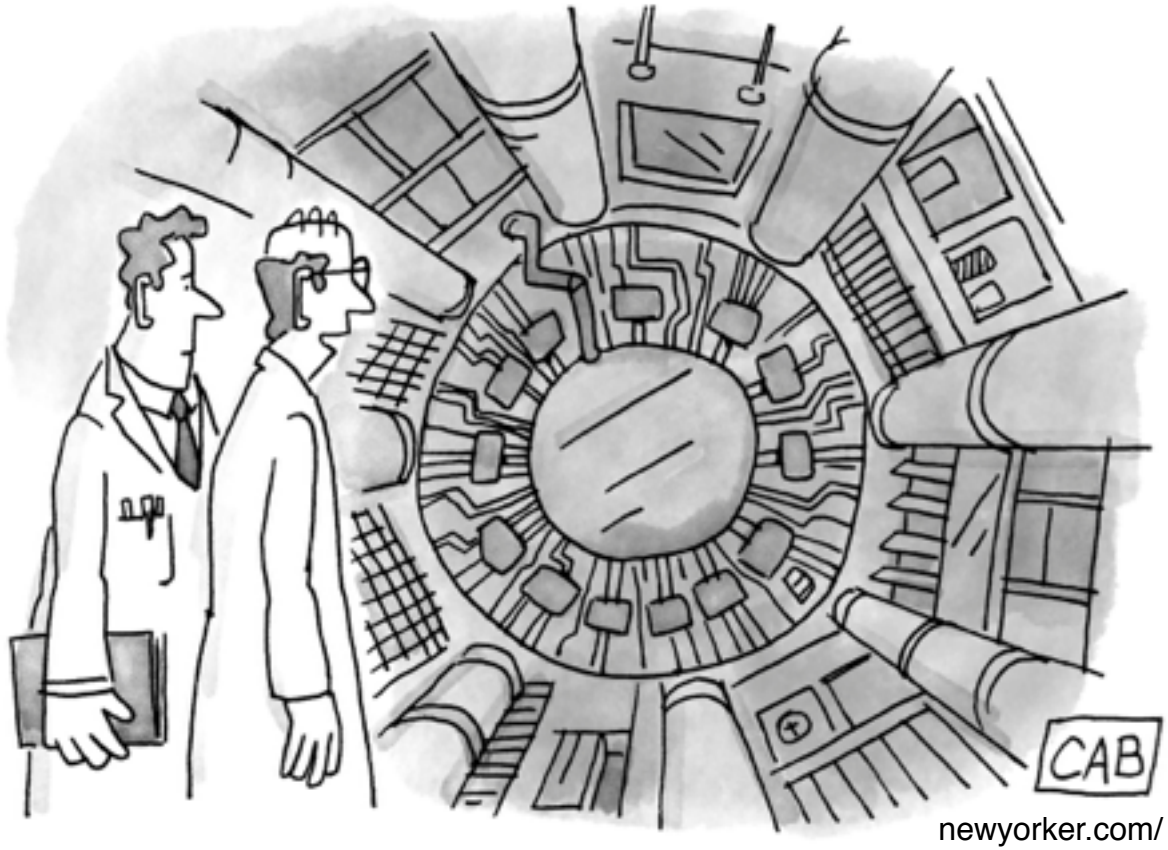
Dark matters at the LHC

and their mediators

This talk:
ATLAS
CMS



newyorker.com/
cartoons/a18624

Tae Min
Hong

LHCP, Shanghai
May 18, 2017

http://indico.cern.ch/e/517784

University of
Pittsburgh

Dark matter at LHC is a hit

I wrote a macro to do scour the arXiv

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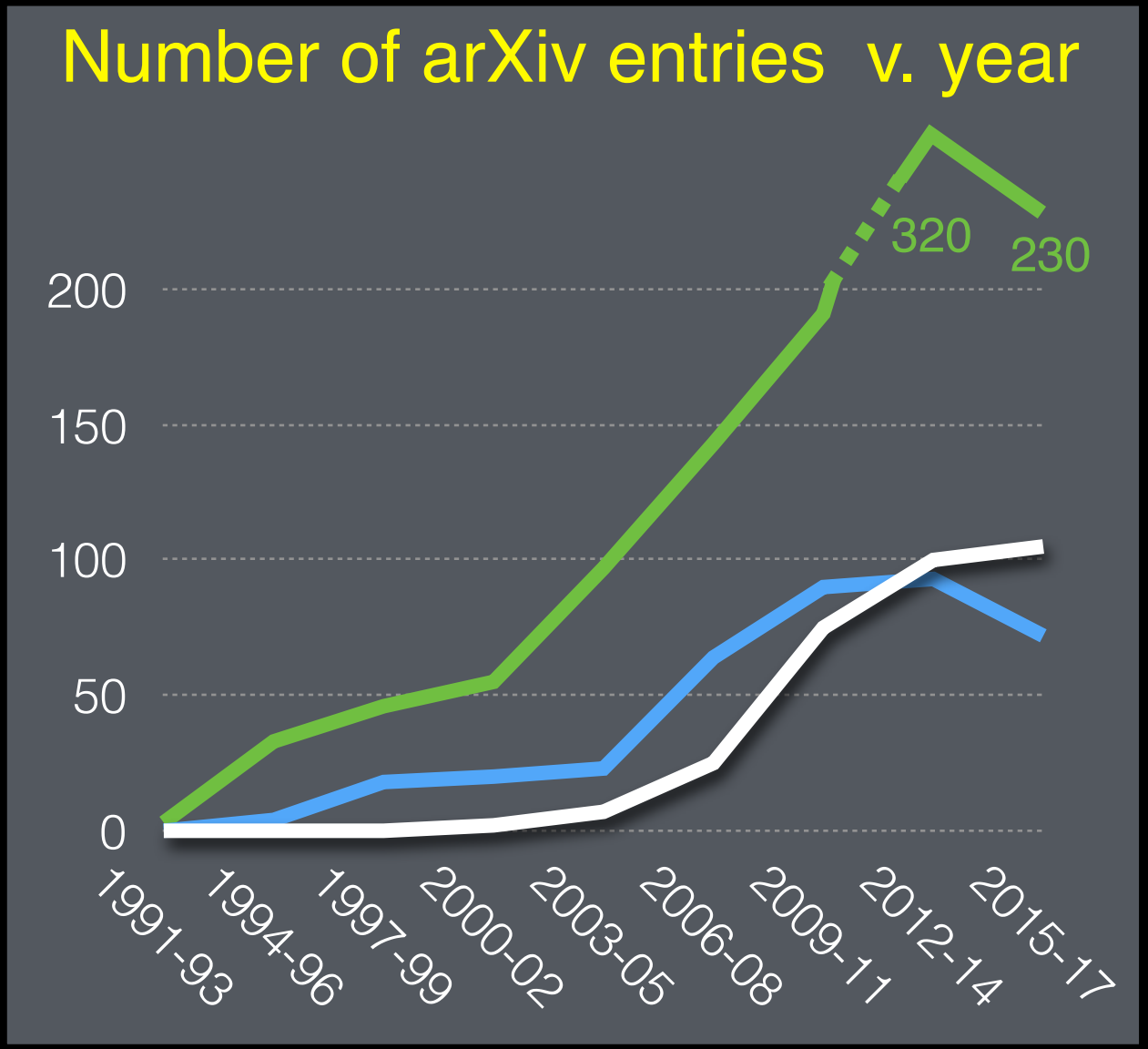


Search terms in title

LHC + HIGGS

LHC + DM

DARK MATTER

300 total!

LHC + SUSY

SUPERSYMMETRY

← Scaled up 2017 since it's < ½ over

"Dark matter + LHC" is among the most popular topics

This talk

≥ ⅔ of attendees have "CERN" in registration, so not introducing LHC, ATLAS, CMS.

Objectives

- Complementarity
- Searches
- Tools: trigger, boosted jets, …

Homework

- See parallel talks
- Visit websites
  - CMS [see p24, 39]
  - ATLAS [see p24, 40]
- Ask me! [tmhong@pitt.edu]

Dark matter

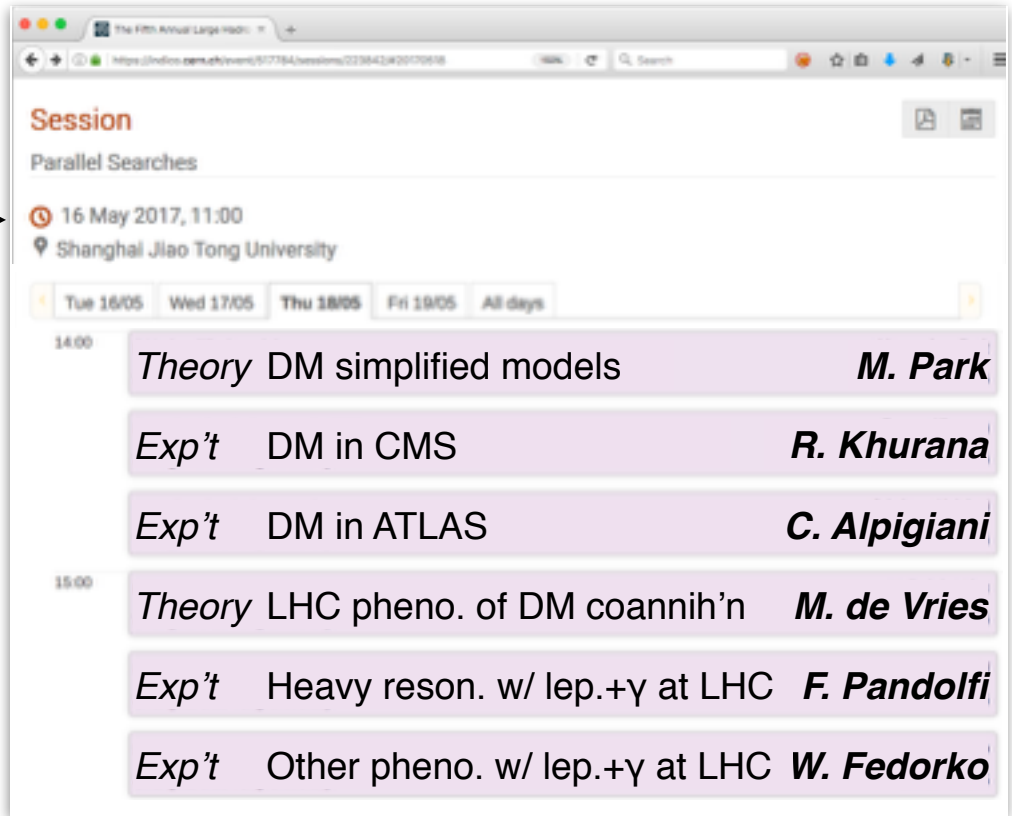
Mono-x $x = j$, γ, Z, W, H, b, t

jet EW BOSONS H. FLAVOR

Mediators

Via di-jets

Higgs



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Zen of dark matter

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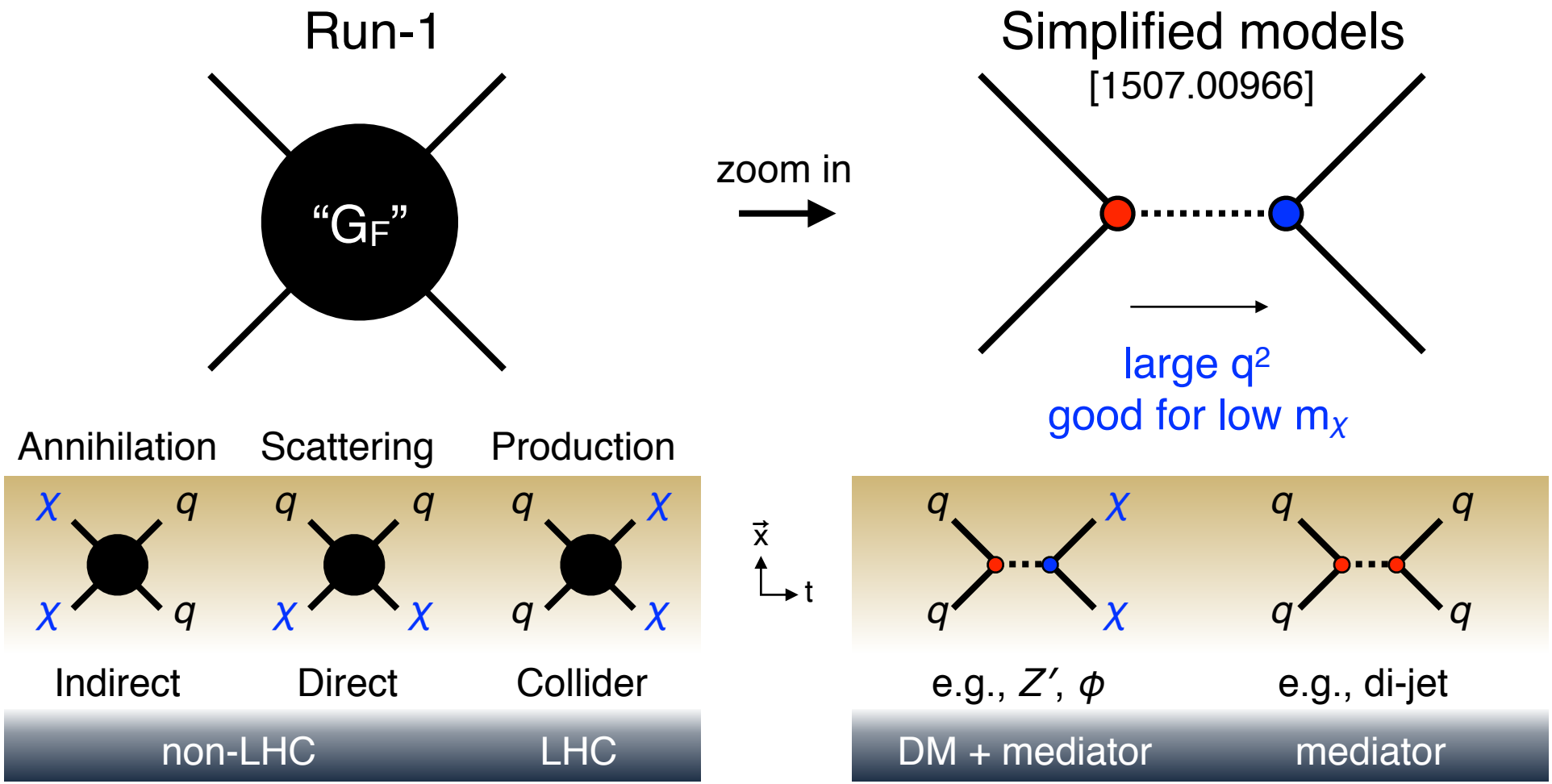
WIMP miracle is guide. Freeze out gives ~ relic density.



LHC designed to probe the weak scale, suitable here.

Complementary in approaches

Neutral third party

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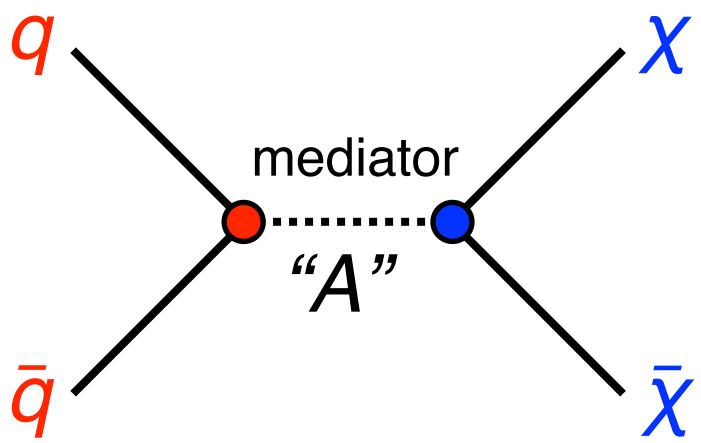
Features of mediator

prompt, colorless, etc.

	spin 0	spin 1
Charge Q	$Q_{med} = 0$ for s-channel	
Mass m	unknown	
Dark sector bosons similar to	H [1609.09079]	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	$\propto$ mass	$\propto$ charge
Consequences	$m_b \gg m_d$	$Q_b = Q_d$
Example chan.	mono-b	di-jet

Complementary in channels

Lagrangian parameters



$g_q\, \bar{q} q A$ matter-mediator

$g_{DM}\, \bar{\chi} \chi A$ DM-mediator

$g_q\, m_q\, m_{med}$ ❶ known ❷

$g_{DM}\, m_{DM}\, m_{med}$ ❸ ❹ redundant

matrix element = 4 parameters

2d plots must assume 2 other param.

Complementarity non-LHC v. LHC

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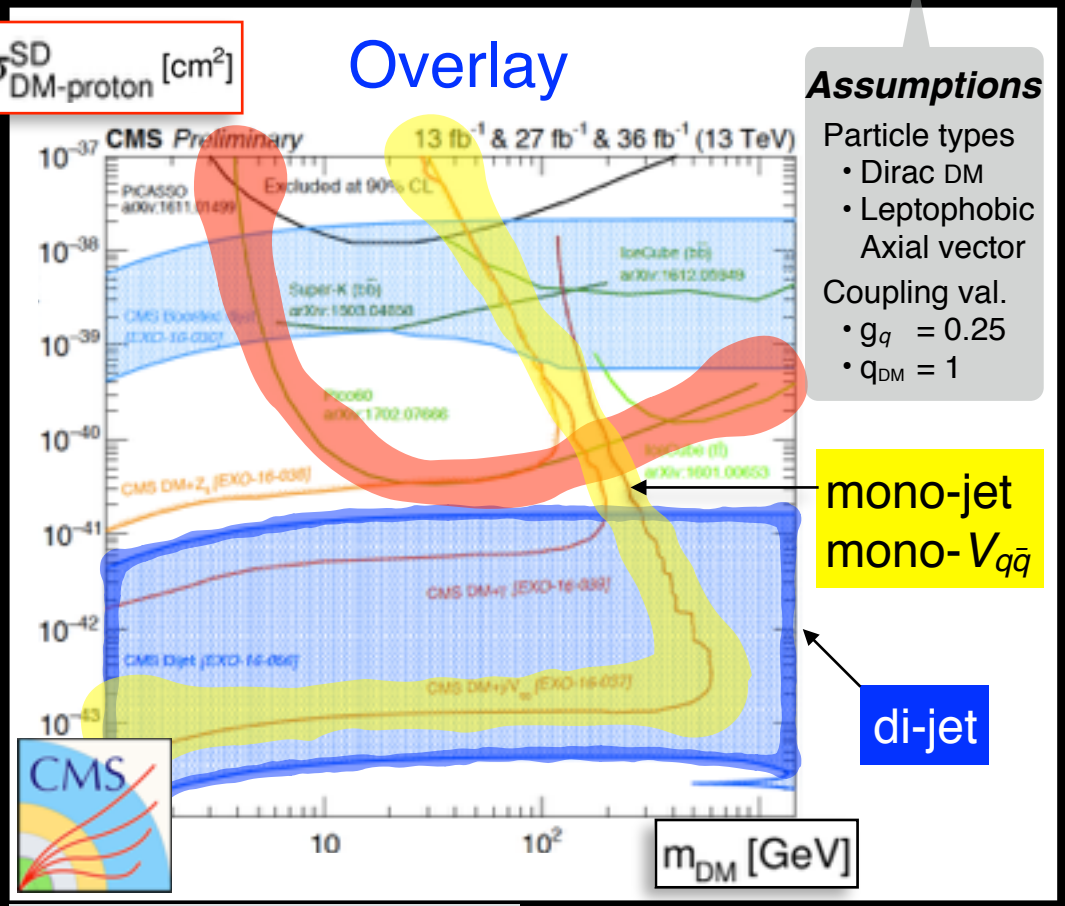
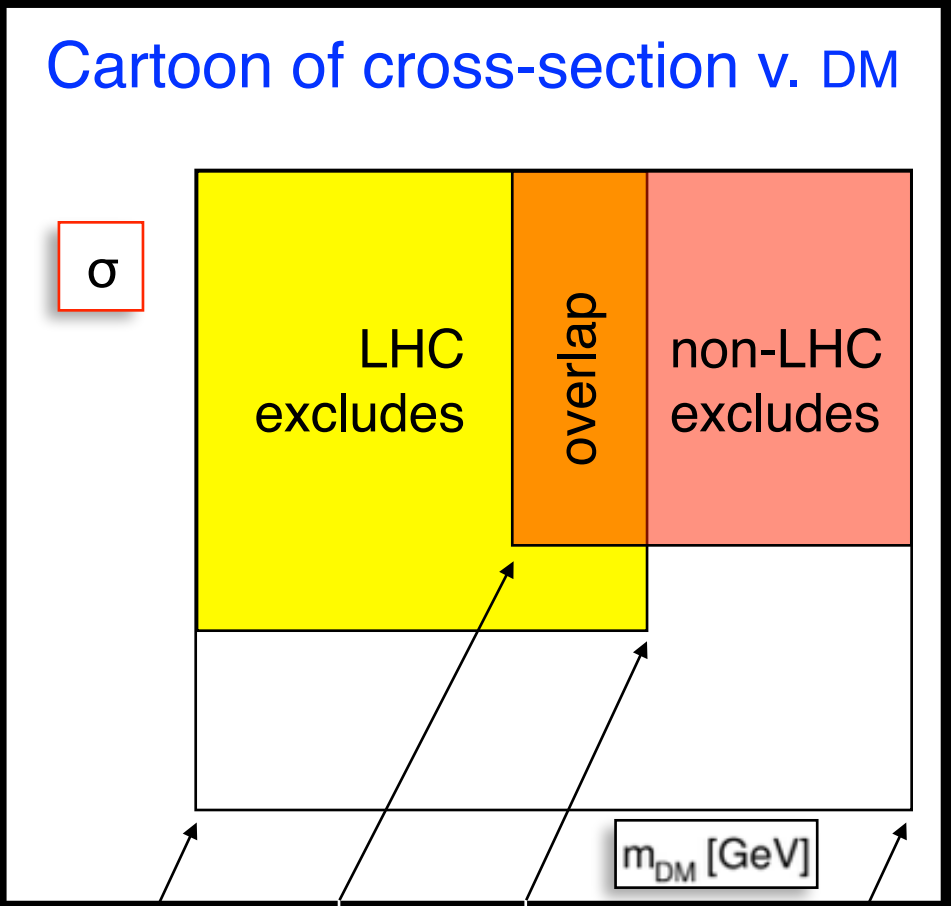
Generic features for benchmark ($g_{DM} = 1$, $g_q = ¼$)

CERN-LPCC-2016-001



From Mar. 2017, [CDS: 2256873]



Also have complementarity among various LHC results

Much ado about "x"

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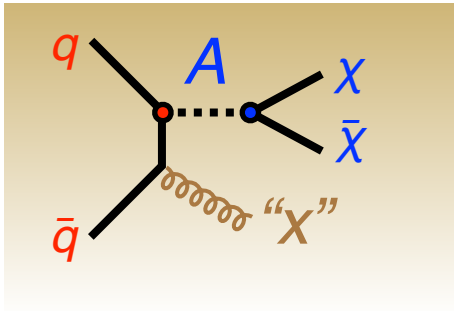

Search $pp \to \chi\bar{\chi}$ + "x"

- MET is recoil against "x"
- $Z_{\nu\bar{\nu}} \leftrightarrow A_{\chi\bar{\chi}}$ indistinguishable

General

- Estimate with γ and/or $W_{l\nu}$ control sample

Drell-Yan	W - Z similarity
• Very high stats	• Higher stats
• QCD produced	• Can produce EW

- "x" can be
  - Single object or res., e.g., jet, γ, $W_{l\nu}$, $W_{q\bar{q}}$, Z_{ll}, $H_{b\bar{b}}$
  - System of non-resonant objects, e.g., $b\bar{b}_{non\text{-}res}$

x	objects	notes
Jet	$P_T \gtrsim 100$ MET $\gtrsim 200$	classic
Photon	$P_T \gtrsim 200$ MET $\gtrsim 200$	low rate
Weak bosons	l^+l^-	clean
	$q\bar{q}$	rate, boosted
Higgs boson	$b\bar{b}$	60%
	$\gamma\gamma$	clean 0.5% lower trig.
Heavy flavors	b, $b\bar{b}$	Fermi-LAT?
	t, $t\bar{t}$	3rd gen.

Dark matter + mono-jet

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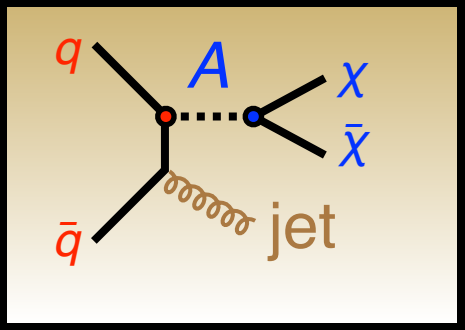


Mono-jet

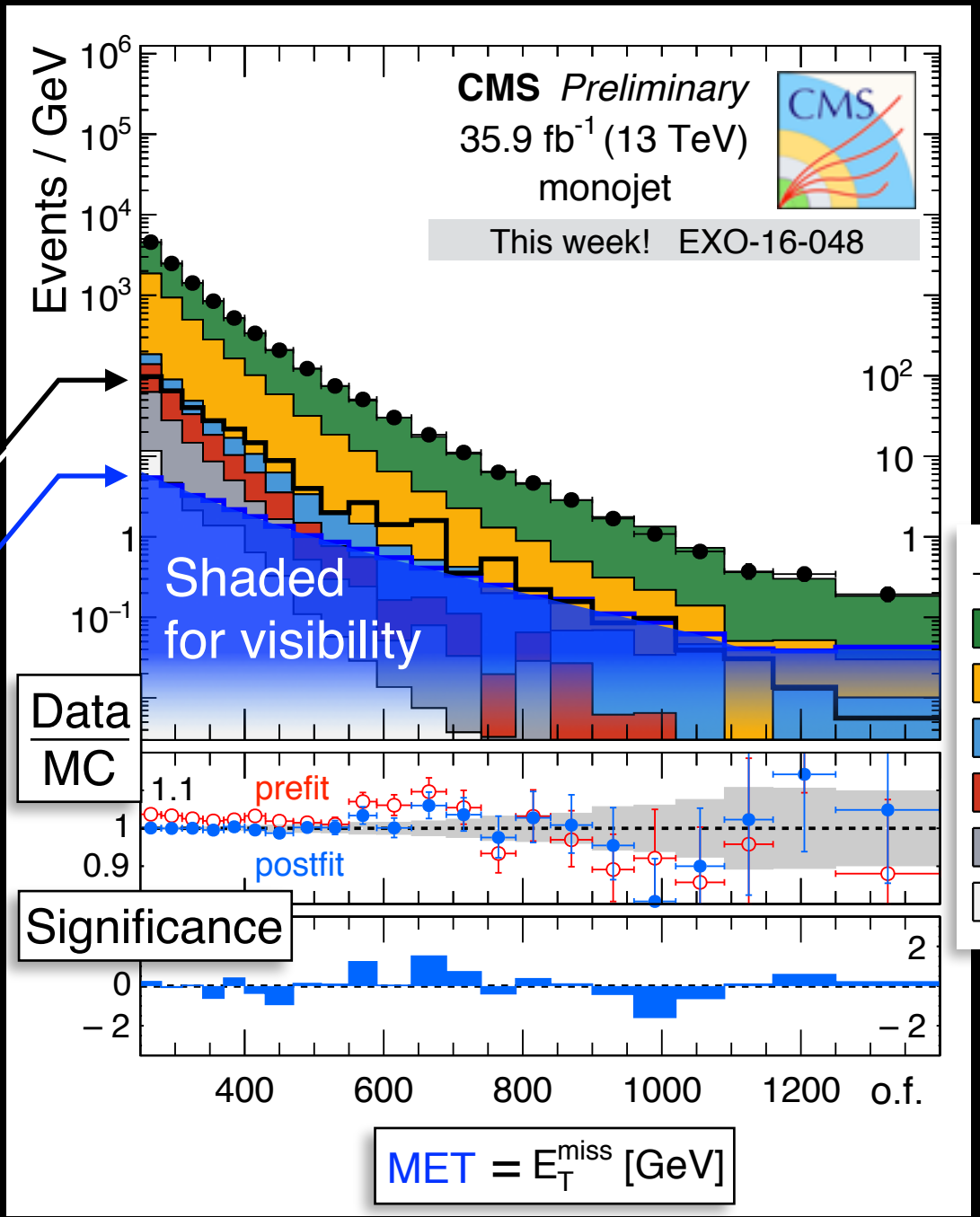
Signal models

Higgs invisible

Axial-vector
$m_{med} = 2$ TeV
(more later)

MET ≳ 200 GeV v. largest processes

- Kills di-jet, multi-jet
- Kills $t\bar{t}$
- Kills W, Z, γ



MET + mono-jet

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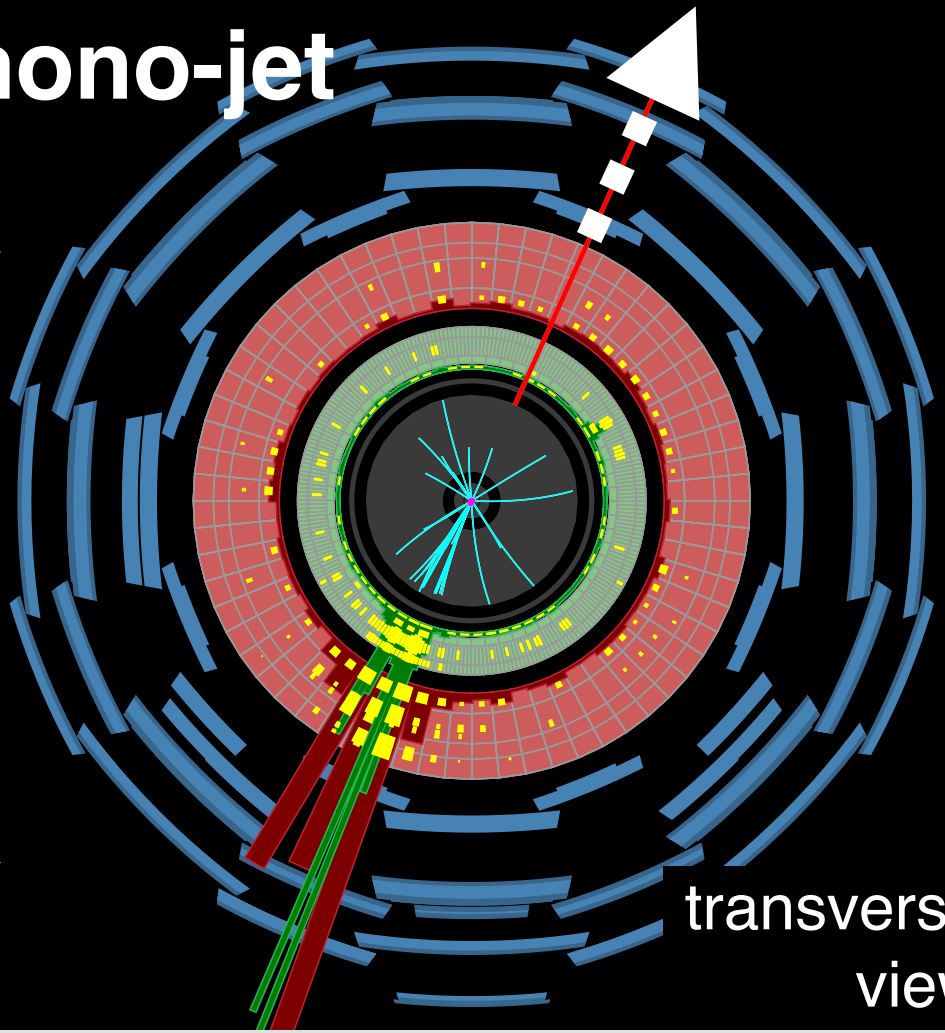
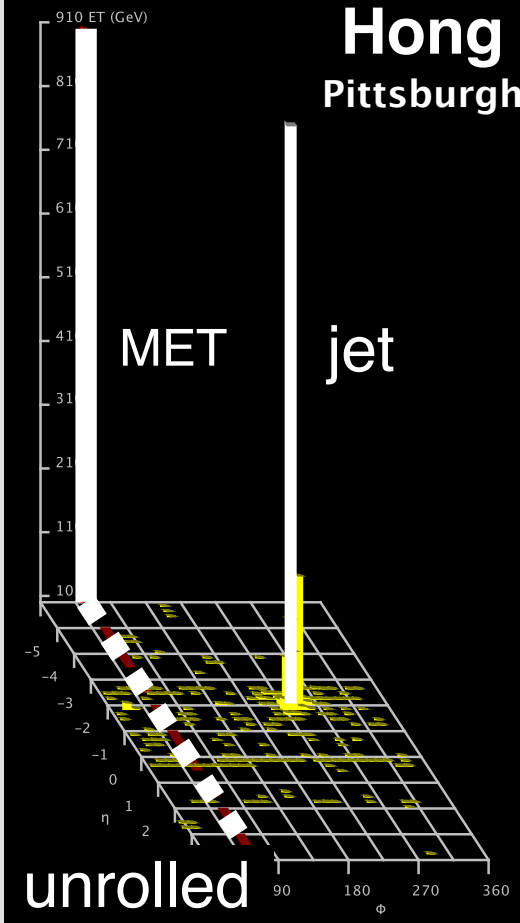
MET ⟶
954 GeV

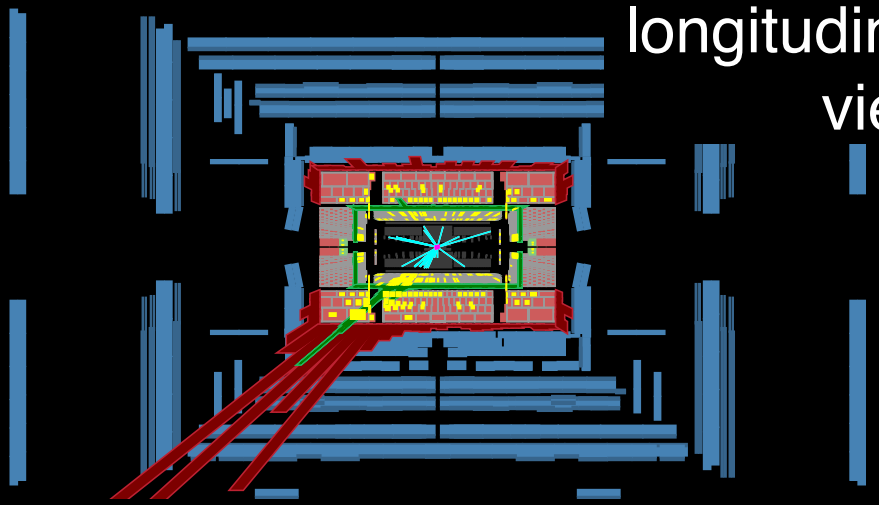
jet ⟶
973 GeV



transverse view



unrolled cylinder



longitudinal view

jet ⟶

March 2016,
http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-03/

ATLAS EXPERIMENT

Run Number: 279284, Event Number: 606734214

Date: 2015-09-14 12:05:34 CEST

Dark matter + mono-(jet, photon)

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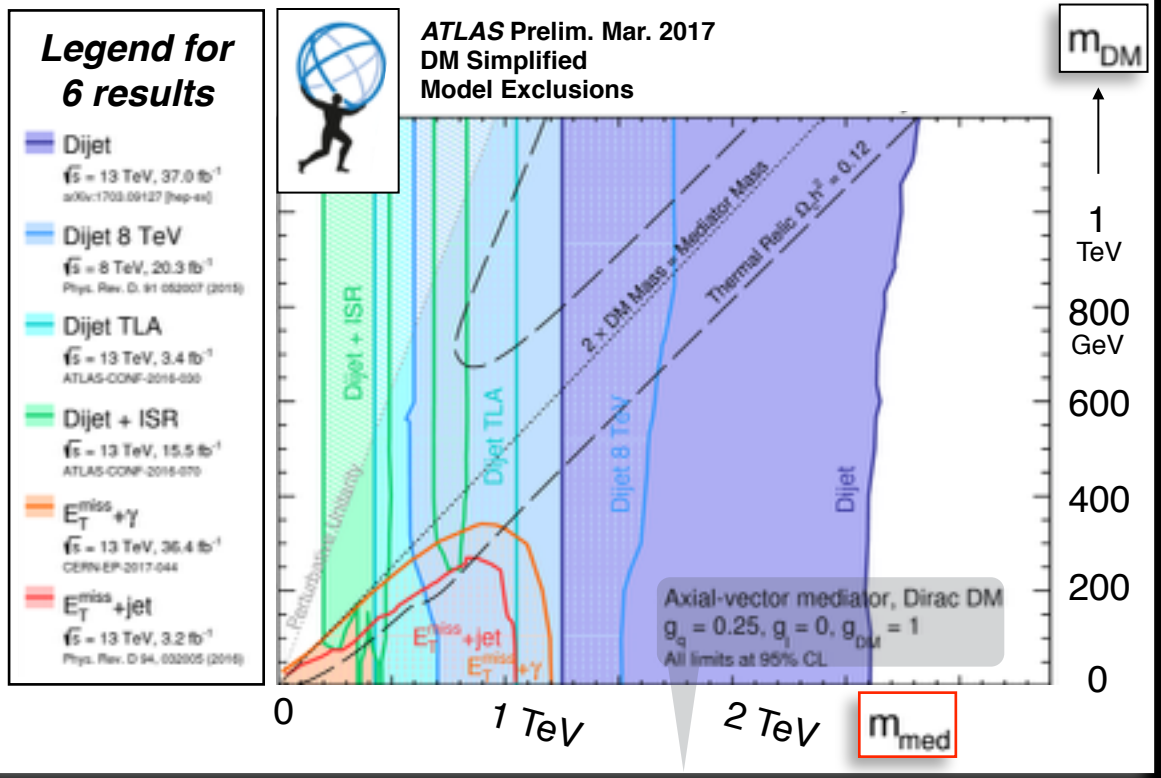
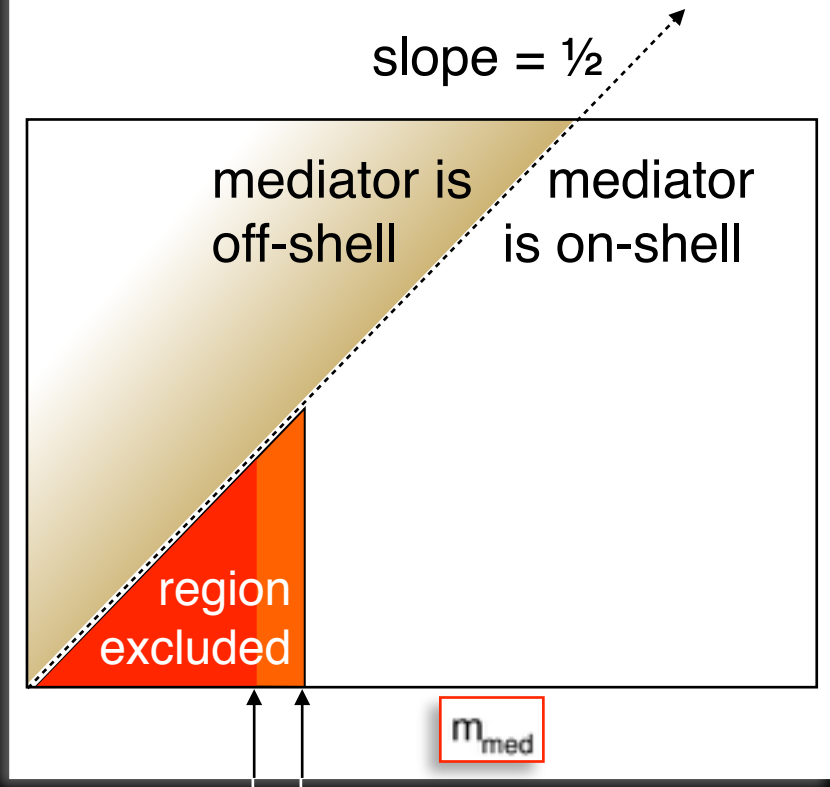
Exclude in (m_{med} v. m_{DM}) 2d plane, must fix (g_{DM} , g_q)

Overlay of mediator v. DM



March 2017, http://cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatter_Summary

Cartoon of mediator v. DM



Complementary coverage regions

Dark matter + mono-photon

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Exclude in ($\sigma_{\text{DM-proton}}$ v. m_{DM}) 2d plane [see also p34]

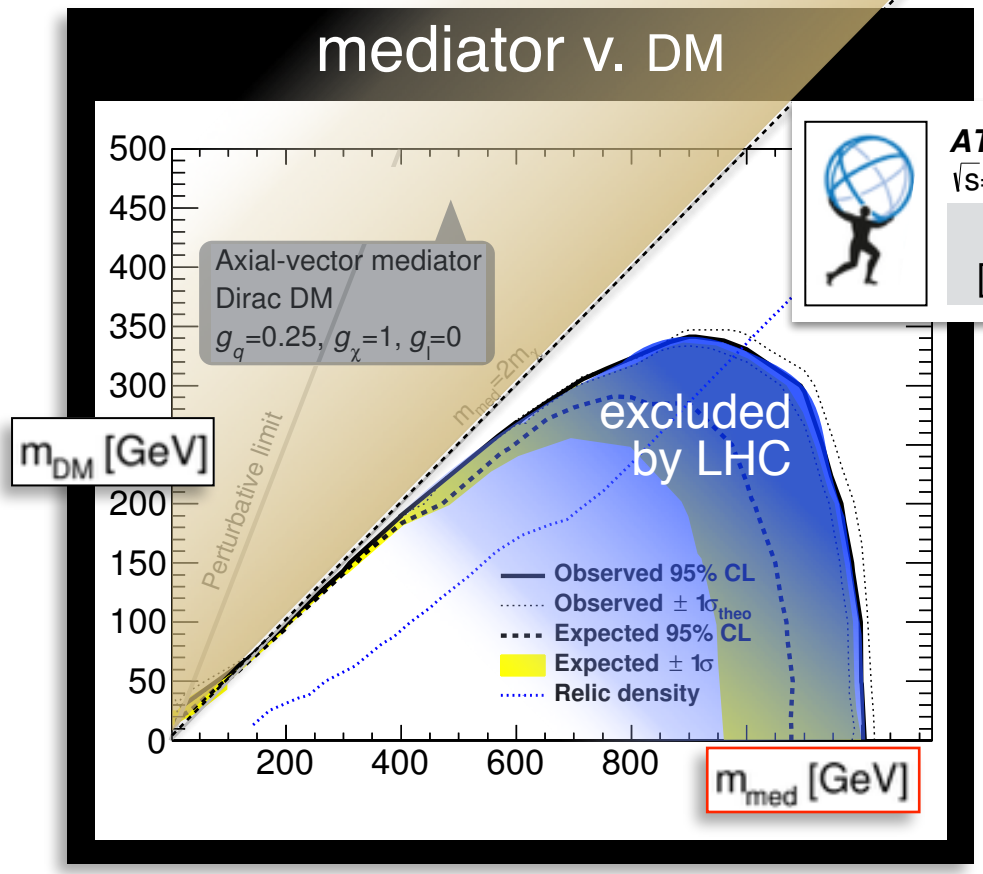
- σ is function of m_{med}, see right

$$\sigma^{\text{SD}}_{\text{DM-}p} \sim \left(g_q \cdot g_{\text{DM}} \cdot \frac{m_{\text{DM-}p}}{(m_{\text{med}})^2} \right)^2$$

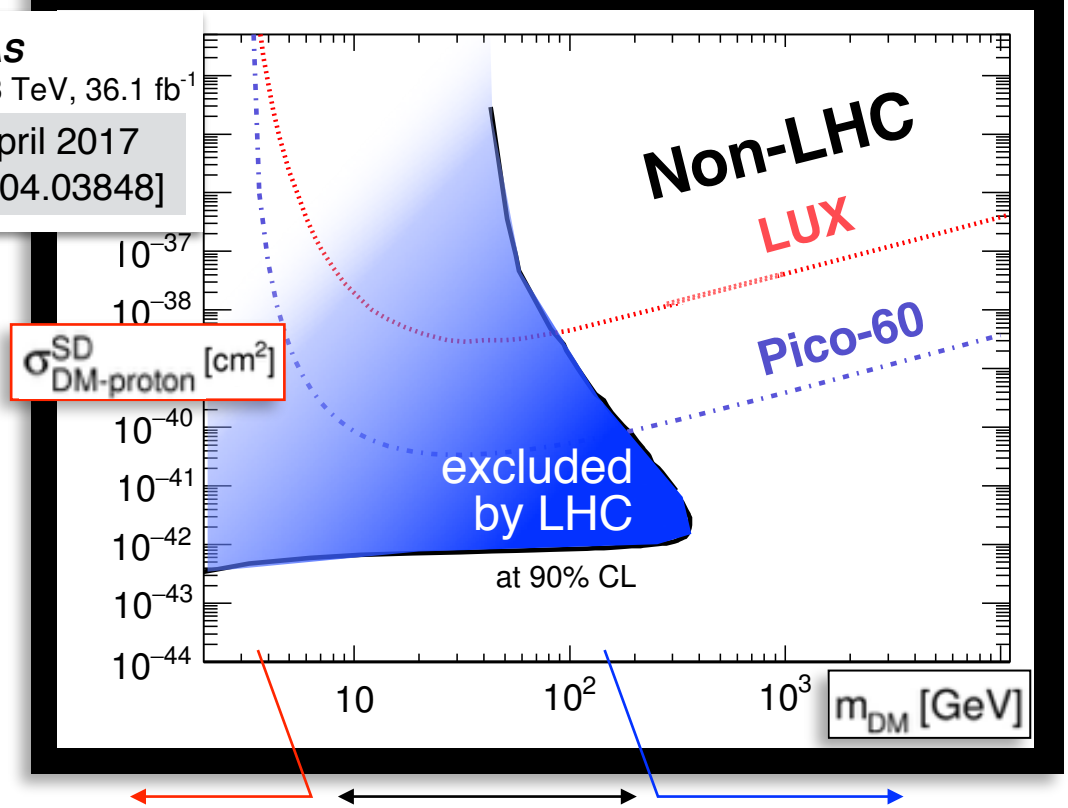
Fix Scan

mediator is off-shell ↔ on-shell

mediator v. DM



cross-section v. DM



LHC sensitive overlap *non-LHC*

Dark matter + mono-Higgs

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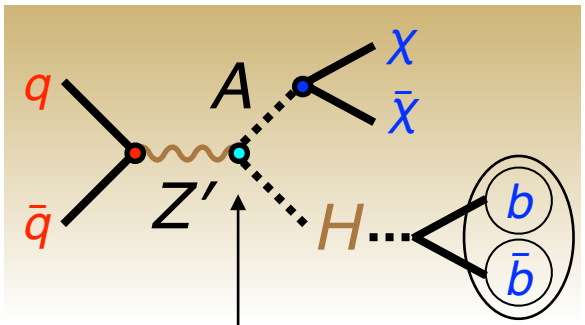


Precision Higgs imp't

$$\Delta R = \frac{2m_H}{P_T}$$

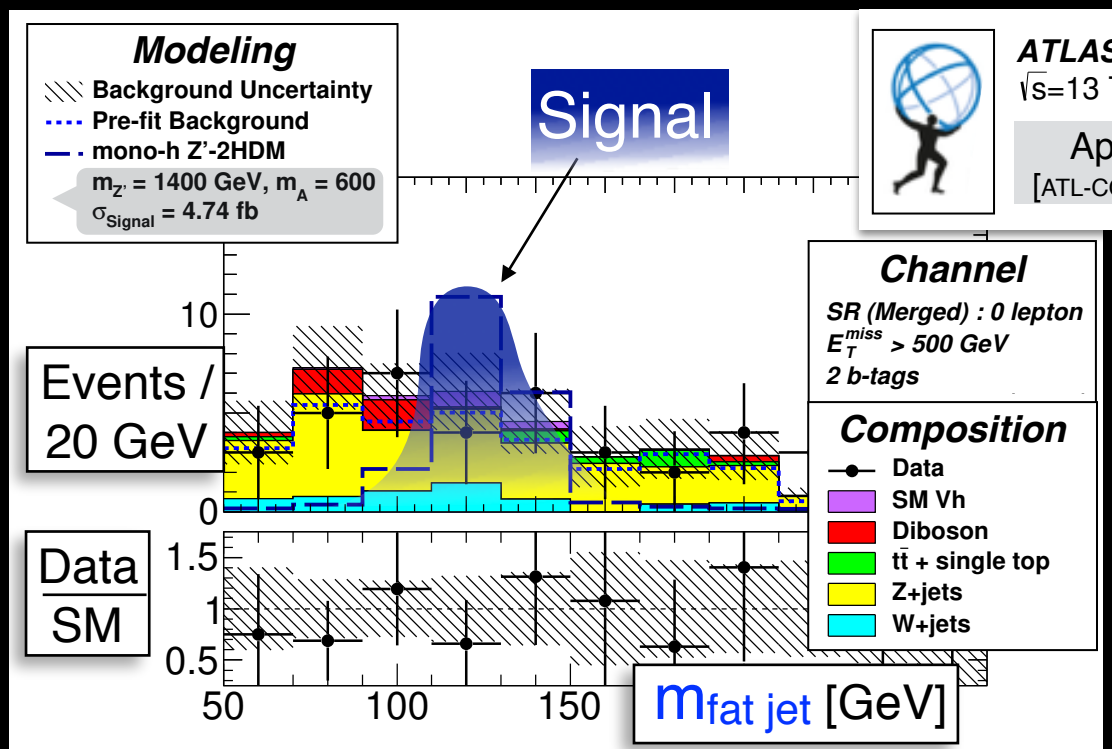
Challenges

- $\sigma_{Higgs} \sim O(pb)$
- Gap in m_A - $m_{Z'}$
- Large par. space

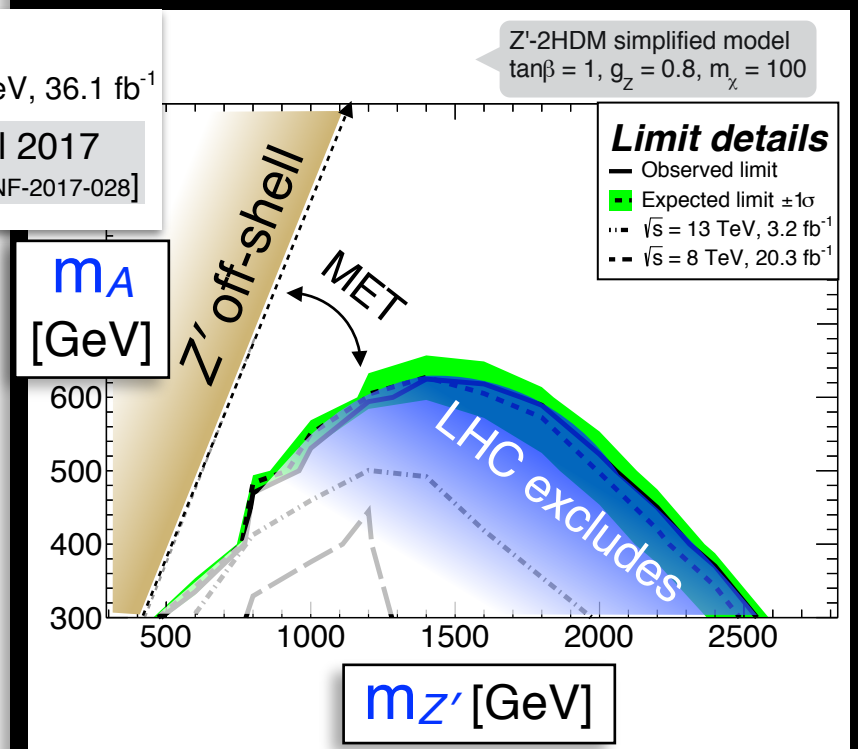
Solutions

- Channels: boosted…
- MET trigger threshold
- Fix tan β (m_A v. $m_{Z'}$)
- *Consider DM sector*

Distribution of boosted jet



Two mediators: *A* v. *Z′*



Joke

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Once you have a collider,

Toroids

newyorker.com/
cartoons/a18624

every problem starts to look like a particle.

your analysis

dark matter

Mediator via di-jet

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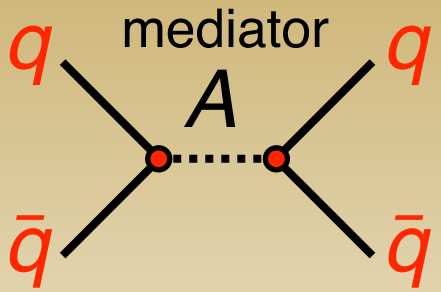


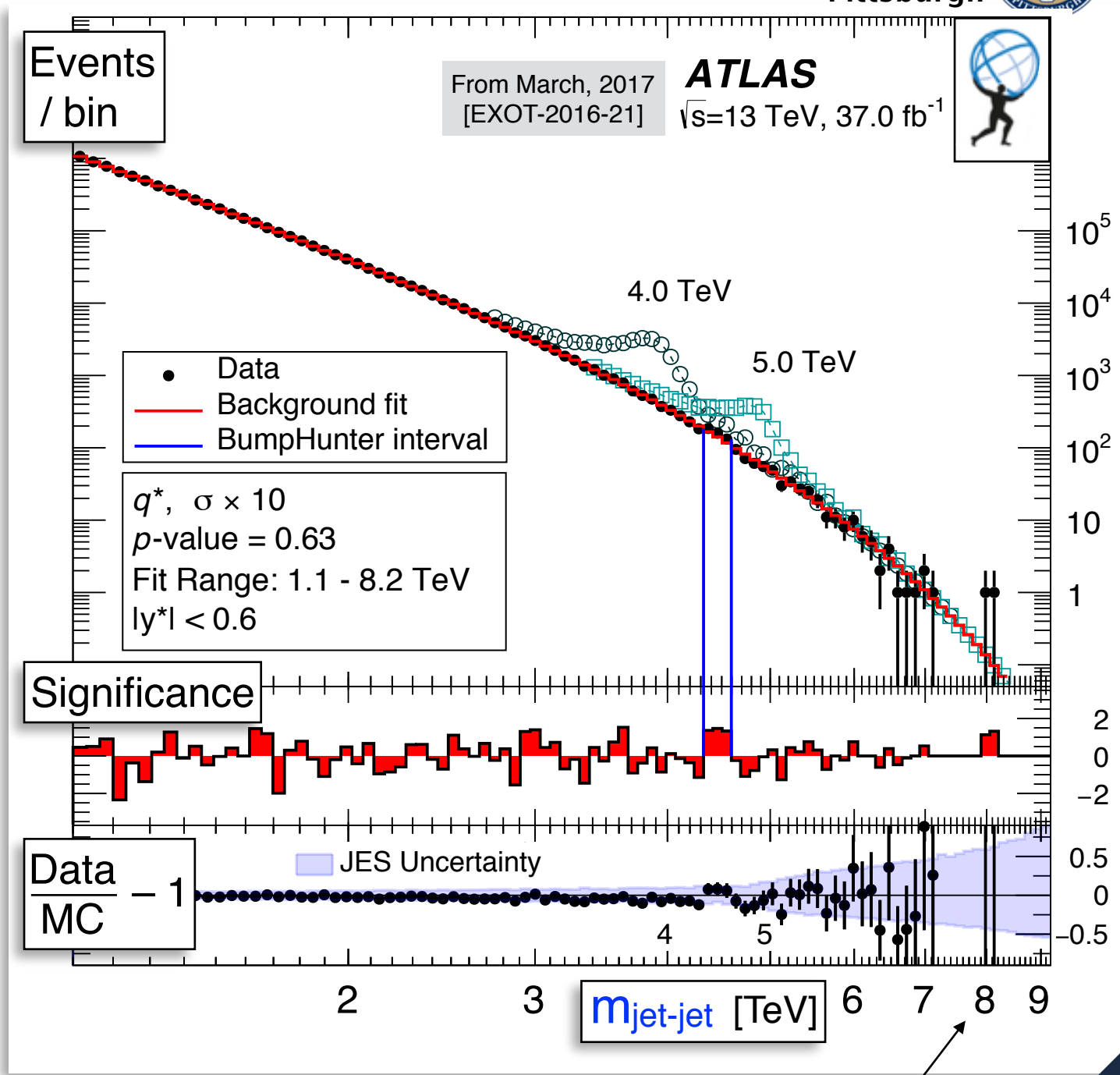
Challenges

- Di-jets high rate
- $m_{jet\text{-}jet}$ threshold

Solutions

- ISR jet / photon
- Boosted jet-jet
- Save trig.-level (more later)

Display of event here next slide



Di-jet (no MET!)

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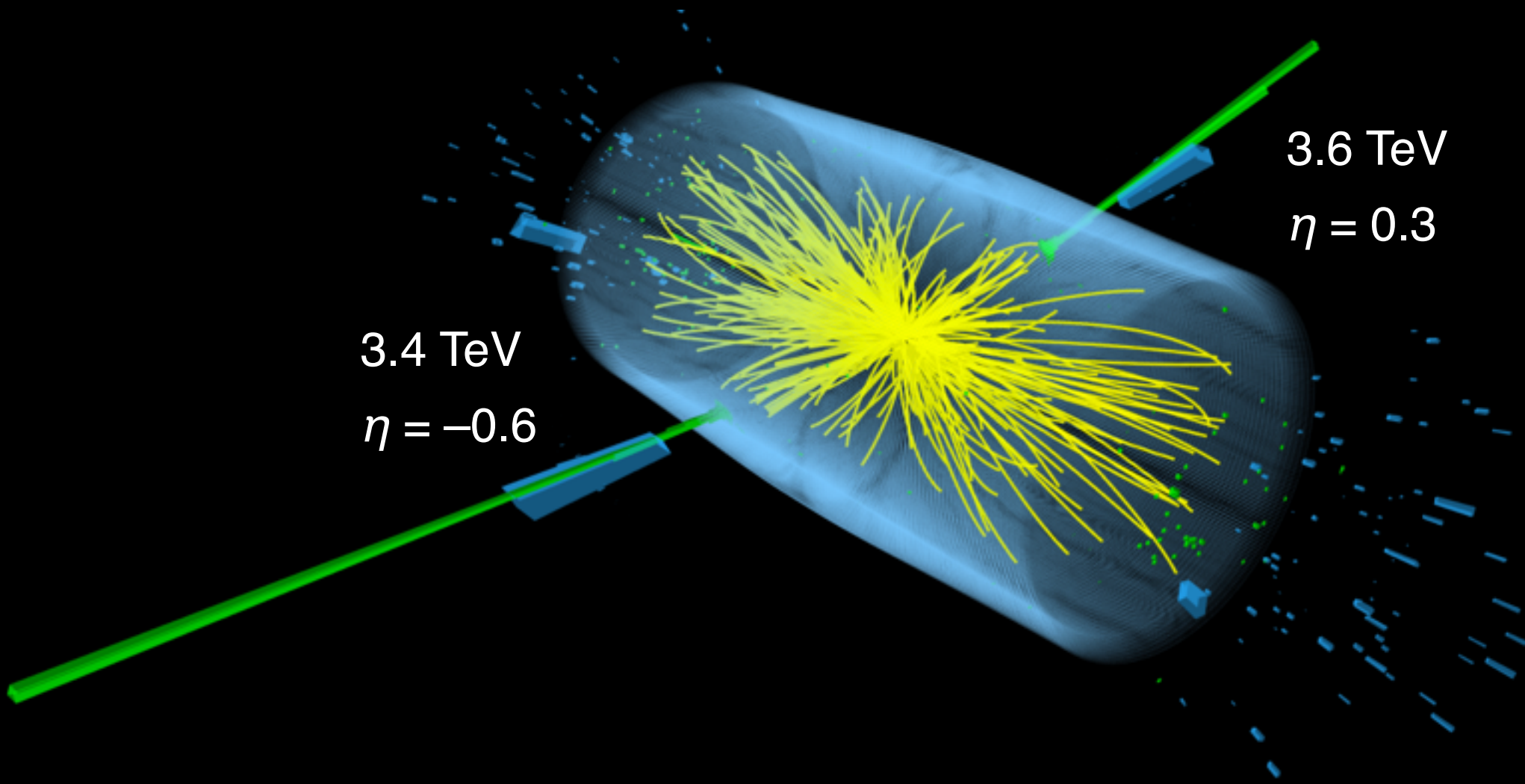

Invariant mass

- $m_{jet\text{-}jet}$ = 7.7 TeV
- among the highest recorded

From August 2016, [CDS: 2203615]

CMS Experiment at the LHC, CERN
Data recorded: 2016-May-11 21:40:47.974592 GMT
Run / Event / LS: 273158 / 238962455 / 150

Trigger-level

New tools, reach lower

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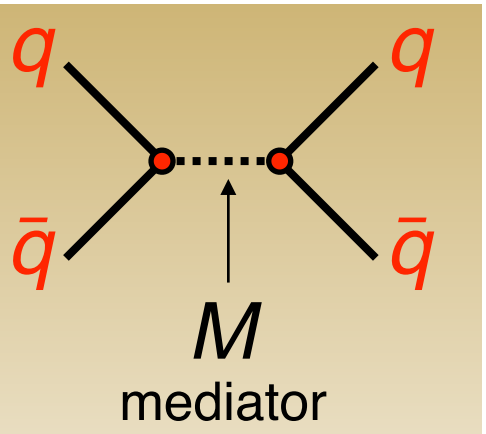


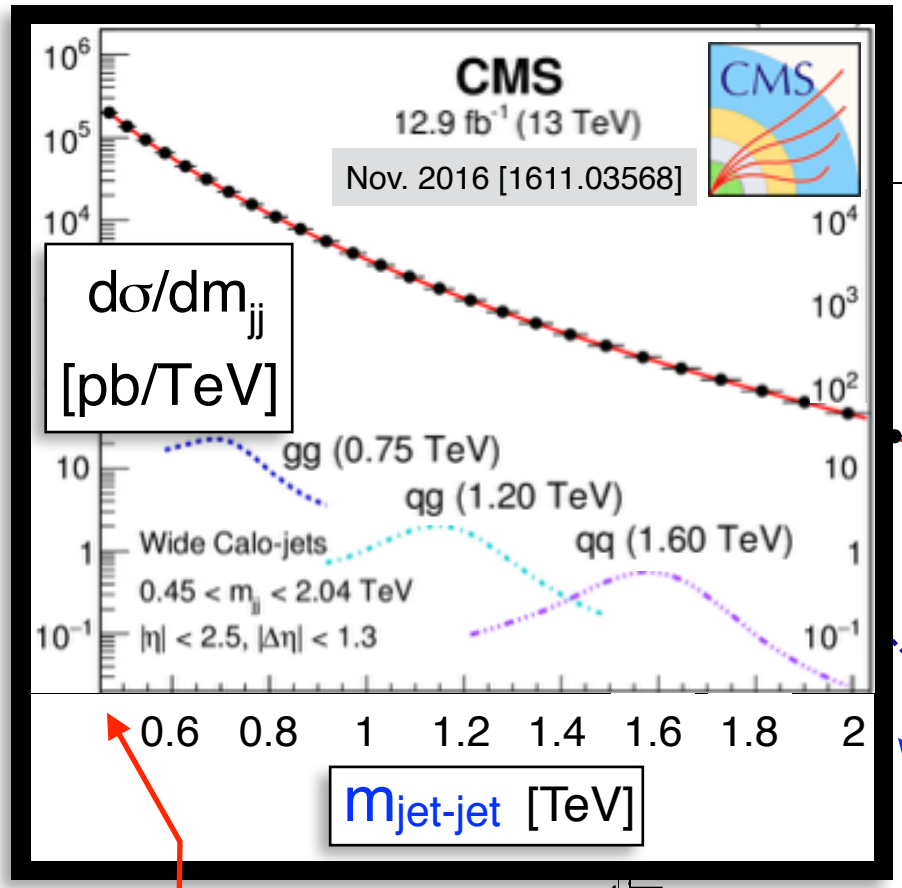
Full event, 1 MB

- Rate increase

Jet info, 1 kB

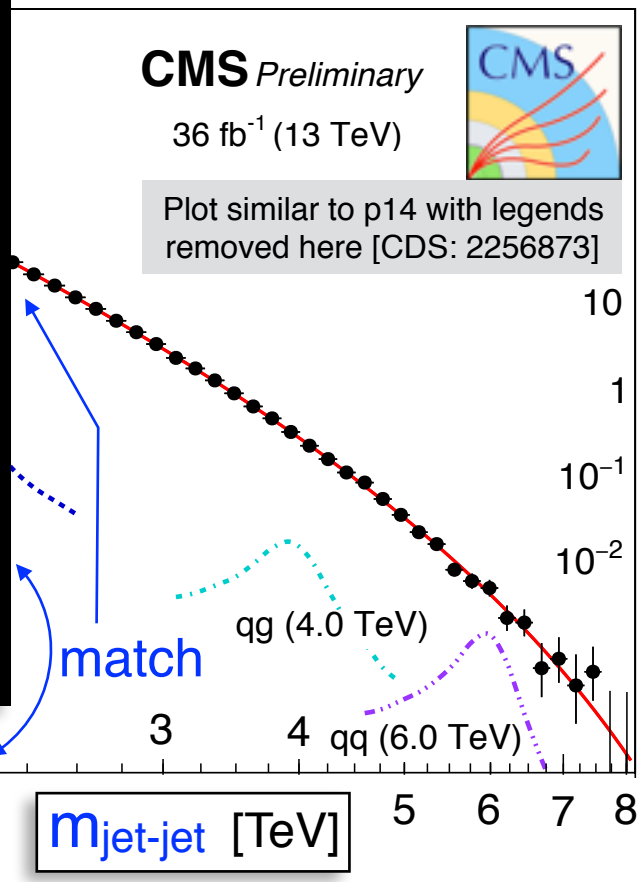
- CMS scouting
- ATLAS trigger-level

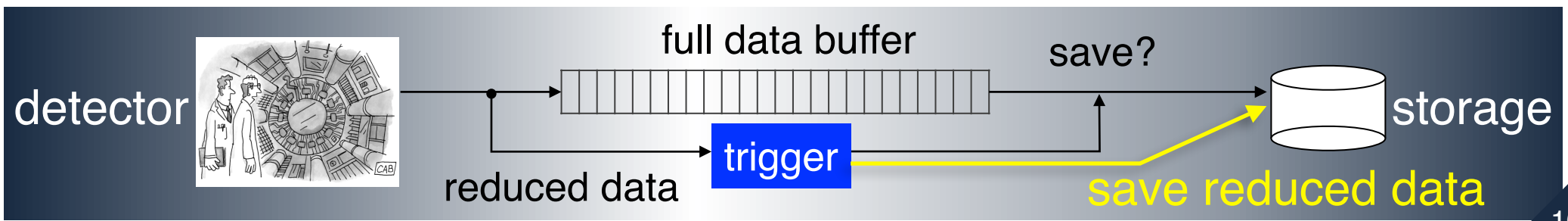
http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-030/



down to 100s!

similar to p14





Di-jet (no MET!)

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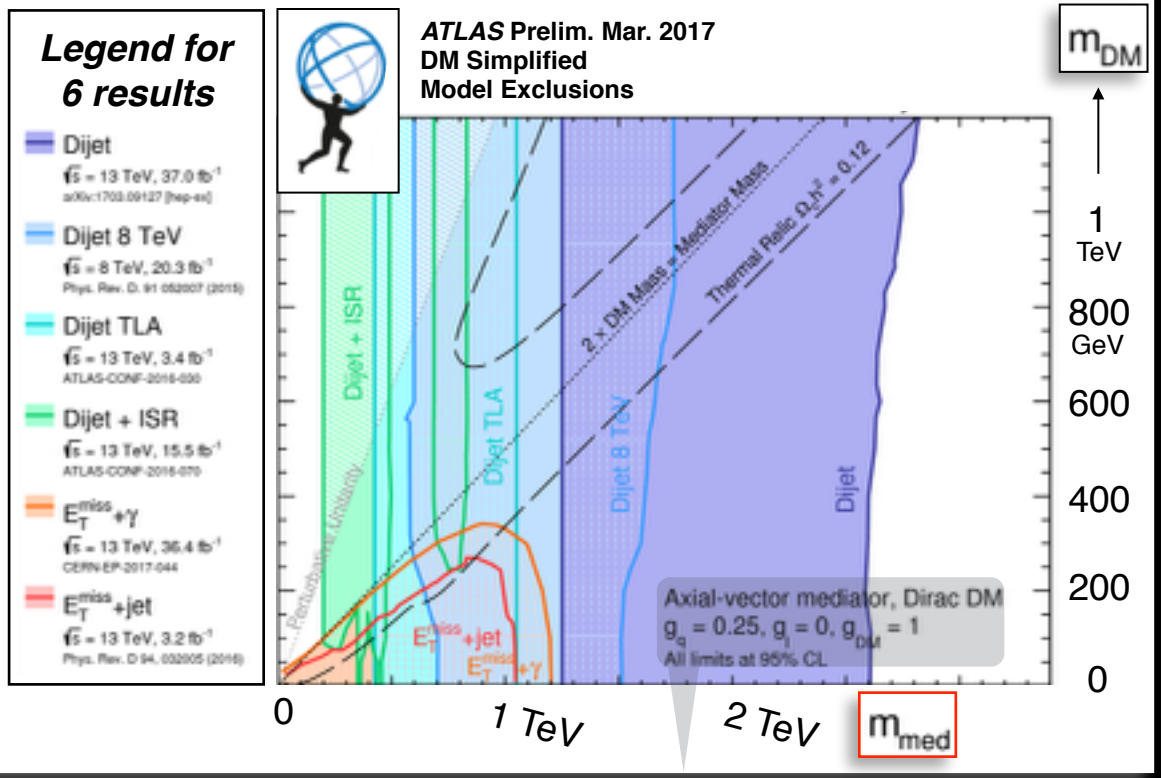
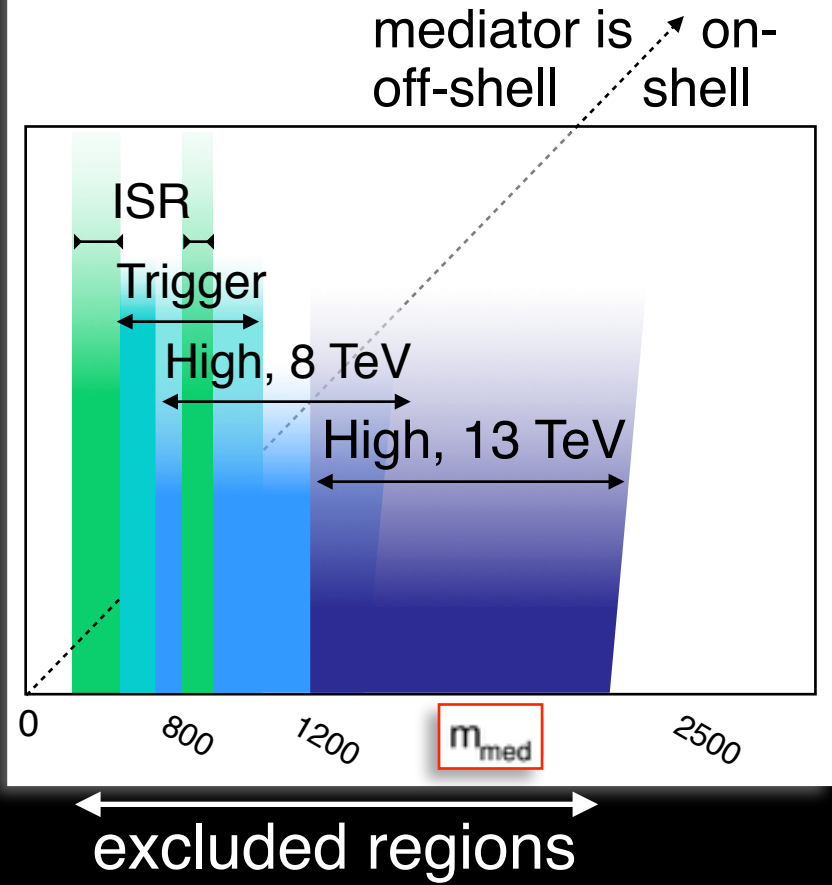
Exclude in (m_{med} v. m_{DM}) 2d plane, must fix (g_{DM} , g_q)

Overlay of mediator v. DM



March 2017, http://cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatter_Summary

Cartoon of mediator v. DM



Vertical lines: $q\bar{q} \rightarrow A \rightarrow q\bar{q}$ is independent of m_{DM}

Below diagonal: $A \rightarrow \chi\bar{\chi}$ allowed, wider Γ_{med} due to phase space

Fine print is very important!

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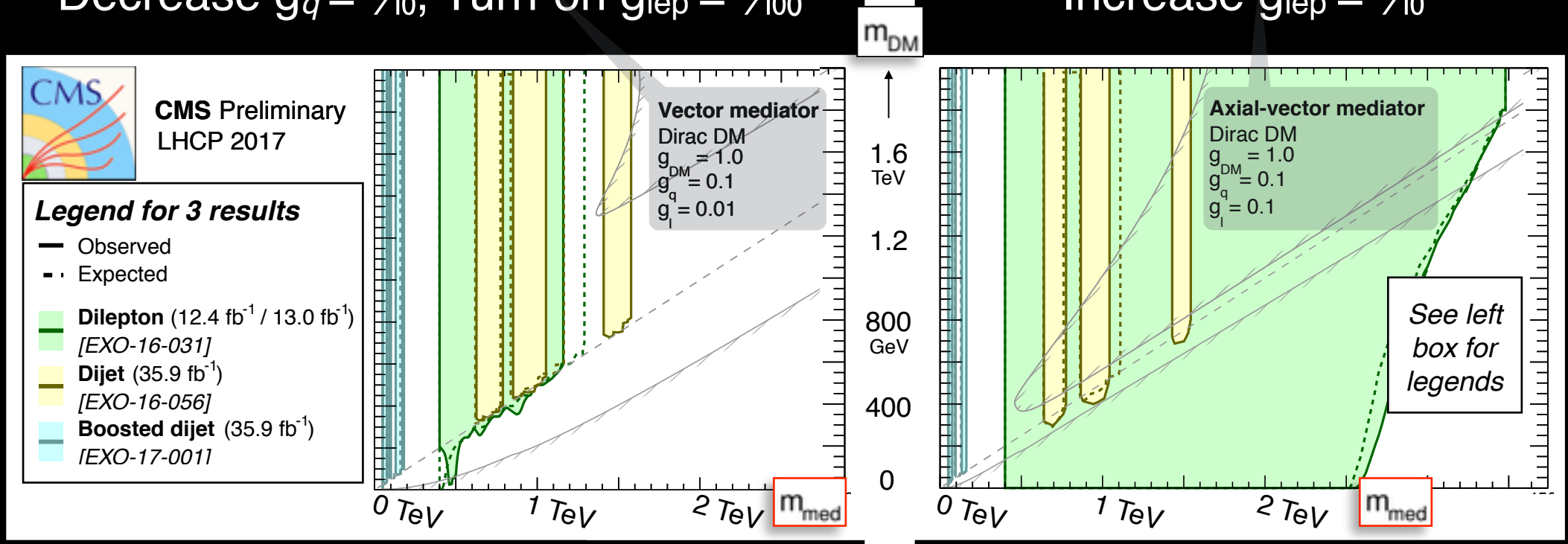
Alternate (g_{DM} , g_q , g_{lep}) alters conclusions [also see p36, 37]

Decrease $g_q = 1/10$, Turn-on $g_{lep} = 1/100$

Increase $g_{lep} = 1/10$



May 2017, http://cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM_summary_plots_LHCP_2017.pdf

No overlap in on-shell

Dilepton results more imp't

Overlapping coverages important for robustness

Higgs mediator

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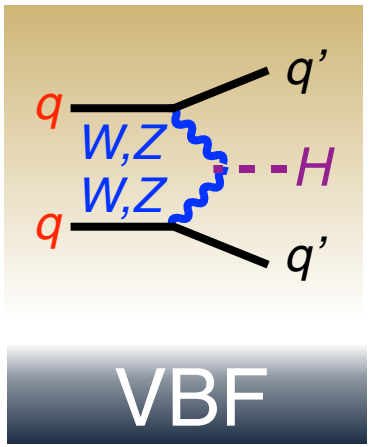
best sensitivity

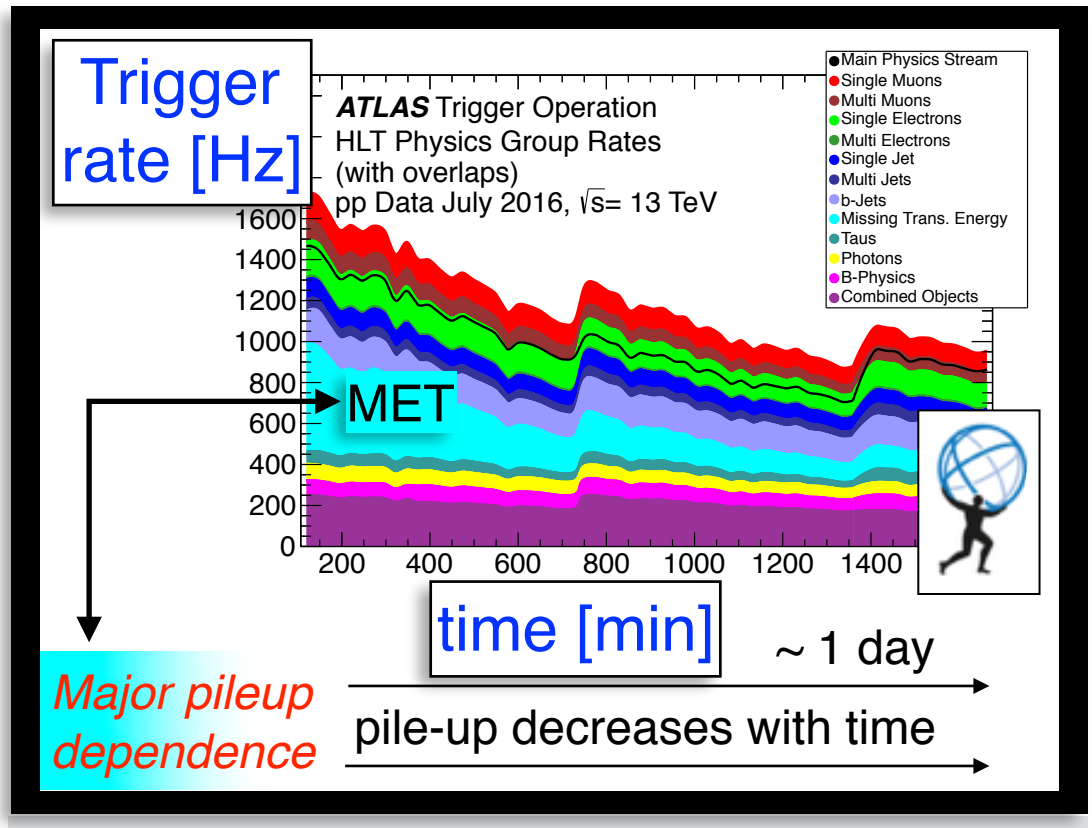


Challenges

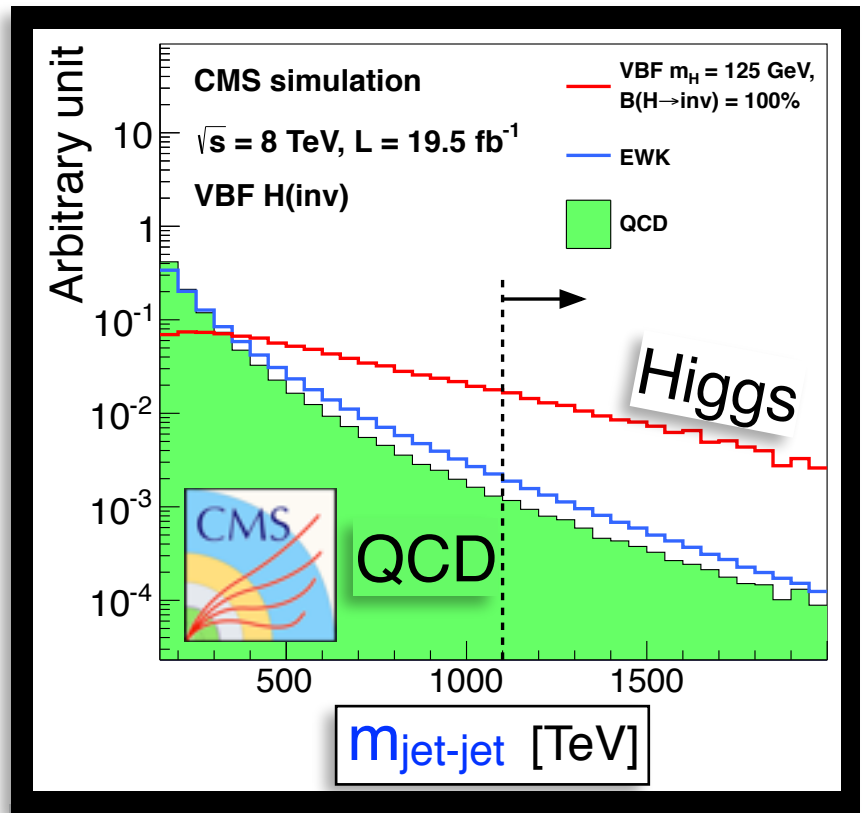
- Not many var. for VBF
- MET trigger has higher pileup dependence, left

Solutions

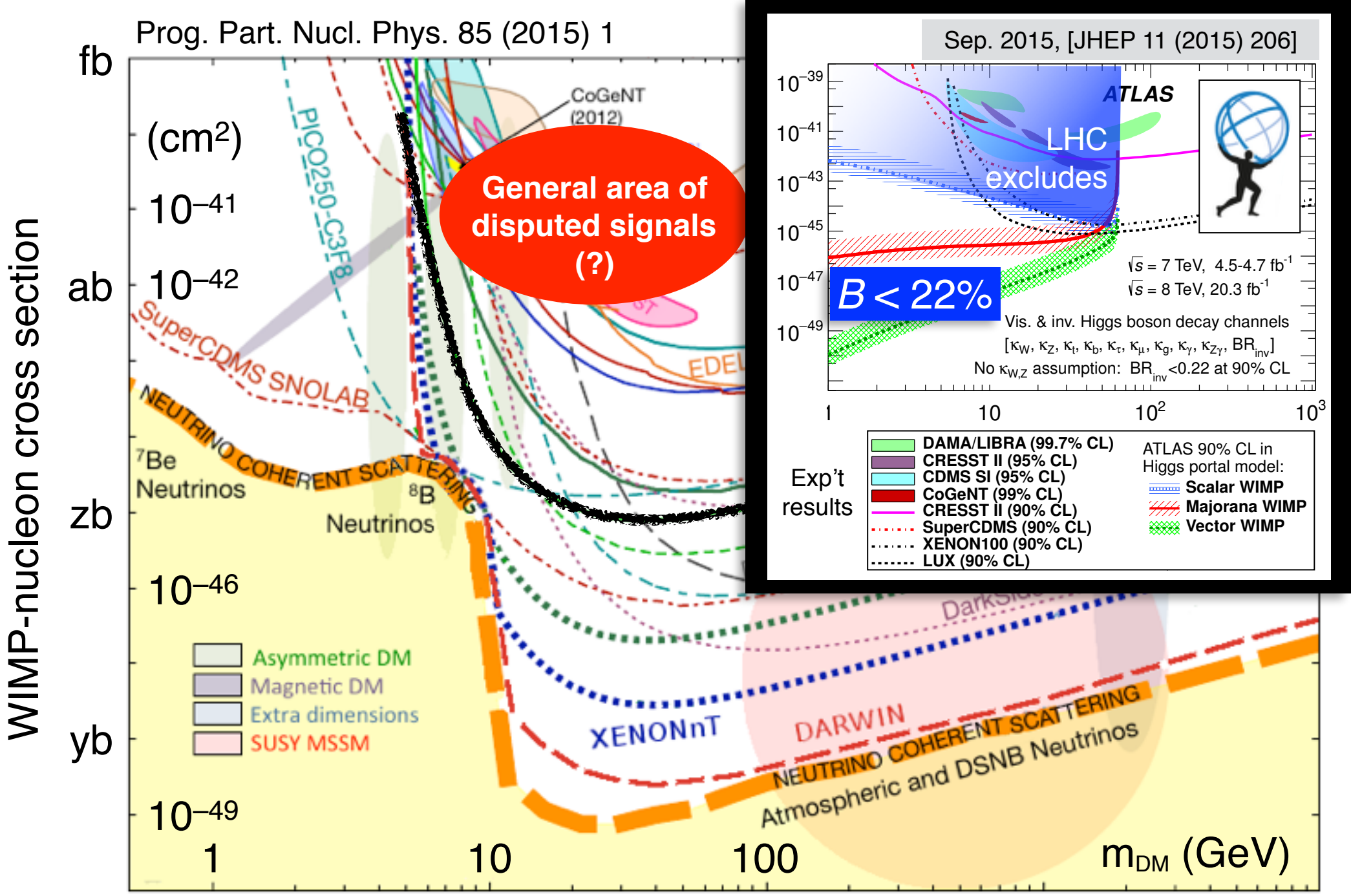
- Background est. imp't
- *Keep MET trigger threshold v. pileup*
- *Can trig. on jets, right*



July 2016, http://cern.ch/twiki/pub/AtlasPublic/TriggerOperationPublicResults/



From [1404.1344], also Mar. 2017 [1610.09218]



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Search for invisible or *measure Higgs decays*

Higgs mediator

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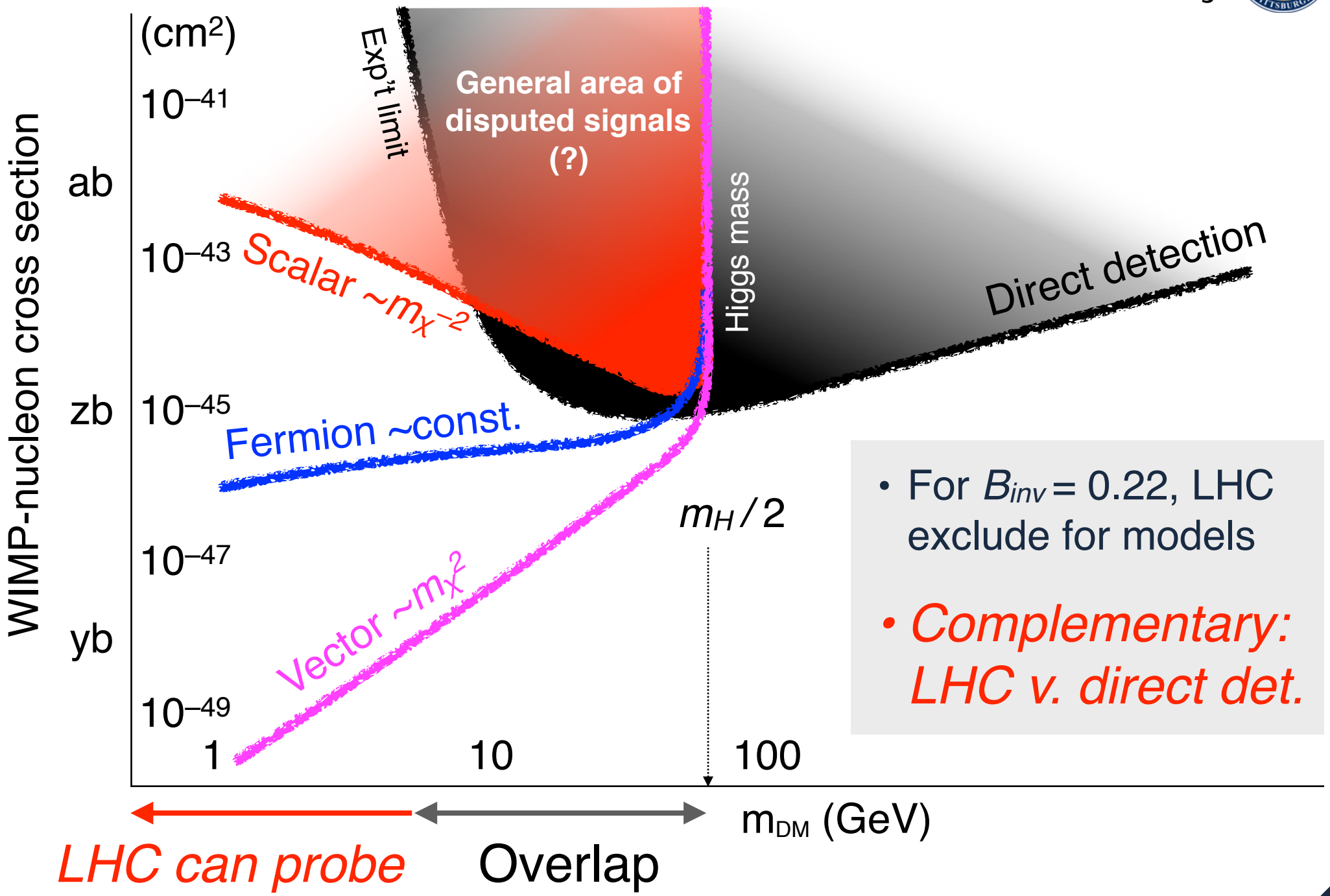

- For $B_{inv} = 0.22$, LHC exclude for models
- *Complementary: LHC v. direct det.*

Conclusion

EFT → simplifed

Dark matter → Dark matter sector ← more meas'ts

Dark matter(s)
Mediator(s)
Known matters

Many interesting topics not discussed here, e.g.,

- Scalars with color
- Dark γ / Z with looooooooooooooooooooooooooooooooooong lifetime
- SUSY that conserves R parity

Extra

References cited

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Slide	Links
1, 12	http://www.newyorker.com/cartoons/a18624
2	http://arxiv.org/find/all/1/ti:+AND+lhc+AND+dark+matter/0/1/0/2015,2016,2017/0/1? [and so forth]
3	http://indico.cern.ch/event/517784/sessions/223842/#all.detailed
4	http://arxiv.org/abs/1507.00966
5	http://arxiv.org/abs/1609.09079
6	http://arxiv.org/abs/1603.04156 http://cds.cern.ch/record/2256873
8	http://arxiv.org/abs/1703.016511
9, 17, 37	http://cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatter_Summary
10	http://arxiv.org/abs/1703.016511
11	http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-03/
12	http://arxiv.org/abs/1704.03848
14	http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/
15	http://cds.cern.ch/record/2203615
16	http://arxiv.org/abs/1611.03568 http://cds.cern.ch/record/2256873
18	http://cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM_summary_plots_LHCP_2017.pdf
19	http://cern.ch/twiki/pub/AtlasPublic/TriggerOperationPublicResults/ http://arxiv.org/abs/1404.1344 http://arxiv.org/abs/1610.09218
20, 21, 28	http://dx.doi.org/10.1016/j.ppnp.2015.07.001 [http://arxiv.org/abs/1507.03800] http://dx.doi.org/10.1007/JHEP11(2015)206
Extra	
25	http://dx.doi.org/10.1007/JHEP01(2015)037
27	http://arxiv.org/abs/1704.03848
29	http://cds.cern.ch/record/2208044
30	http://dx/doi.org/10.1140/epjc/s10052-014-2980-6 [http://arxiv.org/abs/1404.1344]
31	http://arxiv.org/abs/1603.07739
32	http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/
33	http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-32/
34	http://arxiv.org/abs/1703.01651
35	http://arxiv.org/abs/1702.07666
36	http://indico.cern.ch/event/623880 contribution from C. Doglioni
38	http://cern.ch/twiki/pub/AtlasPublic/MissingEtTriggerPublicResults/metxs_vs_mu.pdf
39	http://cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
40	http://cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Projection

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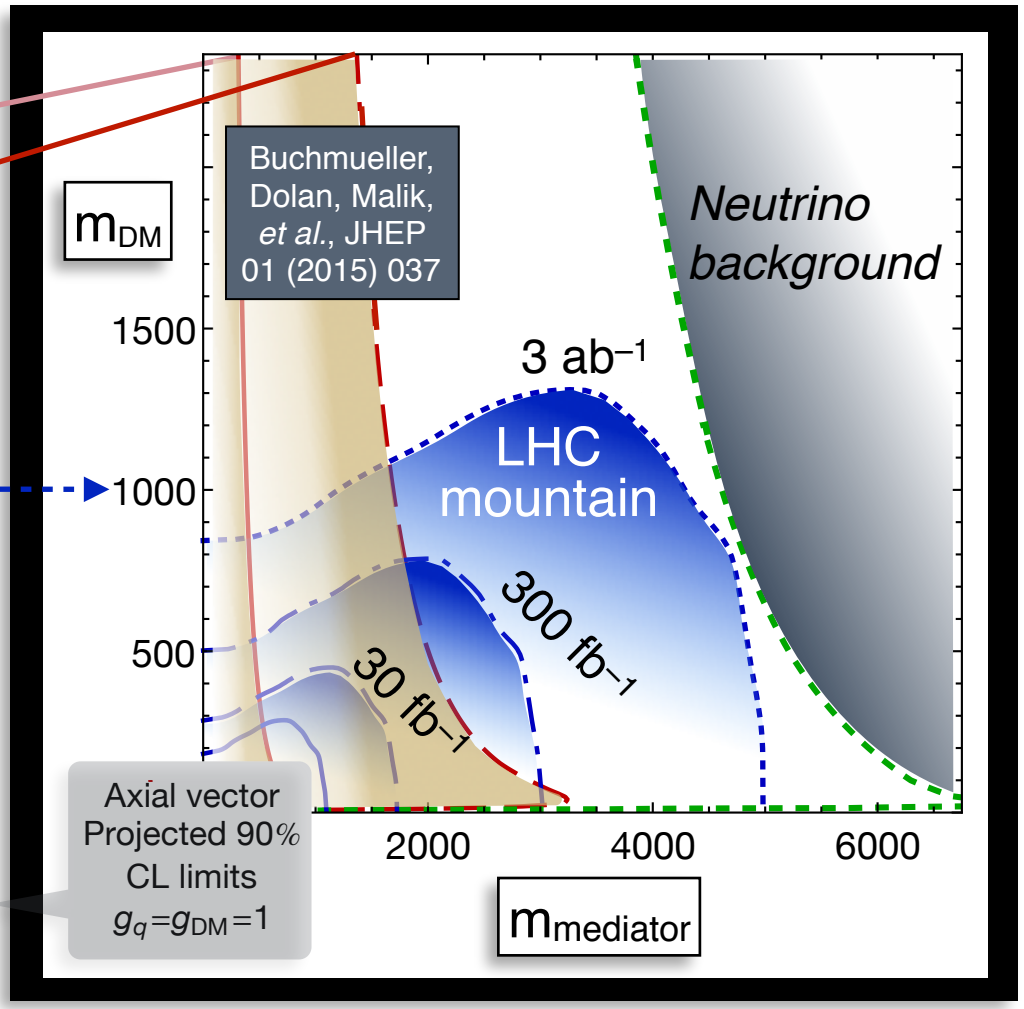
m_{DM} reach TeV at HL-LHC

Non-LHC:
LUX '13
LZ 10 ton yr



NB. Not same v. plots in this talk

Complementarity continues

Too long; didn't read recap

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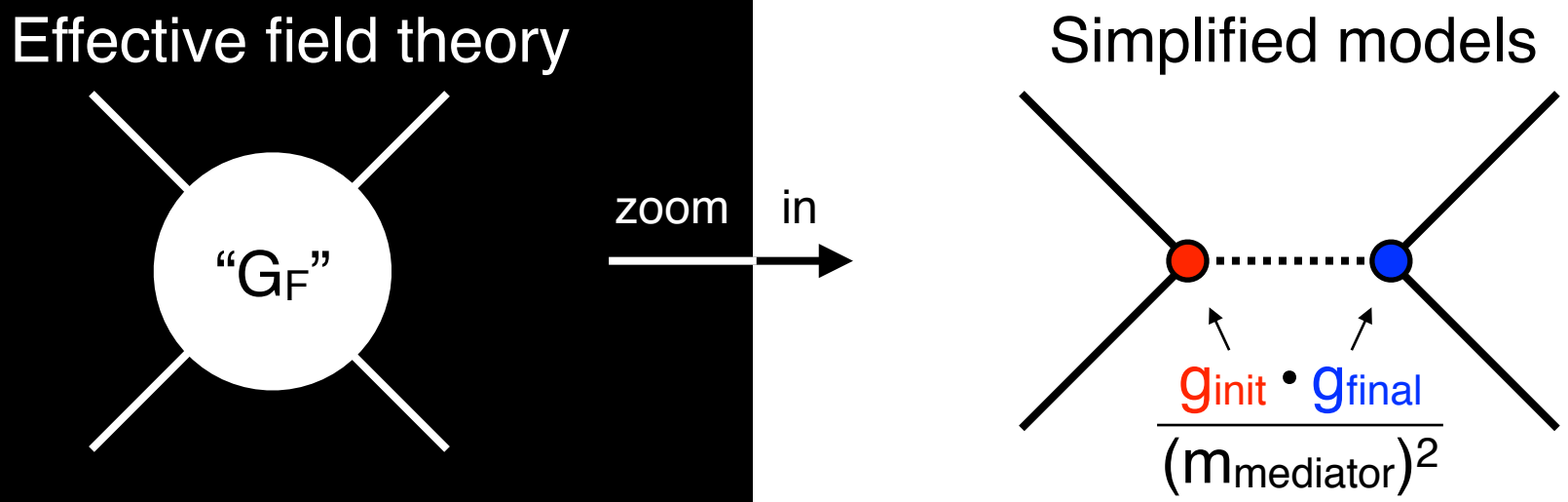

dark matter

dark matter mediator

Improved understanding
of the dark matter sector

Dark matter + mono-photon

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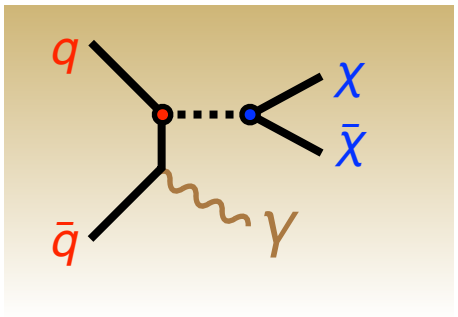
Search $pp \to \chi\bar{\chi} + \gamma$

- "χ" = γ for recoil

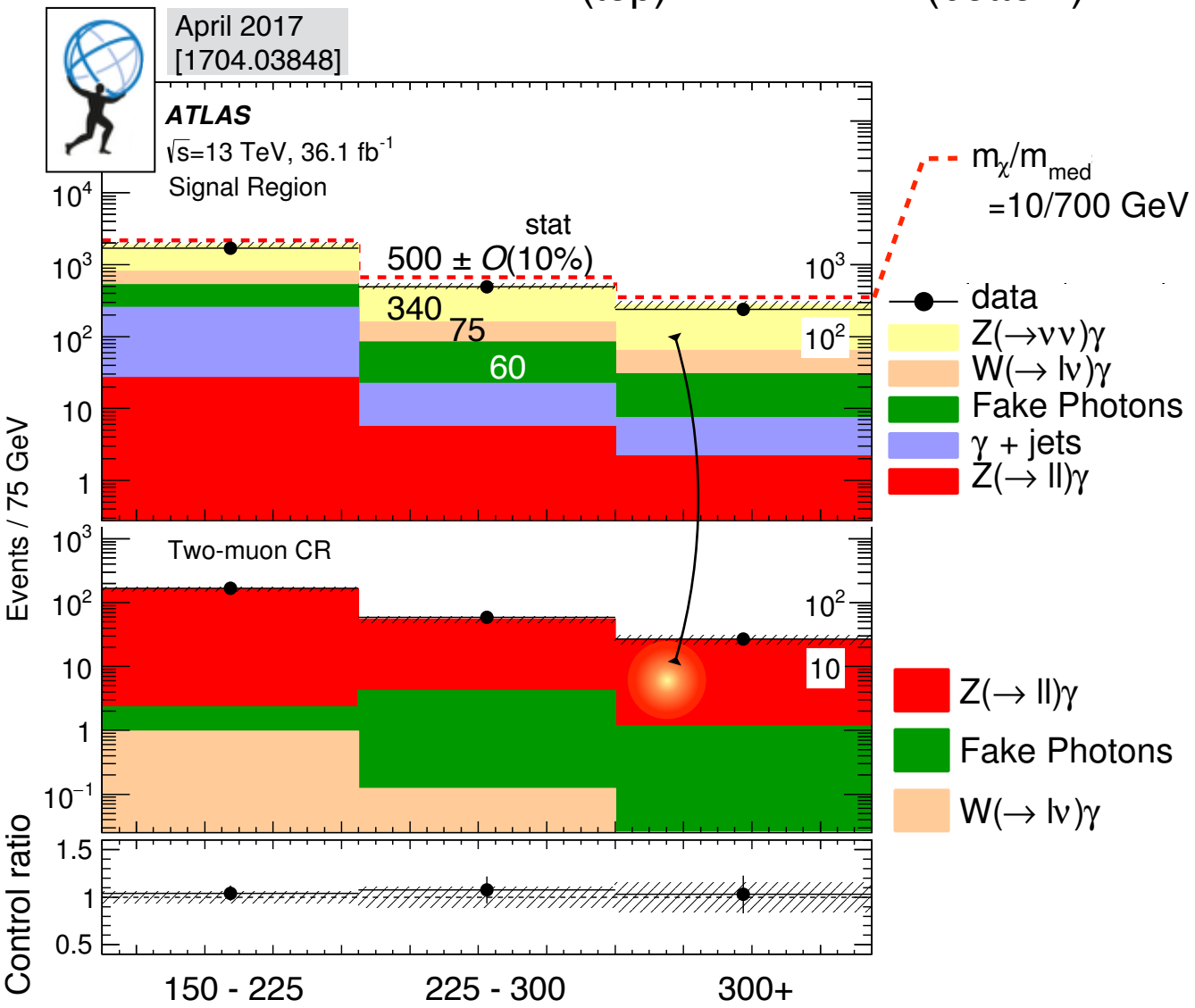


- Irreduc. $Z_{\nu\bar{\nu}} \leftrightarrow M_{\chi\bar{\chi}}$
- Estimate using Z_{ll}

Experimental

- O(100) events will improve with data
- γ trigger > 140 GeV

MET distribution: signal enhanced, μμ control (top) (bottom)



Mediator via di-jet

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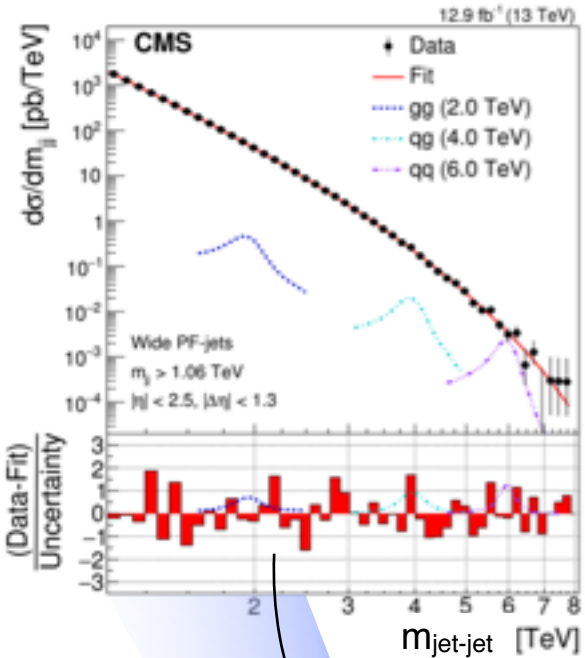
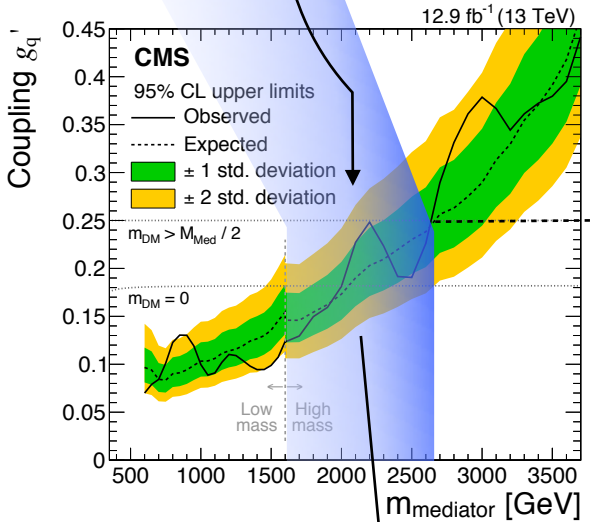
Last year's result (with blip) for pedagogy

$m_{jet\text{-}jet}$

Little blip

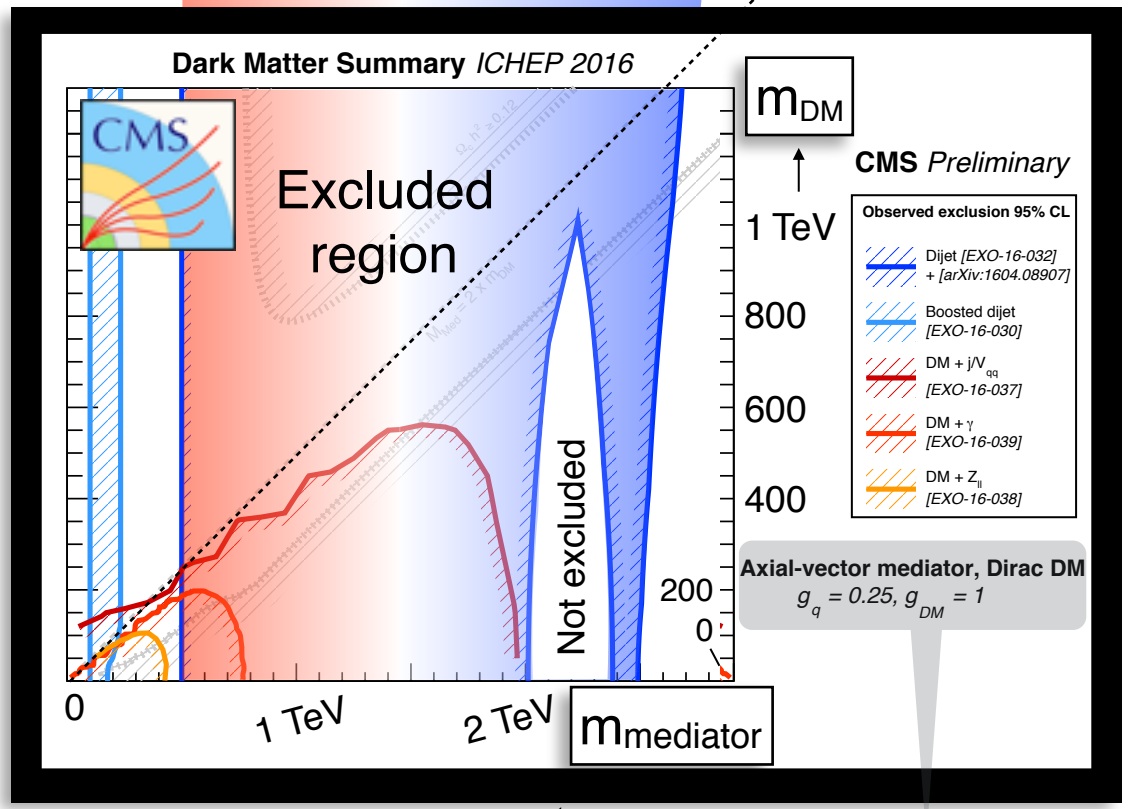
Limit





Left side by next slides Right side by left plots

slope = ½



Exclusion excludes blip

Assumptions on 2 params.

Invisible Higgs interpretation

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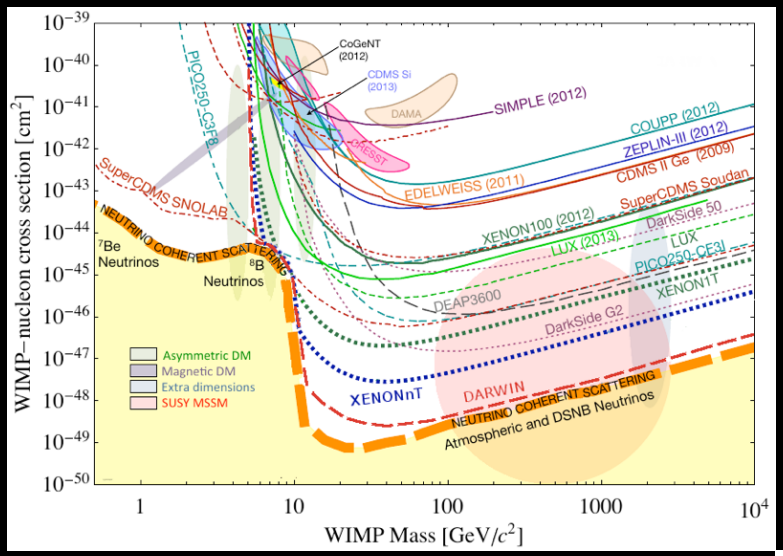


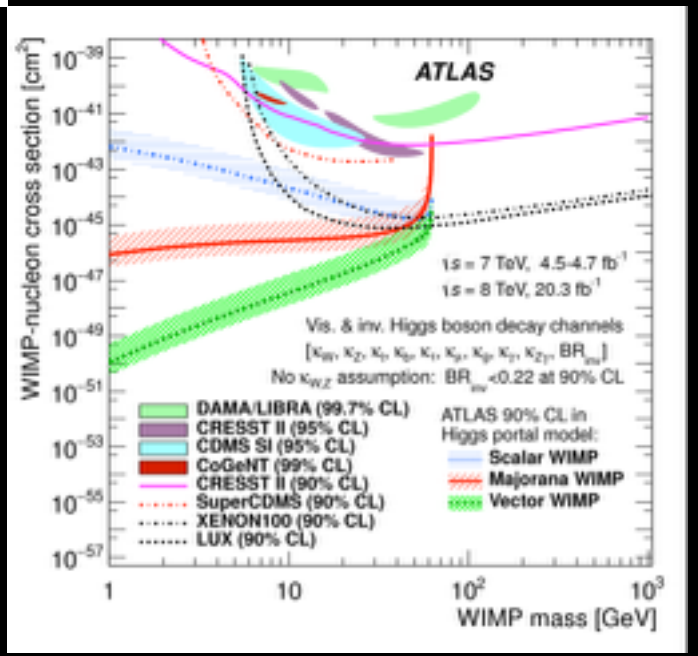
Many direct detection results

LHC measurement

$\sigma \sim \Gamma_{inv} \cdot \begin{cases} (m_\chi)^2 \\ (m_\chi)^0 \\ (m_\chi)^{-2} \end{cases}$

DM interpretation

DM model



Higgs-DM models

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CMS Run-1 paper on VBF and *ZH*, EPJC 74 (2014) 2980

9 Dark matter interactions

We now interpret the experimental upper limit on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$, under the assumption of SM production cross section, in the context of a Higgs-portal model of DM interactions [7–9]. In these models, a hidden sector can provide viable stable DM particles with direct renormalizable couplings to the Higgs sector of the SM. In direct detection experiments, the elastic interaction between DM and nuclei exchanged through the Higgs boson results in nuclear recoil which can be reinterpreted in terms of DM mass, M_χ, and DM-nucleon cross section. If the DM candidate has a mass below $m_\mathrm{H}/2$, the invisible Higgs boson decay width, Γ_inv, can be directly translated to the spin-independent DM-nucleon elastic cross section, as follows for scalar (S), vector (V), and fermionic (f) DM, respectively [8]:

$$\sigma^{\mathrm{SI}}_{\mathrm{S-N}} = \frac{4\Gamma_\mathrm{inv}}{m_\mathrm{H}^3 v^2 \beta} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_\mathrm{N})^2}, \tag{8}$$

$$\sigma^{\mathrm{SI}}_{\mathrm{V-N}} = \frac{16\Gamma_\mathrm{inv} M_\chi^4}{m_\mathrm{H}^3 v^2 \beta (m_\mathrm{H}^4 - 4M_\chi^2 m_\mathrm{H}^2 + 12M_\chi^4)} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_N)^2}, \tag{9}$$

$$\sigma^{\mathrm{SI}}_{\mathrm{f-N}} = \frac{8\Gamma_\mathrm{inv} M_\chi^2}{m_\mathrm{H}^5 v^2 \beta^3} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_\mathrm{N})^2}. \tag{10}$$

Here, m_N represents the nucleon mass, taken as the average of proton and neutron masses, 0.939 GeV, while $\sqrt{2}v$ is the Higgs vacuum expectation value of 246 GeV, and $\beta = \sqrt{1 - 4M_\chi^2/{m_\mathrm{H}}^2}$. The dimensionless quantity f_N [8] parameterizes the Higgs-nucleon coupling; we take the central values of $f_\mathrm{N} = 0.326$ from a lattice calculation [69], while we use results from the MILC Collaboration [70] for the minimum (0.260) and maximum (0.629) values. We convert the invisible branching fraction to the invisible width using $\mathcal{B}(\mathrm{H} \to \mathrm{inv}) = \Gamma_\mathrm{inv}/(\Gamma_\mathrm{SM} + \Gamma_\mathrm{inv})$, where $\Gamma_\mathrm{SM} = 4.07$ MeV.

The future of invisible Higgs

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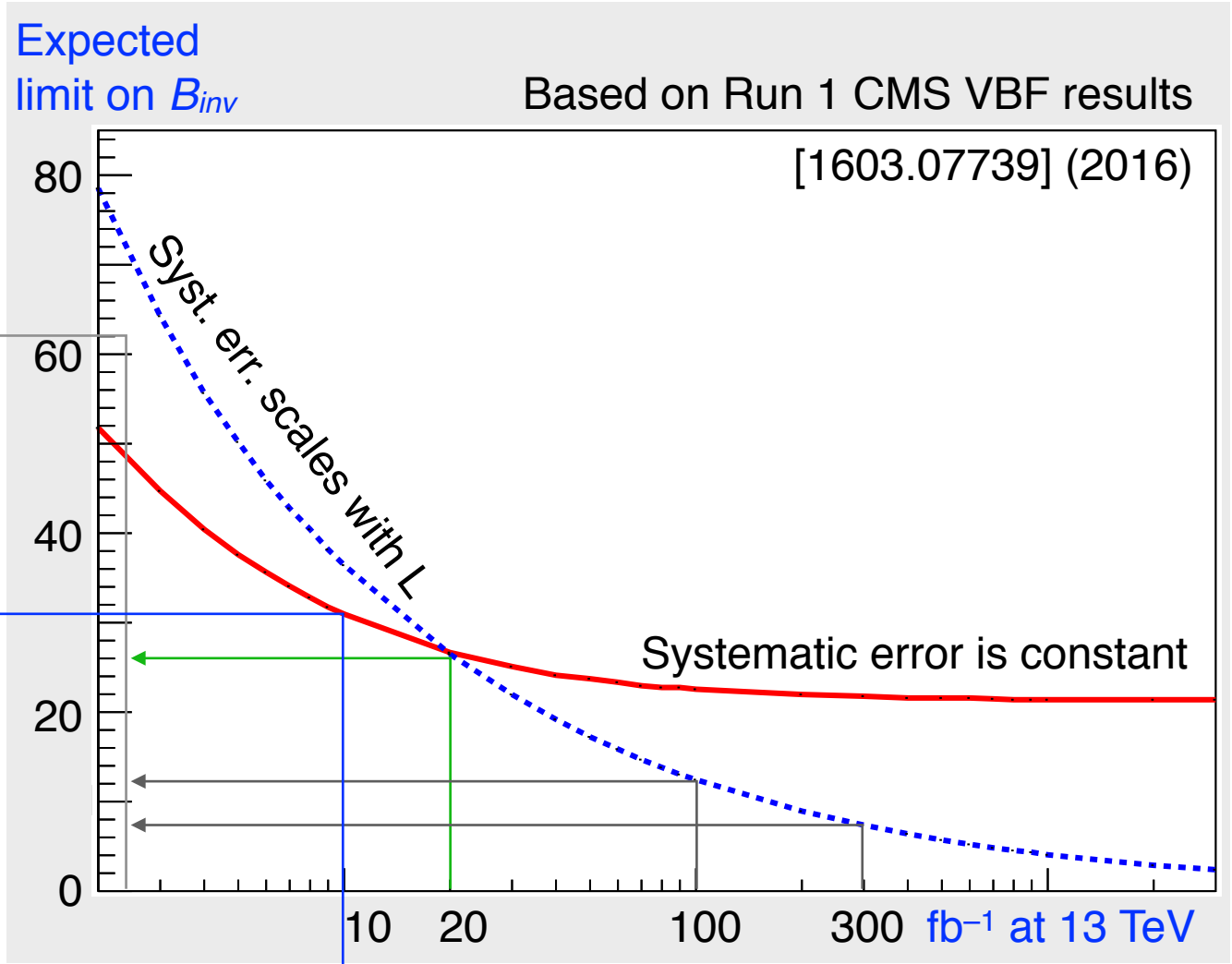
Luminosity projections

CMS Run-2 VBF results with 2.3 fb^{-1}

- Limit 69% (62%)
- *Z* norm'd w/ *W*

ATLAS Run-1 VBF

- Limit 28% (31%)
- *Z* norm'd w/ *W*



Need 10 fb^{-1} of 13 TeV reach Run 1

We'll try for < 20% in Run 2

Maybe possible? < 10% in Run 3

Di-jet (no MET!)

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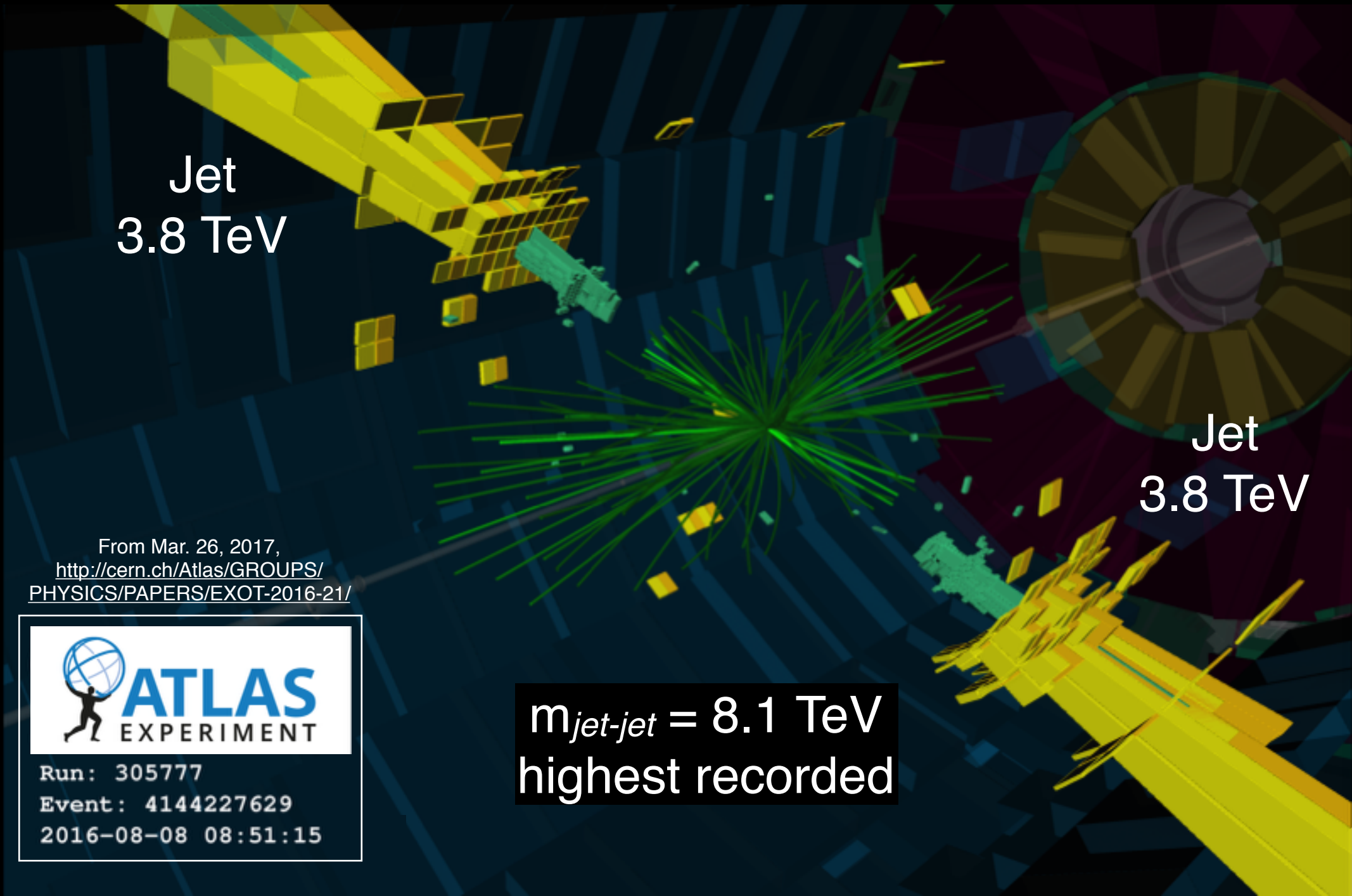

MET + photon

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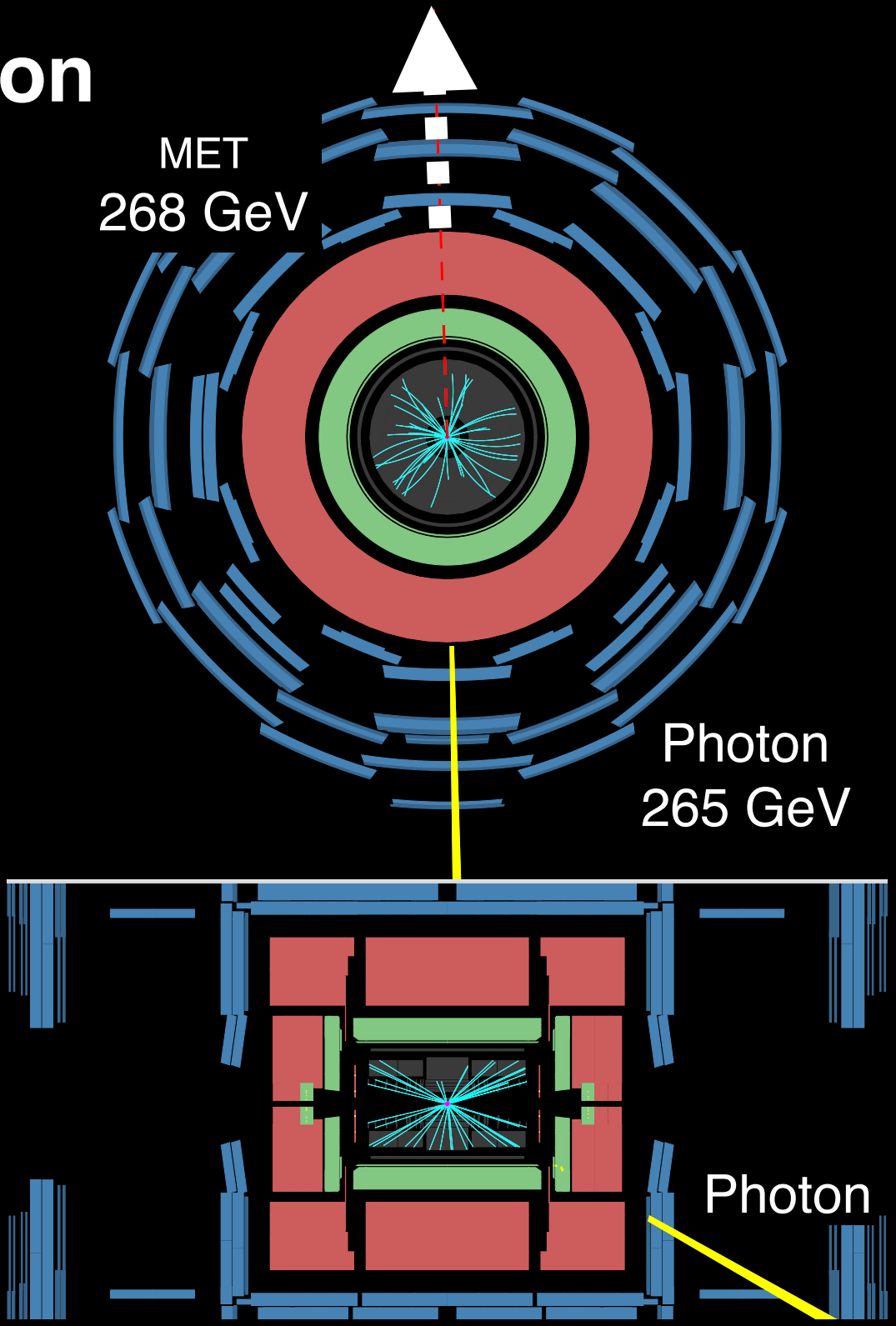

From April 12, 2017,
http://cern.ch/Atlas/GROUPS/
PHYSICS/PAPERS/EXOT-2016-32/

ATLAS EXPERIMENT

Run Number: 305811, Event Number: 1150484630

Date: 2016-08-08 22:56:19 CEST

Mono-jet CMS version of p11

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Exclude in ($\sigma_{\text{DM-proton}}$ v. m_{DM}) 2d plane

- σ is function of m_{med}, see right

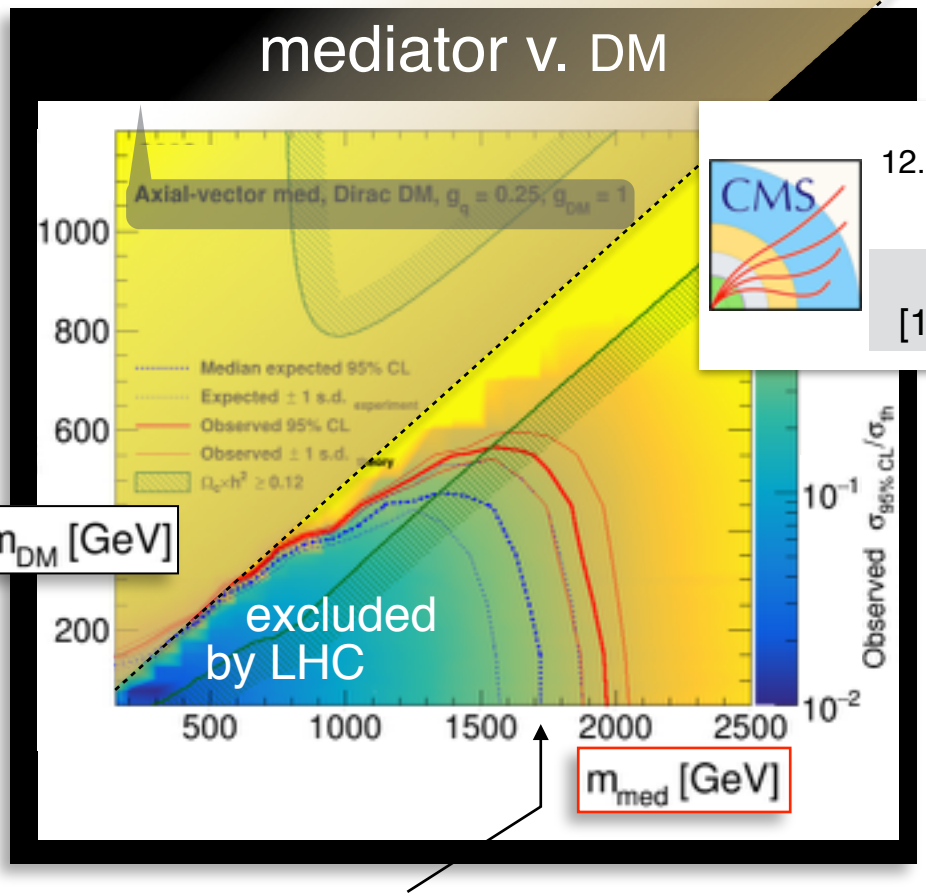
$$\sigma^{\text{SD}}_{\text{DM-}p} \sim \left(g_q \cdot g_{\text{DM}} \cdot \frac{m_{\text{DM-}p}}{(m_{\text{med}})^2} \right)^2$$

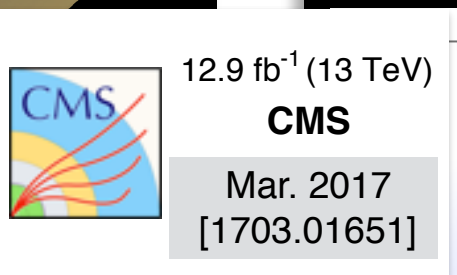
mediator is off-shell

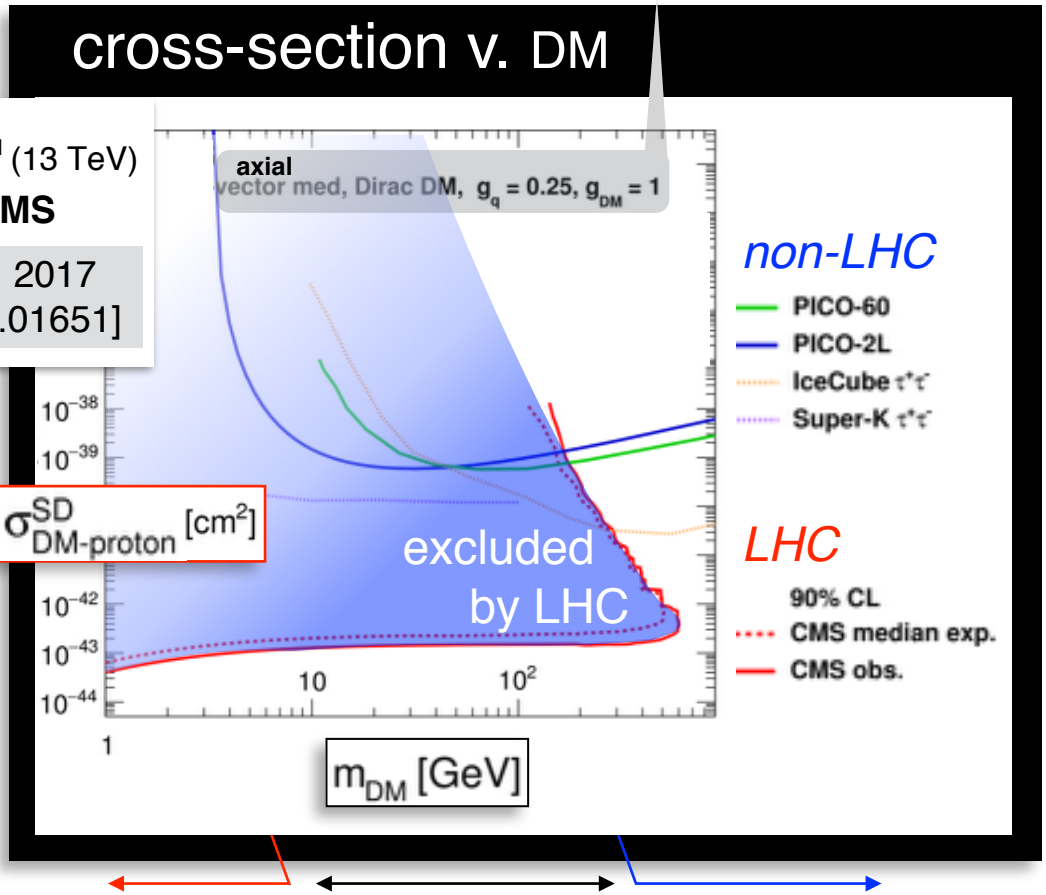
on-shell

Fix

Scan







To m_{med} = 1.7 TeV

LHC sensitive overlap *non-LHC*

PICO results

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Exclude in (m_{med} v. m_{DM}) 2d plane

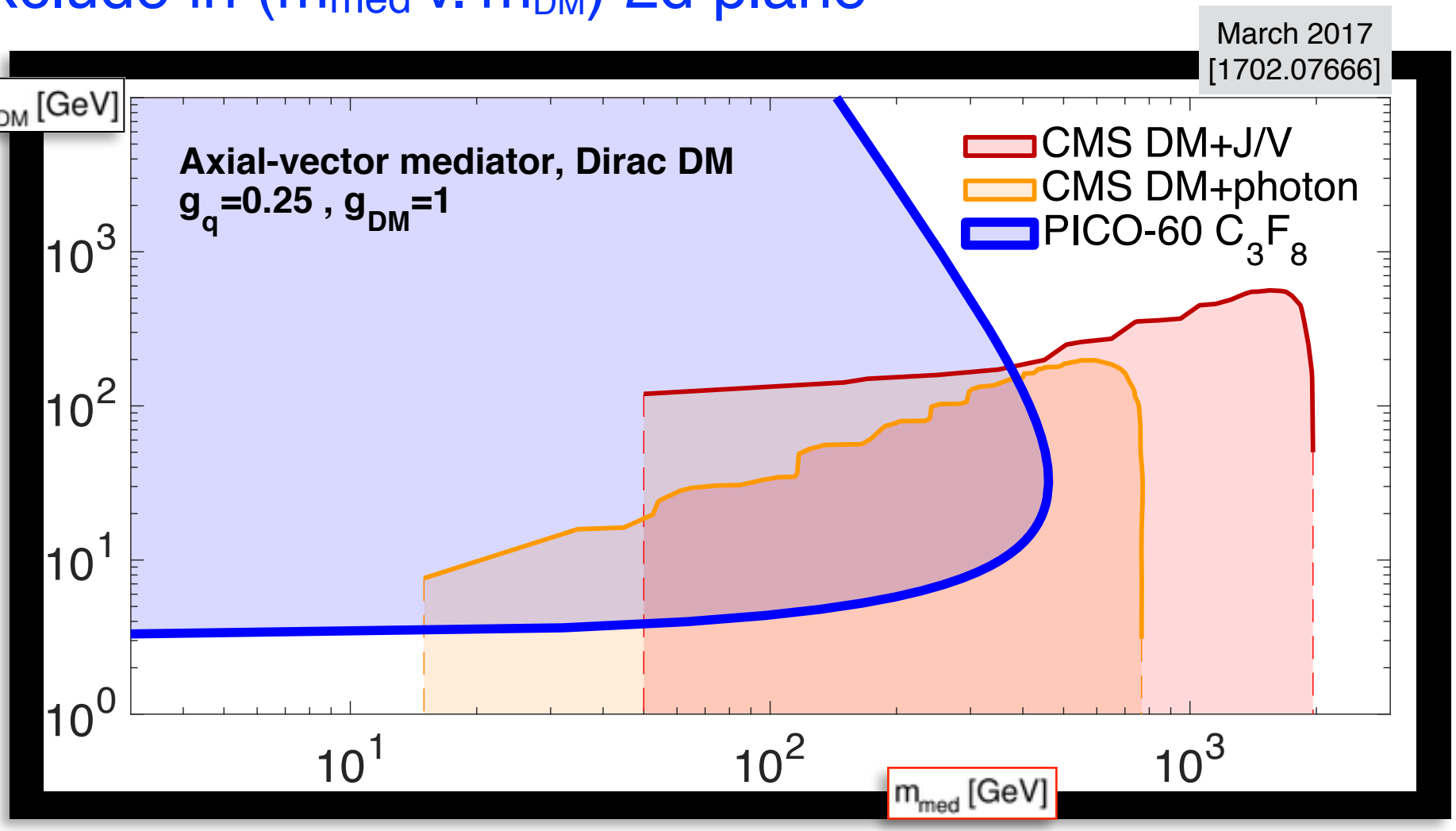

FIG. 6. Exclusion limits at 95% C.L. in the $m_{\rm DM} - m_{\rm med}$ plane. PICO-60 constraints (thick blue) are compared against collider constraints from CMS for an axial-vector mediator using the monojet/mono-V (red) [32] and mono-photon (orange) [33] channels. A similar analysis by ATLAS can be found in [52].

Illustrative examples

Results depending on coupling assumptions

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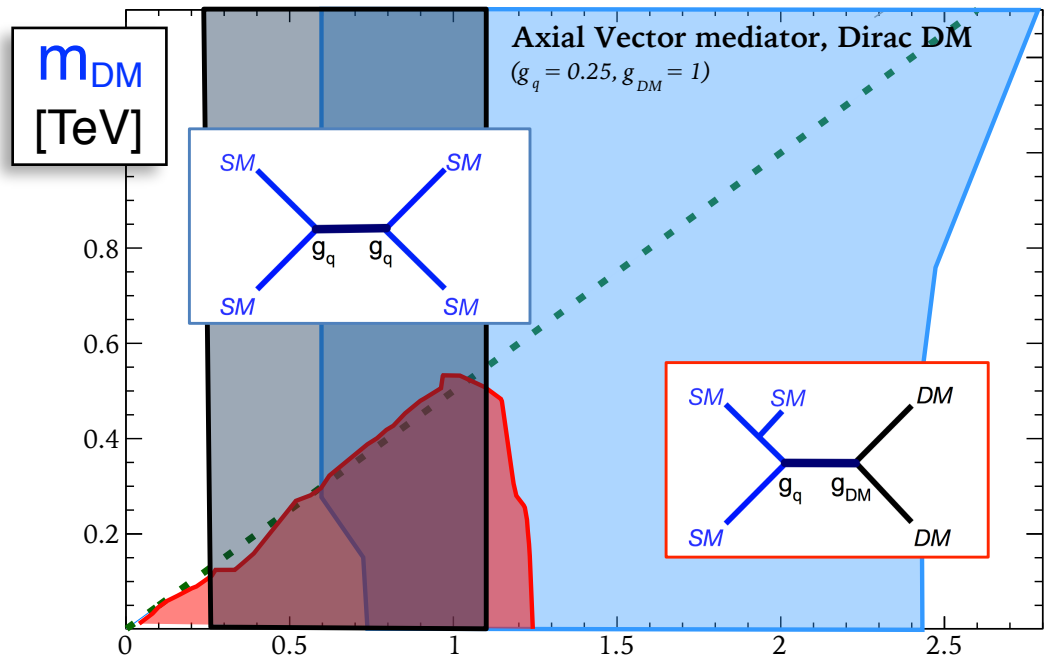

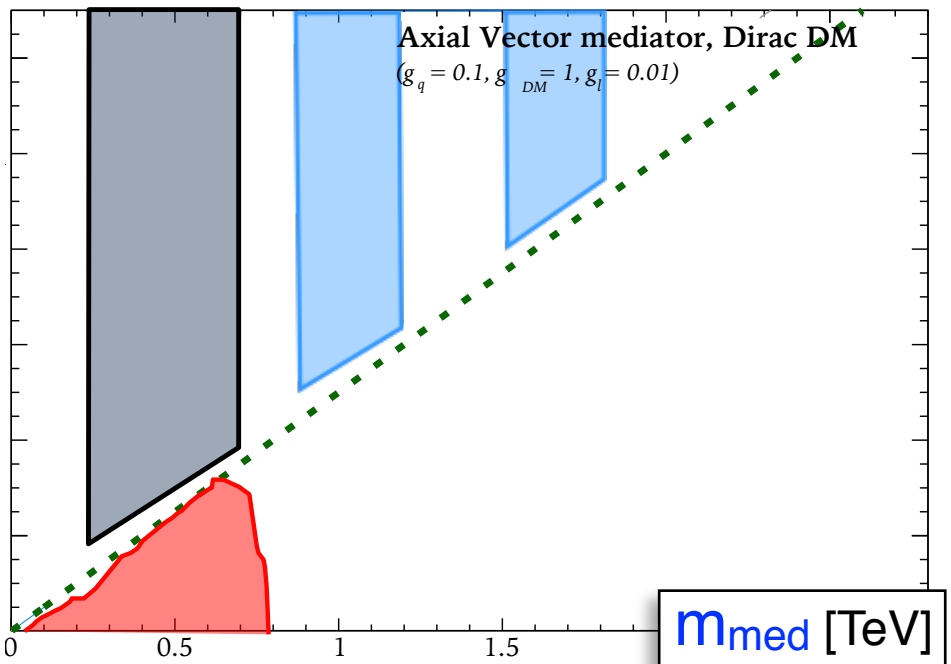

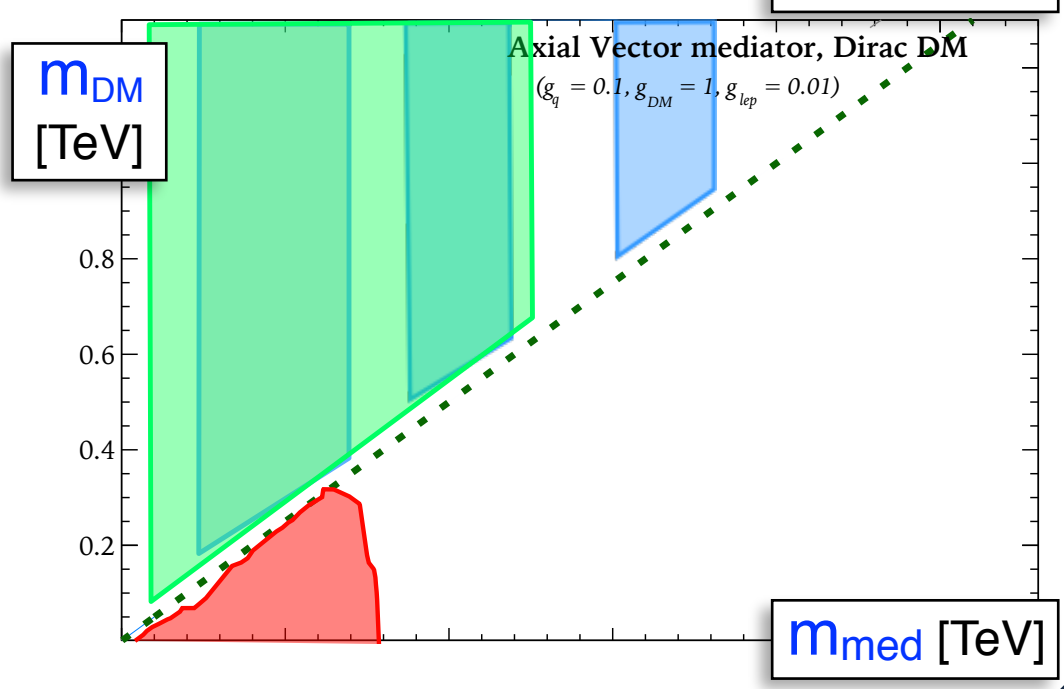

Legends

- Searches for DM particles
- Dijet searches for DM mediators
- Low-mass dijet searches for DM mediators
- Dilepton searches for DM mediators

From C. Doglioni, A. Boveia (see p24)

Fine print is very important

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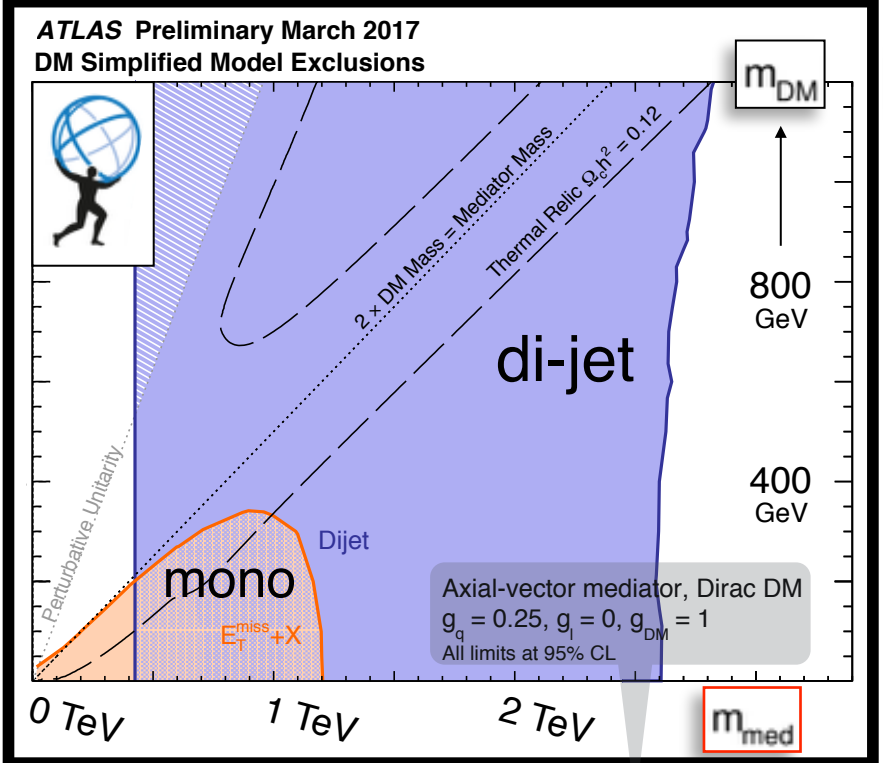
Alternate (g_{DM} , g_q , g_{lep}) alters conclusions [also see p36]

Same plot as p17

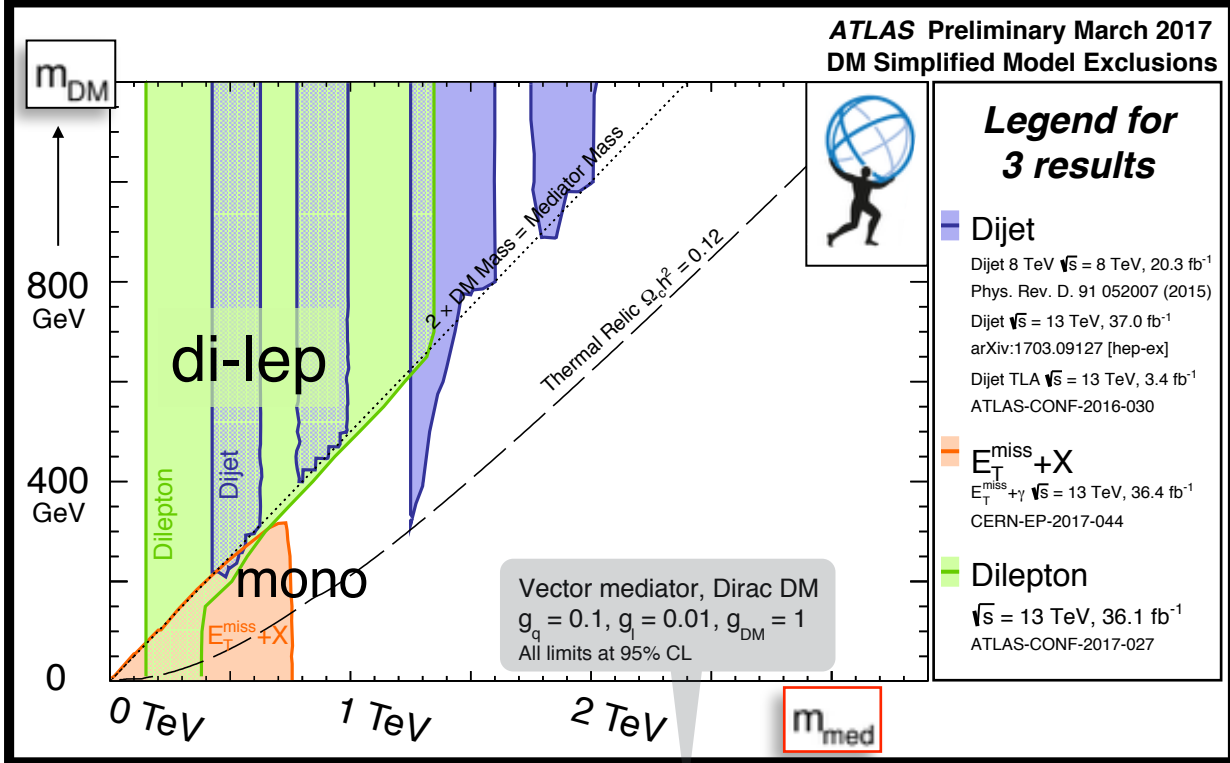
- ($g_{DM} = 1$, $g_q = ¼$, $g_{lep} = 0$)



Overlap in on-shell triangle

Modify coupling assumptions

- Keep $g_{DM} = 1$, decr. g_q = ⅒, incr. g_{lep} = 1⁄100



Lose overlap in on-shell region

Overlapping coverages important for robustness

Pile-up dependence of MET trigger

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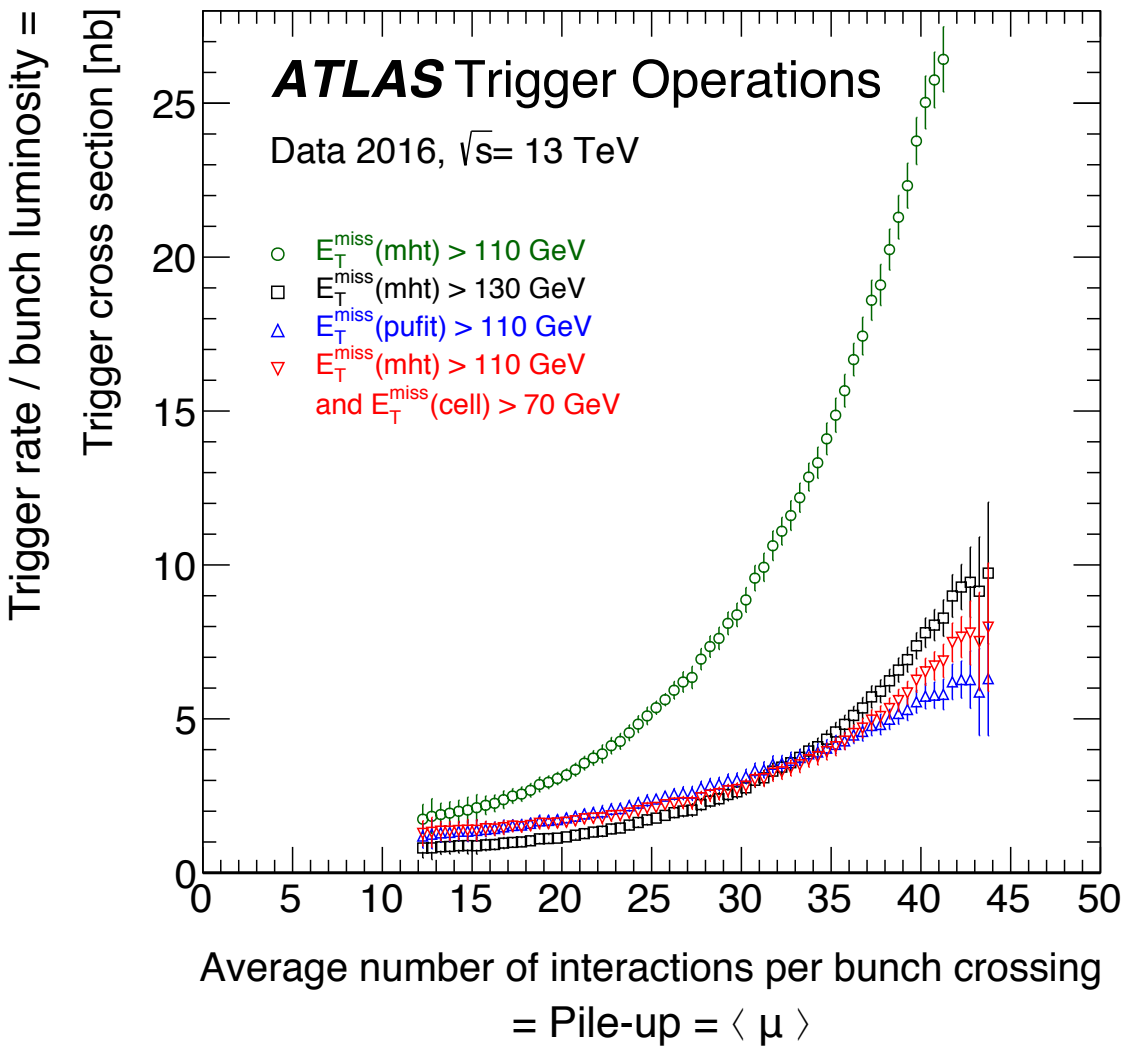

NB.

- A flat line on the right plot = linear dependence for rate
- A non-flat line on the right plot = polynomial / exponential dependence for rate

http://cern.ch/twiki/pub/AtlasPublic/MissingEtTriggerPublicResults/metxs_vs_mu.pdf

Notice of new CMS results

Past week (http://cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO)

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CMS PAS EXO-16-048 *Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson using 35.9 fb^{-1} of data at $\sqrt{s}$ = 13 TeV*

A search for dark matter and extra dimensions are presented using events containing an imbalance in transverse momentum and one or more energetic jets. The data of proton-proton collisions at the LHC were collected with the CMS detector, and correspond to an integrated luminosity of 35.9 fb^{-1}. Results are presented in terms of limits on the dark matter production in association with jets or vector bosons in a simplified models, nonthermal dark matter models, and fermion portal dark matter models. Re- sults are also interpreted in terms of the decay of the standard model Higgs boson to invisible particles and as limits on the Planck scale in the ADD model with large extra spatial dimensions.

CMS PAS EXO-16-052 *Search for dark matter, invisible Higgs boson decays, and large extra dimensions in the ll + E_T^{miss} final state using 2016 data*

A search for new physics in events with a Z boson produced in association with large missing transverse momentum with the CMS experiment at the LHC is presented. The search is based on the 2016 data sample of proton-proton collisions at $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 35.9 fb^{-1}. The results of this search are interpreted in terms of a simplified model of dark matter production with spin-0 or spin-1 mediators, a standard model Higgs boson decaying invisibly and produced in association with the Z boson, as well as a model with large extra spatial dimensions. For all models, no significant deviation from the background expectation is found, and limits are set with respect to relevant model parameters.

CMS PAS EXO-16-054 *Search for dark matter produced in association with a Higgs boson decaying to two photons*

A search for the associated production of dark matter with a Higgs boson which decays into two photons is presented. The search uses data from proton-proton col- lisions at a center-of-mass energy of 13 TeV, collected with the CMS detector at the LHC in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1} Results are in- terpreted in the context of two dark matter models: a two-Higgs-doublet-Z' model where the Z' decays to a pseudoscalar and a standard model-like Higgs Boson and a baryonic Z' simplified model. The search is performed categorizing the events based on the amount of missing transverse momentum in order to also be sensitive to hy- pothetical signals with small amounts of missing transverse momentum. After the final selection, no significant evidence for dark matter particle production has been observed. Two-Higgs-doublet-Z' signals with a pseudoscalar mass of 300 GeV are excluded at 95% of CL for Z' masses below 900 GeV. Baryonic Z' models with a dark matter mass of 1 GeV are excluded at 95% of CL for Z' masses below 800 GeV.

Notice of new ATLAS results

Past month (http://cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults)

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arXiv:1704.03848 *Search for dark matter at $\sqrt{s}$=13 TeV in final states containing an energetic photon and large missing transverse momentum with the ATLAS detector*

Results of a search for physics beyond the Standard Model in events containing an energetic photon and large missing transverse momentum with the ATLAS detector at the Large Hadron Collider are reported. As the number of events observed in data, corresponding to an integrated luminosity of 36.1 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV, is in agreement with the Standard Model expectations, exclusion limits in models where dark-matter candidates are pair-produced are determined. For dark-matter production via an axial-vector or a vector mediator in the s-channel, this search excludes mediator masses below 750-1200 GeV for dark-matter candidate masses below 230-480 GeV at 95% confidence level, depending on the couplings. In an effective theory of dark-matter production, the limits restrict the value of the suppression scale M_* to be above 790 GeV at 95% confidence level. A limit is also reported on the production of a high-mass scalar resonance by processes beyond the Standard Model, in which the resonance decays to Zγ and the Z boson subsequently decays into neutrinos.

ATLAS-CONF-2017-027 *Search for new high-mass phenomena in the dilepton final state using proton-proton collisions $\sqrt{s}$=13 TeV with the ATLAS detector*

A search is conducted for new resonant and non-resonant high-mass phenomena in dielectron and dimuon final states. The search uses 36.1 fb^{-1} of proton-proton collision data, collected at $\sqrt{s}$=13 TeV by the ATLAS experiment at the LHC in 2015 and 2016. The dilepton invariant mass is used as the discriminating variable. No significant deviation from the Standard Model prediction is observed. Upper limits at 95% credibility level are set on the cross-section times branching ratio for resonances decaying to dileptons, which are converted into lower limits on the resonance mass, up to 4.1 TeV for the E6-motivated Z'_χ. Lower limits on the $\ell\ell qq$ contact interaction scale are set between 23.5 TeV and 40.1 TeV, depending on the model.

ATLAS-CONF-2017-028 *Search for Dark Matter Produced in Association with a Higgs Boson Decaying to $b\bar{b}$ at $\sqrt{s}$=13 TeV with the ATLAS detector*

Several extensions of the Standard Model predict associated production of Dark Matter particles with a Higgs boson. Such processes are searched for in final states with missing transverse momentum and a Higgs boson decaying to a $b\bar{b}$ pair with the ATLAS detector using 36.1 fb^{-1} of pp collisions at a center-of-mass energy of 13~TeV at the LHC. The observed data are in agreement with the Standard Model and limits are placed on the associated production of Dark Matter particles and a Higgs boson for a simplified Dark Matter model and without extra model assumptions.

LHC timeline

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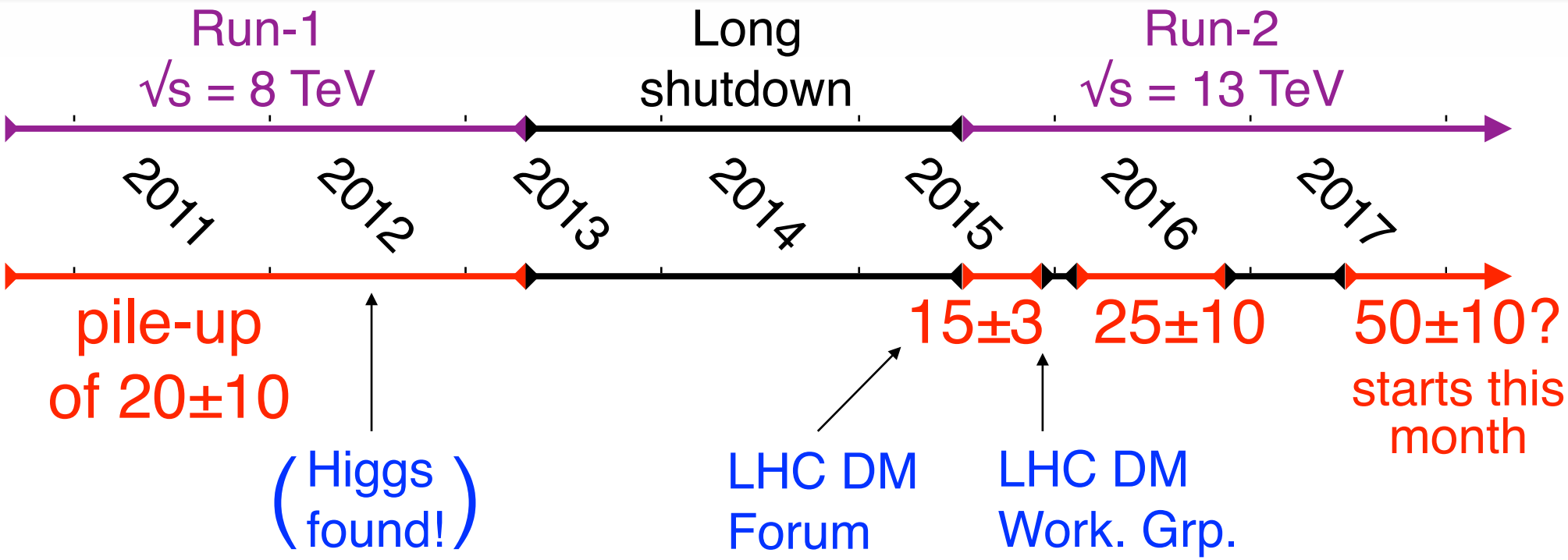
same

$\sigma_{pp\to\text{inelastic}} = (\gg 10^{10}) \cdot \sigma_{pp\to\text{DM}}$ $\quad \sigma_{pp\to\text{DM}} \cdot L = N_{pp\to\text{DM}}$

Experimental difficulty
Why dislike pile-up

$\ll$

Increase *pp* luminosity
Why need pile-up



DM Benchmark Models for Early LHC Run-2 Searches
Report of the ATLAS/CMS Dark Matter Forum
July 2015, revised Aug. 2016 [1507.00966]

Personal thanks

Dr. P. Chang
UC San Diego

I thank Philip for discussions on collider dark matter searches, dijet strengths and limitations, invisible Higgs, and general outlook.

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FNAL

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U Washington

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Dr. A. Tuna
Harvard U

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Dr. B. Carlson
U Pittsburgh

I thank Ben for discussions on invisible Higgs, MET triggers, and trigger rates.