LHC Searches for Exotic Phenomena

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On the behalf of the ATLAS, CMS, LHCb Experiments

ICFA 2017 Seminar

Ottawa, Canada

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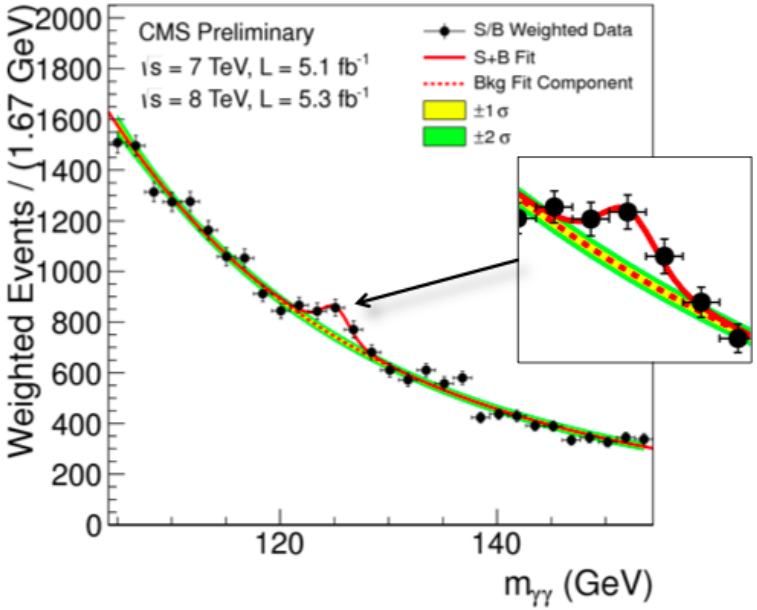
What Characterizes Exotics Searches?

No precise model to guide us

Standard Model:

Predicted Higgs boson

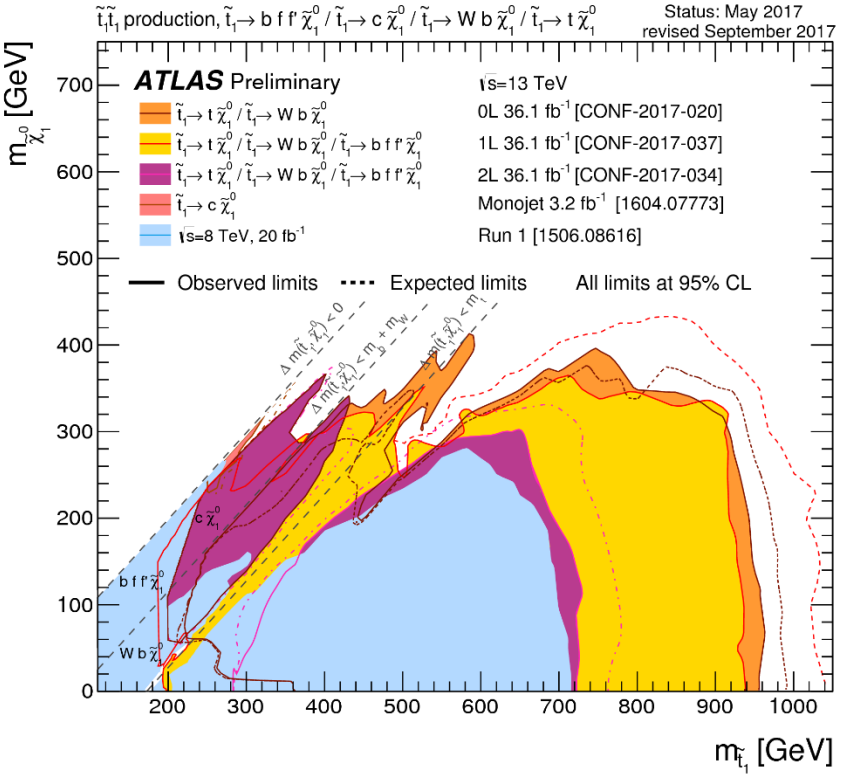


[Phys. Lett. B 716 (2012) 1-29]

[Phys. Lett. B 716 (2012) 30-61]

No unified parameter phase space

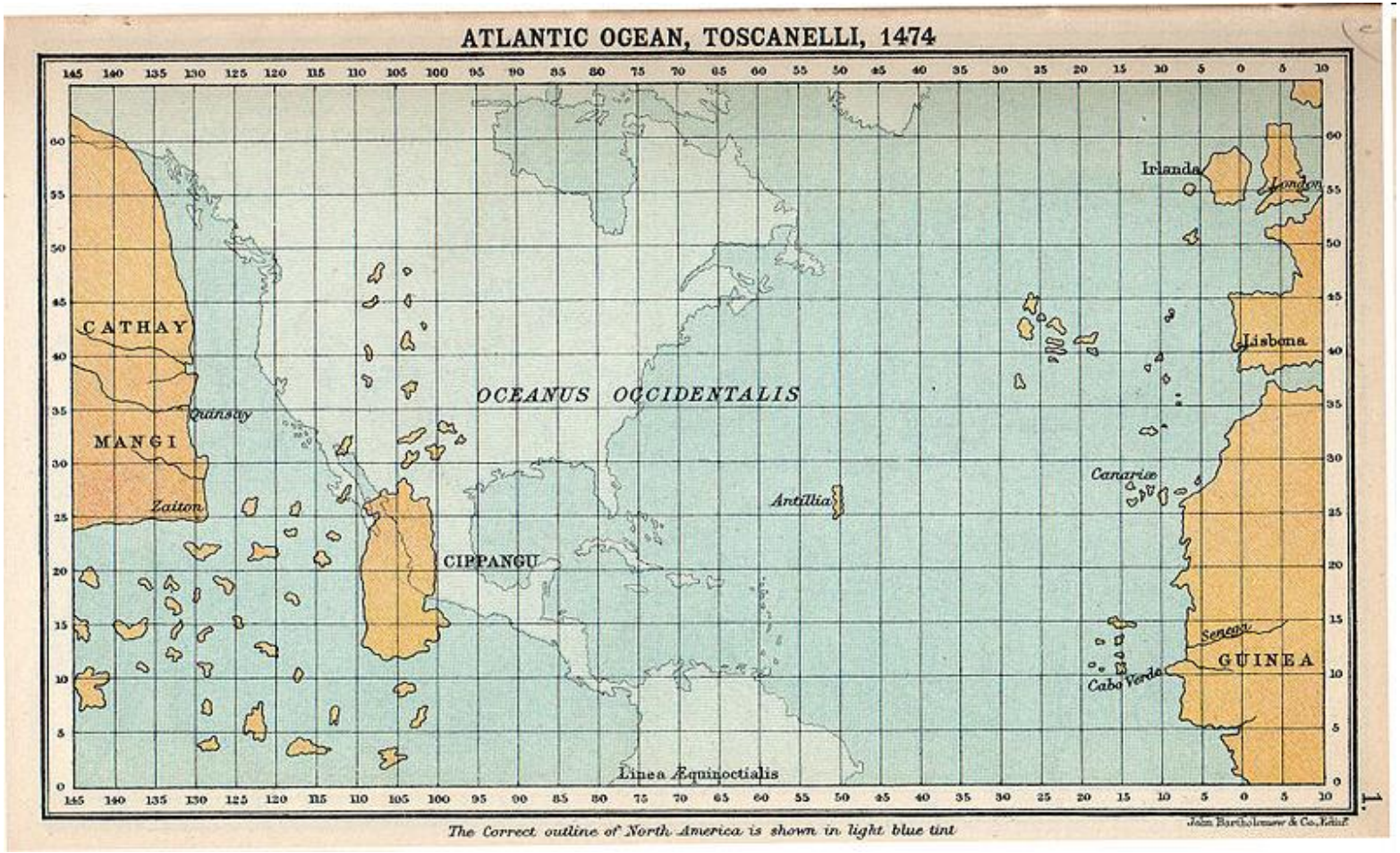
Supersymmetry Searches:



Exotics Searches

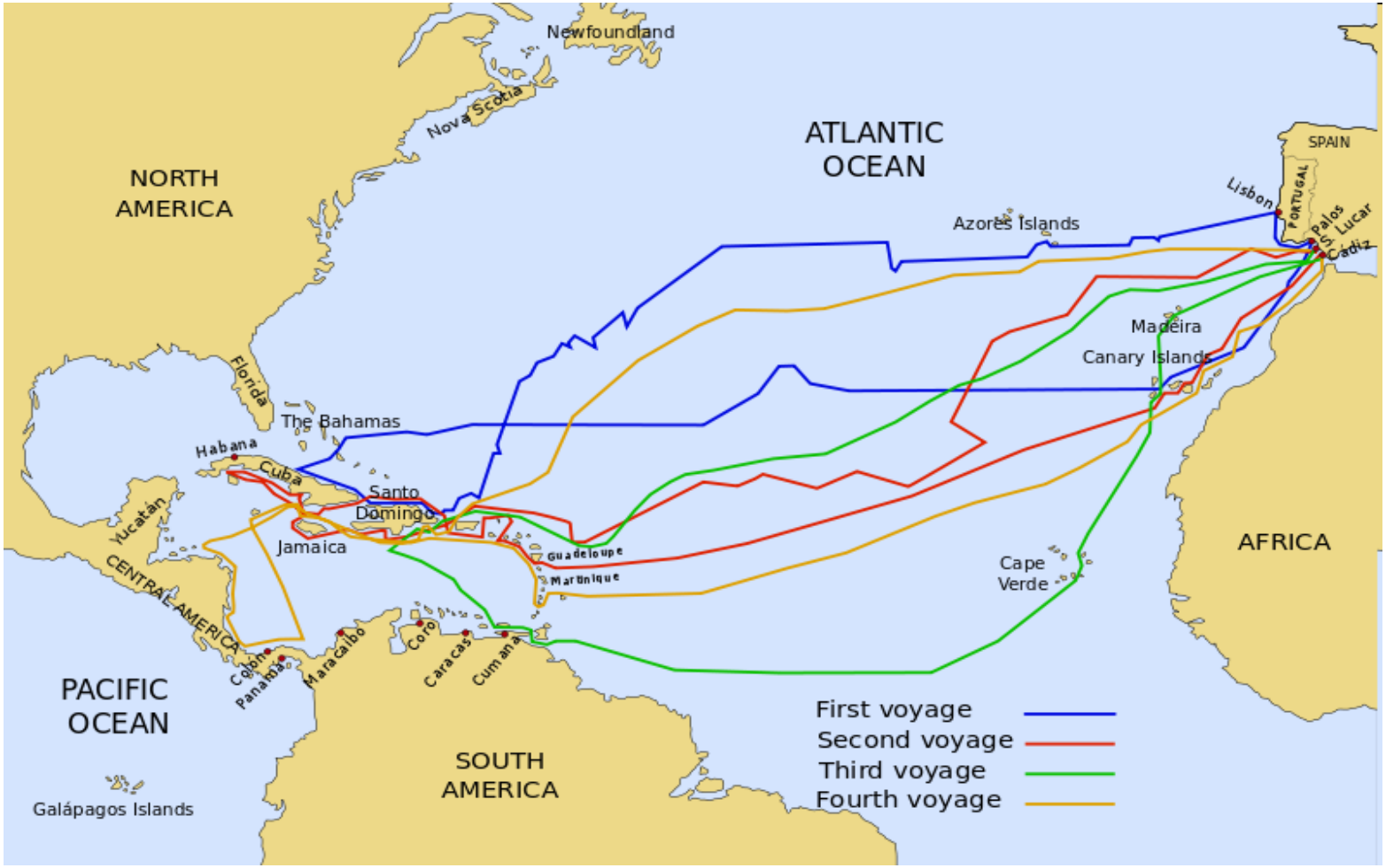
- Cover wide range of final states
- Cover vast range of models
- Largely model independent
  - Look for resonances
  - Look for any disagreement

The Role of Models in “most” Exotics Searches



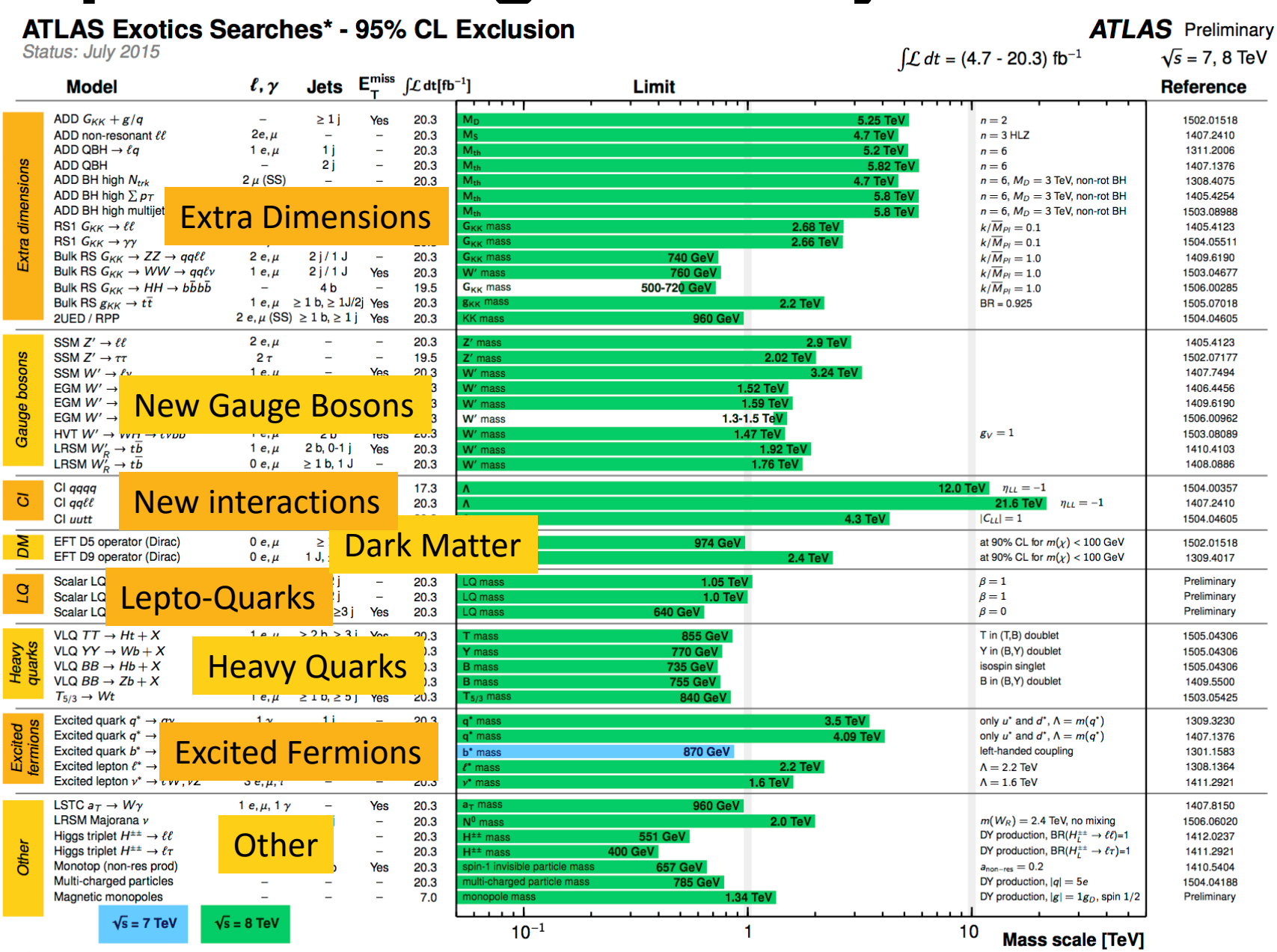
Toscanelli's model of the geography of the Atlantic Ocean, which directly influenced Columbus's plans

The Role of Models in “most” Exotics Searches



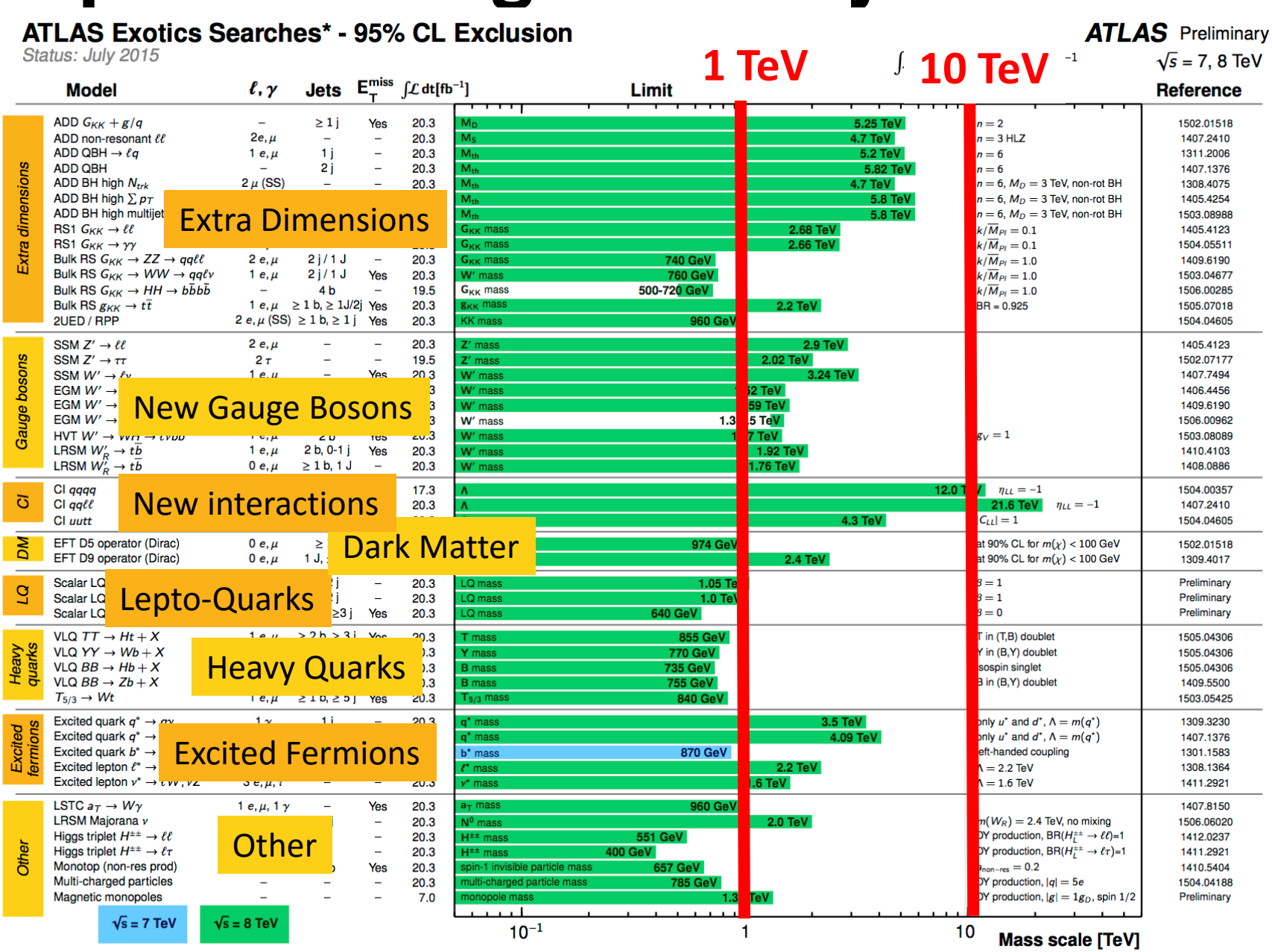
Columbus’ Voyages

Exploration range of LHC by mid 2015



*Only a selection of the available mass limits on new states or phenomena is shown.

Exploration range of LHC by mid 2015



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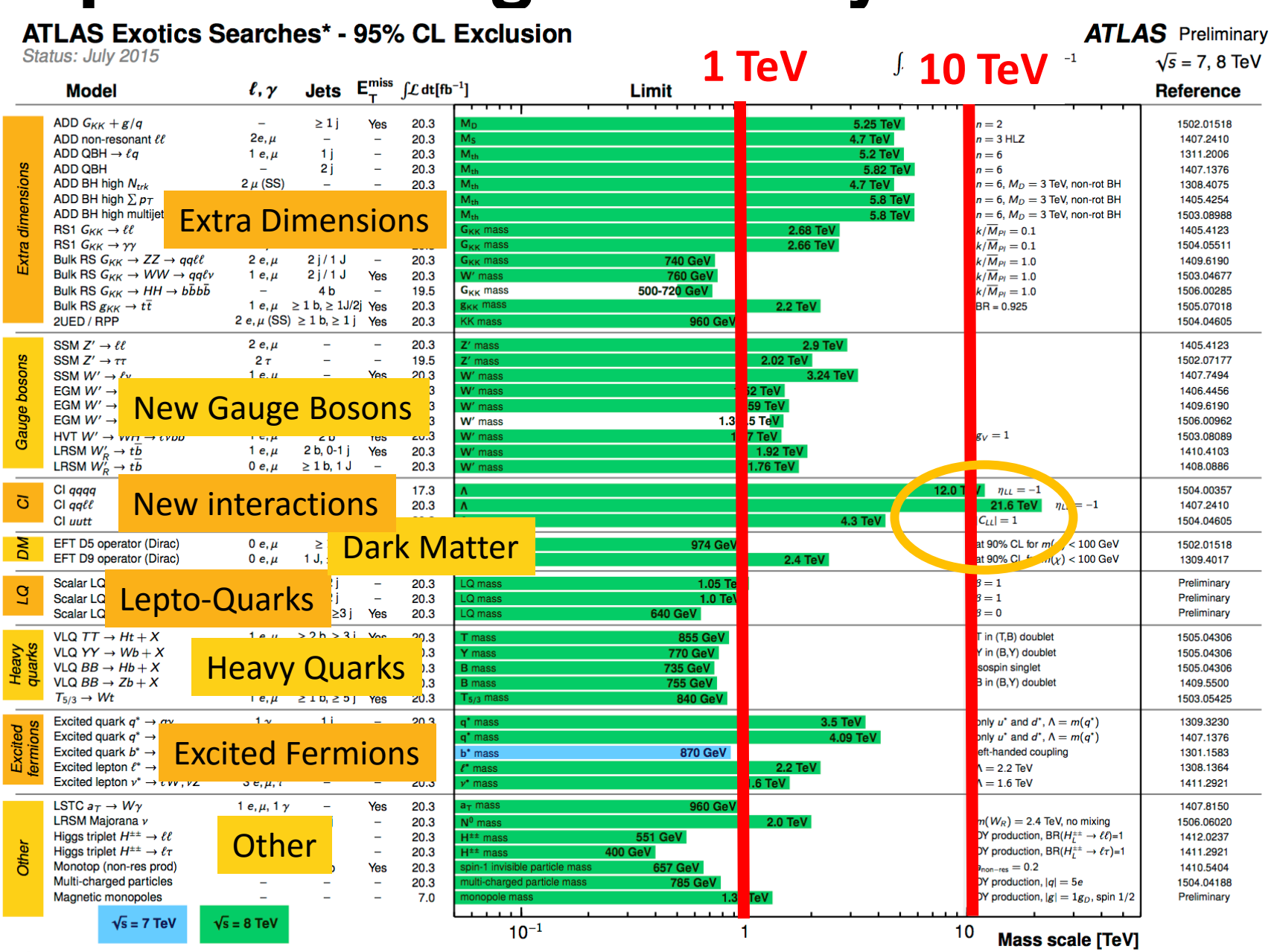
Exploration range of LHC by mid 2015



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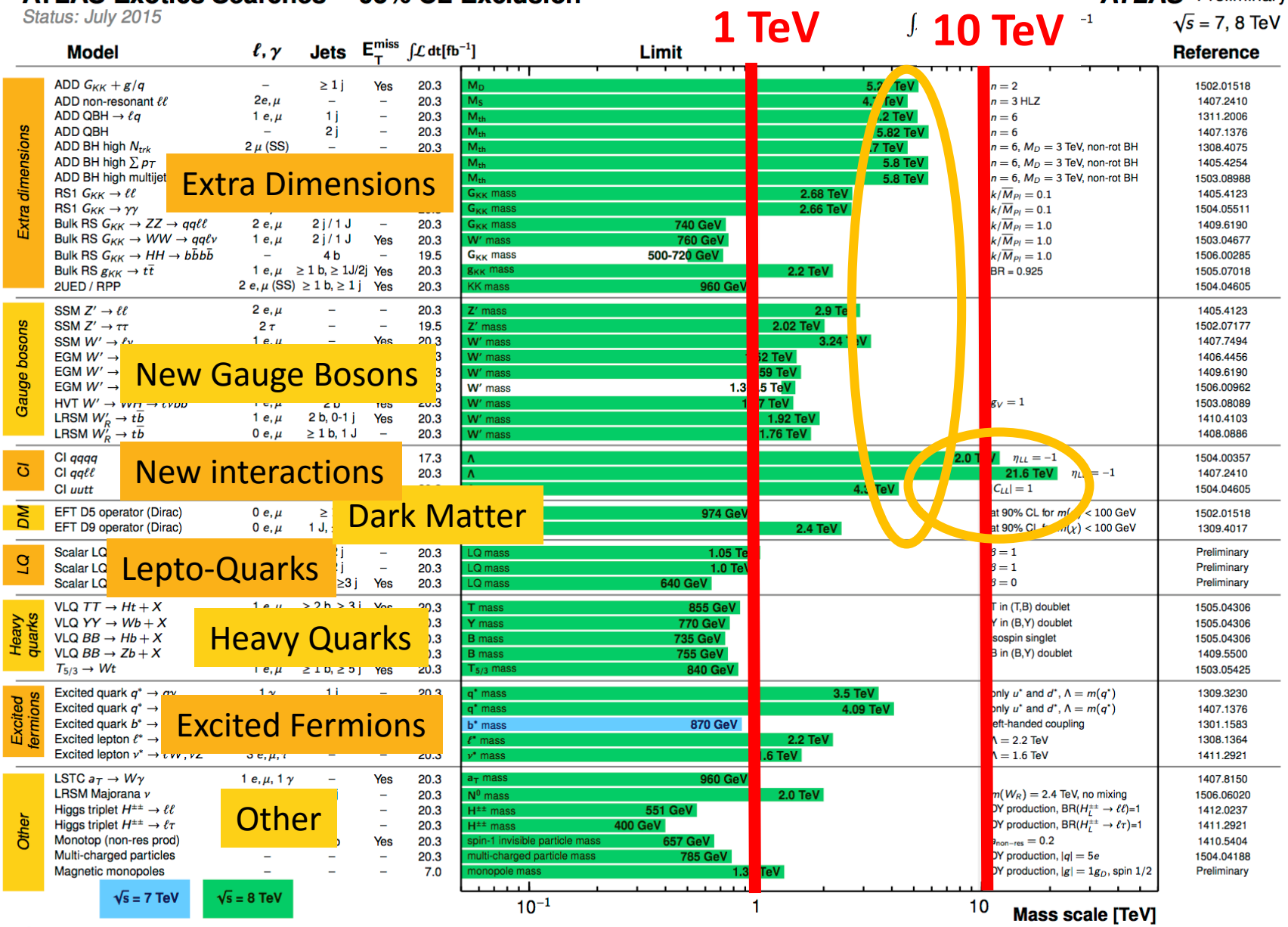
Exploration range of LHC by mid 2015



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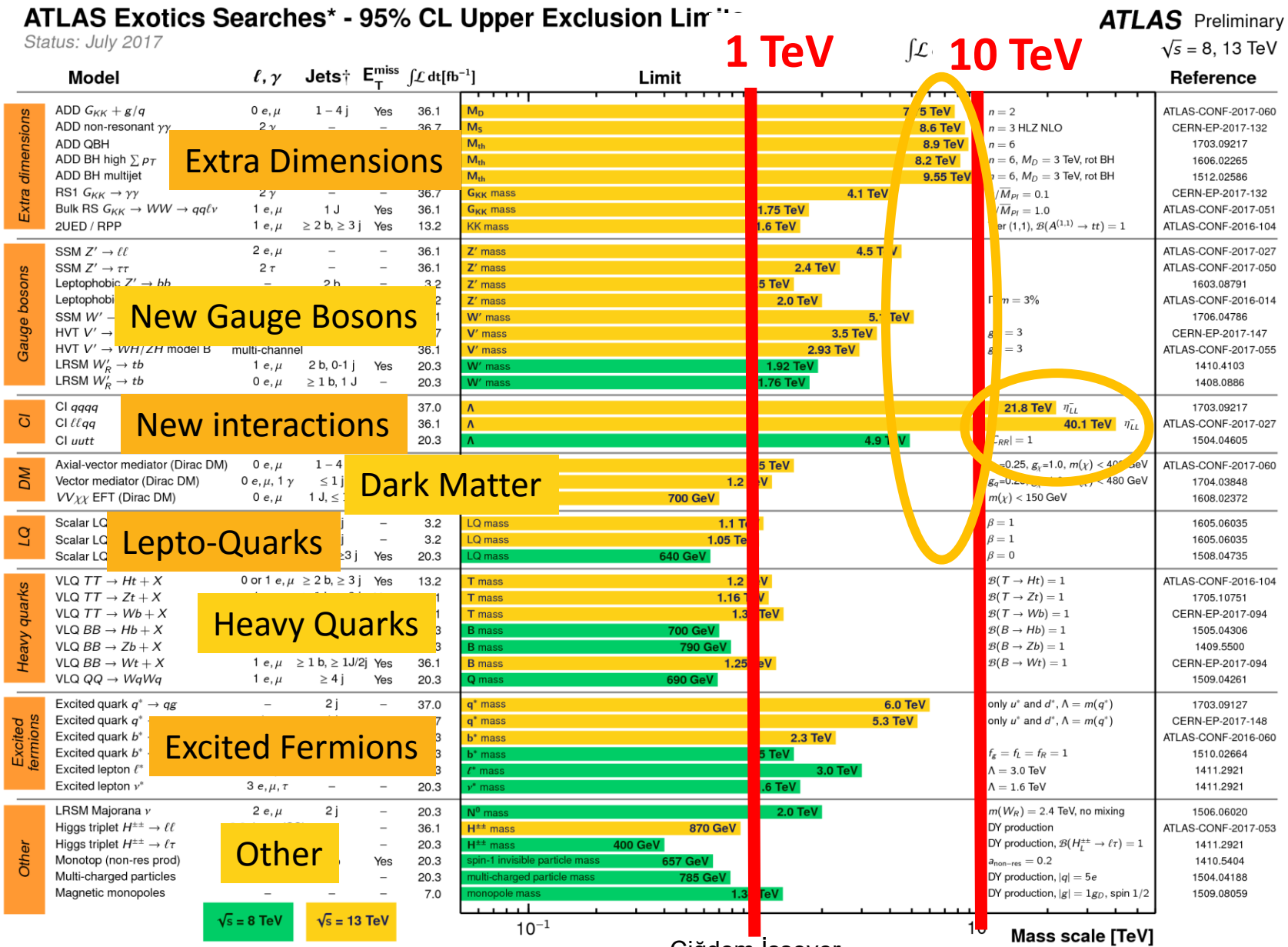
Exploration Range of the LHC by mid 2017



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†Small-radius (large-radius) jets are denoted by the letter j (J).

Çiğdem İşsever

At the beginning of our journey

~ 35 fb^{-1} data analysed

1% of what LHC + HL-LHC will deliver

Two new windows to probe nature...

Top-quark (1995, Tevatron)

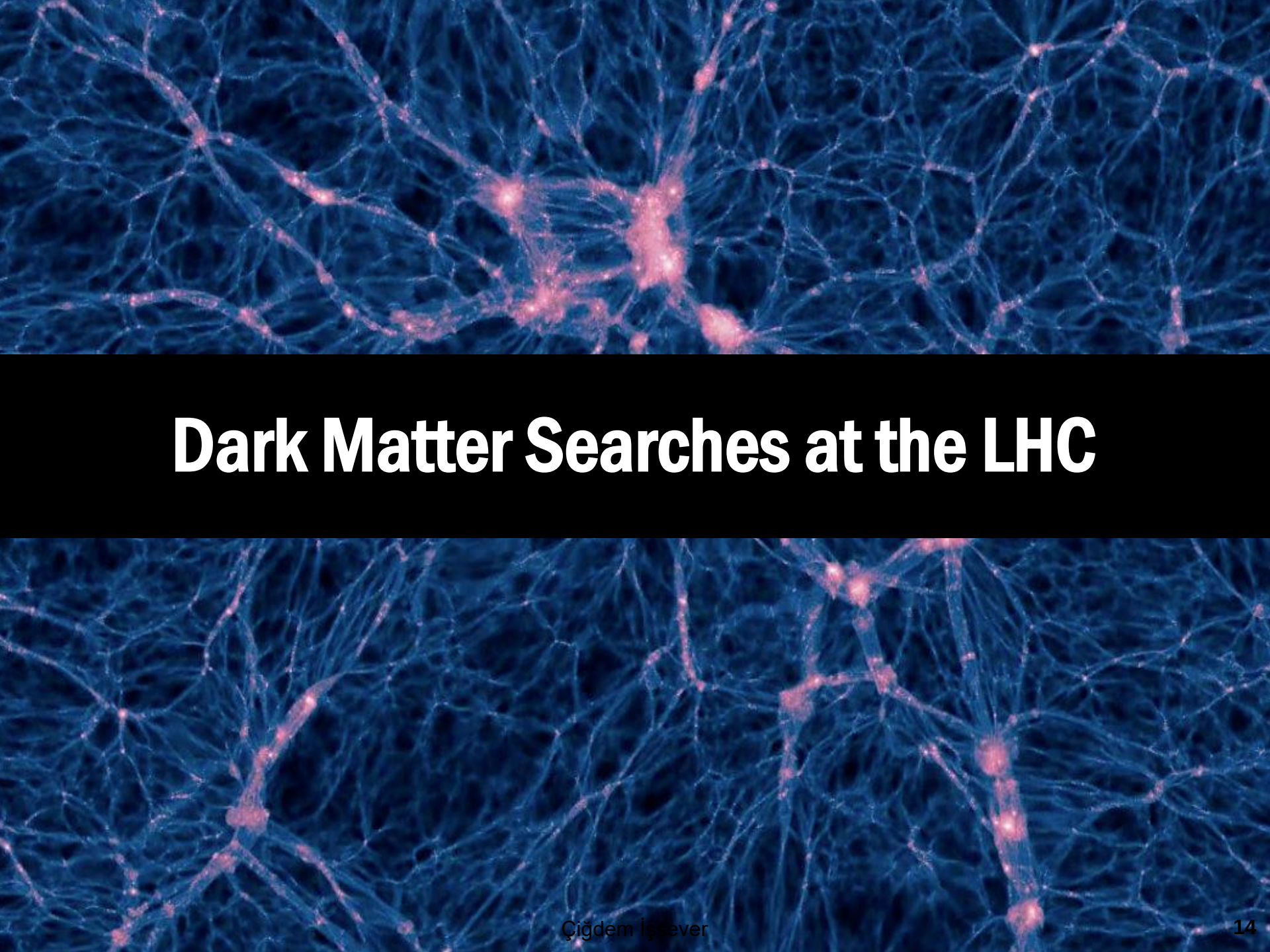
Higgs boson (2012, LHC)

Our “gravitational waves”....

Comment about the selection of results

Focus on one topic

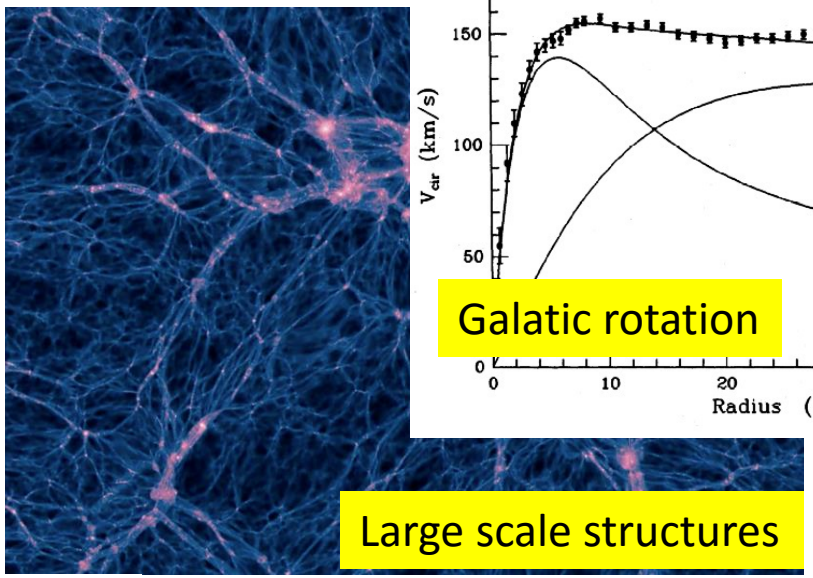
ATLAS Public Exotics Results are HERE
CMS Public Exotics Results are HERE
LHCb Public Exotics Results are HERE



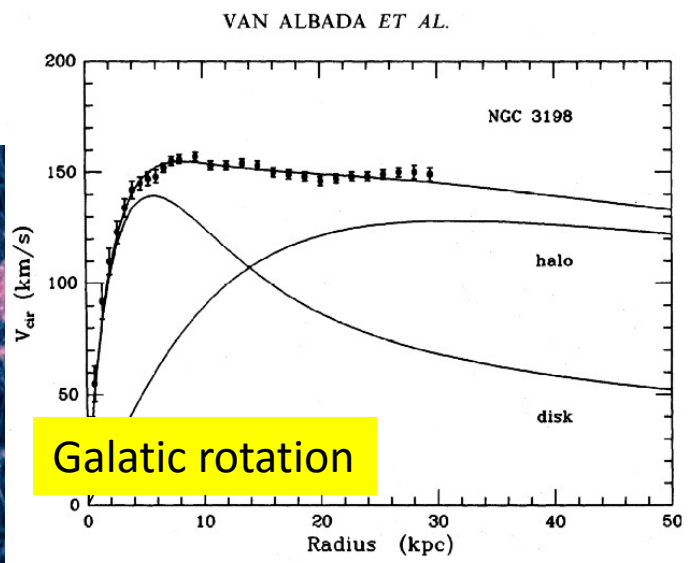
Dark Matter Searches at the LHC

Strong Evidence...

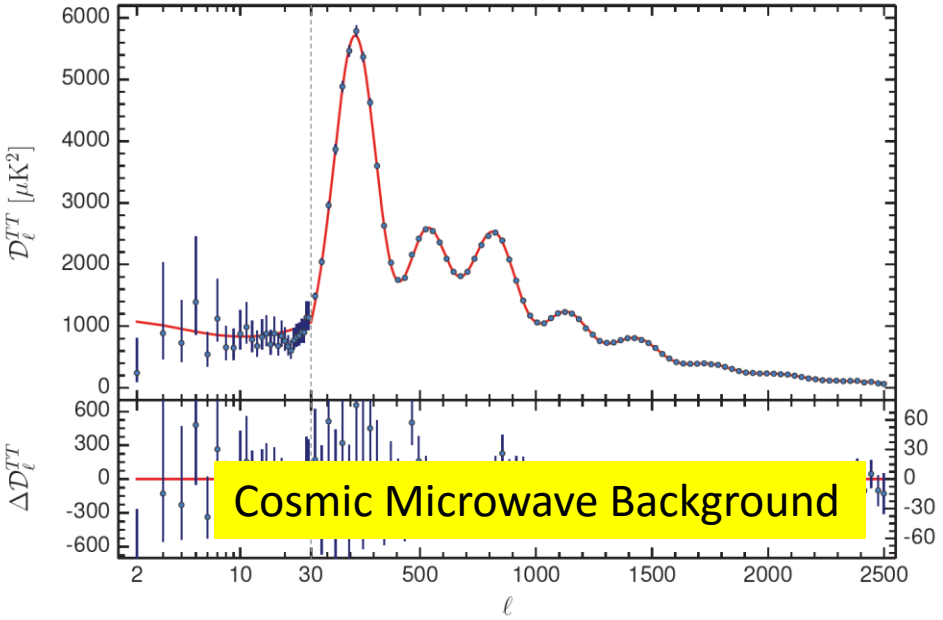
Gravitational Lensing



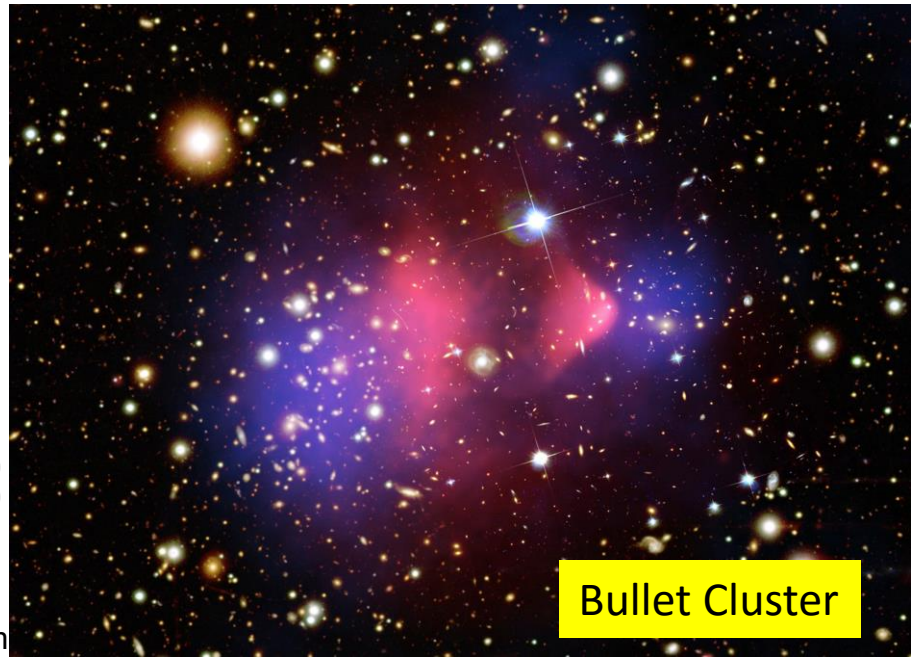
Large scale structures



Galatic rotation

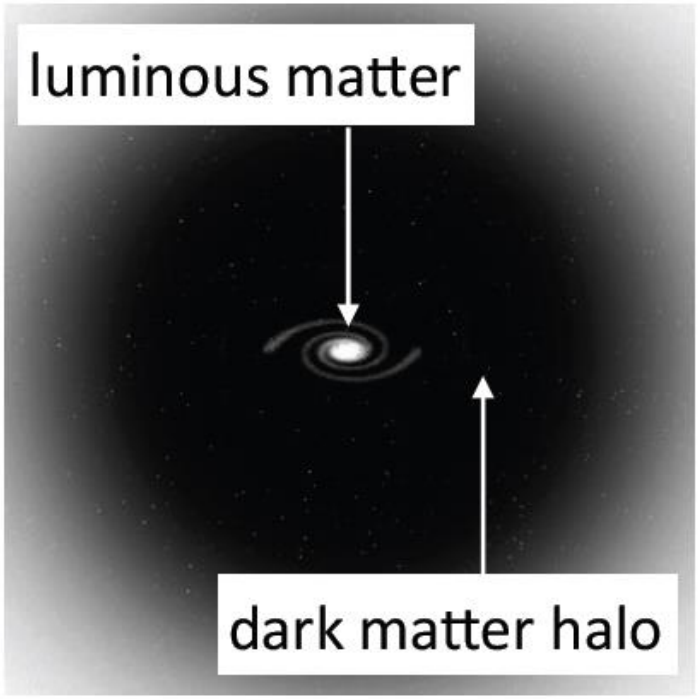


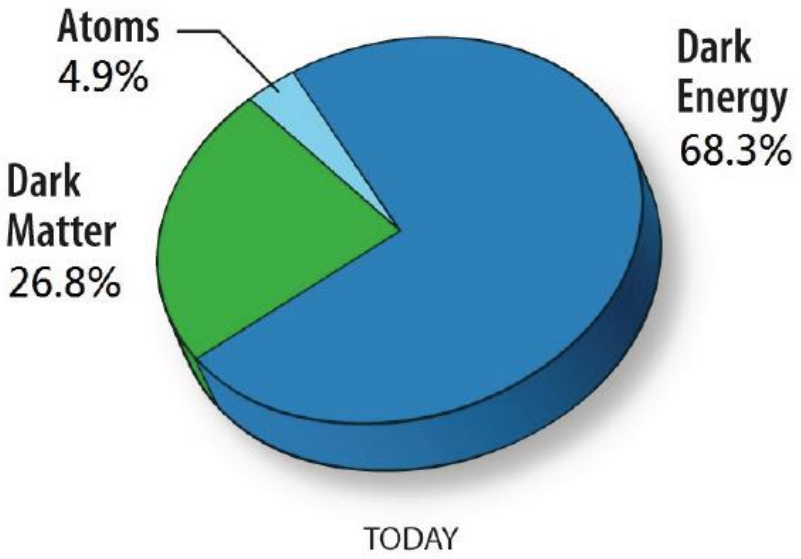
Cosmic Microwave Background



Bullet Cluster

What we know about Dark Matter



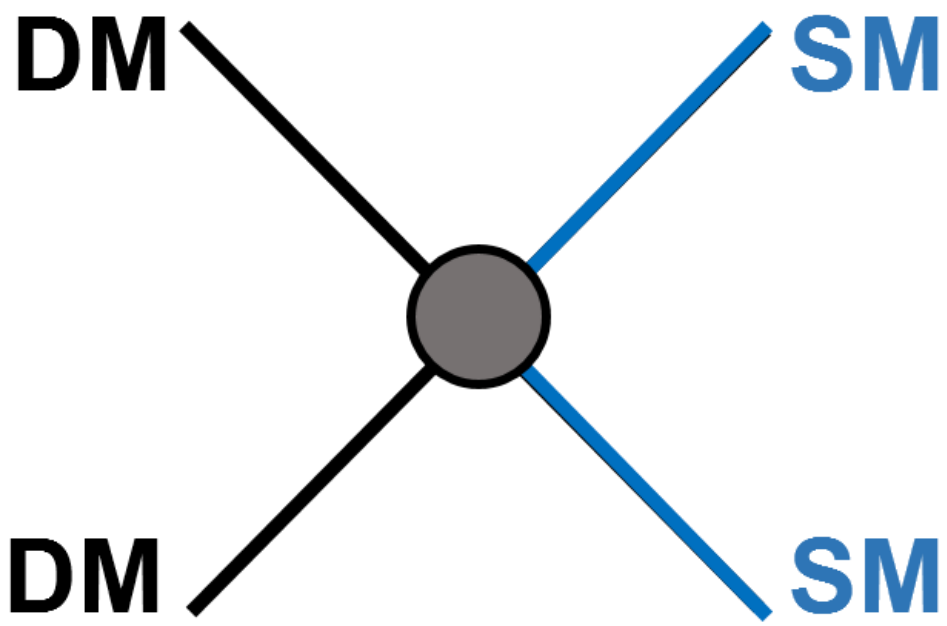


Strong astrophysical evidence for the existence of dark matter

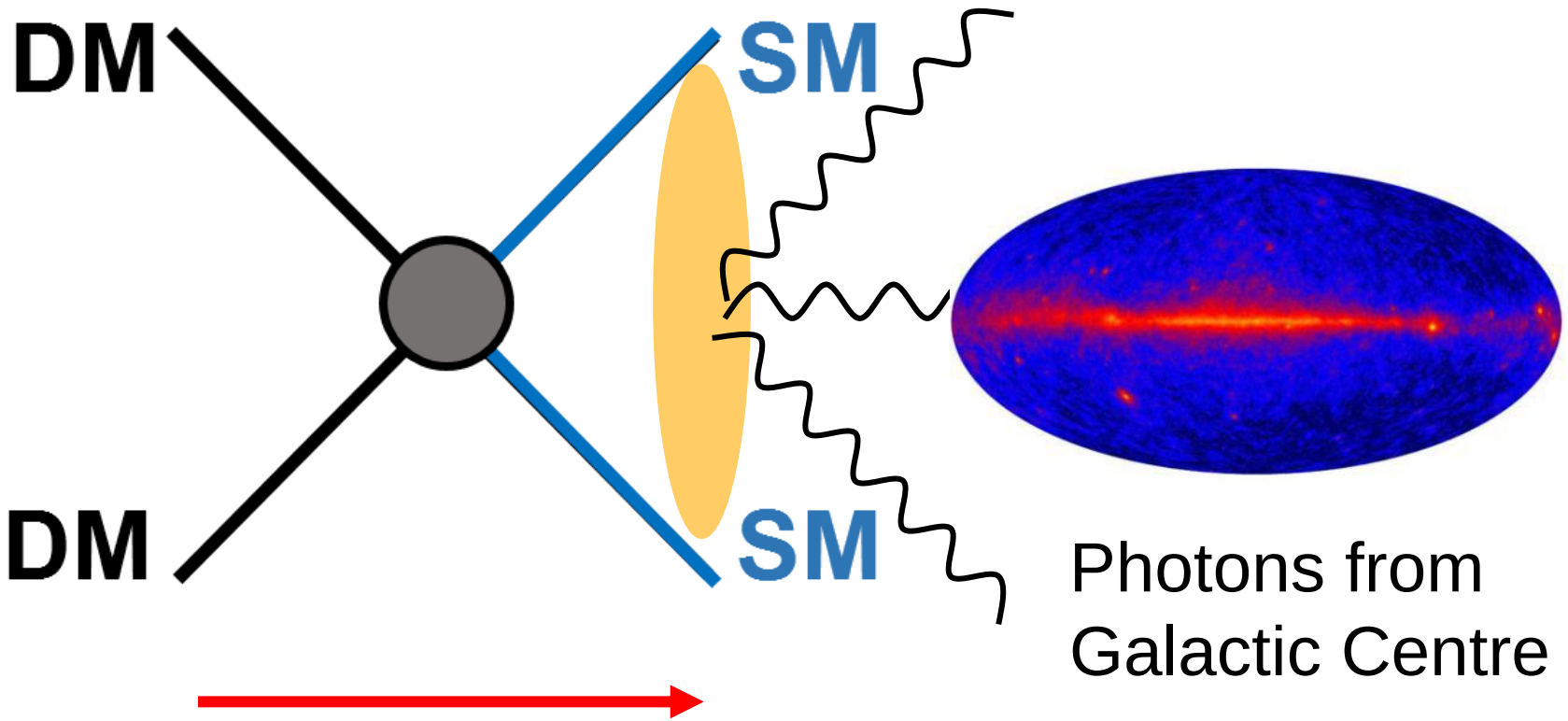
What we know about Dark Matter

- Massive
- Non-relativistic (slow)
- Long lived (old)
- No electric or colour charge
- Very weakly interacting with ordinary matter
- Subject to gravity interactions

Dark Matter (DM) interaction with ordinary matter (SM)

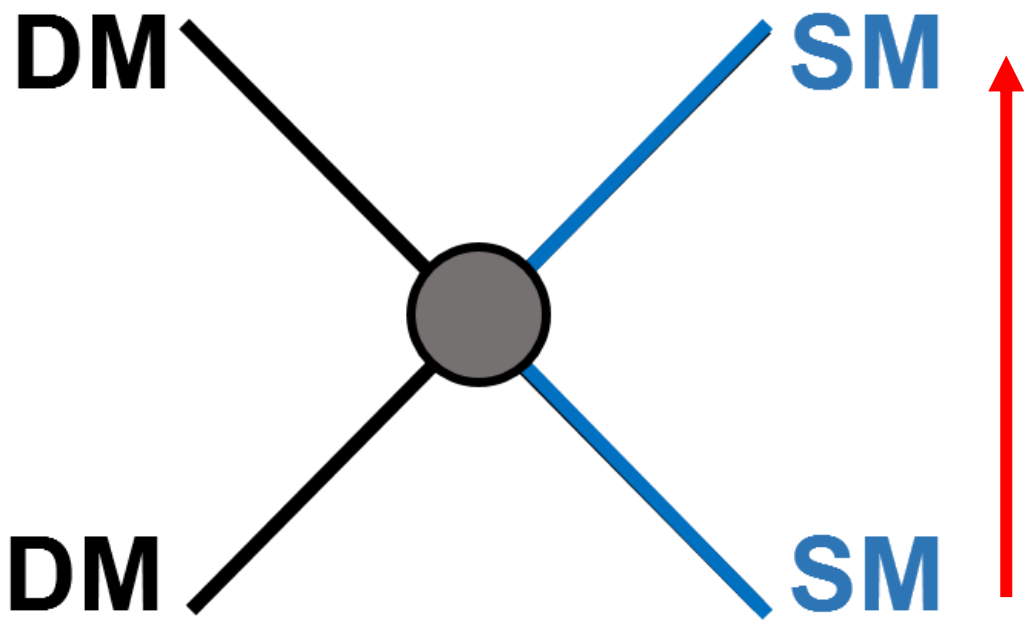


Experimental detection of Dark Matter

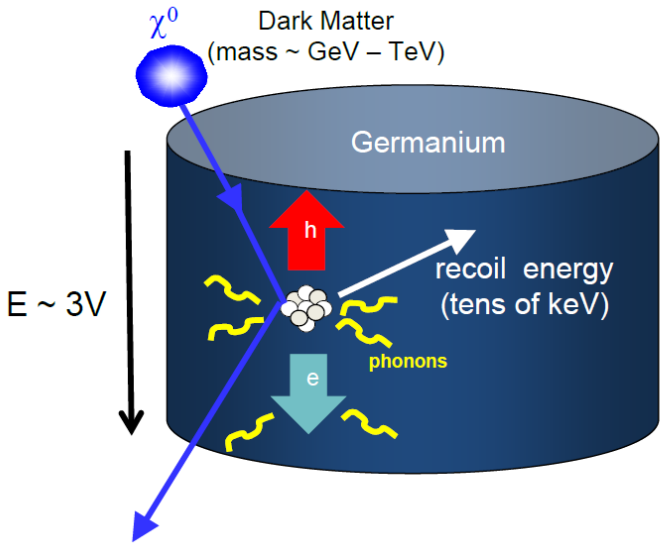


“break it”: indirect detection

Experimental detection of Dark Matter

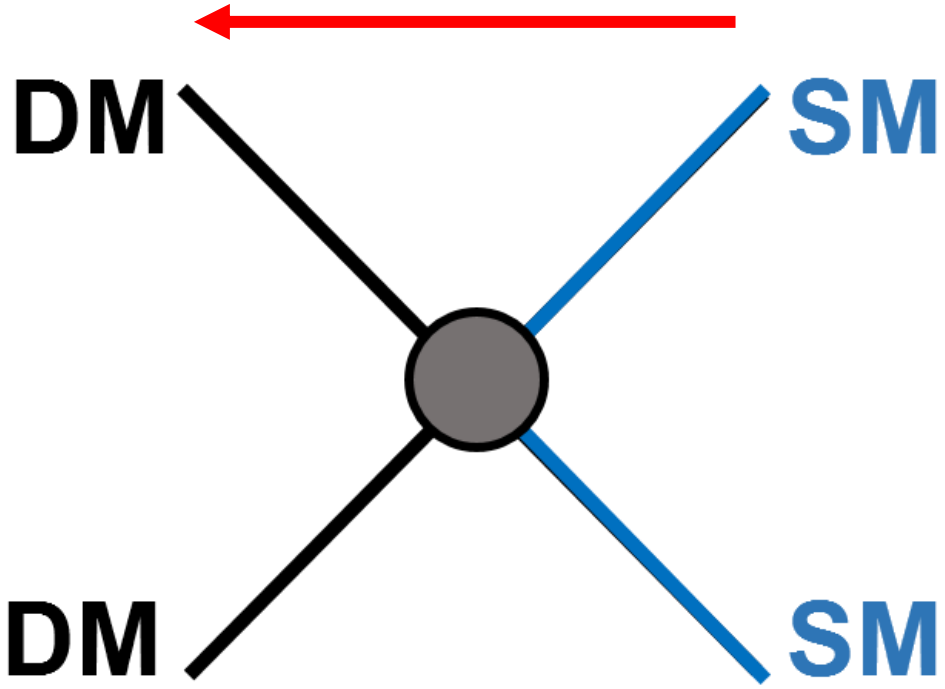


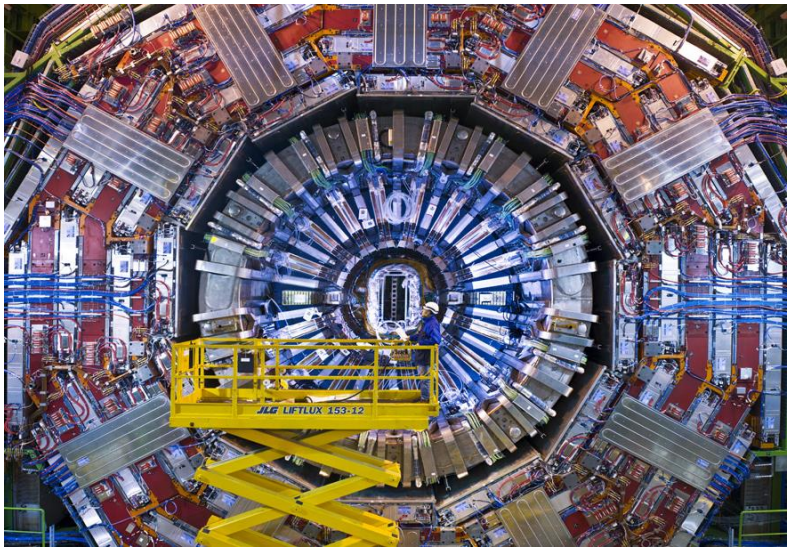
"shake it"
direct detection



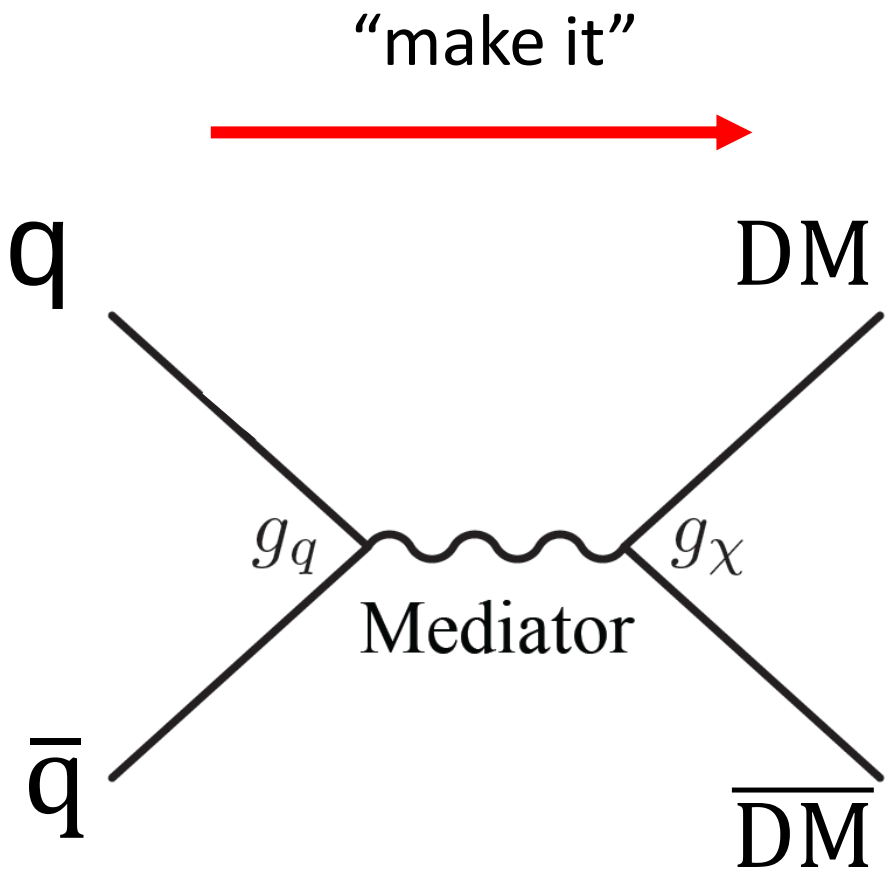
Experimental detection of Dark Matter

"make it": Collider Production



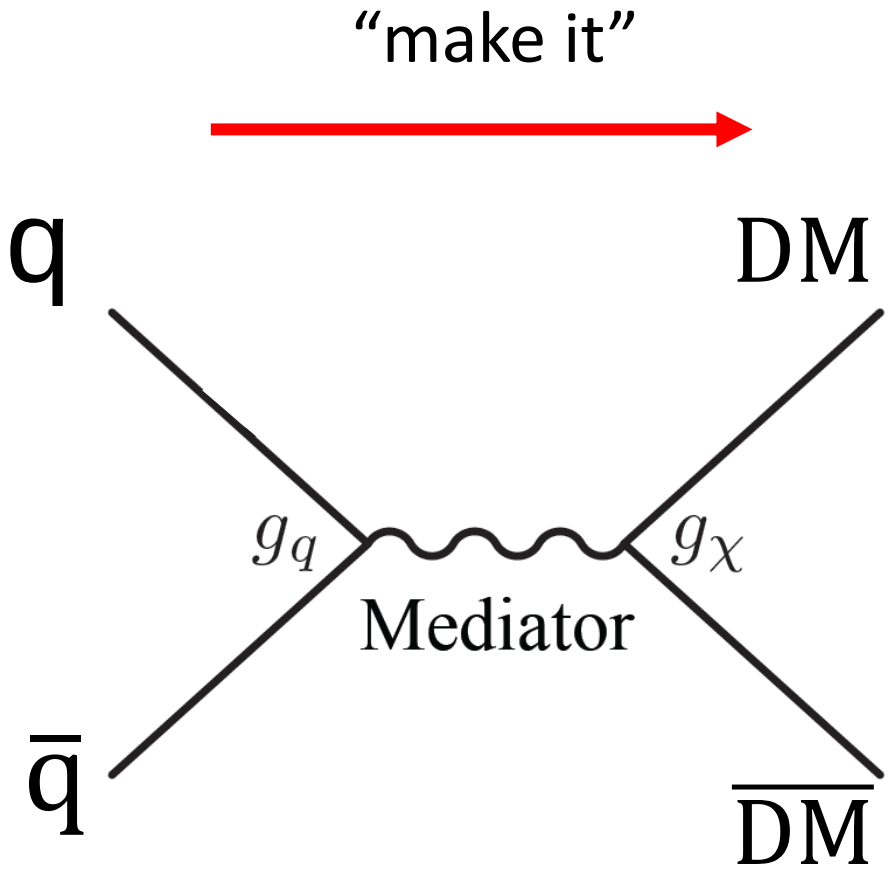


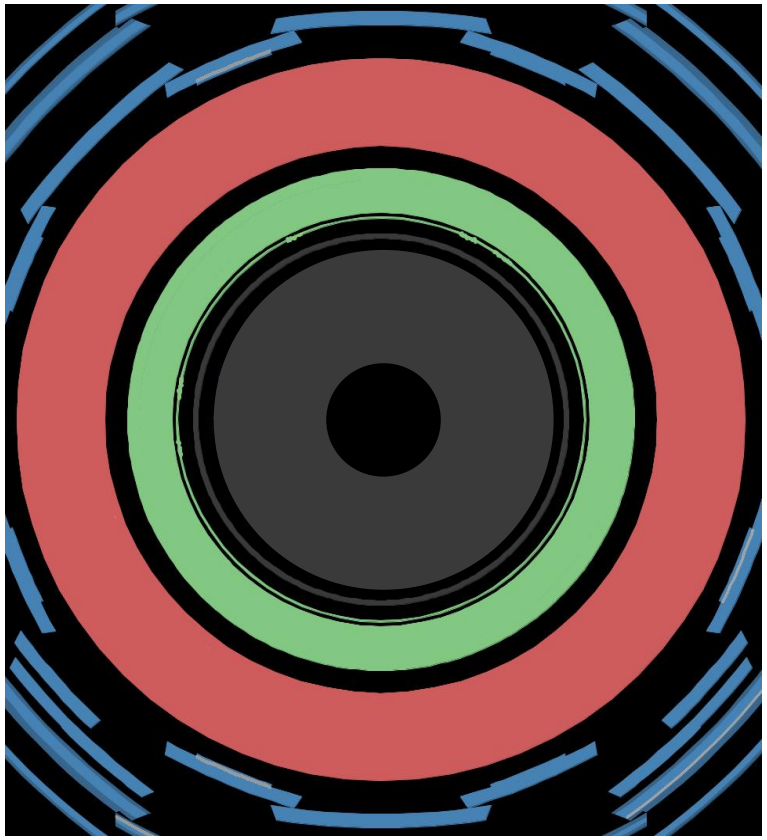
Dark Matter at Collider: Simplified Model



g_q and g_χ coupling strengths

Dark Matter at Collider: Simplified Model

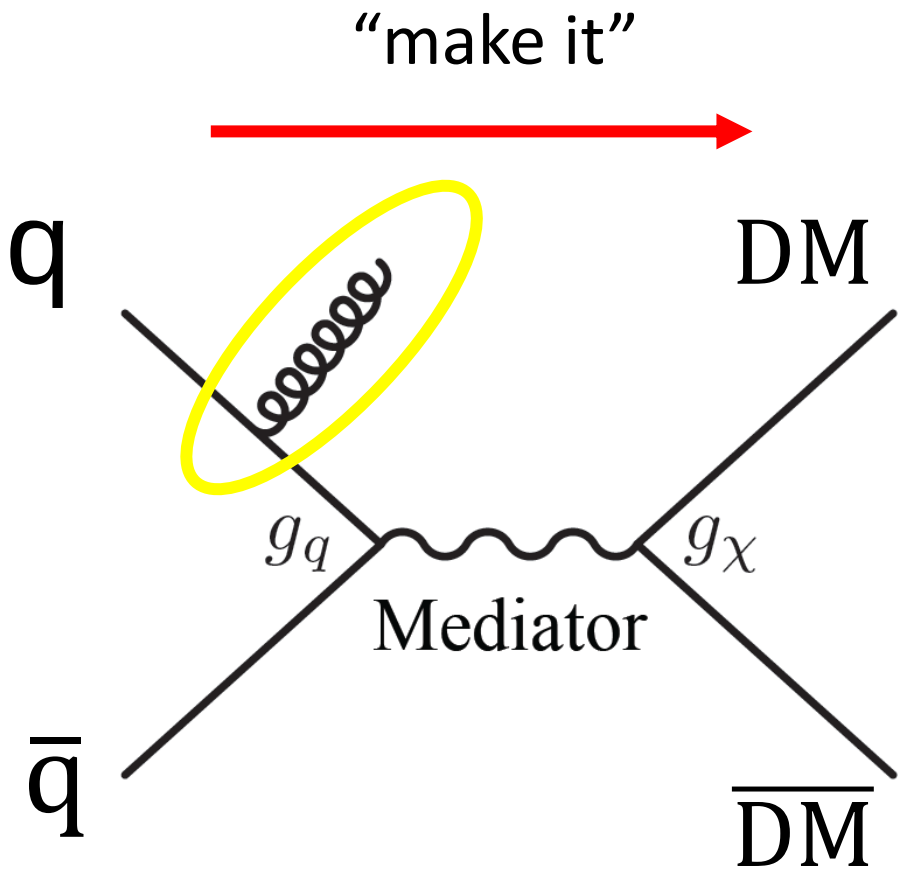


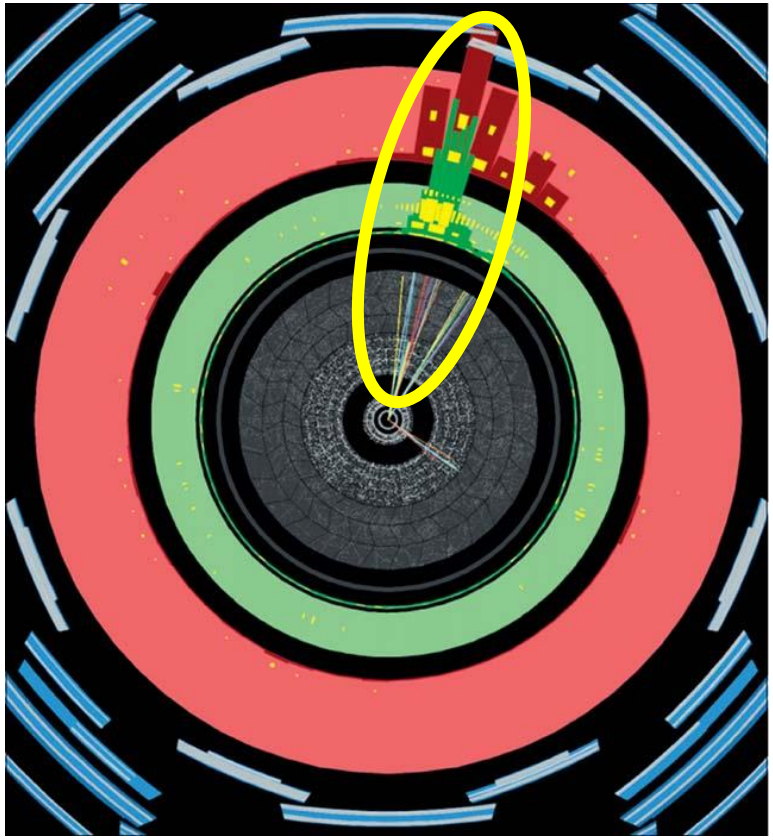


g_q and g_χ coupling strengths

Empty detector

Dark Matter at Collider: Simplified Model

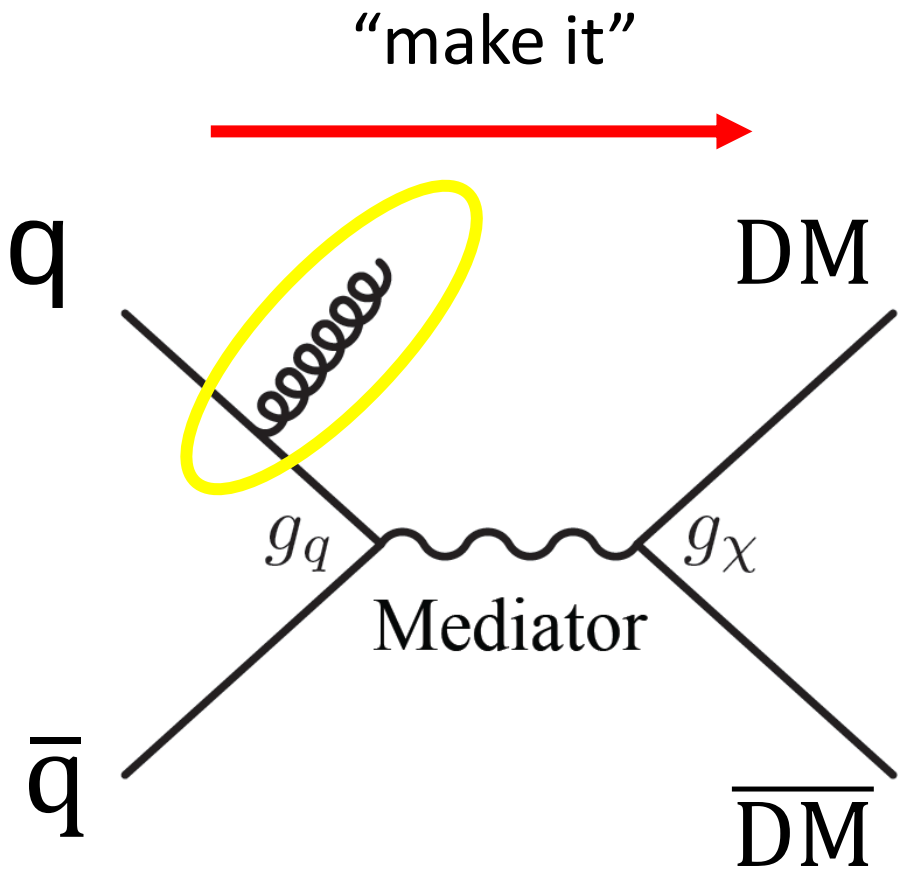


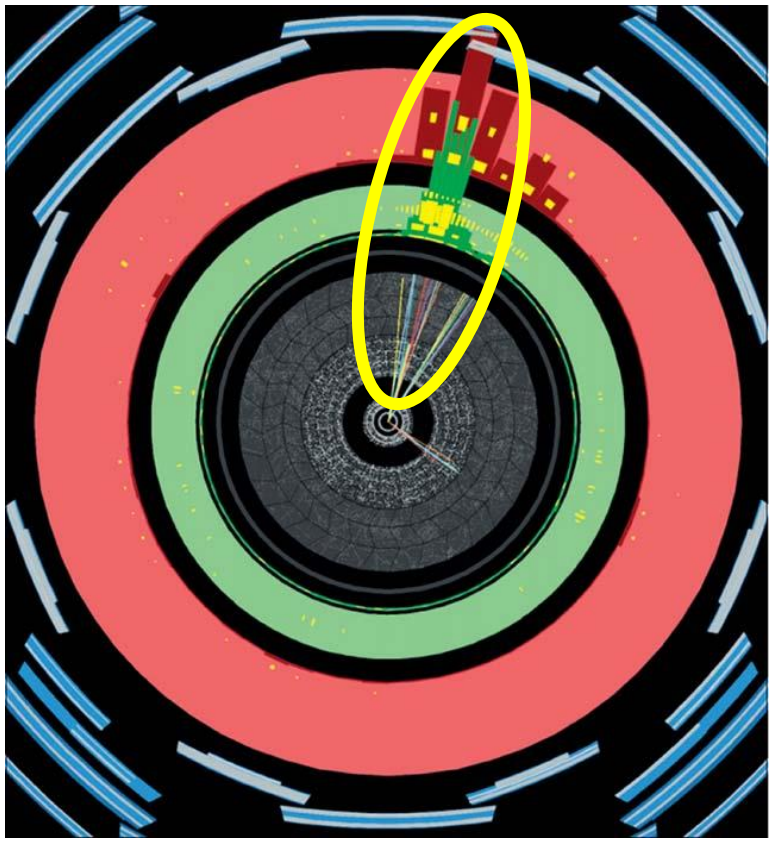


g_q and g_χ coupling strengths

Empty detector + something

Dark Matter at Collider: Simplified Model





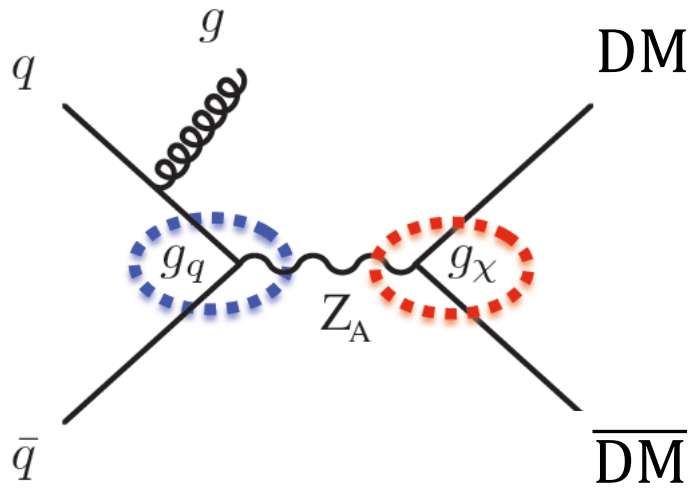
g_q and g_χ coupling strengths

Empty detector + something

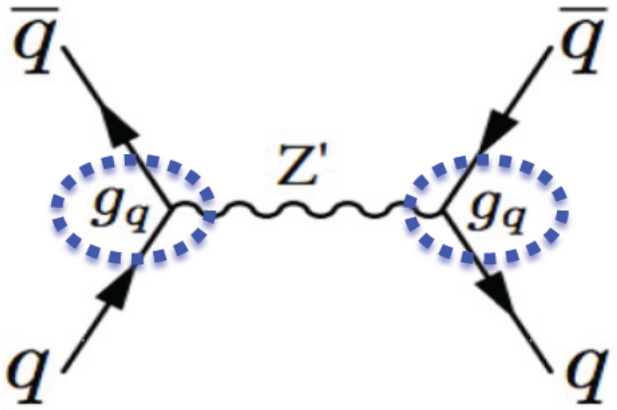
$$E_T^{miss} + X$$

Simplified Model

$SM \rightarrow mediator \rightarrow DM$

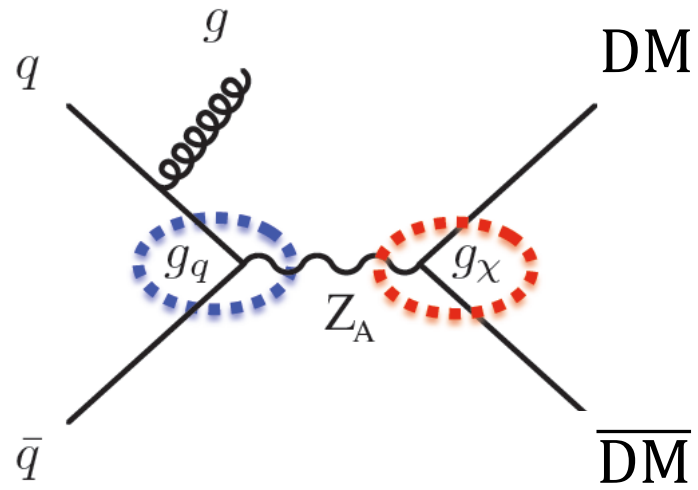


$SM \rightarrow mediator \rightarrow SM$



Simplified Model

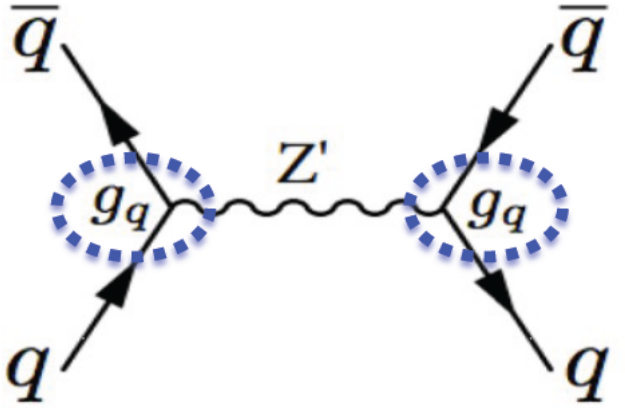
$SM \rightarrow mediator \rightarrow DM$



→Mono-X signature

E_T^{miss} + jet, W/Z/H, γ, …

$SM \rightarrow mediator \rightarrow SM$

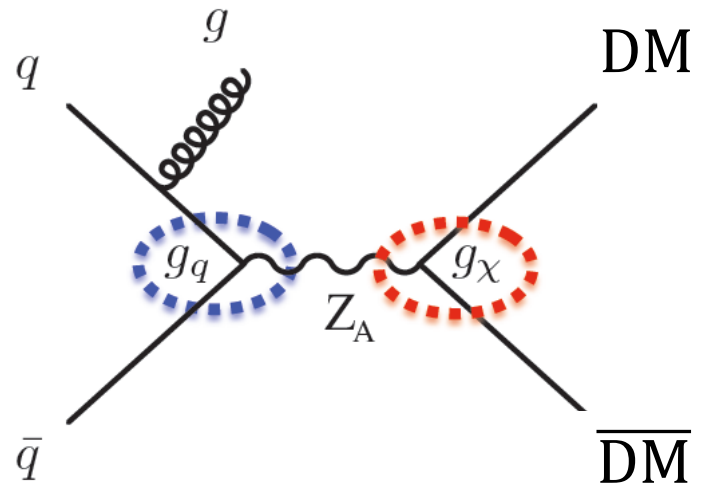


→resonant production

Dijet, ditop, dilepton…..

Simplified Model

$SM \rightarrow mediator \rightarrow DM$



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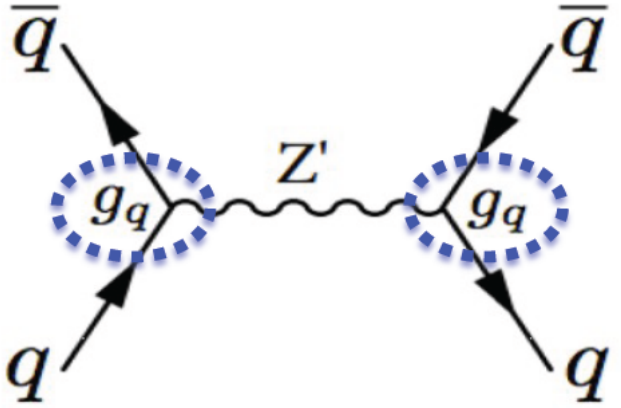
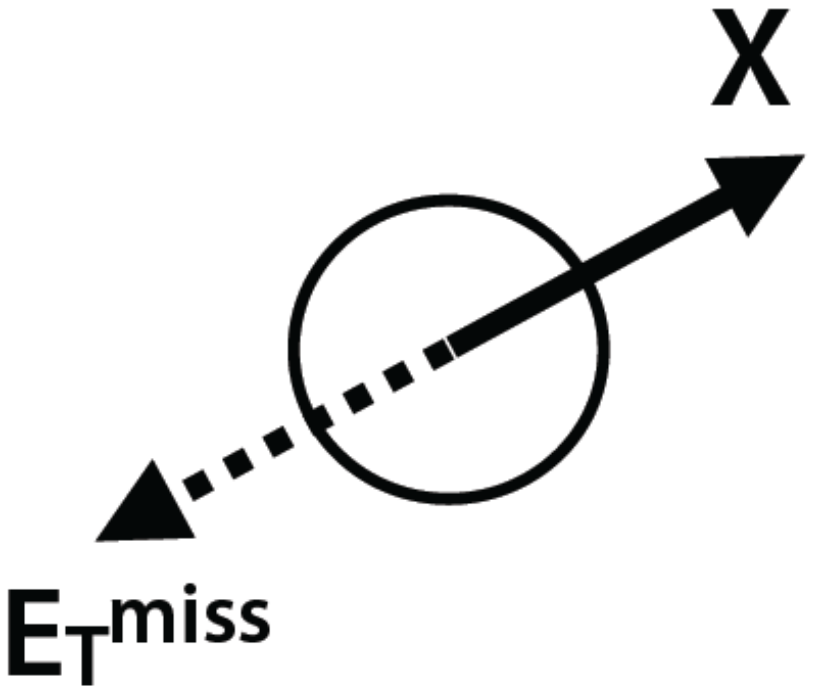


→resonant production

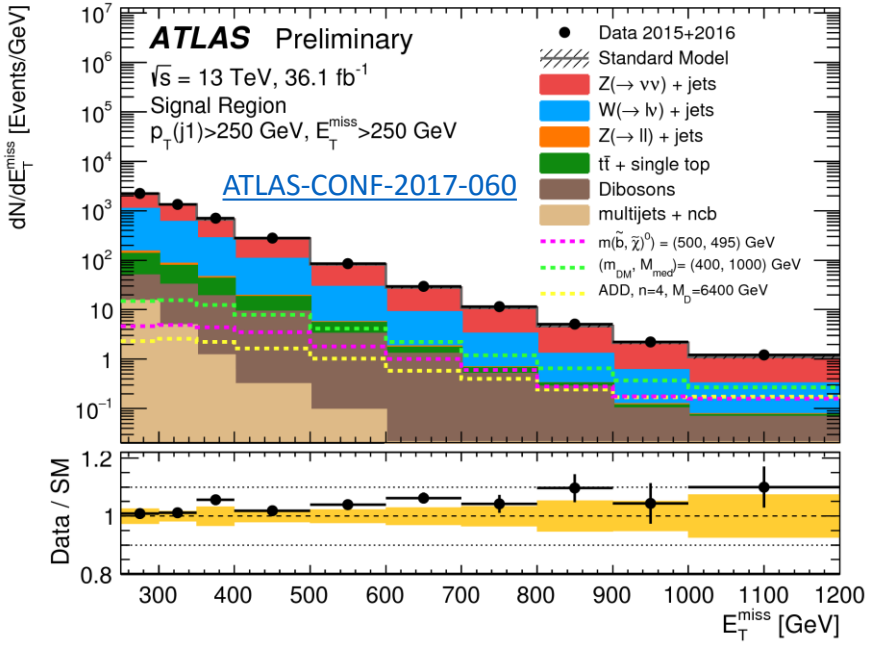
Dijet, ditop, dilepton…..

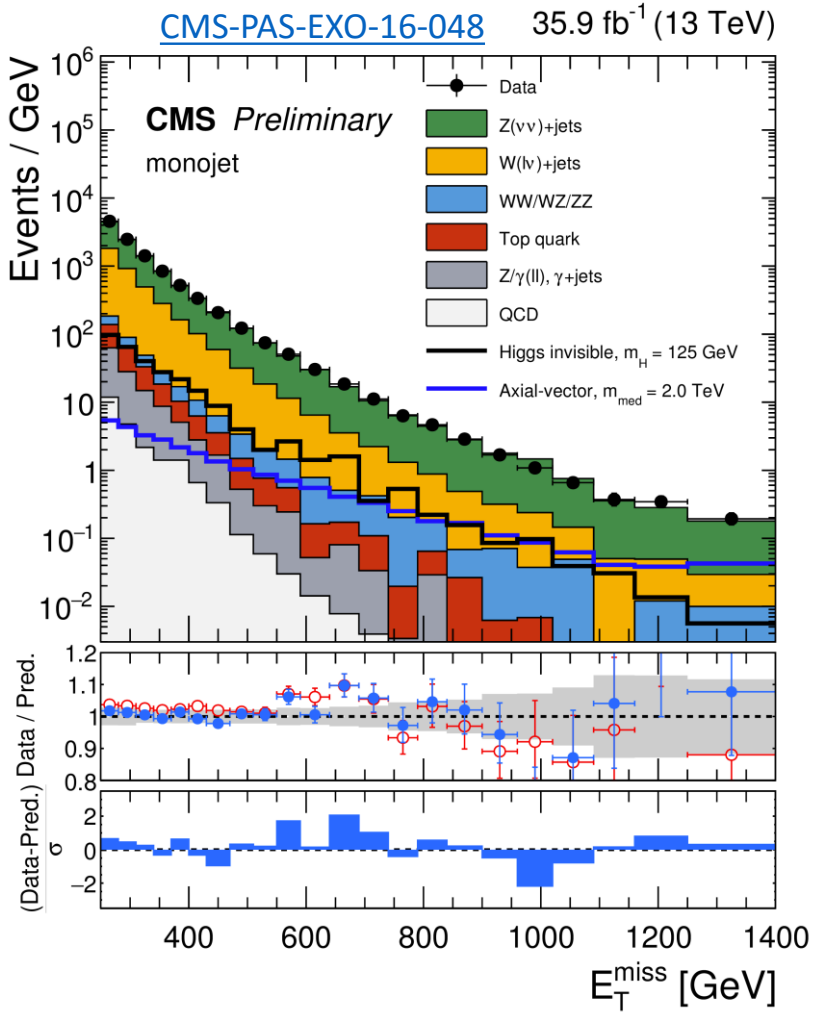
	spin 0		spin 1	
Charge	Q=0 for s-channel			
Lorentz structure	Scalar	$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	Vector	$g_q \sum_q V_\mu \bar{q} \gamma^\mu q$
	Pseudoscalar	$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f} \gamma^5 f$	Axial-vector	$g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma^5 q$
Coupling	∝ mass		∝ charge	

Mono-X Searches



Mono-jet





ATLAS

- $E_T^{miss} > 250$ GeV, $\Delta\varphi(\text{jet}, p_T^{miss}) > 0.4$
- Jet $p_T > 250$ GeV, $|\eta| < 2.4$
- $N_{jets} \leq 4$

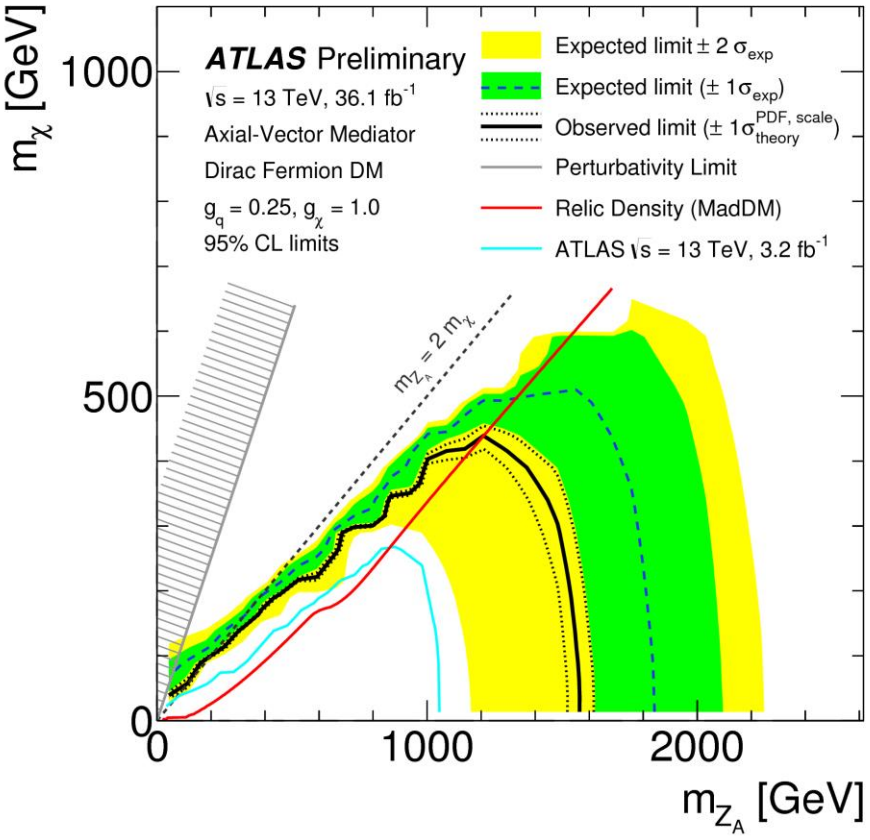
CMS

- $E_T^{miss} > 250$ GeV
- Jet $p_T > 100$ GeV, $|\eta| < 2.5$

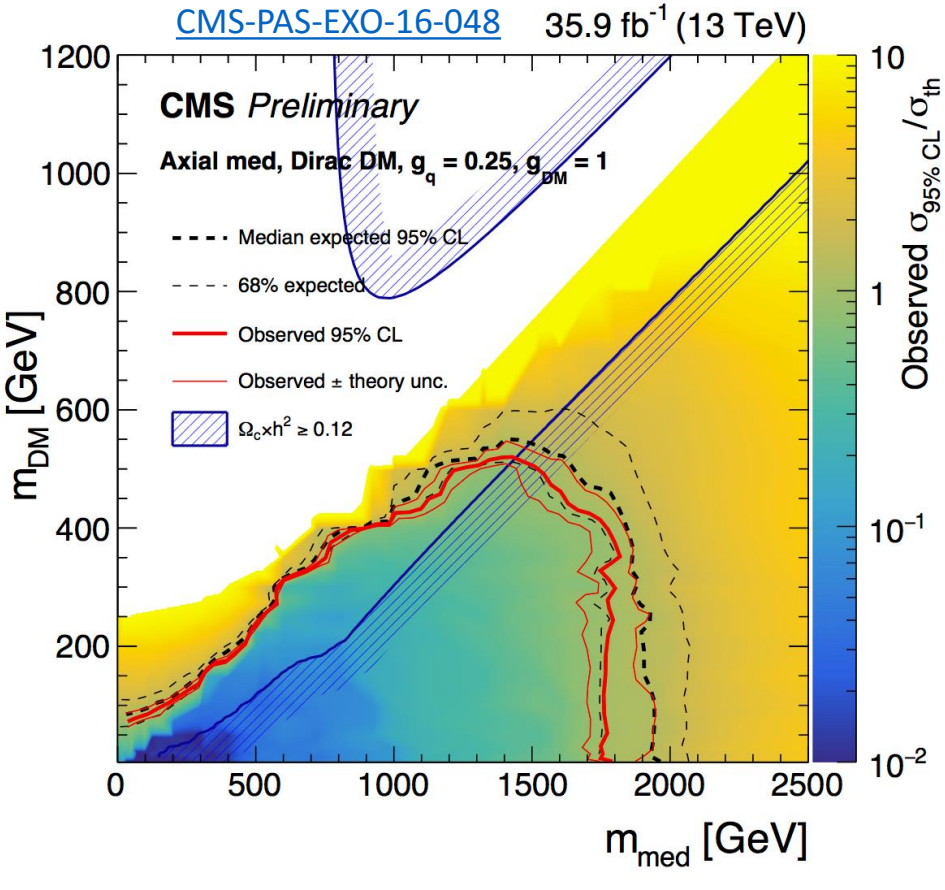
Mono-jet

Axial-vector mediator

ATLAS-CONF-2017-060



CMS-PAS-EXO-16-048

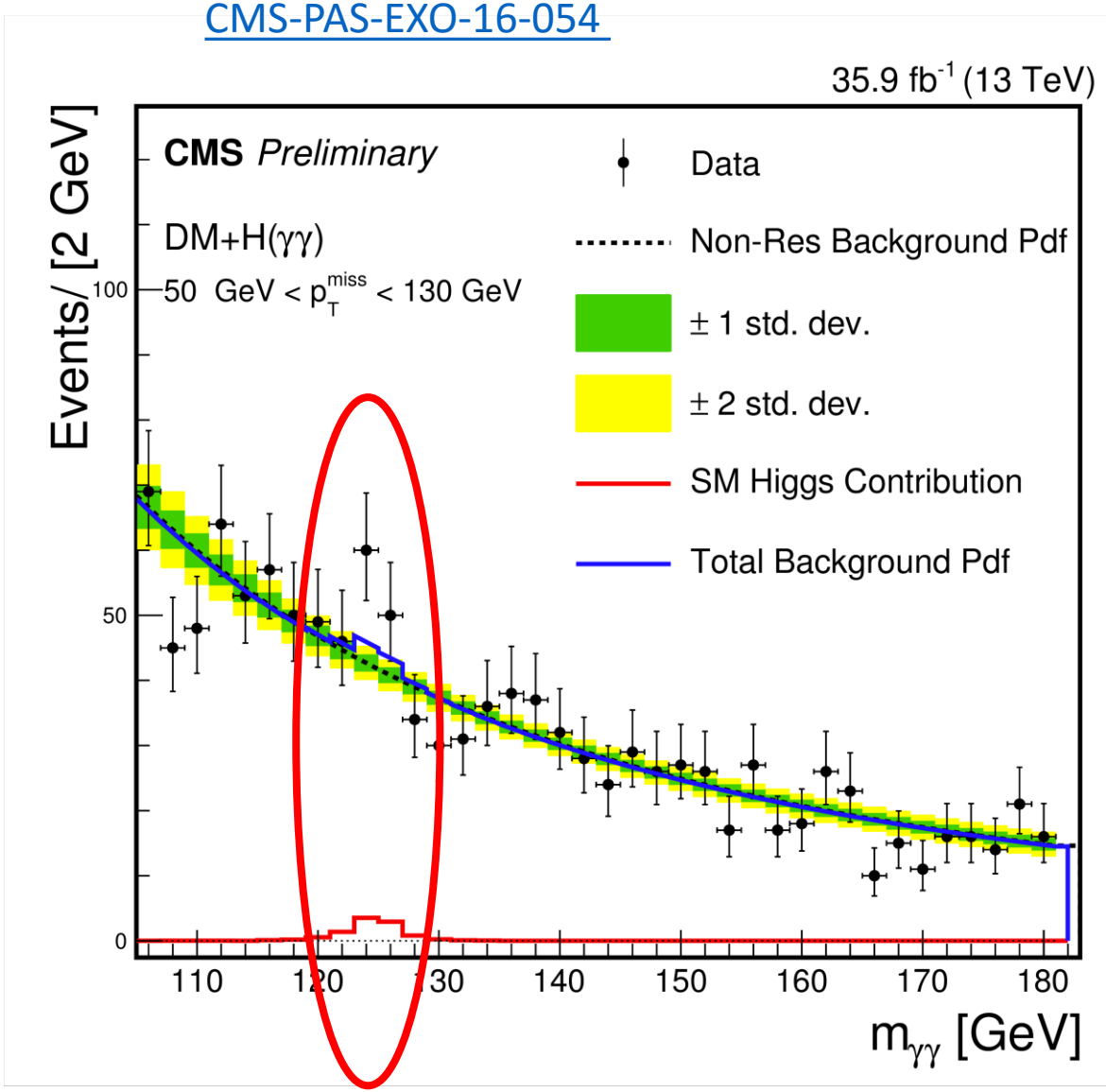


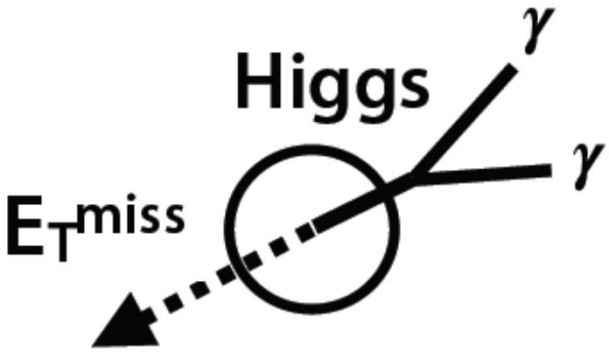
For vector and axial-vector interactions:

- Mediator mass excluded up to 1.6 – 1.8 TeV
- DM mass excluded up to 400 – 700 GeV

Mono-Higgs

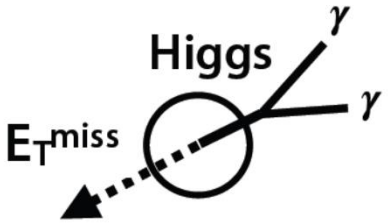
CMS-PAS-EXO-16-054

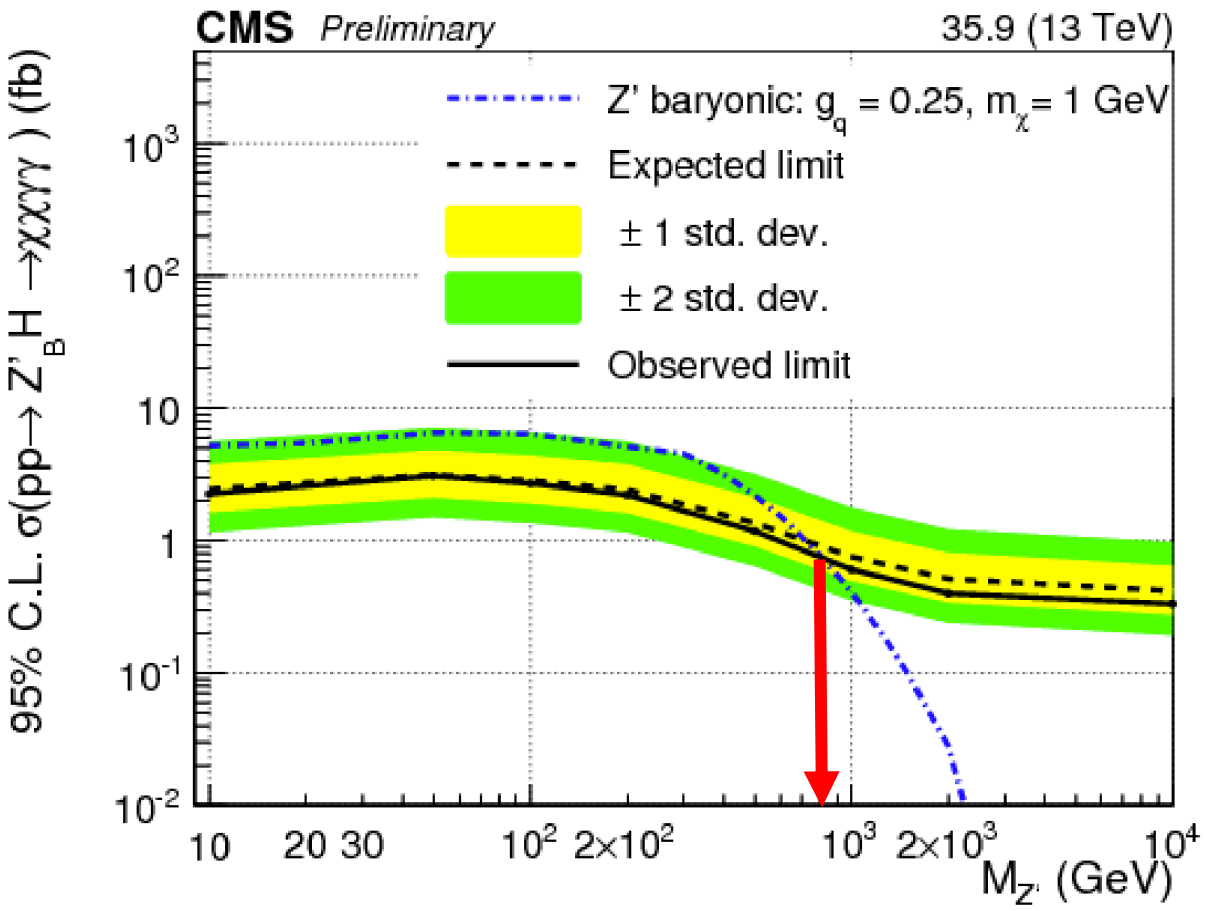


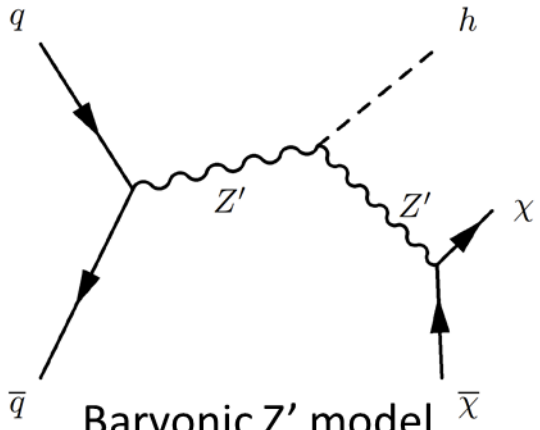


Mono-Higgs

CMS-PAS-EXO-16-054



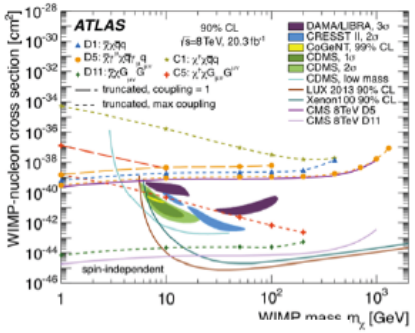




Baryonic Z' model
Non resonant

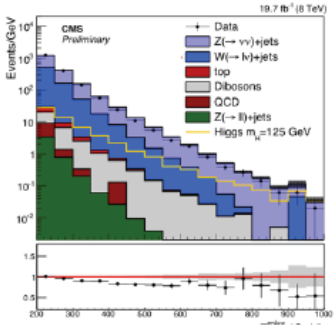
Mediator masses excluded up to 0.8 TeV for m(DM) = 1 GeV for baryonic Z' model

Mono-Mania!



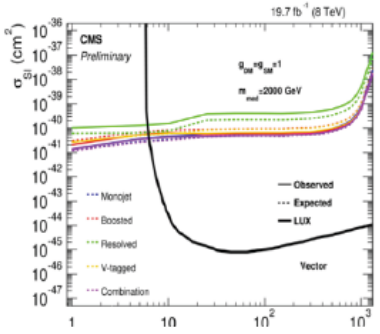
ATLAS Monojet

EPJC (2015) 75:299



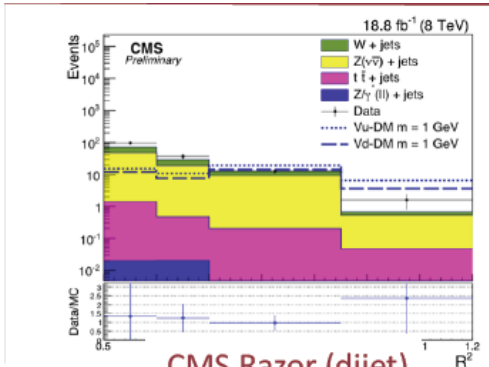
CMS j/V (mono/dijet)

PAS-EXO-12-055



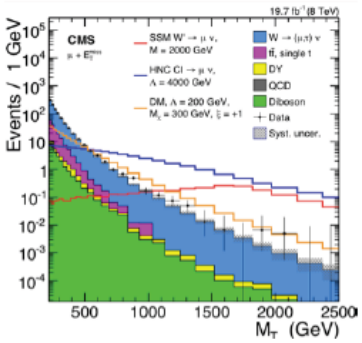
CMS j/V (mono/dijet)

PAS-EXO-12-055



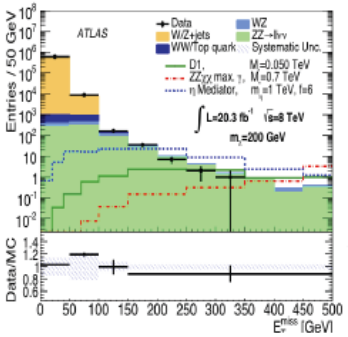
CMS Razor (dijet)

PAS-EXO-14-004



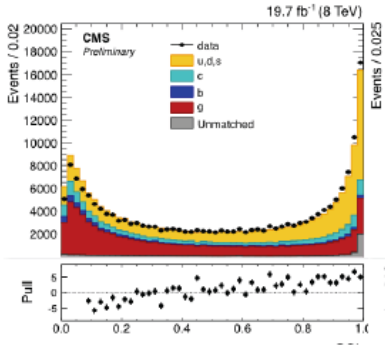
CMS, ATLAS MonoW

PRD 91, 092005, JHEP 09 (2014) 037 (2015)



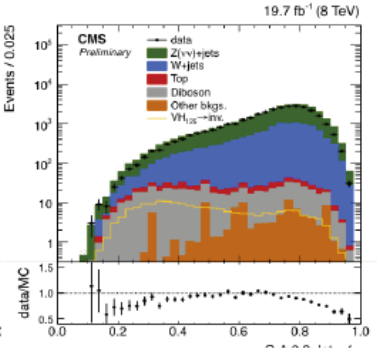
CMS, ATLAS MonoZ

EXO-12-054, PRD 90, 012004 (2014)



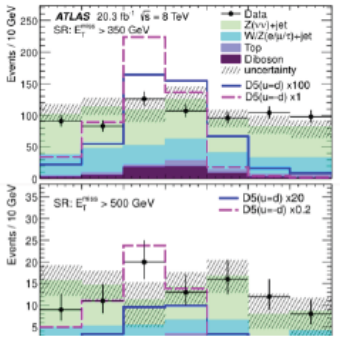
CMS MonoV (resolved)

PAS-EXO-12-005, PAS-JME-14-002



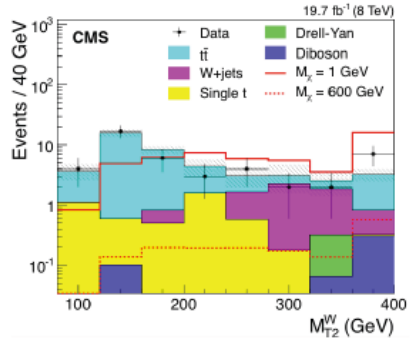
CMS MonoV (boosted)

EXO-12-005/JME-14-002



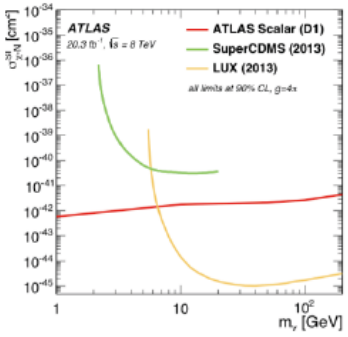
ATLAS MonoV (boosted)

ATLAS, PRL 112, 041802 (2014)



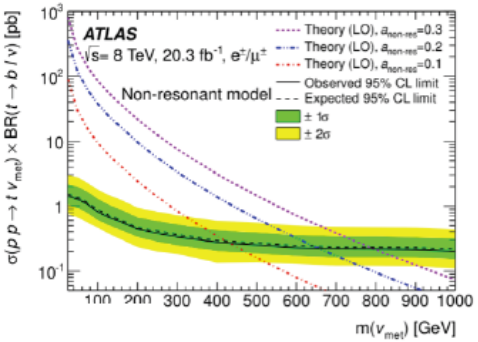
CMS TopPairs

CMS, JHEP 06 (2015) 121



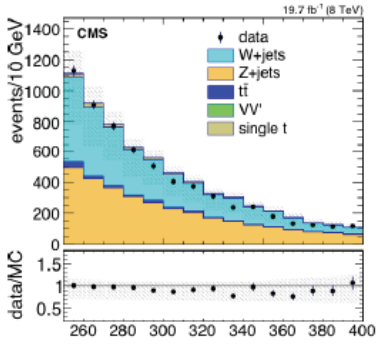
ATLAS TopPairs

ATLAS, EPJC (2015) 75:92



CMS MonoTop

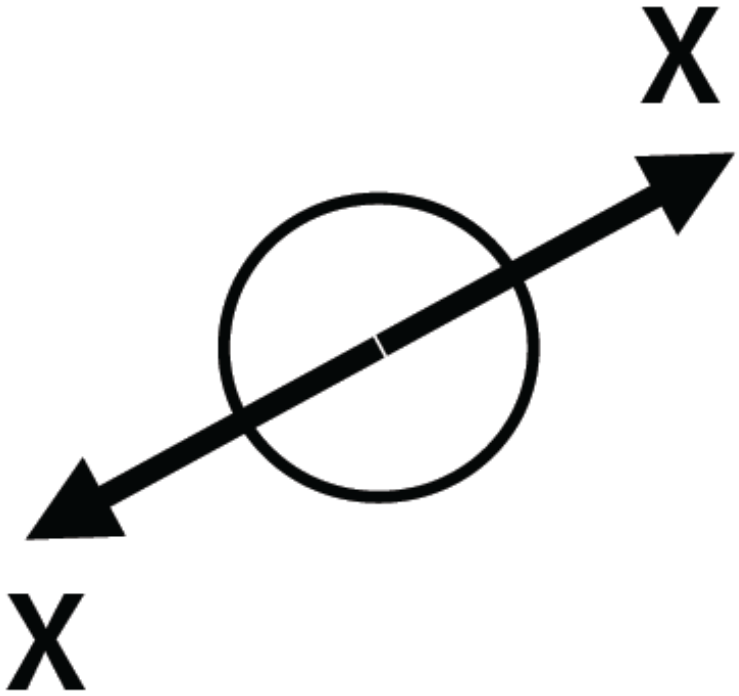
CMS, PRL 114 (2015) 101801



ATLAS MonoTop

ATLAS, JHEP 11 (2014) 118

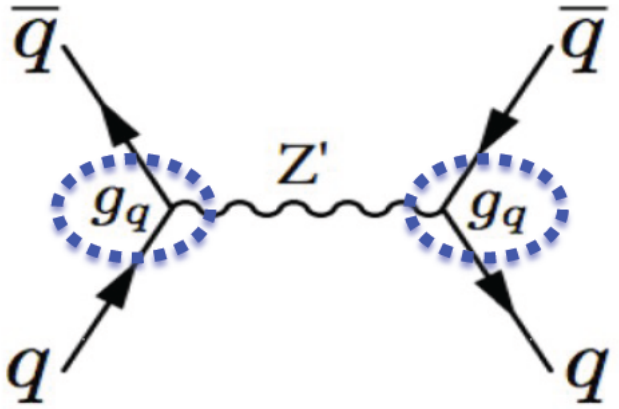
Mediator Searches

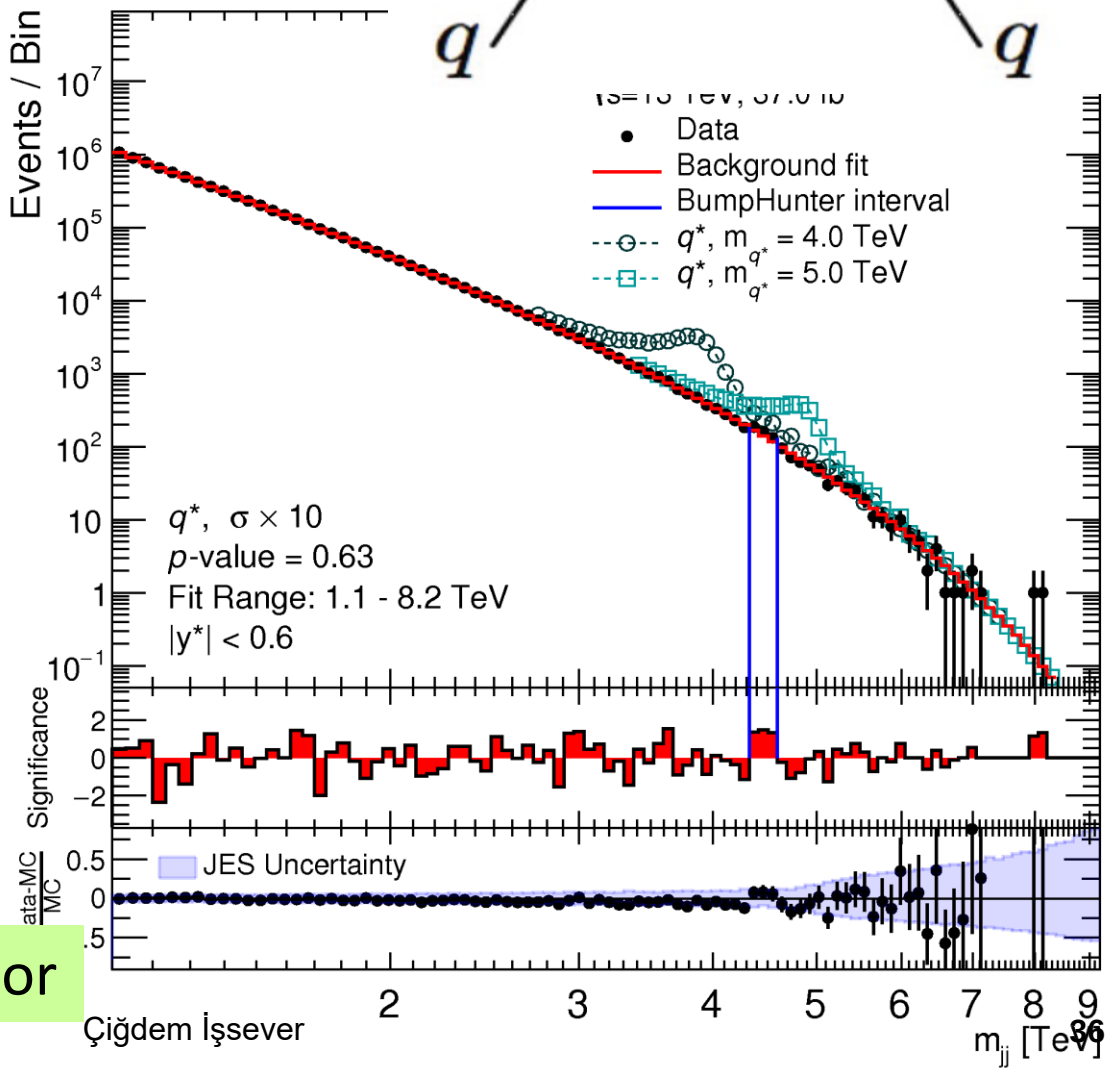


Di-jet searches

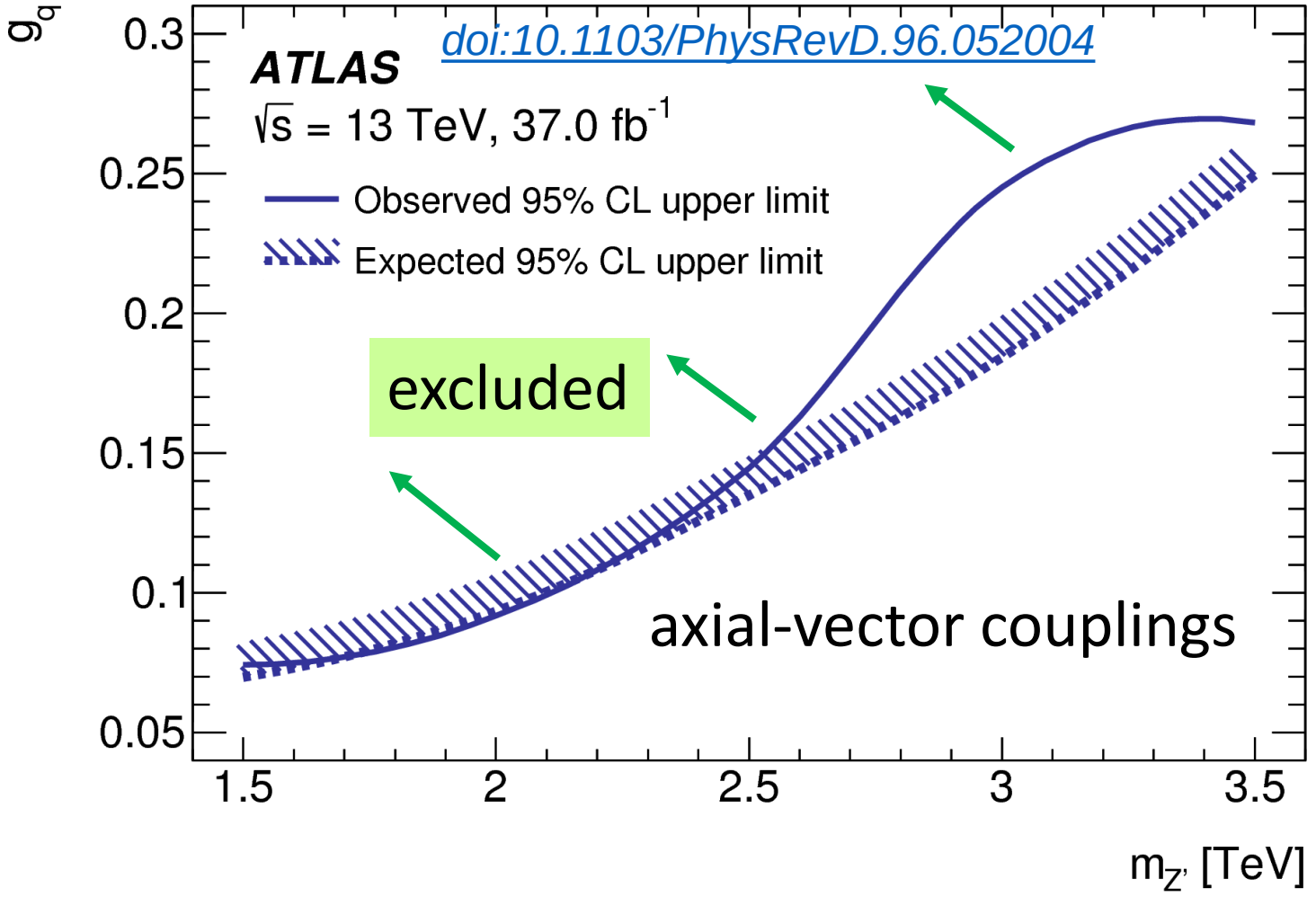
- Look for resonance above fit
- Analysis limited by trigger
  - 1-jet trigger E_T ~ 380 GeV
  - Implies m(jj) > 1.1. TeV
- Dedicated analysis used for lower-mass searches

Strong limits on DM mediator





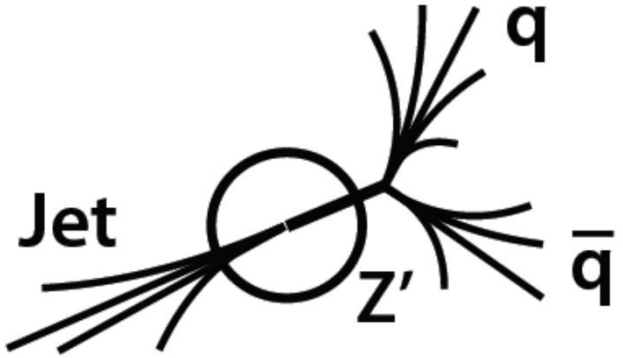
High-mass dijet searches



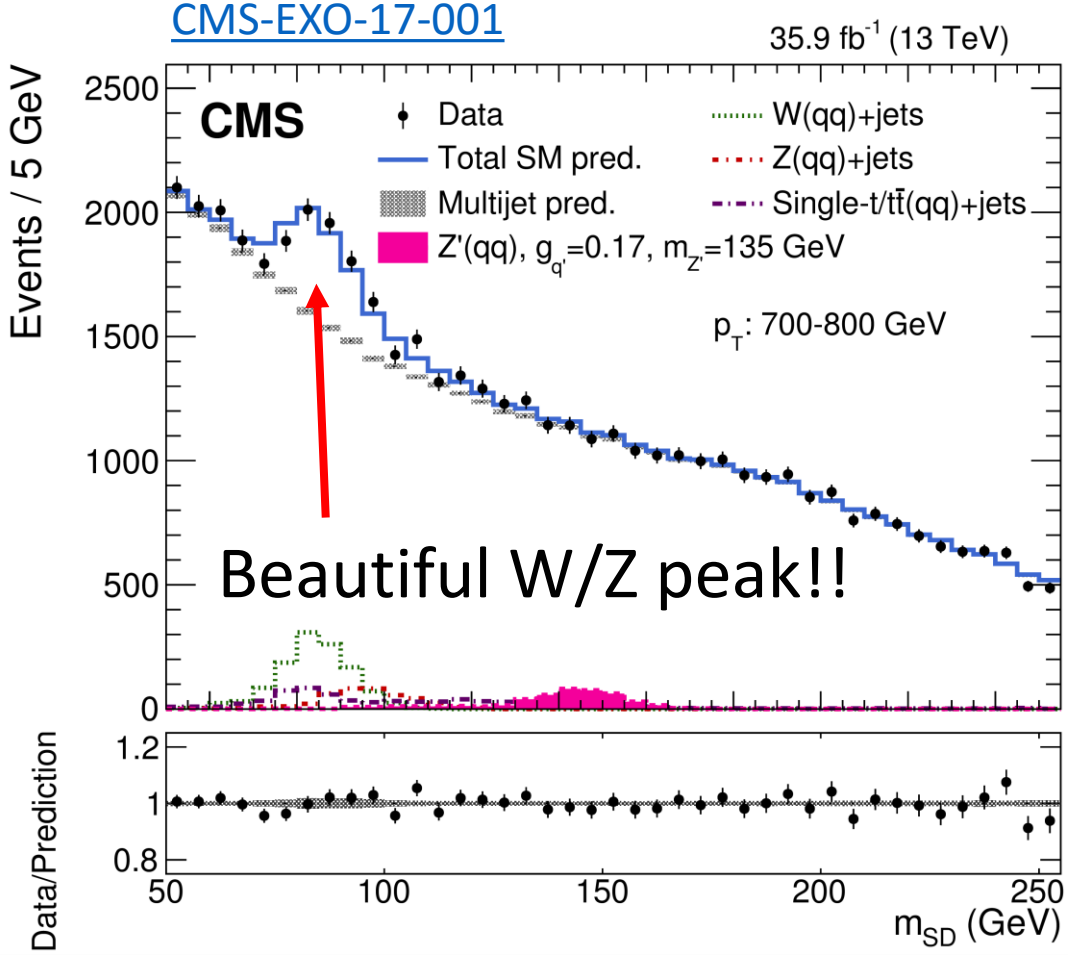
Mediator masses excluded between 1.5 TeV and 3.5 TeV
Couplings excluded between 0.07 and 0.28

Low-mass di-jet searches

Search for low-mass particles using ISR boost



CMS-EXO-17-001

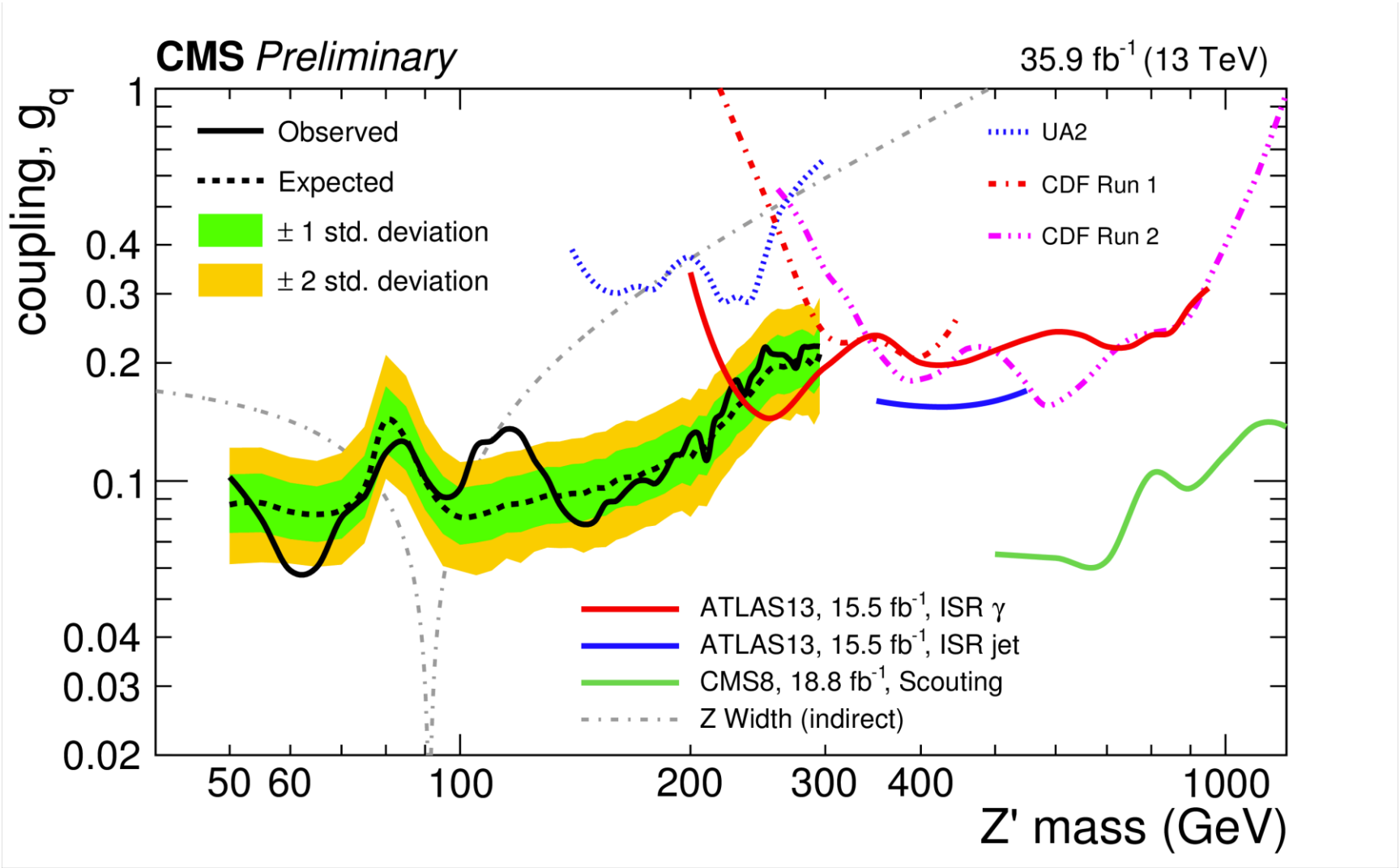


New Techniques

- Large-R jet
- Jet substructure
- Data-driven bkg

ATLAS and CMS Low-mass di-jet searches

CMS-PAS-EXO-17-001

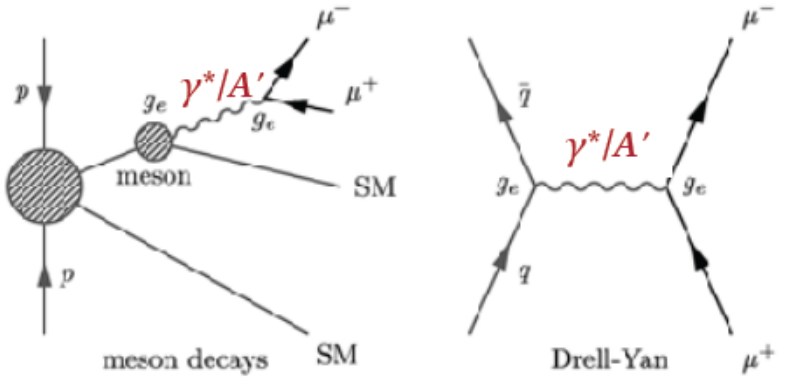


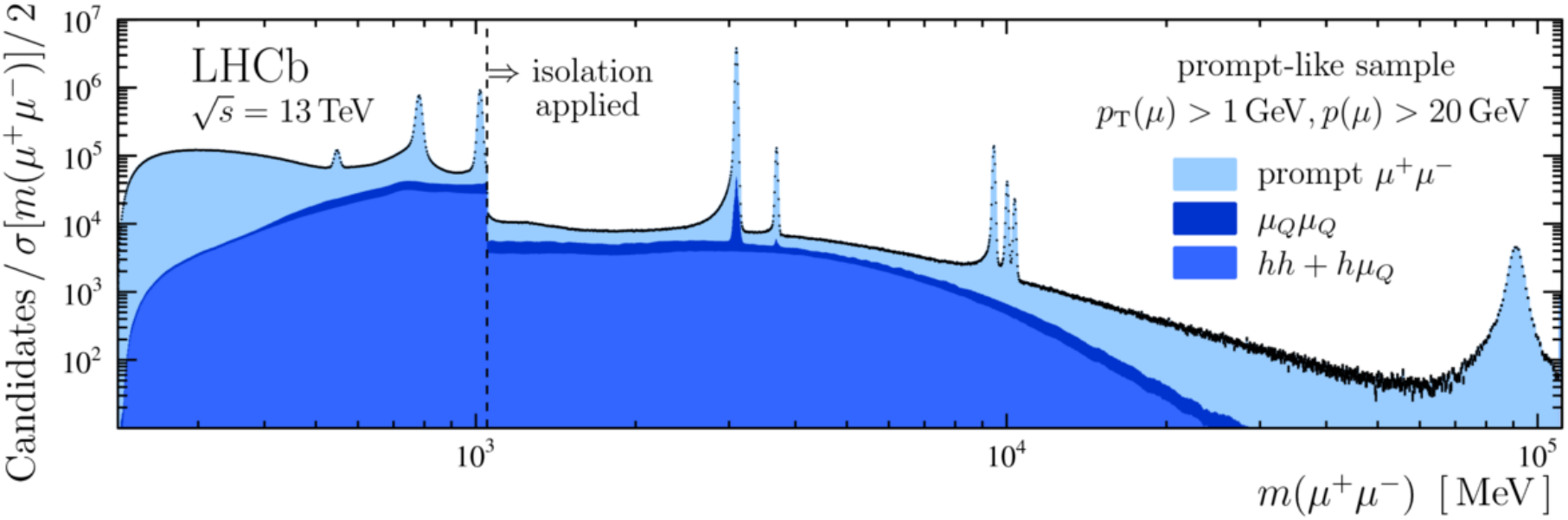
Mediator masses down to 50 GeV explored!

DM Mediator Search @ LHCb

arXiv:1710.02867

- Dark Photon Searches: A’





DM Mediator Search @ LHCb

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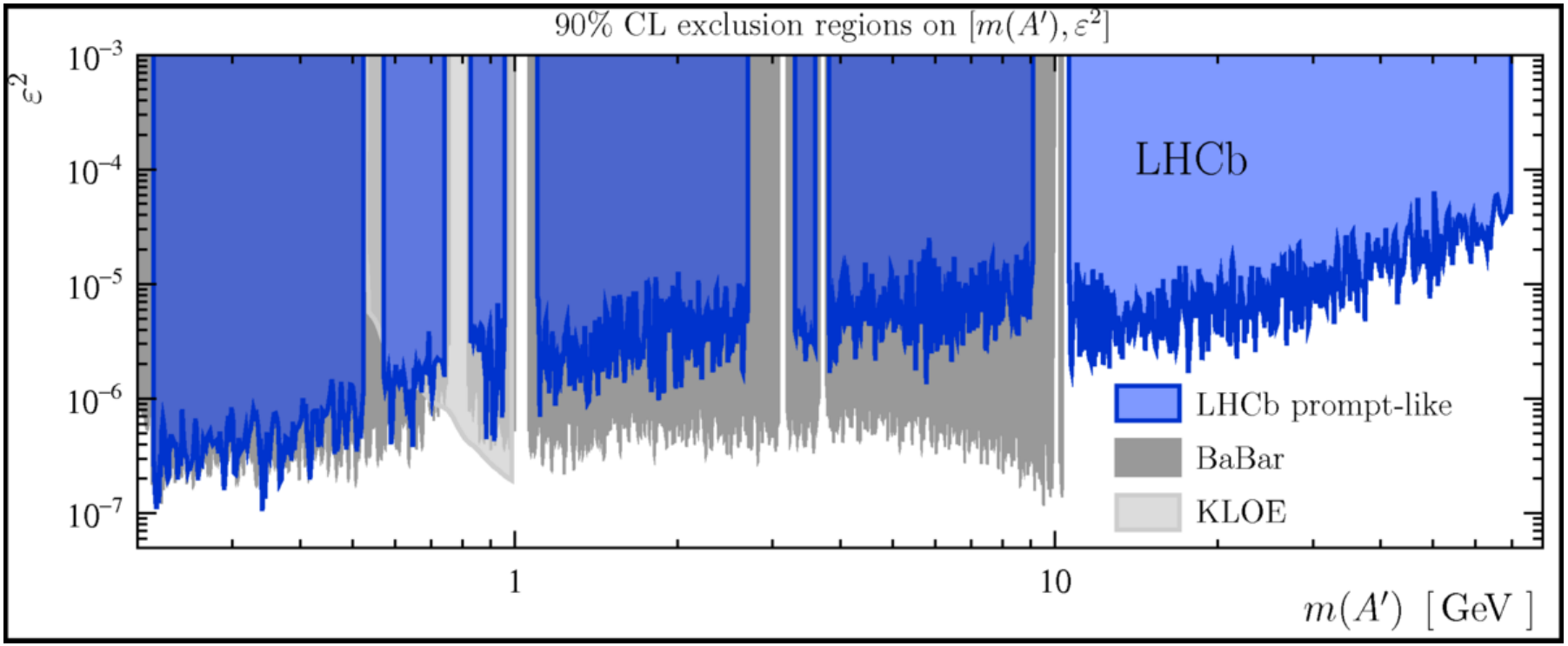
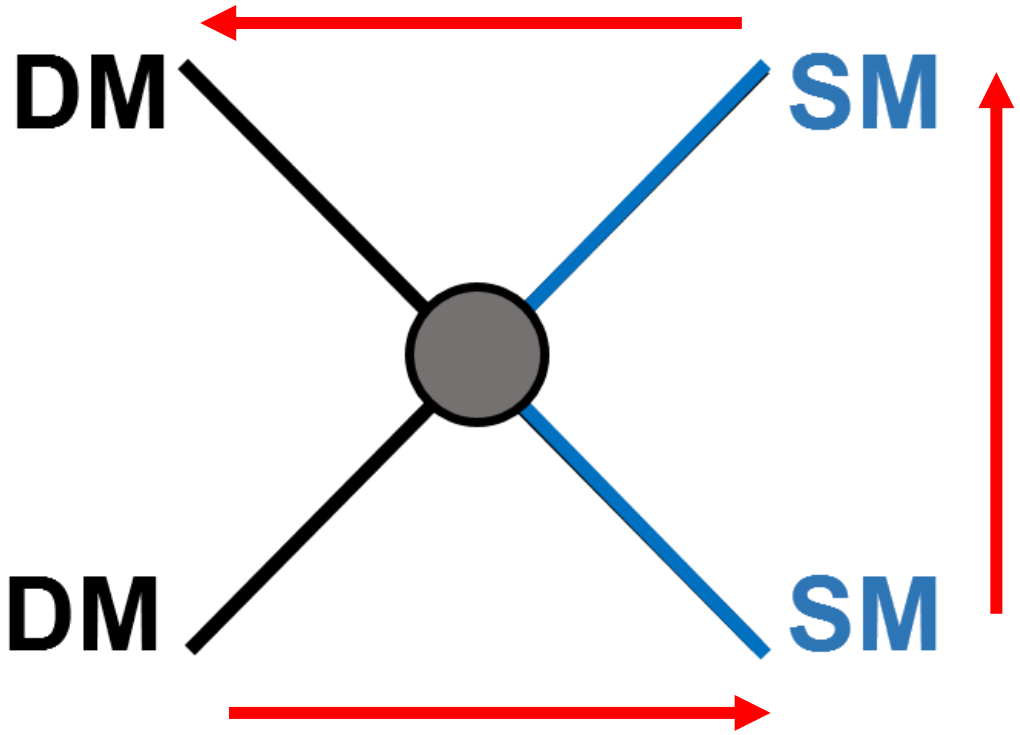
- Dark Photon Searches: A’



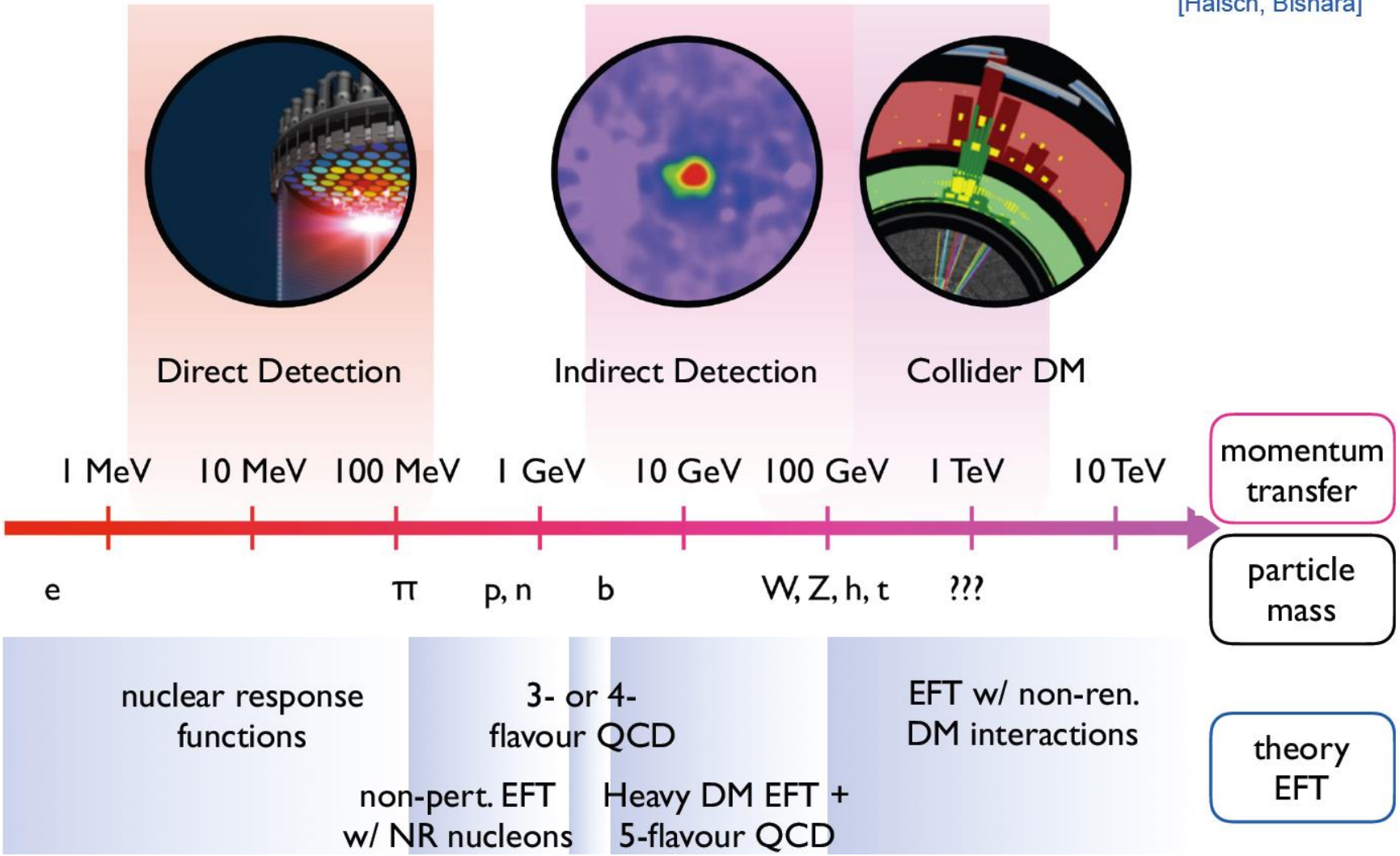
No significant excess found
First limit on dark photons for $m(A') > 10$ GeV
Already competitive for $m(A') < 0.5$ GeV

Comparison with Non-Collider Searches



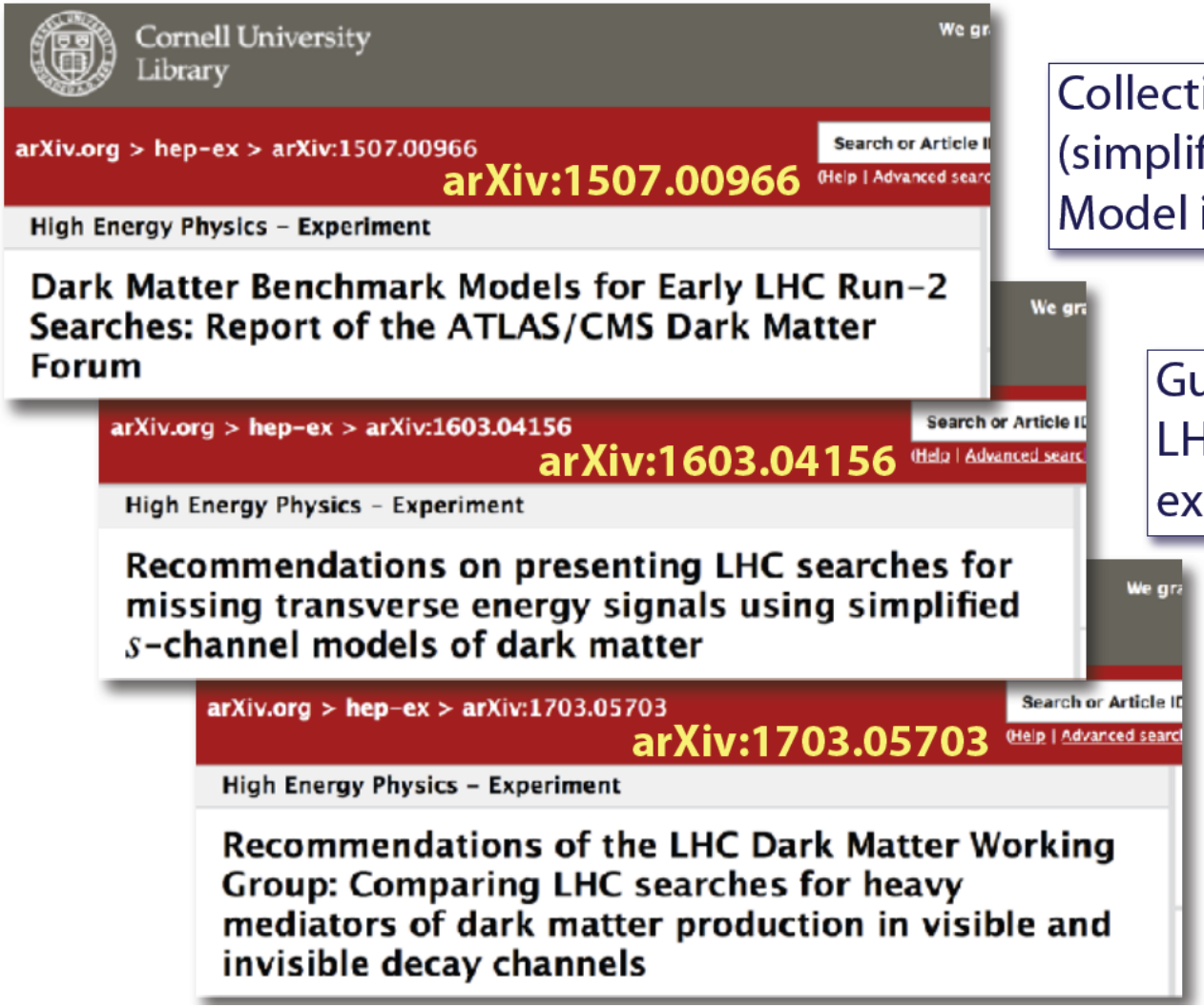
Relevant Scales for DM Searches

[Haisch, Bishara]



Comparisons across scales not straight forward!!

LHC DM Working Group



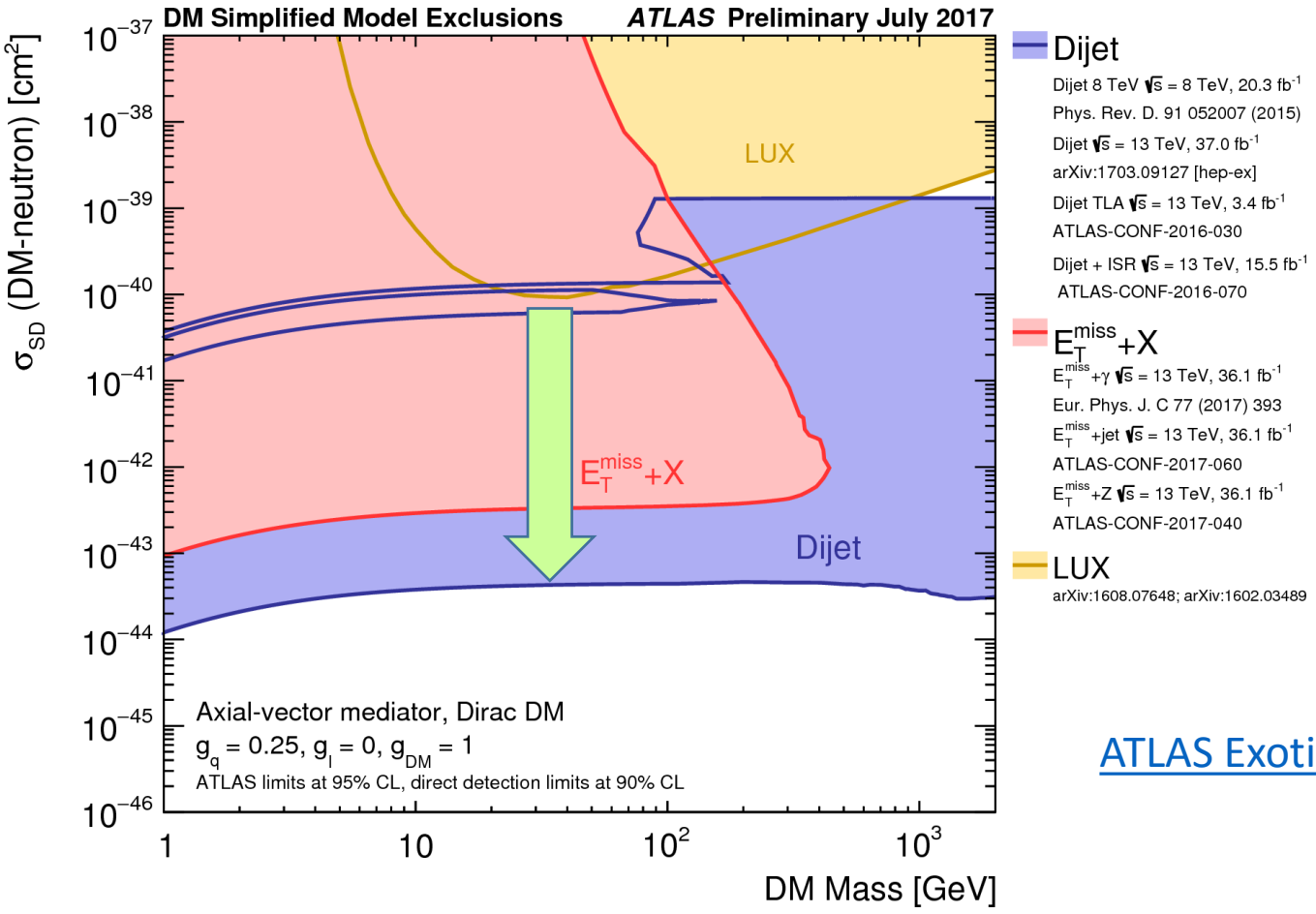
Collection of DM models (simplified models, EFT), Model implementation

Guidelines to compare LHC results with DD/ID experiments

Guidelines to present Mono-X and visible signatures for heavy mediators

Comparison with Direct Detection

Spin-dependent DM-neutron cross section vs m_{DM}



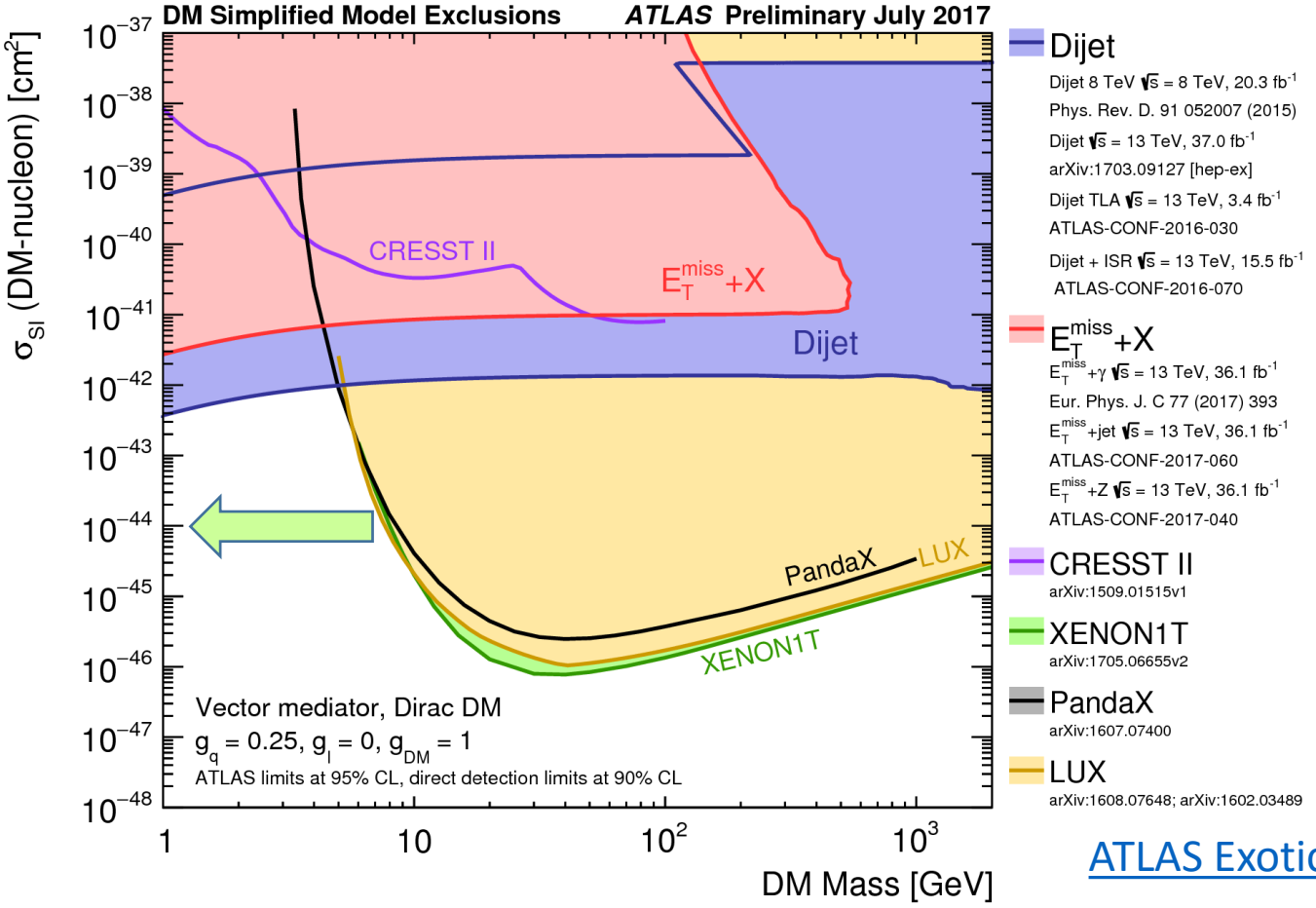
[ATLAS Exotics Summary]

For these model assumptions:

Collider searches have ~3 orders better sensitivity for σ_{SD}(DM-nucleon)

Comparison with Direct Detection

Spin-independent DM-nucleon cross section vs m_{DM}



ATLAS Exotics Summary

For these model assumptions:
Collider searches are sensitive at low DM for σ_{SI}(DM-nucleon)

Summary

- **Searches for Exotic searches in general**
  - **We have explored O(10 GeV) to 10 TeV mass/energy scales**
  - **Only 1% of the LHC data analysed --- we are at the beginning**
  - **New probes: Top quark and Higgs boson**

- **Dark Matter Searches are thriving at the LHC**
  - For vector and axial vector interactions
    - Dark Matter masses up 400 GeV – 700 GeV (mono-jet) excluded
    - Mediator mass up to 1.6 – 1.8 TeV (mono-jet) excluded
    - Mediator mass up to 1.2 TeV (mono-photon) excluded
    - Mediator mass up to 0.7 TeV (mono-Z) excluded
    - LHCb Dark Photon limits m(A)>10 GeV

- **LHC DM searches complement non-collider DM searches**
  - $m_{DM} < O(10\ GeV)$

Where to go from here?

- Direct searches → more and more systematic limited
  - **Better experimental techniques** will be developed
  - **Better theoretical** uncertainties needed
  - **Constrain backgrounds via measurements**
  - **Look at low mass AND high mass**
- Indirect searches (measurements) rising

My thoughts on colliders for the future:

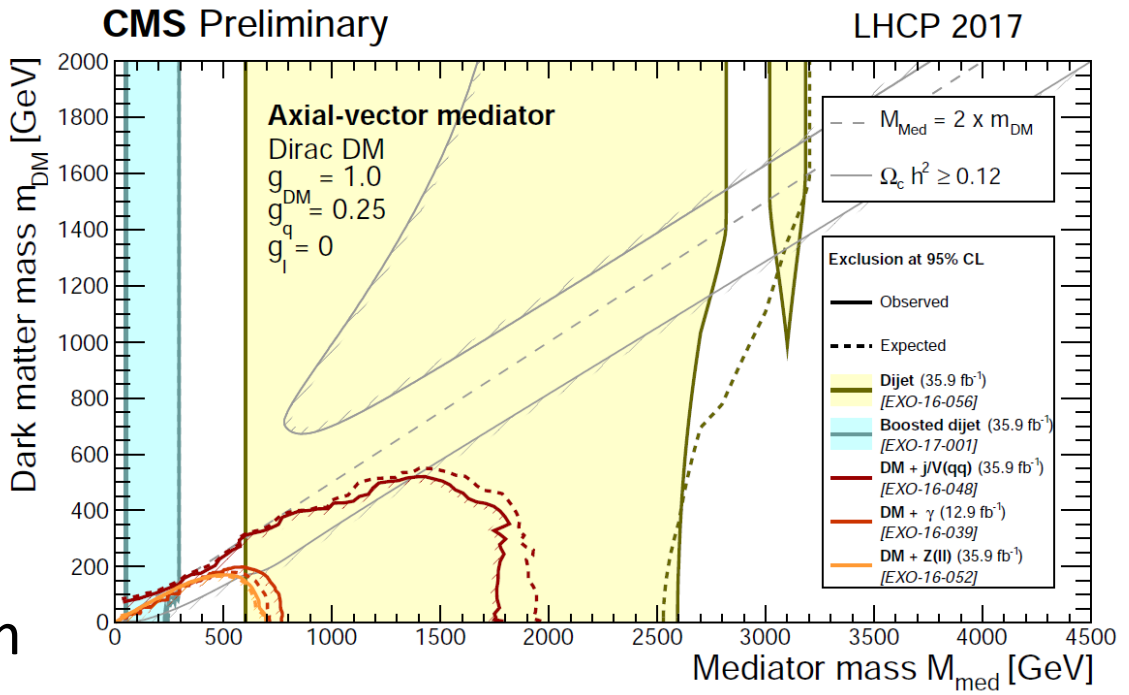
- **Precision Higgs and top collider (e-e+ collider)**
  - **Will give us direction where to look**
- **DM Collider**

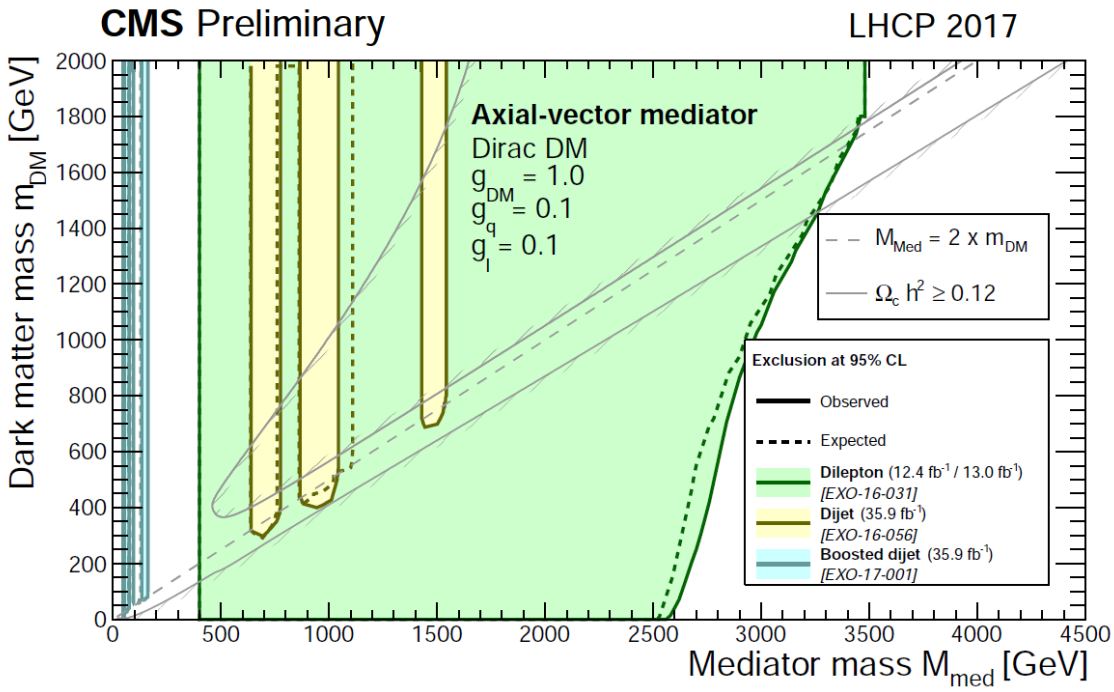
Backup Slides

Mono-X & Mediator Searches

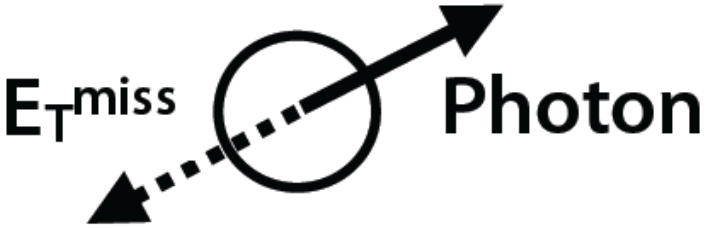
- Picture changes with choice of couplings
  - Strong constraints from di-lepton search if $g_l>0$
  - Dijet and mono-X constraints weakened when $g_q = 0.25 \rightarrow 0.1$

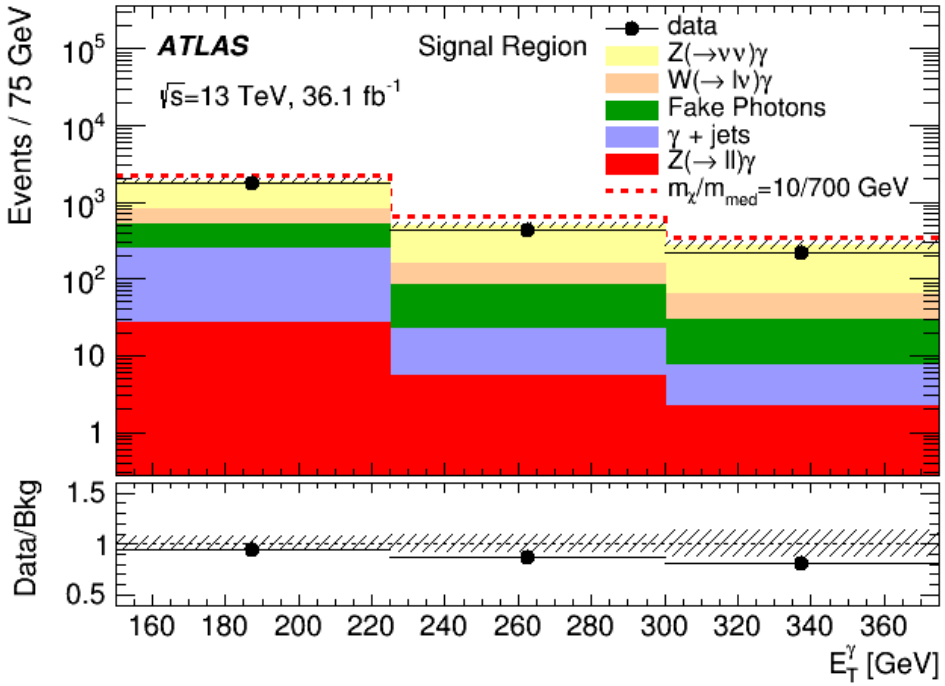
[CMS DM Summary]

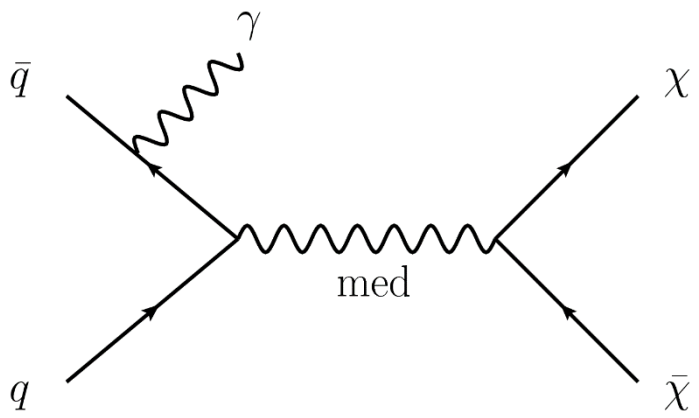




Mono-photon

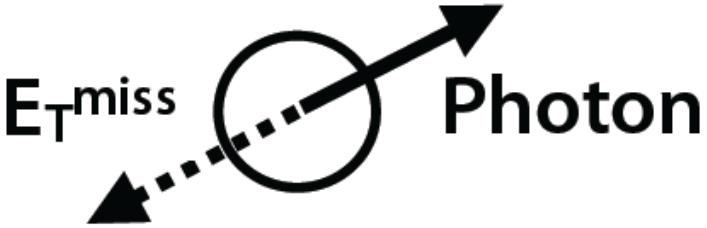


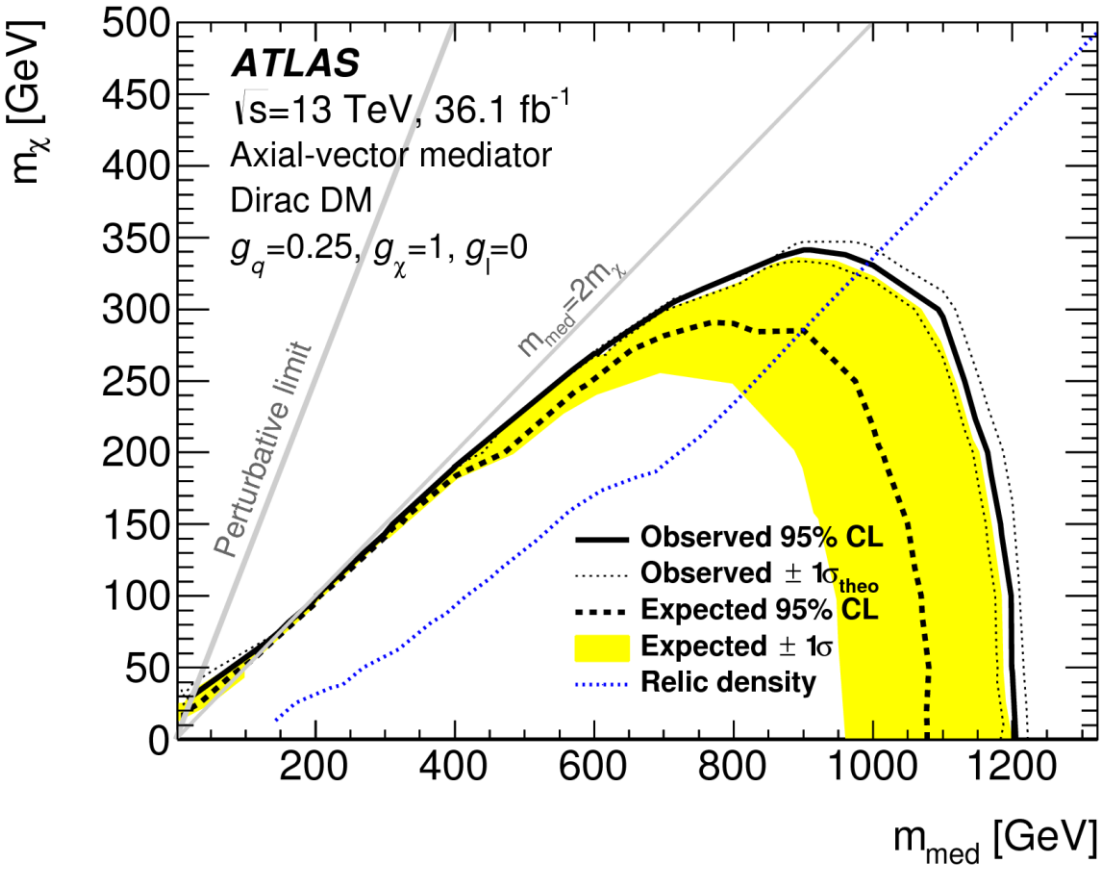




- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_T^{miss}/\sqrt{\sum E_T} > 8.5\ \text{GeV}^{1/2}$
- $\Delta\varphi(\text{photon}, E_T^{miss}) > 0.4$
- $N_{jets}(p_T > 30\ \text{GeV}, |\eta| < 4.5) \leq 1$

Mono-photon



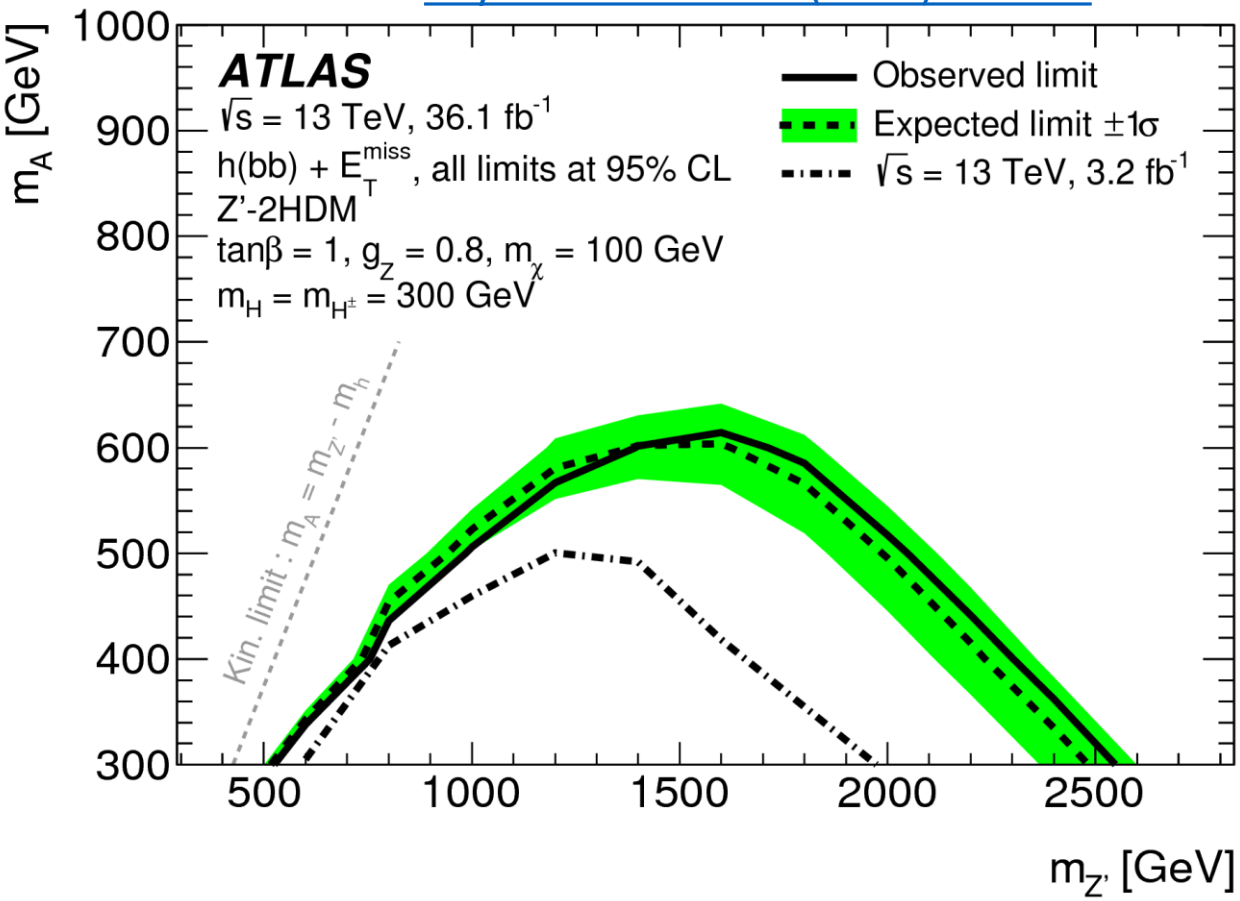


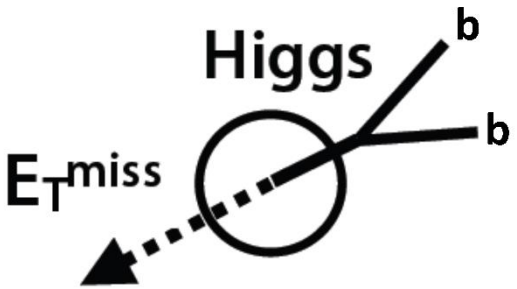
For vector and axial-vector interactions:

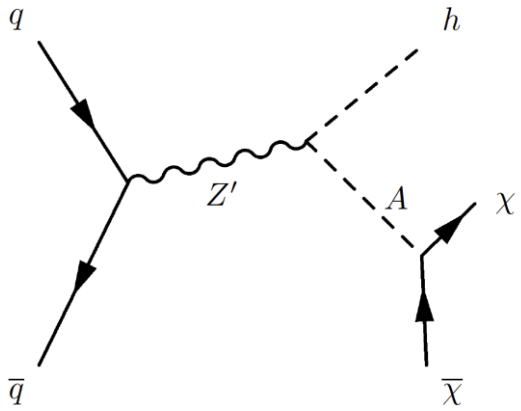
- Mediator mass excluded up to 1.2 TeV
- DM mass excluded up to 340 - 480 GeV

Mono-Higgs

Phys. Rev. Lett. 119 (2017) 181804





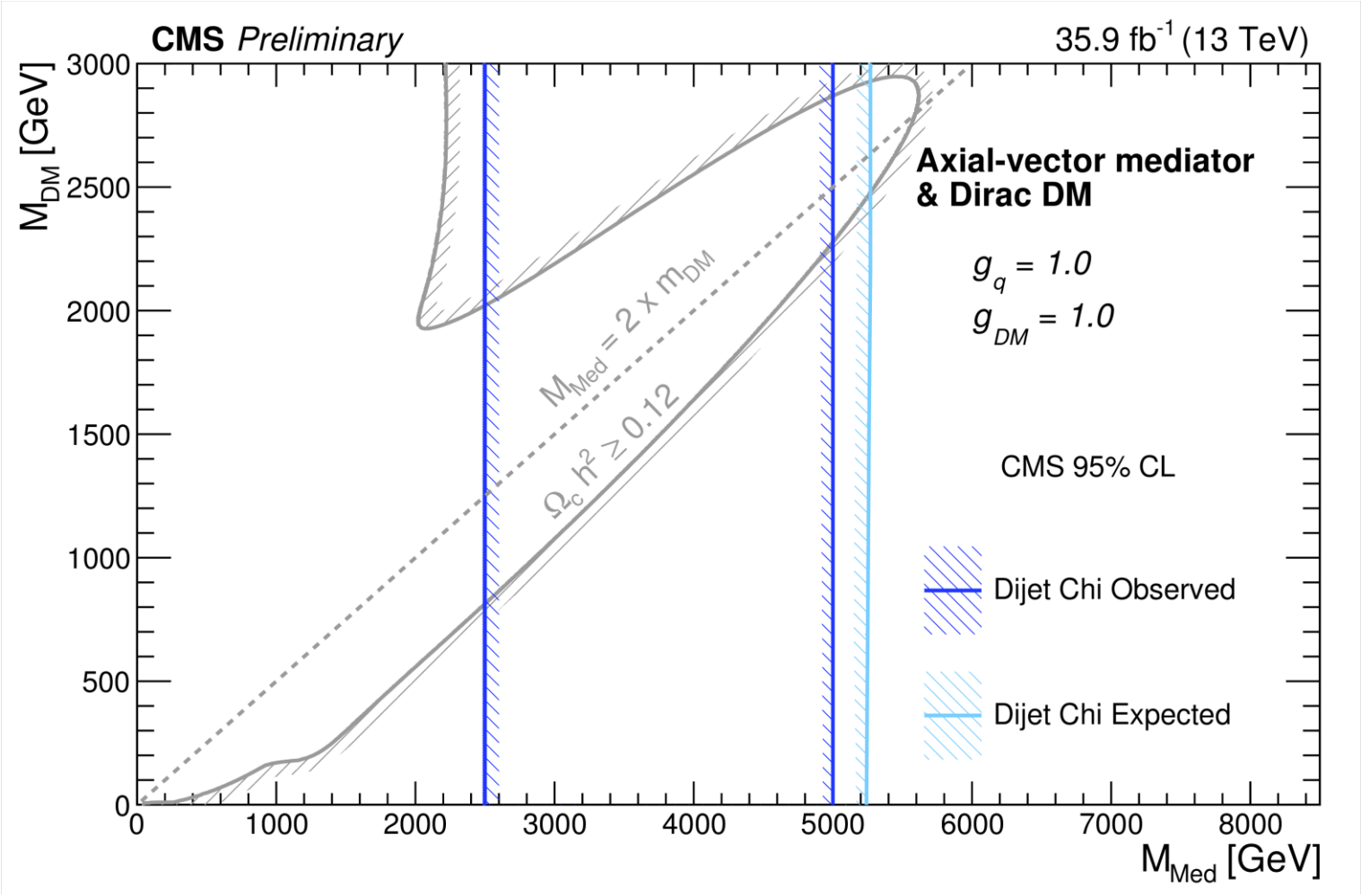


2HDM

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

CMS angular di-jet search

CMS-PAS-EXO-16-046



Mediator masses excluded between 2.5 TeV and 5.0 TeV

Era of Boosted Techniques

- Search for heavy new particles m >> 1TeV
- Final state consist of particles of m ~ O(100 GeV)

- OR

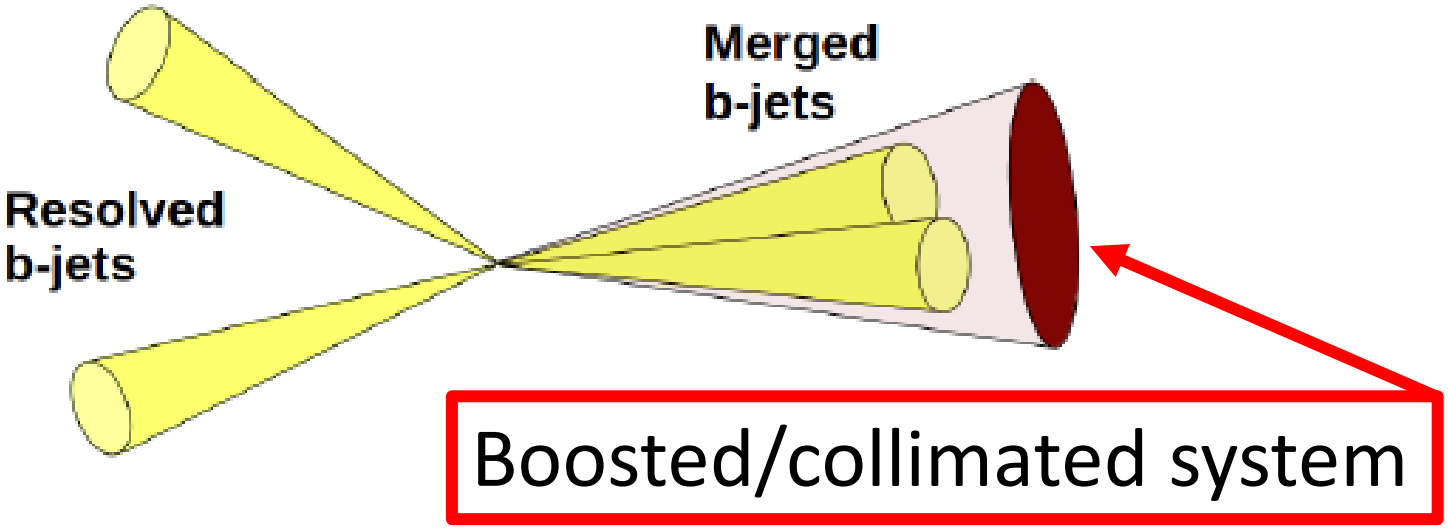
- Search for light particles + something they recoil against

➔ Final state objects are heavily boosted!

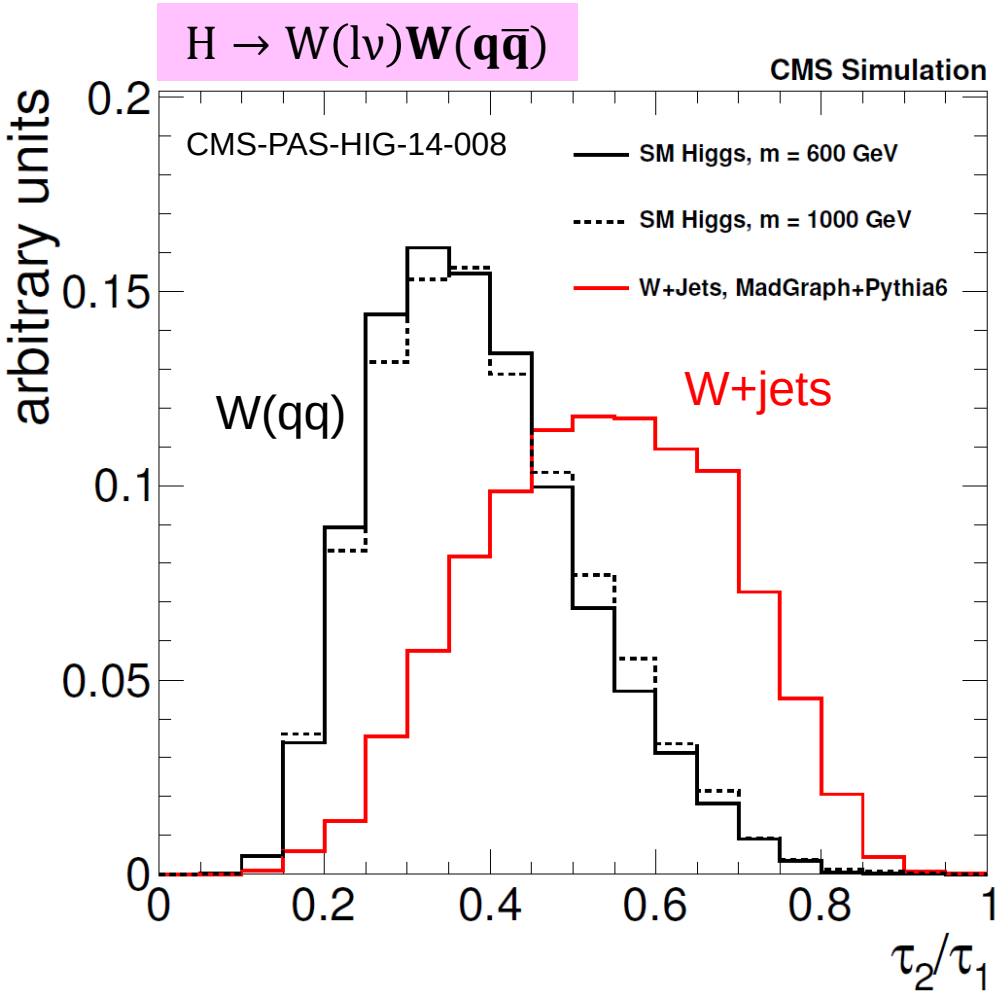
For example $H \rightarrow b\bar{b}$

distance of decay products: $\Delta R \sim \frac{2m}{p_T}$

$p_T > 250$ GeV b-quark pair within $\Delta R < 1$



Jet substructure: N-subjettiness τ_{21}



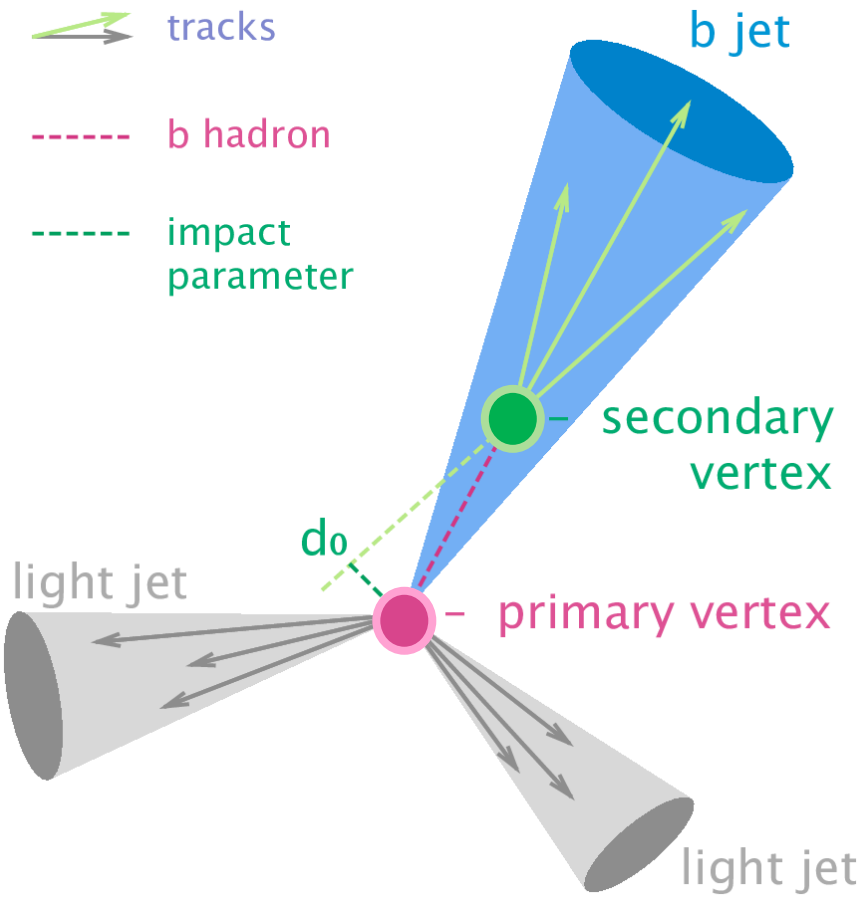
arxiv:1011.2268

τ_N : pT-weighted distance between constituents and N axes

How compatible jet with having N axis

small τ_2/τ_1: more two- than one-prong like

b-quark Identifikation (ID) – wichtig für 2H Prozesse



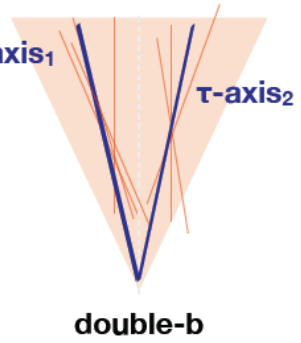
Standard b-quark ID: beinträchtig durch Kollimation bei hohen transversal Impulsen

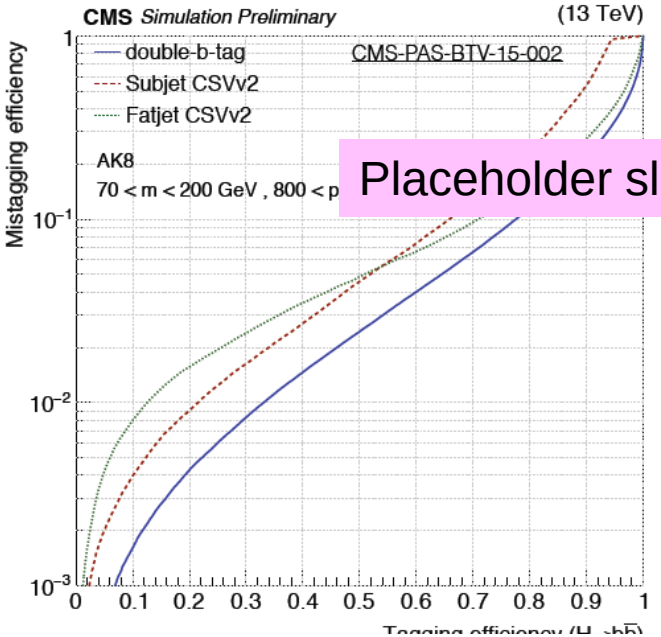
New advanced H→bb taggers

Higgs-tagging

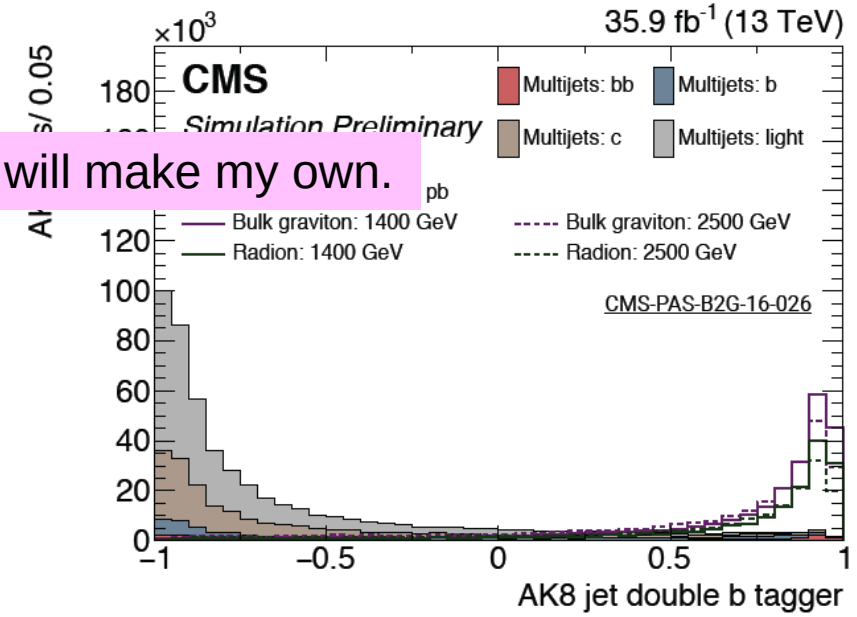
- Tag H→b$\bar{b}$ jet with MVA based tagger
  - input related to observables from SV and tracks associated to each τ-axis (27 total)
- Factor ~2 higher rejecting rate compared to standard b-tag methods

Axes obtained by undoing last step of jet clustering algorithm



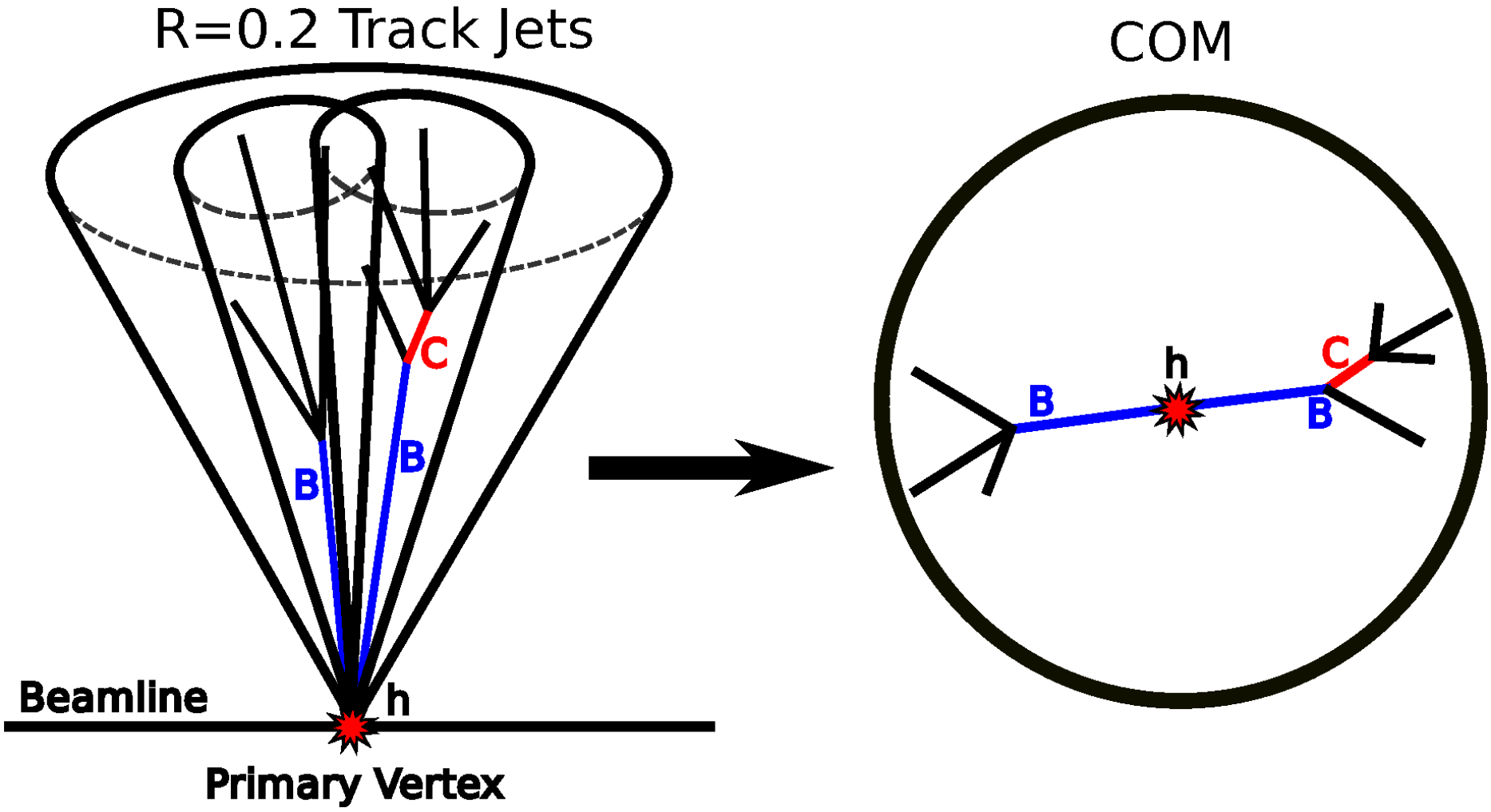


Placeholder slide will make my own.



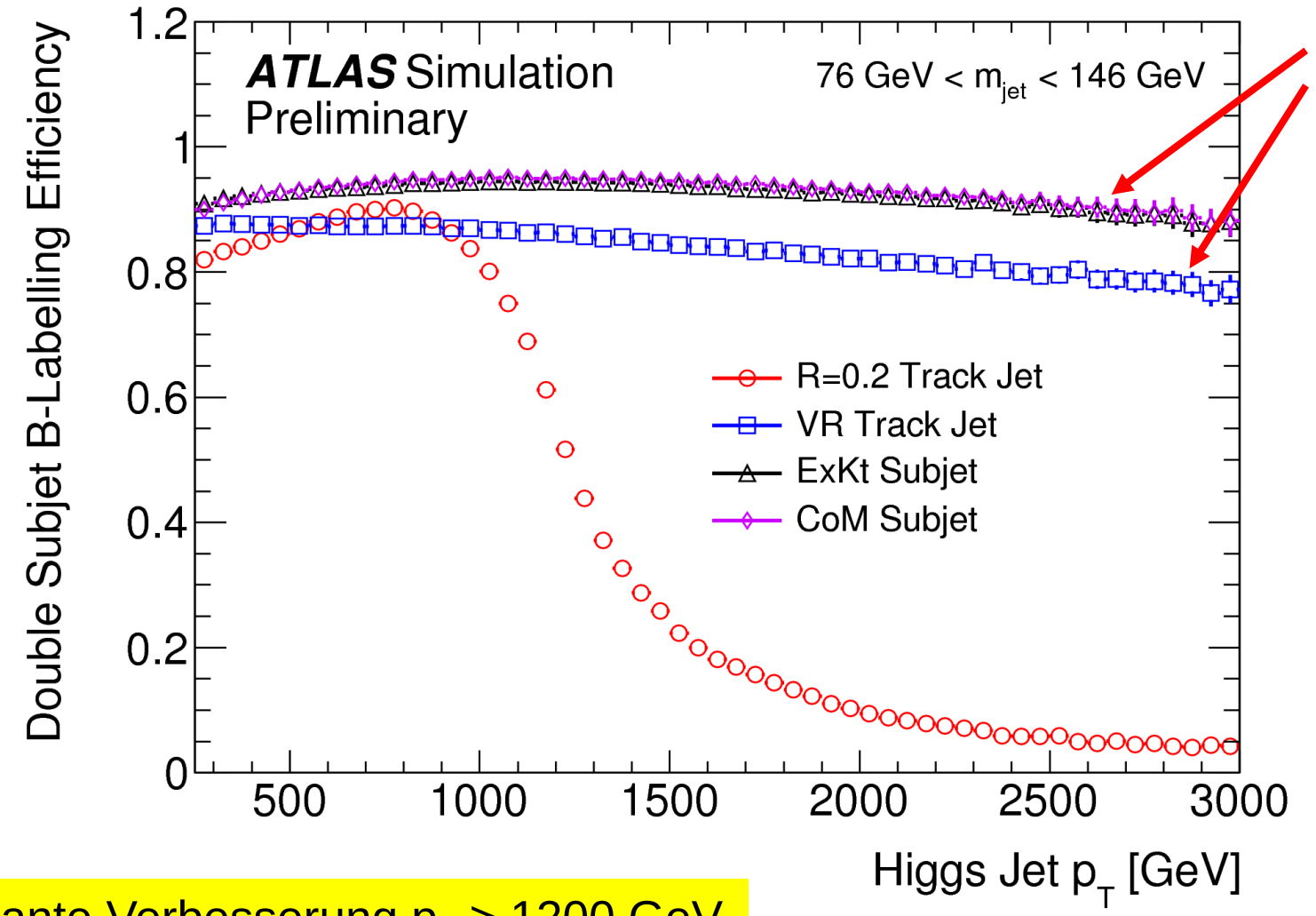
Neue b-quark ID: Centre of Mass (COM)

ATL-PHYS-PUB-2017-010



Neue b-quark ID Effizienzen

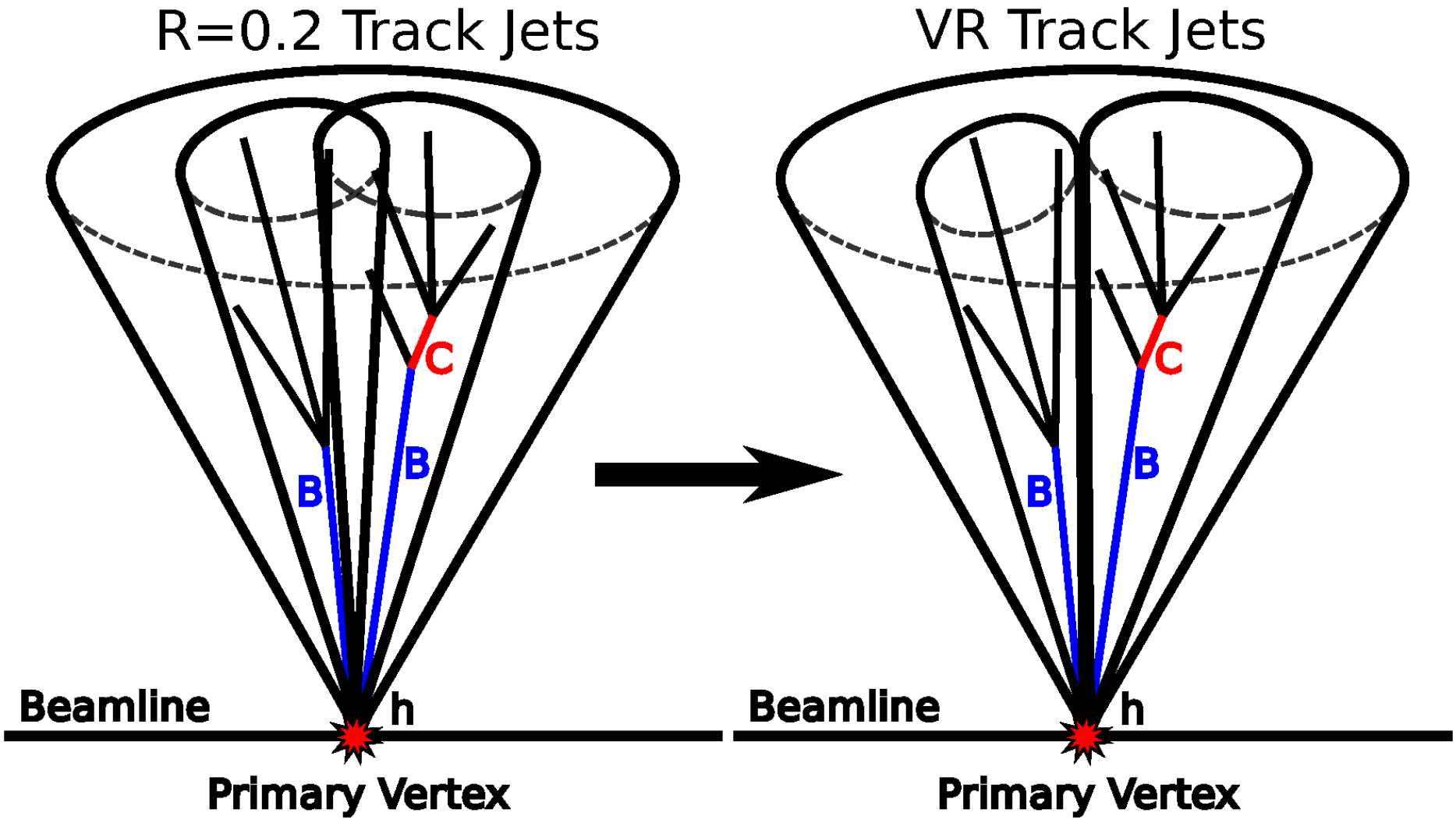
ATL-PHYS-PUB-2017-010

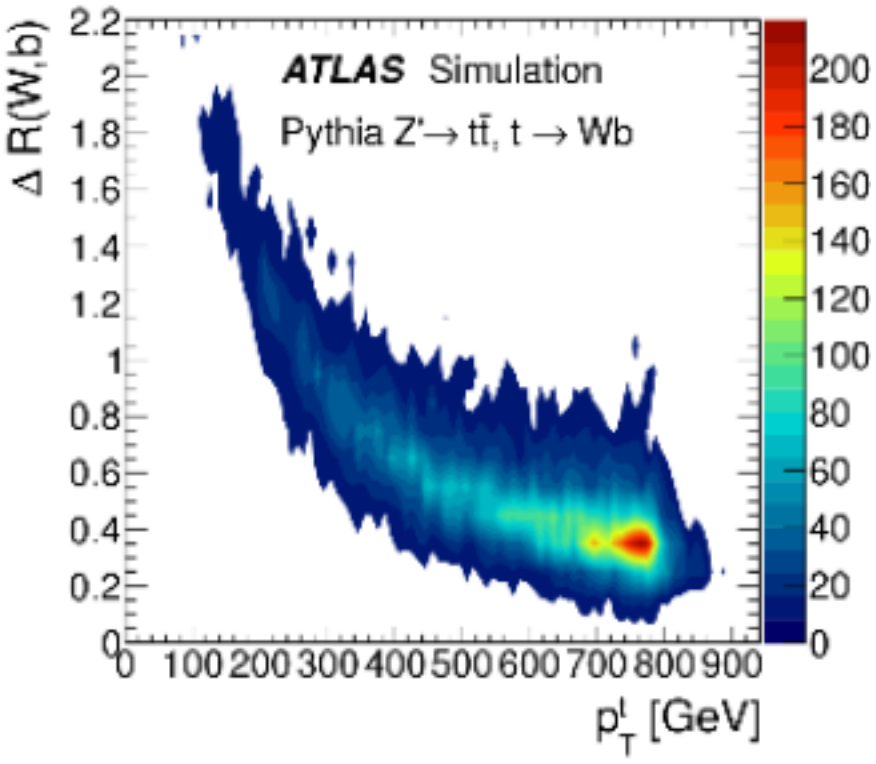


Signifikante Verbesserung p_T > 1200 GeV

Neue b-quark ID: Variable Radii

ATL-PHYS-PUB-2017-010




ATLAS Simulation
Pythia Z'→ tt̄, t → Wb
Δ R(W,b)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 100 200 300 400 500 600 700 800 900
p_T^l [GeV]
200
180
160
140
120
100
80
60
40
20
0