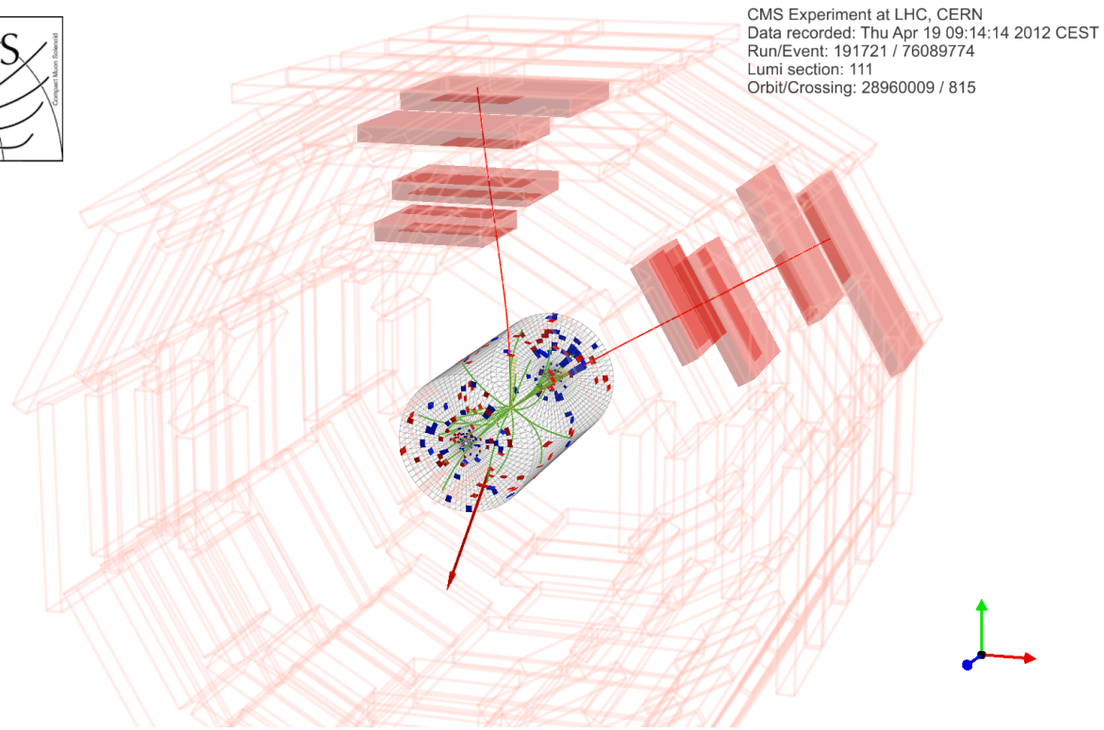
QCD IN HIGGS & BSM: RESULTS FROM ATLAS & CMS

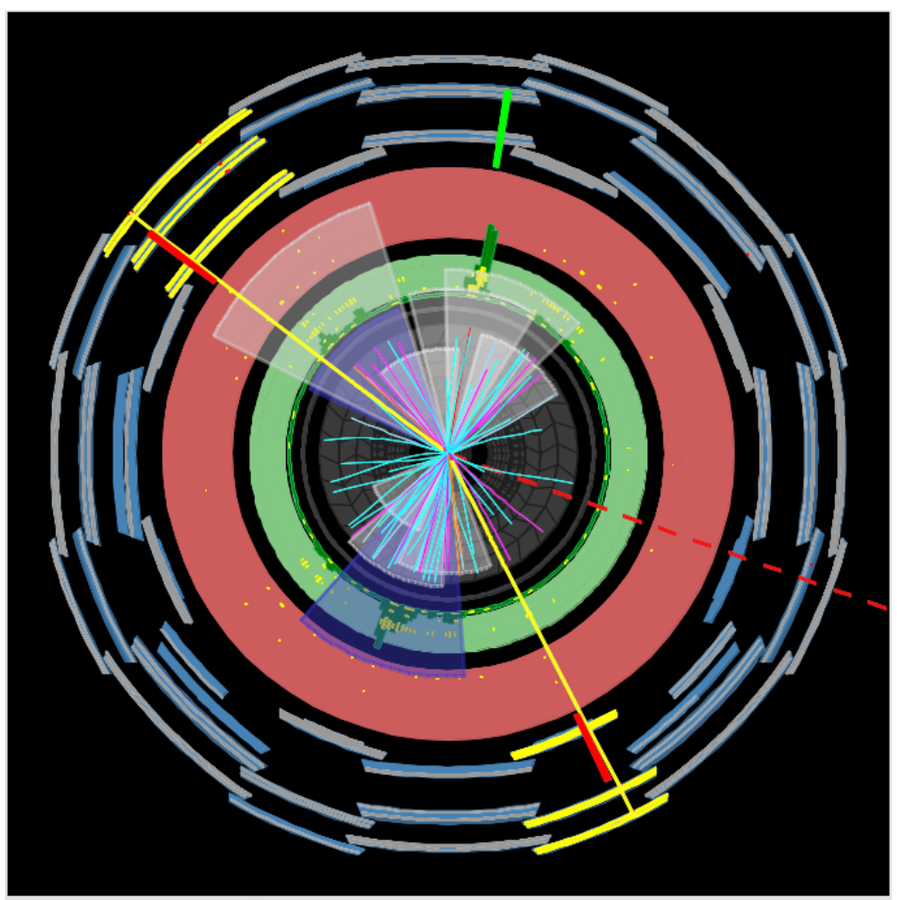
QCD@LHC - 2015 - LAUREN TOMPKINS - STANFORD UNIVERSITY

OUTLINE

- Big picture
- Higgs: Getting to know the newest member of the Standard Model
- Going beyond the Standard Model
- New analysis techniques: getting boosted

THE BIG PRETTY PICTURE





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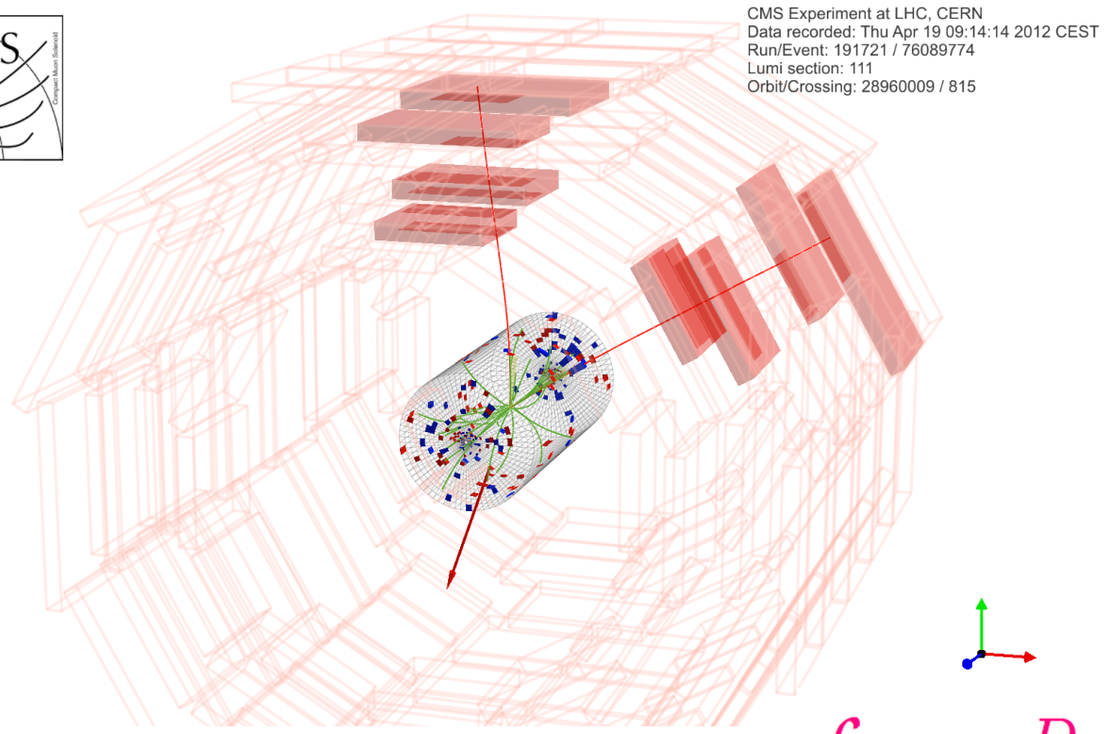

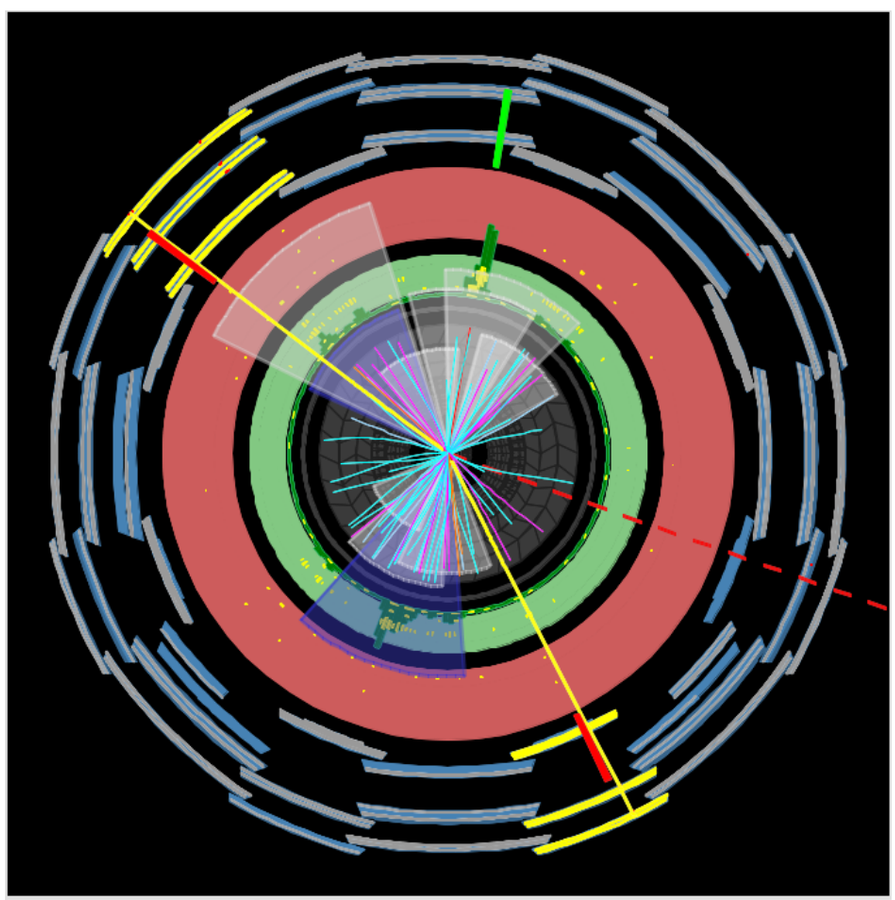

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons

Higgs self-couplings

Couplings to fermions

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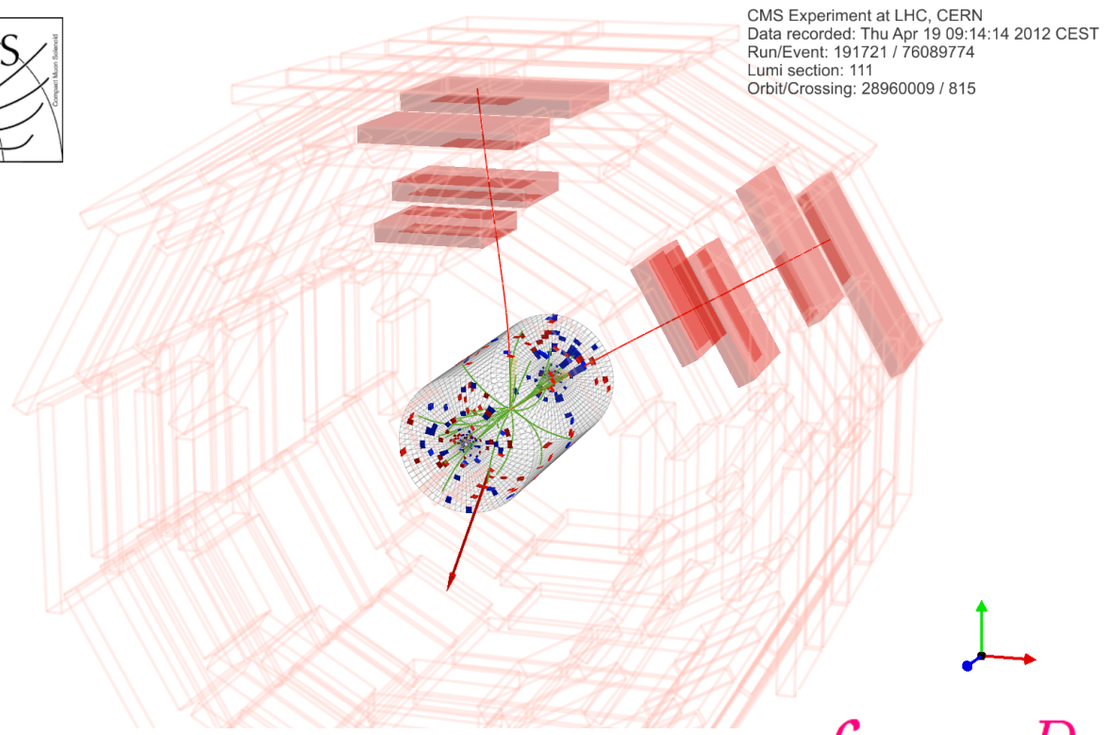

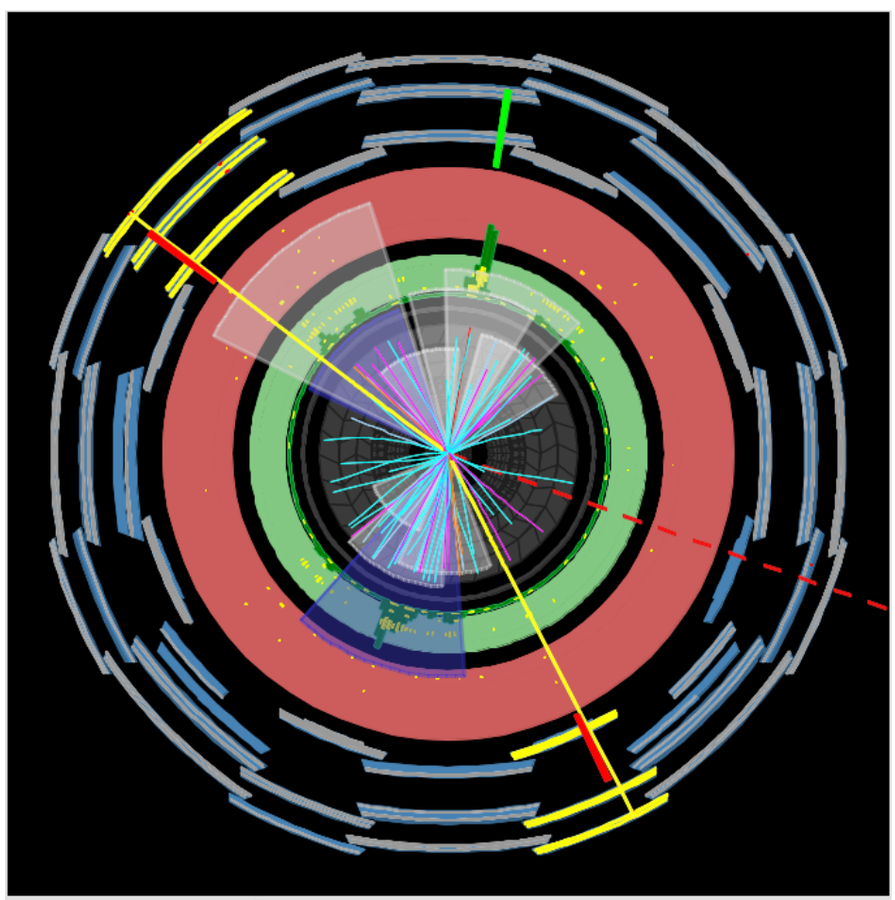

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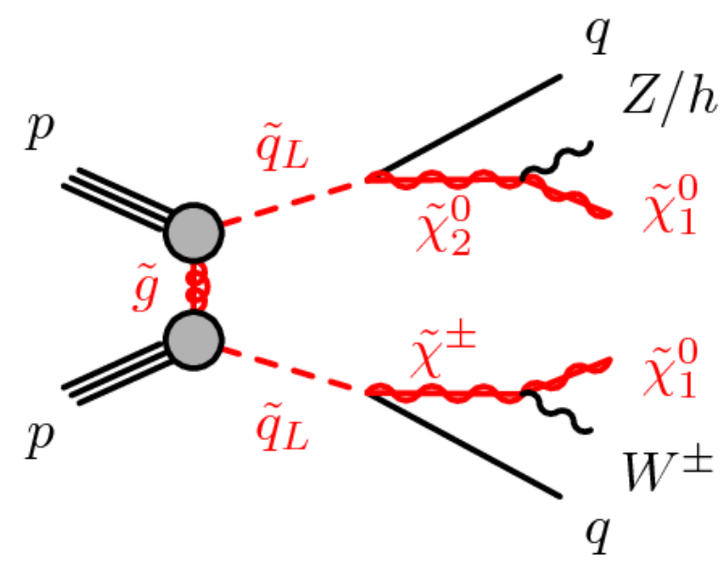

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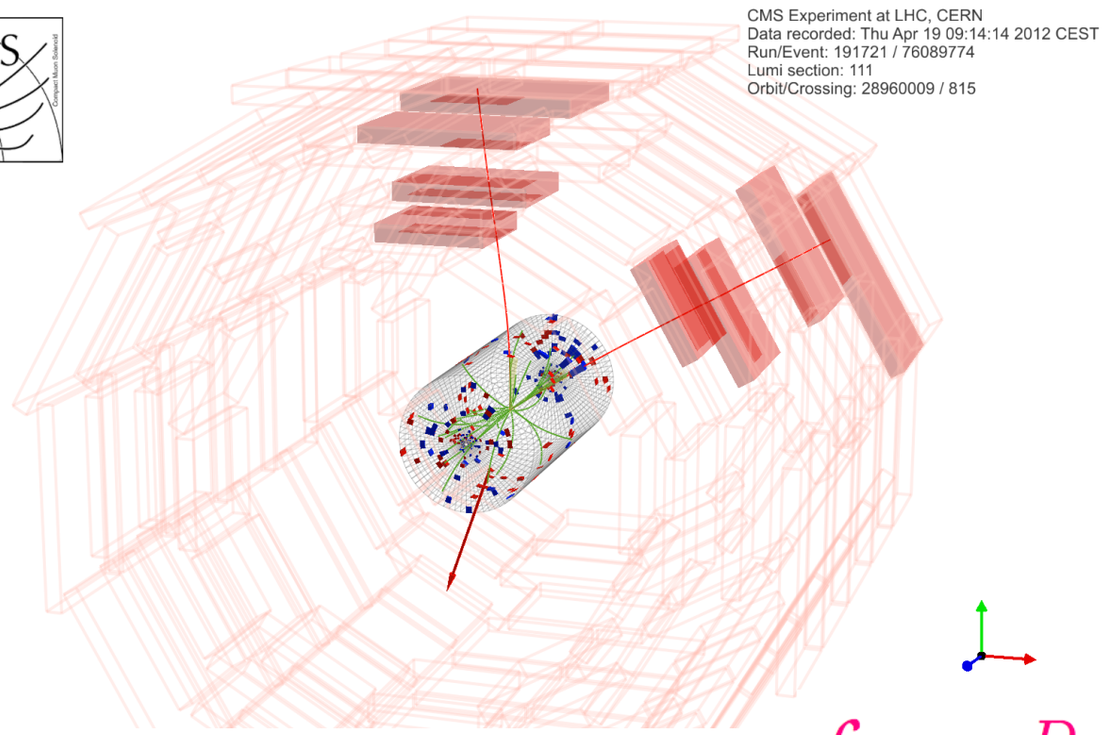
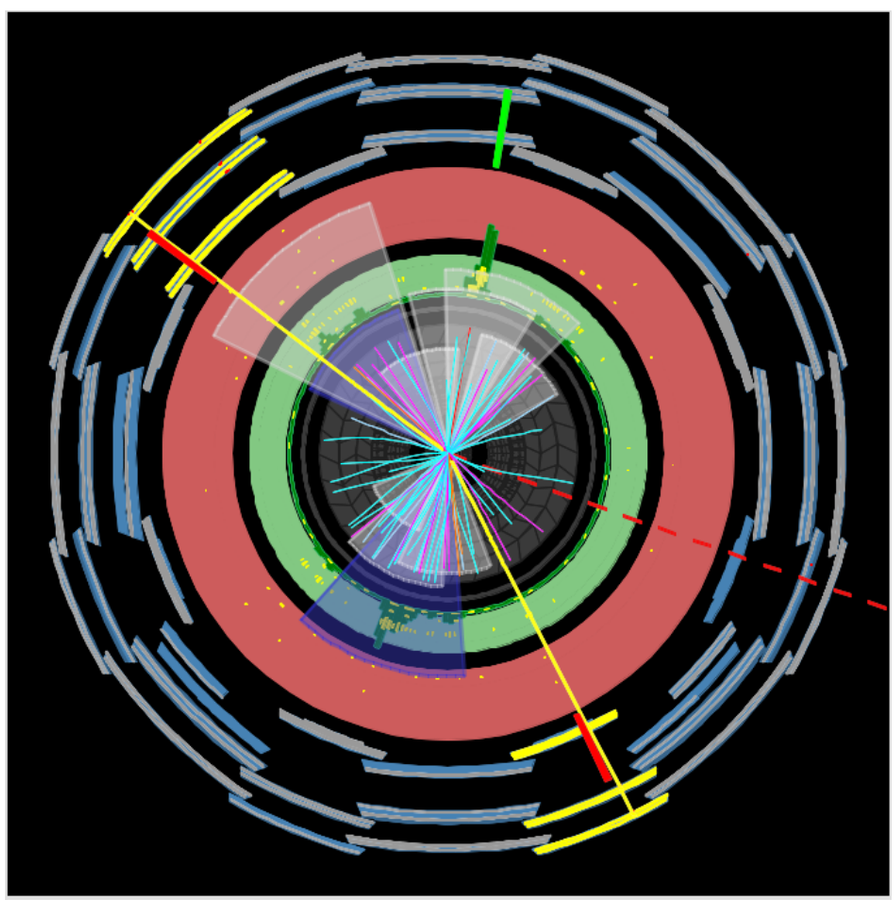


Reconstruction, Simulation, Calculations



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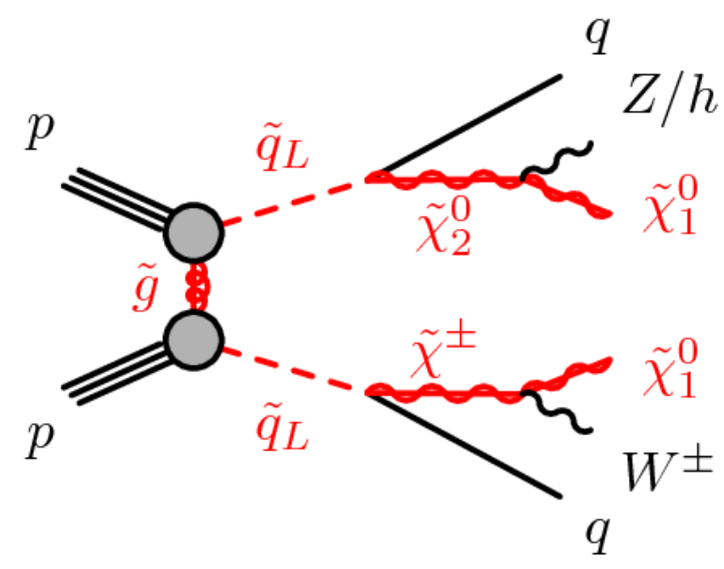
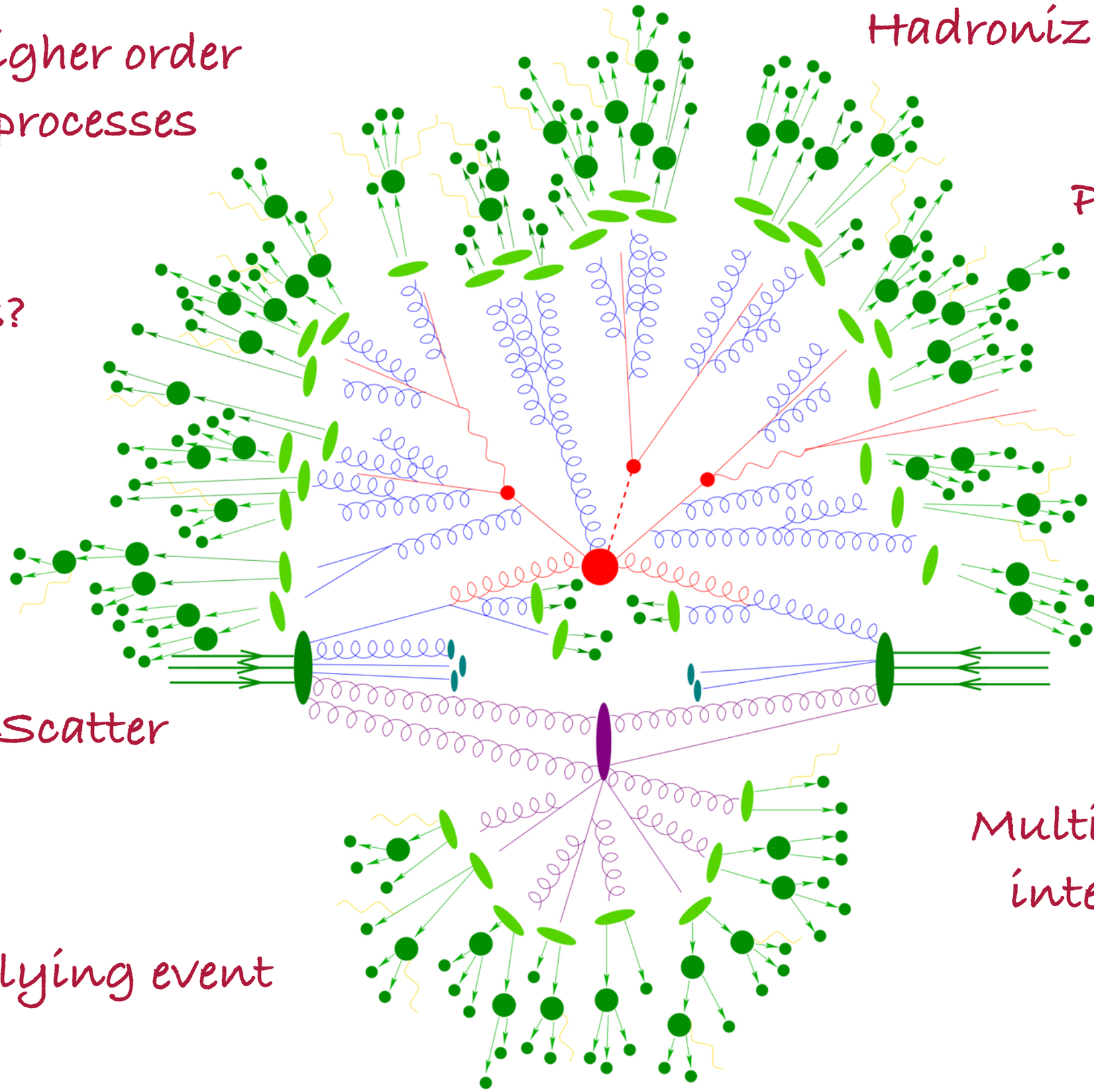


REALITY (SORT OF)



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- Add any necessary analysis specific tweaks to this procedure!
  - e.g., α_S variations, Stewart-Tackmann and/or jet-veto-efficiency methods, quark mass treatments, variations of substructure variables

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  - ~95% detector uptime for CMS & ATLAS
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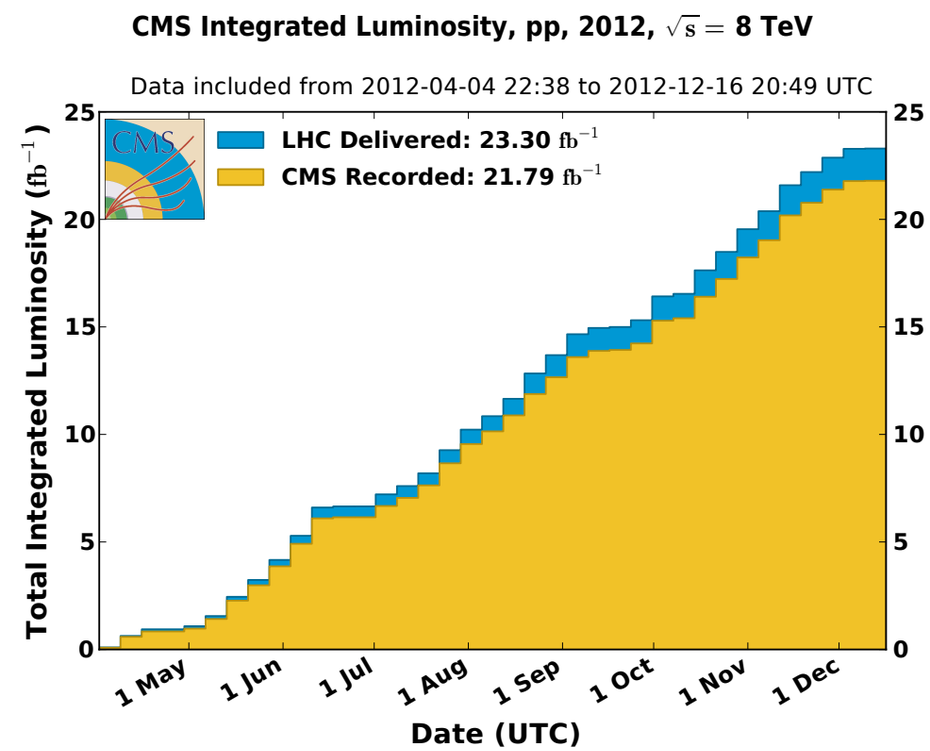

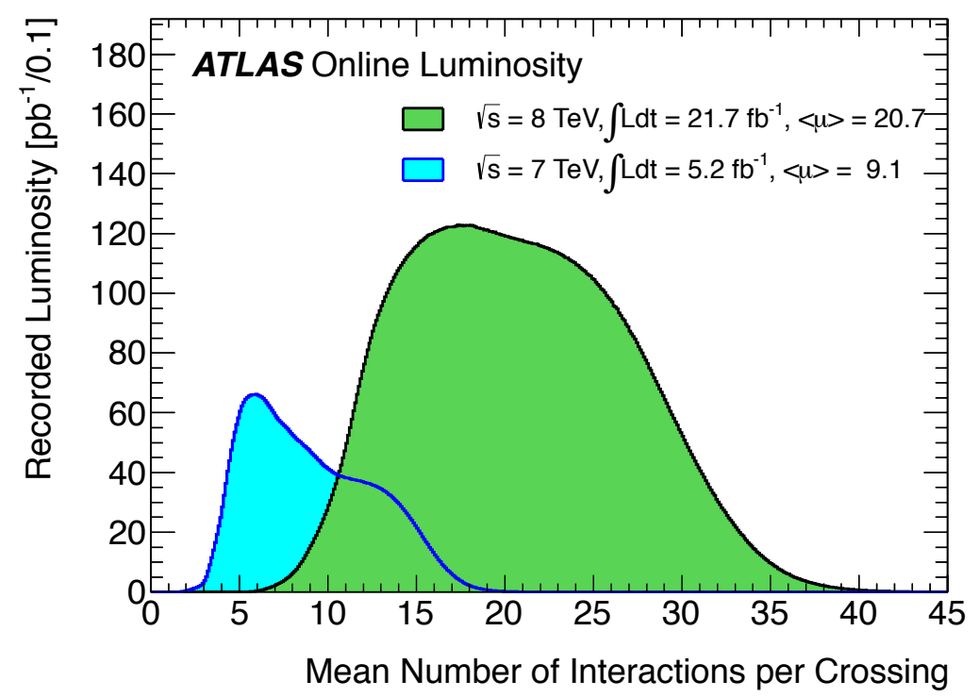

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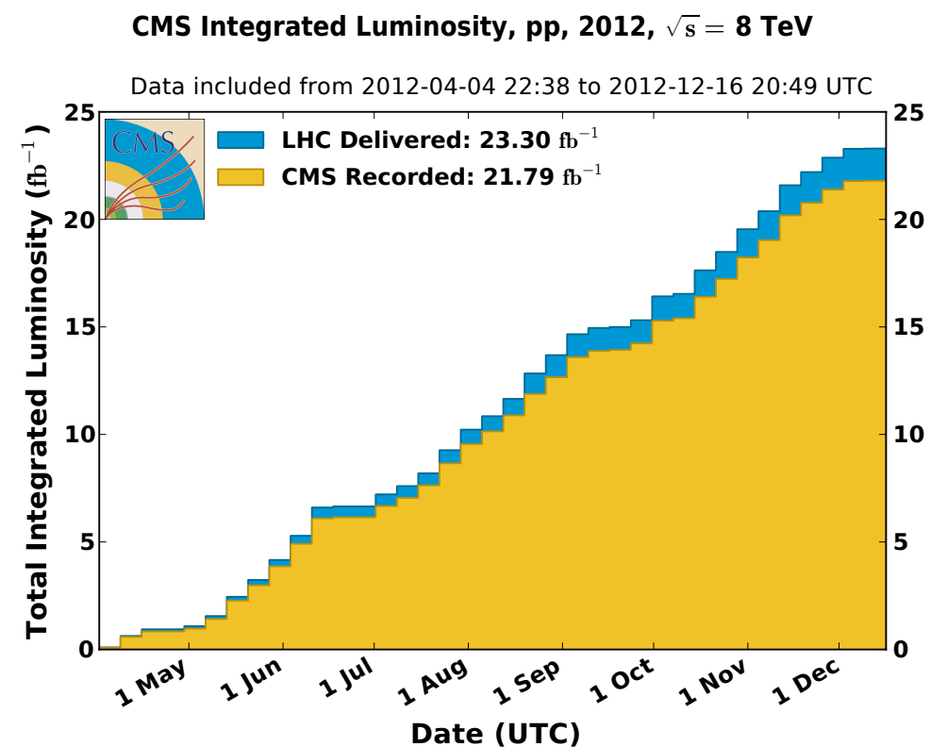

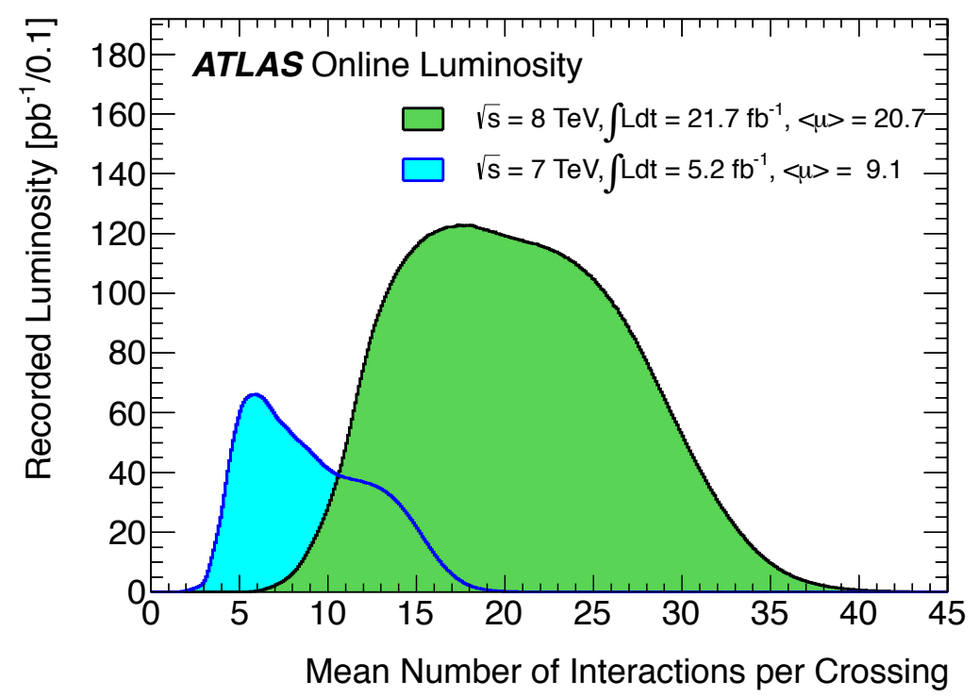

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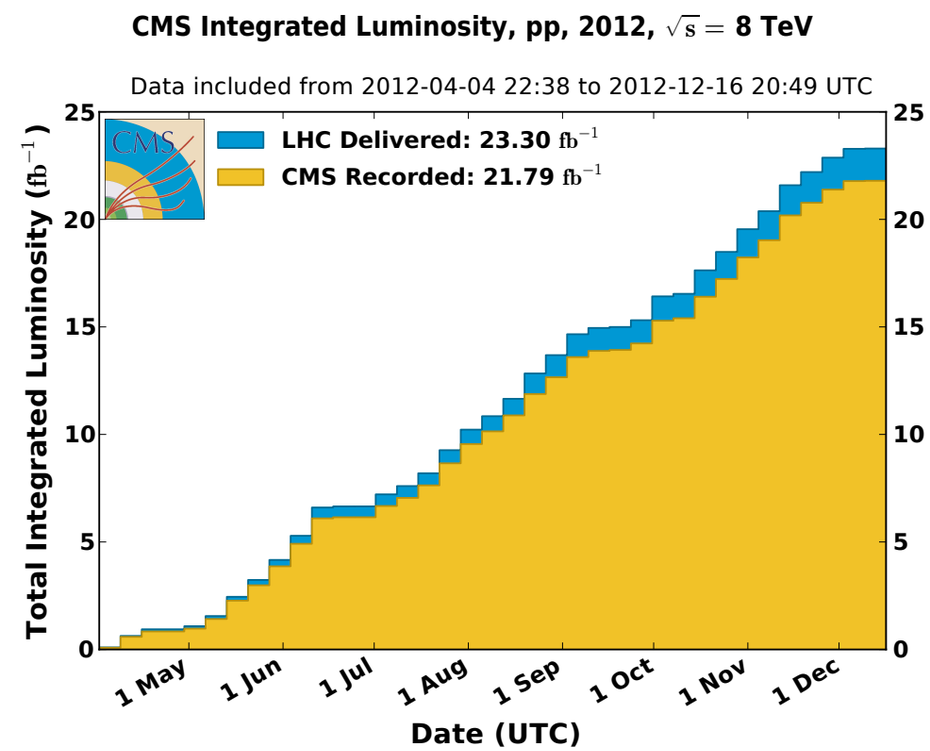

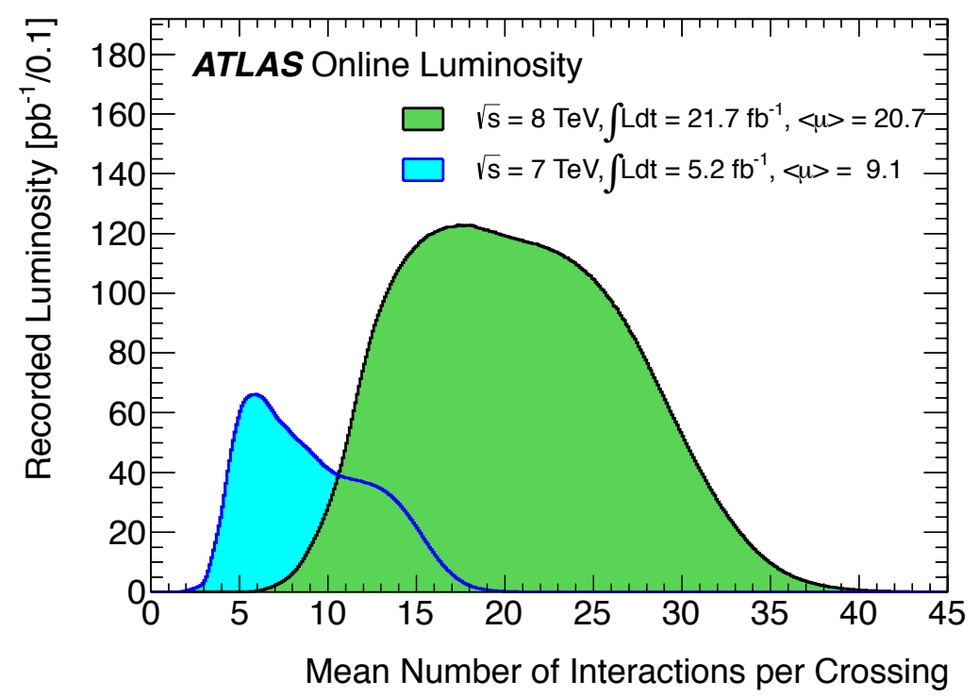

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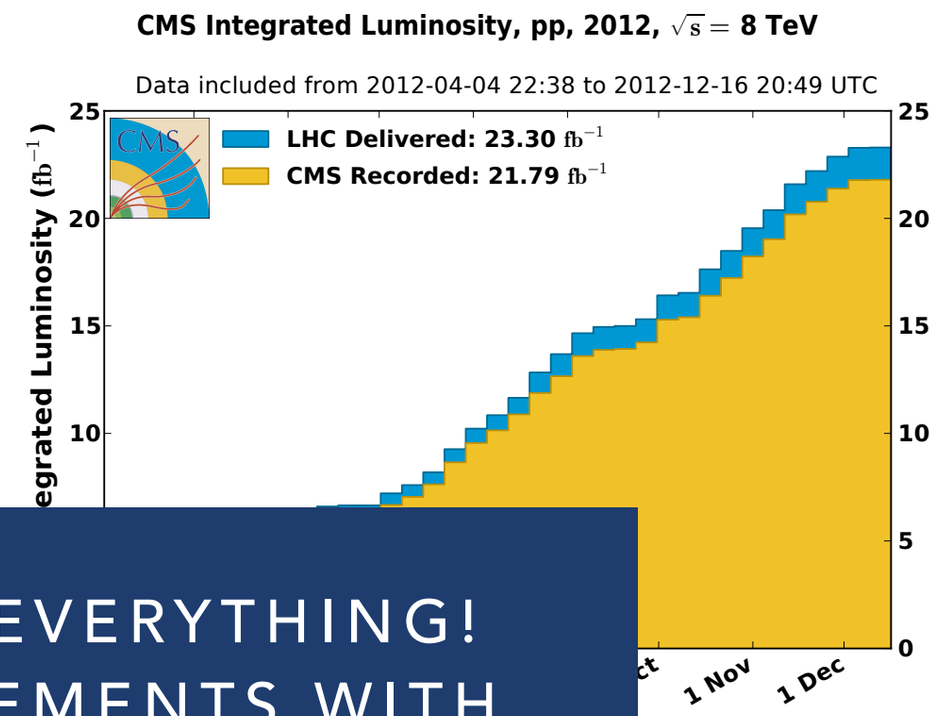
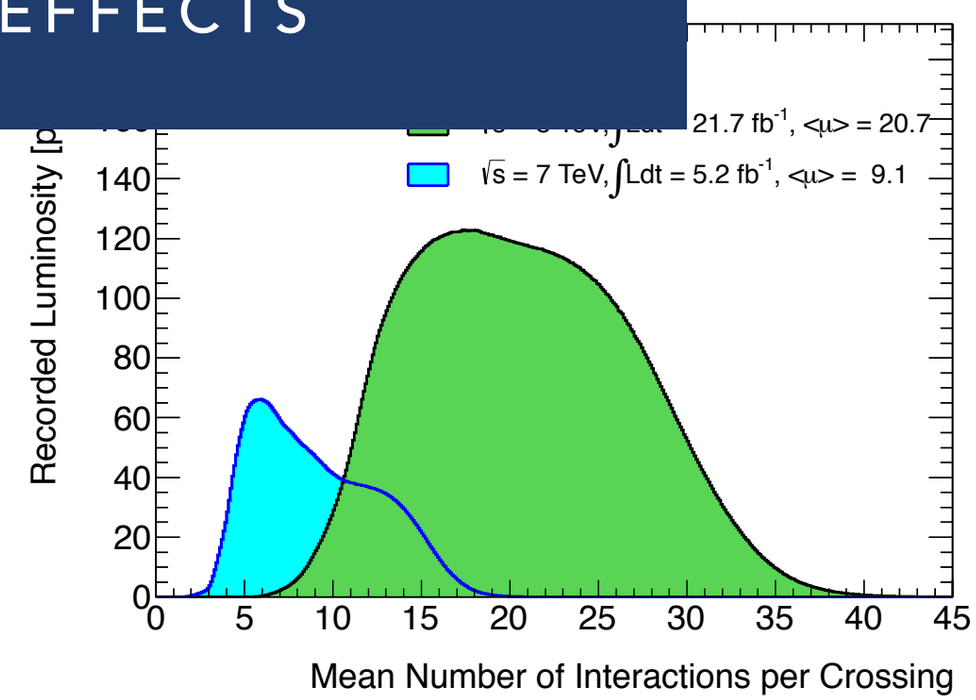
CAN'T POSSIBLY COVER EVERYTHING!
WILL FOCUS ON MEASUREMENTS WITH IMPORTANT QCD EFFECTS





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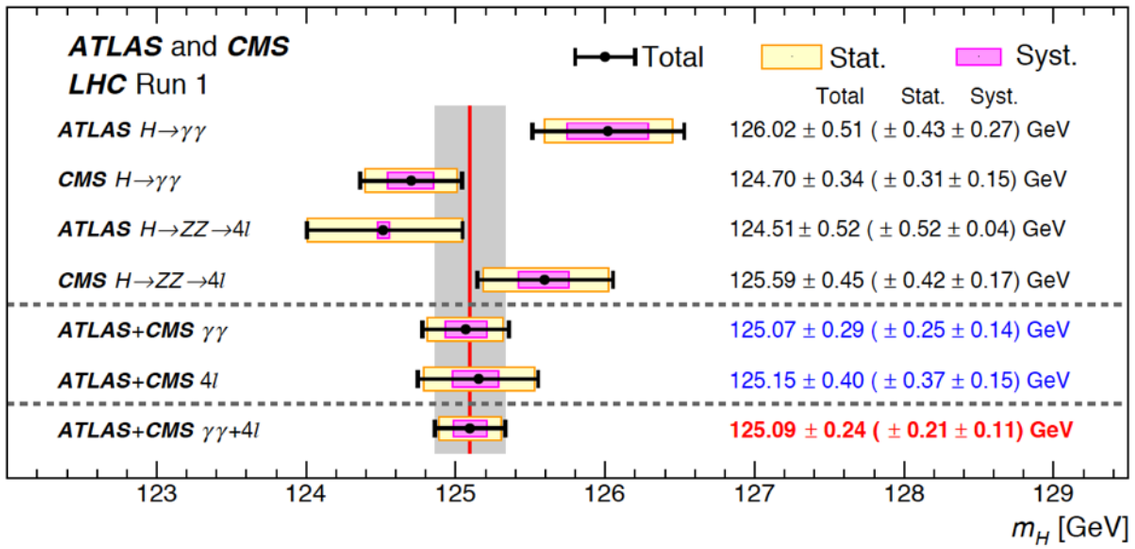
- What does it look like?
  - Mass**, width**, spin, parity

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{scale}) \pm 0.02\,(\text{other}) \pm 0.01\,(\text{theory})\ \text{GeV},$$

CERN-PH-EP/2015-075
2015/03/27



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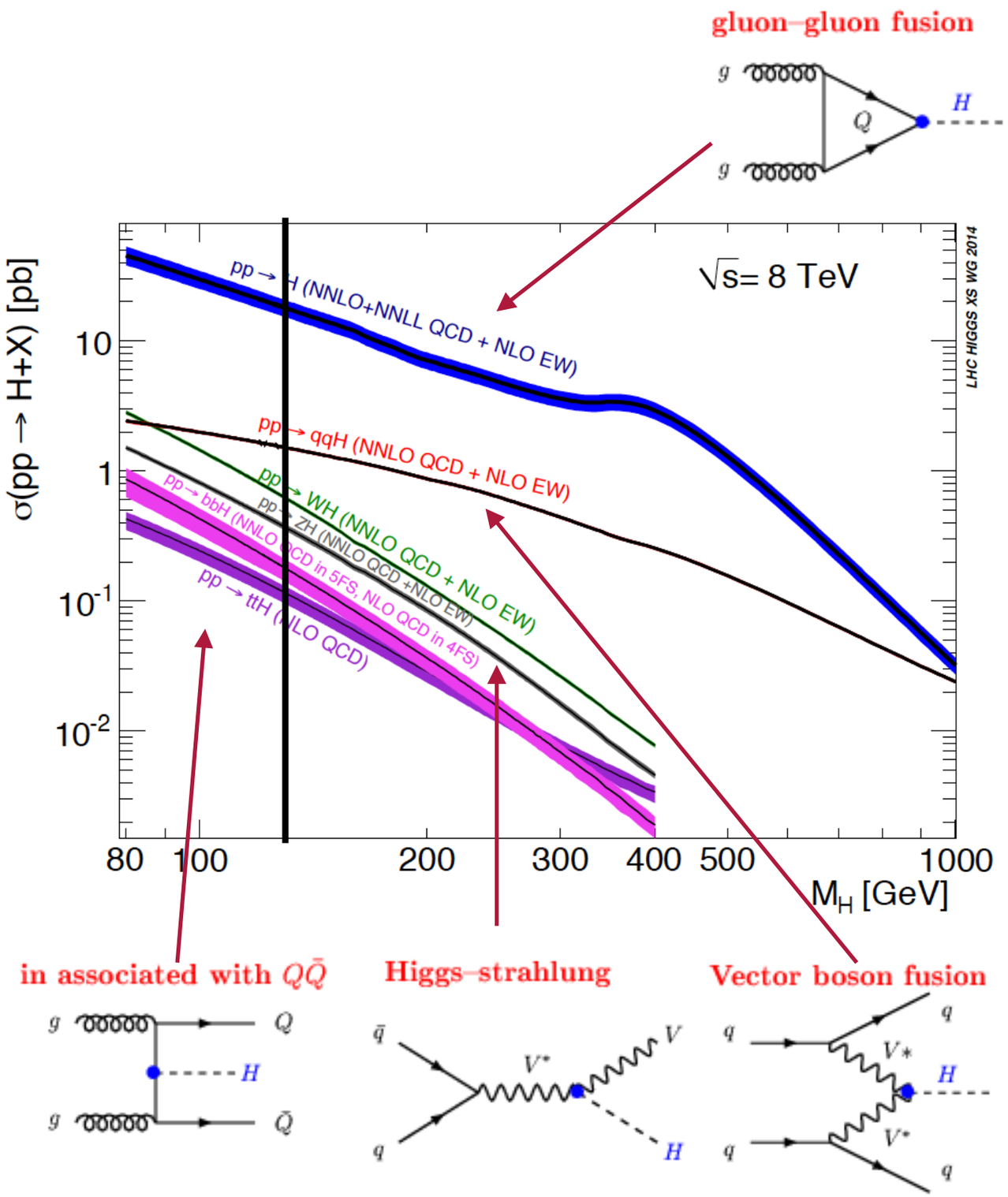

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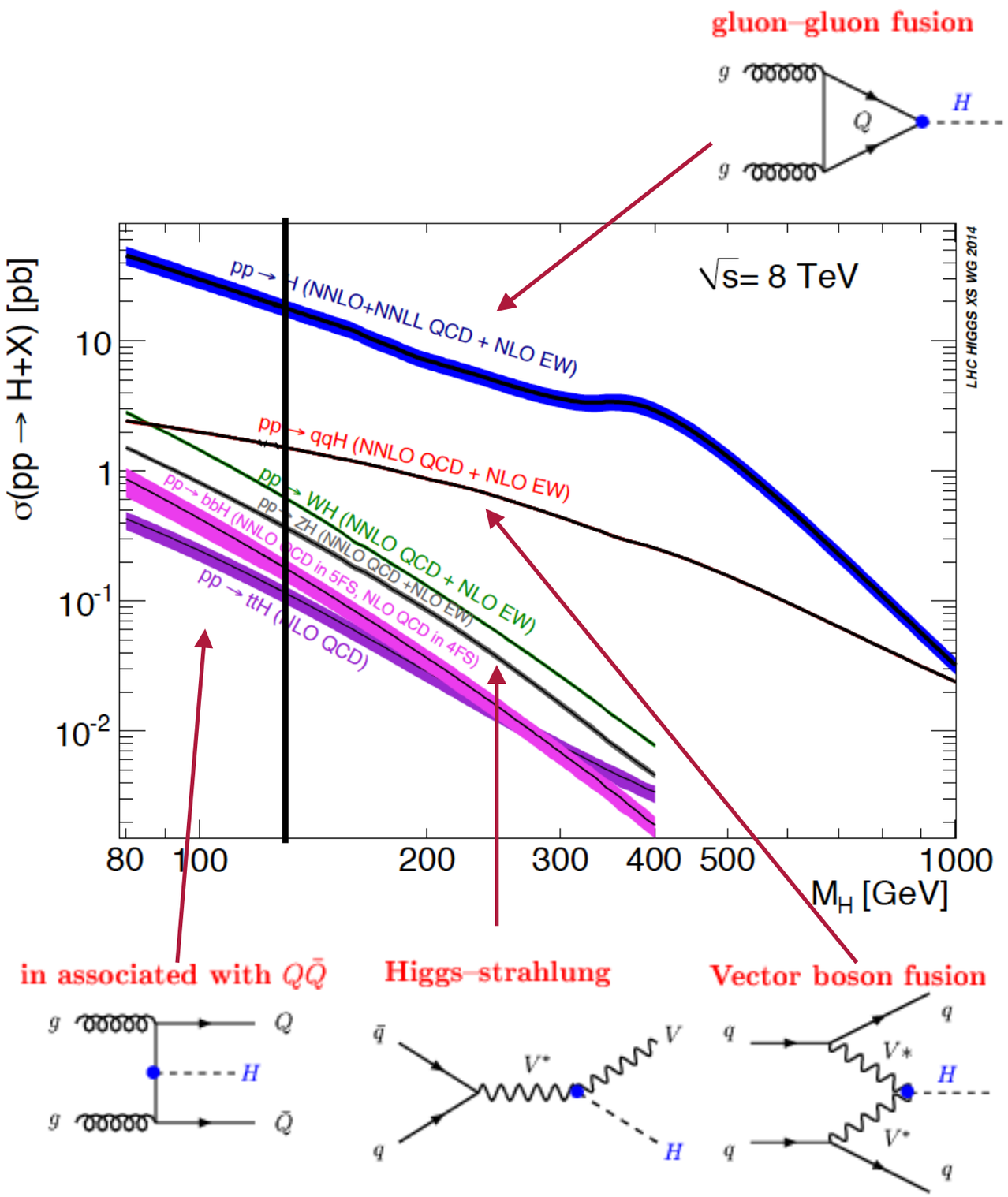

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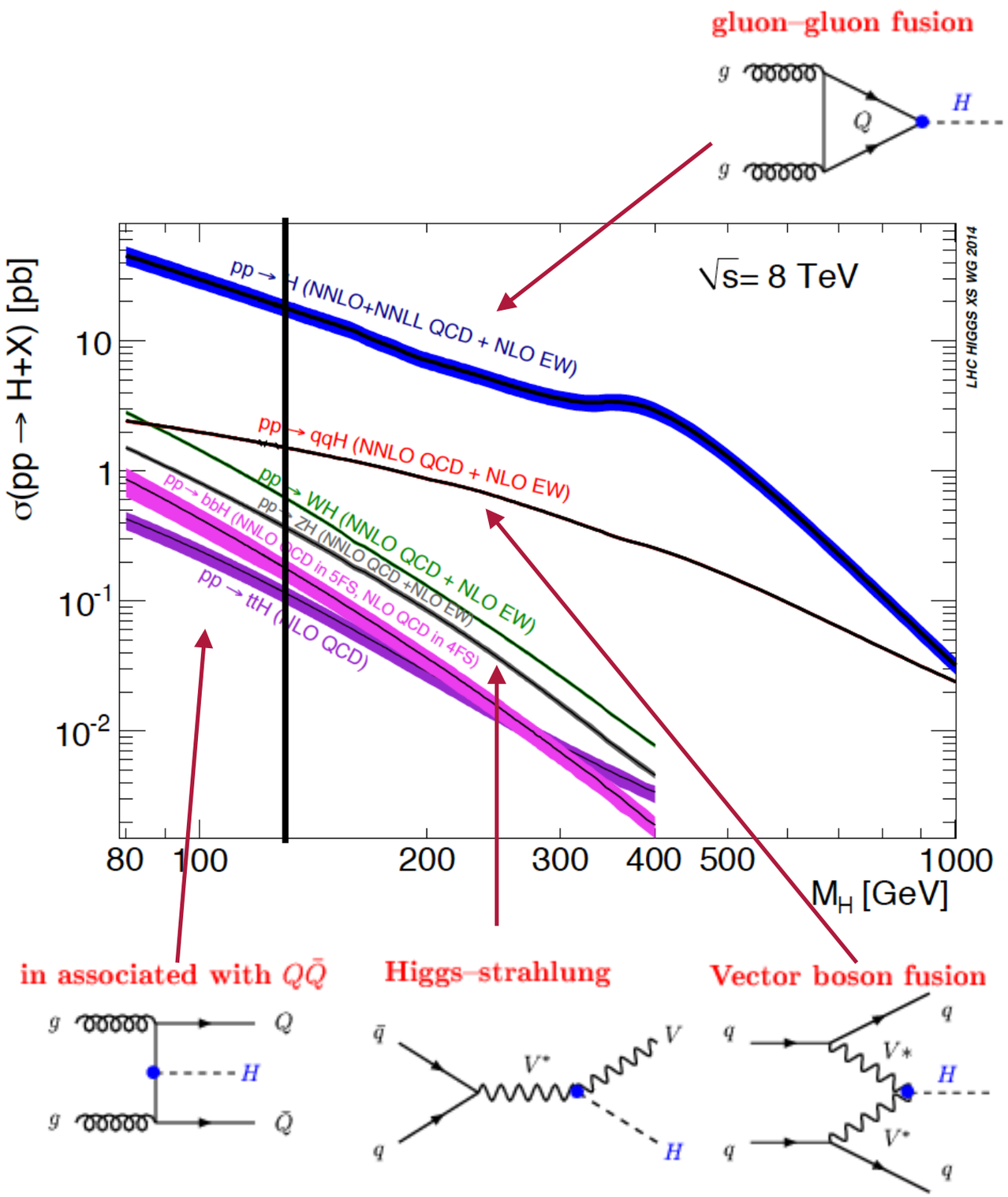
- Does it act the way we think it should?
  - **Cross-sections and differential distributions**



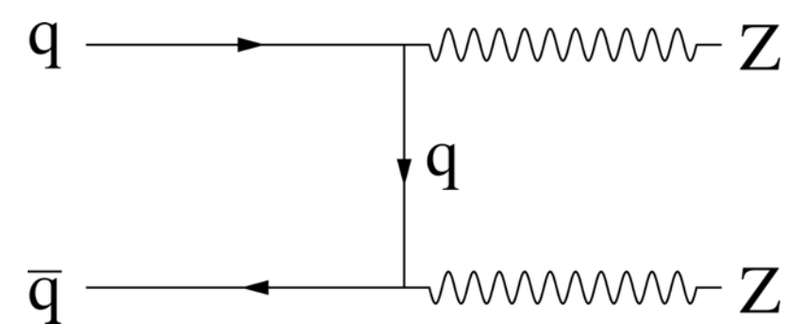
WIDTH FROM $H \to ZZ$

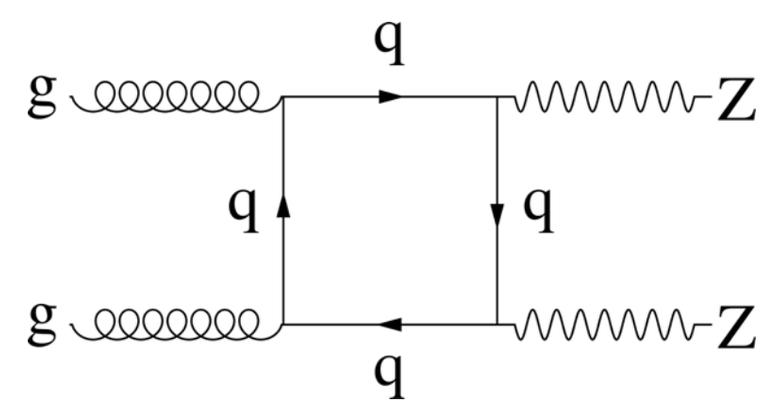
CMS: Phys. Lett. B 736 (2014) 64
ATLAS: Eur. Phys. J. C (2015) 75:335

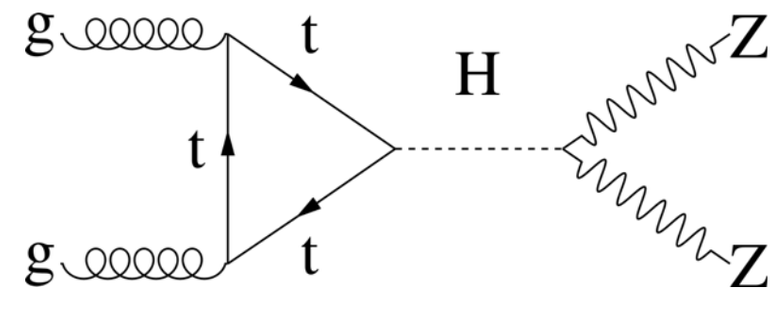
WIDTH FROM H➛ZZ

- Use ratio of on-shell to off-shell gg production cross-sections to measure width

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$







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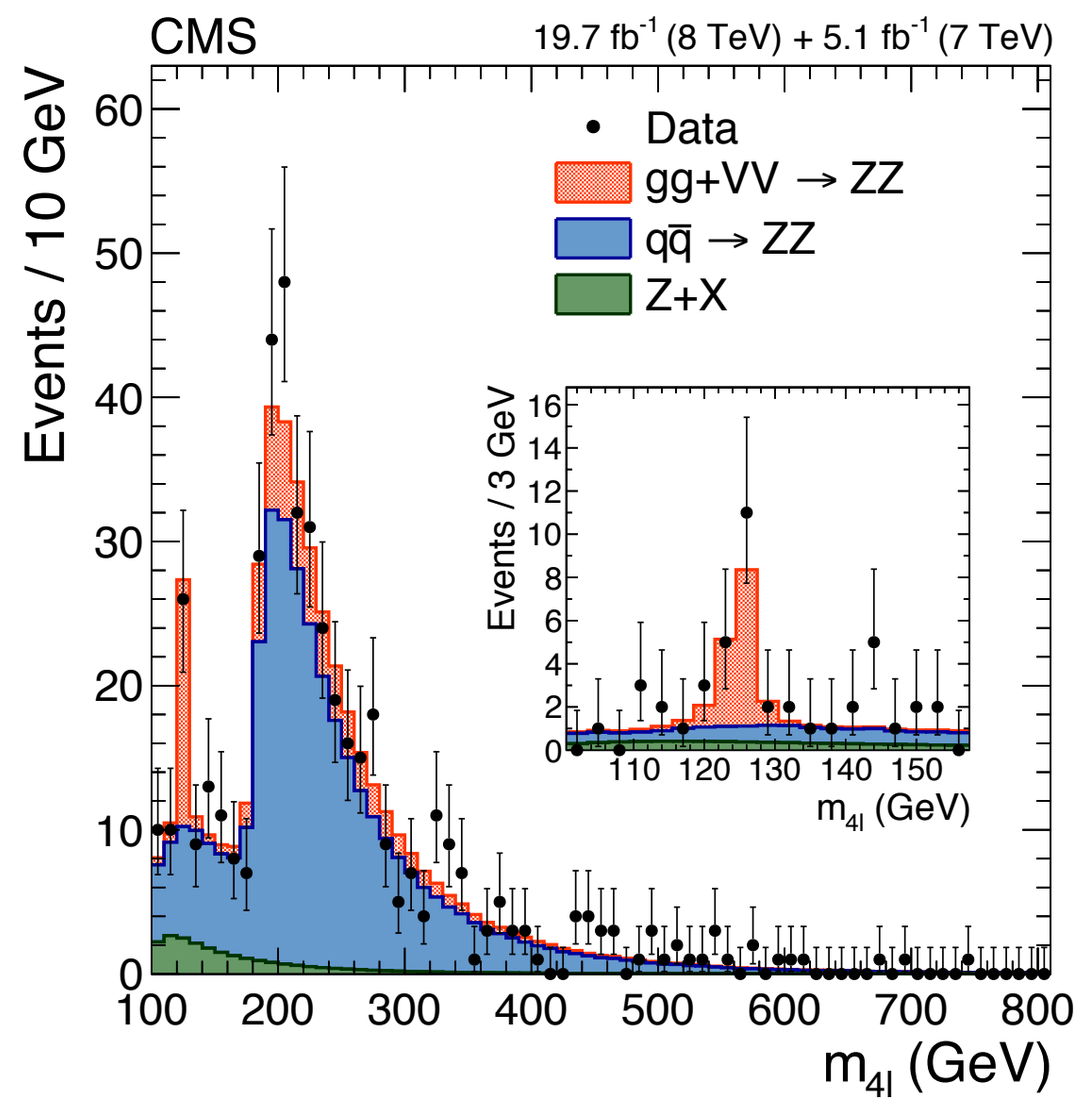

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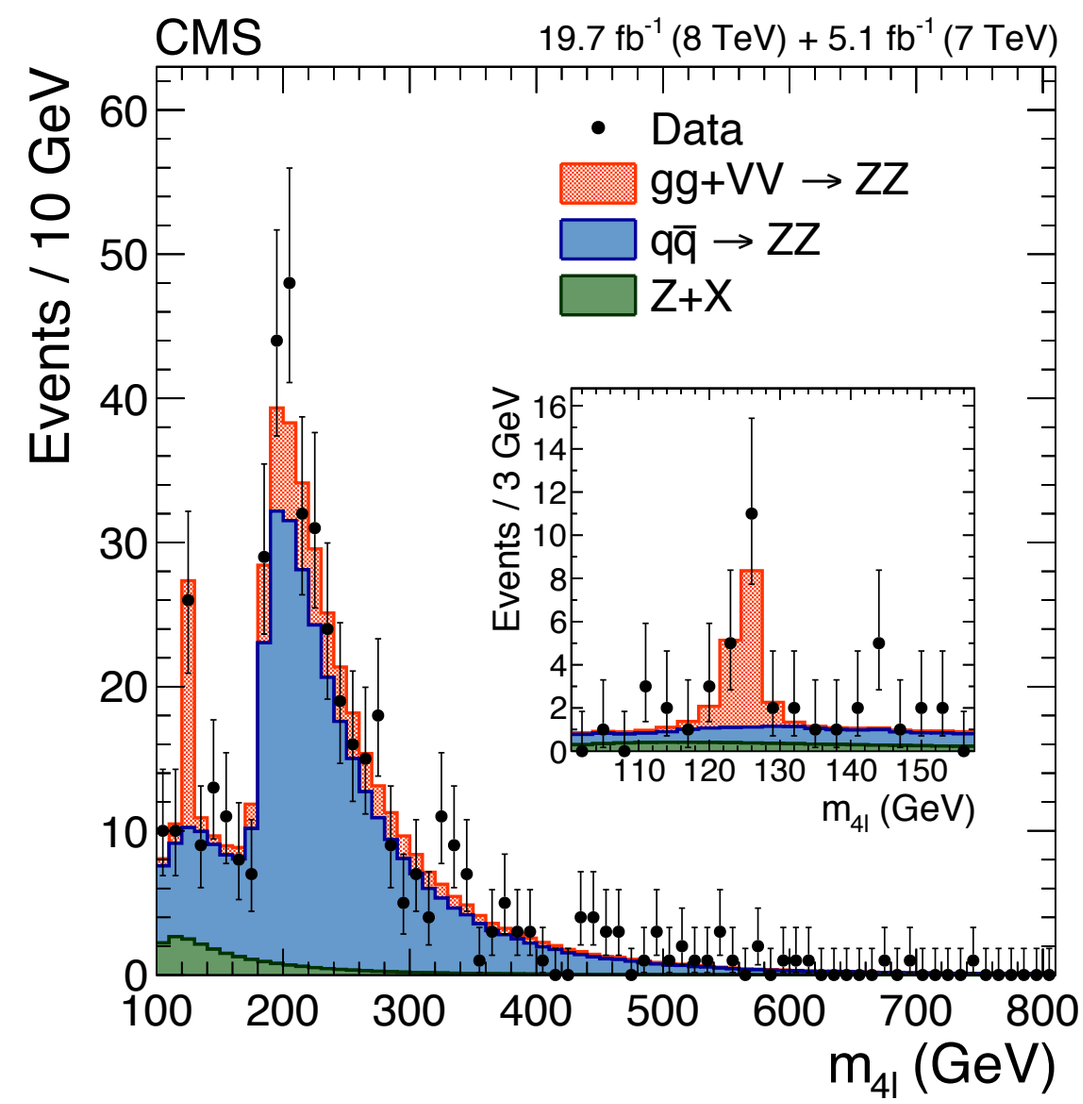
- Need to isolate gg component: Enhance gg contribution with MELA discriminant

$$\mathcal{D}_{gg} = \frac{\mathcal{P}^{gg}_{tot}}{\mathcal{P}^{gg}_{tot} + \mathcal{P}^{q\bar{q}}_{bkg}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{bkg}}{a \times \mathcal{P}^{gg}_{sig} + \sqrt{a} \times \mathcal{P}^{gg}_{int} + \mathcal{P}^{gg}_{bkg}}\right]^{-1}$$

$$(m_{Z_1}, m_{Z_2}, \mathbf{\Omega})$$



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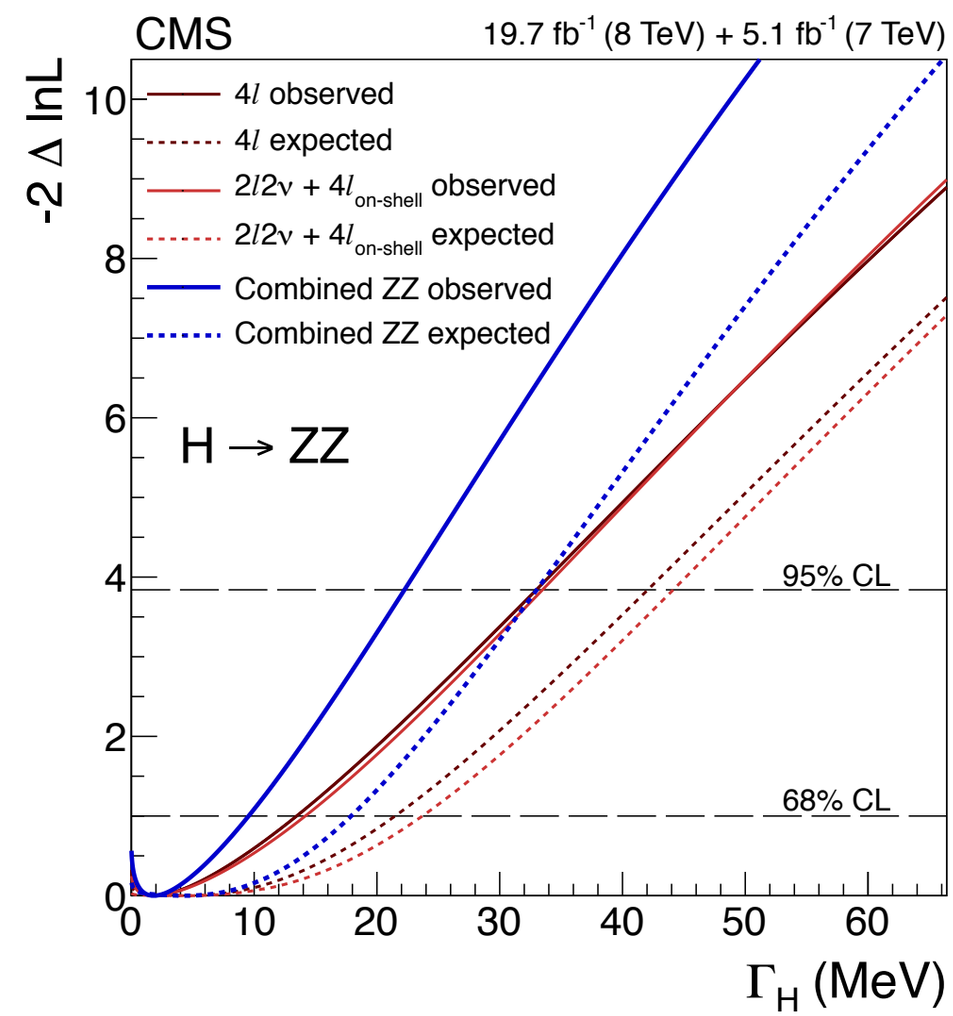

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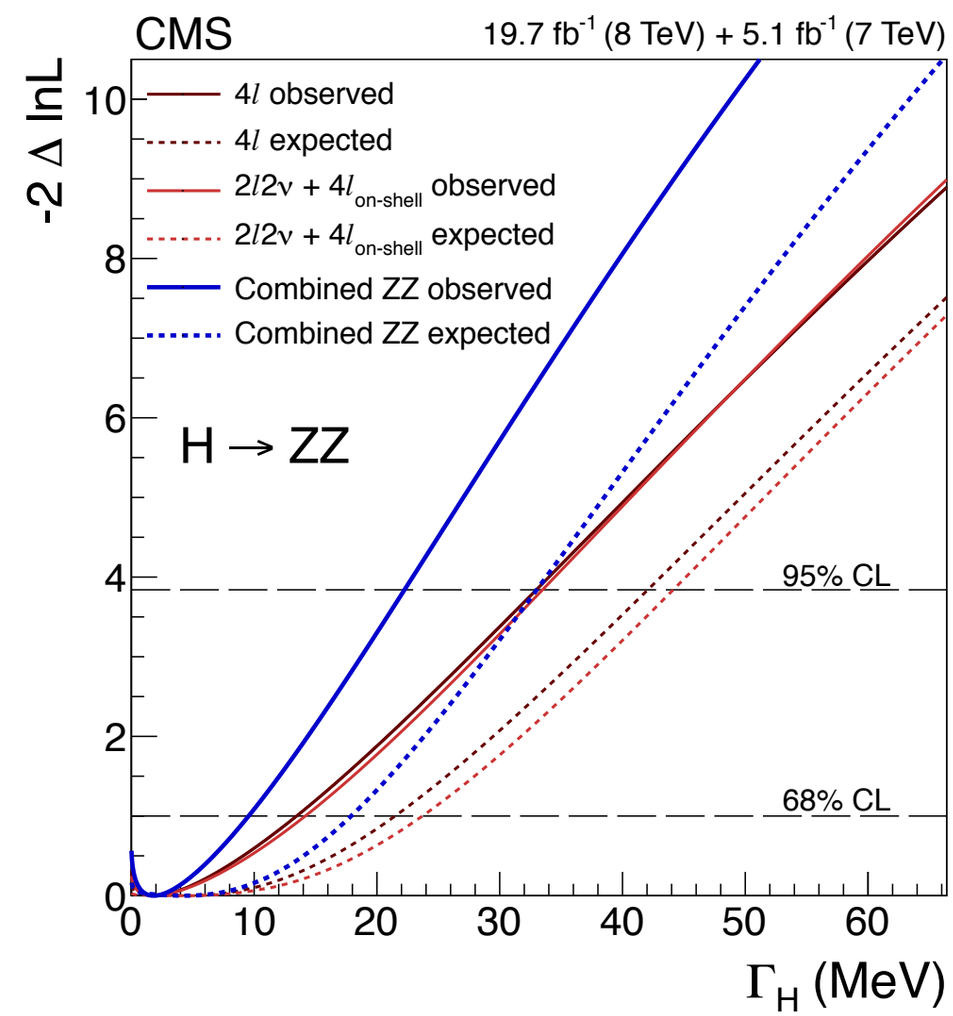

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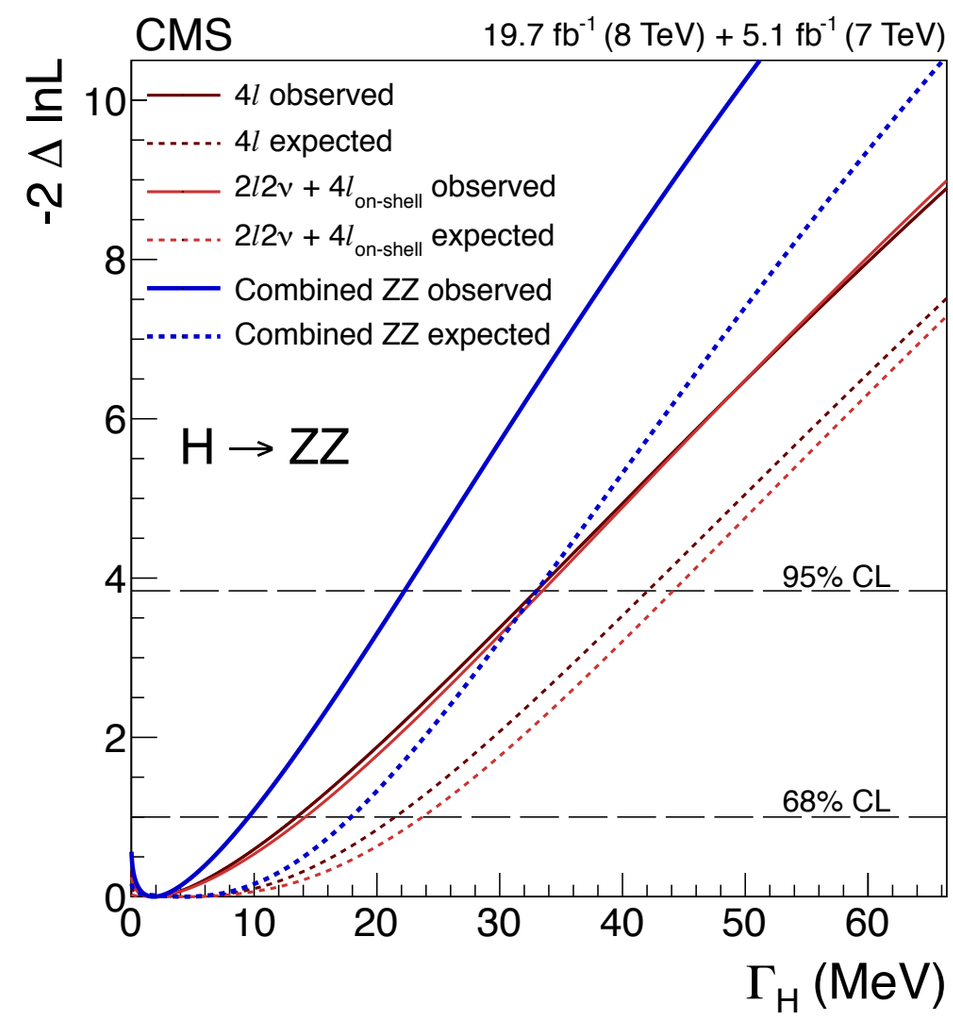

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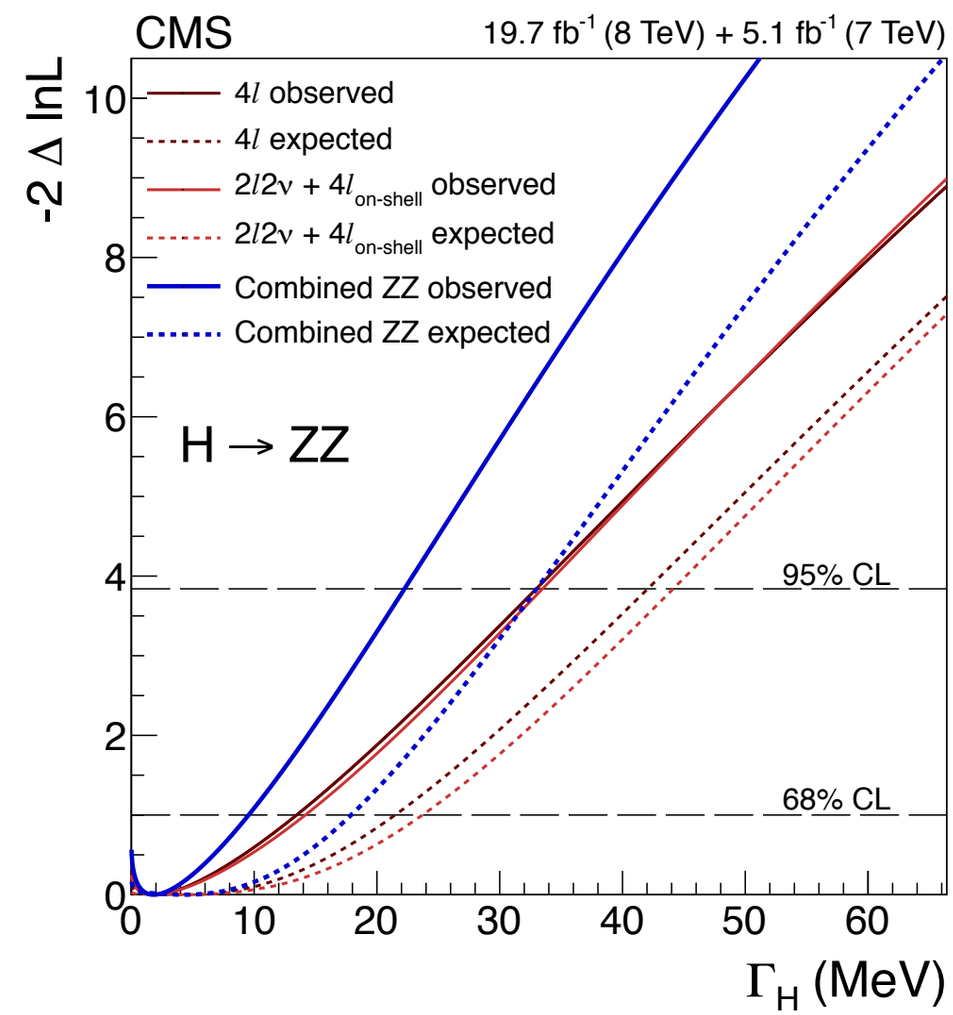

Relies on no new physics assumption (on-shell & off-shell couplings are the same)!

Would have tighter constraints if new physics existed: CMS arXiv:1507.06656

PRODUCTION

- By combining all Run I observations, can measure signal strength of different production processes
  - Assuming SM BR

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	$\sqrt{s}$ = 8 TeV		Combined $\sqrt{s}$ = 7 and 8 TeV	
ggF	$1.23^{+0.25}_{-0.21}$	$\left[^{+0.16}_{-0.16}\ ^{+0.10}_{-0.08}\ ^{+0.16}_{-0.11}\right]$	$1.23^{+0.23}_{-0.20}$	$\left[^{+0.14}_{-0.14}\ ^{+0.09}_{-0.08}\ ^{+0.16}_{-0.12}\right]$
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VH	0.93 ± 0.39	$\left[^{+0.37}_{-0.33}\ ^{+0.20}_{-0.18}\ ^{+0.12}_{-0.06}\right]$	0.80 ± 0.36	$\left[^{+0.31}_{-0.30}\ ^{+0.17}_{-0.17}\ ^{+0.10}_{-0.05}\right]$
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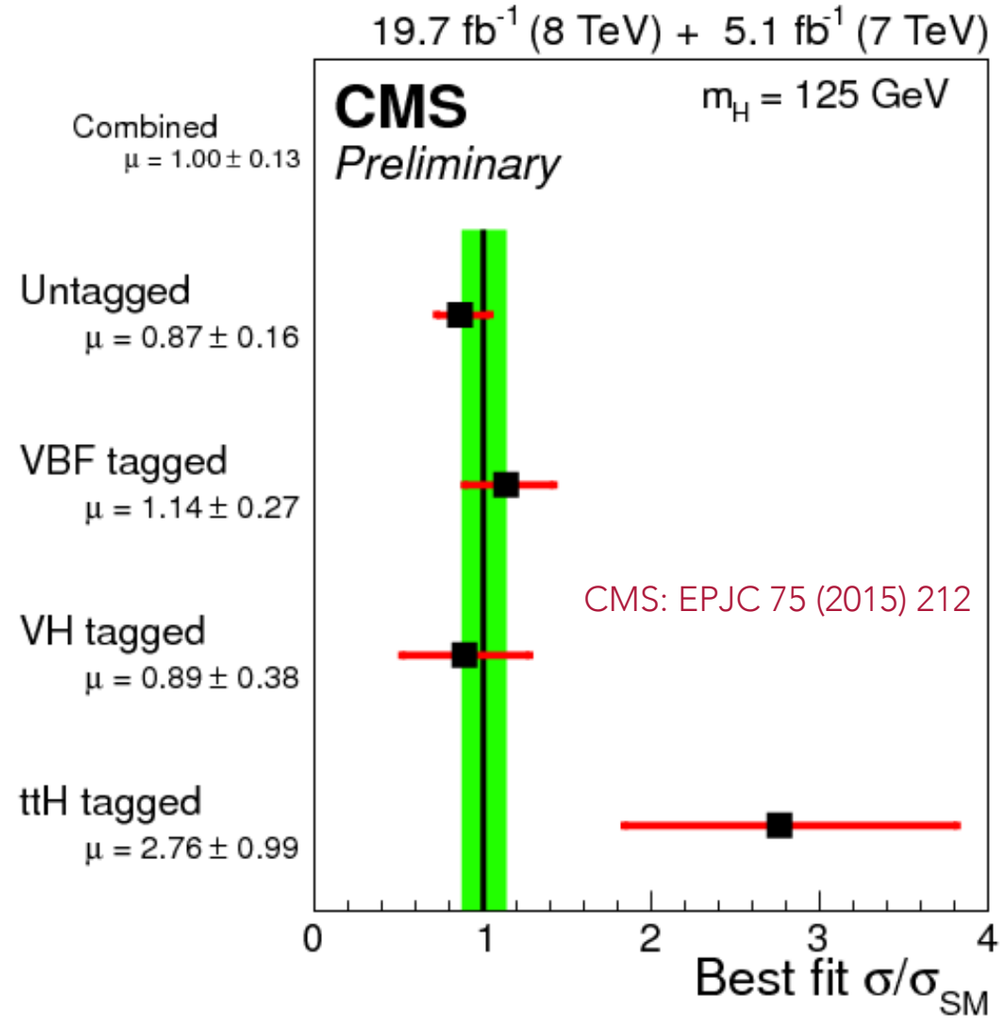

CMS: EPJC 75 (2015) 212

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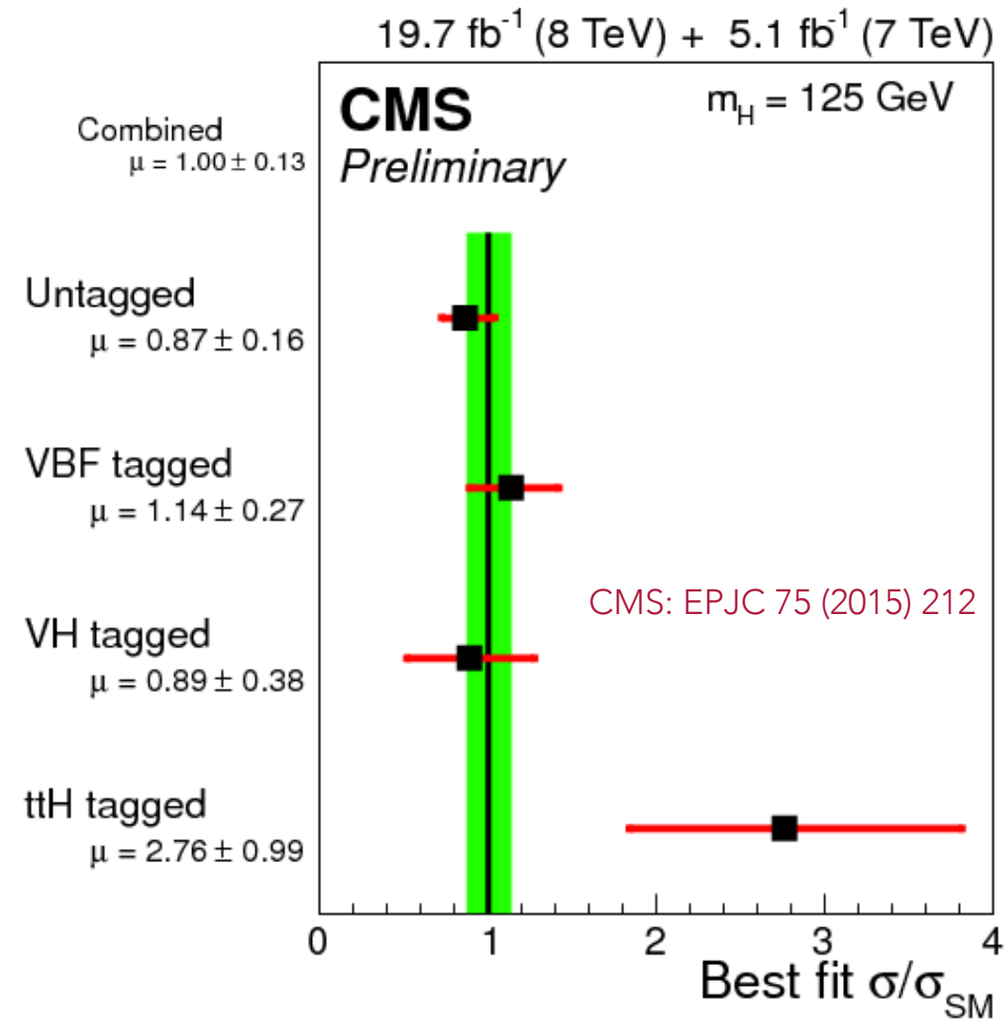
Stat.

Sys.

Theory



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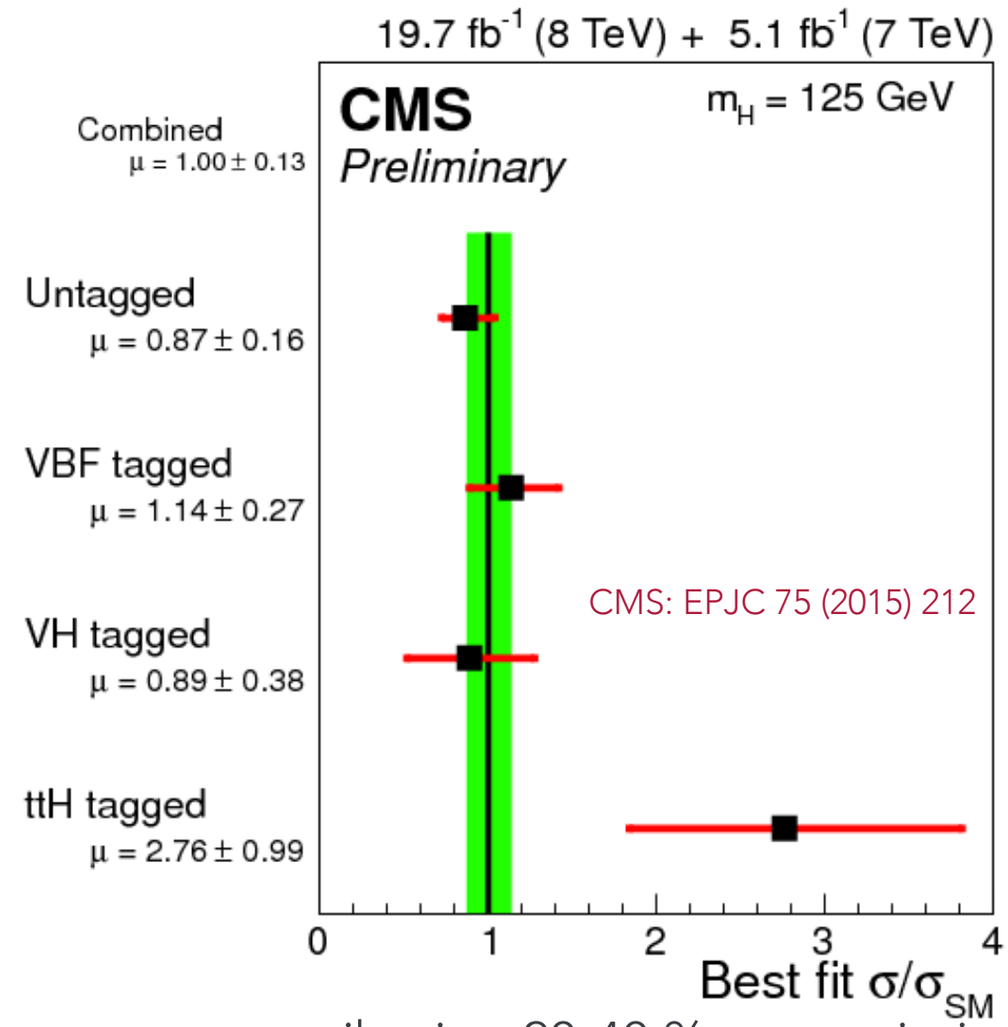
Stat. Sys. Theory



CMS: EPJC 75 (2015) 212

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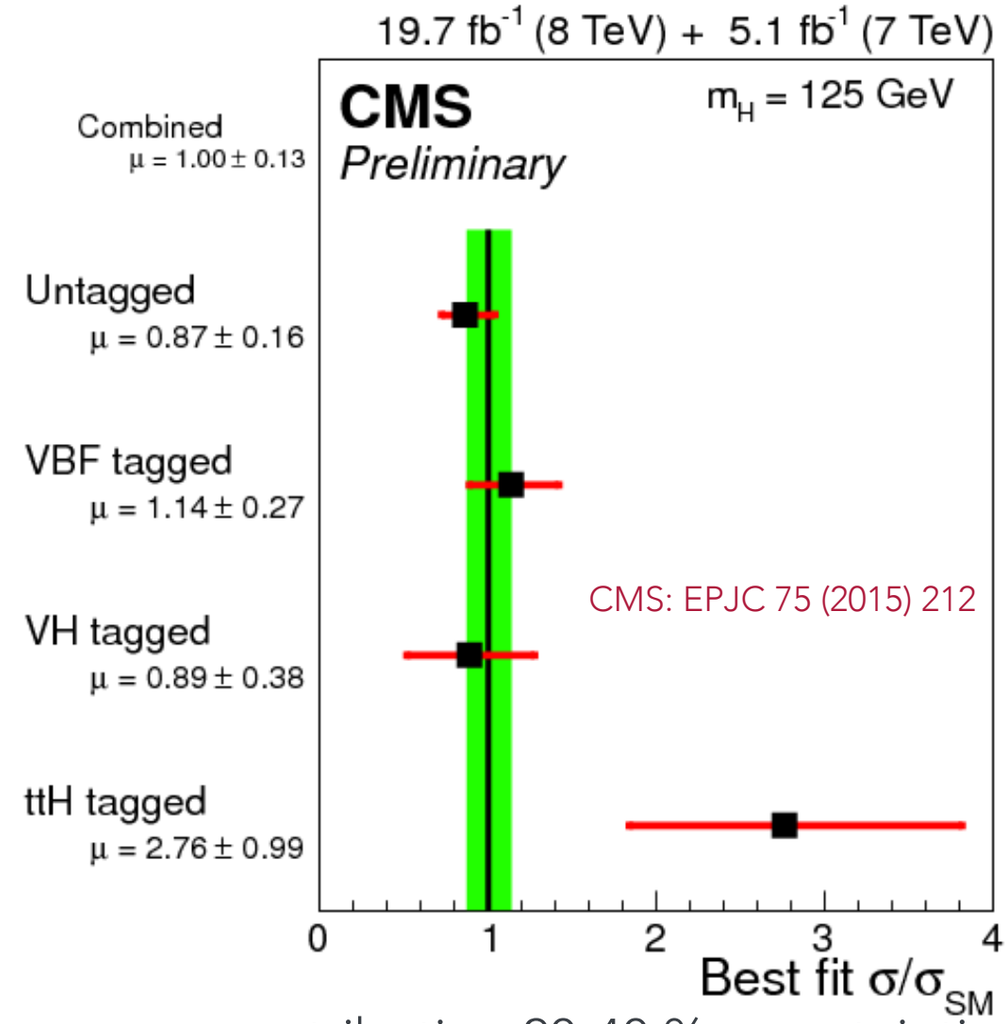

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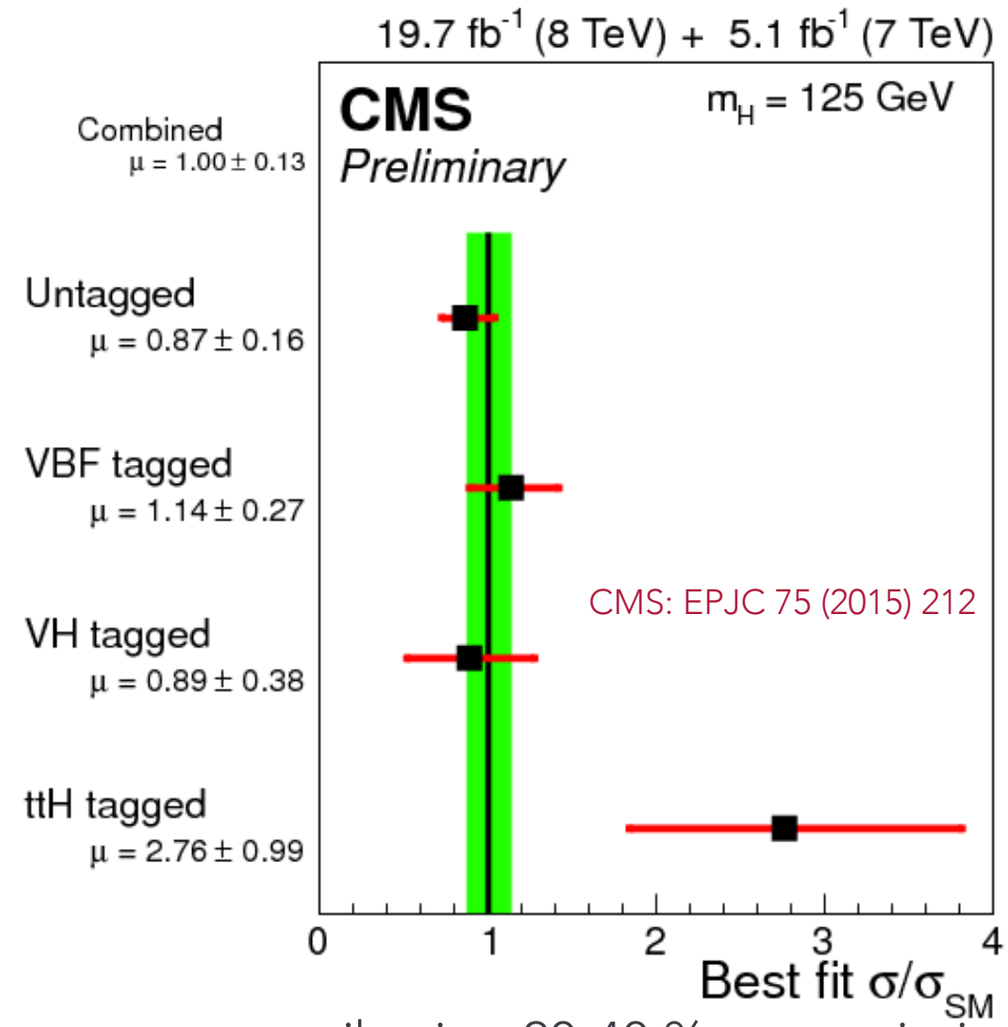

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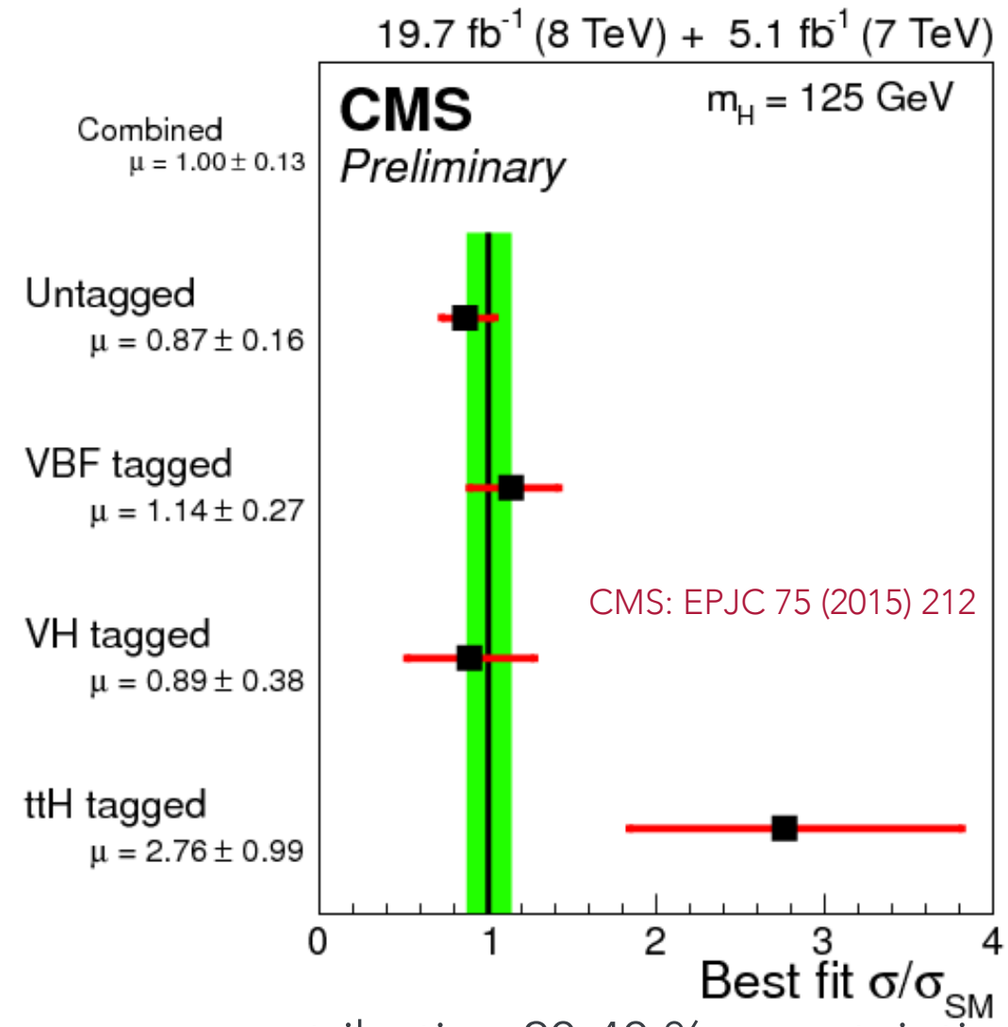

CMS: EPJC 75 (2015) 212

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  - Theory uncertainties dominate ggF process determination
    - Current QCD scale in NNLO+NNLL (+7-8%) and PDF+alpha_s (+-8%) uncertainties
  - VBF uncertainties are comparable to experimental uncertainties: dominated by ggF contamination from jet veto

JET COUNTING & VETOS

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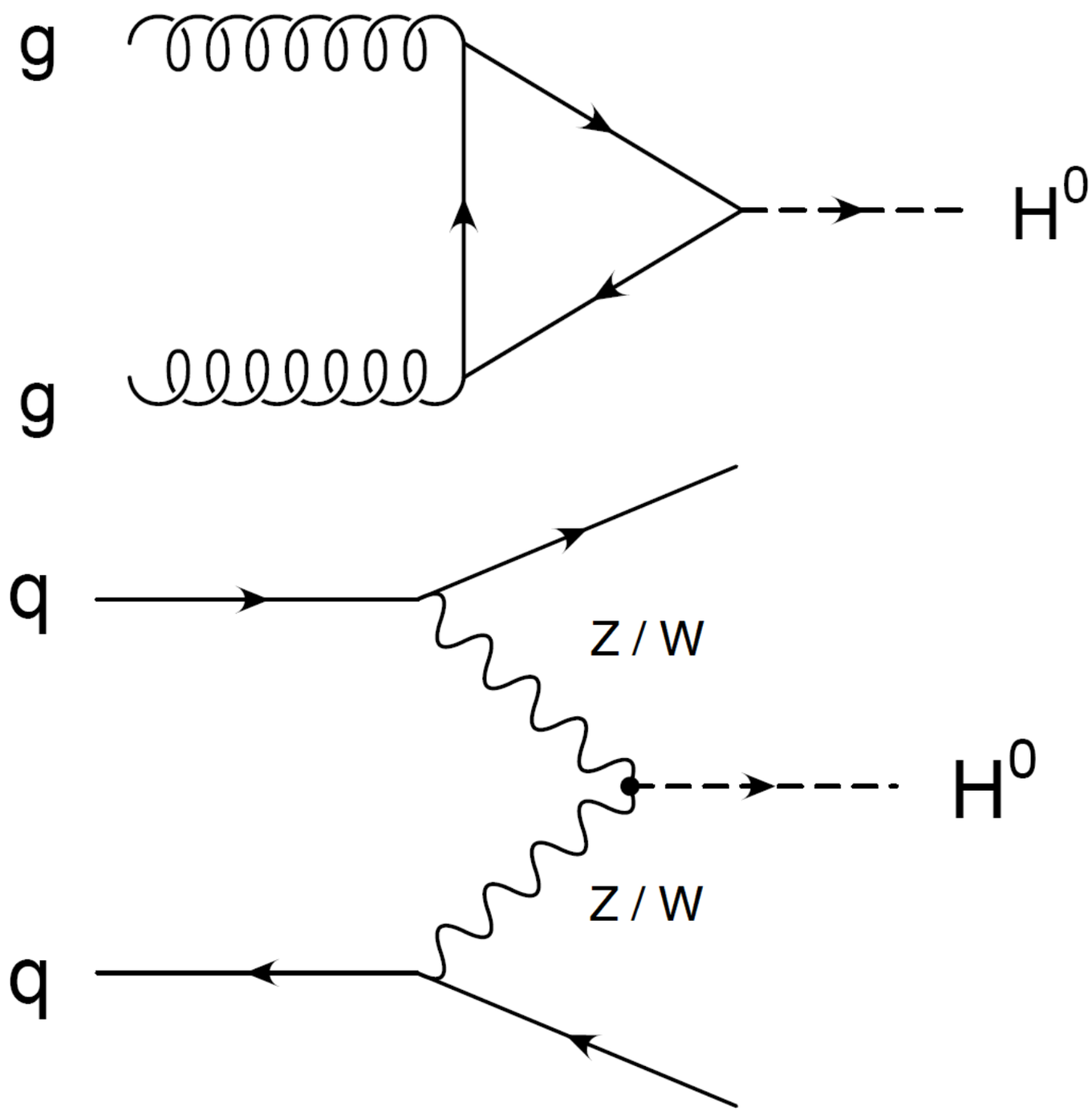
- Production type determined by event jet properties



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Eur. Phys. J. C 75 (2015) 212

Decay tag and production tag		Expected signal composition
$H \to \gamma\gamma$ [18], Section 2.1		
$\gamma\gamma$	Untagged	76–93% ggH
	2-jet VBF	50–80% VBF
	Leptonic VH	≈95% VH (WH/ZH ≈ 5)
	E_T^{miss} VH	70–80% VH (WH/ZH ≈ 1)
	2-jet VH	≈65% VH (WH/ZH ≈ 5)
	Leptonic ttH	≈95% ttH
	Multijet ttH	>90% ttH
$H \to ZZ \to 4\ell$ [16], Section 2.2		
4μ, $2e2\mu/2\mu2e$, $4e$	Untagged	≈90% ggH
	2-jet	42% (VBF + VH)

JET COUNTING & VETOS

- Production type determined by event jet properties
- Large uncertainties on ggF contamination estimated with:
  - Stewart-Tackmann procedure (arXiv:1107.2117, FO), Jet Veto Efficiency (arXiv:1209.1817, NLL resummed)
  - Active area for improvement in Run II

Process	$gg \to H, q\bar{q}/gg \to b\bar{b}H/t\bar{t}H$	$qq' \to Hqq'$	$q\bar{q} \to W/ZH$	ZZ^*
	VBF enriched category			
Theoretical cross section	20.4%	4%	4%	8%
Underlying event	6.6%	1.4%	–	–
Jet energy scale	9.6%	4.8%	7.8%	9.6%
Jet energy resolution	0.9%	0.2%	1.0%	1.4%
Total	23.5%	6.4%	8.8%	12.6%
	VH-hadronic enriched category			
Theoretical cross section	20.4%	4%	4%	2%
Underlying event	7.5%	3.1%	–	–
Jet energy scale	9.4%	9.3%	3.7%	12.6%
Jet energy resolution	1.0%	1.7%	0.6%	1.8%
Total	23.7%	10.7%	5.5%	12.9%
	VH-leptonic enriched category			
Theoretical cross section	12%	4%	4%	5%
Leptonic VH-specific cuts	1%	1%	5%	–
Jet energy scale	8.8%	9.9%	1.7%	3.2%
Total	14.9%	10.7%	6.6%	5.9%
	ggF enriched category			
Theoretical cross section	12%	4%	4%	4%
Jet energy scale	2.2%	6.6%	4.0%	1.0%
Total	12.2%	7.7%	5.7%	4.1%

Phys. Rev. D 91, 012006 (2015)

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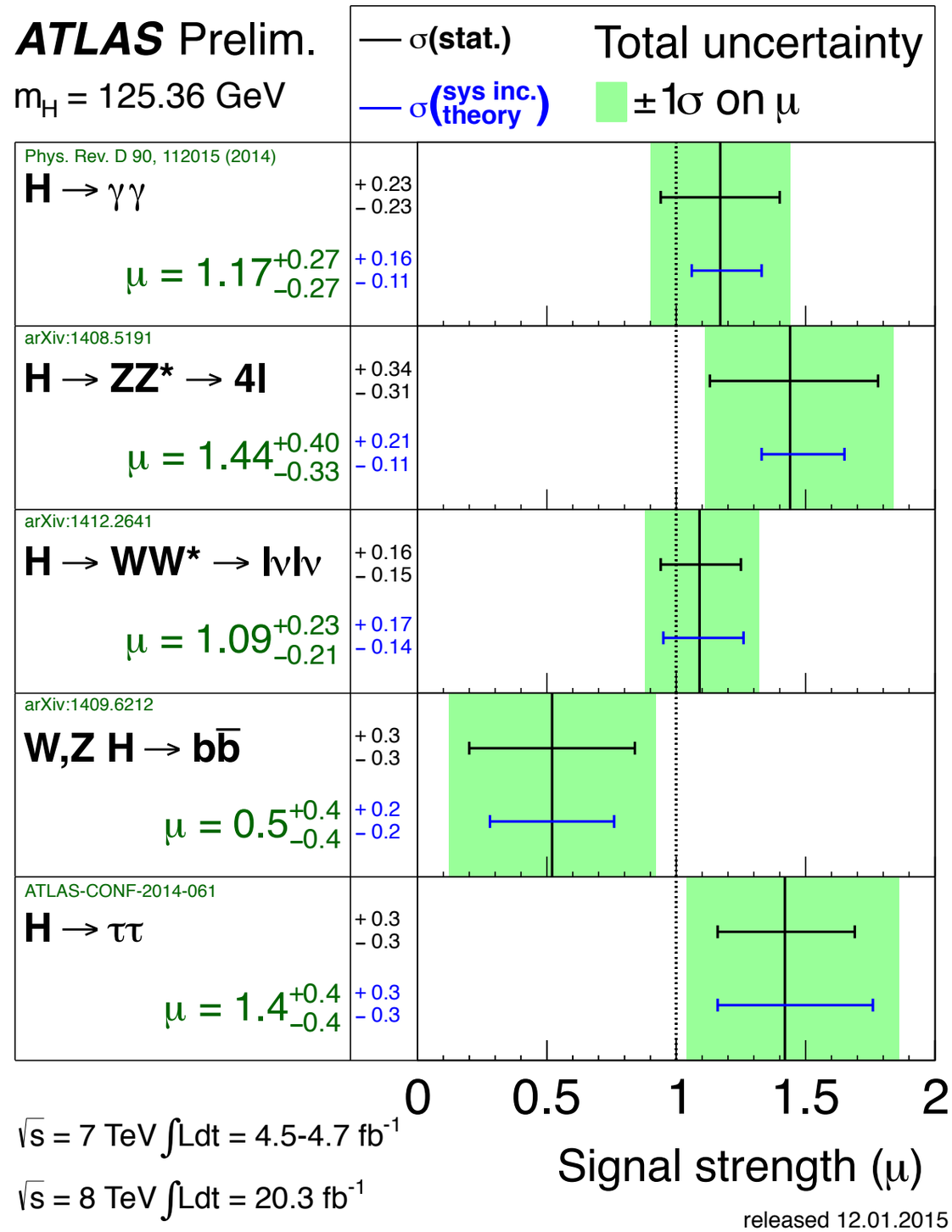
Theoretical cross section	12%	4%	4%	4%
Jet energy scale	2.2%	6.6%	4.0%	1.0%
Total	12.2%	7.7%	5.7%	4.1%

Phys. Rev. D 91, 012006 (2015)

COUPLINGS

- Measuring fermionic couplings is a key part of Higgs program
- bs and taus branching ratios & top coupling targeted



$$\mu = \frac{\sigma_{\rm obs}}{\sigma_{\rm SM}}$$

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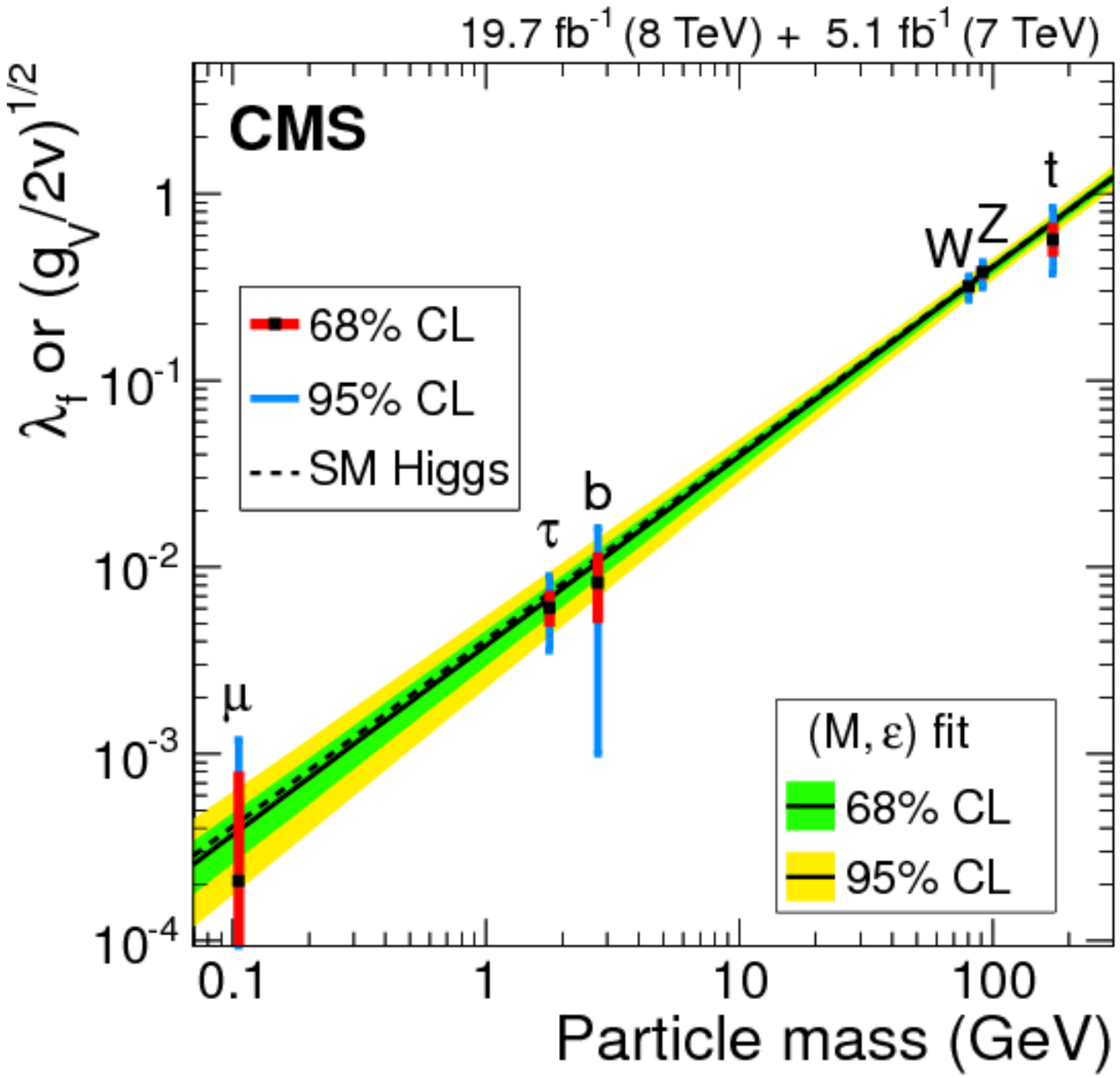
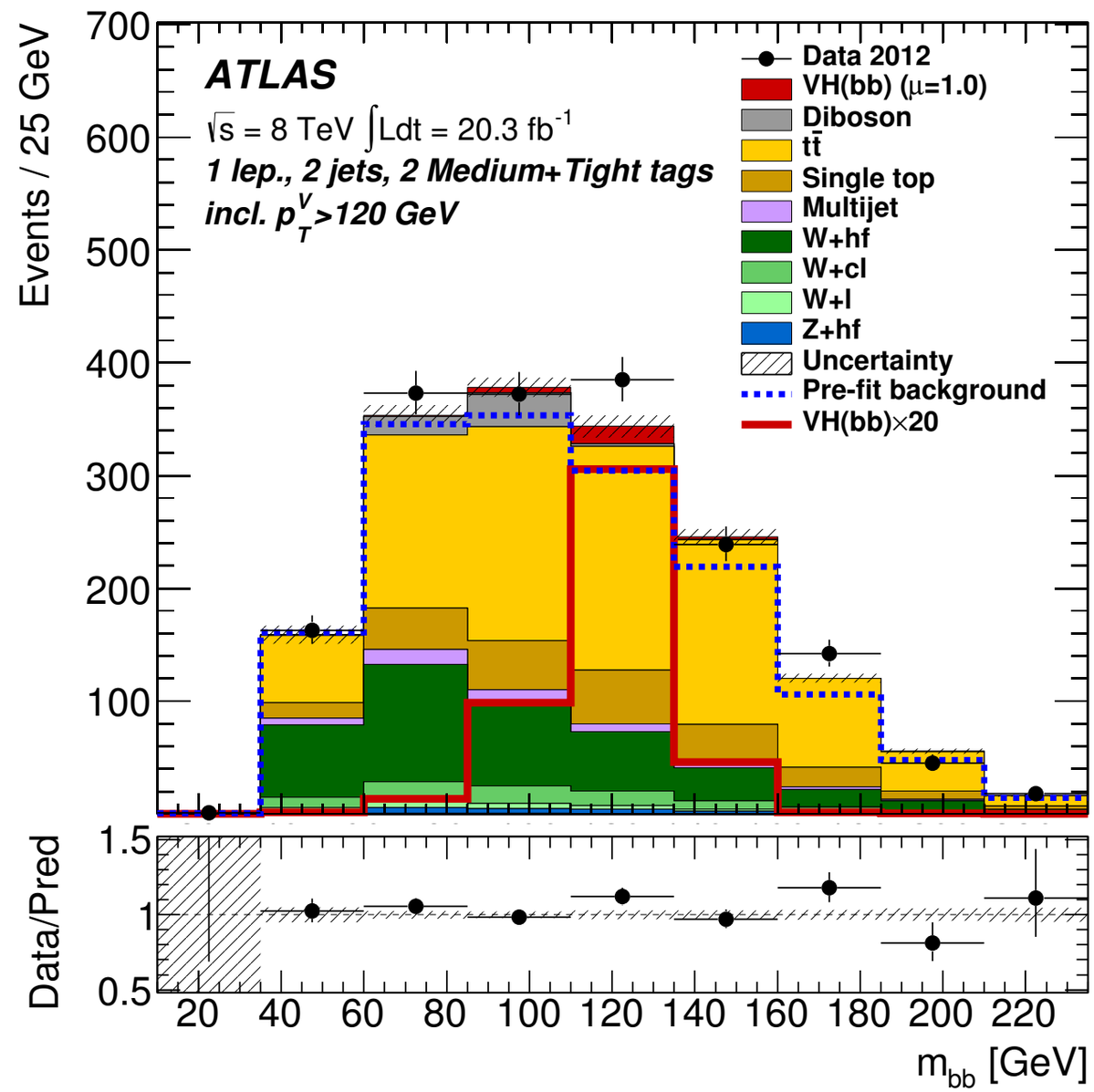


VH→bblν(ll)(νν)

ATLAS: JHEP01(2015)069
CMS: PRD 89 (2014) 012003

VH➛bblν(ll)(νν)

- Challenging measurement with many signal regions & complex backgrounds



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VH➛bblν(ll)(νν)

- Challenging measurement with many signal regions & complex backgrounds
- Theory systematics dominate over experimental uncertainties

Source of uncertainty		σ_μ
Total		0.41
Statistical		0.32
Systematic		0.26
Experimental uncertainties		
Jets		0.08
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.03
Leptons		0.01
b-tagging$^{(*)}$	b-jets	0.07
	c-jets	0.04
	light jets	0.04
Luminosity		0.03
Theoretical and modelling uncertainties		
Signal		0.07
Floating normalisations	W+jets	0.06
	Z-jets	0.03
	$t\bar{t}$	0.04
Background modelling	W+jets	0.11
	Z-jets	0.08
	$t\bar{t}$	0.05
Single-top		0.04
Diboson		0.02
Multijet		0.06

ATLAS: JHEP01(2015)069
CMS: PRD 89 (2014) 012003

VH➛bblν(ll)(νν)

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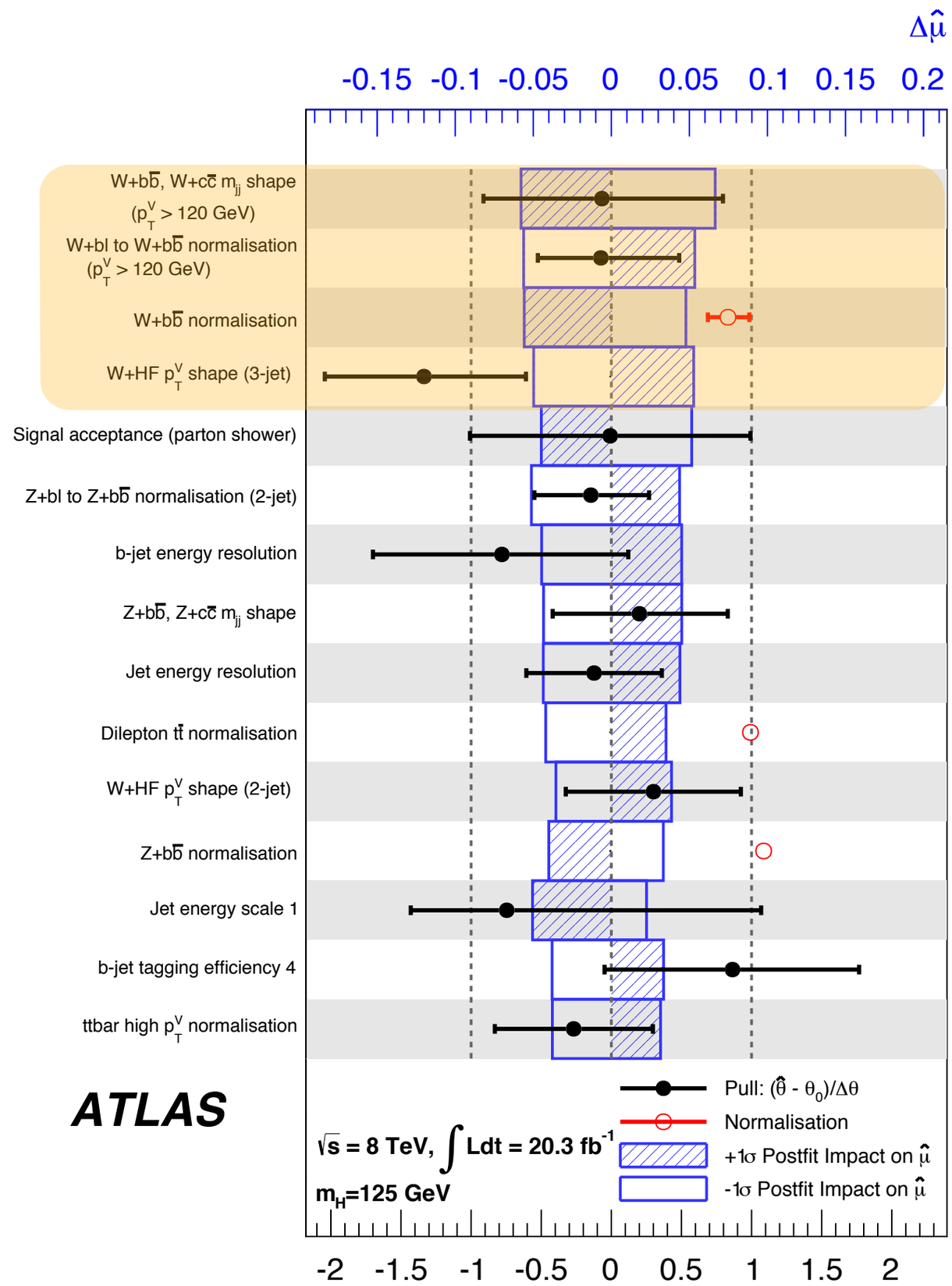
- Theory systematics dominate over experimental uncertainties
- **Largest uncertainty: V + hf**



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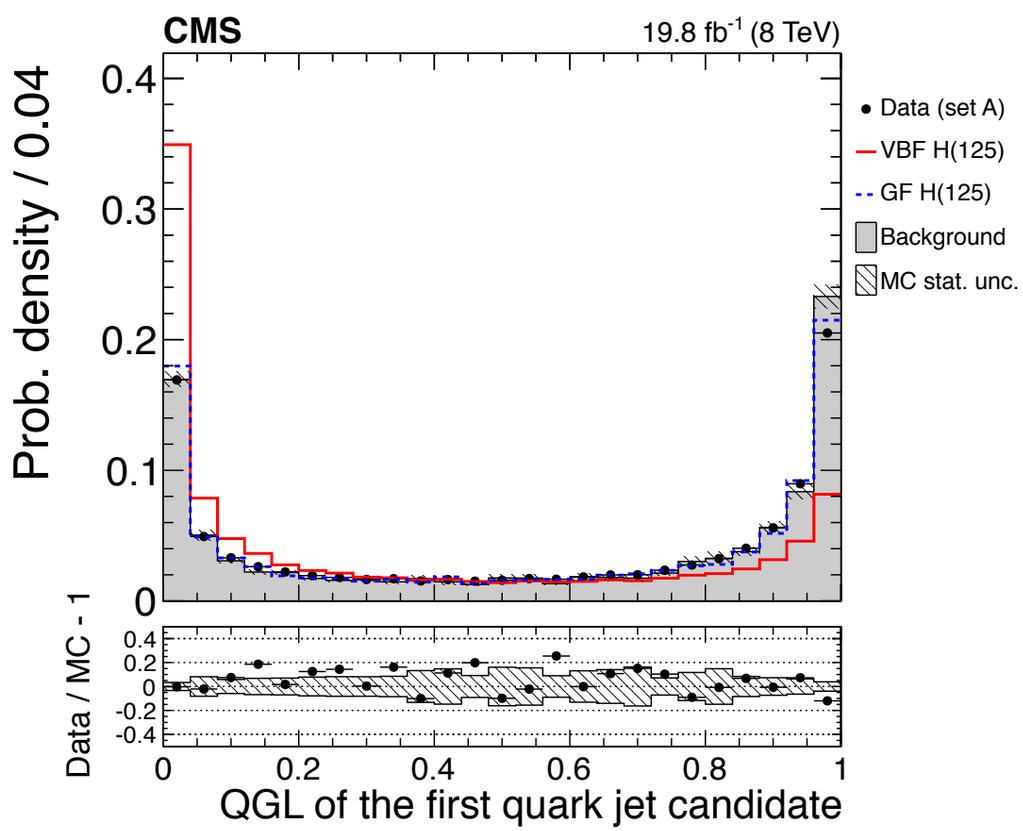
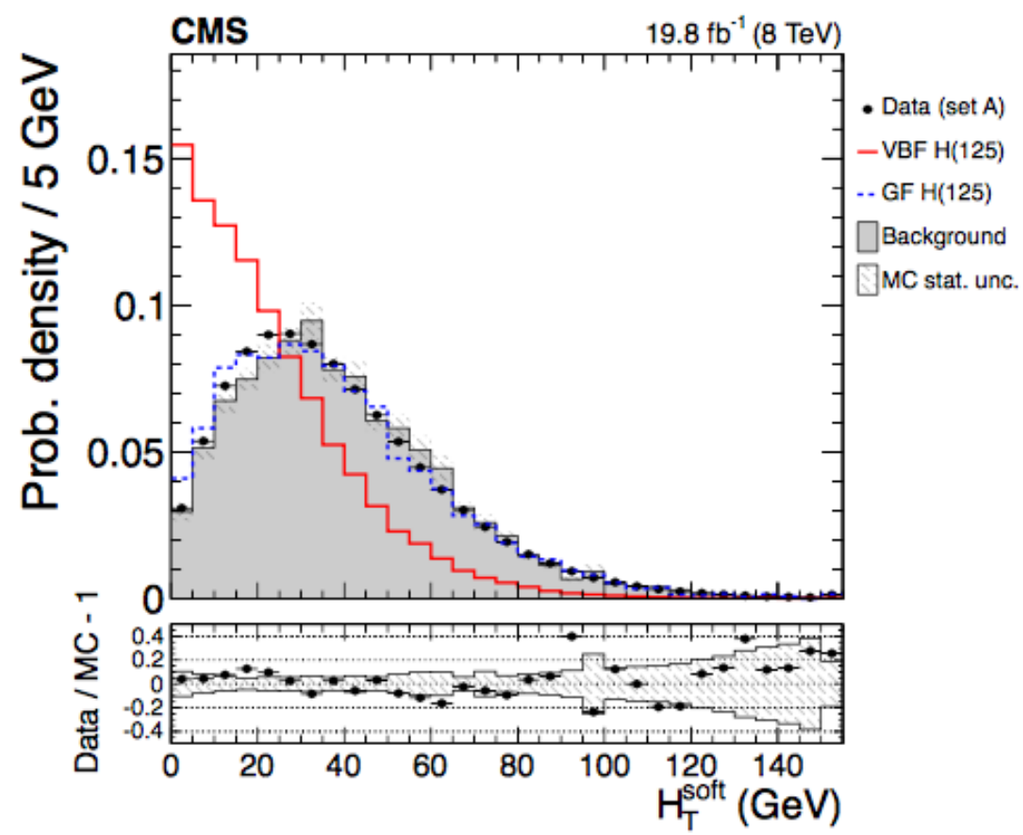
VBF H➛bb

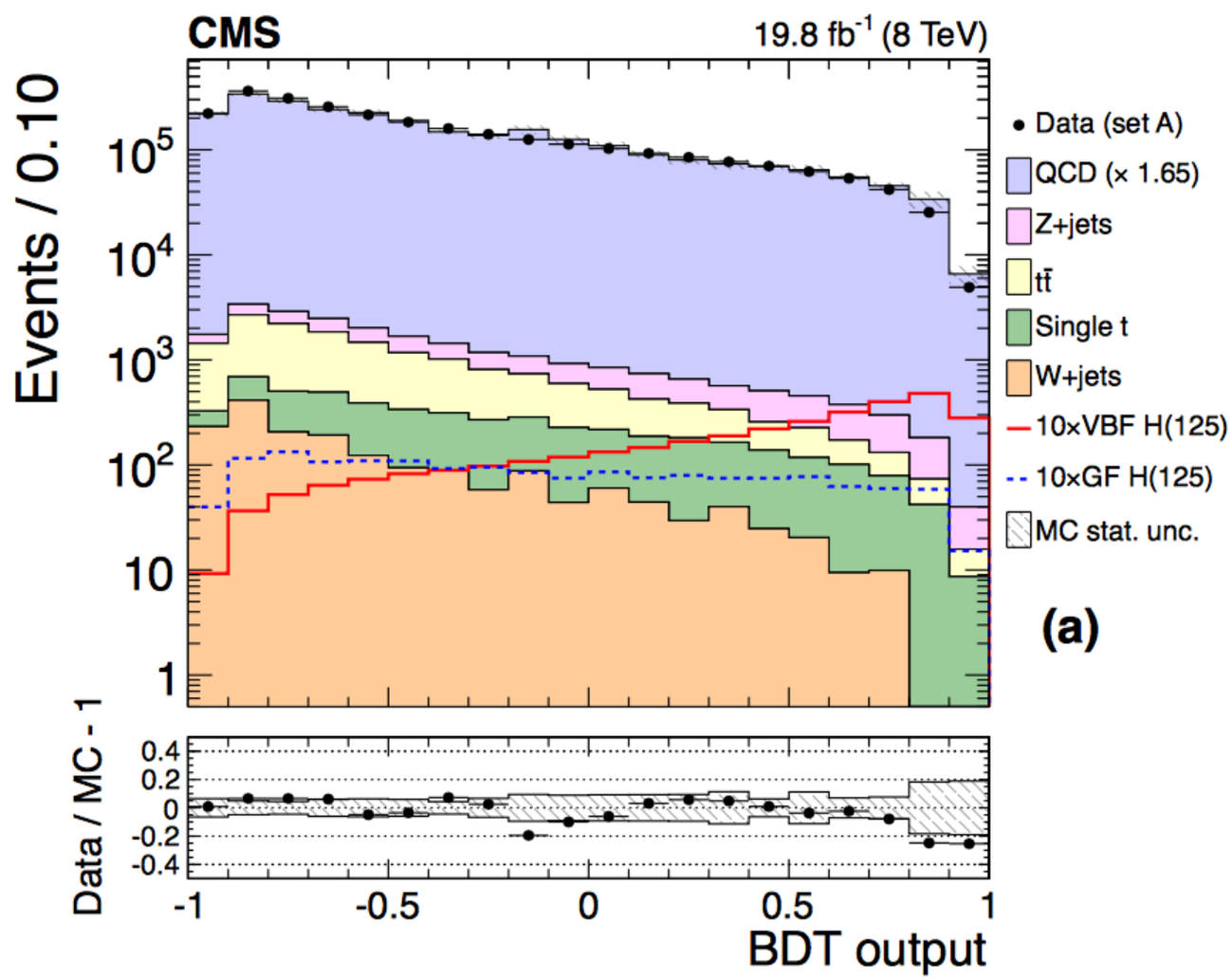
- New CMS measurement exploits lower energy QCD phenomena to enhance all hadronic final state
  - Quark-gluon discrimination (RMSs of jet constituents in η-Φ,jet asymmetry pull,jet particle multiplicity, max energy fraction carried by consitutent)
  - Scalar sum of soft hadronic activity built from soft track-jets
- Relies on good modeling of fragmentation and soft QCD effects!





CMS arXiv:1506.01010

- Use QGL, soft activity (HT & $N_{softjets}$), production & decay dynamics in BDT to define signal regions: best S/B 1.7%; 50-7% ggF contamination



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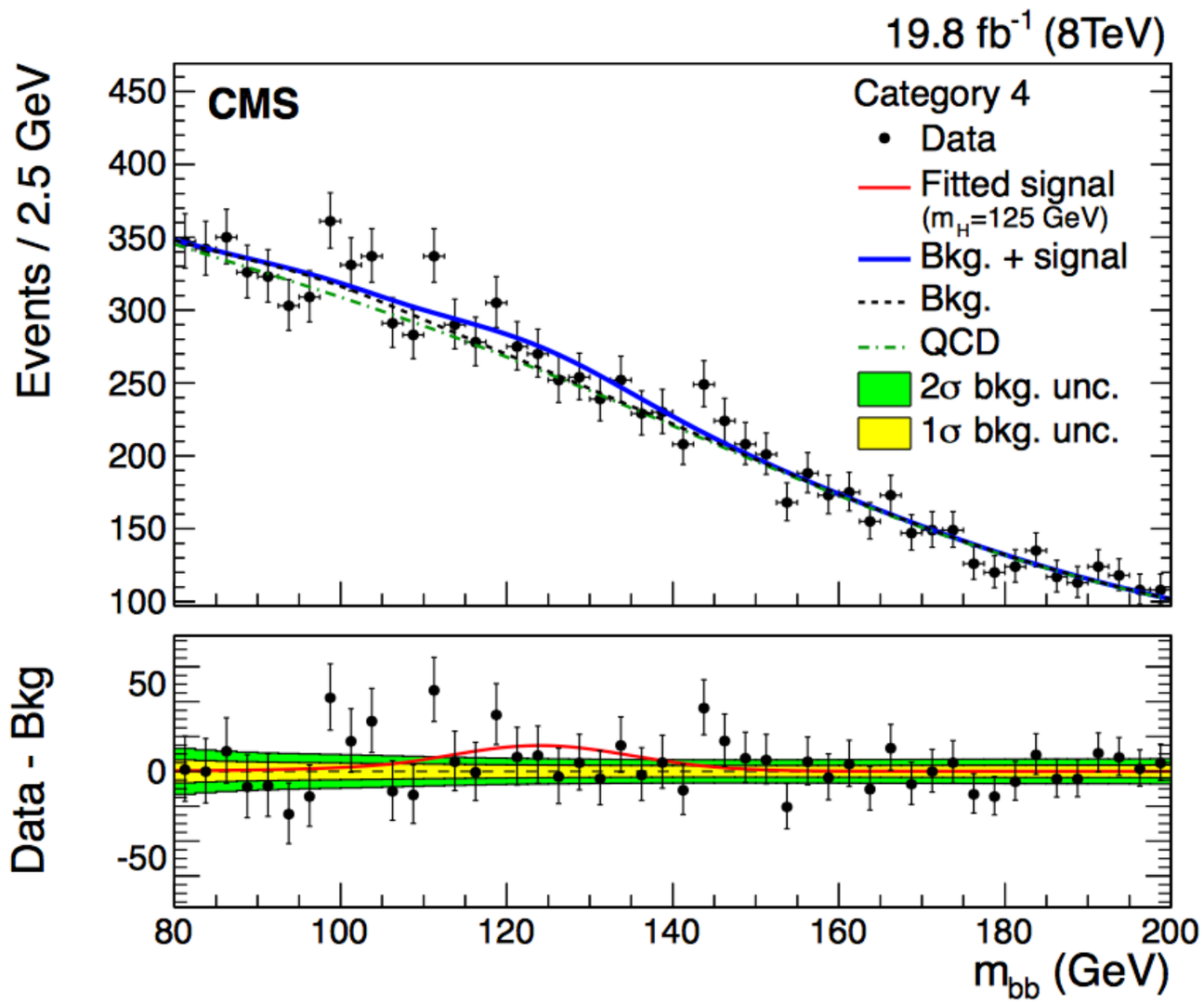
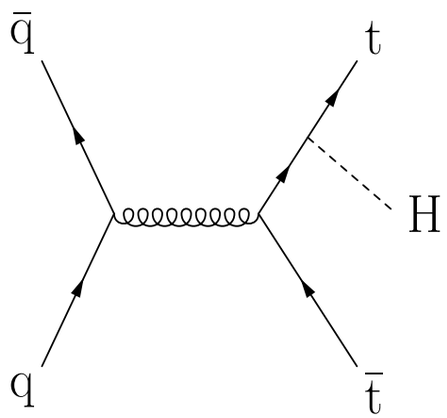
- Fit M_{bb} spectra to extract signal: $\mu = 2.8^{+1.6}_{-1.4}$

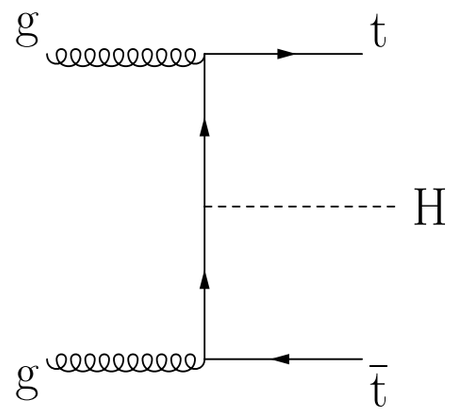


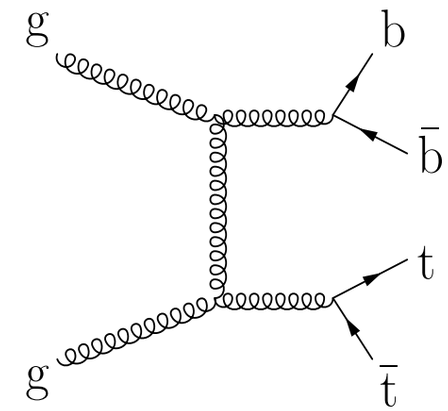
Background uncertainties		
QCD shape parameters	determined by the fit	
QCD bkg. normalization	determined by the fit	
Top quark bkg. normalization	30%	
Z/W+jets bkg. normalization	30%	
Uncertainties affecting the signal	**VBF signal**	**GF signal**
JES (signal shape)	2%	
JER (signal shape)	10%	
Integrated luminosity	2.6%	
Branching fraction ($H \to b\bar{b}$)	2.4–4.3%	
JES (acceptance)	6–10%	4–12%
JER (acceptance)	1–4%	1–9%
b-jet tagging	3–9%	3–10%
Quark/gluon-jet tagging	1–3%	1–3%
Trigger	1–6%	5–20%
Theory uncertainties	**VBF signal**	**GF signal**
UE & PS	2–7%	10–45%
Scale variation (global)	0.2%	7.7–8.1%
Scale variation (categories)	1–5%	1–5%
PDF (global)	2.8%	7.5%
PDF (categories)	1.5–3%	3.5–5%

CMS: arXiv:1506.01010

TOP COUPLING







- Measurement of ttH allows direct access to top yukawa coupling
- Busy final state:
  - 4-6 jets, 1-2 leptons, missing energy from t & H decay
- Most dominant backgrounds include QCD production of multiple heavy flavor quarks (ttbb, ttb,ttcc)
  - Many scales involved for signal & backgrounds!
- Analyses use multivariate and matrix-element discriminants for highest sensitivity

CMS ANALYSIS EXAMPLE

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- Test two sets of hypotheses with event discriminants:
  - ttH vs QCD tt+bb (kinematics & dynamics)
  - tt+lf vs. tt+hf (b-tagging information)

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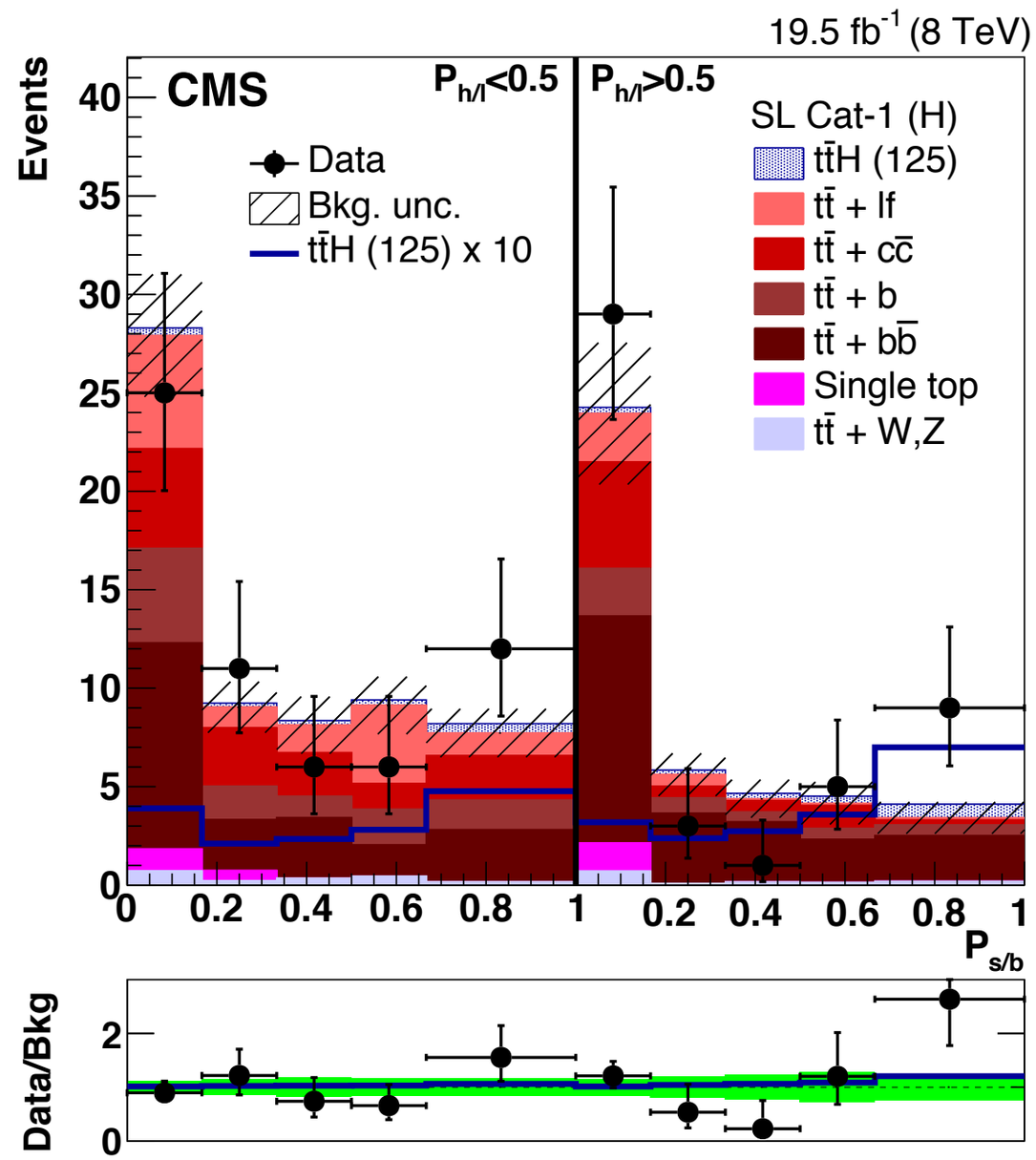
- Test two sets of hypotheses with event discriminants:
  - ttH vs QCD tt+bb (kinematics & dynamics)
  - tt+lf vs. tt+hf (b-tagging information)
- Discriminants built from MC:
  - ttH: Pythia 6 w/NLO x-section normalization
  - tt+jet: Madgraph+Pythia normalized to NNLO + NNLL



Eur. Phys. J. C 75 (2015) 251

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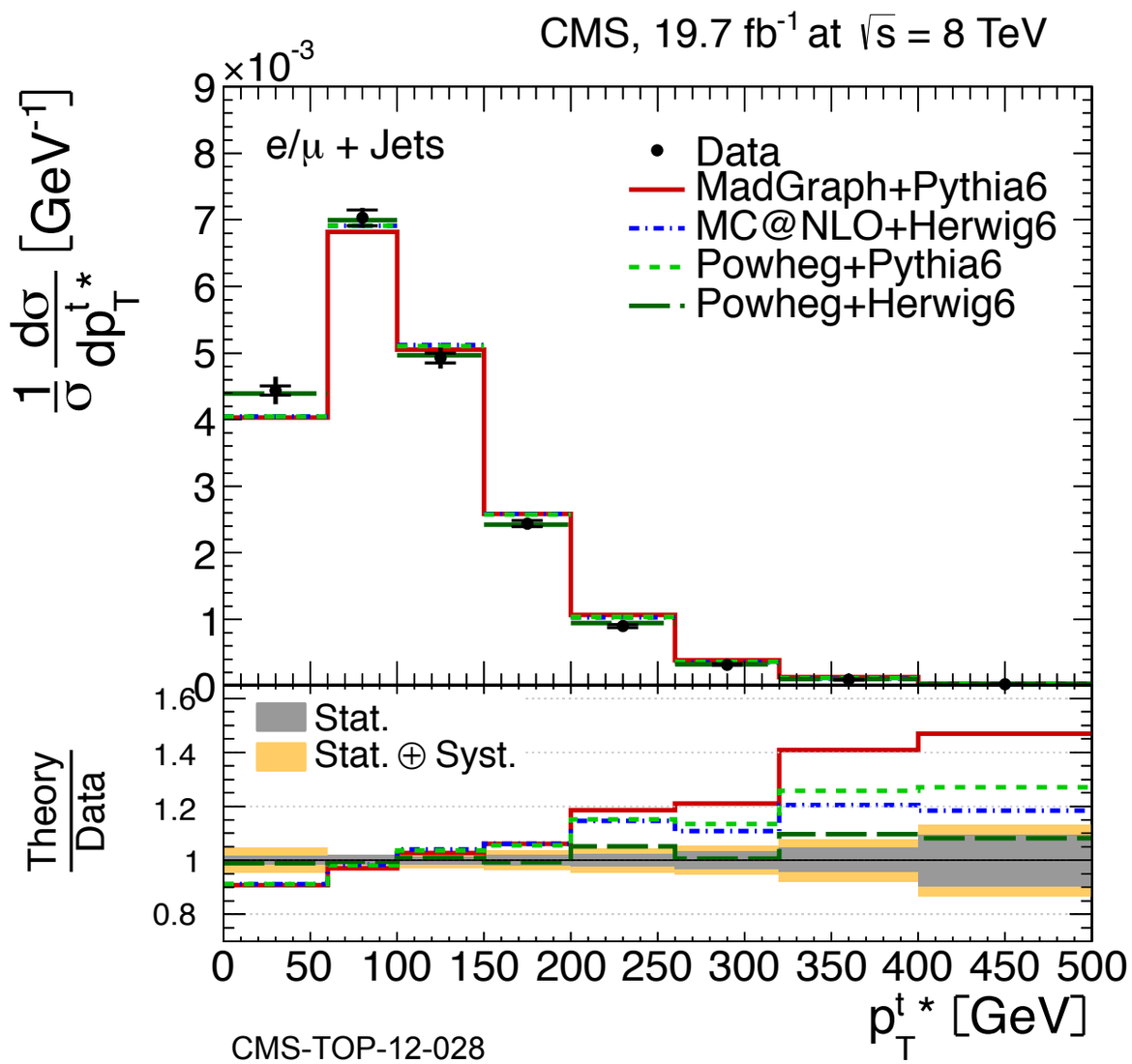

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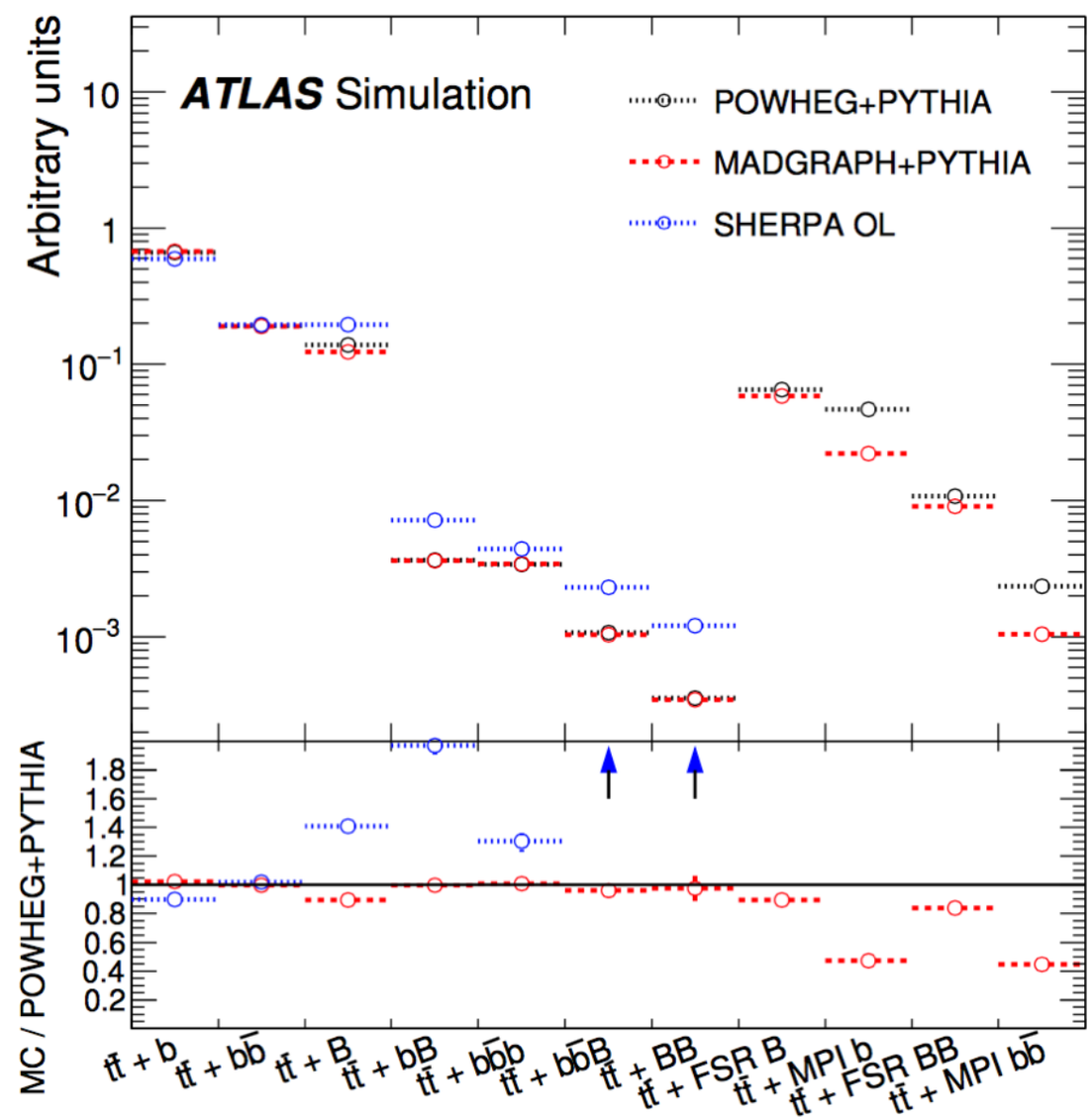

Eur. Phys. J. C (2015) 75:349

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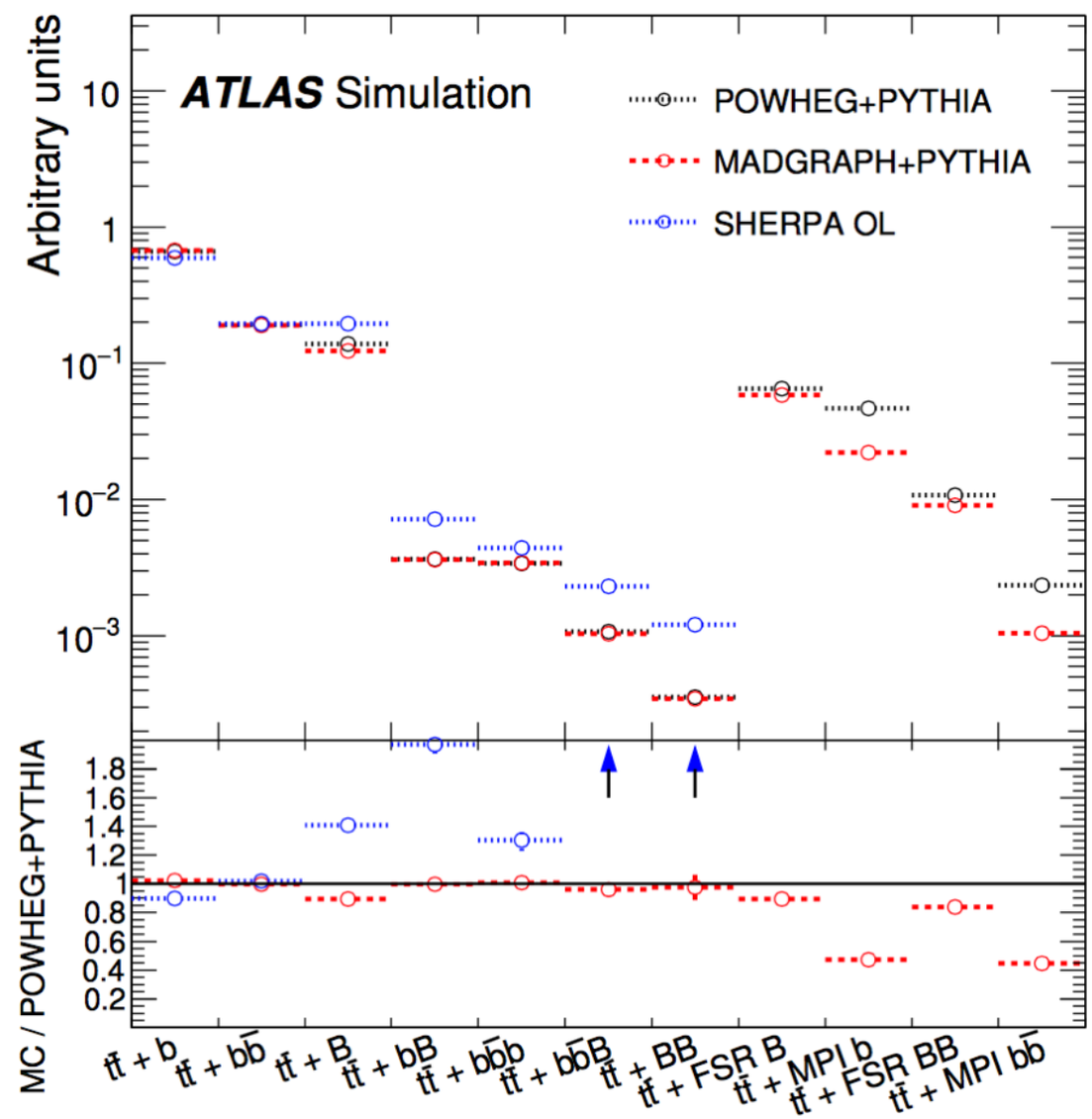
Source	Rate uncertainty	Shape	Process		
			$t\bar{t}H$	$t\bar{t}$+jets	Others
Experimental uncertainties					
Integrated luminosity	2.6%	No	✓	✓	✓
Trigger and lepton identification	2–4%	No	✓	✓	✓
JES	4–13%	Yes	✓	✓	✓
JER	0.5–2%	Yes	✓	✓	✓
b tagging	2–17%	Yes	✓	✓	✓
Theoretical uncertainties					
Top p_T modelling	3–8%	Yes		✓	
μ_R/μ_F variations	2–25%	Yes		✓	
$t\bar{t}+b\bar{b}$ normalisation	50%	No		✓	
$t\bar{t}+b$ normalisation	50%	No		✓	
$t\bar{t}+c\bar{c}$ normalisation	50%	No		✓	
Signal cross section	7%	No	✓		
Background cross sections	2–20%	No		✓	✓
PDF	3–9%	No	✓	✓	✓
Statistical uncertainty (bin-by-bin)	4–30%	Yes	✓	✓	✓

Eur. Phys. J. C 75 (2015)



Eur. Phys. J. C (2015) 75:349

FIDUCIAL CROSS-SECTIONS

- Most precise channels (**γγ**, ZZ) give stringent tests of predictions
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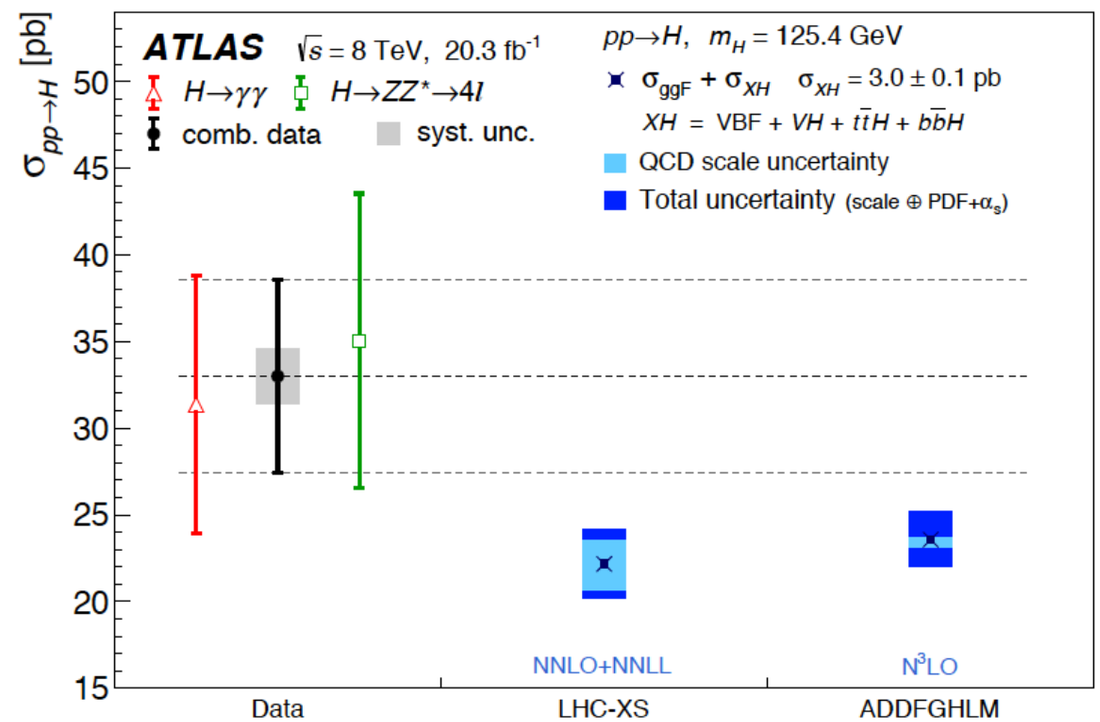

Physics Letters B 738 (2014) 234-253

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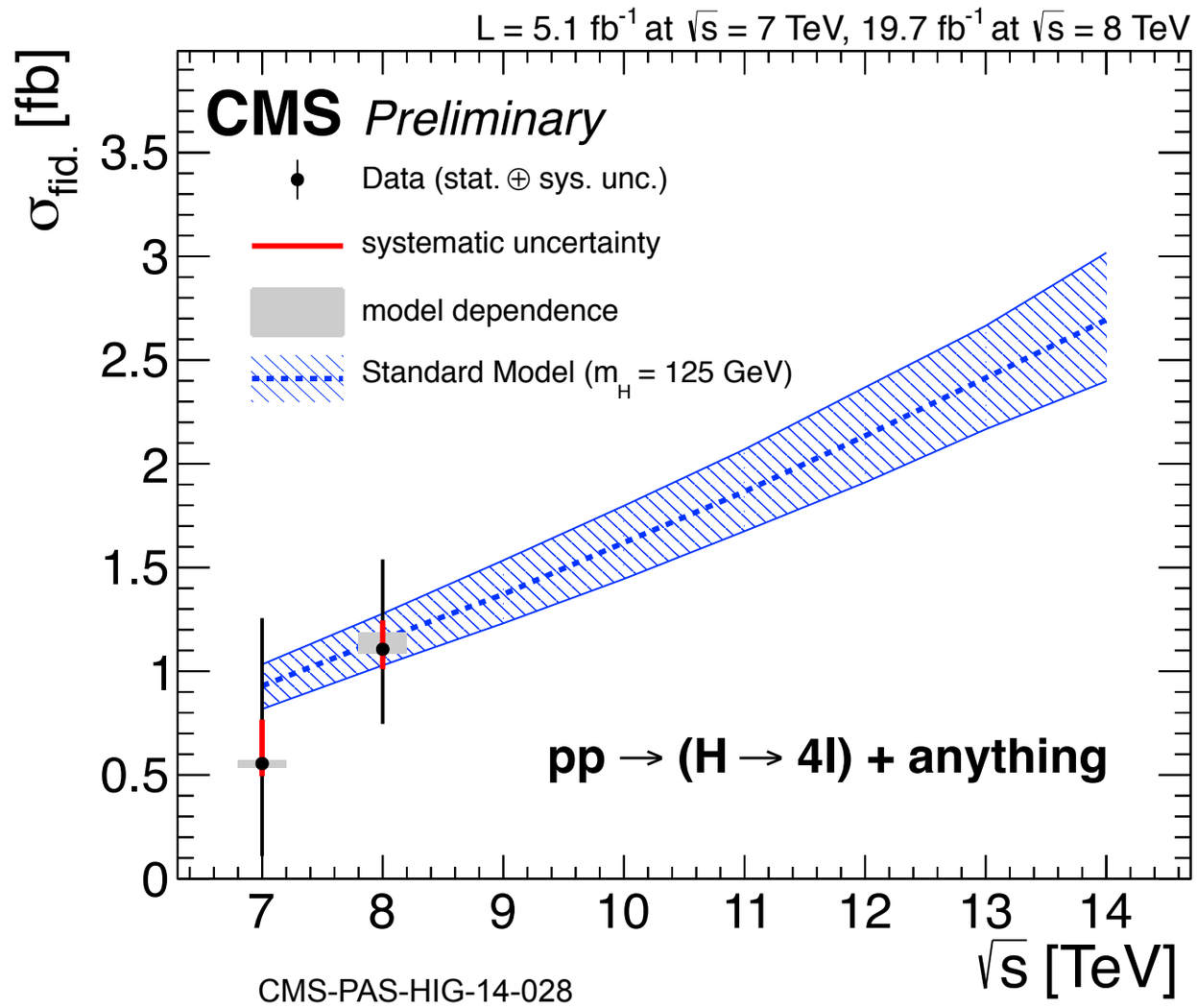
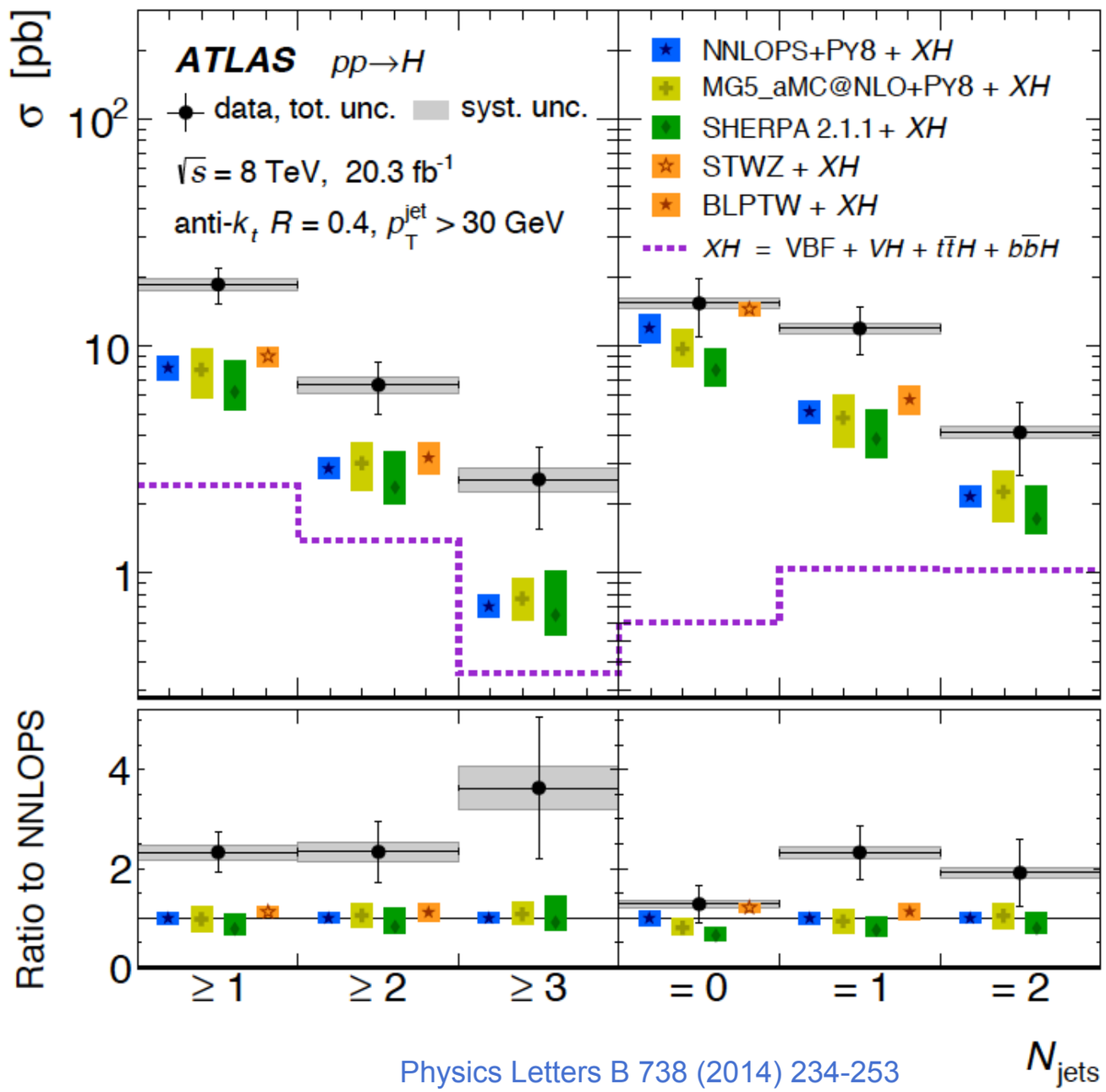


DIFFERENTIAL DISTRIBUTIONS

- Sizeable differences in H +jet rates between MCs & data
  - Important consequences for jet veto
- Data systematic uncertainties comparable theory uncertainties



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DIFFERENTIAL DISTRIBUTIONS

- Shape comparison yields harder H p_T spectrum in data
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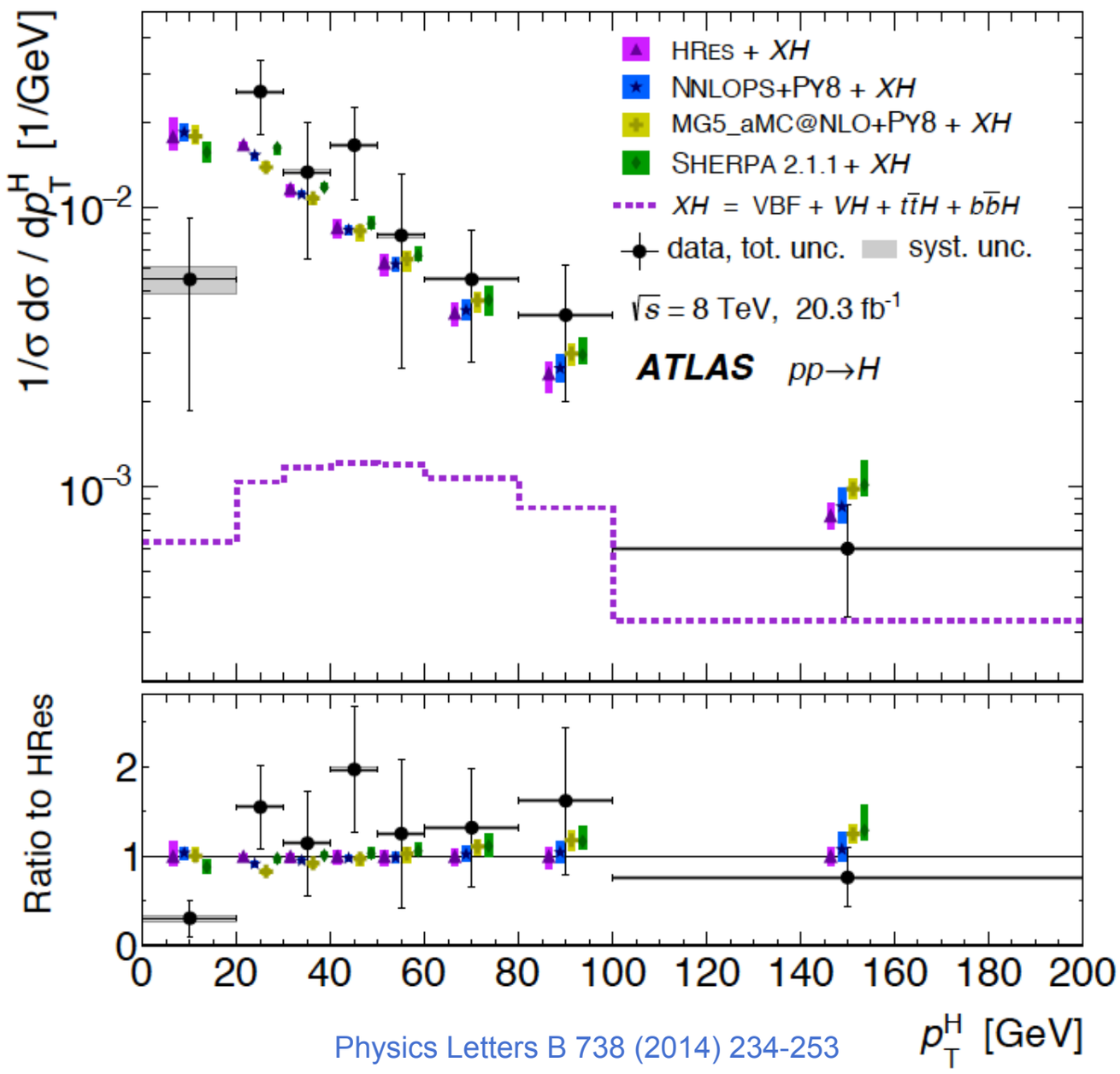

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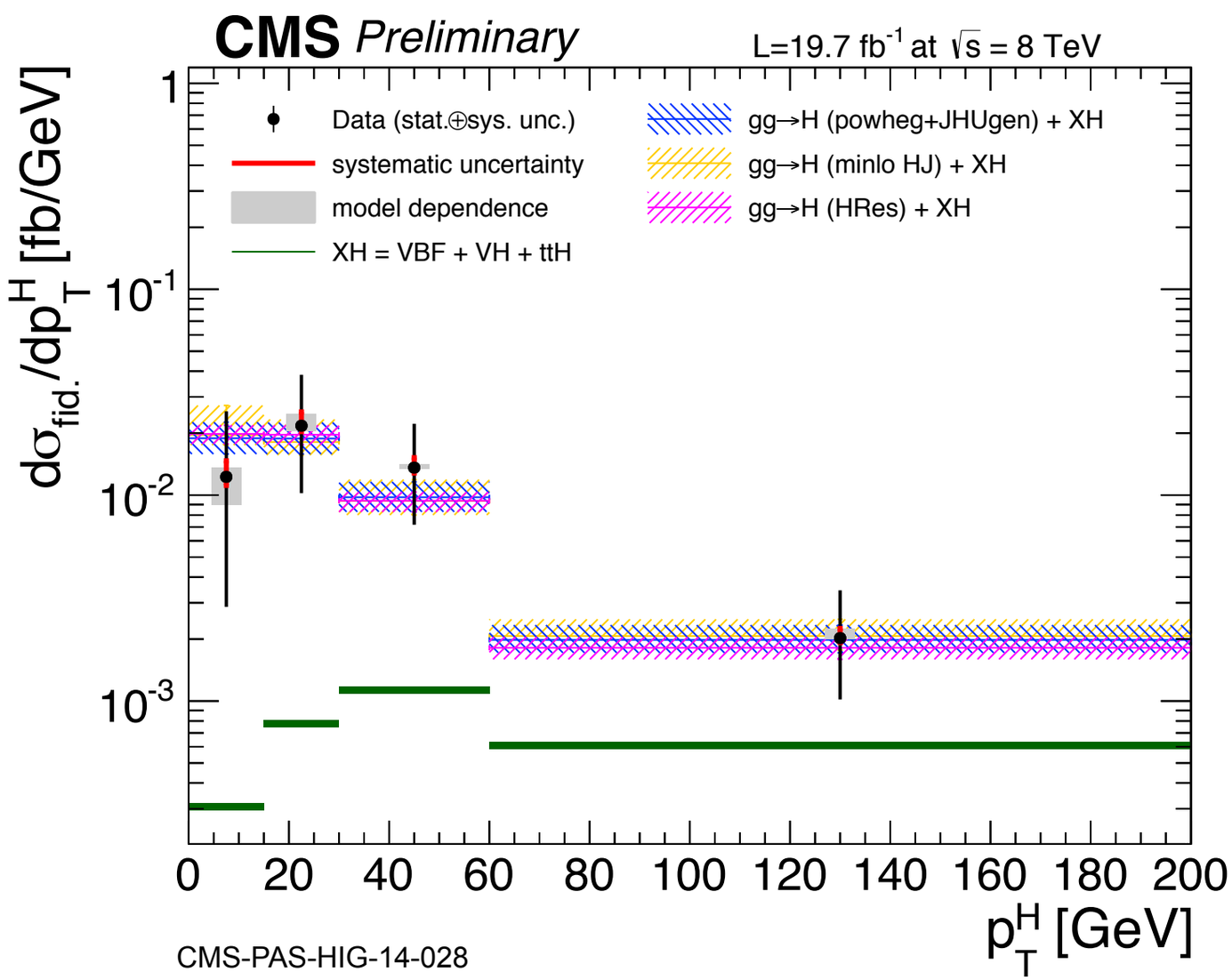
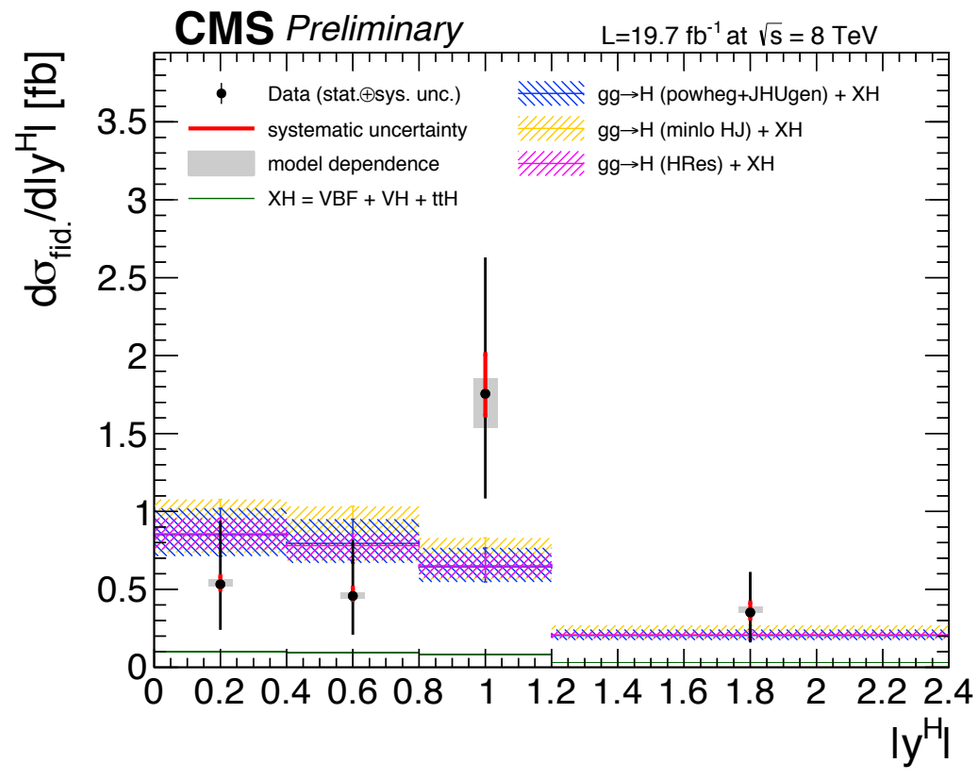
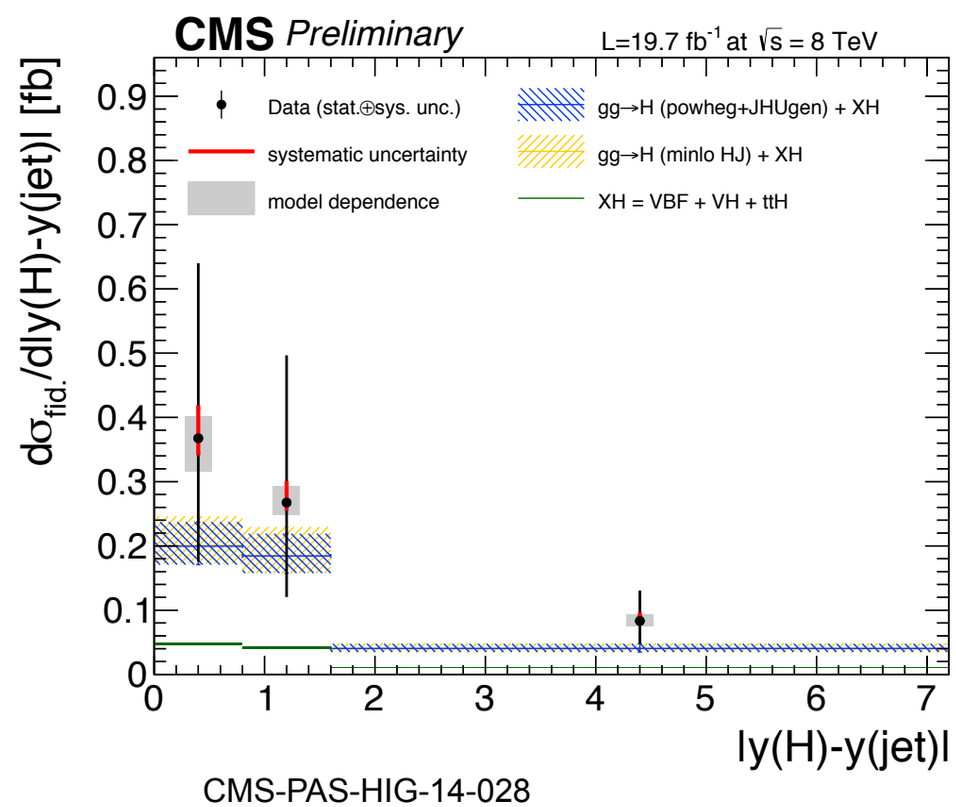


DIFFERENTIAL DISTRIBUTIONS

- Also testing rapidity distributions in inclusive and H +jet events
- Higher statistics measurements will be quite important for Runs II & III





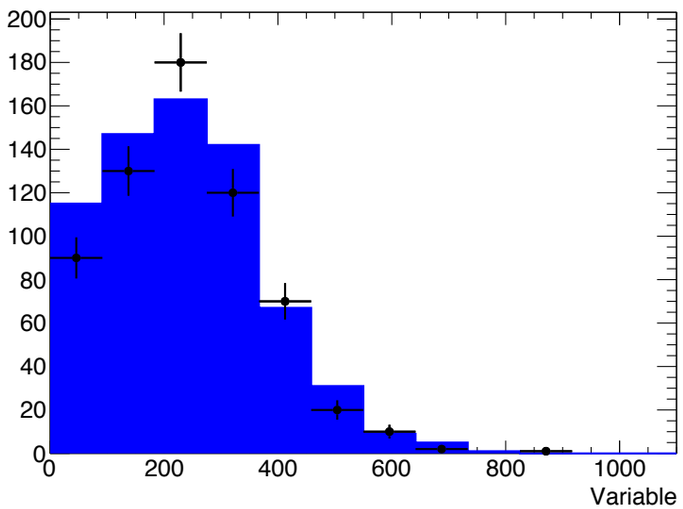
CMS-PAS-HIG-14-028

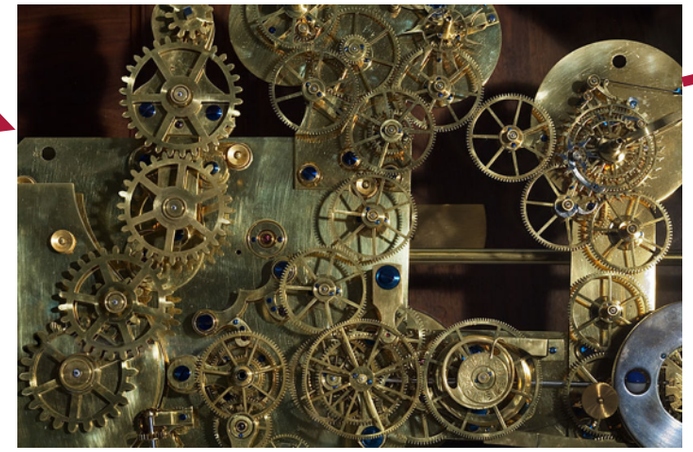
OUTLINE

- Big picture
- Higgs: Getting to know the newest member of the Standard Model
- **Going beyond the Standard Model**
- New analysis techniques: getting boosted

THE BSM FORMULA

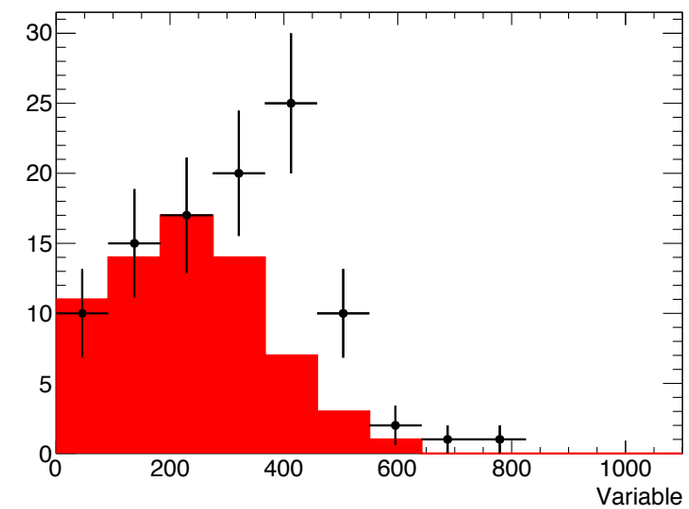
Define Control Region



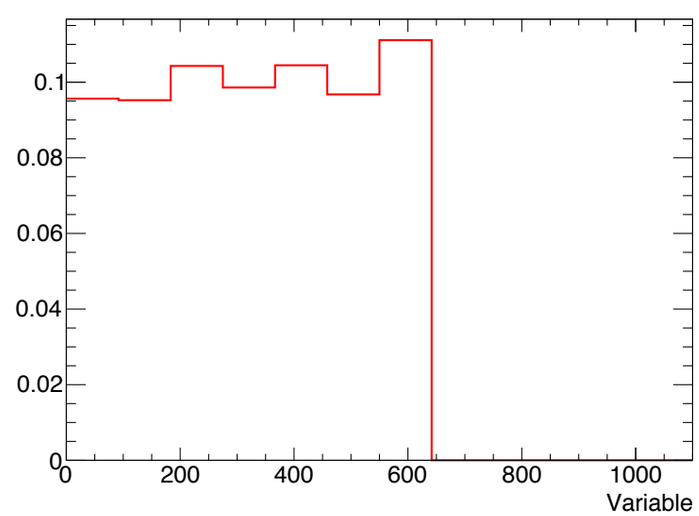


Input to fit machinery

Do simultaneous fits to signal & control regions to extract signal

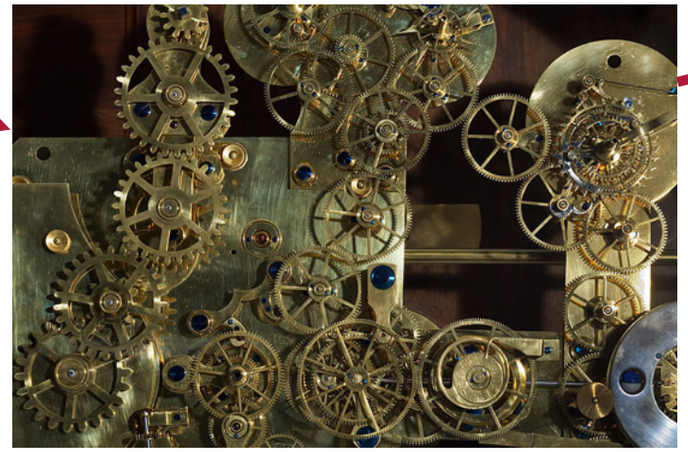


Look in Signal region



Determine transfer factor to Signal Region from MC

THE BSM FORMULA



Input to fit machinery

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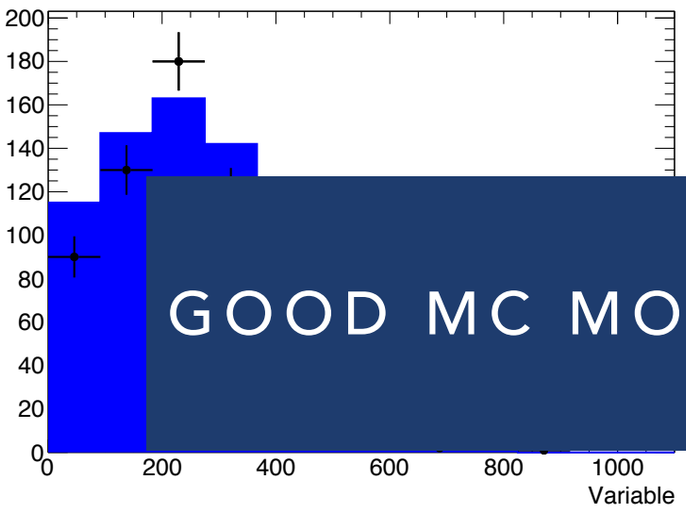

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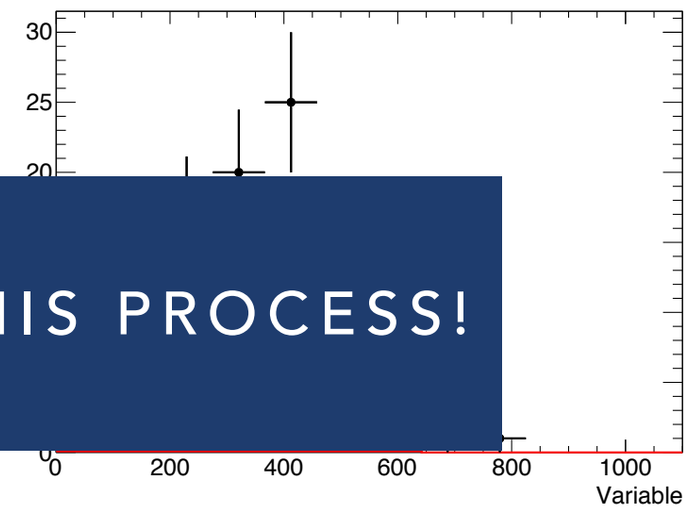
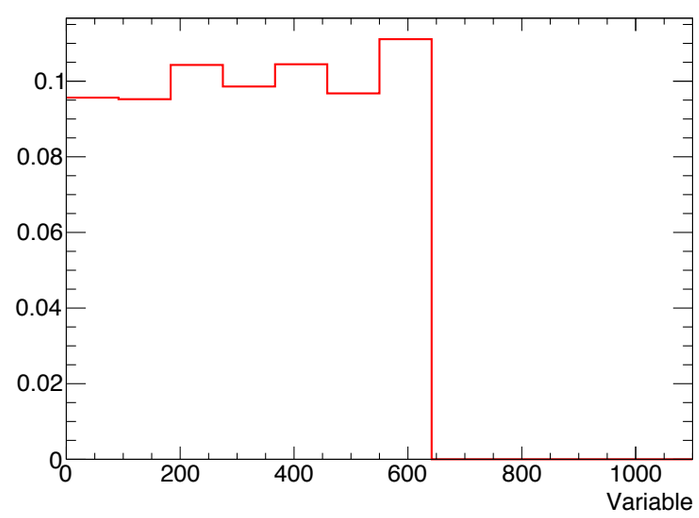


GOOD MC MODELING IS CRITICAL TO THIS PROCESS!

Look in Signal region



Determine transfer factor to Signal Region from MC

BACKGROUND STATE OF THE ART

- Most Run 1 searches are concluded, combinations in progress

arXiv.org > hep-ex > arXiv:1507.05525

High Energy Physics – Experiment

Summary of the searches for squarks and gluinos using $\sqrt{s}$ = 8 TeV pp collisions with the ATLAS experiment at the LHC

ATLAS Collaboration

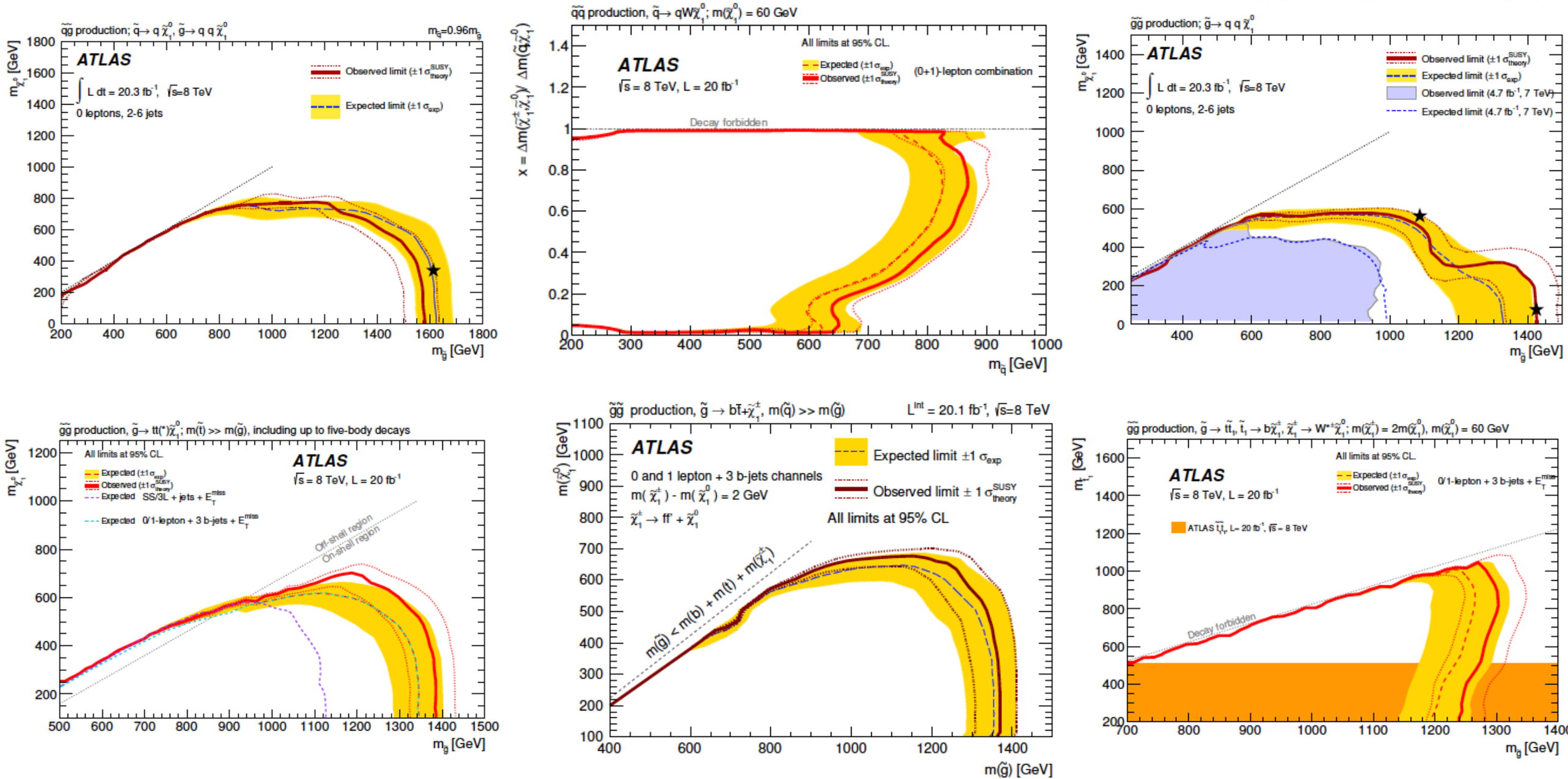
(Submitted on 20 Jul 2015)

Process	Generator	Cross-section order in α_s	Tune	PDF set
$W(\to \ell\nu)$+jets	SHERPA 1.4.1 [75]	NNLO [76]	SHERPA default	CT10 [77]
$Z/\gamma^*(\to \ell\ell)$+jets	SHERPA 1.4.1	NNLO [76]	SHERPA default	CT10
Drell–Yan ($8 < m_{\ell\ell} < 40$ GeV)	SHERPA 1.4.1	NNLO [78]	SHERPA default	CT10
$Z/\gamma^*(\to \ell\ell)$ + jets ($10 < m_{\ell\ell} < 60$ GeV)	ALPGEN 2.14 [79] + HERWIG 6.520 [82, 83] + JIMMY [84]	NNLO [78]	AUET2 [80]	CTEQ6L1 [81]
γ+jets	SHERPA 1.4.1	LO	SHERPA default	CT10
$t\bar{t}$	POWHEG-BOX 1.0 [85–87] + PYTHIA 6.426 [90]	NNLO+NNLL [88, 89]	PERUGIA2011C [91, 92]	CT10
$t\bar{t}$	SHERPA 1.4.1	NNLO+NNLL	SHERPA default	CT10
Single top				
t-channel	ACERMC 3.8 [93] + PYTHIA 6.426	NNLO+NNLL [94]	AUET2B [95]	CTEQ6L1
s-channel, Wt	MC@NLO 4.03 [96, 97] + HERWIG 6.520	NNLO+NNLL [98, 99]	AUET2B	CT10
$t\bar{t}$ +W/Z boson	MADGRAPH 5 1.3.28 [100] + PYTHIA 6.426	NLO [101–103]	AUET2B	CTEQ6L1
Dibosons WW, WZ, ZZ, $W\gamma$ and $Z\gamma$	SHERPA 1.4.1	NLO [104, 105]	SHERPA default	CT10

- Most signal samples are LO generators, cross-sections at NLO + NLL

- Can combine many (13) analyses and test against both full and simplified models
  - Typically, experimental errors slightly larger or on par with theory signal uncertainties

ATLAS: arxiv1507.05525v1



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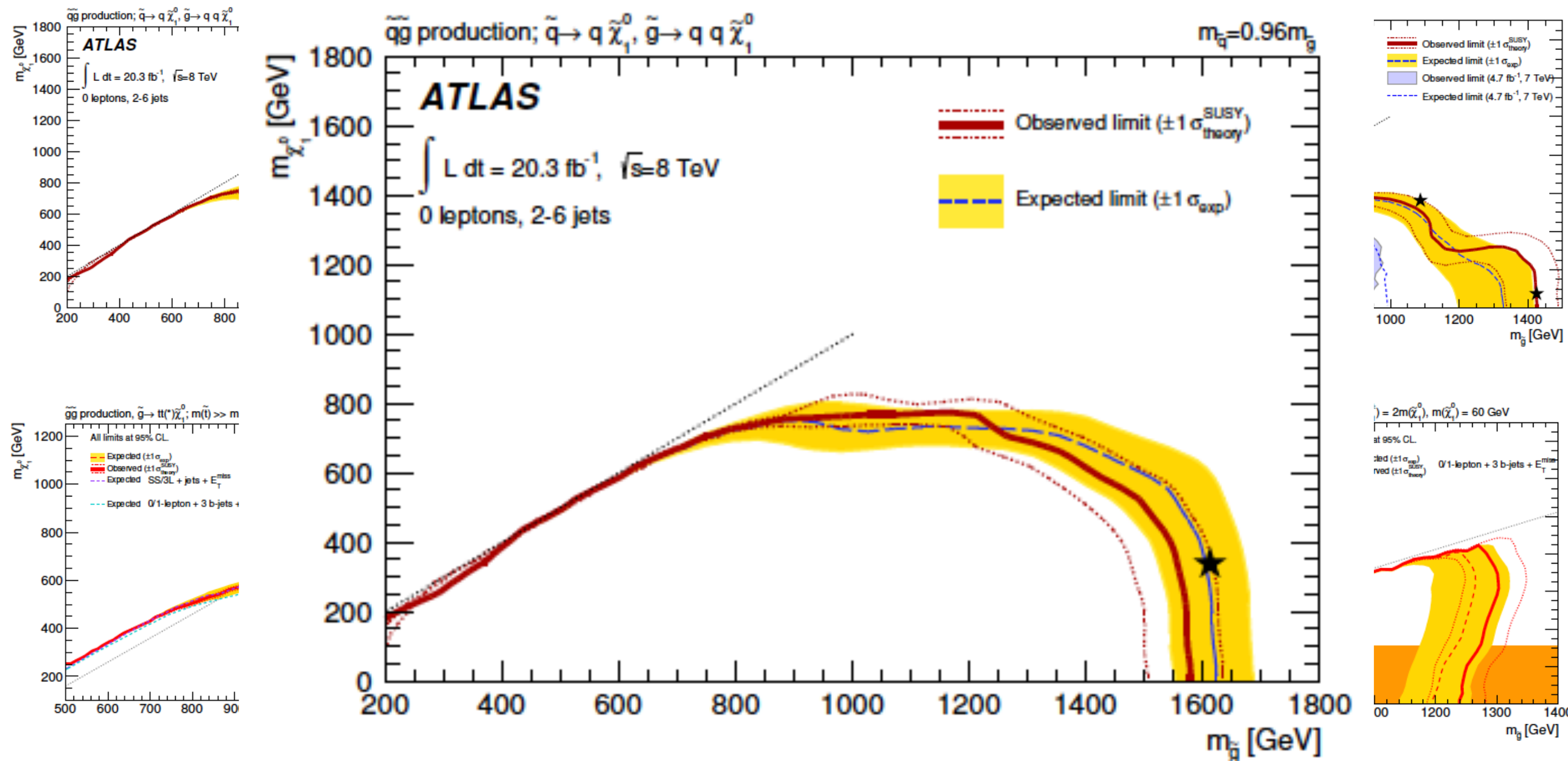
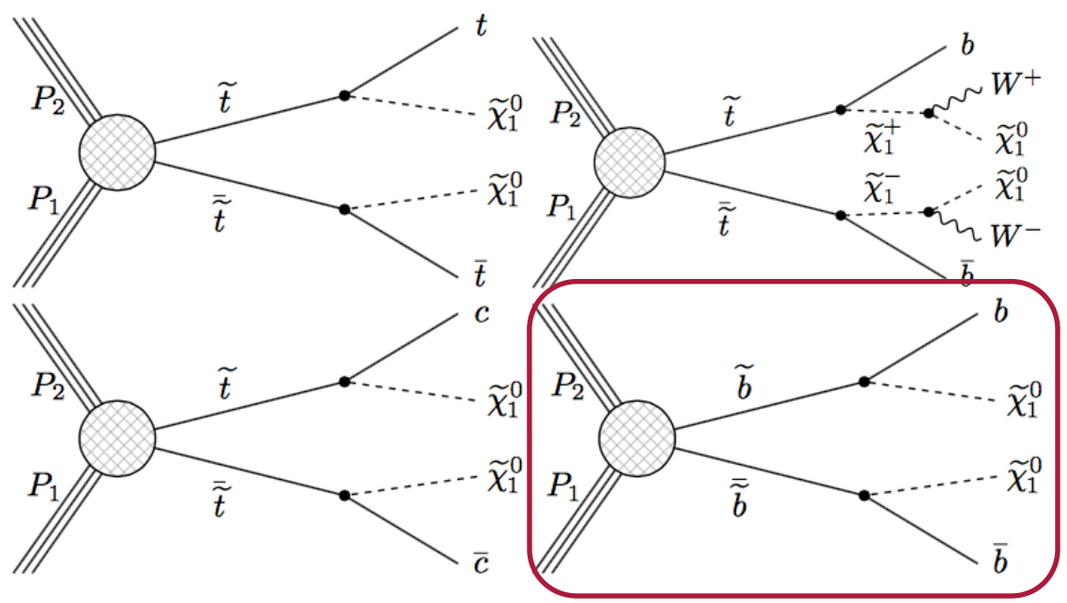


AN EXAMPLE: 3RD GEN SQUARKS IN ALL HADRONIC FINAL STATES



- Signal: 1 or 2 b-jets with large missing energy (MET)
  - Require high transverse mass (built from MET & subleading jet)
  - Signal regions binned in in contransverse mass

$$(M_{\mathrm{CT}})^2 = [E_{\mathrm{T}}^{j_1} + E_{\mathrm{T}}^{j_2}]^2 - [\vec{p}_{\mathrm{T}}^{j_1} - \vec{p}_{\mathrm{T}}^{j_2}]^2 = 2p_{\mathrm{T}}^{j_1} p_{\mathrm{T}}^{j_2} [1 + \cos\phi(j_1, j_2)]$$

  - Include ISR search region with high p_T non b-tagged jet

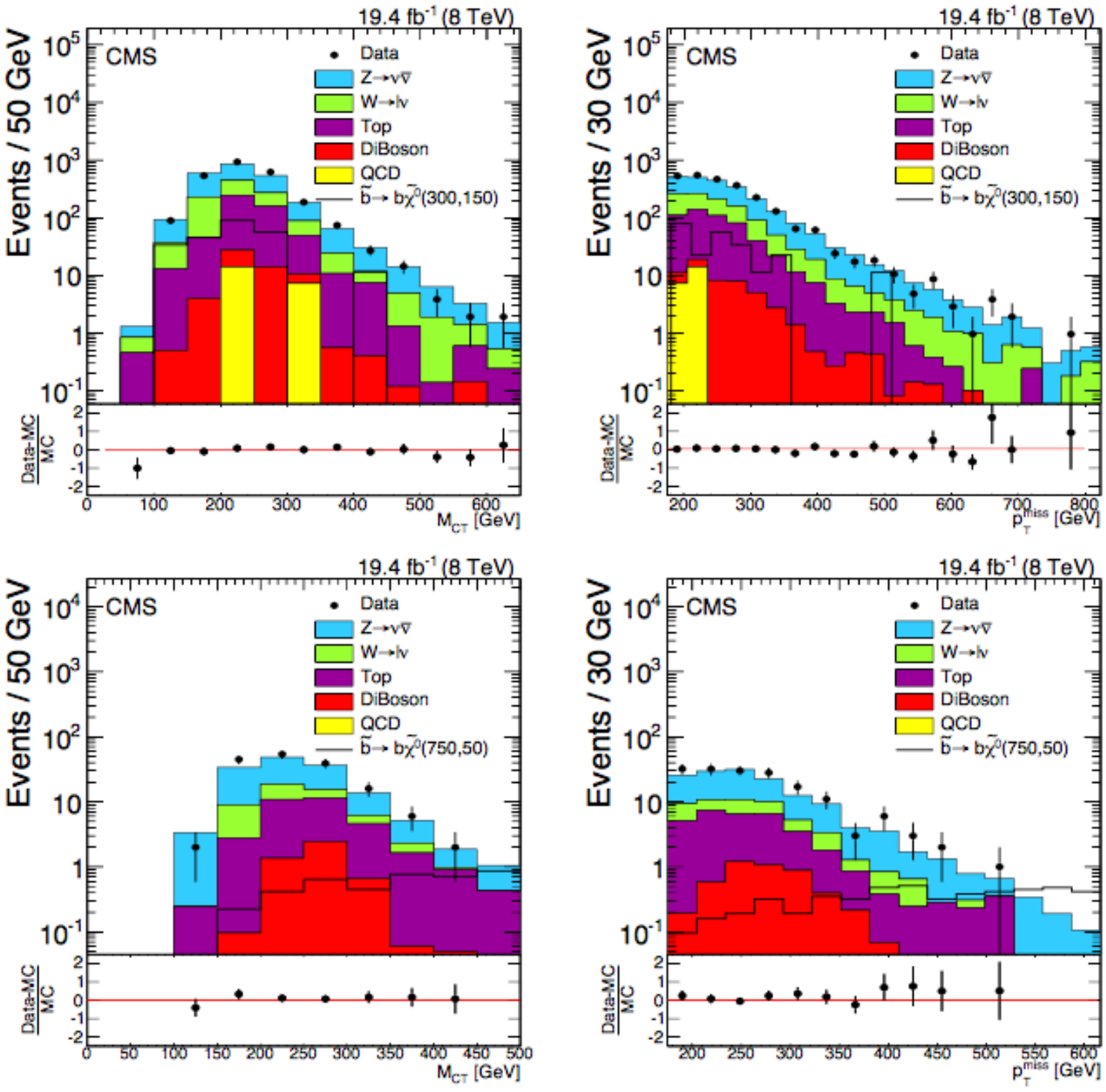
CMS 1503.08037

- Background estimation is key:
  - Dominated by Z/W+jets, ttbar
- For each signal region, define W➛lν control region

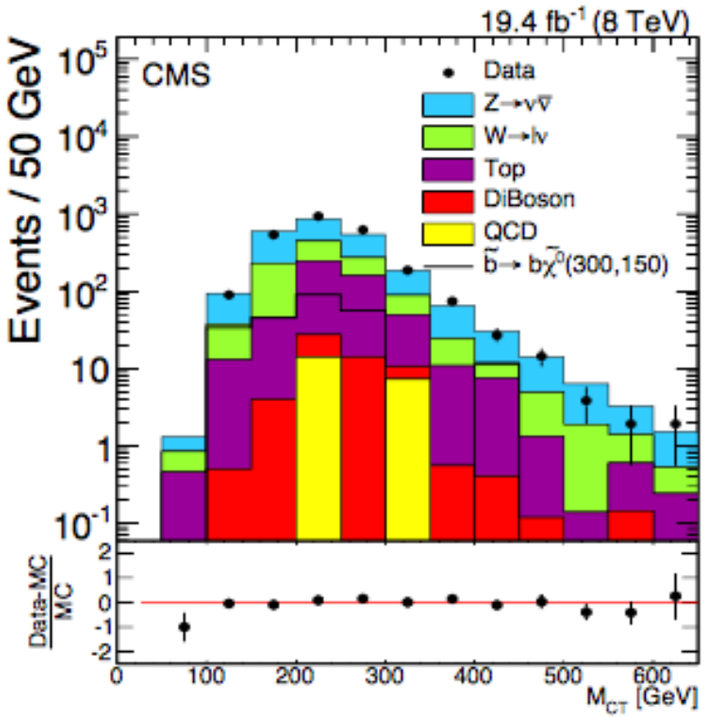
$$N_{\mathrm{SR}}^{\mathrm{pred}}(Z \to \nu\bar{\nu}; M_{\mathrm{CT}}, p_{\mathrm{T}}^{\text{non-b}}, N_{\text{b jets}}) = N_{\mathrm{CR}}^{\mathrm{obs}}(M_{\mathrm{CT}}, p_{\mathrm{T}}^{\text{non-b}})\, R_{\mathrm{SR/CR}}^{\mathrm{MC}}(M_{\mathrm{CT}}, p_{\mathrm{T}}^{\text{non-b}}, N_{\text{b jets}})$$

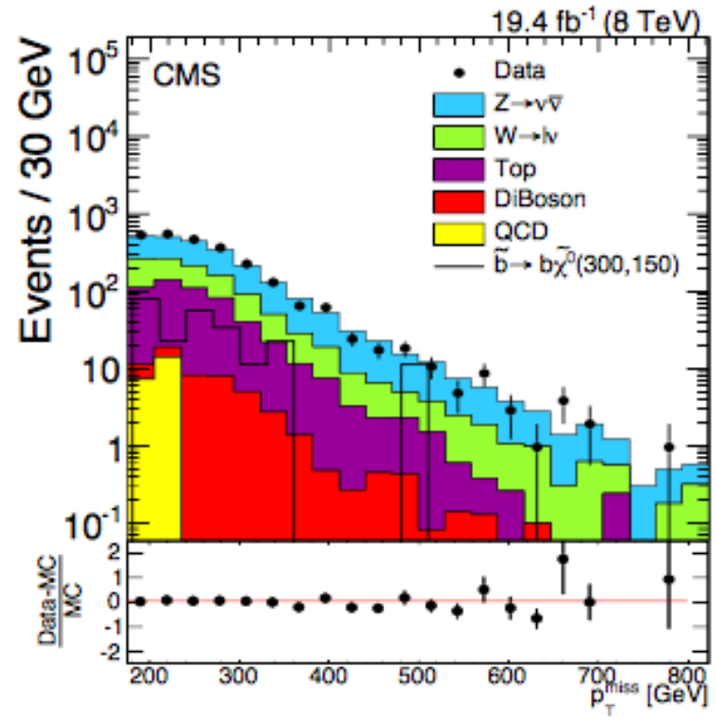
- Assess systematic on procedure by MC closure test, variations of non-W contributions, Z+hf modeling, normalization of contributions taken from MC

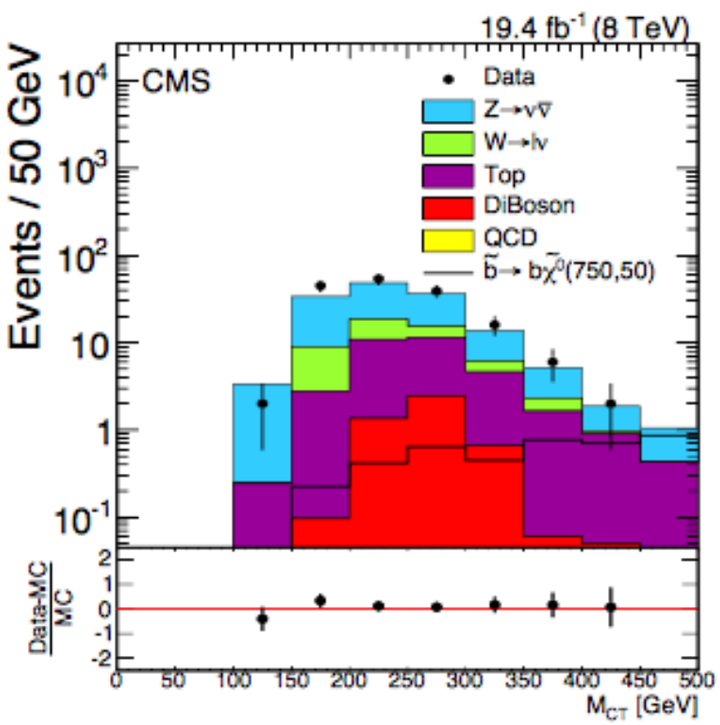
	$N_{\text{b jets}}$	M_{CT} <250	M_{CT} $\in [250, 350]$	M_{CT} $\in [350, 450]$	M_{CT} >450	ISR
$Z(\nu\bar{\nu})$ +jets	1	848±12±79	339±8±52	48.0±3.0±6.0	8.1±1.6±1.7	176±24±21
$t\bar{t}$, $W(\ell\nu)$ +jets	1	645±24±57	381±17±38	36.0±4.9±5.7	7.8±2.6±2.0	171±5±25
QCD multijets	1	25.0±9.4±5.2	16.0±7.4±2.8	0.0±1.0±1.2	negligible	3.2±0.2±4.6
Rare processes	1	18.0±9.2	18.0±8.9	1.1±0.5	0.3±0.1	5.4±2.7
Total	1	1540±100	754±68	85±10	16.0±4.1	356±41
$Z(\nu\bar{\nu})$ +jets	2	60.0±3.4±7.1	28.0±2.4±3.8	3.9±0.9±1.0	0.7±0.6±0.6	6.6±0.4±1.2
$t\bar{t}$, $W(\ell\nu)$ +jets	2	29.0±2.9±5.5	17.0±2.5±3.3	2.4±0.9±0.6	0.0±0.2±0.2	19.0±1.8±3.4
QCD multijets	2	1.9±0.7±0.4	1.2±0.8±0.2	0.0±0.1±0.1	negligible	0.4±0.1±0.7
Rare processes	2	1.8±0.9	3.4±1.7	0.1±0.1	0.1±0.1	0.4±0.4
Total	2	93±10	50.0±6.4	6.5±1.7	1.0±0.9	26.0±4.1

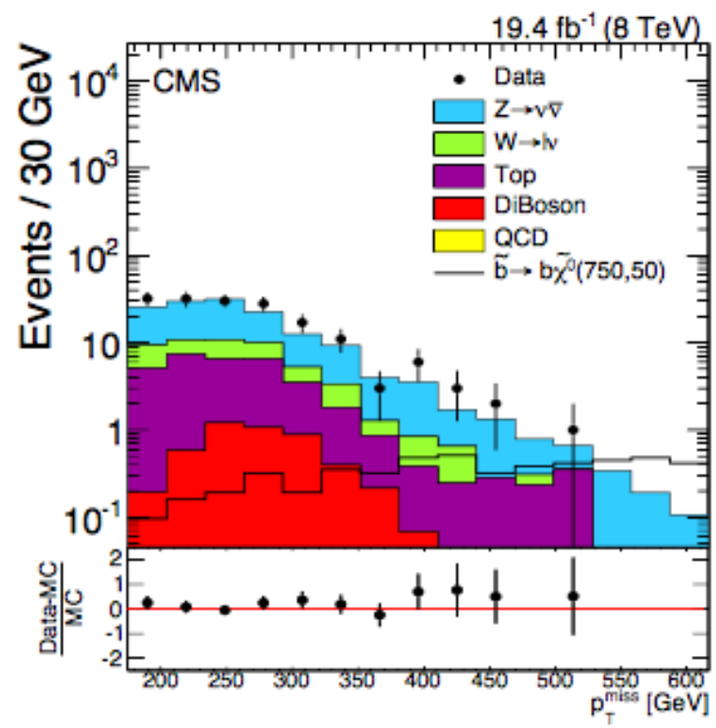


- Good data/MC agreement is found in signal regions

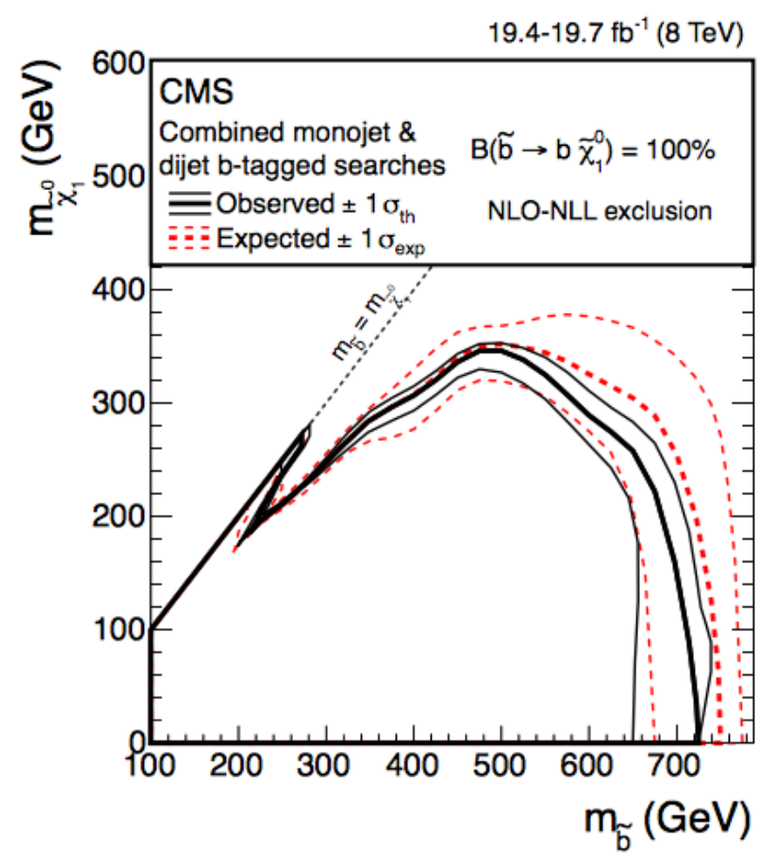








- Good data/MC agreement is found in signal regions
- Combine and set limits!

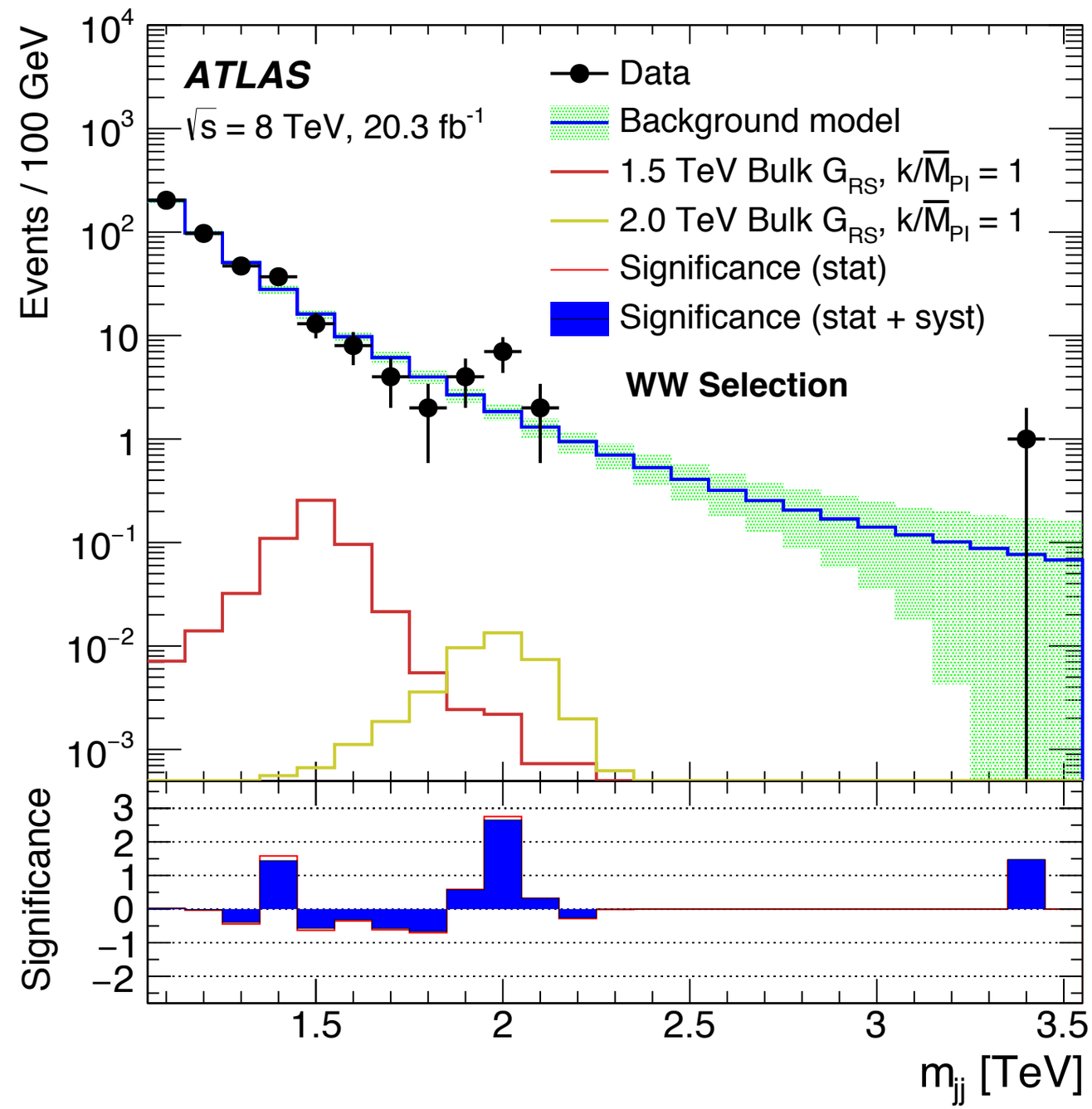


GENERIC DIBOSON RESONANCES

ATLAS: arXiv:1506.00962

GENERIC DIBOSON RESONANCES

- Hint of excess @ 2 TeV in all hadronic di-boson resonance search



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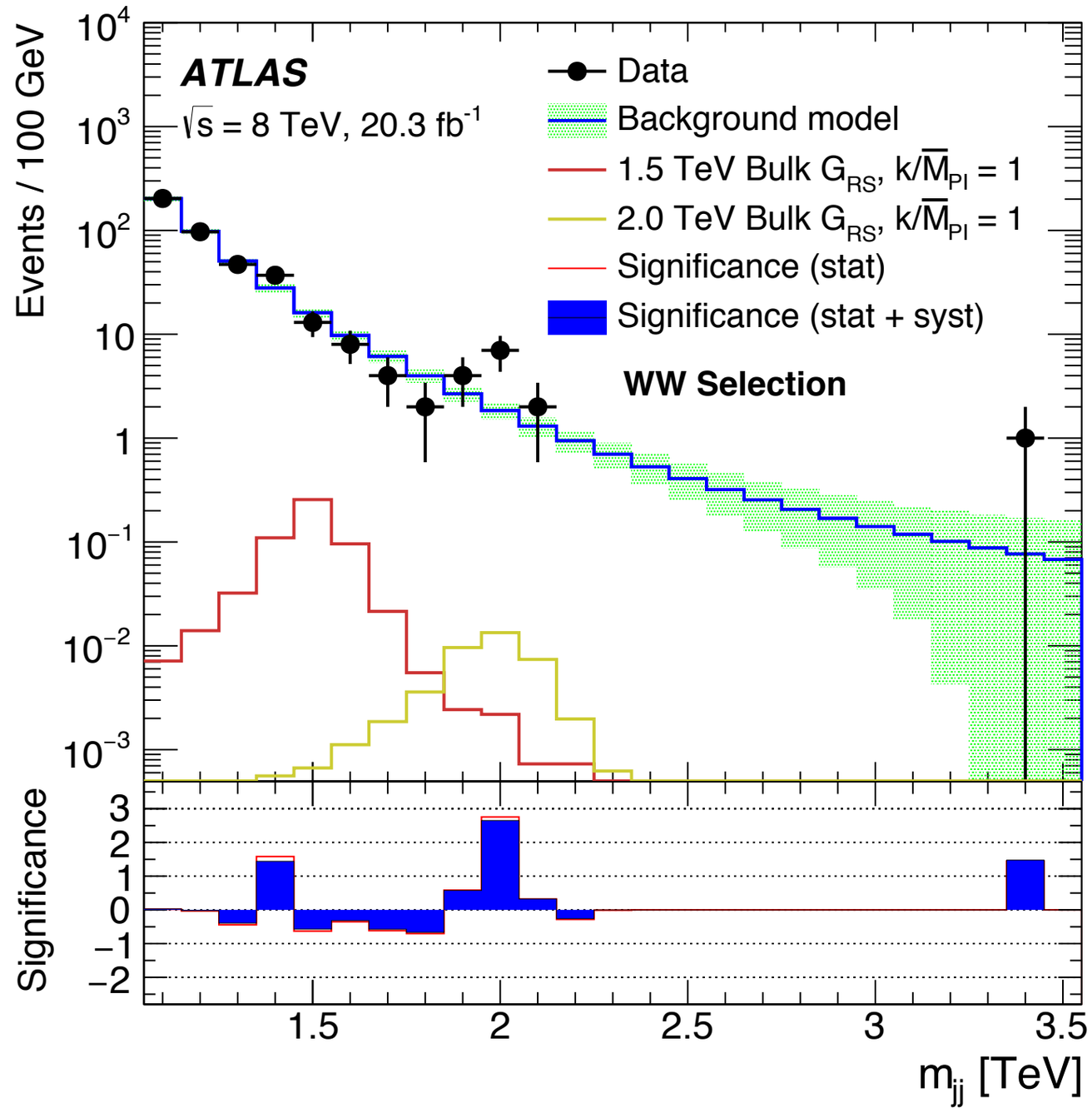
- Select events using jet mass, properties and substructure variables



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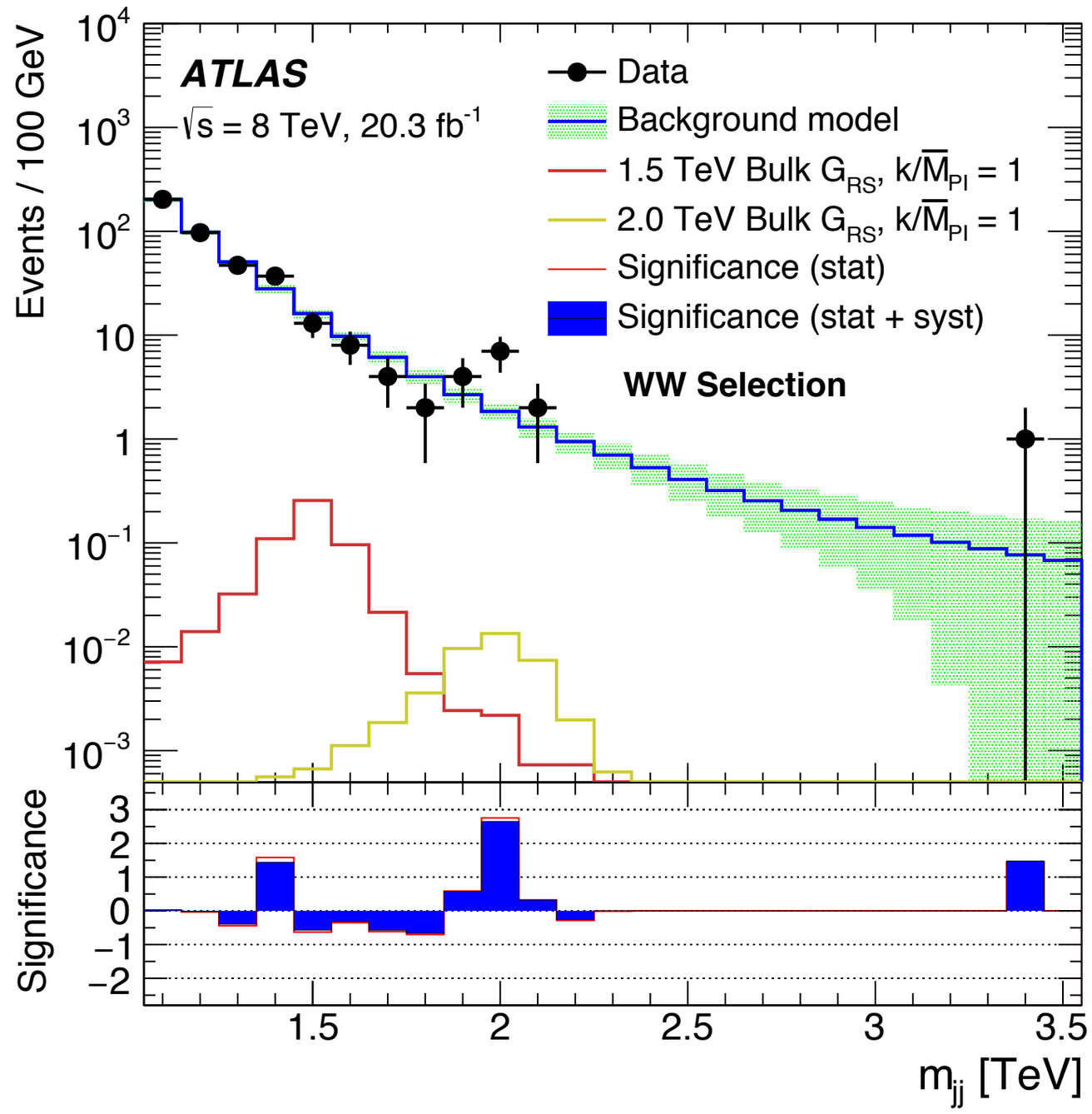

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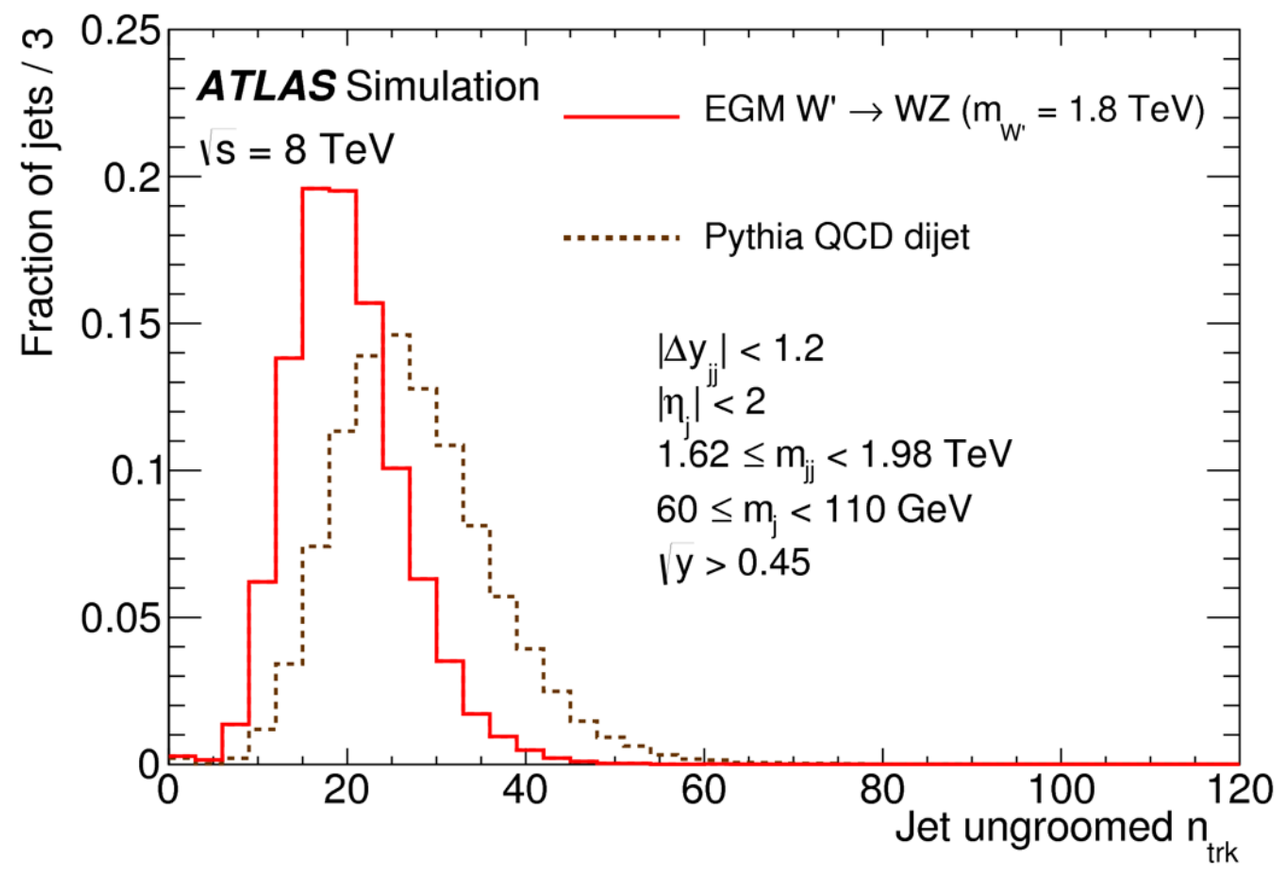
GENERIC DIBOSON RESONANCES

- Hint of excess @ 2 TeV in all hadronic di-boson resonance search
- Select events using jet mass, properties and substructure variables
- Fit to smoothly falling dijet mass spectrum
- Majority of uncertainties arise from use of jet properties

Source	Uncertainty
Efficiency of the track-multiplicity cut	20.0%
Jet mass scale	5.0%
Jet mass resolution	5.5%
Subjet momentum-balance scale	3.5%
Subjet momentum-balance resolution	2.0%
Parton shower model	5.0%
Parton distribution functions	3.5%
Luminosity	2.8%



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OUTLINE

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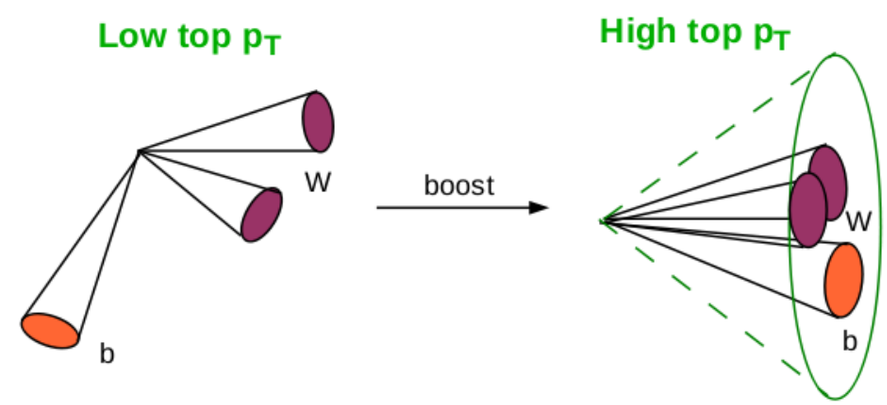
- Going beyond the Standard Model
- **New analysis techniques: getting boosted**

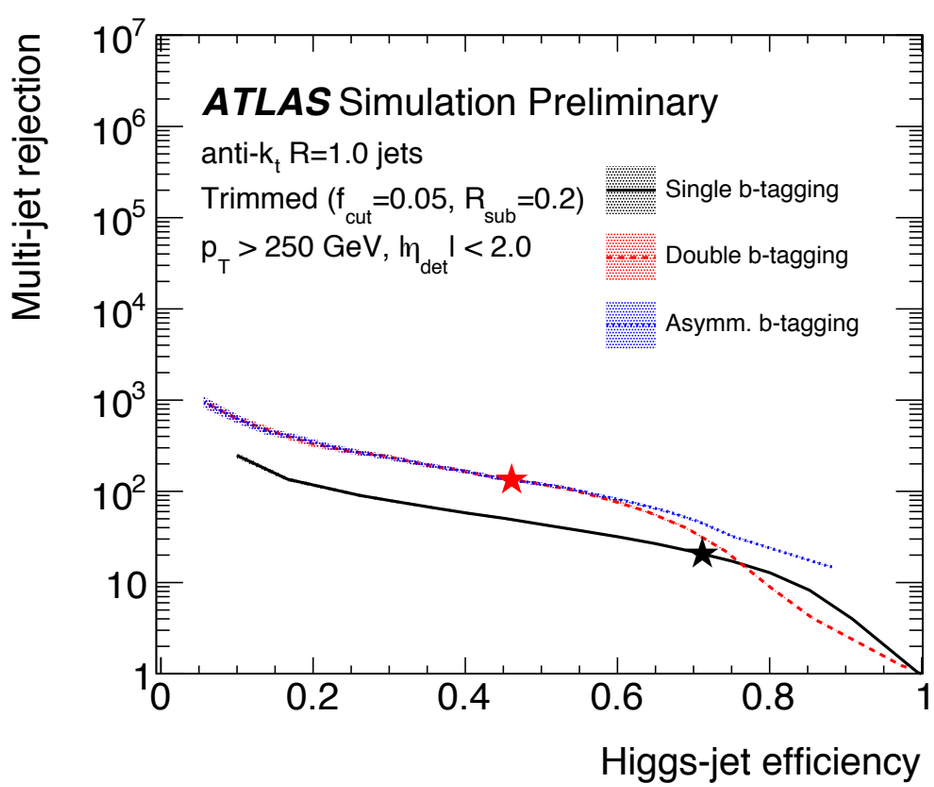
More details: BOOST 2015

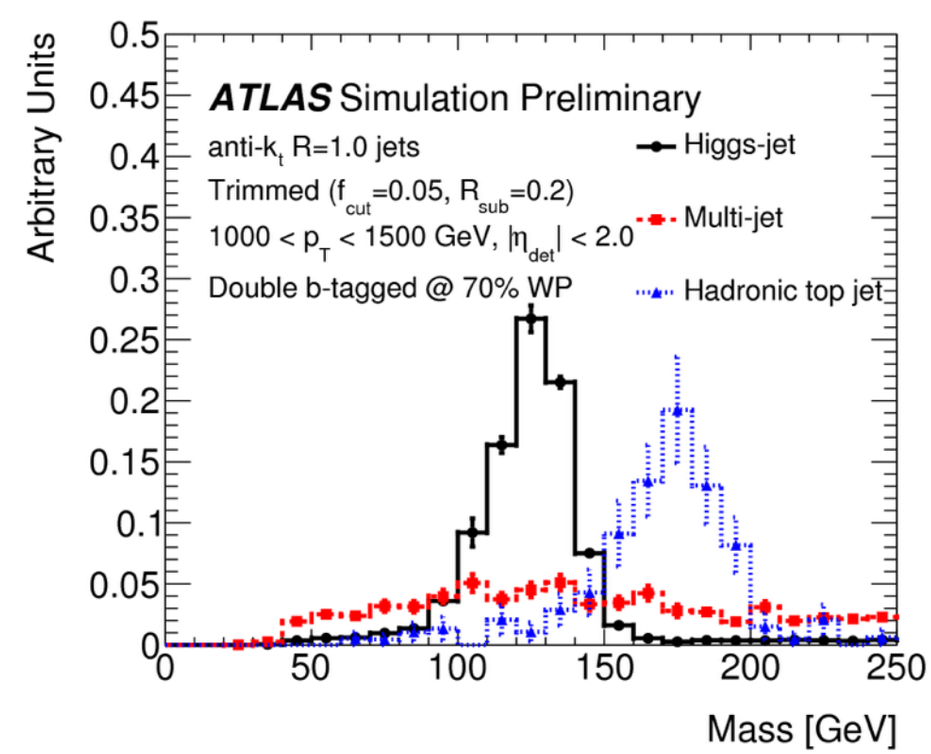
NEW TOOLS FOR USING JETS

- Confluence of theory and experimental improvements and √s increase are making us sensitive to the details of jets
  - Jet mass, constituents properties
- Makes use of hadronic decays possible!
  - Used in several Run I analyses, many planned for Run II



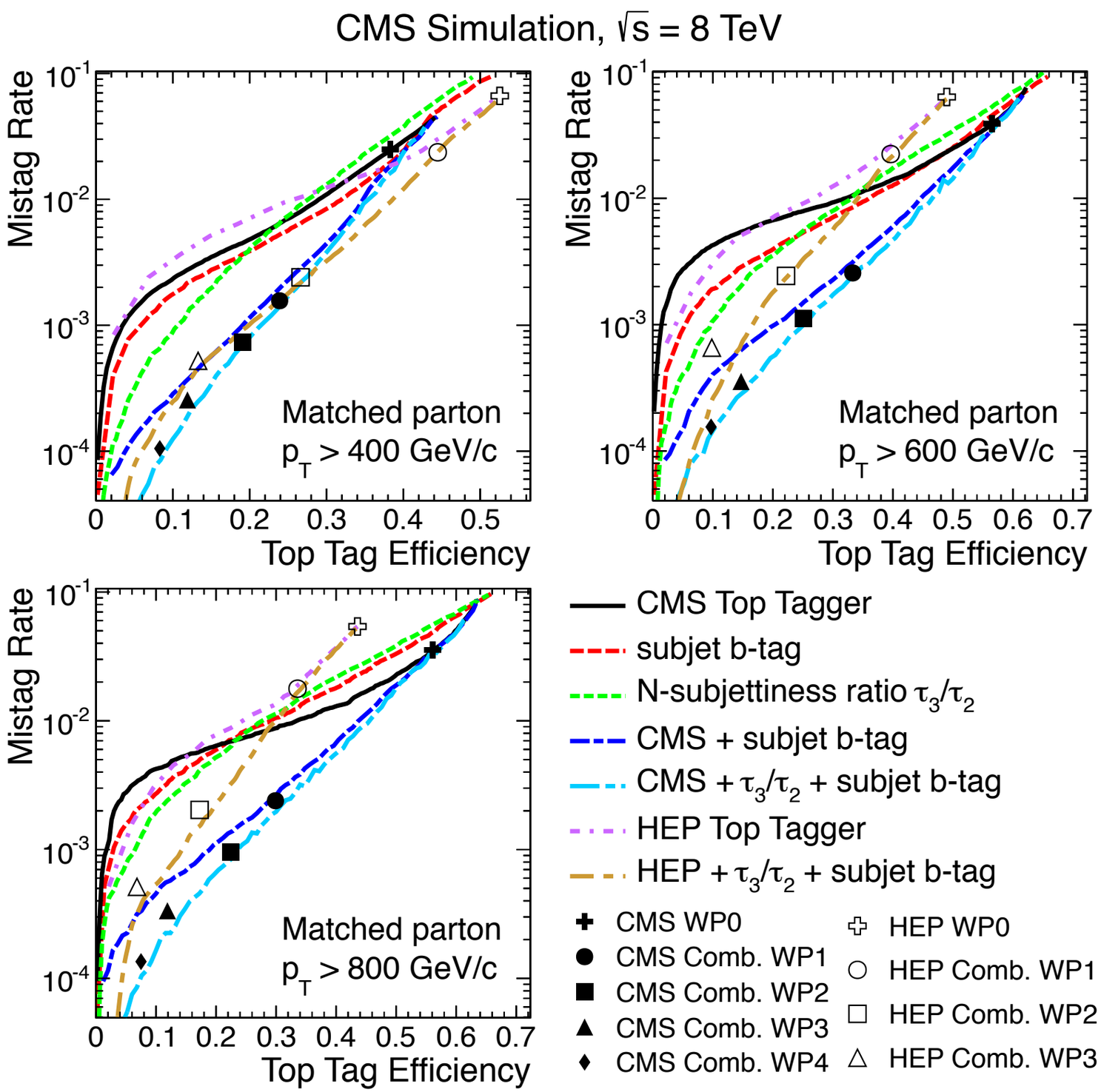
Emily Thompson

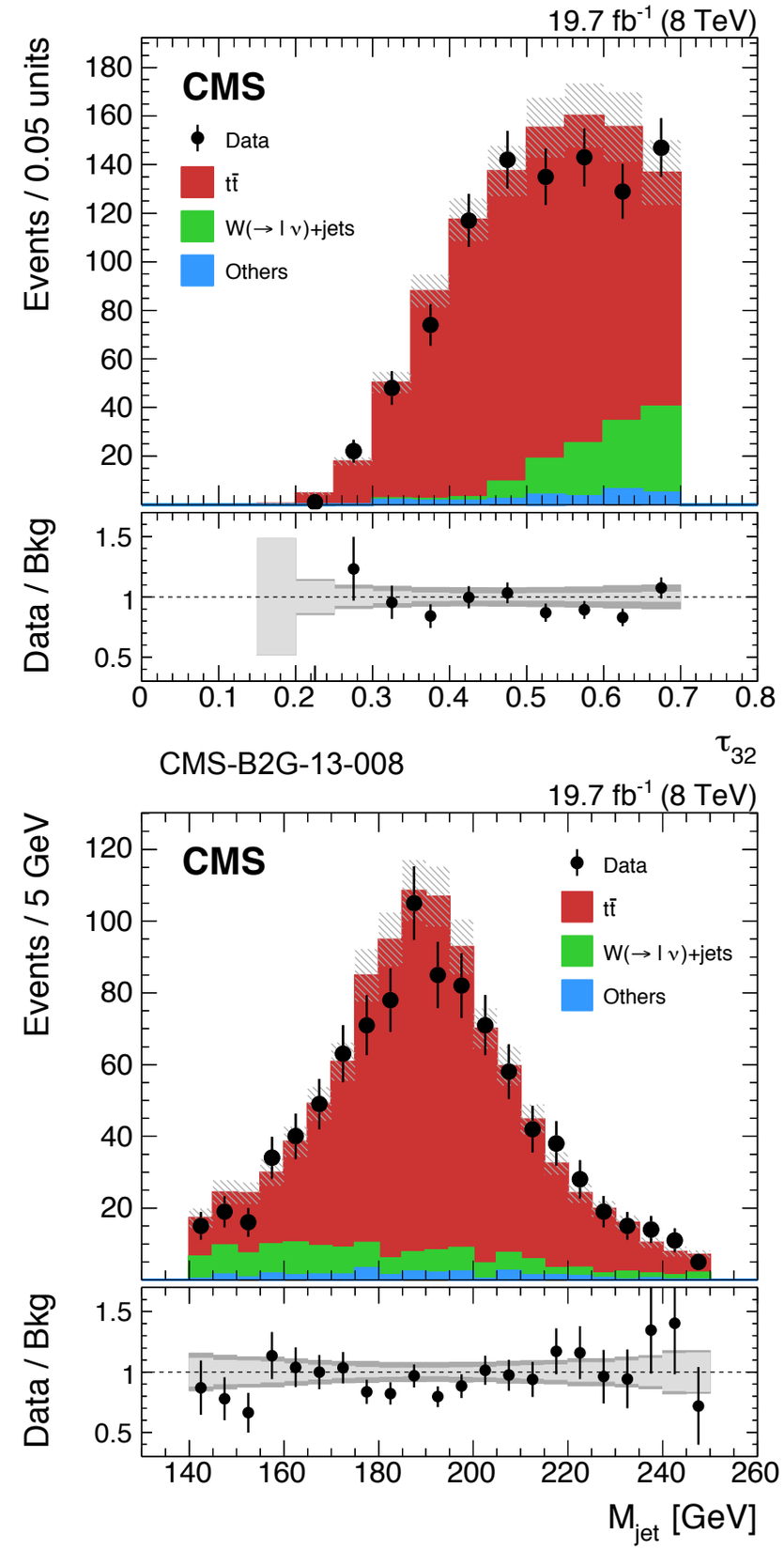




ATL-PHYS-PUB-2015-035

- Wide open parameter space for taggers: tops, Higgs, W/Z bosons, quark-gluon



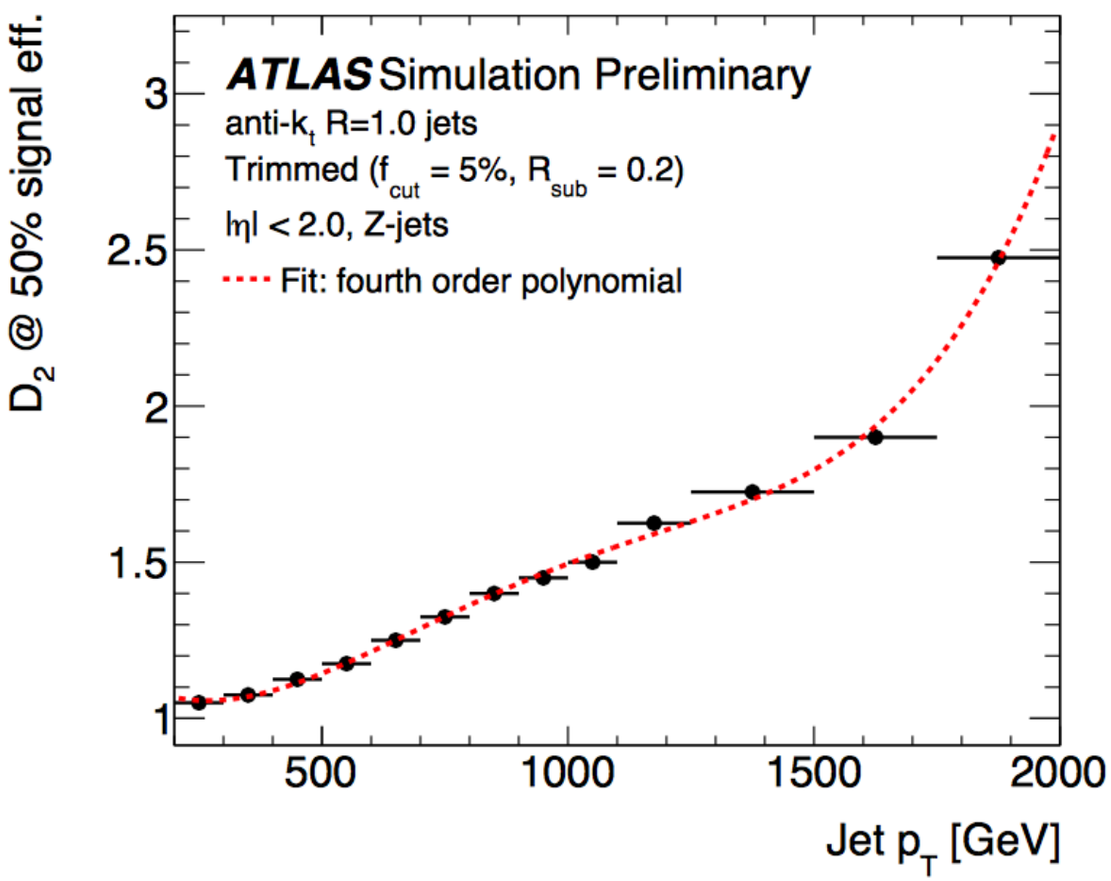


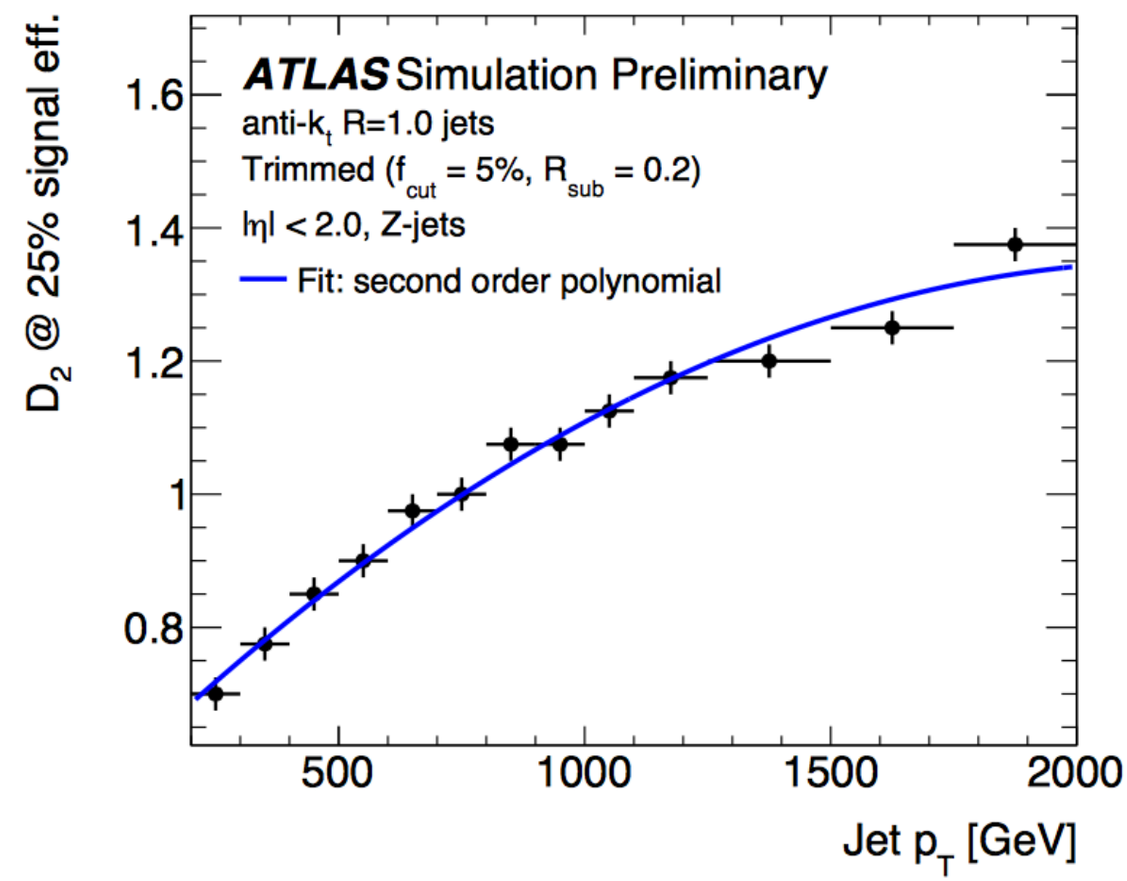
- However, uncertainties can be significant

$$D_2^\beta = \frac{e_3^\beta}{(e_2^\beta)^3} = \frac{\sum_{i<j<k} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} (R_{ij} R_{ik} R_{kj})^\beta}{(\sum_{i<j} p_{\mathrm{T}_i} p_{\mathrm{T}_j} R_{ij}^\beta)^3}$$

ATL-PHYS-PUB-2015-033

W/Z-boson tagging using substructure variables





- However, uncertainties can be significant

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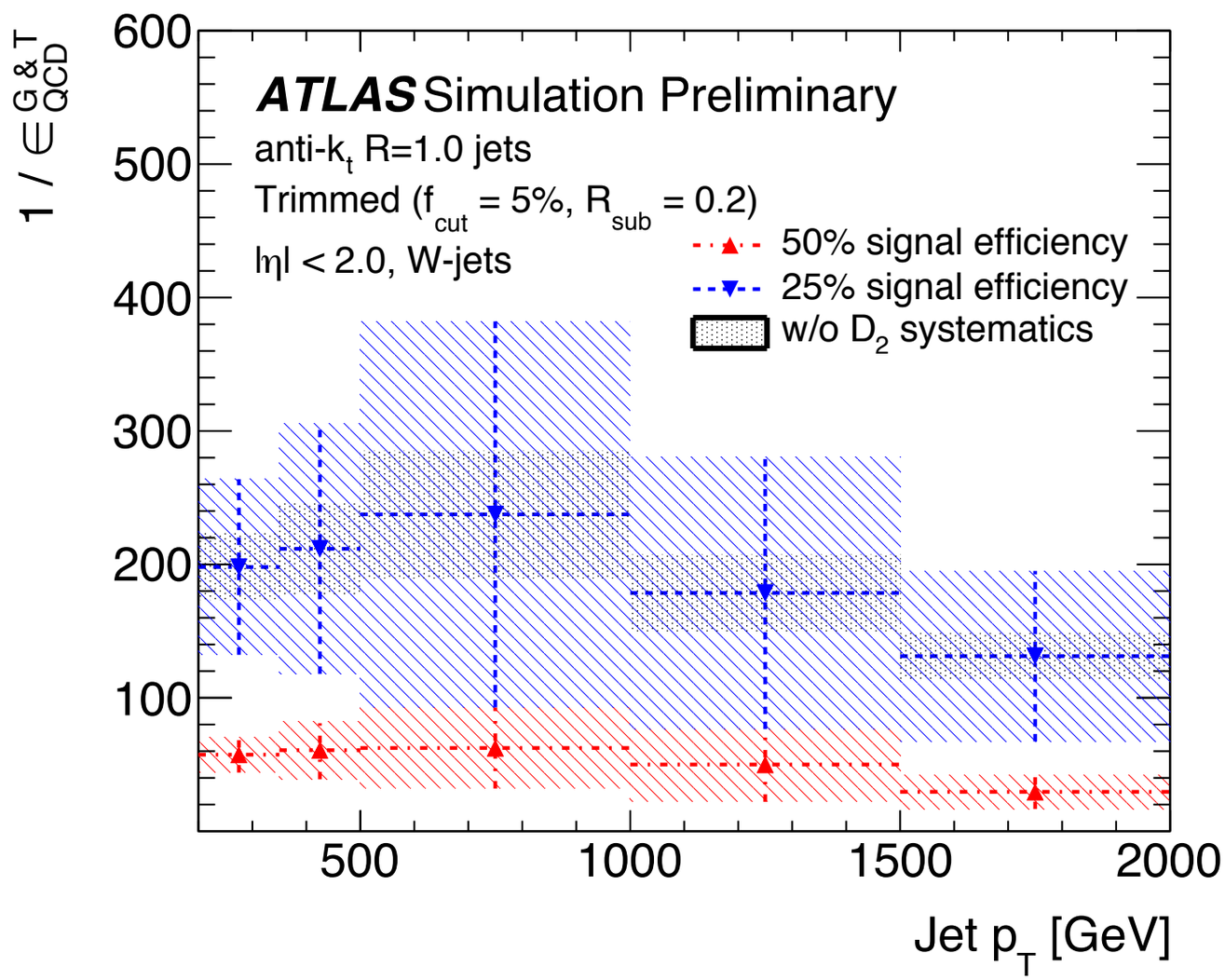

- However, uncertainties can be significant

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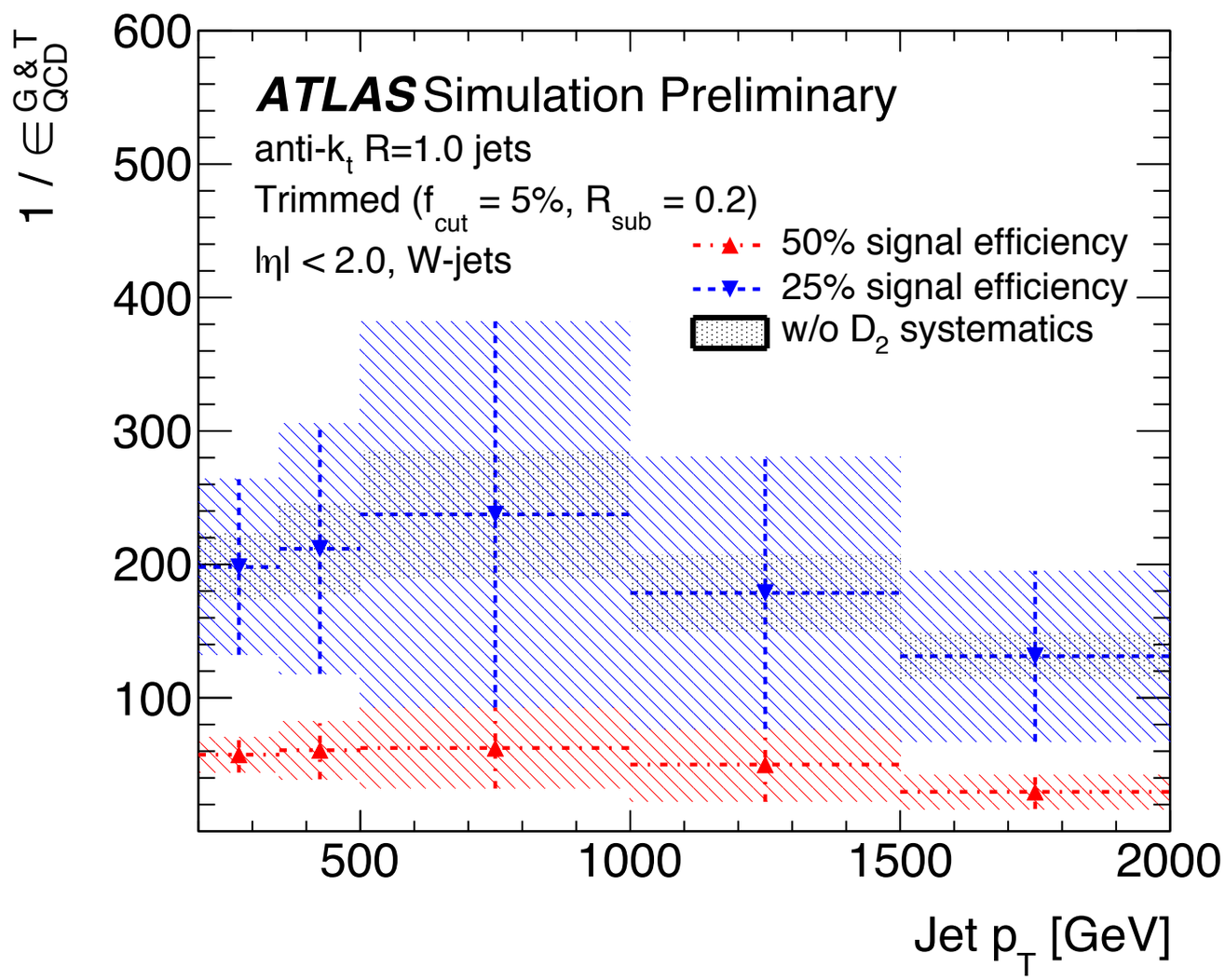


- Expected to be a very active development area in Run II with close collaboration with theorists!

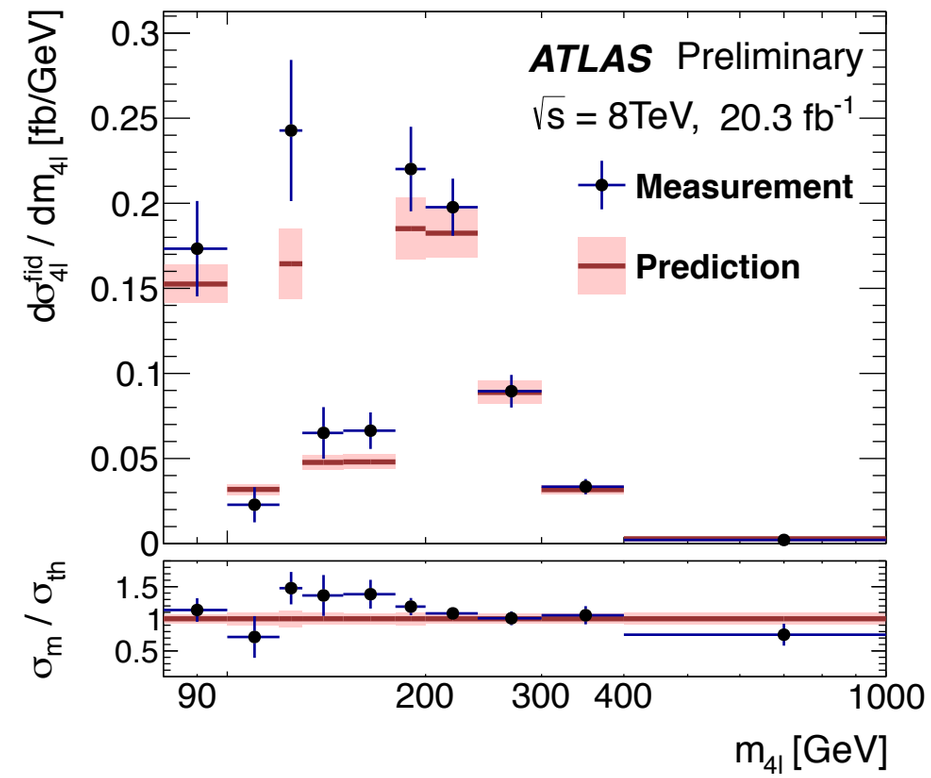
CONCLUSIONS

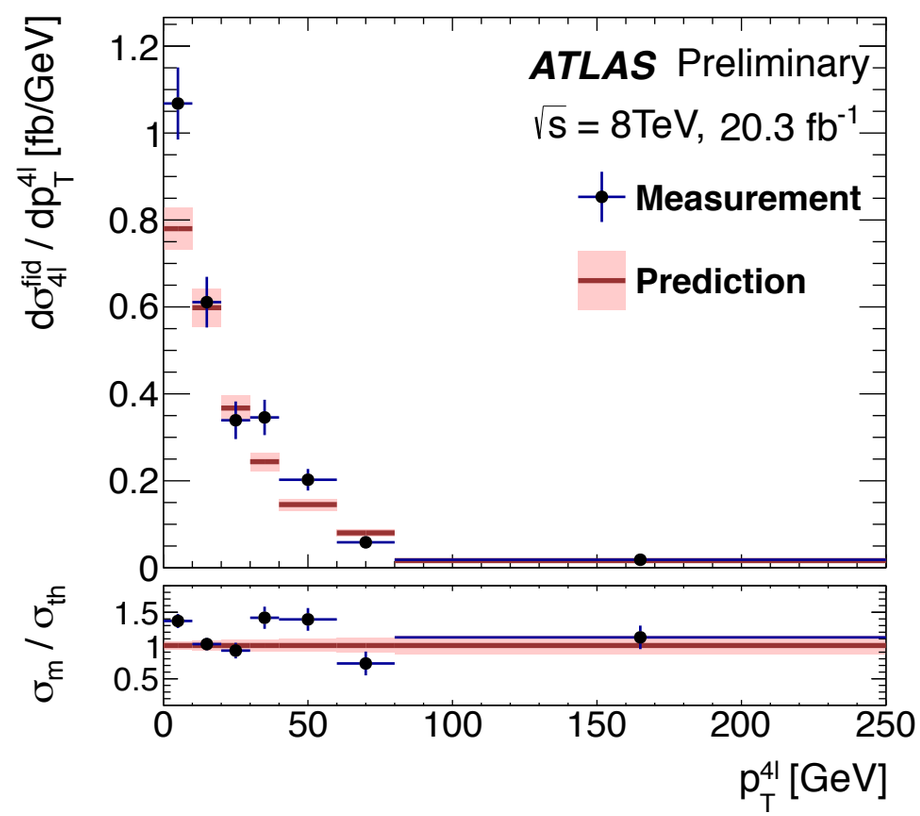
- Wide range of QCD calculations and models used in Higgs & BSM measurements
- Run 1 analyses had important uncertainties due to PDFs, heavy flavor production, jet substructure and soft(ish) QCD effects
- Looking forward to pushing the limits in Run II!
  - Lots of recent theory improvements still to be incorporated

BACK-UP

ZZ K-FACTORS

- QCD ZZ production only known to LO:
  - CMS width analysis uses same k-factors as NNLO Higgs calculation based on arXiv: 1312.2397
  - ATLAS width measurement reported as function of unknown K-factor
  - Key place for theory development
- K-factor measured as a function m_{4l}, p_T^{4l} in ATLAS-CONF-2015-031

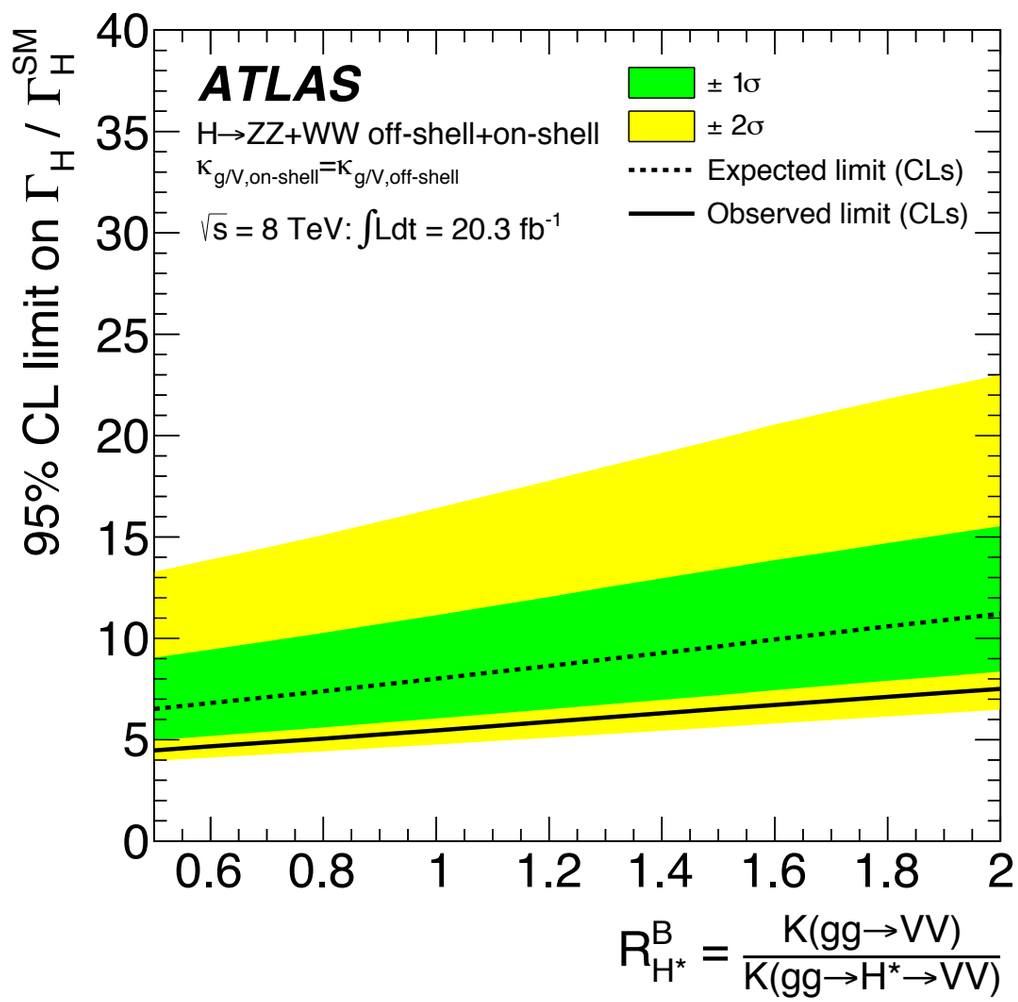




CMS: JHEP 05 (2014) 104

ATLAS WIDTH LIMITS

Eur. Phys. J. C (2015) 75:335



- ATLAS width results as a function of relative K-factors

DIBOSON RESONANCE

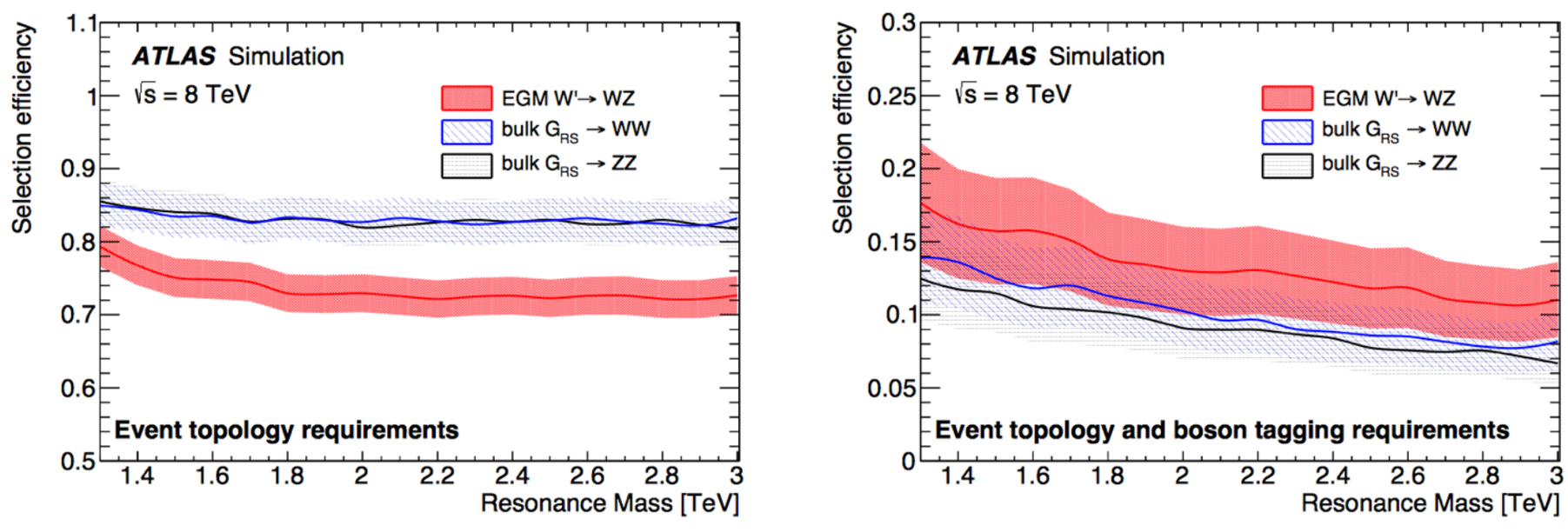
Table 2: Parameters for the mass-drop filtering algorithm used to groom C/A jets. The choice of μ_f parameter corresponds to no mass-drop requirement being imposed in the grooming procedure.

Filtering parameter	Value
$\sqrt{y_f}$	0.2
μ_f	1
R_r	0.3
n_r	3

$$\sqrt{y} \equiv \min(p_{T\,j_1}, p_{T\,j_2}) \frac{\Delta R_{(j_1,j_2)}}{m_0} \geq \sqrt{y_f},$$

Boson Tagging Requirements

$$\sqrt{y} \geq 0.45,\ n_{trk} < 30, \text{ and } |m_j - m_V| < 13 \text{ GeV}$$



(a) (b)

Figure 2: Event selection efficiencies as a function of the resonance masses for EGM $W' \to WZ$ and bulk $G_{RS} \to WW$ and ZZ for simulated events with resonance mass within 10% of the nominal signal mass. In (a), the event topology requirements are applied to EGM $W' \to WZ$, $G_{RS} \to WW$ and $G_{RS} \to ZZ$ samples, while in (b), the WZ, WW and ZZ boson tagging selections are also applied in the EGM $W' \to WZ$, $G_{RS} \to WW$ and $G_{RS} \to ZZ$ samples respectively and the efficiencies shown are corrected by the simulation–to–data scale factor. The width of the bands in each figure indicates both the statistical and systematic uncertainties.

FULL EVENT DISPLAY FROM FIRST SLIDE