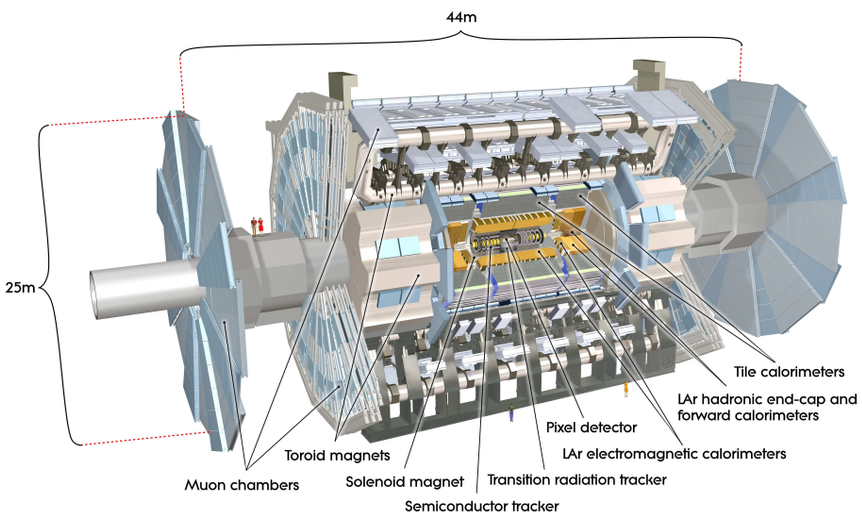
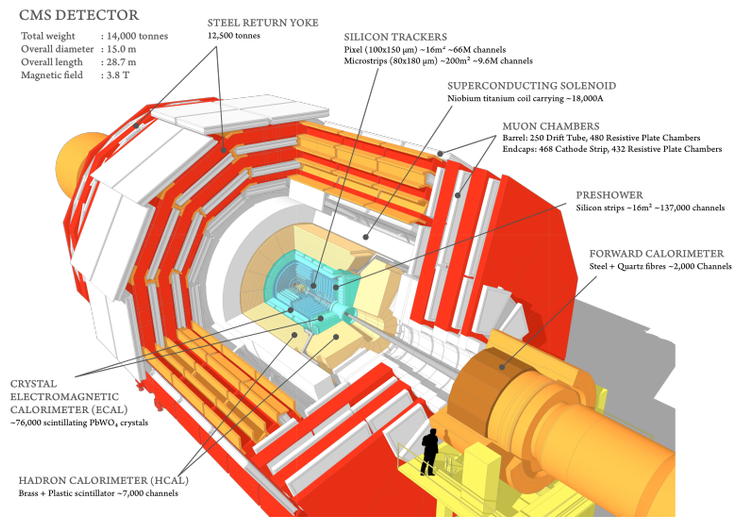
Highlights from SUSY and Exotics

On behalf of the ATLAS and CMS Collaborations

October, 12 2017

Ben Carlson†





University of Pittsburgh

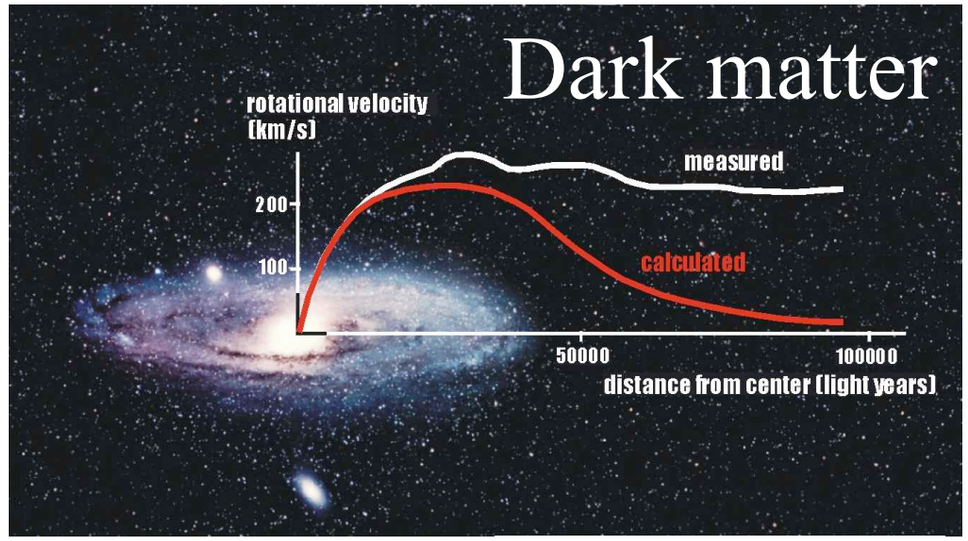
†bcarlson@cern.ch

http://phyast.pitt.edu/people/ben-carlson

Presentation themes

Much of what I will discuss in some way solves:

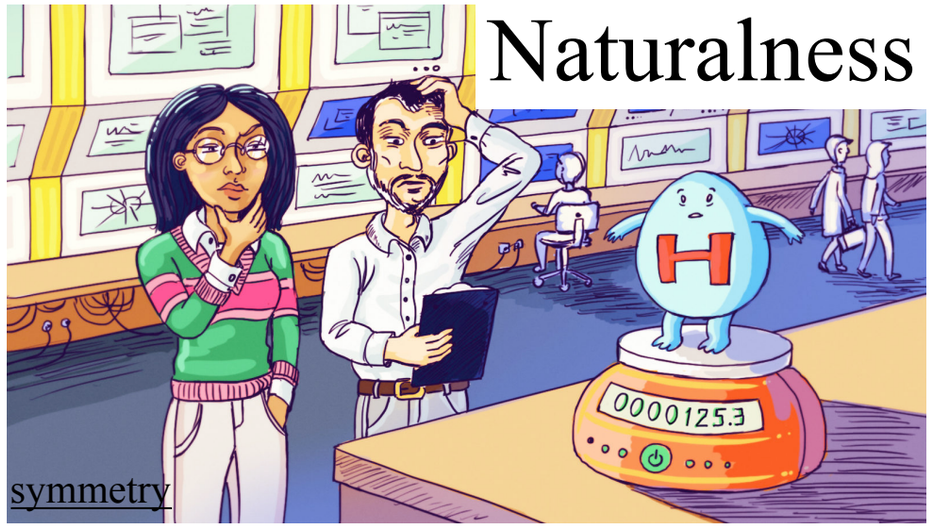
- Dark matter
- Naturalness

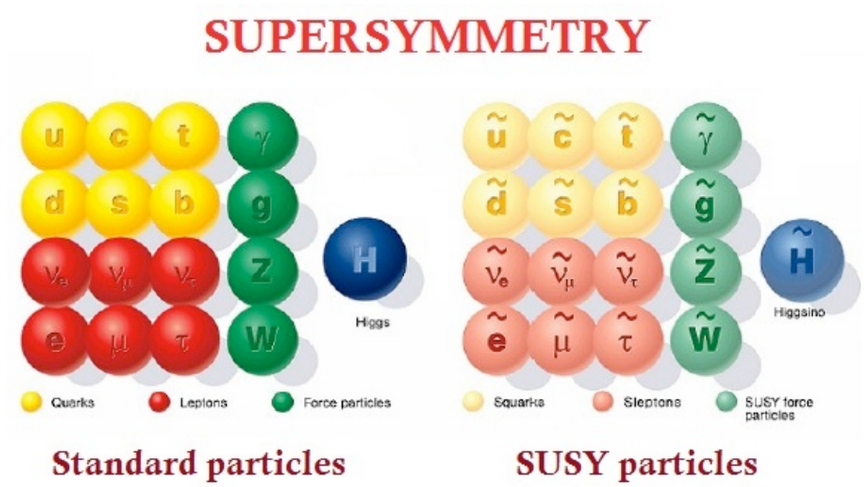


Presentation order

- Mediator searches: dijets, trigger, ISR
- Mono-X, X = j,γ (can also be SUSY searches)
- SUSY: third generation (can also be DM searches)
- SUSY: EW searches

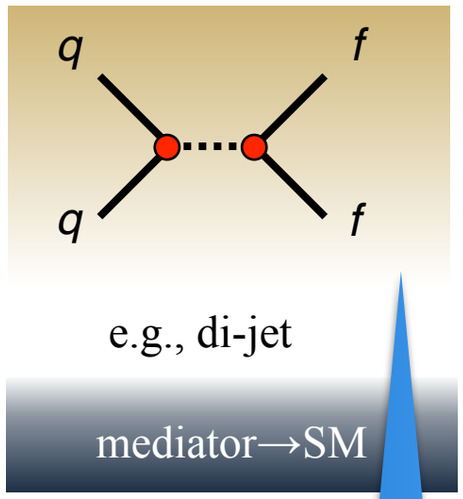
Not discussed: BSM Higgs decays, long lived, hadronic VV resonances… and lots more





credit: CERN

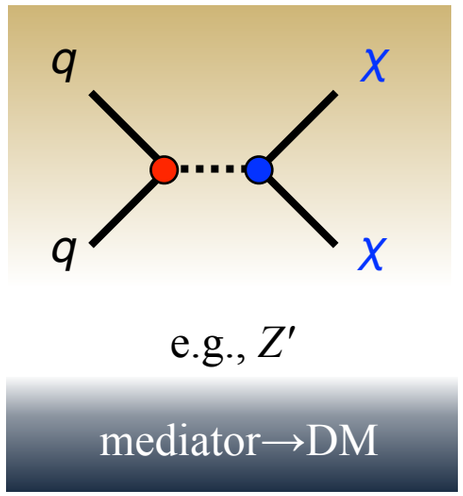
Collider dark matter search methods



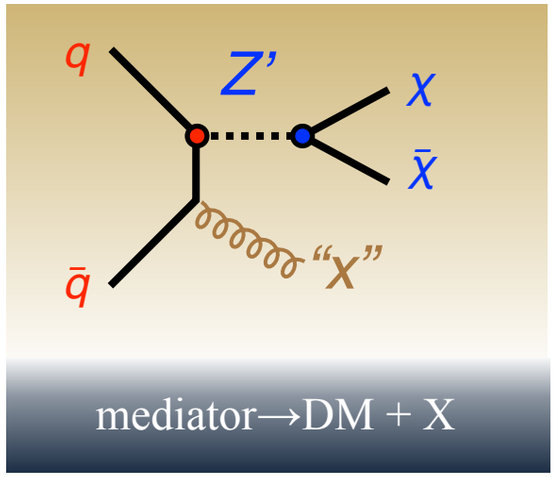
Discussed in this talk: only dijet decays

Direct mediator searches: dijet (dilepton) resonances

Details, see DM working group recommendations: arXiv 1703.05703



Add "X"



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

Discussed in this talk (shaded)

Not exactly diagrams shown above

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, $t\bar{t}$

Search for the mediator: dijet resonances

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

$p_T = 3.79$ TeV

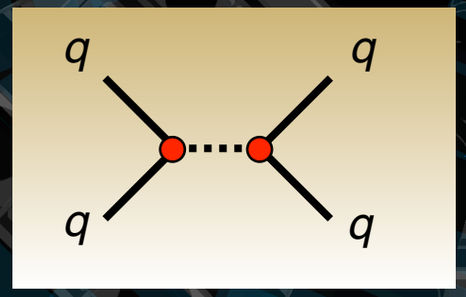
$p_T = 3.79$ TeV

EM calorimeter energy

Tracks

Hadronic calorimeter energy

ATLAS EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST



e.g., di-jet

mediator

Direct mediator search: dijet events

Transverse view

Phys. Rev. D 96, 052004

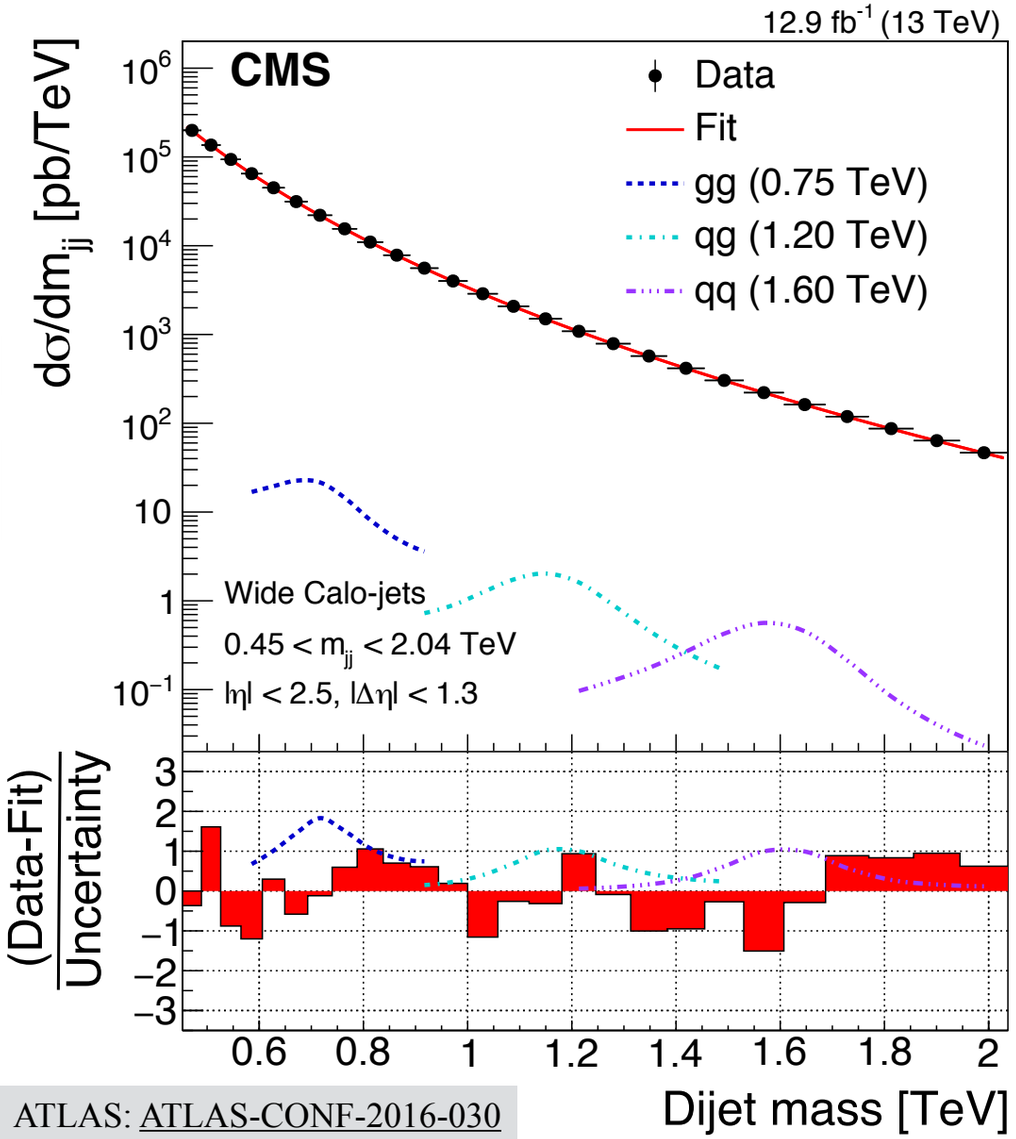
Mediator via dijet

Data scouting: save jets computed in trigger
"No" bandwidth limit → lower mass reach

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

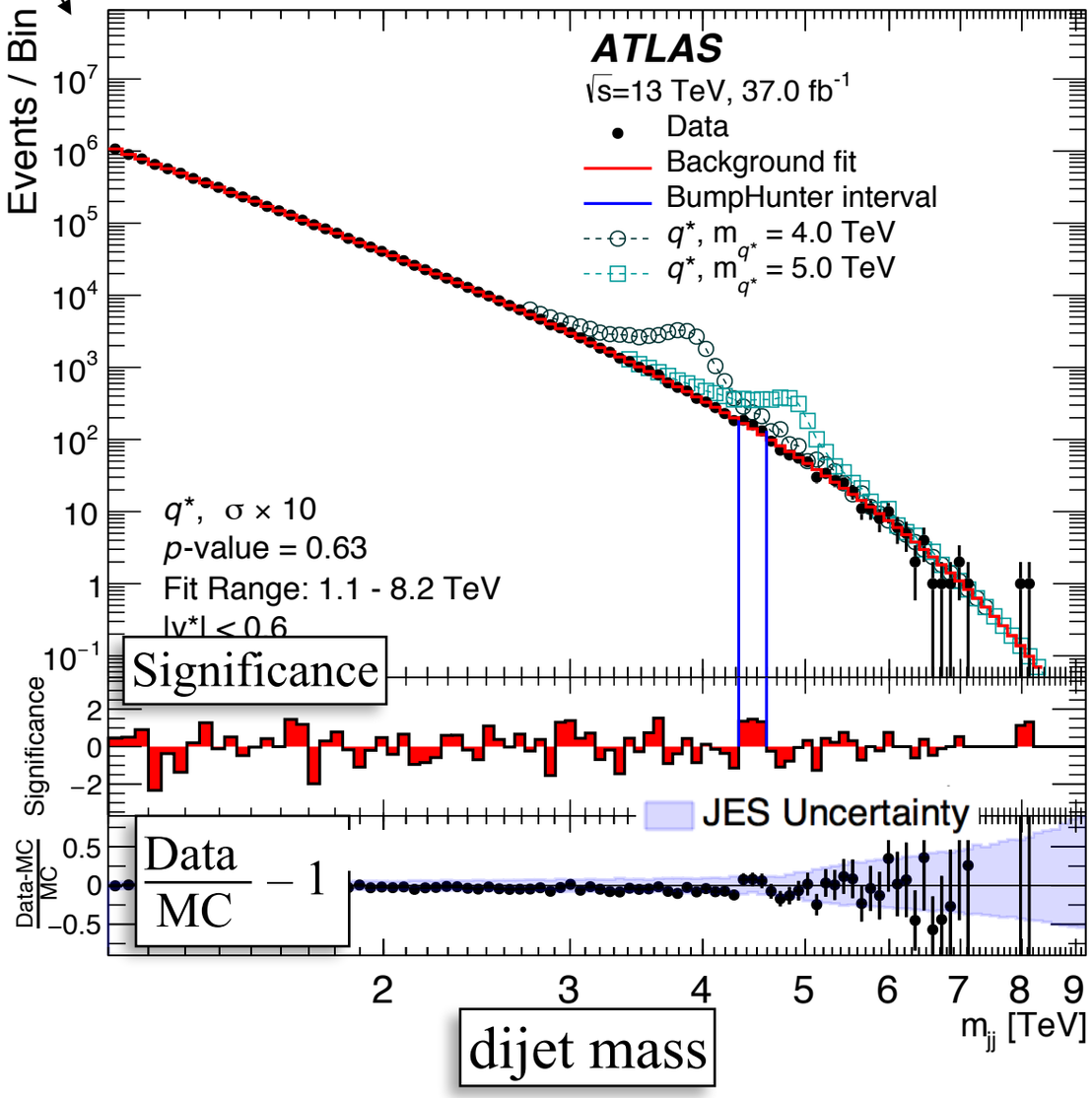
CMS: Data scouting

ATLAS: Trigger level analysis

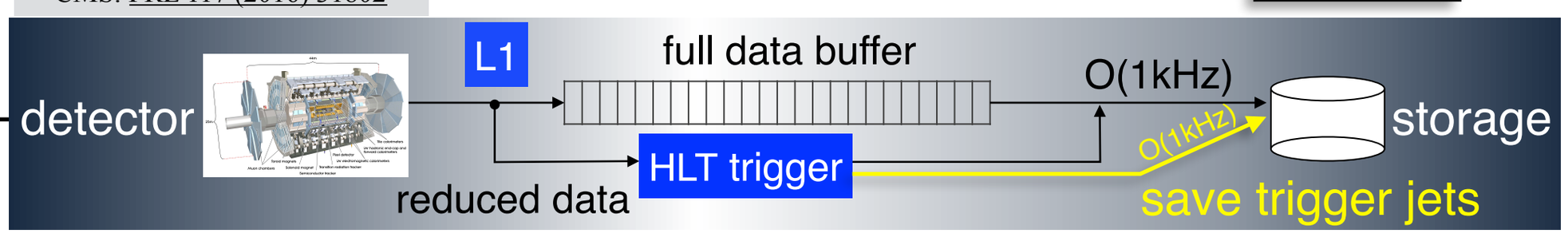


different units

CMS: PLB 769, (2017) 520 ATLAS: Phys. Rev. D 96, 052004

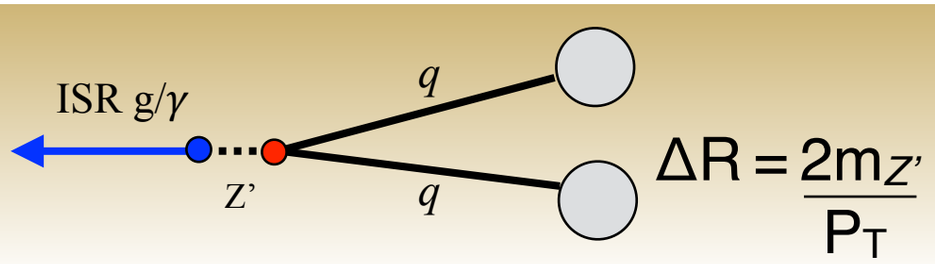


ATLAS: ATLAS-CONF-2016-030
CMS: PLB 769, (2017) 520
CMS: PRL 117 (2016) 31802



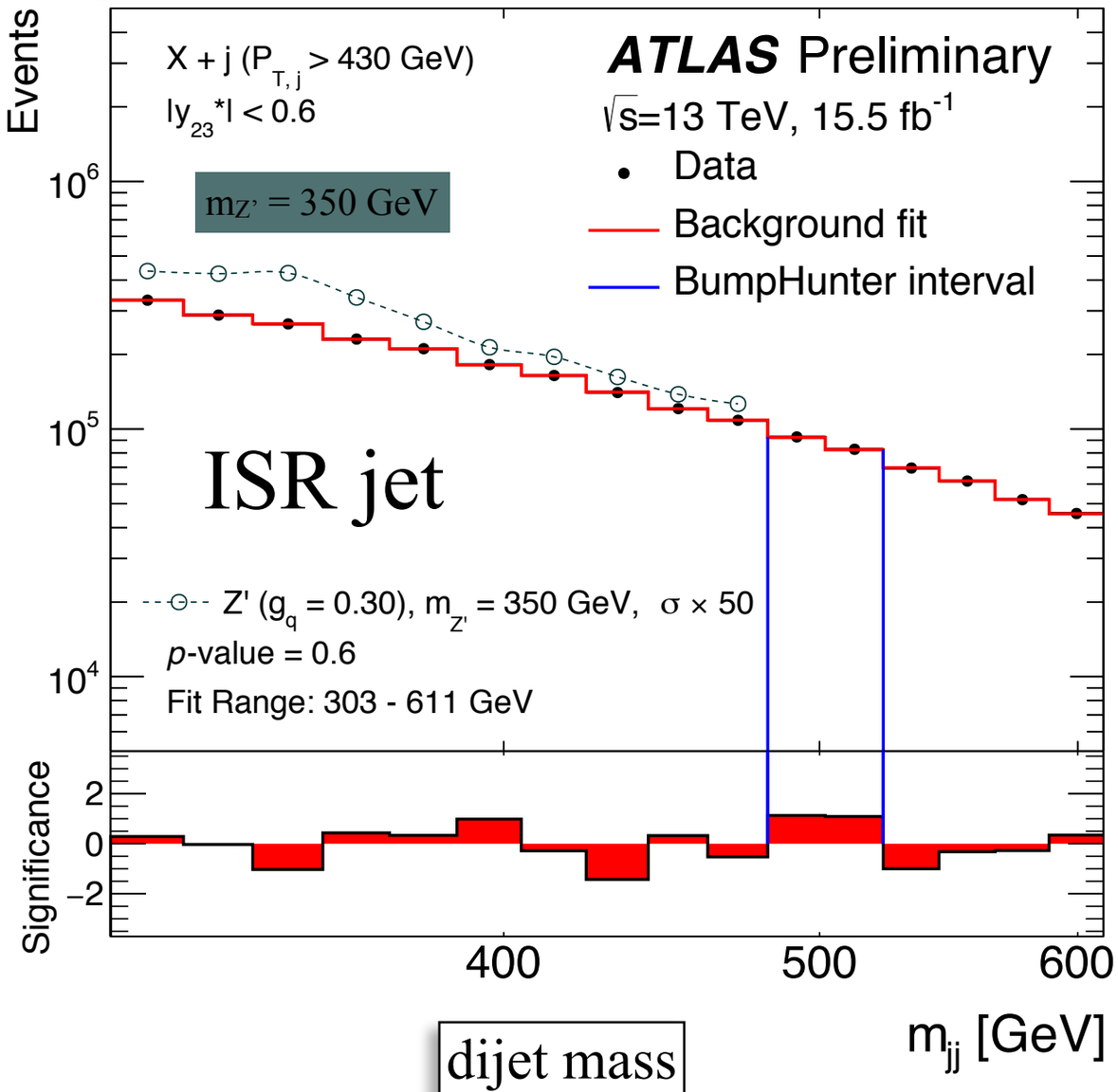
Mediator boosted by ISR: resolved

ATLAS-CONF-2016-070



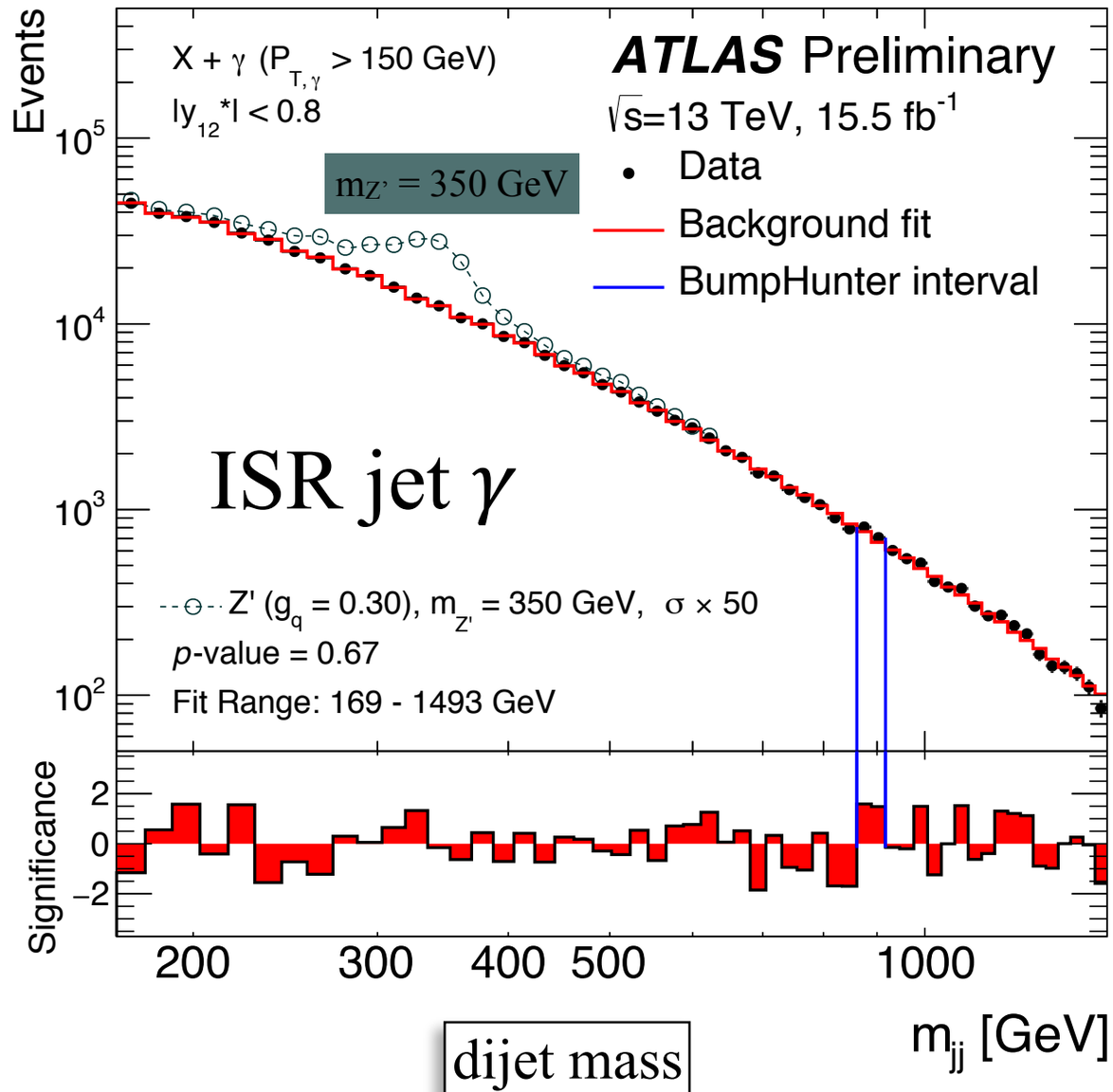
Add an ISR jet(γ), boost the mediator
High-p_T final state for **trigger**

ISR: jet, p_T > 350 GeV
Z' reconstruction: resolved R = 0.4



dijet mass

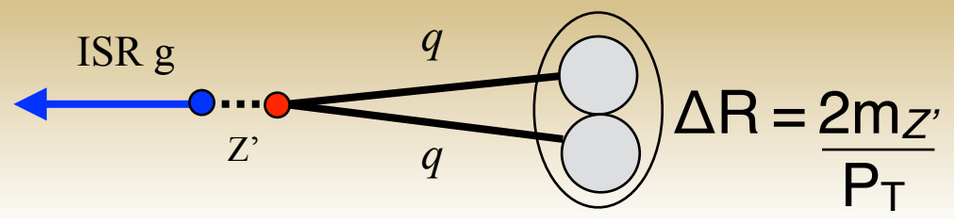
ISR: γ p_T > 150 GeV
Z' reconstruction: resolved R = 0.4



dijet mass

$m_{Z'}$: 170-1500 GeV

Mediator boosted by ISR: substructure



At high p_T, decay products **merged**
Utilize substructure techniques

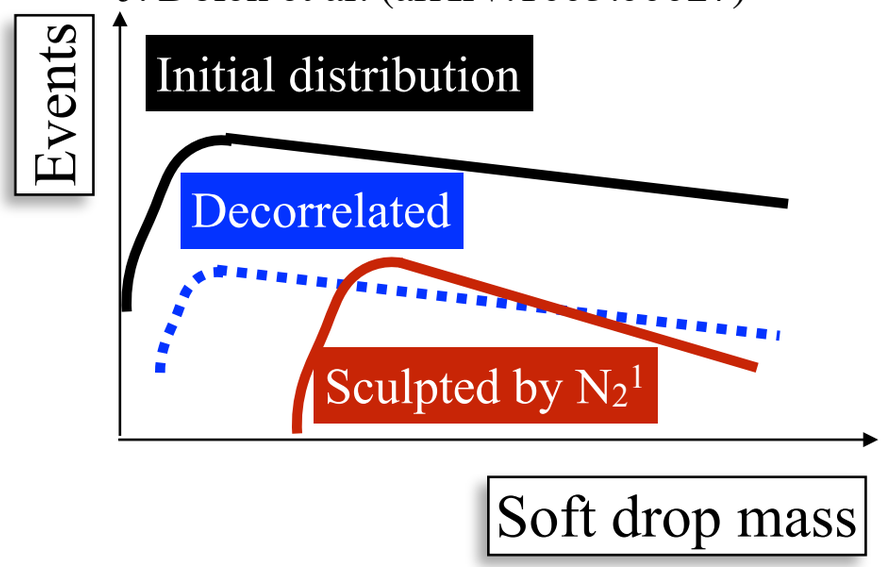
PRL 119 (2017) 111802
EXO-17-001

Substructure references:
I. Moult et al. (arXiv: 1609.07483), A. Larkoski et al. (arXiv:1402.2657)

Use standard **substructure** techniques

- Soft drop mass: groomed to remove contamination
- Z': 2-prong, QCD: 1-prong → $\mathbf{N_2^1}$
- $N_2^{1,DDT}$: designed to not sculpt m_{SD} for QCD
  (new method for decorrelation)

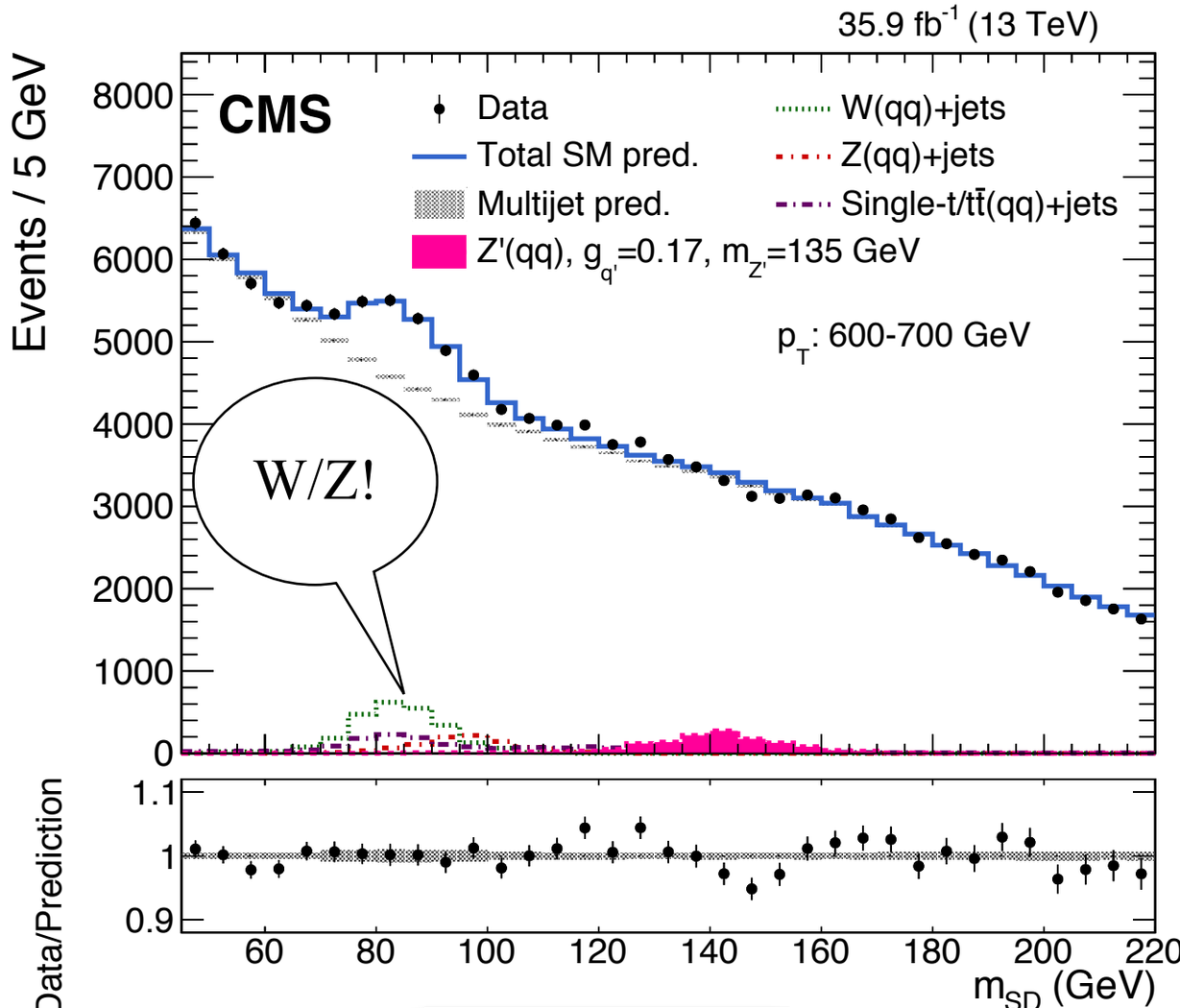
J. Dolen et al. (arXiV:1603.00027)



Main background: QCD

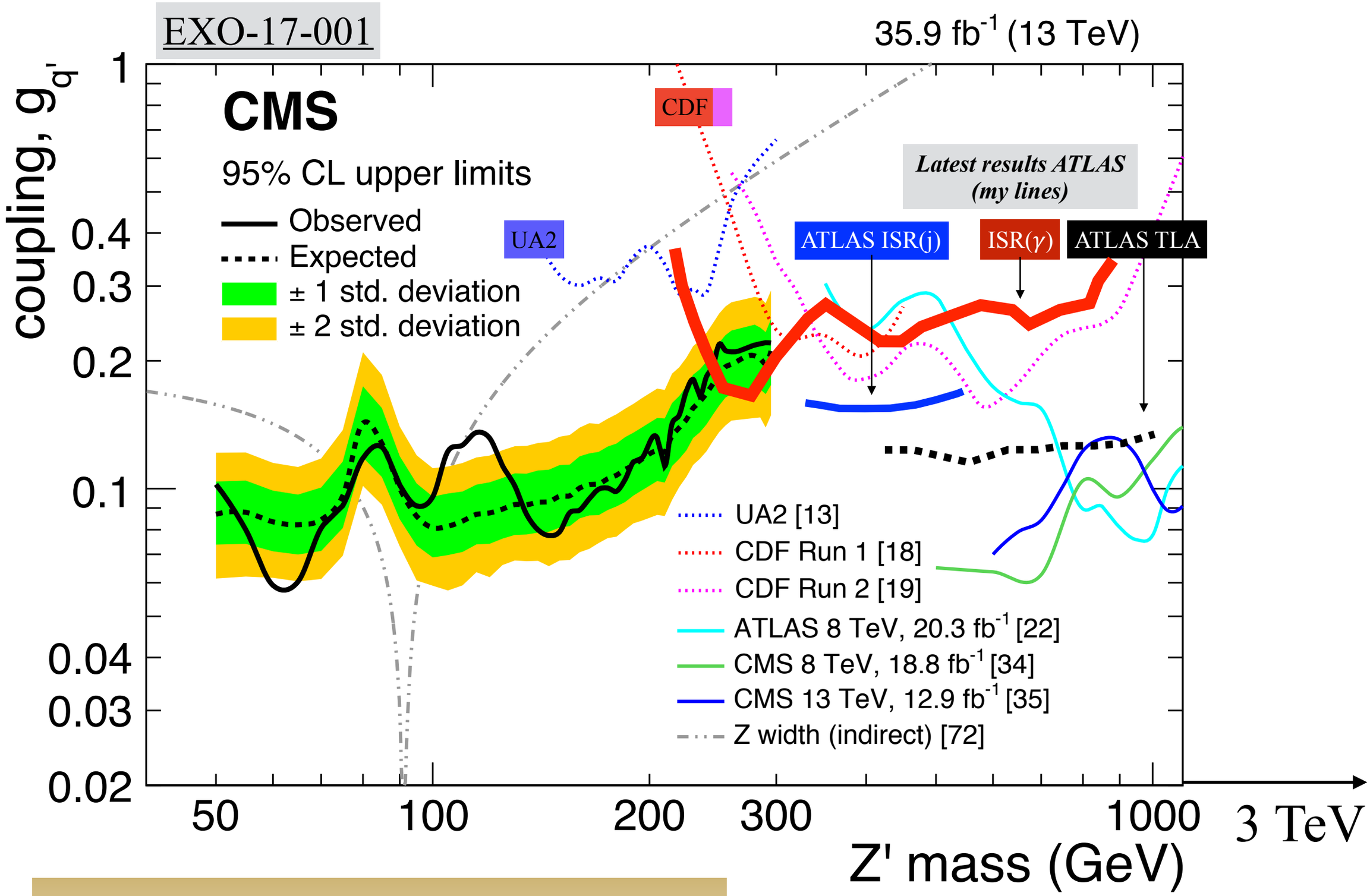
- Estimated by inverting $N_2^{1,DDT}$ then fitting

Trigger: H_T or R = 0.8 jet w/ mass cut
Z' reconstruction: (substructure) soft drop



Soft drop mass

Summary of dijet searches



Best constraints for $M_{Z'} < 250$ GeV from substructure techniques

Search for DM "X": Mono-jet

Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

Extreme signature:
One high-p_T jet recoiling against "nothing"

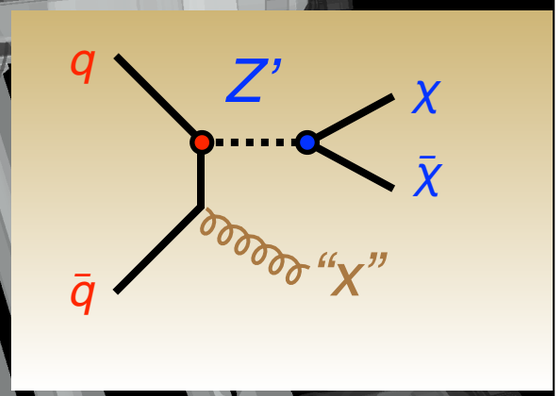
Jet
p_T = 1707 GeV

Hadronic calorimeter energy

EM calorimeter energy

Tracks

MET
MET = 1735 GeV



"Longitudinal" view

ATLAS-CONF-060

ATLAS EXPERIMENT

MET

Jet recoiling against invisible
(χχ)

Transverse view

Mono-jet

MET > 250 GeV

- Easy to trigger
- Kills **QCD**

(in addition to $\Delta\phi(j,MET) > 0.4$)

Lepton veto kills

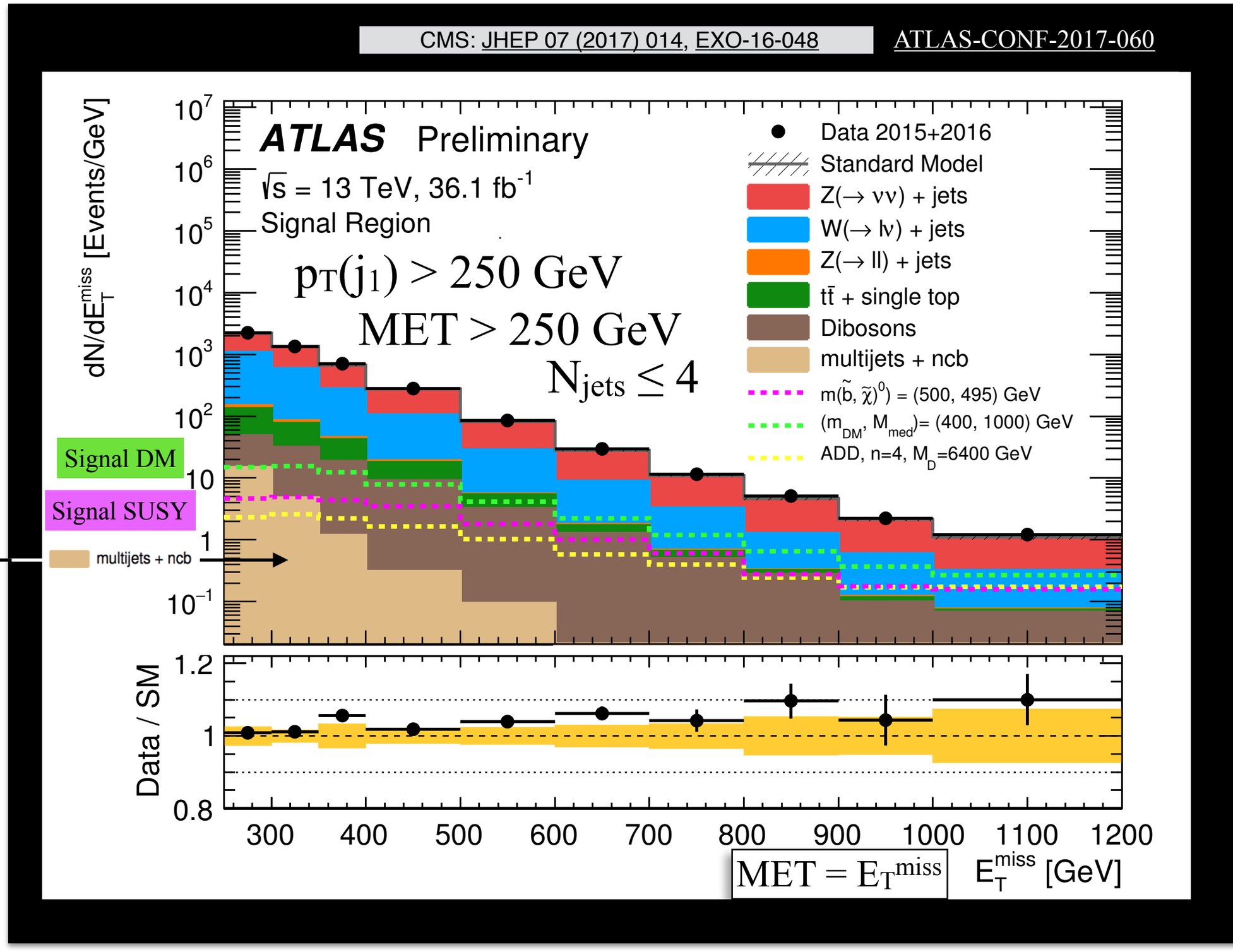
- Top (mostly)
- $W \rightarrow \ell\nu$

Blue background:

ℓ is not reconstructed

Mono-photon:
CMS EXO-16-039
ATLAS Eur. Phys. J. C. (2017) 393

CMS: JHEP 07 (2017) 014, EXO-16-048 ATLAS-CONF-2017-060



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

Mono-jet background estimation

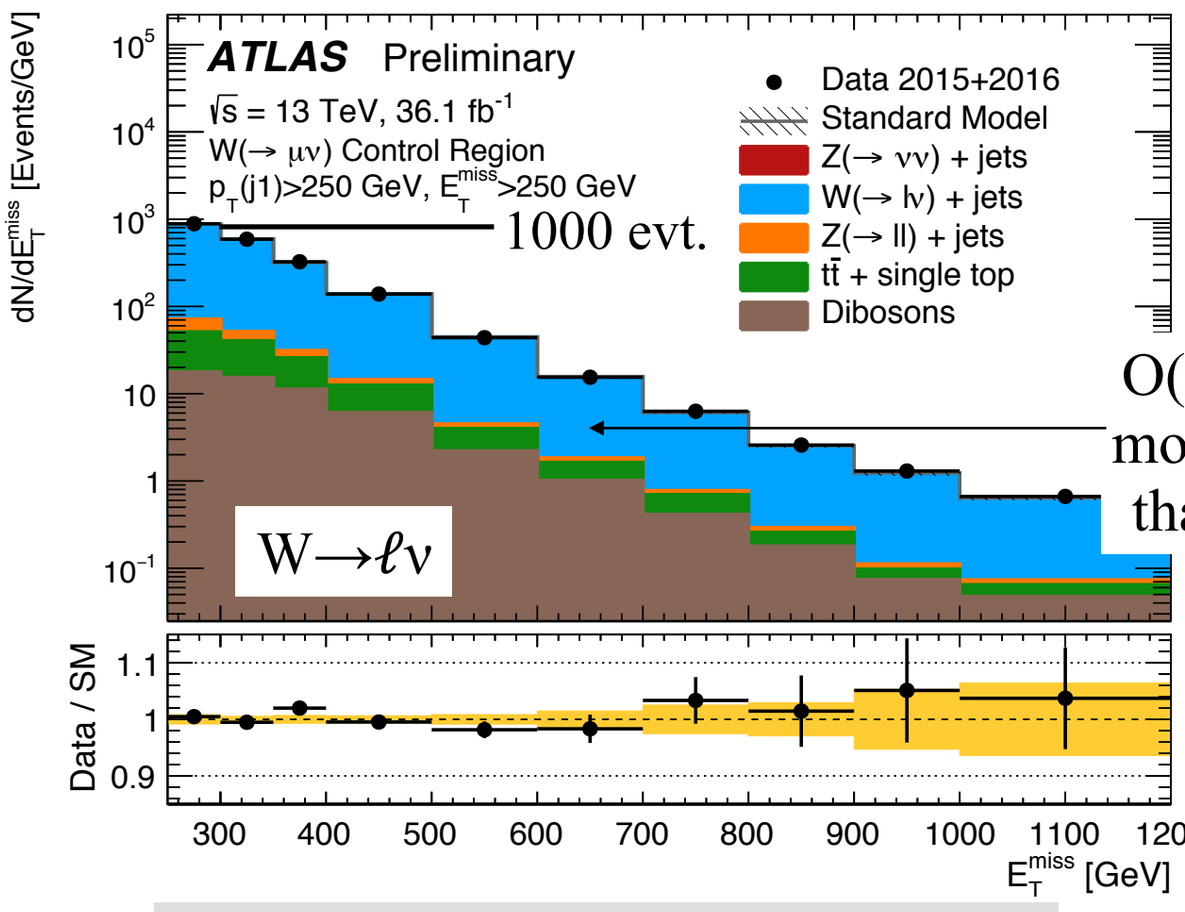
Estimate from CRs using simultaneous fit

- $W\to\ell\nu$
- $Z\to\ell\ell$

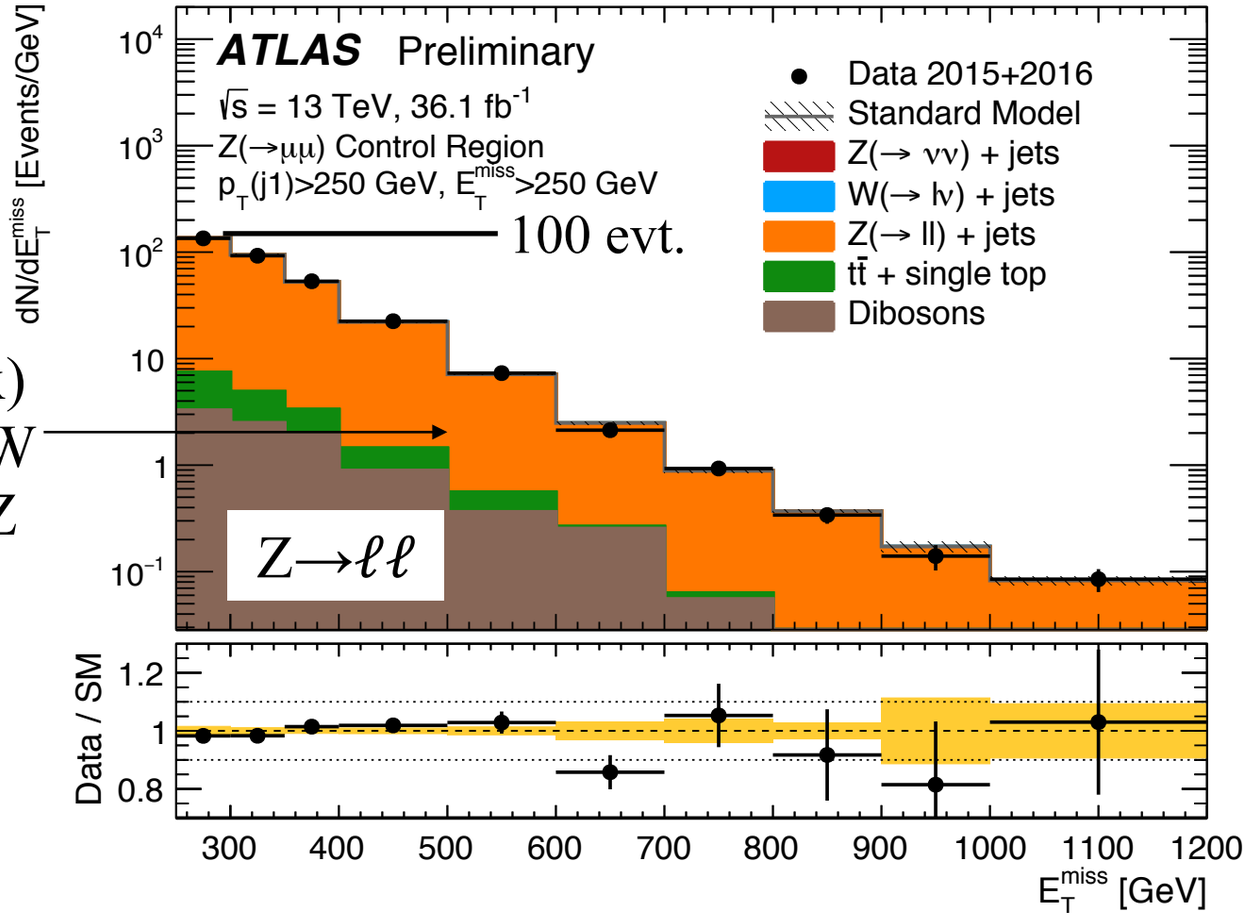
More CR stats:
Use $W\to\ell\nu$ to constrain $Z\to\nu\nu$

$W\to\ell\nu$ constraint motivated by branching fractions

- x10 more $W\to\ell\nu$ than $Z\to\ell\ell$
- Requires detailed calculation on correlations between W and Z
- Calculated at NNLO, J. Lindert et al. (arXiv: 1705.04664)



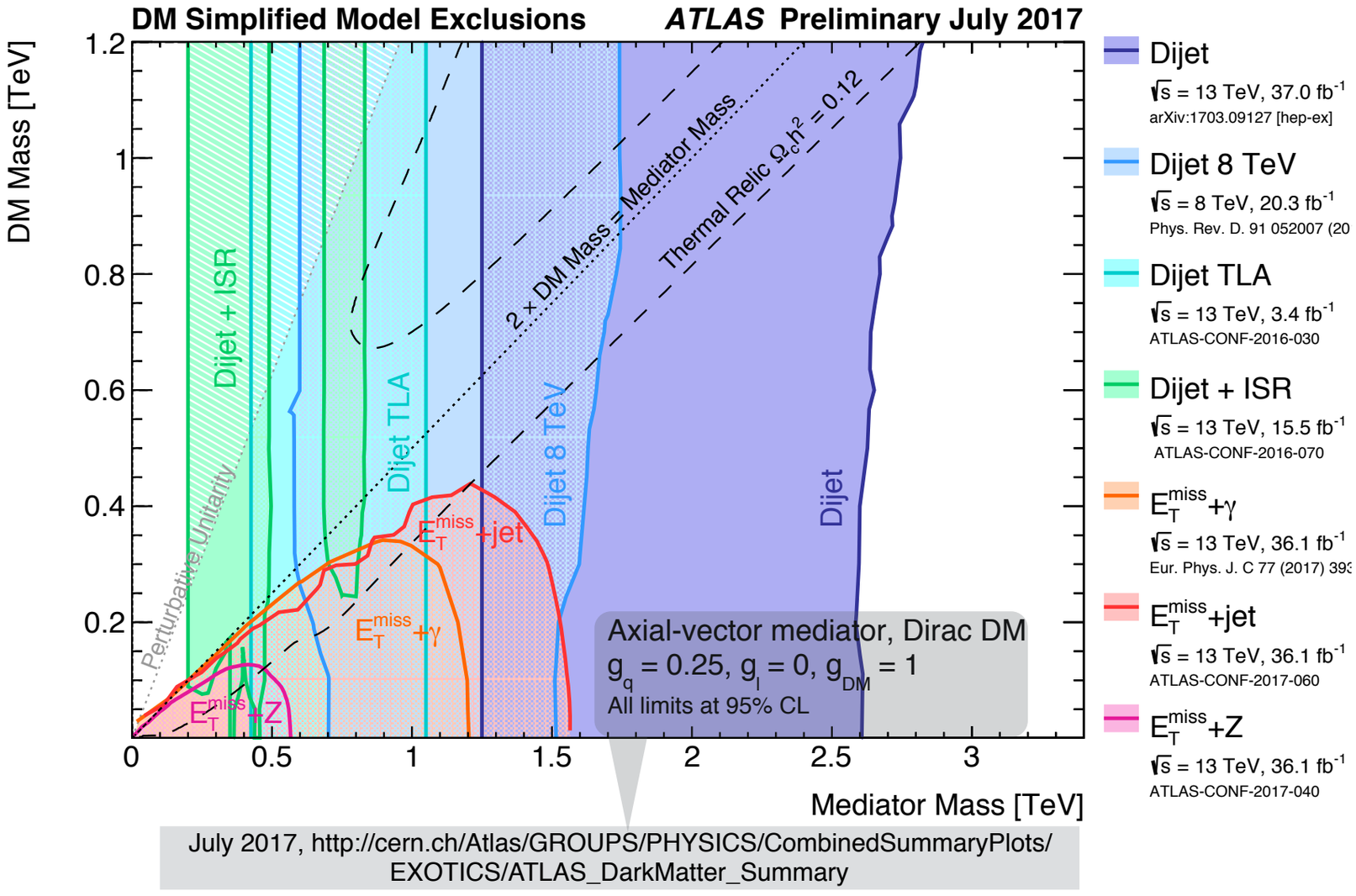
O(10x) more W than Z



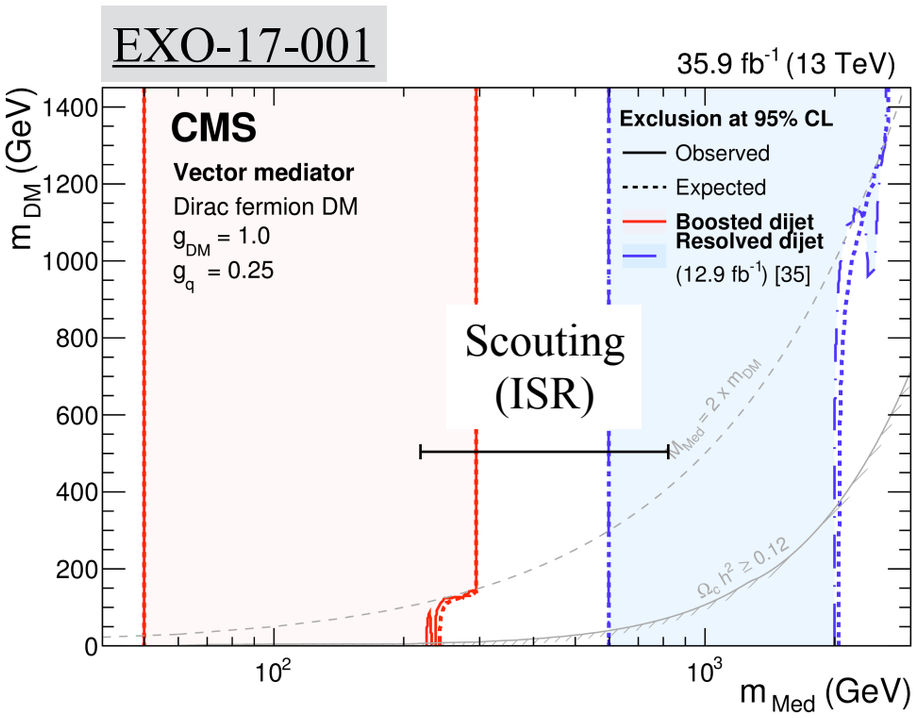
Systematic uncertainties
Jet energy scale (resolution): 0.5-5.0%
Theory: 0.5-2.0%

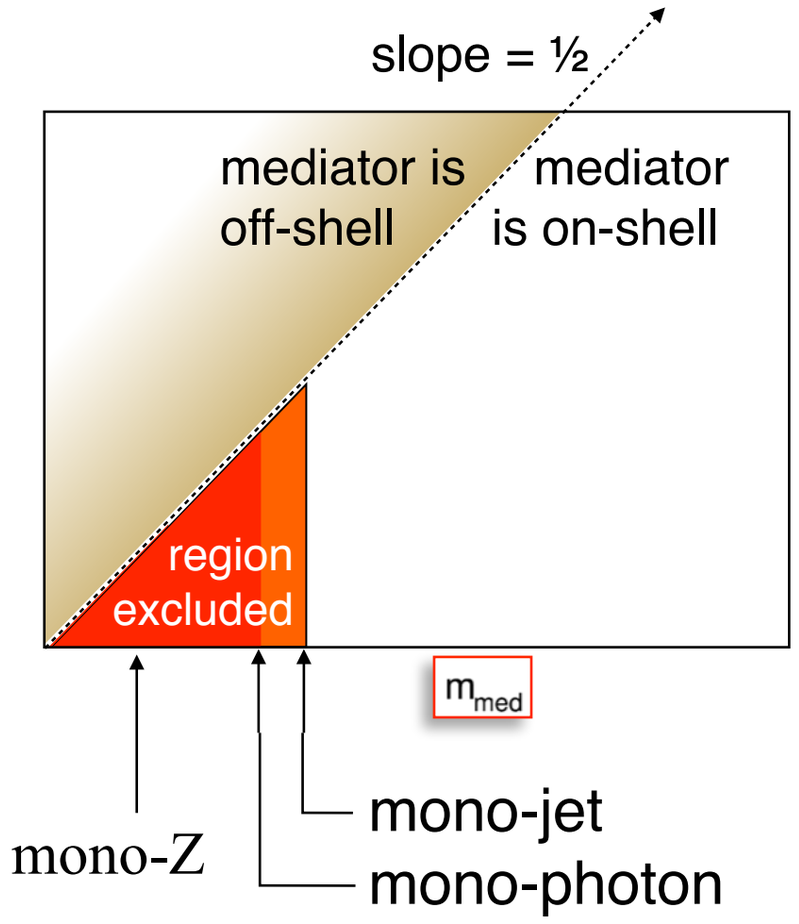
O(1000) $Z\to\nu\nu$

DM exclusions summary



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

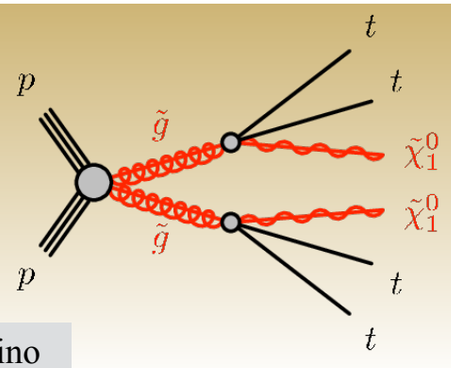




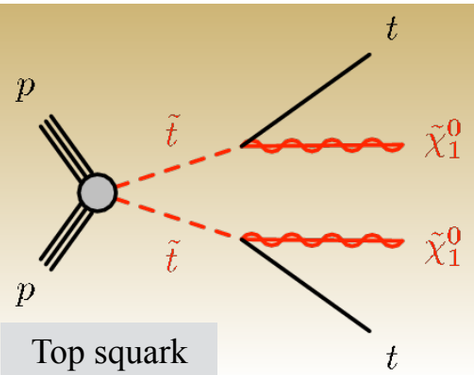
Vertical bands: covered by dijet searches (top right cartoon)
Triangular region: covered by mono-X (lower right cartoon)

Note: Discussed dijets, clean **dilepton** sensitive if $g_l > 0$.
Complimentary sensitivity (see backup)

Squarks & gluinos

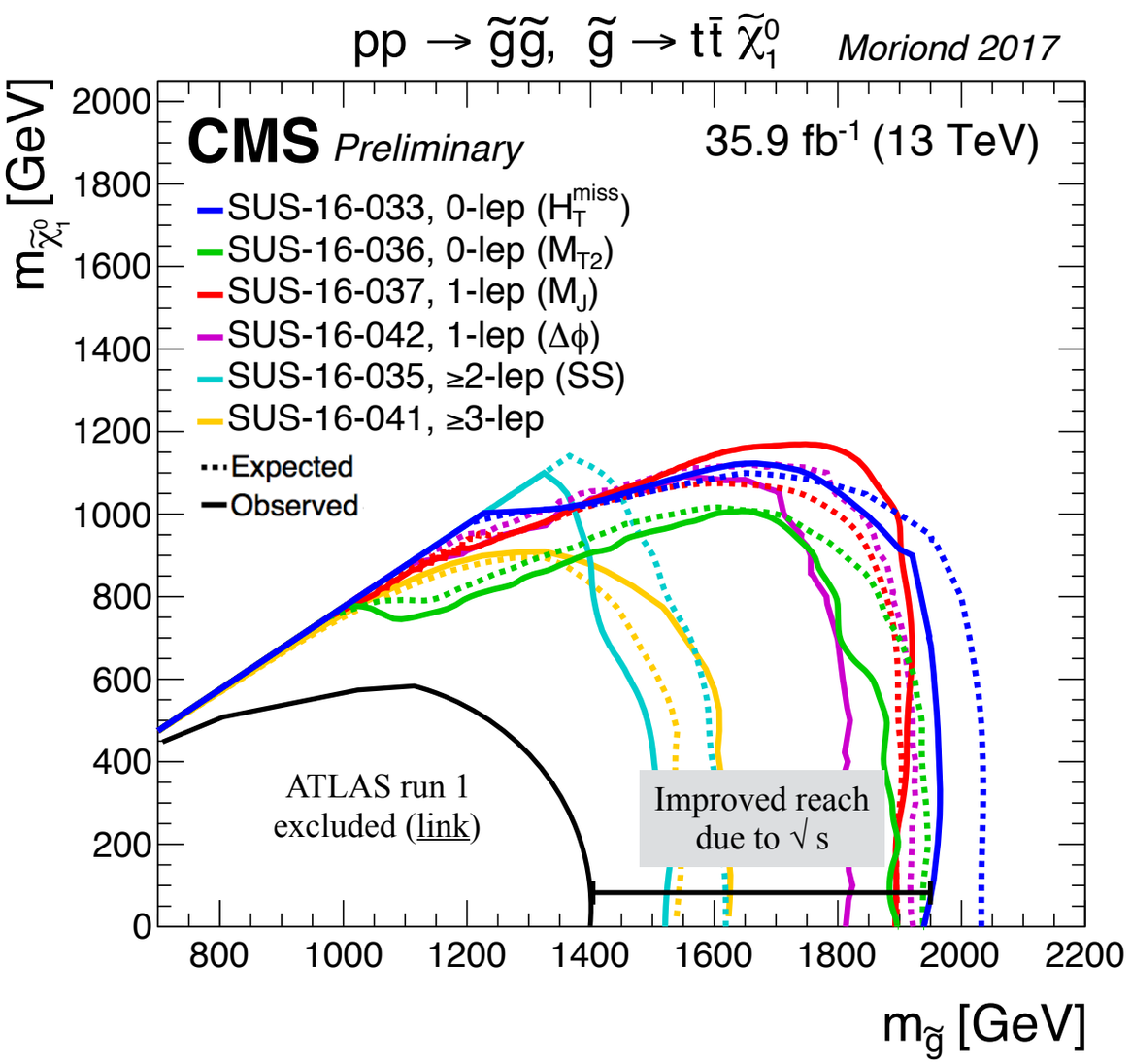


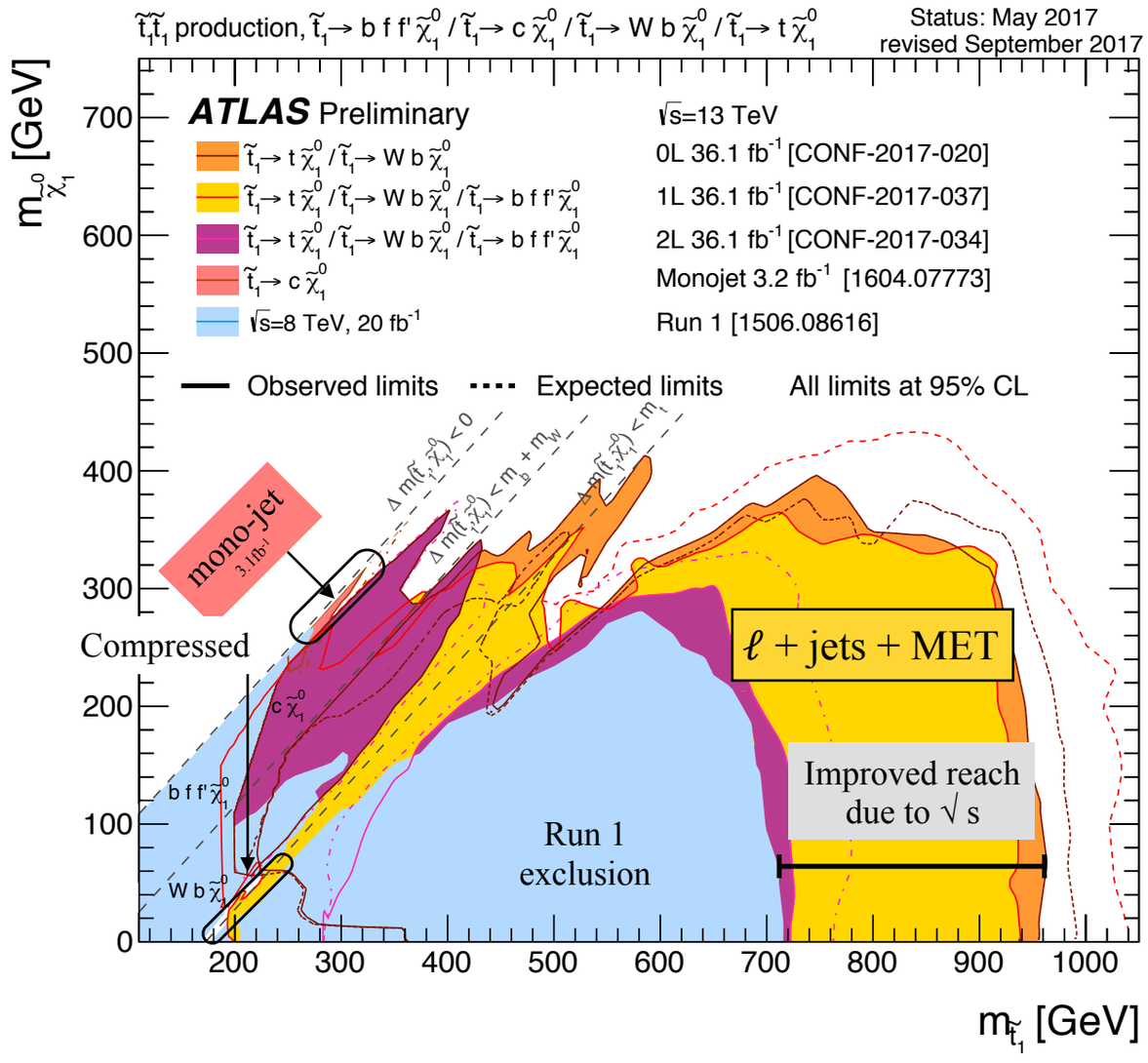
Gluino



Top squark

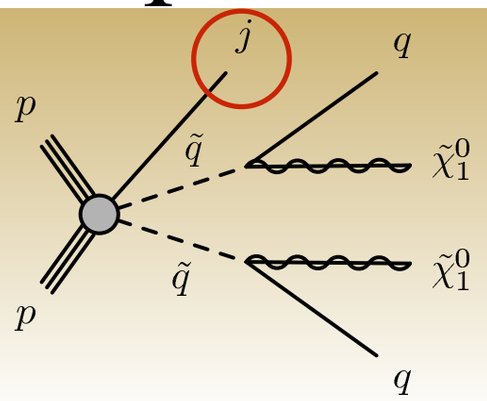
- *Often* high multiplicity events (jets, lepton)
- Compare with DM where usually just X





Some difficult holes in compressed regions,
M(top squark) - M(top) < 5 GeV

Compressed SUSY with mono-jet

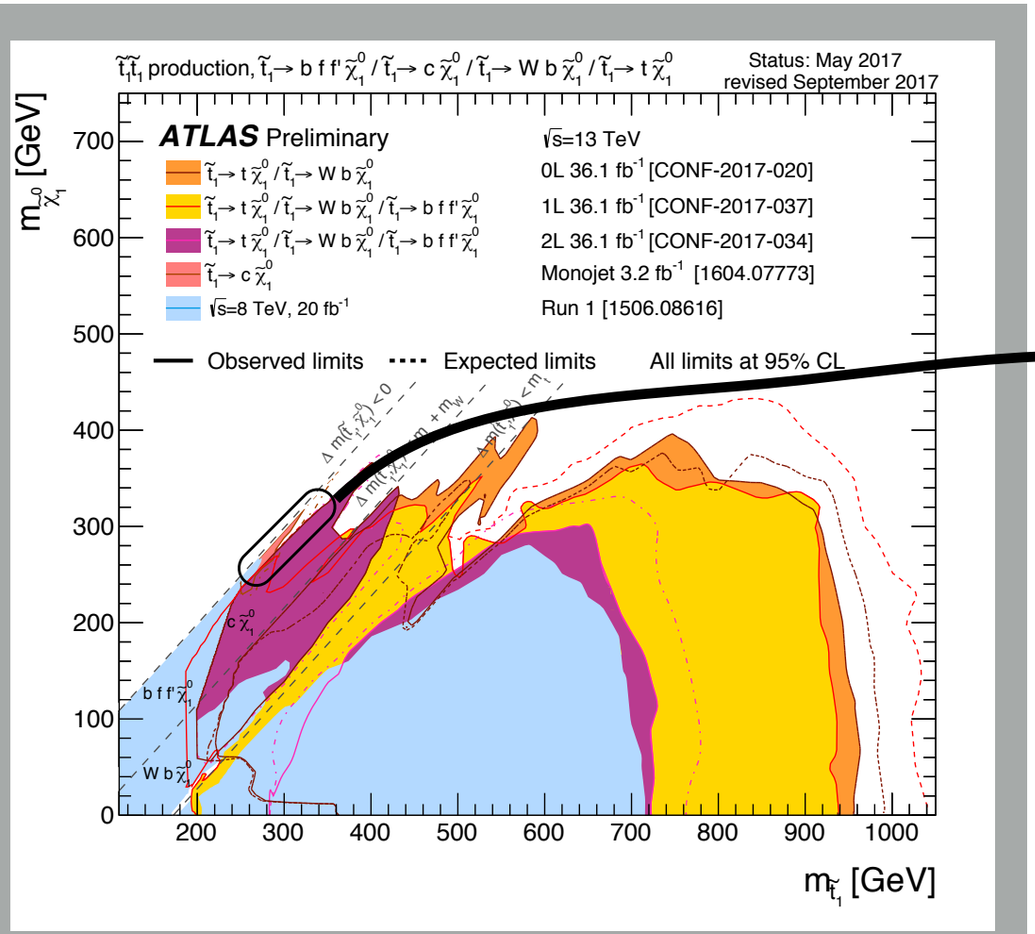


ISR jet

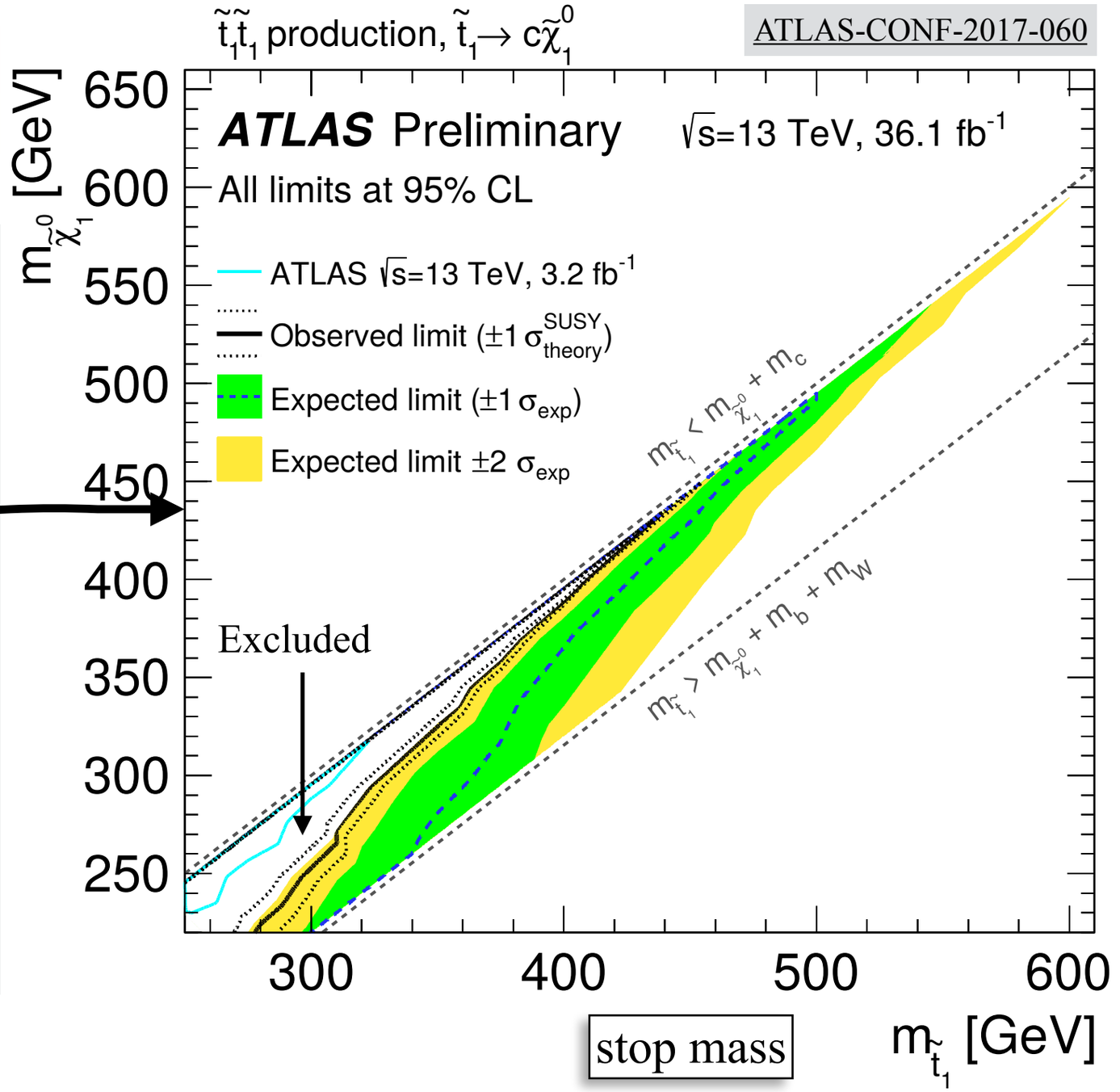
Boost the system with a hard ISR jet

- Invisible decay products would otherwise be too soft
- Improves sensitivity for compressed scenarios (mass splitting small)

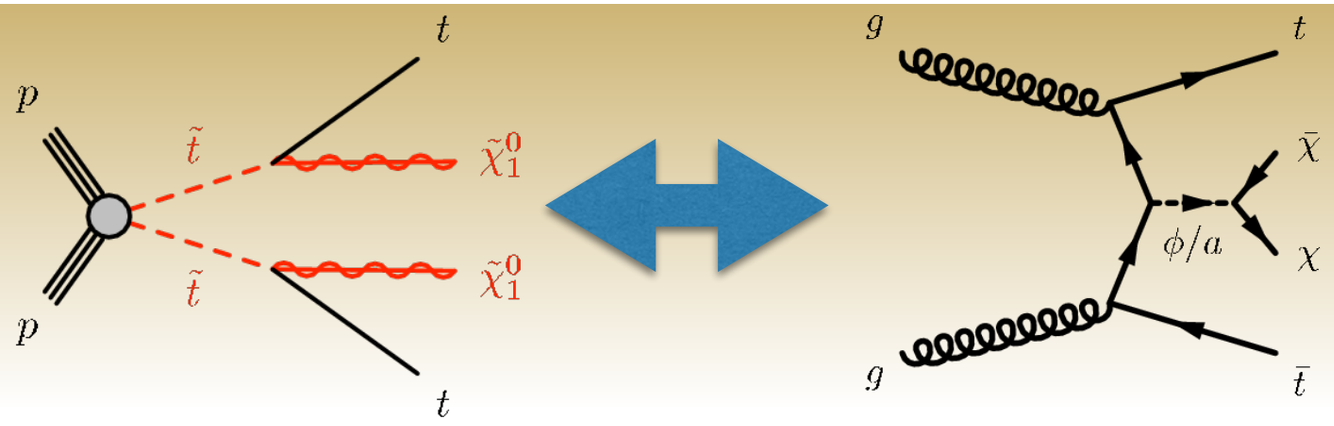
Sensitivity to compressed region from mono-jet



Also sensitive to squarks and sbottoms



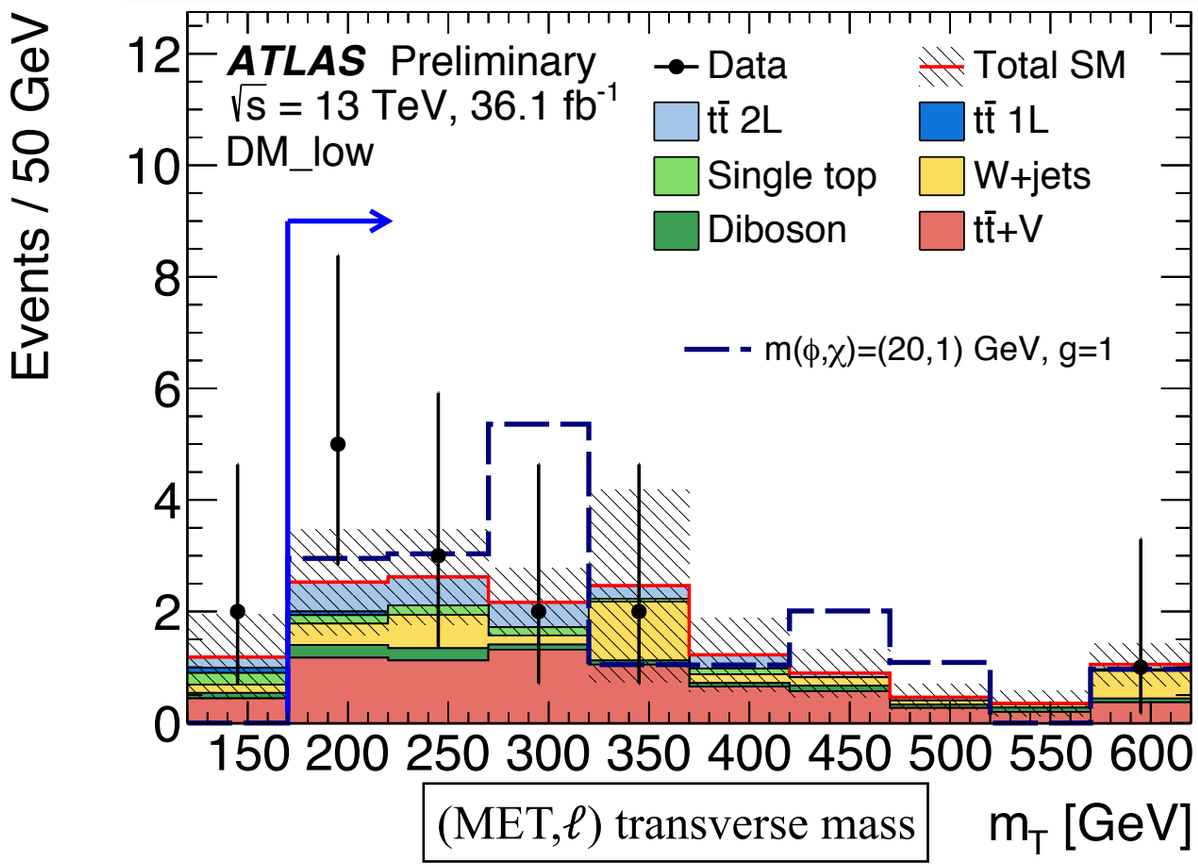
SUSY searches also look for DM



ℓ + jets + MET

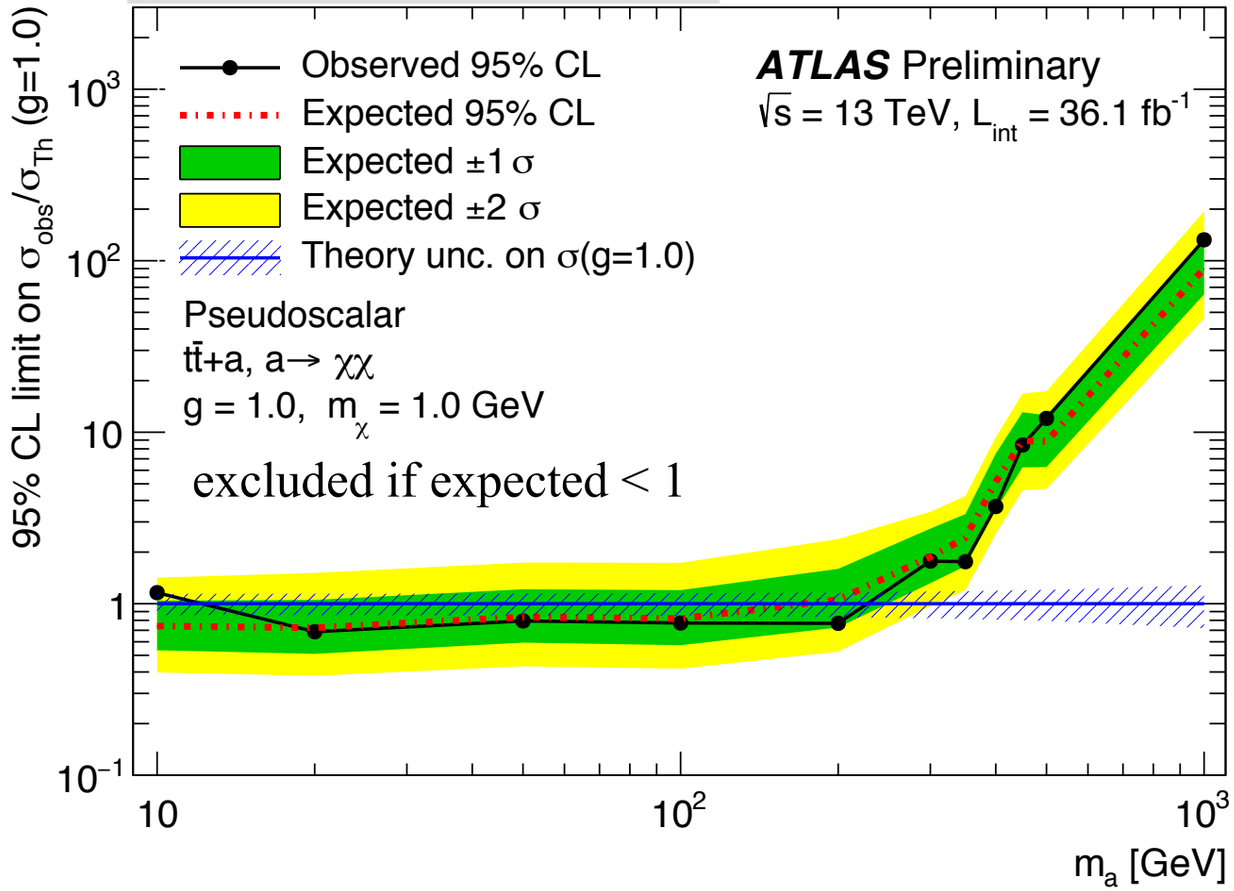
- Significant sensitivity improvement (yellow band on exclusion curve)
- **13 SR** optimized signal regions

Dedicated bin optimized for DM



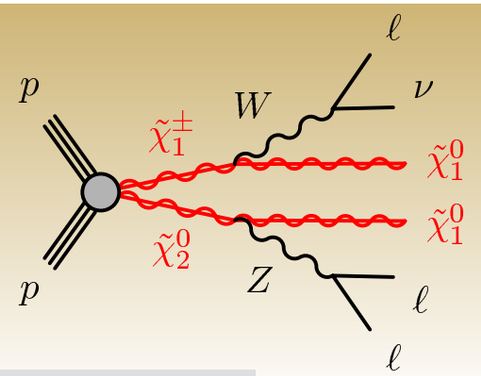
$p_T(e)$ or $p_T(\mu)$ > 5 GeV or 4 GeV
MET > 320 GeV
Njets ≥ 4

ATLAS-CONF-2017-037



EW SUSY

ATLAS-CONF-2017-039



EW SUSY production

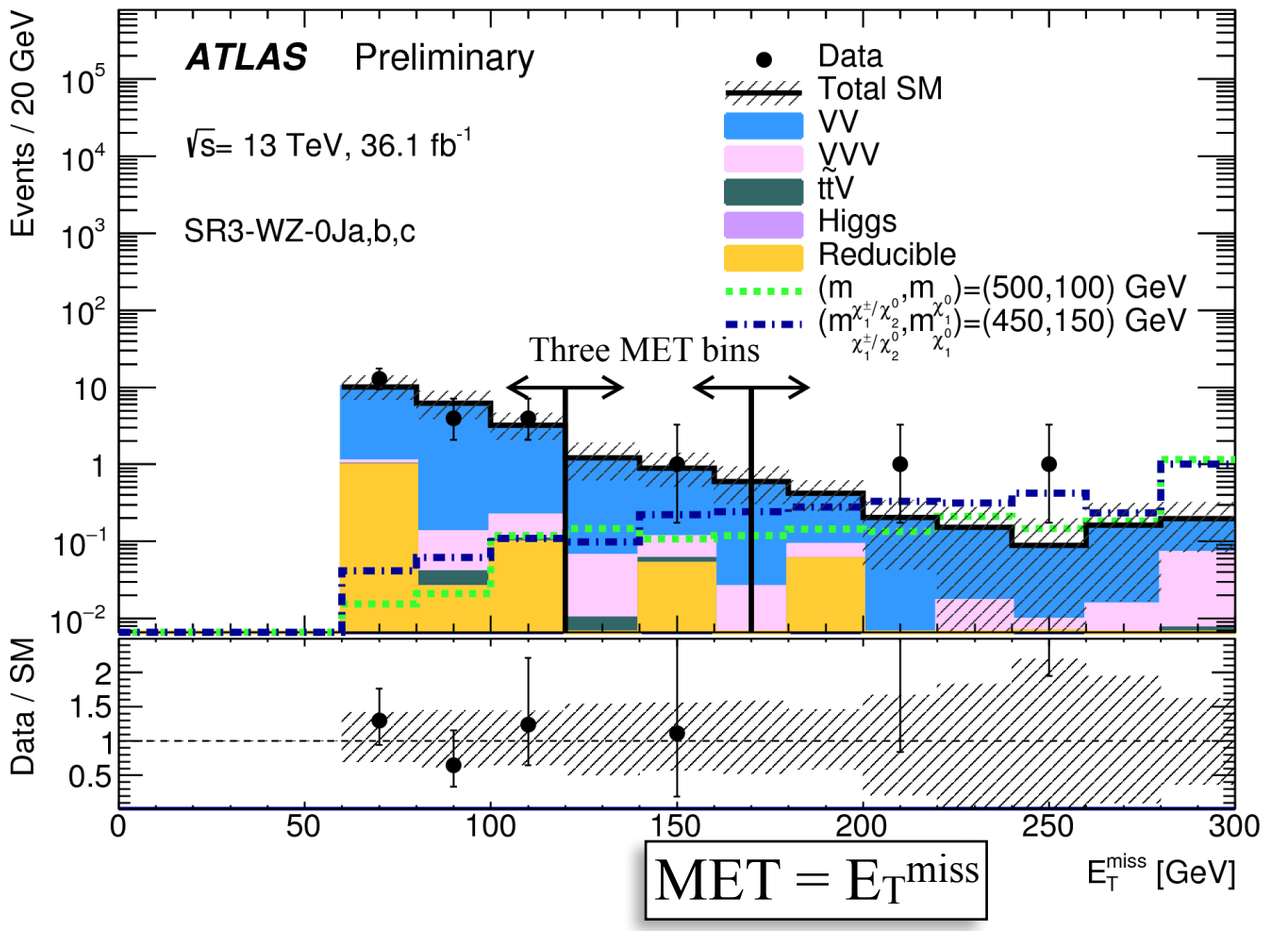
One example of EW SUSY (left) decays to W(Z)

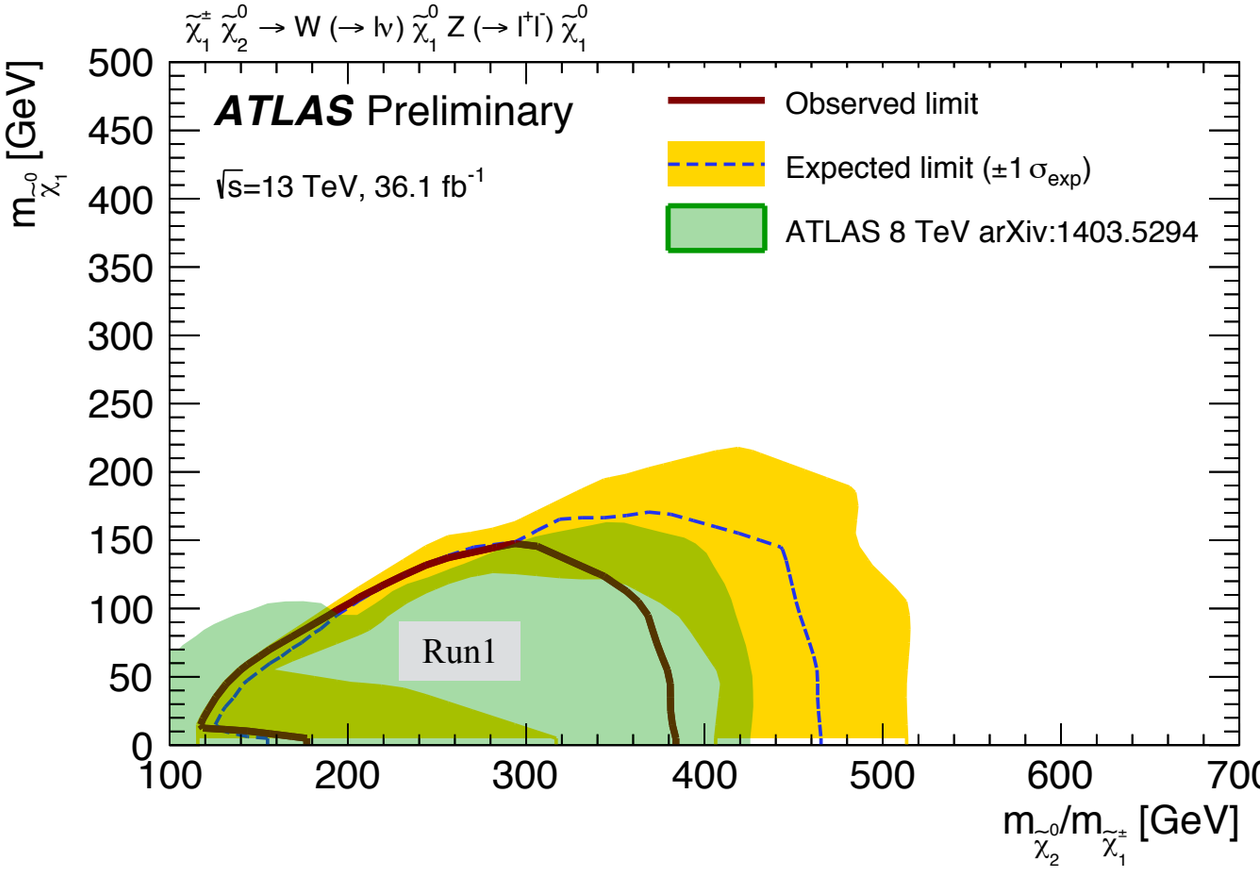
- Target leptons + MET
- 2 leptons: same sign, opposite sign
- >3 leptons

Sensitivity to other diagrams…

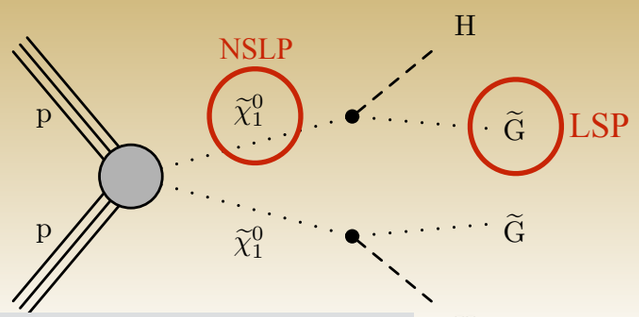
Three leptons
ℓ = e,μ, $p_T(\ell) > 10$ GeV
At least one opposite sign pair:
$81 < M(\ell\ell) < 102$ GeV

+ many more bins





EW SUSY: HH



EW SUSY production in GMSB

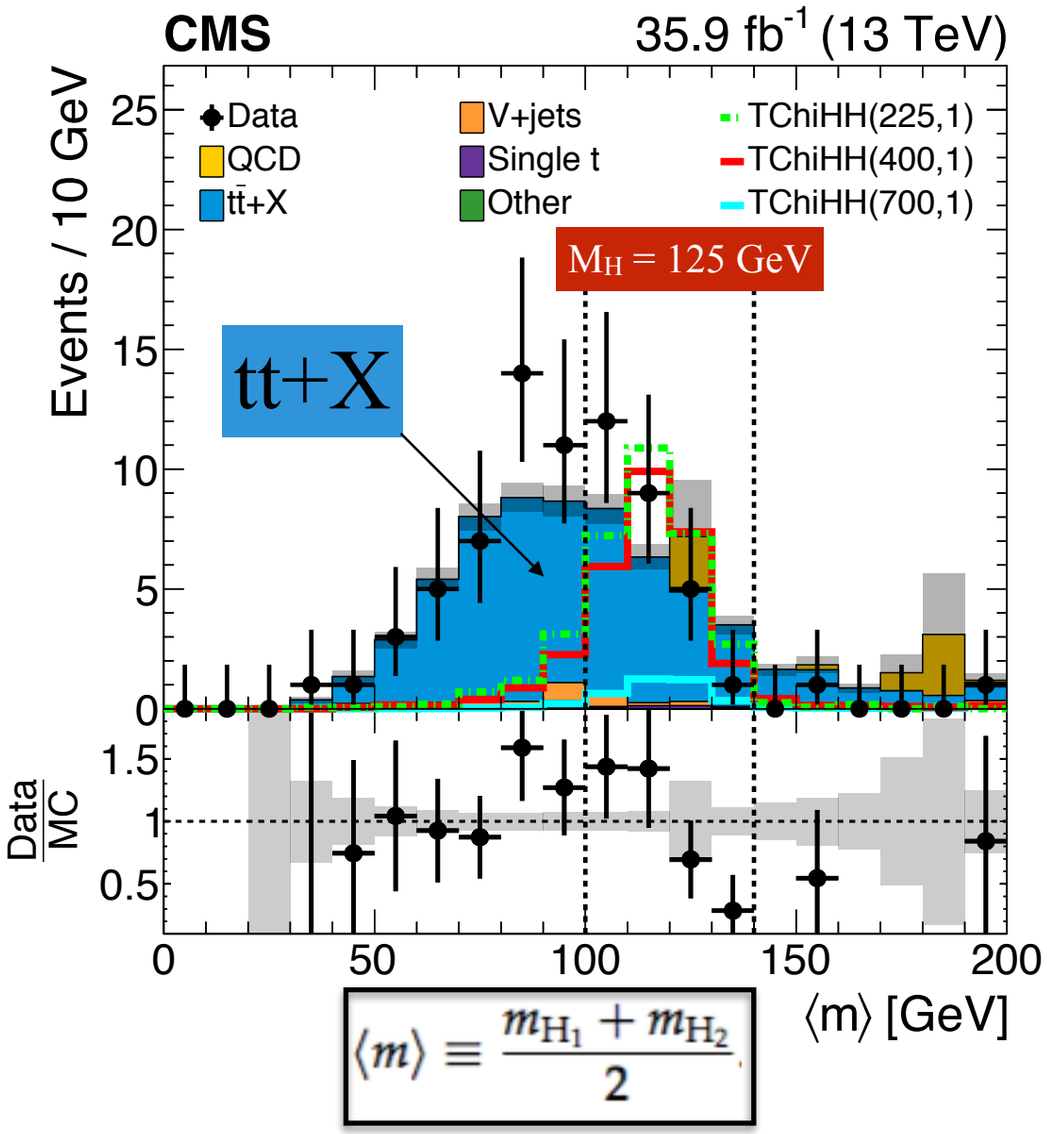
EW SUSY production, decays to H (Z)

CMS: SUS-16-044
CMS: SUS-16-039

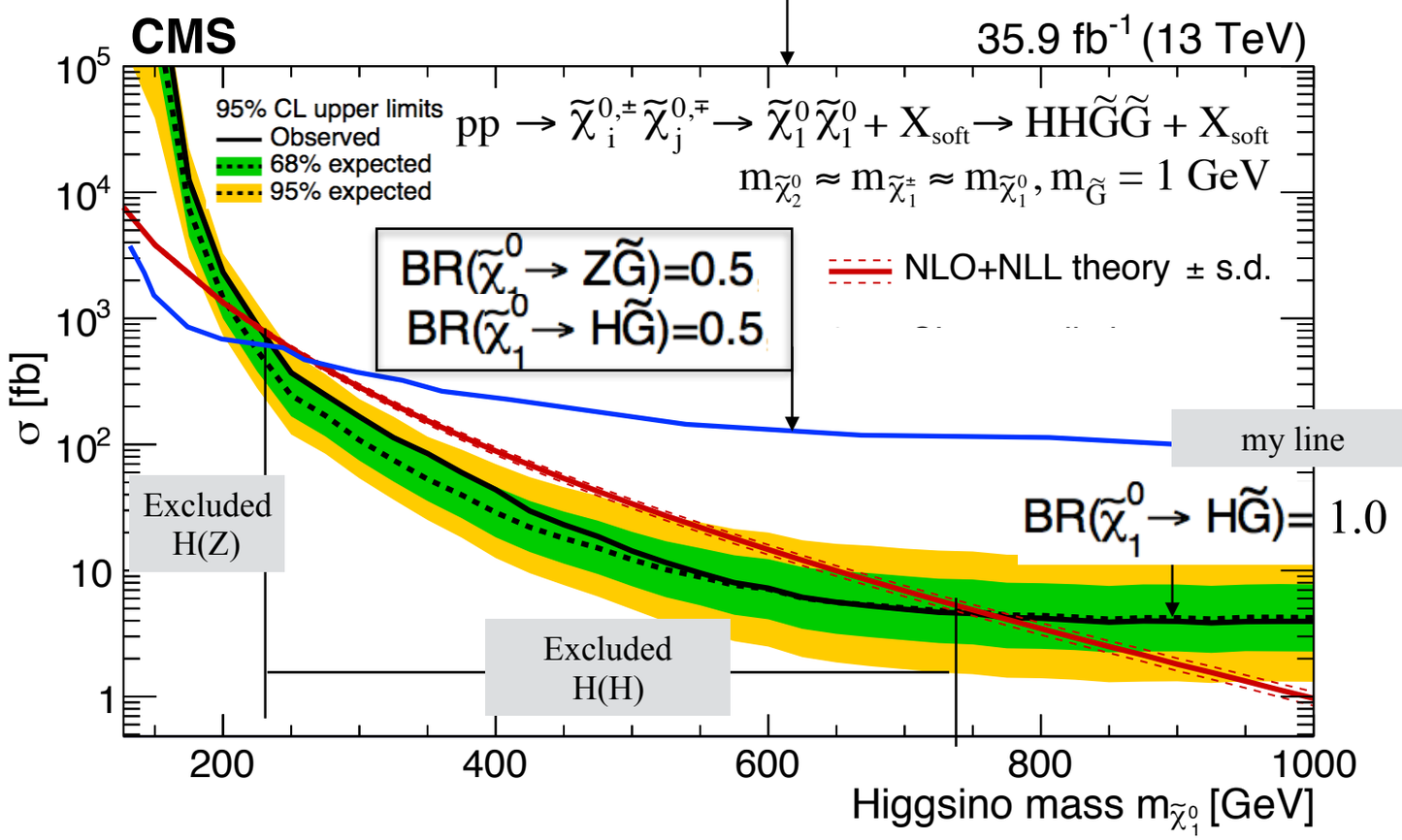
HH + MET search
- Trigger: MET
- Highest Br: $H \to bb$, 4 b-jets
- MET > 150 GeV

HZ → leptonic searches
(similar to last slide)

Combinatorics from 4 jets, pick
the one that minimizes $\Delta m = |m_{H1} - m_{H2}|$

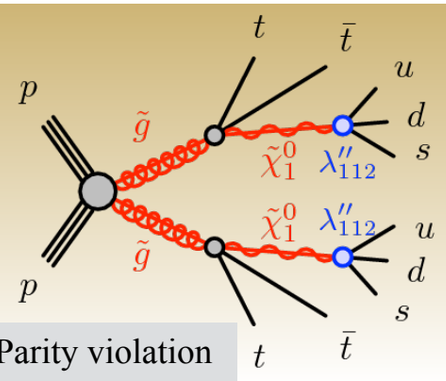


χ^0 ($\chi^\pm$) ~ mass degenerate (but large enough to be prompt)
χ^0 gets a cross section boost

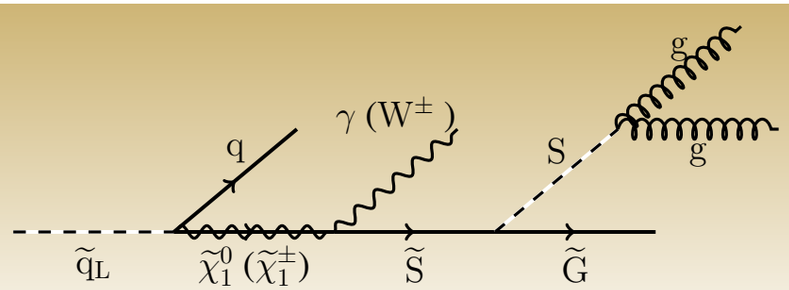


Turn on coupling to Z (blue line):
better sensitivity at low mass

Hidden SUSY: low MET



R-Parity violation



Stealth SUSY

Some models trade MET for multiplicity

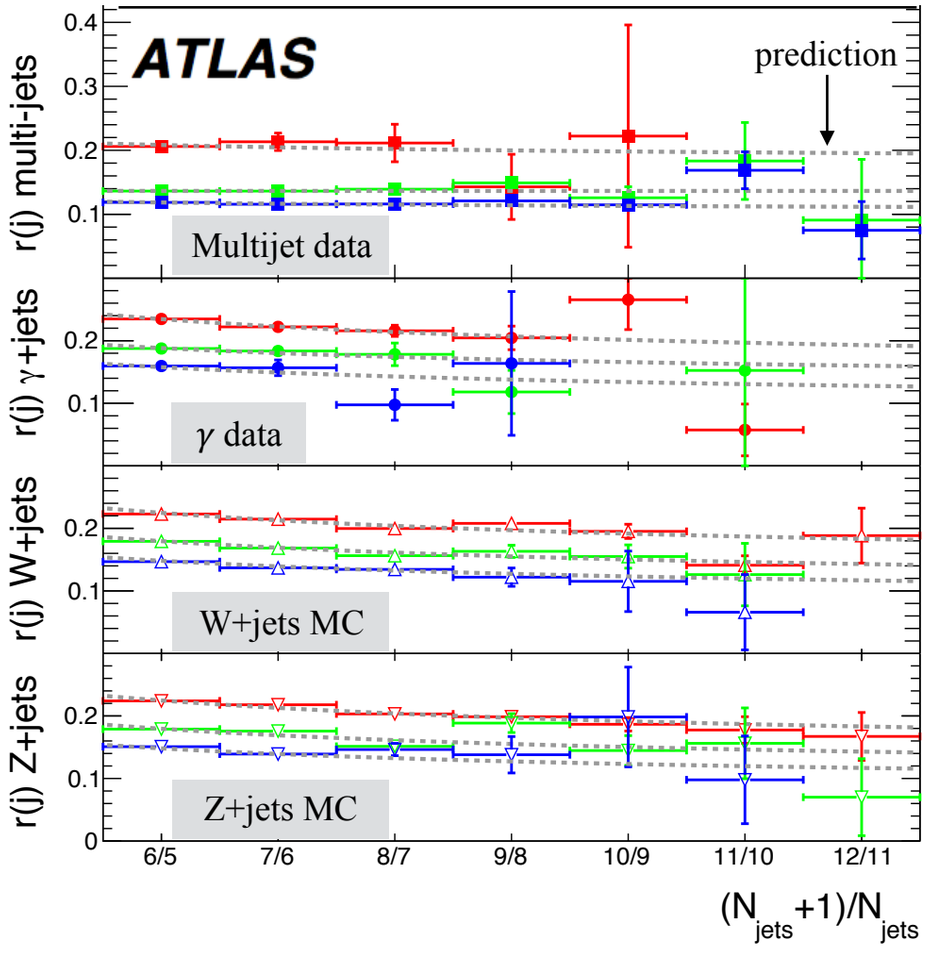
- R-parity violation, stealth SUSY
- New general *ATLAS* ℓ + jets search

Partially in response to J. Evans, Y. Kats, D. Shih, M. Strassler JHEP 1407 (2014) 101

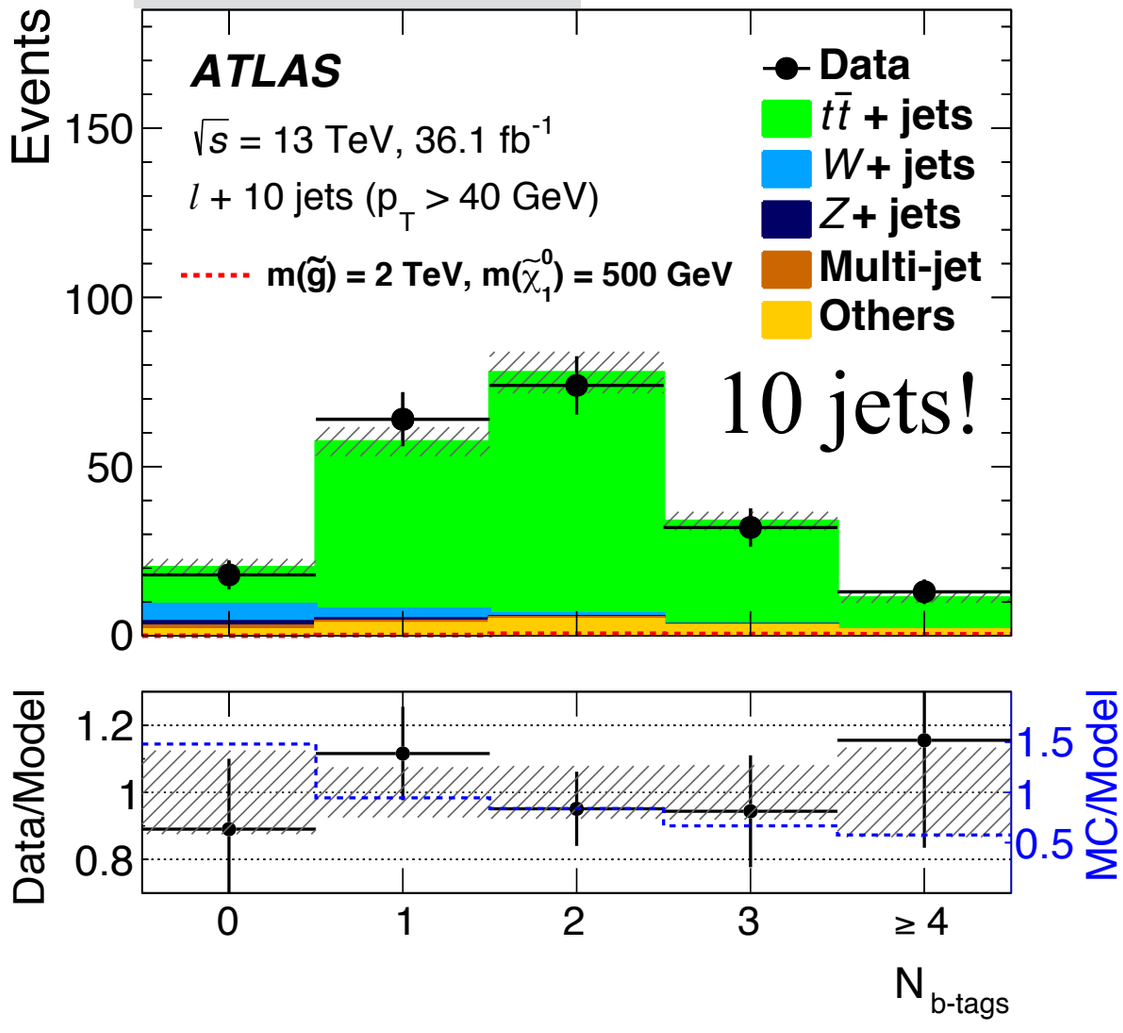
Non-exhaustive list of SUSY searches without MET

ATLAS searches	CMS searches
ATLAS-CONF-2017-036	Phys. Lett. B 743 (2015) 503
ATLAS-CONF-2017-025	Phys. Lett. B 770 (2017) 257
	Phys. Lett. B 760 (2016) 178

Background estimate: Poisson scaling
Ratio independent of Njets



JHEP 09 (2017) 88

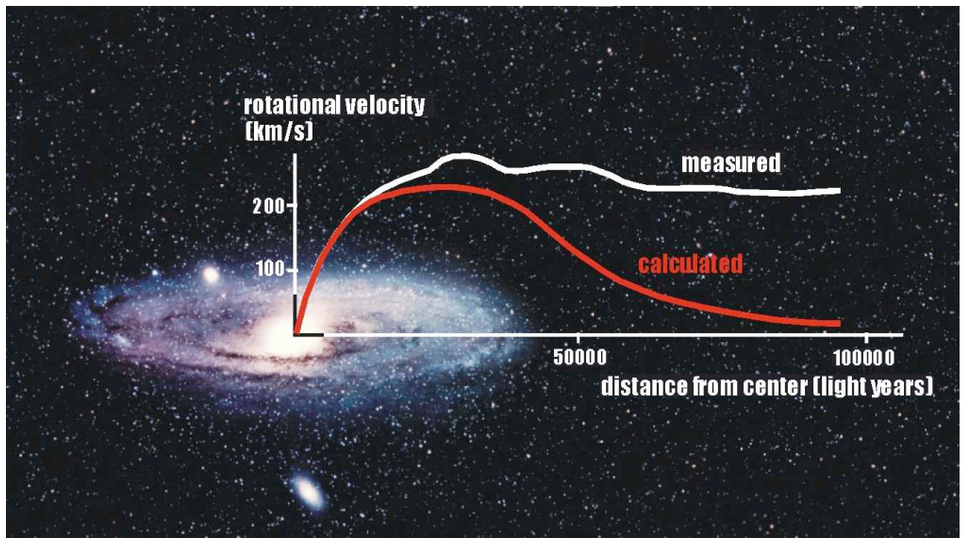


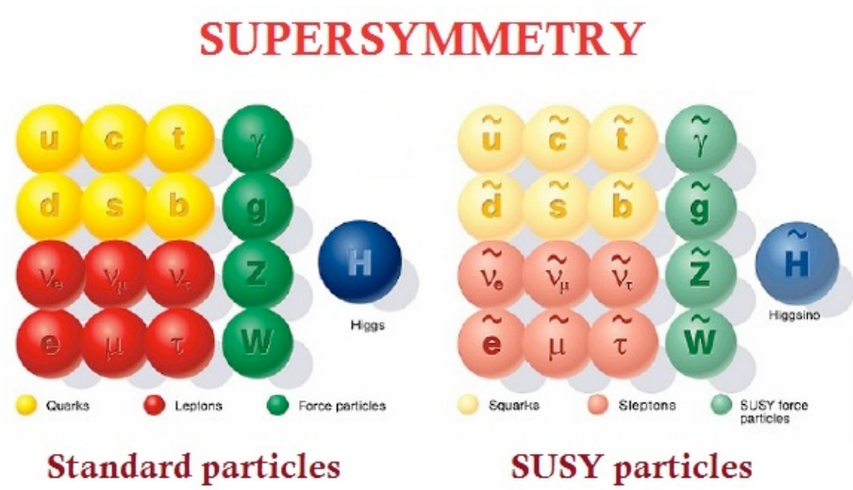
Conclusion

Started with two general guiding principles

- Dark matter
- Naturalness

Discussed searches for both SUSY and Exotics





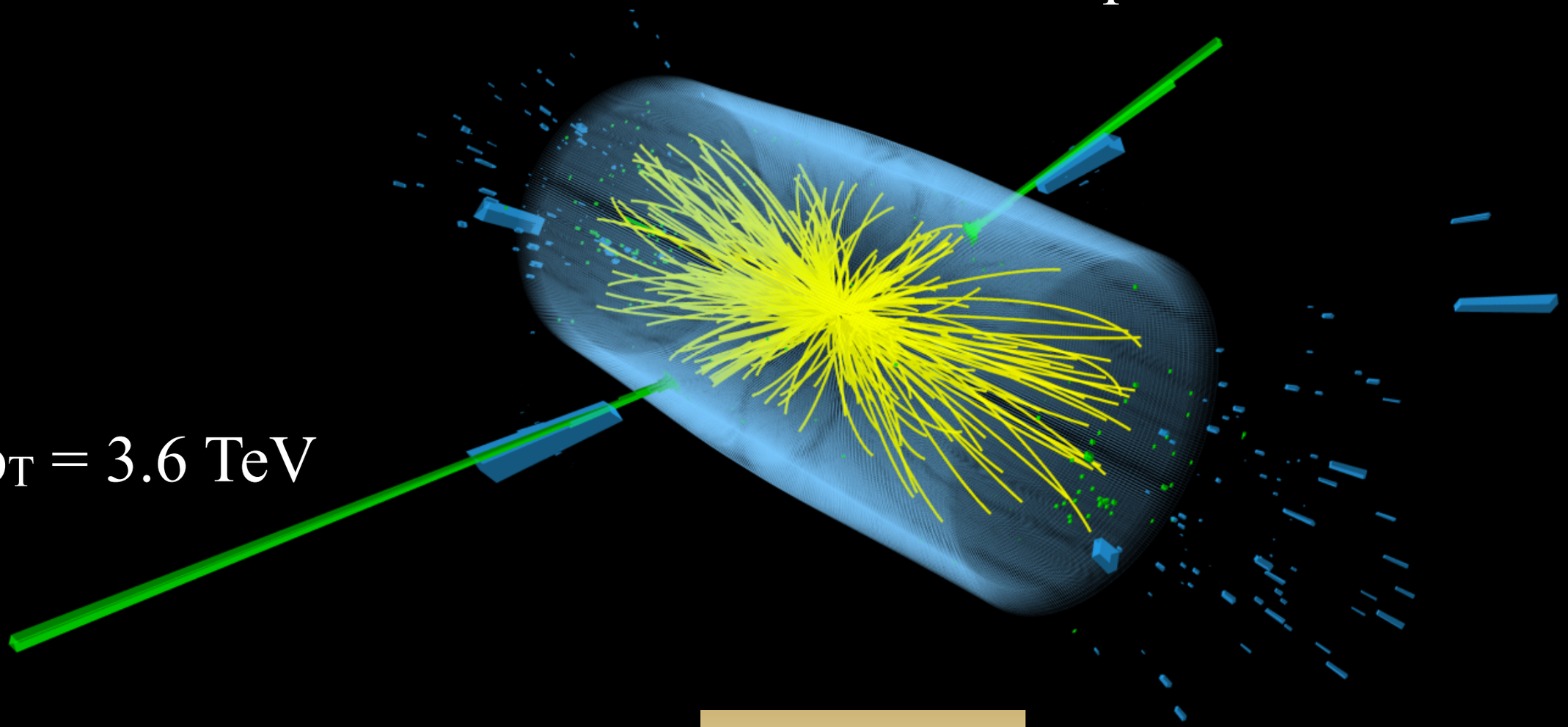
credit: CERN

- Searching for SUSY and exotics can have a significant overlap

Backup

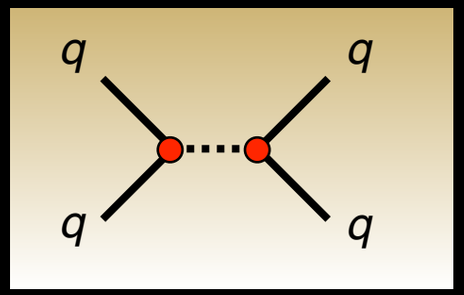
Among the highest dijet mass event recorded: *mjj = 7.7 TeV*

p_T = 3.4 TeV



p_T = 3.6 TeV

Direct mediator search: dijet events



e.g., di-jet

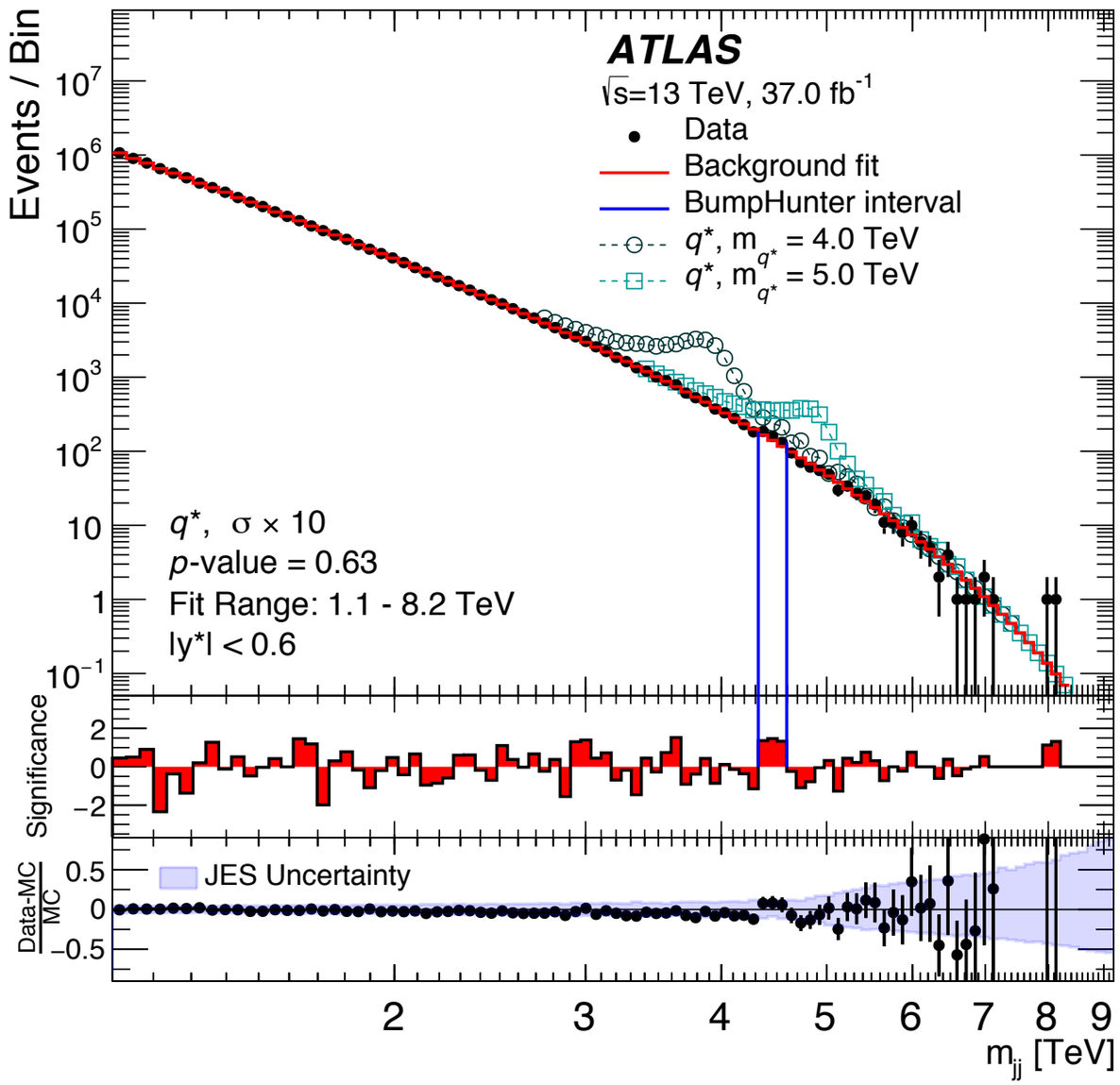
mediator

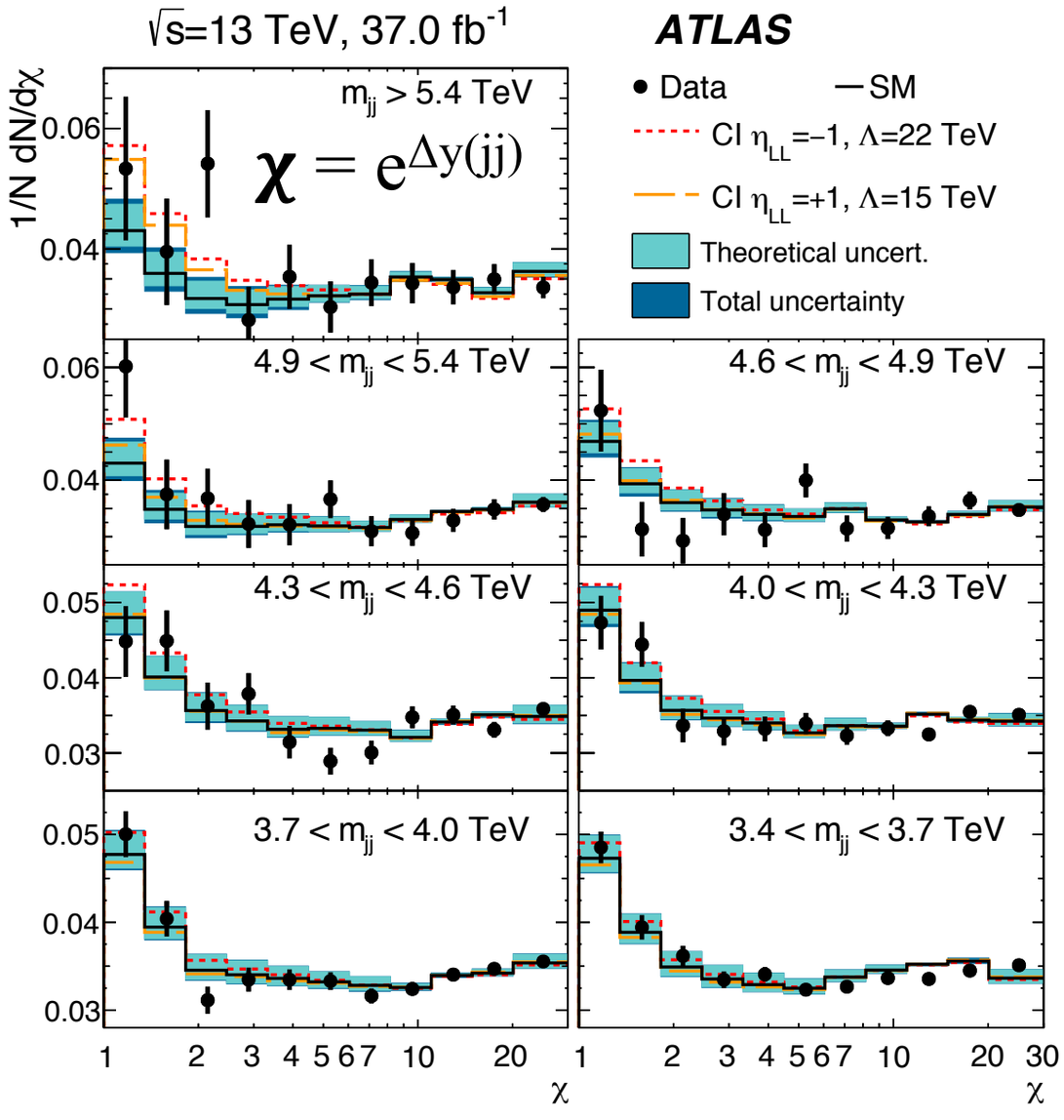
From August 2016, [CDS: 2203615]

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

Angular variables

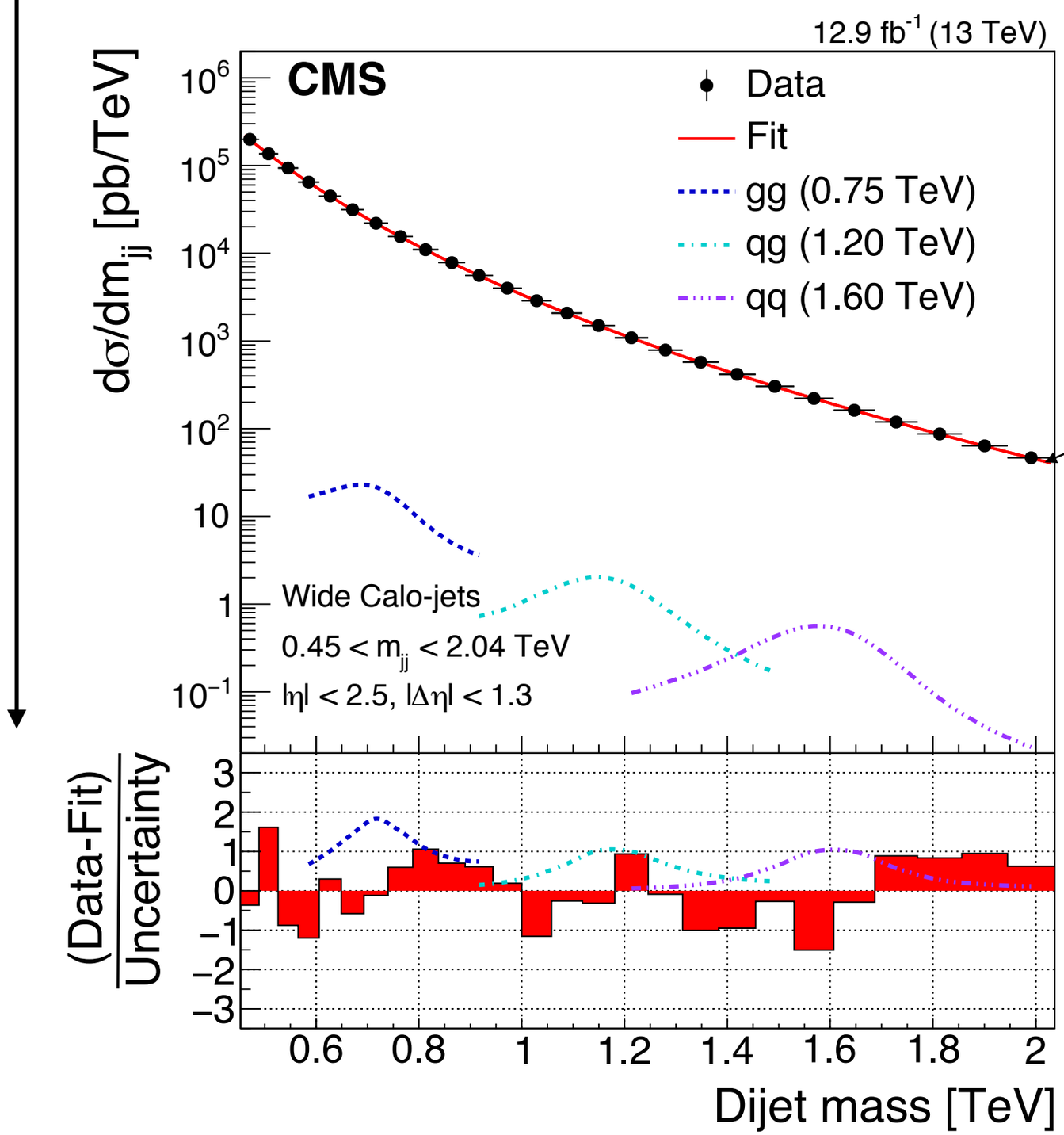
- Also look at angular variables for each *mjj* bin (right)

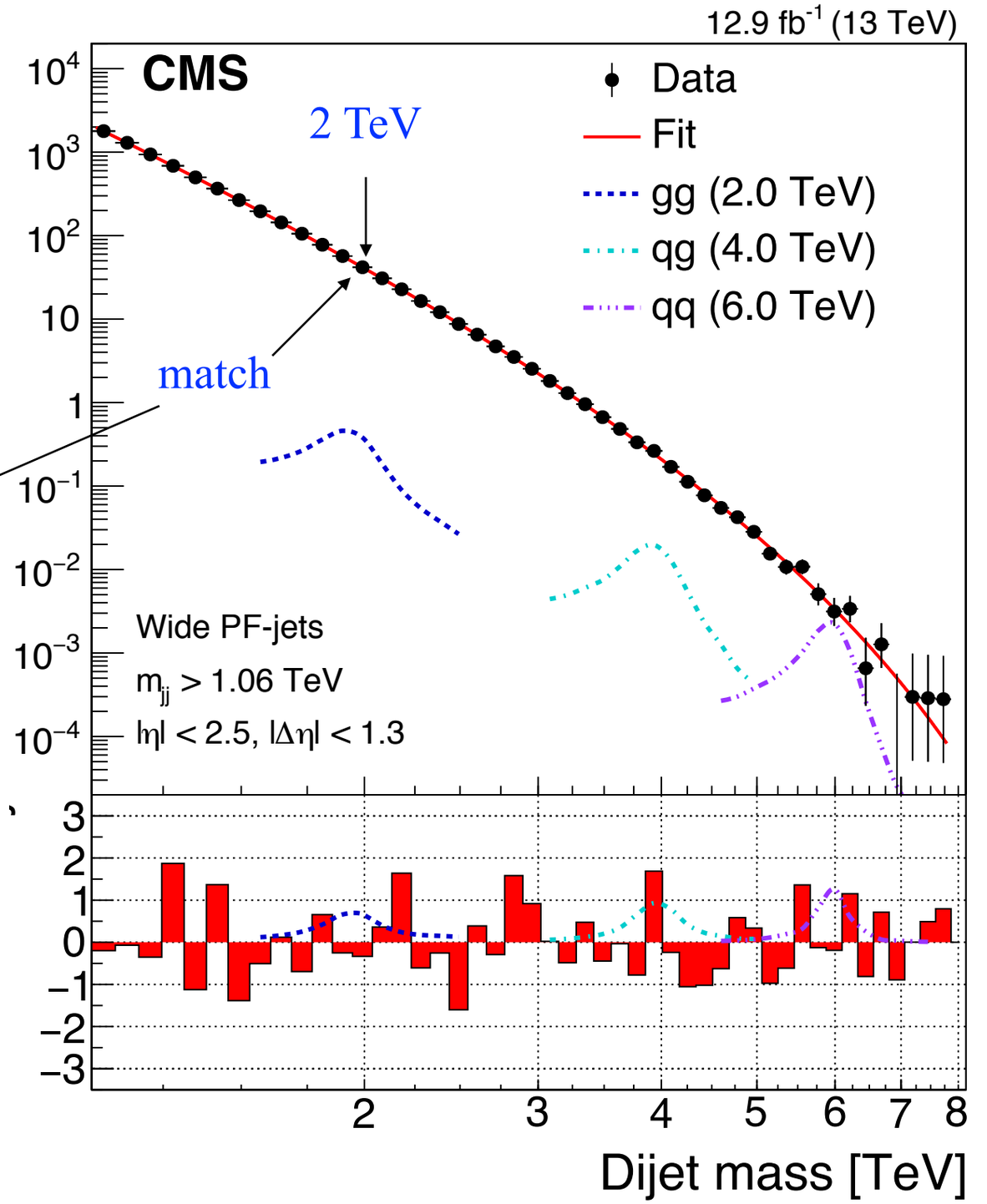




CMS dijet search

9 orders of magnitude!

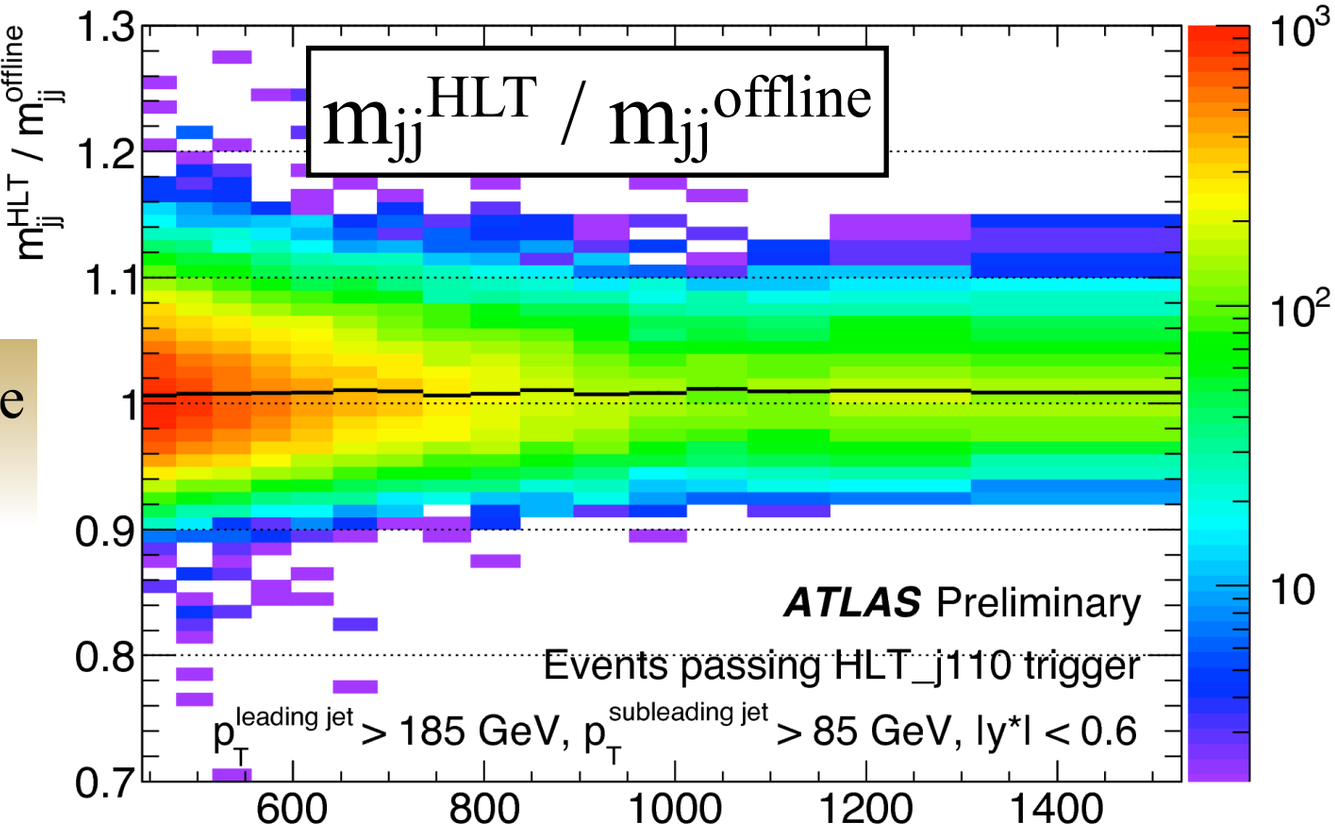




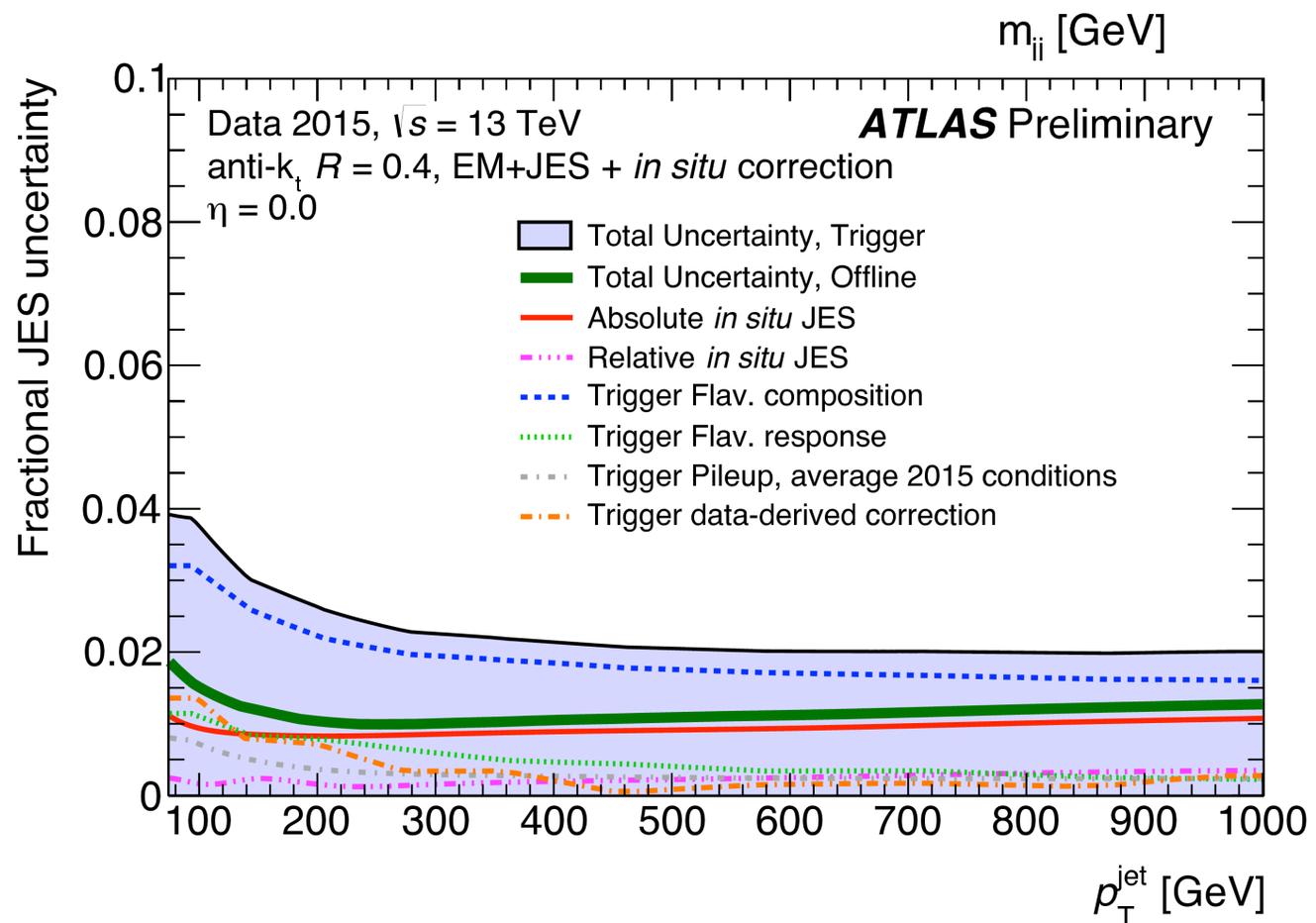
PLB 769, (2017) 520
PRL 117 (2016) 31802

ATLAS TLA details

Validation of HLT jets with respect to offline jets.

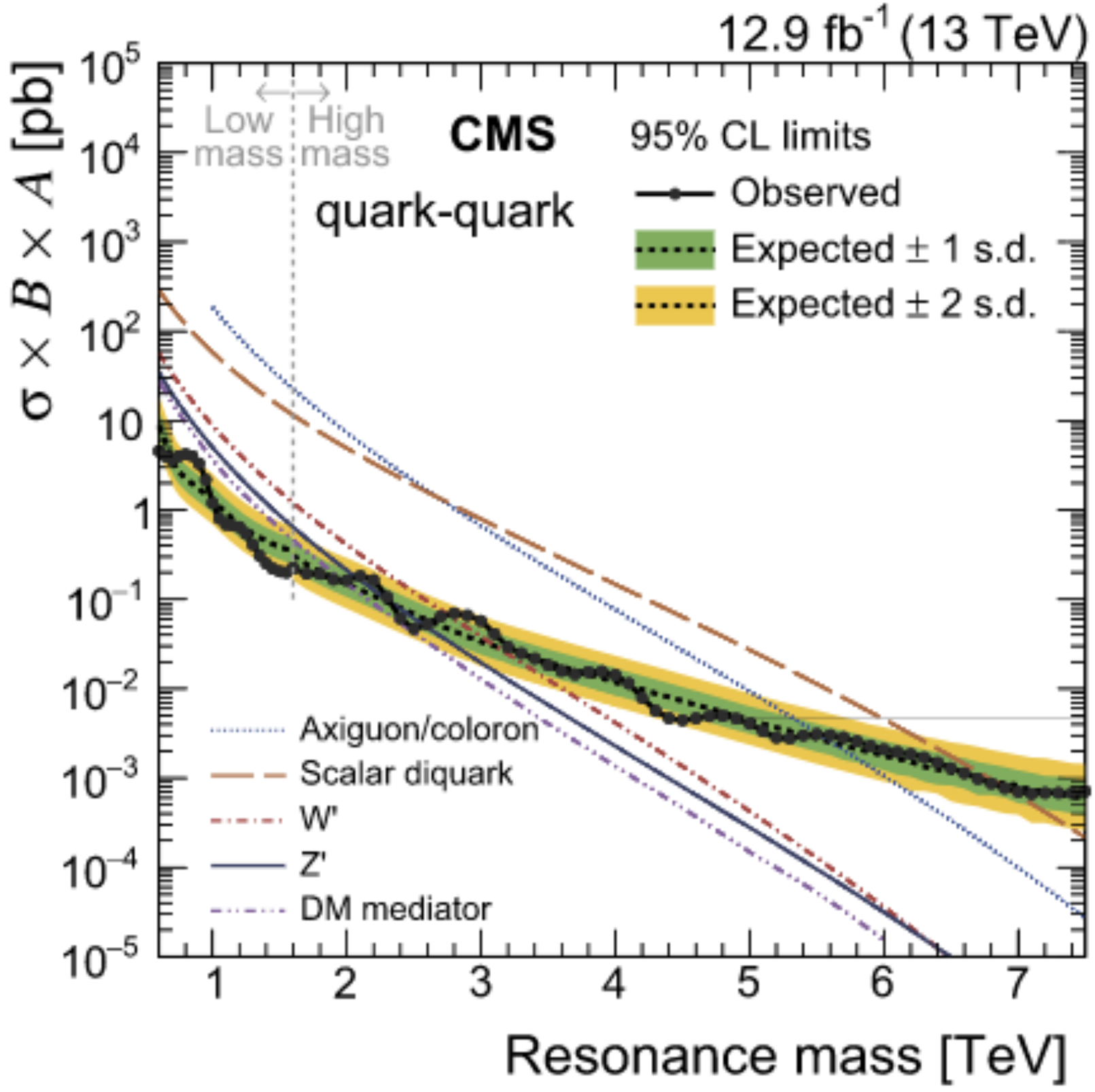


Jet energy scale, comparing the JES in the HLT vs. offline



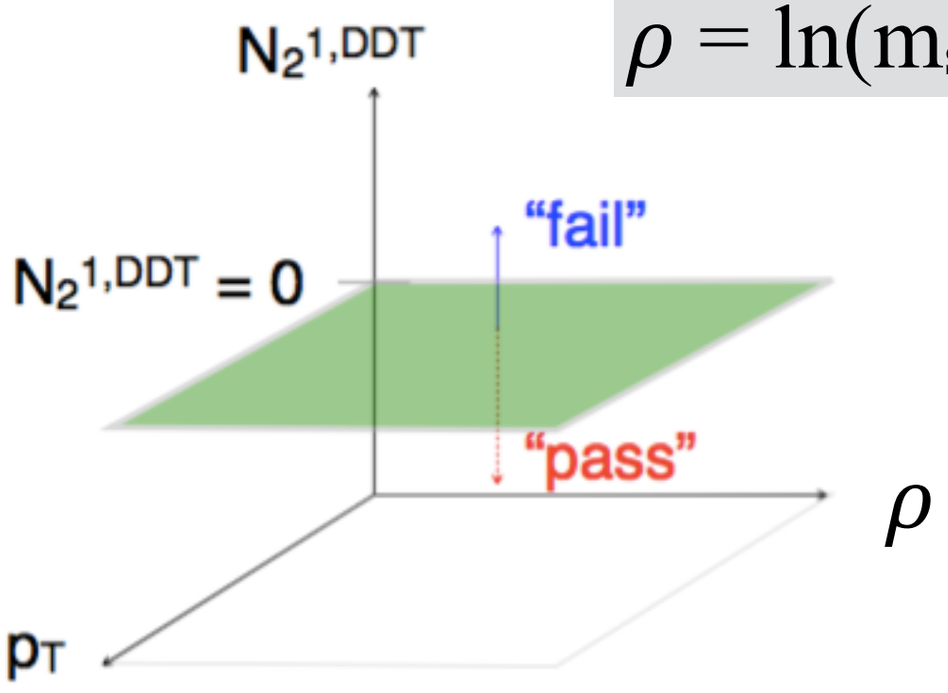
CMS dijet search

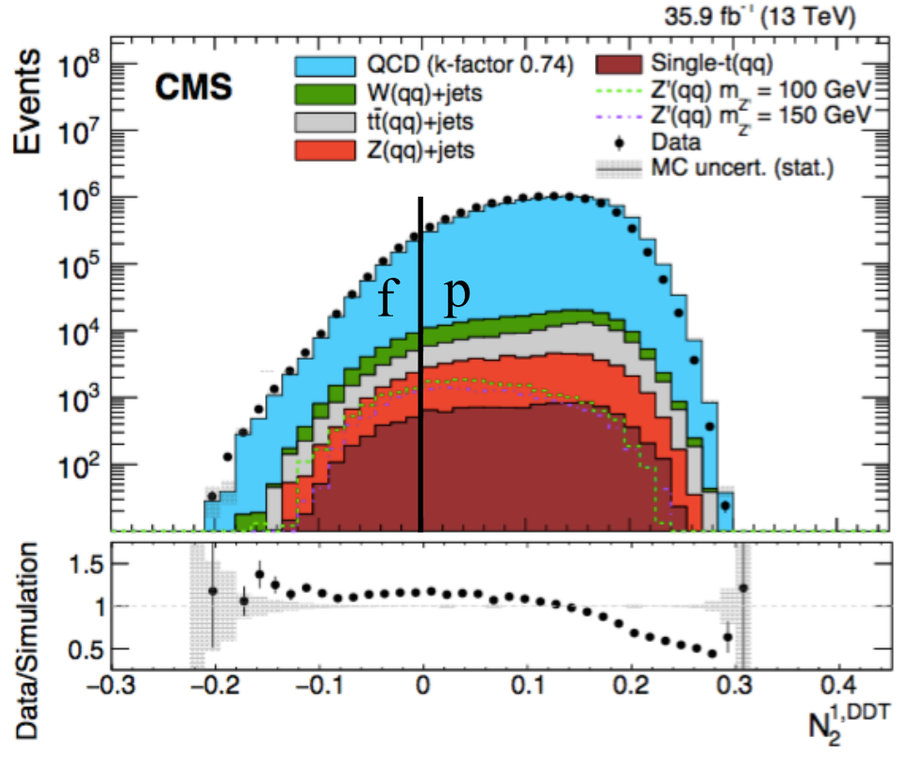
PLB 769, (2017) 520



Soft drop: background estimate

$$\rho = \ln(m_{sd}^2/p_T^2)$$

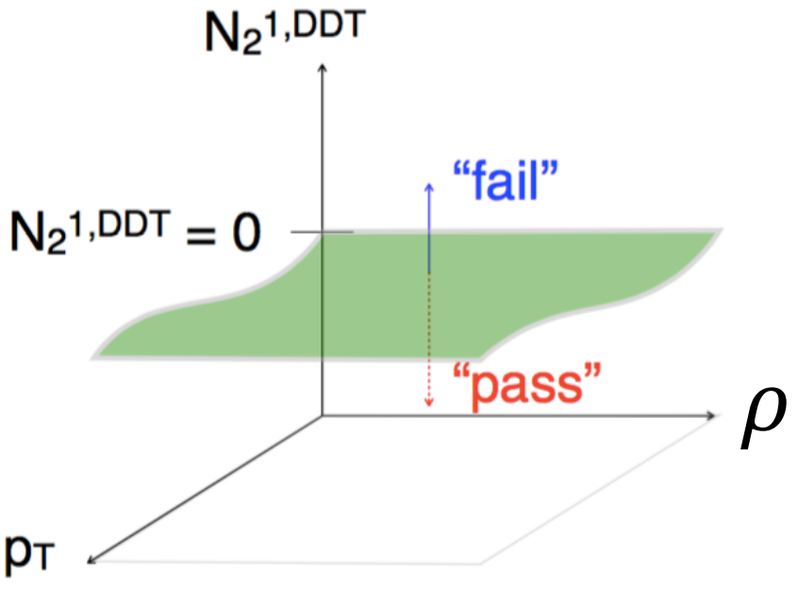




$$n_{\text{pass}}^{\text{QCD}}(m_{\text{SD}}, p_{\text{T}}) = \boxed{R_{\text{p/f}}(\rho(m_{\text{SD}}, p_{\text{T}}), p_{\text{T}})}\, n_{\text{fail}}^{\text{QCD}}(m_{\text{SD}}, p_{\text{T}})$$

constant 5% by construction, same m_{SD} shape

Data/MC not perfectly flat

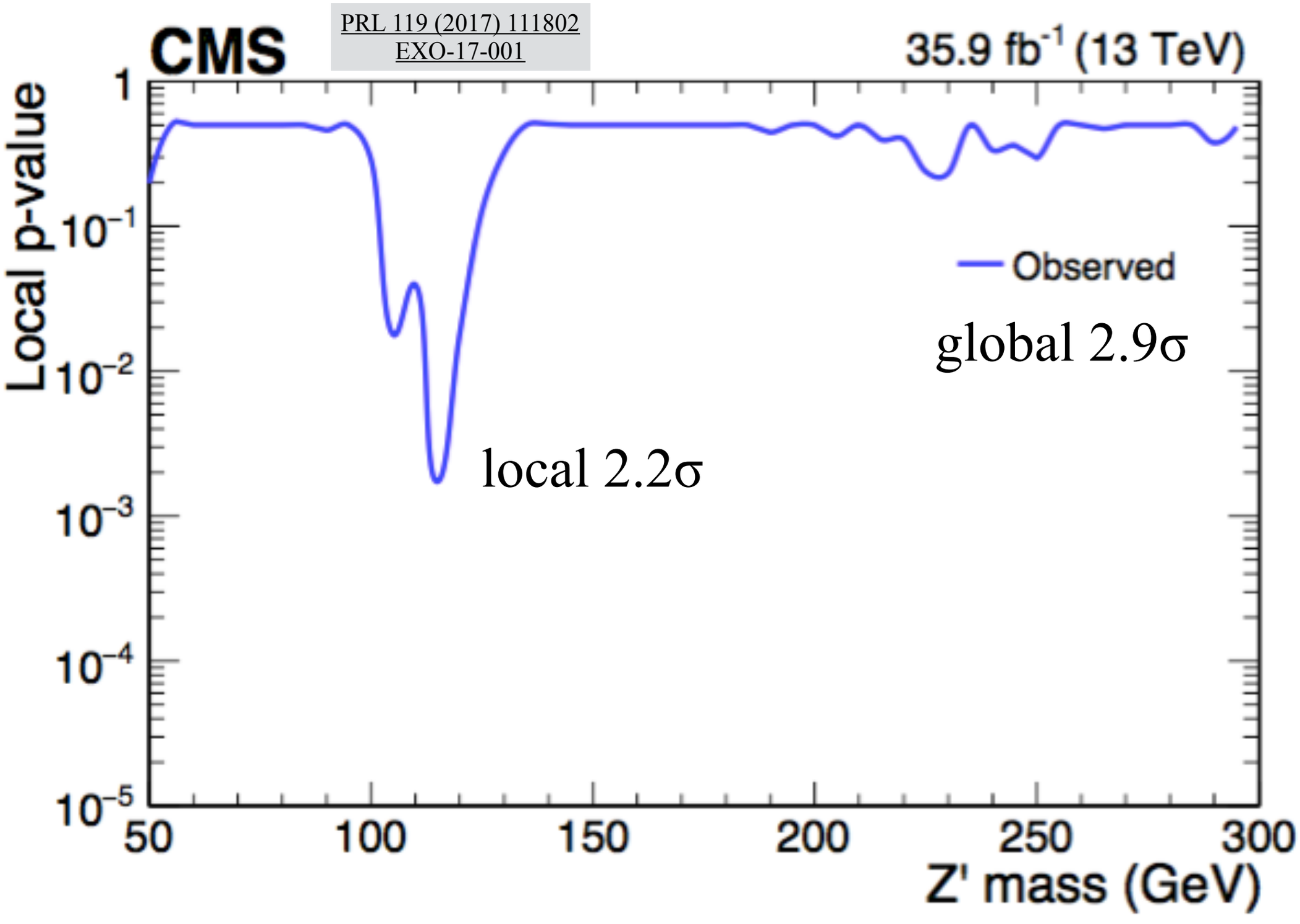


Data / MC differences in $R_{p/f}$

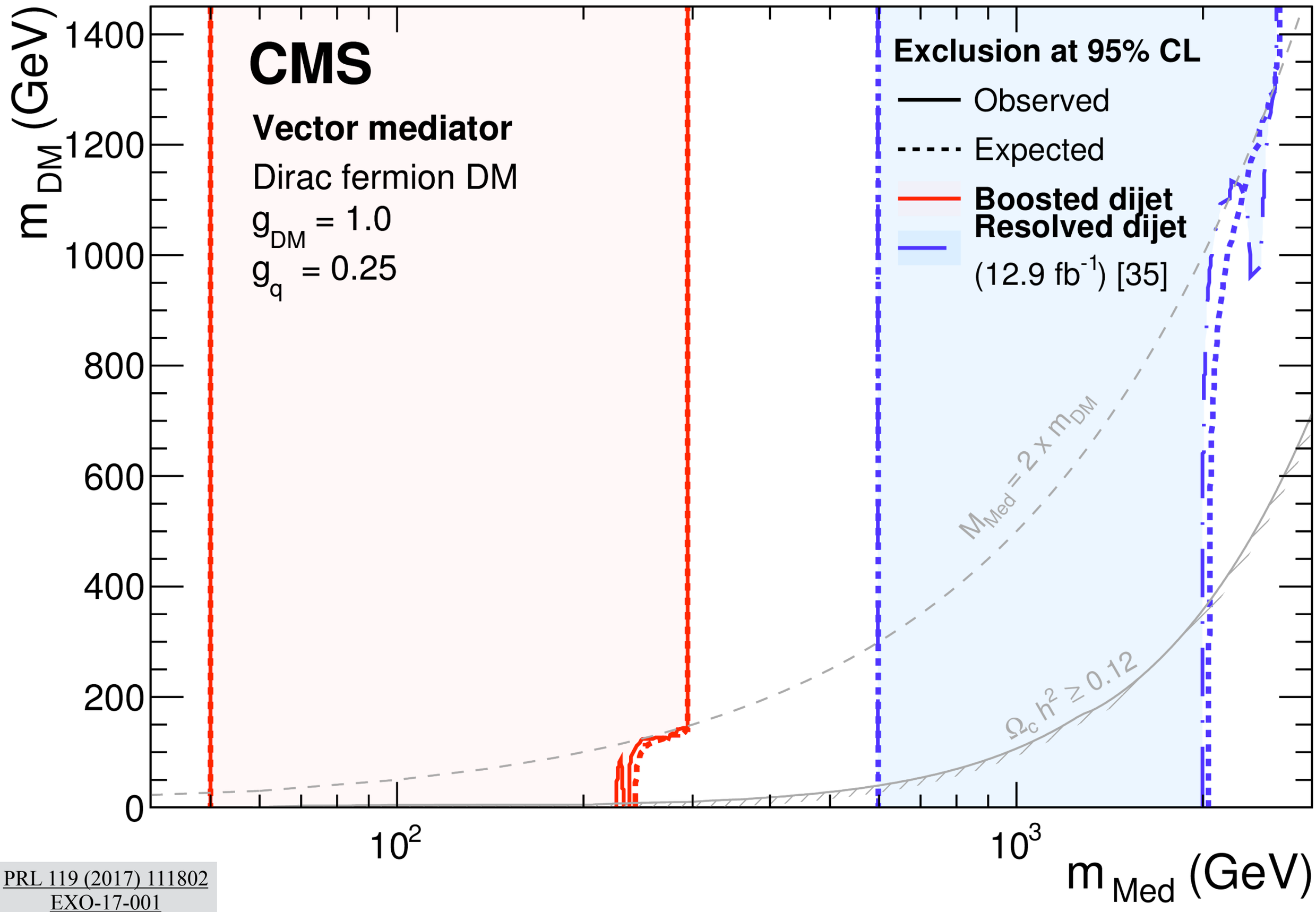
Expand then fit (including sig.)

$$\begin{aligned} R_{\text{p/f}}(\rho, p_{\text{T}}) = \epsilon_{\text{QCD}}(1 &+ a_{01}p_{\text{T}} + a_{02}p_{\text{T}}^2 + \cdots \\ &+ (a_{10} + a_{11}p_{\text{T}} + a_{12}p_{\text{T}}^2 + \cdots)\rho \\ &+ (a_{20} + a_{21}p_{\text{T}} + a_{22}p_{\text{T}}^2 + \cdots)\rho^2 + \cdots) \end{aligned}$$

p-value for bkg. only fit

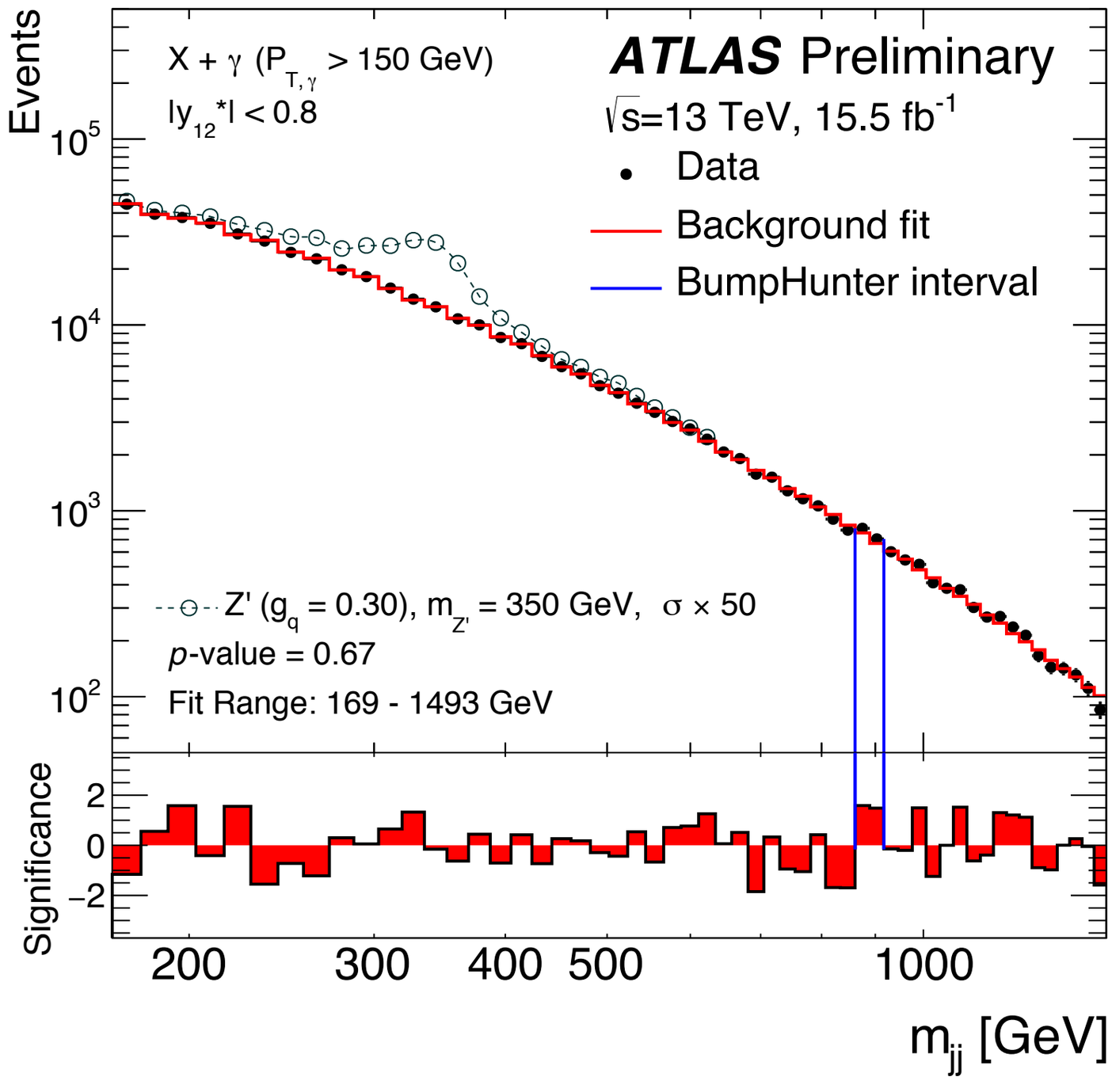


CMS DM summary

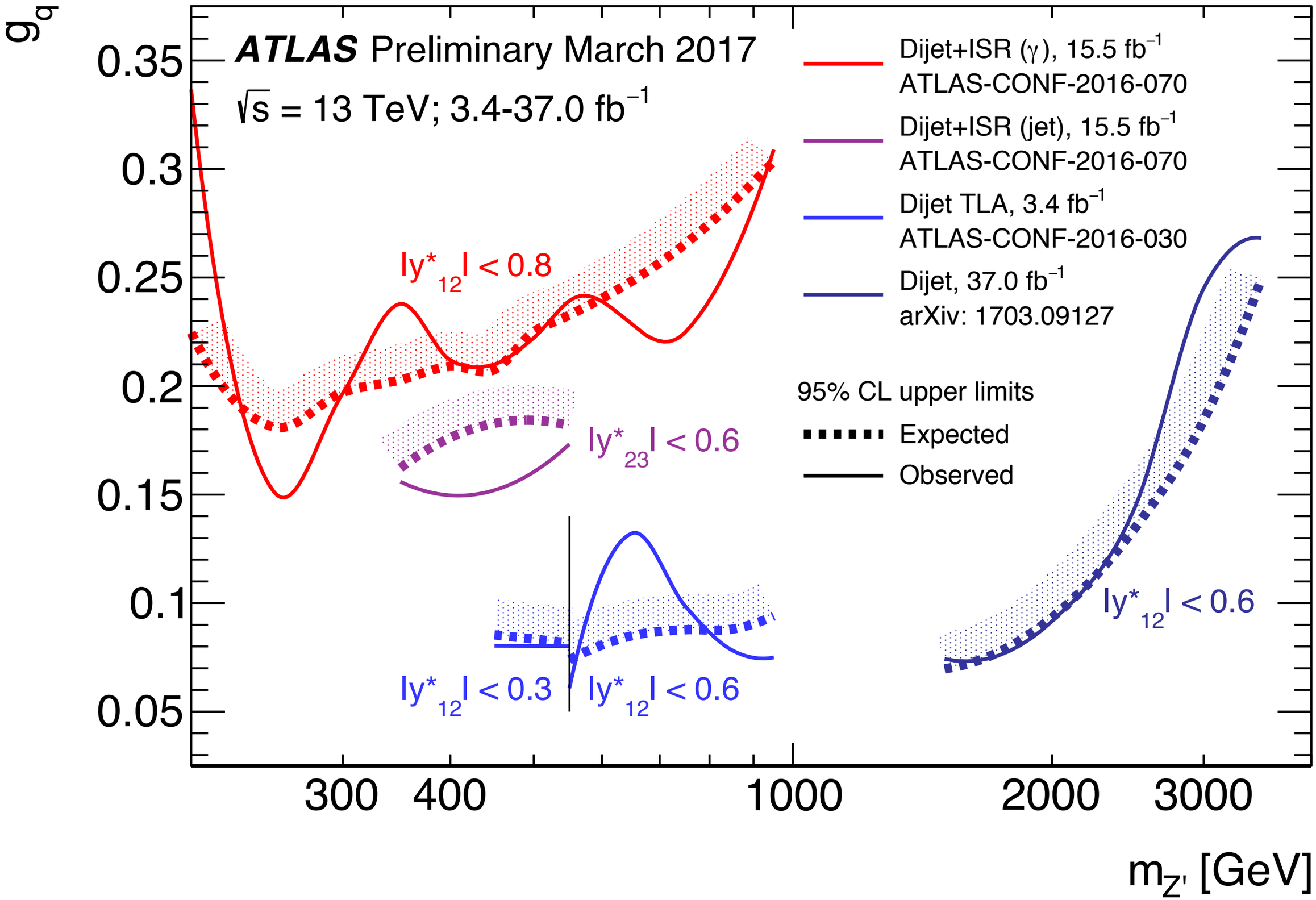


PRL 119 (2017) 111802
EXO-17-001

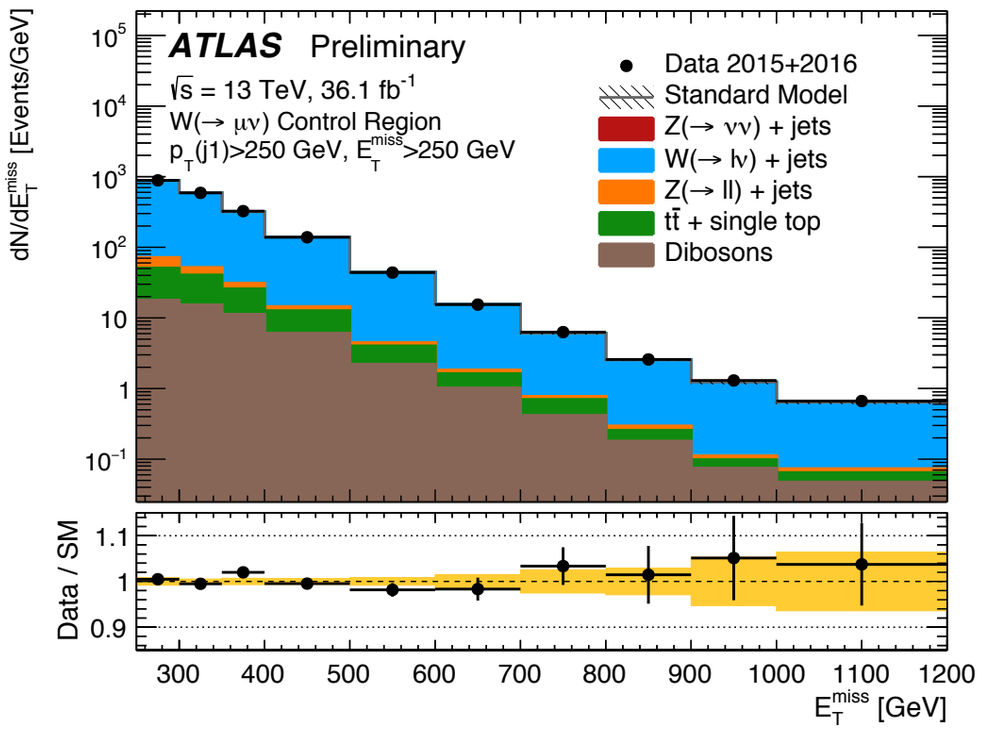
Mediator via ISR photon + resonance

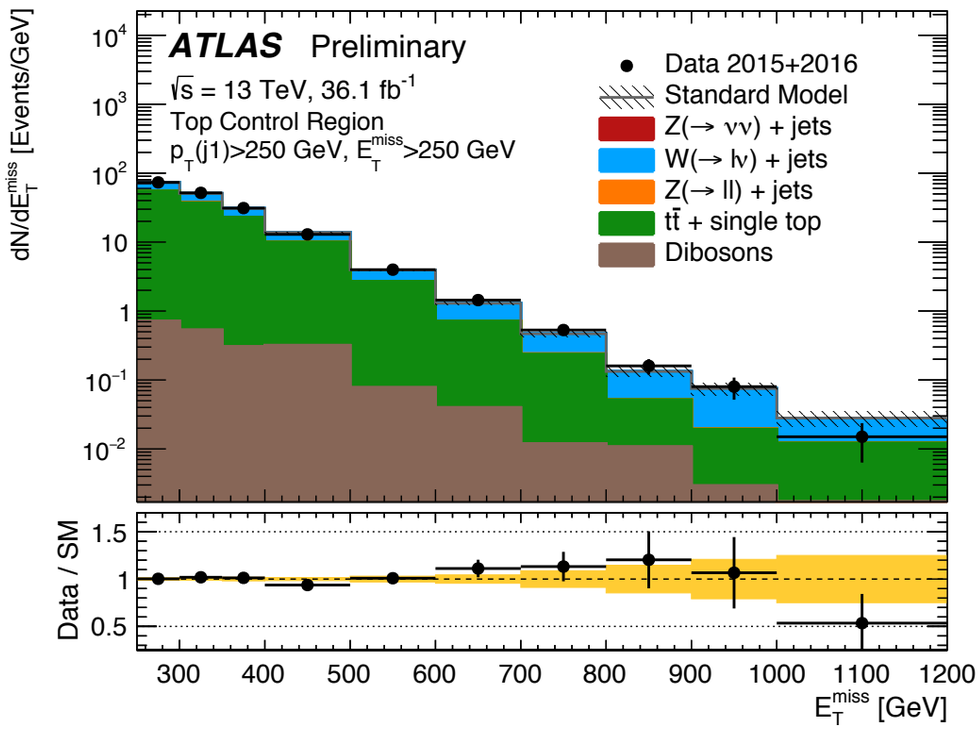


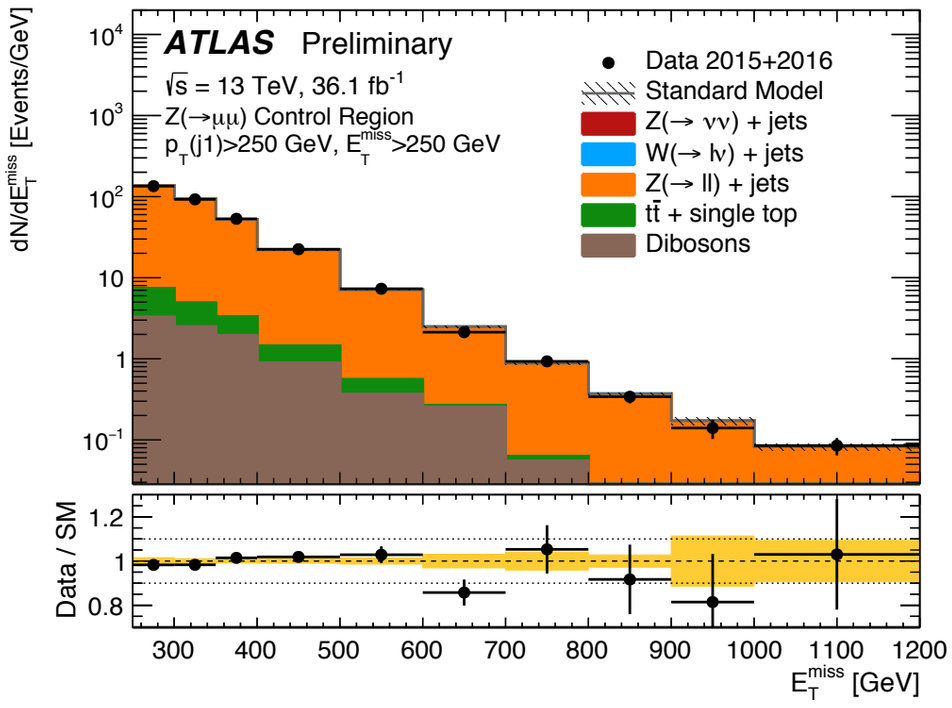
Dark matter summary



Mono-jet background estimation



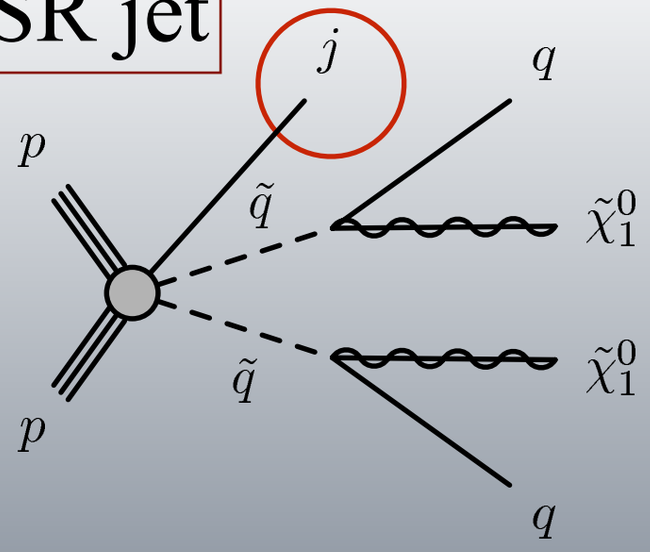




W, Z and top control samples

Mono-jet sbottom sensitivity

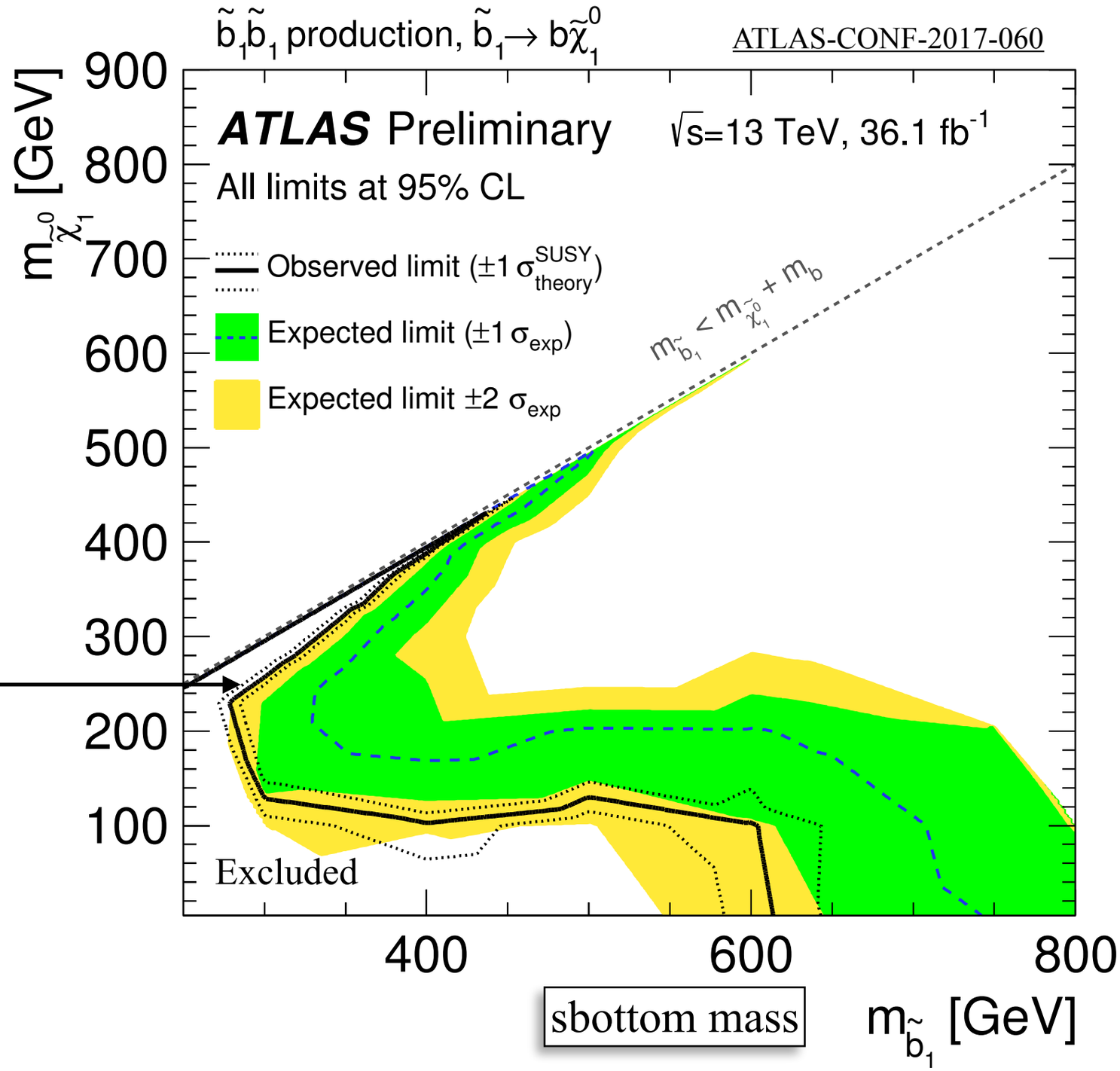
ISR jet



Also sensitive to third generation

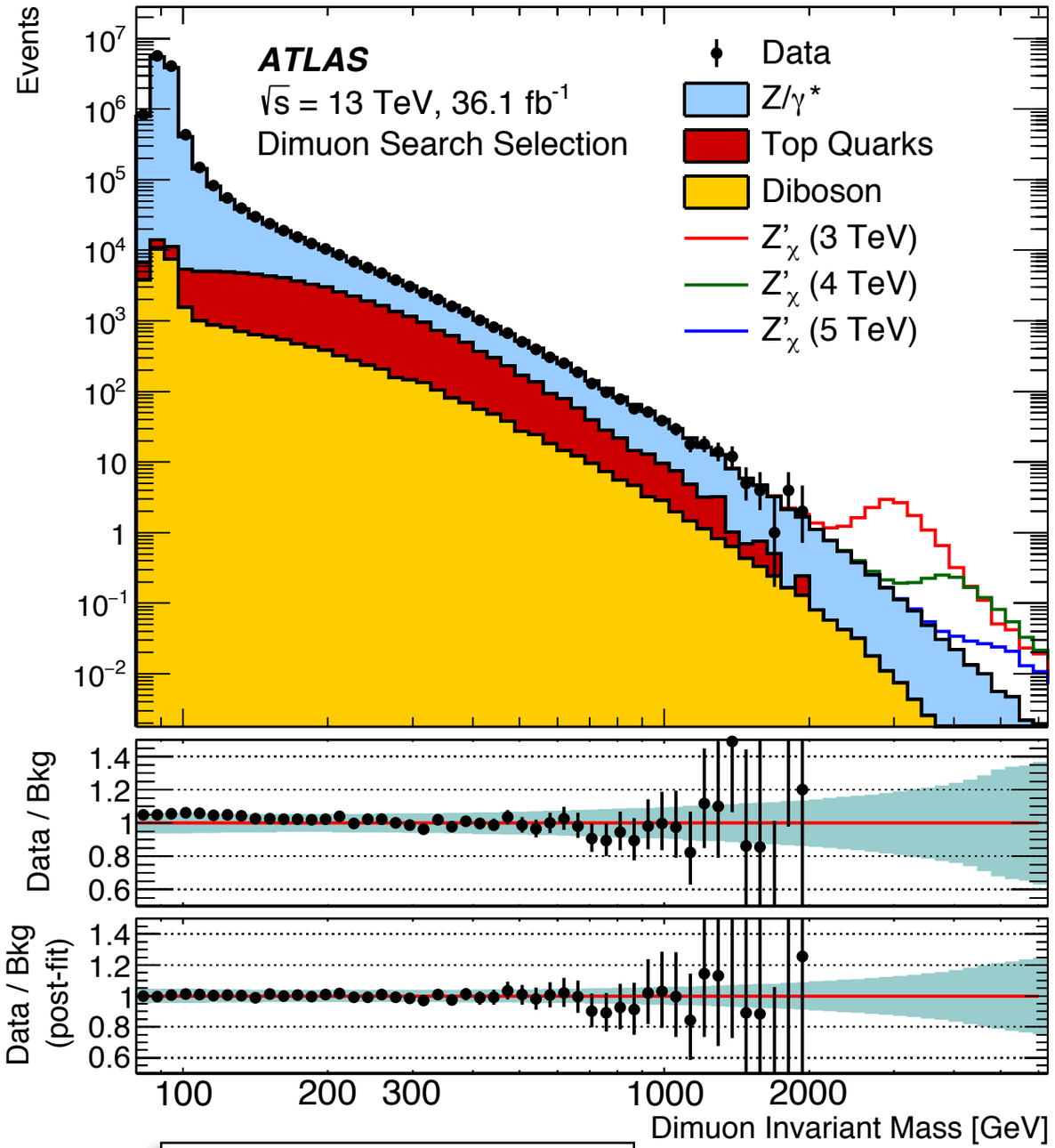
ISR jet boosts SUSY decay

Because of hard ISR jet, particularly sensitive to compressed scenarios.

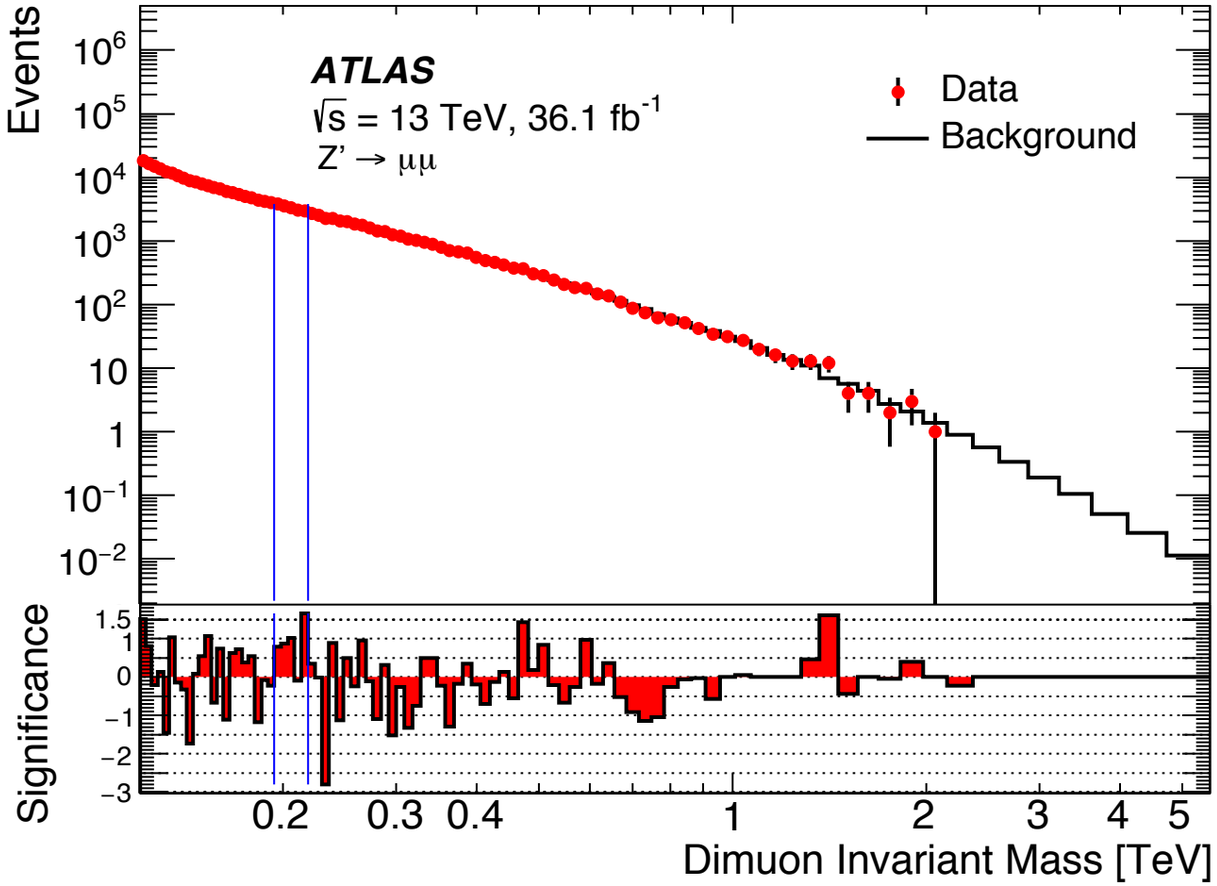


Dilepton searches

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

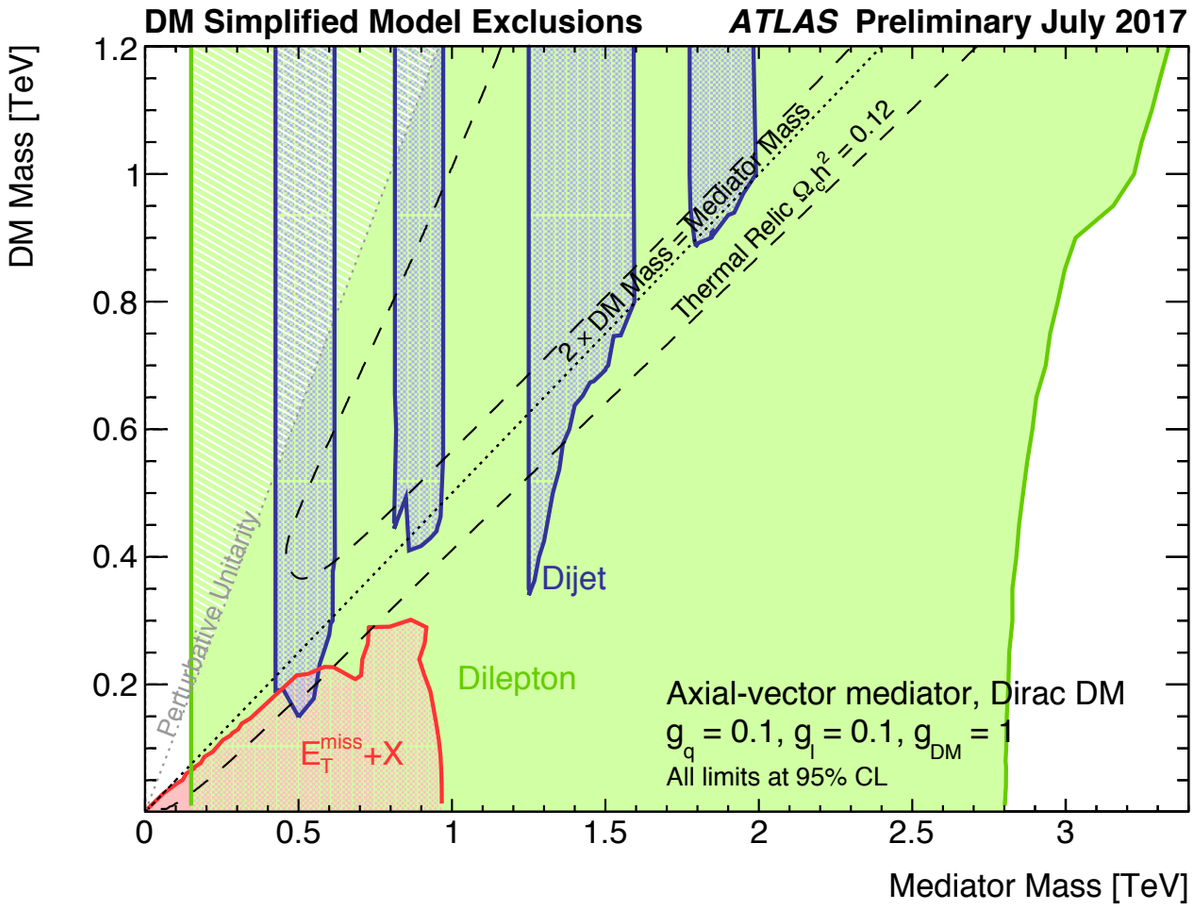


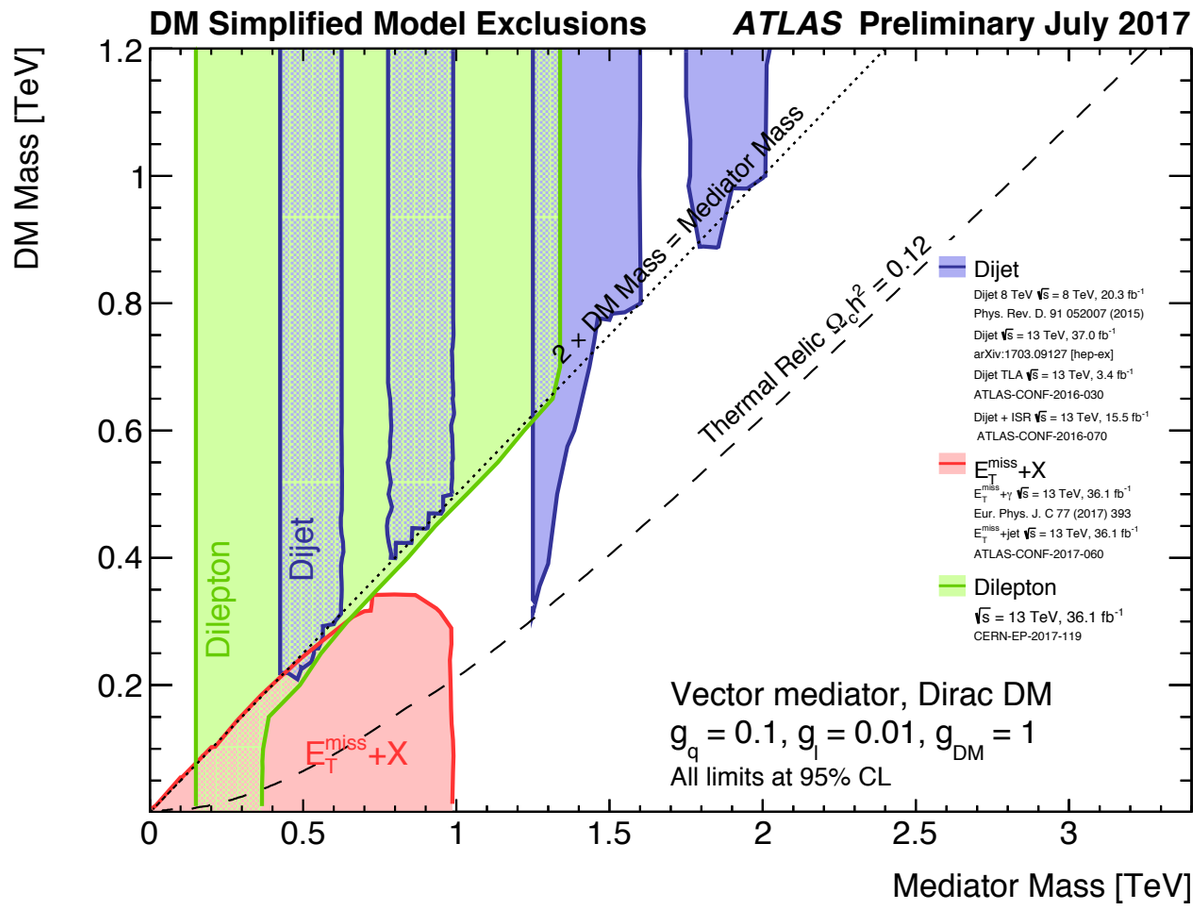
Dilepton mass (GeV)



EXOT-2016-05

Comparison of dijet and dilepton searches

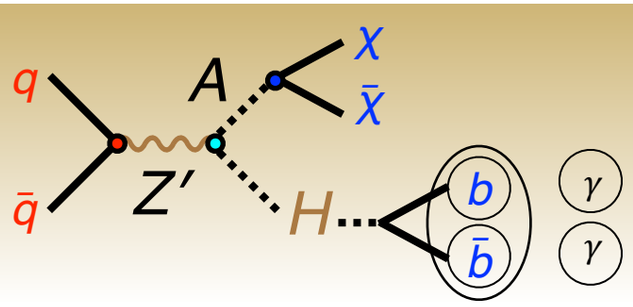




https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

Overlap in coverage

Mono-Higgs

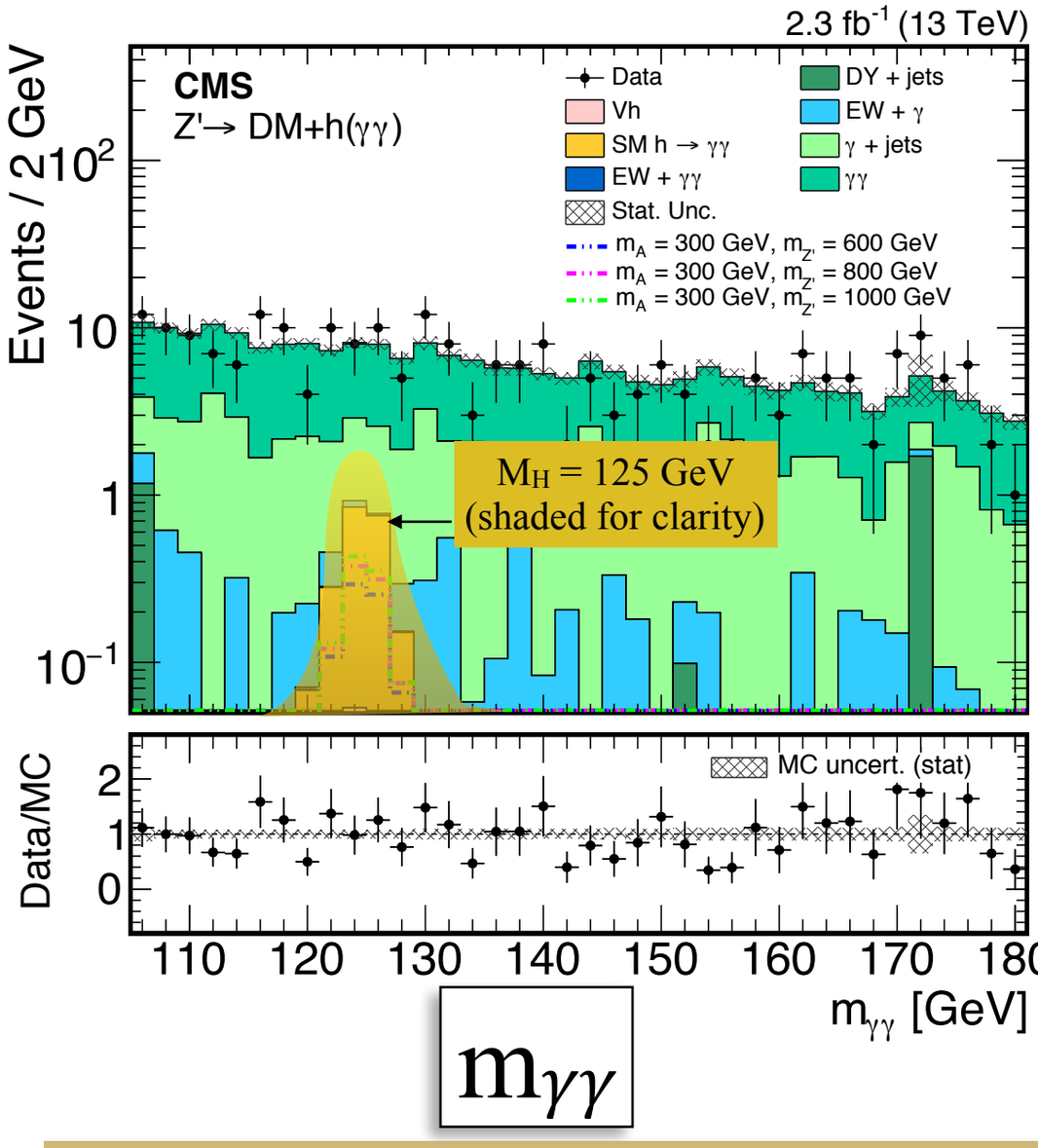


DM recoils against the Higgs

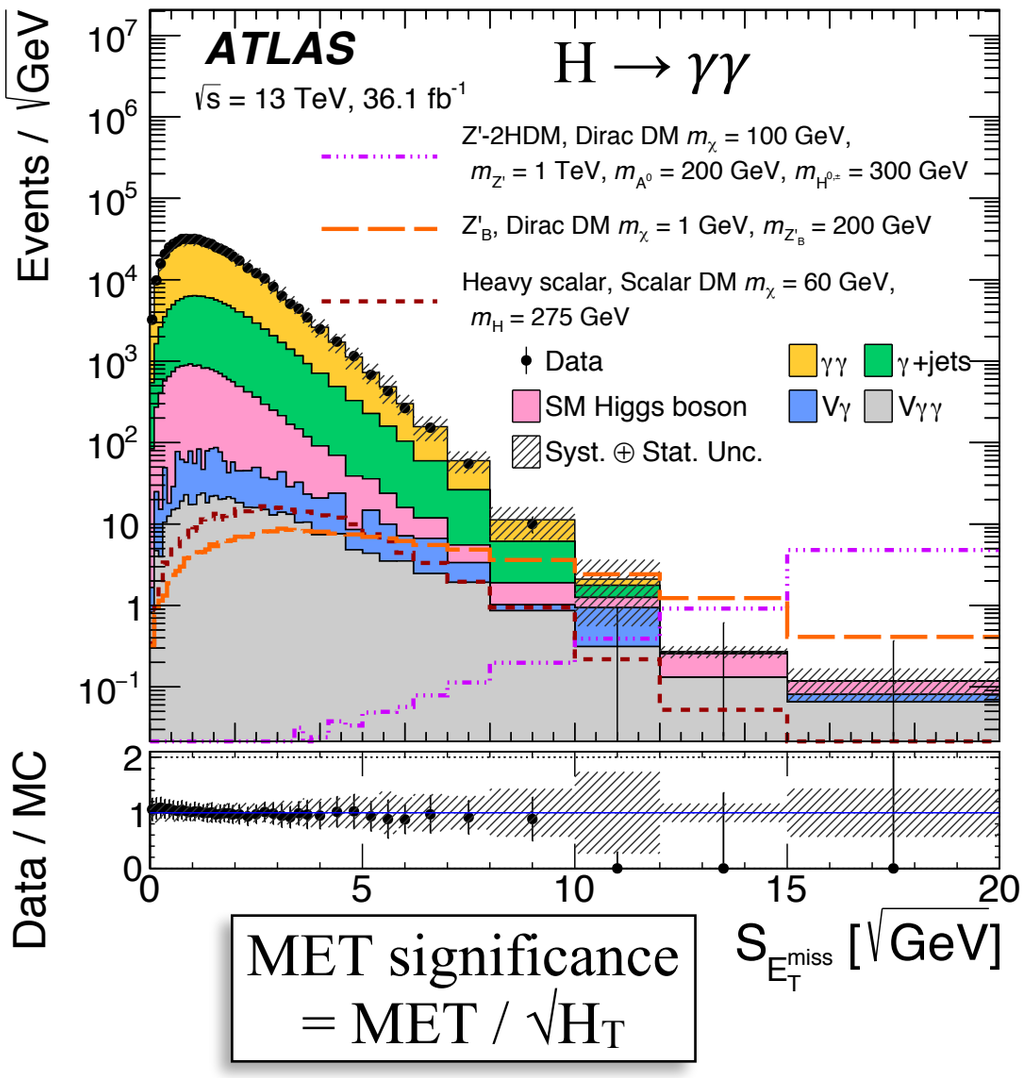
- Boosted (resolved) H → bb
- Resolved H → $\gamma\gamma$

High rate
Clean signature

Mono-Higgs
CMS bb and $\gamma\gamma$: EXO-16-012
ATLAS H → bb: EXOT-2016-25
ATLAS H → $\gamma\gamma$: HIGG-2016-18



$m_{\gamma\gamma}$

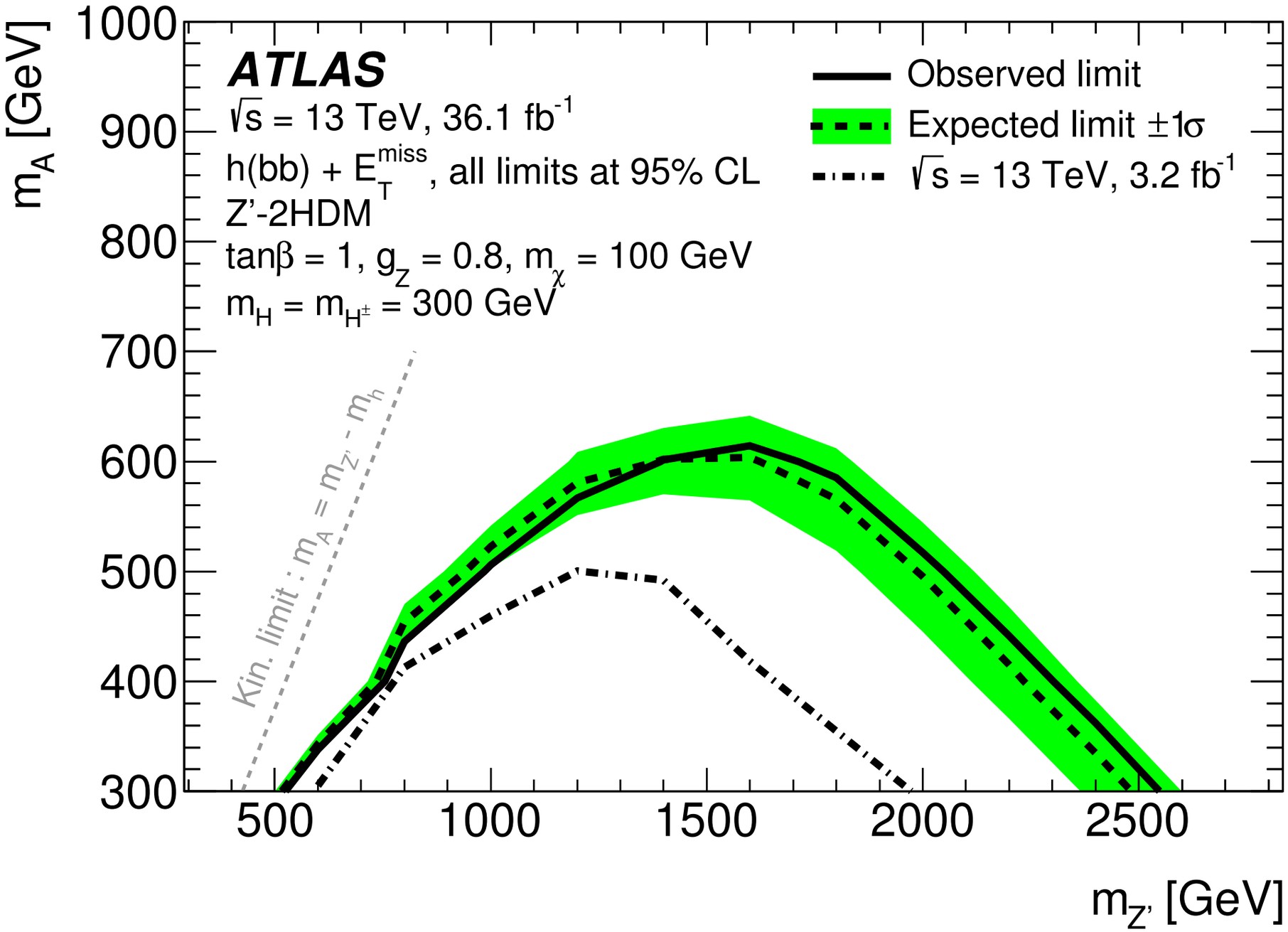


MET significance
= MET / $\sqrt{H_T}$

Clean diphoton mass peak

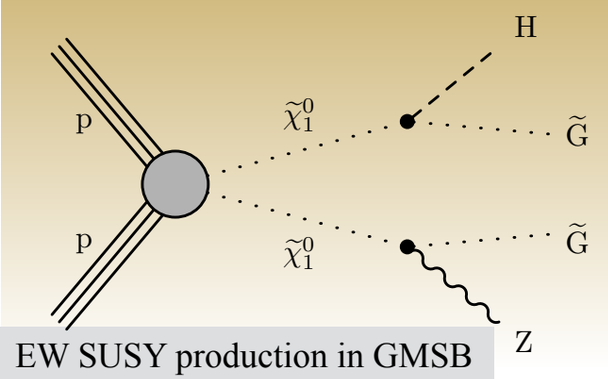
Signal tends to have very high MET

Mono-Higgs interpretation



EW SUSY: HZ

CMS:SUS-16-039
ATLAS: ATLAS-CONF-2017-039



EW SUSY production in GMSB

Could also couple to Z(W)

- Target multileptons + MET
- 2 leptons: same sign, opposite sign
- >3 leptons