ATLAS Physics Results

A selection of recent ATLAS results with major MPP contributions

MPP Project Review, December 17th-18th, 2018

T.G. McCarthy, on behalf of the MPP ATLAS Group

Overview

MPP plays a leading role in many physics measurements and searches @ ATLAS.

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Analyses showcased today fall under 3 general categories:

- Top Quark Physics
- Higgs Physics
- Searches for BSM Physics

Today only able to highlight a <u>small subset</u> of recent ATLAS results.

(In particular: those results with significant **MPP** contributions)

For more details + many other measurements, refer to the following links:

ATLAS EXPERIMENT

- Standard Model Public Results
- Top Quark Public Results
- Higgs Public Results
- Exotics Public Results
- Supersymmetry Public Results

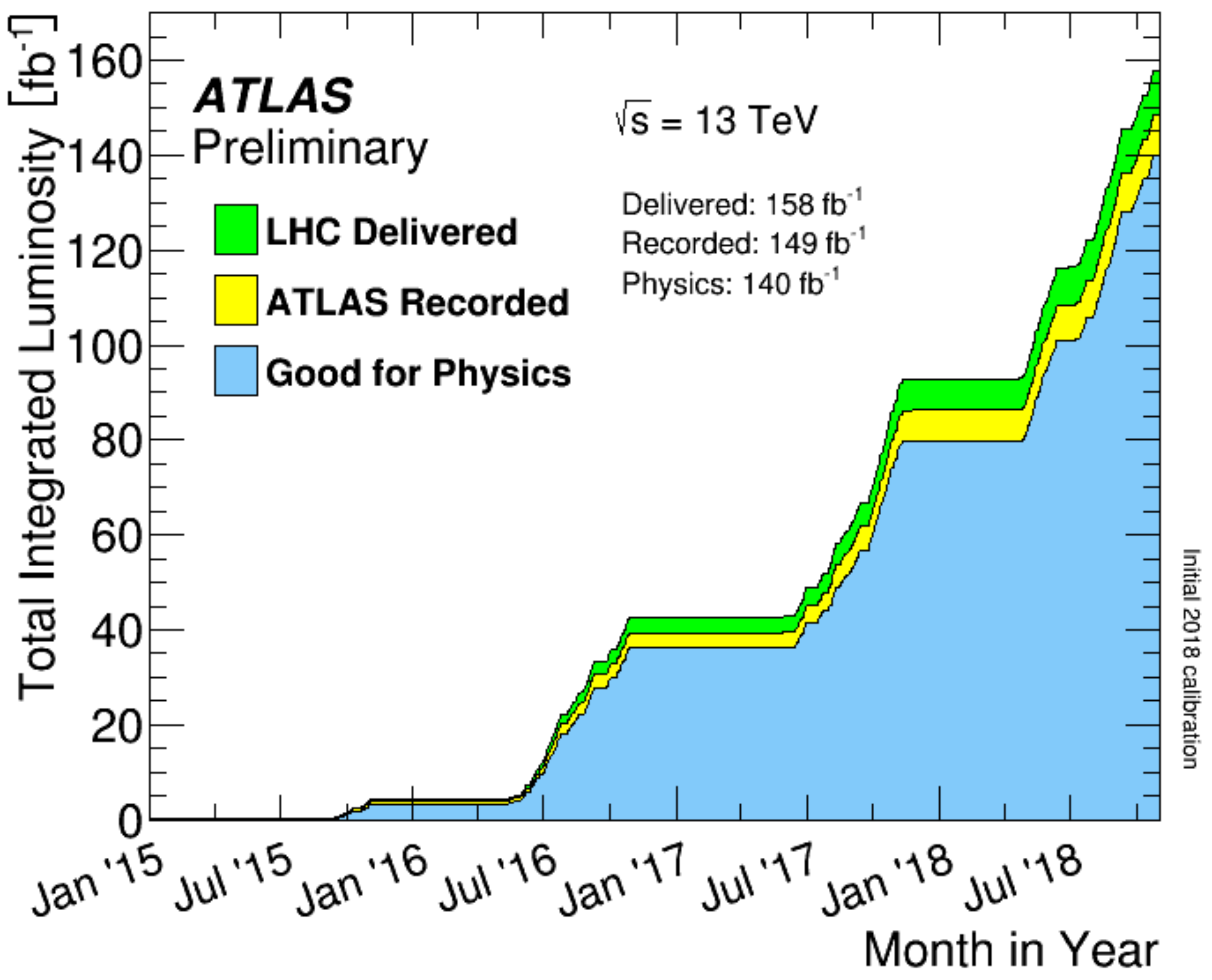
Overview

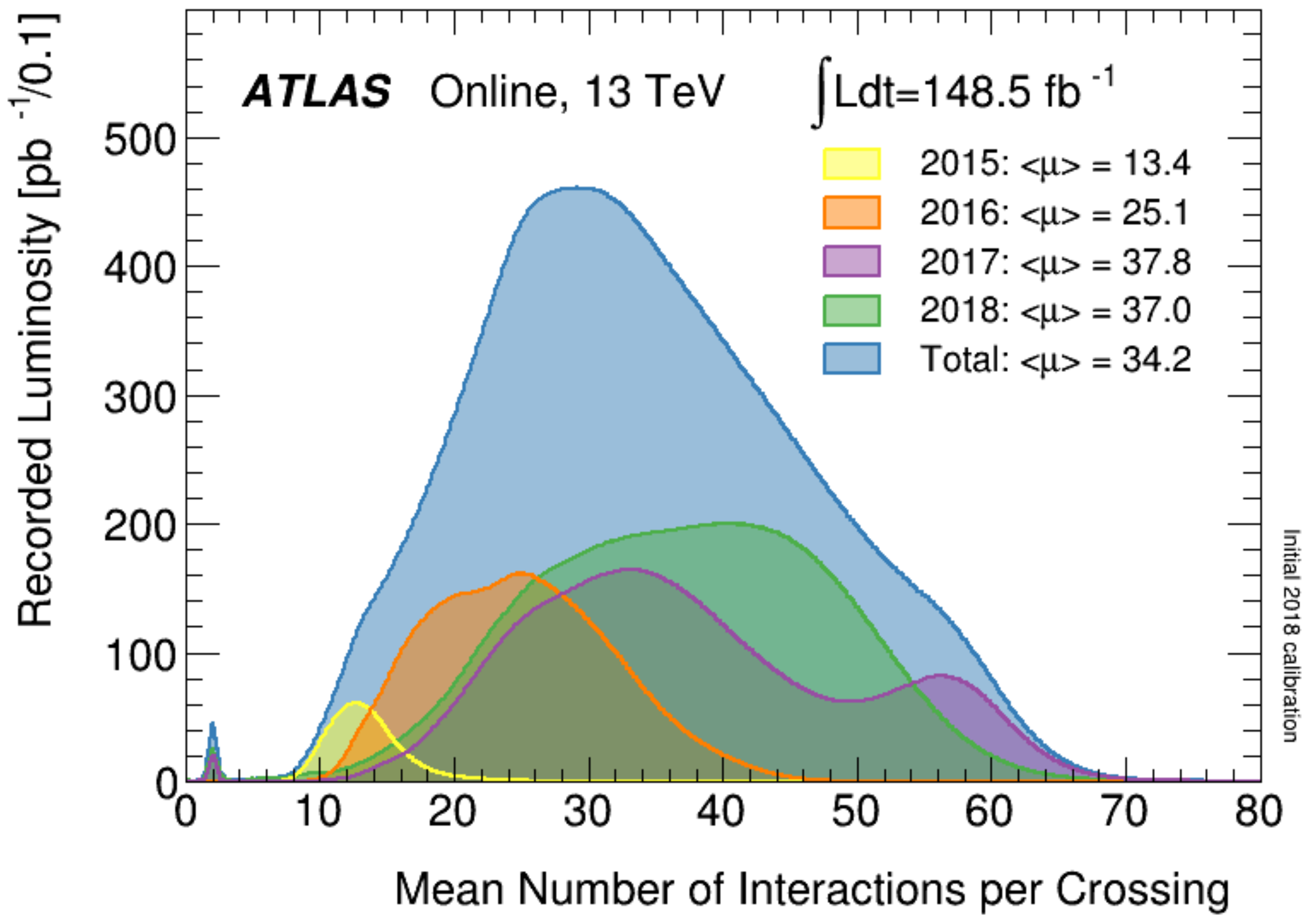
- very successful physics program @ LHC over past few years!

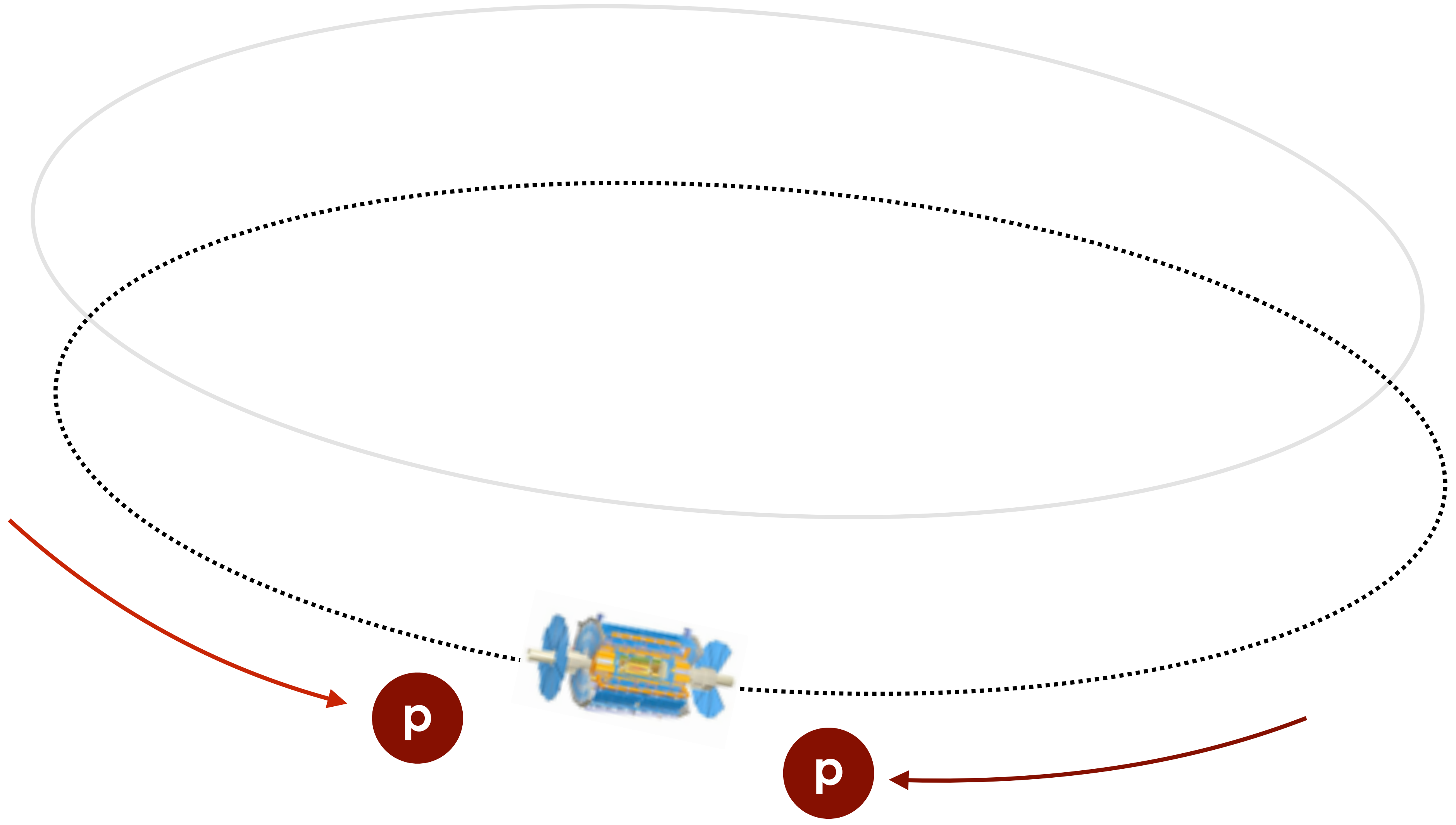
Results highlighted today based on (at least portions of) the following p-p datasets:

- **Run 1**: ~ 4.6 fb^{-1} @ $\sqrt{s}$ = 7 TeV *(2011)*
  ~ 20.3 fb^{-1} @ $\sqrt{s}$ = 8 TeV *(2012)*
- **Run 2**: ~ 140 fb^{-1} @ $\sqrt{s}$ = 13 TeV (originally anticipated ≈ 100 fb^{-1})

- several challenges posed by increased pile-up activity in Run 2 (+ a variety of pile-up mitigation techniques to counter these challenges)
- several rare, previously inaccessible SM processes now within reach
- expanded dataset will allow for much more stringent limits to be placed on several BSM physics models







(reference for plots)

Luminosity Public Plots

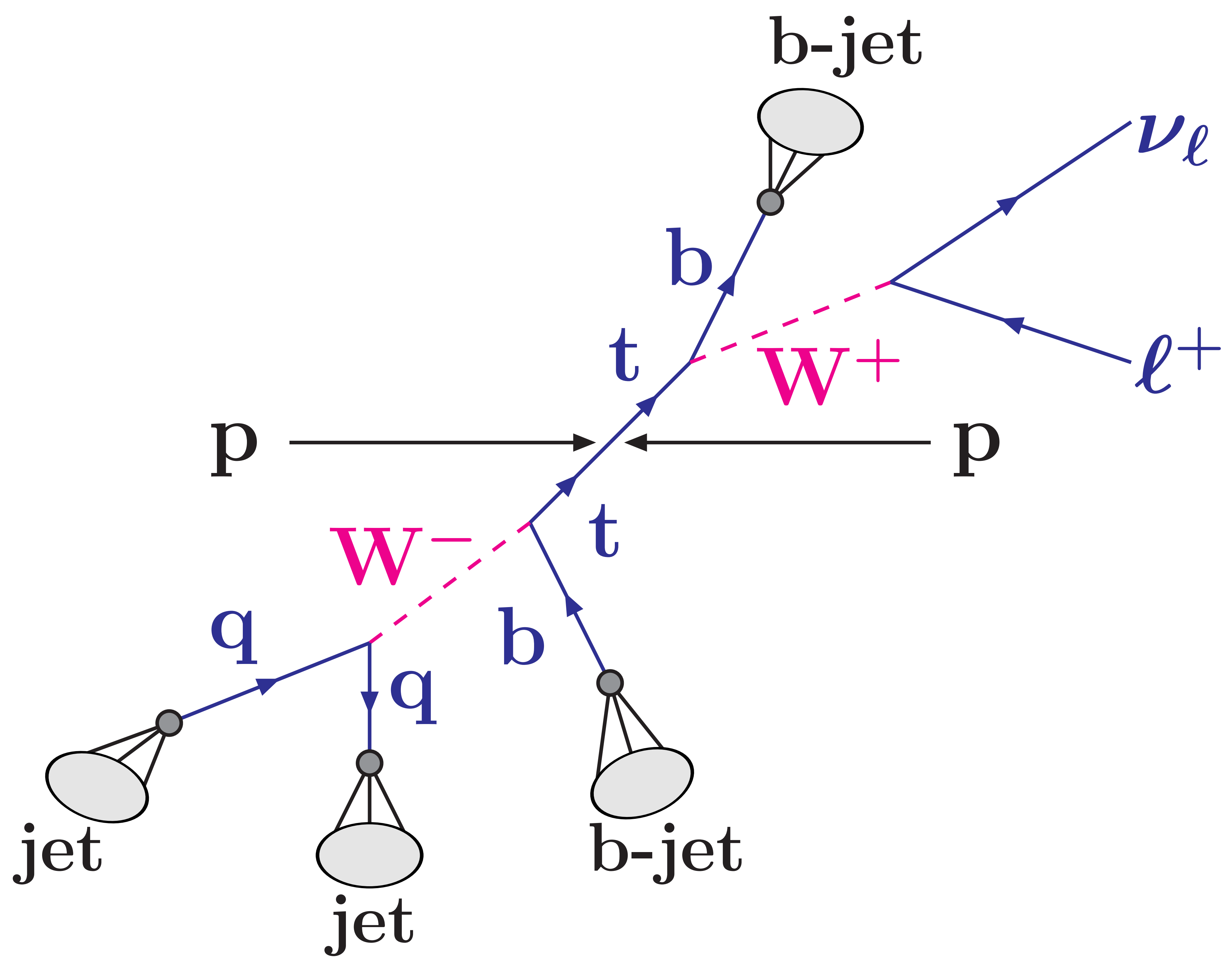
T.G.McCarthy
Max-Planck-Institut für Physik

Top Quark Physics

New Precision Top Quark Mass (m_{top}) Measurement @ $\sqrt{s}$ = 8 TeV

Submitted to EPJC [1]

- target $t\bar{t}$ signal events in **ℓ+jets channel**
- ℓ+jets channel strikes a good balance:
  - ✓ high $t\bar{t}$ branching ratio ~44% (good statistics)
  - ✓ low backgrounds



- selection of a single high-p_T charged lepton where ℓ = e, μ and consider equally either:

  ℓ^+ (from top quark, depicted **right**)

  or ℓ^- (from anti-top quark)

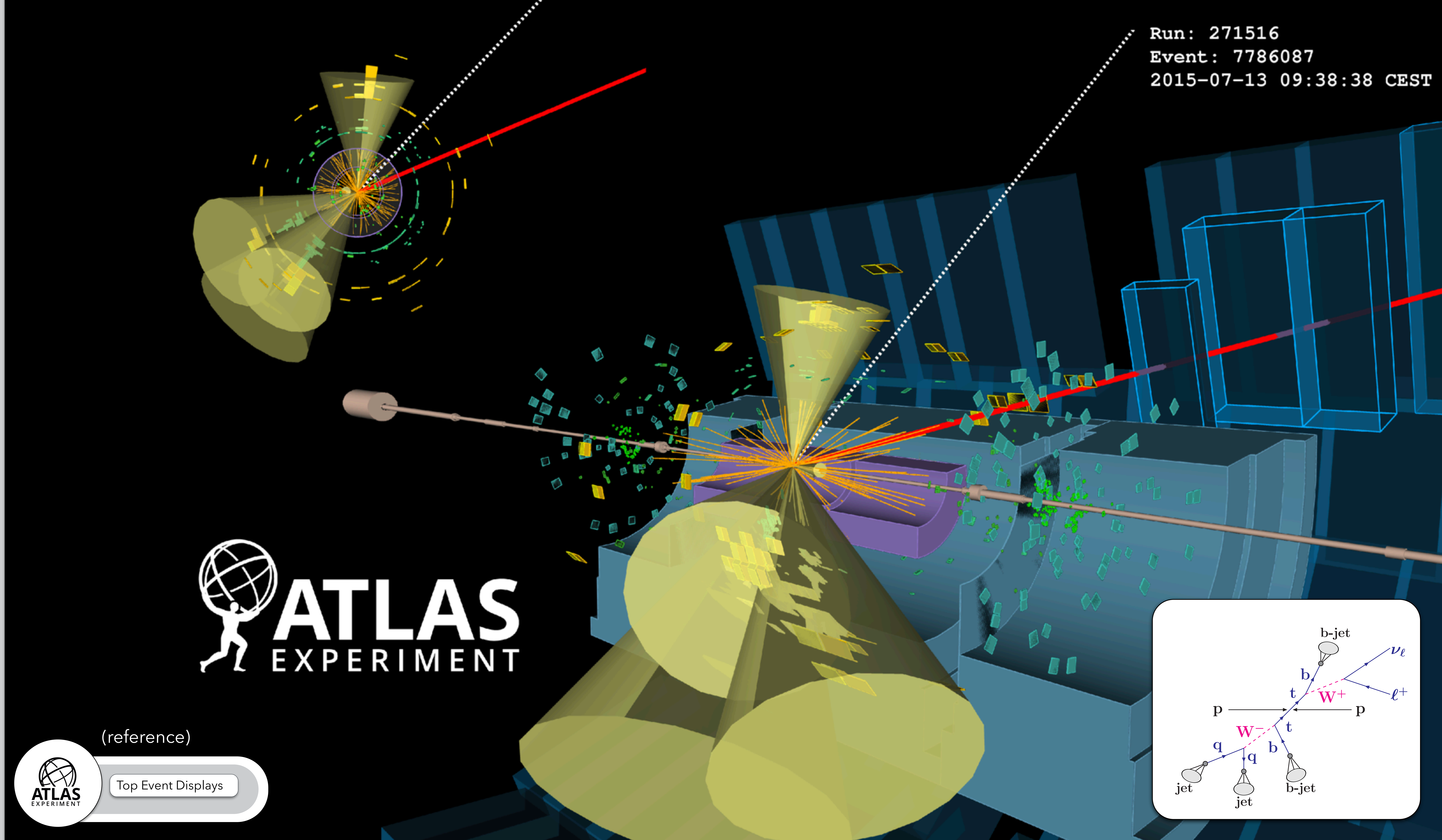
- measurement employs version of a so-called **template method**, common in such analyses:

1. select measurable observable sensitive to m_{top}
2. construct 'template' distributions from simulated $t\bar{t}$ events with varying input m_{top} values
3. observable is constructed from events in measured data
4. fit is performed to the data to return best estimate of m_{top}

In this case extend idea to a **3D template method**
(accept loss in statistical precision → gain in systematic precision)

Reason: target two of the largest systematic uncertainties

JES	**J**et **E**nergy **S**cale
bJES	**b-J**et **E**nergy **S**cale



(reference)

Top Event Displays

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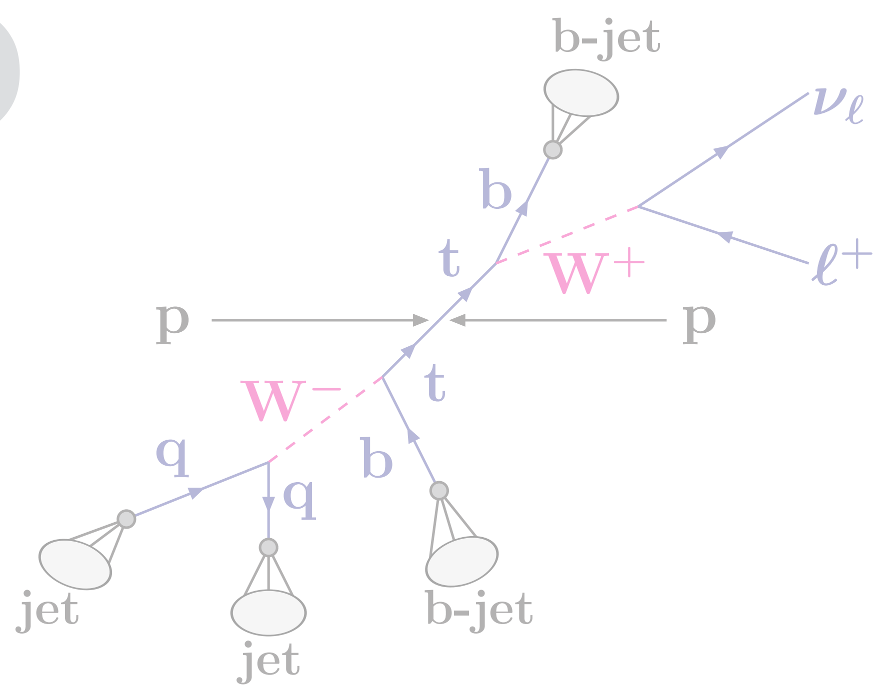
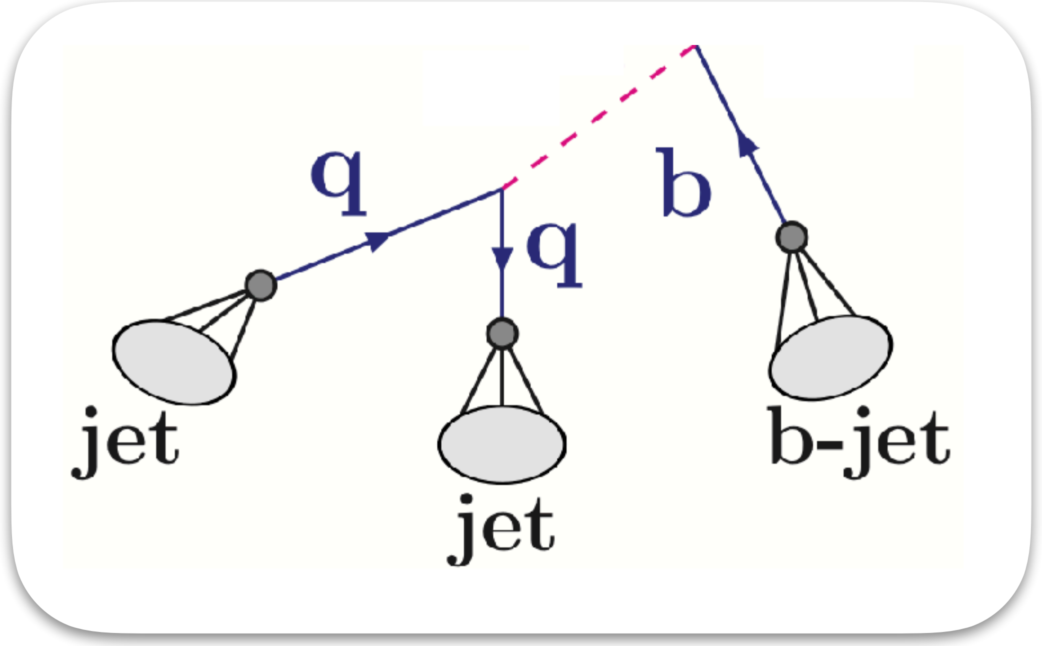
New Precision Top Quark Mass (m_{top}) Measurement @ $\sqrt{s}$ = 8 TeV

Submitted to EPJC [1]

1D



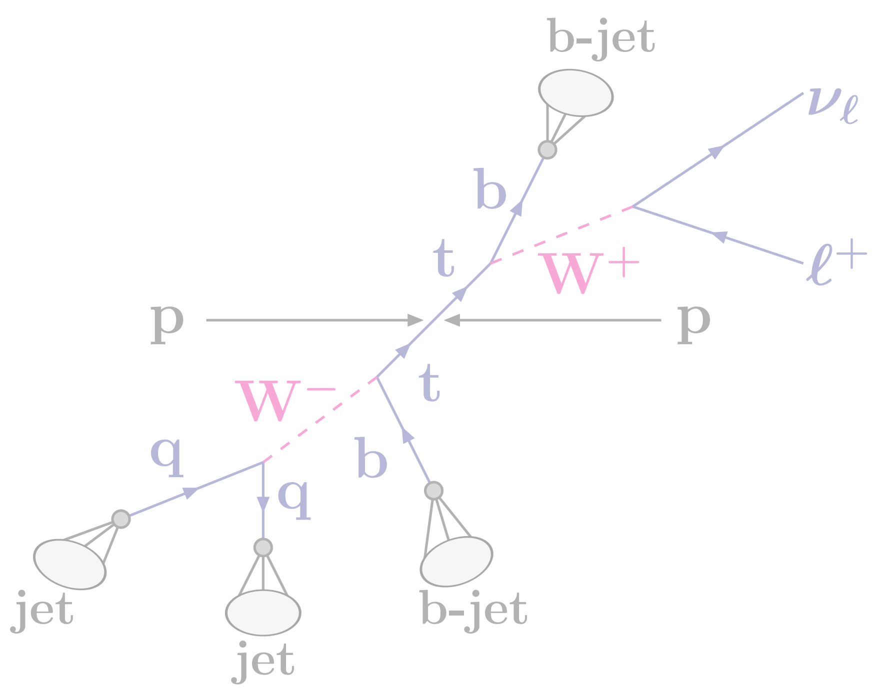


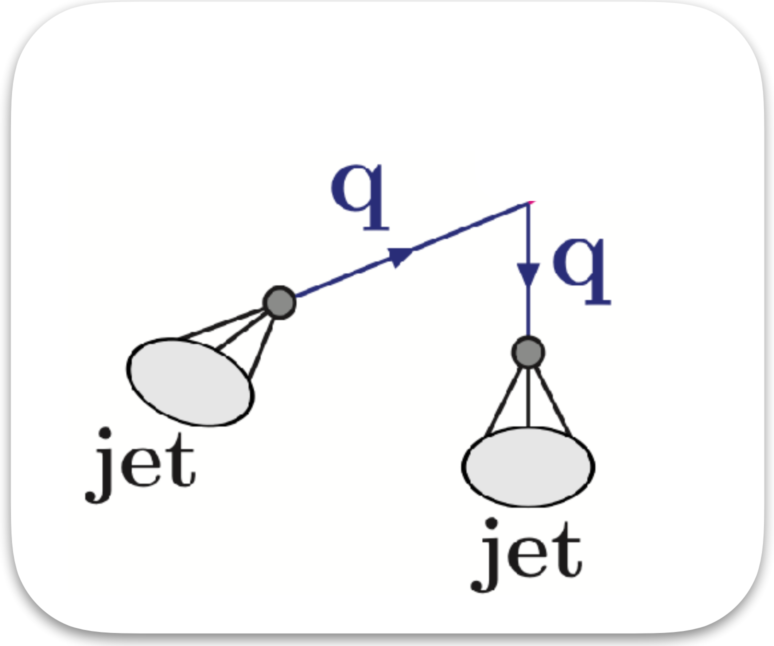
1st observable

$$m_{top}^{reco}$$

- reconstructed top quark mass (from kinematic likelihood fit output)
- strongly dependent on true m_{top}
- suffers from uncertainties in (**b**)**JES**

2D



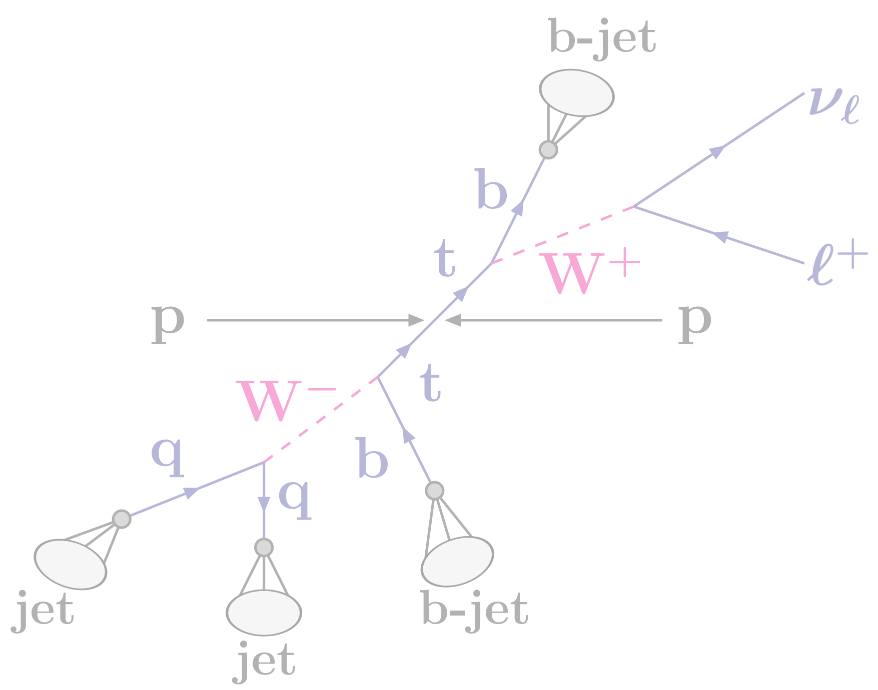


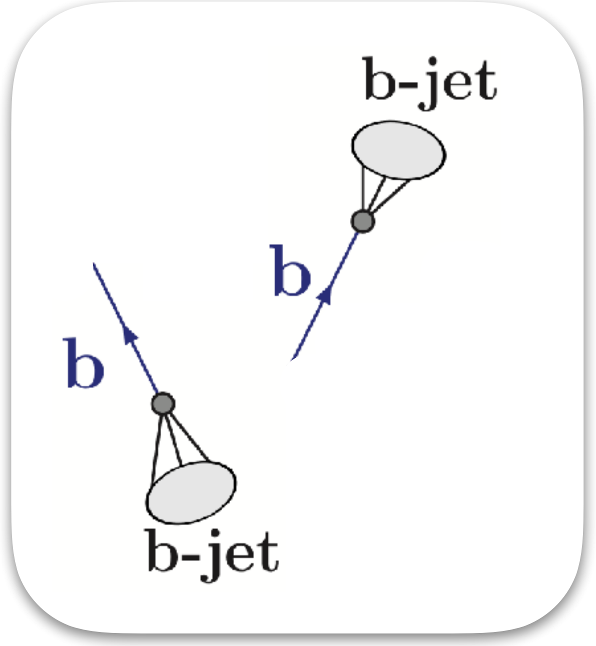
2nd observable

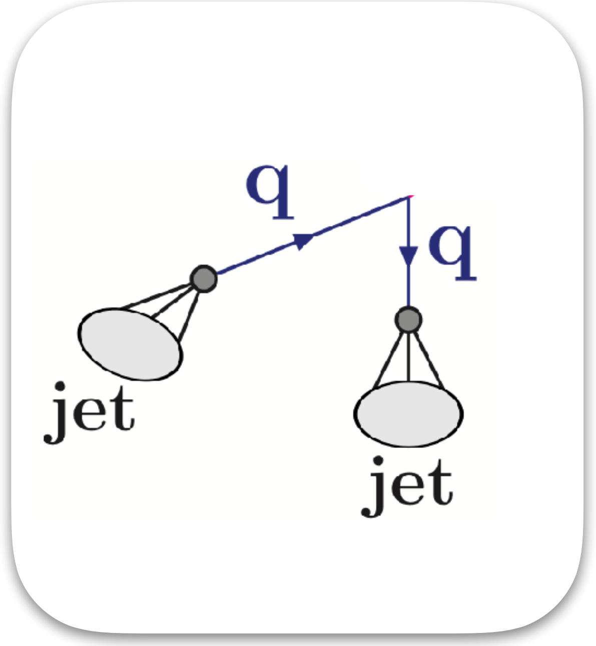
$$m_{W}^{reco}$$

- reconstructed 2-jet invariant mass (based on jet ↔ quark assignment from fit)
- **provides handle on JES**
  2nd estimator: global **J**et **S**cale **F**actor (JSF)

3D







3rd observable

$$R_{bq}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{q_1} + p_T^{q_2}} \propto \frac{JSF \times bJSF}{JSF}$$

- ratio of p_T sum (b-jets vs. light jets) (based on jet ↔ quark assignment from fit)
- **provides handle on bJES**

New Precision Top Quark Mass (m_{top}) Measurement @ $\sqrt{s}$ = 8 TeV

Submitted to EPJC [1]

- using a 3D approach
  (*i.e.* simultaneous extraction of m_{top}, JSF, bJSF)
  → **JSF** & **bJSF** absorb most of the JES uncertainties, such that overall one gains in the final m_{top} precision:

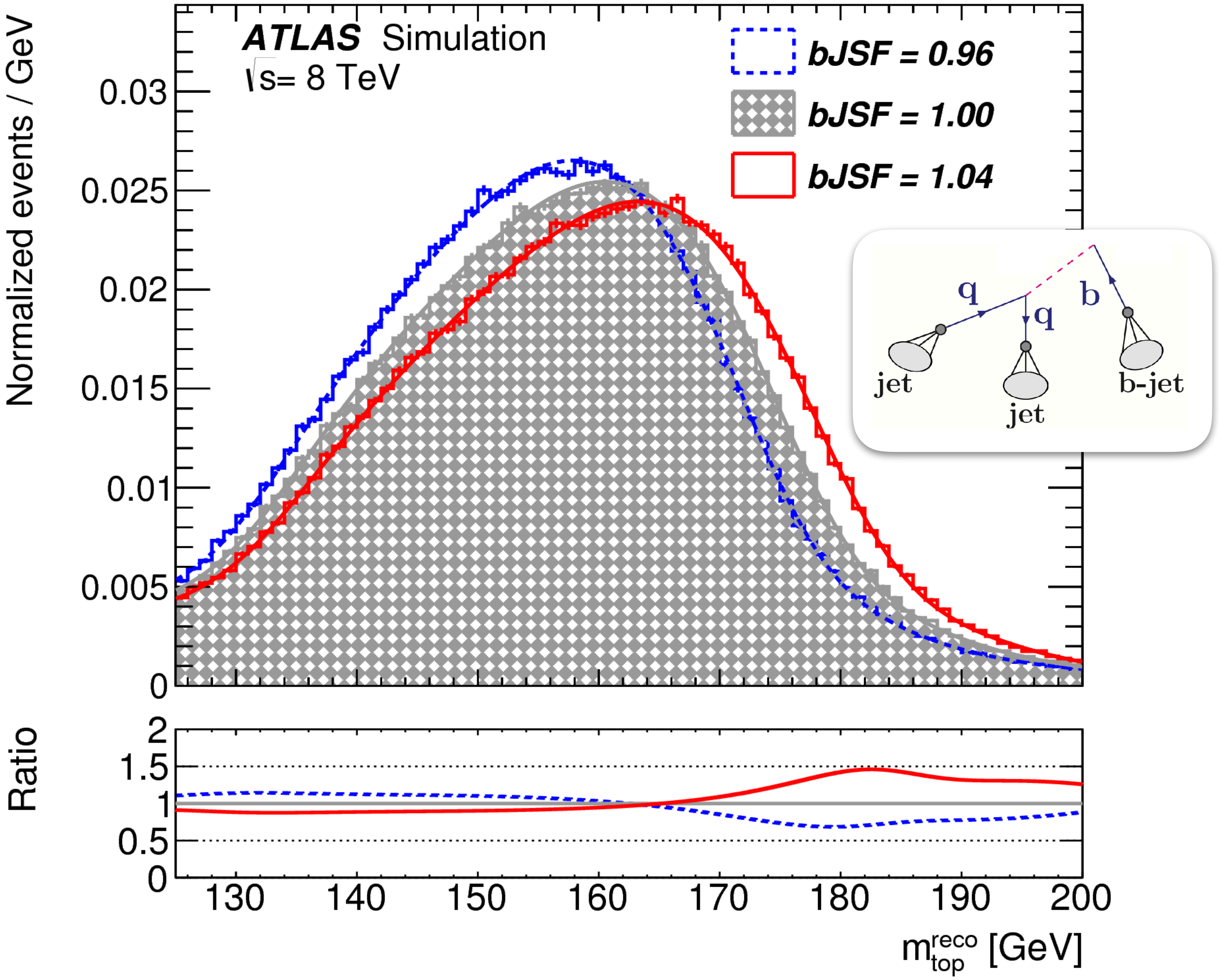
2D vs. **3D**

$$\delta_{bJES}^{2D\ (syst)} > \sqrt{\left(\delta_{bJES}^{3D\ (syst)}\right)^2 + \left(\delta_{bJES}^{(stat)}\right)^2}$$

$$0.47\ \text{GeV} > \sqrt{(0.03\ \text{GeV})^2 + (0.35\ \text{GeV})^2}$$

Clear gain in moving from **2D → 3D**!

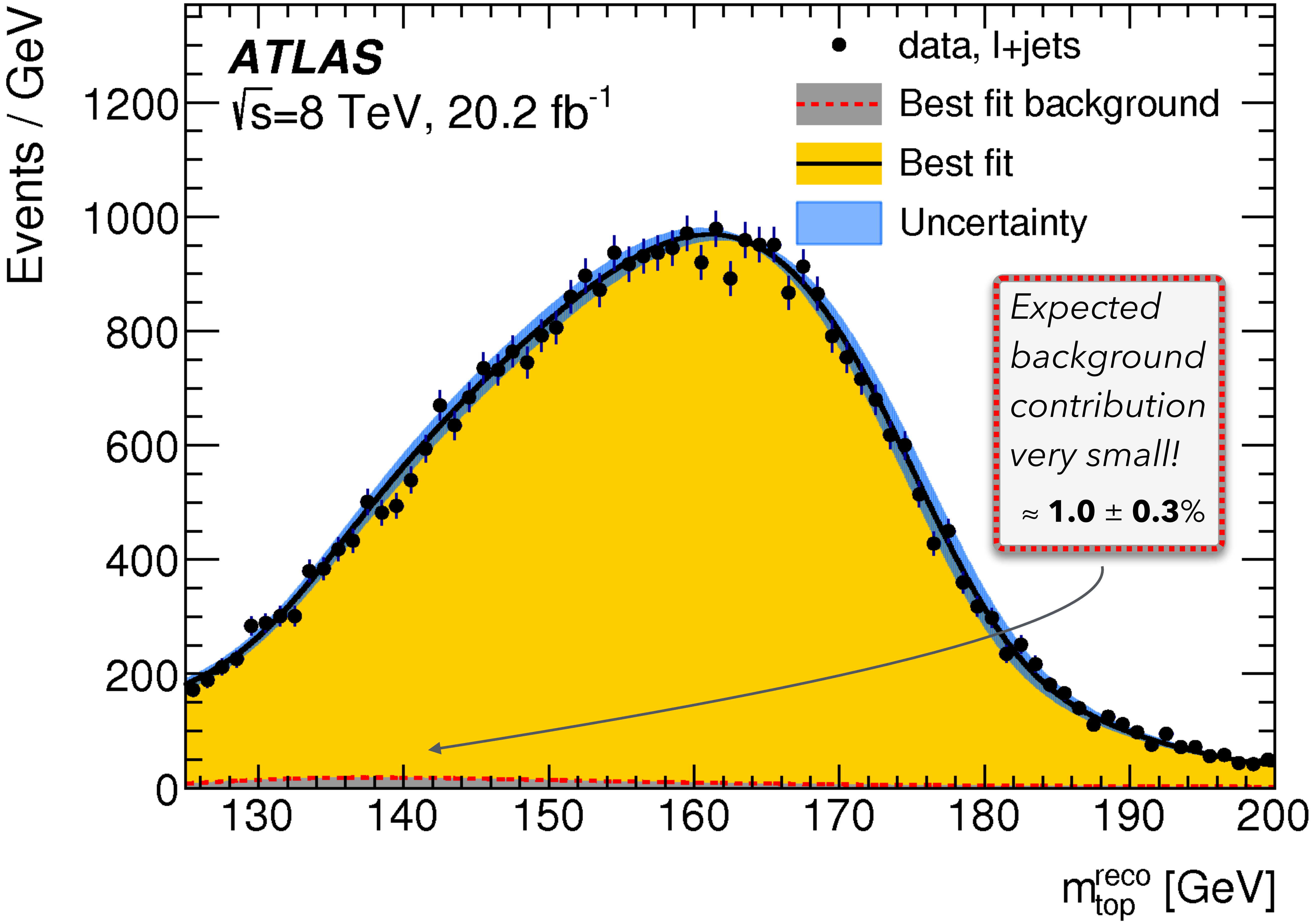
(+ this gain will be enhanced with more statistics)

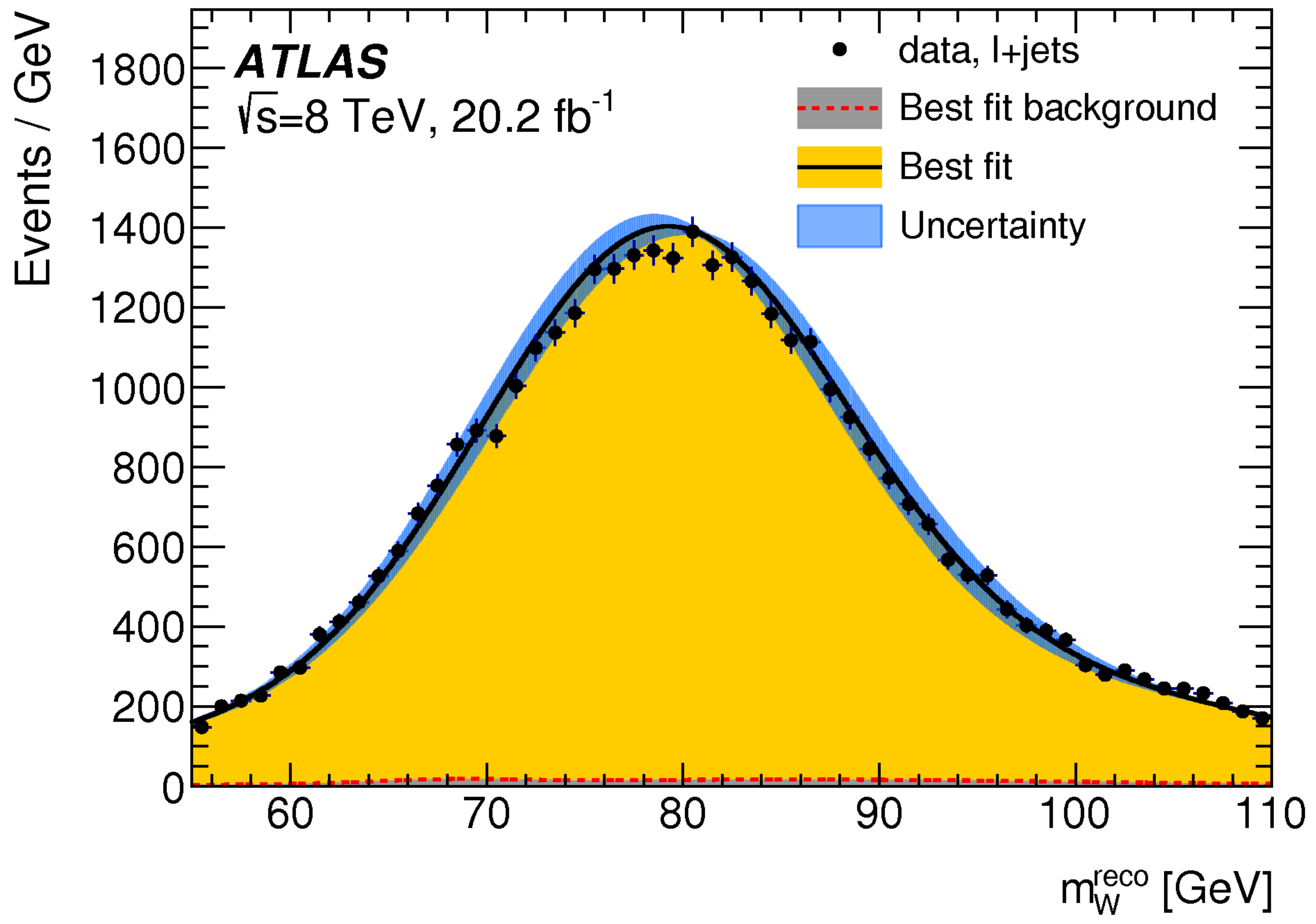


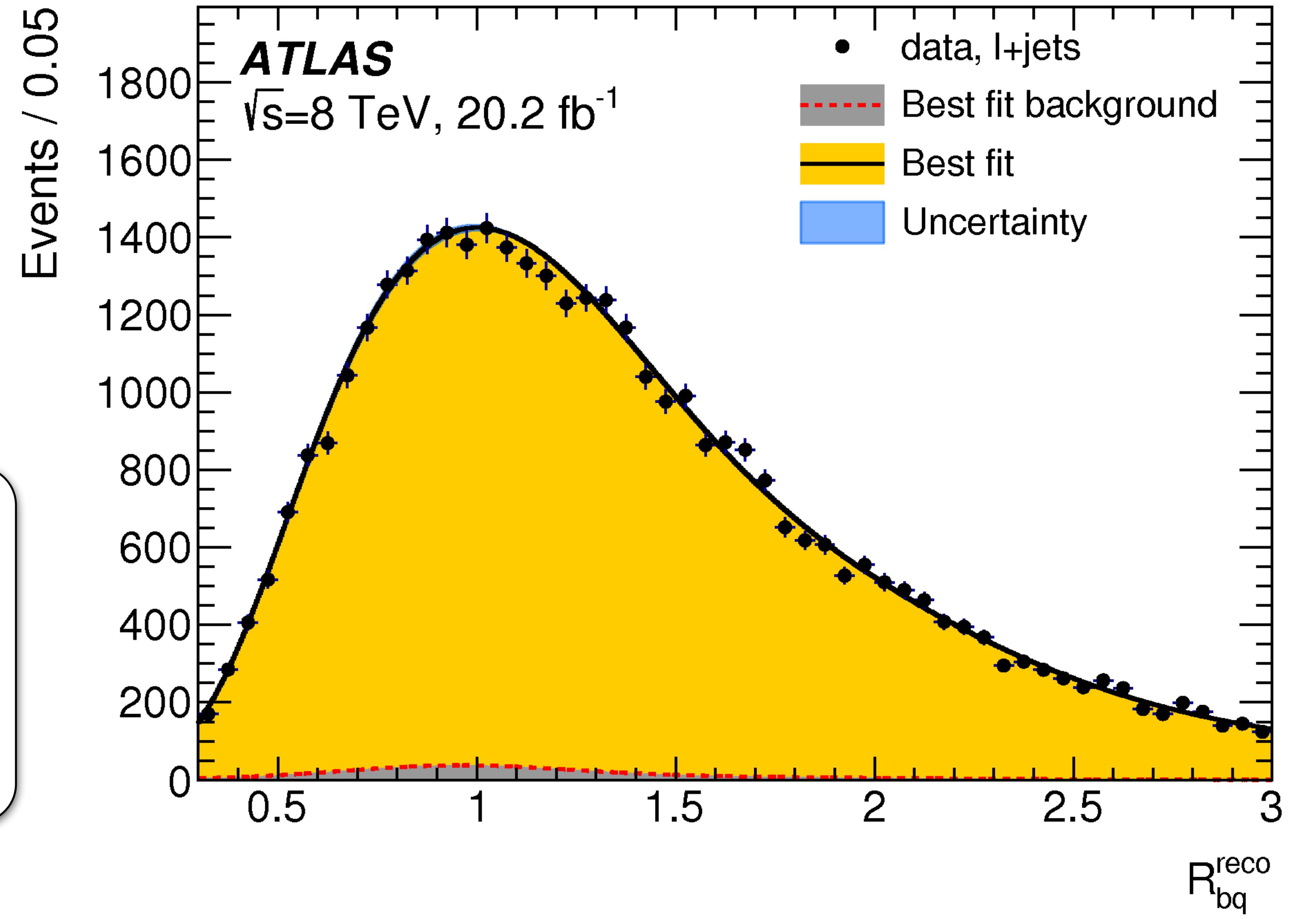
- analysis further employs **boosted decision tree (BDT)** to separate events with correct jet ↔ quark association from remaining events

New Precision Top Quark Mass (m_{top}) Measurement @ $\sqrt{s}$ = 8 TeV

Submitted to EPJC [1]







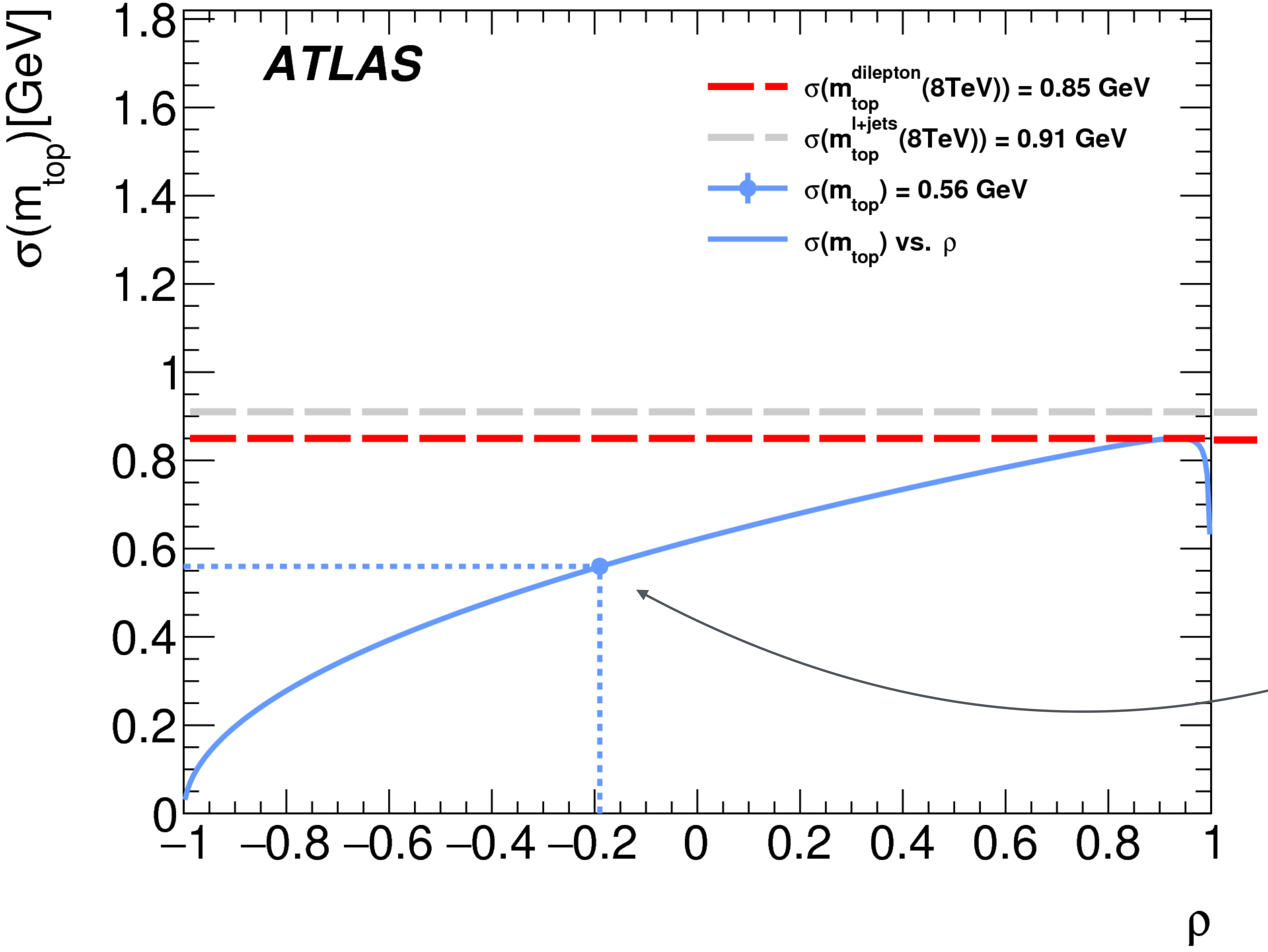
- final likelihood fit to data yields:
  (note statistical uncertainties only!)

$$m_{top} = 172.08 \pm 0.39 \text{ (stat) GeV}$$
$$\text{JSF} = 1.005 \pm 0.001 \text{ (stat)}$$
$$\text{bJSF} = 1.008 \pm 0.005 \text{ (stat)}$$

New Combination of ATLAS m_{top} Measurements ($\sqrt{s}$ = 7, 8 TeV)

Submitted to EPJC [1]

- combination of all Run 1 ATLAS results from standard 3 $t\bar{t}$ decay channels (dileptonic, ℓ+jets, all-hadronic)
- correlations evaluated for each source of systematic uncertainty



total m_{top} precision from ℓ + jets @ $\sqrt{s}$ = 8 TeV

total m_{top} precision from dilepton @ $\sqrt{s}$ = 8 TeV

$\rho\ (\ell + \text{jets, dilepton}) = -0.19$

Properly evaluating and exploiting input correlations **improves final m_{top} precision**!

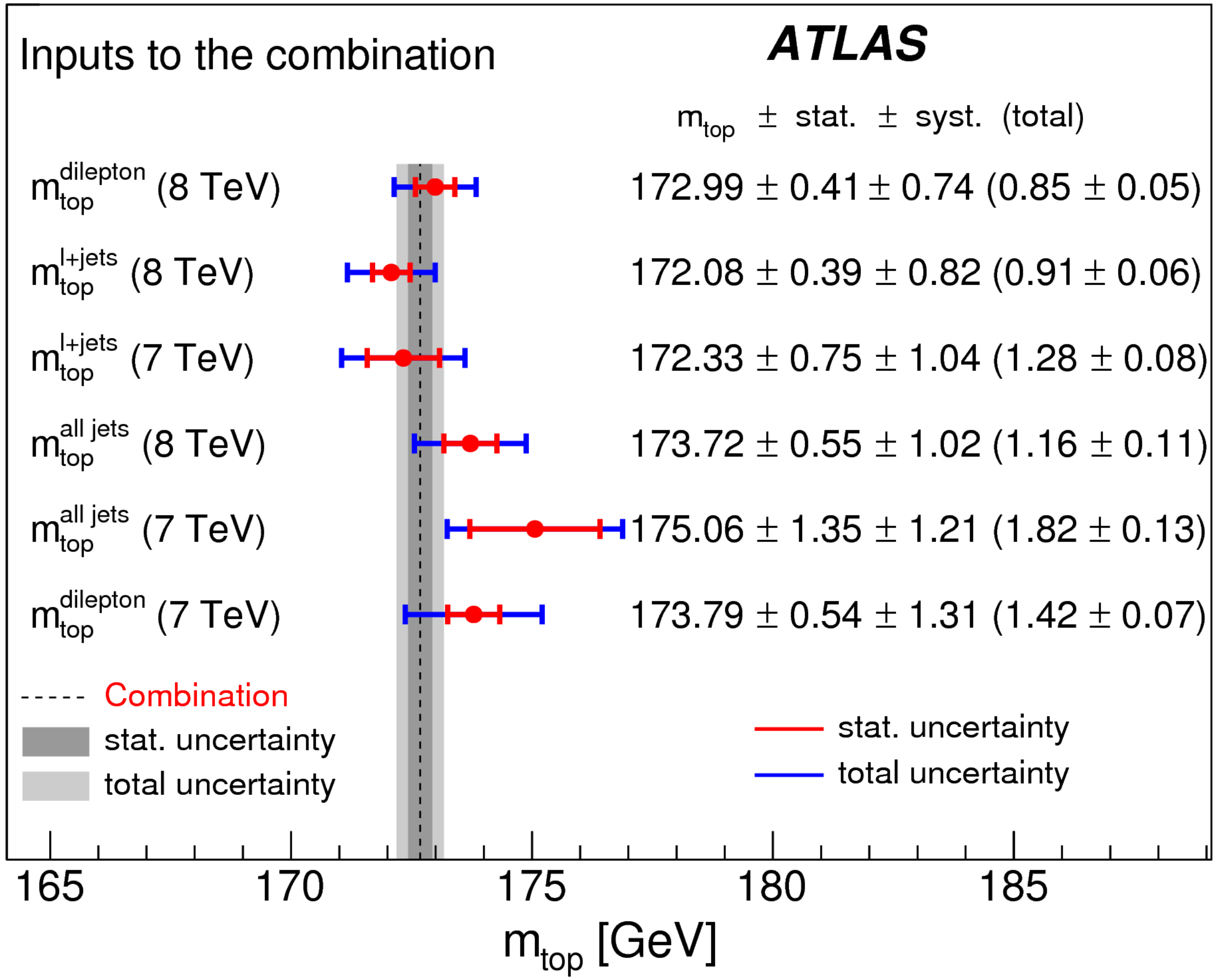
NB: only one example between two input measurements!

New Combination of ATLAS m_{top} Measurements

Submitted to EPJC [1]

- individual measurements were combined successively (ordered according to their overall impact)

Note that analyzers from **MPP** played a leading role in **all 6 measurements**!



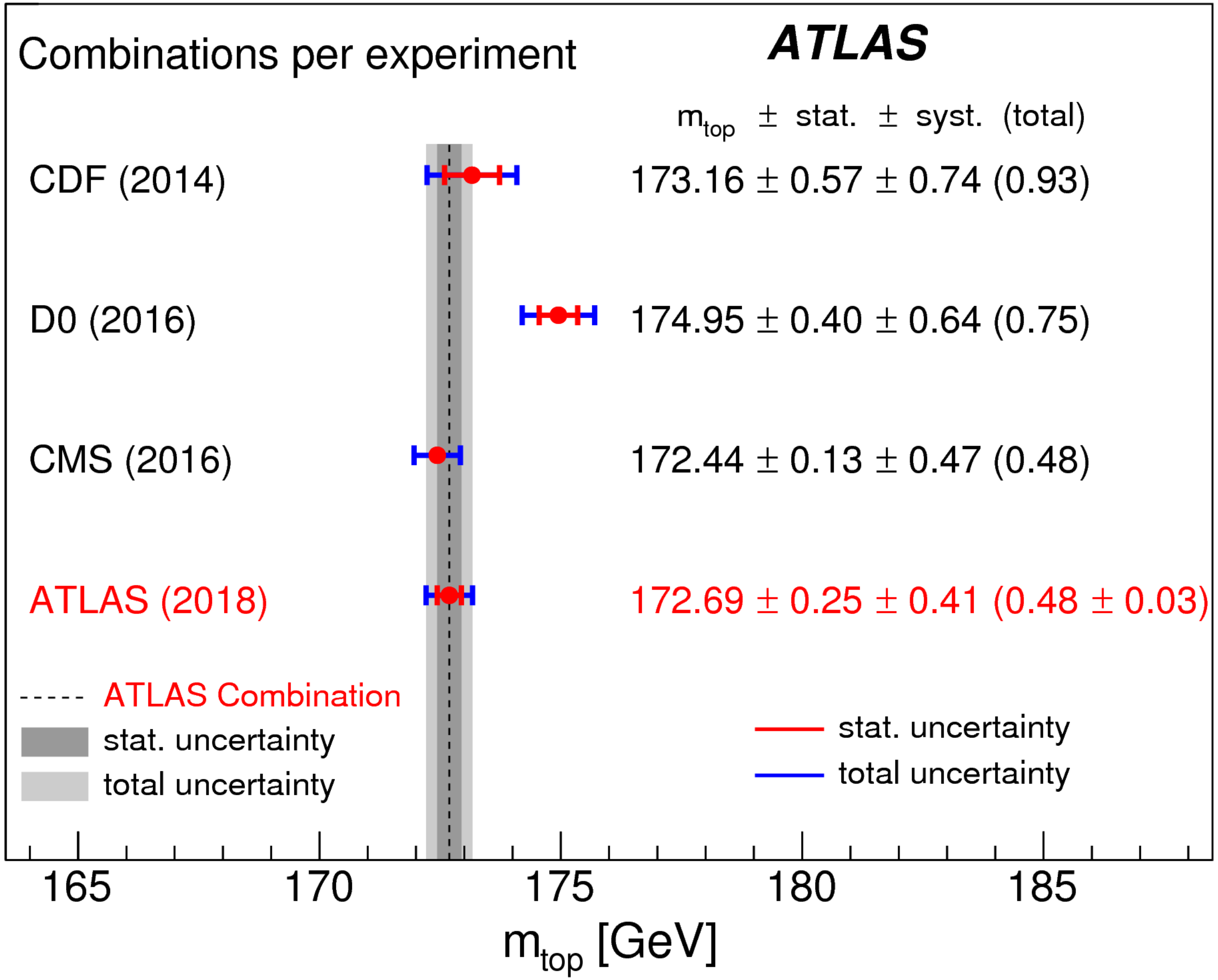
- **final combined result**: $m_{top} = 172.69 \pm 0.25\ (\text{stat}) \pm 0.41\ (\text{syst})\ \text{GeV}$
- result is dominated by the first 3 measurements *(as listed above)*
- new ATLAS combined result provides **44**% improvement relative to the best single input result (*cf.* CMS ~ **4**%)

New Combination of ATLAS m_{top} Measurements

Submitted to EPJC [1]

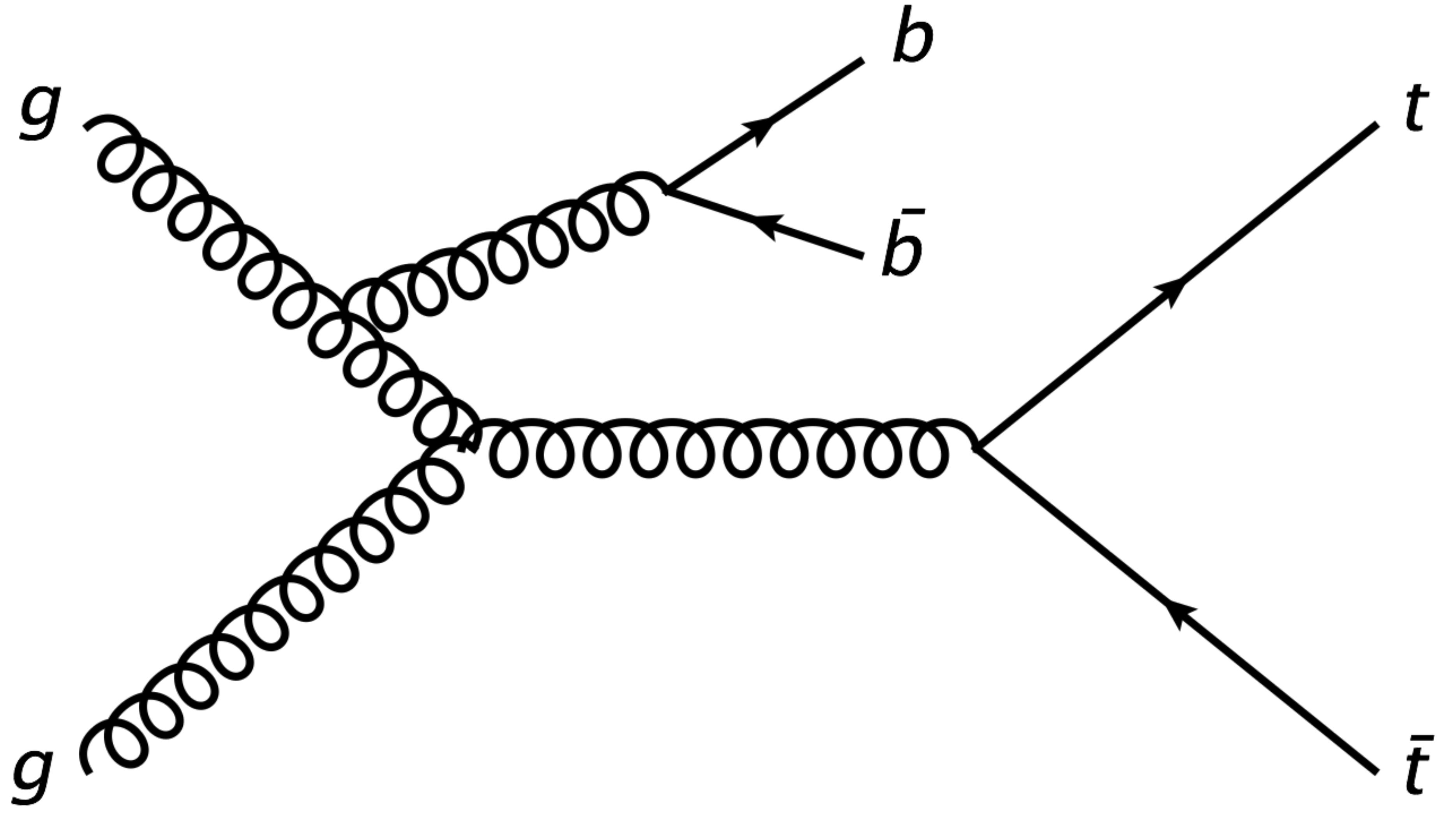
- new ATLAS combined result more precise than the results from CDF and D0 experiments
- ATLAS precision similar to most recent CMS combination

$$\frac{\sigma_{m_{top}}}{m_{top}} \approx 0.28\ \%$$



Studies of Other Processes Featuring Top Quarks

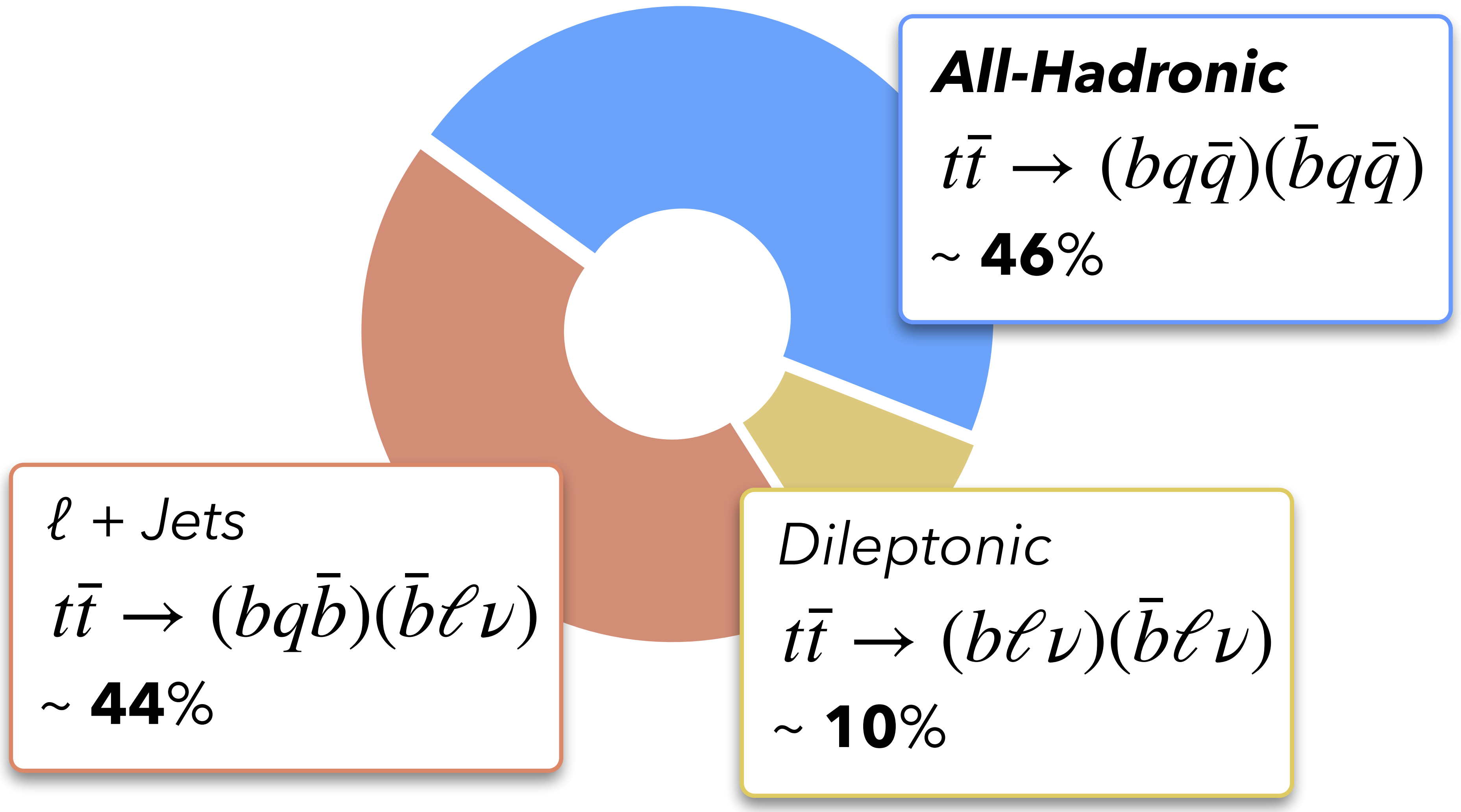
- study of $t\bar{t}b\bar{b}$ process provides natural setting to probe dynamics of heavy-flavour quark production @ LHC
- multi-scale process ($\sqrt{s}$, m_t, m_b, …)
- $t\bar{t}b\bar{b}$ also a leading background for $t\bar{t}H$ ($H \to b\bar{b}$)



improved knowledge of $t\bar{t}b\bar{b}$ process
→
improved results in $t\bar{t}H$ measurements

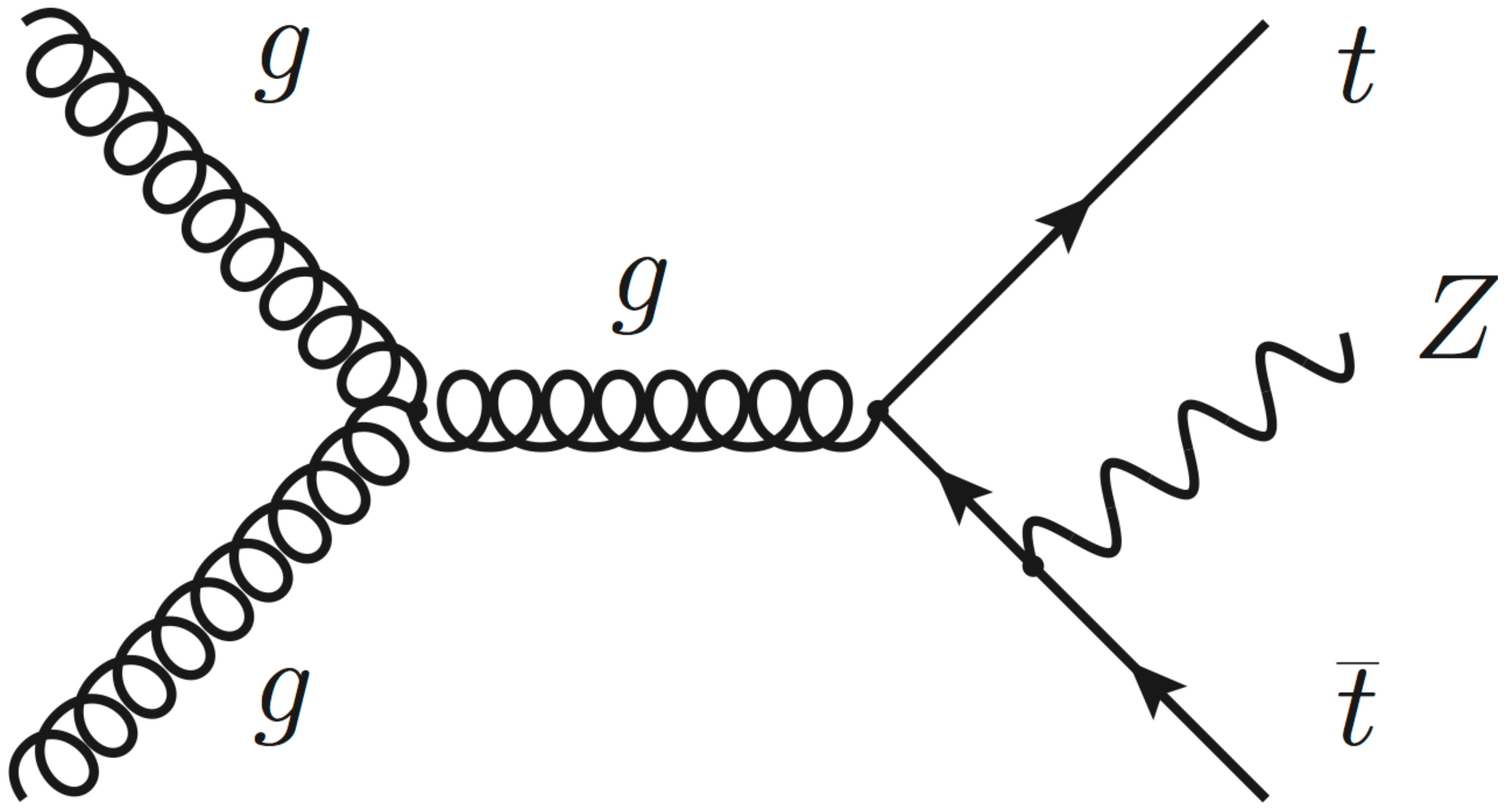
- work by **MPP** group to perform differential cross-section measurement in events in the all-hadronic (0-lepton) channel
- all-hadronic $t\bar{t}b\bar{b}$ final state offers sensitivity to BSM physics
- **advantages**: full reconstruction, large BR
- fruitful dialogue with theory community: simulation of $t\bar{t}b\bar{b}$ events
- well suited to calorimeter group expertise with jets and hadronic signatures
- draw on previous experience with all-hadronic $t\bar{t}$ decays (precision top quark mass measurement @ $\sqrt{s}$ = 8 TeV)

$t\bar{t}$ Decay Modes



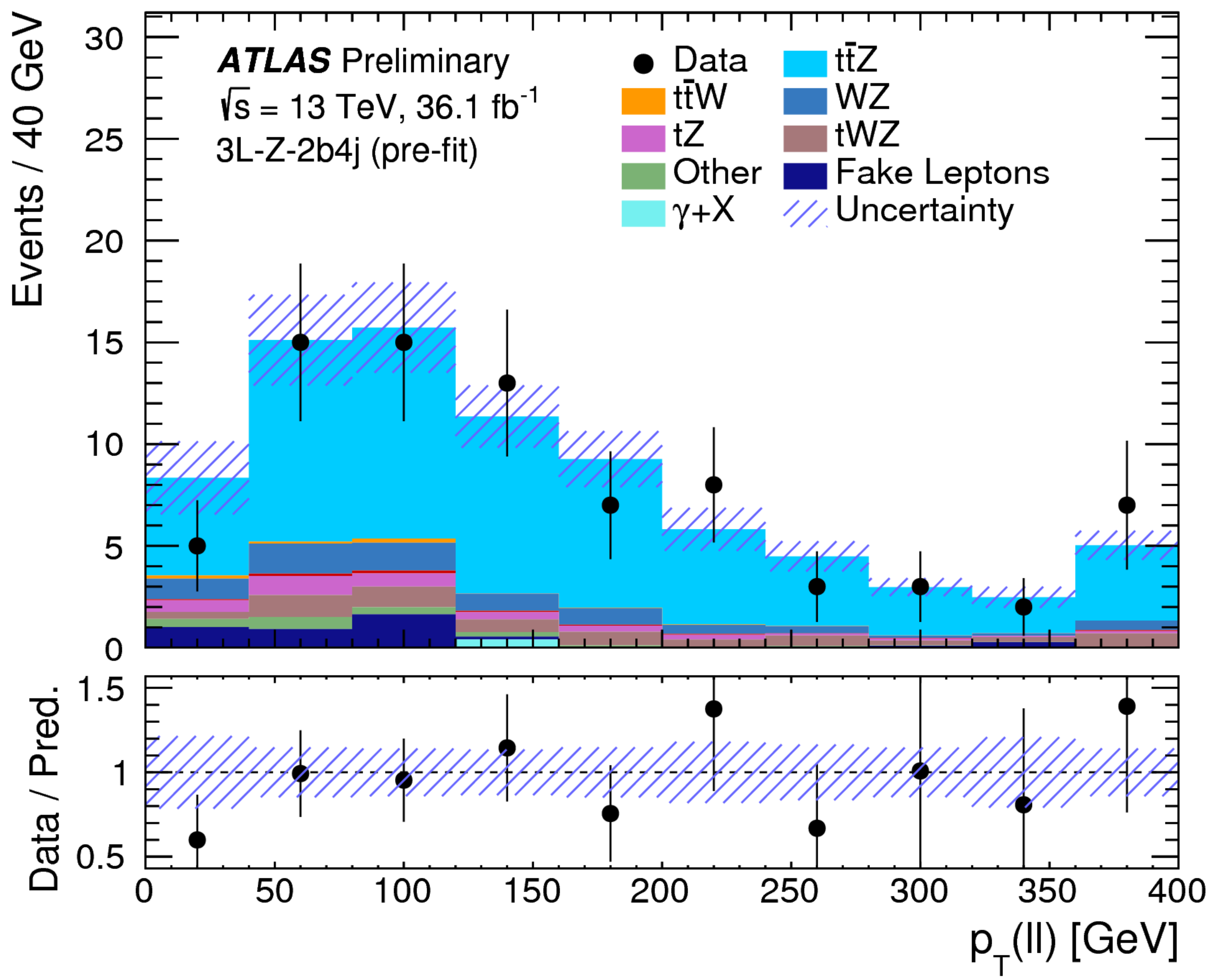
Studies of Other Processes Featuring Top Quarks

(previous ATLAS result) ATLAS-CONF-2018-047 [2]



- $t\bar{t}Z$ production at LHC a rare SM process (accessible @ Run 2!)
- important background in many SM + BSM searches at $\sqrt{s}$ = 13 TeV (*e.g.* $t\bar{t}H$, $t\bar{t}t\bar{t}$, various multi-lepton SUSY searches)
- direct access to $t\bar{t}Z$ coupling and $t\bar{t}$ spin correlations
- previous ATLAS cross-section measurement ($t\bar{t}Z$ + $t\bar{t}W$ combined) performed with subset of Run-2 data (36.1 fb^{-1}) *(example below)*

- leading sensitivity in 3ℓ channel ($t\bar{t} \to \ell$+jets, $Z \to \ell\ell$)
- also consider 2ℓ and 4ℓ channels
- strong **MPP** involvement in extended Run-2 analysis (140 fb^{-1}) planned differential $t\bar{t}Z$ cross-section measurement including:
  - development of advanced $t\bar{t}$ reconstruction techniques
  - background suppression strategies in all channels



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Higgs Physics

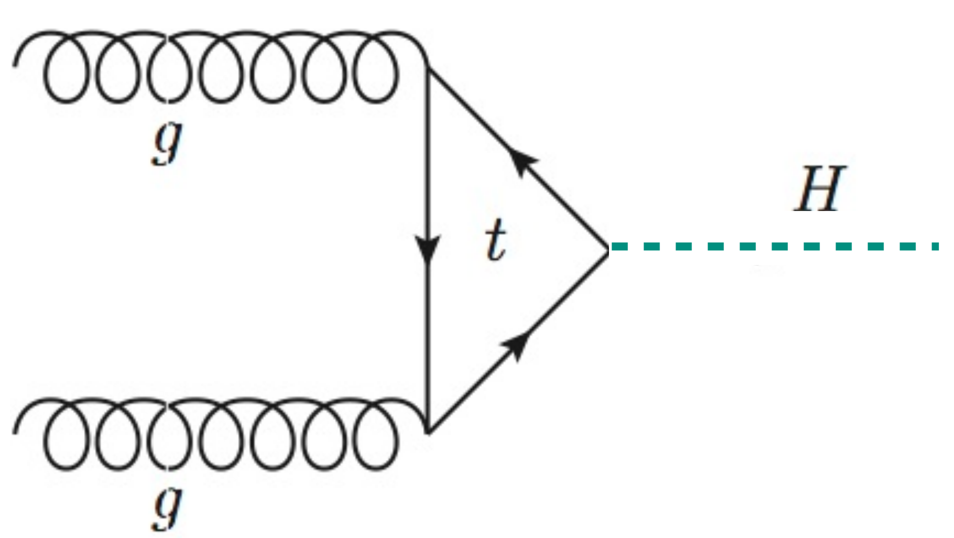
Higgs Boson Properties

- offers unique tests of the Standard Model, but also interpretations in **theories beyond the SM** (*e.g.* Effective Field Theories, CP violation)
- generally SM Higgs measurements fall under two categories:

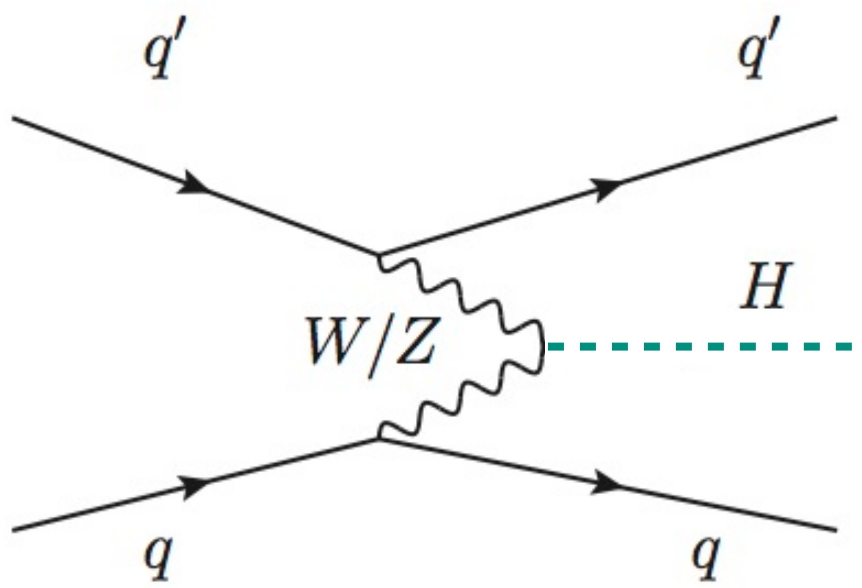
1. Higgs boson mass measurements
2. Cross-section measurements based on key production and decay mechanisms (coupling properties)

Higgs Production Modes @ LHC

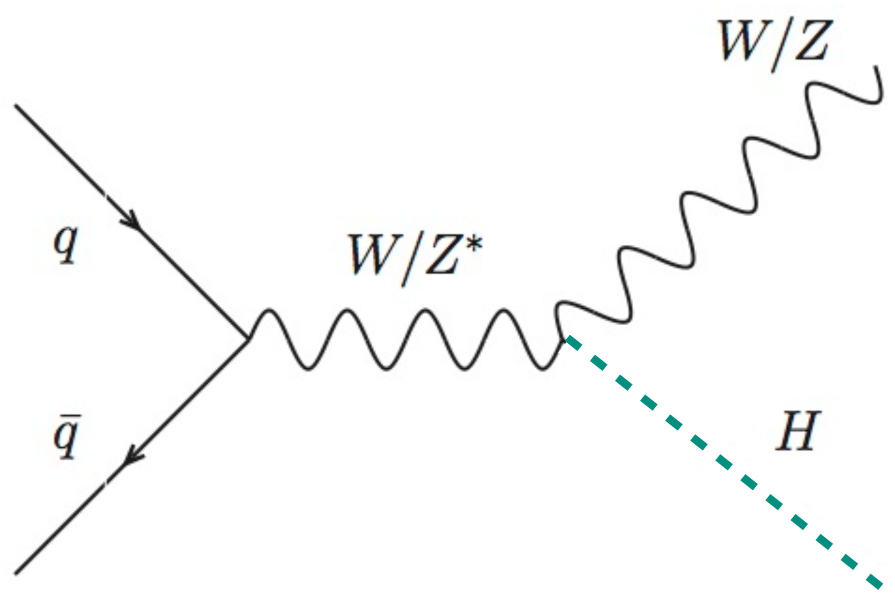
ggF *(~87.4%)*



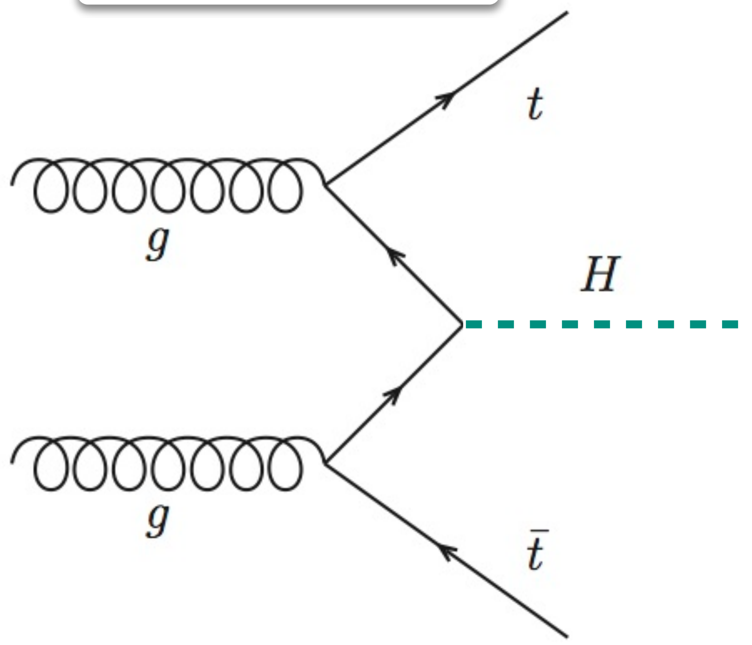
VBF *(~6.8%)*



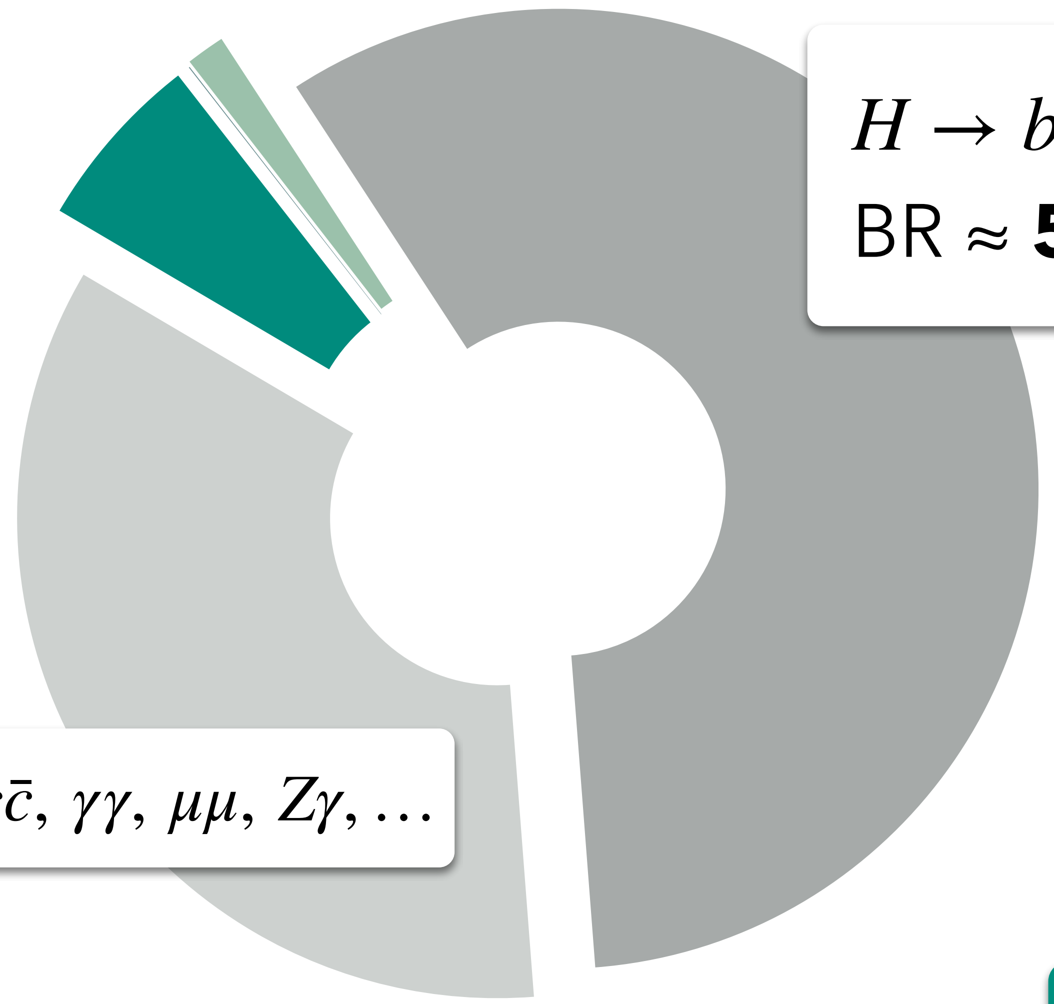
VH *(~4.1%)*



ttH *(~0.9%)*



Higgs Decay Modes



$H \to b\bar{b}$
BR ≈ **58%**

$H \to gg, c\bar{c}, \gamma\gamma, \mu\mu, Z\gamma, \ldots$

Channels with direct MPP involvement

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
$H \to WW^* \to \ell\nu\ell\nu$
BR ≈ **1.3%**

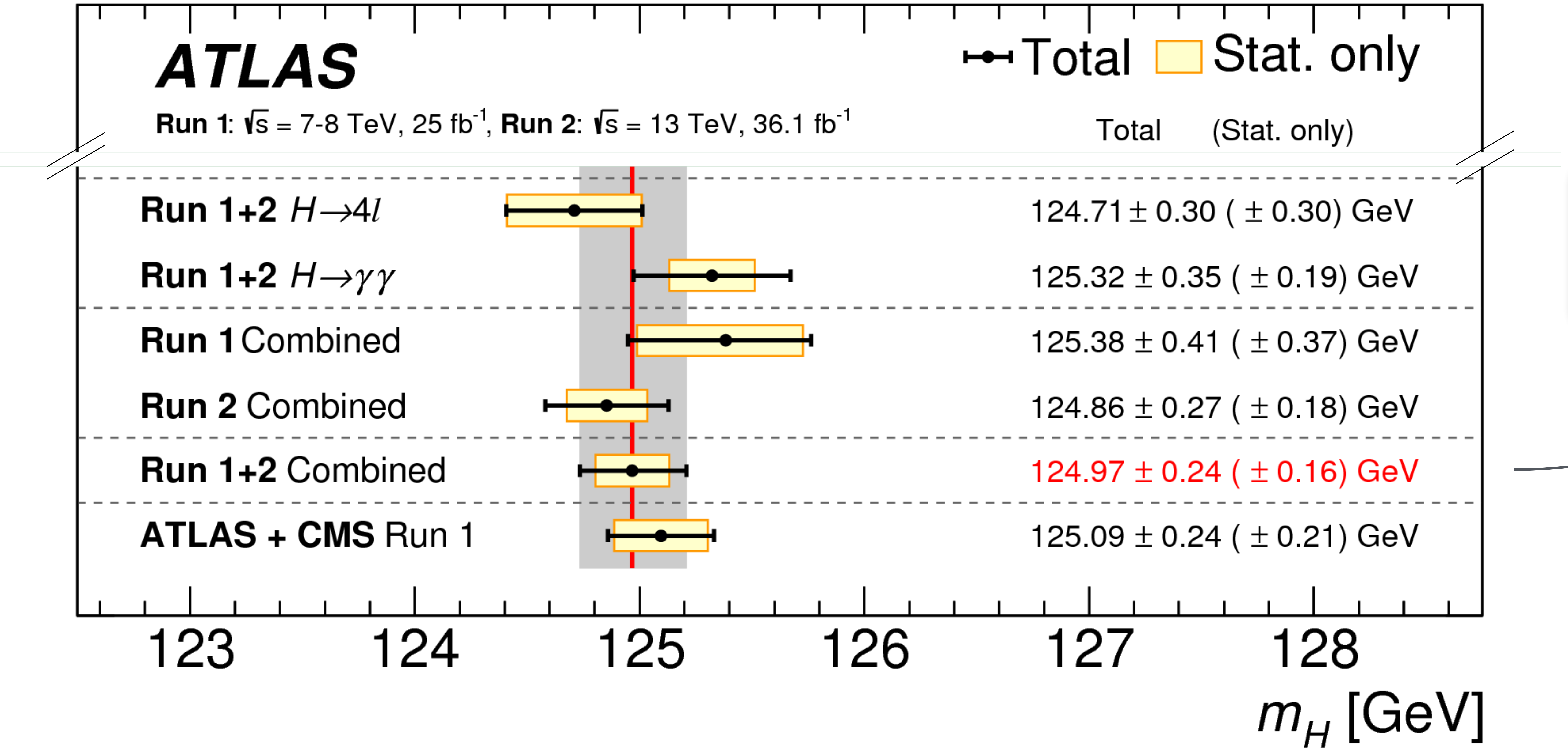
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
$H \to ZZ^* \to 4\ell$
BR ≈ **0.03%**

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
$H \to \tau\tau$
BR ≈ **6%**

Higgs Boson Mass (m_H) Measurements

Phys. Lett. B 784 (2018) 345 [3]

- m_H measurement has been performed for the first time with ATLAS Run-2 data (including 2015/2016)
- measurement performed in the 2-photon ($\gamma\gamma$) and 4ℓ (**MPP**) decay channels



$$\frac{\sigma_{m_H}}{m_H} \approx 0.19\,\%$$

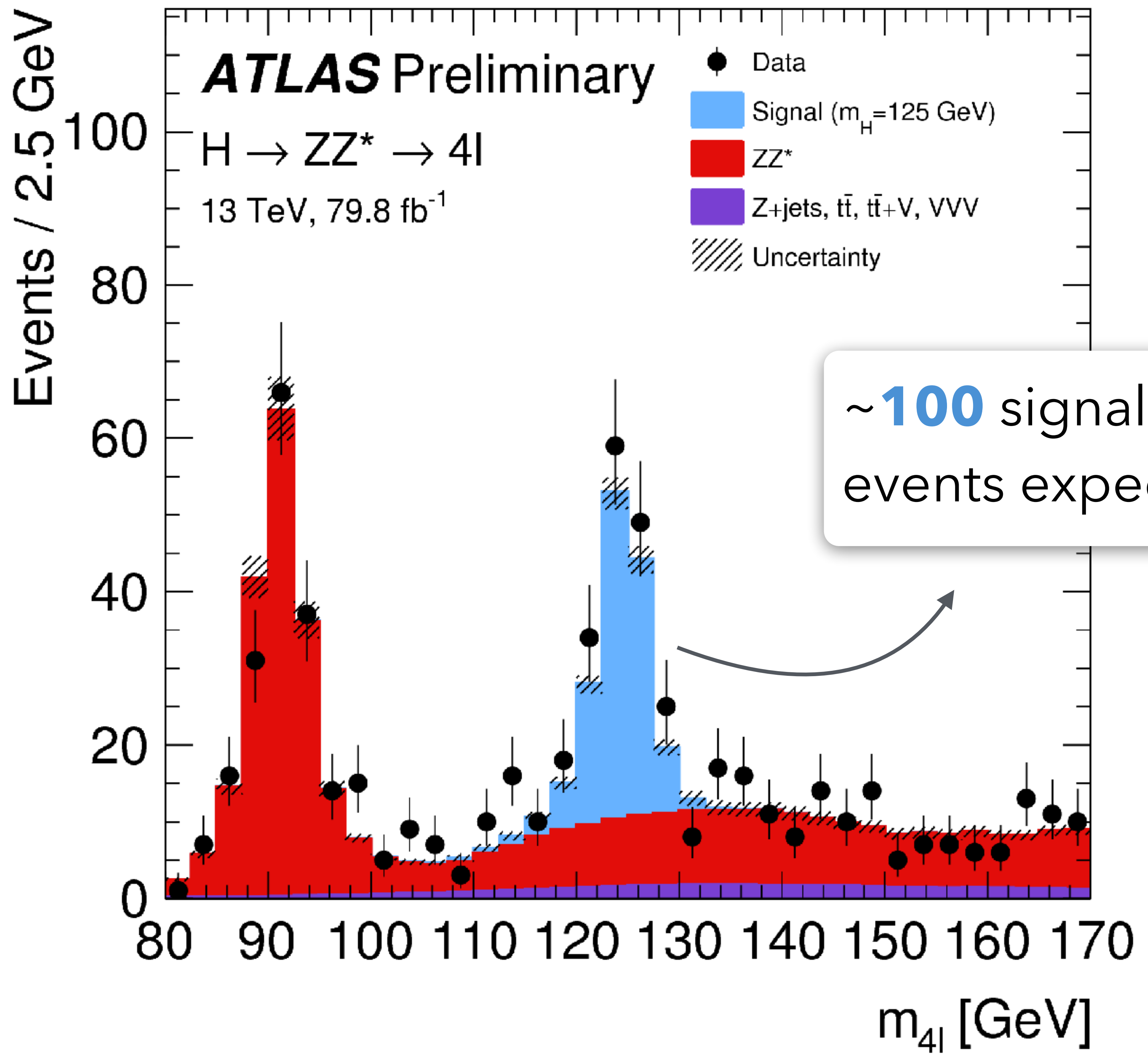
- results in improvement in precision w.r.t. combined Run-1 ATLAS+CMS result
- precision of a future ATLAS full Run-2 combination will be driven by result in the H → 4ℓ channel (world's smallest systematic uncertainty on m_H of 0.04%!)

Precision achieved thanks to dedicated muon calibration **led by MPP**!

Higgs Coupling Properties: $H \to ZZ^* \to 4\ell$

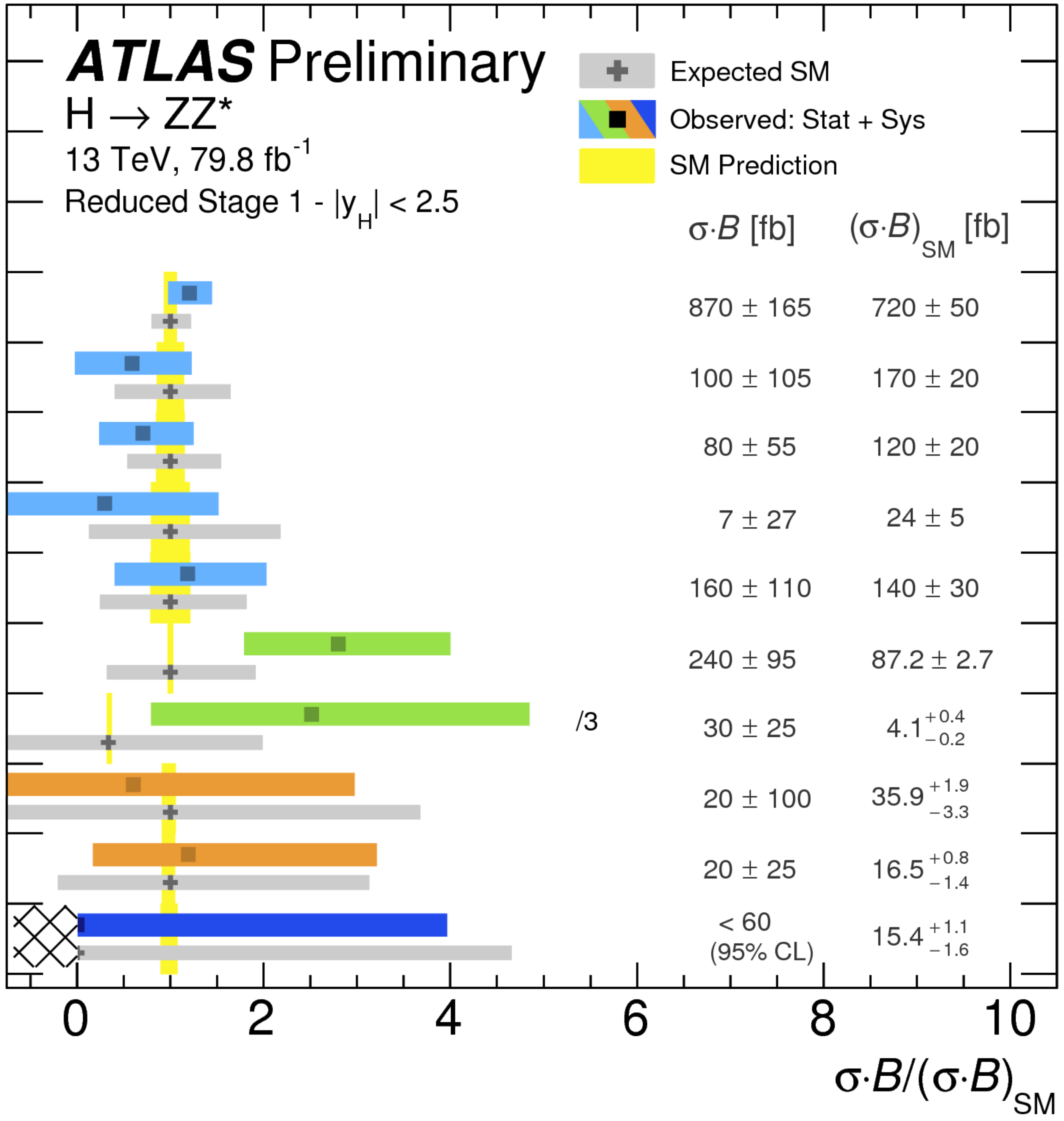
ATLAS-CONF-2018-018 [4]

- **2×** more data compared with last year → allows for finer categorization!
  - access key production modes in different dedicated regions of phase space



~**100** signal events expected!

- **ggF** (0 jet)
- **ggF** (1 jet, low p_T^H)
- **ggF** (1 jet, medium p_T^H)
- **ggF** (1 jet, high p_T^H)
- **ggF** (2 jets)
- **VBF** (low p_T^{jet})
- **VBF** (high p_T^{jet})
- **VH** (hadronic V decay)
- **VH** (leptonic V decay)
- **ttH**



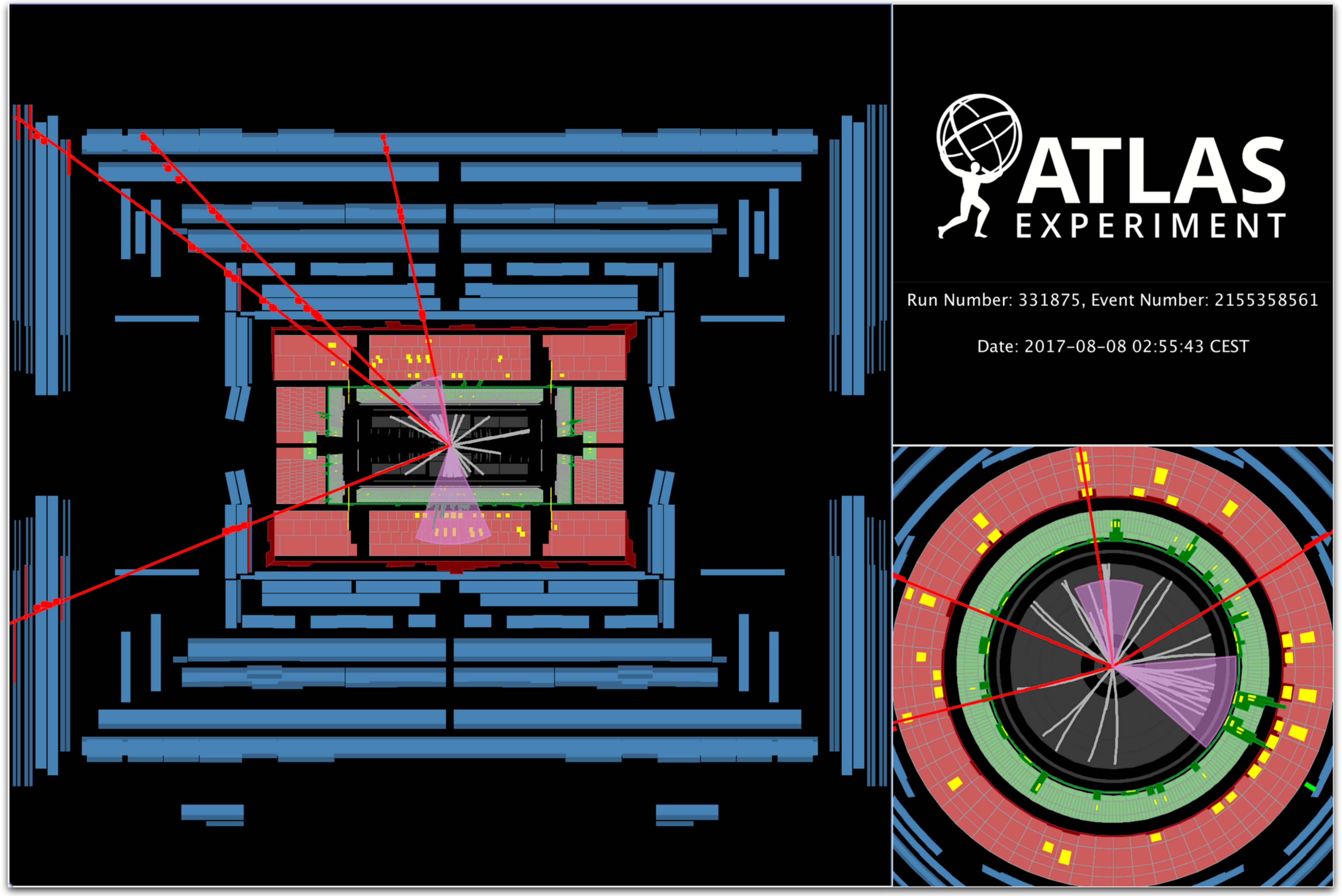
- statistical uncertainties still dominate in such measurements
- for the first time sensitivity to VH and $t\bar{t}H$ production modes in the 4ℓ channel! (V = W,Z)

In Progress: Projections for High-Luminosity LHC (**HL-LHC**), as an input to the European Strategy of Particle Physics

VH and tt̄H Production

Phys. Lett. B 786 (2018) 59 [5]   Phys. Lett. B 784 (2018) 173 [6]

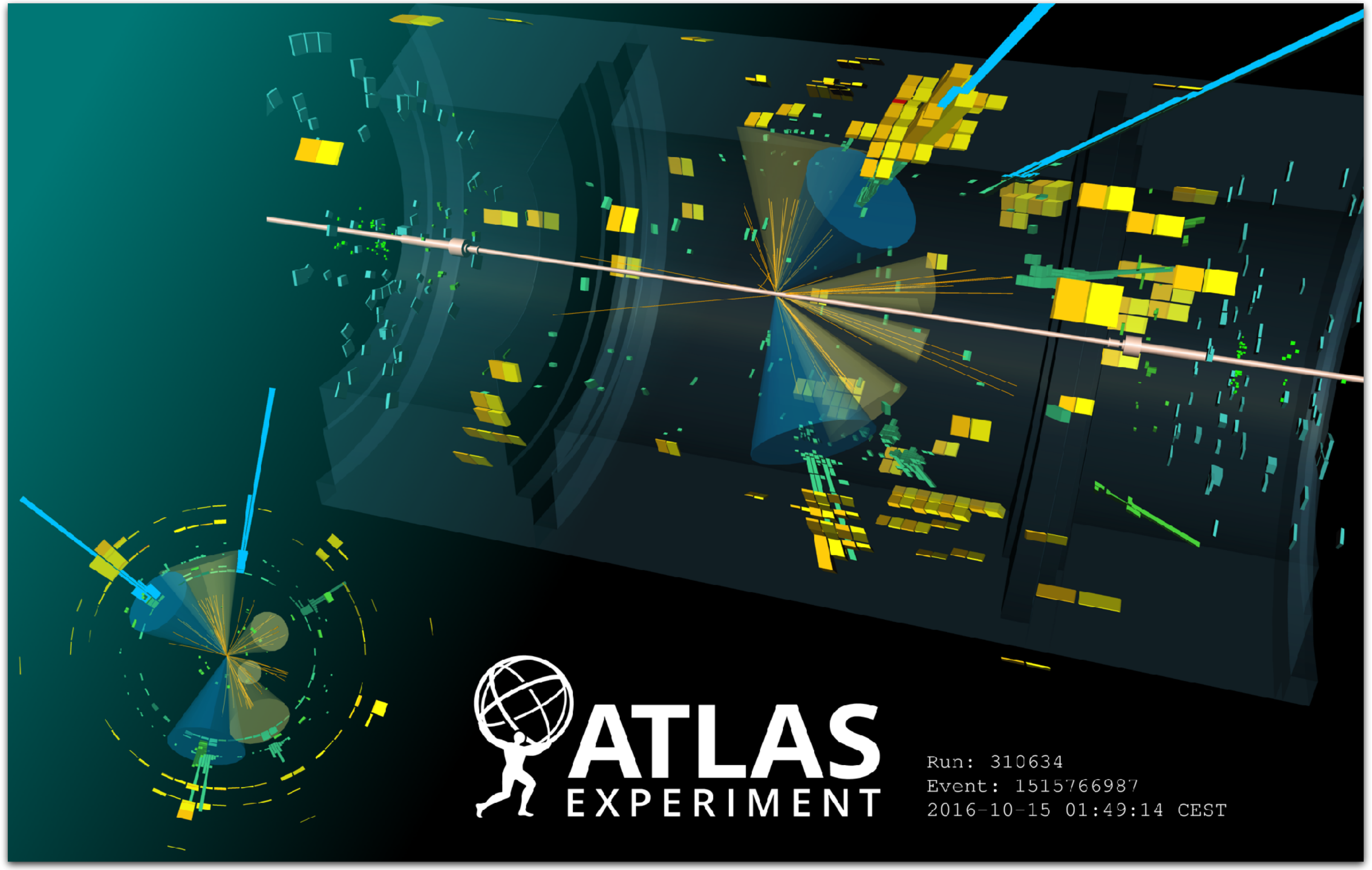
- analysis of H → ZZ^{*} → 4ℓ channel contributes to the **first** direct ATLAS observation of **VH** and **tt̄H** production modes



Sample VH Candidate Event Display

$$pp \rightarrow ZH \rightarrow (q\bar{q})(\mu\mu\mu\mu)$$

(event display reference) ATLAS-CONF-2018-018 [4]



Sample tt̄H Candidate Event Display

$$pp \rightarrow t\bar{t}H \rightarrow (bq\bar{q})(\bar{b}q\bar{q})(\gamma\gamma)$$

(event display reference) Phys. Lett. B 784 (2018) 173 [6]

VH and $t\bar{t}H$ Production

Phys. Lett. B 786 (2018) 59 [5]
Phys. Lett. B 784 (2018) 173 [6]

- analysis of $H \to ZZ^* \to 4\ell$ channel contributes to the **first** direct ATLAS observation of **VH** and **$t\bar{t}H$** production modes

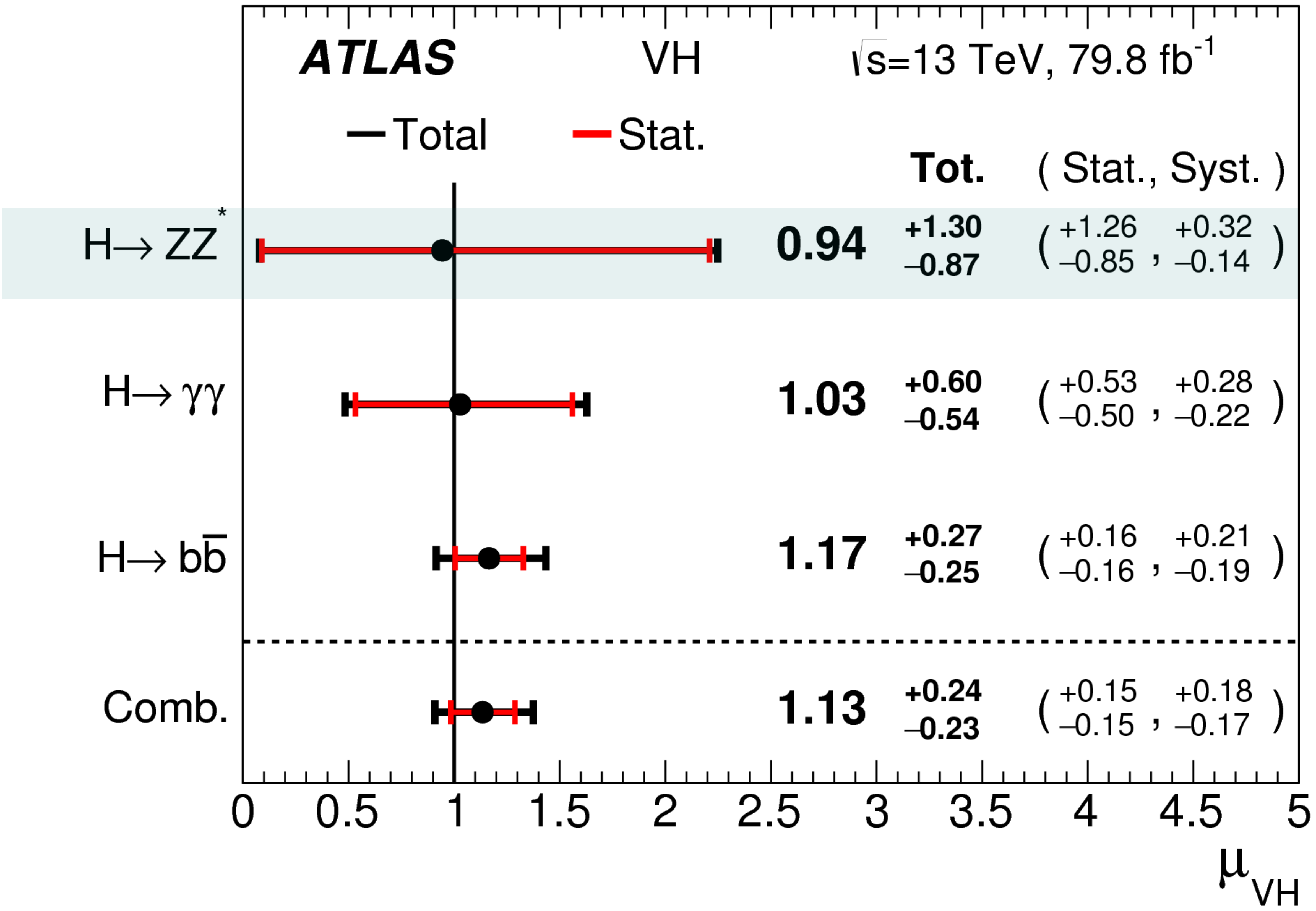
Couplings to Vector Bosons

- previously observed in **VBF** and $H \to WW^* \to \ell\nu\ell\nu$
- now confirmed in associated **VH** production mode

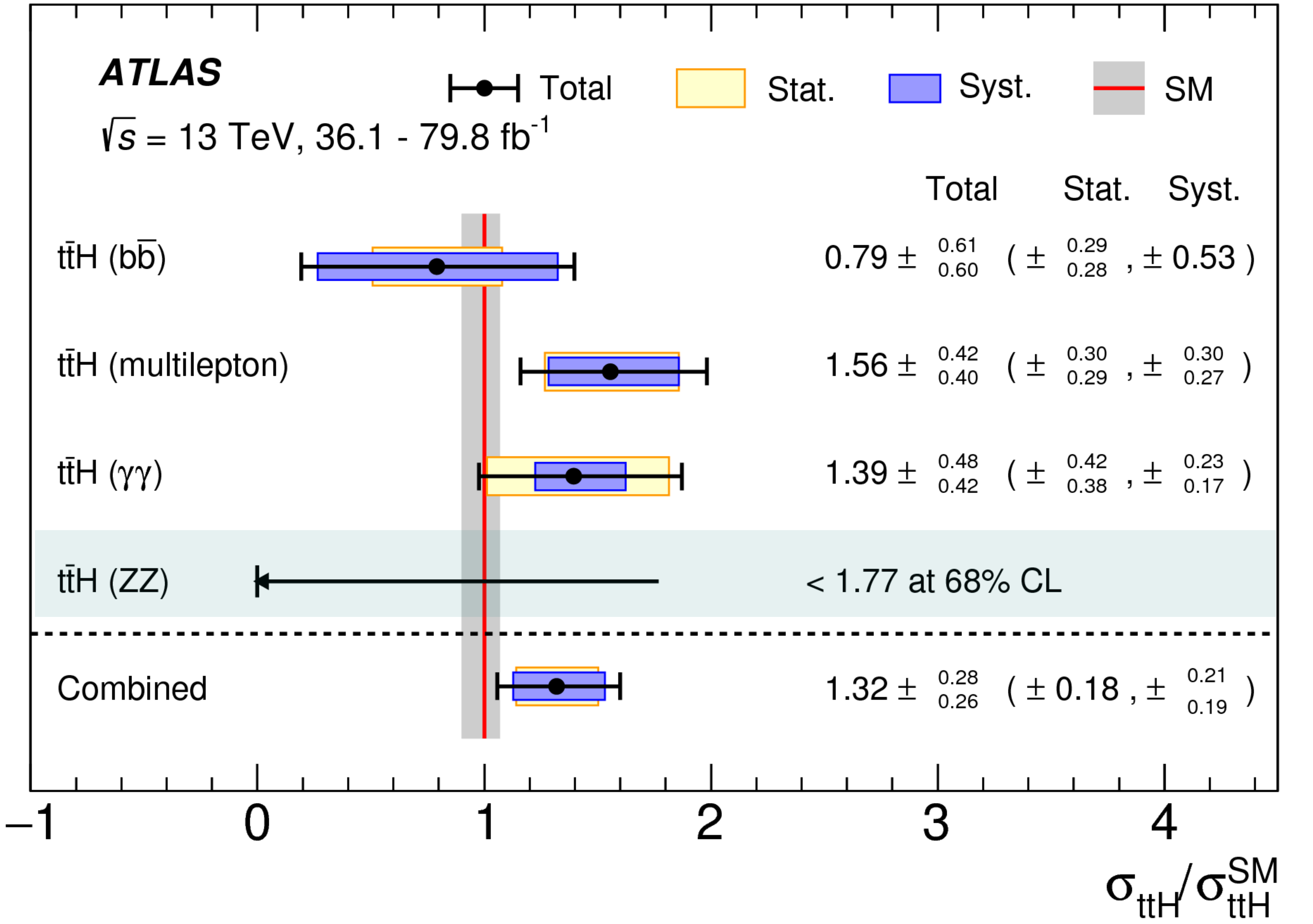
First Direct Probe of Top Yukawa Coupling

- **$t\bar{t}H$** very rare, but <u>important</u> SM process:
  → observation requires combination of several decay channels!
- complex final-state signatures: $t\bar{t}H \to (\ell\nu b, jjb)(\ell\nu b, jjb)(b\bar{b}, \gamma\gamma, \tau\tau, WW, ZZ)$

*VH observation with **5.3σ** significance*



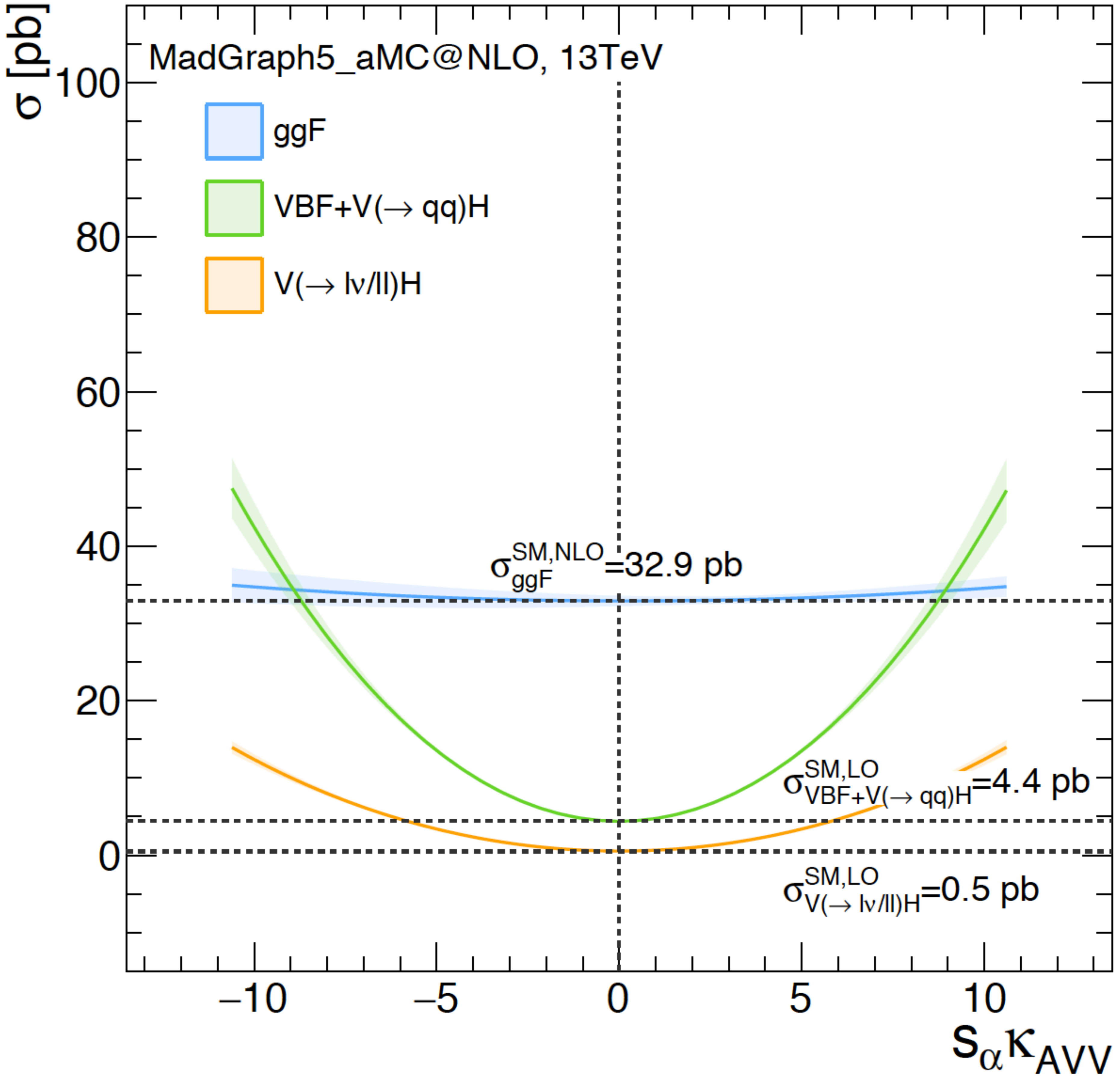
*$t\bar{t}H$ observation with **6.3σ** significance*



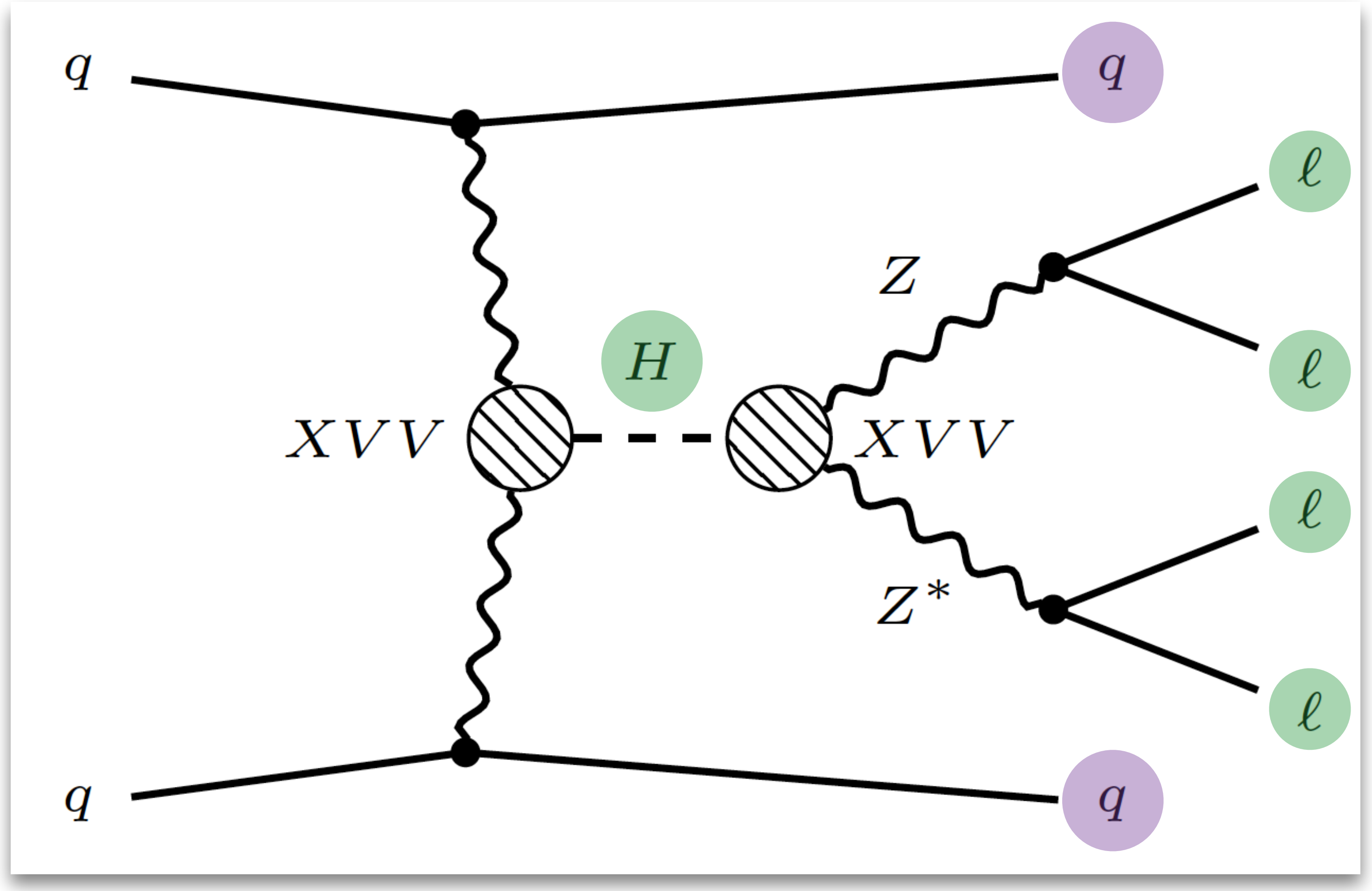
EFT Interpretation: $H \to ZZ^* \to 4\ell$

CERN-THESIS-2018-073 [7]

- measured production cross sections (*ggF*, *VBF*, *VH*) can be used to constrain certain extensions of the SM in the context of **Effective Field Theory** (EFT)
  (*via* additional contact-interaction terms suppressed by an energy scale Λ)
- non-zero (i.e. non-SM) terms introduced via EFT can affect **differential** distributions (strong sensitivity to BSM physics!)



Above: *Higgs cross section vs. CP-odd EFT parameter.*



Example of differential variables:

$\Delta\phi(j,j)$ from $q\bar{q}$

p_T^H, where $H = \ell\ell\ell\ell$

- **MPP** group early adopters of employing EFT interpretation in analyses
- now leading ATLAS efforts for EFT-related studies in Higgs sector!

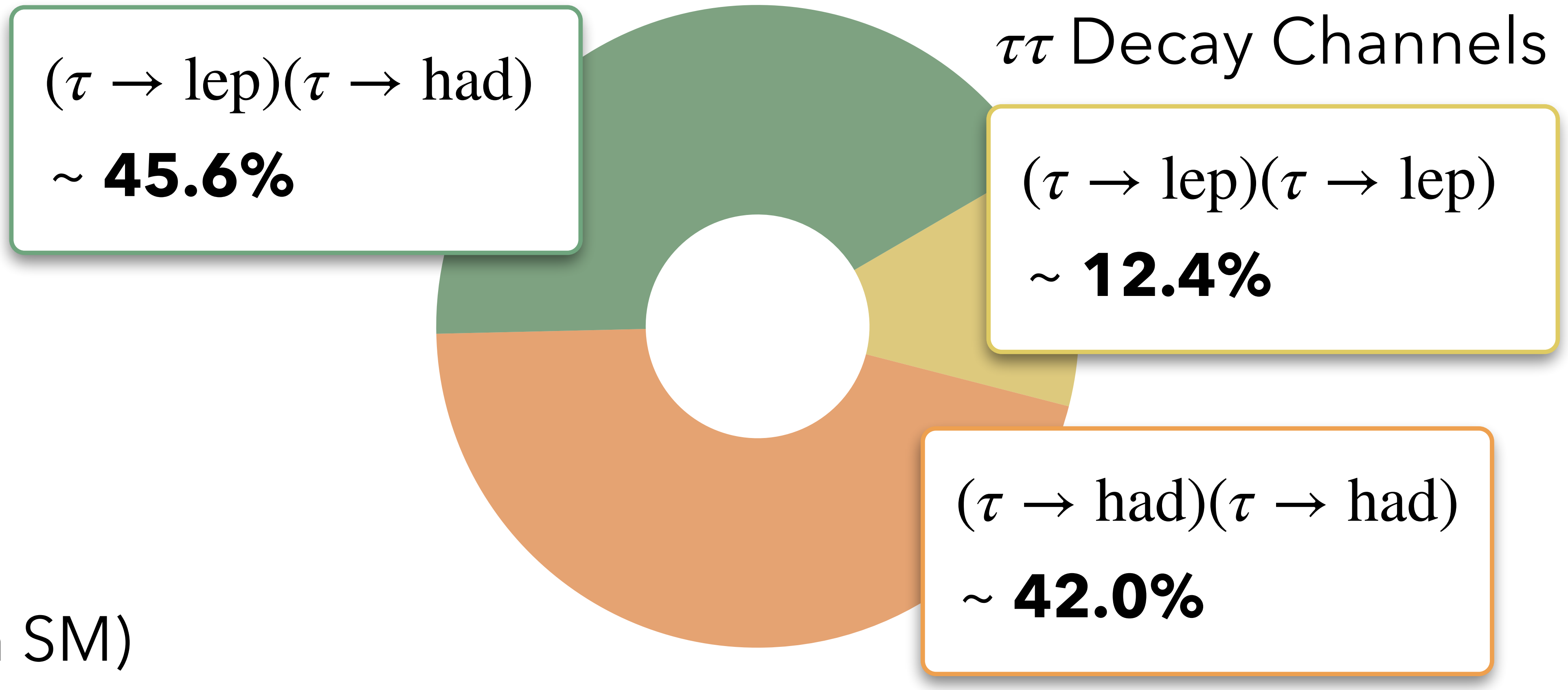
In Progress:

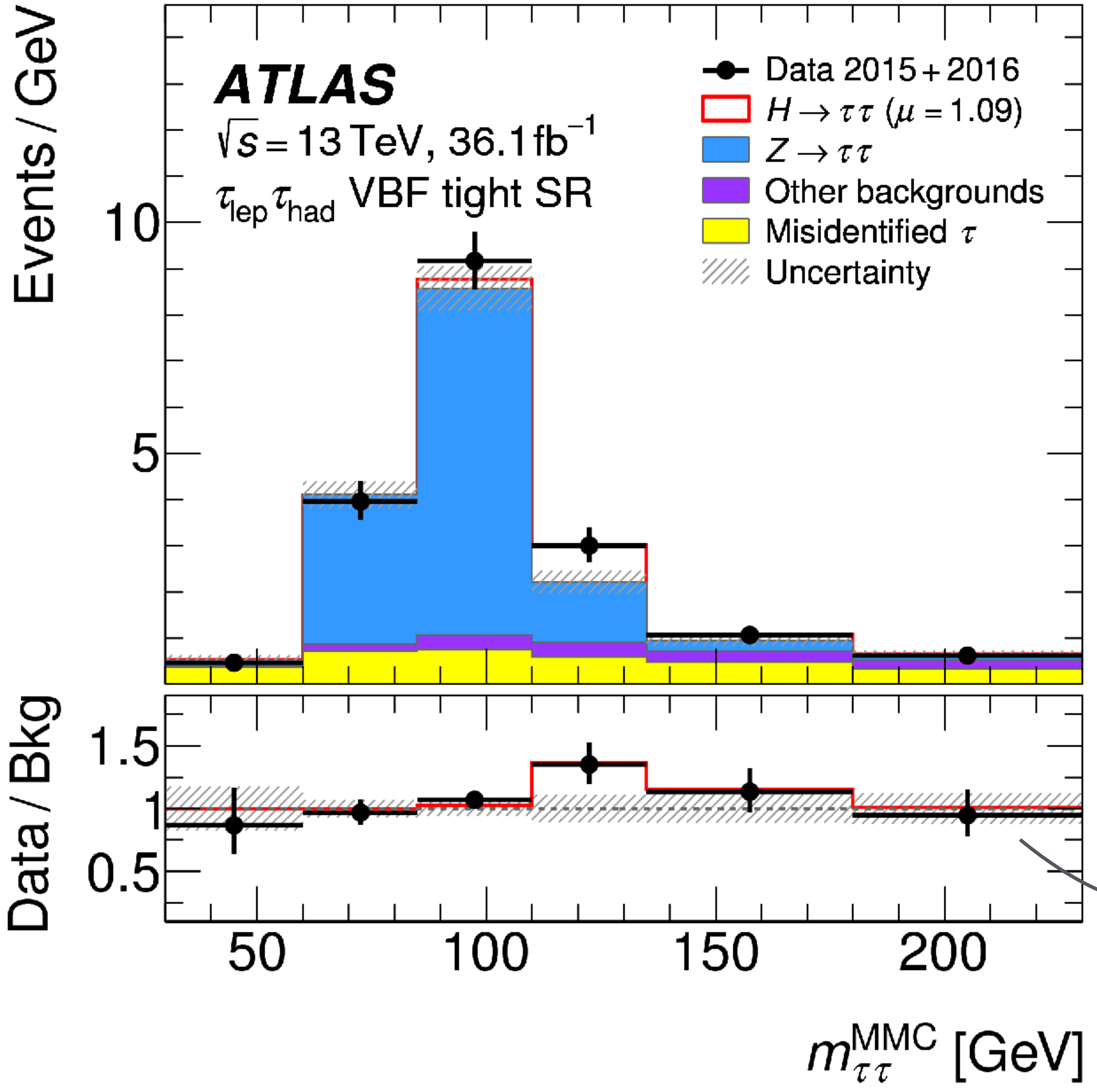
- ○ Search for CP violation using sensitive differential distributions
- ○ EFT interpretation with full Run-2 dataset (also in the H→WW channel)

Observation of Higgs Coupling to Fermions: $H \to \tau\tau$

Submitted to Phys. Rev. D [8]

- top quark coupling to **3rd generation quarks** (*via* $t\bar{t}$H)
- this result confirms top quark coupling to **3rd generation leptons** (τ) based on ATLAS data alone (previous observation relied on combined ATLAS+CMS results)
- analysis targets all 3 $\tau\tau$ decay channels *(right)*
- ggF and VBF cross-sections measured separately (good agreement with SM)





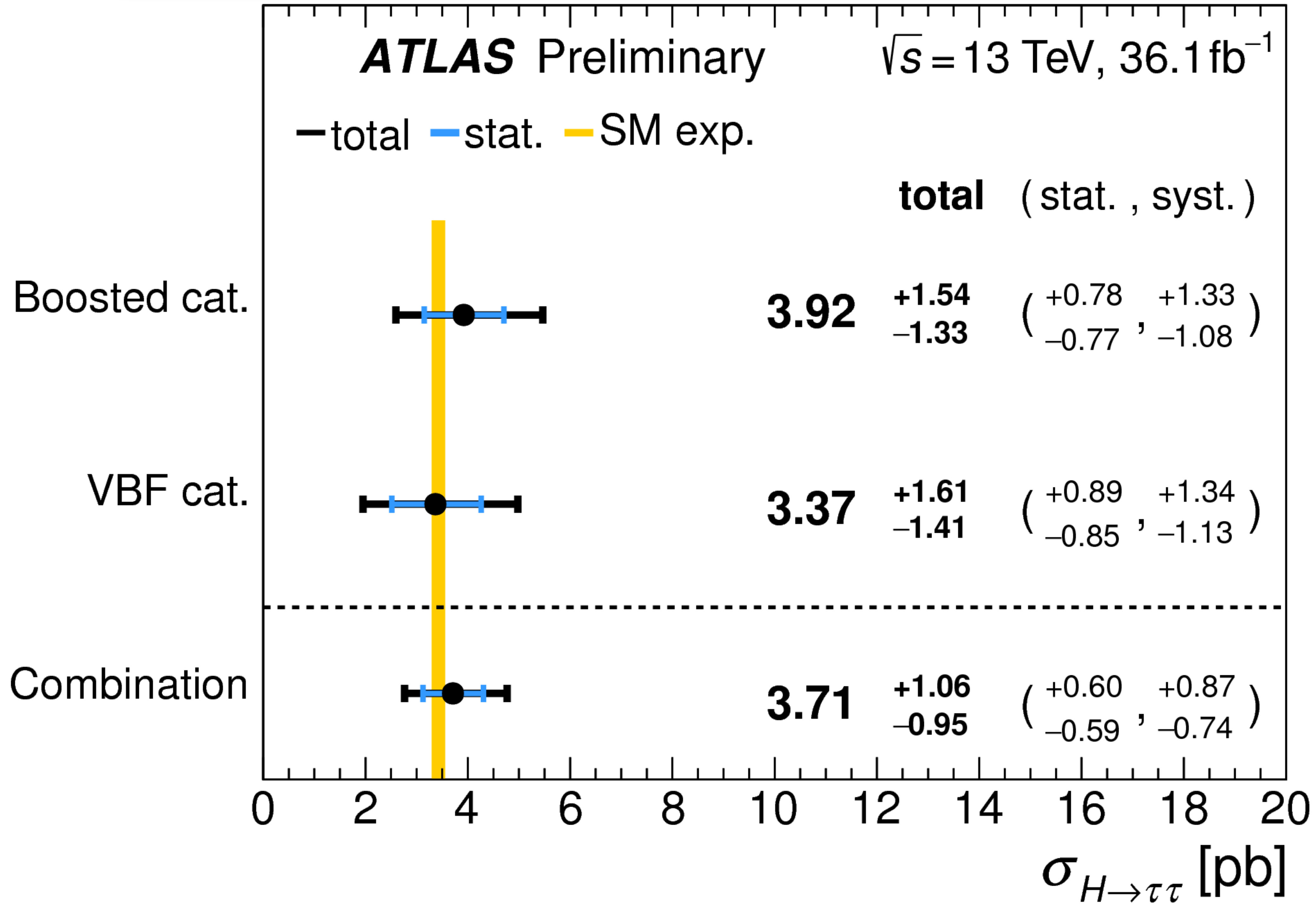
***Left**: Reconstructed invariant $\tau\tau$ mass distribution in one of the selected SRs*

(MMC = 'missing-mass calculator')

$(\tau \to \text{lep})(\tau \to \text{had})$

(S+B)/B

*Observed (expected) signal significance: **6.4σ** (5.4σ)*



BSM Physics Searches

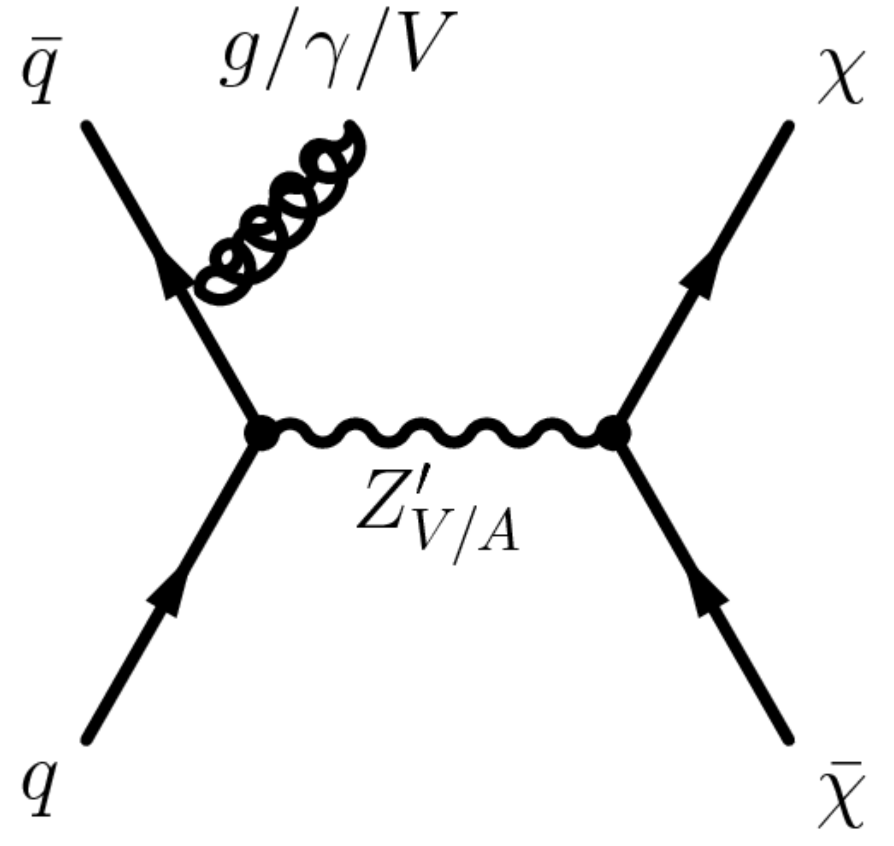
T.G.McCarthy
Max-Planck-Institut für Physik

Search for WIMP Dark Matter

(reference for plot)

Exotics Public Results

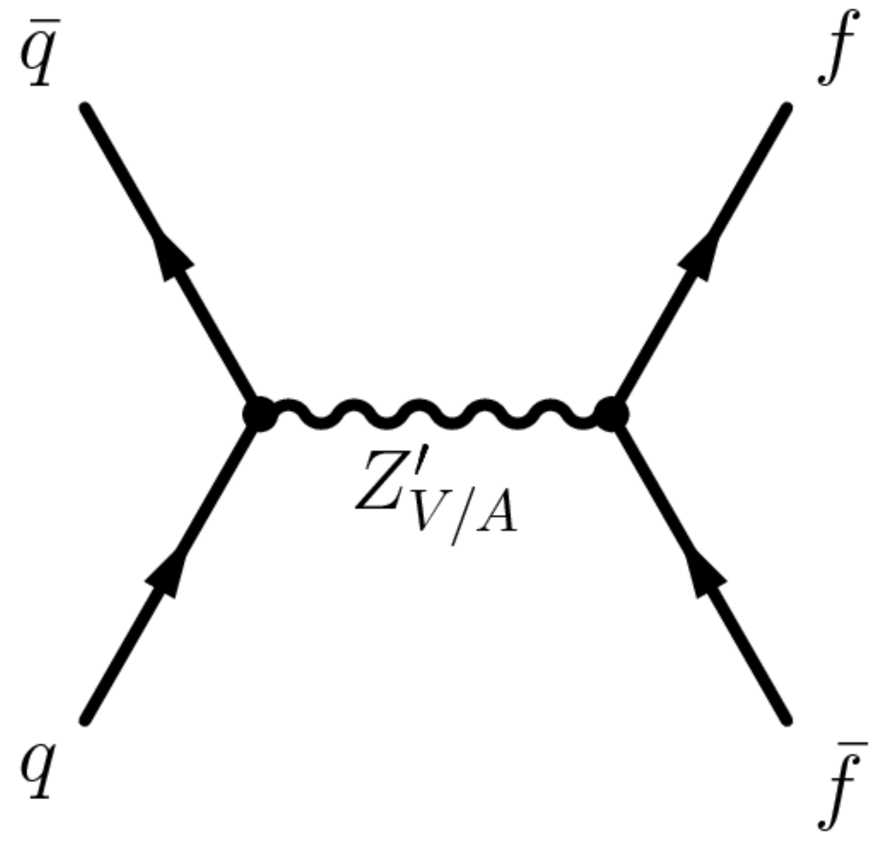
- general search campaign featuring several experimental signatures
  → interpreted in the context of simplified dark matter (DM) models:



E_T^{miss} + X

('mono-X')

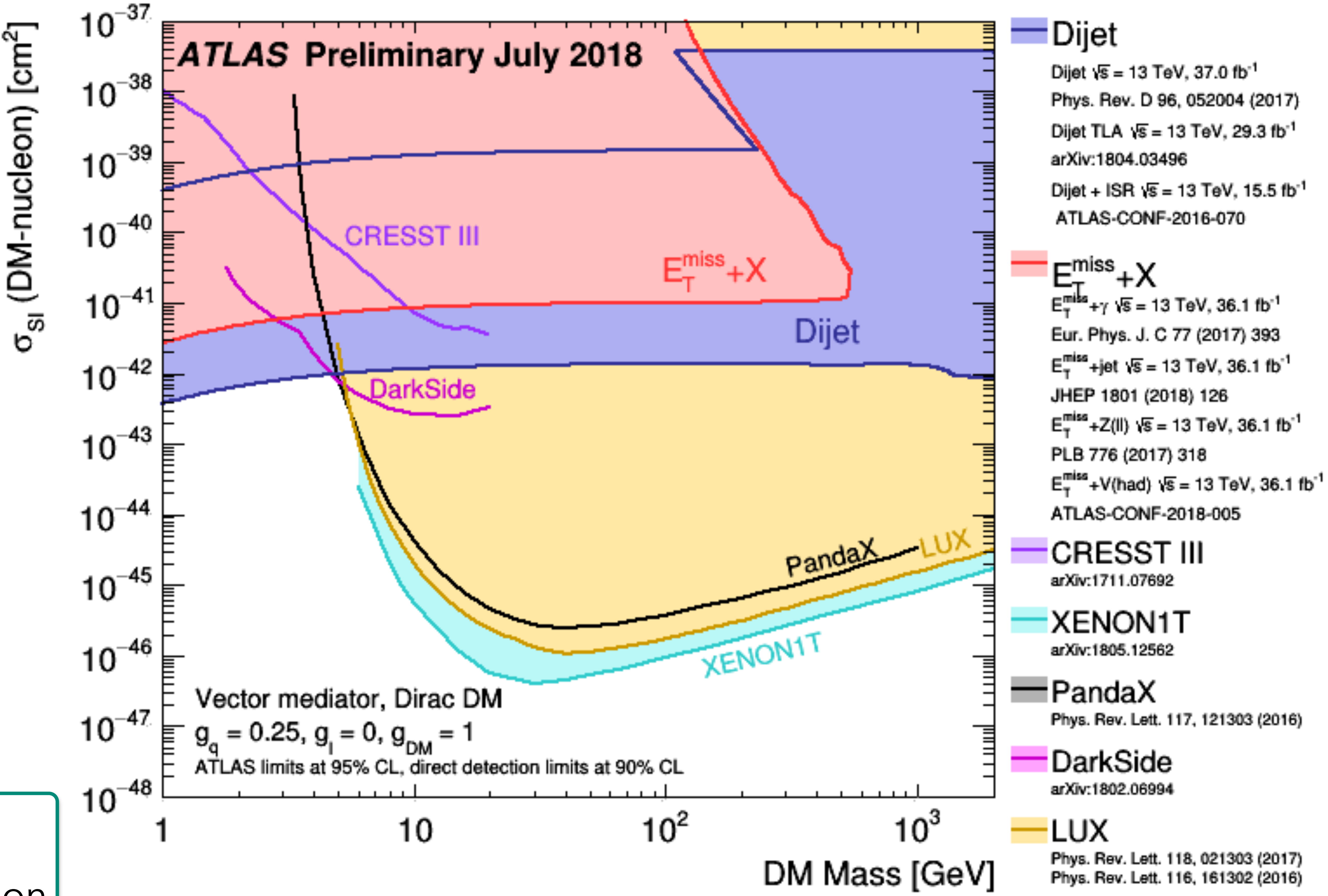
- DM produced in association with initial-state radiation
- other production mechanisms (w/o ISR) also considered



Dijet, Dilepton

- complementary signature
- indirect search for mediator decays to fermionic SM final states

- complementary to direct-detection experiments:
  - ✓ sensitivity to low-mass WIMP dark matter
  - ✓ spin-dependent interactions



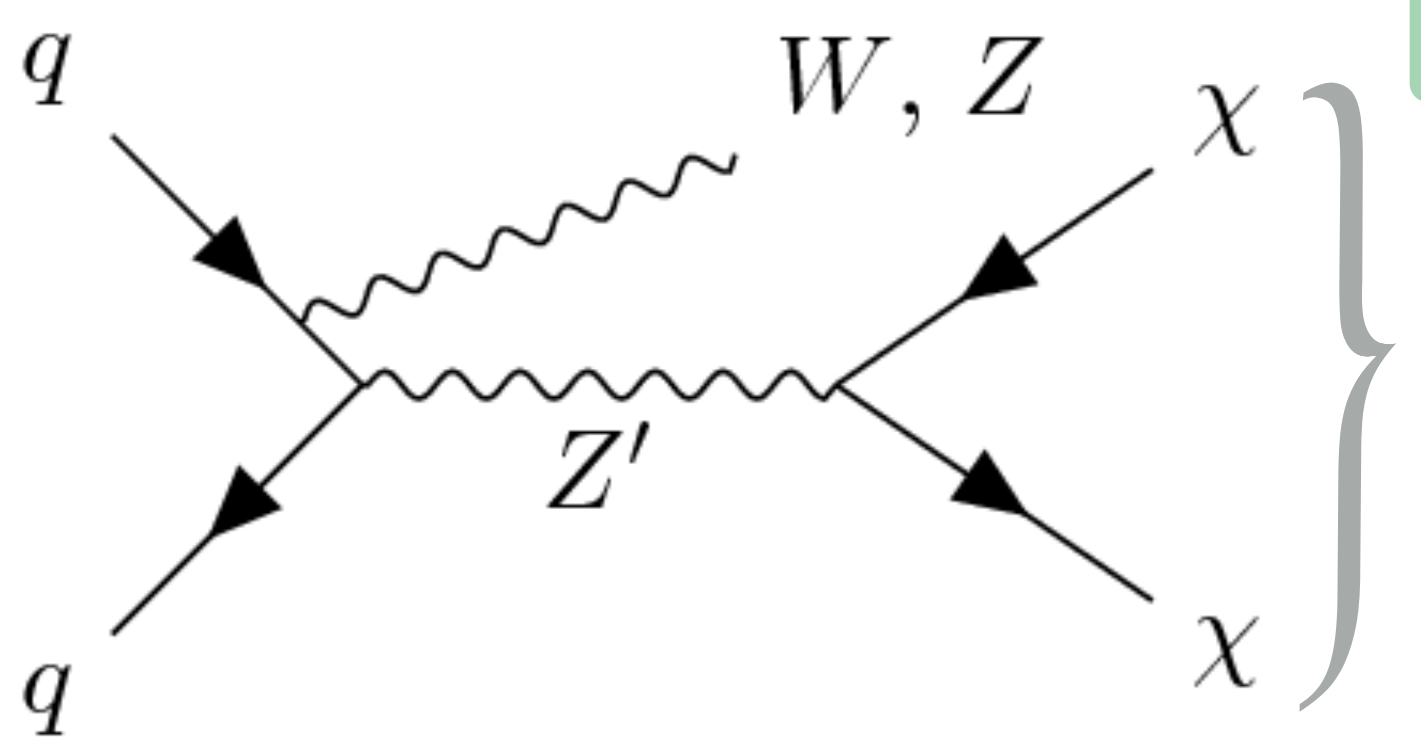
Involvement by ***MPP*** *group for various search categories:*

mono-H($b\bar{b}$) / mono-V(jj) / mono-jet / combination

Dark Matter Search: Mono-W/Z ($q\bar{q}$)

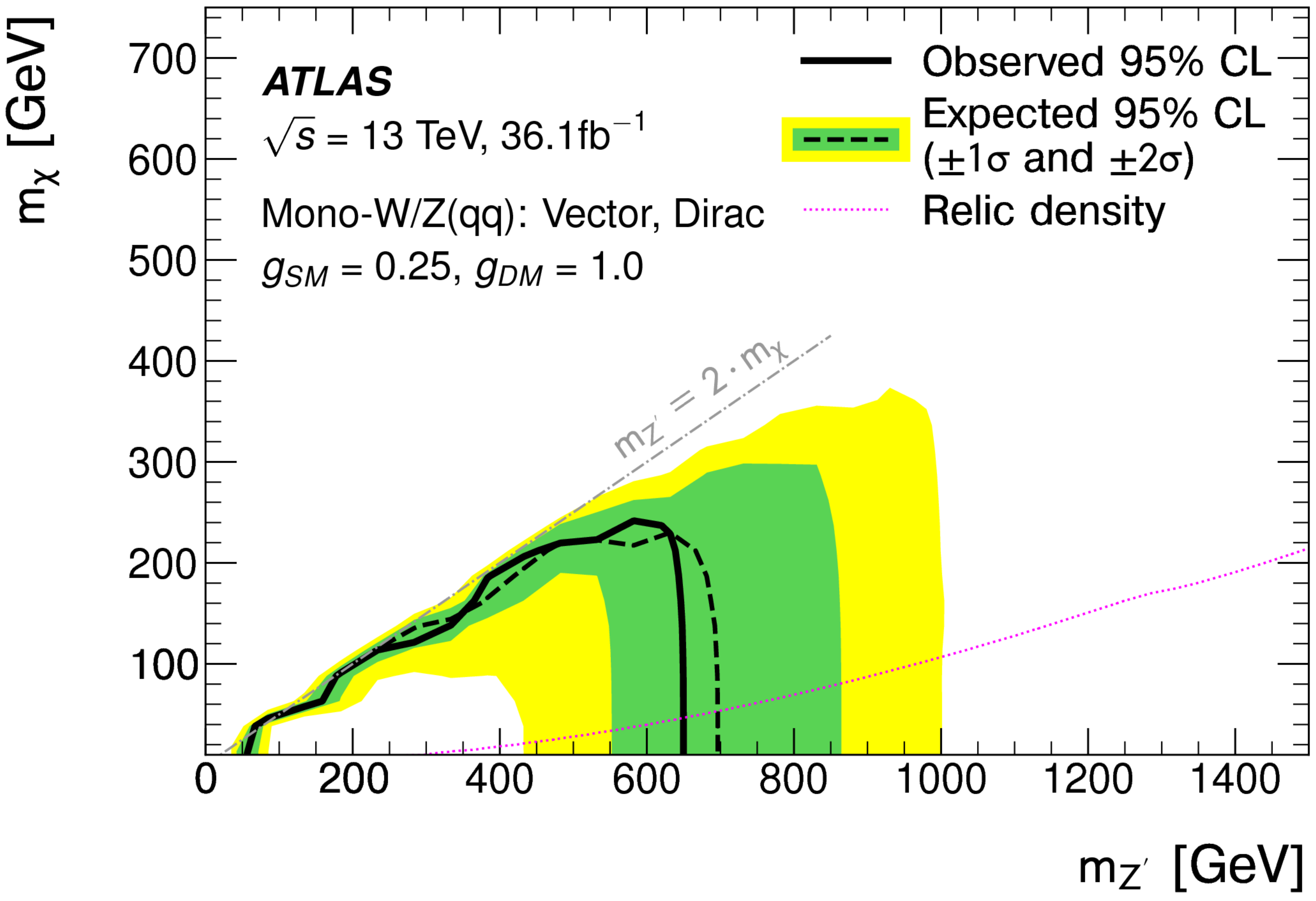
JHEP 10 (2018) 180 [9]   ATLAS-CONF-2018-054 [10]

- analysis considers $V \to q\bar{q}$ decays (jets)
- **experimental signature**: large E_T^{miss} + di-jet resonance
  (if W/Z highly boosted: $q\bar{q} \to$ single large-R jet)
- consider both cases: 1 large-R jet / 2 small-R jets



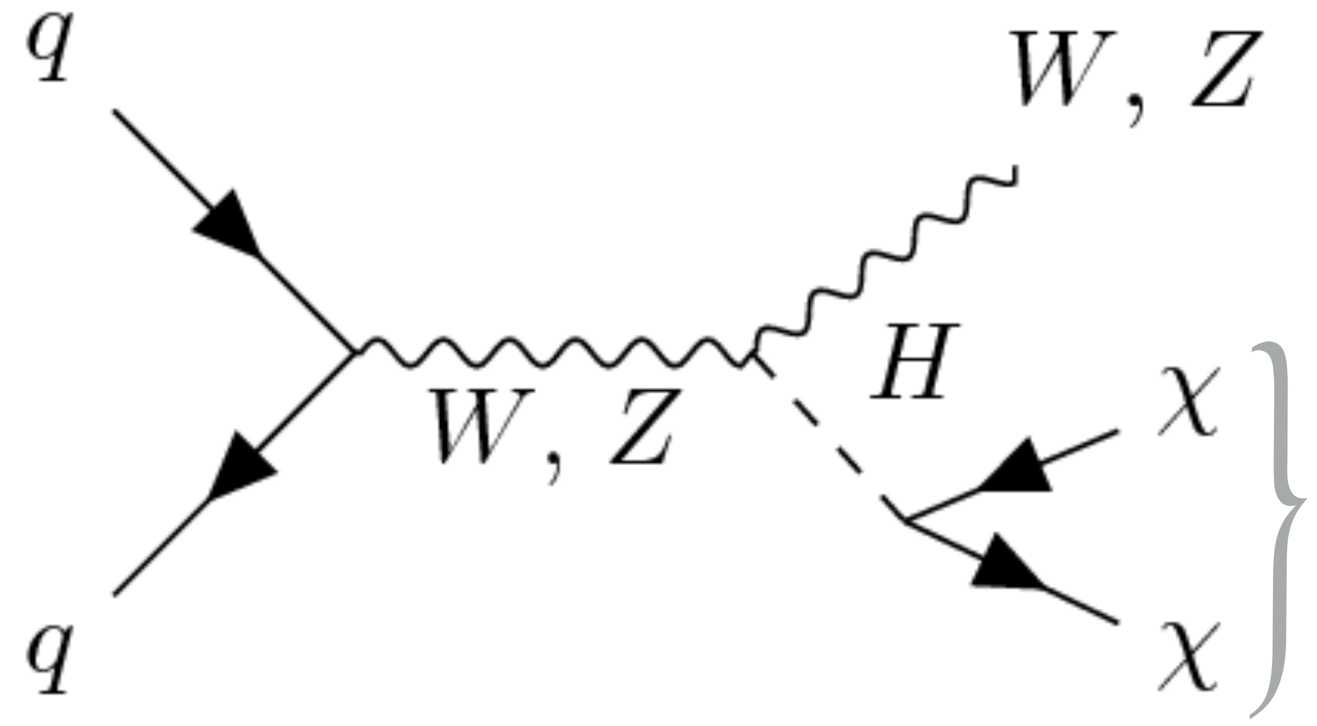
$$W \to q\bar{q}, Z \to q\bar{q}$$

$$E_T^{miss}$$



Above: *interpretation for the vector mediator model.*

- search employing **full Run-2 dataset** in preparation for mono-jets (most sensitive), including mono-V($q\bar{q}$) final state



$$E_T^{miss}$$

- alternative interpretation in context of **invisible Higgs boson decays**

$$BR(H \to \text{invisible}) < 0.83$$ @ 95% C.L.

- Run 1&2 **combination** for such invisible decays just made public! [10]

$$BR(H \to \text{invisible}) < 0.26$$

$$V(q\bar{q})H(\text{inv}) + Z(\ell\ell)H(\text{inv}) + VBF(jj + E_T^{miss})$$

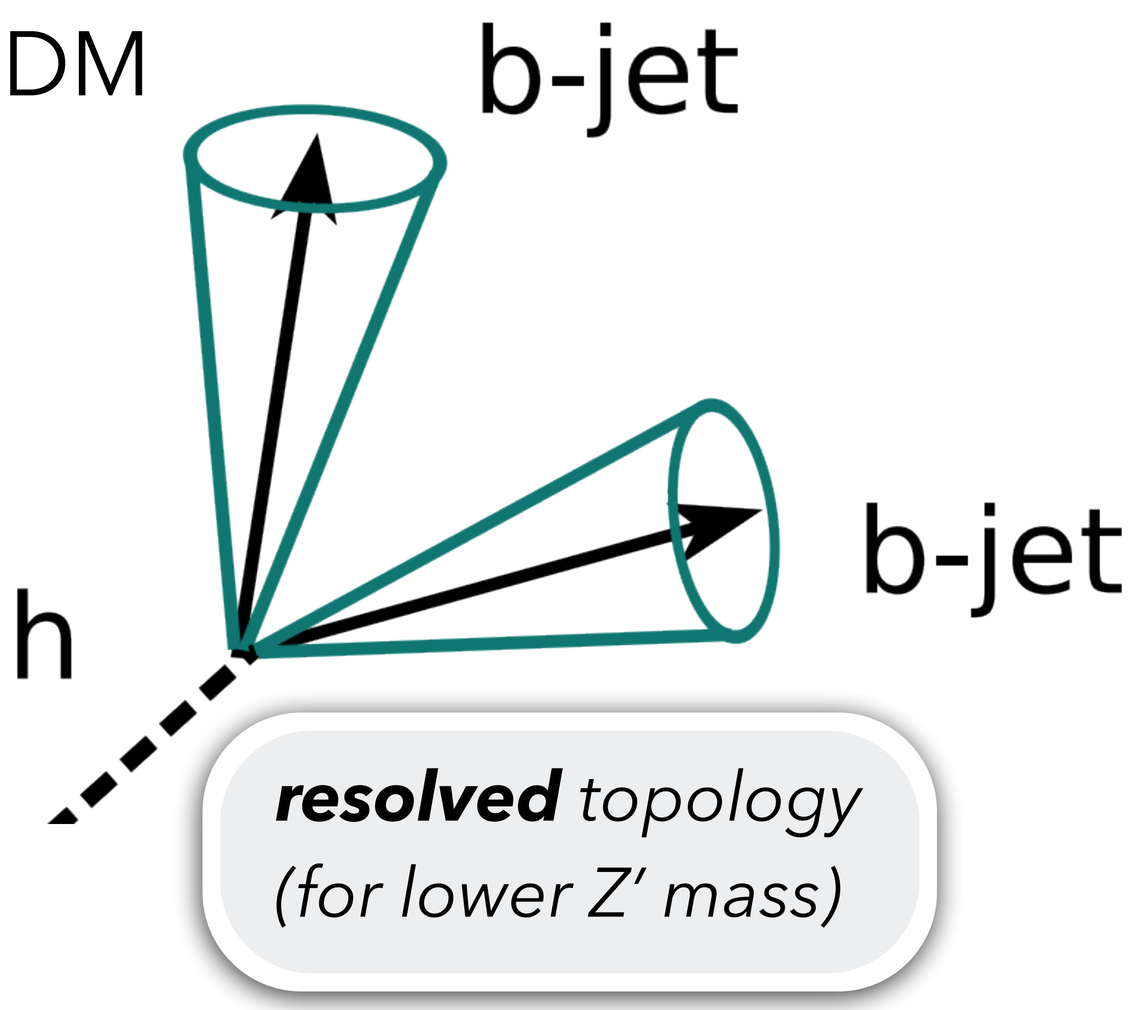
Dark Matter Search: Mono-Higgs ($b\bar{b}$)

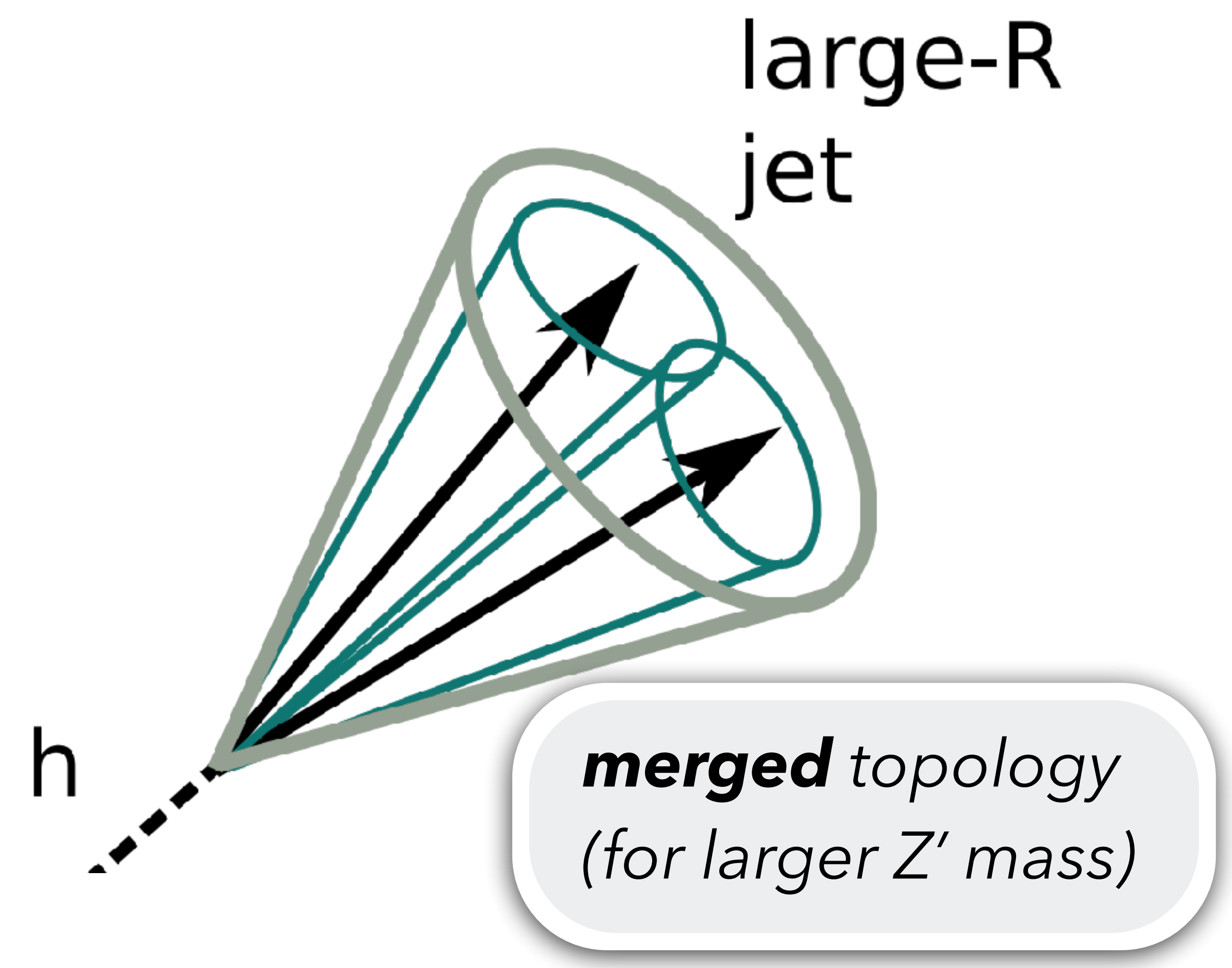
ATLAS-CONF-2018-039 [11]

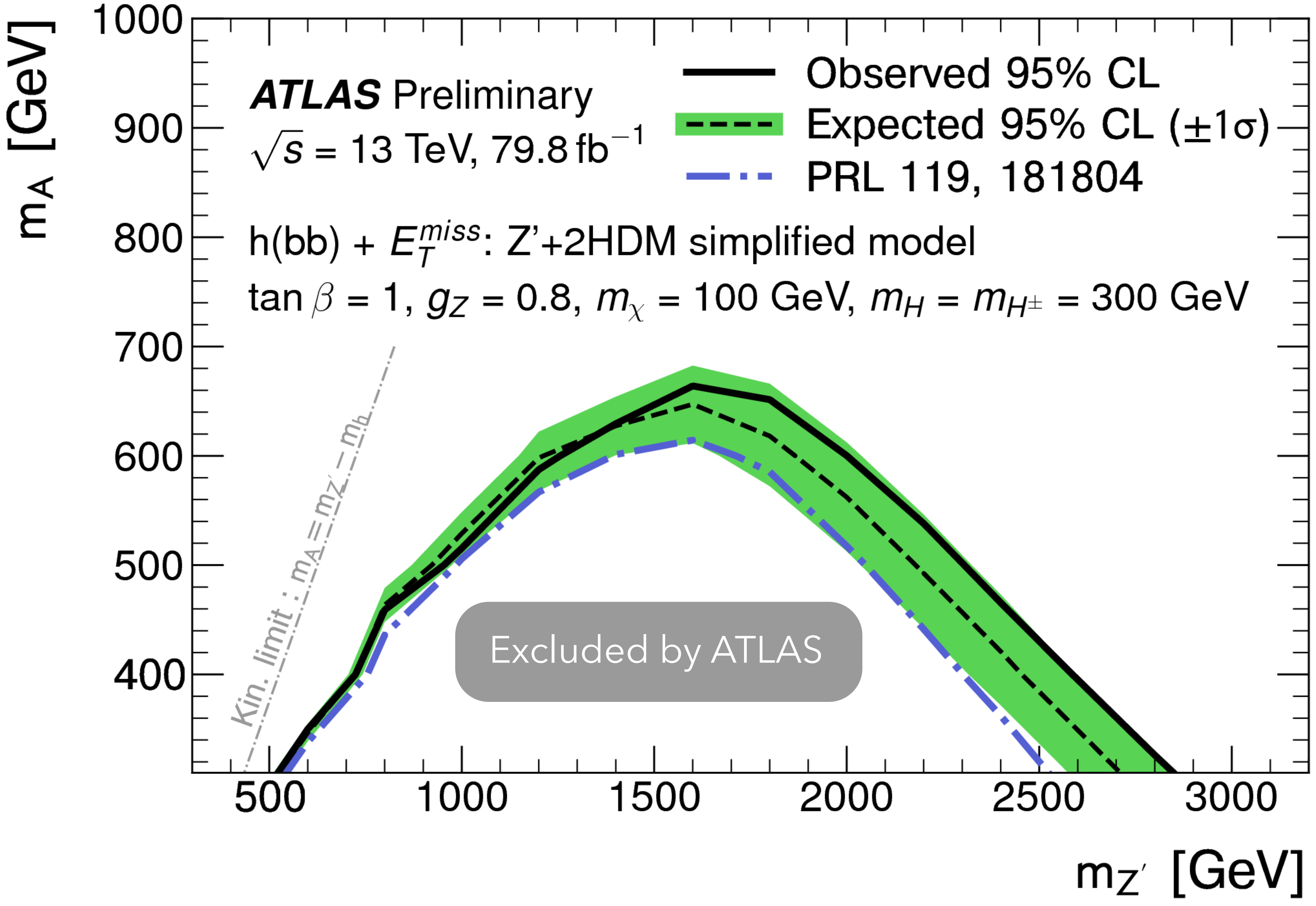
- direct probe of possible Higgs boson interactions with DM

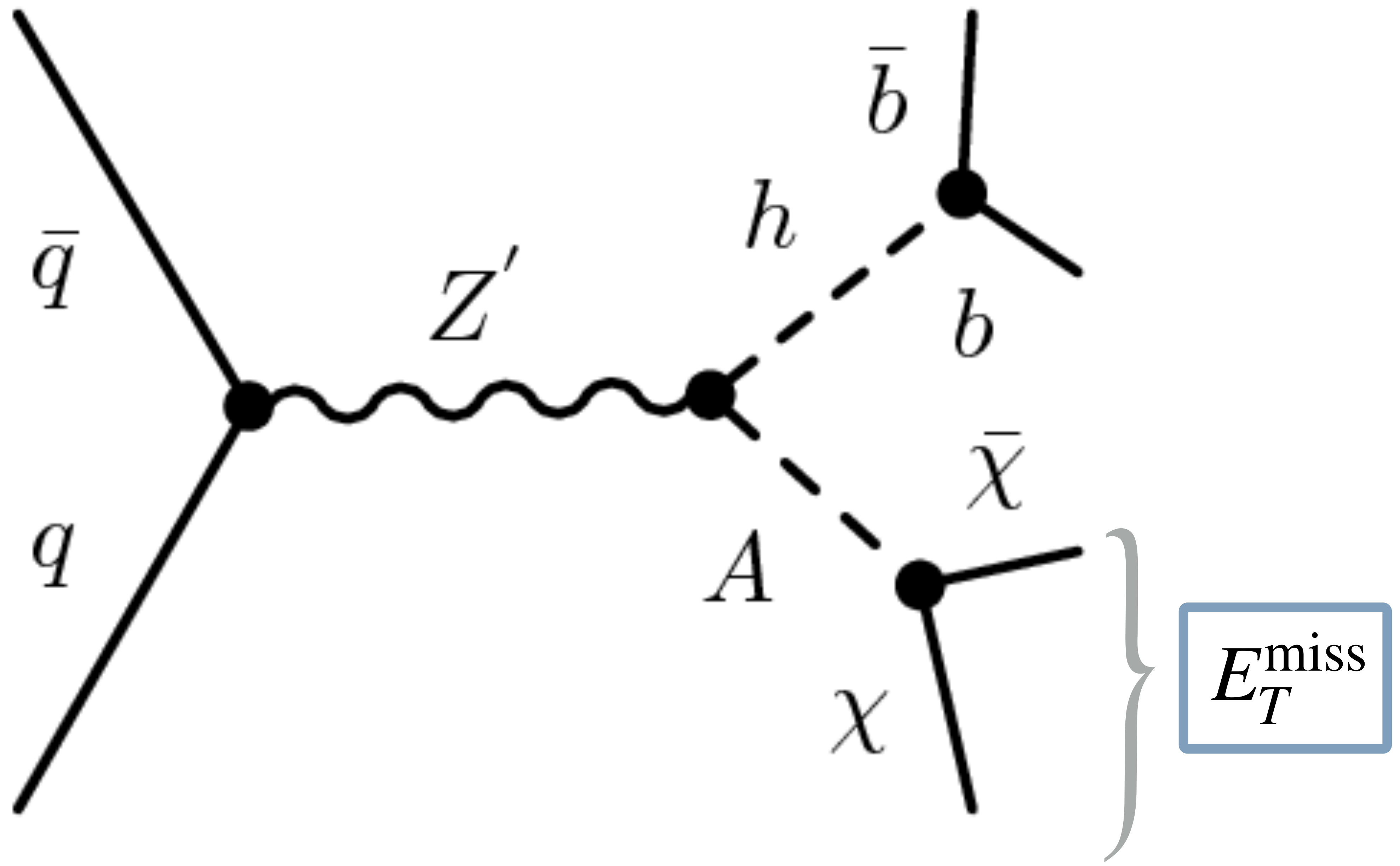
Consider both **resolved** and **merged** topology.
(similarly to mono-W/Z on previous slide)

Discriminating observable:
di-jet or large-R jet invariant mass or E_T^{miss}





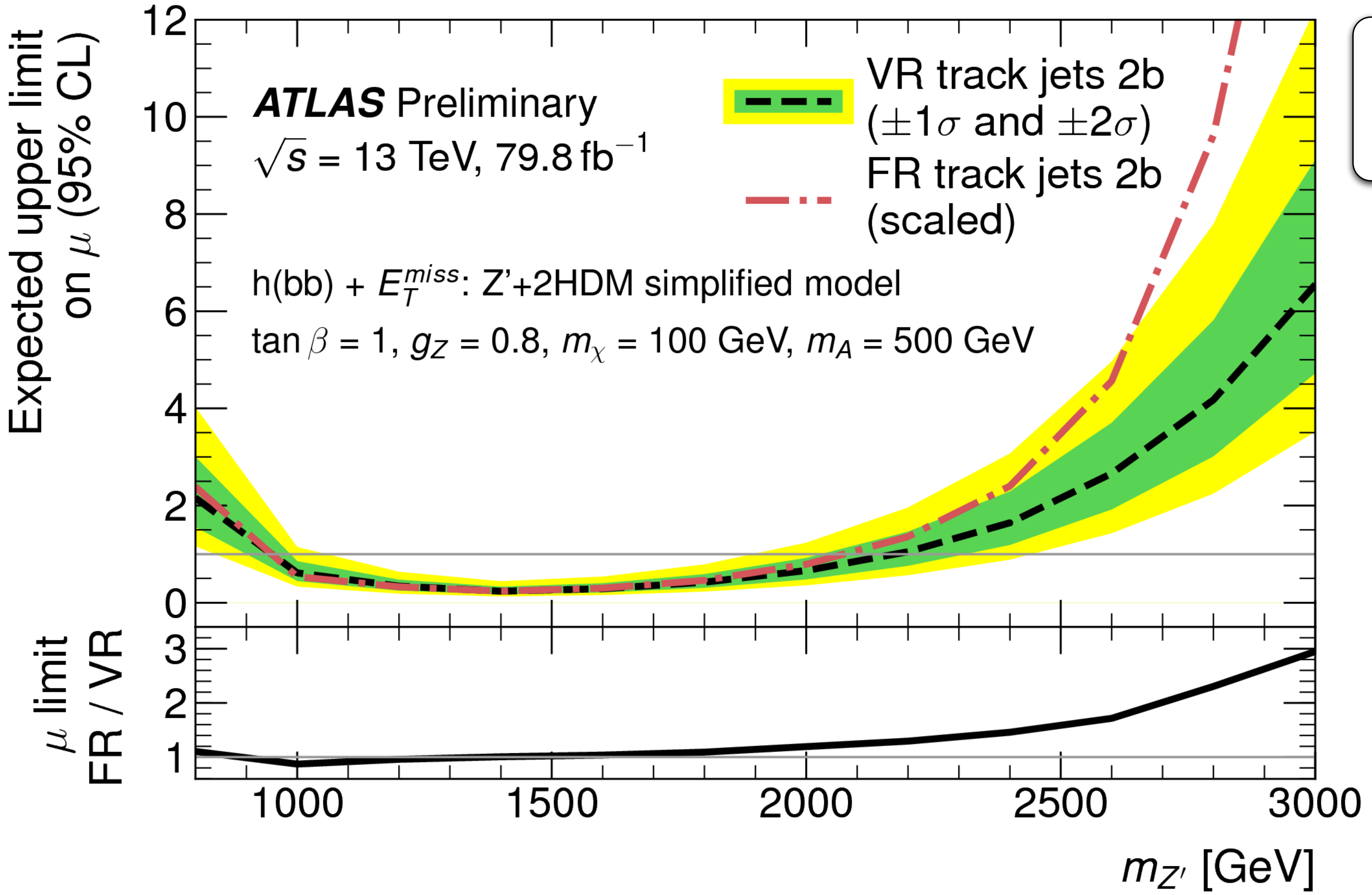




Dark Matter Search: Mono-Higgs ($b\bar{b}$)

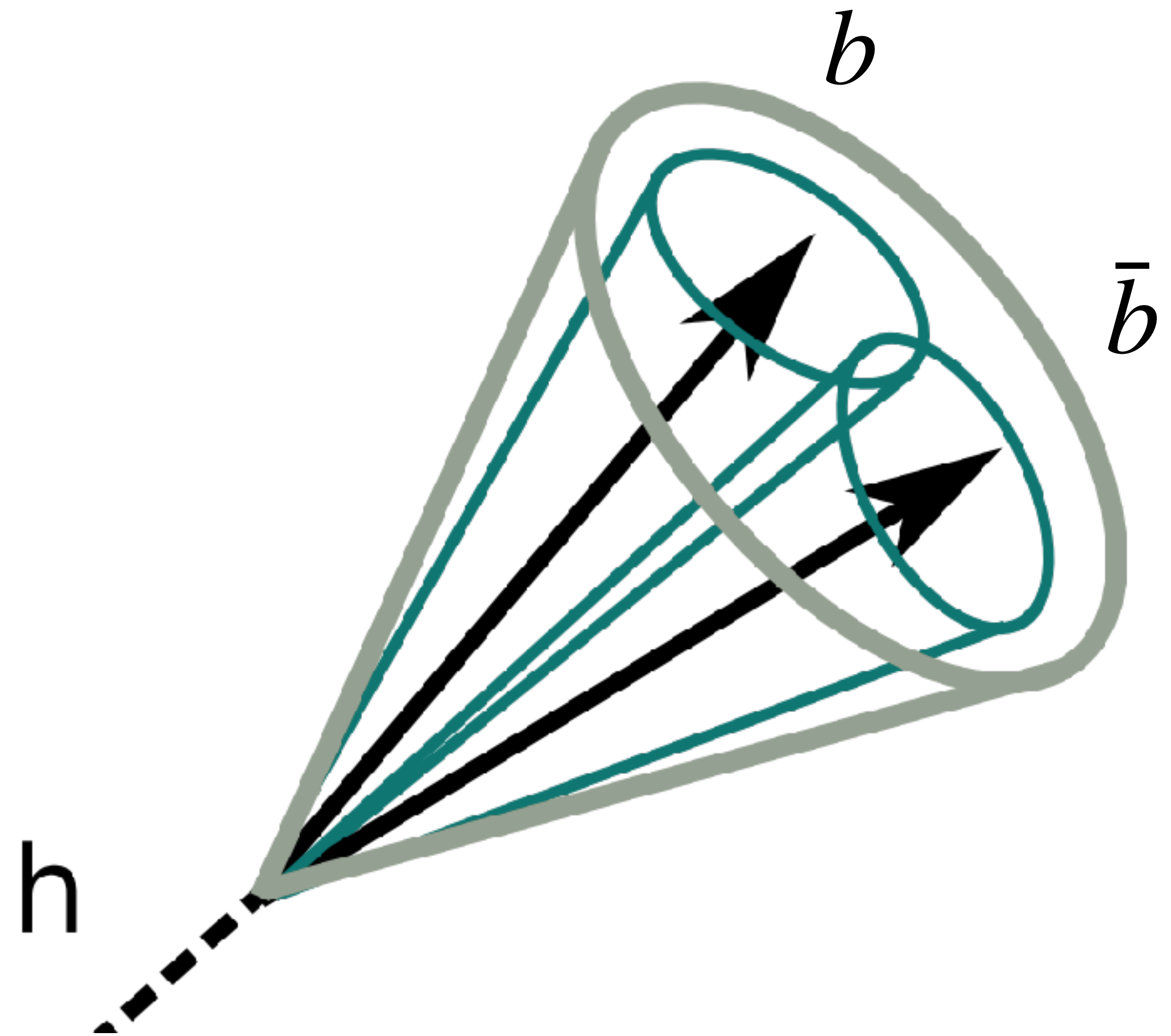
ATLAS-CONF-2018-039 [11]

- significant improvements on the analysis side compared with last year!
  e.g. use of **VR** jets (p_T^H dependent) **greatly increases efficiency** to identify $H \to b\bar{b}$ events
- increase in efficiency consequently allows much stronger limits to be placed (*e.g.* on $m_{Z'}$)
- improvements on the analysis side are driving the enhanced limits (rather than just increase in statistics)



FR: *fixed radius*
VR: *variable radius*

For <u>high-mass</u> mediators, e.g. Z′
(i.e. boosted Higgs bosons)

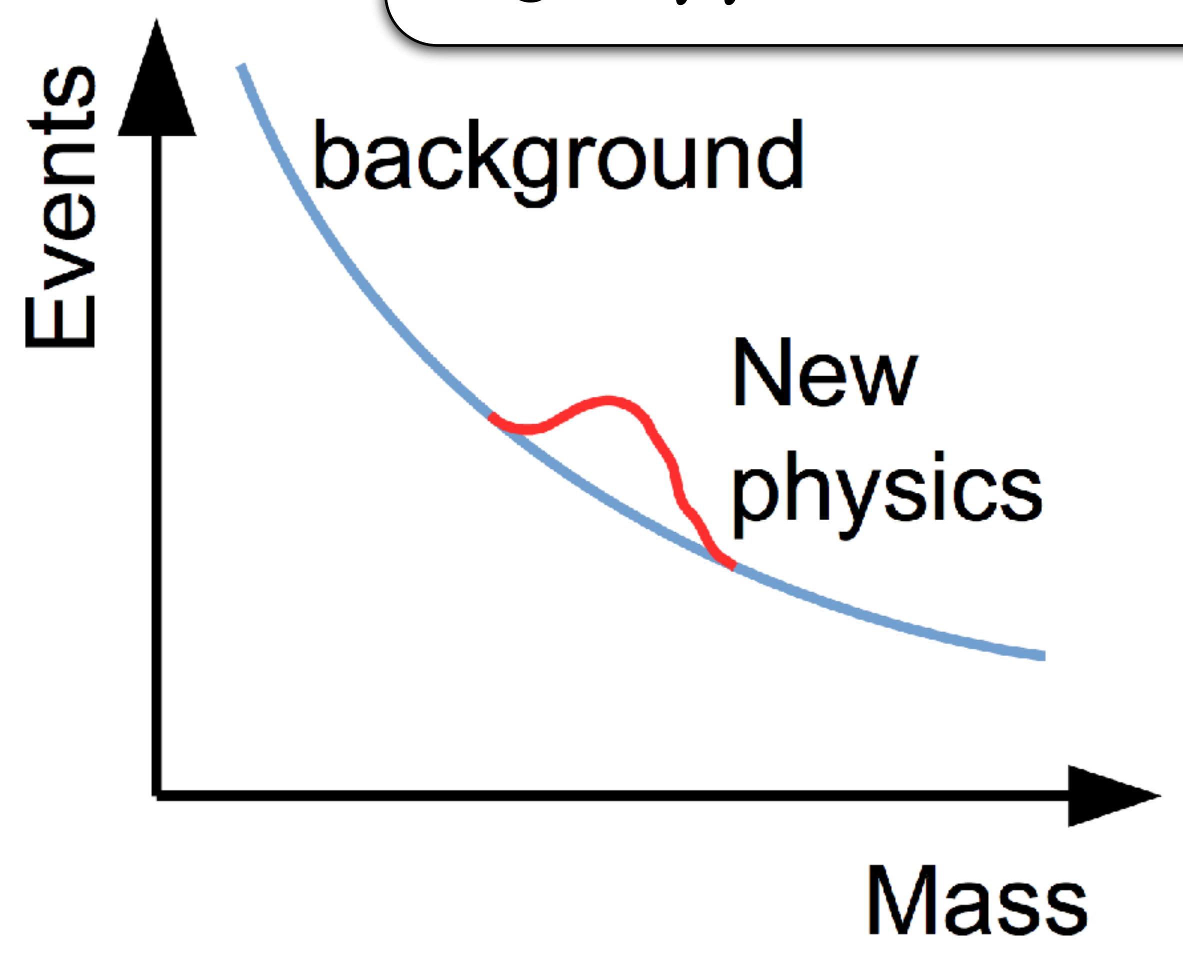


- result employing **full Run-2 dataset** in preparation

Search for New Heavy Resonances

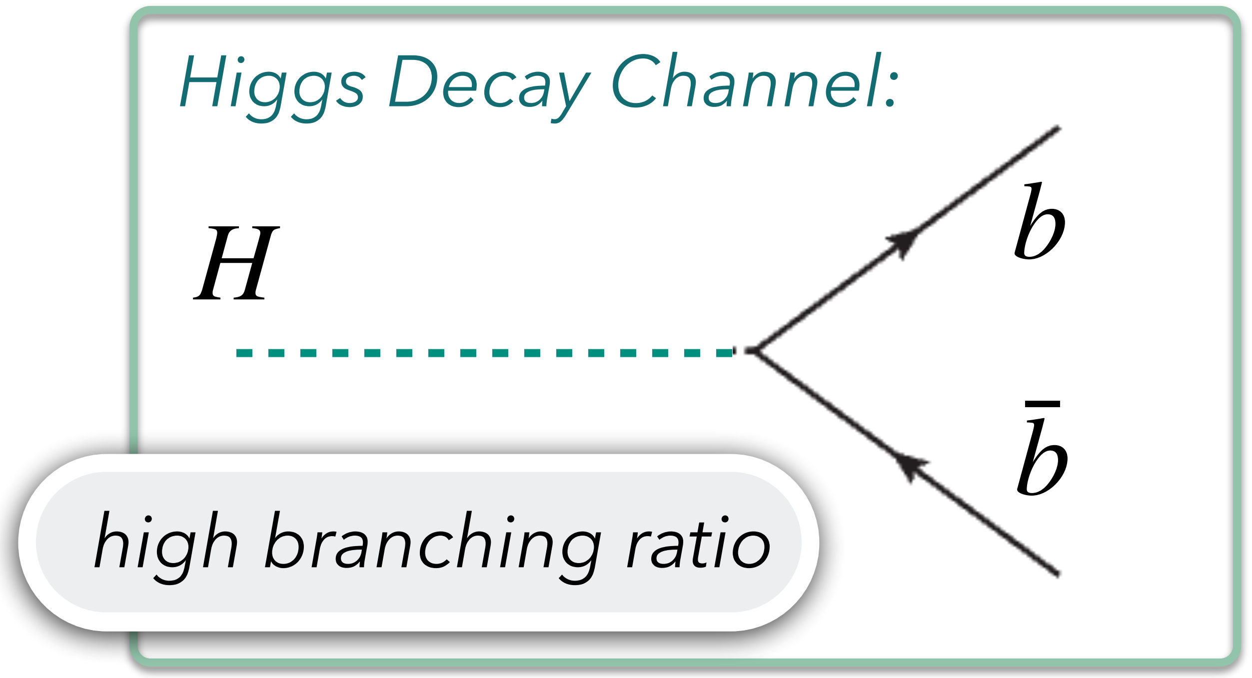
- general category of searches for **new heavy particles** based on their decays to known SM bosons:

e.g. $\gamma\gamma$, WW, ZZ, WZ, HH, WH, ZH

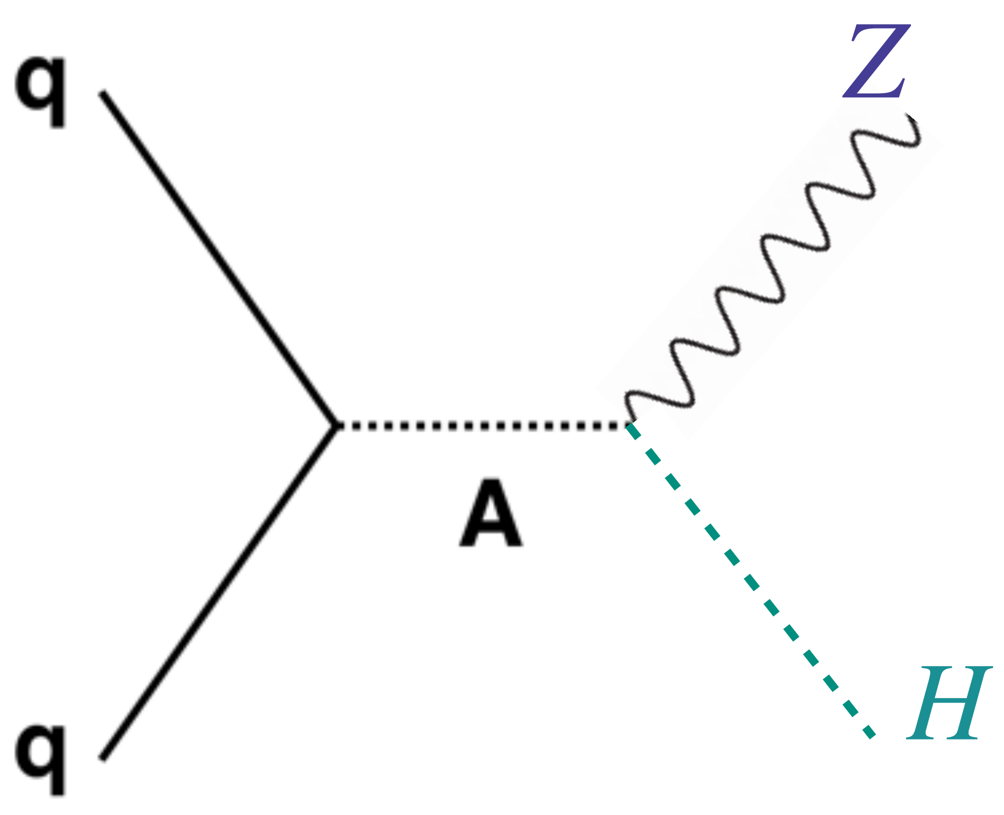


- such searches have only a **small model dependence**
- presence of new particles would cause a **bump** in **invariant di-boson mass spectrum**

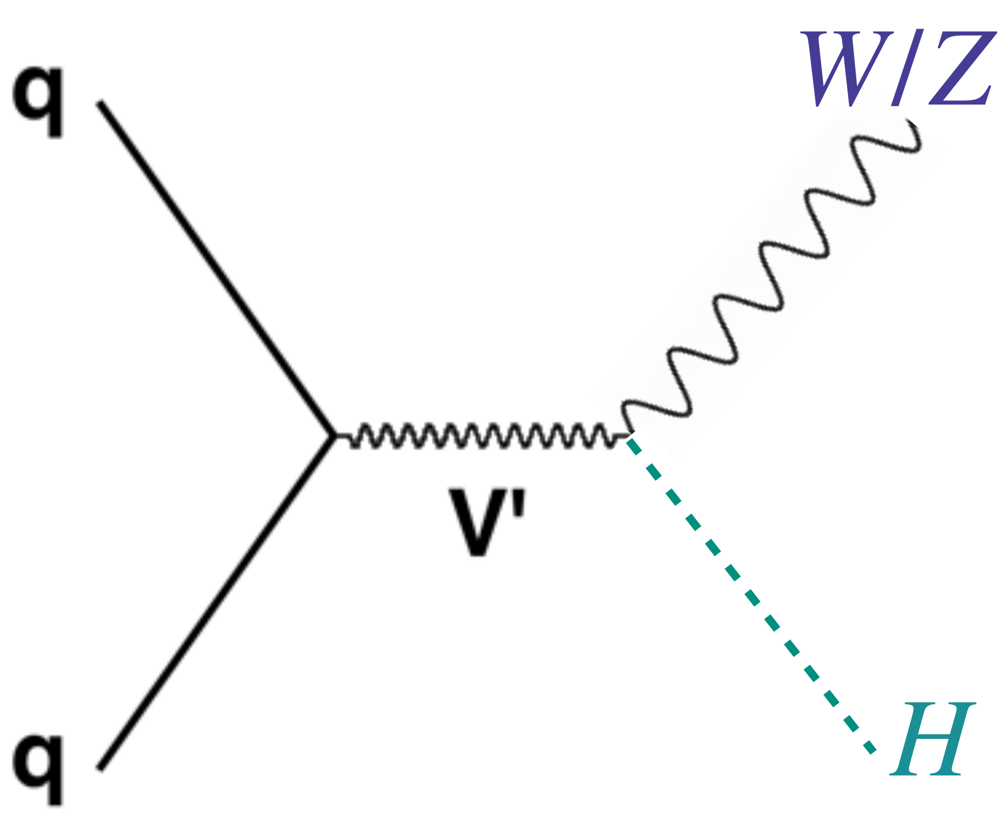
(In)famous example: di-photon bump near $m_{\gamma\gamma} \approx 750$ GeV.
(has now since disappeared with more data)



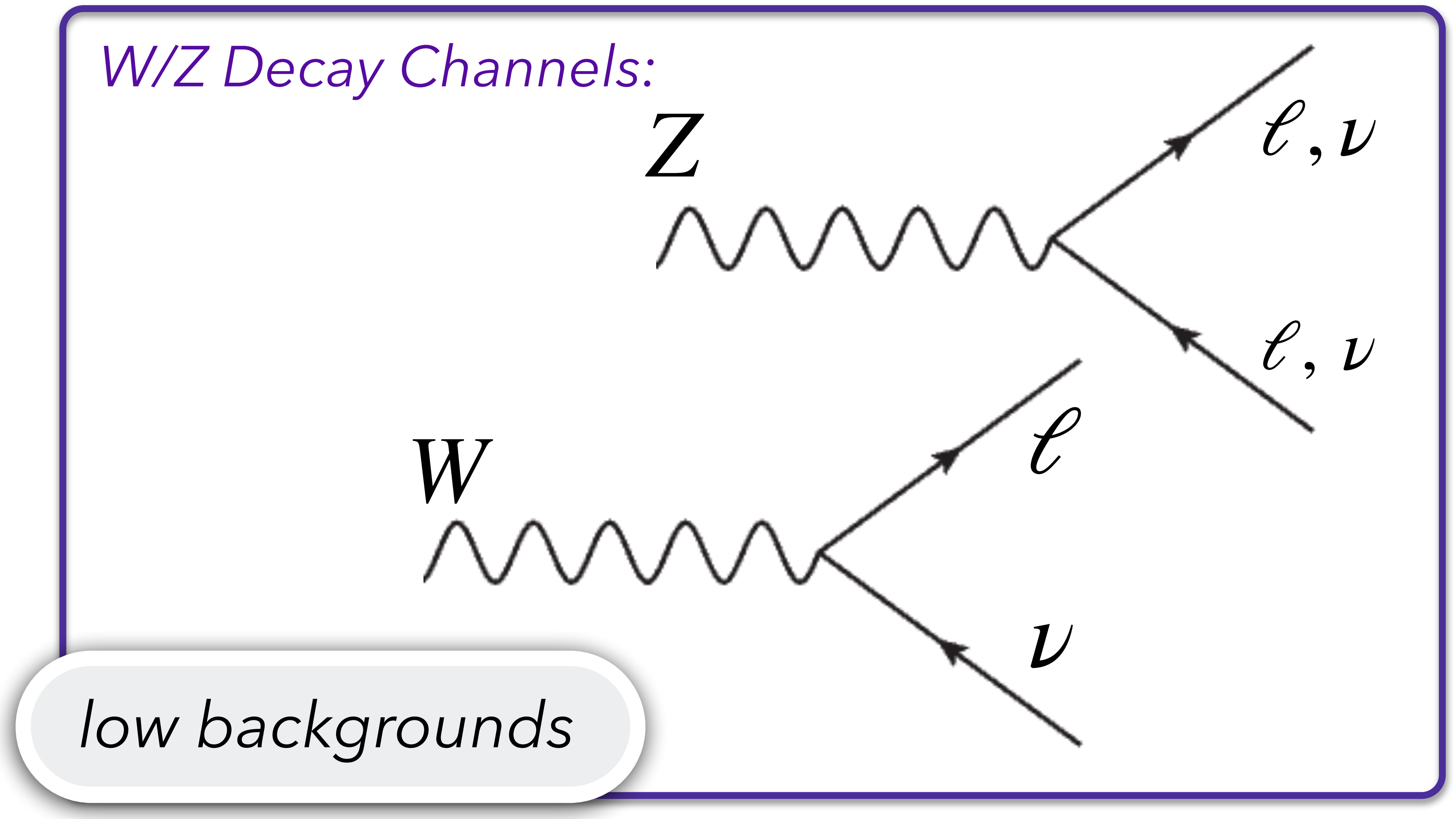
- WH and ZH searches led by **MPP**:



*Search for **Spin-0 particle** in 2-Higgs-Doublet Model (2HDM)*



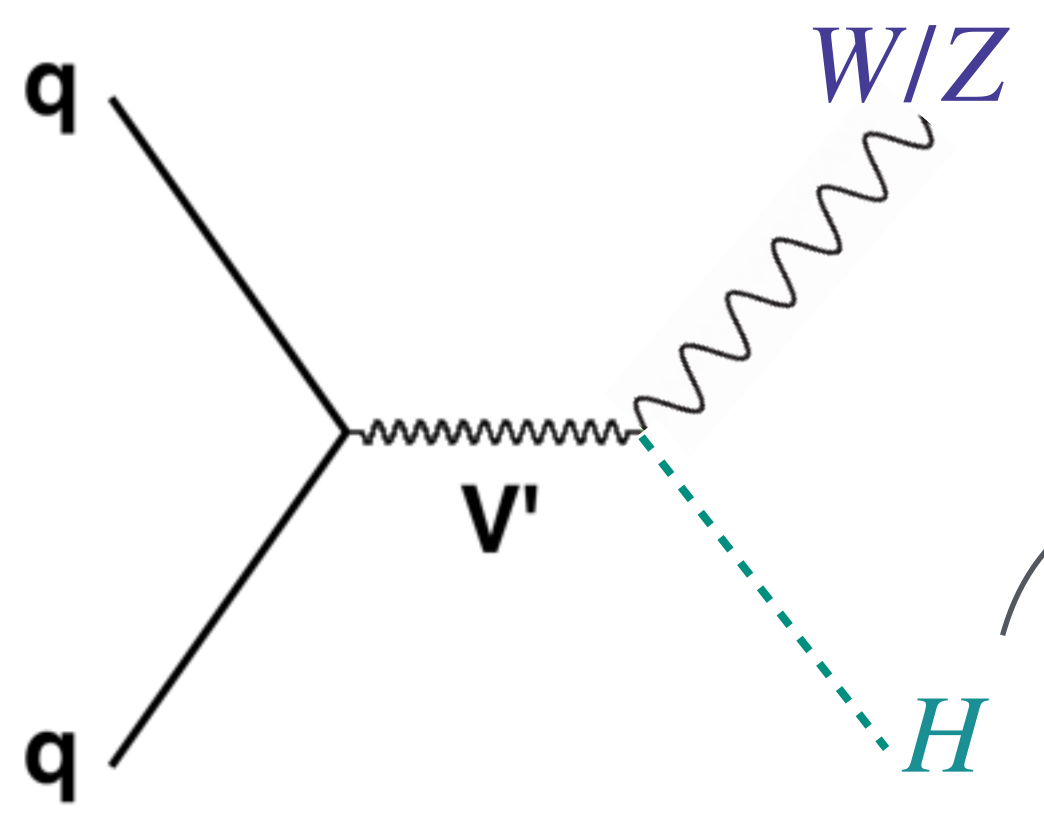
*Search for **Spin-1 particle** in Heavy-Vector-Triplet Model (HVT), **V′** = W′+, W′-, Z′*



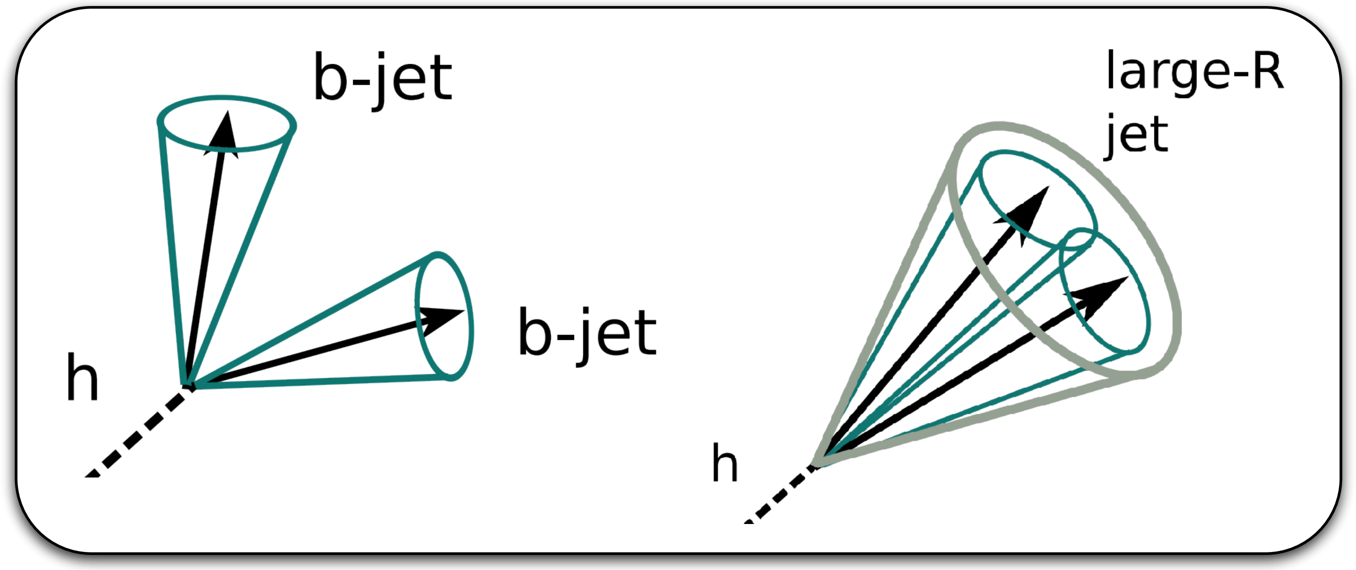
Search for VH Resonances (V = W,Z)

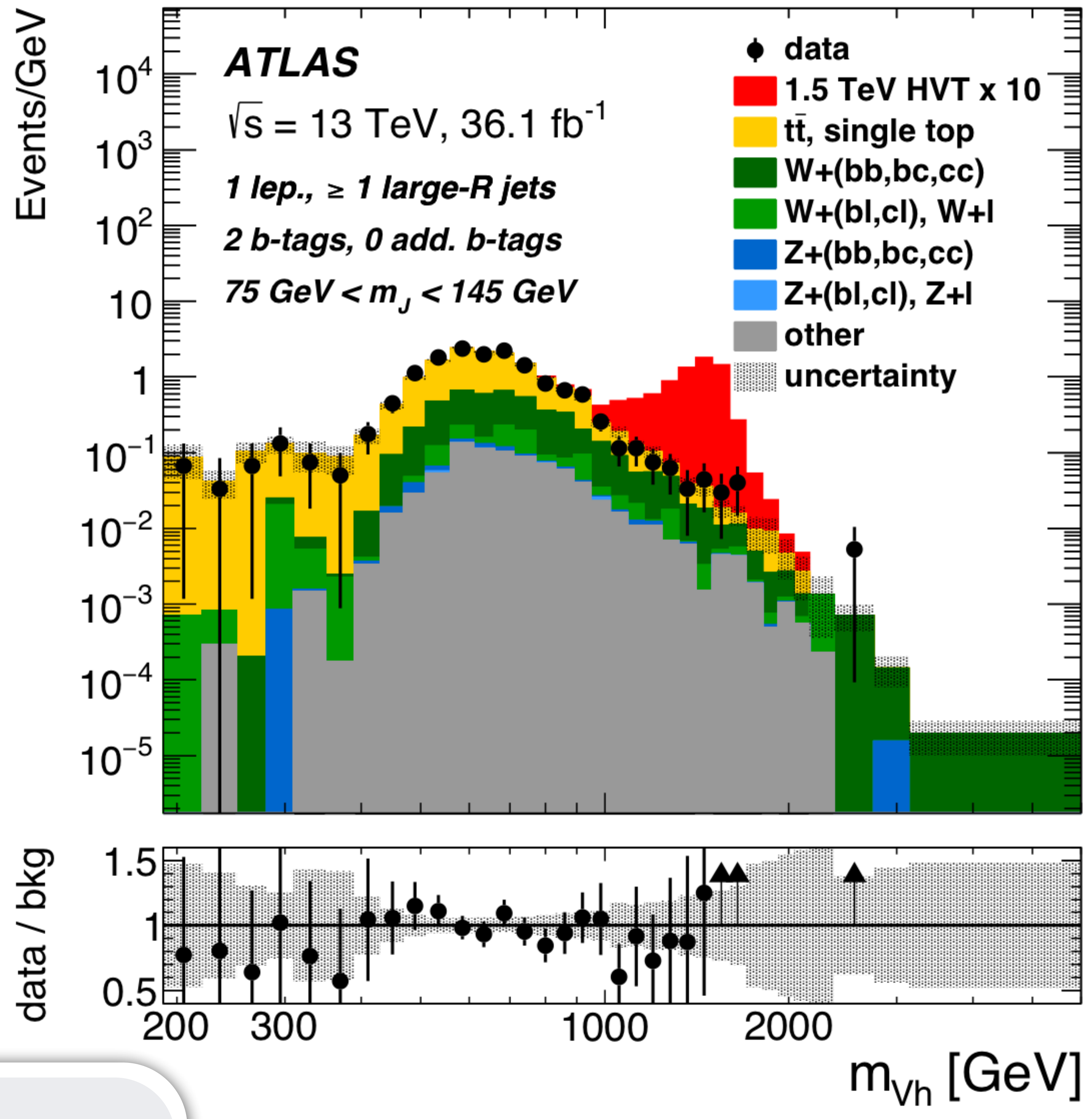
JHEP 03 (2018) 174 [12]

- **Run 2 data** (2015/2016) $\sqrt{s}$ = @ 13 TeV: exclude HVT resonances with masses up to 3 TeV



(as before)



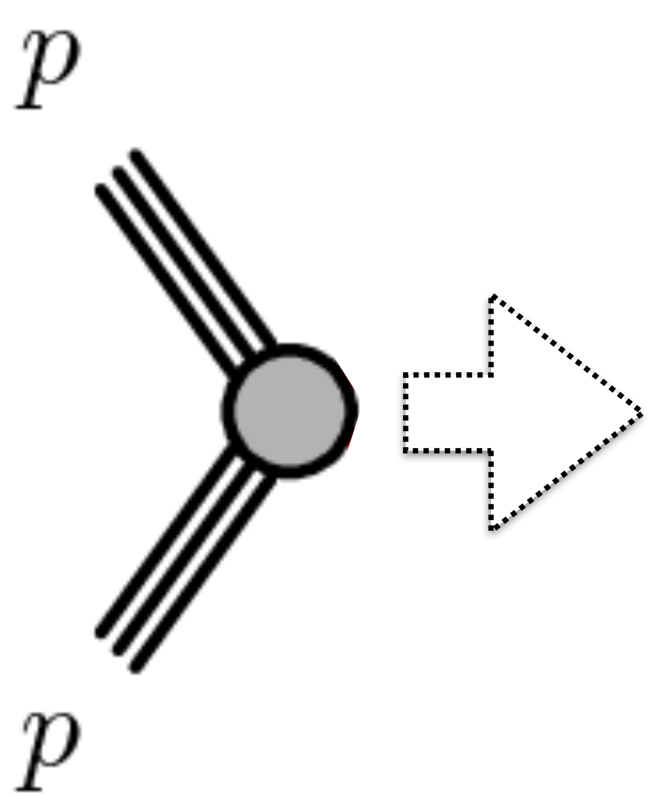


- efficient identification of **b-jets** (notably for $H \to b\bar{b}$) crucial for enhancing the signal sensitivity
- challenges addressed:
  - **calibration** of b-jet taggers with data
  - **b-tagging** optimization (machine learning to identify tracks from B-decays)
  - optimization of **boosted Higgs jet** identification *(paper in preparation)*
- major improvements expected from the Higgs jet tagging *(e.g. mass window, jet substructure, b-tagging)*
- optimized analysis employing **full Run-2 dataset** in preparation

Supersymmetry (SUSY): 4ℓ Searches

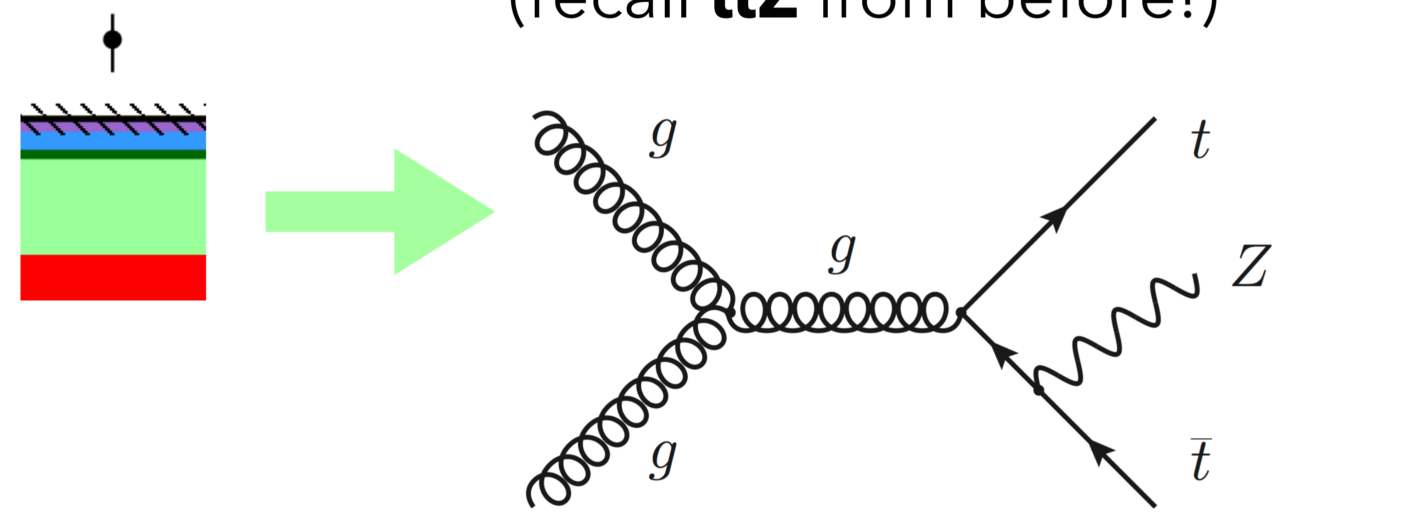
Phys. Rev. D 98 (2018) 032009 [13]

- general category of searches with ≥ 4-lepton signatures (keep search as model-independent as possible)
- consider both **R-parity violating (RPV)** and **R-parity conserving (RPC)** signals (choice governs allowed SUSY particle decays)
- search effort driven by **MPP** since Run 1



≥ ***4ℓ*** *(e, μ, τ)* + ***X***

(recall **tt̄Z** from before!)



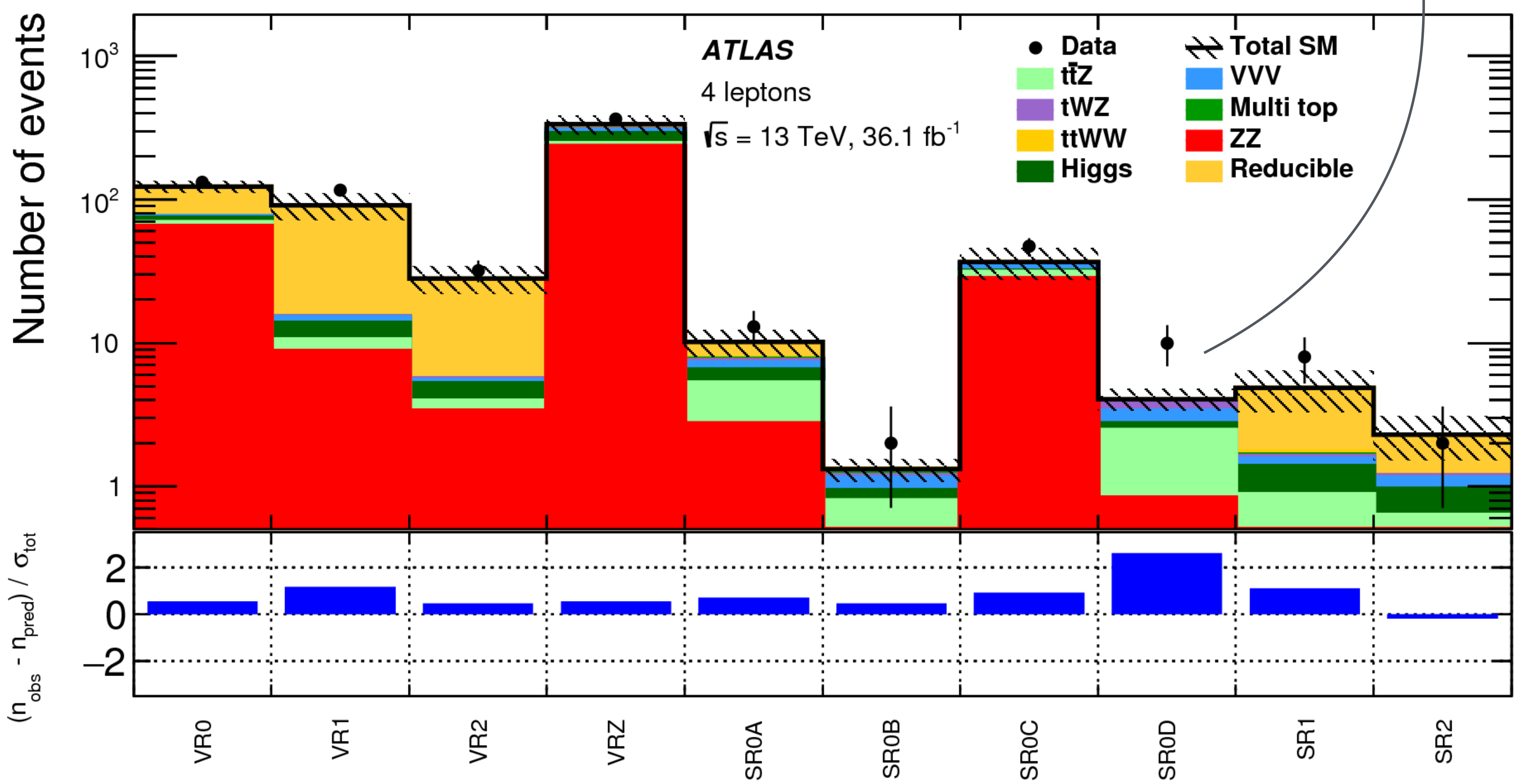
R-parity:

$$(-1)^{3(B-L)+2S}$$

S = spin, B = baryon number, L = lepton number

- consider cases with up to 2 hadronically decaying τ leptons
- searches performed in a variety of signal regions (**SR**)
- some **SR**'s apply Z requirement(s), in other **SR**'s apply veto(s)

*Observe **2.3σ** for SR with 4ℓ and large E_T^{miss}*



Supersymmetry (SUSY): R-Parity Violating Searches

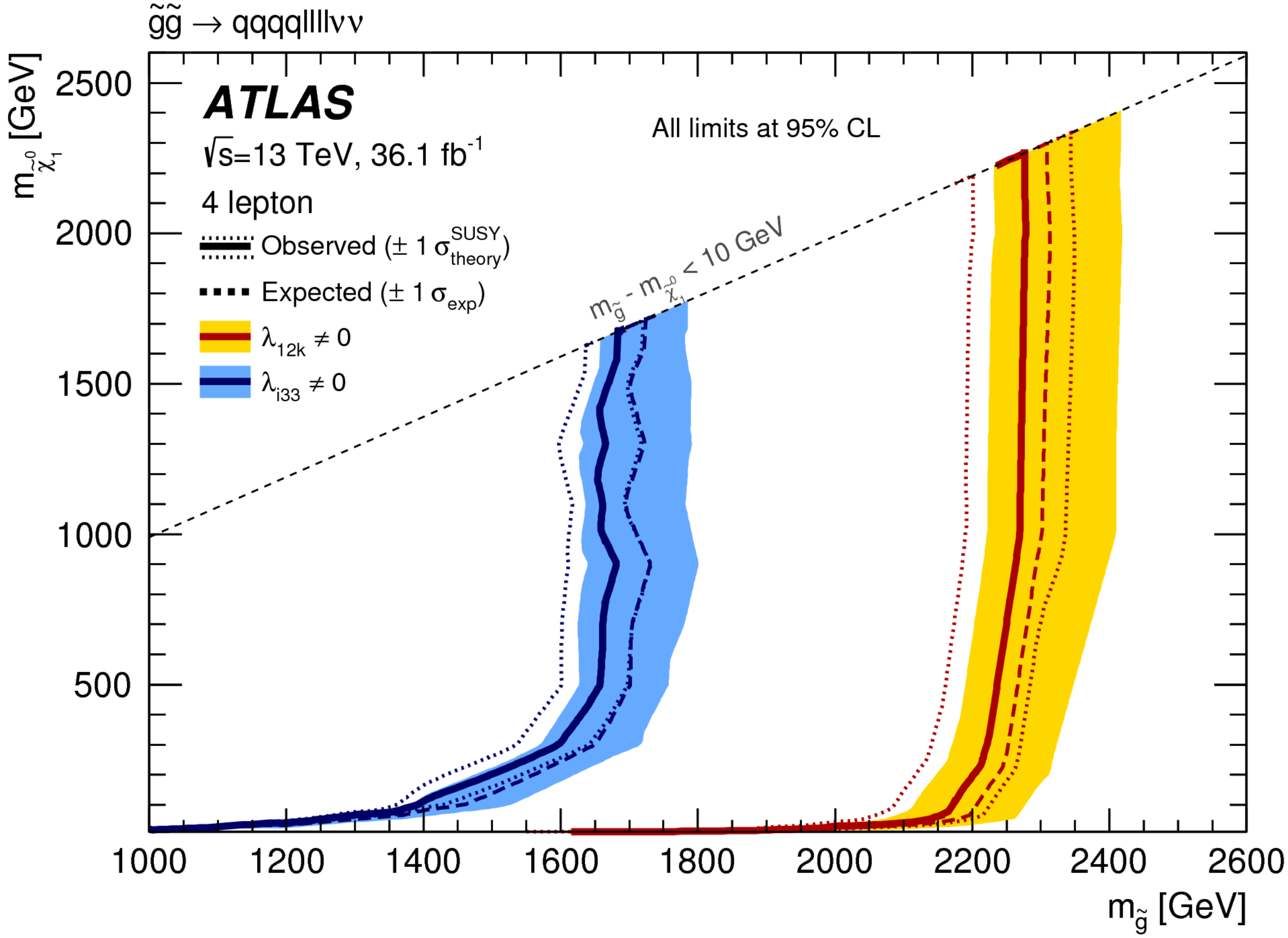
Phys. Rev. D 98 (2018) 032009 [13]

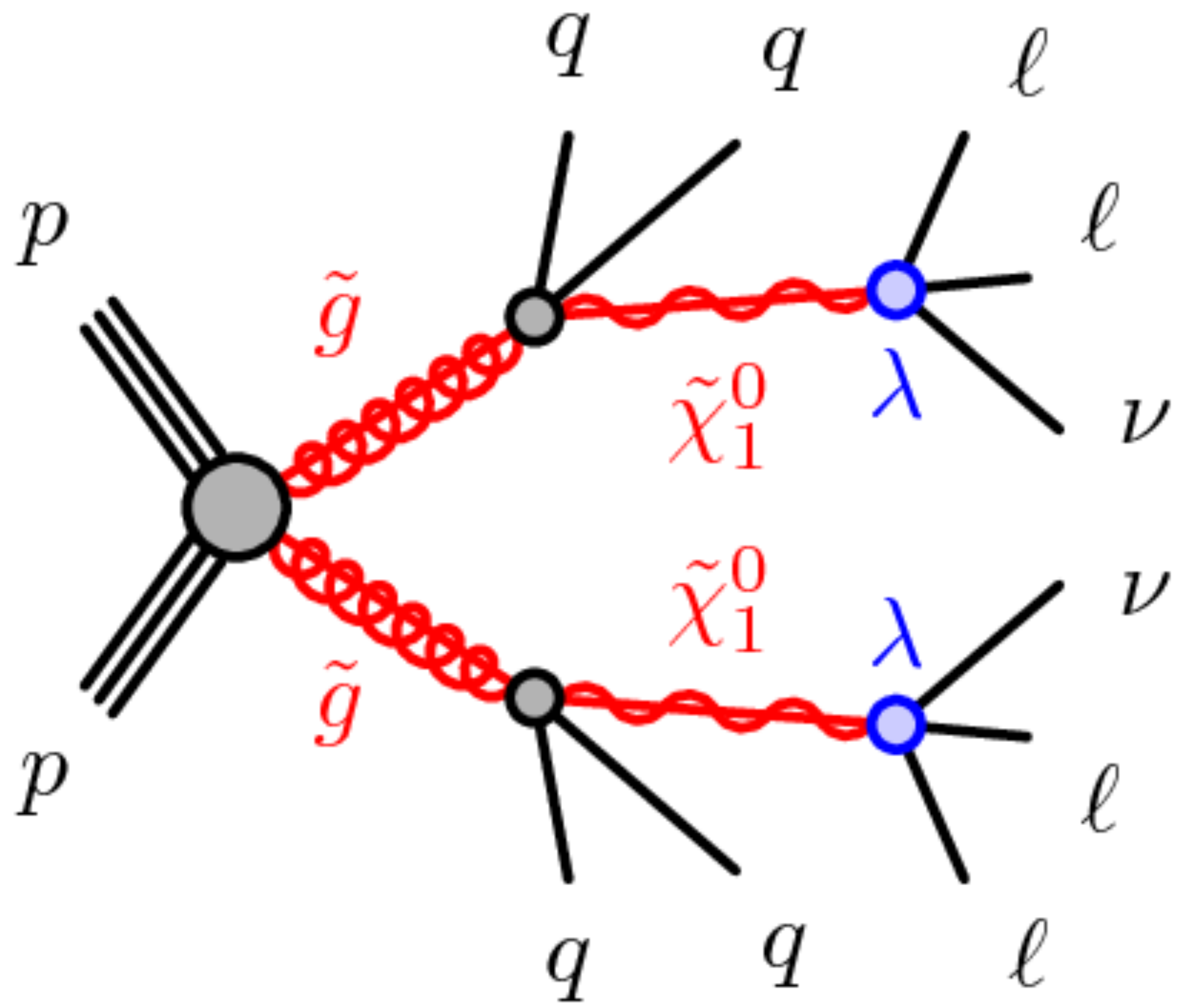
- *e.g.* can consider **lepton-number-violating term** in the superpotential of the modified Lagrangian:

$$W_{LL\bar{E}} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k$$

λ_{ijk} *term depends on lepton flavour involved (e,μ,τ)*

Scenario	$\tilde{\chi}^0_1$ branching ratios		
$LL\bar{E}12k$	$e^+e^-\nu$ (1/4)	$e^\pm\mu^\mp\nu$ (1/2)	$\mu^+\mu^-\nu$ (1/4)
$LL\bar{E}i33$	$e^\pm\tau^\mp\nu$ (1/4)	$\tau^+\tau^-\nu$ (1/2)	$\mu^\pm\tau^\mp\nu$ (1/4)



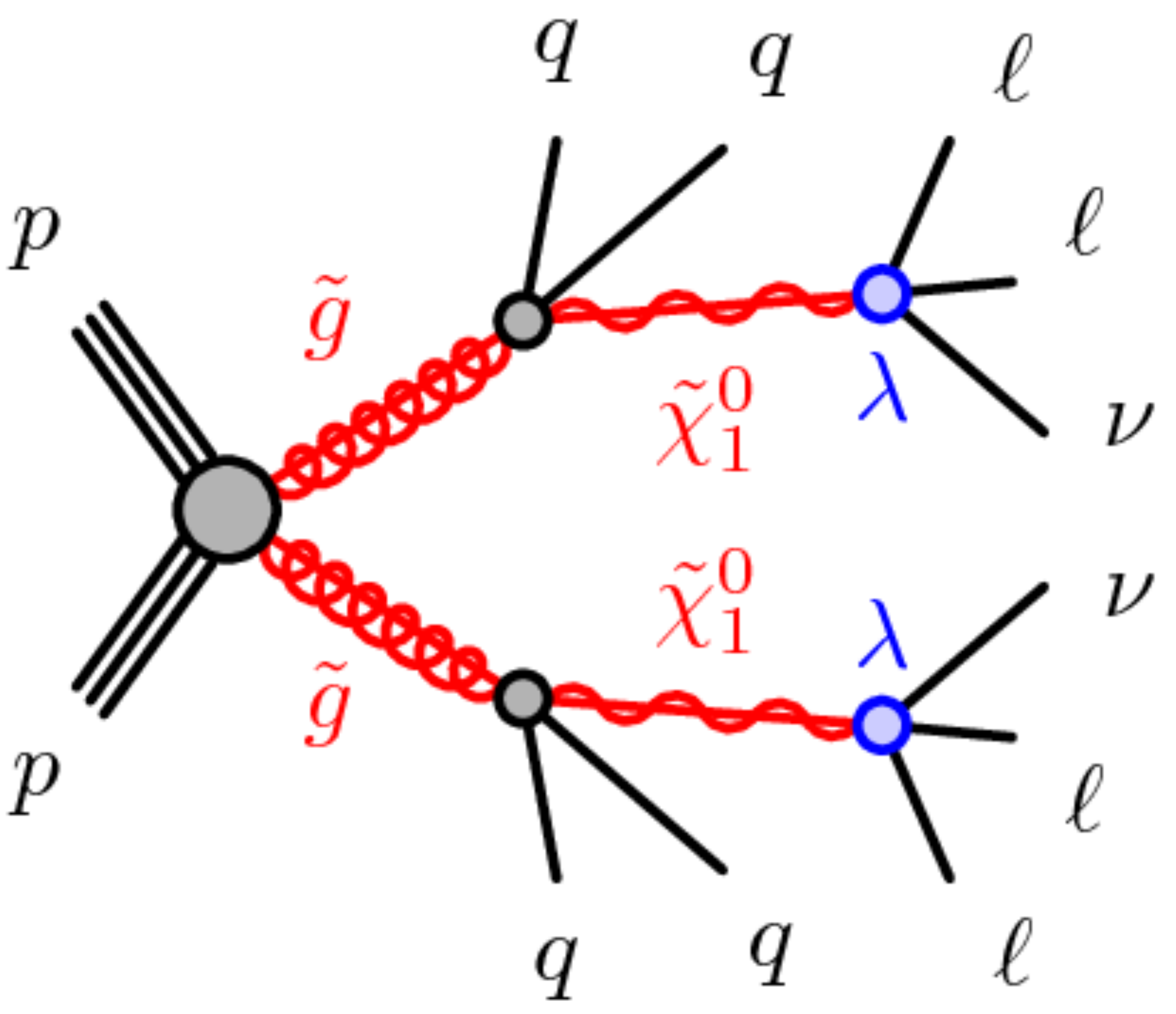


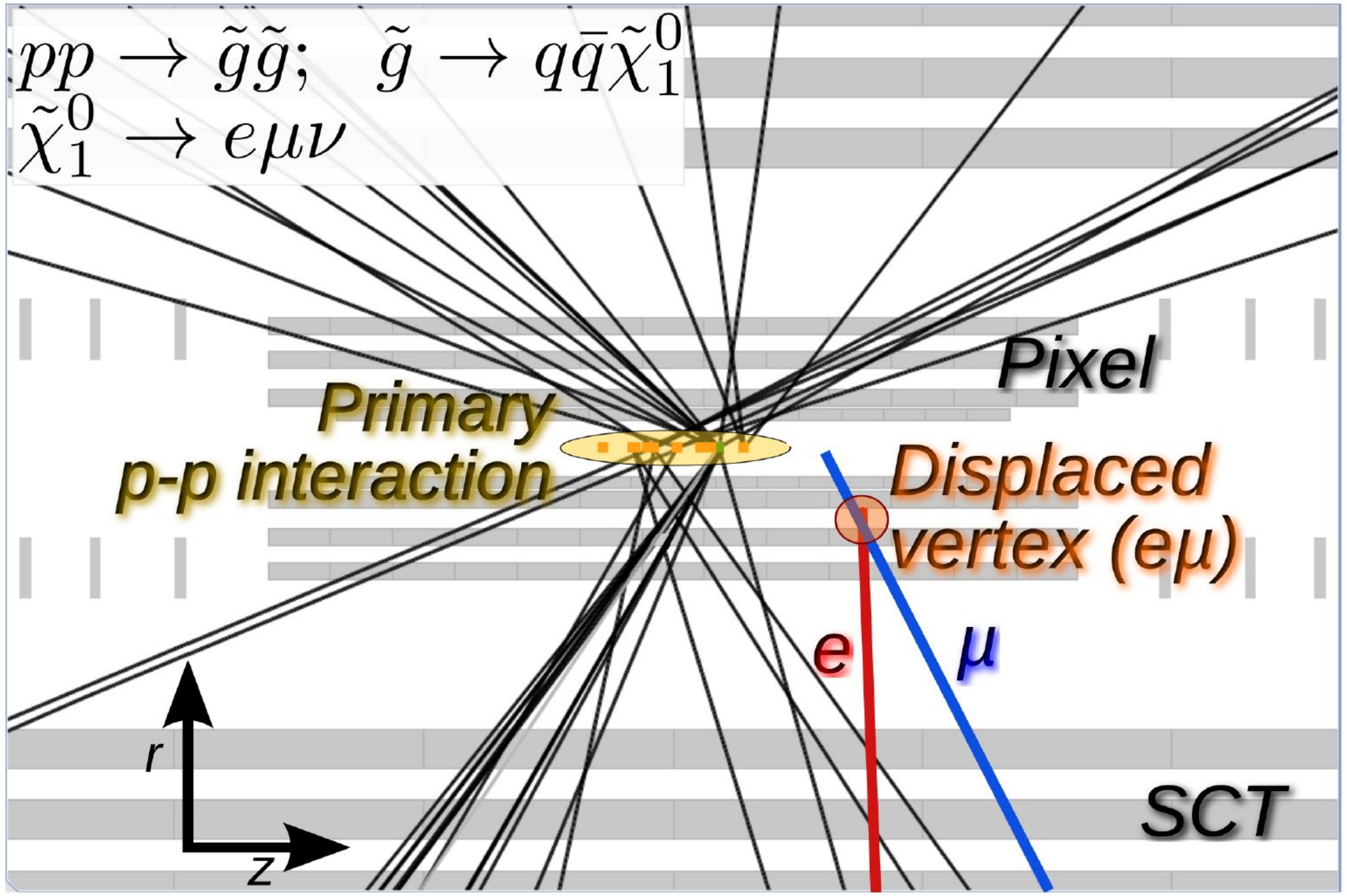
- strongest limits able to be placed on **Gluino** mass (**n**ext-to-**l**ightest **S**USY **p**article)
- similar diagrams for **Wino** (NLSP) or **Slepton** (NLSP)
- in general scenarios with $\lambda_{12k} \neq 0$ (e,μ) or $\lambda_{i33} \neq 0$ (τ) excluded up to 1-2 TeV (NLSP mass scale)

Supersymmetry (SUSY): R-Parity Violating Searches

(event display reference only) CERN-THESIS-2015-095 [14]

- separate analysis targets **displaced vertices** associated with two charged leptons in the inner detector (*e.g.* ***eμ***)
- search is sensitive to long-lived particles with lifetimes on the order of **ps** to **ns**
- model-independent search
- **interpretation**: supersymmetric model with RPV neutralino ($\tilde{\chi}_0^1$) decay
- search effort driven by **MPP** since Run 1

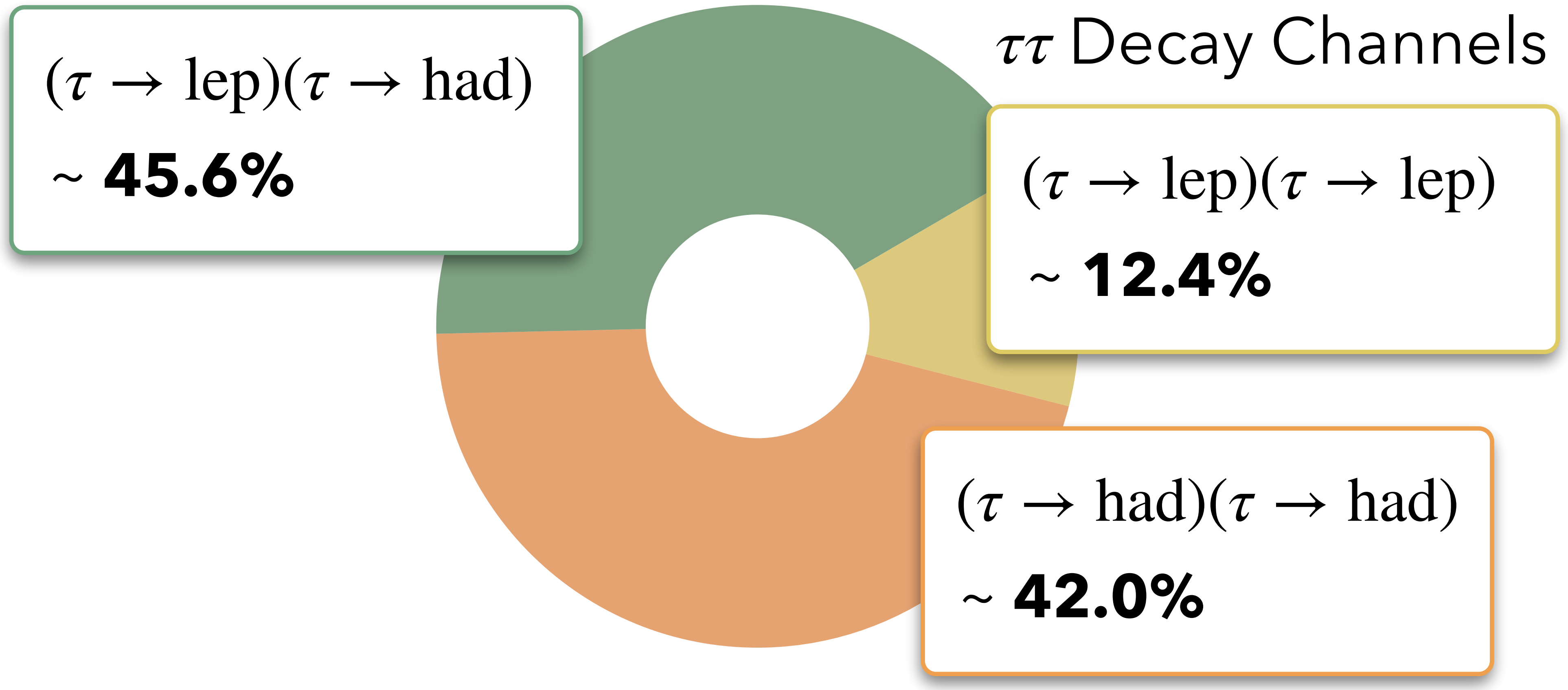




In Preparation: Paper based on 2016 √s = 13 TeV ATLAS data

Supersymmetry (SUSY): Direct Stau Searches ($\tilde{\tau}$)

JHEP 10 (2017) 096 [15]

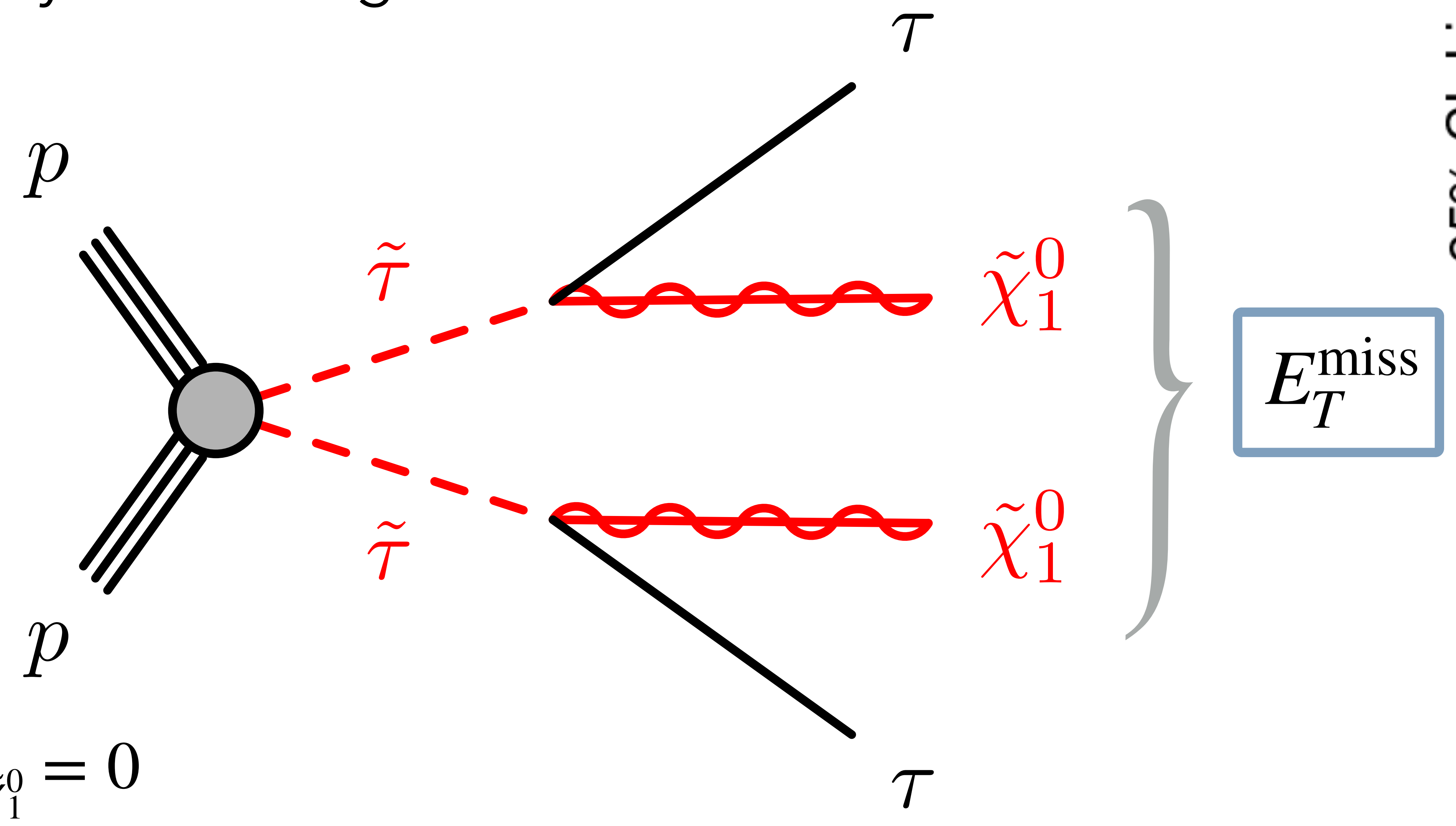


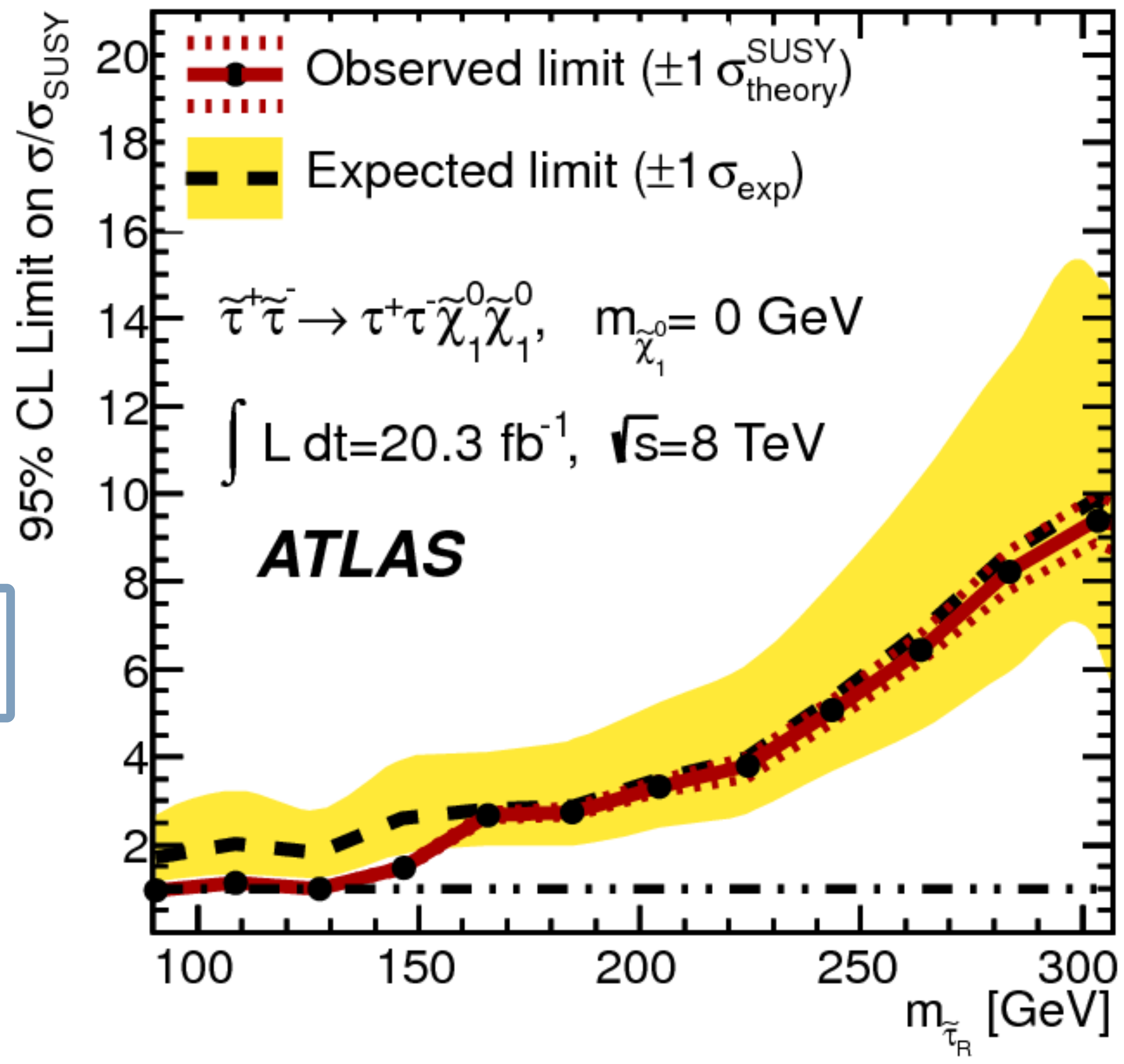
- **motivation:** light supersymmetric τ partners could play role in co-annihilation of neutralino ($\tilde{\chi}_0^1$), leading to a DM relic density consistent with cosmological observations
- mass expected to be O(100 GeV) range in gauge-mediated and anomaly-mediated SUSY breaking scenarios
- **challenge:** cross-section expected to be very small
- **MPP** group leading the efforts for searches in two $\tau\tau$ channels:

$(\tau \to \text{lep})(\tau \to \text{had})$ | $(\tau \to \text{had})(\tau \to \text{had})$

- cut- <u>and</u> MVA-based searches optimized to achieve large sensitivity in the range:

$$100 \leq m_{\tilde{\tau}} < 200 \text{ GeV}$$



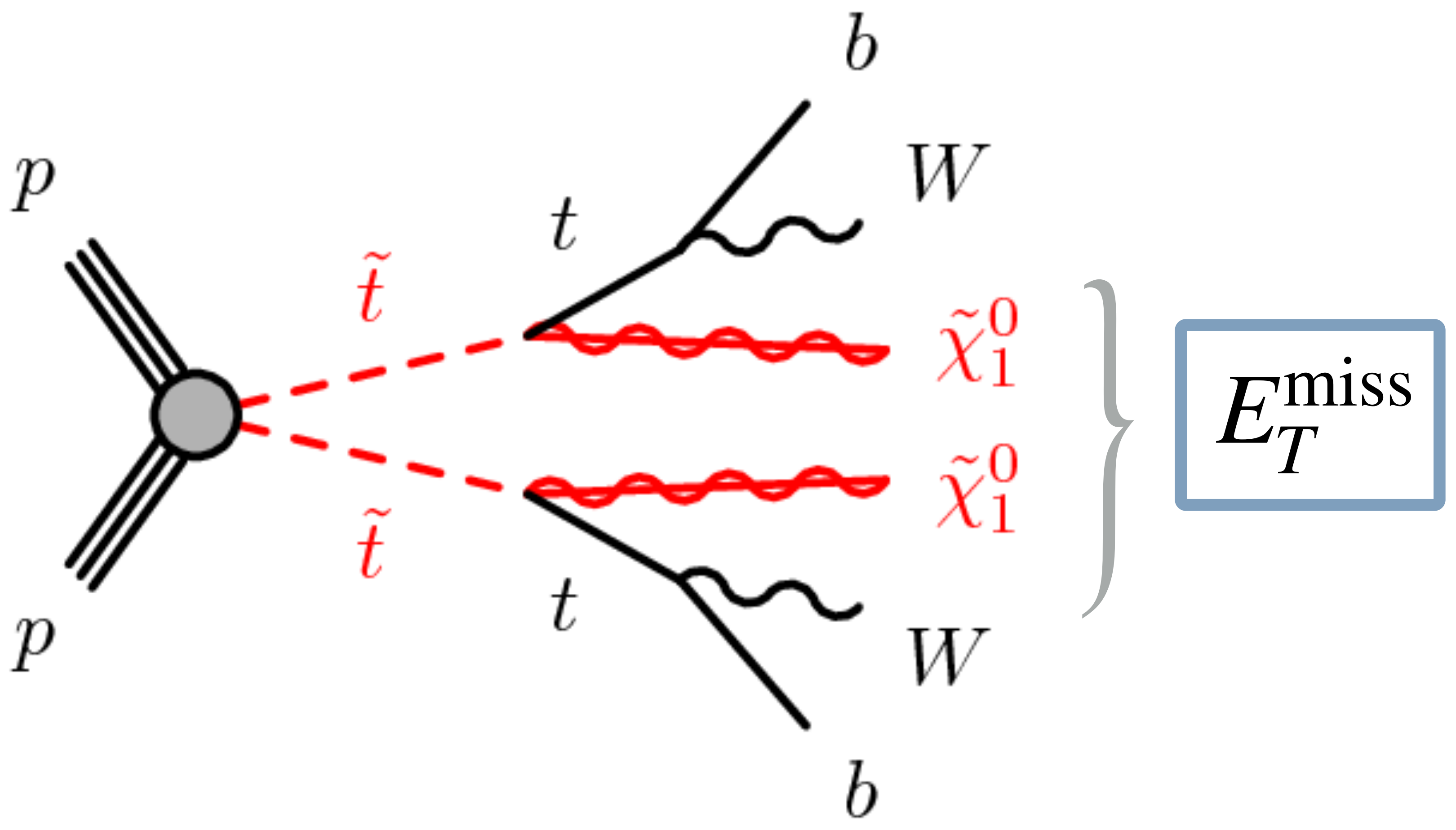


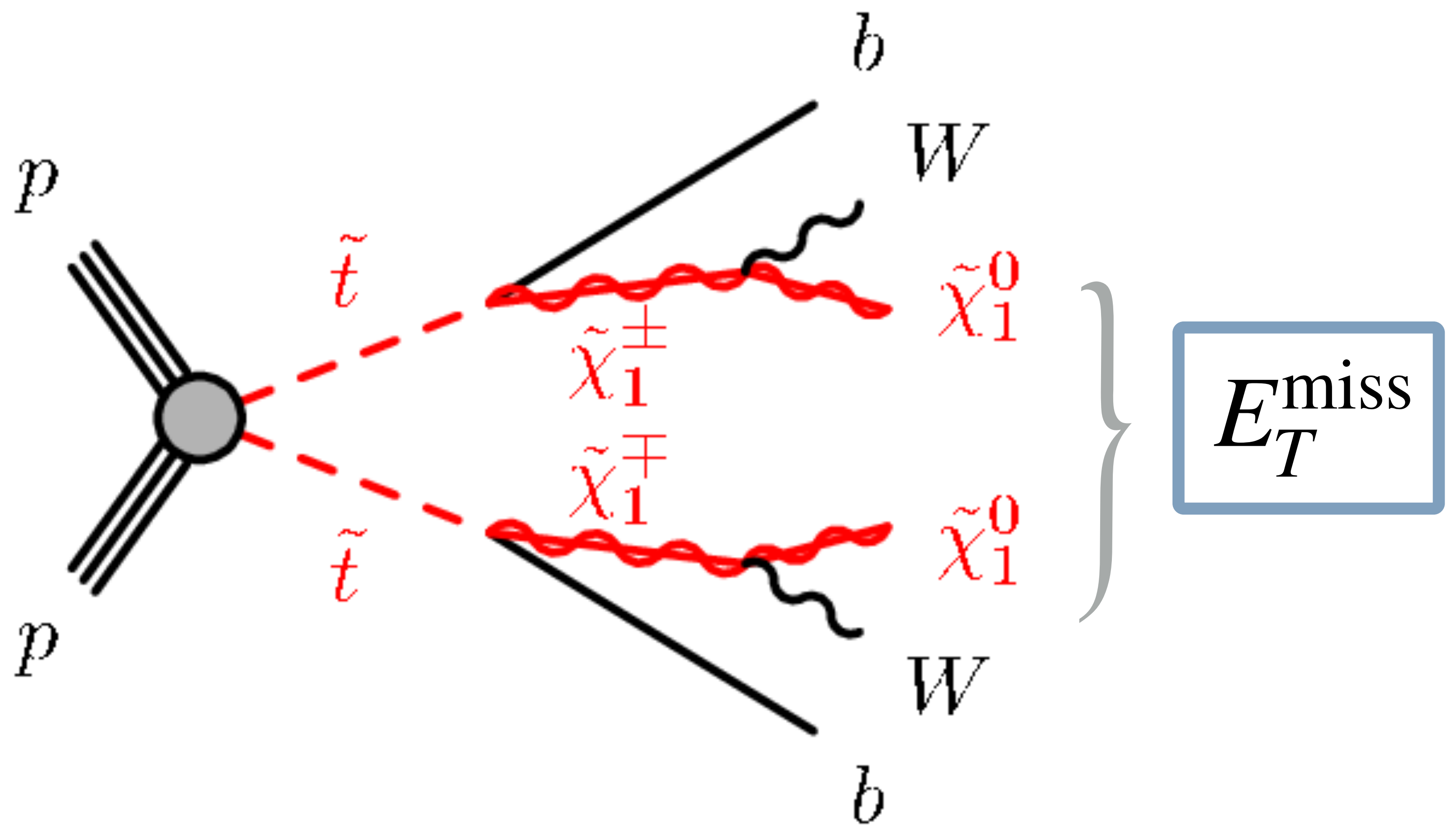
***Right**: One exclusion result for case of mass neutralino:* $m_{\tilde{\chi}_1^0} = 0$

Supersymmetry (SUSY): Stop Searches ($\tilde{t}$)

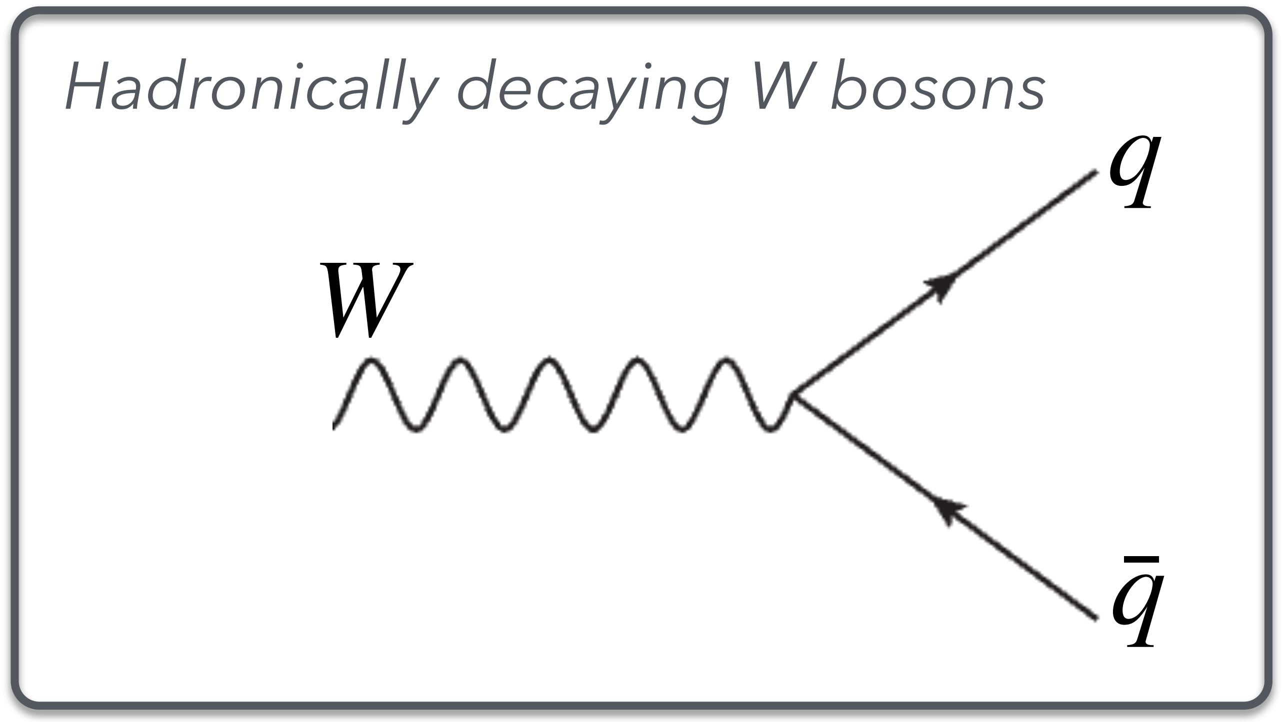
JHEP 12 (2017) 085 [16]

- another search targeting supersymmetric top quark partner in the all-hadronic channel driven by **MPP** efforts

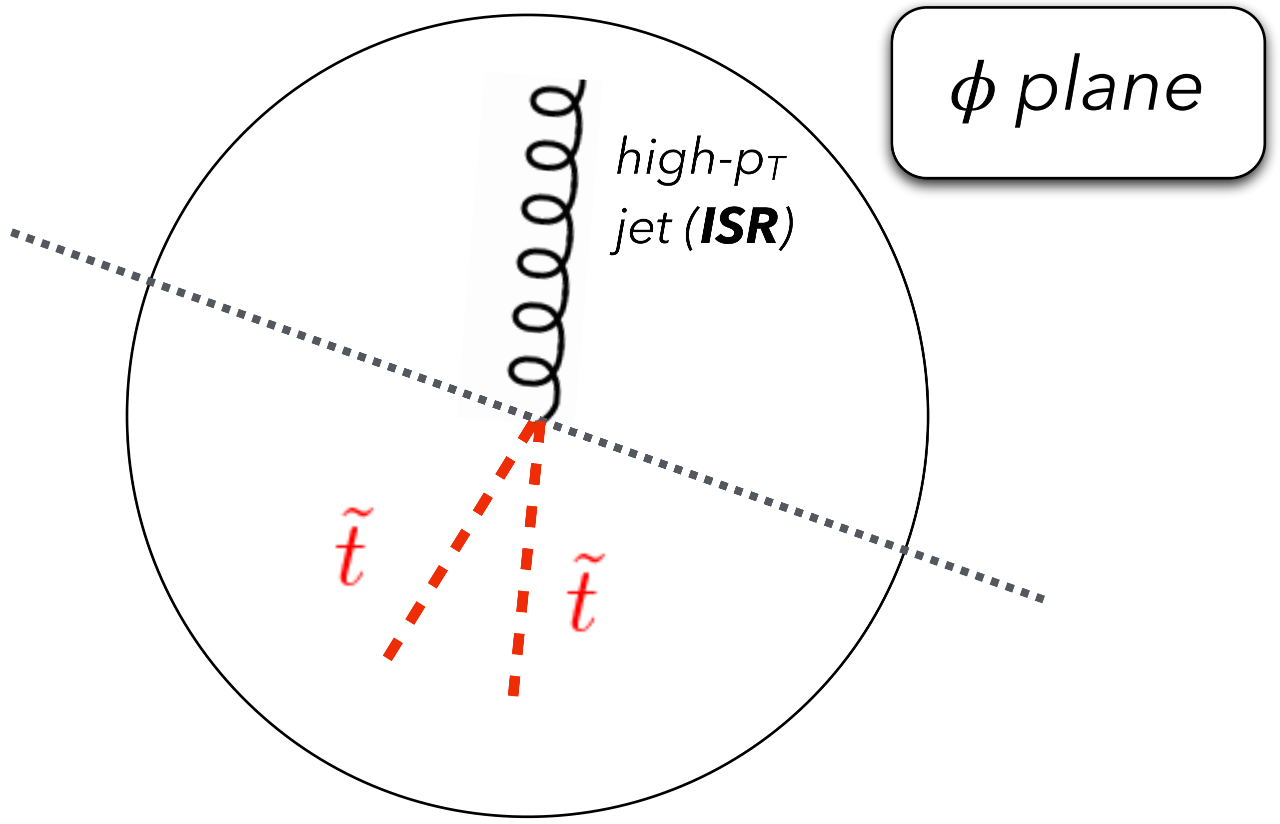




- search performed in several dedicated signal regions featuring various requirements on hadronic jets (including b-tagged jets) + E_T^{miss}



- complex final states with various backgrounds
- employs background estimation from dedicated control regions
- target both **boosted** and **resolved** regimes



- **new for Run 2**: specifically address challenging phase-space region where $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \approx m_t$ by targeting events where SUSY system recoils against a high-p_T ISR jet

Supersymmetry (SUSY): Stop Searches ($\tilde{t}$)

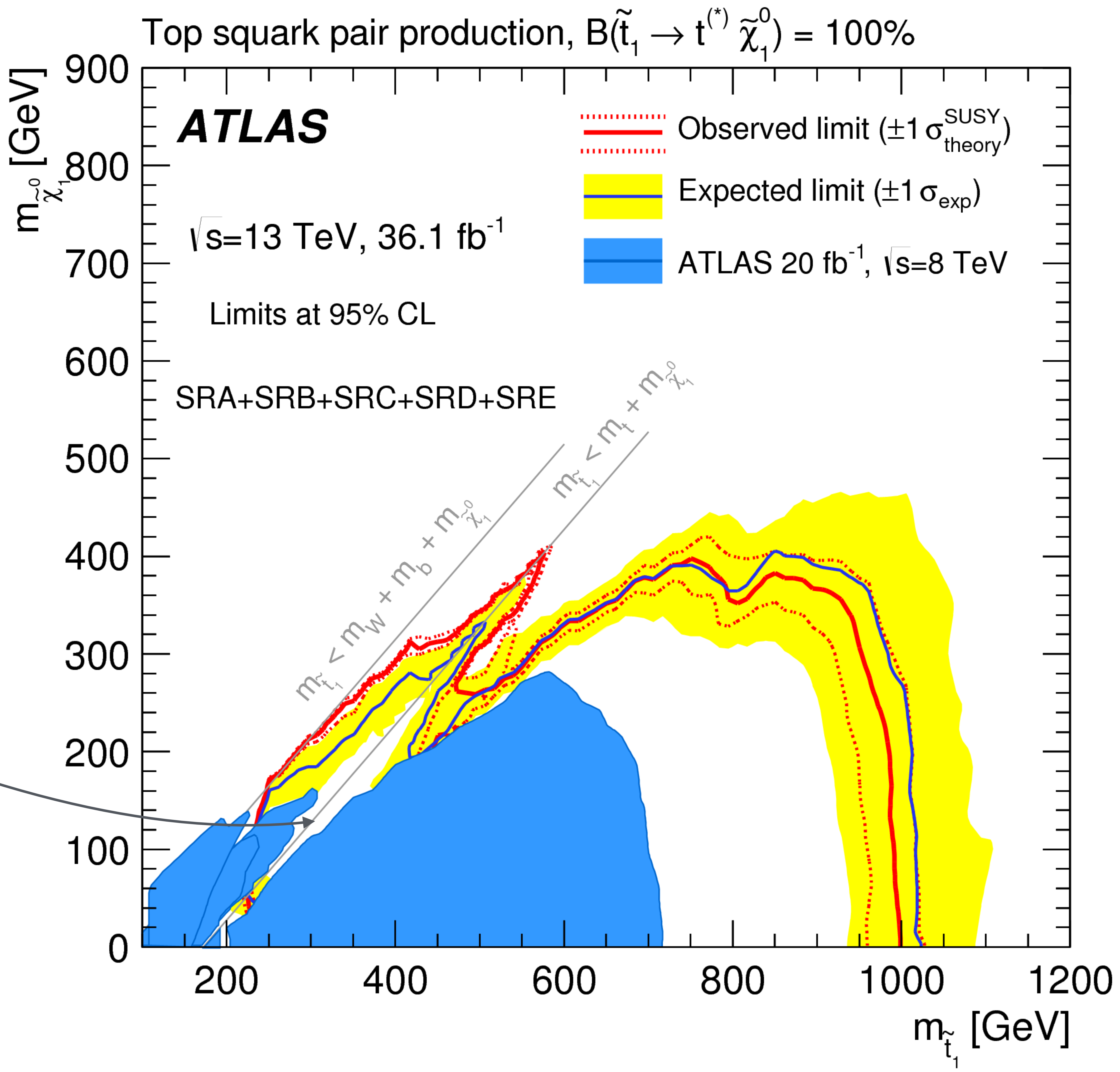
JHEP 12 (2017) 085 [16]

- significant increase in sensitivity due both to luminosity increase (statistics) and to analysis improvements
- allows for new stringent limits to be placed on stop and neutralino masses:

$m_{\tilde{t}_1}$ $m_{\tilde{\chi}_1^0}$

NB: challenging kinematic region (similar to SM $t\bar{t}$) referred to on previous slide

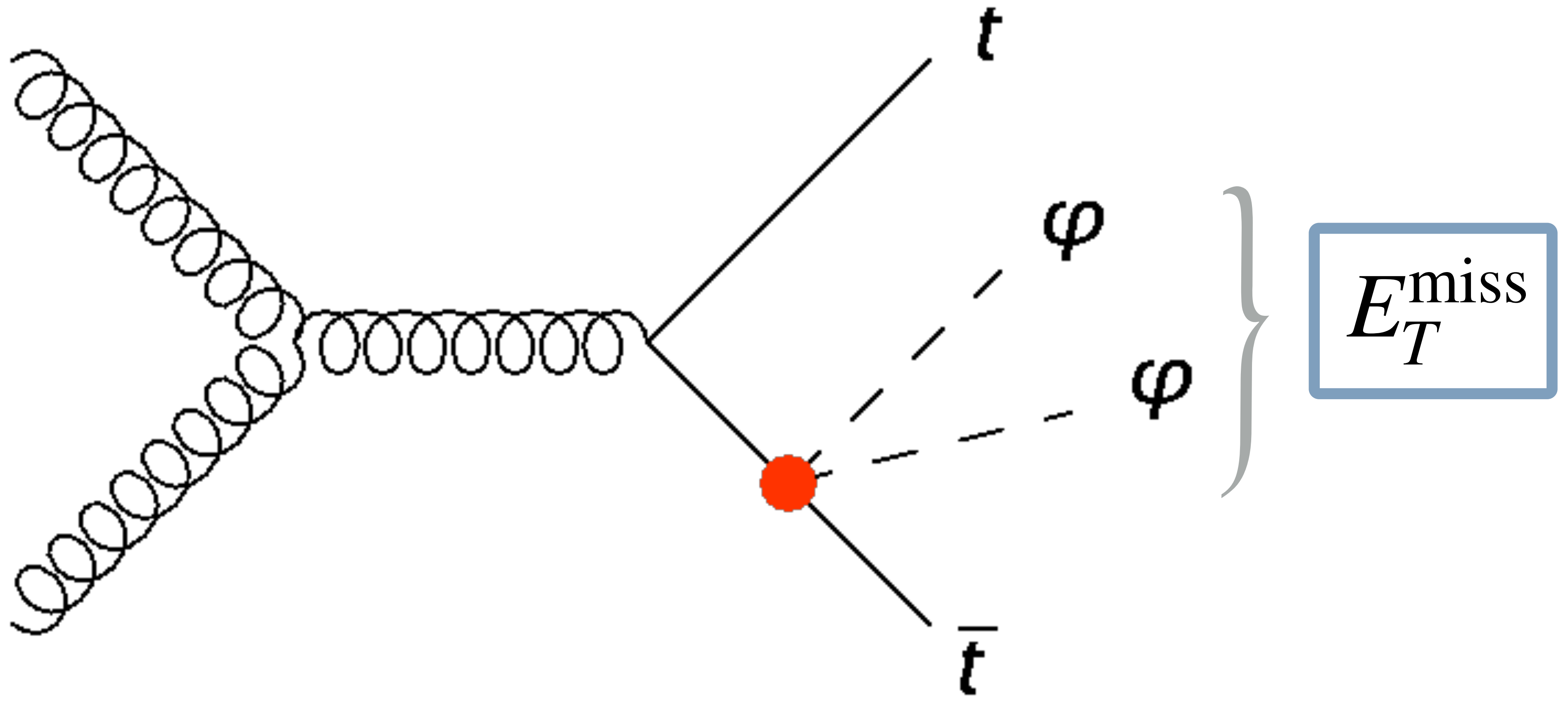
$$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \approx m_t$$



Re-Interpretation ($t\bar{t}$ + E_T^{miss}): Dark Energy Search

ATL-PHYS-PUB-2018-008 [17]

- accelerated expansion of the universe can be explained by a scale-dependent modification of **General Relativity**
- motivation based on an extension of the SM in context of EFT:



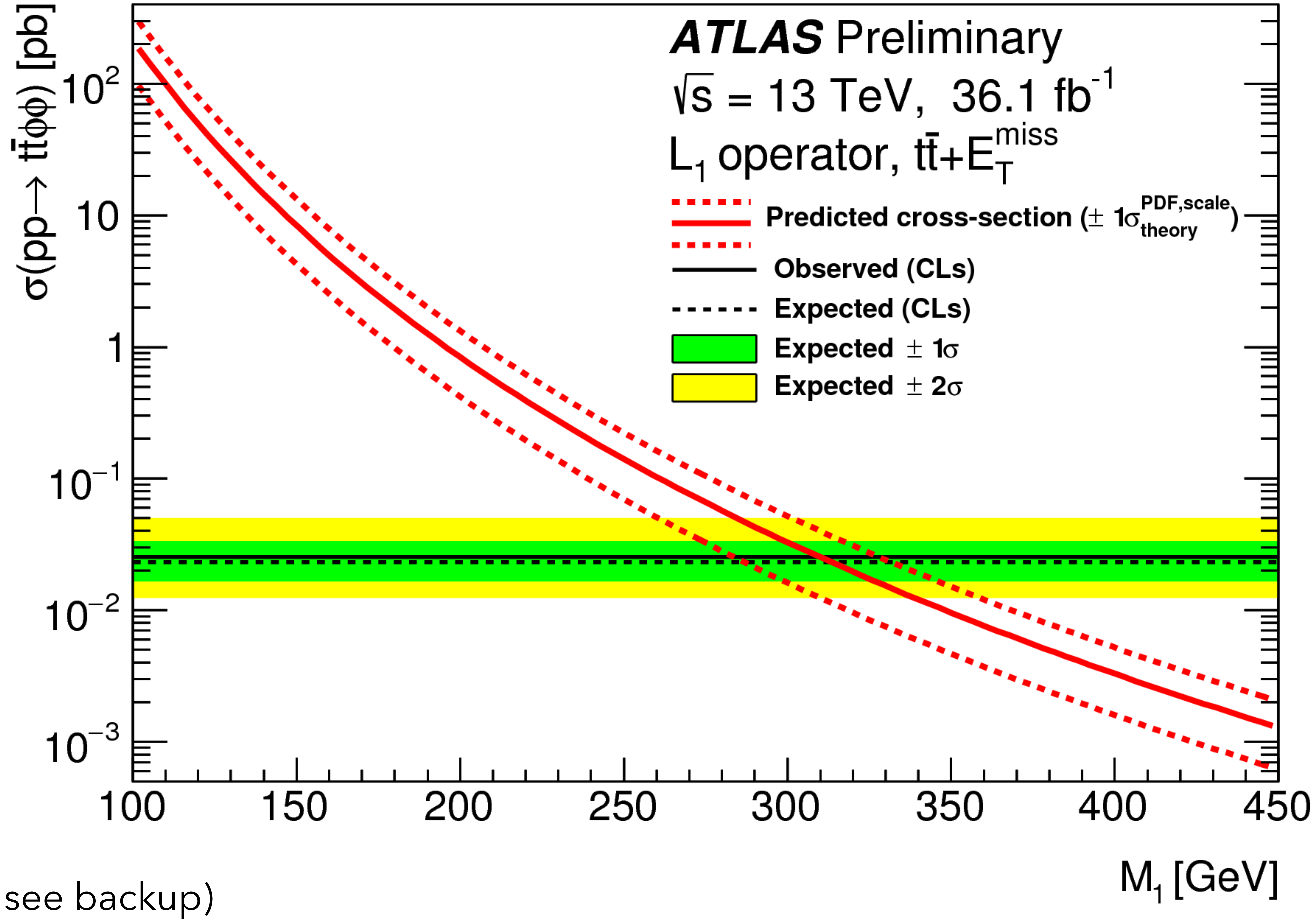
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{9} c_i \mathcal{L}_i \qquad \mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_\nu$$

Reference: *Brax et al.* [18]

- only consider leading term:
  coupling of DE to SM proportional to Yukawa coupling

- becomes a search for $t\bar{t}$ + E_T^{miss} (as on previous slide)
- re-interpretation of SUSY stop search with same all-hadronic + E_T^{miss} final state signature

First collider-based constraints on Dark Energy!



(a further analysis with same signature performed for DM search – see backup)

Summary

- **MPP** group members actively involved in wide range of ATLAS analyses:

Top Quark Physics

✓ involvement in precision m_{top} measurements in **all standard $t\bar{t}$ decay channels**

✓ leading contribution to new ATLAS combination of Run 1 direct m_{top} measurements

✓ actively involved in searches for other SM processes involving top quarks (*e.g.* $t\bar{t}b\bar{b}$, $t\bar{t}Z$) (crucial for understanding backgrounds in BSM searches + sensitivity to BSM physics themselves!)

Higgs Physics

✓ leading contribution to a number of precision Higgs boson measurements (including recent ATLAS observation of $H \rightarrow \tau\tau$ decays and **$t\bar{t}H$** and **VH** production modes)

✓ Higgs boson mass measurement in the $H \rightarrow 4\ell$ channel (featuring **world's lowest systematic uncertainty** on m_H)

✓ strong effort in further improving the Higgs boson coupling measurements and searches for CP violation with full Run-2 dataset (established leaders in EFT studies!)

Searches for BSM Physics

✓ coordination of a broad range of searches with various final-state signatures

✓ searches sensitive to a number of leading BSM physics models (*e.g.* extensions of the Higgs sector, SUSY, DM, DE, generic new heavy resonances)

✓ no new physics yet… but **140 fb^{-1}** analyses in the pipeline (+ preparation for Run 3 & HL-LHC!)

Stay tuned for results with the full Run-2 dataset!

Thank you for your attention

References + Additional Material

References

[1] ATLAS Collaboration, *Measurement of the top quark mass in the $t\bar{t} \to$ lepton + jets channel from $\sqrt{s}$ = 8 TeV ATLAS data and combination with previous results*, Submitted to EPJC (October 2018).

[2] ATLAS Collaboration, *Measurement of the $t\bar{t}W$ and $t\bar{t}Z$ cross sections in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, ATL-CONF-2018-047 (September 2018).

[3] ATLAS Collaboration, *Measurement of the Higgs boson mass in the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels with $\sqrt{s}$ = 13 TeV pp collisions using the ATLAS detector* , Phys. Lett. B 784 (2018) 345.

[4] ATLAS Collaboration, *Measurements of the Higgs boson production, fiducial and differential cross sections in the 4ℓ decay channel at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, ATL-CONF-2018-018 (June 2018).

[5] ATLAS Collaboration, *Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector* , Phys. Lett. B 786 (2018) 59.

[6] ATLAS Collaboration, *Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector*, Phys. Lett. B 784 (2018) 173.

[7] K. Ecker *et al.*, *Measurement of the Higgs boson tensor coupling in $H \to ZZ^* \to 4\ell$ decays with the ATLAS detector – How odd is the Higgs boson?*, CERN-THESIS-2018-073, MPP-2018-139 (May 2018).

[8] ATLAS Collaboration, *Cross-section measurement of the Higgs boson decaying into a pair of tau-leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Submitted to Phys. Rev. D. (November 2018).

[9] ATLAS Collaboration, *Search for dark matter i events with a hadronically decaying vector boson and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, JHEP 10 (2018) 180.

[10] ATLAS Collaboration, *Combination of searches for invisible Higgs boson decays with the ATLAS experiment*, ATLAS-CONF-2018-054, (November 2018).

[11] ATLAS Collaboration, *Search for Dark Matter Produced in Association with a Higgs Boson decaying to $b\bar{b}$ at $\sqrt{s}$ = 13 TeV with the ATLAS Detector using 79.8 fb-1 of proton-proton collision data*, ATLAS-CONF-2018-039 (July 2018).

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[17] ATLAS Collaboration, *Search for scalar dark energy in $t\bar{t} + E_T^{miss}$ and mono-jet final states with the ATLAS detector*, ATL-PHYS-PUB-2018-008 (June 2018).

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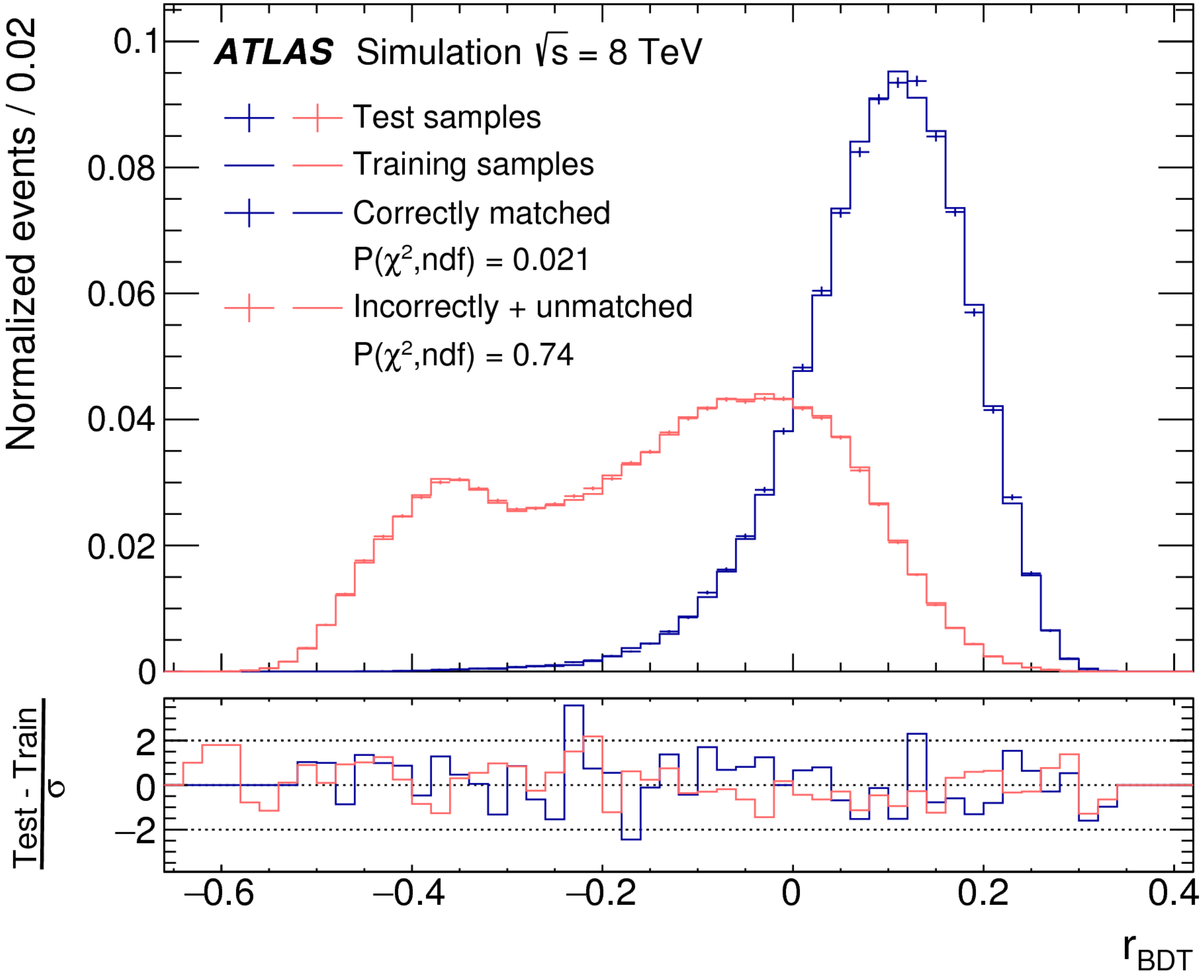
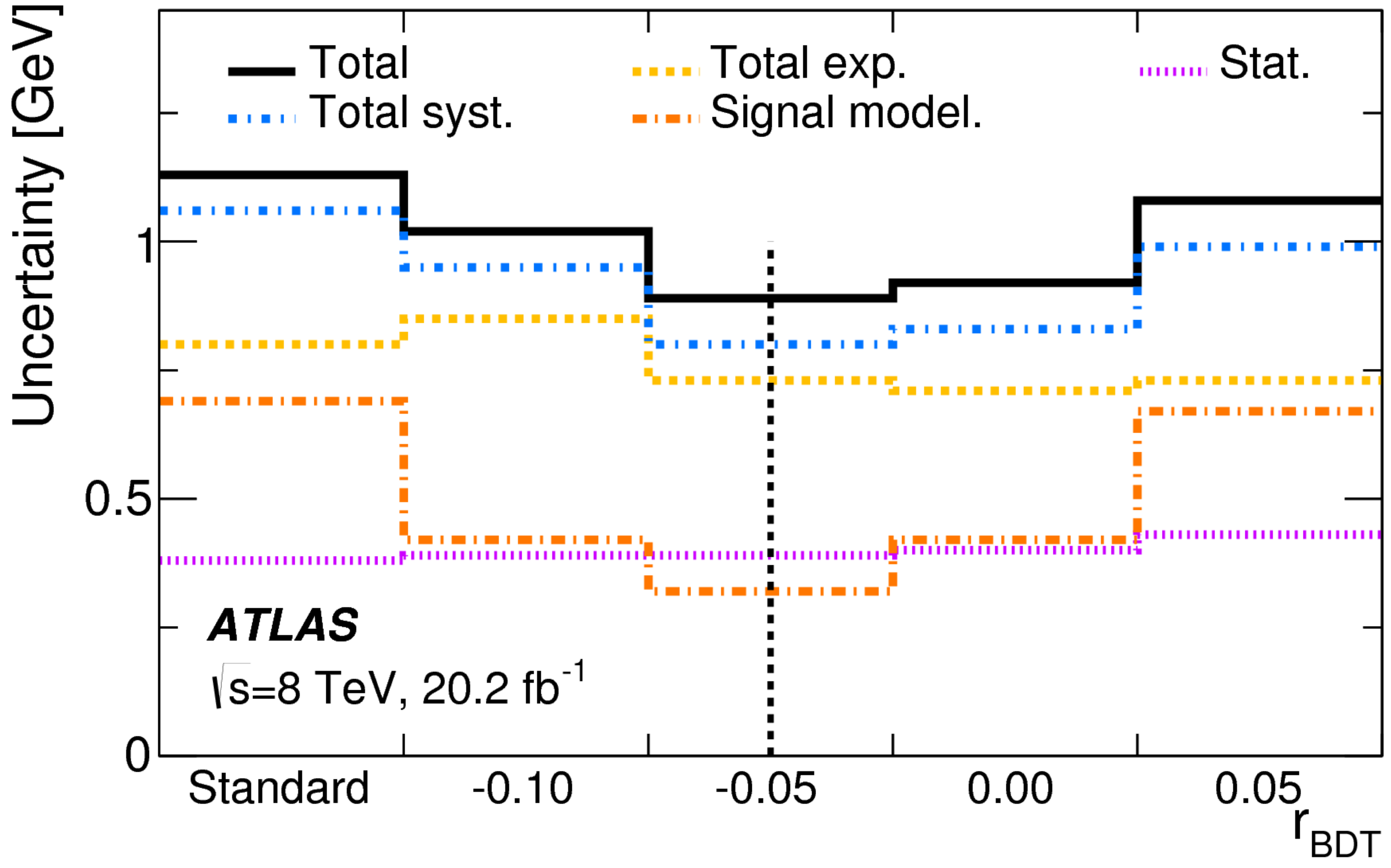
[20] ATLAS Collaboration, *Constraints on mediator-based dark matter models using $\sqrt{s}$ = 13 TeV pp collisions at the LHC with the ATLAS detector* , ATLAS-CONF-2018-051 (November 2018).

New Precision Top Quark Mass (m_{top}) Measurement @ $\sqrt{s}$ = 8 TeV

Submitted to EPJC [1]





- measurement employs a multivariate analysis technique (BDT) to separate:
  - **events with correct jet ↔ quark associations**
  - **remaining events**
    (i.e. unmatched or incorrect signal $t\bar{t}$ events)

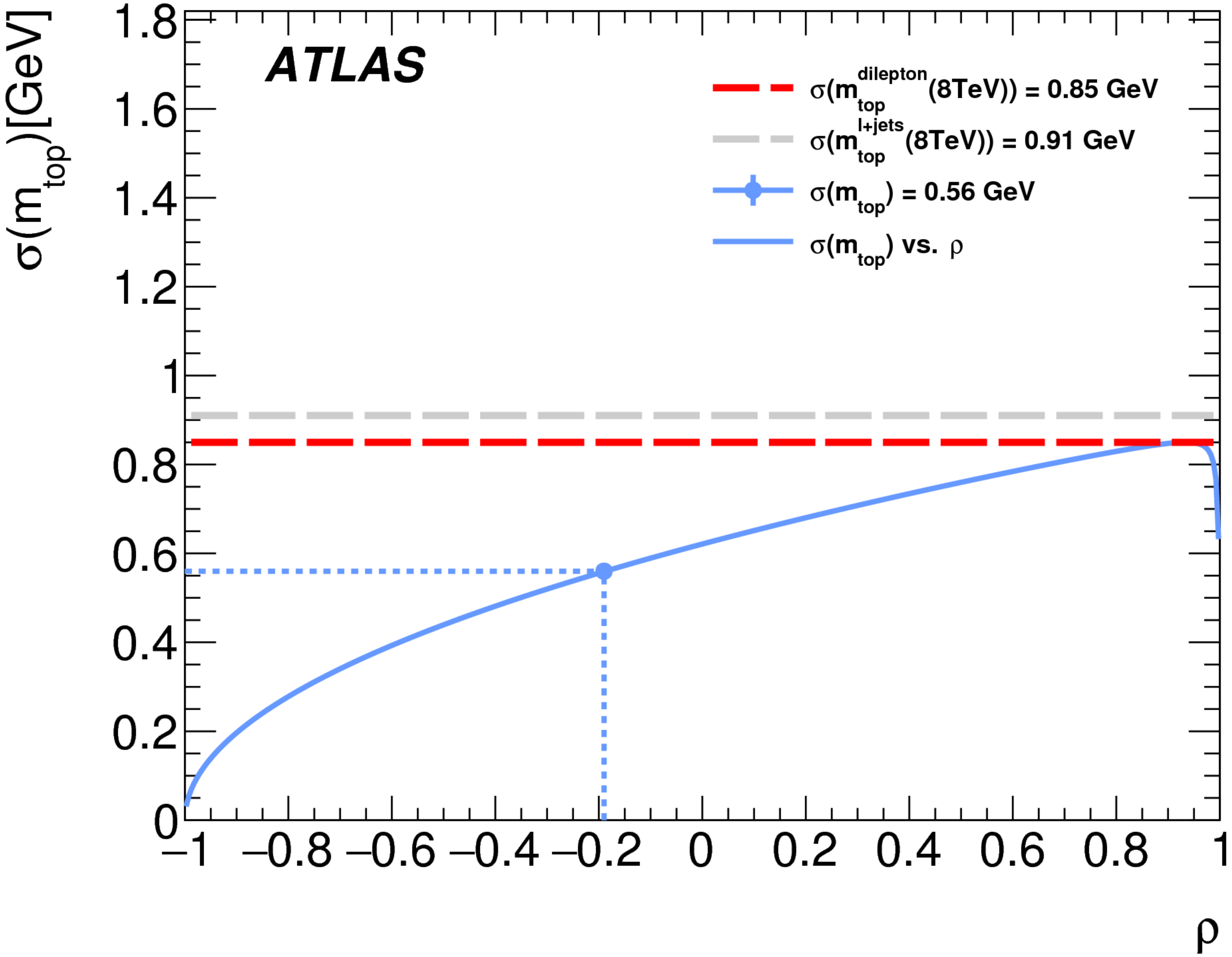
- allows for optimization: select BDT cut value to yield smallest total systematic uncertainty *(above right)*
- optimization both reduces **total uncertainty on m_{top}** (1.13 → 0.91 GeV) and reduces **correlation** with other $t\bar{t}$ measurements

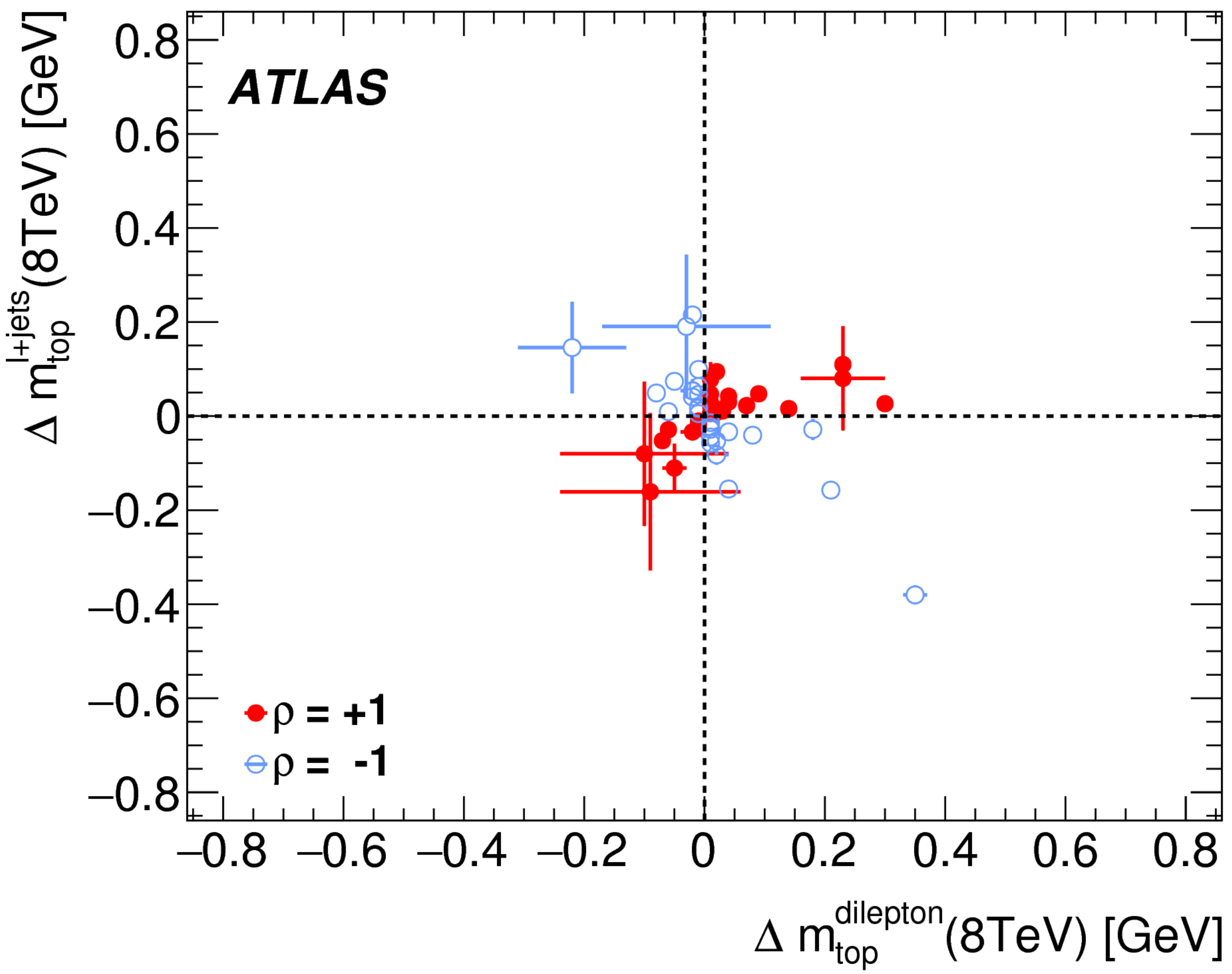
e.g. for two ATLAS measurements @ $\sqrt{s}$ = 8 TeV: **ρ (ℓ + jets, dileptonic) ≈** -0.02 → **-0.19** *(important for combination)*

New Combination of ATLAS m_{top} Measurements ($\sqrt{s}$ = 7, 8 TeV)

Submitted to EPJC [1]

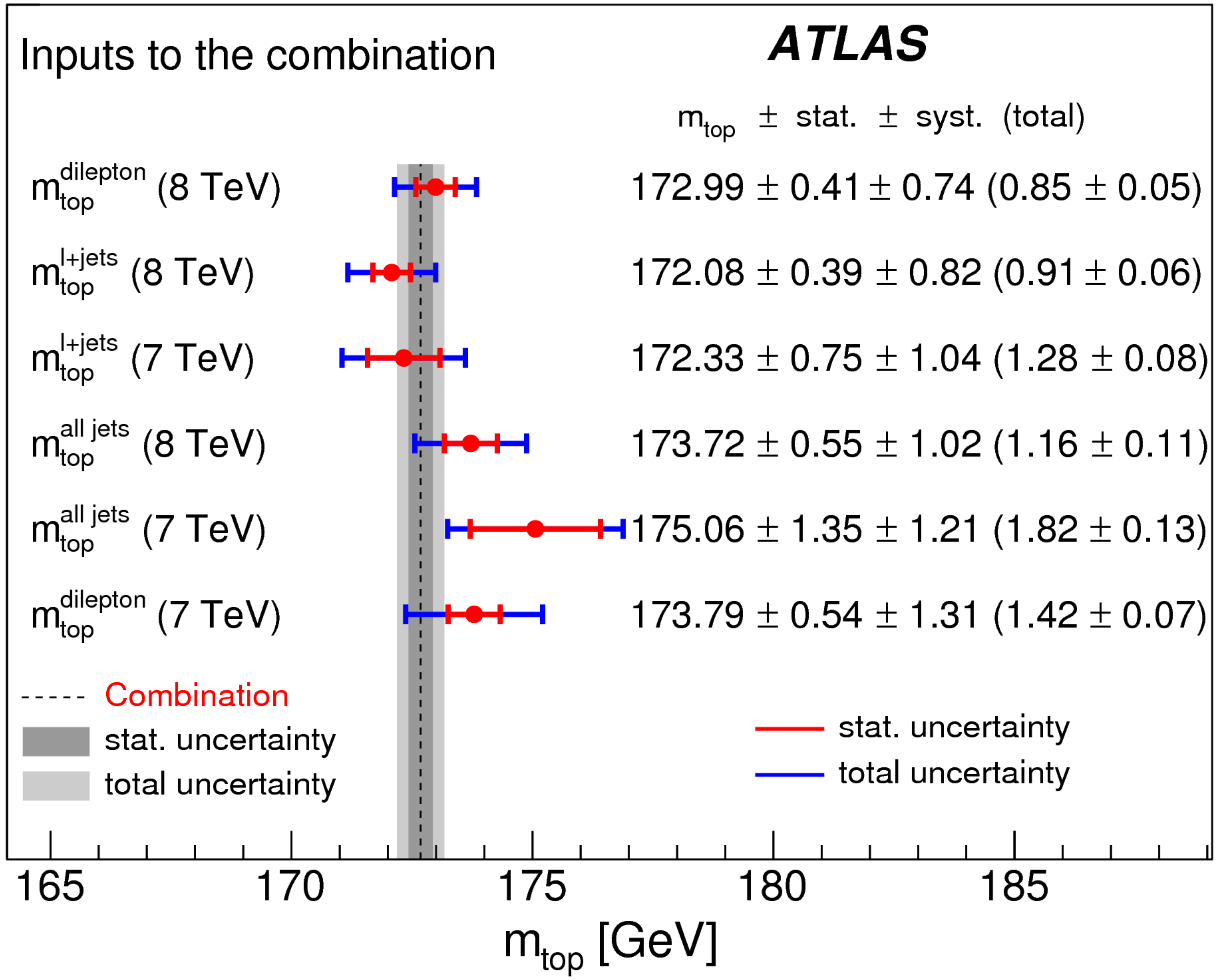
- combination of all Run 1 ATLAS results from standard 3 $t\bar{t}$ decay channels (dileptonic, ℓ+jets, all-hadronic)
- final combined uncertainty strongly depends on the estimator correlations
- correlations were evaluated for each source of systematic uncertainty
- statistical uncertainty on systematic sources also evaluated and exploited in order to properly evaluate the stability of the combination

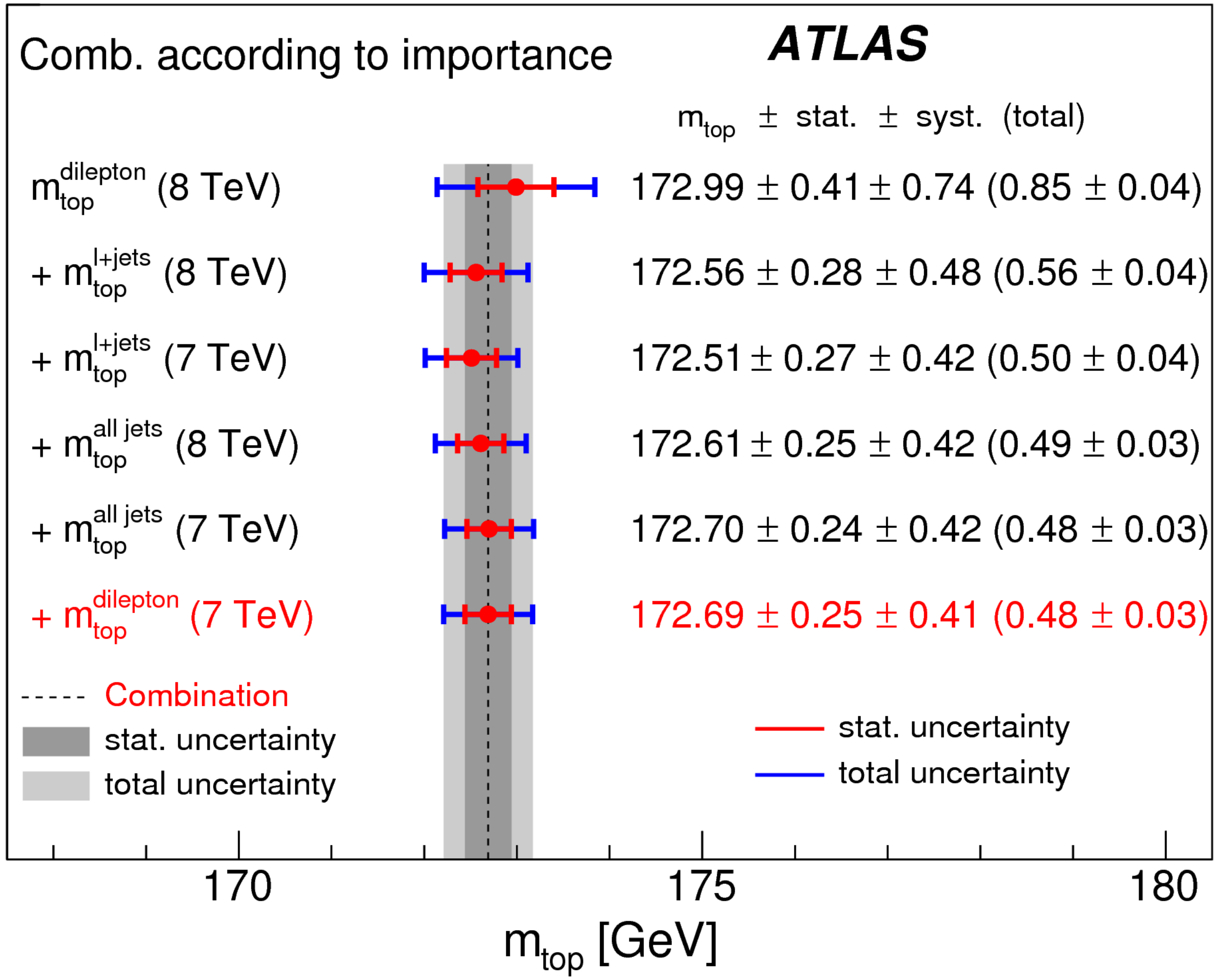




New Combination of ATLAS m_{top} Measurements

Submitted to EPJC [1]



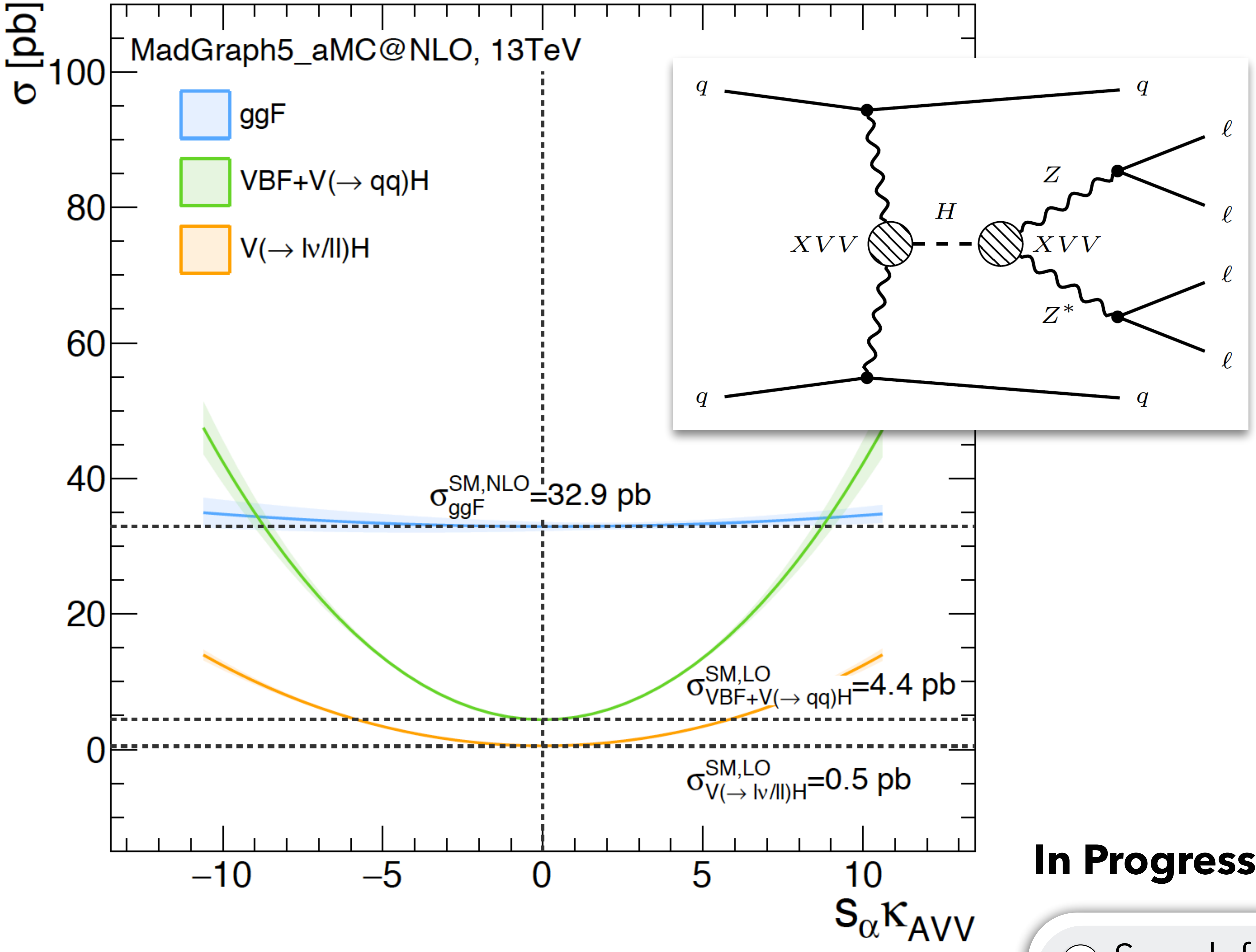


- individual measurements were combined successively (ordered according to their overall impact)
- note that analyzers from **MPP** played a leading role in **all 6 measurements**!
- final combined result: $m_{top} = 172.69 \pm 0.25\ (\mathrm{stat}) \pm 0.41\ (\mathrm{syst})\ \mathrm{GeV}$
- result is dominated by the first 3 measurements *(shown above right)*
- new ATLAS combined result provides **44**% improvement relative to the best single input result (*cf.* CMS ~ **4**%)

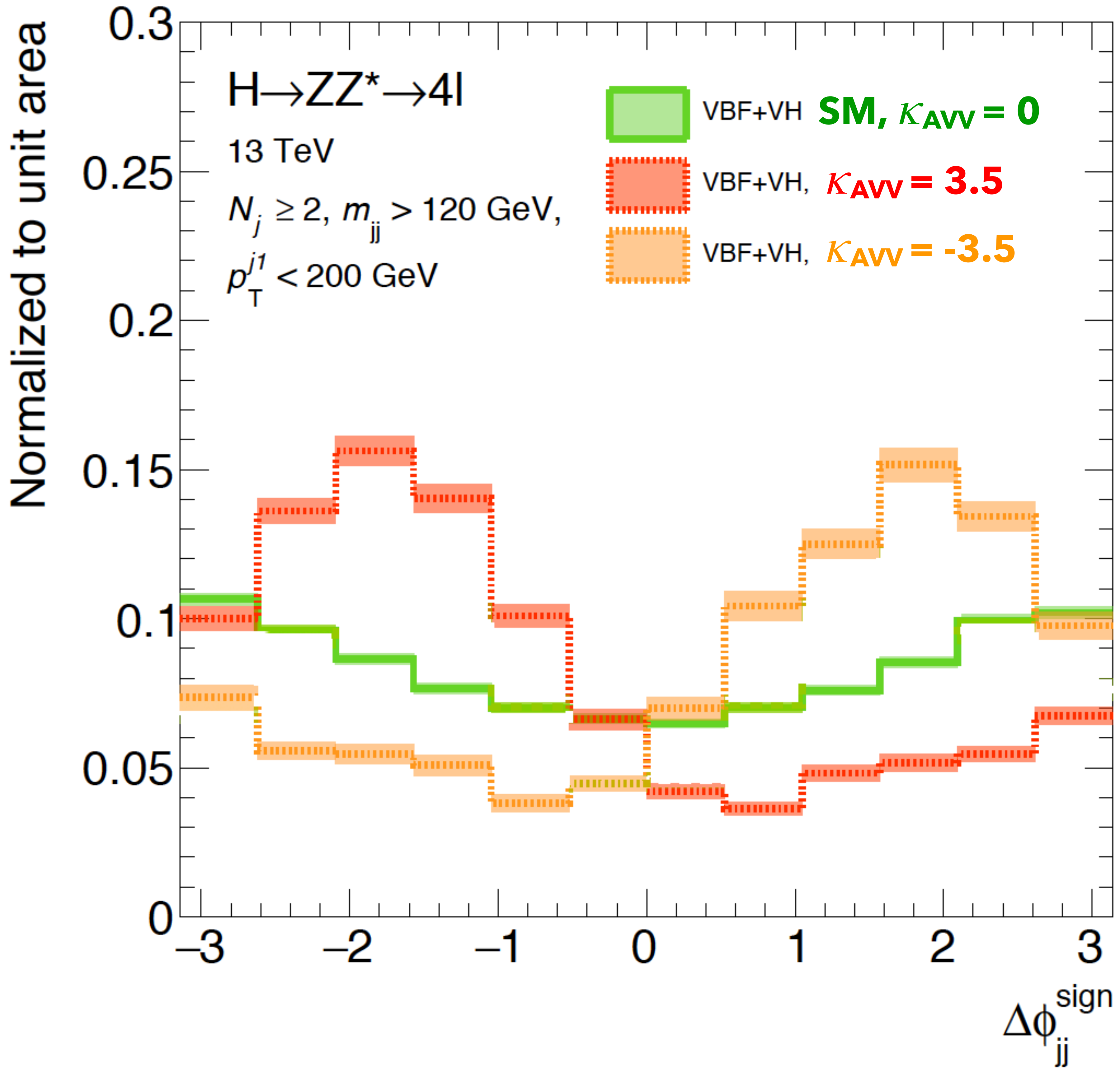
ETF Interpretation: $H \to ZZ^* \to 4\ell$

CERN-THESIS-2018-073 [7]

- measured production cross sections (***ggF***, ***VBF***, ***VH***) can be used to constrain certain extensions of the SM in the context of **Effective Field Theory** (EFT)
  (*via* additional contact-interaction terms suppressed by an energy scale Λ)



Above: *Higgs cross section vs. CP-odd EFT parameter.*



In Progress:

- ○ Search for CP violation using sensitive differential distributions (e.g. above)
- ○ EFT interpretation with full Run-2 dataset (also in the H→WW channel)

Combination of Search for Invisible Higgs Boson Decays

ATLAS-CONF-2018-054 [10]

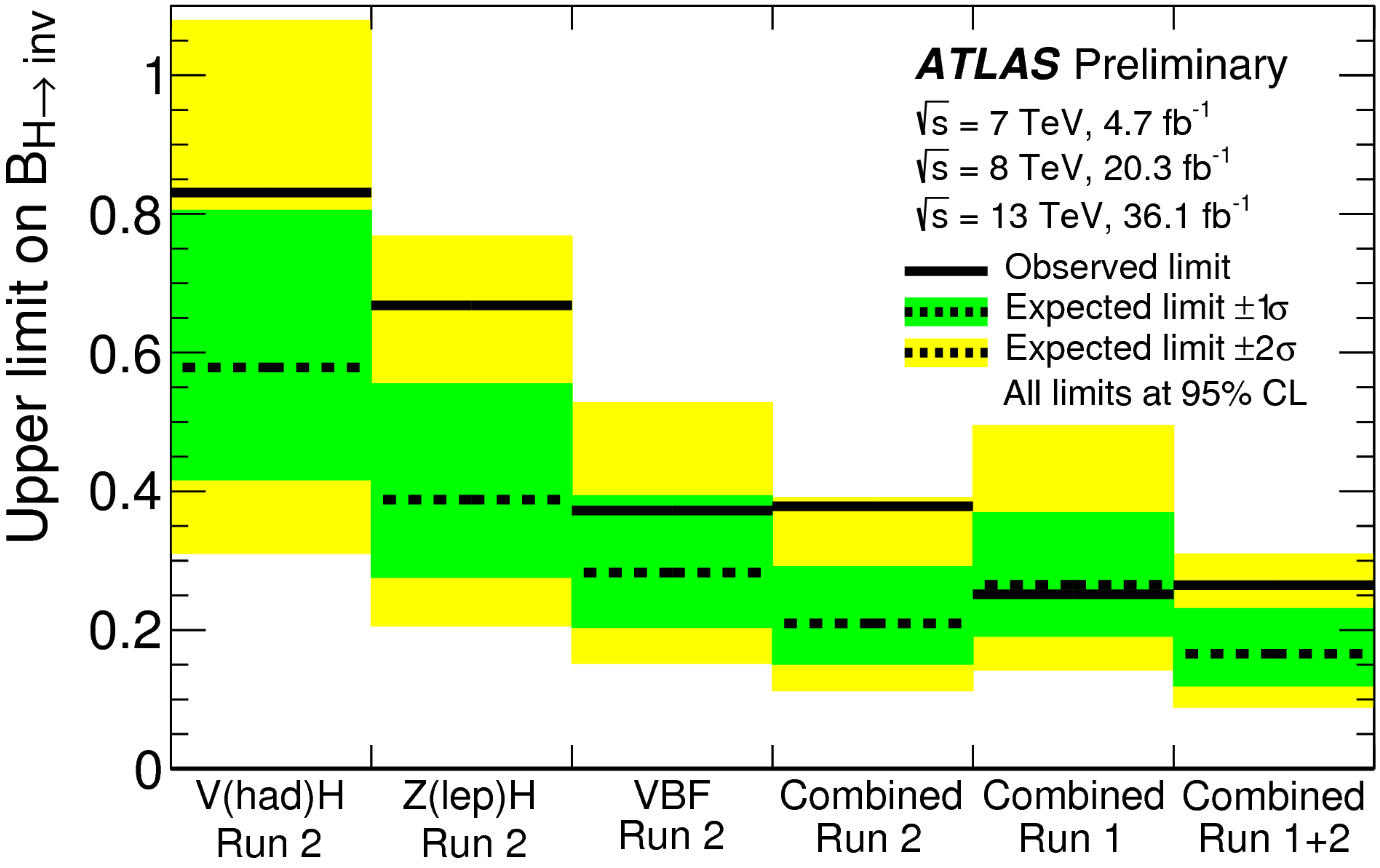
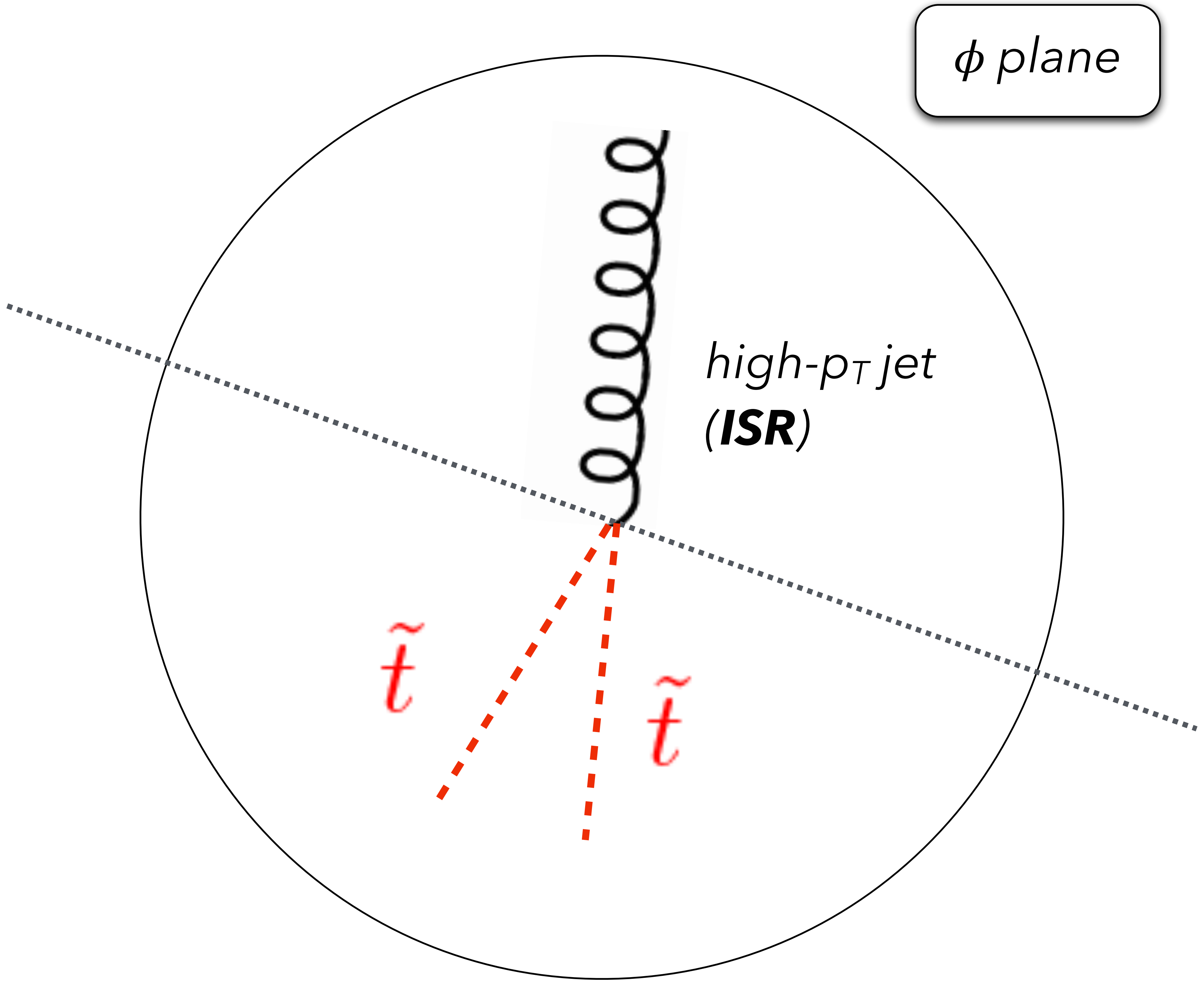


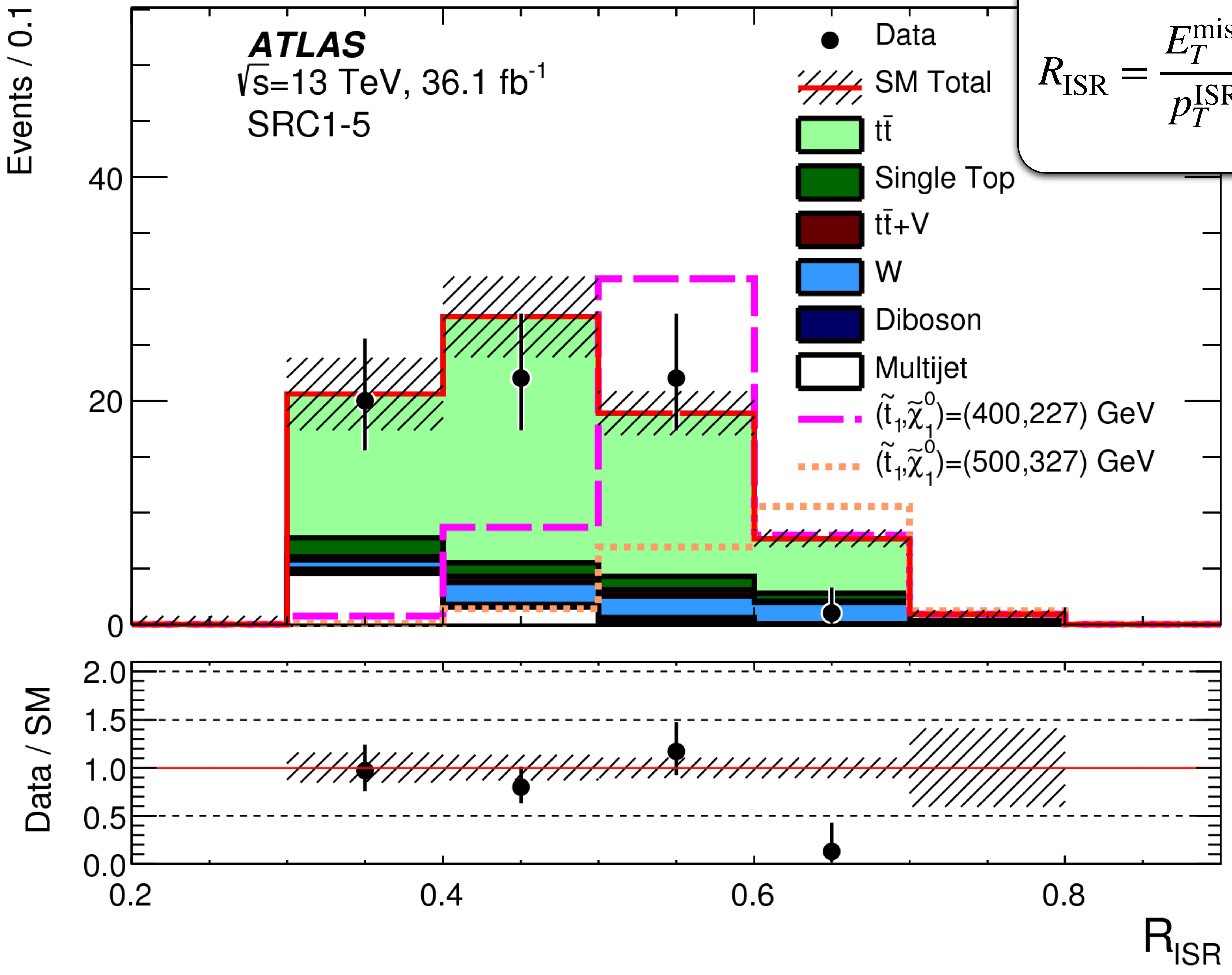
Figure 2 *(caption taken from reference): The observed and expected upper limits on $B_{H\to inv}$ at 95% CL from direct searches for invisible decays of the 125 GeV Higgs boson and statistical combinations.*

Supersymmetry (SUSY): Stop Searches ($\tilde{t}$)

JHEP 12 (2017) 085 [16]

- **new for Run 2**: specifically address challenging phase-space region where by targeting events where SUSY system recoils against a high-p_T ISR jet (> 400 GeV)



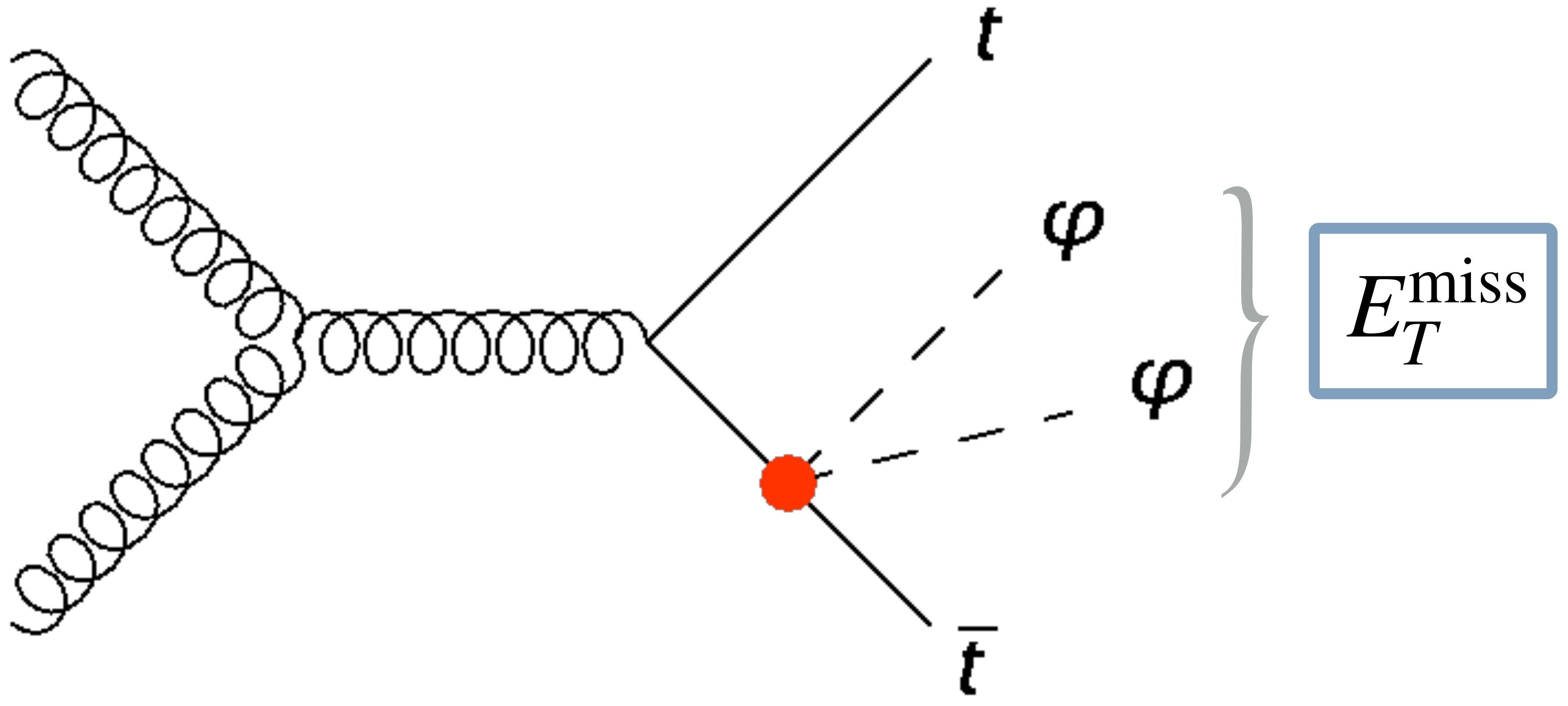


$$R_{\mathrm{ISR}} = \frac{E_T^{\mathrm{miss}}}{p_T^{\mathrm{ISR}}} \sim \frac{m_{\tilde{\chi}^1_0}}{m_{\tilde{t}_1}}$$

Re-Interpretation ($t\bar{t}$ + E_T^{miss}): Dark Energy Search

ATL-PHYS-PUB-2018-008 [17]

- accelerated expansion of the universe can be explained by a scale-dependent modification of **General Relativity**
- motivation based on an extension of the SM in context of EFT:



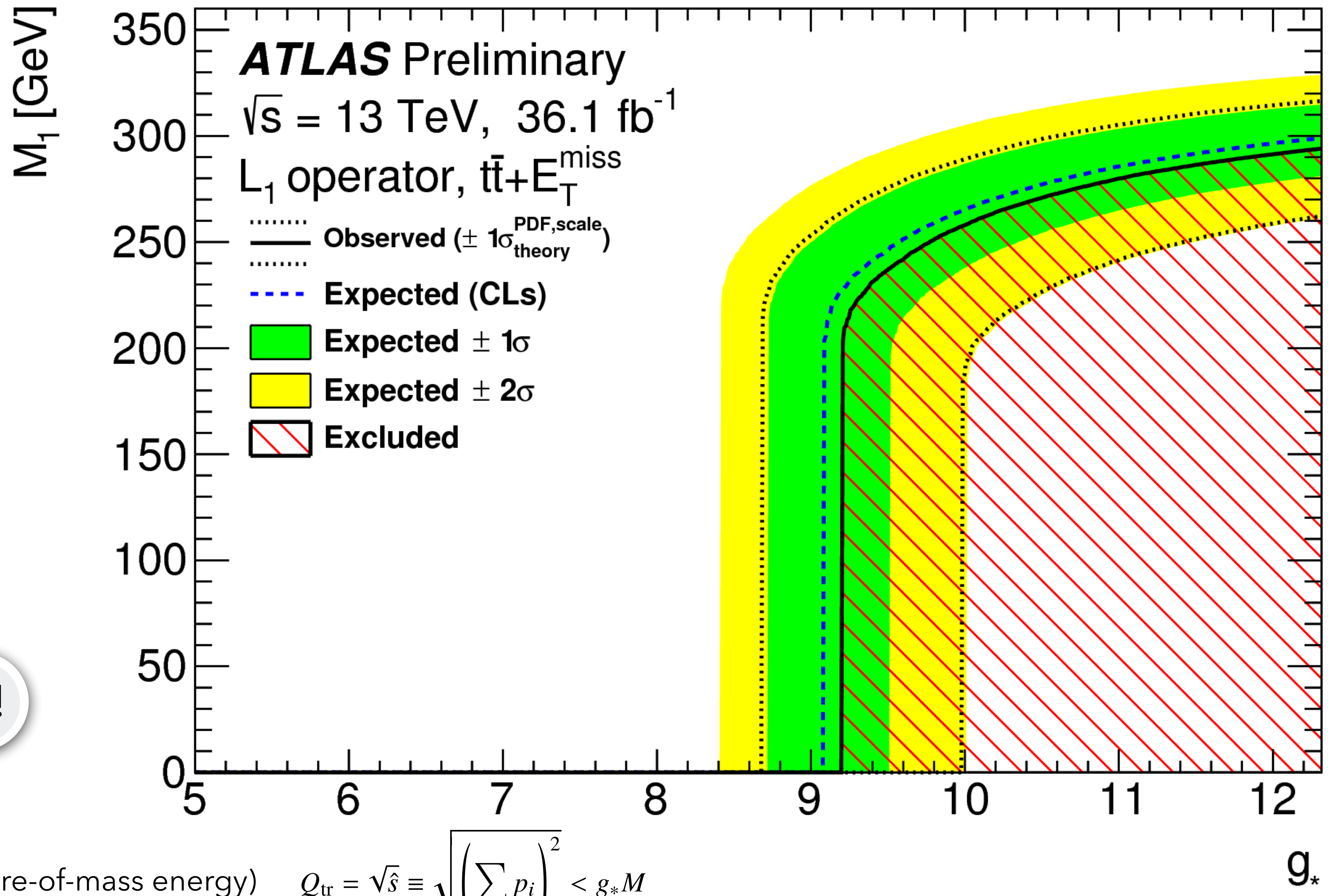
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{i=1}^{9} c_i \mathcal{L}_i \qquad \mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_\nu$$

Reference: *Brax et al.* [17]

- only consider leading term:
  coupling of DE to SM proportional to Yukawa coupling

- becomes a search for $t\bar{t}$ + E_T^{miss} (as before)
- re-interpretation of SUSY stop search with same all-hadronic $t\bar{t}$ final state signature

First collider-based constraints on Dark Energy!

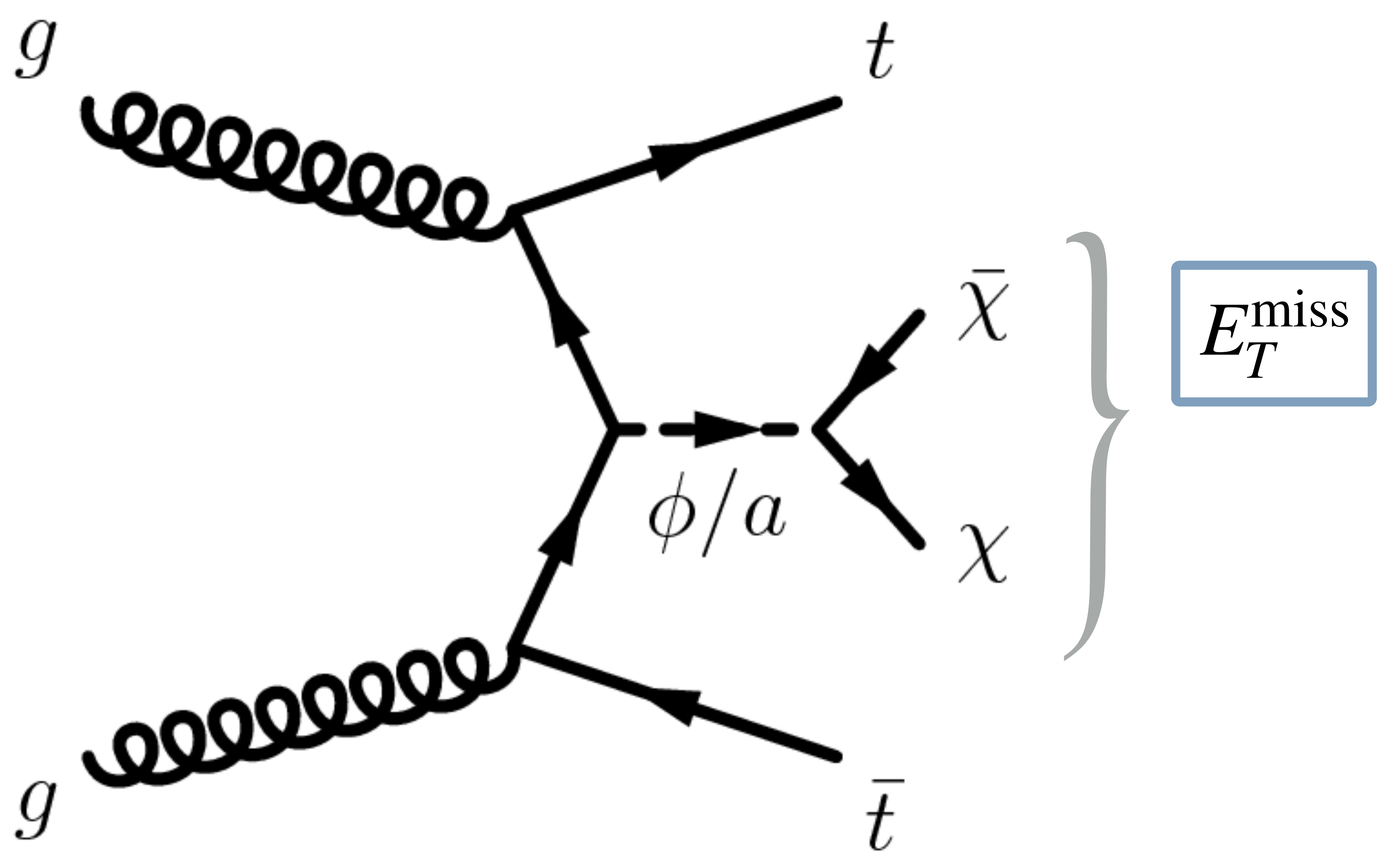


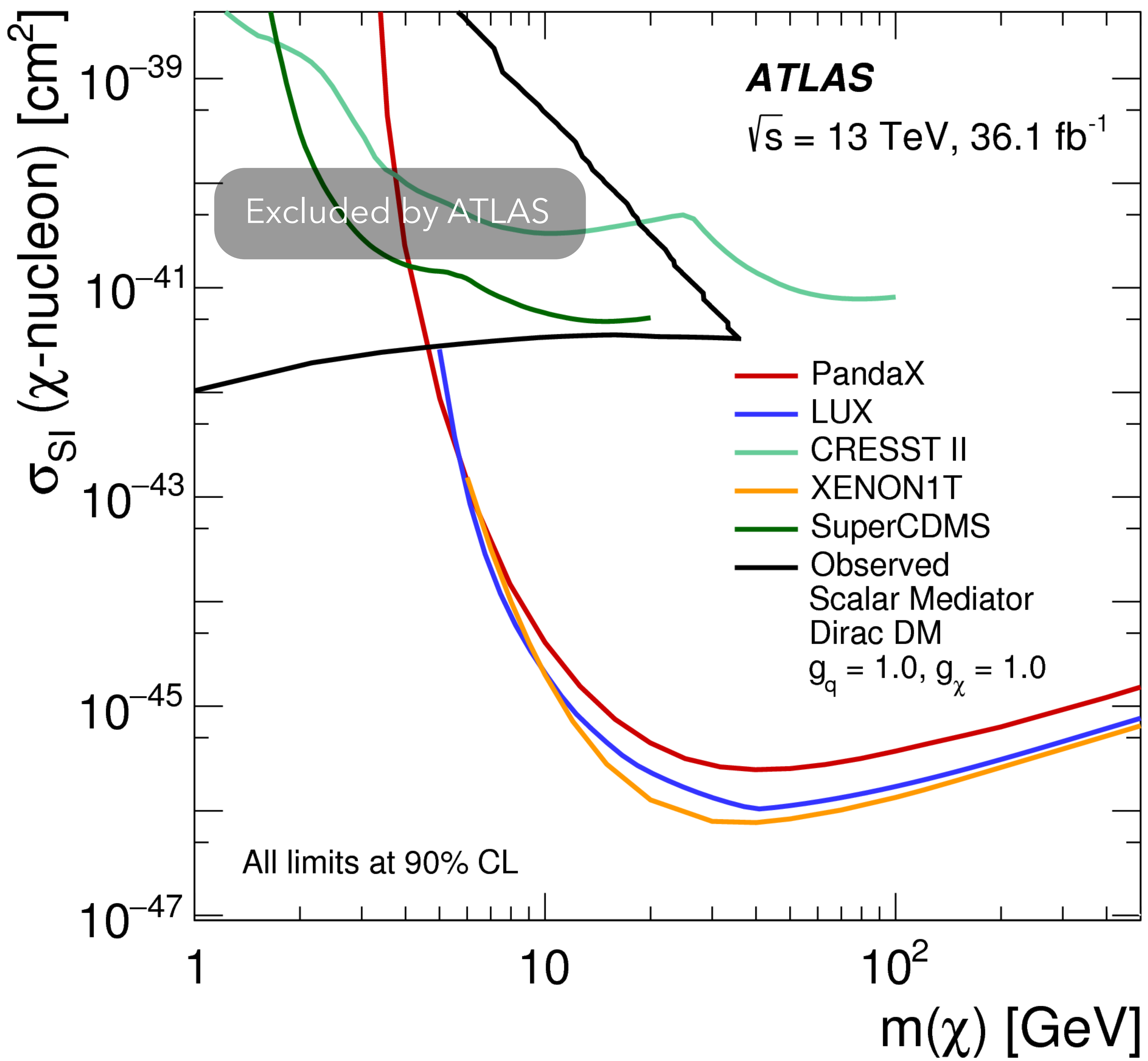
Limit plot in context of g* and M (relating their product to the partonic centre-of-mass energy) $Q_{\rm tr} = \sqrt{\hat{s}} \equiv \sqrt{\left(\sum_i p_i\right)^2} < g_* M$

Dark Matter Search with $t\bar{t}$ + E_T^{miss} Final State

Eur. Phys. J. C. 78 (2018) 18 [19]

- additional search with the same final state: **dark matter** (DM) production with a new scalar mediator ϕ/a
- similarly performed in the all-hadronic $t\bar{t}$ channel



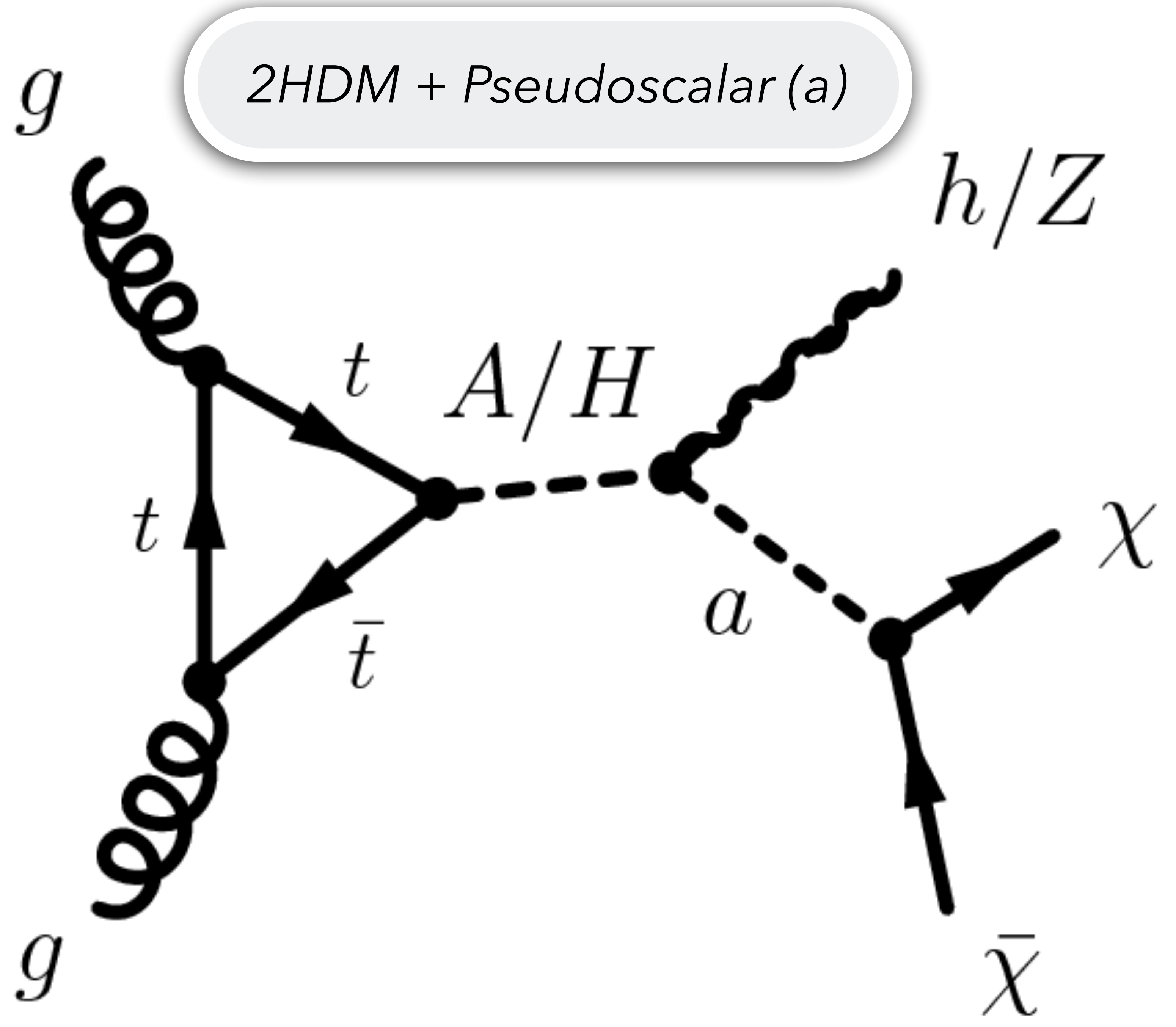


- slightly softer p_T spectra (compared with SUSY signal prediction on previous slide)
- set limits on DM-nucleon cross section and DM mass within the **scalar mediator model**

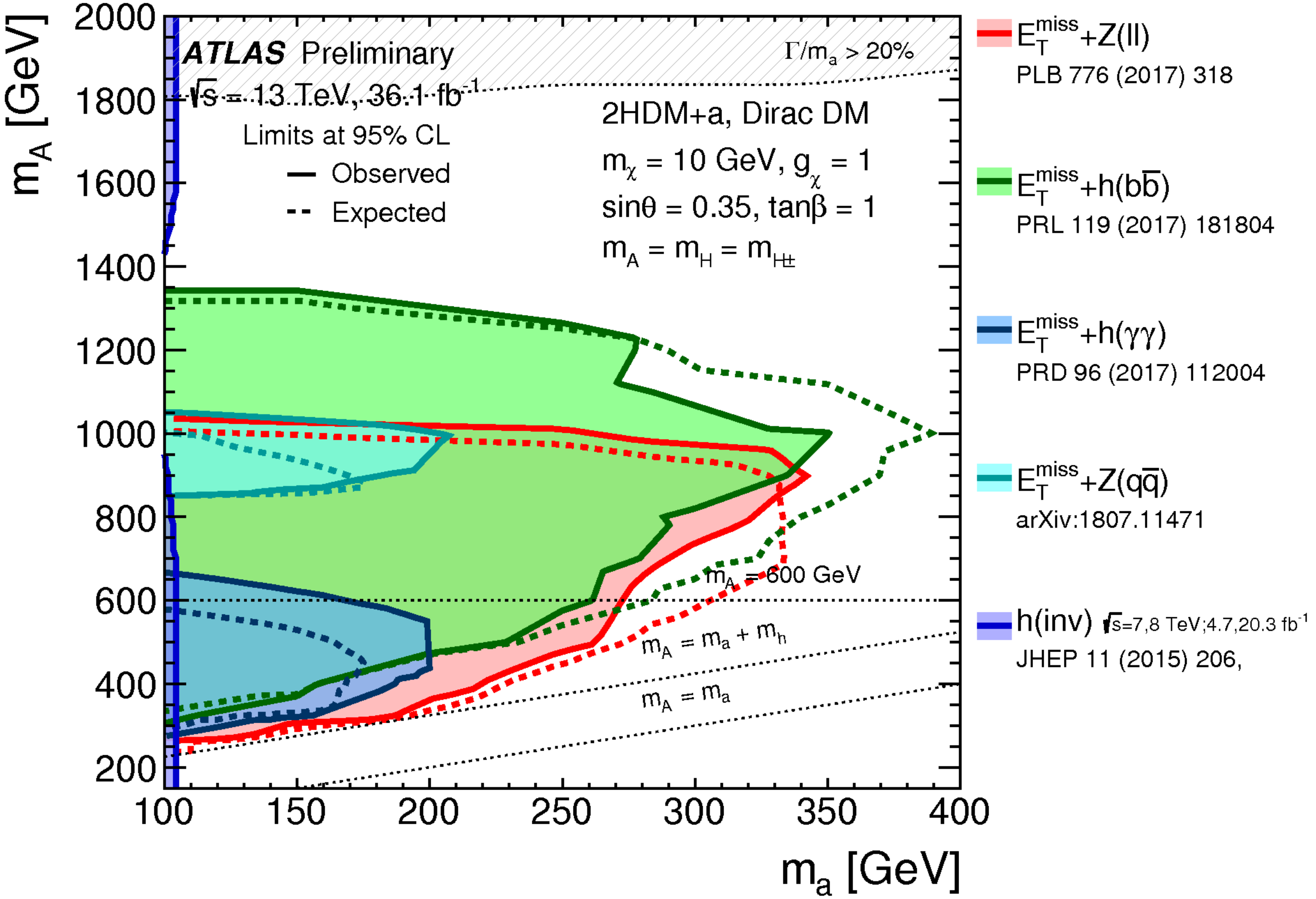
Summary of Dark Matter Searches

(first ATLAS limits on 2HDM+a!) ATLAS-CONF-2018-051 [20]

- **mono-V(jj)** and **mono-H($b\bar{b}$)** measurements contribute to an overall summary of Dark-Matter searches
- group together analyses with same underlying benchmark models (e.g. vector mediator model)
- in addition, **new signal models** are introduced and several analyses are **re-interpreted** in the new context (using RECAST* framework)



UV complete model, dedicated to LHC searches (small cross section for direct detection)



***RECAST**: framework for re-interpretations of a given analysis in context of other signal models but featuring similar final-state signatures. Saves simulation resources and helps for data preservation.

Peak Instantaneous Luminosity Values

L_{peak} (Run 1 @ $\sqrt{s}$ = 7 TeV) ≈ 0.0035 pb^{-1} / s

L_{peak} (Run 1 @ $\sqrt{s}$ = 8 TeV) ≈ 0.0077 pb^{-1} / s

L_{peak} (Run 2 @ $\sqrt{s}$ = 13 TeV) ≈ 0.0214 pb^{-1} / s

(**Conversion**: 1.0 × 10^{33} cm^{-2} s^{-1} = 0.001 pb^{-1} s^{-1})

Cross-Section Values

$\sigma_{t\bar{t}Z}$ ≈ 0.137 pb ($\sqrt{s}$ = 7 TeV) JHEP11(2012)056

$\sigma_{t\bar{t}Z}$ ≈ 0.206 pb ($\sqrt{s}$ = 8 TeV) JHEP11(2012)056

$\sigma_{t\bar{t}Z}$ ≈ 0.839 pb ($\sqrt{s}$ = 13 TeV) LHCHXS WG

$t\bar{t}Z$

	Total Produced	Rate @ Peak Luminosity
Run 1		
4.7 fb^{-1} ($\sqrt{s}$ = 7 TeV)	~640	~1.7 / hr
20.3 fb^{-1} ($\sqrt{s}$ = 8 TeV)	~4200	~ 5.7 / hr
Run 2		
140 fb^{-1} ($\sqrt{s}$ = 13 TeV)	~120k	~ 1 / min

** rates refer to production alone to give rough values (no detector-related efficiencies considered!)*

(reference for plot)

Standard Model Public Results