QCD in BSM & Higgs

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Overview

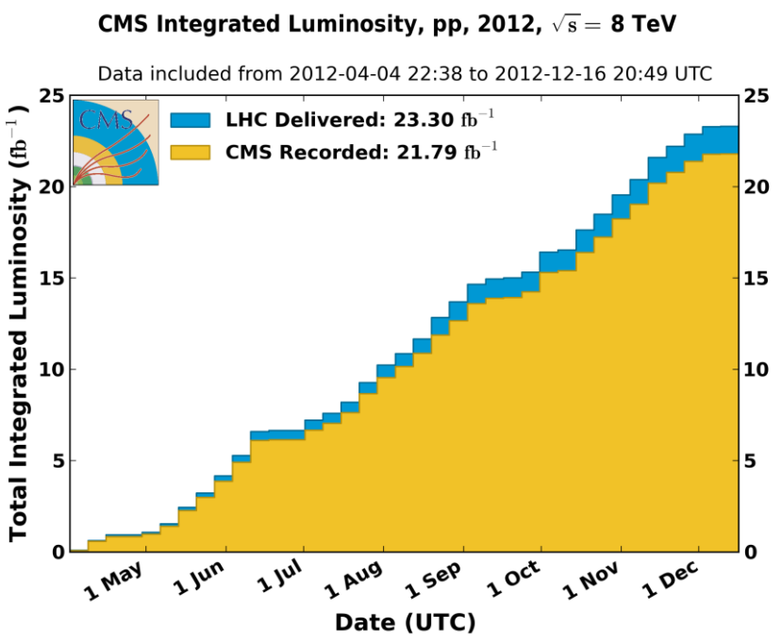
- The Run 2 (usual) lifetime of a search
- Power of the all hadronic search
- The bumps in the road ahead

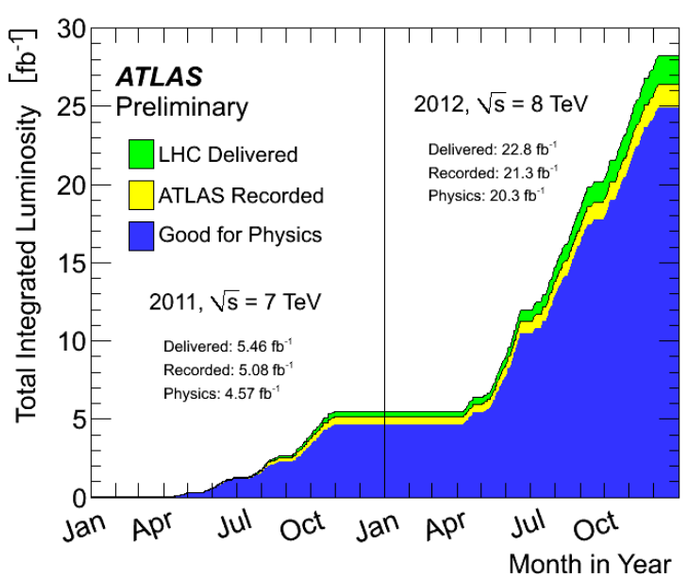
As per usual with this sort of talk only a sampling of the possible topics are discussed.
SUSY not discussed

Apologies if your favorite topic is not included.
Please mention in discussion afterwards!

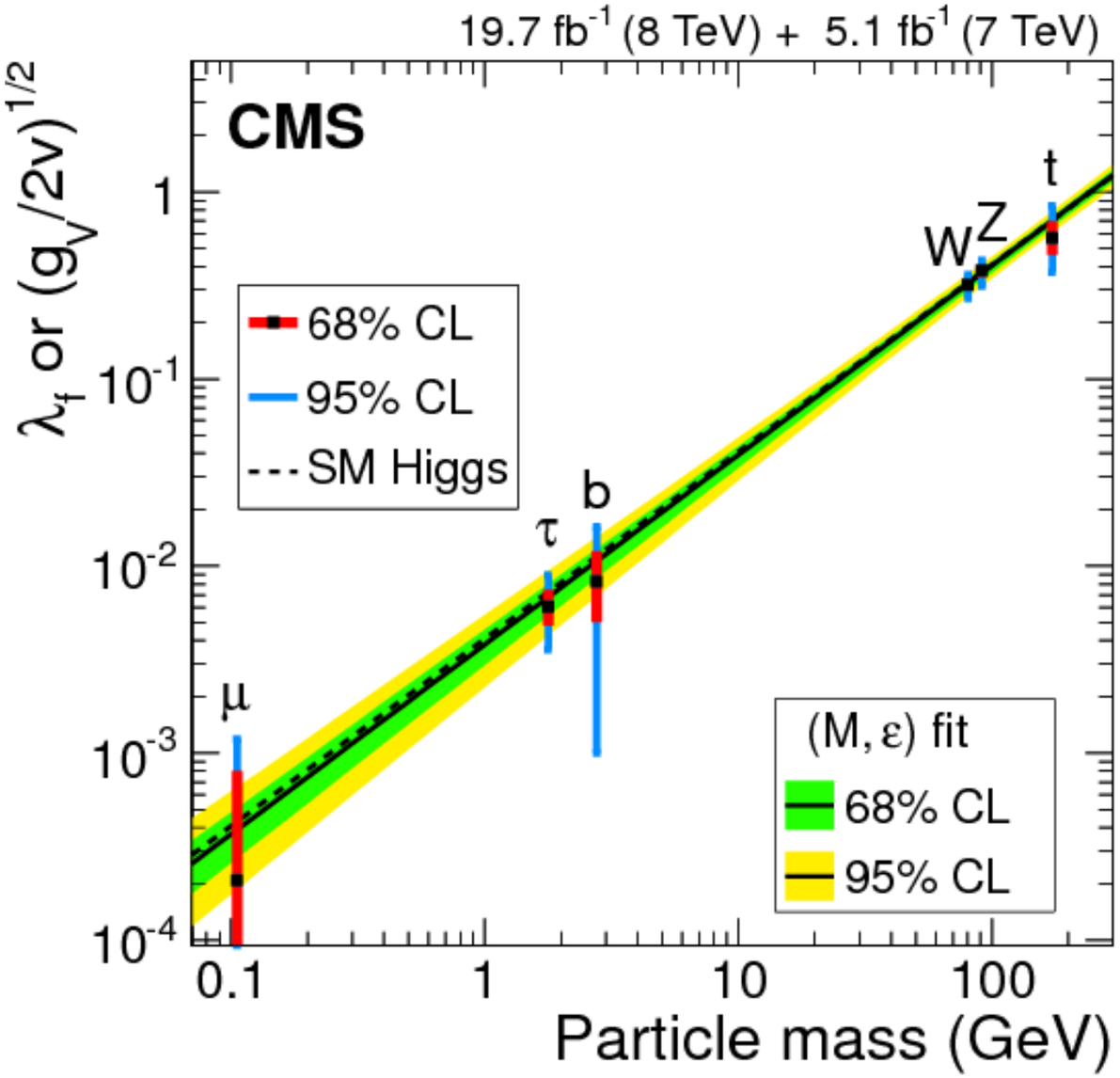
Run 1: Success!

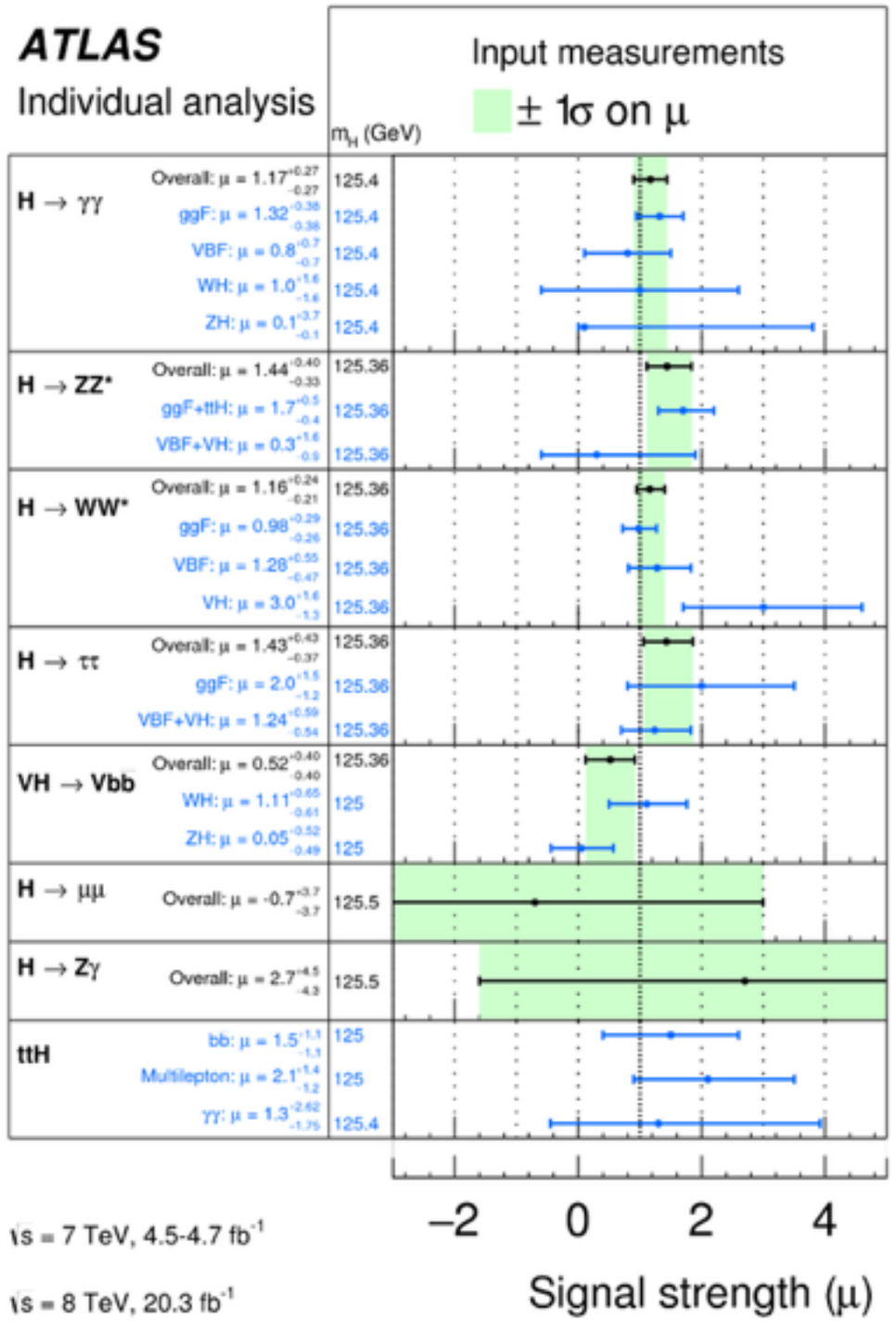
- ~500 papers submitted by each ATLAS & CMS
- Wide range of precision measurements
- Extensive searches with 1 or 2 interesting features
- A new particle, confirmation of our understanding of mass





Run 1: Higgs-centric!





All Higgs results are consistent with the Standard Model

Eur. Phys. J. C (2016) 76:6

Run 2

- Need something unexpected to advance our knowledge
- Do things that have never been done...
  - Probing physics at unexplored energies
    - Unprecedented rates of pp collisions
- Using state-of-the-art tools

Exciting times!!

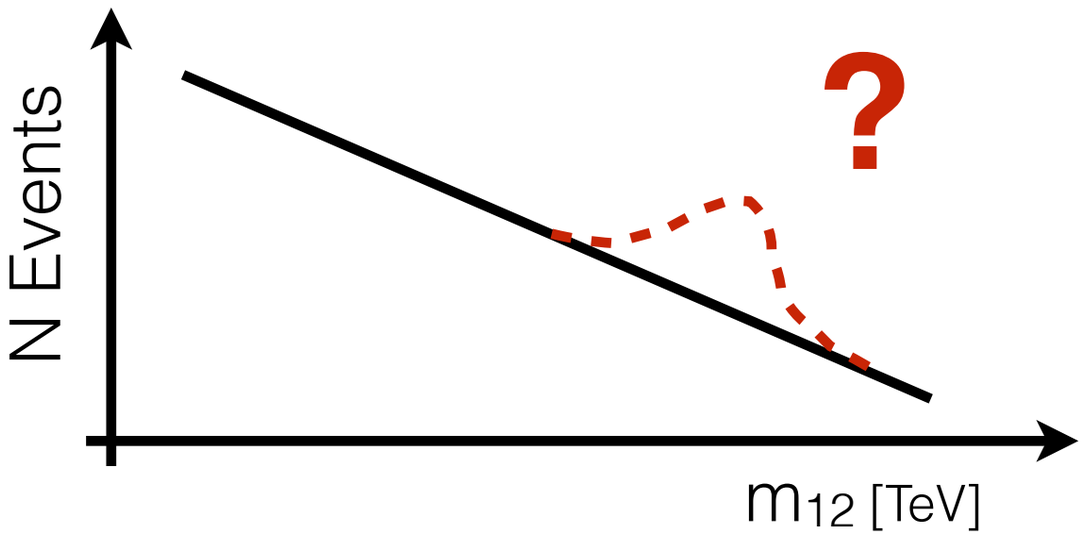
- **Recipe for discovery: Expect the unexpected**
  - ***NB: New physics can hide in the uncertainties!***

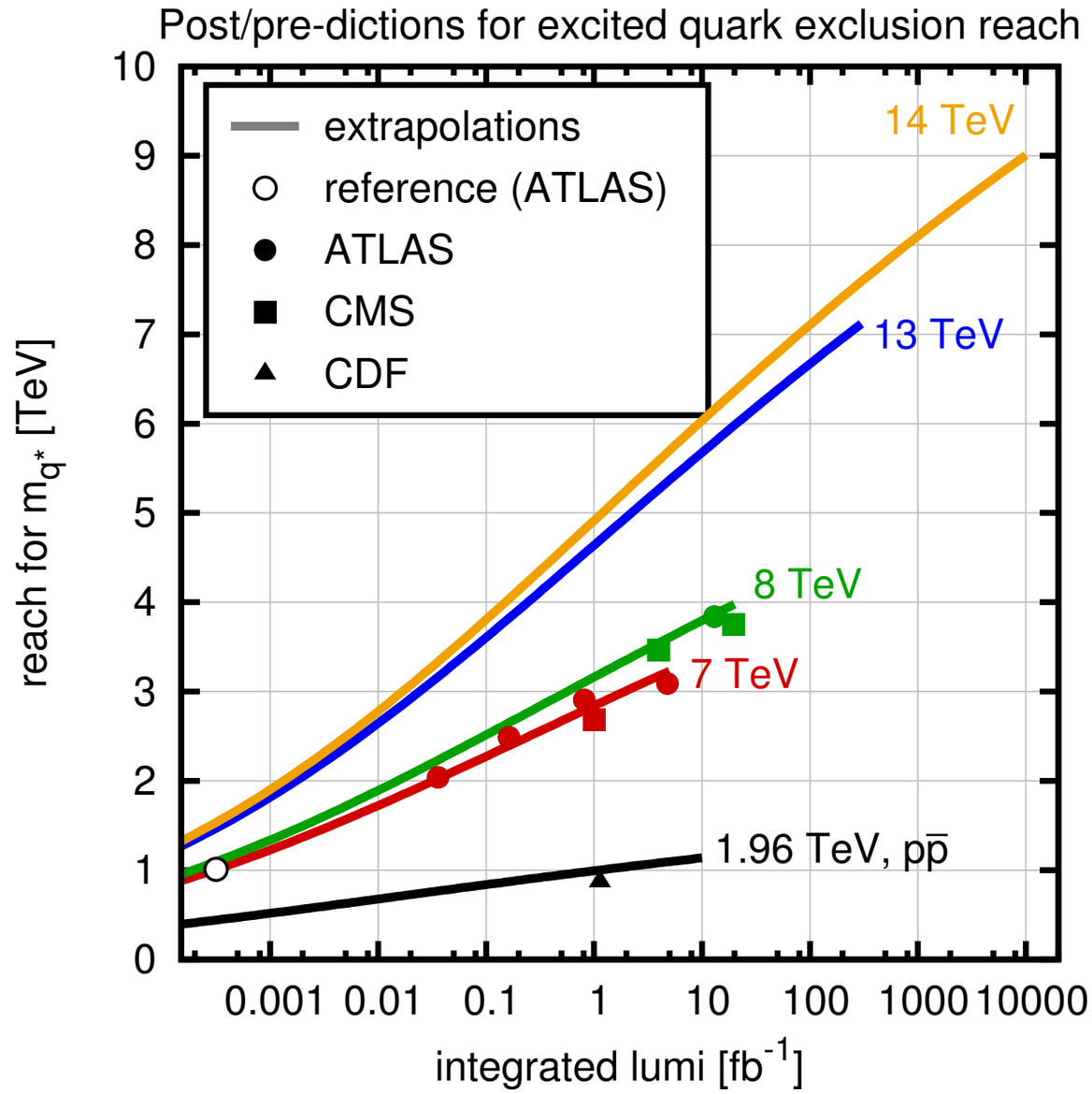
The lifetime of a Run 2 search

(the simplest example)

Run 2: Searches

- At start, profit from increase in √s to probe higher masses than Run 1



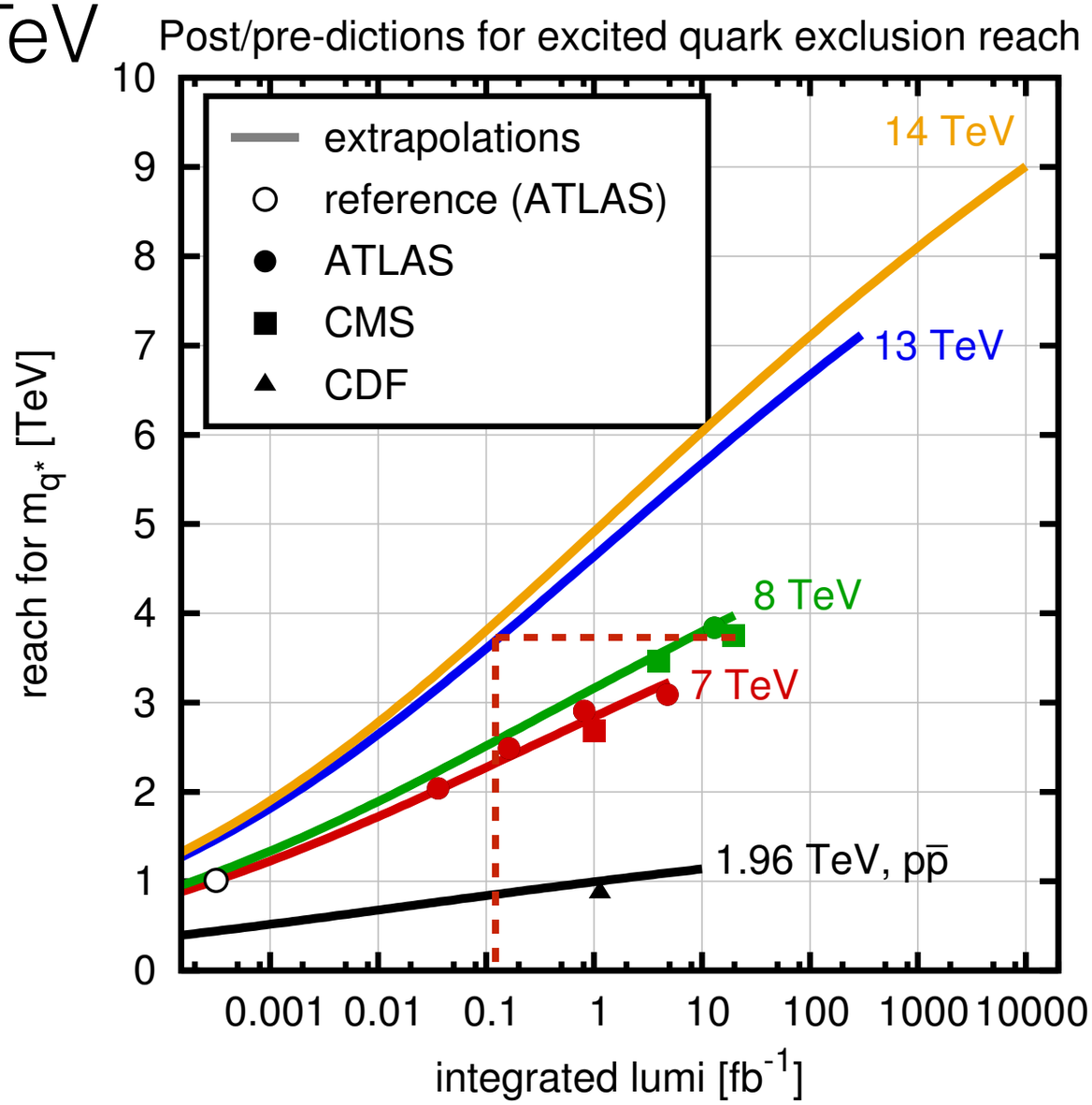


Run 2: Searches

- potential for discovery was huge out of the gate and it was in *QCD* signatures were we started

- 20/fb @ 8 TeV ~ 0.2/fb @ 13 TeV

short game -
get a quick and
robust background
estimation and get
the results out!



Run 2: Searches

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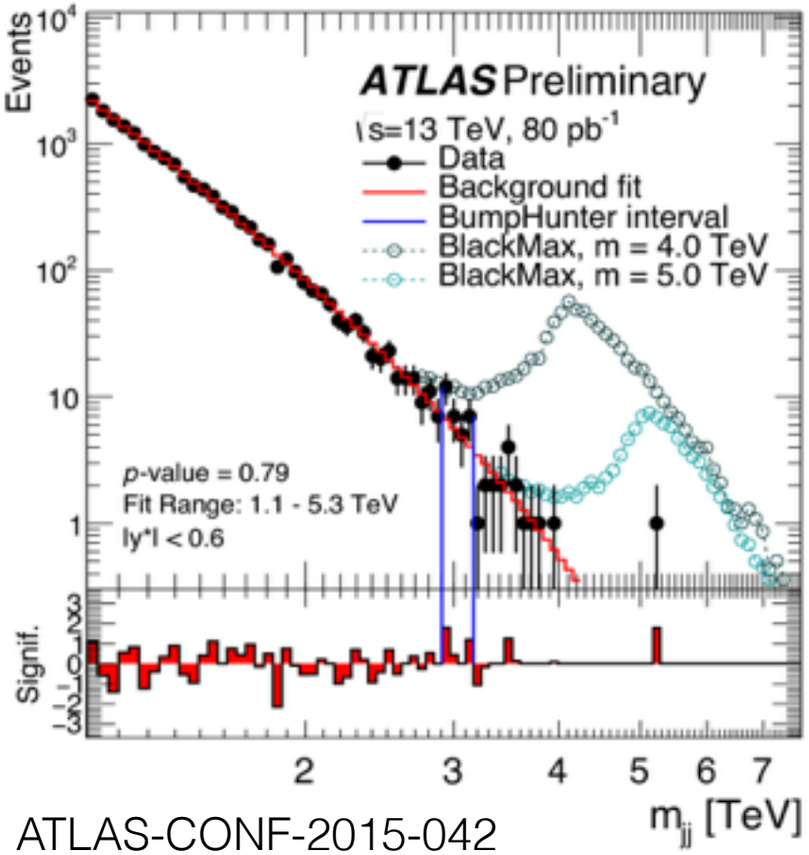
- Black holes searches were even more exciting



ATLAS-CONF-2015-042

model QCD with fit:

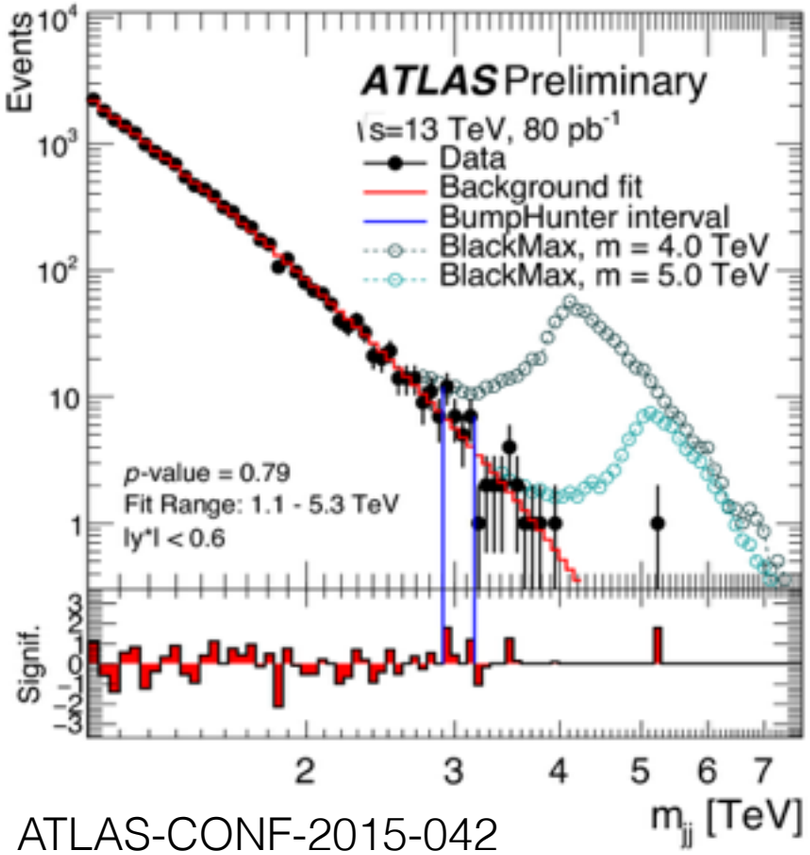
$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\mathrm{jj}}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

largest concern: smoothness

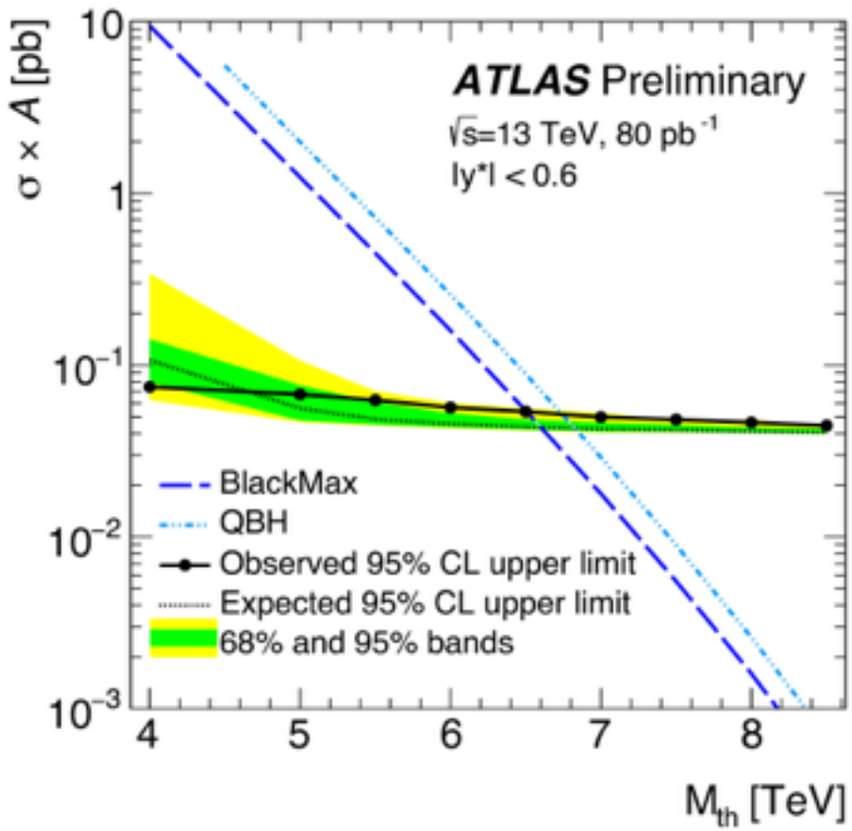
Run 2: Searches

- potential for discovery was huge out of the gate and it was in *QCD* signatures were we started

- Huge jump in reach from √s



ATLAS-CONF-2015-042



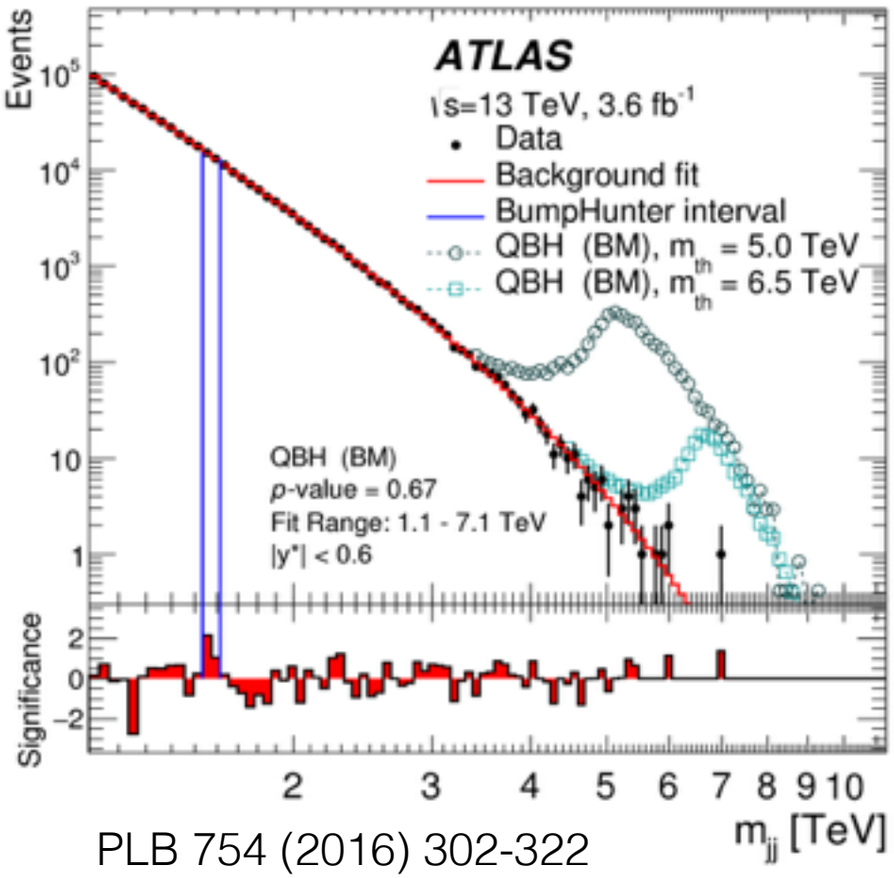
- Limits: 5.6–>6.5 TeV

expected limit @ 5 TeV: 0.057 pb

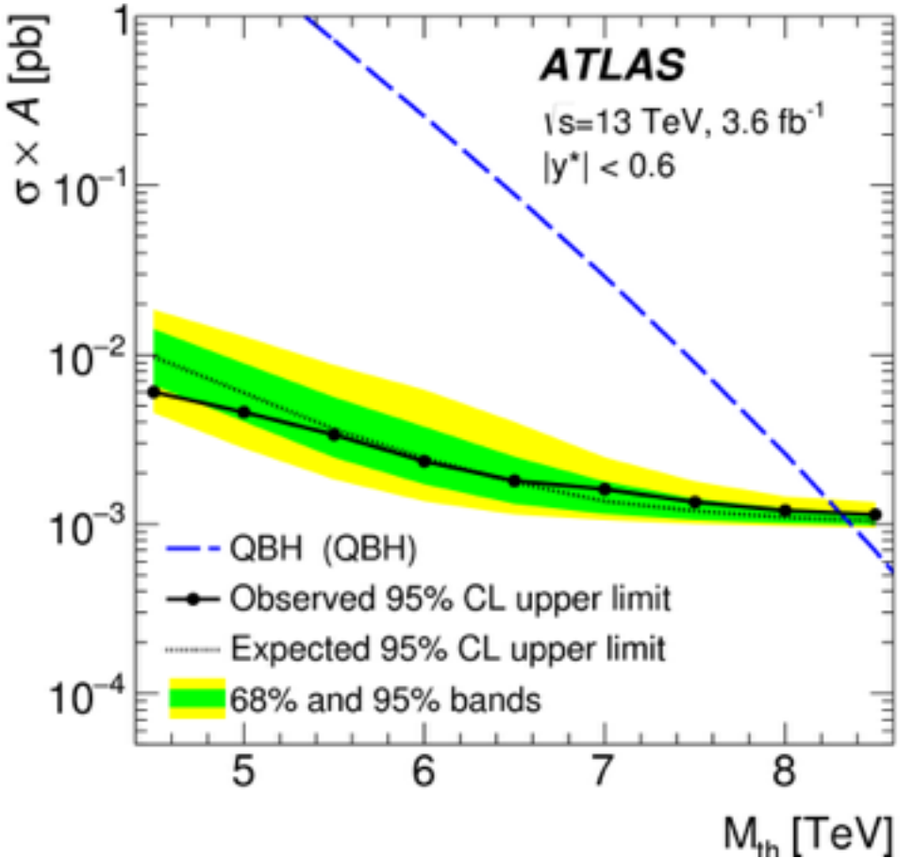
Search Lifetime

- potential for discovery was huge out of the gate and it was in *QCD* signatures were we started

- mass reach grows like log(L) [1.5 TeV for factor 50]



PLB 754 (2016) 302-322



- Limits: 6.5–>8.1 TeV

expected limit @ 5 TeV: 0.006 pb

sqrt(3.6/0.08)

Search Lifetime

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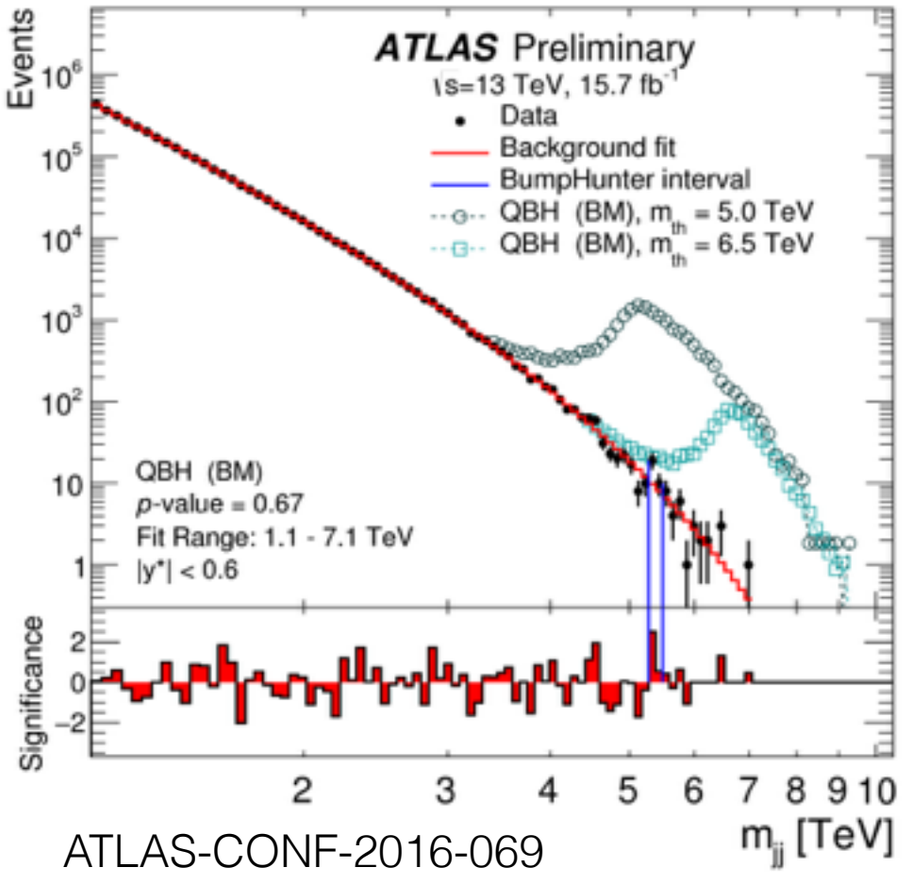
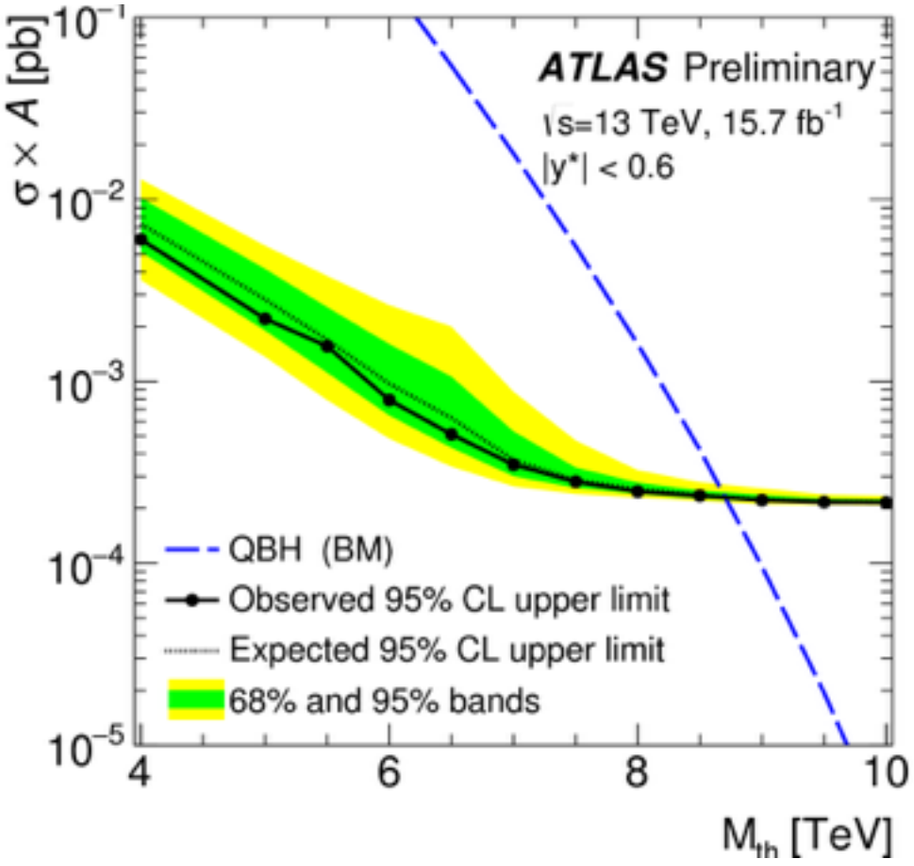
- mass reach grows like log(L) [1.5 TeV for factor 50]



ATLAS-CONF-2016-069



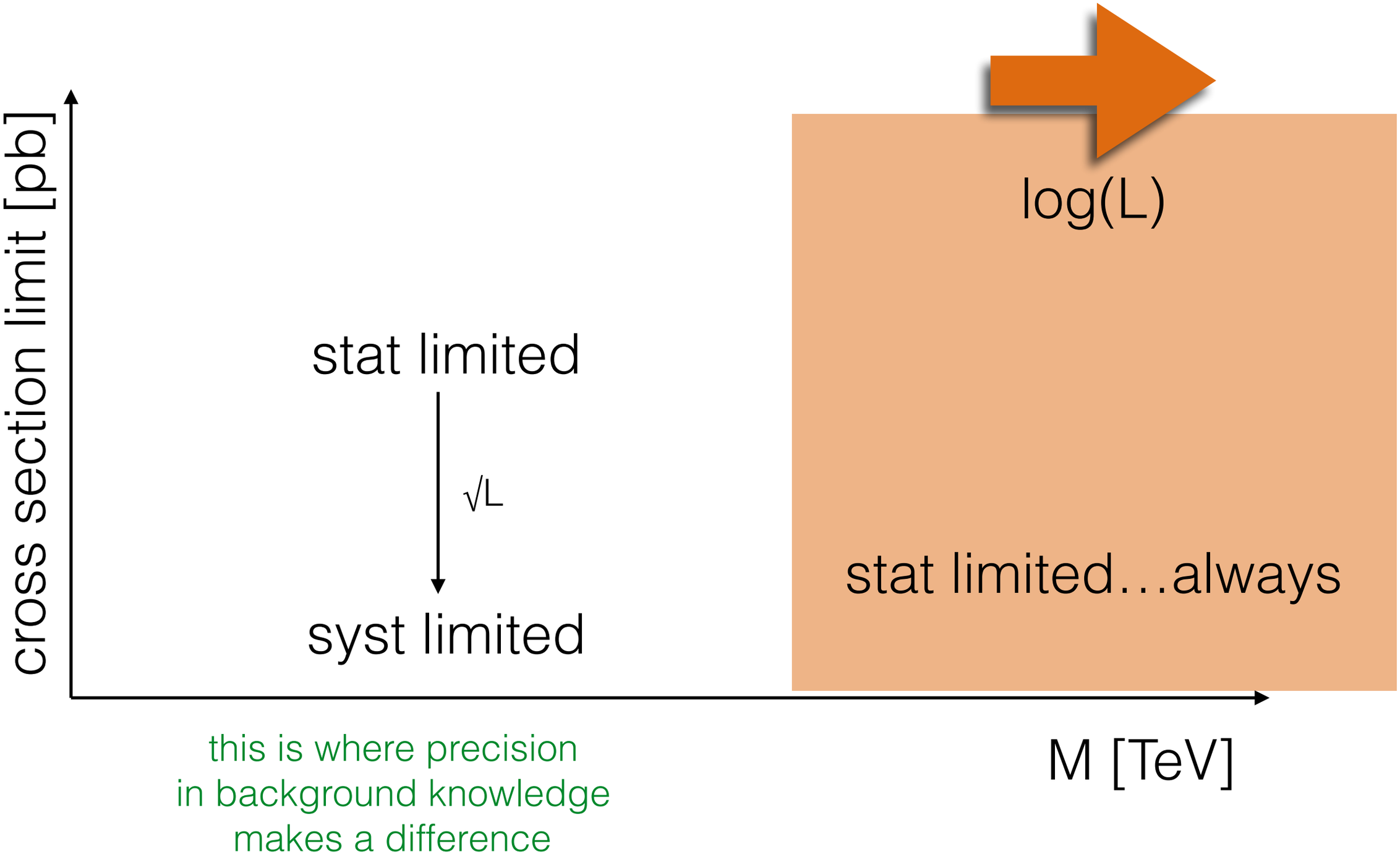
- Limits: 8.1–>8.7 TeV

expected limit @ 5 TeV: 0.003 pb

cross section limit shrinks like √L

sqrt(15.7/3.6)

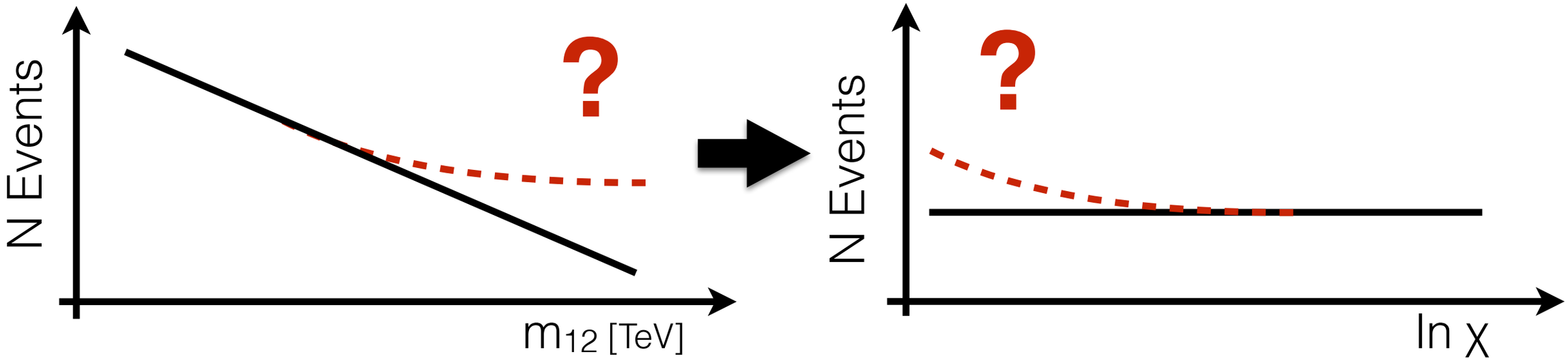
Search Lifetime

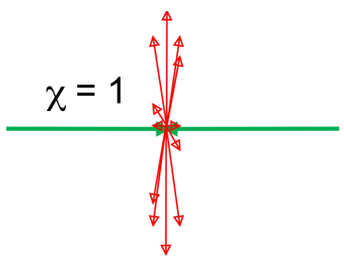


psychology - how low can you go??

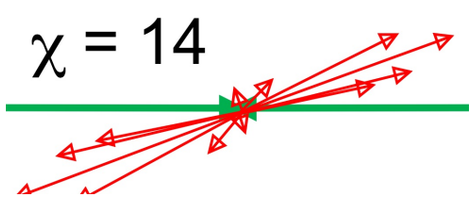
Besides Bumps

- The simplicity of the bump hunt leaves a weakness
  - insensitivity to non-resonant behavior
- **Complementary search needed!**





New physics = isotropic decays



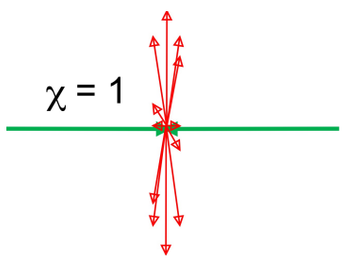
Rutherford scattering

$\chi = e^{2y^*} = e^{\Delta y} \sim 1 + \cos\Theta^* / 1 - \cos\Theta^*$

Besides Bumps

- The simplicity of the bump hunt leaves a weakness
  - insensitivity to non-resonant behavior
- **Complementary search needed!**

Bkgd: Pythia with NLO QCD+EW corrections



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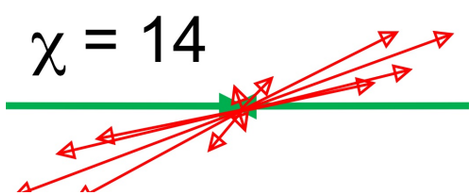

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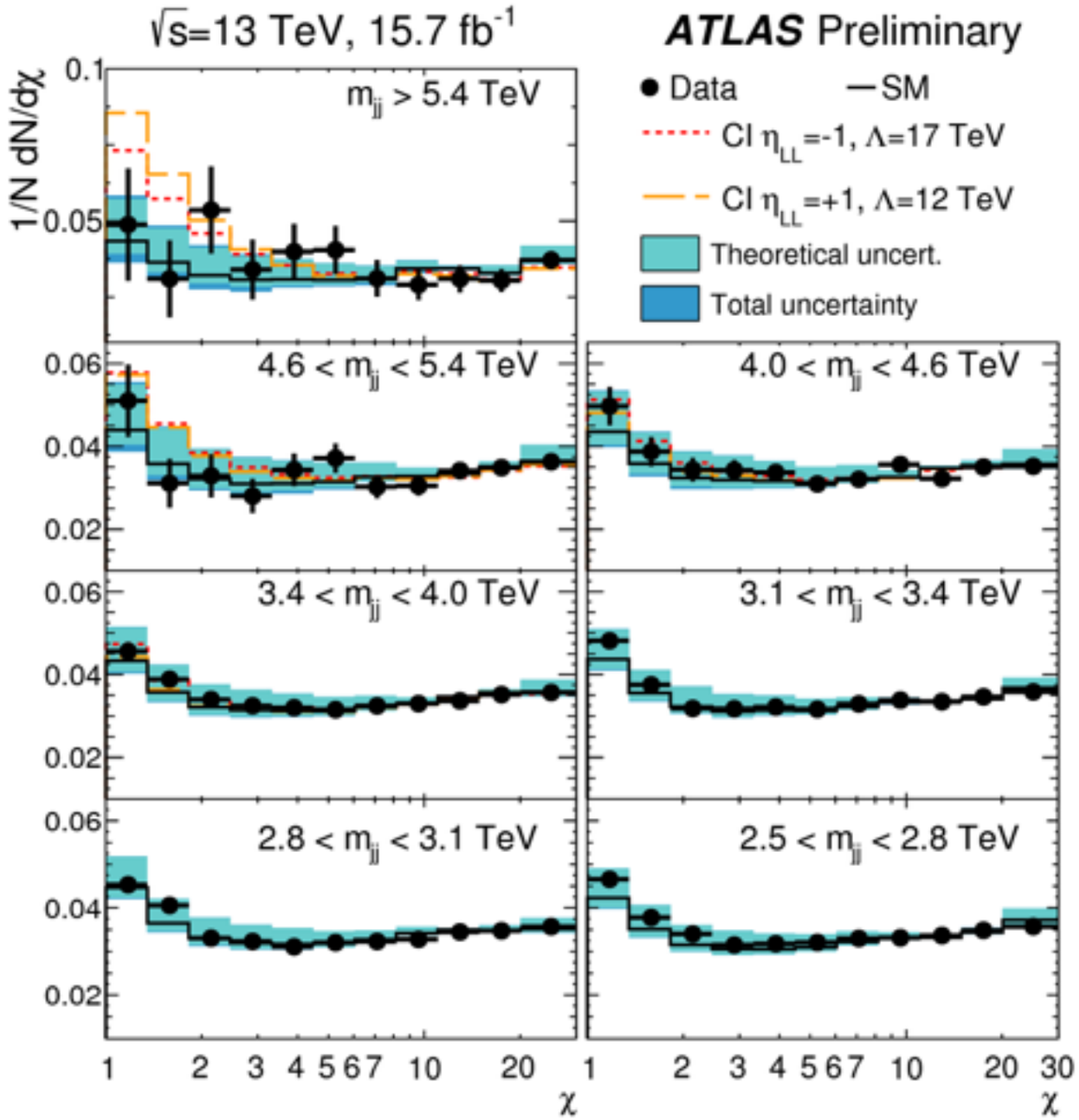
ATLAS-CONF-2016-069



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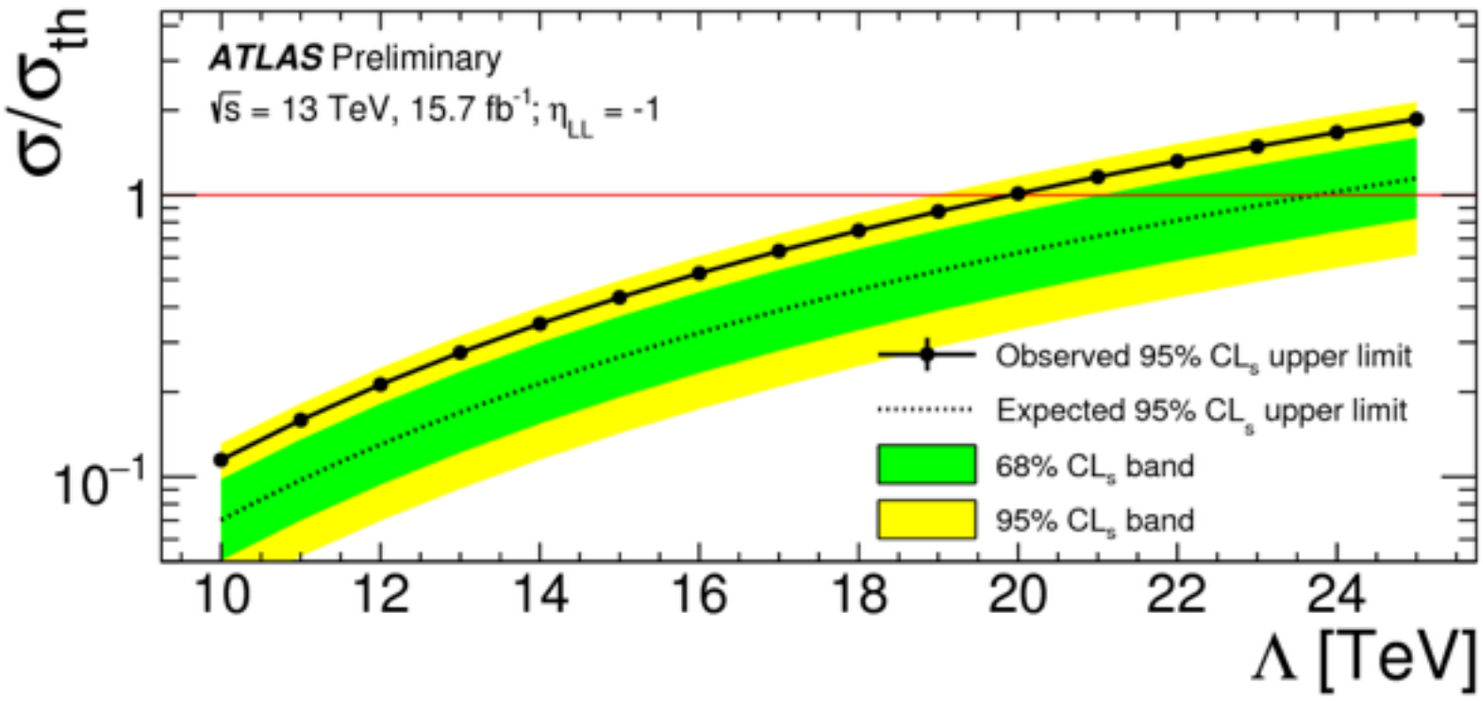
ATLAS-CONF-2016-069

- **Complementary search needed!**



Bkgd: Pythia with NLO QCD+EW corrections

Λ=scale of new physics

this is where precision
in background knowledge
makes a difference

QCD Community

- The foundation of a long and health physics program:

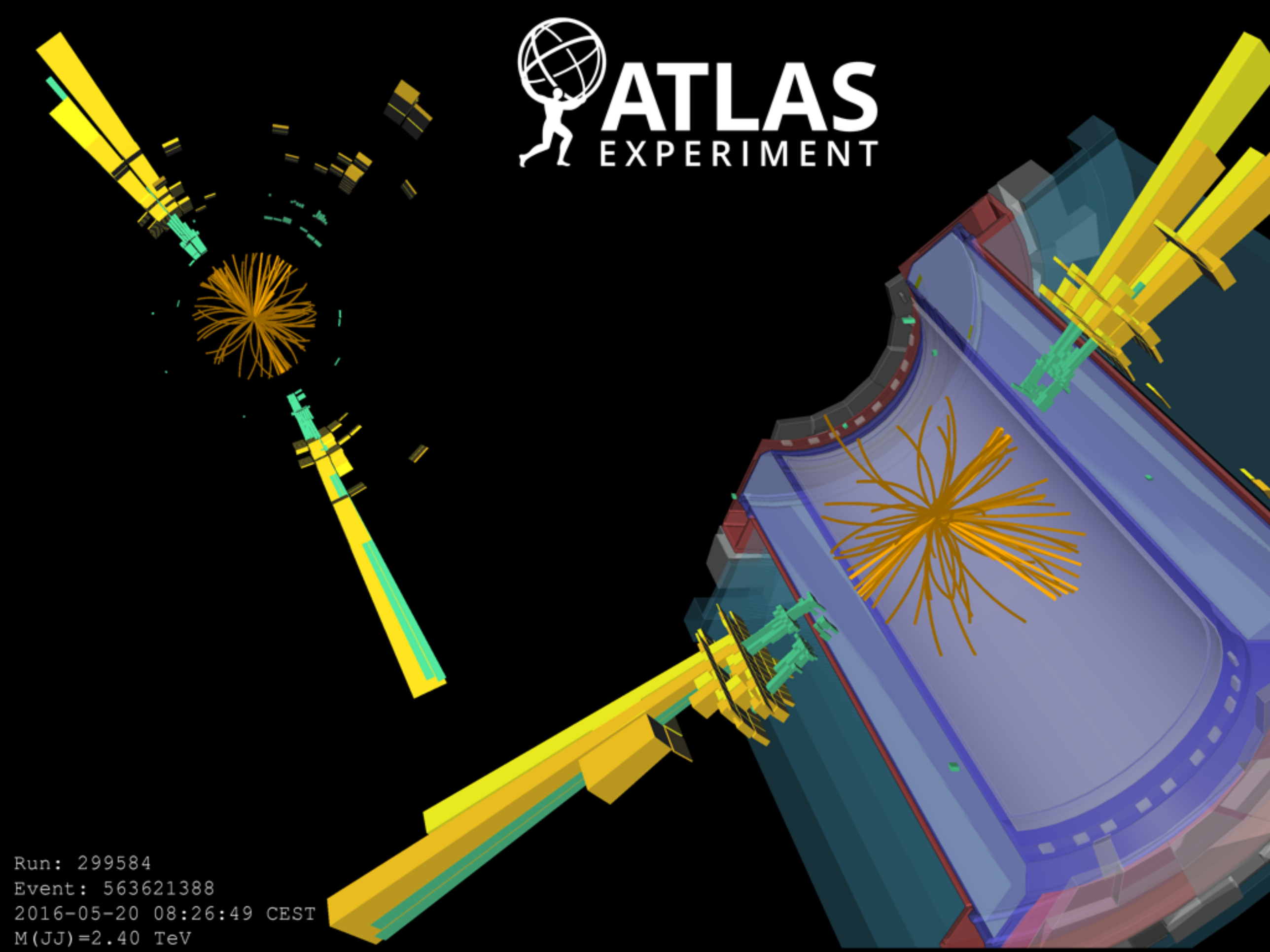
1. Great operations: accelerator and detector
2. Robust object reconstruction / identification
3. Precise ***measurements & calculations*** are the shoulders of the giants we stand on

QCD Precision

- Three cases where precise knowledge of QCD is/ will be the **important** in the long run [personal view]

1. Substructure: How far can the data driven corrections go?
2. MET searches: PDFs and transfer factors
3. H(bb)

1. **Substructure: How far can the data driven corrections go?**


ATLAS
EXPERIMENT
Run: 299584
Event: 563621388
2016-05-20 08:26:49 CEST
M(JJ)=2.40 TeV

QCD in Searches

- Most analyses: designed to **suppress QCD**:
  - Use Leptons, Missing ET, photons
  - QCD contribution described by cocktail of MC predictions plus data driven approach
  - But…

QCD in Searches

- Most analyses: designed to **suppress QCD**:
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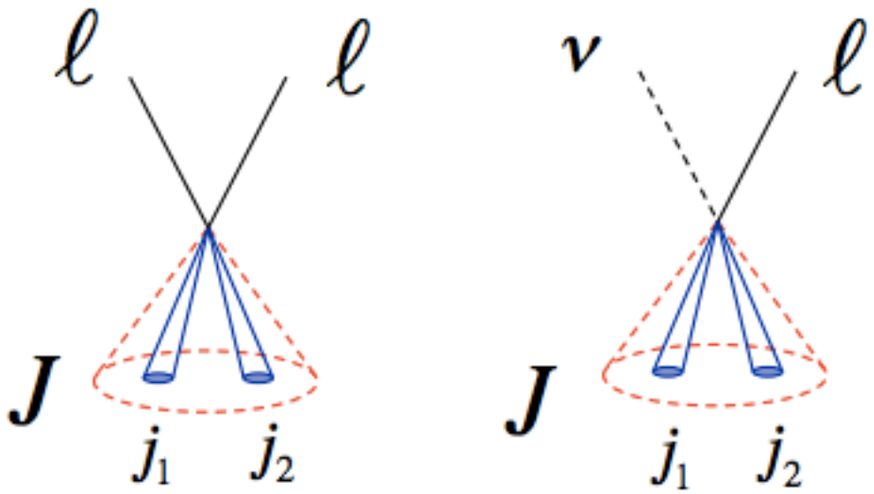
  - QCD contribution described by cocktail of MC predictions plus data driven approach
  - But…All Hadronic Searches are the leading edge of search programs i.e….(small sampling)
    - (HVT->)VV->qqqq
    - (HVT->)VH->qqbb
    - (G->)HH->bbbb
- … very dependent on substructure techniques

Boosted Vs

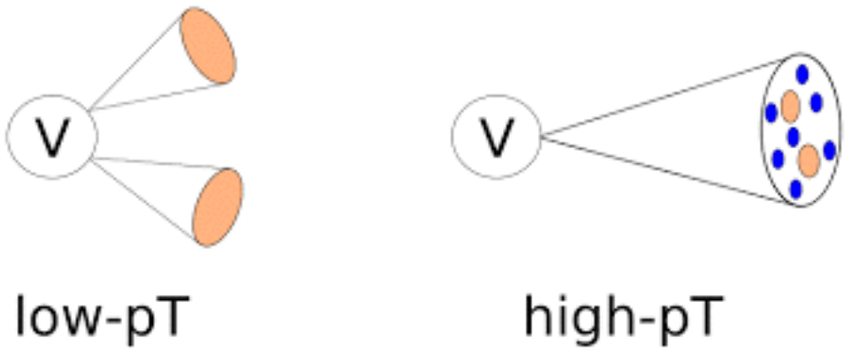
- Heavy things decaying to W or Z's

leptons triggers
to suppress
QCD backgrounds



heavily rely on MC with
(complicated) profile likelihoods

embrace QCD
suppress bkgd rate
with substructure

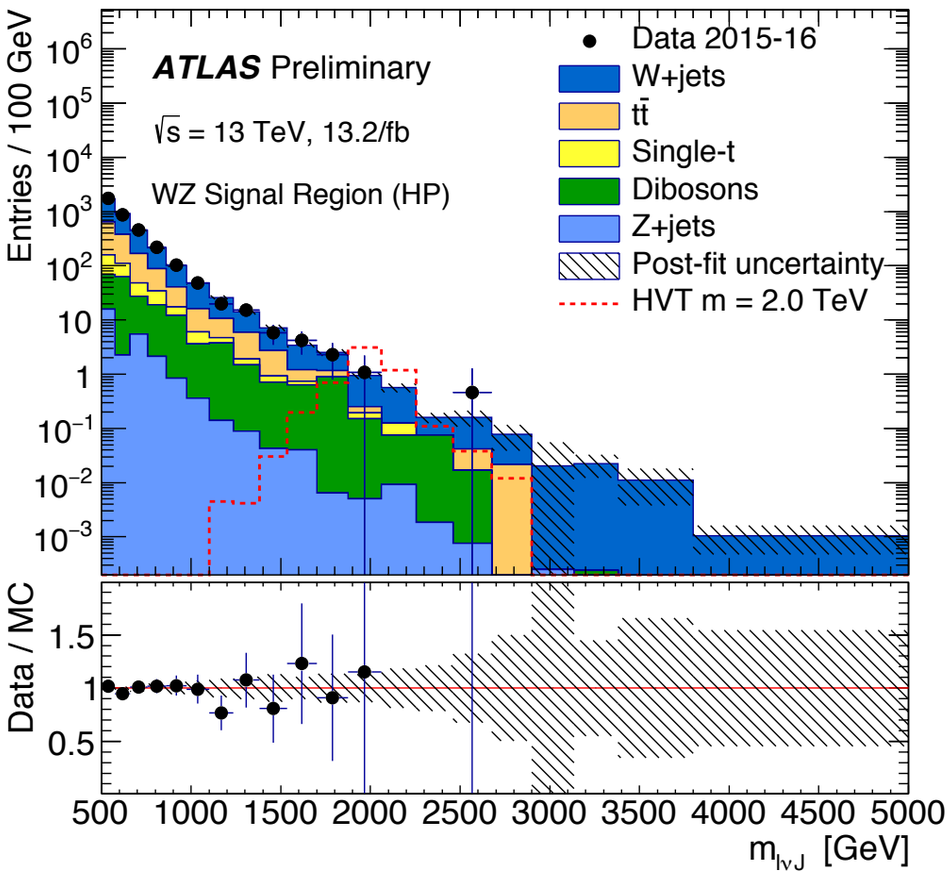


model QCD with fit
validate with MC

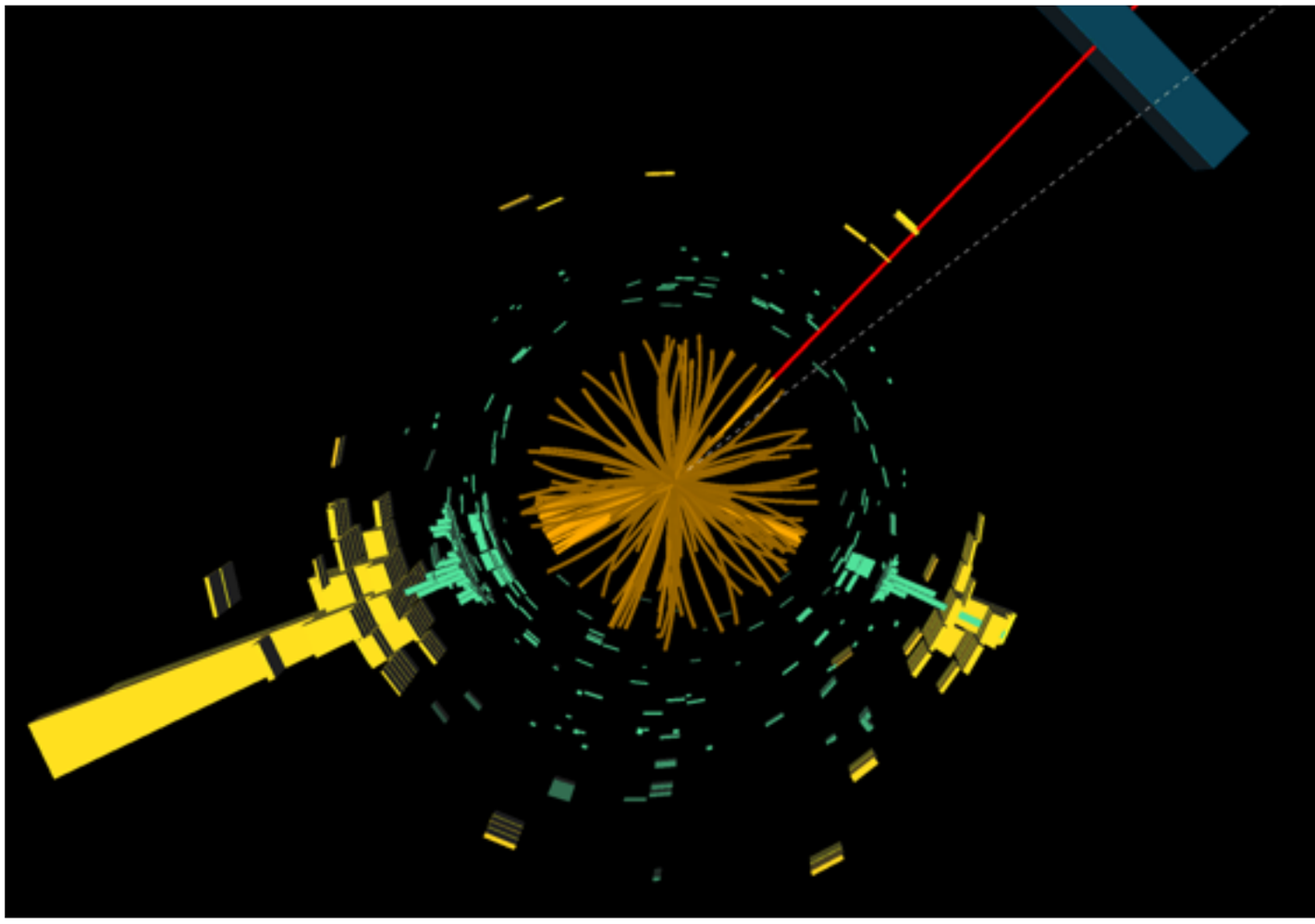
Boosted Vs

- Heavy things decaying to W or Z's

leptons triggers



ATLAS-CONF-2016-062

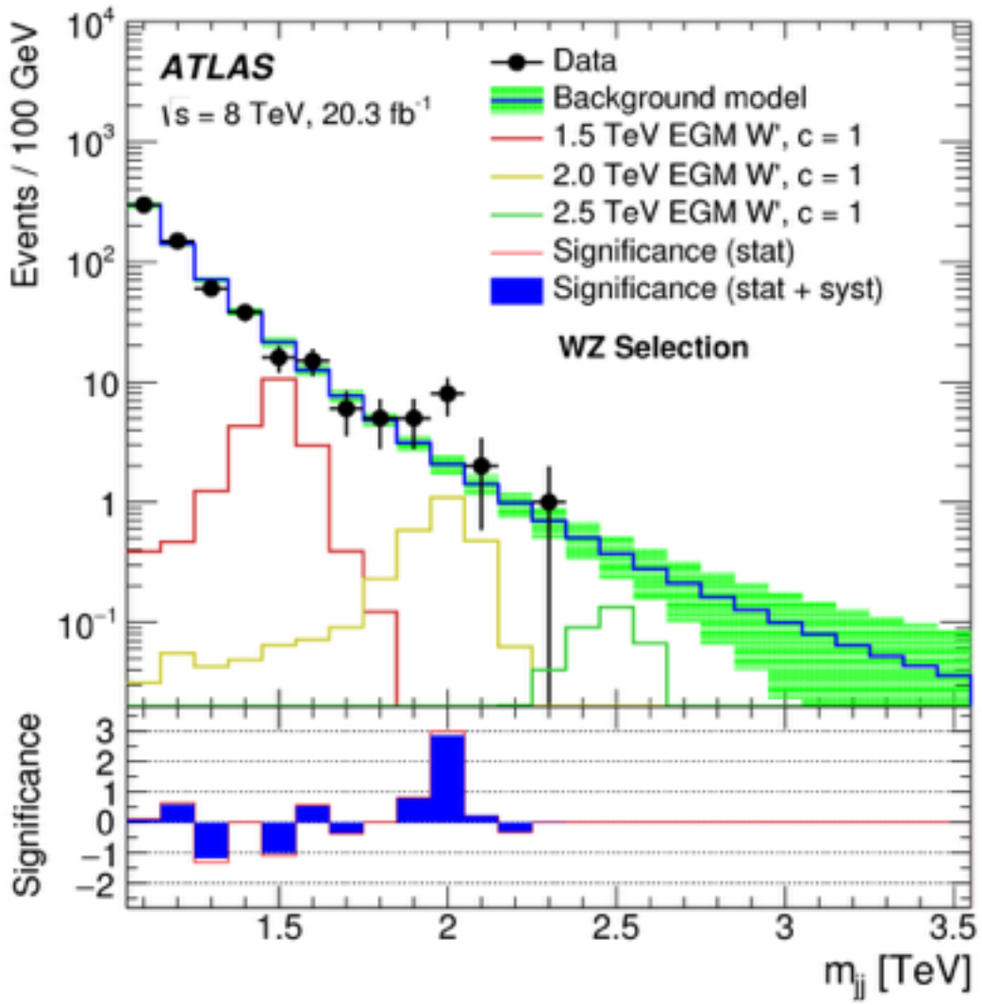


heavily rely on MC with (complicated) profile likelihoods

profile likelihoods facilitate searching in the presence of ignorance *of backgrounds*

Boosted Vs

- Heavy things decaying to W or Z's then to **jets**
- Run 1 excitement

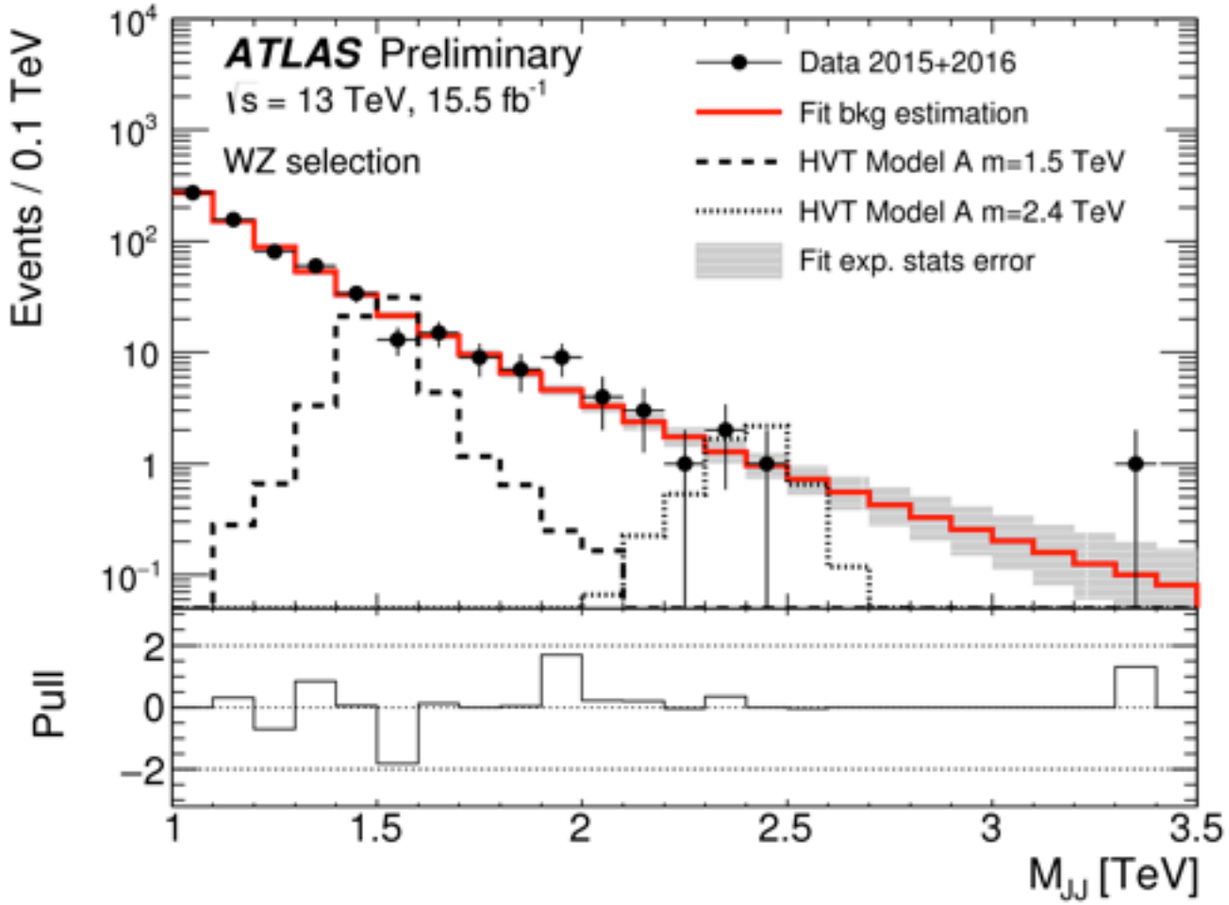


model QCD with fit:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\mathrm{jj}}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

Boosted Vs

- Heavy things decaying to W or Z's then to **jets**
- Run 1 excitement did not return for Run 2



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Recall:

largest concern: smoothness

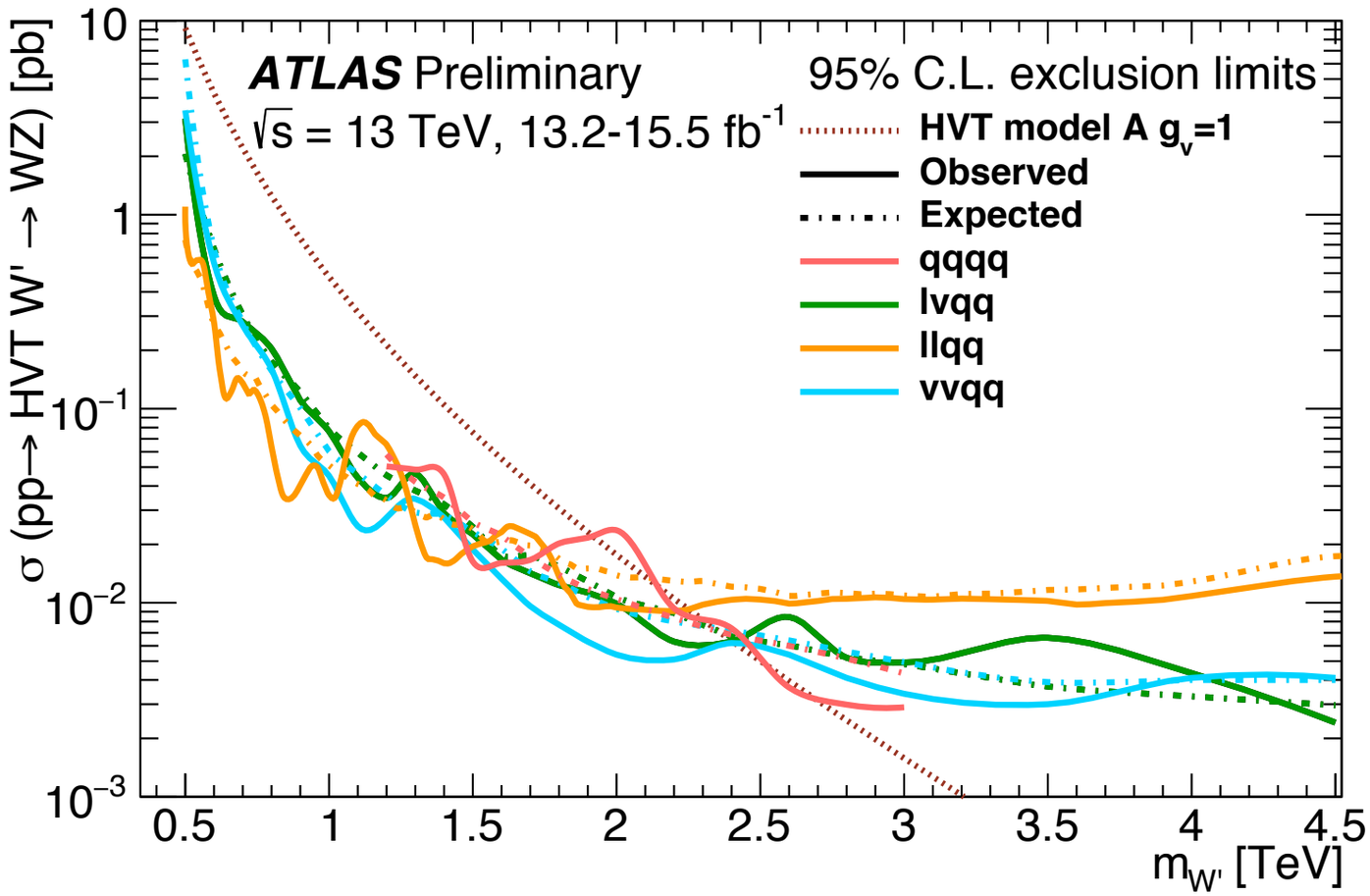
Boosted Vs

2-lepton, 1-lepton, 0-lepton(MET, JJ)

low mass
good mass resolution
good to trigger

→

high mass
High signal yield



Run 2 data does not support Run I excess

Controlling Substructure

- Understanding jet substructure is critical for physics above the EW symmetry breaking scale

- How do we control it? Data Driven!

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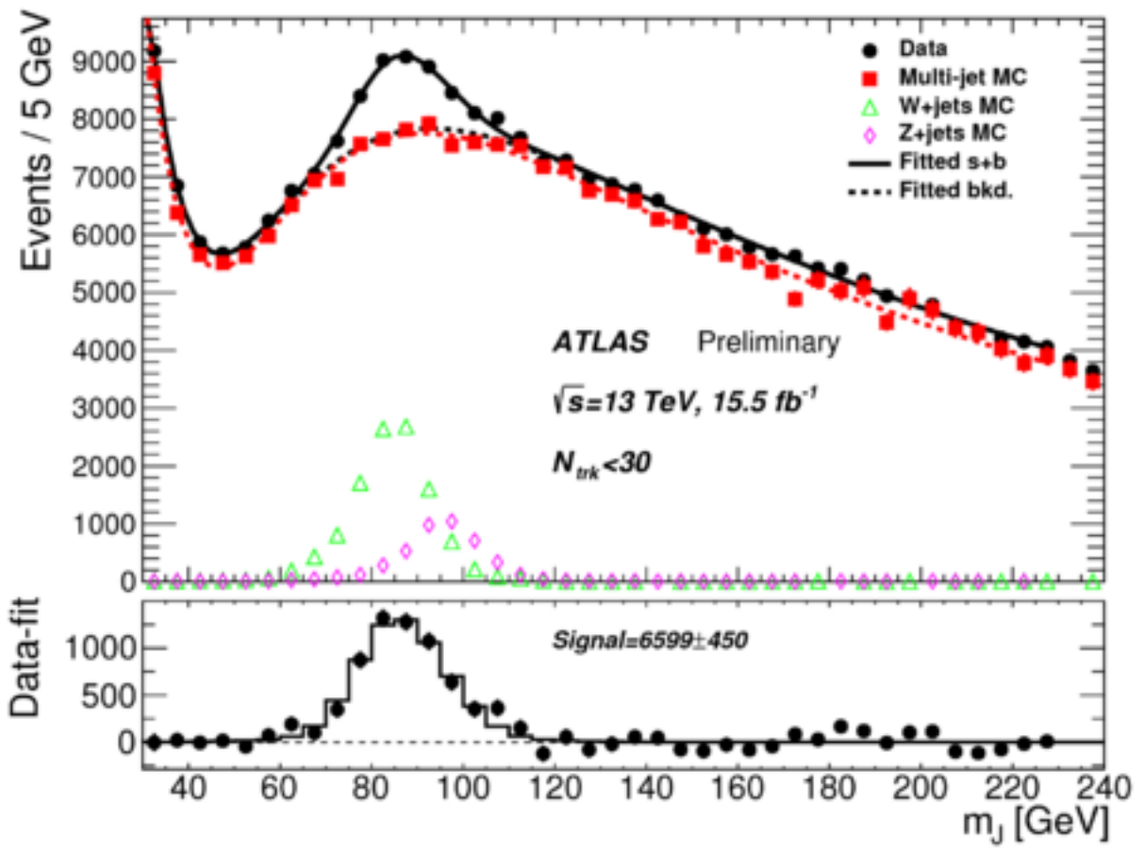

N_{trk}: A powerful variable for experimentalists but MC-dependent & non-perturbative

More theoretically robust variables could help?

Controlling Substructure

- Understanding jet substructure is critical for physics above the EW symmetry breaking scale

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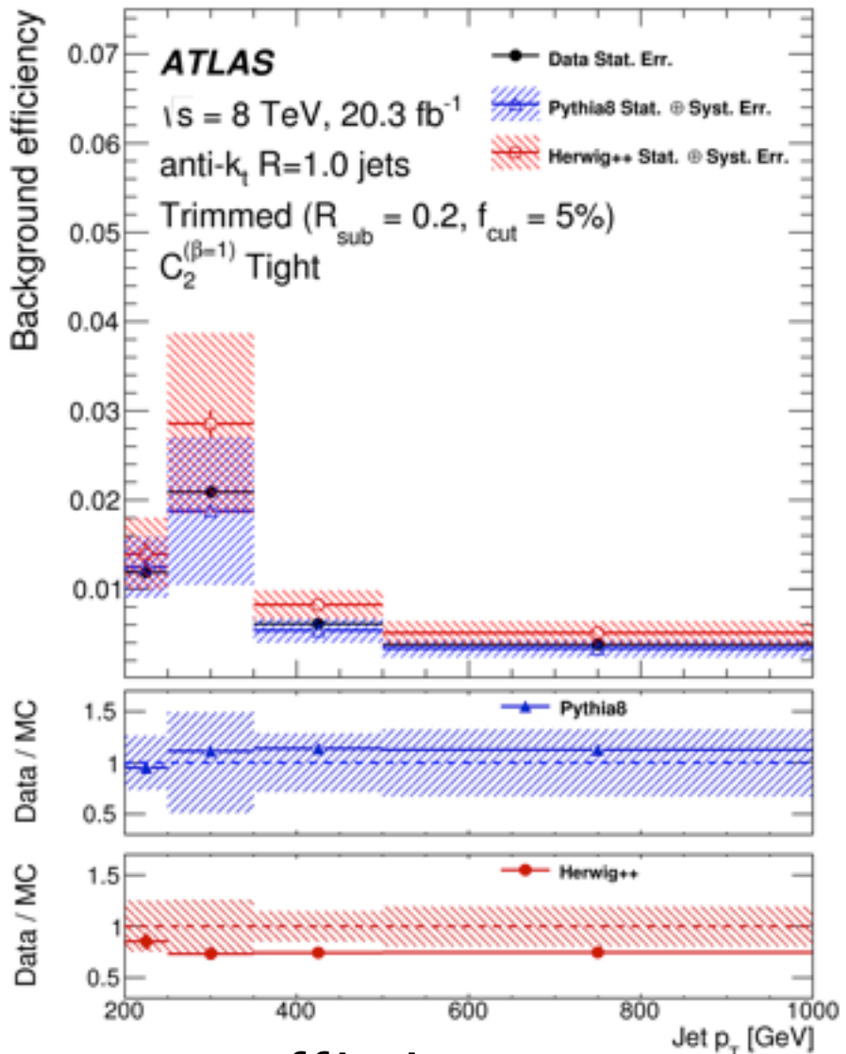
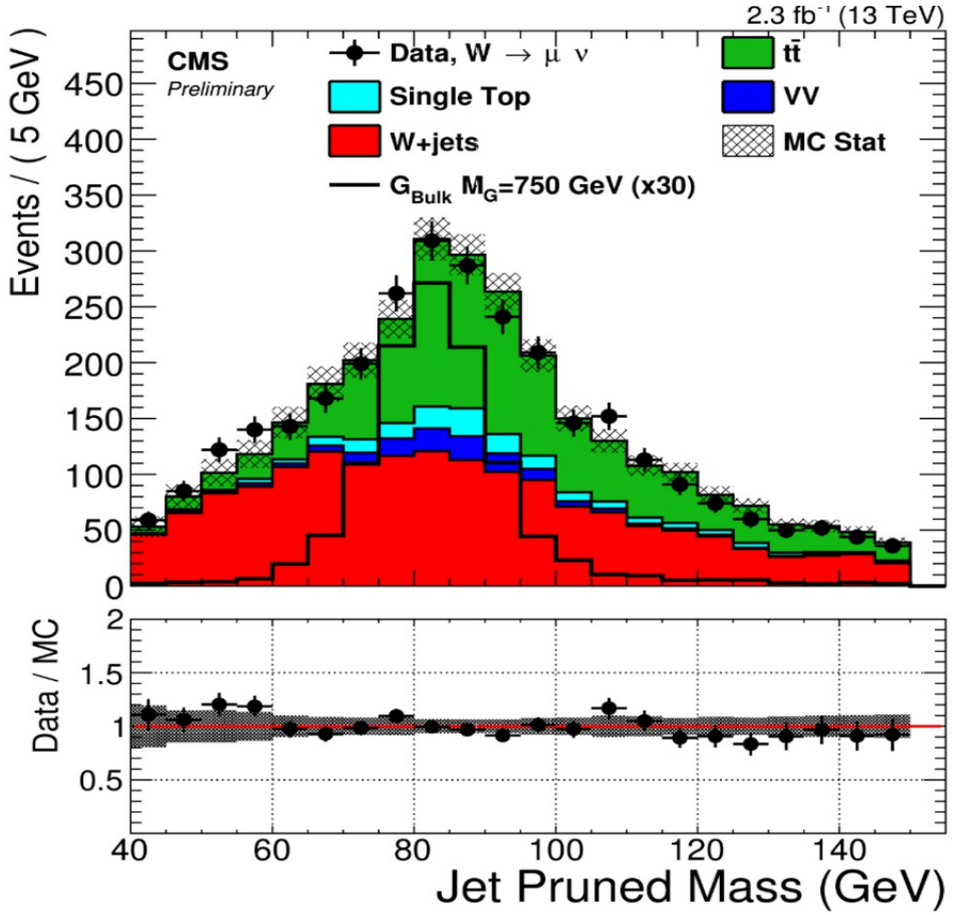
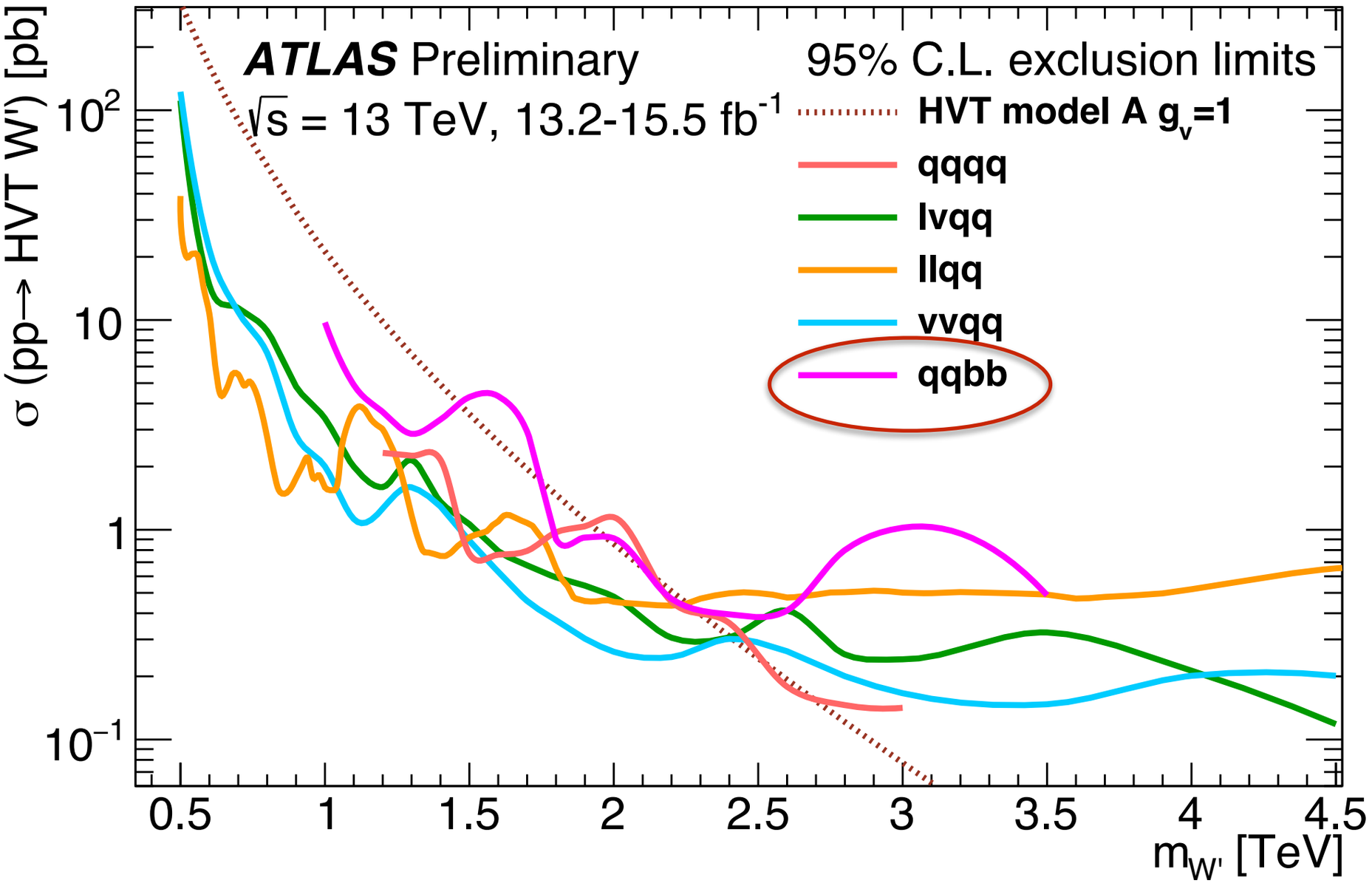


efficiency EPJC 76(3), 1-47



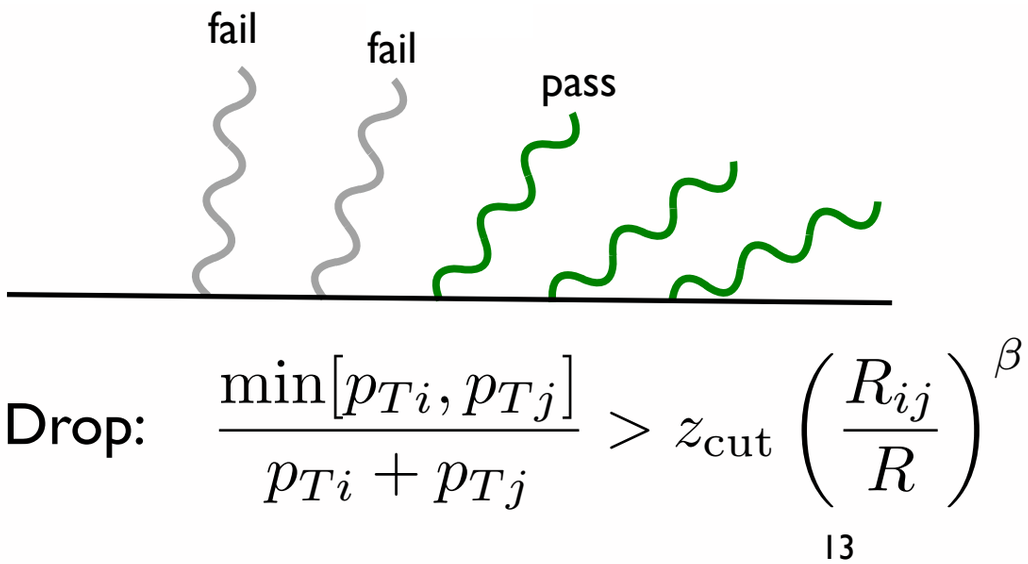
energy

Boosted V/Hs


ATLAS Preliminary
√s = 13 TeV, 13.2-15.5 fb-1
95% C.L. exclusion limits
HVT model A gv=1
qqqq
lvqq
llqq
vvqq
qqbb
σ (pp→ HVT W') [pb]
10²
10
1
10⁻¹
0.5
1
1.5
2
2.5
3
3.5
4
4.5
mW' [TeV]

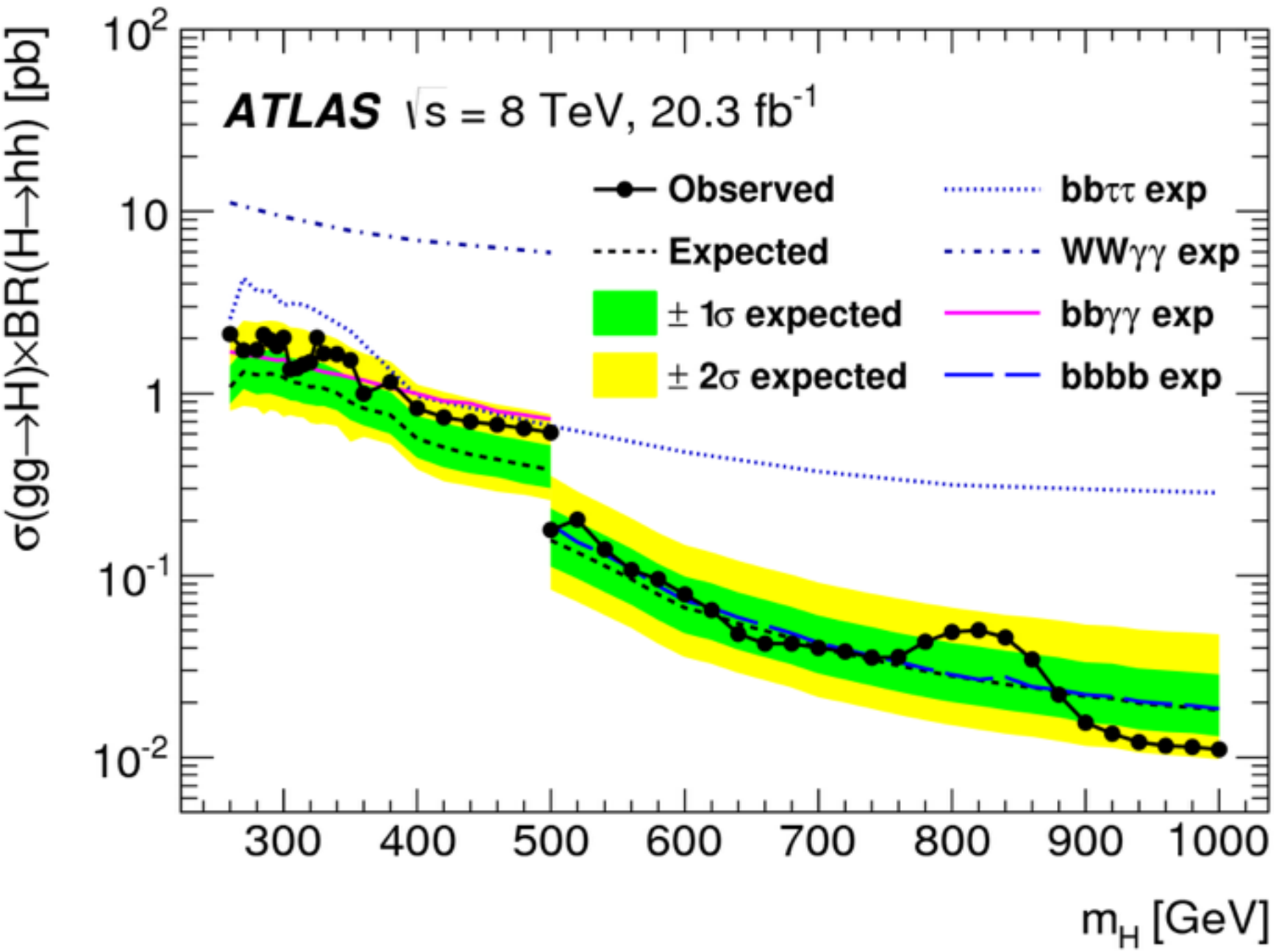
Boosted Hs

- The Higgs discovery gave us a new search tool
  - similar to diboson searches, maximal signal yield with hadronic decays (b's!!!)
- Added complexity of flavor tagging



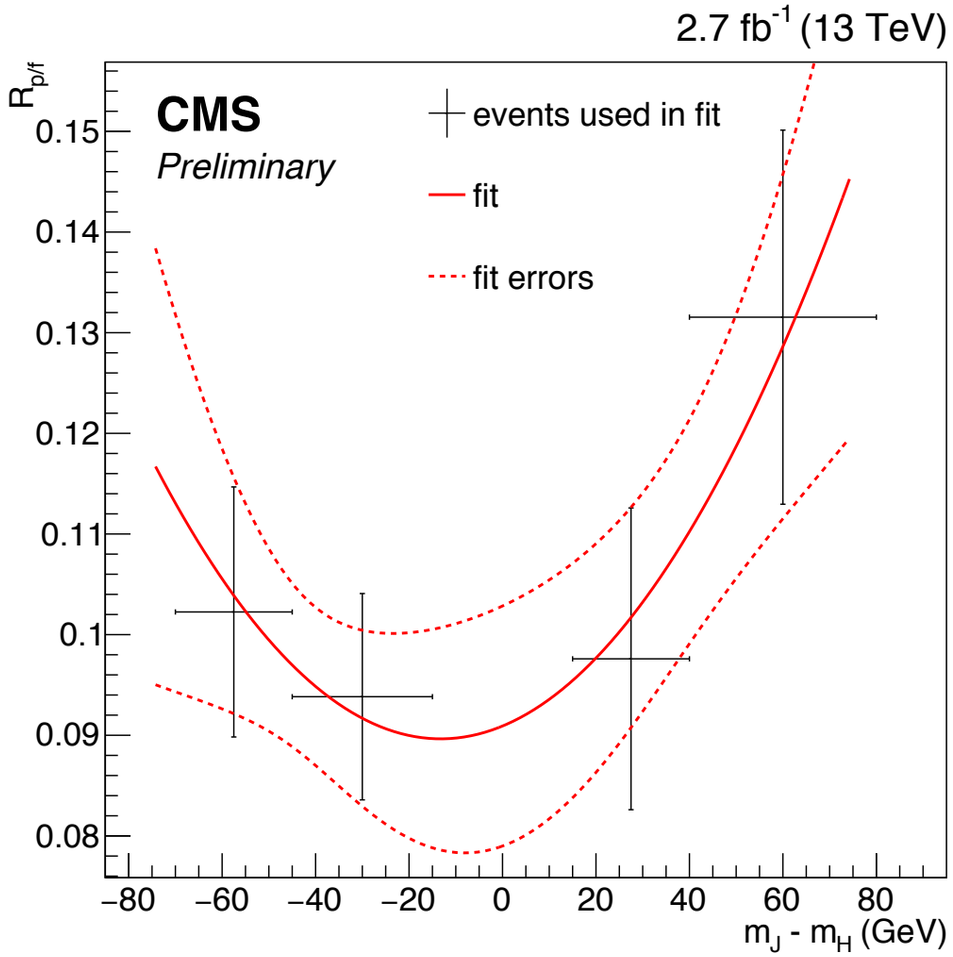
tagging subjets vs matching tagged track jets

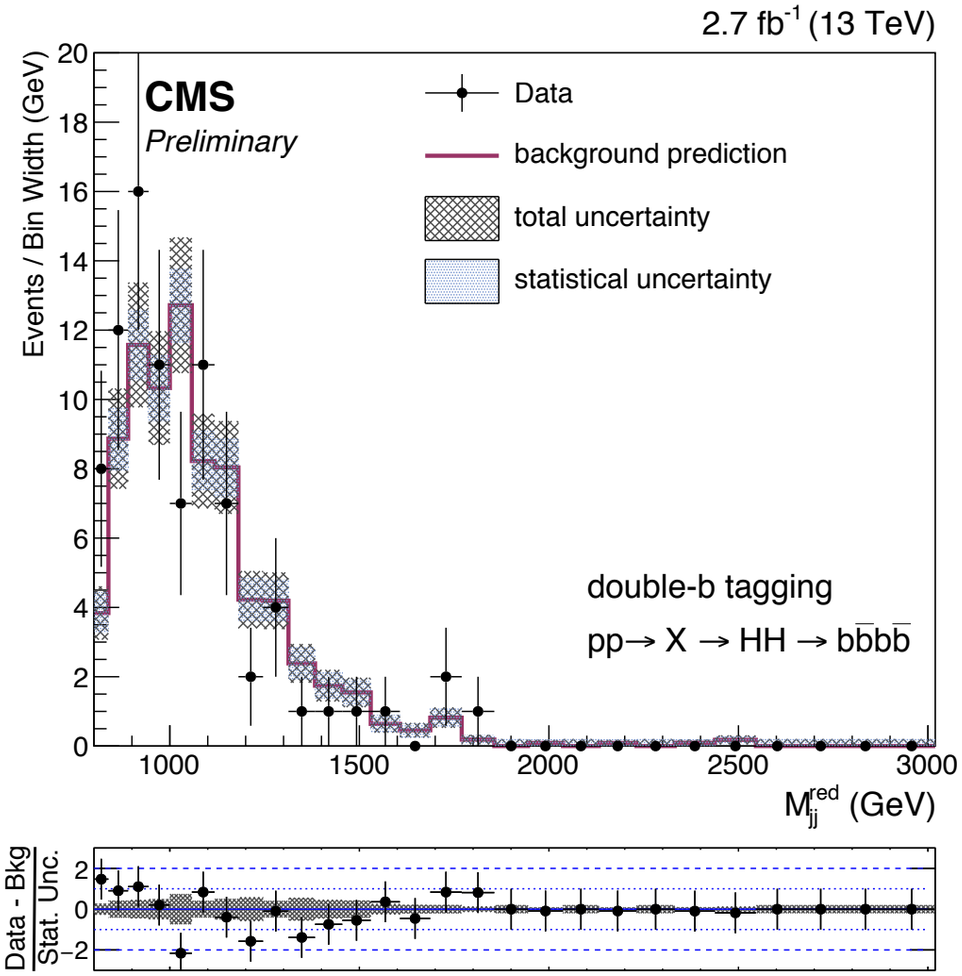
Boosted Hs



13 TeV summary plot not available … yet

Boosted Hs





CMS employs 2 different data driven background methods profiting from comparison

Here: Expanded ABCD method (alphabet) using untagged events to model tagged events

Is This Enough?

- Do we understand substructure enough to:
  - Check our cuts do not sculpt the background
  - Check our background models are accurate
  - ***Perform non-resonant searches based on MC driven backgrounds?***

Also searches for X>YY->jjjj exist!
(covers RPV SUSY)

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2012: Open question in preparation for Run 2

Calculations

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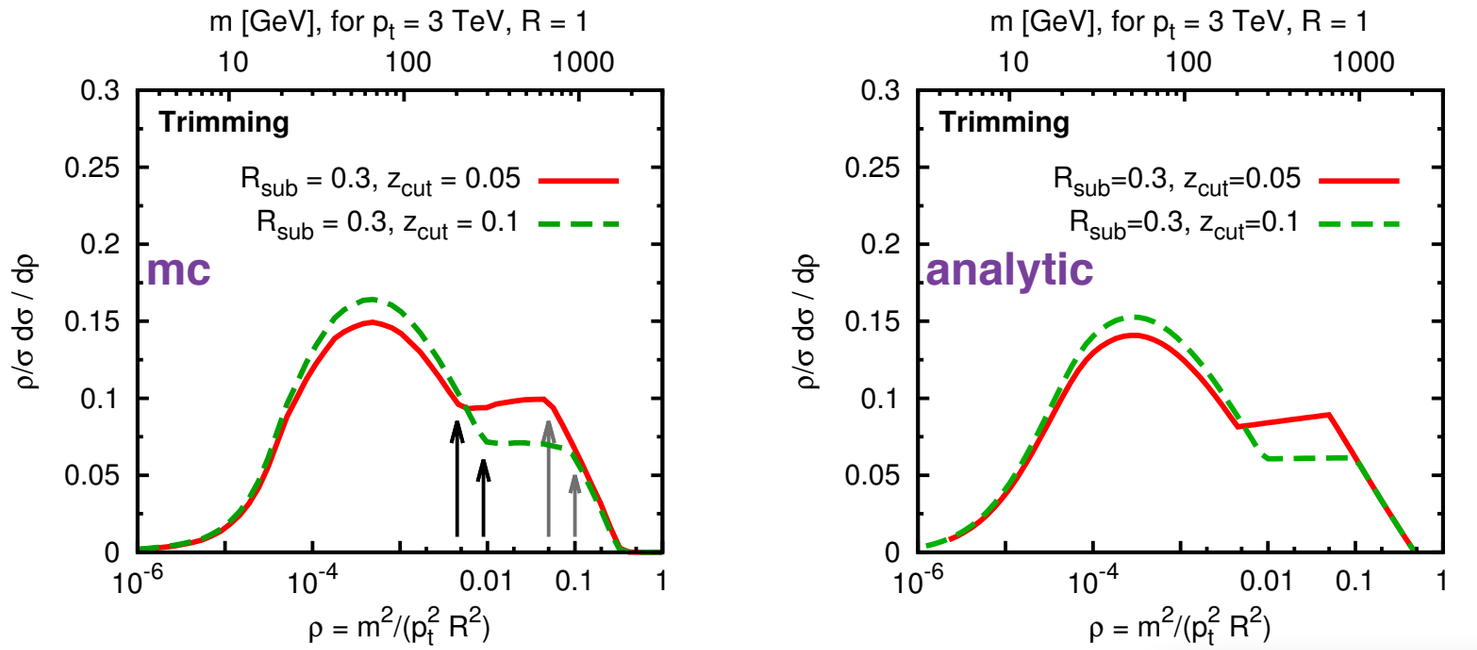
2012: Open question in preparation for Run 2
2013: There is hope!

[Dasgupta, Fregoso, Marzani, Salam '13]
[Larkoski, Marzani, Soyez, Thaler '14]



$r^2 z_{cut}$ z_{cut}

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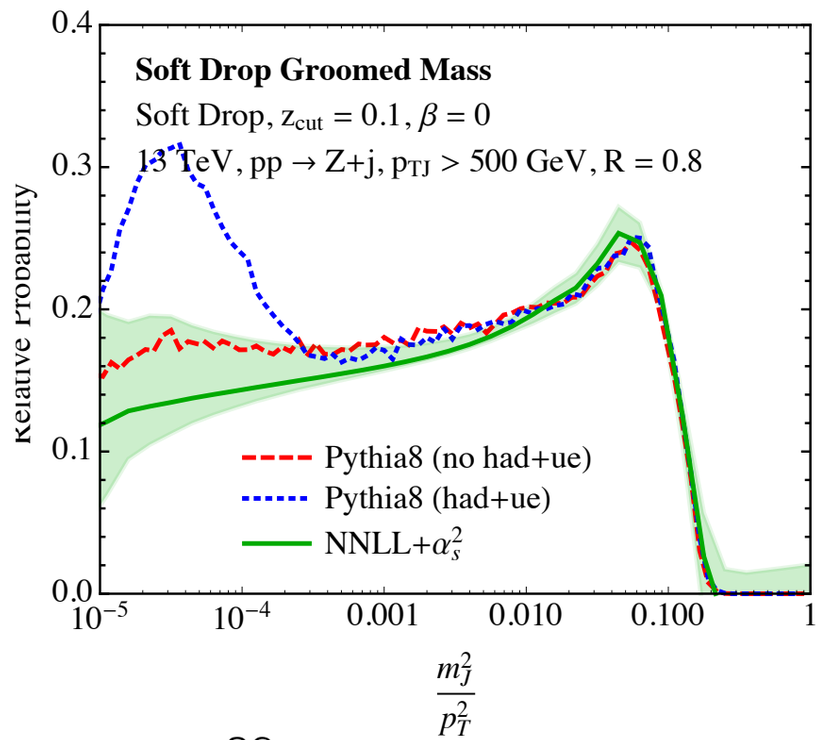

[Frye, Larkoski, Schwartz, Yan '16]

[See P. F. Monni, T. Becher talks]

Measurements!?

- Do we understand substructure enough to:
  - Check our cuts do not sculpt the background
  - Check our background models are smooth
  - ***Perform non-resonant searches based on MC driven backgrounds?***

2012: Open question in preparation for Run 2
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2016: Precision
2017: Measurements!?

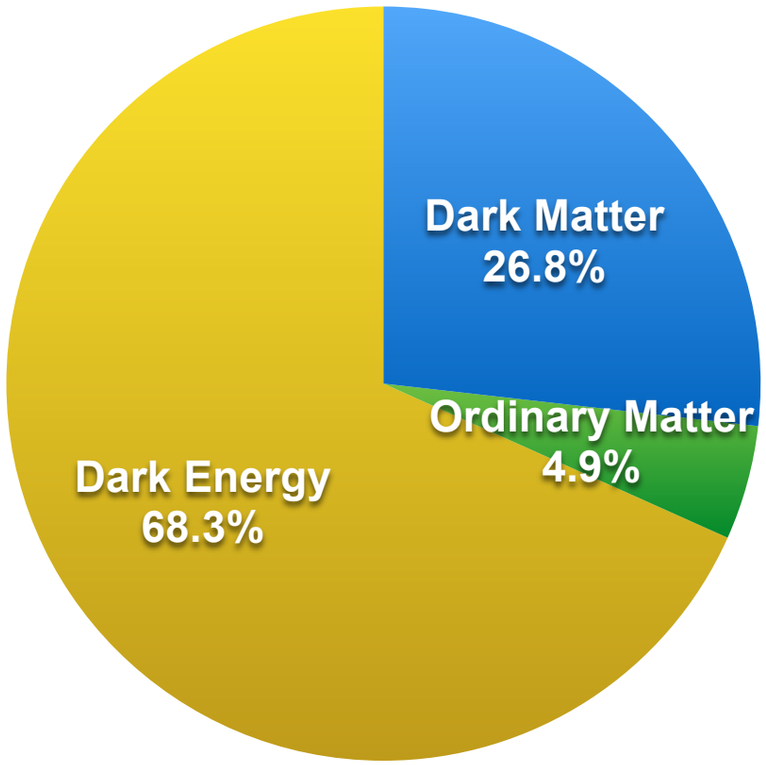
- **2. MET searches: PDFs and transfer factors**

MET Based Searches

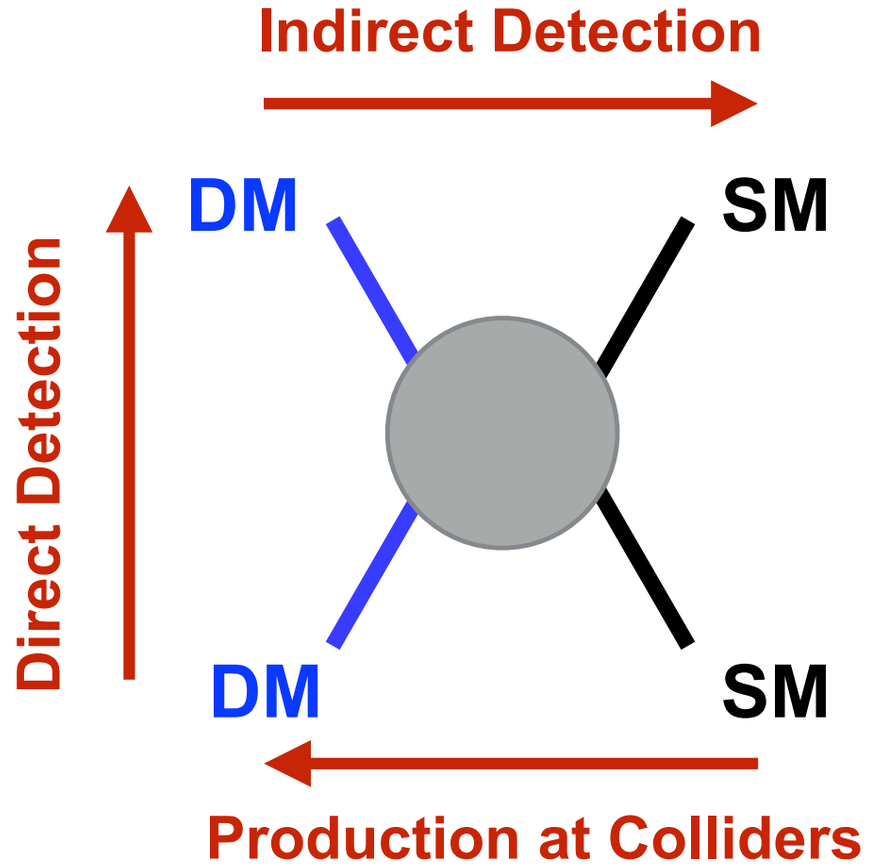
- Motivation - non-interacting or long life time
- Long lifetime - requires detailed detailed understanding of detector (will not cover here)
- MET based - “MET is hard to model”
  - The use of CRs and transfer factors

MET Based Searches

- Motivation: Dark Matter (one of many)

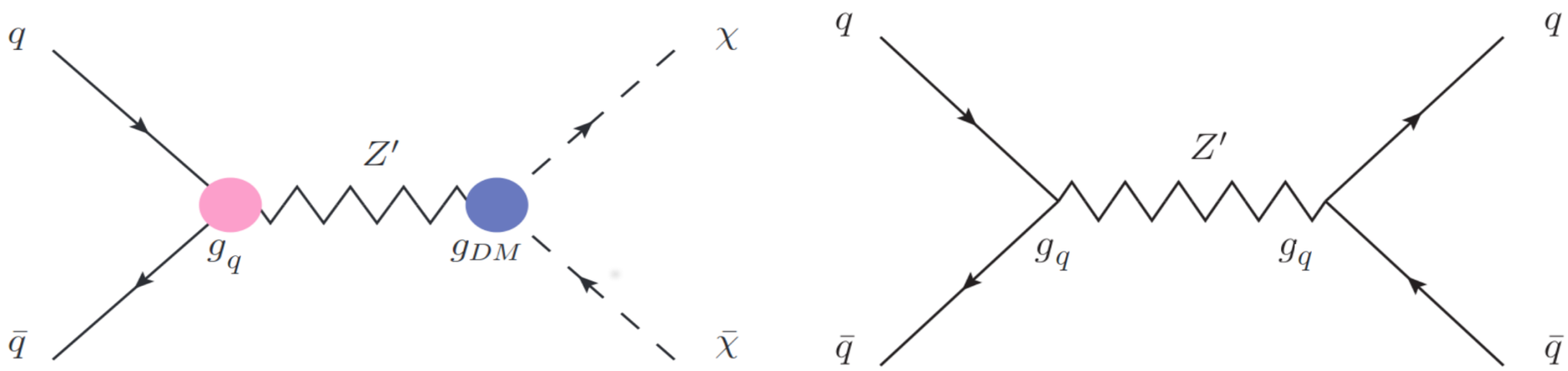


Matter/Energy Today



MET Based Searches

- Motivation: Dark Matter (one of many)



Two new particles
Z' mediator of mass M_R
DM candidate χ of mass m_χ

Two new couplings
coupling g_{SM} of Z' to quarks
coupling g_{DM} of Z' to χ

- Simple model to communicate results of many experiments

MET Based Searches

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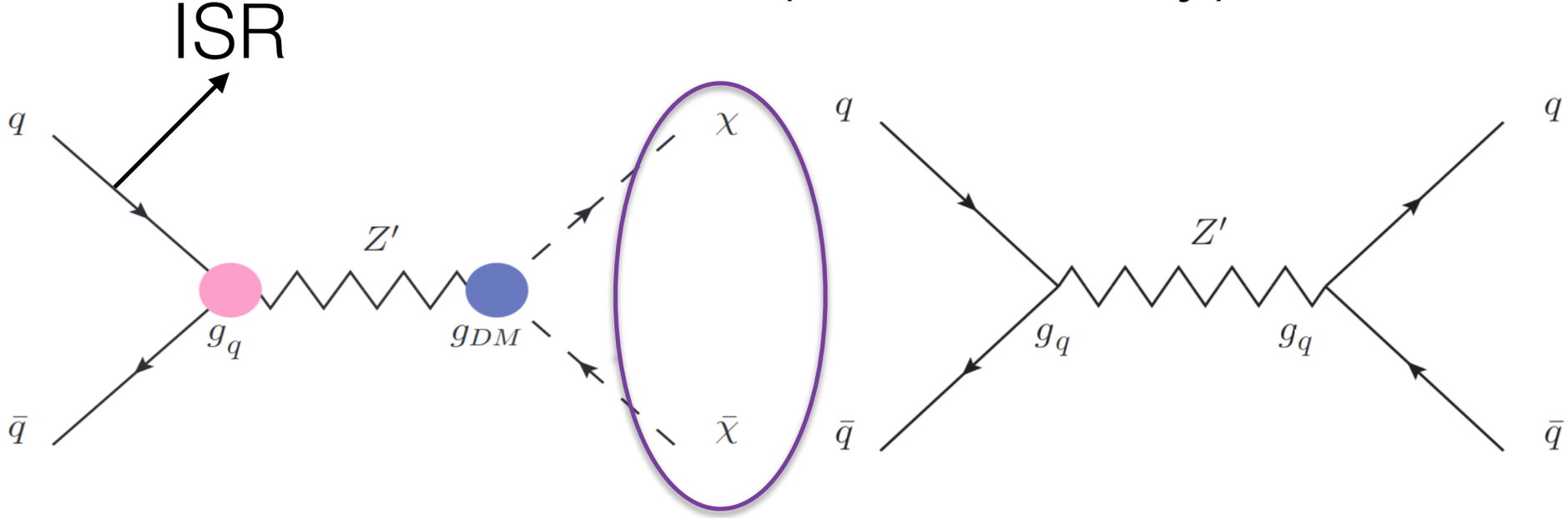

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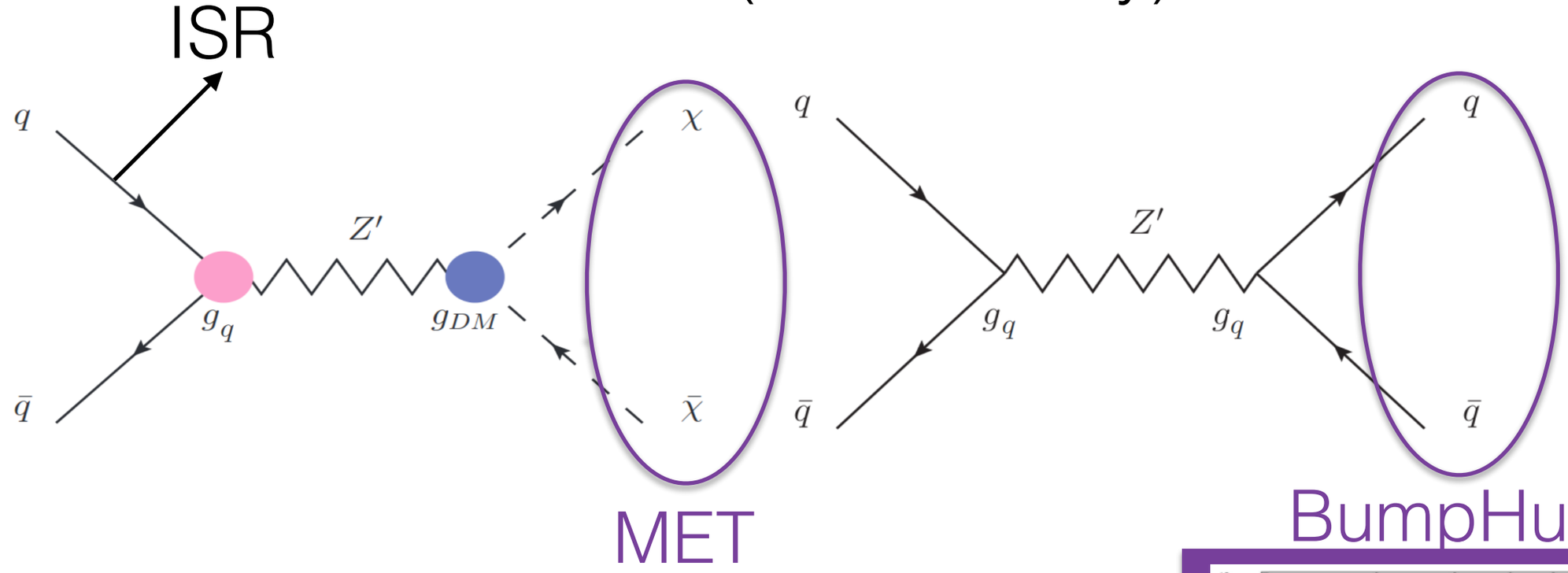

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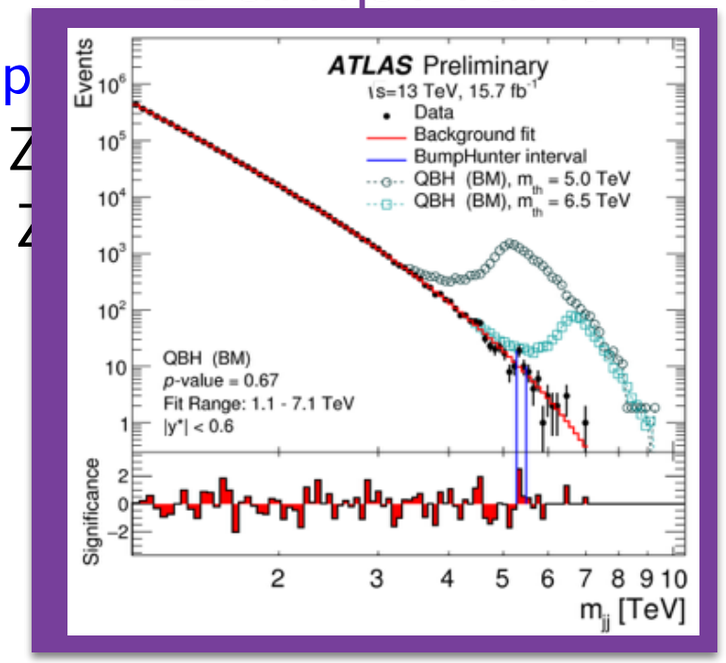
DM candidate χ of mass m_χ

Two new coup

coupling g_{SM} of Z

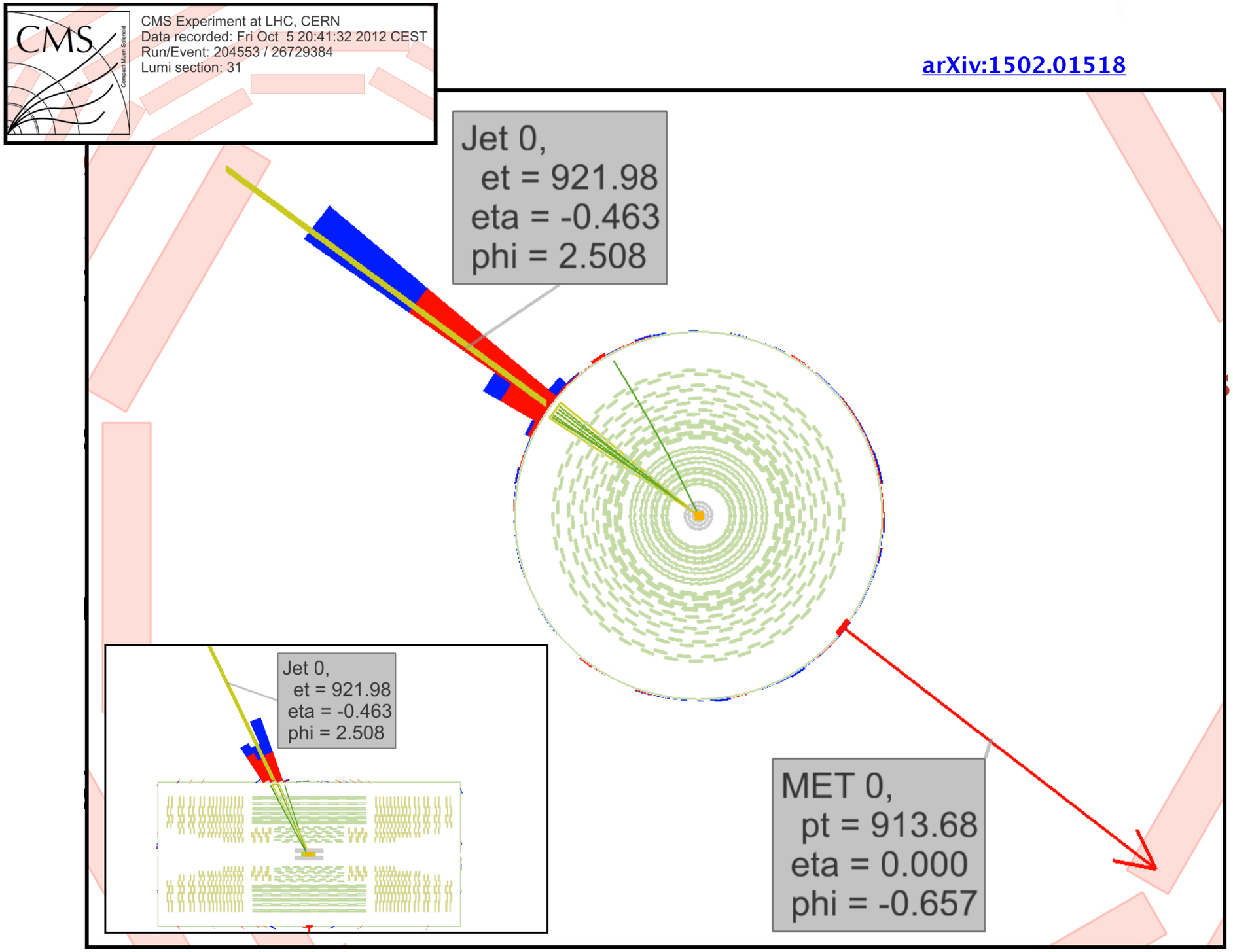
coupling g_{DM} of Z



- Simple model to communicate results of many experiments

Mono-Jet

arXiv:1502.01518

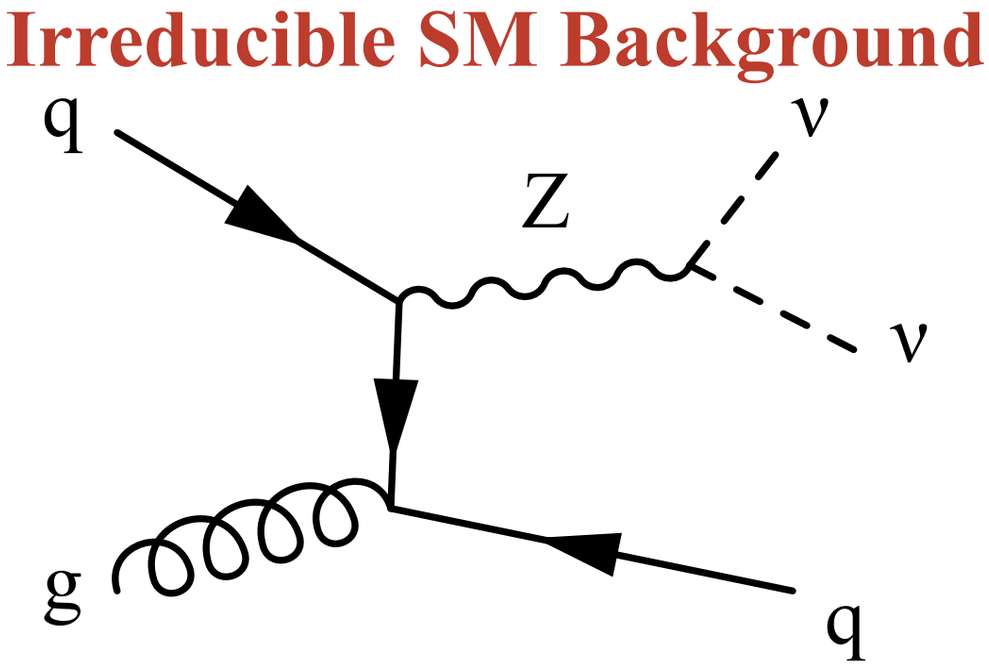


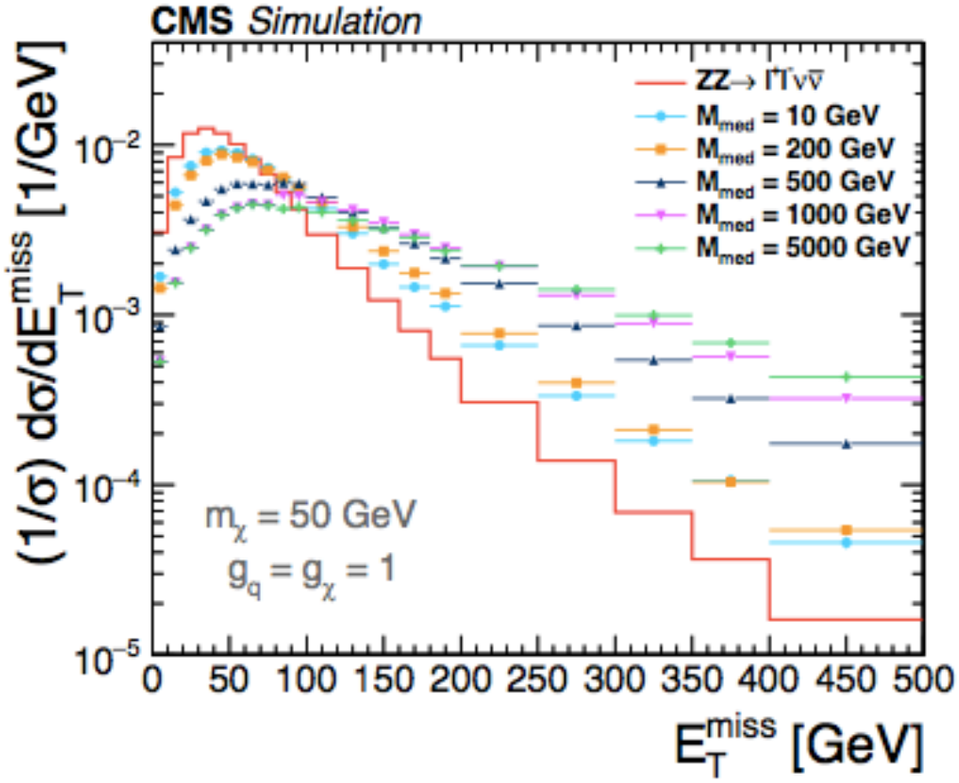
Looking for new phisics in MET tails

Modeling MET

- Model MET by transferring information from control regions (CRs) to signal regions

- Possible CRs by replacing Z->νν with:
  - Z->μμ/ee
  - W->μν/eν
  - γ





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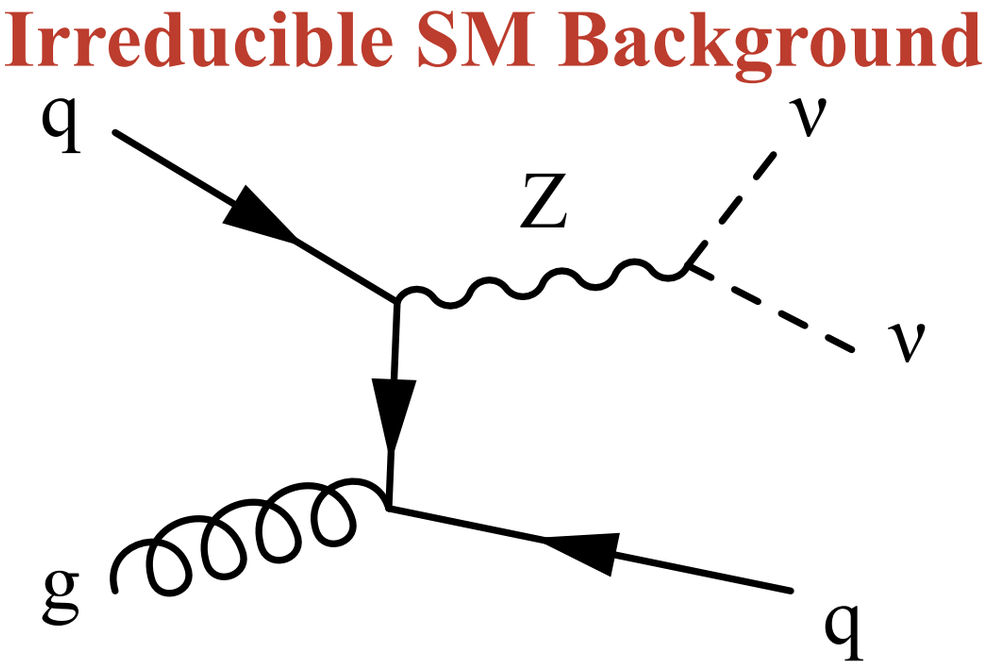
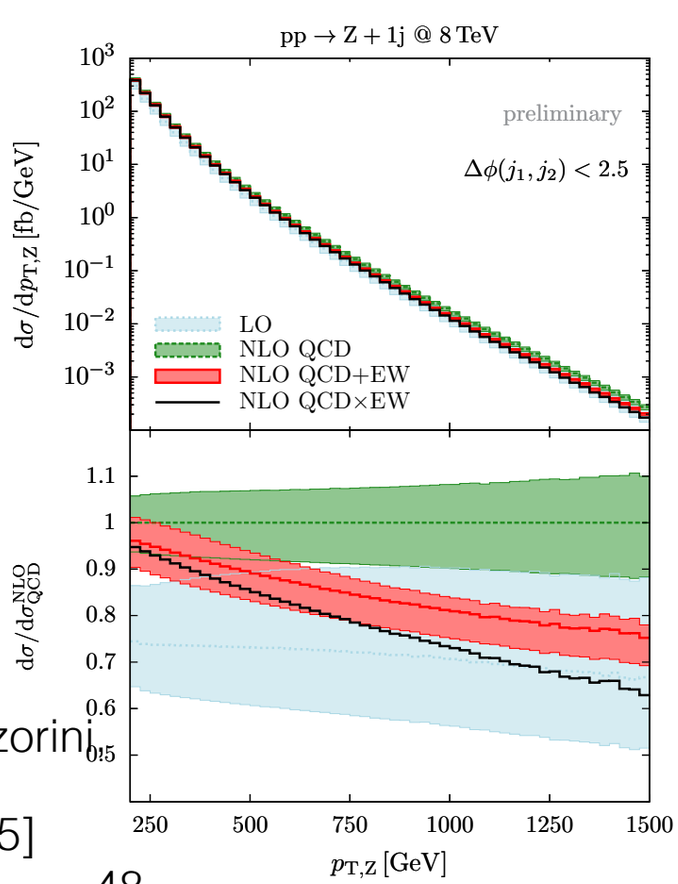
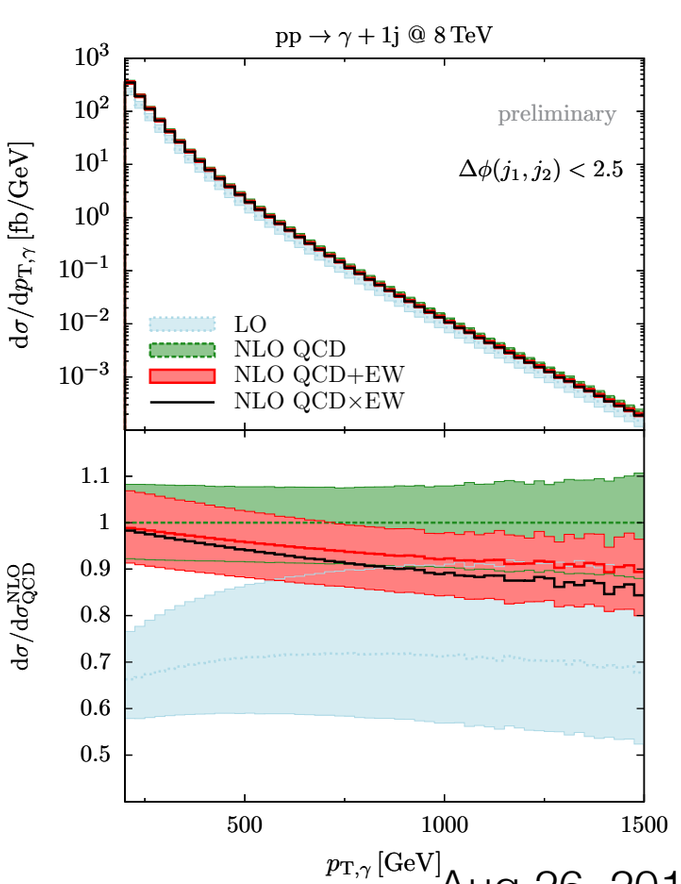
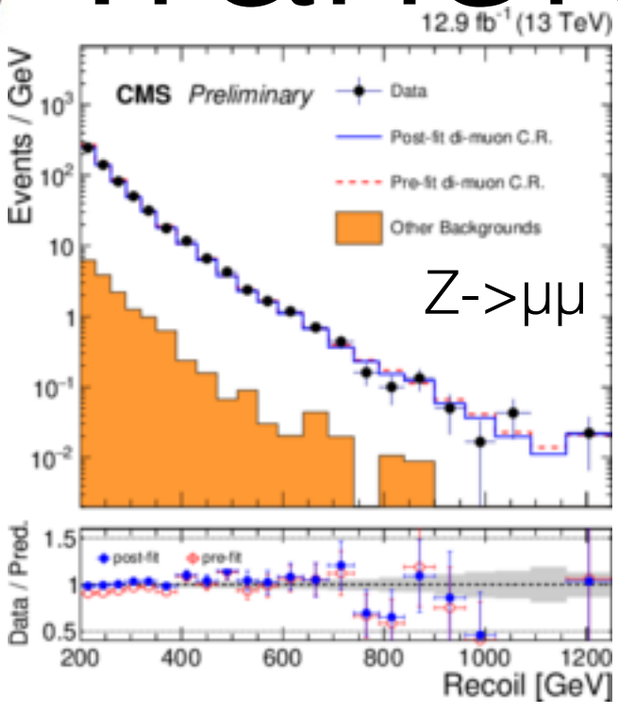


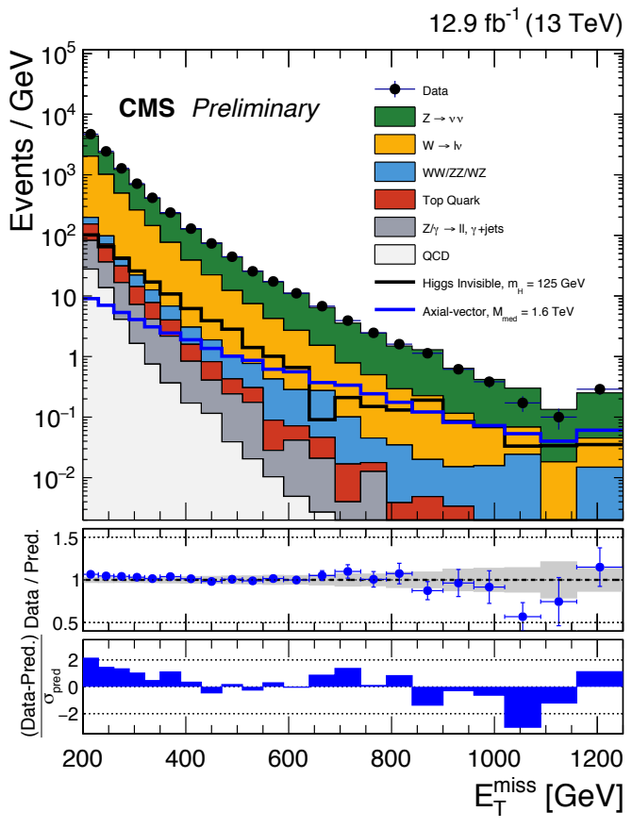
[S. Kallweit, J. M. Linderta, S. Pozzorini, M. Schönherr, P. Maierhöfer '15]



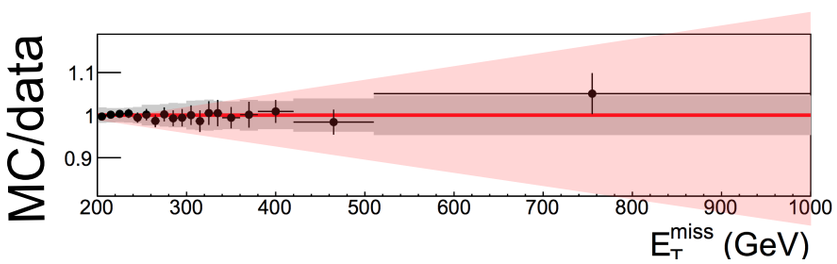


Transfer Factors





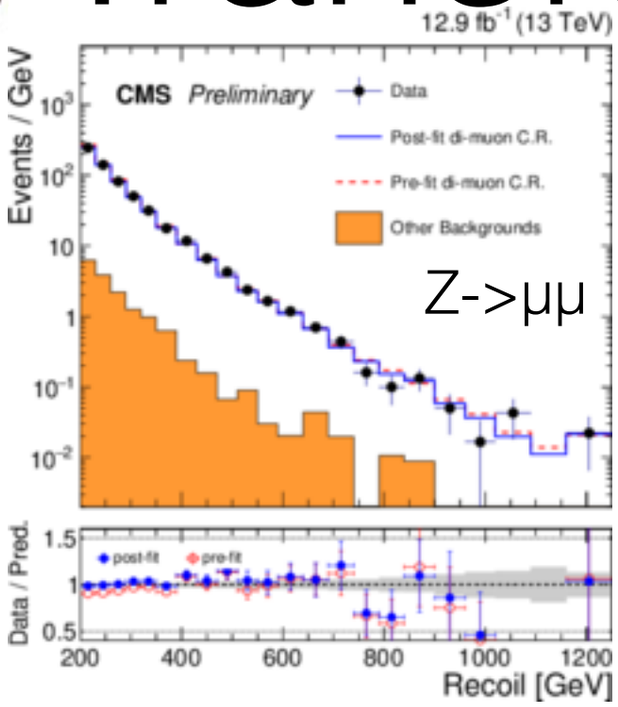
Adapted from P. Harris @ NPKI

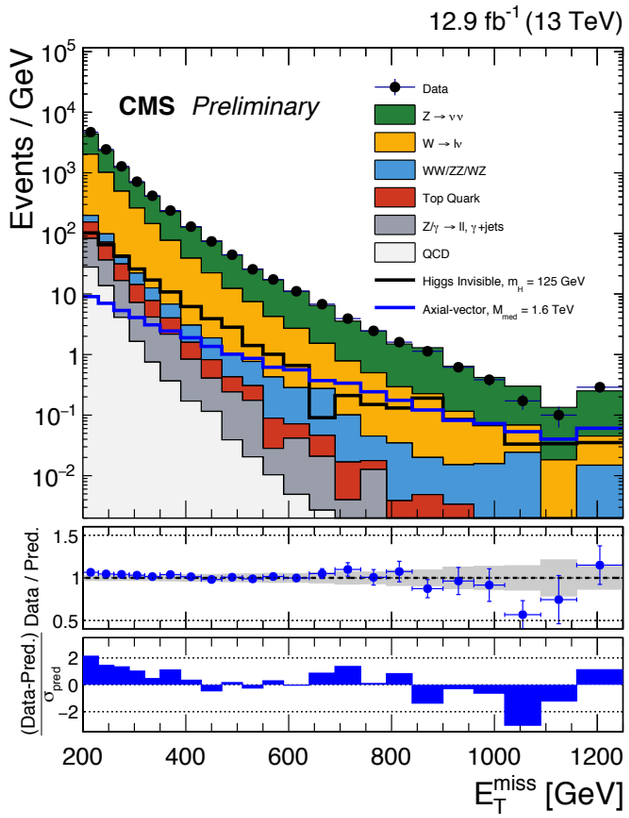


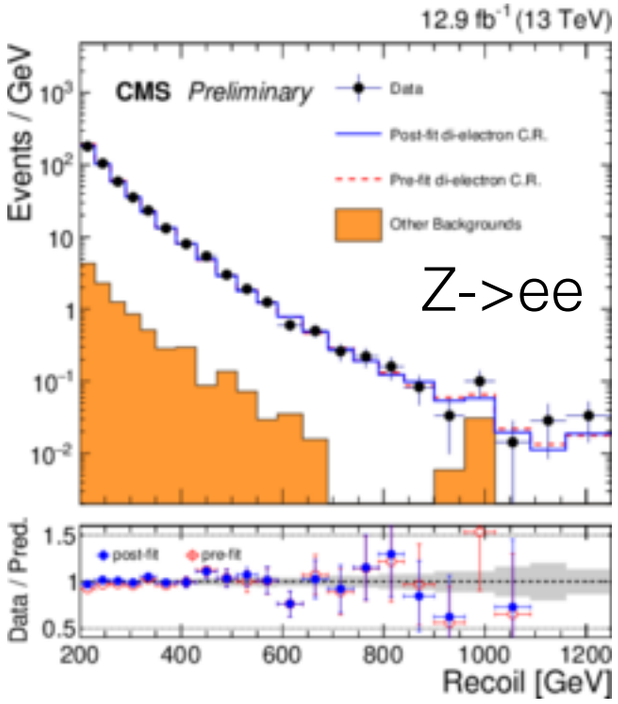
CMS-EXO-16-010

1 Control region
100% uncertainty @ 1 TeV

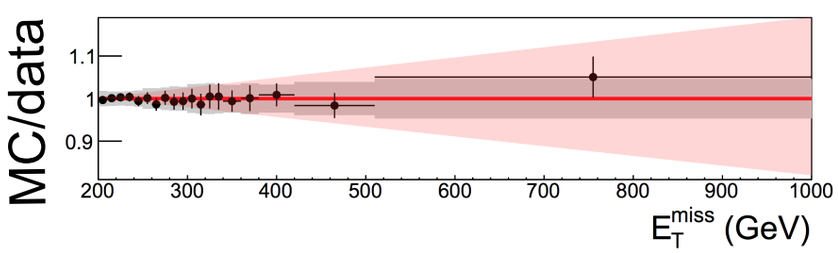
Transfer Factors







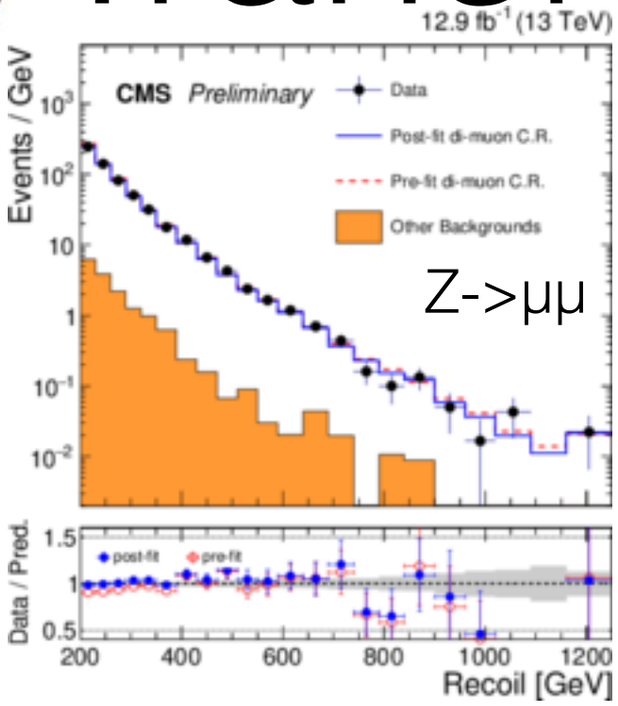
Adapted from P. Harris @ NPKI

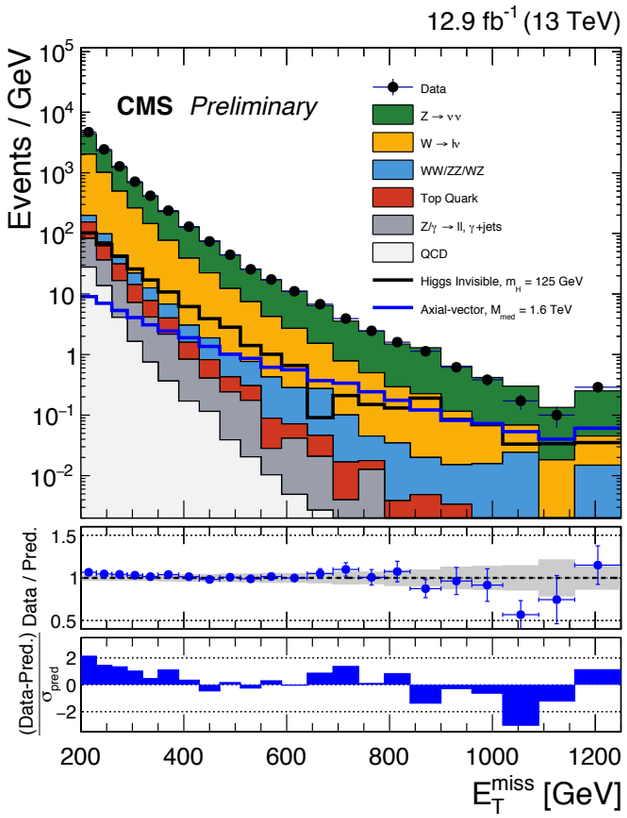


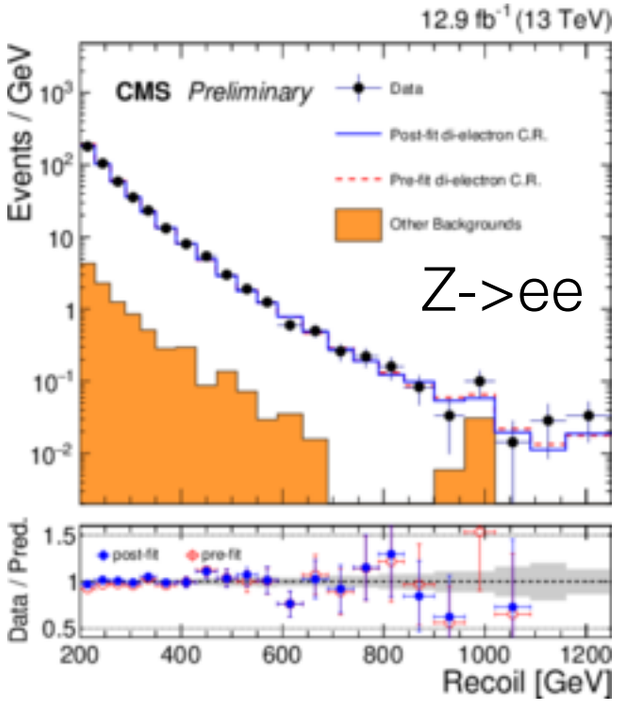
2 Control regions
60% uncertainty @ 1 TeV

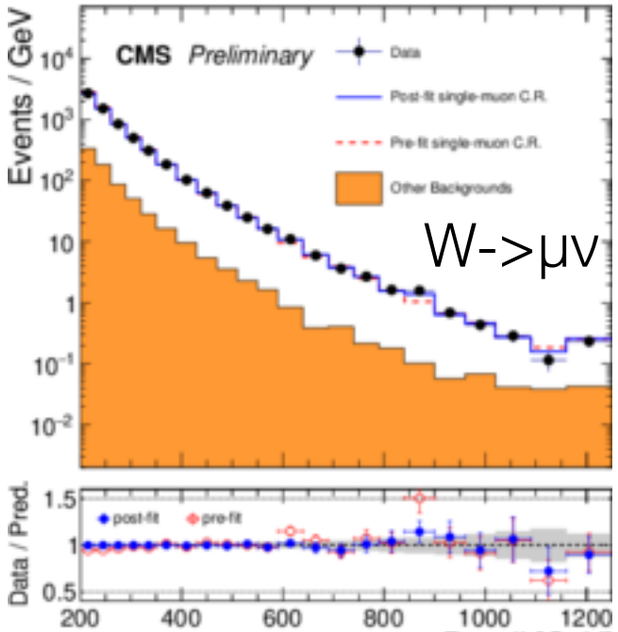
CMS-EXO-16-010

Transfer Factors

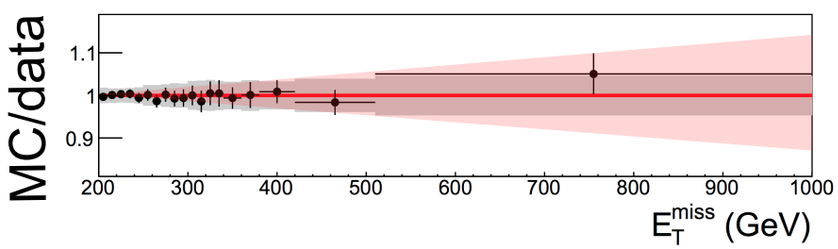








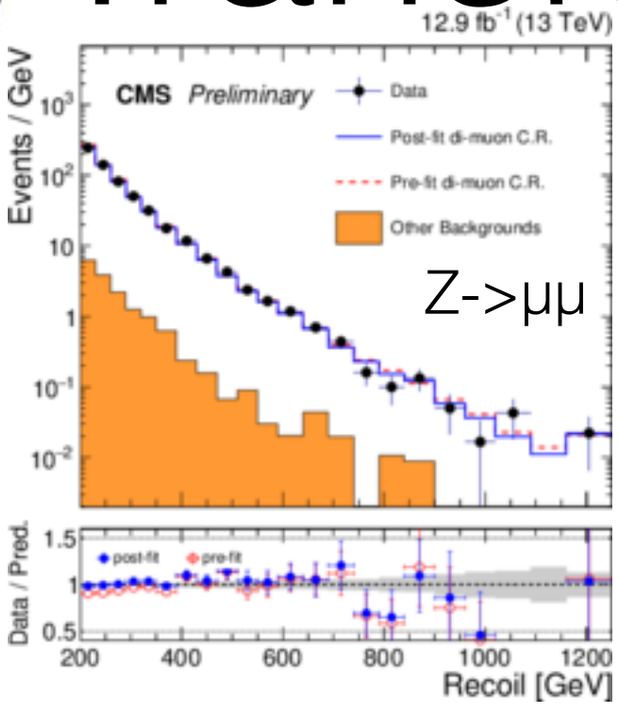
Adapted from P. Harris @ NPKI

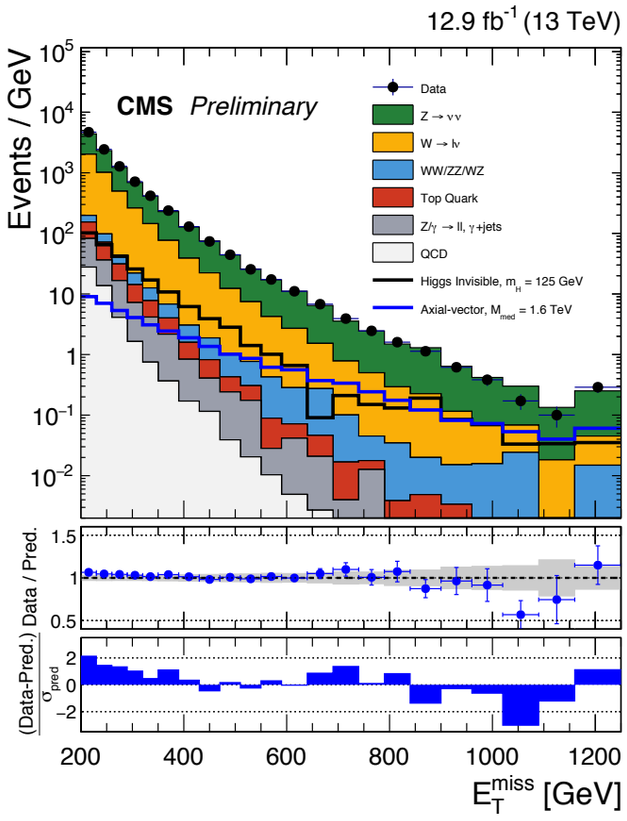


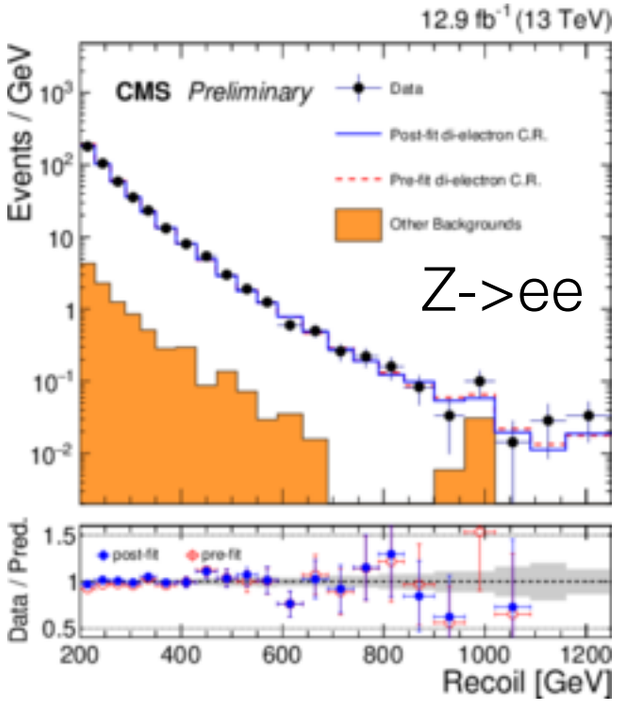
CMS-EXO-16-010

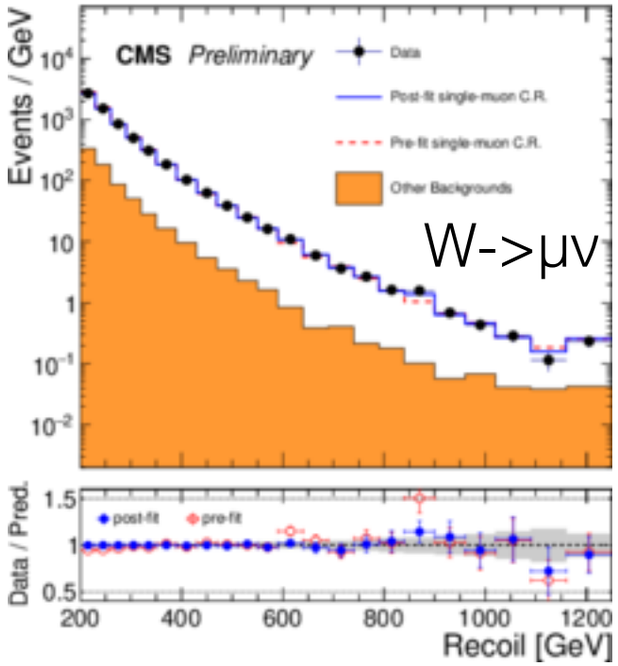
3 Control regions
40% uncertainty @ 1 TeV

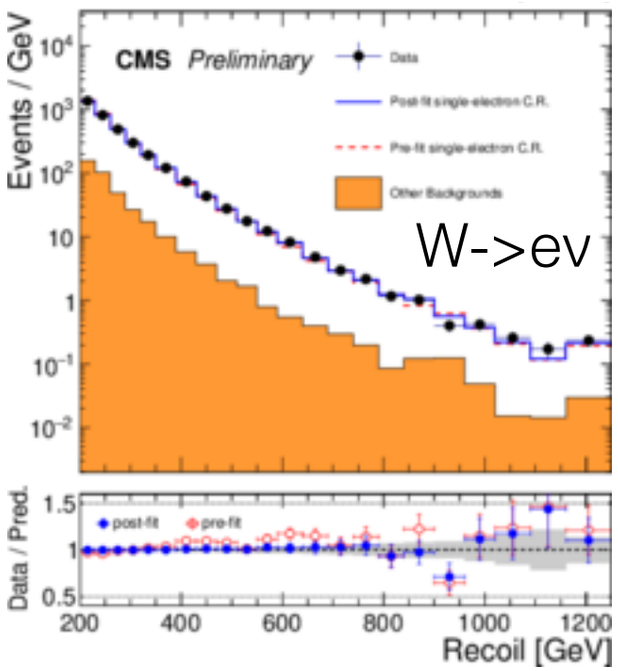
Transfer Factors





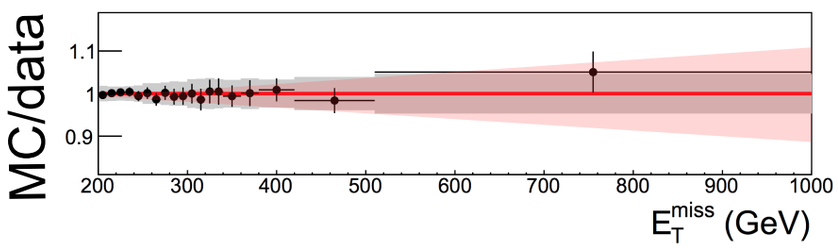






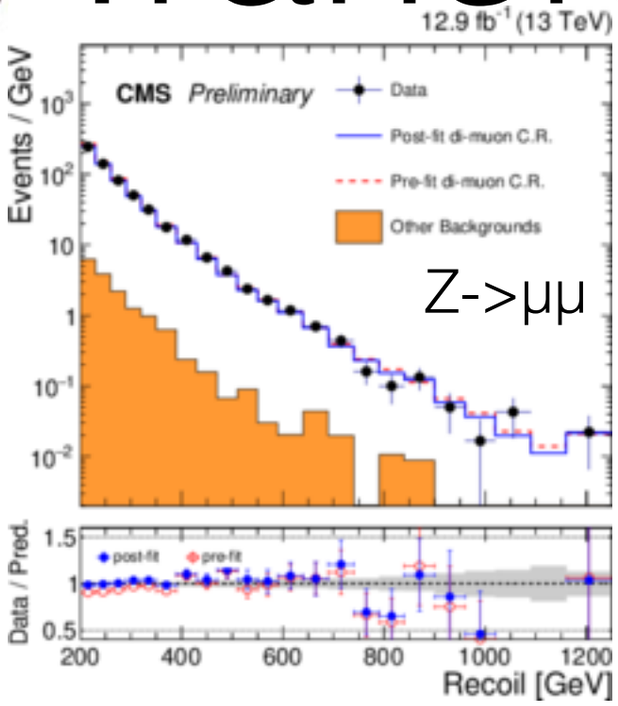
CMS-EXO-16-010

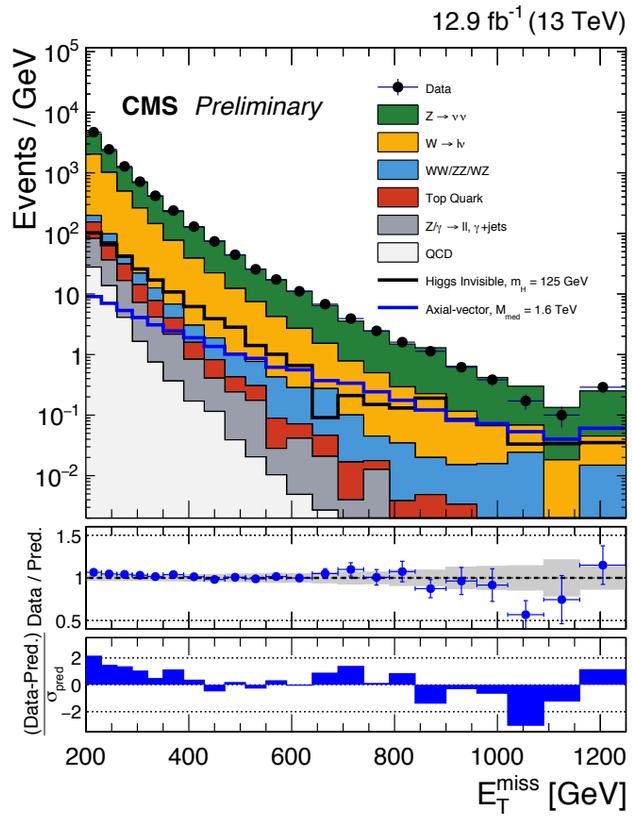
Adapted from P. Harris @ NPKI

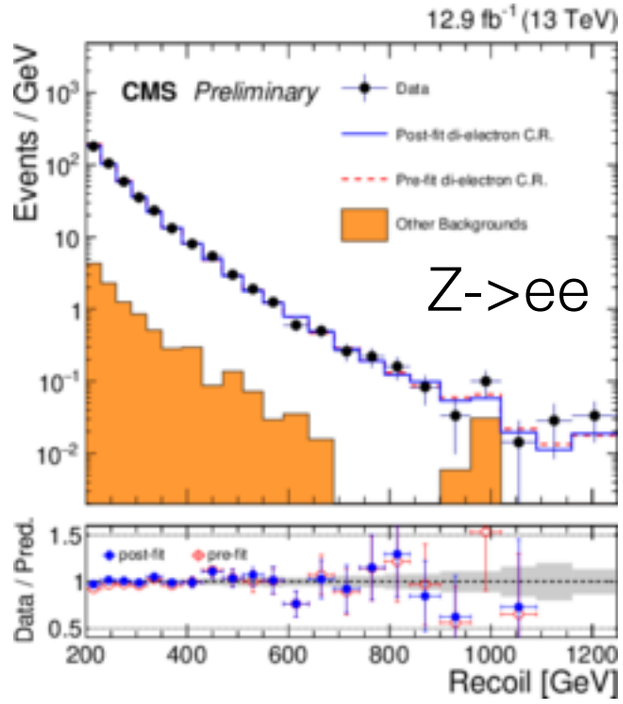


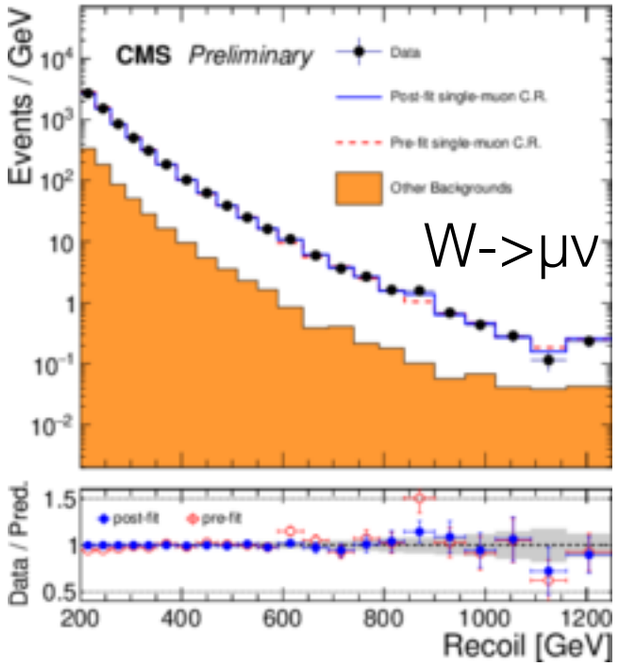
4 Control regions
30% uncertainty @ 1 TeV

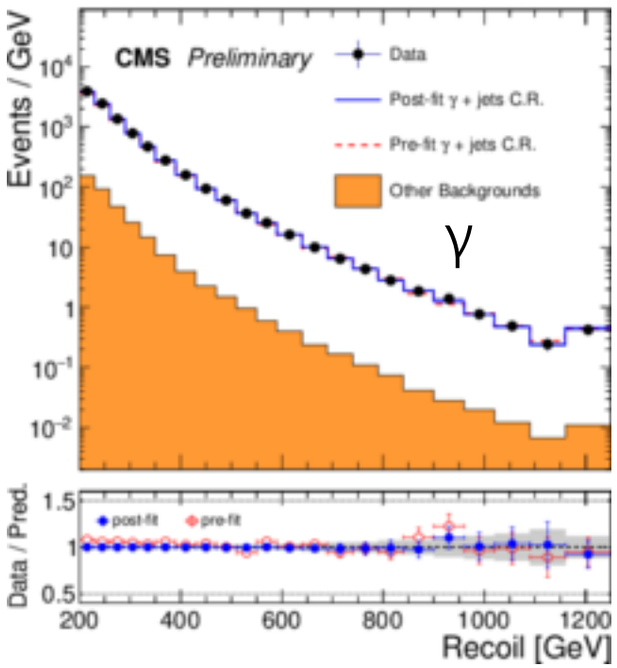
Transfer Factors

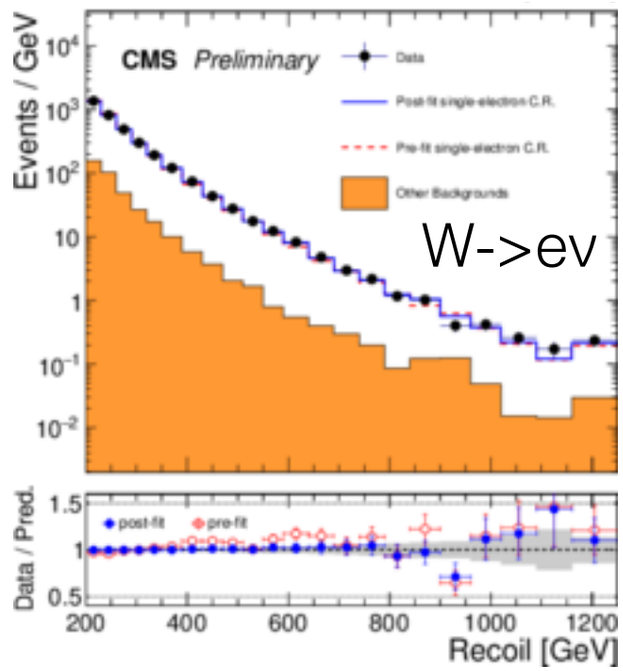






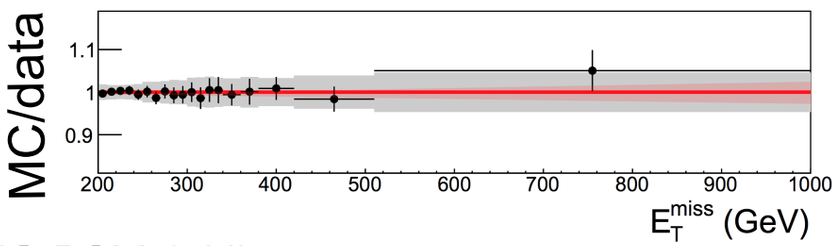






CMS-EXO-16-010

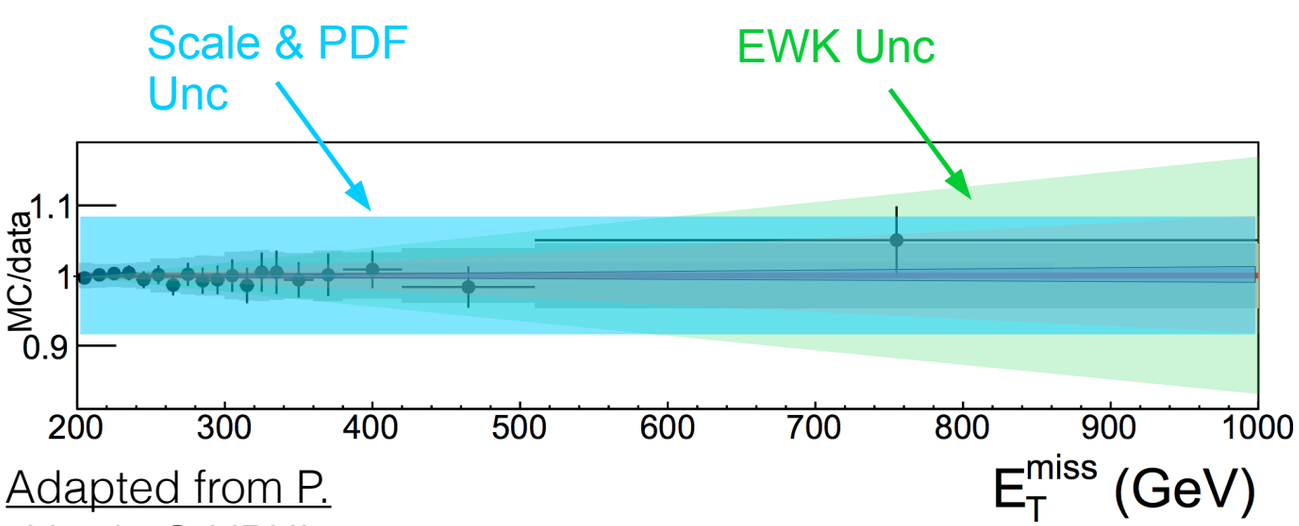
Adapted from P. Harris @ NPKI



5 Control regions
15% uncertainty @ 1 TeV

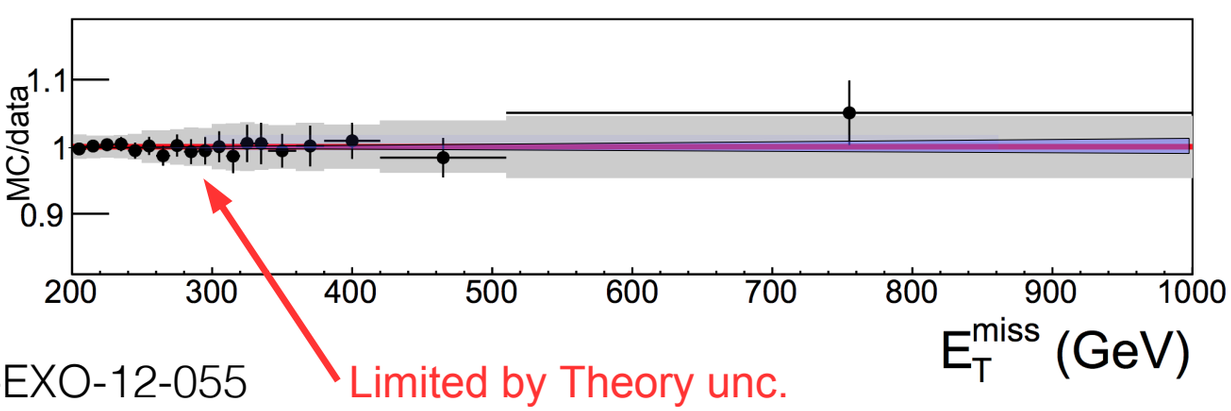
CRs & Transfer Factors

- To maximize the sensitivity CMS uses data to constrain
  - scale systematics for Z & gamma+jets
  - EWK corrections (in a given MET bin)



Adapted from P. Harris @ NPKI

stat limited here



CMS-EXO-12-055

CRs & Transfer Factors

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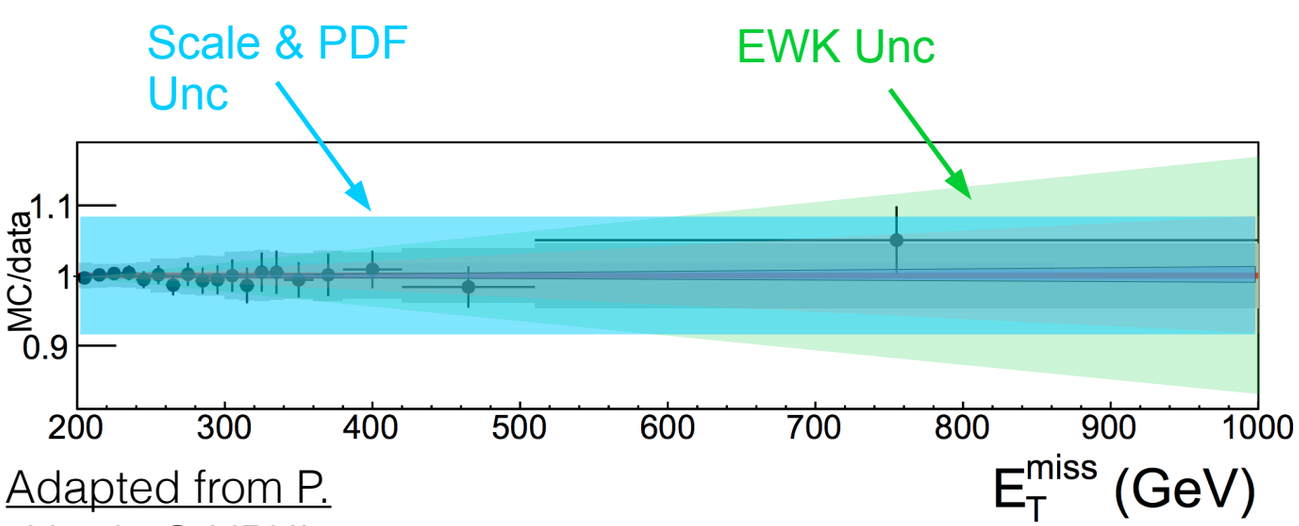
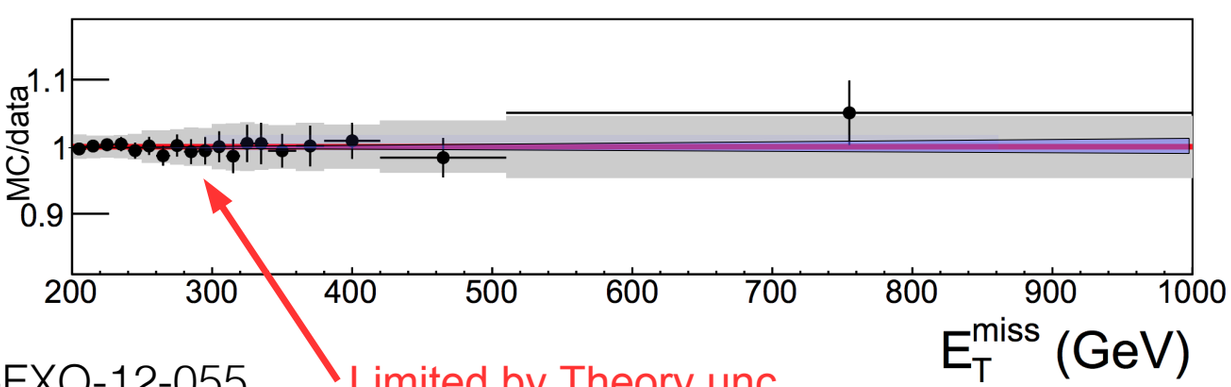


Adapted from P. Harris @ NPKI

stat limited here

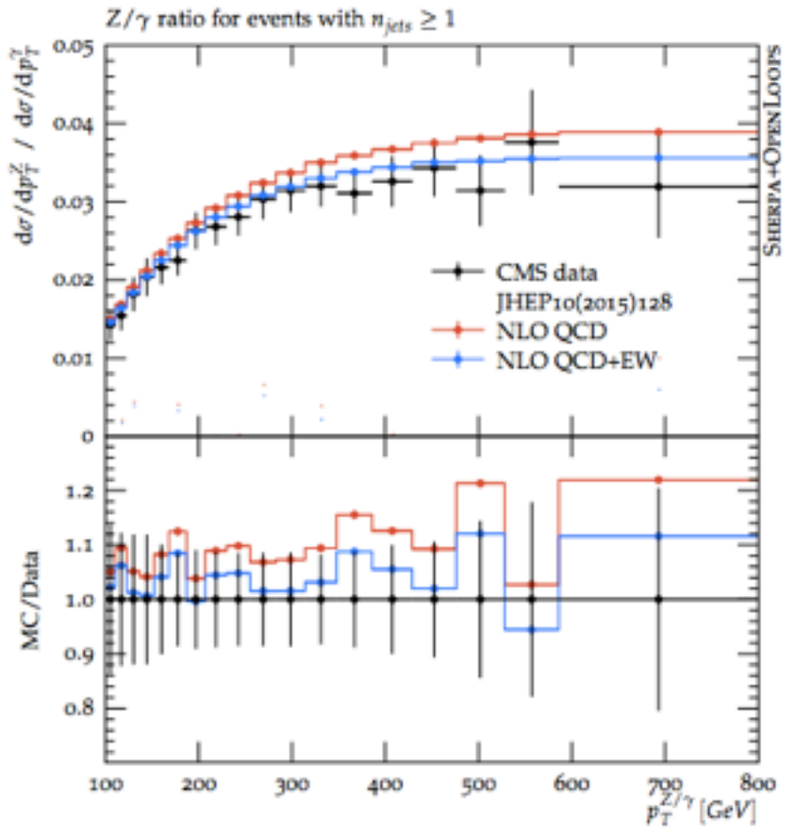


More simplistic approach taken by ATLAS

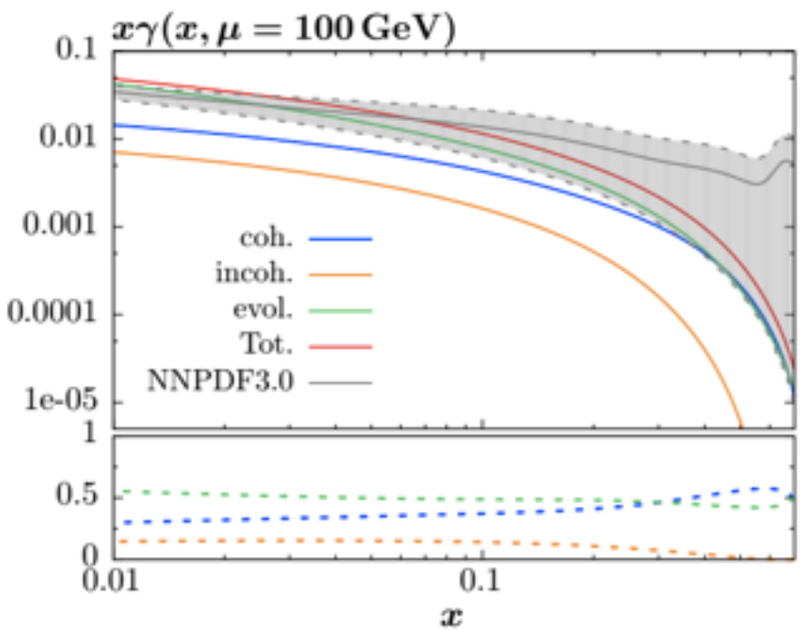
CMS-EXO-12-055

Progress!

- Looking forward to the direct impact on these analyses



See: K Mueller, V. A. M. Radescu, L. Harland-Lang, E. Rizv, S. Prestel,



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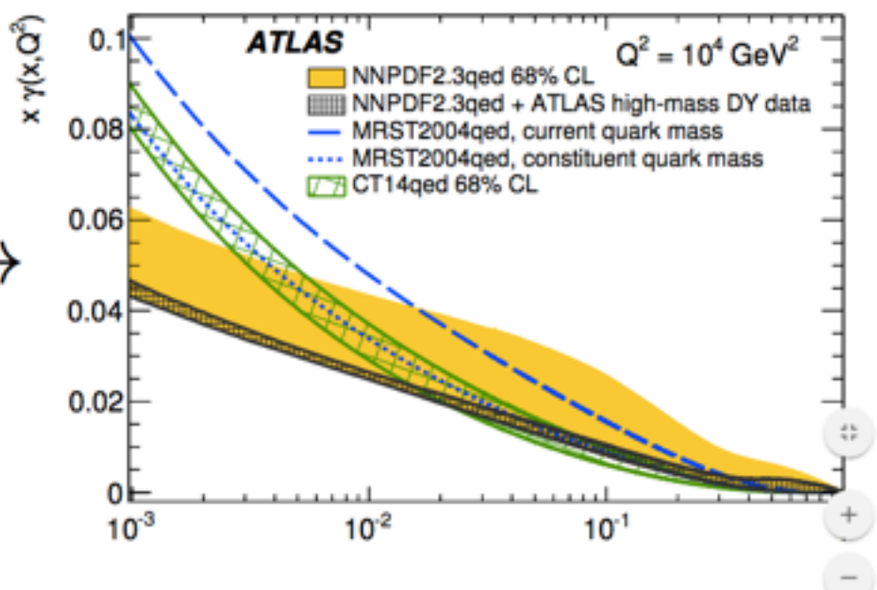
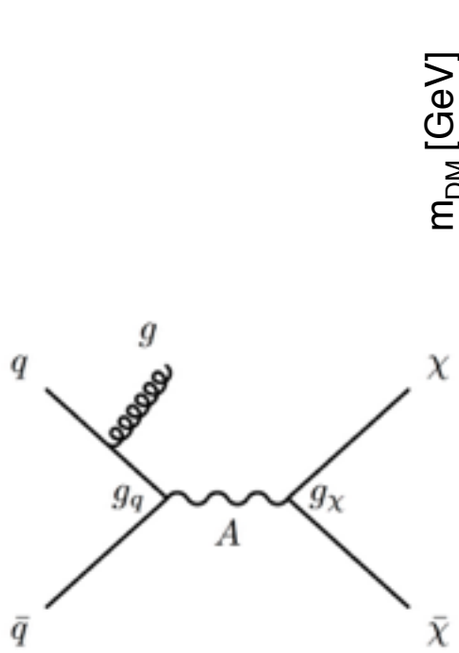
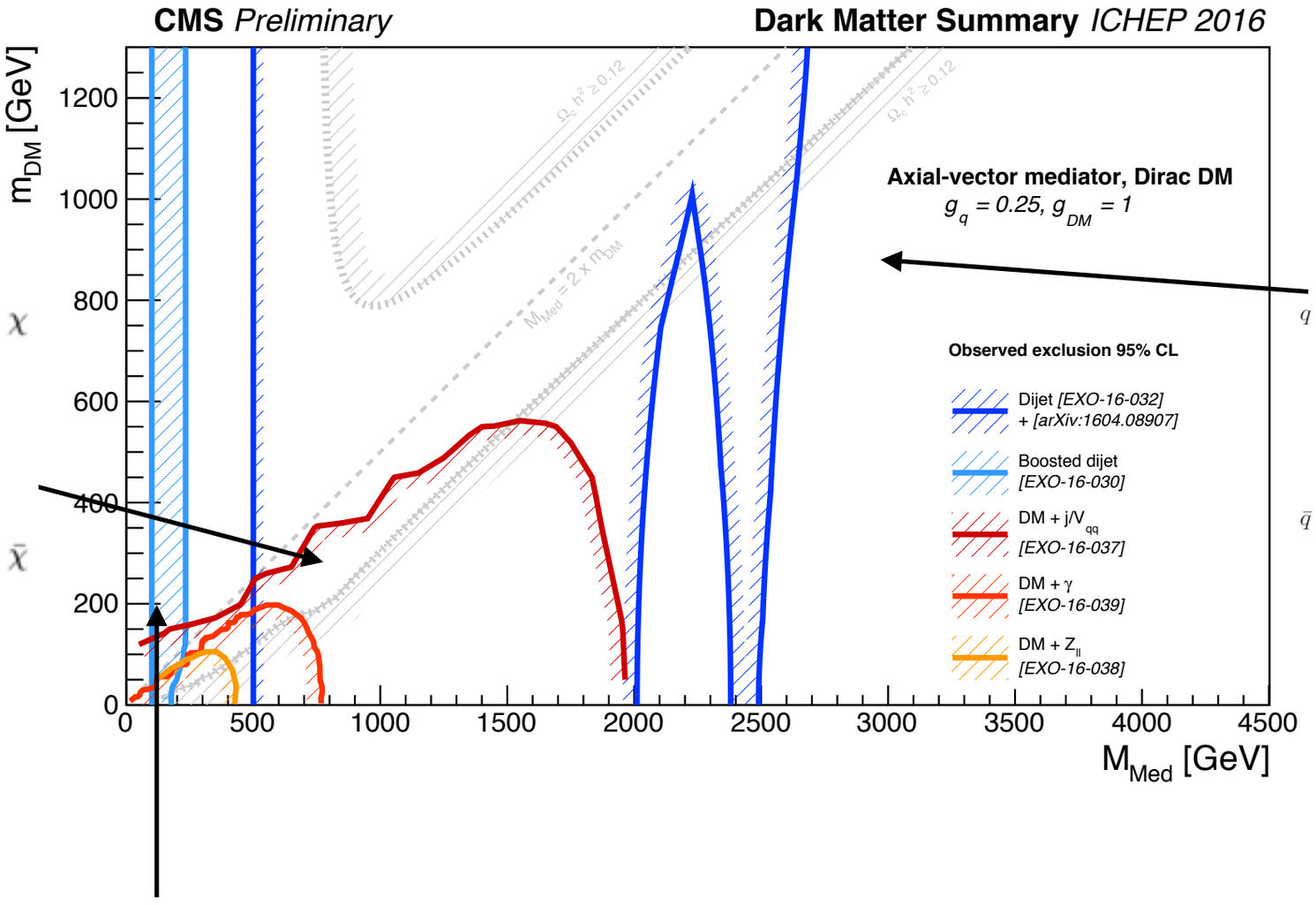
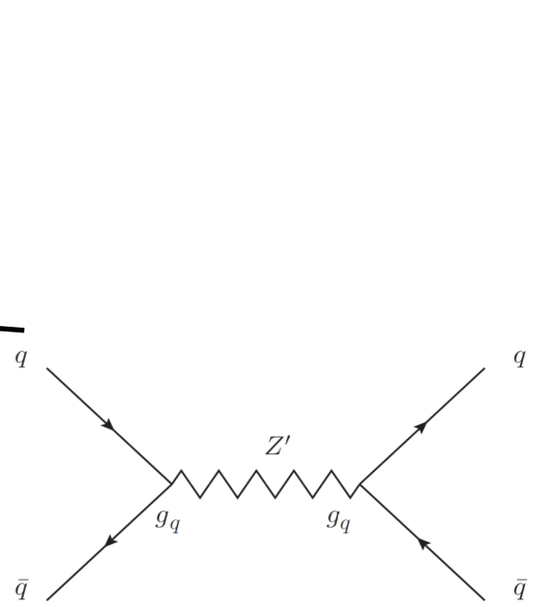


Simplified Dark Matter Model

- For ***this coupling***, model is alive only at high M_{med}



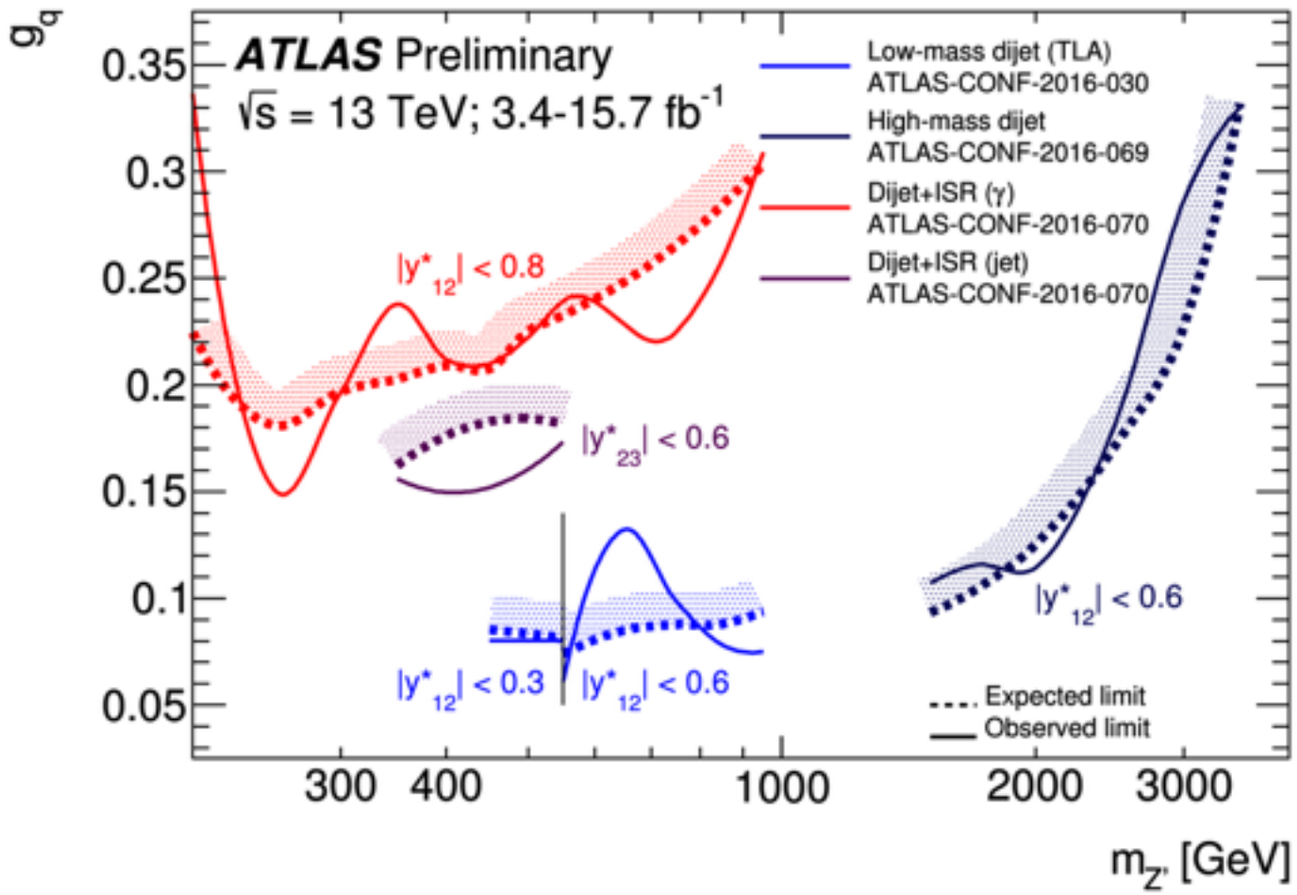




substructure analysis here!

Bump Hunt -> Non Res

ATLAS Summary Plot



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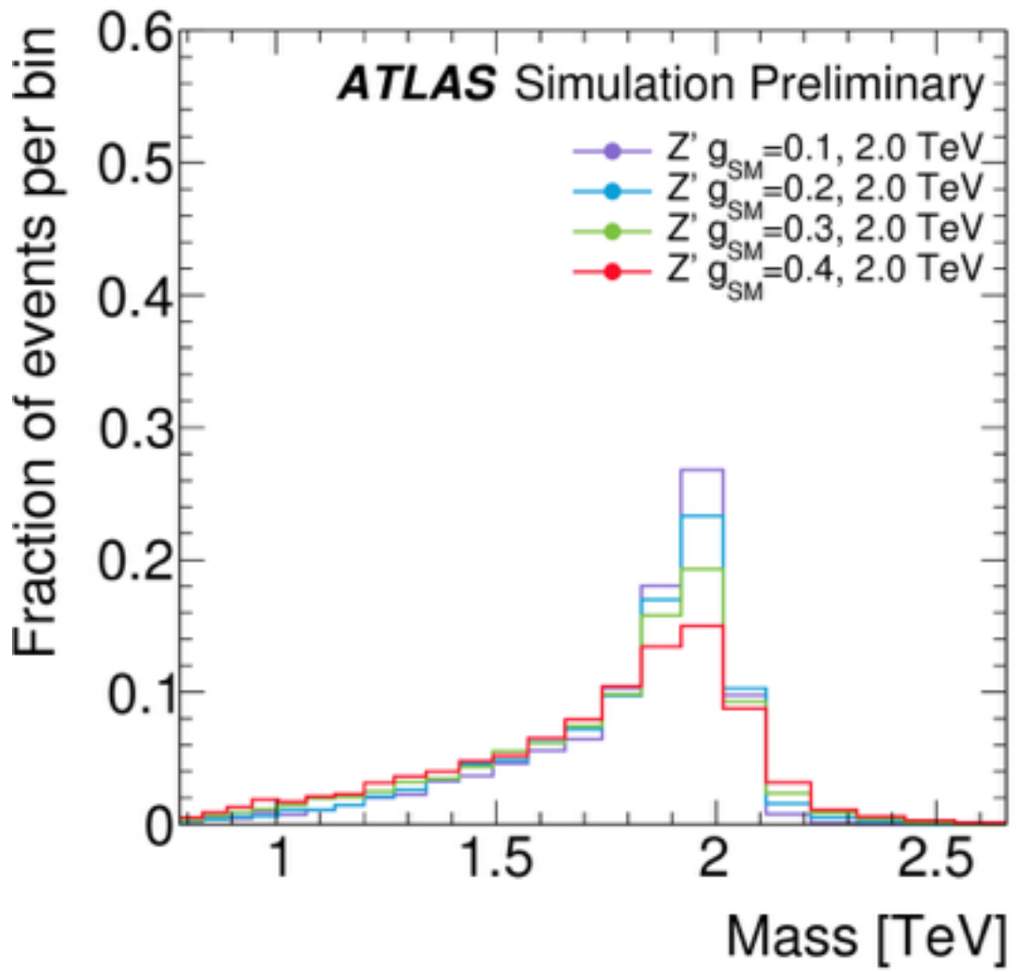
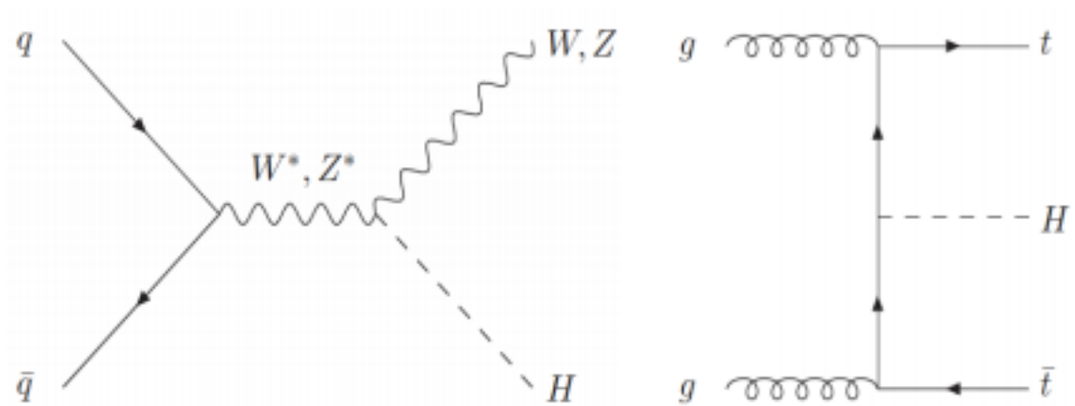


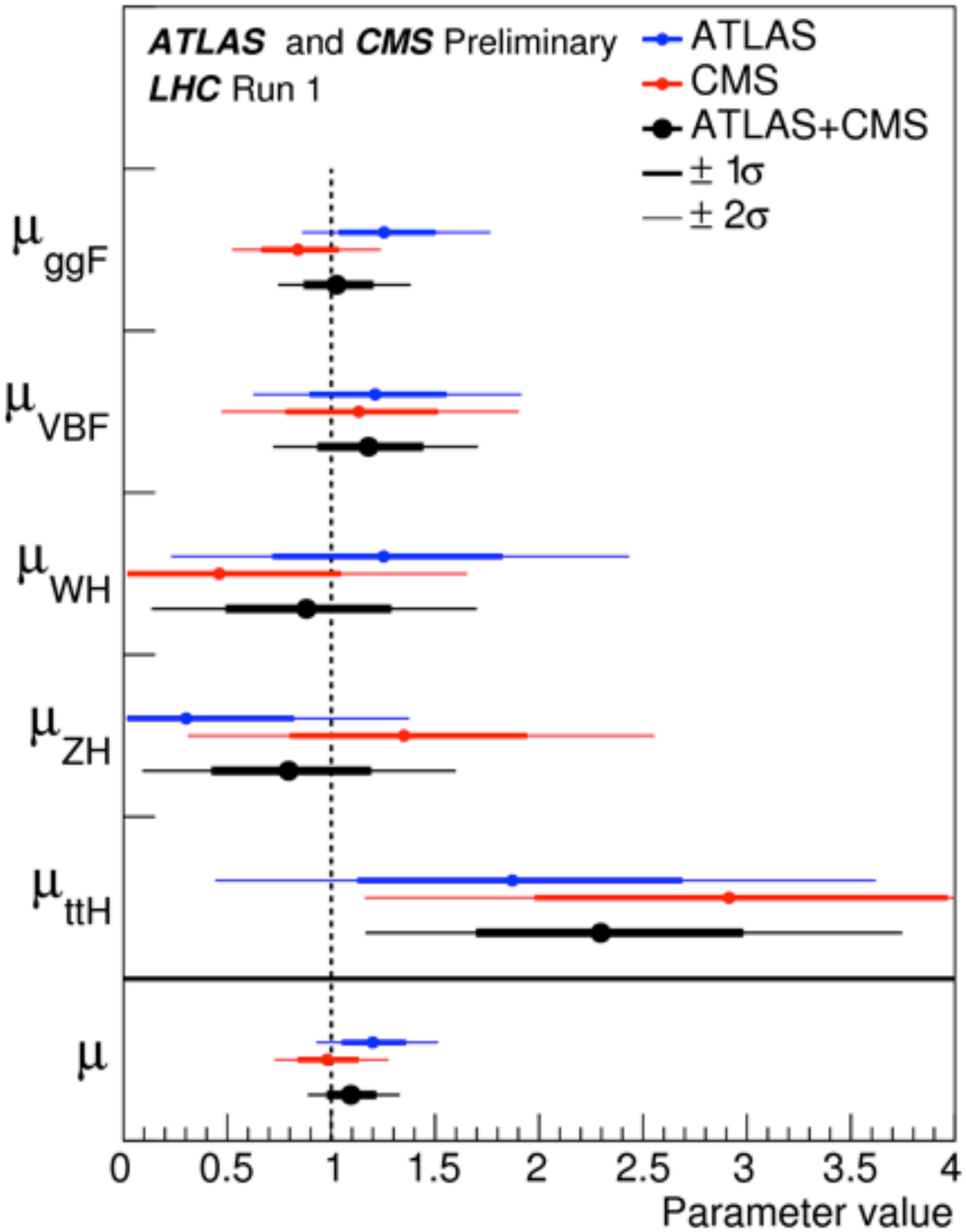
An example of the transition from a bump hunt to a less/non-resonant search in the same kinematic regime

- **3: H(bb)**

H(bb)

- We have yet to observe H(bb): **BR=58%**
- Three ways to go: VH(bb), ttH(bb), VBF
  - concentrating here on the more sensitive 2
- Both ***extremely hard analyses*** as they sit on top of tremendous & difficult SM backgrounds
- backgrounds:
  - ttH: tt+X
  - VH: every SM process

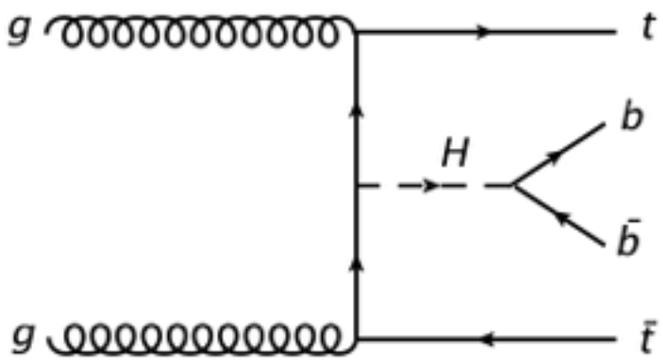




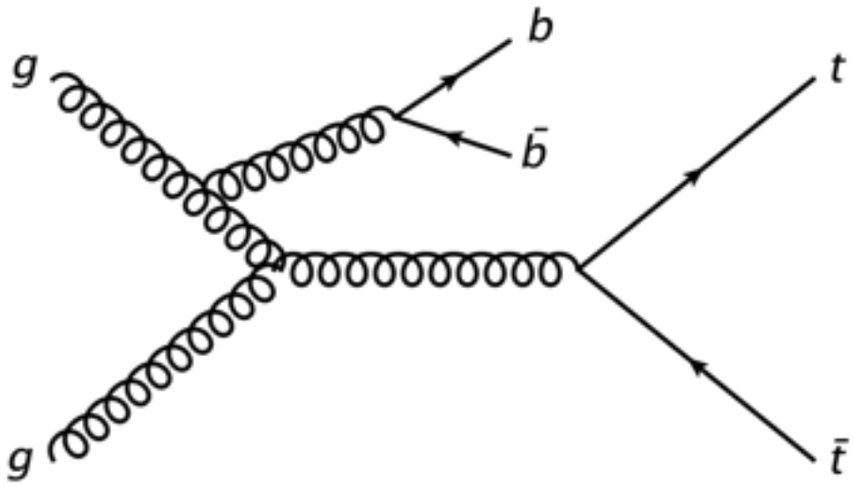
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

ttH(bb)

- To get to



- must fight with



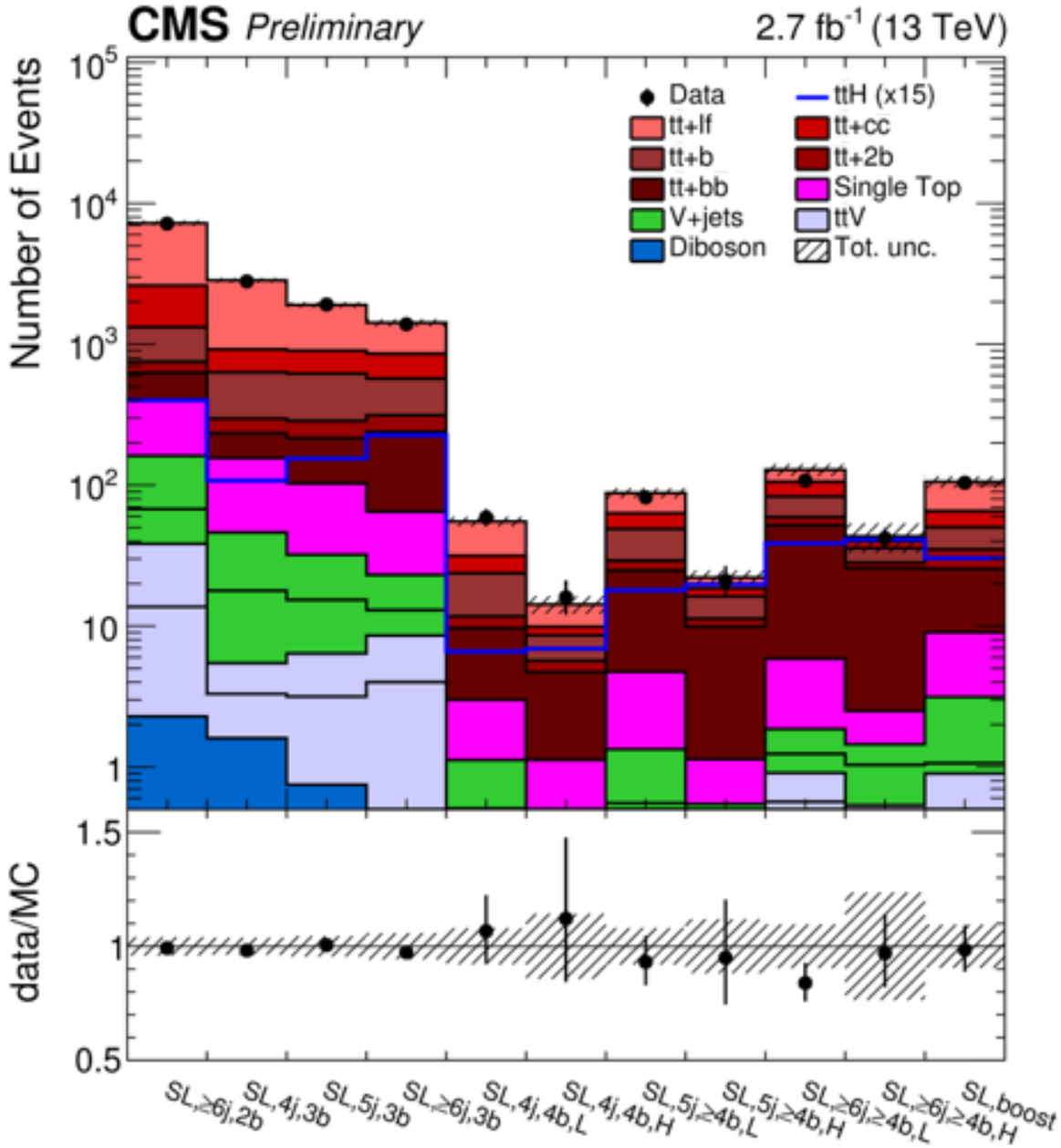
[see S. Pozzorini, K. Lie, GK Krintiras, N. Castro]

Extensively discussed in this conference!
Progress on measurement and theory side - **great news!**

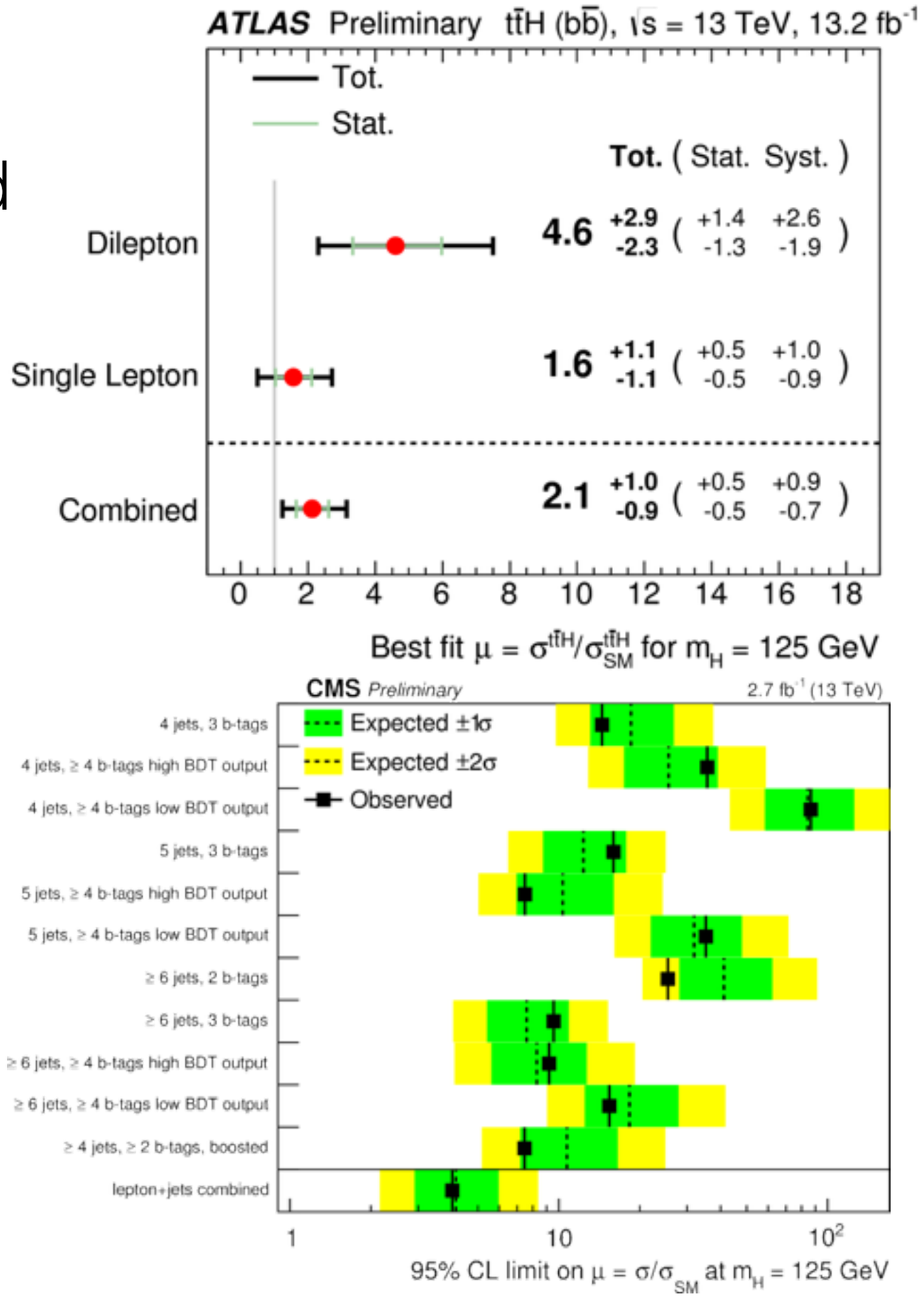
ttH(bb)

- Already systematically limited

  See J. Thomas-Wilsker Talk



ATLAS-CONF-2016-080



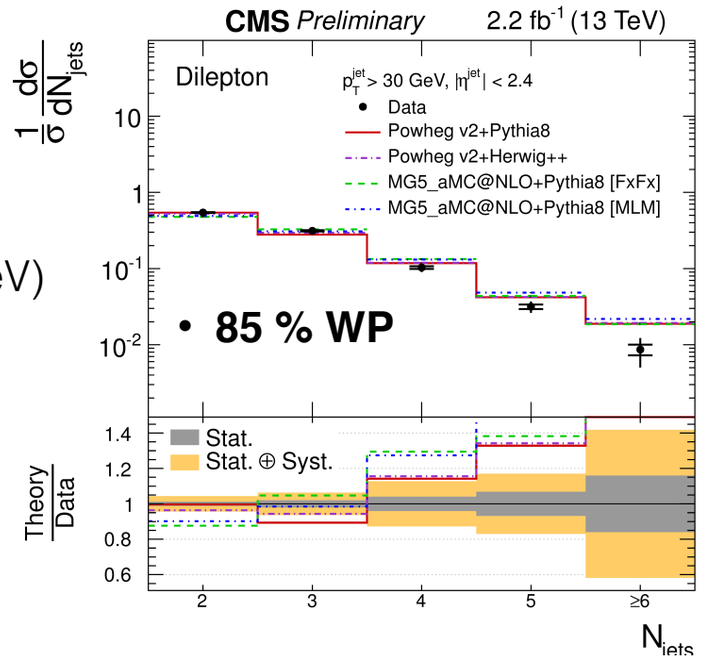
CMS PAS HIG-16-004

tt+jets

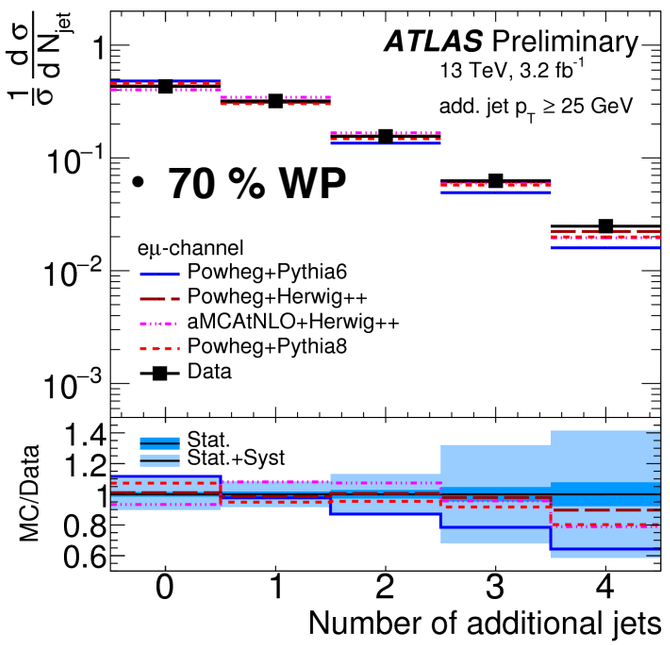
- ATLAS & CMS disagreements do not agree!

	Generators
CMS	• **Powheg+Pythia8 with CUETP8M1 tune (default tt generator for Moriond EW)** • MG5_aMC@NLO+Pythia8 with FxFx matching (up to 2 extra partons at NLO) • Powheg+Herwig++ with EE5C tune
ATLAS	• **Powheg+Pythia6 with P2012 tune (default tt generator for Moriond EW)** • MG5_aMC@NLO+Herwig++ with UE-EE-5 • Powheg+Herwig++ with UE-EE-5 • Powheg+Pythia8 with A14 tunes (*Main31*, pThard = 0 and hdamp = mtop)

- Jet pT CMS (ATLAS) 30 GeV (25 GeV)
- **ATLAS and CMS have opposite trends in data/MC**



CMS-PAS-TOP-16-011

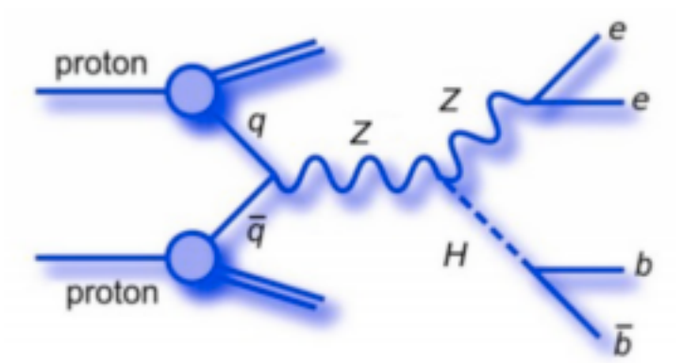


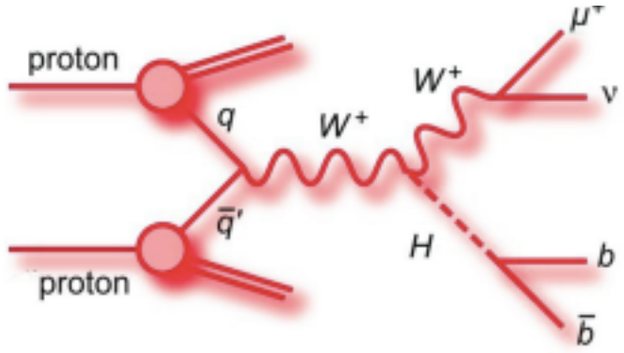
ATLAS-CONF-2015-065

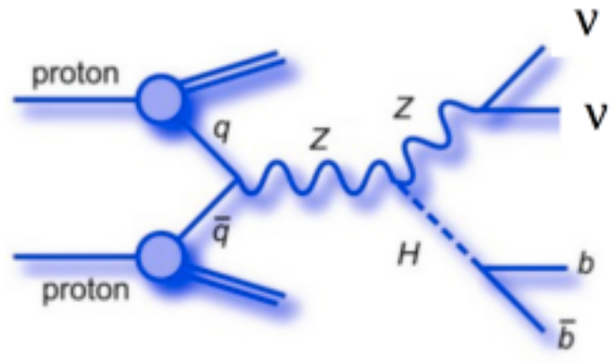
VH(bb)

[see N. Chernyavskaya talk]

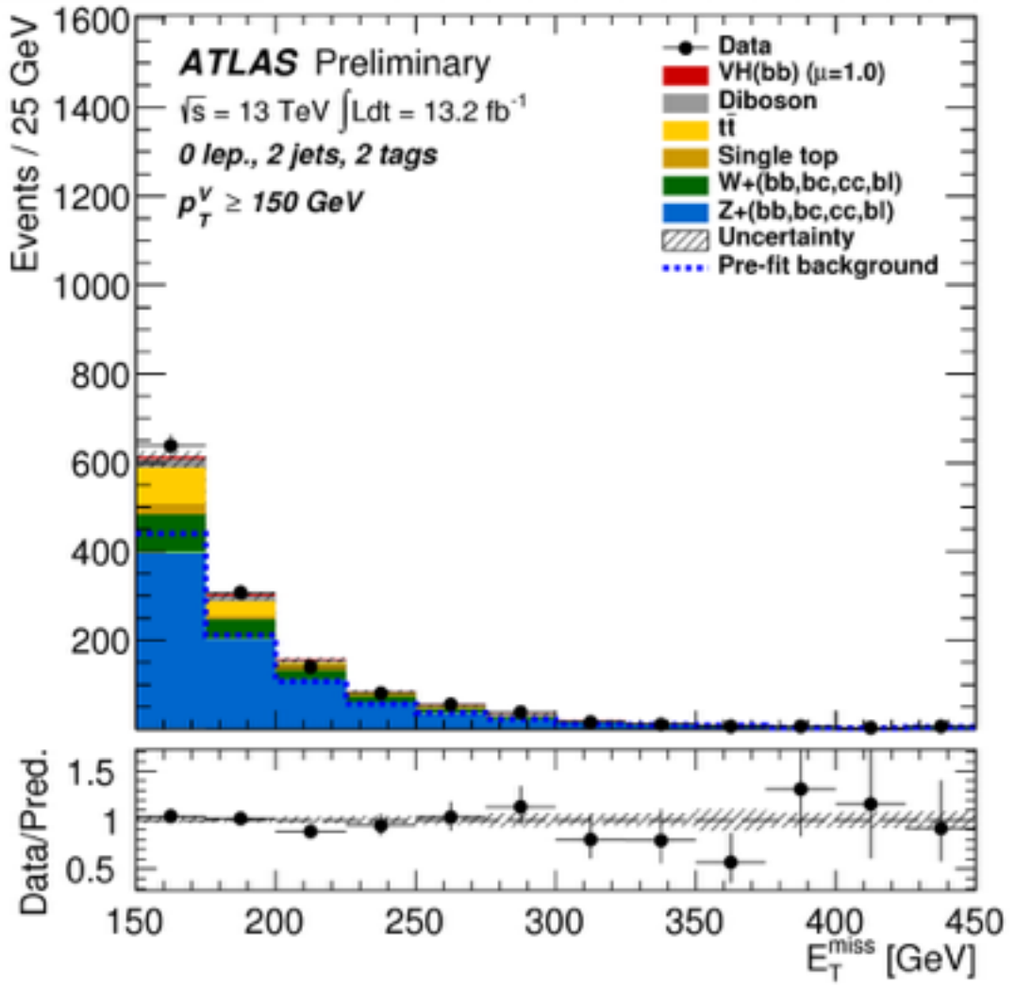
- Three channels, using leptonic decay of W,Z







- Sensitivity maximal at high VpT
  - does not reach out to where substructure is profitable (used in searches)
- Dominant channel is 0-lepton (1-lepton did not profit from increase √s)

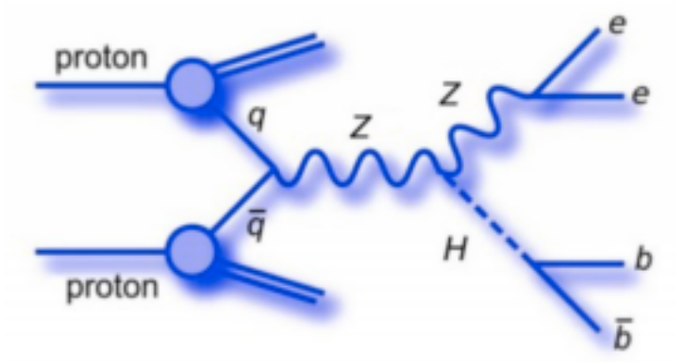


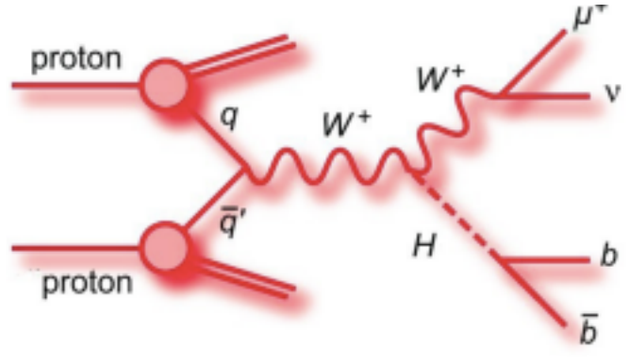
ATLAS-CONF-2016-091

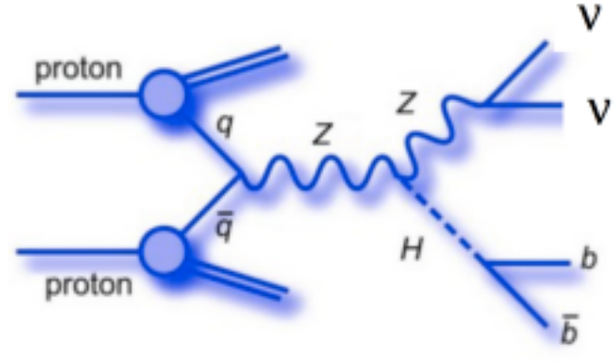
VH(bb)

[see N. Chernyavskaya talk]

- Three channels, using leptonic decay of W,Z







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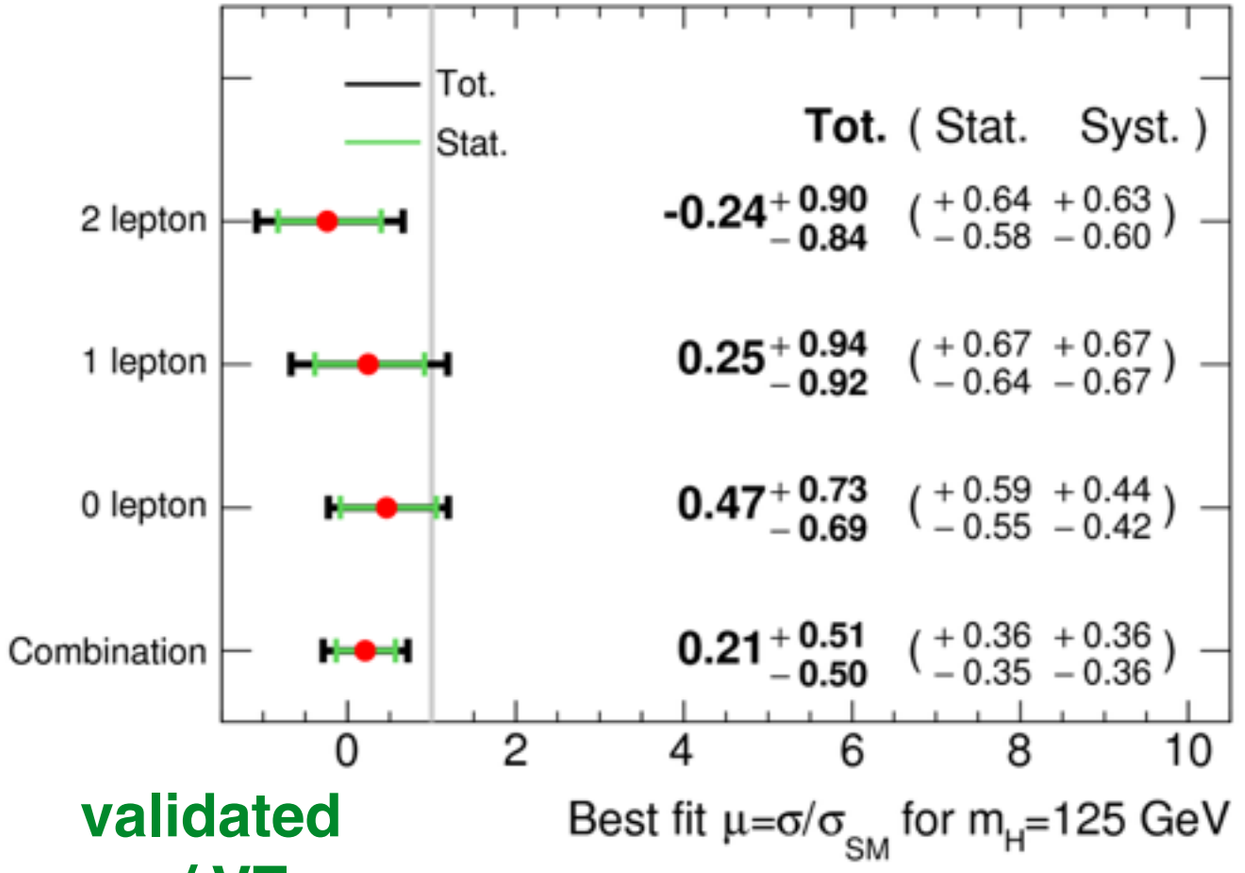
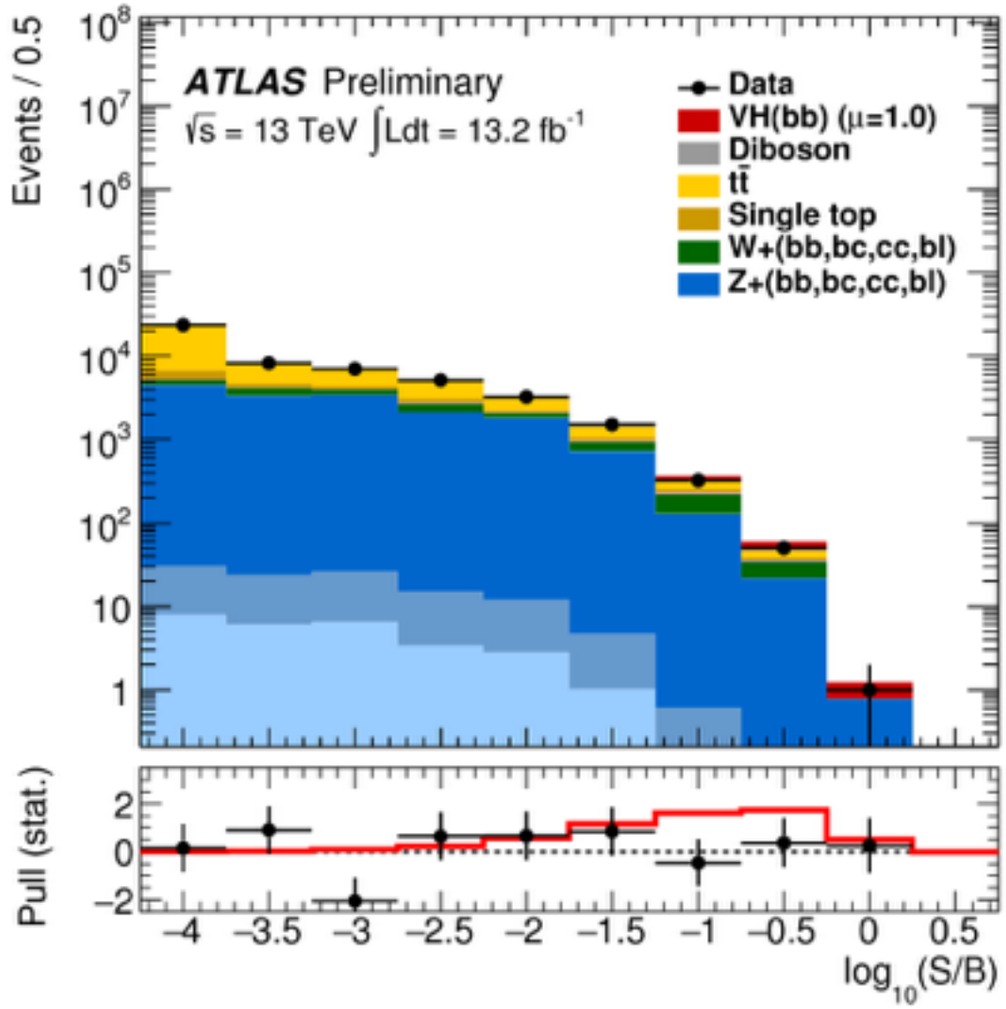


validated w/ VZ

ATLAS-CONF-2016-091

VH(bb)

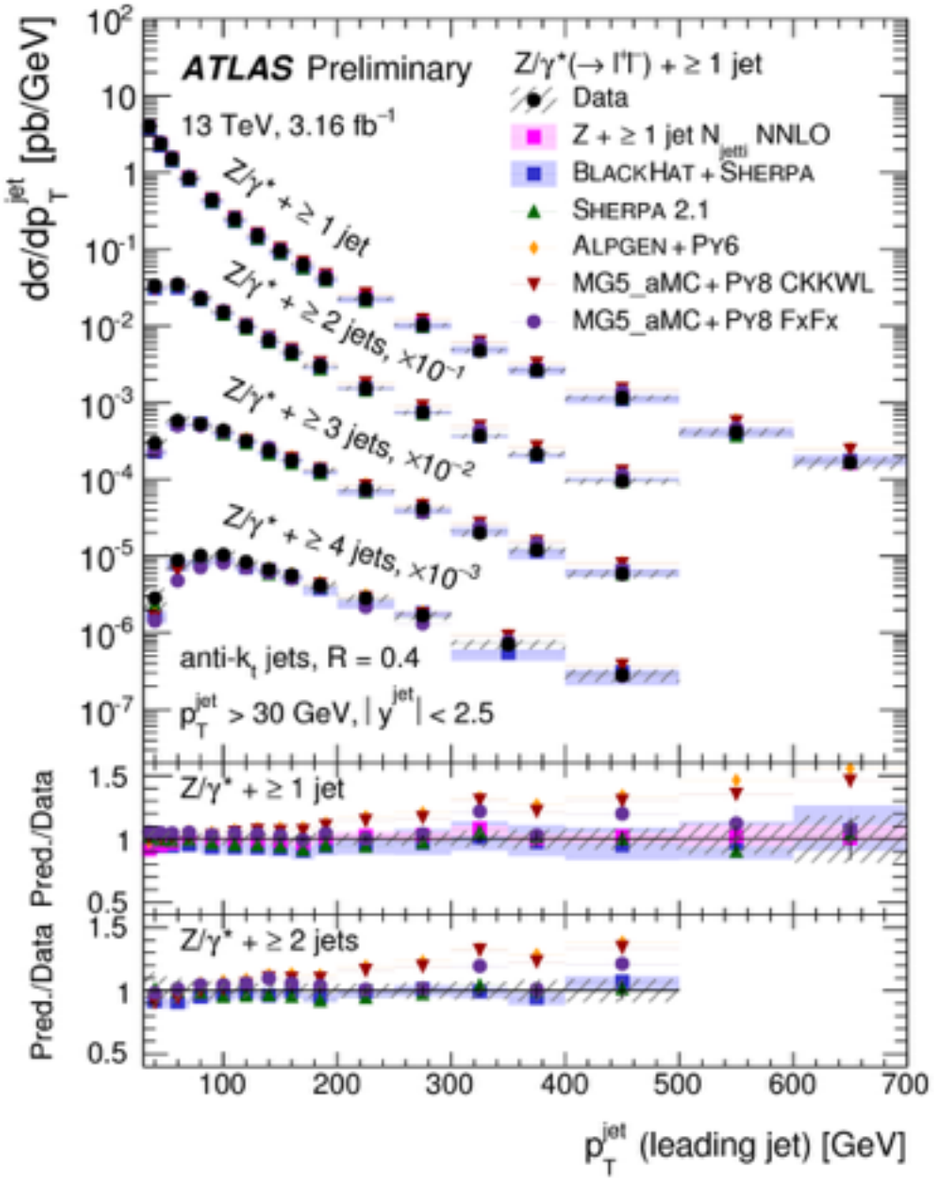
- Z+Heavy Flavor is the dominant background in the most sensitive region
  - ttbar (2jet) and W+Heavy Flavor also very important



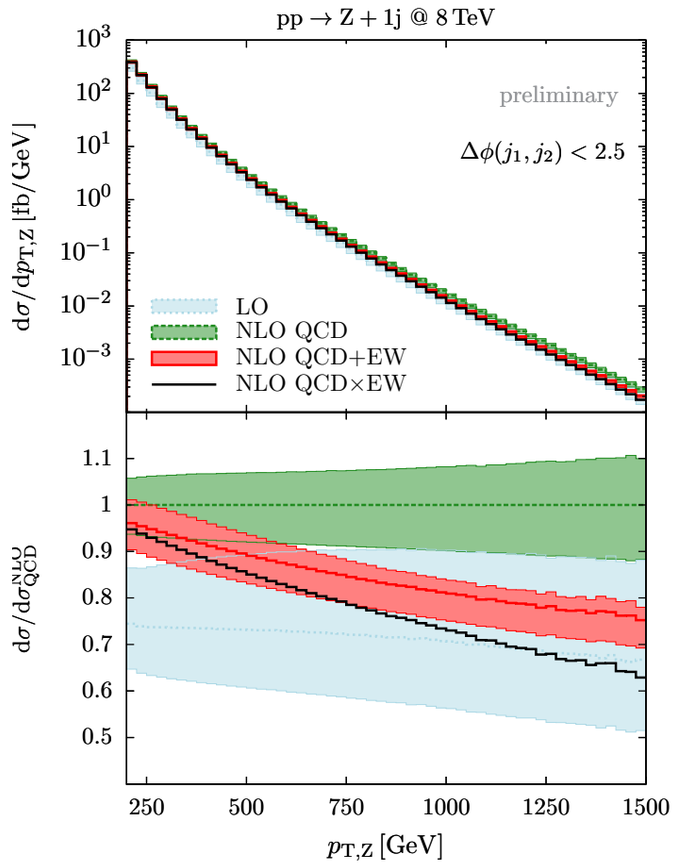
ATLAS-CONF-2016-091

Z+Heavy Flavor

- A basic survey of what is out there.

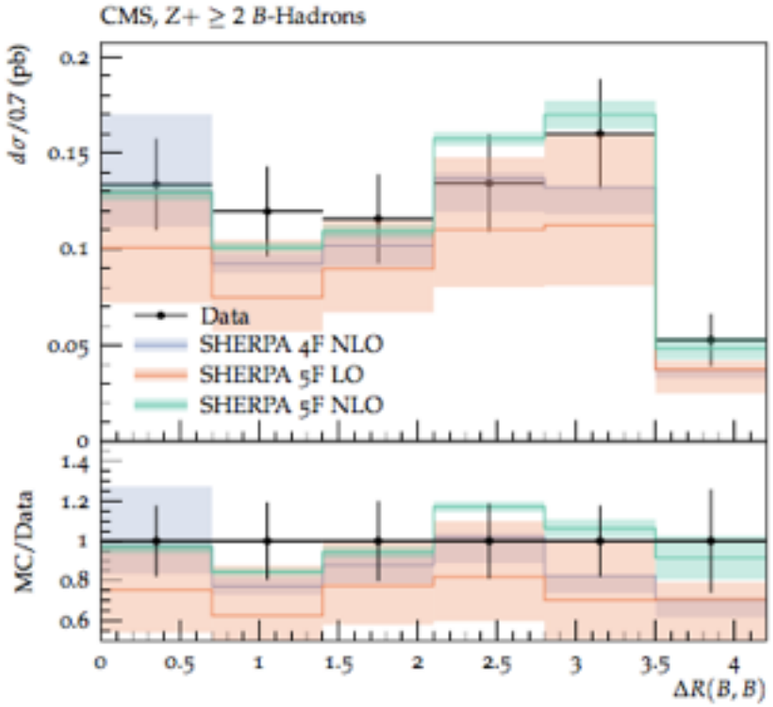


ATLAS-CONF-2016-046
[see J. Bossio, F. Zhang talk]



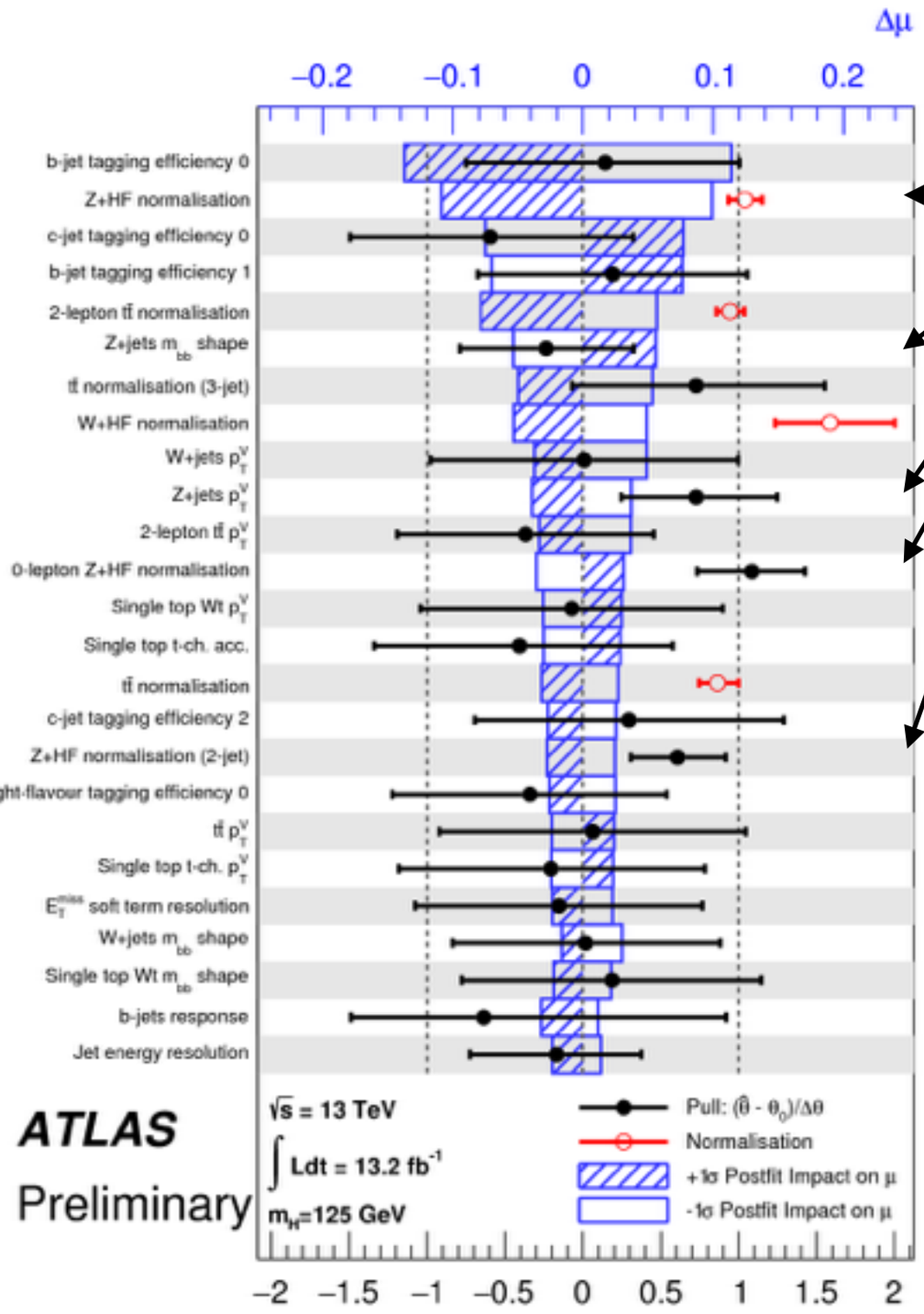
[S. Kallweit, J. M. Linderta, S. Pozzorini
M. Schönherr, P. Maierhöfer '15]

[see S. Uccirati talk]



Les Houches 2015
SM Group Report
arXiv:1605.04692

Z+Heavy Flavor



Z+HF Jets

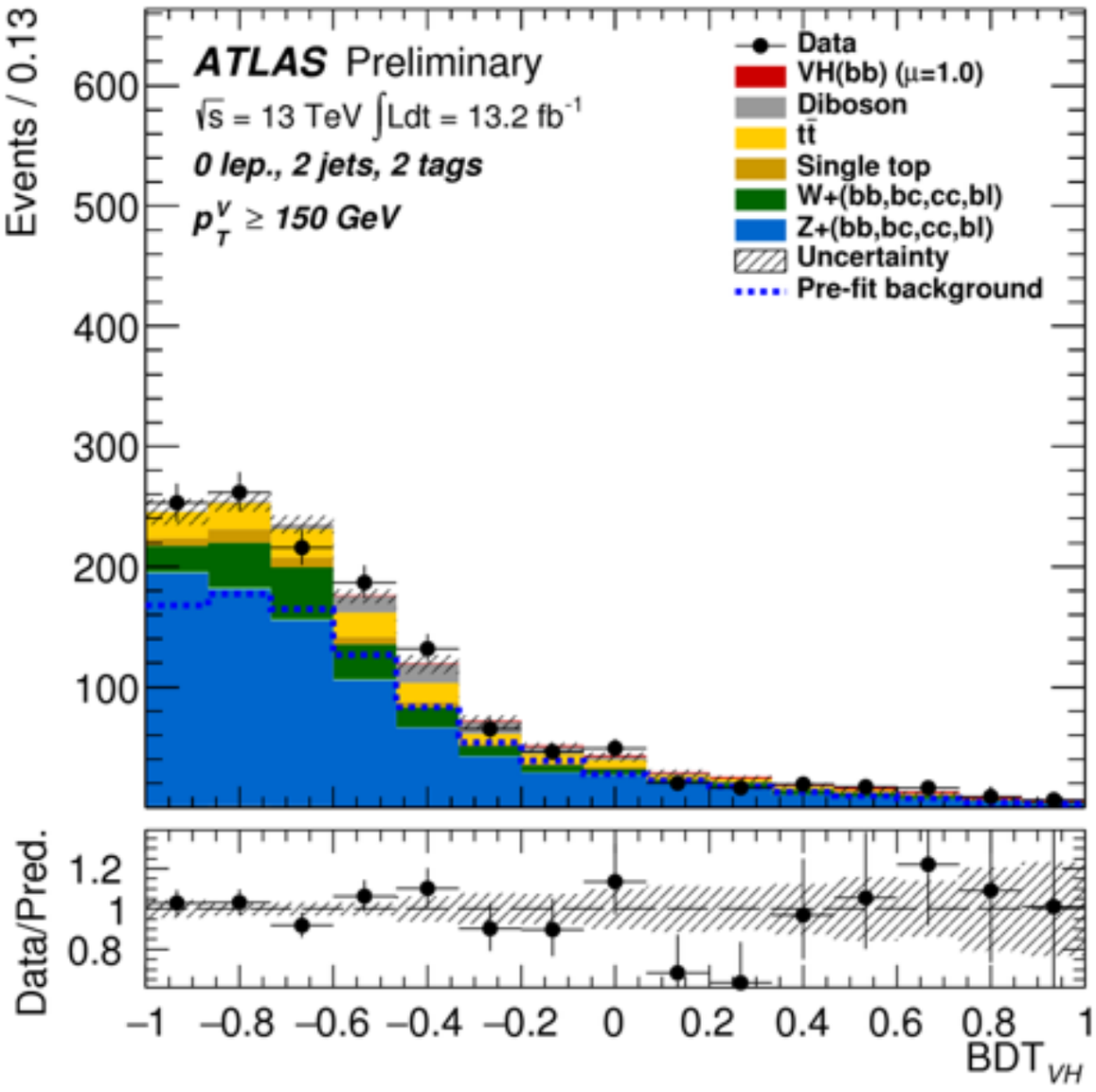
	Z+jets
Zl normalisation	18%
Zcl normalisation	23%
Zbb normalisation	Floating
Zbc-to-Zbb ratio	14-27%
Zcc-to-Zbb ratio	7-31%
Zbl-to-Zbb ratio	15-38%
0-to-2 lepton ratio	26%
2-to-3 jet ratio	28% (0-lepton) and 25% (2-lepton)
p_{T}^{V}, m_{bb}	S

Systematics from MC comparisons/variations, data/MC in control regions

EW corrections?

ATLAS-CONF-2016-091

Phase Space



Multivariate analysis (BDT)

Are we modeling properly all regions isolated by this MVA technique?

What can the theory community say about this?

ATLAS-CONF-2016-091

In the long run

arXiv.org > hep-ph > arXiv:1606.05296

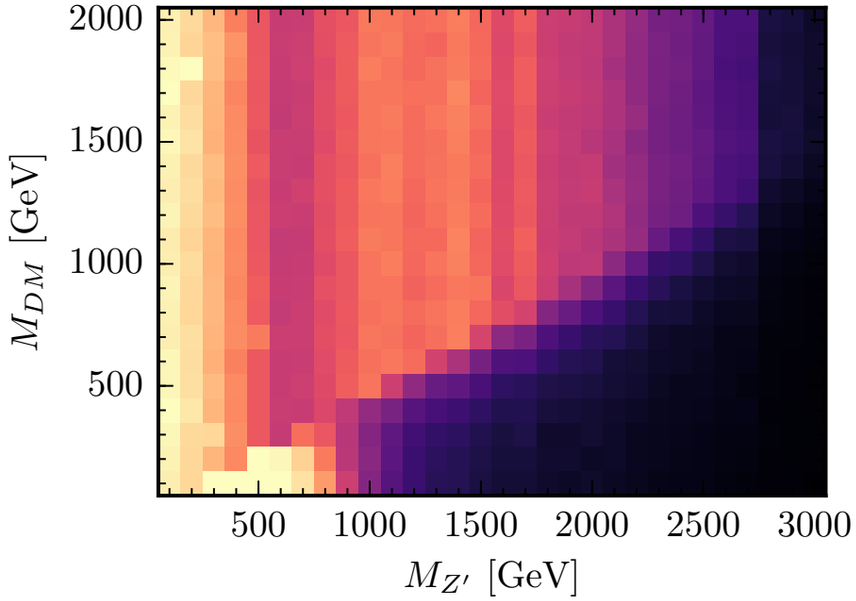
High Energy Physics - Phenomenology

Constraining new physics with collider measurements of Standard Model signatures

Jonathan M. Butterworth, David Grellscheid, Michael Krämer, David Yallup

(Submitted on 16 Jun 2016)

A new method providing general consistency constraints for Beyond-the-Standard-Model (BSM) theories, using measurements at particle colliders, is presented. The method, `Constraints On New Theories Using Rivet', Contur, exploits the fact that particle-level differential measurements made in fiducial regions of phase-space have a high degree of model-independence. These measurements can therefore be compared to BSM physics implemented in Monte Carlo generators in a very generic way, allowing a wider array of final states to be considered than is typically the case. The Contur approach should be seen as complementary to the discovery potential of direct searches, being designed to eliminate inconsistent BSM proposals in a context where many (but perhaps not all) measurements are consistent with the Standard Model. We demonstrate, using a competitive simplified dark matter model, the power of this approach. The Contur method is highly scaleable to other models and future measurements.



(a) $g_q = 0.25$ and $g_{\mathrm{DM}} = 1$

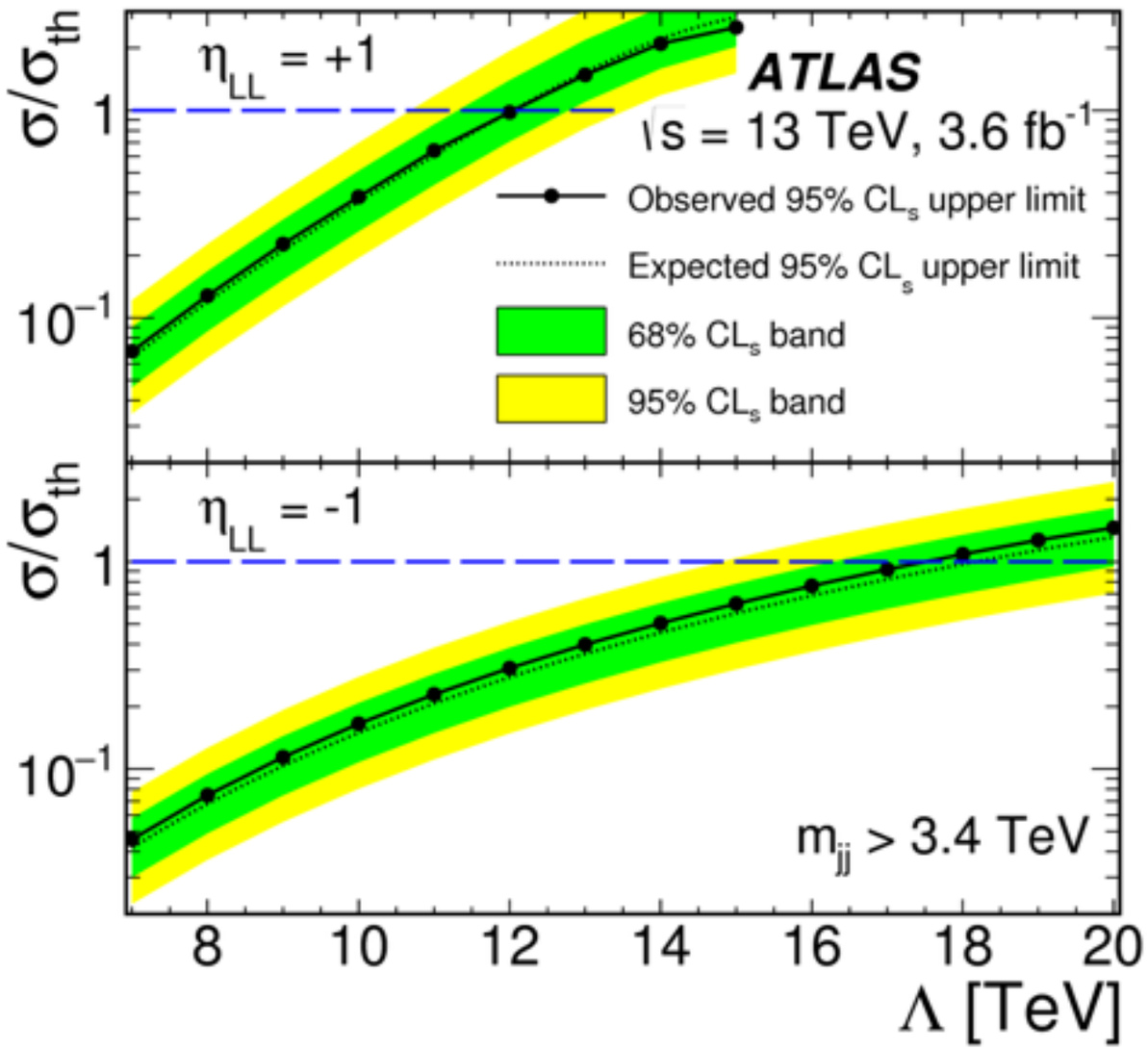
What will be the legacy* papers of the LHC?

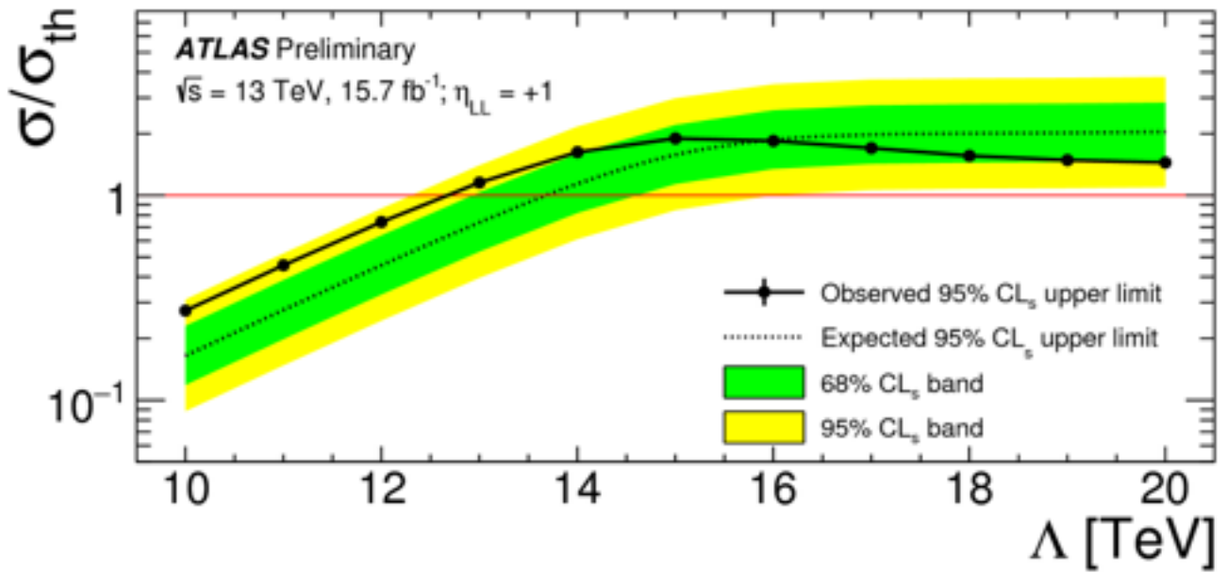
*including in between runs

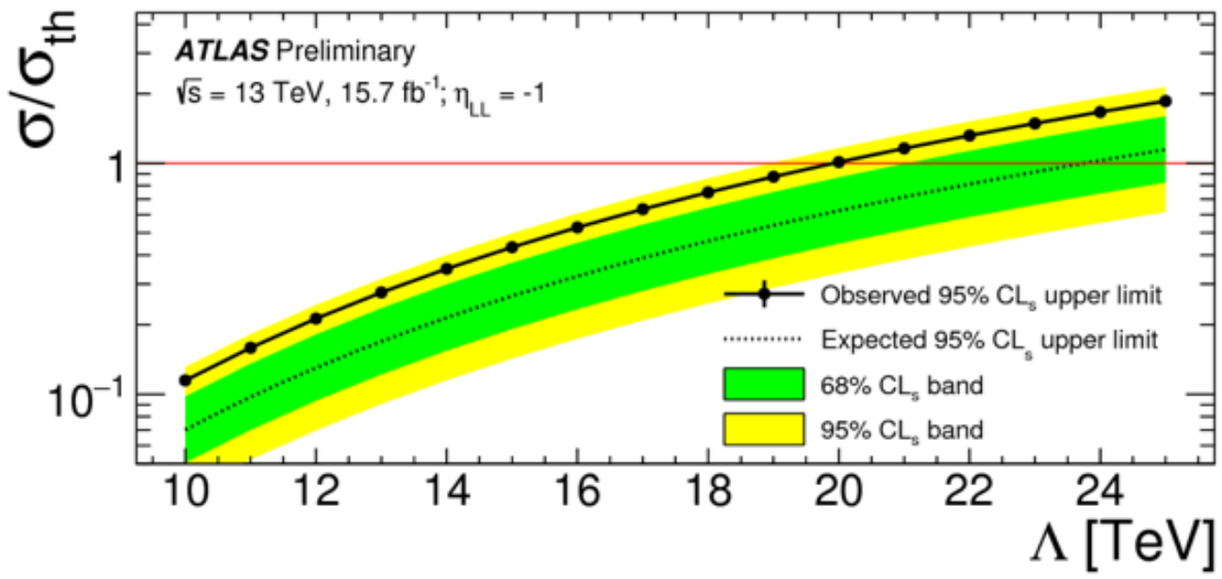
Conclusions

- Run 2 is here and we are burning through the data
  - QCD based searches are an important part of searches
- As Run 2 progress the bulk of the phase space for many searches will be **systematically limited**
  - there will always be stat limited tails and new low rate SM processes coming into reach
- *Do we have the patience to put in the hard work needed to beat down those systematic errors?*
  - of course! Already under way
  - **The bedrock of this program is precision measurements!**
- But how far do we have to go? As far as we can …

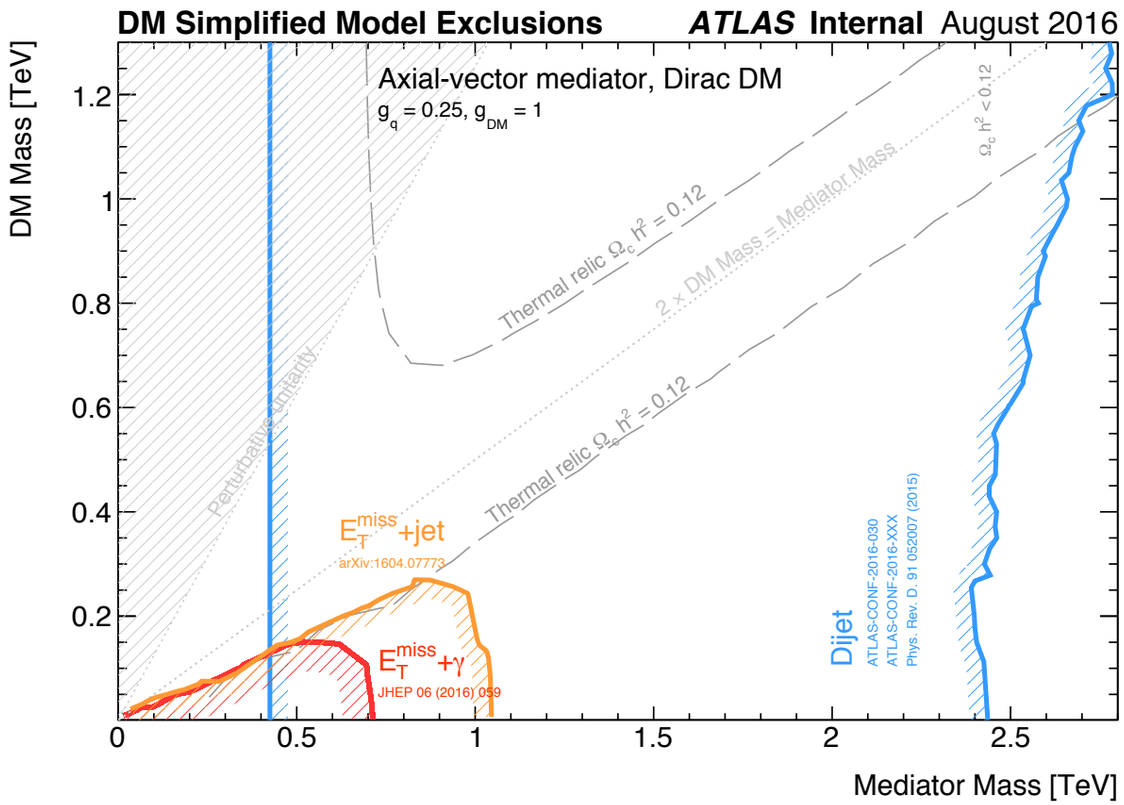
Besides Bumps

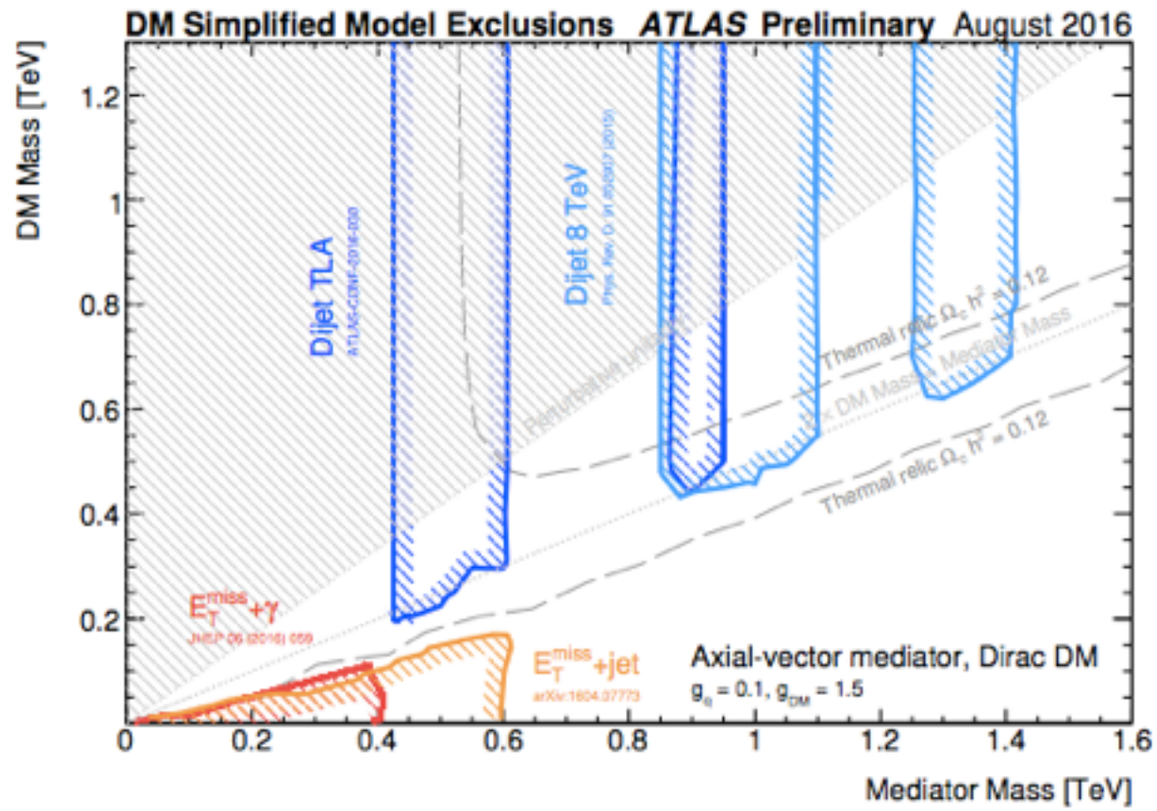




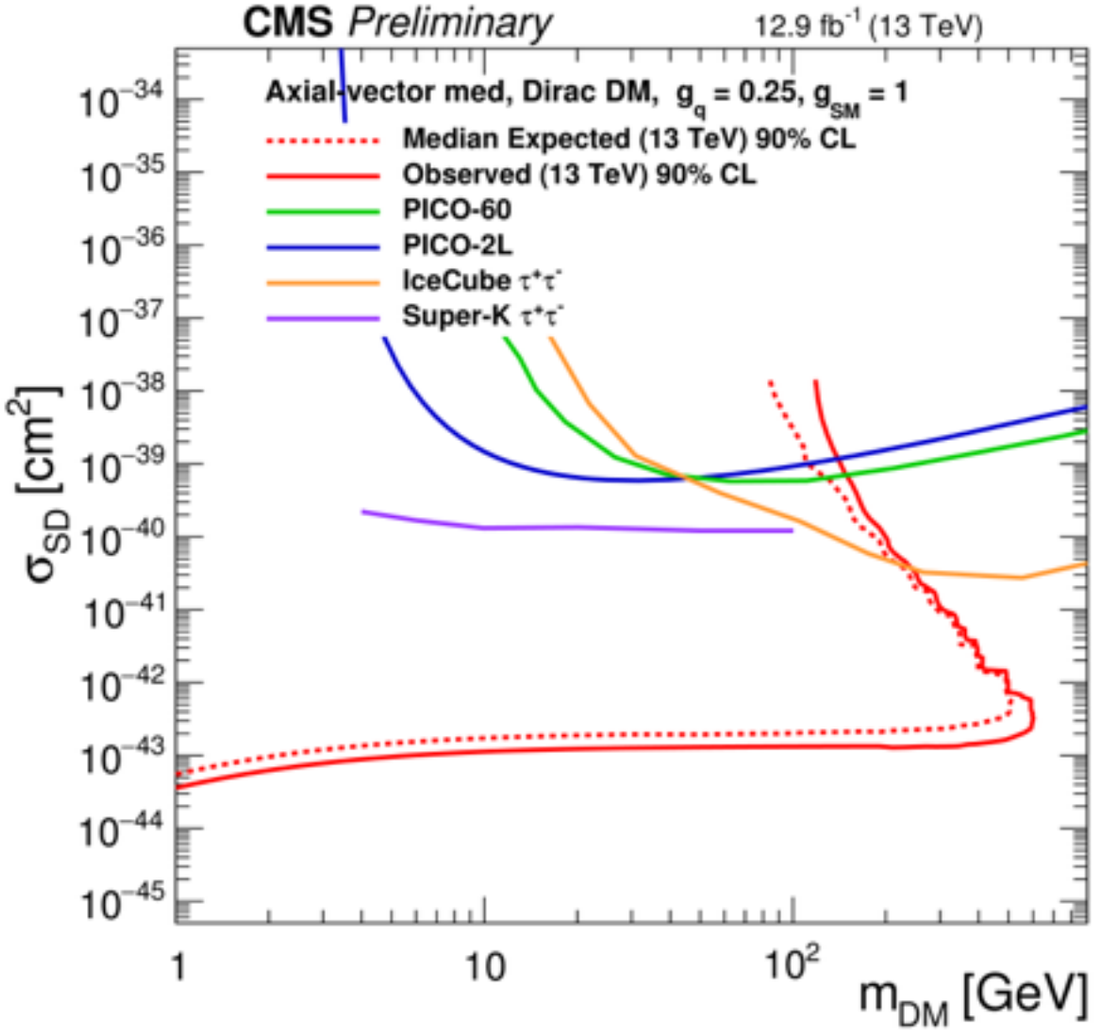


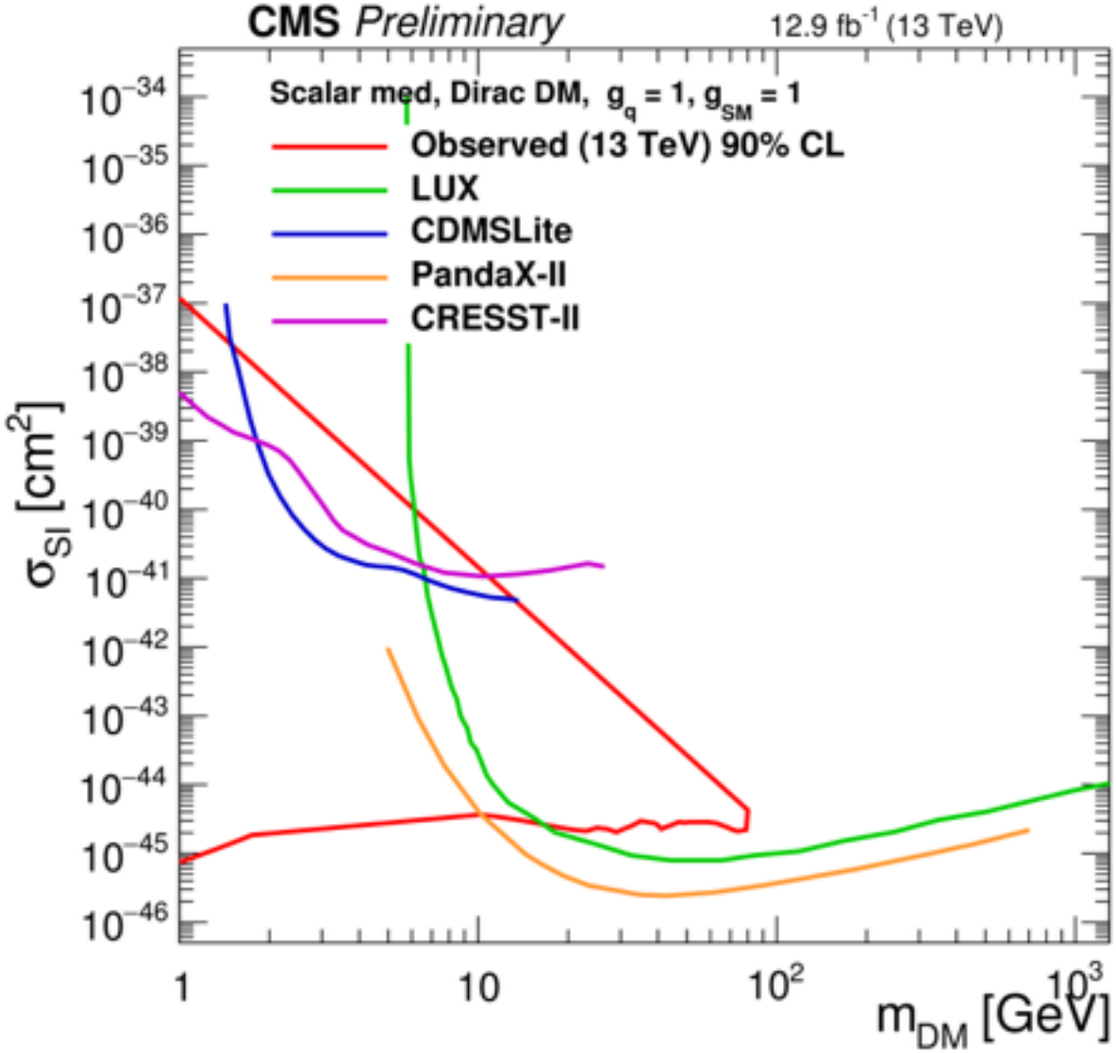
DM @ ATLAS


DM Simplified Model Exclusions
ATLAS Internal August 2016
Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_{DM} = 1$
DM Mass [TeV]
Mediator Mass [TeV]
Thermal relic $\Omega_c h^2 = 0.12$
2 x DM Mass = Mediator Mass
$\Omega_c h^2 < 0.12$
Perturbative unitarity
E_T^{miss}+jet
arXiv:1604.07773
E_T^{miss}+γ
JHEP 06 (2016) 059
Dijet
ATLAS-CONF-2016-030
ATLAS-CONF-2016-XXX
Phys. Rev. D. 91 052007 (2015)


DM Simplified Model Exclusions
ATLAS Preliminary August 2016
DM Mass [TeV]
Mediator Mass [TeV]
Dijet TLA
Dijet 8 TeV
Thermal relic $\Omega_c h^2 = 0.12$
E_T^{miss}+γ
JHEP 06 (2016) 059
E_T^{miss}+jet
arXiv:1604.07773
Axial-vector mediator, Dirac DM
$g_q = 0.1$, $g_{DM} = 1.5$

Complementarity





Substructure in 1 slide

- trimming: recluster jet constituents with k_t $R=R_{sub}$, drop if $p_T^{sub}/p_T<f_{cut}$

- pruning: recluster with C/A, killing wide angle with ΔR_{12} $>R_{cut}$ x $2M/p_T$ and soft with $f_2<Z_{cut}$

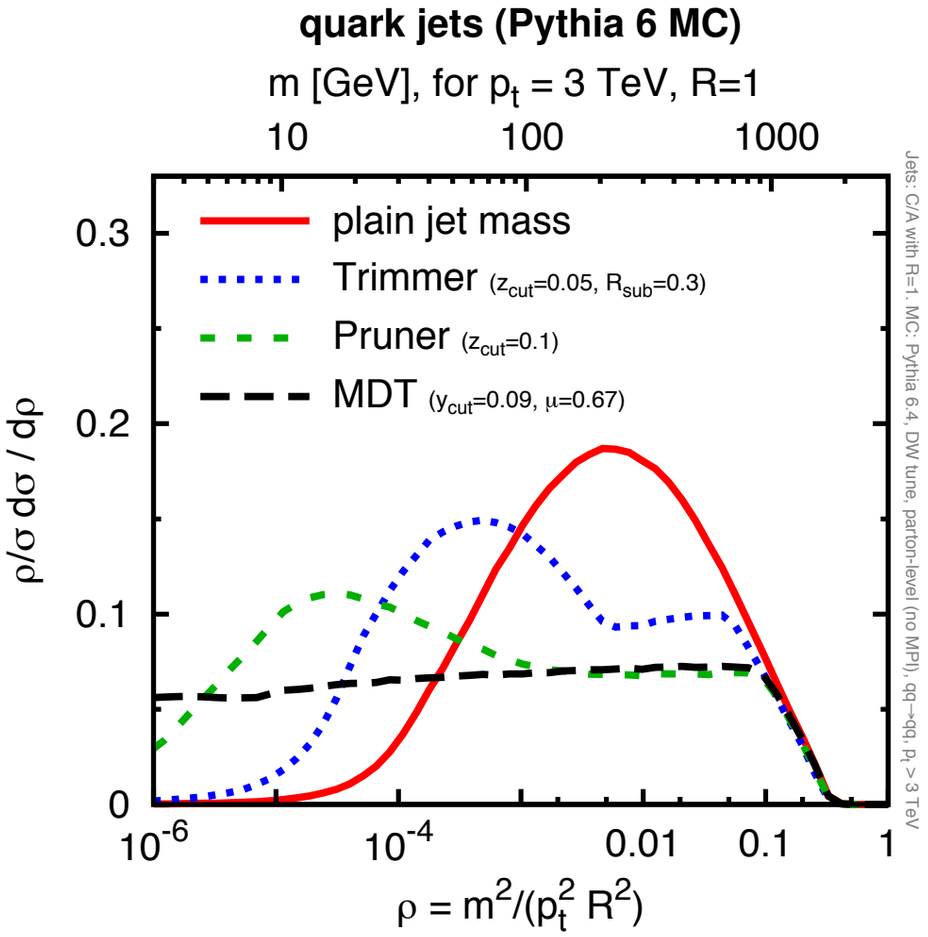
- mass drop: de-cluster until significant mass drop $m_{j1}<um_j$ and not too asymmetric

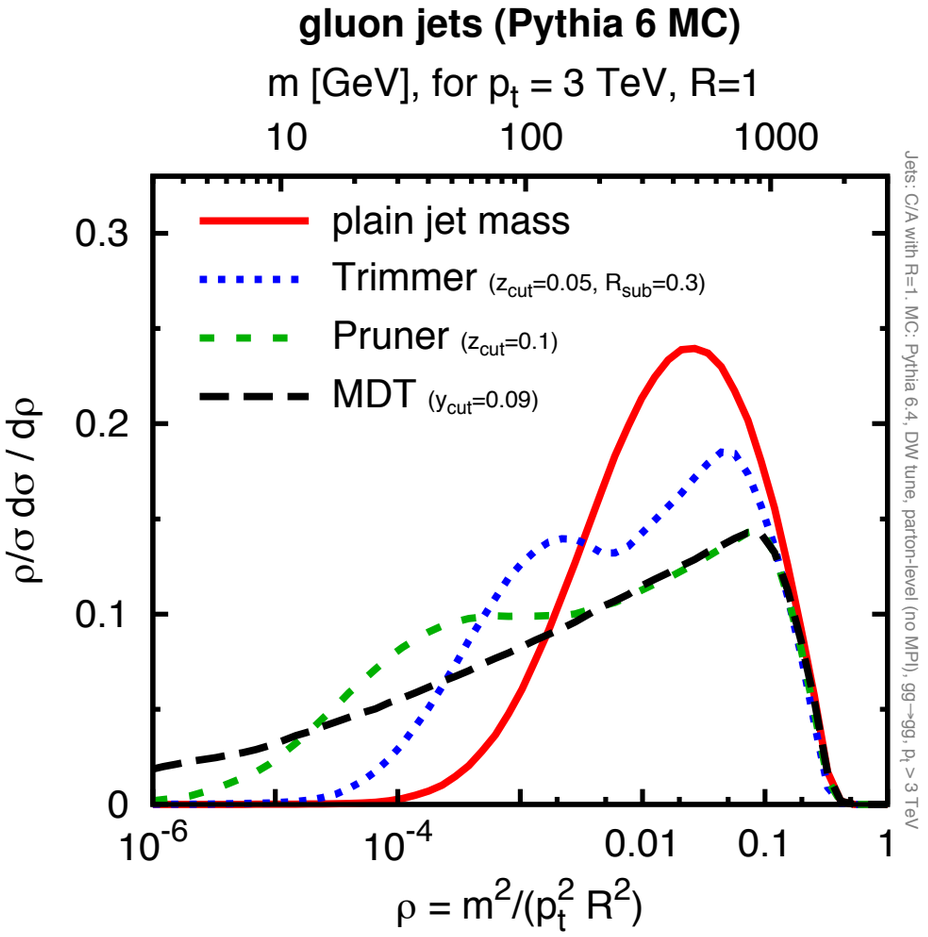
- soft drop: remove soft wide-angle radiation

- n-subjetiness: how likely composed of n-subjets

- D2: A variation on the ratio of energy correlations which optimizes the separation between one-prong and two-prong decays, in analytical terms

Substructure

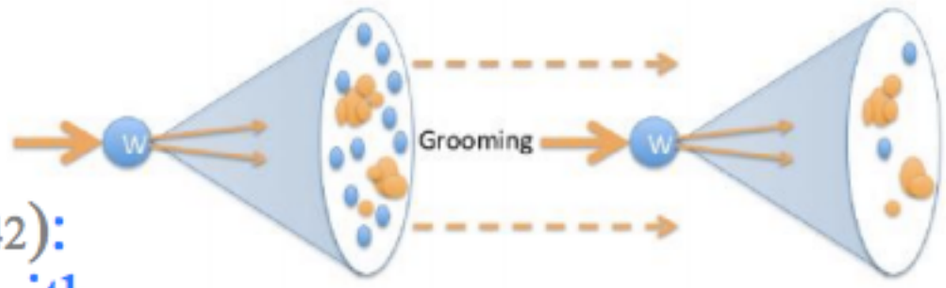




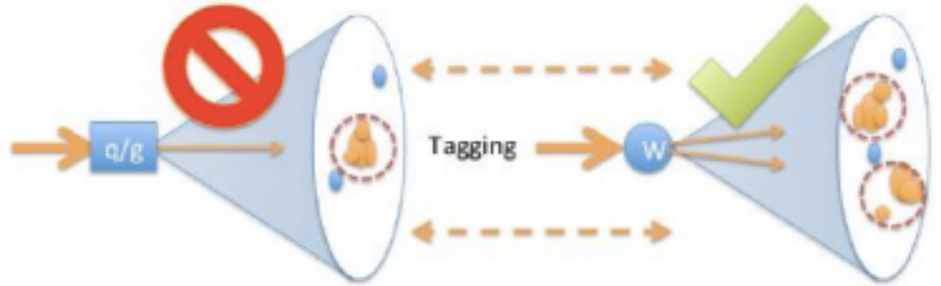
[Dasgupta, Fregoso, Marzani, Salam '13]

ATLAS Substructure

- **Grooming:** to minimize impact of energy deposits from pile-up interactions
  - ATLAS mainly uses "Trimming" (arXiv:0912.1342): re-cluster with k_t R=0.2 and remove sub-jets with $p_{\mathrm{T}}^{\mathrm{subjet}} / p_{\mathrm{T}}^{\mathrm{jet}} < 0.05$

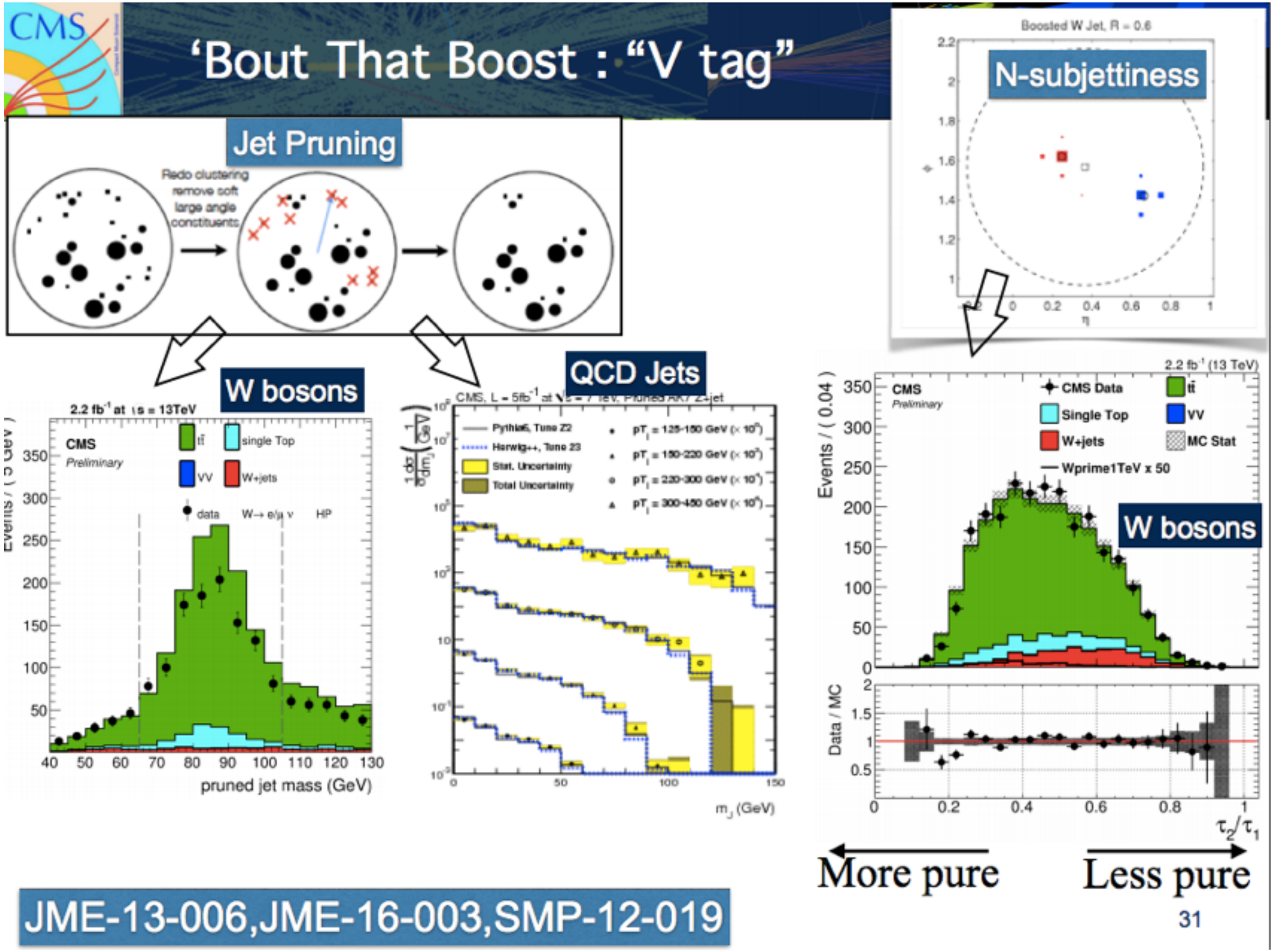


- **W/Z boson tagging:** ATL-PHYS-PUB-2015-033
  - m_J consistent with m_W/m_Z within ±15GeV
    - W and Z windows overlap
  - Sub-structure consistent with two-prong decay
    - Most popular variable: $D_2^{(\beta=1)}$ (arXiv: 1409.6298, 1507.03018)
    - Typical WP: ε=50%, QCD rejection factor ~50



- **Higgs boson (b-) tagging:** ATL-CONF-2016-039
  - Match to anti-k_t R=0.2, b-tagged track-jets

CMS Substructure



JME-13-006,JME-16-003,SMP-12-019