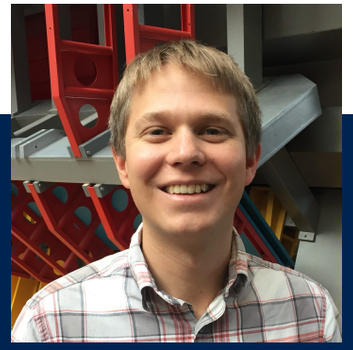
Searching for Dark Matter with the ATLAS Detector

On behalf of the ATLAS collaboration

Lake Louise Winter Institute

February 12, 2019

https://indico.cern.ch/e/760557/



Ben Carlson

University of Pittsburgh

ATLAS experiment

Outline

1. Introduction

- Simplified models of dark matter
- ATLAS detector

2. Search for the mediator

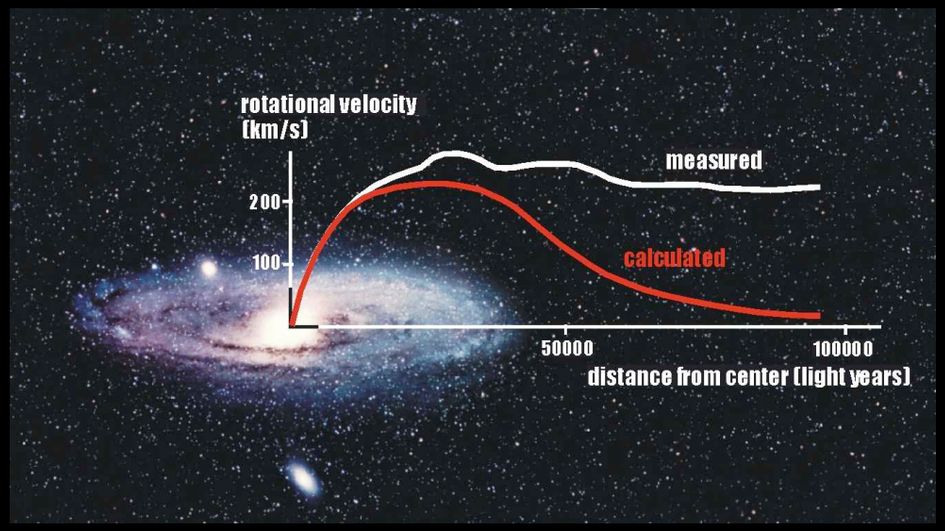
- Dijet resonance
- Boosted jet searches
- Summary plot

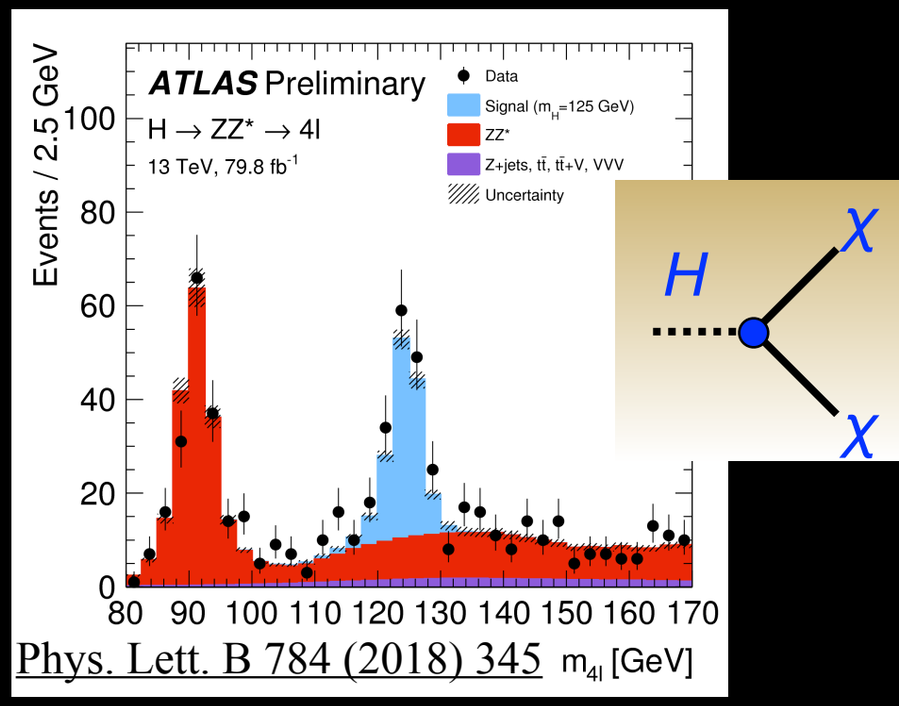
3. Search for recoiling DM

- Jet + MET
- Higgs decays to invisible

4. Implications

- Comparison to direct detection





Phys. Lett. B 784 (2018) 345

Finding dark matter

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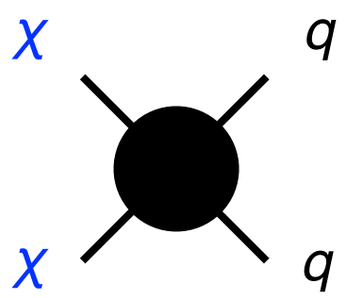
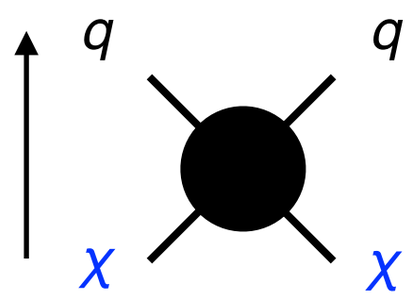
Annihilation



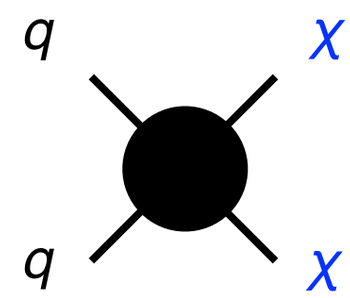
Indirect

Scattering

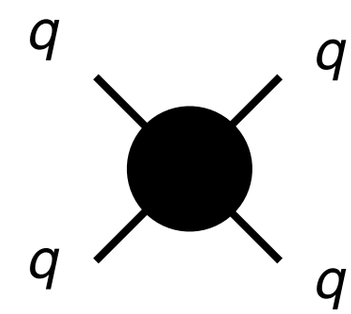


Direct

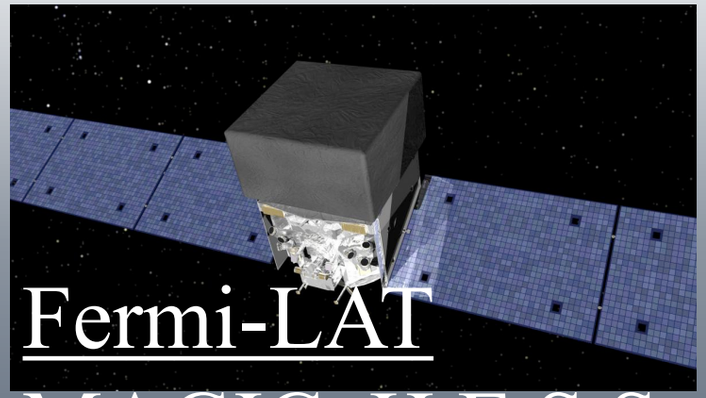
Production



Mediator



Collider



MAGIC, H.E.S.S., Planck…

LUX, Panda-X, Picasso…

Dark matter at colliders

1703.05703, 1810.09420
(DM working group)

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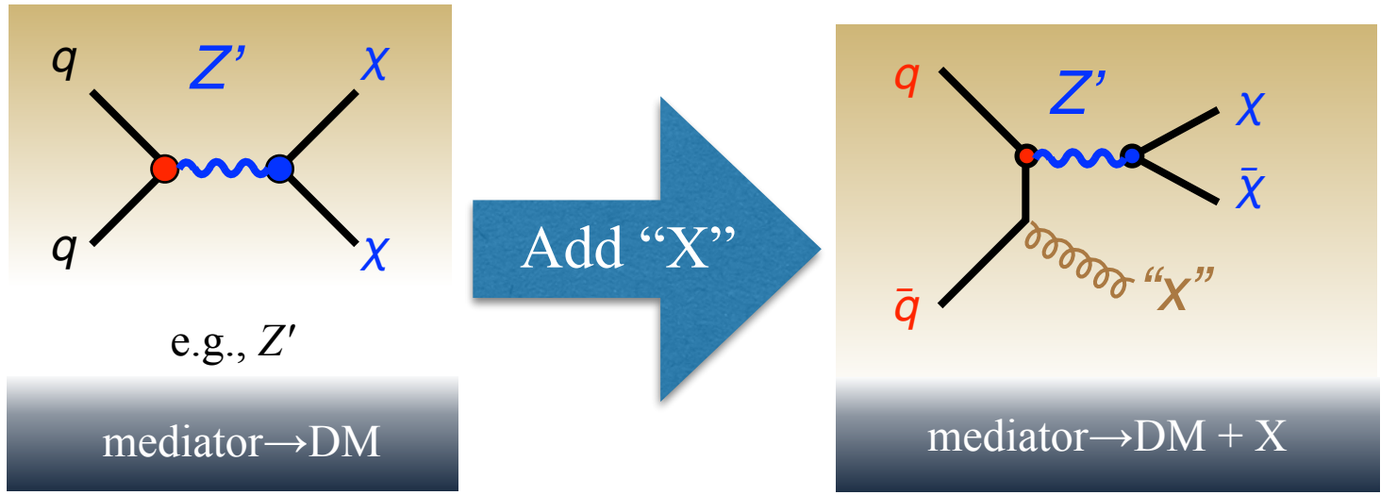
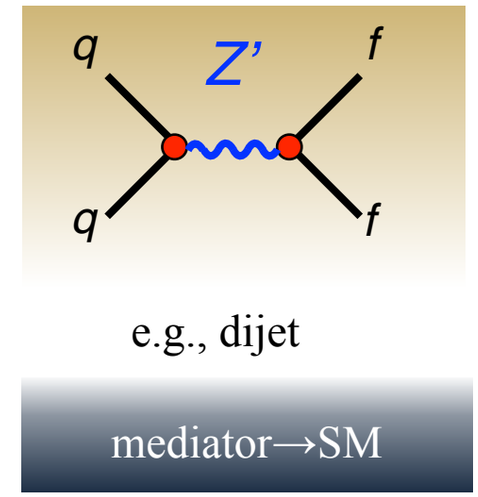


Look for stable dark matter candidate by requiring that the system recoil against a visible "x"

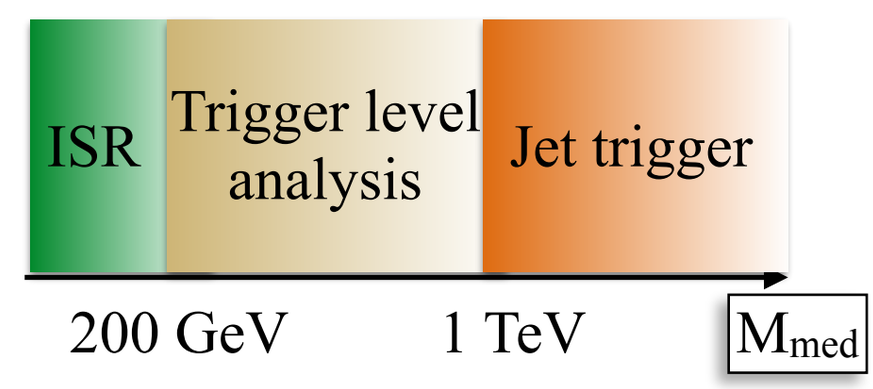
x	objects
Jet	$P_T \gtrsim 250$ GeV MET $\gtrsim 250$ GeV
Photon	$P_T \gtrsim 150$ GeV MET $\gtrsim 150$ GeV
Weak bosons (W/Z)	l^+l^-
	$q\bar{q}$
Higgs boson	$b\bar{b}$
	$\gamma\gamma$
Heavy flavors	$b, b\bar{b}$
	$t, t\bar{t}$

A wide range of models for different "x"



Direct mediator searches: **dijet** (dilepton) resonances

Trigger technique



ATLAS detector

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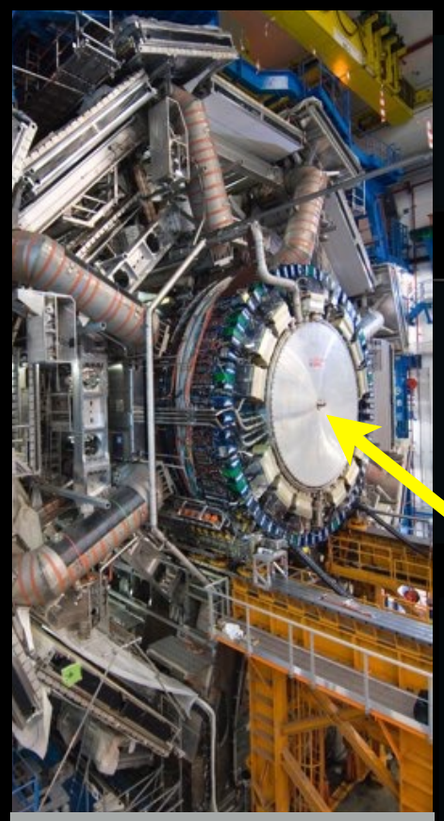
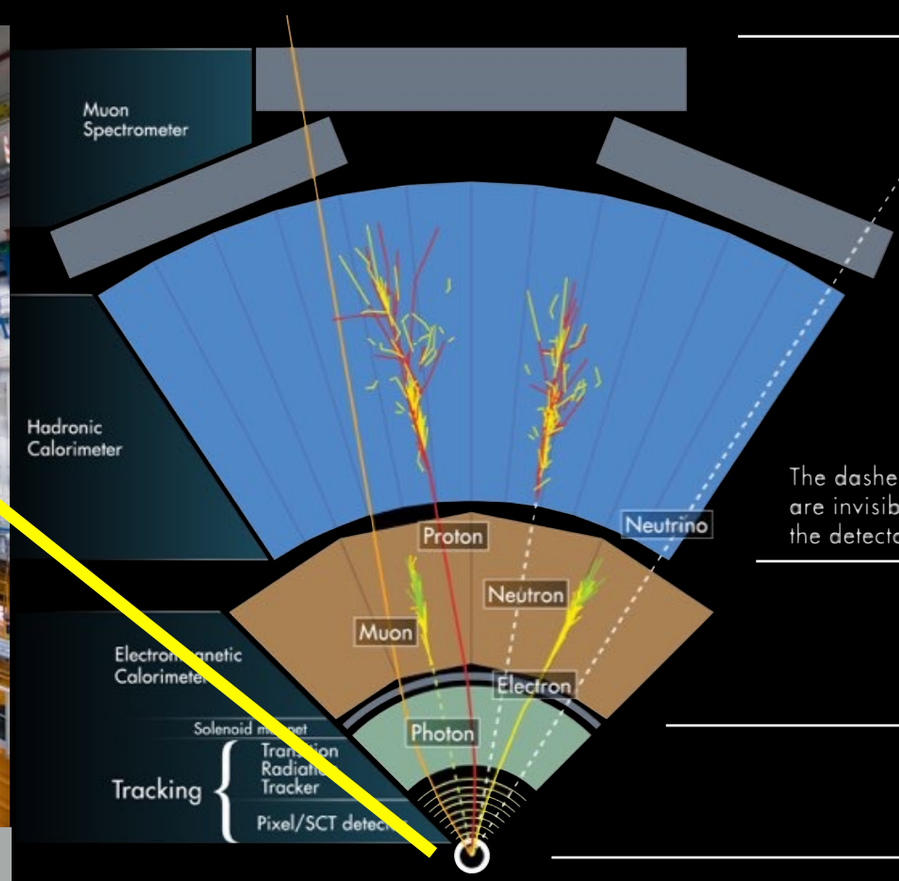
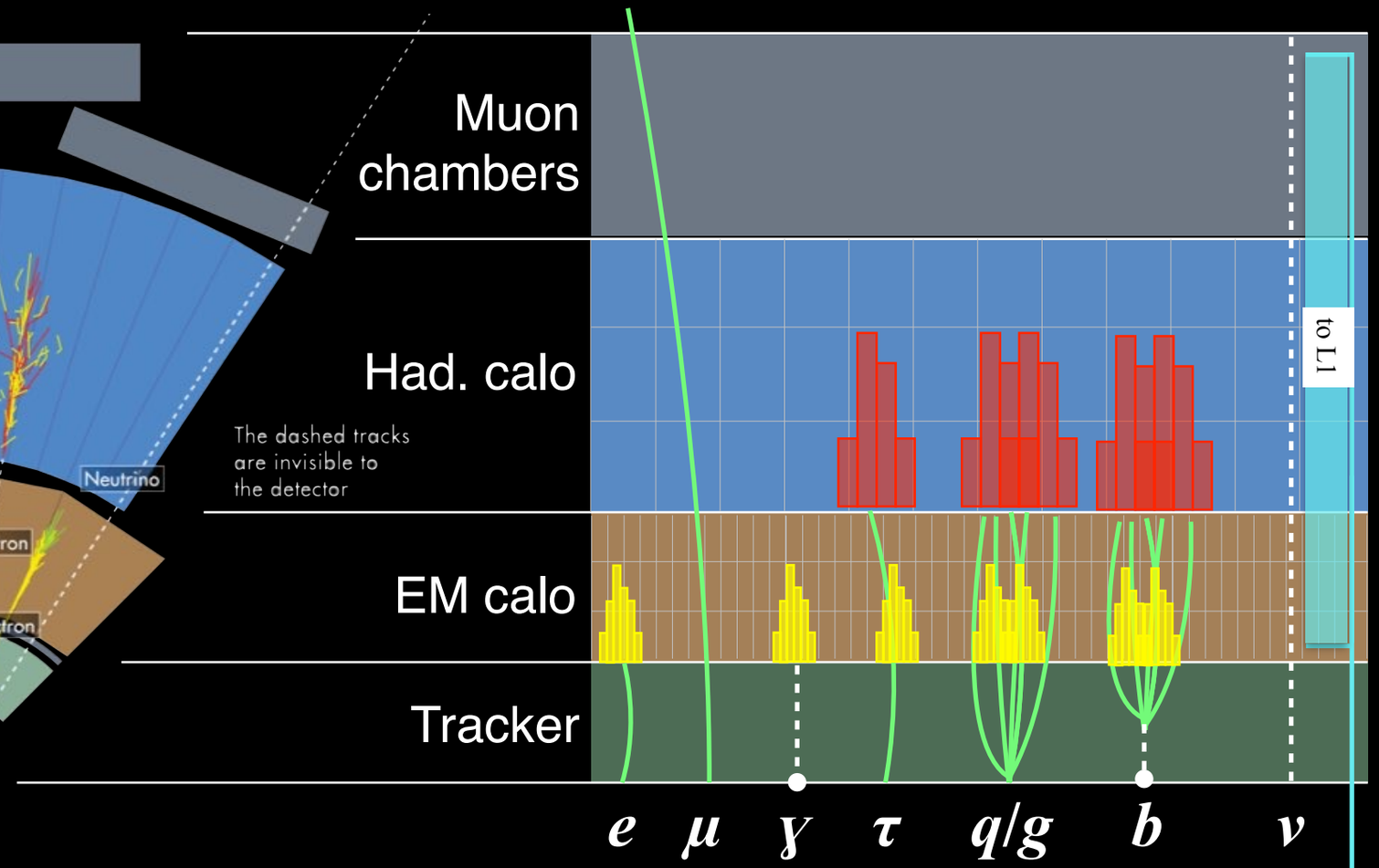


ATLAS



Beam Pipe



Hardware trigger (L1): select in 2.2 μs

40 MHz

coarse calorimeter and muon to L1

100 kHz

full calorimeter and muon data to HLT

Software trigger (HLT) select in ~0.1 s

~1 kHz

Save to permanent storage

Search for dijet resonances

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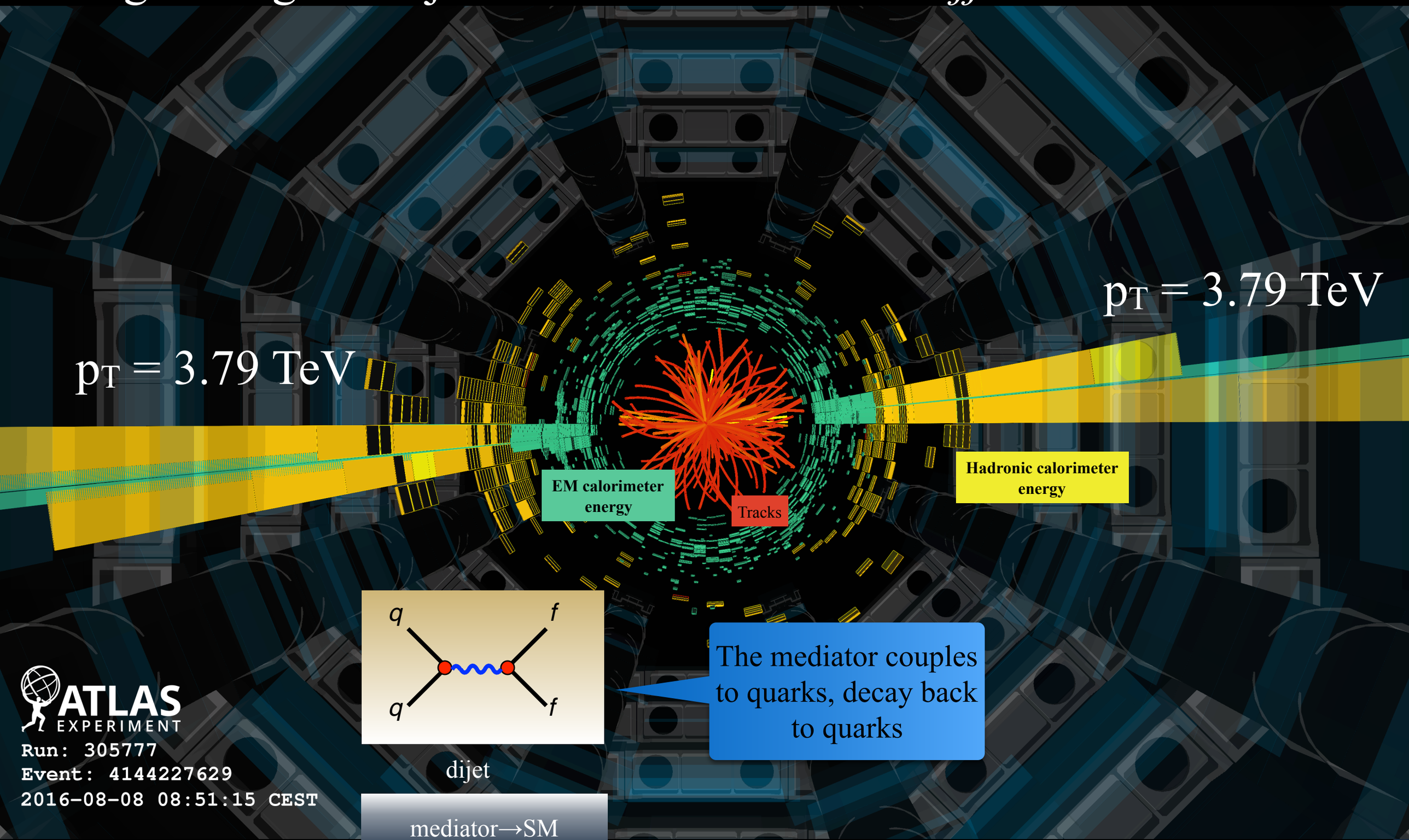
Among the highest dijet mass event recorded: *mjj = 8.12 TeV*



Phys. Rev. D 96, 052004

Search for dijets

Phys. Rev. D 96, 052004
Phys. Rev. Lett. 121 (2018) 081801

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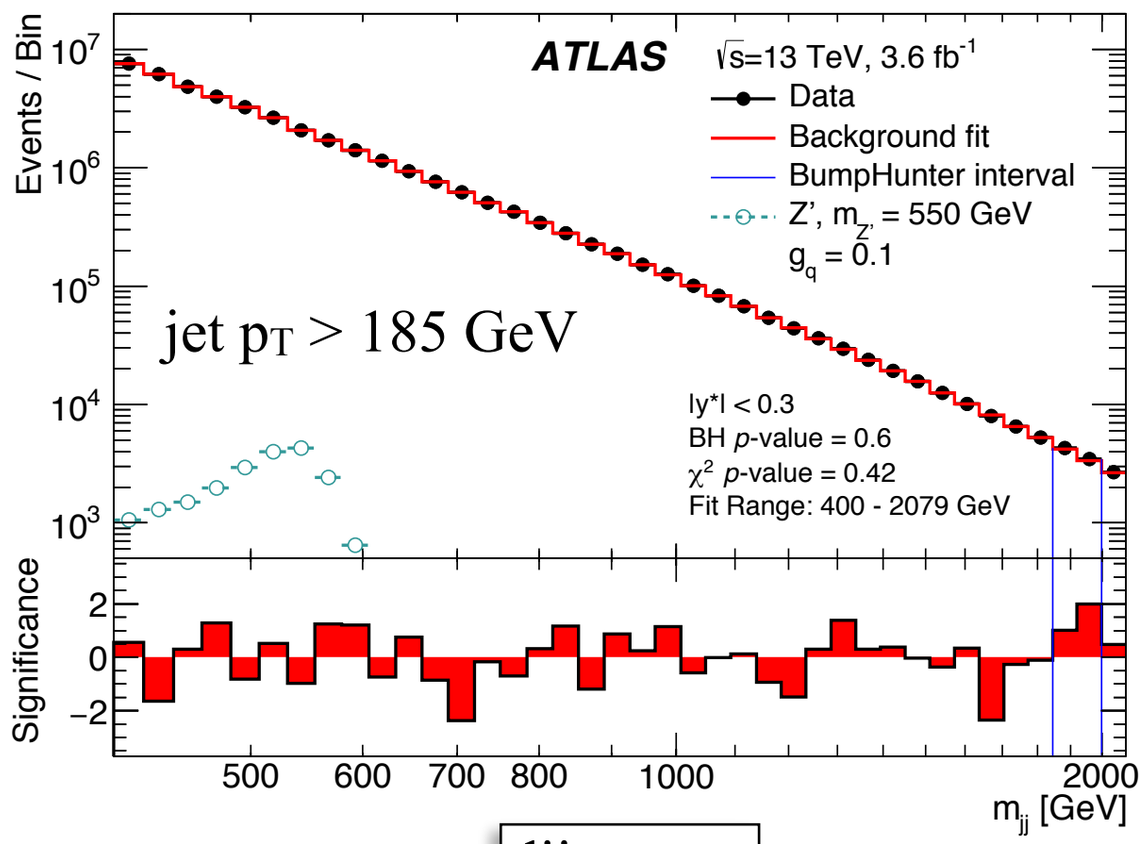
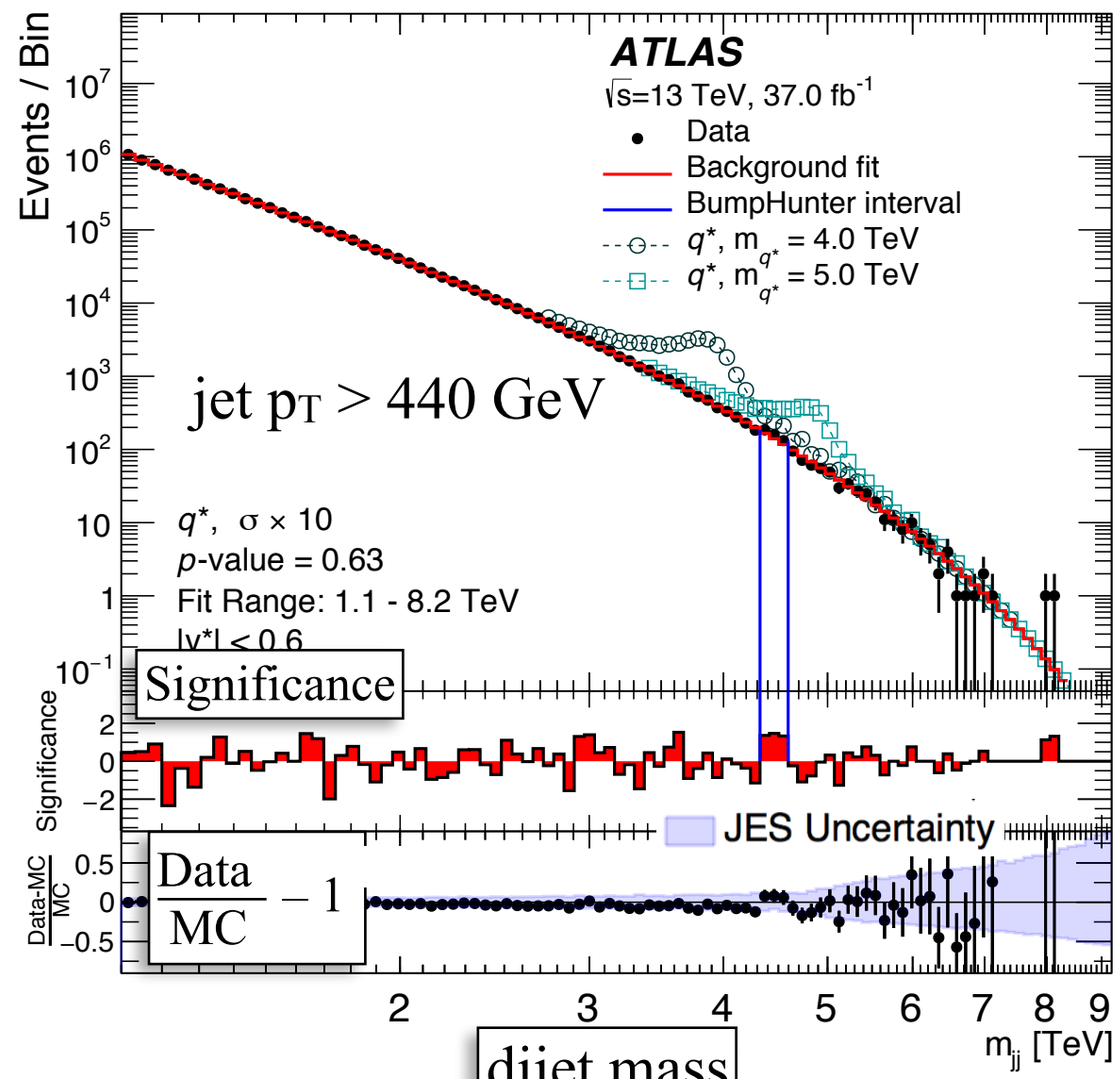
Large signal on a large background; signature is a ‘bump’

Trigger level analysis: save jets from HLT
“No” bandwidth limit → lower mass reach

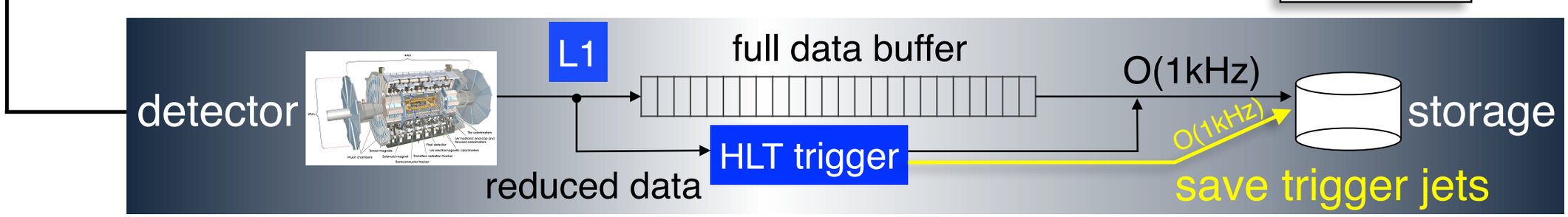


dijet mass

Offline analysis on triggered events:
Full offline event → best jet resolution



dijet mass



Initial state radiation

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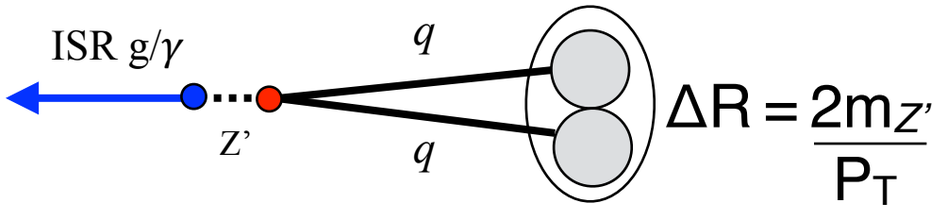
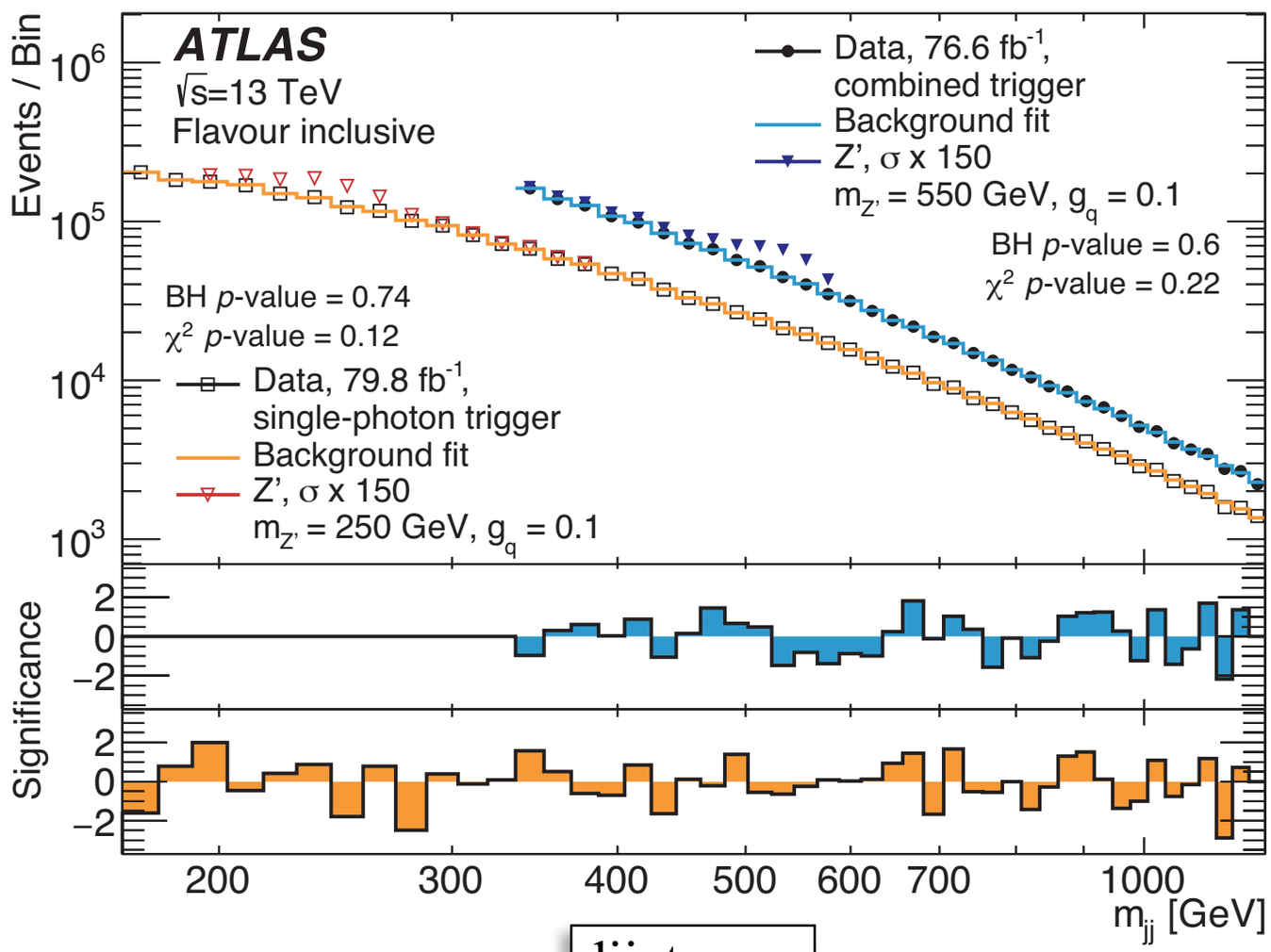


Trigger using an ISR photon

- $p_T > 140$ GeV
- $p_T > 85$ GeV, 2 x jet $p_T > 50$ GeV

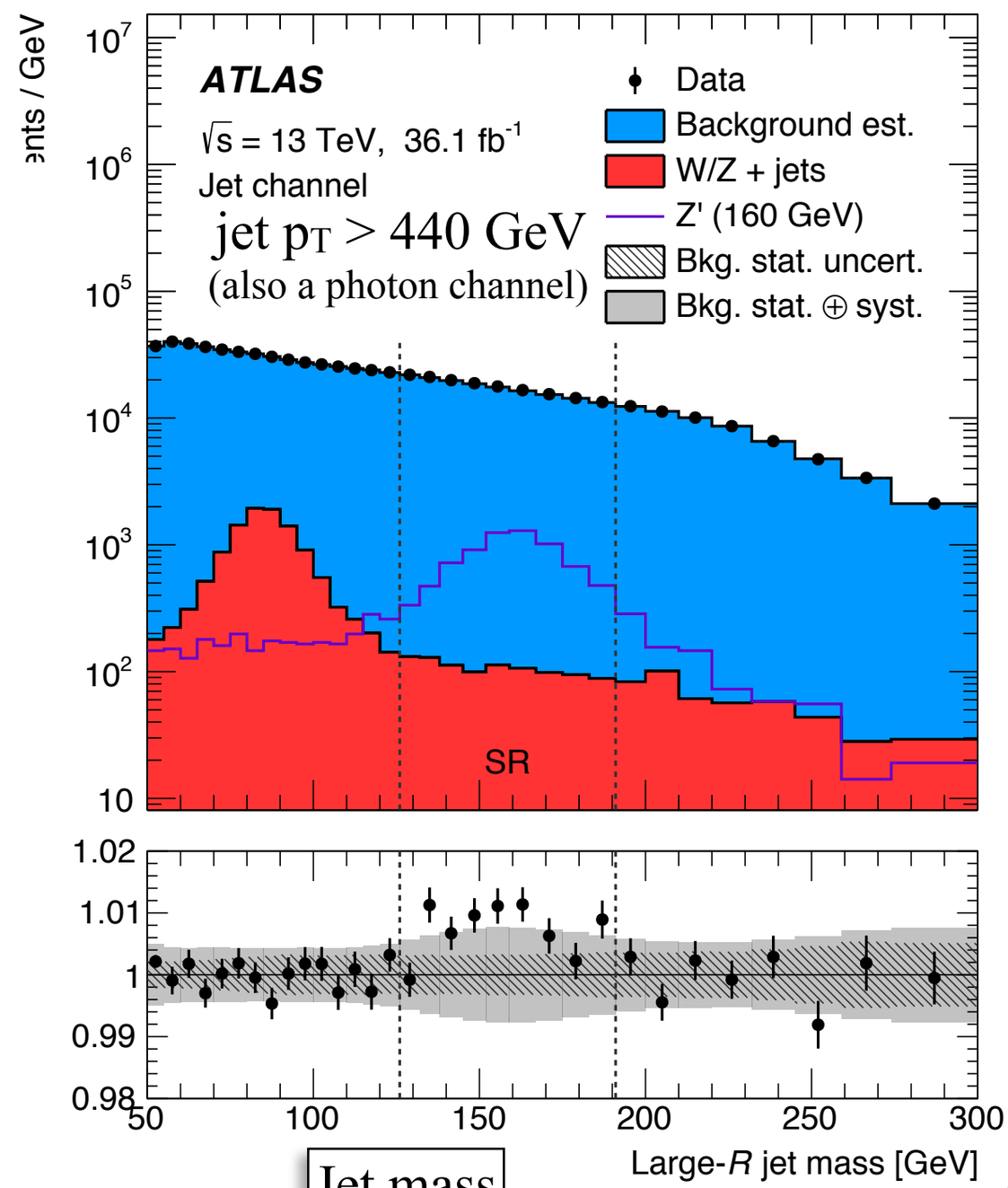


dijet mass

(compute mass from two jets)

Boost the system, sub-structure techniques:

- τ_{21} to reduce QCD
- decorrelated tagger for estimating QCD



Jet mass

Additional channels

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
ATLAS-CONF-2018-051

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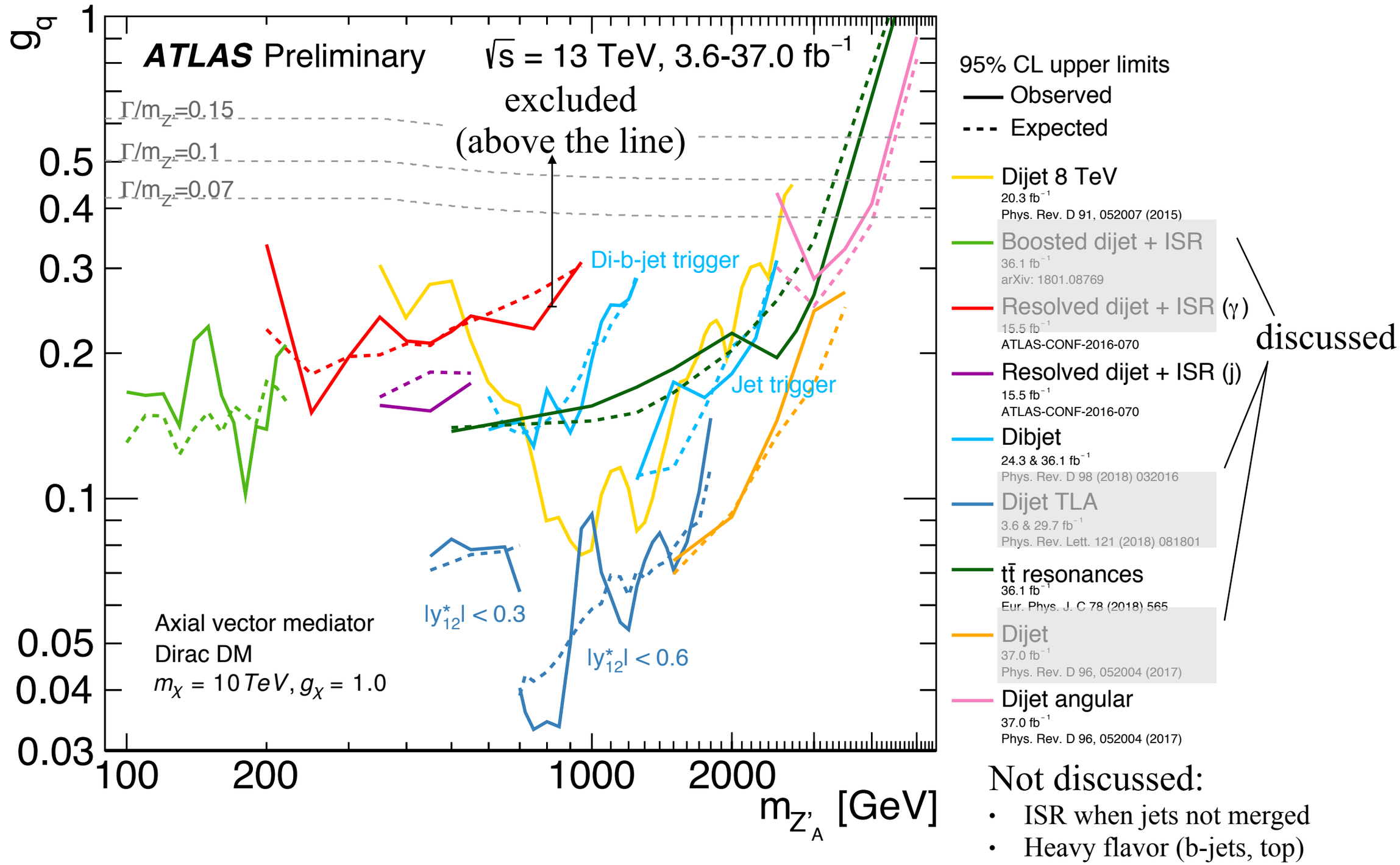

Not discussed:

- ISR when jets not merged
- Heavy flavor (b-jets, top)

Sensitivity to couplings as small as 0.05

M_{med}: 100 GeV - 3.5TeV

Missing transverse momentum

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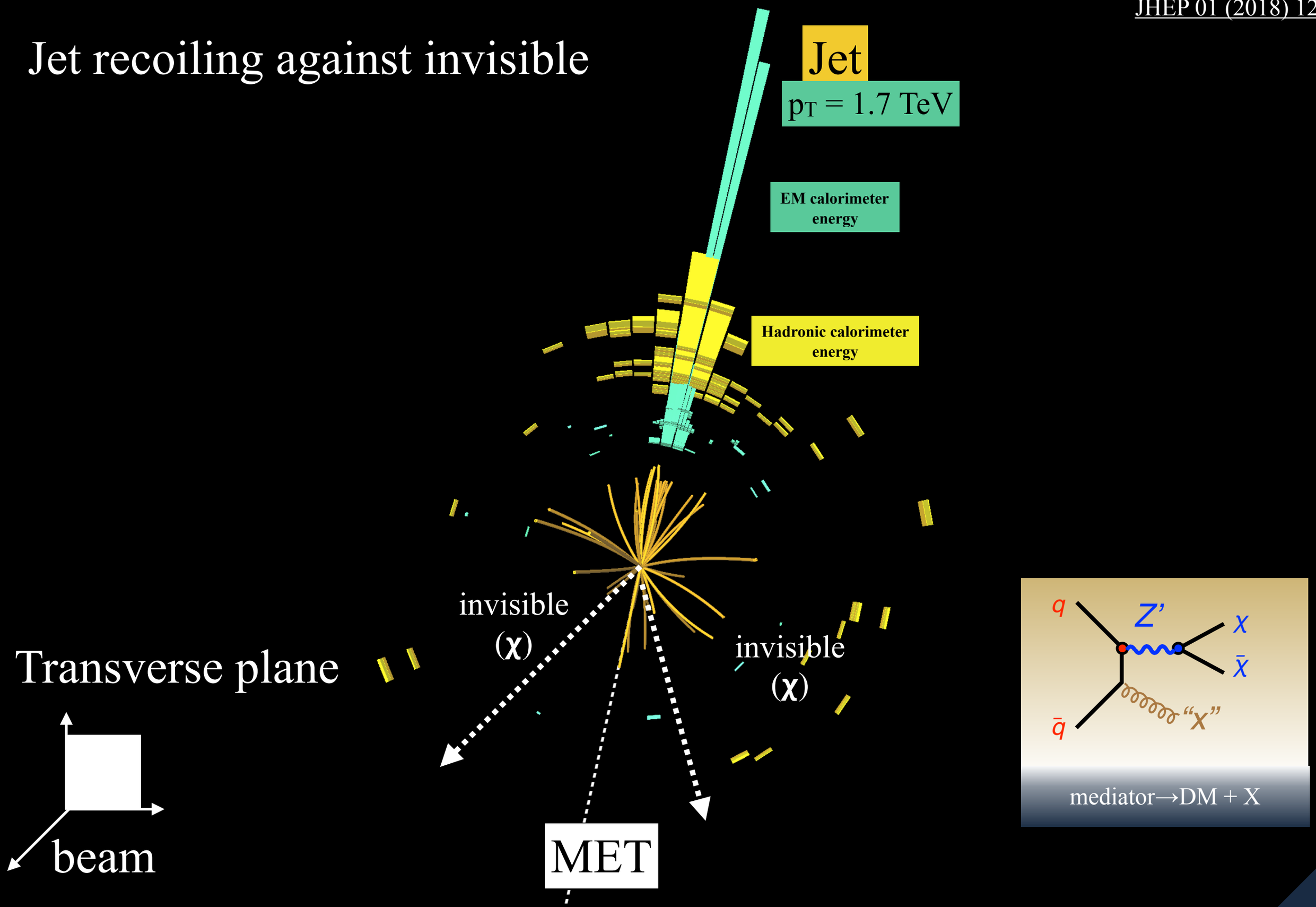
JHEP 01 (2018) 126

Jet recoiling against invisible



Single ISR jet + MET

JHEP 01 (2018) 126

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MET > 250 GeV

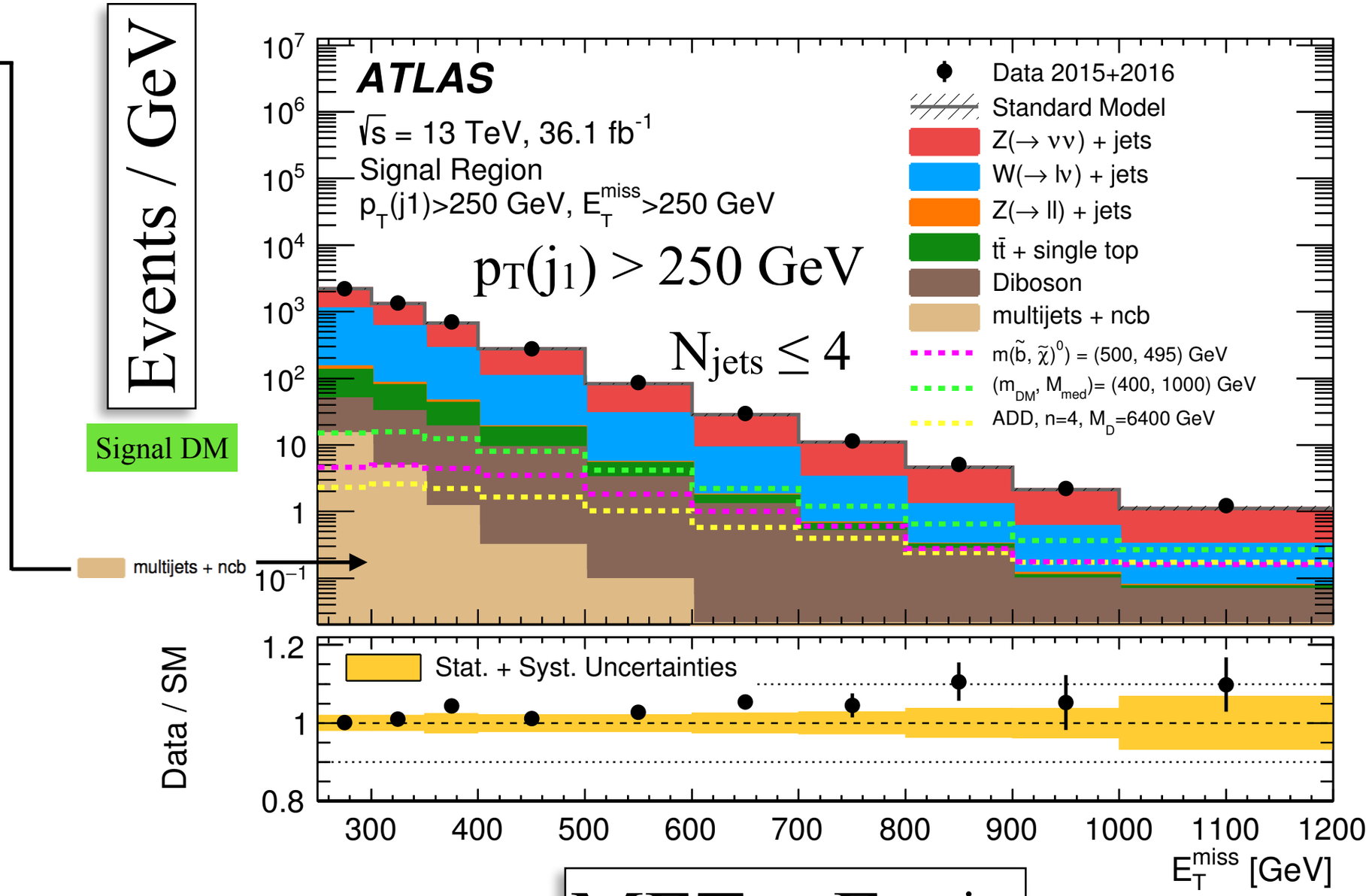
- Easy to trigger
- Kills **QCD**
- *$\Delta\phi(j,MET) > 0.4$*

Lepton veto kills

- Top (mostly)
- $W \rightarrow \ell\nu$

Blue background:

ℓ is not reconstructed



$$\text{MET} = E_T^{miss}$$

Dominant backgrounds: $W \rightarrow \ell\nu$ (lost lepton) and $Z \rightarrow \nu\nu$

Dijet vs. MET +X

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
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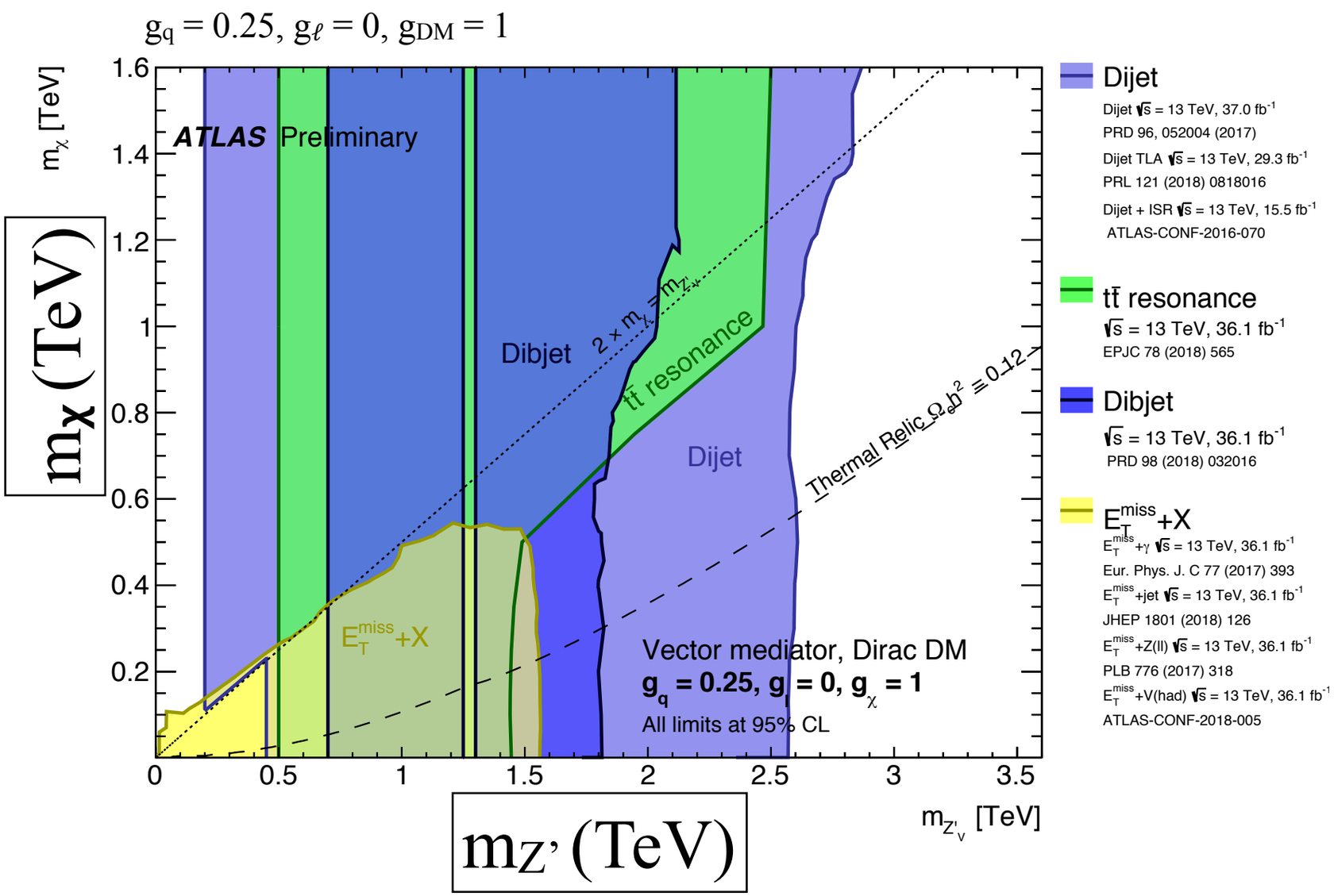
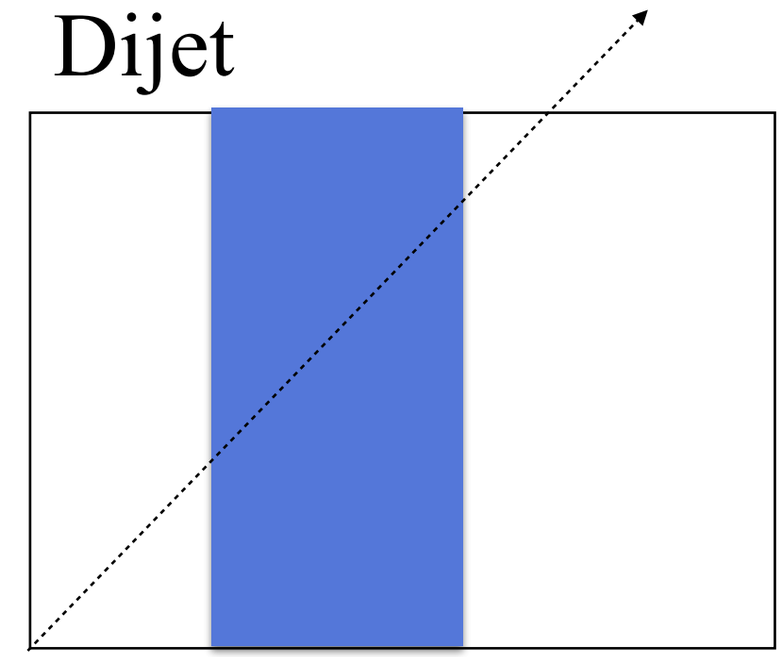
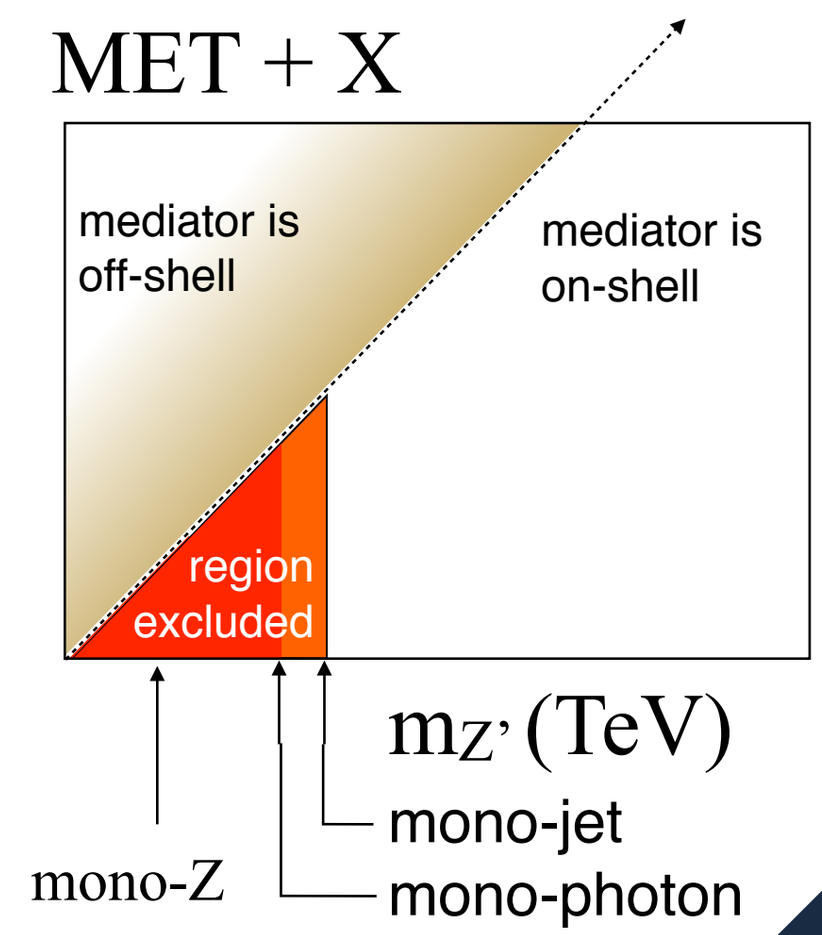
Vertical band: search for the mediator directly
Triangular region: MET + X searches



Dijet



MET + X



Assuming no coupling to leptons. If $g_\ell > 0$, **dilepton** searches are sensitive (backup)

Higgs is the mediator

EXOT-2016-37
(Submitted to PLB)

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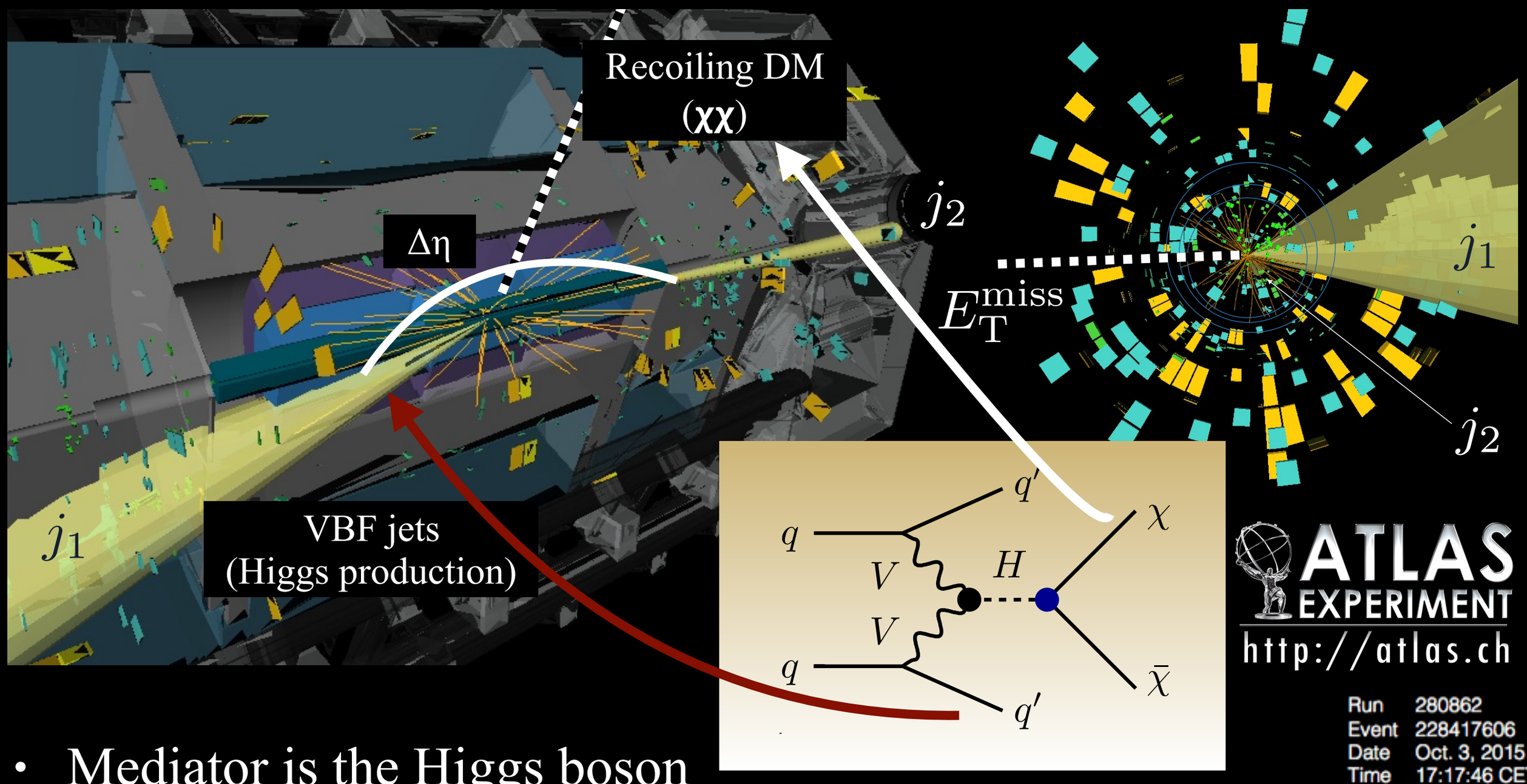
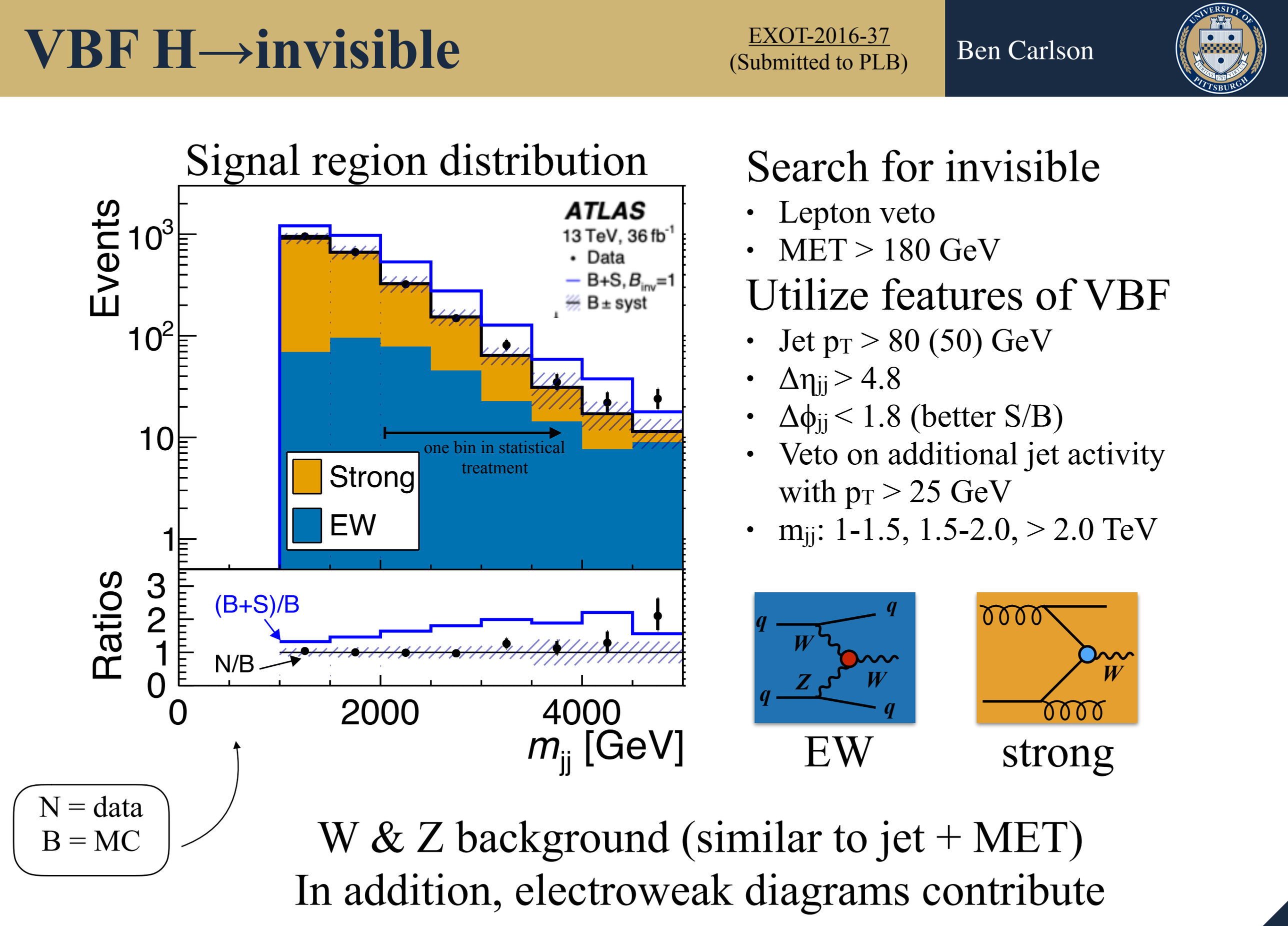


- Mediator is the Higgs boson
- Signature: Vector boson fusion, large MET
- Trigger: MET

VBF H→invisible

EXOT-2016-37
(Submitted to PLB)

Ben Carlson



Summary H→invisible

ATLAS-CONF-2018-054
ATLAS-CONF-2018-031

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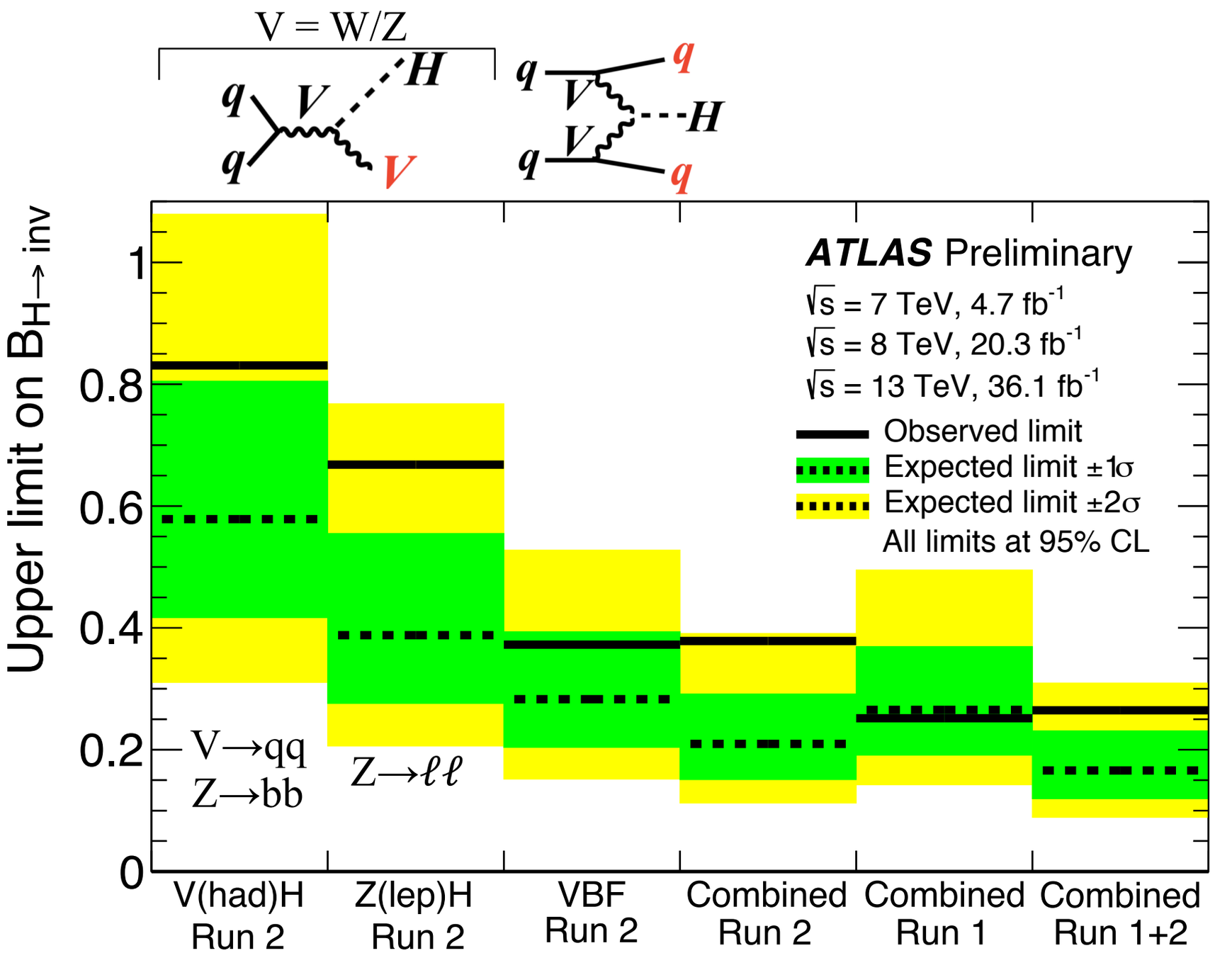
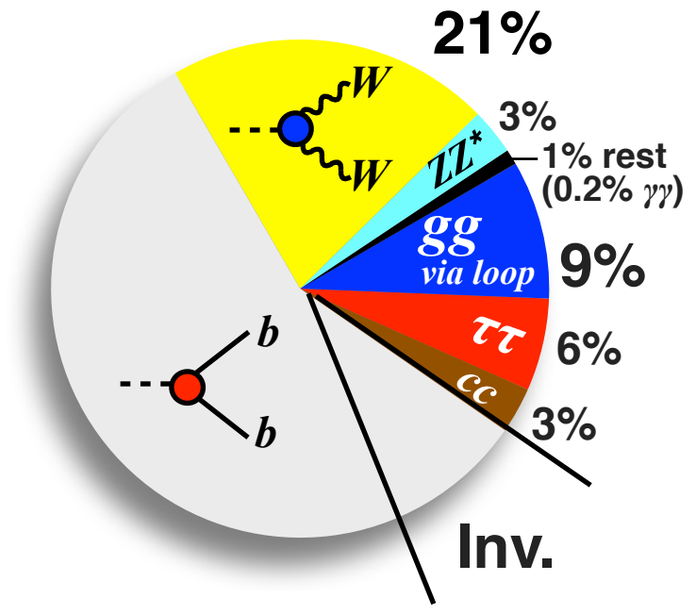


Exp: 28% Obs: 37%

Exp: 21% Obs: 38%

Exp: 17% Obs: 26%

Standard Model decay fractions



SM shrink within meas. uncertainty, add invisible

26%

Fit to visible Measurements

Uncertainties correlated when possible; between Run 1 and 2 generally not correlated

Direct detection comparison

EXOT-2016-37
(Submitted to PLB)

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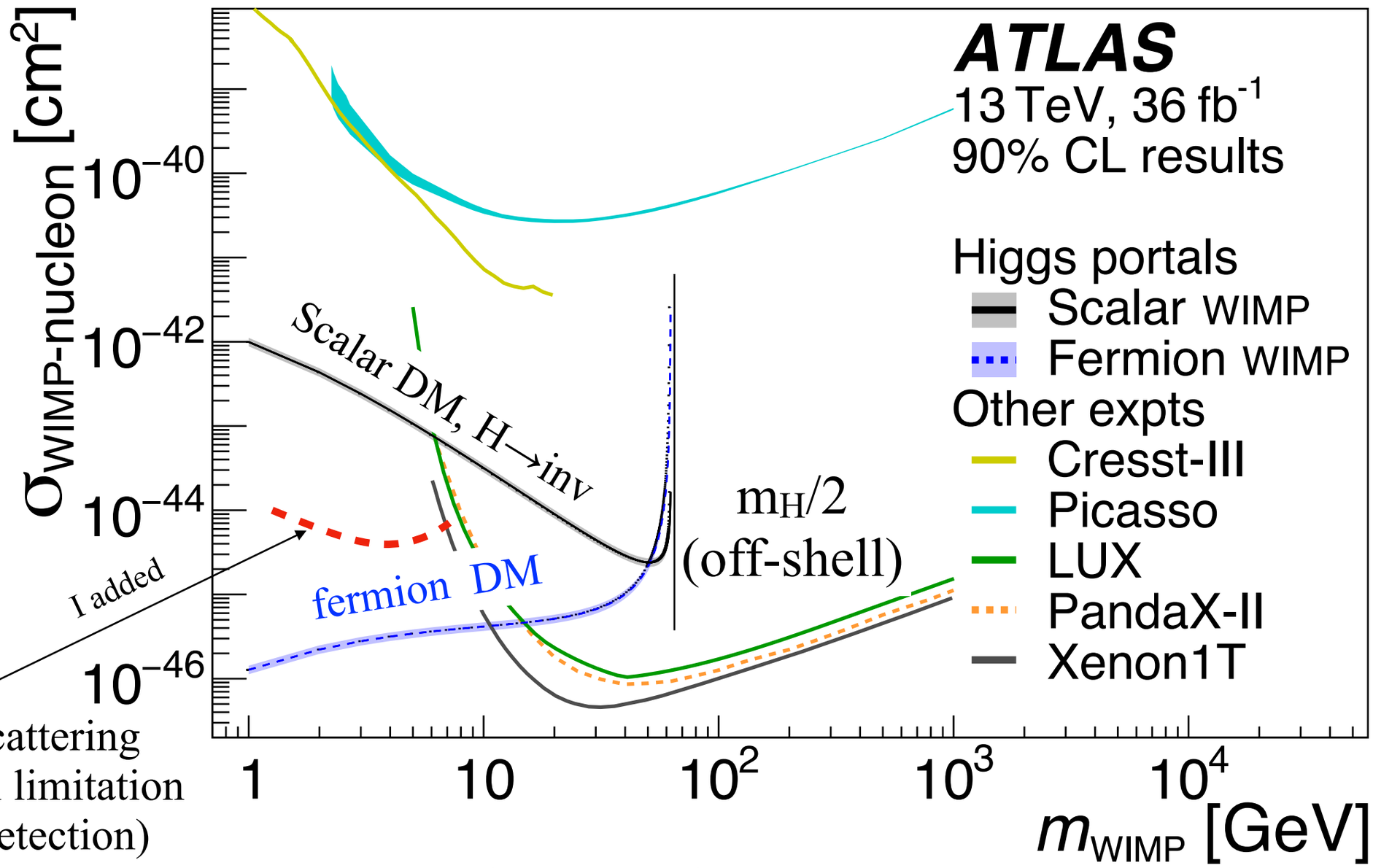
Comparing limits from H→inv to direct detection

- Assumes: Higgs is the only mediator; one species of dark matter



neutrino scattering (fundamental limitation for direct detection)

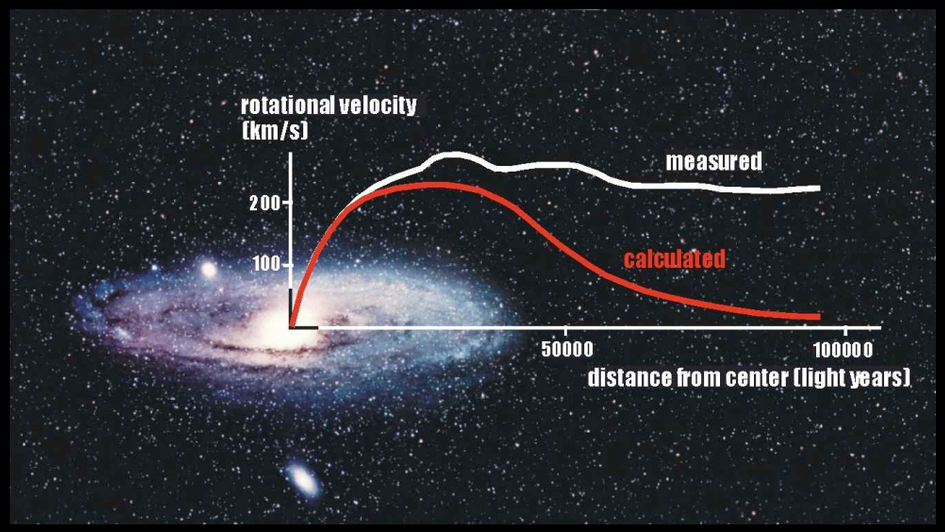
Prog. Part. Nucl. Phys. 85 (2015) 1

Similar comparisons for Z' mediator model

Conclusions

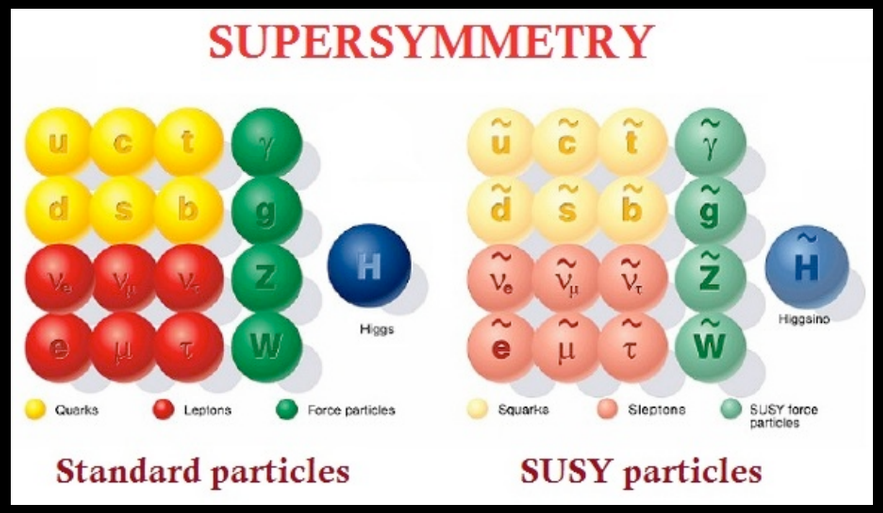
1. Discussed

- Searches for the mediator (dijets)
- Jet + MET
- Higgs decays to invisible (VBF)
- Comparison to direct detection



2. What's next

- More data to analyze!
- Many results shown use 1/4 recorded data
- Further improvements: reduce uncertainties, new triggers (VBF)
- ATLAS upgrade preparing for Run 3



Not discussed: supersymmetry; can also provide a DM candidate. Rich set of experimental signatures and searches

Backup

ATLAS data

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

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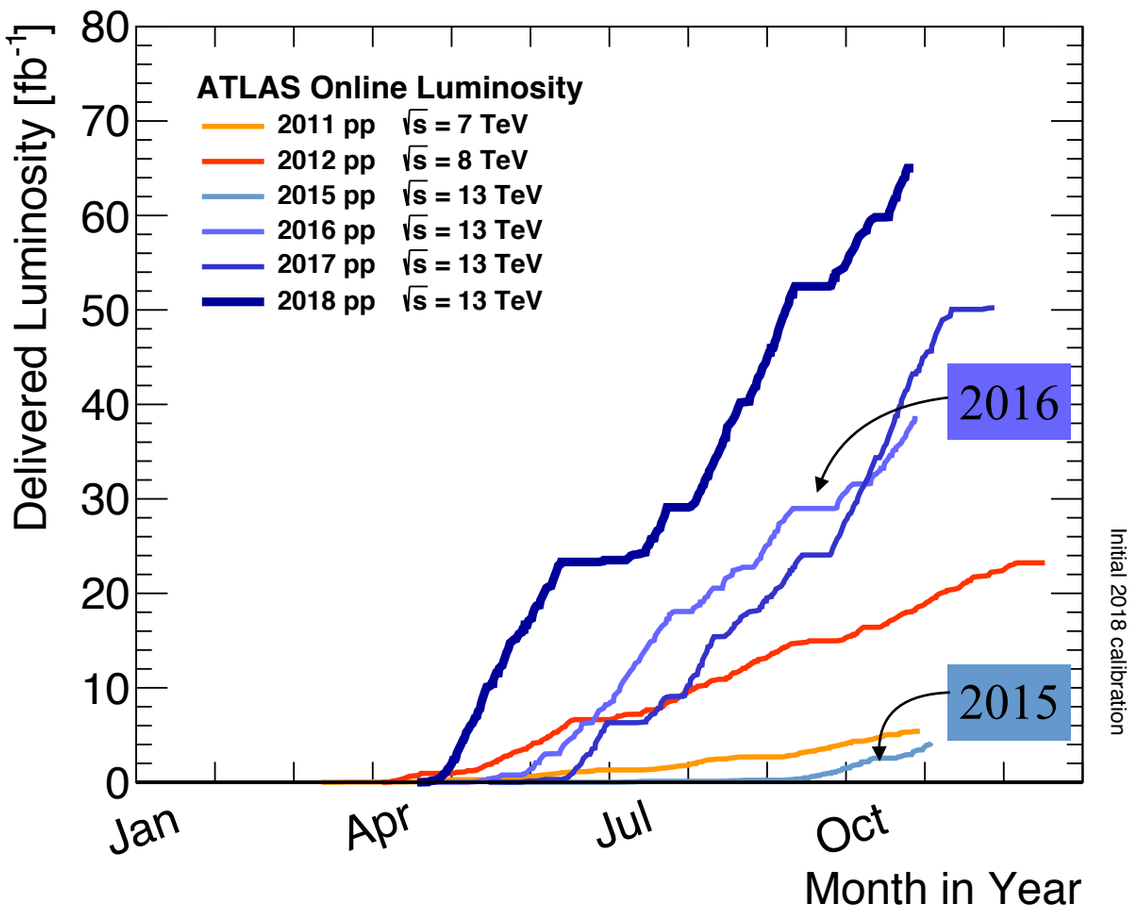
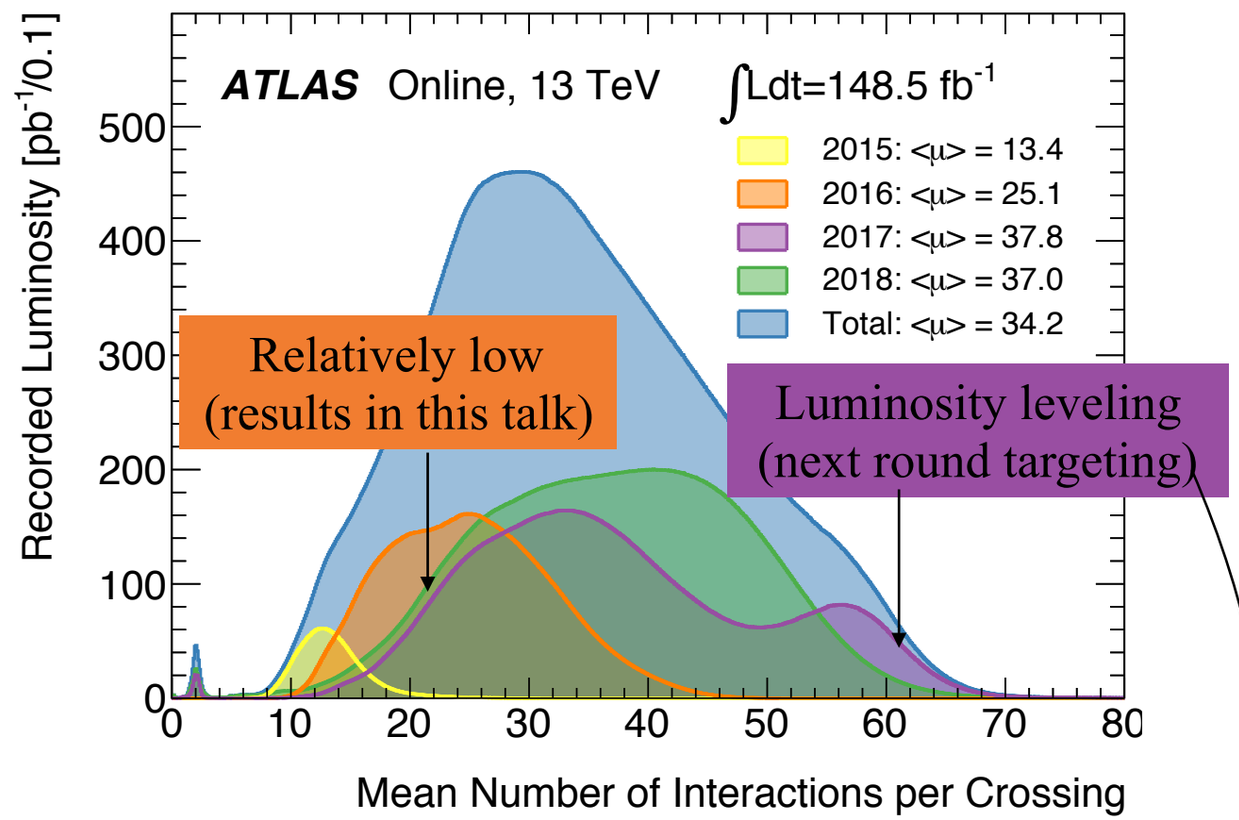
The slope dramatically increased over the seven years plotted

At the cost of increasing pileup

multiple interactions per bunch crossing





This talk is only about 2015 + 2016 data, L = 36.1 fb^{-1}

In total, recorded a total integrated luminosity of **149fb^{-1}**

come back to a few specific challenges related to pileup at the end of the talk

Higgs measurements

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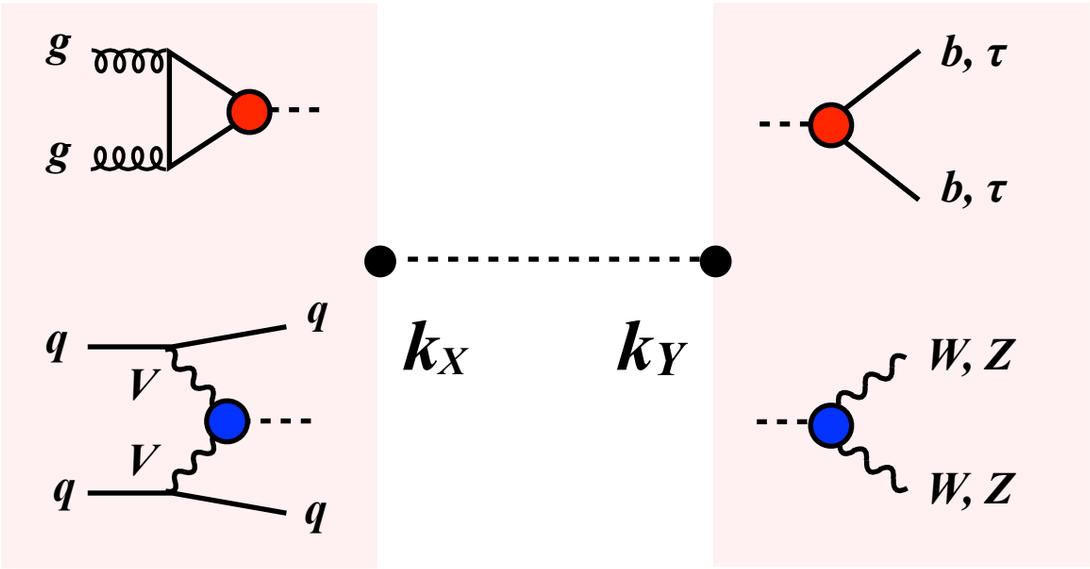


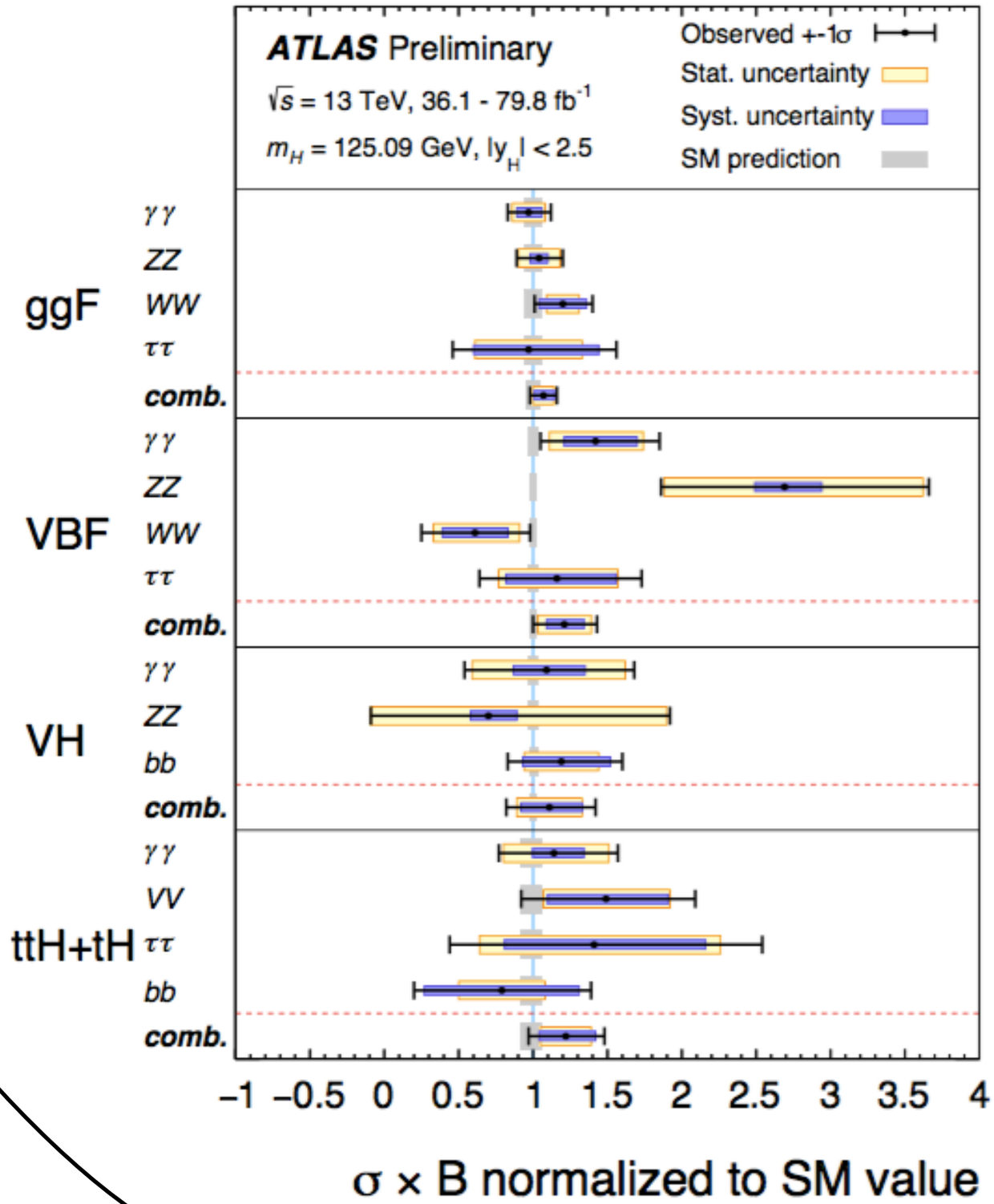
Production X Decay Y

Simultaneous fit of production and decay modes

$$\mu = \frac{N_{\text{observed signal}}}{N_{\text{expected signal}}}$$

Global signal strength

$$\mu = 1.13^{+0.09}_{-0.08}$$



Constraints on undetected

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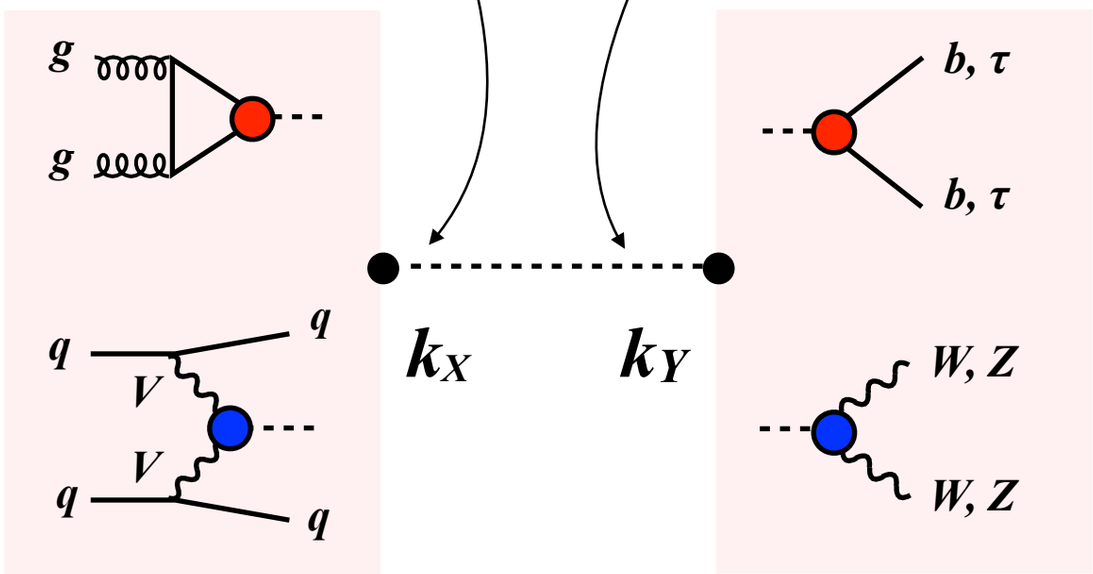
Fix production

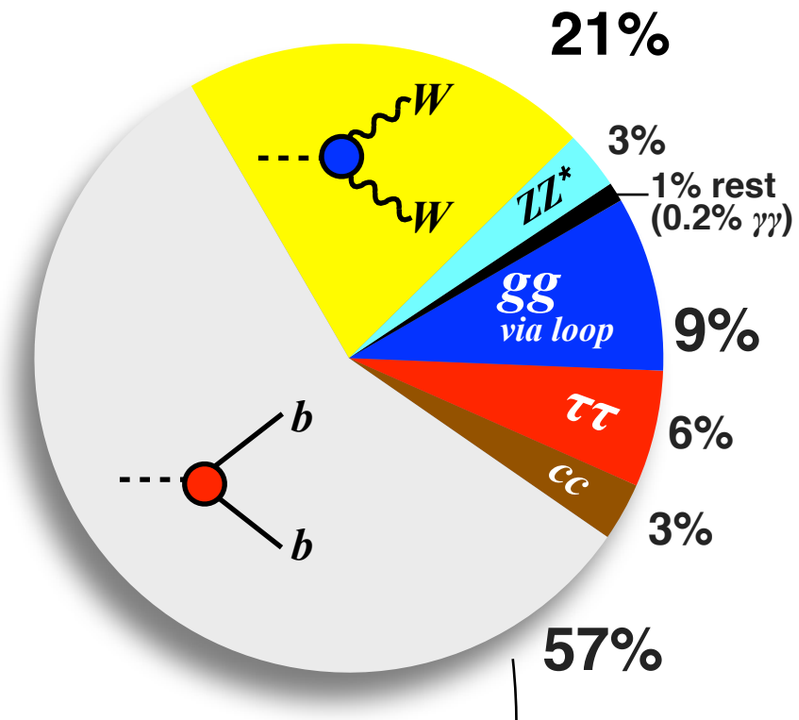
Float decays



Production X

Decay Y

SM Higgs branching fractions



Simultaneous fit of SM couplings undetected

$$k^2_b \cdot BR_{bb} + k^2_{WW} \cdot BR_{WW} + \ldots BR_{undetected}$$

Input: Standard Model BR

Fit: k and upper limit on $BR_{undetected}$

Assuming: $k_V < 1$ (k_W, k_Z)

Constraints on undetected

ATLAS-CONF-2018-031

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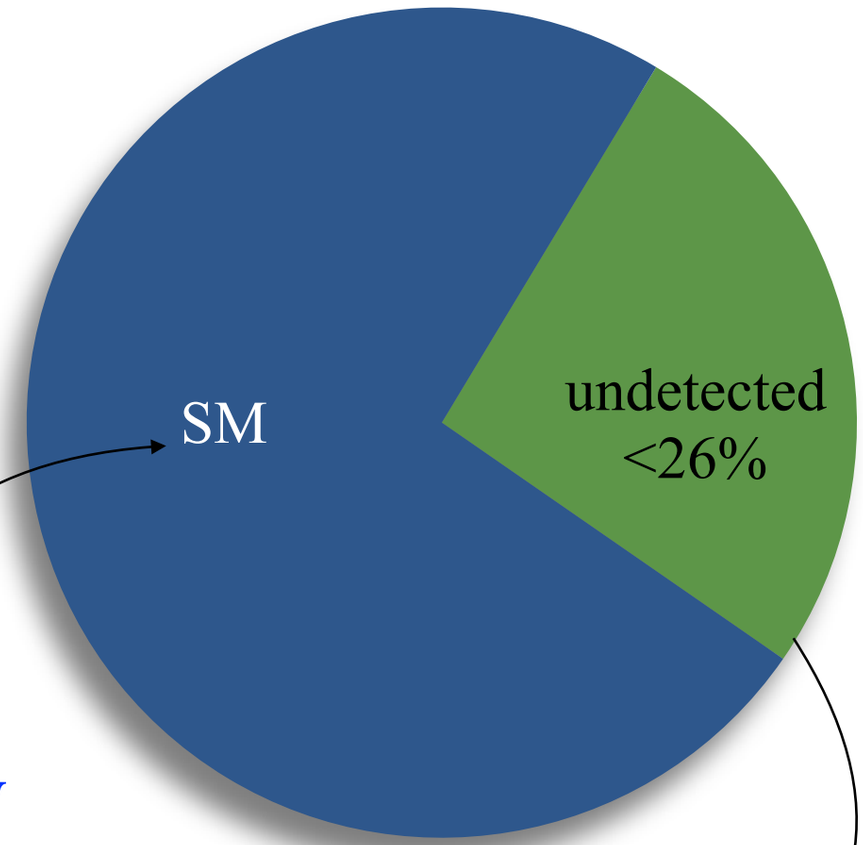
Higgs measurements:
Br(undetected) < 26%

Hypothetical branching fraction scenario allowed by Higgs measurements



Allows for BSM including

1. Invisible
2. Not covered by Higgs measurements (4b)
3. Deviations in SM Higgs searches not yet sensitive (cc)

BR to SM processes may decrease

Allowing for more…

Undetected decays

Features of VBF

ATLAS: JHEP 01 (2016) 172

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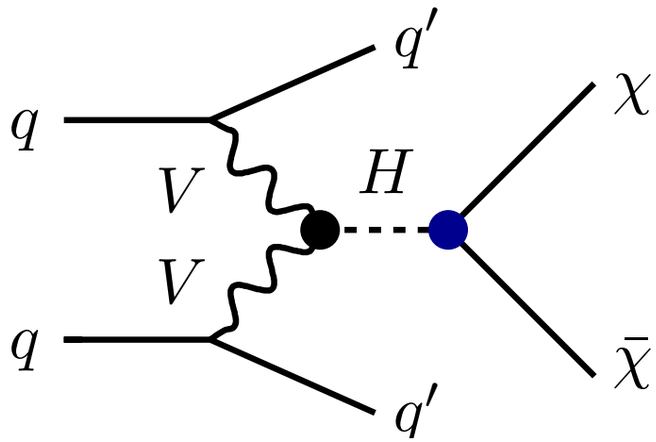
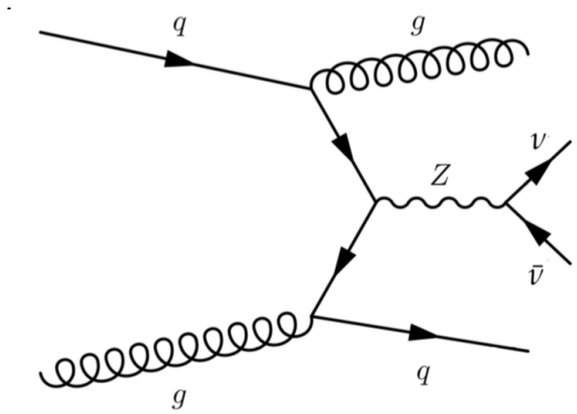
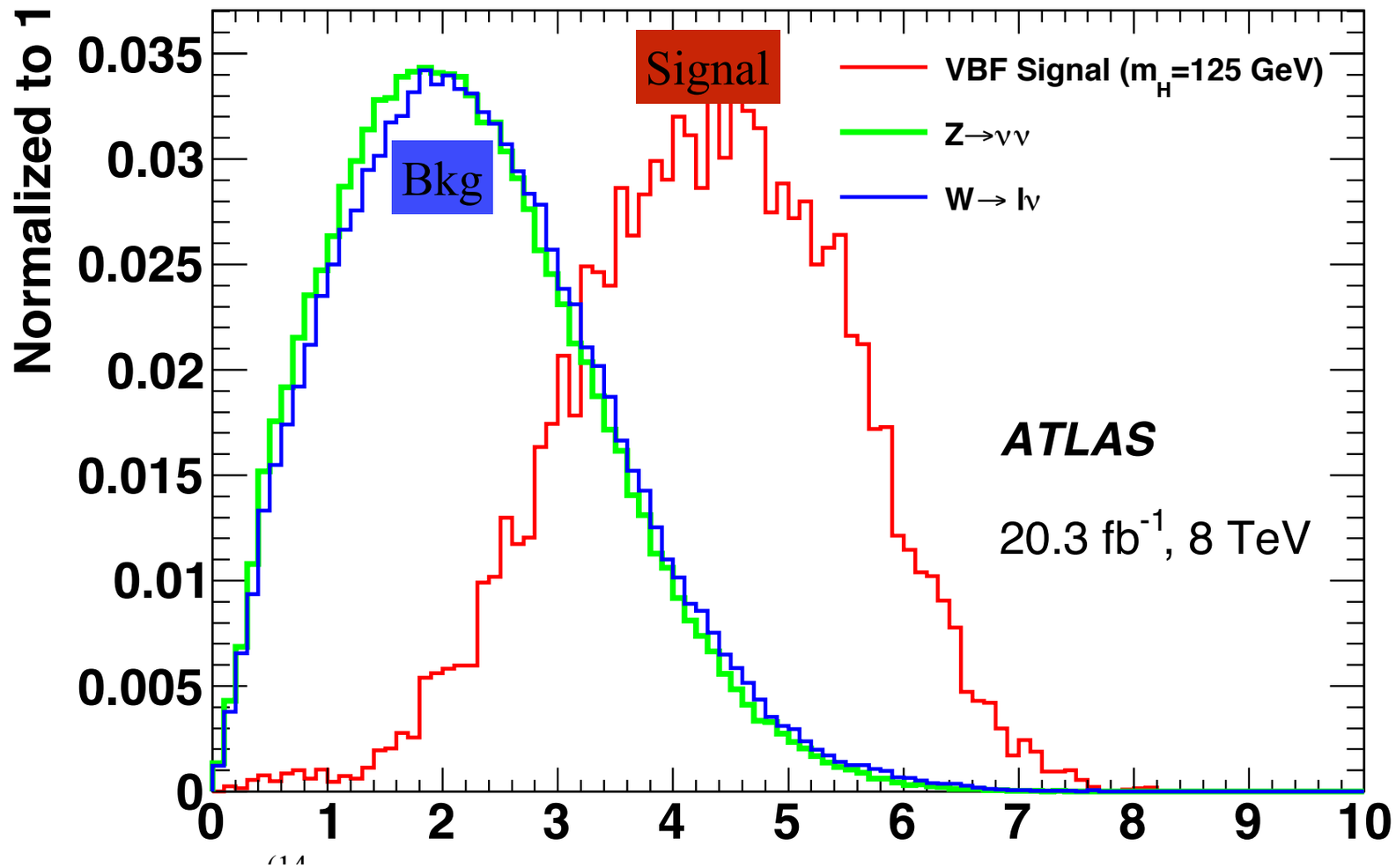
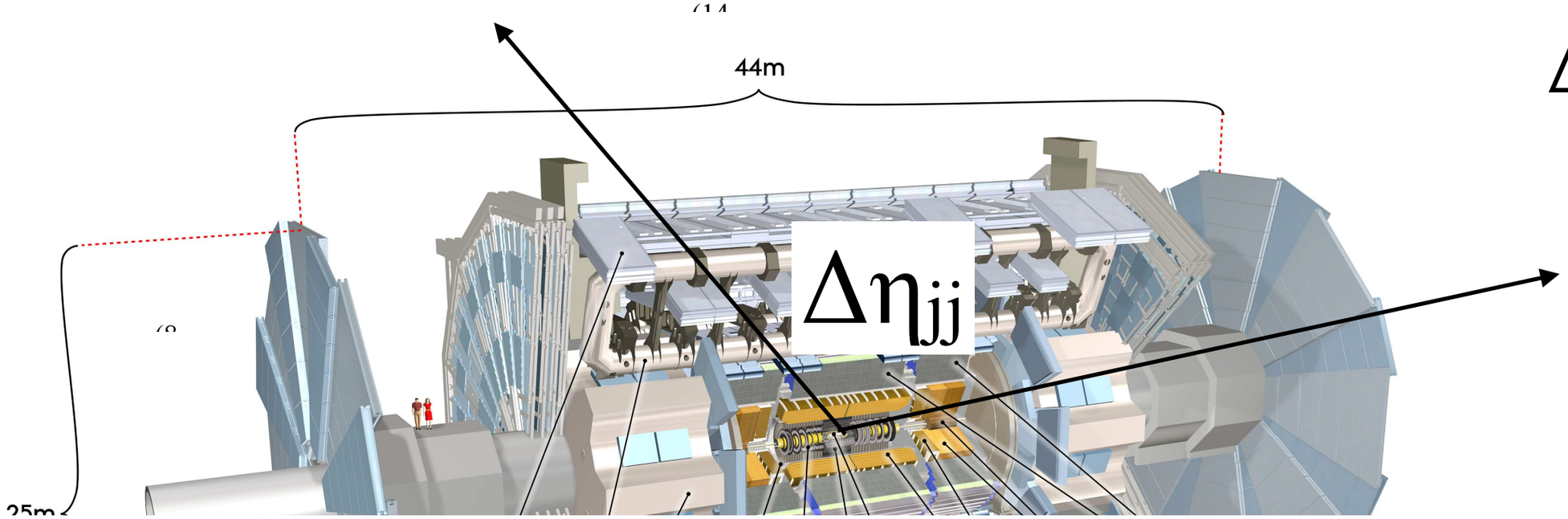




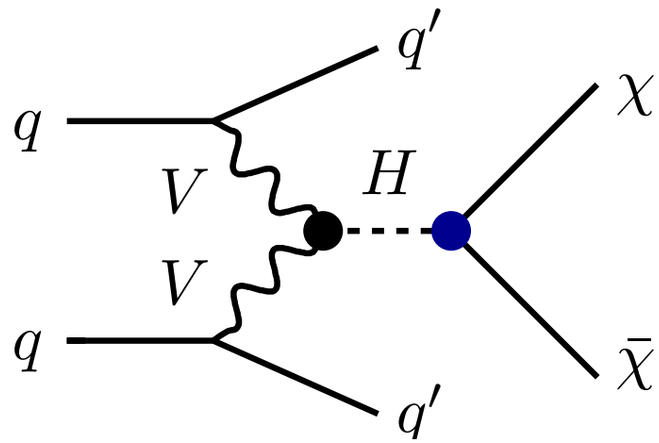


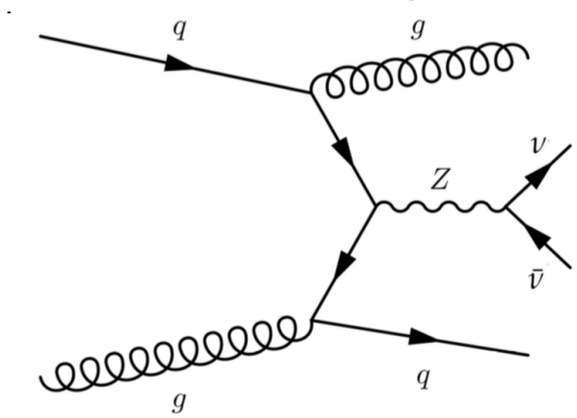


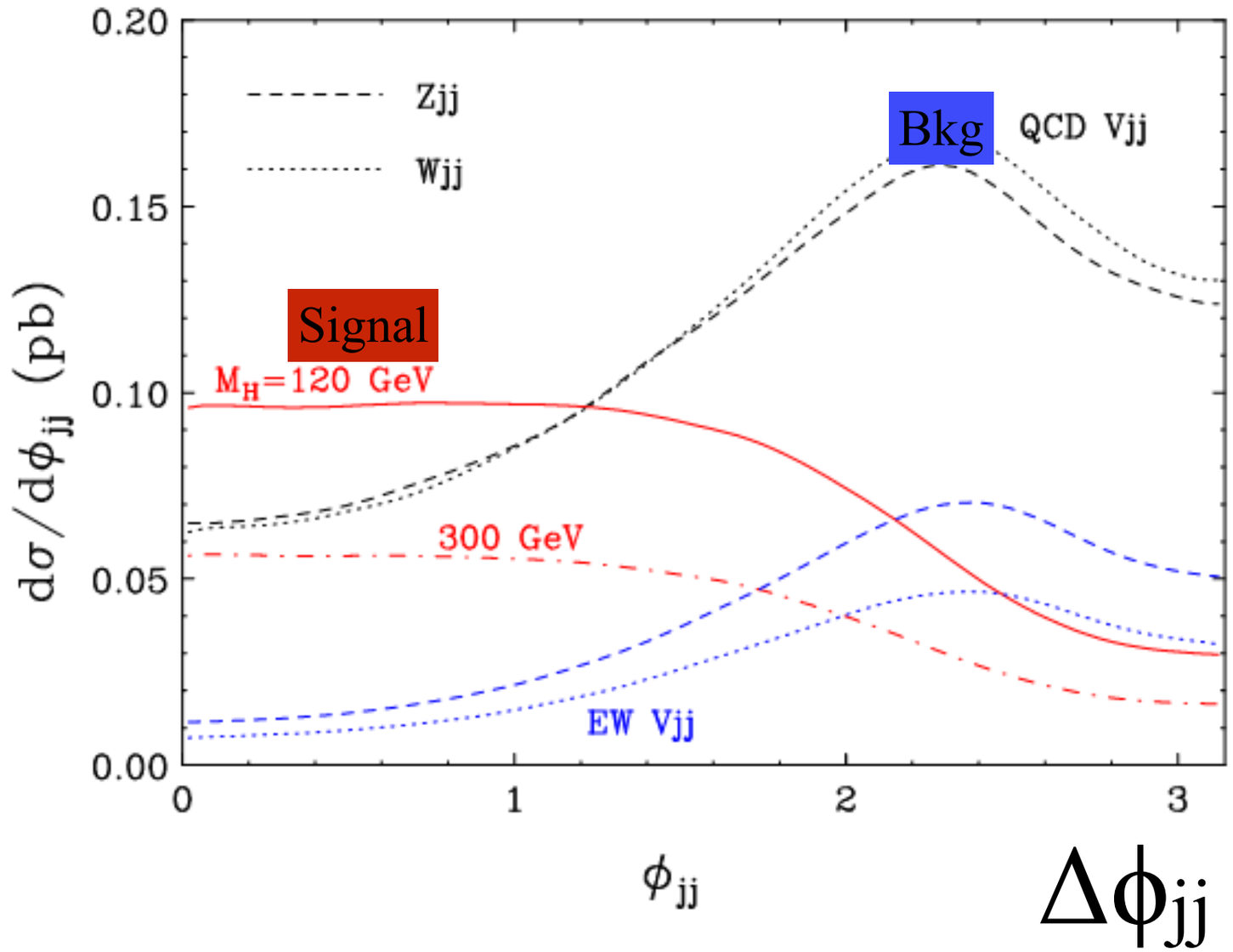
Features of VBF

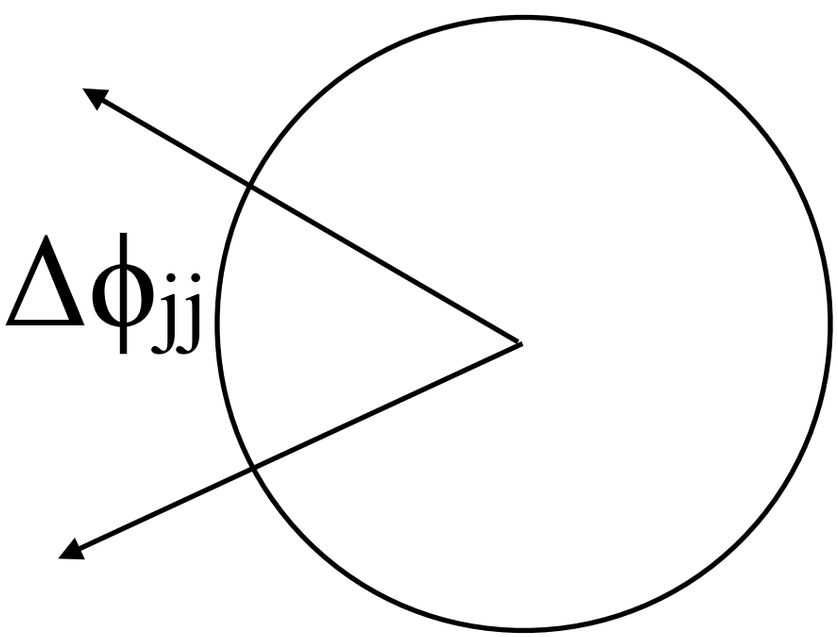
Zeppenfeld, Rainwater, PRD 60 (1999) 113004

Ben Carlson









Transverse plane

Signal — Jets recoil against Higgs (small Δφ)

Bkg — Jets back to back (φ)

QCD background

ATLAS: 1809.06682
(Submitted to PLB)

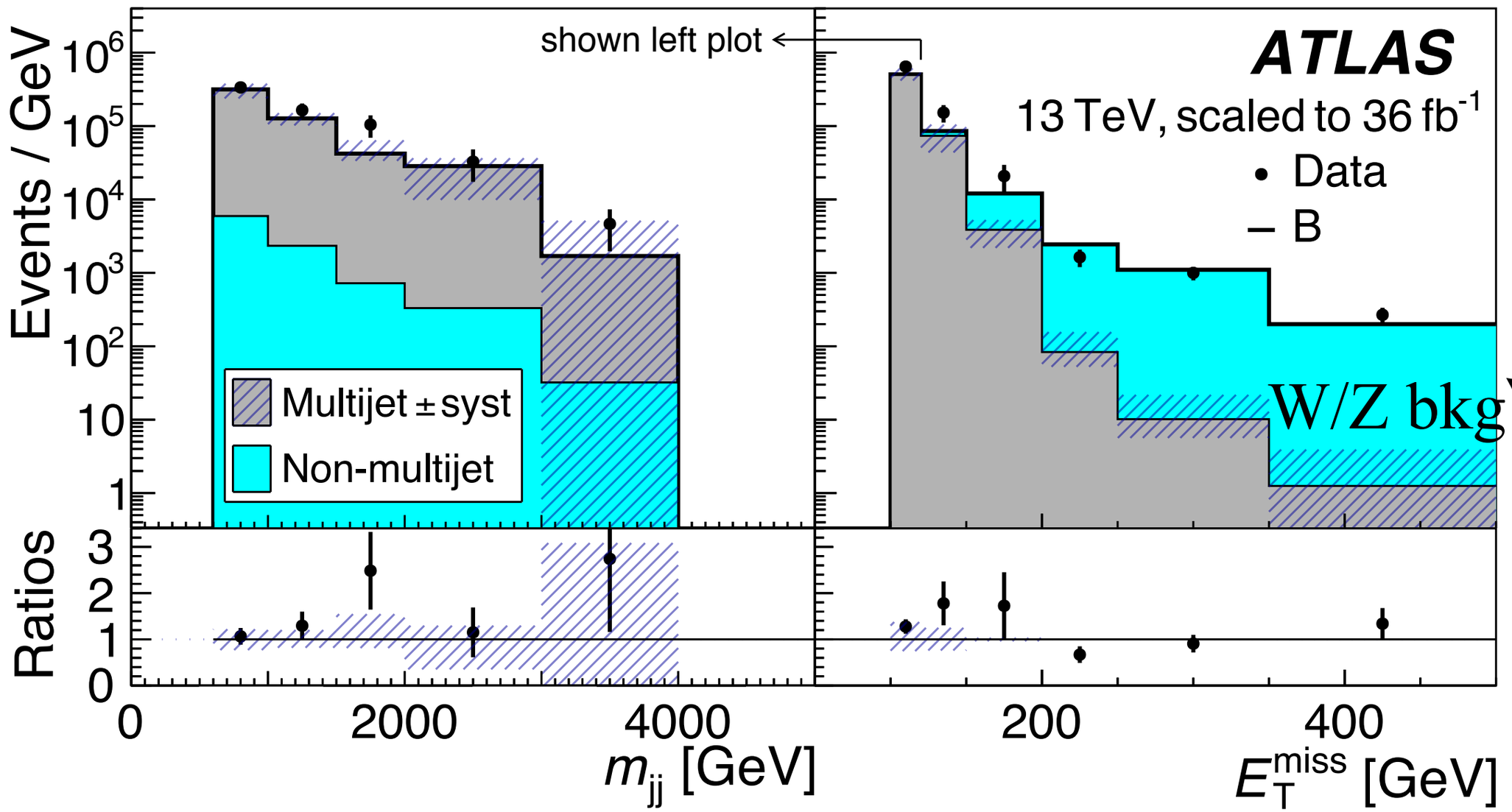
Ben Carlson

Estimate using data

Define a dedicated sample, test method

- Good agreement between prediction and data

- MET > 100 GeV
- m(jj) > 600 GeV
- $|\Delta\eta(jj)| > 3.0$
- $1.8 < |\Delta\phi| < 2.7$
- j_3 p_T: 25-50, j_4 p_T < 25 GeV

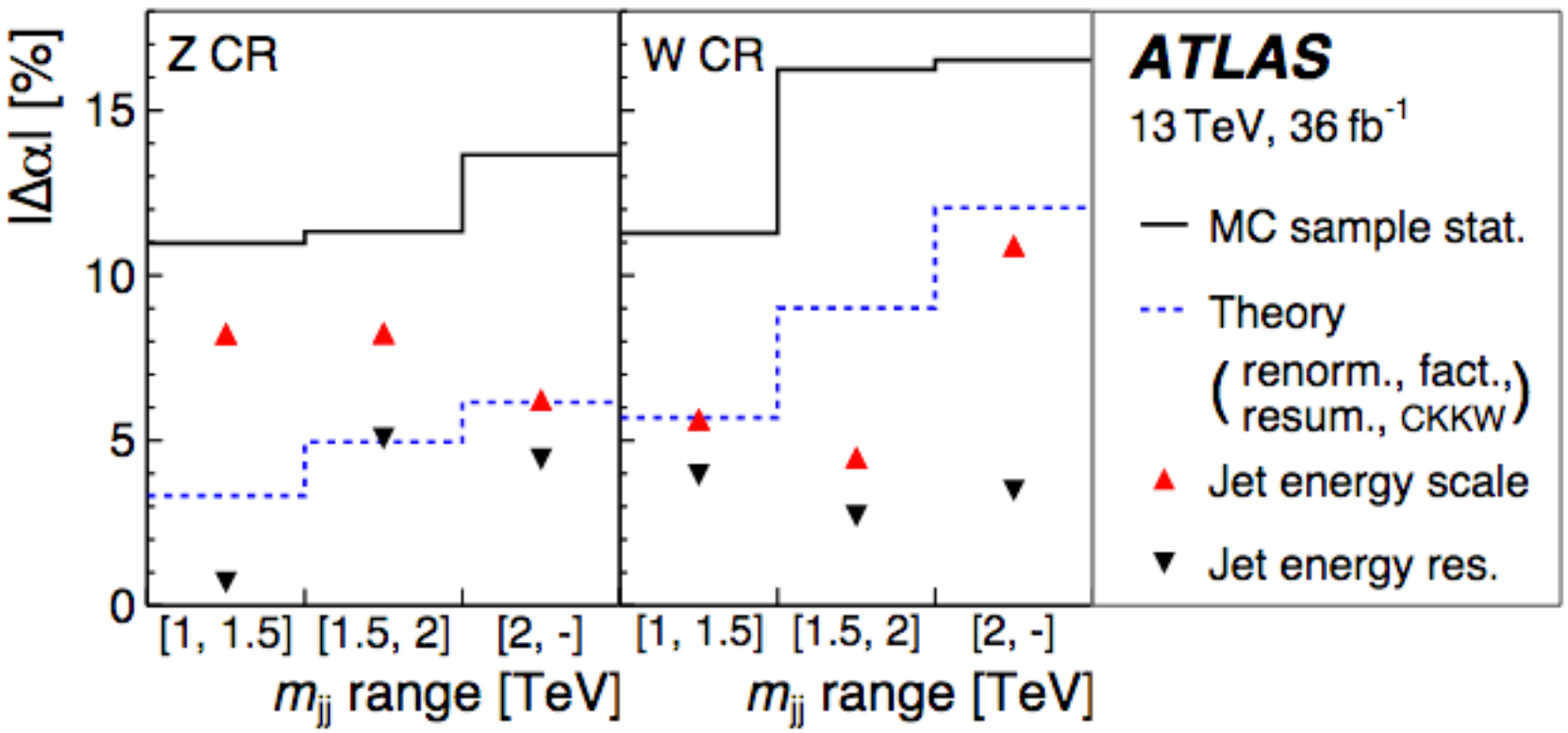


QCD falls off rapidly with MET

Systematics

ATLAS: 1809.06682
(Submitted to PLB)

Uncertainty on the ratio of events in SR/CR



Cancelation in the ratio

- Theory
  - Renormalization/factorization: 20% before ratio
  - CKKW jet matching uncertainty dominates
- Experiment
  - Jet scale and resolution: 1-4% in ratio (per term)
  - Total impact of JES significant though (29 terms)
- MC stats: dominant unc.
  - More on how to address this later

Systematics impact

ATLAS: 1809.06682
(Submitted to PLB)

Evaluate relative impact on sensitivity

Remove from calculation, redo sensitivity study

Limited size of MC sample →

Extrapolate to higher luminosity →

Source	ΔB/B
Theory	10%
Jet scale	10%
Jet resolution	2%
MC stats	12%
Data stats	21%

Major gains in sensitivity require systematic uncertainty reduction improvement

Higgs portal model

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

9 Dark matter interactions

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

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

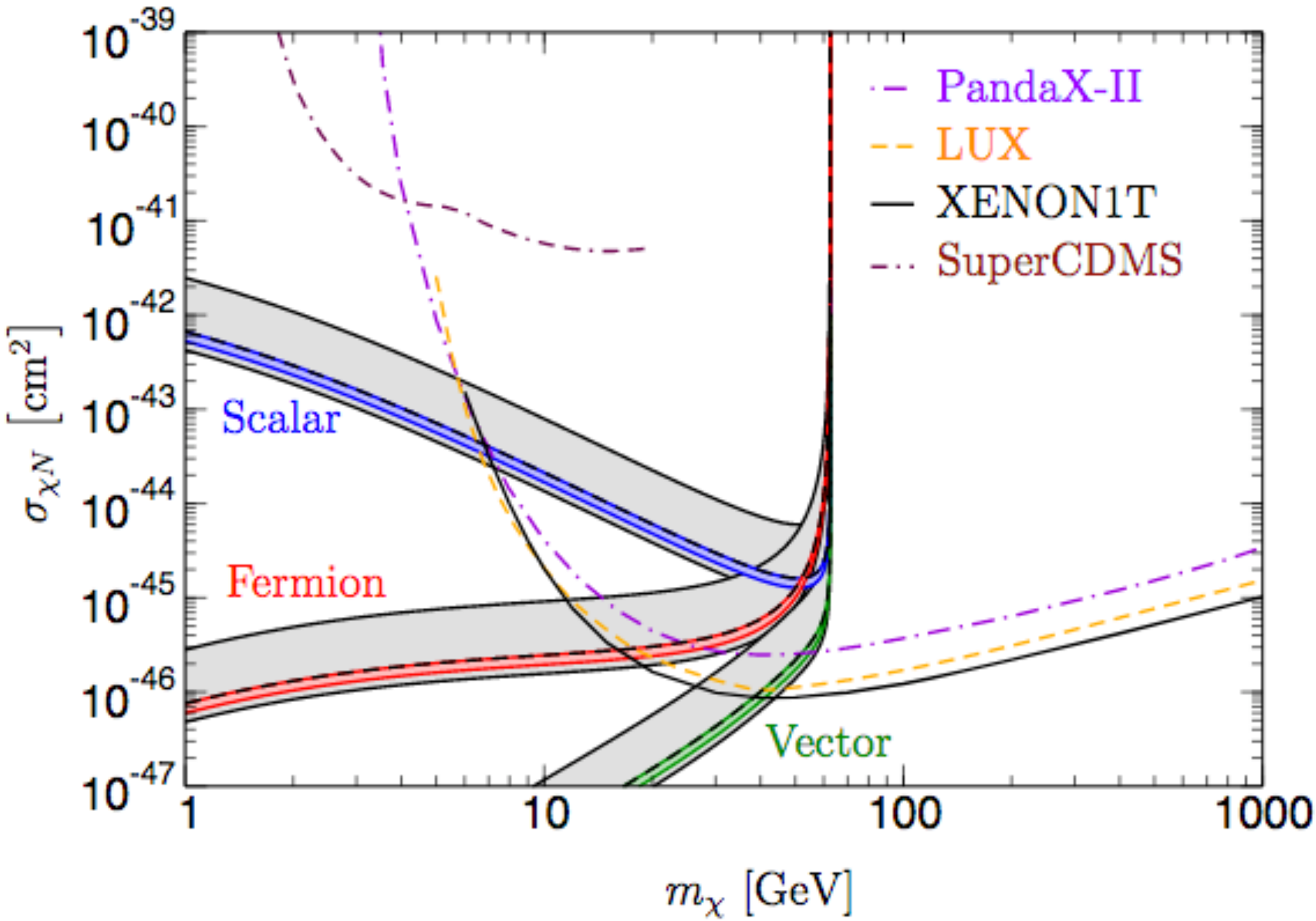
$$\sigma^{\mathrm{SI}}_{\mathrm{V-N}} = \frac{16\Gamma_\mathrm{inv} M_\chi^4}{m_\mathrm{H}^3 v^2 \beta (m_\mathrm{H}^4 - 4M_\chi^2 m_\mathrm{H}^2 + 12M_\chi^4)} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_N)^2}, \tag{9}$$

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

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

Lattice impact

M. Hoferichter et al. 1708.02245



Less “simple” models

Ben Carlson

arXiv: 1701.08134

Reopening the Higgs Portal for Singlet Scalar Dark Matter

J. A. Casas [a], D. G. Cerdeño [b,a], J. M. Moreno [a] and J. Quilis [a]

[a] Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid, 28049, Madrid, Spain

[b] Institute for Particle Physics Phenomenology, Department of Physics
Durham University, Durham DH1 3LE, United Kingdom

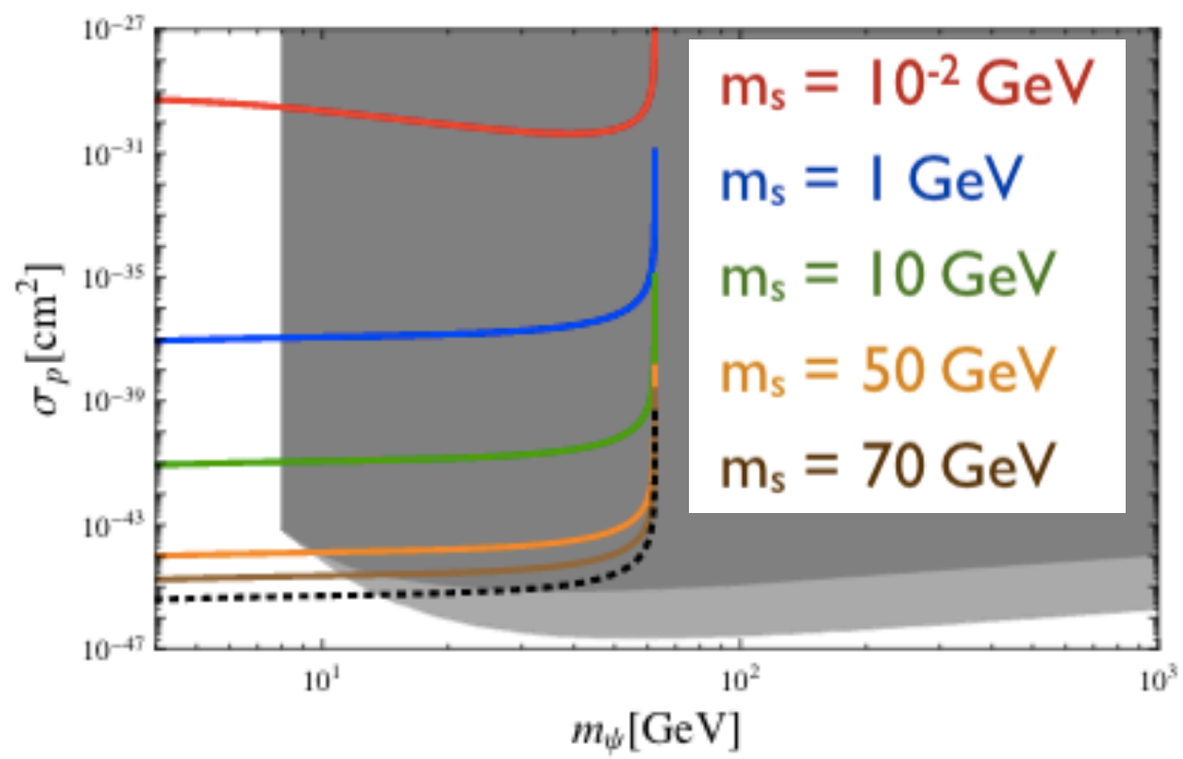
arXiv: 1405.3530

Invisible Higgs Decay Width vs. Dark Matter Direct Detection Cross Section in Higgs Portal Dark Matter Models

Seungwon Baek,* P. Ko,† and Wan-Il Park‡
School of Physics, KIAS, Seoul 130-722, Korea
(Dated: August 24, 2018)

As expected, more detailed models loosen constrains from the benchmark model

Fermion dark matter

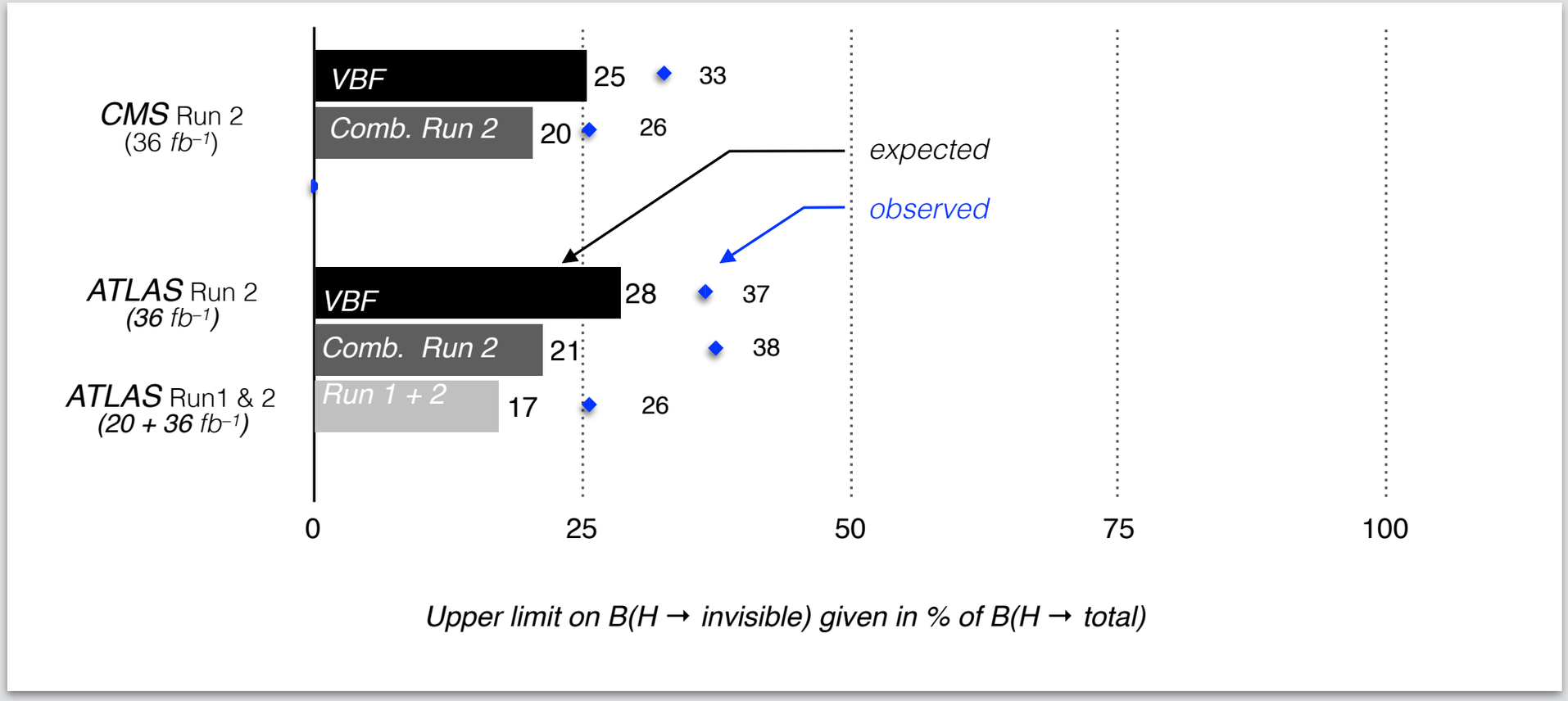


Dashed line: simple Higgs portal model
Grey: exclusion from LUX

Comparing ATLAS & CMS

Ben Carlson

Summary showing driving channels of sensitivity



Sources:

J. High Energy Phys.

11 (2015) 206

01 (2016) 172

02 (2017) 135

Phys. Letters B

776(2018)318–337

arXiv

1809.06682

1809.05937

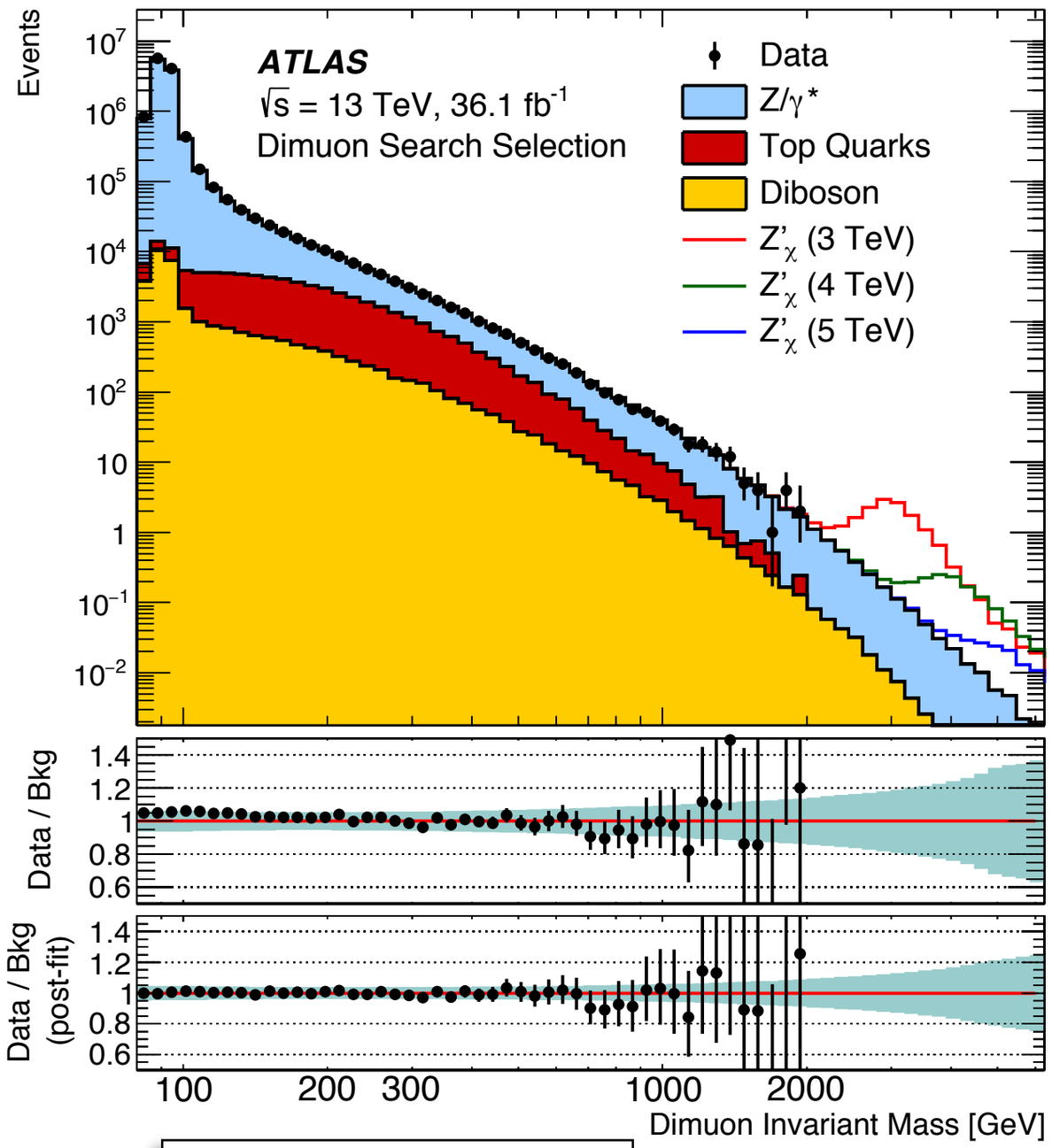
ATLAS-CONF-2018-054

Dilepton searches

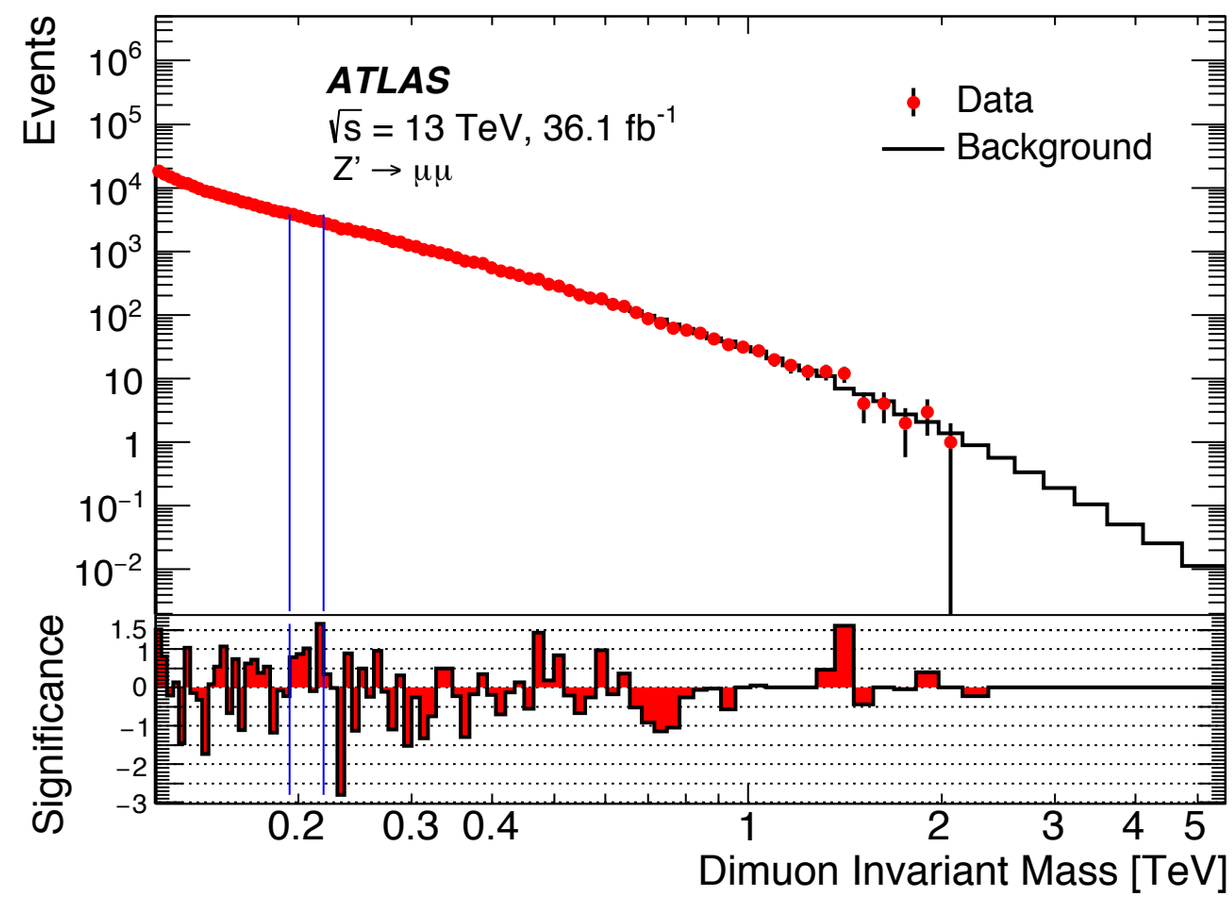
EXOT-2016-05

Ben Carlson

Dial down the coupling to quarks, turn up the coupling to leptons



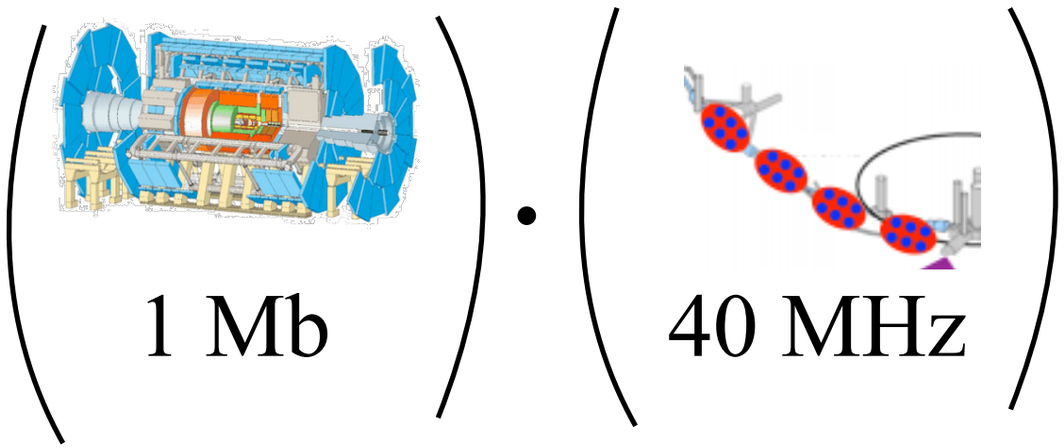
Dilepton mass (GeV)



Trigger

Ben Carlson

Event size · Event rate = 40 Tb/s

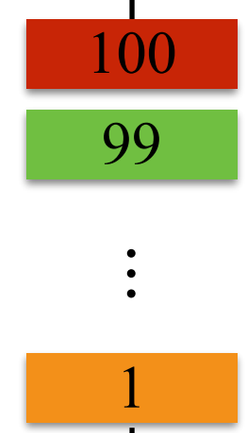


Time

2.5μs

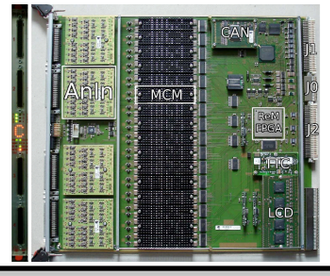
O(1s/event)

Partial data



Full data buffer

FPGAs

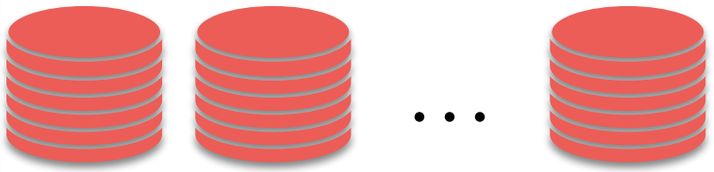


Custom electronics
reduce rate
100 kHz

100 Gb/s

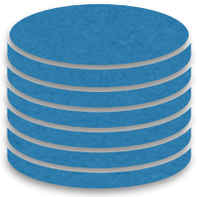
50k CPUs

Software
reduce rate
1kHz



Temporary storage

1 Gb/s



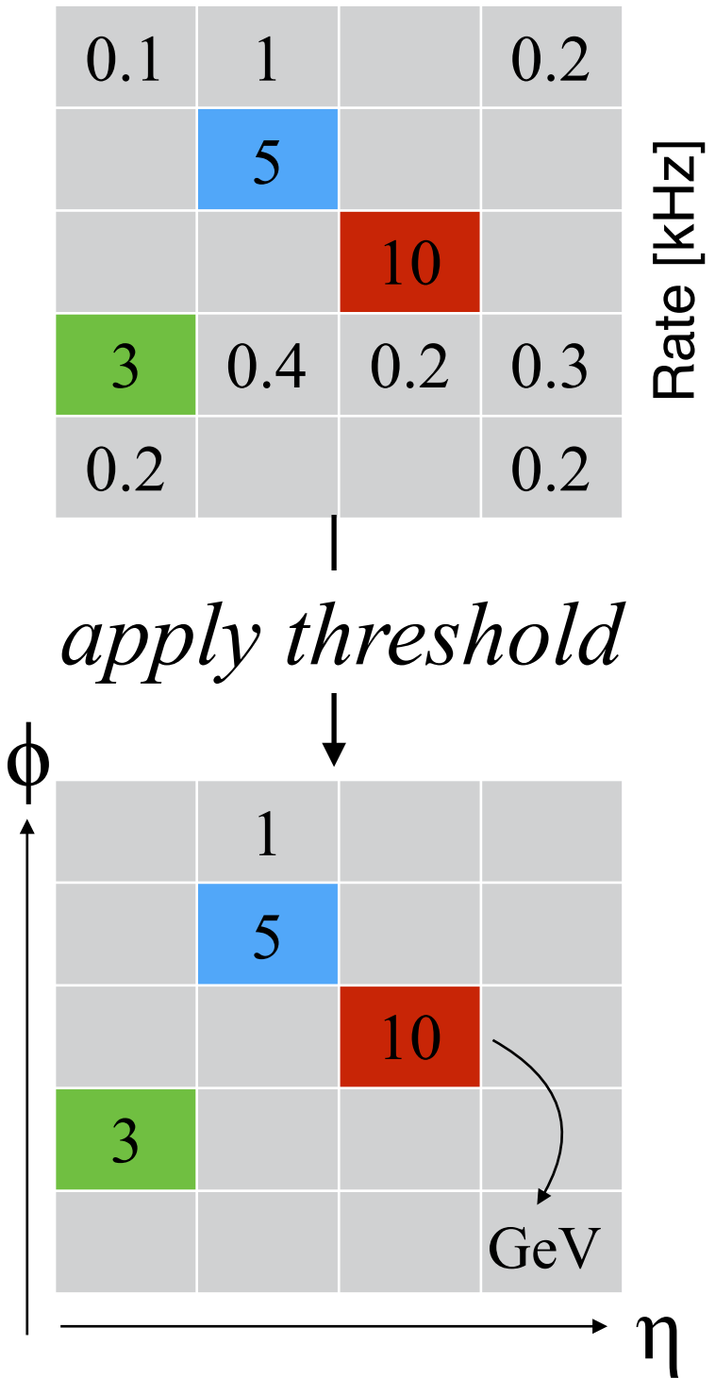
Permanent storage

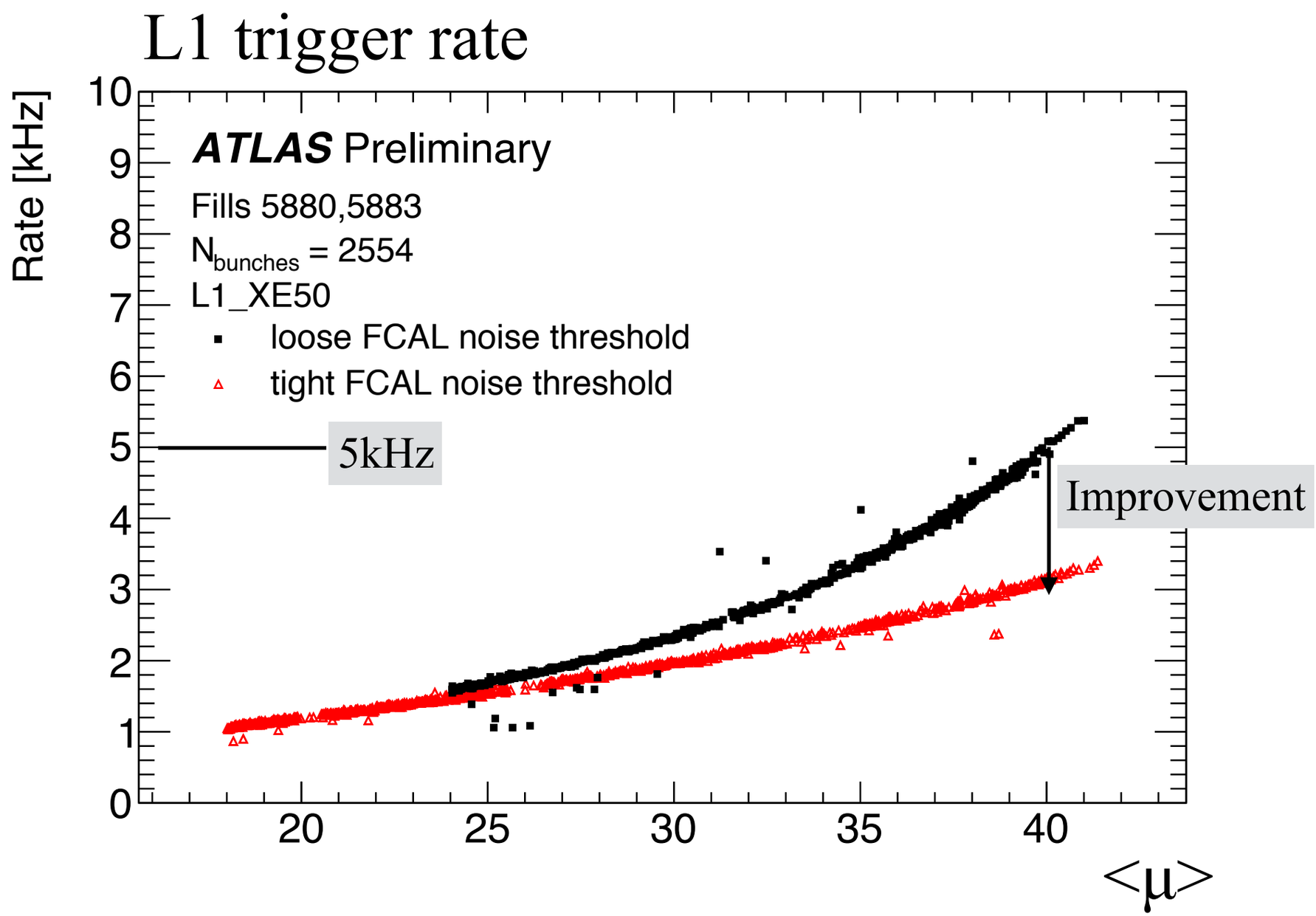
L1 MET trigger

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MissingEtTriggerPublicResults

Ben Carlson

- L1 trigger MET trigger rate is sensitive to pileup
- Reduced by raising the E_T threshold per trigger tower





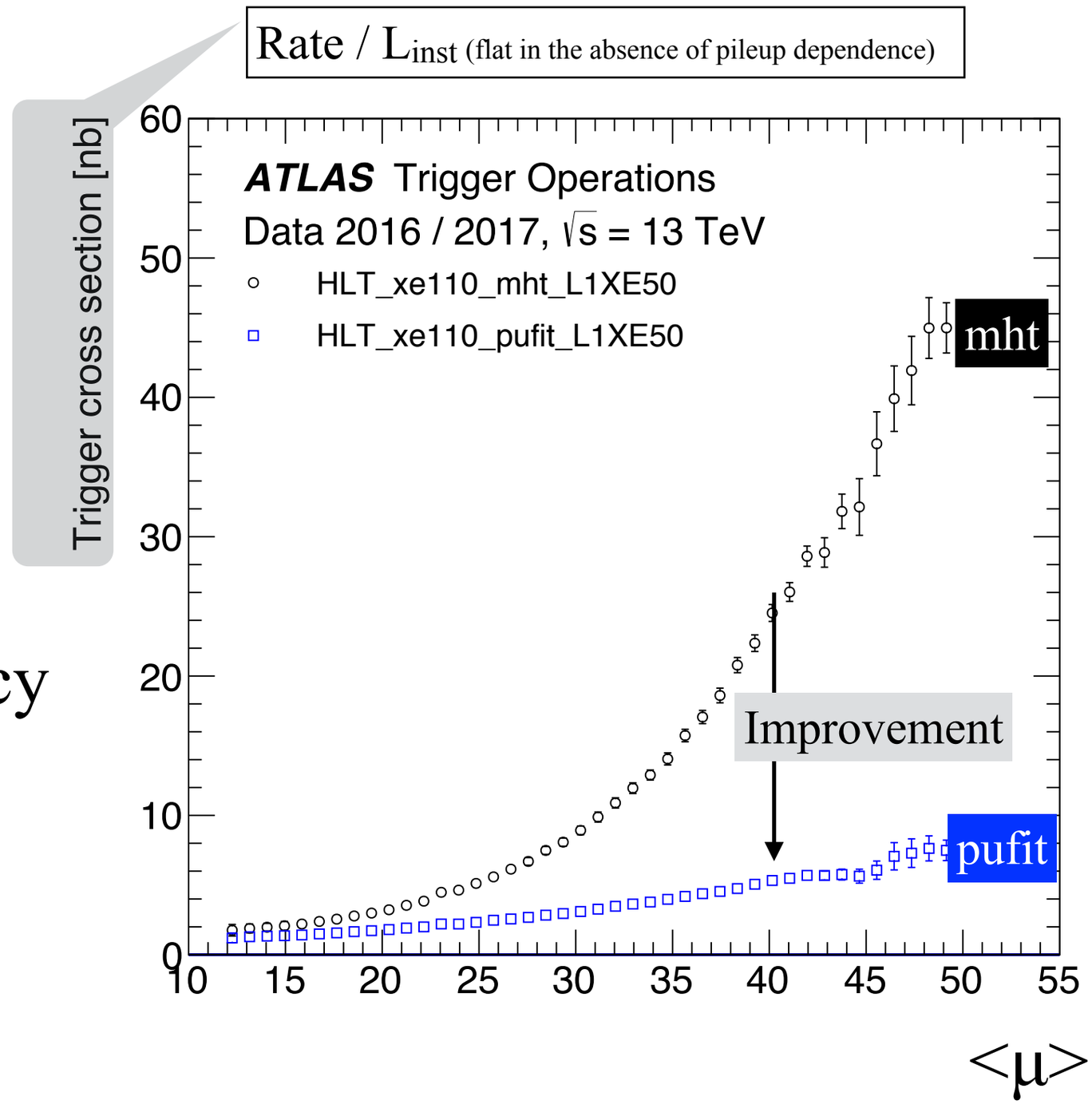
HLT MET trigger

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MissingEtTriggerPublicResults

Ben Carlson

- HLT (software) trigger rate also sensitive to pileup
- Reduced the rate by developing new algorithm to remove pileup

1/5 the rate; same efficiency

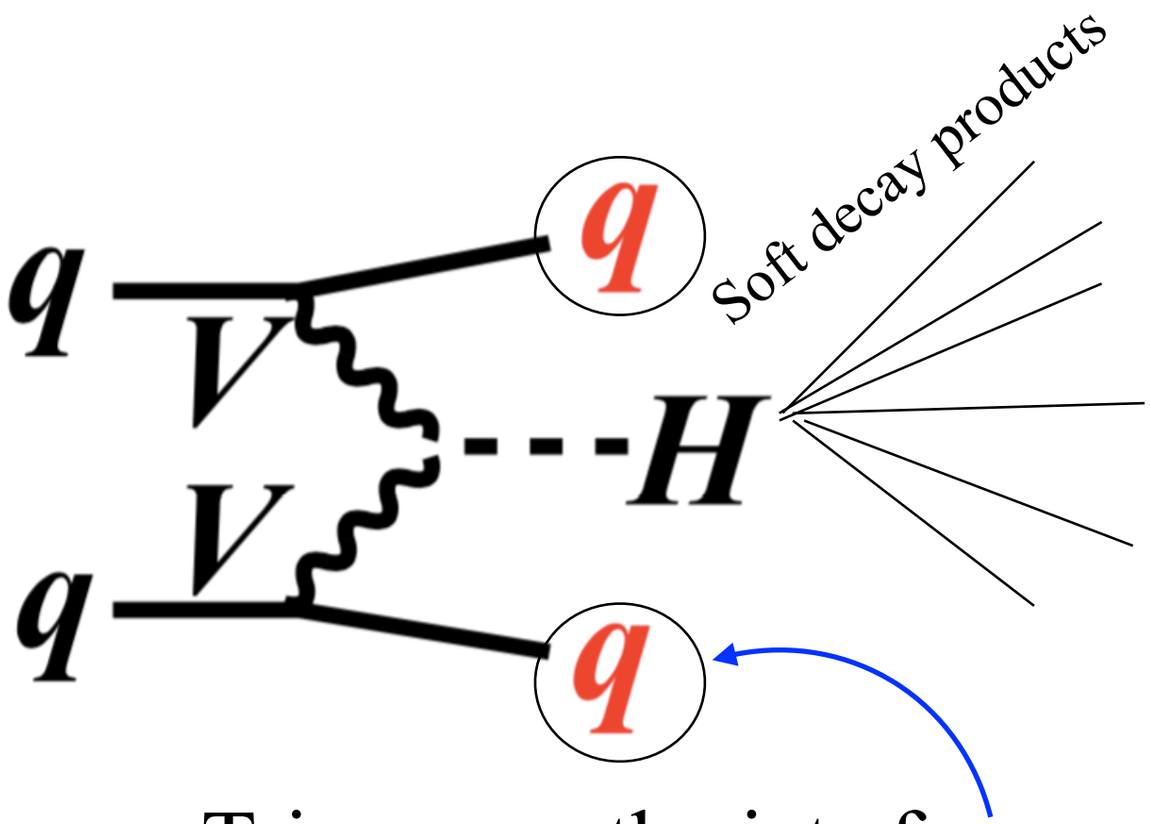


VBF trigger

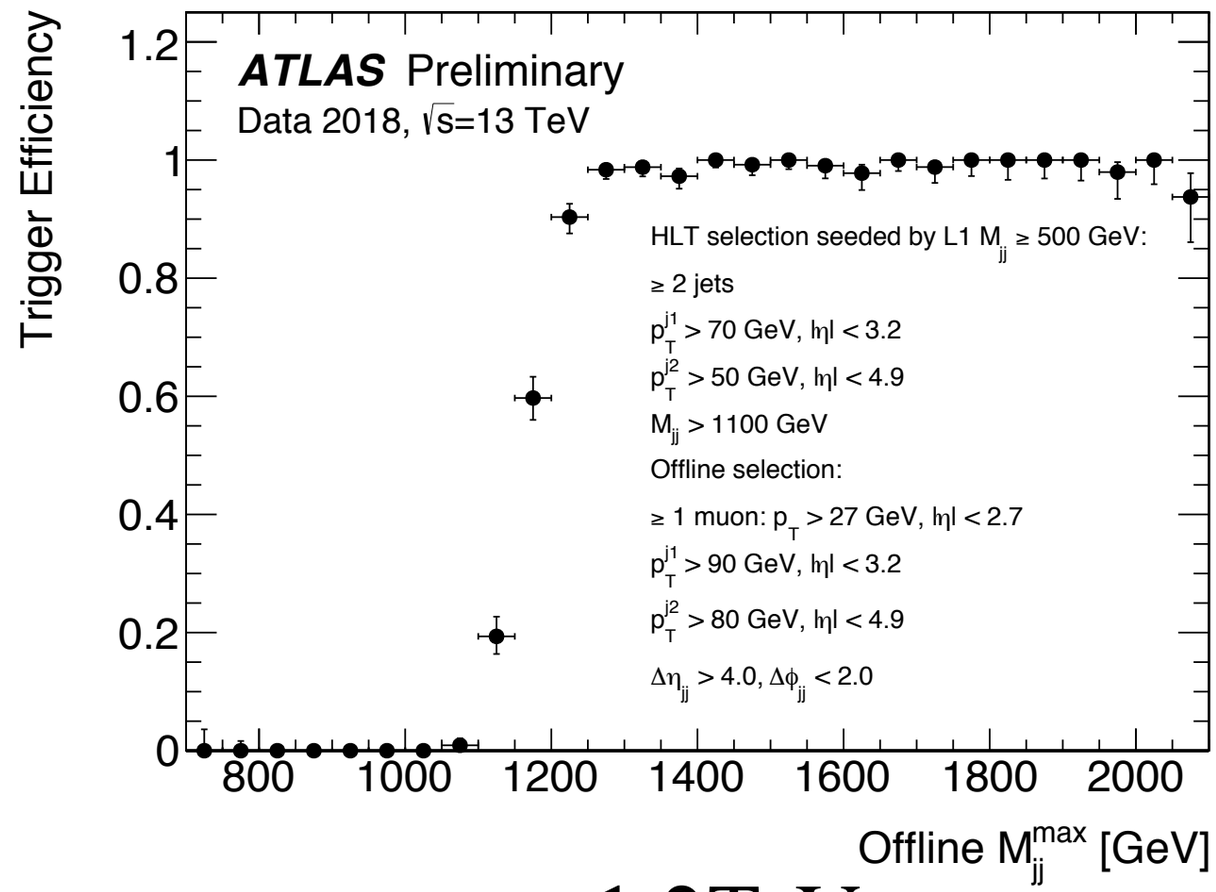
Link

Ben Carlson

Inclusive trigger to target VBF events, regardless of decay products



Trigger on the jets from vector boson fusion

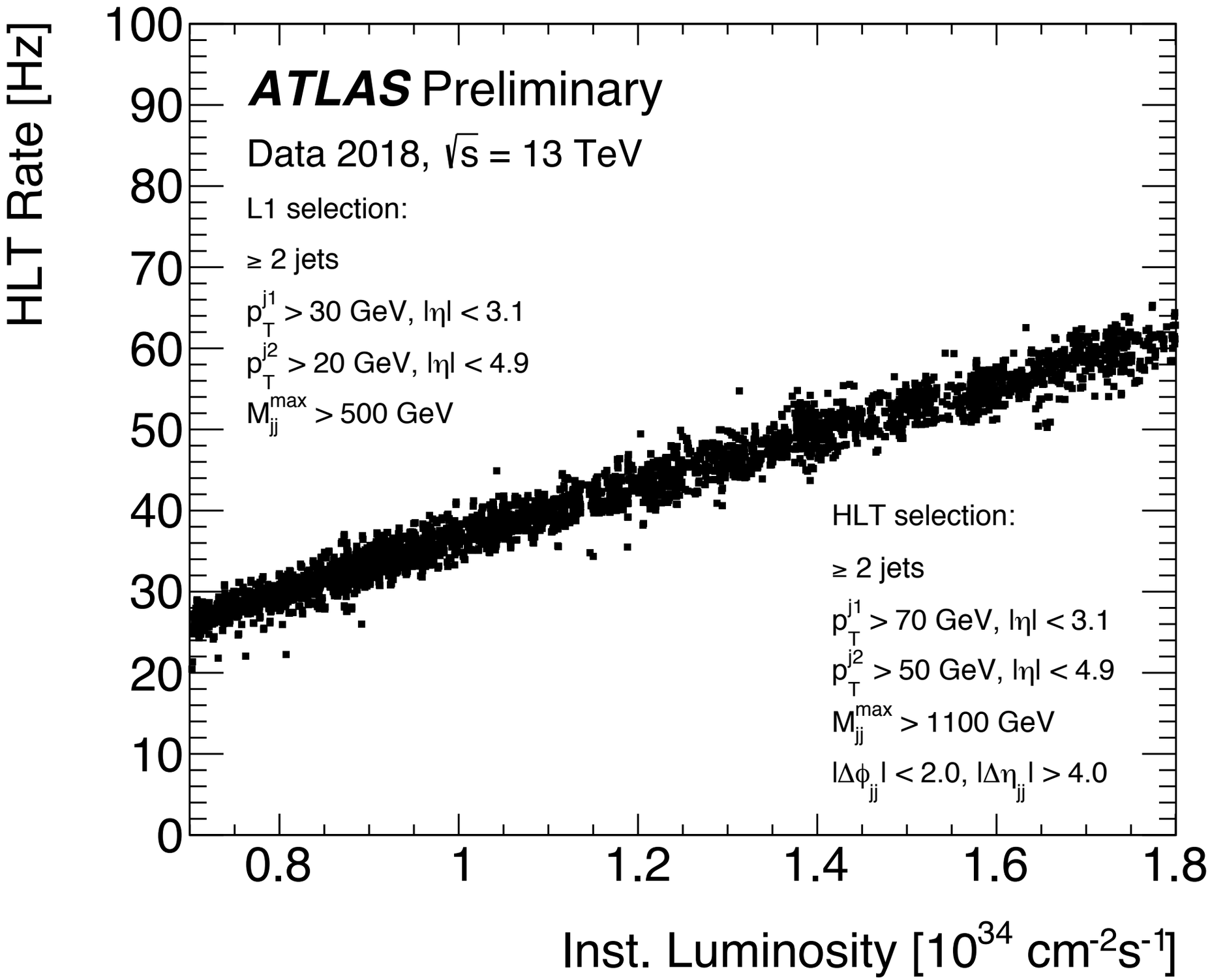


$m_{jj} > 1.2\text{TeV}$

VBF trigger rate

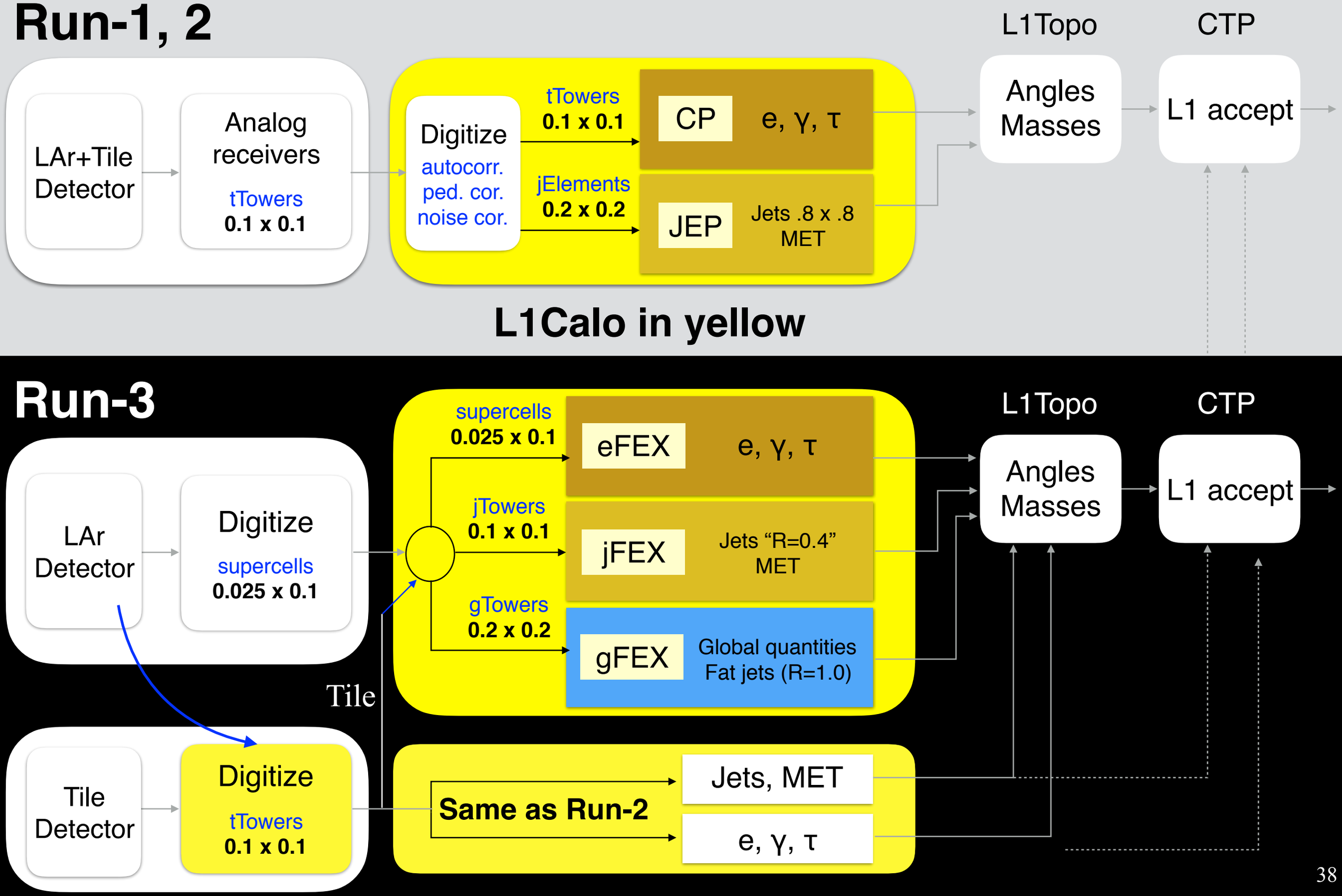
Link

Ben Carlson



Upgrade (starting now!)

Ben Carlson



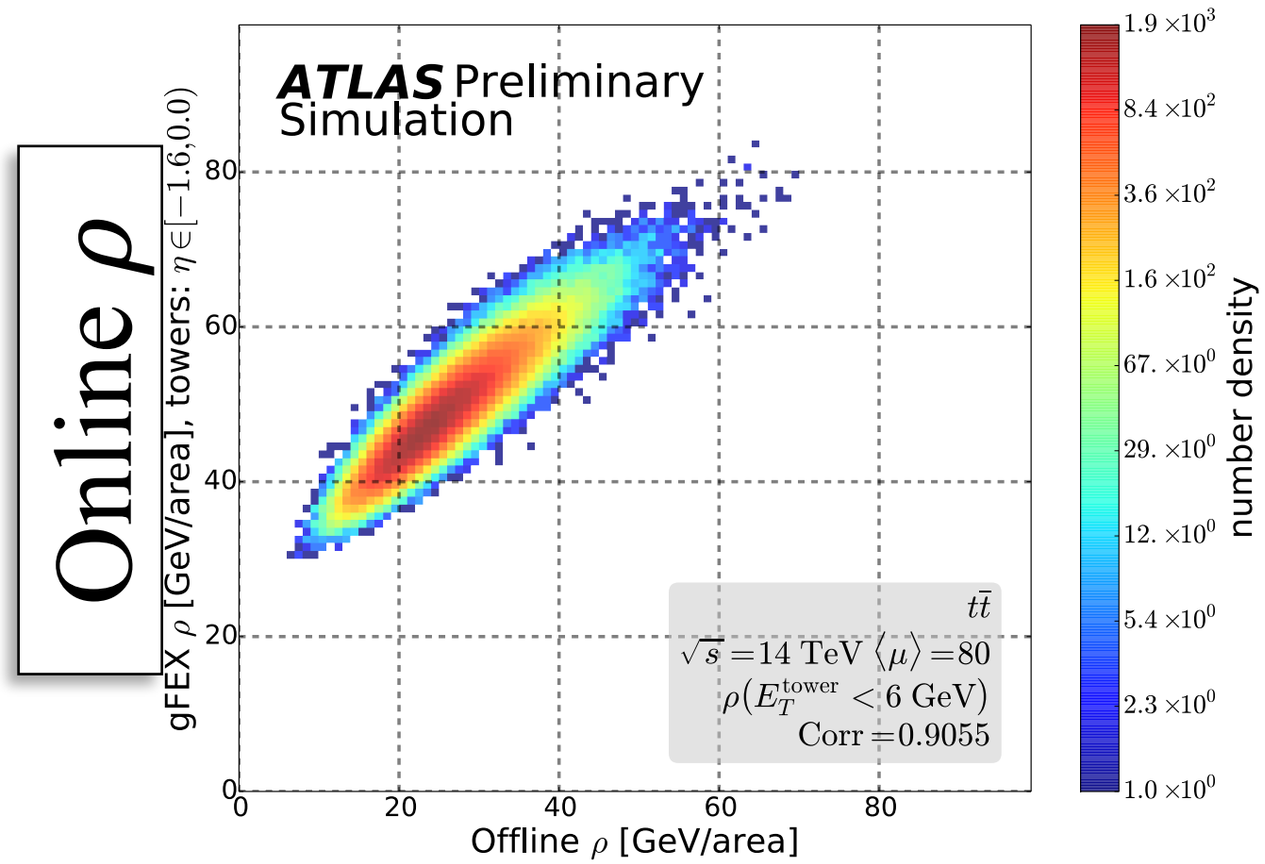
Impact: jets and MET

ATL-COM-DAQ-2014-087
L1Calo public (July 2018)

Ben Carlson

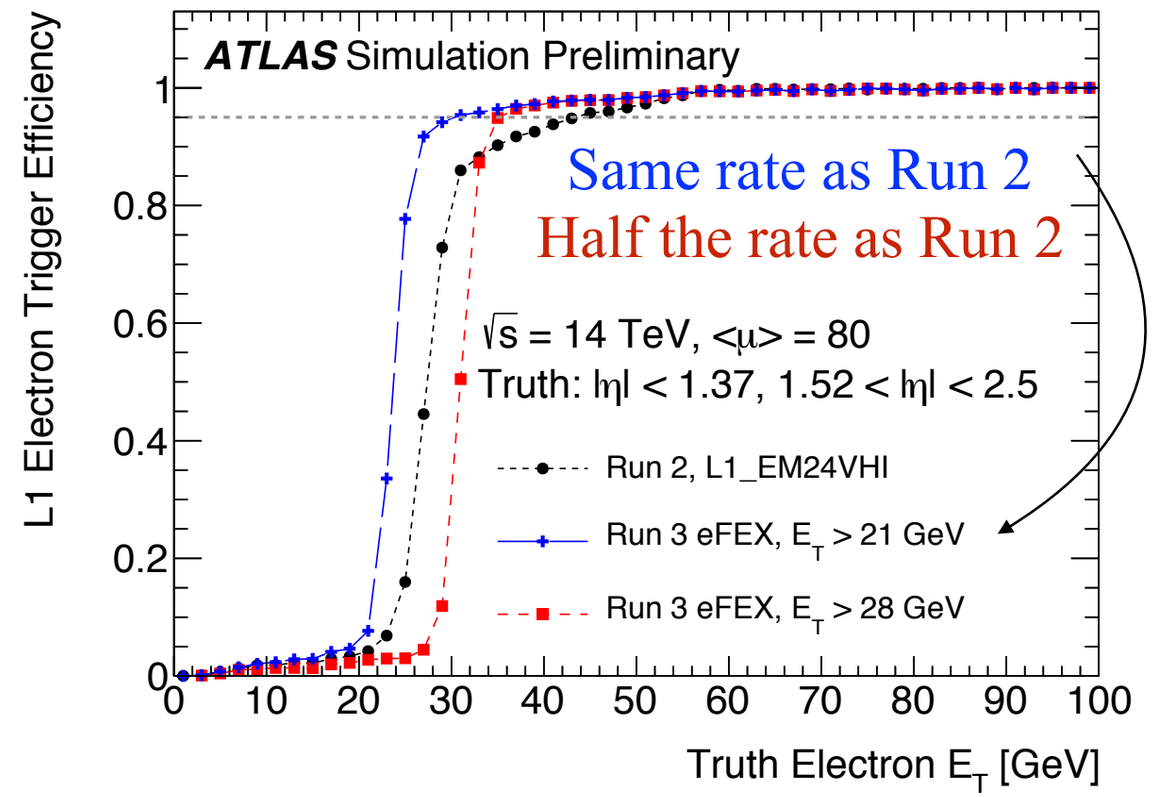
Improving MET

MET is sensitive to pileup
Working on pileup subtraction for L1



Dramatic improvement

(Uses additional granularity to target electrons)



Lots of rate saved, use it for DM triggers?