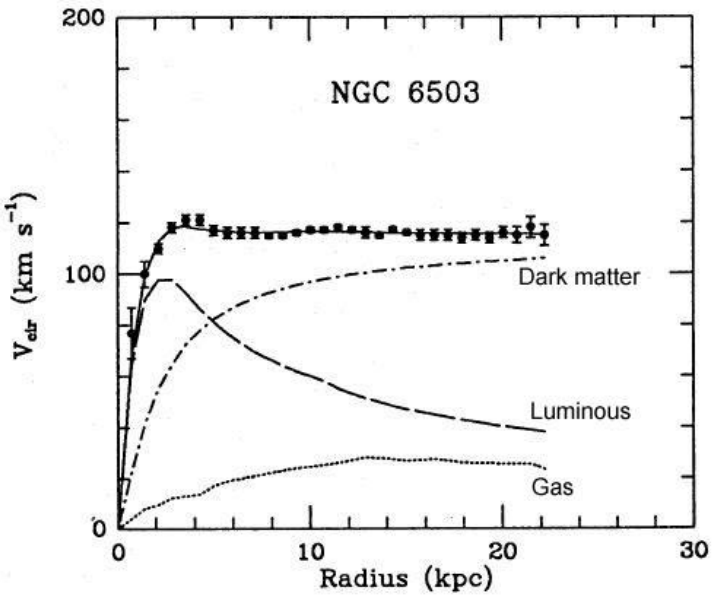
Dark Matter Searches at the LHC

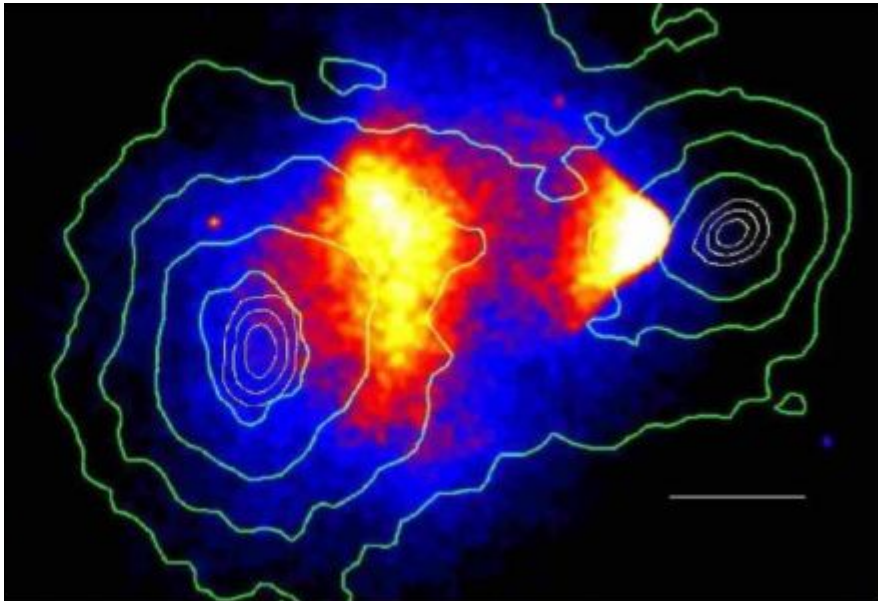
(this would include ~~all~~ some of the mono-object searches for example … *and also dijet searches?!?!*)

Sam Meehan
The University of Washington
5 June 2018

Why Dark Matter?

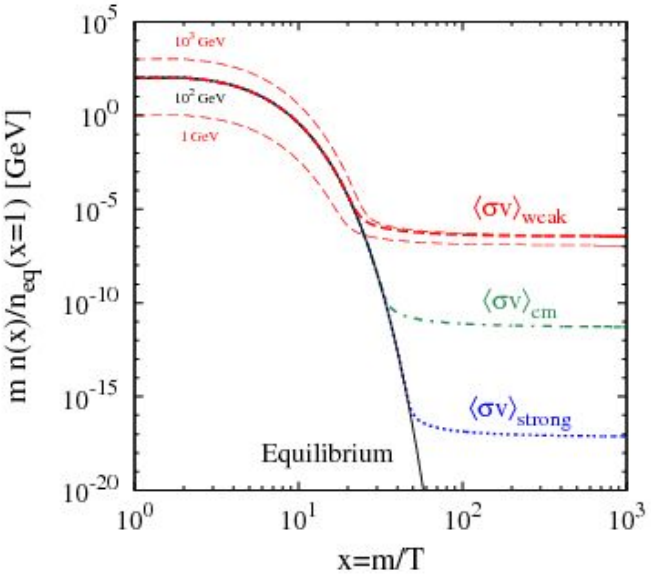
- Because it exists!
  - Clear empirical direction beyond the Standard Model
- 5x more abundant than ordinary matter! ➜ It's a big deal!

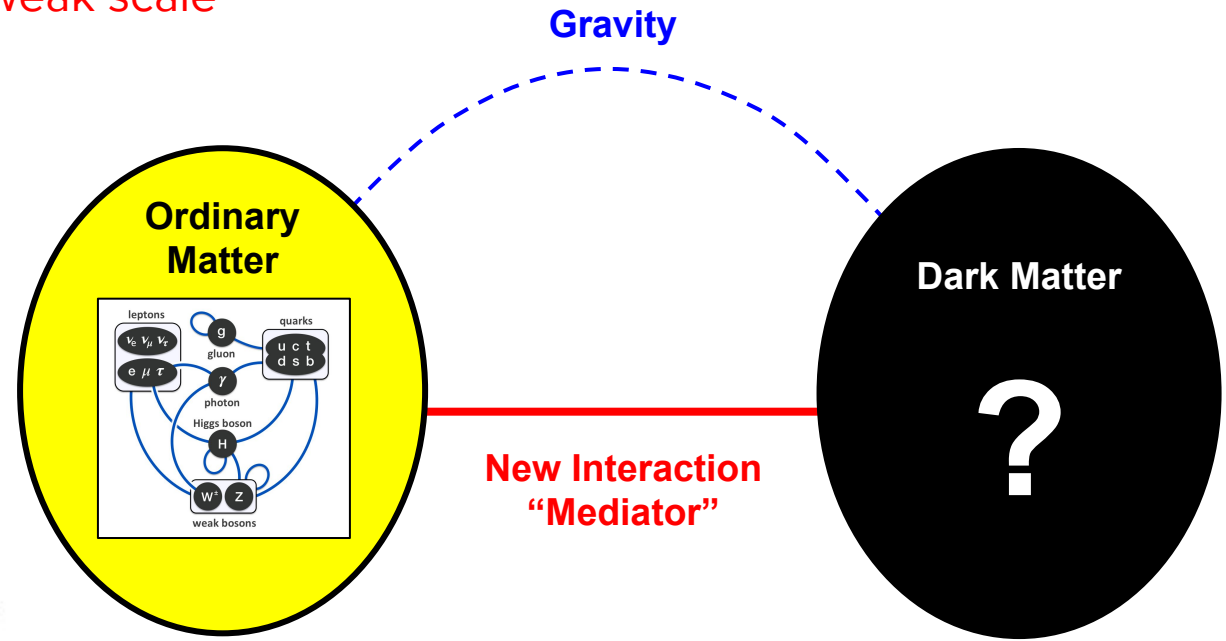




What do we know about it?

- Everything we know about dark matter comes from non-interactions and gravity
  - electrically neutral, non-baryonic, long-lived, slow-ish moving
- Other interactions are weak scale

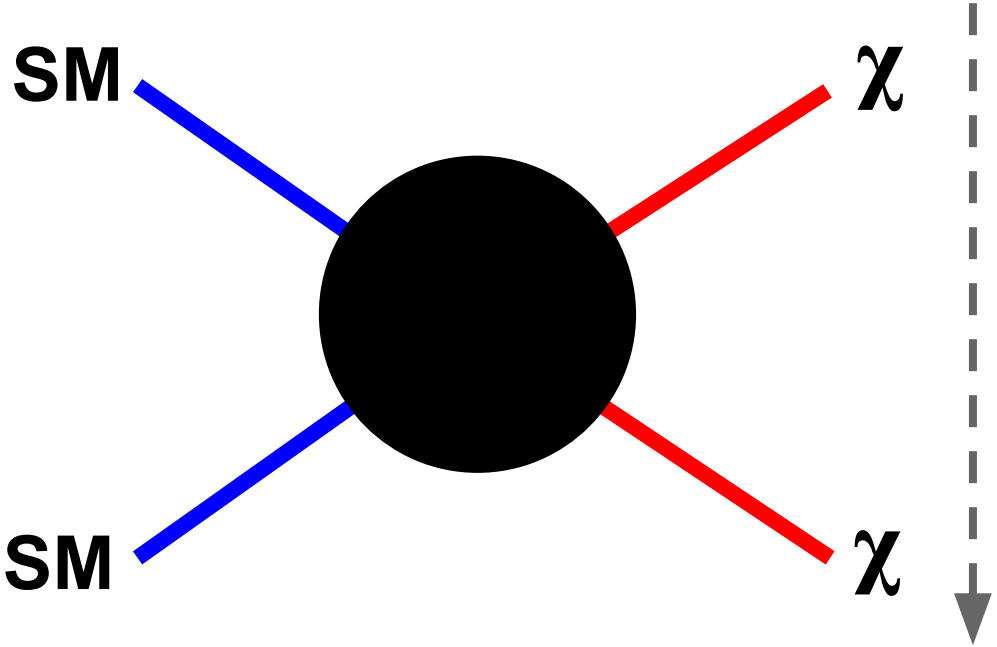


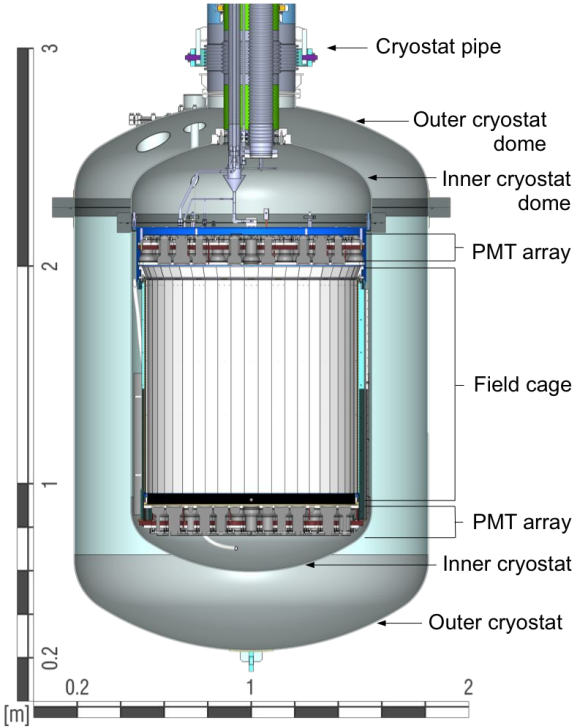


See also Kimberly Palladino

One Big Team

- Dark matter requires a global perspective on the search program
  - Direct detection (DD) + Indirect detection (ID) + Direct “production”





See also Mariangela Lisanti

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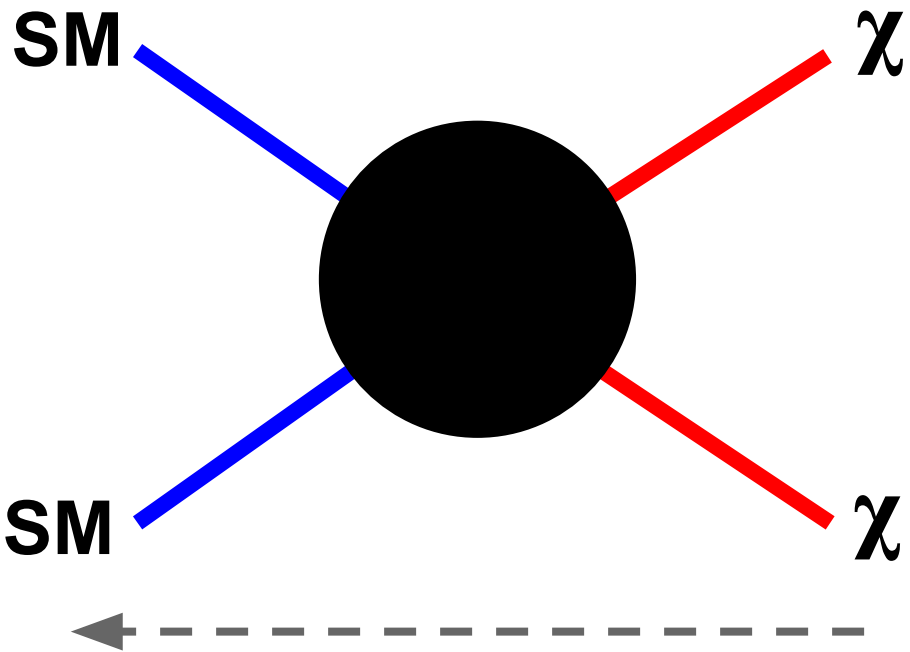

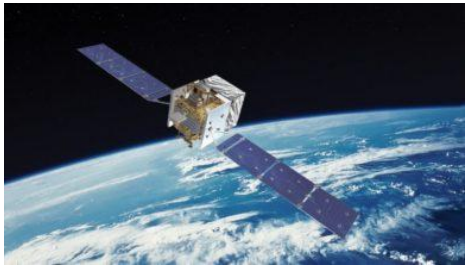

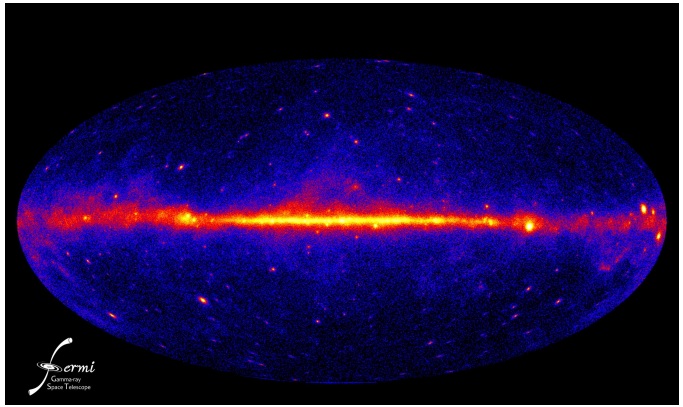

[See also Ryu Sawada DM@LHC Conf.]

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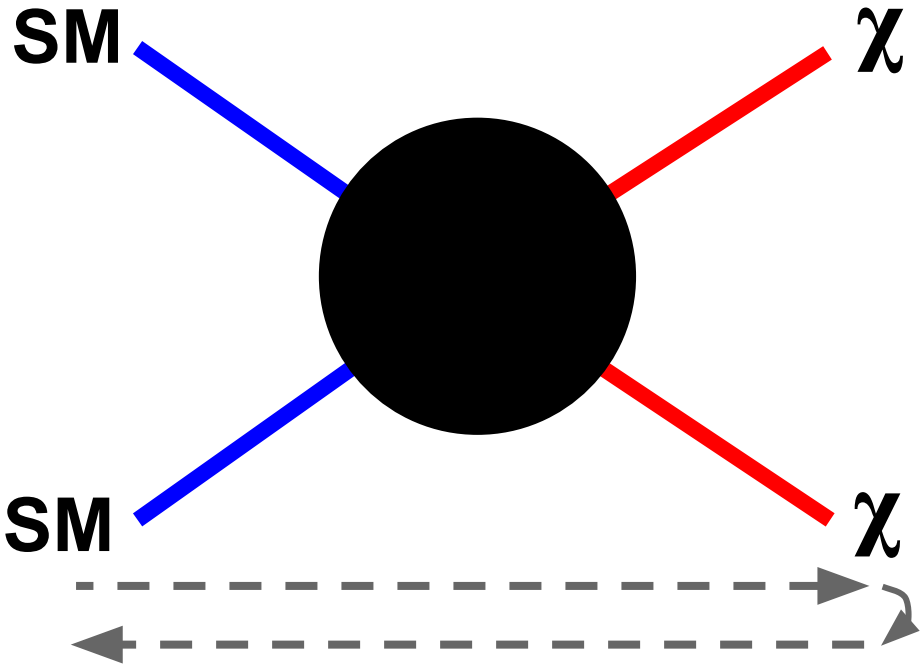
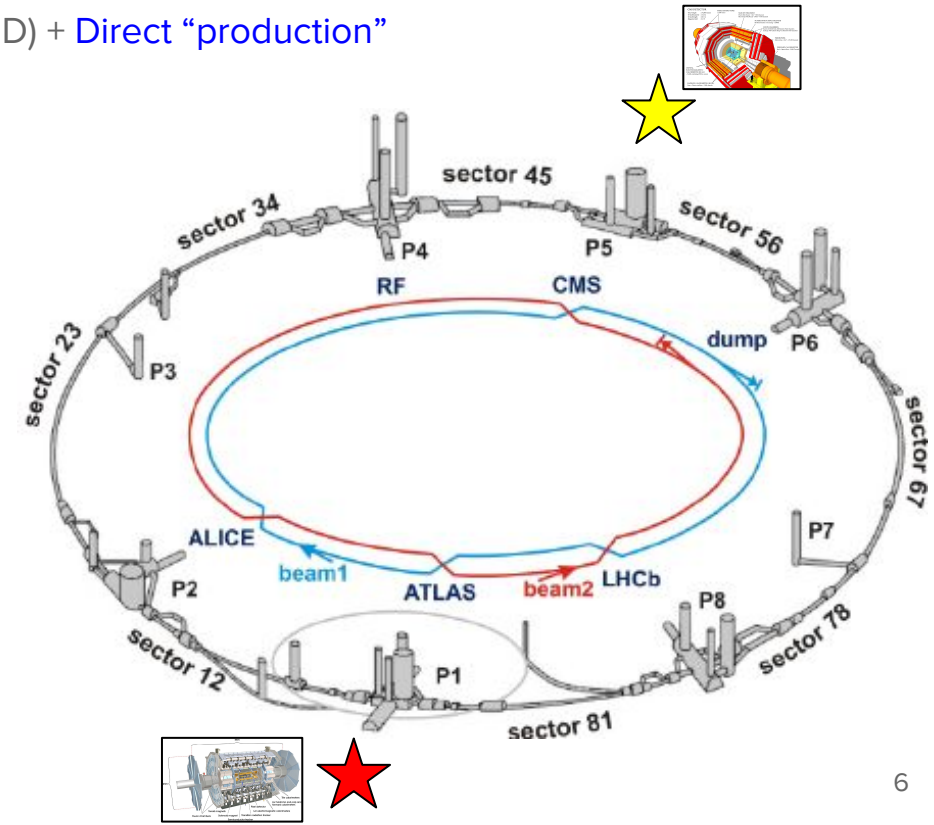


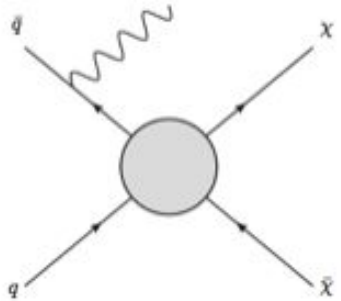


See also Nadja Strobbe

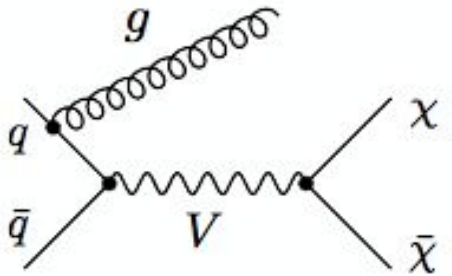
Why Dark Matter … at the LHC?

- Dark Matter is a cosmological “problem” adopted by the LHC
  - We can make complementary statements to DD and ID
  - And when we (eventually) see it, we can study it in the lab
- Caveat : We need some theoretical framing of the question

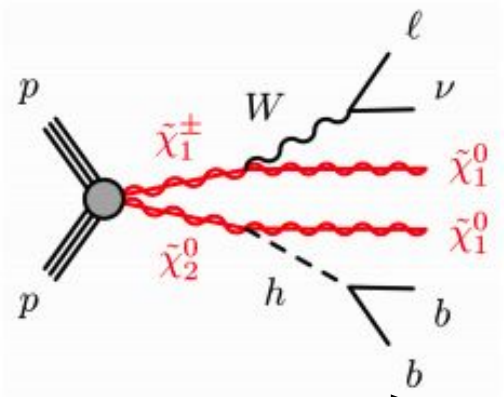
Effective Theories
(Run 1 bias)



Simplified Models
(Run 2 bias)



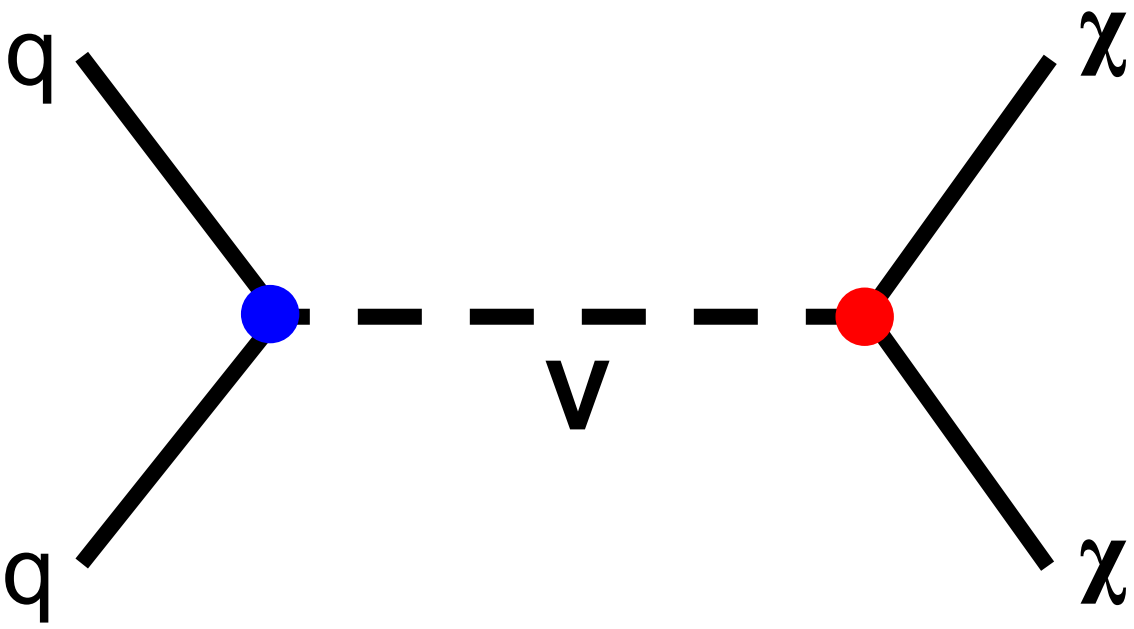
Complete Models
(SUSY)



More agnostic
Less “insightful”

More complete
More complex

The Lamppost



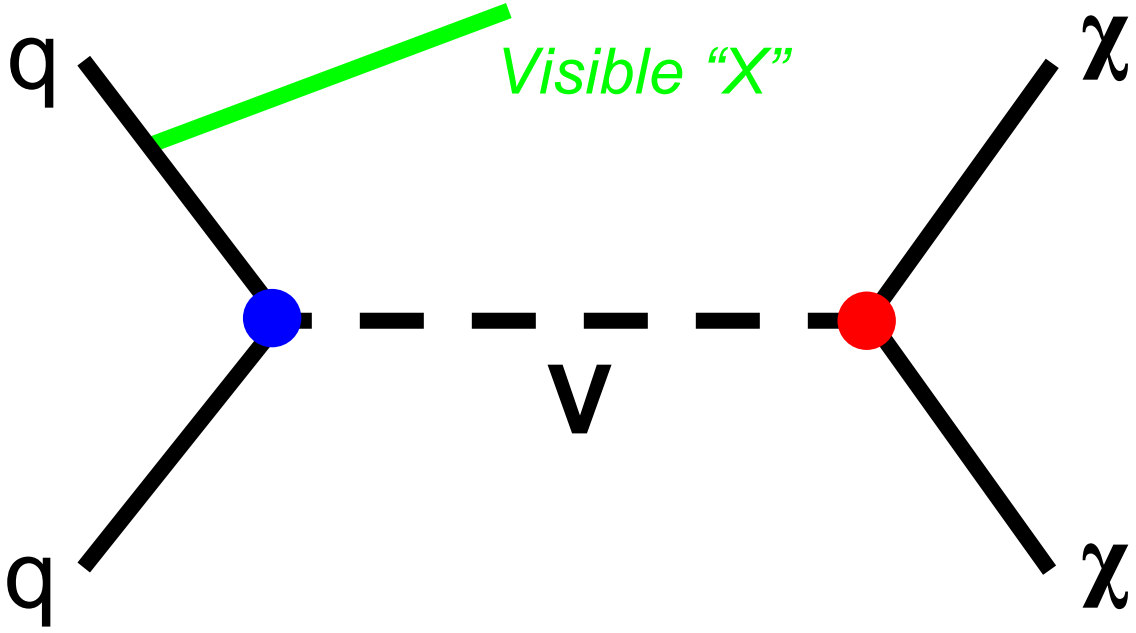
$g_q q\bar{q}A$ $g_{DM}\chi\chi\bar{A}$

Model Parameters

$$\left\{ \begin{array}{c} g_q \\ m_{med} \\ g_{DM} \\ m_{DM} \end{array} \right\}$$

1507.00966

The Lamppost - "Mono-X"



Model Parameters

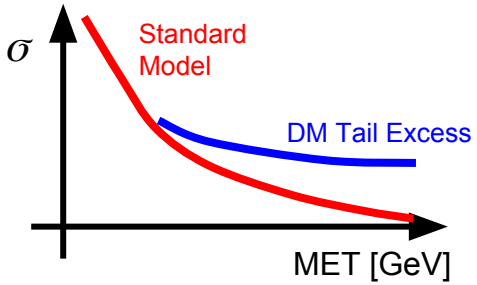
$$\left\{ g_q,\ m_{med},\ g_{DM},\ m_{DM} \right\}$$

1507.00966

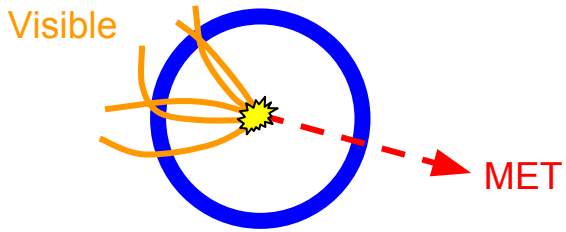
General Strategy

- Similar generic strategy followed by all Mono-X searches
  - Searching for excess in energy imbalance - missing transverse energy/momentum = “MET”

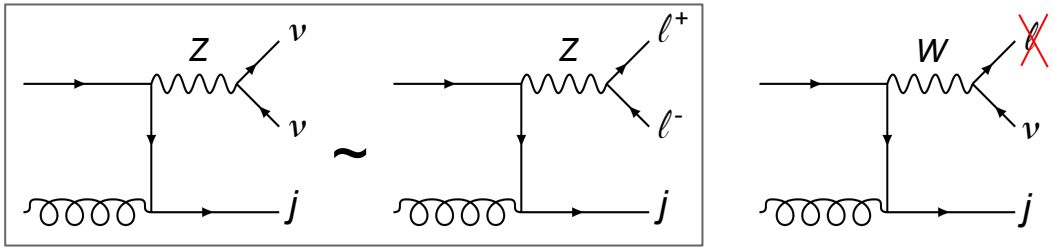
***(1) Goal** - Search for excess in MET tail*



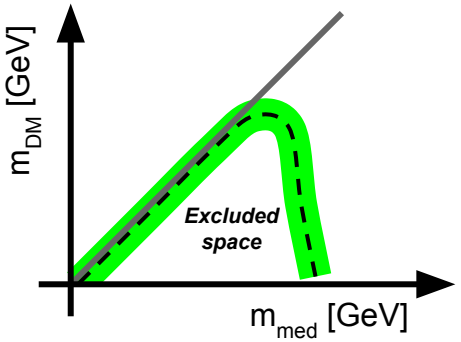
***(2) Select** - Select events with “X”*
- veto other activity (i.e. e,μ)



***(3) Backgrounds** - Z(νν)+“X” , W(lν) lost lep, ttbar*
- dedicated CRs to correct MC

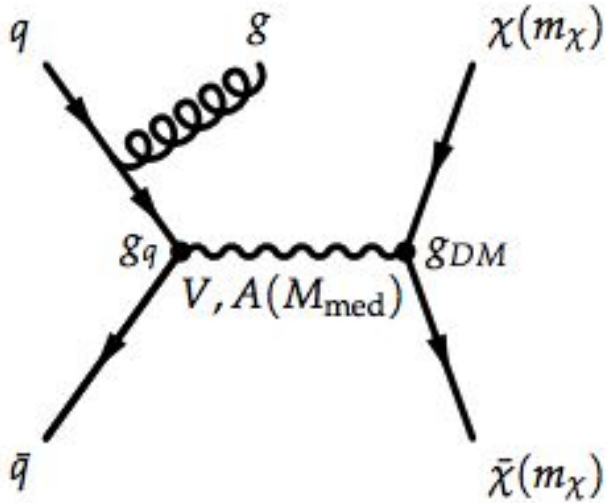


(4) Constraints
- Choose $\{g_q, g_{DM}\}$ → *Exclude* $\{m_{med}, m_{DM}\}$

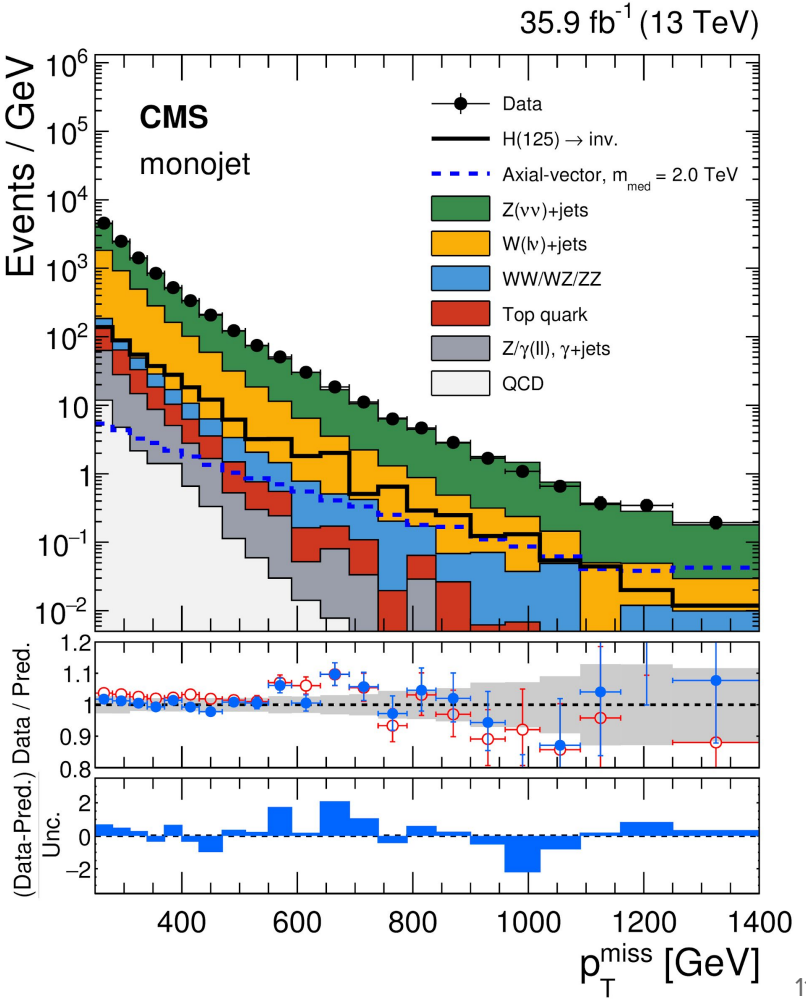


MonoJet

- Visible “X” is a gluon = monojet
  - Not new idea - first at UA1/UA2 in 1980’s
- Jets and nothing else … seems easy.

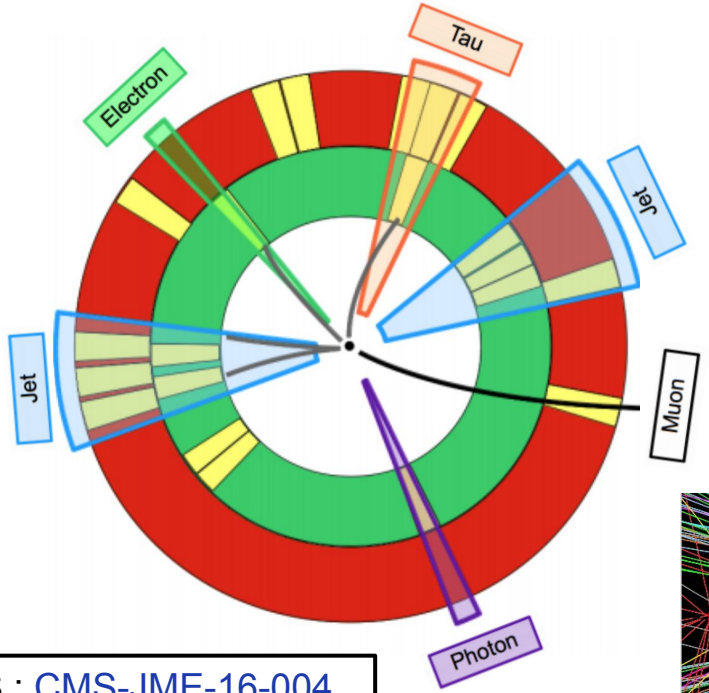


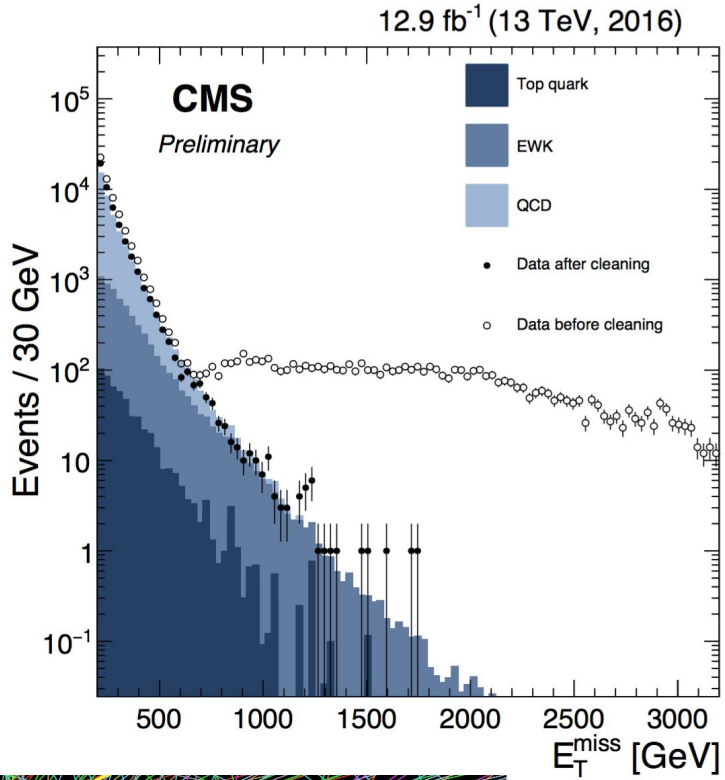
CMS : EXO-16-048
ATLAS : EXOT-2016-27

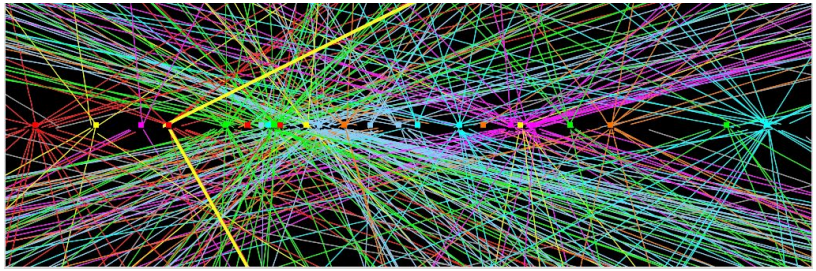


Ahhhh signal?

- Accurate/precise hadronic reconstruction (jets and MET) is hard
  - Beam halo, dead cells, noise bursts, pileup



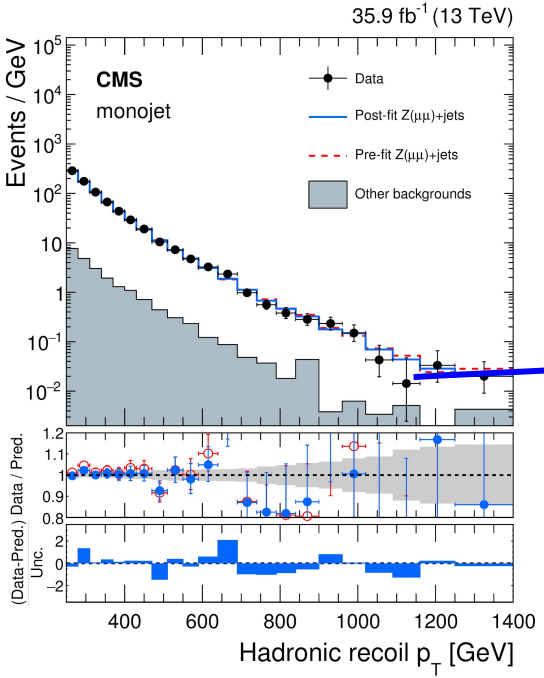


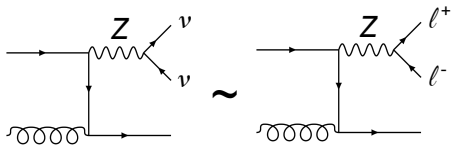


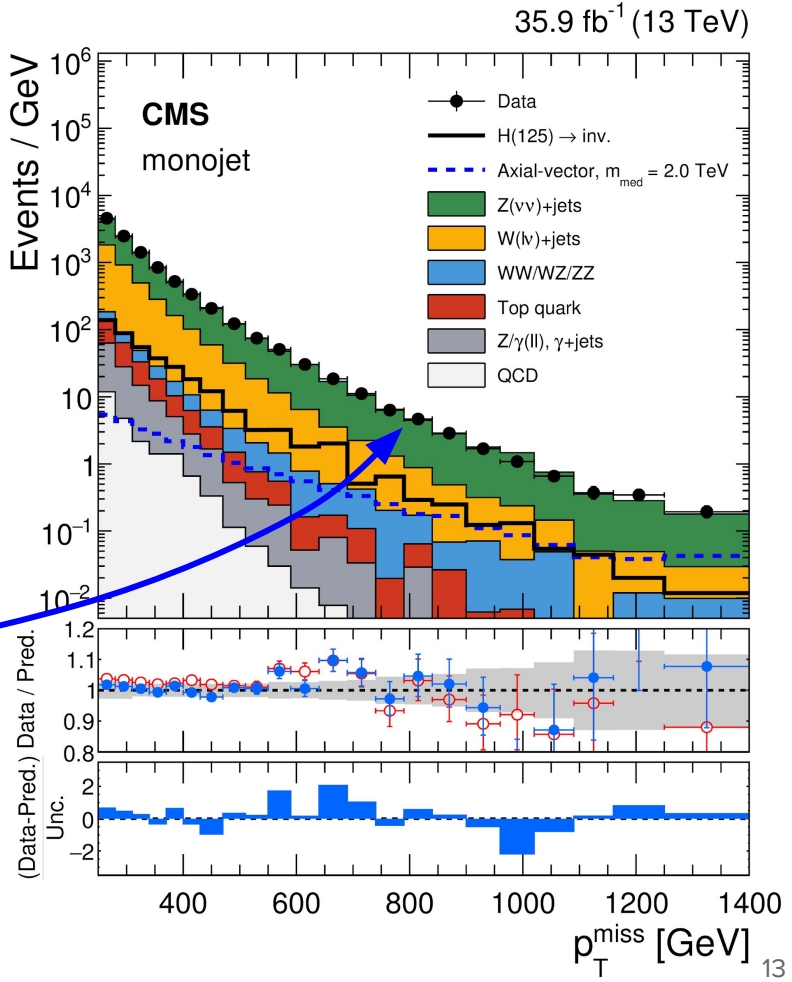
CMS : CMS-JME-16-004
ATLAS : PERF-2016-07

Backgrounds

- Primary backgrounds come from
  - Z(νν)+jets : real MET and real jets ➔ irreducible
  - W(lν)+jets : lose a lepton due to reconstruction
- Challenge is to understand them precisely

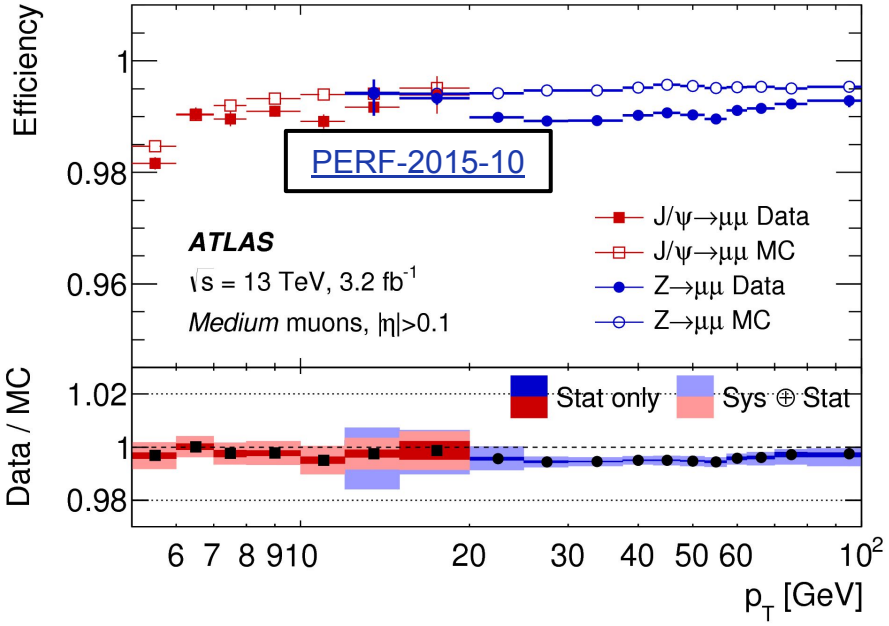


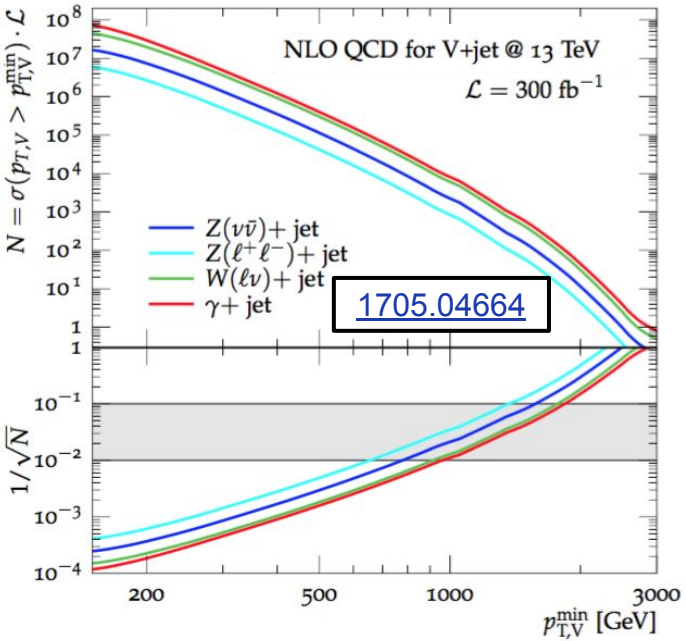




Backgrounds - Experiment & Theory

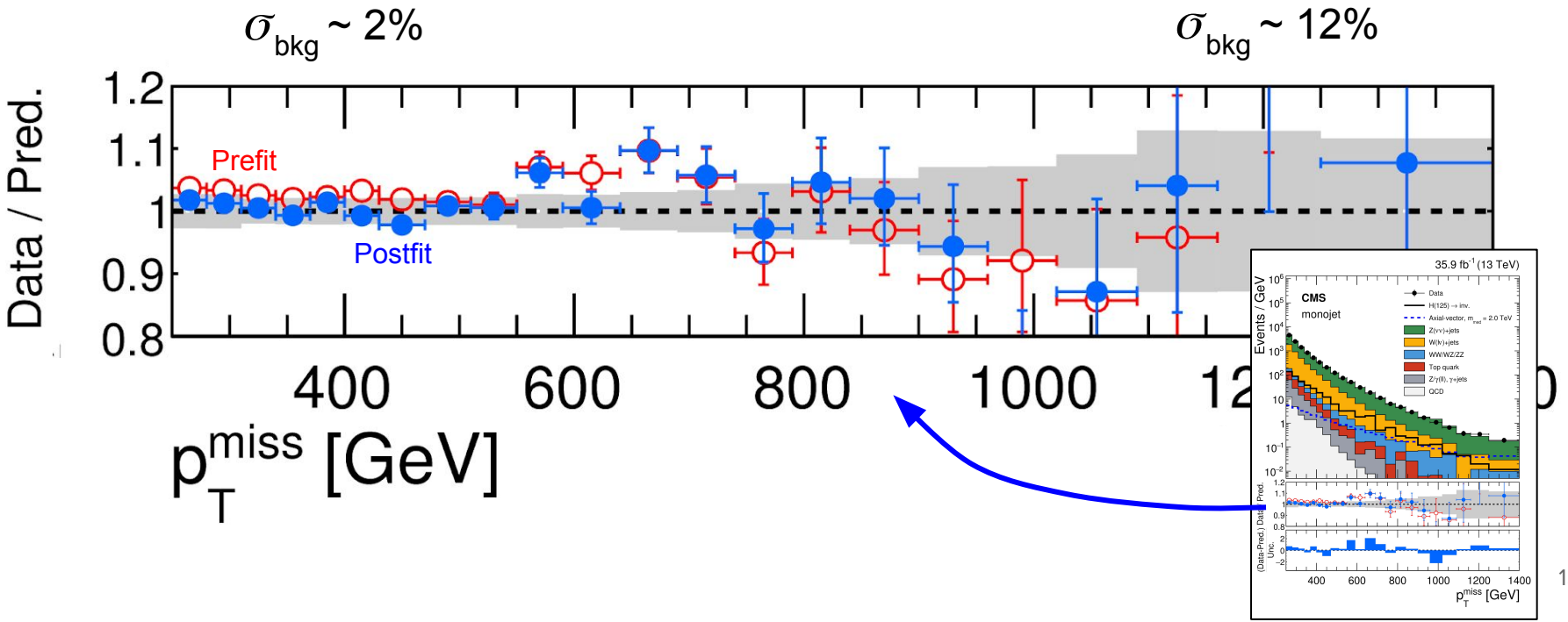
- Charged leptons are invaluable for SM measurements
  - Calibrate kinematics and identification efficiency to level of ~1%
- Precise theory of differential backgrounds is crucial for MC-based estimation
  - (1) lower uncertainties & (2) constrain high energy prediction with low energy data





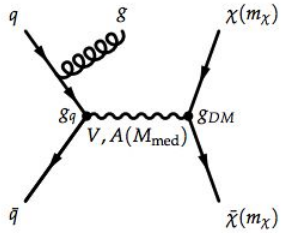
A “Precision Search”

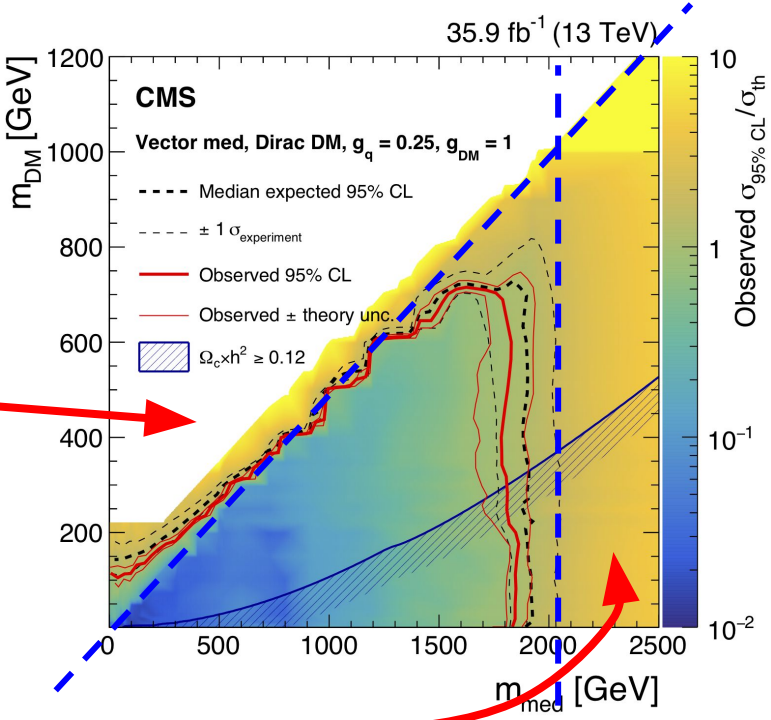
- Canonical searches are entering a precision era : searches ➔ measurements
- MonoJet is limited by the exp. systematic uncertainties on charged leptons
  - … and we veto charged leptons!



MonoJet

- Benchmark sensitivity for simplified model
  - Concensus by both CMS and ATLAS on models and how to interpret them - [1603.04156]

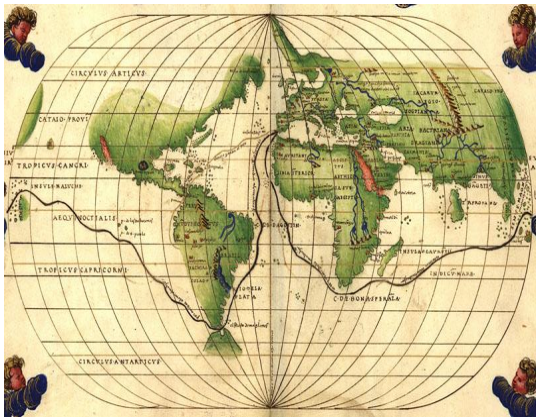




Low σ in off-shell (m_{med}<2m_{DM}) region

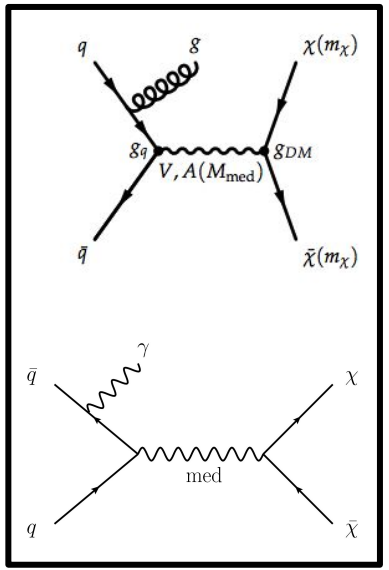
Low σ for high m_{med}

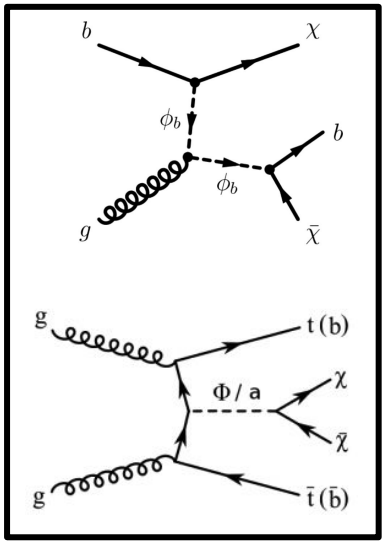
~



The Mono-X Family

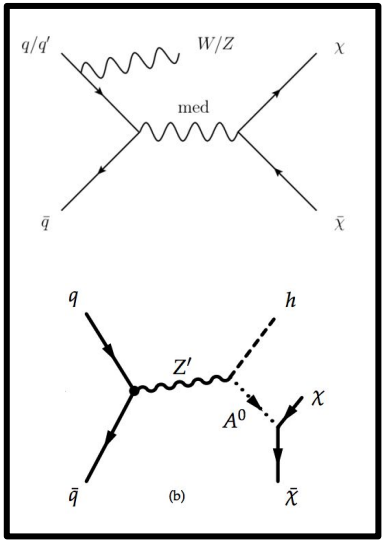
Jet
Photon



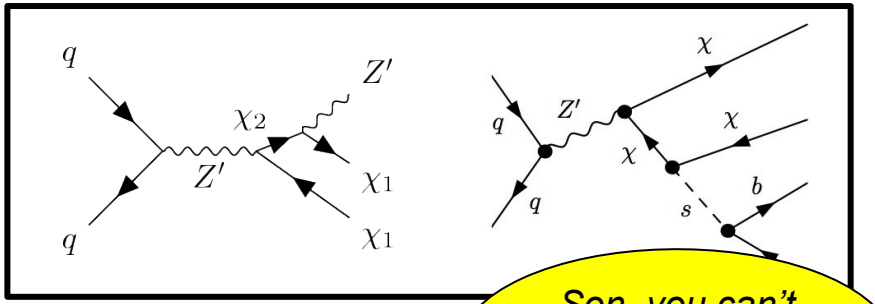


Heavy
Flavor

W/Z or Higgs



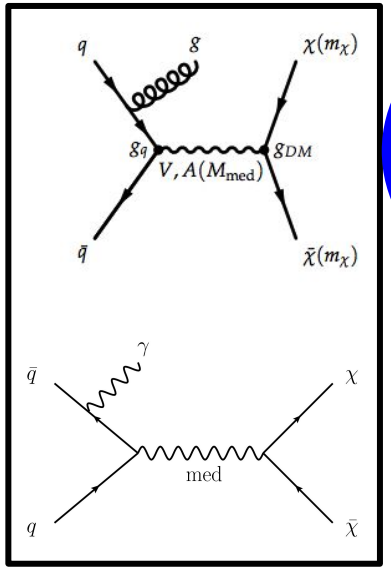
"Mono-BSM" (Z', h)

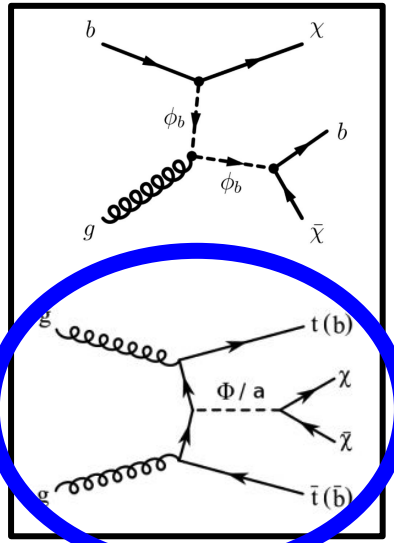


Son, you can't have more than one mediator!

The Mono-X Family

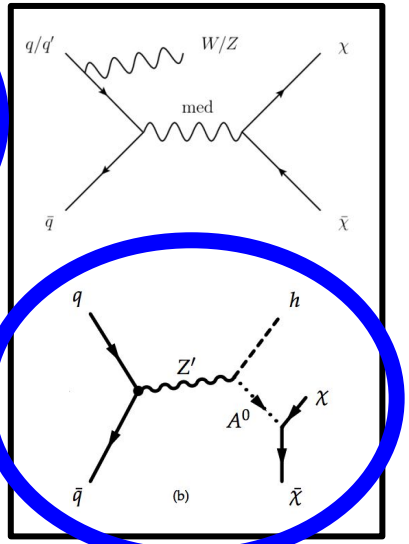
Jet
Photon





Heavy Flavor

W/Z or Higgs



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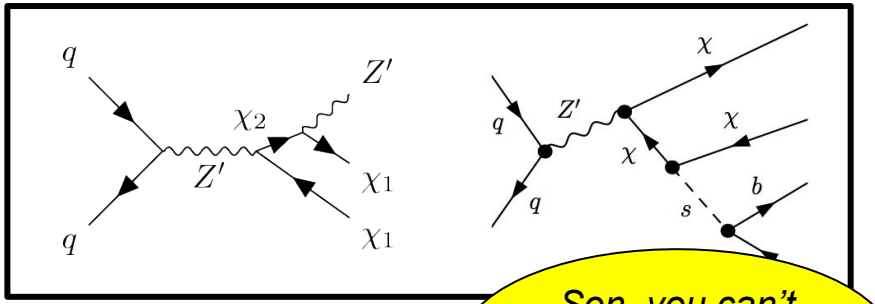
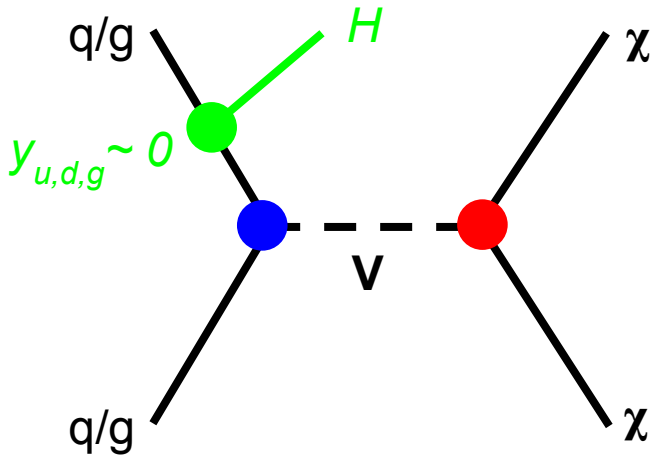
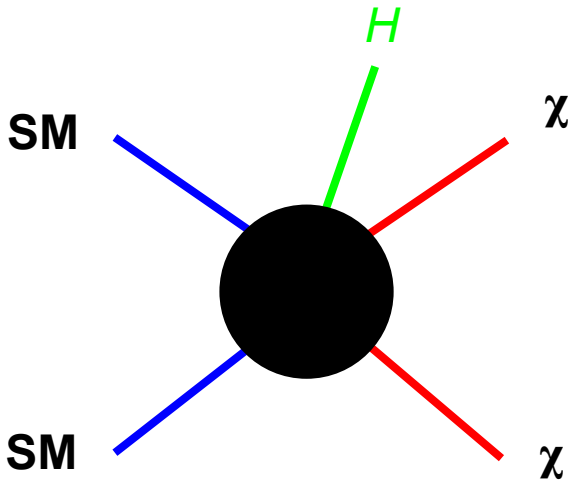


Son, you can't have more than one mediator!

Mono-Higgs : Why?

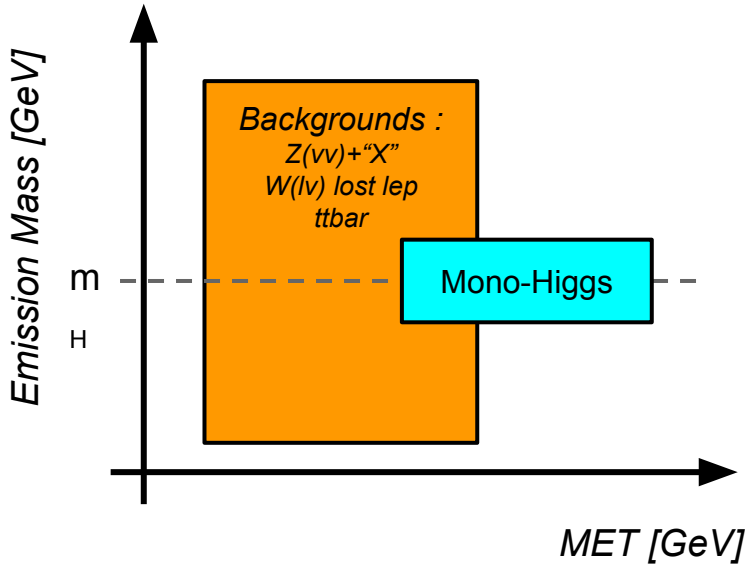
- Canonical mono-jet/photon/W/Z from initial state radiation (ISR)
  - Standard model emission provides a trigger
- Higgs cannot come as ISR emission ➜ directly probes the coupling “blob”

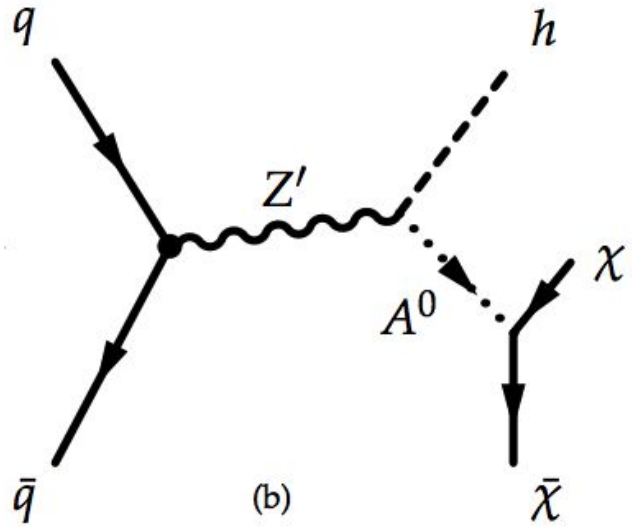




Mono-Higgs : Why?

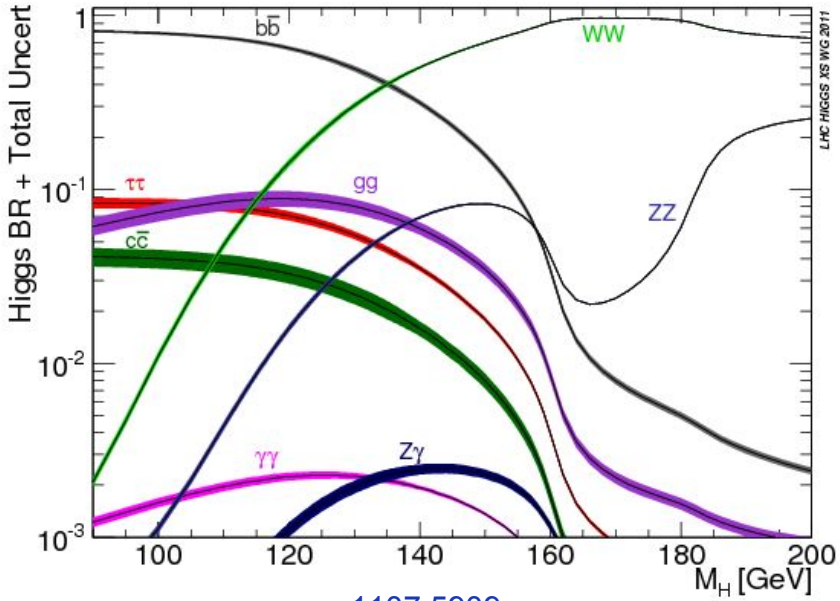
- Signature extended beyond just a high MET tail
  - The visible portion of the event has a characteristic energy scale/mass
- Benchmark model includes a 2HDM (5 new higgses) and a Z'
  - "Spanning the space of signatures"





Mono-Higgs

- Higgs is now well-integrated into the dark matter LHC search program
- But which decay mode is best?



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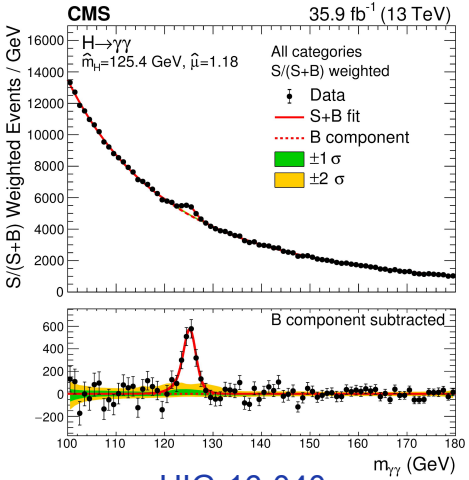
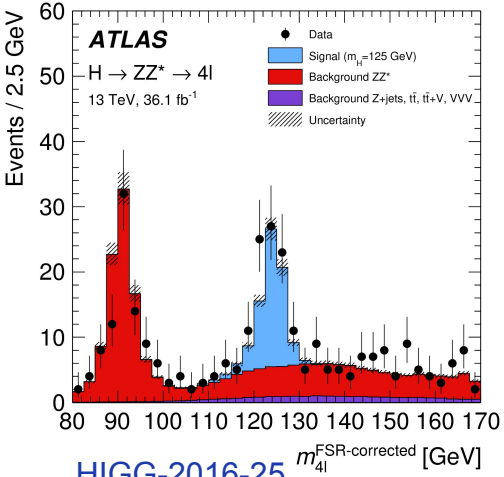
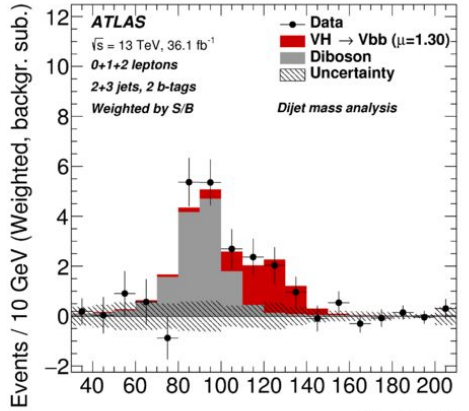


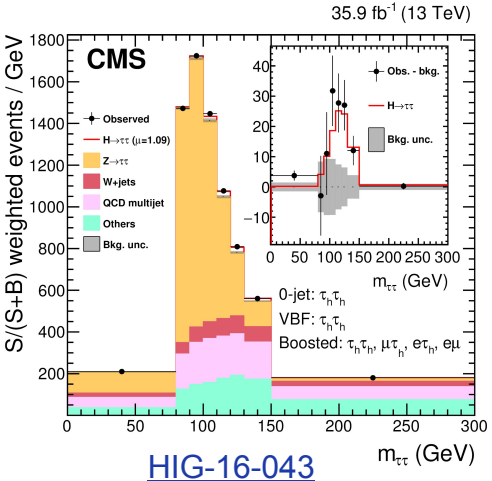
HIG-16-040



HIGG-2016-25



HIGG-2016-29

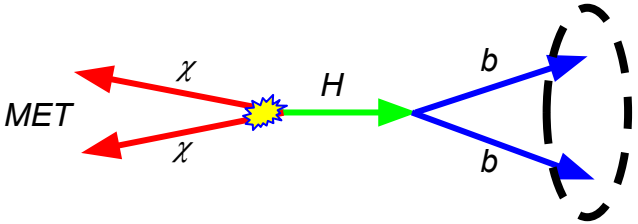


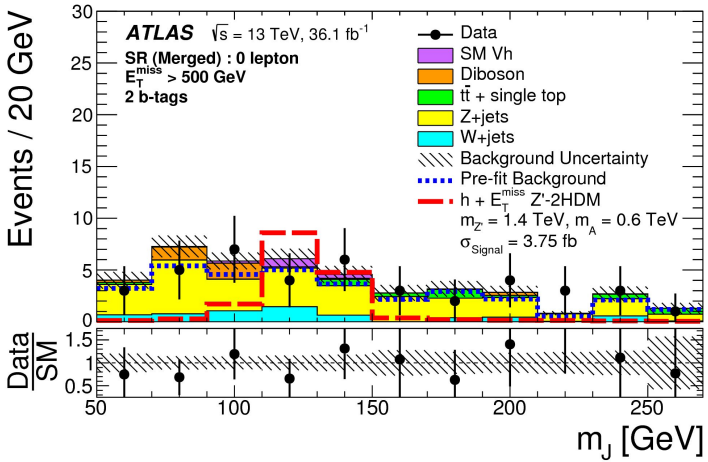
HIG-16-043

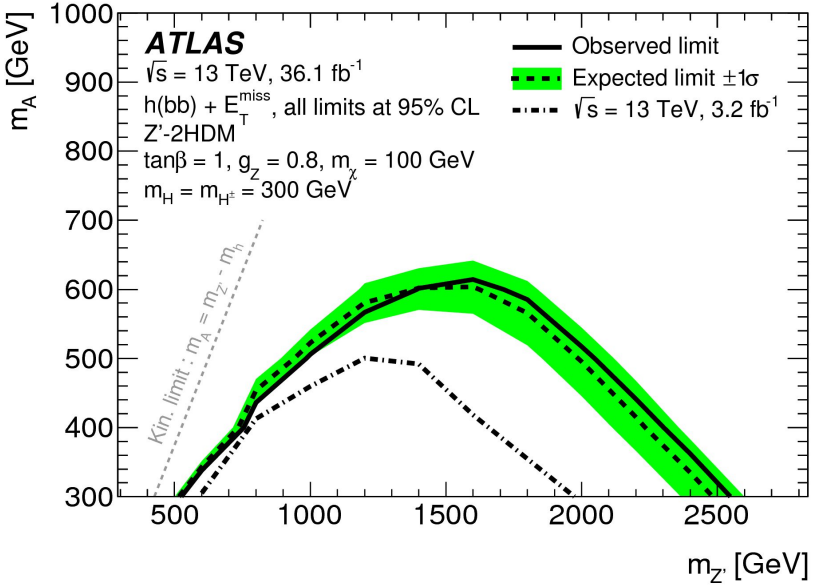
Mono-Higgs(bb)

ATLAS : EXOT-2016-25
CMS : B2G-17-004

- Taking advantage of Br(H → bb) ~60% extends kinematic reach
  - Requires dedicated reconstruction techniques for boosted topologies (“jet substructure”)
- Double differential search in (m_{bb}, MET)



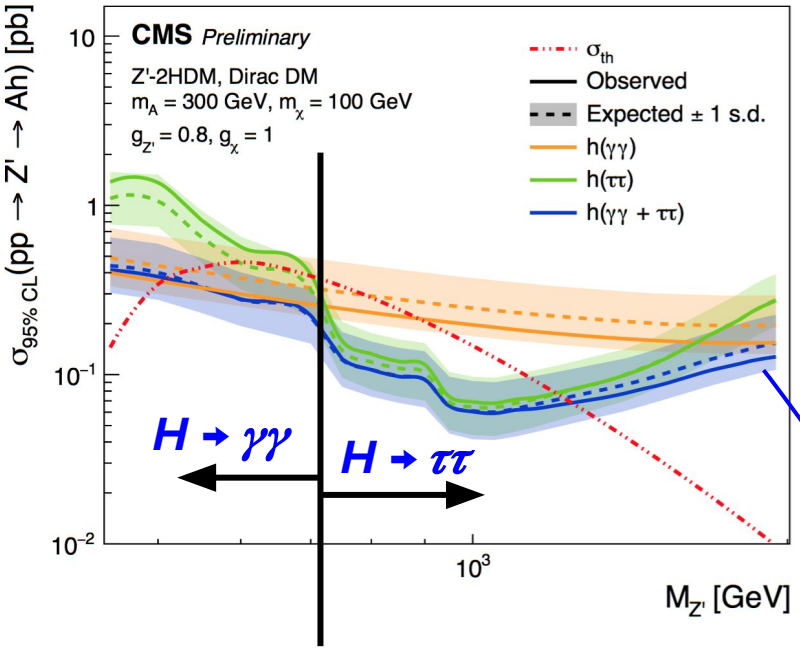


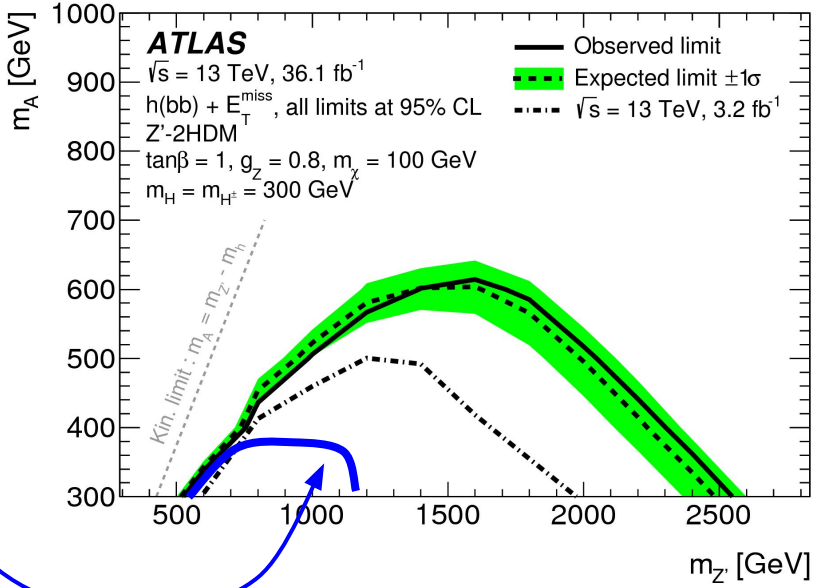


Mono-Higgs($\gamma\gamma/\tau\tau$)

ATLAS : HIGG-2016-18
CMS : EXO-16-055

- Other channels are less reliant on MET triggers
  - (1) Probe low MET signatures & (2) More robust against pileup
- Suffer greatly from the low Br(H → $\gamma\gamma/\tau\tau$)

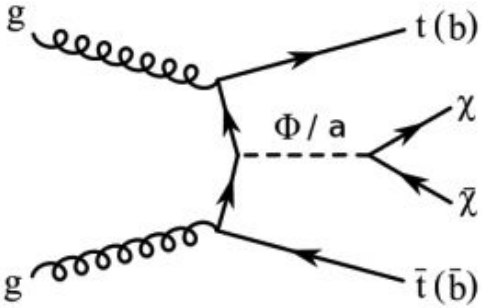


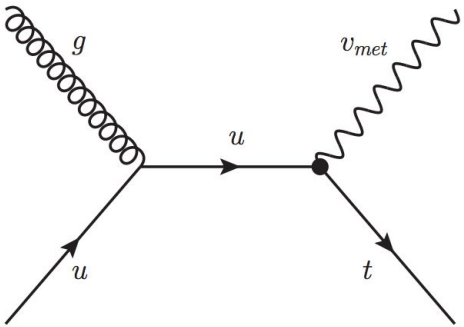


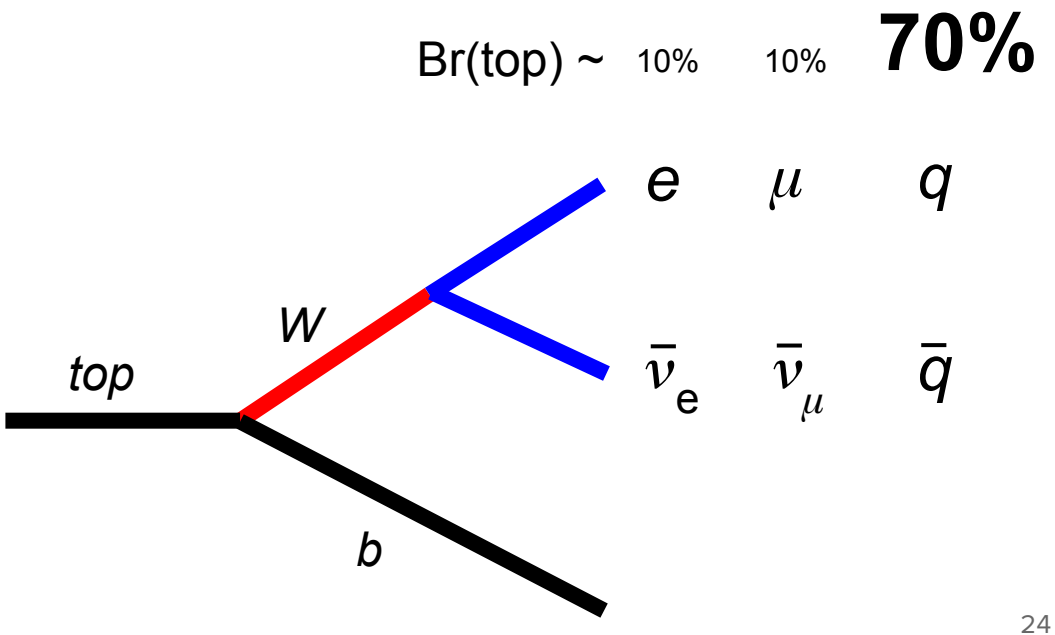
“Mono” Heavy Flavor

CMS : EXO-16-049, EXO-16-005
ATLAS : SUSY-2016-18

- Preferential couplings of heavy flavor to the mediator?
  - Scalar mediator, flavor changing mediator ...
- Top-quark decays = “experimental playground” (i.e. decay modes, full detector)







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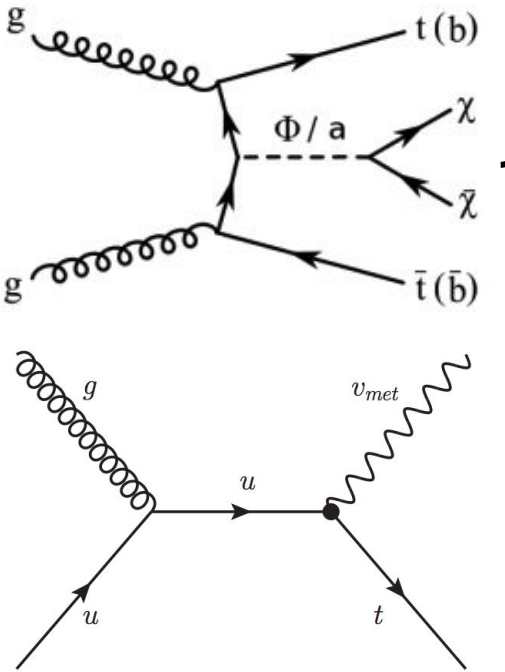
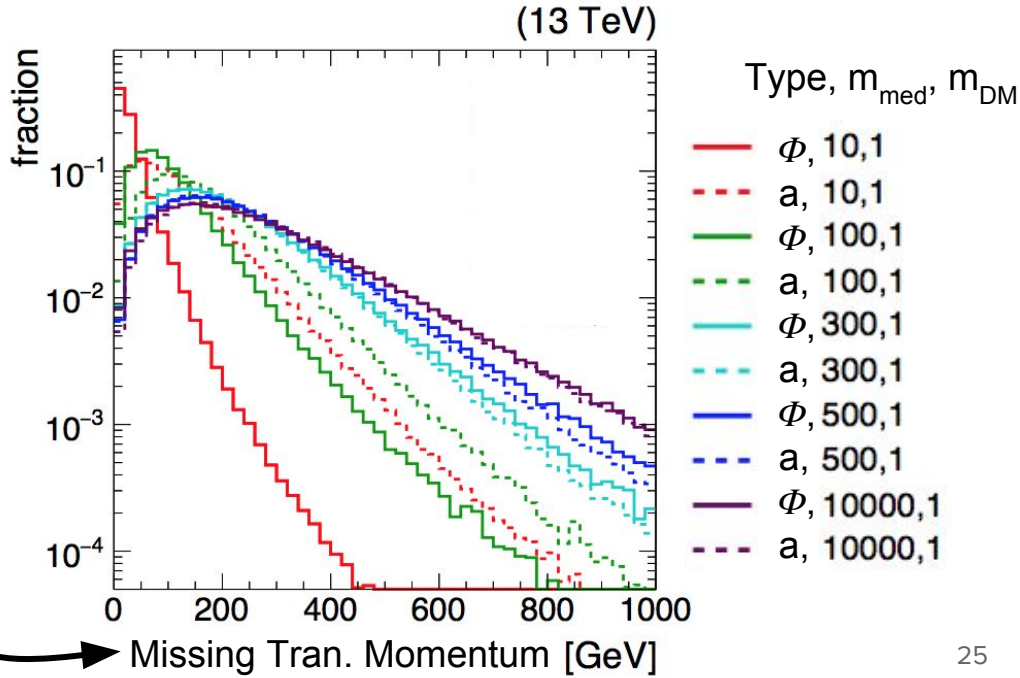
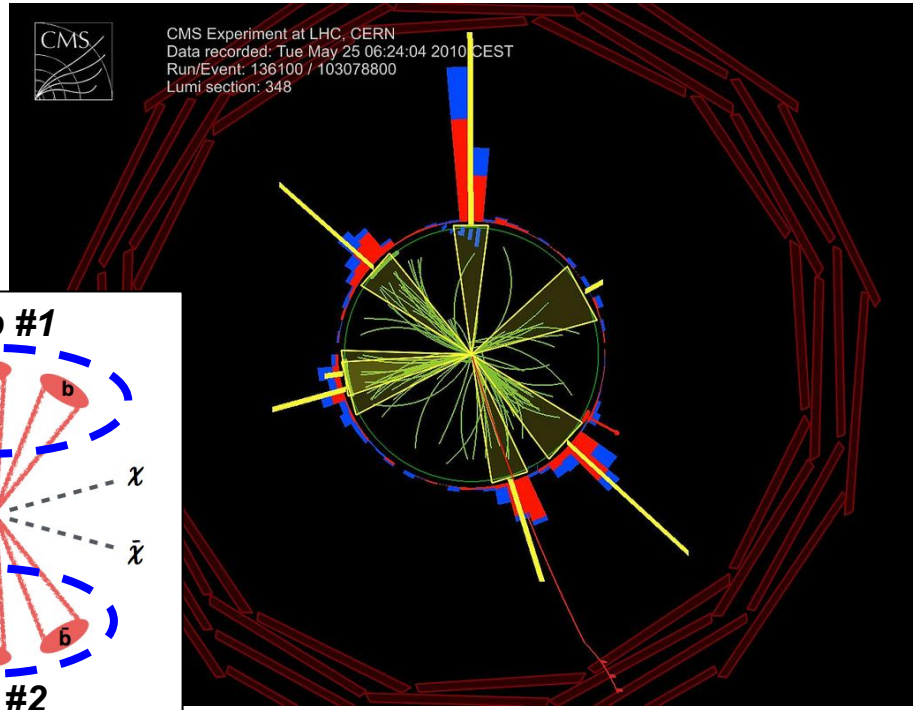
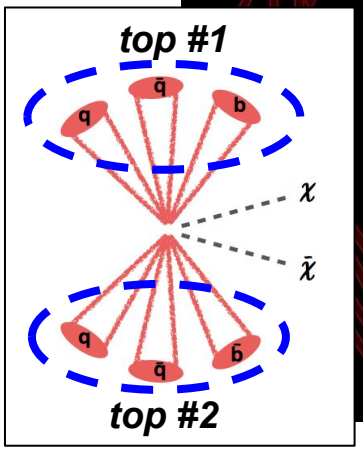


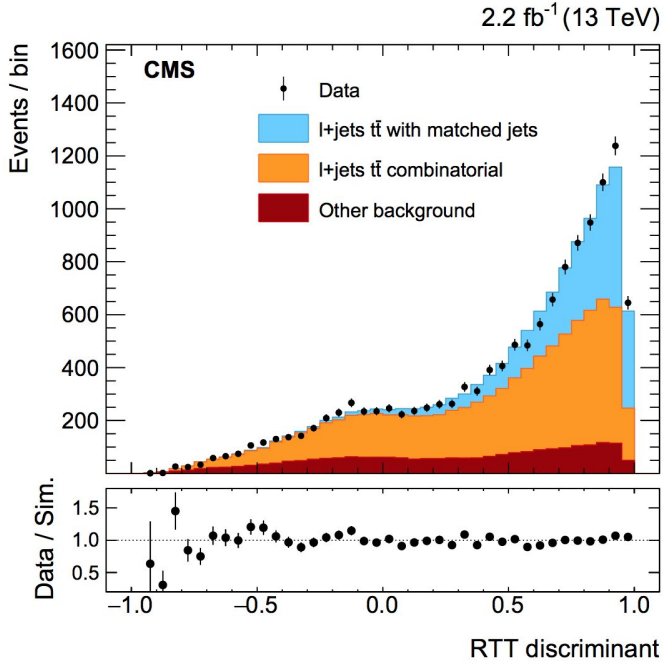


“Mono” Heavy Flavor

- Dedicated “resolved top tagger” designed to identify jet triplets
  - MVA(top quark kinematic fit, b-jet identification score, topological angles)



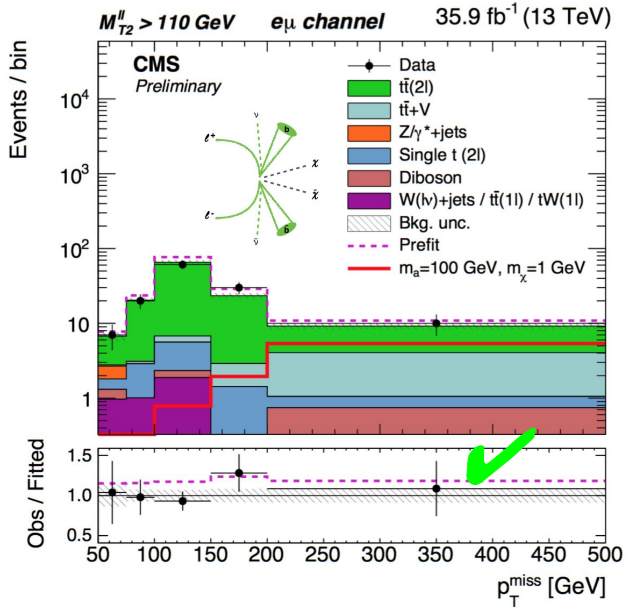




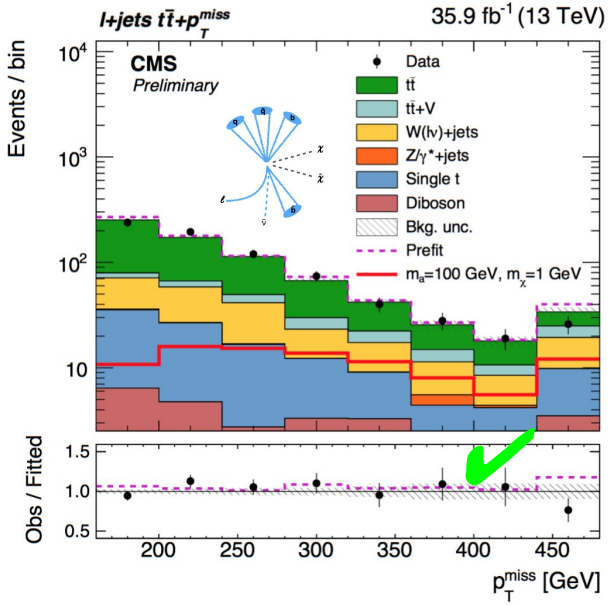
“Mono” Heavy Flavor

- Statistical combination of multiple orthogonal searches
  - Beneficial if sensitivity is comparable between individual searches

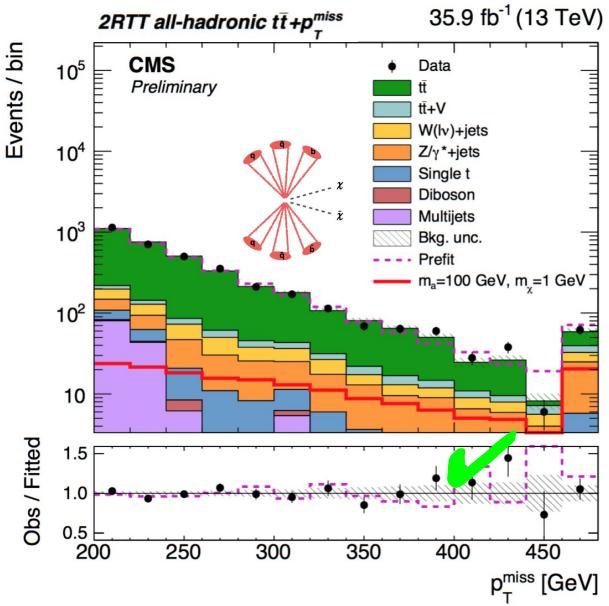
2 Lepton



1 Lepton

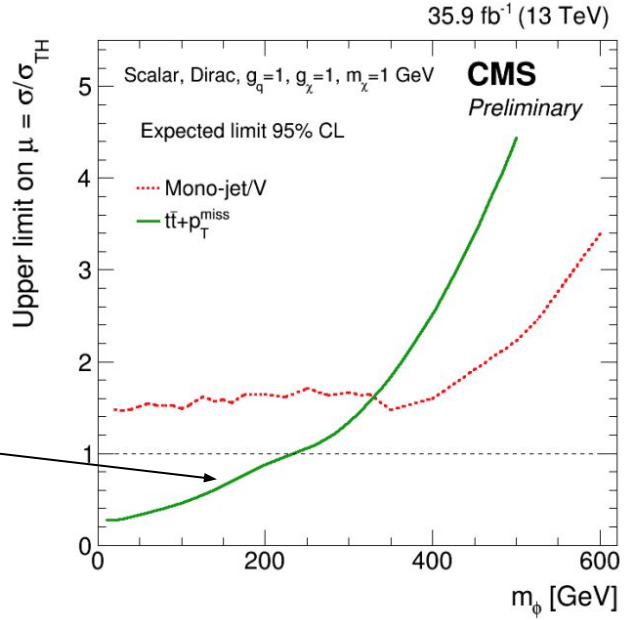


0 Lepton

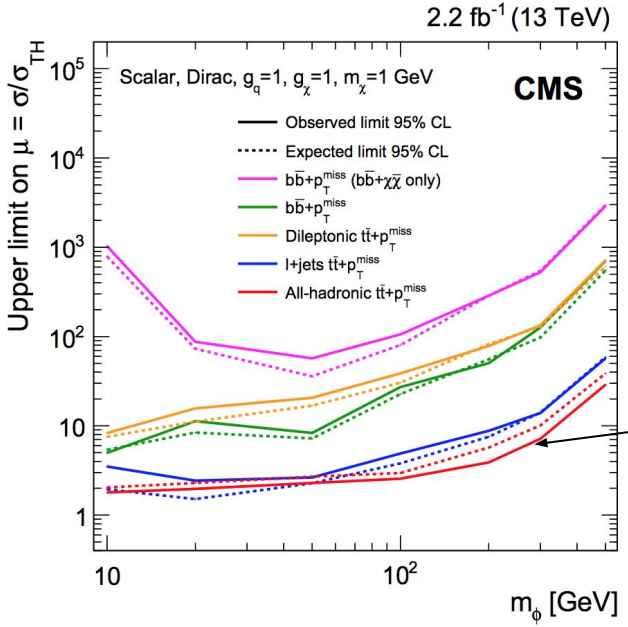


“Mono” Heavy Flavor

- Complementary region of phase space accessible that MonoJet “fails” to probe
- Pushing the combined performance (i.e. top tagging) capabilities of our detectors allows LHC experiments to maximally exploit dataset

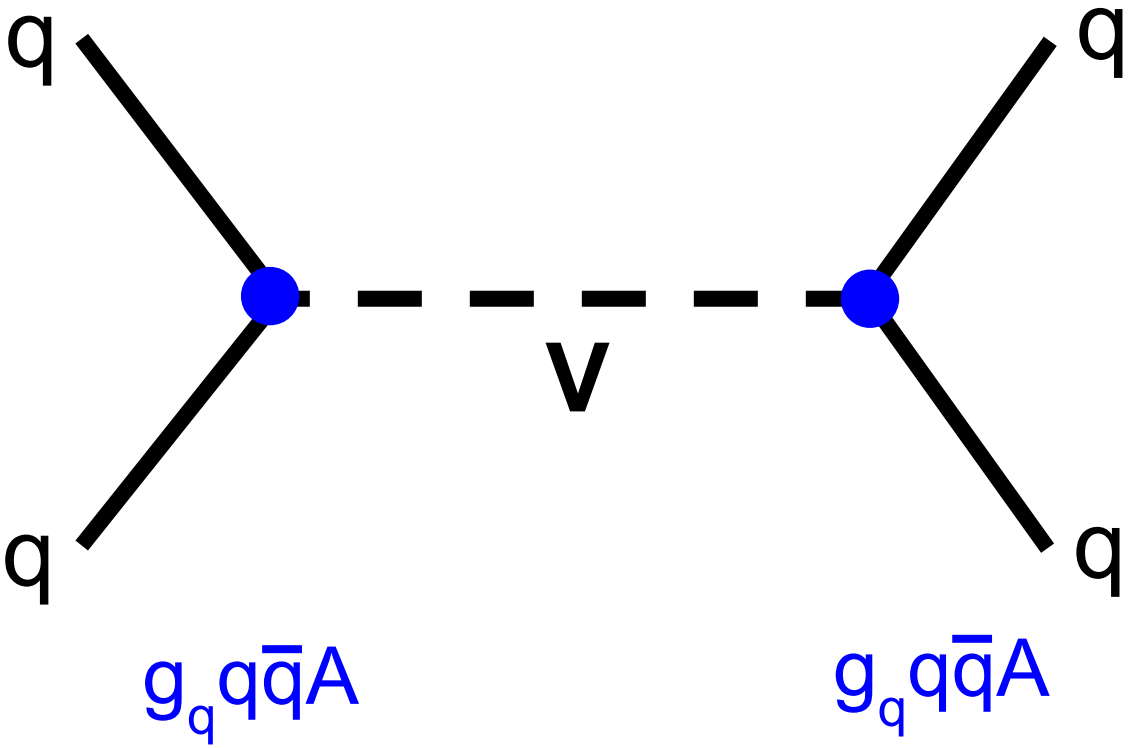


Low mass region more accesible to tt+MET



Fully hadronic (0 Lepton) channel drives sensitivity

The Lamppost - "Di-Jets"



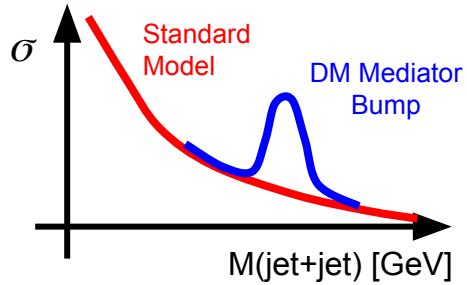
Model Parameters

$$\left\{ g_q,\ m_{med},\ \cancel{g_{DM}},\ \cancel{m_{DM}} \right\}$$

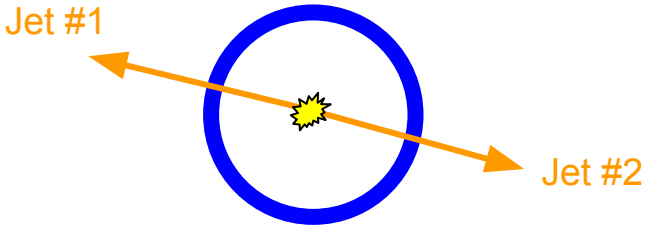
General Strategy

- Similar generic strategy followed by all DiJet searches
  - Searching for resonance excess in the di-jet invariant mass - "bump hunt"

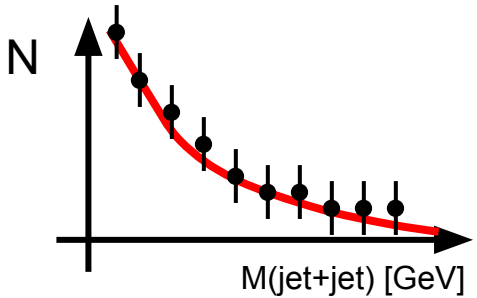
***(1) Goal** - Search for resonant excess*



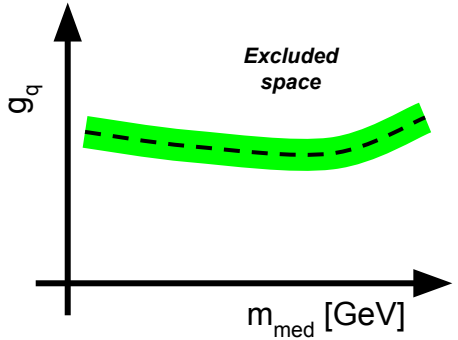
***(2) Select** - Trigger directly or with associated activity*
- Select decay products of X → qq



***(3) Backgrounds** - Assume QCD is "smoothly falling"*



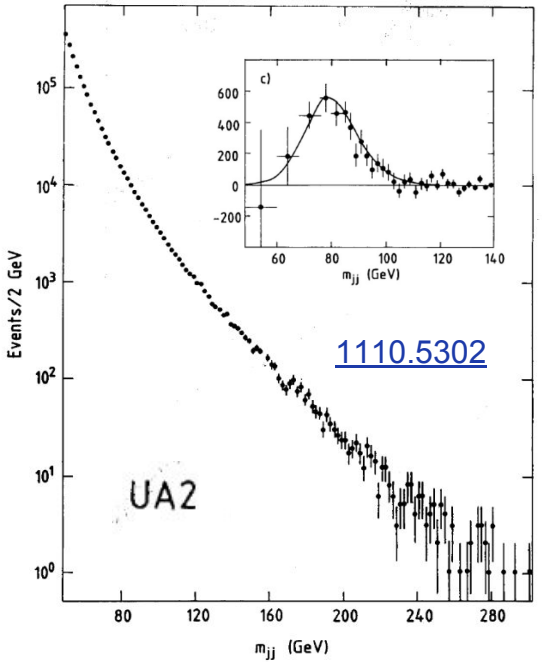
***(4) Constraints** - Exclude region of* $\{g_q, m_{med}\}$



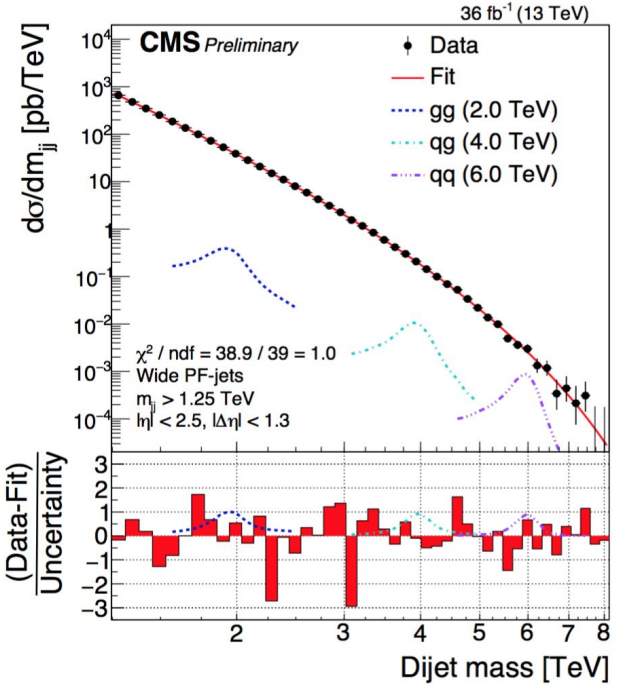
High Mass Dijet

CMS : EXO-16-056
ATLAS : EXOT-2016-21

- General strategy for flagship high mass dijet has not changed since SppS days
  - High mass means something markedly different now …
- Results interpreted as limit on $\{m_{med}, g_q\}$ from benchmark scenarios

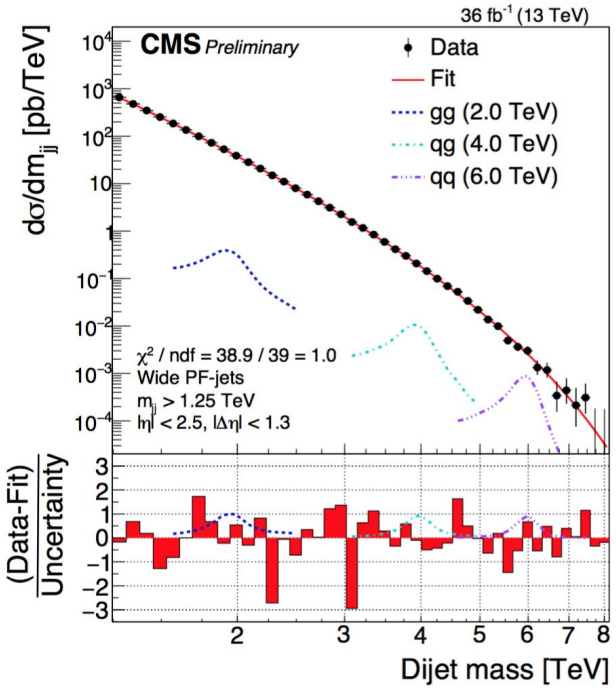


~ 30 years

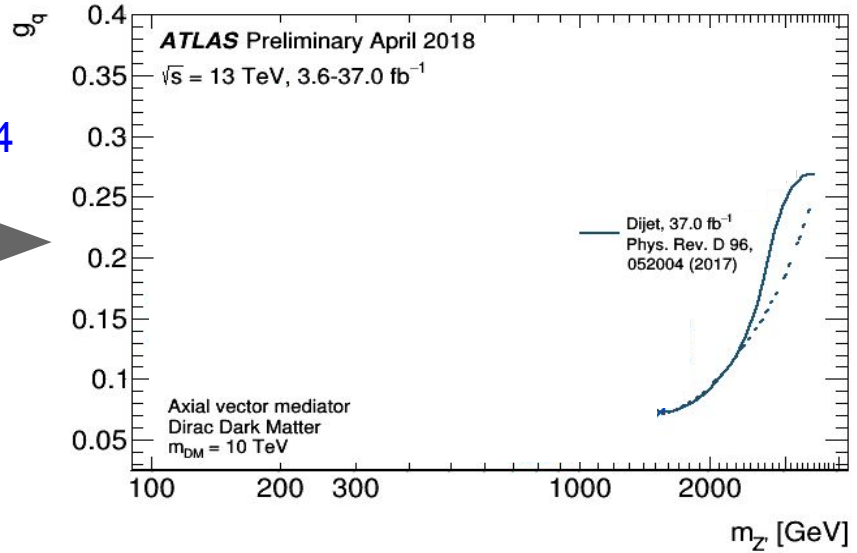


High Mass Dijet

- Covers the region m(X)>1.5 TeV effectively
  - Lower m(X) limited by trigger acceptance/rate → p_T(jet, HLT)>500 GeV



$\sigma \sim g_q^4$



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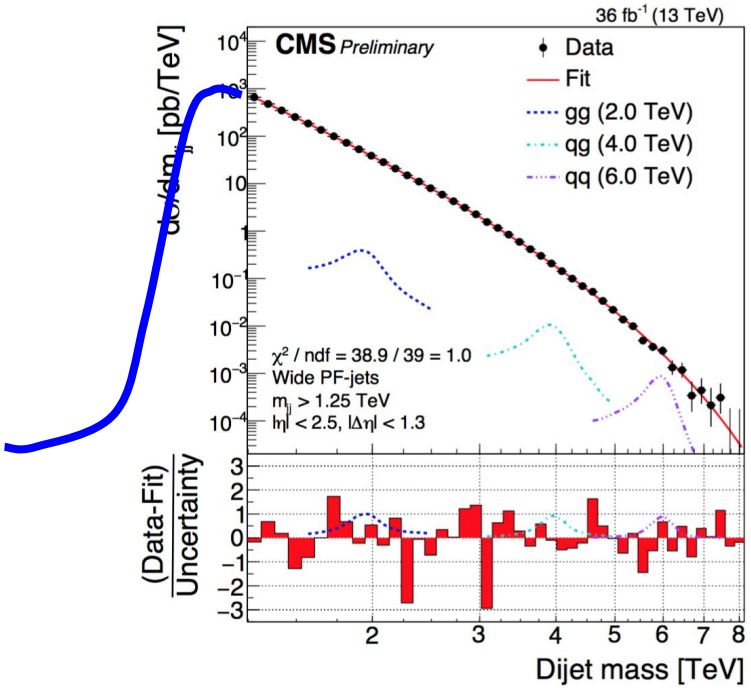

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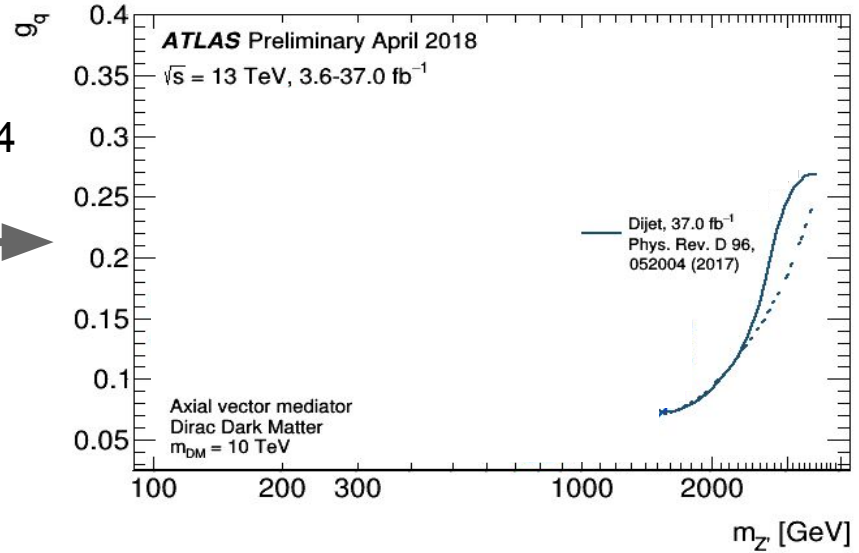
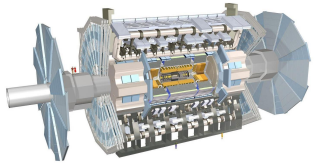
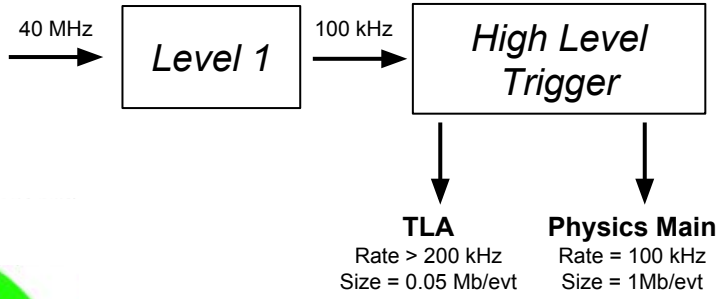


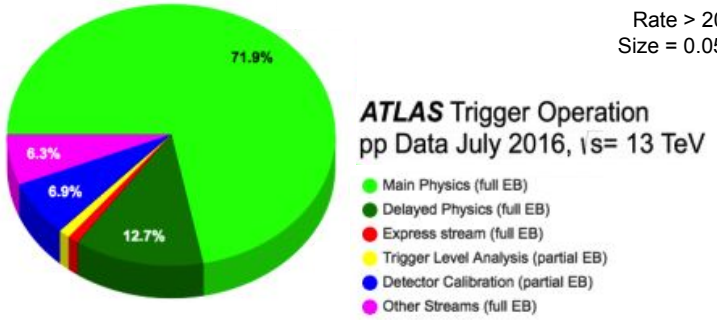
Dijet TLA

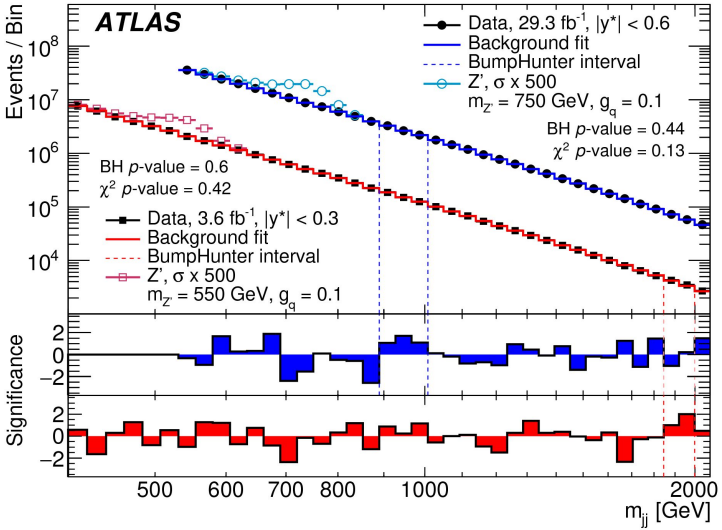
CMS : EXO-16-056
ATLAS : EXOT-2016-20

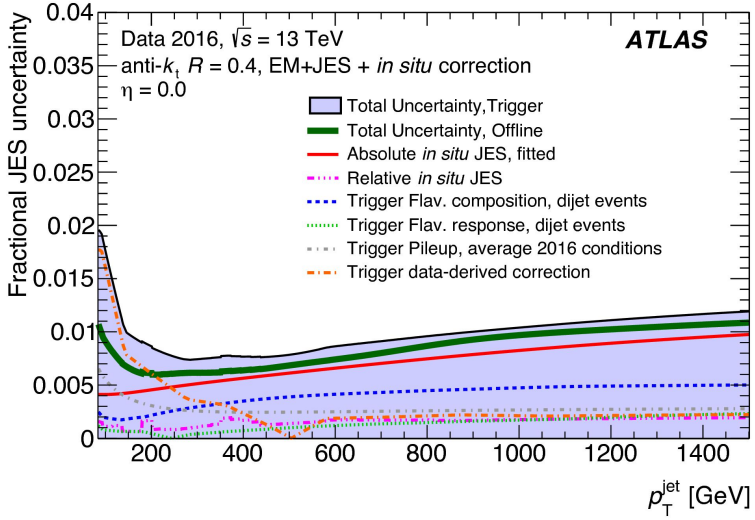
- Mitigate HLT limitation by moving to L1 limitation ➔ “trigger level analysis” (TLA)
  - Precise understanding of trigger calibrations
  - Gain access to m_{med} = [500,1500] GeV range











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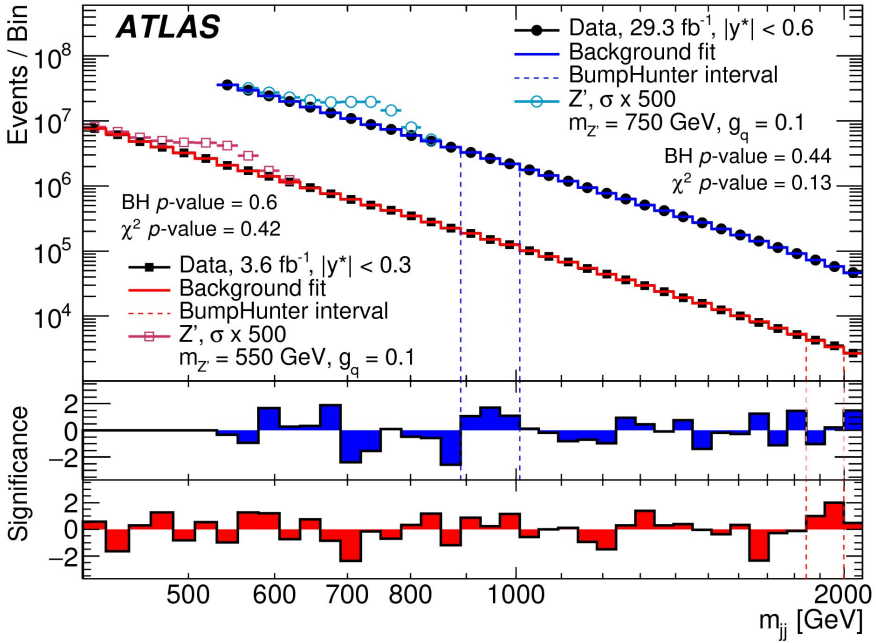
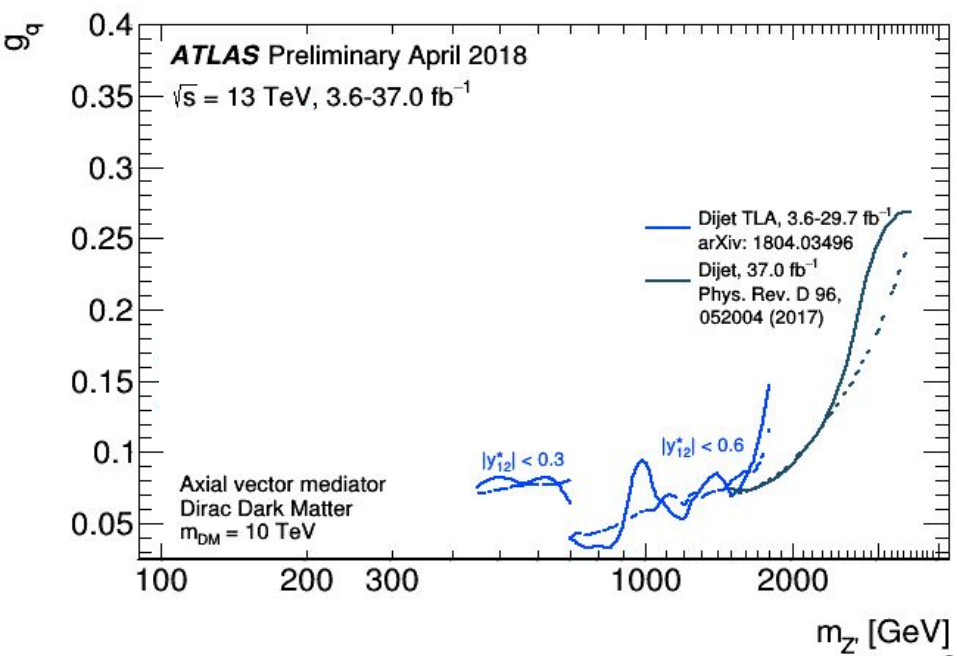
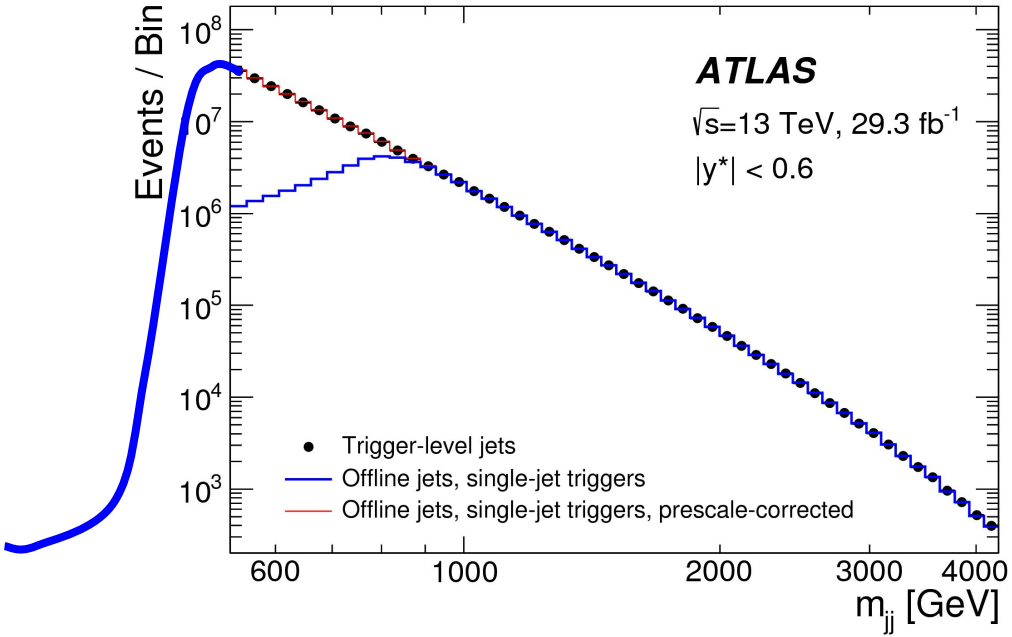


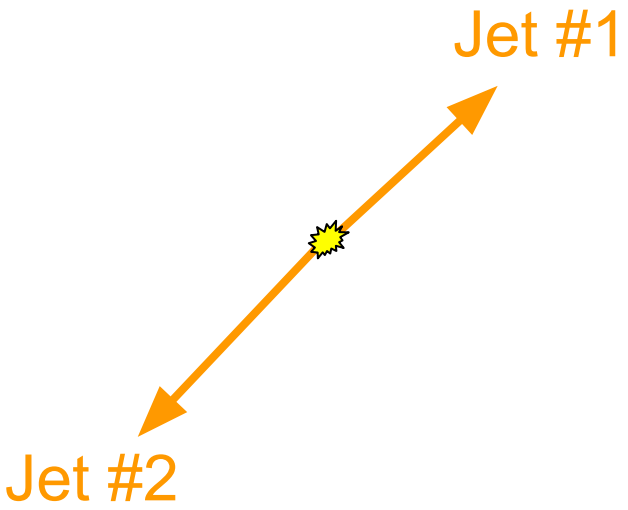


Dijet TLA

- Trigger level reconstruction will eventually be limited by L1 rate (100 kHz)
  - Kinematic thresholds are decreased p_T(jet, L1)>100 GeV … but still exist

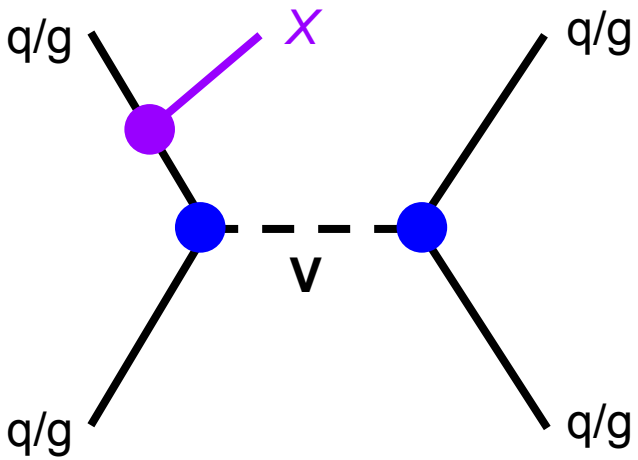


$$m(J1+J2) \sim E_{J1} \times E_{J2} \times \sqrt{1 - \cos\theta_{12}}$$



ISR + X(qq → jj)

- Pass the trigger responsibility to another object in the event
  - Pro : m(JJ) is only correlated to 2nd order with pT(trigger)
  - Con : Cross section hit by requirement of 2 → 3 process



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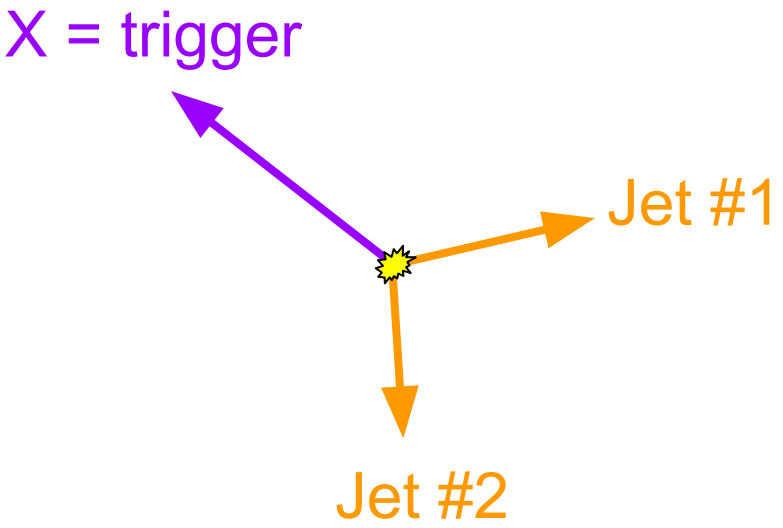
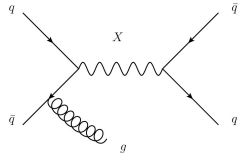


ISR + X(qq → jj)

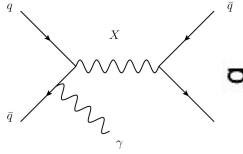
CMS : n/a
ATLAS : EXOT-2016-070

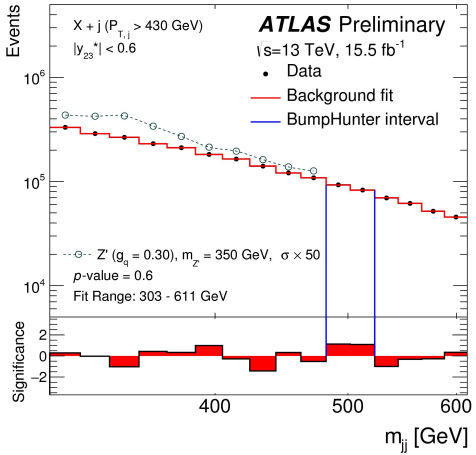
- Pass the trigger responsibility to another object in the event
  - Pro : m(JJ) is only correlated to 2nd order with pT(trigger)
  - Con : Cross section hit by requirement of 2 → 3 process

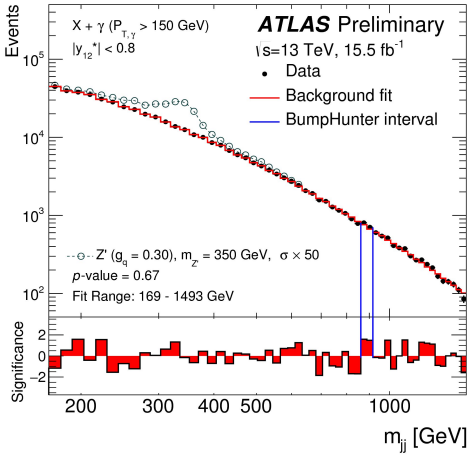
ISR jet

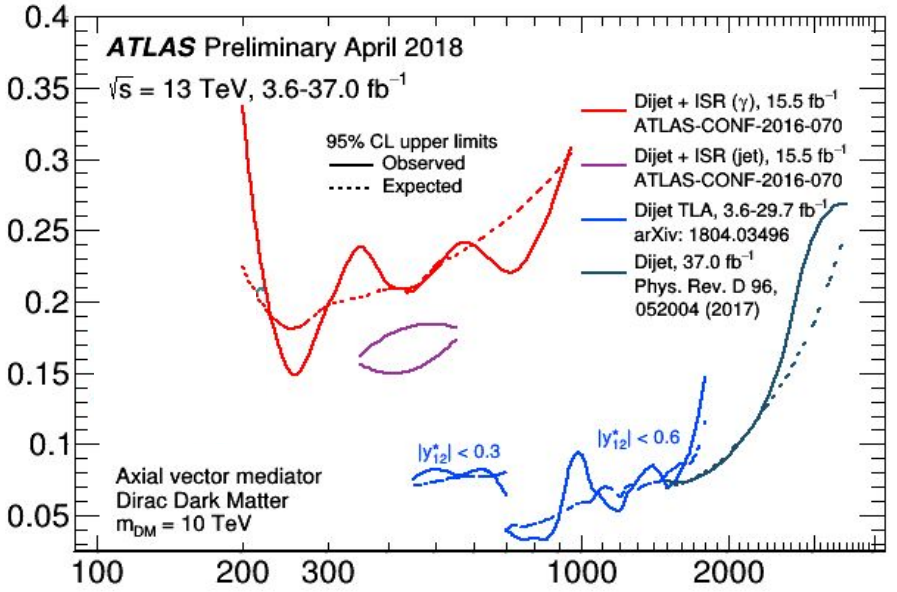


ISR photon







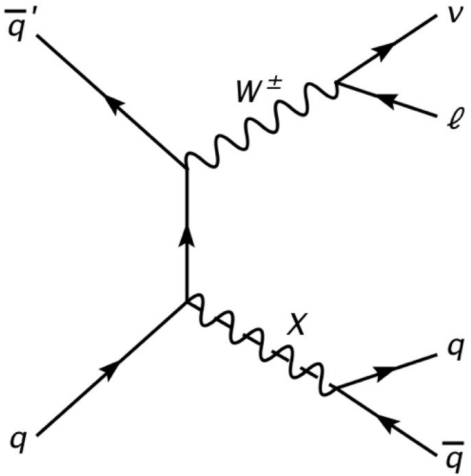


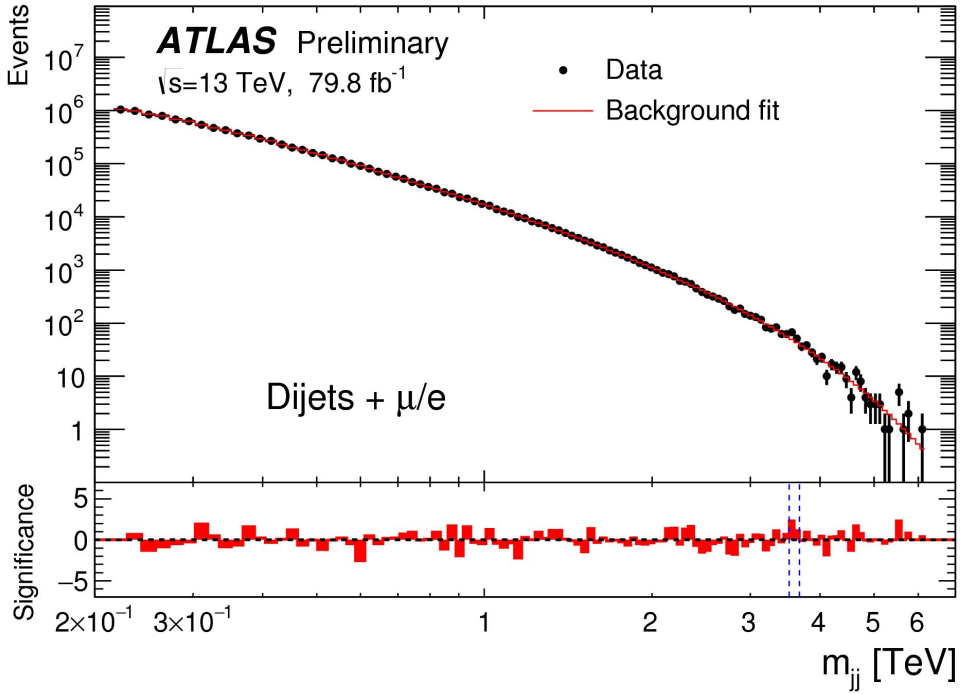
Link to Source

ISR(Lepton) + X(qq → jj)

L_{int} = 80 fb^{-1}

- Jet and photon object trigger thresholds continually increase
  - Increasing pileup, increasing luminosity, …
- Leptons are “always” clean

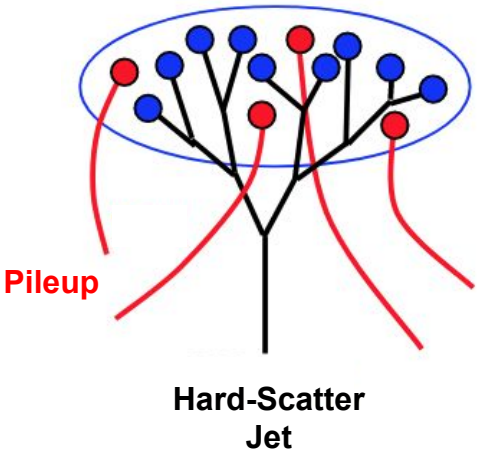


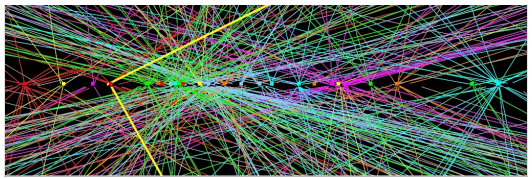


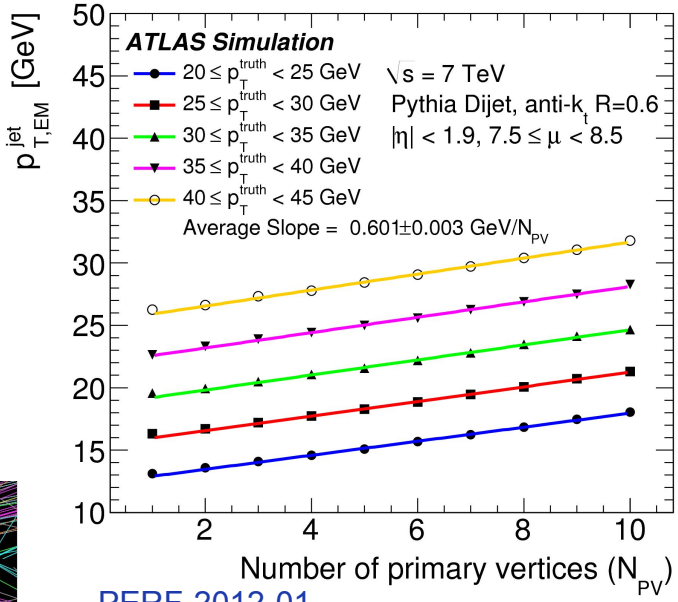
CMS : n/a
ATLAS : ATLAS-CONF-2018-015

ISR+X(qq → jj) Limitations

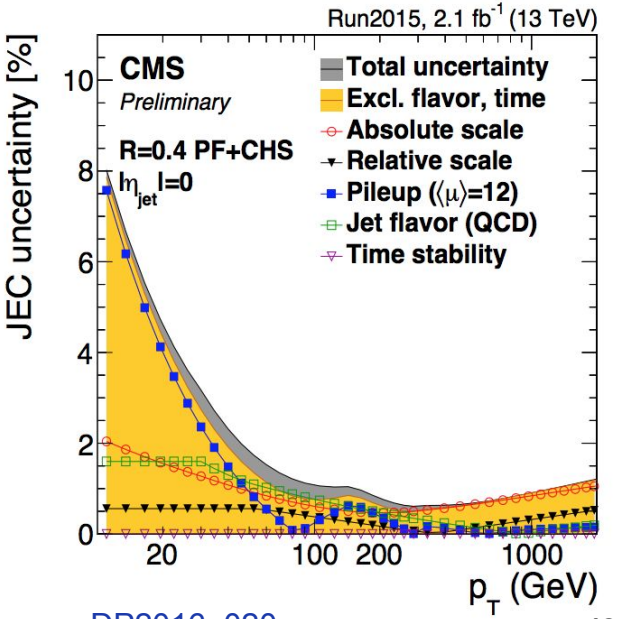
- "ISR+X" searches are limited by (1) trigger and eventually (2) jet reconstruction
- Low mass ➔ lower p_T ➔ pileup contamination becomes a larger problem
  - Larger resolution, larger corrections, larger uncertainties …







PERF-2012-01



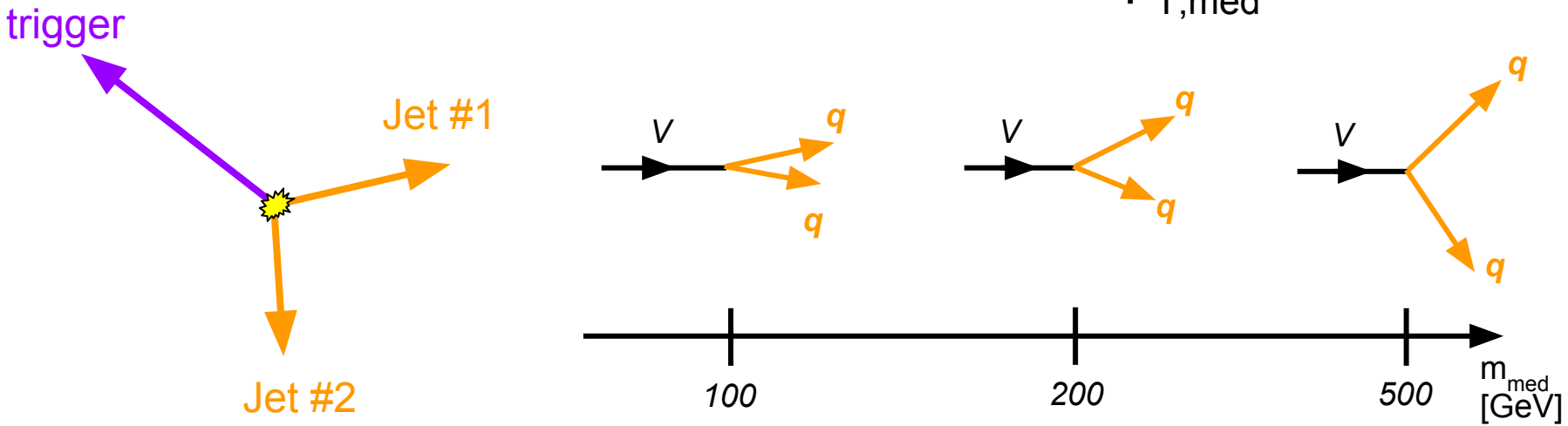
DP2016_020

ISR+X(qq → J)

- With decreasing m(X) : Di-jet ➔ *Fat-JET*
  - Boosted topology resulting from trigger requirement - no intrinsic mass splitting

$$m(J1+J2) \sim E_{J1} \times E_{J2} \times \sqrt{1 - \cos\theta_{12}}$$

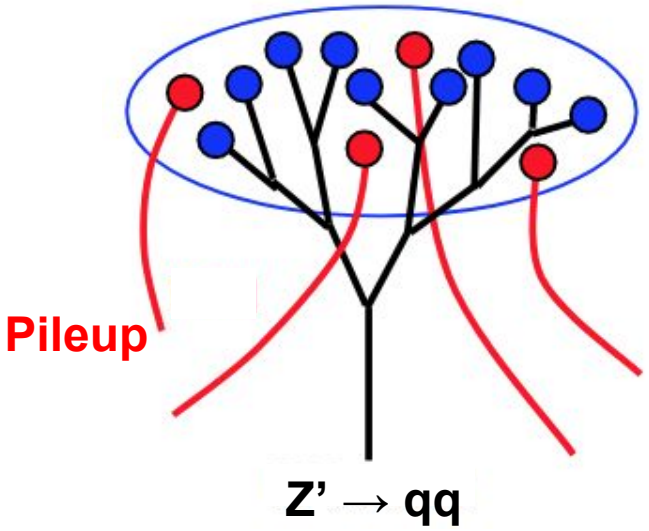
$$dR(q,q) \sim \frac{2m_{med}}{p_{T,med}}$$

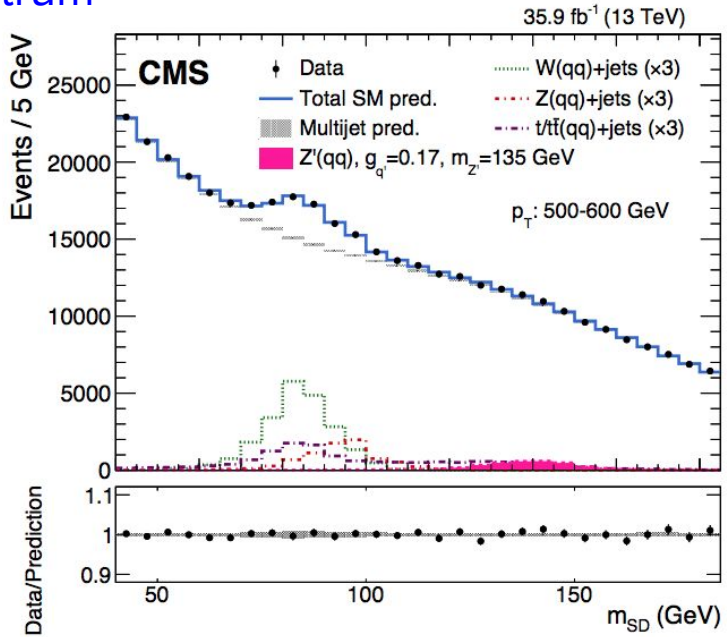


ISR+X(qq → J)

CMS : EXO-17-001
ATLAS : EXOT-2017-01

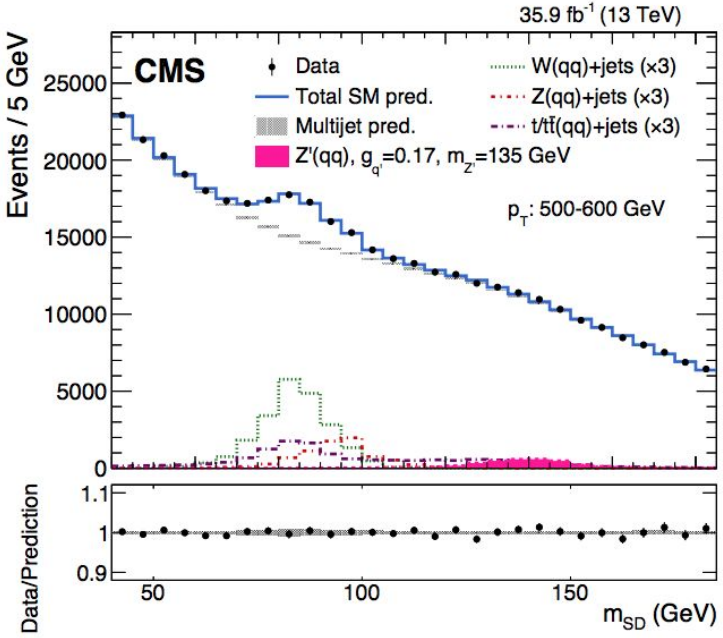
- Analysis is akin to doing dijet analysis in small region of interest
  - Step 1 : Open jet cone radius to capture full Z' ➔ qq decay - R~1.0 (standard = 0.4)
  - Step 2 : Pick apart jet to remove unwanted radiation (ISR/Pileup) - Trimming, SoftDrop
  - Step 3 : "Tag" jet via auxiliary jet shape observable - tailored to preserve smoothly falling spectra
- Examine smoothly falling jet mass spectrum

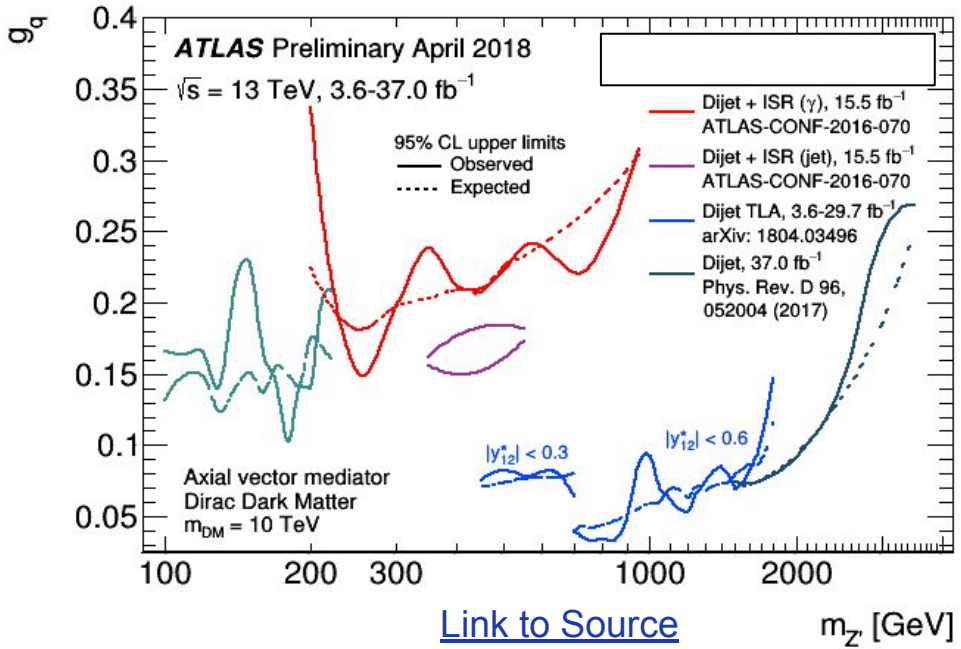




ISR + X(qq → J)

- Can probe down to m_{med}=50 GeV
  - Experimental challenge : How low can we go?
- Question : How low is “necessary”?



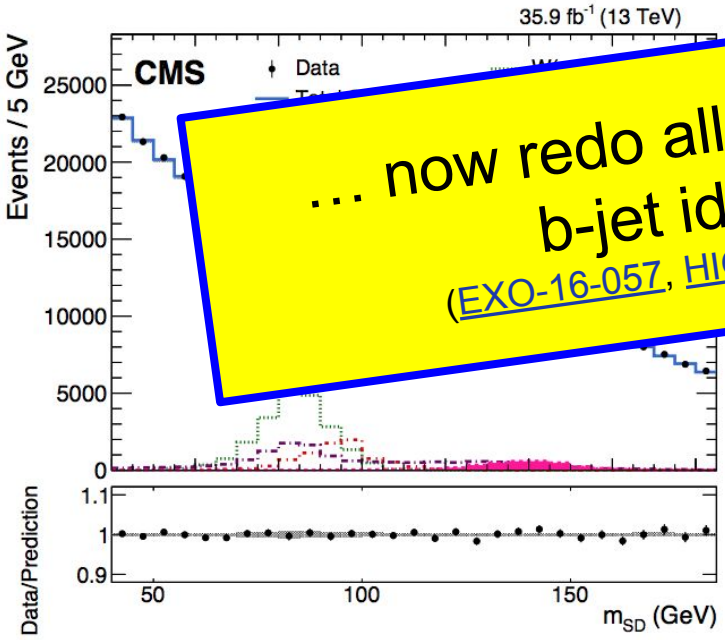


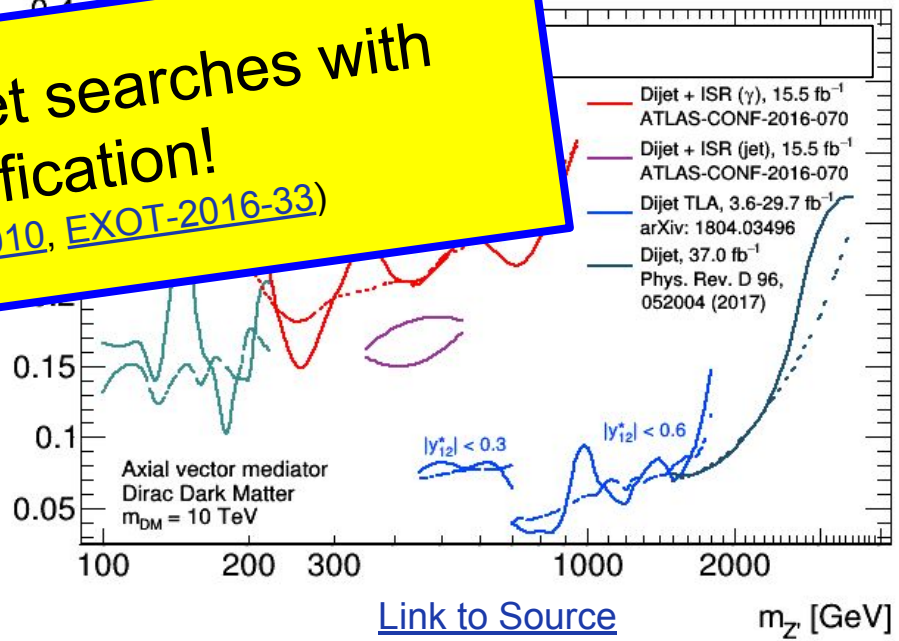
Link to Source

ISR + X(qq → J)

- Can probe down to m_{med}=50 GeV
  - Experimental challenge : How low can we go?
- Question : How low is “necessary”?

… now redo all dijet searches with b-jet identification!
(EXO-16-057, HIG-17-010, EXOT-2016-33)



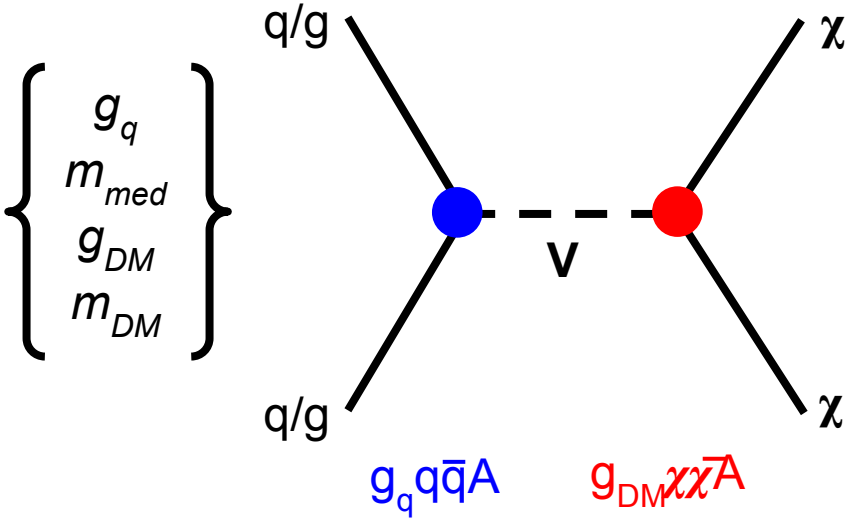


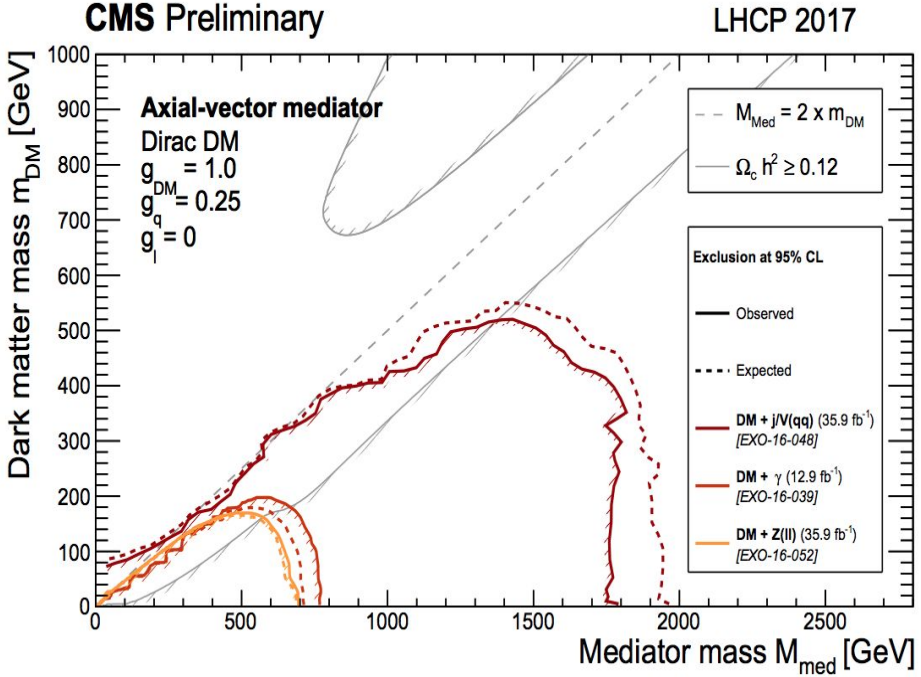
Link to Source

What do we learn?

CMS : Summary Plots
ATLAS : Summary Plots

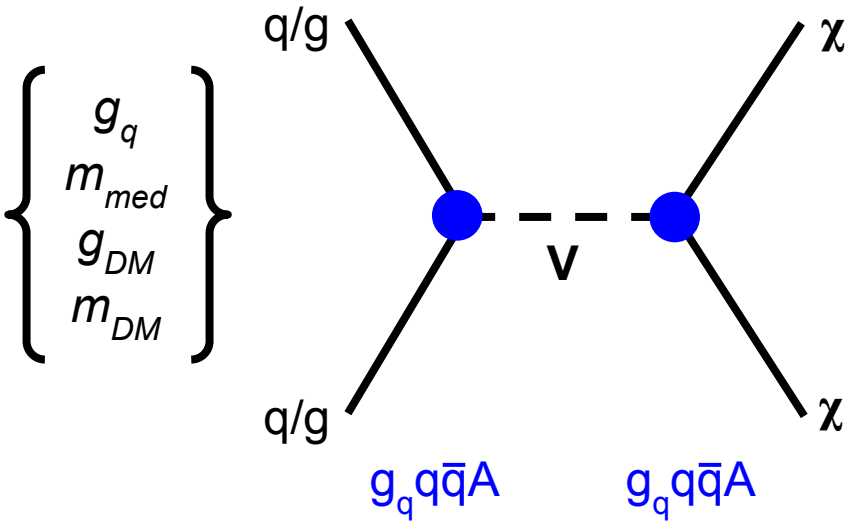
- Mono-X Searches : MonoJet is a very strong “catch all” signature
  - Not the strongest for all scenarios - e.g. preferential HF couplings
  - Probably not a discovery channel ➜ new signatures are welcomed!

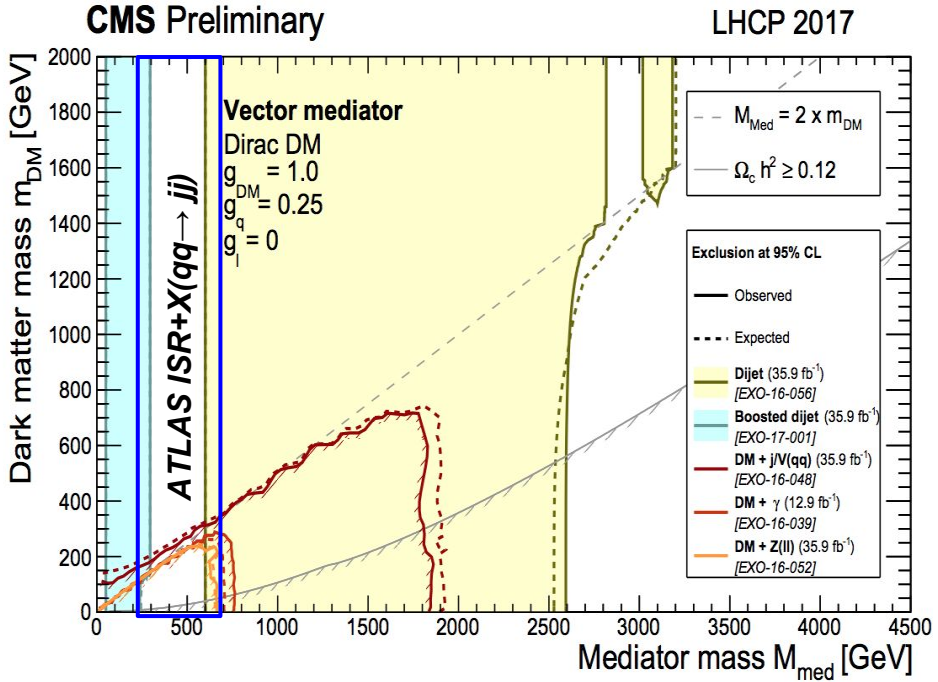




What do we learn?

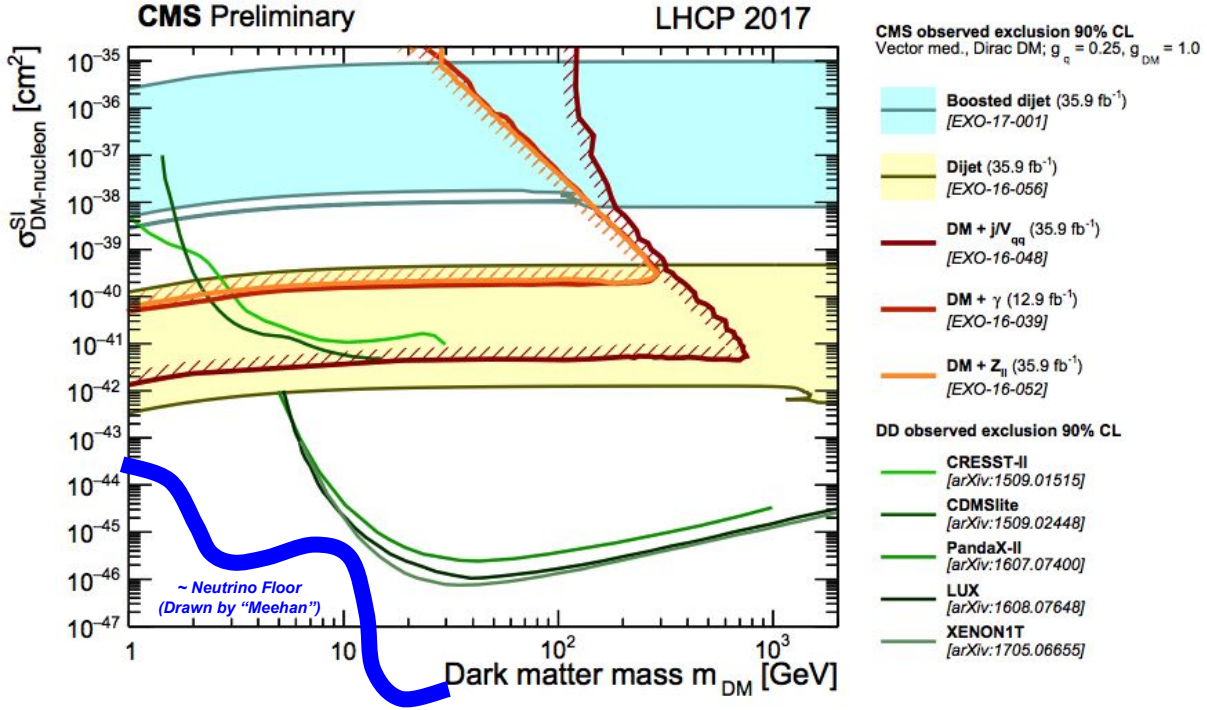
- Dijet-like Searches : Low-mass is the new High-mass
  - Jet substructure is very useful beyond the “high-boost” region





What do we learn?

- LHC experiments are complementary to DD/ID
  - … for a specific model choice!!!!
- Approaching the neutrino floor …



1603.04156

Conclusions

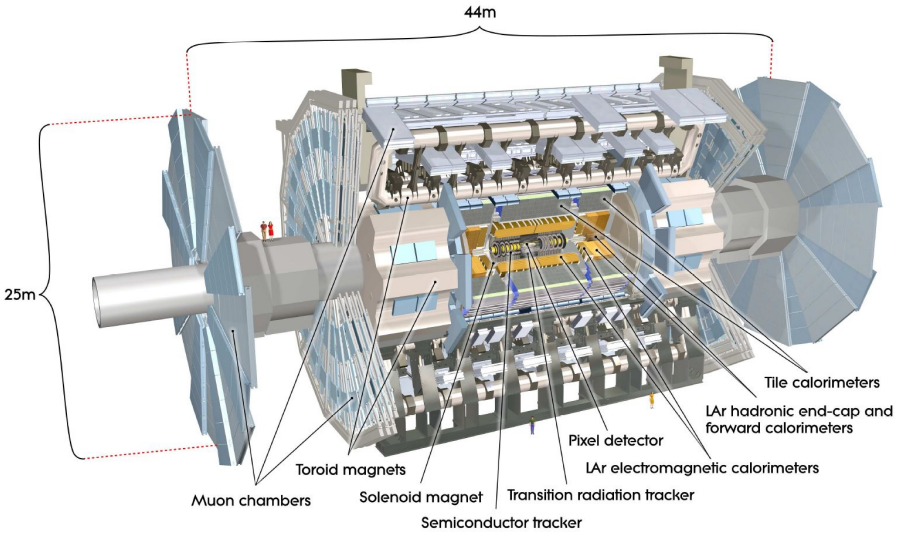
- Nothing seen as of yet
  - 36 fb^{-1} of data well-scrutinized ➔ 120 fb^{-1} by December!
  - Discovery likely to come with new signatures
- Era of “precision” searches!
  - Leptons are limiting a search that *by design* doesn’t want leptons
  - ~1% fluctuation in calibrations give 3 sigma bumps
  - Precision hadronic physics / jet substructure

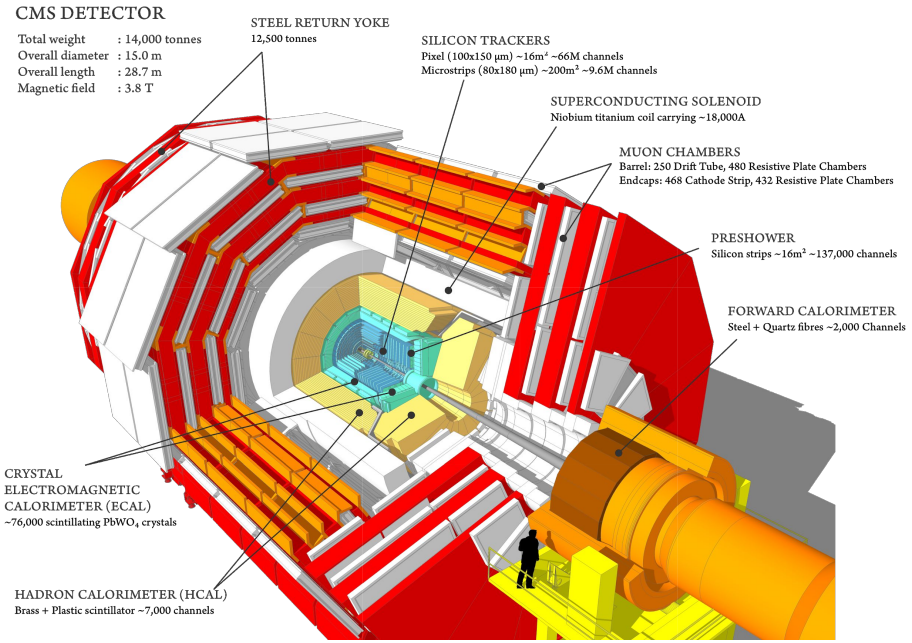
Thank You!

BONUS STUFF

ATLAS/CMS Detector Overview

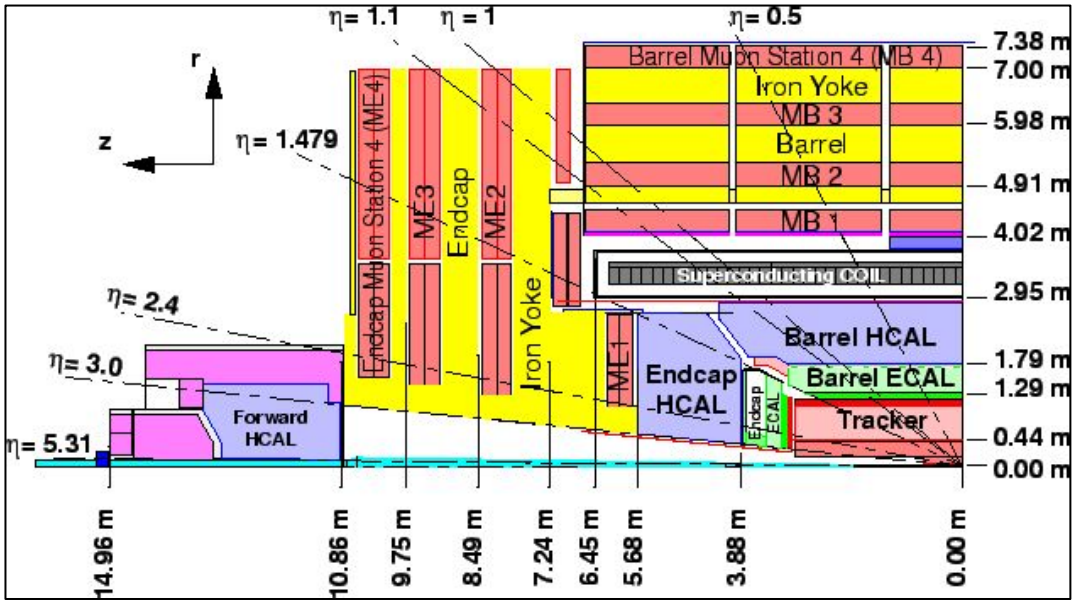
- Very similar goals achieved by different detector technologies



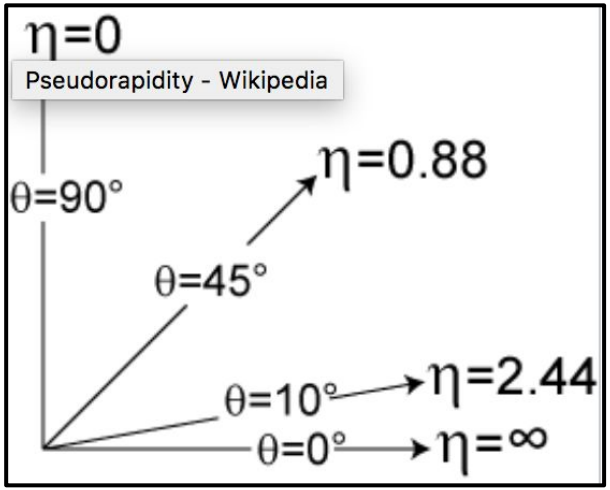


Pseudorapidity

- Pseudorapidity is the collider polar angle
  - https://en.wikipedia.org/wiki/Pseudorapidity

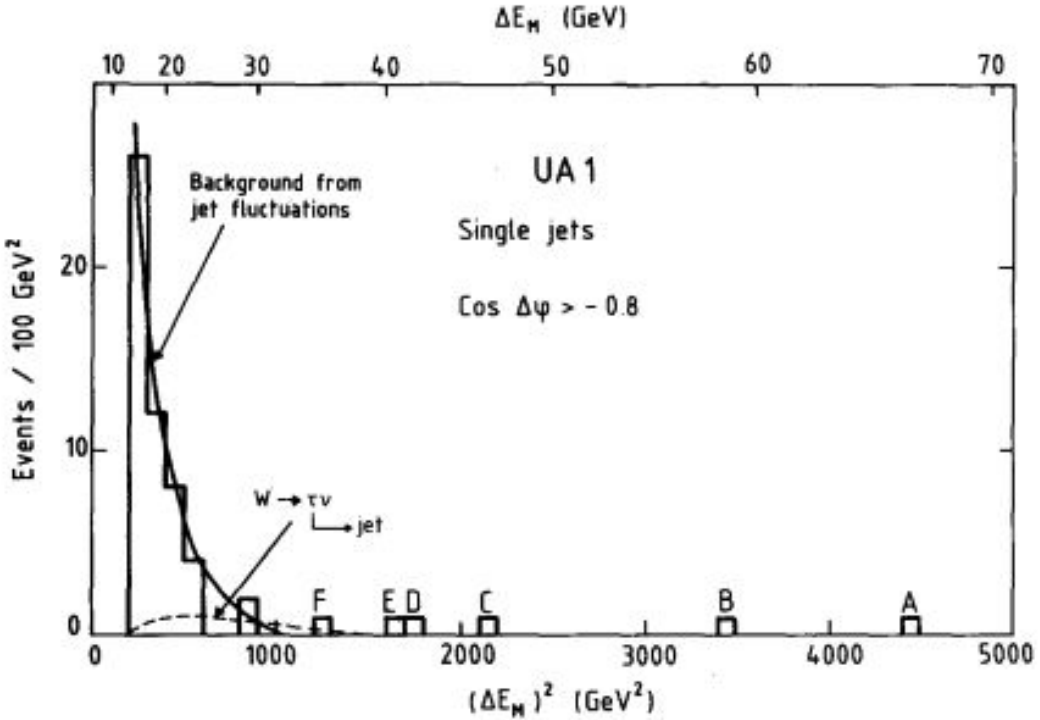


$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



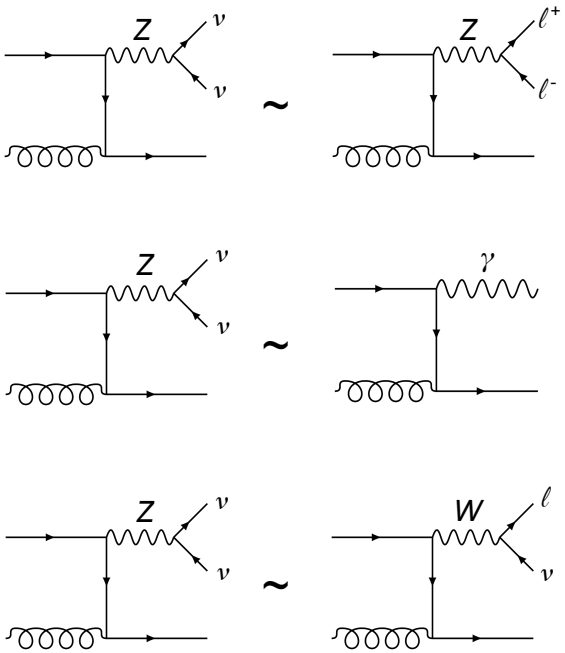
UA1 MonoJet

Experimental observation of events with large missing transverse energy accompanied by a jet or a photon (S) in pp collisions at s = 540 GeV

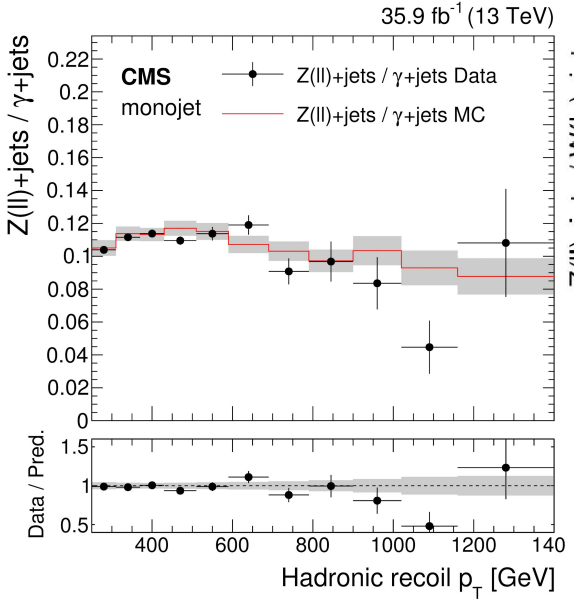


Backgrounds - Experiment & Theory

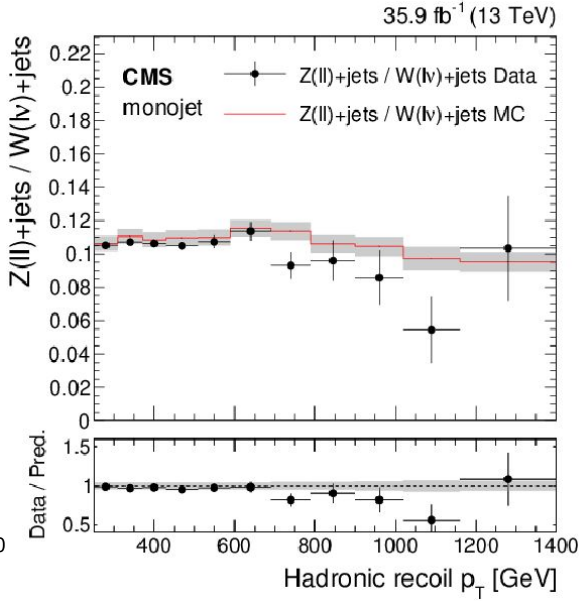
- Charged leptons are invaluable for SM measurements
  - Calibrate kinematics and identification efficiency to level of ~1%
- Precise theory of differential backgrounds is crucial for MC-based estimation



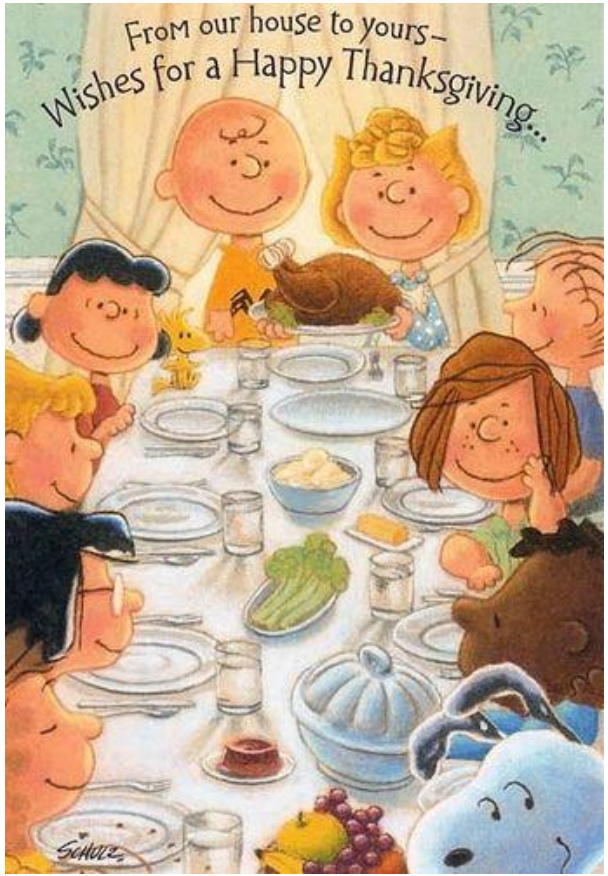
"Z = γ"



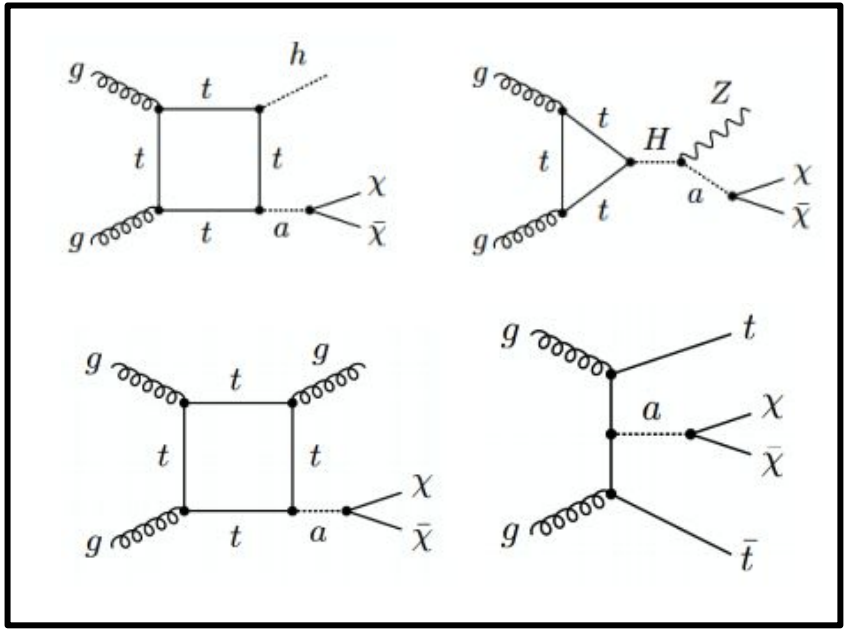
"W = Z"



The Mono-X Family

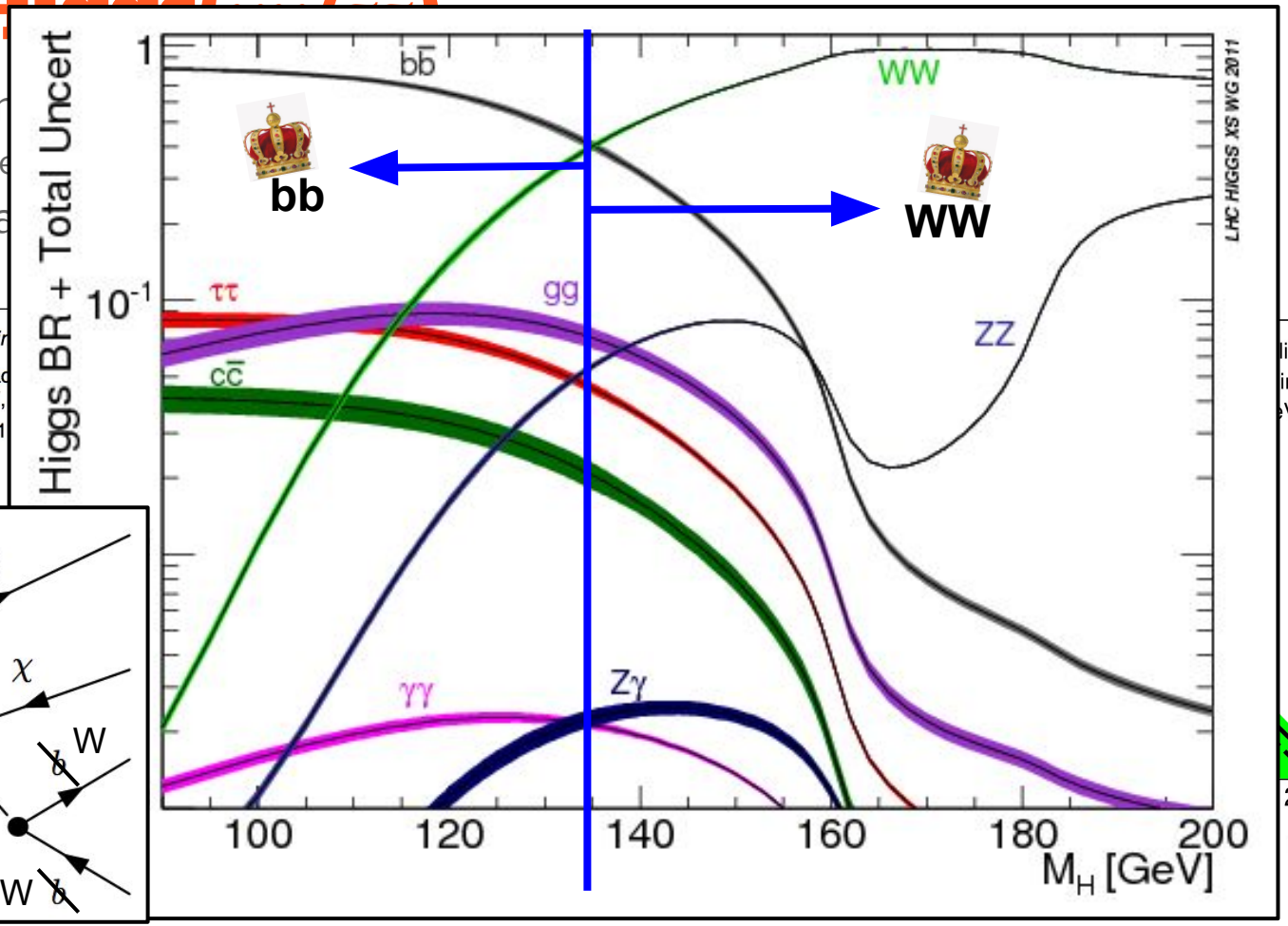


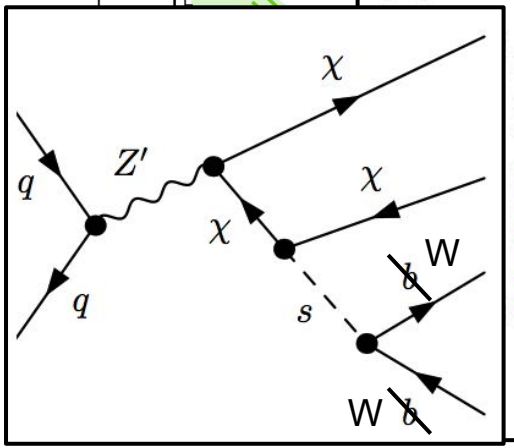
2HDM+Pseudoscalar

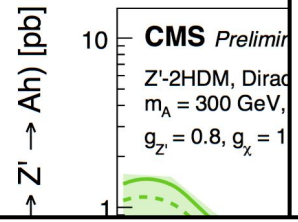


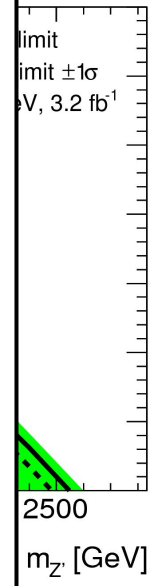
Mono-Higgs(→ / →)

- Other char
  - (1) Probe
- Suffer grea



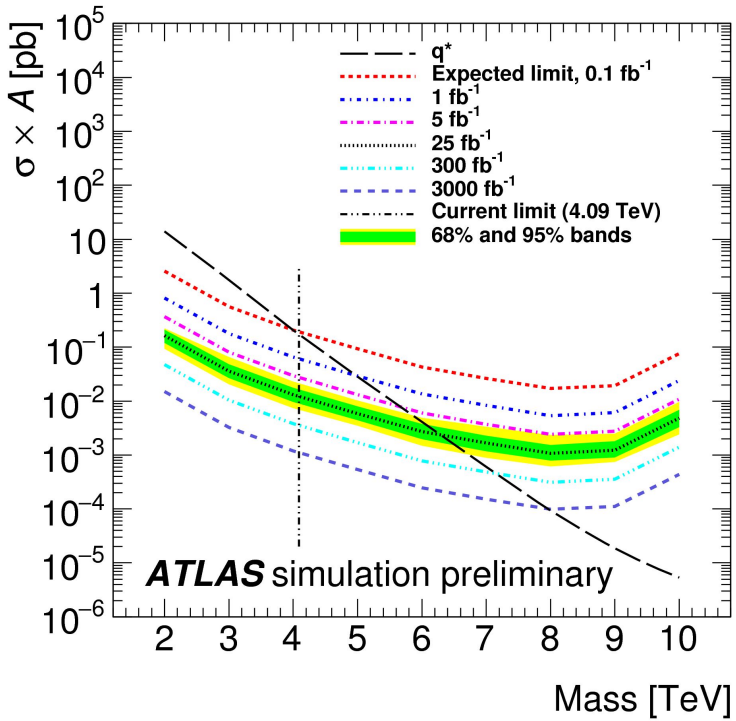






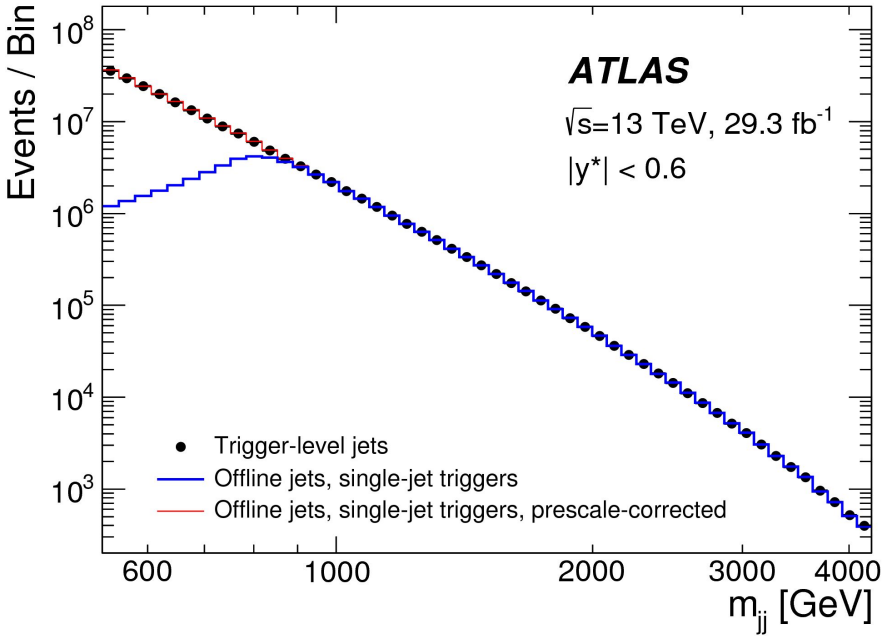
High Mass Dijet Search in the Future

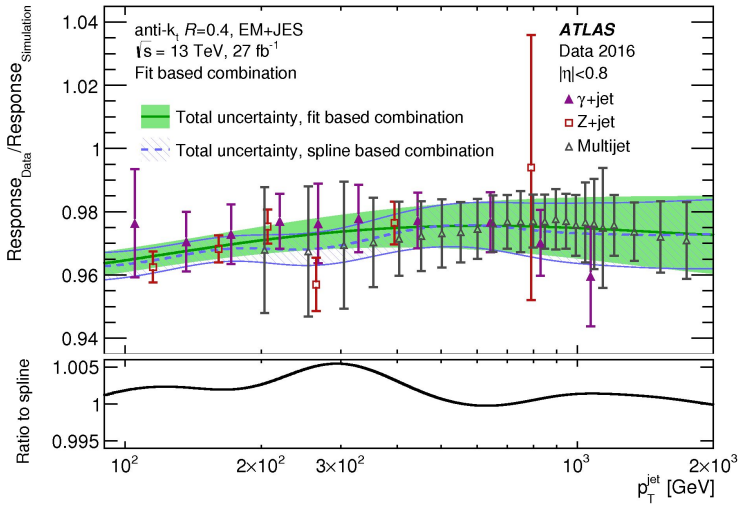
- Diminishing returns with more luminosity only : ATL-PHYS-PUB-2015-004



Lumi [fb^{-1}]	*Limit [pb]*
0.1	0.227
1	0.061
5	0.031
25	0.014
300	0.004
3000	0.001

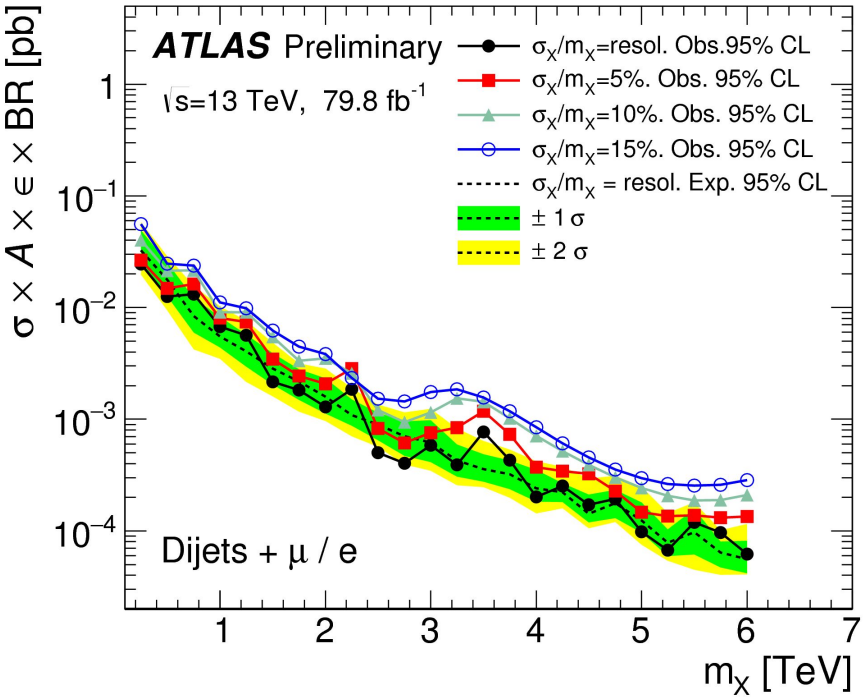
Trigger Level Dijets





ISR(Lepton) + X(qq → jj)

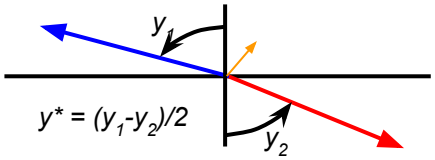
- Generic limits on Gaussian-shaped signals are set and can be used for reinterpretation

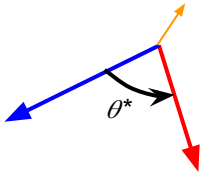


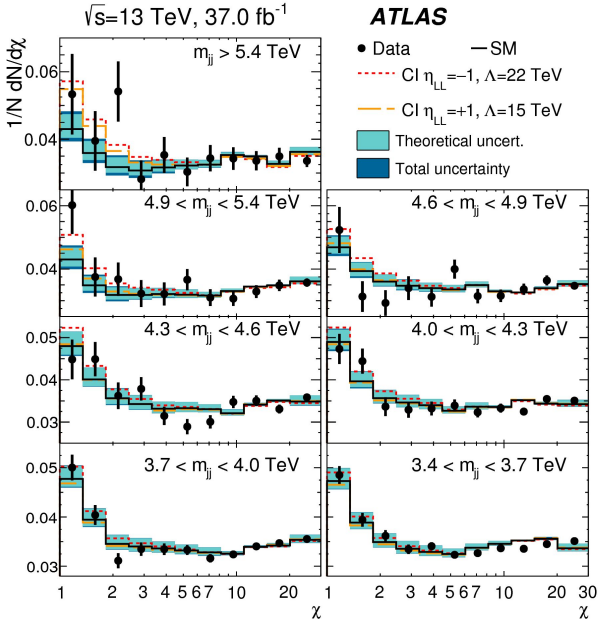
Dijet Angular - Wide Resonances

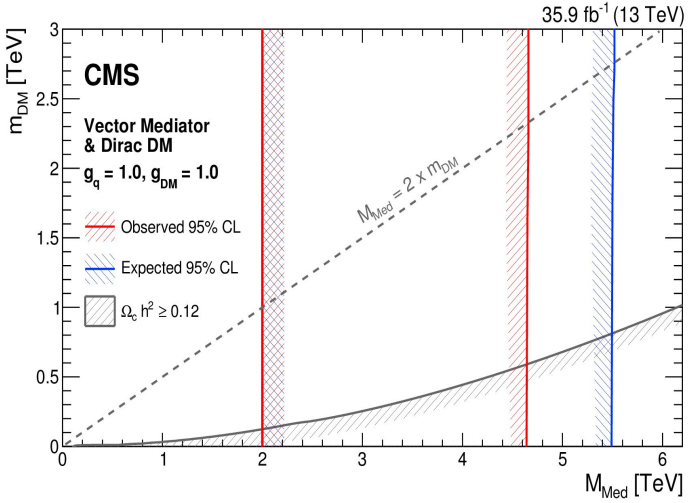
- High mass dijet can only search for narrow bumps (detector resolution limited)
- Looking at angular properties allows to search for wide resonances
  - CMS : EXO-16-046 and ATLAS : EXOT-2016-21

$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



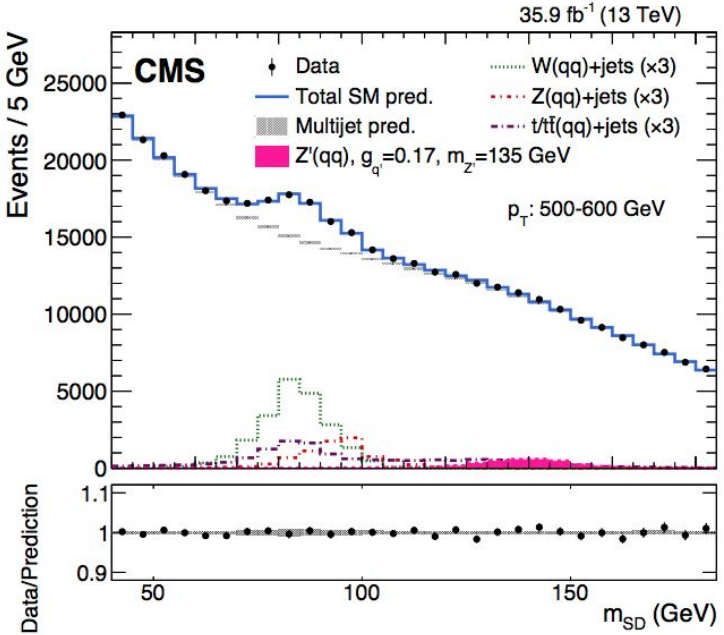


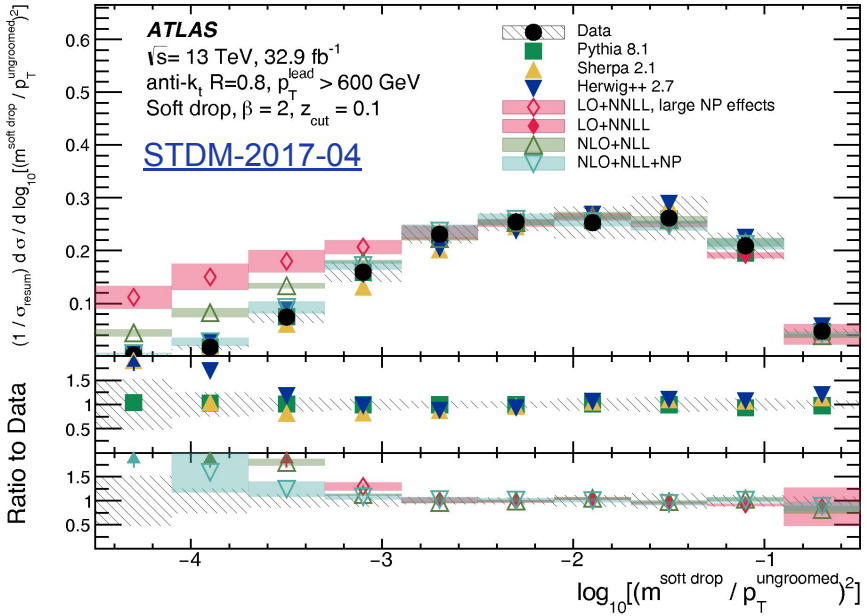




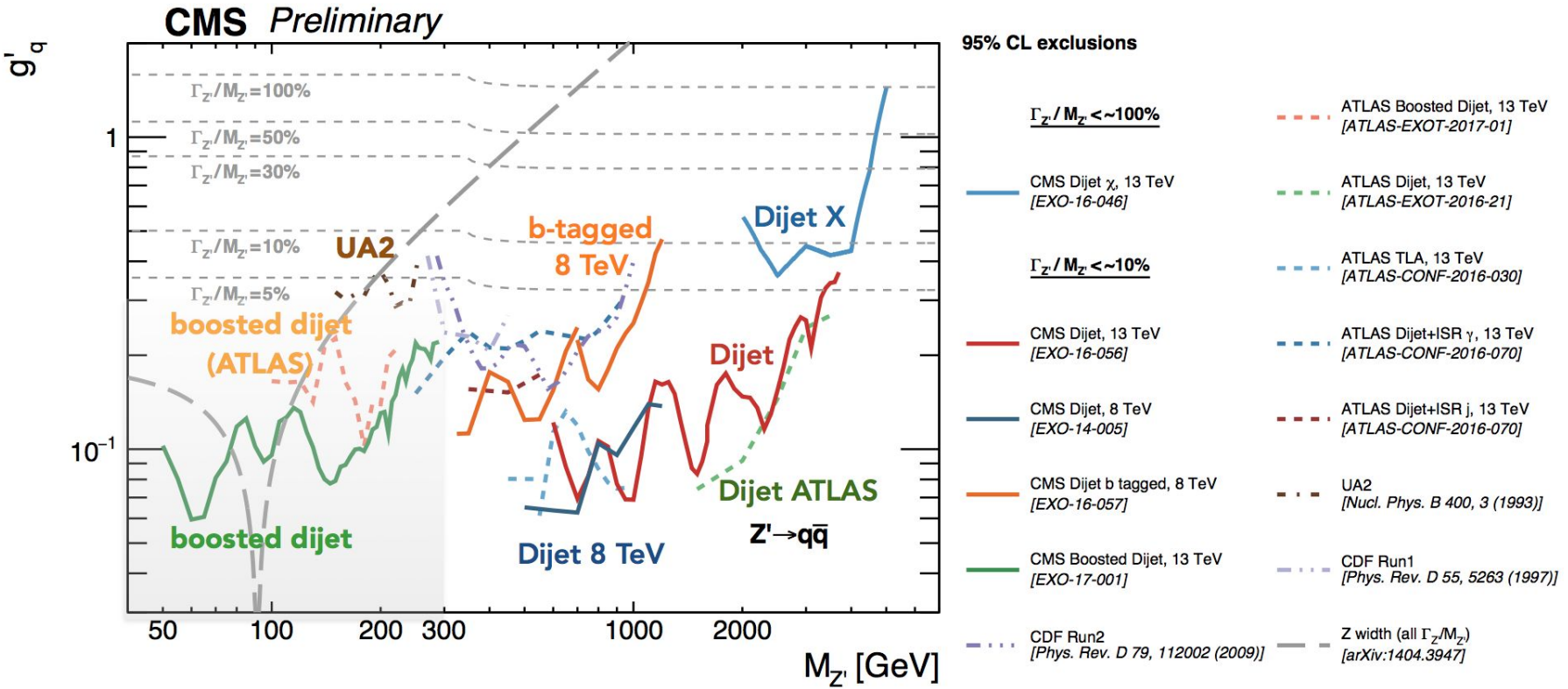
ISR+X(qq → J)

- Opens access to the lowest mass phase space yet : $m_{med} < 100$ GeV
- Progress being made in step with theoretical understanding and experimental measurements of the observables exploited in the searches

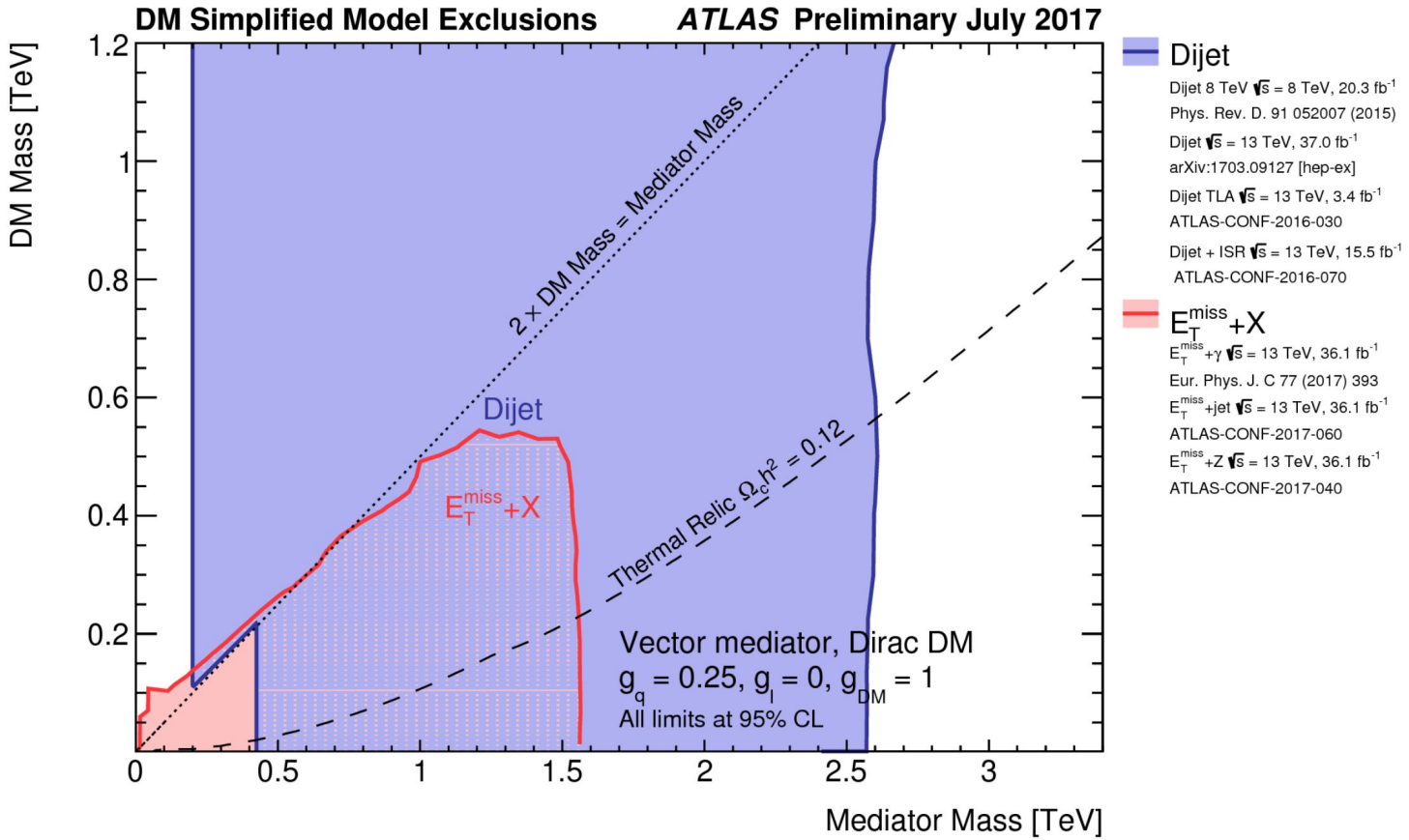
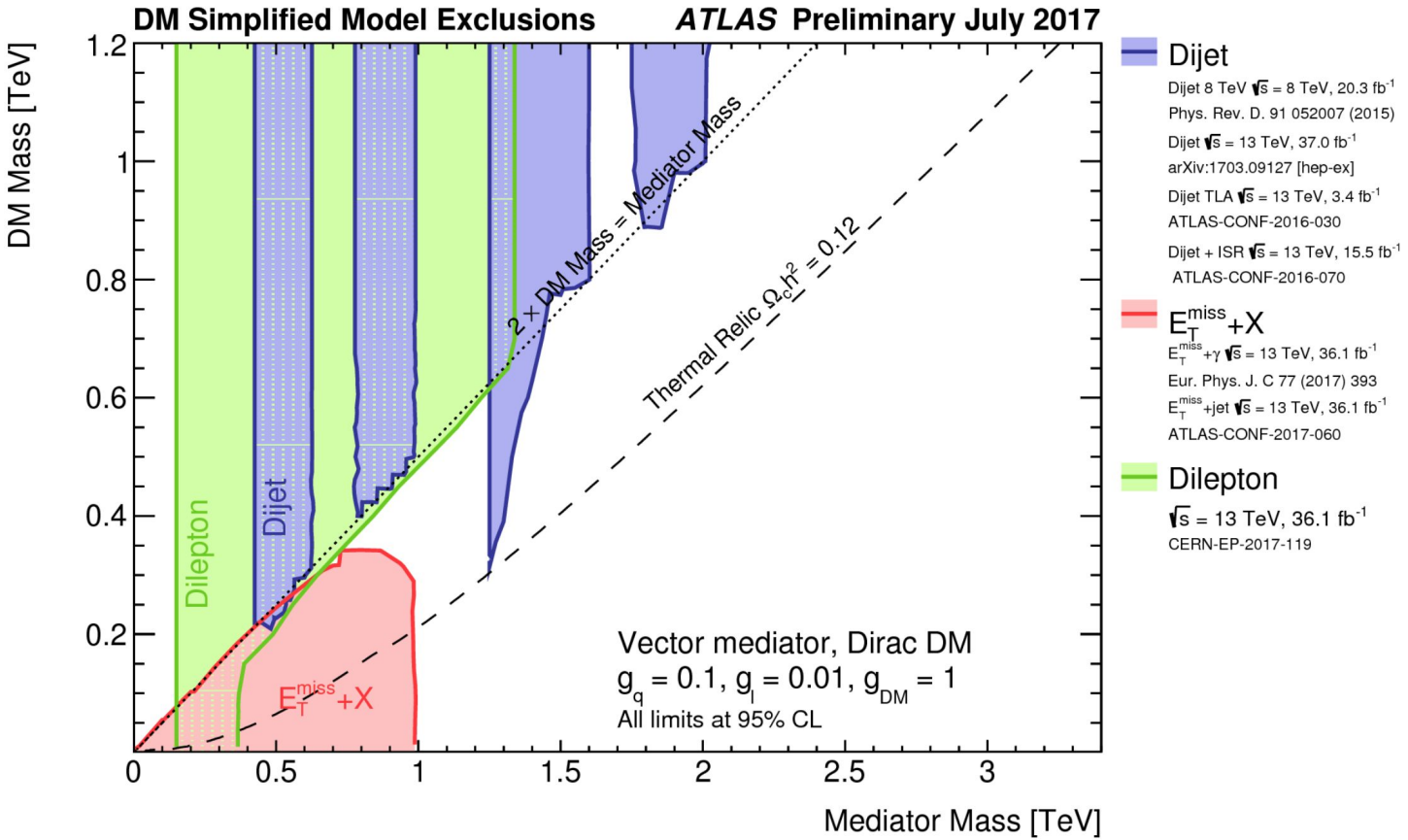




Coupling Exclusion - CMS



Leptonic Couplings - What?!?! (Without)



Leptonic Couplings - What?!?! (With)