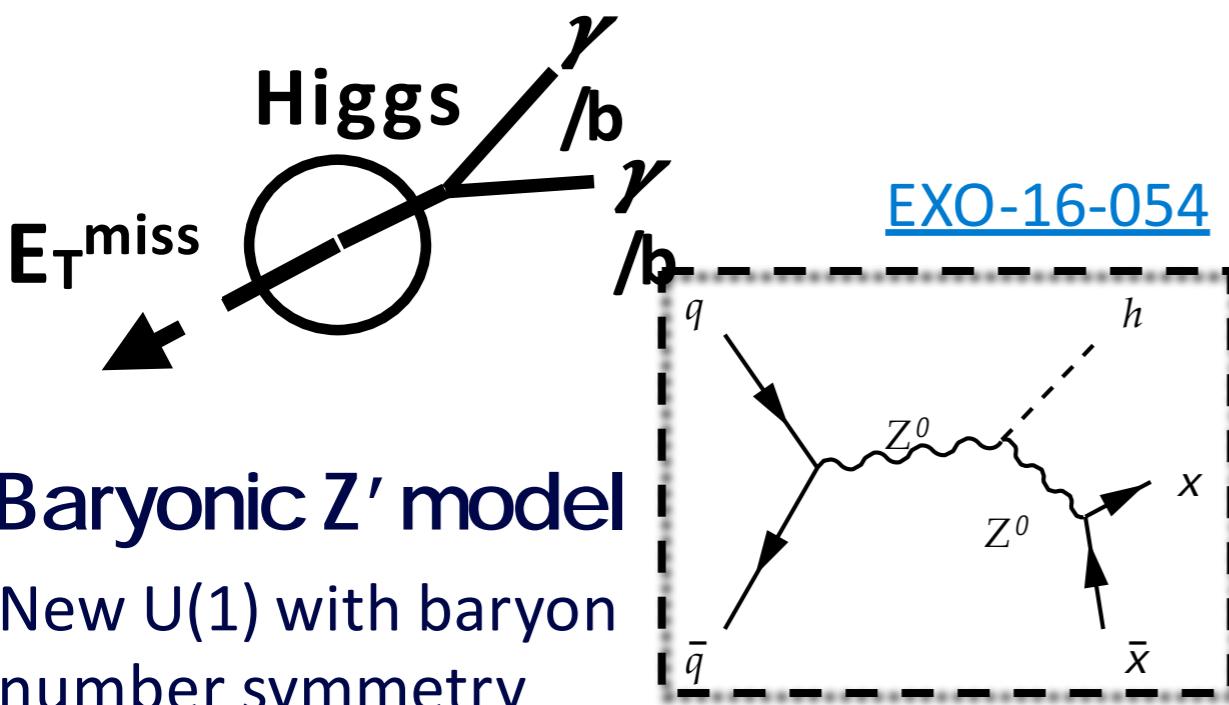


- Photon  $E_T > 150 \text{ GeV}, |\eta| < 2.37$
- $E_T^{\text{miss}}/\sqrt{\sum E_T} > 8.5 \text{ GeV}^{1/2}$
- $\Delta\phi(\text{photon}, E_T^{\text{miss}}) > 0.4$
- $N_{\text{jets}}(p_T > 30 \text{ GeV}, |\eta| < 4.5) \leq 1$

For vector & axial-vector interactions :

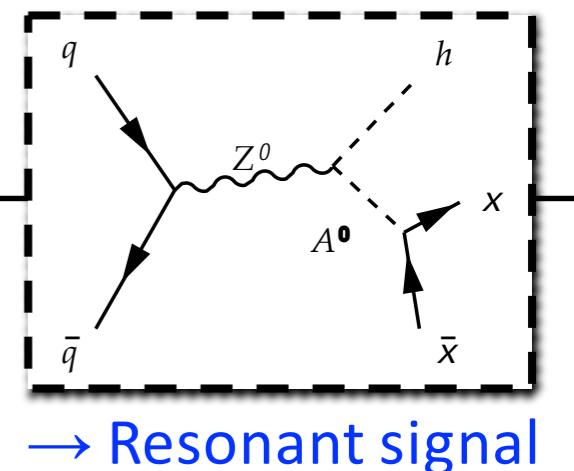
- Mediator mass excluded up to 1.2 TeV
- DM mass excluded up to 340-480 GeV

# Mono-Higgs



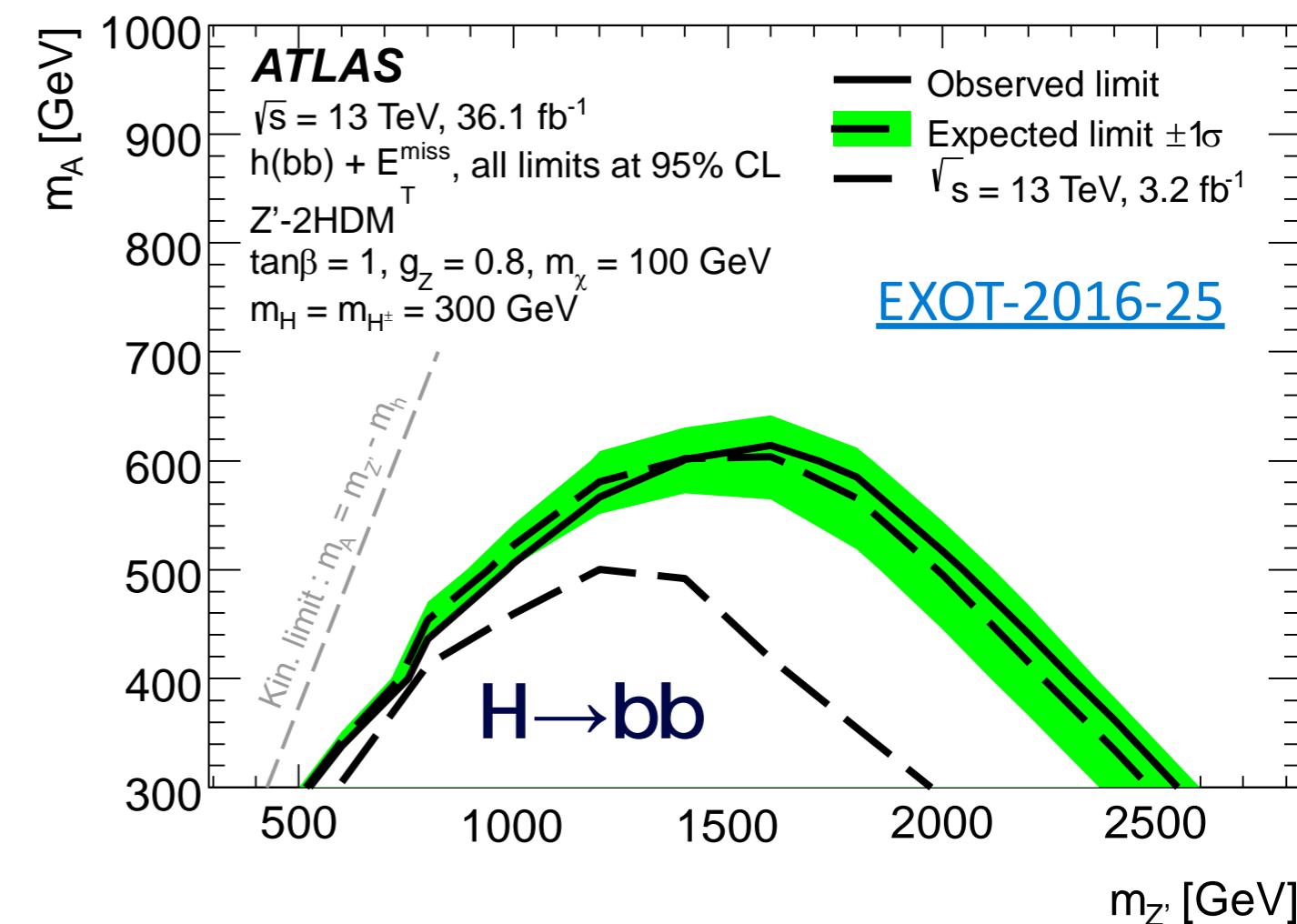
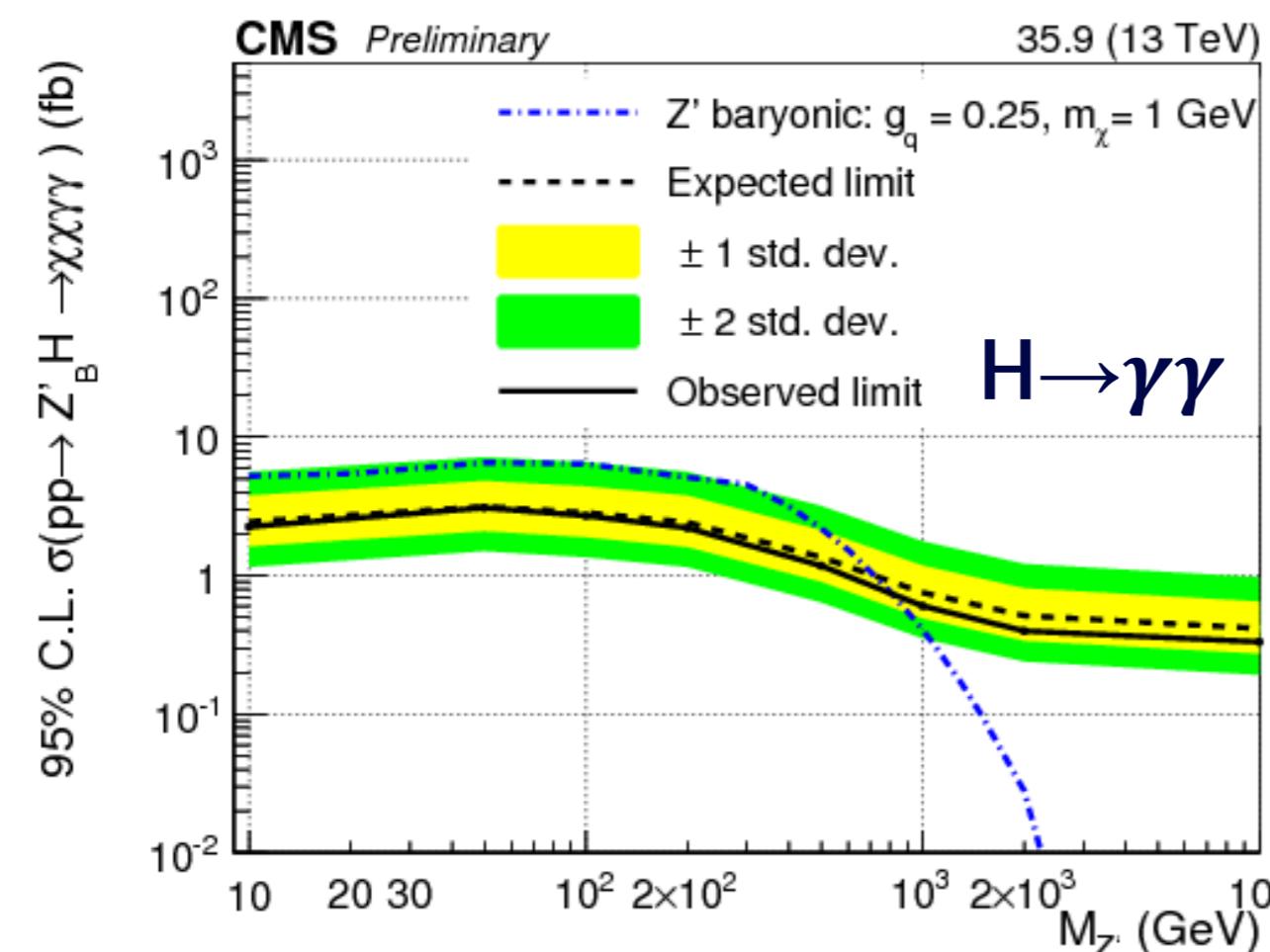
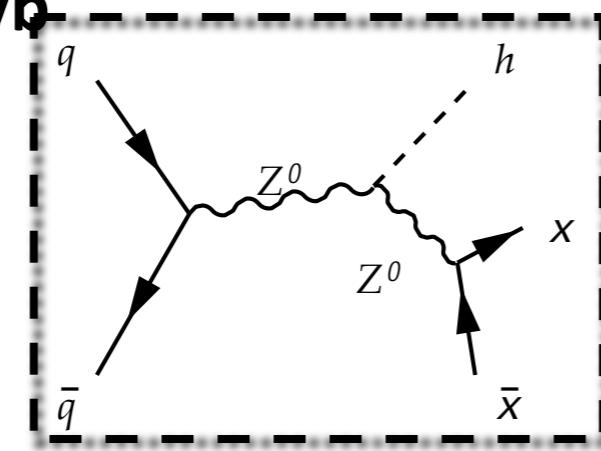
# Z'-2HDM model

New pseudo-scalar  
→ DM pair



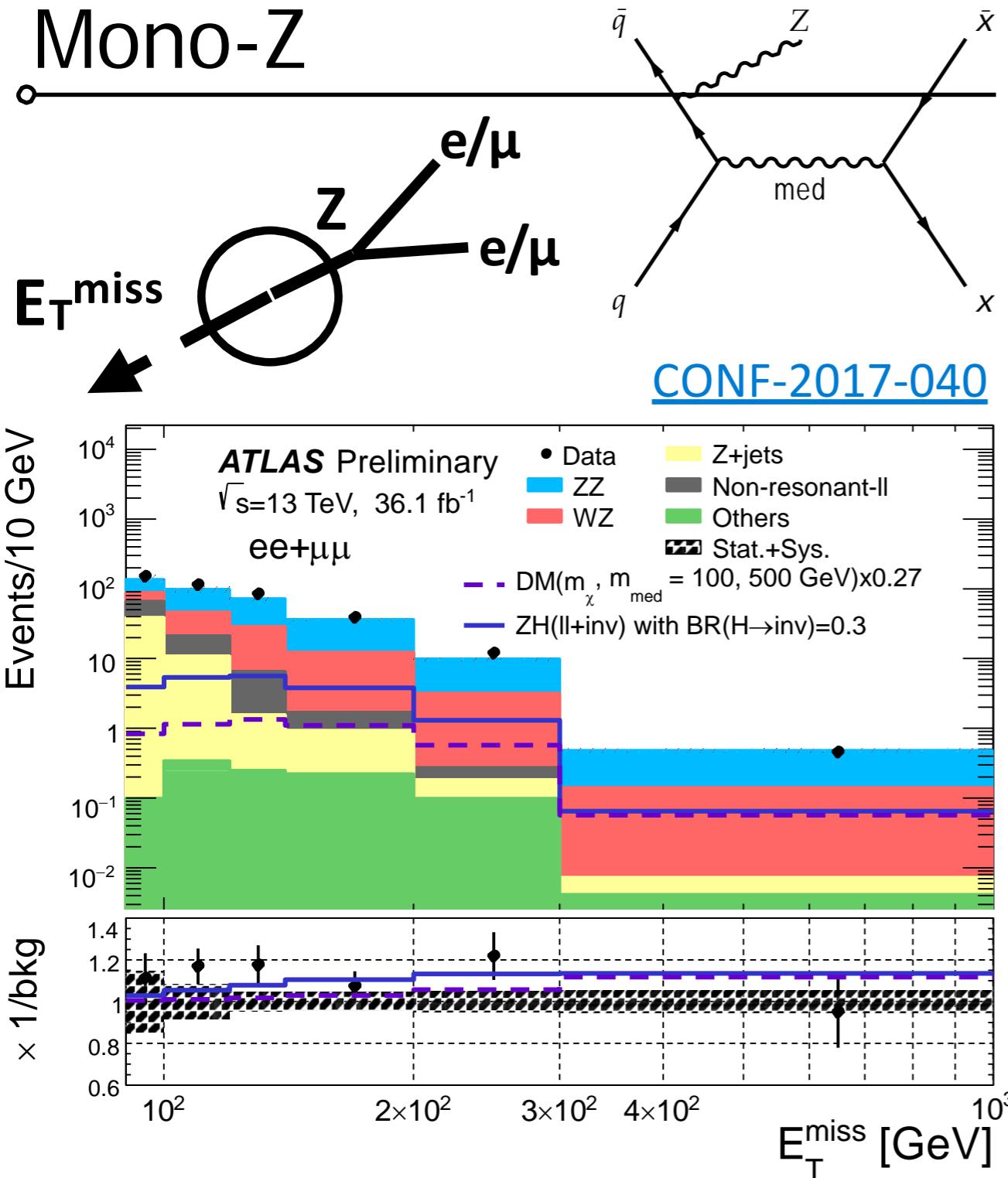
# Baryonic Z' model

New U(1) with baryon number symmetry



- Z' mass excluded up to 0.8 TeV for Baryonic Z' model
- Z' (A) mass excluded up to 2.6 (0.6) TeV for Z'-2HDM model

# Mono-Z



[CONF-2017-040](#)

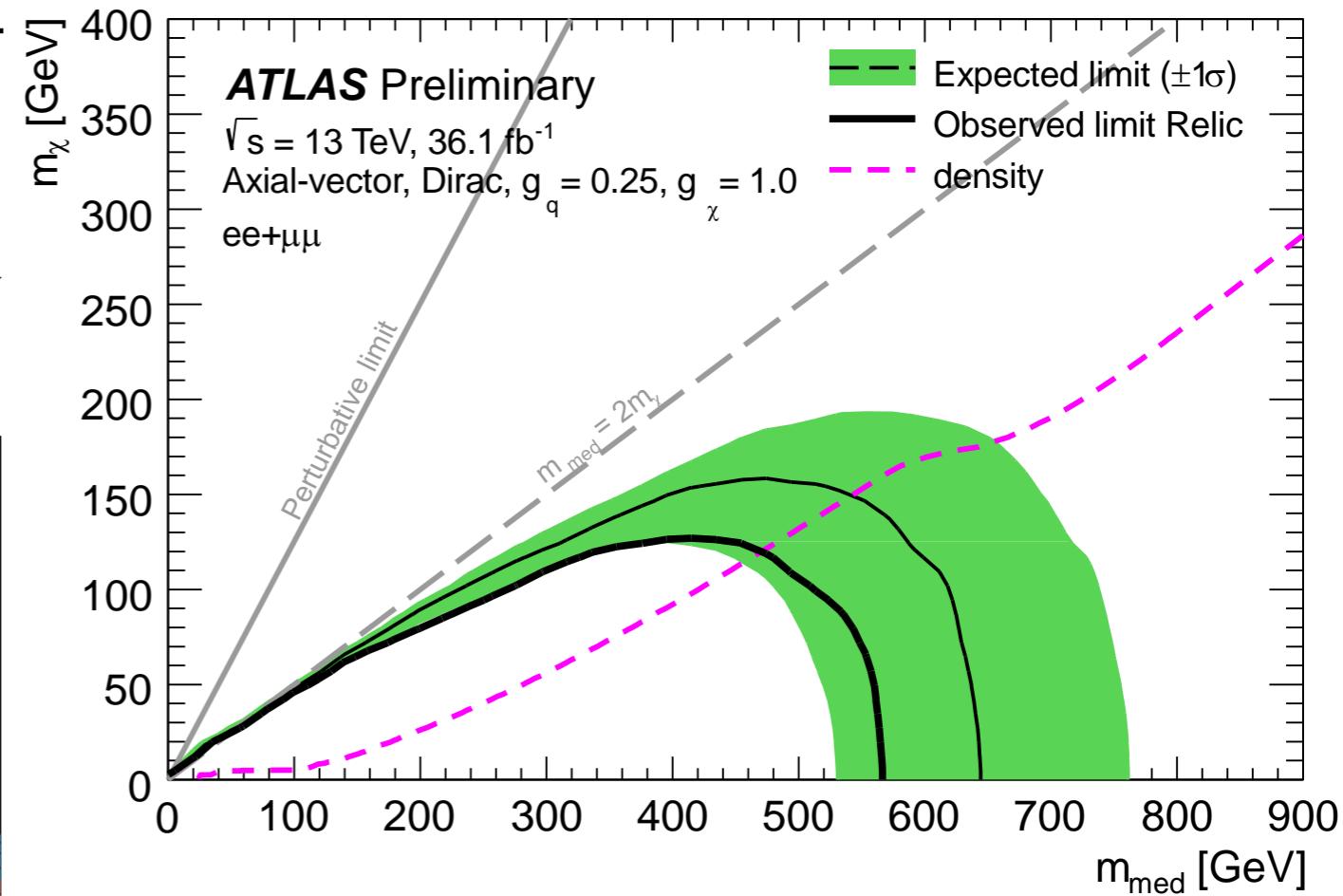
- 2 OS leptons  $p_T > 30/20 \text{ GeV}$

- $76 < m_{\text{ll}} < 106 \text{ GeV}, \Delta R_{\text{ll}} < 1.8$

- $E_T^{\text{miss}} > 90 \text{ GeV}, E_T^{\text{miss}} / H_T > 0.6$

- $\Delta\phi(\text{ll}, E_T^{\text{miss}}) > 2.7, N_{\text{b-jets}} = 0$

# Axial-vector mediator



## Limits for $\text{BR}(H \rightarrow \text{Invisible})$

$\text{BR}_{H \rightarrow \text{inv}}$ limit	Exp.	Obs.
$ee + \mu\mu$	$39^{+17-11}\%$	67%

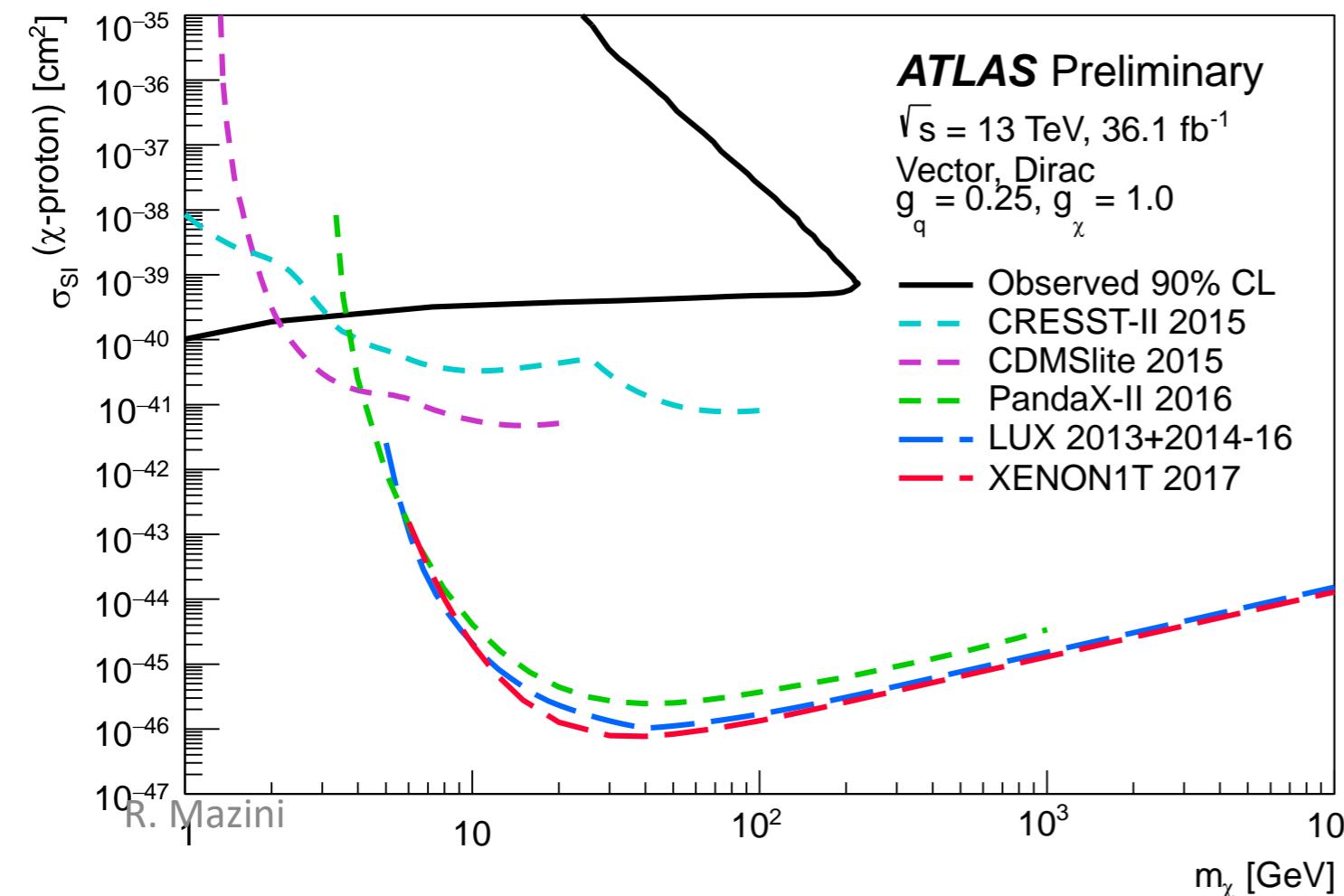
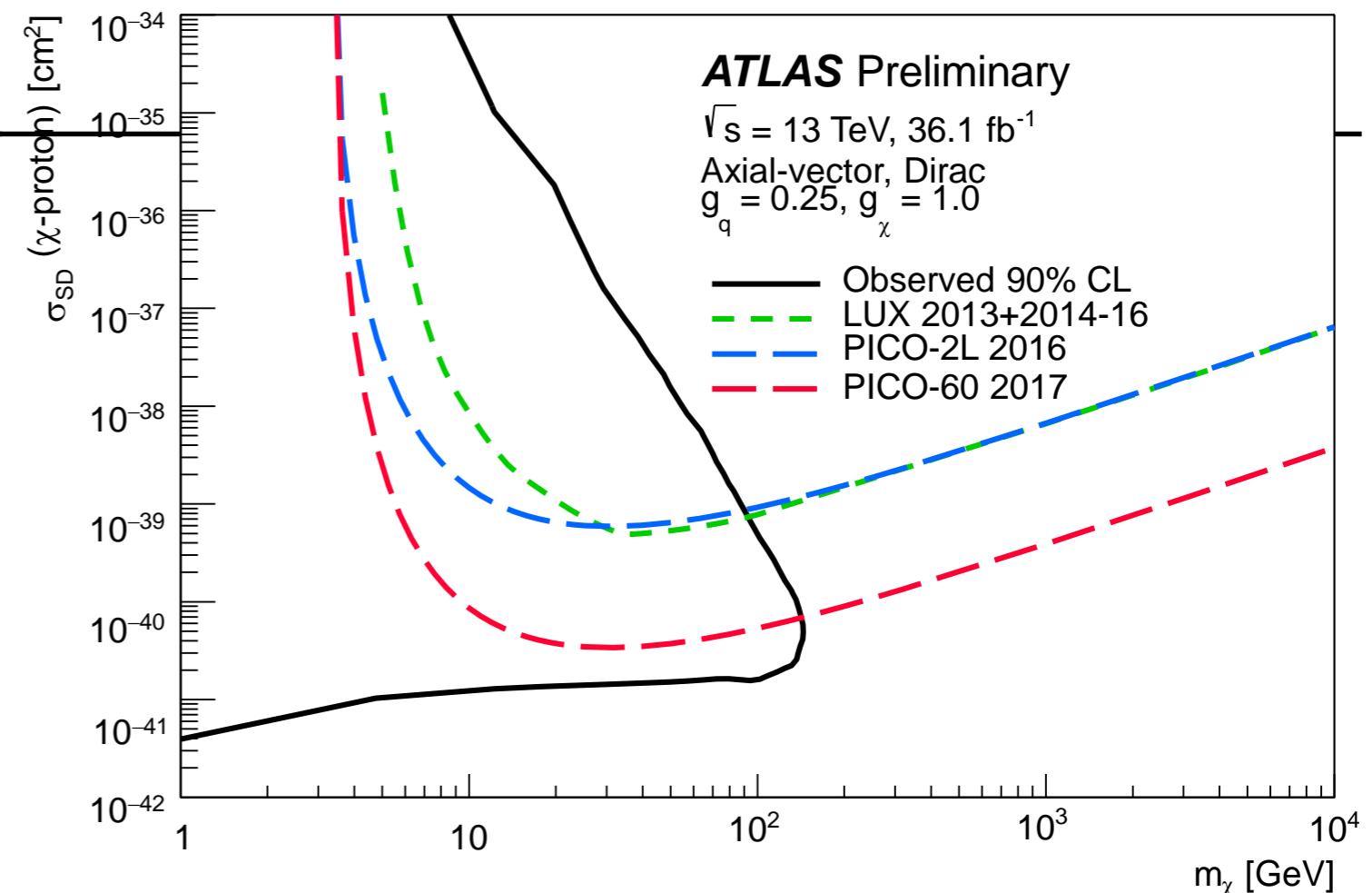
SM  $\sigma_{ZH}$  cross section assumed

[EXO-16-052](#)

CMS  $\text{BR}_{H \rightarrow \text{inv}}$  limit ( $ZH \rightarrow \text{ll+inv}$ ) :  
40% Obs., 42% Exp.

# Mono-Z

- Comparison with non-collider experiments
- Assuming vector or axial-vector mediator and a fermion DM candidate



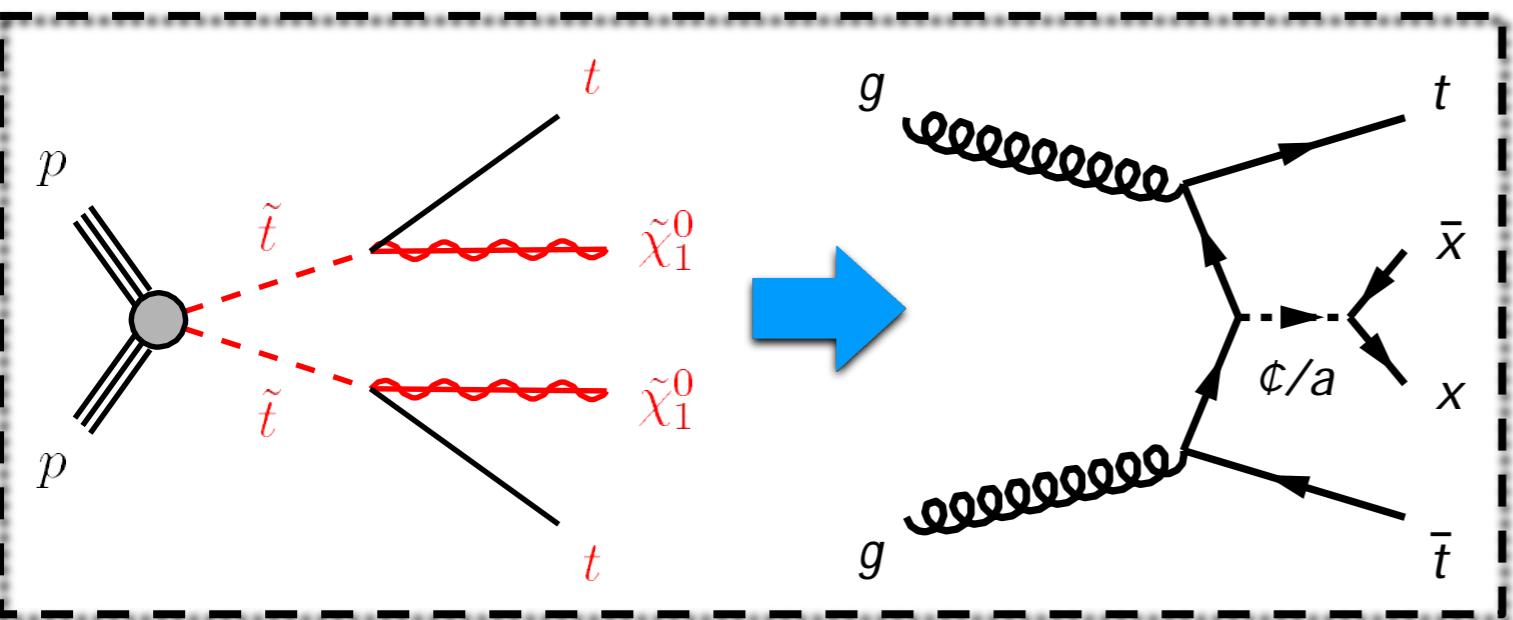
- Better limits on  $\sigma$  in the axial-vector hypothesis for lower mass DM.

$t\bar{t} + E_{miss}^T$

SUS-17-001

## SUSY re-interpretation

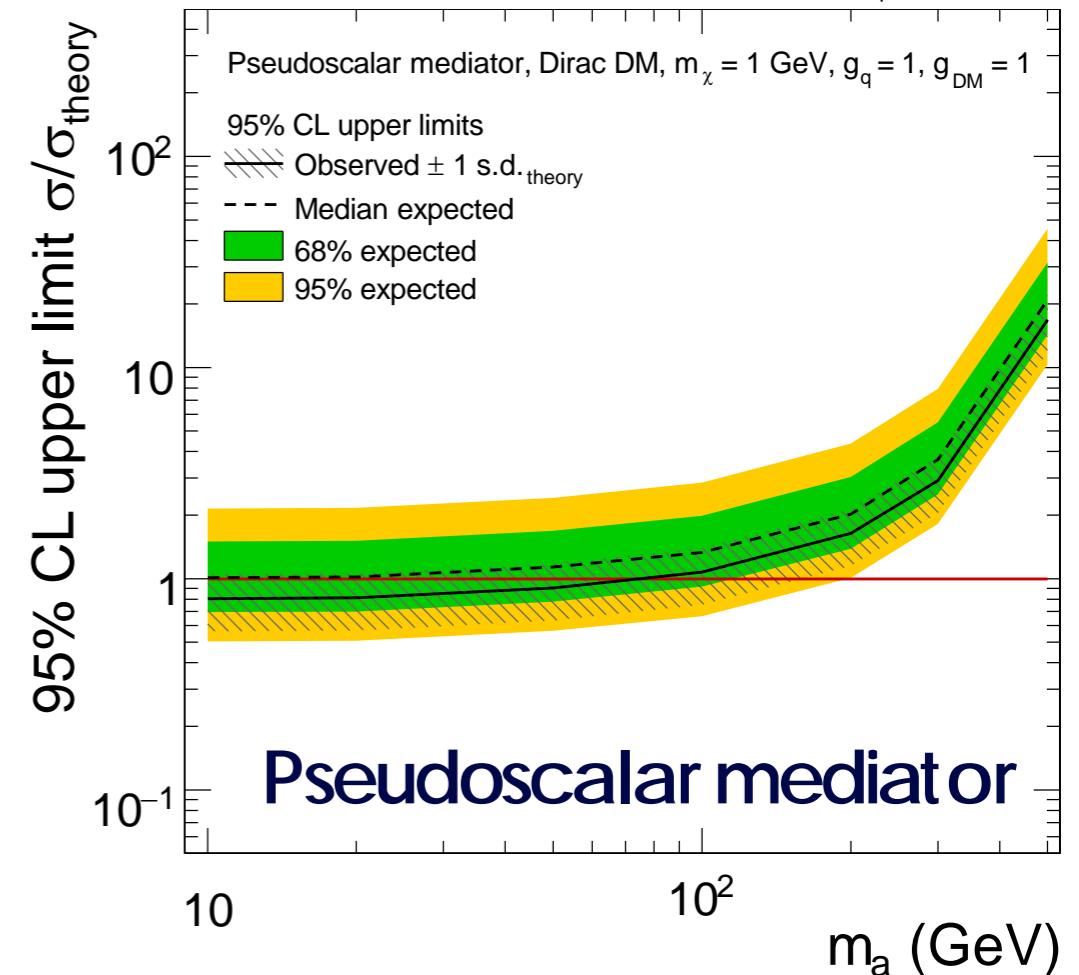
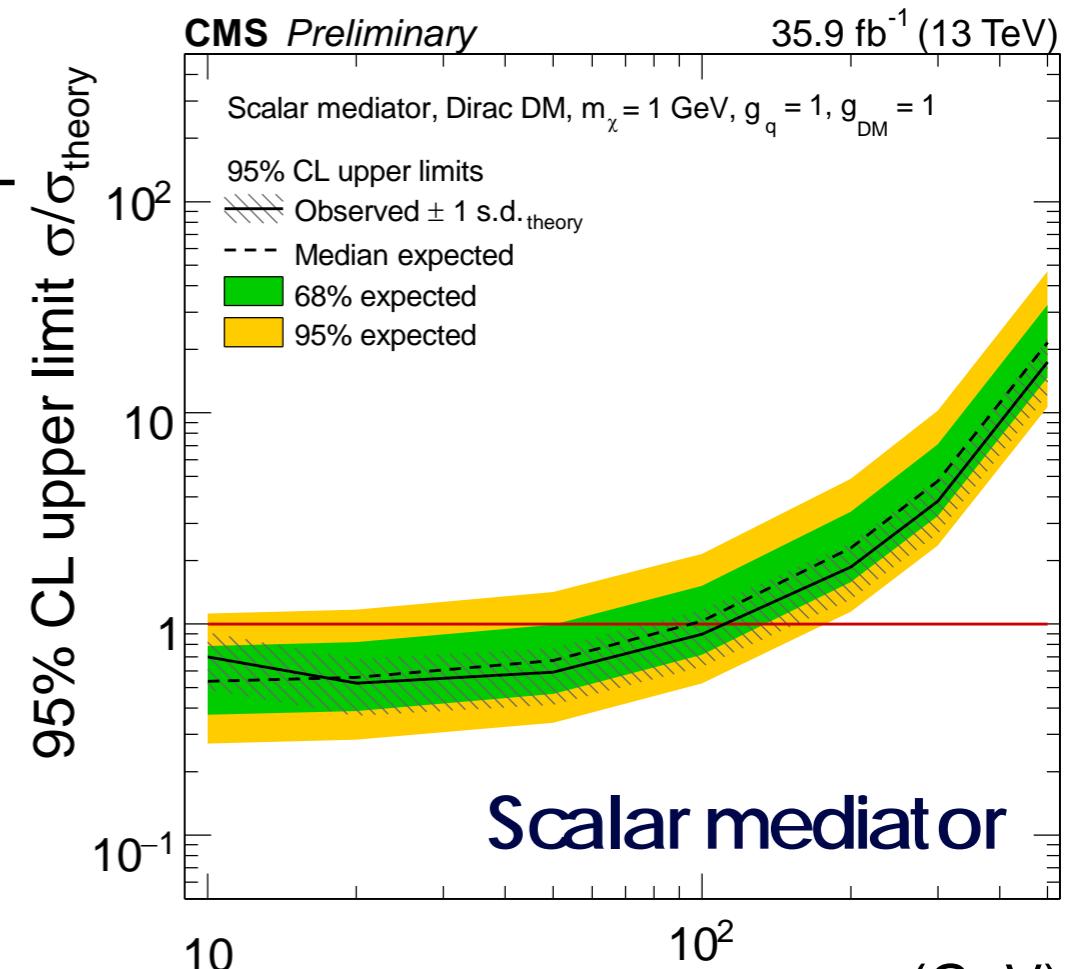
Interpretation of scalar-top searches for scalar and pseudoscalar mediators



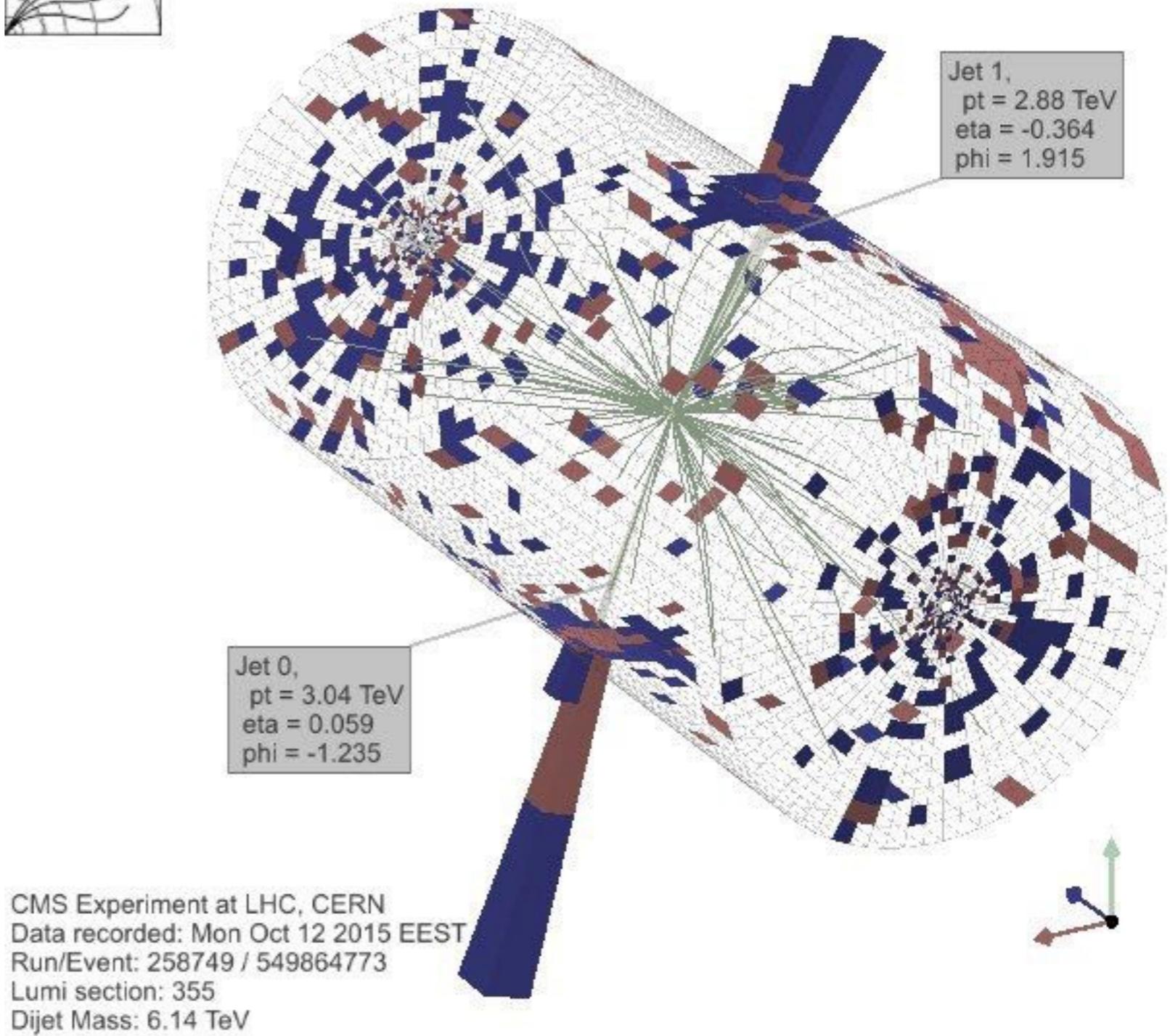
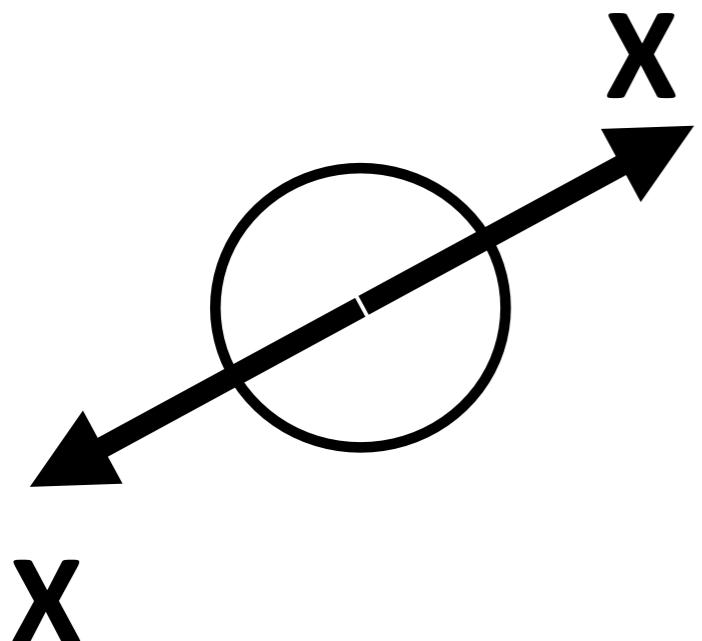
### Scalar-top search:

- di-lepton events ( $ee$ ,  $\mu\mu$ ,  $e\mu$ )
- $N_{\text{jets}} \geq 2$ ,  $N_{\text{b-jets}} \geq 1$
- $E_T^{\text{miss}} > 80 \text{ GeV}$ ,  $E_T^{\text{miss}}/\sqrt{H_T} > 5 \text{ GeV}^{1/2}$

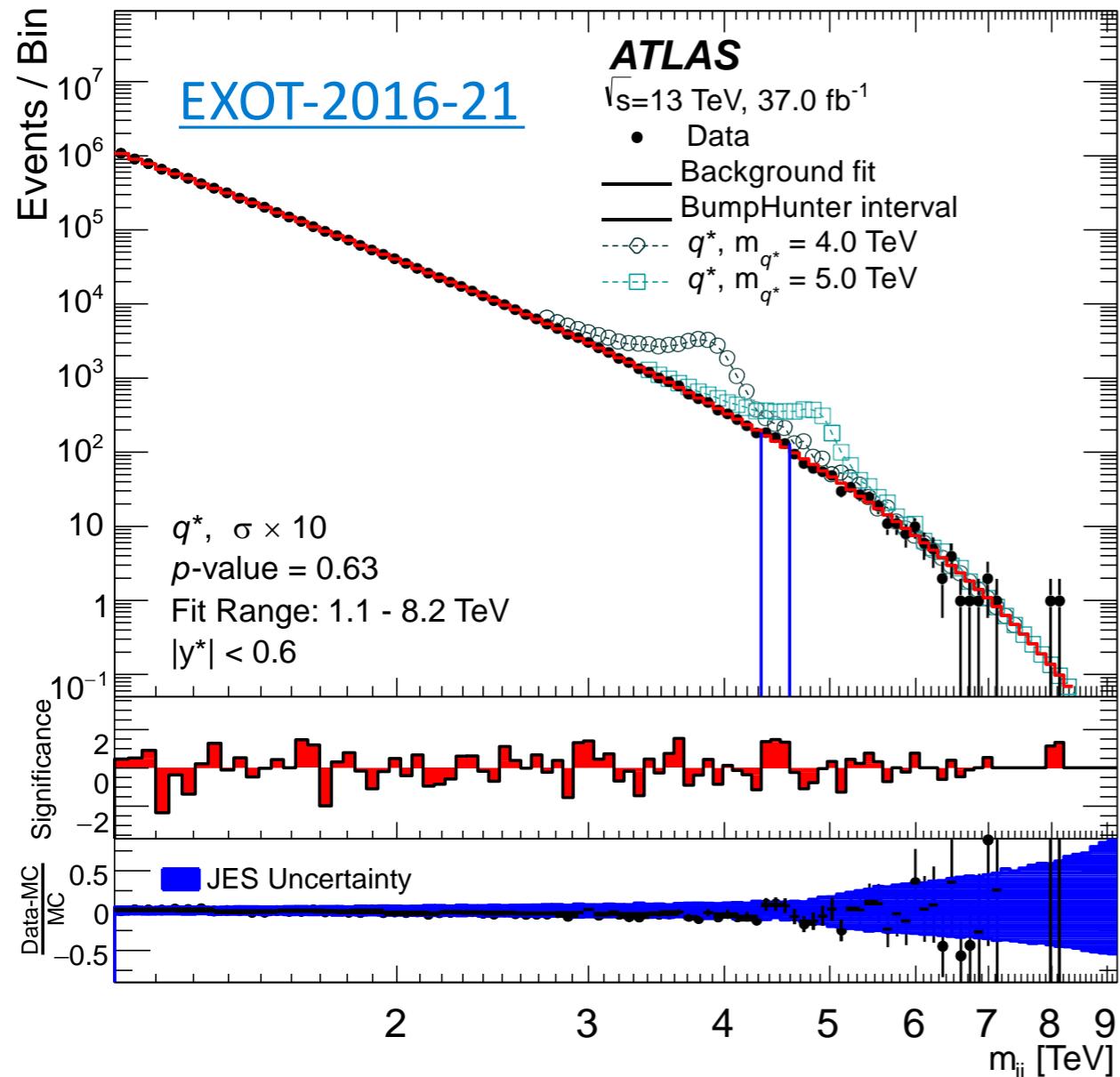
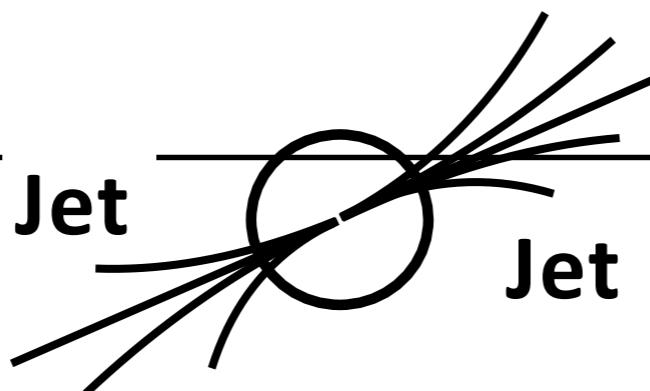
Transverse mass variables used to suppress  $t\bar{t}$  background



# Mediator Searches



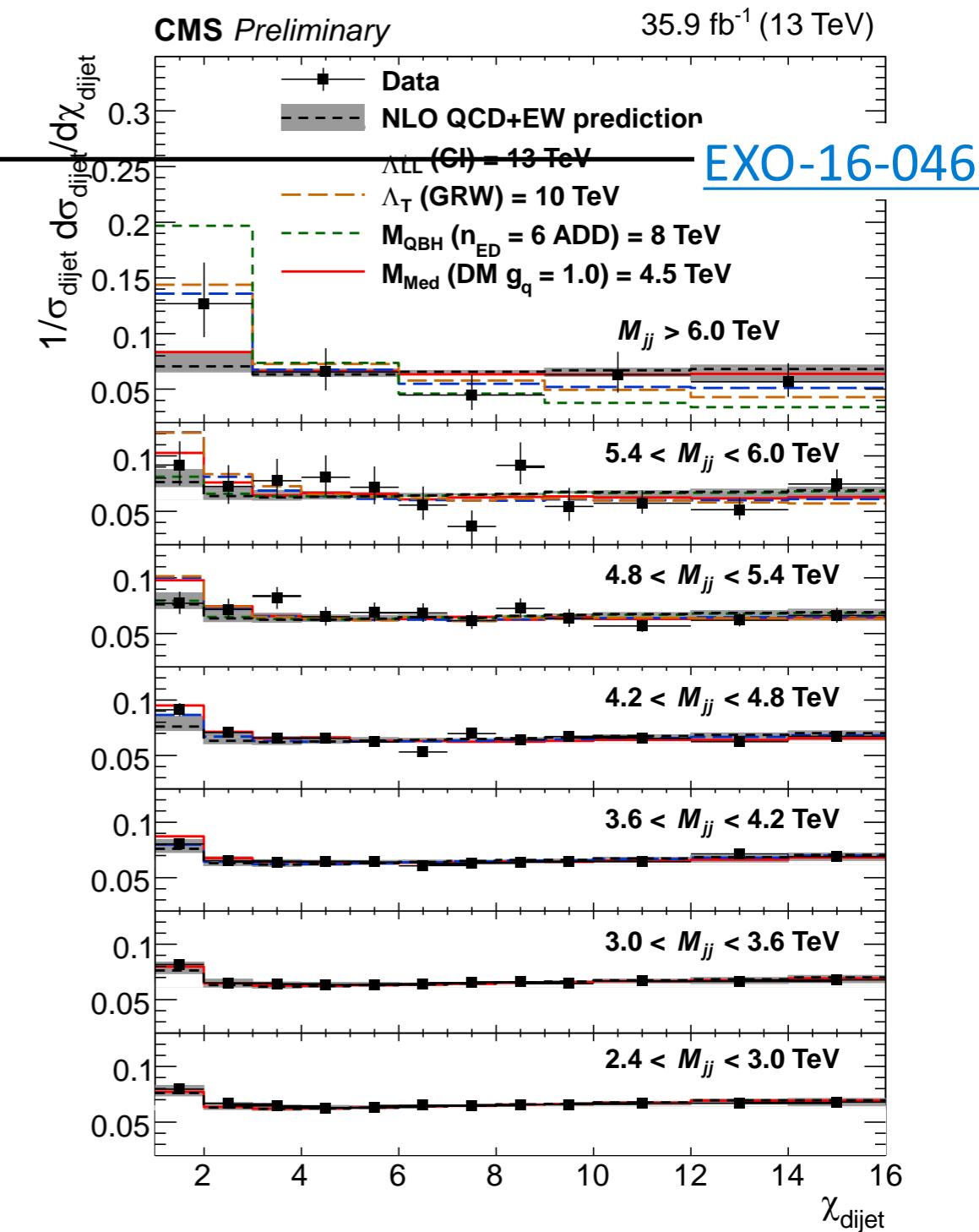
# High-Mass Dijet



Bump hunting with smooth function fit

$$f(x) = p_1 (1 - x)^{p_2} x^{p_3} \quad x = m_{jj} / s$$

→  $q^*$  limit = 6 TeV (ATLAS, CMS)



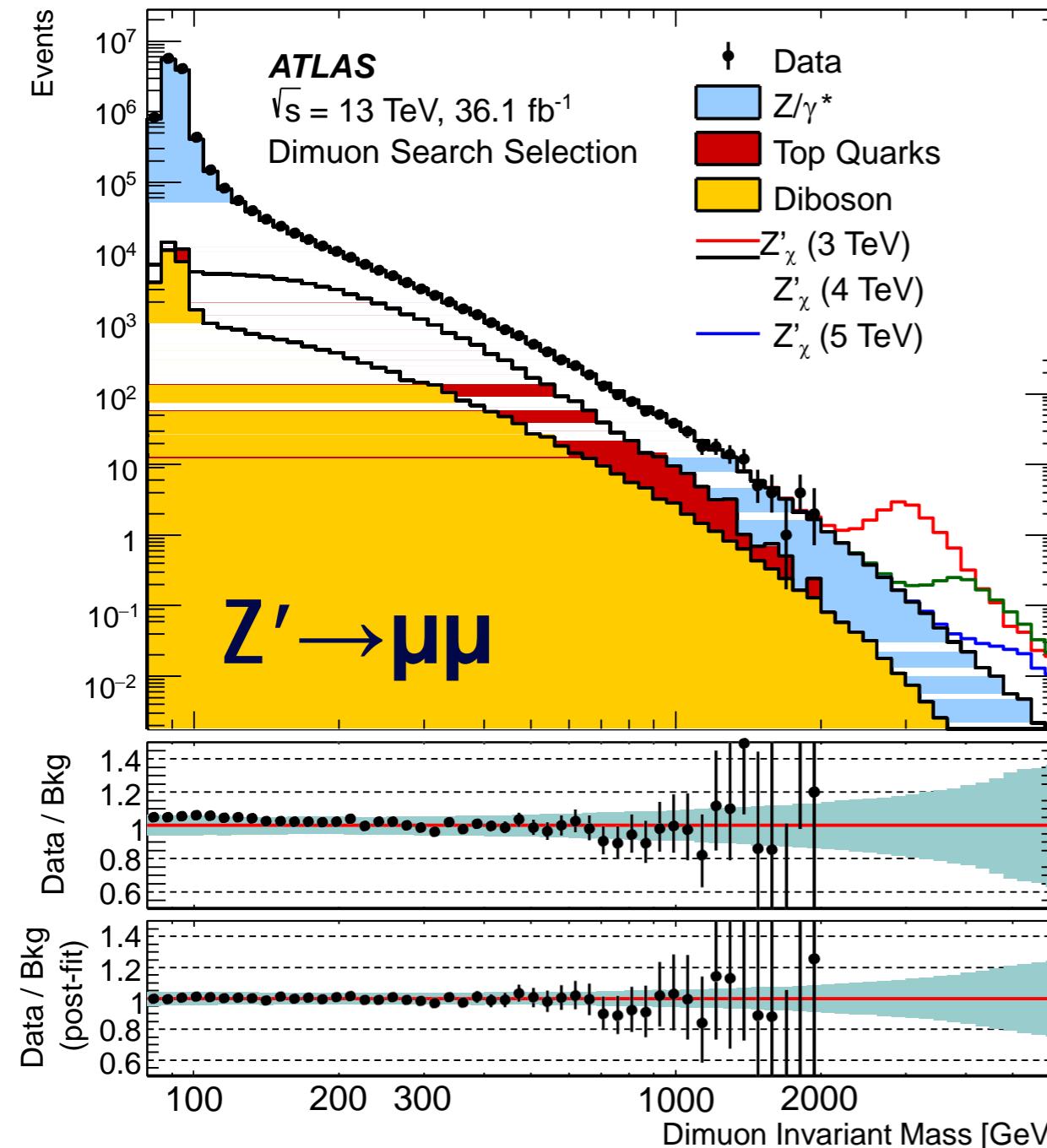
Probing contact Interaction  
with large angle scattering

$$x = e^{|y_1 - y_2|} C \frac{1 + \cos h}{1 - \cos h}$$

Comparison with pQCD prediction

# Dilepton

[EXOT-2016-05](#)

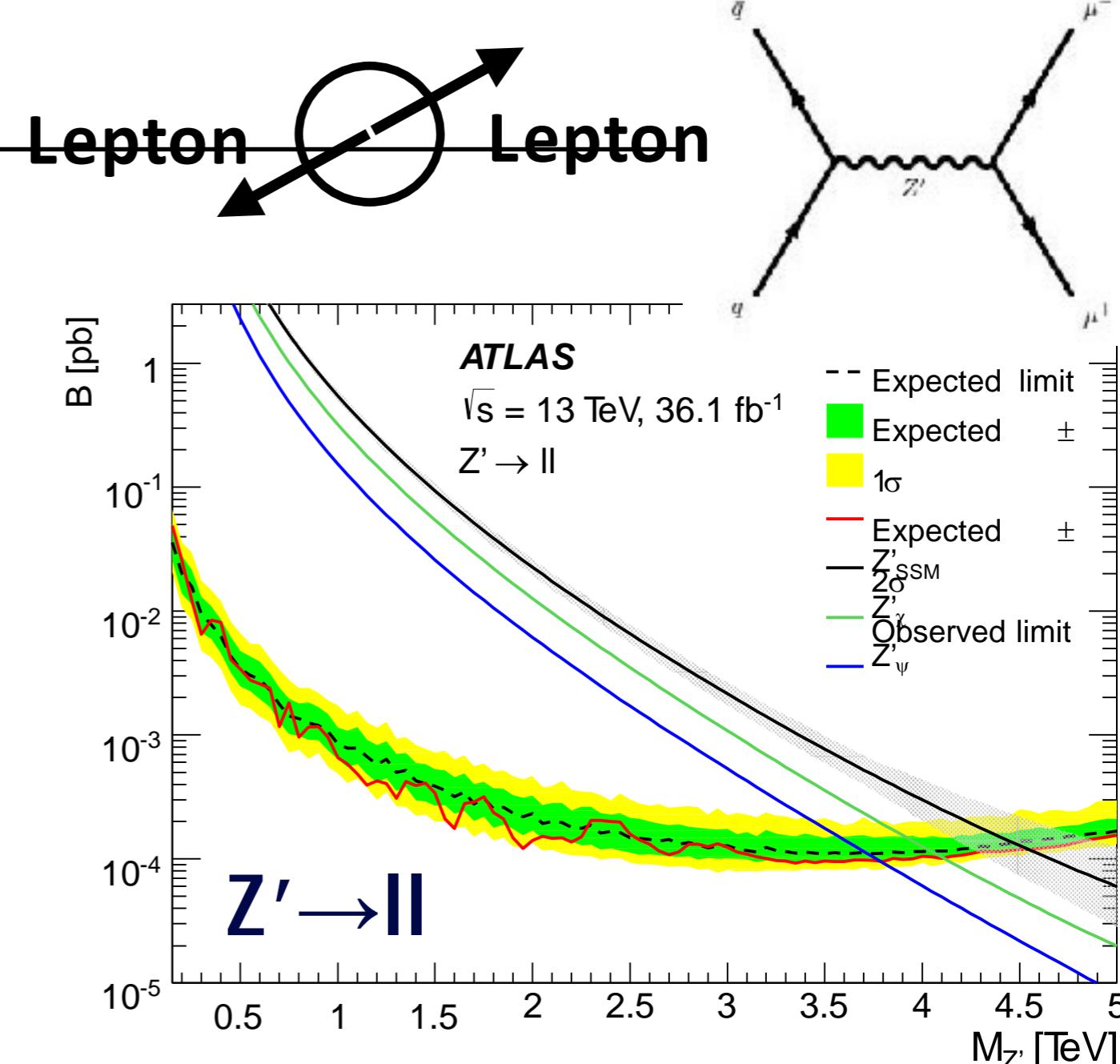


► 2e or 2 $\mu$  :  $p_T > 30 \text{ GeV}$ , loose isolation

►  $m_{\parallel} > 80 \text{ GeV}$  (OS for 2 $\mu$ )

$Z/\gamma^*$  background using MC with mass-dep. k-factor (NNLO QCD+NLO EW)

# Lepton



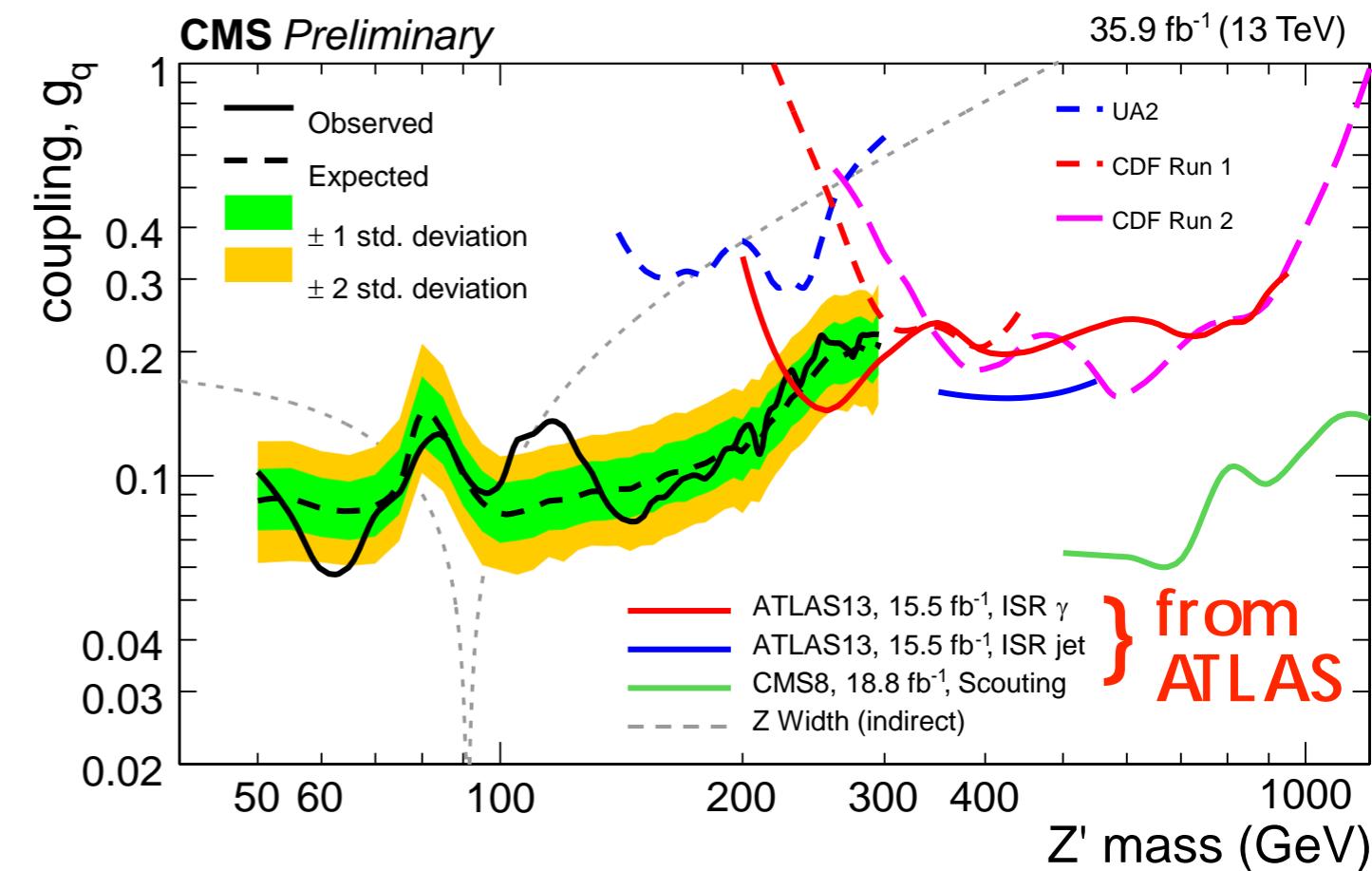
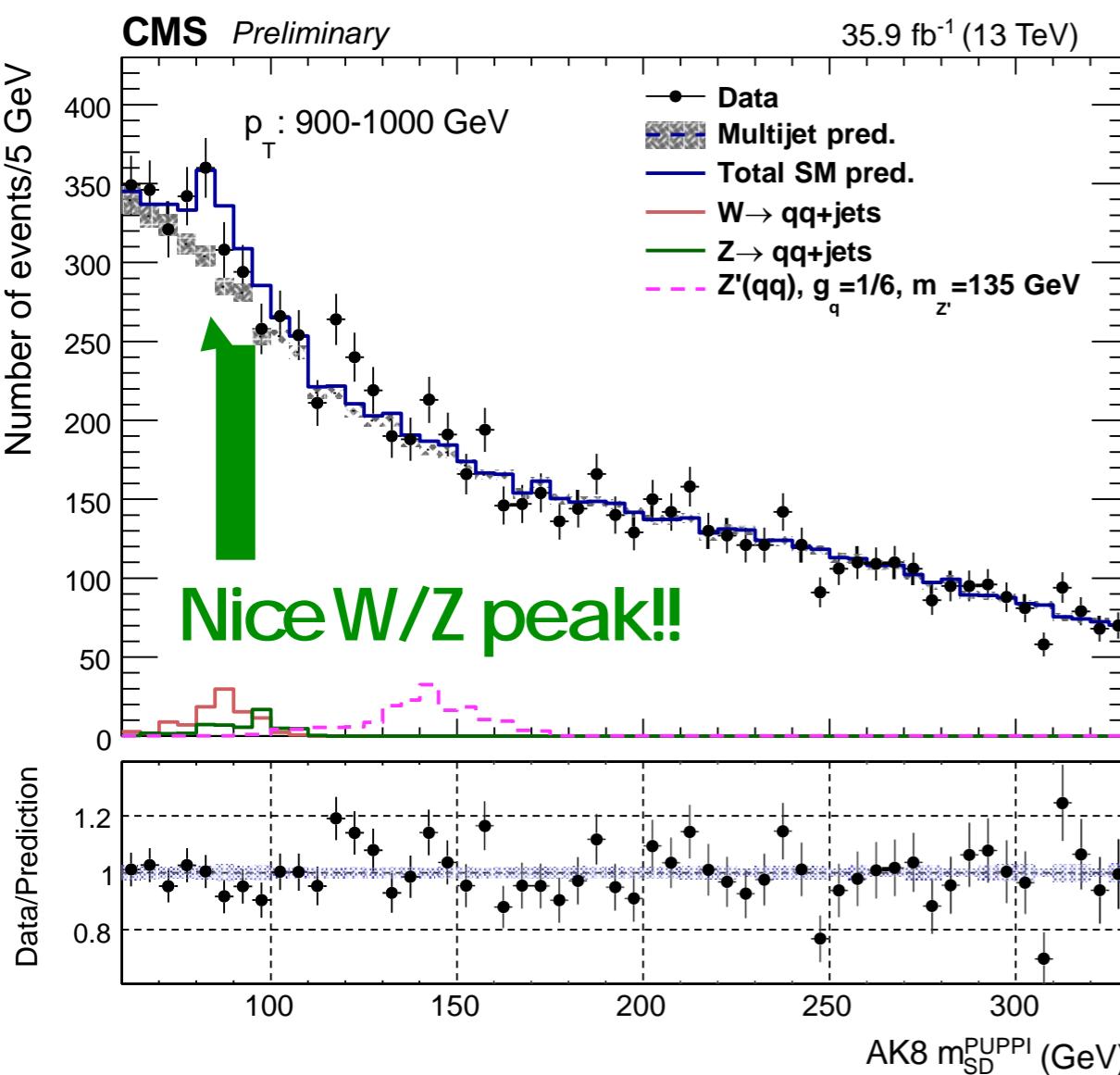
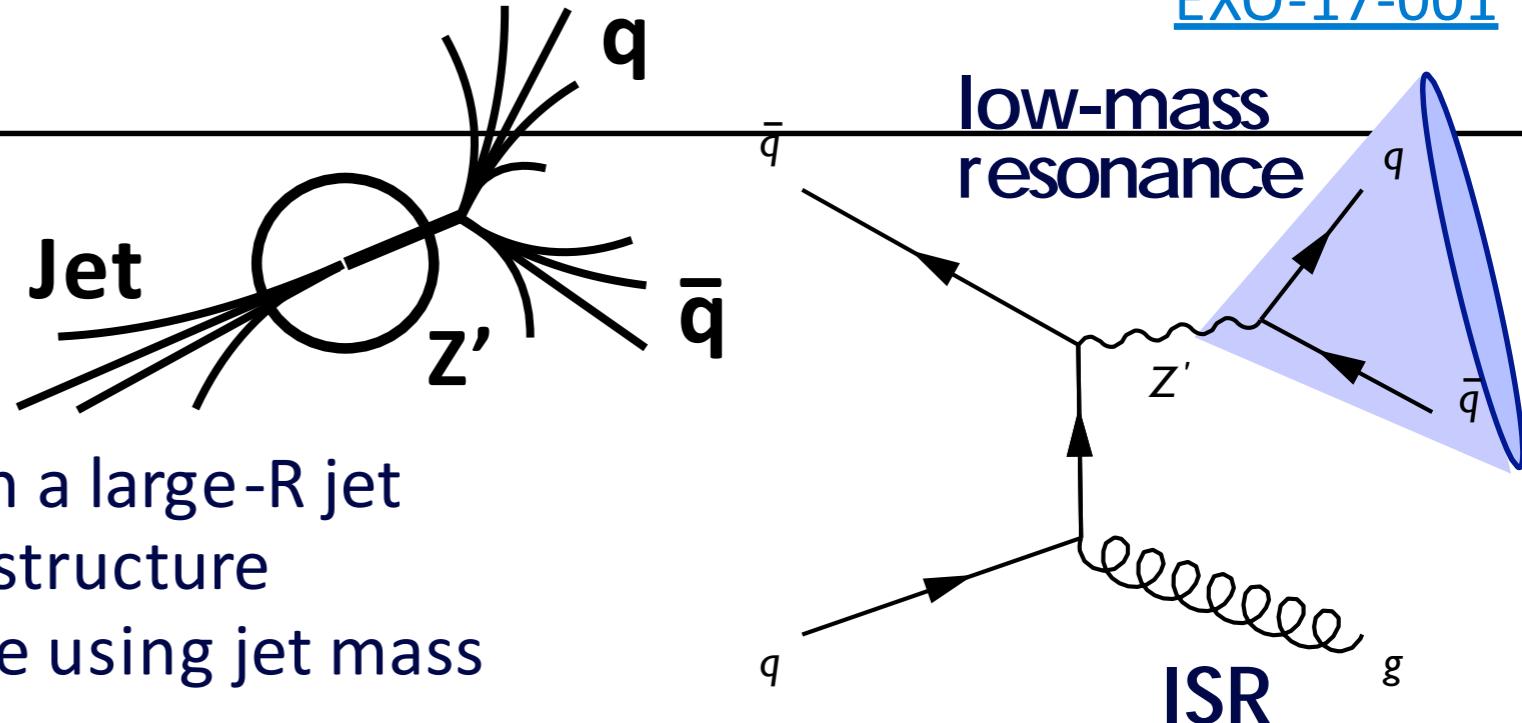
## Mass limits for Sequential SM $Z'$

$Z'_{SSM}$ limit [TeV]	Exp.	Obs.
ee	4.3	4.3
$\mu\mu$	3.9	4.0
$\ell\ell$	4.5	4.5

# Low-Mass Dijet

Search for low-mass new particle using ISR boost

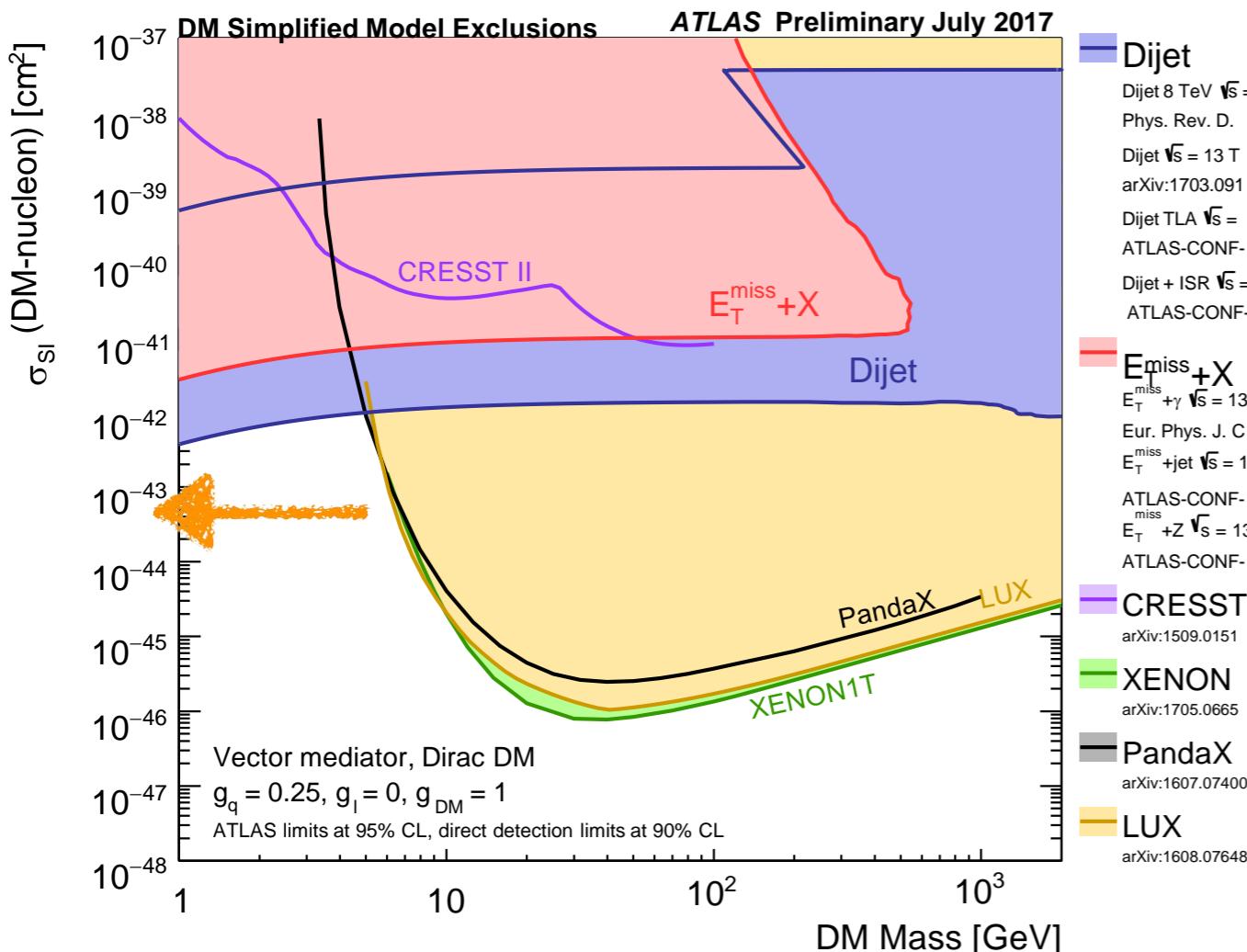
- Reconstruct boosted  $Z' \rightarrow qq$  with a large-R jet
- Discriminate signal using jet substructure
- Data-driven background estimate using jet mass



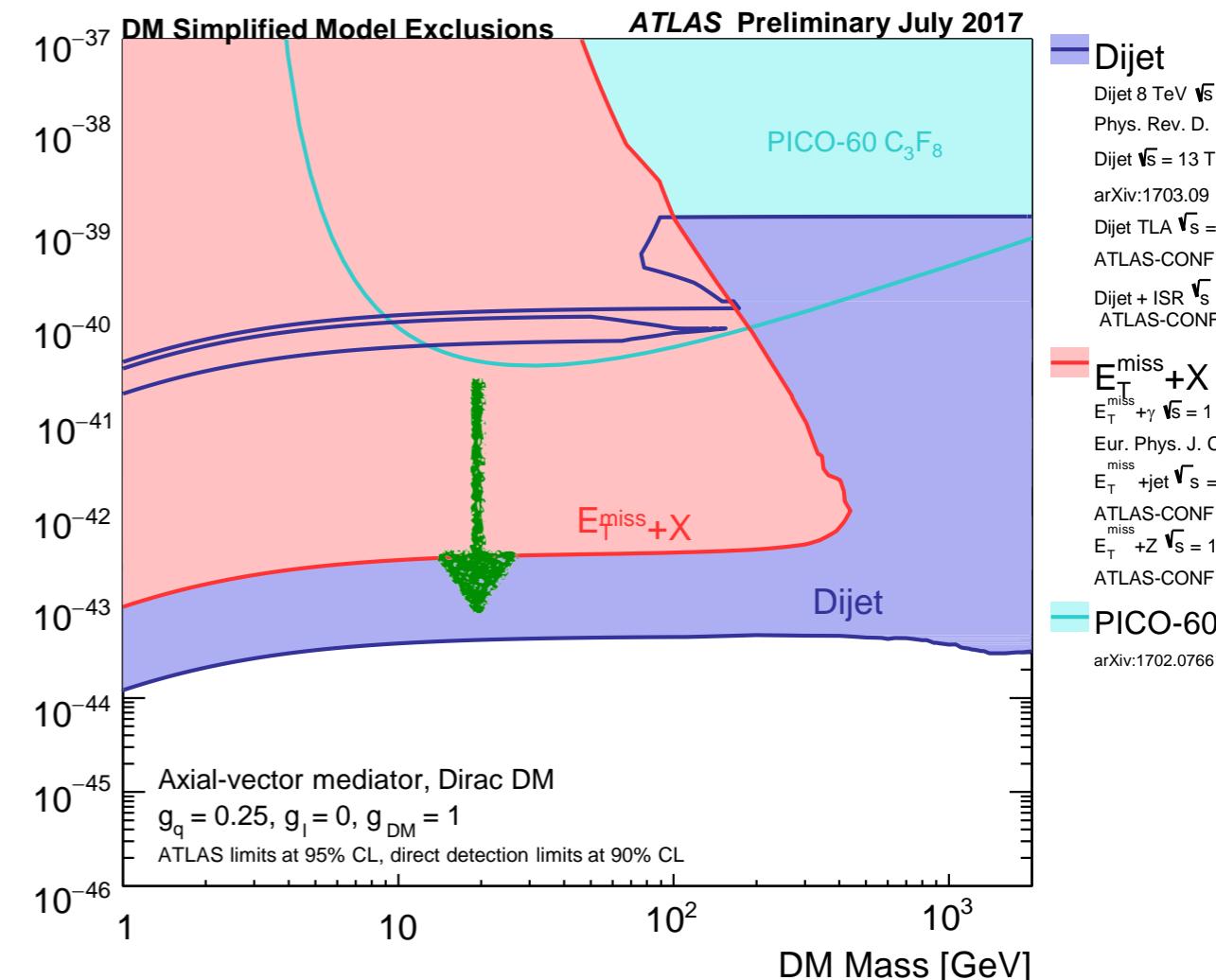
- Allowed to cover the  $Z'$  mass down to  $\sim 30 \text{ GeV}$
- High-mass dijets above  $\sim 1 \text{ TeV}$

# Comparison with DD

## Spin-independent DM-nucleon cross section vs $m_{\text{DM}}$



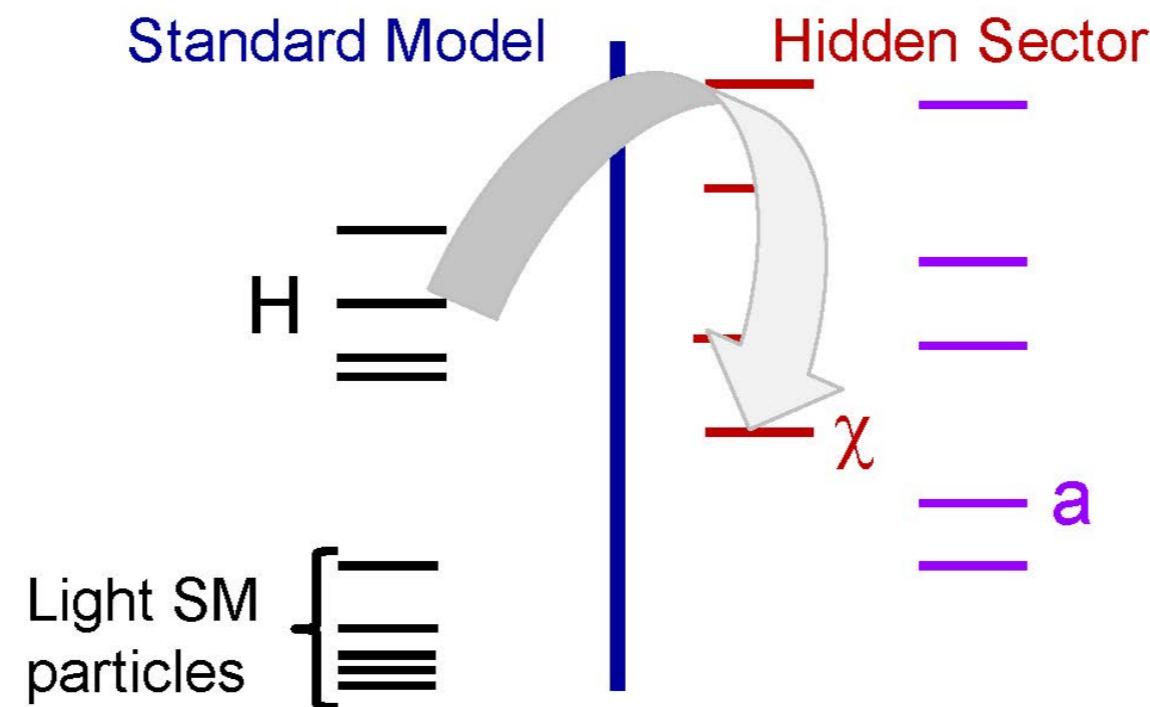
## Spin-dependent DM-proton cross section vs $m_{\text{DM}}$



*Under the model assumptions:* collider searches

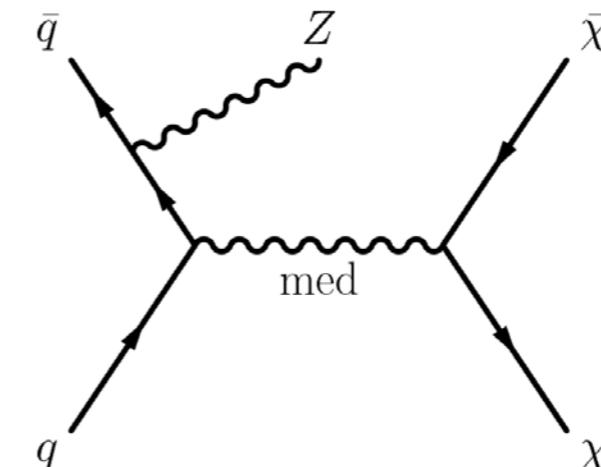
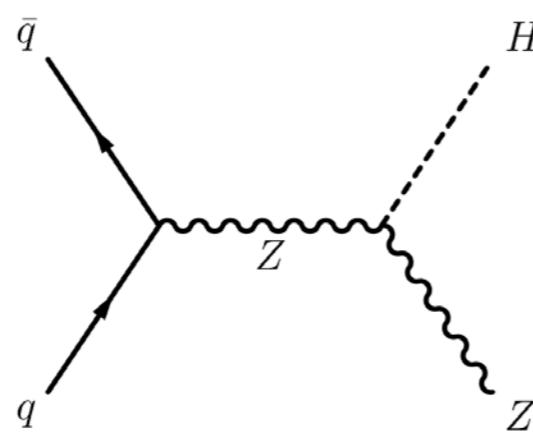
- ▶ are sensitive at low DM ( $<\sim 5$  GeV) for  $\sigma_{\text{SI}}$  (DM-nucleon)
- ▶ have  $\sim 3$  orders of magnitude better sensitivity for  $\sigma_{\text{SD}}$  (DM-nucleon)

# Searches for Invisible Higgs decay



# Invisible Higgs: search in the ZH production mode

- Combined Run I results mainly driven by the VBF mode:  $B(H \rightarrow \text{inv}) < 0.25$  @ 95%CL
- Look for  $pp \rightarrow ZH \rightarrow ll + E_T^{\text{miss}}$ . Clear signature of  $Z \rightarrow ee$  or  $Z \rightarrow \mu\mu$  plus missing transverse momentum from invisible Higgs decay
- In the SM, the invisible decay ( $H \rightarrow ZZ \rightarrow vvvv$ ) of the Higgs boson has  $B(H \rightarrow \text{inv}) = 1.06 \times 10^{-3}$
- Use to place upper limit on  $B(H \rightarrow \text{inv})$  assuming SM ZH production.
- Also interpret in DM models with BSM axial-vector mediator and decay to WIMP pair

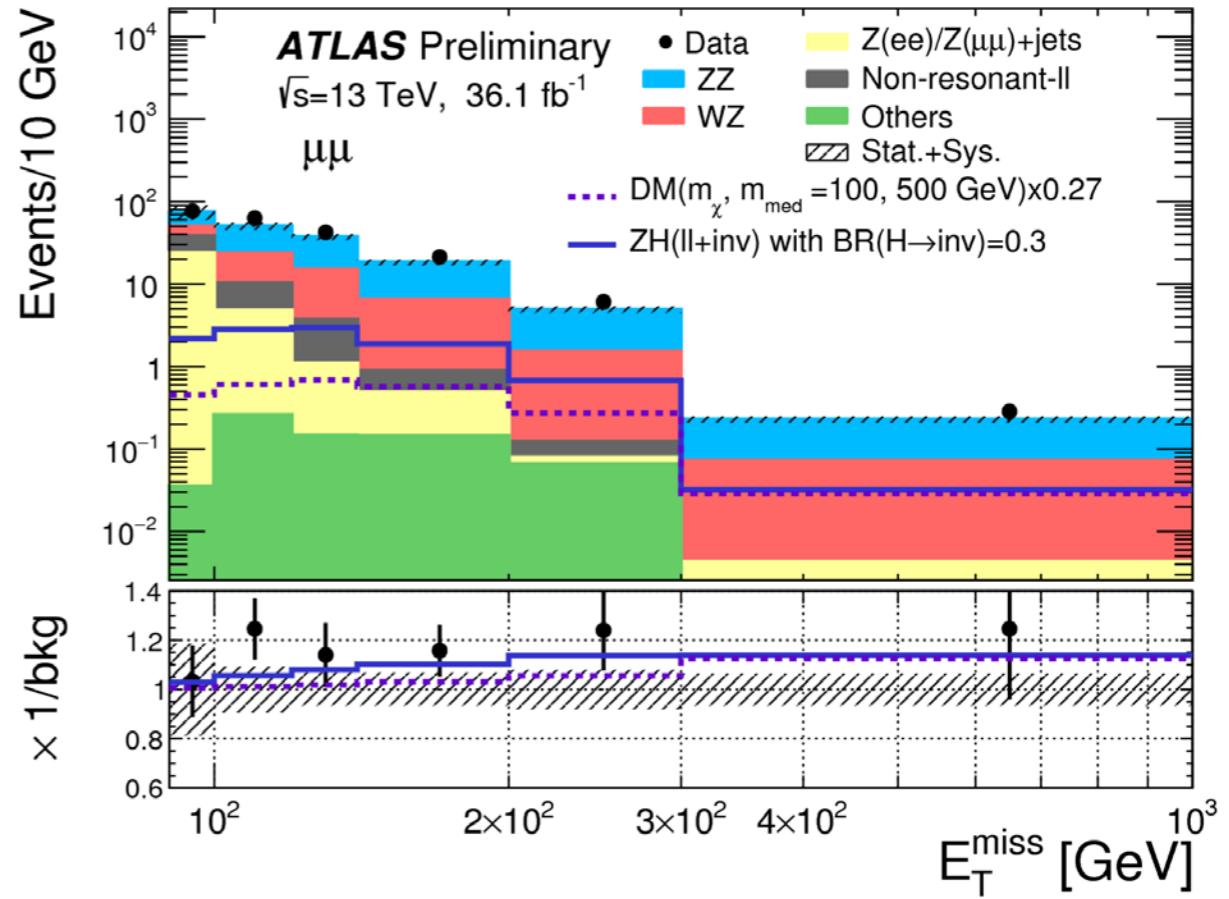
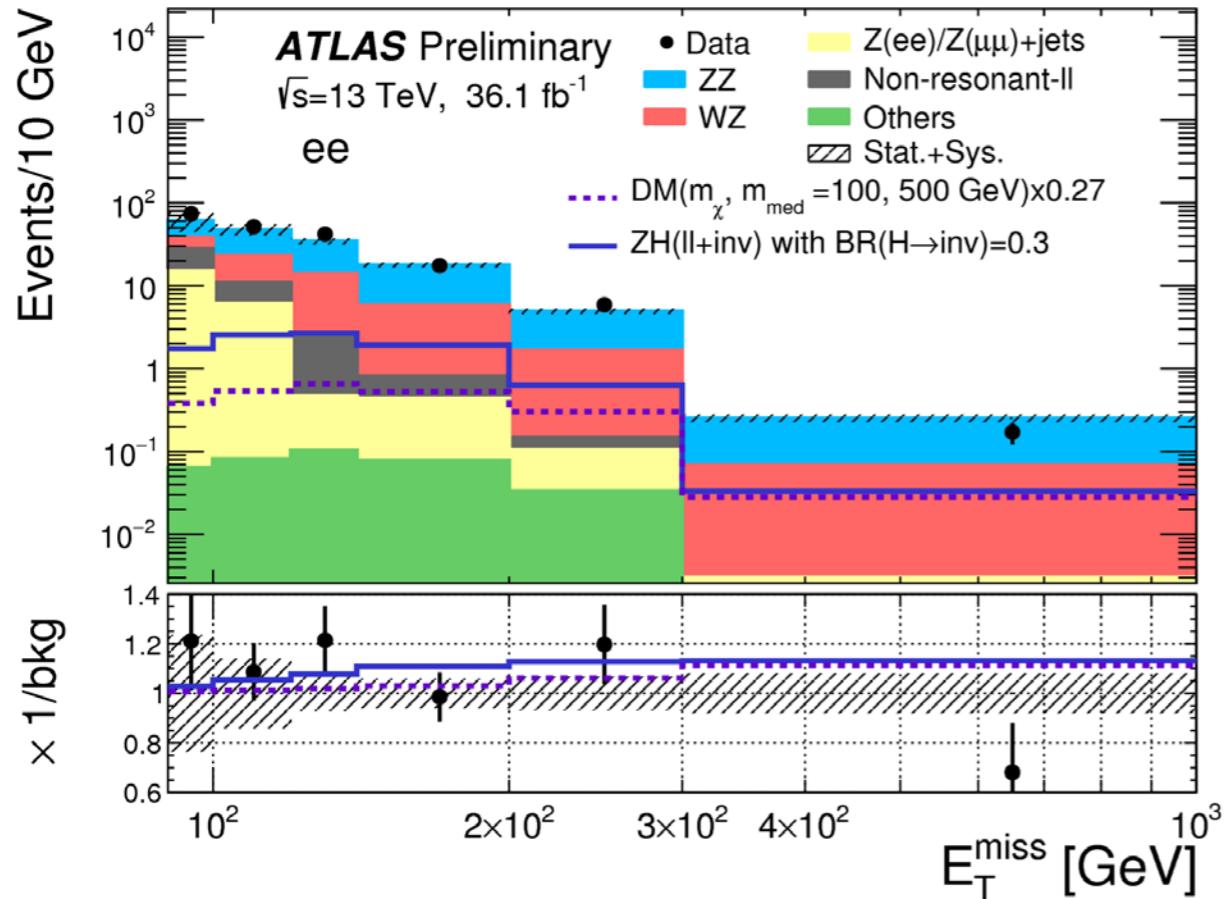


# Invisible Higgs search @ Run 2

- Combination of high efficiency lepton triggers
- Event selection mainly driven by  $E_T^{\text{miss}}$  and its balance w-r-t to Z boson

Selection criteria	
Two leptons	Two opposite-sign leptons, leading (subleading) $p_T > 30(20)$ GeV
Third lepton veto	Veto events if any additional lepton with $p_T > 7$ GeV
$m_{\ell\ell}$	$76 < m_{\ell\ell} < 106$ GeV
$E_T^{\text{miss}}$ and $E_T^{\text{miss}}/H_T$	$E_T^{\text{miss}} > 90$ GeV and $E_T^{\text{miss}}/H_T > 0.6$
$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{\text{miss}})$	$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{\text{miss}}) > 2.7$ radians
$\Delta R_{\ell\ell}$	$\Delta R_{\ell\ell} < 1.8$
Fractional $p_T$ difference	$ p_T^{\ell\ell} - p_T^{\text{miss,jet}}  / p_T^{\ell\ell} < 0.2$
$b$ -jets veto	$N(b\text{-jets}) = 0$ with $b$ -jet $p_T > 20$ GeV and $ \eta  < 2.5$

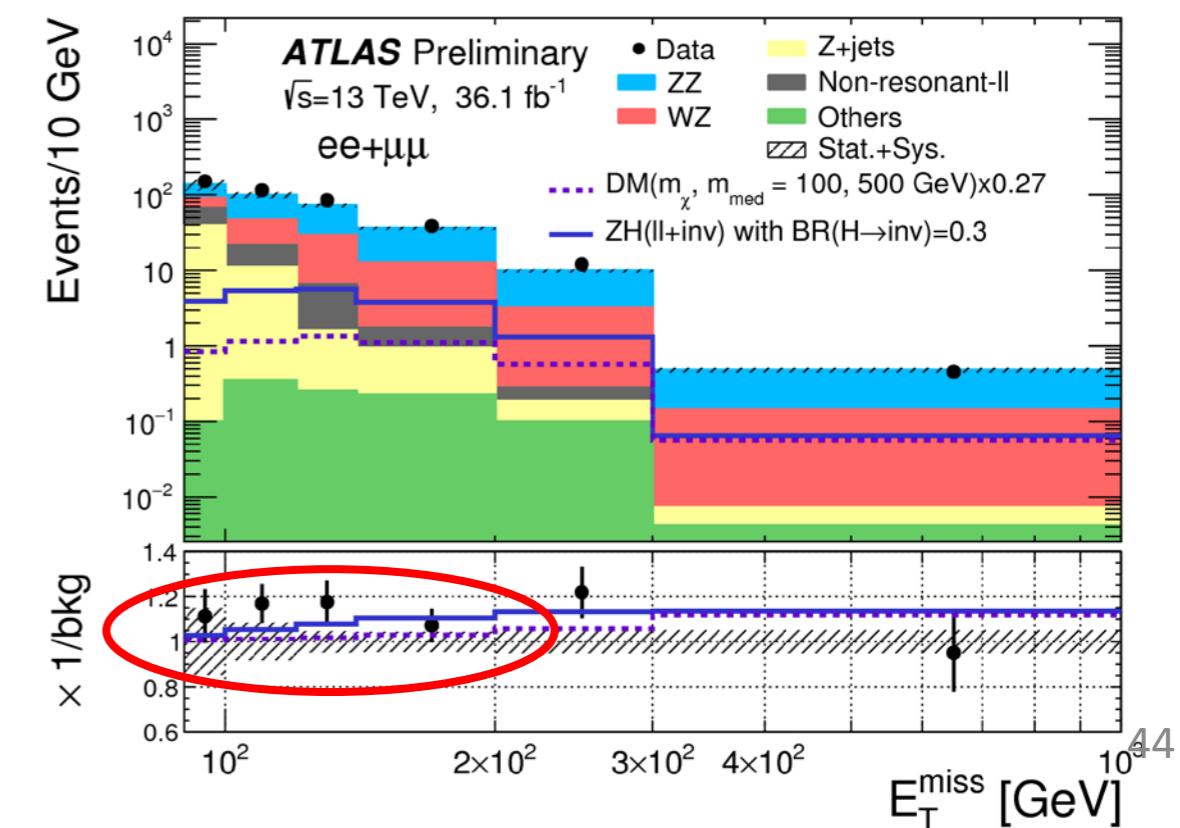
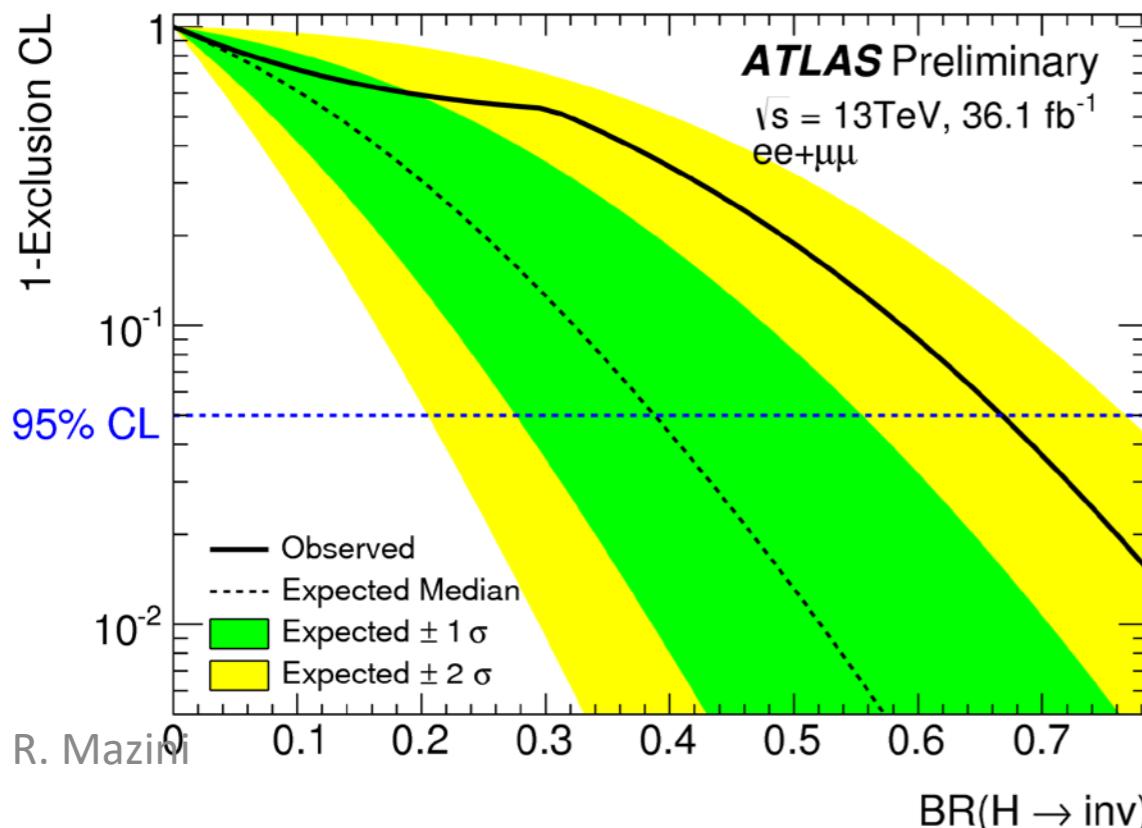
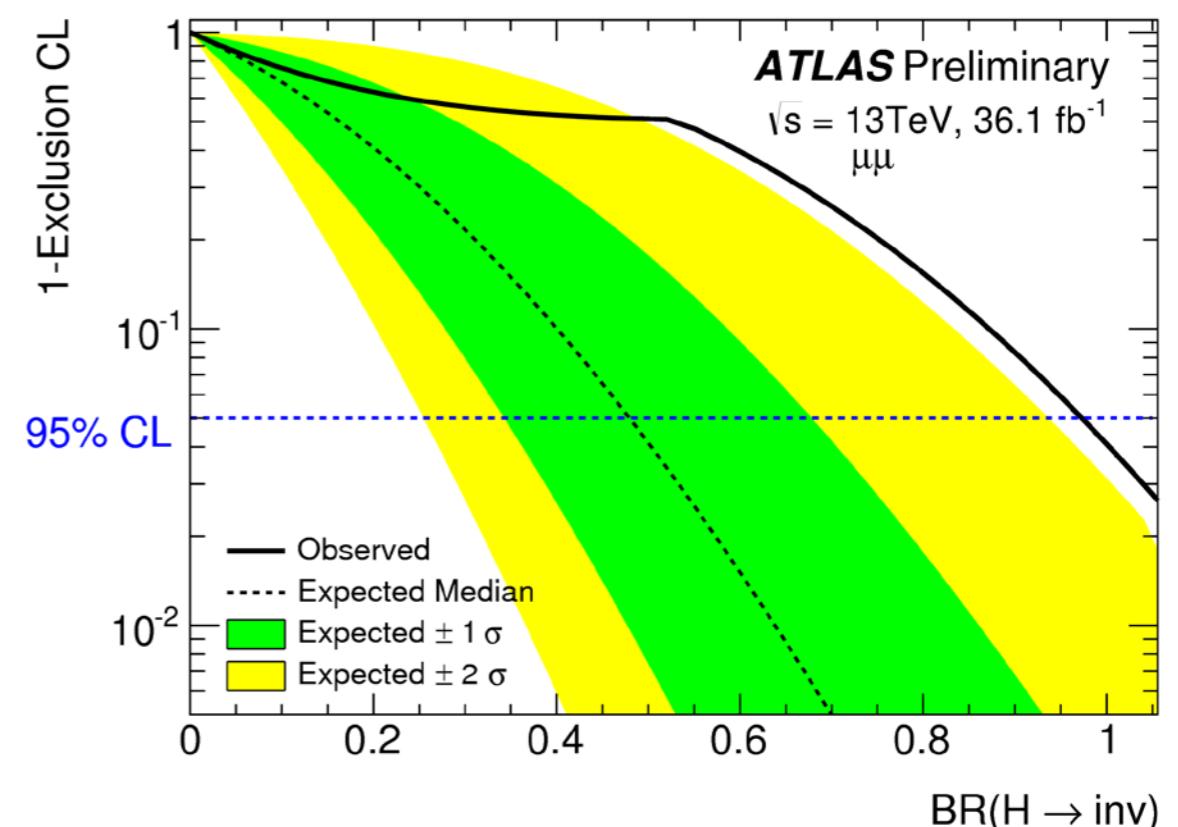
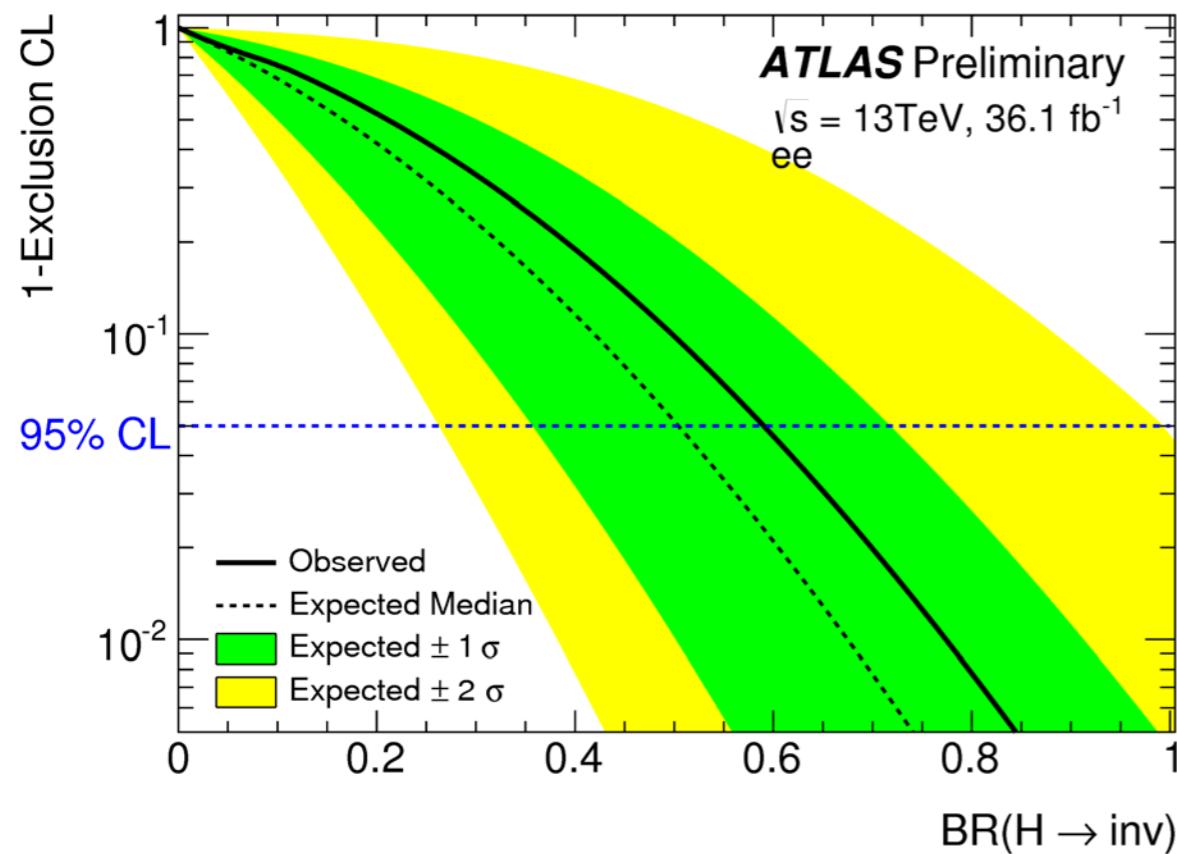
# Invisible Higgs: $E_T^{\text{miss}}$ results



- Similar sensitivity for ee and  $\mu\mu$
- Mainly SM background (ZZ, WZ) at High  $E_T^{\text{miss}}$
- Small excess in  $\mu\mu$  ( $2.2\sigma$ ) and  $1.5\sigma$  for combined ee+ $\mu\mu$

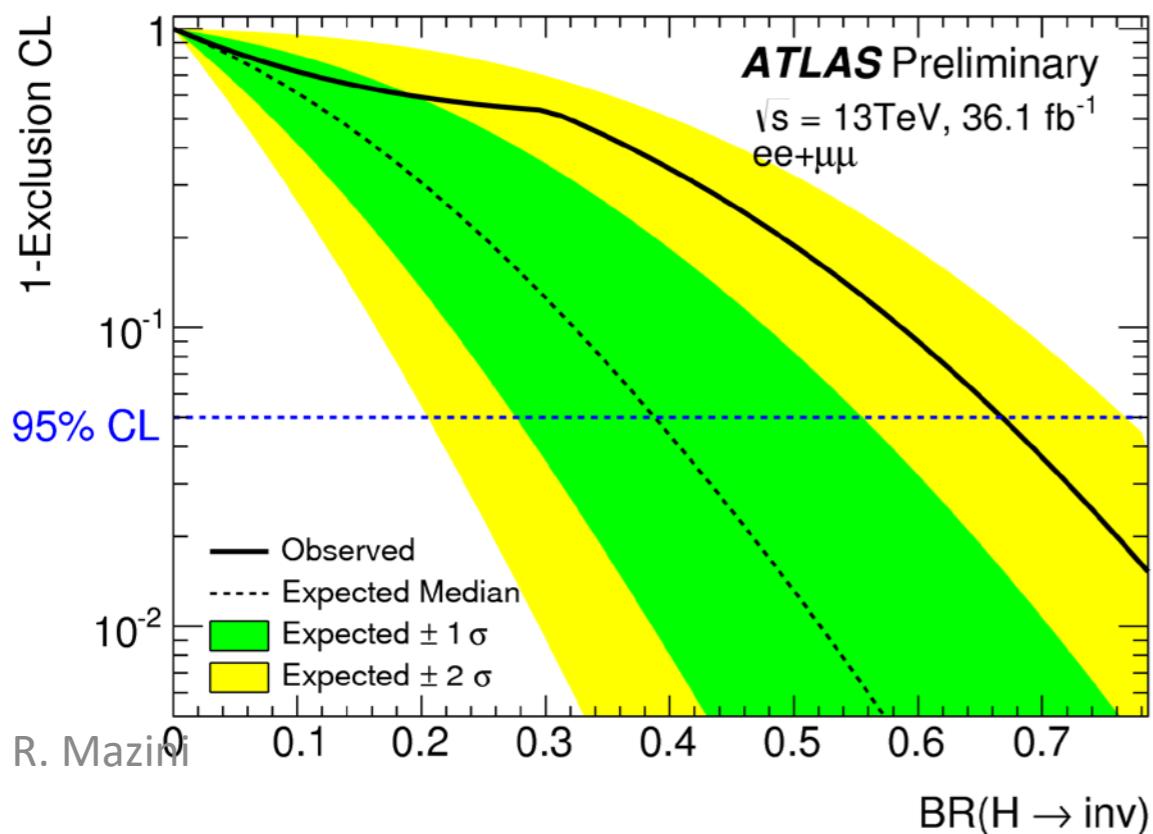
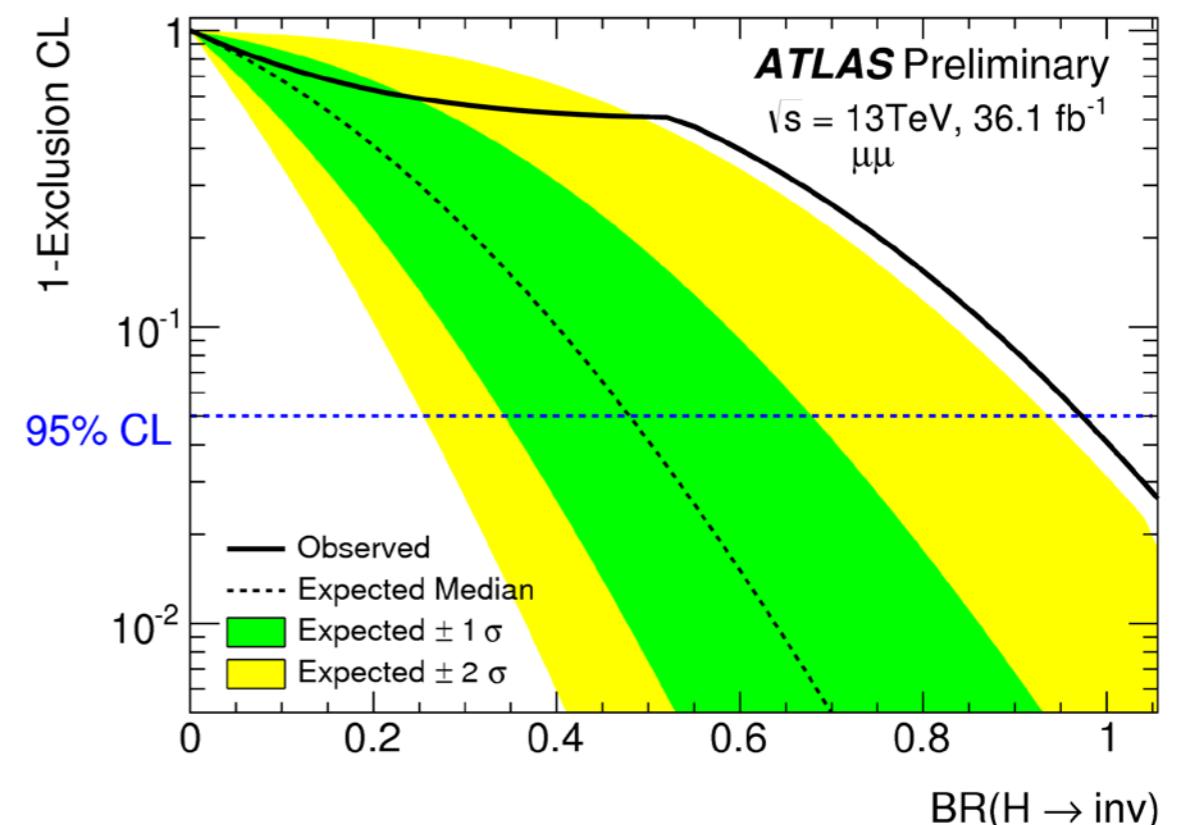
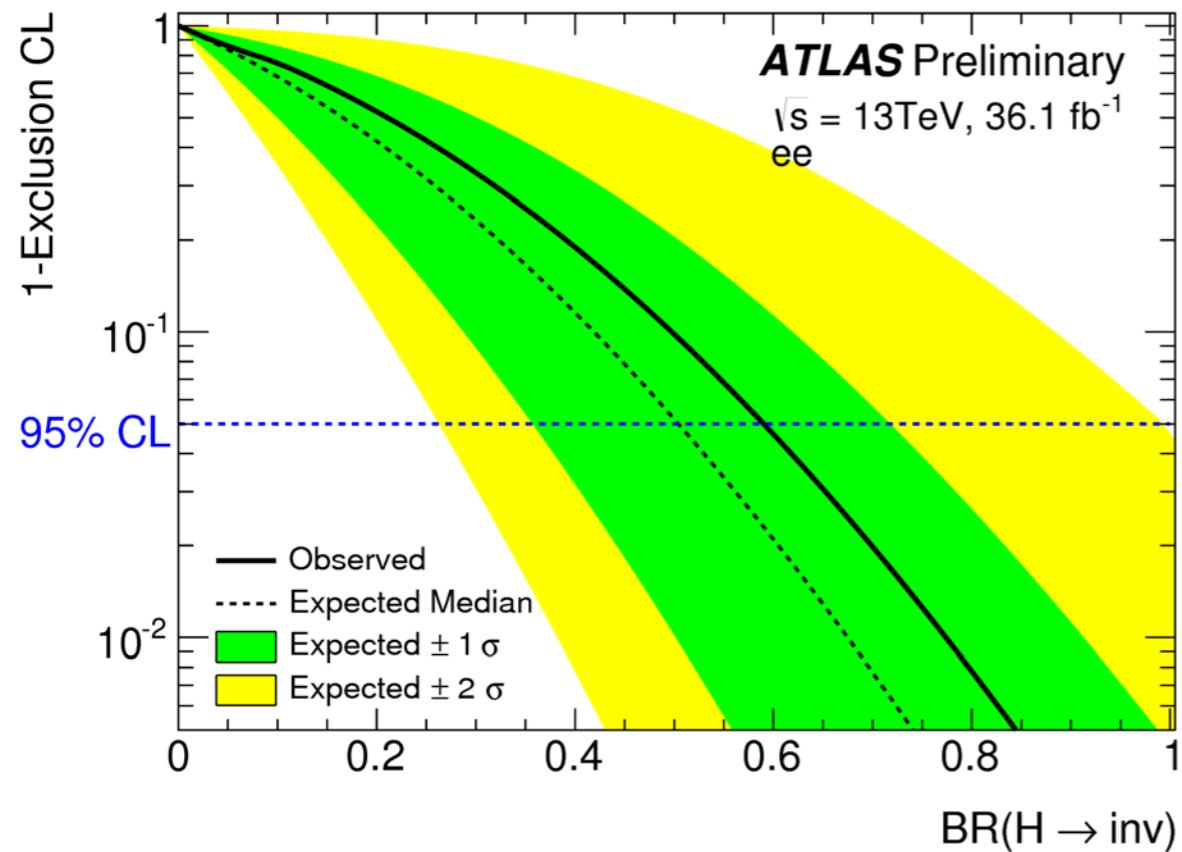
Final State	ee	$\mu\mu$
Observed Data	437	497
Signal		
$ZH \rightarrow \ell\ell + \text{inv}$ ( $\text{BR}_{H \rightarrow \text{inv}} = 30\%$ )	$32 \pm 1 \pm 3$	$34 \pm 1 \pm 3$
$\text{DM } (m_{\text{med}} = 500 \text{ GeV}, m_\chi = 100 \text{ GeV}) \times 0.27$	$10.8 \pm 0.3 \pm 0.8$	$11.1 \pm 0.3 \pm 0.8$
Backgrounds		
$qq\text{ZZ}$	$212 \pm 3 \pm 15$	$221 \pm 3 \pm 17$
$gg\text{ZZ}$	$18.9 \pm 0.3 \pm 11.2$	$19.3 \pm 0.3 \pm 11.4$
$WZ$	$106 \pm 2 \pm 6$	$113 \pm 3 \pm 5$
$Z + \text{jets}$	$30 \pm 1 \pm 28$	$37 \pm 1 \pm 19$
Non-resonant- $\ell\ell$	$30 \pm 4 \pm 2$	$33 \pm 4 \pm 2$
Others	$1.4 \pm 0.1 \pm 0.2$	$2.5 \pm 2.0 \pm 0.8$
Total Background	$399 \pm 6 \pm 34$	$426 \pm 6 \pm 28$

# Invisible Higgs: Results



R. Mazini

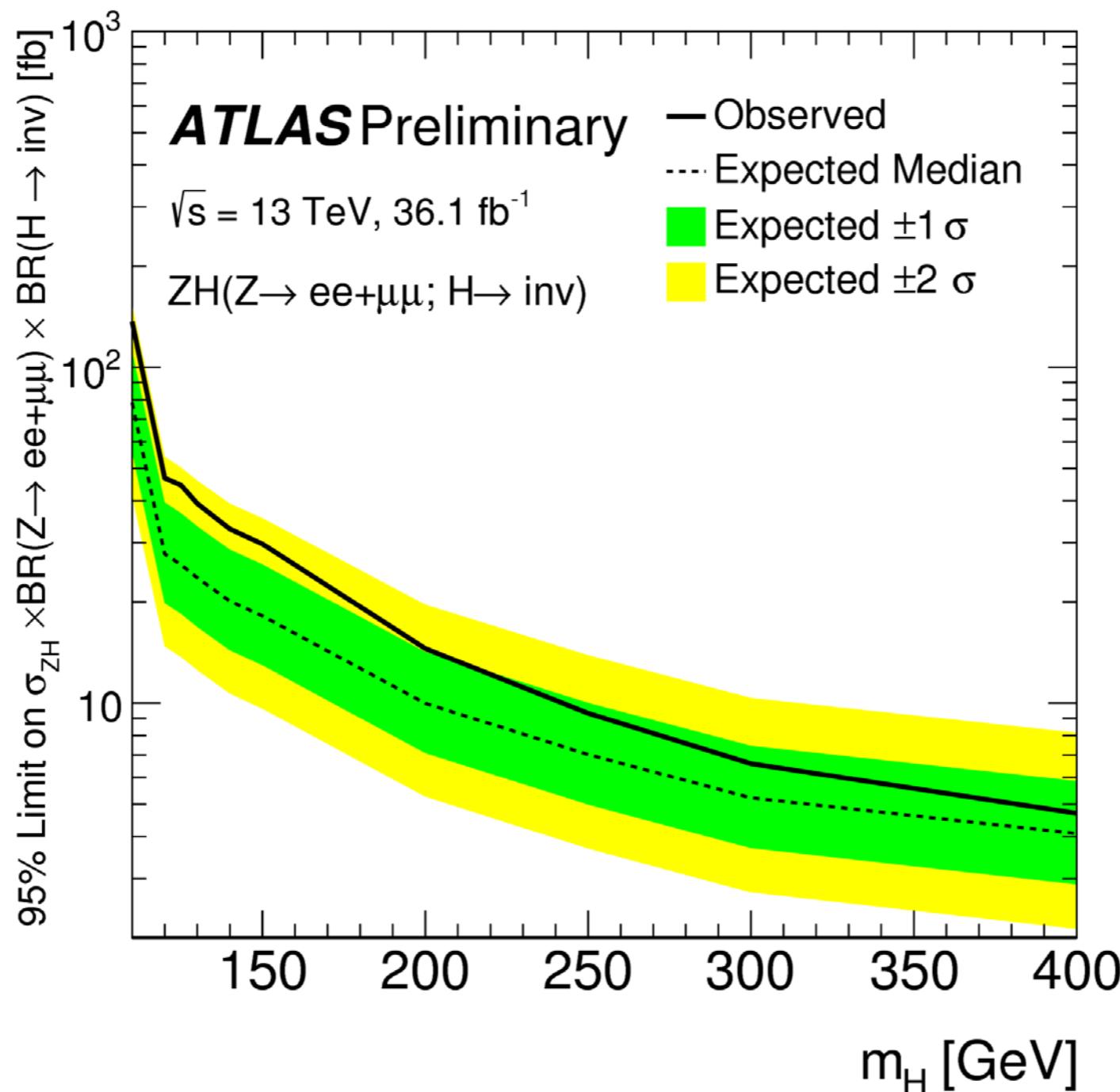
# Invisible Higgs: Results



	Exp. $BR_{H \rightarrow \text{inv}}$ Limit $\pm 1\sigma \pm 2\sigma$	Obs. $BR_{H \rightarrow \text{inv}}$ Limit
$ee + \mu\mu$	39% $^{+17\%}_{-11\%} \ ^{+38\%}_{-18\%}$	67%
$ee$	51% $^{+21\%}_{-15\%} \ ^{+49\%}_{-24\%}$	59%
$\mu\mu$	48% $^{+20\%}_{-14\%} \ ^{+46\%}_{-22\%}$	97%

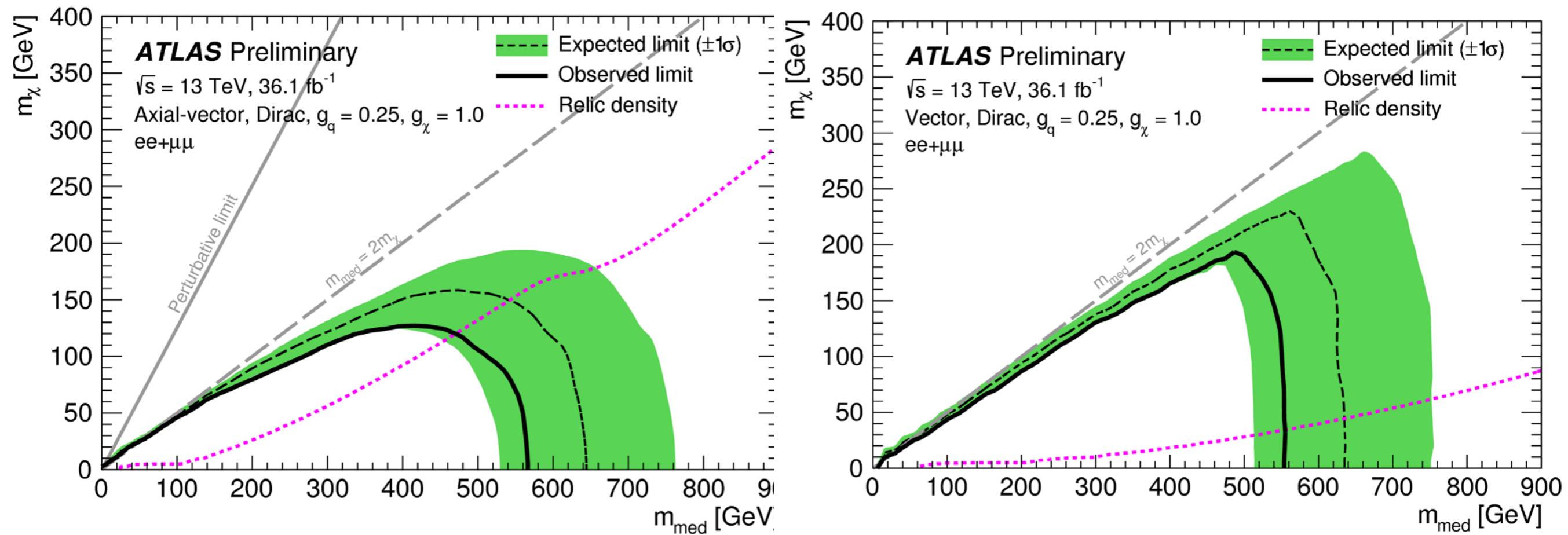
- Exclusion limit on  $B(H \rightarrow \text{inv.})$  assuming SM ZH cross section. **Observed (Expected) limit of 67% (39%).** Run 1 results were 75% (62%)

# Invisible Higgs: BR limit vs. $m_H$



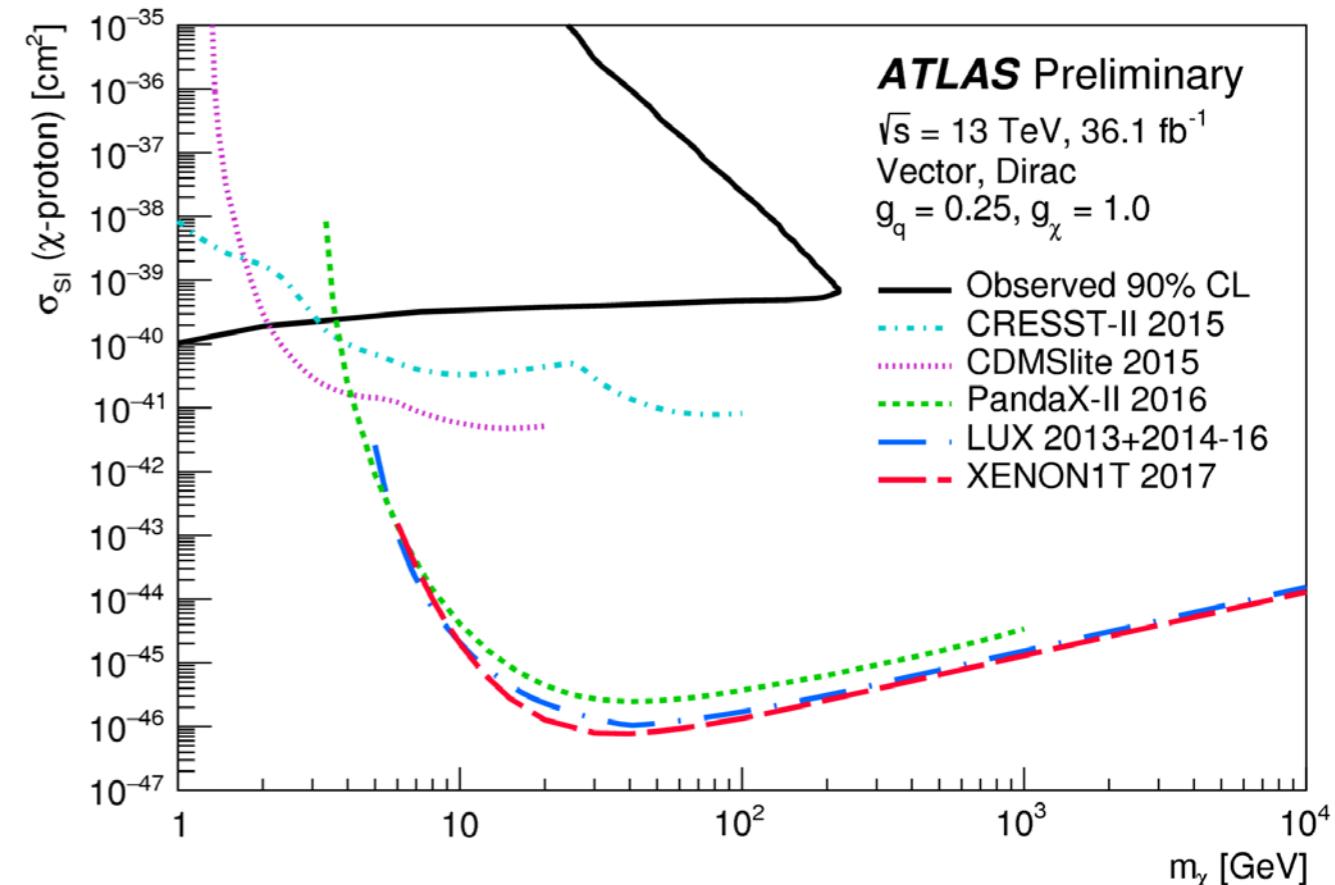
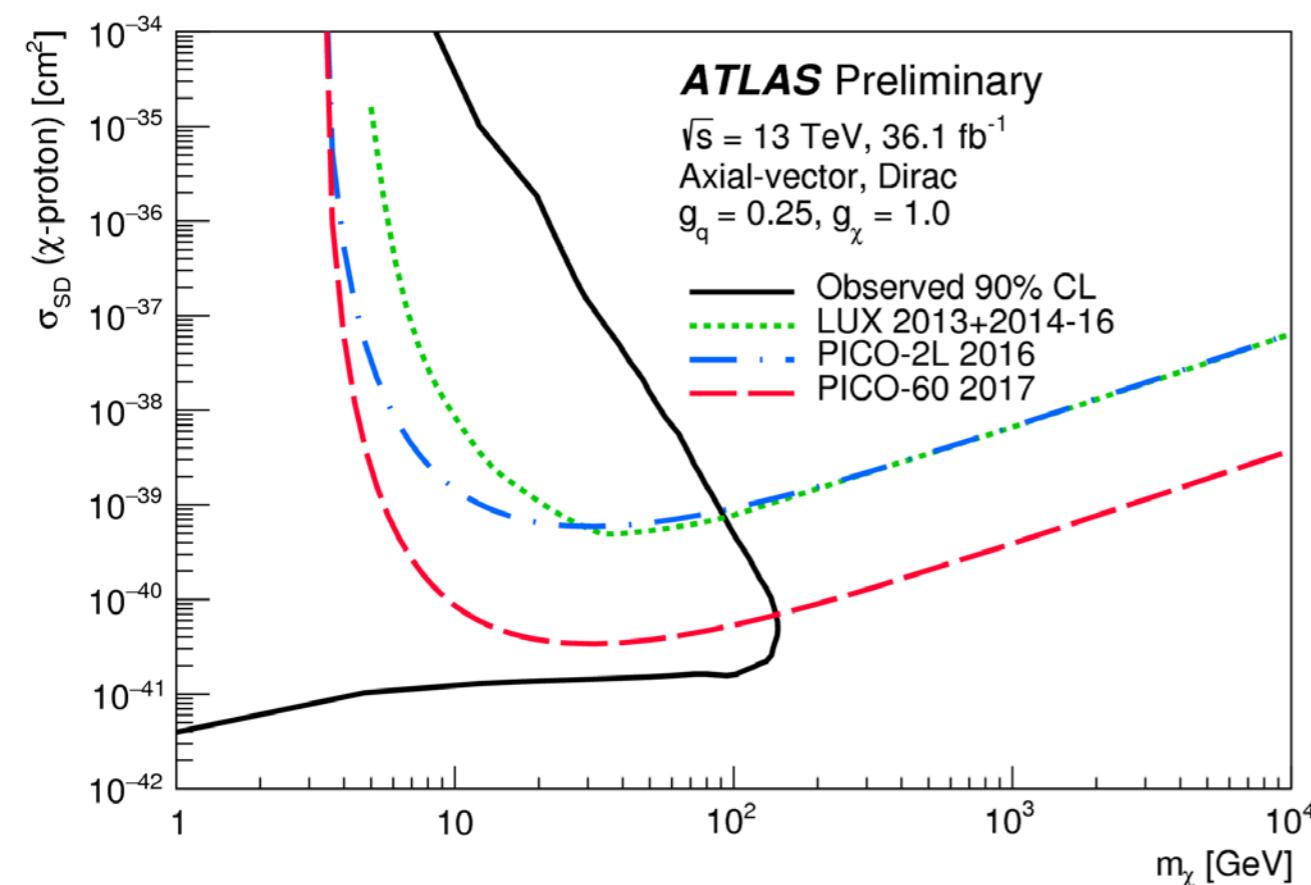
- “Model independent” measurement
- Slight excess in [120—180]GeV mainly driven by the  $\mu\mu$  decay channel.

# Invisible Higgs: DM Interpretation



- 95% CL exclusion limit in 2D  $m_\chi$  and  $m_{\text{med}}$ . DM models assuming a vector or an axial-vector mediator, fermionic WIMPs, and a specific scenario of the coupling parameters ( $g_\chi = 1, g_q = 0.25$ ).
- mediator mass  $m_{\text{med}}$  is excluded up to 560 GeV for a light WIMP
- WIMP mass  $m_\chi$  is excluded up to 130 GeV for  $m_{\text{med}} = 400$  GeV.

# Invisible Higgs: DM-nucleon limits



Better sensitivity for Axial-vector, fermion models in the WIMP mass range

# The Future: challenges & complementarity

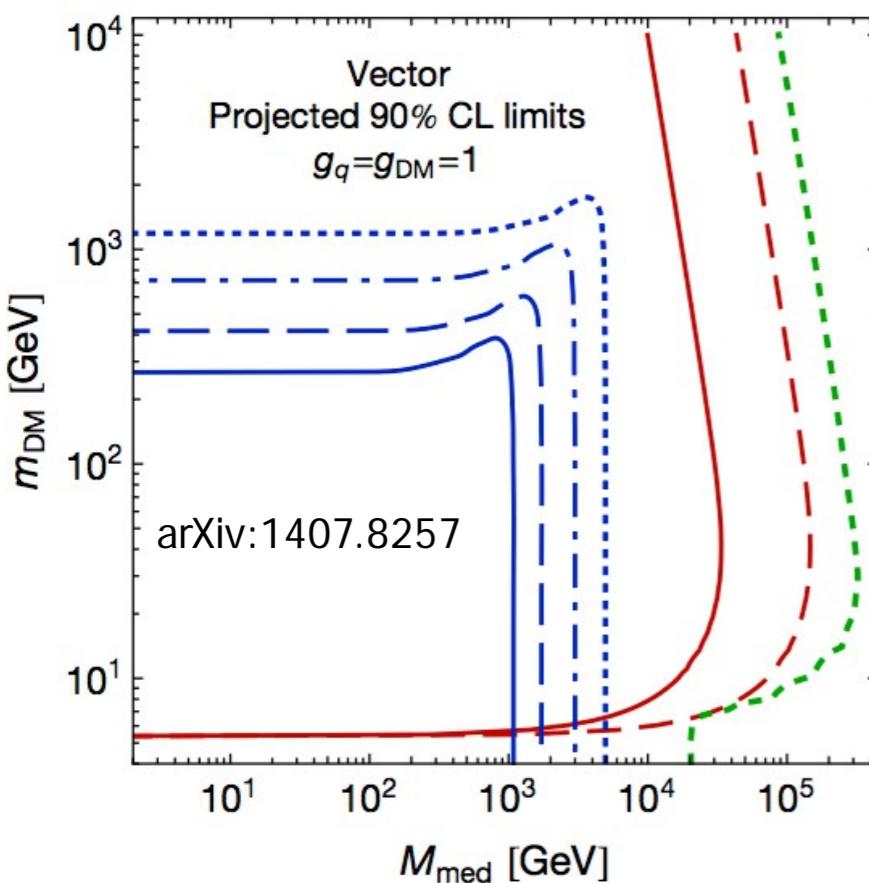
## expected luminosity

Results now:  $36 \text{ f b}^{-1}$   
end of 2018:  $120 \text{ f b}^{-1}$   
end of 2023:  $300 \text{ f b}^{-1}$   
HL-LHC ( $\sim 2035$ ):  $3000 \text{ f b}^{-1}$

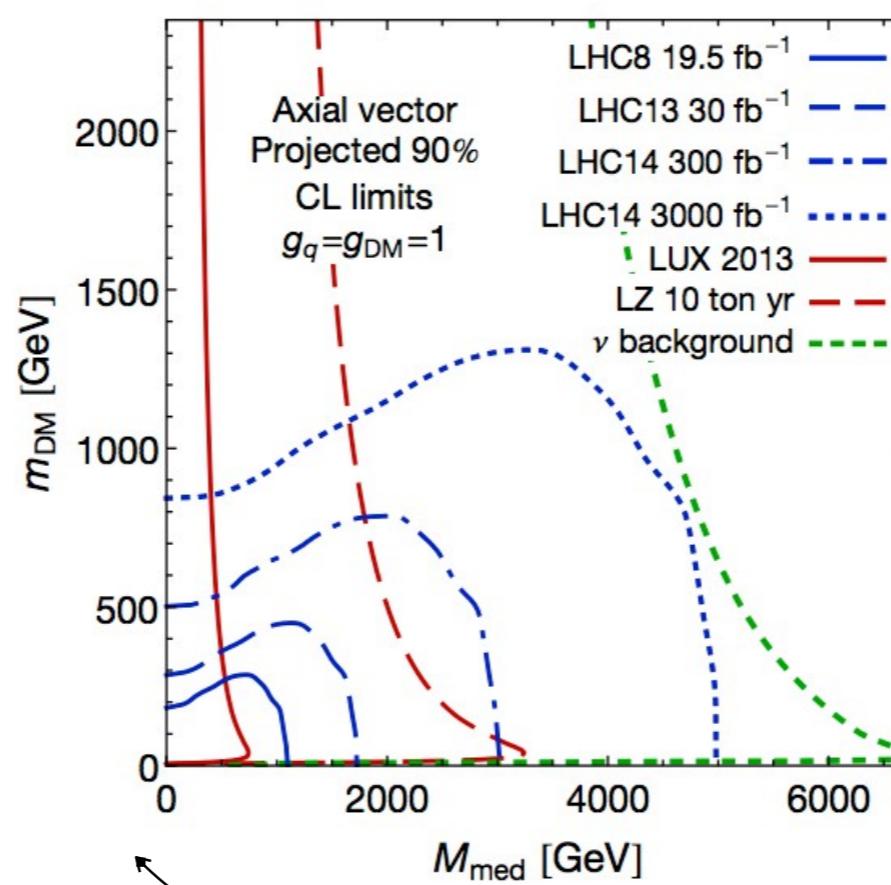
see also <https://indico.cern.ch/event/539266>

- balance between sensitivity to low-momentum signals (e.g. spin-zero) and robustness at very high energy
  - trigger & detector performance are crucial!
- explore lower-cross-section extensions of the SM (SUSY, long-lived particles...)

## vector

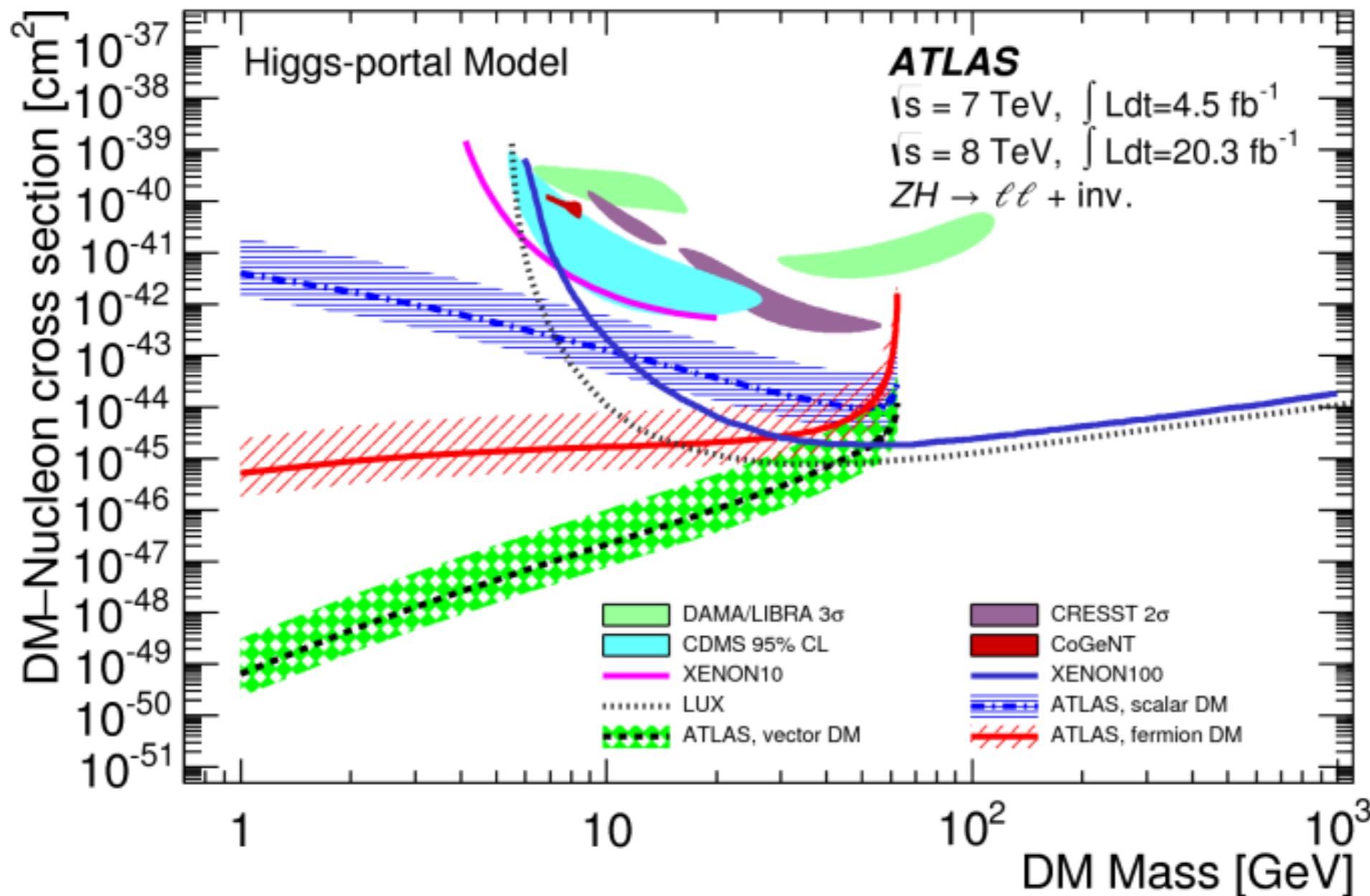


## axial-vector



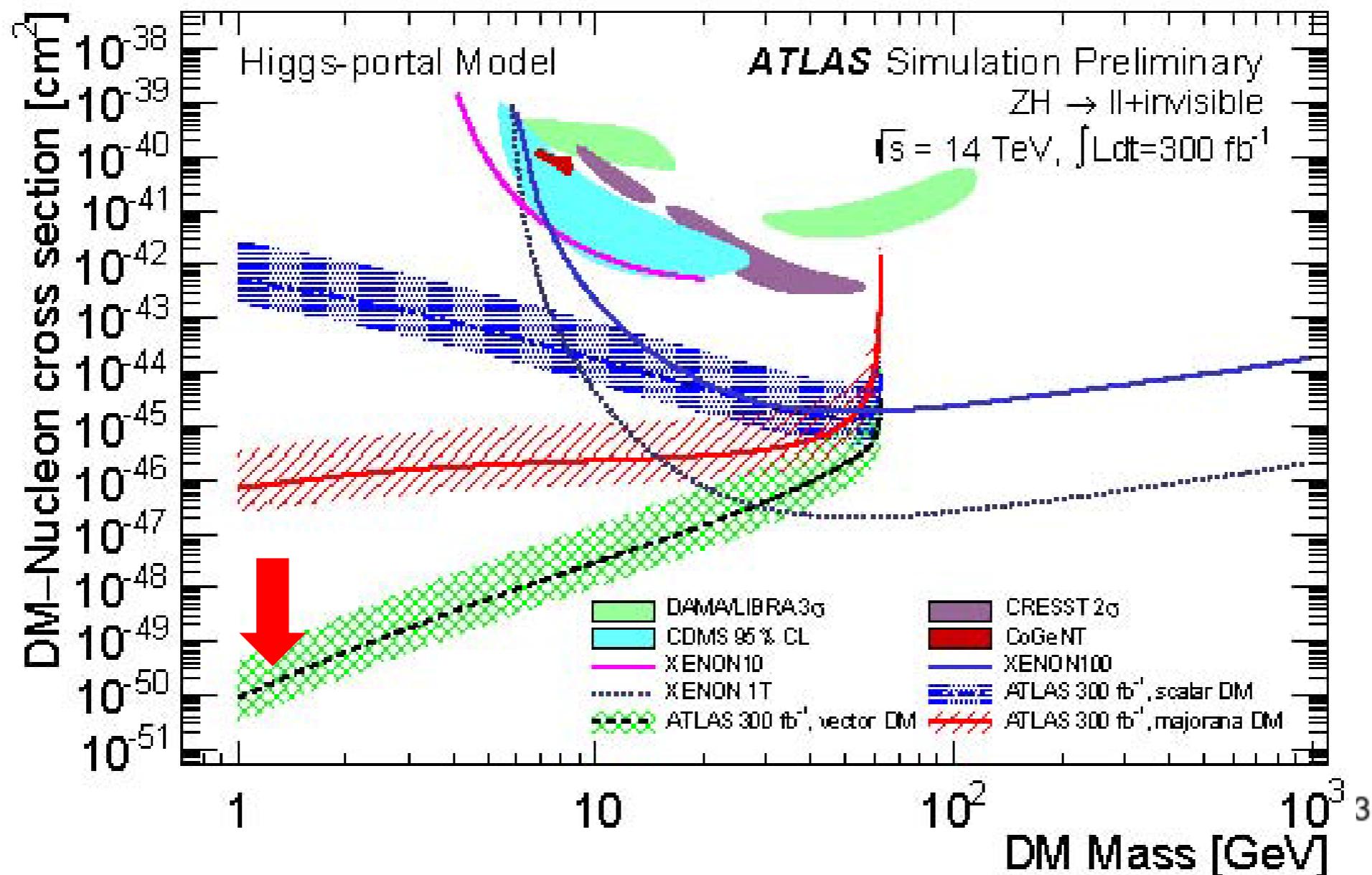
could extend the  $m_{\text{DM}}$  sensitivity up to 0.5 TeV in ~6 years (mind the couplings!)

# Prospects for Invisible Higgs searches



From Run 1 measurements

# Prospects for Invisible Higgs searches



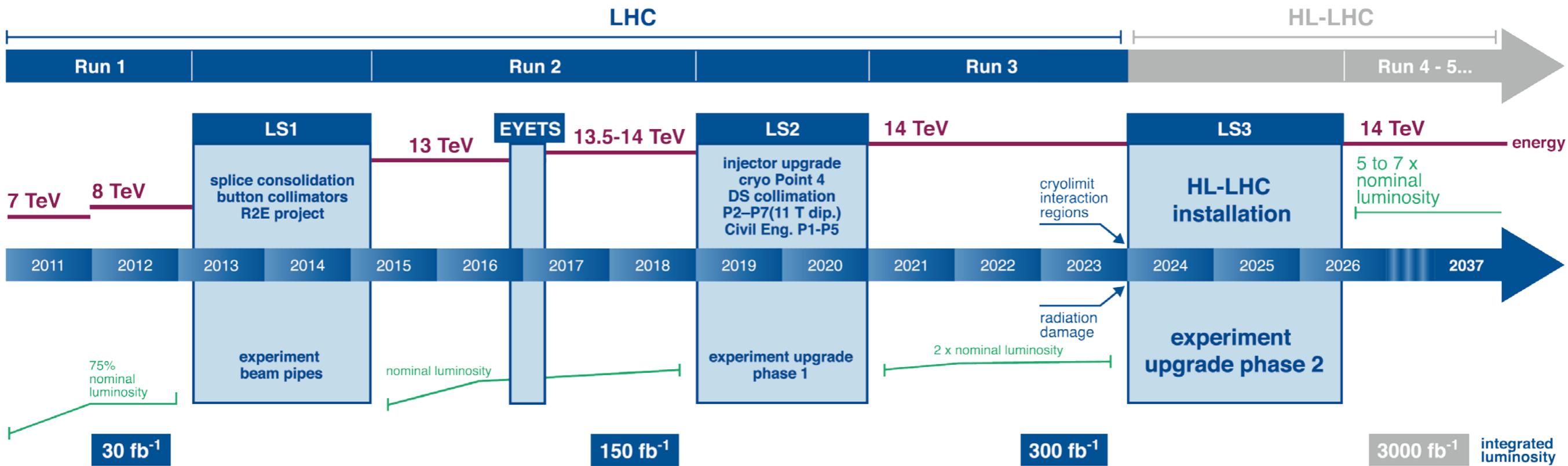
Assuming similar detector performances but with scaled-up systematics uncertainties

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# The ATLAS upgrade program for LH-LHC

The accelerator  
The detector  
The physics

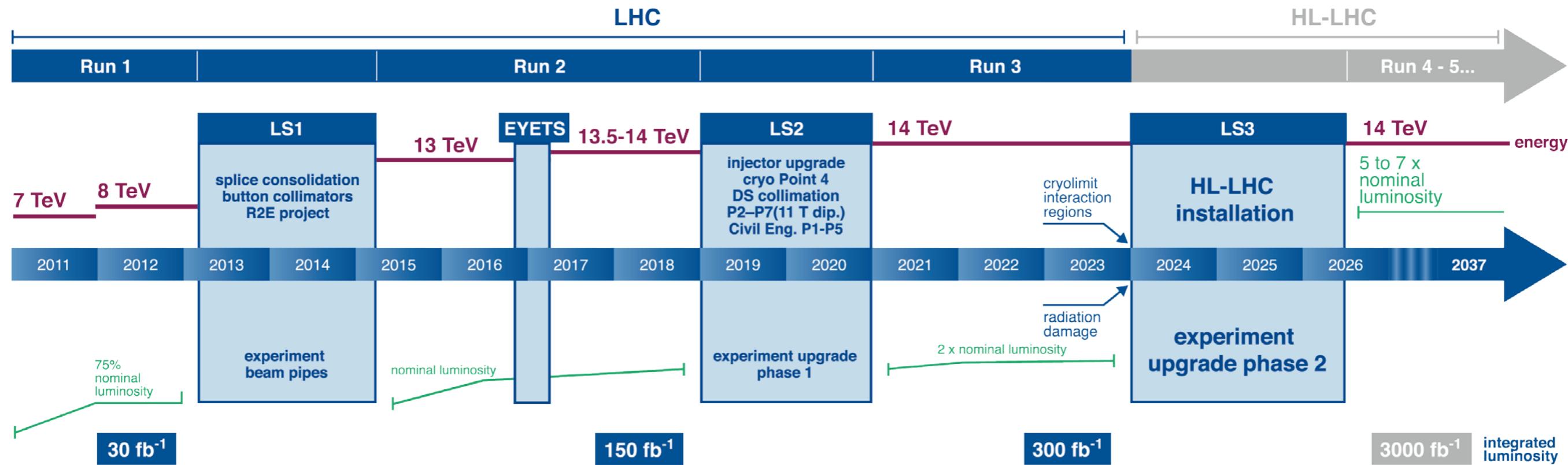
# LHC / HL-LHC Plan



Run 1 Magnet Run 2 at Phase I Run 3 at Phase II HL-LHC:  
 splice update ~full design upgrades original upgrades ten times  
 energy (injectors) design lumi (final focus) design lumi

HL-LHC mode	Peak Luminosity (cm <sup>-2</sup> s <sup>-1</sup> )	Mean number of interactions per bunch-crossing <math>\langle\mu_{PU}\rangle</math>	Integrated luminosity (fb <sup>-1</sup> )
Baseline	$5 \times 10^{34}$	140	3000
Ultimate	$7.5 \times 10^{34}$	Acadmia Sinica 200	4000

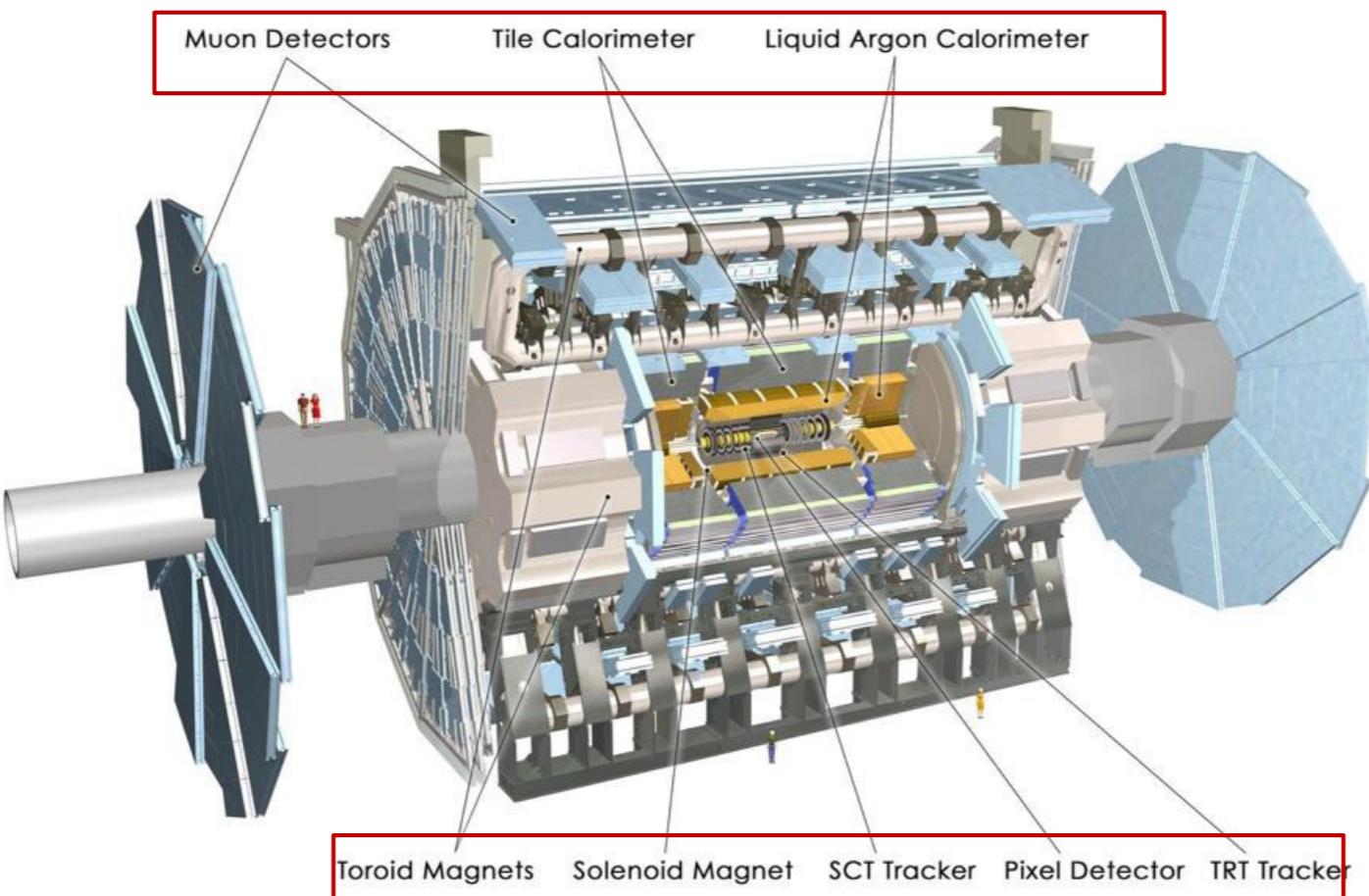
# LHC / HL-LHC Plan



Run 1	Magnet splice update	Run 2 at ~full design energy	Phase I upgrades (injectors)	Run 3 at original design lumi	Phase II upgrades	HL-LHC: ten times design lumi
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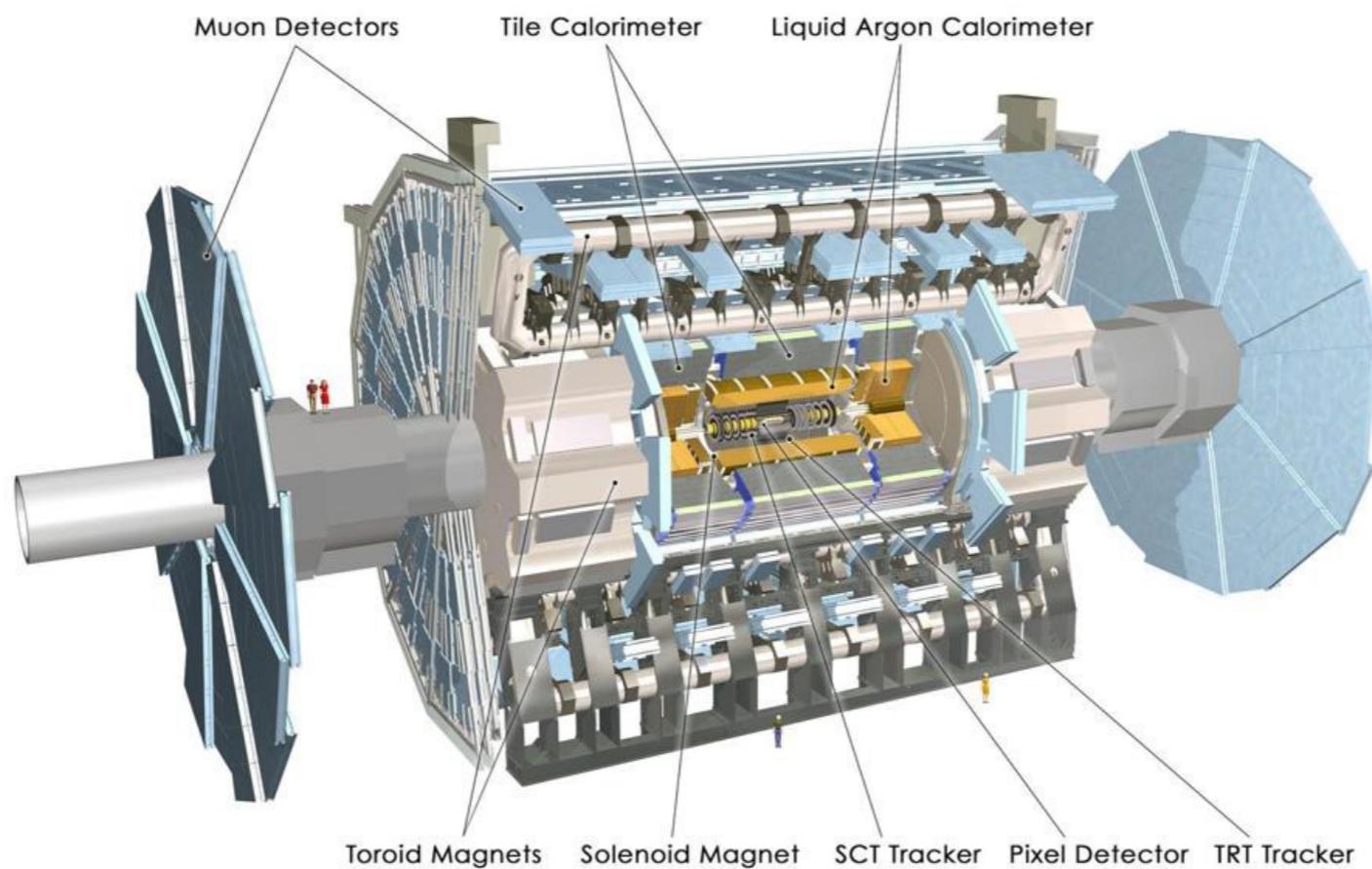
Full exploitation of LHC is top priority in Europe & US for high energy physics  
 Operate HL-LHC with 5 (nominal) to 7.5 (ultimate)  $\times 10^{34} \text{cm}^{-2}\text{s}^{-1}$  to collect 3000/fb in order ten years.

# The tools for HL-LHC: ATLAS upgrade



# The tools for HL-LHC: ATLAS upgrade

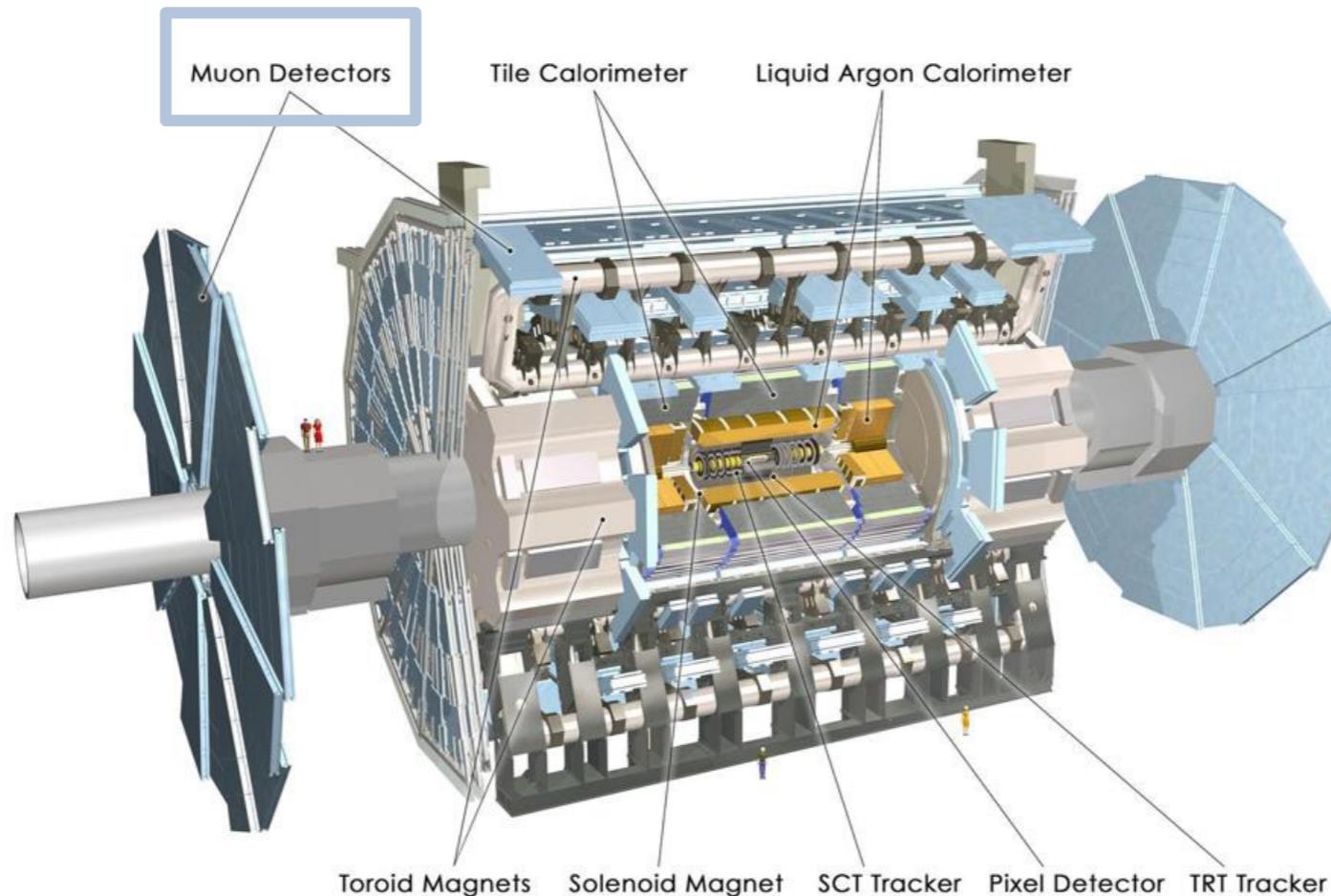
TDAQ upgrade  
→ Increased latencies and rates :  
--L0[6μs, 1MHz]  
--L1[30μs,400kHz]



# The tools for HL-LHC: ATLAS upgrade

TDAQ upgrade  
→ Increased latencies and rates :  
--L0[6μs, 1MHz]  
--L1[30μs, 400kHz]

Muon readout and trigger upgrades.  
New Barrel trigger layer

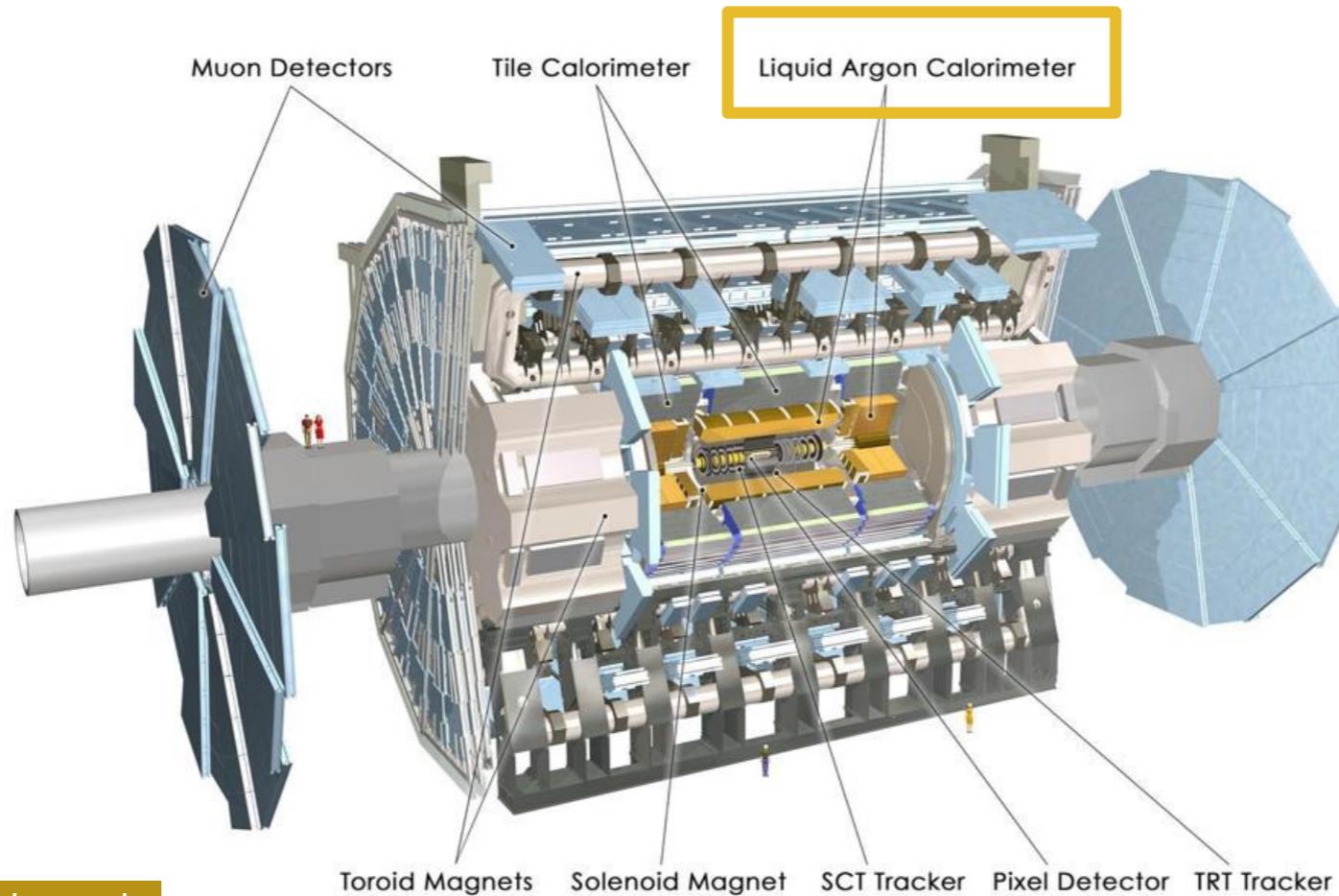


# The tools for HL-LHC: ATLAS upgrade

TDAQ upgrade  
→ Increased latencies and rates :  
--L0[6μs, 1MHz]  
--L1[30μs,400kHz]

Muon readout and trigger upgrades.  
New Barrel trigger layer

LArg; new FrontEnd and BackEnd electronics for faster readout

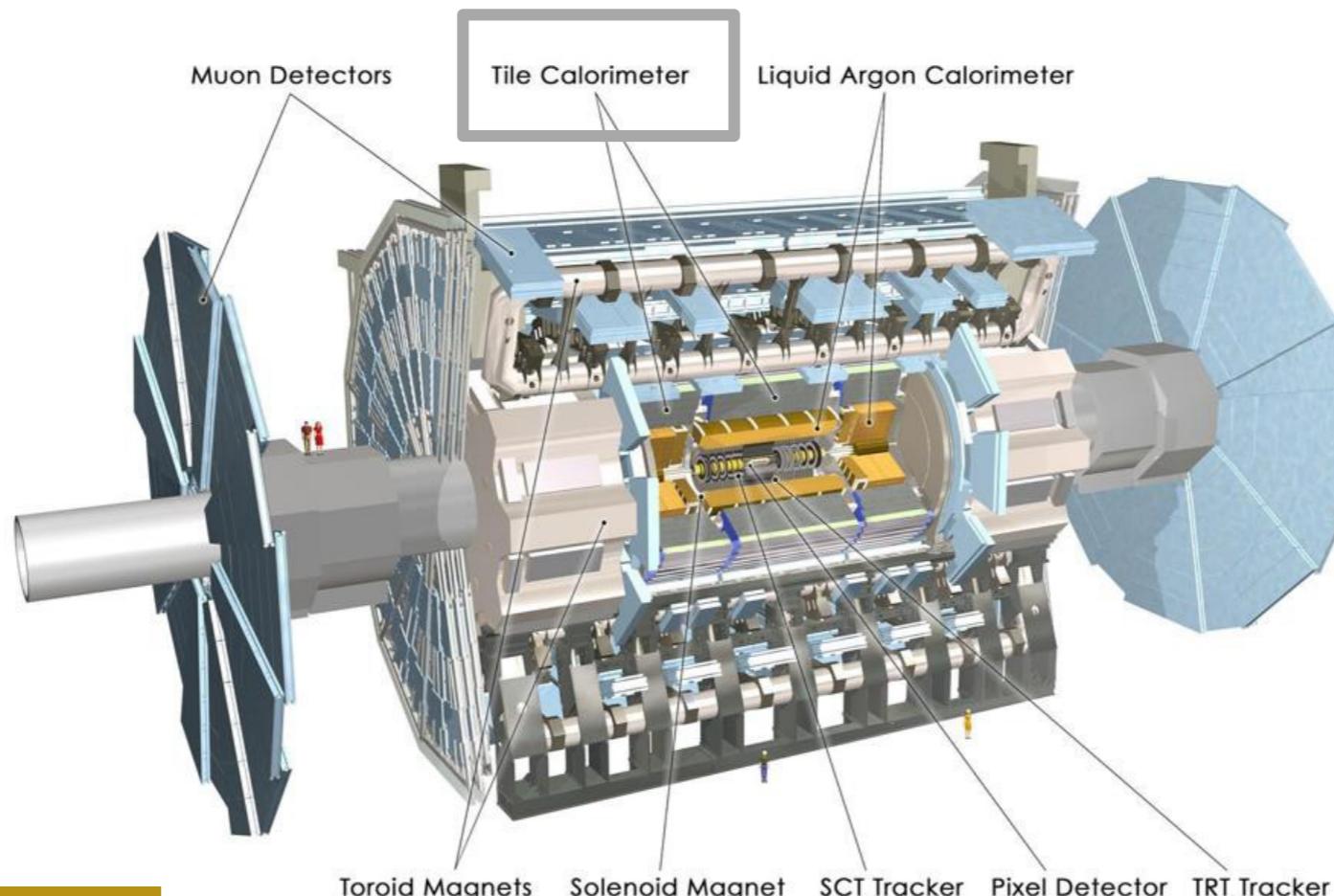


# The tools for HL-LHC: ATLAS upgrade

TDAQ upgrade  
→ Increased latencies and rates :  
--L0[6μs, 1MHz]  
--L1[30μs, 400kHz]

Muon readout and trigger upgrades.  
New Barrel trigger layer

LArg; new FrontEnd and BackEnd electronics for faster readout



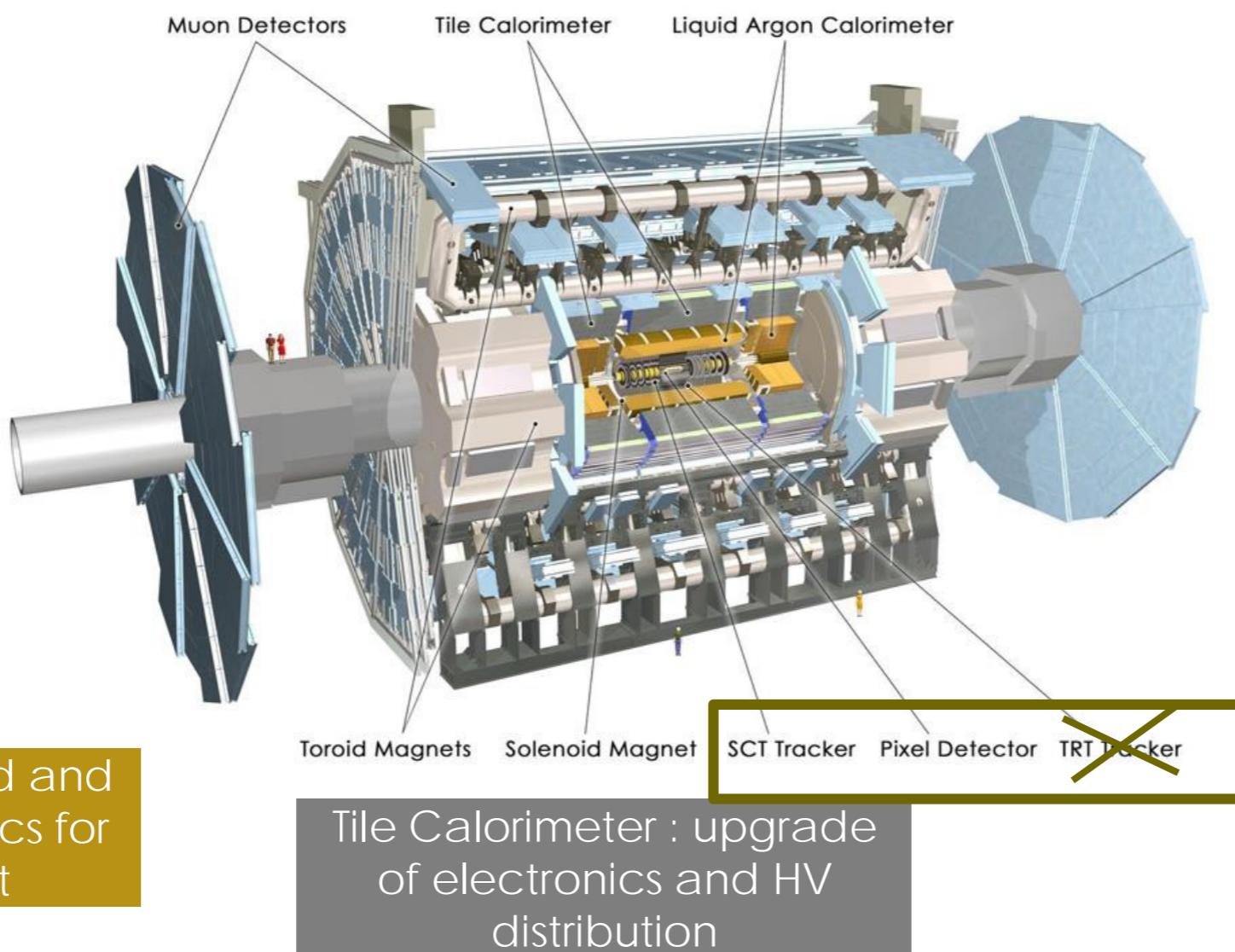
Tile Calorimeter : upgrade of electronics and HV distribution

# The tools for HL-LHC: ATLAS upgrade

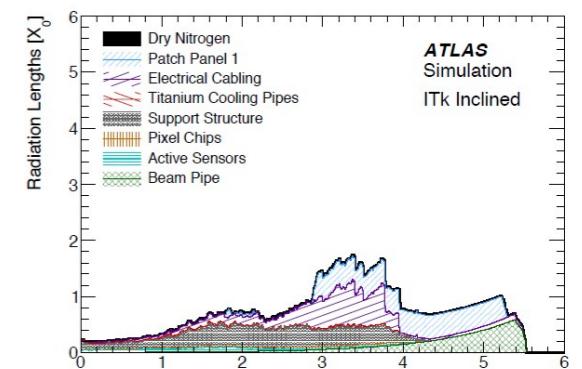
TDAQ upgrade  
→ Increased latencies and rates :  
--L0[6μs, 1MHz]  
--L1[30μs, 400kHz]

Muon readout and trigger upgrades.  
New Barrel trigger layer

LArg: new FrontEnd and BackEnd electronics for faster readout



08/2017  
RFQ  
SS  
Inner Detector: full replacement by a all-silicon one ( $\approx 165\text{m}^2$ ), extending up to  $|\eta| = 4$ . At most  $1.75 \times X_0$



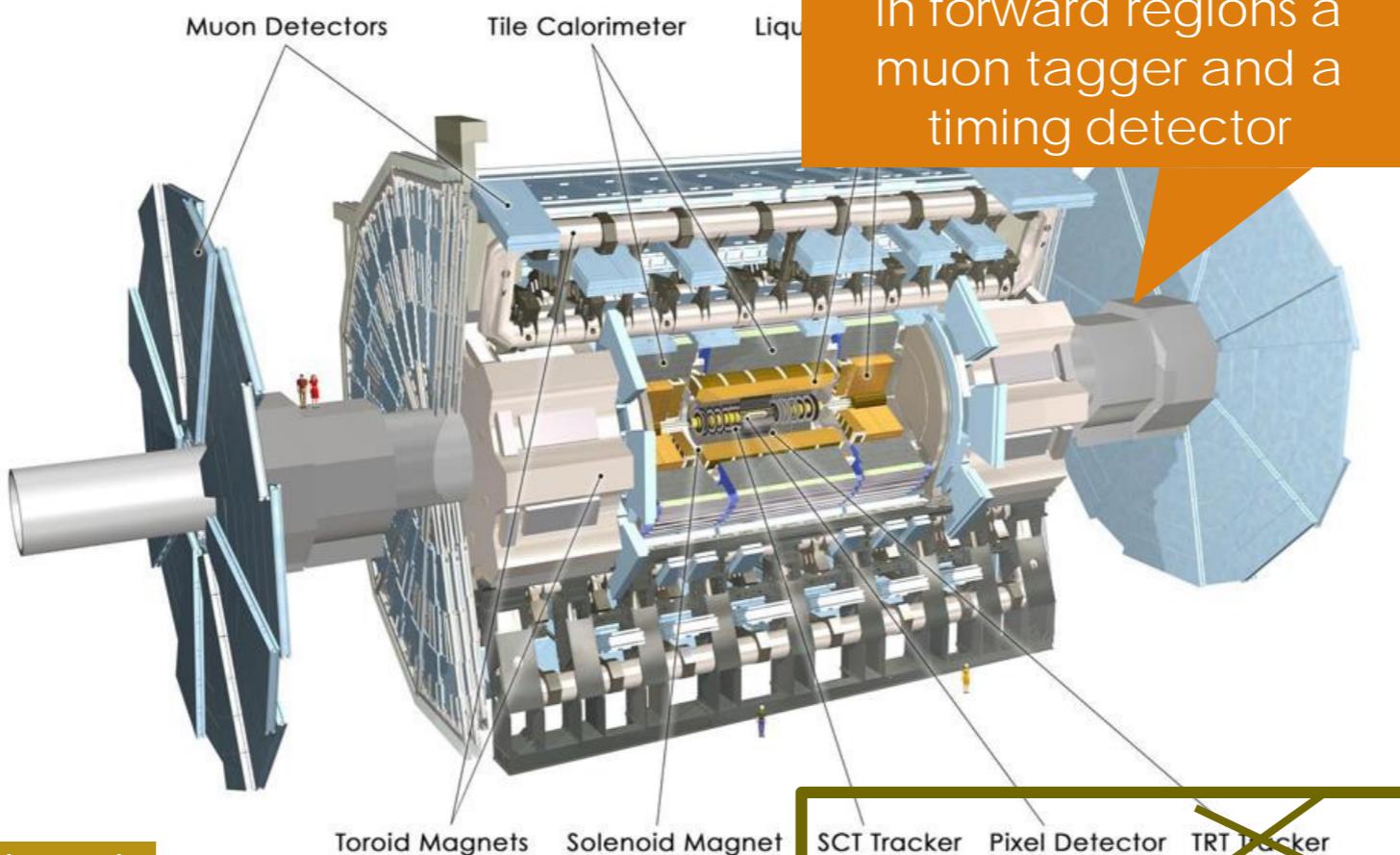
Tracker extension up to  $|\eta| = 4$  crucial for pileup rejection and VBF sensitivity

# The tools for HL-LHC: ATLAS upgrade

TDAQ upgrade  
→ Increased latencies and rates :  
--L0[6μs, 1MHz]  
--L1[30μs, 400kHz]

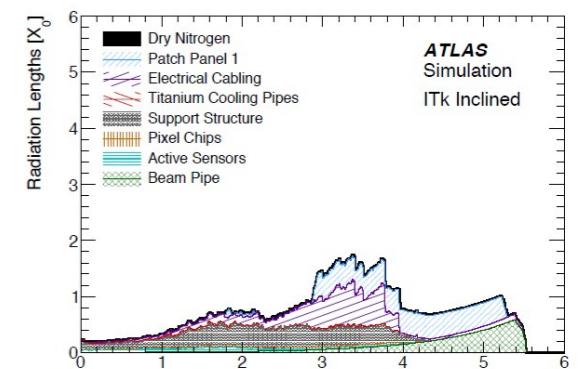
Muon readout and trigger upgrades.  
New Barrel trigger layer

LArg: new FrontEnd and BackEnd electronics for faster readout



Tile Calorimeter : upgrade of electronics and HV distribution

08/2017  
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Detector: full replacement by a all-silicon one ( $\approx 165\text{m}^2$ ), extending up to  $|\eta| = 4$ . At most  $1.75 \times X_0$



Tracker extension up to  $|\eta| = 4$  crucial for pileup rejection and VBF sensitivity

# Trigger Menu @ ATLAS ( HL-LHC )

<b>HL-LHC @ <math>7.5 \times 10^{34}</math></b>	Offline $p_T$ Threshold [GeV]	Offline $ \eta $	<b>L0</b> Rate [kHz]
isolated Single $e$	22	< 2.5	200
forward $e$	35	2.4 – 4.0	40
single $\gamma$	120	< 2.4	66
single $\mu$	20	< 2.4	40
di- $\gamma$	25	< 2.4	8
di- $e$	15	< 2.5	90
di- $\mu$	11	< 2.4	20
$e - \mu$	15	< 2.4	65
single $\boxtimes$	150	< 2.5	20
di- $\boxtimes$	40,30	< 2.5	200
single jet	180	< 3.2	60
fat jet	375	< 3.2	35
four-jet	75	< 3.2	50
$H_T$	500	< 3.2	60
$E_T^{\text{miss}}$	200	< 4.9	50
jet + $E_T^{\text{miss}}$	140,125	< 4.9	60
forward jet <sup>***</sup>	180	3.2 - 4.9	30
Total			<b>1MHz</b>

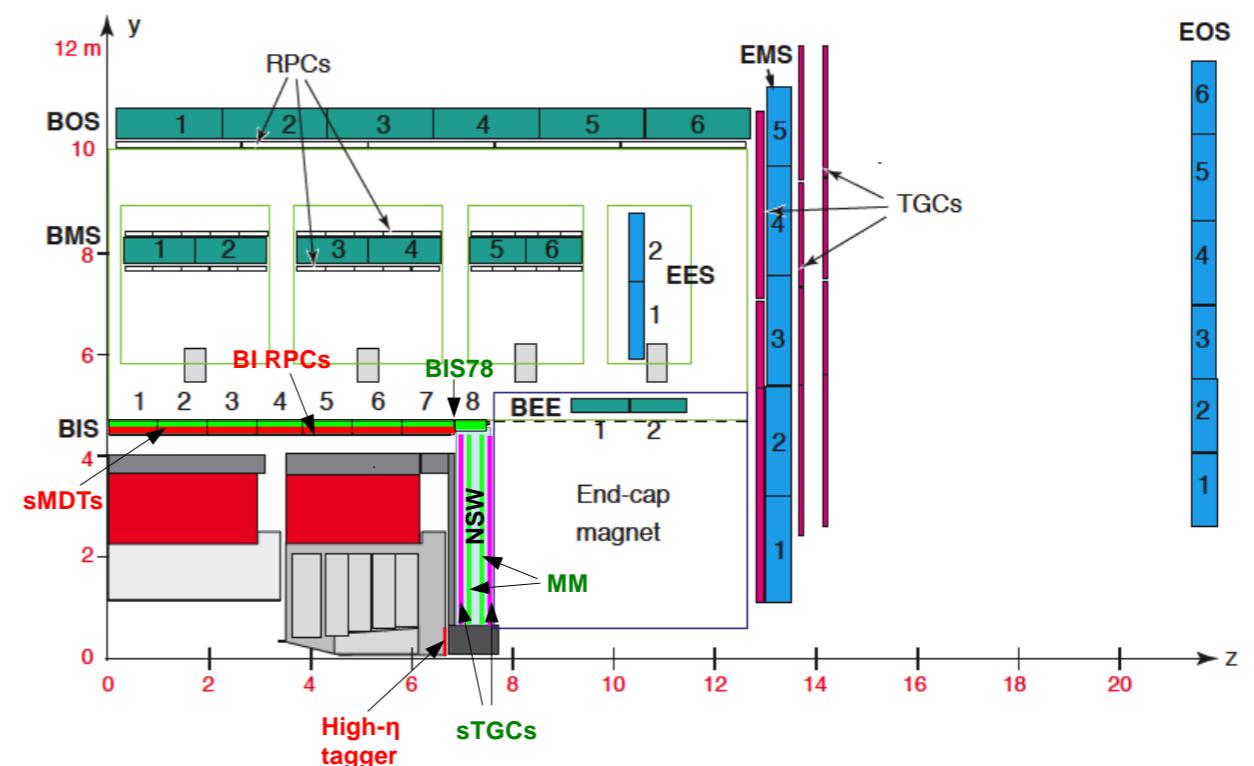
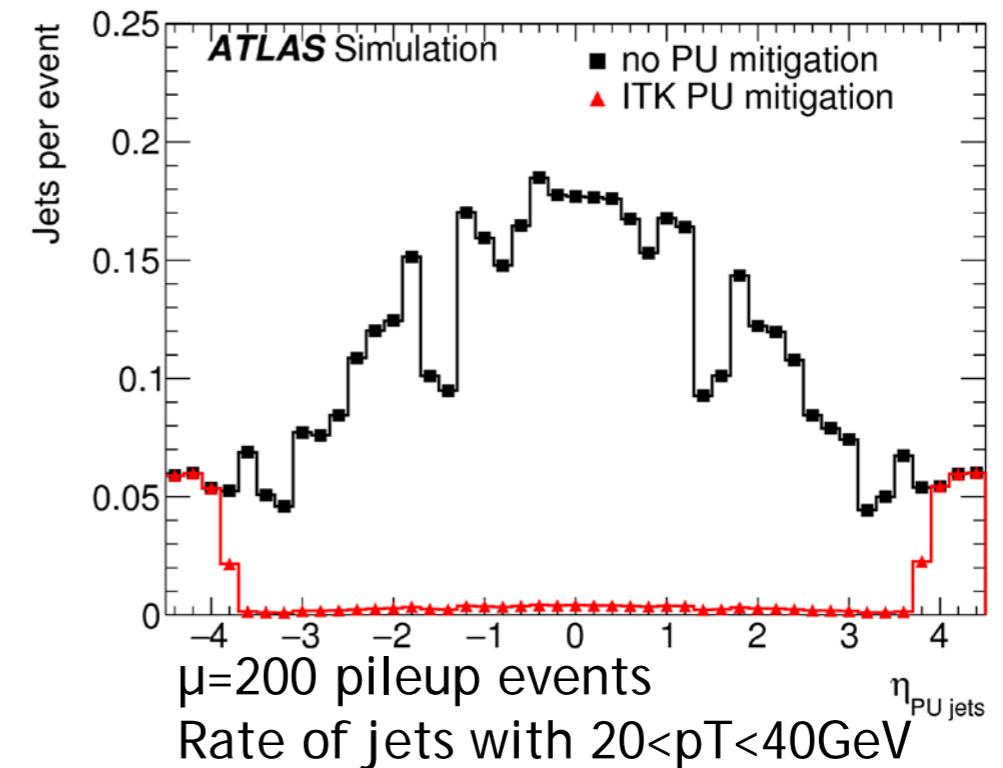
ex : single-lepton

	Run-1	Run-2	<b>HL-LHC</b>
	$0.8 \times 10^{34}$	$2.0 \times 10^{34}$	<b><math>7.5 \times 10^{34}</math></b>
<b>1e</b>	25 GeV	32	<b>22 GeV</b>
<b>1μ</b>	25 GeV	27	<b>20 GeV</b>

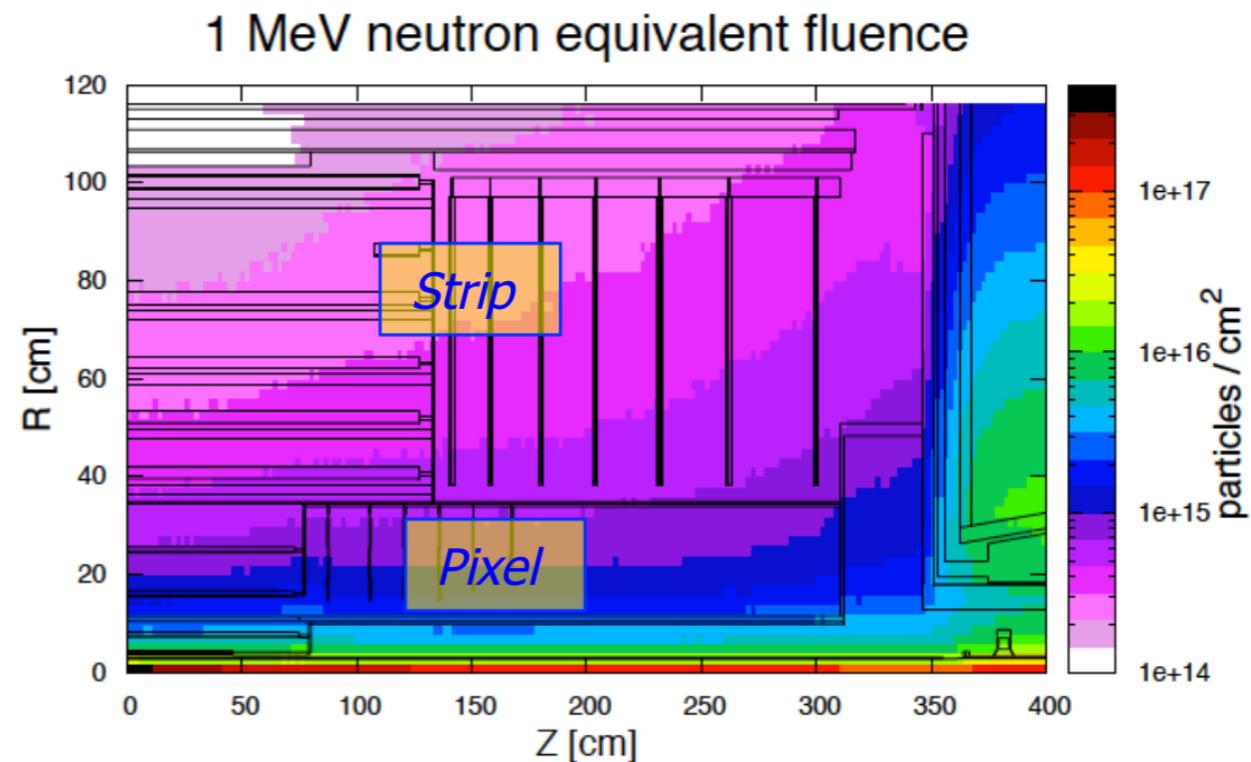
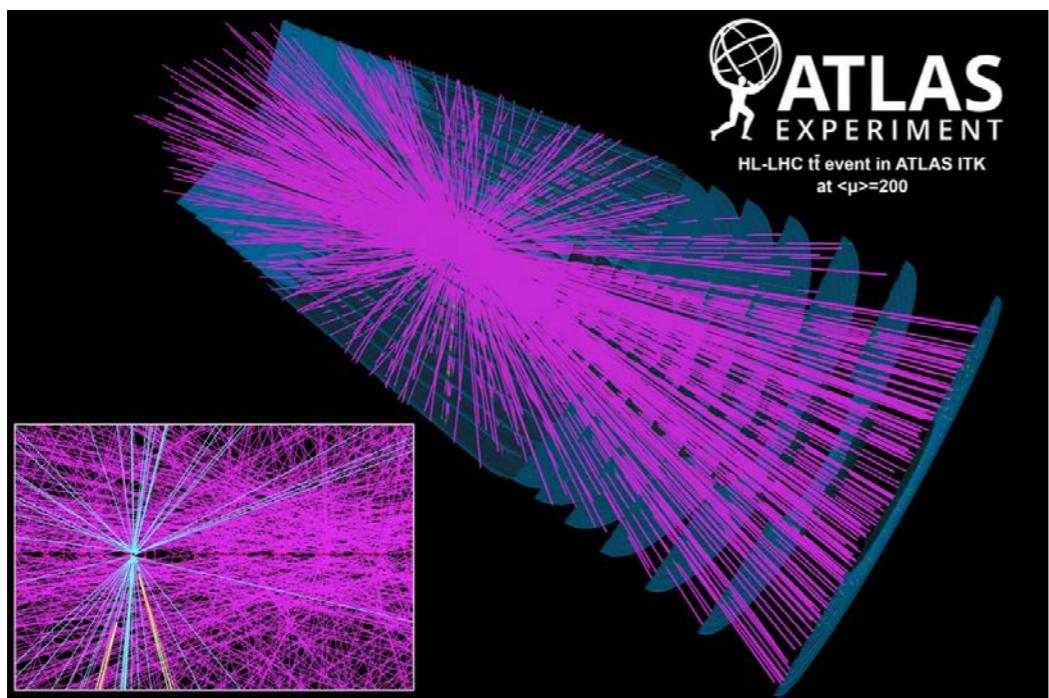
Aim : similar threshold as Run-1 & Larger Geom. acceptance

# Phase-II for HL-LHC

- New all-silicon tracker ITk
  - Extending to  $|\eta| < 4.0$
  - L1 track trigger
- Calorimeter electronics upgrade (full info at trigger level)
- Muon system upgrades (fill gaps in trigger coverage with new inner barrel chambers; new front-end electronics)
- Trigger-DAQ upgrades
- New projects:
  - High granularity timing detector for the forward region
  - Muon high- $\eta$  tagger

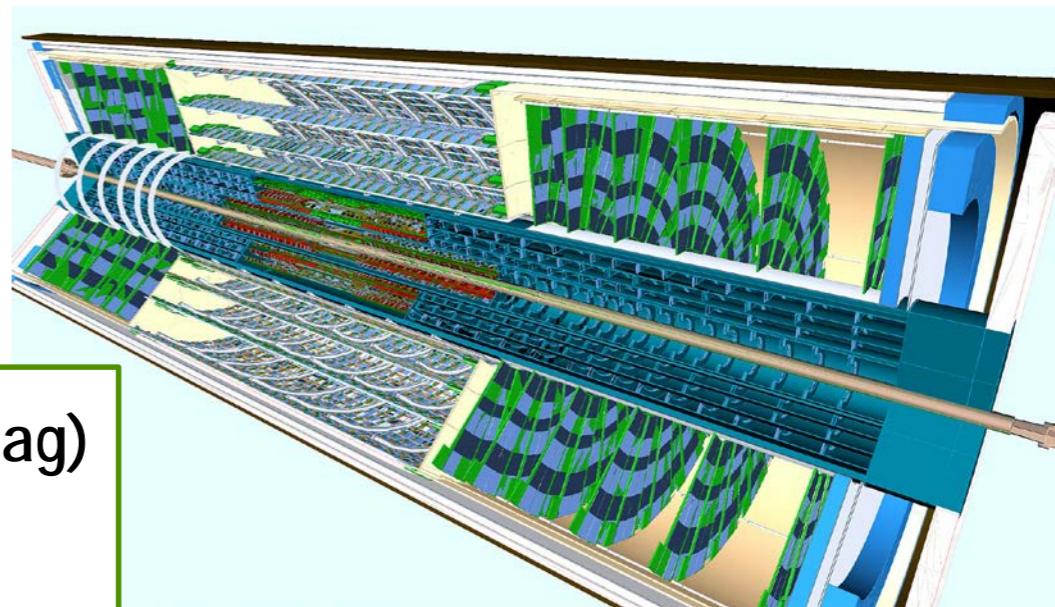


# NEW Inner Tracker ( ITK )



- inst. Lumi. :  $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- mean # of int. per bunch :  $\langle\mu\rangle \sim 200$  ( high track density , high radiation )

- Performance (resolution , efficiency , Vertex → b-tag) to be maintained or better
- radiation tolerant

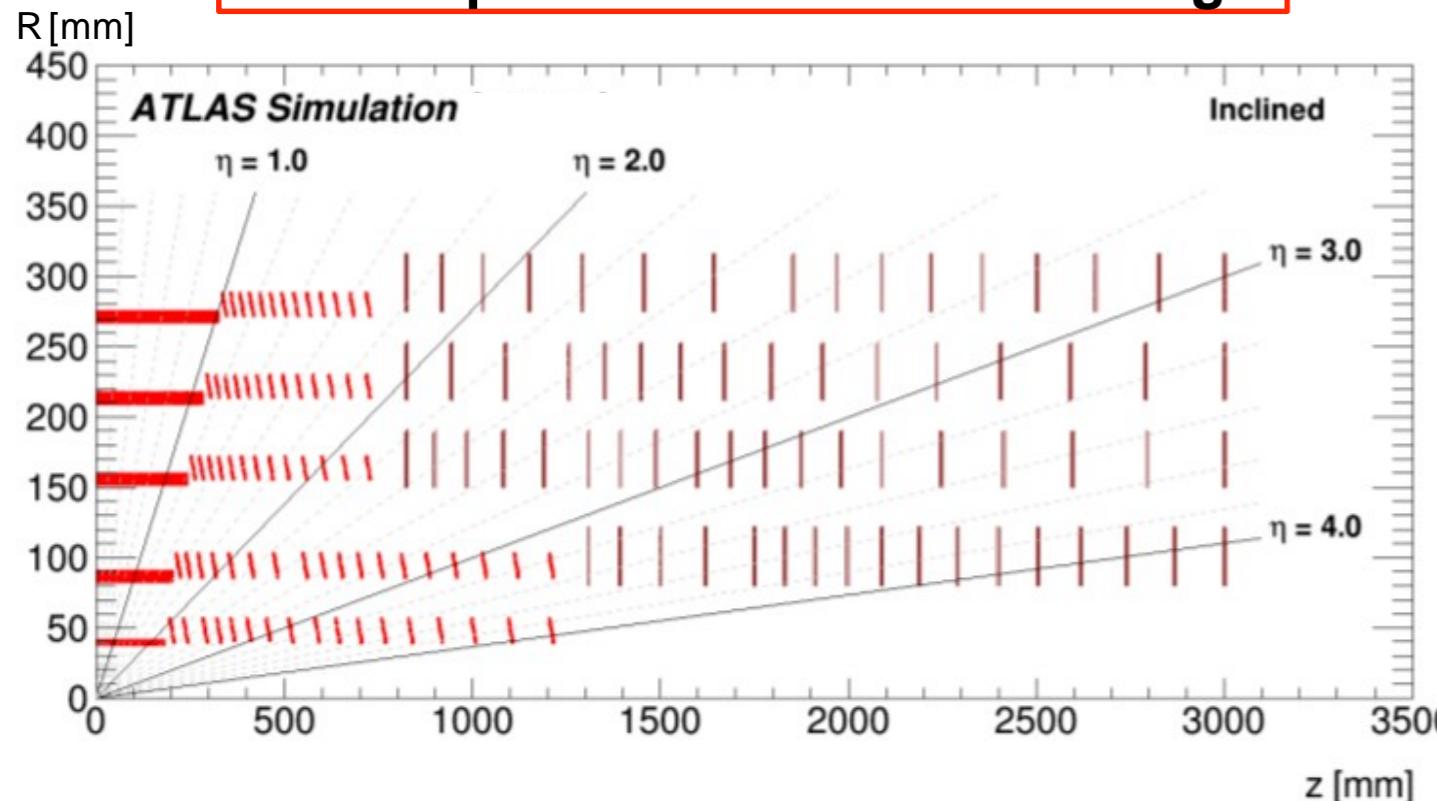


# PIXEL & STRIP Layout

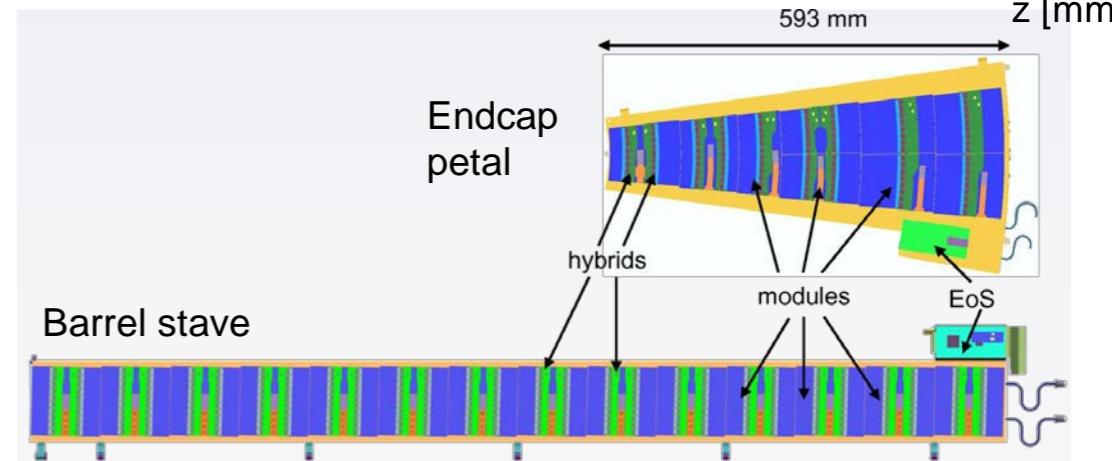
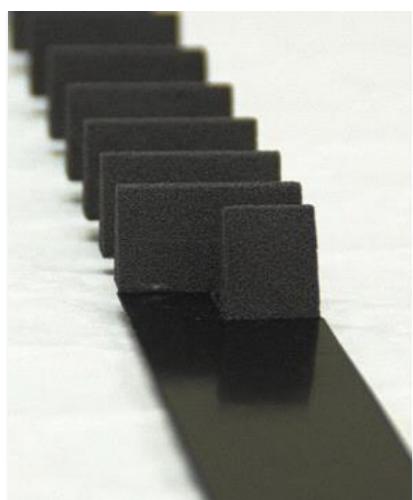
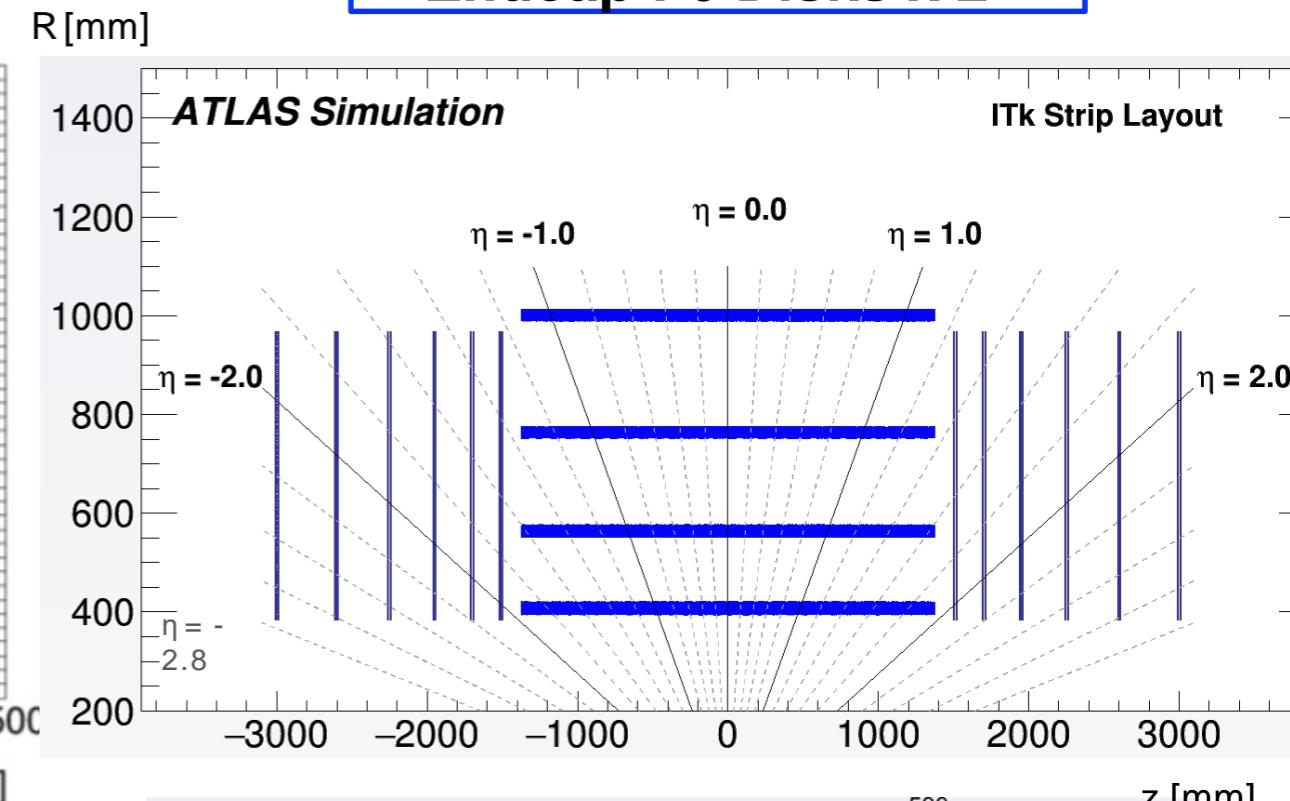
PIXEL

STRIP

- Barrel : 5 layer
- Endcap : inclined modules + Rings



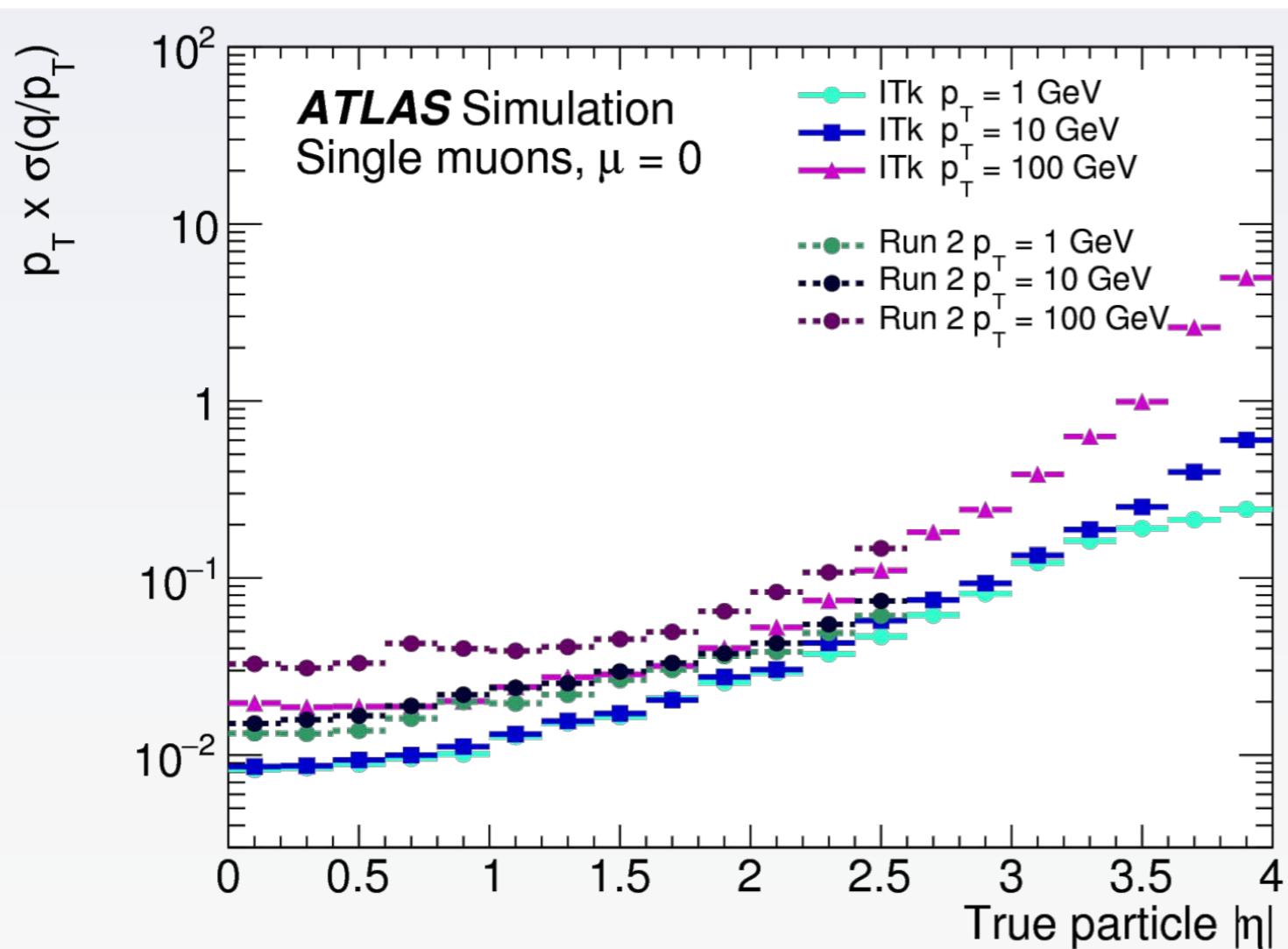
- Barrel : 4 layer
- Endcap : 6 Disks x 2



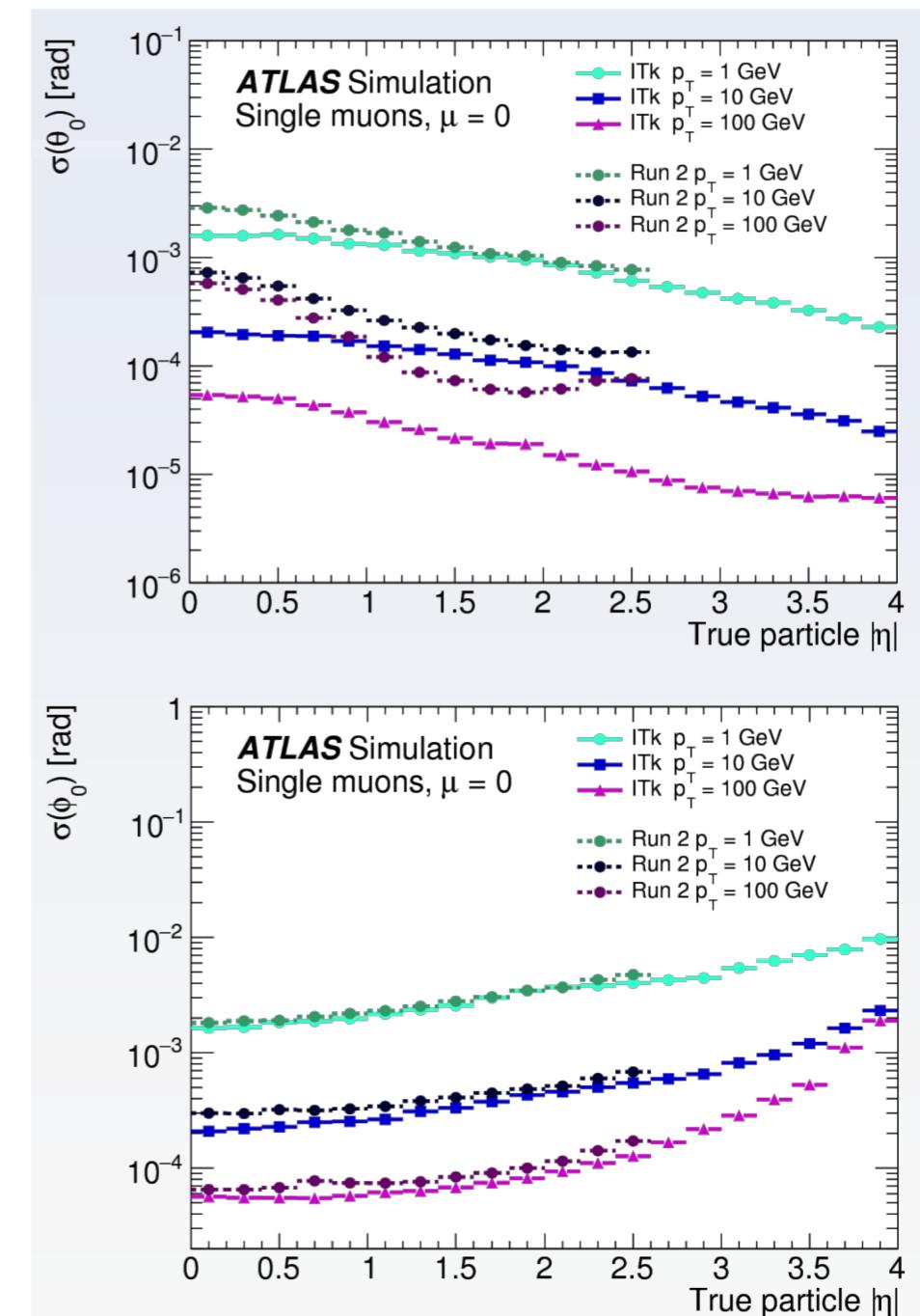
- $R < 1\text{m}$  ; all Silicon sensor
- $|n| < 4.0$  ( NEW :  $2.5 < |n| < 4.0$  )

# Performance : resolution ( $p_T$ , $\theta_0$ , $\phi_0$ )

## momentum resolution



## angular resolution

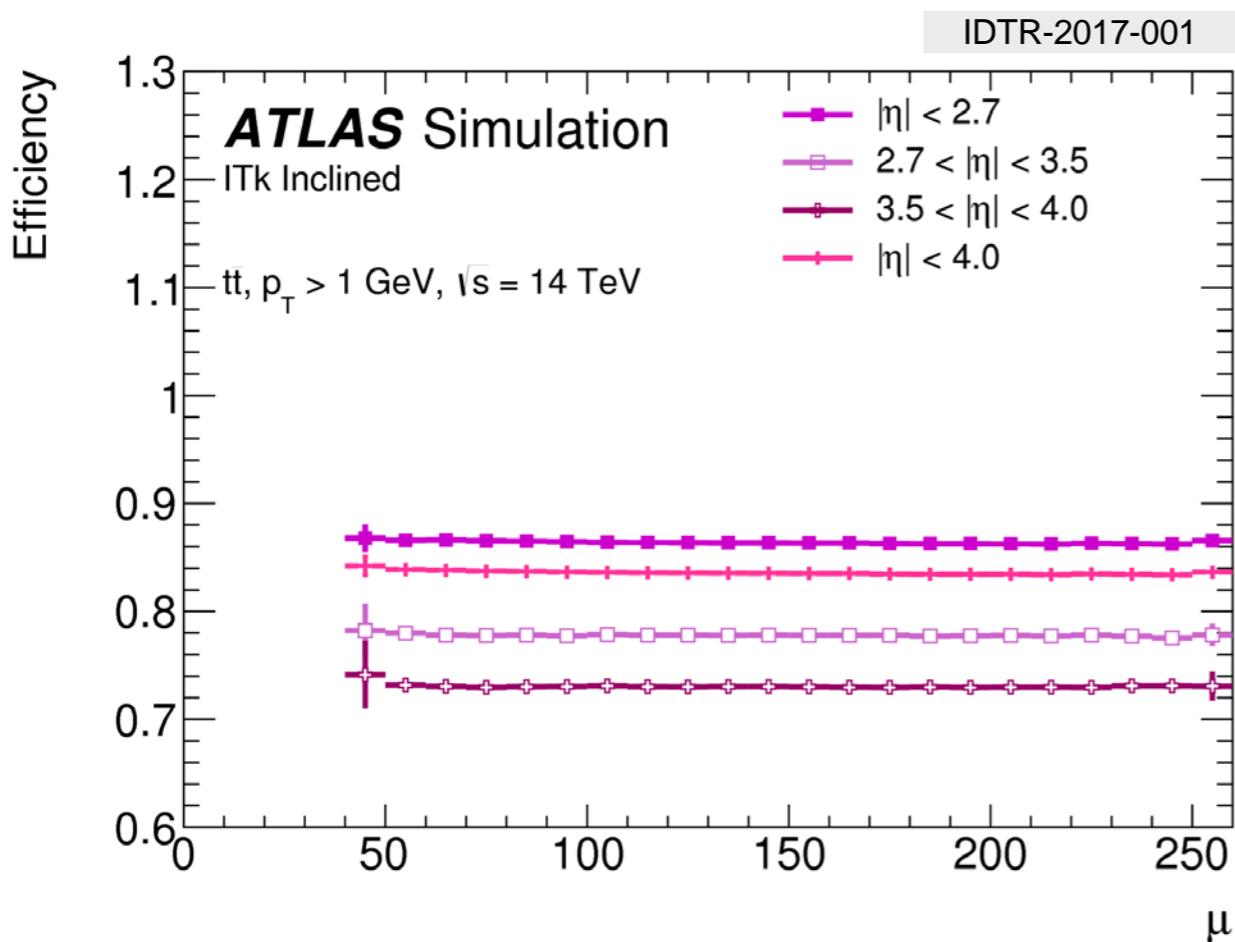


estimation : using single- $\mu$  tracks

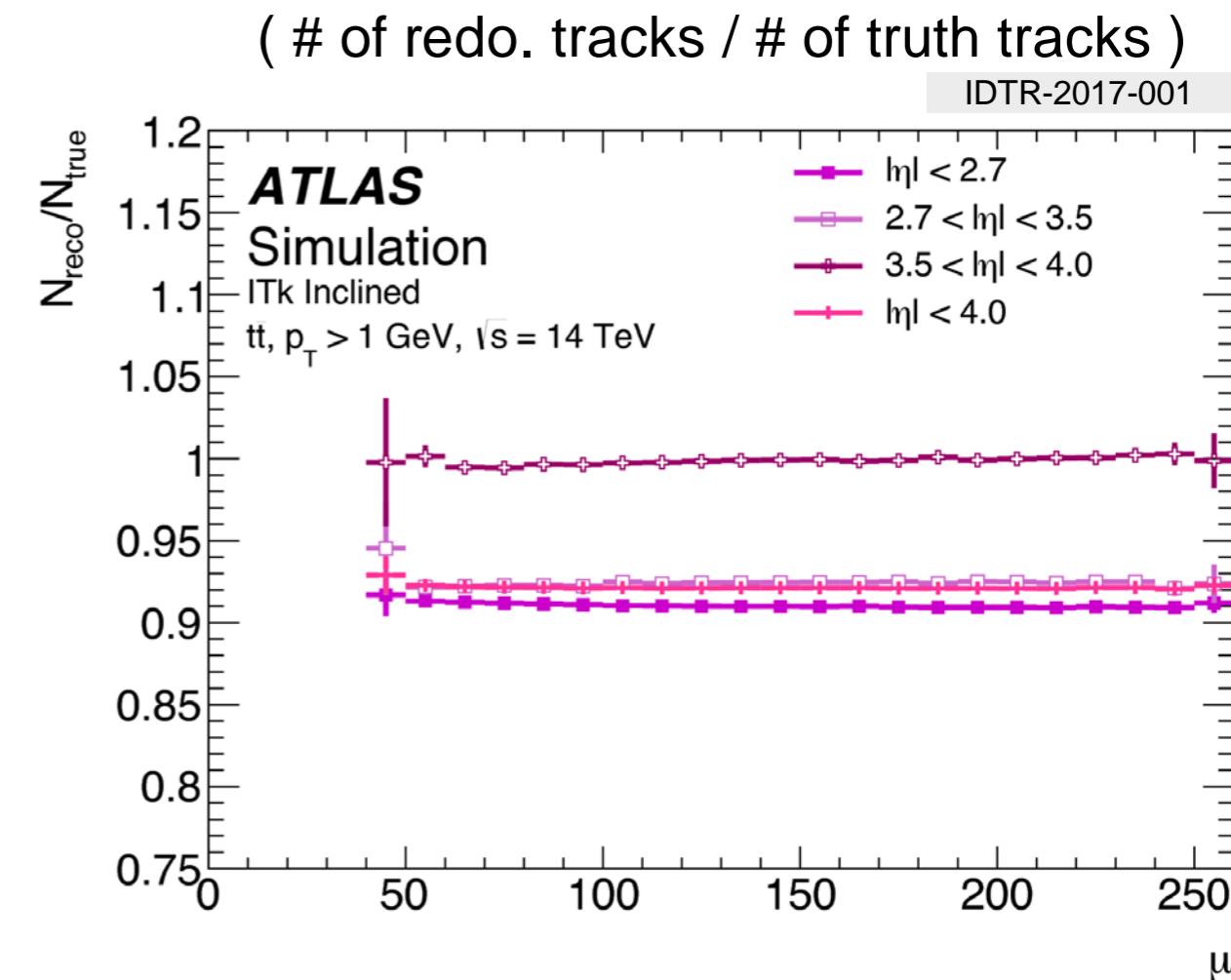
large improvements [  $p_T$  ,  $\theta_0$  ] w.r.t. the current system  
( the coverage up to  $|\eta| < 4.0$  )

# Performance : $\langle \mu \rangle$ dependence

## tracking efficiency



## fake track ratio



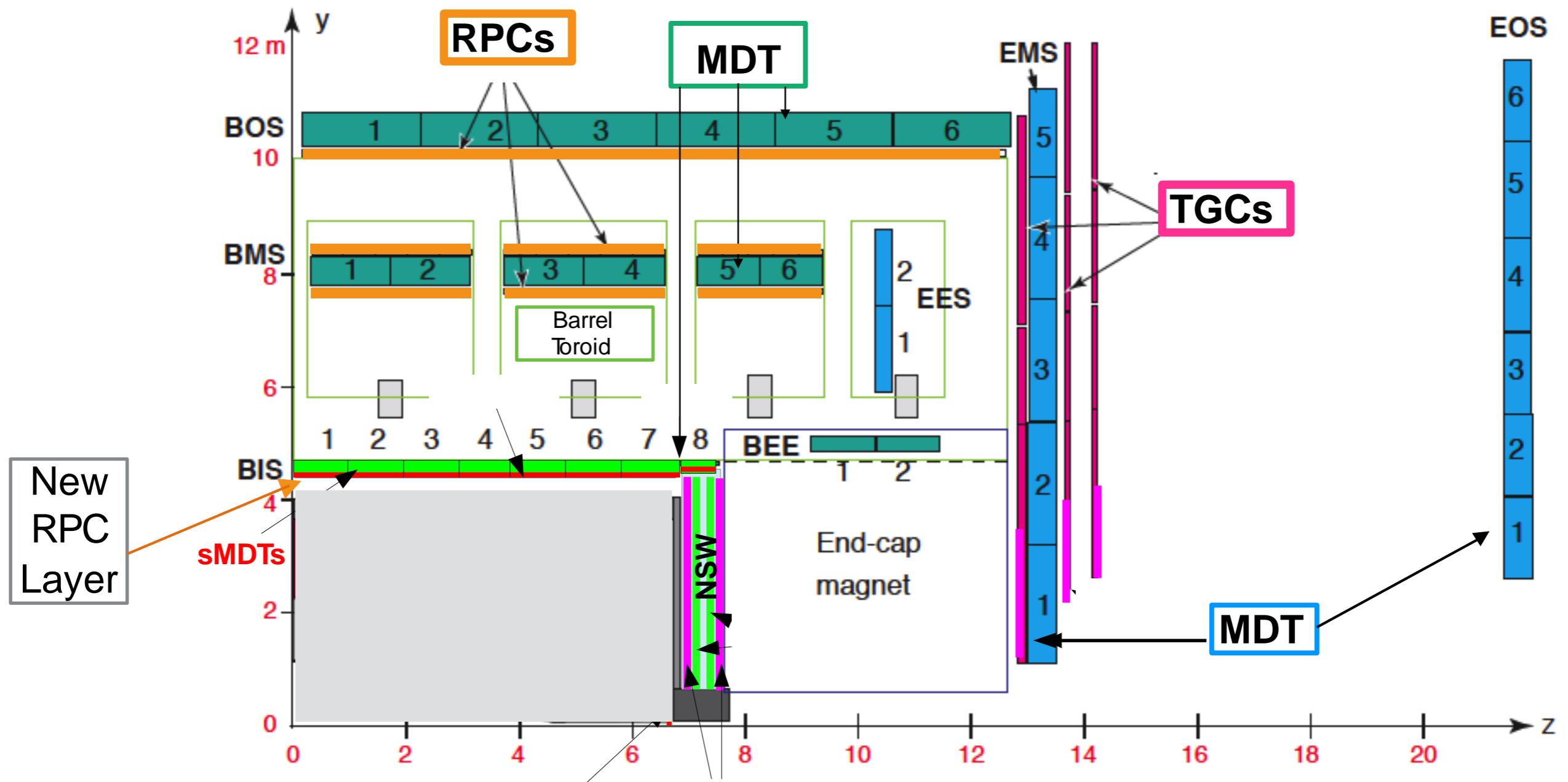
the tracking efficiency is ( almost )

unchanged up to  $\mu=250$  for all the  $|\eta|$  regions

mostly independent to  $\langle \mu \rangle$

no problem with fakes up to  $\mu = 250$

# ATLAS Muon Spectrometer

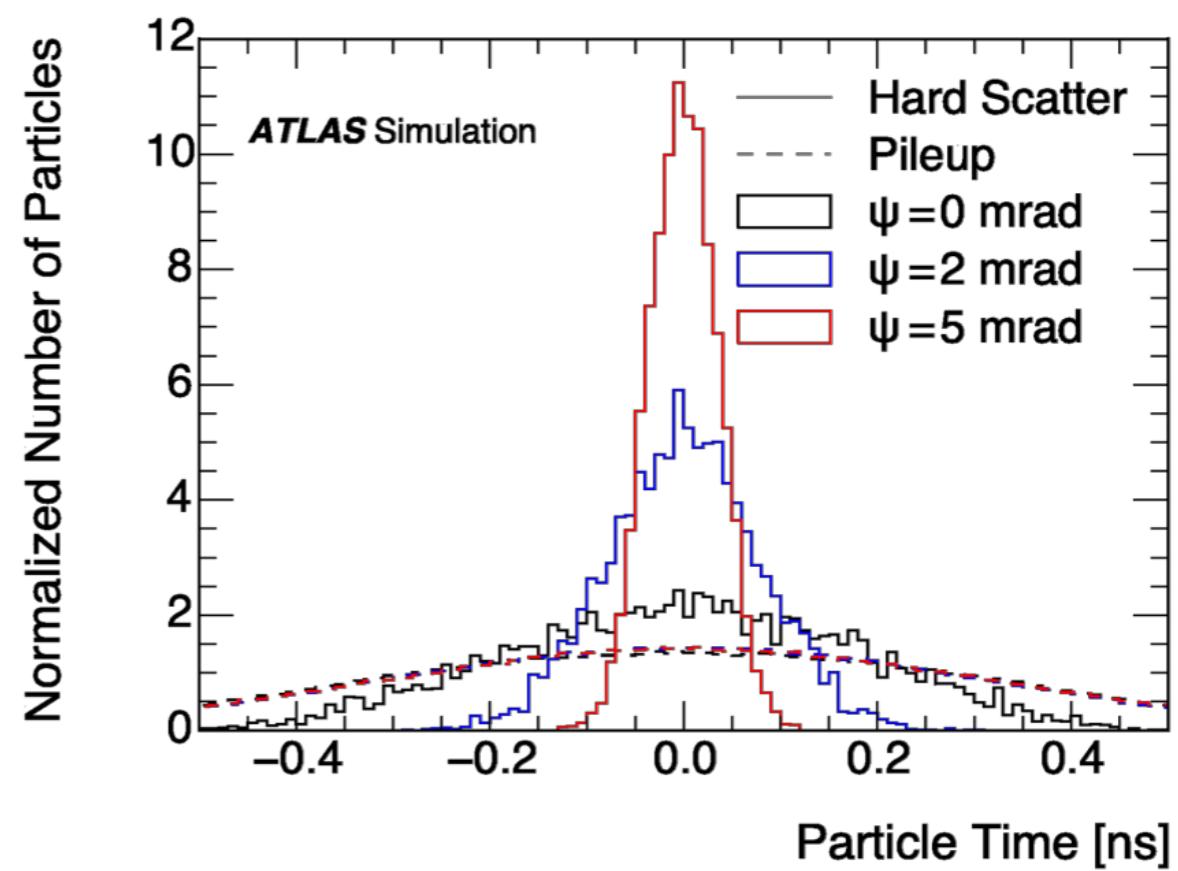
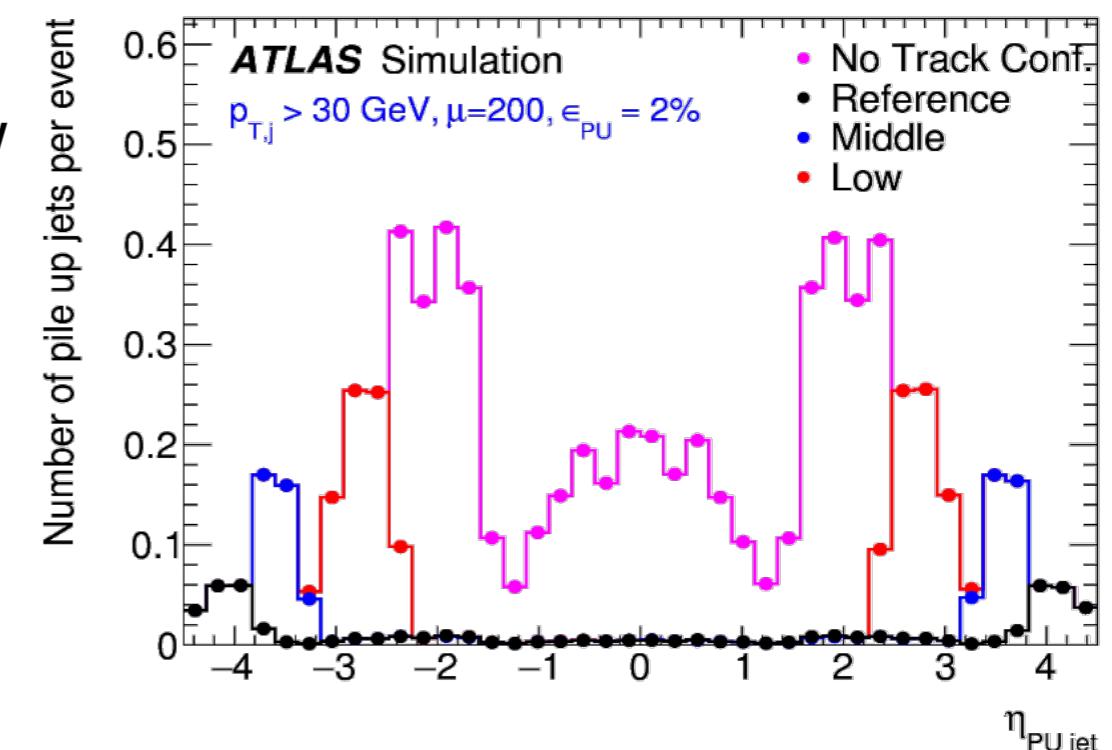
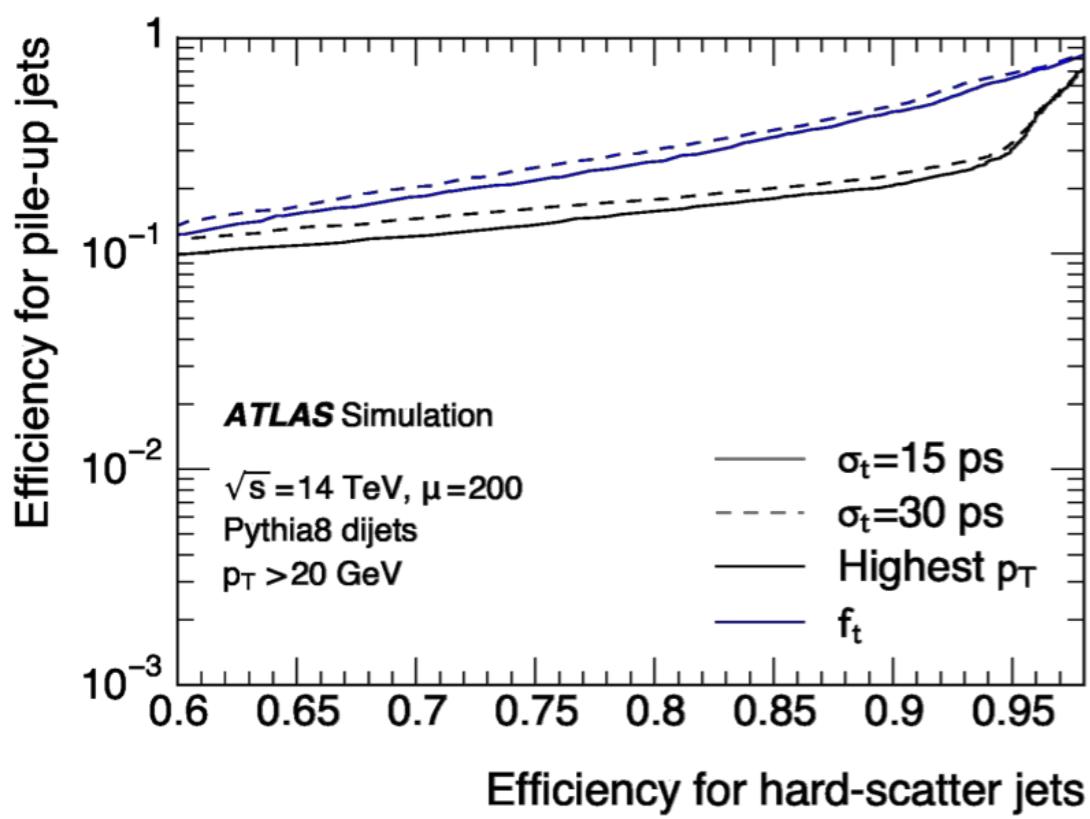


- A complex of Trigger chamber (RPC / TGC + NSW) and Precision tracker (MDT, NSW)
- To cope with longer latency & higher trigger rate, **all** the electronics to be replaced
- MDT (max. Drift-Time  $\sim 700\text{ns}$ ) to be a part of **Hardware  $\mu$ -Trigger**
- **ALL the hits** of TGC/RPC/MDT sent to off-detector  $\rightarrow$  process Trigger

# HGTD Motivation

## Time - Pileup Rejection

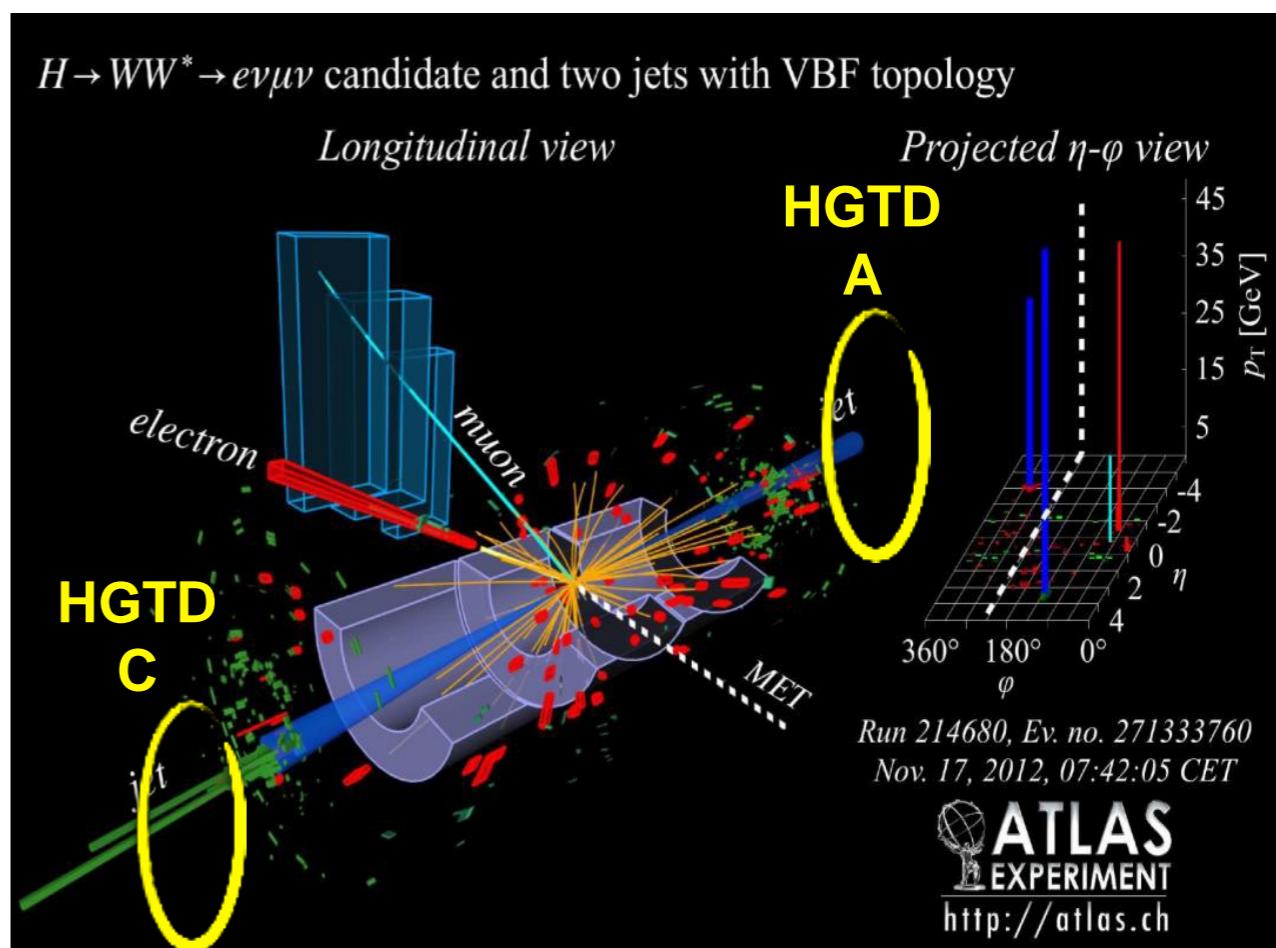
- ✓ High probability of vertices in close proximity
- ✓ Time information helps pileup rejection
- ✓ Pileup distribution extremely peaked at forward  $1.8 < |\eta| < 3.2$  were tracker not completely implemented
- ✓ Track confirmation rejection at 2% for central region but degrades towards end caps



# HGTD Motivation

## Important EW channels

- ✓ Potential of HGTD as a L (40MHz)  
Time trigger for the VBF 0channel
- ✓ Lower jet  $P_T$  thresholds and  
extend accessible phase space
- ✓ Largest potential in hadronic final  
state VBF channels (also offline),  
preferentially forward peaked:  
 $H \rightarrow bb$ ,  $H \rightarrow Inv.$ ,  $HH \rightarrow bbbb$
- Pre-shower option :

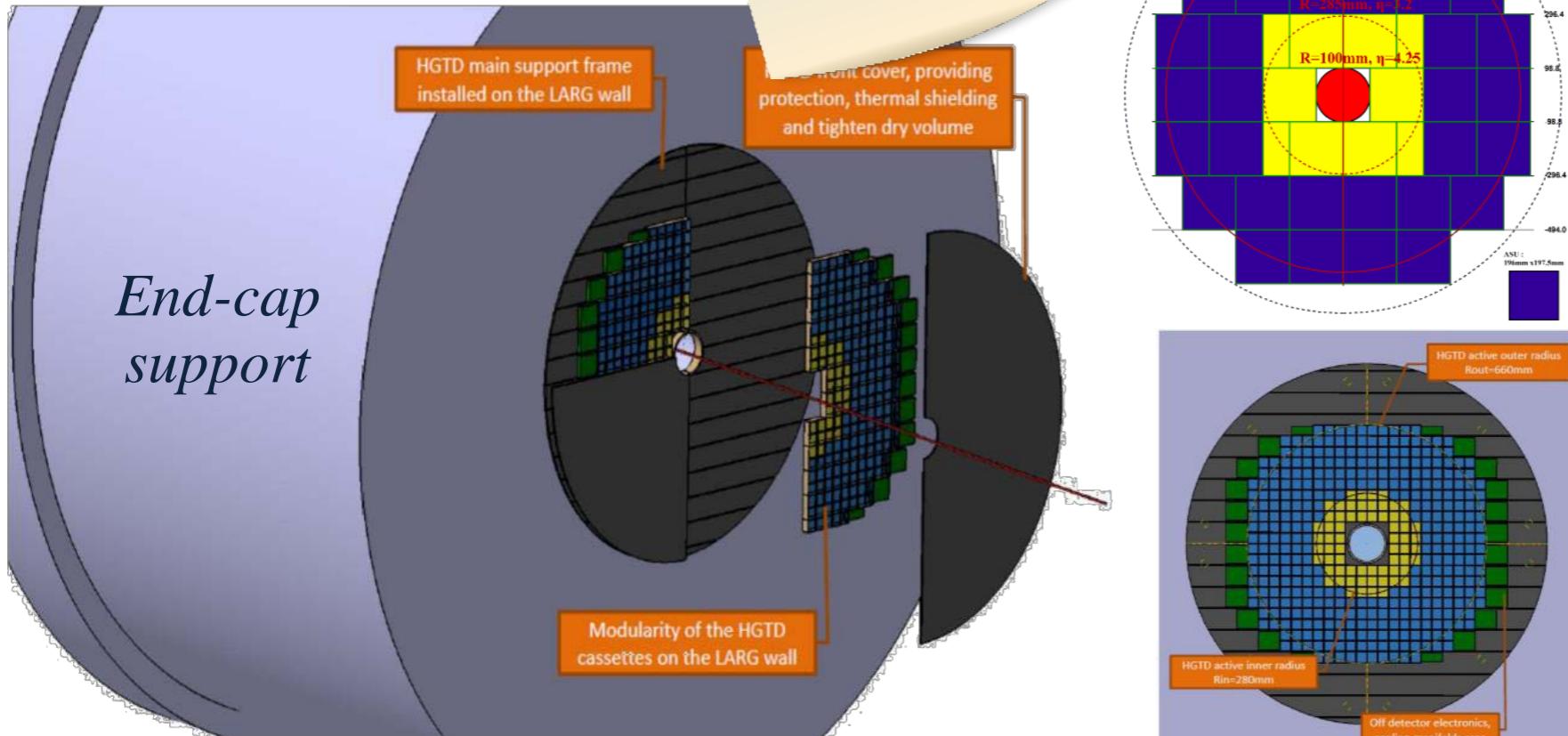


- Improve forward electron/photon reconstruction
- Interesting for search in  
 $H \rightarrow aa \rightarrow \gamma\gamma jj$

<u>Trigger</u>	<u>SD value</u>	<u>physics</u>
di- $\gamma$	25-25 GeV	di-photon
di- $\tau$	40-30 GeV	$H \rightarrow \tau\tau$
4-jet	75 GeV	$H \rightarrow bb$ , $HH \rightarrow 4b$
$E_T^{\text{miss}}$	200 GeV	$H \rightarrow Inv.$

# HGTD System

## Geometry



### Specifications for 2023

**Coverage**  $2.4 < \eta < 4.2$

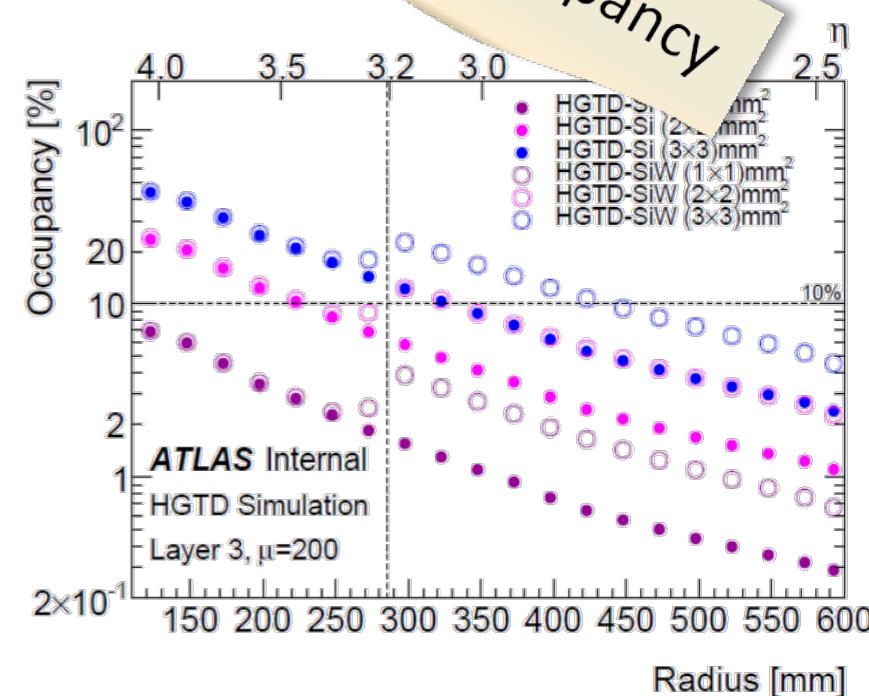
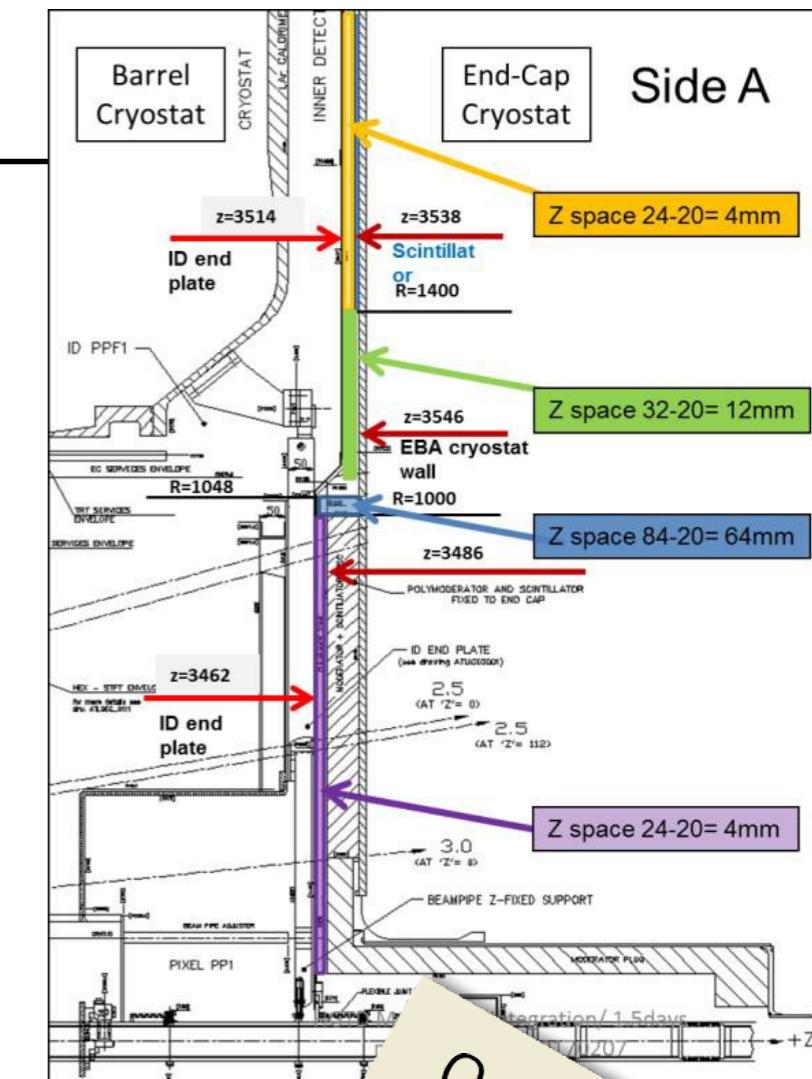
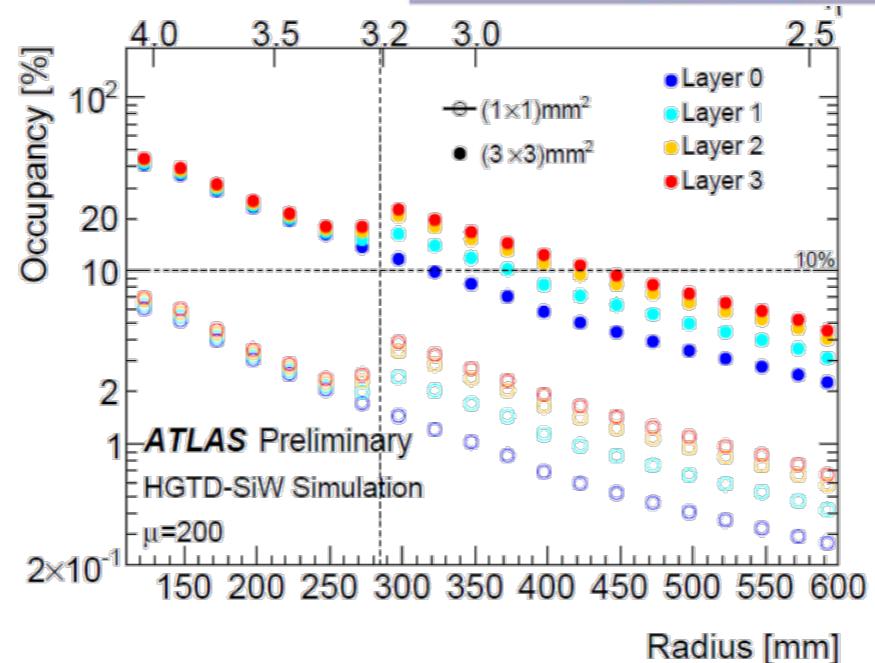
$R_{\min}$  11 cm

$R_{\max}$  65 cm

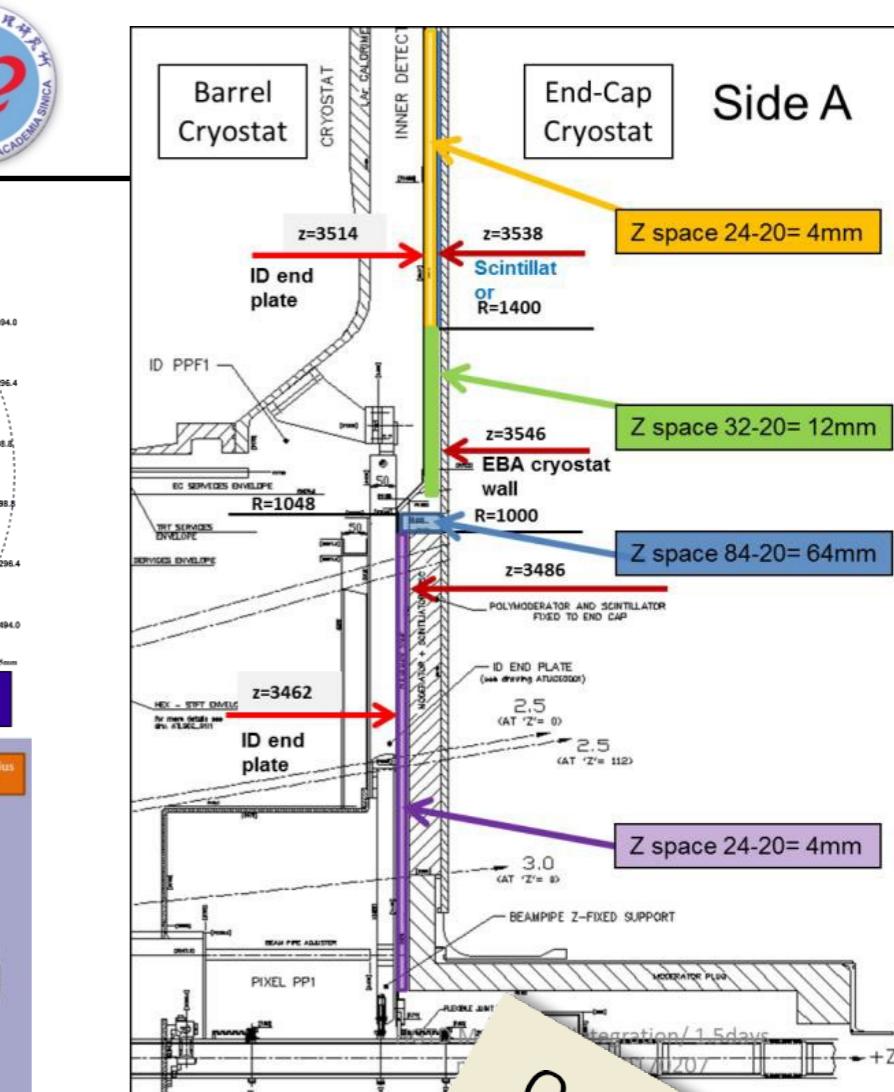
$\Delta z$  ~ 6 cm

$\Delta t$  < 50 ps

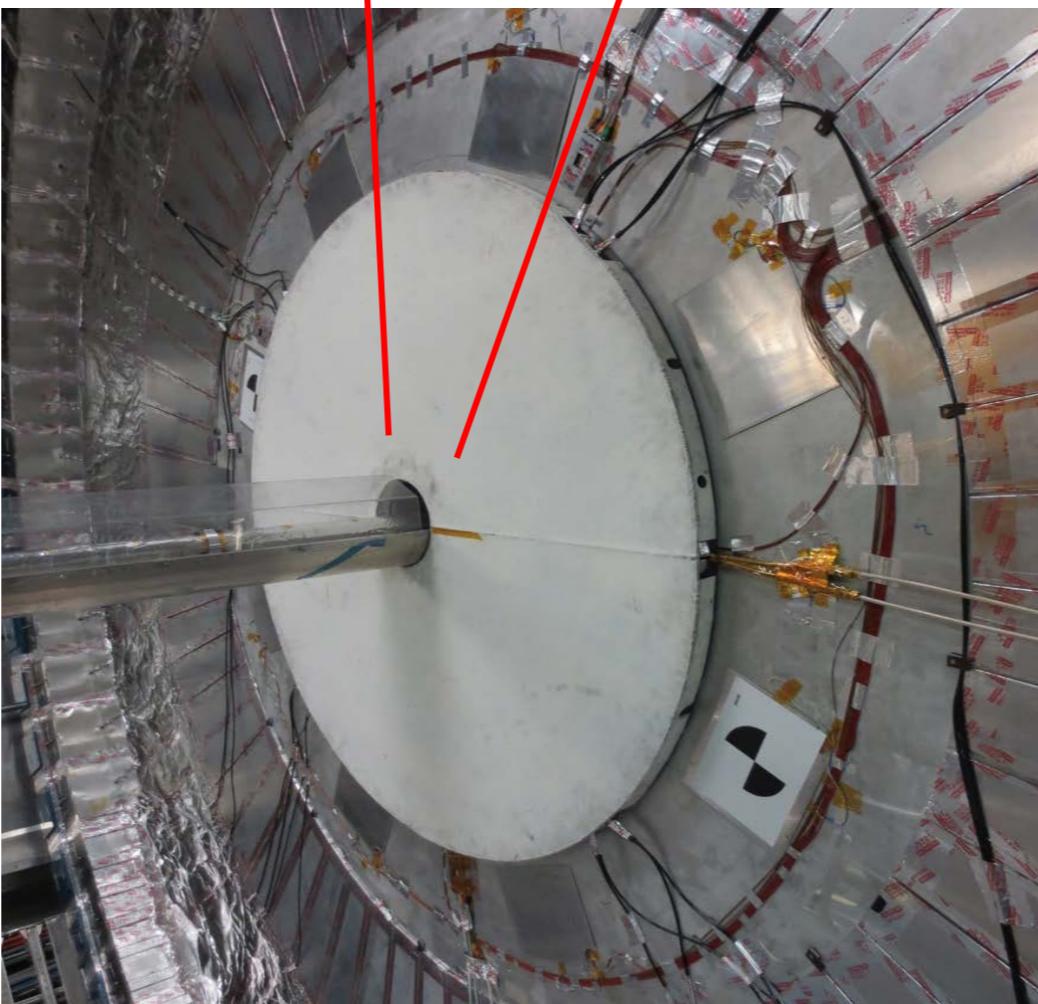
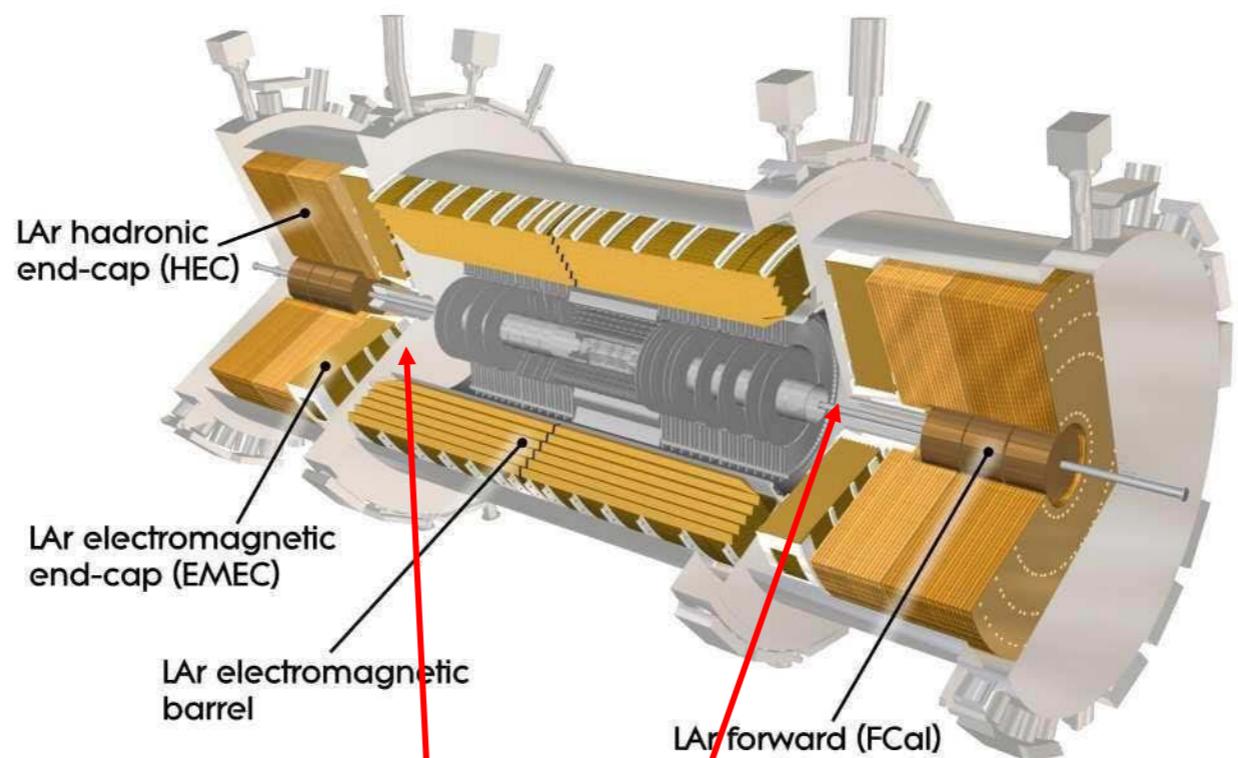
**Cell Size** 1 mm<sup>2</sup>



*Occupancy*



# HGTD location

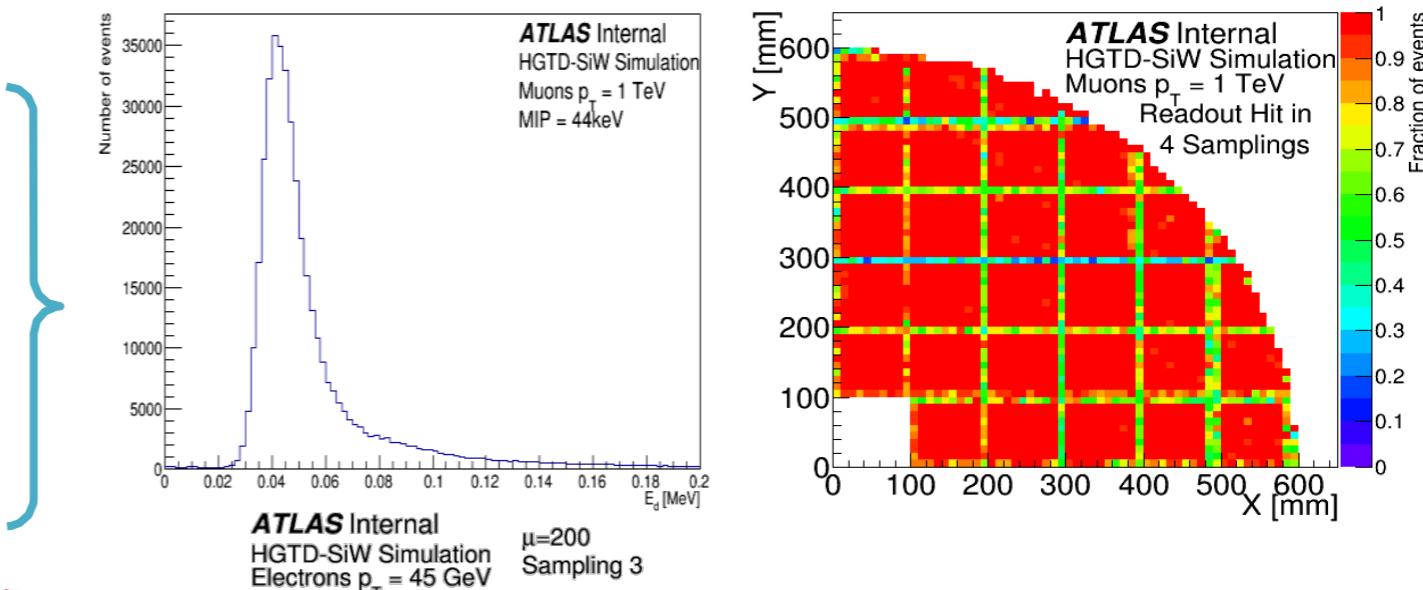


# HGTD System

## Performance

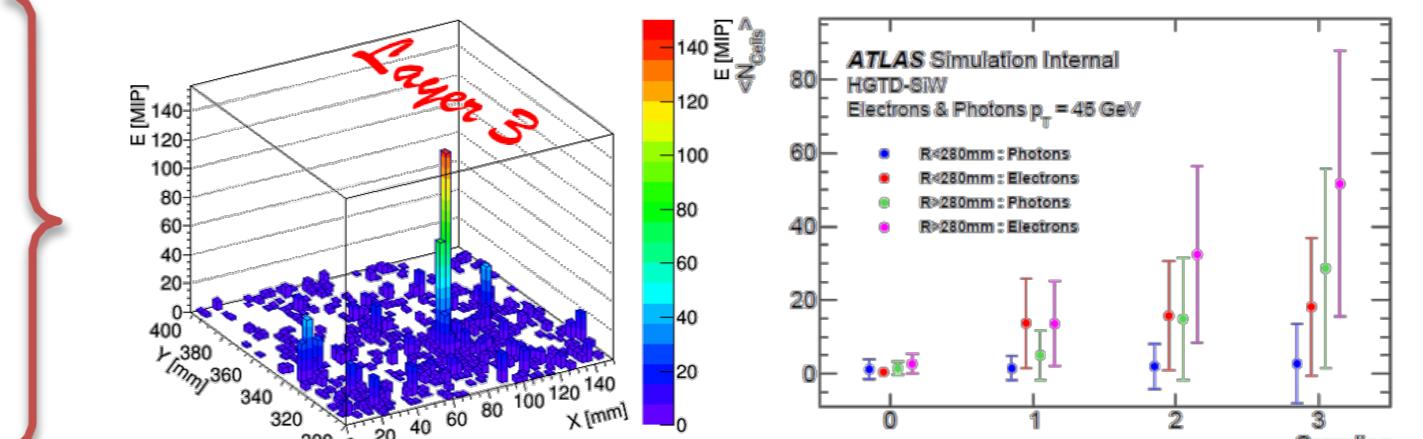
### Muons

- ✓ 1 TeV muons simulation
- ✓ 98.88% efficiency for 4 layers
- ✓ 0.044 MeV/muon at 150  $\mu\text{m}$
- ✓ 50% of inefficiency from zones



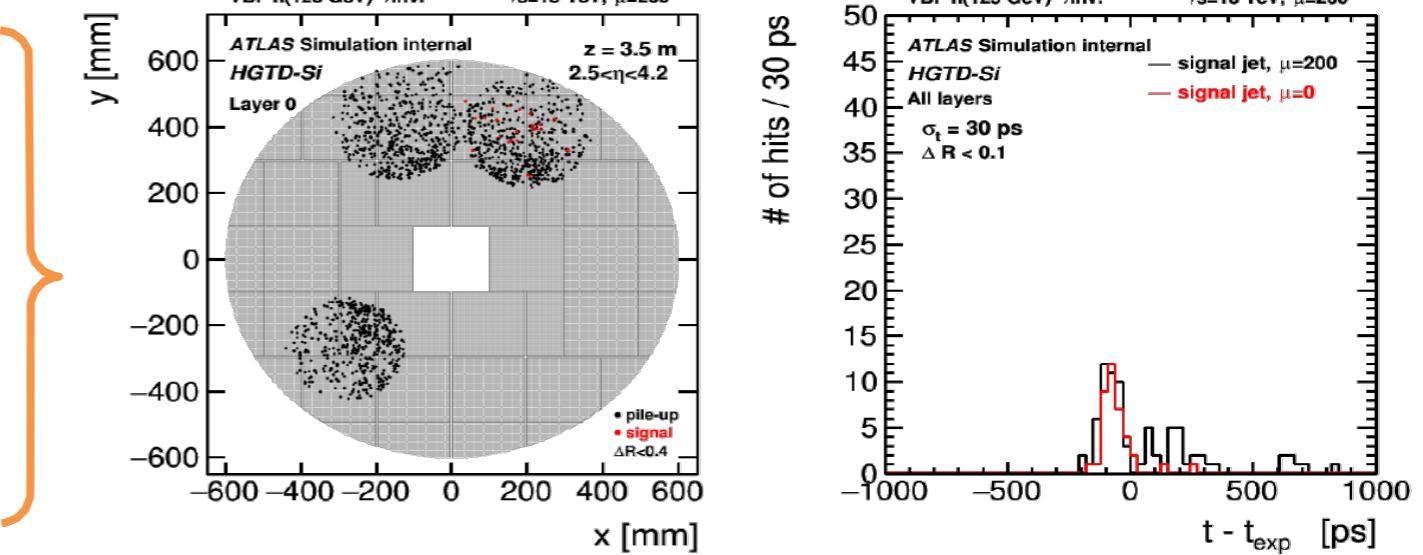
### Electrons

- ✓  $Z \rightarrow ee$  sample at  $\mu = 200$
- ✓ 45 GeV  $P_T$  e and  $\gamma$
- ✓ 6mm radius EM clusters
- ✓ 70 HGTD cells per cluster
- ✓ Dynamic range of 50 psec/MIP



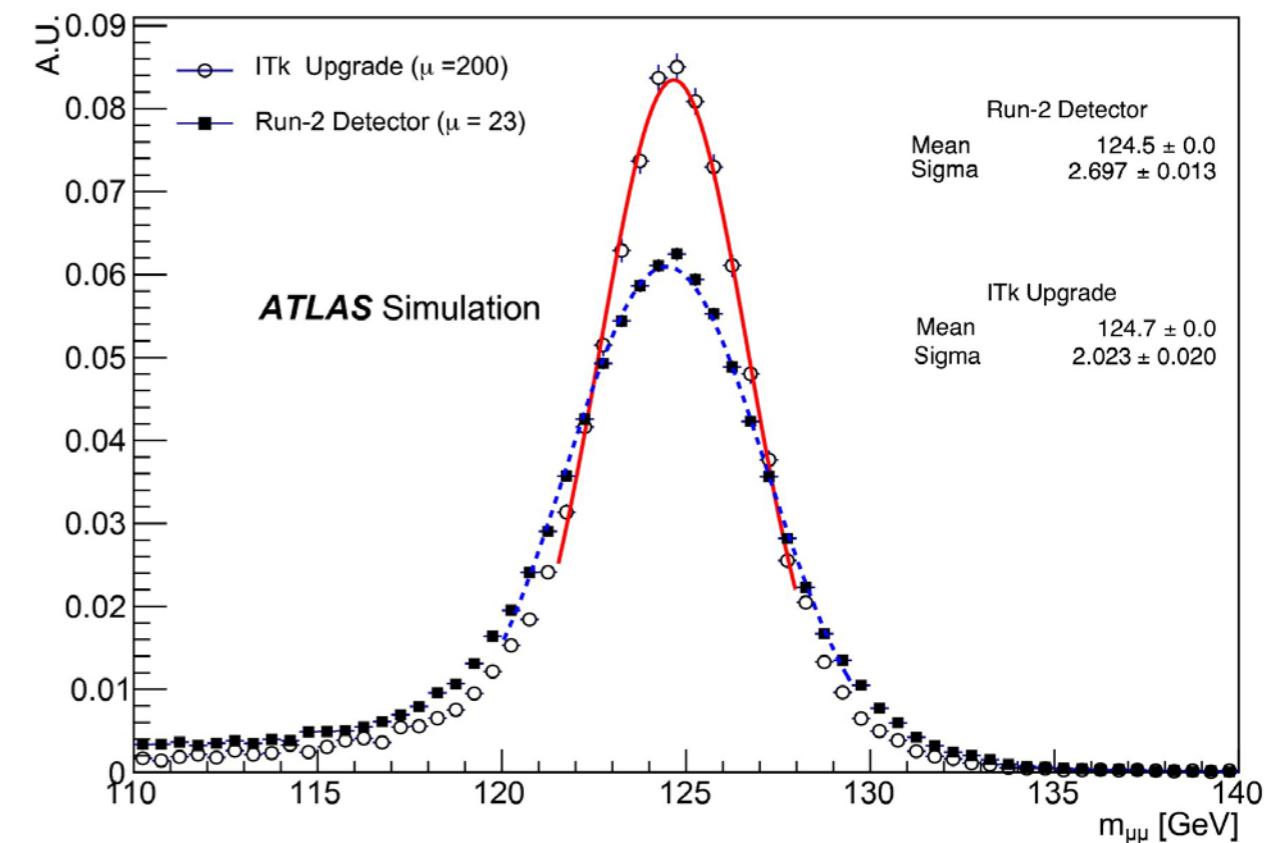
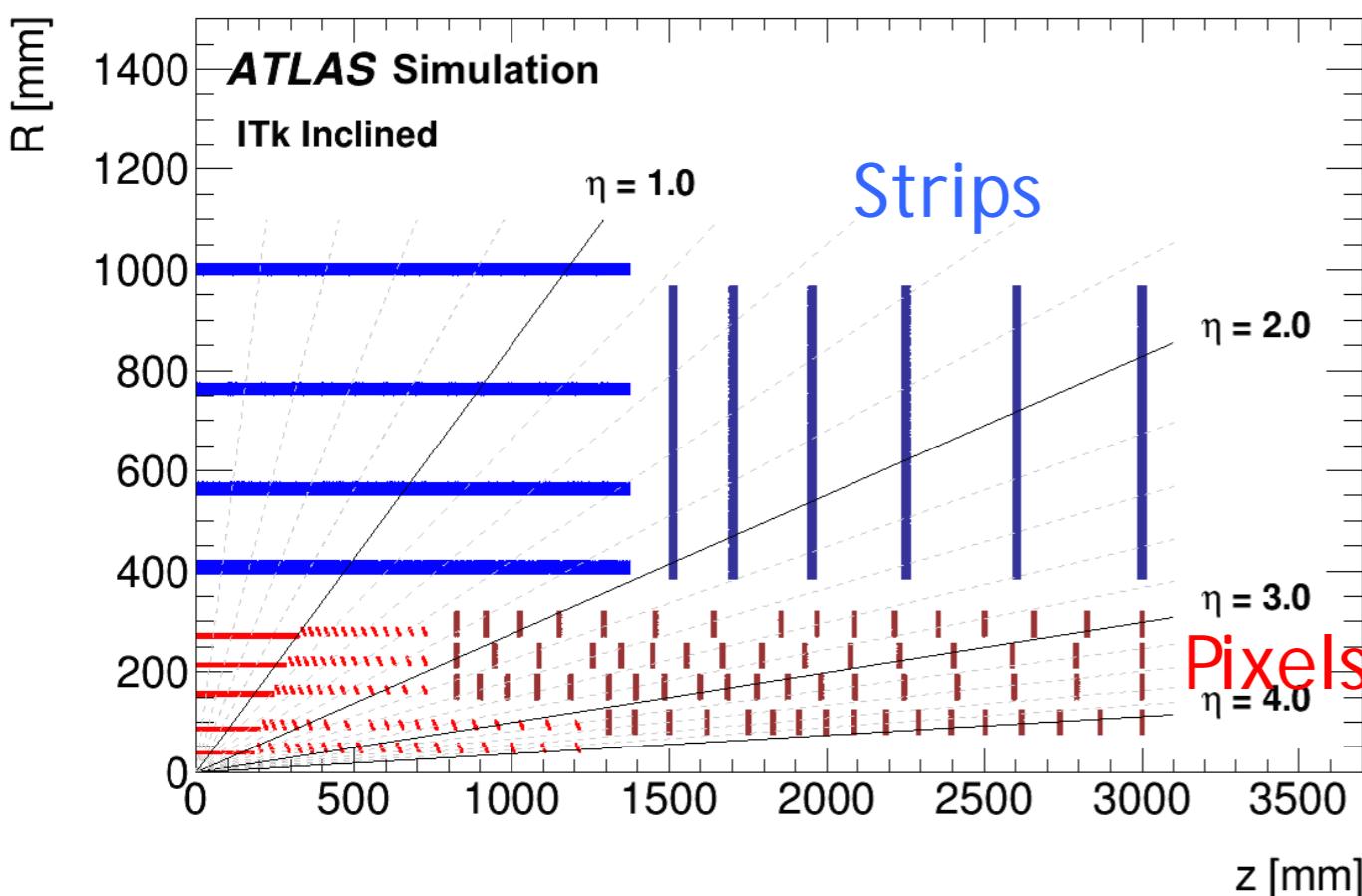
### Jets

- ✓  $H(125 \text{ GeV}) \rightarrow \text{Inv.}$  sample with jet  $P_T = 72 \text{ GeV}$
- ✓ Expected peak in time distribution
- ✓ ~90% signal purity at  $\Delta R < 0.1$



# HL-LHC studies in progress

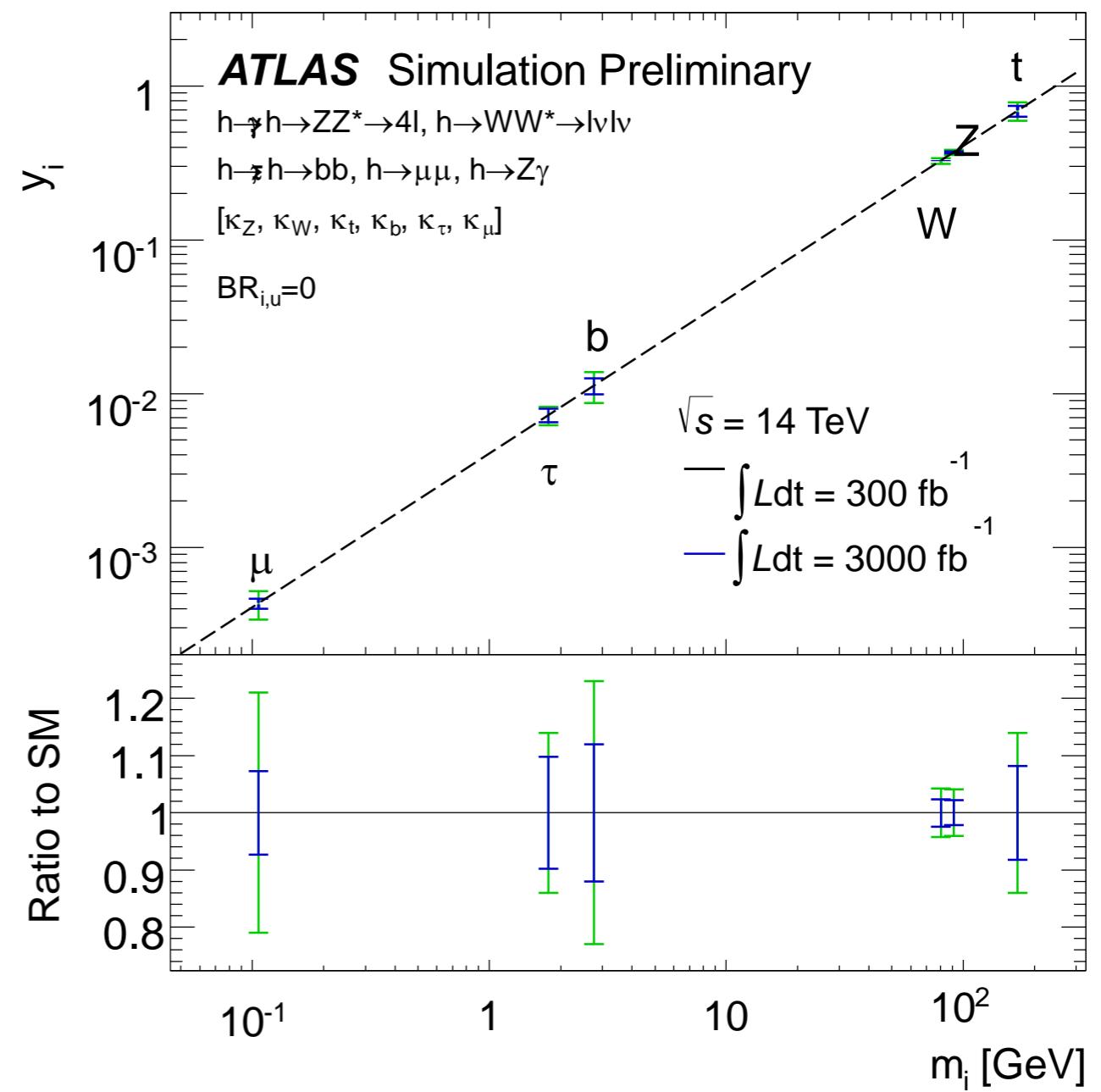
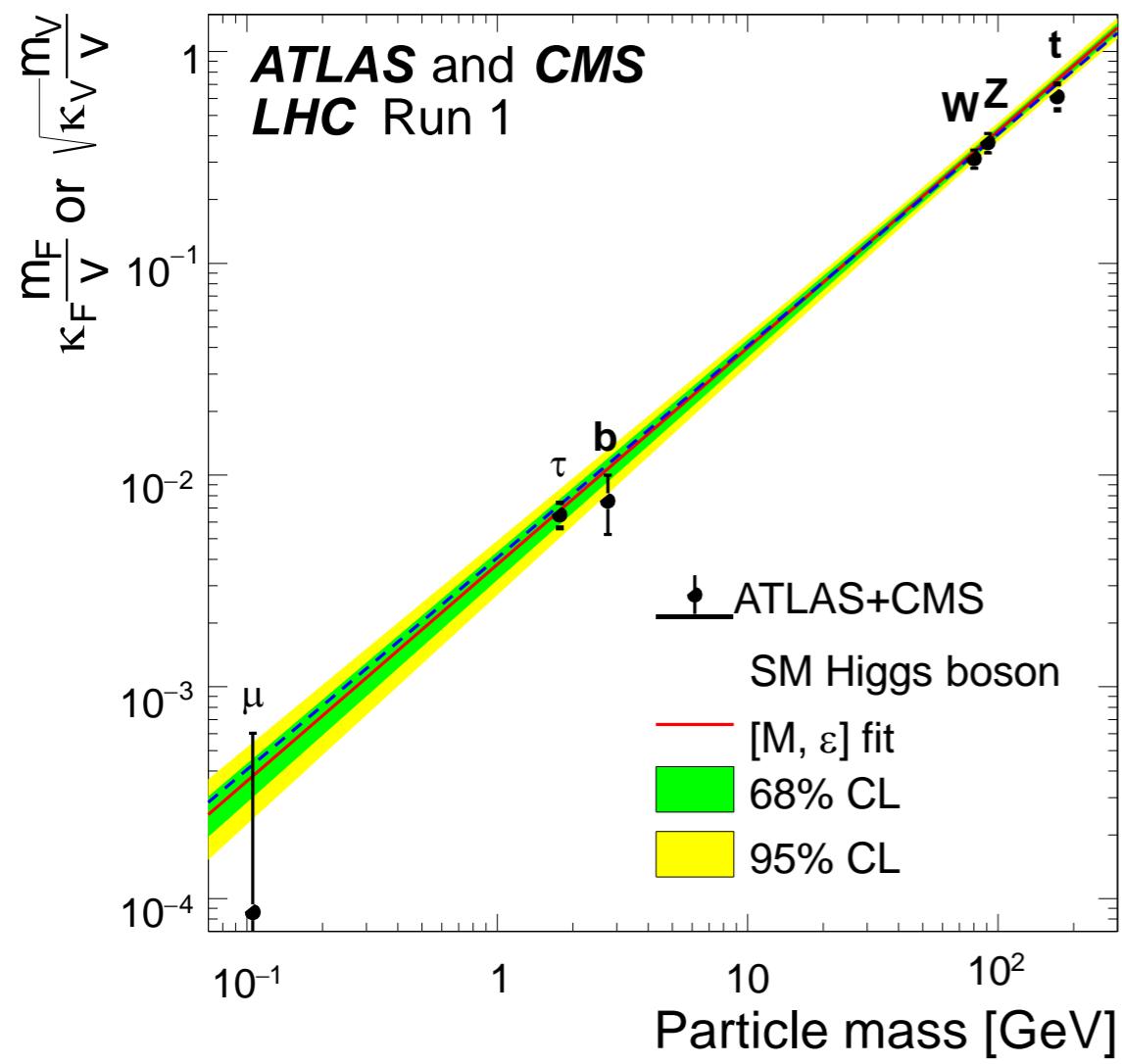
- Present efforts are focussing on TDRs for each Phase 2 upgrade
  - Demonstrate that the detector and trigger choices meet the required performance
  - ITk layout from the Strip TDR and improvement in  $H\bar{a} \mu\mu$  mass



- More comprehensive physics prospects planned for Update of European Strategy for Particle Physics
- HGTD TDR planned for end of 2018

# Higgs boson

- Example coupling plots from Run 1 and for HL-LHC
  - Typical precision improves from 10% to 4%. H $\rightarrow \mu\mu > 7\sigma$



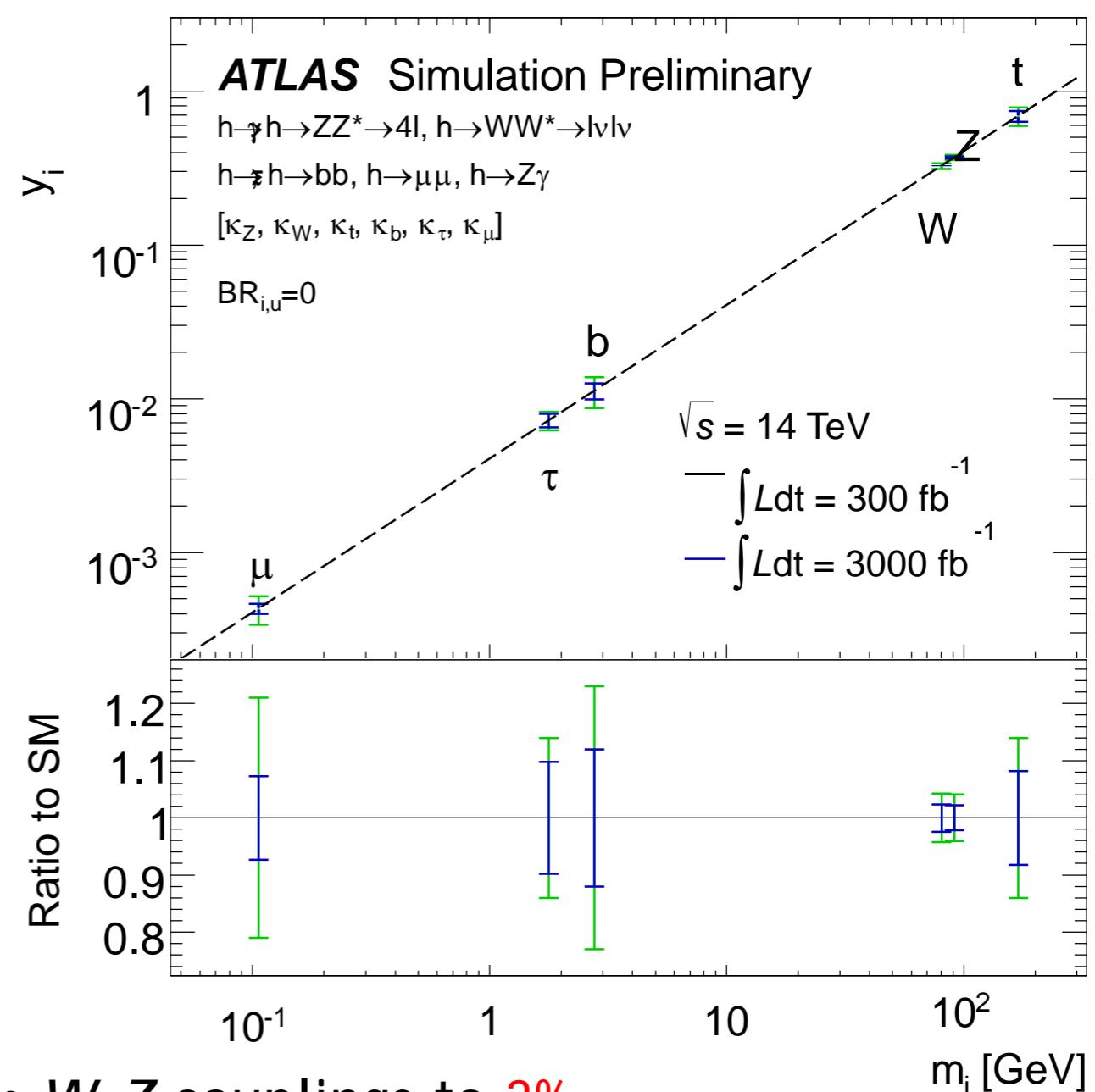
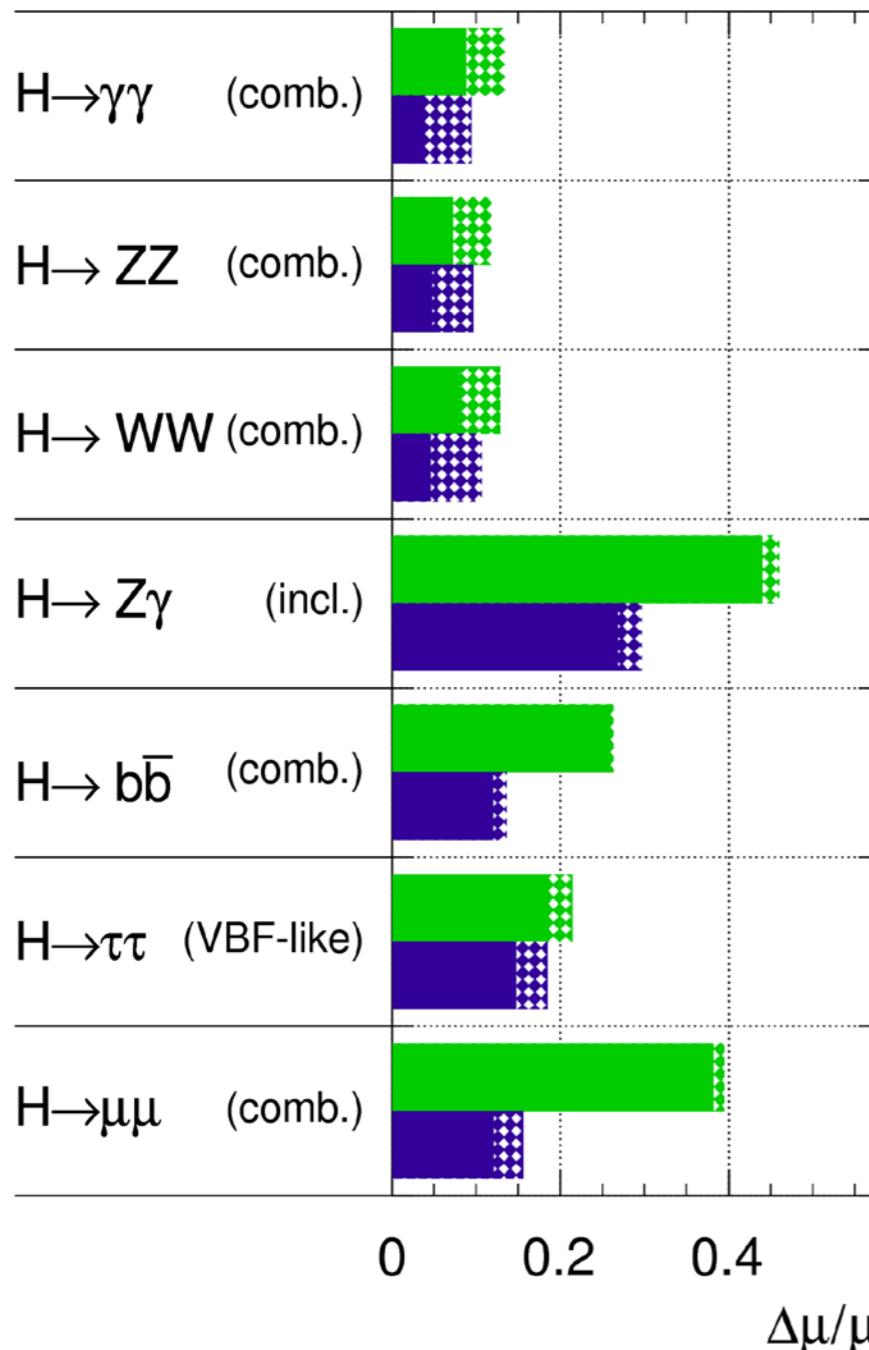
# Higgs boson



- Example coupling plots from Run 1 and for HL-LHC
  - Typical precision improves from 10% to 4%. H  $\rightarrow \mu\mu > 7\sigma$

**ATLAS** Simulation Preliminary

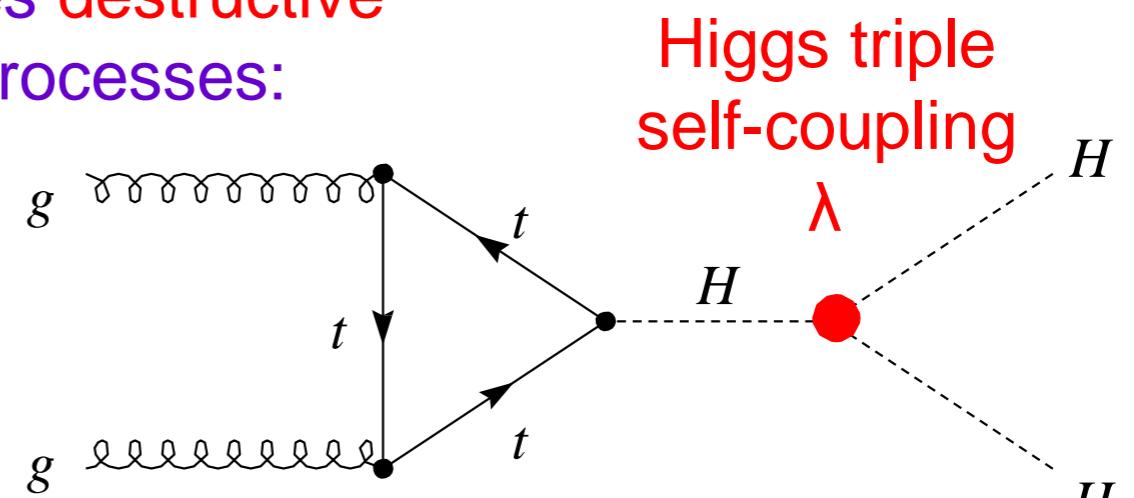
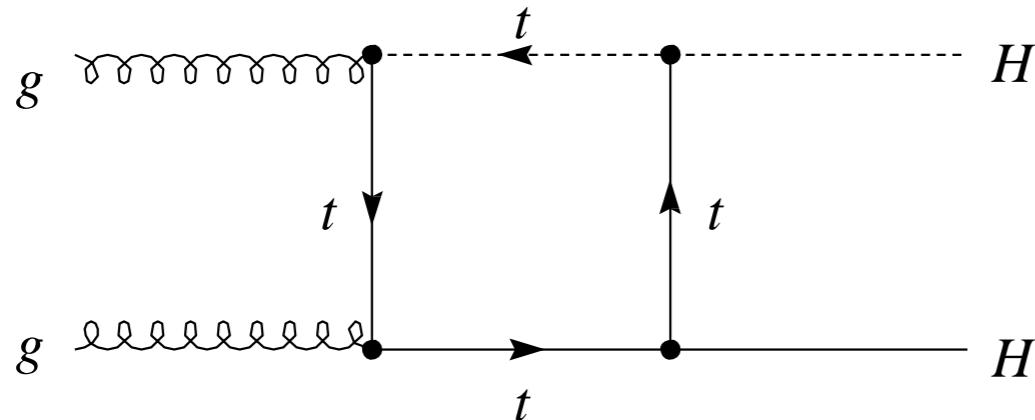
$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$



- $W, Z$  couplings to 3%
- Muon coupling to 7%,  $t, b, \tau$  couplings to 8-12%

# Higgs boson pair production

- Higgs boson pair production includes **destructive interference** between two types of processes:



- ~factor 2 increase in cross section if  $\lambda \rightarrow 0$
- Will have to combine several decay modes and both experiments to have evidence
- More generally – explore electroweak symmetry breaking in Vector Boson Scattering

NNLO  $\sigma^{\text{SM}}=40.8 \text{ fb}$

Channel	Events in 3/ab	Significance for $HH$ ( $\lambda=1$ )
bbbb	40000	0.6 $\sigma$
bbWW	30000	(ttbar backgr)
bb $\tau\tau$	9000	0.6 $\sigma$
WWWW	6000	
$\gamma\gamma bb$	320	1.05 $\sigma$
YYYY	1	

# Higgs rare decays

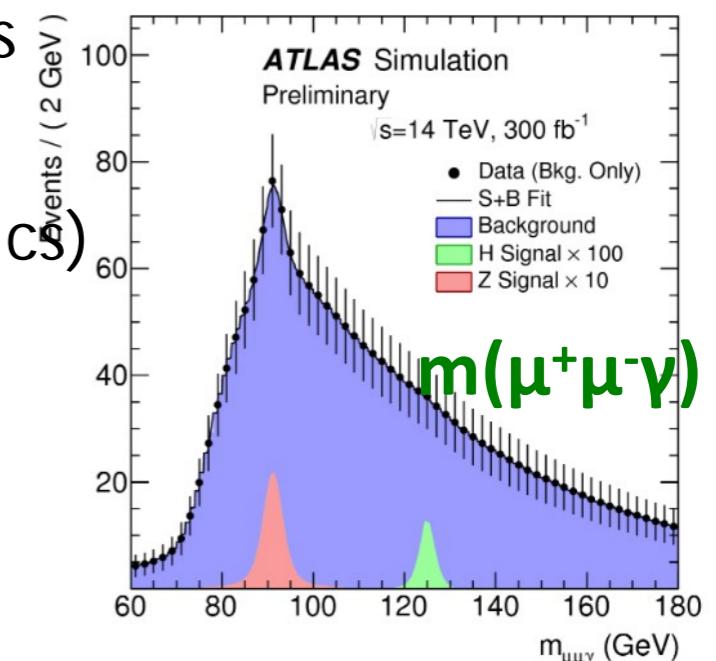
- $H \rightarrow J/\Psi (\rightarrow \mu^+ \mu^-) \gamma$  (with  $\langle \mu_{PU} \rangle = 140$ ,  $L = 3000 \text{ fb}^{-1}$ )

(ATL-PHYS-PUB-2015-043)

- Higgs coupling to c-quark. Run-1 detector performances
- MVA analysis  $m_{\mu^+ \mu^- \gamma}$  in [115, 135] GeV
- 3 signal events and 1700 background (with no systematic ; cs)

**BR ( $H \rightarrow J/\Psi (\rightarrow \mu\mu)\gamma$ ):  $44^{+19}_{-22} \times 10^{-6}$  (95% C.L.)**

**SM:  $2.9 \pm 0.2 \times 10^{-6}$  (Run-1 Limit:  $1.5 \times 10^{-3}$ )**

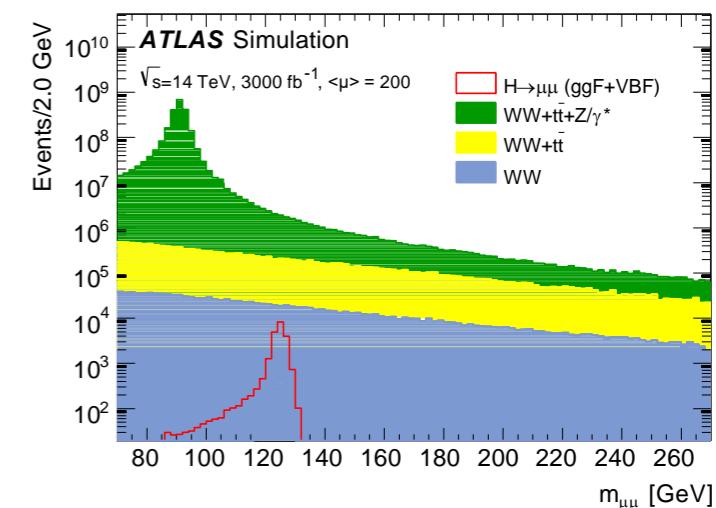


- $H \rightarrow \mu^+ \mu^-$  (with  $\langle \mu_{PU} \rangle = 200$ ,  $L = 300/3000 \text{ fb}^{-1}$ )
- Low BR, high  $Z/\gamma^*$  background, high mass resolution
- Based on Run-1 analysis,  $m_{\mu^+ \mu^-}$  in [110, 160] GeV]
- Total background shape and normalization on data-driven
- ITK-Upgrade -> improve **mass resolution by 25%** (w.r.t Run-2)

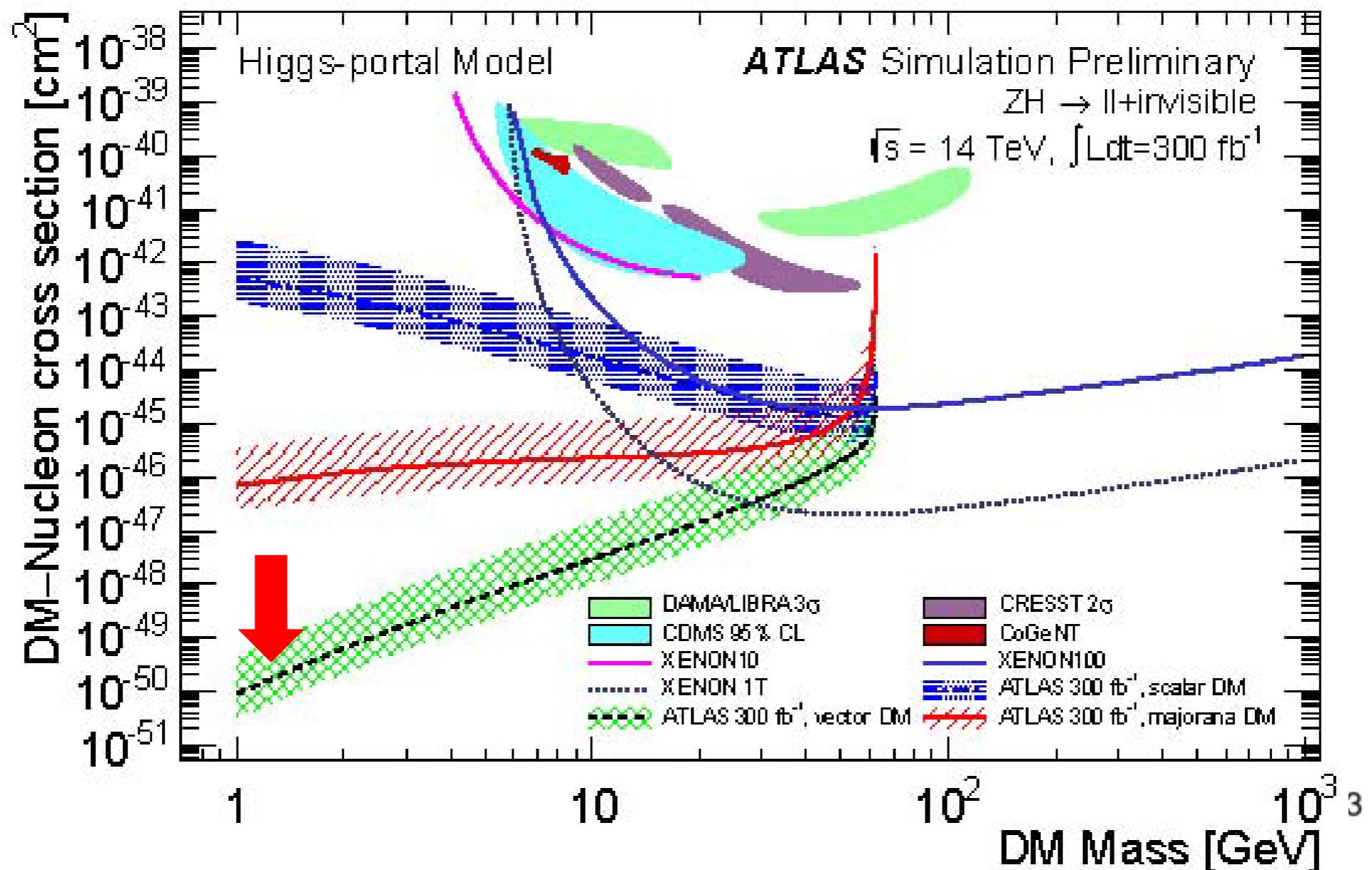
**$Z_0$ :  $2.3\sigma$  (300  $\text{fb}^{-1}$ )     $7.0\sigma$  (3000  $\text{fb}^{-1}$ )**

**$\Delta\mu/\mu$ :     $46\%$  (300  $\text{fb}^{-1}$ )     $21\%$  (3000  $\text{fb}^{-1}$ )**

(ATL-TDR-025 LHCC-017-055)



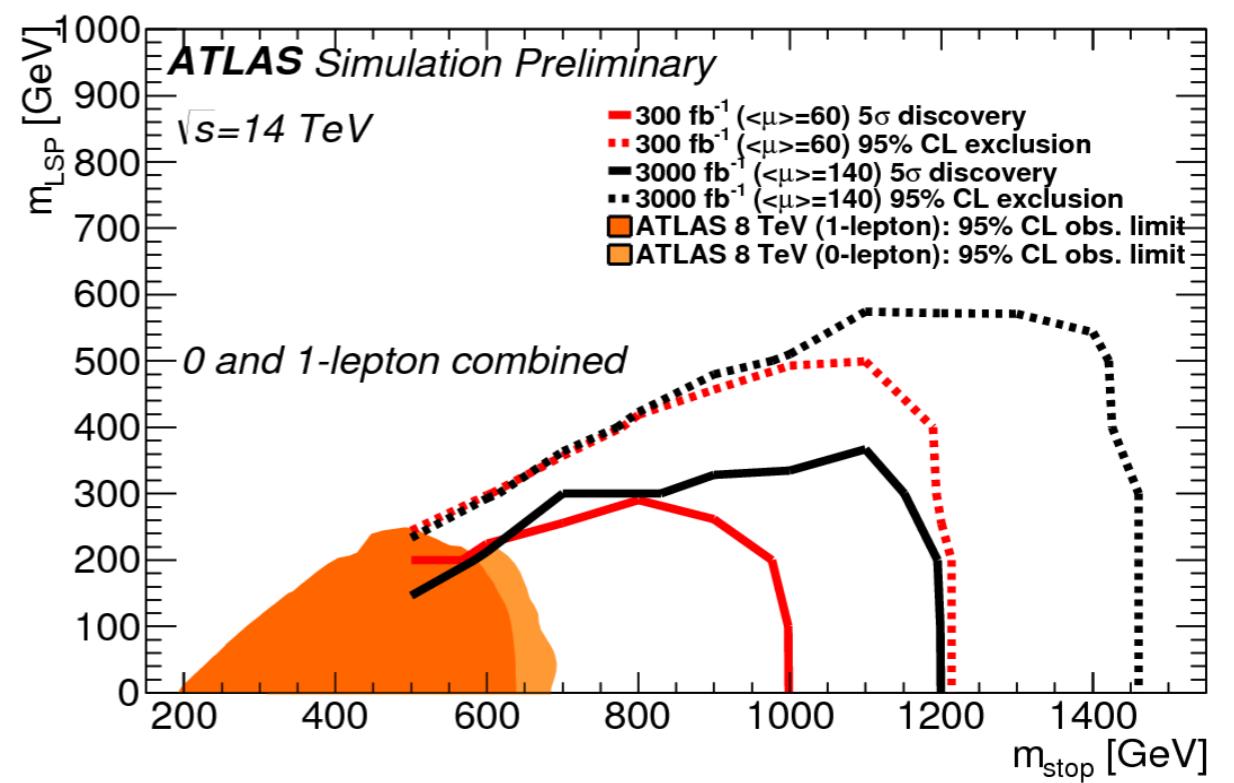
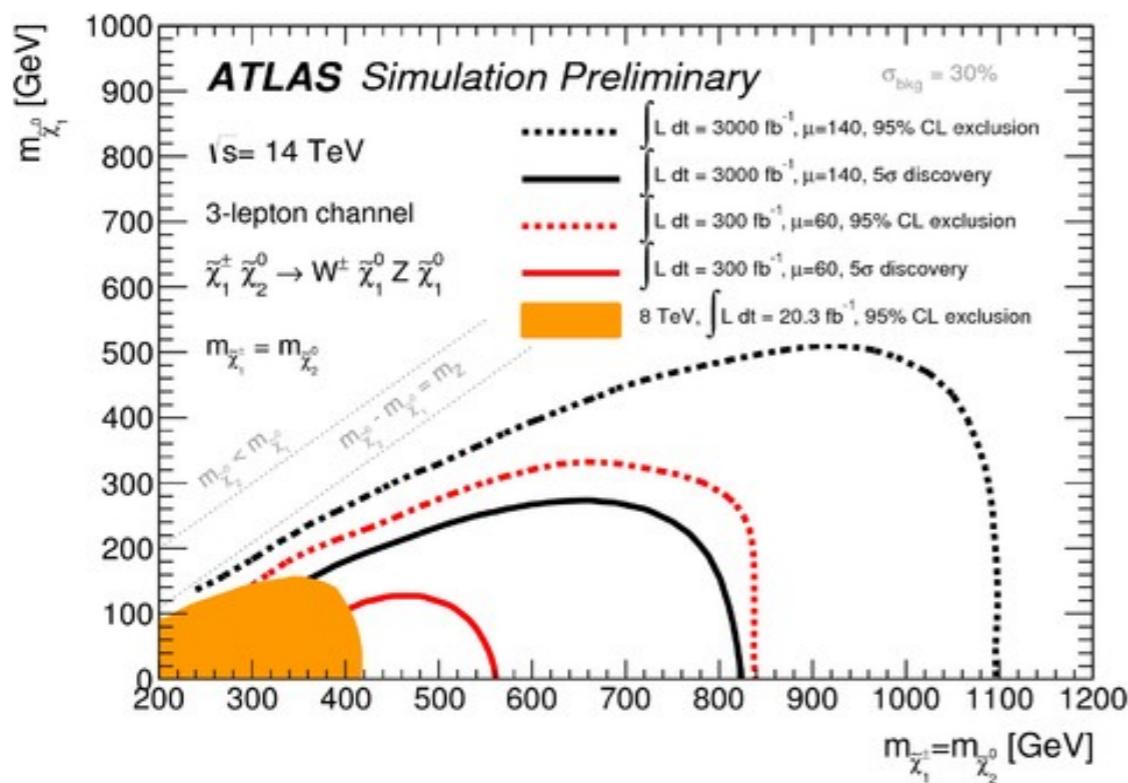
# Invisible Higgs Decay and DM



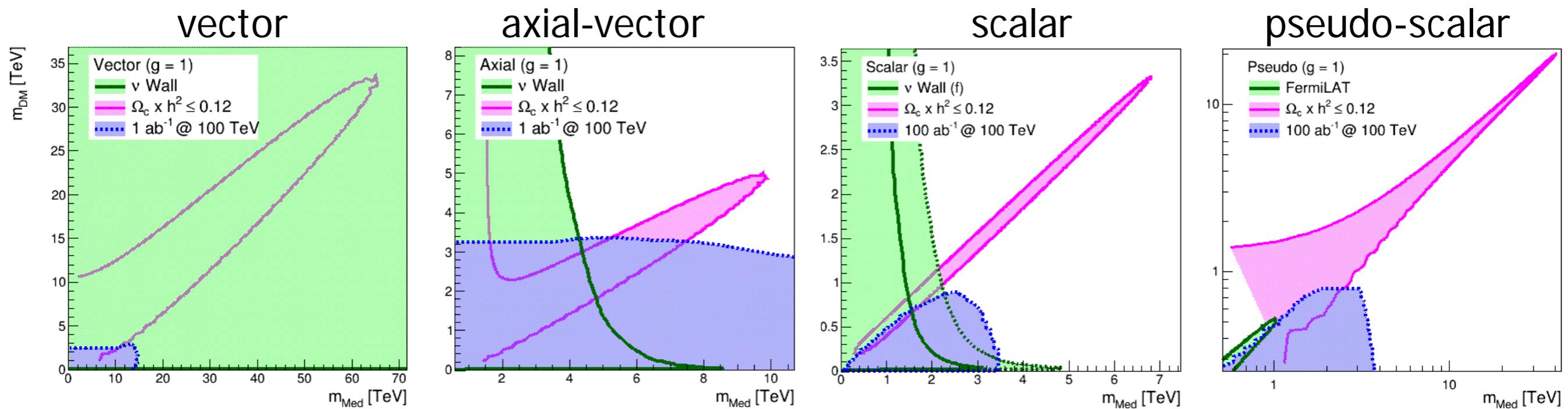
One order of magnitude better sensitivity lower masses with  $300 \text{ fb}^{-1}$

# Search reach (300/fb vs 3000/fb)

- Electroweak SUSY, extend from 500-600 GeV to 800-900 GeV
- Scalar top/bottom, few 100 GeV increase in reach



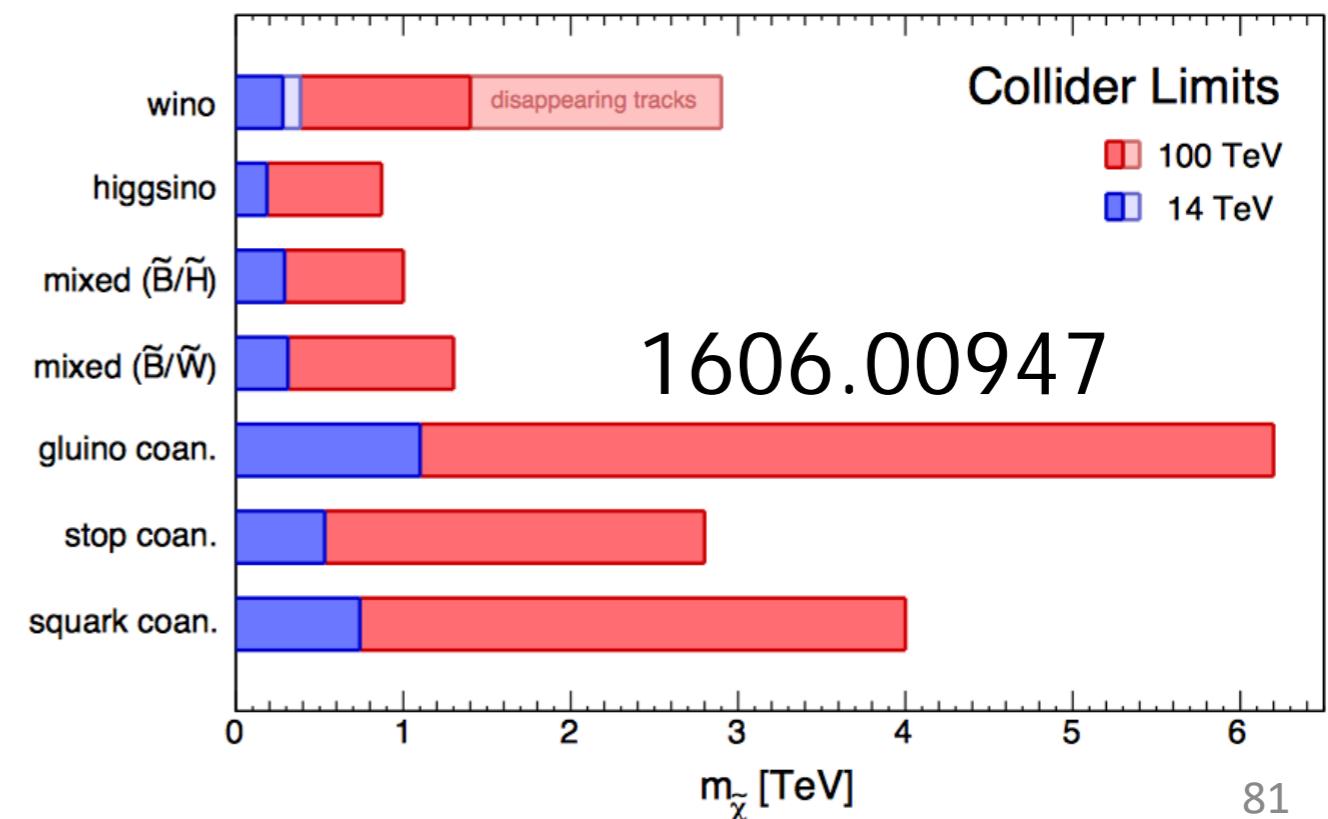
# Beyond the LHC



green:  $xsec \leftarrow$  neutrino bkg  
 blue:  $1000 \text{ fb}^{-1} @ 100 \text{ TeV}$   
 red: compatible with measured  
 relic density

(for some choice  
 of the couplings)

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



# Summary

## extensive DM search programme at ATLAS

- complementary to dedicated experiments for  $m_{DM} < \sim 100$  GeV
- Invisible Higgs offers a unique opportunity to explore the dark sector.  
⇒ Close to the limits on BSM H decay

## more data, new challenges

- balance between sensitivity to low-momentum signals (e.g. spin-zero) and robustness at very high energy
  - trigger & detector performance are crucial!
- explore lower-cross-section extensions of the SM EFT use can be complementary to simplified models approaches.
- may extend LHC reach to  $m_{DM} \sim 500$  GeV in the next ~6 years  
may lower with one order of magnitude the DM-nucleon cross section with the coming LHC data.

### expected luminosity

Results now:  $36 \text{ f b}^{-1}$   
end of 2018:  $120 \text{ f b}^{-1}$   
end of 2023:  $300 \text{ f b}^{-1}$   
HL-LHC (~2035):  $3000 \text{ f b}^{-1}$

see also <https://indico.cern.ch/event/539266>

# Some ATLAS references

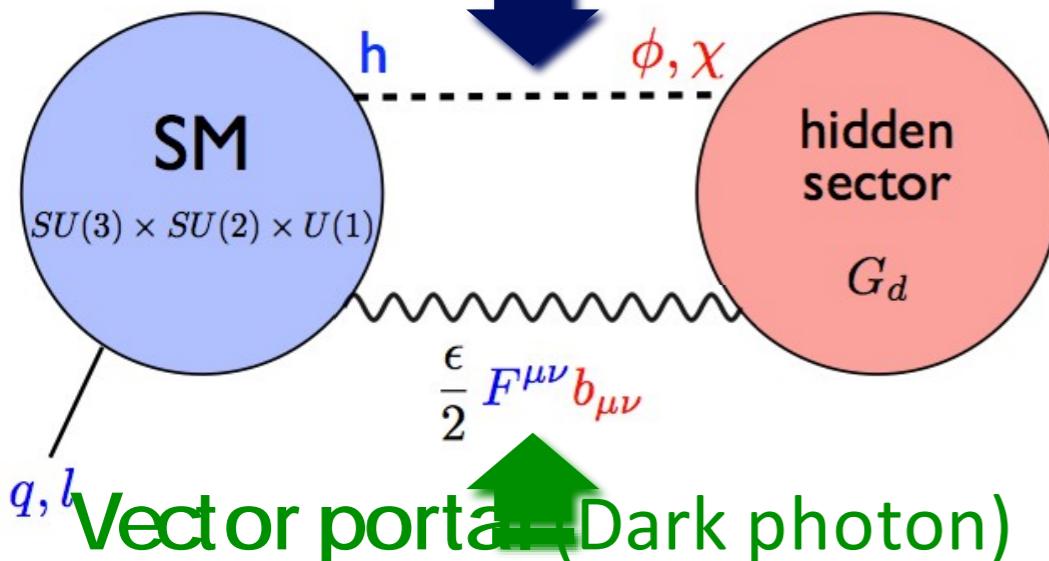
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- MET+ $\gamma$ : [Eur. Phys. J. C 77 , 6 \(2017\) 393](#)
- MET+a(1-L): [ATL-CONF-2017-037](#)
- MET+Z(II): [ATL-CONF-2017-040](#)
- MET+W/Z(had): [Phys. Lea. B 763 \(2016\) 251](#)
- MET+jet: [ATLAS-CONF-2017-060](#)
- Z(vv)/Z(II) cross-section: *to appear*
- MET+H(bb): [ATLAS-CONF-2017-028](#)
- MET+H(gg): [arXiv:1706.03948](#)
- MET+H(4l): [ATLAS-CONF-2015-059](#)
- MET+bb: [ATLAS-CONF-2016-086](#)
- MET+a(had): [ATLAS-CONF-2016-077](#)
- MET+a (2-L): [ATLAS-CONF-2016-076](#)
- di-jet: [hap://arxiv.org/abs/arXiv:1703.09127](#)
- di-jet TLA: [ATLAS-CONF-2016-030](#)
- di-jet ISR: [ATLAS-CONF-2016-070](#)
- dilepton: [ATLAS-CONF-2017-027](#)
- abar resonance: [ATLAS-CONF-2016-014](#)
- summary plots: [haps://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html](#)
- SUSY EW 2-3l: [ATLAS-CONF-2017-039](#)
- chargino/neutralino tau: [ATLAS-CONF-2017-035](#)
- chargino long-lived (disapp track): [ATLAS-CONF-2017-017](#)
- SUSY pMSSM scan: [JHEP09\(2016\)175](#)

# **Backup**

# Dark Sector

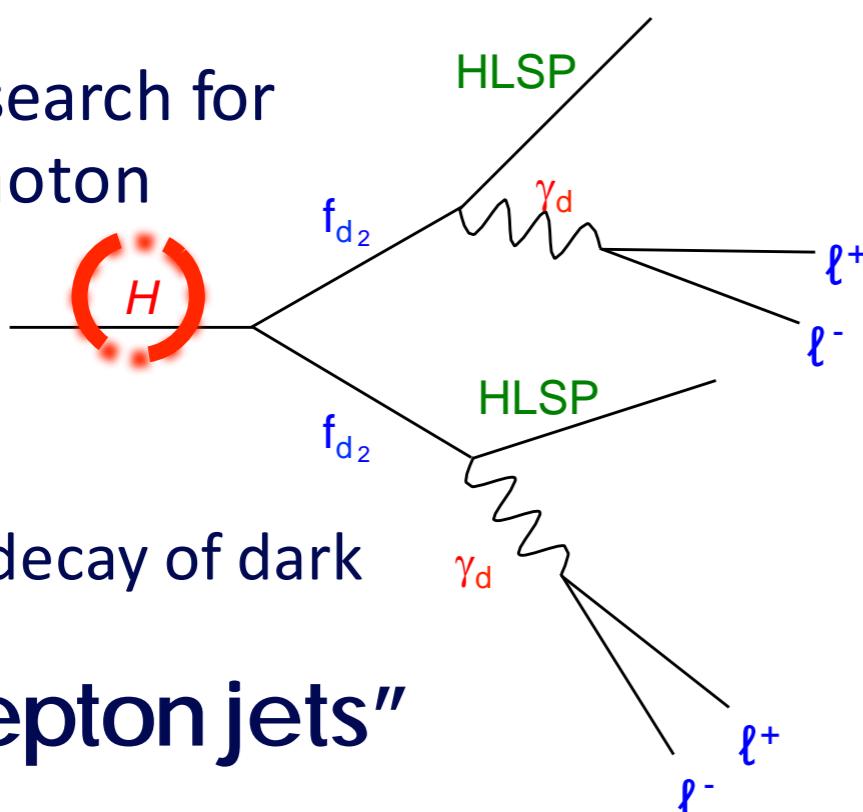
## Higgs portal (Scalar DM)



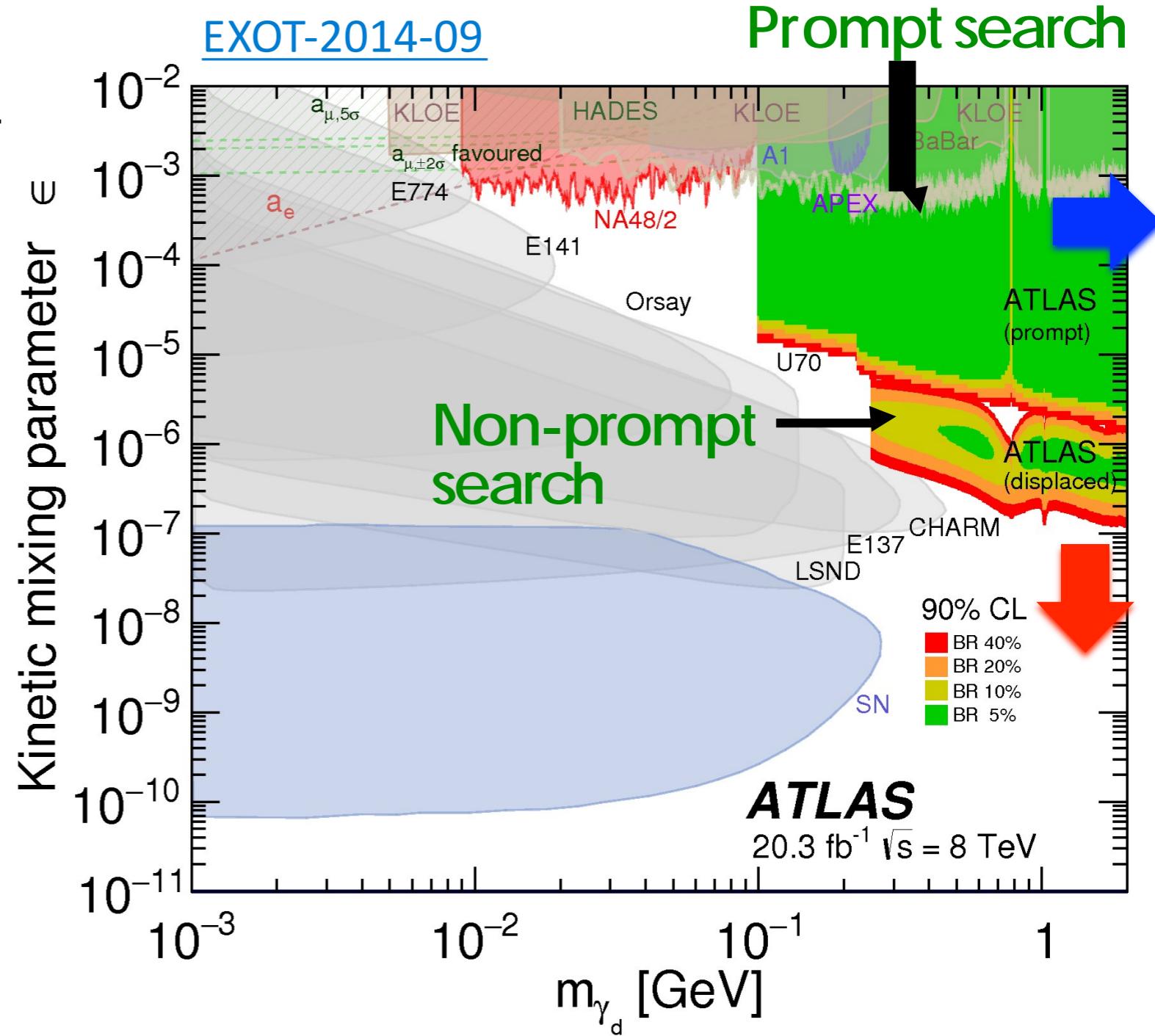
## Vector portal (Dark photon)

- ▶ Kinetic mixing (strength  $\sim \epsilon e$ ) between SM and Dark photons
- ▶ Small mixing  $\rightarrow$  long lifetime

ATLAS search for dark photon



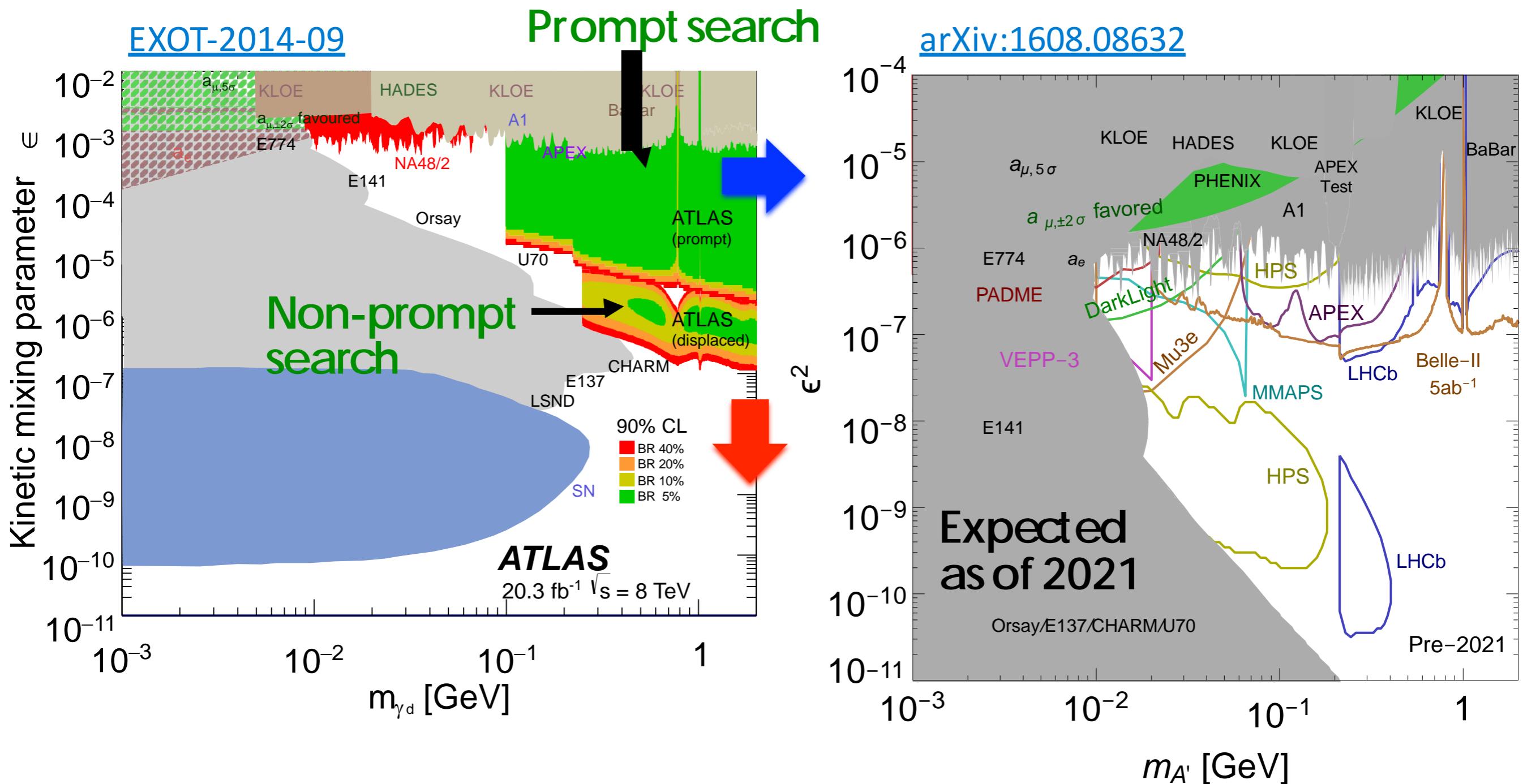
Visible decay of dark photon  
⇒ “Lepton jets”



- ▶ LHC extending the reach towards high  $m_{\gamma_d}$  and low  $\epsilon$  regions
- ▶ Complementary to future fixed-target/beam-dump experiments

See poster by A. Policicchio!!

# Dark Photon

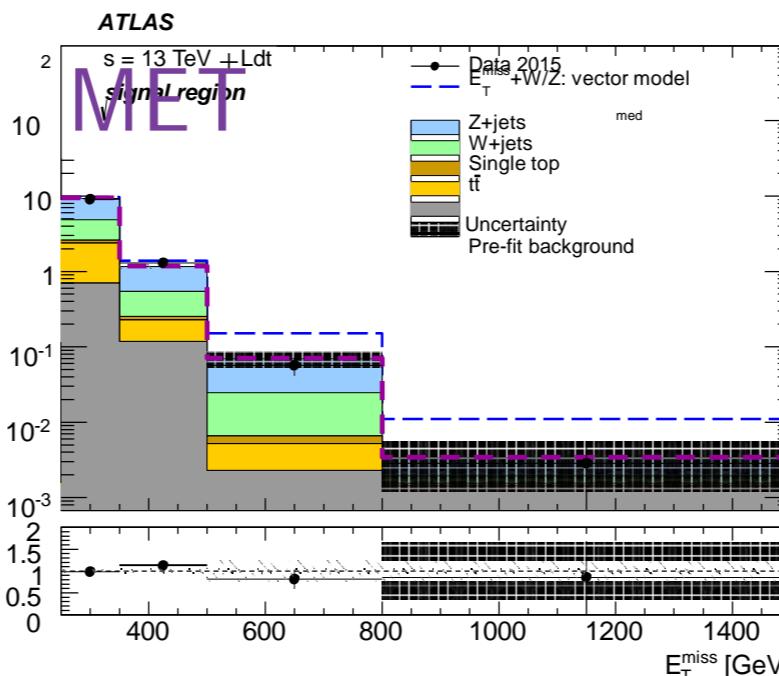


- LHC extending the reach towards high  $m_{\gamma^d}$  and Low  $\epsilon$  regions
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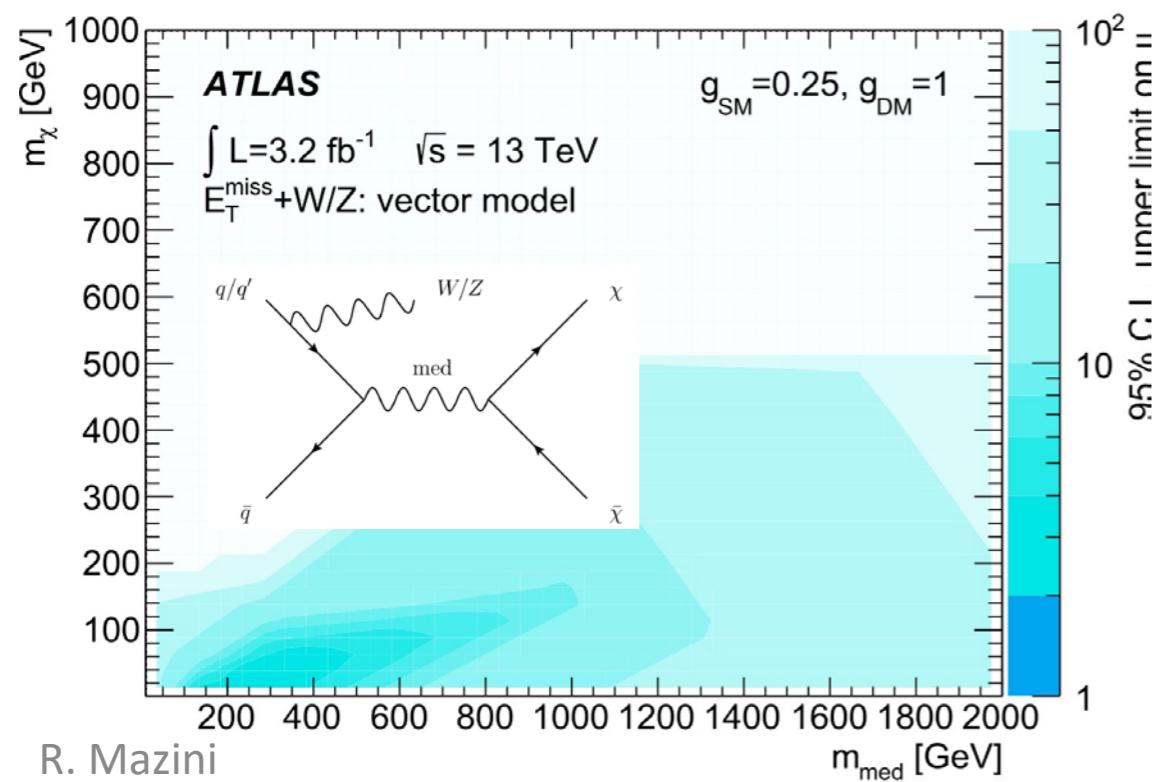
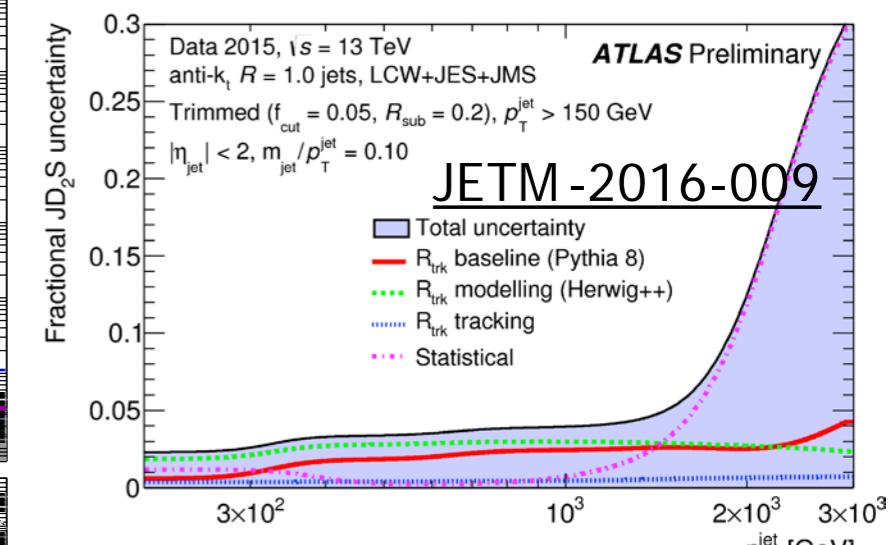
trimmed large-R jet (anY-kT R=1.0), MET > 250 GeV

- with 1 $\mu$ 1b CR for reducing abar uncertainYes

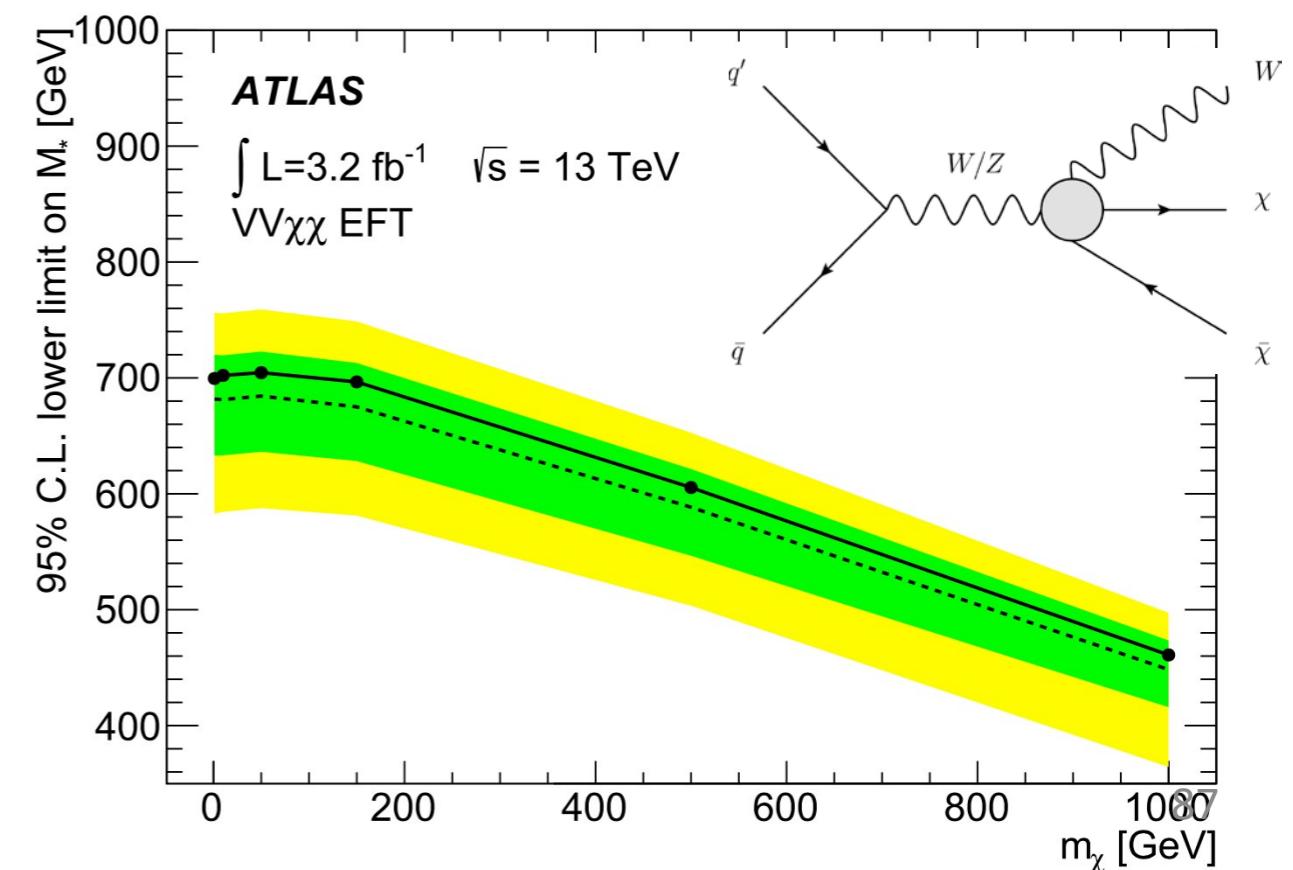
boson tagging based on jet mass and p<sub>T</sub>-dependent cut on 2-prongness ("D<sub>2</sub>",  $\varepsilon \sim 50\%$ ), main uncertainty on total bkg (5-13%)



D<sub>2</sub> scale uncertainty



R. Mazini



# $Z(vv)/Z(l\bar{l})$ cross-section ratio measurement

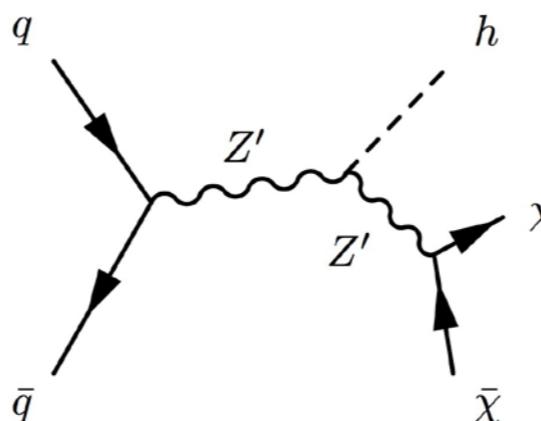
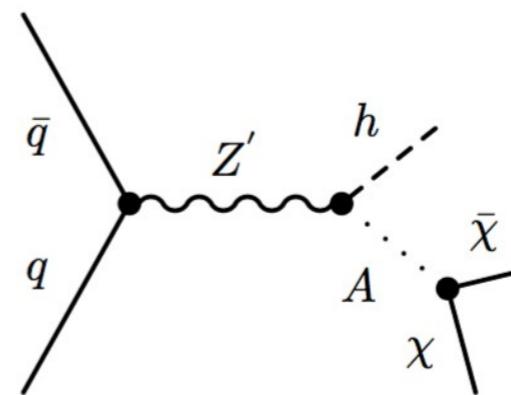
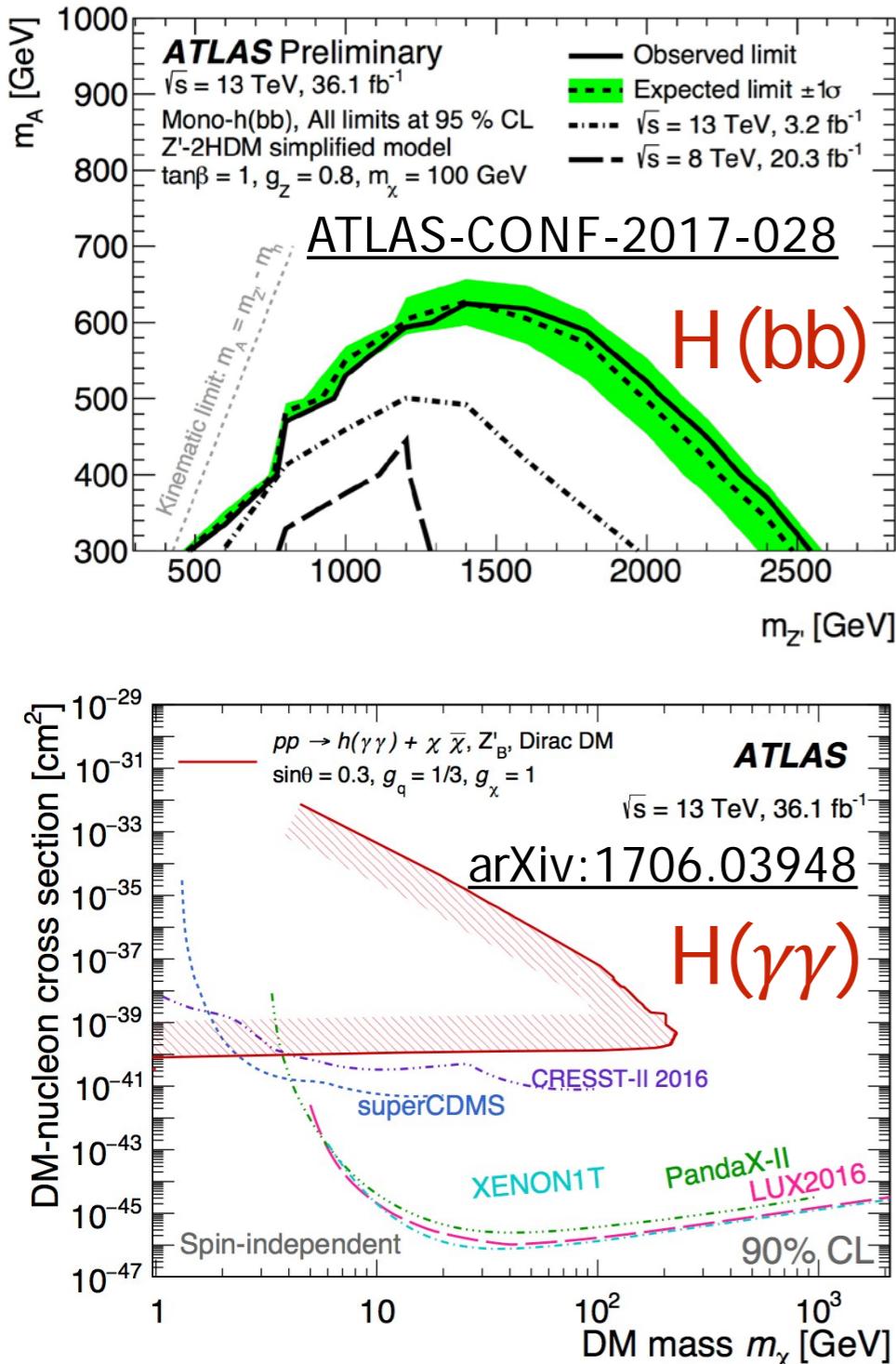
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Numerator and denominator	$\geq 1$ jet	VBF
$p_T^{\text{miss}}$		$> 200 \text{ GeV}$
(Additional) lepton veto	No $e, \mu$ with $p_T > 7 \text{ GeV},  \eta  < 2.5$	
Jet $ y $		$< 4.4$
Jet $p_T$		$> 25 \text{ GeV}$
$\Delta\phi_{\text{jet}_i, p_T^{\text{miss}}}$	$> 0.4$ , for the four leading jets with $p_T > 30 \text{ GeV}$	
Leading jet $p_T$	$> 120 \text{ GeV}$	$> 80 \text{ GeV}$
Subleading jet $p_T$	–	$> 50 \text{ GeV}$
Leading jet $ \eta $	$< 2.4$	–
$m_{jj}$	–	$> 200 \text{ GeV}$
Central-jet veto	–	No jets with $p_T > 25 \text{ GeV}$
<b>Denominator only</b>		$\geq 1$ jet and VBF
Leading lepton $p_T$		$> 80 \text{ GeV}$
Subleading lepton $p_T$		$> 7 \text{ GeV}$
Lepton $ \eta $		$< 2.5$
$m_{\ell\ell}$		66–116 GeV
$\Delta R$ (jet, lepton)		$> 0.5$ , otherwise jet is removed

# Z(vv)/Z(l l) cross-section ratio measurement

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<b>Systematic uncertainty source</b>	Low $p_T^{\text{miss}}$ [%]	High $p_T^{\text{miss}}$ [%]	Low $m_{jj}$ [%]	High $m_{jj}$ [%]
Lepton efficiency	+3.5, -3.5	+7.6, -7.1	+3.7, -3.6	+4.6, -4.4
Jets	+0.8, -0.7	+2.2, -2.8	+1.1, -1.0	+9.0, -0.5
$W \rightarrow \tau\nu$ from control region	+1.2, -1.2	+4.6, -4.6	+1.3, -1.3	+3.9, -3.9
Multijet	+1.8, -1.8	+0.9, -0.9	+1.4, -1.4	+2.5, -2.5
Correction factor statistical	+0.2, -0.2	+2.0, -1.9	+0.4, -0.4	+3.8, -3.6
$W$ statistical	+0.5, -0.5	+24, -24	+1.1, -1.1	+6.8, -6.8
$W$ theory	+2.4, -2.3	+6.0, -2.3	+3.1, -3.0	+4.9, -5.1
Top cross-section	+1.5, -1.8	+1.3, -0.1	+1.1, -1.2	+0.5, -0.4
$Z \rightarrow \ell\ell$ backgrounds	+0.9, -0.8	+1.1, -1.1	+1.0, -1.0	+0.1, -0.1
<b>Total systematic uncertainty</b>	+5.2, -5.2	+27, -26	+5.6, -5.5	+14, -11
<b>Statistical uncertainty</b>	+1.7, -1.7	+83, -44	+3.5, -3.4	+35, -25
<b>Total uncertainty</b>	+5.5, -5.4	+87, -51	+6.6, -6.5	+38, -27

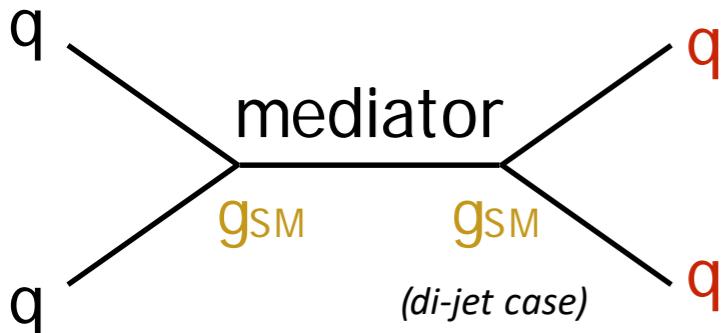


Higgs boson as a discovery tool!

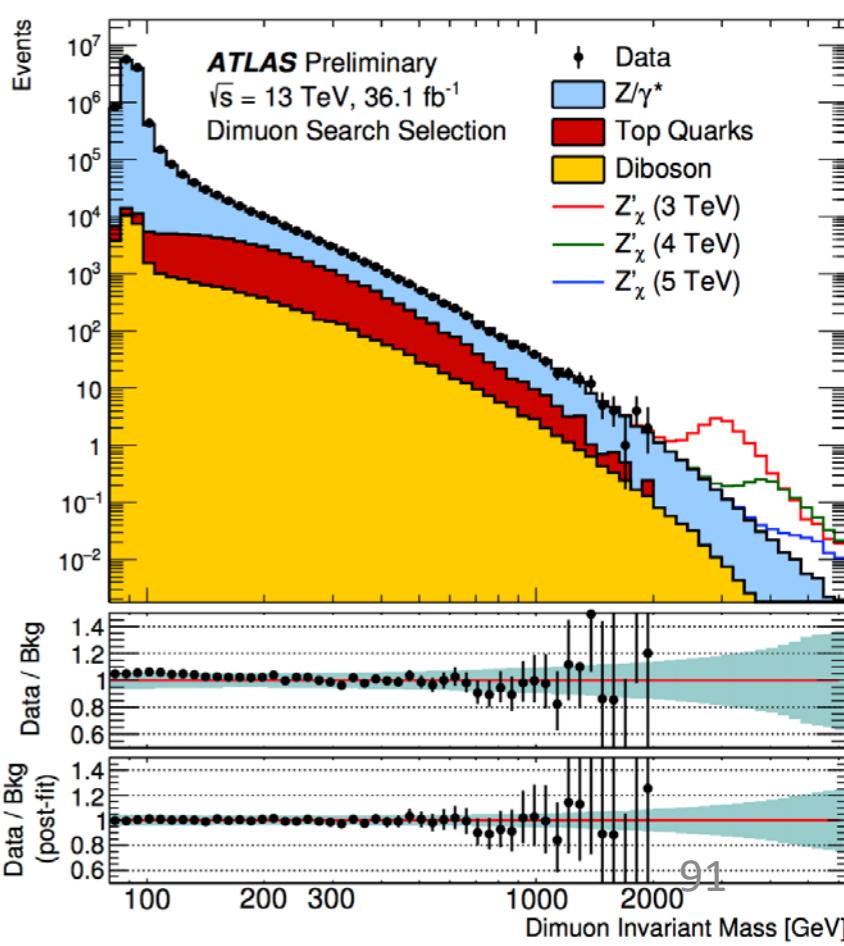
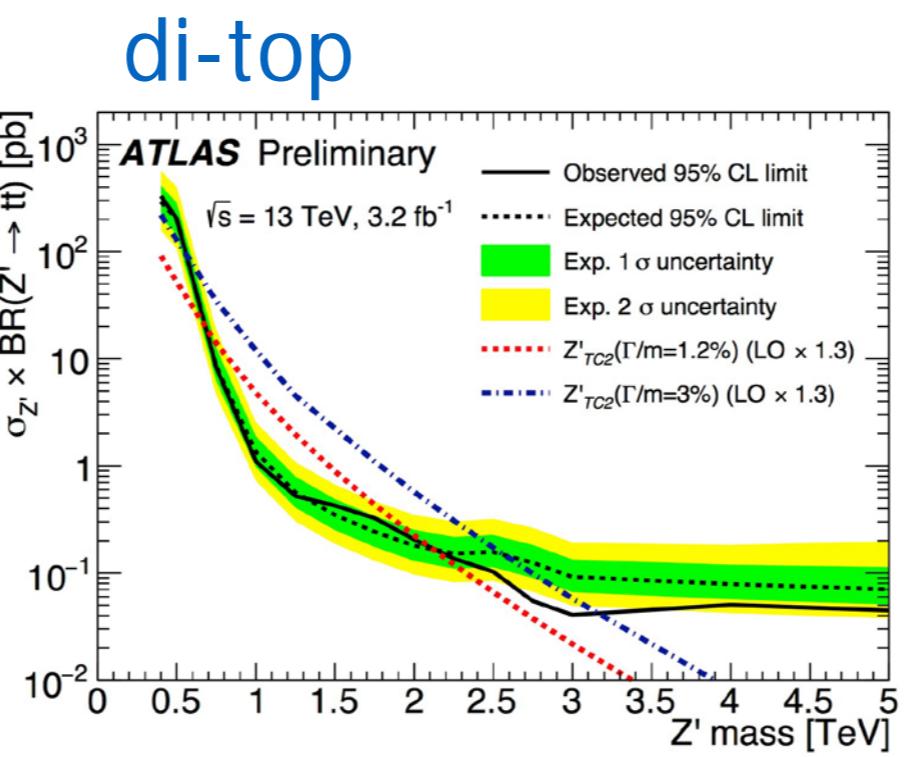
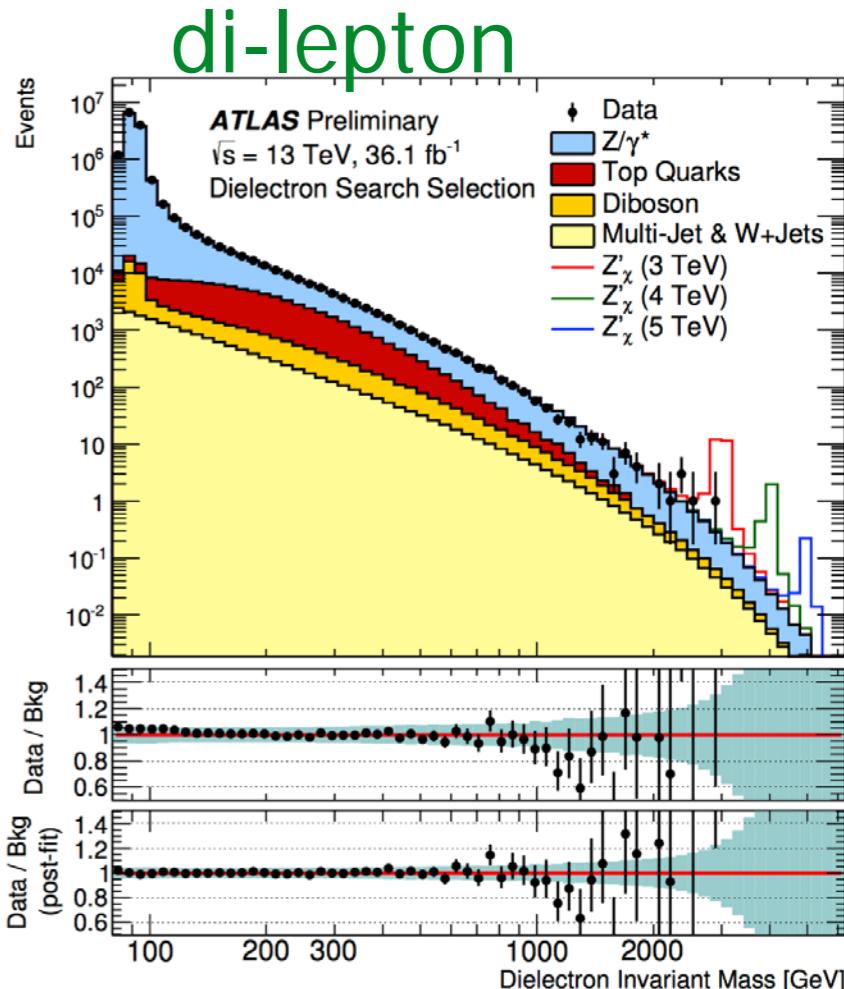
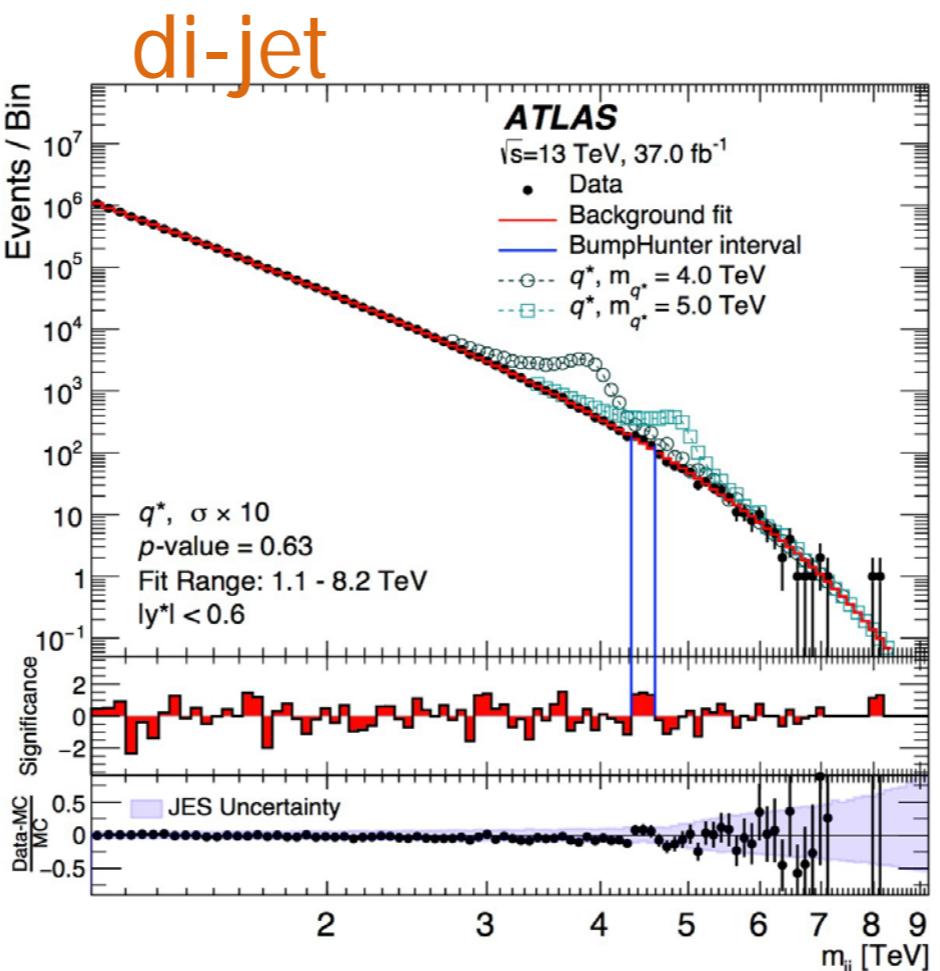
- probe couplings between a new mediator and Higgs sector
- most sensitive channel is H(bb)+MET
  - use  $m_{bb}$  as discriminant in resolved and boosted regimes ( $\text{MET} </> 500 \text{ GeV}$ )
- bkg from  $Z(vv) + \text{jet}$ ,  $W + \text{jet}$  and  $a\bar{a}, 1\mu$  and  $2\mu/2e$  CRs

also MET+H(4l) (ATLAS-CONF-2015-059)

# Di-X

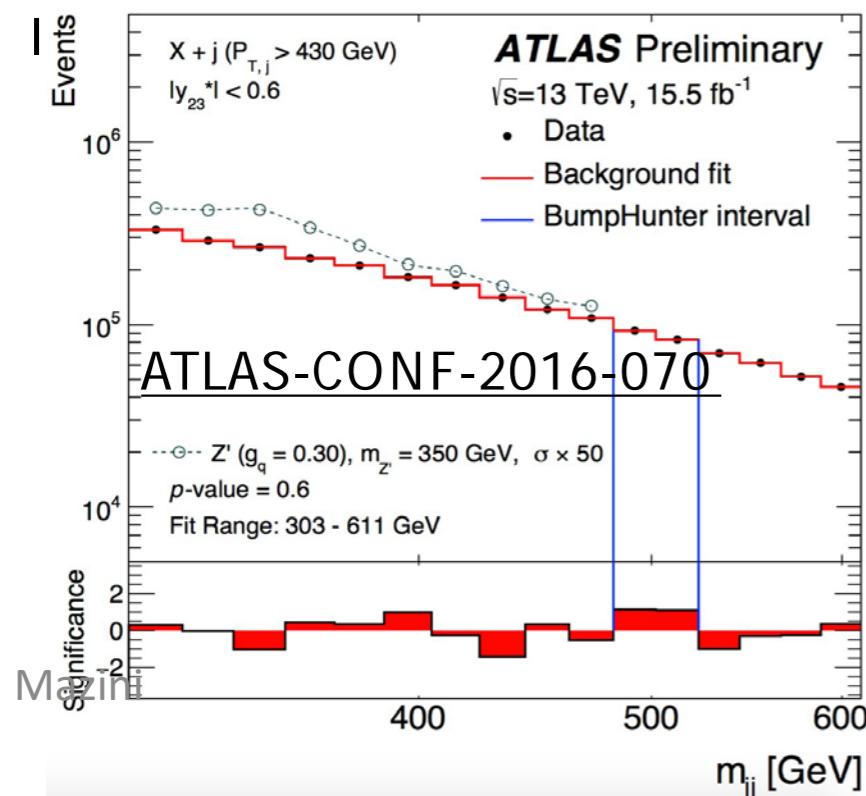
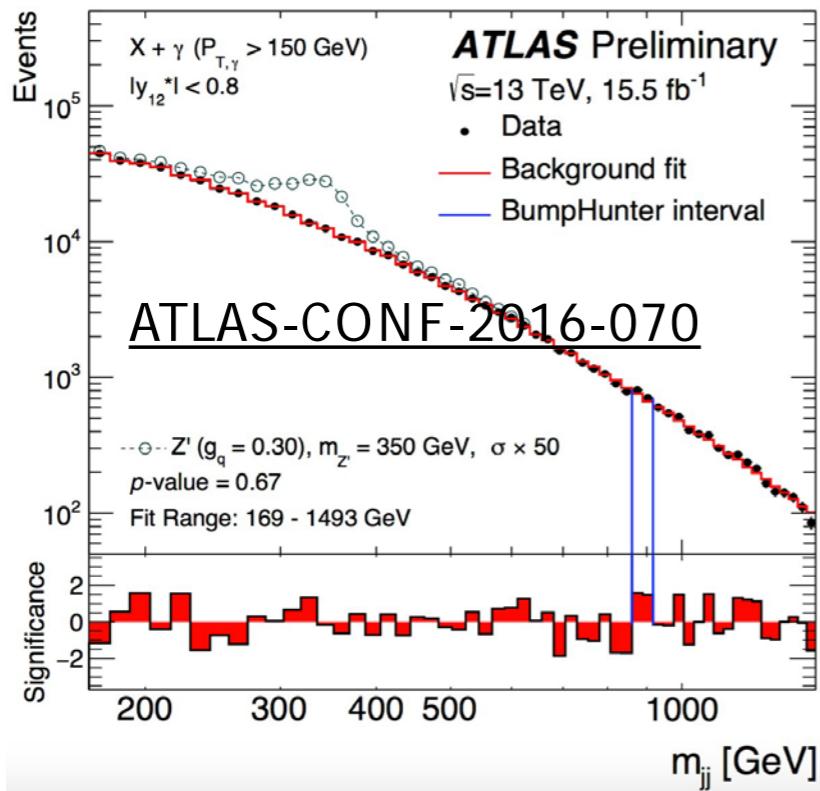


- look directly for the mediator of the SM - DM interaction
  - di-jet below 1 TeV uses data-scouting and ISR tagging
- if mediator couples to leptons, strong constraints from di-lepton searches
  - a resonance searches could also contribute in spin-0 scenarios

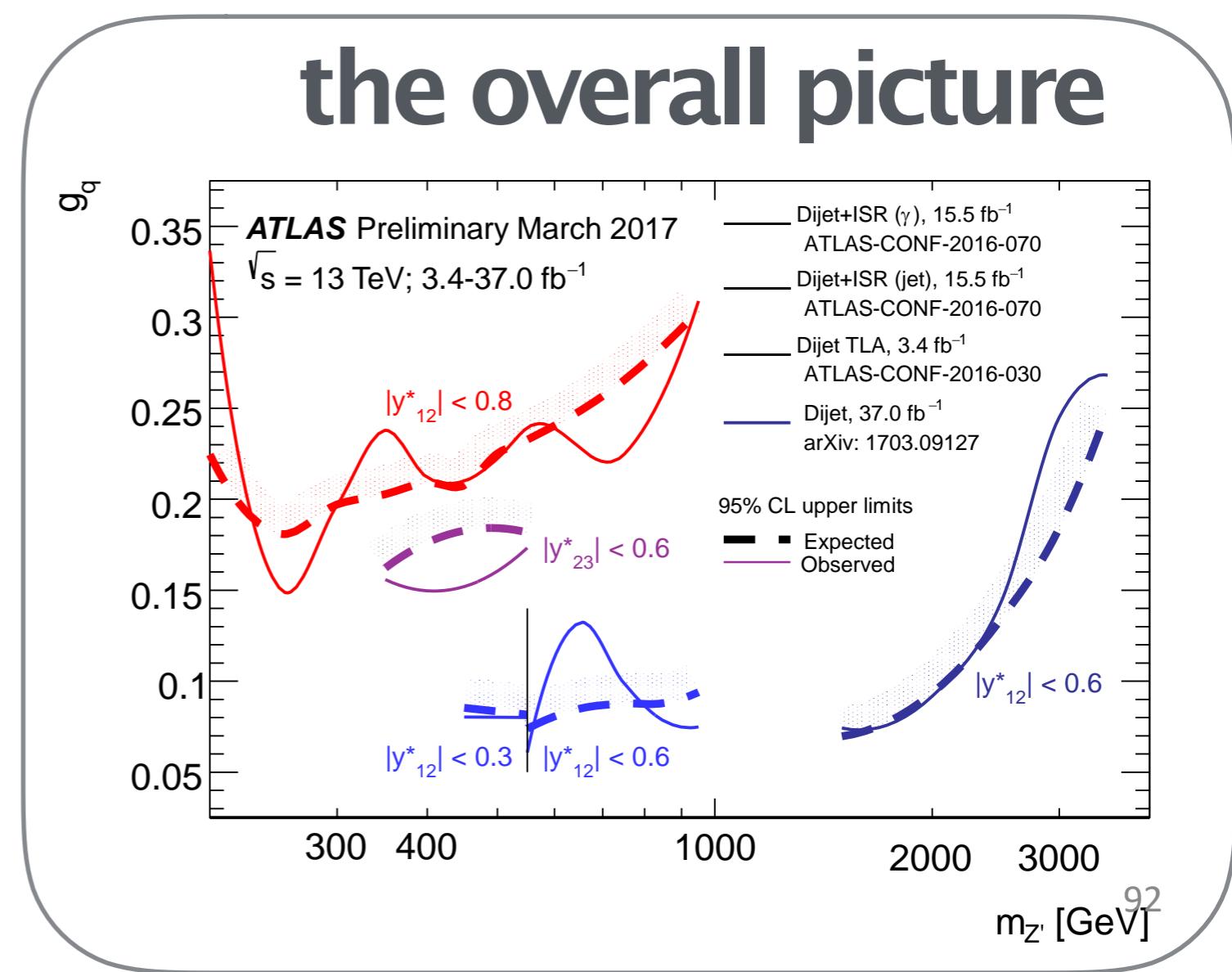


# Dijet search strategies, compared

## dijet+ISR photon/jet



- ISR photon
  - one photon with  $p_T > 150$  GeV
  - 2 jets with  $p_T > 25$  GeV,  $|y^*| < 0.8$
- ISR jet
  - one jet with  $p_T > 430$  GeV
  - 2 jets with  $p_T > 25$  GeV,  $|y^*| < 0.6$
- extend range to lower masses



# The simplified models link to direct detection

**DD** looks for non-relativistic nucleus-DM scattering

- 90% CL limits on  $\sigma_{\text{SI}}$  and  $\sigma_{\text{SD}}$ , vs  $m_{\text{DM}}$ 
  - SI ( $J^{PC}=0^+, 1^+$ ) usually shown assuming  $\sigma^p = \sigma^n$

$$\sigma_{\text{SI}} = \frac{f^2(g_q) g_{\text{DM}}^2 \mu_{n\chi}^2}{\pi M_{\text{med}}^4}$$

$0^+$   $\sigma_{\text{SI}} \approx 1.1 \times 10^{-39} \text{ cm}^2 \cdot \left(\frac{g_{\text{DM}} g_q}{1}\right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}}\right)^2$

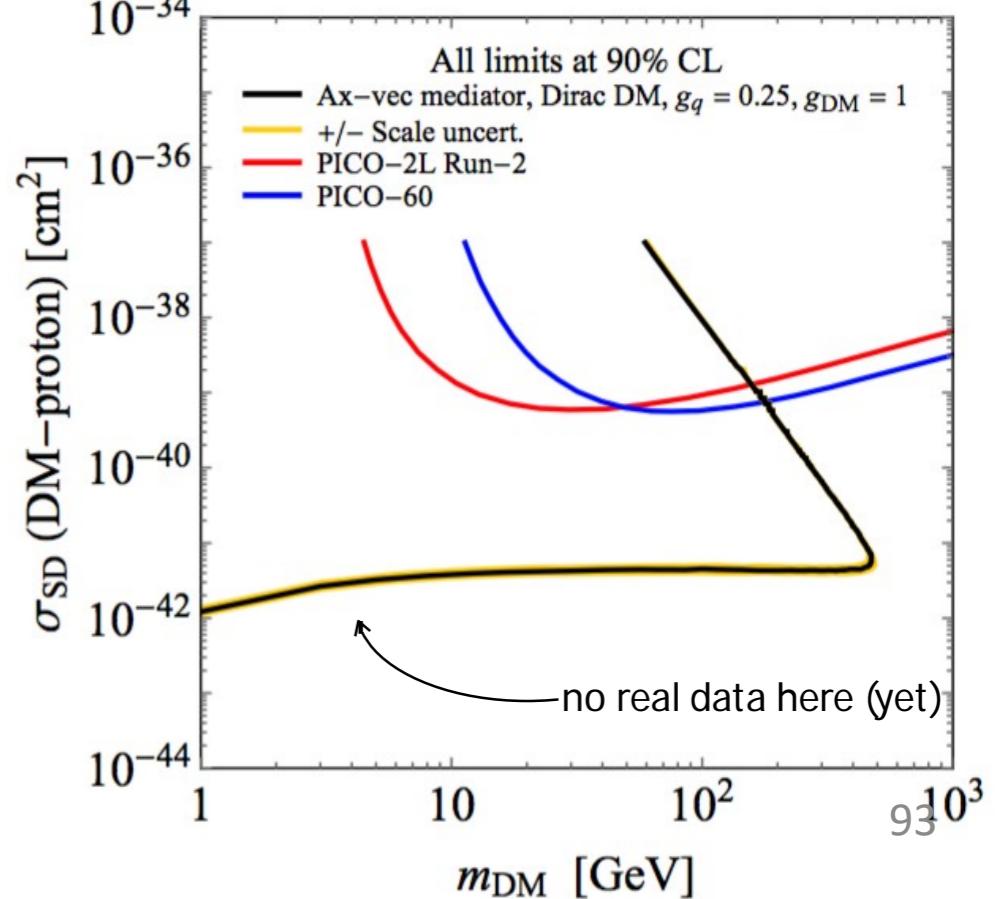
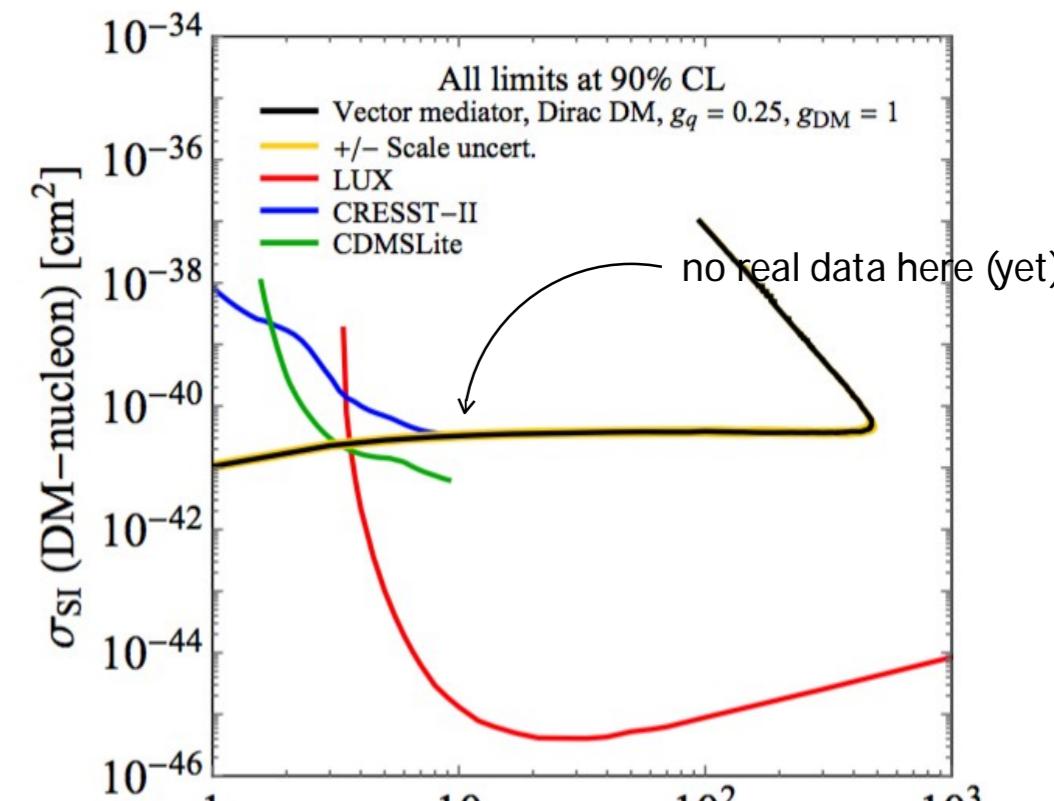
$0^-$   $\sigma_{\text{SI}} \approx 0$  (suppressed by velocity dependent terms)

$1^+$   $\sigma_{\text{SI}} \approx 6.9 \times 10^{-43} \text{ cm}^2 \cdot \left(\frac{g_{\text{DM}} g_q}{1}\right)^2 \left(\frac{125 \text{ GeV}}{M_{\text{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}}\right)^2$

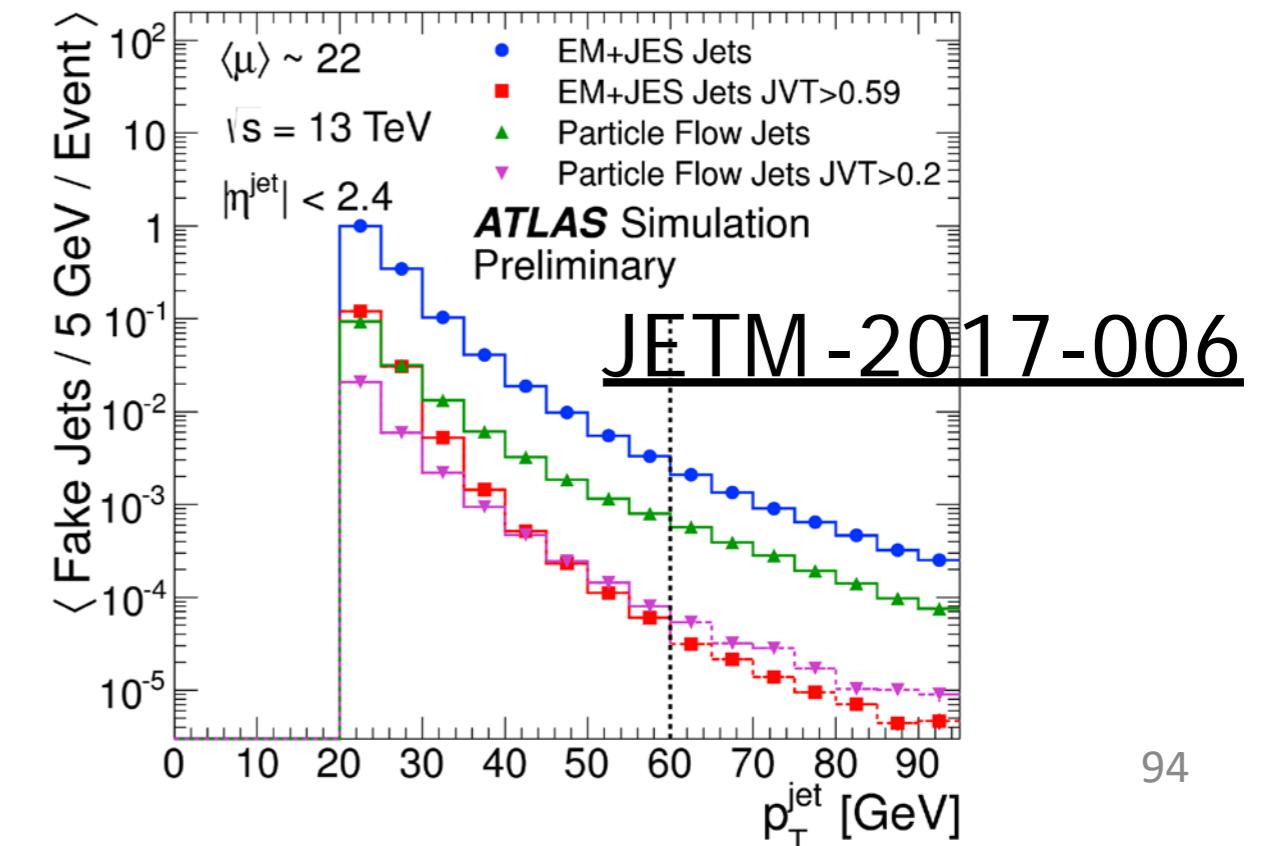
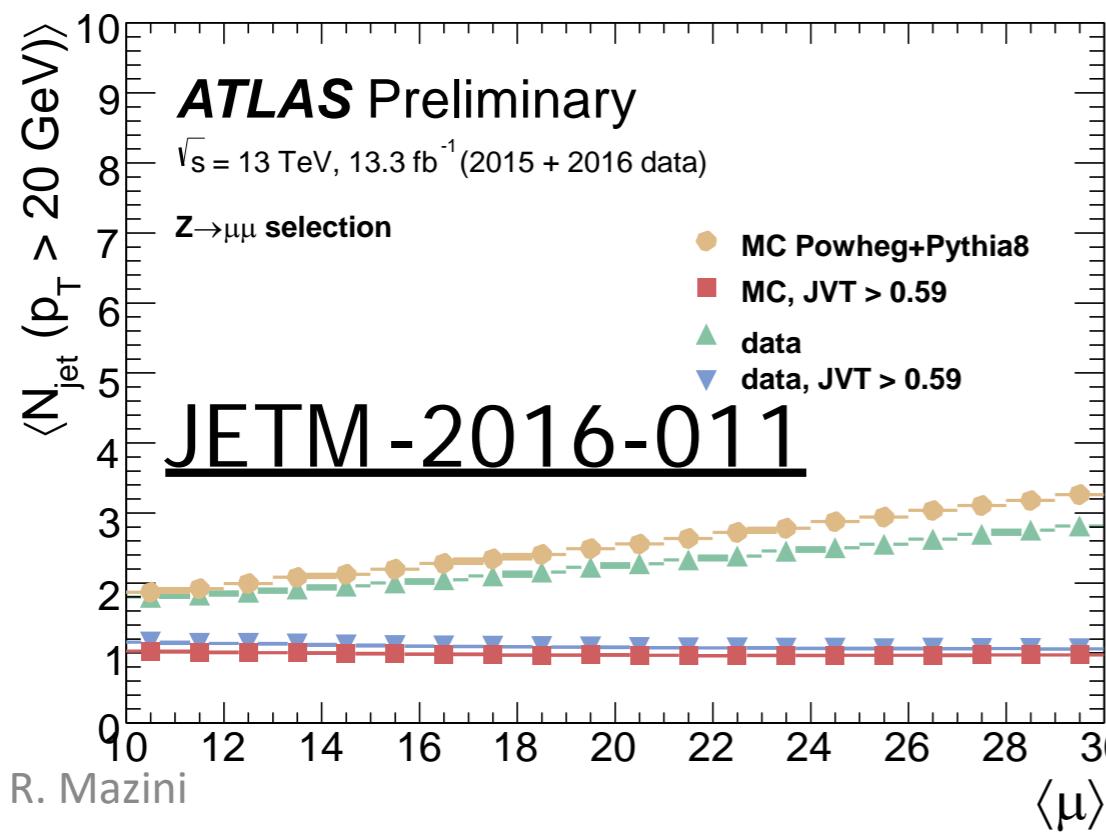
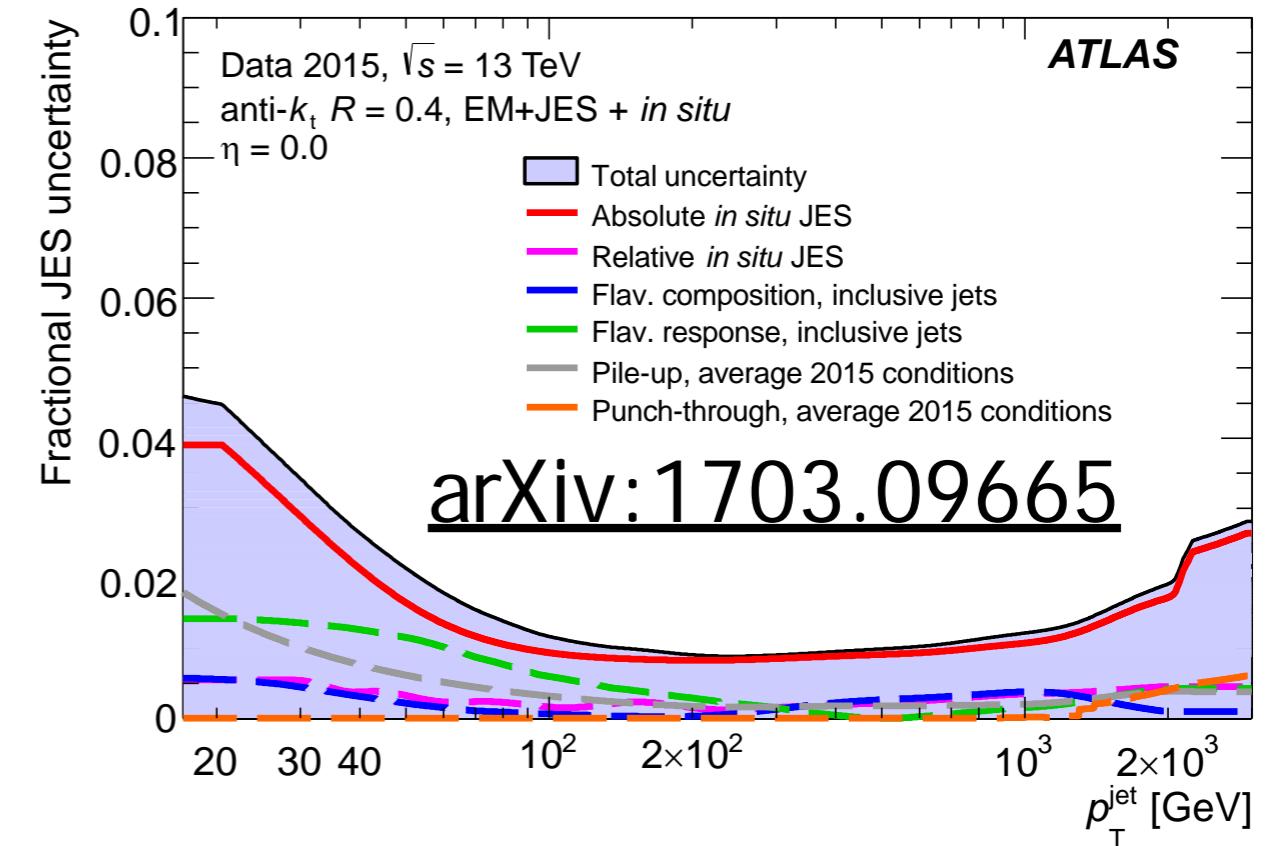
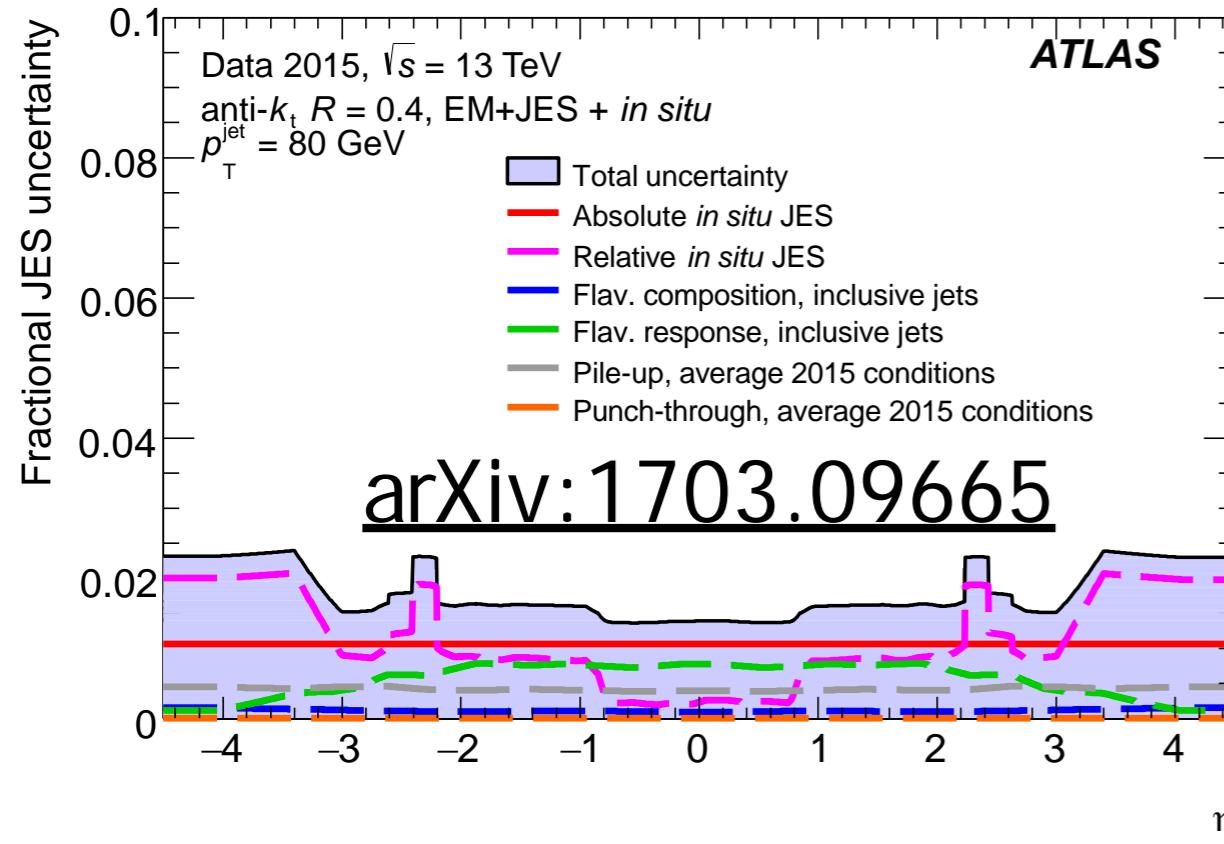
- SD ( $J^{PC}=1^-$ ) sensitive to either p (PICO, ...) or n (LUX, XENON100, ...), through isotope spin (more difficult, need odd #p...)
- LHC result is the same for p and n
- Ice-cube limit depends on assumed annihilation channel - weak for qq, no comparison possible for WW/ll which we exclude from our models ↩ not to be shown

$$\sigma_{\text{SD}} = \frac{3 f^2(g_q) g_{\text{DM}}^2 \mu_{n\chi}^2}{\pi M_{\text{med}}^4}$$

$1^-$   $\sigma_{\text{SD}} \approx 3.8 \times 10^{-41} \text{ cm}^2 \cdot \left(\frac{g_{\text{DM}} g_q}{1}\right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}}\right)^2$

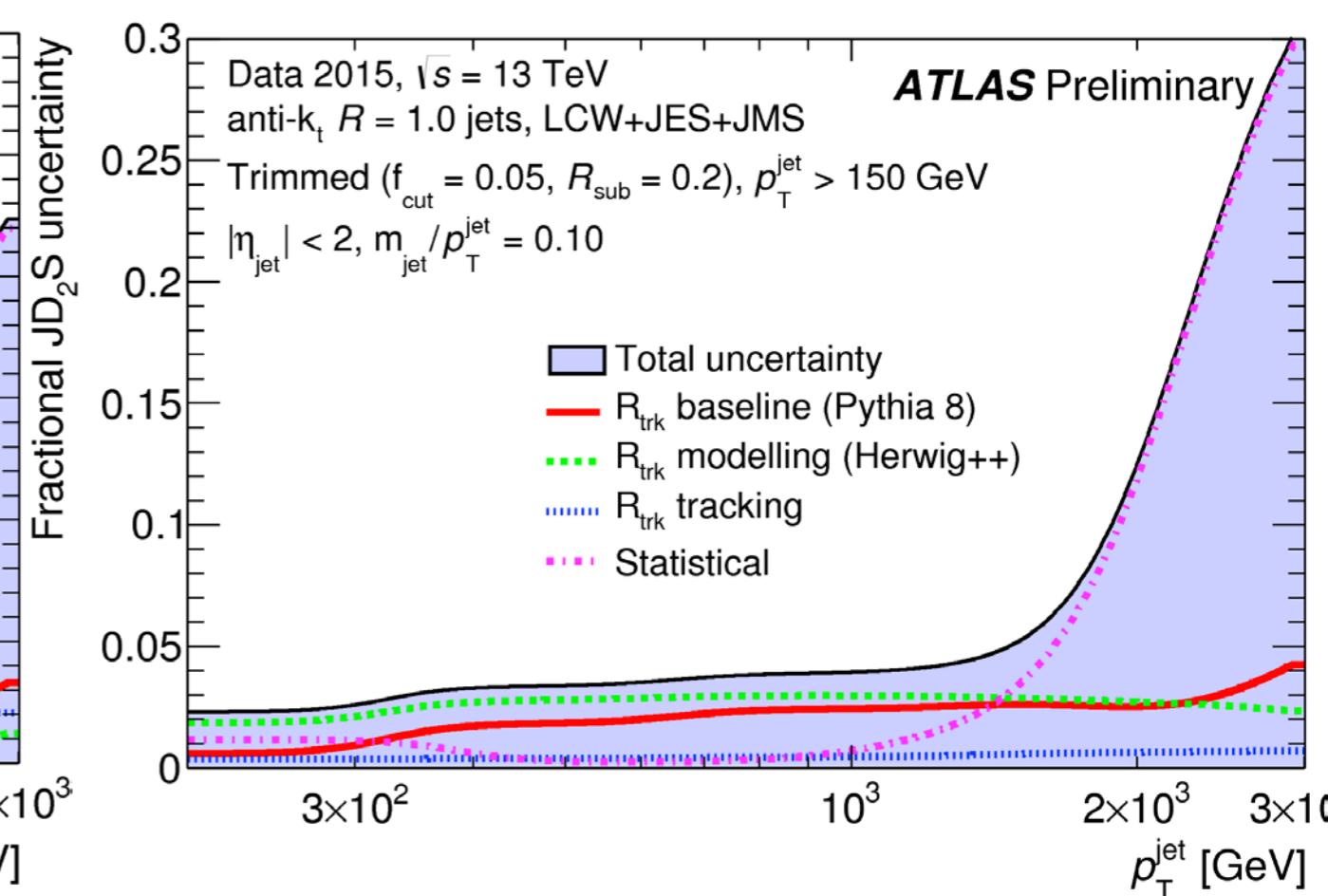
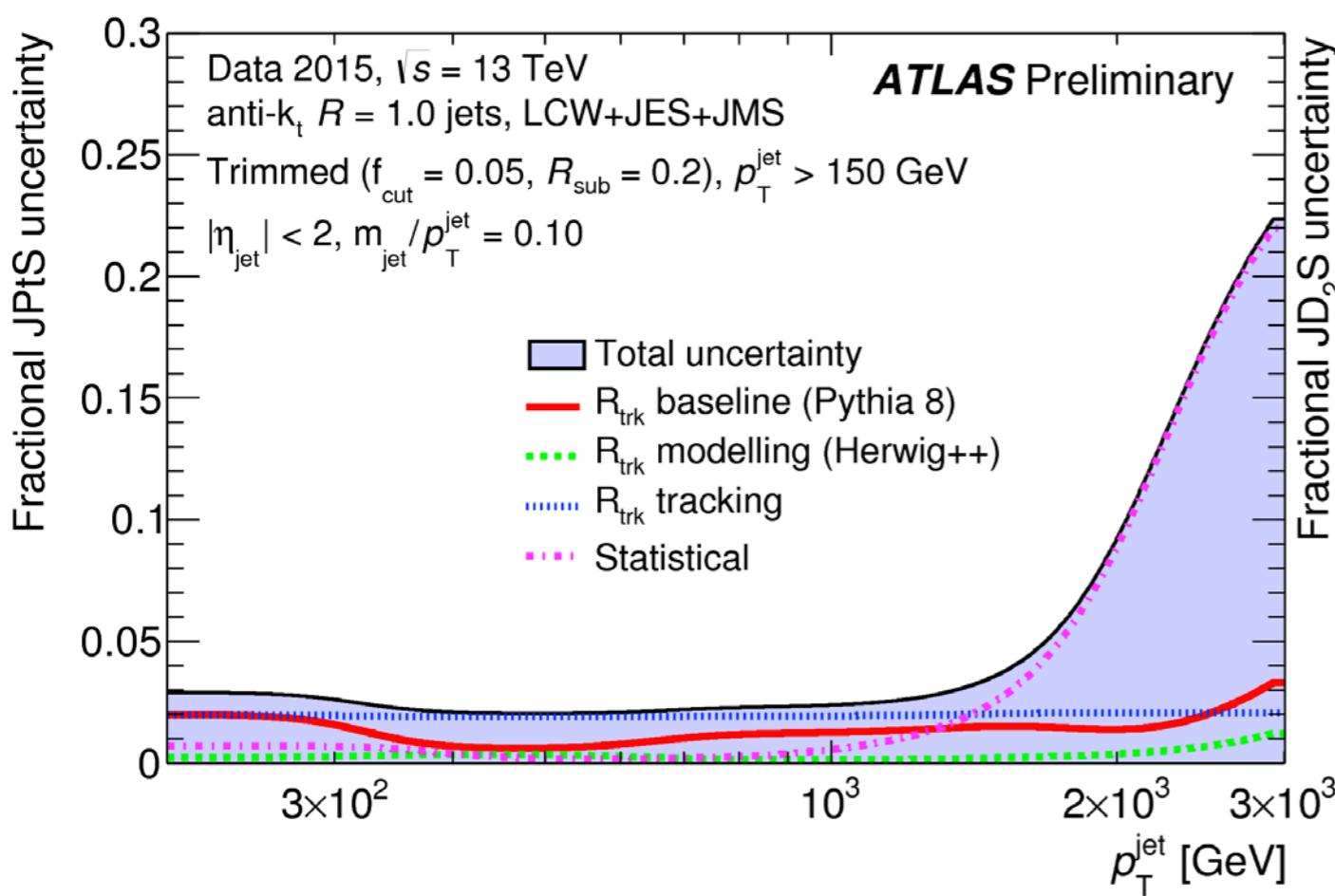


# Jet reconstruction



# Large-R jets

JETM-2016-009



# MET trigger

