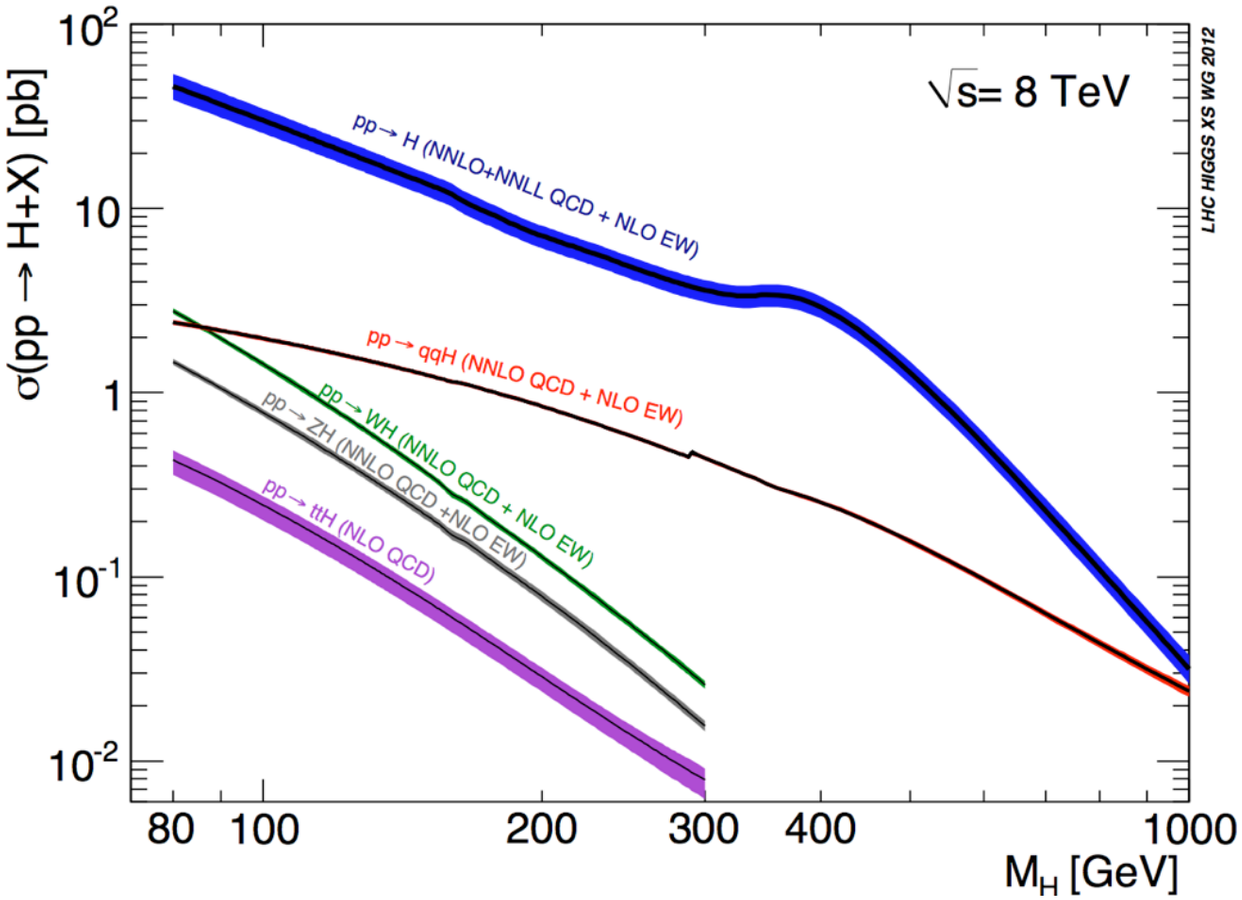
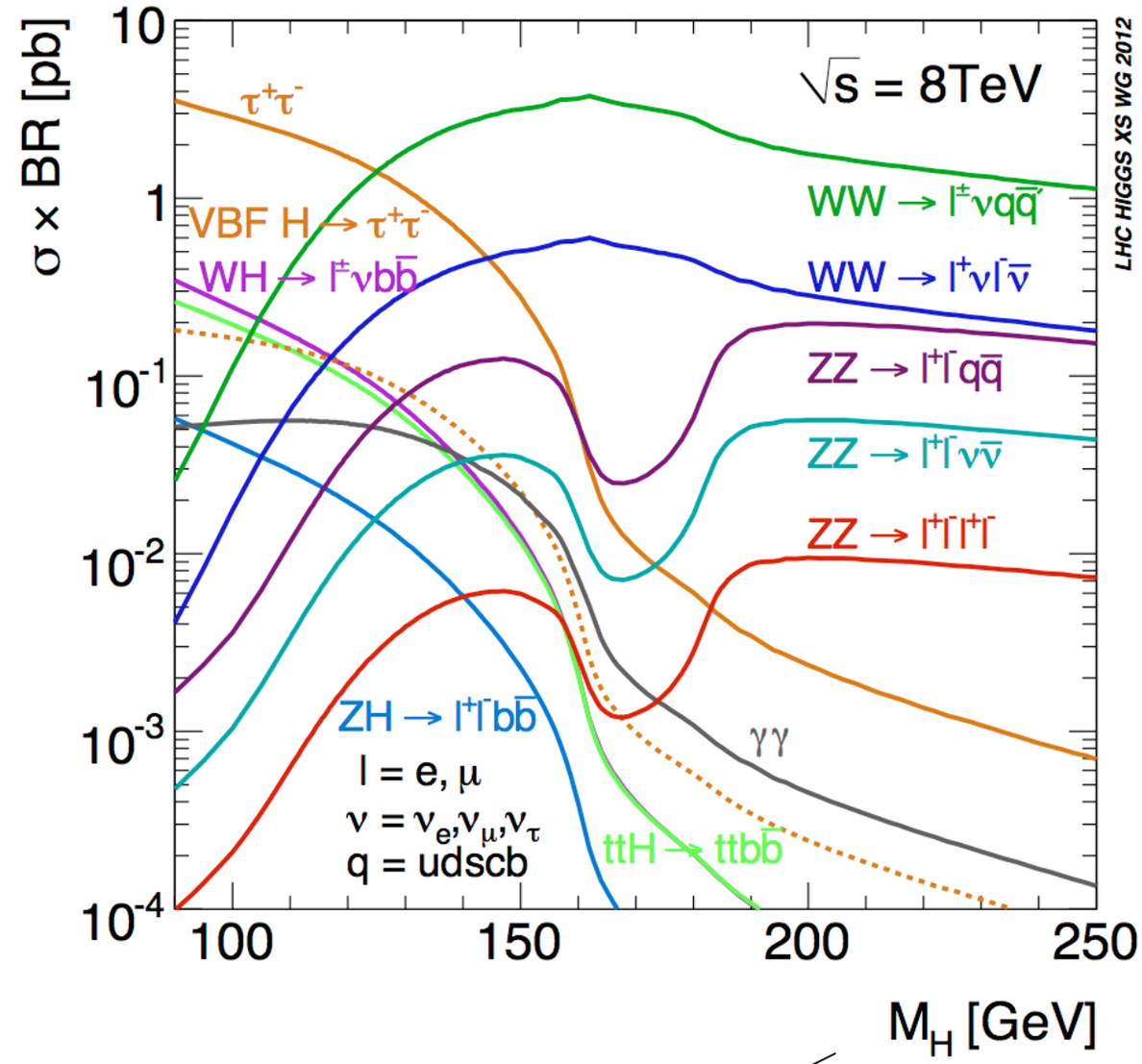
# Dark Matter Searches at ATLAS

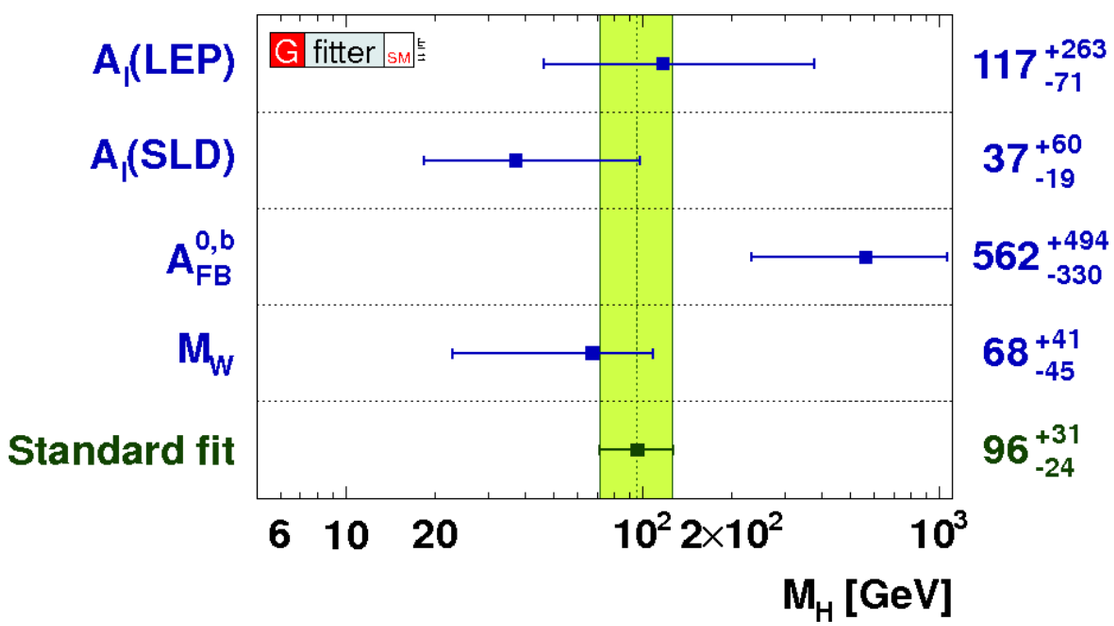
Antonio Boveia (CERN)
6 November 2015

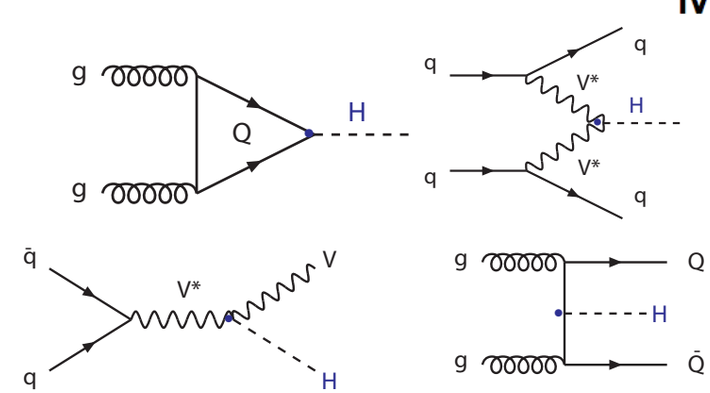
on behalf of the ATLAS Collaboration

# The Recent History of Discovery: An Example Search for "New" Physics



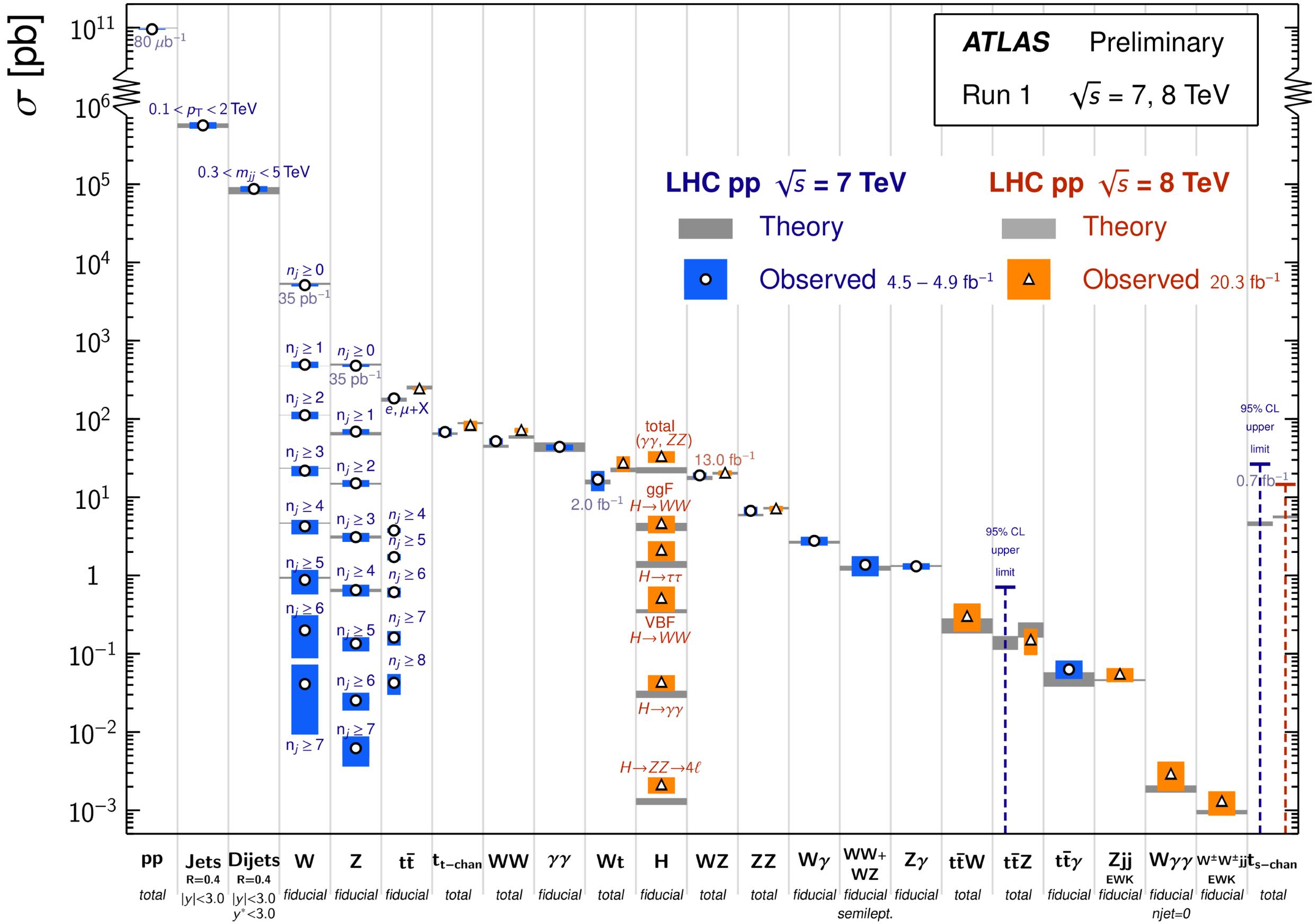




Tom Rizzo: → Searches for 'NP' can be difficult even if we 'know' how & where to look & there's only 1 free parameter : $m_H$

# Standard Model Production Cross Section Measurements

*Status: March 2015*



# How do we make the next discovery?

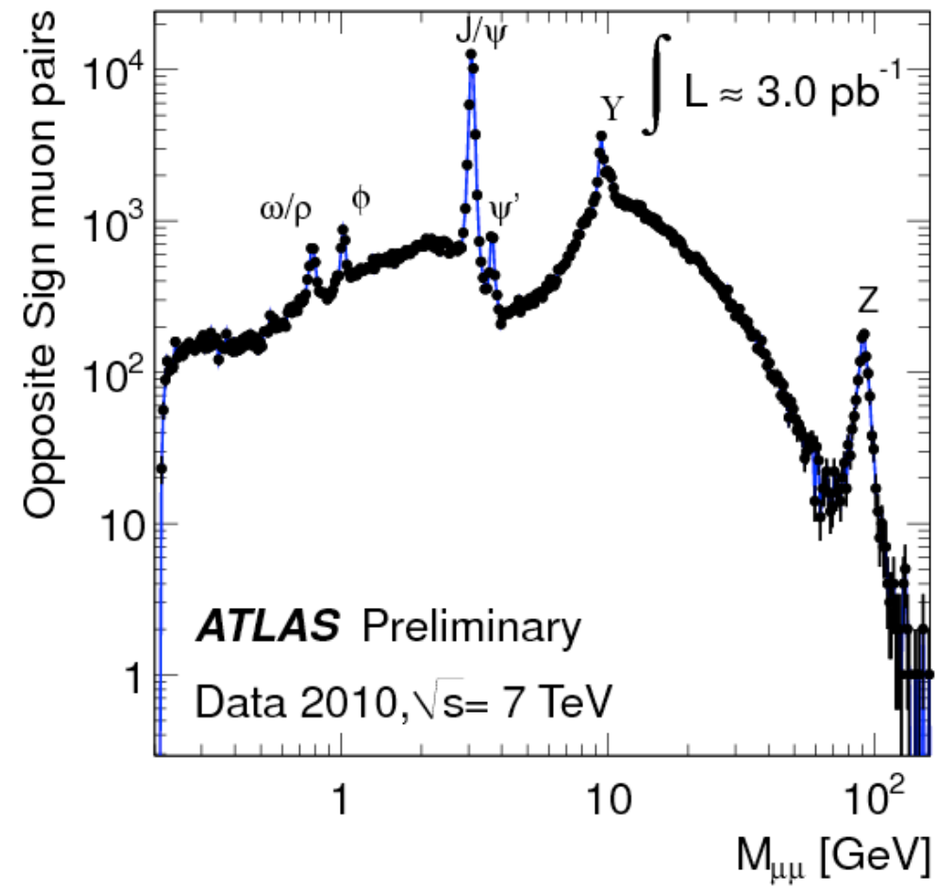
Model frameworks play a very important role

SM has been our guide on a long road (1970's–2010's)

generation(s) of HEP physicists

How we've designed and organized our experiments

Mass resonances: J/Psi, upsilon, [W/]Z, [...top, Higgs]




But since 2012:

Is there new physics before $E_{Planck}$? ($E_{inflation}$?)

No reliable model to drive our work

What is beyond the Standard Model?

What is most important for collider searches to do?

**Dennis Overbye: Physics awaits new options as Standard Model idles**

08/01/06

Experimental clues have yet to produce a 'tsunami moment' that provides a glimpse beyond the equations of particle physics formulated in the 1970s. But physicists are hoping for something bizarre.

Dr. Arkani-Hamed admitted, "My nightmare is that we see nothing at all besides the Higgs," in the new collider.

Symmetry, 8/1/06

# SUSY as a guide?

Tempting familiarity

- 30 years of phenomenology
- 30 years of looking for it

Nice properties

- DM candidate (maybe)
- "natural" (maybe)

But these aren't necessary and can be jettisoned under experimental duress

Having a model in mind is better than nothing:

- a well-studied framework allows more systematic approaches
- but SUSY is not as predictive as SM, and it is far from the only possibility

No evidence that SUSY is correct

**Conley et al. / Eur.Phys.J. C71 (2011) 1697**

Tom Rizzo

## Our p(henomenological)MSSM

- General CP-conserving MSSM with R-parity
- MFV at the TeV scale (CKM)
- Lightest neutralino/gravitino is the LSP.
- 1st/2nd generation sfermions degenerate
- Ignore 1st/2nd generation A-terms &Yukawa's.
- No assumptions wrt SUSY-breaking
- WMAP used as upper bound on thermal relic density

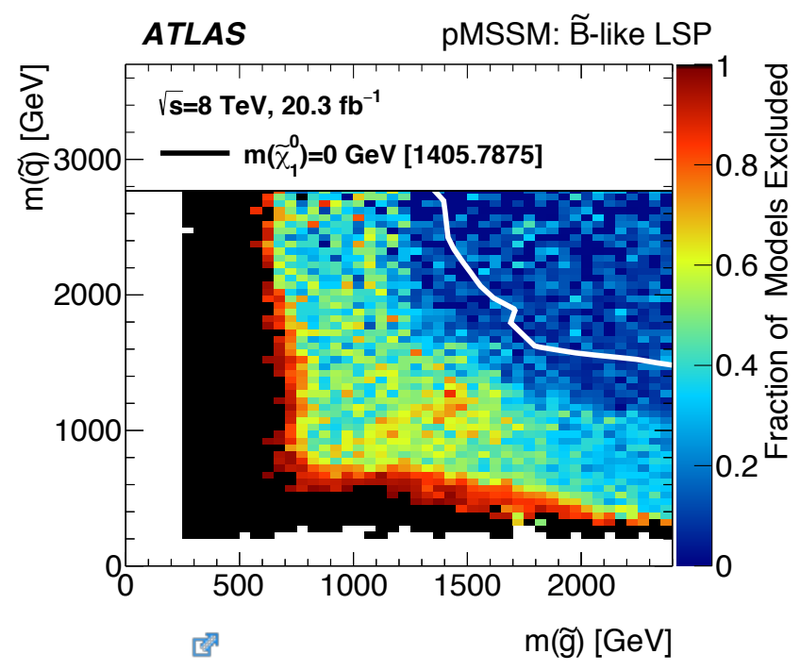
→ the pMSSM with 19/20 parameters

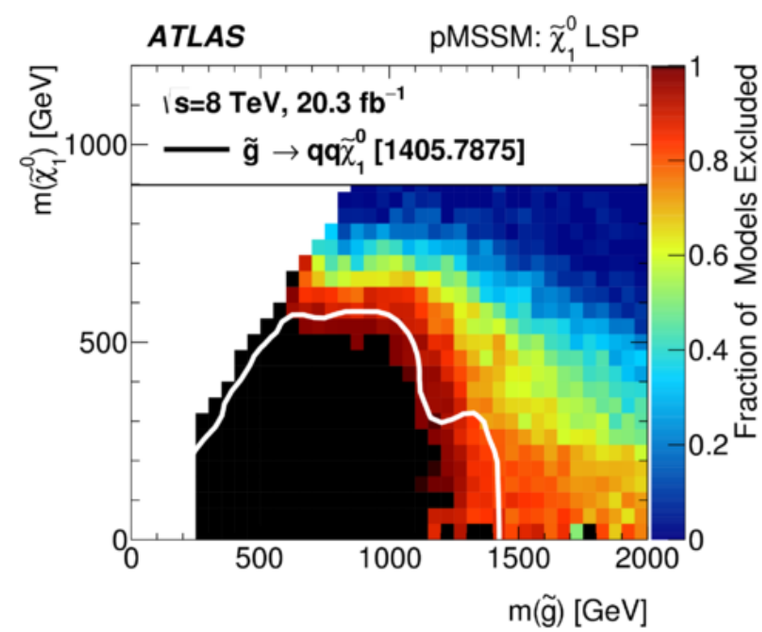
- Two large ~225k model sets with either a neutralino (19) or gravitino (20) LSP
- Smaller (~10k) dedicated sets for low-FT studies & other analyses

$50\ \text{GeV} \le |M_1| \le 4\ \text{TeV}$
$100\ \text{GeV} \le |M_2, \mu| \le 4\ \text{TeV}$
$400\ \text{GeV} \le M_3 \le 4\ \text{TeV}$
$1 \le \tan\beta \le 60$
$100\ \text{GeV} \le M_A, l, e \le 4\ \text{TeV}$
$400\ \text{GeV} \le q_1, u_1, d_1 \le 4\ \text{TeV}$
$200\ \text{GeV} \le q_3, u_3, d_3 \le 4\ \text{TeV}$
$|A_{t,b,\tau}| \le 4\ \text{TeV}$
**$1\ \text{eV} \le m_{3/2} \le 1\ \text{TeV}$ (log prior)**

There's a LOT of space here ; we're going for breadth not depth !

**ATLAS Run 1 pMSSM example constraints, JHEP 10 (2015) 134**



# The Lamp Post Effect

Barbican Art Gallery / http://myfunnyeye.blogspot.co.uk/2014/03/searching-in-dark.html

LTN

The **streetlight effect** is a type of observational bias where people only look for whatever they are searching by looking where it is easiest.[1][2][3]

The parable is told several ways but includes the following details:

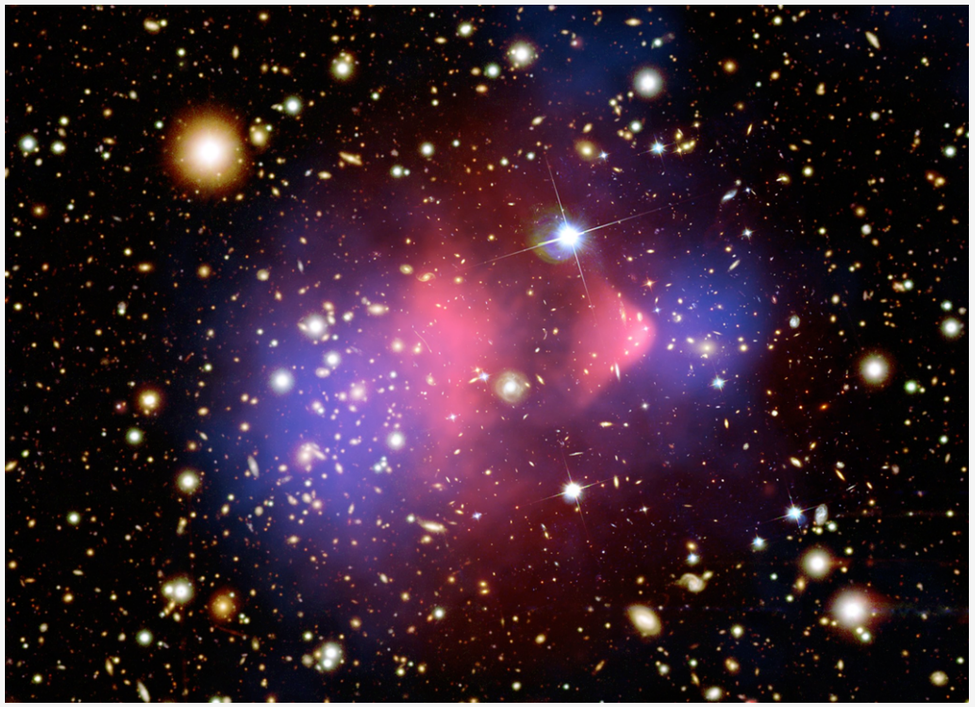
> A policeman sees a drunk man searching for something under a streetlight and asks what the drunk has lost. He says he lost his keys and they both look under the streetlight together. After a few minutes the policeman asks if he is sure he lost them here, and the drunk replies, no, that he lost them in the park. The policeman asks why he is searching here, and the drunk replies, "this is where the light is."[2]

David Freedman apparently coined the phrase "streetlight effect," but the story, and concept, were used much earlier, e.g., by Abraham Kaplan, in his classic work The Conduct of Inquiry: Methodology for Behavioral Science (Harper & Row, 1964), where he refers to this as "the principle of the drunkard's search" (p. 11). Wikipedia

*"I'm searching for my keys"*

# Strongest Clues about BSM Particle Physics Come From Astronomy

Clowe et al: visible mass vs dark mass



Large scale observations: cosmology and galactic astronomy firmly establish **dark matter as fact**

$\Lambda_{CDM}$: rotation curves, CMB, simulations of galactic evolution, grav. lensing, …
e.g. early CMB observations established CDM at >25σ (WMAP 9-year results: $\Omega_c h^2 = 0.1138 \pm 0.0045$)

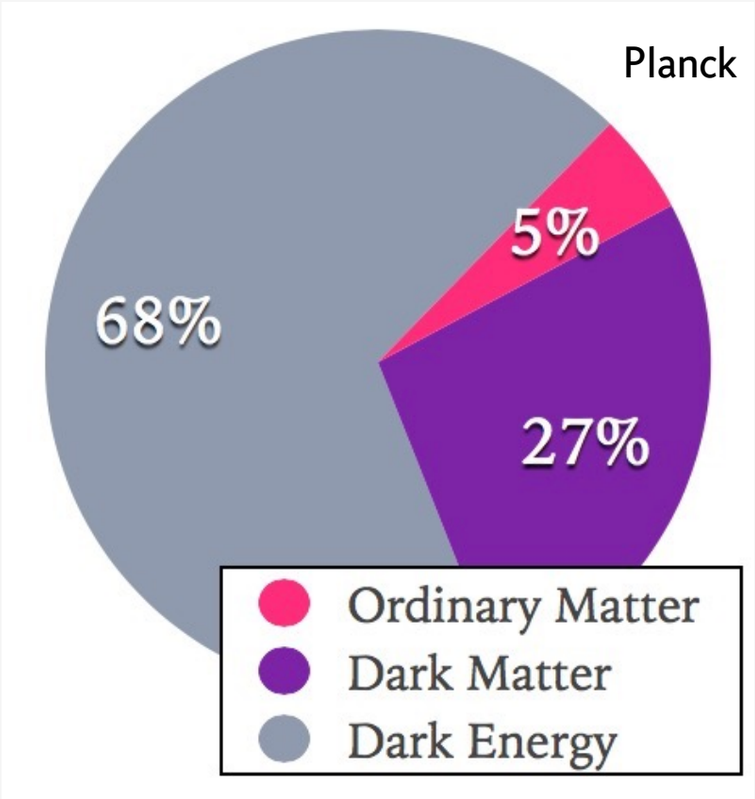
**Particle physics fails to explain this**

Contrast with motivations based on "naturalness" arguments / fine tuning arguments, unification at the Planck scale, dark matter candidates as an afterthought, solutions to the problems of particle theorists…

**This problem deserves a big effort**

WIMP paradigm: dark matter sector talks to Standard Model particles through some sort of 'weak' interaction

*received the most attention, but*
*far from the only possibility*

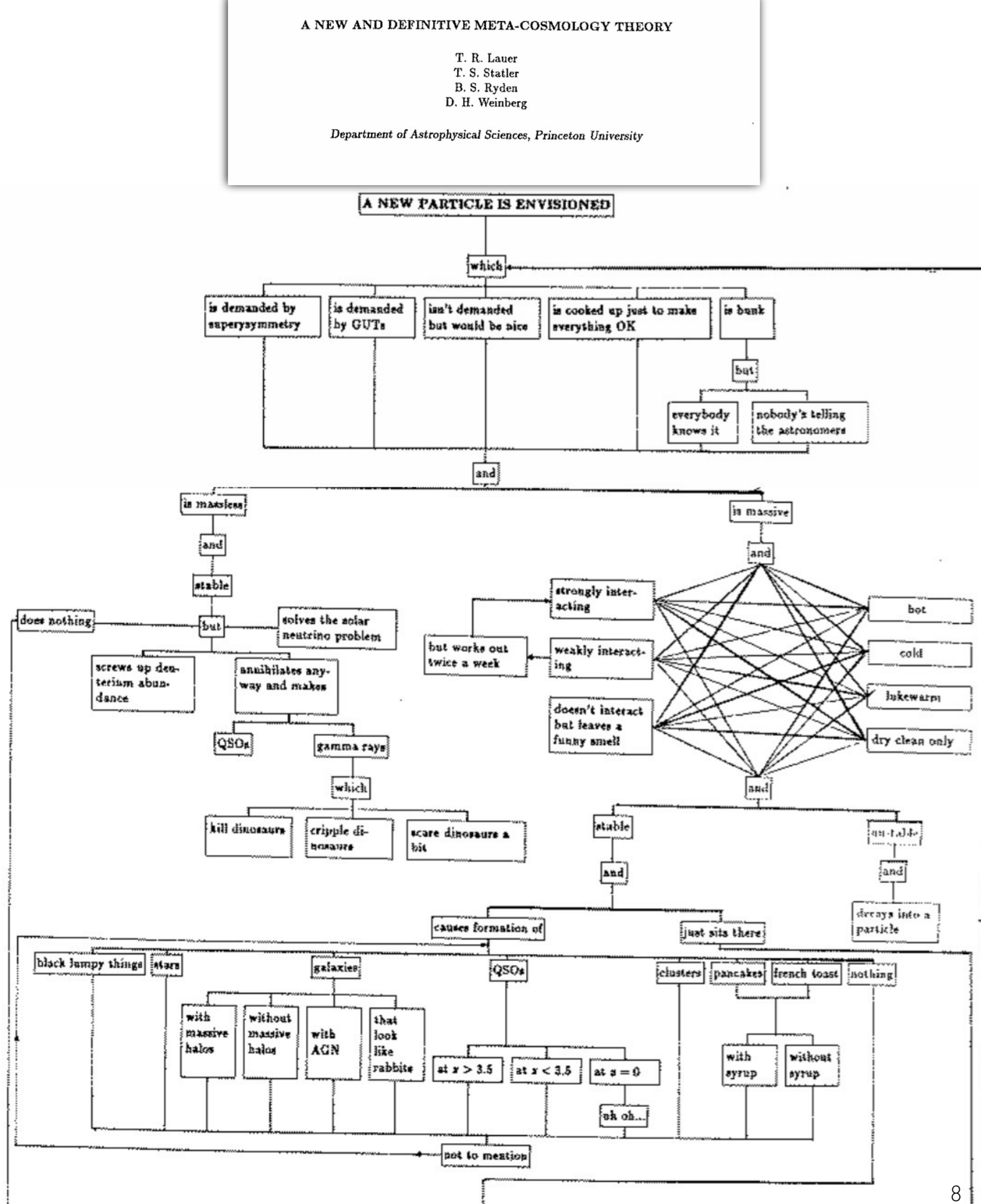


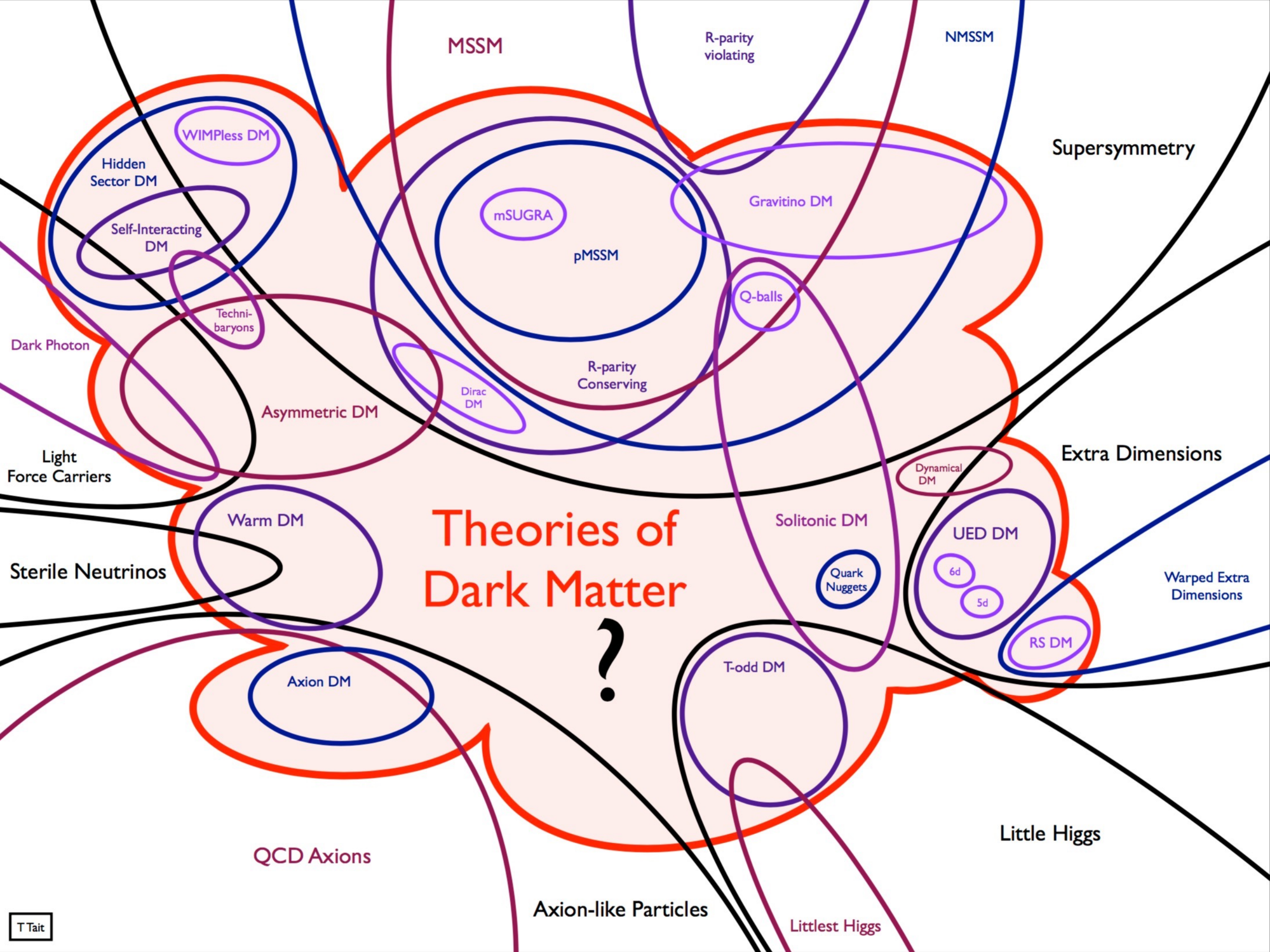
# What do we know about dark matter?

- DM exists…
- DM is not matter described by the Standard Model
- DM interacts gravitationally
- DM is colorless & electrically neutral
- DM is stable on very long timescales
- DM may not be strongly self-interacting,
  **nor must it have any non-gravitational interactions with the SM**
- $\Omega_{DM} \approx 5\ \Omega_M$
  this leaves room for the 'dark sector' to match the complexity of the SM, and then some

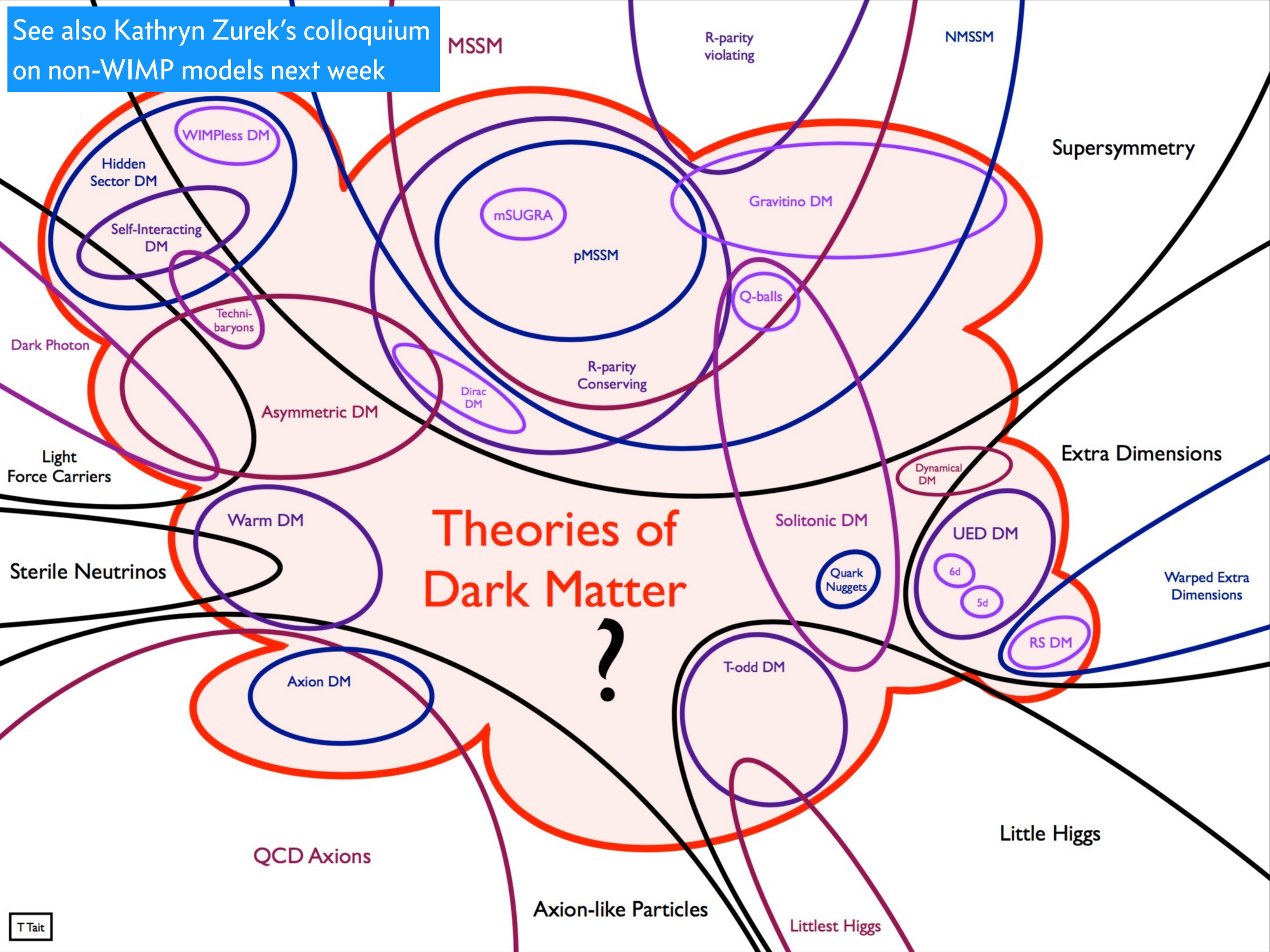
For collider searches, we need to systematically explore models that fit these facts.

What does?

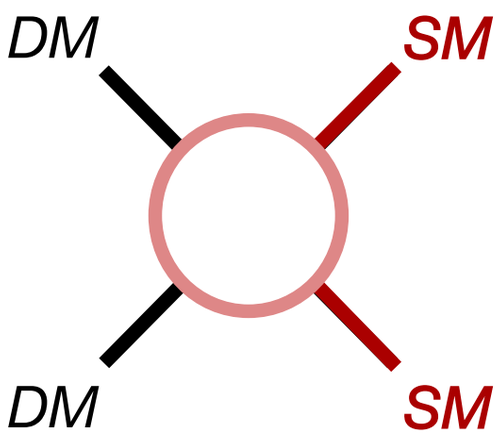



Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
Asymmetric DM
Light Force Carriers
Warm DM
Sterile Neutrinos
Axion DM
QCD Axions
Axion-like Particles
mSUGRA
pMSSM
R-parity Conserving
Dirac DM
Gravitino DM
Q-balls
Solitonic DM
Quark Nuggets
T-odd DM
Littlest Higgs
Dynamical DM
UED DM
6d
5d
RS DM
Extra Dimensions
Warped Extra Dimensions
Little Higgs
T Tait

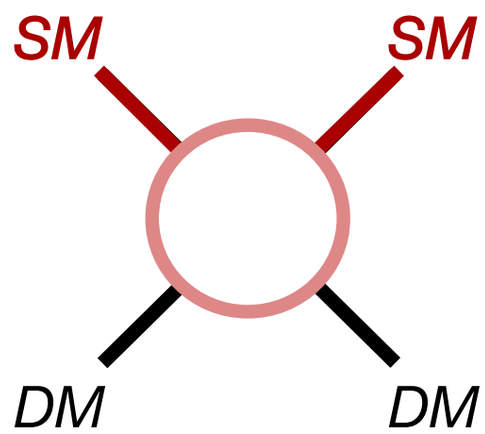
See also Kathryn Zurek's colloquium on non-WIMP models next week



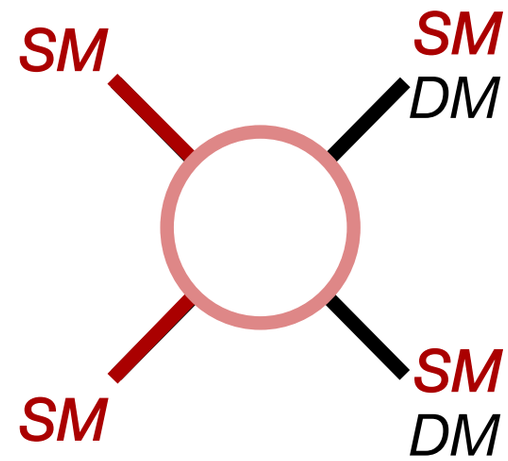
# Complementarity and Effective Field Theory



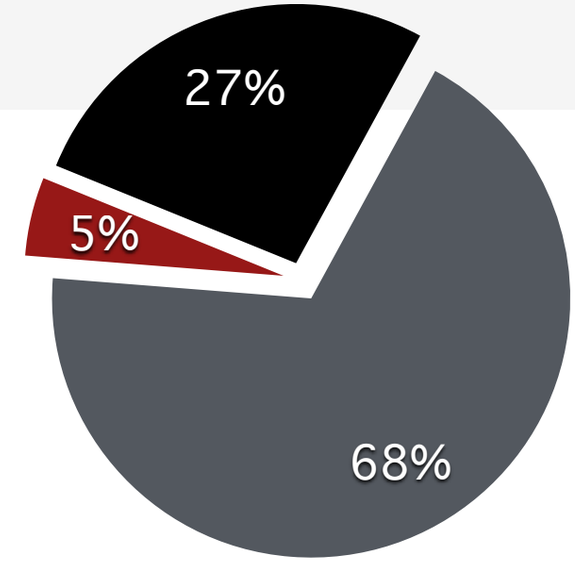

Indirect Detection




Direct Detection




Colliders




A very general approach: assume there is an interaction between DM and SM, and it occurs at an ~inaccessible energy scale

The same diagram describes DM-nucleon scattering, pp collisions, …

Look at low-energy behavior: a 4-fermion contact interaction with a single parameter M*

If the interaction occurs through a heavy s-channel resonance, $M^* = M/\sqrt{(g_q\, g_{dm})}$,

Systematically search collider data for all renormalizable possibilities:

DM: real/complex scalar, Majorana/Dirac fermion

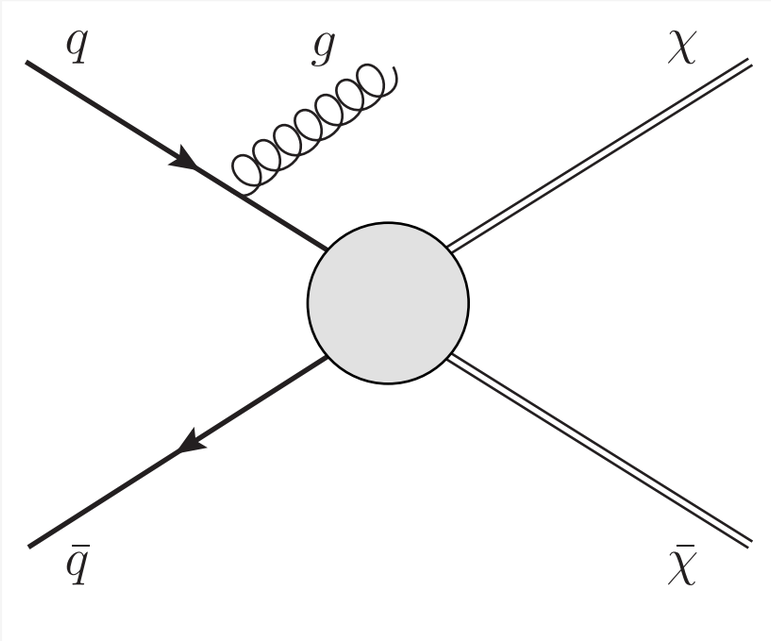
Lorentz structure: scalar, pseudo-scalar, vector, axial-vector, etc.

TABLE I. Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars, respectively.

| 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 | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $im_q/M_*^3$ |
| D4 | $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | $m_q/M_*^3$ |
| 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 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$ | $1/M_*^2$ |
| D8 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ | $1/M_*^2$ |
| 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 | $\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $\alpha_s/4M_*^3$ |
| C1 | $\chi^\dagger\chi\bar{q}q$ | $m_q/M_*^2$ |
| C2 | $\chi^\dagger\chi\bar{q}\gamma^5 q$ | $im_q/M_*^2$ |
| C3 | $\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$ | $1/M_*^2$ |
| C4 | $\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$ | $1/M_*^2$ |
| C5 | $\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$ | $\alpha_s/4M_*^2$ |
| C6 | $\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/4M_*^2$ |
| R1 | $\chi^2\bar{q}q$ | $m_q/2M_*^2$ |
| R2 | $\chi^2\bar{q}\gamma^5 q$ | $im_q/2M_*^2$ |
| R3 | $\chi^2 G_{\mu\nu}G^{\mu\nu}$ | $\alpha_s/8M_*^2$ |
| R4 | $\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/8M_*^2$ |

Goodman et al. (PRD 82 116010)

# The consequences?

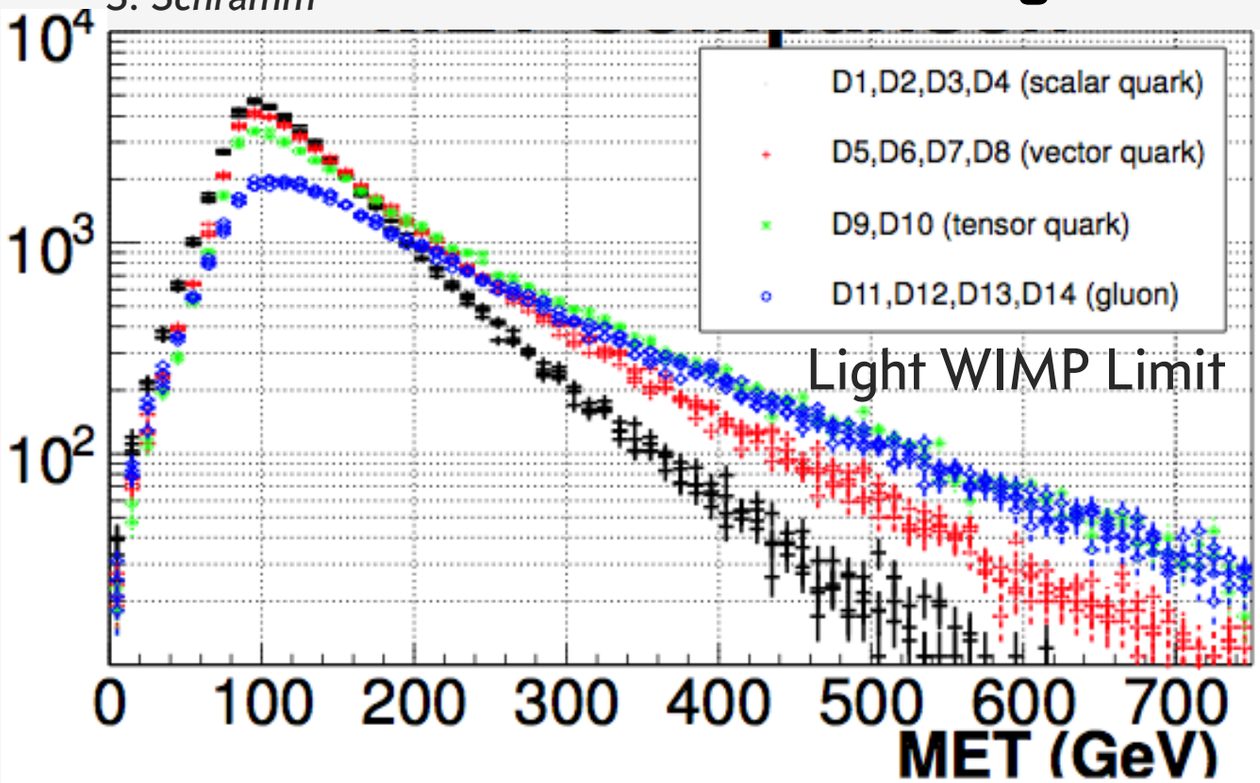


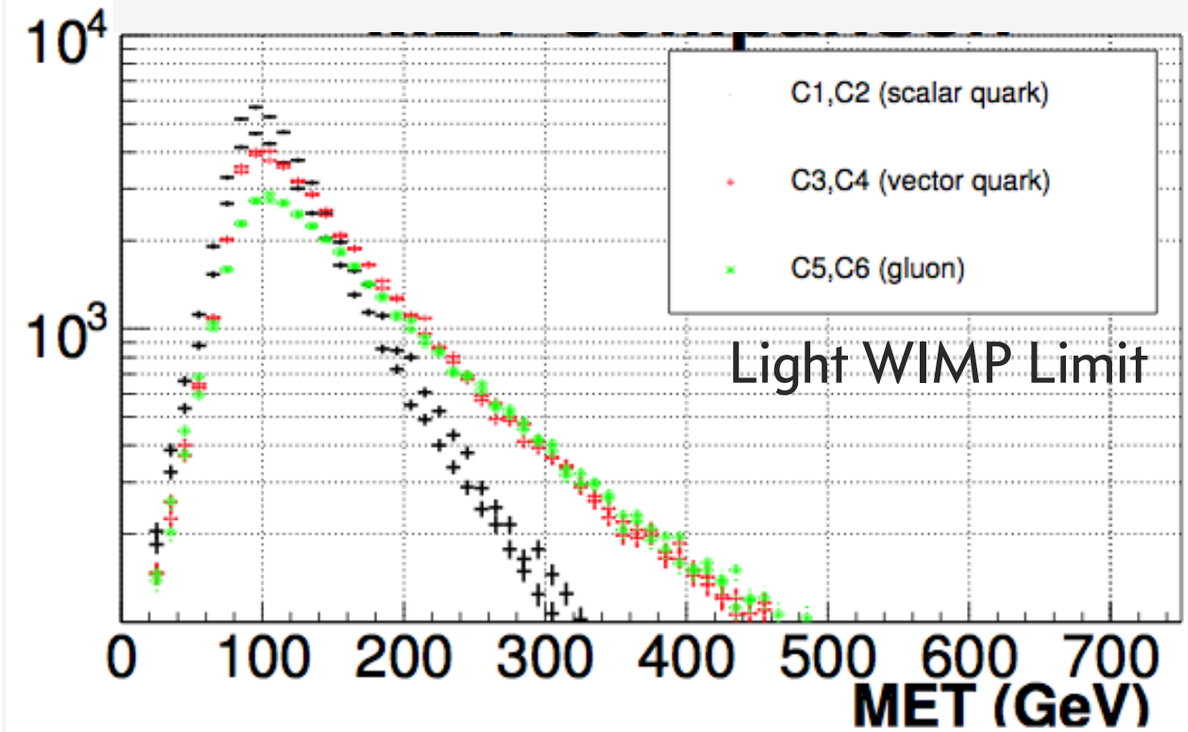

1. DM must be pair produced
2. "MET+proton remnants" is indistinguishable from "backgrounds"
3. We need to "tag" the collision with high $p_T$ ISR
4. The Standard Model predicts what ISR occurs most often…

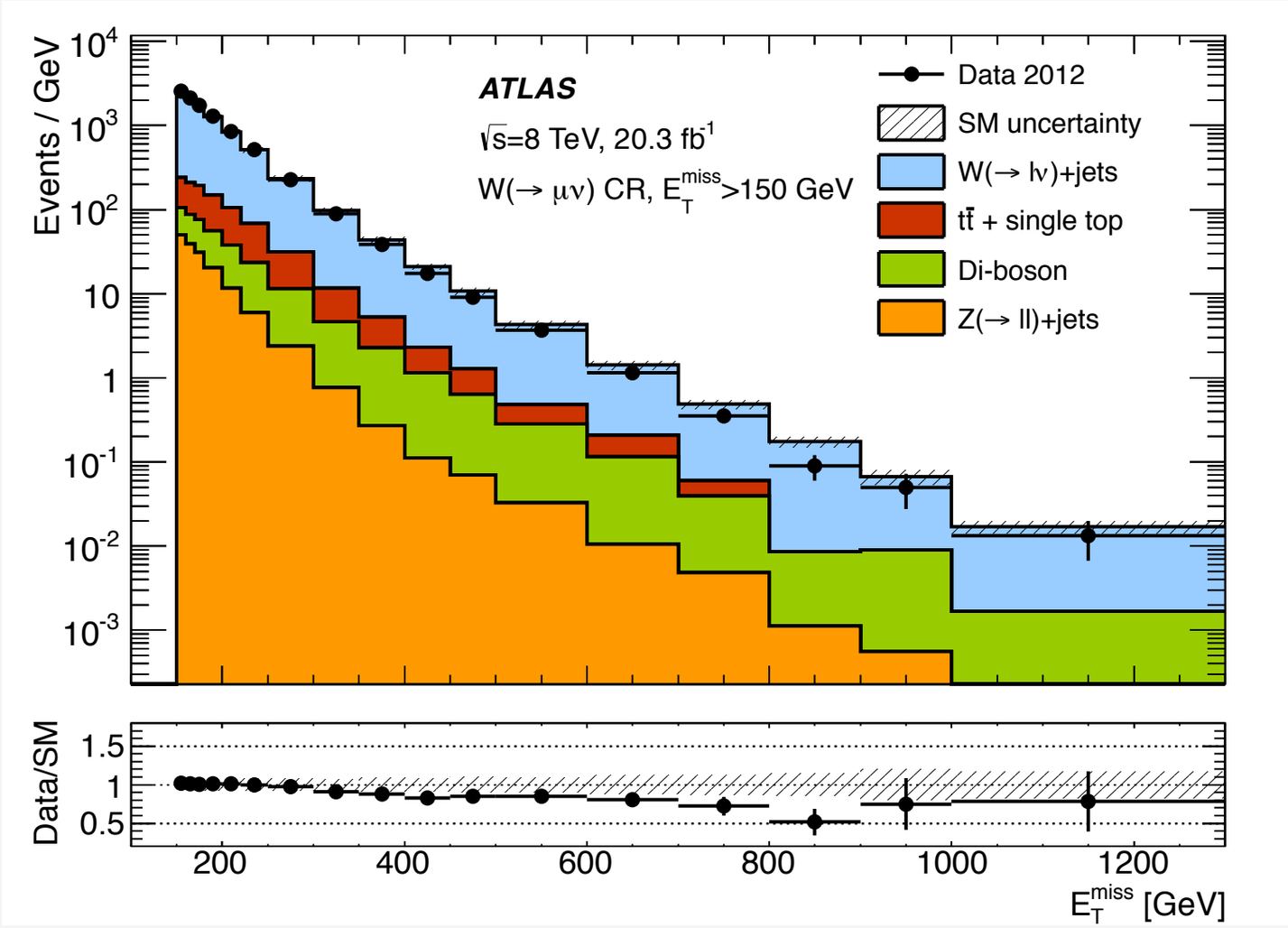
➠ do a mono-jet search

# Missing Transverse Energy for EFT Signals in Monojet Analysis

*S. Schramm*

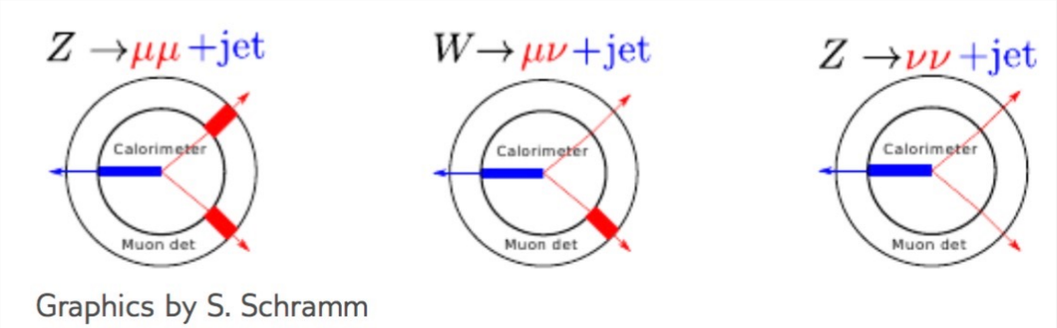



Background estimation:

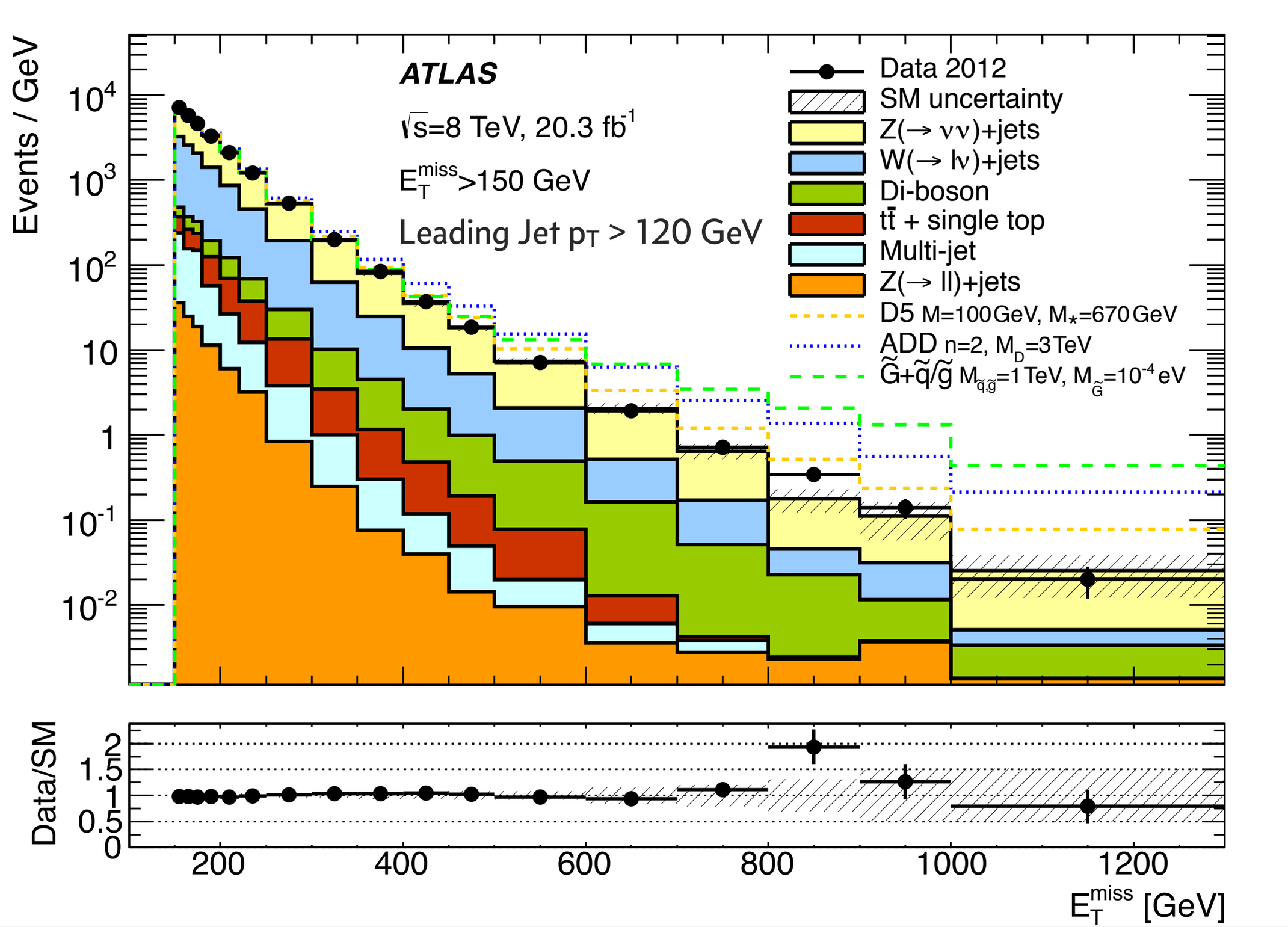
- Dominant background is Zνν+jets
- use transfer factors from W/Z control regions (see CR to the left) as data-driven correction to MC
- (e.g. Z $p_T$ distribution)




BR 3% | Higher cross section,BR | BR 20%

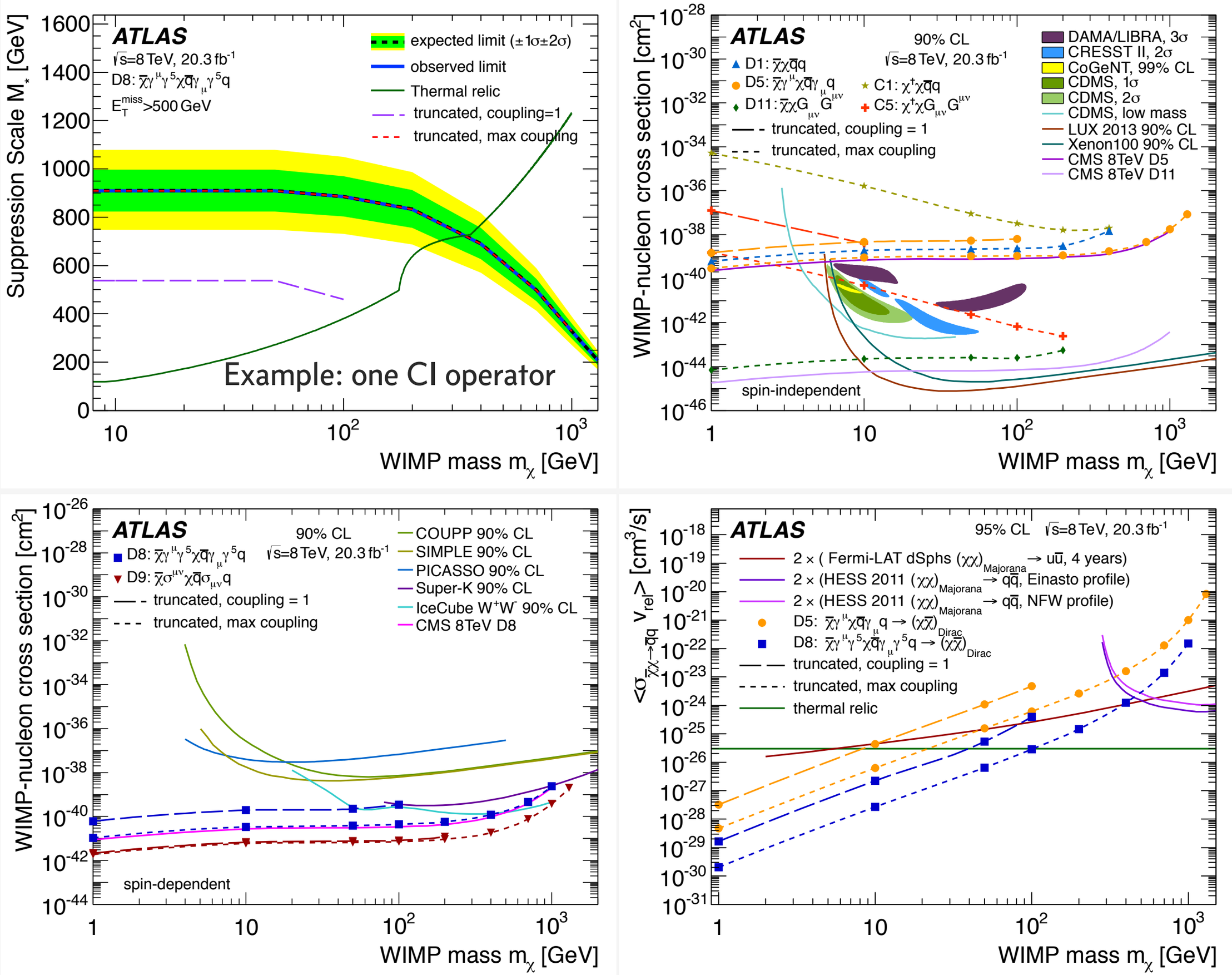
# 8 TeV Mono-jet Search: Results

Eur. Phys. J. C (2015) 75:299




Achieves a total background uncertainty of 3–14%, depending on the transverse momentum; comes from theory (W/Z differences), CR statistics, object reconstruction unc. (jet/MET)

# 8 TeV Mono-jet Result: Connecting EFT limits to Non-collider WIMP Searches

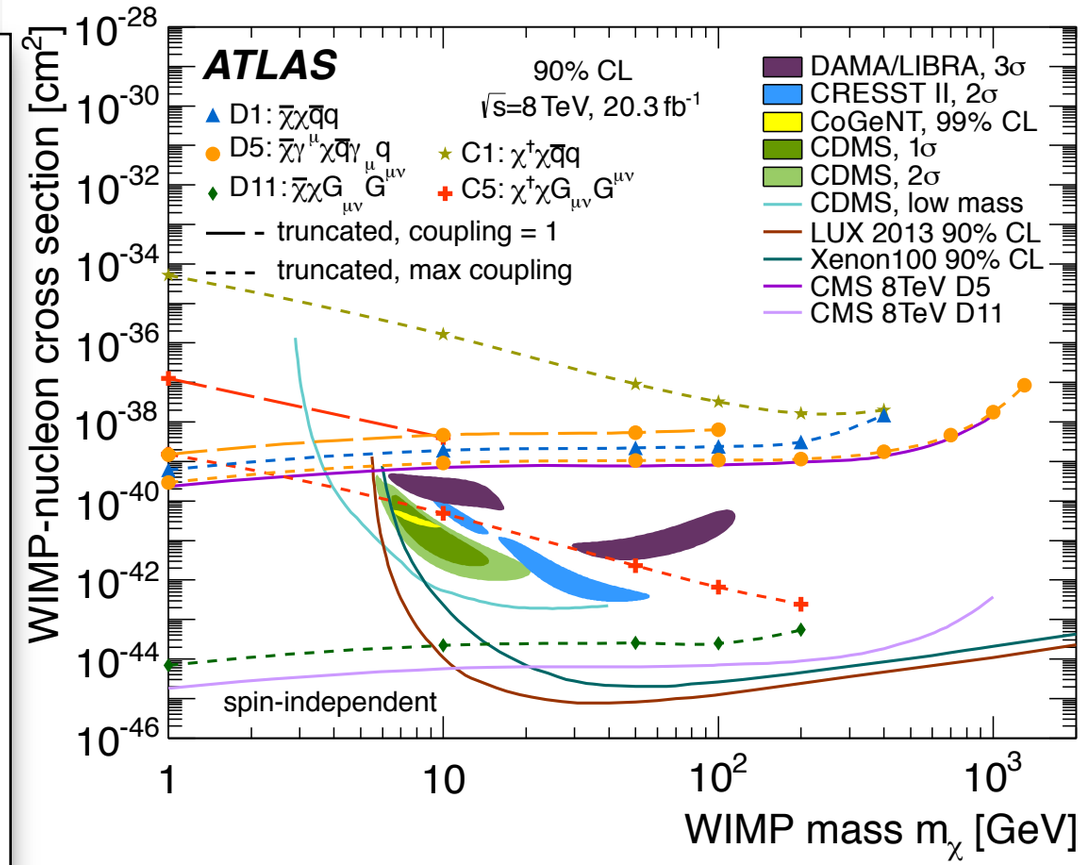


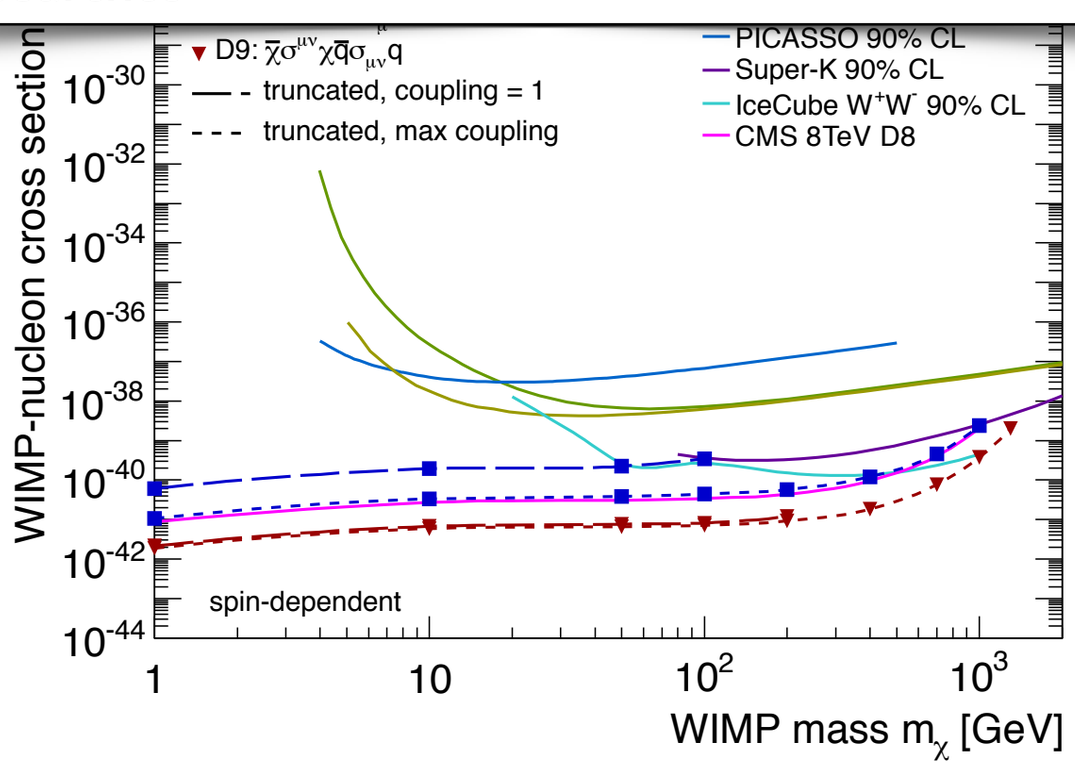
# 8 TeV Mono-jet Result: Connecting EFT limits to Non-collider WIMP Searches

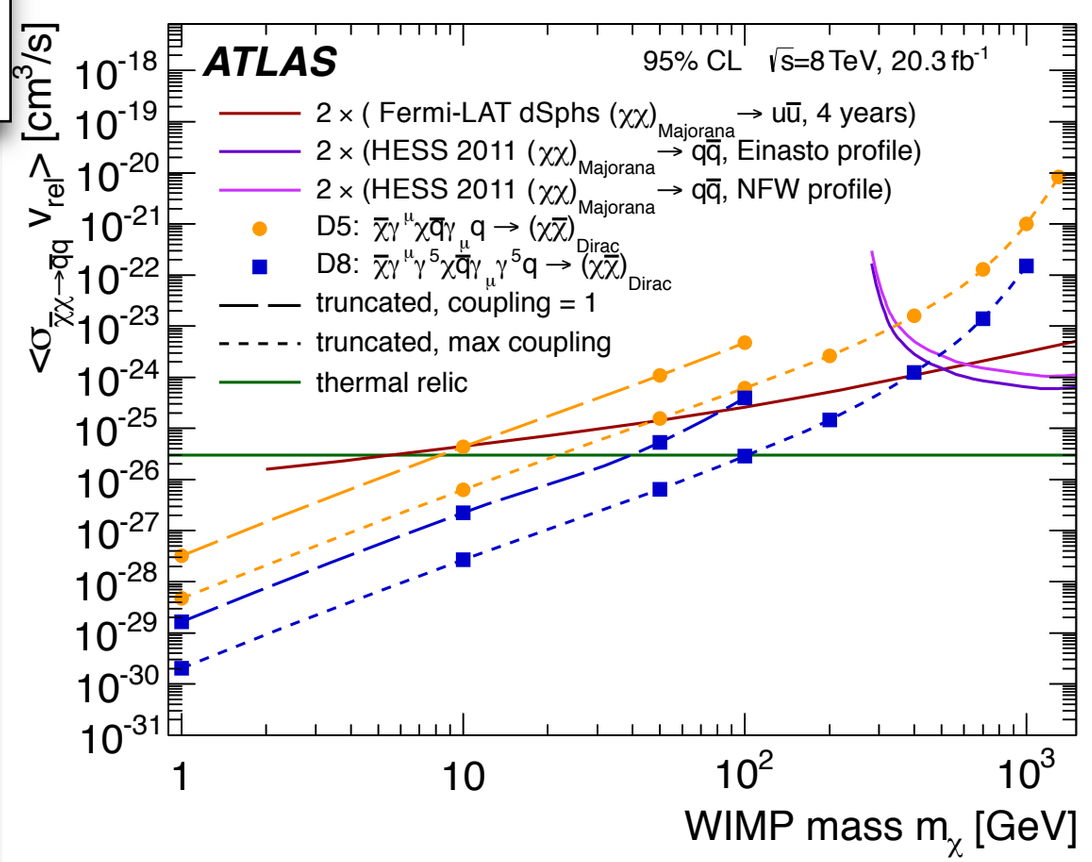
Some lessons:

- Once the WIMP mass is below several hundred GeV (the scale of the cuts on MET and jet $p_T$), the search is insensitive to the WIMP mass—can continue the ~same limit below 1 GeV
- The mono-jet search is insensitive to differences in the CI Lorentz structure which matter a lot for direct-detection searches

These nicely complement the non-collider searches



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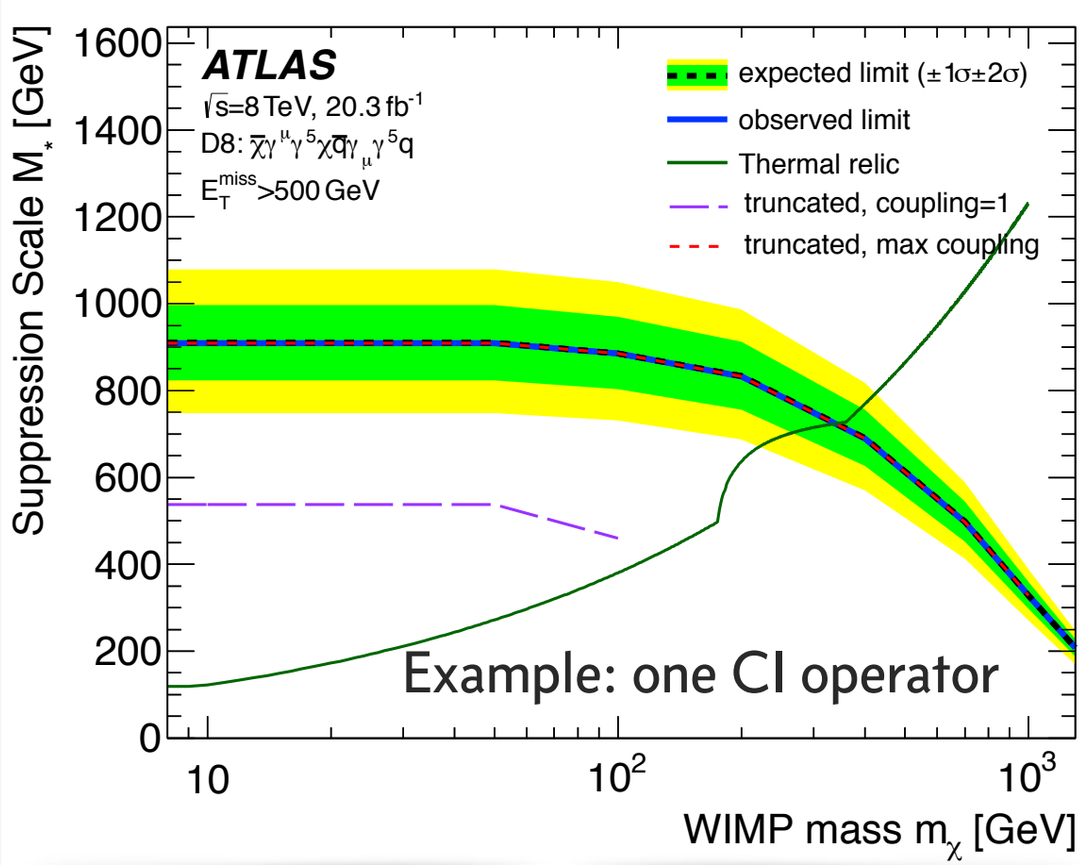
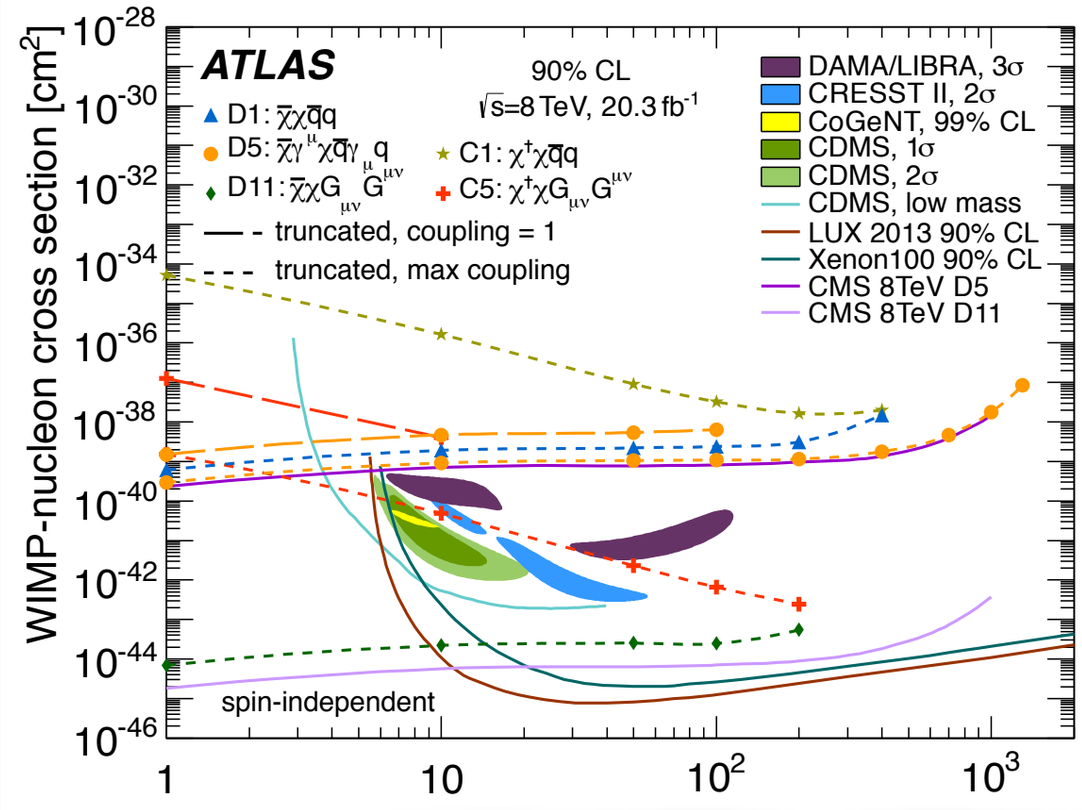
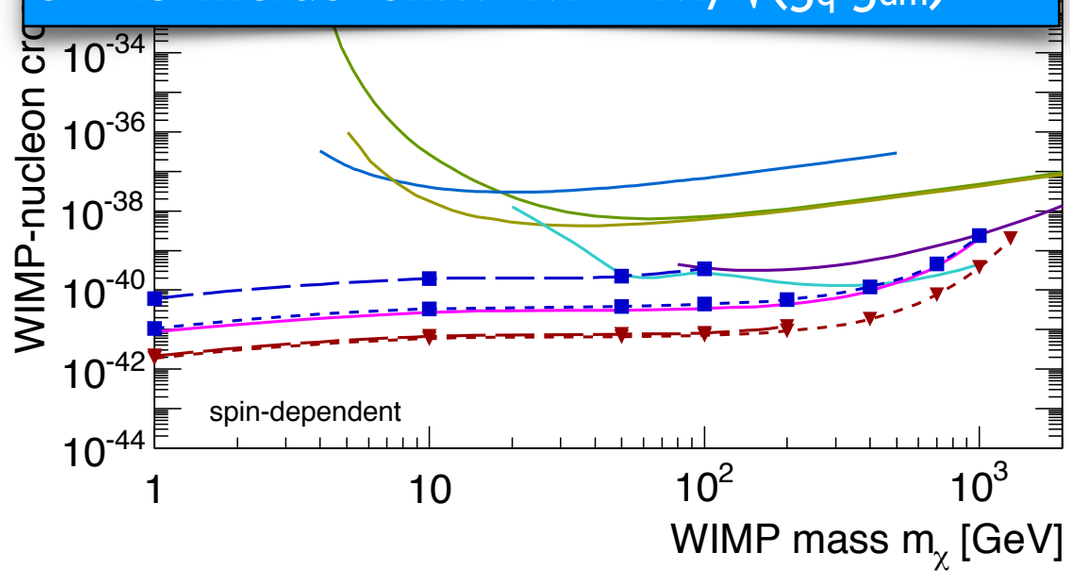
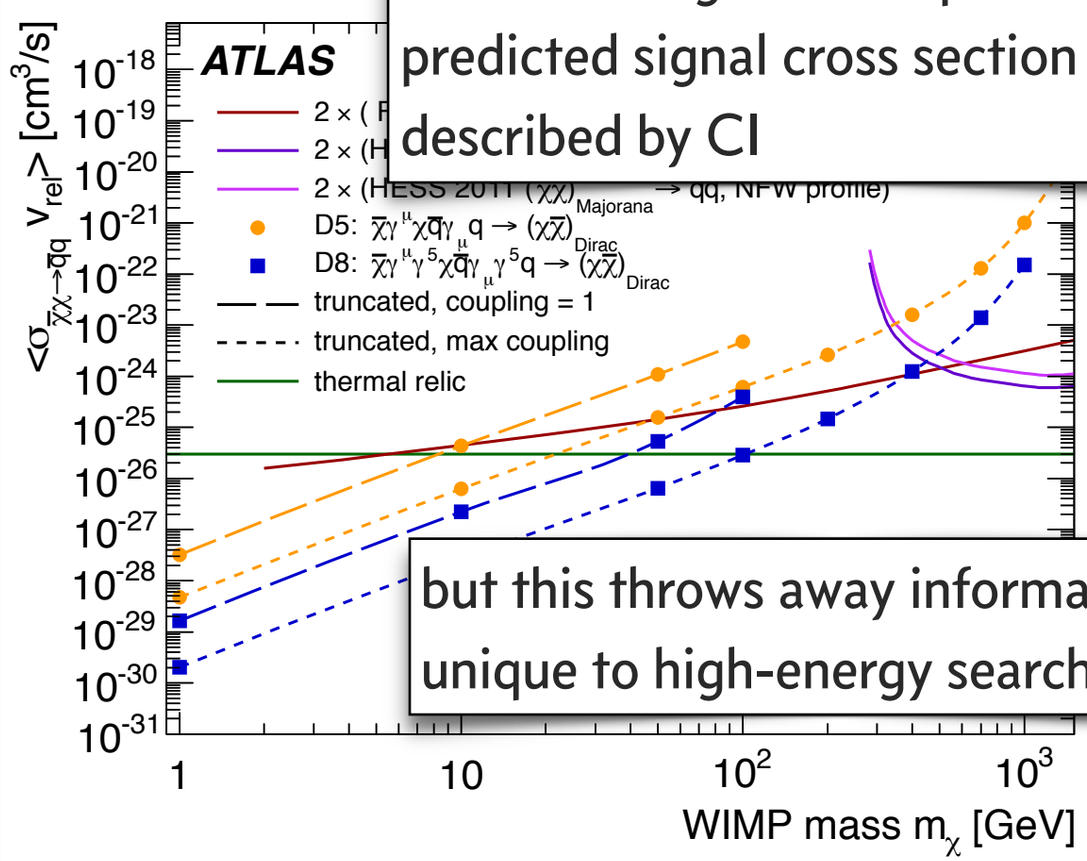



The search is probing CI scales at LHC-scale (and cut-scale) energies. It can be sensitive to the internal structure of the interaction… $M^* = M/\sqrt{(g_q\, g_{dm})}$




Truncation: ignore component of predicted signal cross section not described by CI

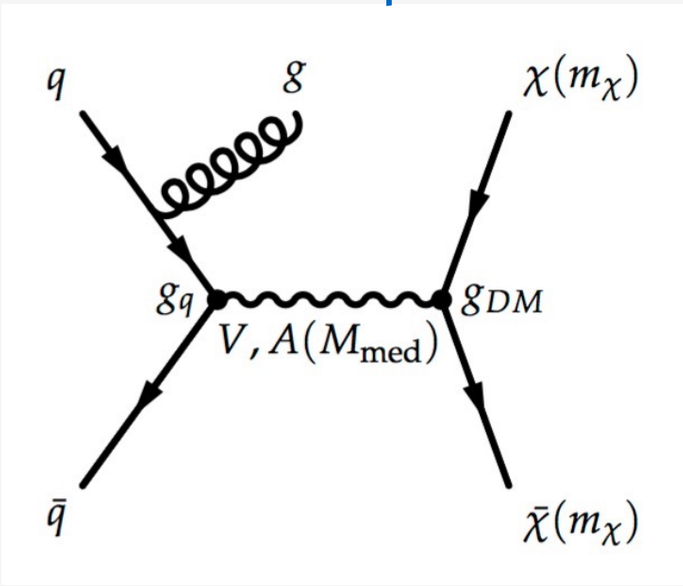


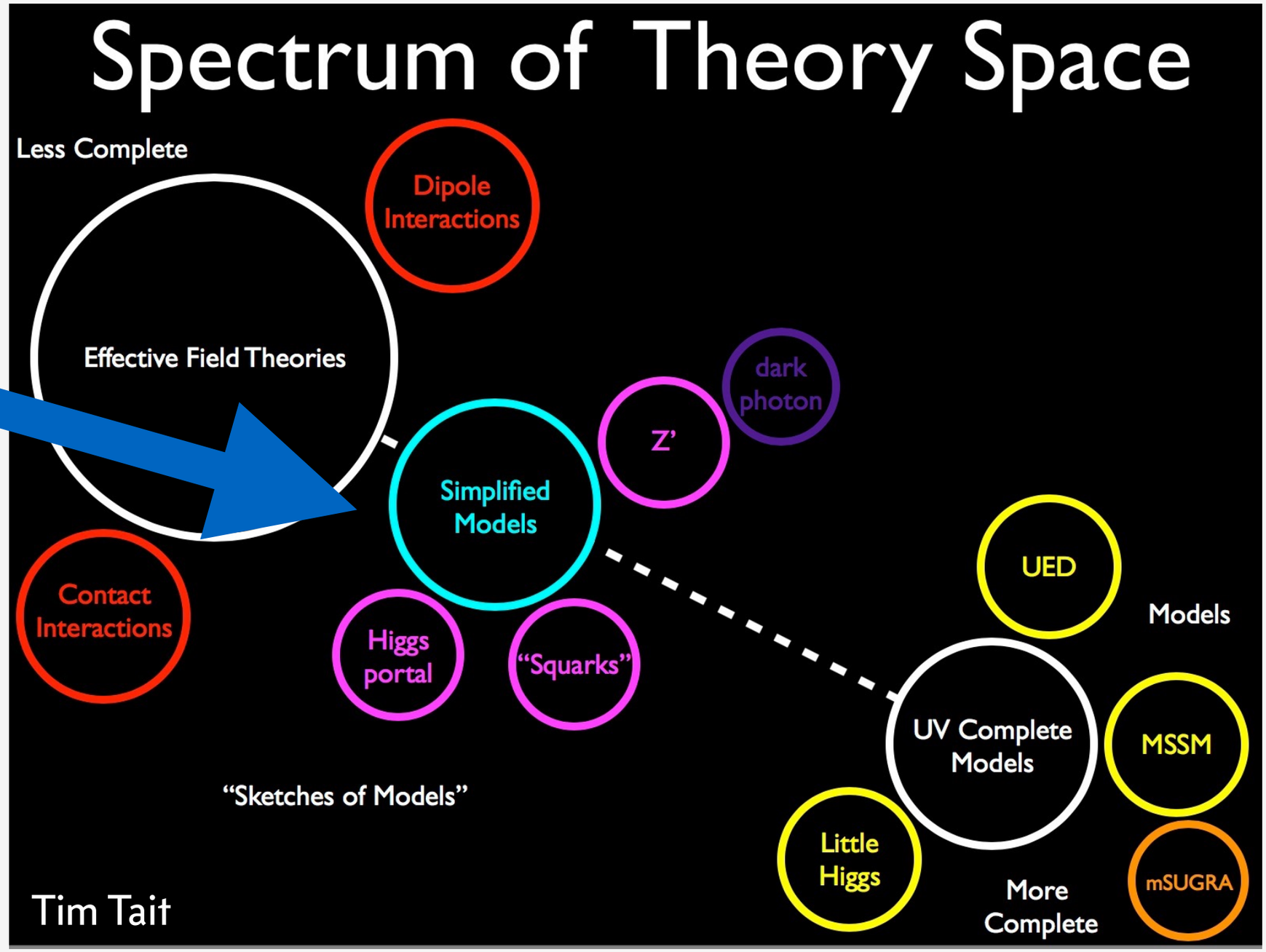

but this throws away information unique to high-energy searches!

# Now what?

Move to a larger set of more complex models,
e.g. add a single new "mediator"

SM-DM interaction mediated by SM particles (heavily constrained except for Higgs) or an additional new particle

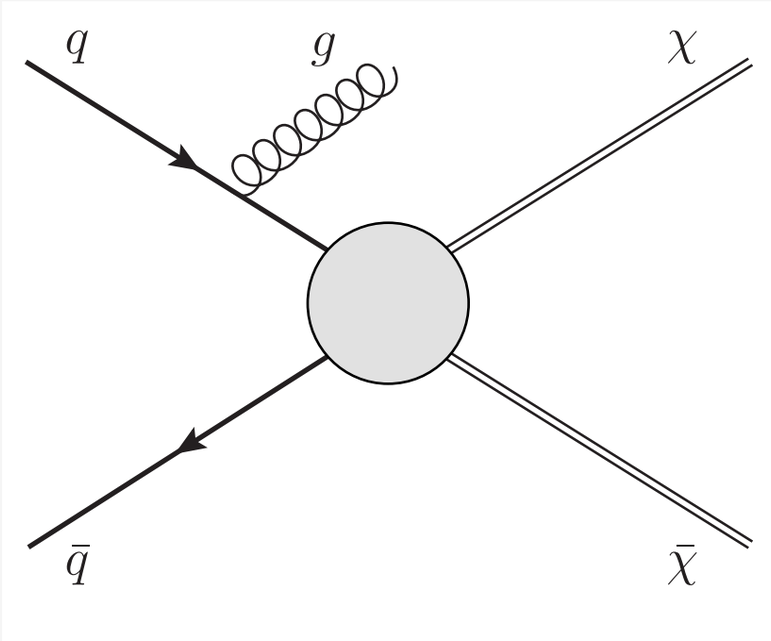



But this change opens up a much richer set of possibilities

*"It is the production and the role of the mediator particle(s) which is of key importance in the collider searches for dark sectors; the actual dark matter is a derivative."*
*—Phys. Rev. D 91, 055009 (2015)*

# Revisiting the consequences

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7 TeV results: Phys.Rev. D87 (2013) 9, 095013

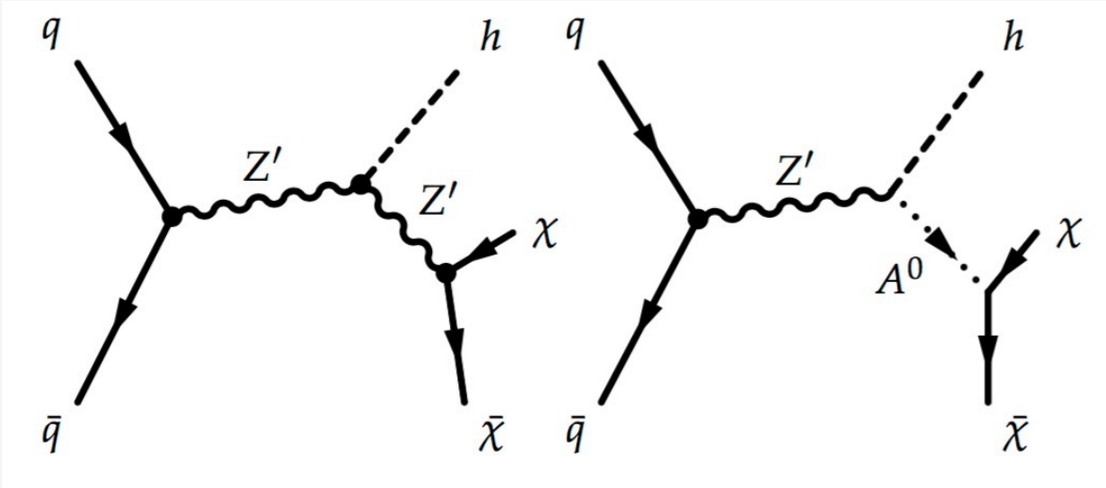
TABLE V: 90% CL limits on $\sigma(pp \to \chi\bar{\chi} + X)$ for $m_\chi = 10$ GeV, theory prediction for $M_\star = 1$ TeV, and limits on $M_\star$ using the D5 operator. In the case of the $Z + \not{E}_T$ final state, the prections include the $Z \to \ell\ell$ branching fraction.

| Channel | Limit $\sigma$ (fb) | Pred. (fb) | Limit $M_\star$ (GeV) | | |
|---|---|---|---|---|---|
| ATLAS jet+$\not{E}_T$ | 1,700 | 370 | 685 | 785 | 795 |
| CMS jet+$\not{E}_T$ | 1,140 | 370 | 750 | | |
| ATLAS $\gamma + \not{E}_T$ | 33 | 3.7 | 580 | 645 | |
| CMS $\gamma + \not{E}_T$ | 35 | 3.7 | 570 | | |
| ATLAS $Z + \not{E}_T$ | 36 | 0.5 | 340 | | |

In this model, mono-jet is nearly the only colllider strategy

# Revisiting the consequences

**When the event "tag" can come from the interaction rather than ISR, then searches beyond mono-jets become much more important**




1. DM must be pair produced
2. "MET+proton remnants" is indistinguishable from "backgrounds"
3. ~~We need to "tag" the collision with high $p_T$ ISR~~
4. ~~The Standard Model predicts what ISR occurs most often…~~

➡ ~~do a mono-jet search~~

7 TeV results: Phys.Rev. D87 (2013) 9, 095013

~~In this model, mono-jet is nearly the only colllider strategy~~

TABLE V: 90% CL limits on $\sigma(pp \to \chi\bar{\chi} + X)$ for $m_\chi = 10$ GeV, theory prediction for $M_\star = 1$ TeV, and limits on $M_\star$ using the D5 operator. In the case of the $Z + \not{E}_T$ final state, the prections include the $Z \to \ell\ell$ branching fraction.

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We gratefully acknowledge support from the Simons Foundation and member institutions



High Energy Physics - Experiment

# Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

*(Submitted on 3 Jul 2015)*

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

Subjects: **High Energy Physics - Experiment (hep-ex)**; High Energy Physics - Phenomenology (hep-ph)

Cite as: **arXiv:1507.00966 [hep-ex]**
(or **arXiv:1507.00966v1 [hep-e**

**Recent LHC Seminar at CERN: "A historic accord"**
**Recent Seminar at Fermilab: "A historic accord"**
**EPS conference summary talk: "a Run-1 highlight"**
**Theory participants: a new model for theory-exp. collaboration**

## Submission history

From: Antonio Boveia [view email]
**[v1]** Fri, 3 Jul 2015 16:54:32 GMT (3860kb

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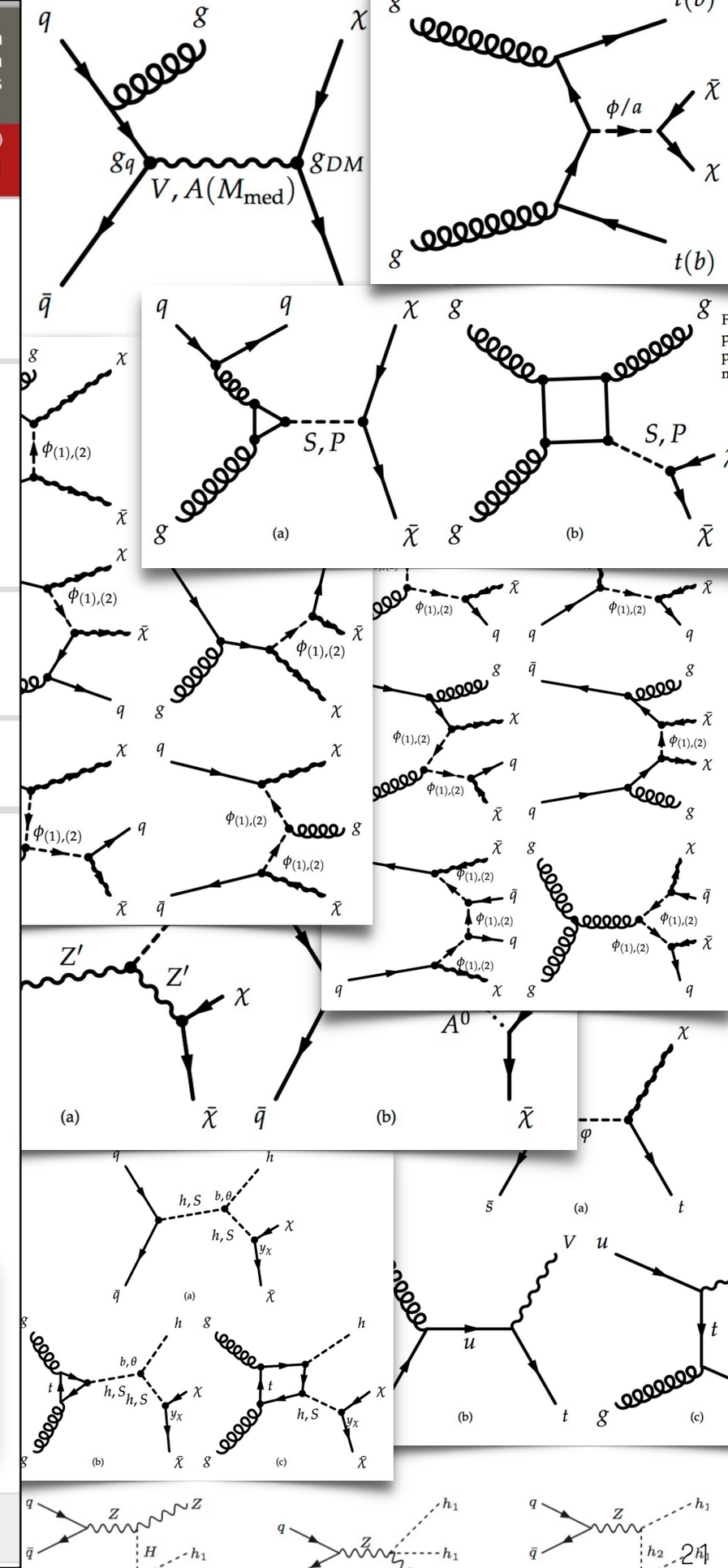


**Benchmark models for ATLAS and CMS Run-2 DM searches**

vector/axial vector mediator, $s$-channel (Sec. 2.1)

| Signature | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| jet + $\not{E}_T$ | **NLO+PS (powheg, SVN r3059)** | [Forl; Foro] | [HKR13; HR15; Ali+10; Nas04; FNO07] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] | [Alw+14; All+14; Deg+12] |
| | NLO (MCFM v7.0) | Upon request | [FW13; Har+15] |
| $W/Z/\gamma + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Fora] | [Alw+14; All+14; Deg+12] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] | [Alw+14; All+14; Deg+12] |

scalar/pseudoscalar mediator, $s$-channel (Sec. 2.2)

| Signature | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| jet + $\not{E}_T$ | **LO+PS, top loop (powheg, r3059)** | [Forn; Form] | [HKR13; HR15; Ali+10; Nas04; FNO07] |
| | LO+PS, top loop (*DMsimp* UFO + MadGraph5_aMC@NLO v.2.3.0) | [New] | [Alw+14; Hir+11; All+14; Deg+12] |
| | LO, top loop (MCFM v7.0) | Upon request | [FW13; Har+15] |
| $W/Z/\gamma + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | | [Alw+14; All+14; Deg+12] |
| $t\bar{t}, b\bar{b} + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Ford] | [Alw+14; All+14; Deg+12] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] | [Alw+14; All+14; Deg+12] |

scalar mediator, $t$-channel (Sec. 2.3)

| Signature | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| jet(s) + $\not{E}_T$ (2-quark gens.) | LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3) | [Forj] | [PVZ14; Alw+14; All+14; Deg+12] |
| jet(s) + $\not{E}_T$ (3-quark gens.) | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Fori] | [Bel+12; Alw+14; All+14; Deg+12] |
| $W/Z/\gamma + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | TBC | [Bel+12; Alw+14; All+14; Deg+12] |
| $b + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forg] | [LKW13; Agr+14b; Alw+14; All+14; Deg+12] |

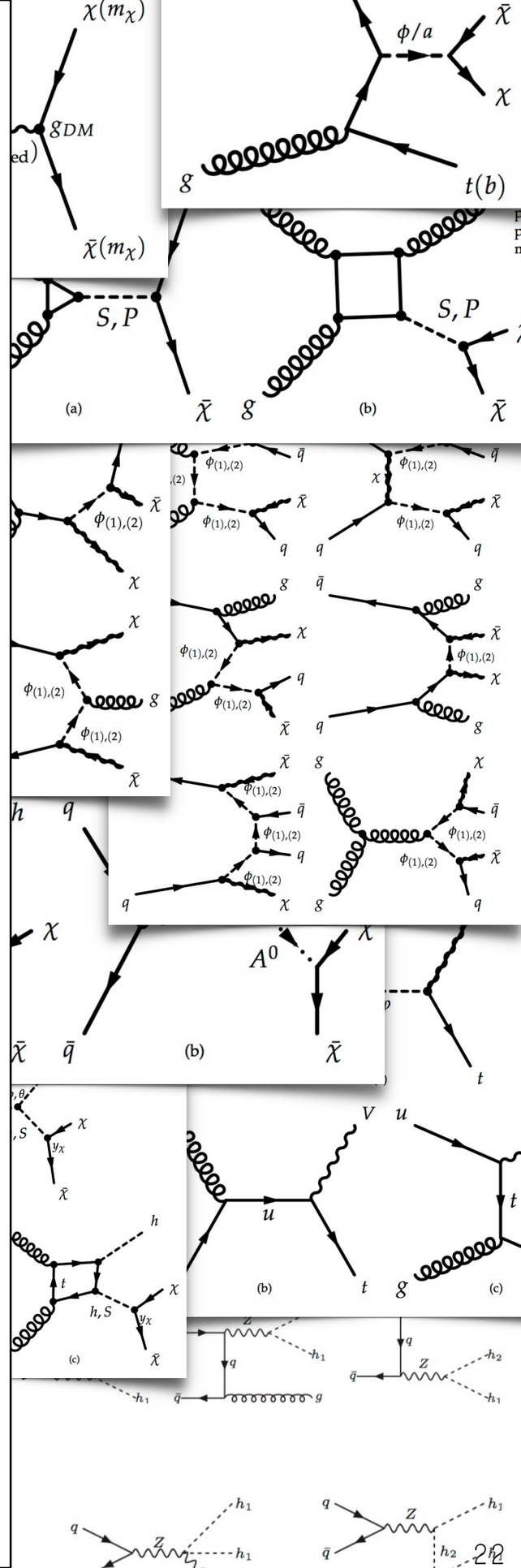
Specific simplified models with EW bosons (Sec. 3.1)

| Signature and model | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| Higgs + $\not{E}_T$, vector med. | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forh] | [Car+14; BLW14b; Alw+14; All+14; Deg+12] |
| Higgs + $\not{E}_T$, scalar med. | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forh] | [Car+14; BLW14b; Alw+14; All+14; Deg+12] |
| Higgs + $\not{E}_T$, 2HDM | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forb] | [BLW14b; Alw+14; All+14; Deg+12] |

Contact interaction operators with EW bosons (Sec. 3.1)

| Signature and model | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| $W/Z/\gamma + \not{E}_T$, dim-7 | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forc] | [Cot+13; Car+13; CHH15; BLW14b; Alw+14; All+14; Deg+12] |
| Higgs + $\not{E}_T$, dim-4/dim-5 | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Fore] | [Car+14; PS14; BLW14b; Alw+14; All+14; Deg+12] |
| Higgs + $\not{E}_T$, dim-8 | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forh] | [Car+14; PS14; BLW14b; Alw+14; All+14; Deg+12] |

Table 6.1: Summary table for available benchmark models considered within the works of this Forum. The results in this document have been obtained with the implementations in bold.



**Benchmark models for ATLAS and CMS Run-2 DM searches**

vector/axial vector mediator, $s$-channel (Sec. 2.1)

| Signature | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| jet + $\not{E}_T$ | **NLO+PS (powheg, SVN r3059)** | [Forl; Foro] | [HKR13; HR15; Ali+10; Nas04; FNO07] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] | [Alw+14; All+14; Deg+12] |
| | NLO (MCFM v7.0) | Upon request | [FW13; Har+15] |
| $W/Z/\gamma + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Fora] | [Alw+14; All+14; Deg+12] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] | [Alw+14; All+14; Deg+12] |

scalar/pseudoscalar mediator, $s$-channel (Sec. 2.2)

| Signature | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| jet + $\not{E}_T$ | **LO+PS, top loop (powheg, r3059)** | [Forn; Form] | [HKR13; HR15; Ali+10; Nas04; FNO07] |
| | LO+PS, top loop (*DMsimp* UFO + MadGraph5_aMC@NLO v.2.3.0) | [New] | [Alw+14; Hir+11; All+14; Deg+12] |
| | LO, top loop (MCFM v7.0) | Upon request | [FW13; Har+15] |
| $W/Z/\gamma + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | | [Alw+14; All+14; Deg+12] |
| $t\bar{t}, b\bar{b} + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Ford] | [Alw+14; All+14; Deg+12] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] | [Alw+14; All+14; Deg+12] |

scalar mediator, $t$-channel (Sec. 2.3)

| Signature | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| jet(s) + $\not{E}_T$ (2-quark gens.) | LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3) | [Forj] | [PVZ14; Alw+14; All+14; Deg+12] |
| jet(s) + $\not{E}_T$ (3-quark gens.) | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Fori] | [Bel+12; Alw+14; All+14; Deg+12] |
| $W/Z/\gamma + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | TBC | [Bel+12; Alw+14; All+14; Deg+12] |
| $b + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forg] | [LKW13; Agr+14b; Alw+14; All+14; Deg+12] |

Specific simplified models with EW bosons (Sec. 3.1)

| Signature and model | State of the art calculation and tools | Implementation | References |
|---|---|---|---|
| Higgs + $\not{E}_T$, vector med. | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forh] | [Car+14; BLW14b; Alw+14; All+14; Deg+12] |
| Higgs + $\not{E}_T$, scalar med. | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forh] | [Car+14; BLW14b; Alw+14; All+14; Deg+12] |
| Higgs + $\not{E}_T$, 2HDM | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Forb] | [BLW14b; Alw+14; All+14; Deg+12] |

Contact interaction operators with EW boson

| Signature and model | State of the art calculation and tools |
|---|---|
| $W/Z/\gamma + \not{E}_T$, dim-7 | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** |
| Higgs + $\not{E}_T$, dim-4/dim-5 | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** |
| Higgs + $\not{E}_T$, dim-8 | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** |

Table 6.1: Summary table for available benchmark models conside

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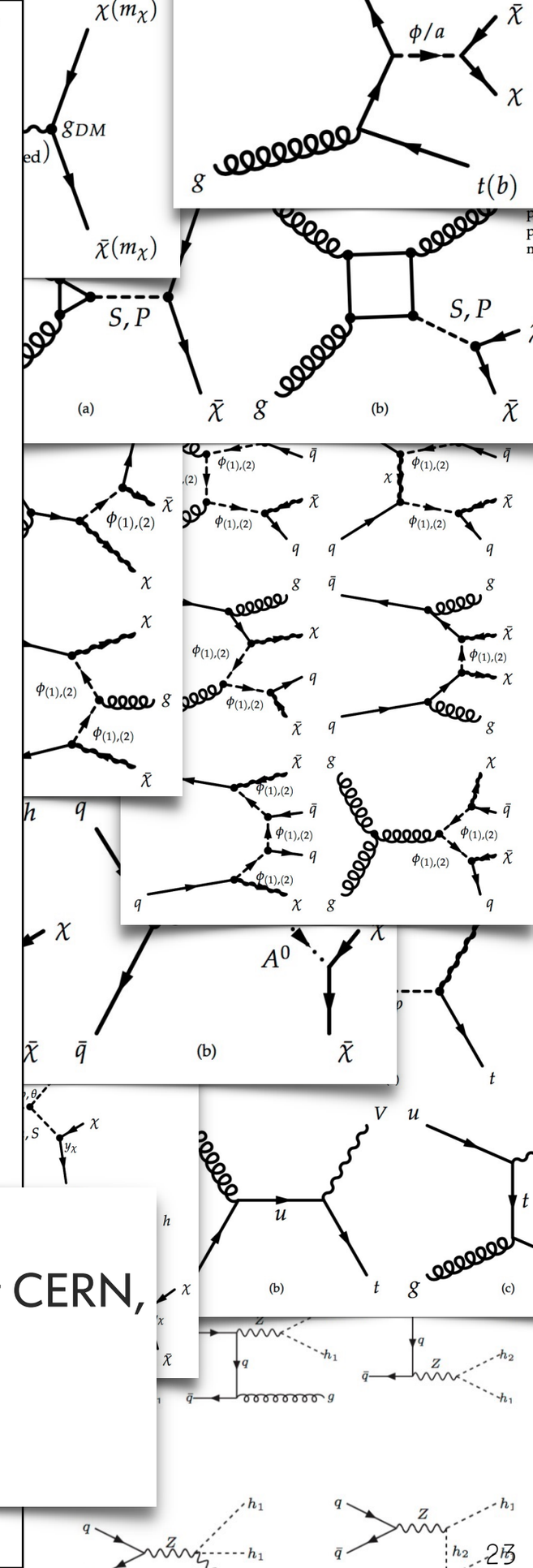


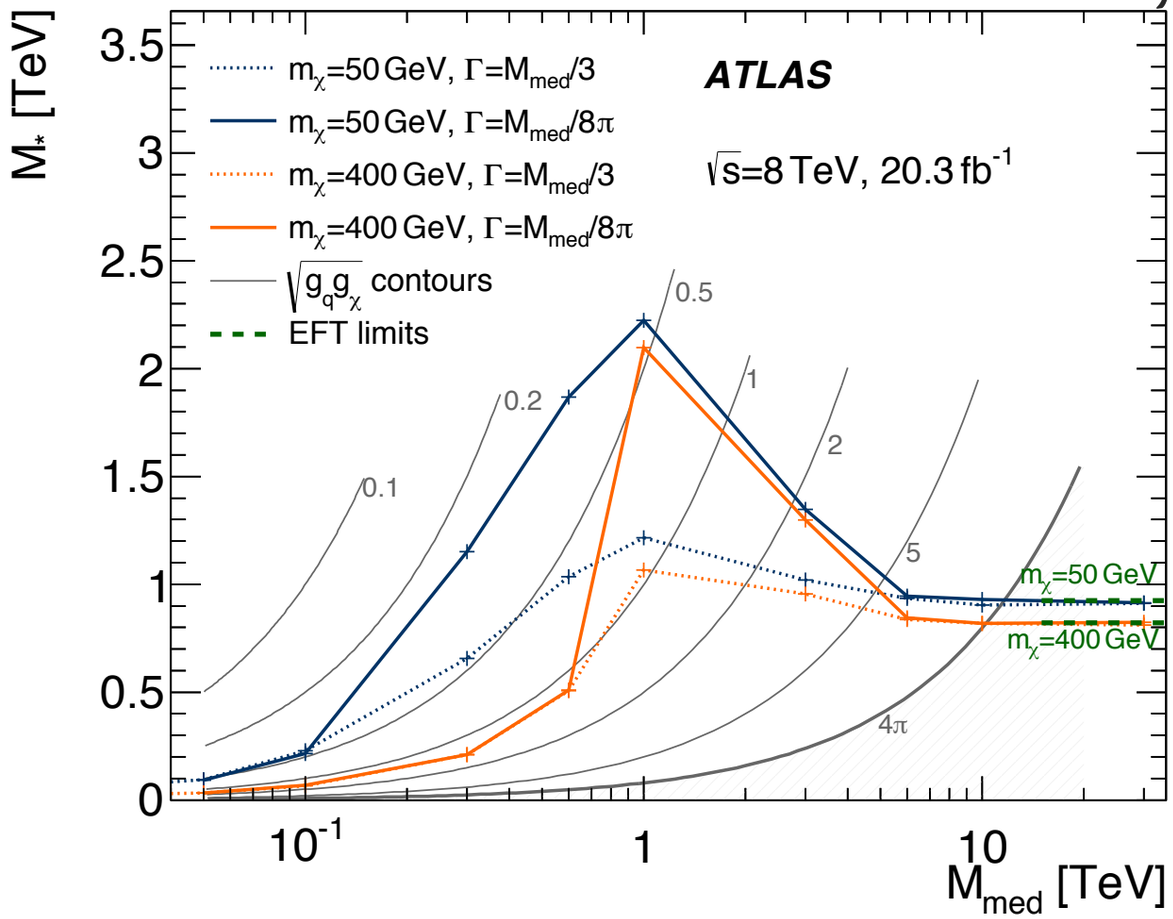
**Much more left to do!**

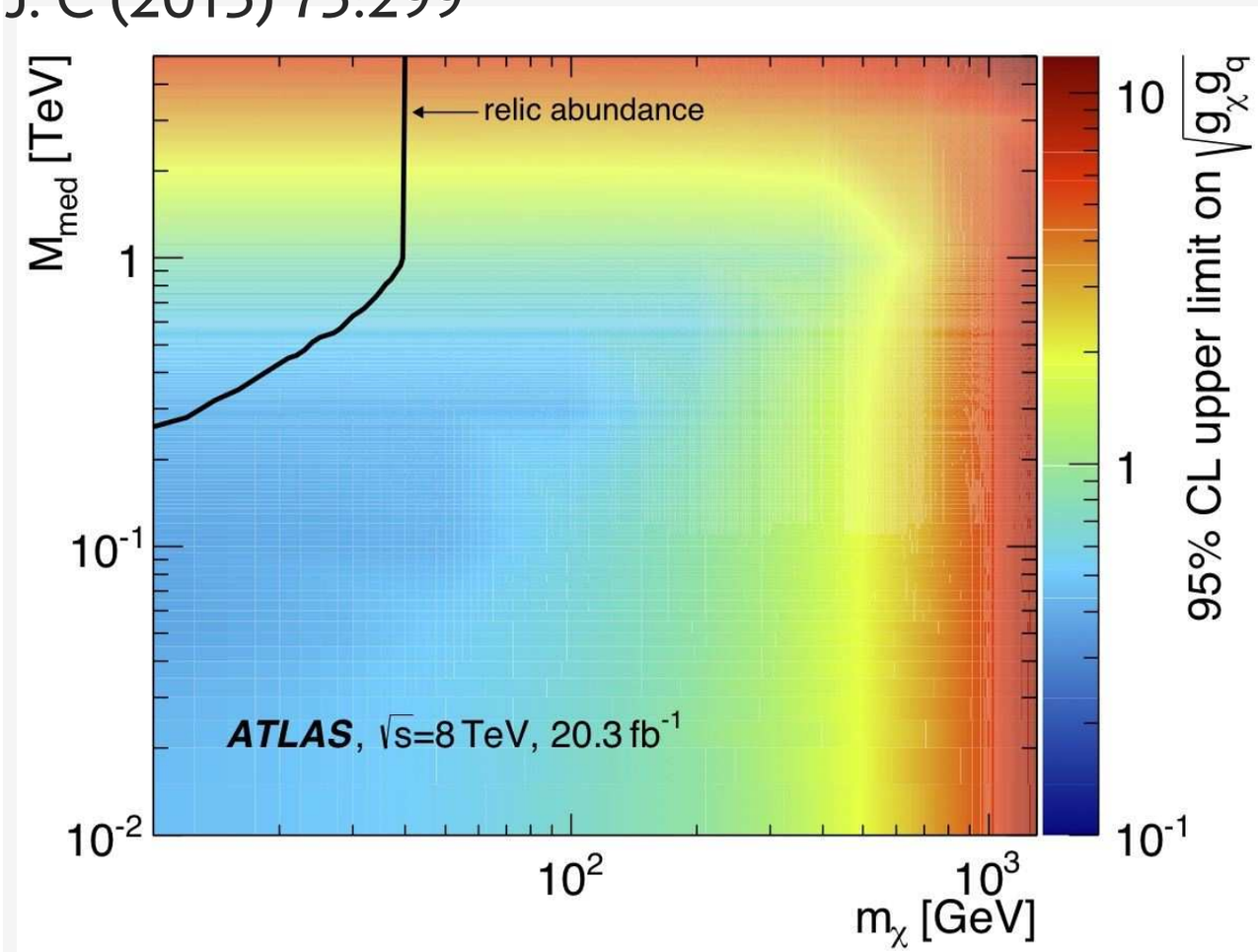
See New LHC Physics Centre at CERN, Dark Matter Working Group

*First Workshop Announced Soon*

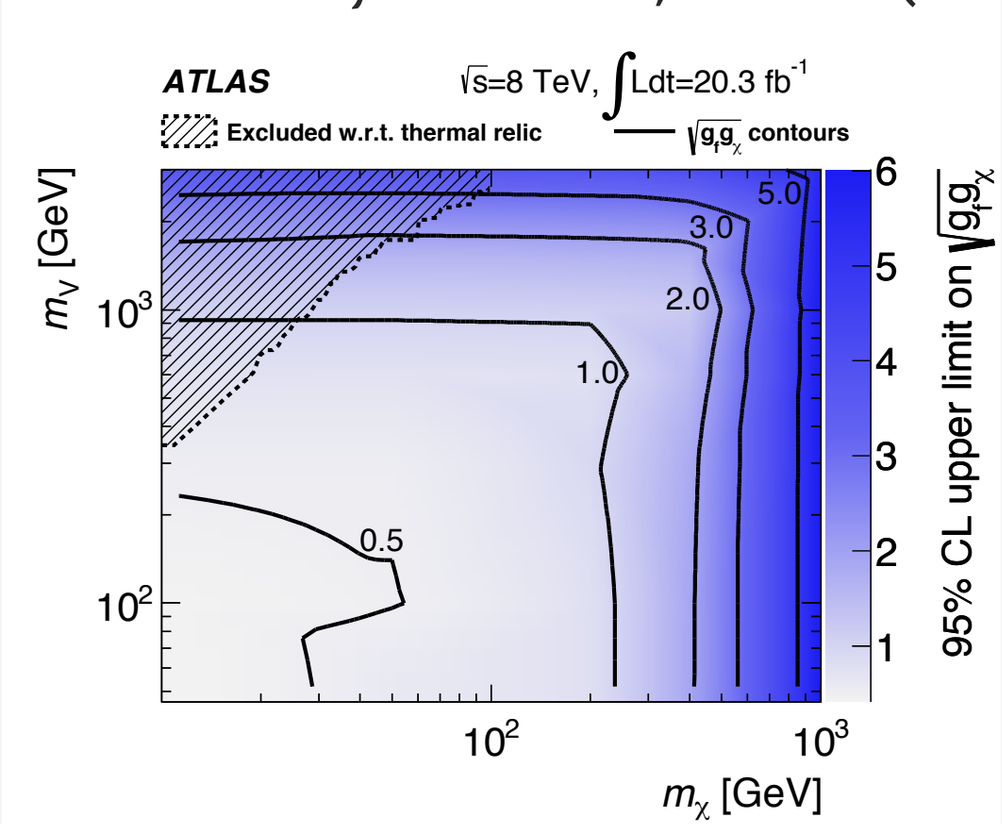
*(2nd Week of December at CERN)*

Mono-Jet: Eur. Phys. J. C (2015) 75:299

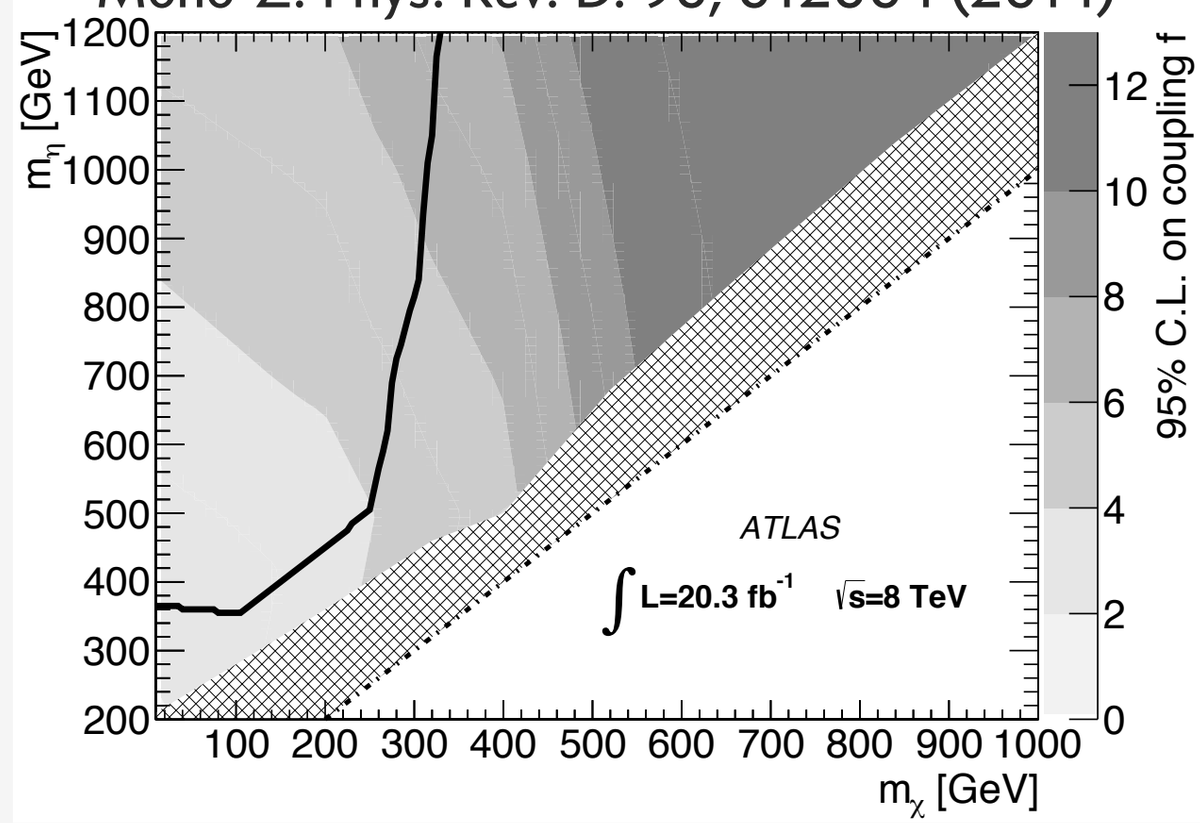


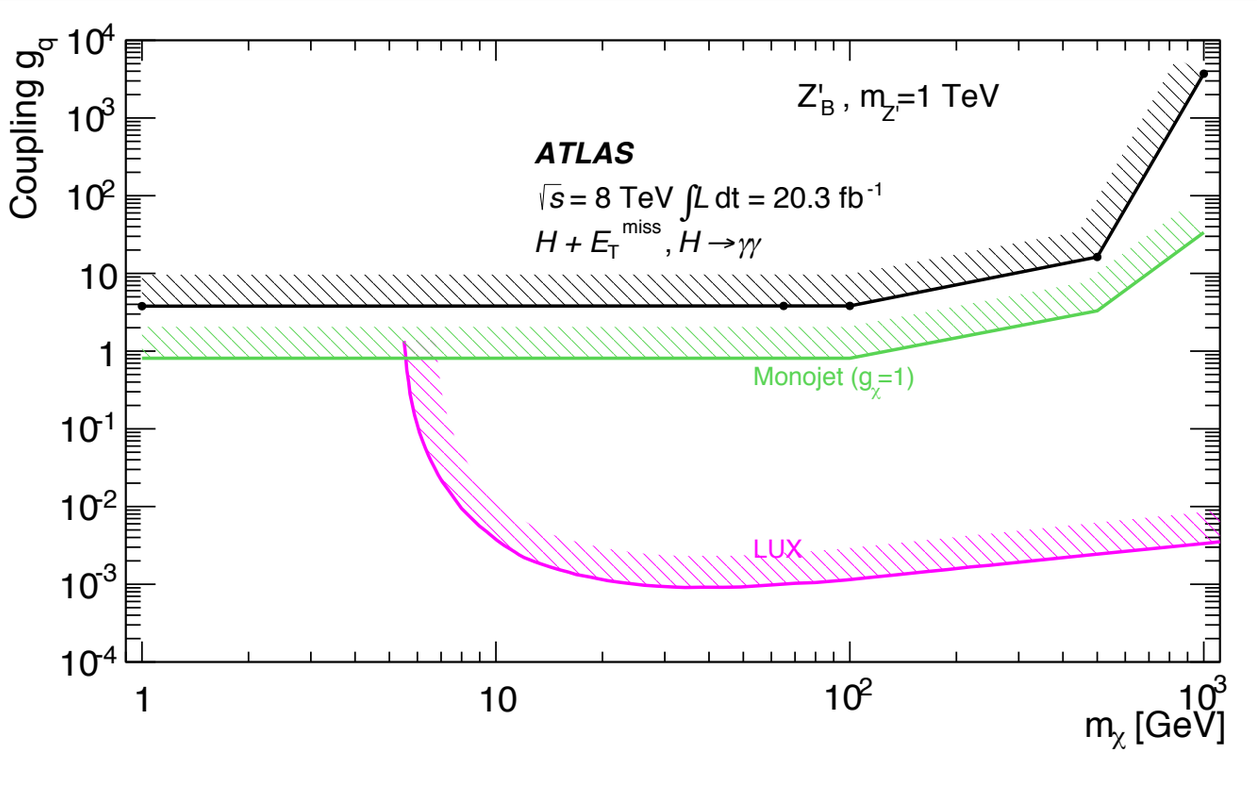

Mono-Photon: Phys. Rev. D 91, 012008 (2015)

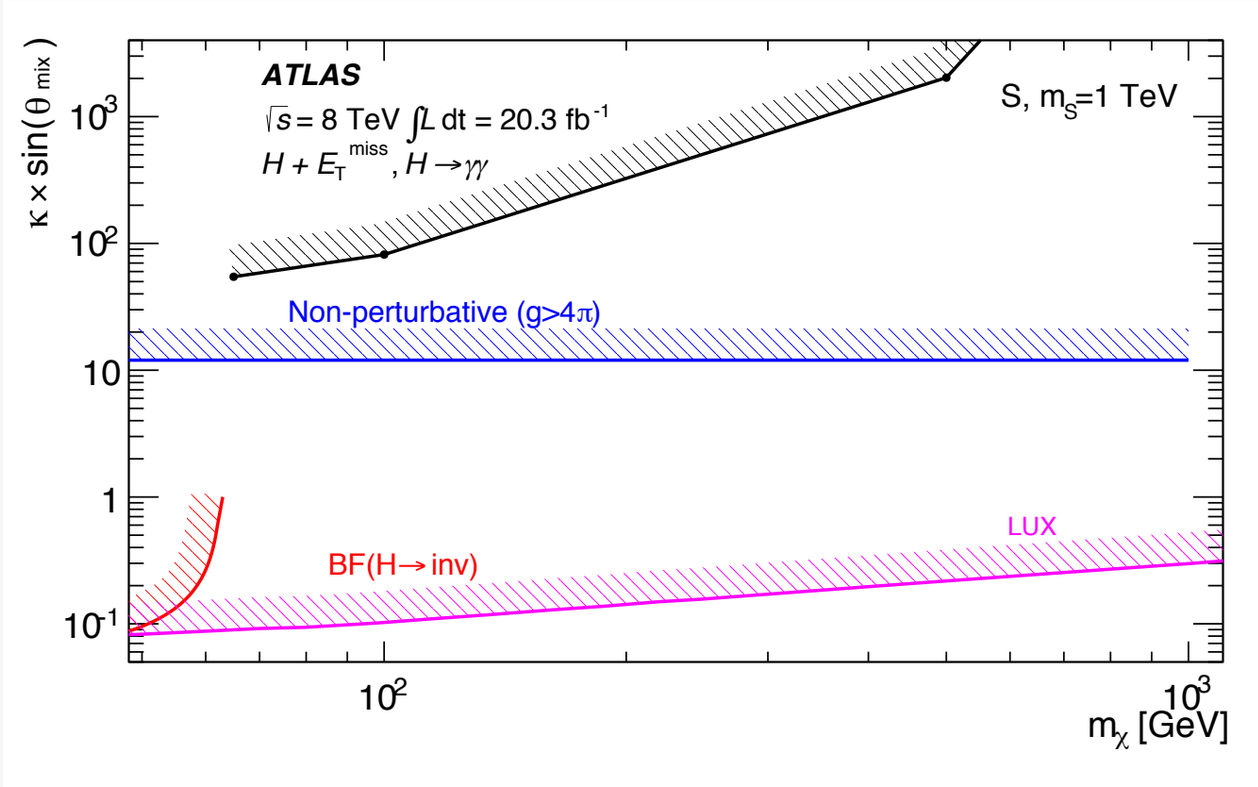



Mono-Z: Phys. Rev. D. 90, 012004 (2014)

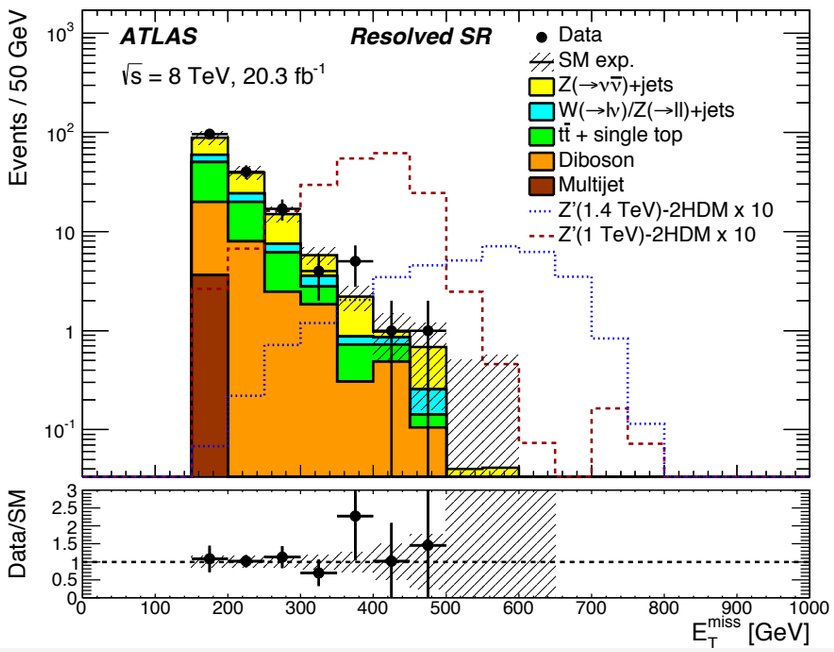


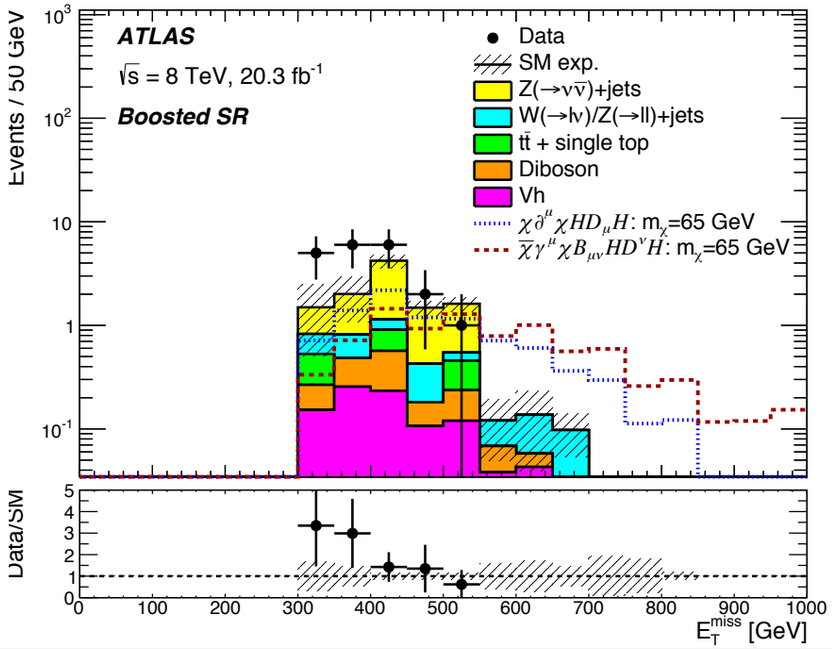
# Mono-Higgs (Diphoton): Phys. Rev. Lett. 115, 131801 (2015)

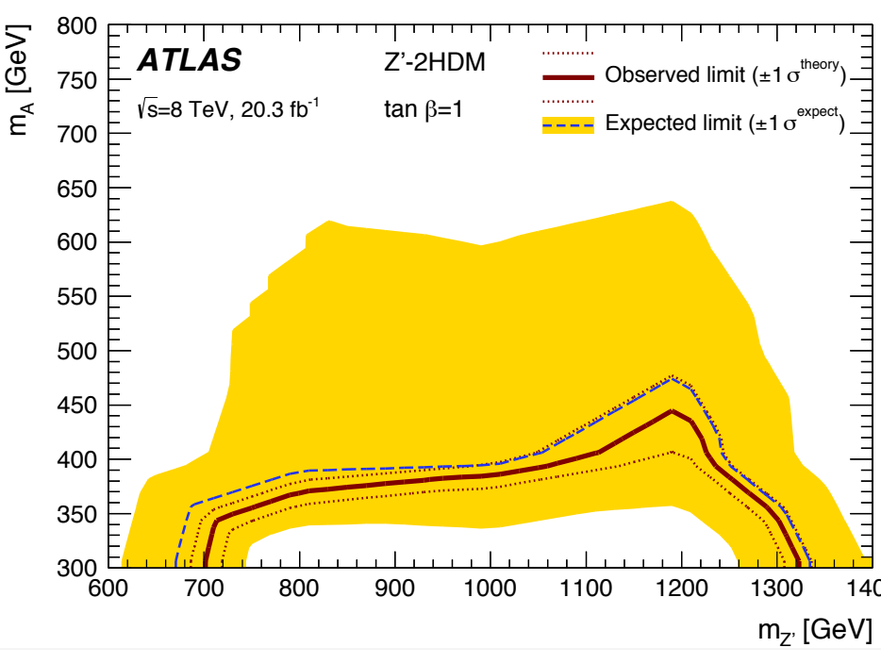



# Mono-Higgs→bb: arXiv:1510.06218




and even more Run 1 results that I don't have time to zoom by….

# Simplified Models: Higgs as the light mediator

arXiv:1509.00672

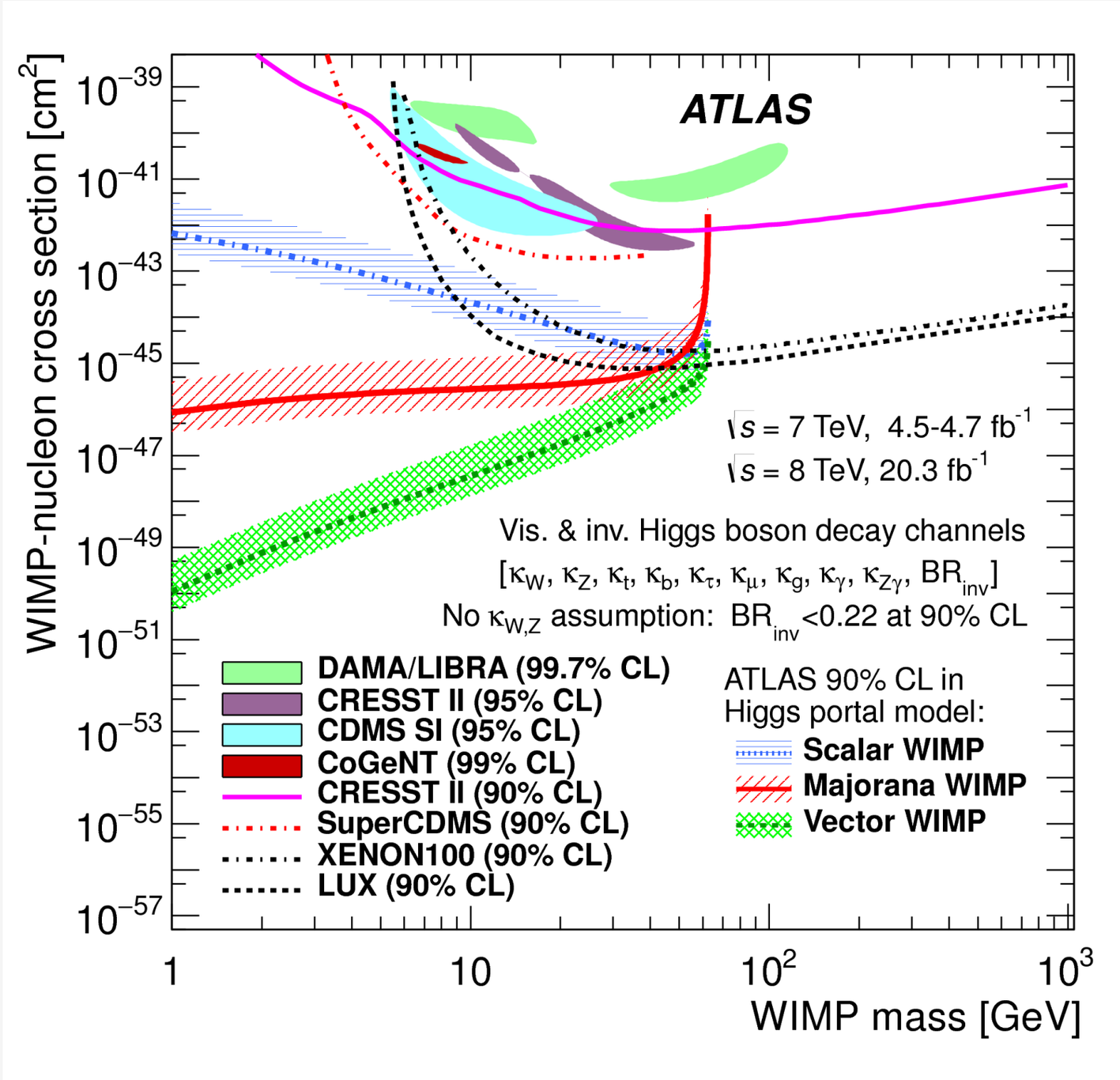
Invisible decays of the Higgs are rare in the SM (ZZ→4ν)

Can constrain invisible Higgs branching fraction through multiple search channels

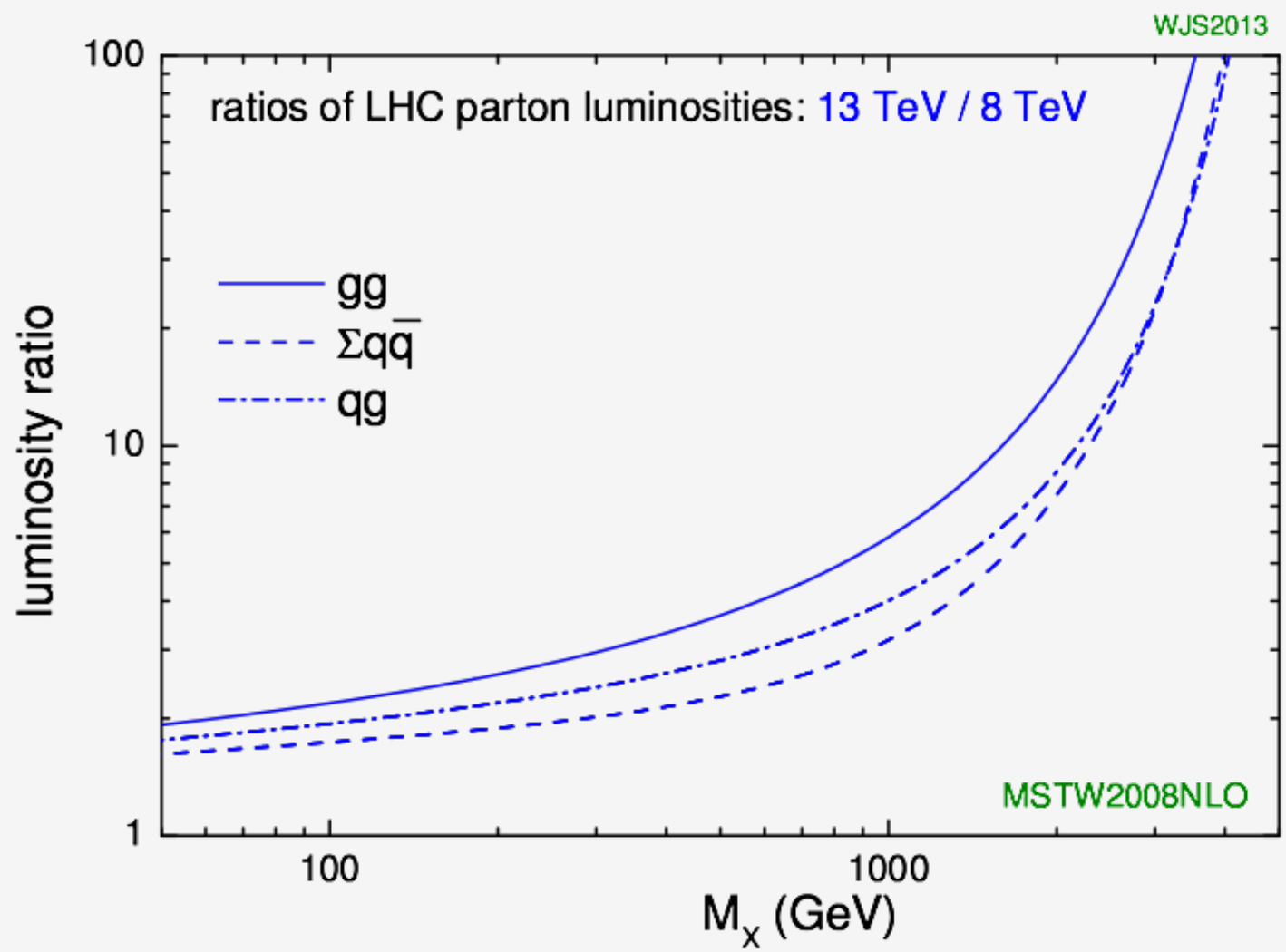
- W/Z+H
- jj H
- mono-W/Z
- mono-jet

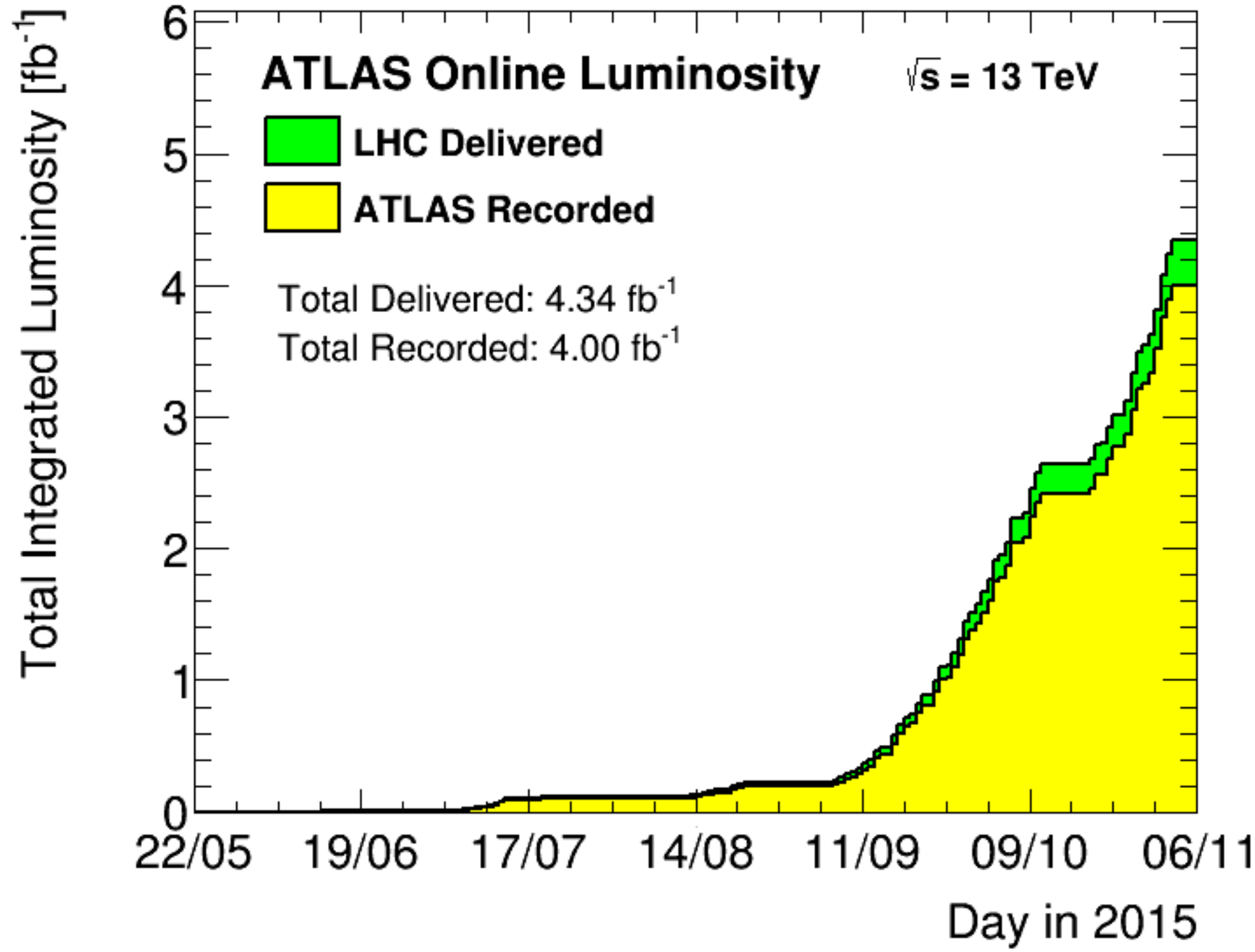
$BR_{inv}$<0.22 yields stringent constraints on certain types of WIMPs

(if Higgs is the sole SM-DM mediator, if $m_{DM} < m_H/2$, and if *no further theory is required*)



# Run 2....


WJS2013
ratios of LHC parton luminosities: 13 TeV / 8 TeV
gg
Σqq̄
qg
MSTW2008NLO
luminosity ratio
100
10
1
100
1000
M_X (GeV)



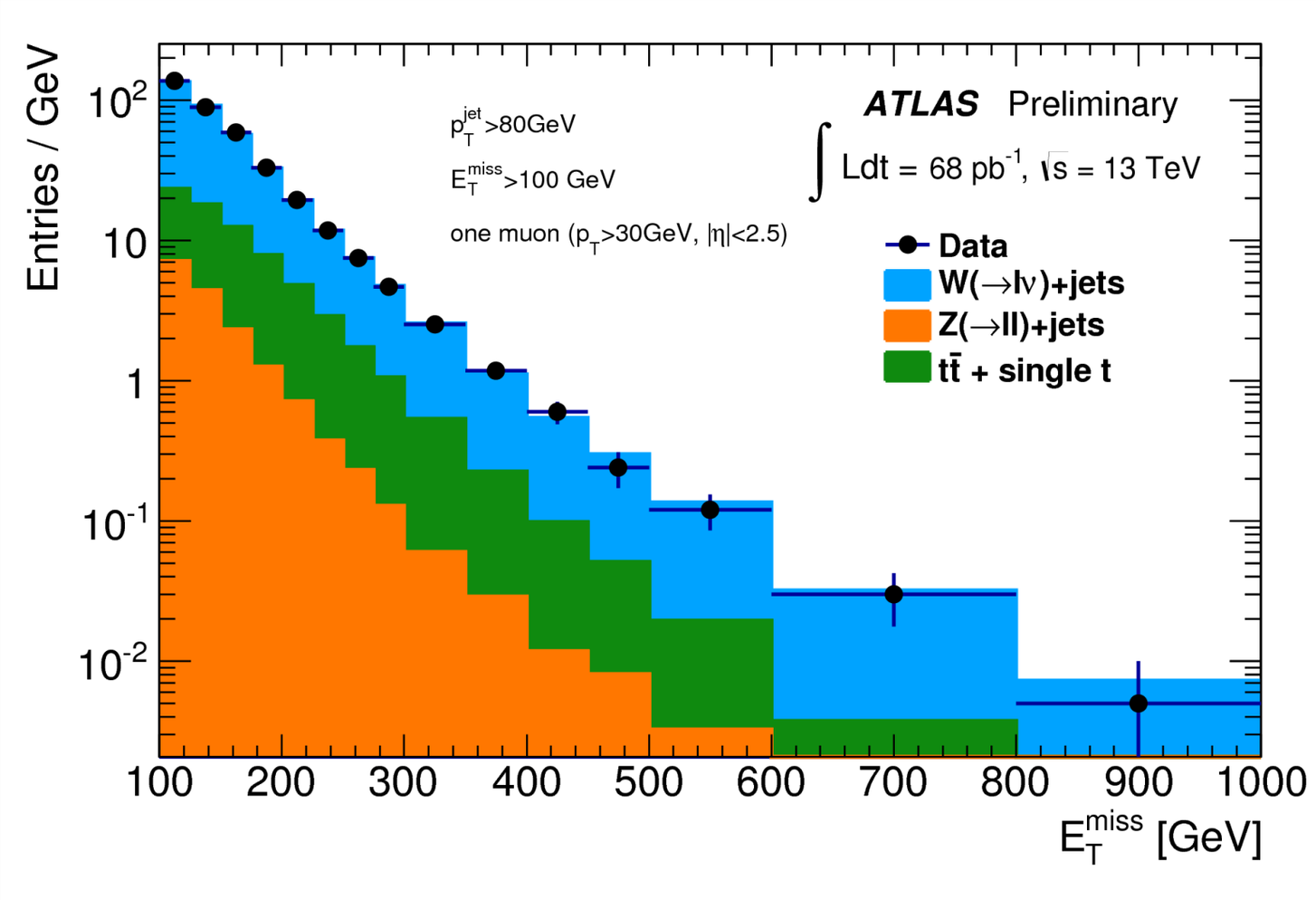

**2015 pp data-taking has just ended**

4/fb recorded (25 ns + 50 ns bunch spacing)

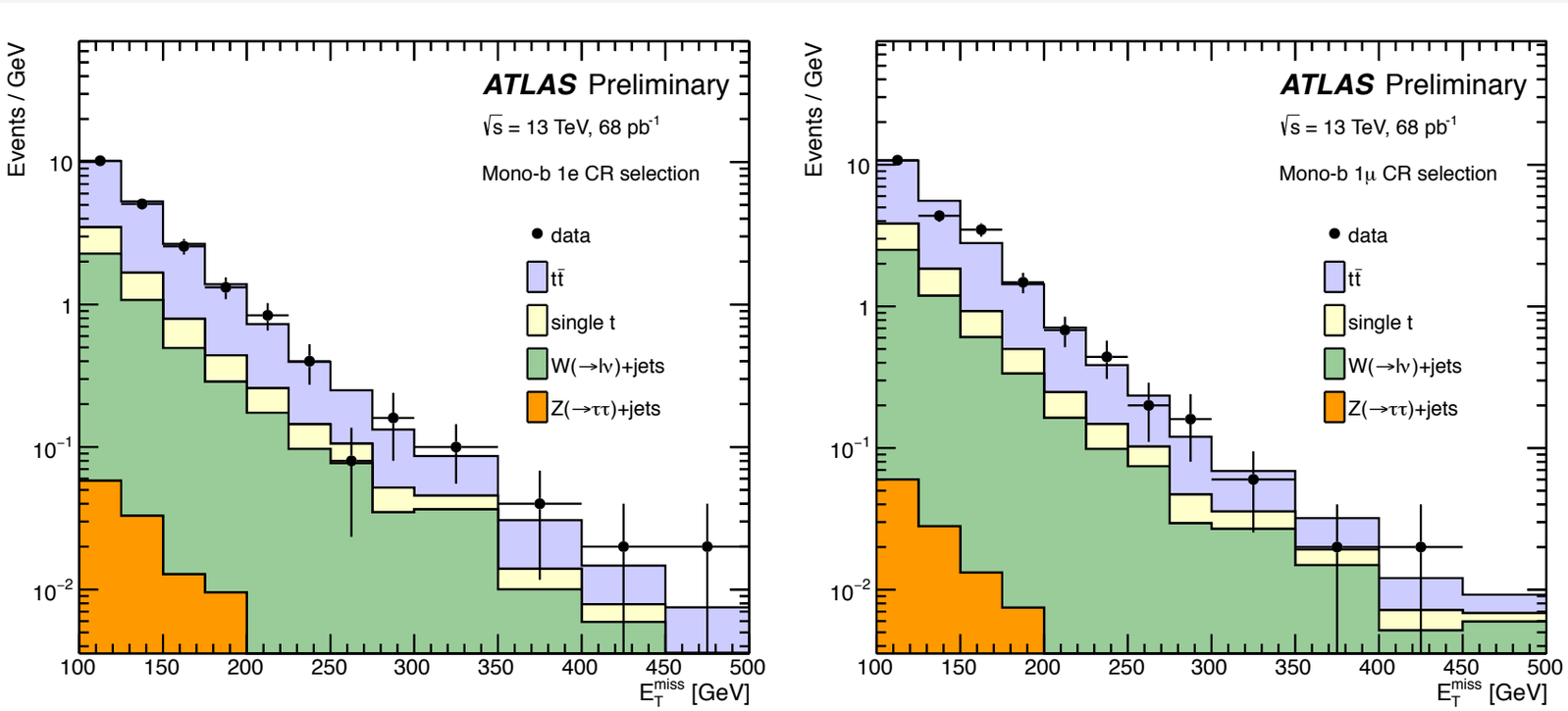
**Latest ATLAS public results: LHCP, 80/pb**

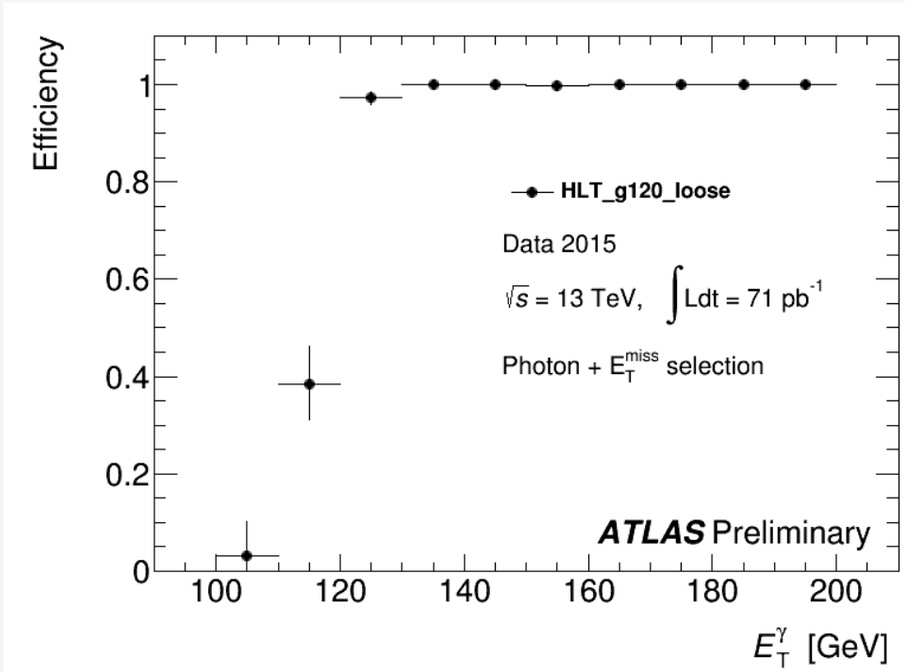
50x this dataset being analyzed now… stay tuned!

# ATLAS Mono-X in Run 2



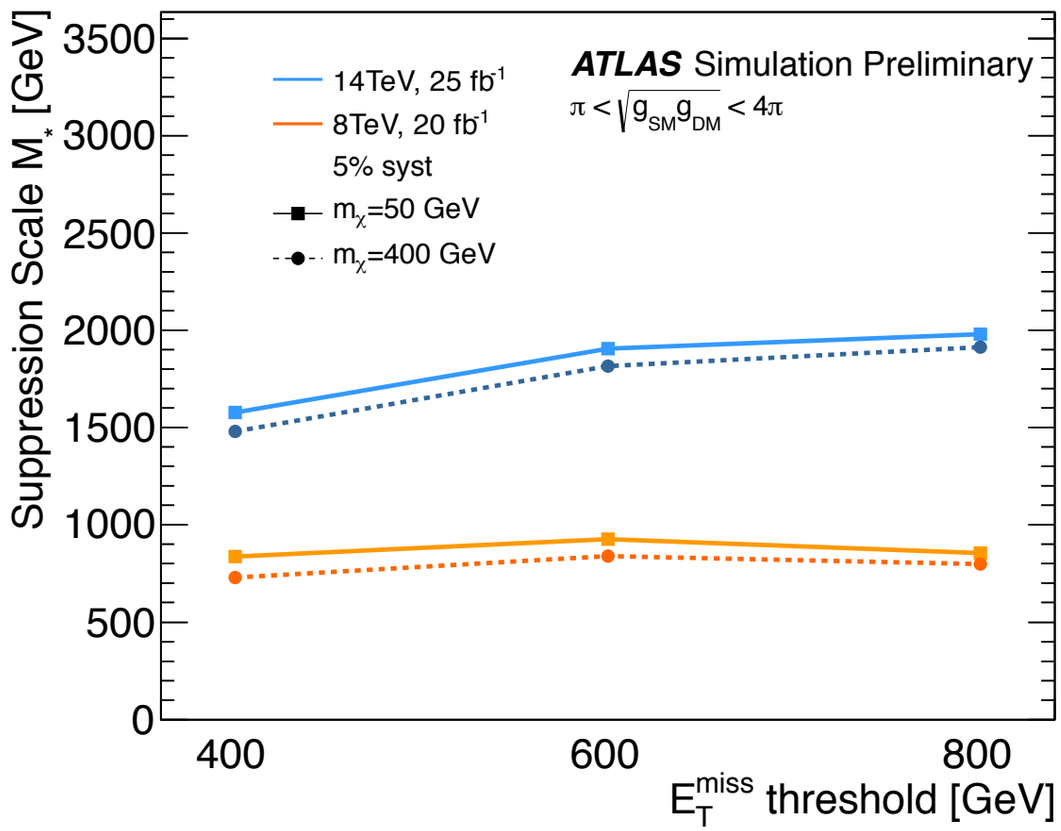

Many interesting dark matter searches underway—a sampling of summer performance plots

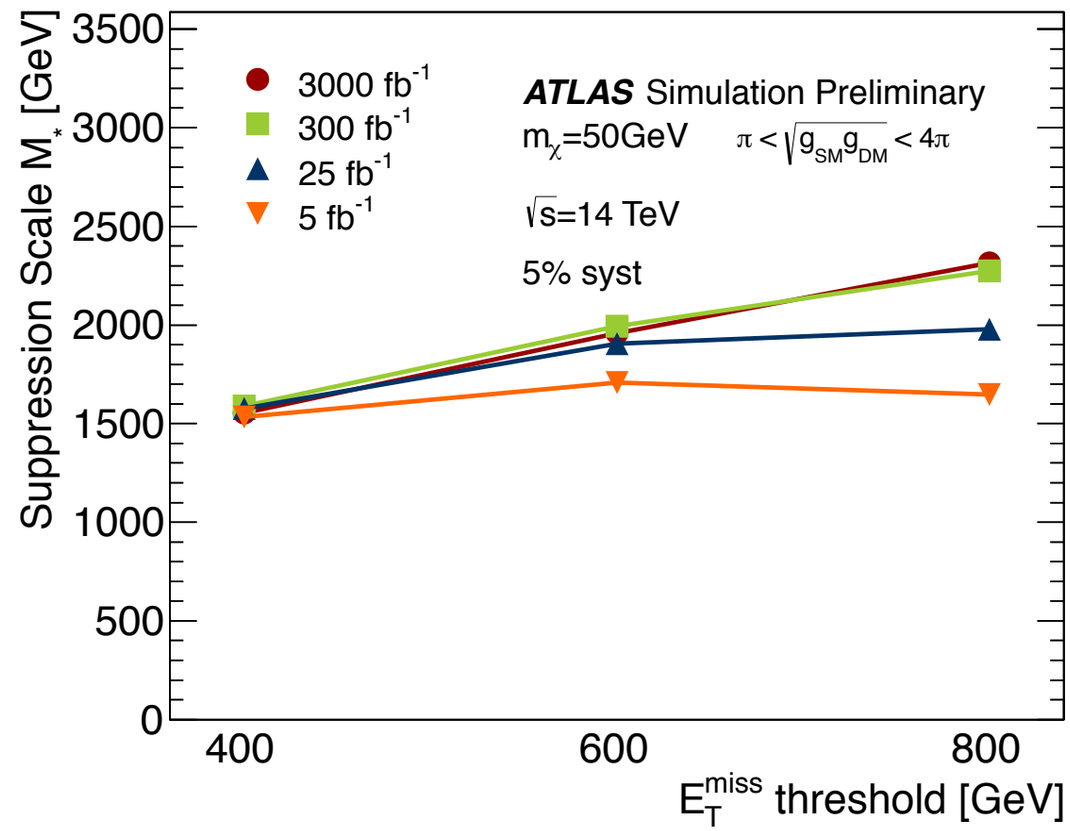


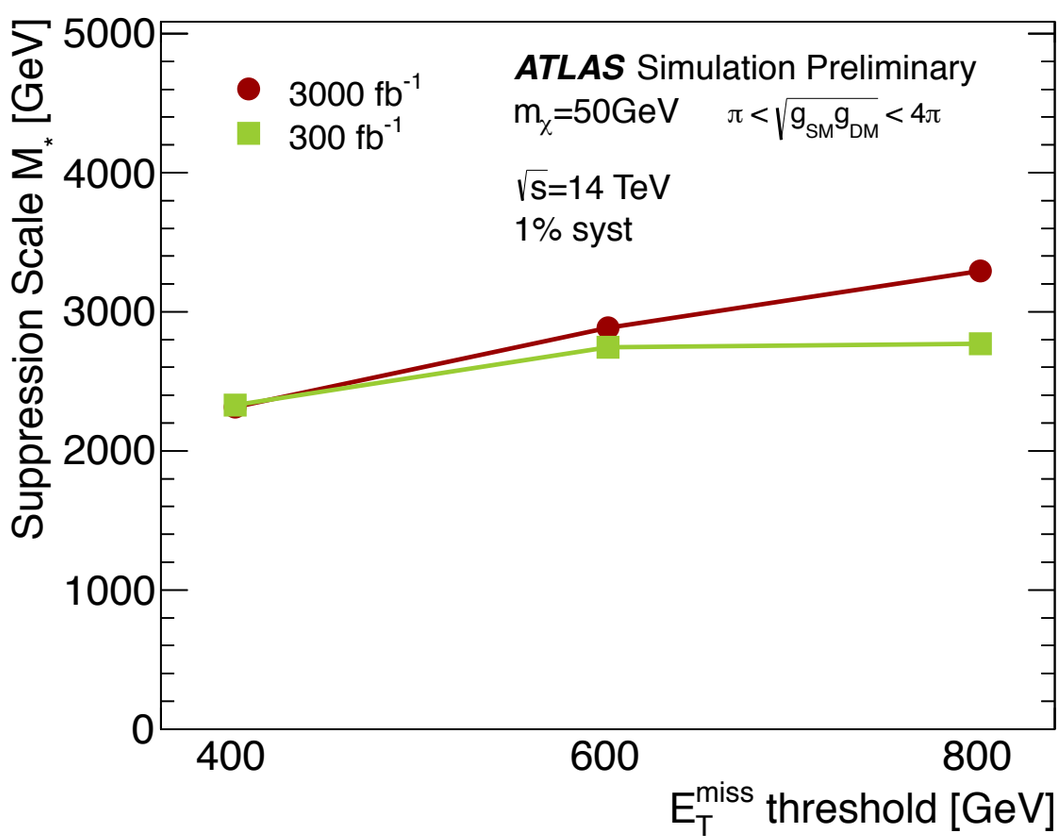



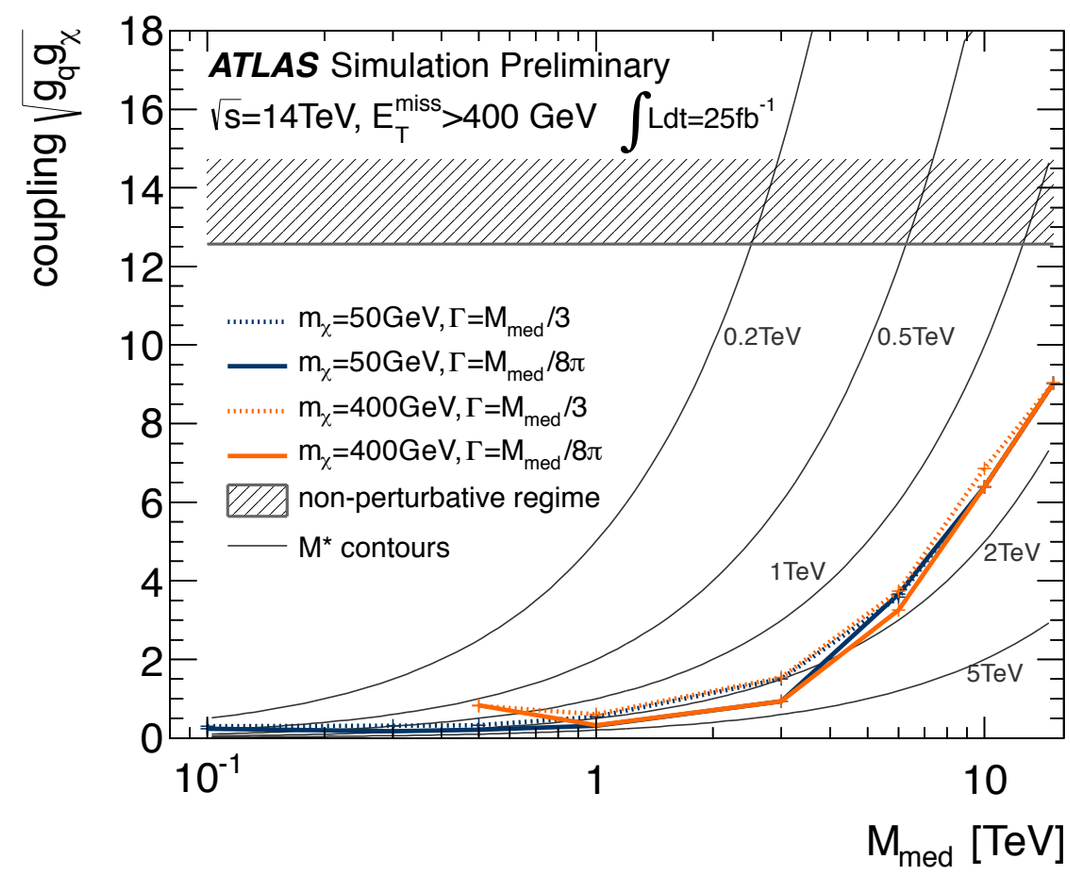
# Early Mono-jet Sensitivity Projections (14 TeV)

ATL-PHYS-PUB-2014-007



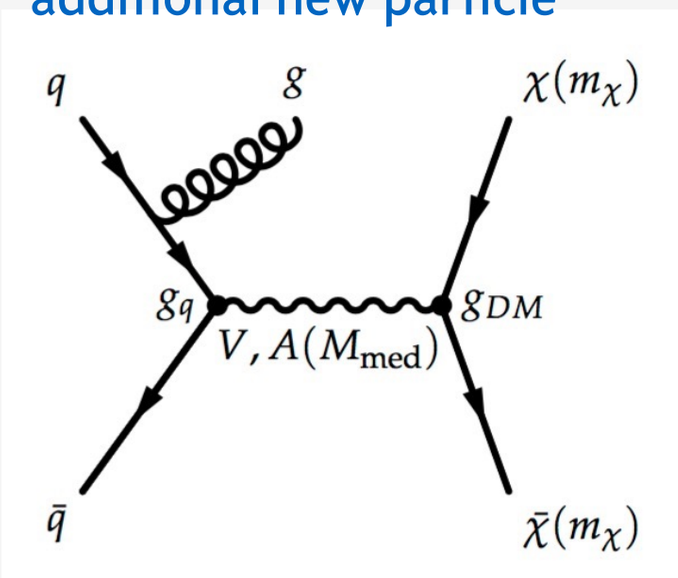



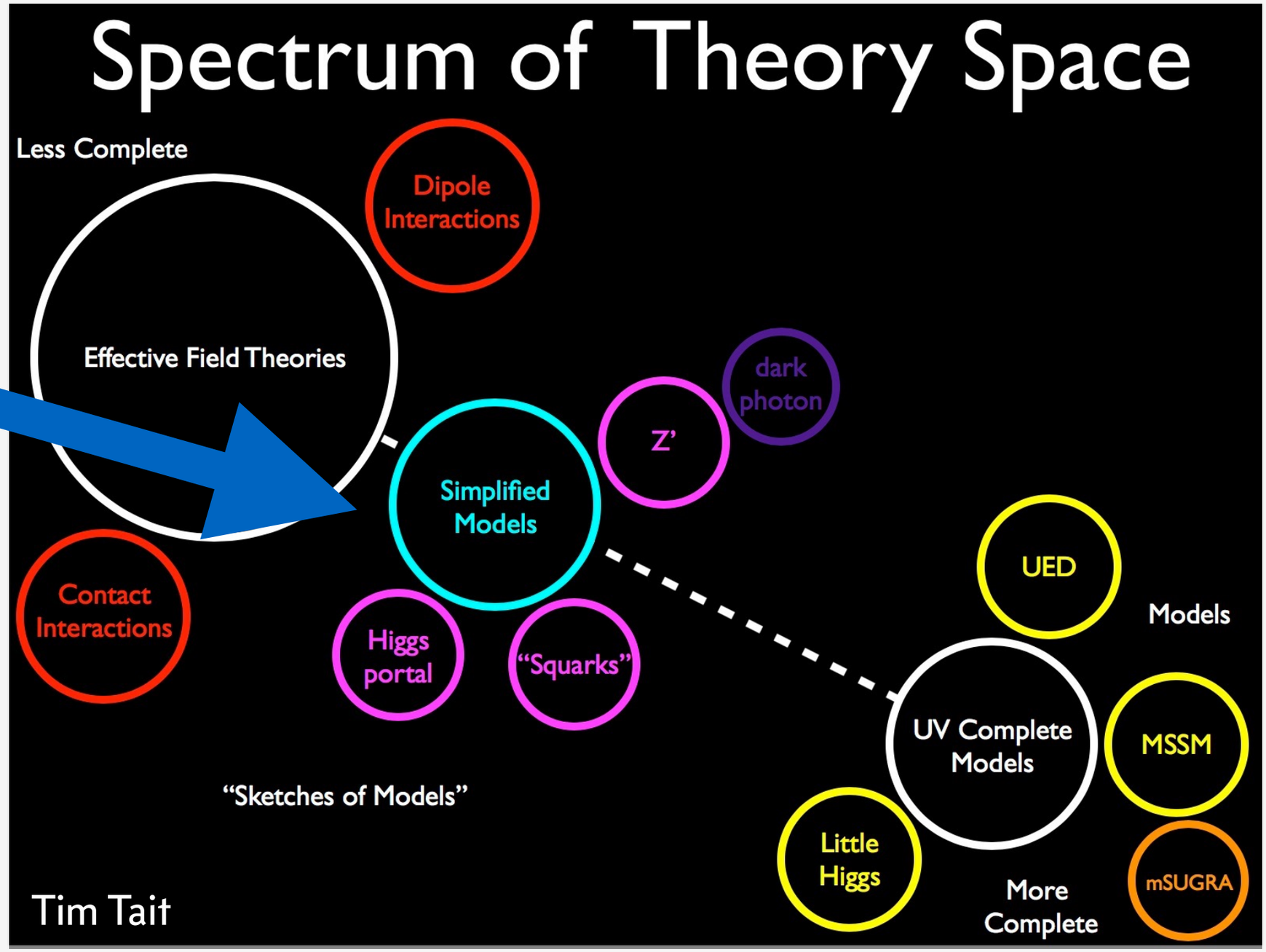

Run 1 equivalent roughly follows the 1 TeV contour

## Remember earlier?

Move to a larger set of more complex models:

SM-DM interaction mediated by SM particles (heavily constrained except for Higgs) or an additional new particle



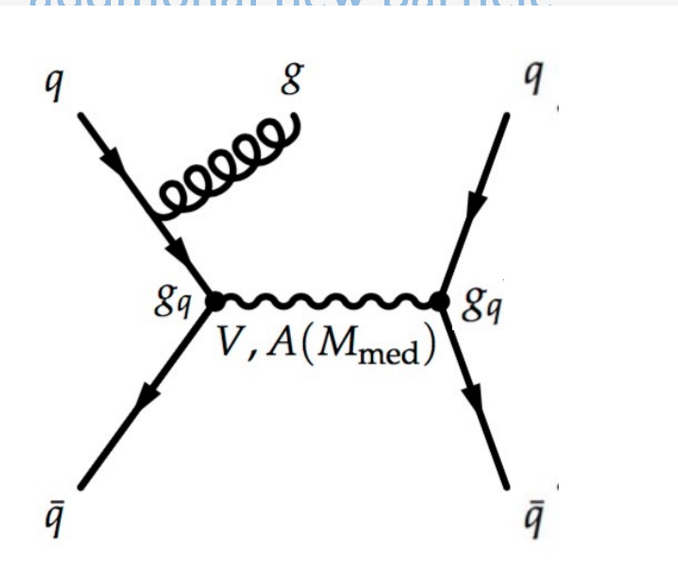

But this change opens up a much richer set of possibilities

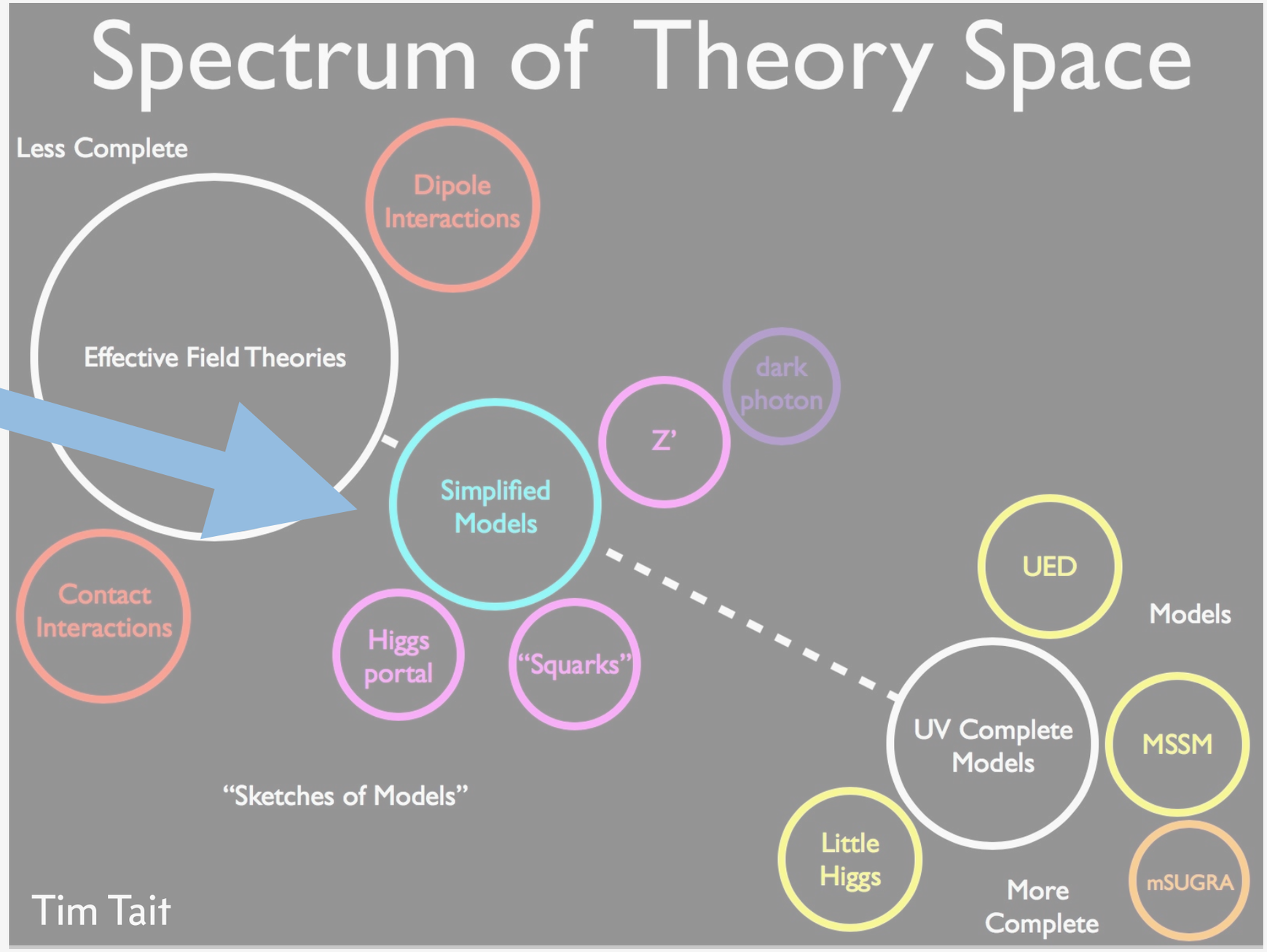
*"It is the production and* ***the role of the mediator particle(s) which is of key importance*** *in the collider searches for dark sectors; the actual dark matter is a derivative."*
*—Phys. Rev. D 91, 055009 (2015)*

# Remember earlier?

Move to a larger set of more complex models:

SM-DM interaction mediated by SM particles (heavily constrained except for Higgs) or an additional new particle




But this change opens up a much richer set of possibilities

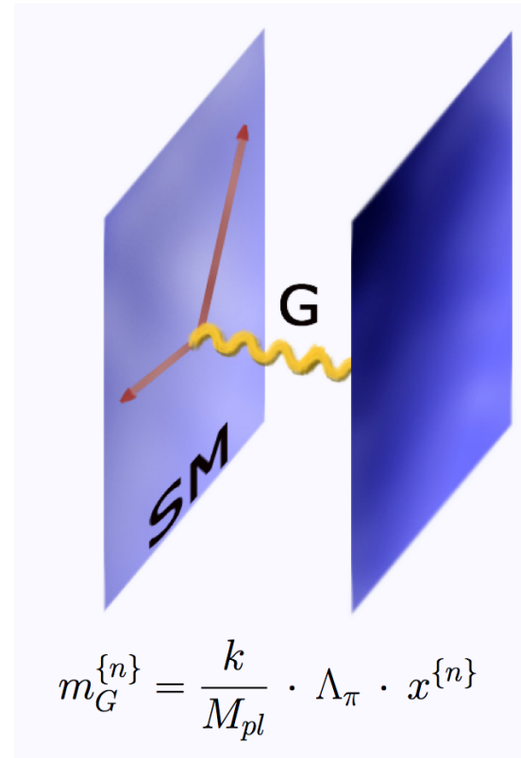
*"It is the production and* ***the role of the mediator particle(s) which is of key importance*** *in the collider searches for dark sectors; the actual dark matter is a derivative."*
*—Phys. Rev. D 91, 055009 (2015)*

# Searches for dijets

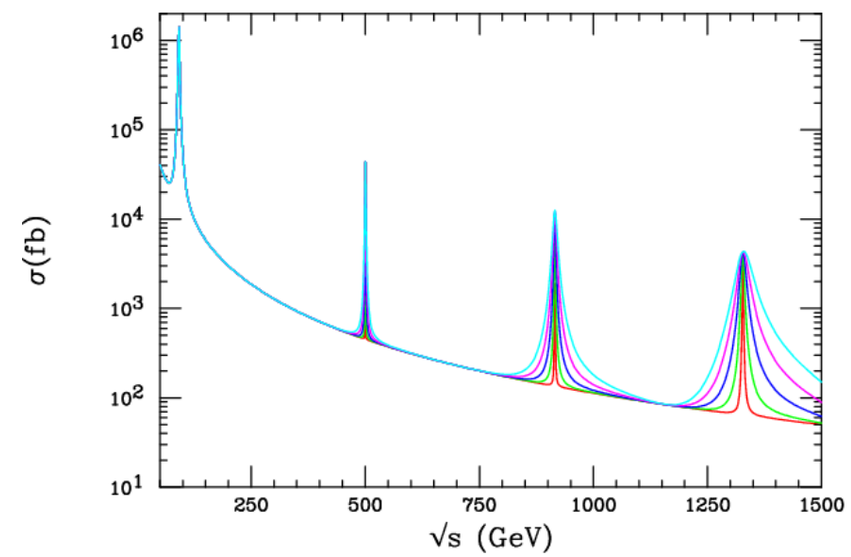
Dijet signals are already plentiful in the SM, and in many other BSM models

Broken extended gauge symmetries, chiral color, axigluons, quantum black holes, KK bosons, composite quarks, …

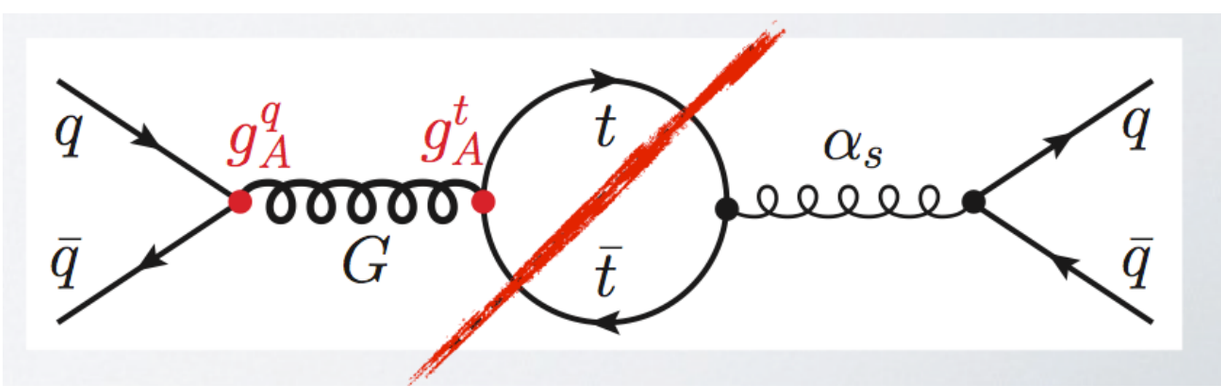
For an excellent review of dijet searches, see Harris & Kousouris, Int. J. Mod. Phys. A26:5005-5055, 2011




$$m_G^{\{n\}} = \frac{k}{M_{pl}} \cdot \Lambda_\pi \cdot x^{\{n\}}$$

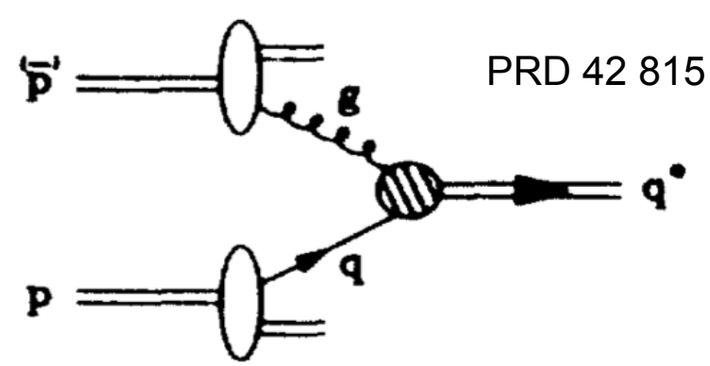



arXiv:1003.1698




$$\mathcal{L} = i g_s \bar{q}\, G^a_\mu T^a \gamma^\mu (g^q_V + \gamma_5 g^q_A)\, q$$

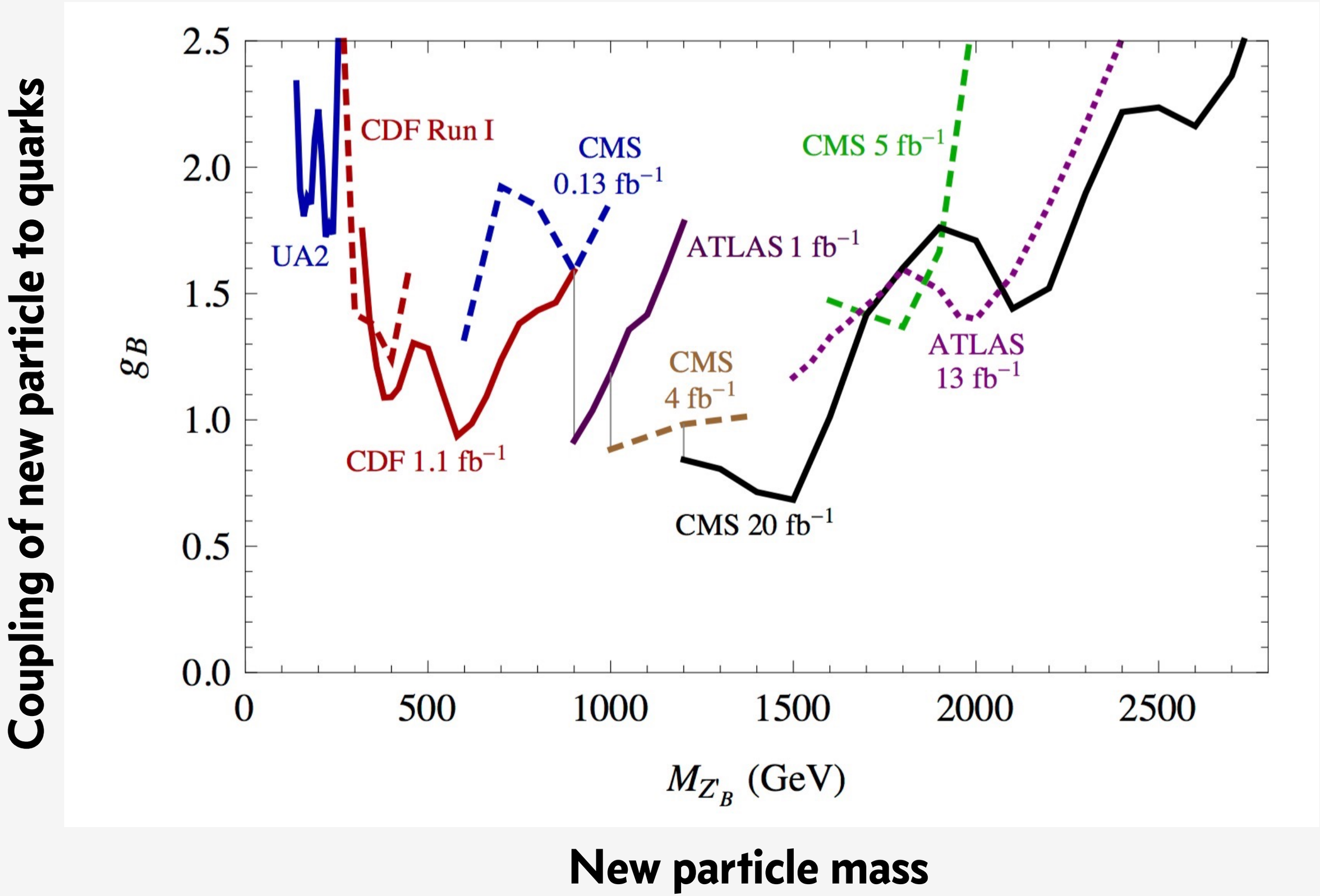
S. Westhoff, J. Shelton




PRD 42 815

# Coupling-Mass Plane for a Leptophobic Z' Model, circa 2013

Dobrescu, Yu **Phys.Rev. D88 (2013) 035021**



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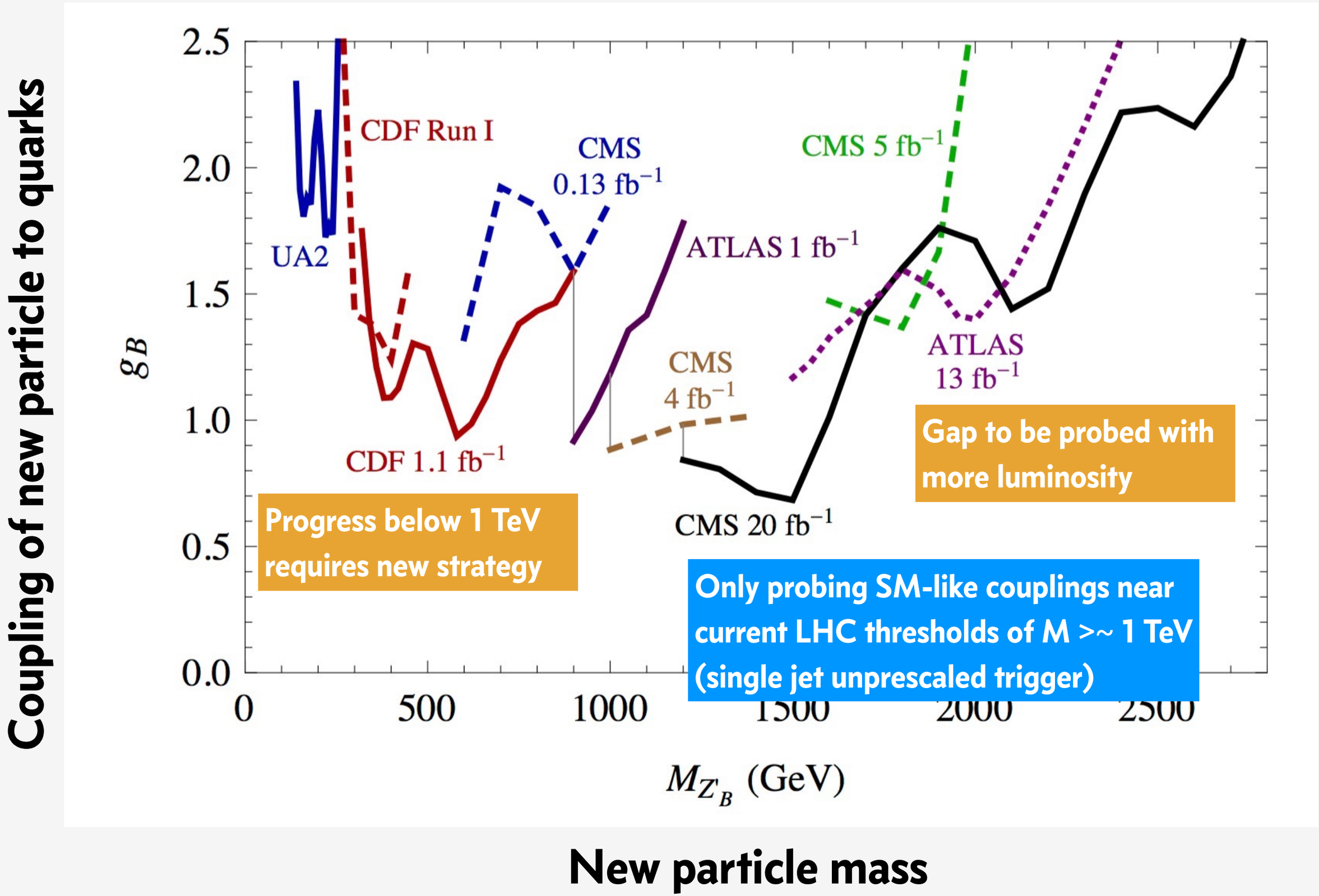



New particle mass

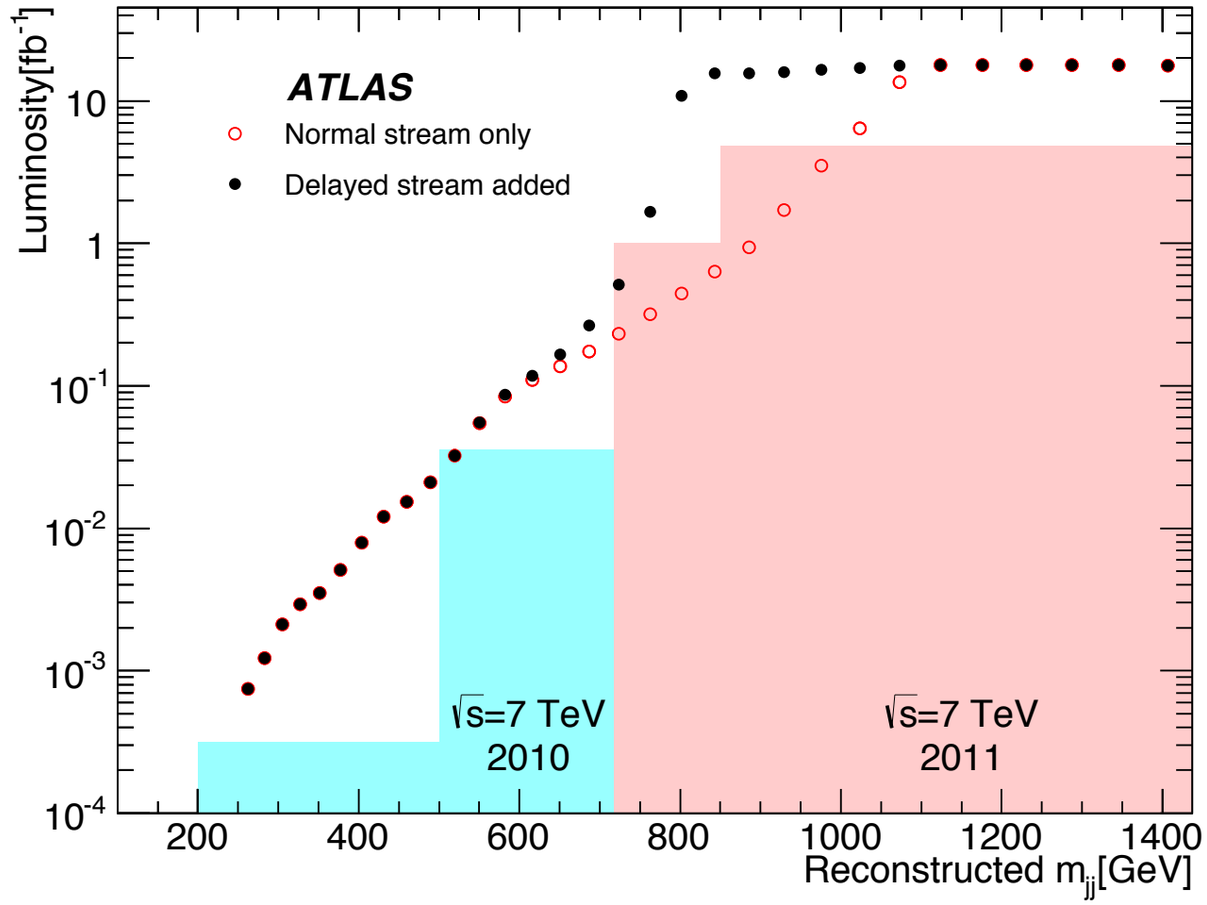
# ATLAS Strategy at 8 TeV

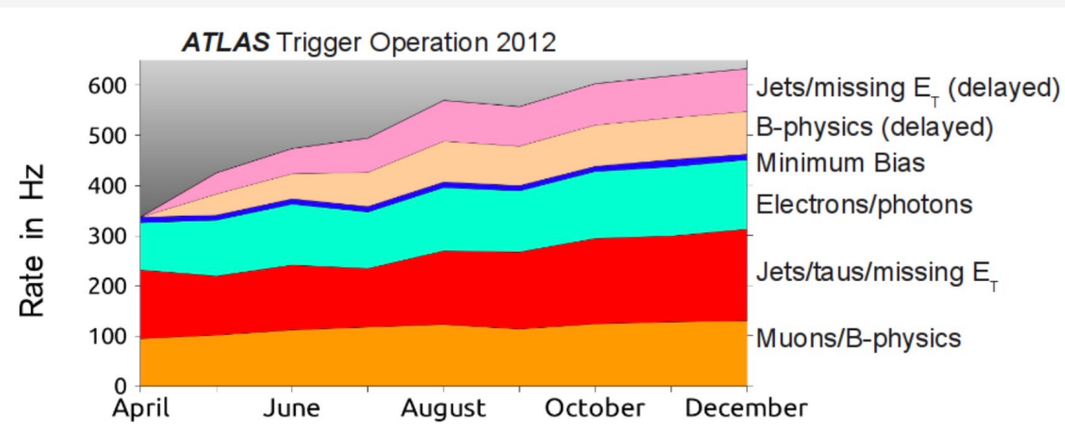
Roughly 2 years from 13/fb to 20/fb result! Why?

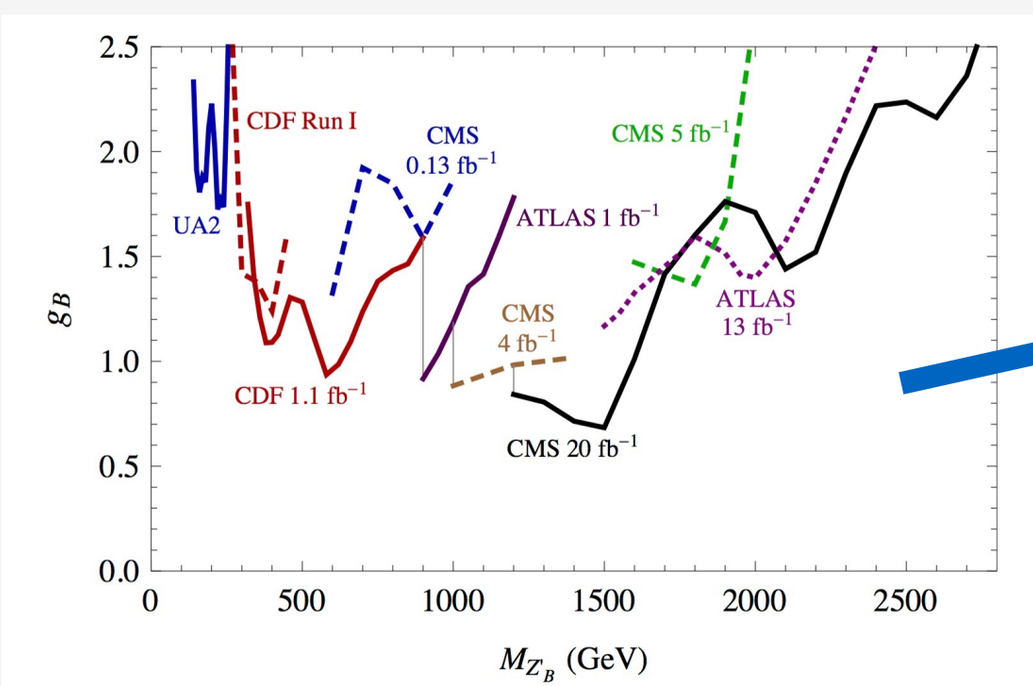
**Low mass was our primary focus**

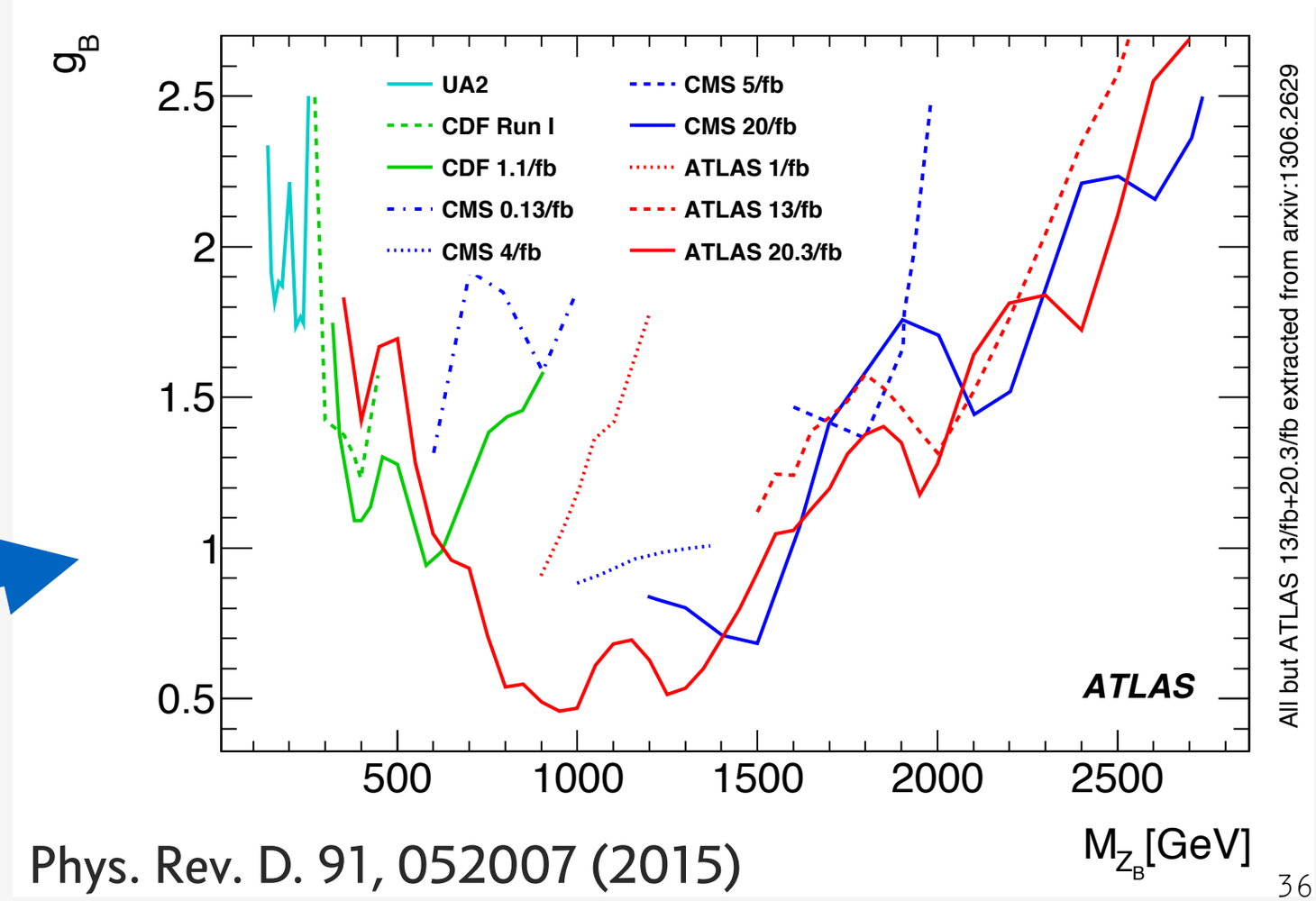
Combine all available prescaled single jet triggers

Reconstruct unprescaled but delayed (parked) events during LS1 shutdown



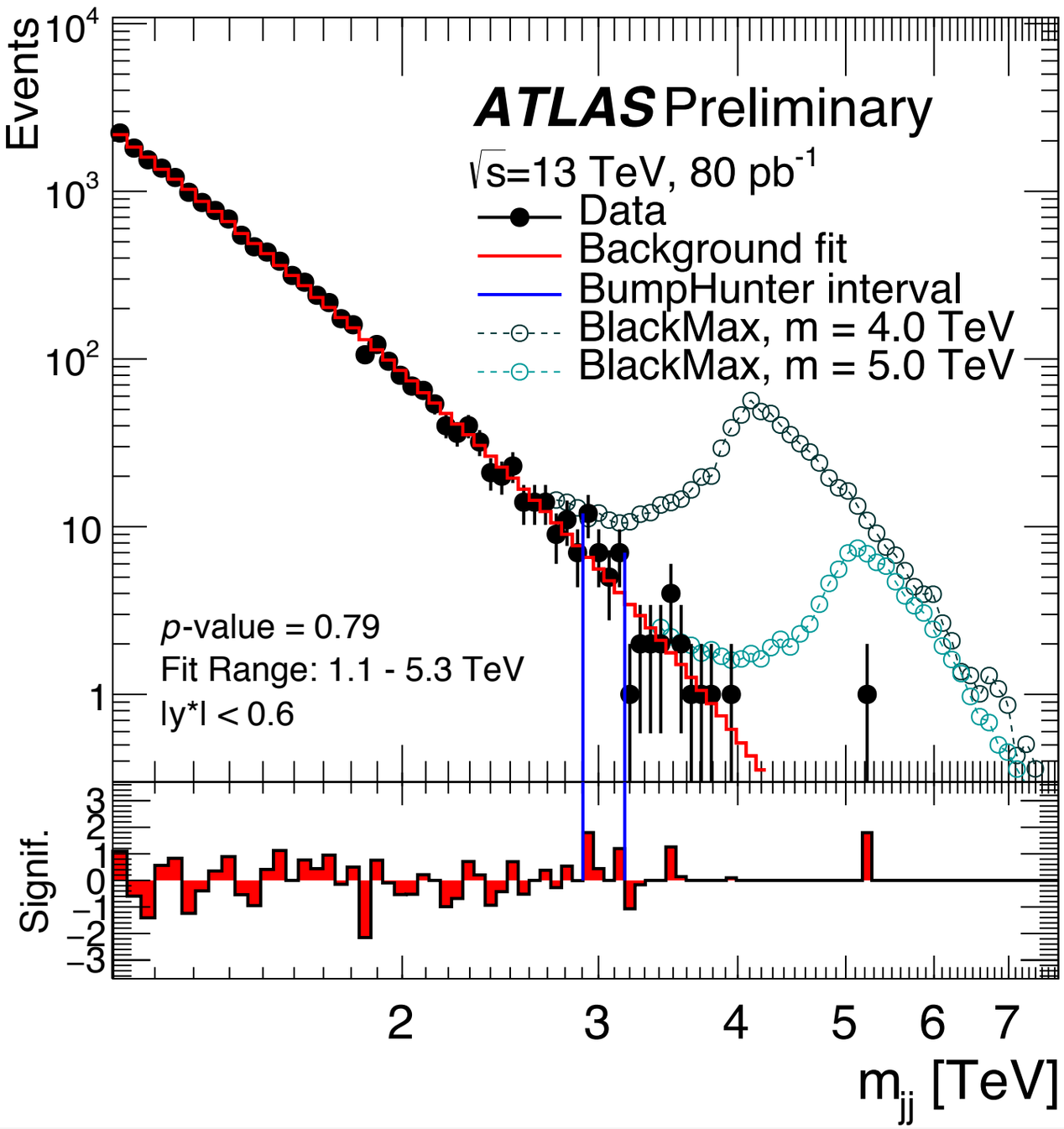




Phys. Rev. D. 91, 052007 (2015)

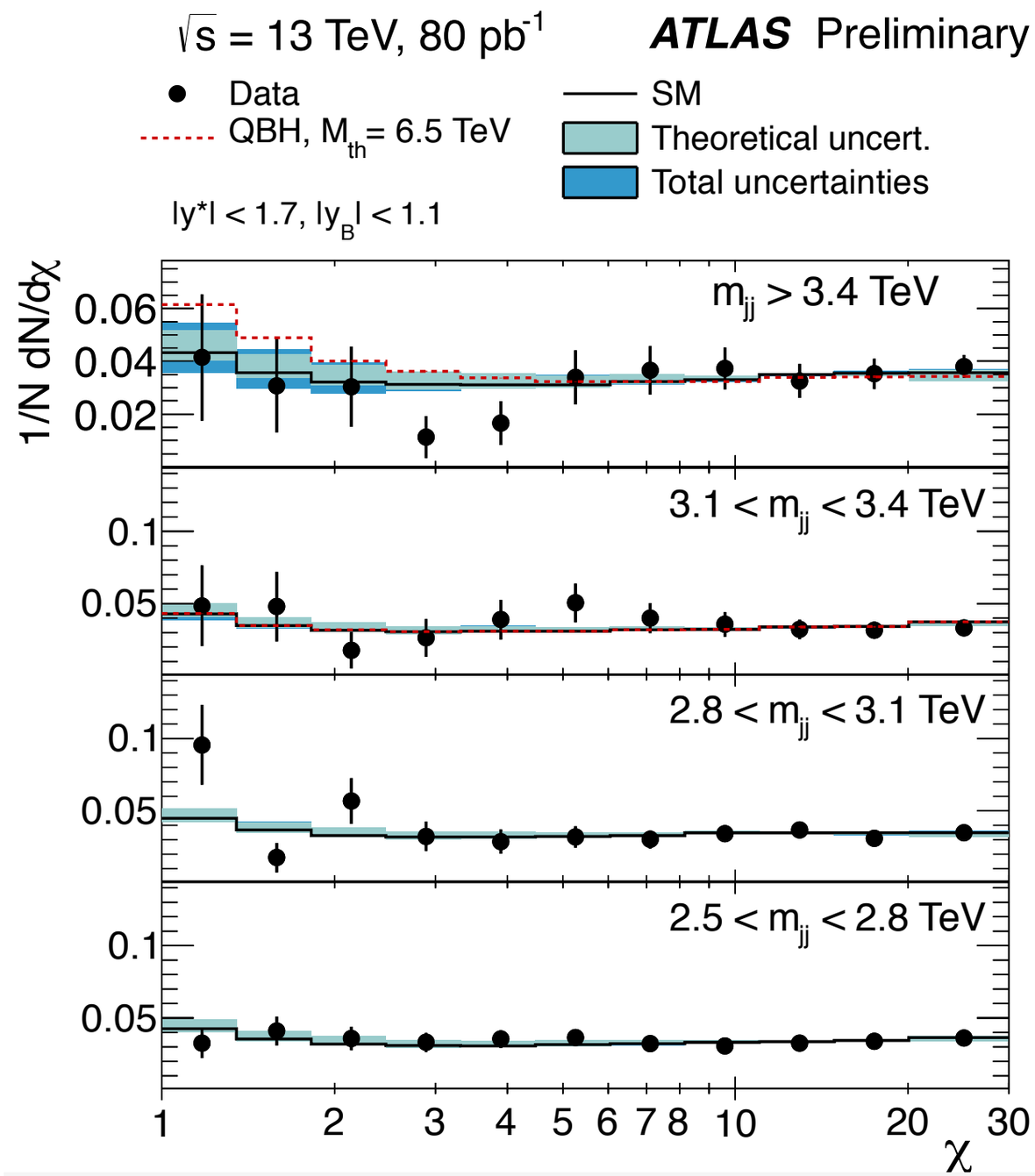
# ATLAS Dijets Searches at 13 TeV

ATLAS-CONF-2015-042

## Resonant analysis




## Non-resonant analysis



# ATLAS Dijets Searches at 13 TeV

ATLAS-CONF-2015-042

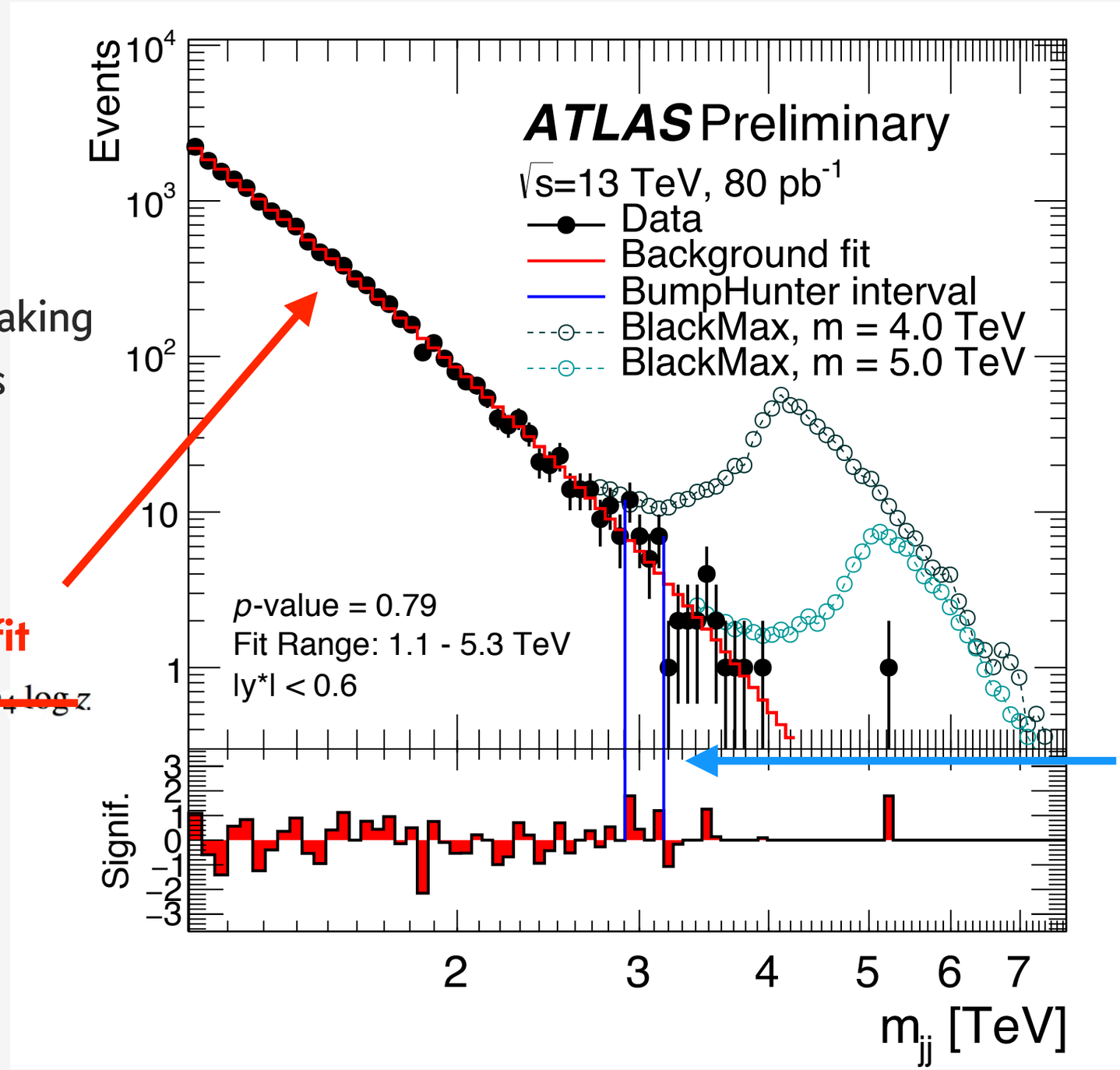
## Resonant analysis

Jet $p_T$ > 410, 50 GeV

$|y^*| = |y_1 - y_2|/2 < 0.6$

$m_{jj}$ > 1.1 TeV

y* cut rejects forward-peaking t-channel QCD processes




**Data-driven background fit**

$$f(z) = p_1(1-z)^{p_2} z^{p_3 + \cancel{p_4 \log z}}$$

**"BumpHunter" most discrepant region 2.91–3.17 TeV (global p-value 0.78)**

# ATLAS Dijets Searches at 13 TeV

ATLAS-CONF-2015-042

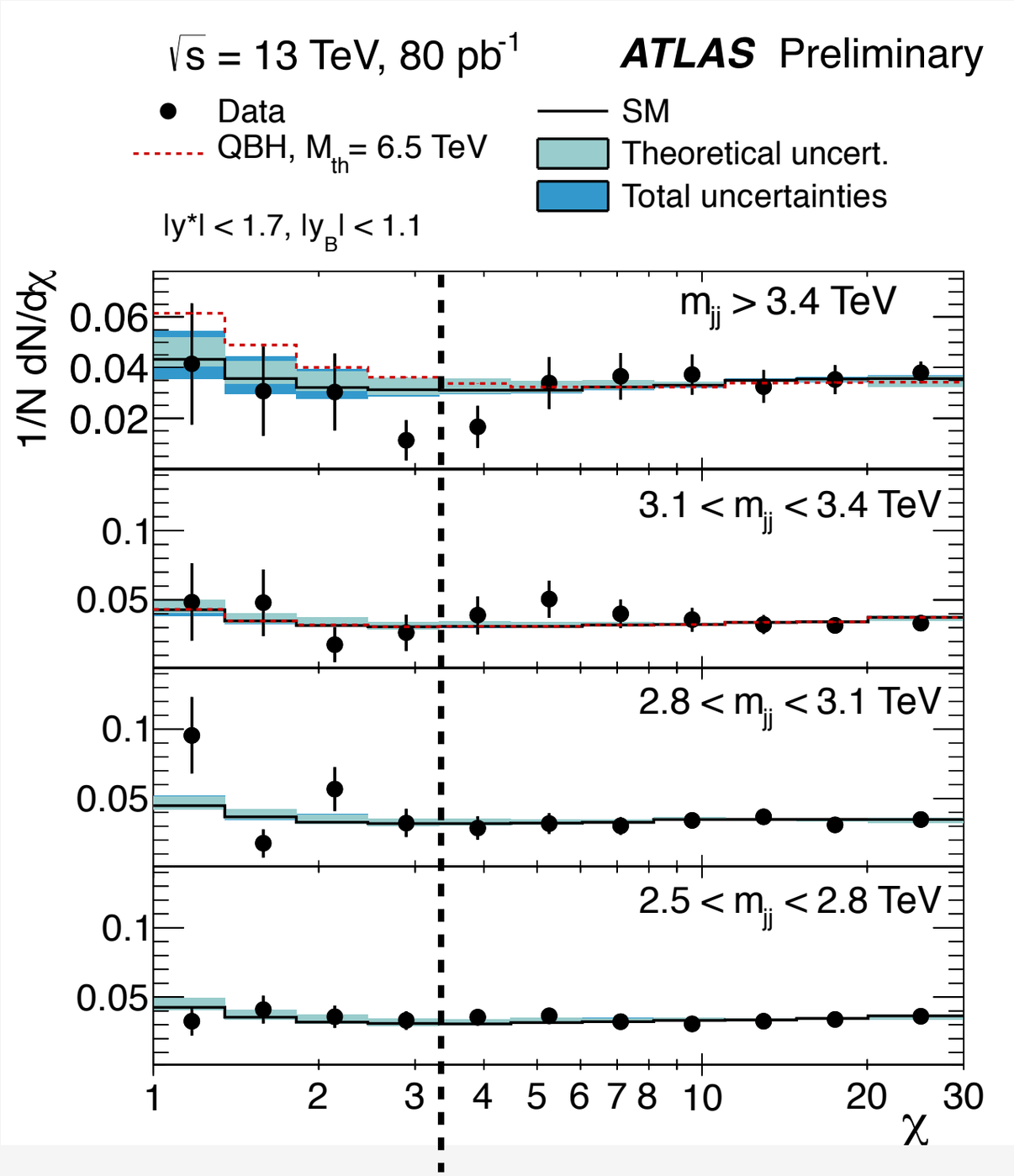
## "Non-resonant" analysis

Jet $p_T$ > 410, 50 GeV

**$|y^*| = |y_1 - y_2|/2 < 1.7$**

**$|y_B| = |y_1 + y_2|/2 < 1.1$**

**$m_{jj}$ > 2.5 TeV**




**$|y^*| = < 0.6$**

Shape comparison uses high y* region to confirm and normalize background prediction with forward-peaking t-channel QCD processes

**Background shape from NLOJet++ / Pythia 8 with electroweak corrections**

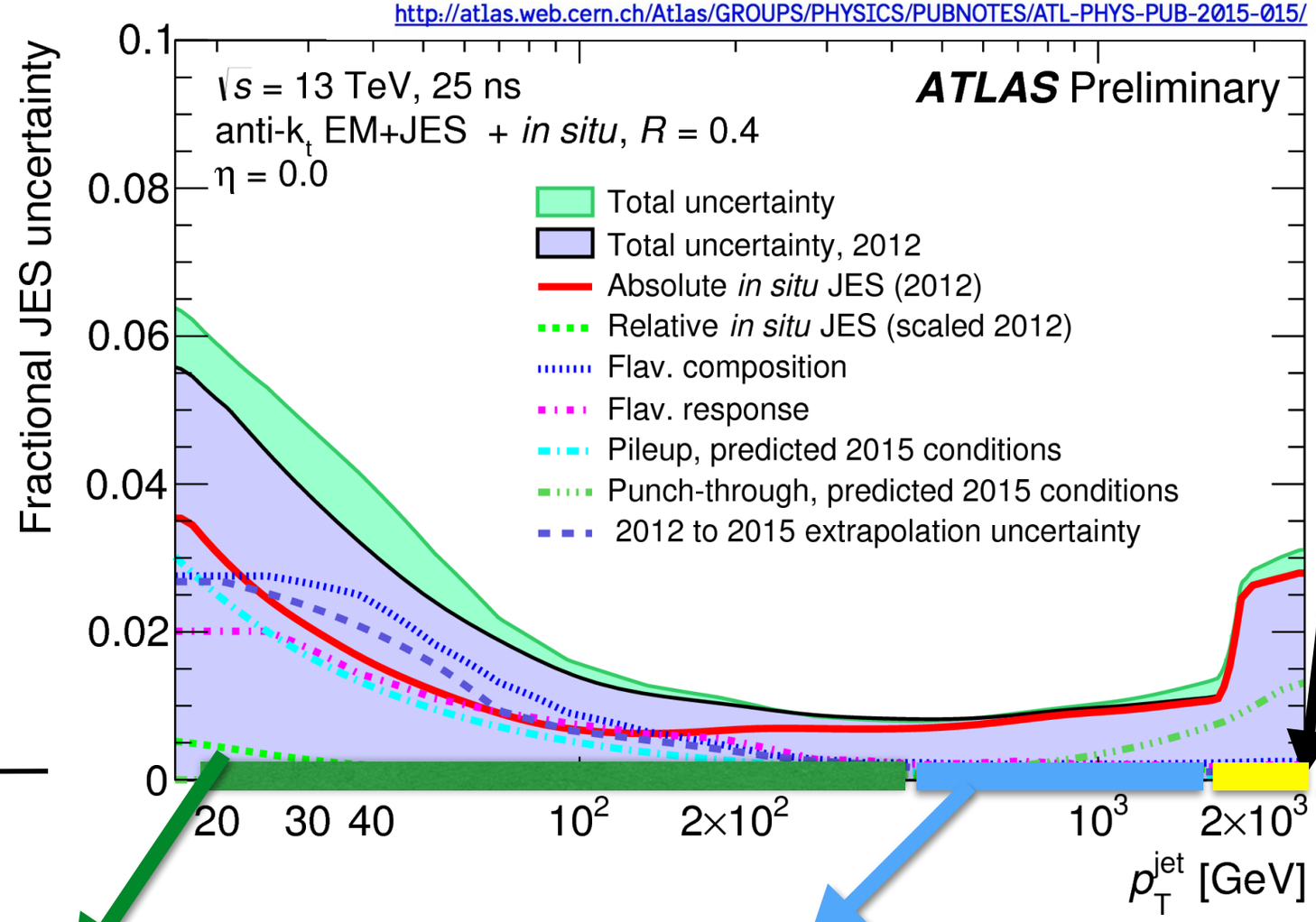
$$k(\chi, m_{jj}) = \frac{\sigma_{\mathrm{NLO}}(\chi, m_{jj})^{\mathrm{NLOJET++}}}{\sigma_{\mathrm{LO+shower}}(\chi, m_{jj})^{\mathrm{Pythia\ 8}}}$$

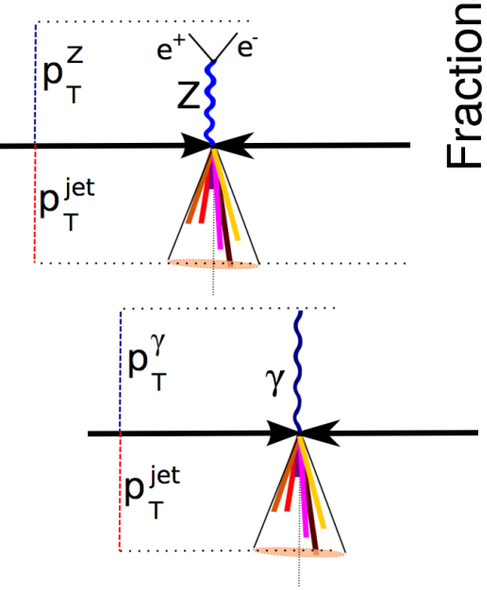
**At high mass, low chi:**
**NLO: up to 15%**
**EW: up to 3%**

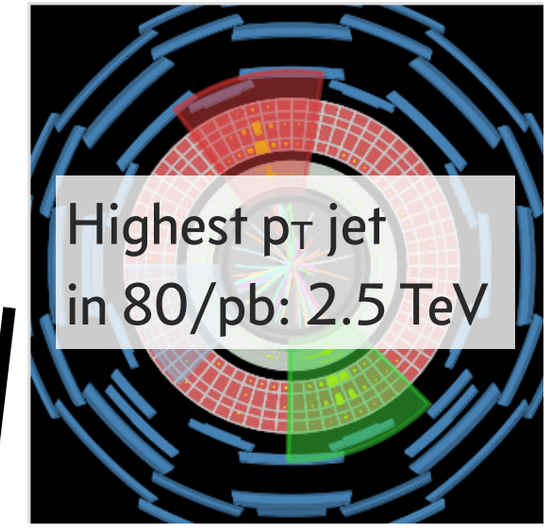
**chi$^2$ prob. 0.57**

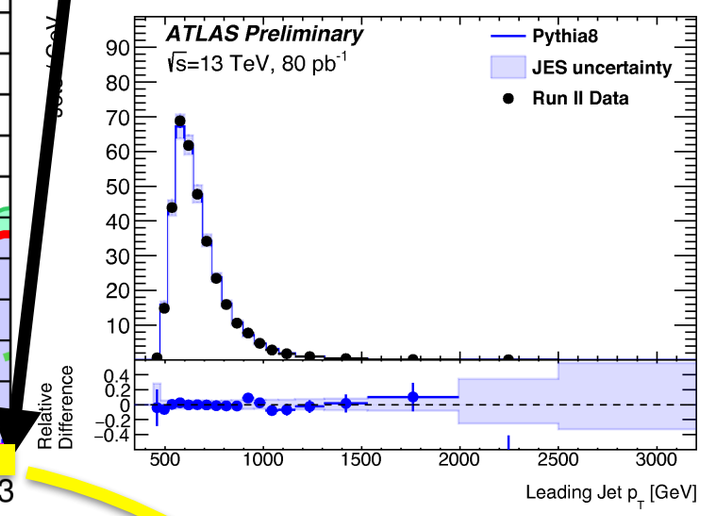
# Jet calibration and uncertainty

http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2015-015/

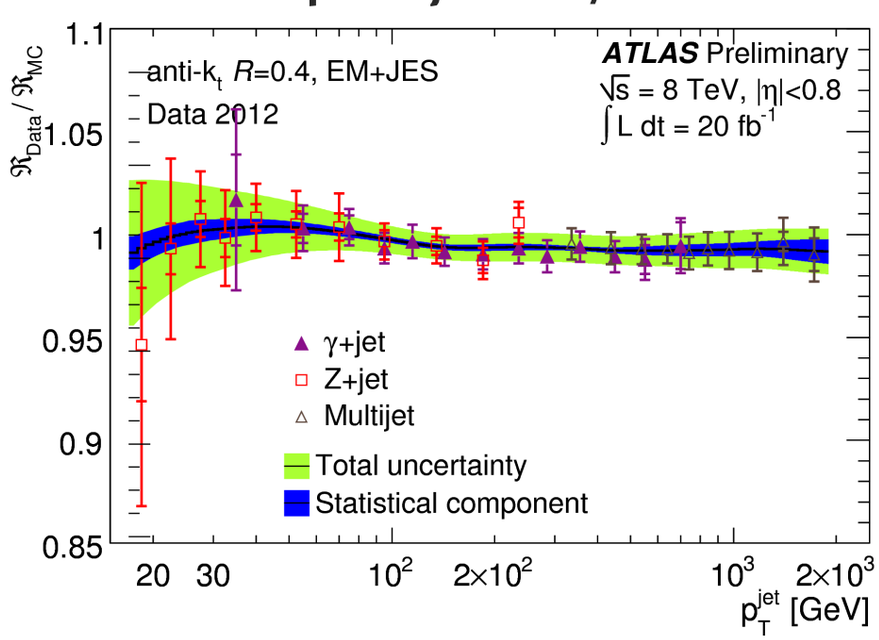


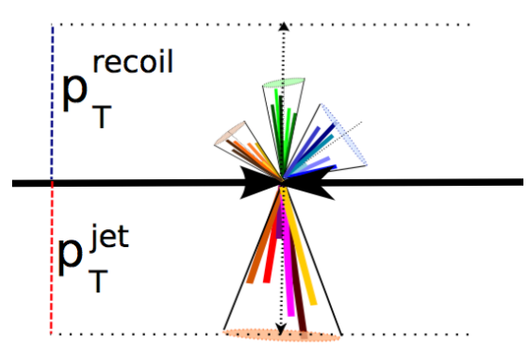



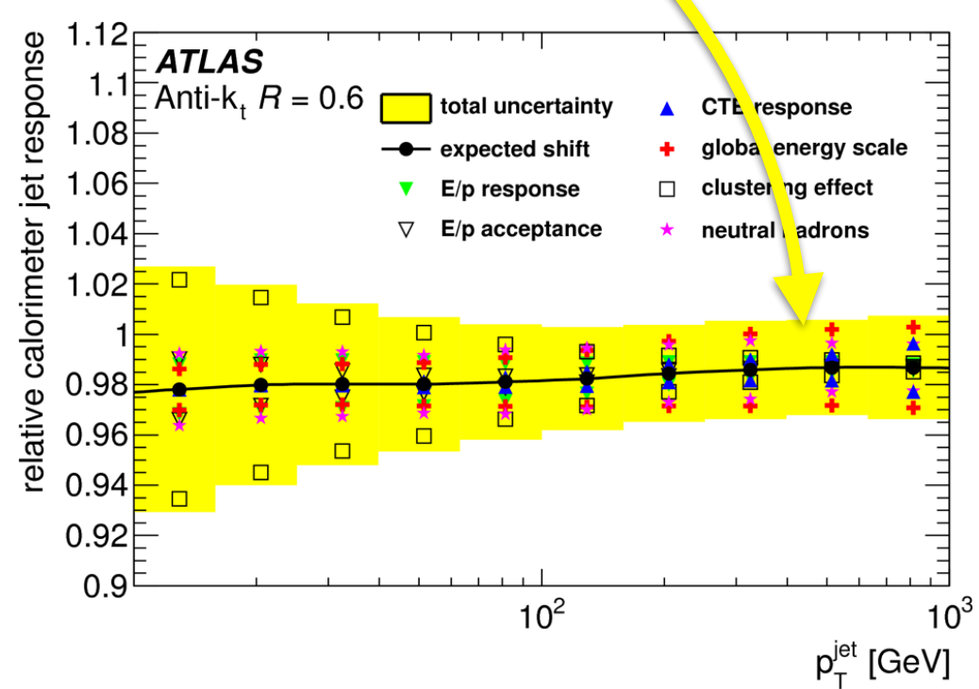

**Well-calibrated object vs probe jet: data/MC**

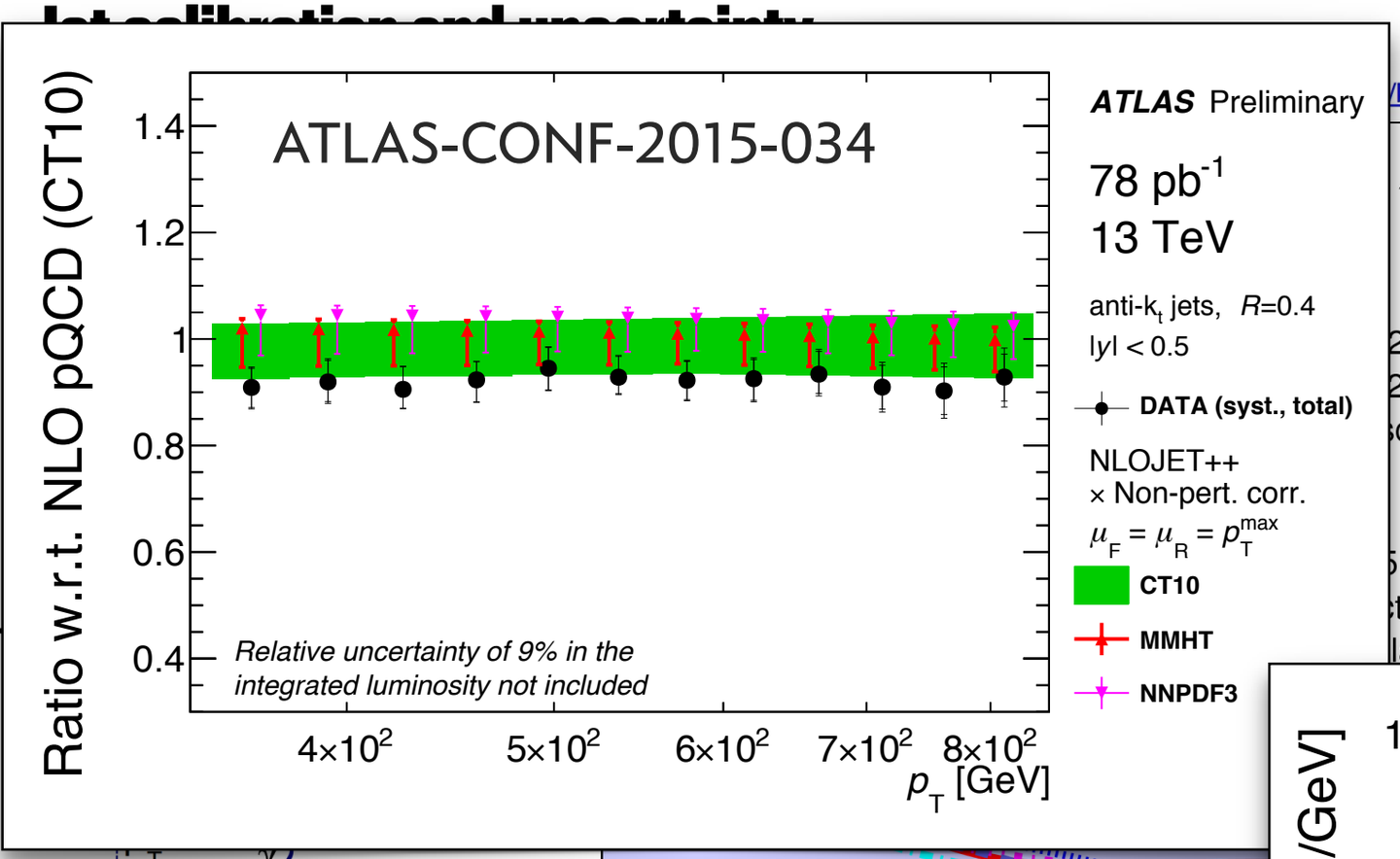


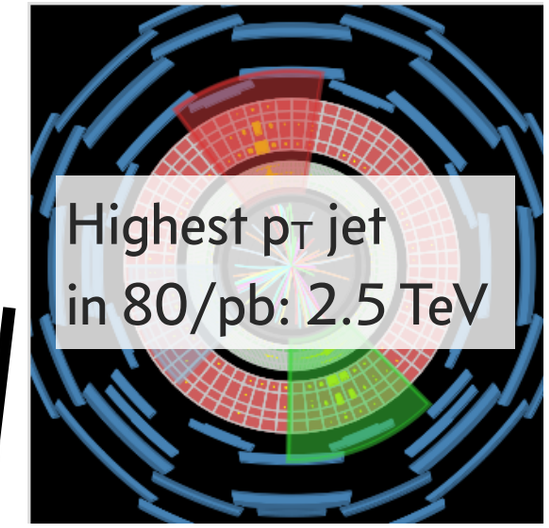

**Balance of high-pT jet with calibrated low-pT recoil system**

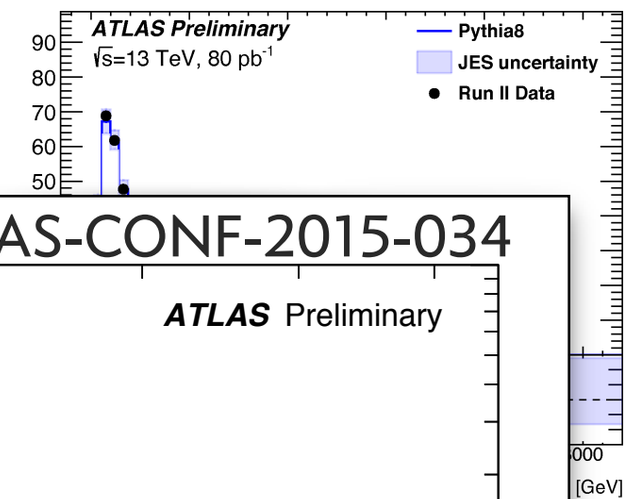


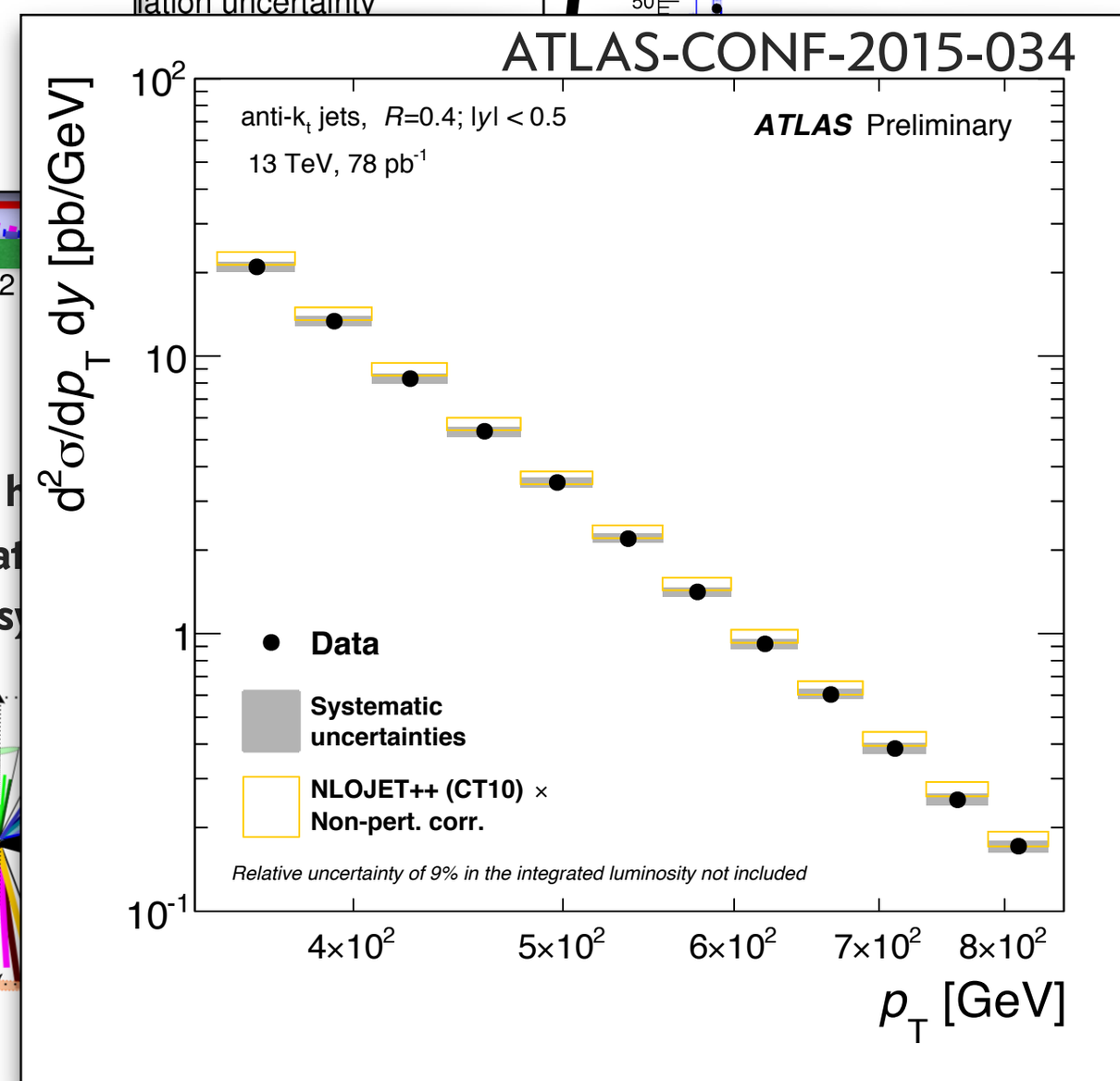

**Propagation of single particle uncertainties to jets**

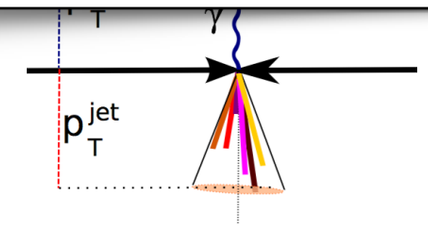




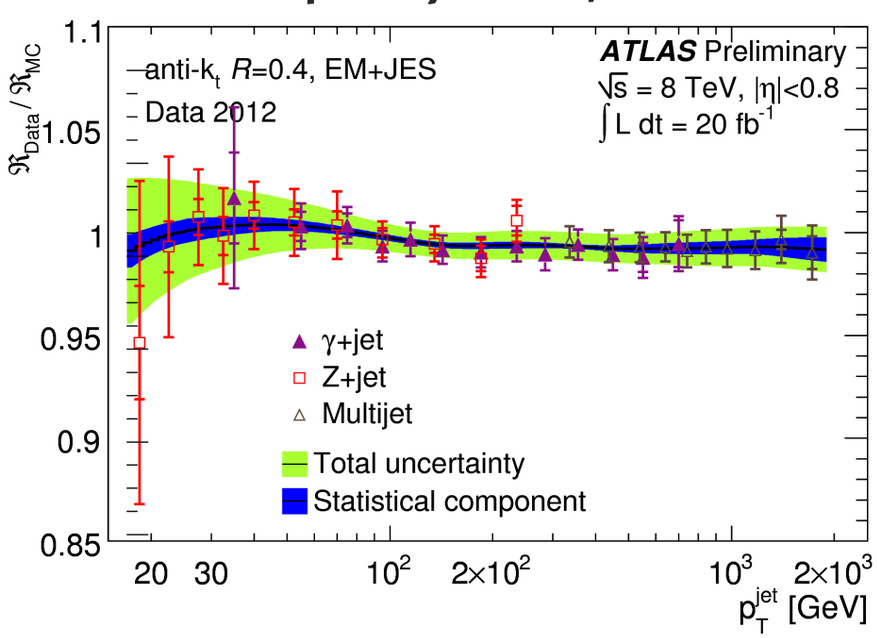



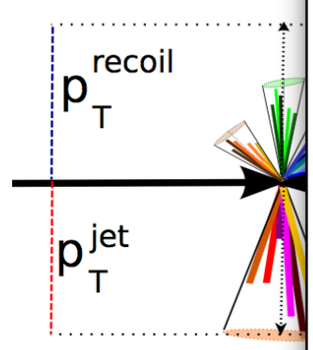




Well-calibrated object
vs probe jet: data/MC



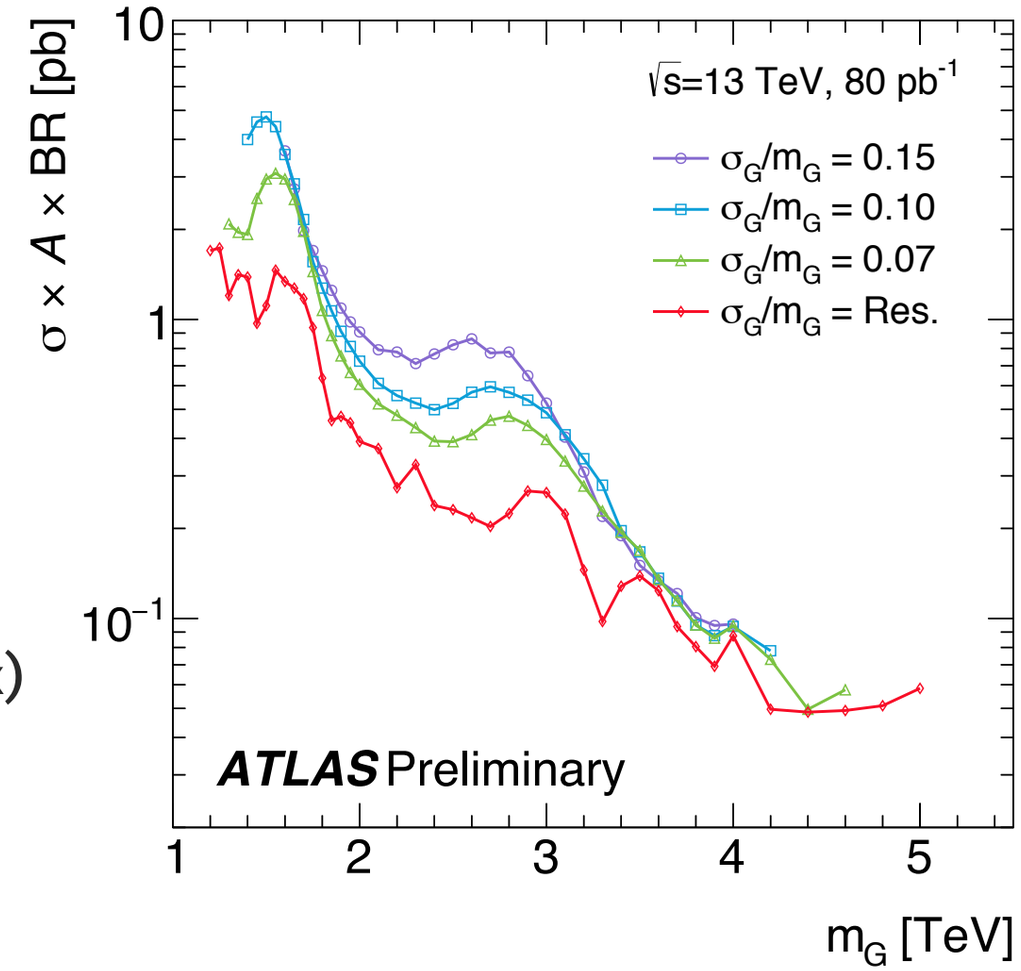

Balance of h
with calibrat
recoil sy

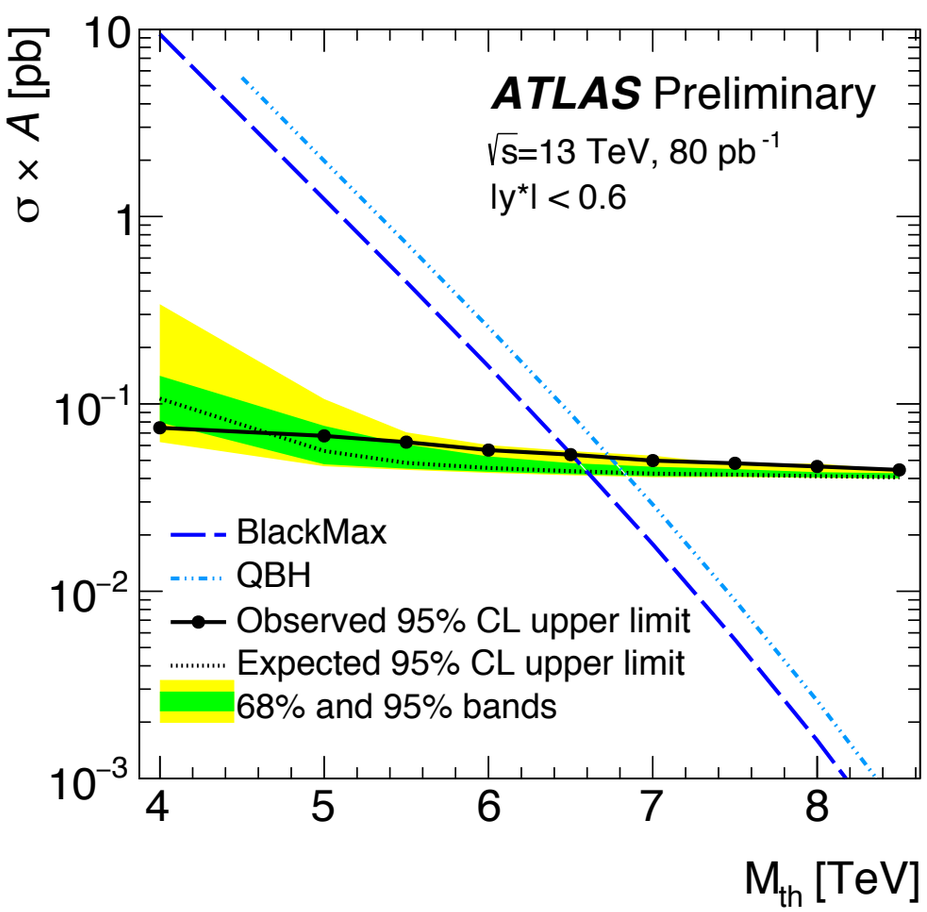


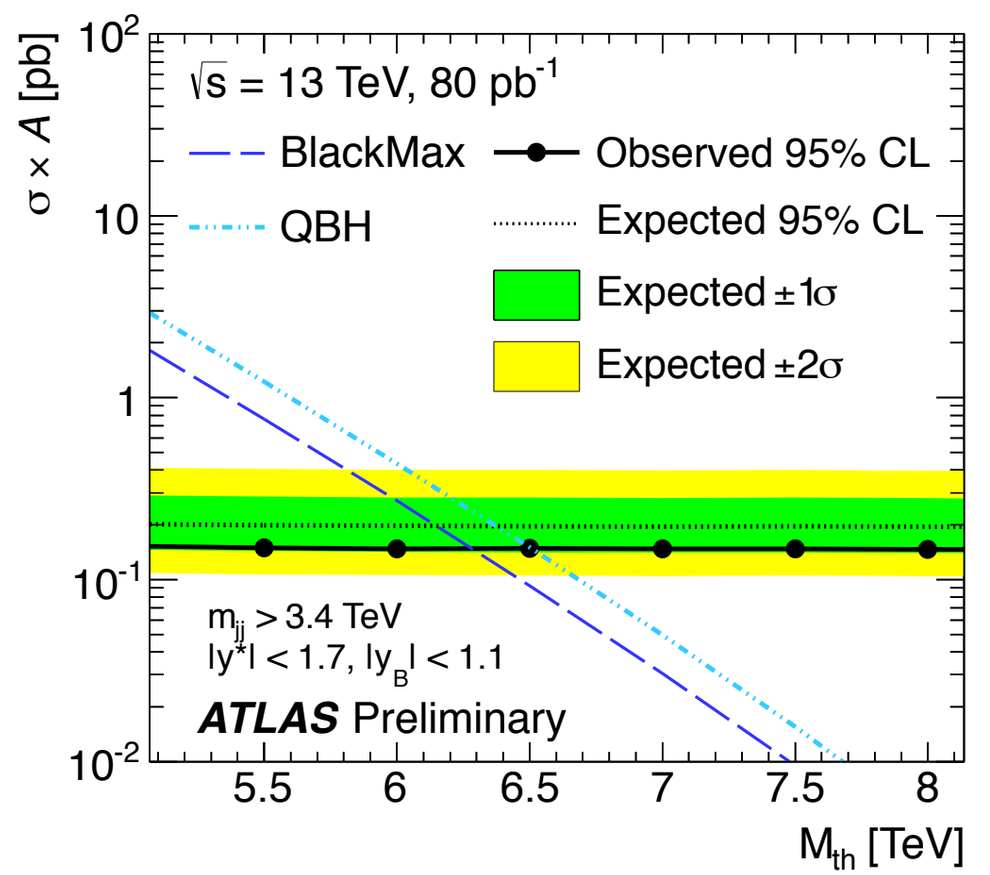
# ATLAS 13 TeV Dijet Limits, 80/pb

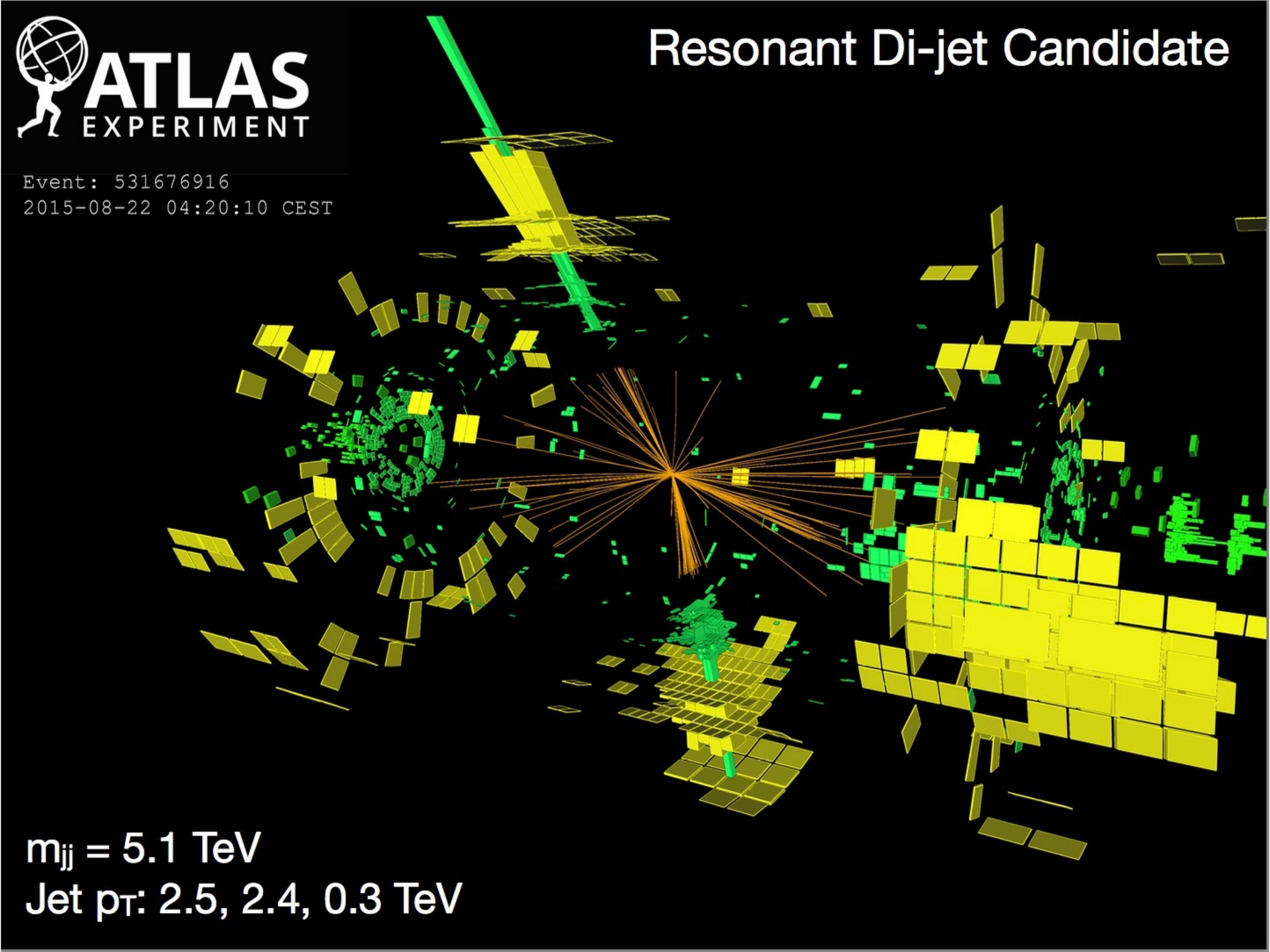
Limits on:

- Gaussian contribution to the $m_{jj}$ distribution
- Two ADD quantum black hole models
  ($n = 6$ and $M_D = M_{th}$)
  Limits are $M_{th} > 6.8$ or 6.5 TeV (QBH or BlackMax)
  Run 1 limits were 5.6–5.7 TeV.

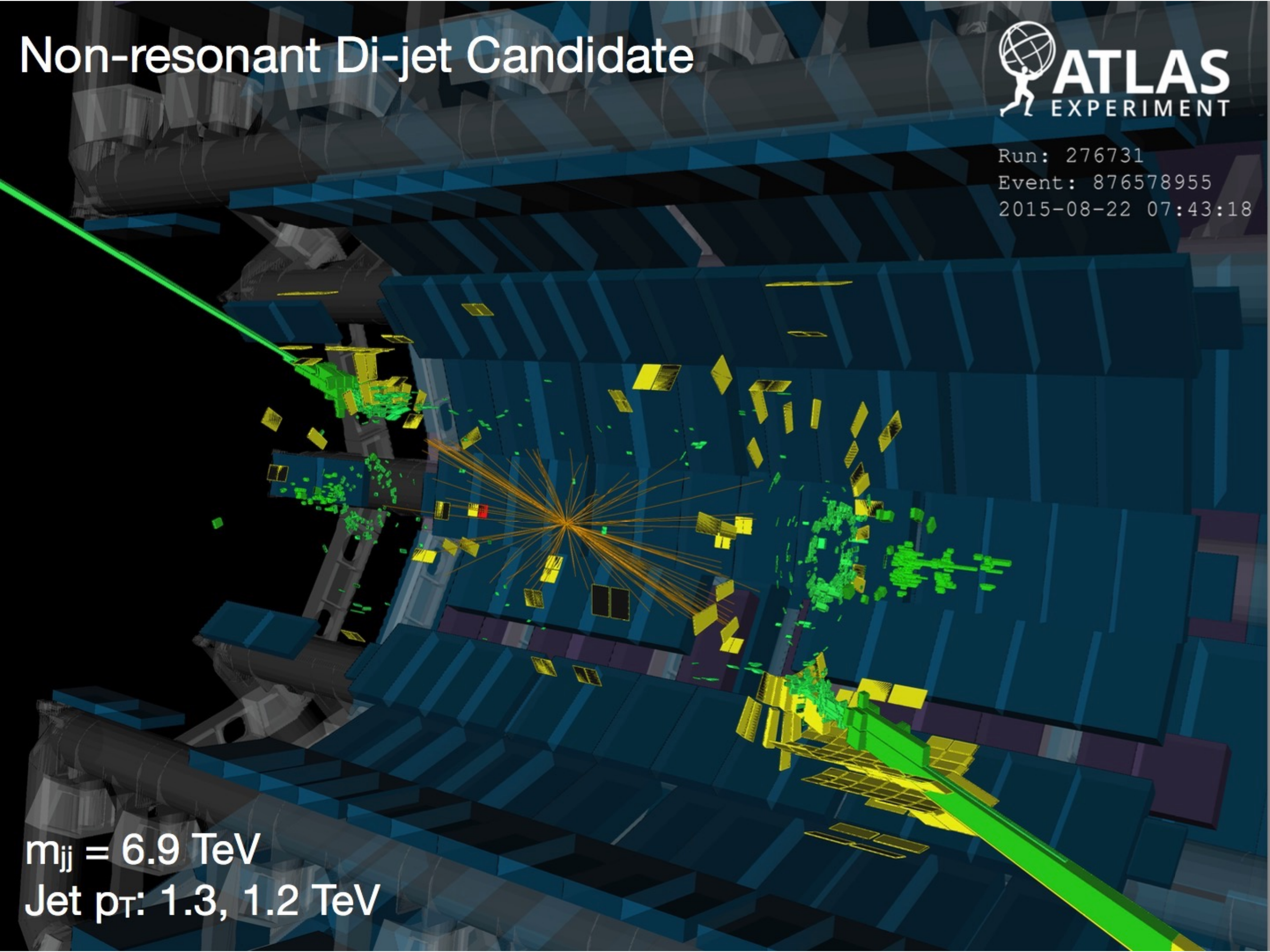



ATLAS
EXPERIMENT
Resonant Di-jet Candidate
Event: 531676916
2015-08-22 04:20:10 CEST
$m_{jj}$ = 5.1 TeV
Jet $p_T$: 2.5, 2.4, 0.3 TeV

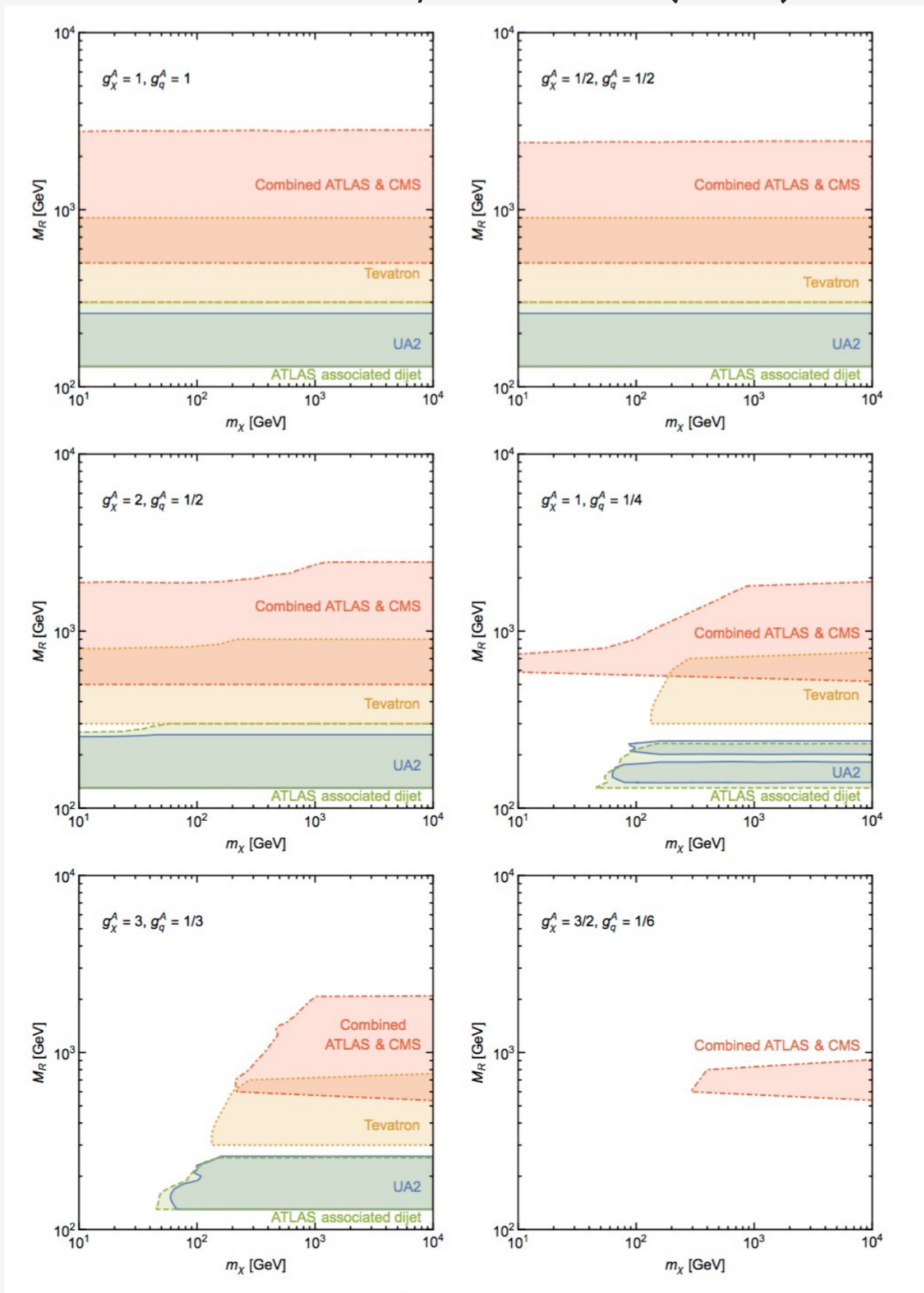
# Non-resonant Di-jet Candidate

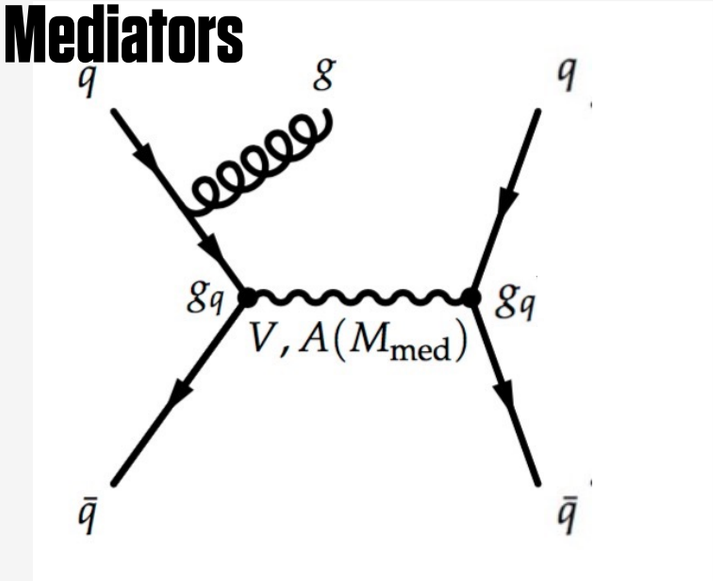



$m_{jj}$ = 6.9 TeV
Jet $p_T$: 1.3, 1.2 TeV

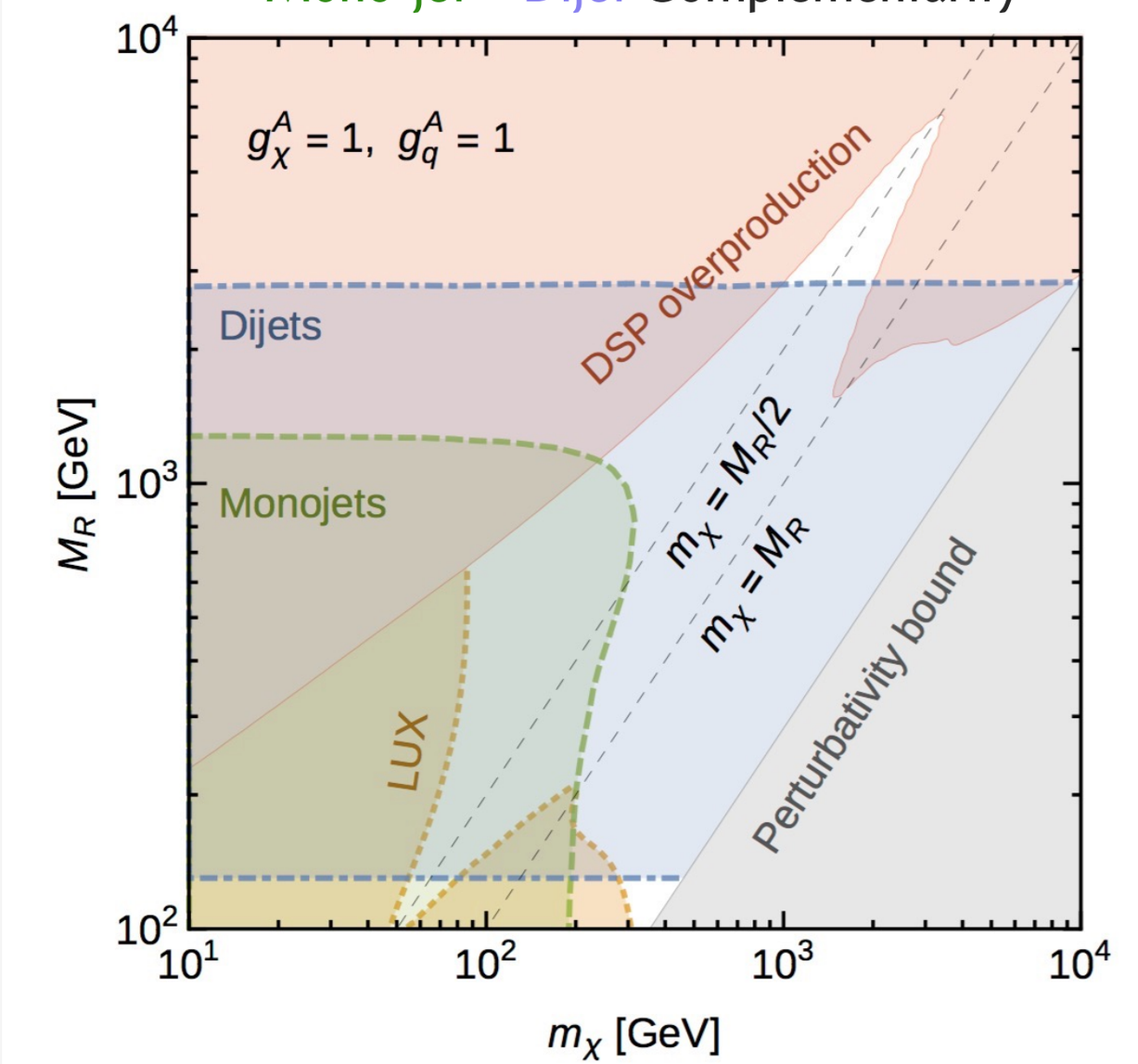
# Benefits of ATLAS/CMS Agreement on Models: Dijet Implications for SM-DM Mediators

Axial-Vector Z′, JHEP 1507 (2015) 089



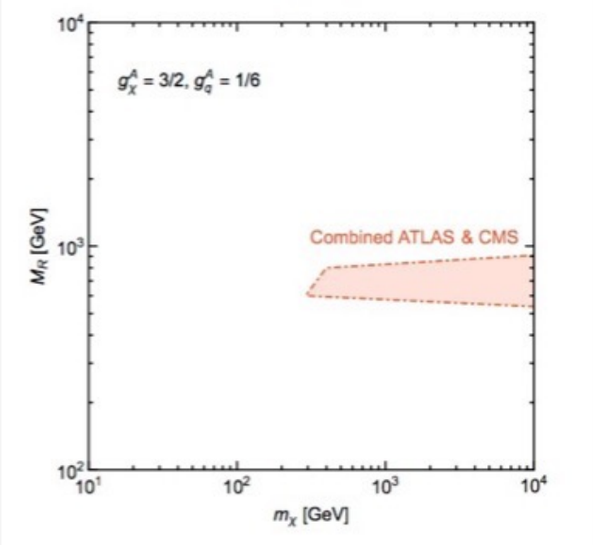




Mono-jet + Dijet Complementarity

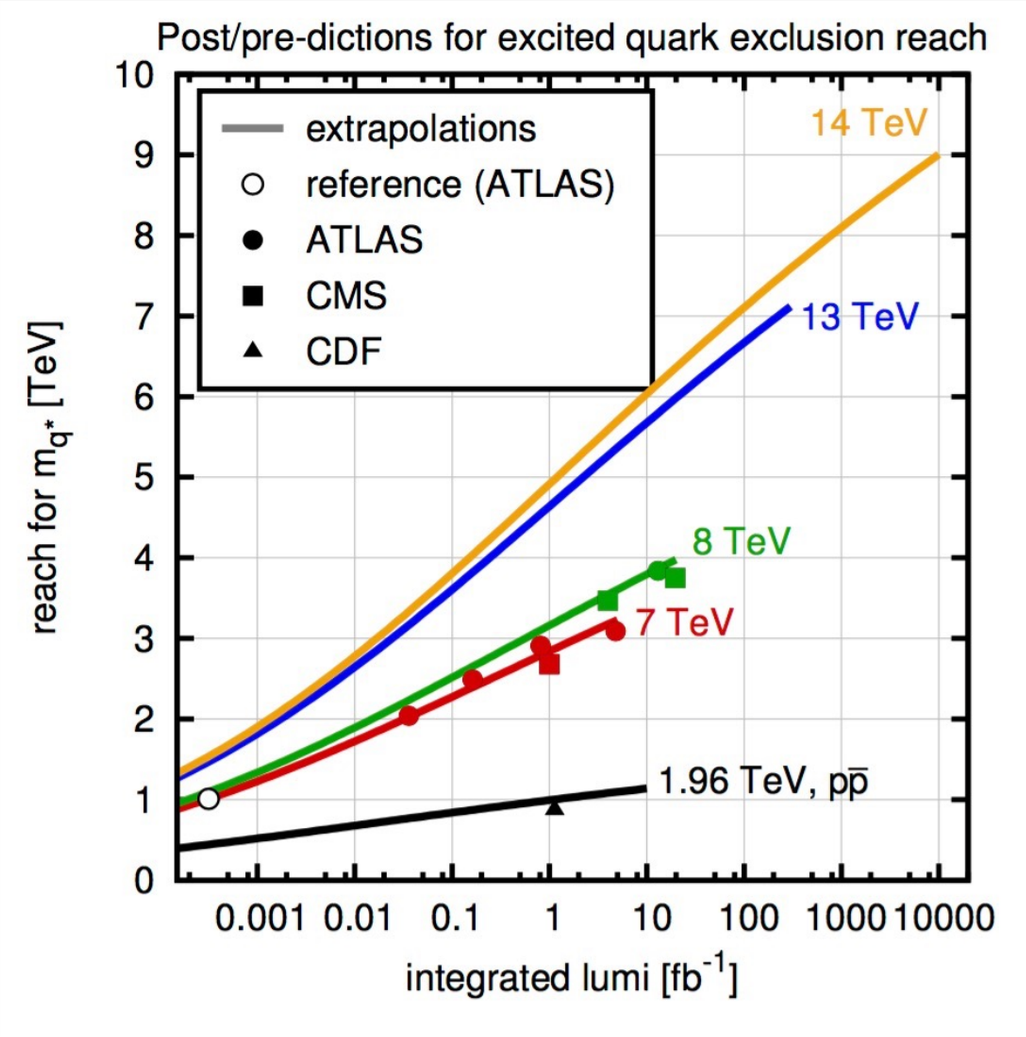


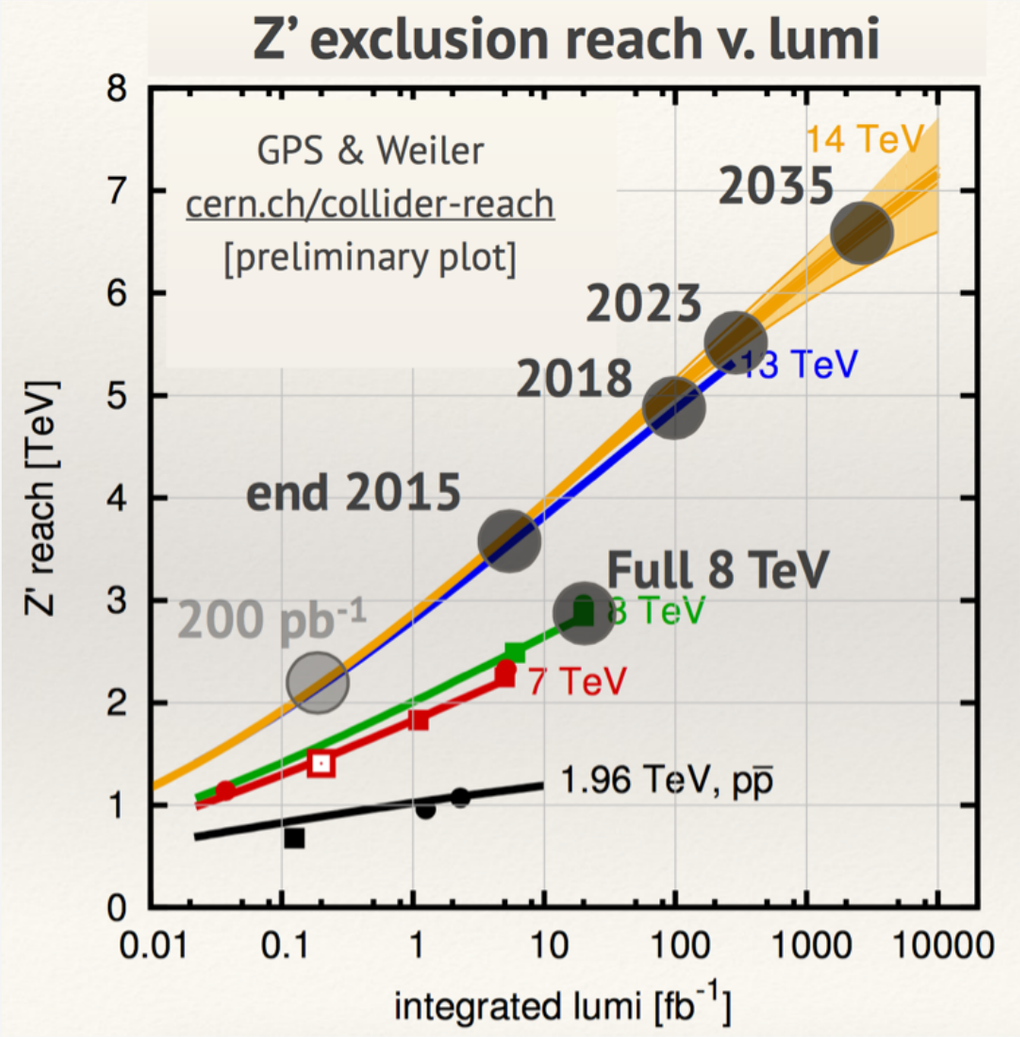
# How to do even better?

Both $M_{Z'}$> 1 TeV and $M_{Z'}$< 1 TeV are unconstrained for plausible but lower $g_q$
Above 1 TeV, add luminosity




Andreas Weiler & Gavin Salam, EPS 2015

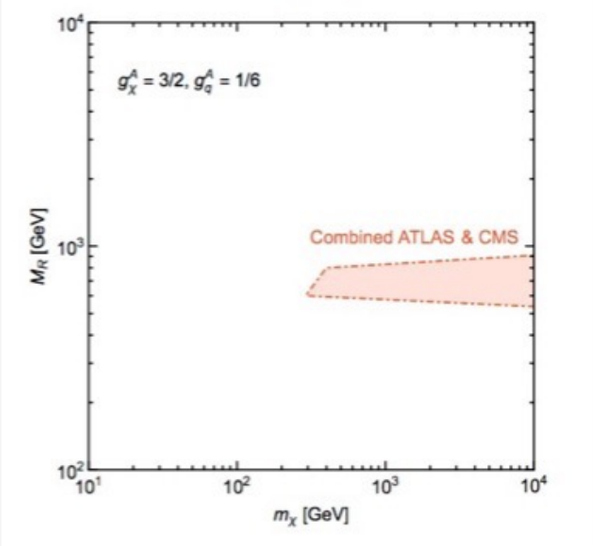



"There's a lot more after this run, but this run is where it's going to happen quickest" (Gavin Salam)

# How to do even better?

Both $M_{Z'} > 1$ TeV and $M_{Z'} < 1$ TeV are unconstrained for plausible but lower $g_q$
Above 1 TeV, add luminosity
Below 1 TeV, something else is needed

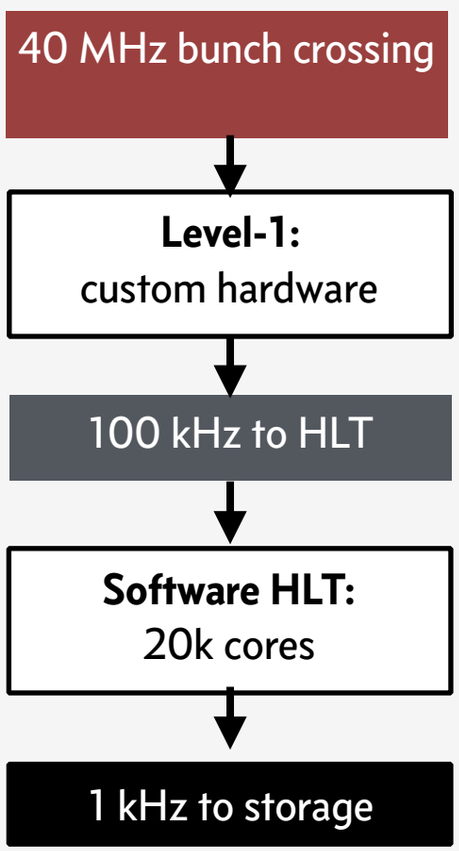



**Trigger bandwidth** = **Recorded event size** x **Recorded event rate**

A fixed resource

Wherever we can reduce this

then we can increase this by a lot!



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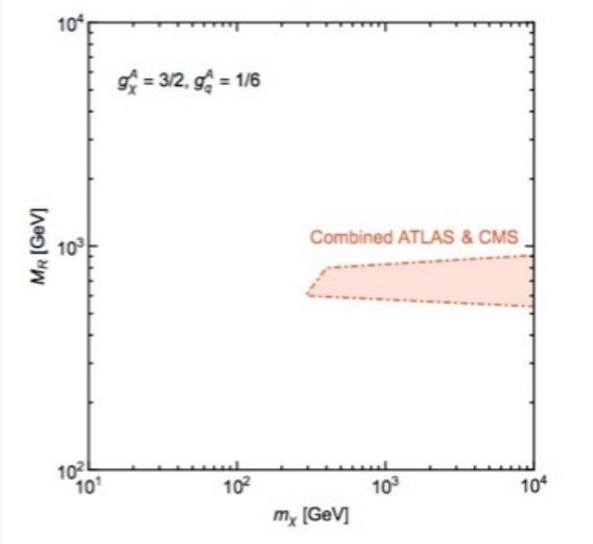
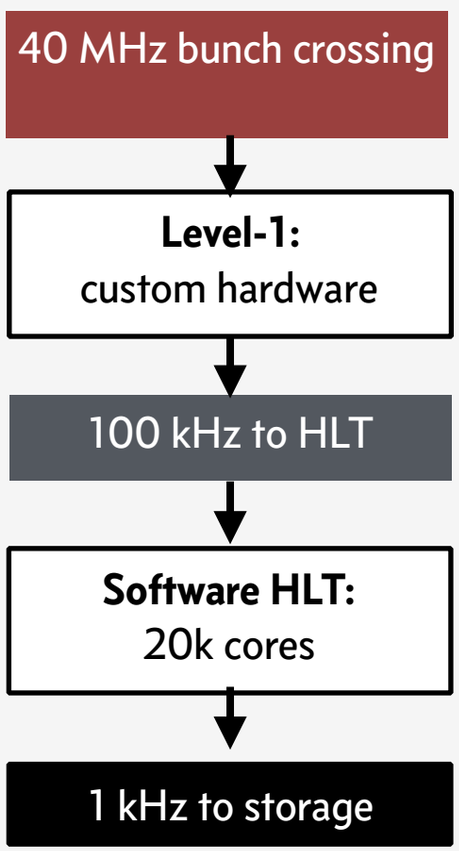
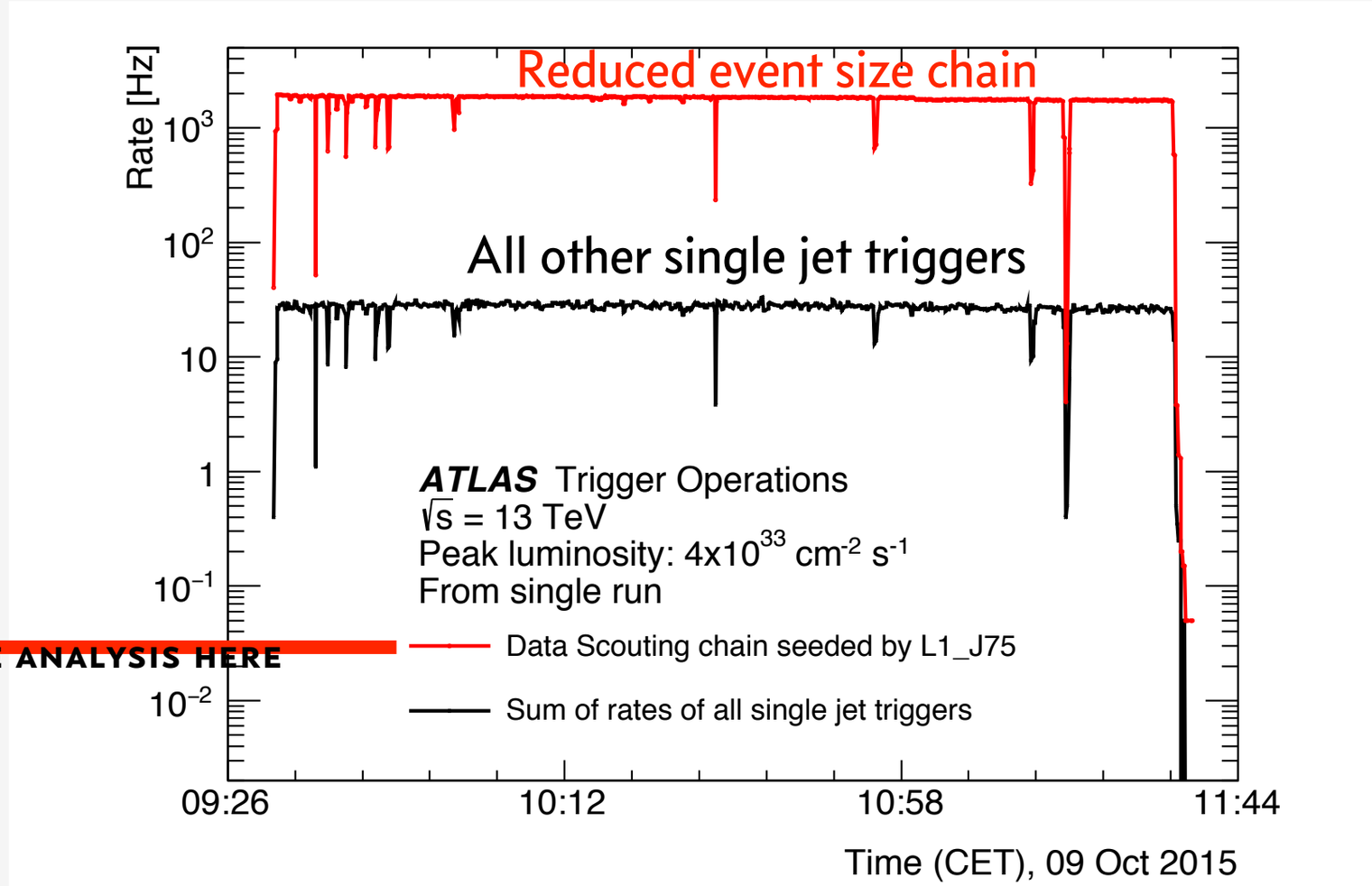



**Trigger bandwidth** = **Recorded event size** x **Recorded event rate**

A fixed resource — Wherever we can reduce this — then we can increase this by a lot!




MOVE ANALYSIS HERE

**Active for most of 2015 data-taking. Stay tuned!**

# Conclusions

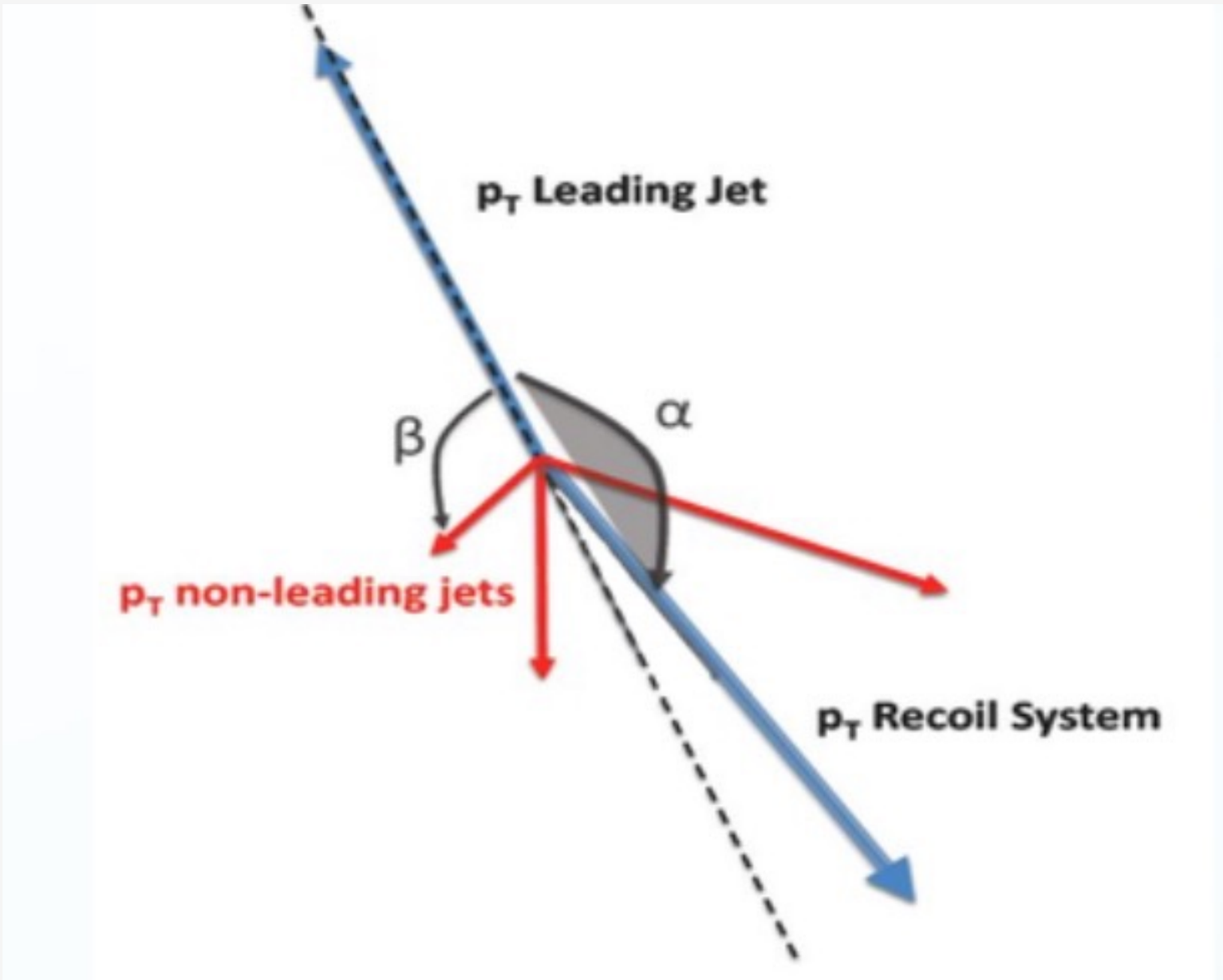
Dark matter is a good motivation for new physics searches at 13 TeV

Wide MET+X search program developed during Run 1
→ Widening much further: more work focused on general DM phenomenology is needed!

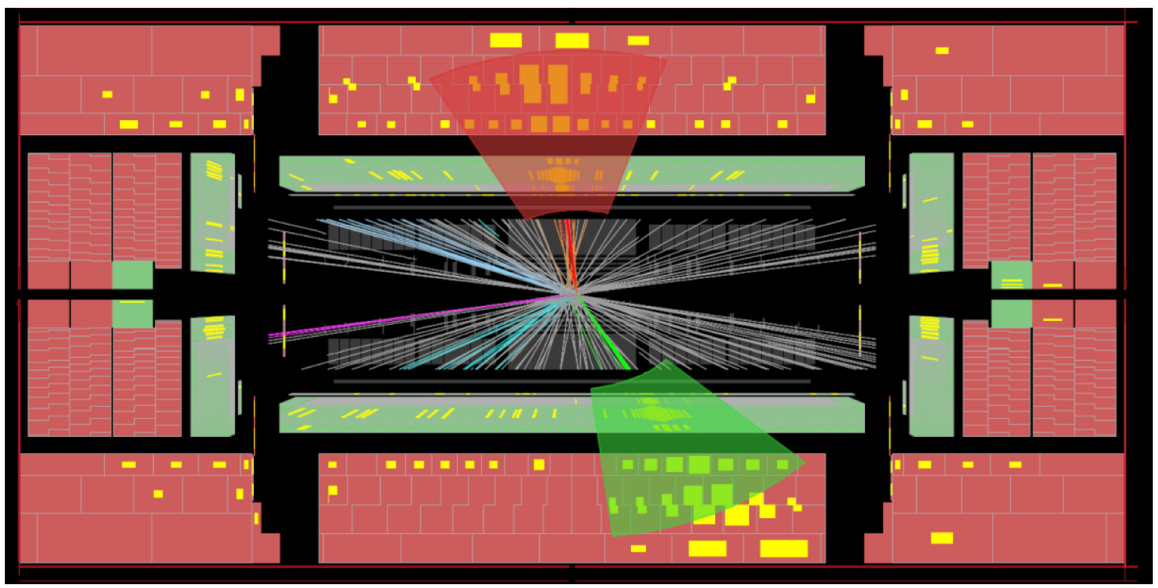
The ability to study the interaction between the dark sector and the SM is a strength of collider experiments
→ building a better picture of these models and the constraints on them
is crucial to seeing how the LHC data can be most useful (see Z′ example)

The LHC cannot conclusively discover dark matter! (only stability on collider timescales)
→ but it may be able to tell us unique information about it

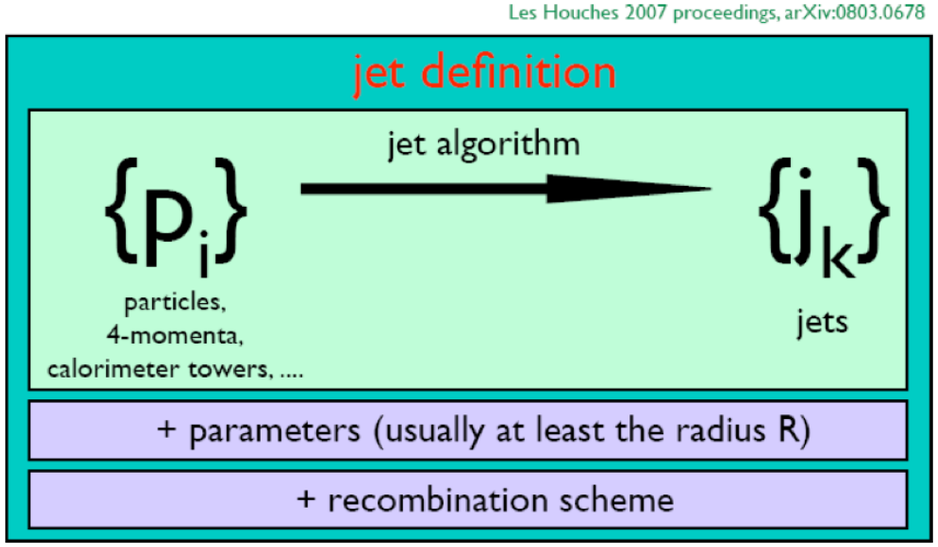
# Additional Slides


$p_T$ Leading Jet
β
α
$p_T$ non-leading jets
$p_T$ Recoil System

# Experimental challenges: Jet Reconstruction



Les Houches 2007 proceedings, arXiv:0803.0678




From M. Cacciari, MPI@LHC08

C. Doglioni

**Algorithm specification: Anti-$k_t$**

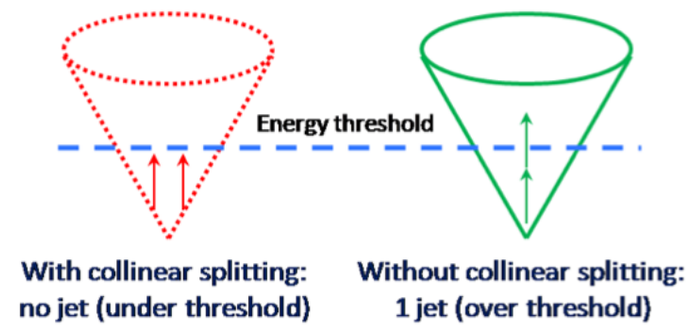
- $d_{i,j} = min(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,i}^2})\frac{\Delta R^2}{D^2}$ ;
  $d_{i,Beam} = \frac{1}{p_{T,i}^2}$
- **D** : algorithm parameter
- Iterate:

1. For every pair of objects $i, j$ calculate $d_{min} = min(d_{i,j}, d_{i,beam})$
2. **If** $d_{min} = d_{i,j}$ recombine objects
   **Else** $i$ is a jet, remove it from list [a]

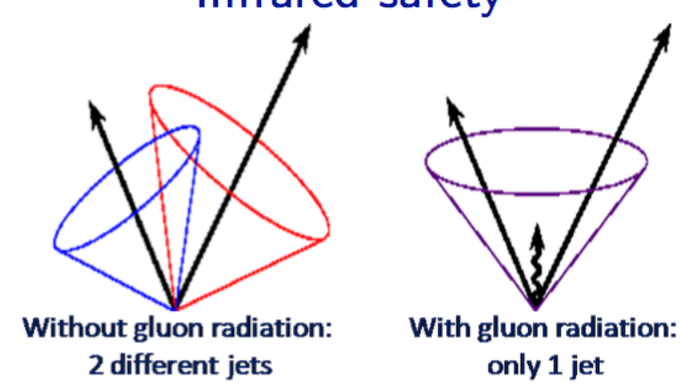
- Recombination starts from **hard** objects

[a] ATLAS default: inclusive algorithm

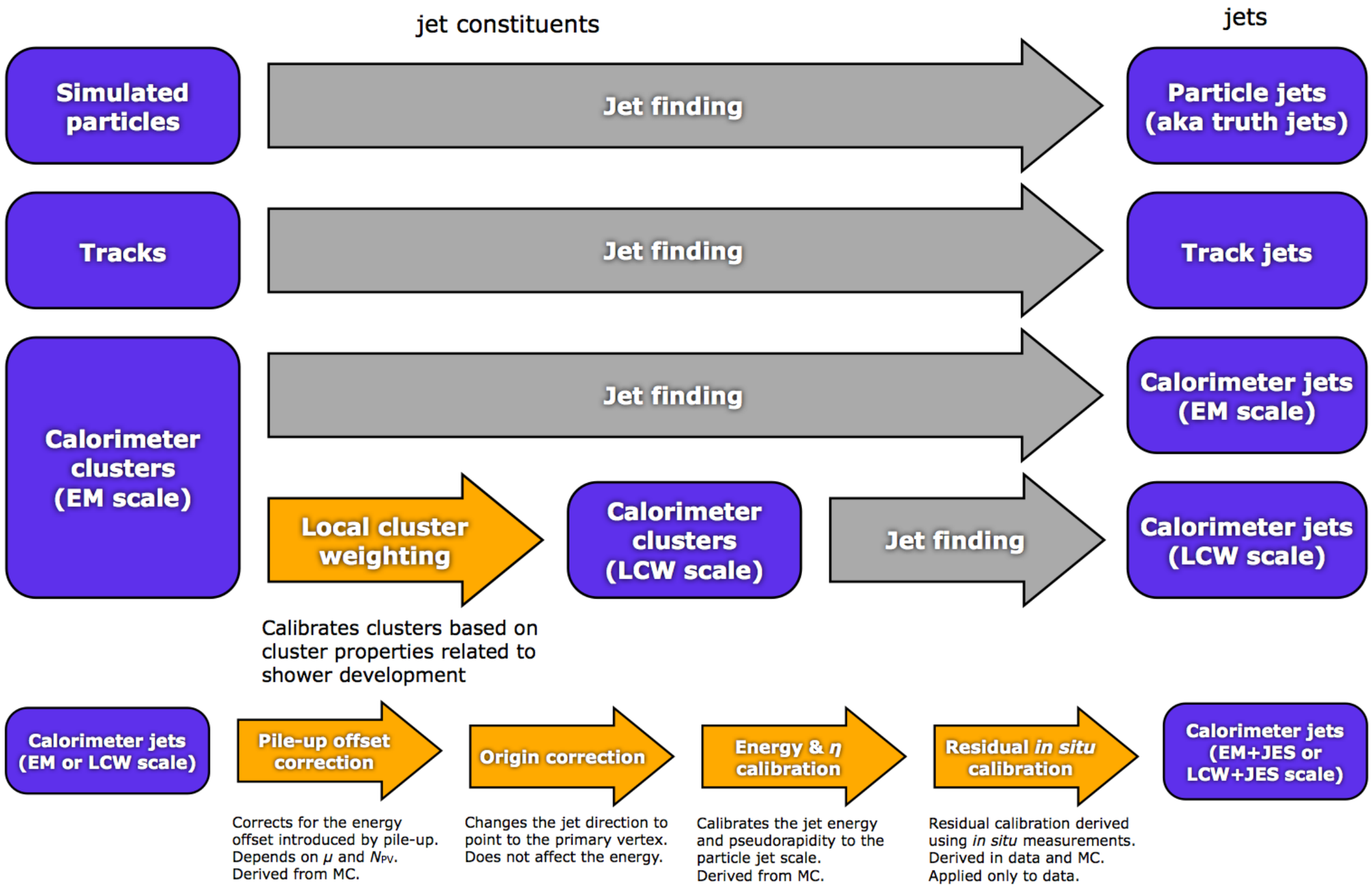
## Collinear safety



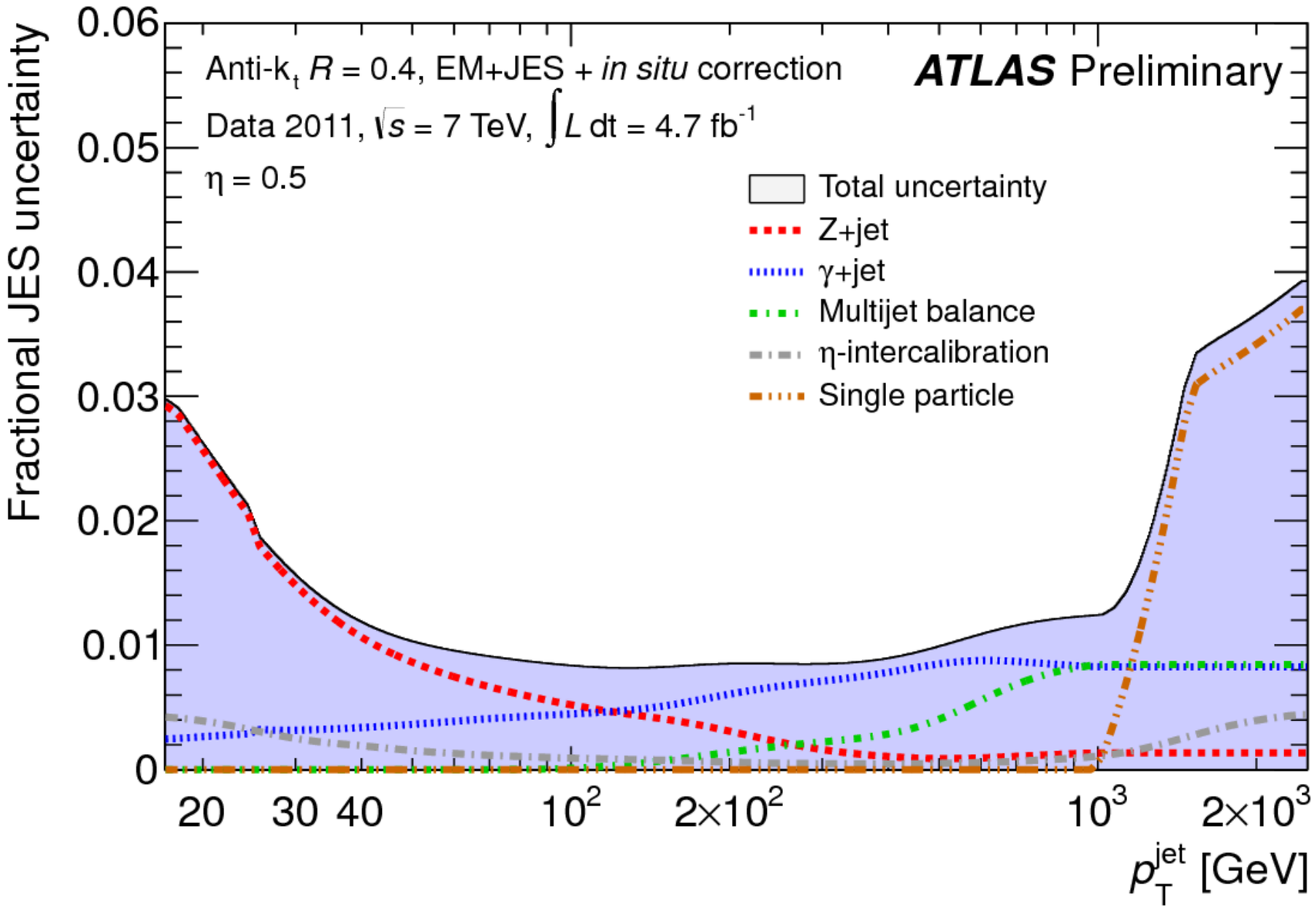

## Infrared safety



# Experimental challenges: Jet Calibration

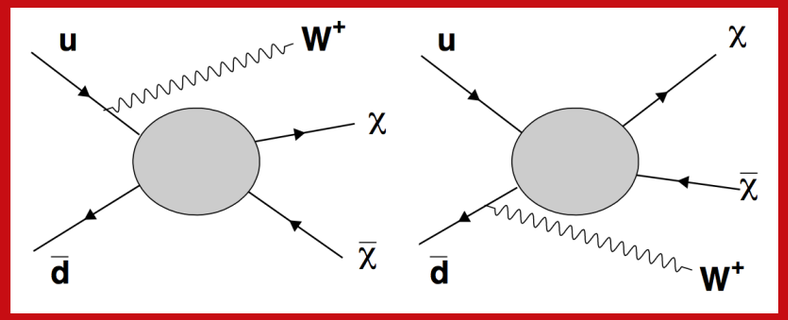


# Experimental challenges: Jet Calibration




**At high $p_T$, uncertainty on JES dominated by single particle uncertainties from test beam convoluted to jets**

# Mono-W/Z (hadronic)




**Tag with single 'fat' jet containing boosted W/Z decay subjets**

C/A-jet: R=1.2, $p_T$ > 250 GeV, |η| < 1.2

**Subjet kinematics consistent with W/Z decay**

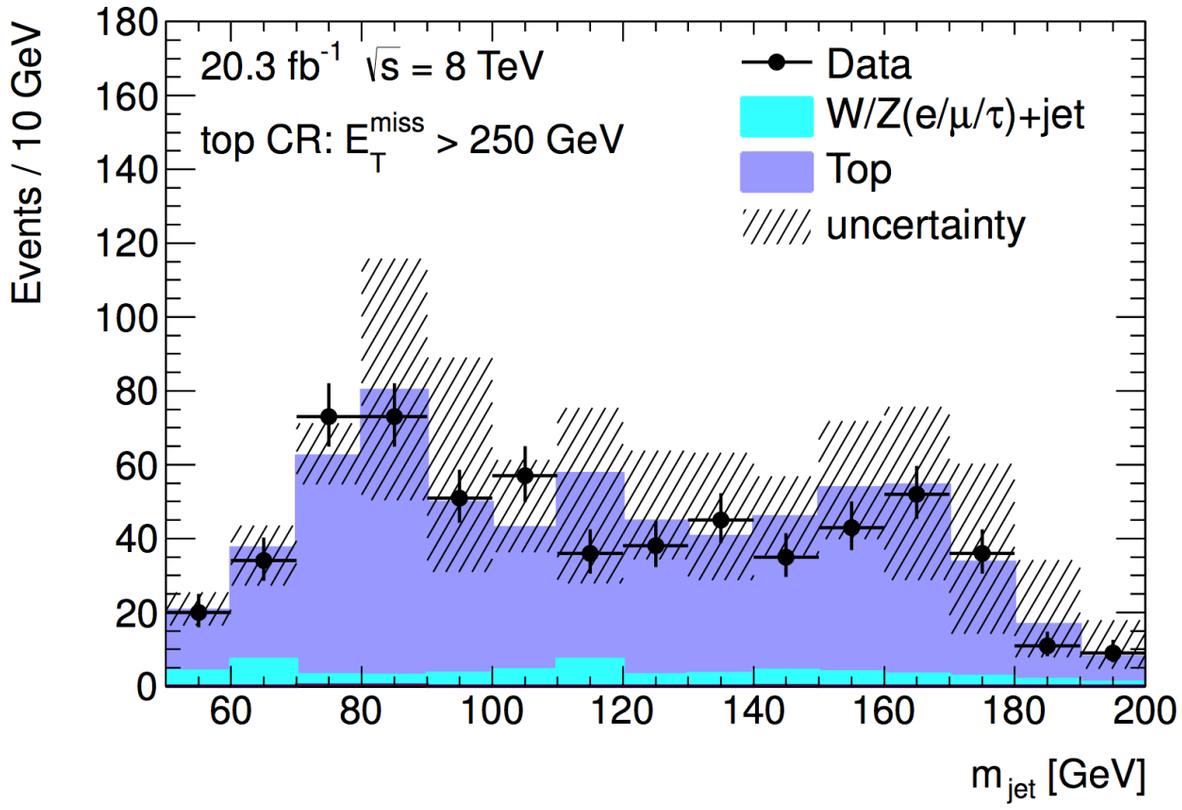
BDRS (Butterworth, Davidson, Rubin, Salam) :

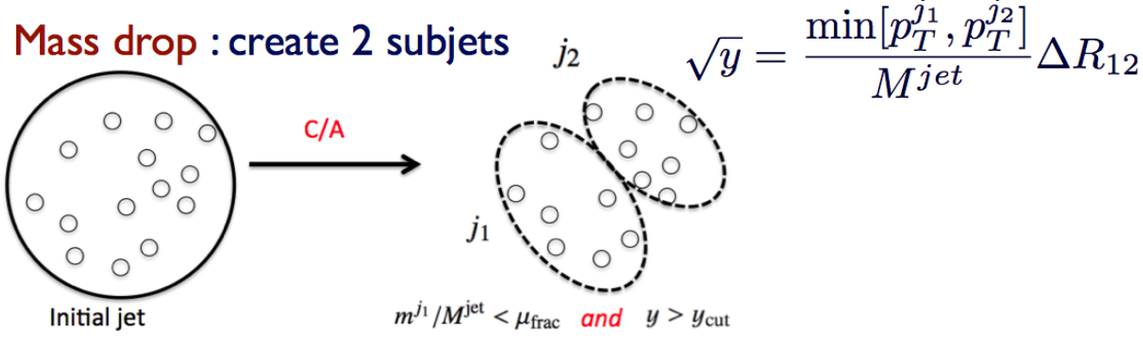
arXiv:0802/2470

Total jet mass 50<$M_{jet}$<120 GeV

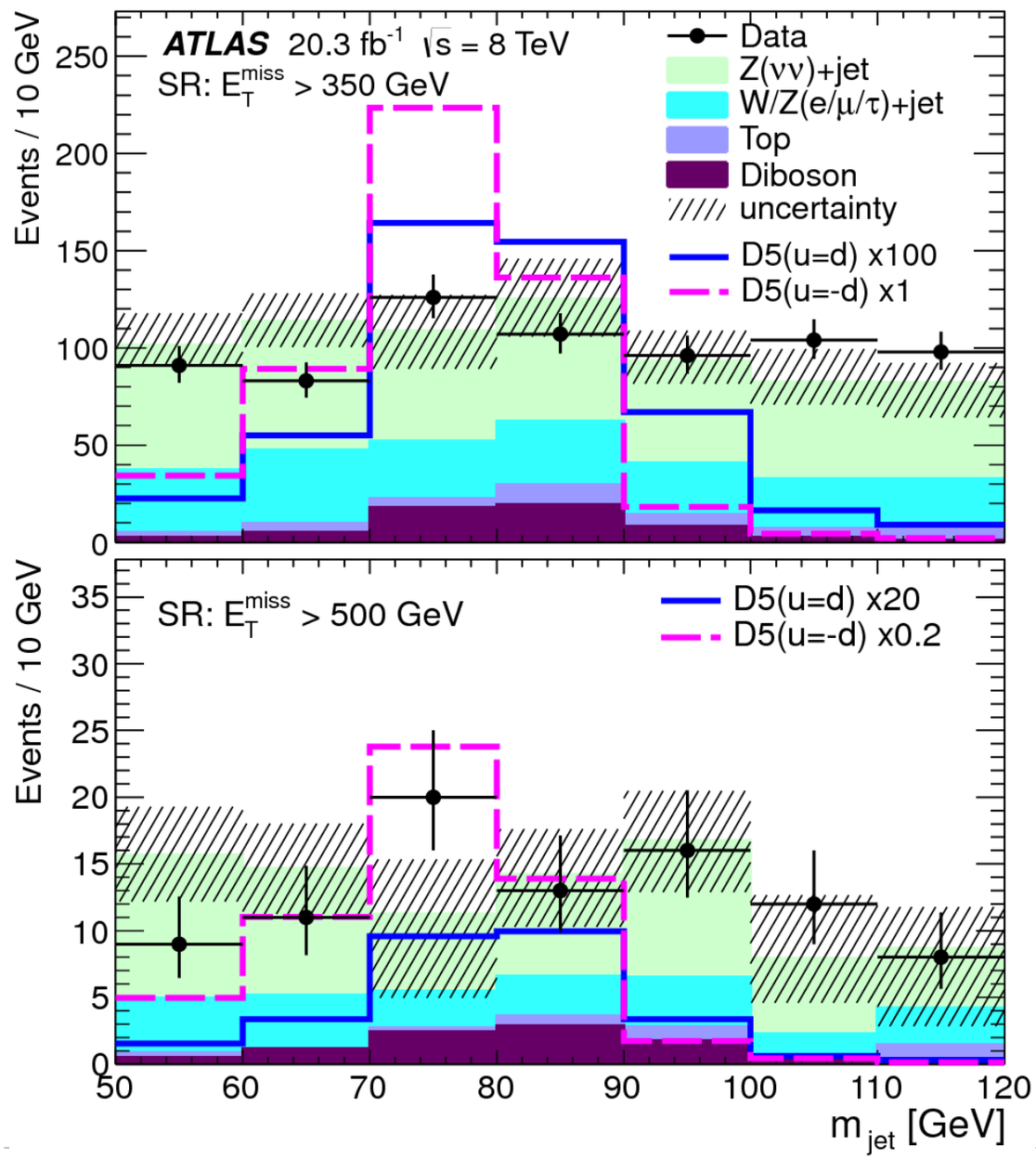
Sub-jet $p_T$ balance ($\sqrt{y}$ > 0.4)

**MET > 350, 500 GeV**



# Mono-W/Z (hadronic) Results




| Process | $E_T^{miss} > 350$ GeV | $E_T^{miss} > 500$ GeV |
|---|---|---|
| $Z \to \nu\bar{\nu}$ | $400^{+39}_{-34}$ | $54^{+7.5}_{-9.6}$ |
| $W \to \ell^{\pm}\nu,\ Z \to \ell^{\pm}\ell^{\mp}$ | $210^{+20}_{-18}$ | $22^{+3.6}_{-4.6}$ |
| $WW, WZ, ZZ$ | $57^{+11}_{-8.0}$ | $9.1^{+1.3}_{-1.1}$ |
| $t\bar{t}$, single $t$ | $39^{+9.9}_{-4.3}$ | $3.7^{+1.7}_{-1.3}$ |
| Total | $710^{+48}_{-38}$ | $89^{+8.6}_{-12}$ |
| Data | 705 | 89 |

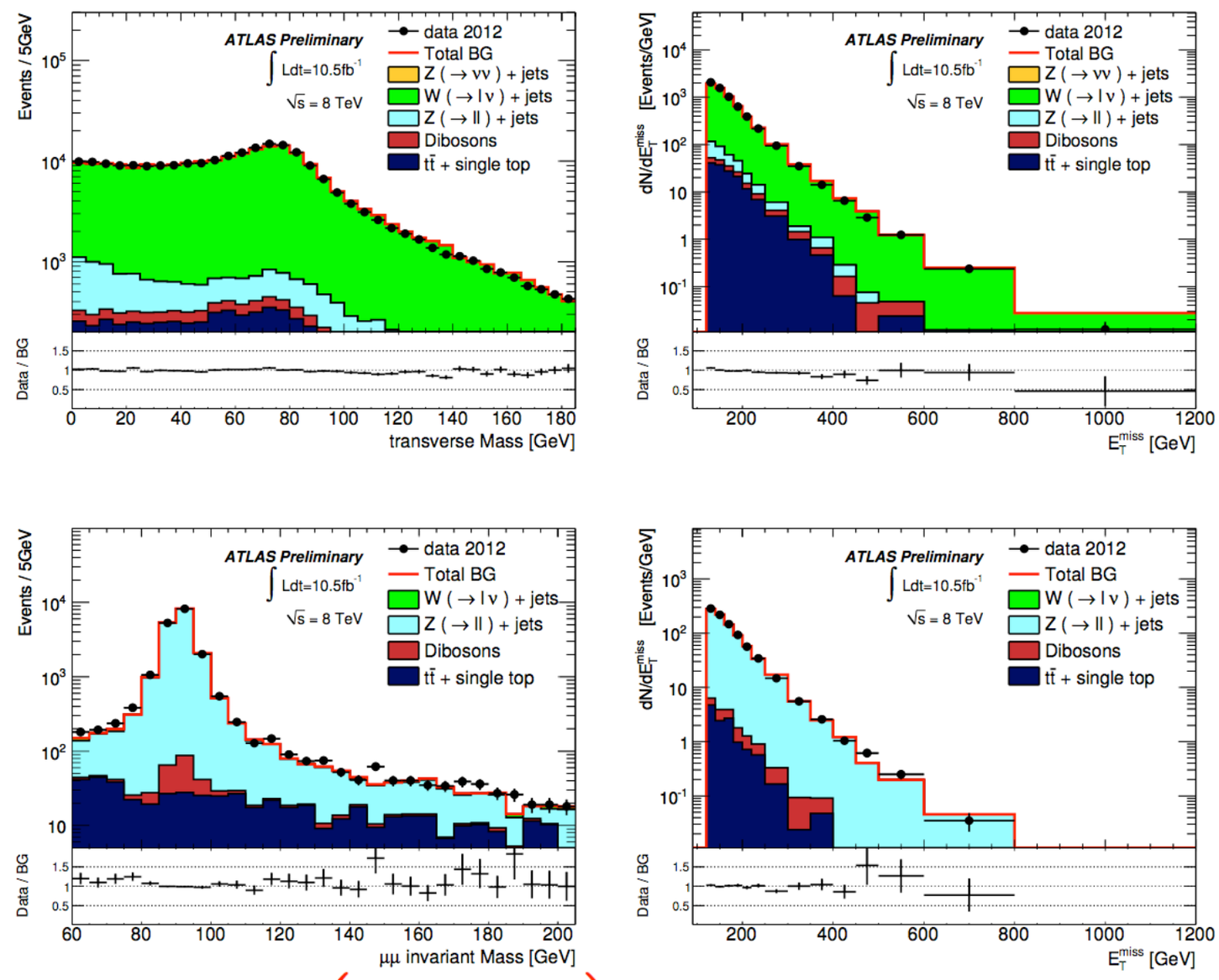
# Electroweak backgrounds

>95% of backgrounds to monojet search are Z->νν and W->lν

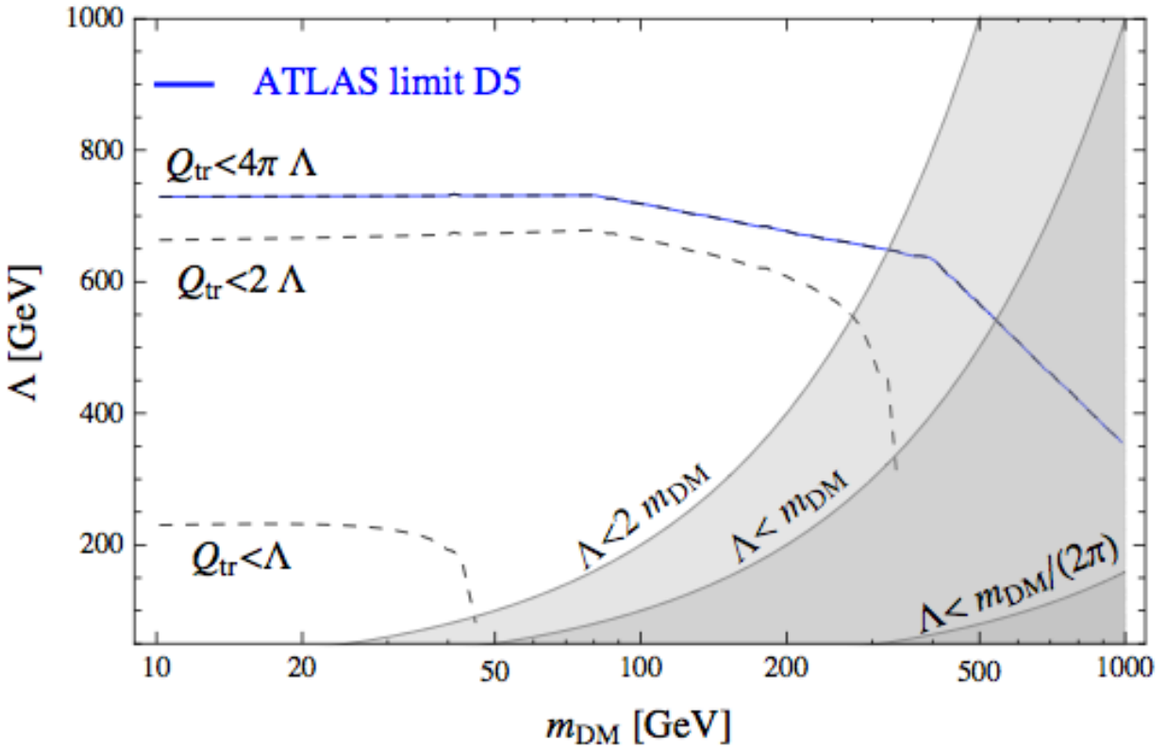
Taken from leptonic W and Z control data

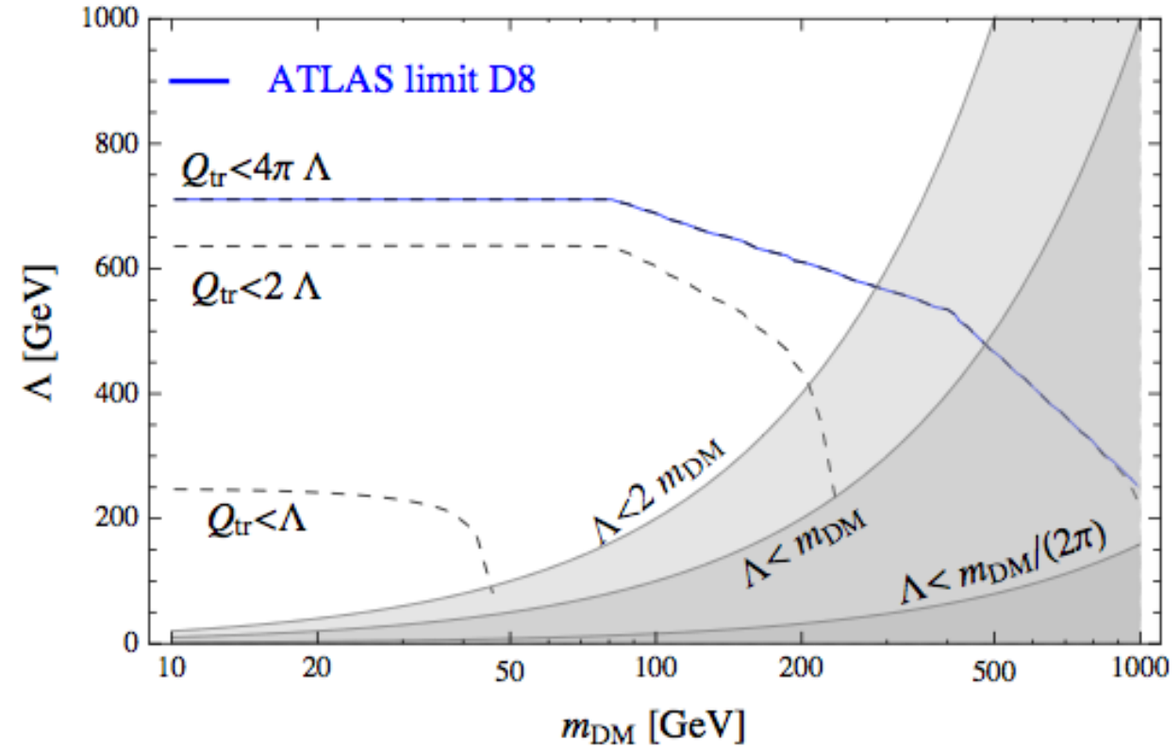
Correct for lepton selection/ veto using MC 'transfer factor'

Systematics improve with more statistics at high boson $p_T$




$$N^{\mathrm{SR}}_{\mathrm{estimate}} = \left(N^{\mathrm{CR}}_{\mathrm{data}} - N^{\mathrm{CR}}_{\mathrm{est,QCD}}\right)\left(1 - f^{\mathrm{bg}}_{\mathrm{EW}}\right)\left(N^{\mathrm{SR}}_{\mathrm{MC}}/N^{\mathrm{CR}}_{\mathrm{MC}}\right)$$



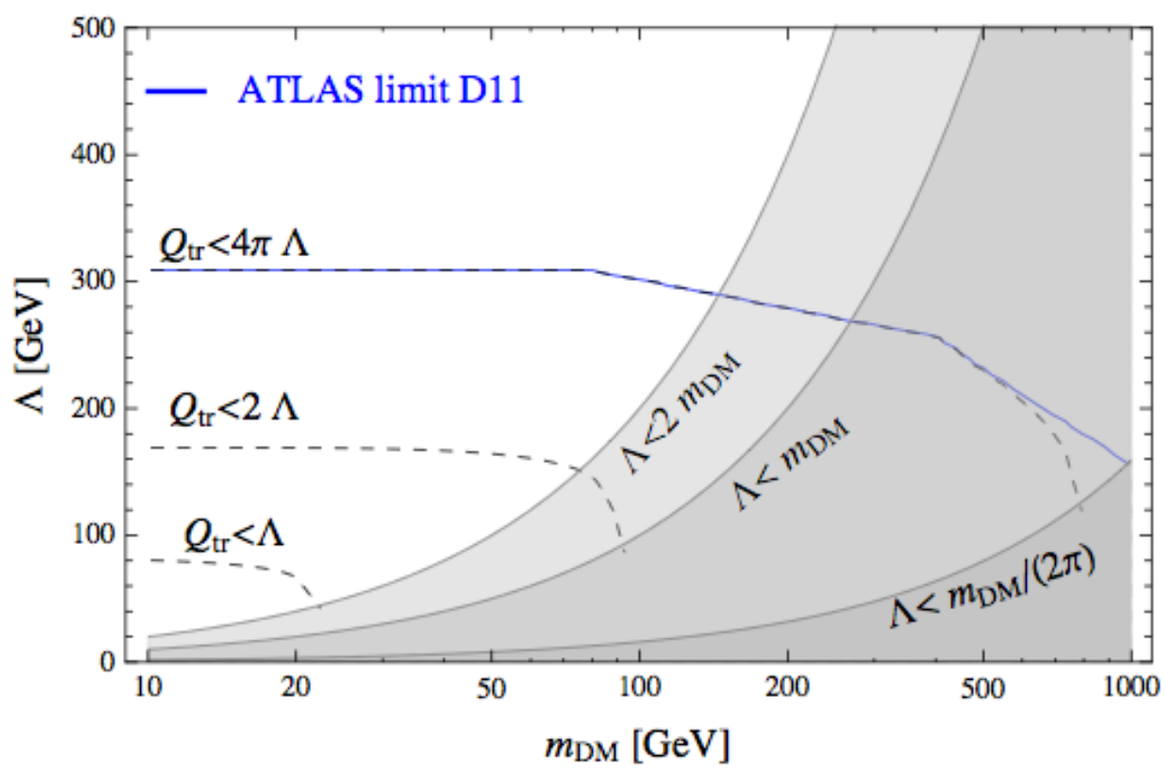

$$\mathcal{O} = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q)$$

$$q\bar{q} \to \chi\chi + \text{jet}$$

$$Q_{tr} = p_q + p_{\bar{q}} - p_{jet}$$

$$Q_{tr} > 2m_{DM}$$

$$\Lambda > \frac{Q_{tr}}{\sqrt{g_q g_\chi}} > \frac{Q_{tr}}{4\pi}$$

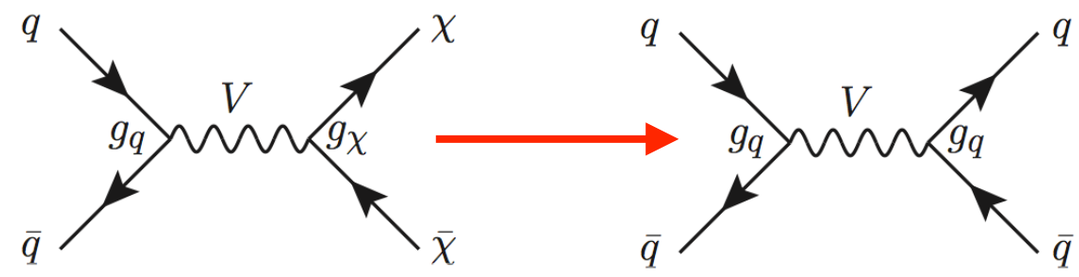



$$R_\Lambda^{tot} \equiv \frac{\sigma|_{Q_{tr}<\Lambda}}{\sigma} = \frac{\int_{p_T^{min}}^{p_T^{max}} dp_T \int_{-2}^{2} d\eta \left.\frac{d^2\sigma}{dp_T d\eta}\right|_{Q_{tr}<\Lambda}}{\int_{p_T^{min}}^{p_T^{max}} dp_T \int_{-2}^{2} d\eta \frac{d^2\sigma}{dp_T d\eta}}$$

# Looking directly for the light mediator

**When the mediator is light, you can look for it directly**

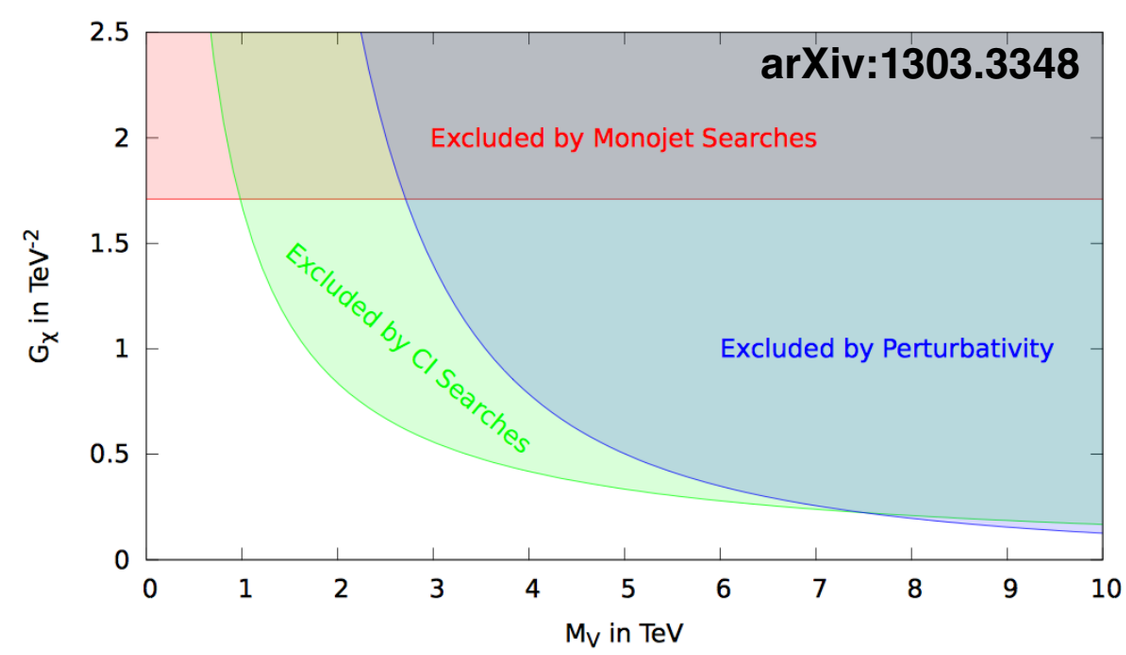
**Looking for something specific is generally a better strategy than looking for something vague...**




$$\mathscr{L}_{\rm UV} = \bar{q}(i\partial\!\!\!/ - M_q)q + \bar{\chi}(i\partial\!\!\!/ - M_\chi)\chi + \frac{1}{2}M_V^2 V_\mu V^\mu - \frac{1}{4}V^{\mu\nu}V_{\mu\nu} - g_q\bar{q}\gamma^\mu P_L q V_\mu - g_\chi\bar{\chi}\gamma^\mu P_L \chi V_\mu$$

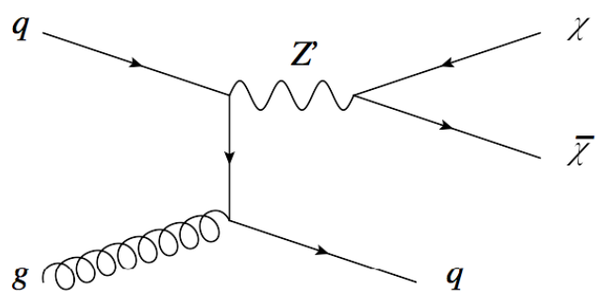
**Coupling to quarks required for WIMP-nucleon interactions and production at colliders**
**=> dijet signature**

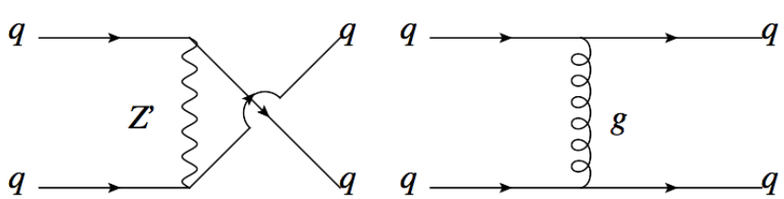
**Dijet contact search powerful in transition region between resonance and full contact interaction**

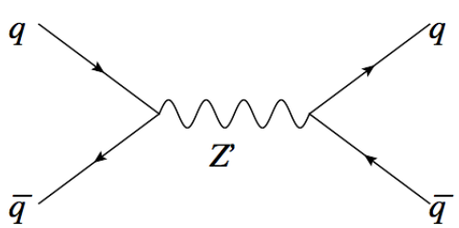


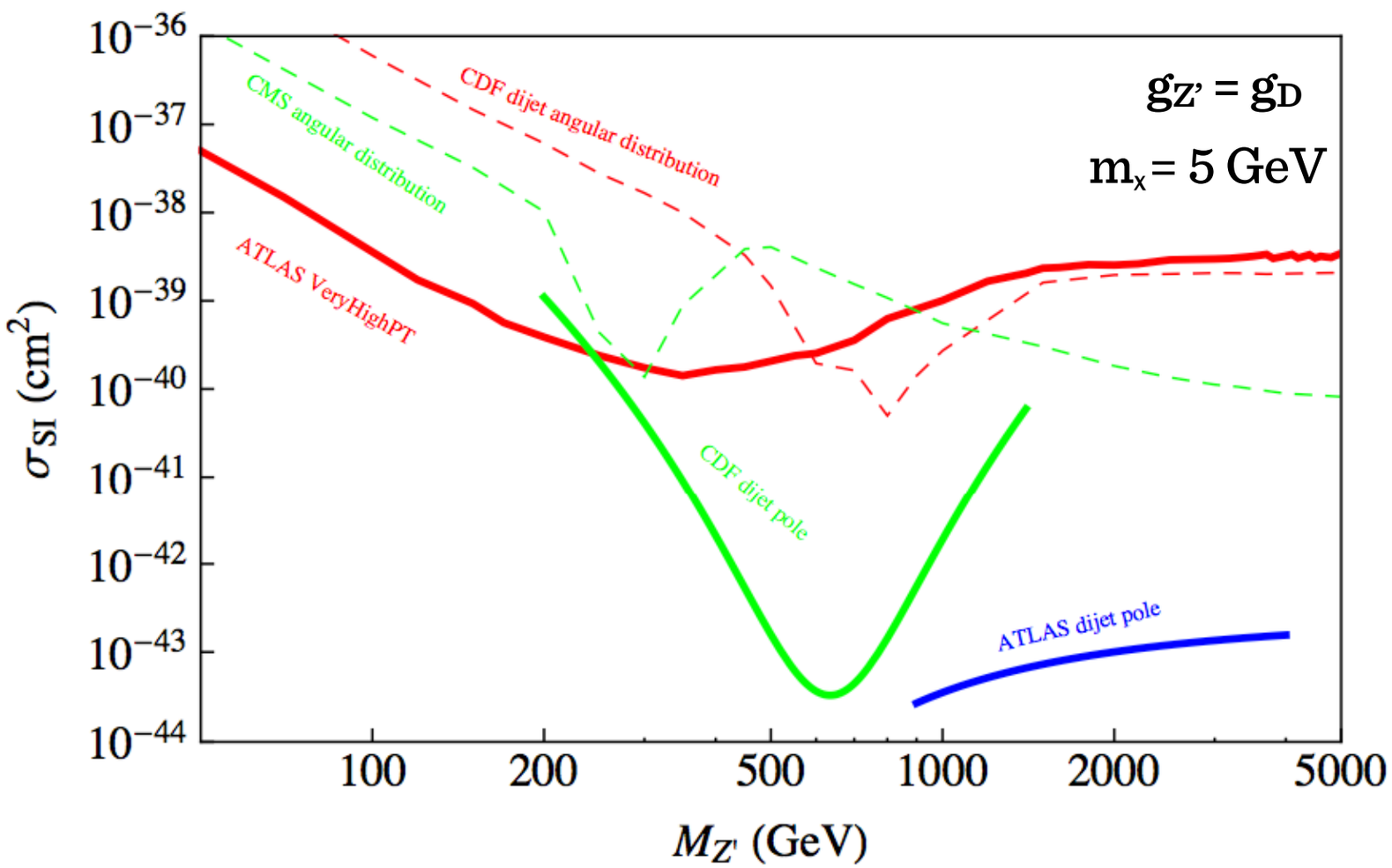
# Simplified: Light dark matter and leptophobic Z′

$$\mathcal{L} = Z'_\mu[(g_{Z'}\bar{q}\gamma^\mu q + g_{Z'5}\bar{q}\gamma^\mu\gamma_5 q) + (g_D\bar{\chi}\gamma^\mu\chi + g_{D5}\bar{\chi}\gamma^\mu\gamma_5\chi)]$$



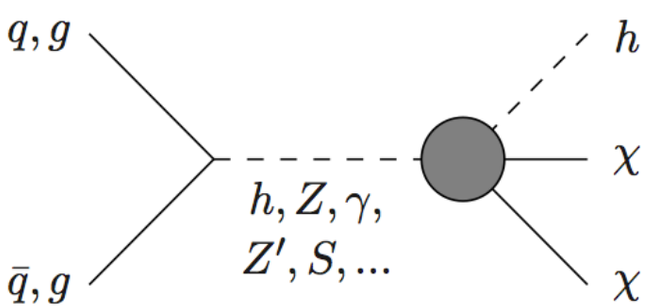



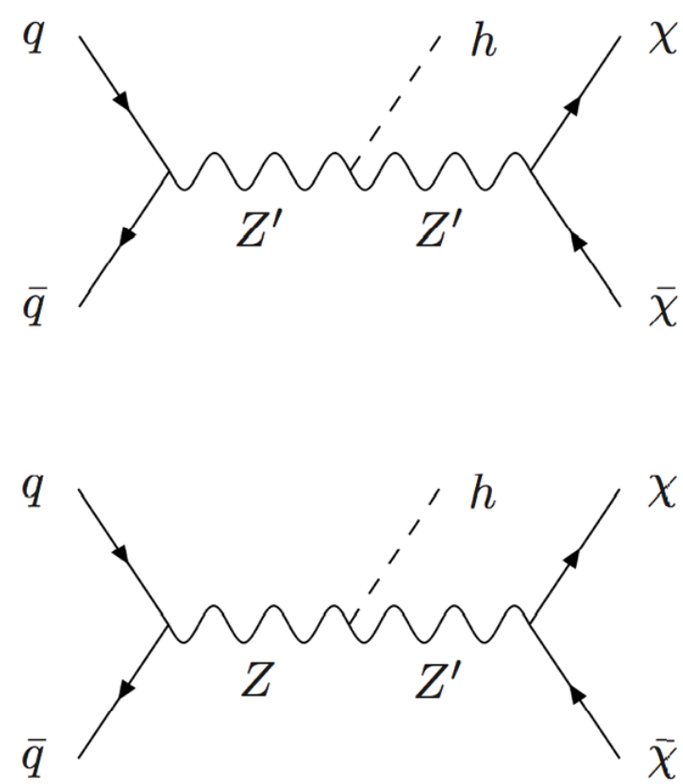



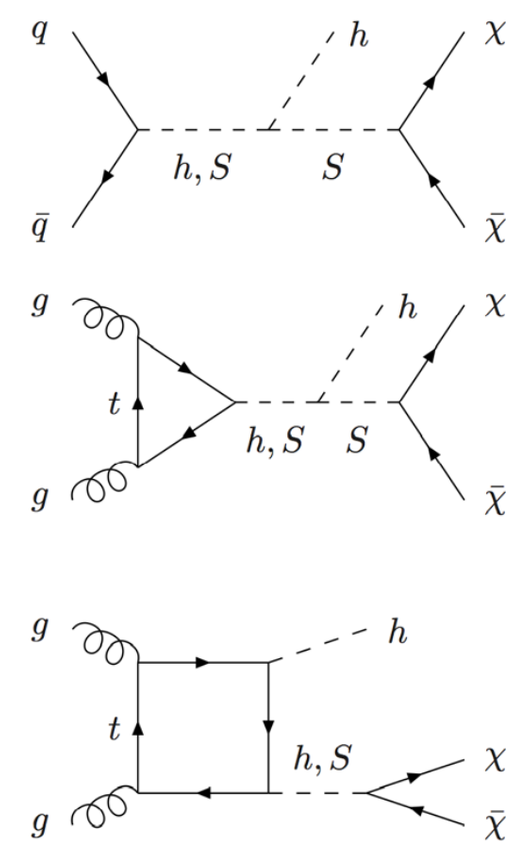
# Mono-Higgs

**EFT**




**Simplified Models**



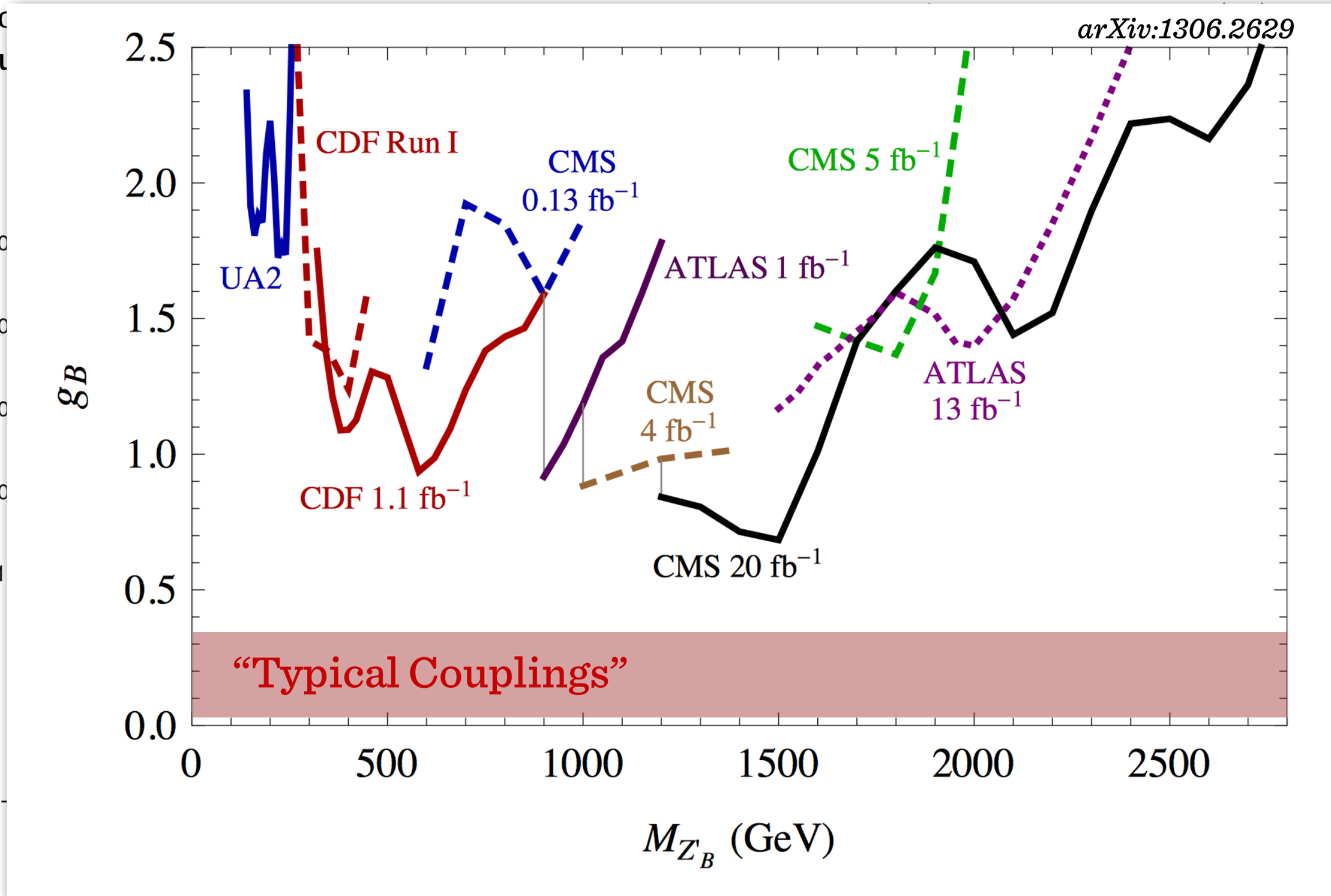

+ ...

# Dijet resonances

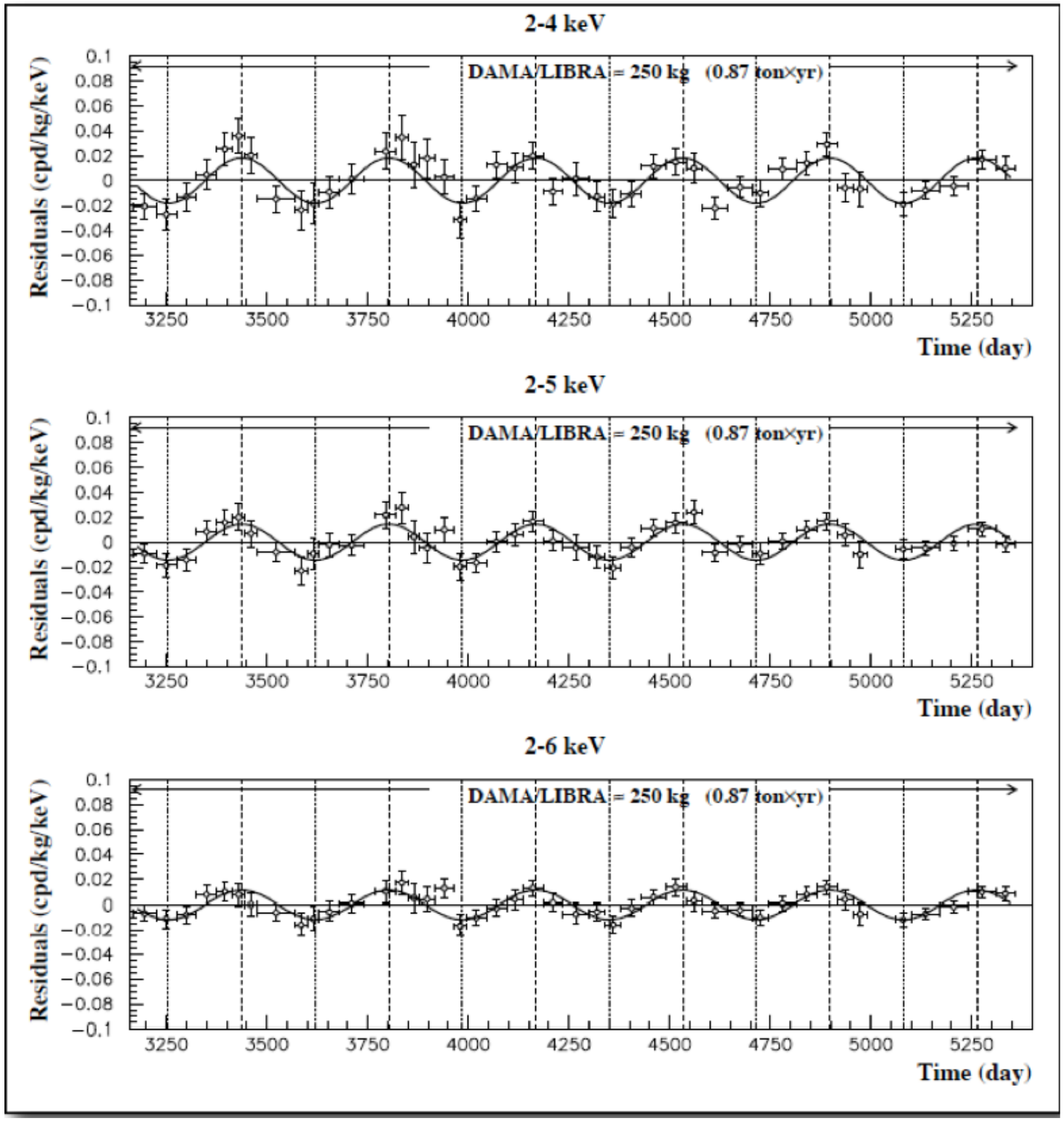
ATLAS-CONF-2012-148

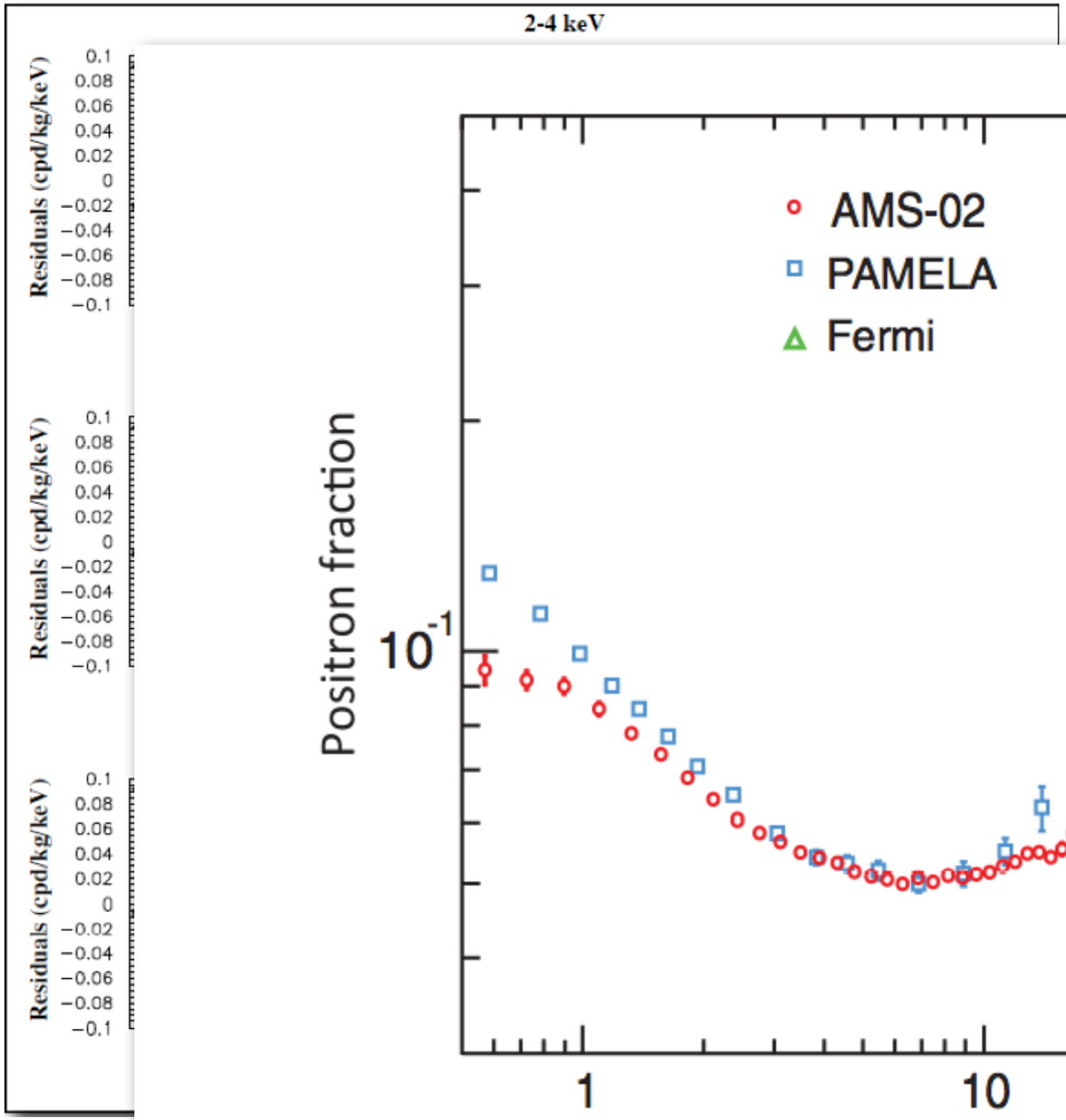
BumpHunt on smooth parameterization of dijet mass distribution

Two
diqu

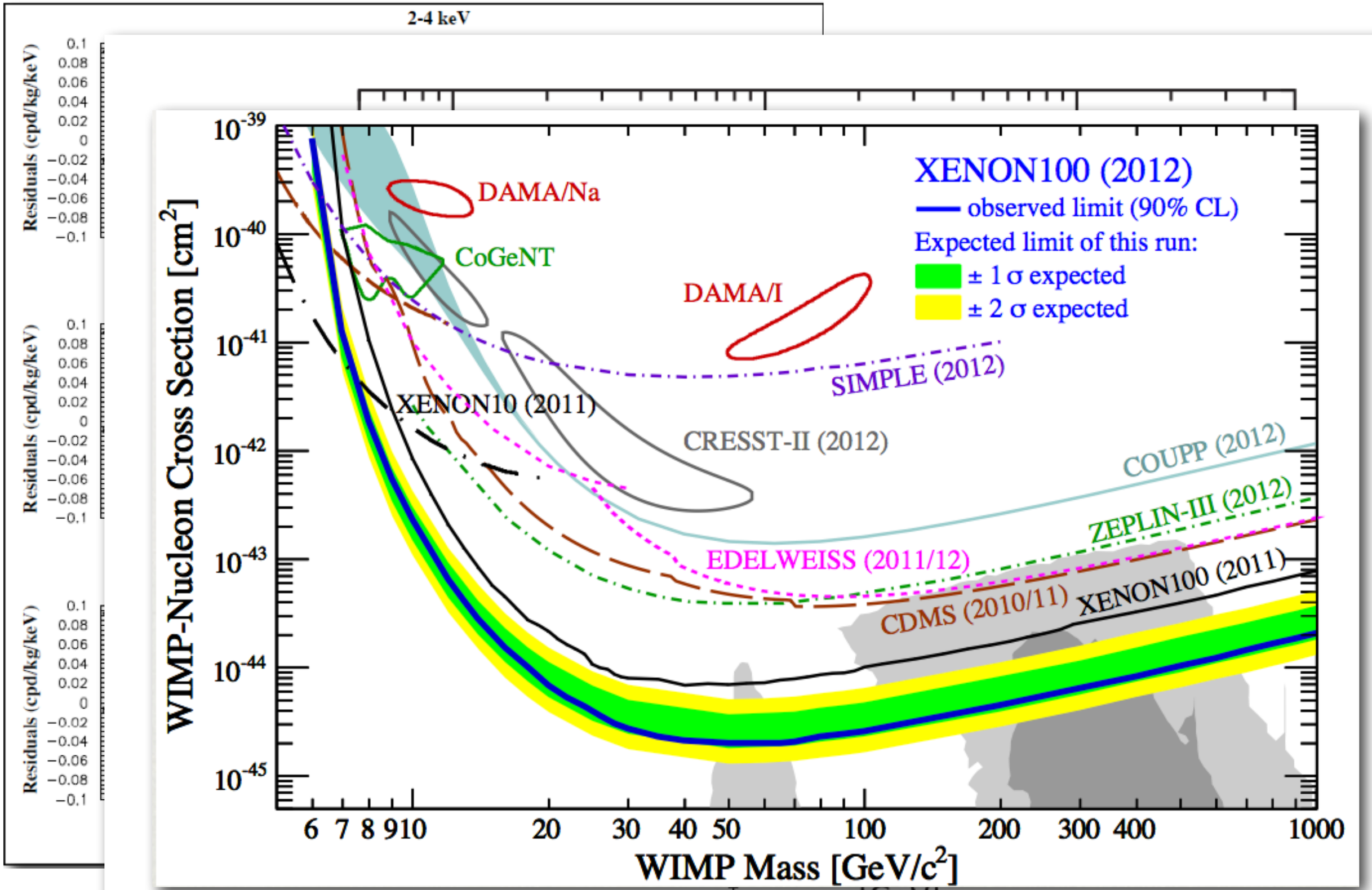


# What would a discovery of dark matter look like?


2-4 keV
DAMA/LIBRA = 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)
2-5 keV
DAMA/LIBRA = 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)
2-6 keV
DAMA/LIBRA = 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)




PRL 110 141102


2-4 keV
Residuals (cpd/kg/keV)
XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
CDMS (2010/11)
XENON100 (2011)
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]
e± energy [GeV]

arXiv:1304.3706v1

# Dark Matter Search Results Using the Silicon Detectors of CDMS II

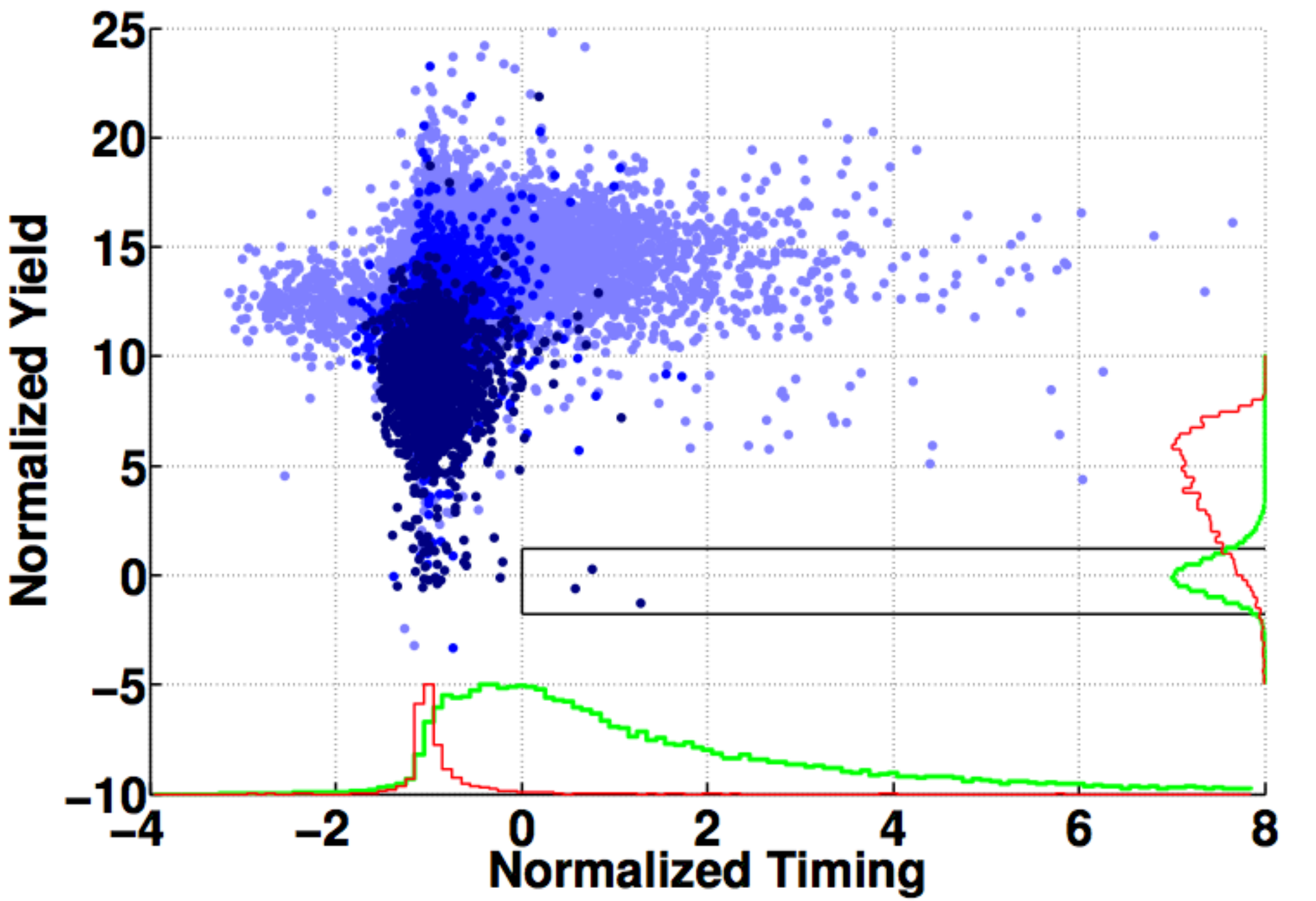
R. Agnese,[13] Z. Ahmed,[14] A.J. Anderson,[2] S. Arrenberg,[20] D. Balakishiyeva,[13] R. Basu Thakur,[15] D.A. Bauer,[15] J. Billard,[2] A. Borgland,[18] D. Brandt,[18] P.L. Brink,[18] T. Bruch,[20] R. Bunker,[7] B. Cabrera,[6] D.O. Caldwell,[10] D.G. Cerdeno,[1] H. Chagani,[17] J. Cooley,[5] B. Cornell,[14] C.H. Crewdson,[3] P. Cushman,[17] M. Daal,[9] F. Dejongh,[15] E. Do Couto E Silva,[18] T. Doughty,[9] L. Esteban,[1] S. Fallows,[17] E. Figueroa-Feliciano,[2] J. Filippini,[14] J. Fox,[3] M. Fritts,[17] G.L. Godfrey,[18] S.R. Golwala,[14] J. Hall,[19] R.H. Harris,[8] S.A. Hertel,[2] T. Hofer,[17] D. Holmgren,[15] L. Hsu,[15] M.E. Huber,[11] A. Jastram,[8] O. Kamaev,[3] B. Kara,[5] M.H. Kelsey,[18] A. Kennedy,[17] P. Kim,[18] M. Kiveni,[7] K. Koch,[17] M. Kos,[7] S.W. Leman,[2] B. Loer,[15] E. Lopez Asamar,[1] R. Mahapatra,[8] V. Mandic,[17] C. Martinez,[3] K.A. McCarthy,[2] N. Mirabolfathi,[9] R.A. Moffatt,[6] D.C. Moore,[14] P. Nadeau,[3] R.H. Nelson,[14] K. Page,[3] R. Partridge,[18] M. Pepin,[17] A. Phipps,[9] K. Prasad,[8] M. Pyle,[9] H. Qiu,[5] W. Rau,[3] P. Redl,[6] A. Reisetter,[12] Y. Ricci,[3] T. Saab,[13] B. Sadoulet,[9,16] J. Sander,[8] K. Schneck,[18] R.W. Schnee,[7] S. Scorza,[5] B. Serfass,[9] B. Shank,[6] D. Speller,[9] K.M. Sundqvist,[9] A.N. Villano,[17] B. Welliver,[13] D.H. Wright,[18] S. Yellin,[6] J.J. Yen,[6] J. Yoo,[15] B.A. Young,[4] and J. Zhang[17]

(CDMS Collaboration)

We report results of a search for Weakly Interacting Massive Particles (WIMPs) with the silicon (Si) detectors of the CDMS II experiment. A blind analysis of data from eight Si detectors, with a total raw exposure of 140.2 kg-days, revealed three WIMP-candidate events with a final surface-event background estimate of $0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$. Other known backgrounds from neutrons and $^{206}$Pb are limited to $< 0.13$ and $< 0.08$ events at the 90% confidence level, respectively. These data place a 90% upper confidence limit on the WIMP-nucleon cross section of $2.4 \times 10^{-41}$ cm$^2$ at a WIMP mass of 10 GeV/$c^2$. Simulations indicate a 5.4% probability that a statistical fluctuation of the known backgrounds would produce three or more events in the signal region. A profile likelihood ratio test that includes the measured recoil energies of the three events gives a 0.19% probability for the known-background-only hypothesis when tested against the alternative WIMP+background hypothesis. The highest likelihood was found for a WIMP mass of 8.6 GeV/$c^2$ and WIMP-nucleon cross section of $1.9 \times 10^{-41}$ cm$^2$.

arXiv:1304.3706v1

# Dark Matter Search Results Using the Silicon Detectors of CDMS II




asu Thakur,[15]
ker,[7] B. Cabrera,[6]
n,[3] P. Cushman,[17]
Figueroa-Feliciano,[2]
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t,[9,16] J. Sander,[8]
Sundqvist,[9]
g,[4] and J. Zhang[17]

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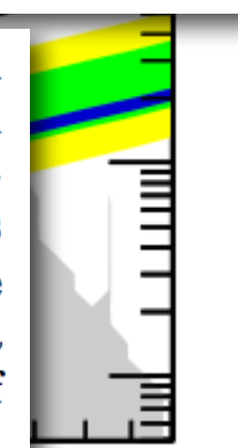
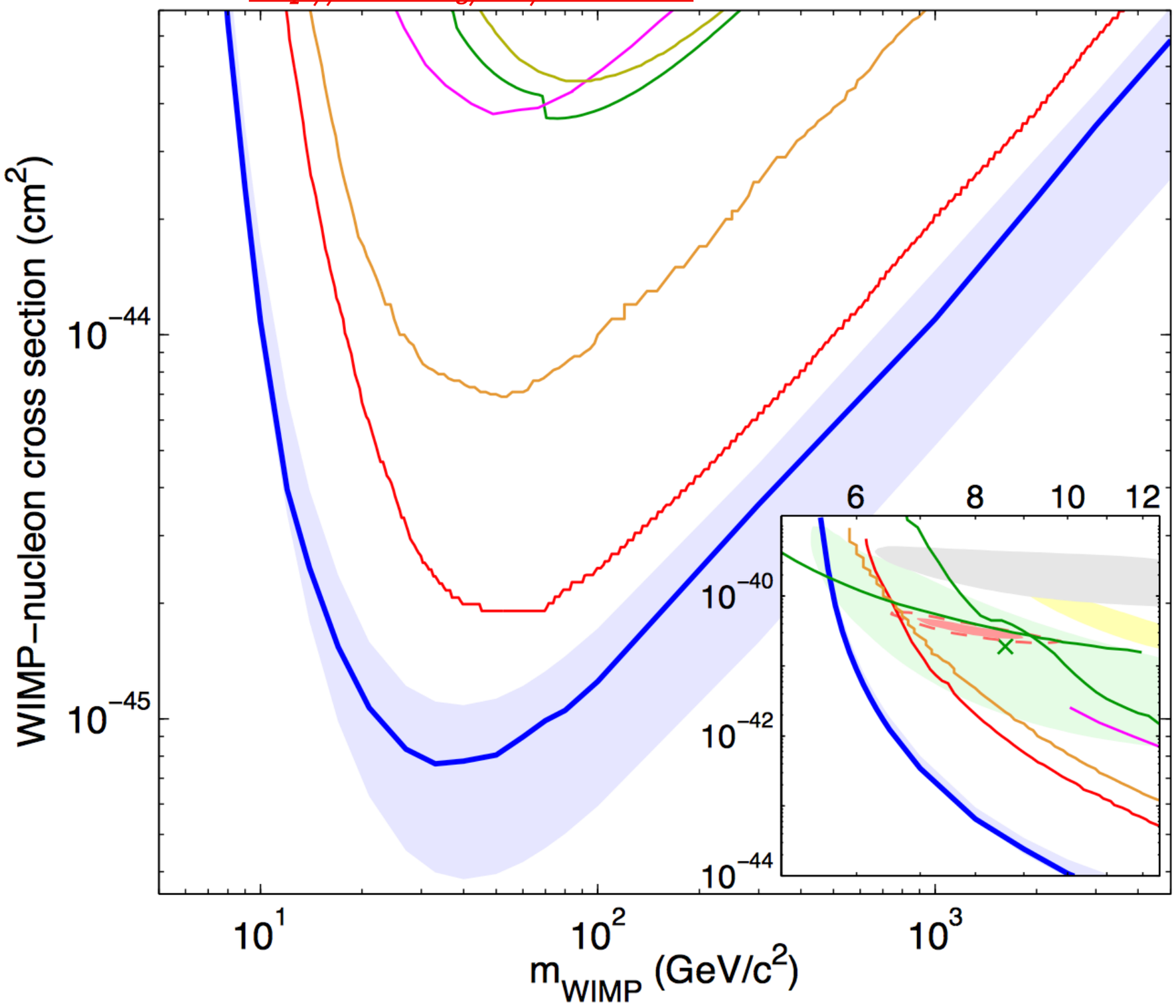


*LUX* http://arxiv.org/abs/1310.8214



# What would a discovery of dark matter look like?

Not this (maybe?)

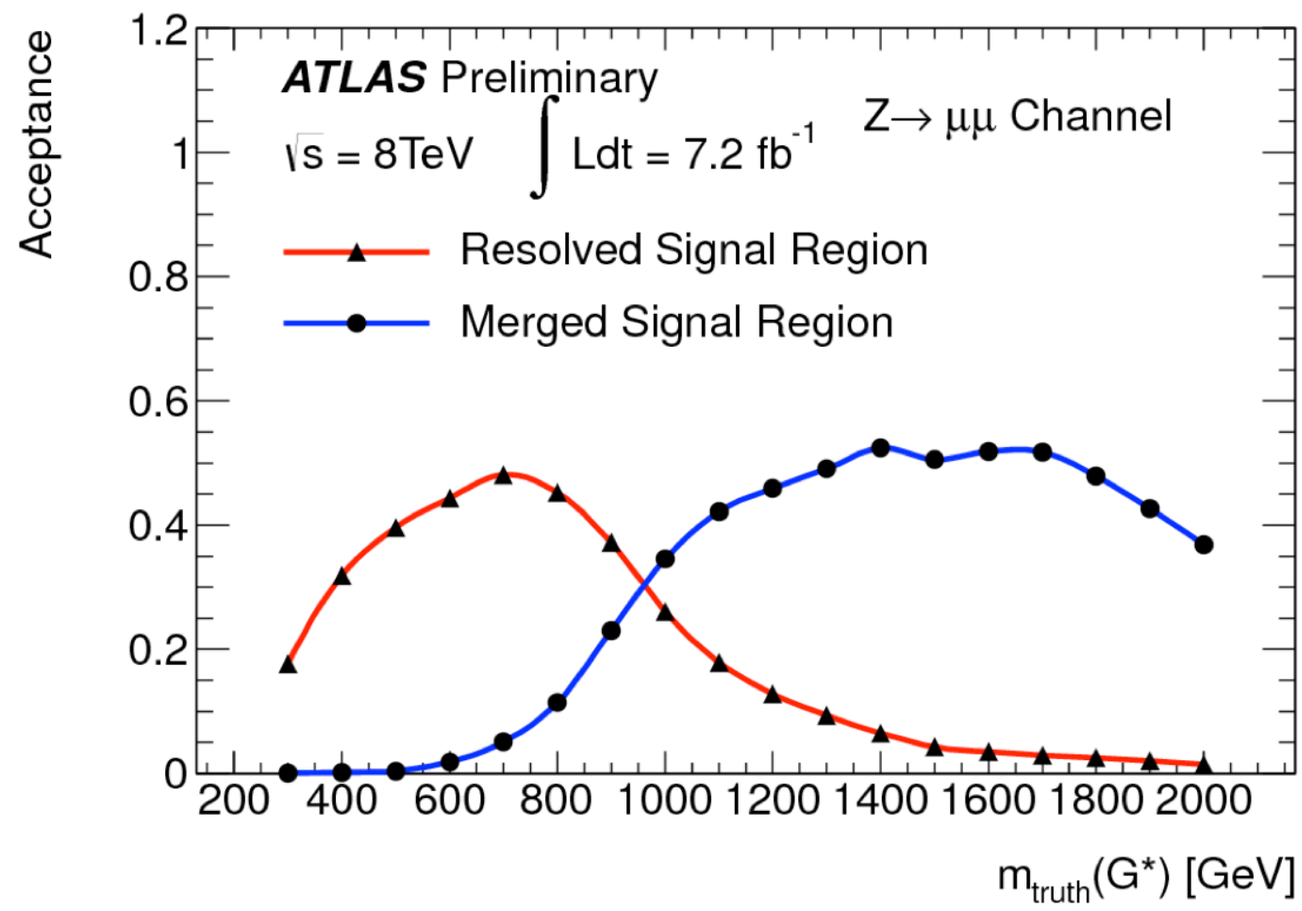
Consistent results, from multiple types of complementary experiments, will be needed

Some (but not all) results resemble light WIMP ~O(10) GeV , $\sigma$~few $10^{-41}$ $cm^2$

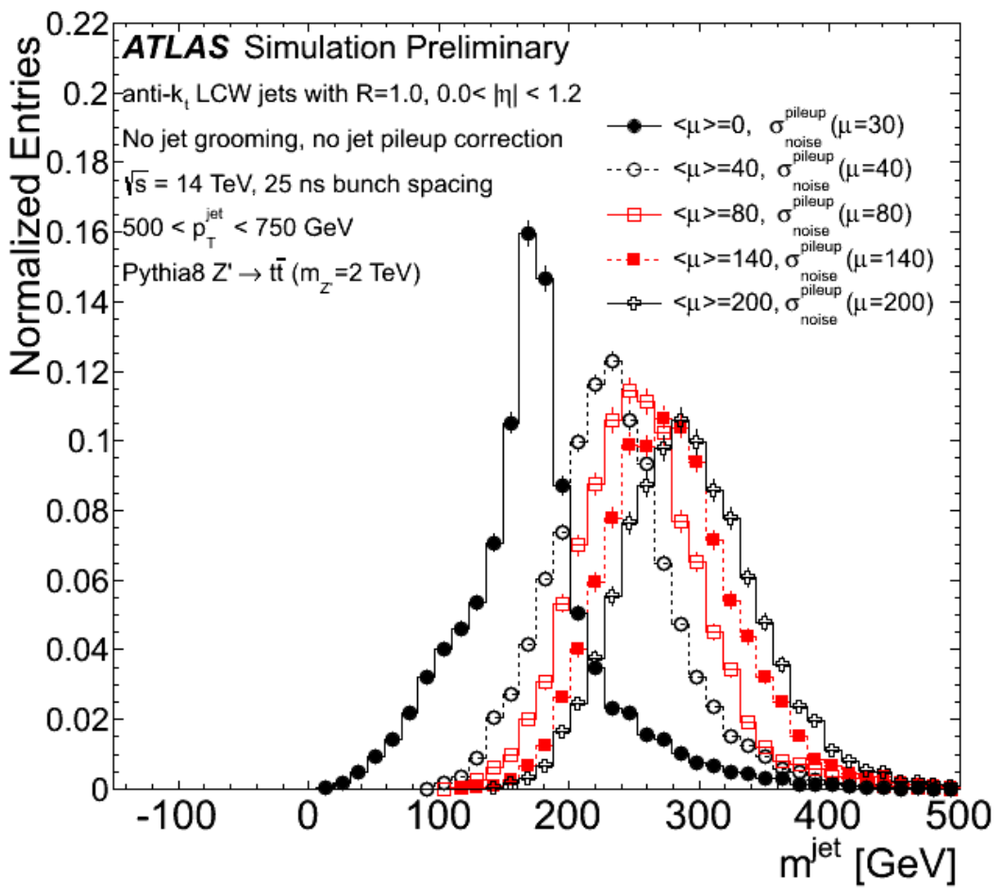
What can the LHC say about this?

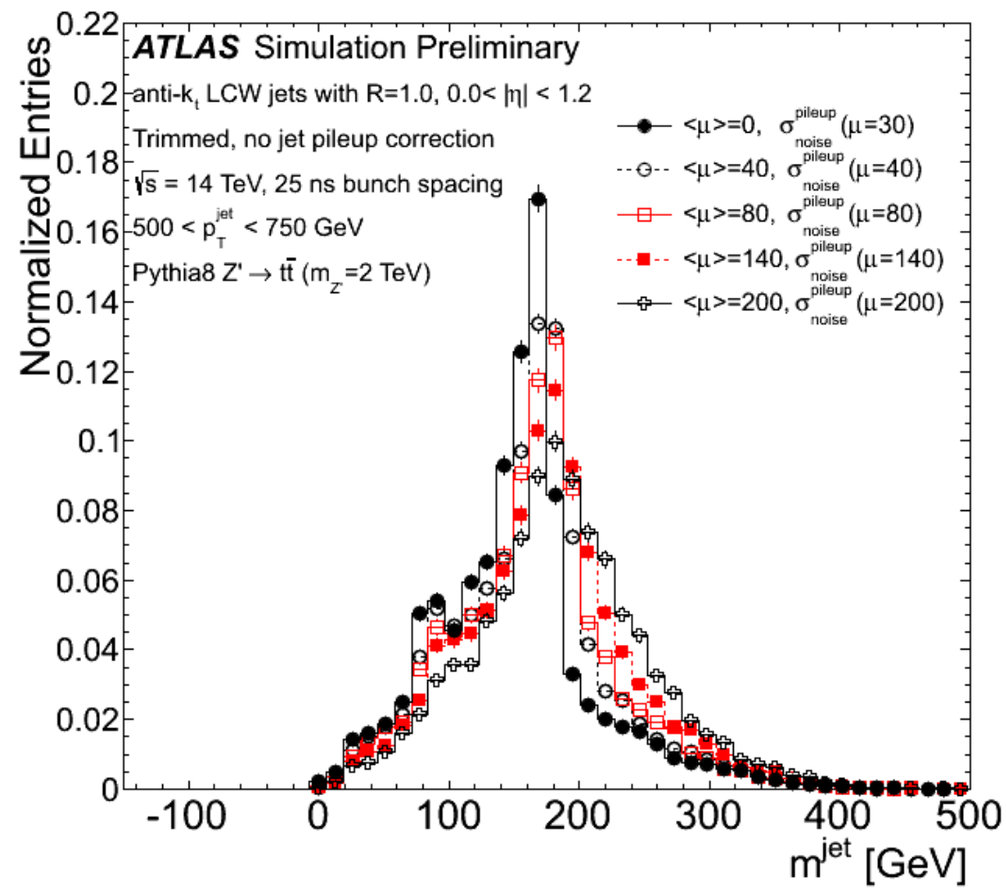
# The Growing Importance of Jet Substructure

- Pair-produced dijet resonances, known mass $m_Z$
  - "Resolved" lljj reconstruction loses efficiency as $p_T^Z >> m_Z$
  - Recover efficiency allowing Z=>jj merged into single jet
  - Suppress 'merged' background with jet substructure

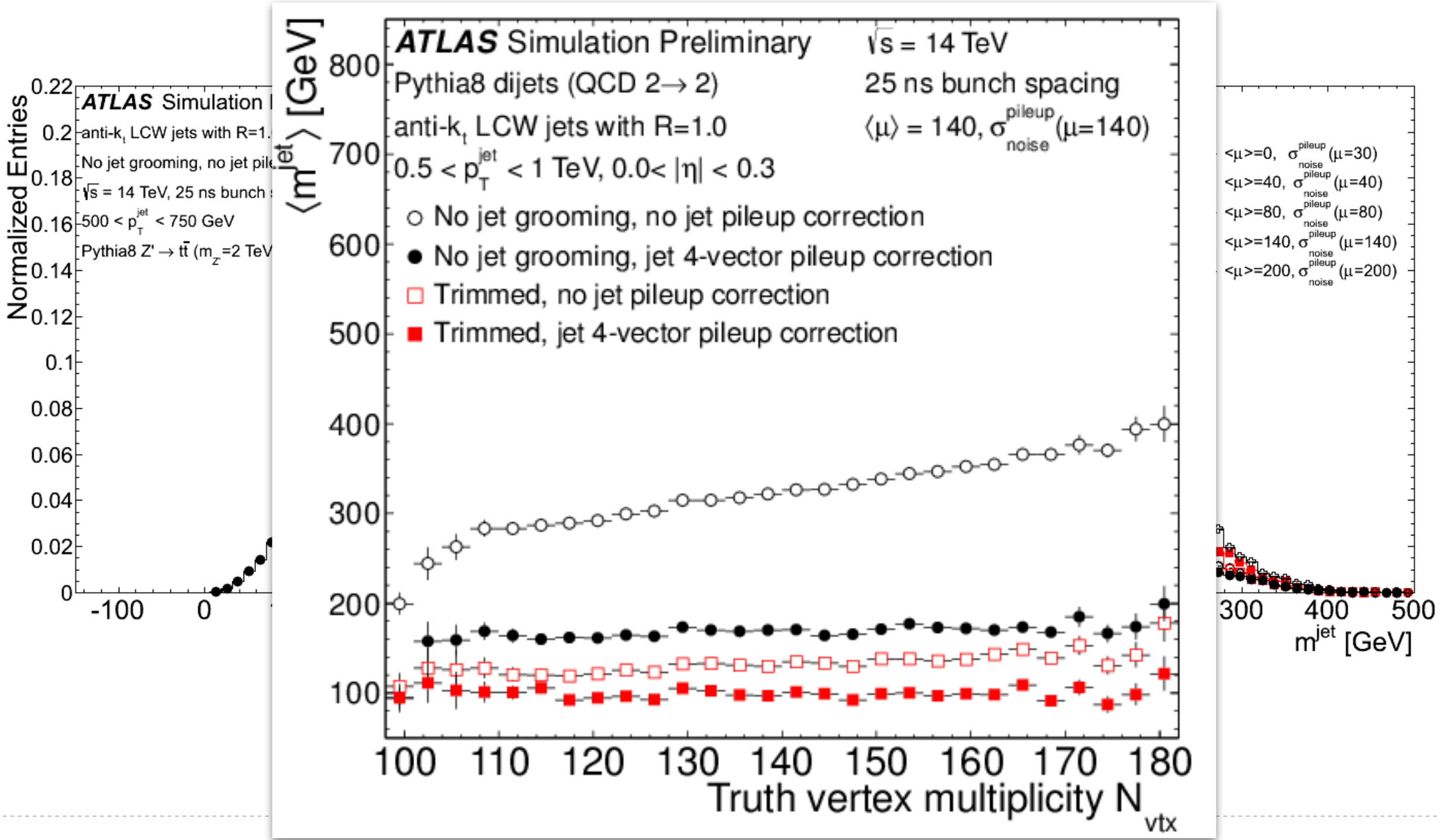


# Pile-up corrected jet substructure



# Pile-up corrected jet substructure



# FTK

*Since exact nature of BSM physics is unknown, trigger flexibility is vital.*

*ATLAS is preparing a Level "1.5" trigger upgrade to provide near-offline quality tracking for the Level 2 trigger algorithms.*

*Within 100 us of each Level 1 accept, FTK will perform $p_T > 1$ GeV tracking over the entire silicon system for the start of HLT processing. It divides tracking into two stages:*

- *Coarse pattern recognition with an associative memory*
- *Full-resolution FPGA track search and fits*

*Designed to handle Phase I pile-up (3x design luminosity)*

---

**Associative memory "road finding"**

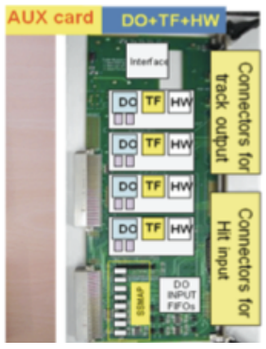
*Analyze a large sample of tracks and construct a frequency-ordered list of all hit patterns generated by the tracks in the detector. Look for each of these patterns in every event.*

- Group consecutive silicon channels into "superstrips" (SS) to reduce the number of unique patterns needed for high efficiency and the size of training track sample.
- Partition silicon detectors into 11 "logical layers."
- Result for high-pileup configuration is typically order 1 billion coarse-granularity hit patterns for $p_T > 1$ GeV tracks over the entire detector (smaller for early system).

**FPGA "track fitting"**

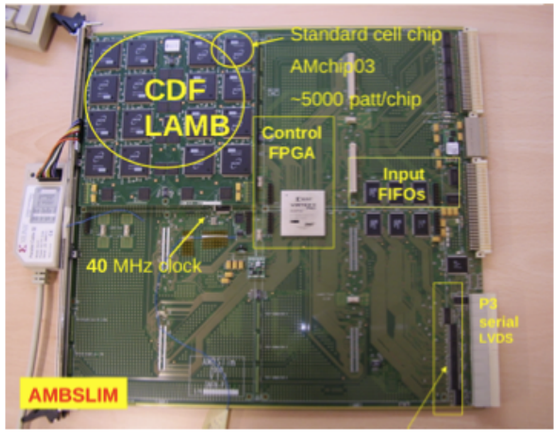
*Within each identified pattern ("road"), fit all full resolution hit combinations and apply a chi^2 cut.*

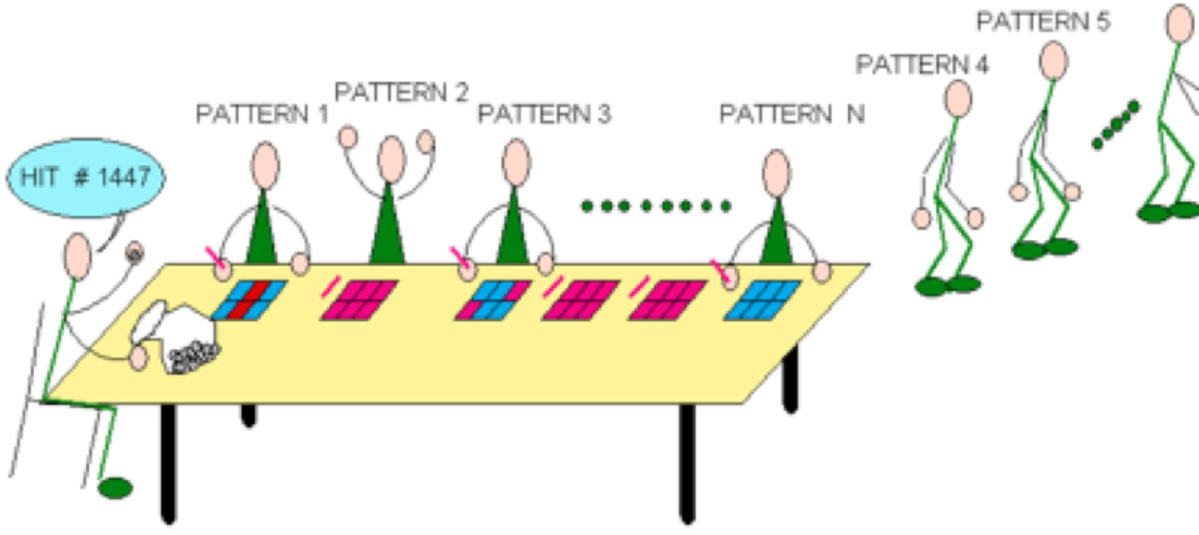
- Linearize the track fit: average track parameters for each combination of modules + first order correction for each hit—excellent approximation suitable for FPGAs with embedded DSPs.
- Full combinations have exactly one hit in each of the logical layers
- "Majority" roads/combinations have one logical layer with no hit.



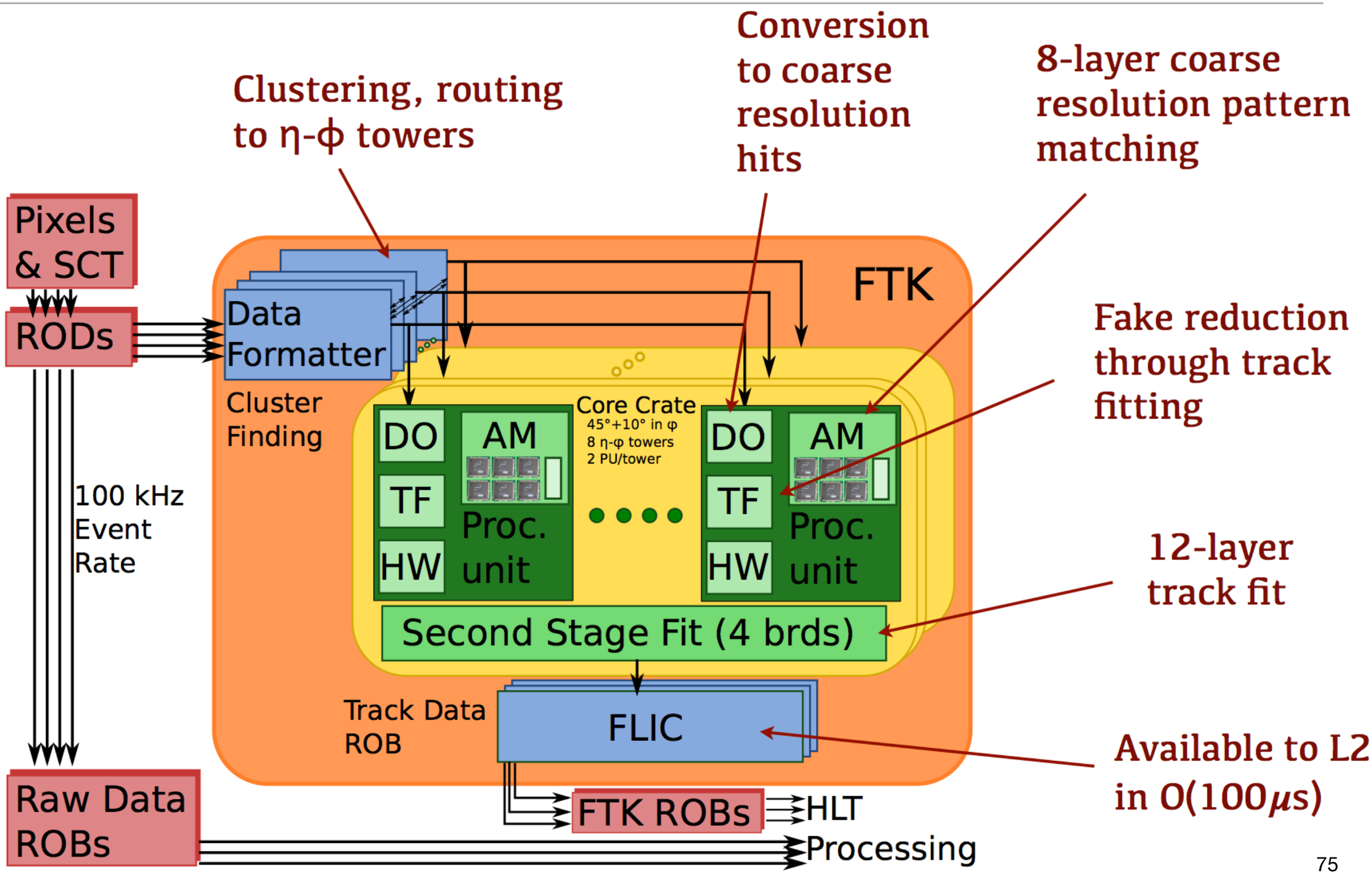

*The associative memory (AM) chip*

- Store each pattern in one cell of memory in a set of custom ASICs. Each cell compares its pattern to silicon data flowing through a common bus.
- When readout is complete, the AM stage is complete; pattern recognition occurs at the silicon readout speed.

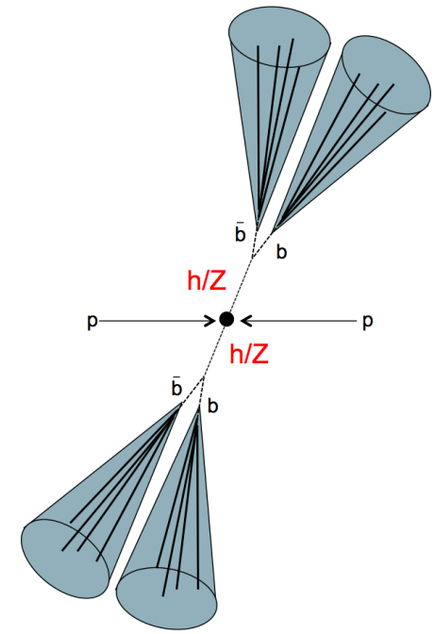


# System Architecture



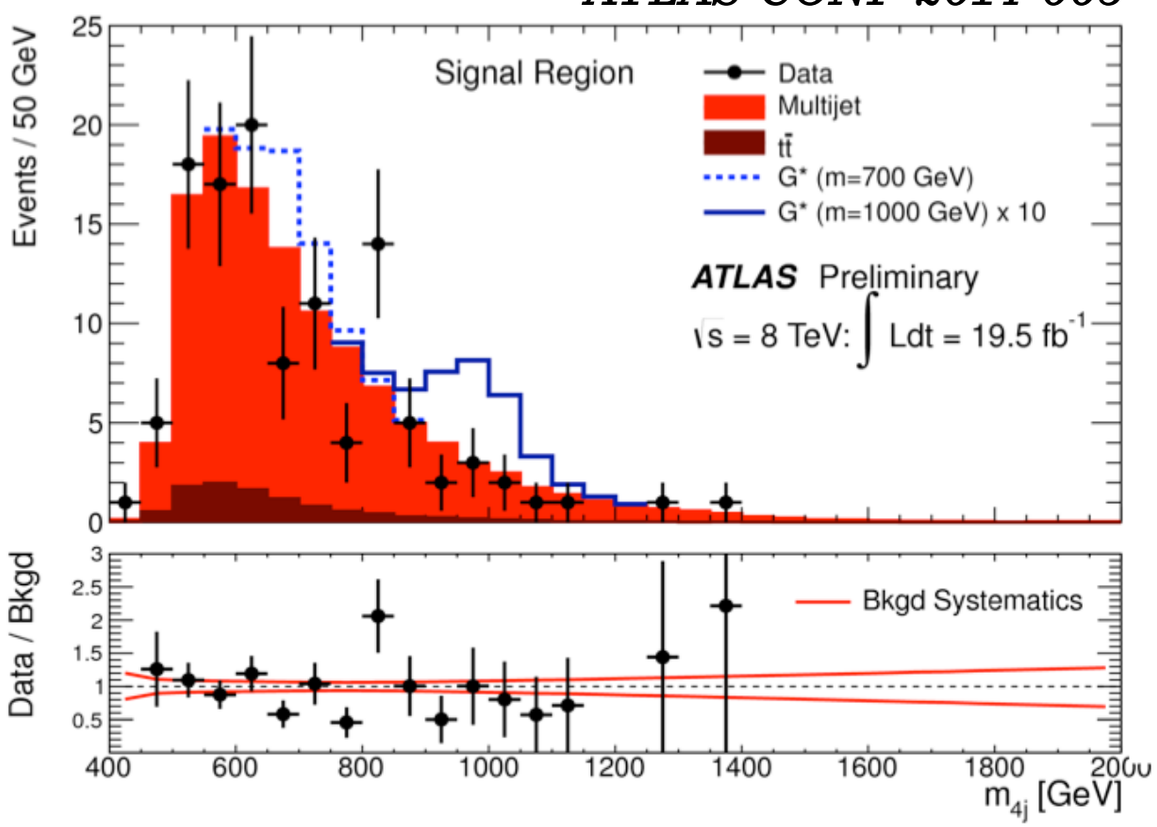
# FTK Example



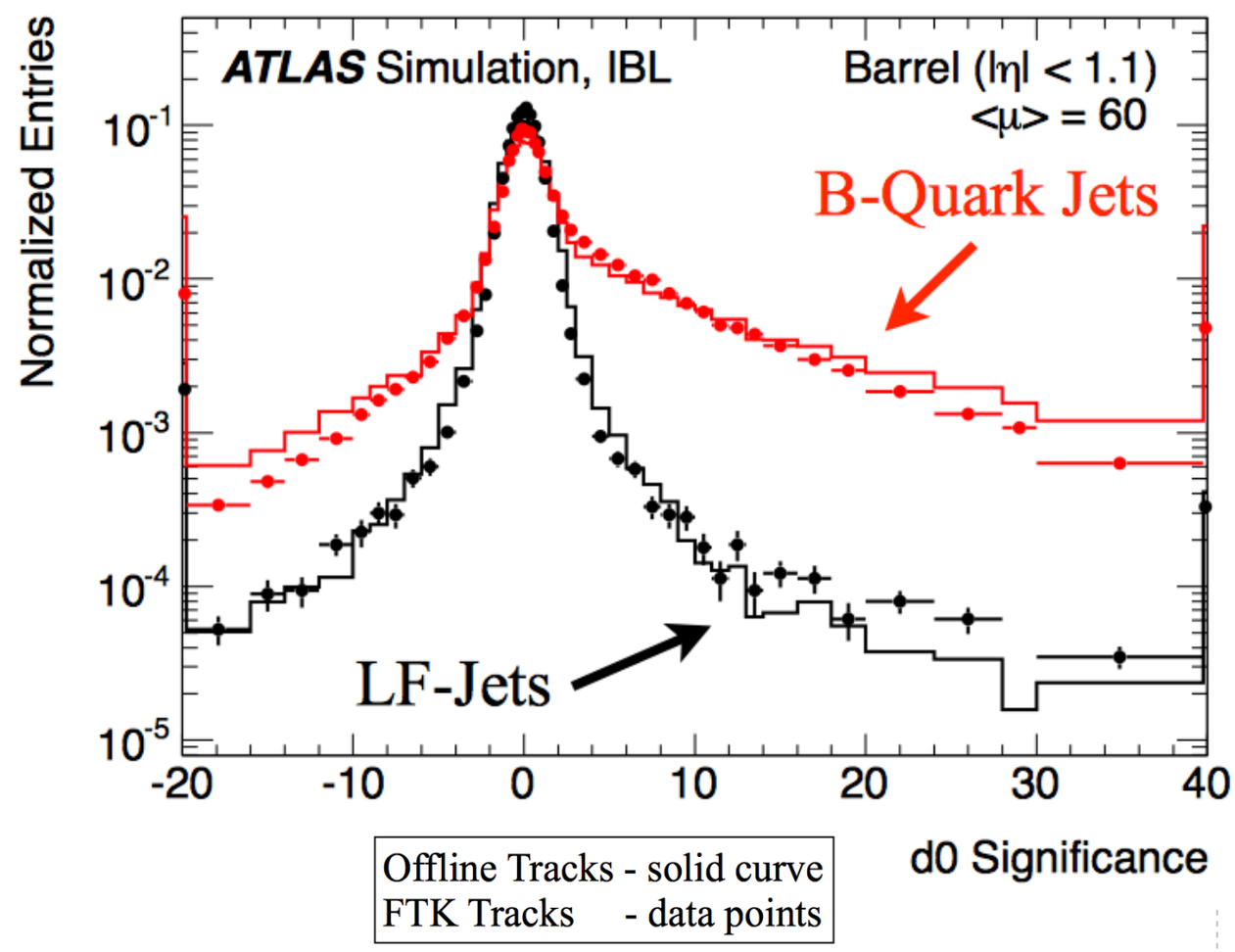

Luke Lambourne

*EF_b45_medium_4j45_a4tchad_L2FS + ...*

*ATLAS-CONF-2014-005*



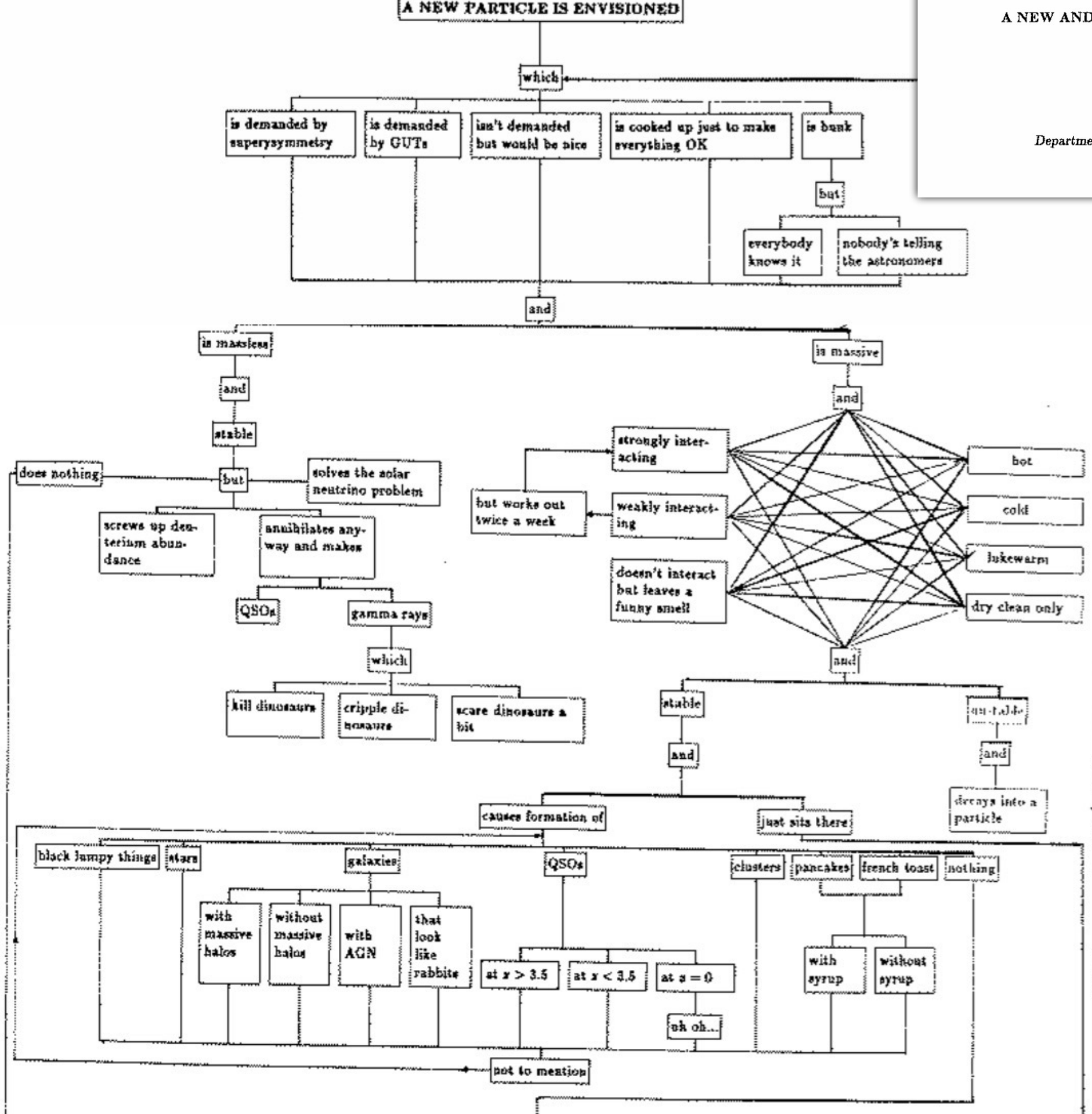

*μ=60 / ttbar /14 TeV / IBL*



A NEW AND DEFINITIVE META-COSMOLOGY THEORY

T. R. Lauer
T. S. Statler
B. S. Ryden
D. H. Weinberg

*Department of Astrophysical Sciences, Princeton University*



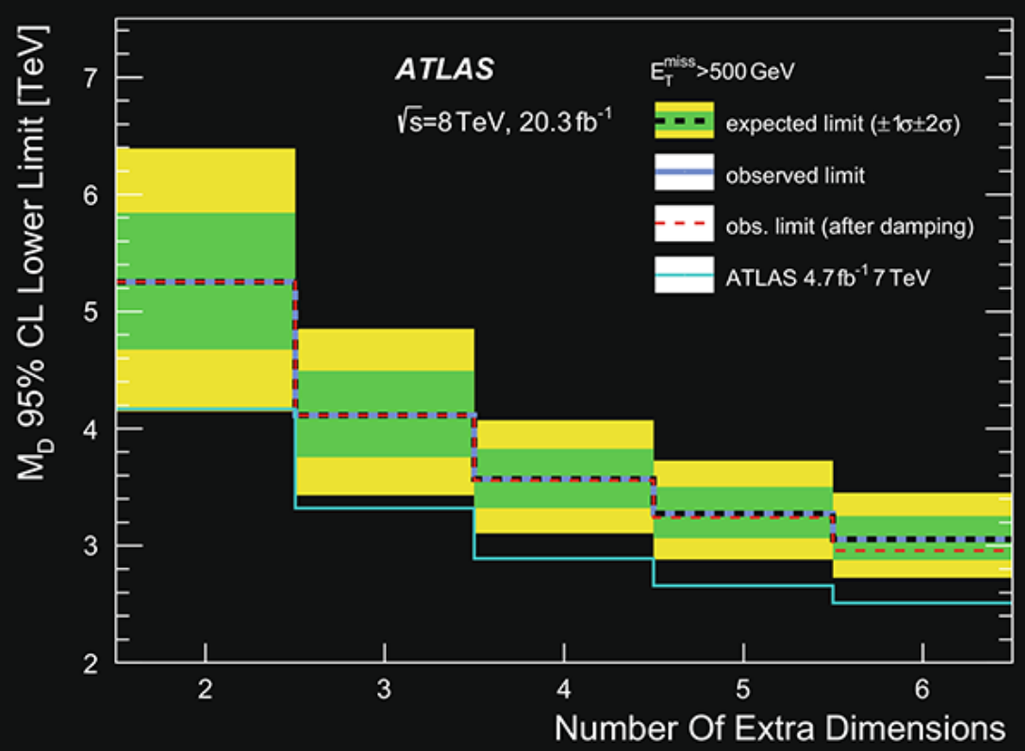
The European Physical Journal

volume 75 · number 7 · july · 2015

# EPJ C

Recognized by European Physical Society

## Particles and Fields

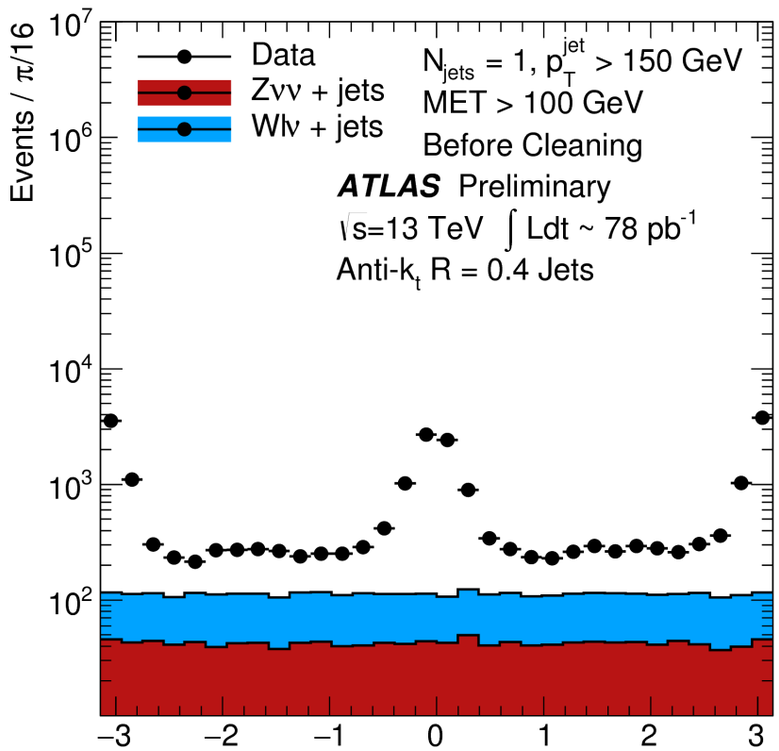


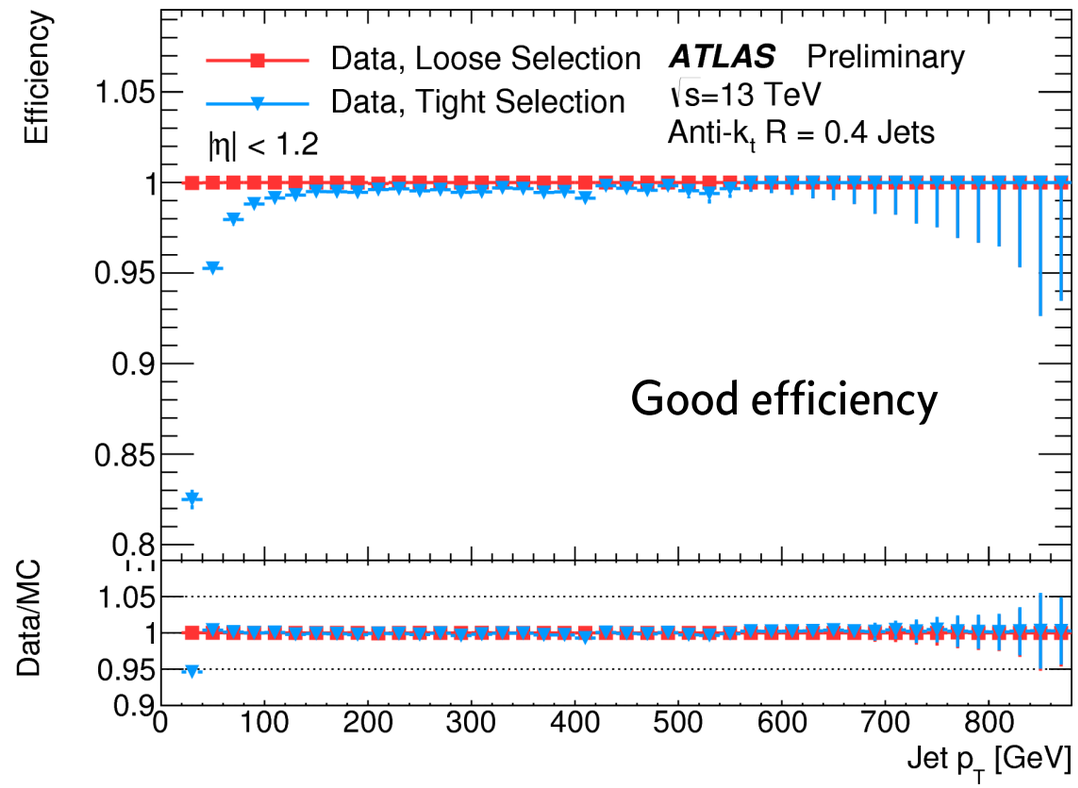

Observed and expected 95 % CL limit on the fundamental Planck scale in $4 + n$ dimensions, $M_D$, as a function of the number of extra dimensions. From ATLAS Collaboration: Search for new phenomena in final states with an energetic jet and large missing transverse momentum in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector.

Società Italiana di Fisica

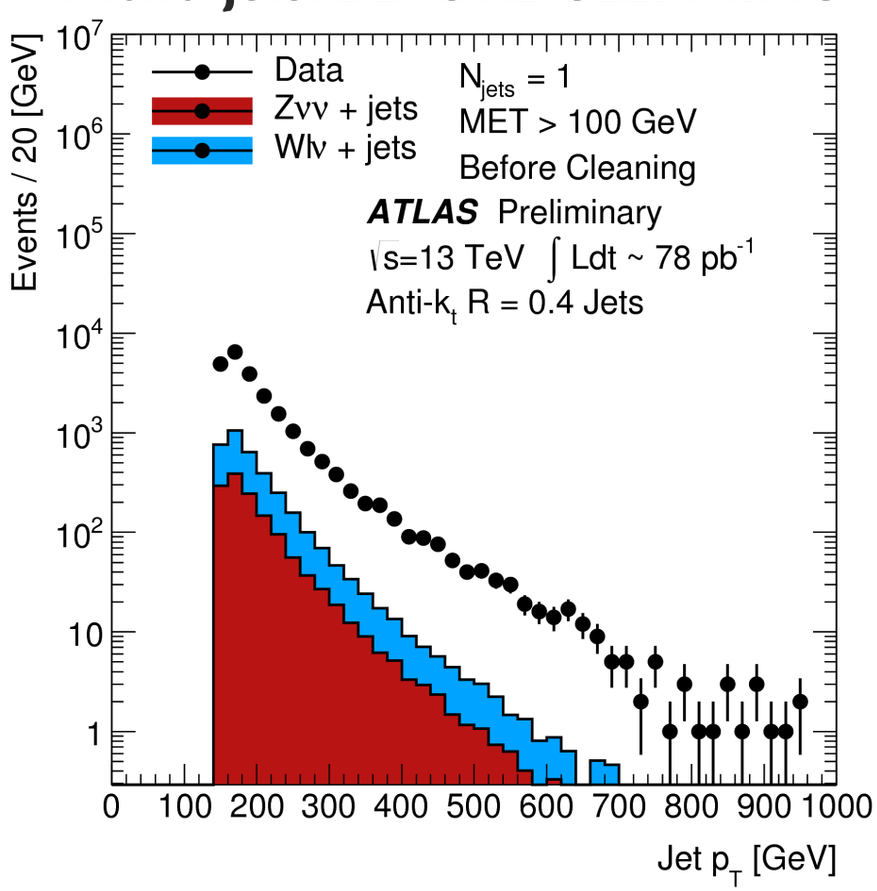
Springer

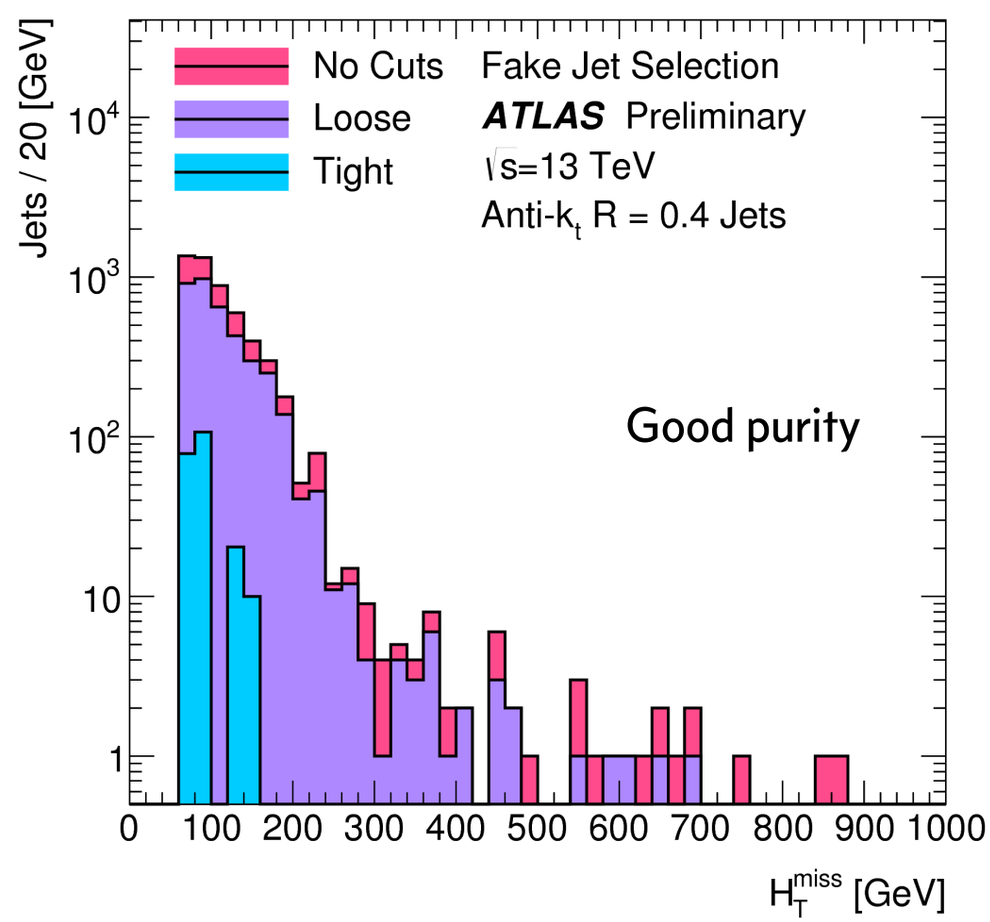
# Rejection of fake jets is crucial

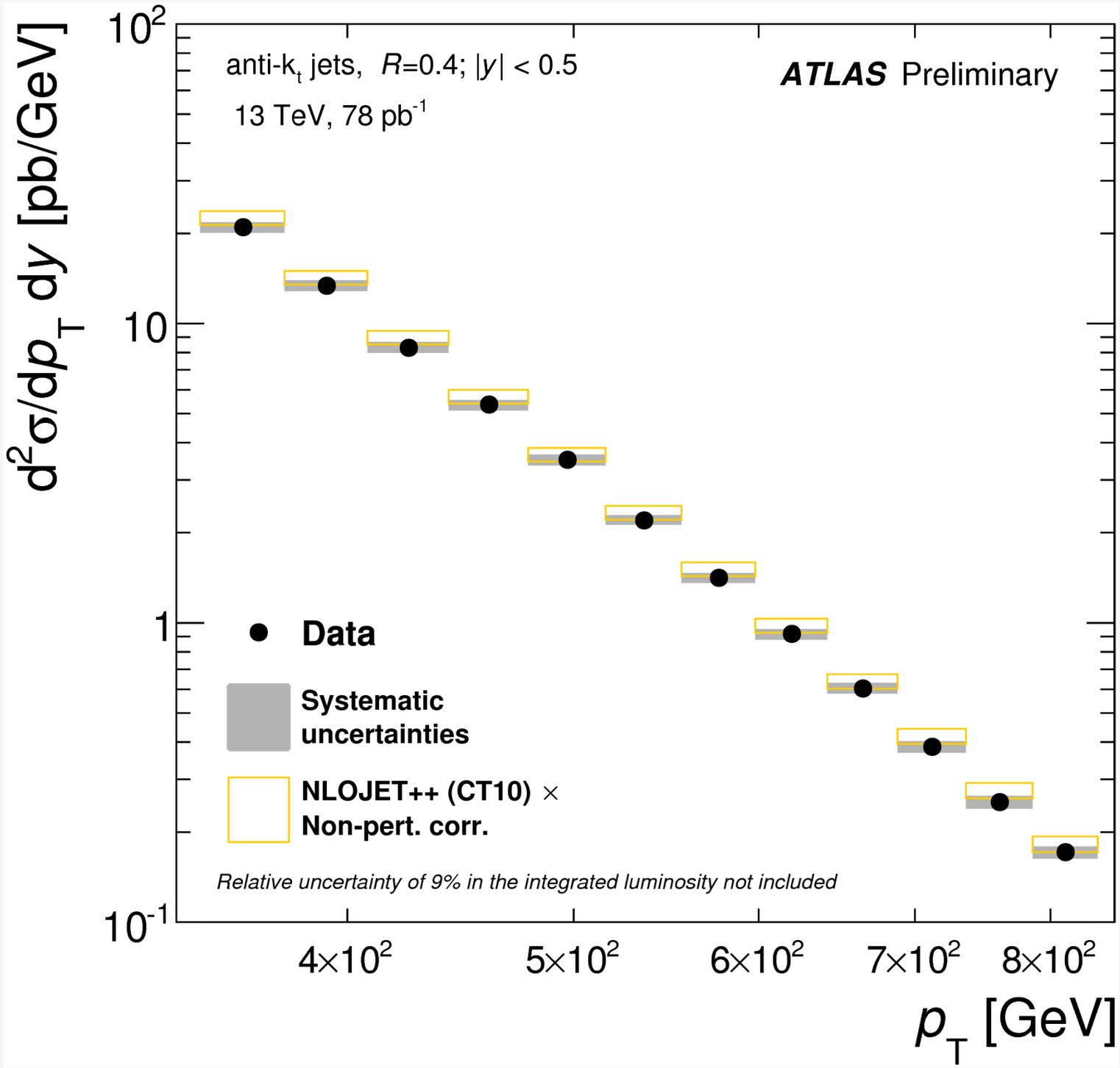


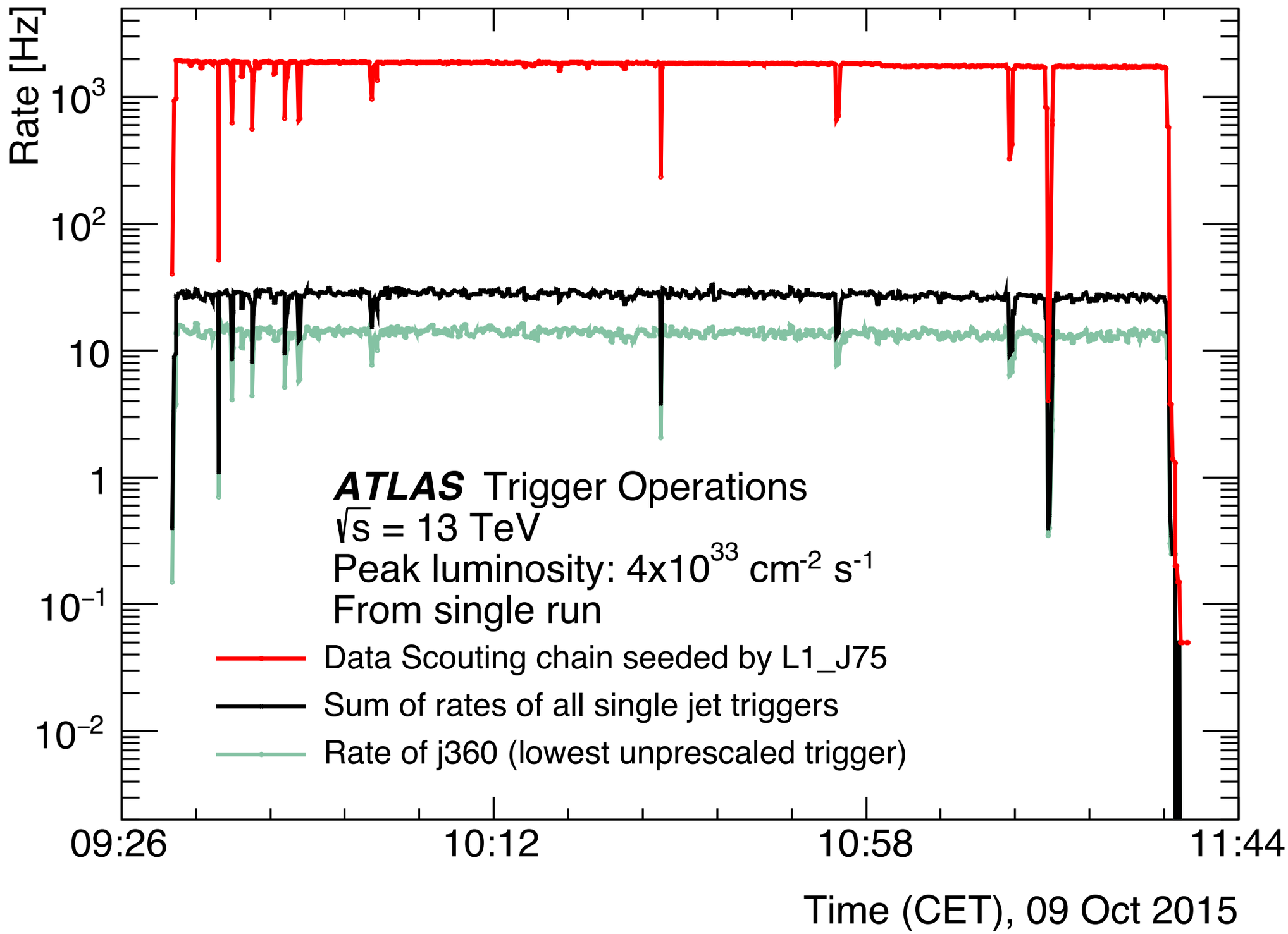




## Mono-jets: BEFORE CLEANING




anti-k$_t$ jets, $R$=0.4; $|y|$ < 0.5
13 TeV, 78 pb$^{-1}$
ATLAS Preliminary
Data
Systematic uncertainties
NLOJET++ (CT10) × Non-pert. corr.
Relative uncertainty of 9% in the integrated luminosity not included
$d^2\sigma/dp_T\,dy$ [pb/GeV]
$p_T$ [GeV]
$10^2$
10
1
$10^{-1}$
$4\times10^2$
$5\times10^2$
$6\times10^2$
$7\times10^2$
$8\times10^2$


Rate [Hz]
$10^3$
$10^2$
10
1
$10^{-1}$
$10^{-2}$
ATLAS Trigger Operations
$\sqrt{s}$ = 13 TeV
Peak luminosity: $4\times10^{33}$ $cm^{-2}$ $s^{-1}$
From single run
Data Scouting chain seeded by L1_J75
Sum of rates of all single jet triggers
Rate of j360 (lowest unprescaled trigger)
09:26
10:12
10:58
11:44
Time (CET), 09 Oct 2015

# Model-agnostic Searches: How to Look for the Unexpected?

# Model-agnostic Searches: How to Look for the Unexpected?

What new physics are we looking for?