Bundesministerium für Bildung und Forschung

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

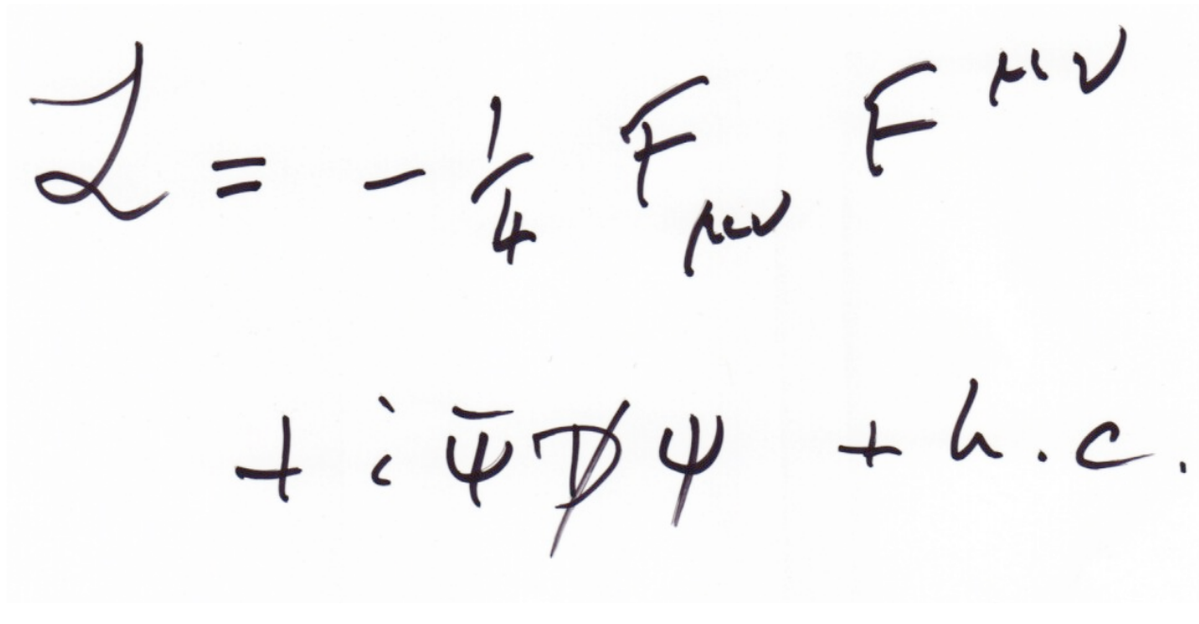
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Boosting the sensitivity to new physical phenomena at the LHC

Roman Kogler
University of Hamburg

HEPHY Vienna
Nov 12, 2019

The Standard Model



- c (SLAC, Brookhaven '74)
- τ (SLAC '75)
- b (Fermilab '77)
- g (DESY, '78-79)
- W/Z (CERN '83)
- t (Fermilab '95)

… did not mention the ν sector

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \Psi + h.c.$$

- c (SLAC, Brookhaven ’74)
- τ (SLAC ’75)
- b (Fermilab ’77)
- g (DESY, ’78-79)
- W/Z (CERN ’83)
- t (Fermilab ’95)

… did not mention the ν sector

$$+ |D_\mu \phi|^2 - V(\phi)$$

← H (CERN ’12)
and its gauge interactions

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \Psi + h.c.$$

- c (SLAC, Brookhaven ’74)
- τ (SLAC ’75)
- b (Fermilab ’77)
- g (DESY, ’78-79)
- W/Z (CERN ’83)
- t (Fermilab ’95)

… did not mention the ν sector

$$+ |D_\mu \phi|^2 - V(\phi)$$

← H (CERN ’12) and its gauge interactions

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

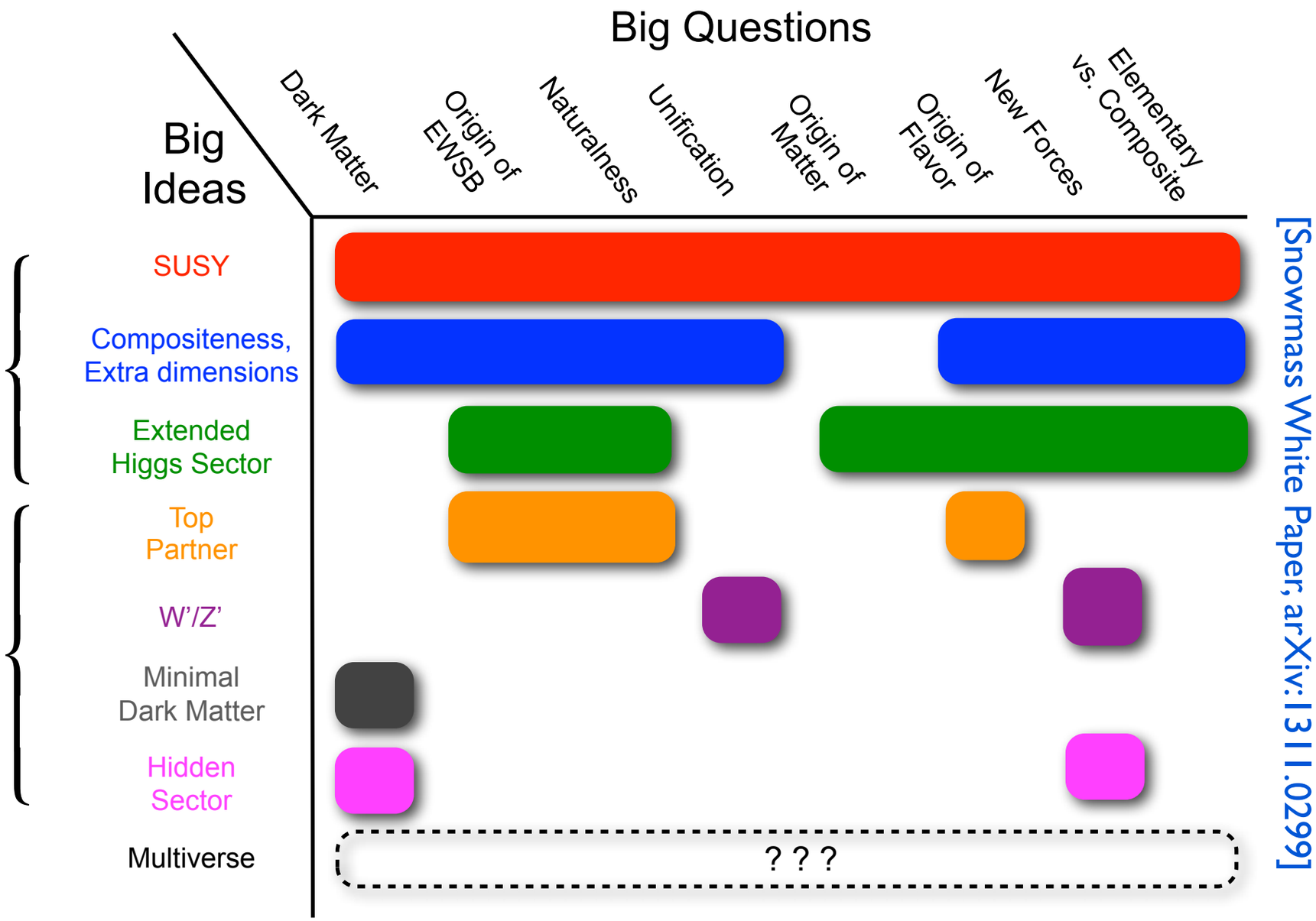
← Yukawa interactions (CERN ’16-18)

Beyond the Standard Model

Complete models

New matter fields / interactions

The unknown



- **Model-based searches**
- **Signature-based searches**

Searches?

Particle physics has coined the term

"Searches for New Physics"

but aren't these just measurements?

Searches?

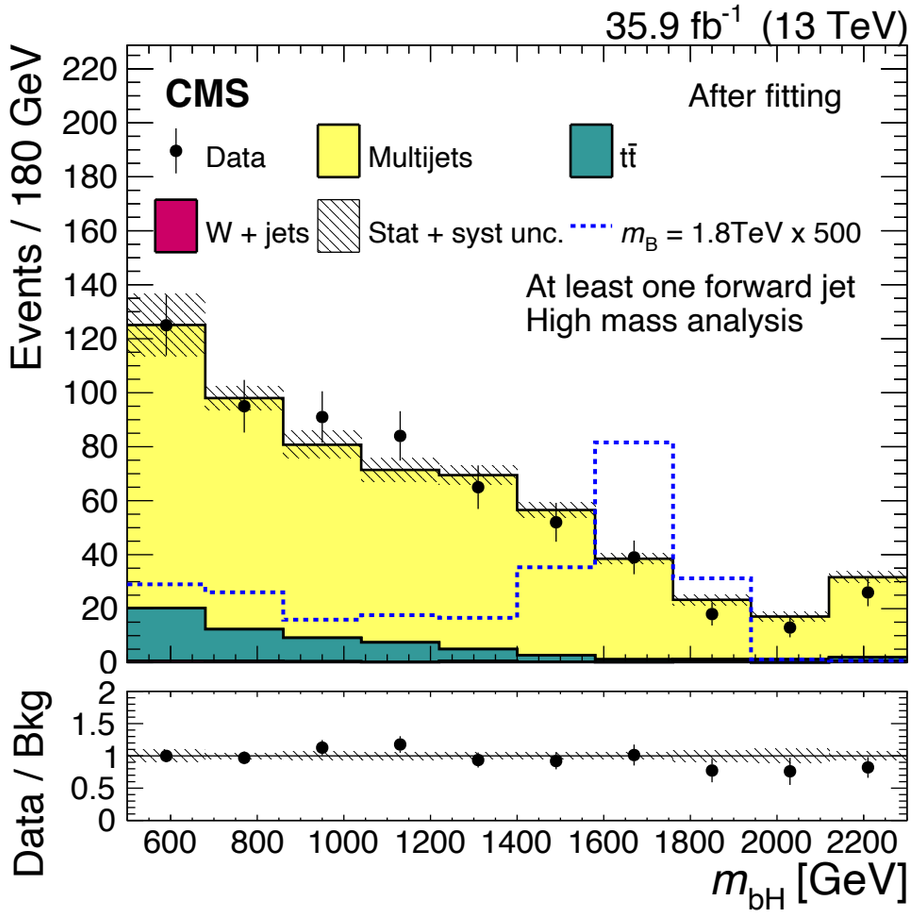
Particle physics has coined the term

"Searches for New Physics"

but aren't these just measurements?

Search for b+H(bb) in EW production

[CMS, JHEP 06, 031 (2018)]



Searches?

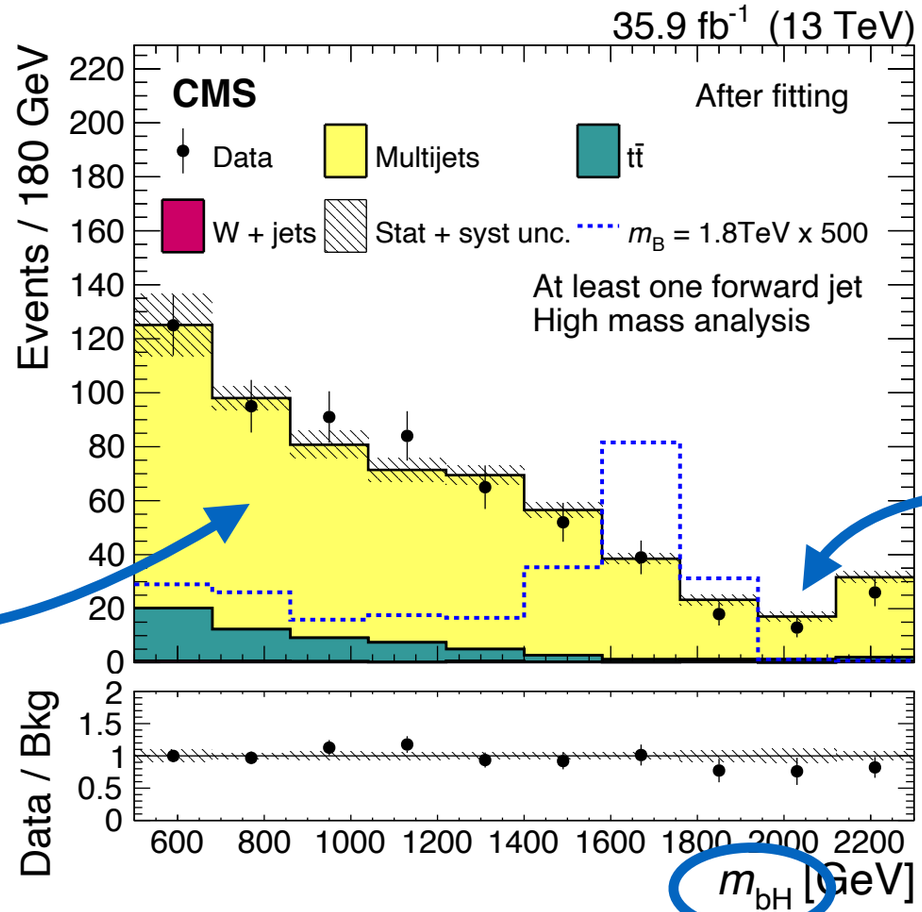
Particle physics has coined the term

"Searches for New Physics"

but aren't these just measurements?

Search for b+H(bb) in EW production

[CMS, JHEP 06, 031 (2018)]



selected events: composted mostly of fakes

tails: small number of events

observable: useless in SM context

Searches?

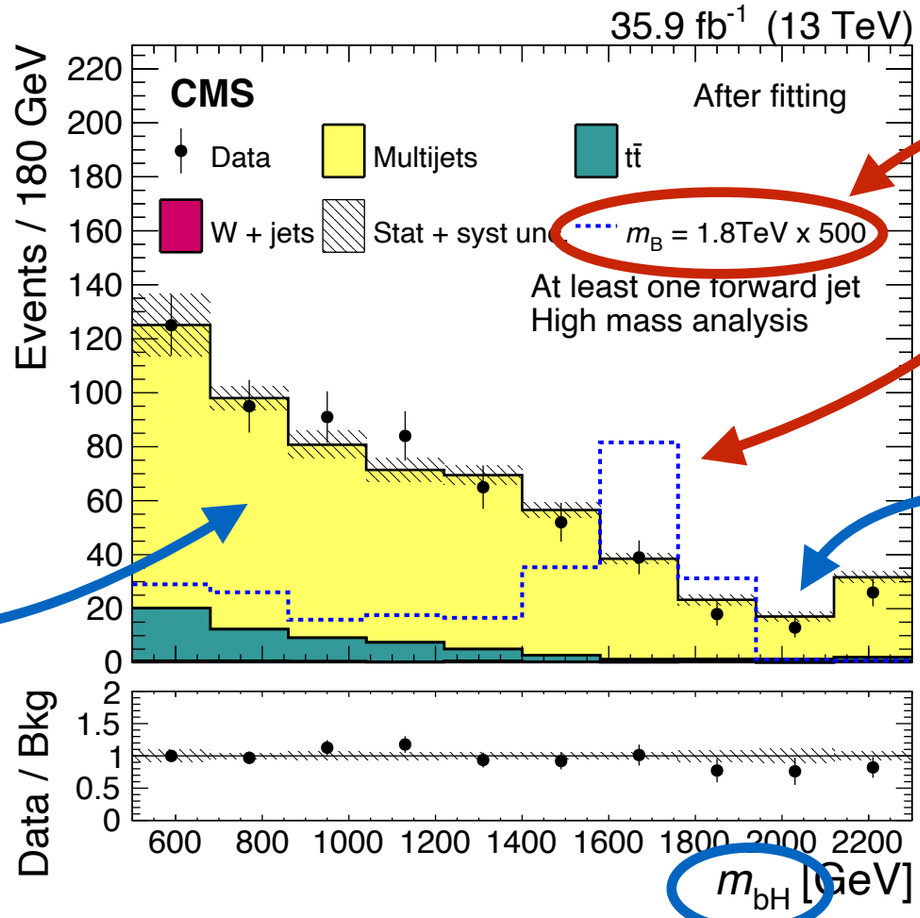
Particle physics has coined the term

"Searches for New Physics"

but aren't these just measurements?

Search for b+H(bb) in EW production

[CMS, JHEP 06, 031 (2018)]



BUT: sensitivity to tiny signal!

selected events: composted mostly of fakes

tails: small number of events

observable: useless in SM context

Overview

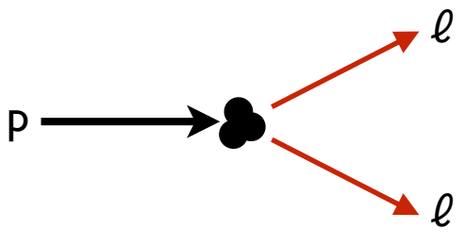
- Methodology
- Searches
  - Diboson resonances
  - tt resonances
  - Vector-like quarks
  - Leptoquarks
- Improving jet substructure methods
- Measurements

Emphasis on new results with personal involvement / interest

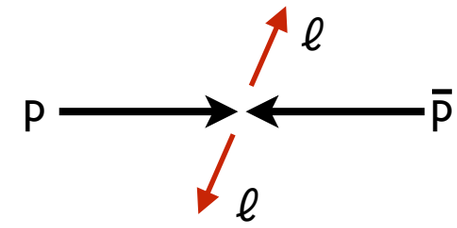
not complete selection

Disclaimer: focus on simple interpretations in benchmark models, more complete interpretations possible and available

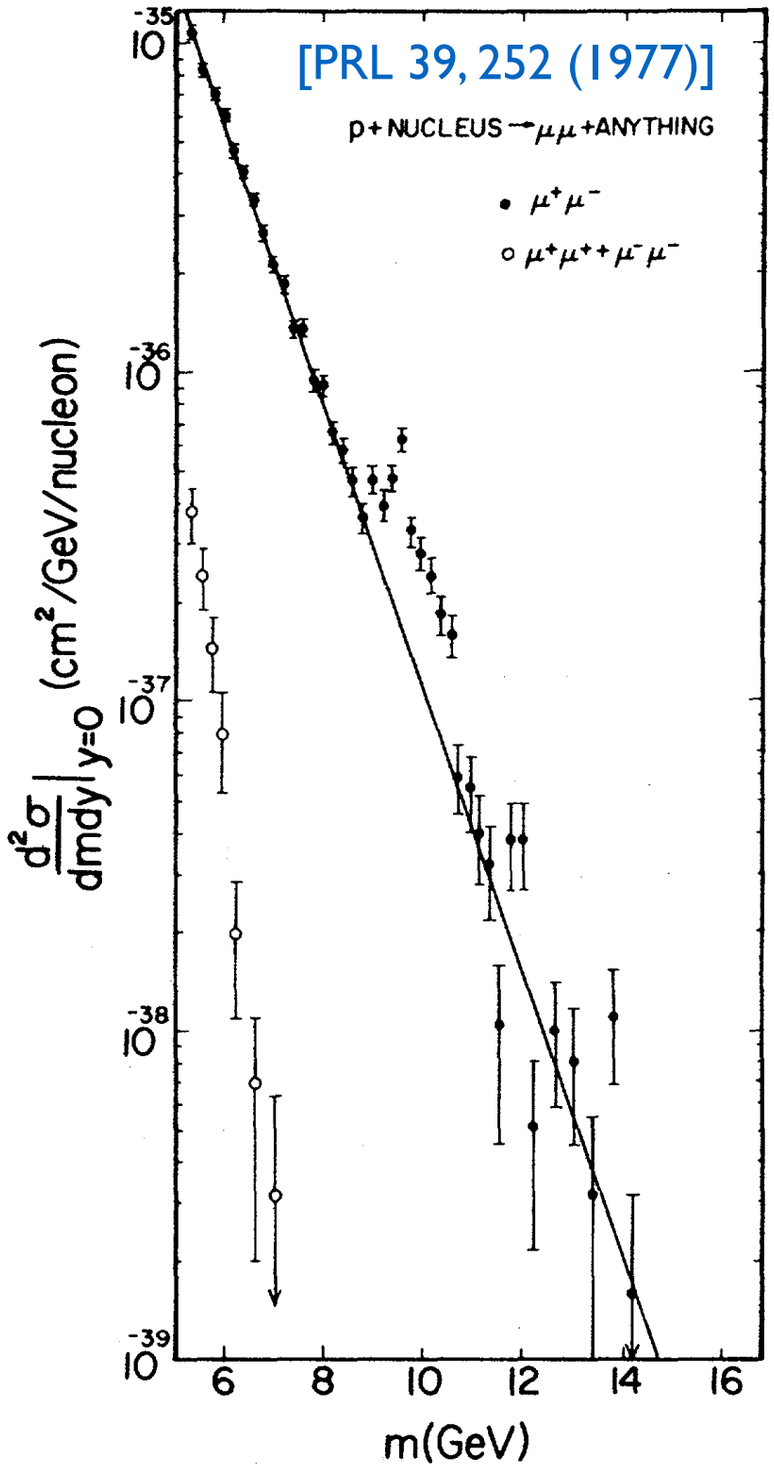
Methodology



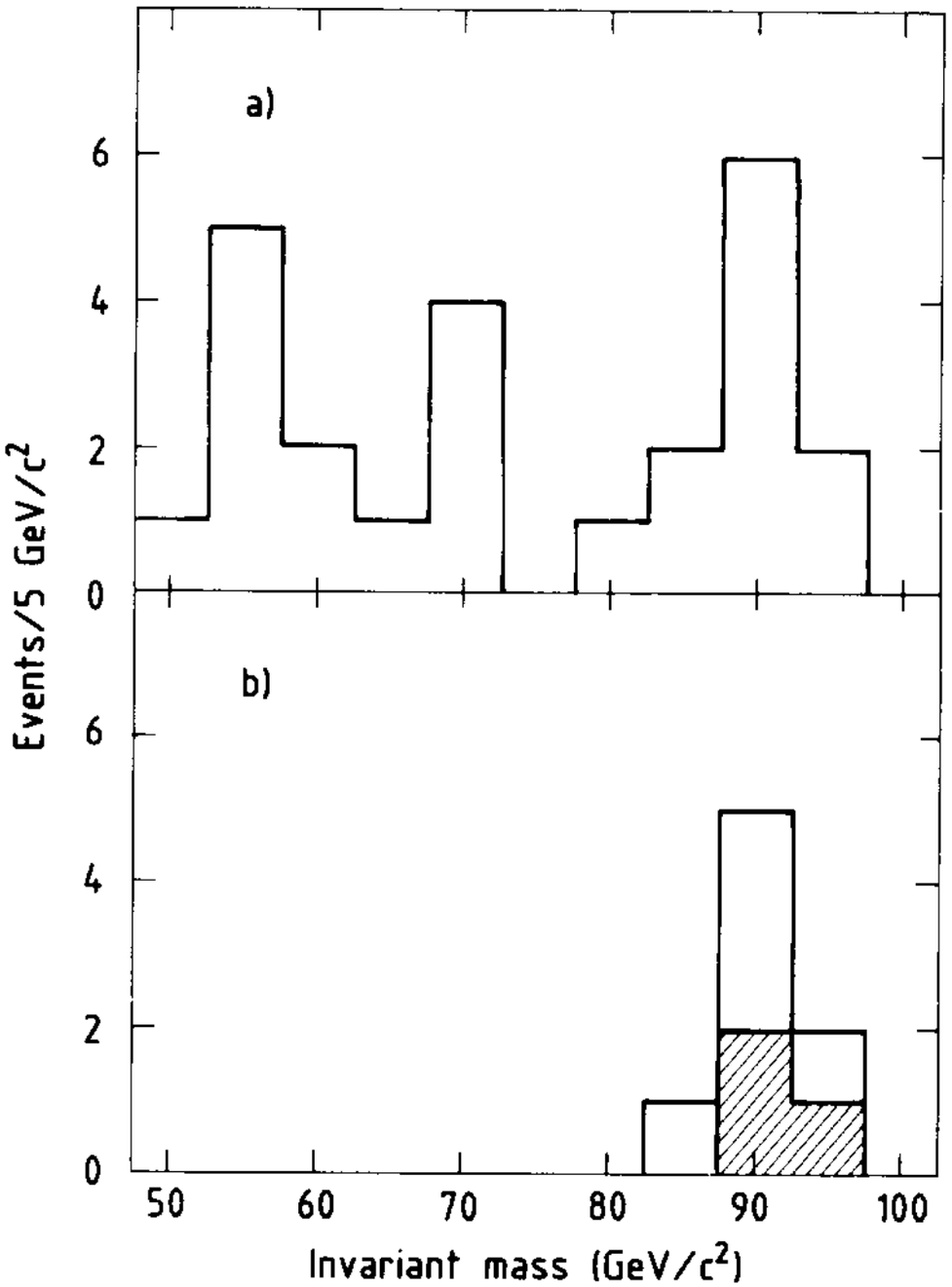
ℓℓ Resonances

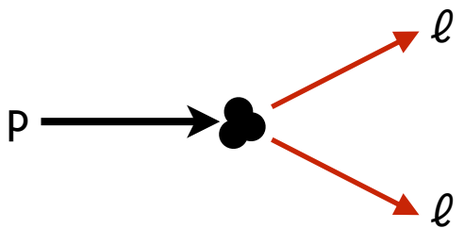


[PRL 39, 252 (1977)]

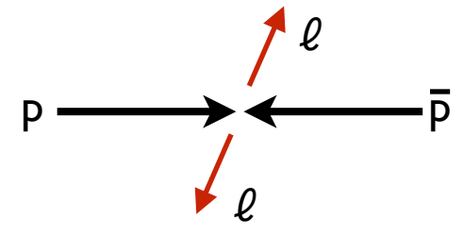


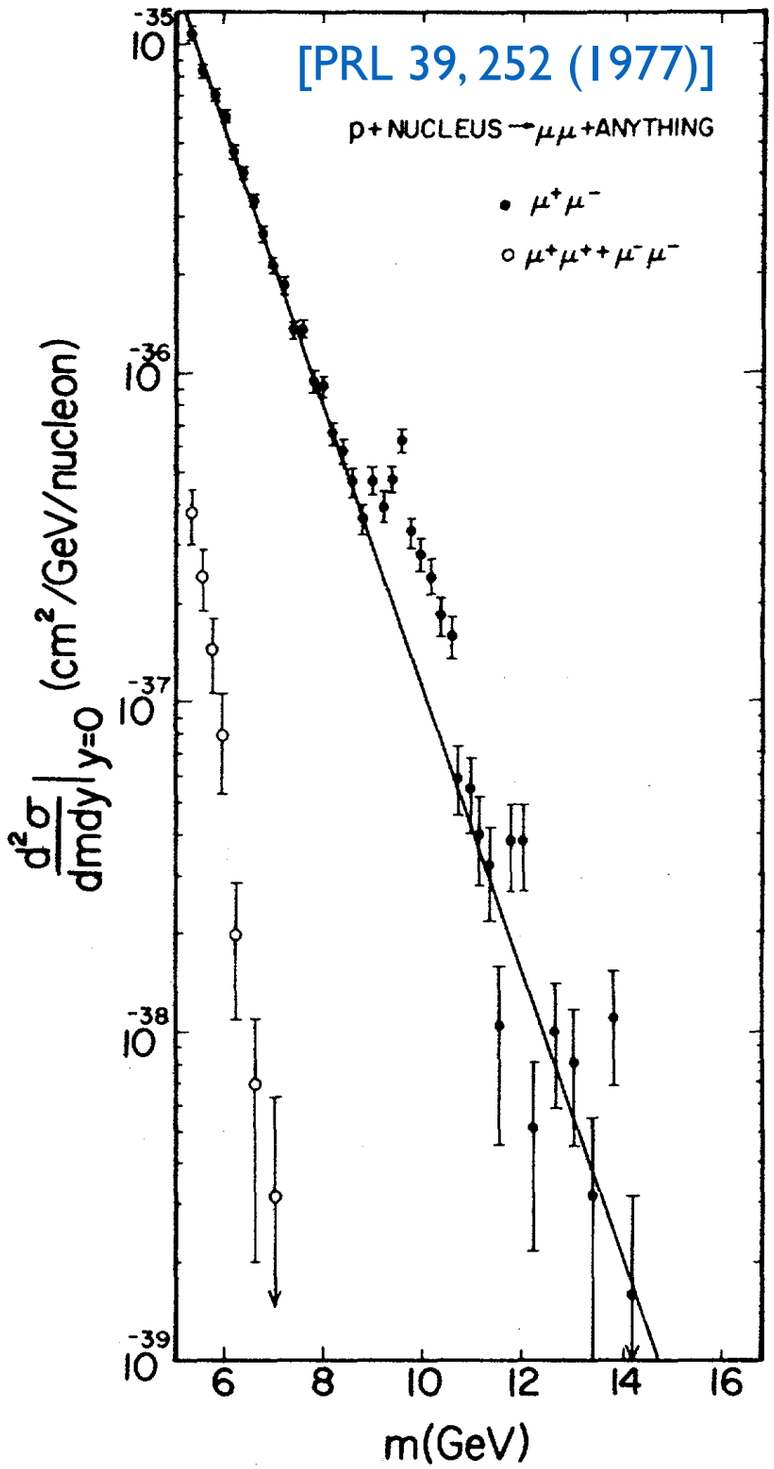
[UA1, PLB126, 398 (1983)
UA2, PLB129, 130 (1983)]



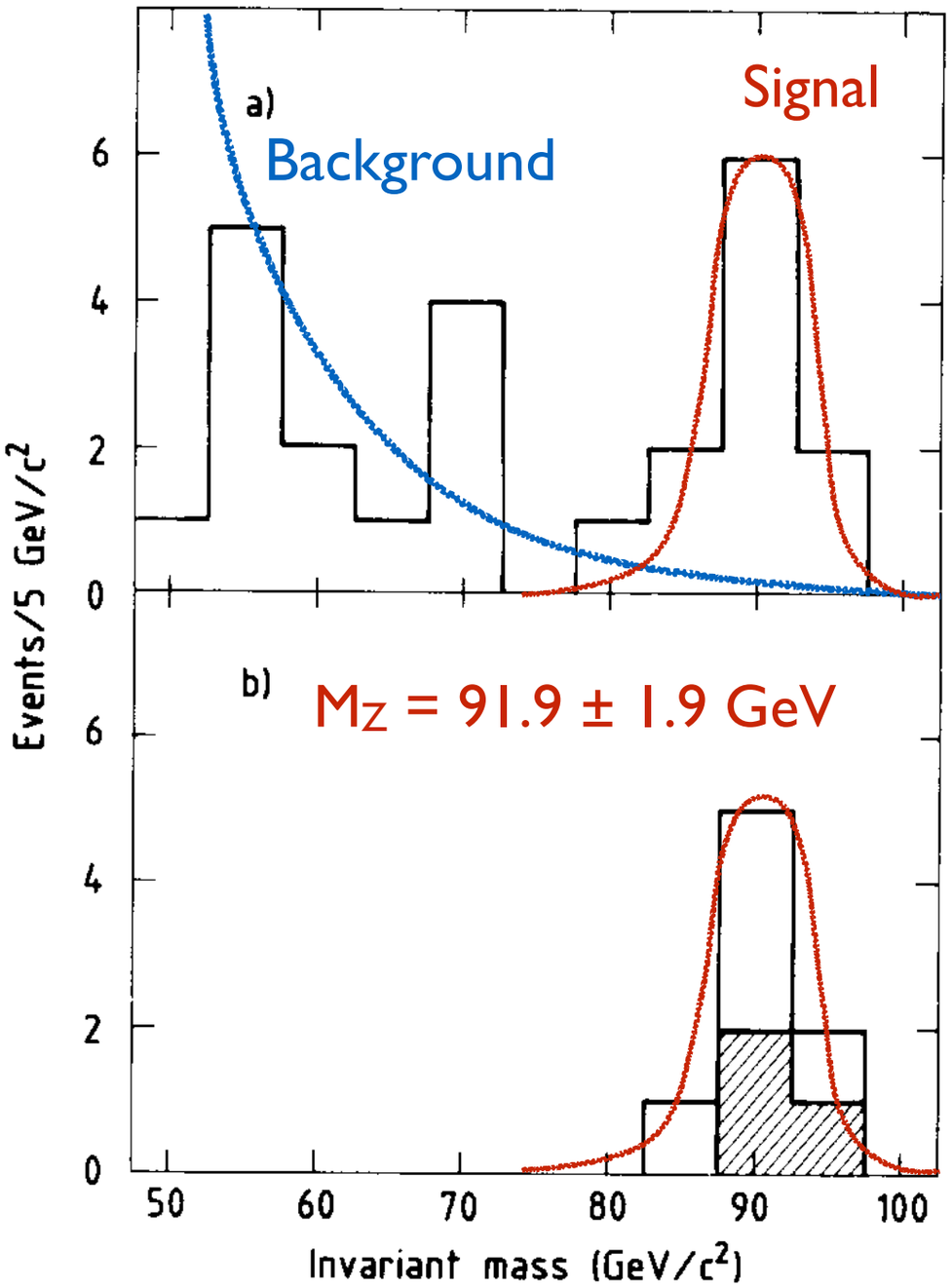


ℓℓ Resonances

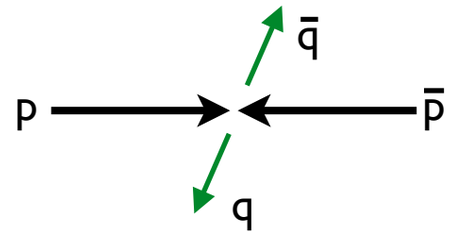




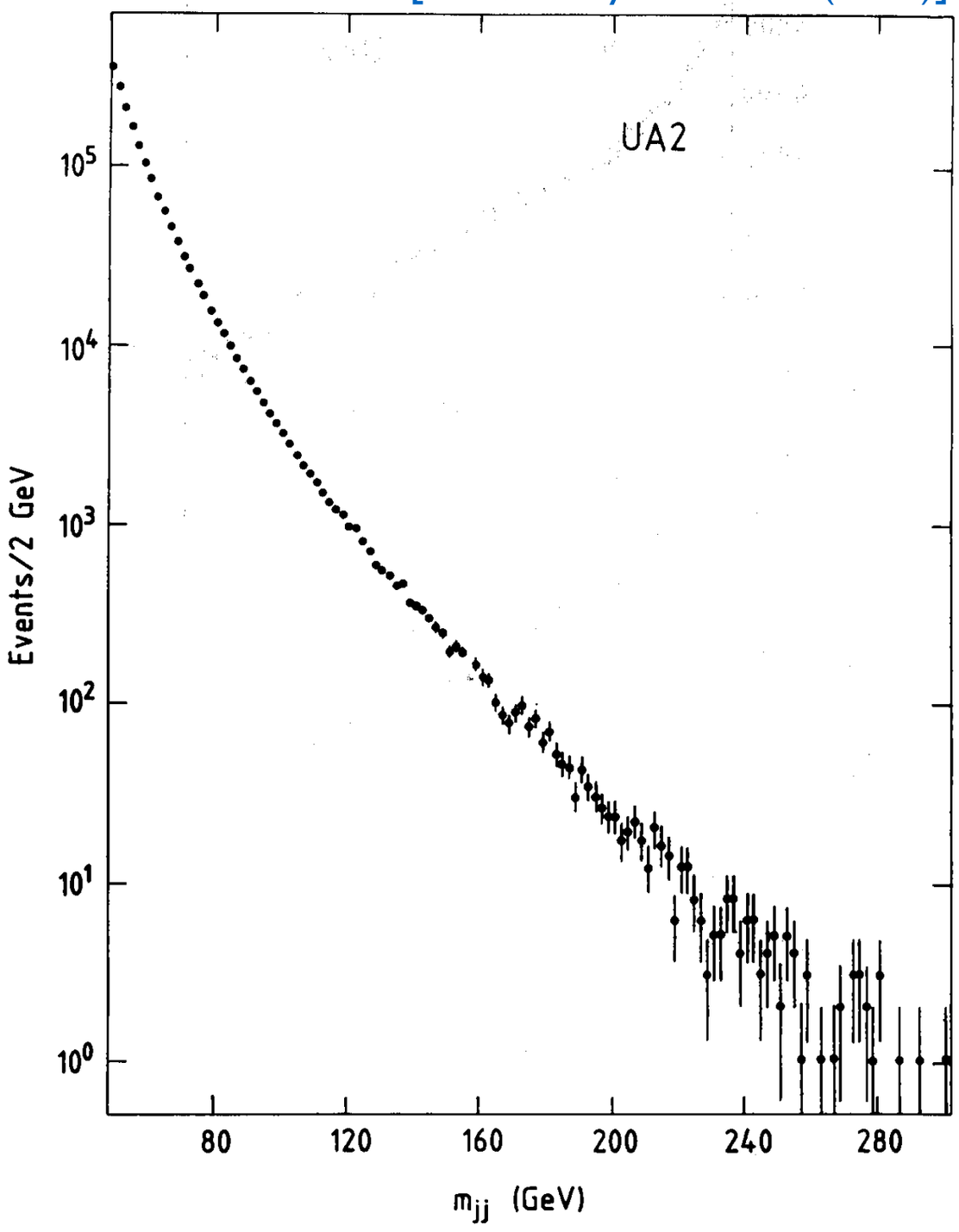
[UA1, PLB126, 398 (1983)
UA2, PLB129, 130 (1983)]



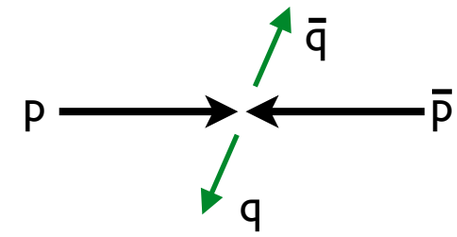
qq/gg Resonances



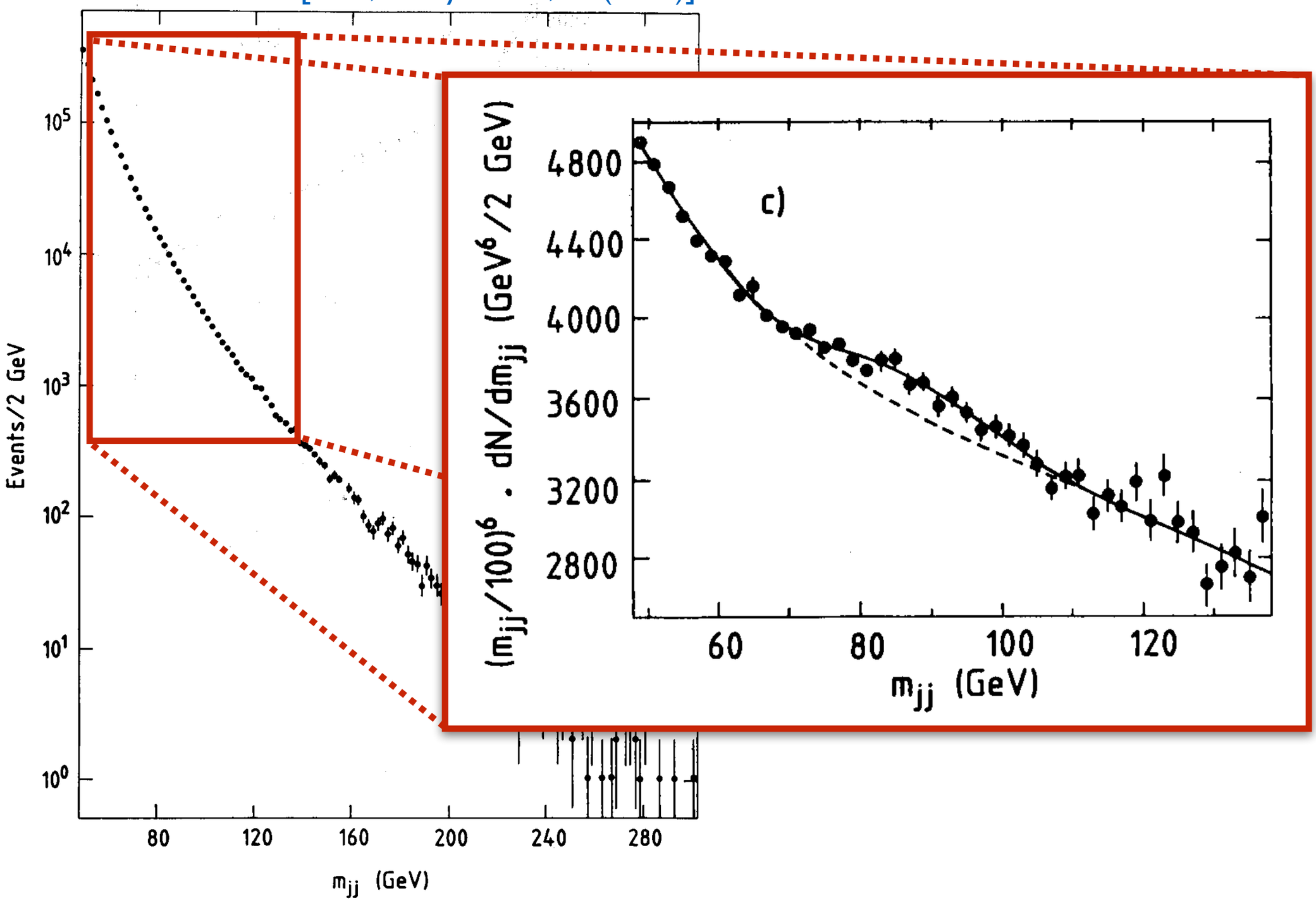
[UA2, Z. Phys. C 49, 17 (1991)]



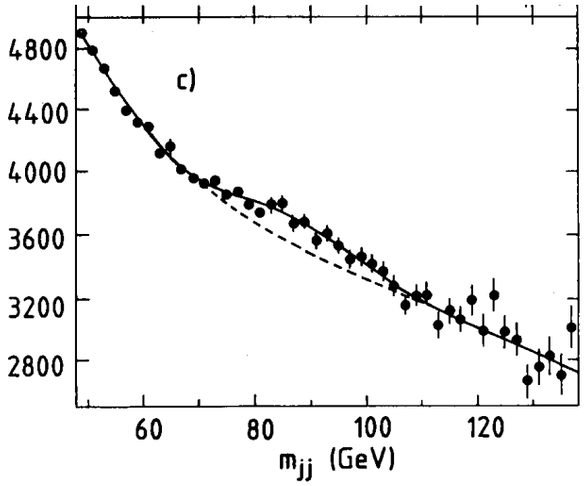
qq/gg Resonances

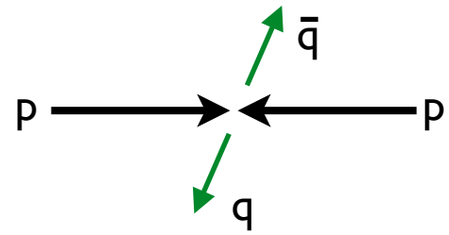


[UA2, Z. Phys. C 49, 17 (1991)]

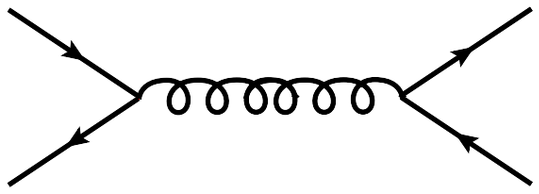


qq/gg Resonances



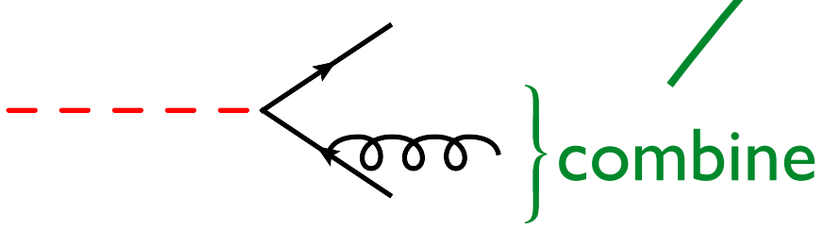


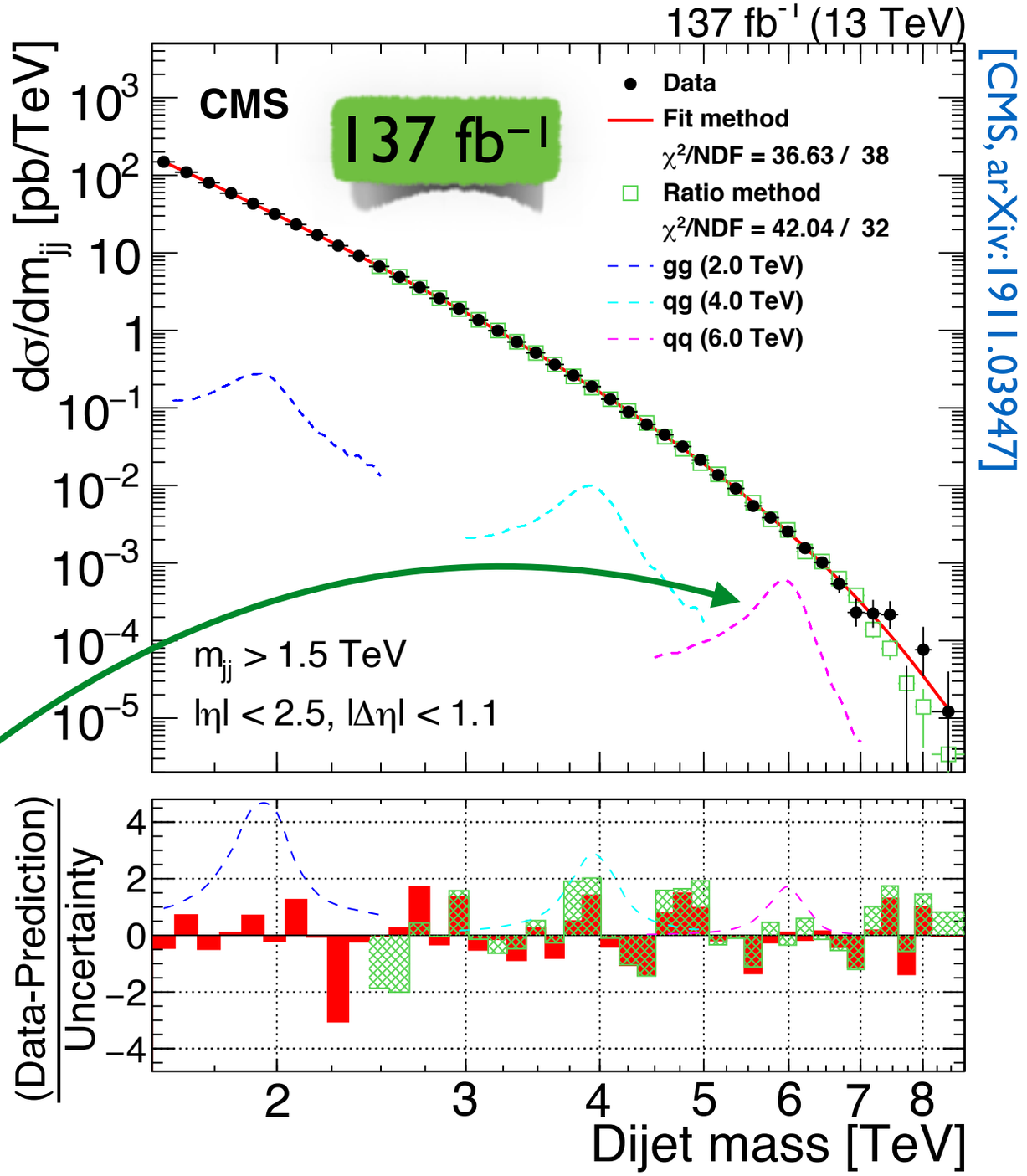
SM



BSM

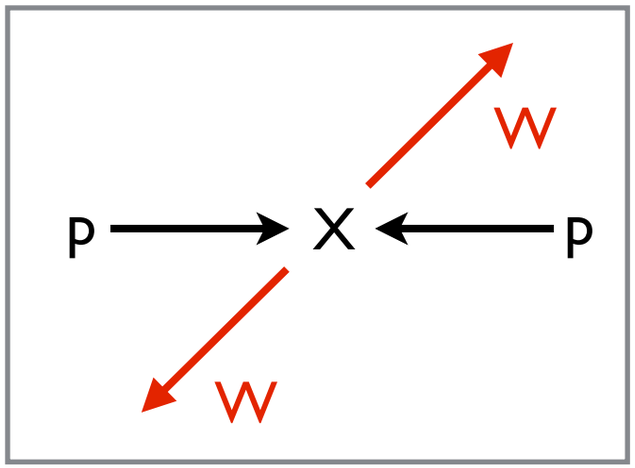
H.O.





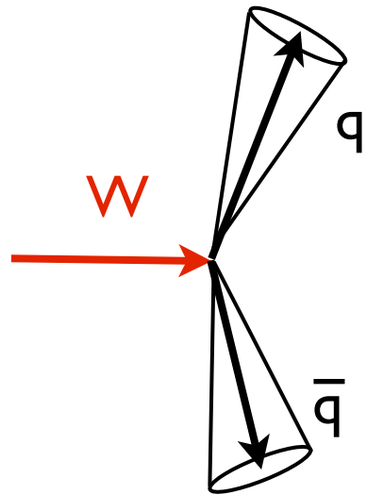
Boost!

pp→X→WW→Jets

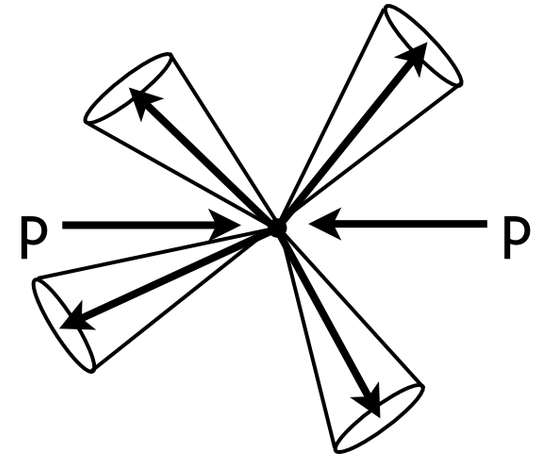


$M_X \sim 2\ M_W$

p_T^W small, $\gamma \lesssim 5$



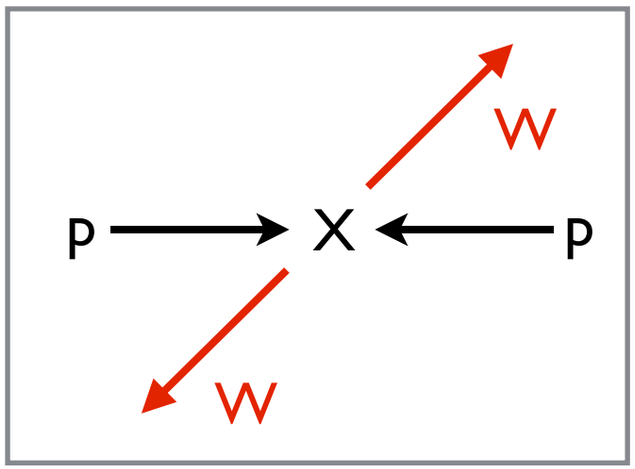
4 jet final state



combinatorics, background!

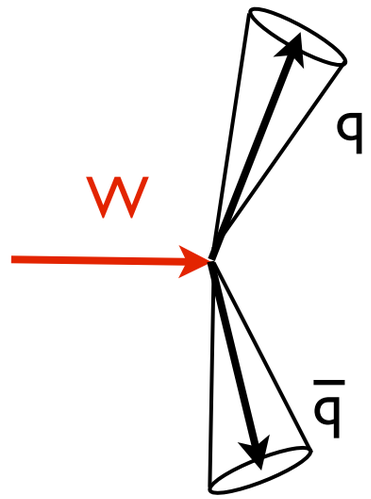
Boost!

pp→X→WW→Jets

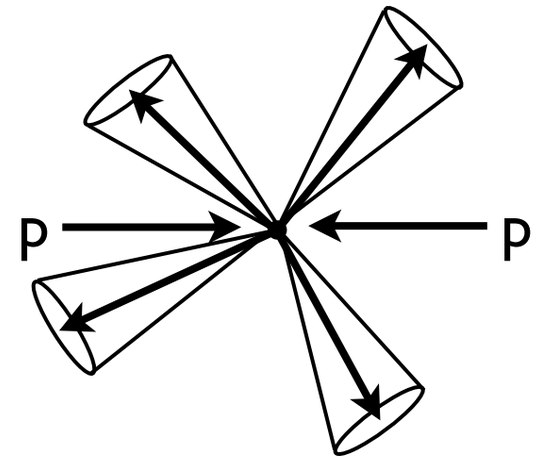


$M_X \sim 2\ M_W$

p_T^W small, $\gamma \lesssim 5$



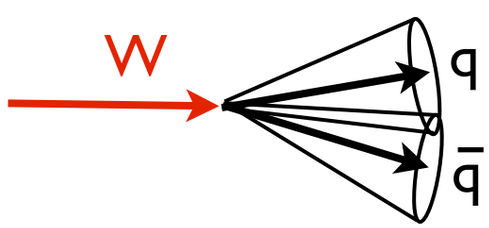
4 jet final state



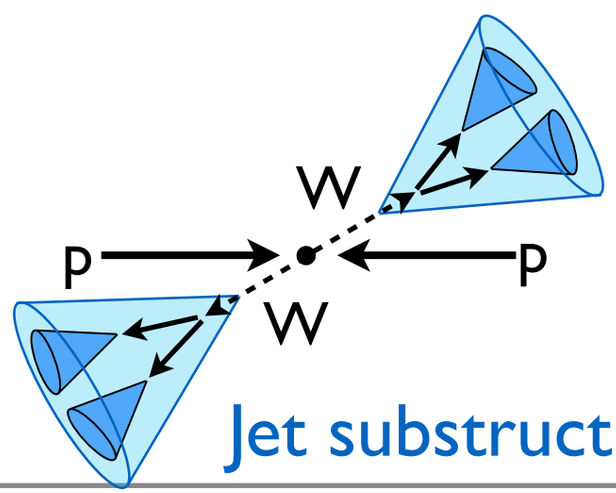
combinatorics, background!

$M_X \gg 2\ M_W$

p_T^W large, $\gamma \gg 5$



Dijet final state

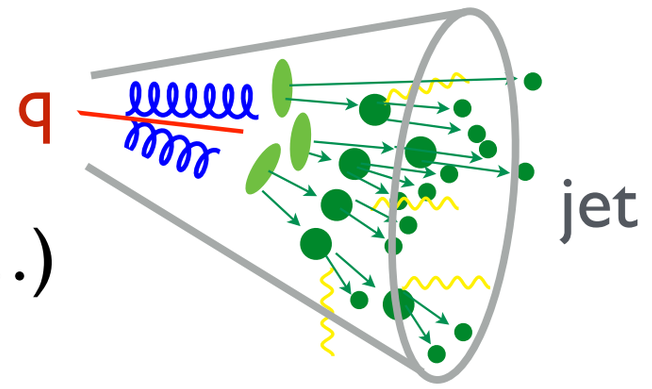


Jet substructure

W/Z/H Boson-Tagging I

Separation of QCD branching and 2-prong structure

1) Jetmass $M_{\text{jet}} = \left(\sum_i p_i \right)^2$



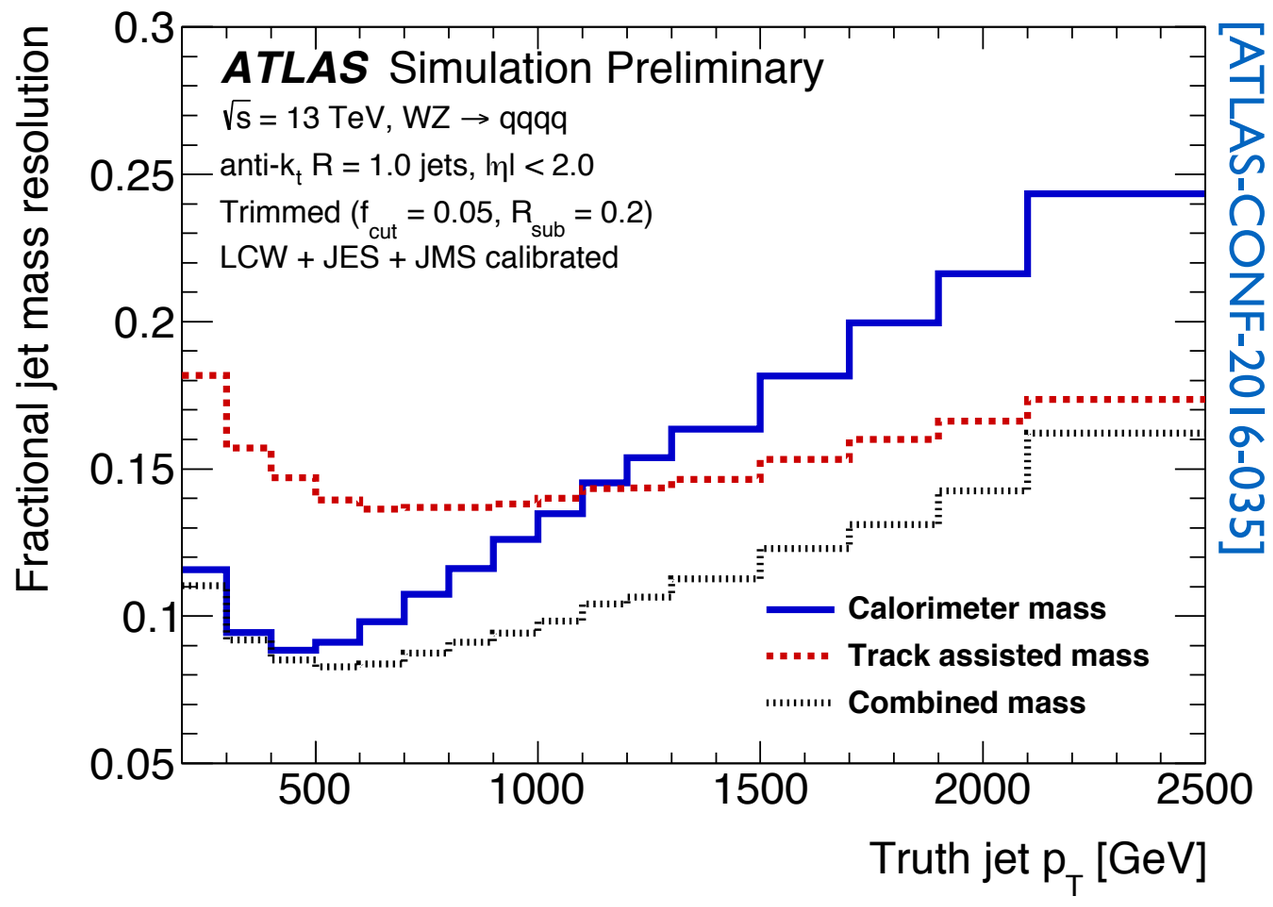
Subject to many systematic sources (rad, had, UE, PU…)

$$\delta M_{\text{UE/PU}} \propto p_T R^4$$

corrections through dedicated algorithms

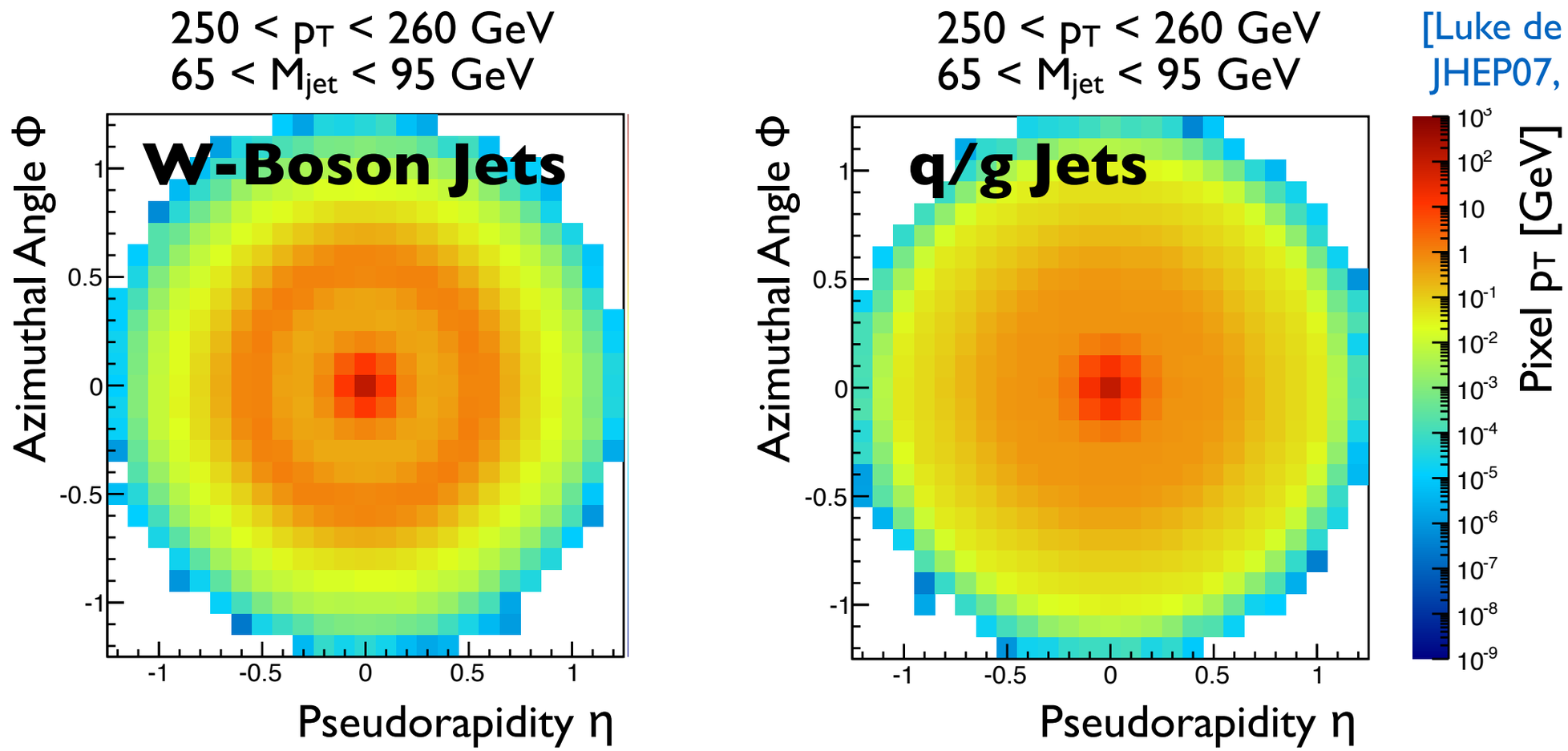
- PF+PUPPI (cal, PU, CMS)
- Track-assisted jet mass (cal, ATLAS)
- Soft-drop (UE/had, CMS)
- Trimming (PU/UE/had, ATLAS)

10-15% misidentification at 70-80% signal efficiency



W/Z/H Boson-Tagging 2

2) Substructure



[Luke de Oliveira et al., JHEP07, 069 (2016)]

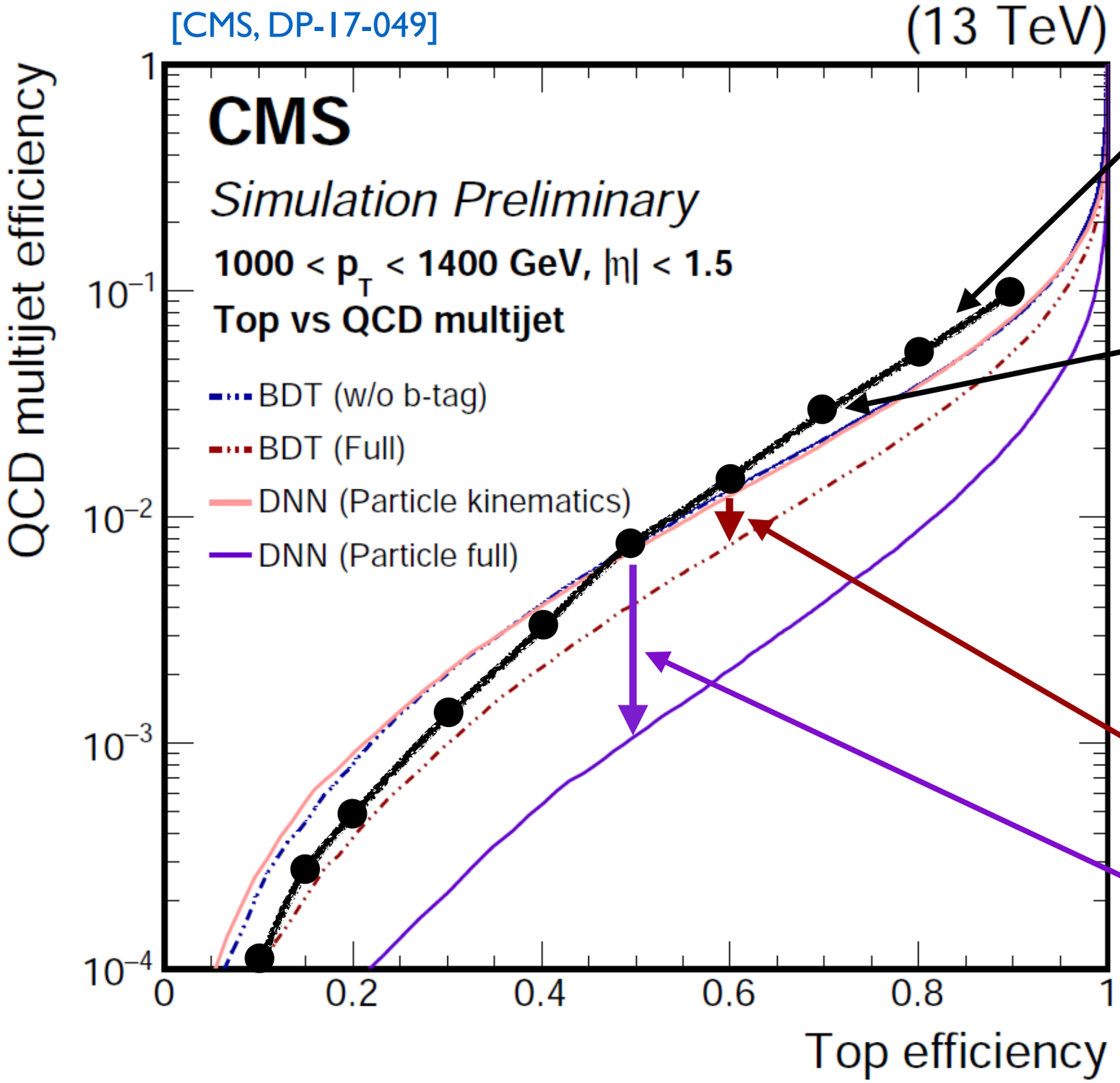
Exploit characteristic radiation pattern

- N-subjettiness ratios τ_2/τ_1 (CMS)
- Energy correlation ratios D_2 (ATLAS)
- Subjet b-tagging for H→bb (ATLAS/CMS)

1-5% misidentification at
50-60% signal efficiency

Top Quark Tagging

[CMS, DP-17-049]



soft drop mass,
$\tau_{3/2}$, subjet b
[CMS-PAS-JME-15-002]

today's standard
2-3% misidentification at
70% signal efficiency

A prime example for machine learning

gain from a BDT

gain from a deep neural network

[see also CMS-PAS-JME-18-002, ATL-PHYS-PUB-2017-004]

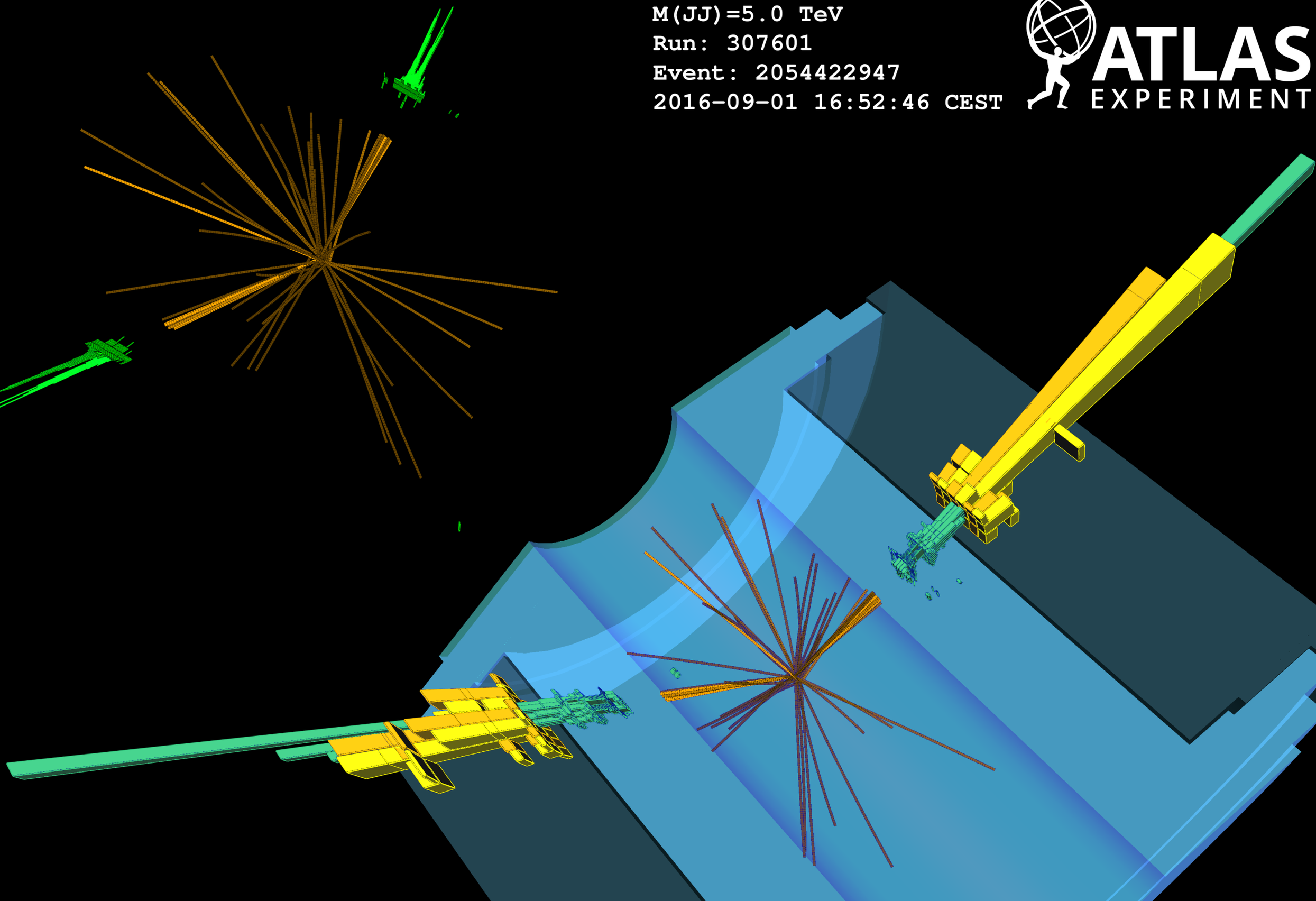
Searches

with heavy SM particles in the final state

Diboson-tagged dijet event, M_{JJ} = 5.0 TeV

M(JJ)=5.0 TeV
Run: 307601
Event: 2054422947
2016-09-01 16:52:46 CEST

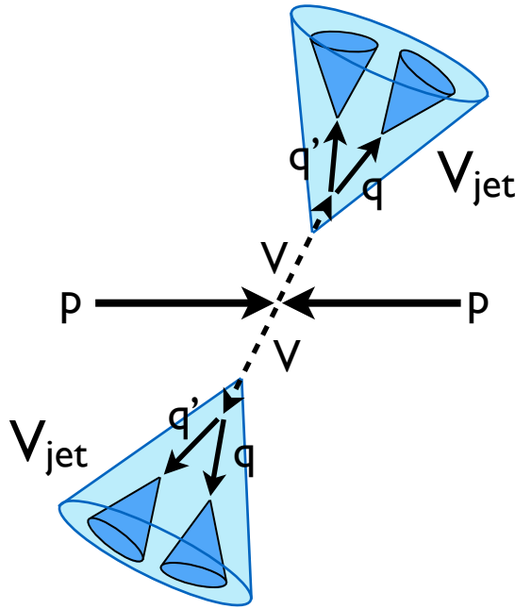
ATLAS EXPERIMENT



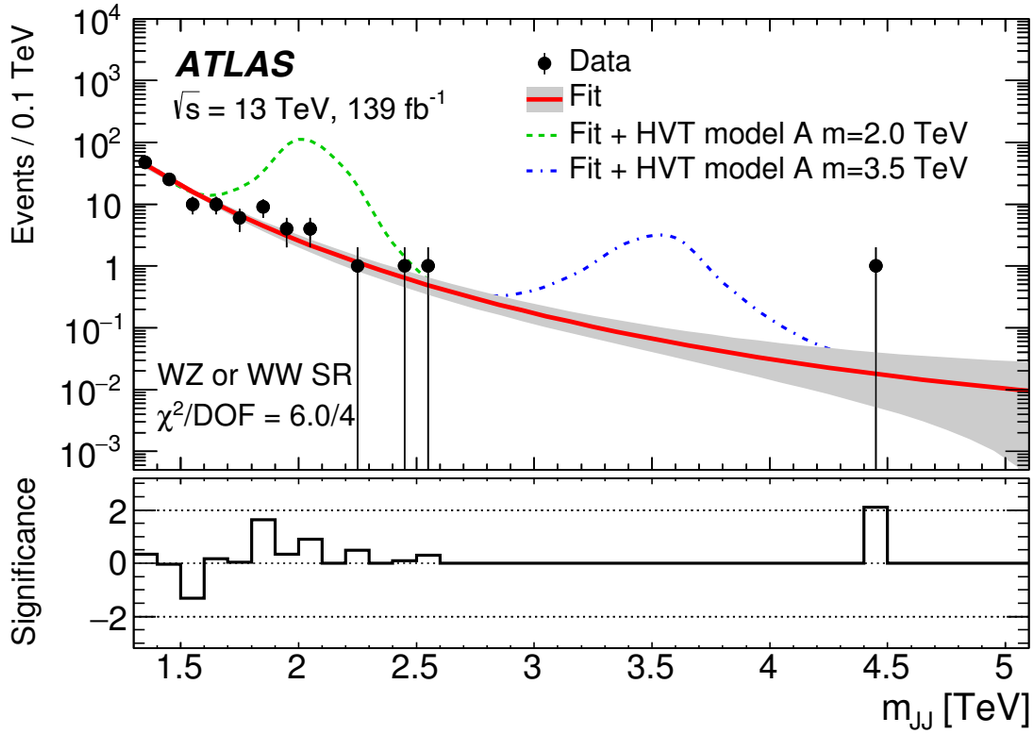
VV Resonances

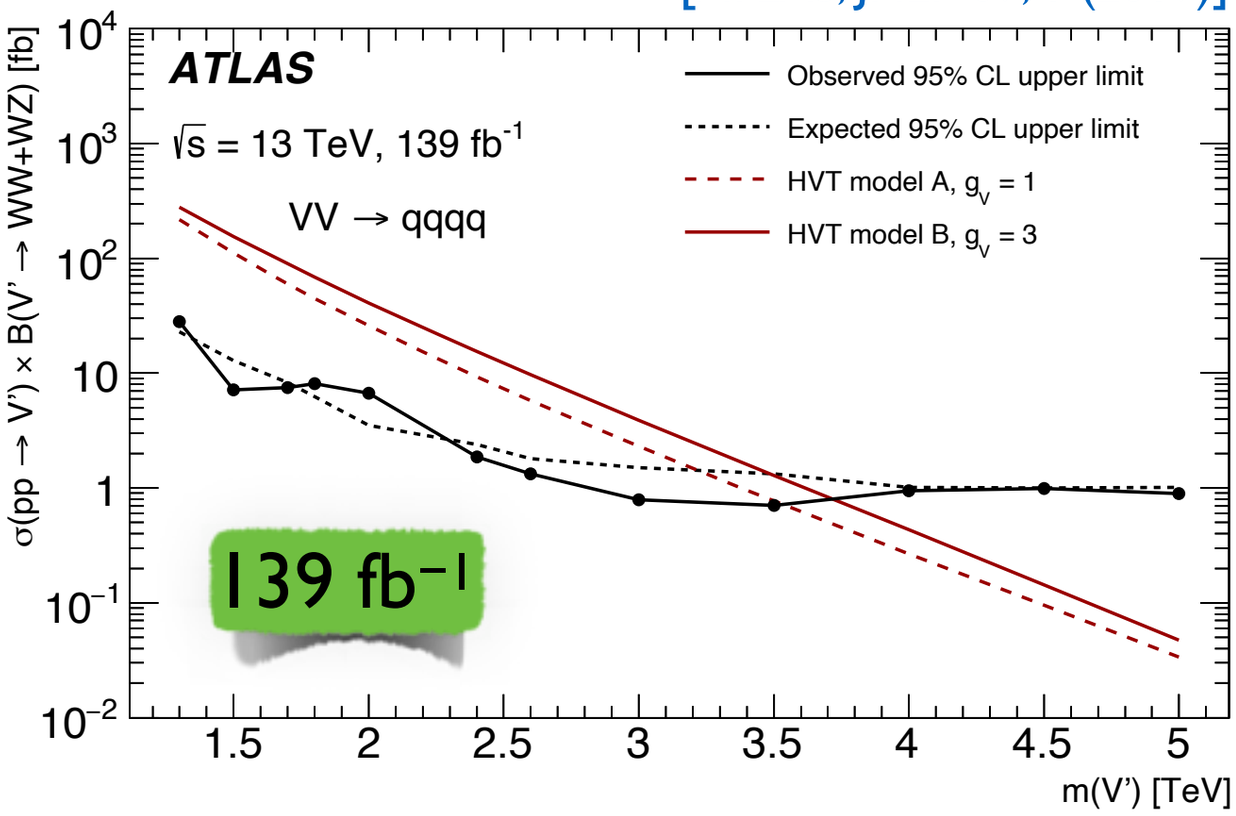
Improved jet substructure resolution with tracking information (TCCs):
50% improvement at high p_T

Optimal S/B with p_T dependent mass and D_2 selections



[ATLAS, JHEP 09, 1 (2019)]

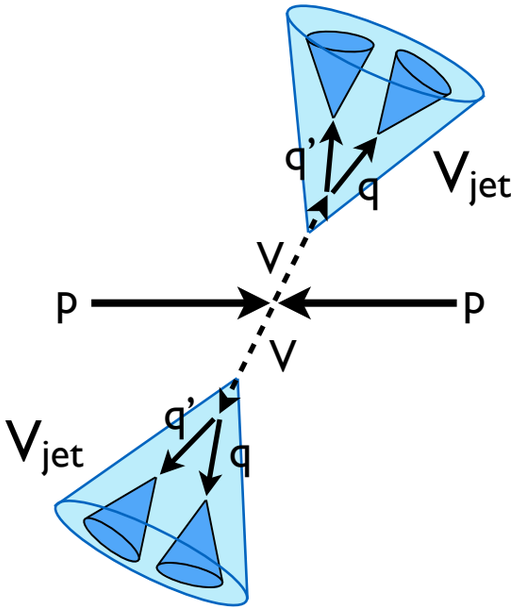




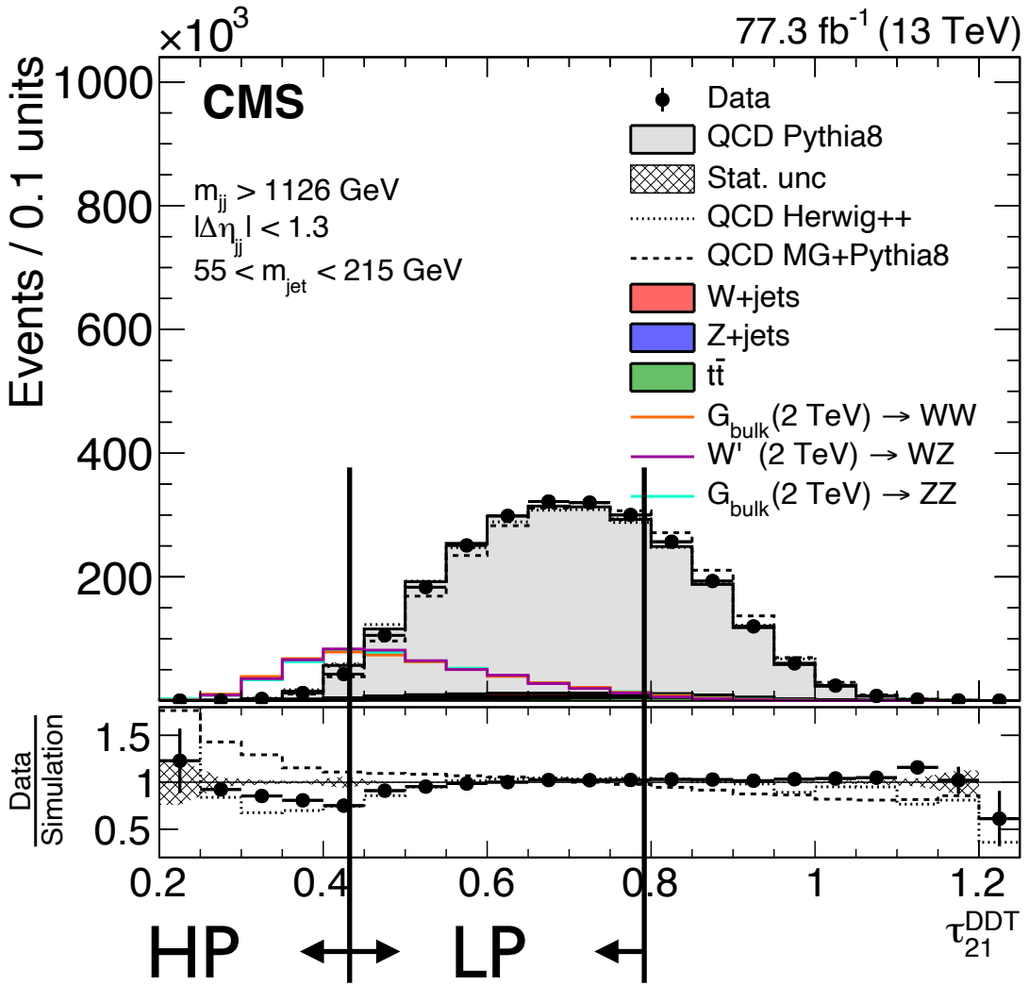
Excluded masses up to 3.5 and 3.8 TeV

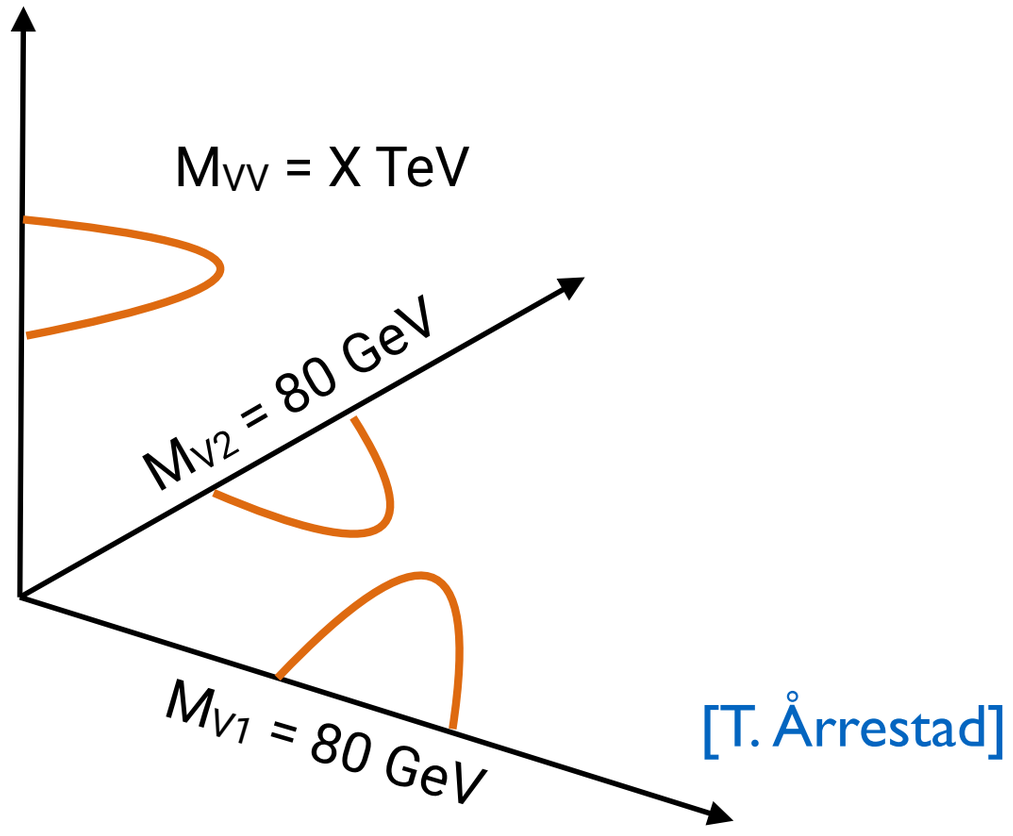
Extension to 4- and 5-prongs: [CMS, arXiv:1806.01058]

VV Resonances



[CMS, arXiv:1906.05977]





[T. Årrestad]

2 Signal categories

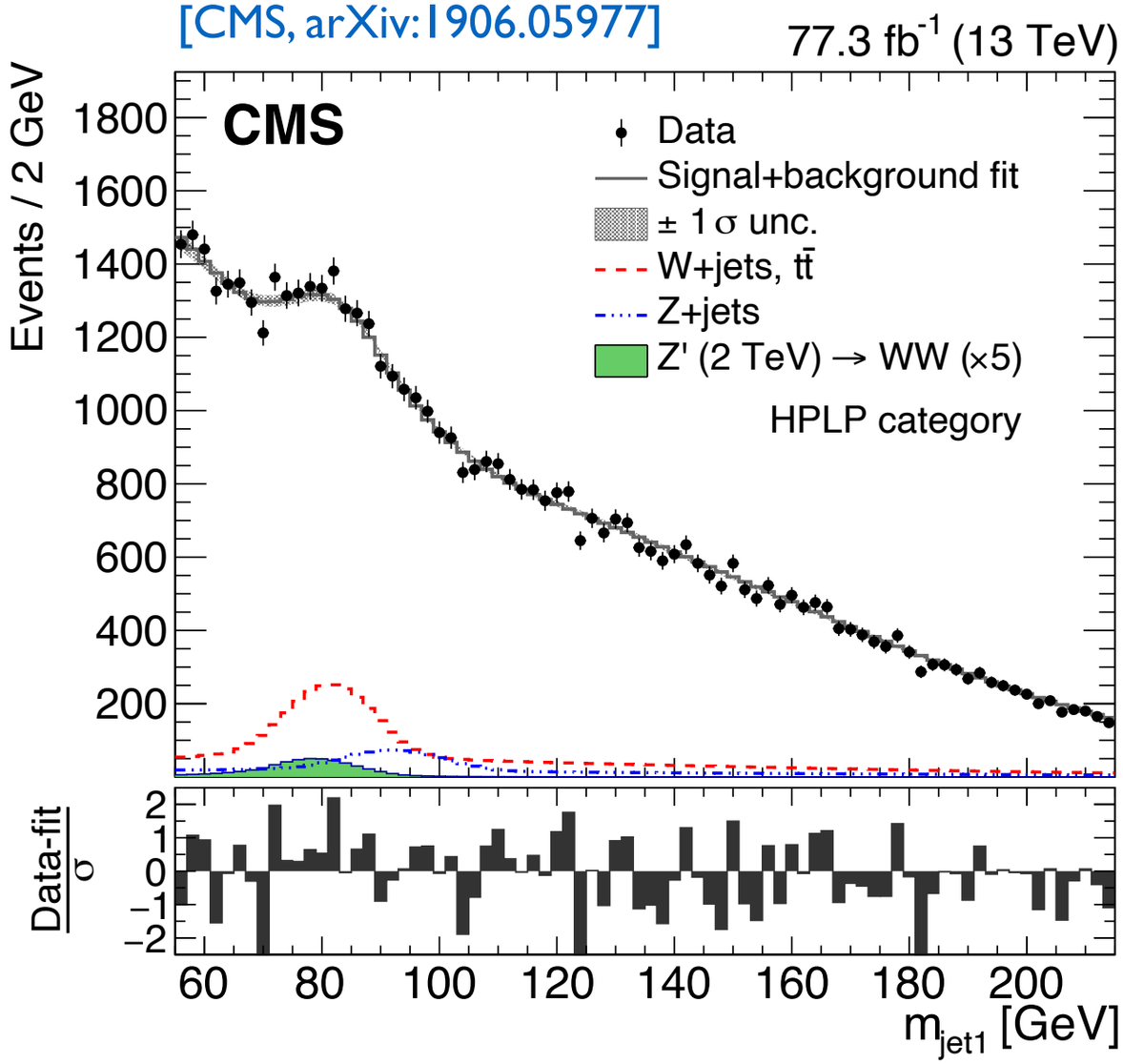
(WW, WZ, ZZ) x (HP, LP)

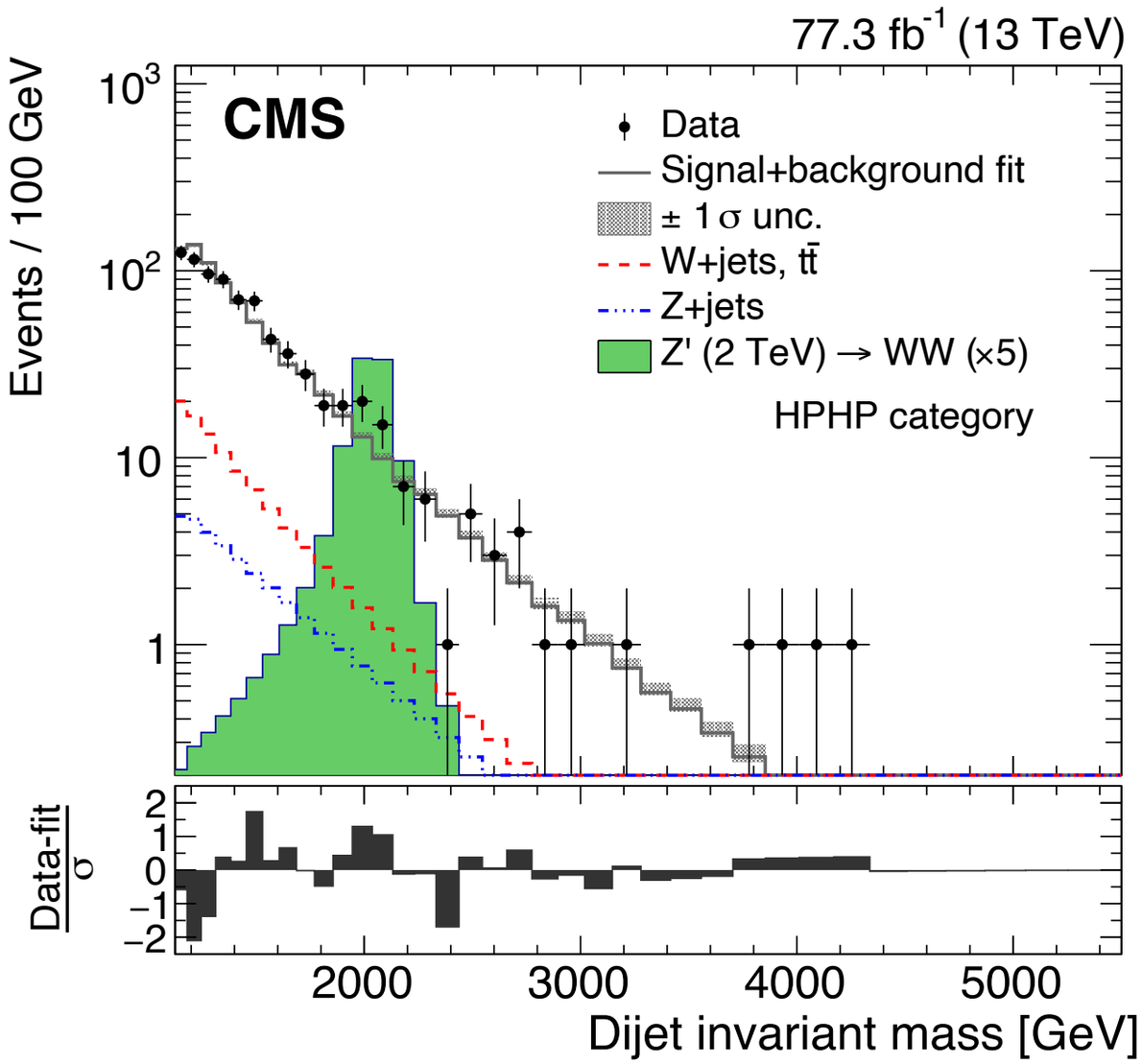
Background estimation

3 dimensional fit in m_{J1}, m_{J2} m_{JJ}

VV Resonances

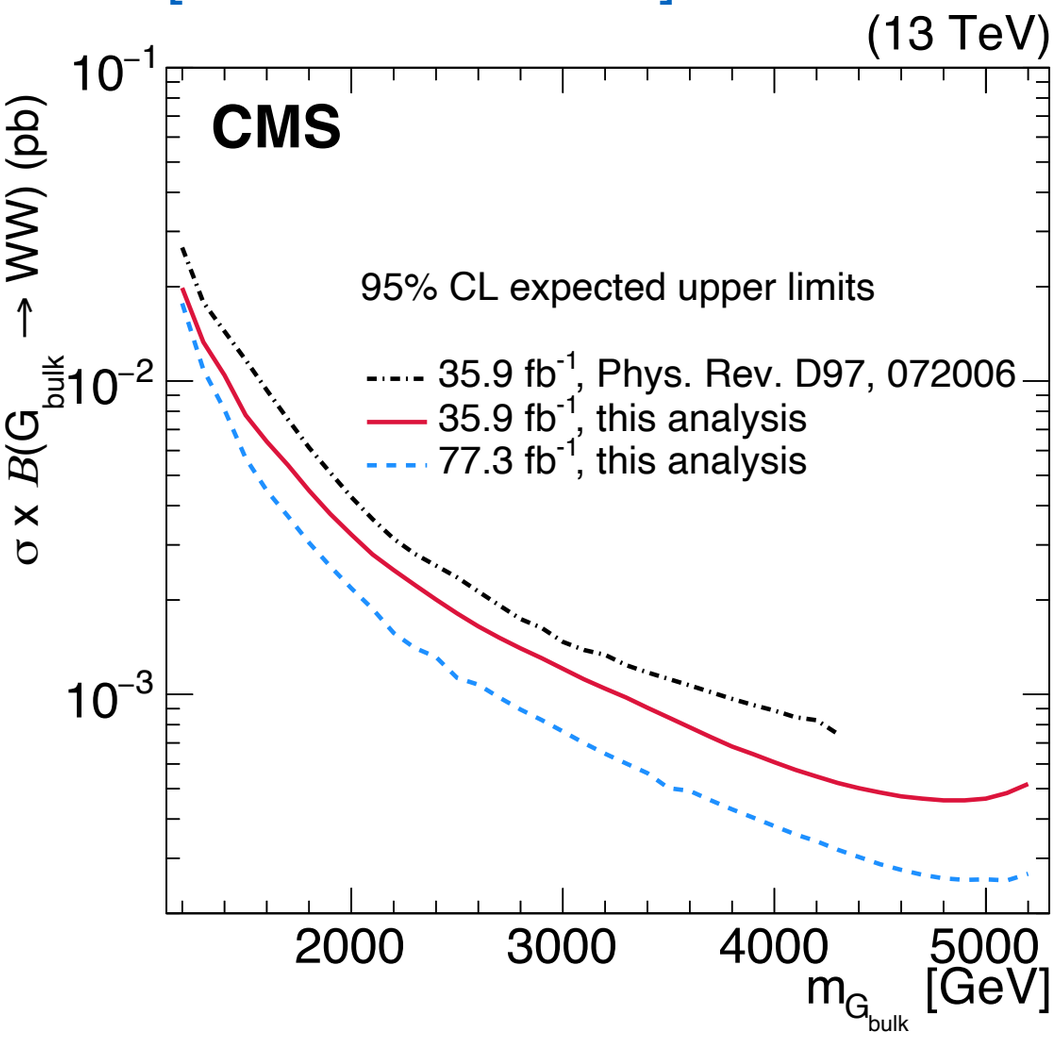
[CMS, arXiv:1906.05977]

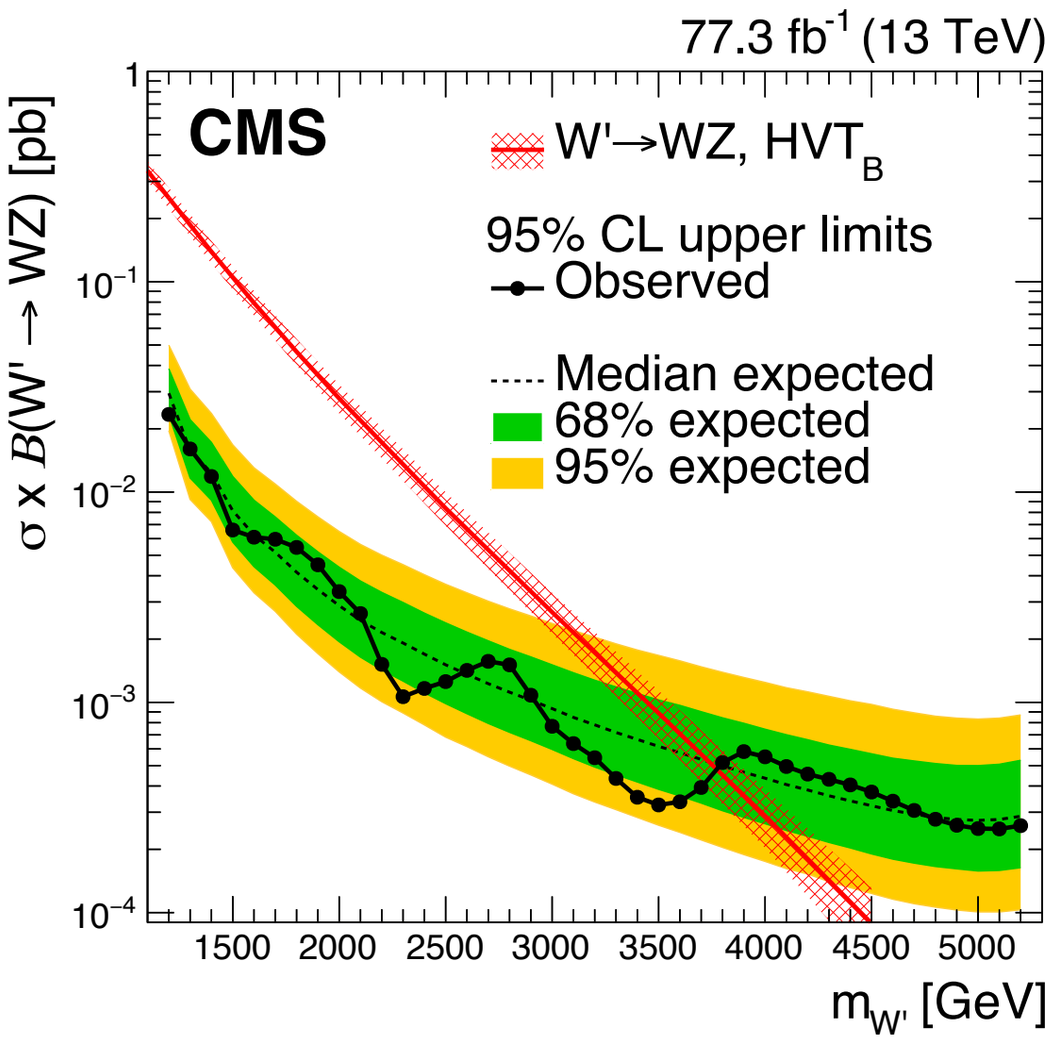




VV Resonances

[CMS, arXiv:1906.05977]

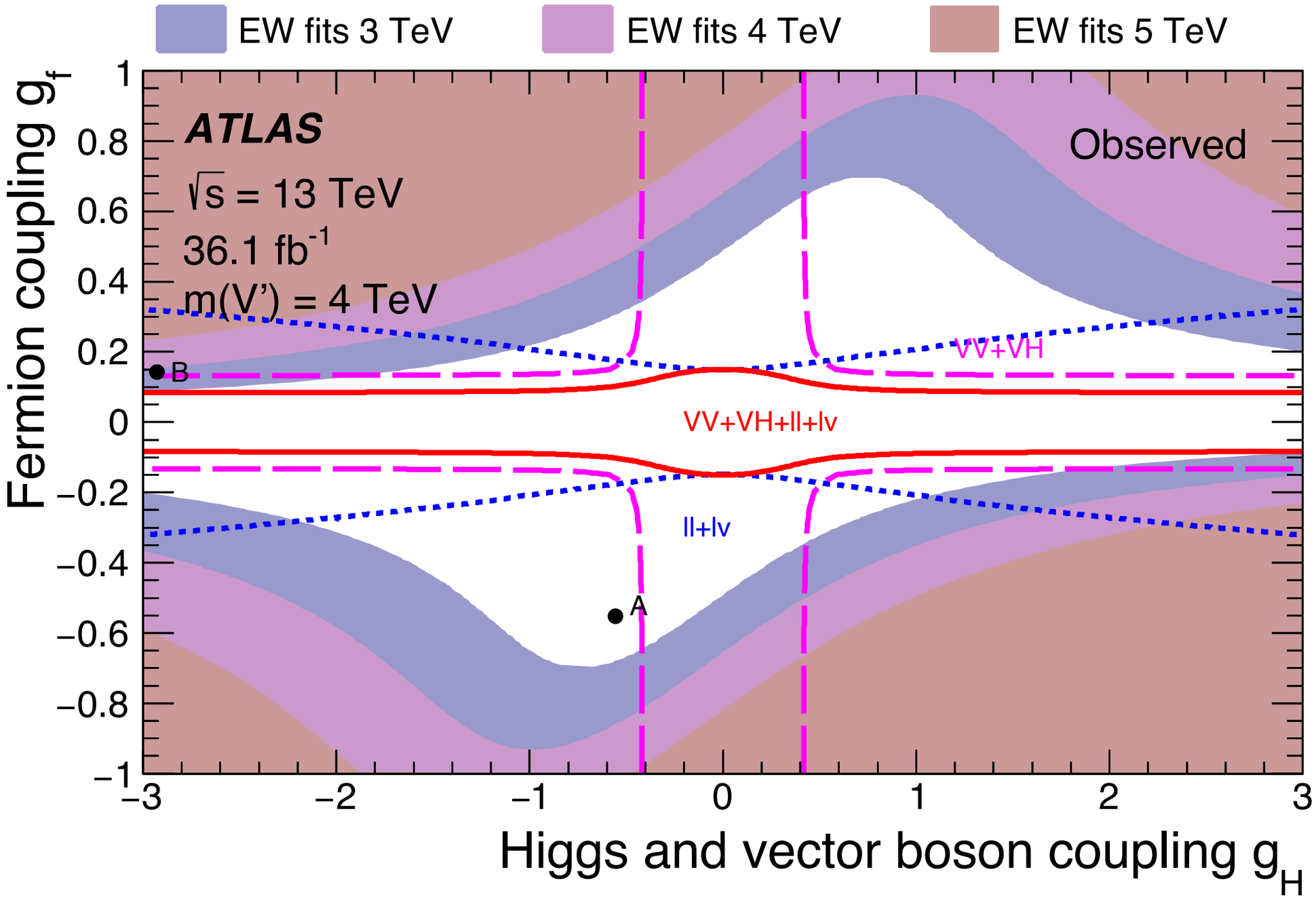




Limits better by 25-50% than ATLAS analysis

VV, VH, ℓℓ, ℓν Combination

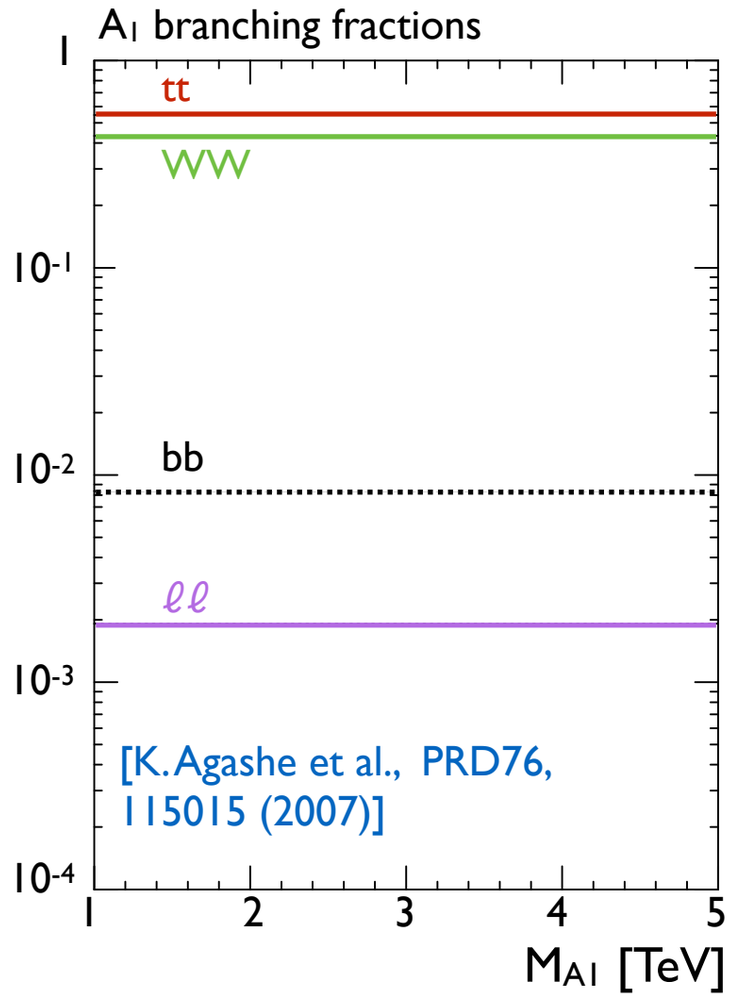
[ATLAS, PRD 98, 052008 (2018)]

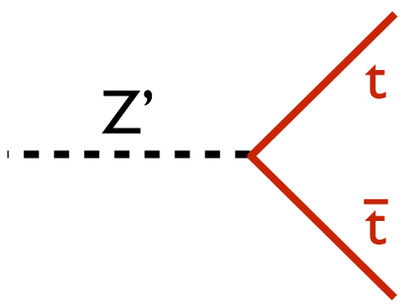


Other Possibilities?

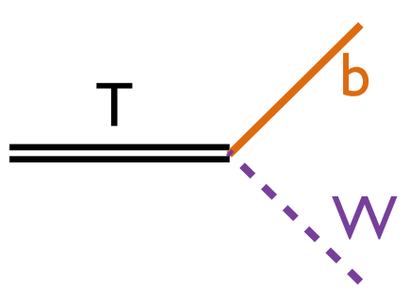
The 3rd Generation

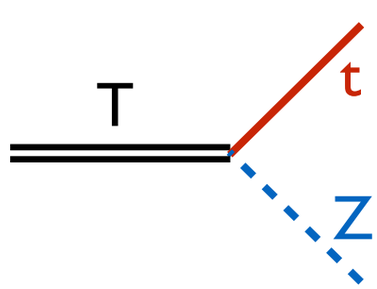
- Focus on t and b quarks in model building
  - Addresses a number of questions (Naturalness, mass hierarchies…)
  - Couplings to t and b dominant
- Weak constraints from EWPO and low energy measurements
- Many incarnations: new gauge groups, extended scalar sectors, extra dimensions…

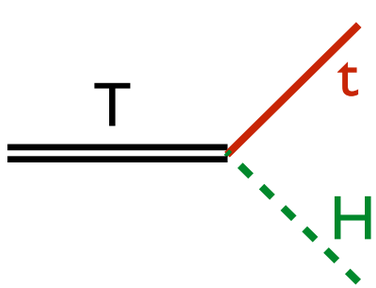




Resonances

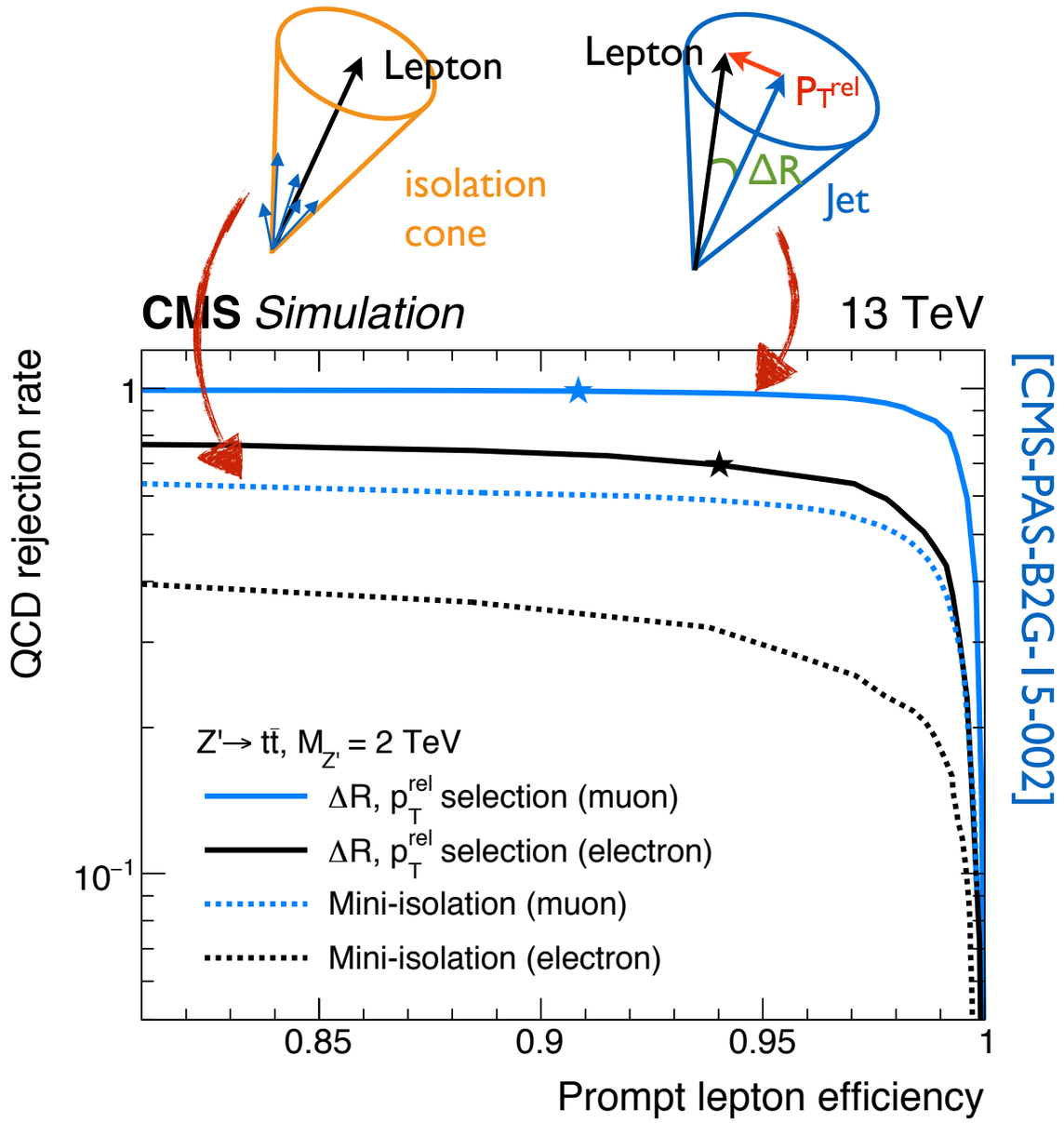


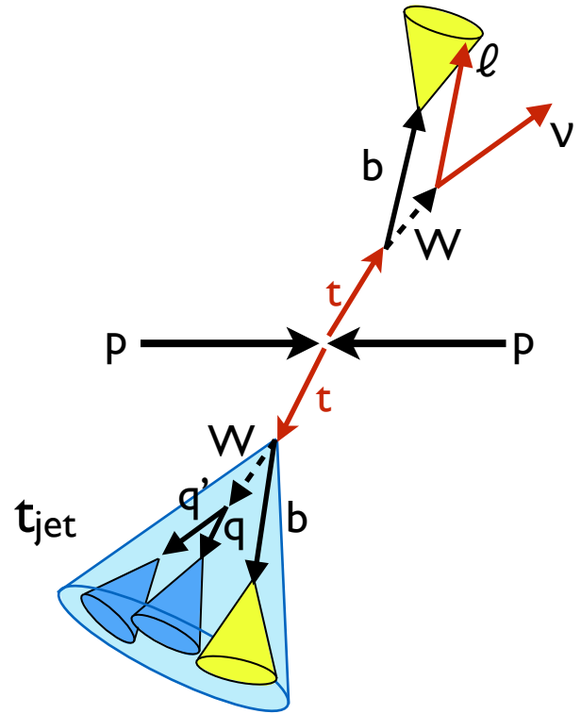


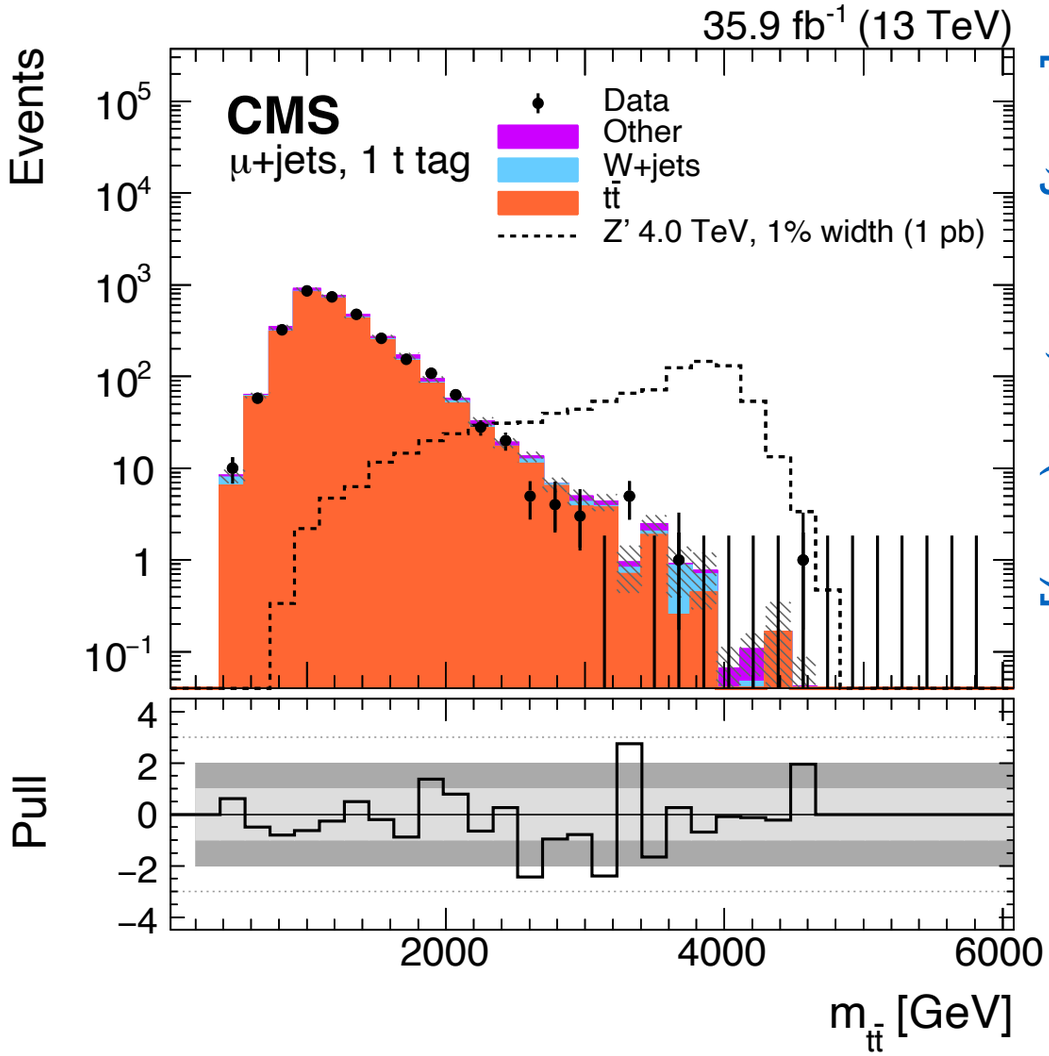


Vector-like quarks (VLQs)

$t\bar{t}$ Resonances

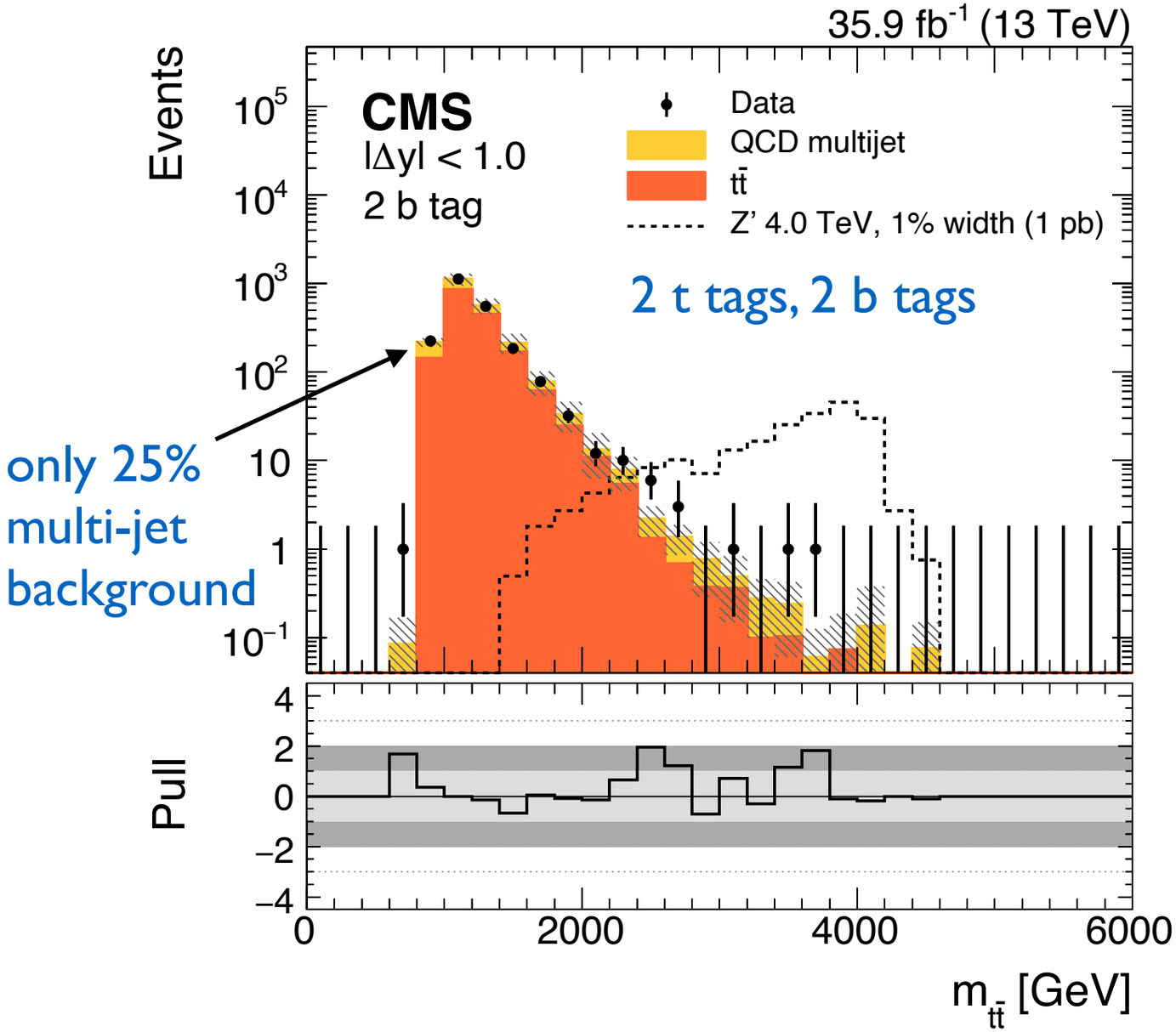




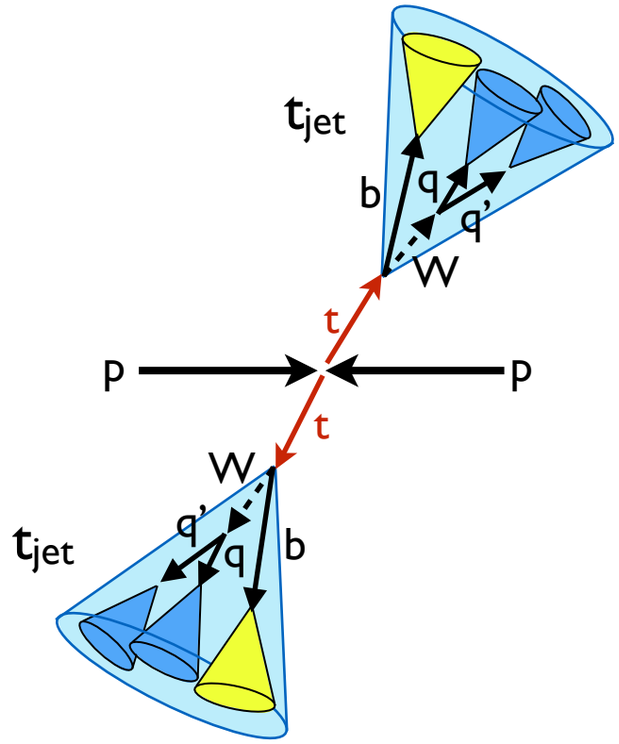


- improved PU mitigation, b-tagging
- BDT for W+jet suppression
- CRs to constrain backgrounds

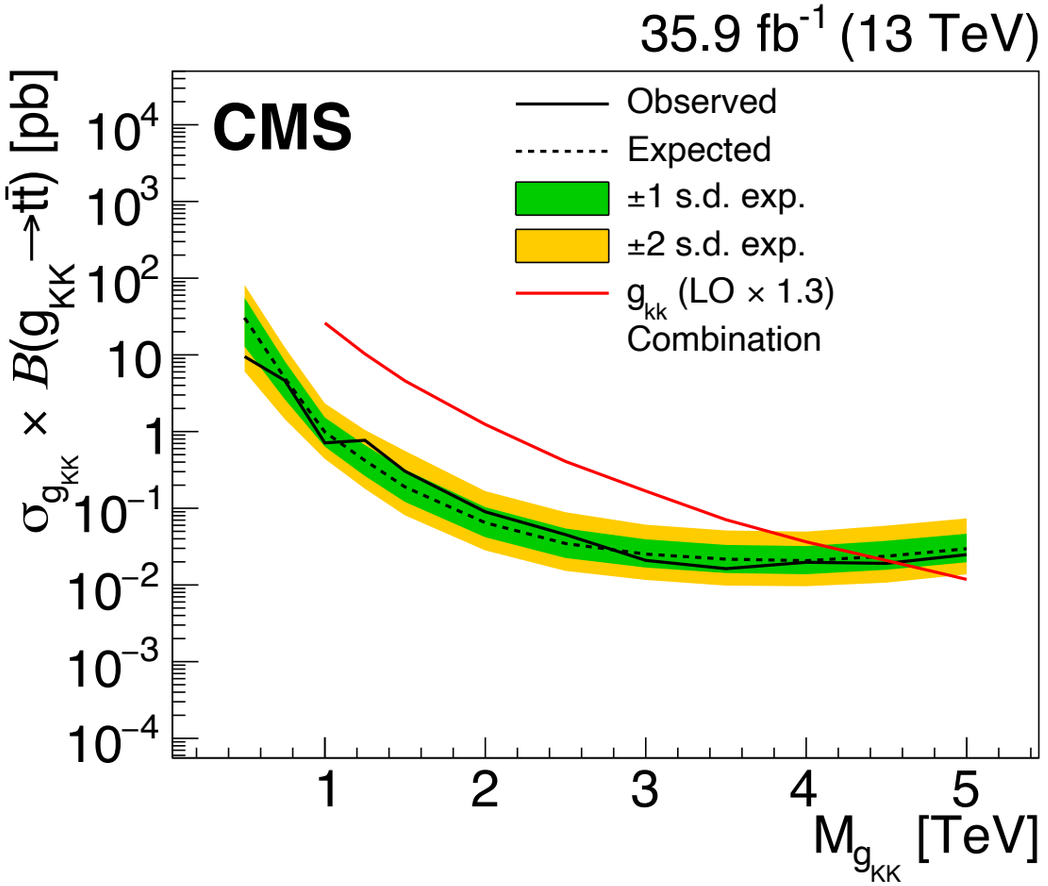
$t\bar{t}$ Resonances



only 25% multi-jet background



[CMS, JHEP 04, 031 (2019)]

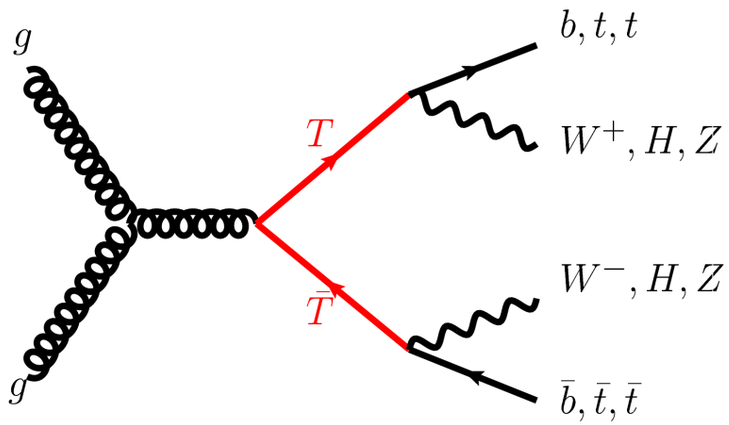


Combination of $\ell\ell$, ℓ+jets and all-hadronic channels:
Kaluza-Klein gluons excluded below **4.6 TeV**

VLQ Pair Production

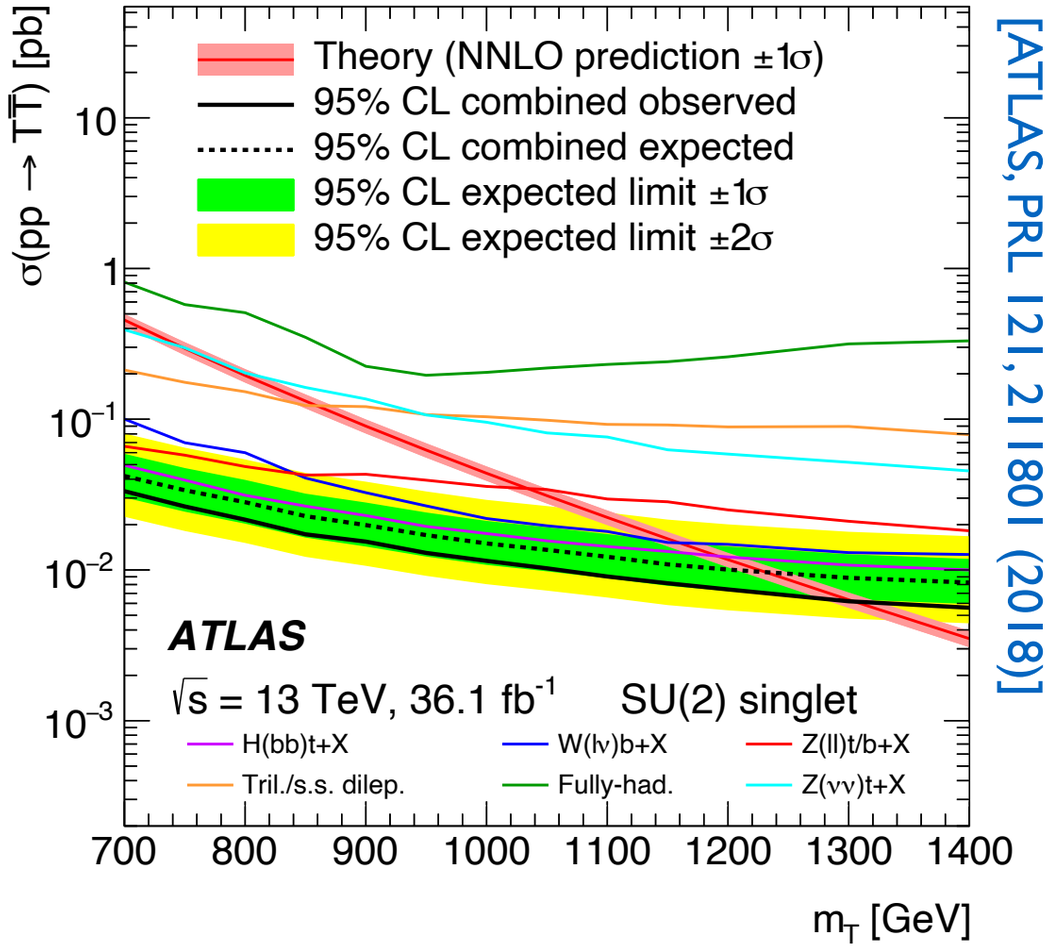
$T\bar{T}$ and $B\bar{B}$ pair production

- Rich phenomenology
  - T → bW, tZ, tH
  - B → tW, bZ, bH



- Numerous searches profit from jet substructure tagging
  - orthogonality: leptonic and hadronic channels (tags)

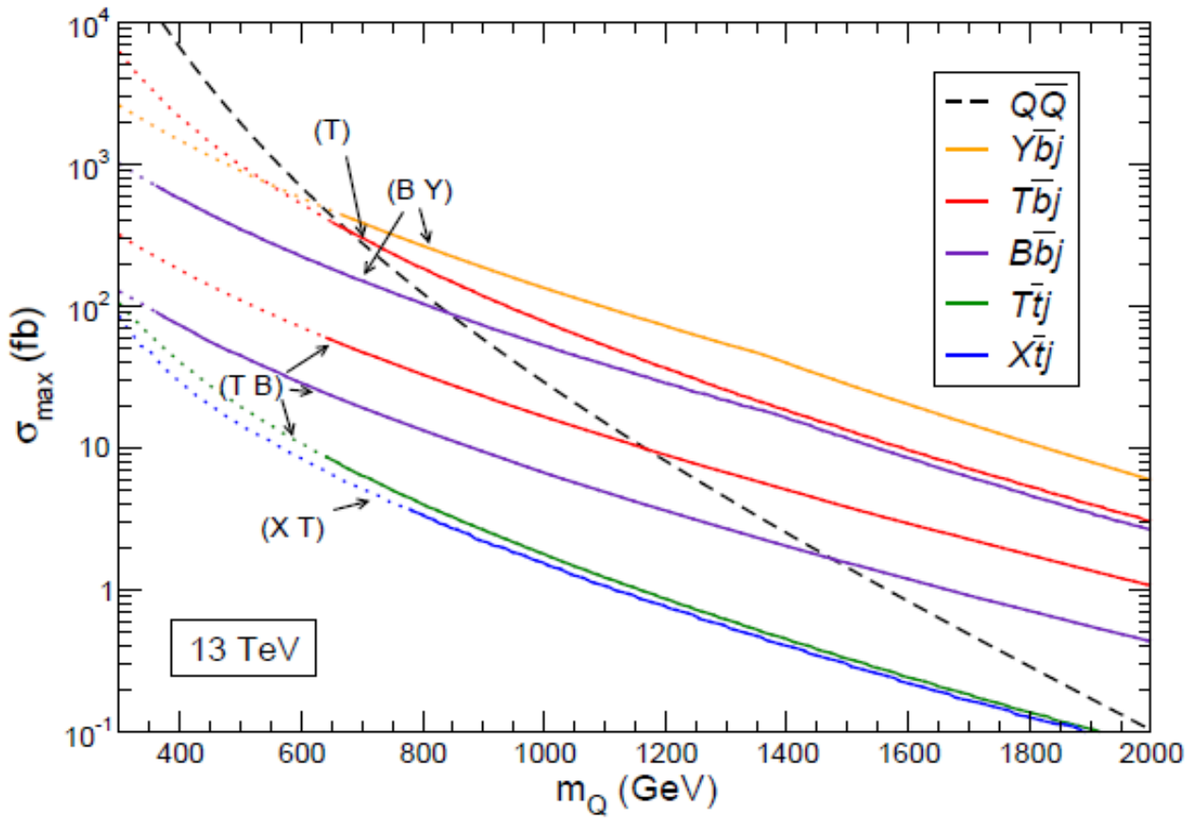
- Grand combination:
  Exclusion of T / B below
  1.3 / 1.2 TeV

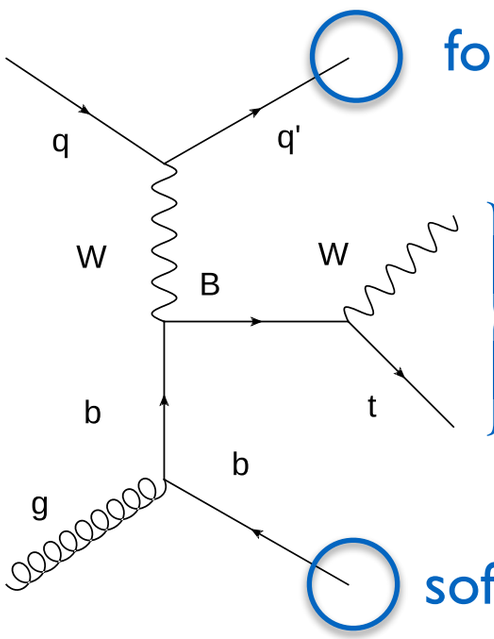


VLQ Single Production

- Electroweak production can dominate for heavy VLQs
- Model dependent cross section:
  - Couplings (mixing parameters)
  - Weak quantum numbers
- Signature: one forward jet and associated production with a heavy quark

[J.A. Aguilar-Saavedra et al., PRD 88, 094010 (2013)]



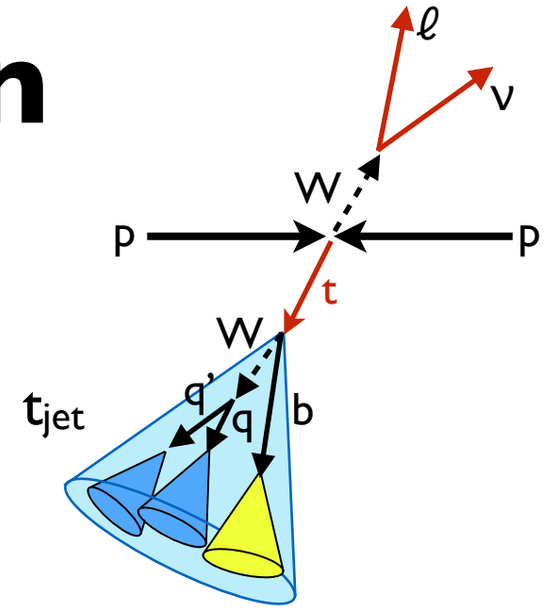


forward jet

highly boosted decays

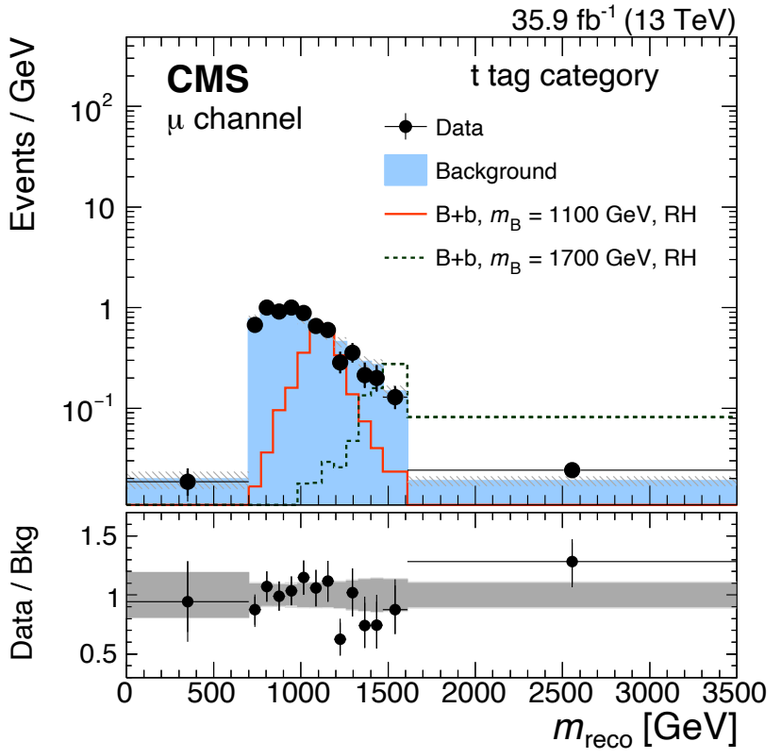
soft quark

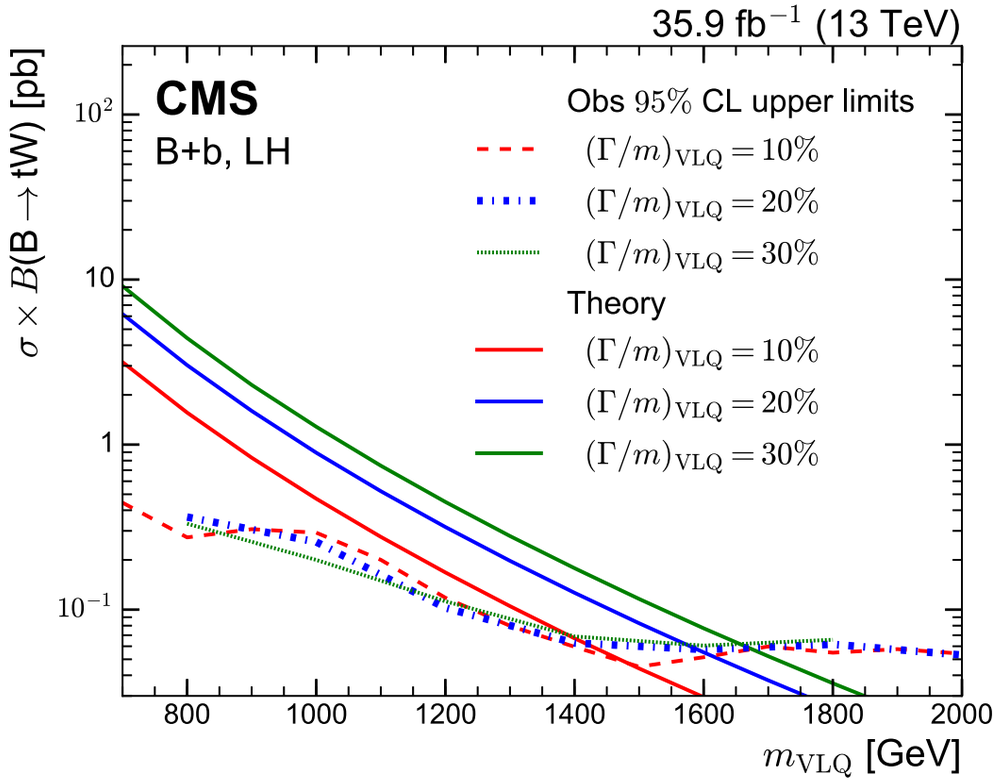
VLQ Single Production



Single B→tW (ℓ+jets)

- Various decay possibilities
  - Jet assignment through t tag or χ^2 probabilities
  - VLQ mass reconstruction with ~10% resolution
- SM backgrounds from control region without forward jet
  - Validation region: small χ^2 values

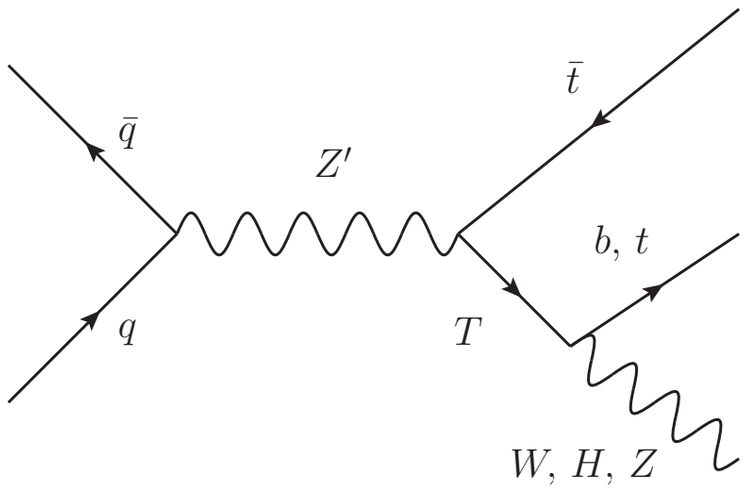




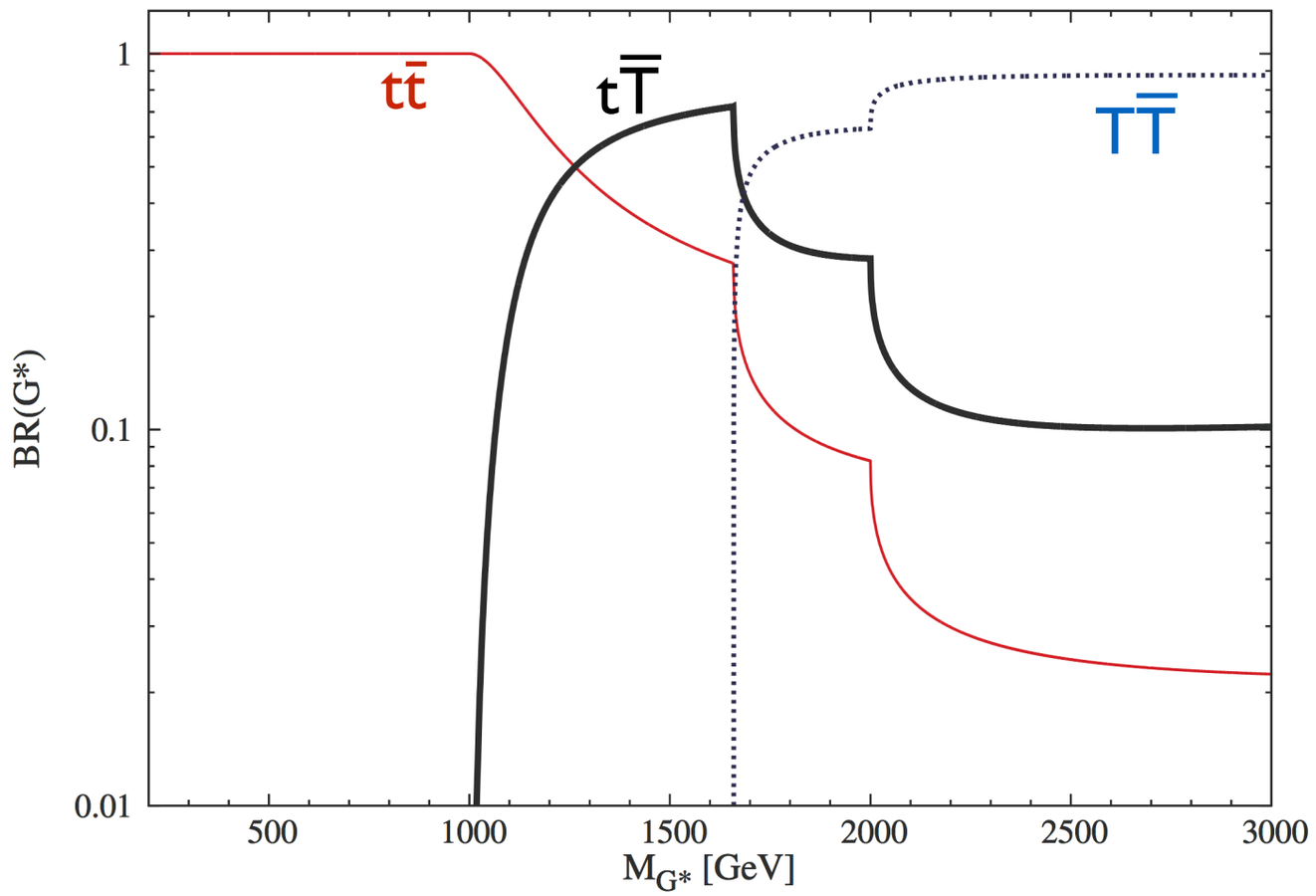
Resonant VLQ Production

No signals in $t\bar{t}$ or $T\bar{T}$ production

- Traditional searches: hole in sensitivity in $t\bar{T}$



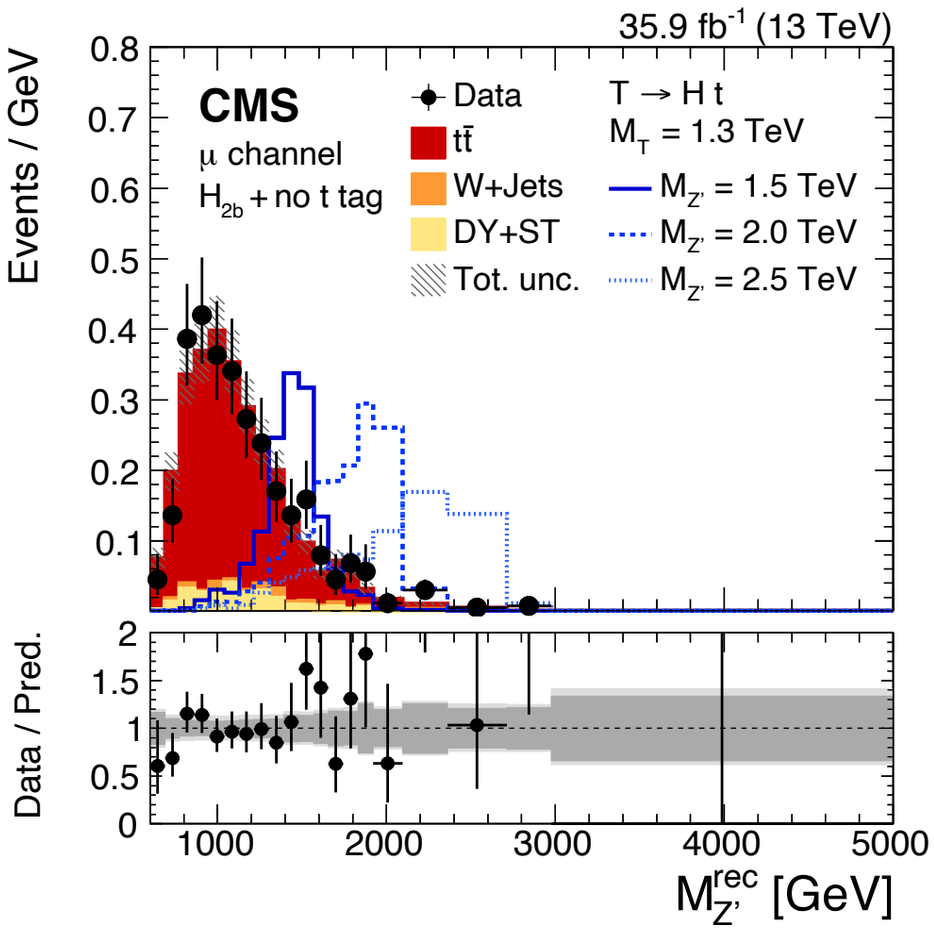
[C. Bini et al., JHEP 1201, 157 (2012)]

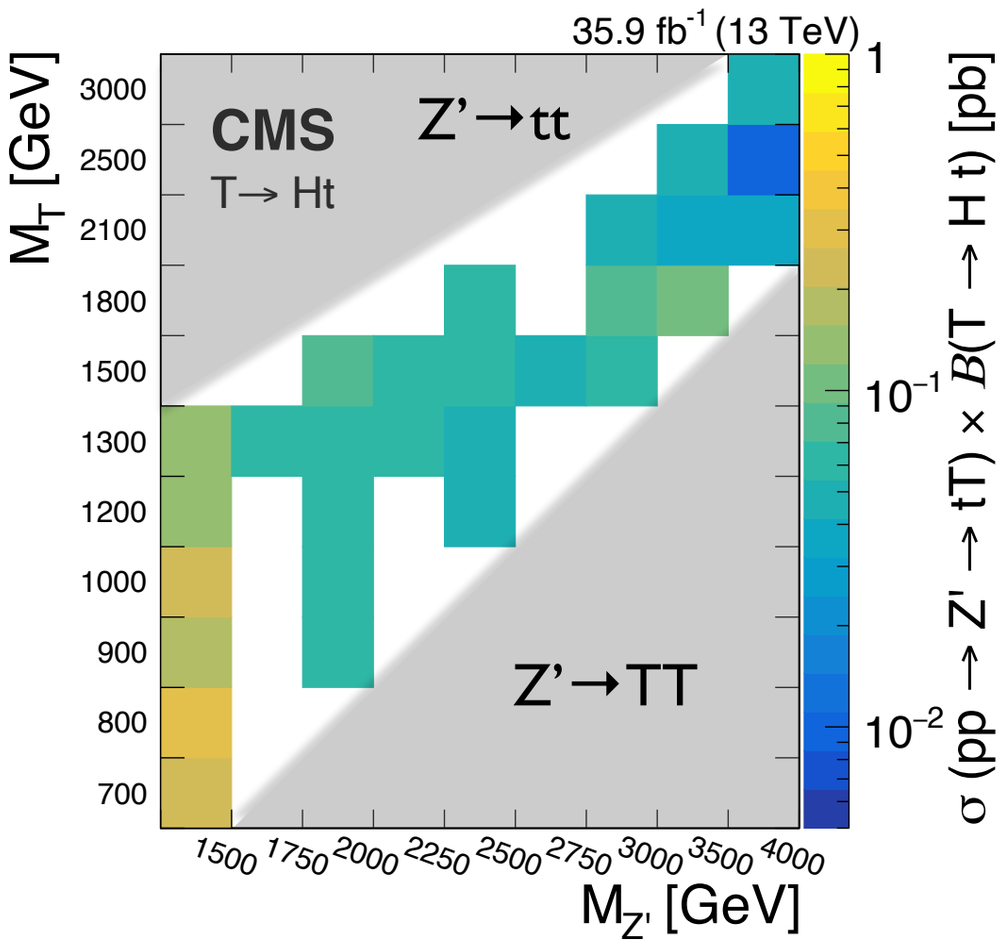


- Final state: resonant $t\bar{t}Z$ and $t\bar{t}H$ production
  - Collimation depends on ratio of Z' and T masses

Resonant VLQ Production

- Search with Z/W/H/t tags
  - Validation of efficiency and mis-identification rates
- Z' reconstruction through minimum of χ^2 term
- Constrain dominant backgrounds from control regions (W+jets, $t\bar{t}$)





Improving Jet Substructure

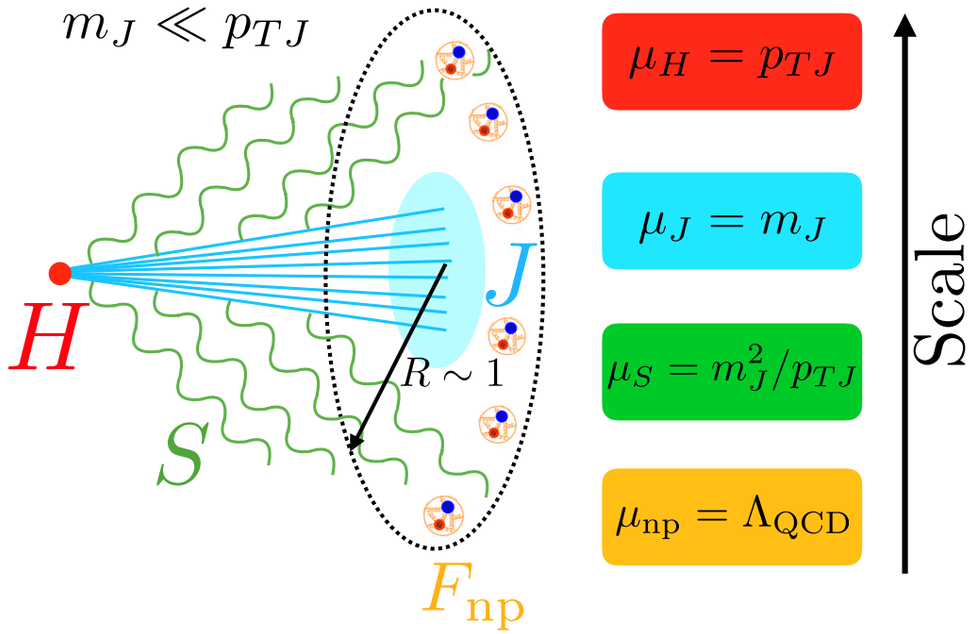
Substructure Taggers

- Groomer (trimming, pruning, mMDT, soft drop…)
- Selection on substructure variables (mass, τ_N, D_N, N_N…)
- Dedicated algorithms (Johns Hopkins, HEP, HOTVR…)
- Machine learning taggers

Impossible to name them all…

Analytical calculations

- Complicated: different scales involved
- Many calculations completed recently
- Knowledge not fully exploited



[Larkoski, Moult, Nachmann, arXiv:1709.04464]

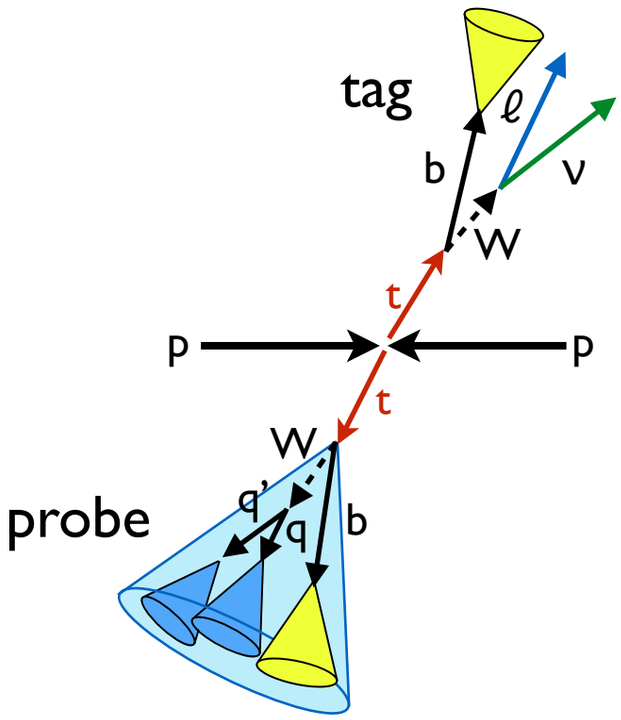
Application in analyses

- Commissioning: dedicated measurements!
- Systematic uncertainties important for performance

Efficiency Measurements

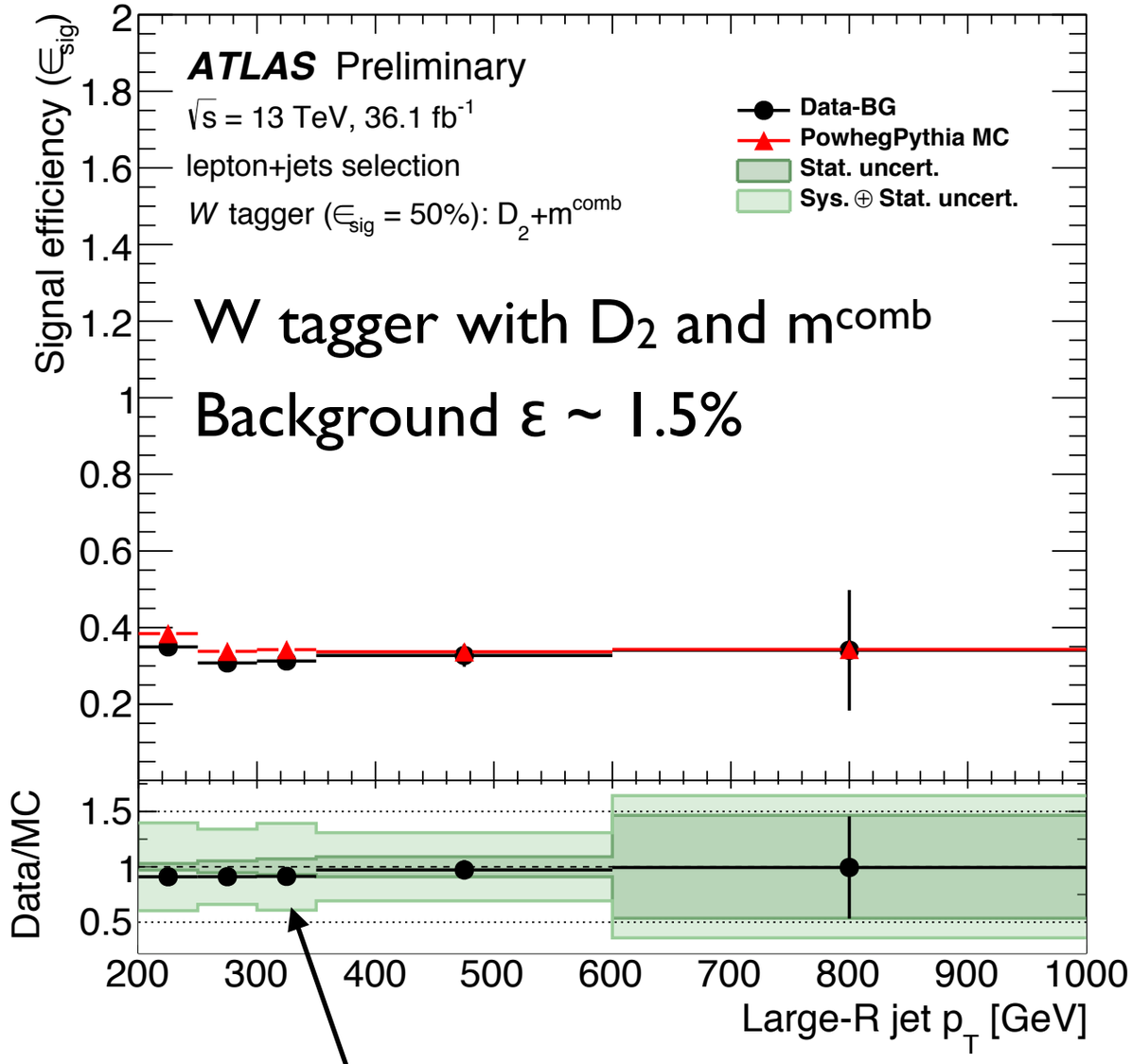
Tag-and-probe measurements

- $t\bar{t}$ production for W and t



- extrapolations to Z and H from simulation

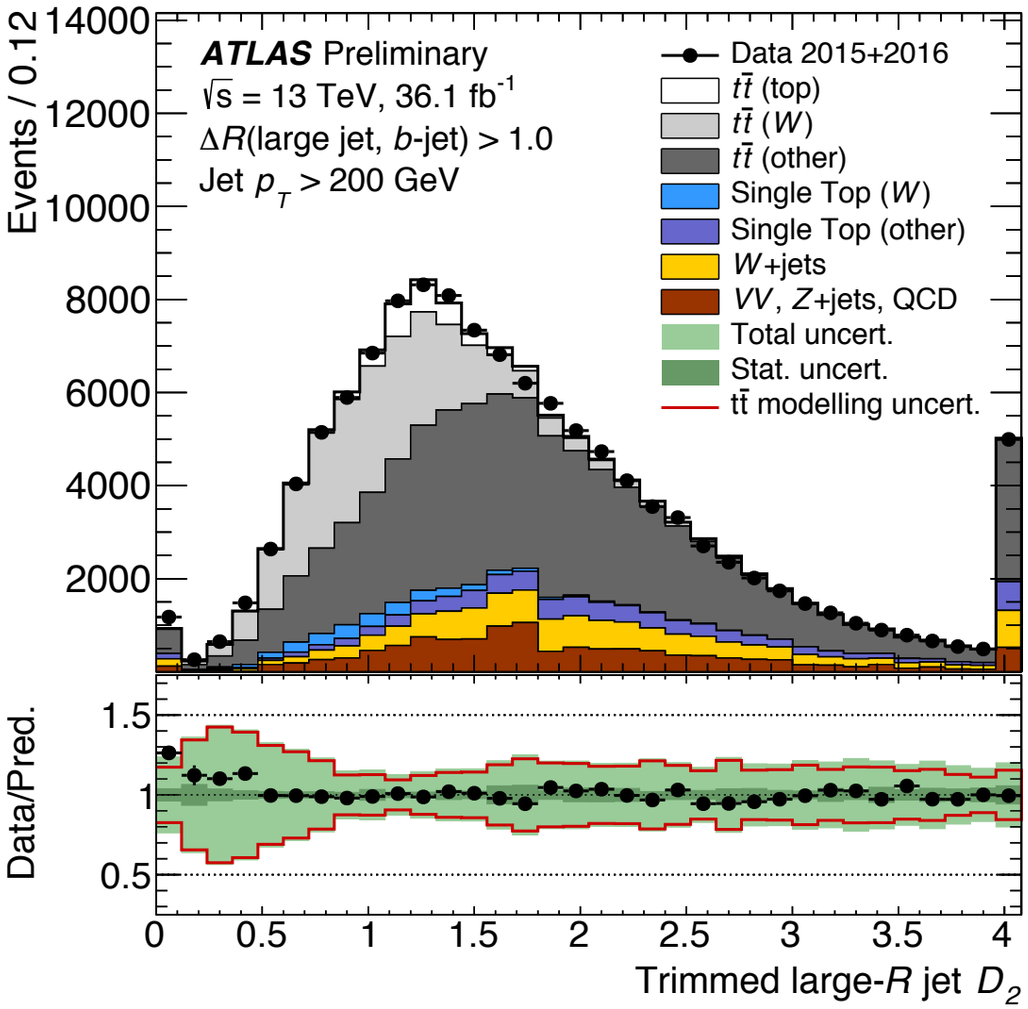
[ATLAS-CONF-17-064]



systematic uncertainty by factor ~5 larger than statistical uncertainty

Modelling of D_2

[ATLAS-CONF-17-064]

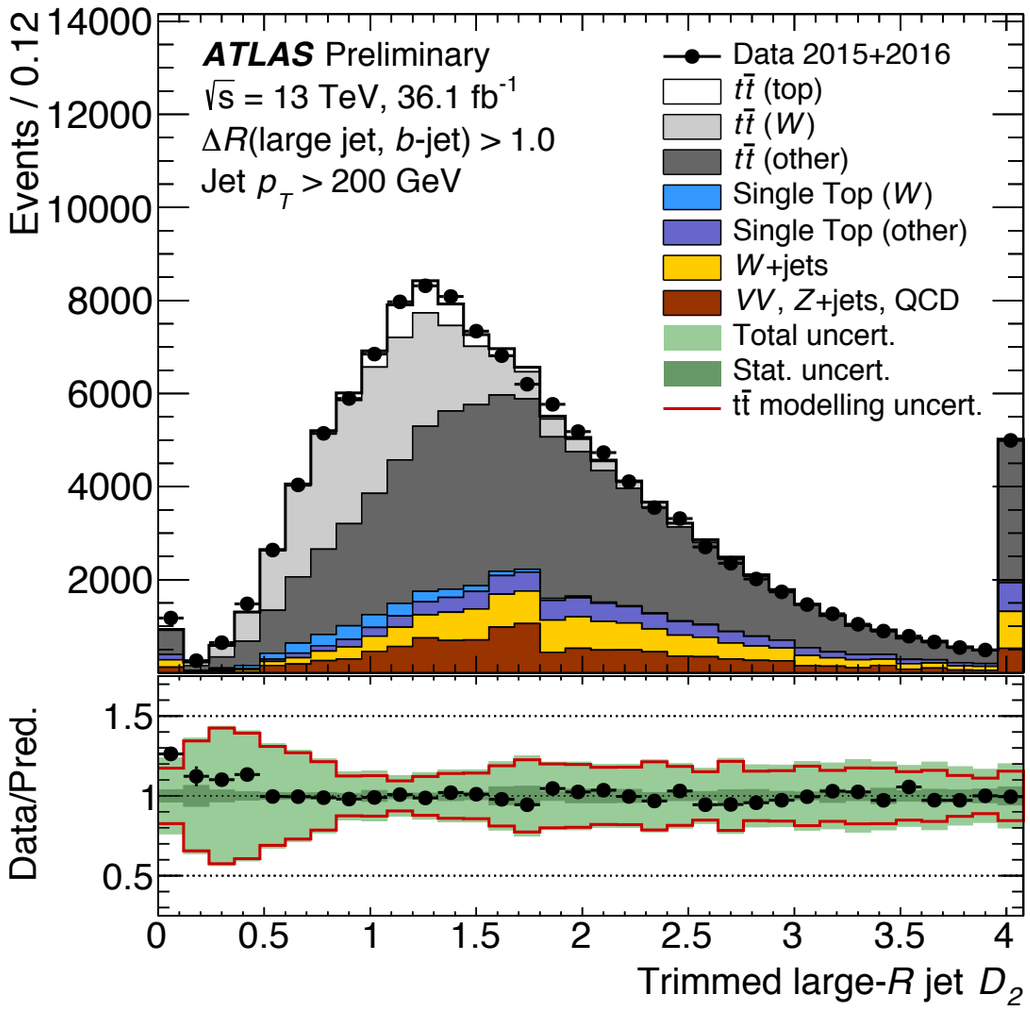


Large modelling uncertainties (radiation, hadronization)

Expected?

Modelling of D_2

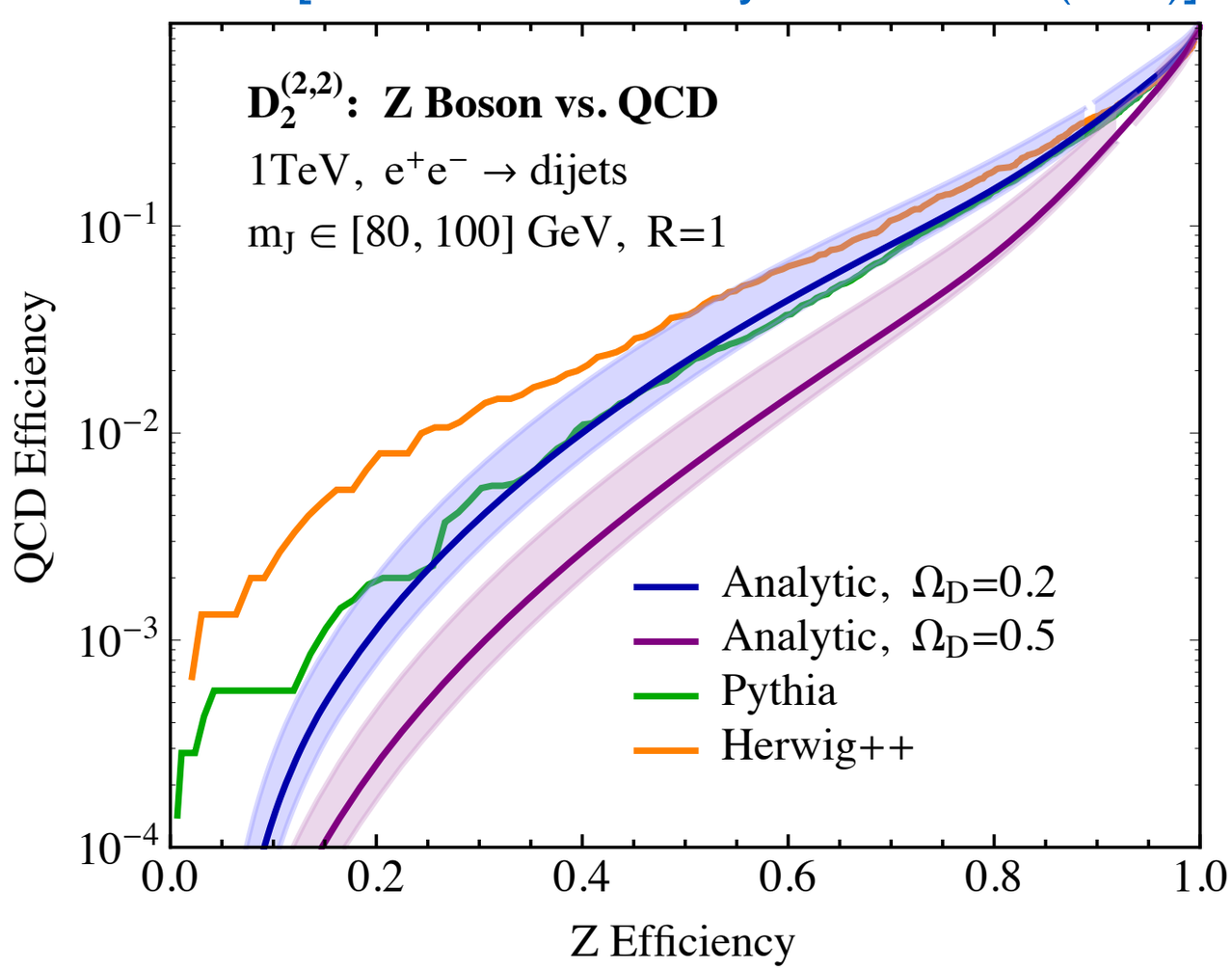
[ATLAS-CONF-17-064]



Large modelling uncertainties (radiation, hadronization)

Expected?

[Larkoski, Moult, Neill, JHEP 1605, 117 (2016)]

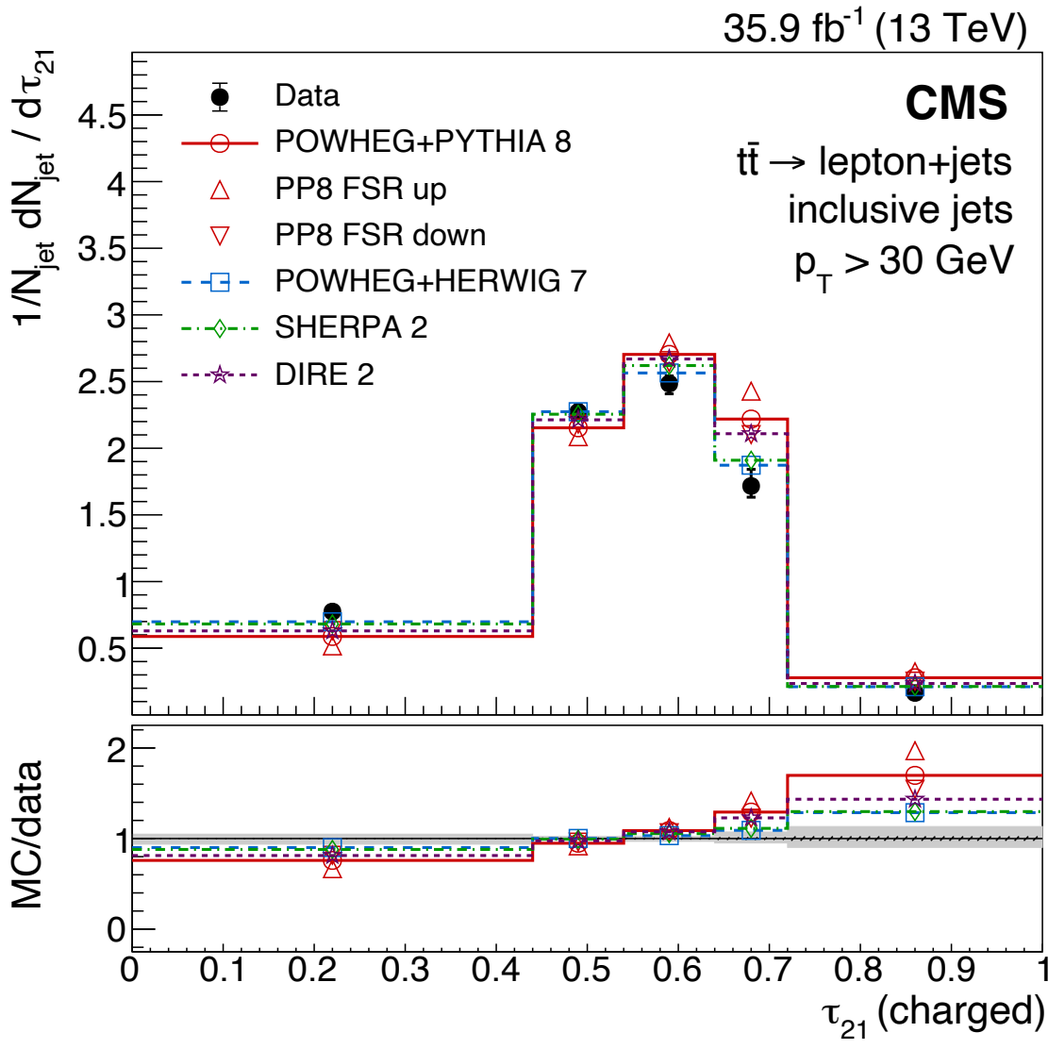


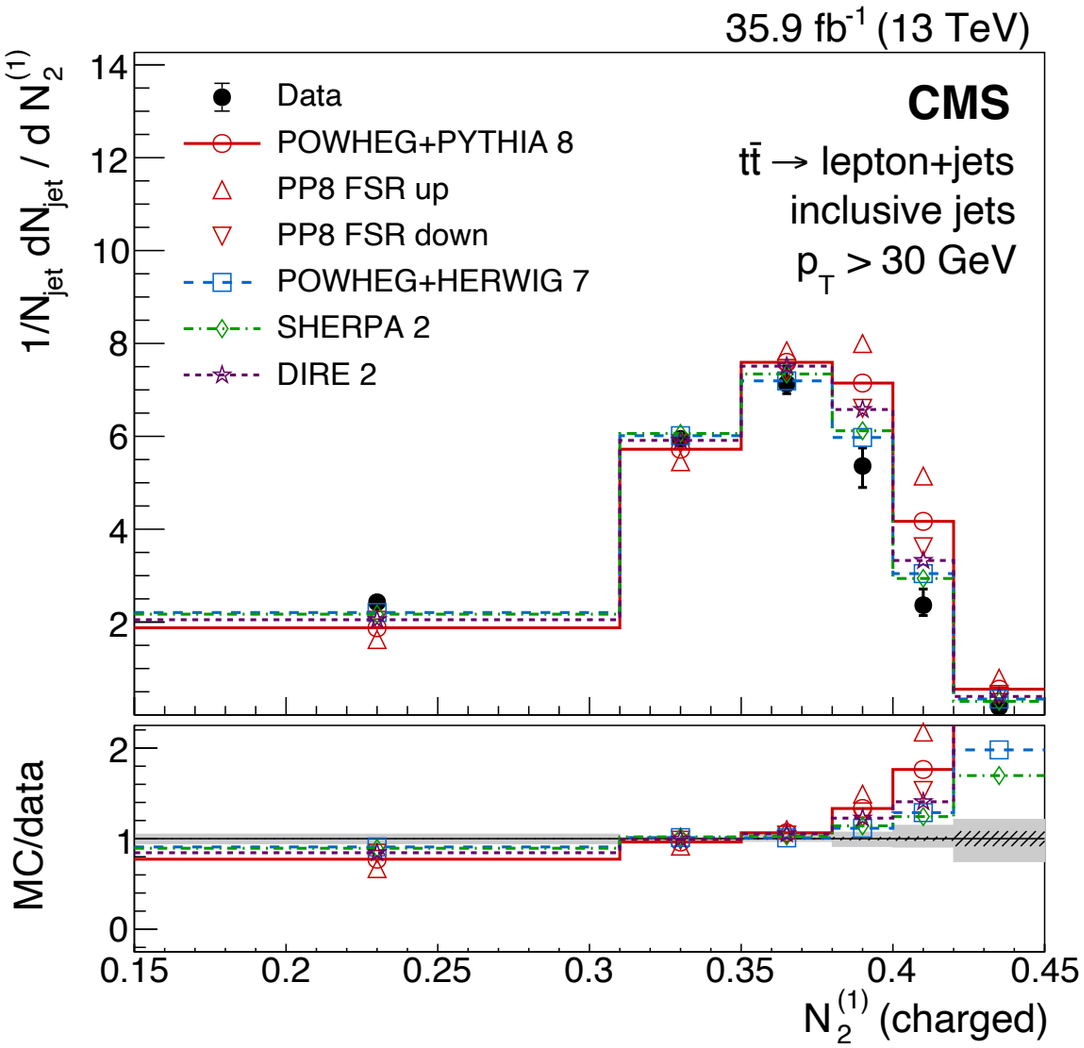
Two-prong structure: smaller phase space for perturbative radiation

→ larger sensitivity to NP effects

Power to the Data: 1. Measurements

[CMS, PRD 98, 092014 (2018)]

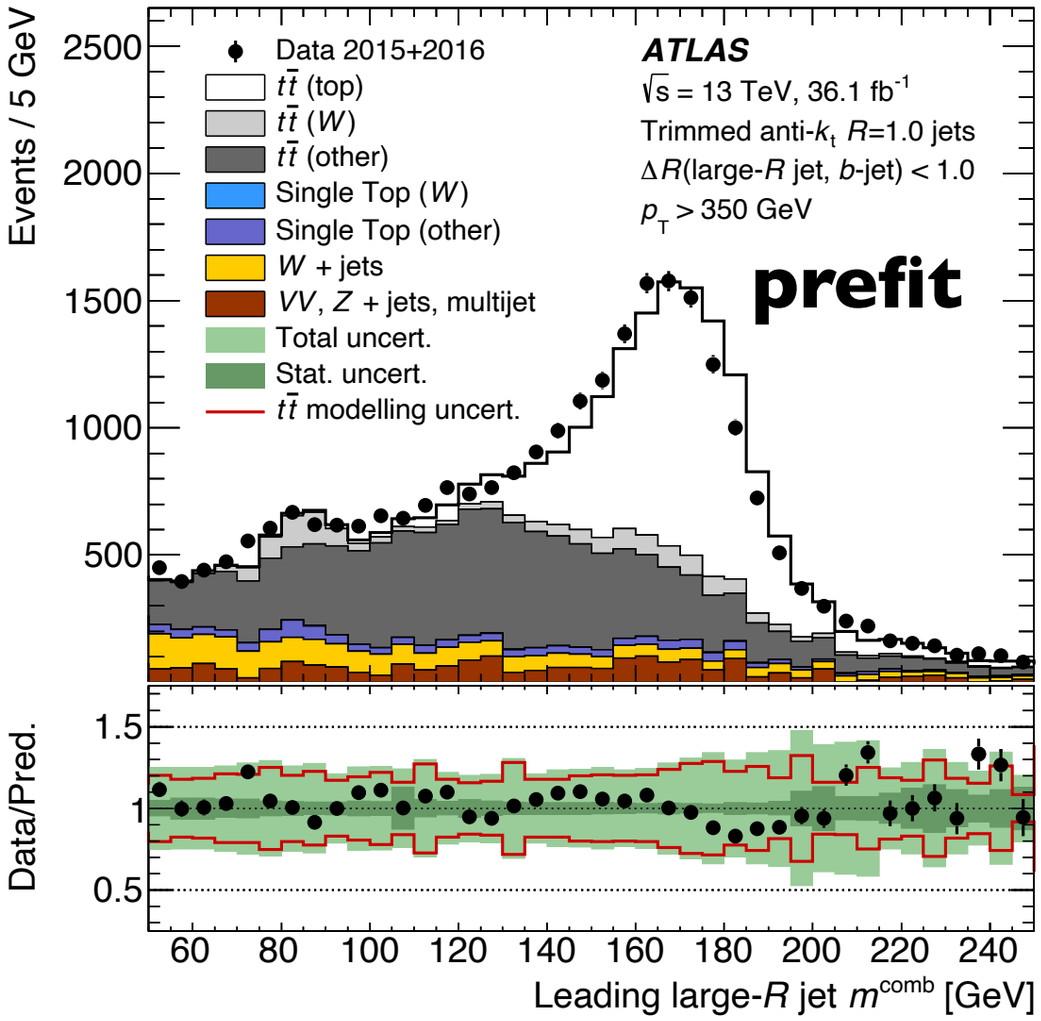




- Unfolded distributions in $t\bar{t}$ production: great!
- Measurement on inclusive small-R jets: 1-prong
- Two- and three-prong measurements not available yet

Power to the Data: 2. In-Situ-Det.

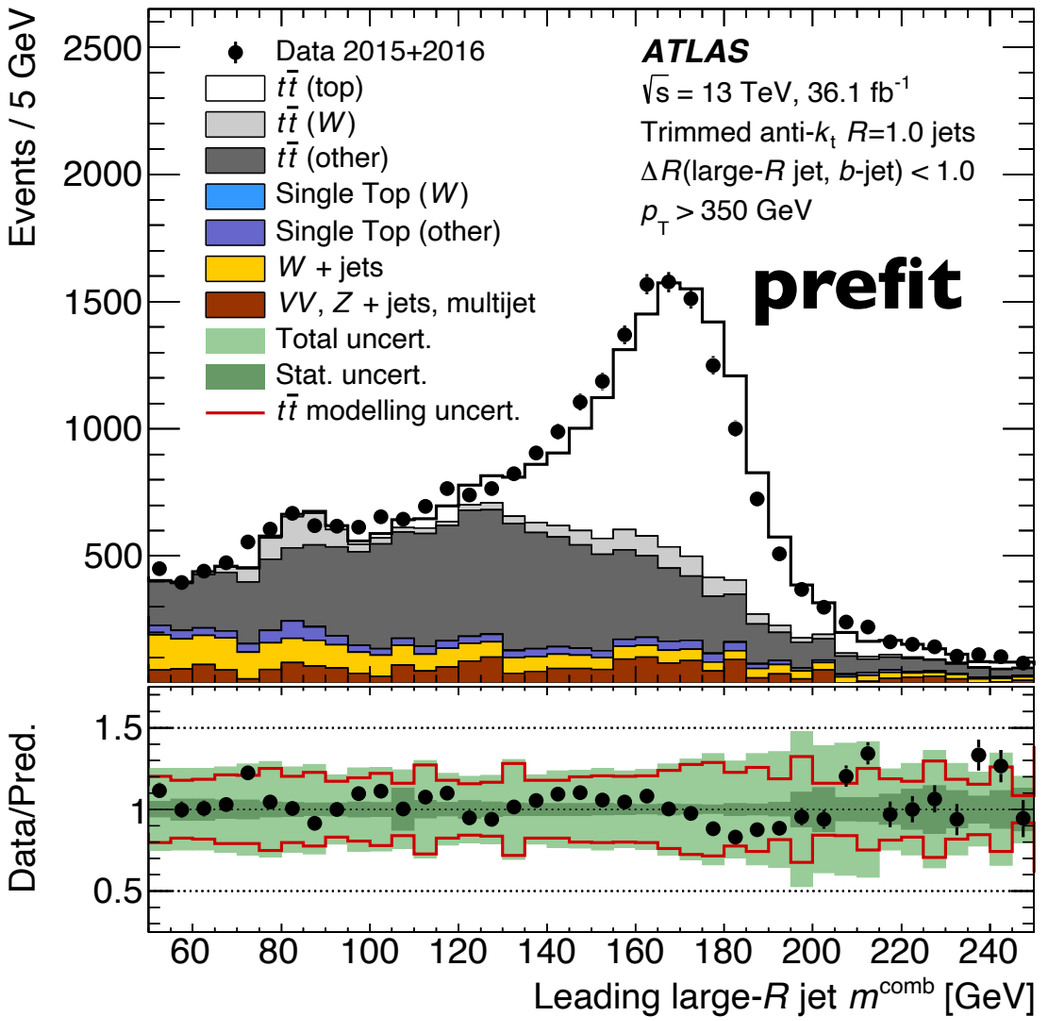
[ATLAS, arXiv:1808.07858]



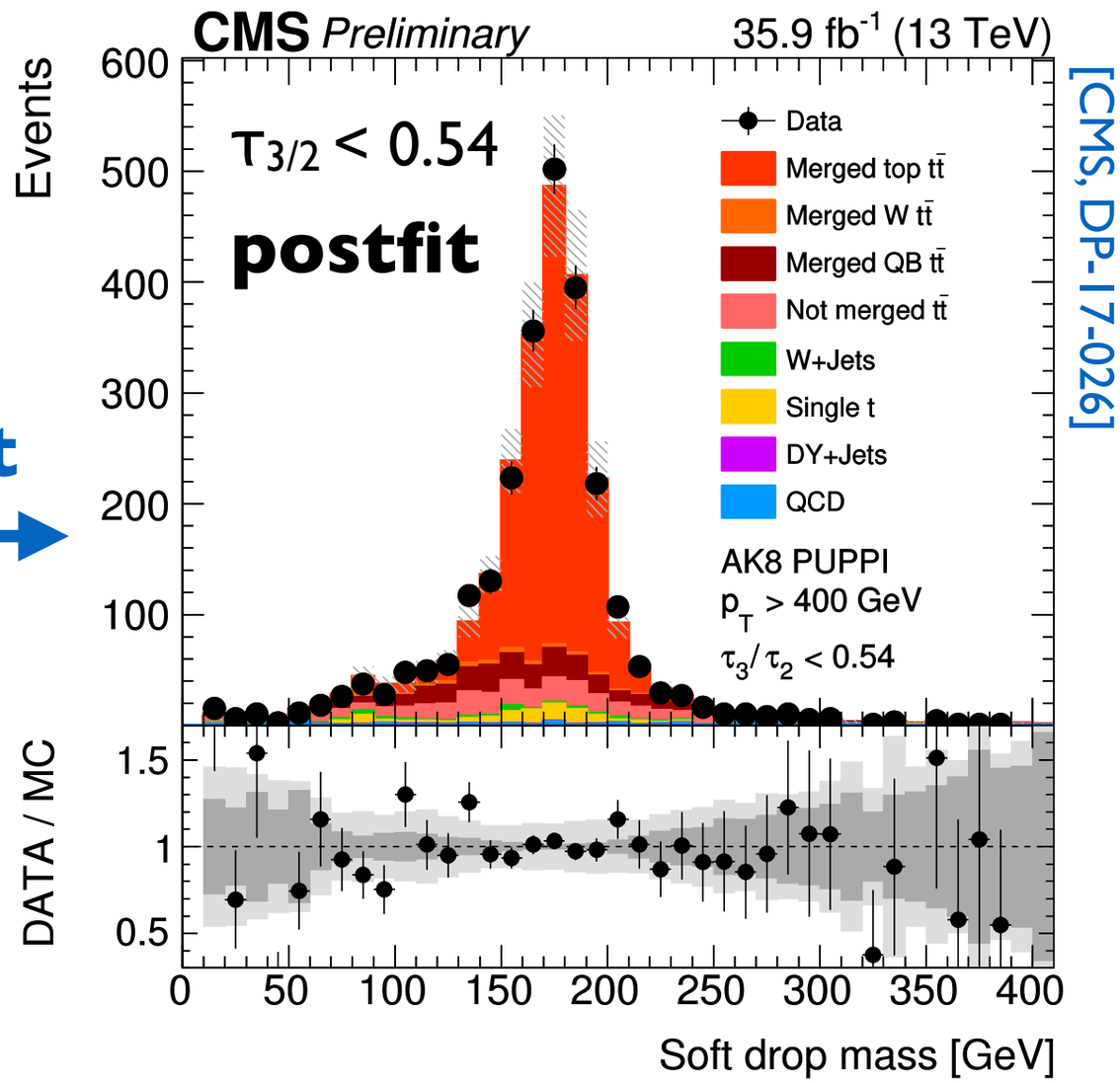
- Fit tagging efficiency and systematic uncertainties simultaneously
- Statistical precision sufficient to constrain modelling uncertainties!
- Can we learn from this for modelling NP effects?

Power to the Data: 2. In-Situ-Det.

[ATLAS, arXiv:1808.07858]

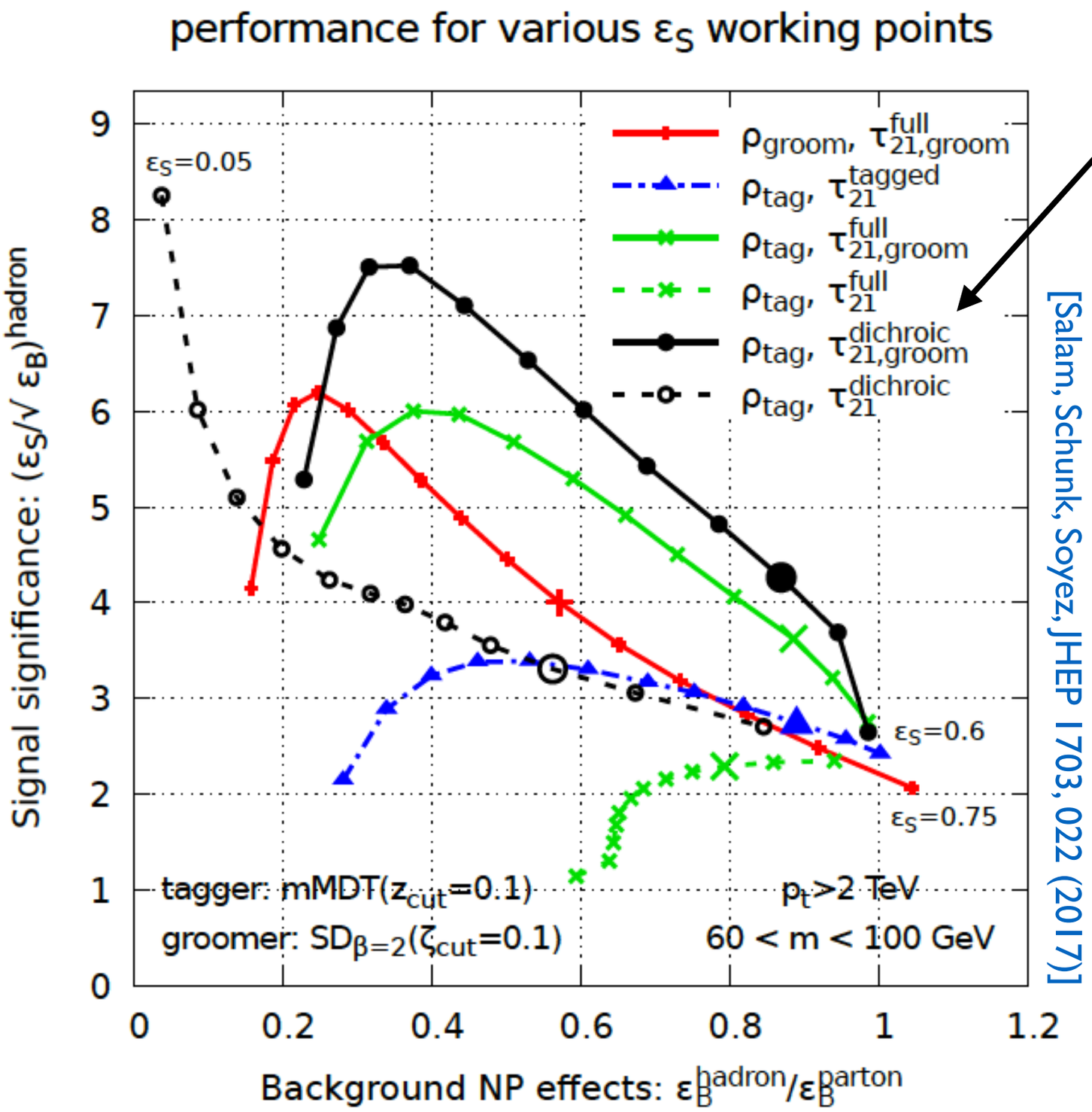


fit



- Fit tagging efficiency and systematic uncertainties simultaneously
- Statistical precision sufficient to constrain modelling uncertainties!
- Can we learn from this for modelling NP effects?

3. Get Help



[Salam, Schunk, Soyez, JHEP 1703, 022 (2017)]

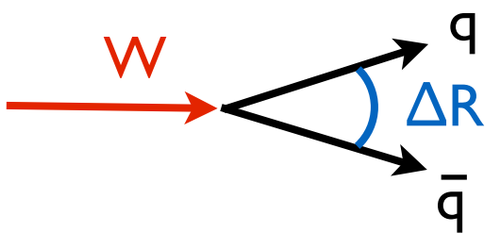
Dichroic τ_{21} ratios

- less sensitive to non-perturbative effects at similar or better signal significance
- could reduce dominant uncertainties considerably
- experimental studies needed
  - full analysis with all systematics included

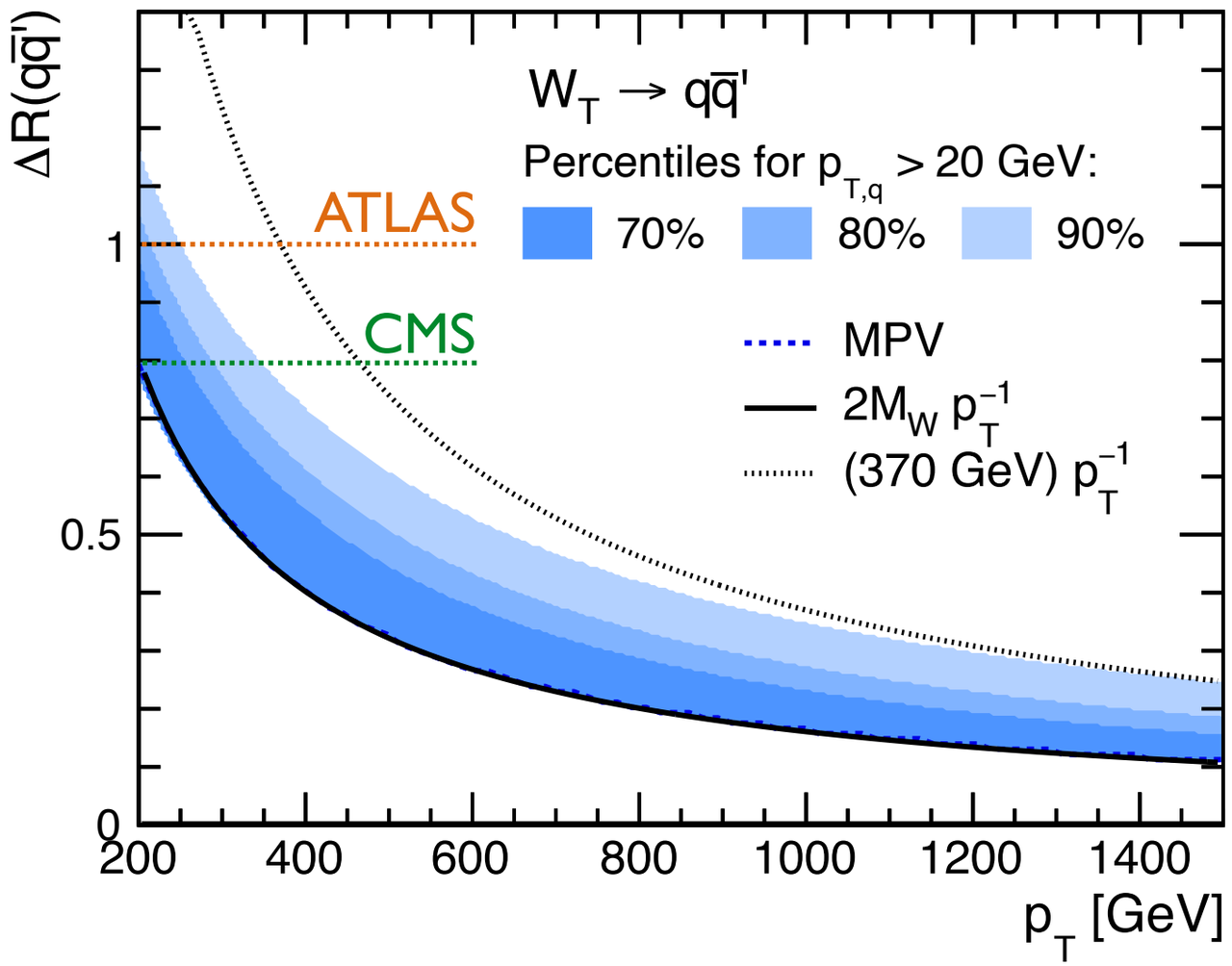
Collimation

- Collimation depends on p_T

$$\Delta R \approx \frac{2M}{p_T}$$ (rule of thumb)



- Ensure high signal efficiency: Jet distance parameter of
  - R = 1.0 (ATLAS)
  - R = 0.8 (CMS)



R~1 optimal for $p_T \lesssim 600$ GeV, catchment area too large at very high p_T

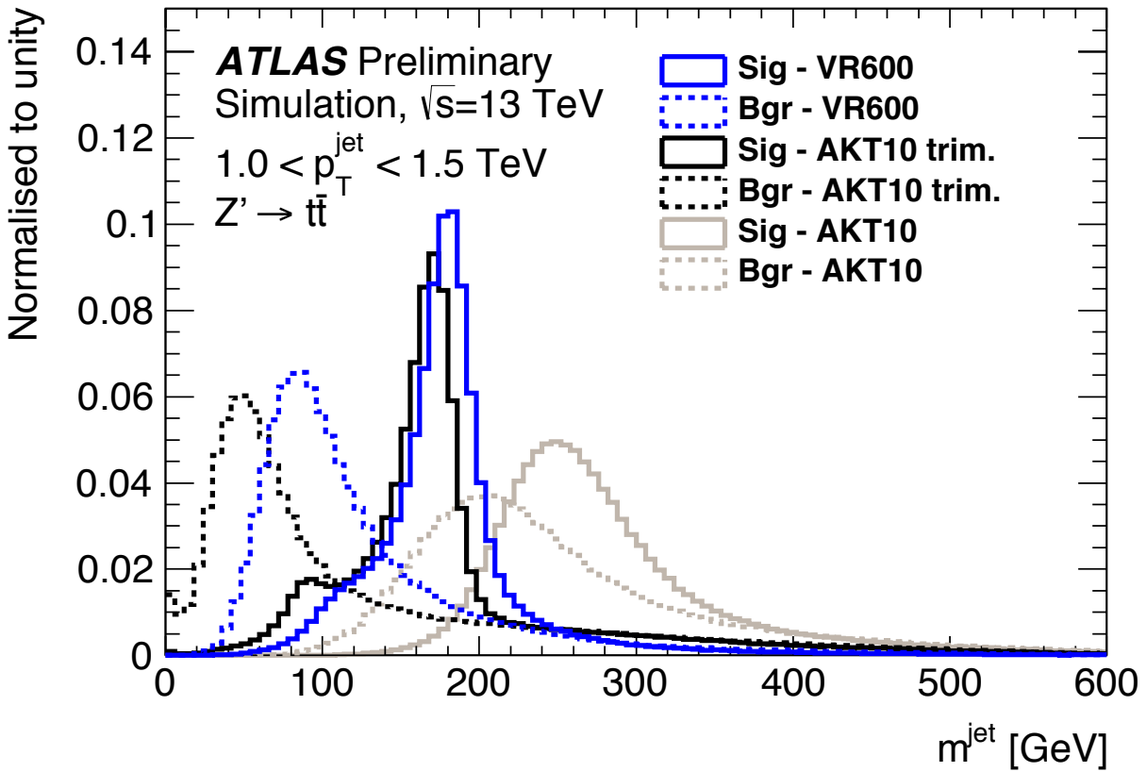
Possible to compensate for $\delta M \sim p_T R^4$ with shrinking R

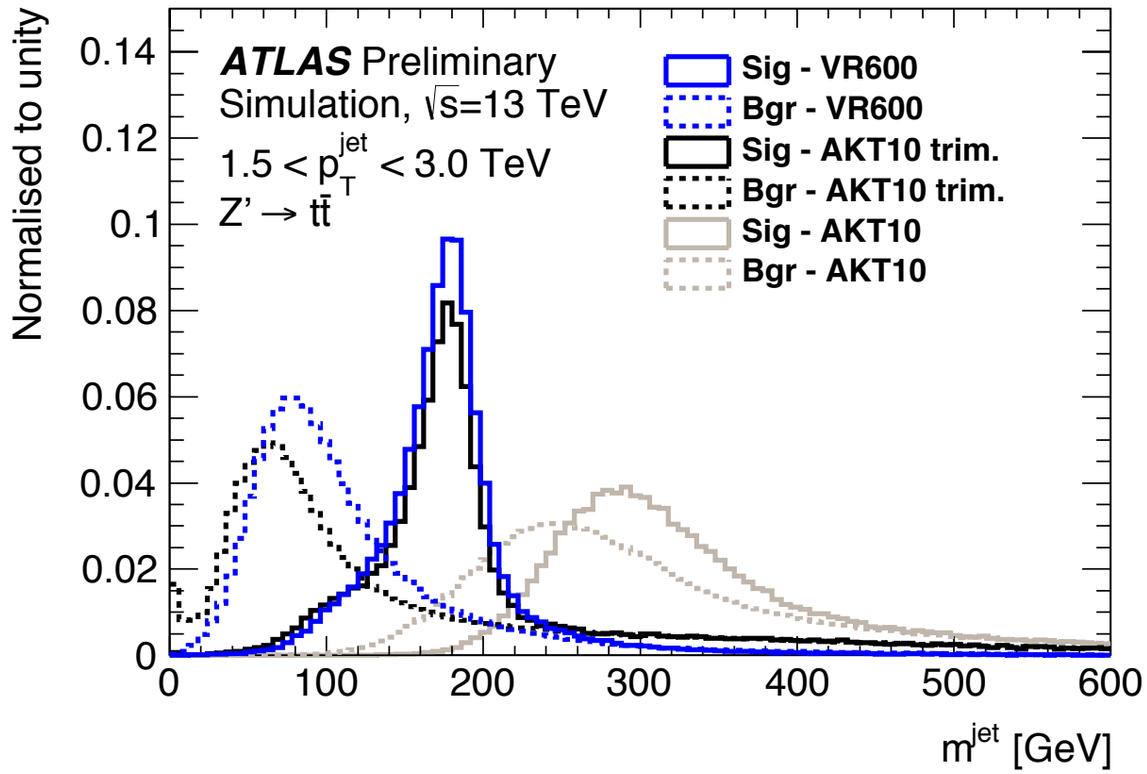
Variable R for W Tagging

Variable R jet clustering [Krohn, Thaler, Wang, JHEP 0906, 059 (2009)]

- IRC safe and computationally not more expensive than other algorithms

[ATLAS, PHYS-PUB-2016-013]

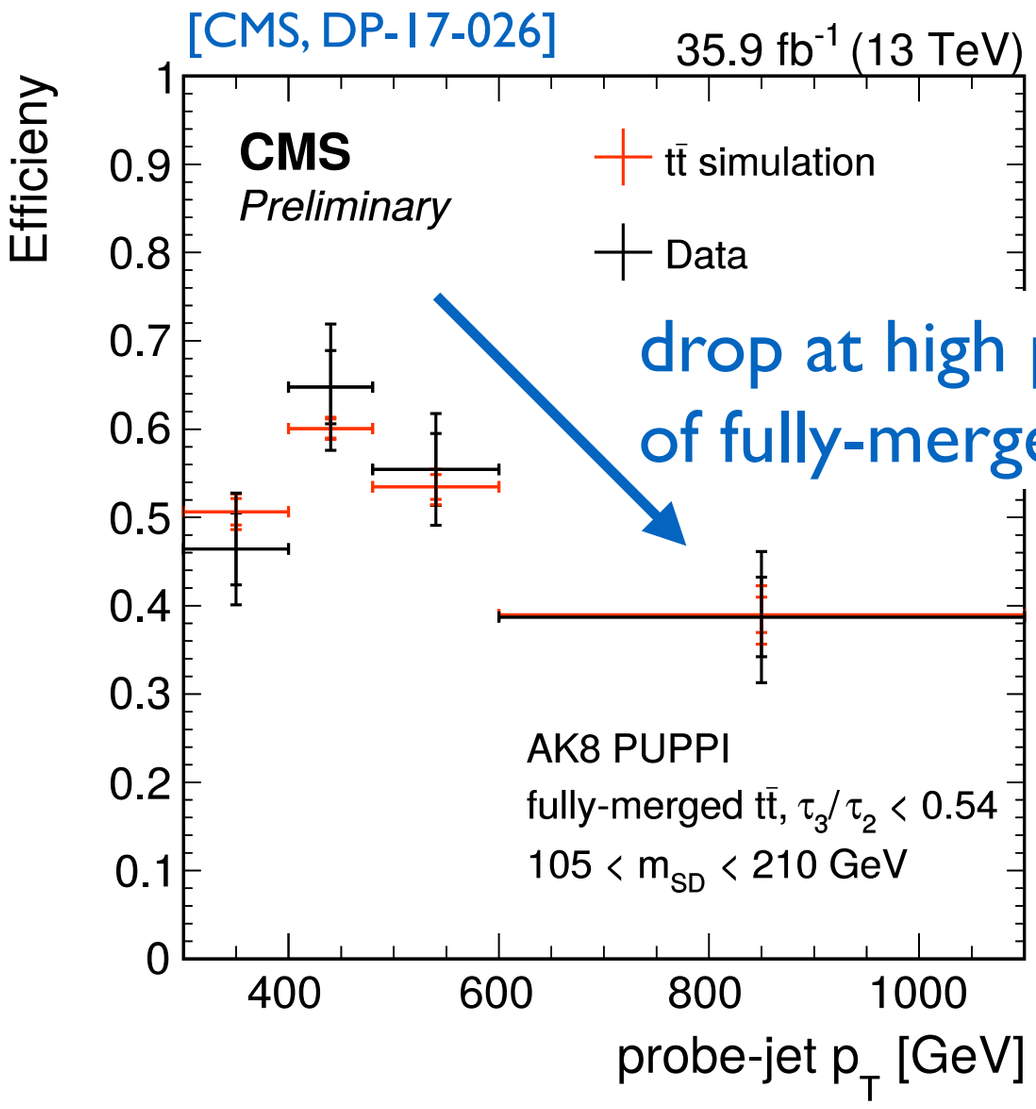




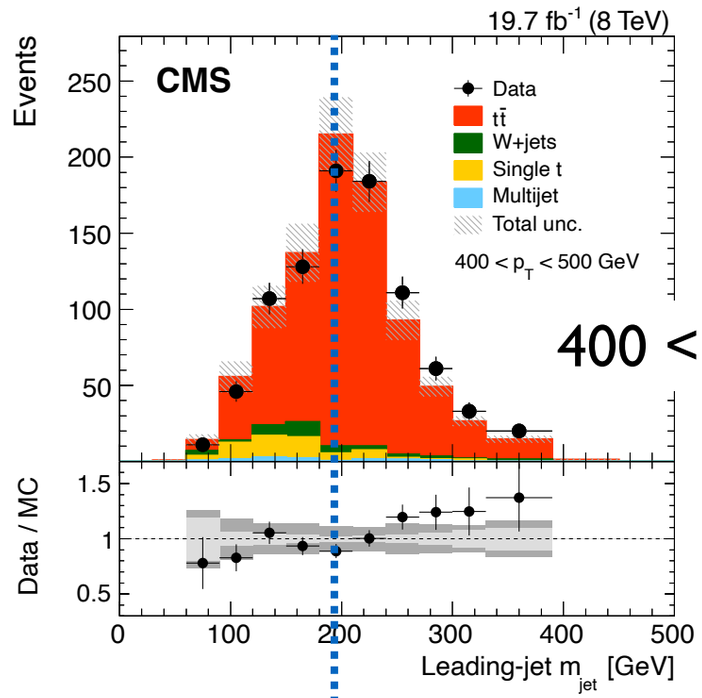
- Signal: similar effect as trimming, background less effected
- Performance studies promising, none with full systematics
- Reduction of modelling uncertainties (esp. NP)?

Top Tagging at High p_T

[CMS, DP-17-026]

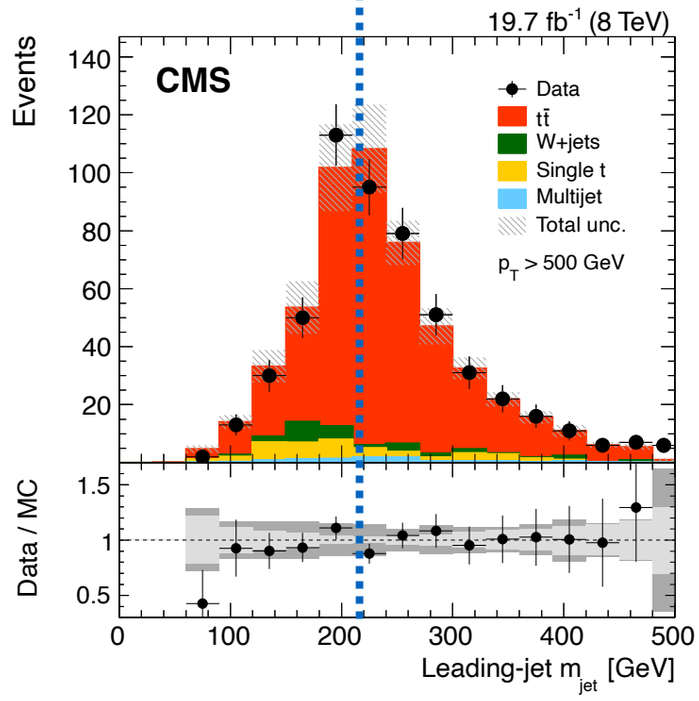


drop at high p_T of fully-merged ε



400 < p_T < 500 GeV

→ peak shifts by ~ 20 GeV



p_T > 500 GeV

Drop at high p_T usually not seen as merged Ws get tagged

[CMS, EPJC 77, 467 (2017)]

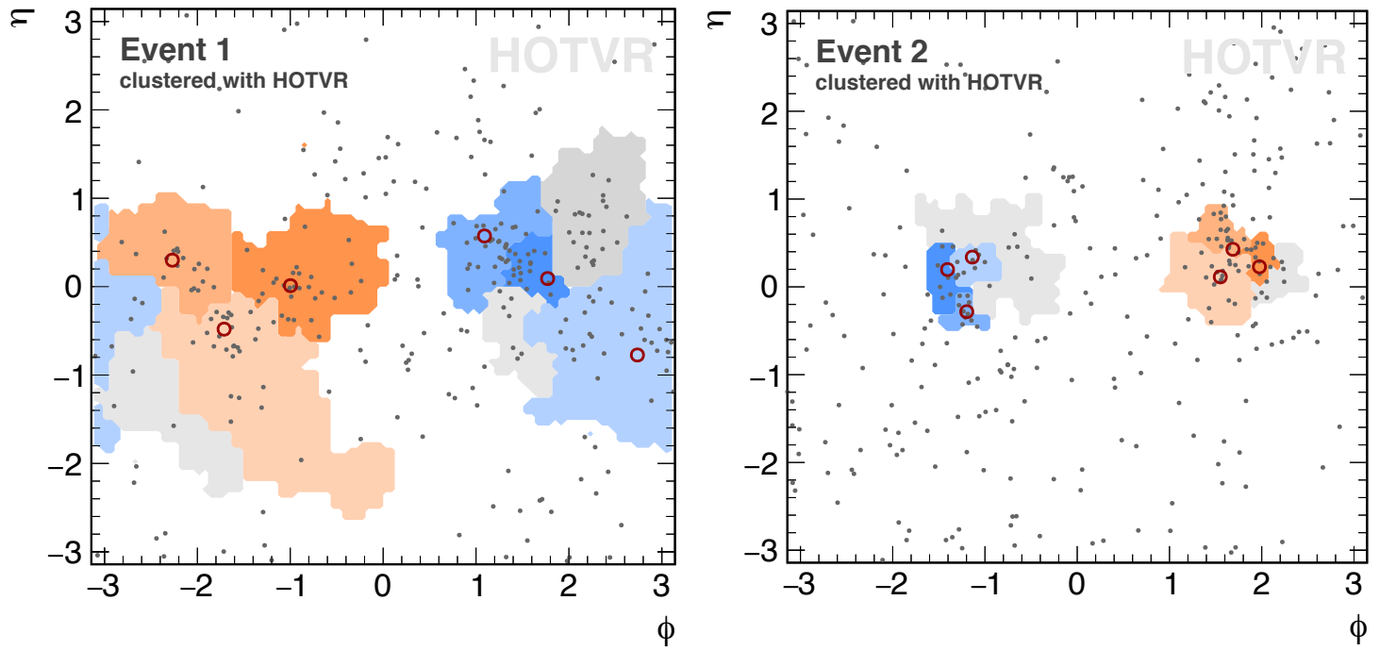
HOTVR

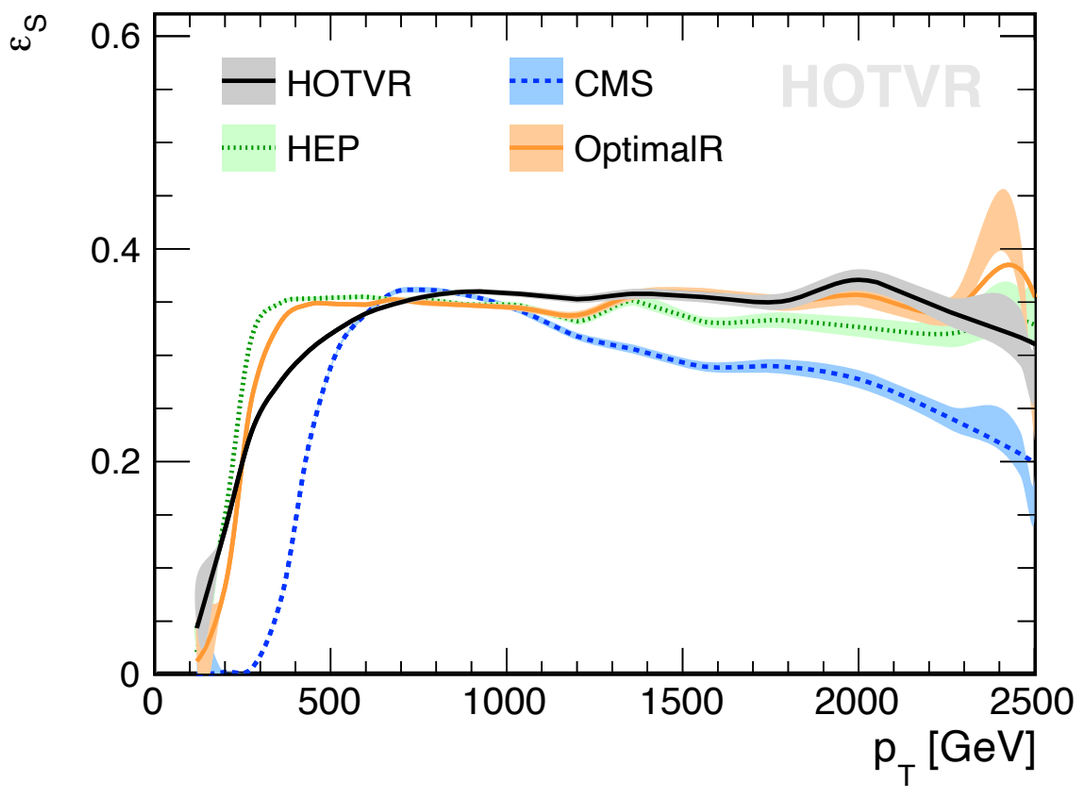
Heavy Object Tagger with Variable R

- Adaptive jet radius with VR
  - drawback: large catchment area at low p_T
- Solution: vetoed jet clustering
  - mass jump condition
  - remove soft/wide angle rad.

  [Stoll, JHEP 04, 111 (2015)]
- Proof of principle:
  Stable performance with little algorithmic complexity
- Interesting in combination with advanced methods!

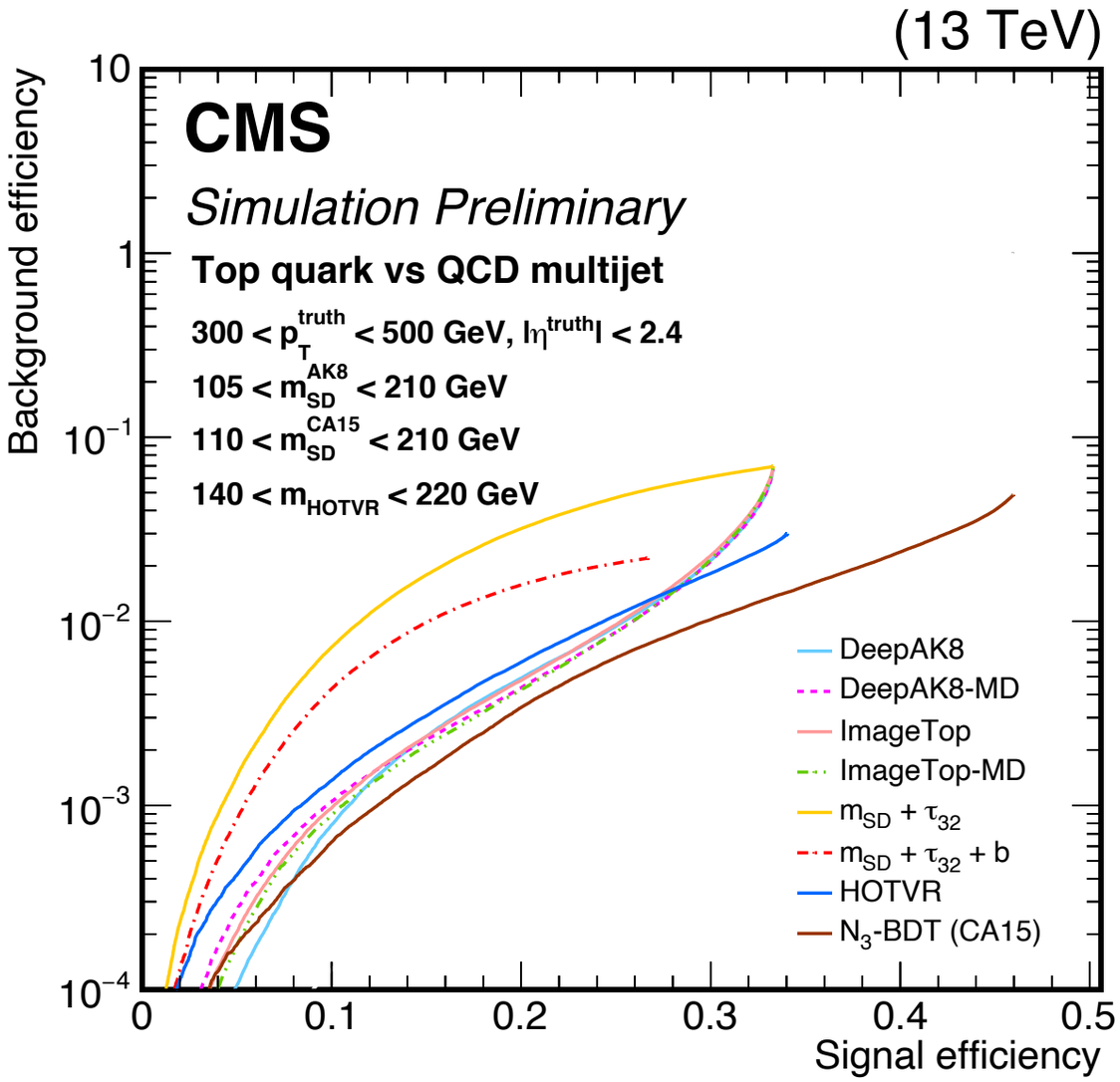
[Lapsien, RK, Haller, EPJ C 76, 600 (2016)]

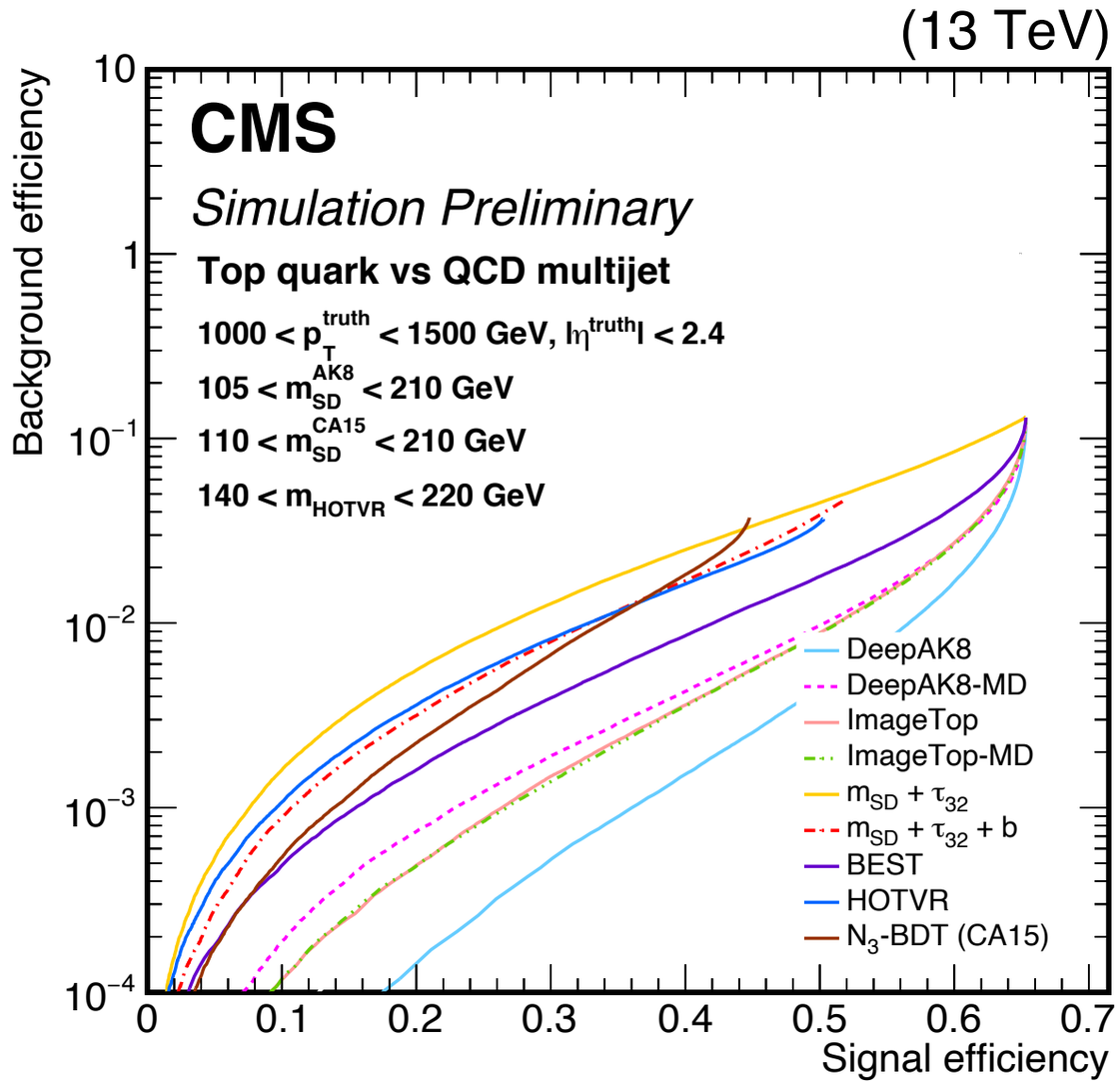




Top Tagger Performance

[CMS-PAS-JME-18-002]

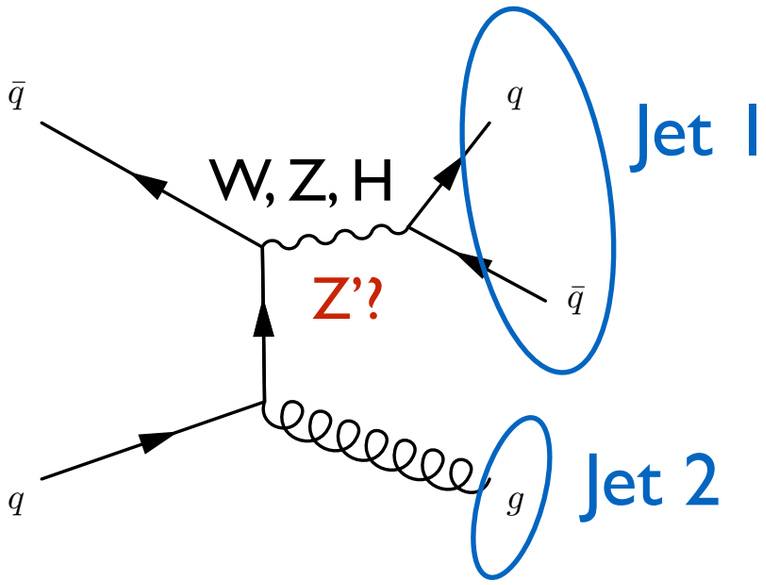




Measurements

with highly boosted final states

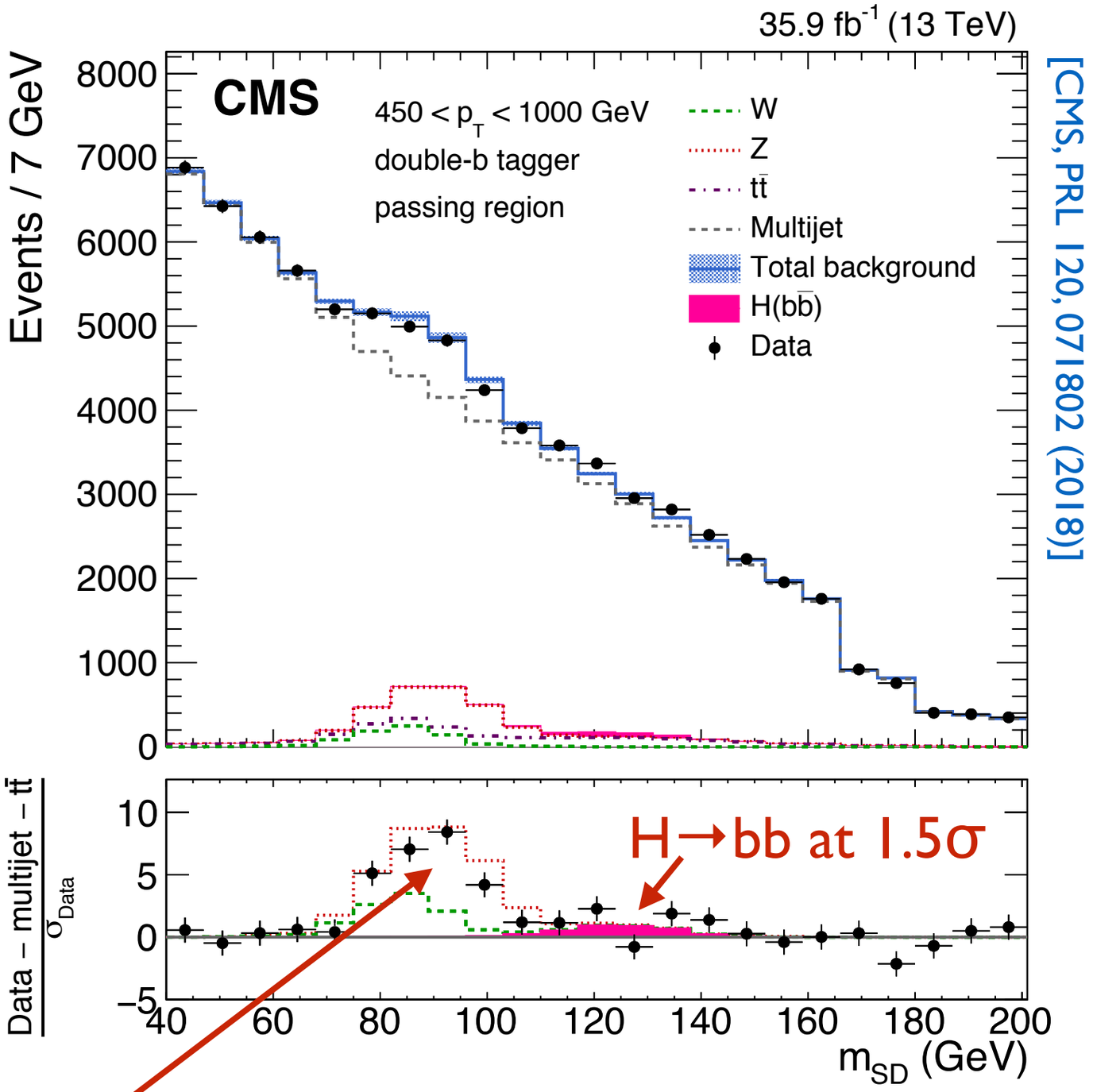
H→bb̄ in H+Jet



First observation of Z→bb̄ in a single jet at an hadron collider

Promising channel for Higgs p_T measurements

Result obtained with $N_2^{1,DDT}$: constant background efficiency!



Z+jet with 5.1σ

Signal resolution of ~10 GeV

$t\bar{t}$ Cross Sections

All-hadronic channel

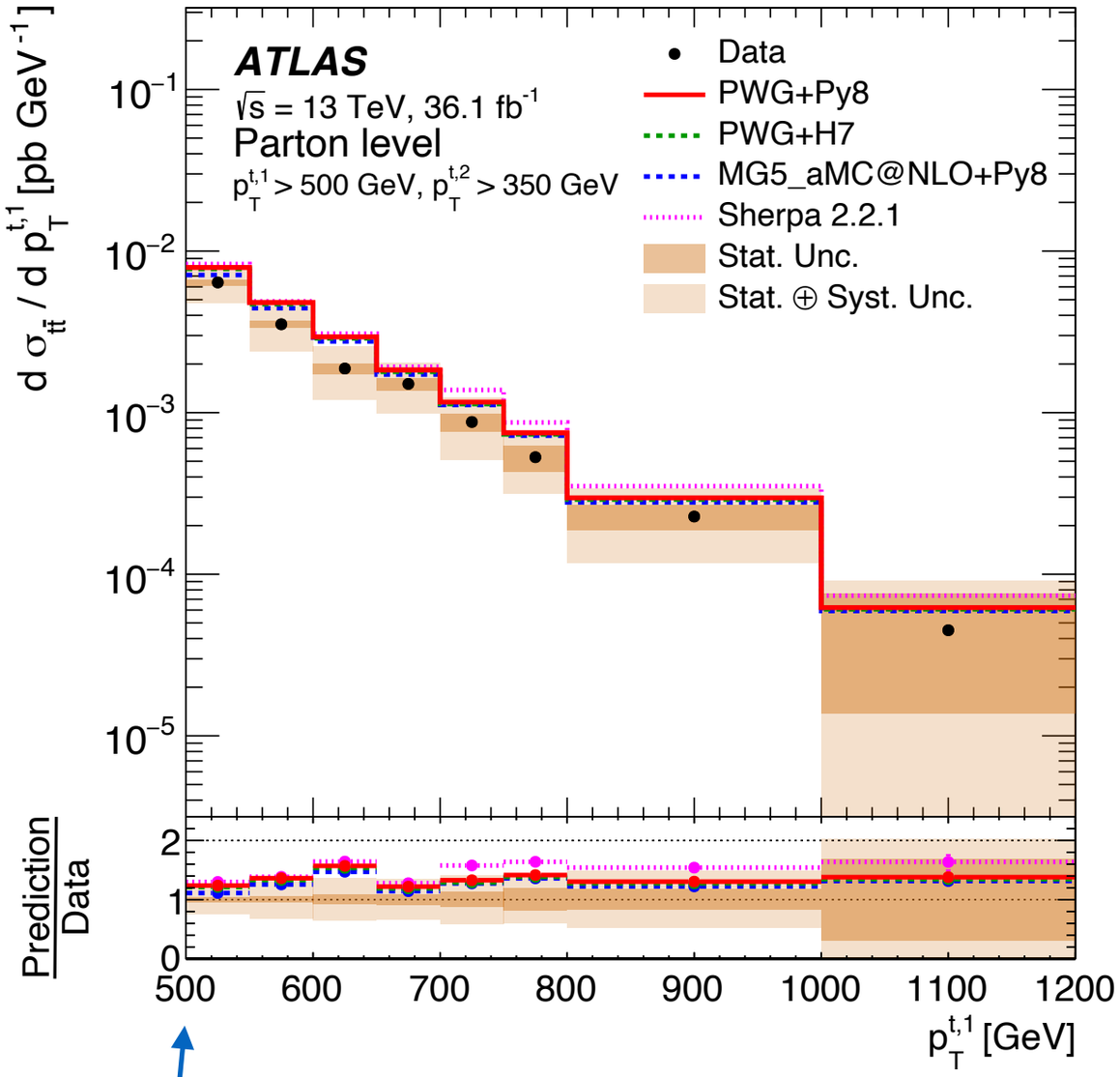
- t tag: jet mass and τ_{32} (p_T dependent cuts)
- t and b tagging offer unique opportunity to constrain backgrounds

2nd large-R jet				
1t1b	J (7.6%)	K (21%)	L (42%)	S
0t1b	B (2.2%)	D (5.8%)	H (13%)	N (47%)
1t0b	E (0.7%)	F (2.4%)	G (6.4%)	M (30%)
0t0b	A (0.2%)	C (0.8%)	I (2.2%)	O (11%)
	0t0b	1t0b	0t1b	1t1b

Leading large-R jet

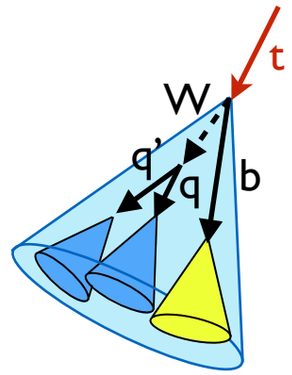
- Leading uncertainties:
  - t and b tagging (12 / 8%)
  - Jet energy scale (6%)
  - Modelling (18%)
  - Statistics: 2%

[ATLAS, PRD 98, 012003 (2018)]



Measurement starts where others stop!

Top Quark Jet Mass

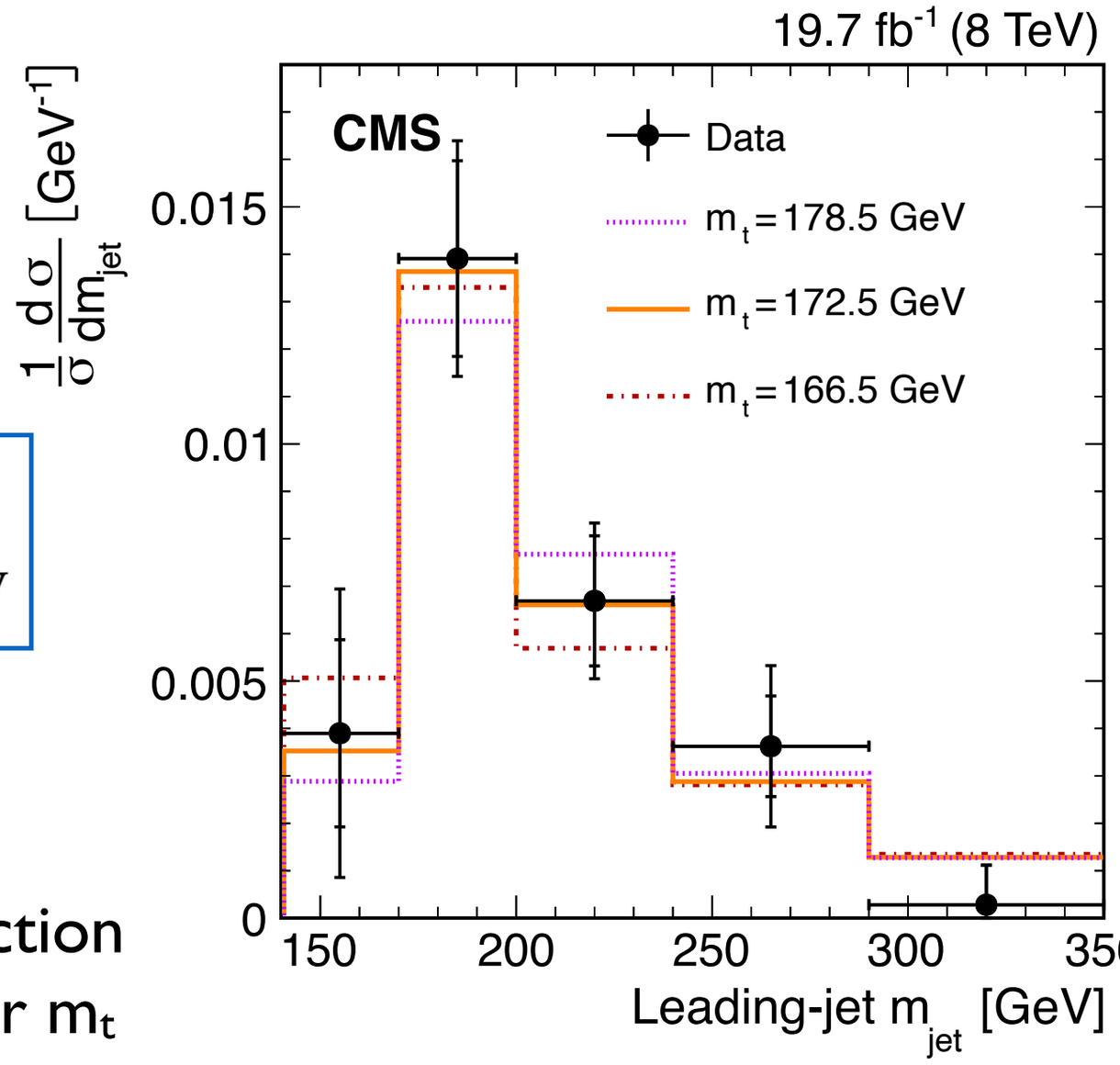


First unfolded measurement: fully-merged top quark decays

- Large CA jets, R = 1.2
  - ✓ sufficient statistics at 8 TeV
  - ✗ susceptibility to PU and UE
- Sensitivity to top quark mass:

$$m_t = 170.8 \pm 6.0\,(\text{stat}) \pm 2.8\,(\text{syst}) \pm 4.6\,(\text{model}) \pm 4.0\,(\text{theo})\,\text{GeV}$$

- Large improvements with 13 TeV data possible
- Will help to establish a firm connection between theory and experiment for m_t



[CMS, EPJC 77, 467 (2017)]

Improvements

[CMS, TOP-19-005]

XCone [I. W. Stewart, F. J. Tackmann, J. Thaler, C. K. Vermilion and T. F. Wilkason, JHEP 1511 (2015) 072]

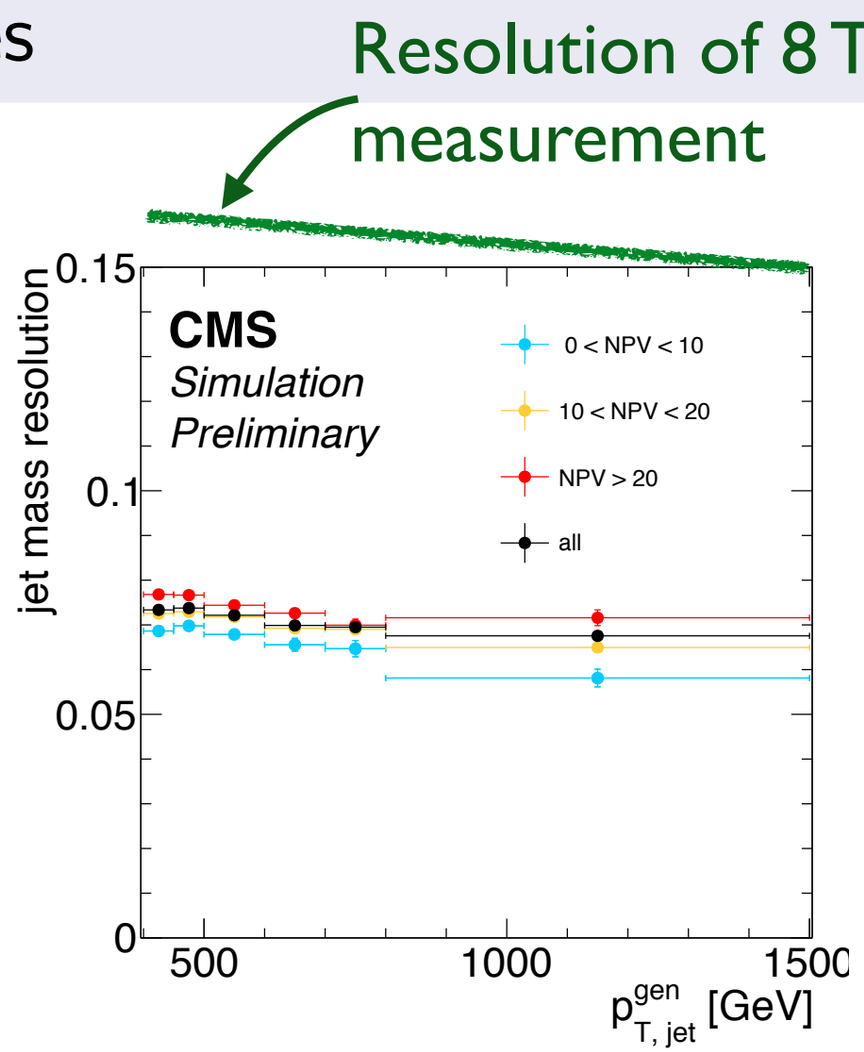
- exclusive jet algorithm $\rightarrow$ returns exactly N jets
- jet axes found by minimizing N-jettiness
- cluster particles inside R around axes

Improvements with XCone

- jet mass resolution (factor of 2)
- particle level width (factor of 2)
- stability against PU and UE
- higher statistical precision

On the arXiv today: 1911.03800,

Submitted to PRL

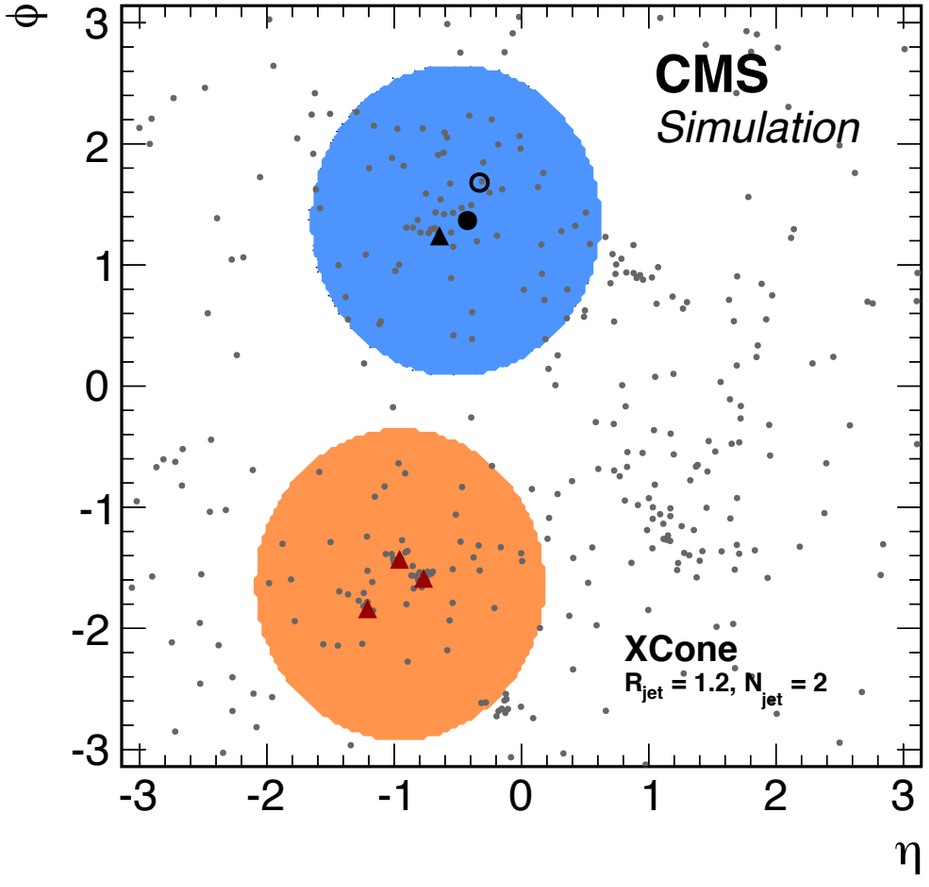


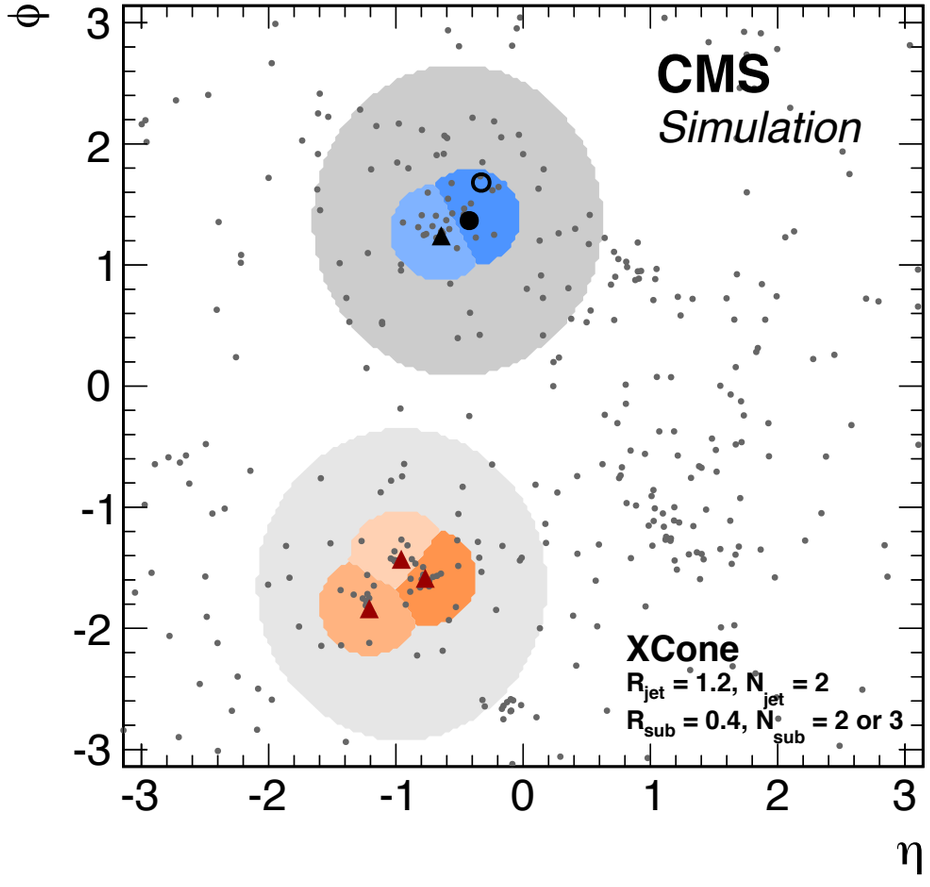
[CMS, TOP-19-005]

Clustering with XCone

set-up for lepton+jets $t\bar{t}$ idea from: [J. Thaler and T. F. Wilkason, JHEP 1512 (2015) 051]

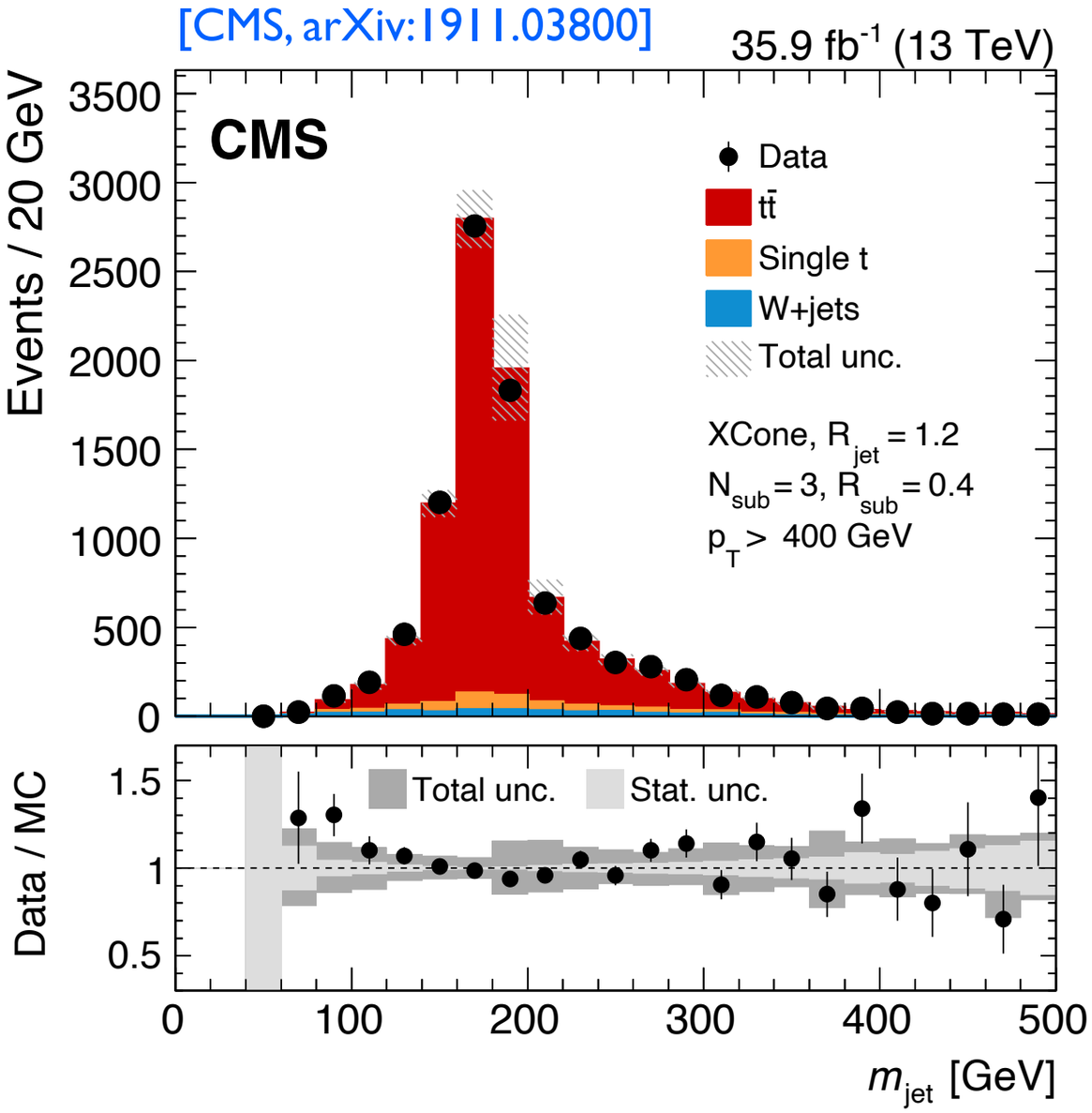
1. find 2 jets with large radius
2. calculate ΔR(lep, jet) for both jets
3. lowest $\Delta R \rightarrow$ leptonic jet; other $\rightarrow$ hadronic jet
4. find subjets: 3 in hadronic jet, 2 in leptonic jet
5. combine subjets to final jet

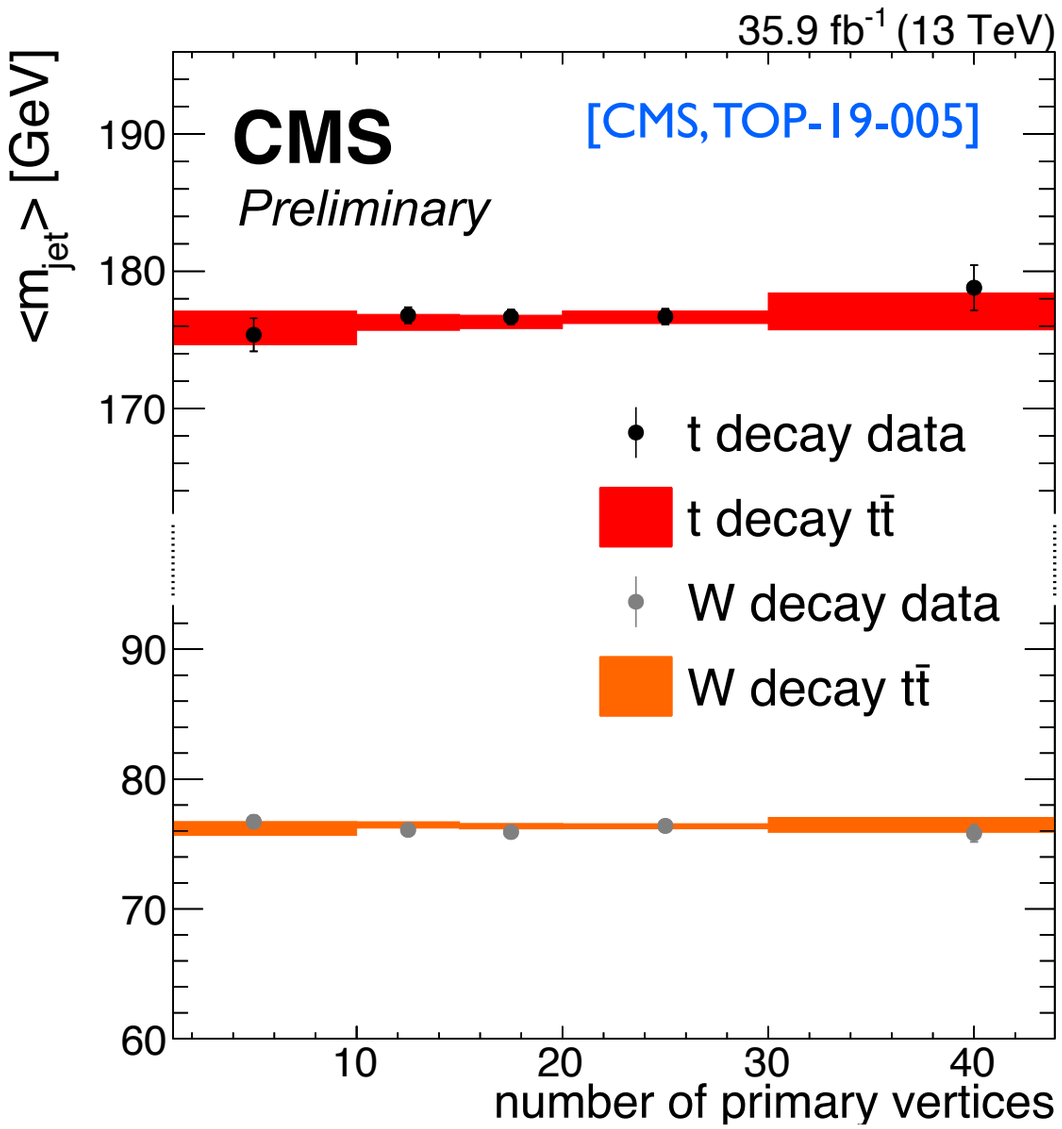




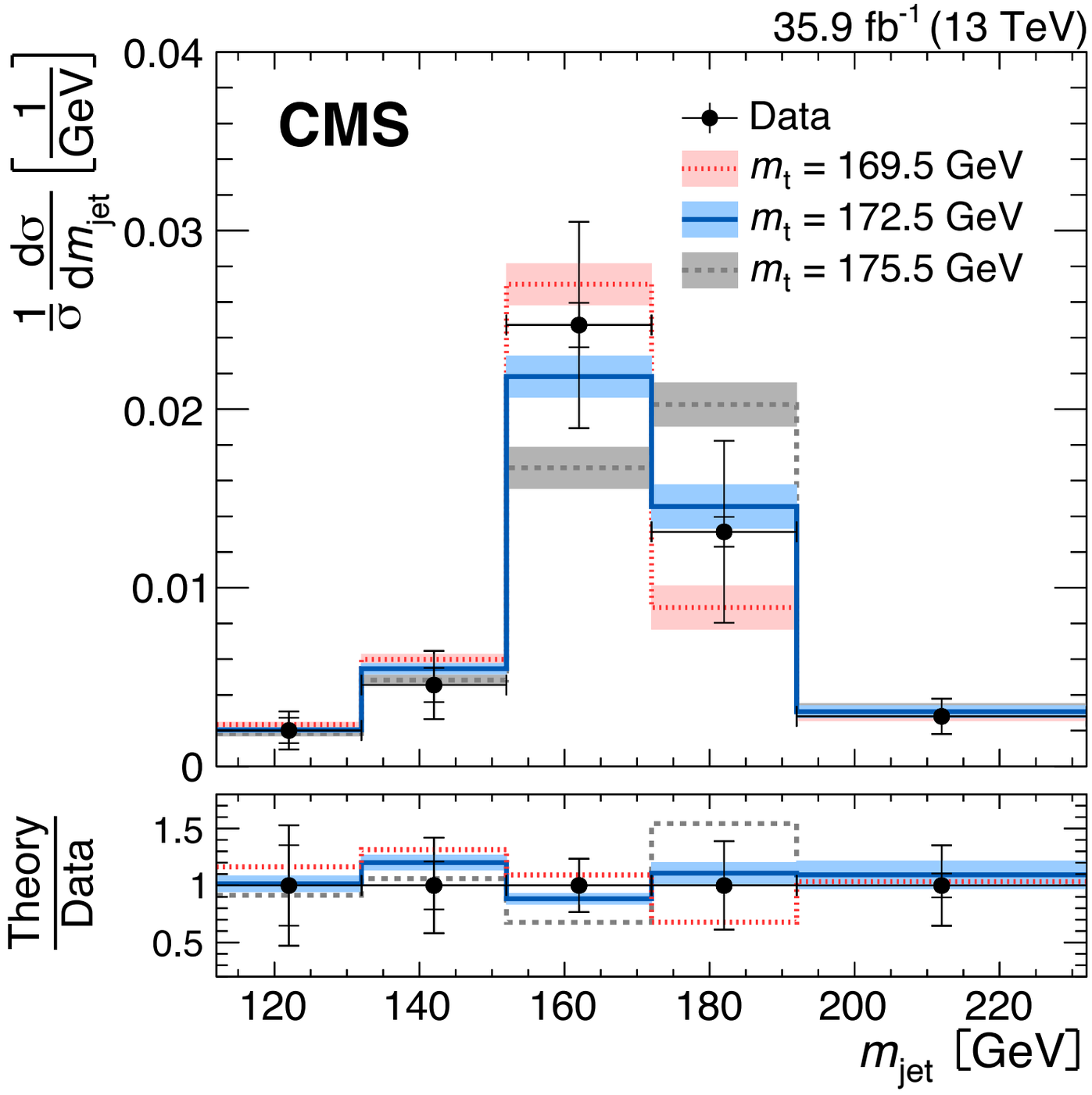
Experimental Performance

[CMS, arXiv:1911.03800]





Jet Mass Measurement



- mjet spectrum well described by event generators

m_t = 172.6 ± 2.5 GeV
(± 0.4_{stat} ± 1.6_{exp}
± 1.5_{model} ± 1.0_{theo})

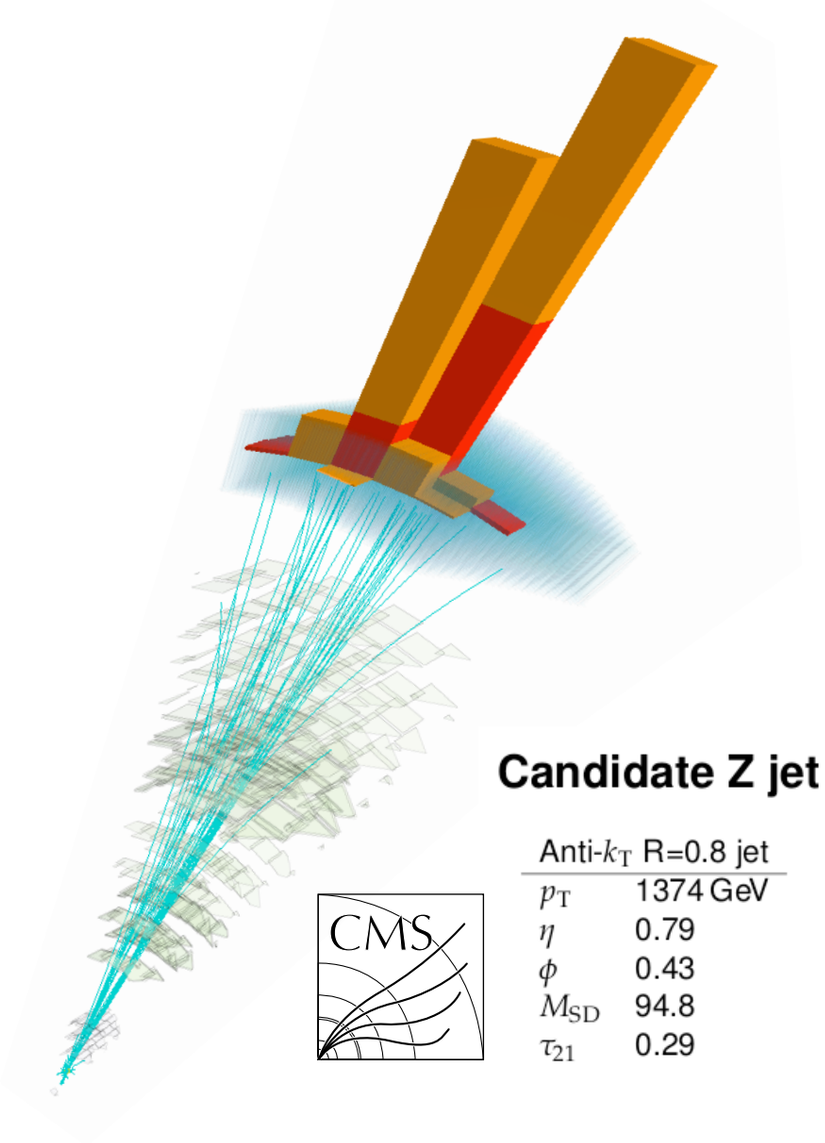
- feasibility of analytical calculations
- opens door for precision measurements in the boosted regime

[CMS, arXiv:1911.03800]

Summary

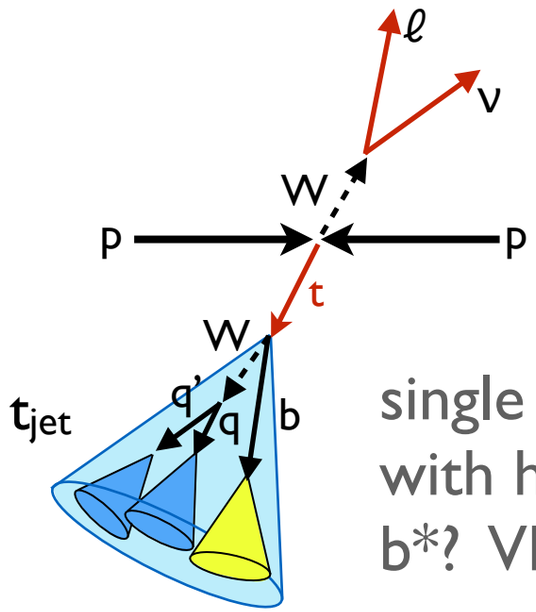
Searches

- Huge gain from jet substructure techniques
- Exciting interplay between:
  - model building
  - tools development
  - commissioning
  - application



Measurements

- Jet substructure goes precision
- Coming years will bring a number of novel measurements using jet substructure
  - $t\bar{t}$, single top, ttW/Z, differential H production, jet mass of top, W and Z…



single top (tW) with high p_T? b*? VLQ?

Additional Material

The Intriguing Flavour Story

- No hints for BSM effects from direct searches so far
  - Never stop looking for all (im)possible signatures

The Intriguing Flavour Story

- No hints for BSM effects from direct searches so far
  - Never stop looking for all (im)possible signatures
- We can get inspired by existing riddles
  - Anomalies in flavour data:

$$R_{D^{(*)}} = \left. \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}l\bar{\nu})} \right|_{l\in\{e,\mu\}}$$ BaBar, Belle, LHCb **3.8 σ**

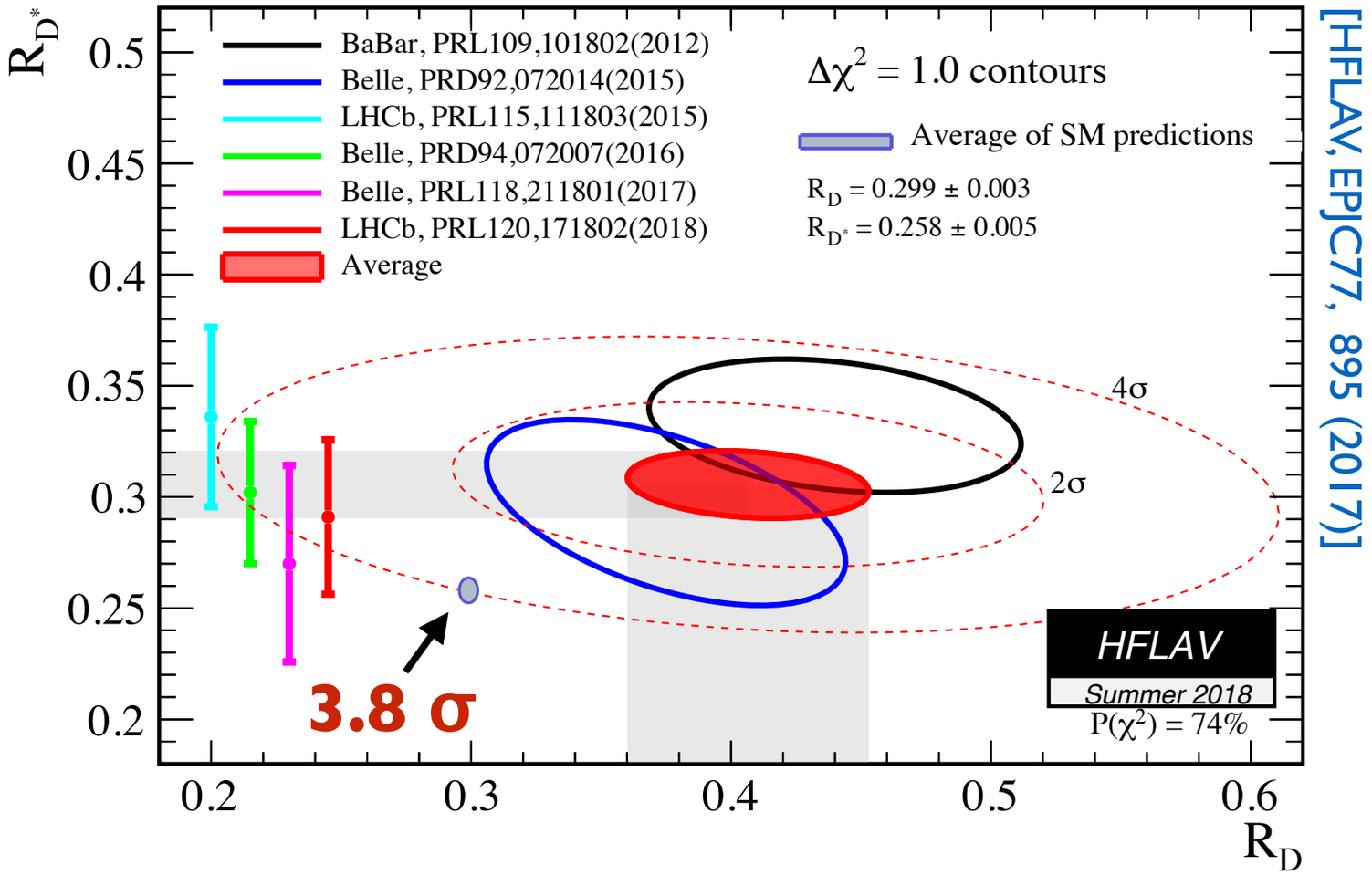
$$R_{J/\psi} = \frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu})}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu})}$$ LHCb **2.0 σ**

$$R^{[q_1^2,q_2^2]}_{K^{(*)}} = \frac{\mathcal{B}'(B \to K^{(*)}\mu\mu)}{\mathcal{B}'(B \to K^{(*)}ee)}$$ LHCb **−2.5 σ**

$(g-2)_\mu$ E821, BNL **3.5 σ**

Consequences at high p_T?

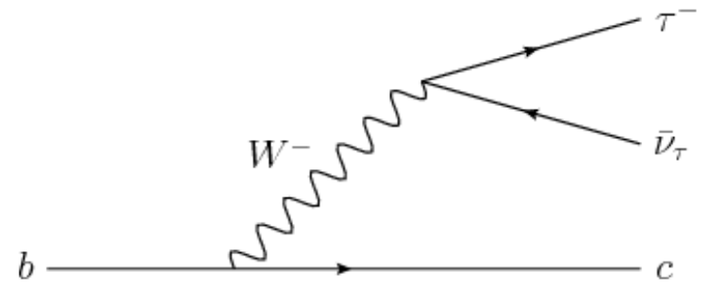
$R_{D(*)}$ and $R_{J/\psi}$



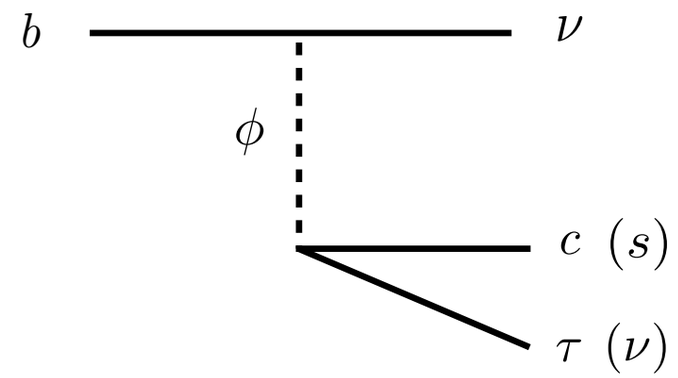
[HFLAV, EPJC77, 895 (2017)]

- Uncertainties in SM prediction
  - form factors for τ vs ℓ decay ~ m_τ
  - strong decay of D*
  - soft photon corrections
  - **total: ~4-5%**

SM weak decay



Possible BSM contribution from LQs

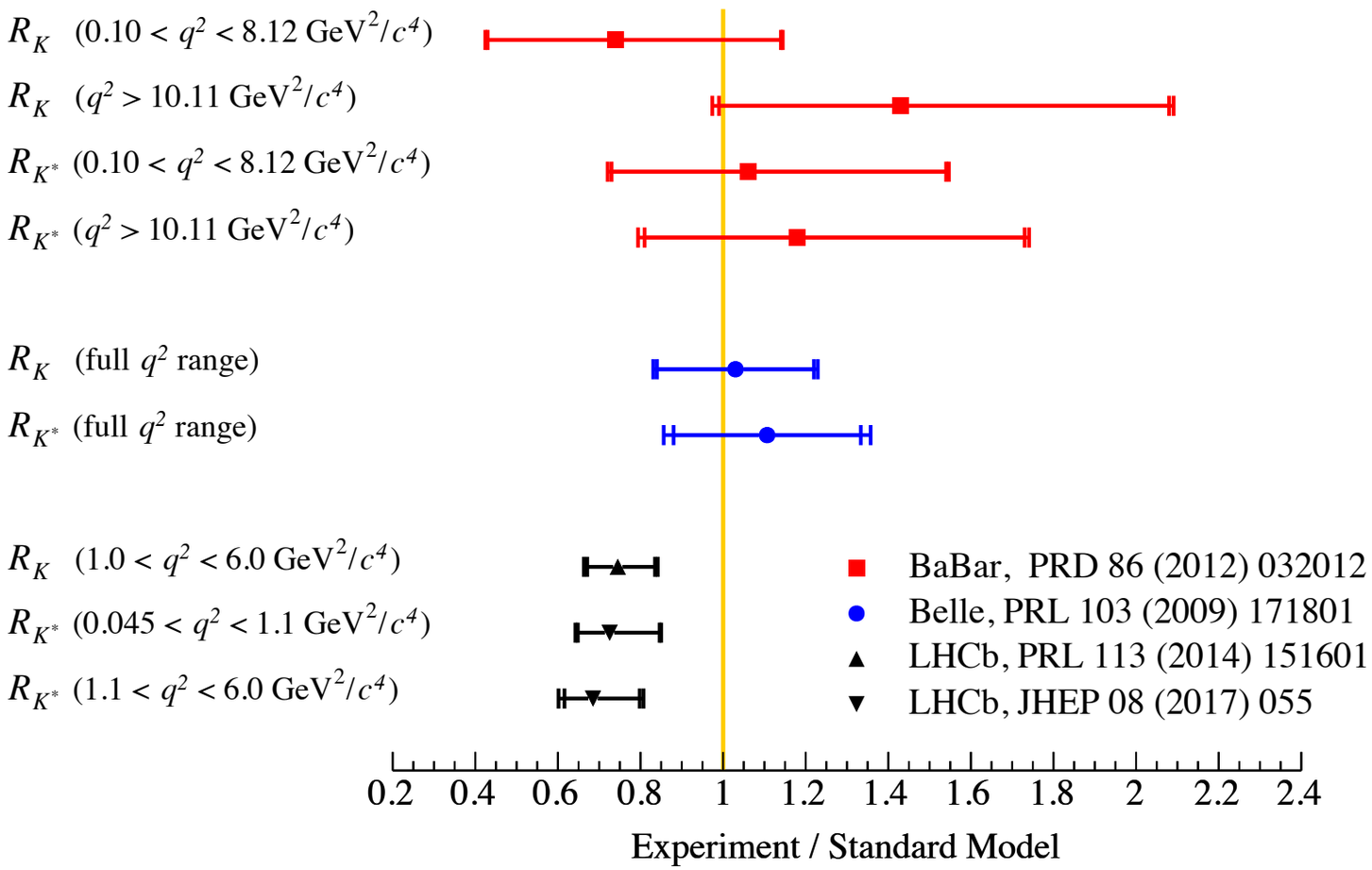


[Bauer, Neubert, PRL 116, 141802 (2016)]

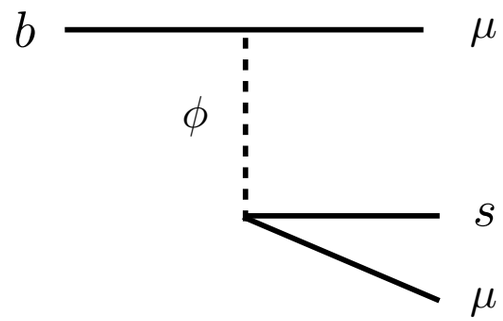
LQ couplings
tree-level: **bτ, cν, cτ, bν**
loop: **tτ, sν, sτ, tν**

$R_{K(*)}^{[q_1^2,q_2^2]}$

[Bifani et al.,arXiv:1809.06229]

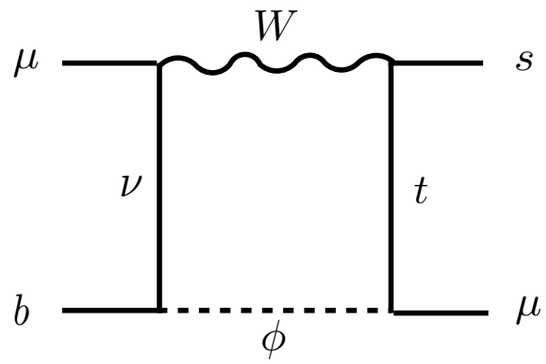


- Hadronic effects negligible
  - except with LFUV, then could have an effect
- LHCb measurements below SM by 2.1 - 2.6σ



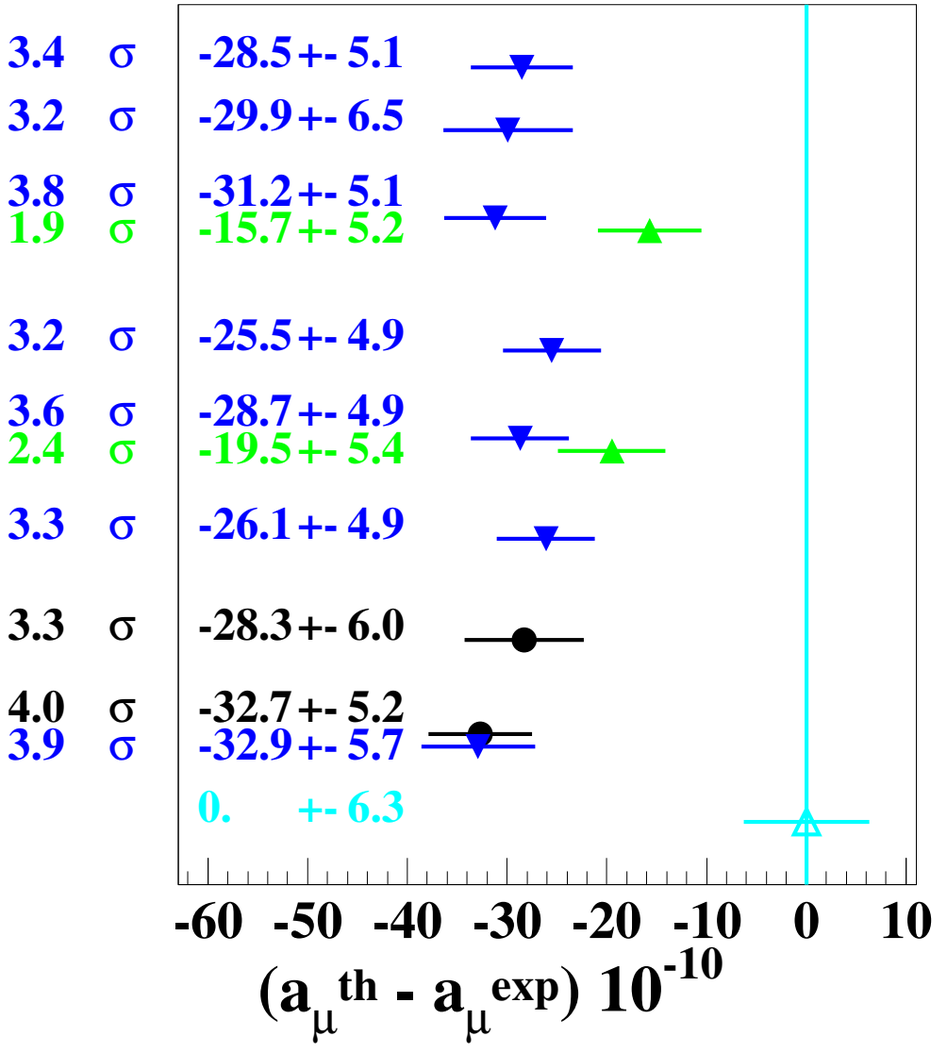
LQ couplings at tree-level: **sμ, bμ**

Can lead to enhancement of SM prediction



LQ couplings loop-induced: **tμ, cμ**

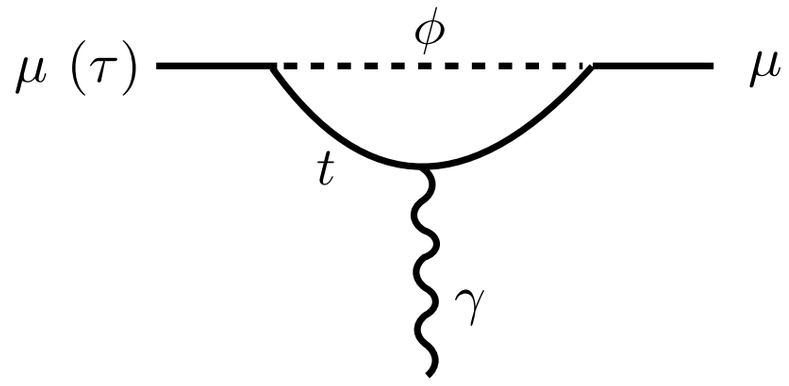
$(g-2)_\mu$



e^+e^-	Hagiwara+ Phys. Lett. B 649 (2007) 173
e^+e^-	Jegerlehner+ Phys. Rep. 477 (2009) 1
e^+e^- / τ	Davier+ Eur.Phys.J. C 66 (2010) 127
e^+e^-	Davier+ Eur.Phys.J. C66 (2010) 1
e^+e^- / τ	Davier+ Eur.Phys.J. C71 (2011) 1515
e^+e^-	Hagiwara+ J.Phys. G38 (2011) 085003
$e^+e^- + \tau$	Jegerlehner+ Eur.Phys.J. C71 (2011) 1632
$e^+e^- + \tau$ / e^+e^-	Jegerlehner arXiv:1511.04473
BNL-E821	Bennett+ Phys. Rev. D73 (2006) 072003

[D. Bernard, arXiv: 1607.07181]

- About 3σ deviation, depending on $\Delta\alpha_{had}$ (e^+e^- or τ decays)
- LQ couplings loop-induced: **tμ**



LQ Phenomenology

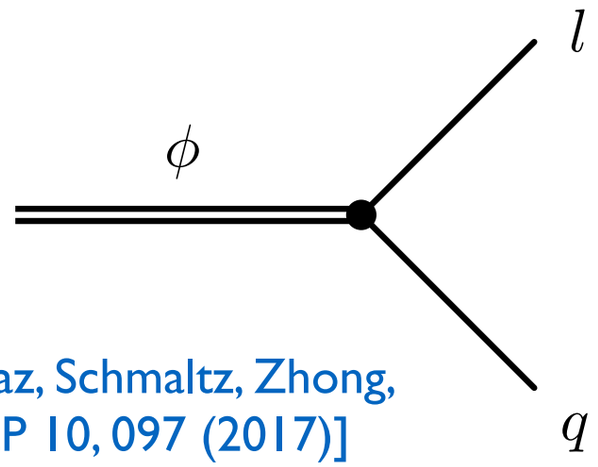
- Nature of possible LQs
  - Model dependent
  - Additional constraints from B(B→Kνν), Δm_{Bs}, $D_{(s)}$→μν…
  - Global fits to flavour data: suggest at least one LQ state with mass O(1-3) TeV

	Y	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
scalar	1/3	S_1	✗*	✓	✗*
	7/6	R_2	✗*	✓	✗
	1/6	$\widetilde{R_2}$	✗	✗	✗
	1/3	S_3	✓	✗	✗
vector	2/3	U_1	✓	✓	✓
	2/3	U_3	✓	✗	✗

Combinations of scalar LQs can explain $R_{K^{(*)}}$ and $R_{D^{(*)}}$, e.g. S_1 and S_3 [79]

[Angelescu et al., arXiv:1808.081

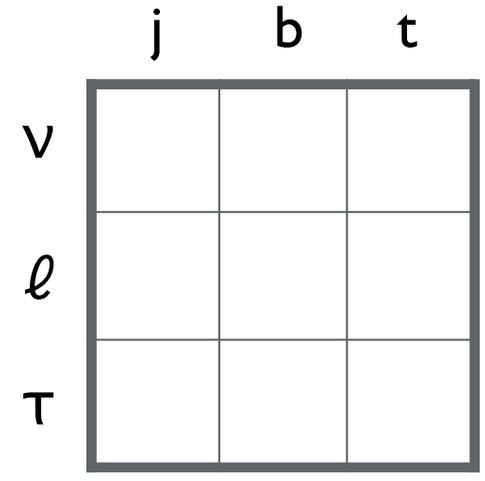
- Probe the full flavour matrix!



[Diaz, Schmaltz, Zhong, JHEP 10, 097 (2017)]

$$Y_{L,R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & Y_{L,R}^{c\mu} & Y_{L,R}^{c\tau} \\ 0 & Y_{L,R}^{t\mu} & Y_{L,R}^{t\tau} \end{pmatrix}$$

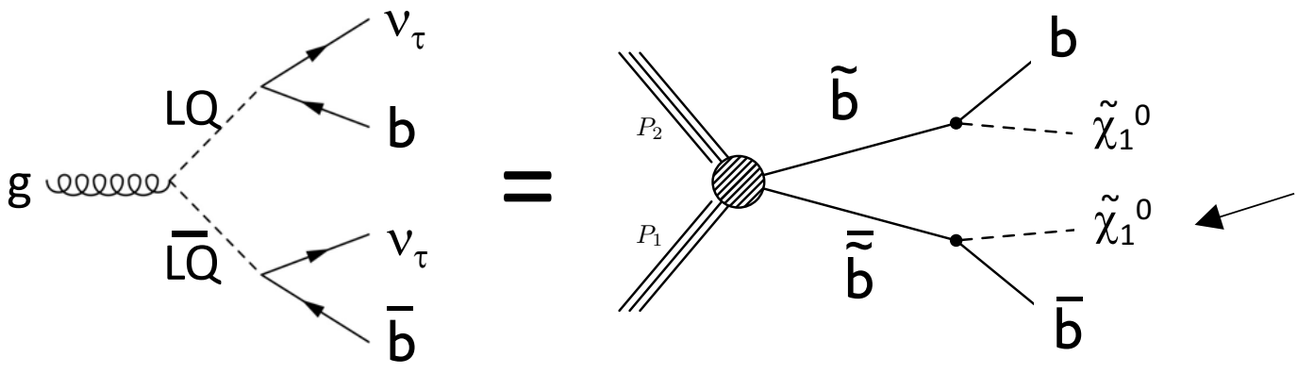
and $\ell_i \to \nu_i$



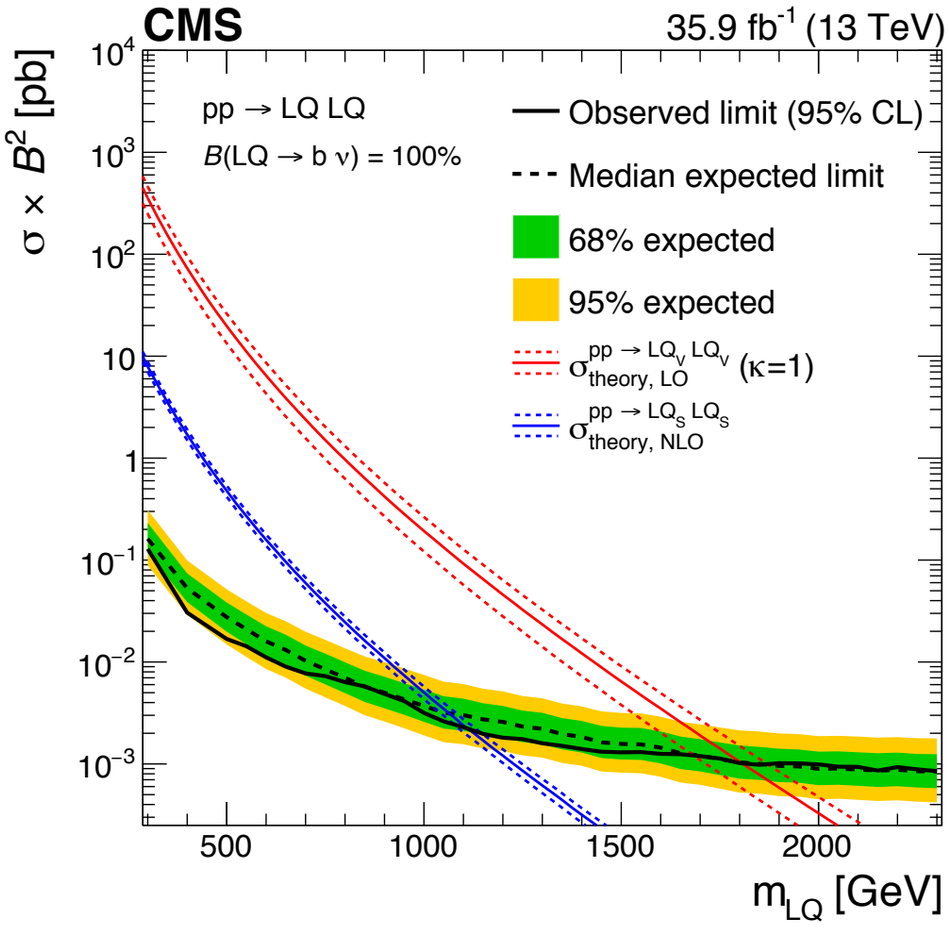
LQ Pair → νν+bb̄(qq̄)

[CMS, PRD 98, 032005 (2018)]

- Reinterpretation of SUSY M_{T2} sbottom search



Both $\tilde{b}$ and LQ are scalar
→ Equivalent under
$m(\chi_1^0) = m(LSP) = 0$



Mass exclusions

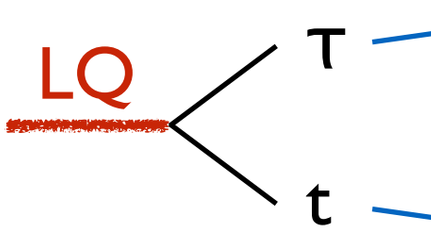
scalar LQs → bν: 1.1 TeV
vector LQs → bν: 1.8 TeV

scalar LQs → tν: 1.0 TeV
vector LQs → tν: 1.8 TeV

Relevant for $R_{D(*)}$ and $R_{K(*)}$

LQ Pair → $\tau\bar{\tau}+t\bar{t}$

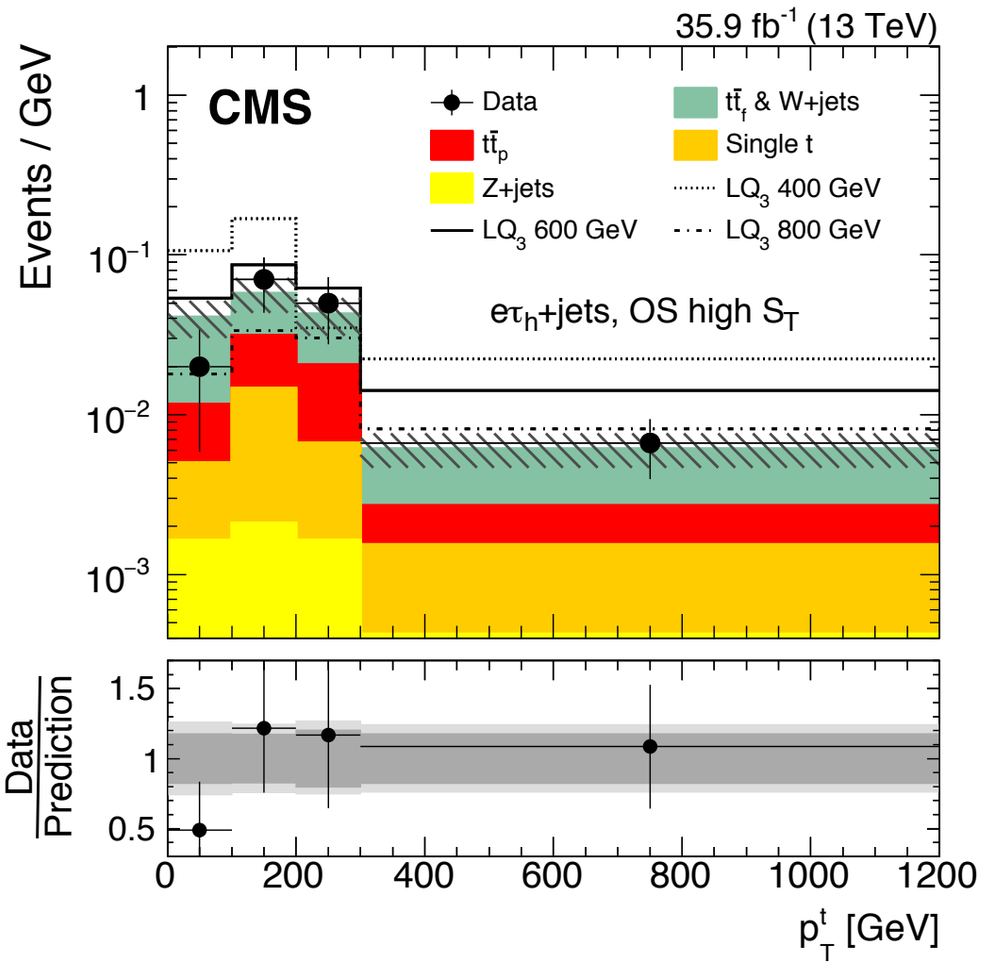
[CMS, EPJC 78, 707 (2018)]

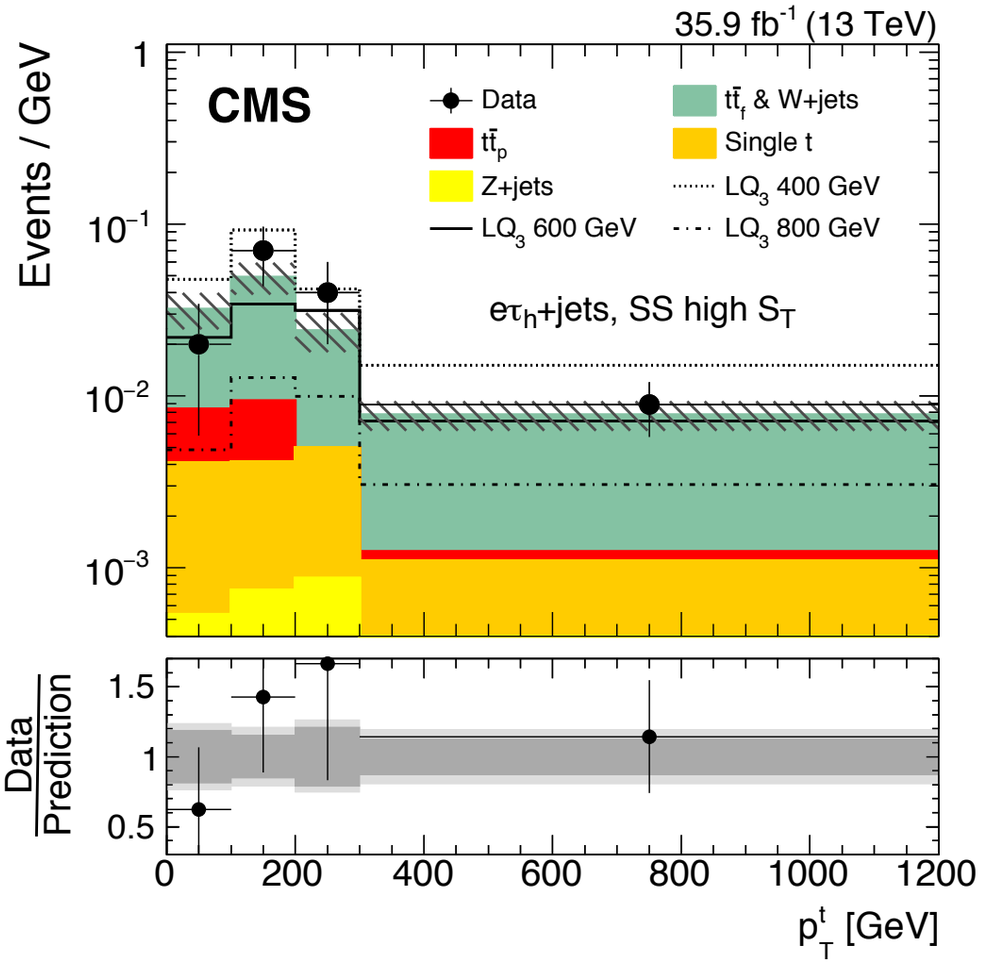


Background estimation through ID inversion

Reconstruct top decay: p^t_T sensitive to m_{LQ}

- Cat A: ℓ + 2τ_h + jets
  Sensitivity for low m_{LQ}
- Cat B: ℓ + τ_h + jets
  Sensitivity for high m_{LQ}



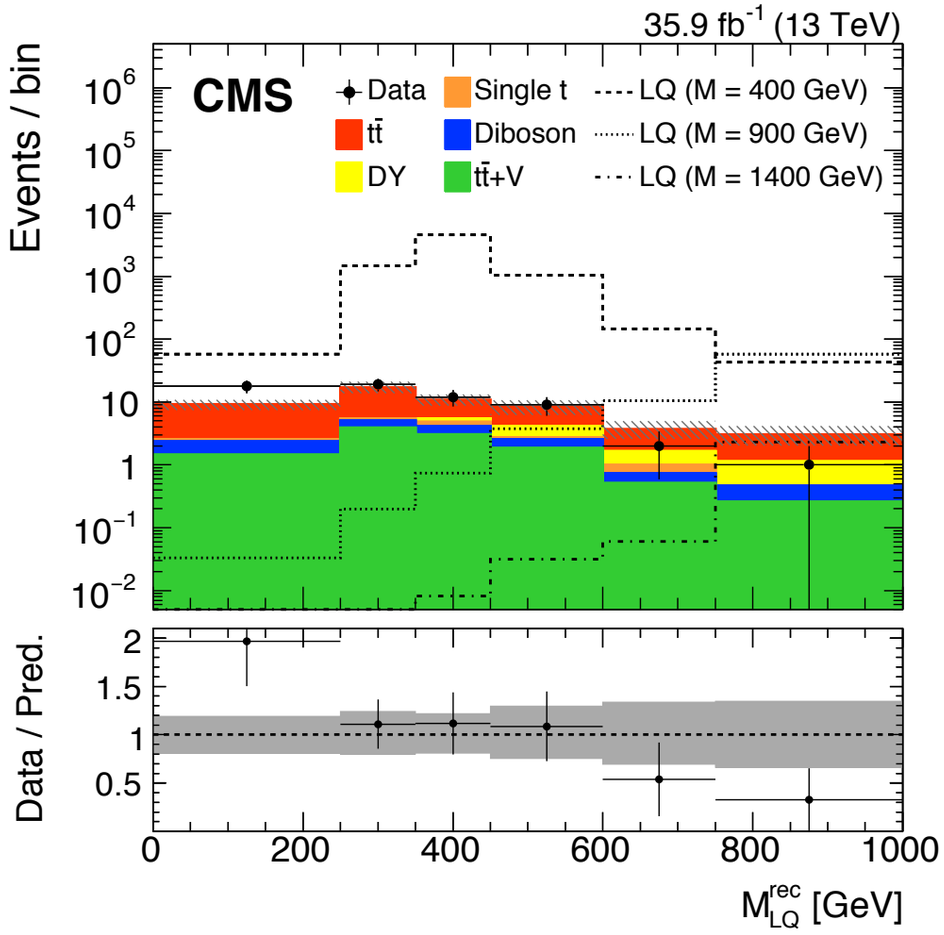


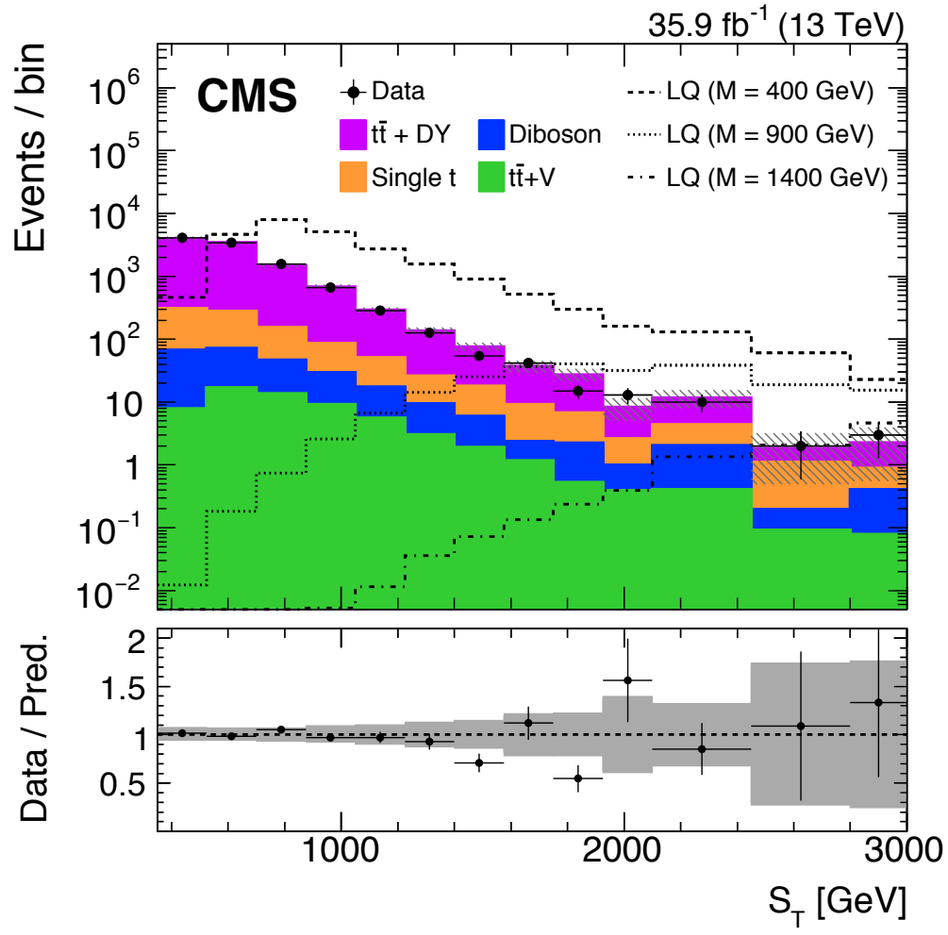
LQ Pair → μμ̄+tt̄ [CMS, PRL 121, 241802 (2018)]

- Up to 4 leptons in final state
  - two signal regions: 2μ+ℓ+jets and 2μ+jets

reconstruct M_{LQ} → measured e and μ misID

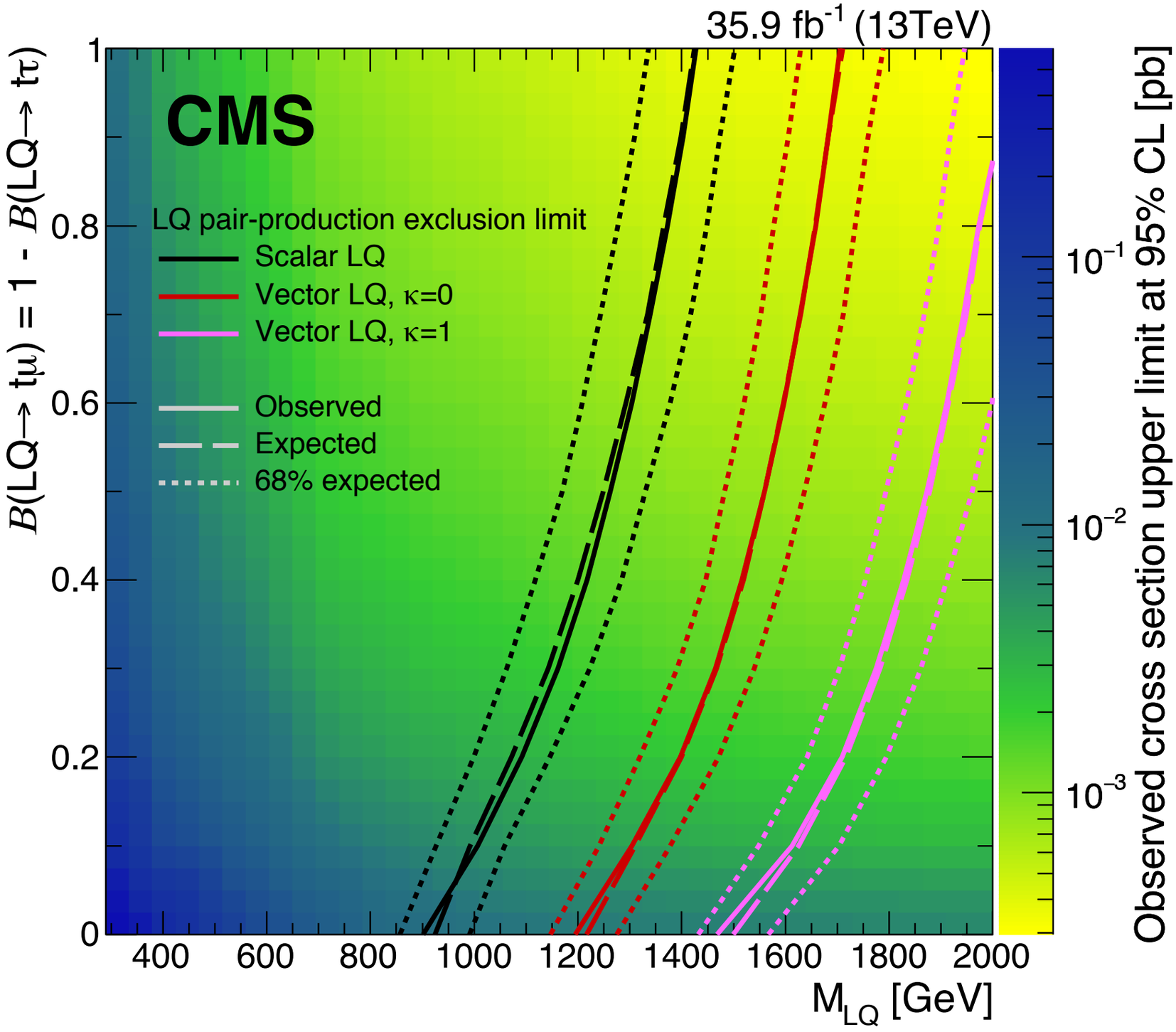
measure S_T → tt̄+DY obtained from 2e+jets CR





Combination

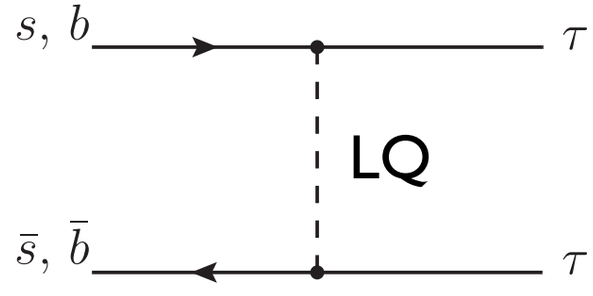
[CMS, PRL 121, 241802 (2018)]



Exclusion between **0.9** and **1.4 TeV** for tτ and tμ (scalar LQs)

Relevant for $R_{D^{(*)}}$, $R_{K^{(*)}}$ and $(g-2)_\mu$

Numerous other interesting channels to explore…

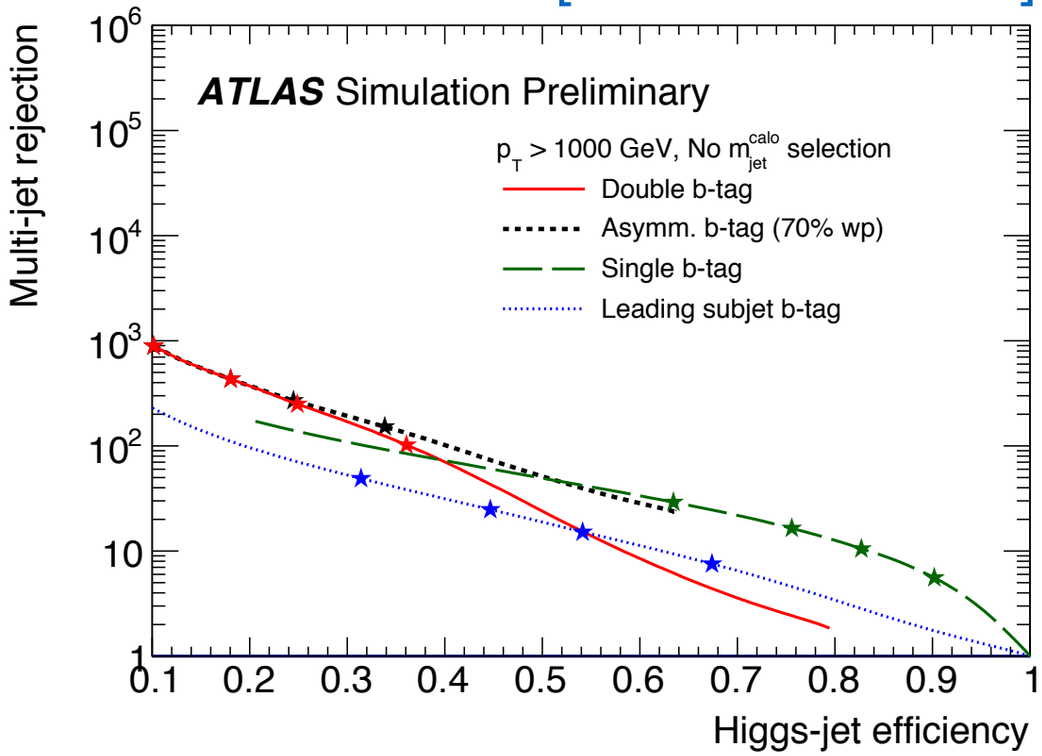


Identifying Boosted H→bb

Subjet b tagging (ATLAS)

Leading track jets with R=0.2 inside a large jet with R=1.0

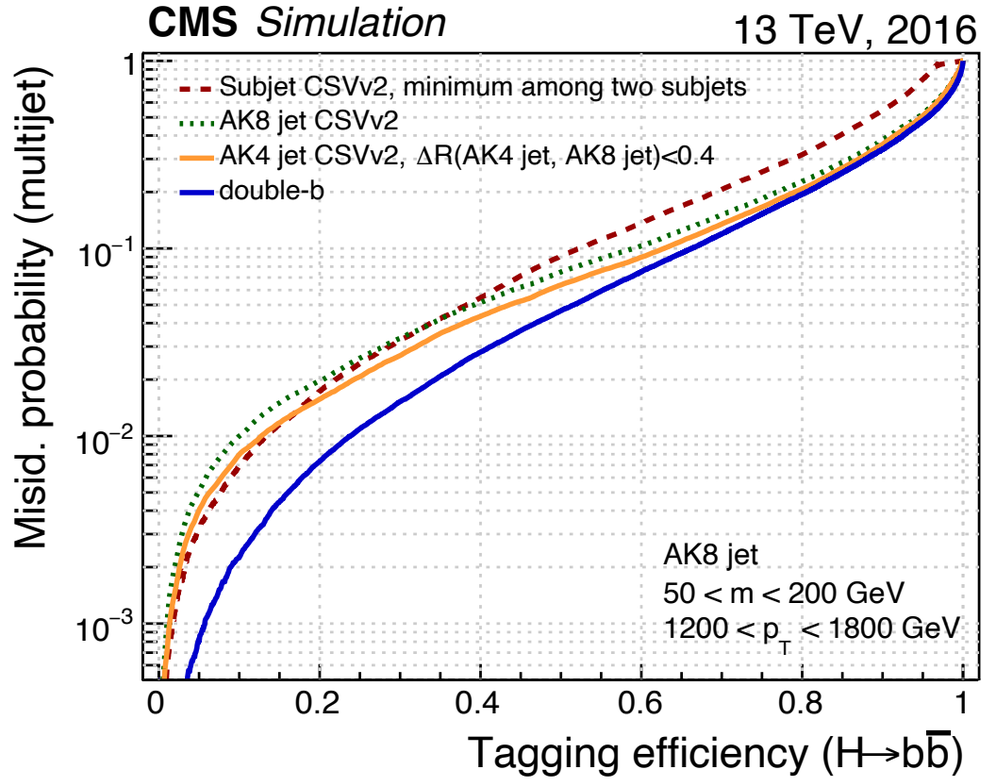
[ATL-CONF-2016-039]



Discrimination against boosted t→bW with double b-tag

Double-b tagger (CMS)

BDT based on track, SV, substructure inputs

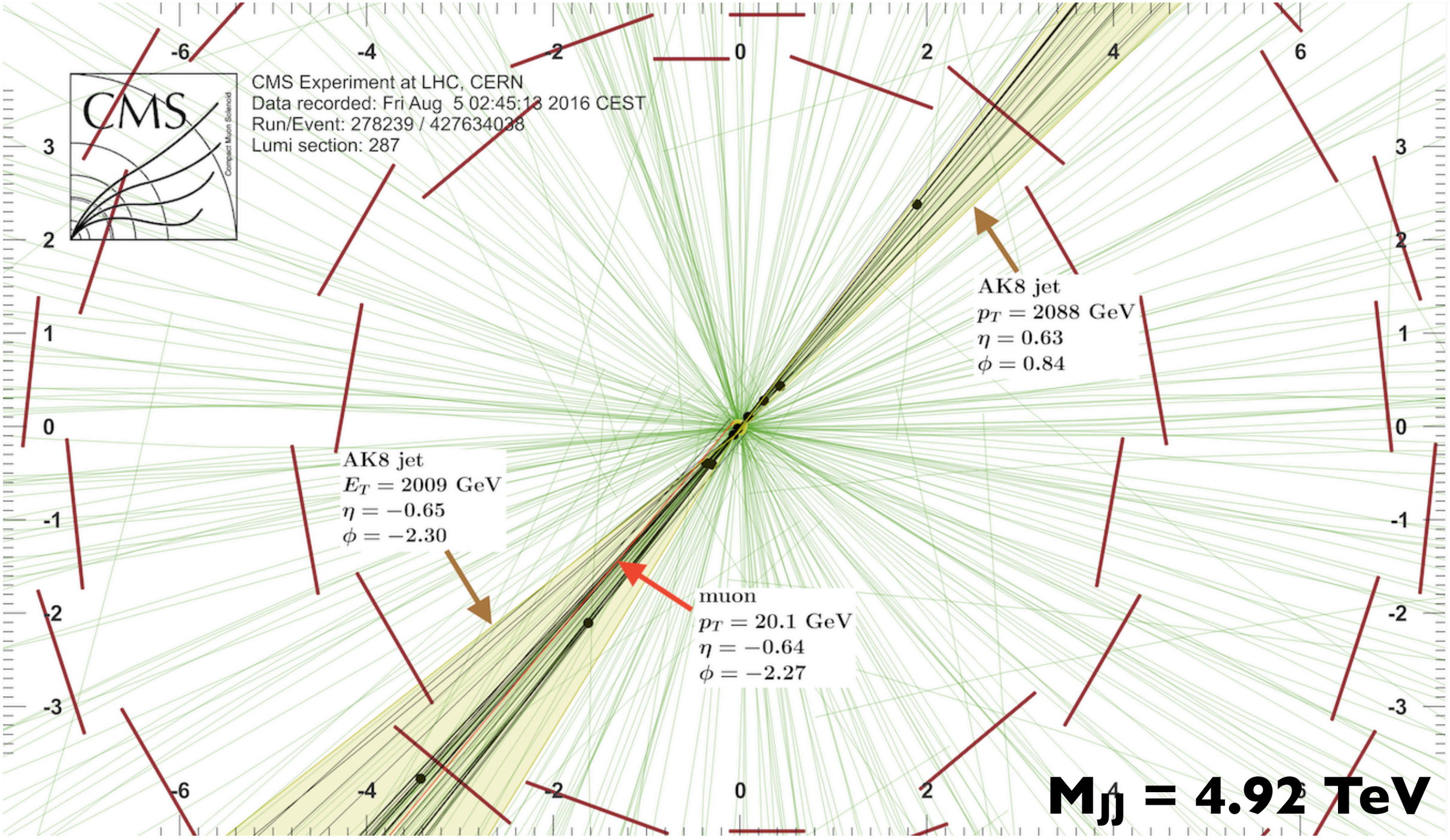


[CMS, JINST 13 (2018) P05011]

Improvement at high p_T, discrimination against g→bb

Boosted H→bb Candidate

[CMS, DP-17-032]



Background Estimates

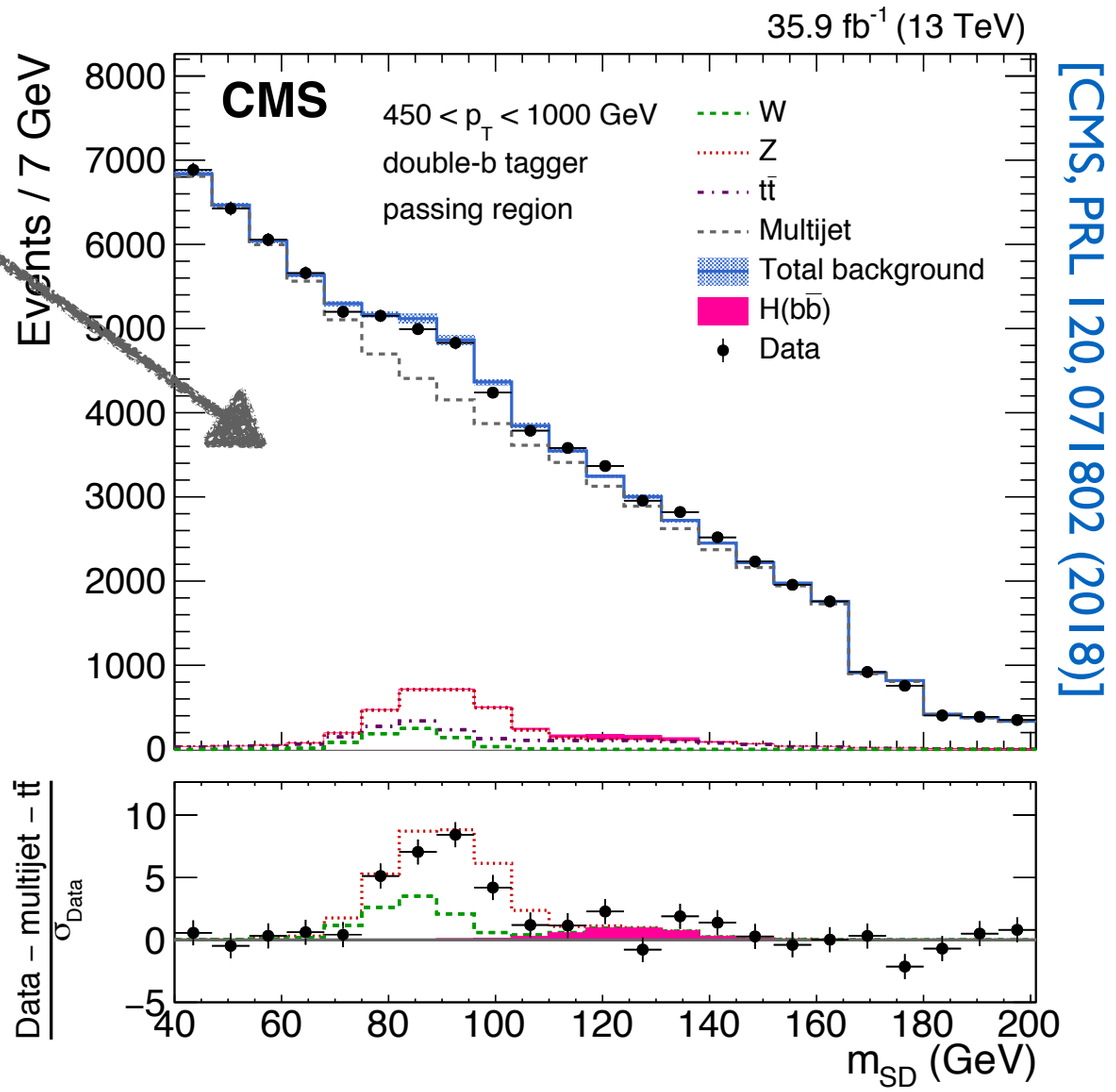
Multi-jet background

A curse

- many orders of magnitude larger than any signal
- modelling very difficult, large uncertainties

and a blessing

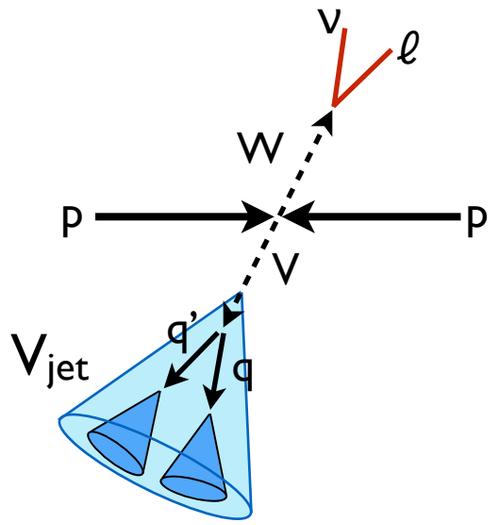
- jet mass: opportunity for dedicated control and validation regions
- precise predictions from data possible with in-situ validations



Numerous methods

- ABCD extrapolations, $R_{p/f}$, decorrelated taggers, transfer factors…

VW Resonances (LJ)



Simultaneous fit to jet mass and resonance mass spectra:

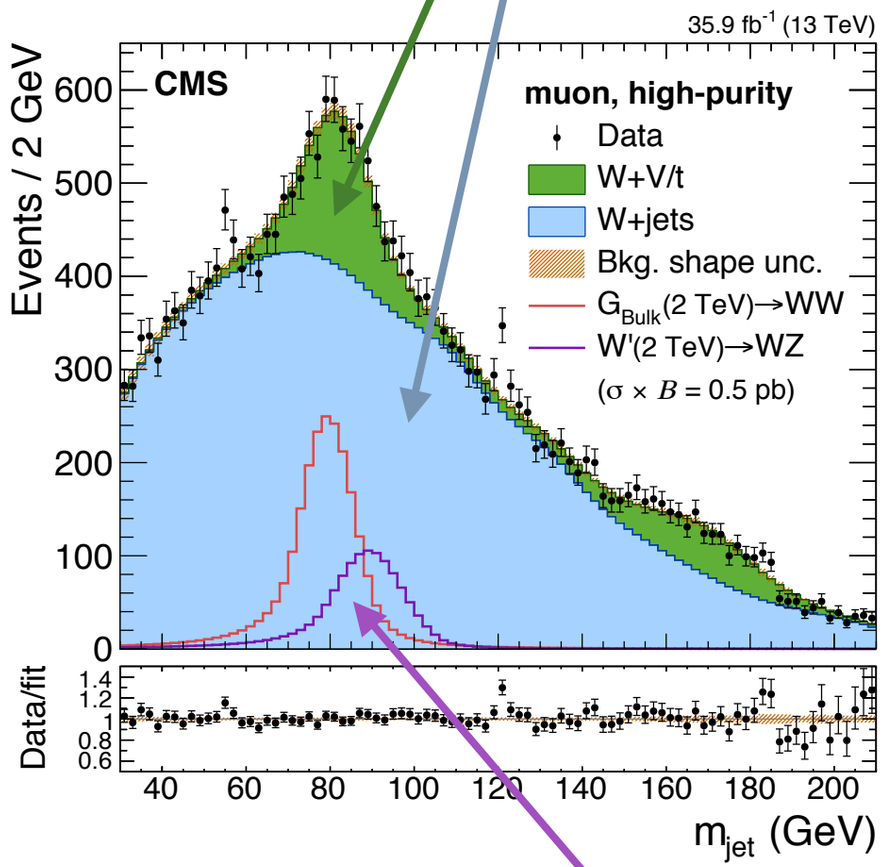
$$P(X \to WV) = P(m_{\text{jet}}, m_{WV} | m_X, \vec{\theta})$$

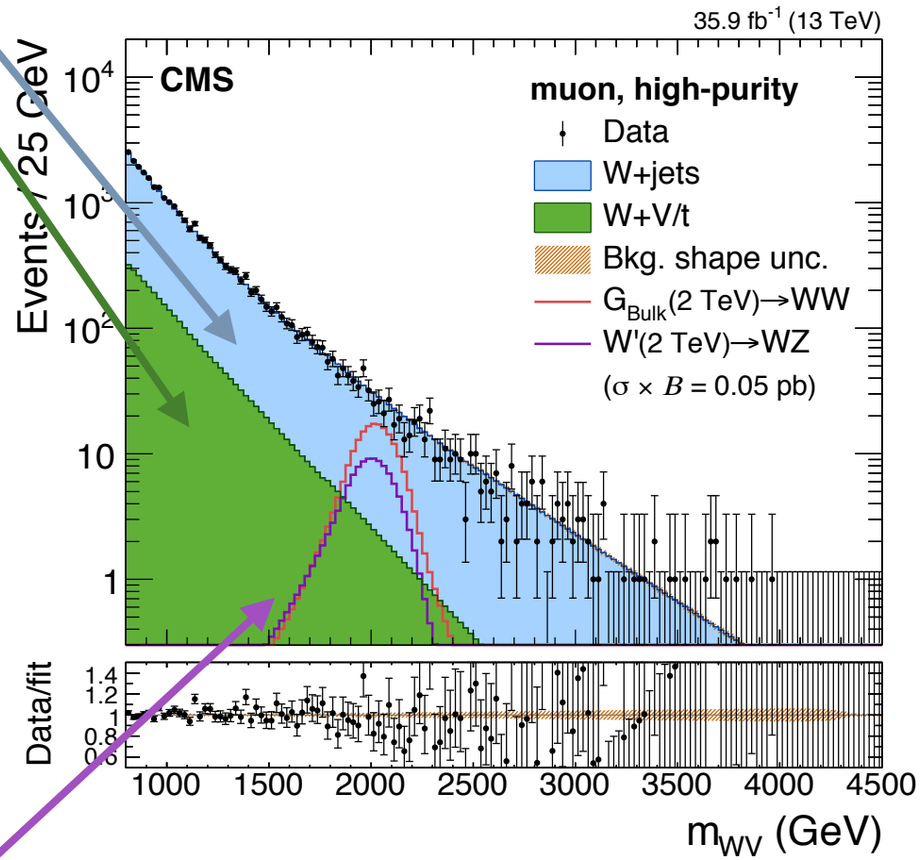
SM bkgd: resonant

non-resonant

non-resonant

[CMS, JHEP 05, 088 (2018)]

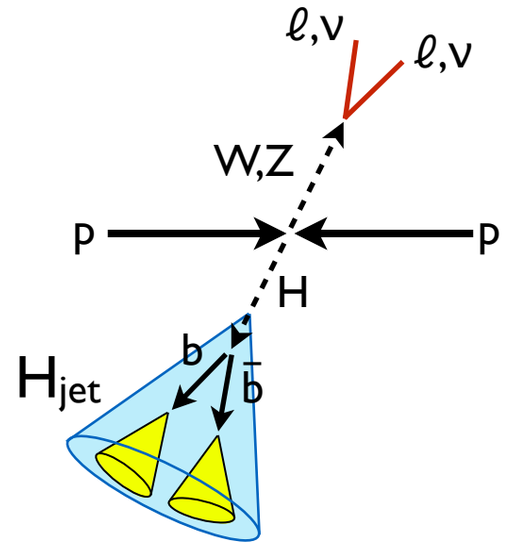




Signal: resonant in m_{jet} and m_{WV}

[see also ATLAS, JHEP 03, 042 (2018)]

VH Resonances

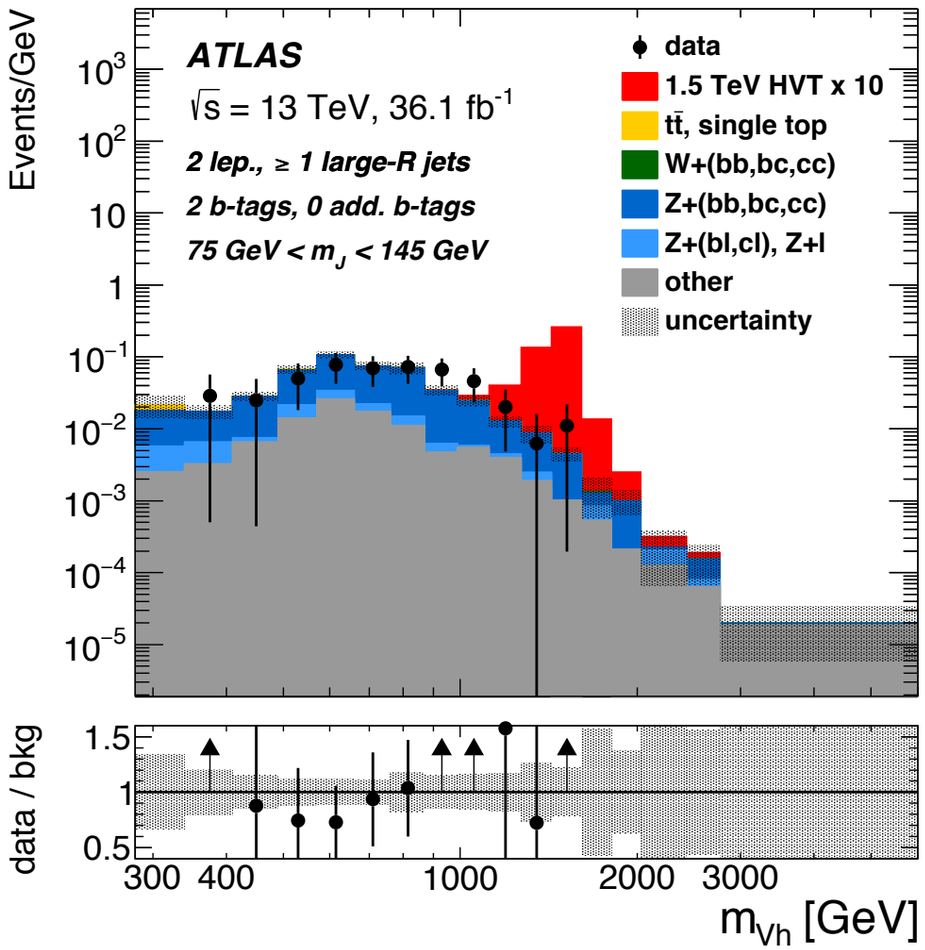


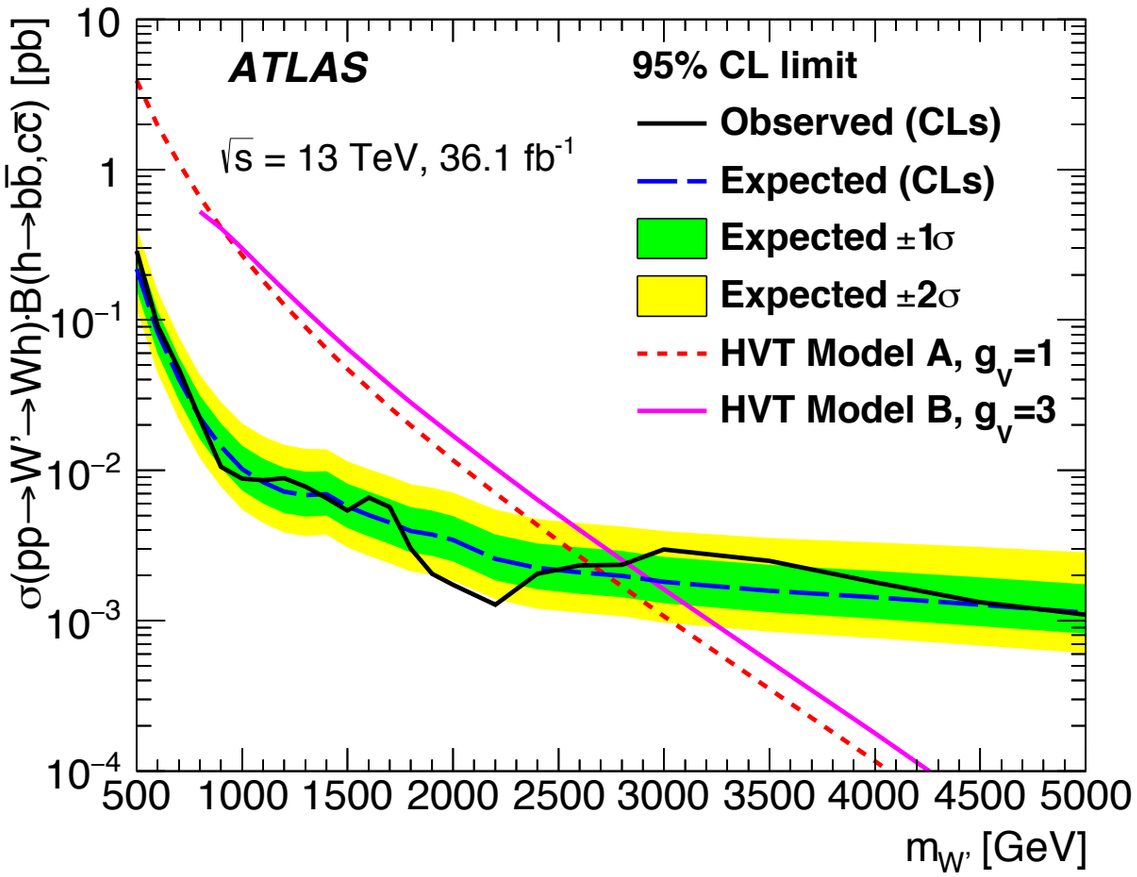
Analysis in 6 categories:

(νν$b\bar{b}$, ℓν$b\bar{b}$, ℓℓ$b\bar{b}$) x (resolved H, merged H)

Very different background compositions in each category, relies on modelling of SM backgrounds

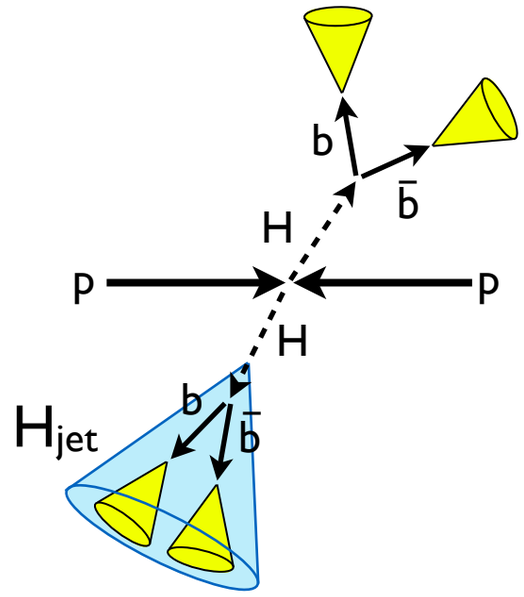
[ATLAS, JHEP 03, 174 (2018)]





[see also CMS-PAS-17-004]

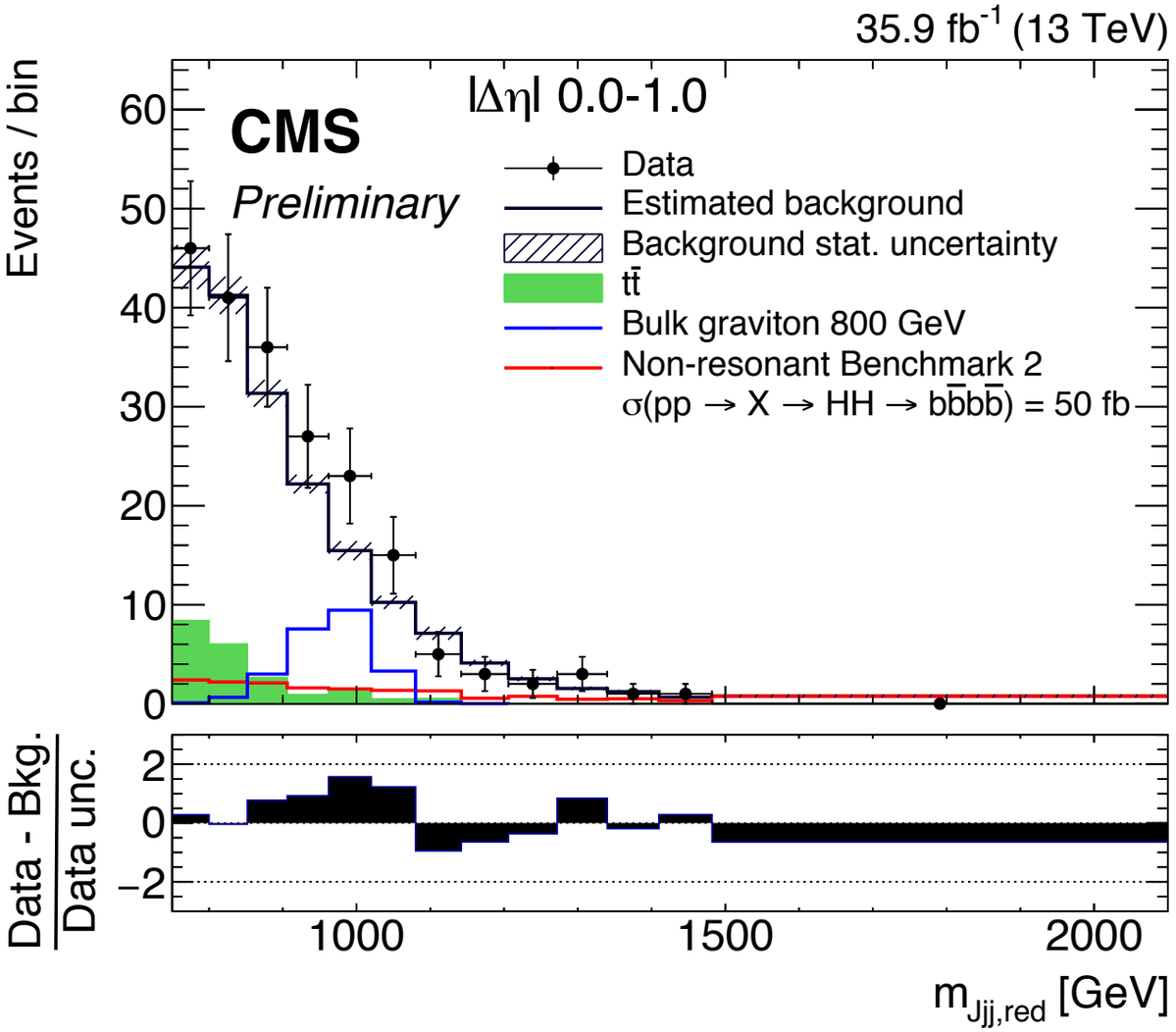
HH → 4b



[CMS-PAS-B2G-17-019]

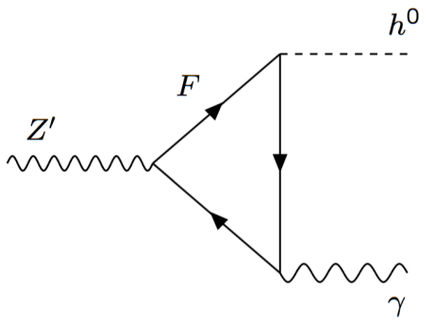
So far uncovered: semi-resolved

- resolved + merged final state
- orthogonal to fully-merged analysis [CMS, PLB 781, 244 (2018)]

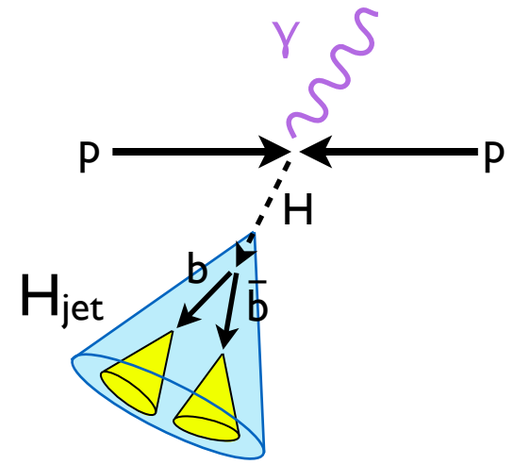


- improves limits on resonant production up to 55%
  - for radion with m = 0.75 - 1.6 TeV
  - above 1.6 - 2 TeV: sensitivity from fully merged analysis
- non-resonant production: better by factors of 2-3 for some benchmarks

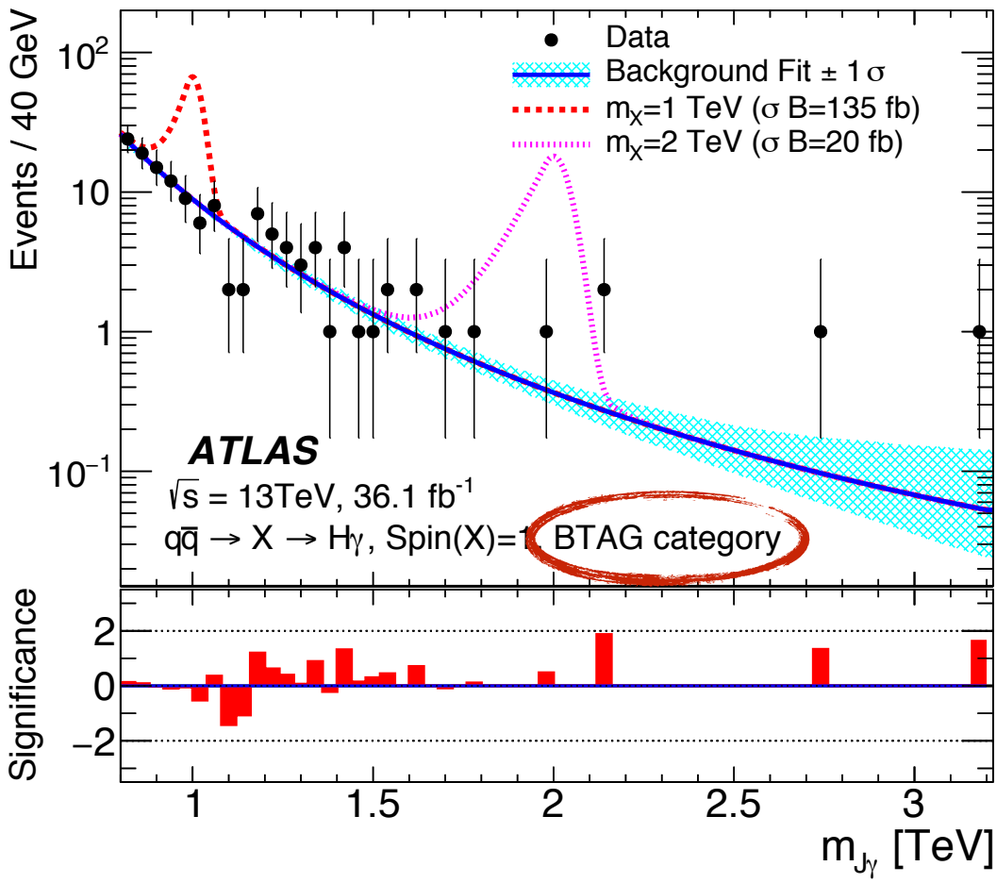
γH Resonances



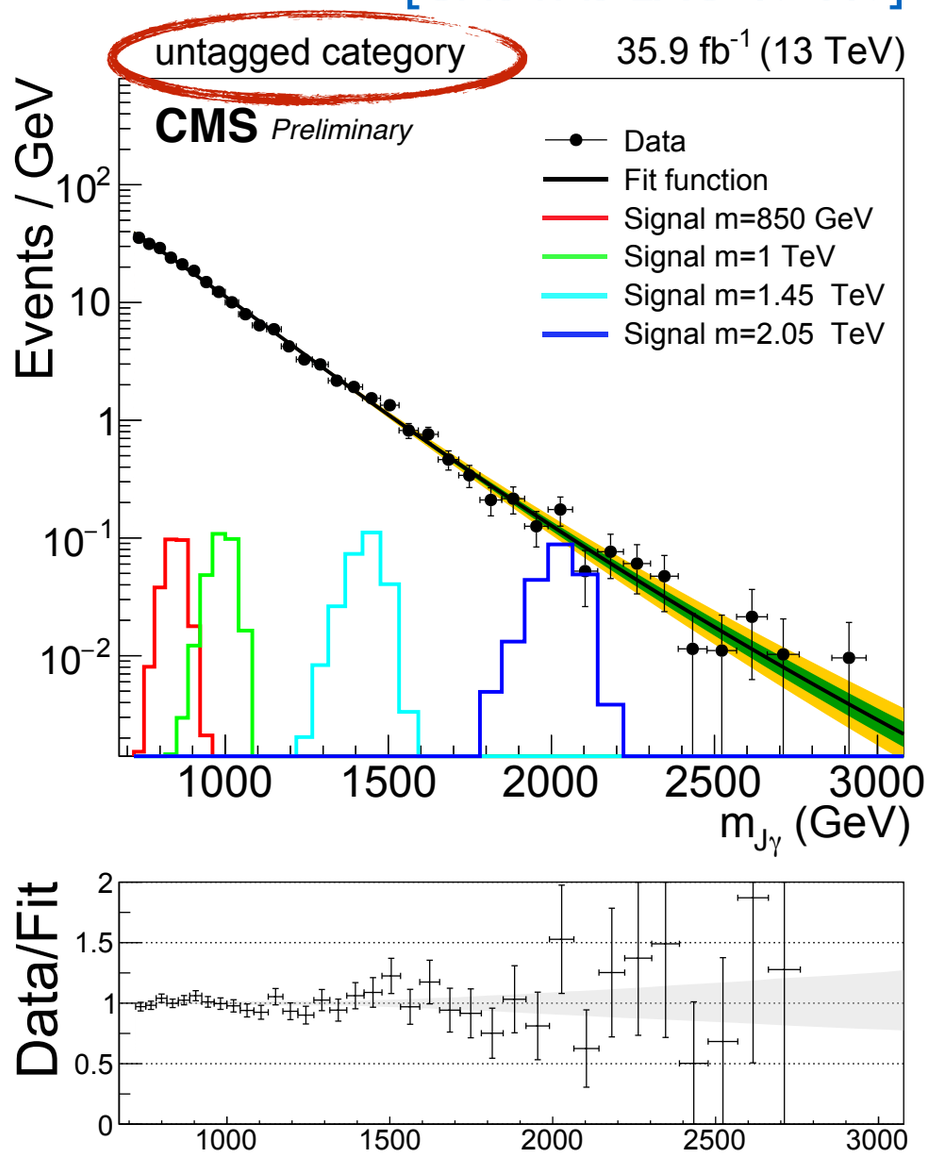
[BA Dobrescu, PJ Fox, J Kearney
EPJC77, 704 (2017)]



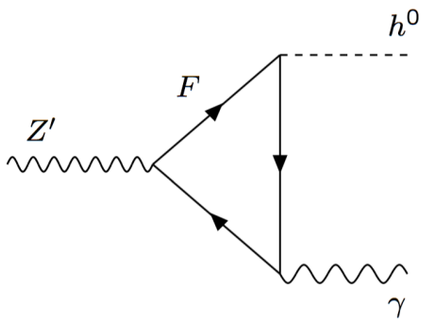
[ATLAS, arXiv:1805.01908]



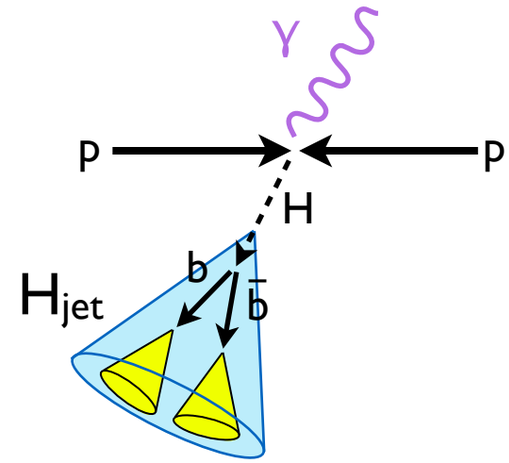
[CMS-PAS-EXO-17-019]



γH Resonances

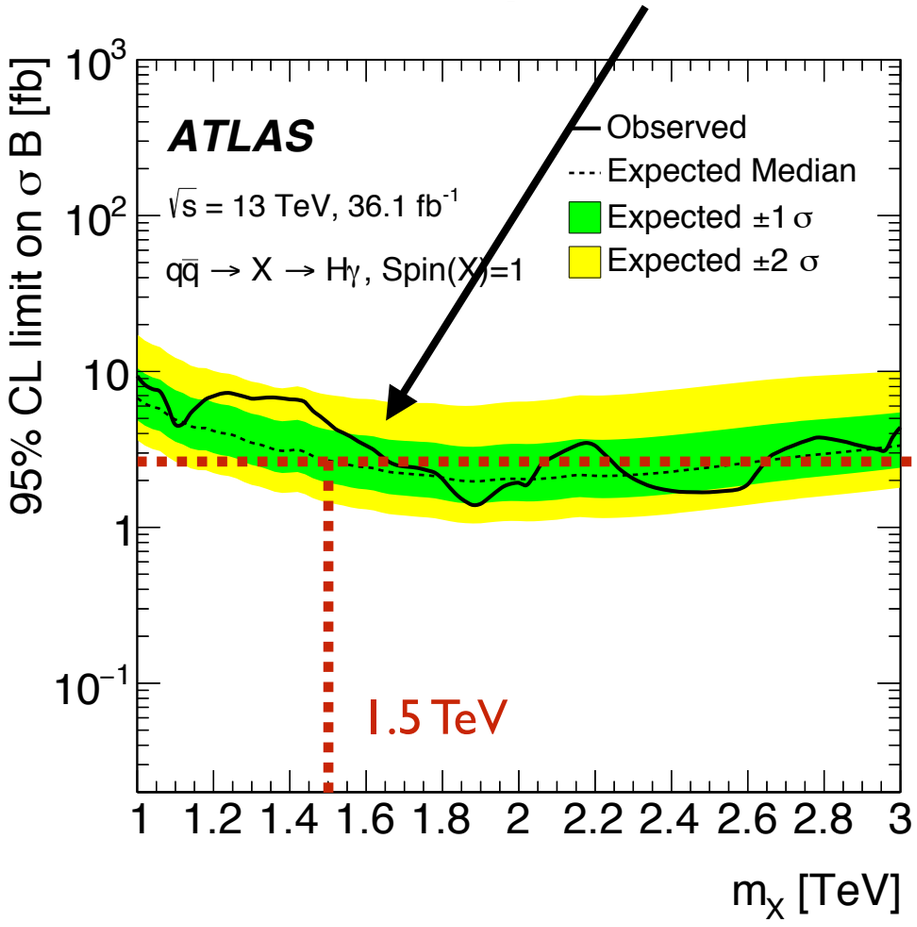


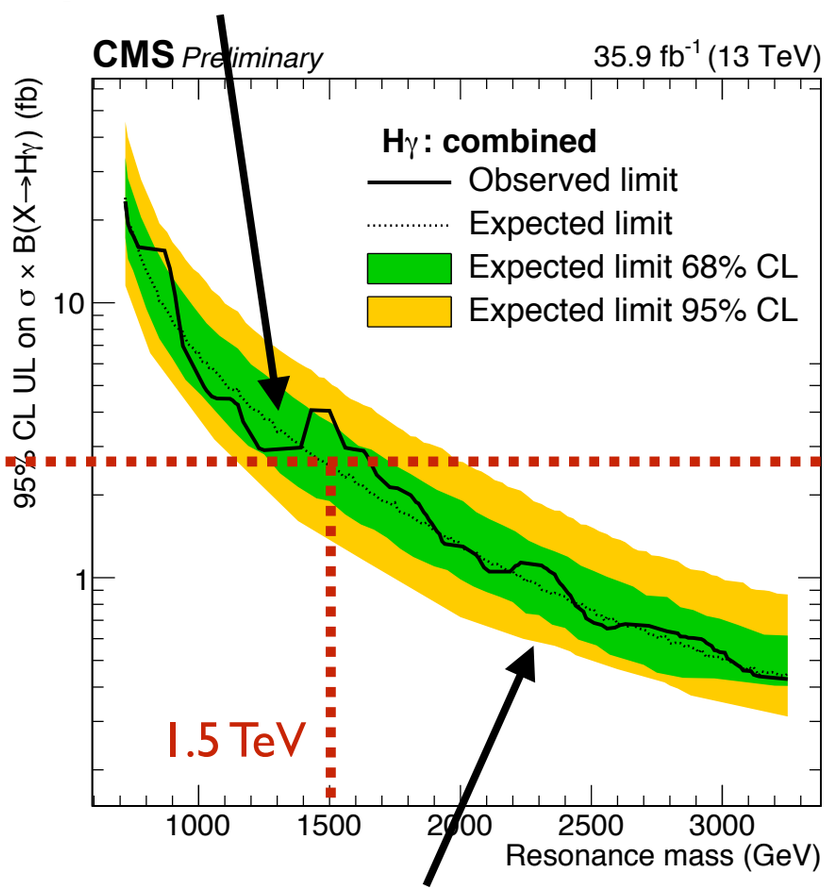
[BA Dobrescu, PJ Fox, J Kearney
EPJC77, 704 (2017)]



[CMS-PAS-EXO-17-019]
[ATLAS, arXiv:1805.01908]

Very similar sensitivity up to 1.5 TeV





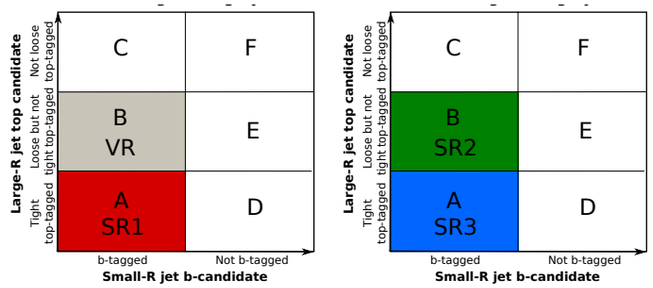
better sensitivity
due to untagged category

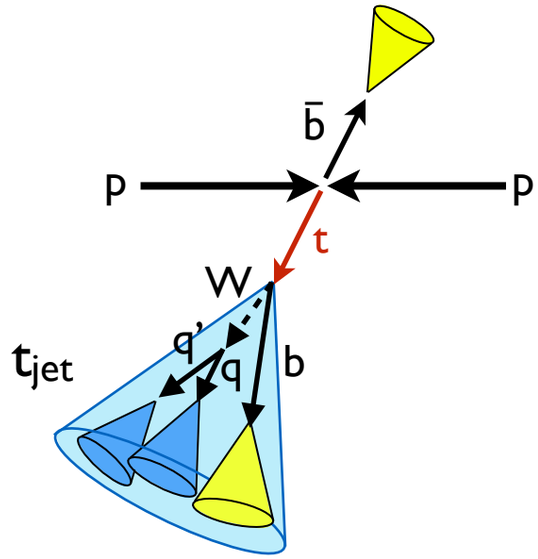
tb and tt Resonances

W' → tb (JJ)

Shower deconstruction used for the first time in an analysis

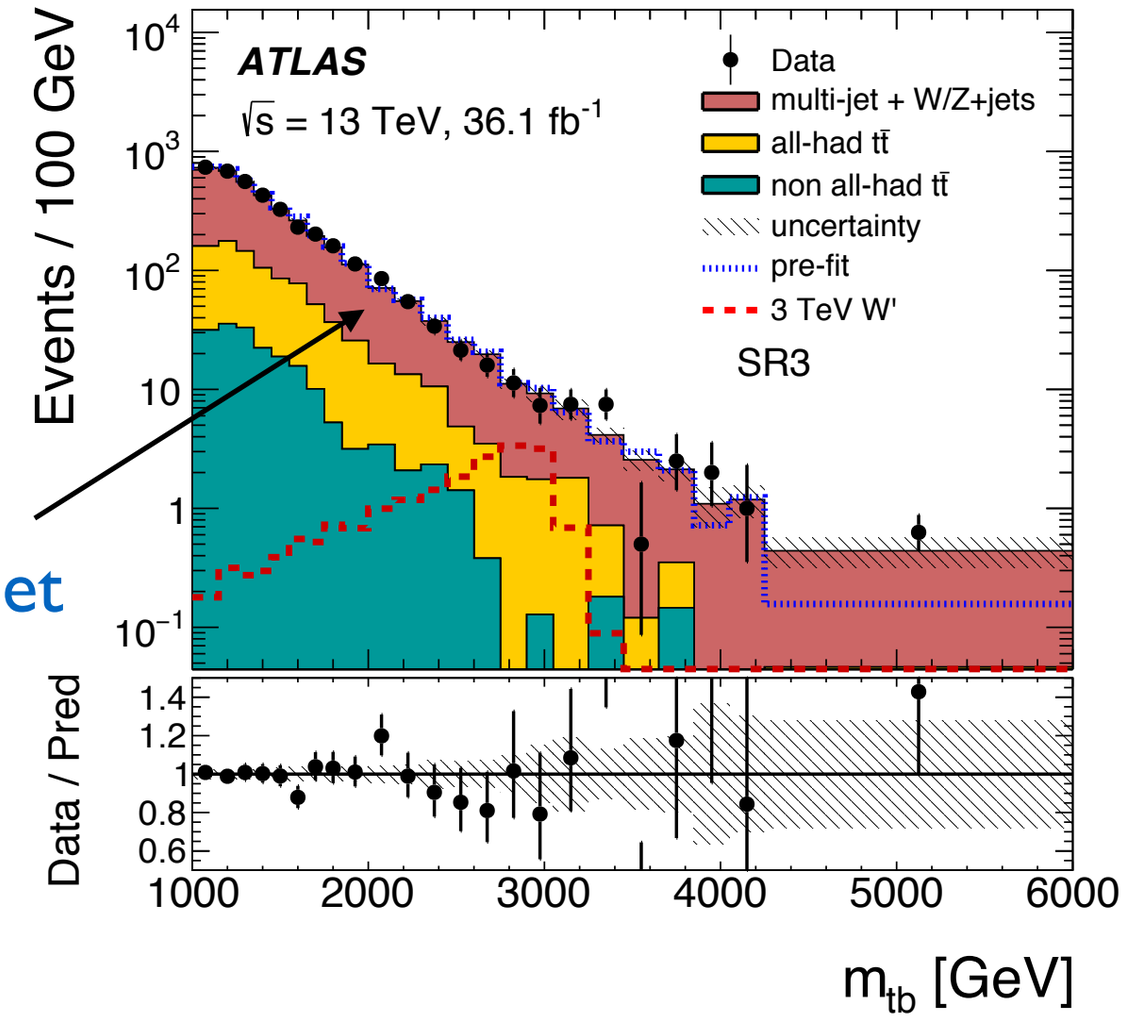
Multi-jet backgrounds: sidebands



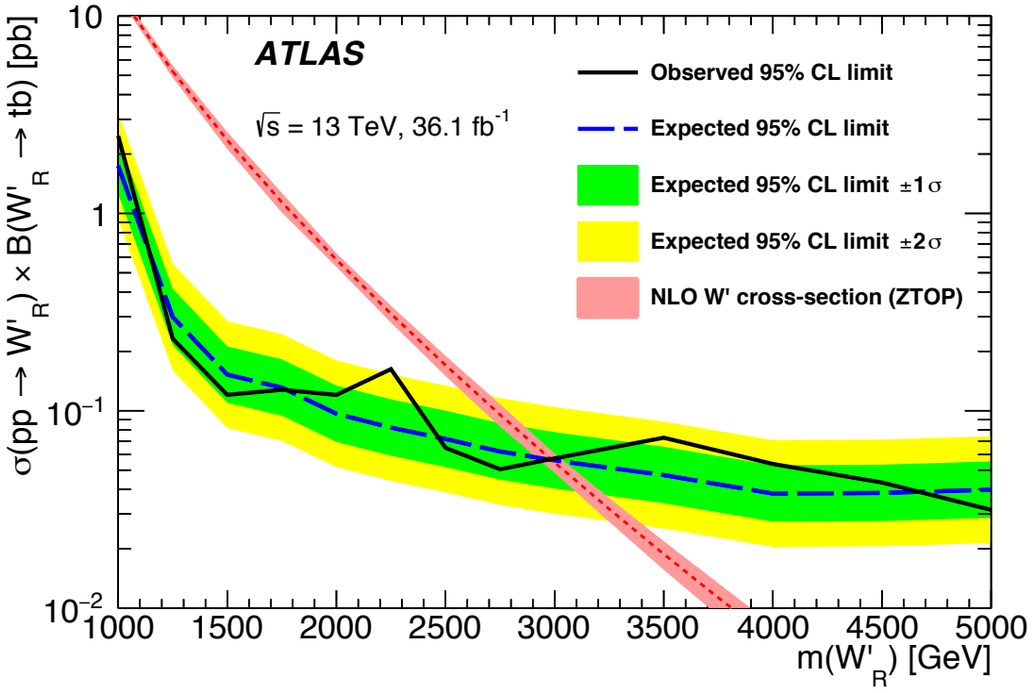


[ATLAS, PLB 781, 327 (2018)]

tight t tag, 2b tags



75% multi-jet bkgd



W_R' exclusion: 3.0 TeV

LJ (CMS): 3.6 TeV

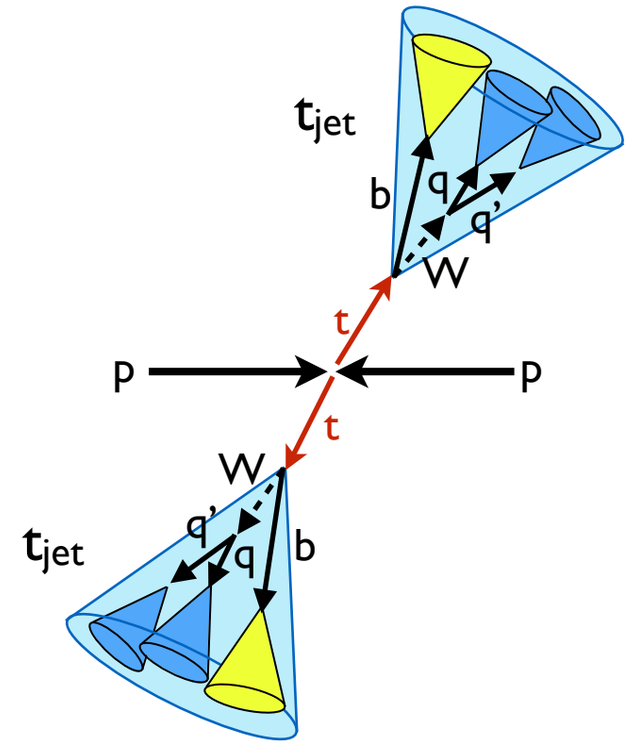
[see also CMS, PLB 777, 39 (2018)]

Z' → tt (LL,LJ,JJ)

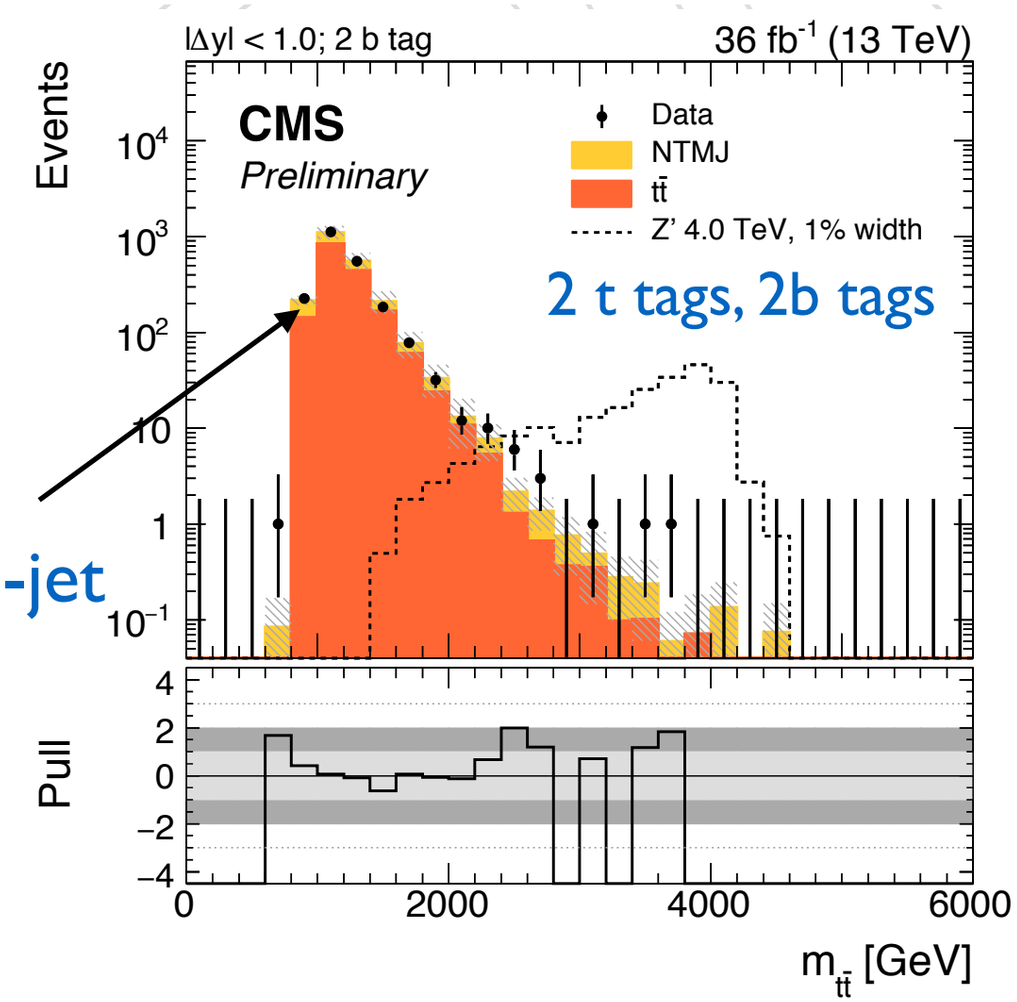
Many improvements since last result

- improved PU mitigation, b-tagging
- BDT for W+jet suppression
- CRs to constrain backgrounds

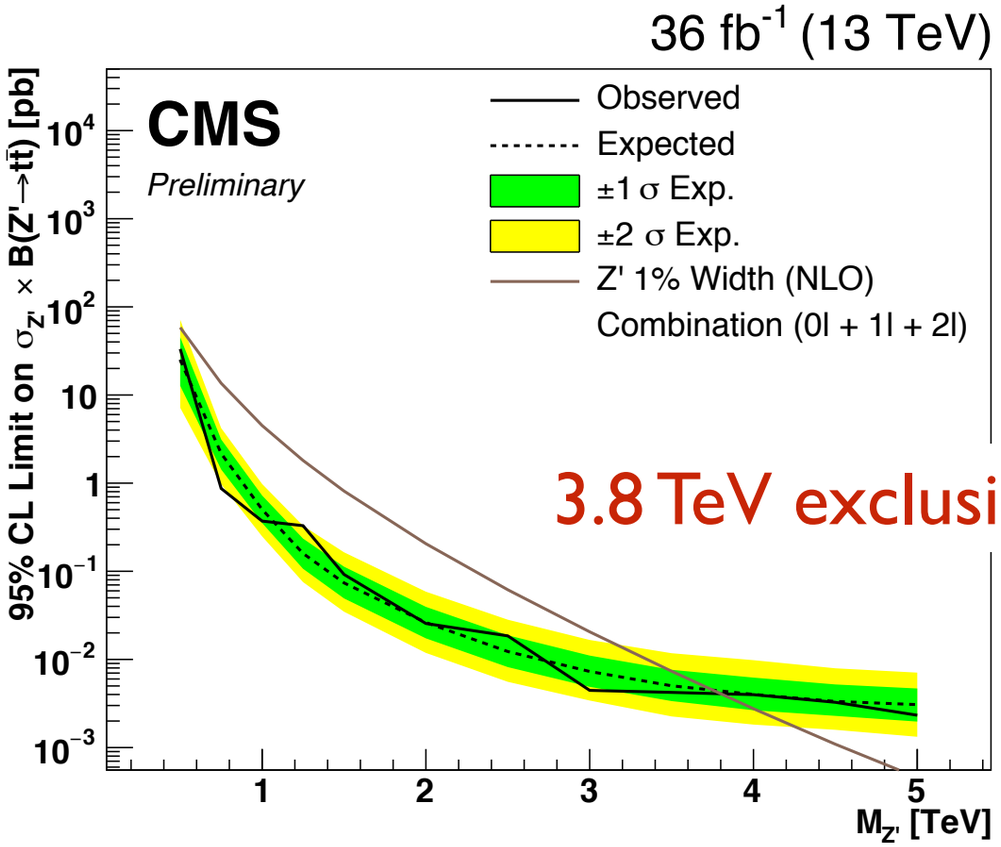
} 10-40% improvement



[CMS-PAS-17-017]



25% multi-jet bkgd

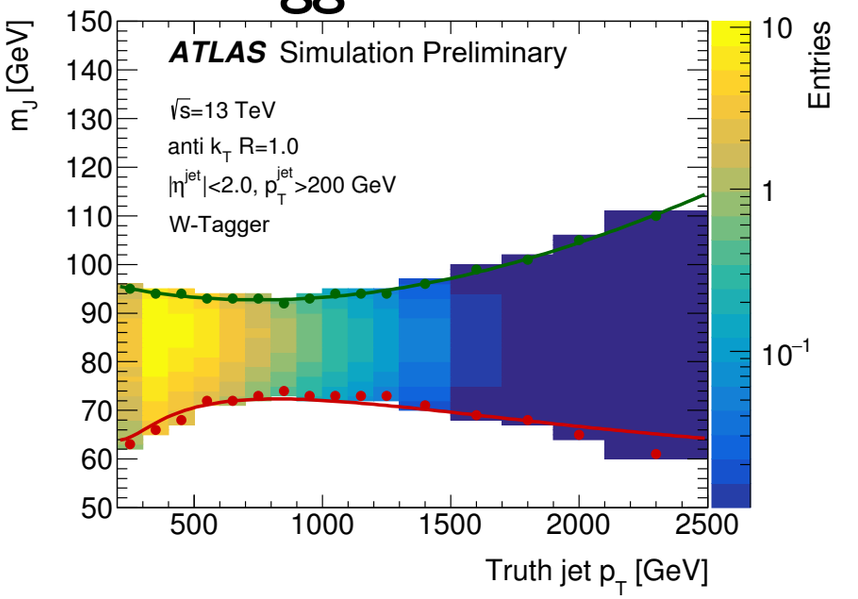


3.8 TeV exclusion

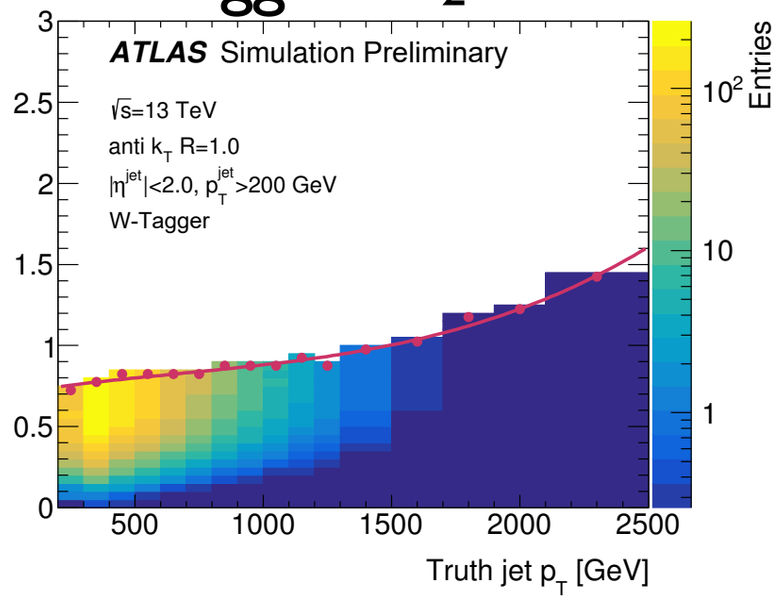
[see also ATLAS, arXiv:1804.10823]

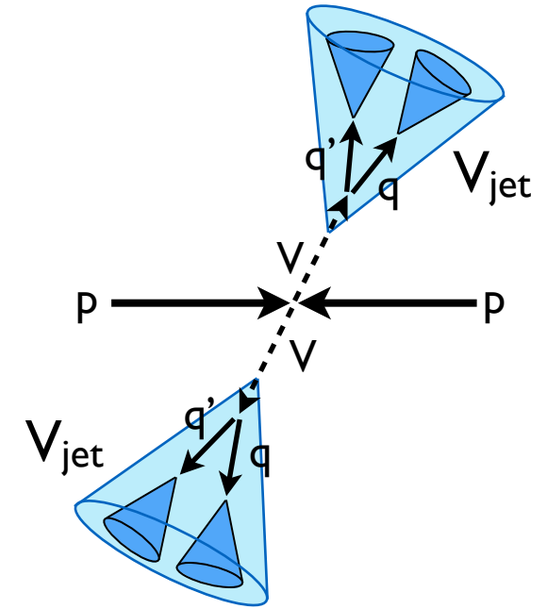
VV Resonances (JJ)

W tagger: mass cuts



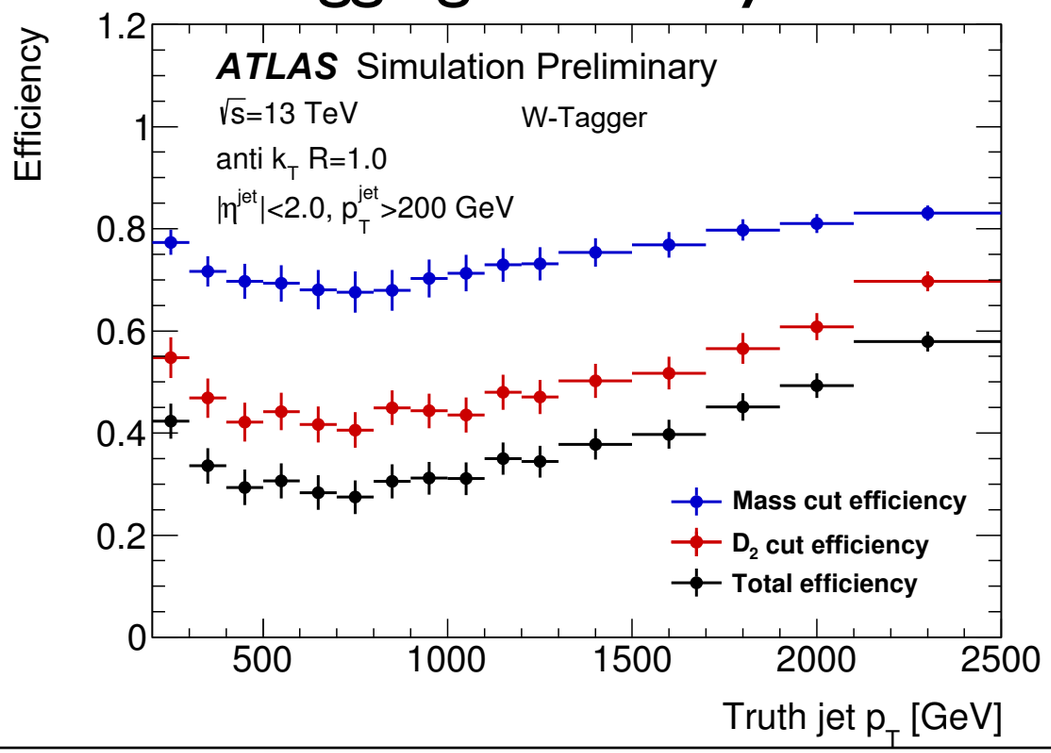
W tagger: D_2 cuts



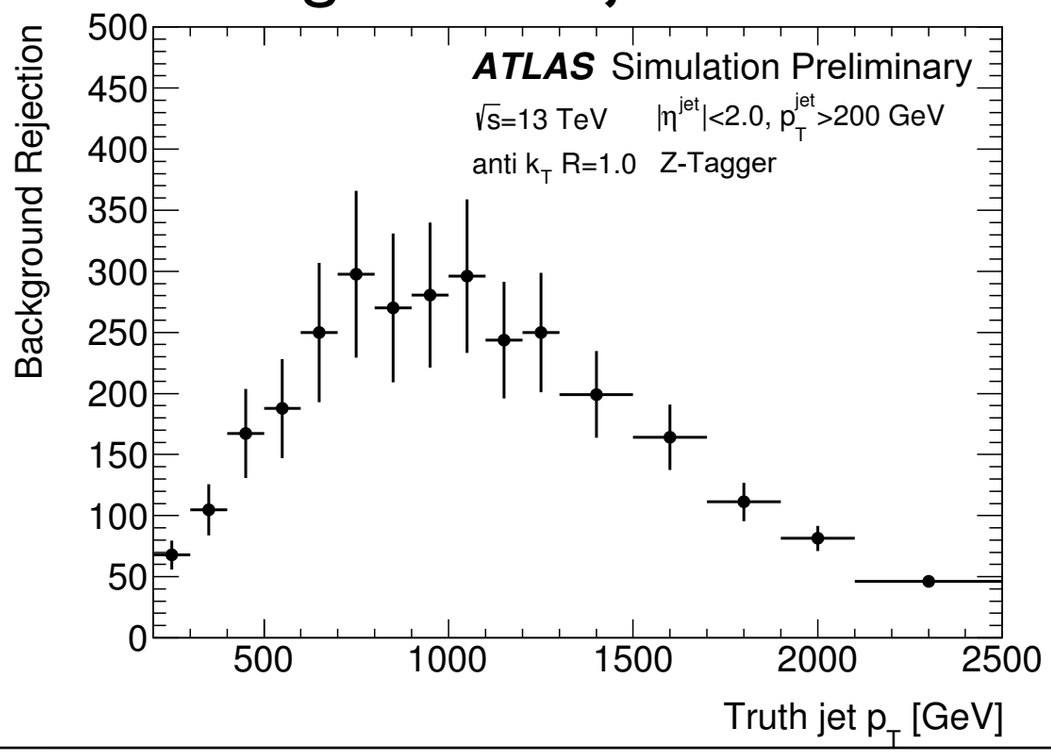


[ATLAS-CONF-2018-016]

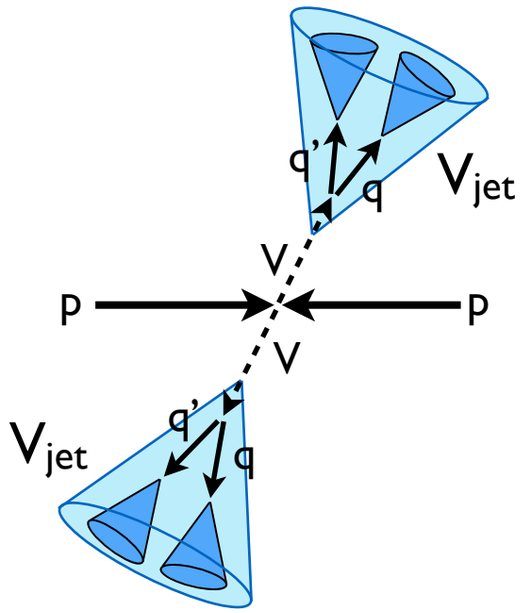
W tagging efficiency



background rejection

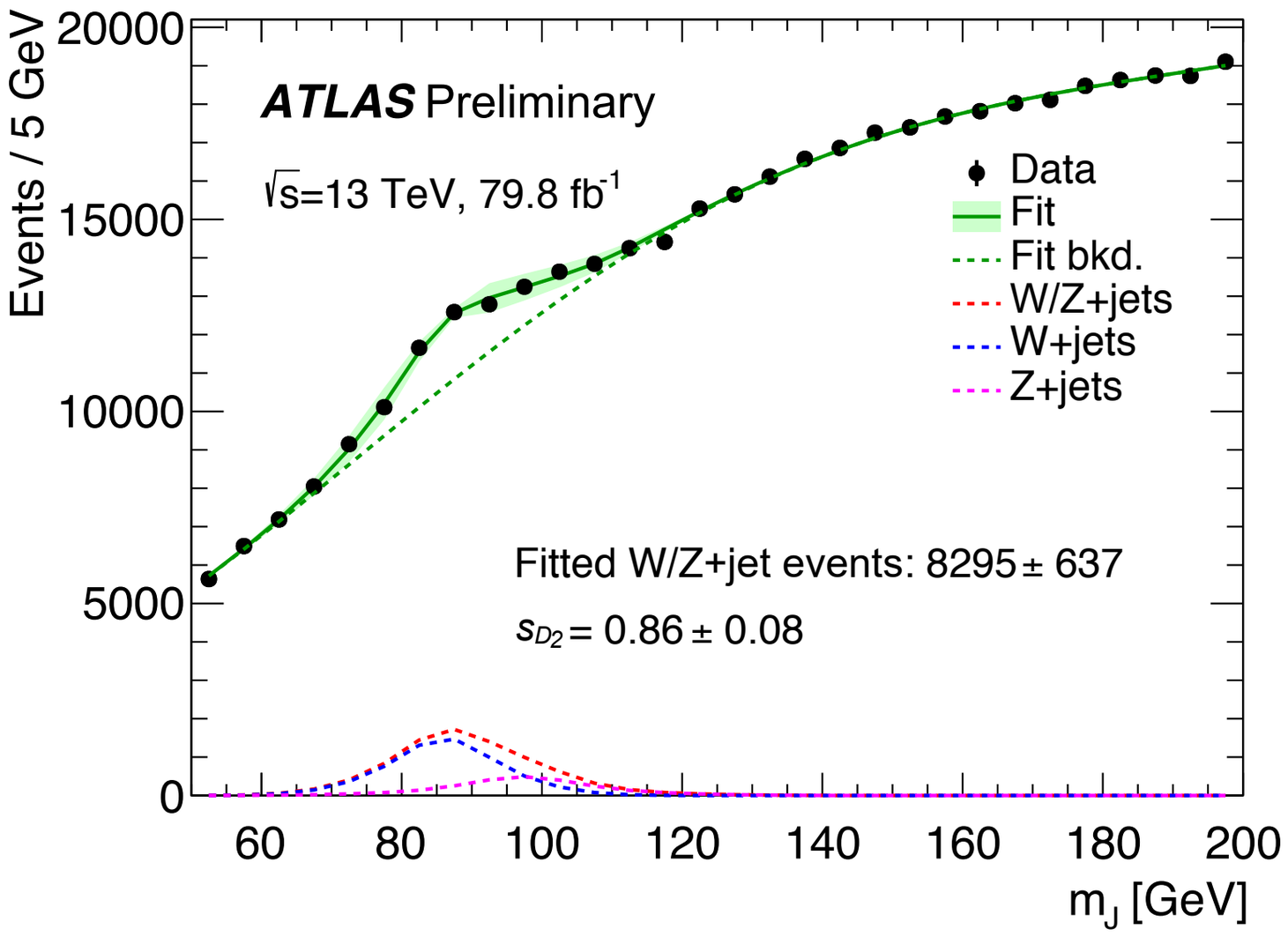


VV Resonances (JJ)

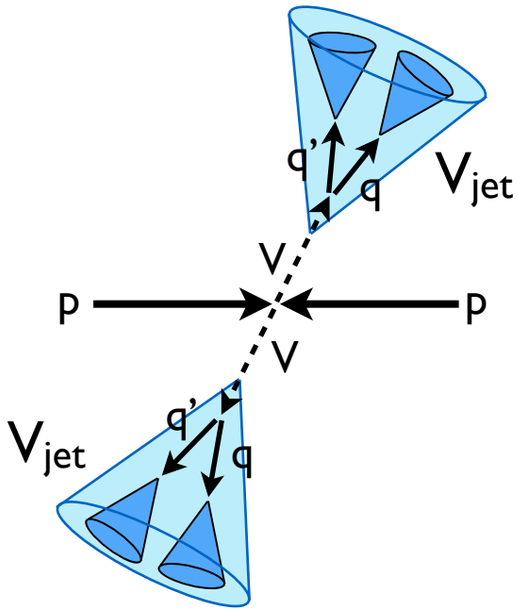


[ATLAS-CONF-2018-016]

W tagger: signal efficiency measurement of D_2 cut

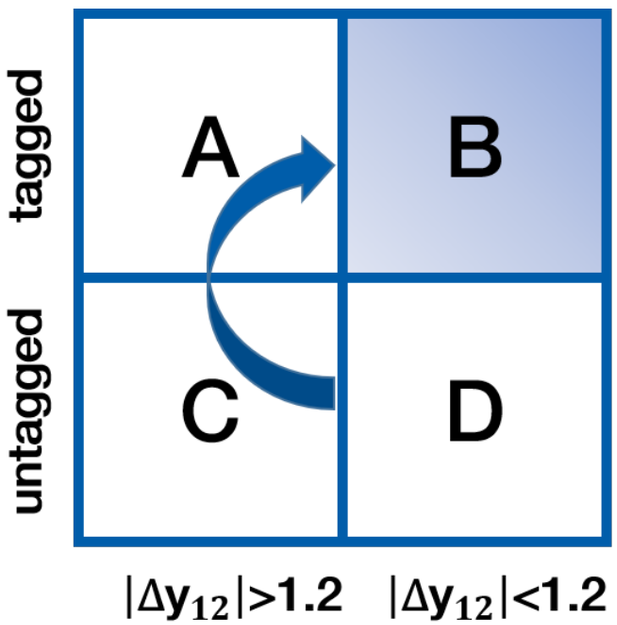


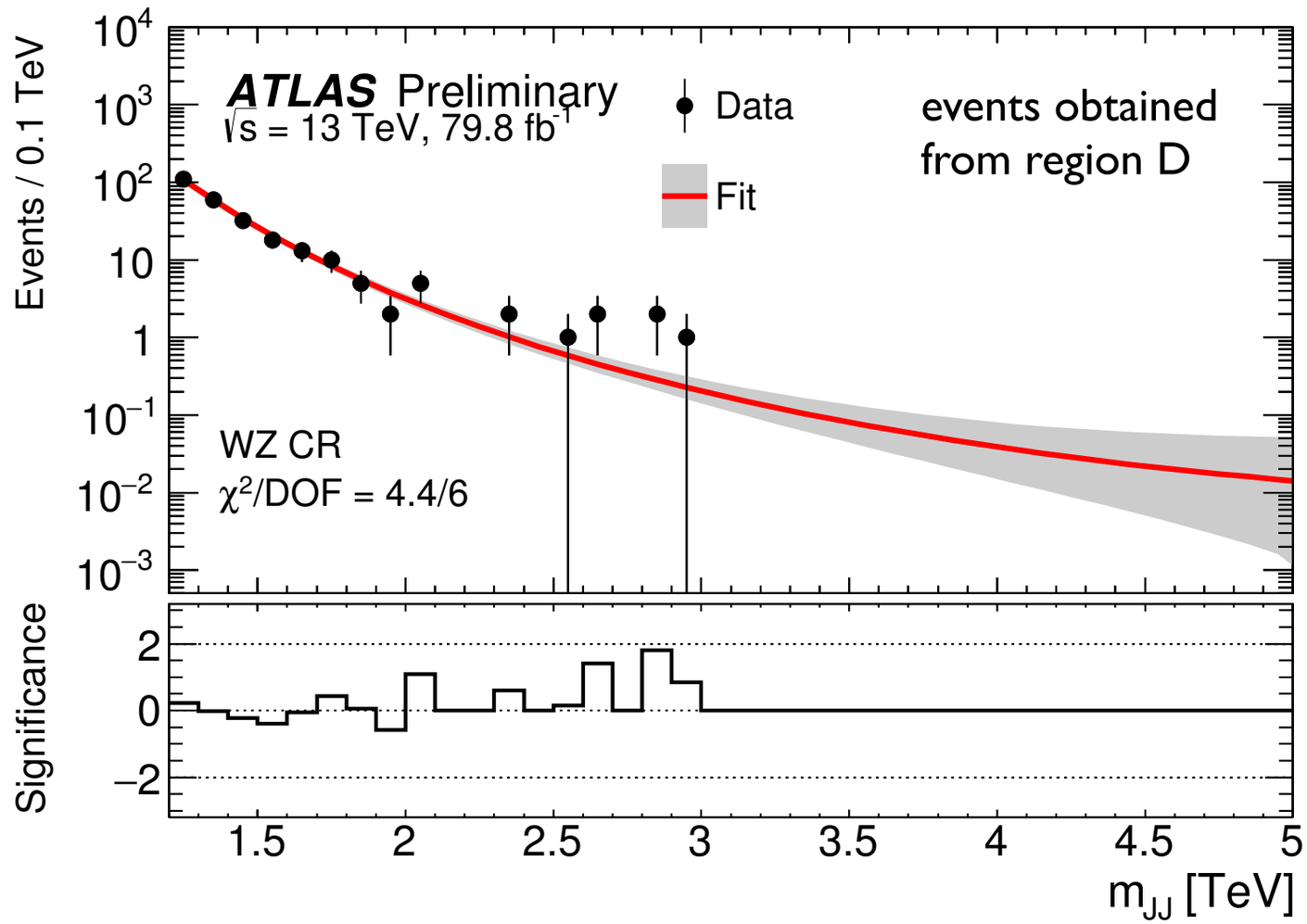
VV Resonances (JJ)



[ATLAS-CONF-2018-016]

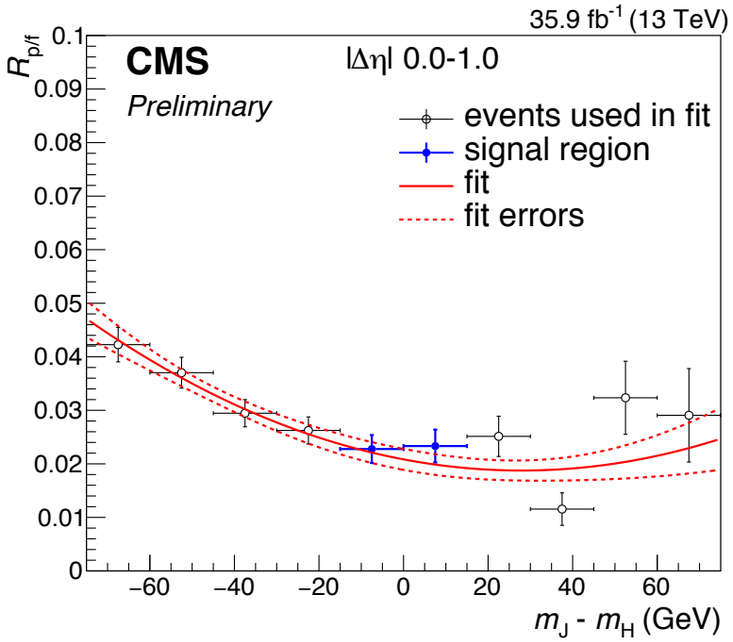
Validating the background model

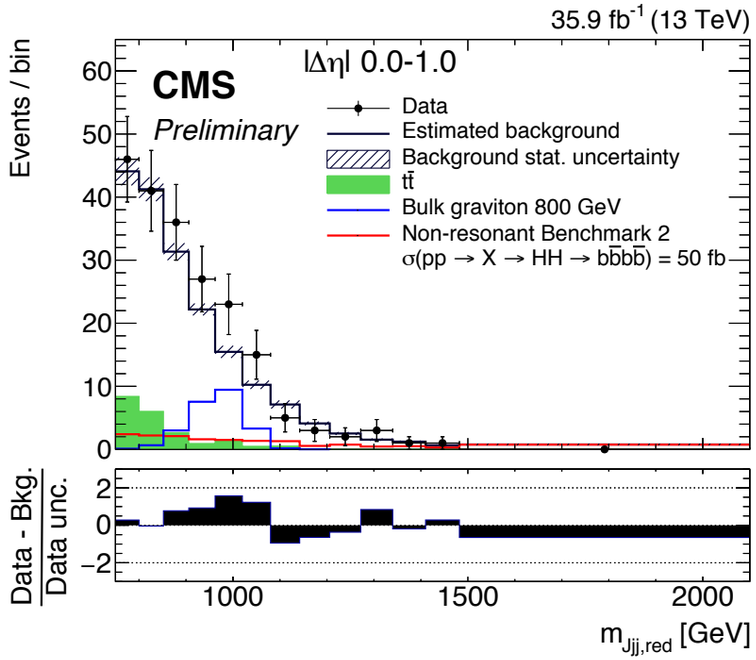


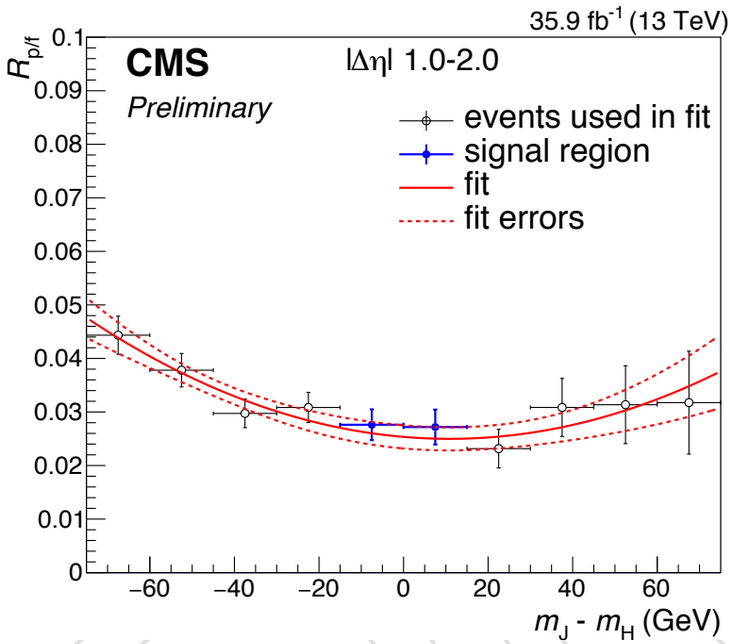


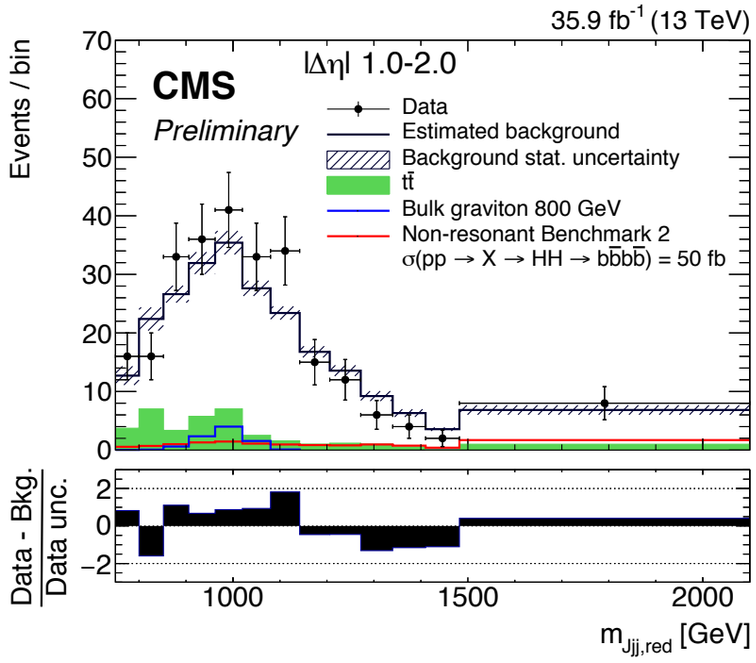
HH → 4b

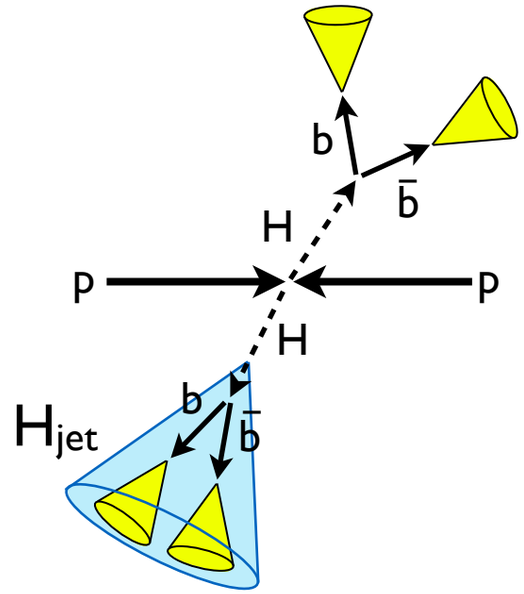
Background estimation through $R_{p/f}$











[CMS-PAS-B2G-17-019]