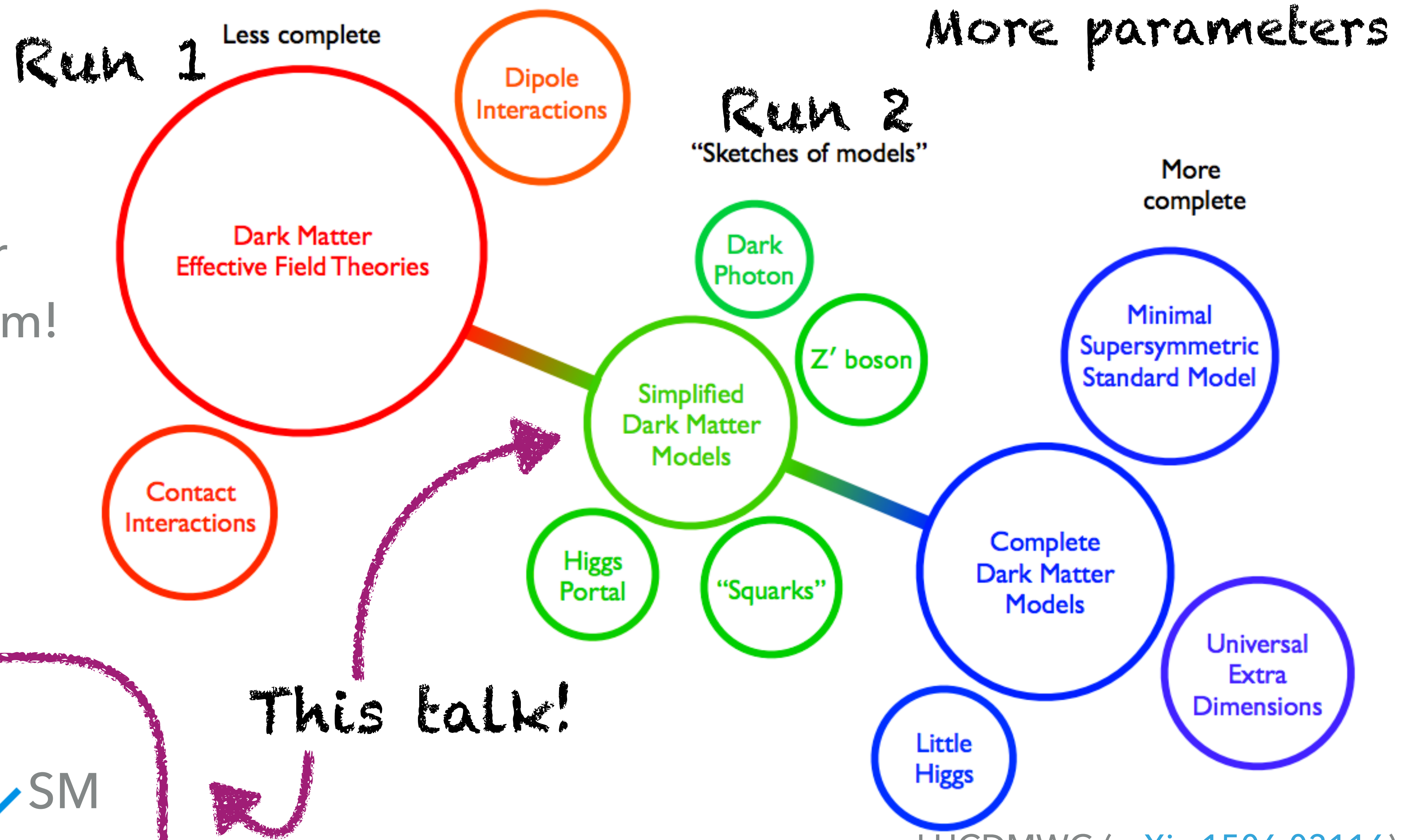
KATE WHALEN (UNIVERSITY OF OREGON), ON BEHALF OF ATLAS & CMS
DM@LHC - U. WASHINGTON - AUGUST 13-16, 2019

SEARCHES FOR DARK MATTER MEDIATORS WITH DIJET FINAL STATES AT THE LHC

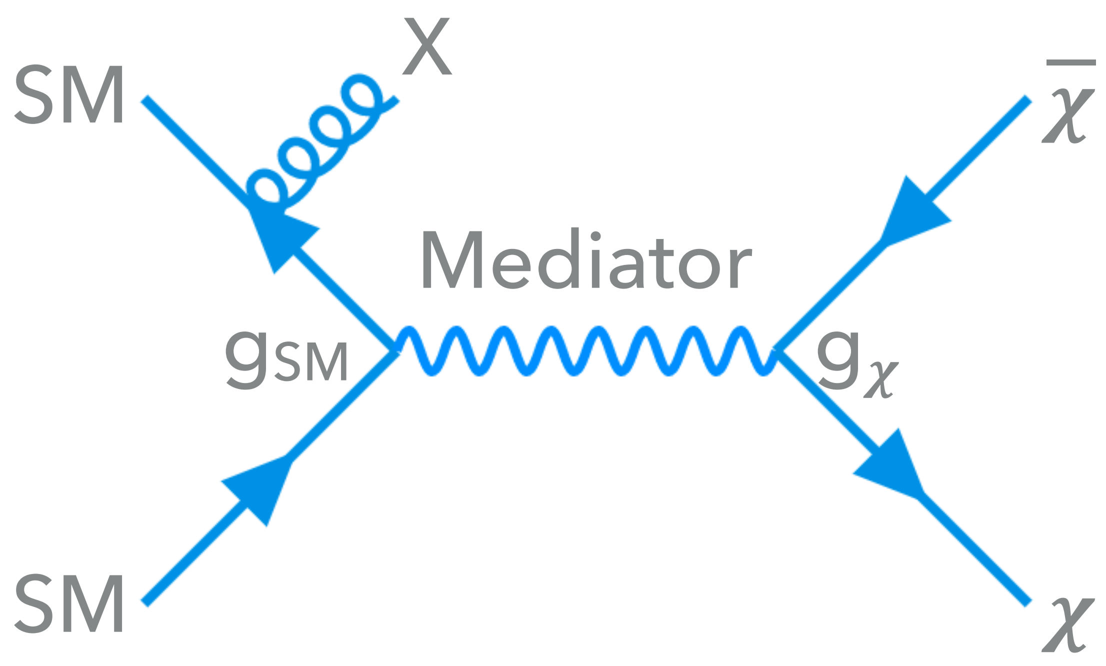
SIMPLIFIED DARK MATTER MODELS AT THE LHC

- Run 2 searches focus on **simplified models**
- Many DM models include a **mediator**, which can decay to dark matter
  - If a mediator is produced from SM particles, it should decay to them!
- Note: searches tend to be **signature-based**
  - Many different model interpretations are possible
  - Benchmark models for LHC searches in Run 2: arXiv:1507.00966



LHCDMWG (arXiv:1506.03116)

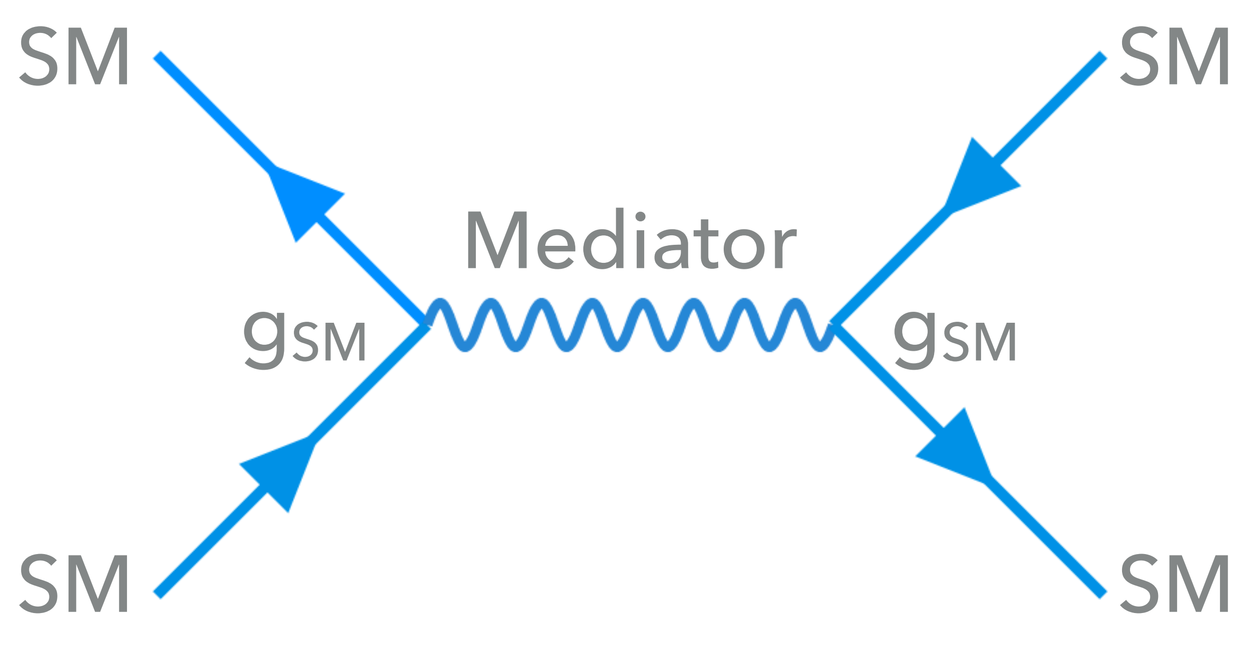
X+MET



DM candidate pair recoiling against X

(X=jet, H, W, Z, γ…)

Di-X resonance



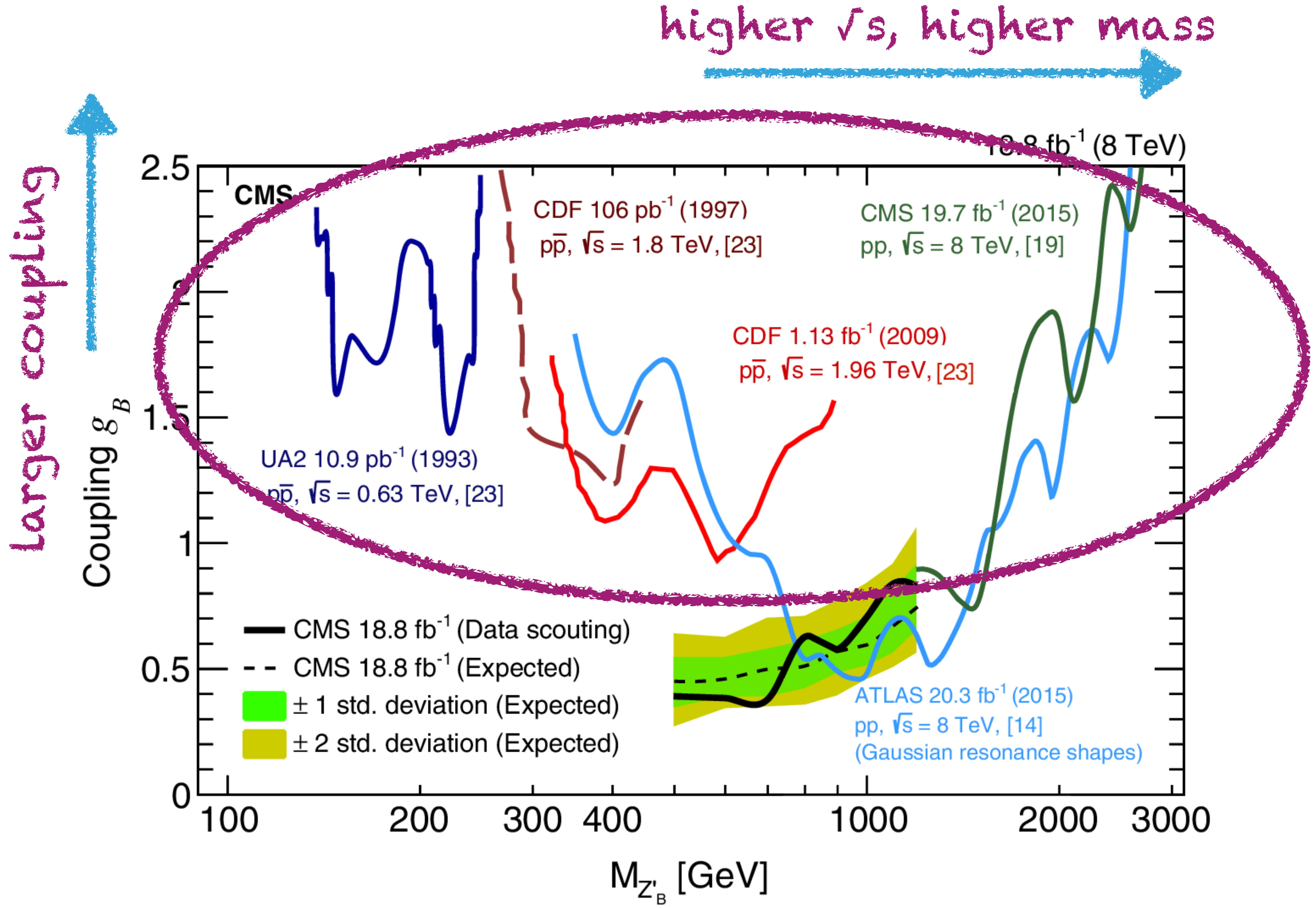
Dijet, dilepton…

(mediator search)

DISCLAIMER! Results are presented in the context of a particular model (dependent on couplings to DM, SM)

DIJET SEARCHES AT COLLIDERS

- Dijet final state has a broad range of interpretations:
  - Z′ (dark matter mediator)
  - W′, W*
  - Quantum black holes
  - Excited quarks
  - Randall-Sundrum gravitons
  - Insert your favourite model here…
- High-mass dijets: "classic" collider channel for new physics



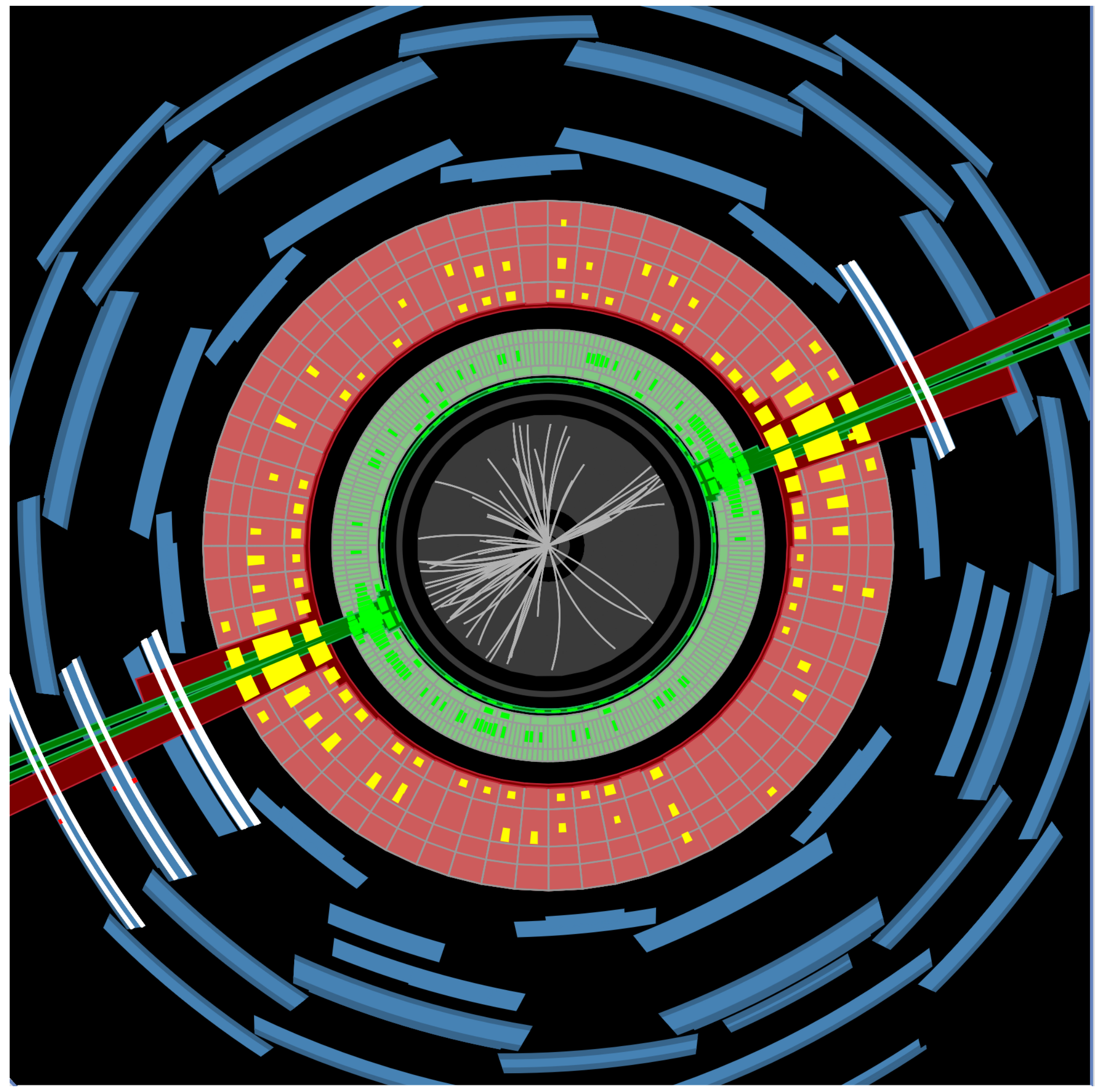
History lesson:
Dijet exclusion limits at the beginning of Run 2
arXiv:1604.08907

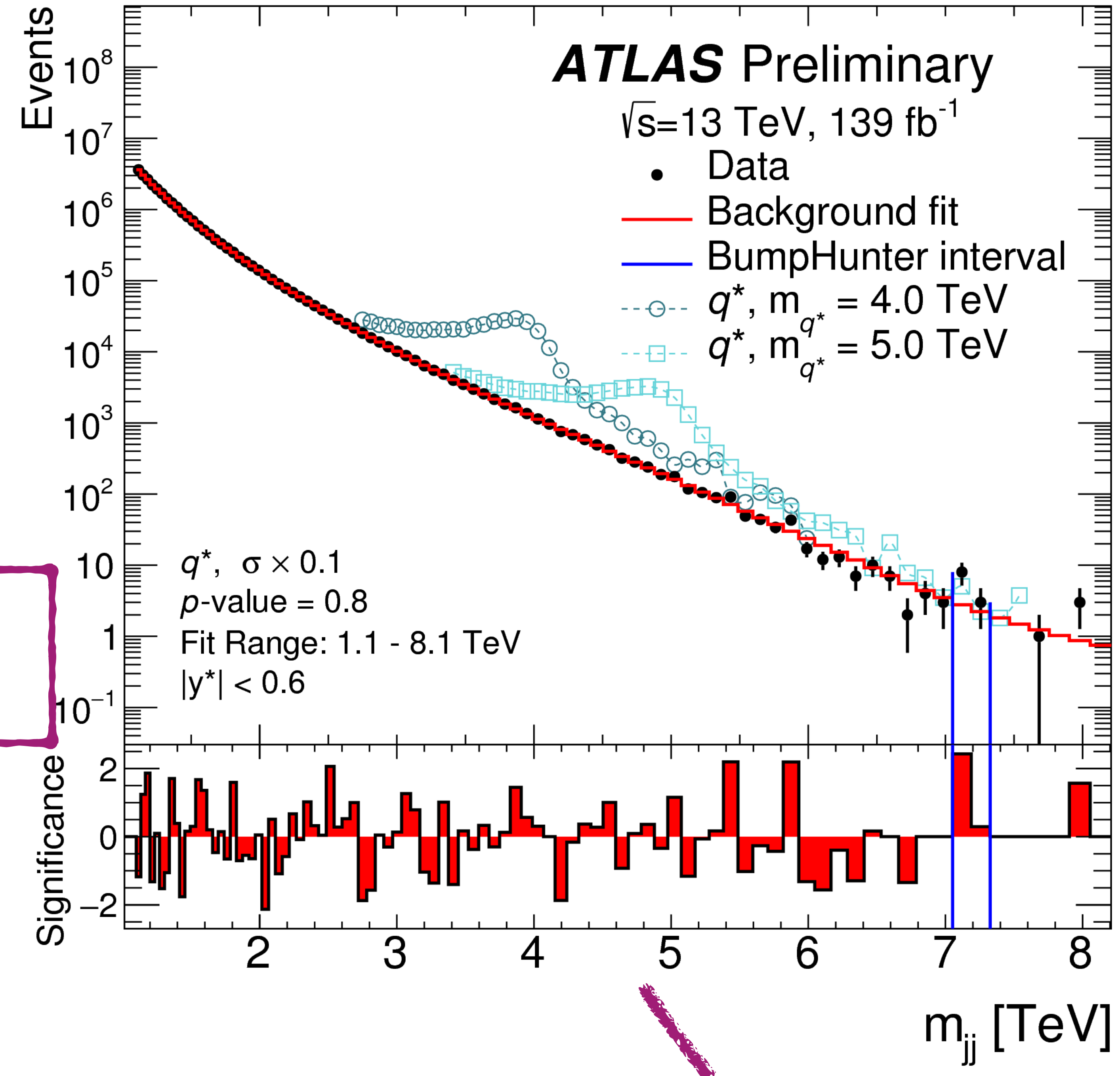
DIJET RESONANCES

ATLAS preliminary full Run 2 result: ATLAS-CONF-2019-007

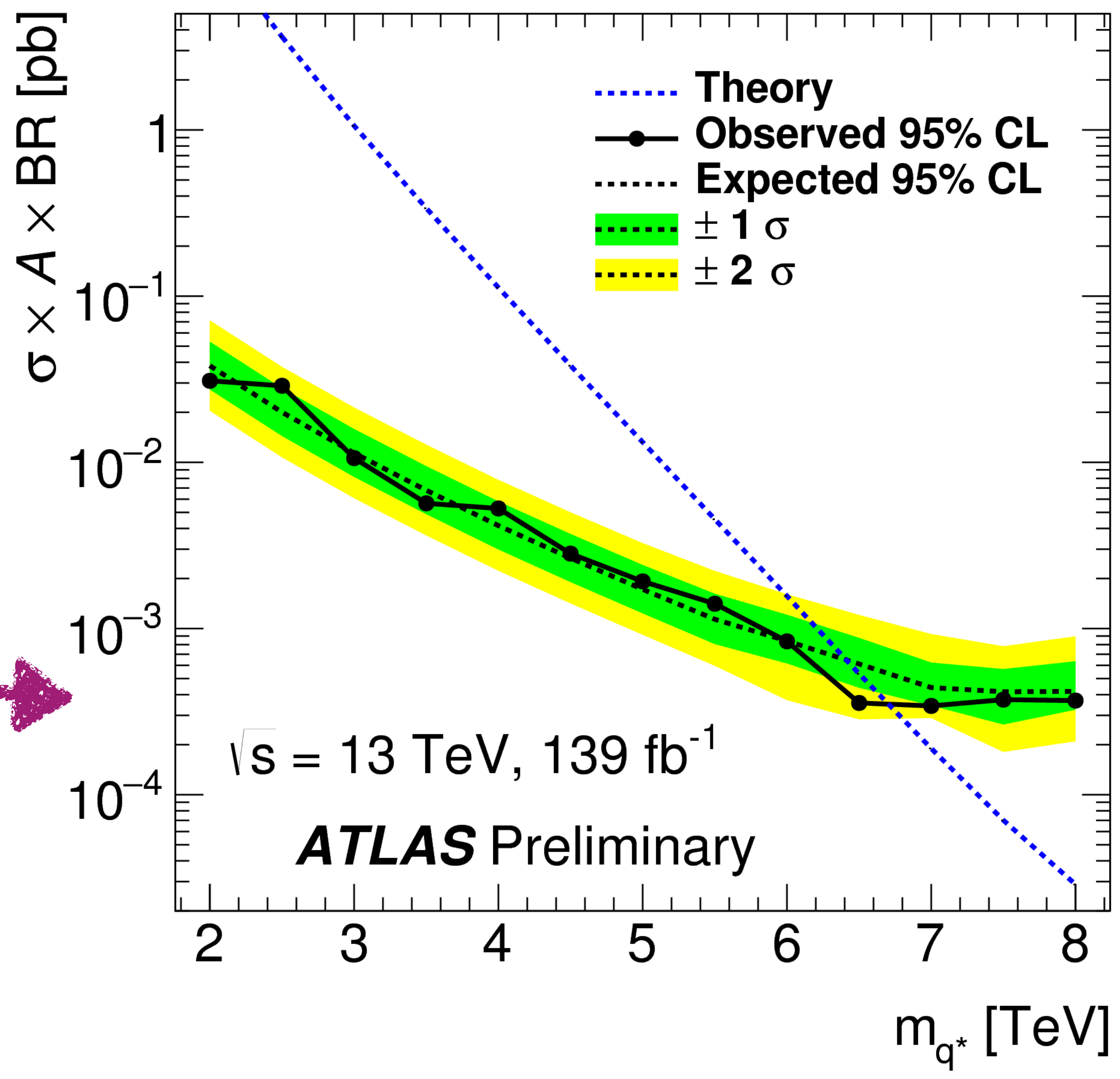
- **Bump hunt**: looking for an excess in the invariant mass distribution
  - Assuming a smoothly-falling QCD background
  - QCD multijet background estimated with a fit to the data
  - ATLAS: sliding-window fit (SWiFt)

$$f(x) = p_1 (1-x)^{p_2} x^{p_3 + p_4 \ln x}, \quad x \equiv m_{jj}/\sqrt{s}$$





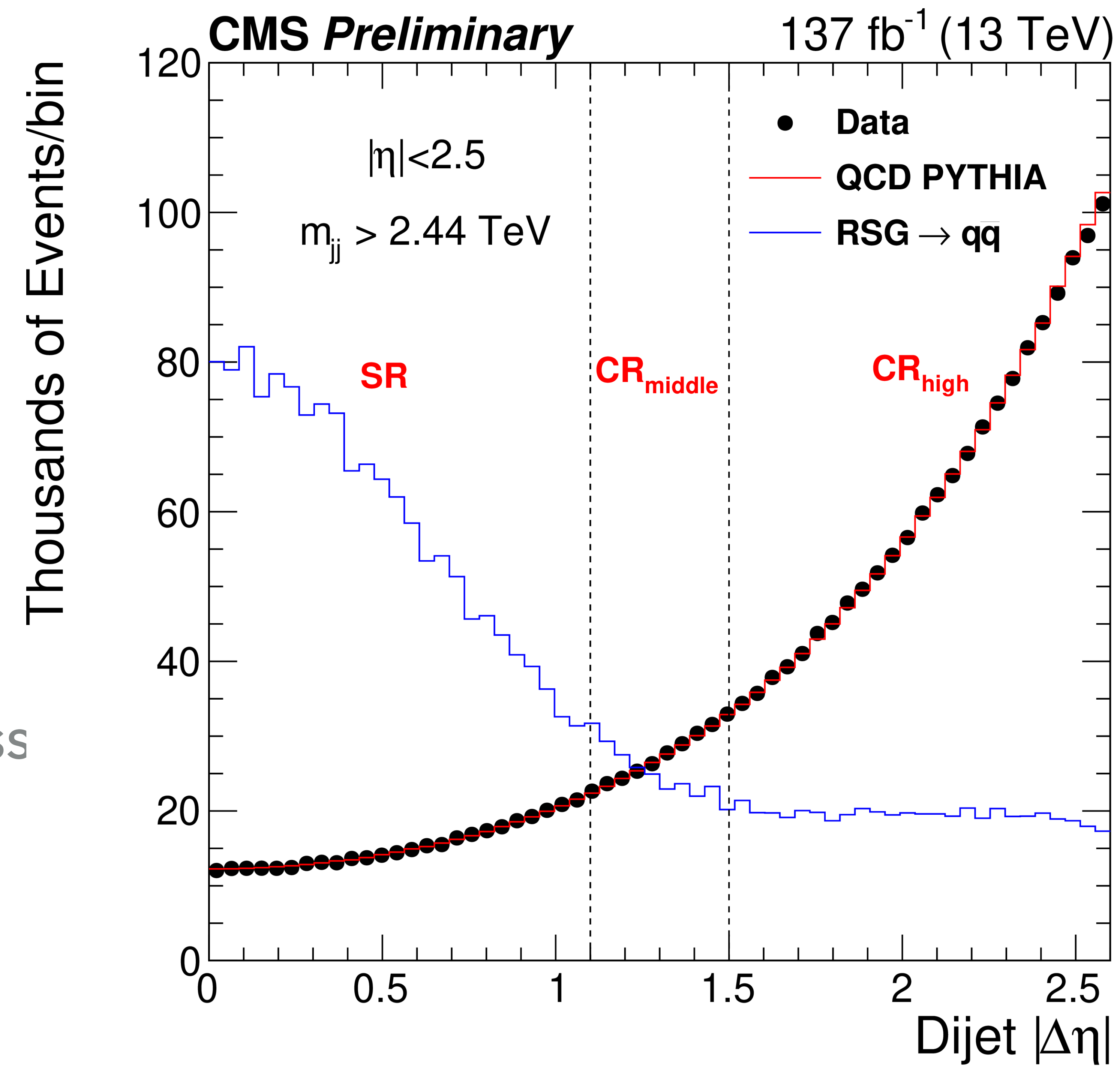
No significant excess?
Set limits and constrain parameter space for DM models!

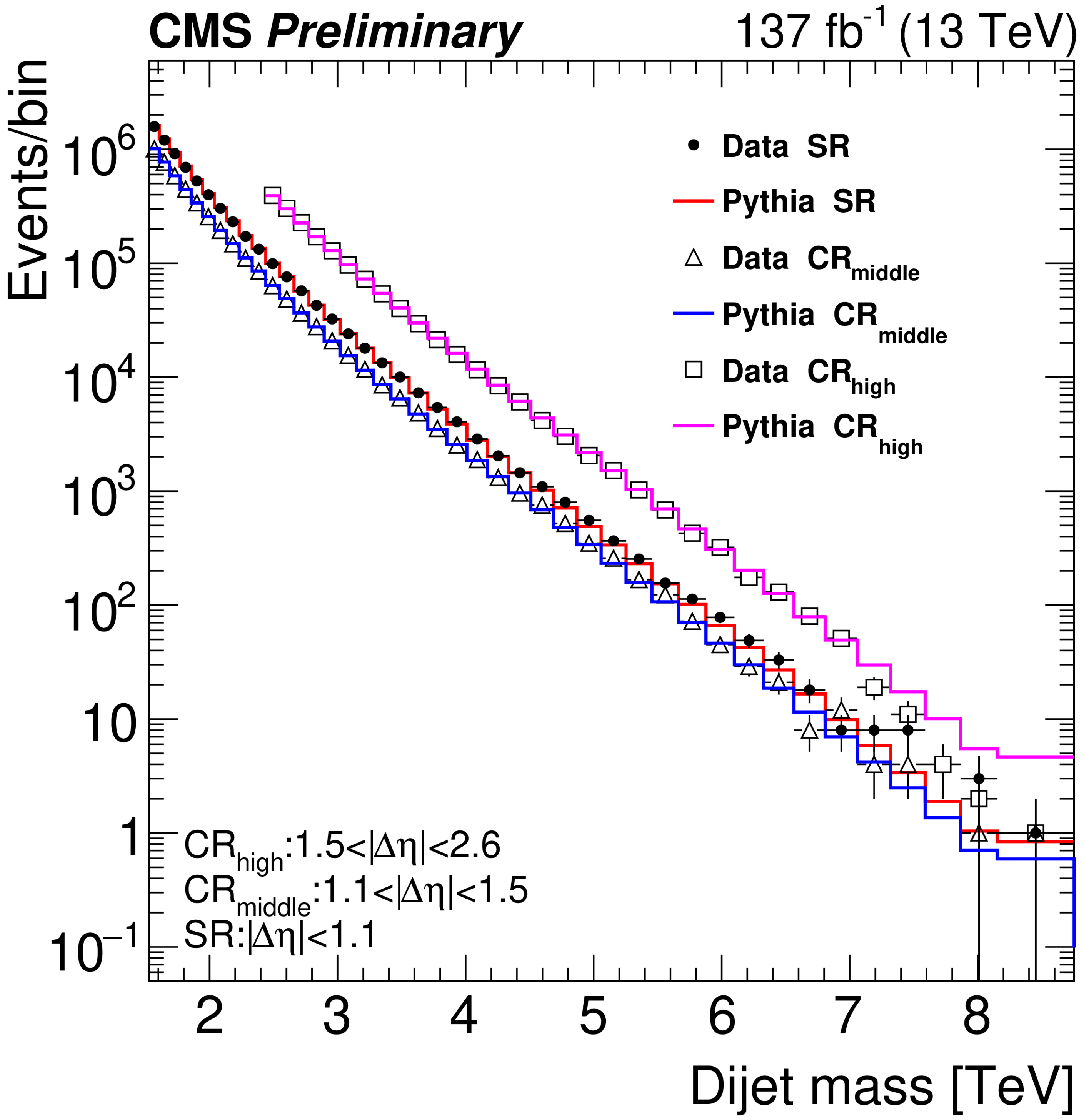


CMS DIJET SEARCH WITH ALTERNATIVE BACKGROUND ESTIMATION

Preliminary full Run 2 results: [CMS-PAS-EXO-19-012/](CMS-PAS-EXO-19-012/)

- Fit with functional form for 1.5 TeV < m_{jj} < 2.4 TeV
- M_{jj} > 2.4 TeV: data-driven background prediction using control regions
  - Higher sensitivity to broad resonances
  - More robust in high-mass tail of m_{jj} distribution
- Signal region (SR): $|\Delta\eta_{jj}| < 1.1$
  - Sharp trigger turn-on for relatively low dijet mass ($m_{jj} \approx 2p_T\cosh(|\Delta\eta_{jj}|/2)$)
- CR_{middle}: $1.1 < |\Delta\eta_{jj}| < 1.5$
  - Constrains systematic uncertainties
- CR_{high}: $1.5 < |\Delta\eta_{jj}| < 2.6$
  - Used to predict QCD background





CMS DIJET SEARCH WITH ALTERNATIVE BACKGROUND ESTIMATION

- Background estimated in SR using transfer factor "R":

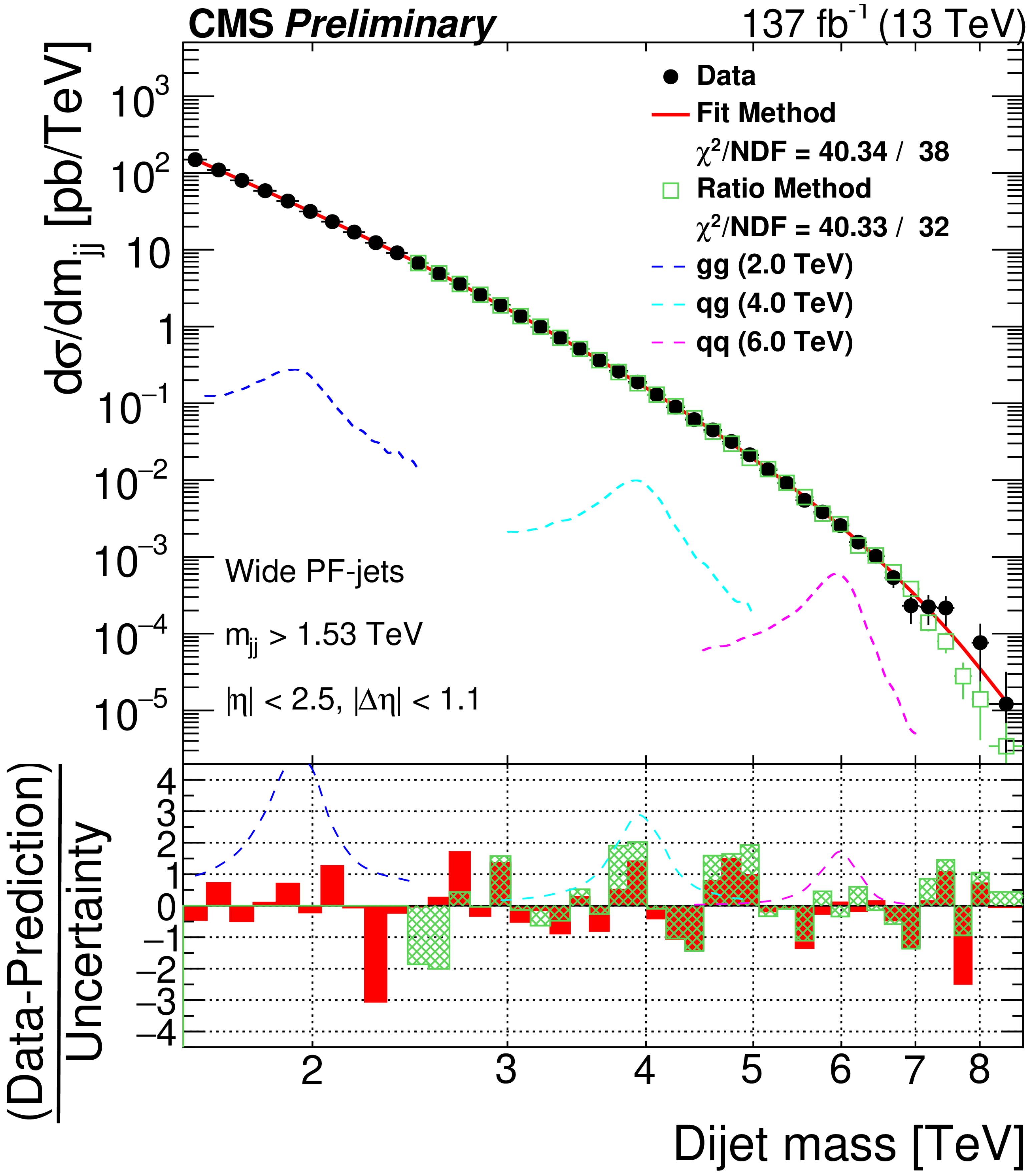
$$N_{\mathrm{SR}}^{\mathrm{Prediction}} = R \times N_{\mathrm{CR_{high}}}^{\mathrm{Data}}$$

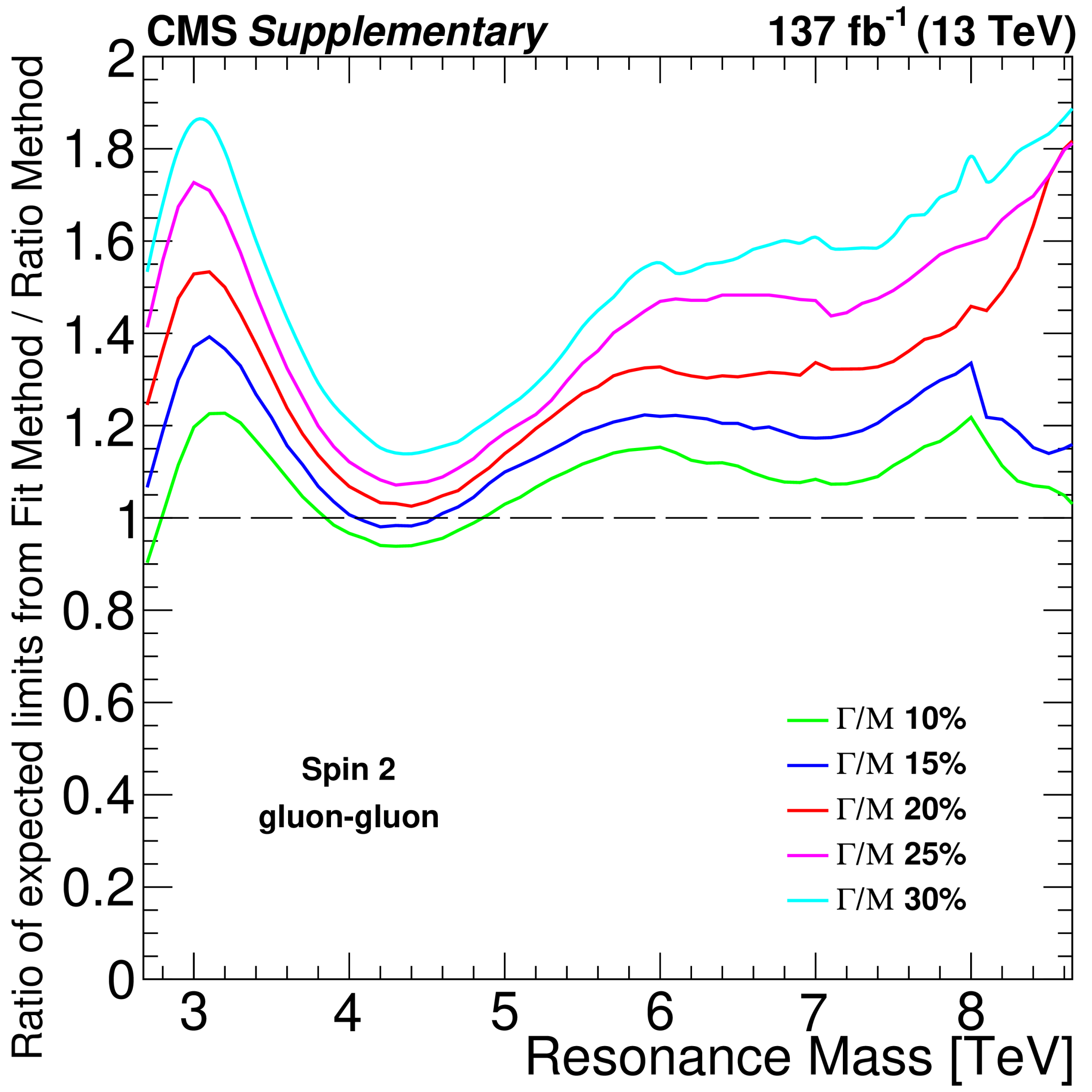
$$R = \mathrm{C} \times N_{\mathrm{SR}}^{\mathrm{Simulation}} / N_{\mathrm{CR_{high}}}^{\mathrm{Simulation}}$$

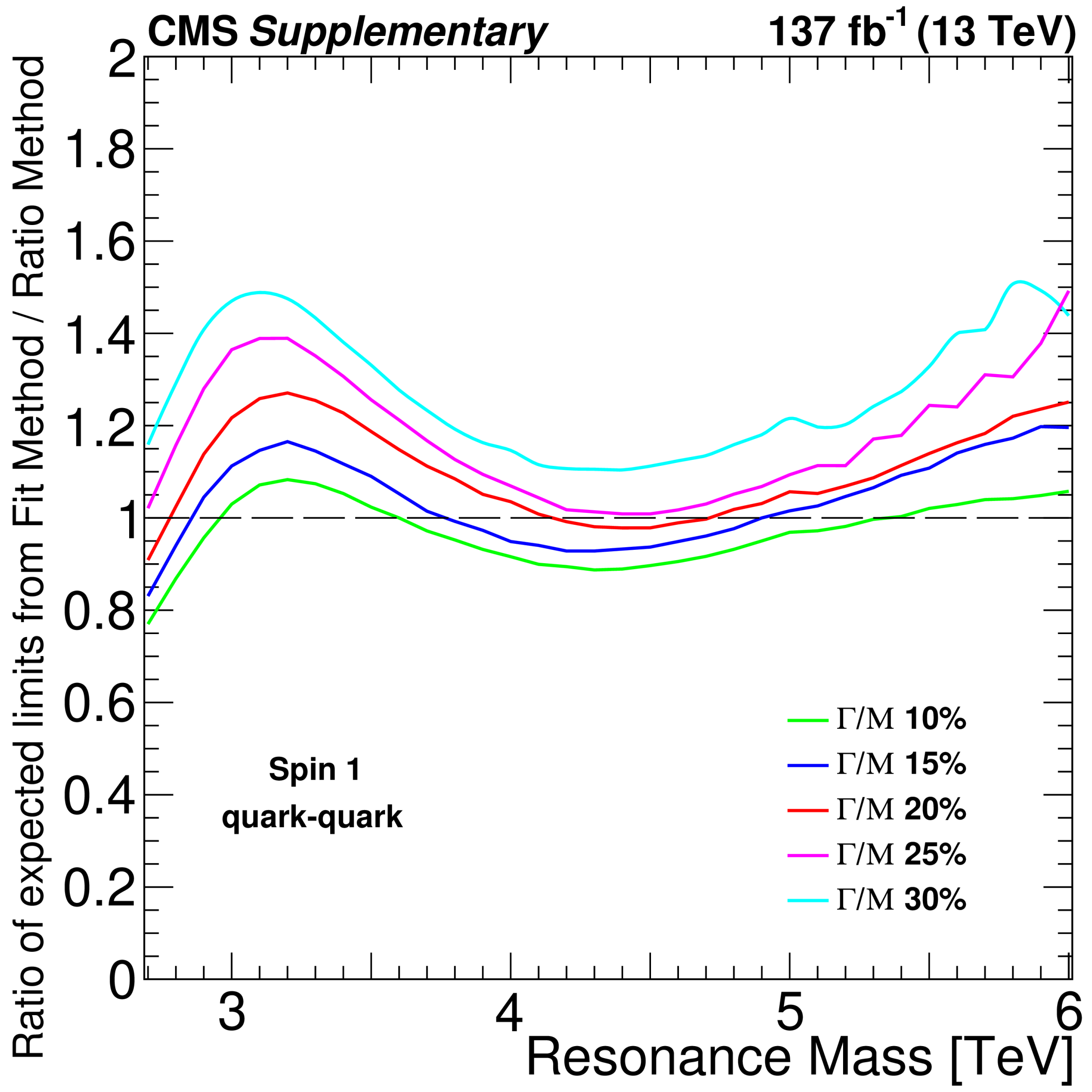
- Transfer factor correction done using simultaneous fit to SR and CRs
  - $\mathrm{CR_{middle}}$ used to constrain p0, p1

$$R_{\mathrm{aux.}} = N_{\mathrm{CR_{middle}}} / N_{\mathrm{CR_{high}}}$$

$$\mathrm{C} = \frac{R_{\mathrm{aux.}}{}^{\mathrm{Data}}}{R_{\mathrm{aux.}}{}^{\mathrm{Simulation}}} = p_0 + p_1 \times (m_{jj}/\sqrt{s})^3$$





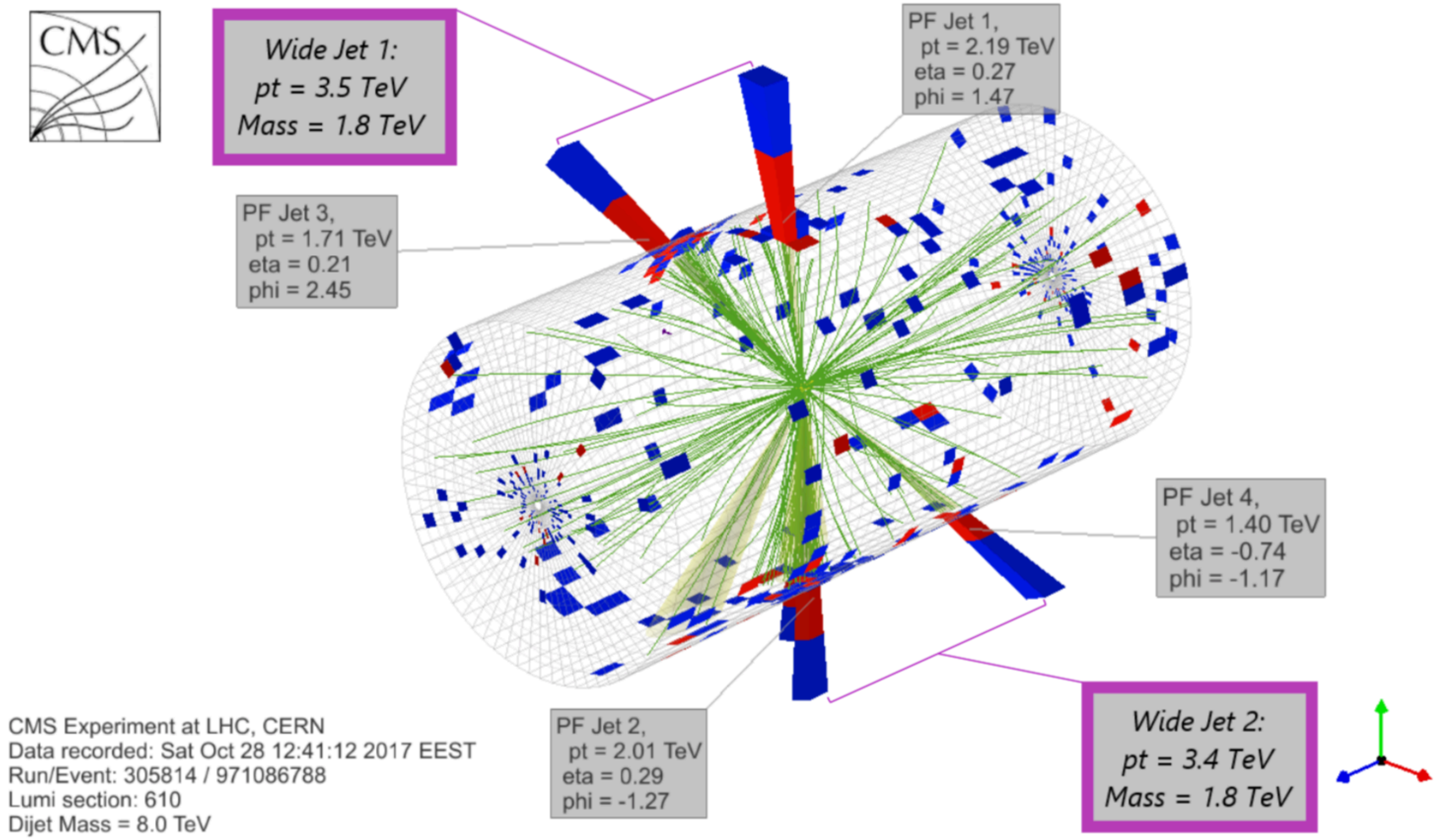


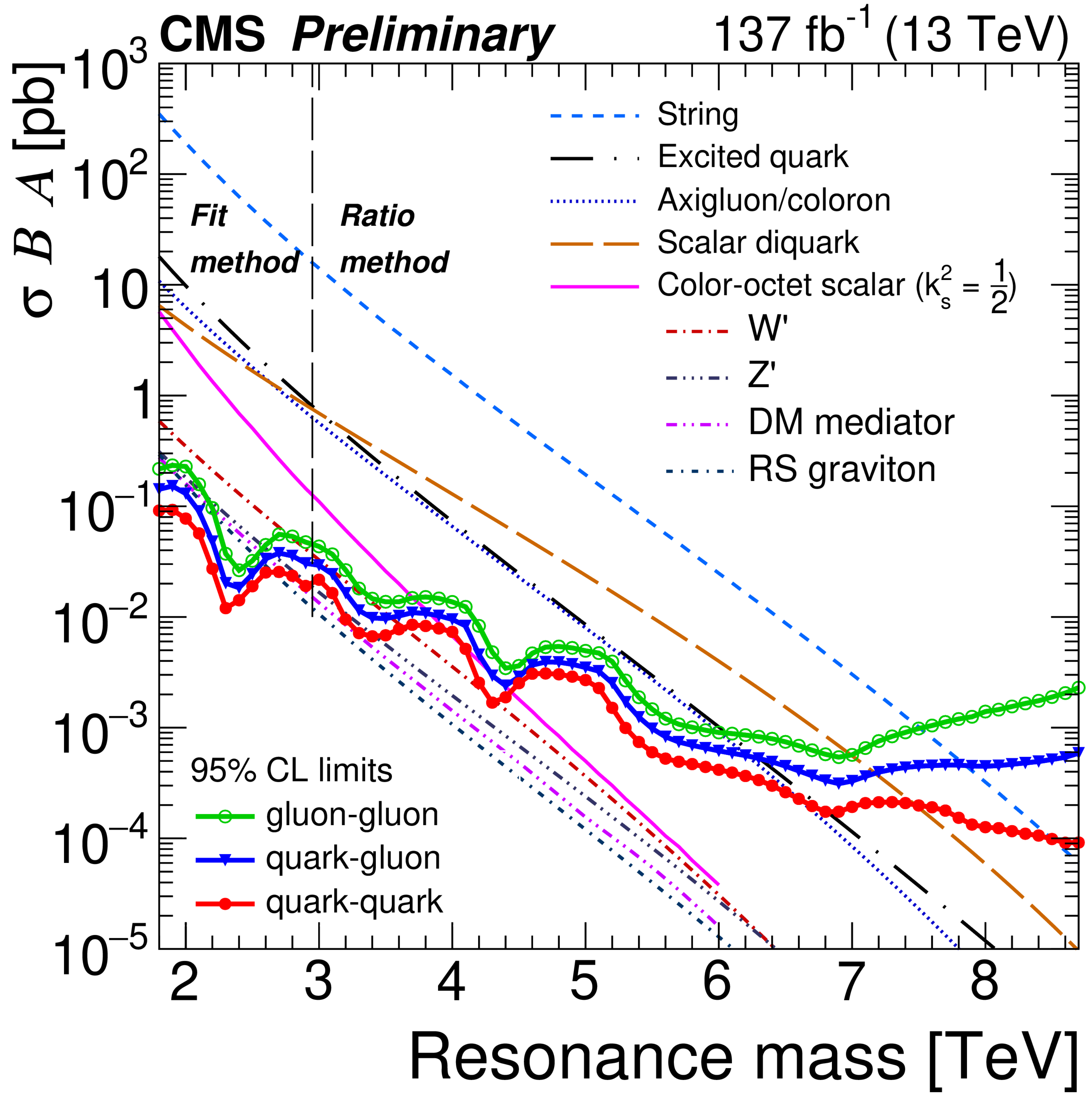
Data-driven "ratio" method yields significant improvement in expected limits for wide resonances

(DM@LHC 2019)

CMS HIGH-MASS DIJET LIMITS

- Exclude Z′ with SM-like couplings below 2.9 TeV and between 3.1 TeV and 3.3 TeV
- Exclude dark matter mediator with mass < 4.7 TeV with Γ/M = 0.25





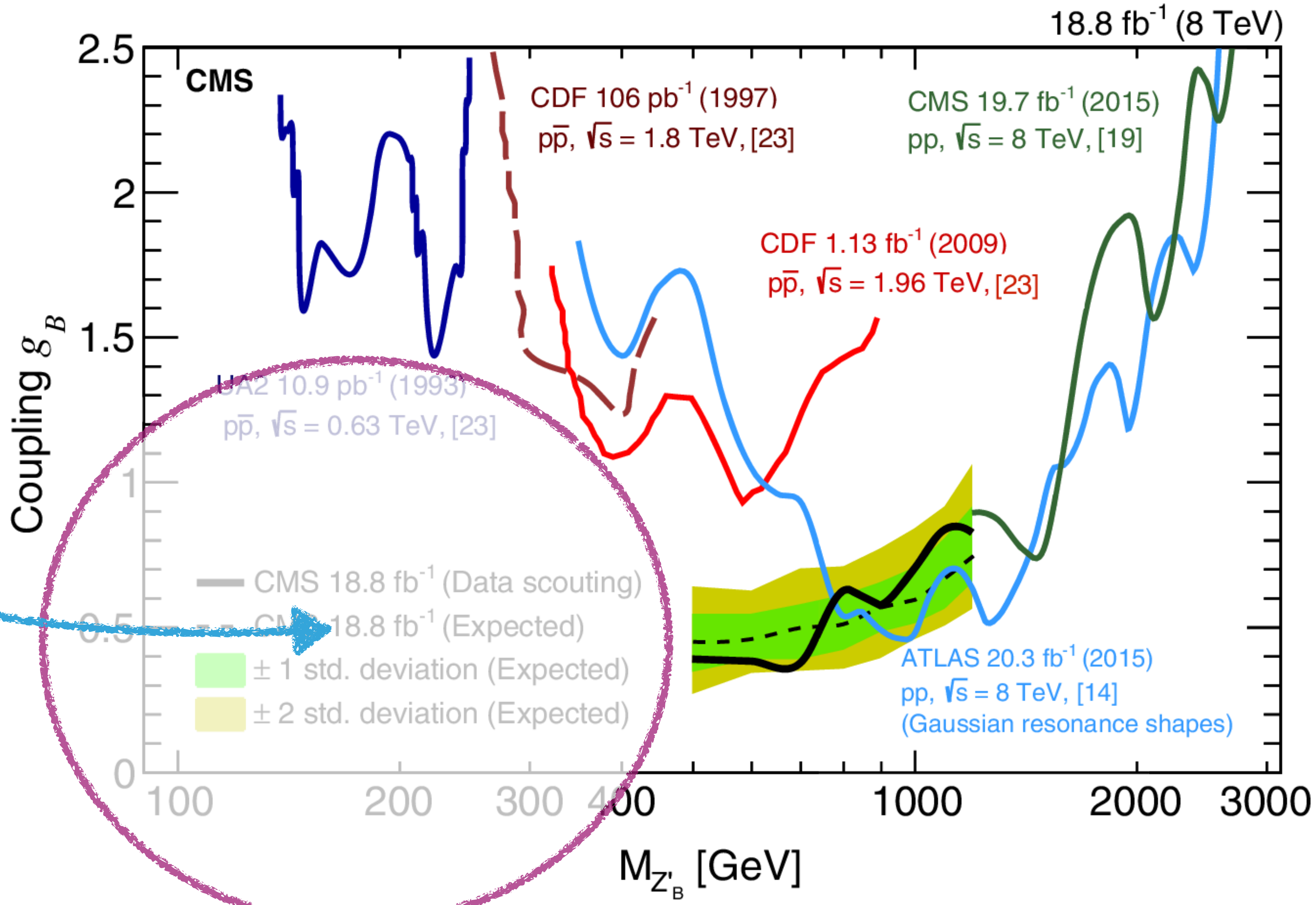
Interesting event with two 1.8 TeV wide jets!

Theory paper: [arXiv:1810.09429]

THE TROUBLE WITH (TRADITIONAL) DIJETS

- Nothing exciting at high-mass end of the spectrum (yet)
- Previous collider results could probe lower masses, but high couplings

WHAT IF NEW PHYSICS IS HIDING DOWN HERE?!?!

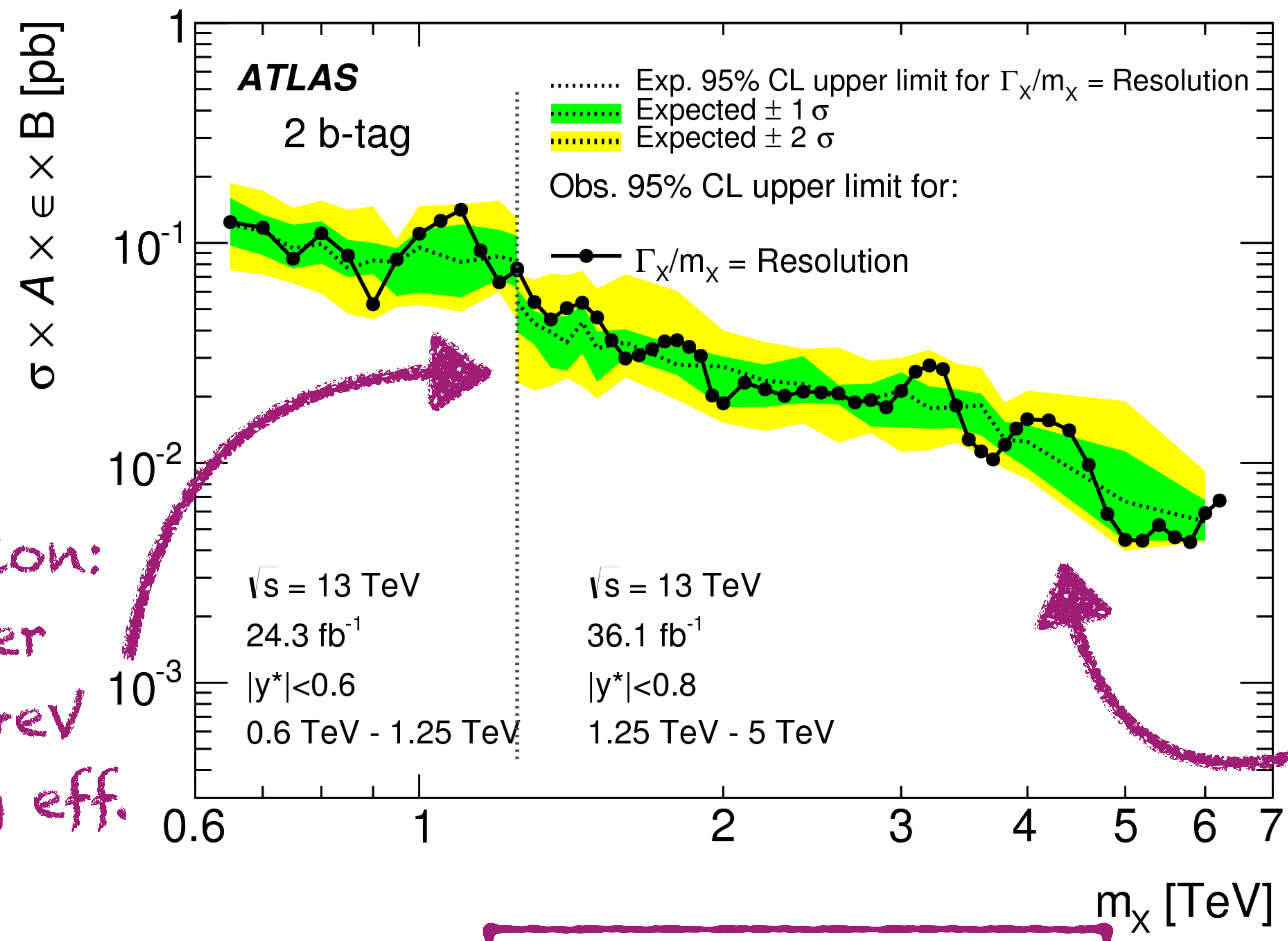


- Many interesting new techniques employed in Run 2 to search for low-mass, weakly-coupled dijet resonances

B-TAGGED DIJETS

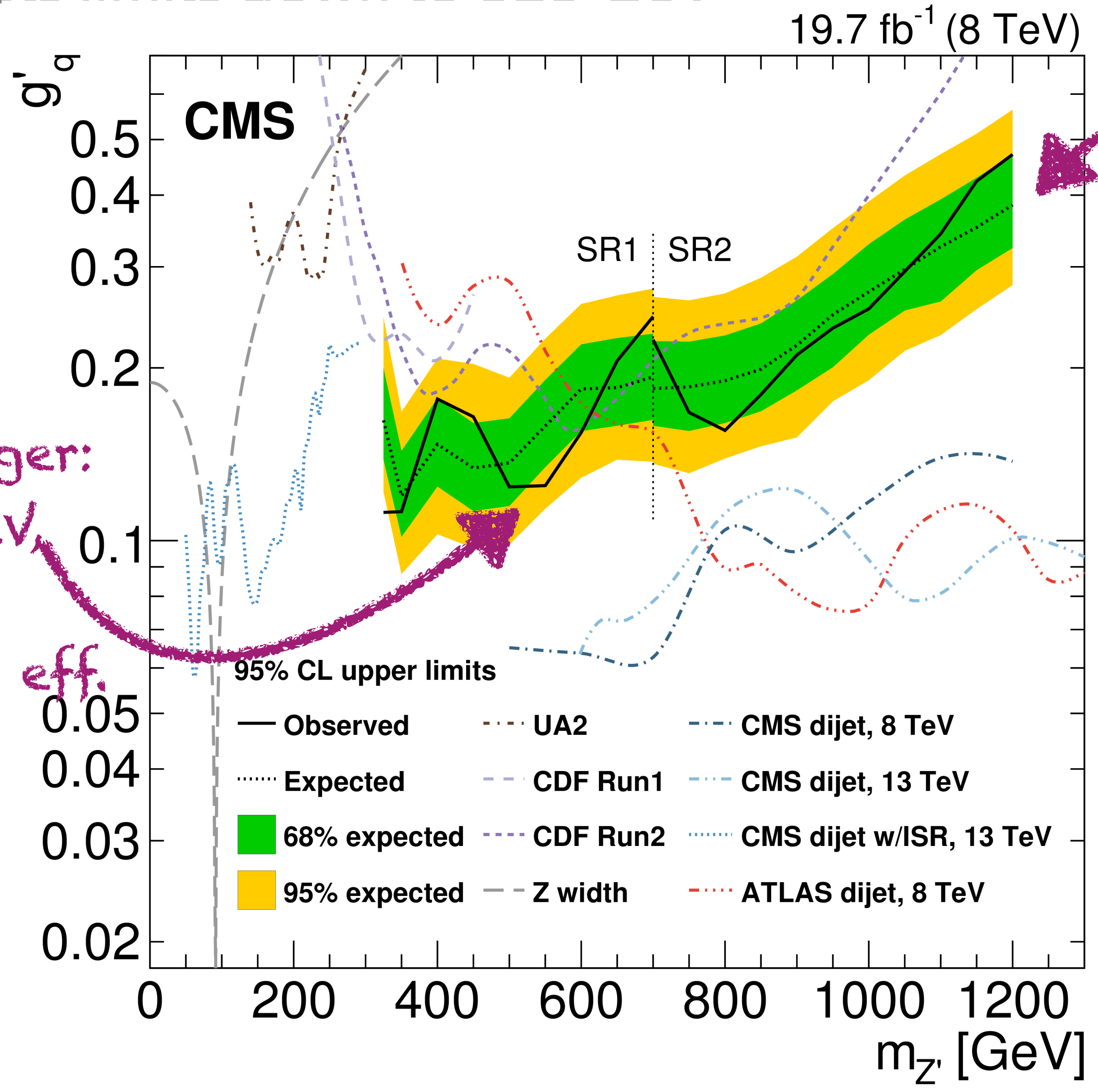
ATLAS: Phys. Rev. D 98 (2018) 032016
CMS: Phys. Rev. Lett. 120 (2018) 201801

- b-tagging in the trigger reduces event rate
  - → lower trigger thresholds → lower masses
- Interesting for models with enhanced coupling to heavy flavour
- ATLAS search sensitive to "intermediate" (~0.5-1 TeV) mass region
- CMS sets limits down to 325 GeV



Low-mass region: di-b-jet trigger p_T > 150, 50 GeV 60% b-tagging eff.

High-mass region: offline b-tagging only

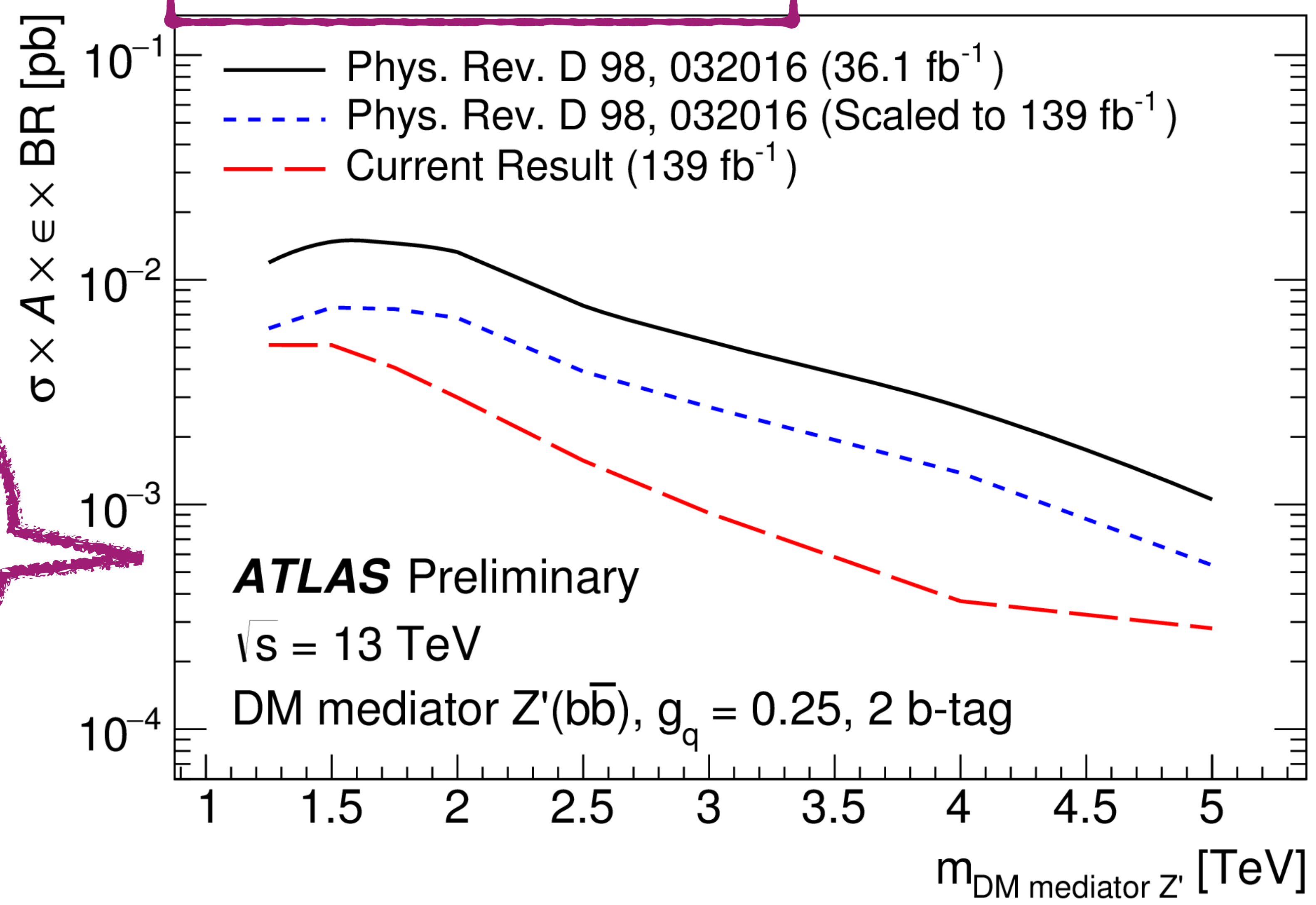


Low-mass trigger: p_T > 80, 70 GeV, $|\Delta\eta_{jj}|$ < 1.7 18% b-tagging eff.

High-mass trigger: p_T > 160, 125 GeV, $|\Delta\eta_{jj}|$ < 2.2 49% b-tagging eff.

New! Offline b-tagging with deep learning neural network dramatically improves ATLAS limits! (Poster by T. Poulsen)

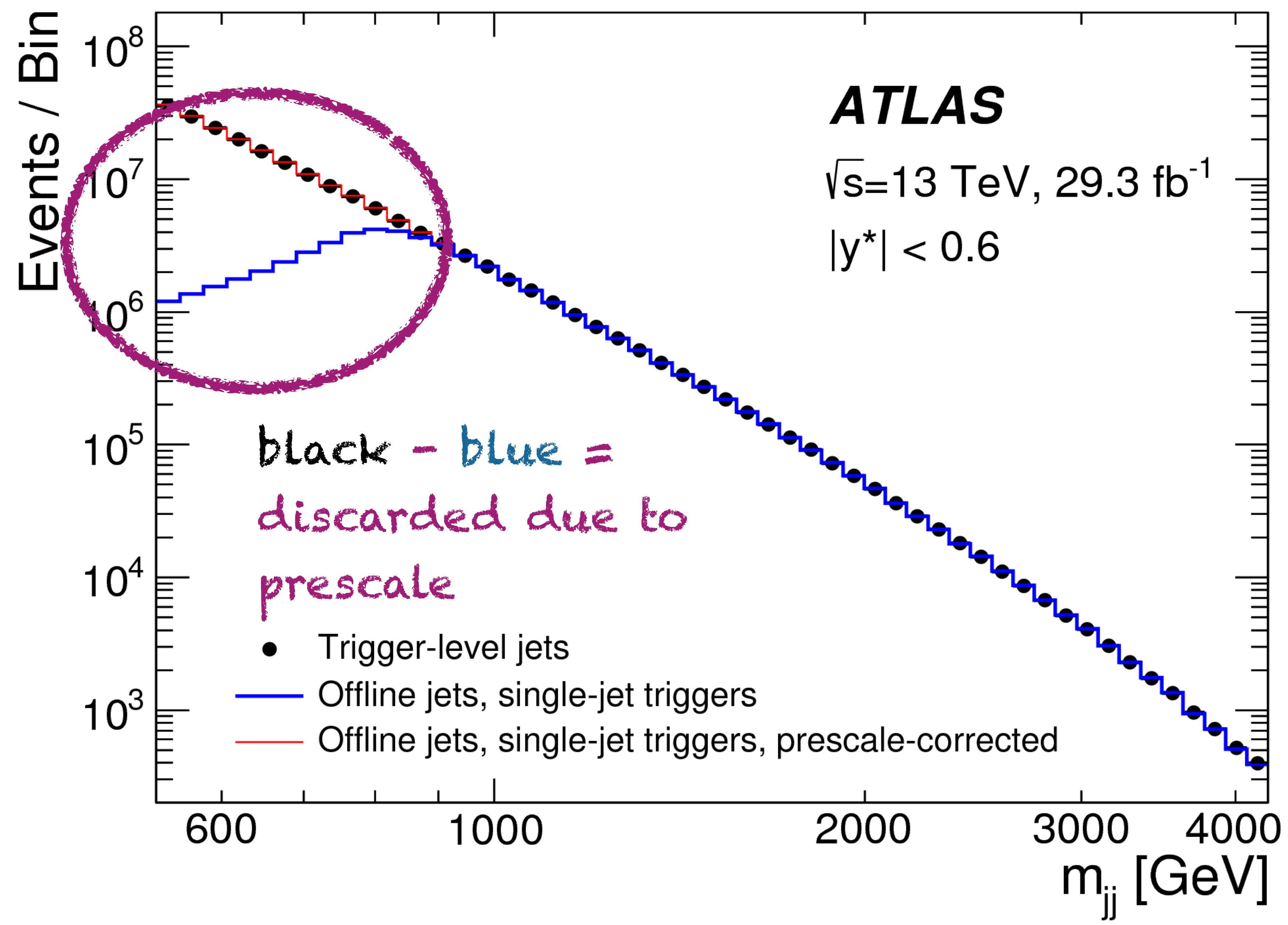
ATLAS: EXOT-2019-03



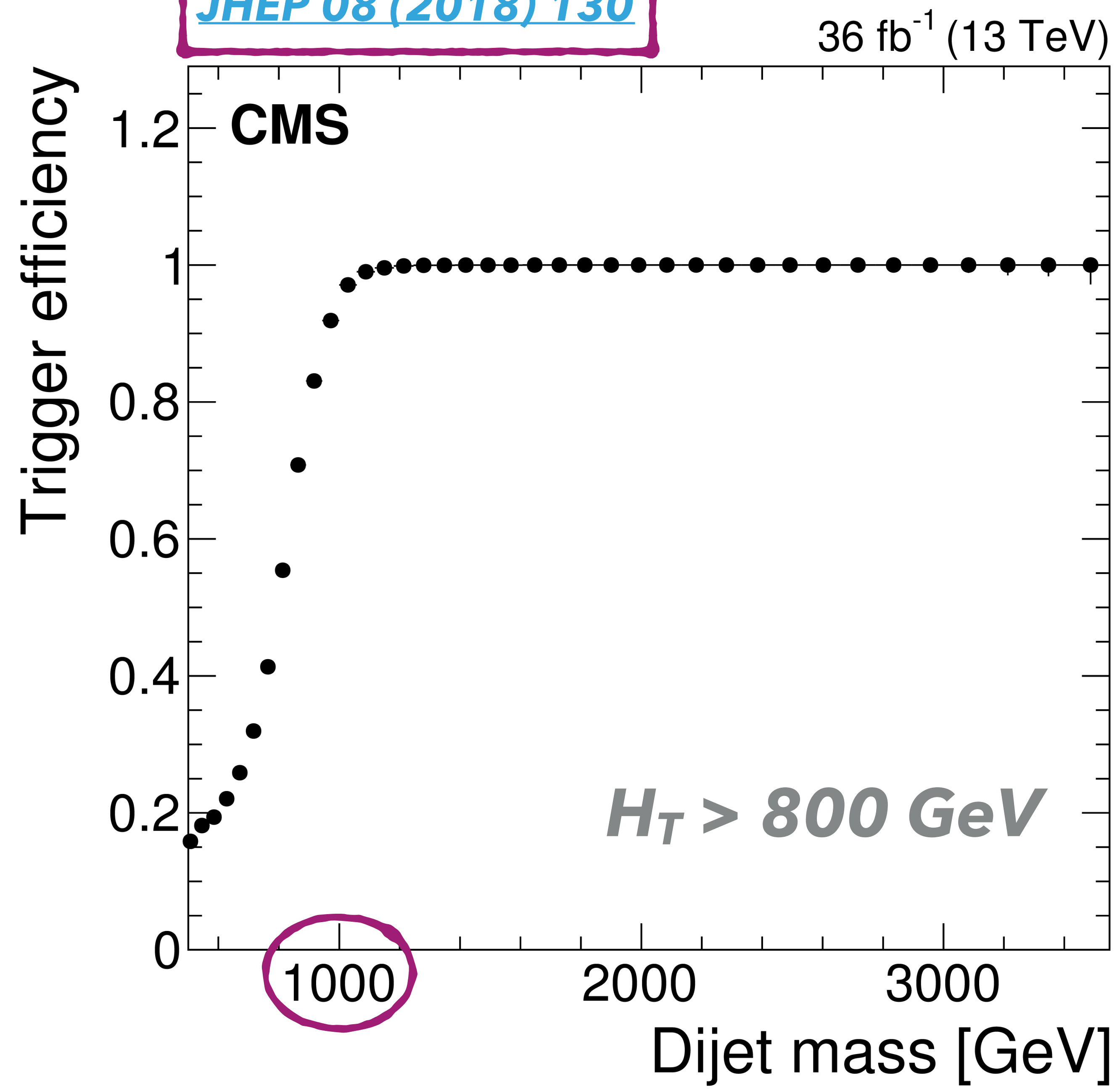
NEW TECHNIQUES: TRIGGER-LEVEL DIJET SEARCHES

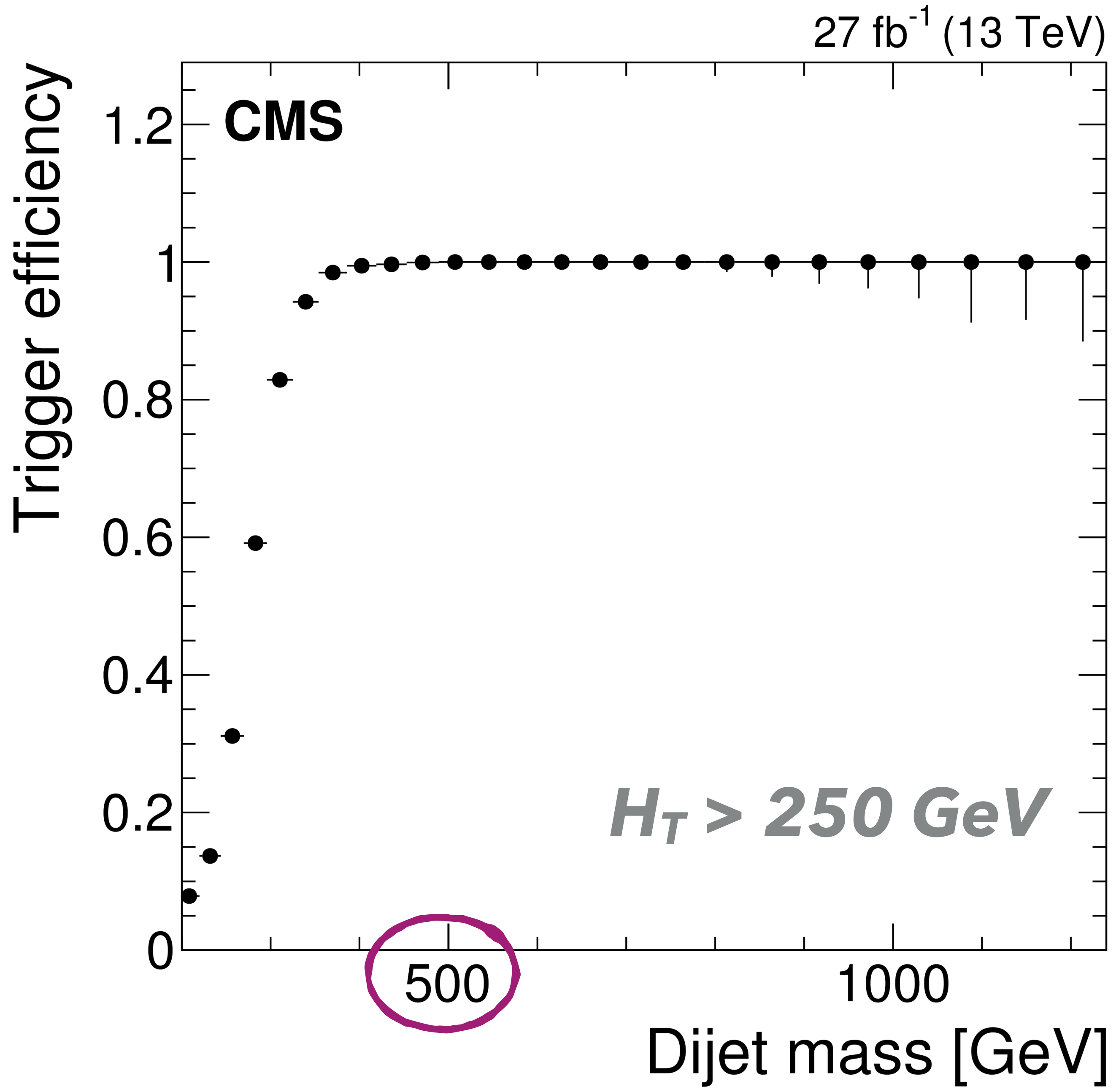
Phys. Rev. Lett. 121 (2018) 081801

- Bandwidth & detector readout limitations force prescaling of single-jet triggers at p_T below ~0.5 TeV
  - Throw away lots of dijet events below m_{jj} ~ 1 TeV!
  - This gets worse as the instantaneous luminosity increases!



JHEP 08 (2018) 130





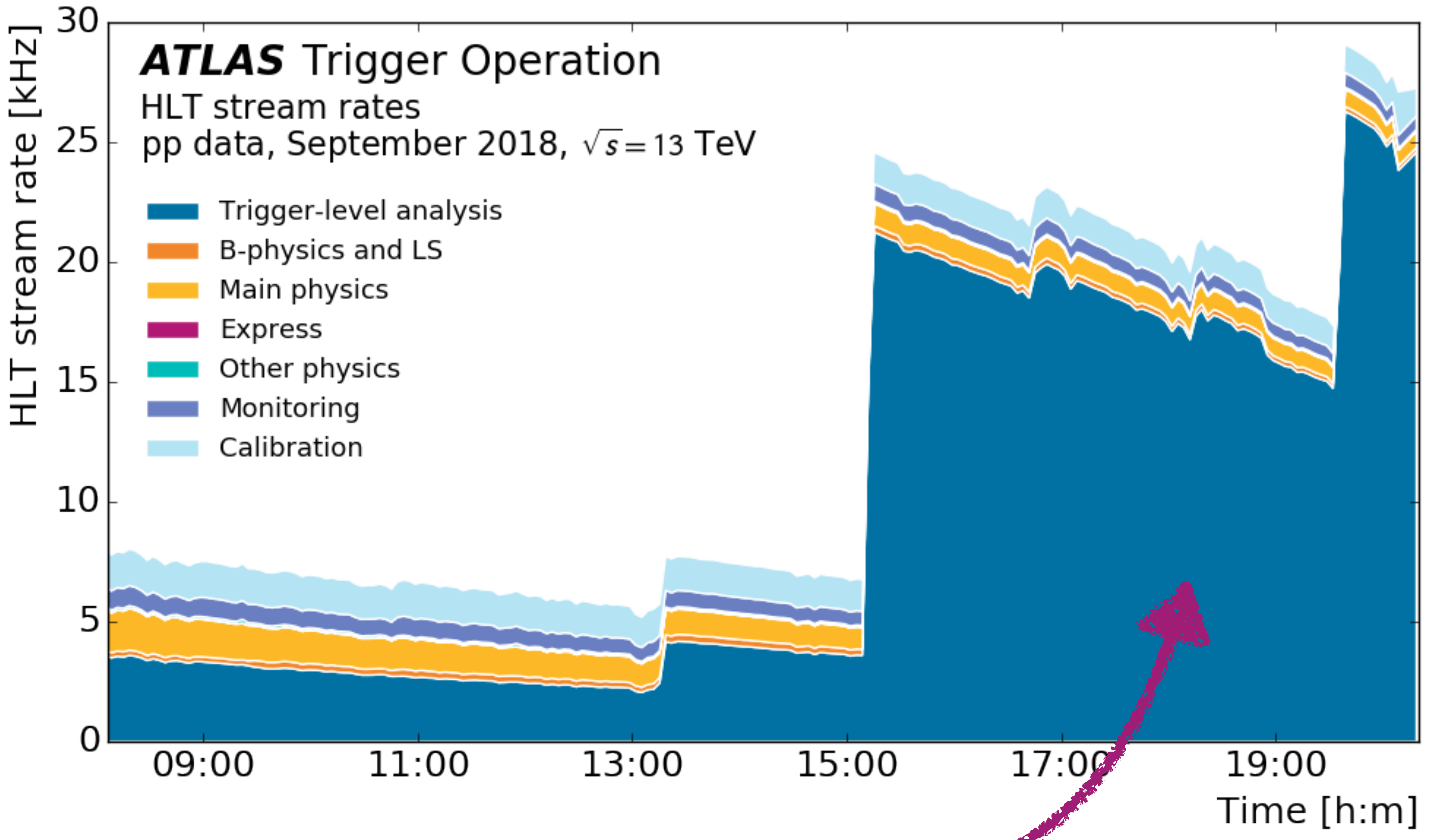
Wouldn't it be nice if we could use this trigger instead..?

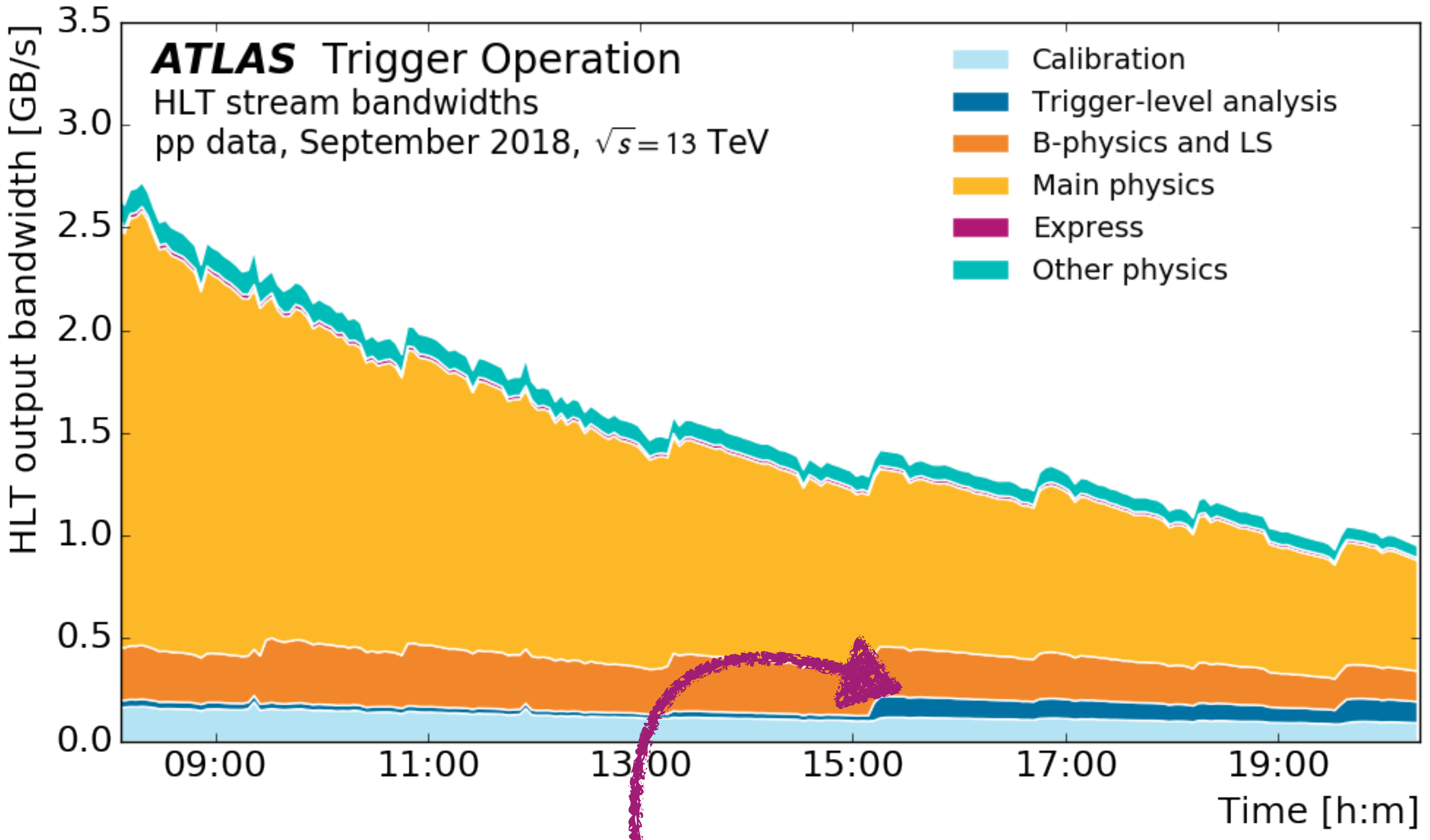
"Traditional" high-mass dijet search

TRIGGER-LEVEL ANALYSIS

ATLAS trigger operation public results

- Gain more data at low thresholds by recording **trigger-level objects** containing limited information
  - Jet four-momentum, identification variables
  - No tracking, muon, calorimeter cell info
  - Event size < 5% of typical fully-built event
- ATLAS end-of-fill strategy:
  - Exploit additional level-1 rate available at end of fill as instantaneous luminosity falls off

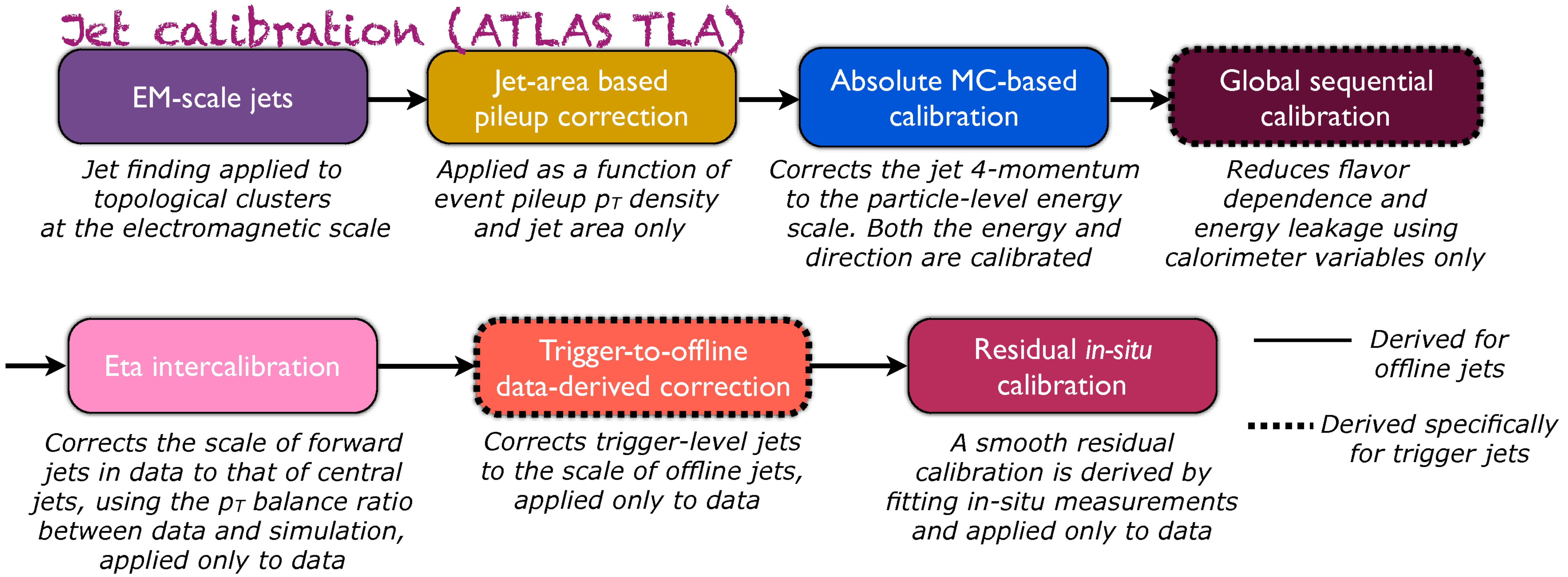


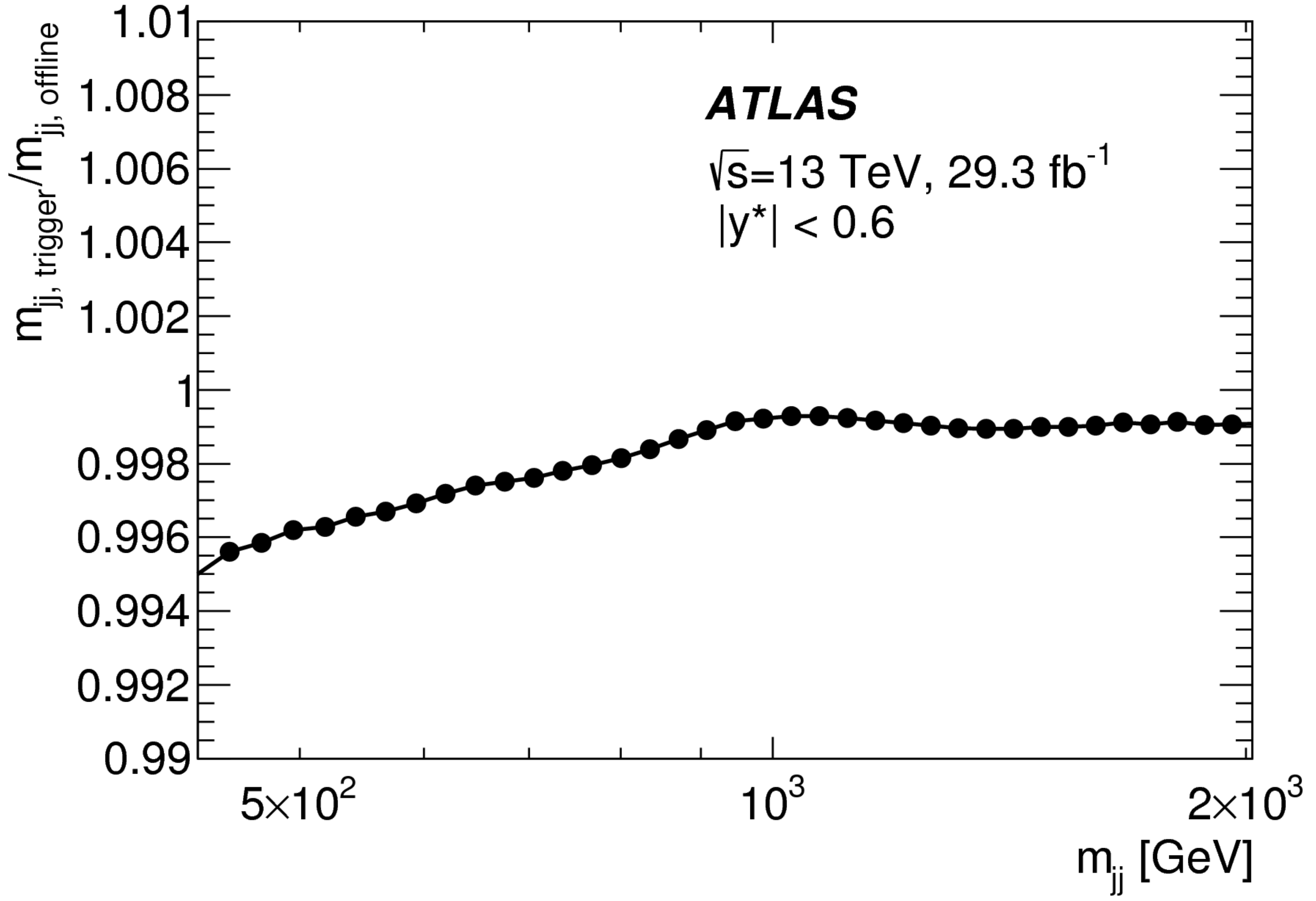


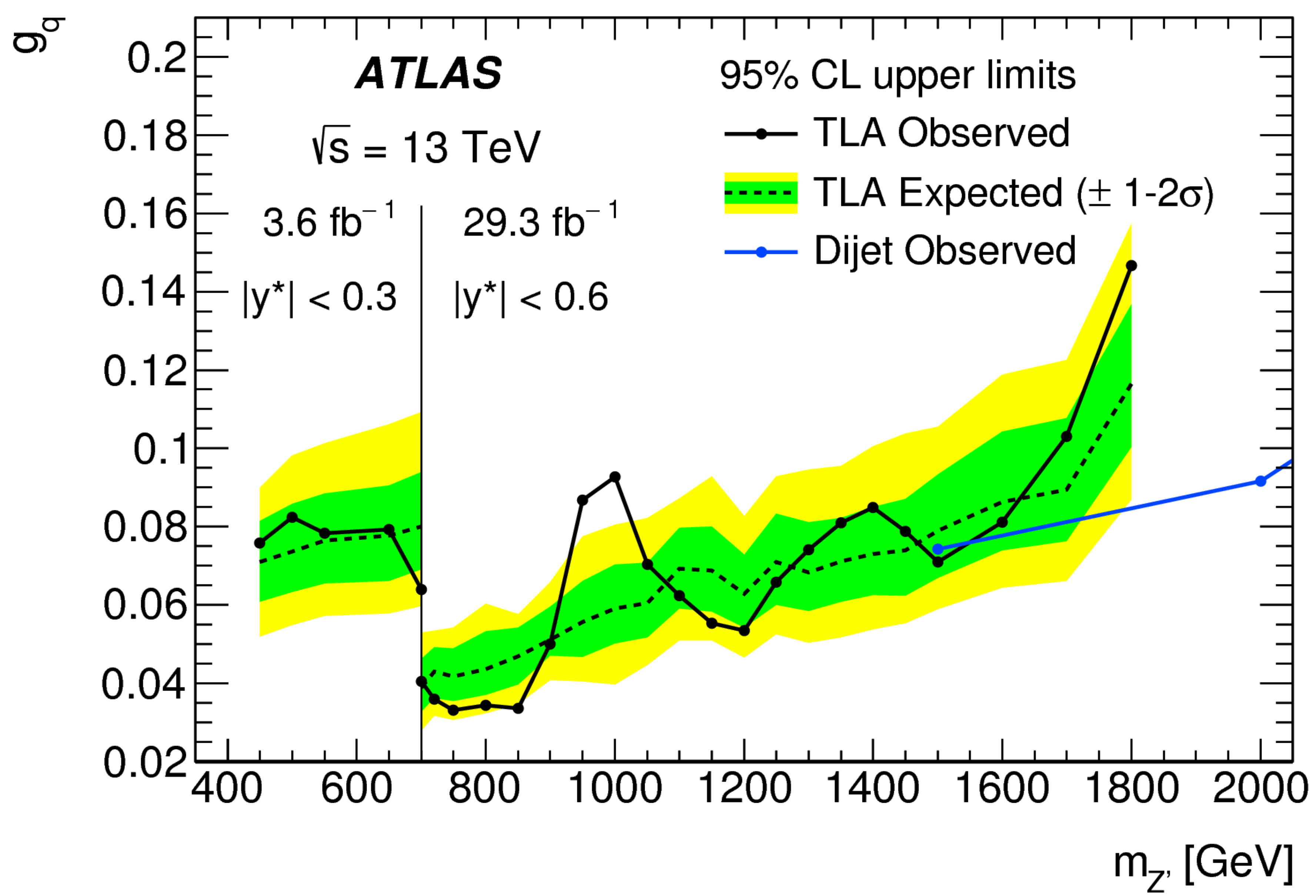
NEW TECHNIQUES: TRIGGER-LEVEL DIJET ANALYSIS

ATLAS: Phys. Rev. Lett. 121 (2018) 081801
CMS: JHEP 08 (2018) 130

- Trigger-level analysis requires a precise understanding of the jet calibration
  - Reproduces offline calibration as closely as possible (no tracking info)
  - Excellent agreement between trigger and offline dijet invariant mass







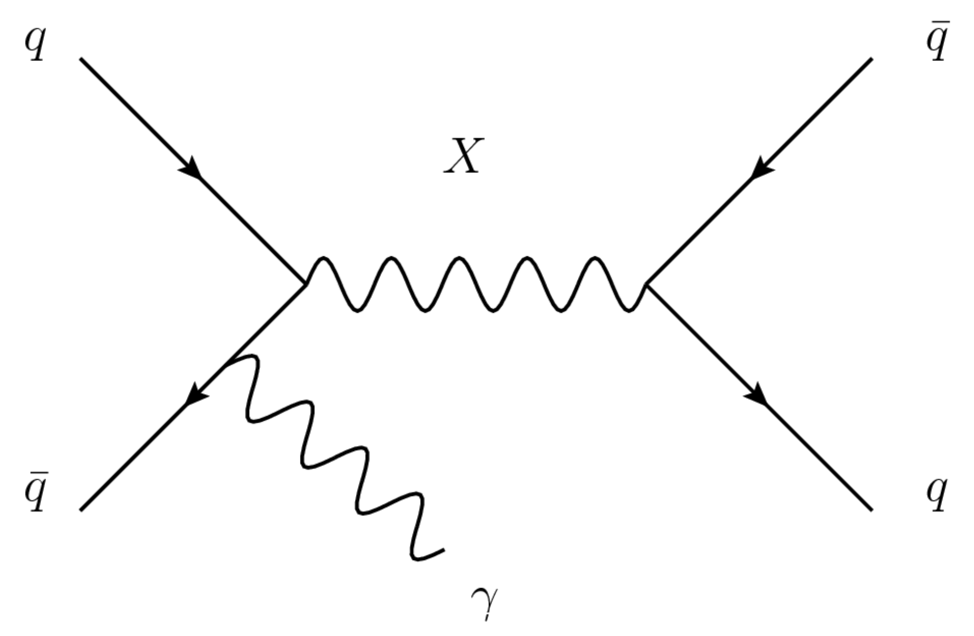
- ATLAS sets limits on couplings for resonance masses between 450 - 1800 GeV
  - Two signal regions corresponding to two trigger thresholds (75 & 100 GeV)
- CMS sets limits down to 600 GeV

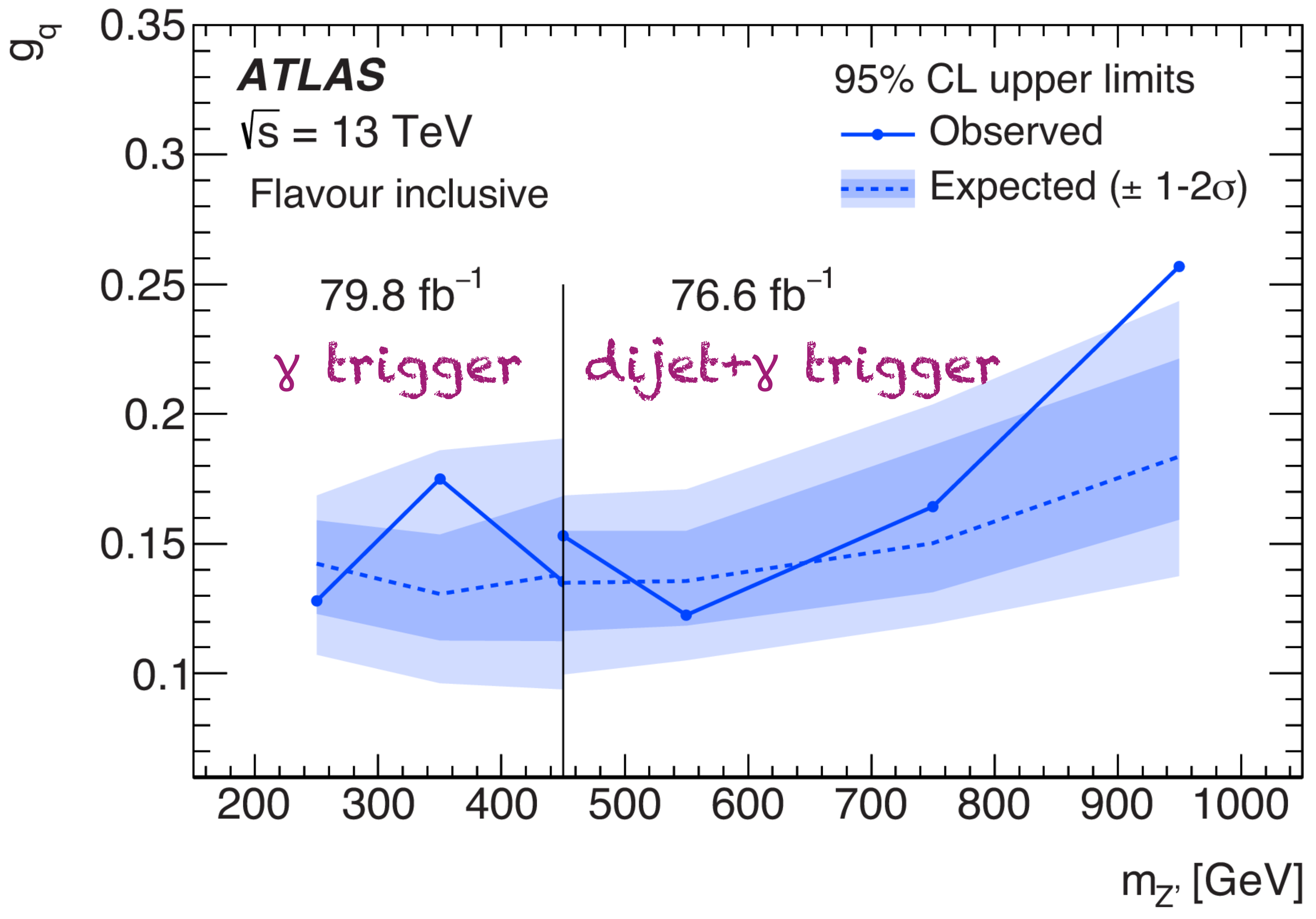
New! CMS 3-jet scouting: CMS-PAS-EXO-19-004

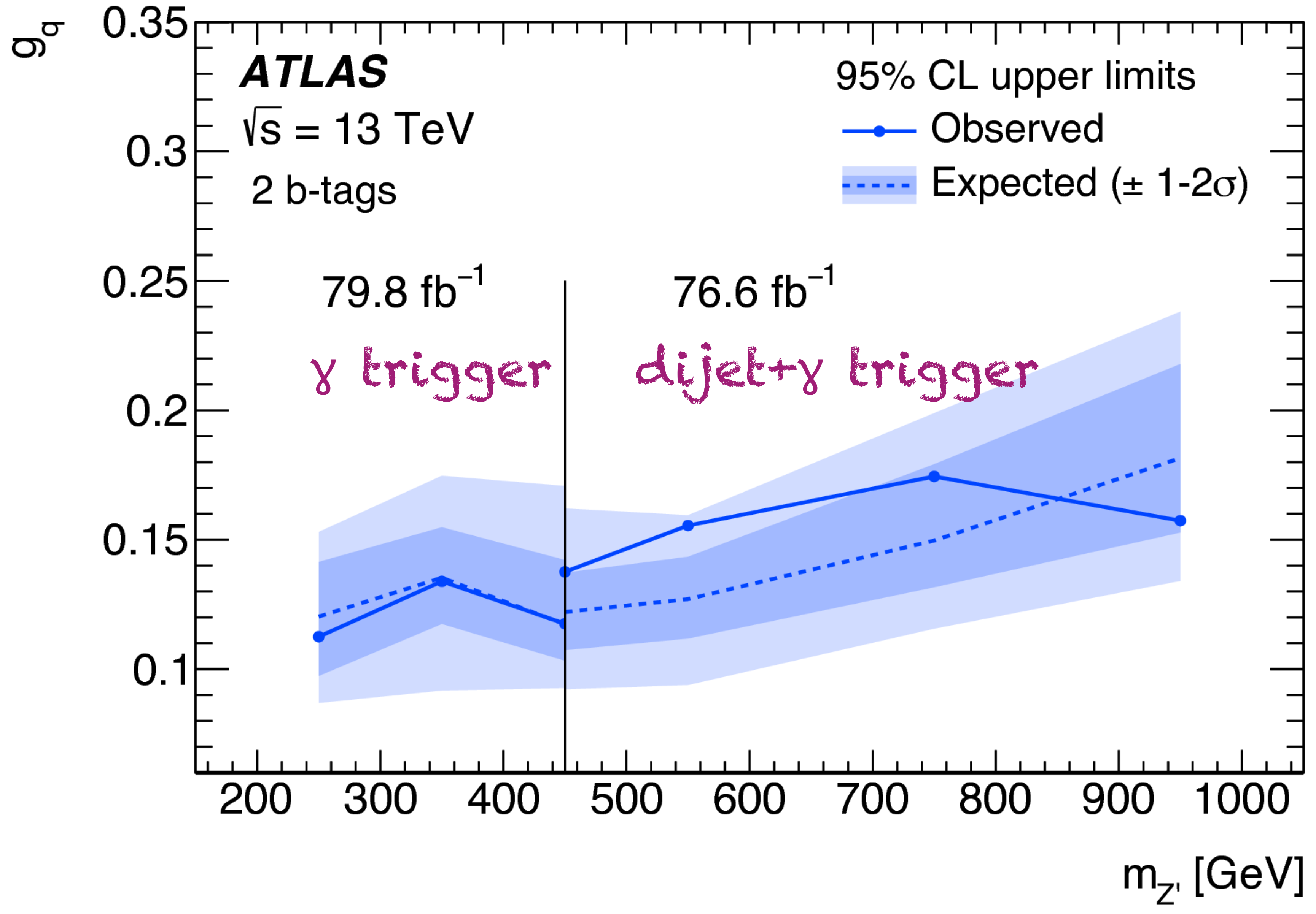
NEW APPROACHES: DIJET+ISR

ATLAS: Phys. Lett. B 795 (2019) 56, resolved dijet (inclusive & b-tagged) + photon, 80 fb^{-1}

- Sensitivity of traditional searches limited by trigger thresholds to $m_{jj} \sim 2p_T^{min}$
- Extend dijet resonance search to even lower masses and smaller couplings by triggering on initial-state radiation (e.g. photon or jet) and search for recoiling dijets
  - Drawback: smaller cross-section due to ISR requirement
- New ATLAS result with 2015-2017 data sets limits on mediator masses down to 225 GeV!



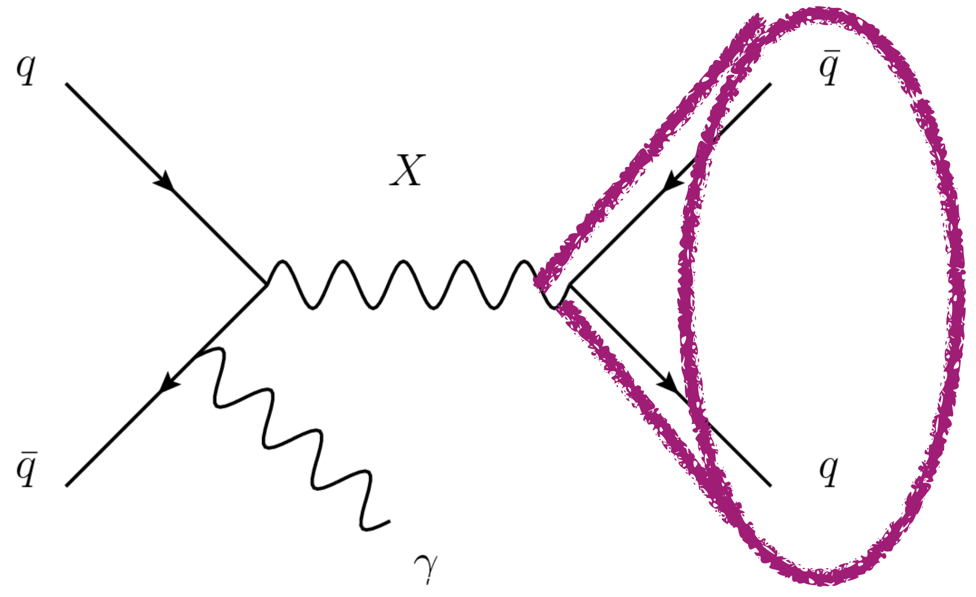


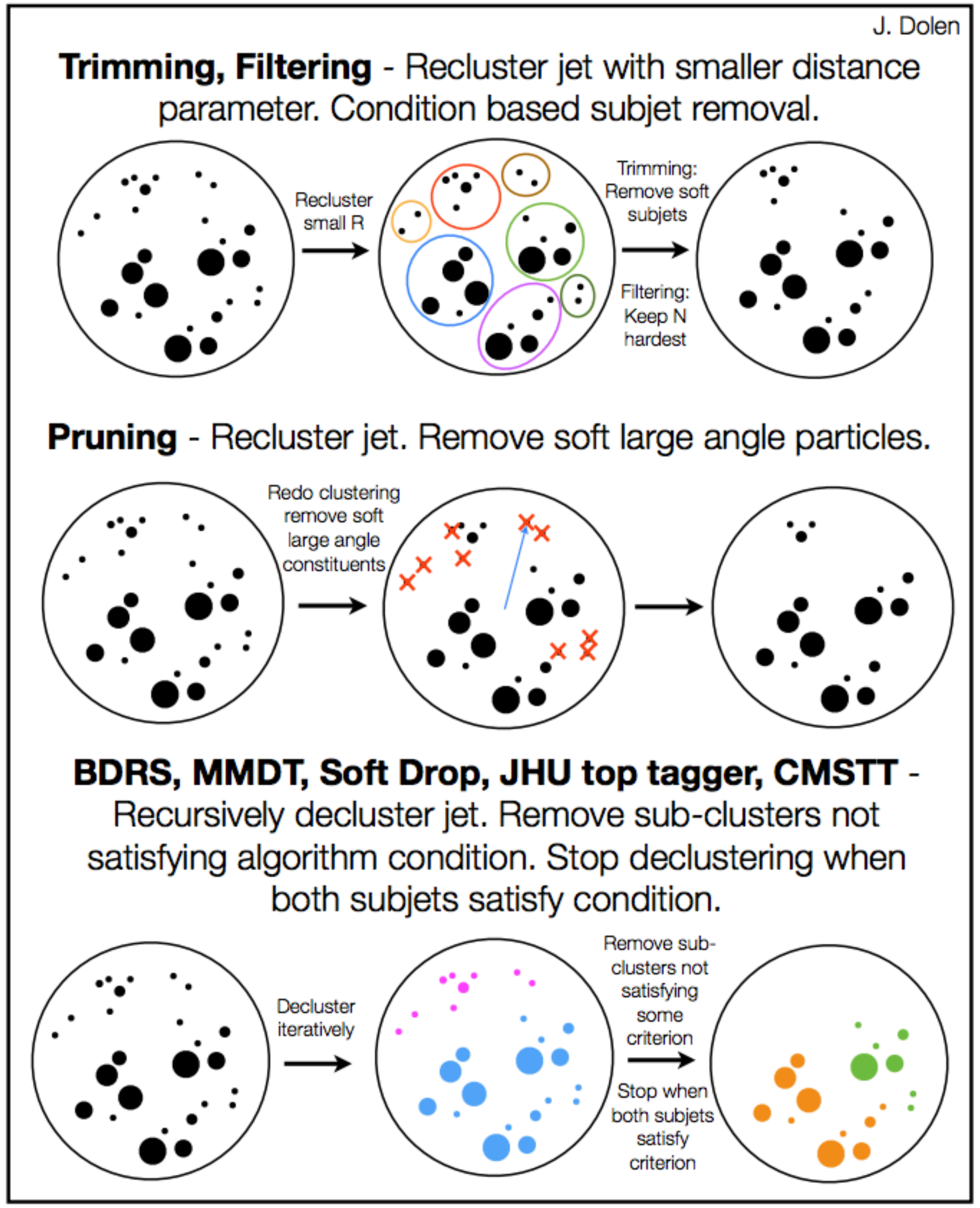


NEW APPROACHES: DIJET+ISR

CMS dijet + ISR photon (2016 data): arXiv:1905.10331
ATLAS: Phys. Lett. B 788 (2019) 316: boosted, 2015-2016 data
ATLAS-CONF-2018-052: boosted b-tagged, 2015-2017 data (in backup)

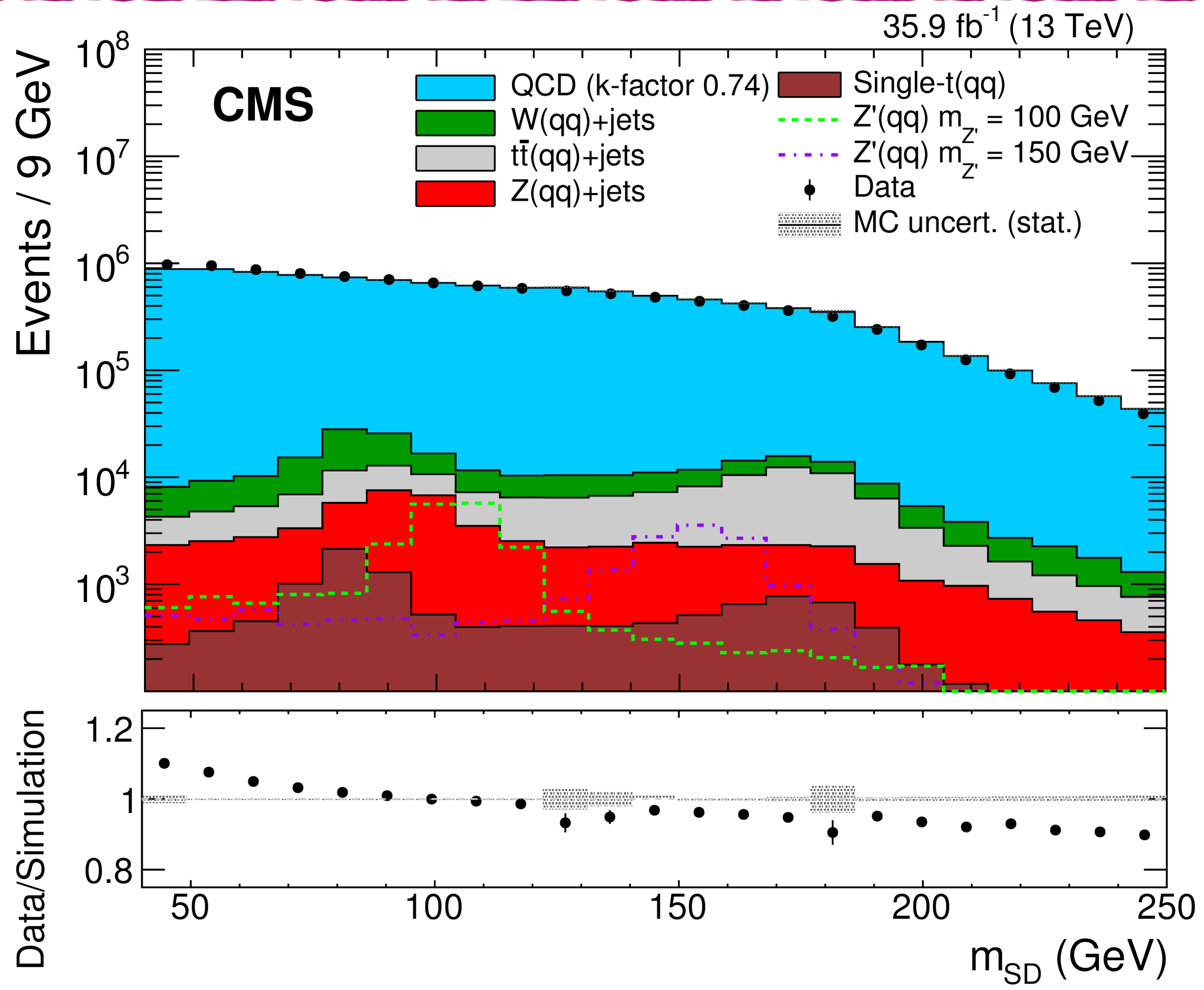
- Boosted dijets allow to push the mass range even lower
- Interesting analysis techniques differing from traditional dijet searches!
- Jet substructure techniques used to select large-R jets with two-pronged substructure
- Jet grooming is critical!
  - ATLAS: trimming
  - CMS: soft-drop mass





BOOSTED DIJET+ISR: BACKGROUND ESTIMATION

CMS boosted dijet + ISR jet: [JHEP 01 (2018) 097]



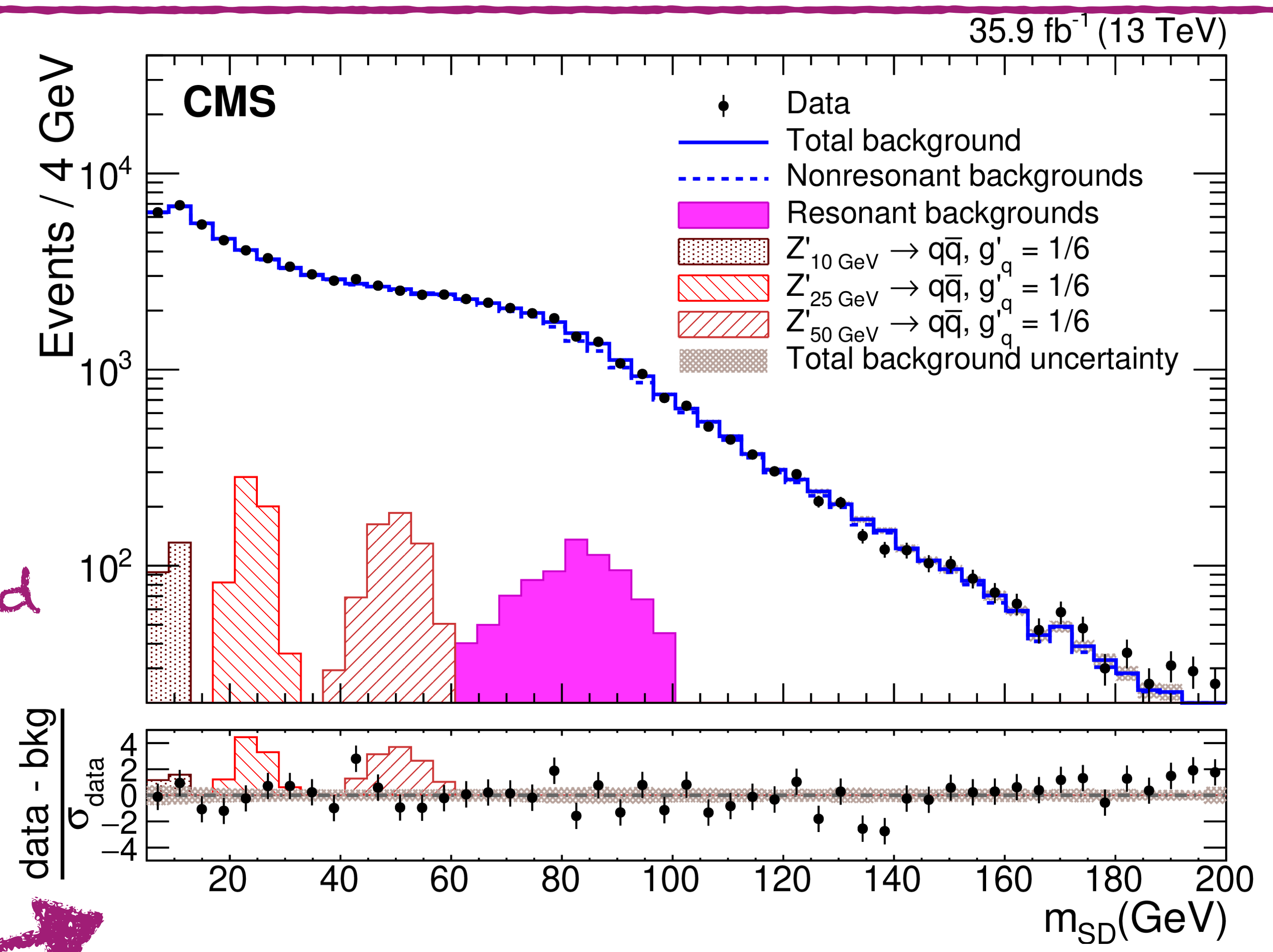
- Data-driven method used to estimate the QCD background
- Energy correlation function N_2^1 ([1609.07483]) used to discriminate 2-pronged signal jets from 1-pronged QCD
  - Correlated with jet mass and p_T
  - Decorrelate to avoid sculpting the mass distribution (DDT method: [1603.00027])

$$N_2^{\mathrm{DDT}}(\rho^{\mathrm{jet}}, p_{\mathrm{T}}^{\mathrm{jet}}) = N_2^1 - X_{10\%}(\rho^{\mathrm{jet}}, p_{\mathrm{T}}^{\mathrm{jet}})$$

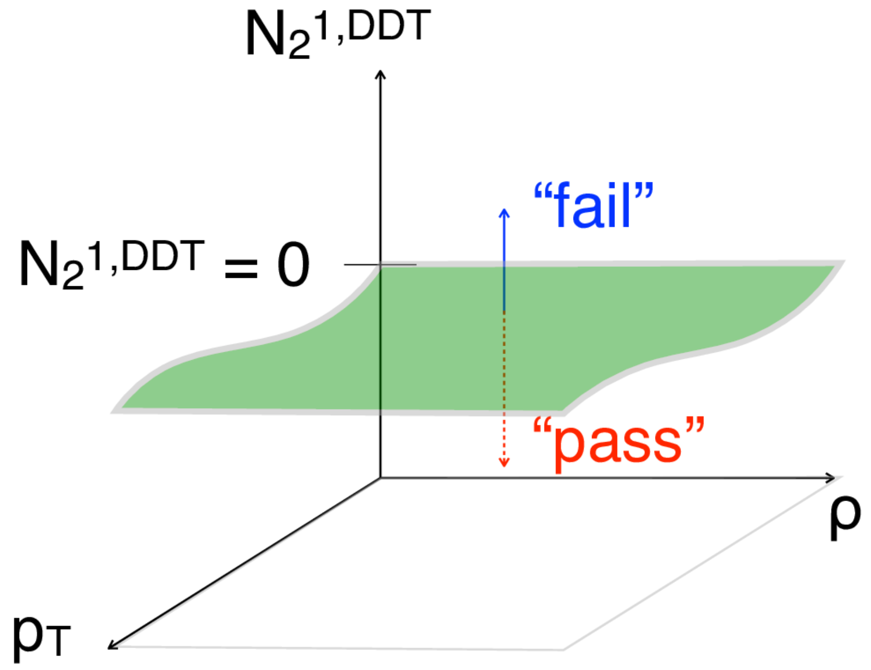
$\rho = \ln(m^2 / p_T^2)$

$X_{10\%}$: value of N_2^1 where a cut would retain 10% of background

CMS dijet + ISR photon (2016 data): [arXiv:1905.10331]



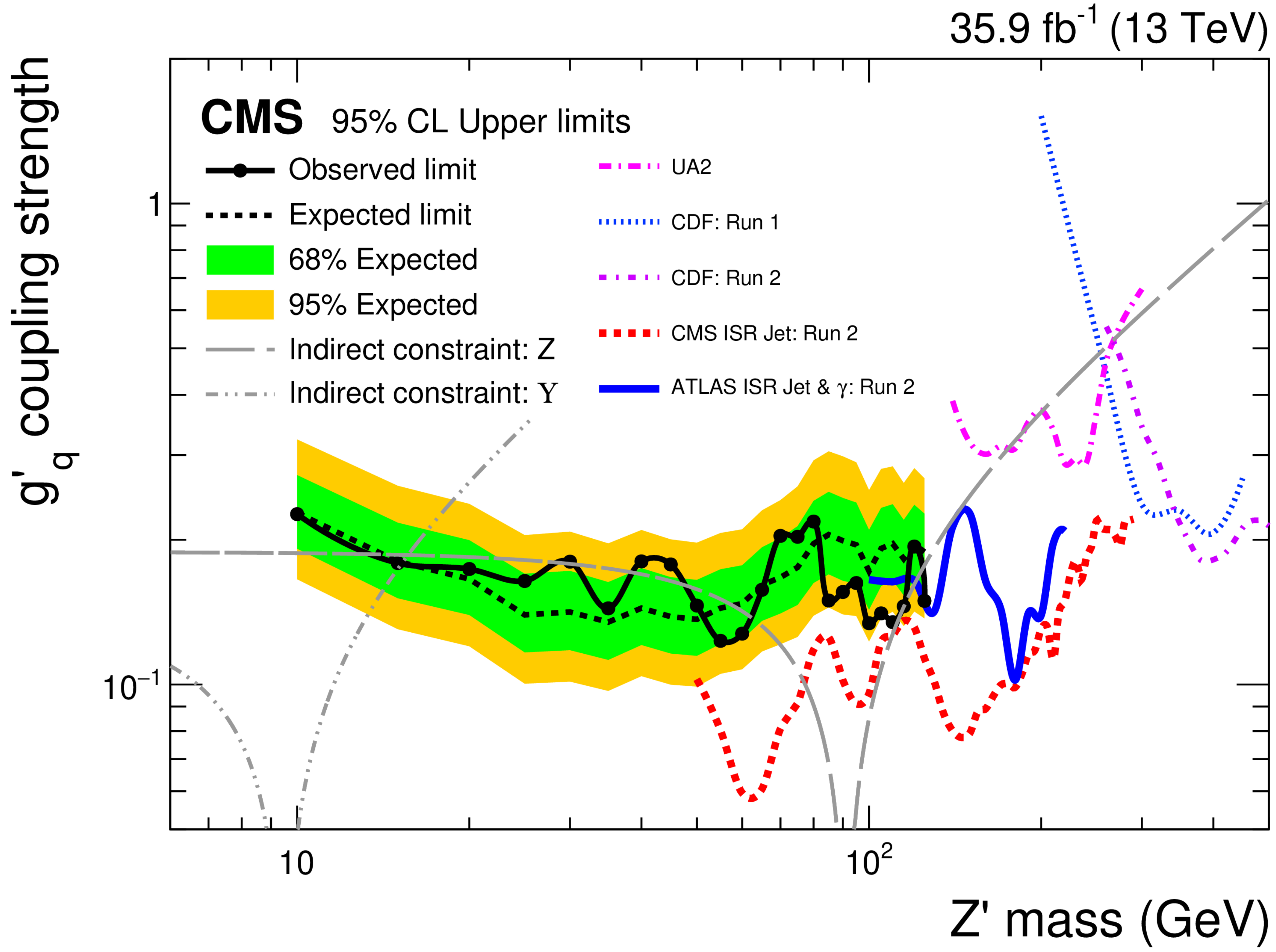
- Transfer factor method used to estimate the QCD background
  - Control region: events failing the substructure (N^{DDT}) selection



Jet mass modelling using soft drop tested down to 10 GeV!

BOOSTED DIJET+ISR RESULTS

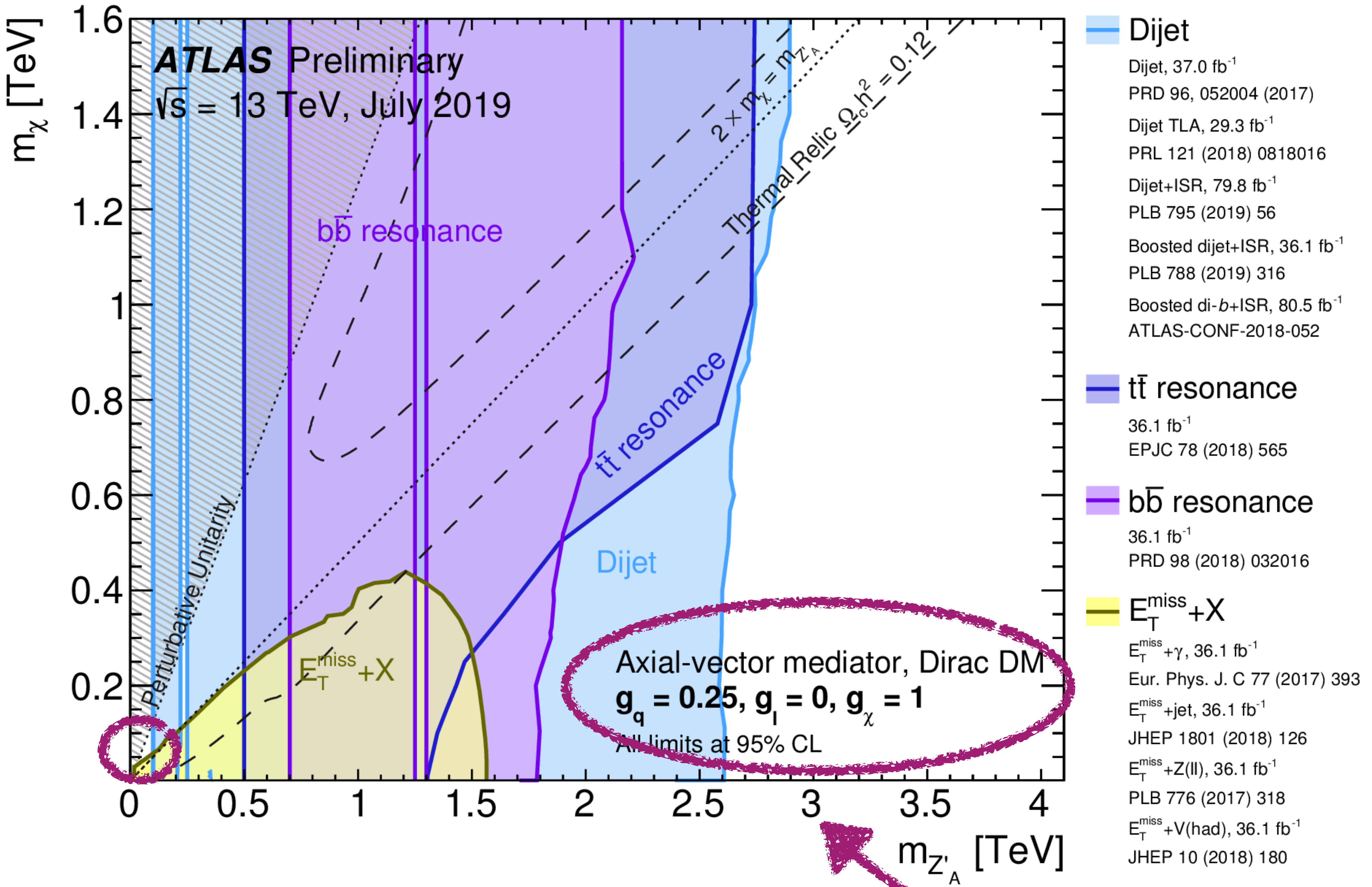
- Dijet + ISR searches probe the lowest mass range yet at the LHC!
  - CMS: 10 GeV (ISR photon), 50 GeV (ISR jet)
  - ATLAS: 100 GeV (ISR photon, jet)
    - New: b-tagged search (*poster by Y. Ng*)
- We are doing a good job of searching in that uncovered corner of parameter space…
  - Unfortunately no significant excesses yet!

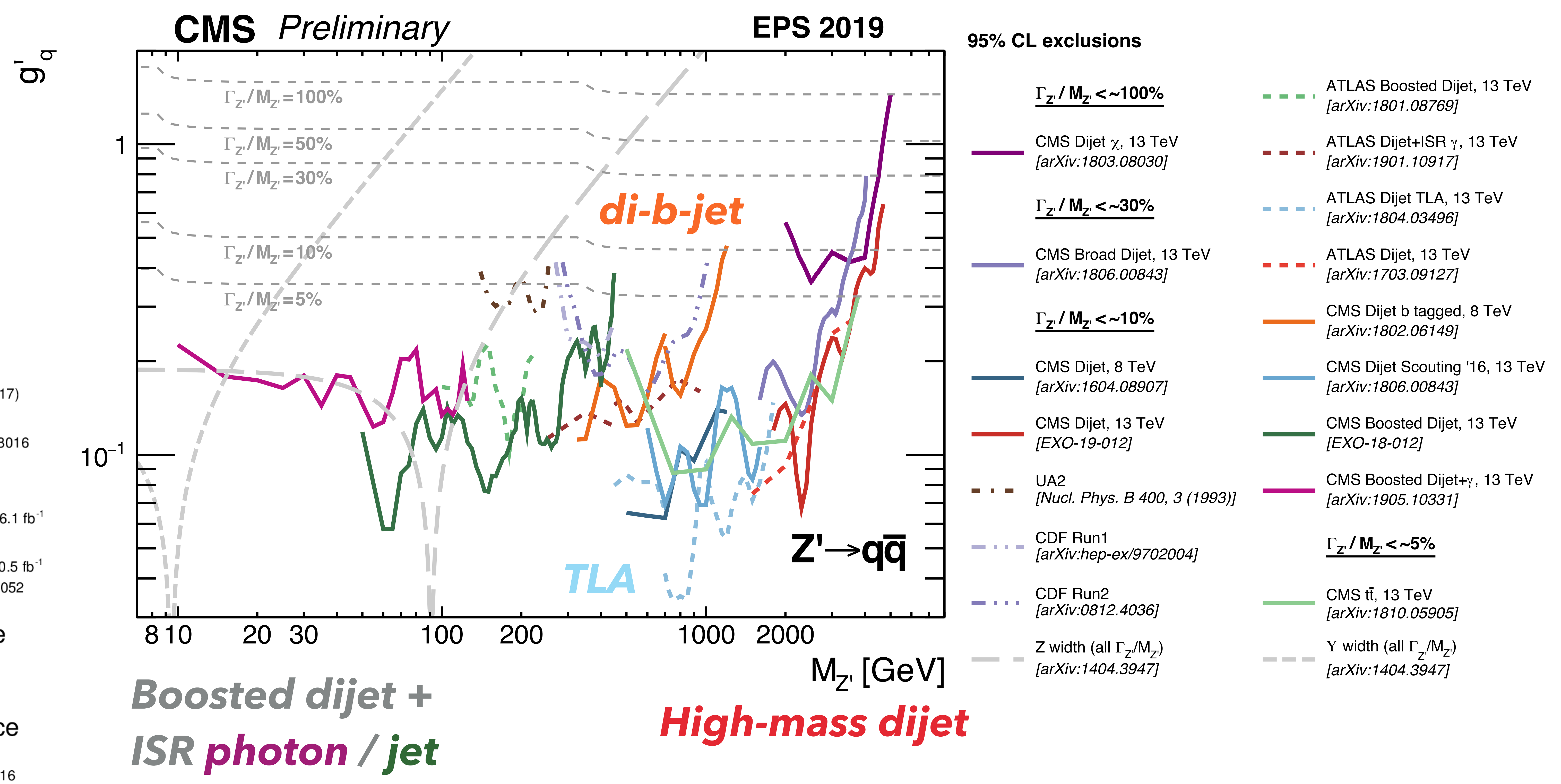


SUMMARY: COMPLEMENTARITY OF DIJET SEARCHES

ATLAS Exotics summary plots
CMS Exotica public results

- Dijet searches cover a wide range of parameter space in the coupling - Z′ mass plane
- Also: excellent complementarity with other dark matter search channels!

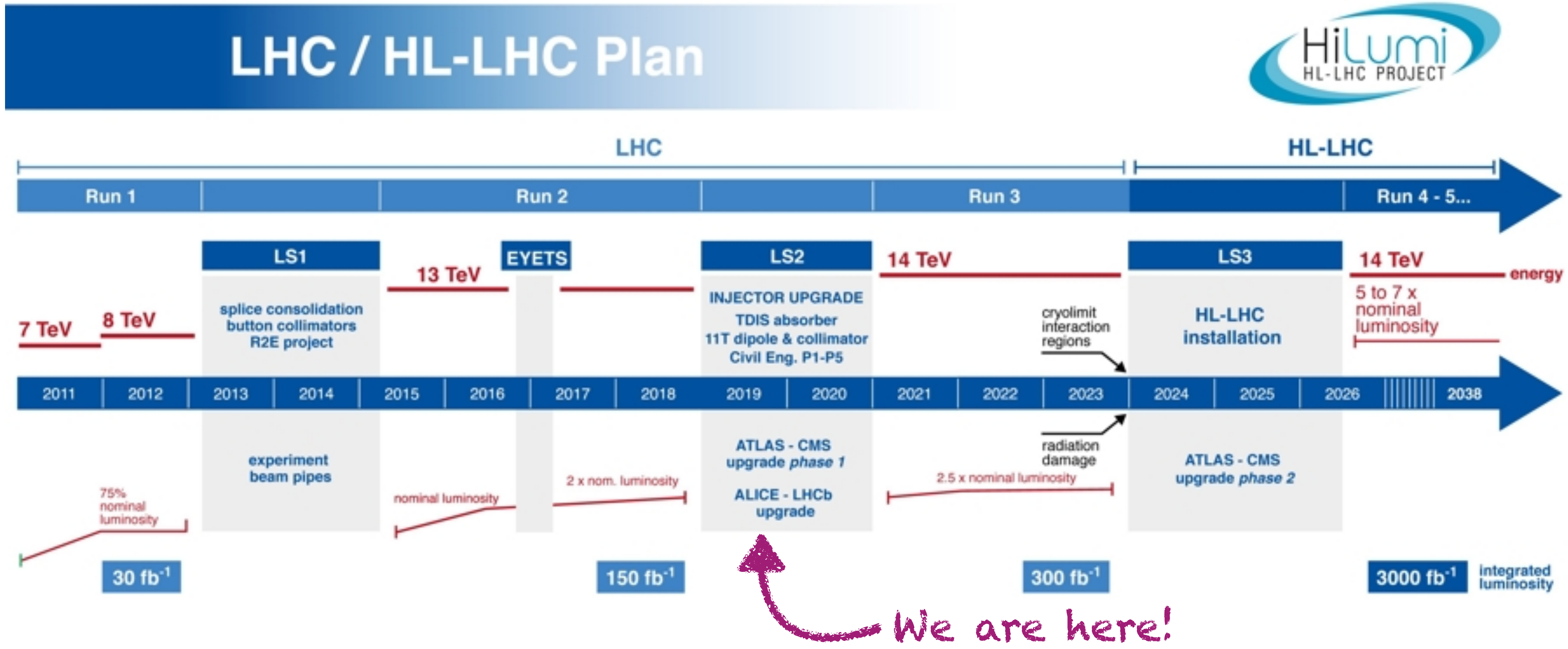


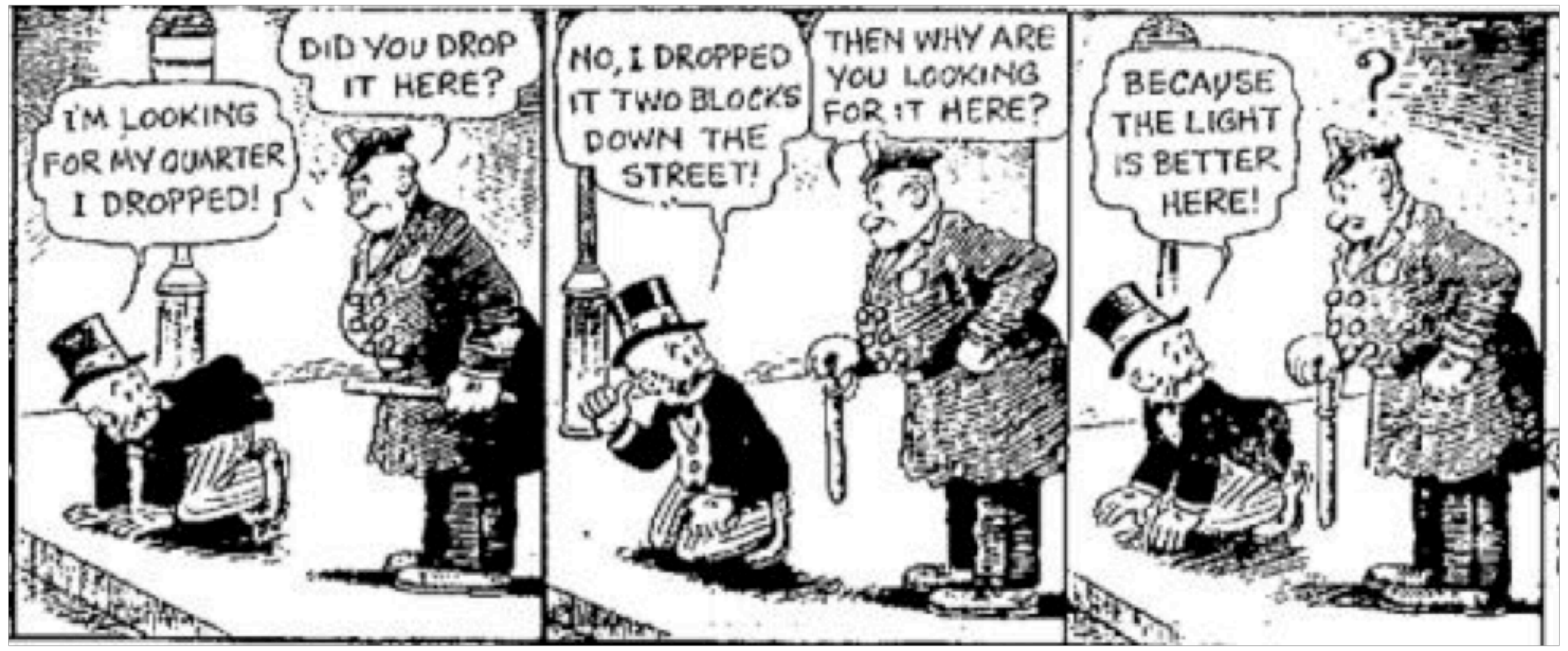


Remember! Exclusion limits shown for a particular model (g_q=0.25). Unexcluded parameter space is larger for weaker couplings!

OUTLOOK ON RUN 3

- Run 3: slow and steady progress from the LHC
  - Small energy increase: 13 –> 14 TeV
  - Slower luminosity doubling time
- Now is the time to focus on improvements to squeeze the most out of our data!
- Boosted object tagging
  - ATLAS gFEX: large-R jets in L1 trigger
- More trigger-level searches to maximize statistics
  - e.g. dijet+ISR TLA
- Improved trigger tracking to reject pileup
  - e.g. FTK (ATLAS fast tracking in hardware)



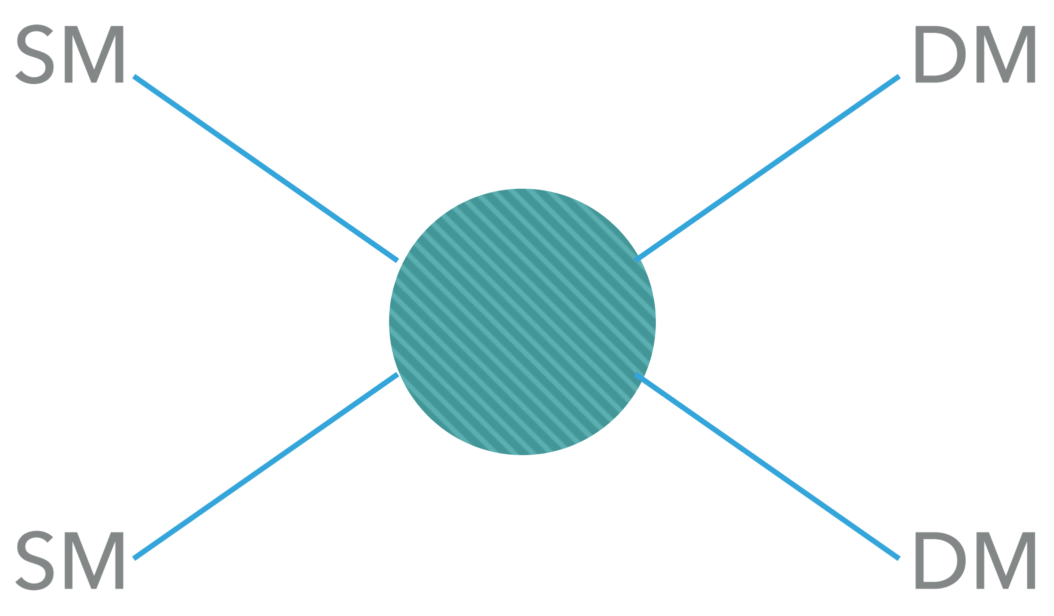


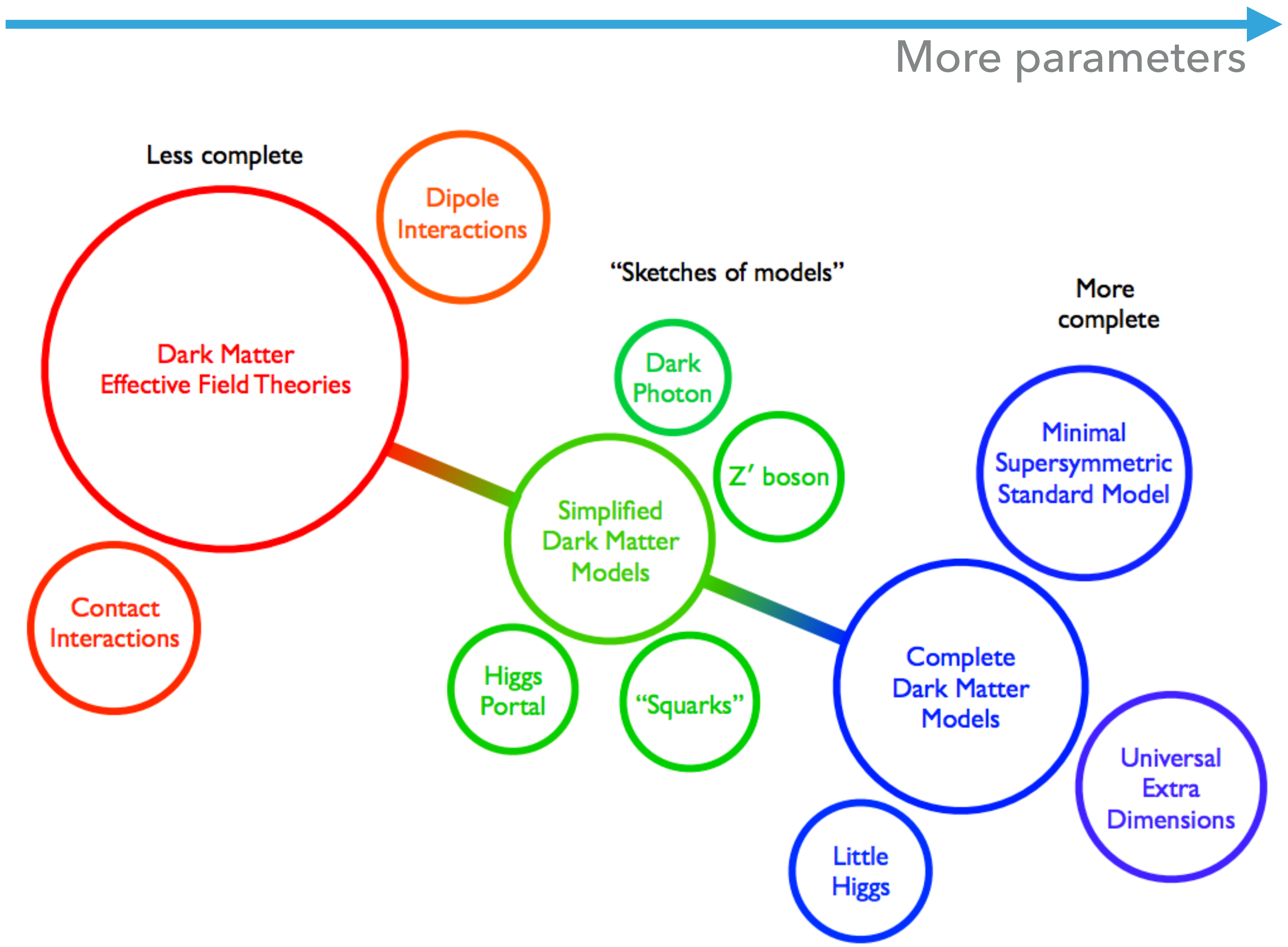
Dont be this guy at the start of Run 3! Invest in trigger and performance work now!

BACKUP

DARK MATTER MODELS AT THE LHC (RUN 1)

- Effective field theories (EFT)
  - Run 1 DM searches at the LHC
  - Contact interactions
  - Described in terms of effective energy scale and m_{DM}
  - Invalid at large momentum transfer: problematic in Run 2 (13 TeV LHC)



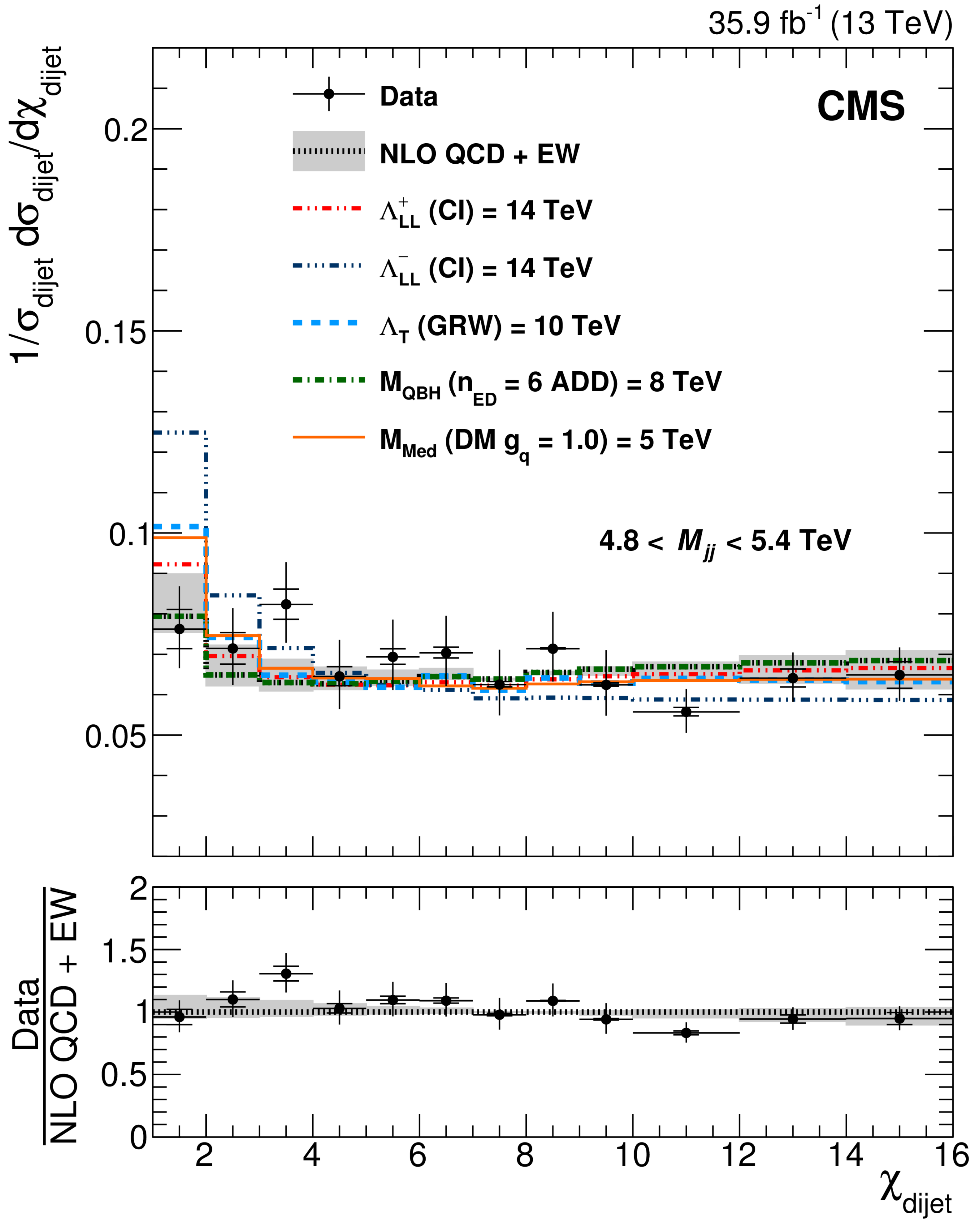


LHCDMWG (arXiv:1506.03116)

DIJET ANGULAR ANALYSIS

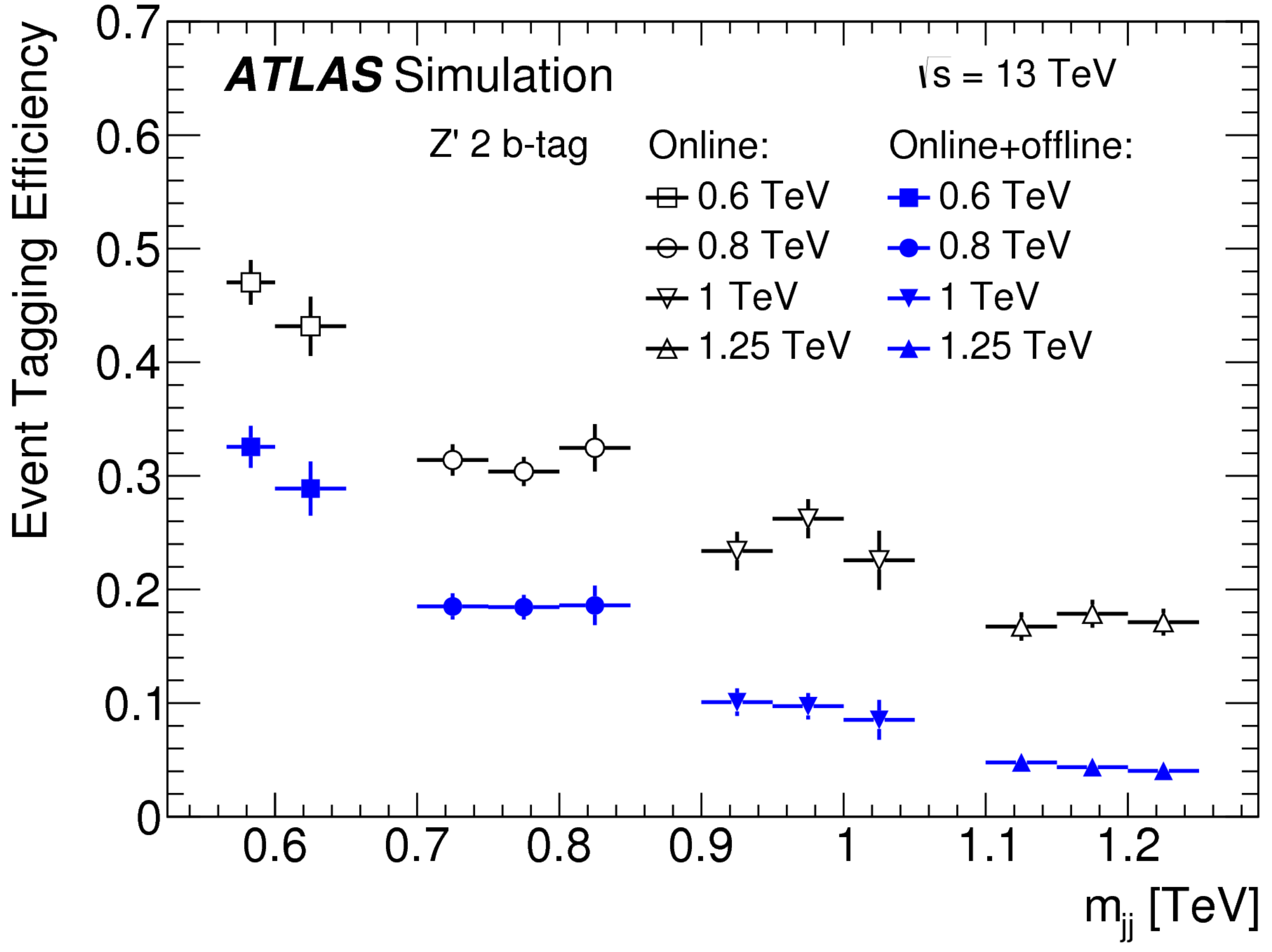
CMS: EPJC 78 (2018) 789
ATLAS: Phys. Rev. D 96 (2017) 052004

- Discrepancies in angular distributions could indicate new physics



$$\chi_{dijet} = e^{|y_1 - y_2|}$$

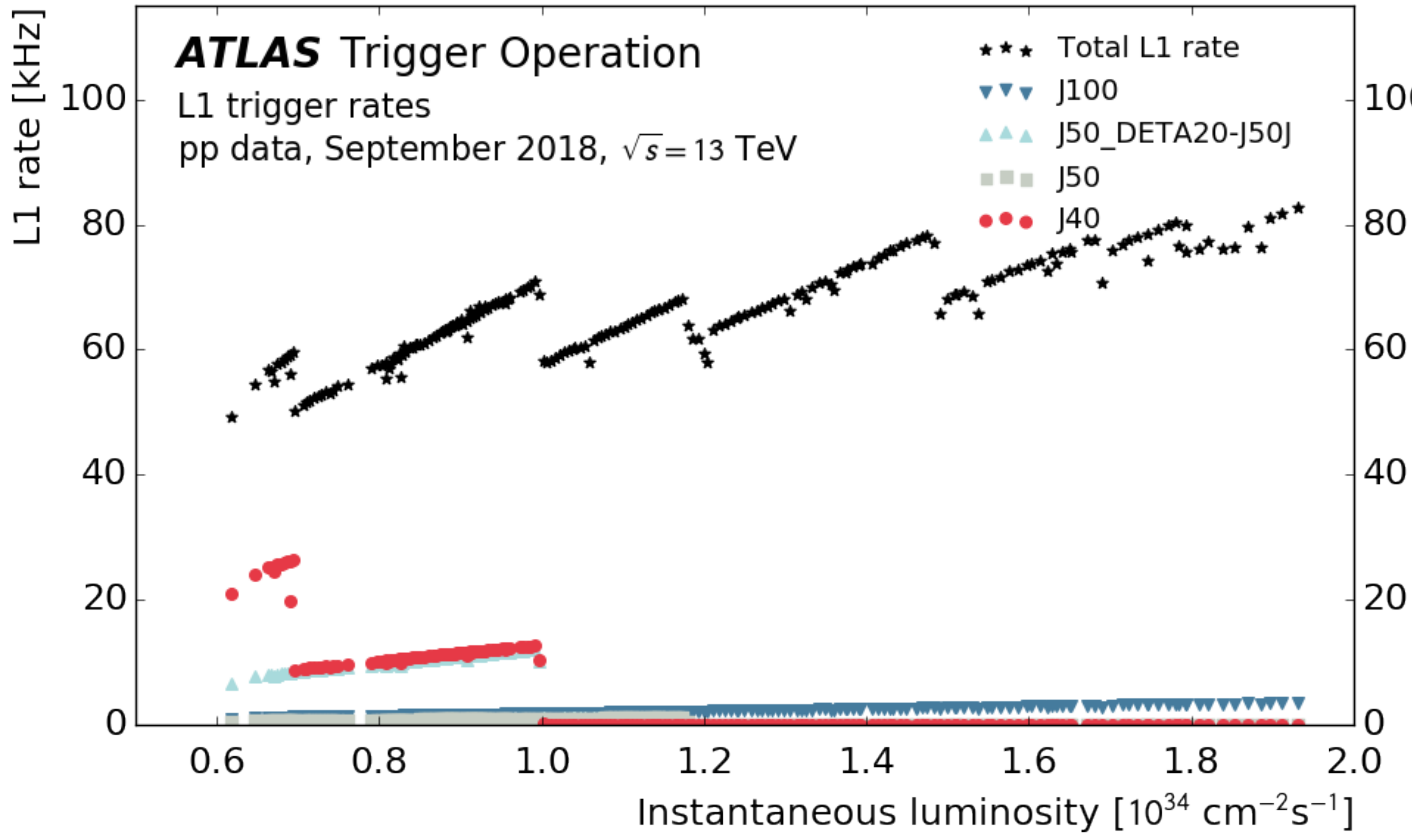
ATLAS B-TAGGING EFFICIENCY

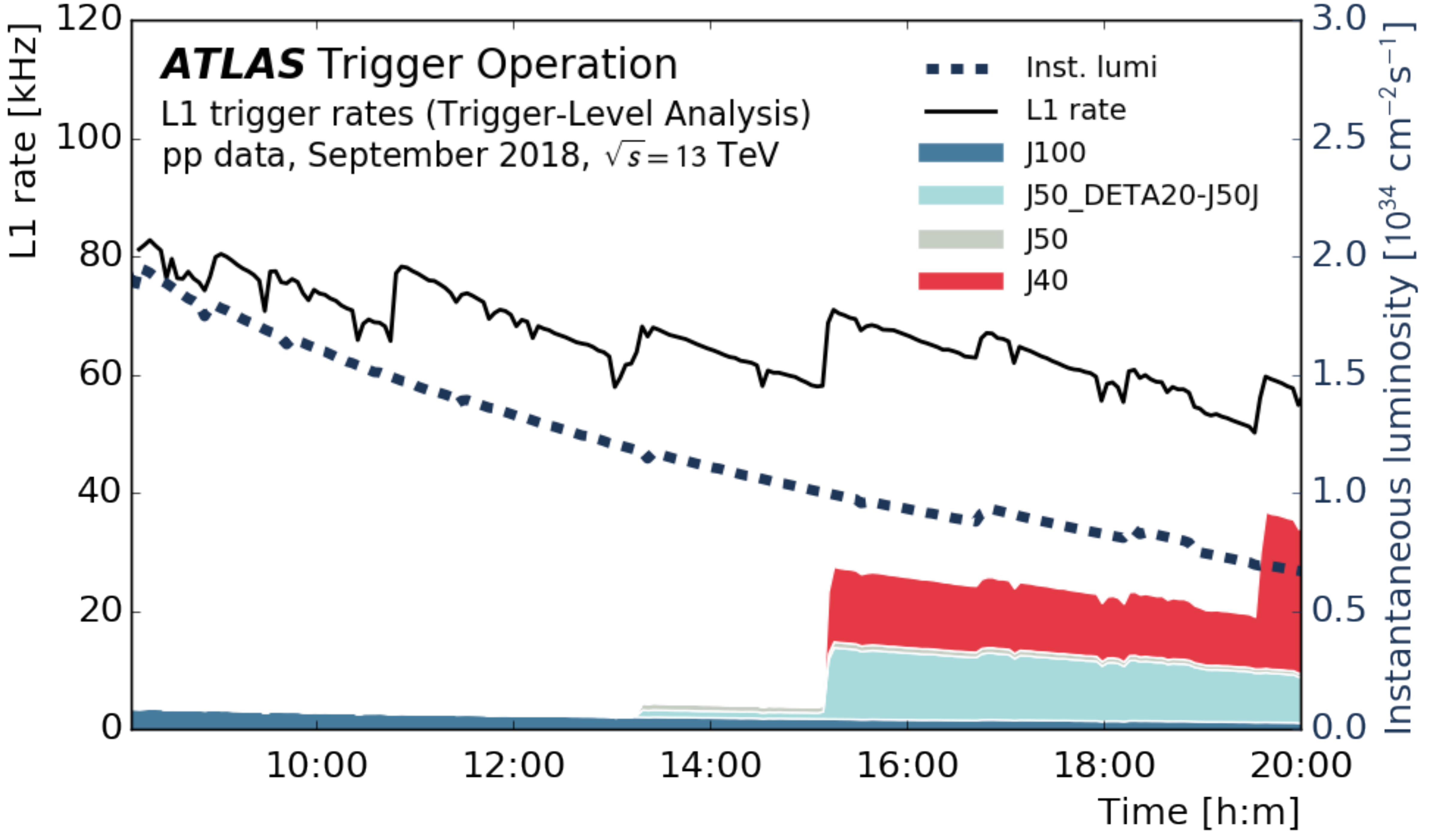


DIJET TRIGGER-LEVEL ANALYSIS: END-OF-FILL STRATEGY

ATLAS trigger operation public results

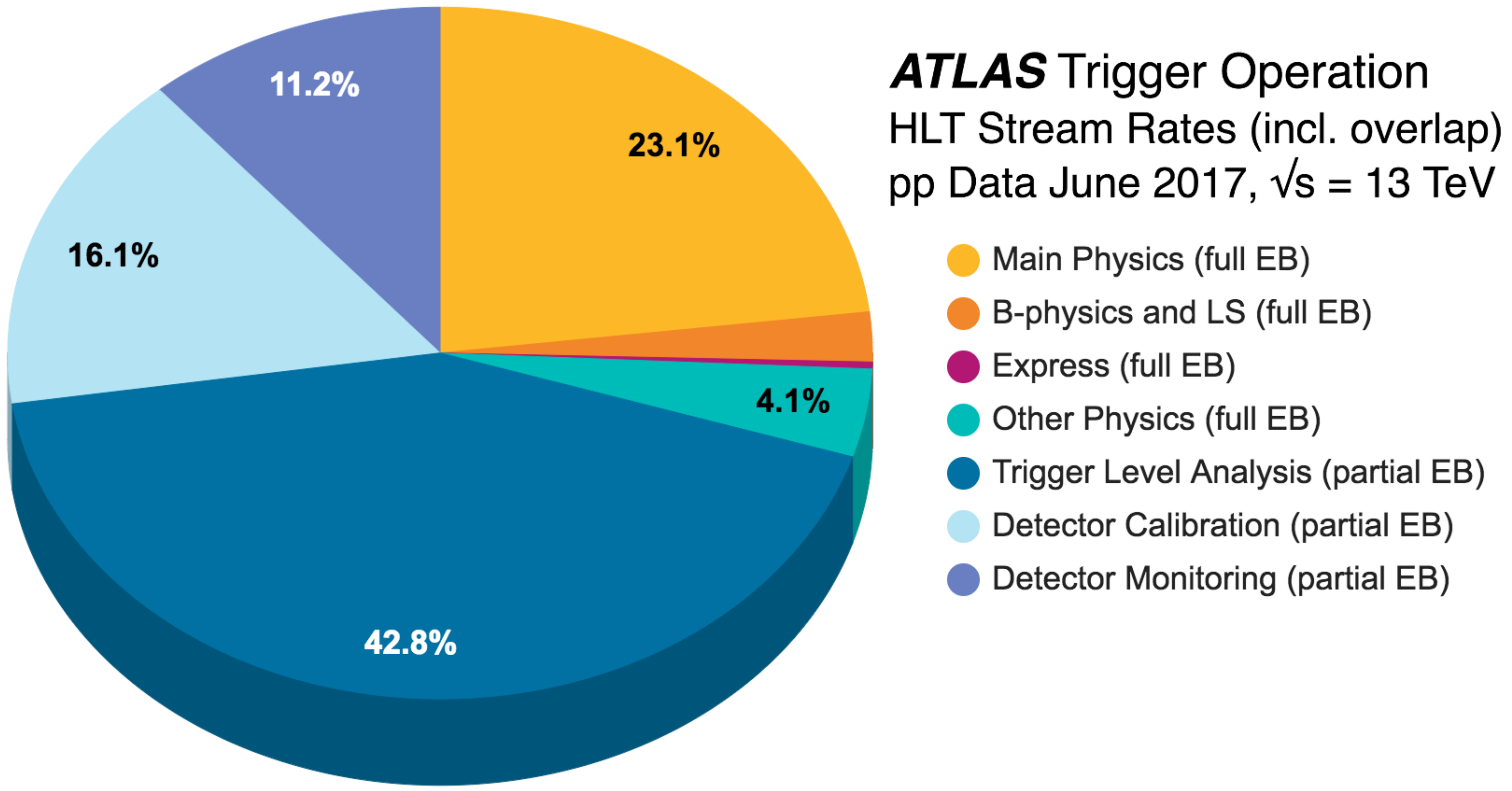
- Additional lower-threshold triggers enabled at end-of-fill when more rate available at level-1 due to decreased instantaneous luminosity

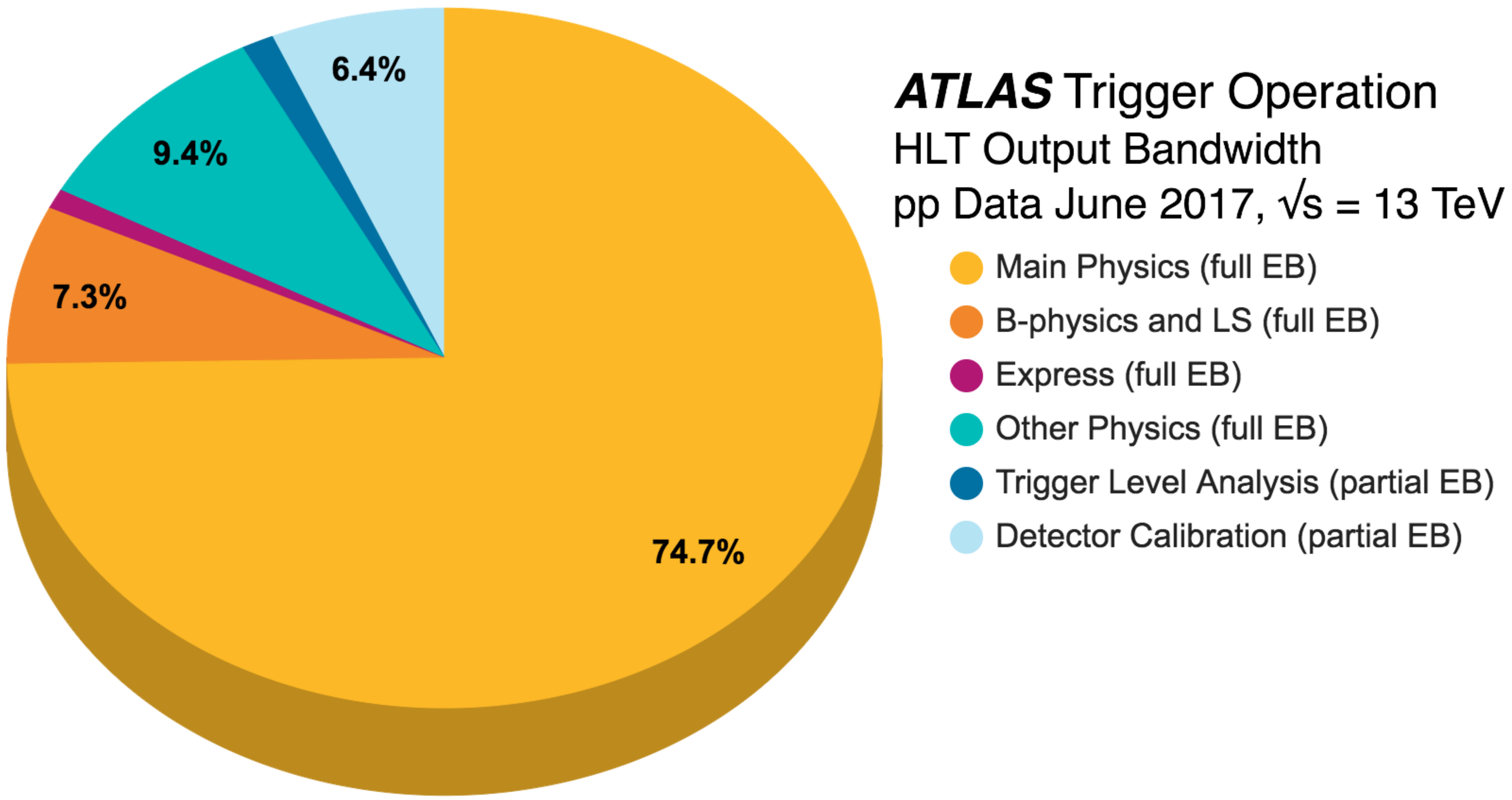




DIJET TRIGGER-LEVEL ANALYSIS: RATE & BANDWIDTH

ATLAS trigger operation public results

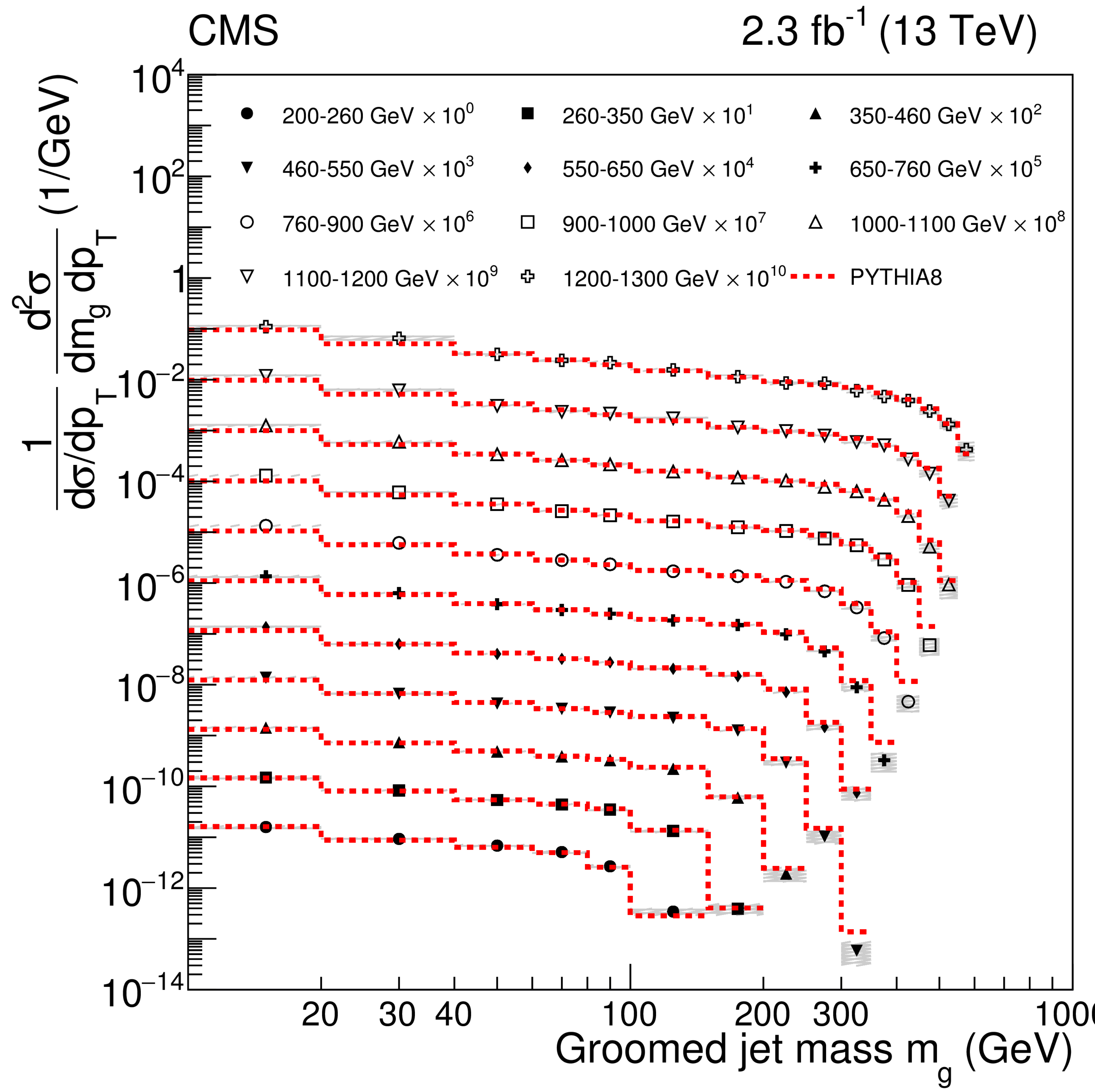




CMS SOFT-DROP JET MASS

JHEP 11 (2018) 113

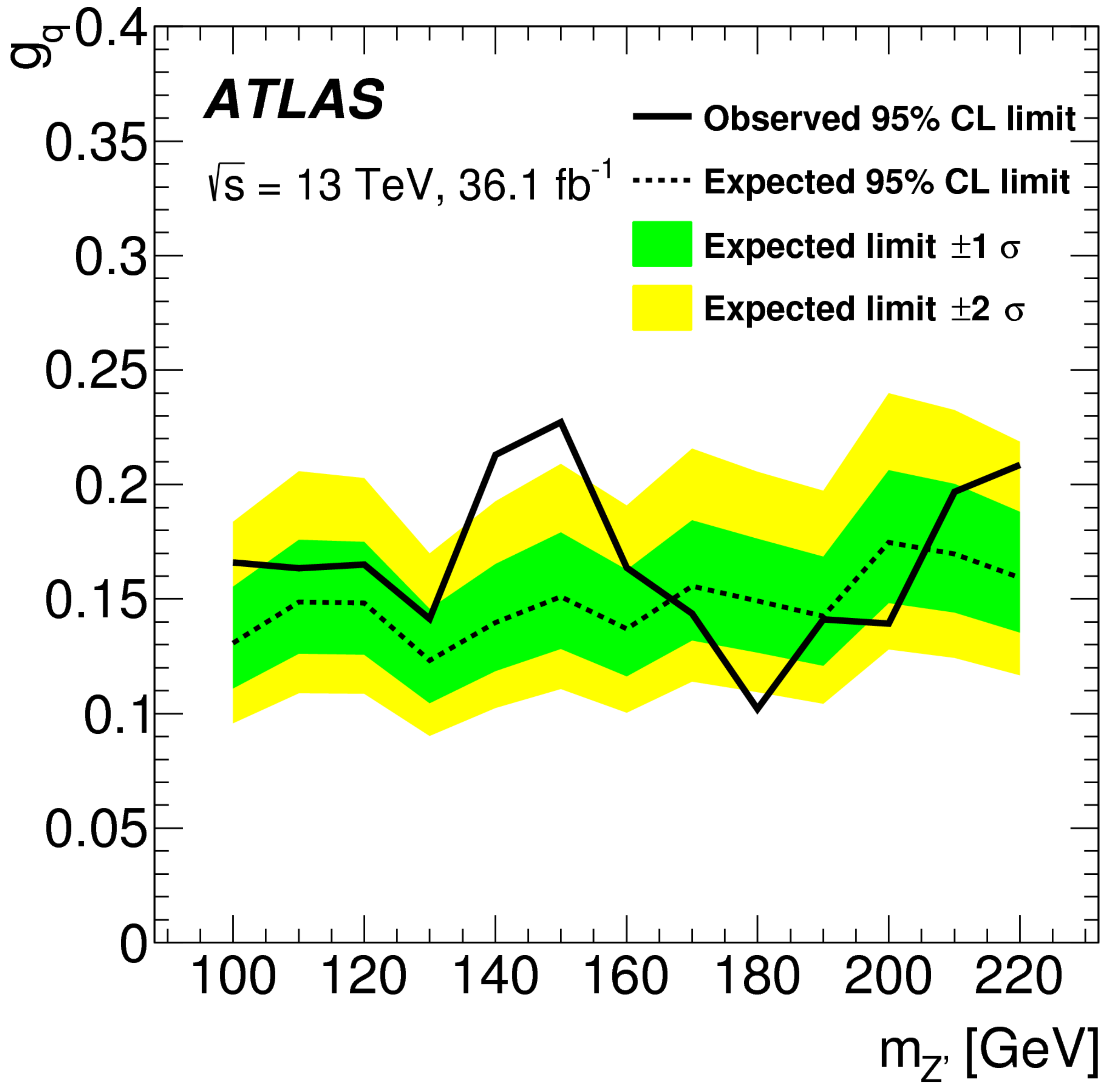
- Jet mass modelling using soft drop tested down to 10 GeV



ATLAS RESULT: BOOSTED DIJET + ISR

Phys. Lett. B 788 (2019) 316: 2015-2016 data

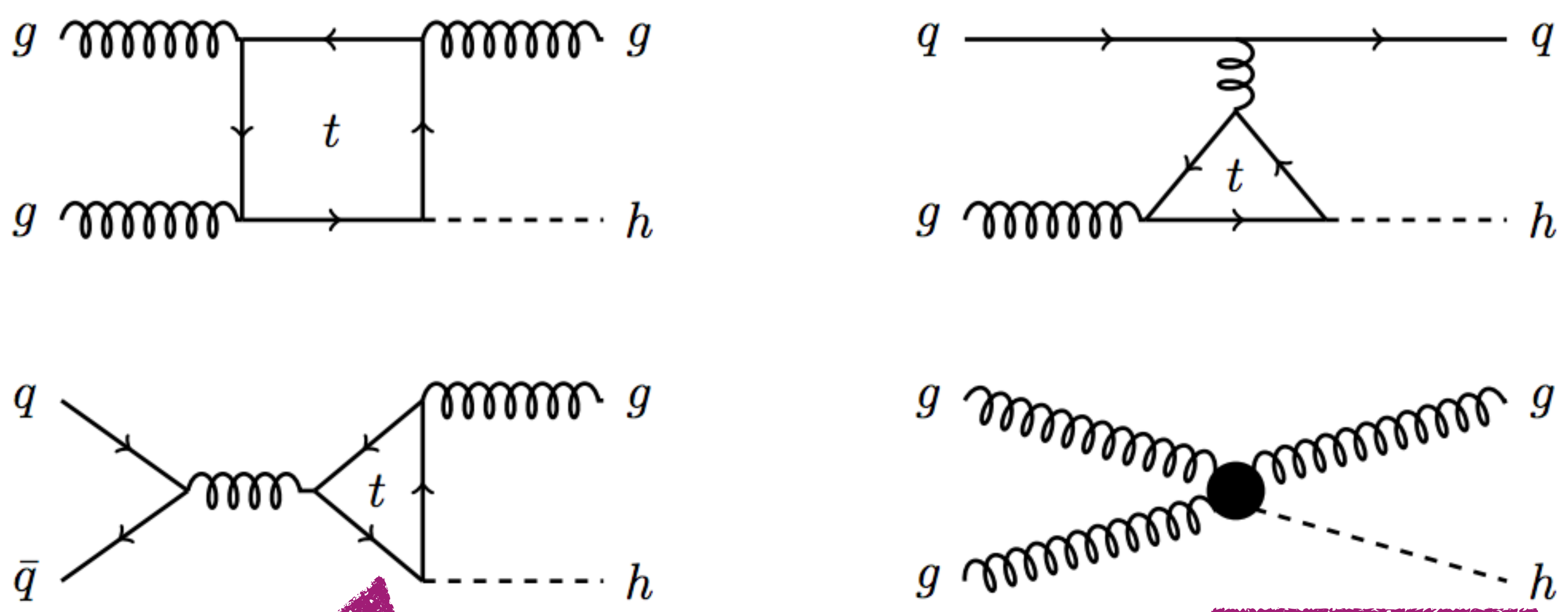
- Dijet + photon / jet (combination):



BOOSTED, B-TAGGED DIJET+ISR

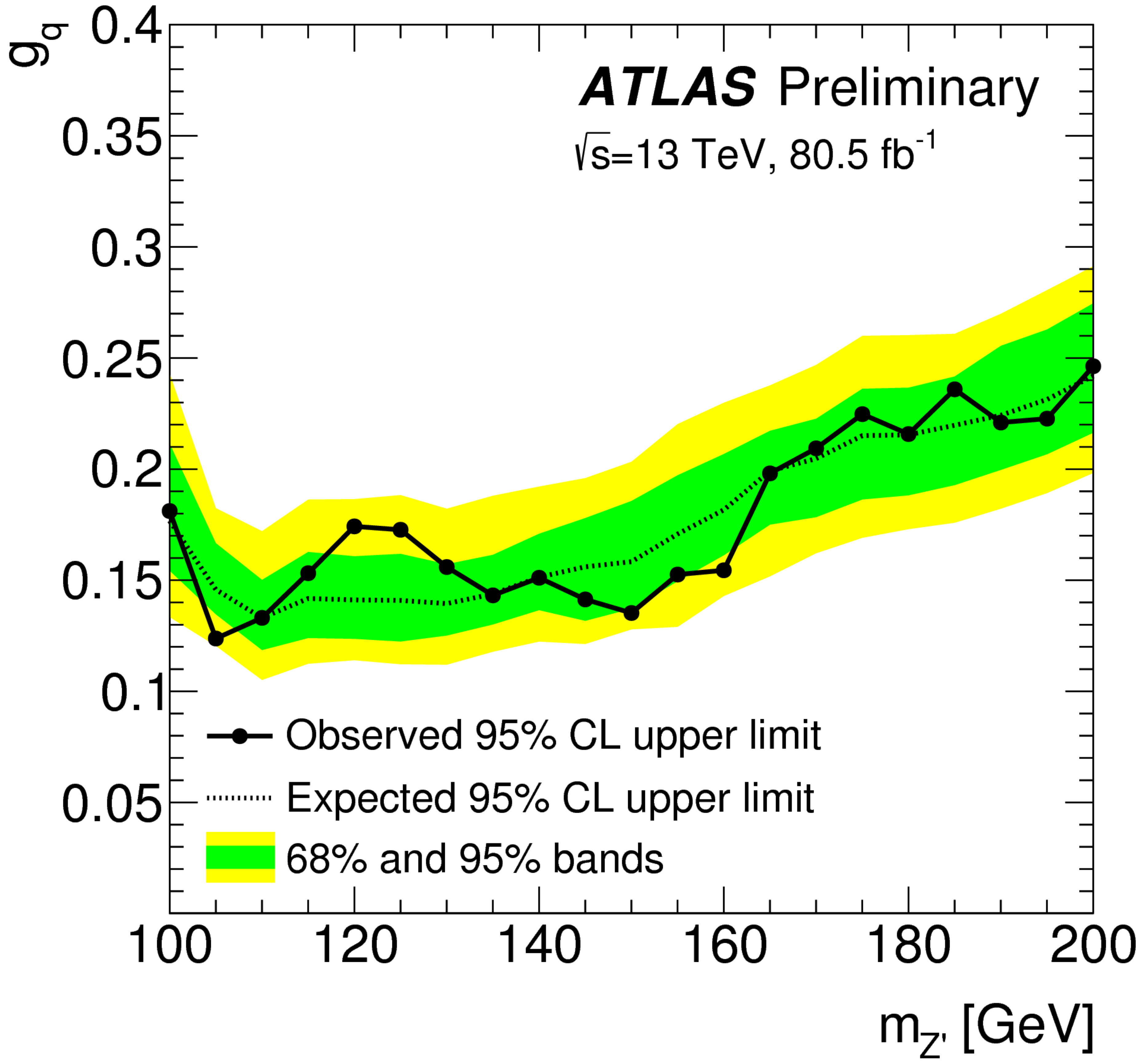
ATLAS-CONF-2018-052

- Preliminary ATLAS result sets limits on Z′ masses as low as 100 GeV
- Also sensitive to enhanced production of boosted $H \to b\bar{b}$
  - At high p_T, Higgs boson production is sensitive to the top-quark loop in the gluon-fusion production mode
  - New physics could result in enhanced boosted Higgs production



arXiv:1312.3317

Replace quarks in the loop by squarks



ATLAS DARK MATTER SUMMARY