



Jeju Island, Korea

Highlights from ATLAS and Future Plans

Massimo Corradi (INFN Roma)
On behalf of the ATLAS Collaboration

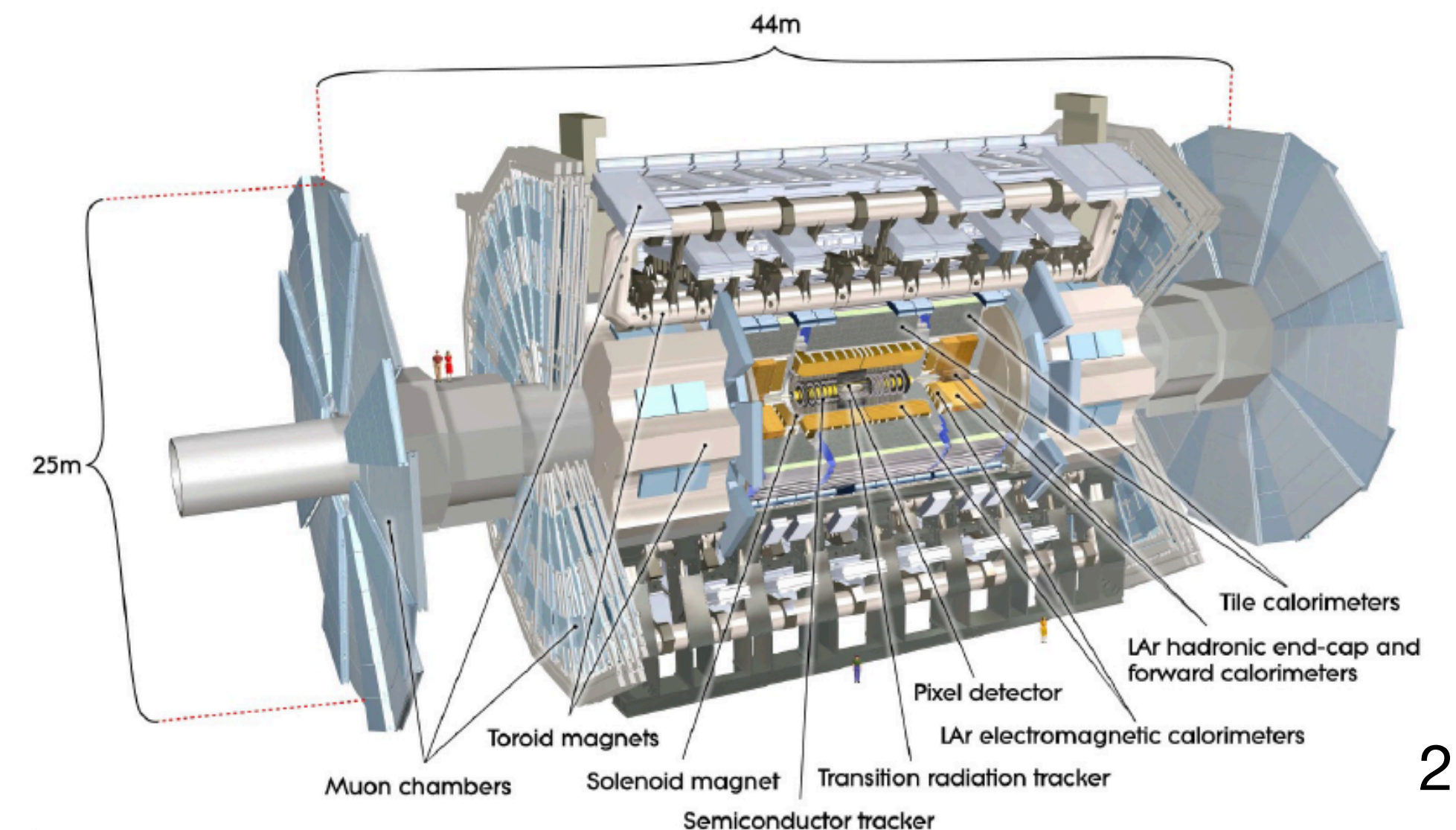
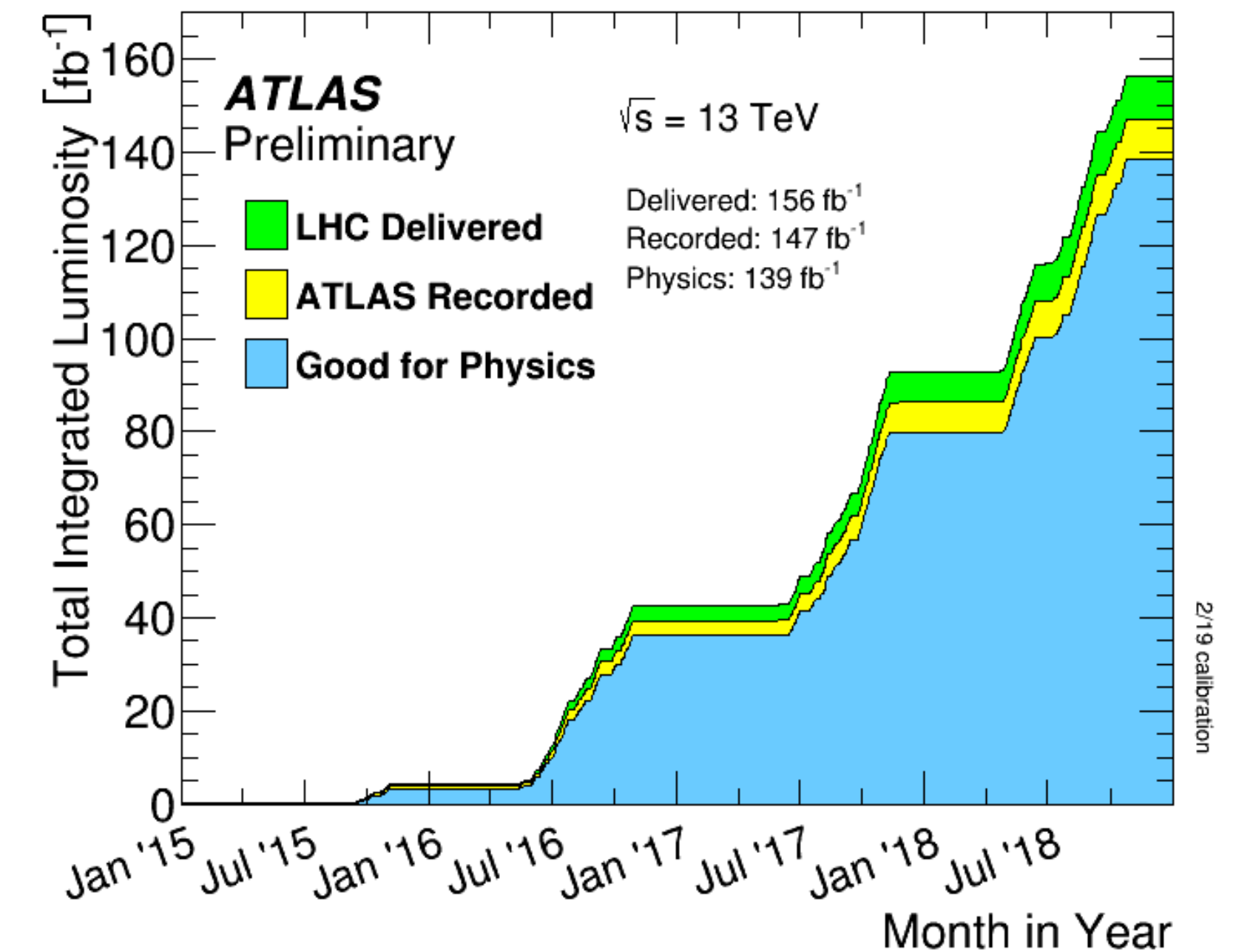


Istituto Nazionale di Fisica Nucleare



- LHC Run2: 2015-2018
- pp center of mass energy : 13 TeV
- Luminosity (Good for Physics): 139 fb⁻¹
- Also heavy-ion collisions (not covered here):
 - Pb+Pb, p+Pb, Xe+Xe
- Special runs at low energy (5.02 TeV) and low-pileup
- ATLAS is a multi-purpose experiment operated by a large experimental collaboration: a vast physics programme
- Many Run-2 results have been published and many analyses are ongoing
- We present here a selection of recent results, released in the last year, and an outlook for future
- New Results on Charmonium and B_c -> see talk by *Semen Turchikhin*

Run 2

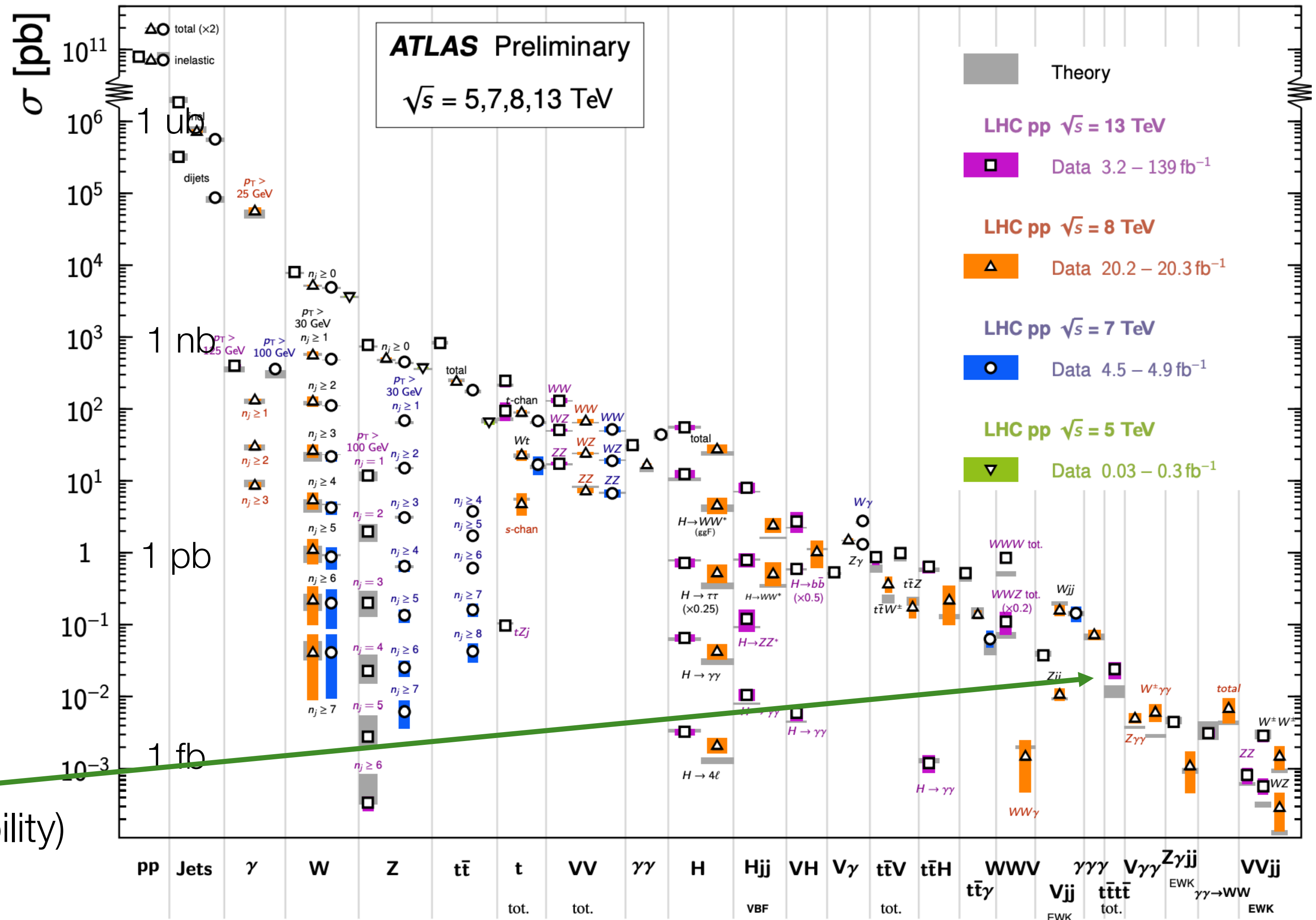


Standard Model Processes

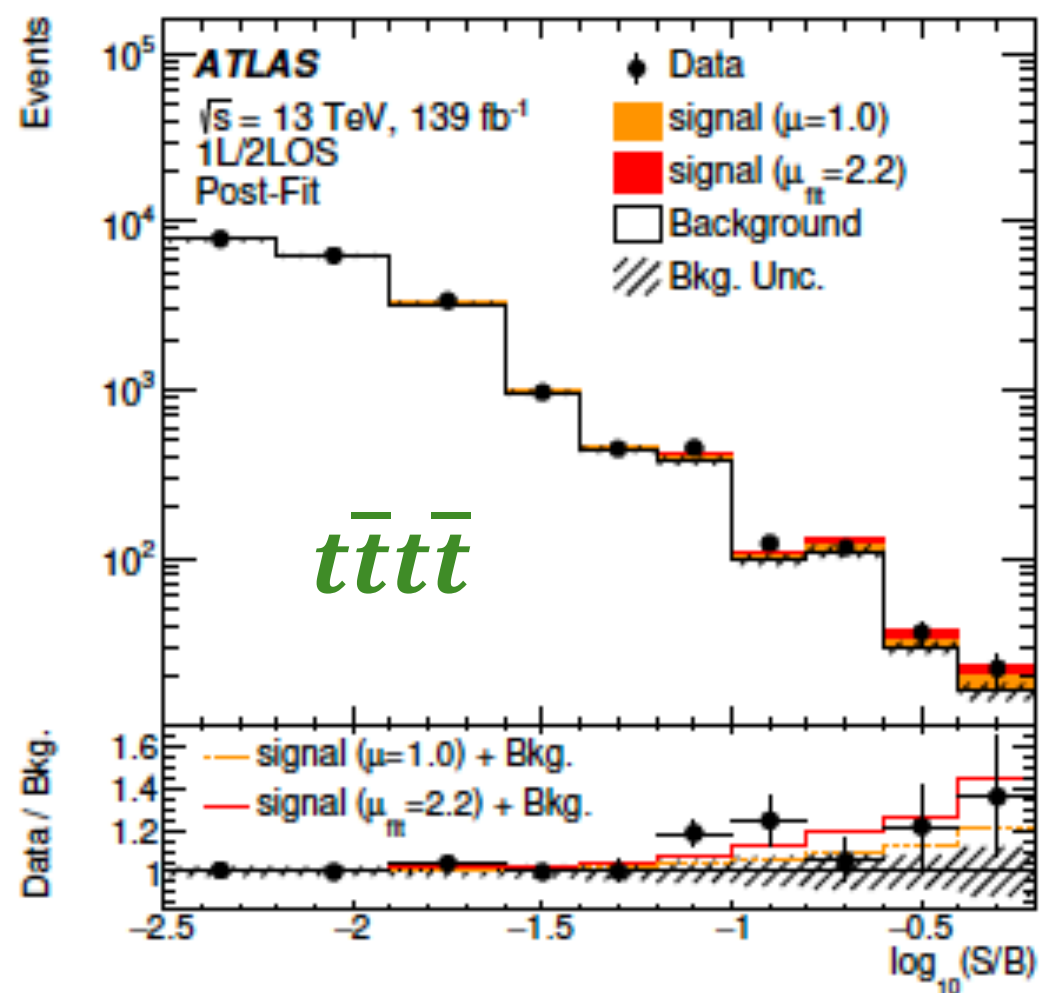
- Cross sections of different processes in pp collisions span many orders of magnitude
- Millions of Z, W, $t\bar{t}$ => precision
- Thousands of H
- Observation of rare channels with tiny SM cross sections e.g. $t\bar{t}t\bar{t}$

Standard Model Production Cross Section Measurements

Status: July 2021

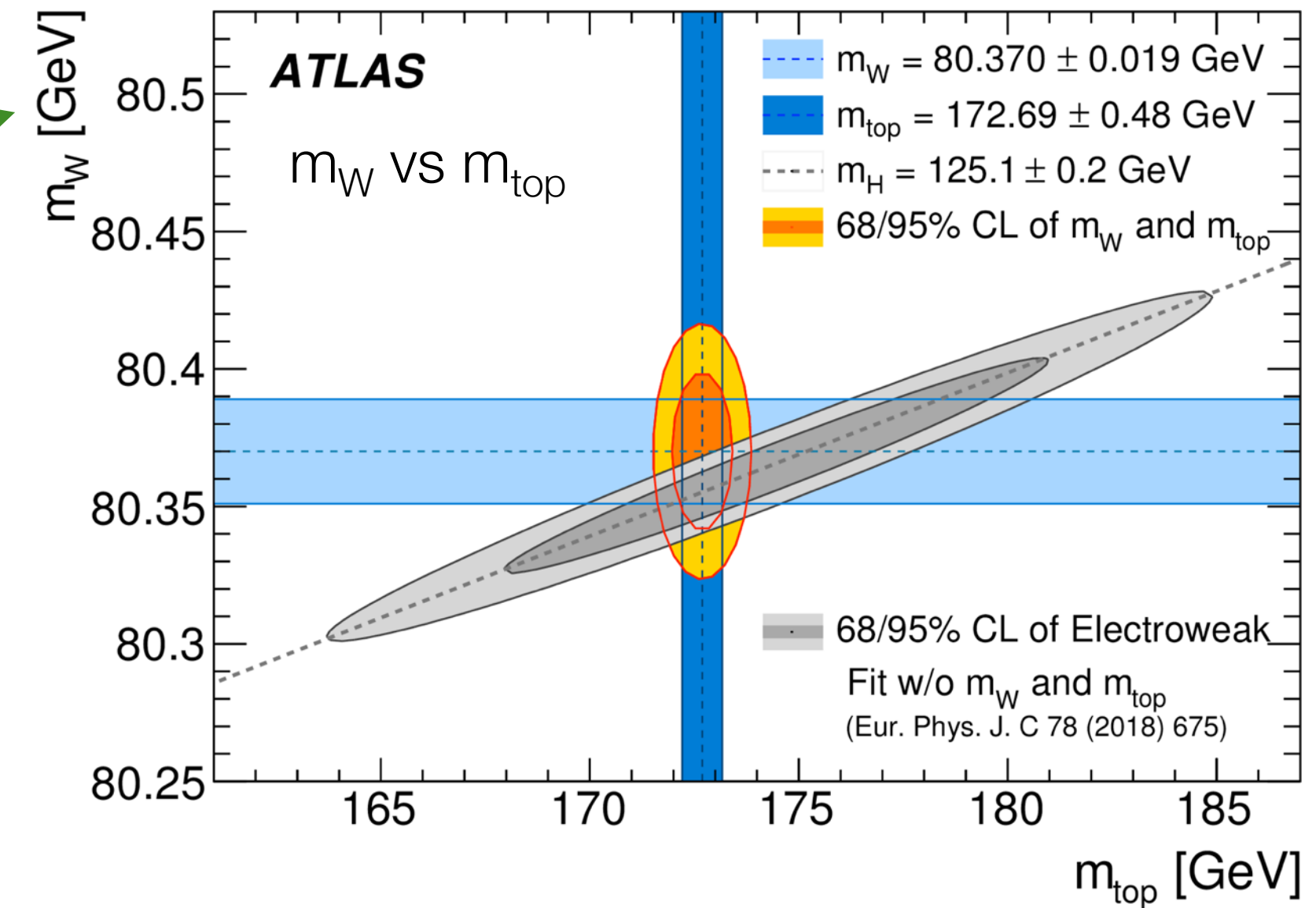


arXiv:2106.11683 acc. by JHEP

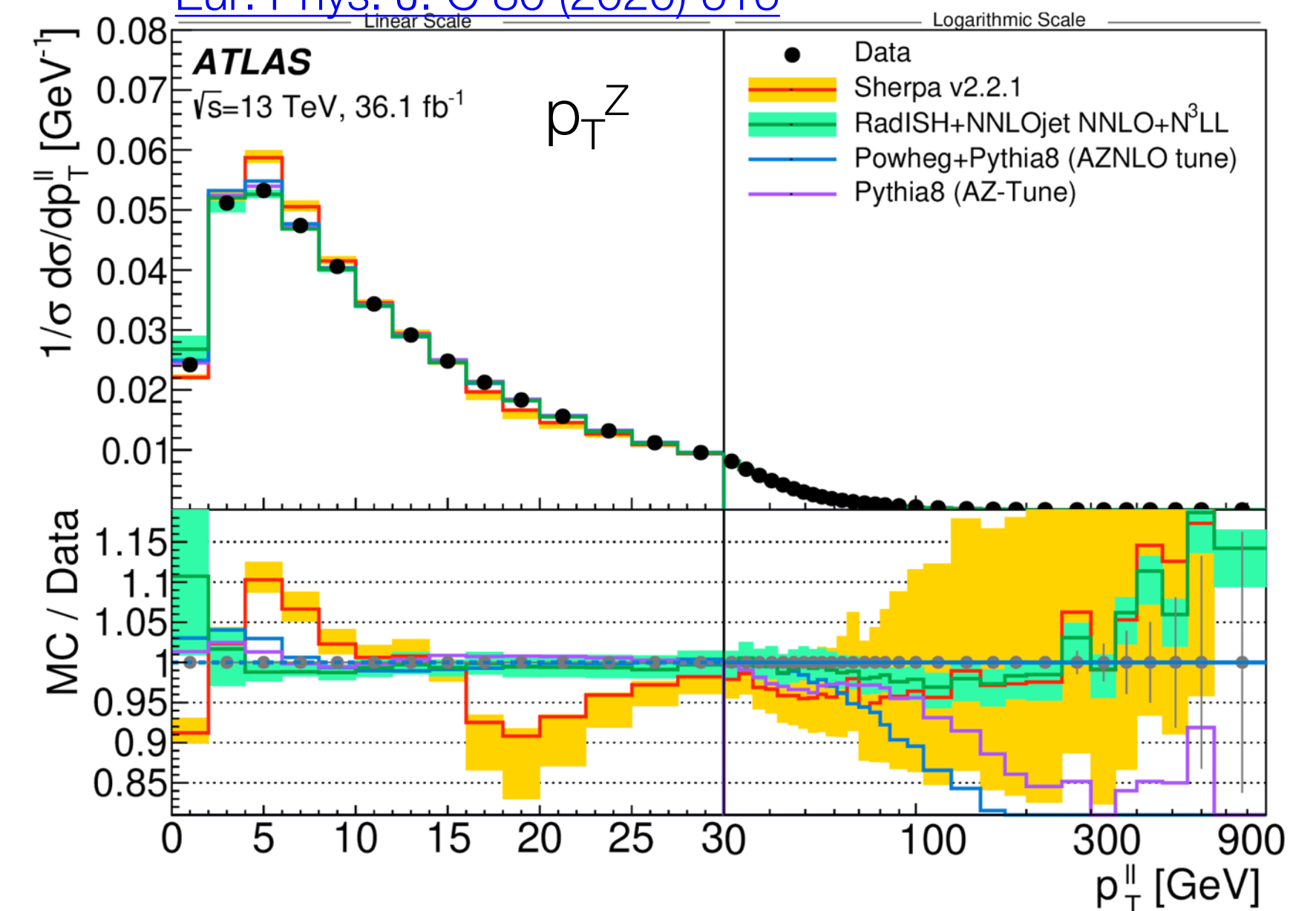


- Precision measurements of SM parameters m_W , $\sin^2(\theta_W)$, exploiting the huge sample of Z and W
- Run-1 measurements limited by theoretical uncertainties:
 - PDF
 - W and Z p_T spectrum
 - Fragmentation
- Program to reduce these uncertainties using direct measurements, e.g. p_T^Z

[Eur. Phys. J. C 78 \(2018\) 110](#)



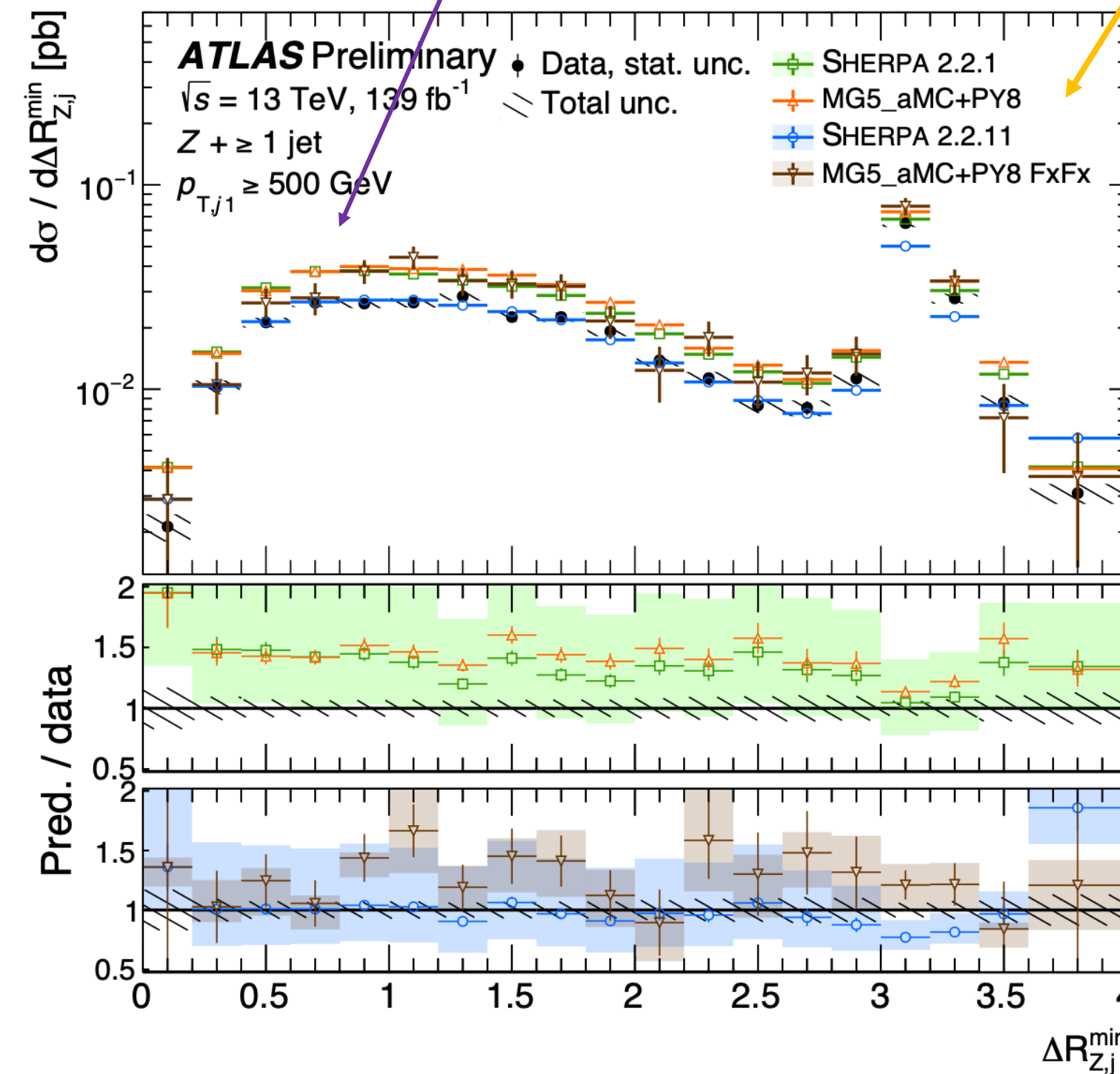
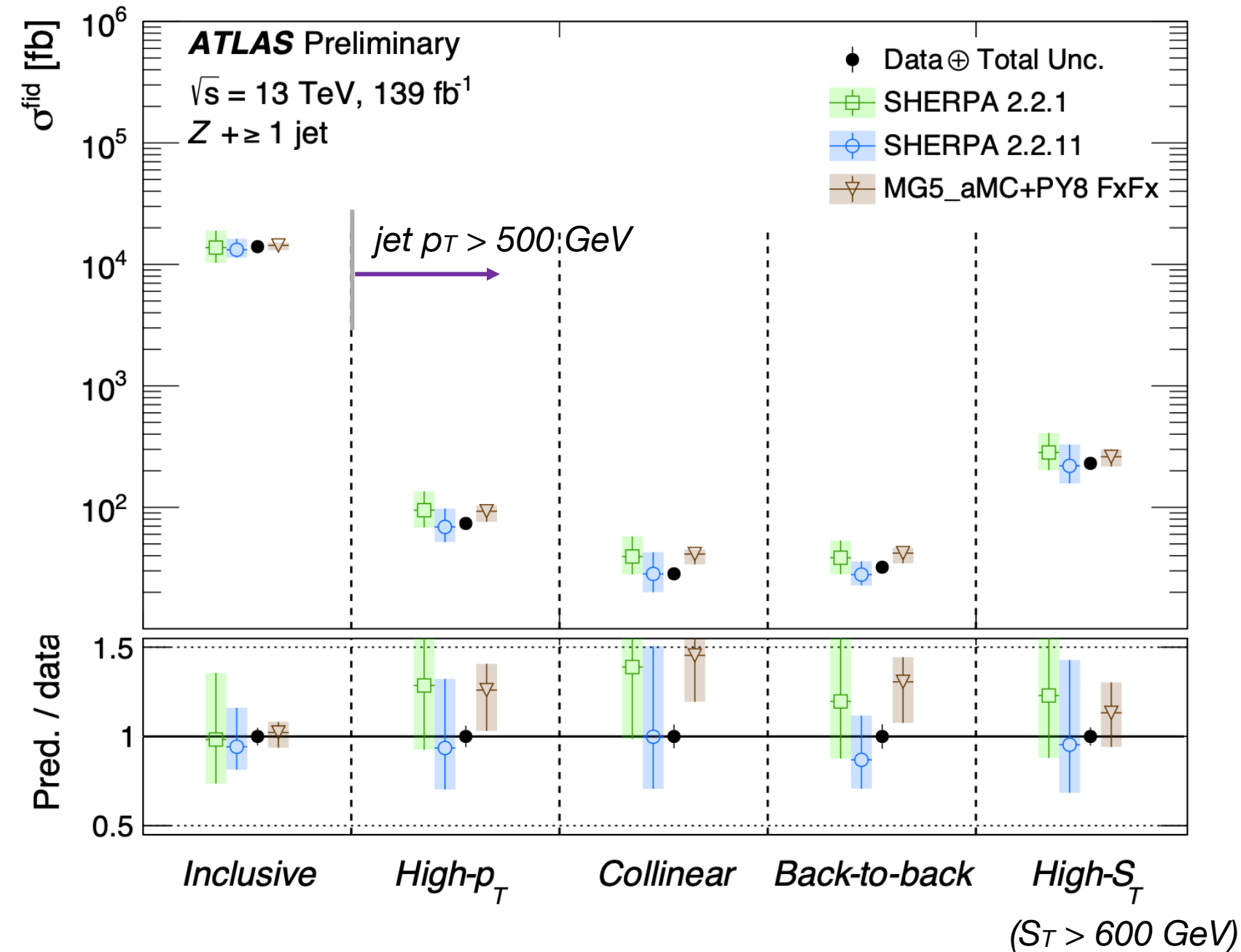
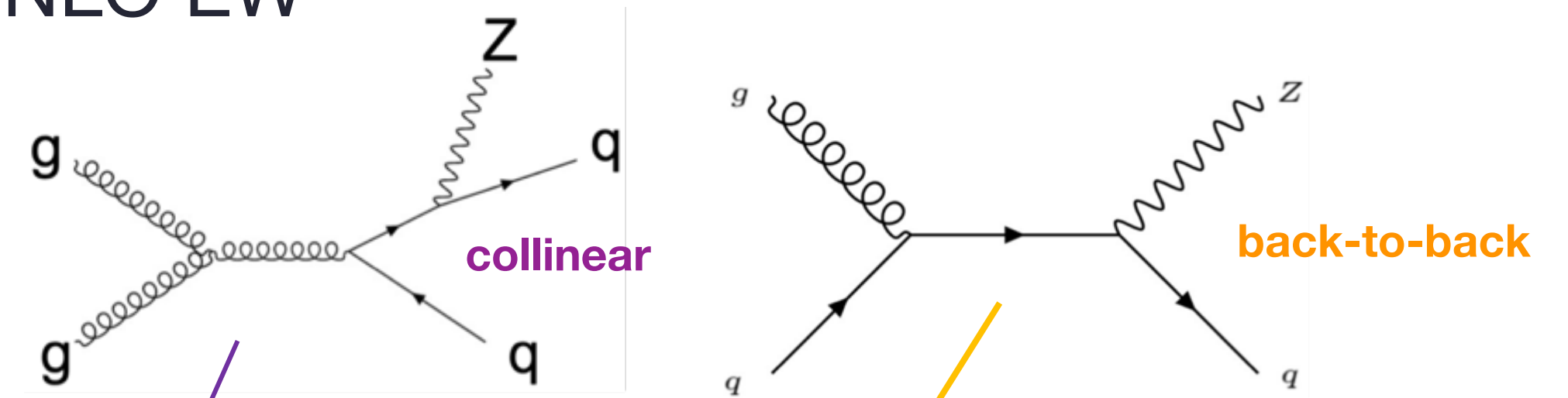
[Eur. Phys. J. C 80 \(2020\) 616](#)



Z-boson + jets production

- Run 2: $\sim 8 \times 10^9$ Z bosons produced
- Test SM in events w/ $Z(\rightarrow ee, \mu\mu)$ and ≥ 1 jet with $p_T > 100\text{GeV}$
 - SM predictions w/ event generators up to NLO QCD + NLO EW
 - Measure cross section in more extreme phase space: collinear vs. back-to-back jet emission, high jet p_T or high sum p_T

ATLAS-CONF-2021-033



improved description with recent event generators :

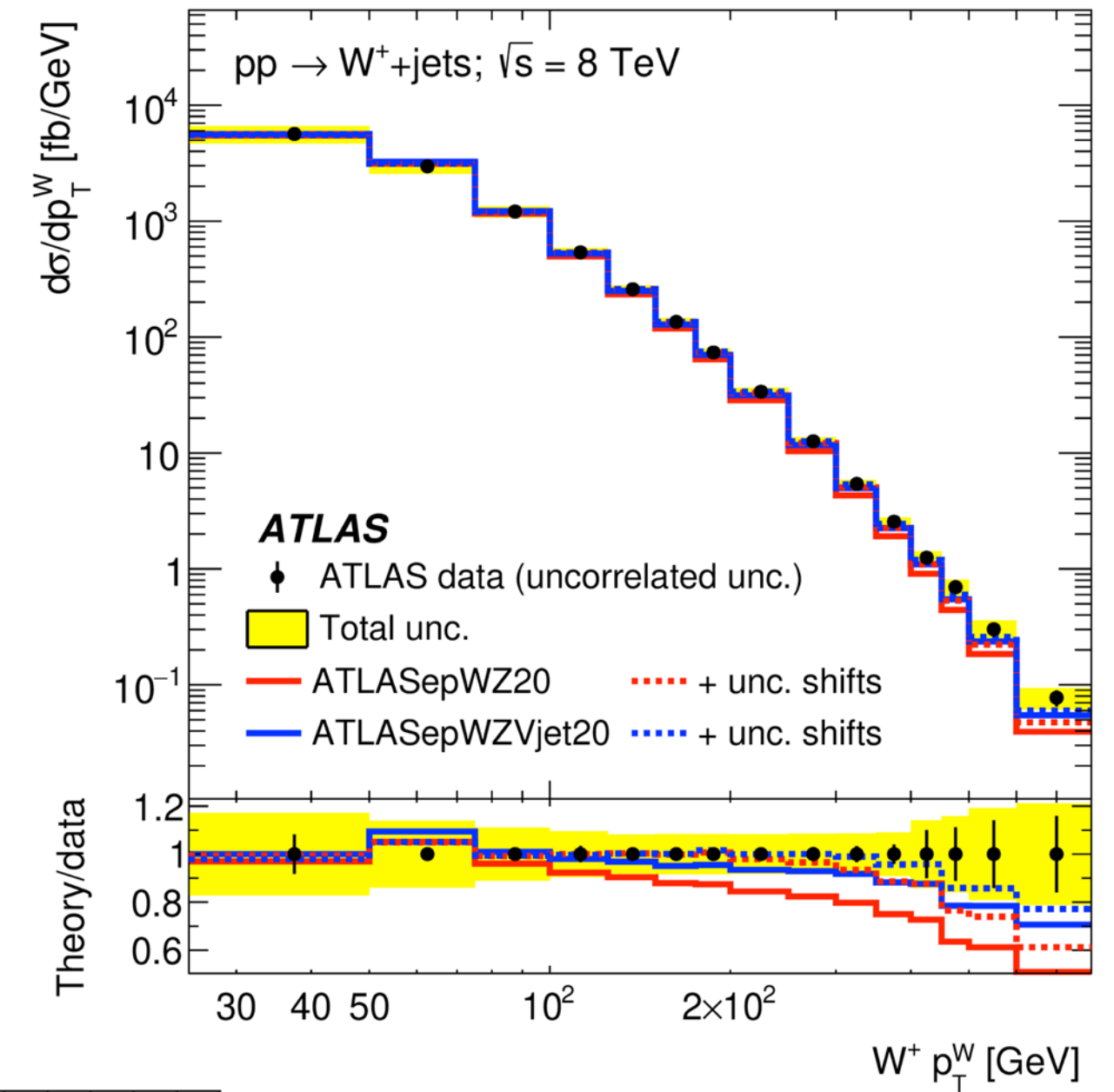
Sherpa 2.2.11 (0-2 partons at NLO, 3-5 partons at LO)

MG5_aMD+PY8 (0-3 partons NLO) Frederix-Frixione merging scheme)

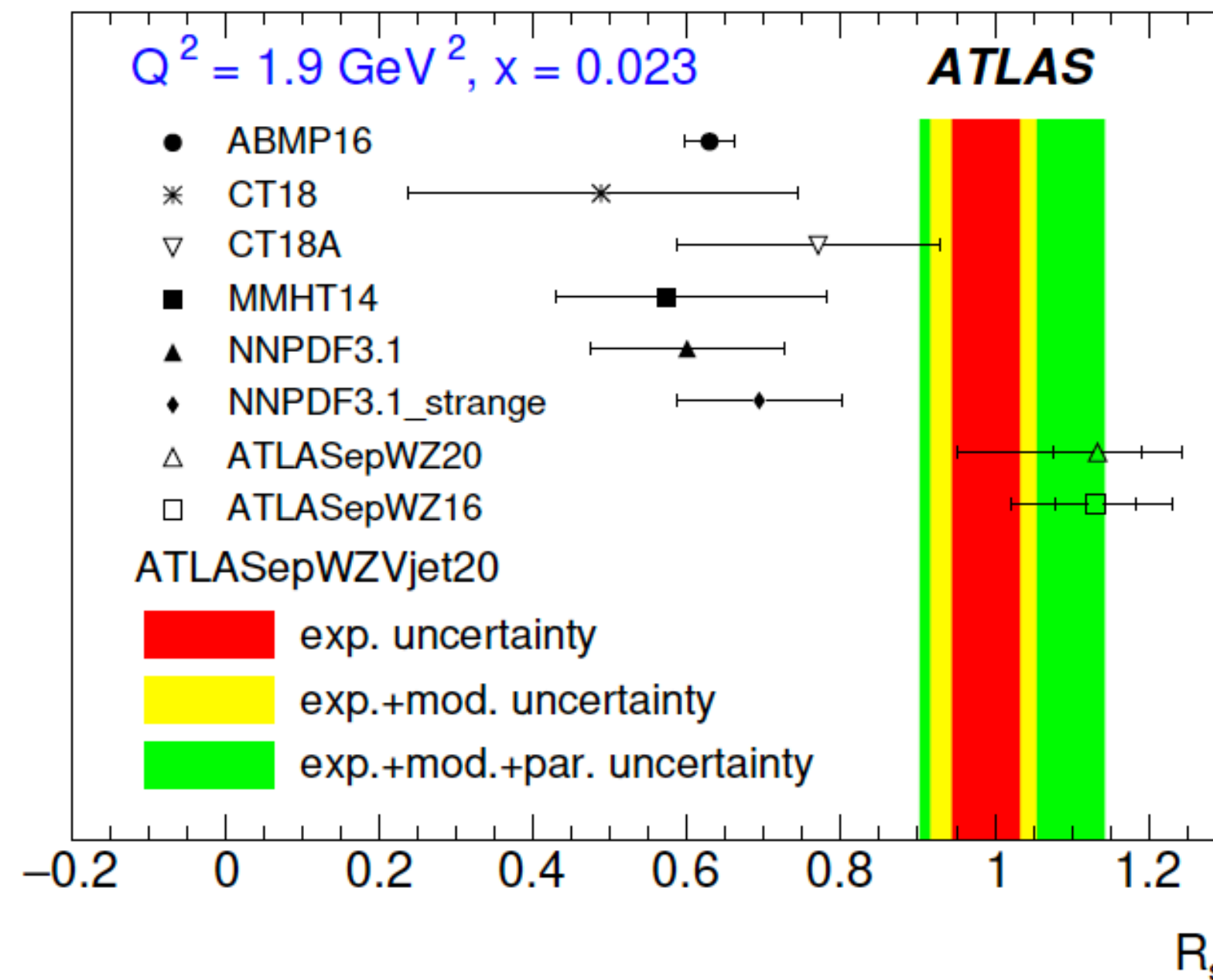
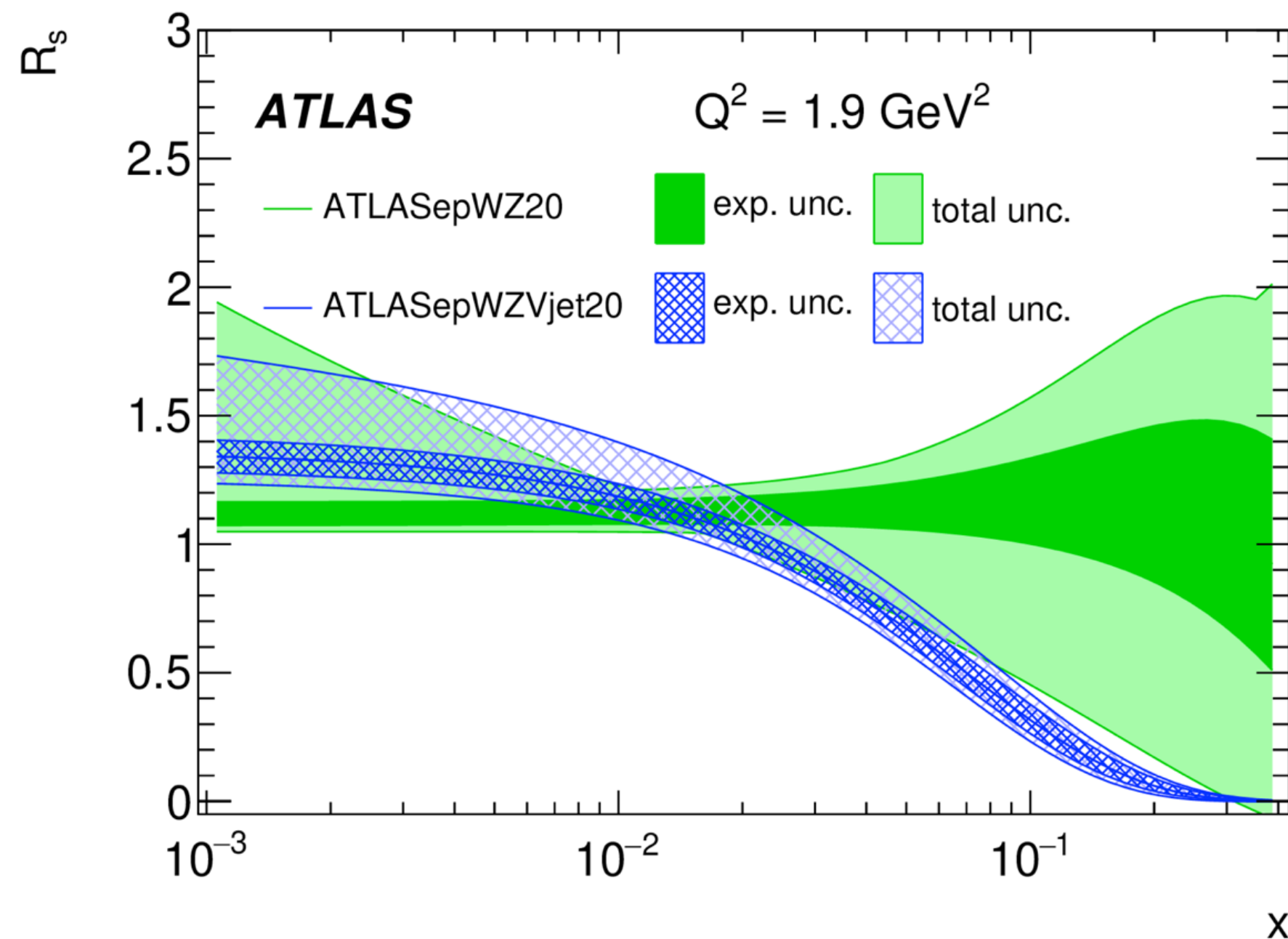
Standard Model: PDFs

- $W, Z/\gamma^*$ data at LHC data can be used to constraint PDFs
- New PDF set ATLASepWZjet20 (HERA + ATLAS W, Z inclusive + W +jet, Z +jet)
- V +Jet measurements help to separate u and d, s
- Unsuppressed strange fraction is confirmed

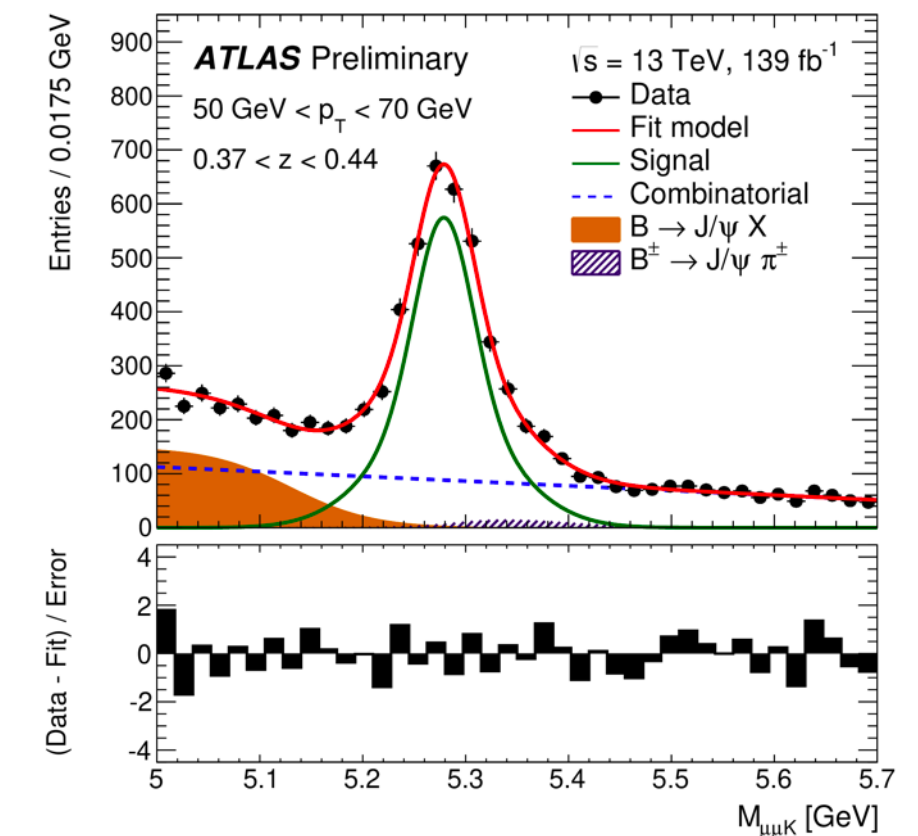
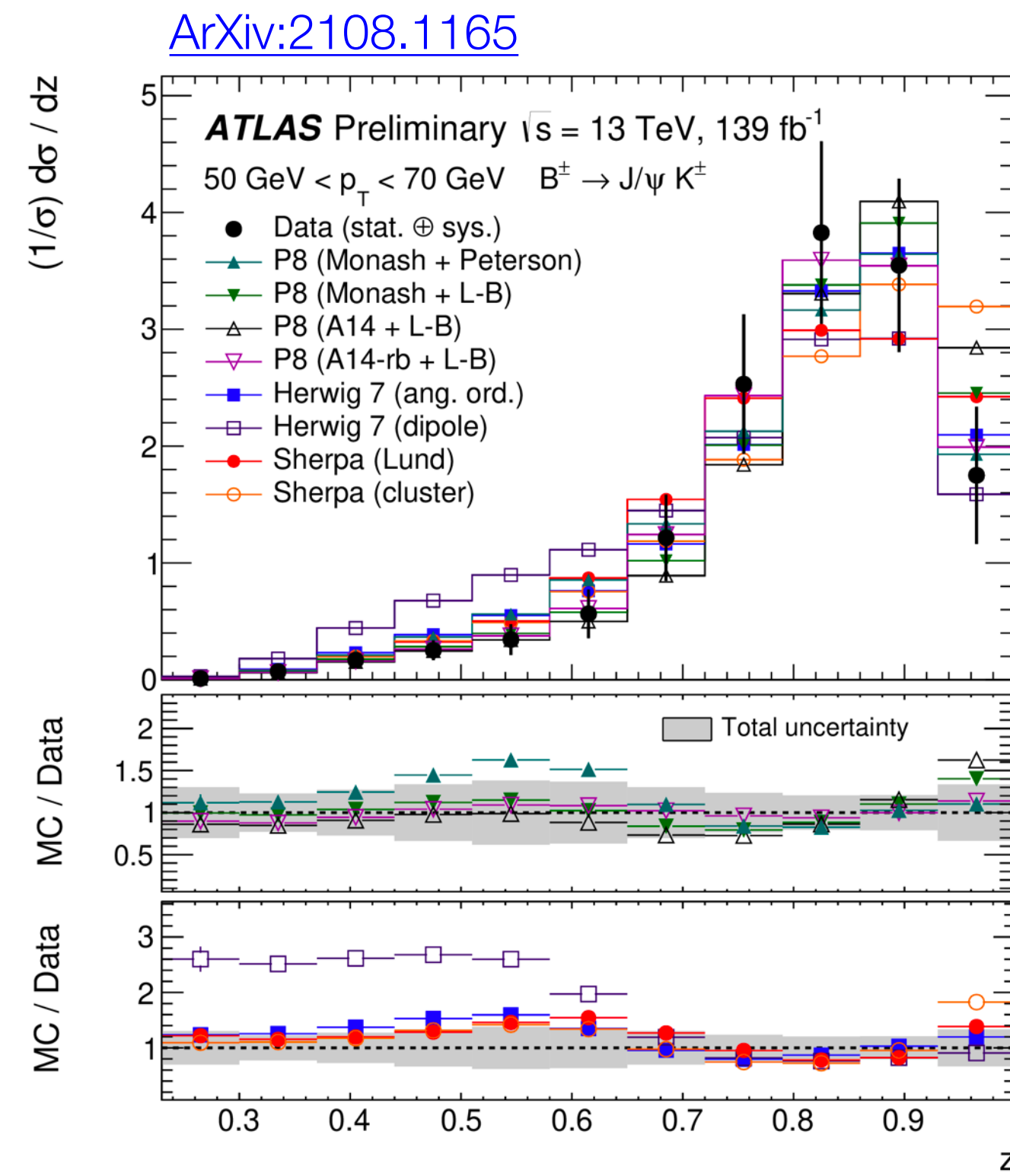
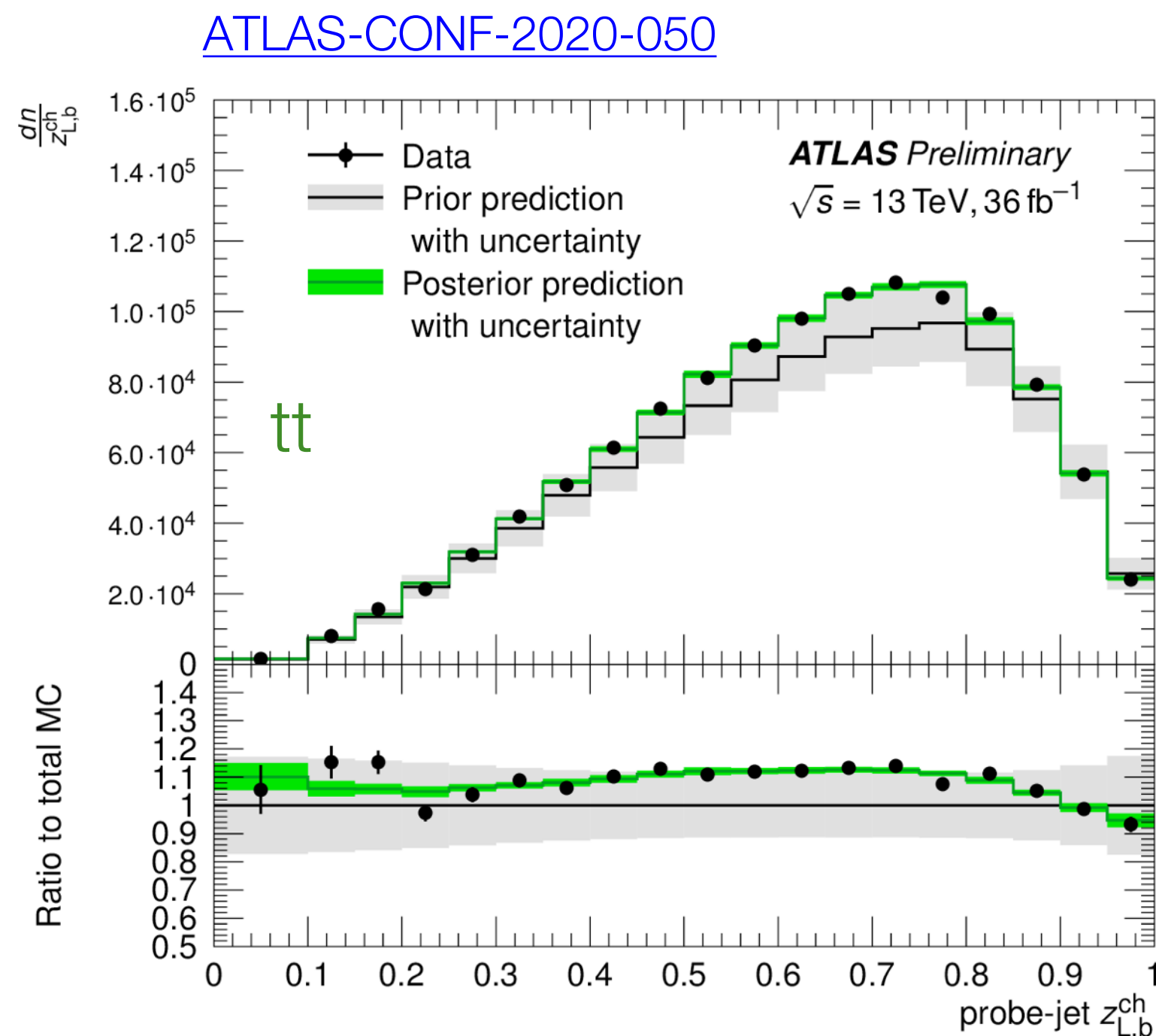
JHEP 07 (2021) 223



$$R_s = (s + \bar{s}) / (u + \bar{u} + d + \bar{d})$$



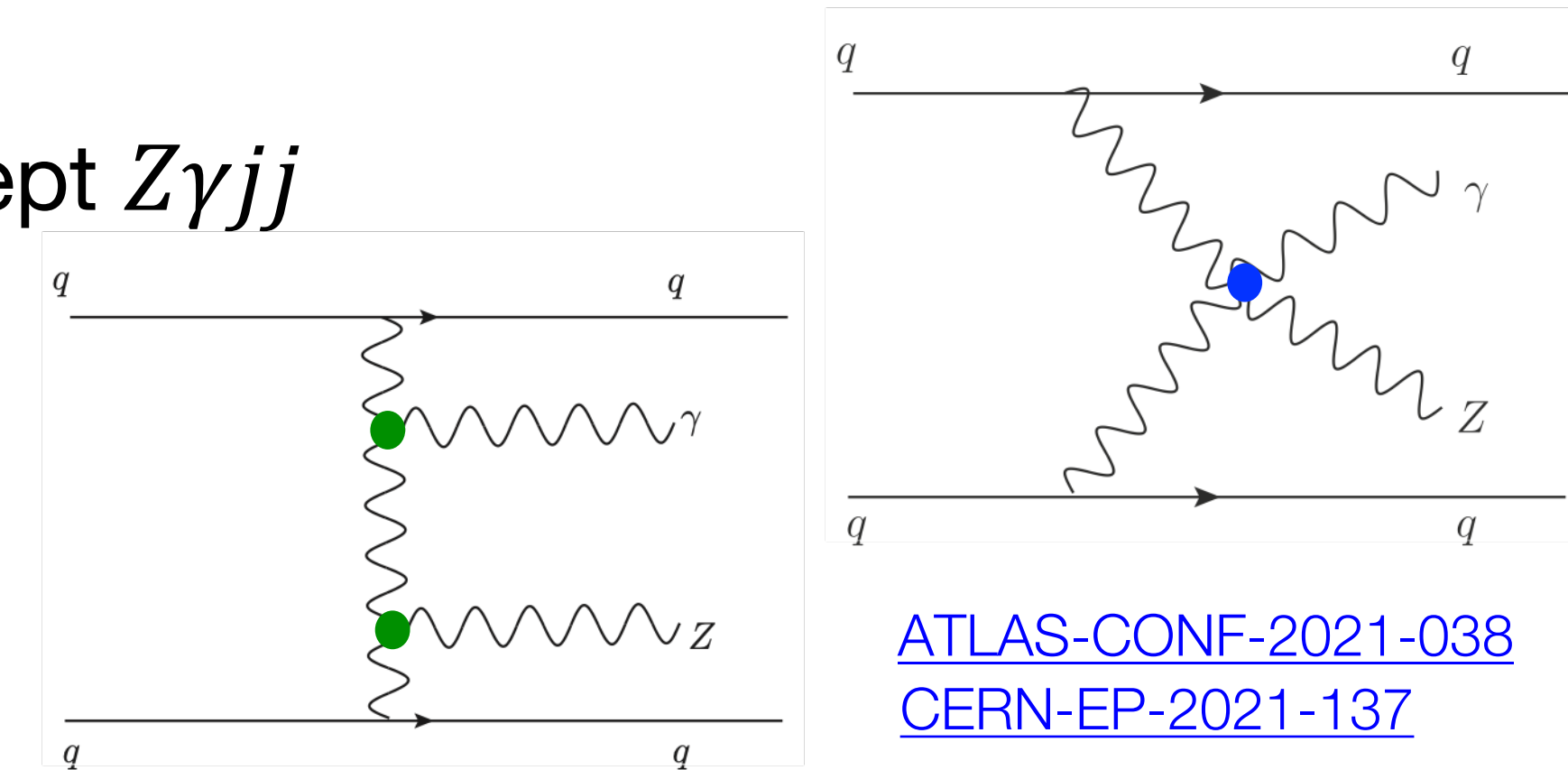
- Fragmentation of b-quarks important in key measurements and searches (e.g. top-quark mass or $H \rightarrow b\bar{b}$)
- Test and improve fragmentation models derived from measurements at e^+e^- colliders
- Use jet-based quantities:
 - $z_{L,b}^{ch}$ = fraction of jet charged-track momentum carried by $B \rightarrow l^+ \nu X$
 - z = fraction of jet momentum carried by reconstructed $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$



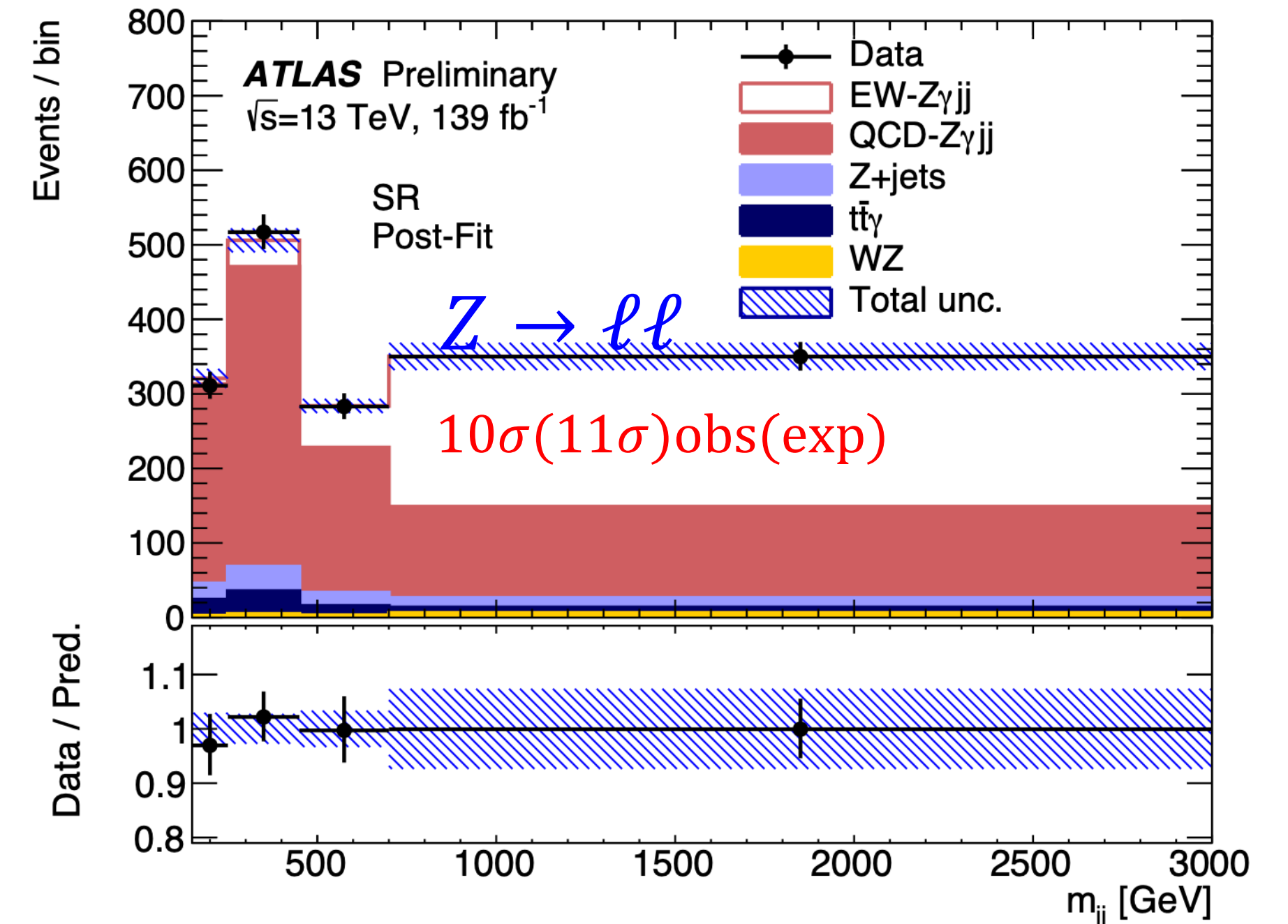
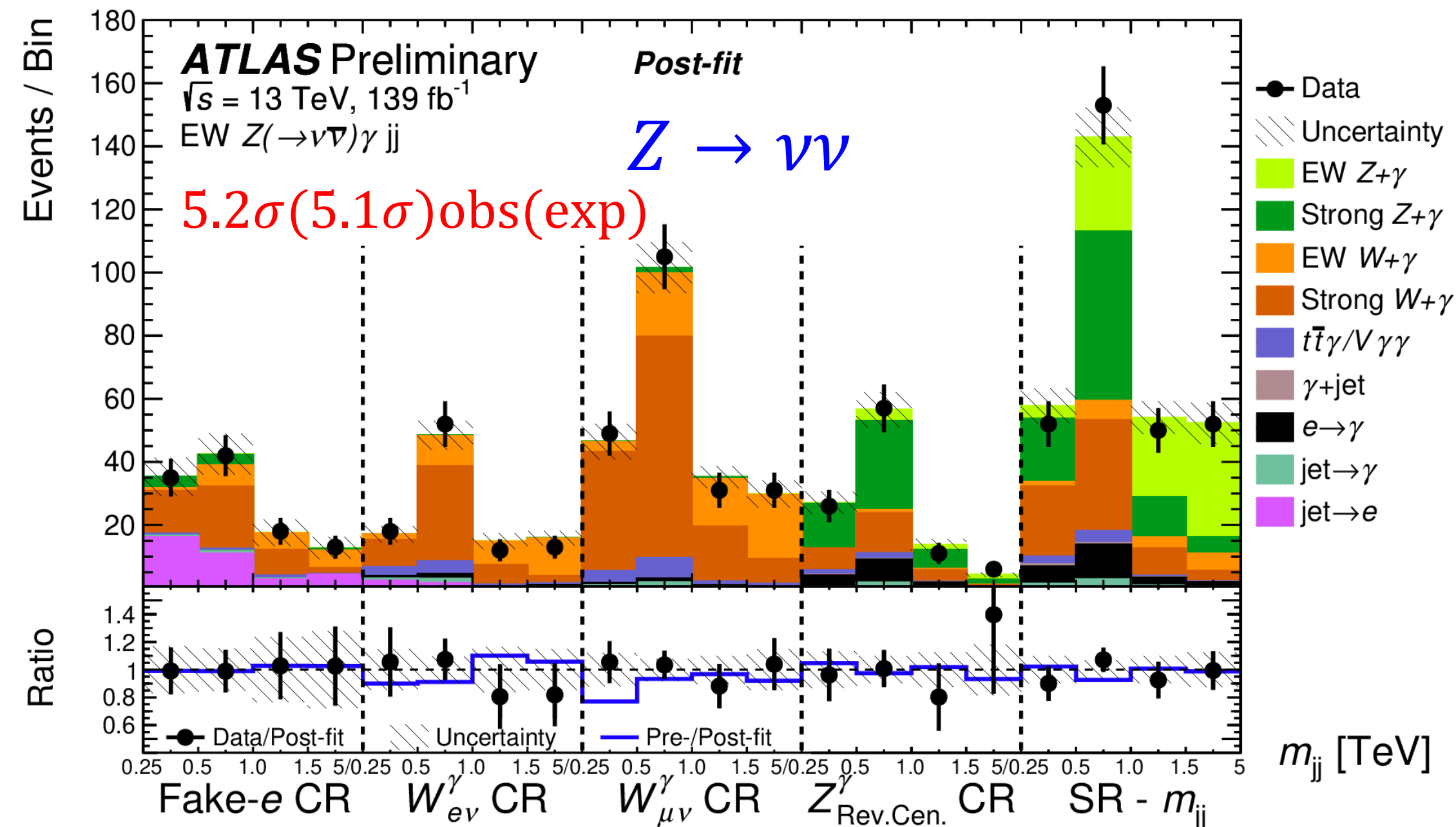
- z distribution also sensitive to rate of gluon splitting to $b\bar{b}$
- Pythia8 and SHERPA generally model data well

Multi-boson production: vector boson scattering

- Key test of EW symmetry
 - > **vector boson self-interactions**
 - > **cubic** and **quartic** couplings; previously observed all $VVjj$, except $Z\gamma jj$
- Events characterized by jets with large mass and rapidity gap
- Signal strength for $Z\gamma jj$ EW production (rel. to LO prediction)
 - $Z \rightarrow \nu\nu$: $\mu_{EW} = 1.03 \pm 0.16(\text{stat}) \pm 0.19(\text{syst})$
 - $Z \rightarrow \ell\ell$: $\mu_{EW} = 0.95 \pm 0.08(\text{stat}) \pm 0.11(\text{syst})$

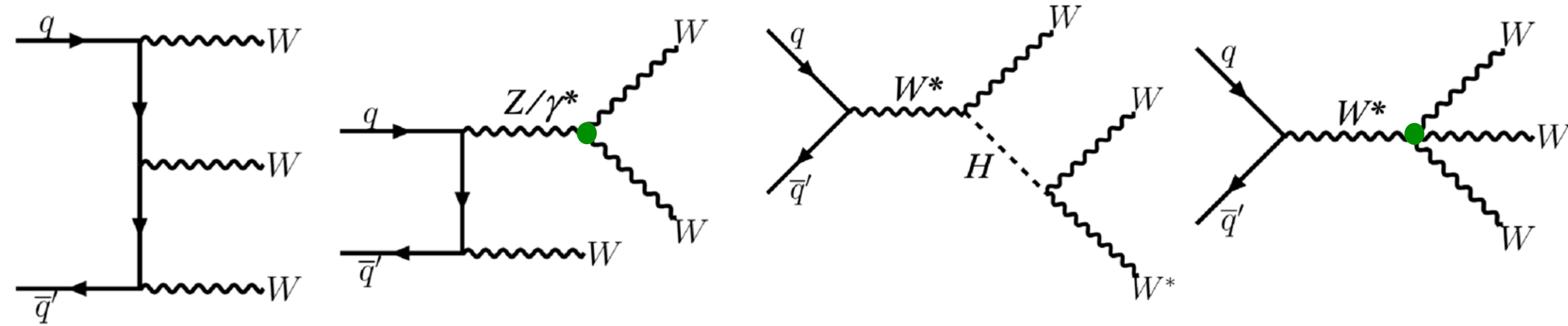


most precise with 13% cross-section uncert.



WWW production

- Rare process providing access to **W/Z self-interactions**
 → **cubic** and **quartic** couplings

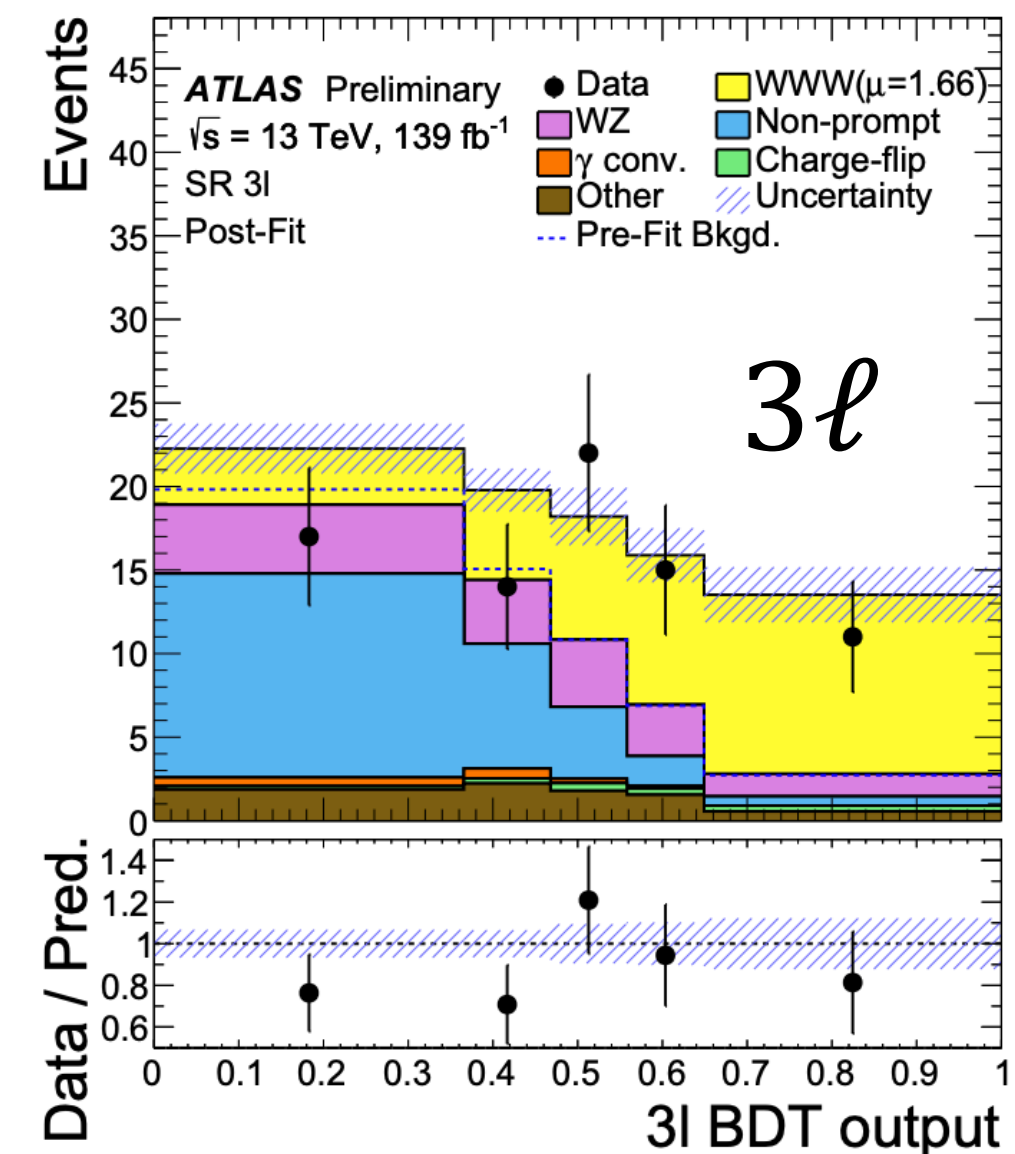
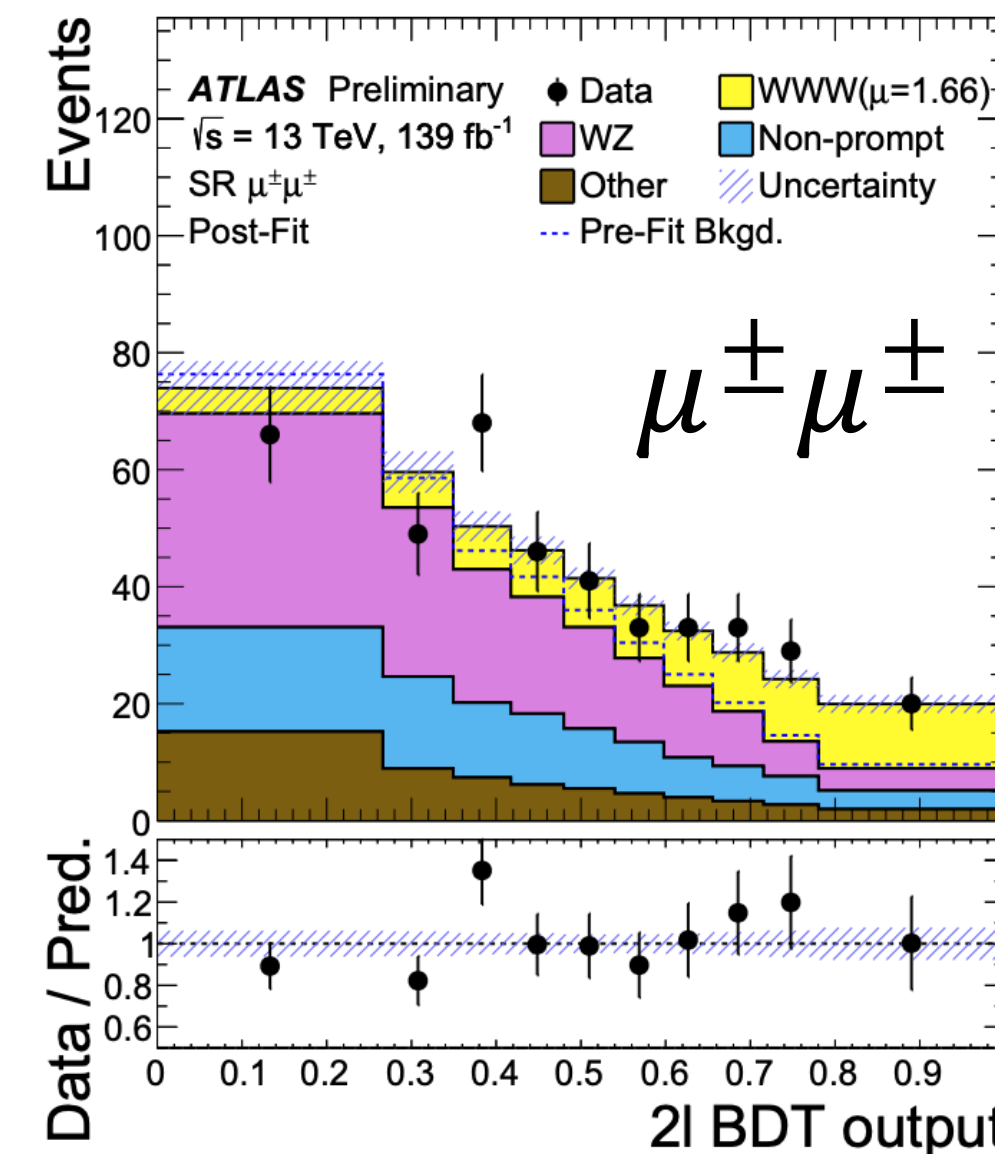
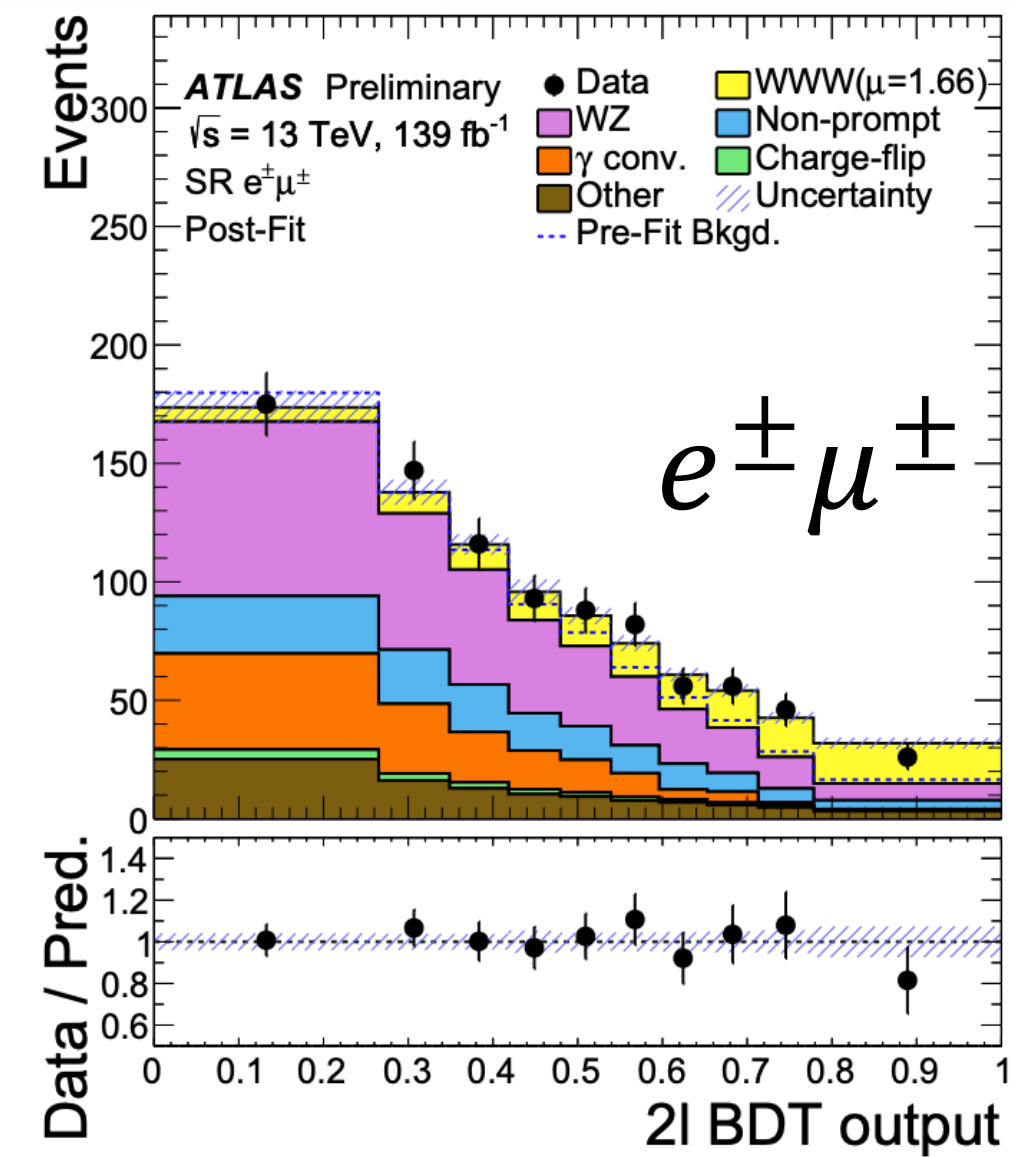
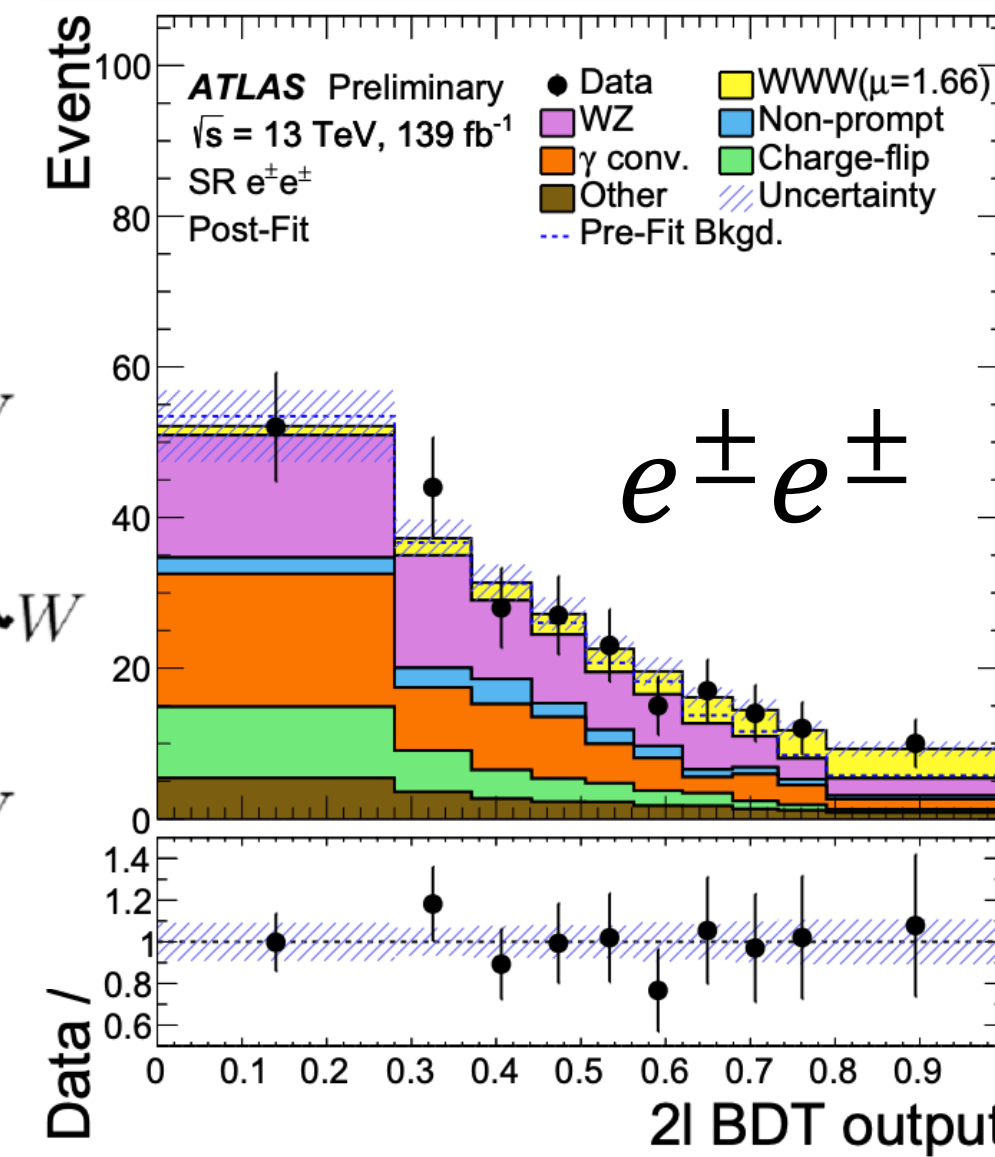


- Channels: $W^\pm W^\pm W^\mp \rightarrow \ell^\pm \nu \ell^\pm \nu q q'$ with $\ell = e, \mu$

- First WWW observation**

$$\sigma(pp \rightarrow W^\pm W^\pm W^\mp) = 850 \pm 100(\text{stat}) \pm 80(\text{syst})\text{fb}$$

Signal strength: 1.66 ± 0.28

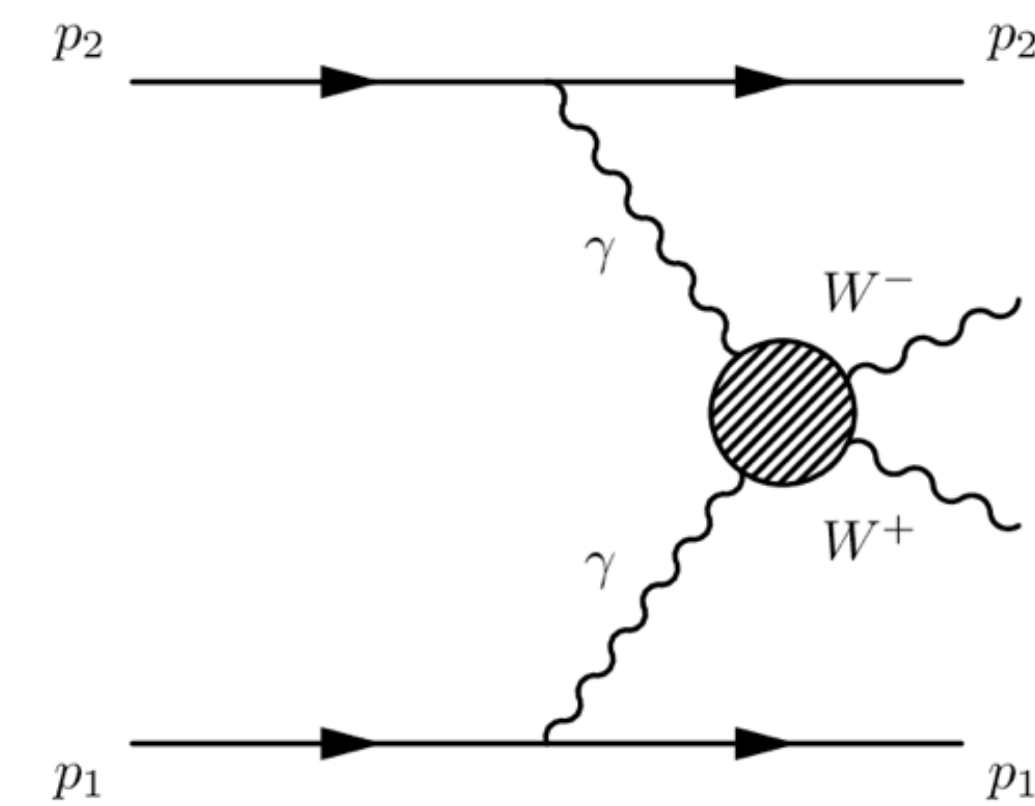
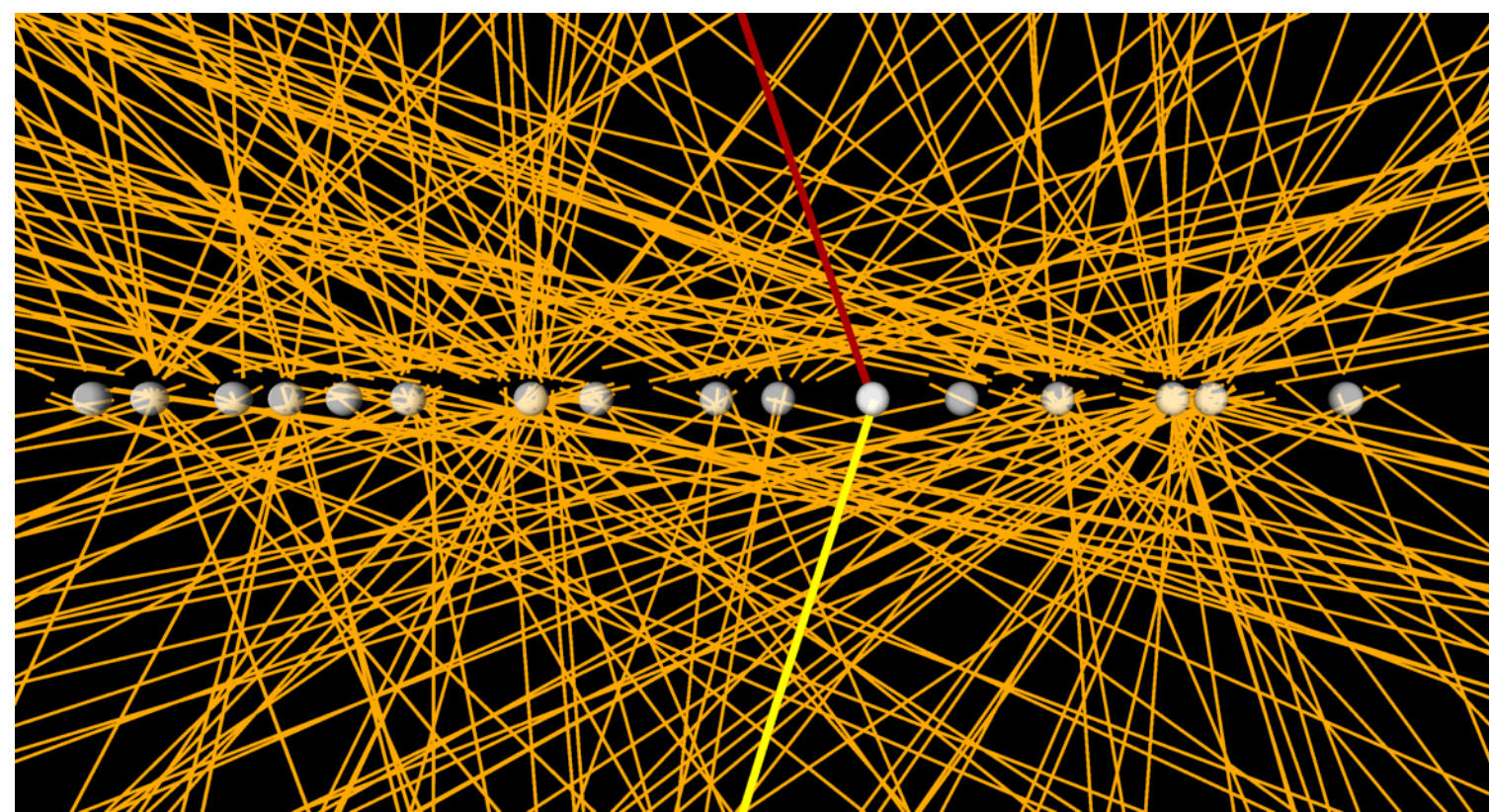


Exclusive WW production

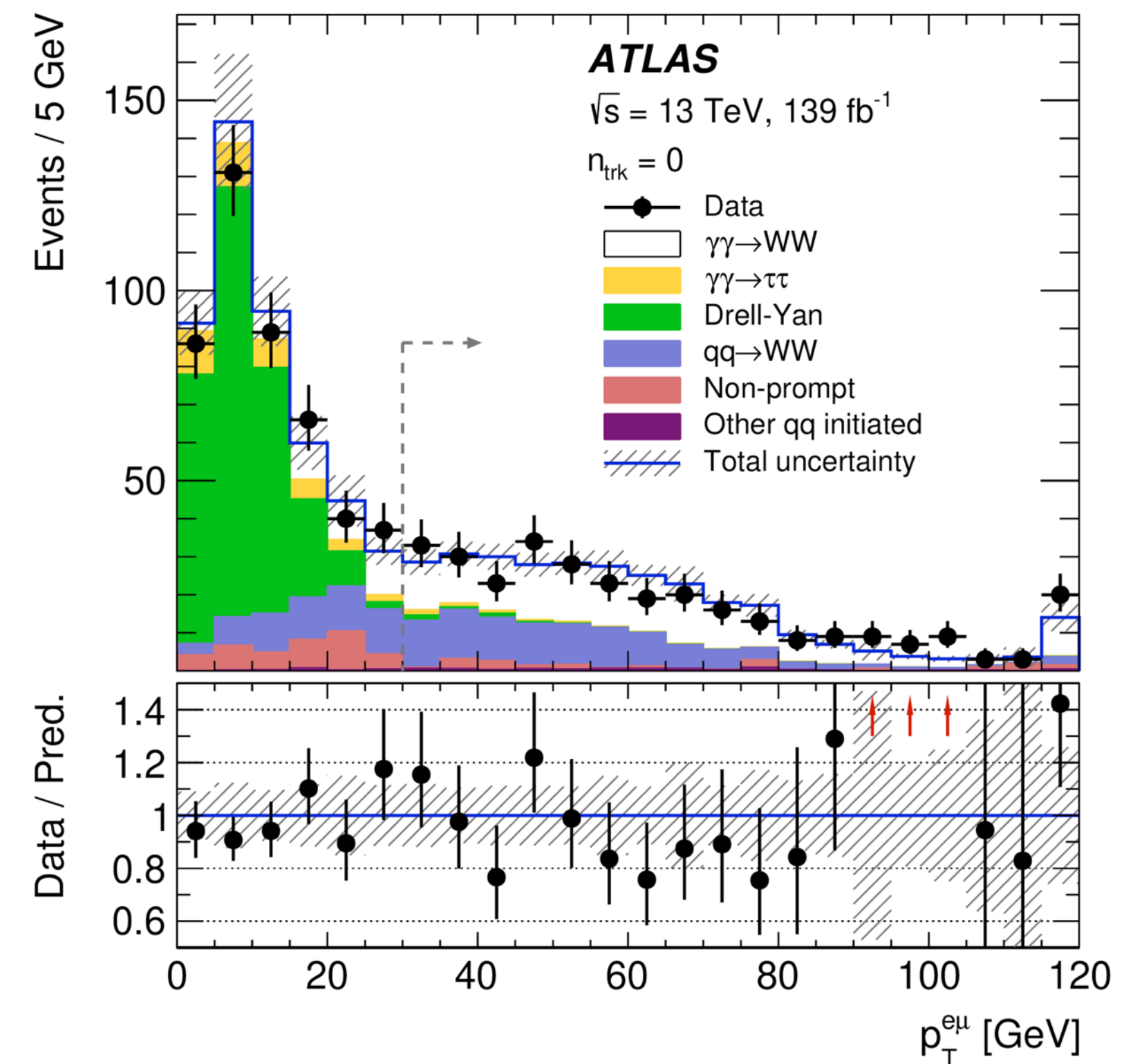
- Exclusive Gamma-gamma-> WW, sensitivity to quartic coupling
- Striking signature: WW and no other tracks emerging from interaction vertex.
- Elastic, single/double-diffractive components
- Channel: opposite charge $W^- \rightarrow e\nu$, $W^- \rightarrow \mu \nu$

$$\sigma_{\text{meas}} = 3.13 \pm 0.31 \text{ (stat.)} \pm 0.28 \text{ (syst.) fb}$$

- In agreement with predictions (MG_aMC@NLO+Py8) once survival factors (0.65-0.82) for proton rescattering are included, consistent with survival factors measured in exclusive di-lepton production



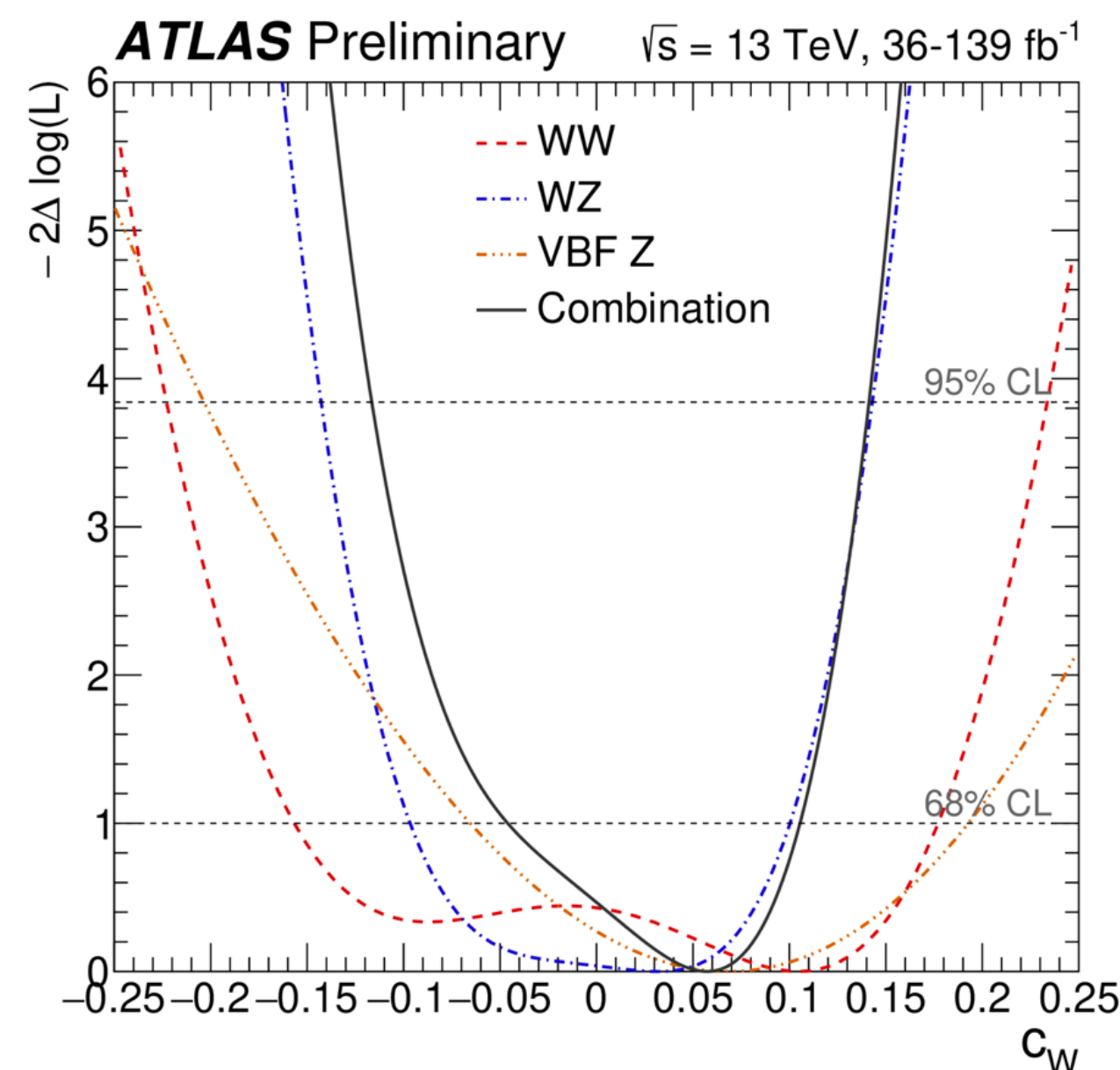
[Phys. Lett. B 816 \(2021\) 136190](#)



- **EFT**: allows to systematically study impact on BSM physics at higher E

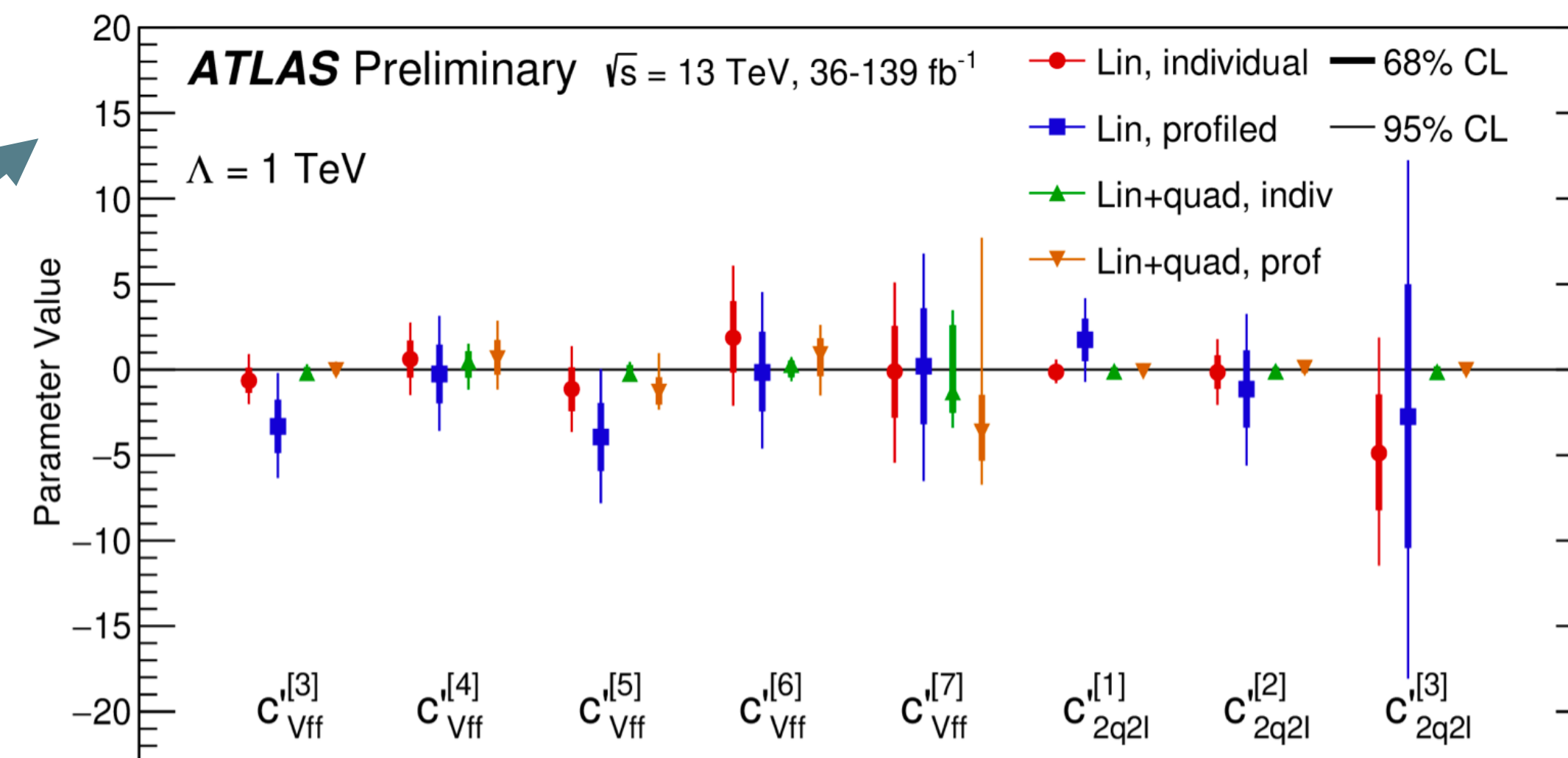
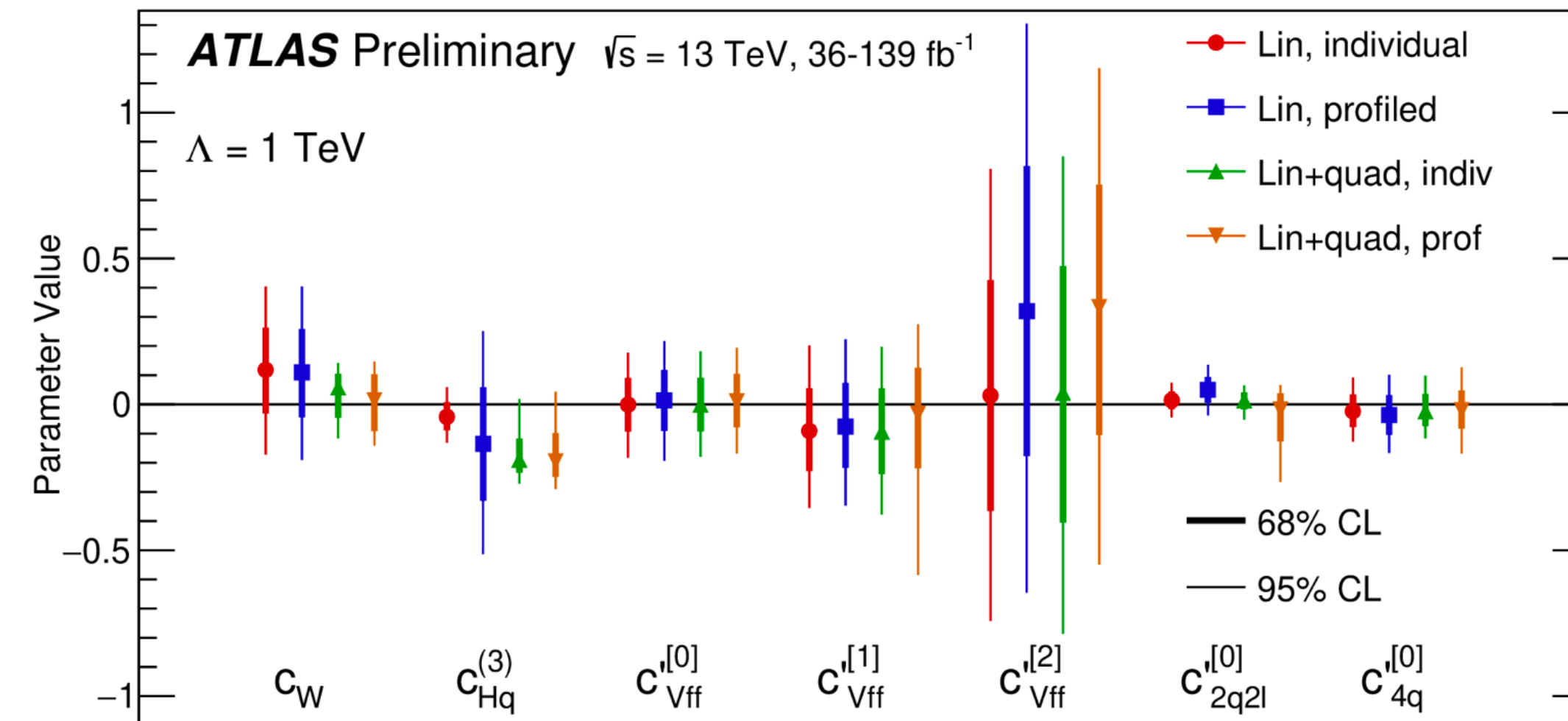
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \dots$$

- Study here is a step toward global EFT fits
- **Input**: 1 differential cross-section for each of WW, WZ, 4-lepton (Z/ZZ*/ZZ), and VBF Z analyses
- **Output**: constrain operators affecting W/Z self-couplings, W/Z couplings to fermions, 4-fermion couplings



Coefficients of all 15 eigenvectors consistent with SM within 2σ

ATL-PHYS-PUB-2021-022

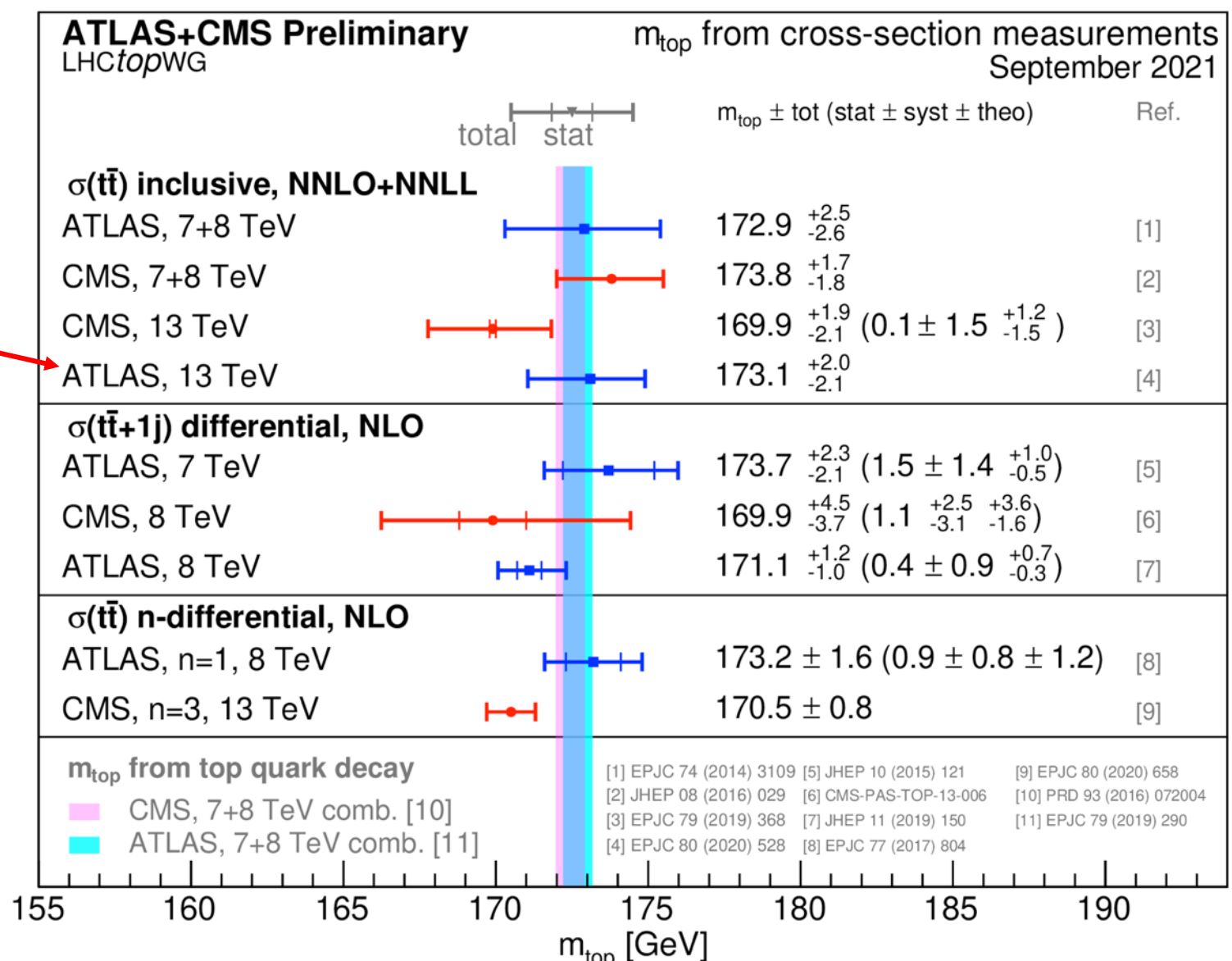
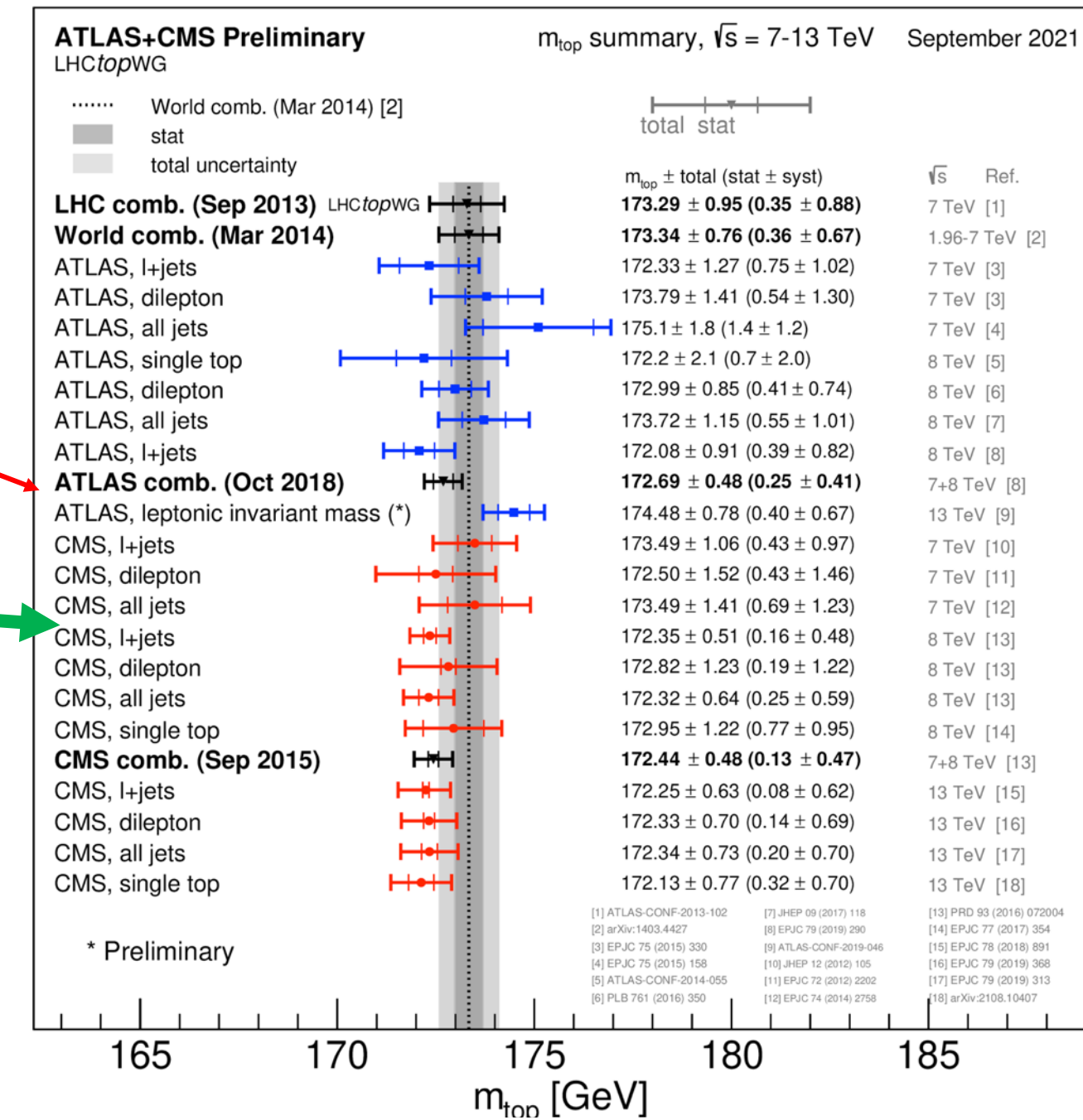


- Run 2: $\sim 1.2 \times 10^8 t\bar{t}$ produced
- Top mass: key SM parameter
- m_{Top} from reconstructed final state, very precise but suffers from hadronization uncertainties $O(\Lambda_{\text{QCD}})$
- Rigorous study of relation between mass from Powheg-Pythia MC-template and MSR mass, fitting fragmentation parameters from data:

$$m_t^{\text{MC}} = m_t^{\text{MSR}}(1 \text{ GeV}) + 80_{-410}^{+350} \text{ MeV}, \quad \text{ATL-PHYS-PUB-2021-034}$$

- Measurement of m_{Top} from cross-sections: closer to theoretical definition but larger uncertainty

Run2

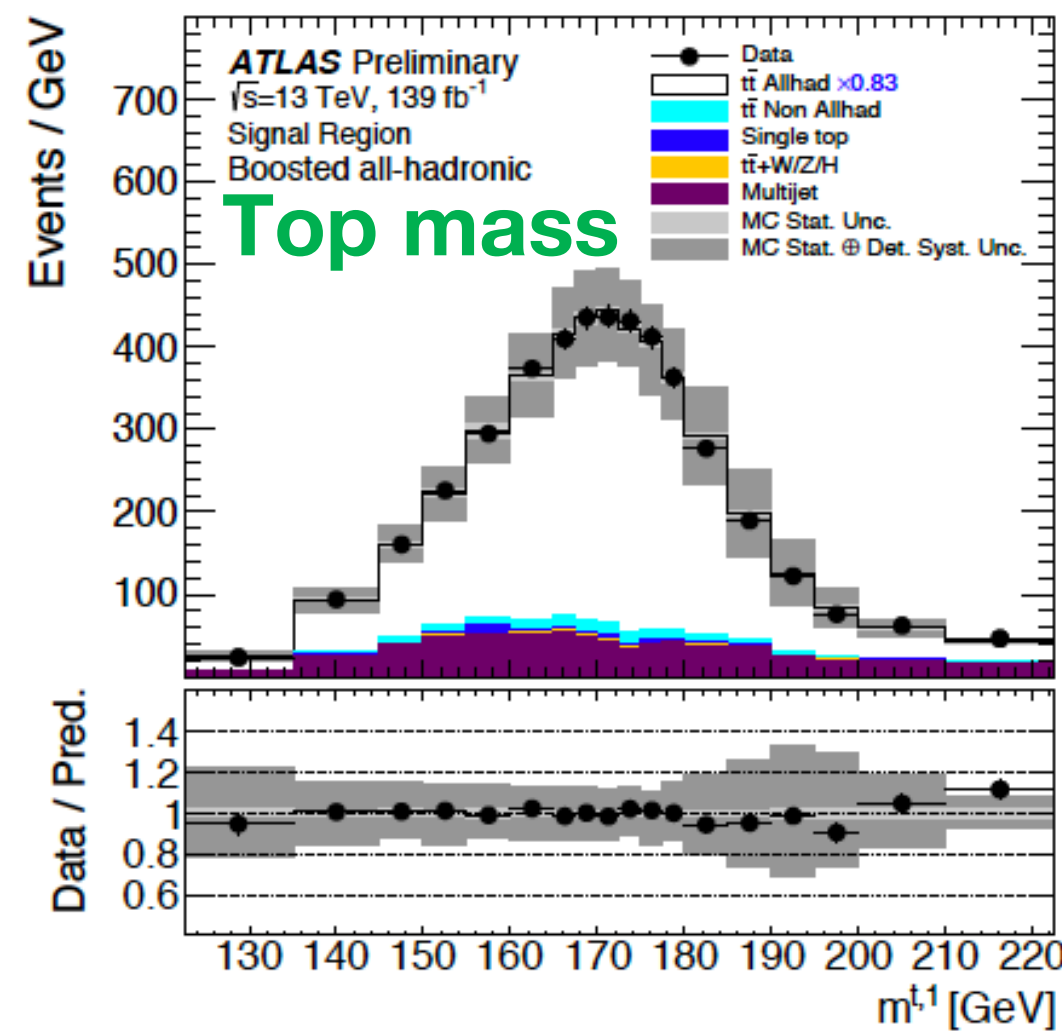
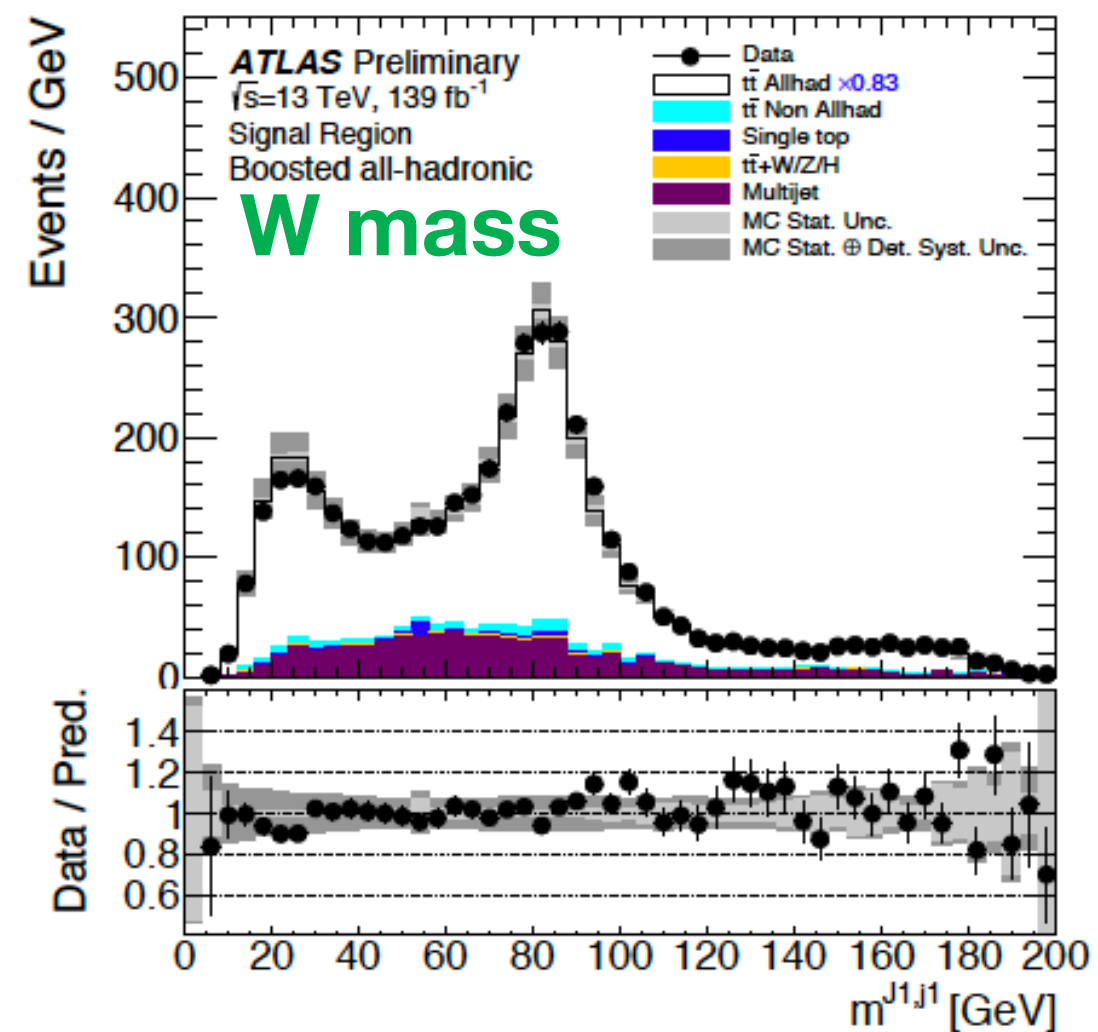
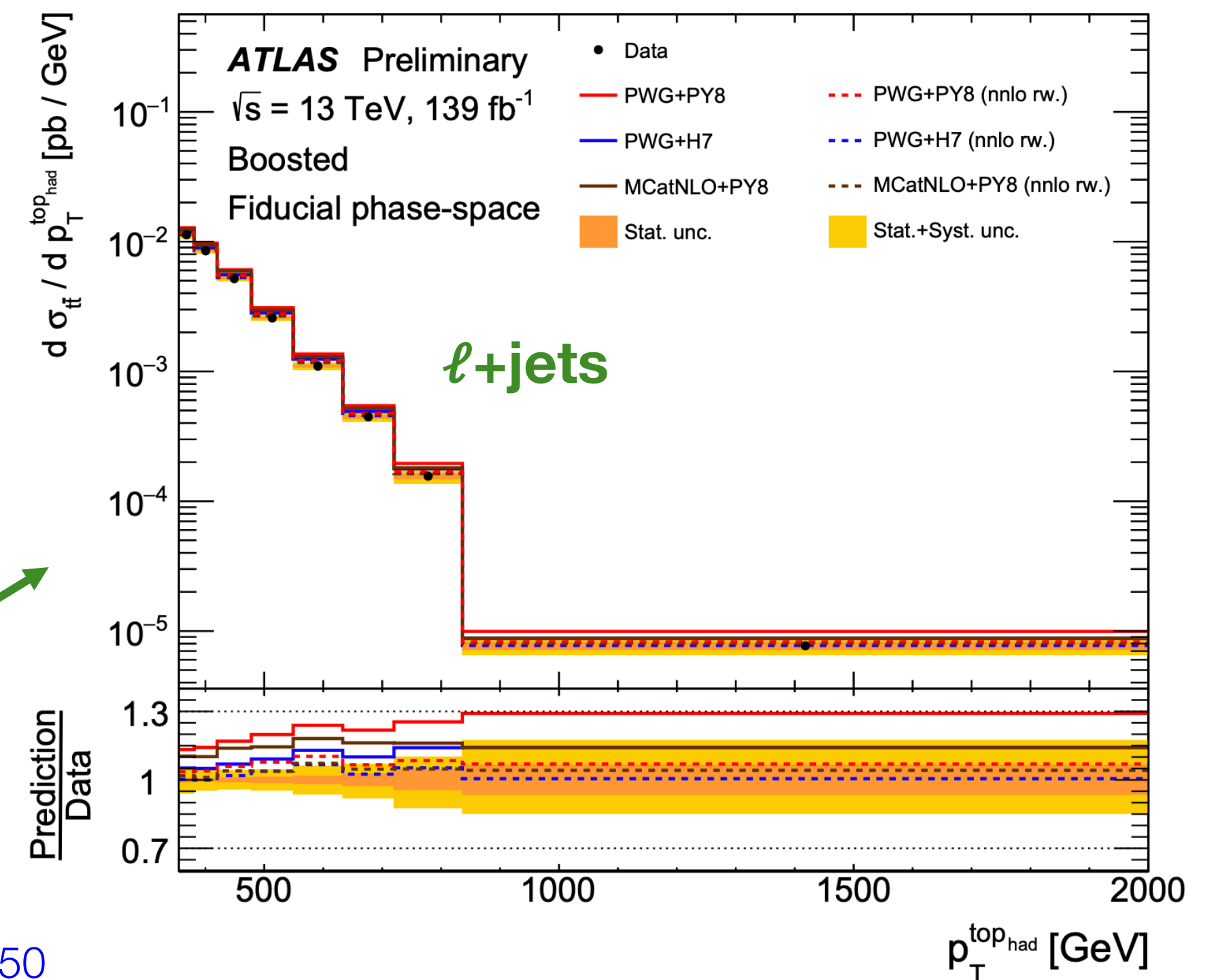


Run2

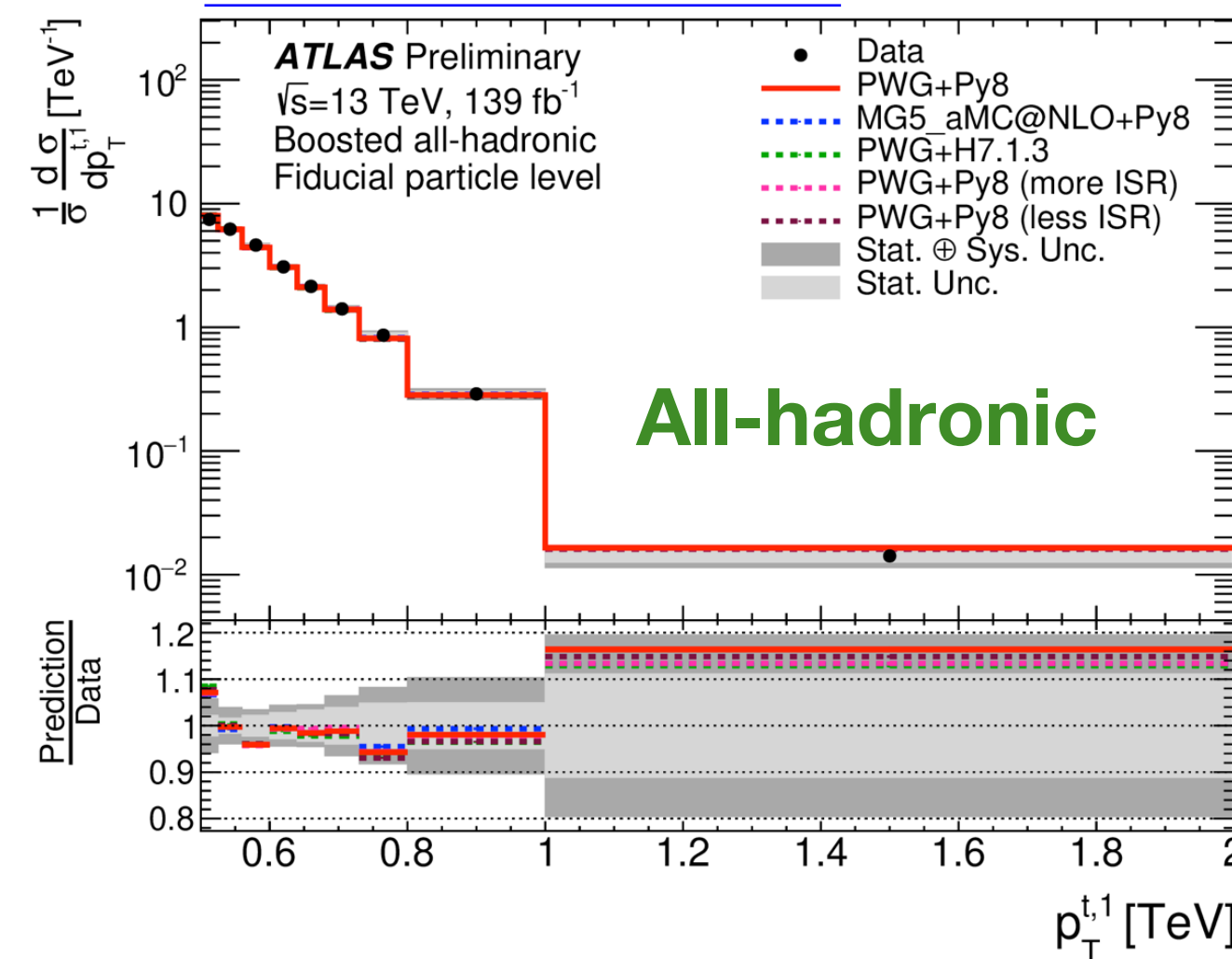
Boosted top-quark production

- Test SM at high p_T^{top} , where deviations expected from BSM
- SM predictions at NNLO QCD + NLO EW
 - ℓ +jets channel: $t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b qq'b$
 - All hadronic channel: $t\bar{t} \rightarrow WbWb \rightarrow qq'b qq'b$
- Reconstruct **hadronic top** as reclustered R=1.0 anti-kt jet
- Energy scale constraint from top (and W) mass
- p_T^{top} spectrum too hard for NLO generators but improves with NNLO calculation

ATLAS-CONF-2021-031

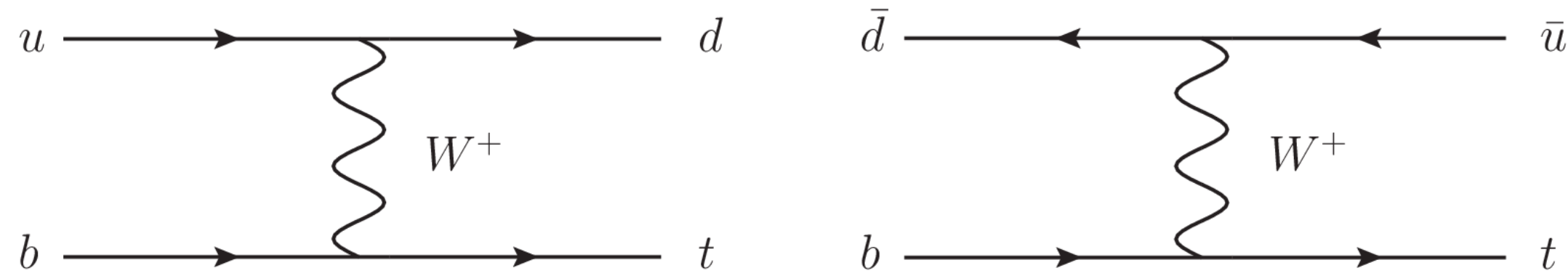


ATLAS-CONF-2021-050

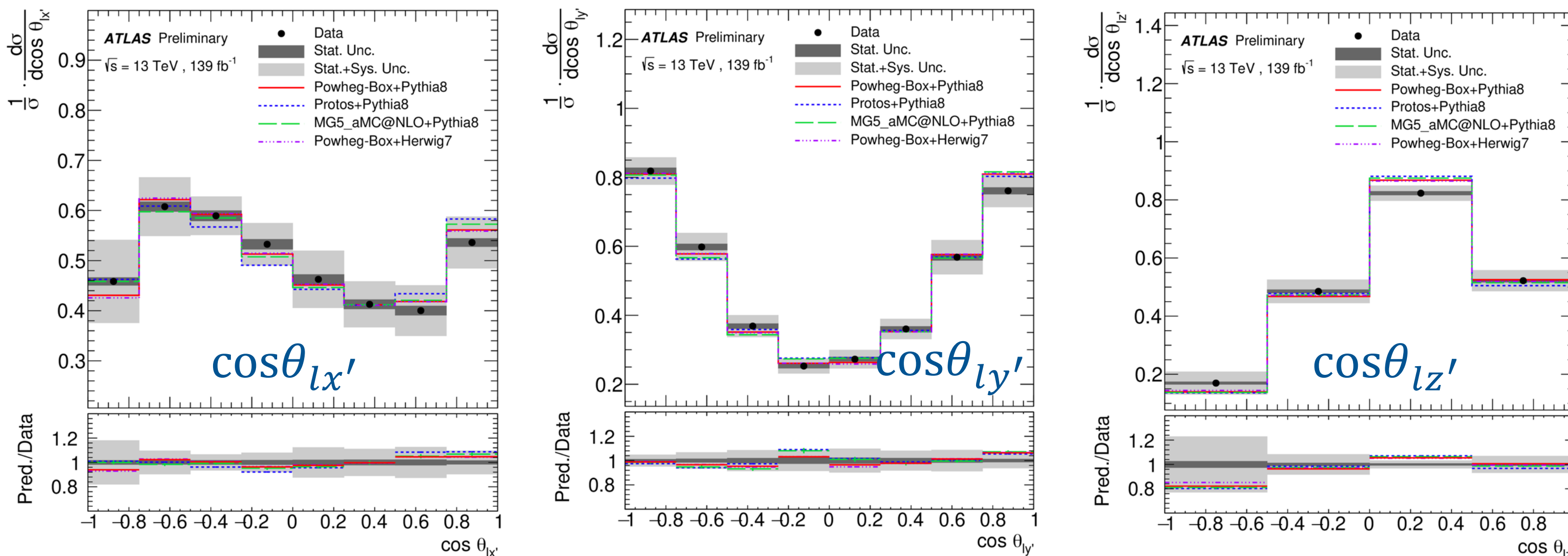
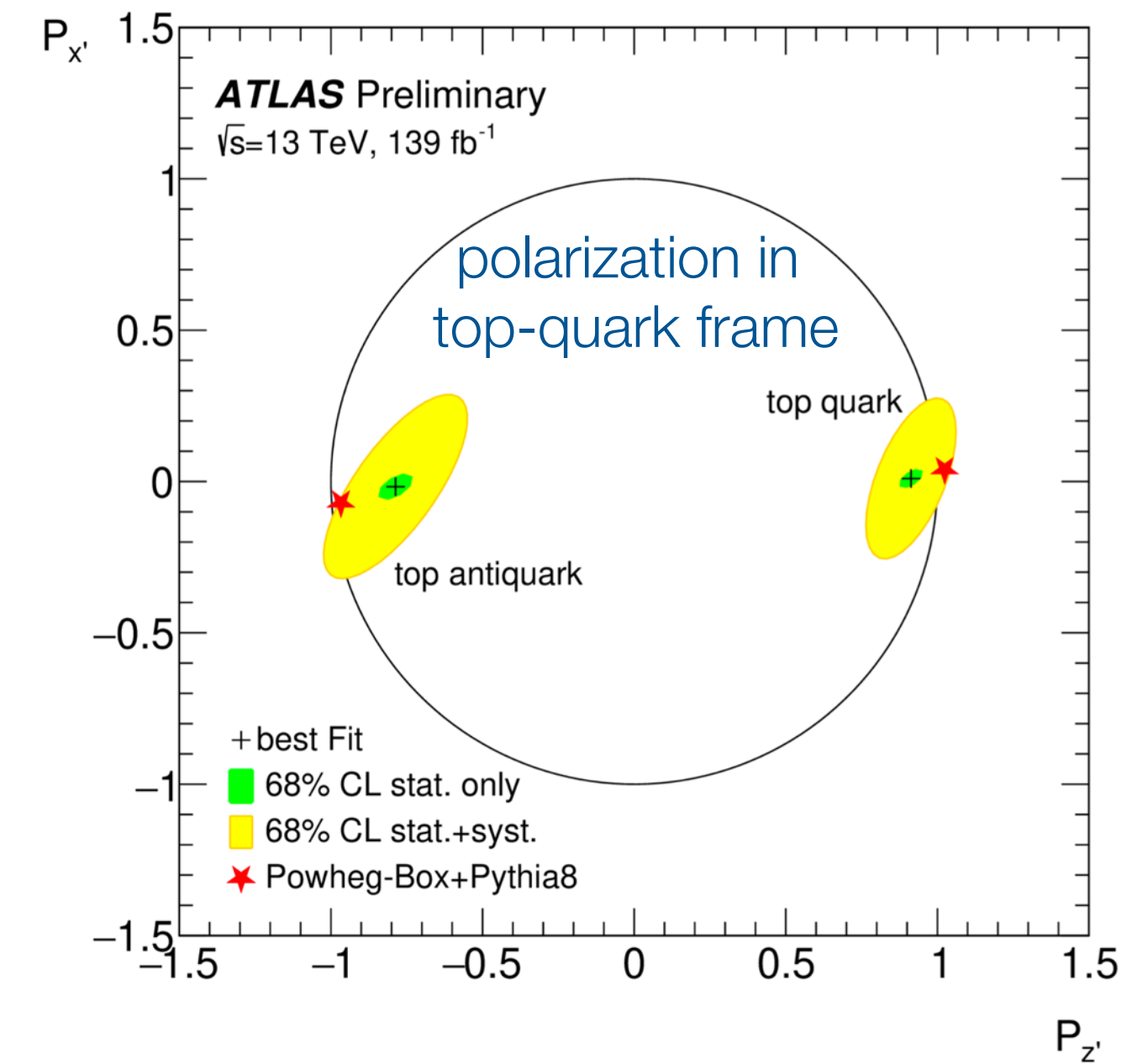
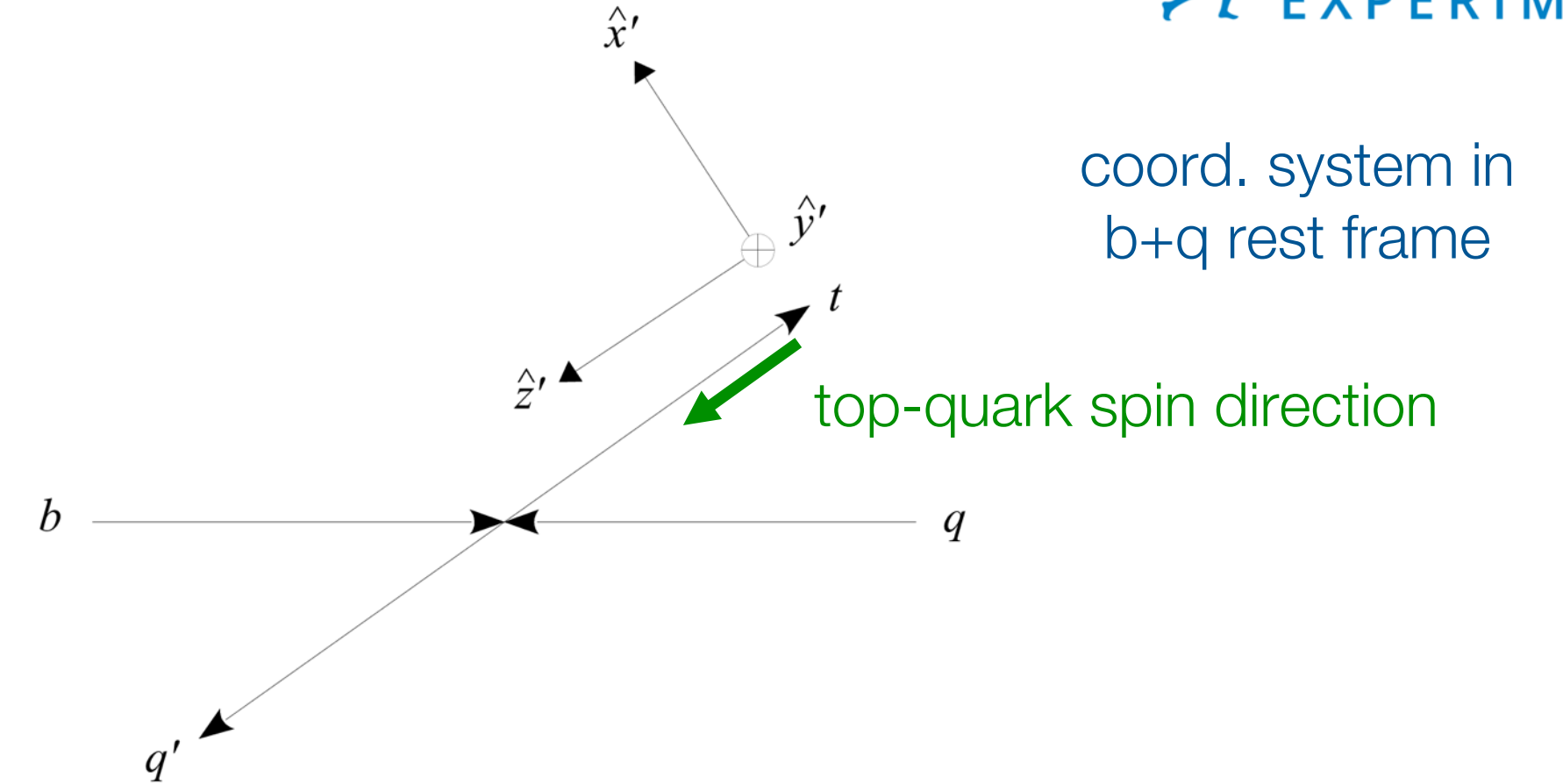


Single-top quark polarization

- t -channel dominates single top-quark production



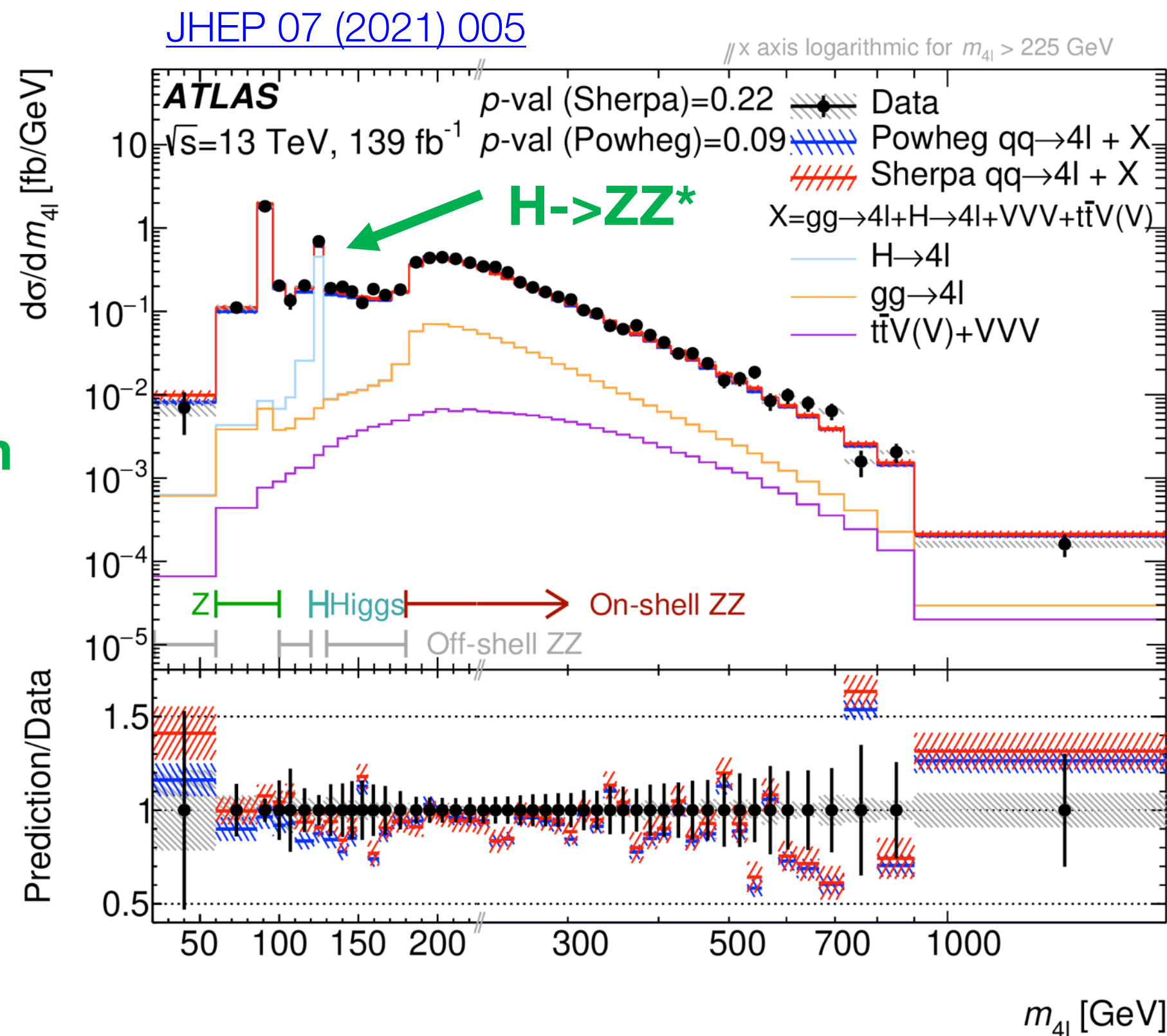
- High polarization expected from V-A structure of CC weak interaction + test BSM impact on tWb vertex
- First measurement of polarization vector in 3-D via angular distributions of lepton (e or μ) from $t \rightarrow b\ell\nu$ decay



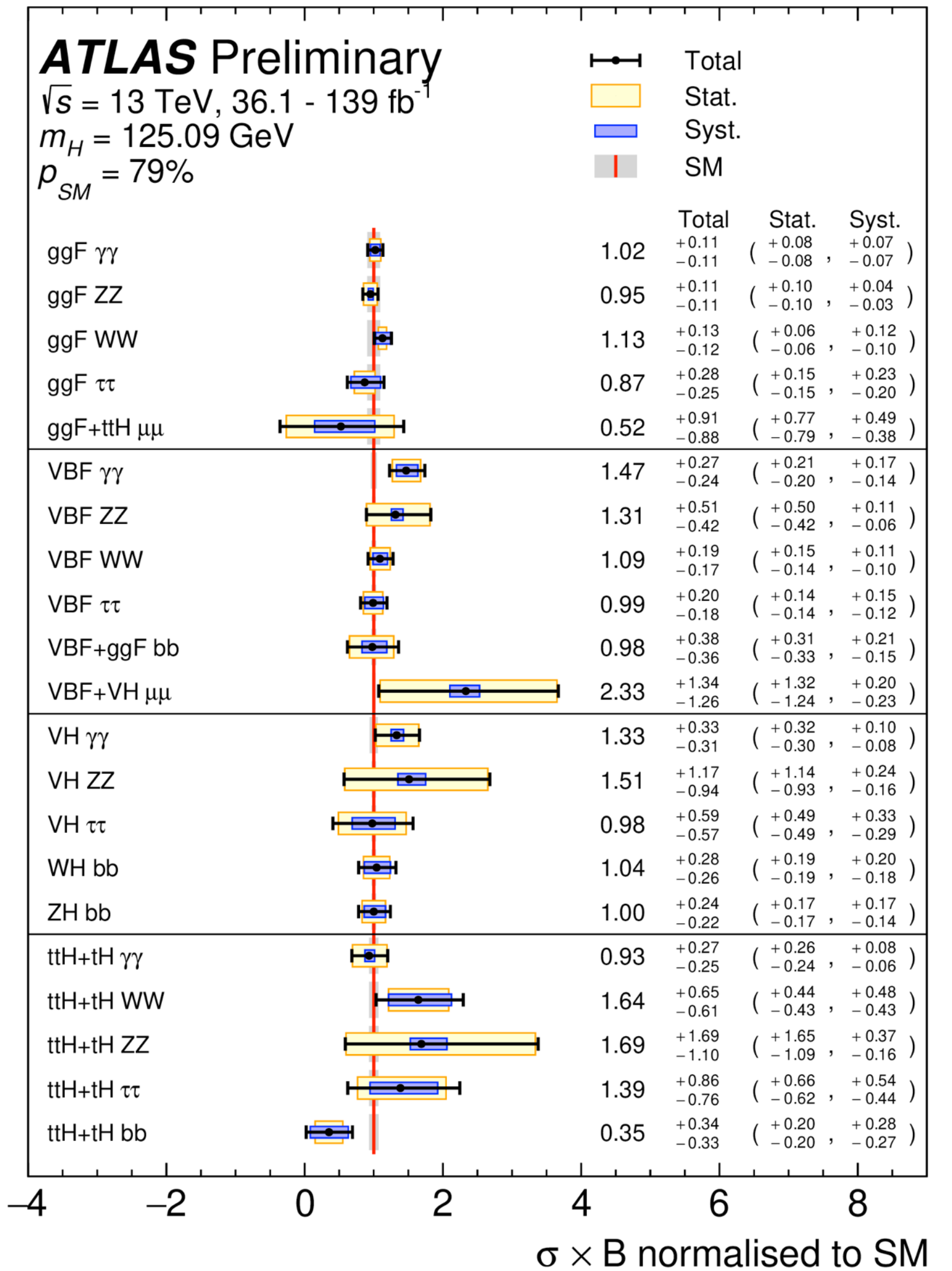
- Constraints placed on Re and Im parts of EFT operator \mathcal{O}_{tW}

- Run 2: $\sim 8 \times 10^6$ Higgs bosons produced
- Program: Categorize by decay channel and prod. mechanism, measure data/theory
- Most precise channels ggF: $H \rightarrow \gamma\gamma$, WW^* , ZZ^* with $\sim 11-13\%$ precision, many Run-2 analyses are ongoing

4-lepton mass spectrum

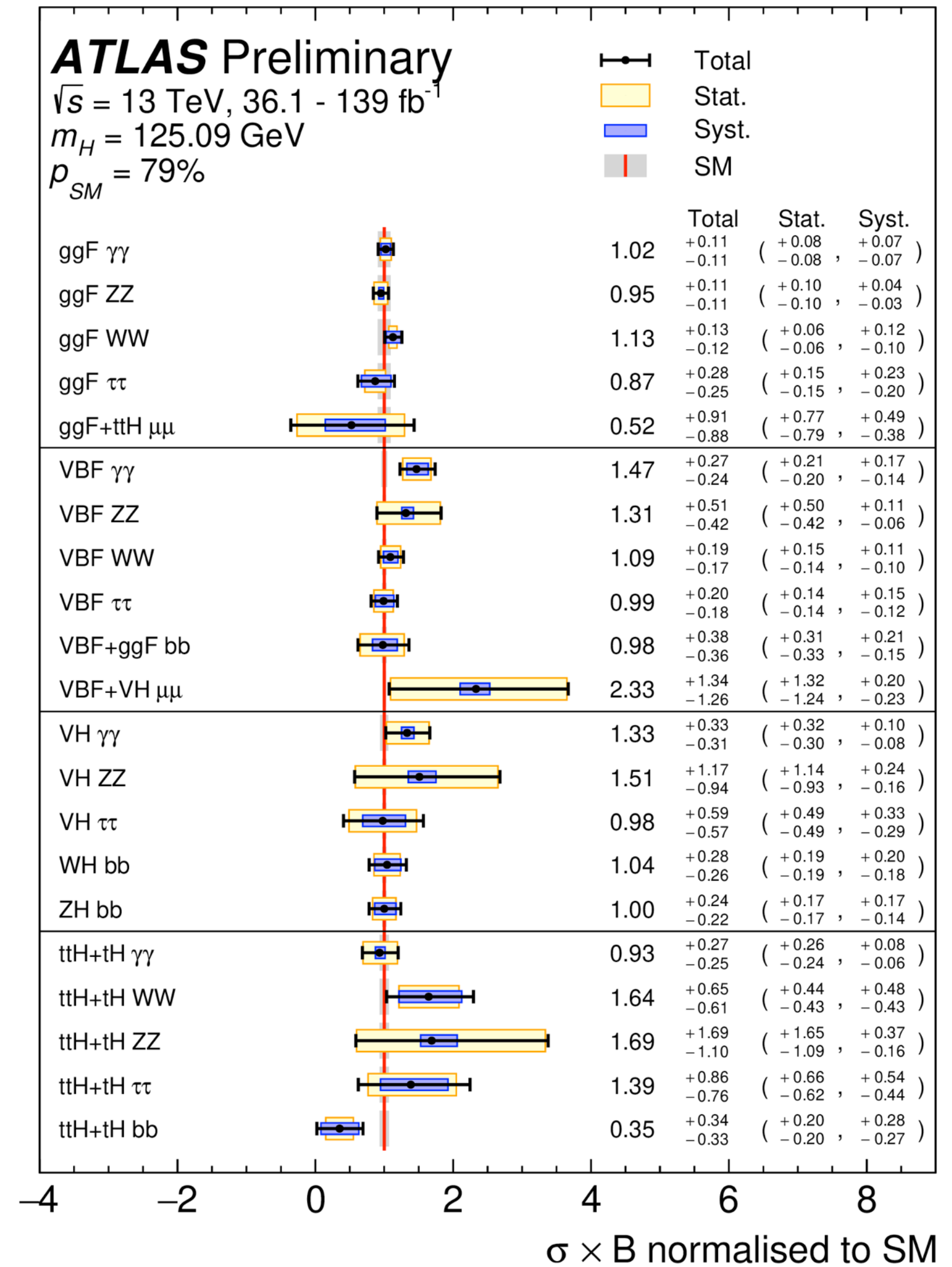
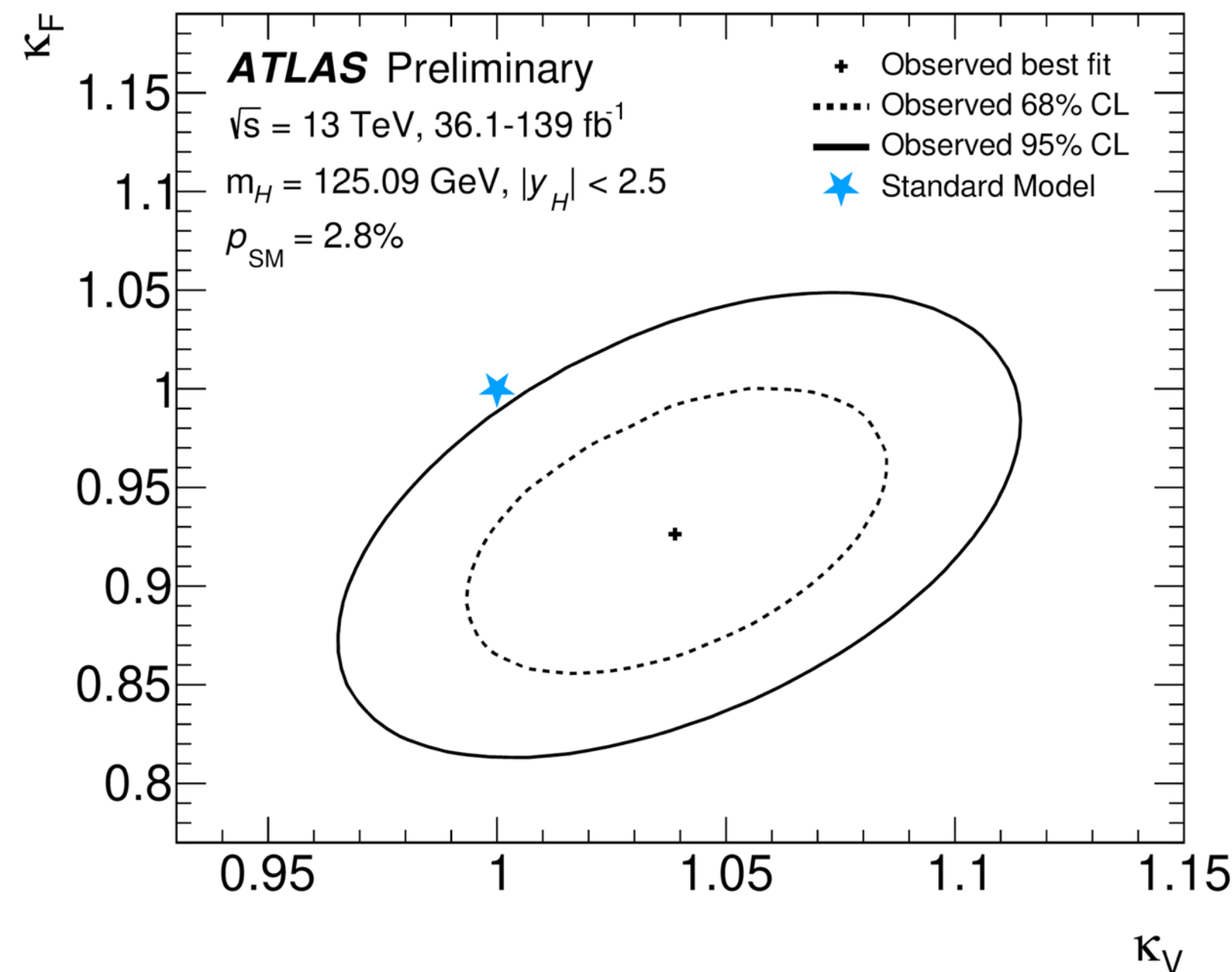
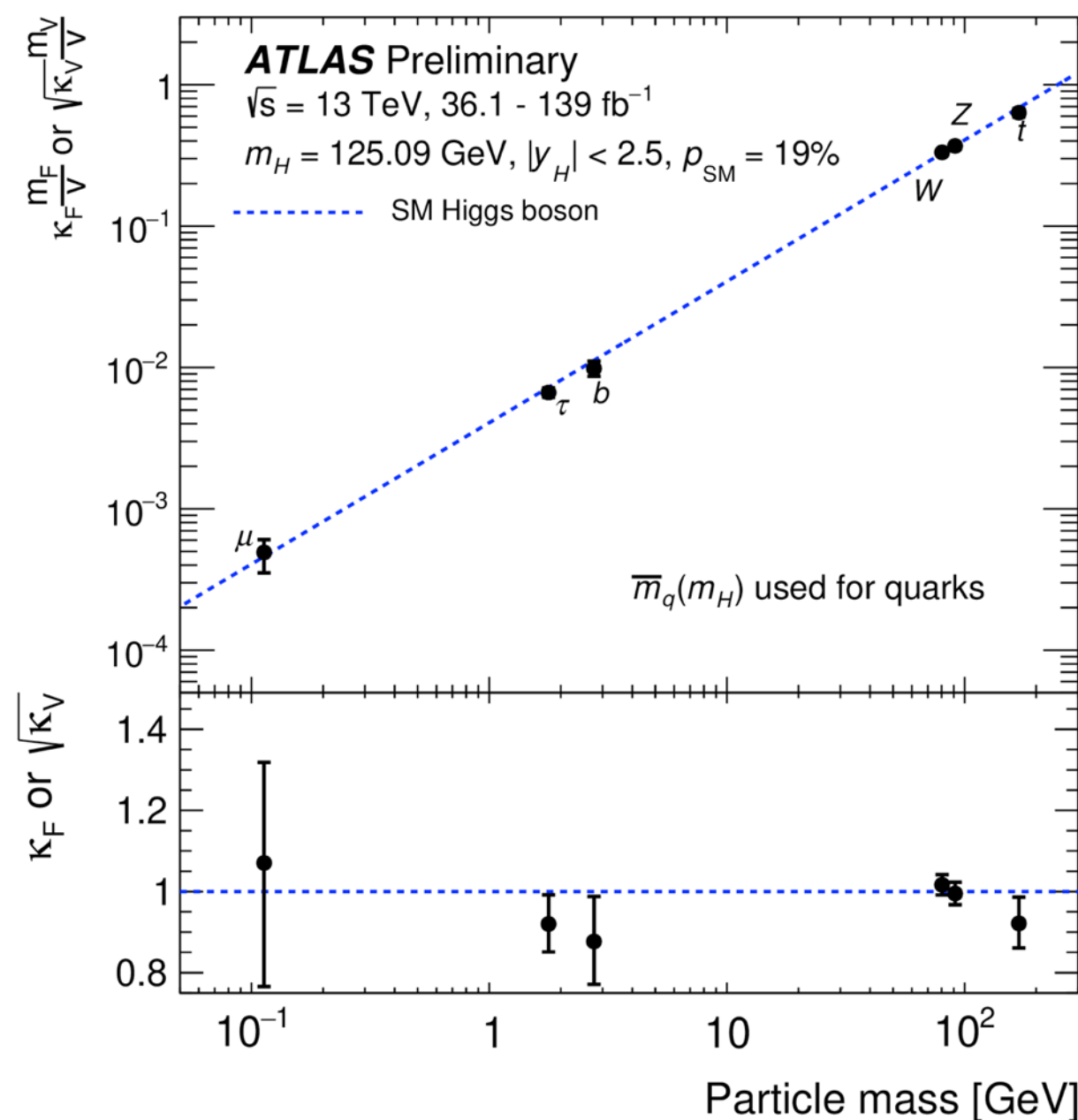


ATLAS-CONF-2021-053



- Run 2: $\sim 8 \times 10^6$ Higgs bosons produced
- Program: Categorize by decay channel and prod mechanism, measure data/theory
- Most precise channels ggF: $H \rightarrow \gamma\gamma, WW^*, ZZ^*$ with $\sim 11-13\%$ precision, many Run-2 analyses are ongoing
- Interpretation with fermion / bosons coupling modifiers

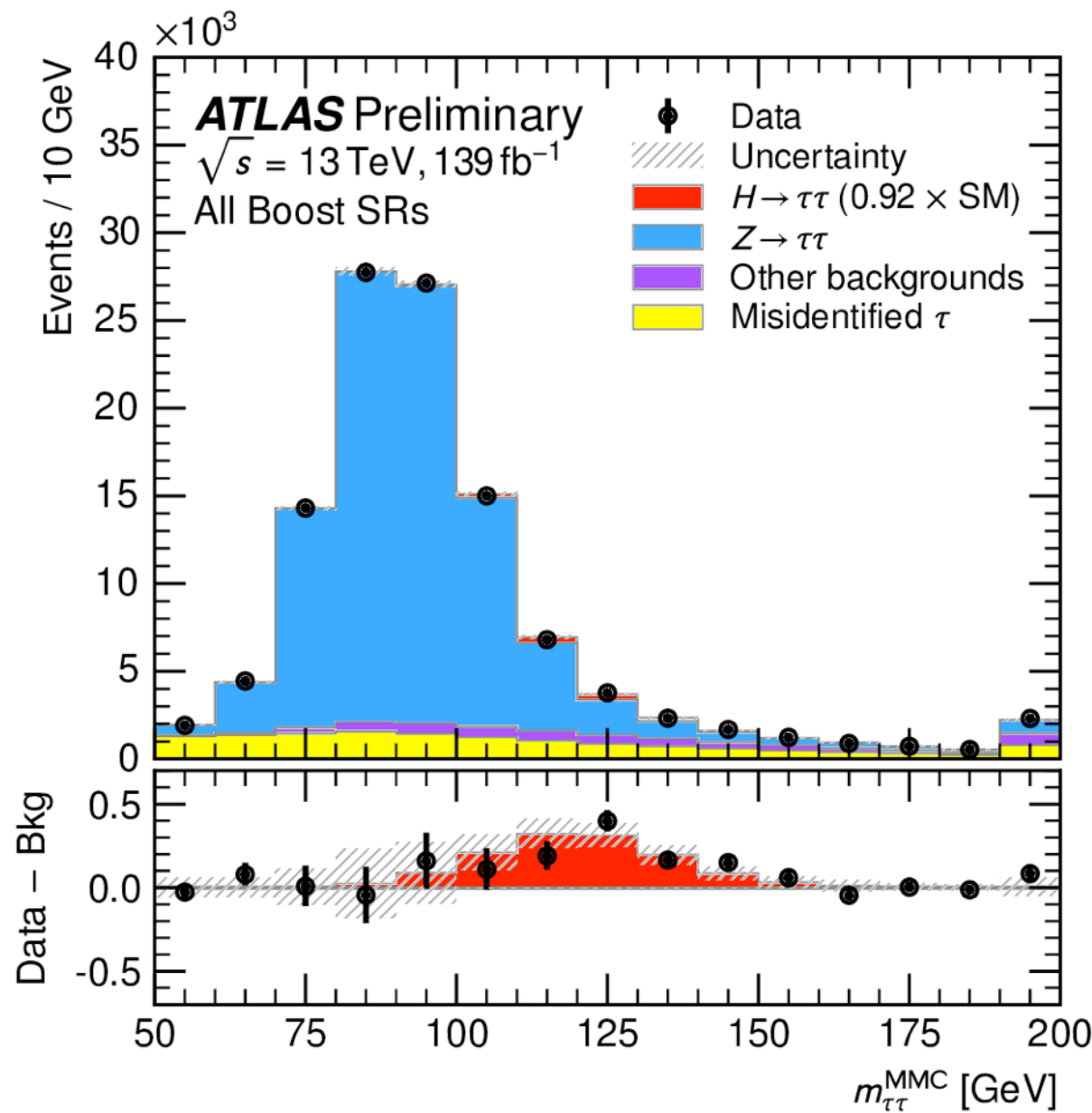
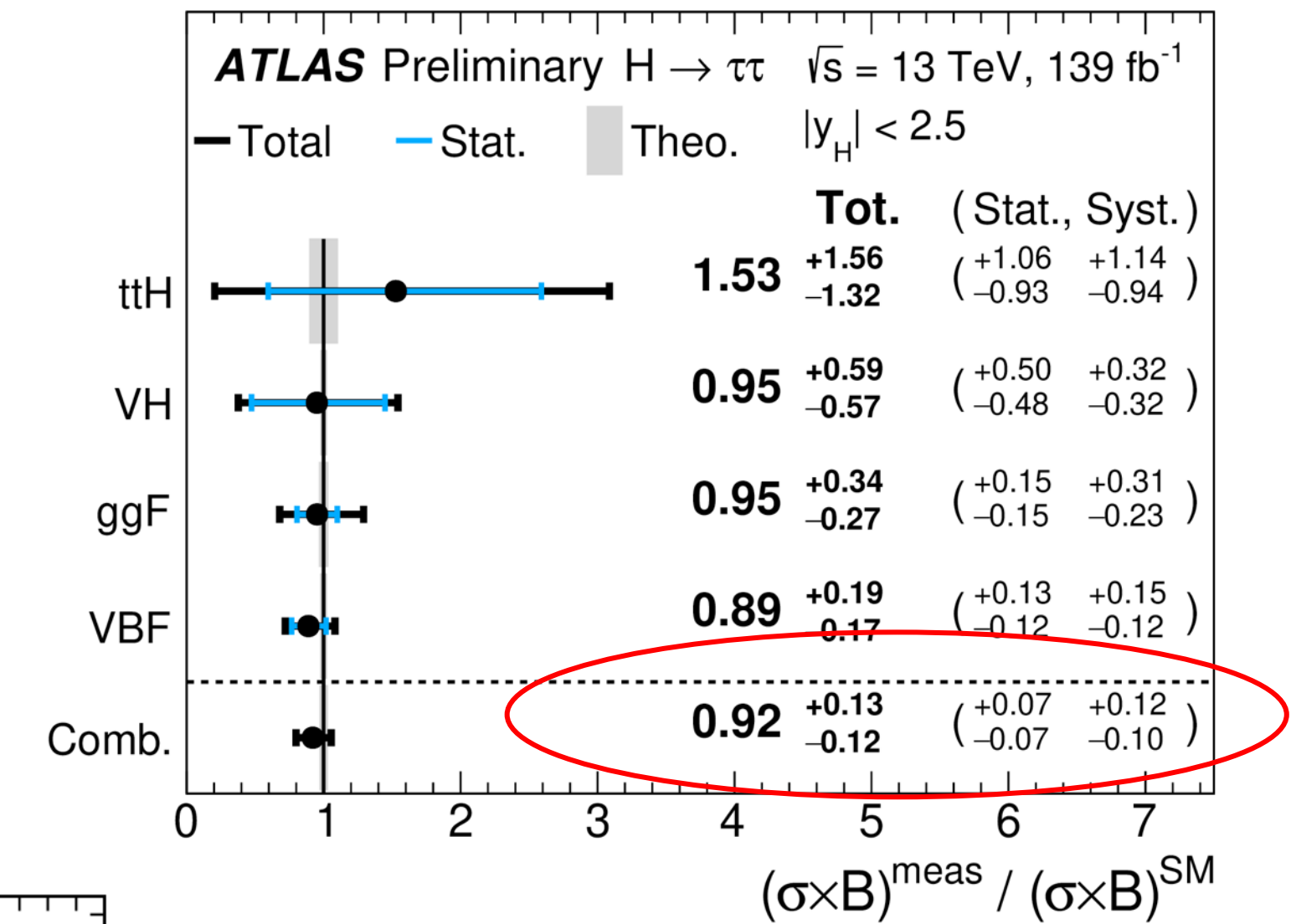
ATLAS-CONF-2021-053



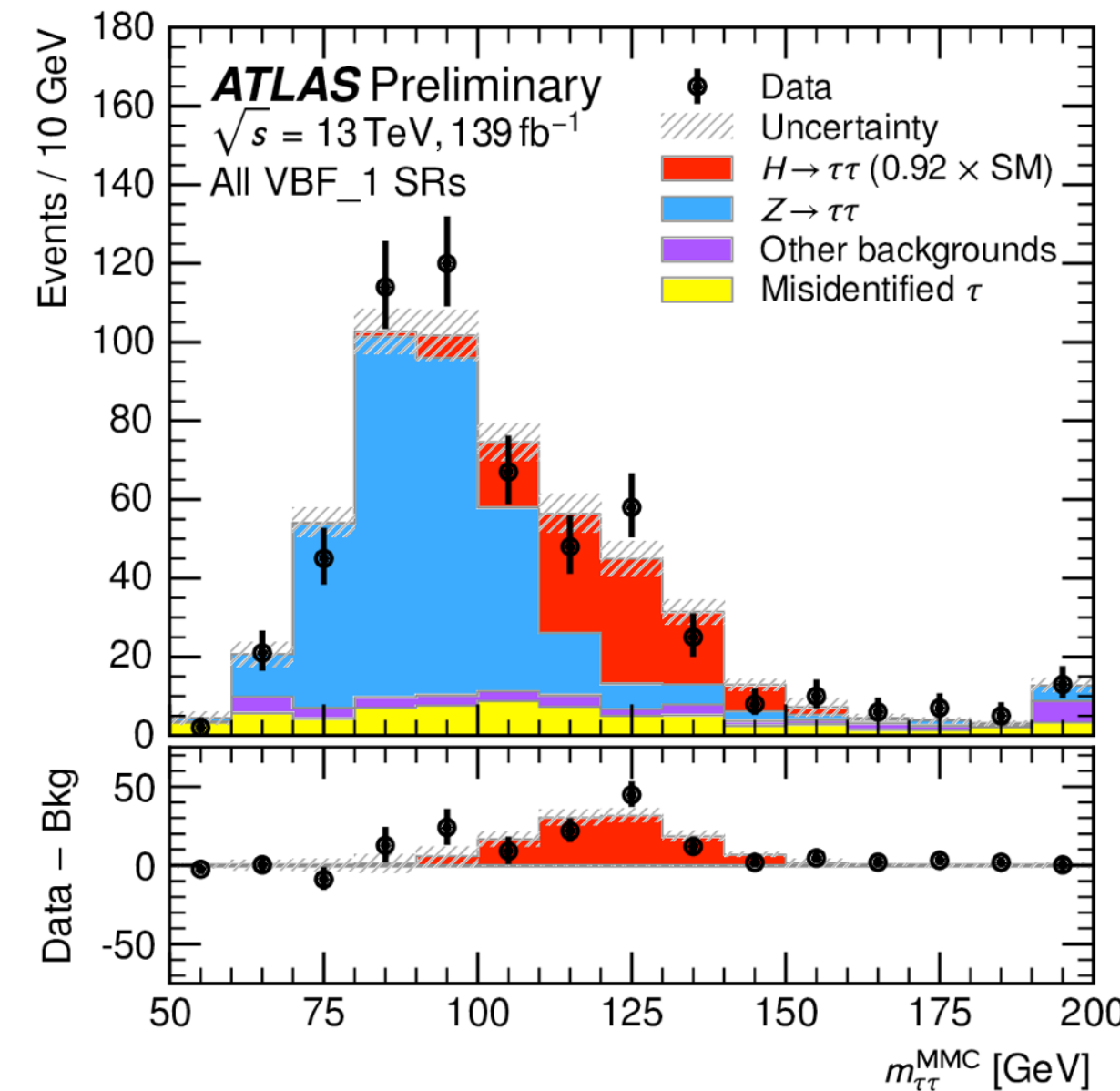
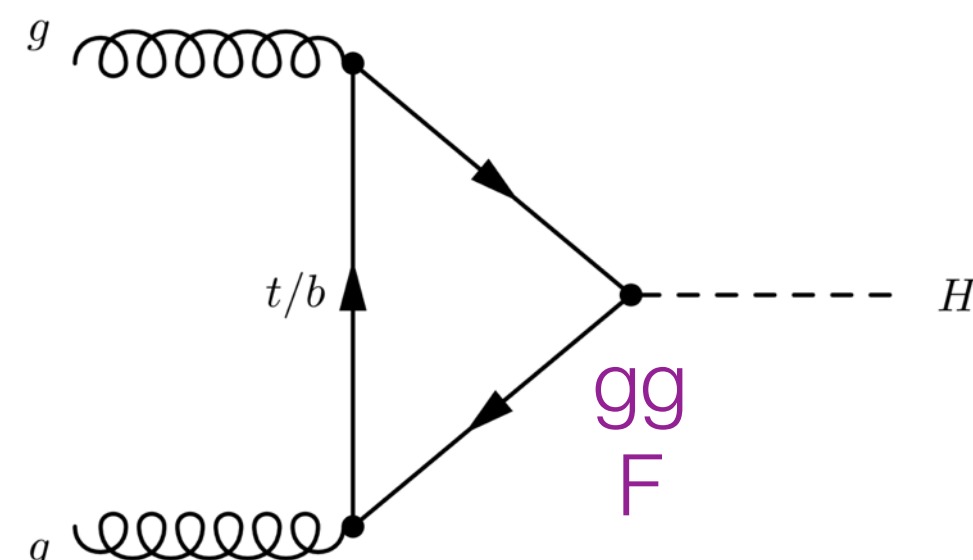
Higgs couplings: τ leptons

- $\mathcal{B}(H \rightarrow \tau\tau) = 6.3\%$ \rightarrow test **Yukawa interactions with leptons**
- Expt. challenge: 2-4 neutrinos in final state, poor mass resolution
- Multiple BDTs used to suppress $Z \rightarrow \tau\tau$ and $t\bar{t}$ background, and categorize event purity for VBF, VH and ttH mechanism
- Dominant $Z \rightarrow \tau\tau$ background from MC, controlled with $Z \rightarrow \ell\ell$ data via kinematic embedding procedure

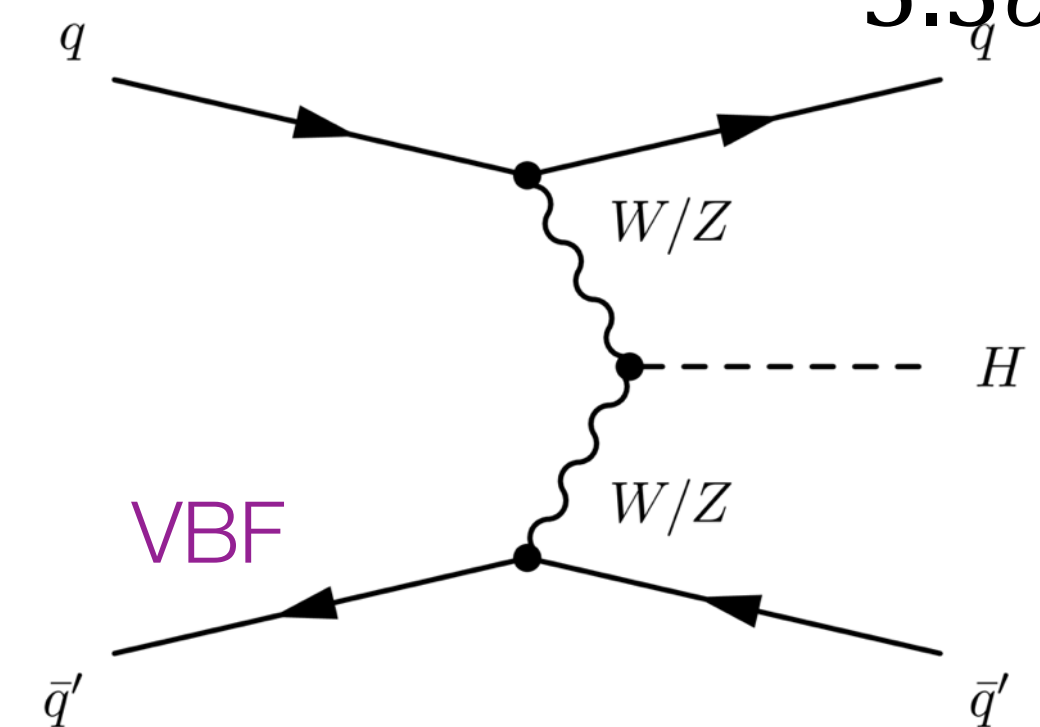
[ATLAS-CONF-2021-044](#)



ggF significance 3.9σ



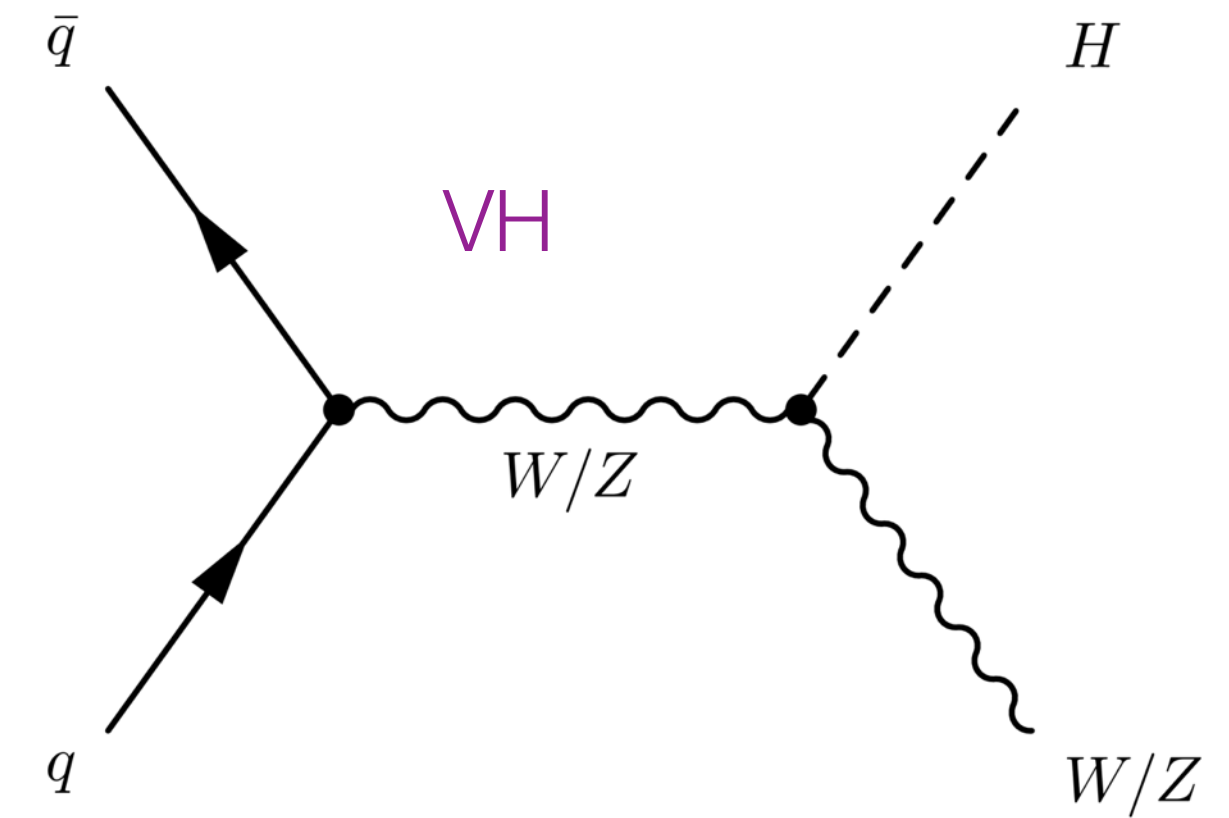
VBF significance 5.3σ



Higgs couplings to 2nd gen quarks

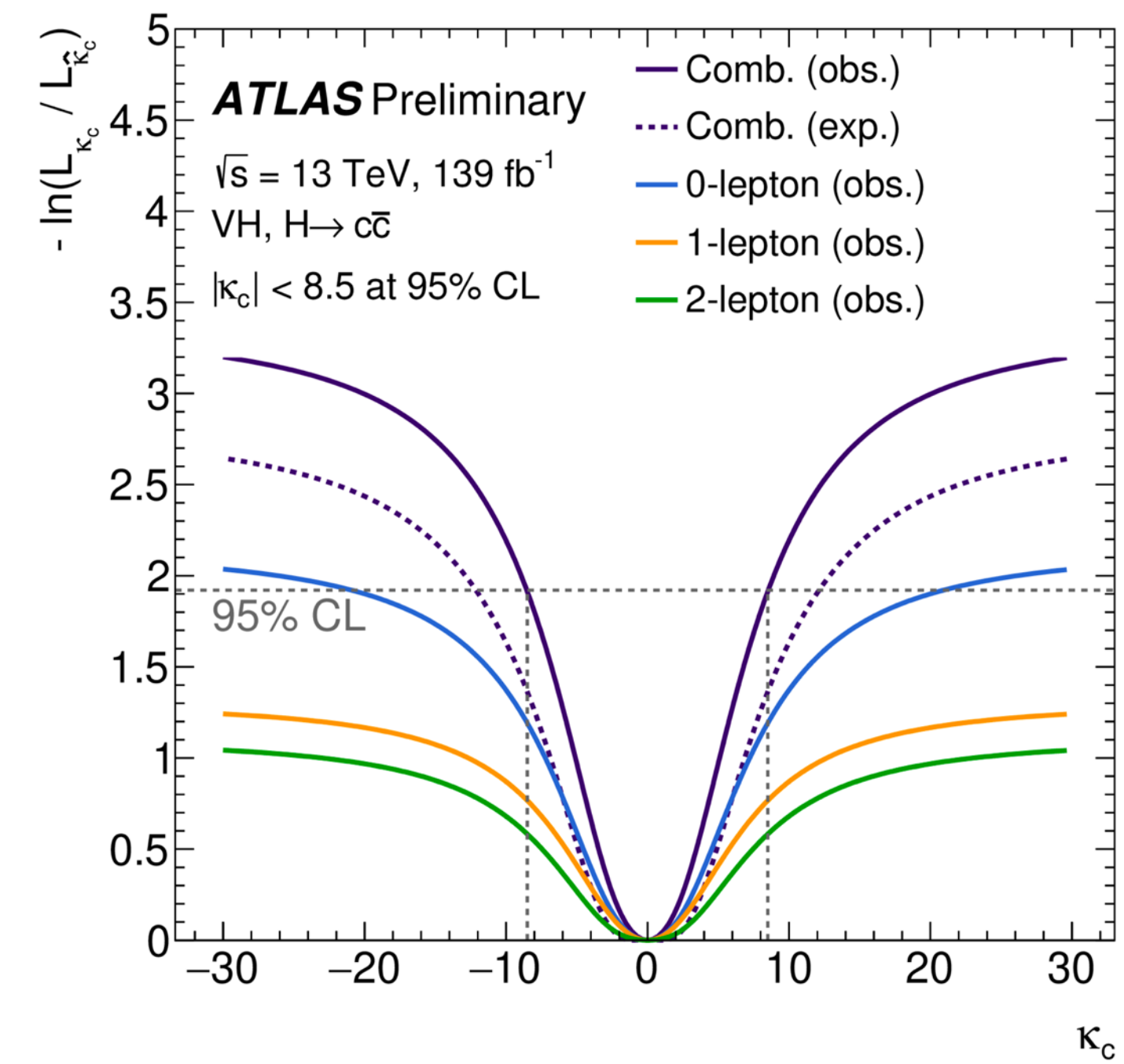
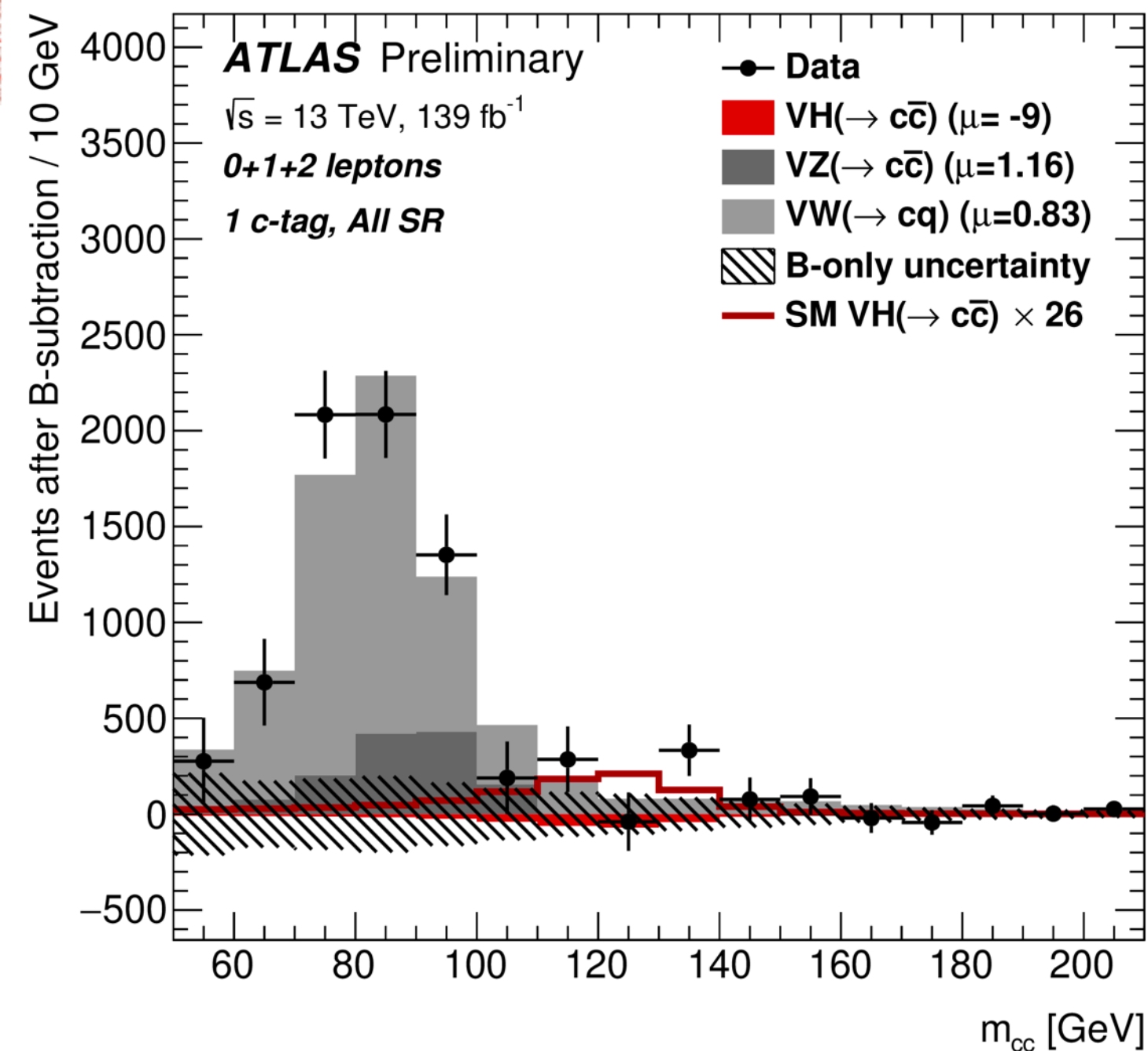
- Test of **Yukawa interactions w/ 2nd generation fermions:** evidence for leptons only
- **Search for $H \rightarrow cc$** in associated $V(\ell\ell, \ell\nu, \nu\nu)H$ production
- Dedicated charm tagging
- Results:

$$VH(\rightarrow cc) < 26 \text{ (31)} \sigma_{SM} \text{ obs(exp)}$$



- Charm Yukawa modifier
 $|\kappa_c| < 8.5(12.4)\text{obs(exp)}$
 first direct constraint

[ATLAS-CONF-2021-021](#)



Di-Higgs production

- **Direct access to Higgs potential**
 - Last part of SM needing direct test
 - Small HH XS (ggF 31 fb @NNLO, VBF 1.7 fb @N3LO)
- HH \rightarrow bbbb (33%), bb $\tau\tau$ (7.3%), bb $\gamma\gamma$ (0.3%)
- **HH \rightarrow bb $\tau\tau$ channel**

- Leptonic and hadronic taus

$$\sigma_{HH}/\sigma_{HH}^{SM} < 4.7(3.9)\text{obs}(\text{exp})$$

[ATLAS-CONF-2021-030](#)

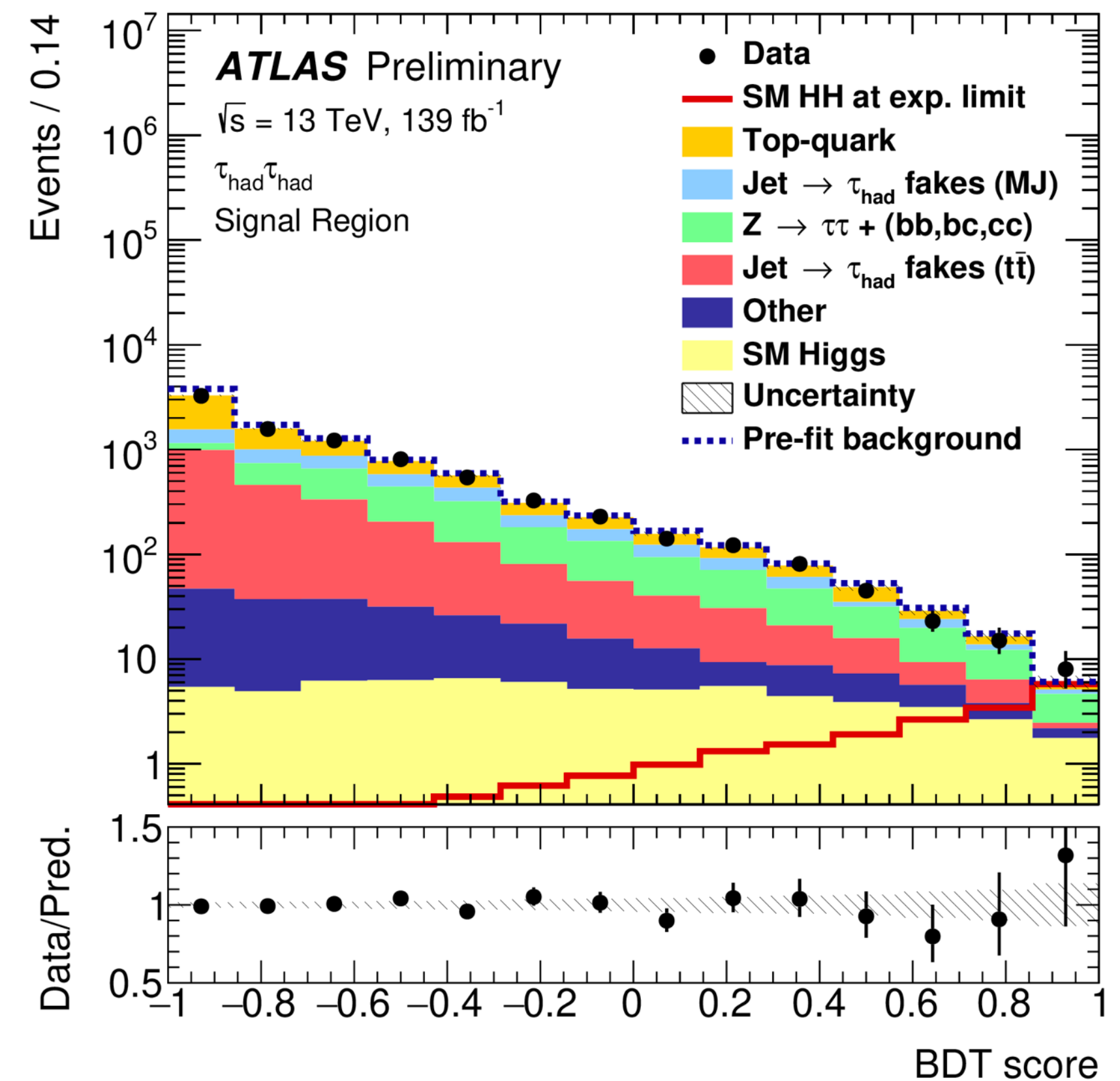
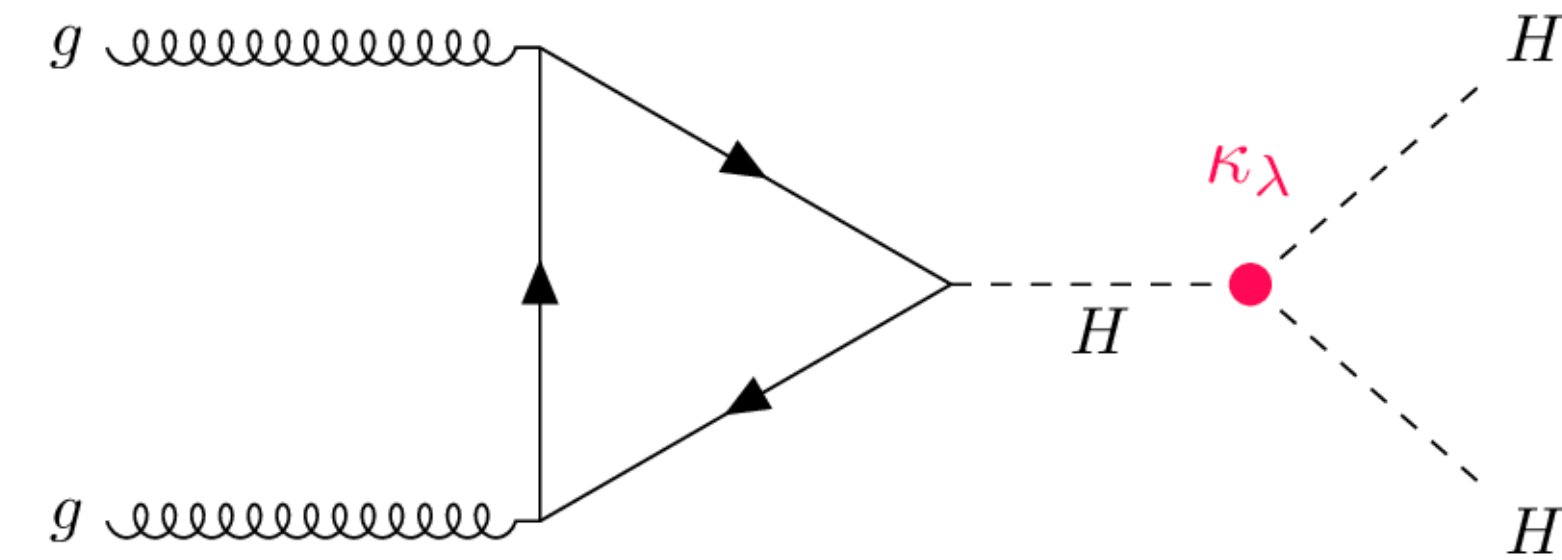
- **HH \rightarrow bb $\gamma\gamma$**

$$\sigma_{HH}/\sigma_{HH}^{SM} < 4.1(5.5)\text{obs}(\text{exp})$$

[ATLAS-CONF-2021-016](#)

factor of 4 -5 improvement over 36 fb⁻¹ analysis

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i\gamma_{ij}\psi_j\phi + \text{hc} + |D_\mu\phi|^2 - V(\phi)$$



Di-Higgs production: combination

- **Combination of**

- $HH \rightarrow bb\tau\tau, bb\gamma\gamma$

- Limit on signal strength < 3.1

- **Limit on modifier κ_λ**

- **Search for HH resonances**

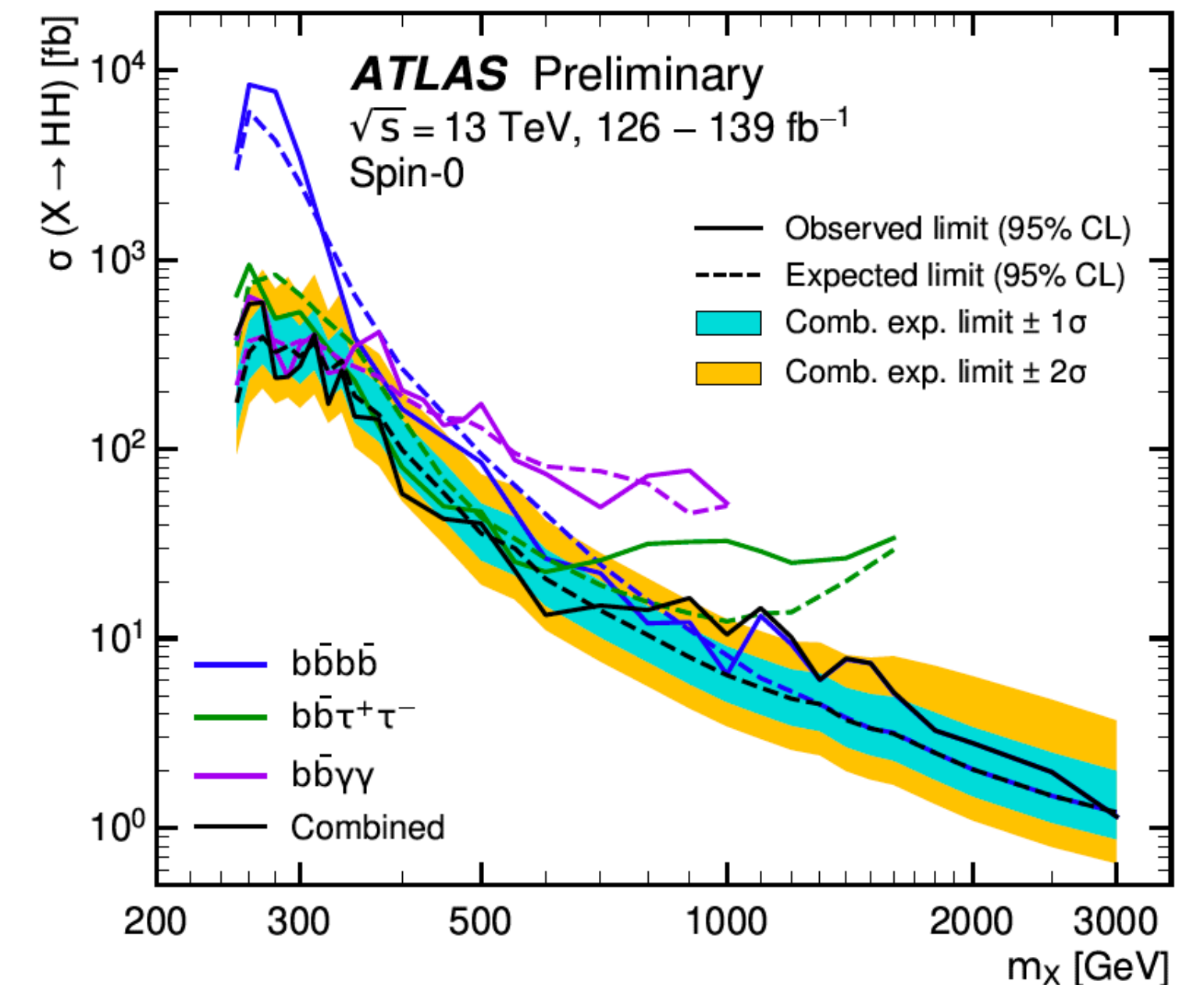
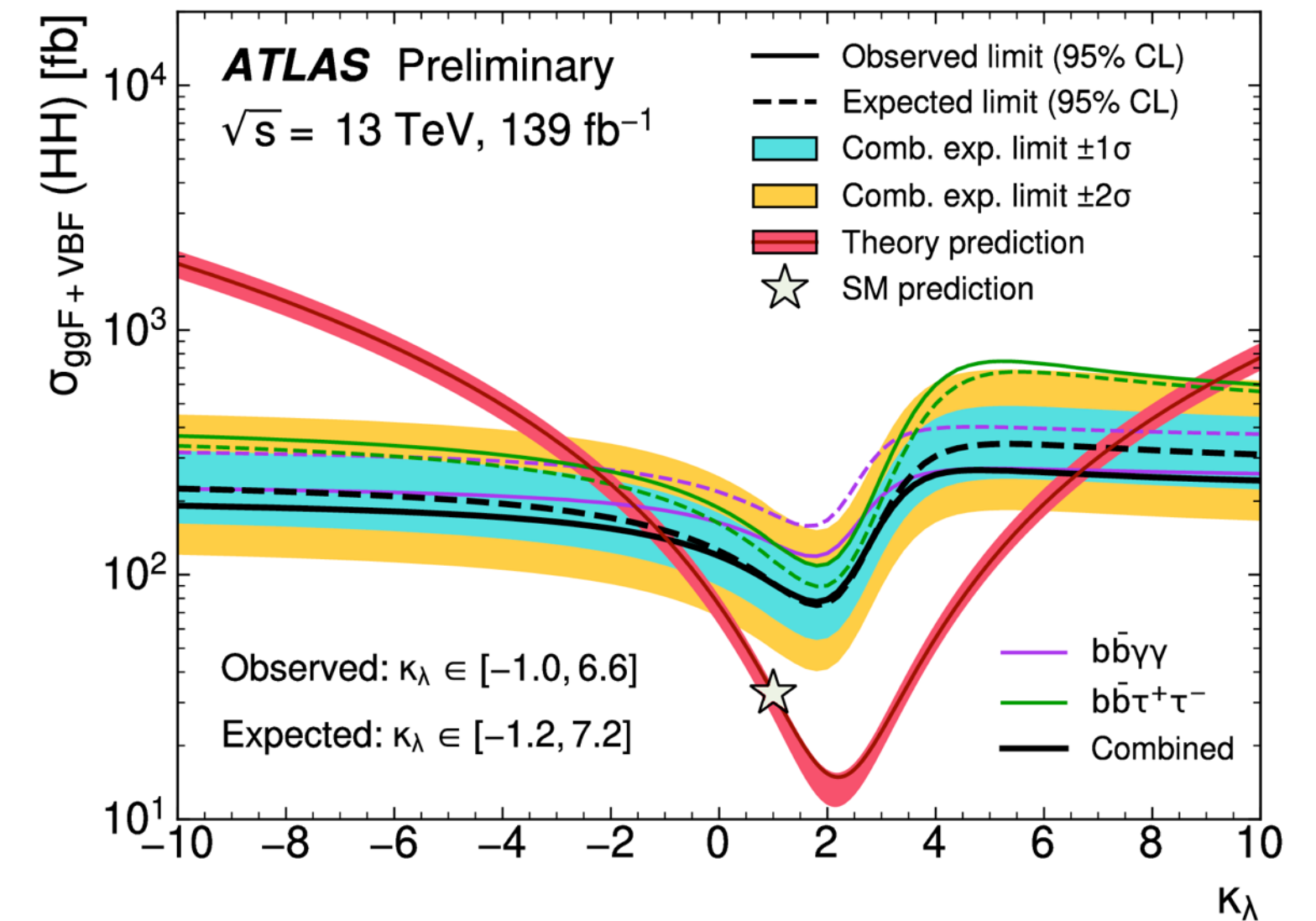
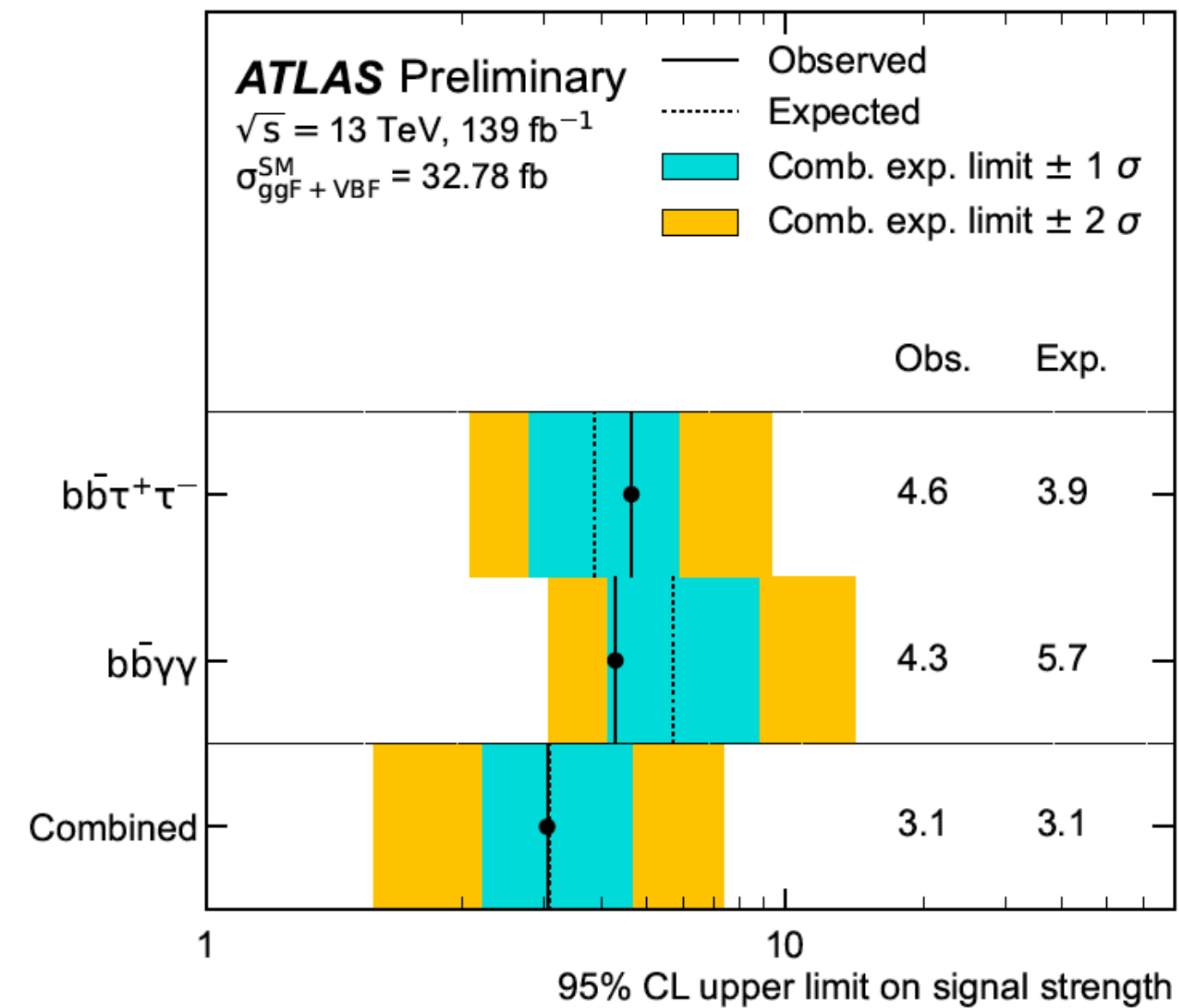
- $HH \rightarrow bbbb$ with both resolved and merged topologies

- Dominates for $m(X) > 700$ GeV

[ATLAS-CONF-2021-035](#)

$HH \rightarrow bbbb, bb\tau\tau, bb\gamma\gamma$

[ATLAS-CONF-2021-052](#)



Direct searches for new Physics

- New limits on SUSY, 2HDM, Dark Matter, Extra Dimensions, Contact Interactions, Lepto-Quarks, Heavy Quarks, Excited fermions etc.
- No deviation from SM found so far
- Not covered here except a pair of examples

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2021

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

ATLAS Preliminary

$\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1-4 j	Yes	139	M_D 11.2 TeV $n=2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_S 8.6 TeV $n=3$ HLZ NLO	1707.04147
	ADD QBH	-	2 j	-	37.0	M_{th} 8.9 TeV $n=6$	1703.09127
	ADD BH multijet	-	≥ 3 j	-	3.6	M_{th} 9.55 TeV $n=6, M_D=3 \text{ TeV, rot BH}$	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	139	G_{KK} mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV $k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $G_{KK} \rightarrow tt$	1 e, μ	$\geq 1 \text{ b, } \geq 1 \text{ J/2j}$	Yes	36.1	G_{KK} mass 3.8 TeV $\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	$\geq 2 \text{ b, } \geq 3 \text{ j}$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	139	Z' mass 5.1 TeV
SSM $Z' \rightarrow \tau\tau$		2 τ	-	-	36.1	Z' mass 2.42 TeV	1709.07242
Leptophobic $Z' \rightarrow bb$		-	2 b	-	36.1	Z' mass 2.1 TeV	1805.09299
Leptophobic $Z' \rightarrow tt$		0 e, μ	$\geq 1 \text{ b, } \geq 2 \text{ J}$	Yes	139	Z' mass 4.1 TeV $\Gamma/m = 1.2\%$	2005.05138
SSM $W' \rightarrow \ell\nu$		1 e, μ	-	Yes	139	W' mass 6.0 TeV	1906.05609
SSM $W' \rightarrow \tau\nu$		1 τ	-	Yes	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025
SSM $W' \rightarrow tb$		-	$\geq 1 \text{ b, } \geq 1 \text{ J}$	-	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043
HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B		1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	2004.14636
HVT $Z' \rightarrow ZH$ model B		0-2 e, μ	1-2 b	Yes	139	Z' mass 3.2 TeV $g_V = 3$	ATLAS-CONF-2020-043
HVT $W' \rightarrow WH$ model B		0 e, μ	$\geq 1 \text{ b, } \geq 2 \text{ J}$	Yes	139	W' mass 3.2 TeV $g_V = 3$	2007.05293
LRSB $W_R \rightarrow \mu N_R$	2 μ	1 J	-	80	W_R mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV, } g_L = g_R$	1904.12679	
CI	CI $qqqq$	-	2 j	-	37.0	Λ 21.8 TeV η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	-	-	139	Λ 35.8 TeV η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	-	139	Λ 1.8 TeV $g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	-	139	Λ 2.0 TeV $g_* = 1$	2105.13847
	CI $tttt$	$\geq 1 \text{ e, } \mu$	$\geq 1 \text{ b, } \geq 1 \text{ j}$	Yes	36.1	Λ 2.57 TeV $ C_{4t} = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1-4 j	Yes	139	m_{med} 2.1 TeV $g_q=0.25, g_\nu=1, m(\chi)=1 \text{ GeV}$	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1-4 j	Yes	139	m_{med} 376 GeV $g_q=1, g_\nu=1, m(\chi)=1 \text{ GeV}$	2102.10874
	Vector med. Z' -2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	m_{med} 3.1 TeV $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$	ATLAS-CONF-2021-006
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	m_{med} 560 GeV $\tan\beta=1, g_\nu=1, m(\chi)=10 \text{ GeV}$	ATLAS-CONF-2021-036
Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV $y=0.4, \lambda=0.2, m(\chi)=10 \text{ GeV}$	1812.09743	
LQ	Scalar LQ 1 st gen	2 e	≥ 2 j	Yes	139	LQ mass 1.8 TeV $\beta = 1$	2006.05872
	Scalar LQ 2 nd gen	2 μ	≥ 2 j	Yes	139	LQ mass 1.7 TeV $\beta = 1$	2006.05872
	Scalar LQ 3 rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.2 TeV $\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$	ATLAS-CONF-2021-008
	Scalar LQ 3 rd gen	0 e, μ	$\geq 2 \text{ j, } \geq 2 \text{ b}$	Yes	139	LQ_3^d mass 1.24 TeV $\mathcal{B}(LQ_3^d \rightarrow t\nu) = 1$	2004.14060
	Scalar LQ 3 rd gen	$\geq 2 \text{ e, } \mu, \geq 1 \text{ } \tau, \geq 1 \text{ b}$	$\geq 1 \text{ j, } \geq 1 \text{ b}$	-	139	LQ_3^d mass 1.43 TeV $\mathcal{B}(LQ_3^d \rightarrow t\tau) = 1$	2101.11582
	Scalar LQ 3 rd gen	0 $e, \mu, \geq 1 \text{ } \tau$	0-2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV $\mathcal{B}(LQ_3^d \rightarrow b\nu) = 1$	2101.12527
Heavy quarks	VLQ $TT \rightarrow Zt + X$	2 $e/2\mu \geq 3e, \mu$	$\geq 1 \text{ b, } \geq 1 \text{ j}$	-	139	T mass 1.4 TeV SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	2(SS) $\geq 3 \text{ e, } \mu$	$\geq 1 \text{ b, } \geq 1 \text{ j}$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	1807.11883
	VLQ $T \rightarrow Ht/Zt$	1 e, μ	$\geq 1 \text{ b, } \geq 3 \text{ j}$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLQ $Y \rightarrow Wb$	1 e, μ	$\geq 1 \text{ b, } \geq 1 \text{ j}$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$	1812.07343
	VLQ $B \rightarrow Hb$	0 e, μ	$\geq 2 \text{ b, } \geq 1 \text{ j, } \geq 1 \text{ J}$	-	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	q^* mass 6.7 TeV only u^* and $d^*, \Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV only u^* and $d^*, \Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	36.1	b^* mass 2.6 TeV	1805.09299
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$	1411.2921
	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV $\Lambda = 1.6 \text{ TeV}$	1411.2921
Other	Type III Seesaw	2,3,4 e, μ	≥ 2 j	Yes	139	N^0 mass 910 GeV	ATLAS-CONF-2021-023
	LRSB Majorana ν	2 μ	2 j	-	36.1	N_R mass 3.2 TeV $m(W_R) = 4.1 \text{ TeV, } g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV DY production, $ q = 5e$	1812.03673
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV DY production, $ g = 1g_D, \text{ spin } 1/2$	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

[†]Small-radius (large-radius) jets are denoted by the letter j (J).

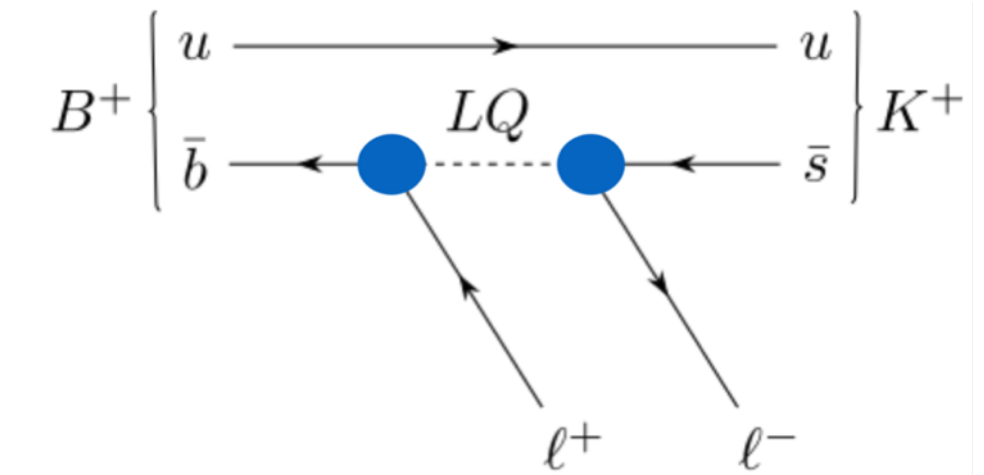
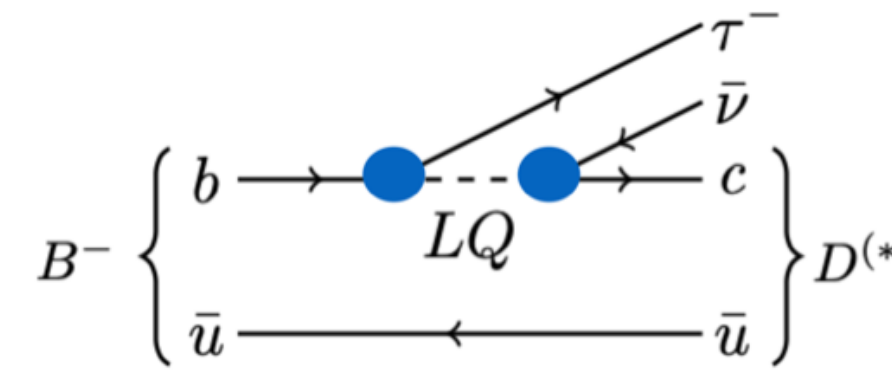
$\sqrt{s} = 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$ partial data $\sqrt{s} = 13 \text{ TeV}$ full data

10⁻¹ 1 10 Mass scale [TeV]

- Recent results from B decays indicate deviations from lepton-flavor universality

both $R(K^{(*)}) = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)}$ and $R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)}$ disagree w/ SM at ~ 3 ($\ell = e, \mu$)

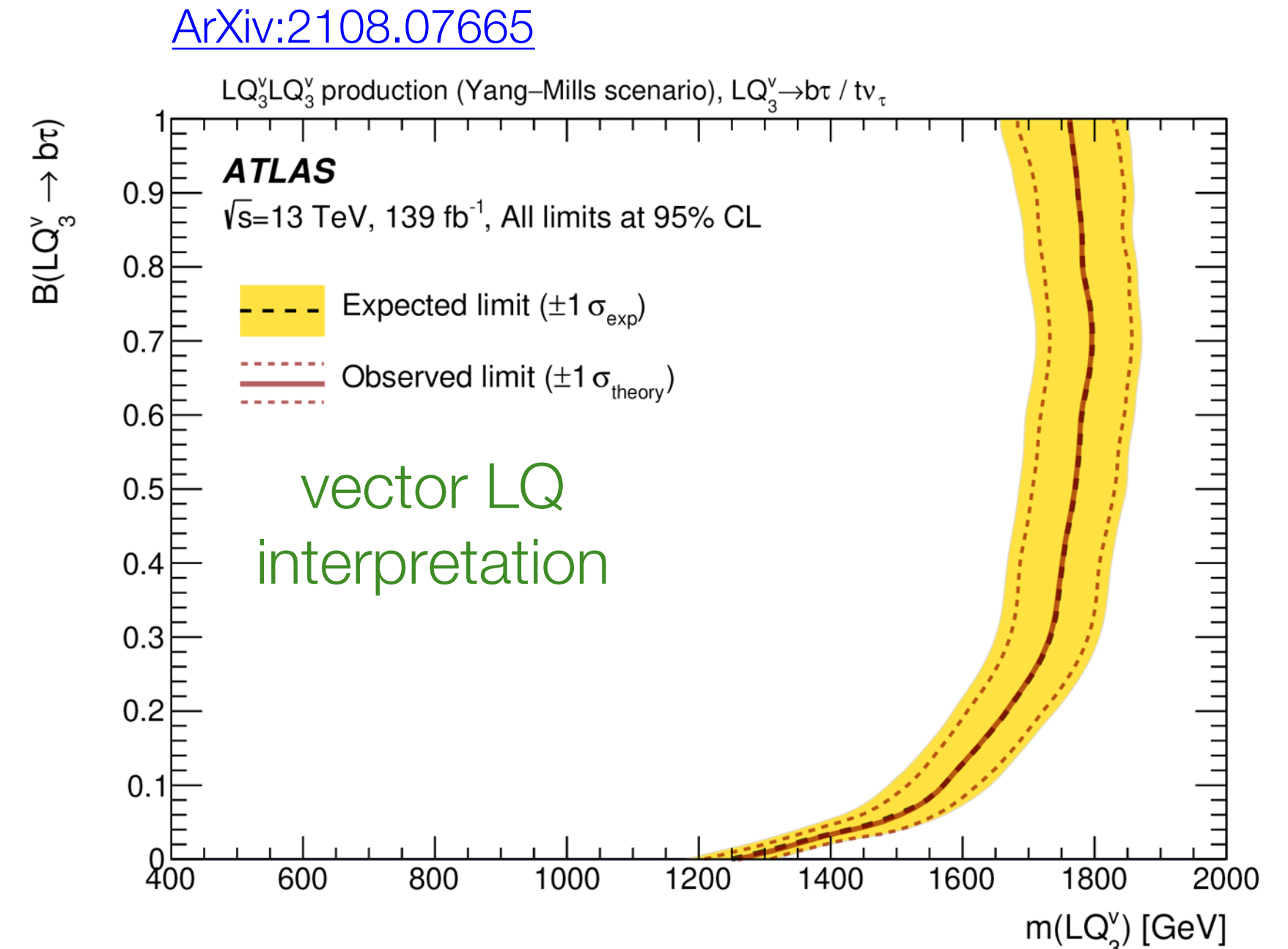
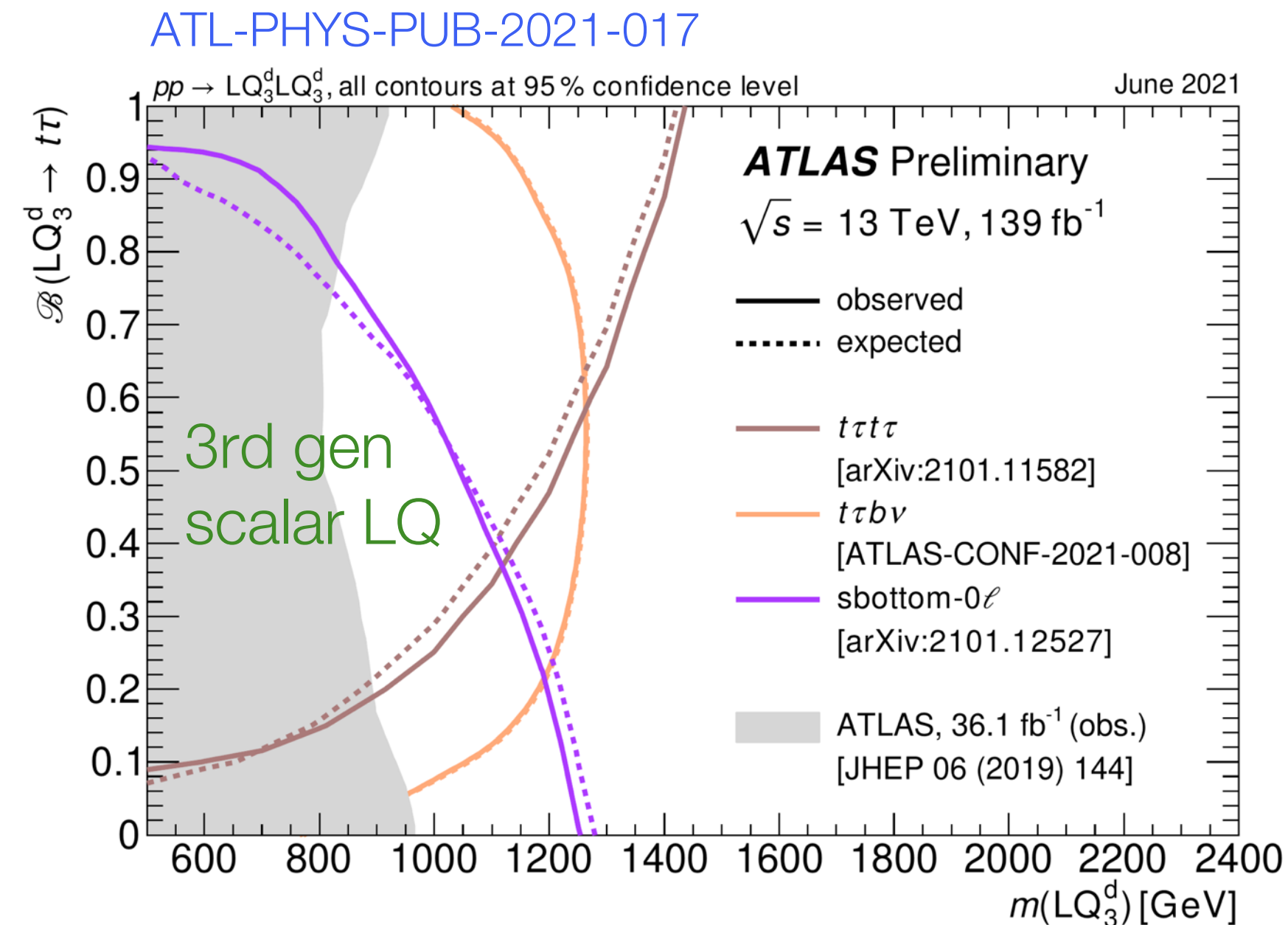
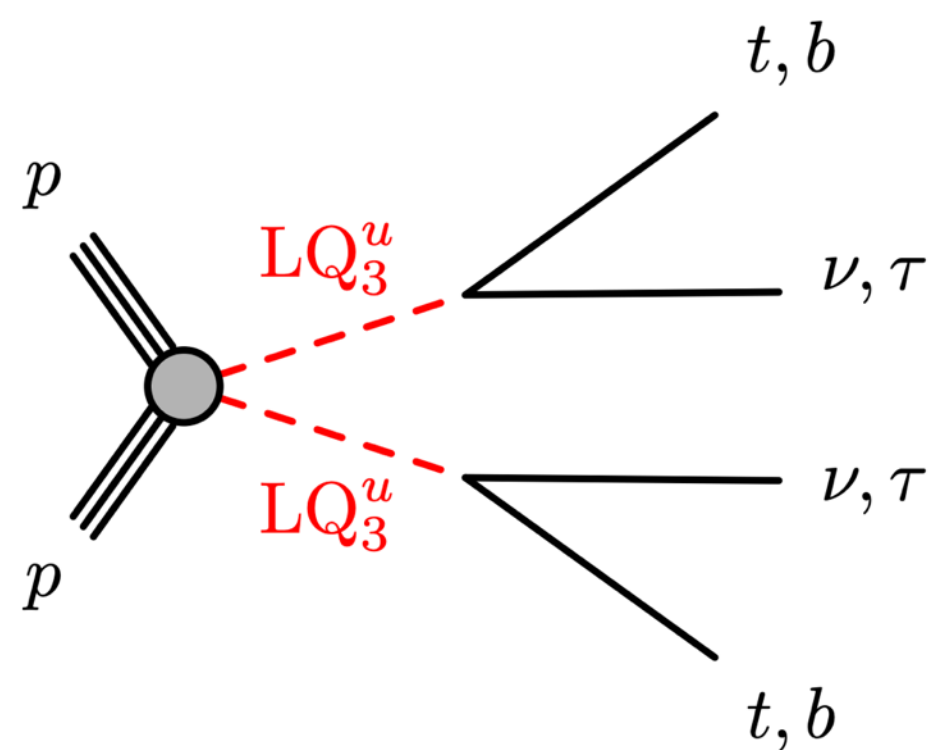
- Leptoquarks are a potential explanation



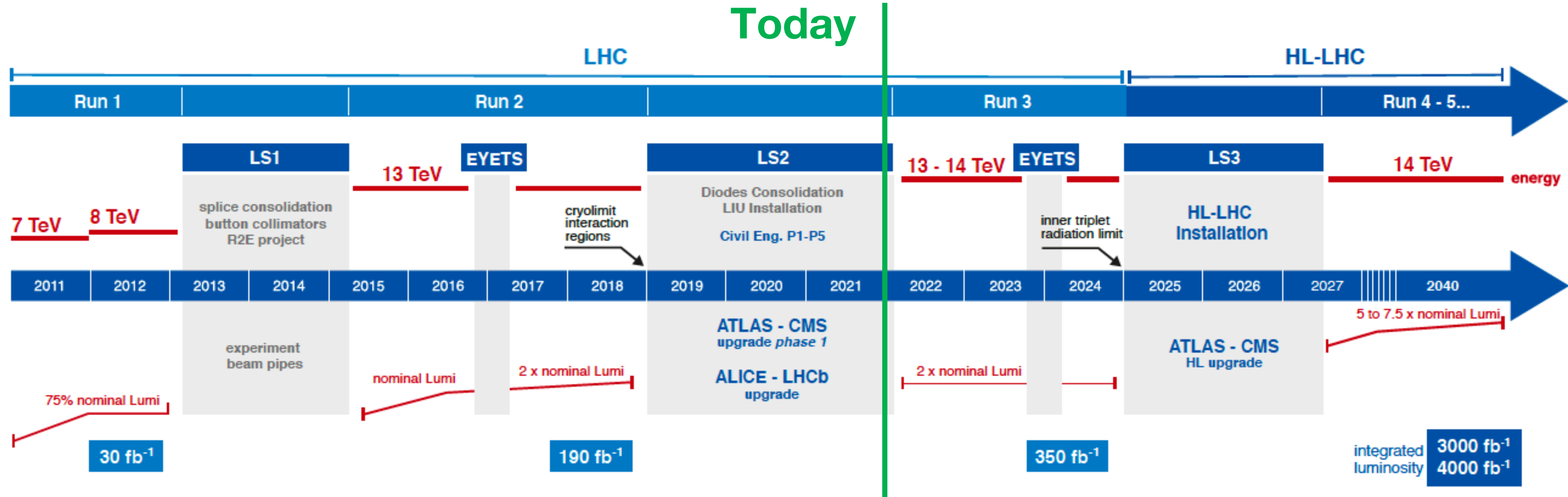
- Search for 3rd gen. LQ pair production in various channels

- Addresses $R(D^{(*)})$ anomaly at ~expected scale**

(diagrams by LHCb and D.Zanzi)



LHC Past, present, future



Long Shutdown 2 (LS2) is near completion: Run-3 will start next year, goal is to collect 2 times the Run-2 luminosity (additional year under discussion => x4 data set ?)

HL-LHC major LHC upgrade, ultimate lumi: 4000 fb⁻¹ (Run3 x10)

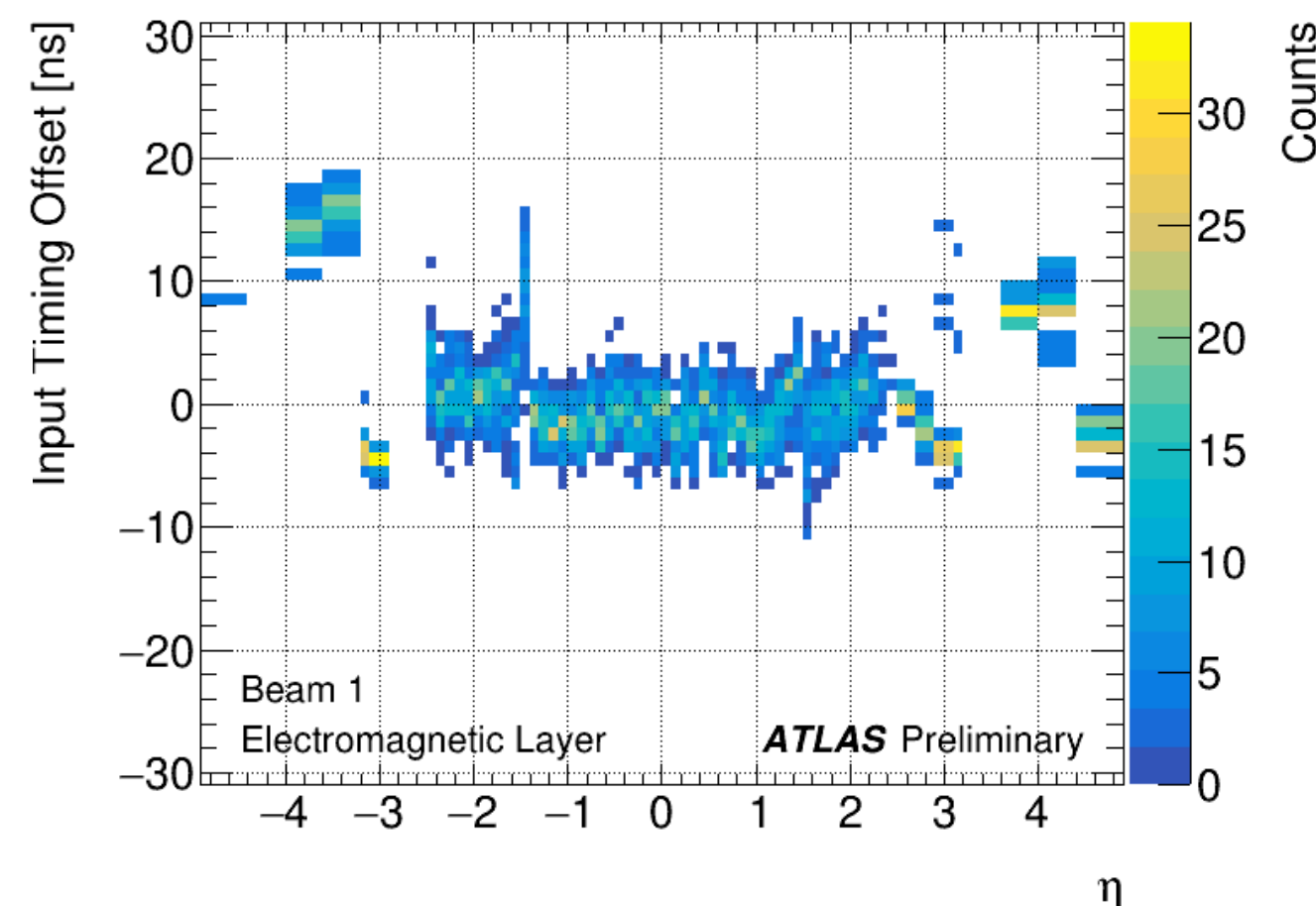
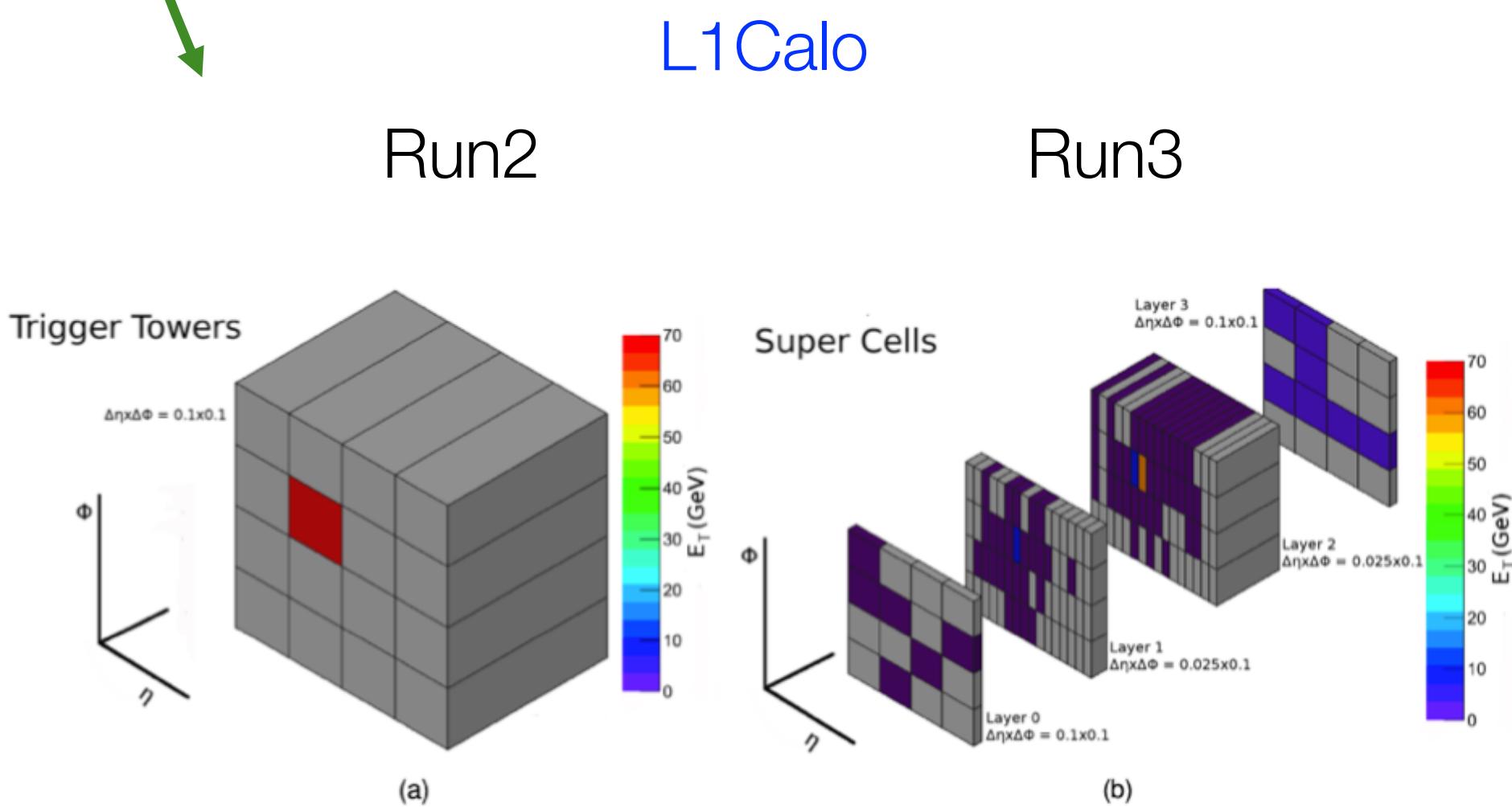
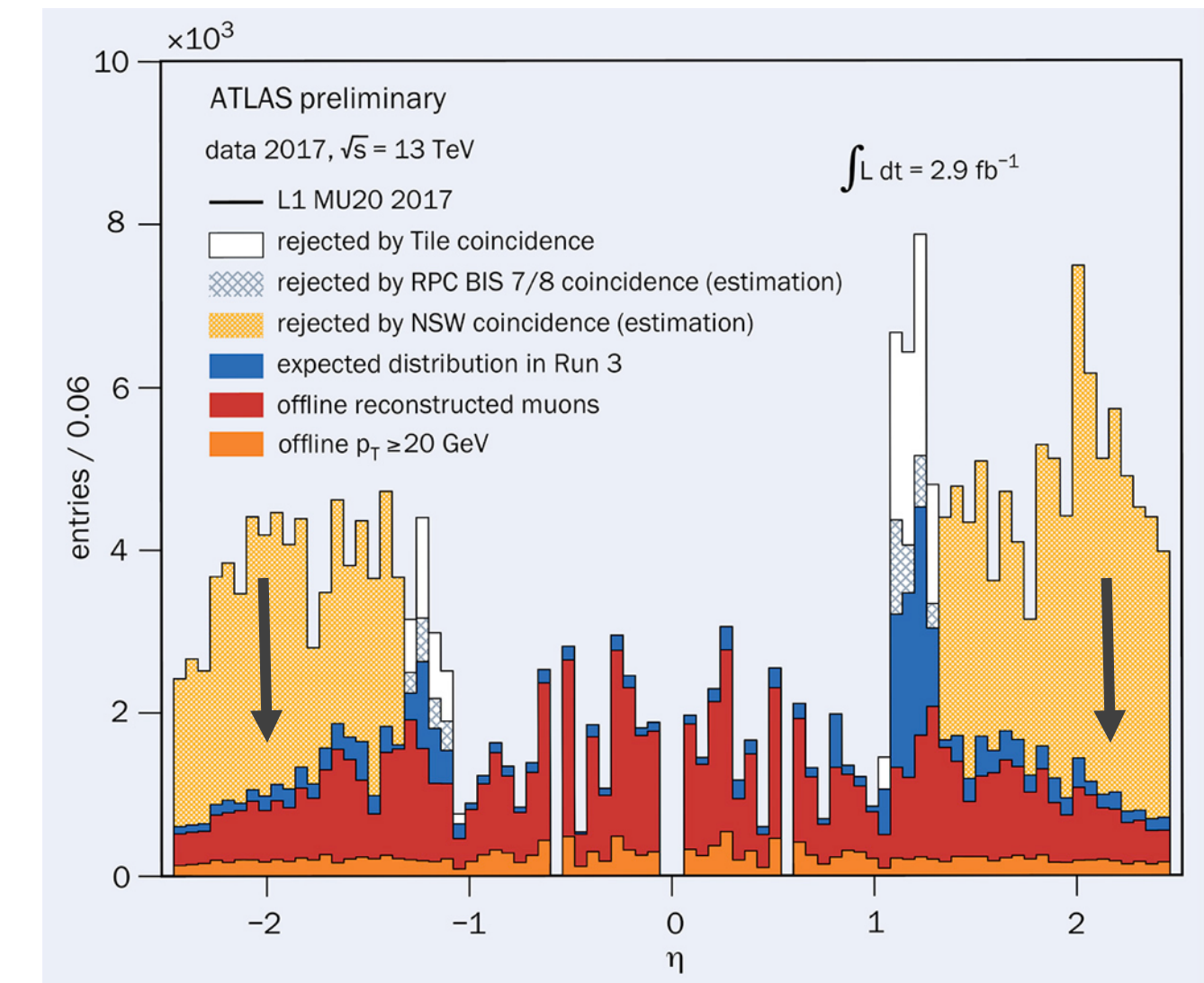
Obtained with flat luminosity profile at $7.5 \times 10^{34} \text{ cm}^2\text{s}^{-1}$ (7.5 x original LHC Luminosity)

Pileup : 200 inelastic pp collisions / bunch crossing

Run 3 : ATLAS phase-I upgrades

- Preparations ongoing w/ maintenance and multiple improvements to trigger, detector, and computing systems, as well as software
- **New for Run 3:**
 - L1-Calorimeter trigger with improved granularity
 - New topological L1 trigger
 - Muons: New Small Wheel (NSW) and new “EndCap” trigger
 - AFP (forward proton tagger) with new time-of-flight capability
 - Increased performance of software algorithms (Multi-Threading)

NSW: Reduction of fake μ triggers



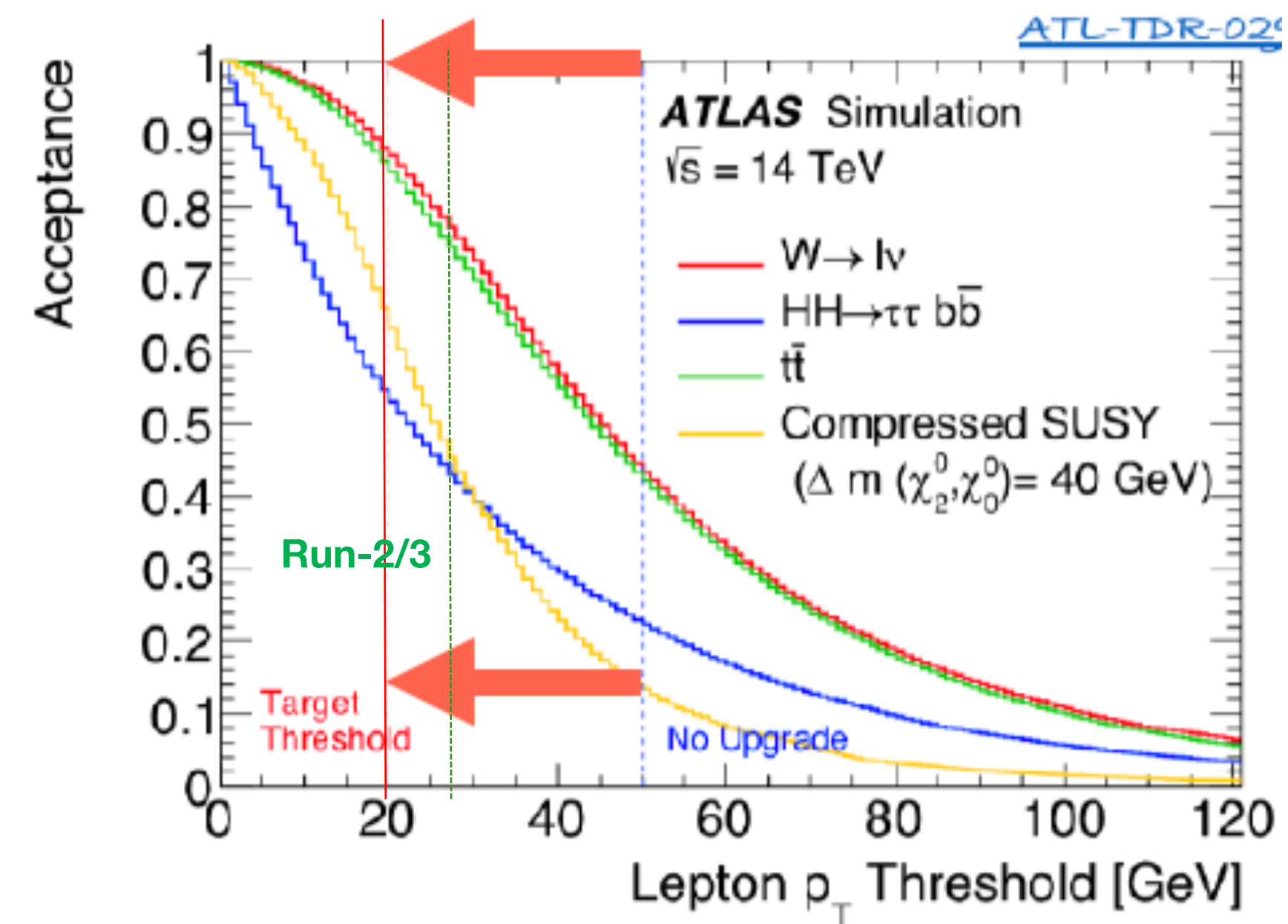
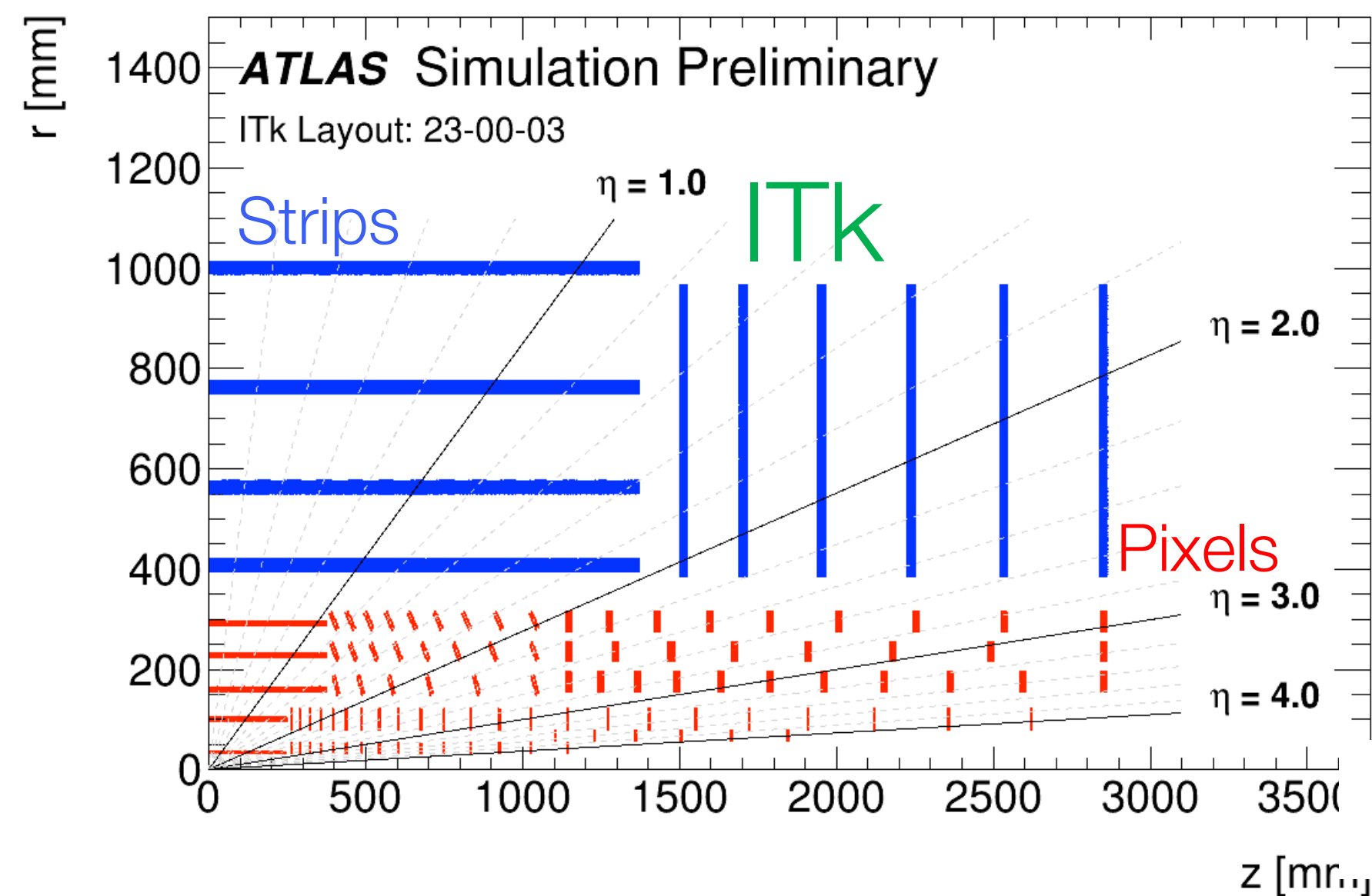
Calibration with beam splashes in October

NSW-A installed in ATLAS



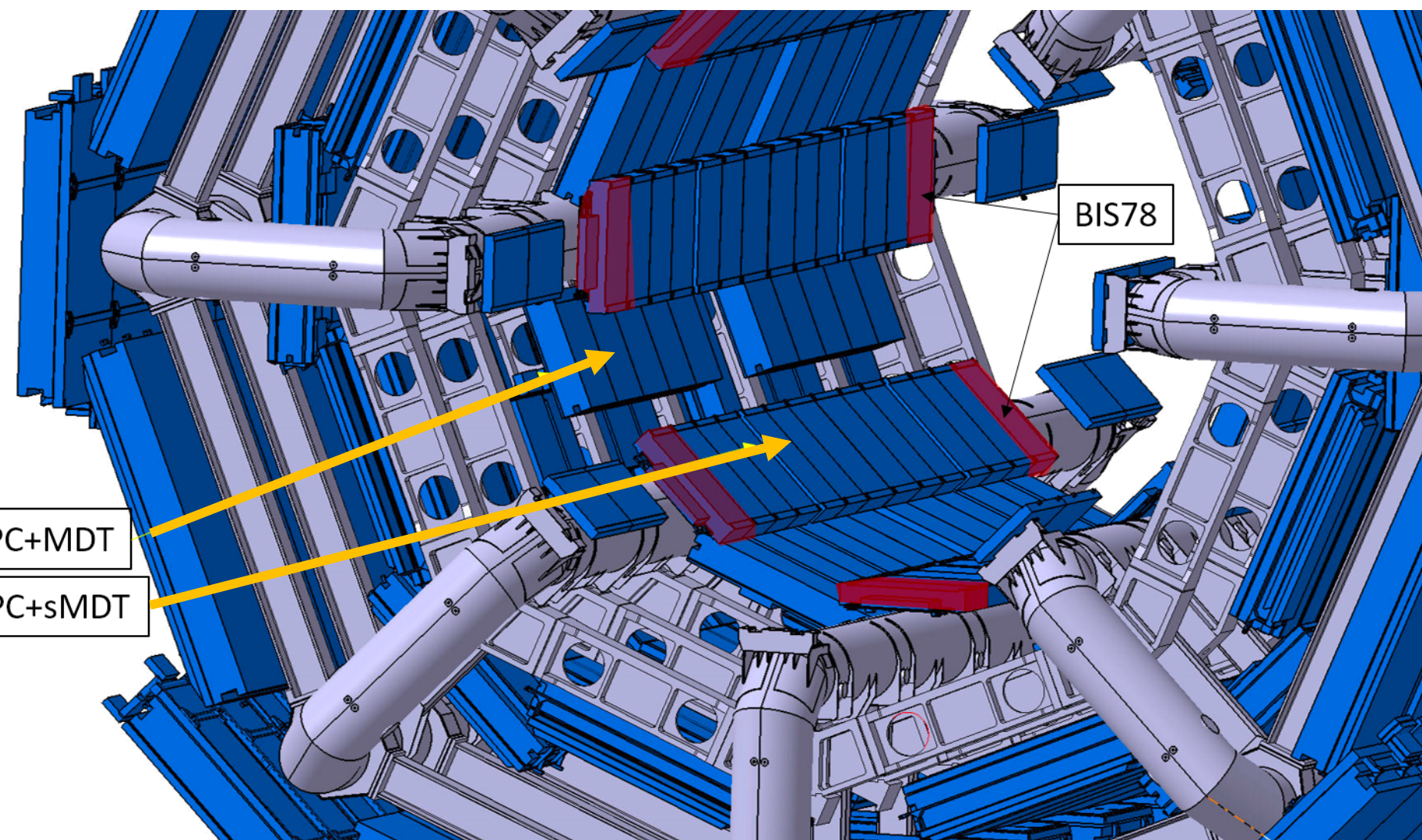
Major ATLAS upgrade to cope with higher luminosity (higher pileup, higher radiation rates, ageing)

- **ITk: new Silicon pixel/strip tracker**
 - Excellent tracking performance (vertexing, p_T resolution, b-tagging) even at highest pileup = 200
 - Extend coverage from $|\eta| < 2.5$ to $|\eta| < 4$
- **Single Hardware Level-0 trigger rate from current 100 kHz to 1 MHz (extendable to 4 MHz)**
 - Lower lepton (and jet) p_T threshold despite higher luminosity
 - Exploit technological advances (high throughput optical transmissions, FPGAs) to perform more sophisticated trigger algorithms, closer to offline rec

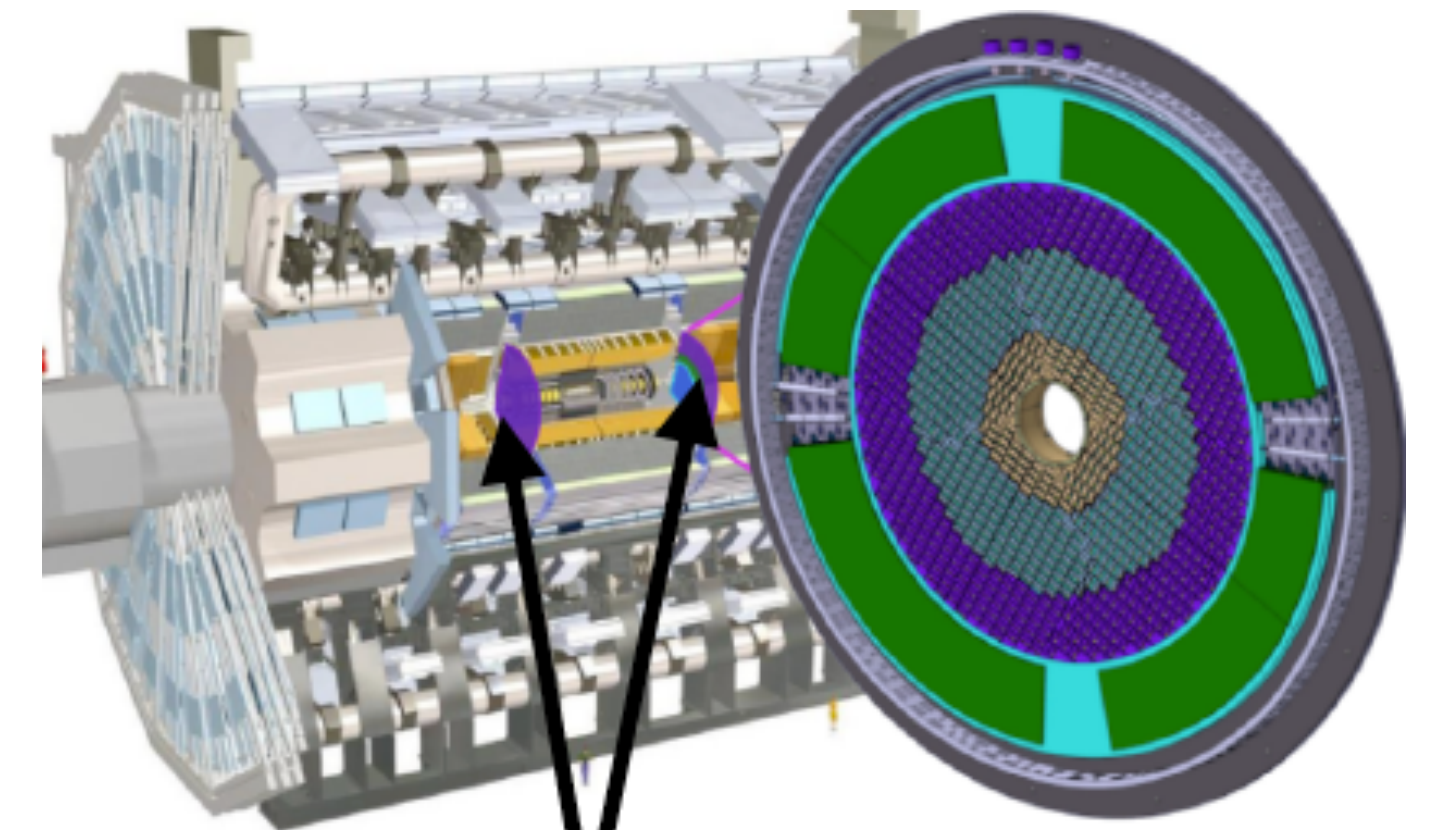
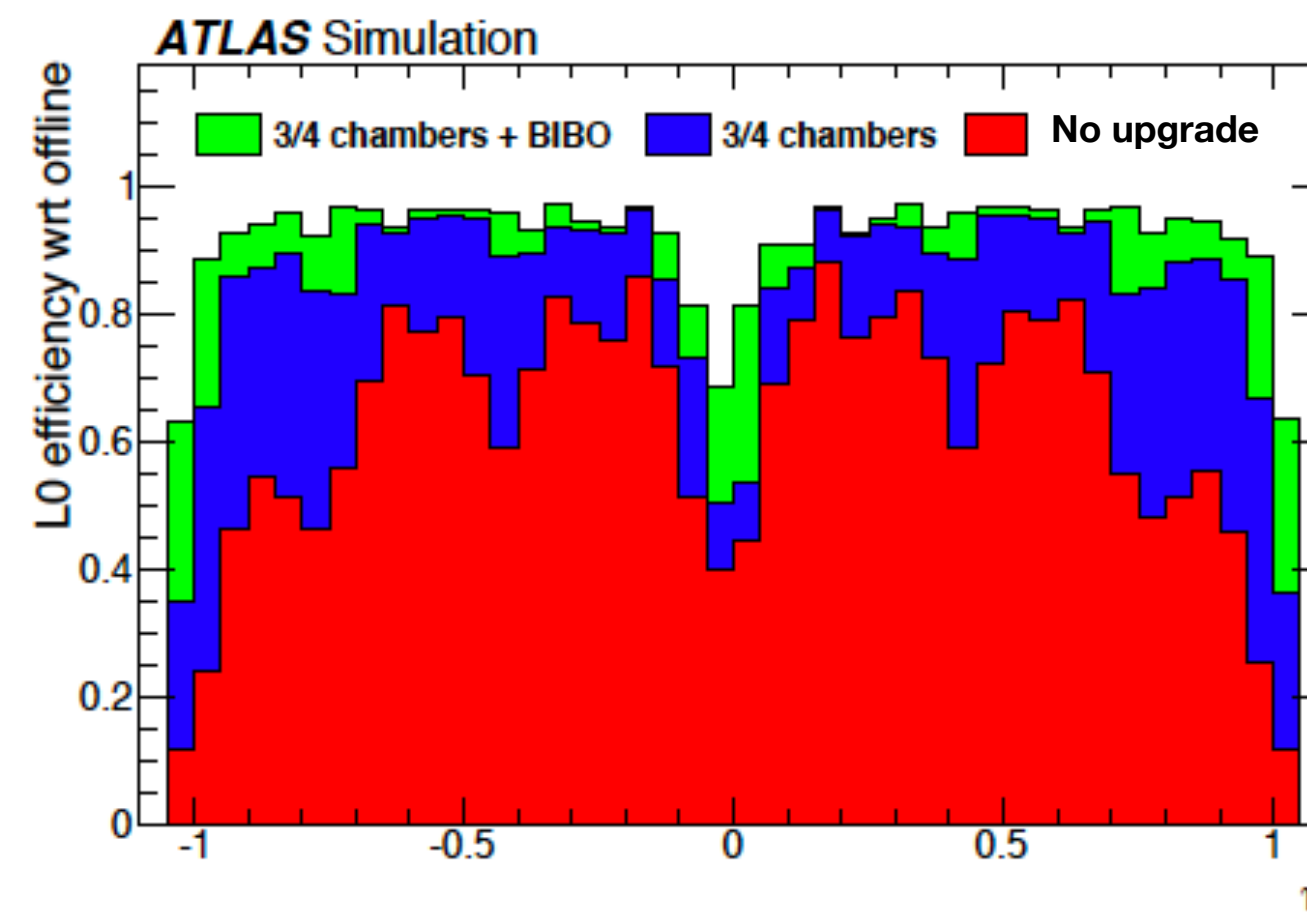


ATLAS Phase-2 Upgrade (2)

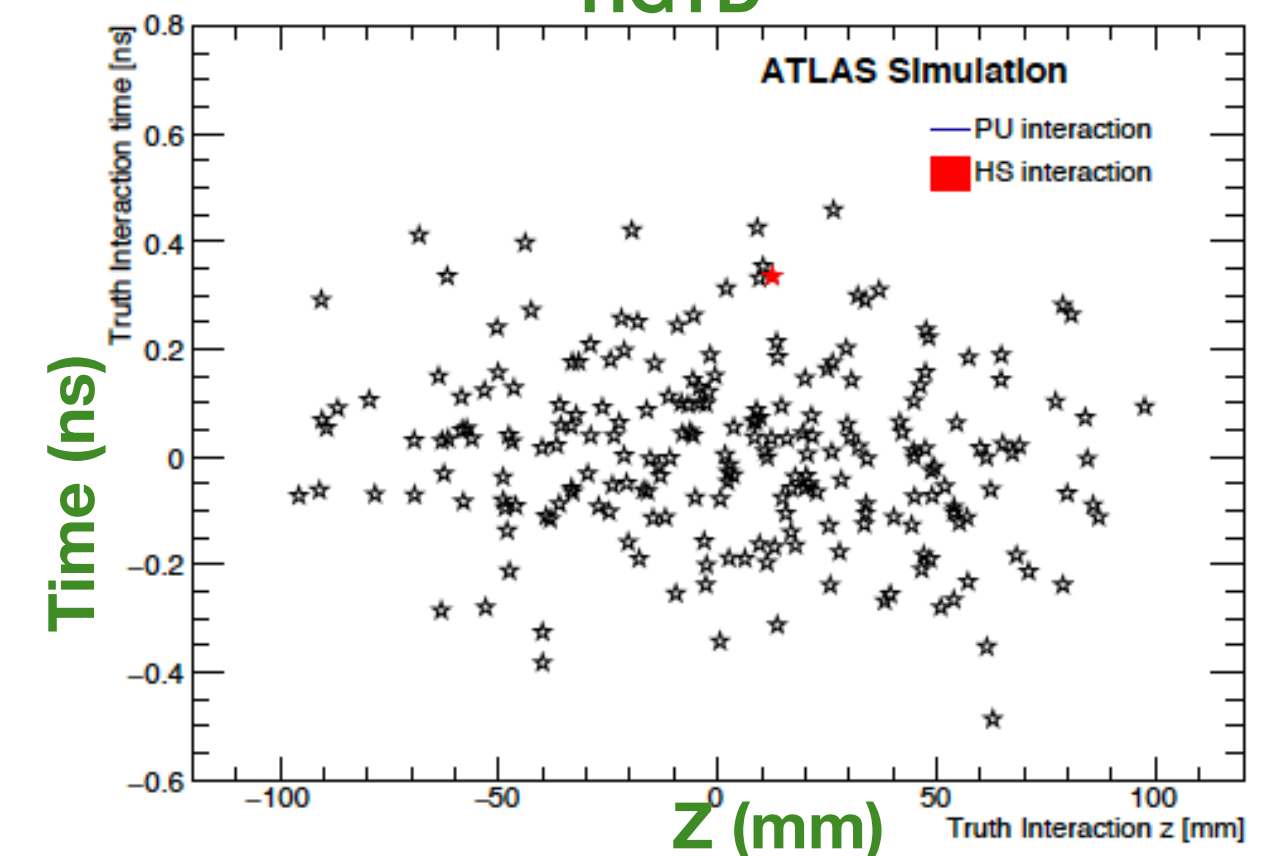
- **New layer of inner chambers in the barrel-inner layer of the muon system**
 - Improve trigger acceptance keeping similar rate (thin gap RPCs + small drift tube (sMDT) chambers)
- **High granularity Timing Detector ($2.4 < |\eta| < 4$)**
 - Separate tracks from different collision vertices using timing: effectively remove tracks/jets from pileup
 - LGAD (Low-Gain avalanche detectors) timing resolution 30-50ps



μ Trigger Acc x Efficiency (worst Case Scenario)



HGTD



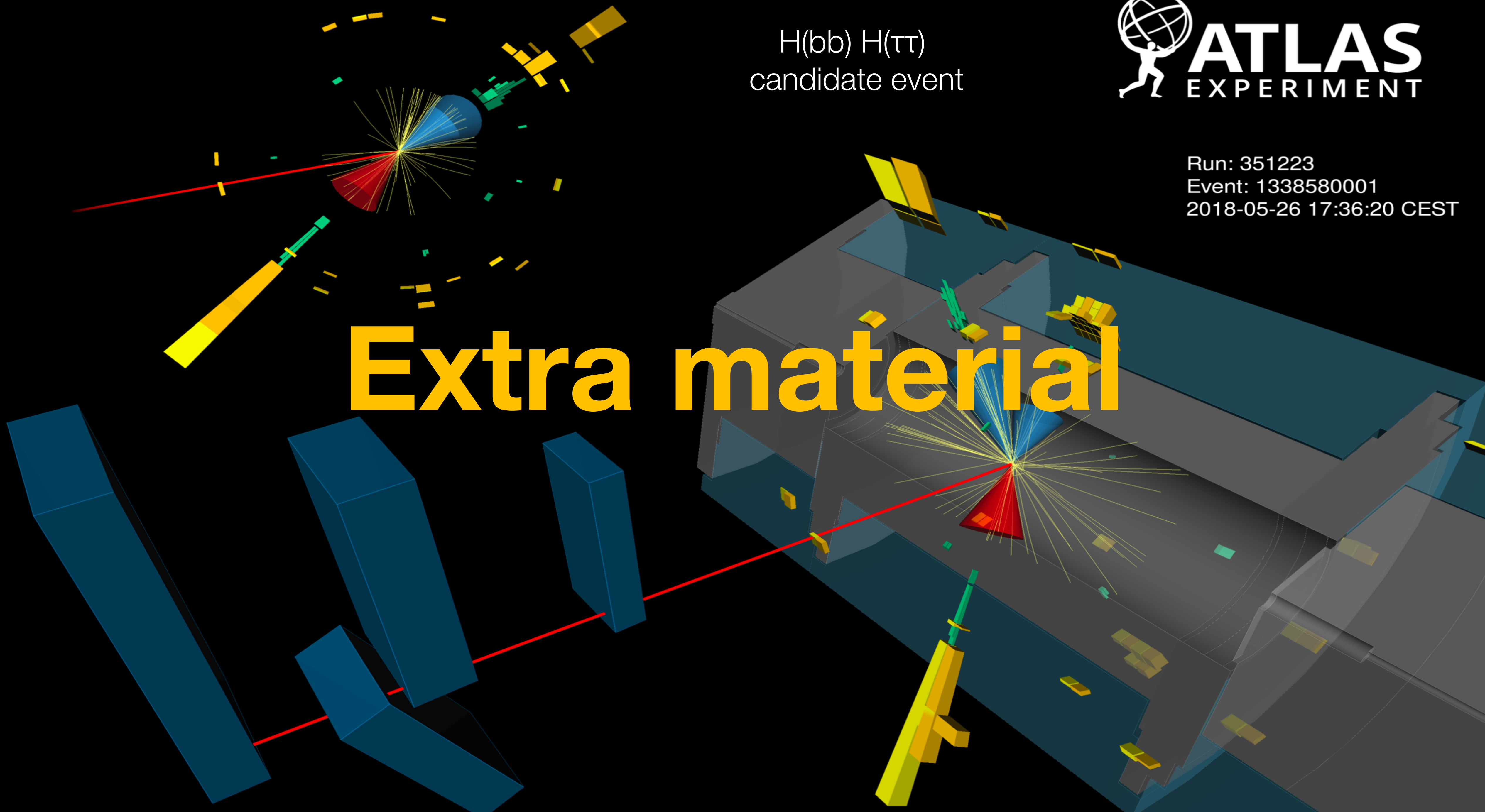
- **Vibrant ATLAS physics program** continues to exploit the Run 2 data gold mine
 - Precision measurements
 - Improving understanding of SM in extreme phase space, measurements of PDF, Fragmentation
 - Progress toward more global approaches, esp. global EFT fits
 - Observation/study of rare processes
 - Large dataset to explore rare processes: $t\bar{t}t\bar{t}$ (4.7σ), WW (8.2σ), or HH prod. ($\sigma_{HH}/\sigma_{HH}^{SM} < 4.1$)
- **Preparations for Run 3 underway**
 - Looking forward to extend physics reach beyond Run 2
- **Very significant effort on Phase-II upgrade for high-luminosity LHC**

H(bb) H(τ)
candidate event



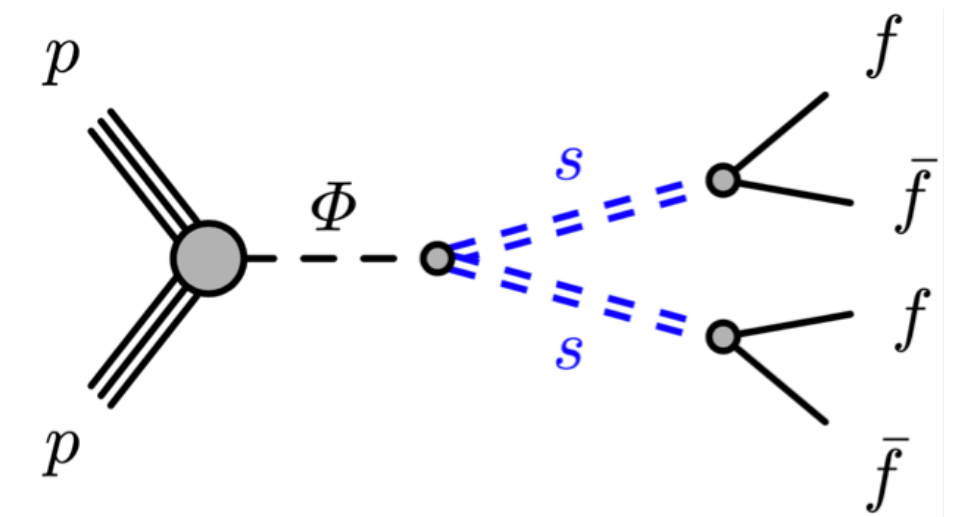
Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST

Extra material



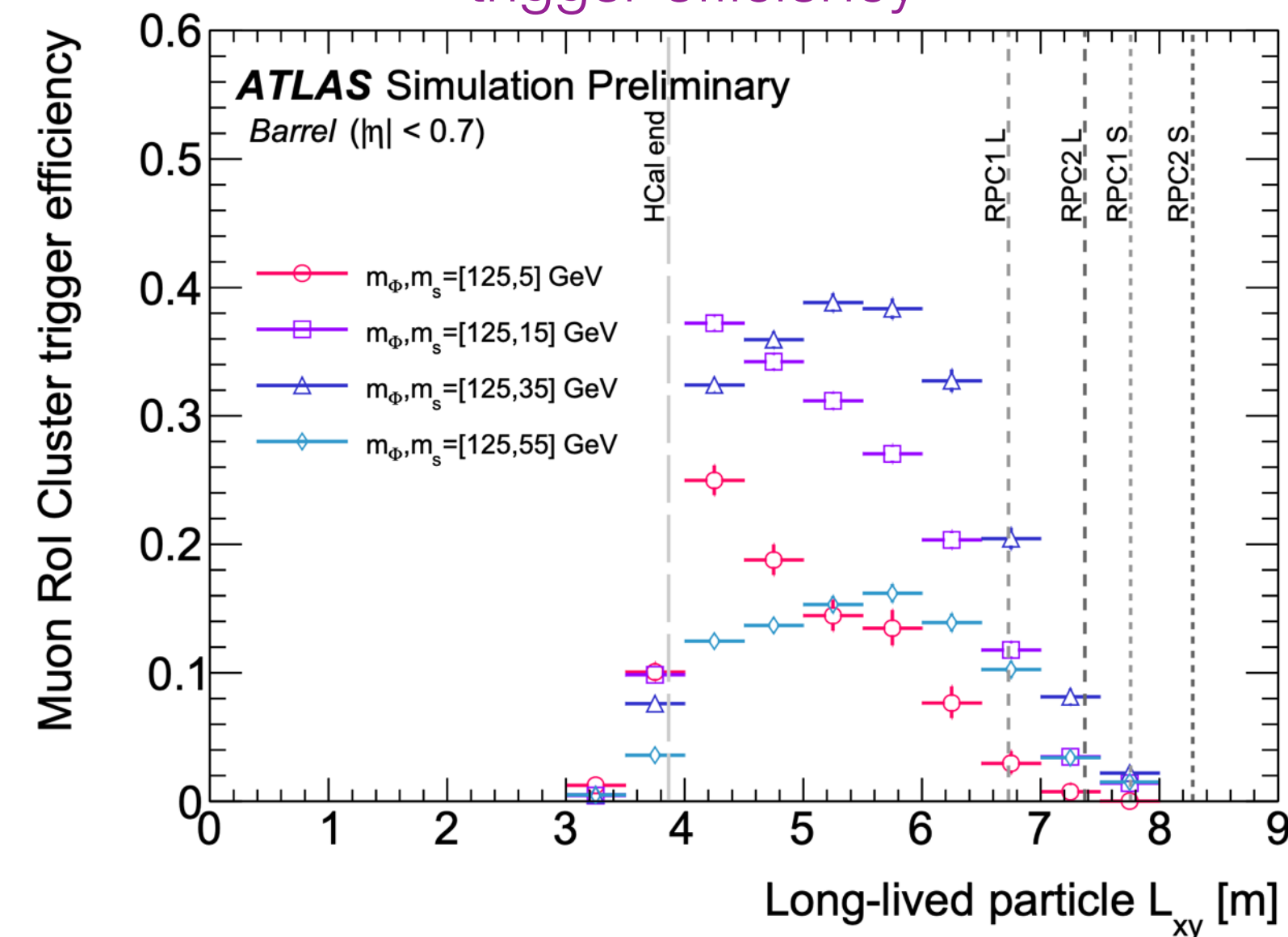
Long-lived particles

- **Higgs portal** / Hidden sector models predict exotic Higgs decays to LLP (s)
- Large expt. program for searching different types of LLPs
- Dedicated muon spectrometer (MS) multi-RoI trigger + track segment and vtx reconstruction in barrel & endcap MS
- Require 2 DVs: 0 events observed w/ 0.32 +/- 0.05 expected bkg

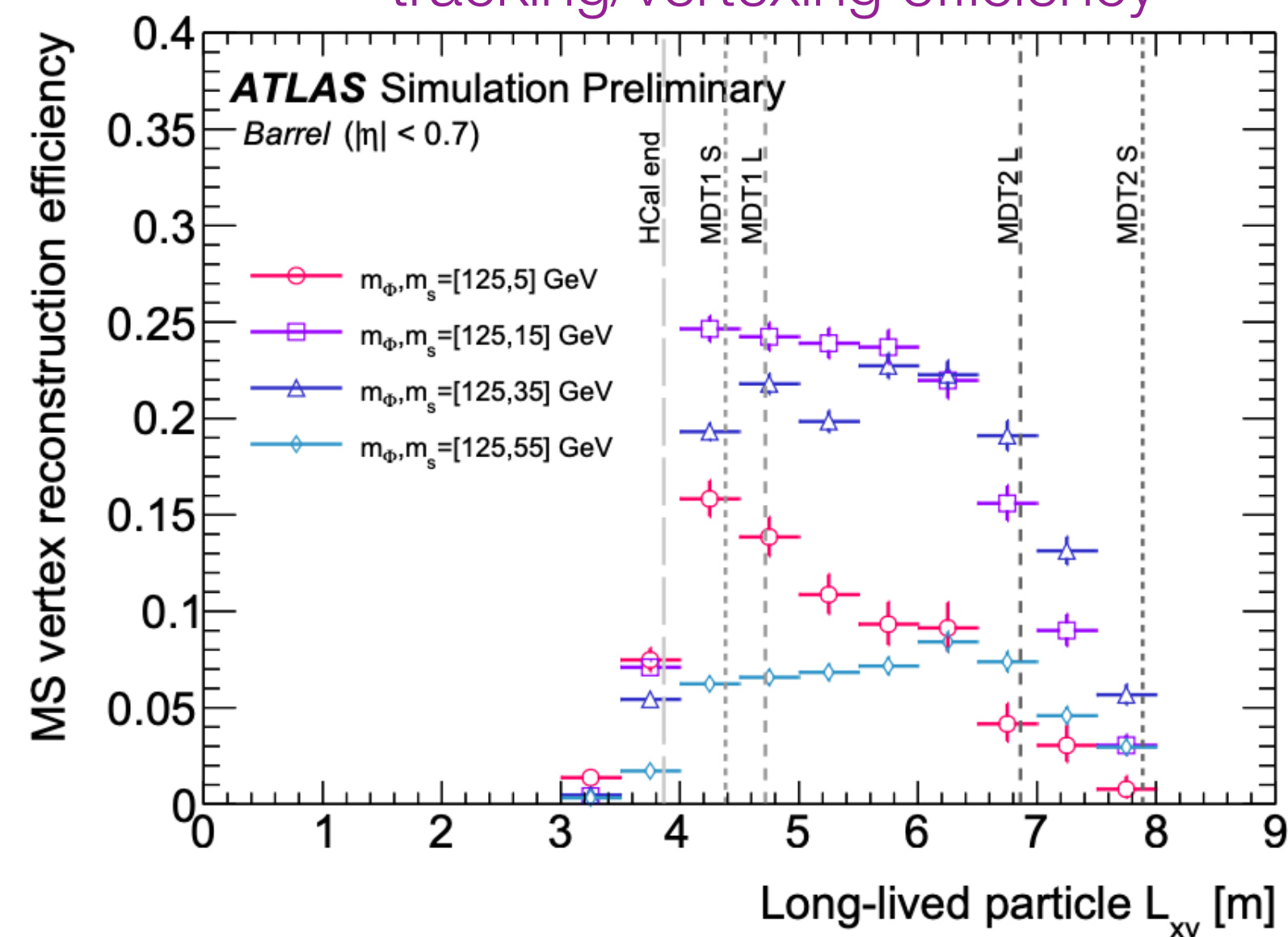


[ATLAS-CONF-2021-032](#)

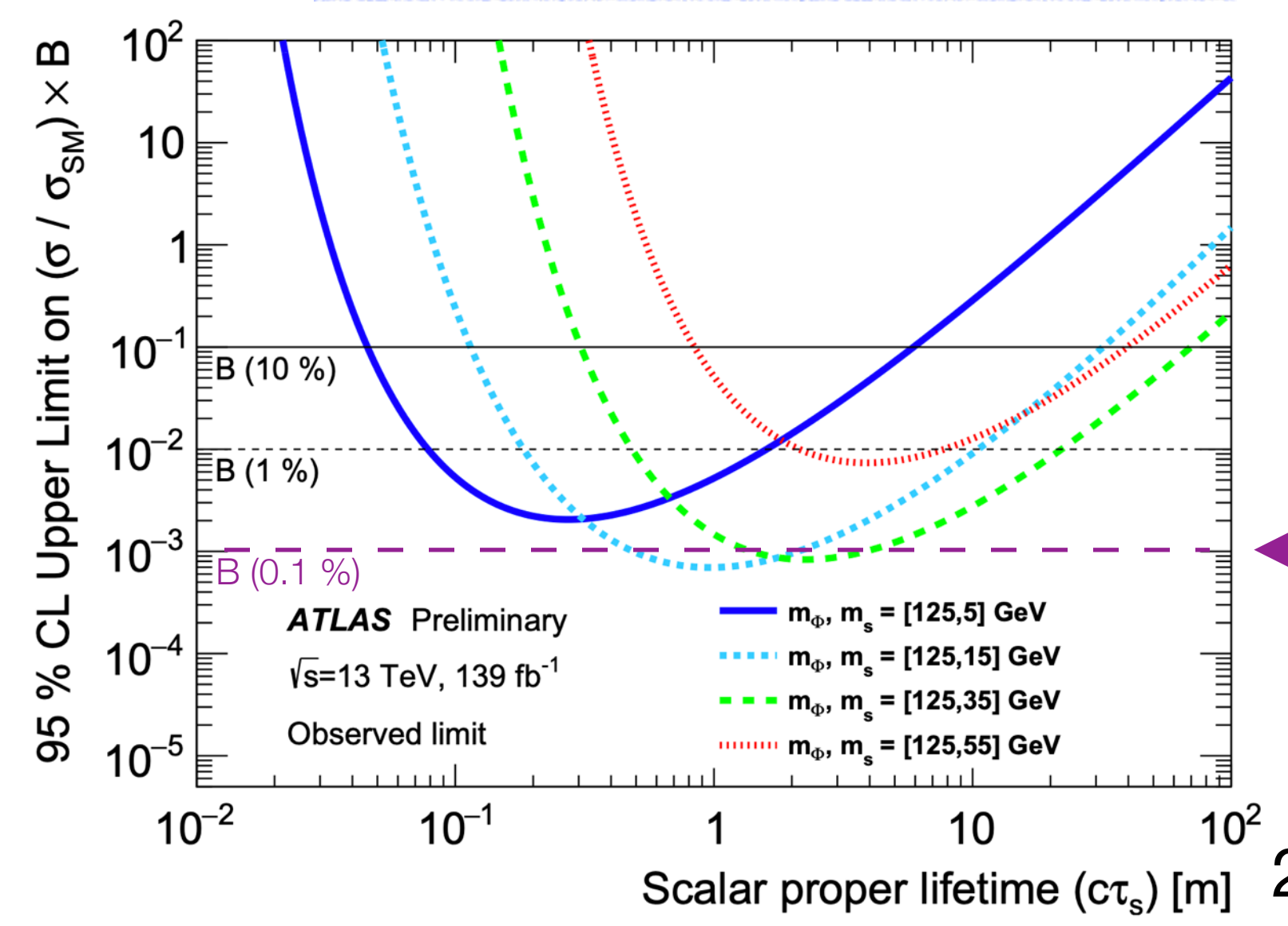
trigger efficiency



tracking/vertexing efficiency



$BF(\Phi(125) \rightarrow ss) = 10\%$
excluded for $\tau(s)$ in range
4 cm – 7.8 m
for $m(s) = 5$ GeV



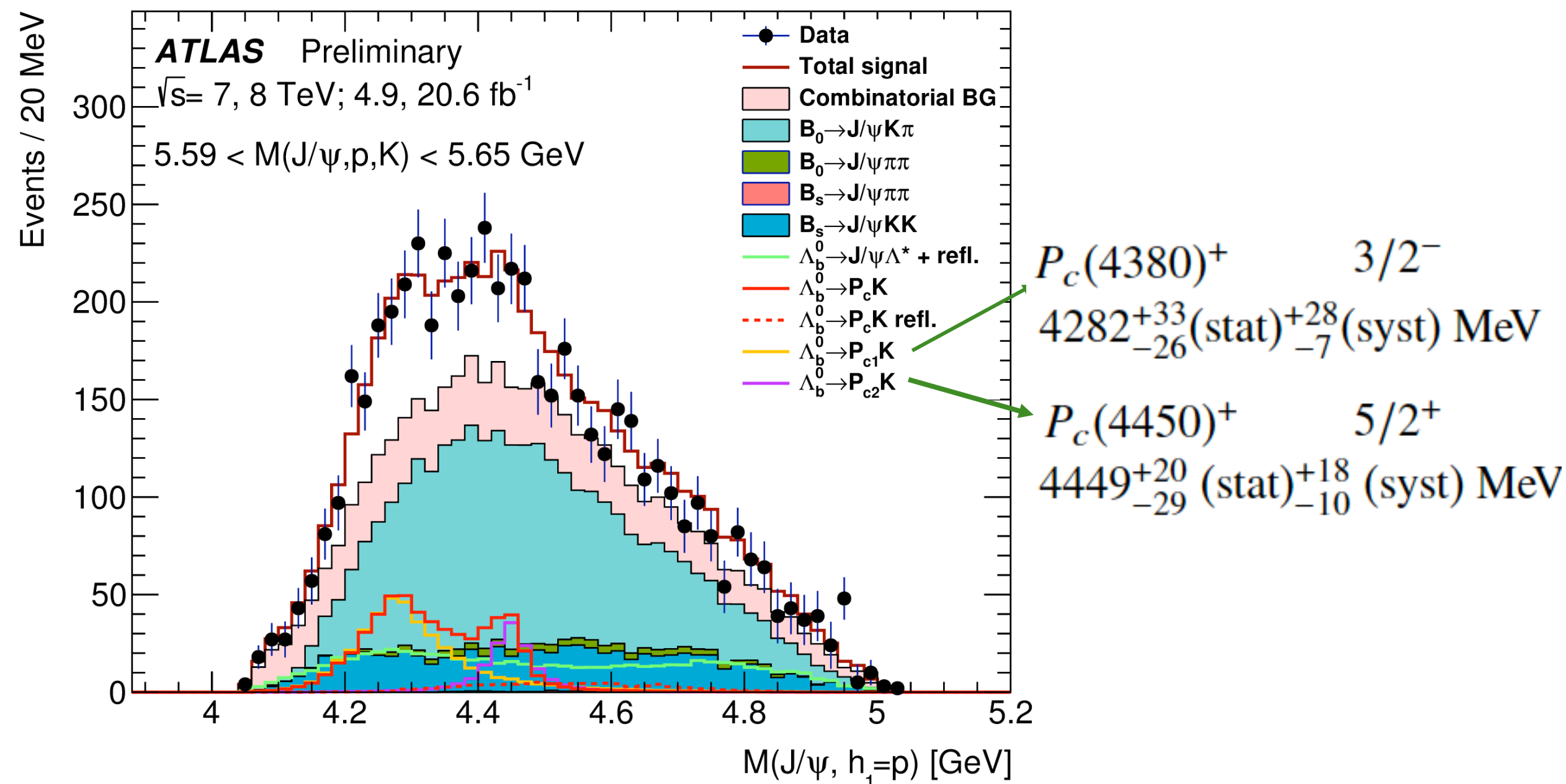
Search for $c\bar{c}uud$ pentaquarks in Λ_b decays

Best fit with two (or more) PQ compatible with LHCb observation

Anyway a fit without PQ but with an extended $\Lambda_b^0 \rightarrow J/\psi \Lambda^{*0}$ decay model is not excluded

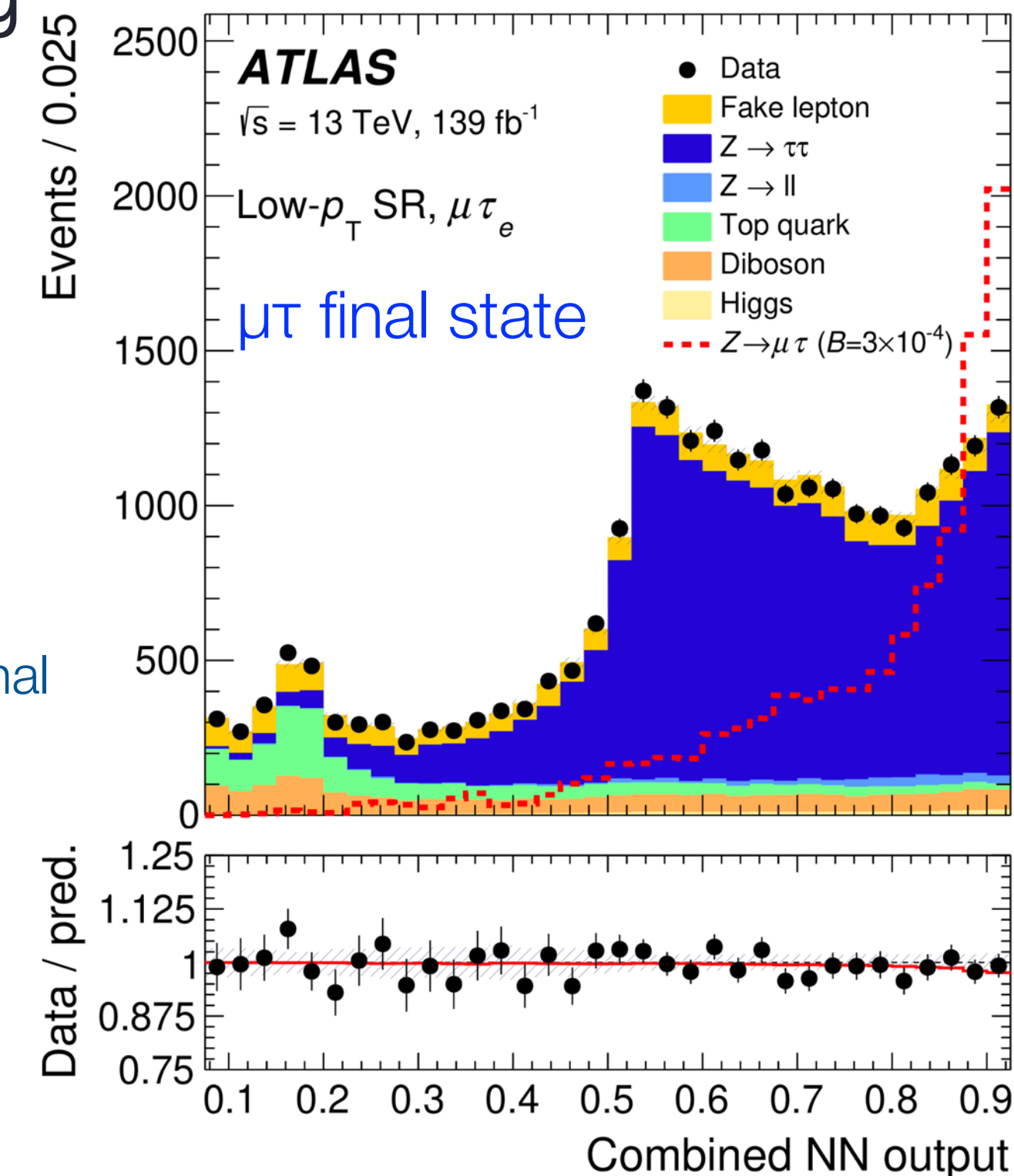
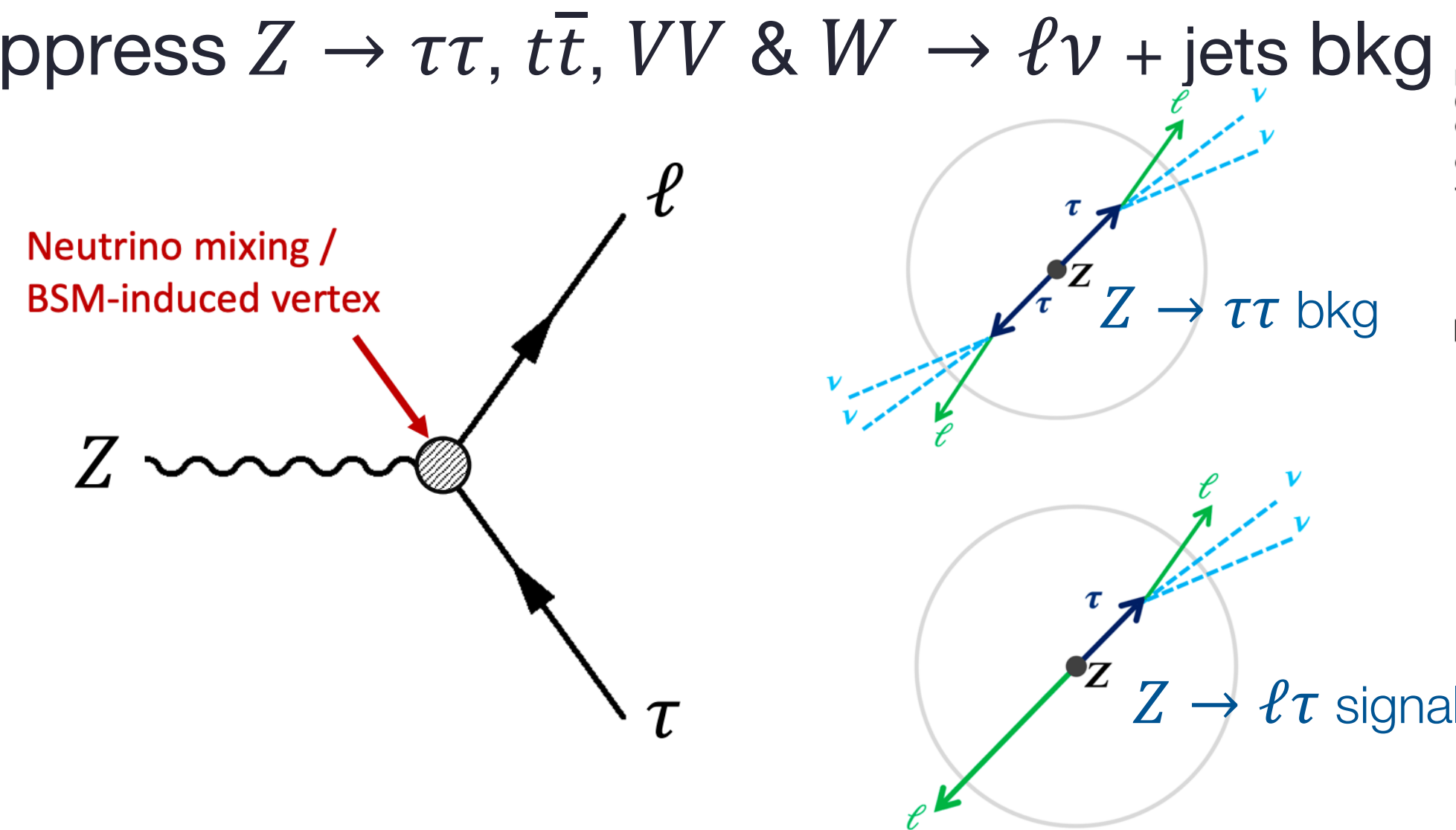
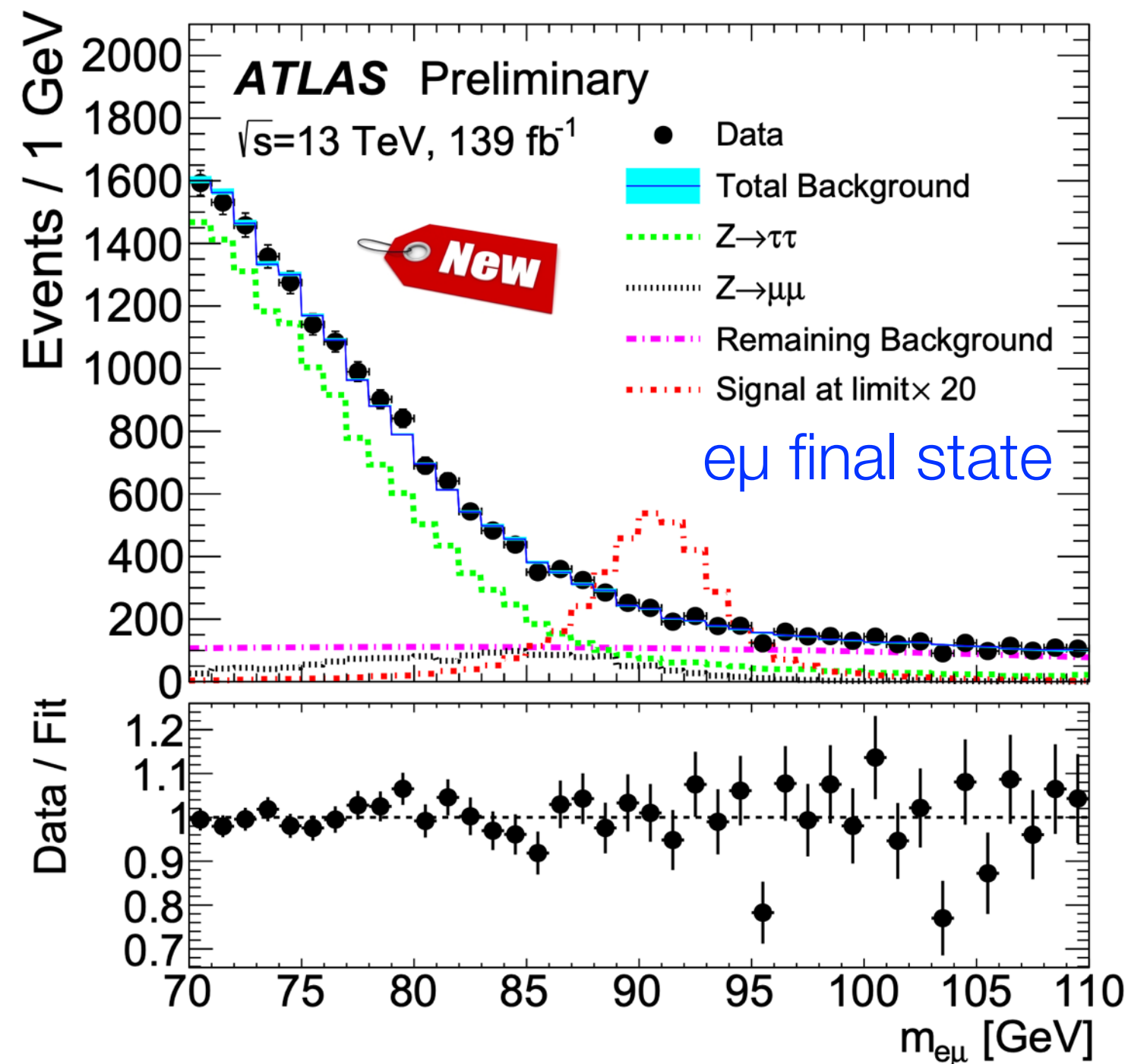


[ATLAS-CONF-2019-048](#)



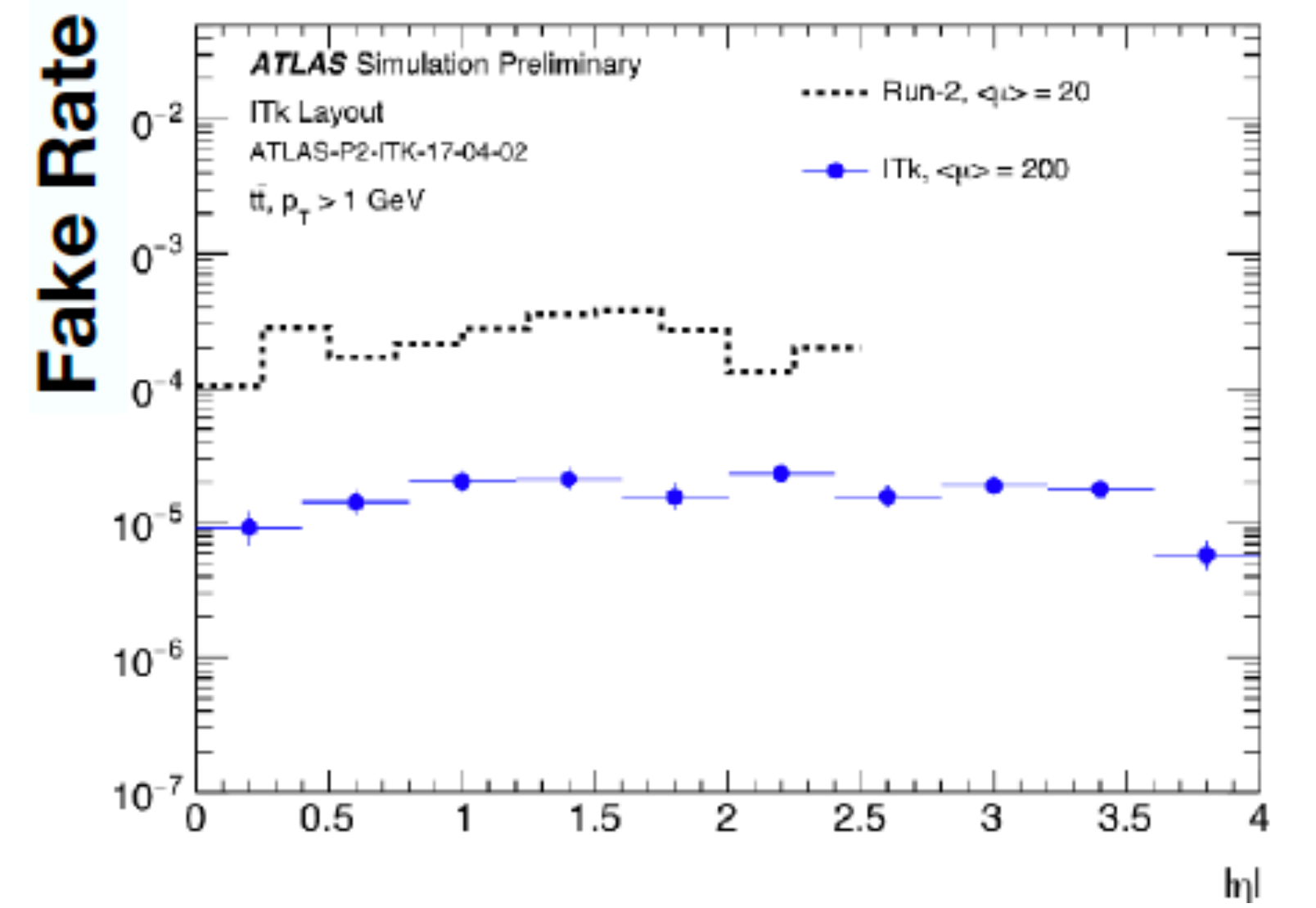
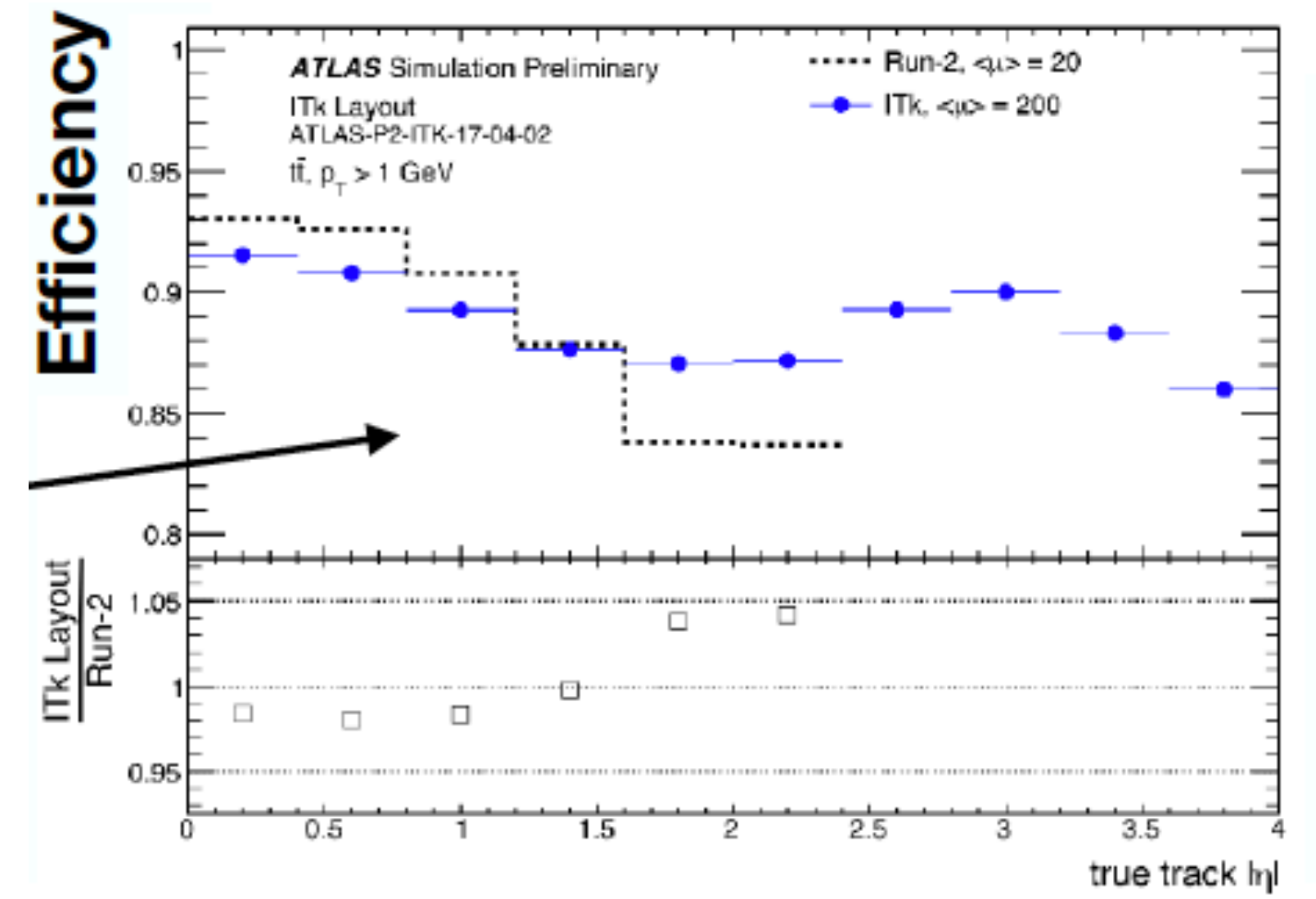
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{BSM}}$$

- Run 2: $\sim 8 \times 10^9$ Z bosons produced
- Lepton flavor violation only observed in neutrino oscillations, \sim negligible for ℓ^\pm in SM
- $Z \rightarrow e \mu$ search based on $m_{\ell\ell}$, w/ reduced uncert. normalizing to $Z \rightarrow ee, \mu\mu$
- $Z \rightarrow e \tau, \mu \tau$ search w/ NNs to suppress $Z \rightarrow \tau\tau, t\bar{t}, VV$ & $W \rightarrow \ell\nu + \text{jets}$ bkg



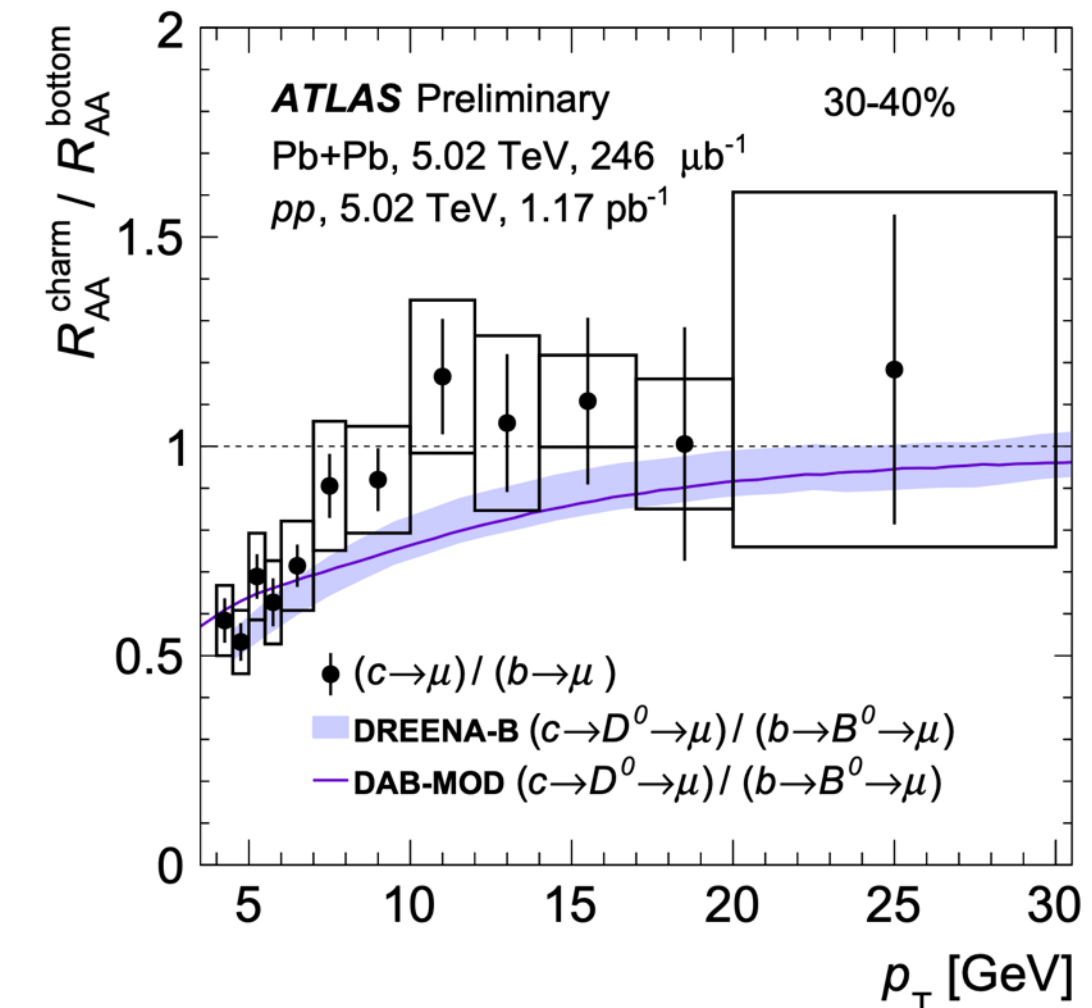
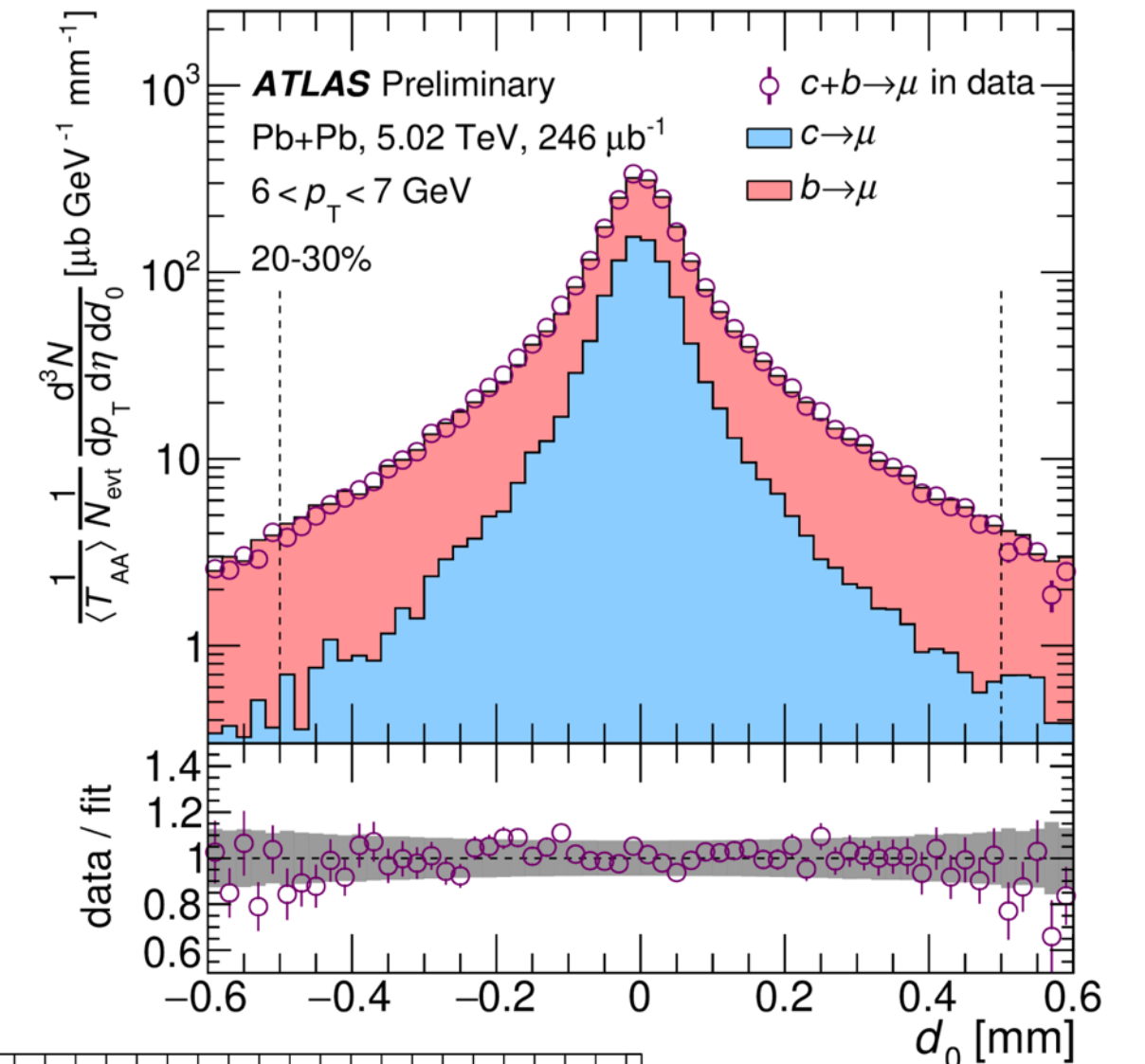
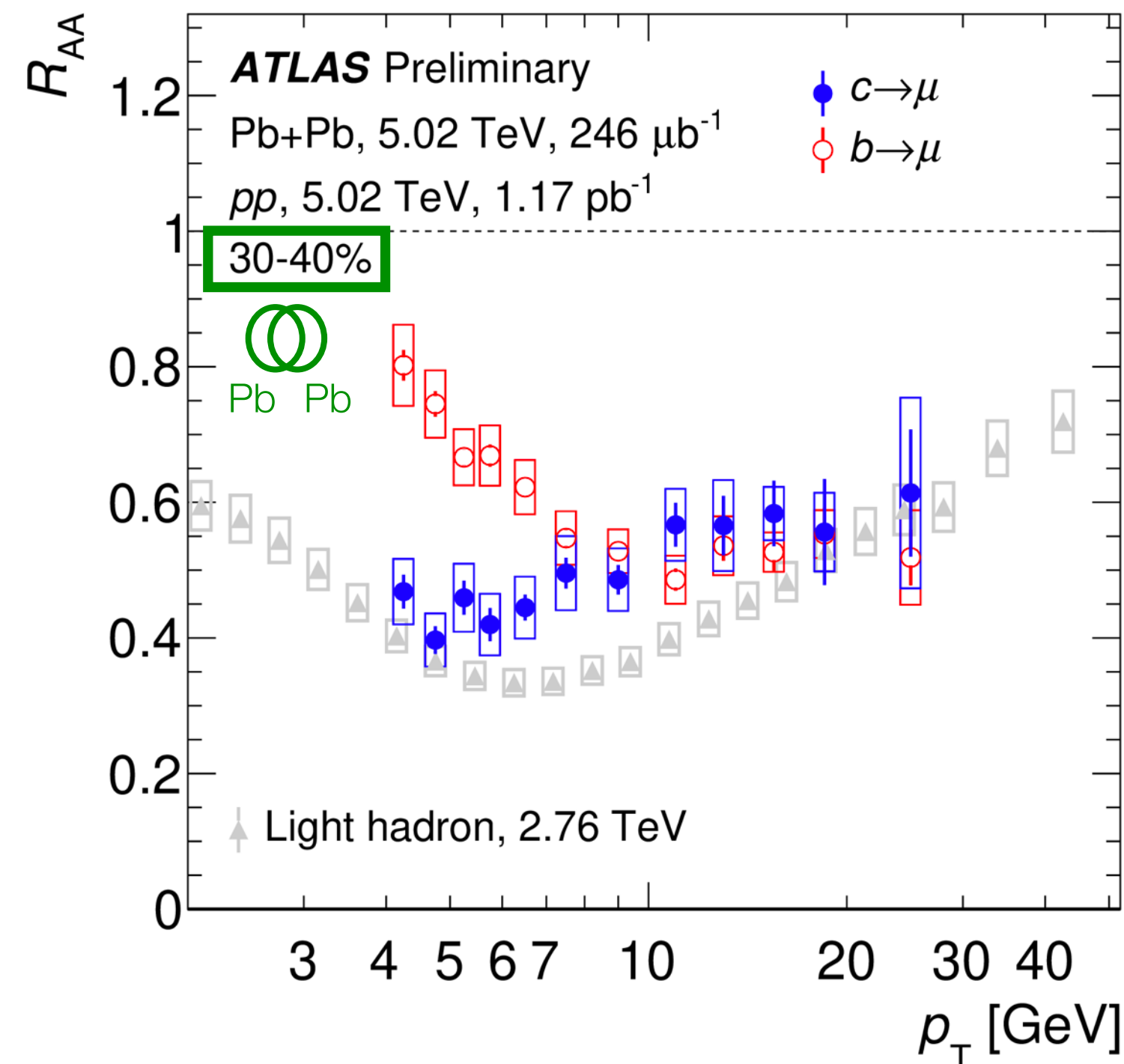
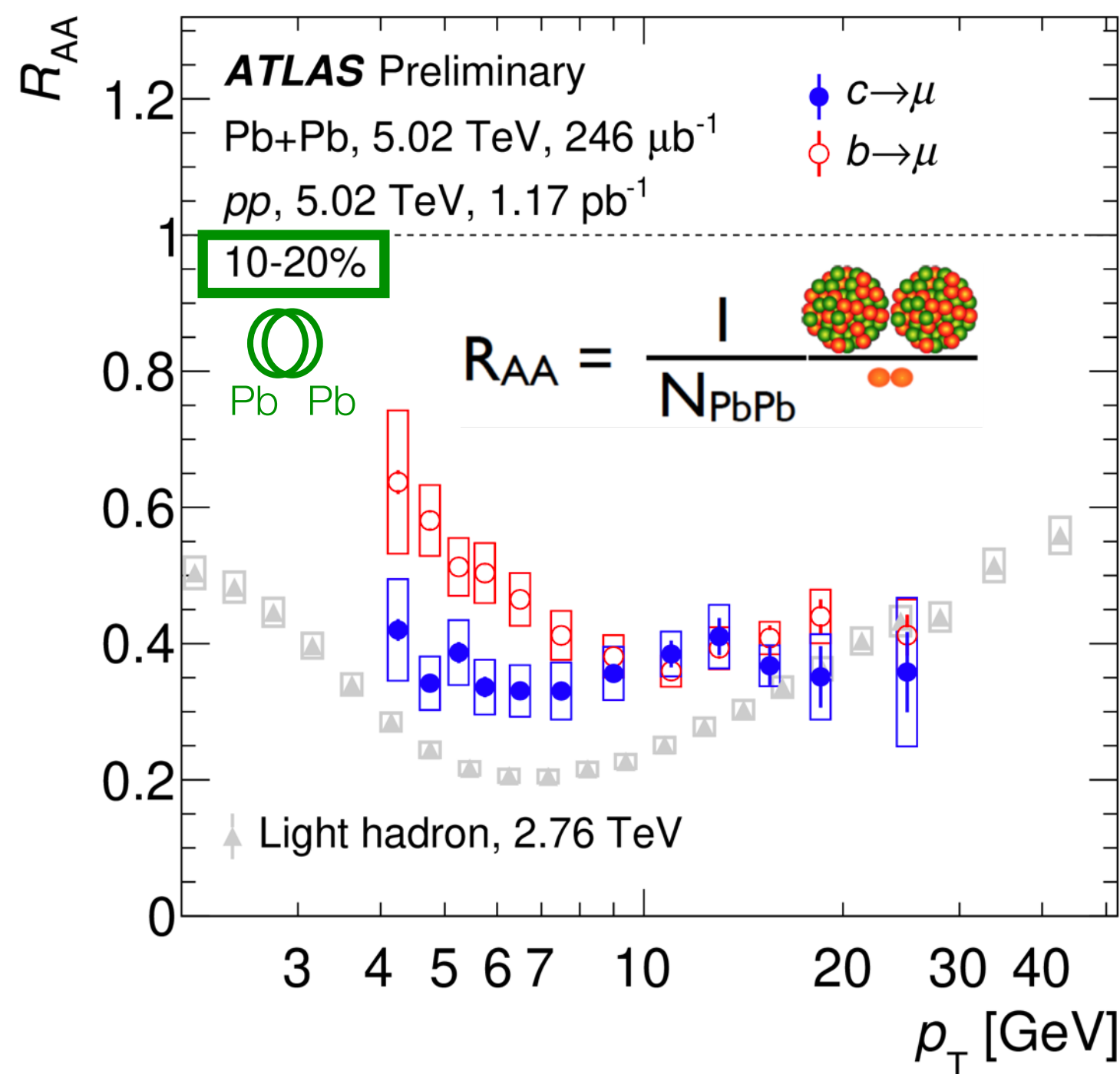
Upper limits at 95% CL	ATLAS	LEP
$B(Z \rightarrow e \mu)$	0.34×10^{-6}	1.7×10^{-6} (OPAL)
$B(Z \rightarrow e \tau)$	5.0×10^{-6}	9.8×10^{-6} (OPAL)
$B(Z \rightarrow \mu \tau)$	6.5×10^{-6}	12×10^{-6} (DELPHI)

- LEP limits surpassed by factors of 5 ($Z \rightarrow e\mu$) and 2 ($Z \rightarrow e\tau, \mu\tau$)



Bottom & charm energy loss in dense nuclear medium

- Study muons from decay of bottom and charm hadrons in pp and PbPb collisions
—> learn about energy loss mechanisms for heavy flavors in quark-gluon plasma
- Light/heavy-flavor hadron separation w/ muon p_T imbalance inner tracker vs. muon spectrometer
- b/c-hadron separation using muon impact parameter
- Stronger nuclear suppression for **charm** vs. **bottom** as predicted
 - Suppression also depends on p_T and **centrality** of PbPb collision





Heavy-ion collisions

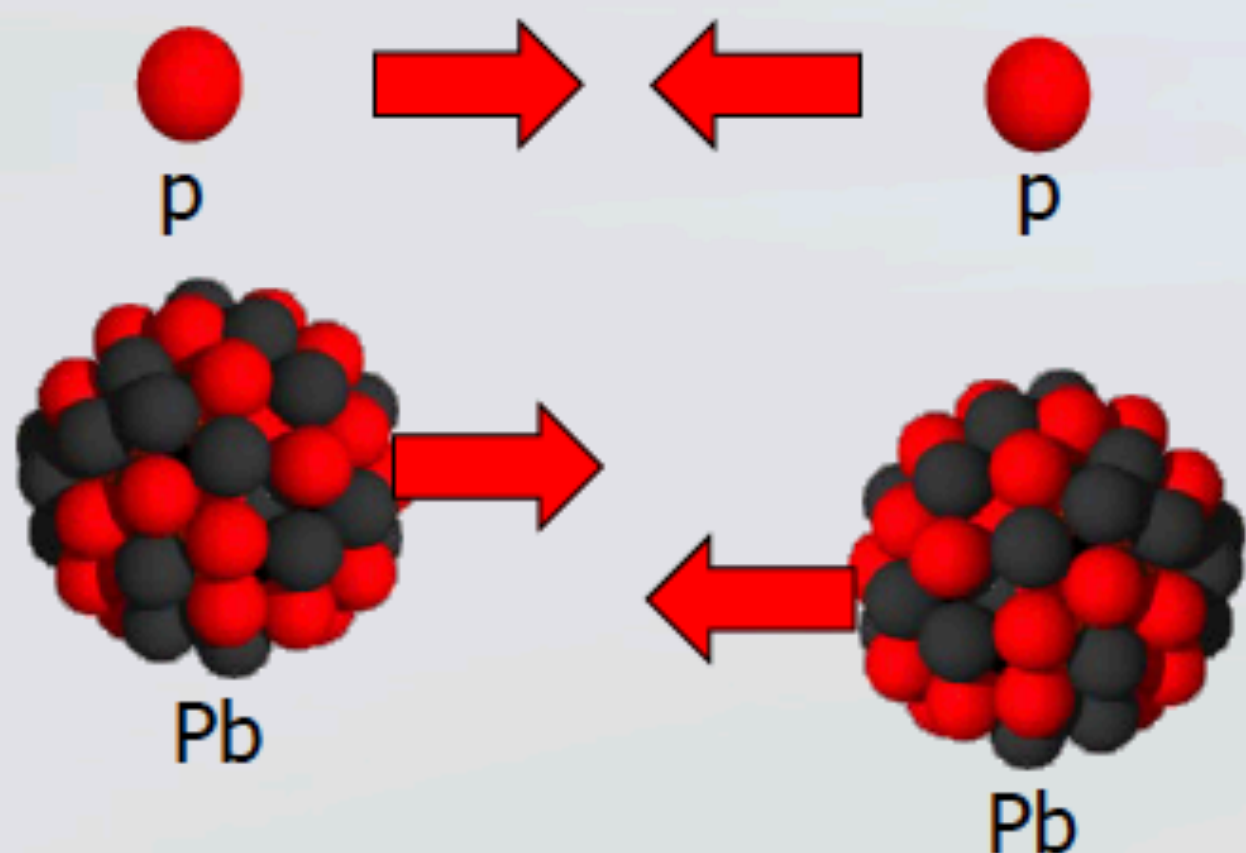
To probe the quark-gluon plasma...

5.02 TeV, PbPb: 246 μb^{-1} , pp: 1.17 pb^{-1}
 $b \rightarrow \mu$, $c \rightarrow \mu$

- Partons lose energy when traverse nuclear medium
- Suppression of small-angle gluon radiation for massive quarks at low p_T

$$R_{AA} = \frac{N_{AA}/N_{evt}}{\langle T_{AA} \rangle \times \sigma_{pp}}$$

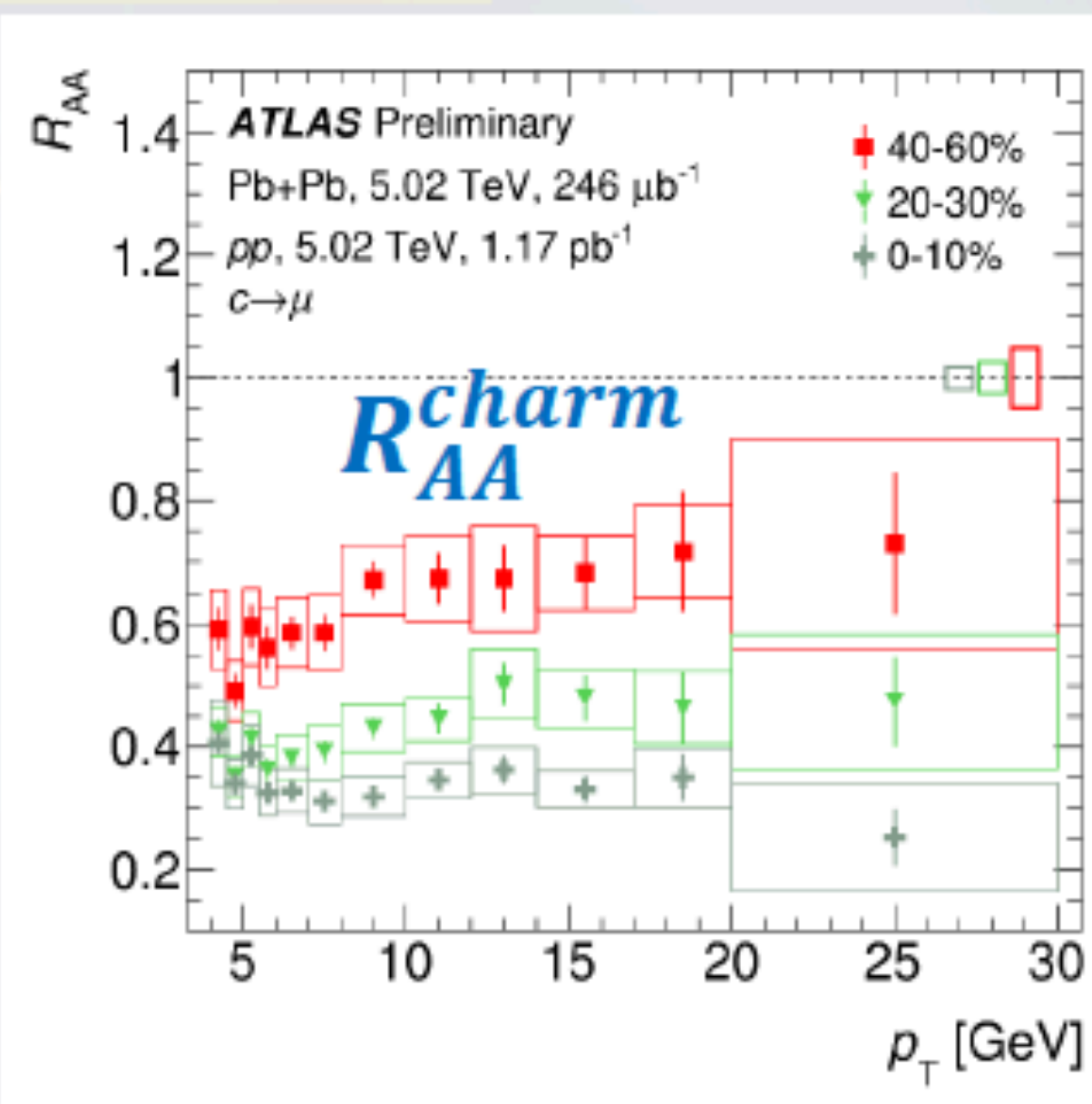
Modification to particle yields compared to pp scattering



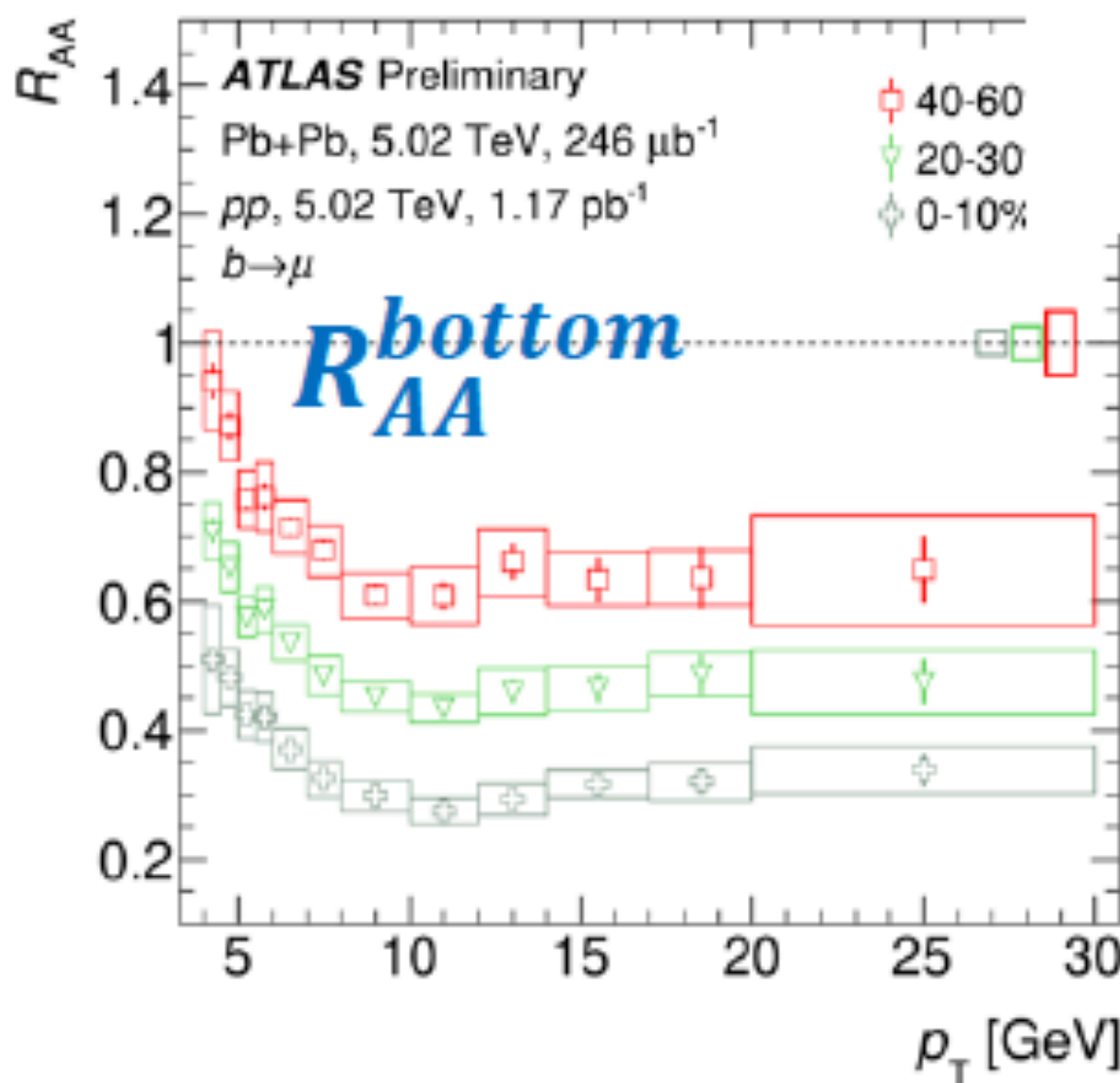
0-10%

40-60%

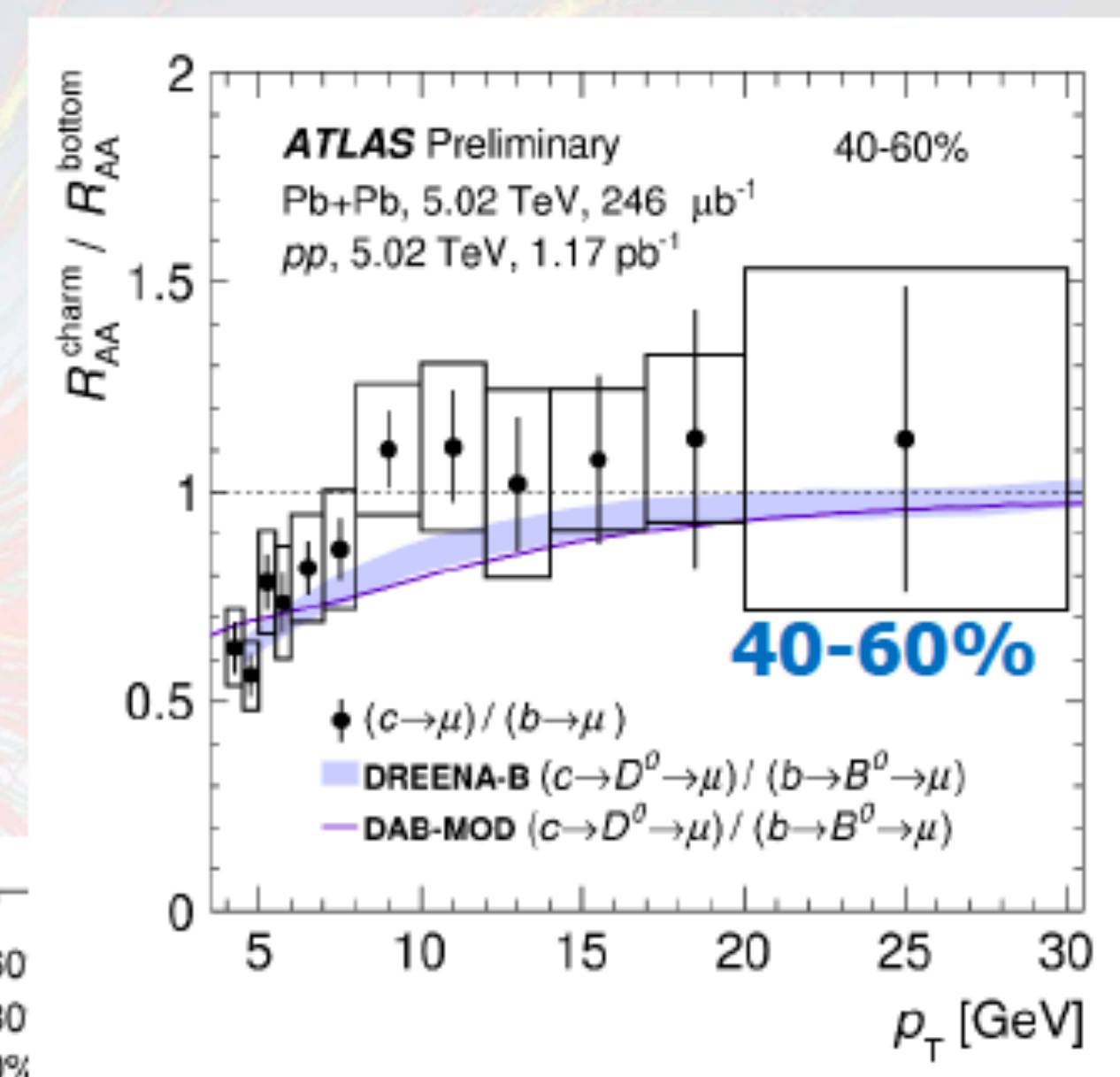
Centrality: overlap of colliding nuclei



Suppression increases monotonically from peripheral to central collisions



Stronger $c \rightarrow \mu$ modification at low p_T

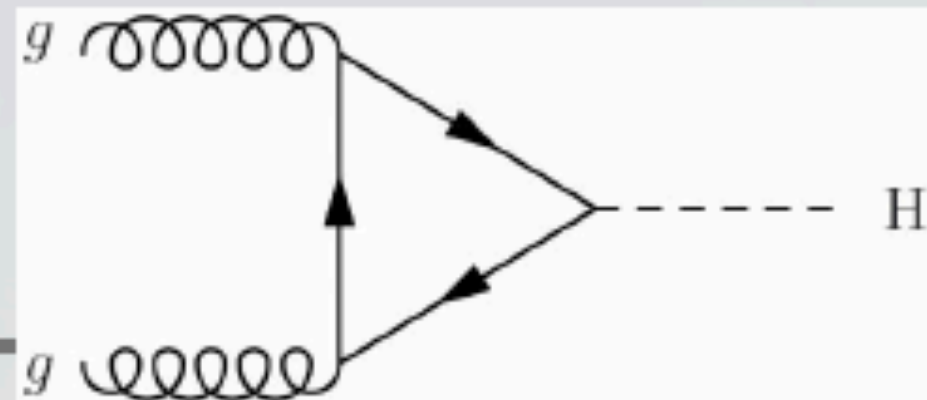


$$\frac{R_{AA}^{charm}}{R_{AA}^{bottom}}$$



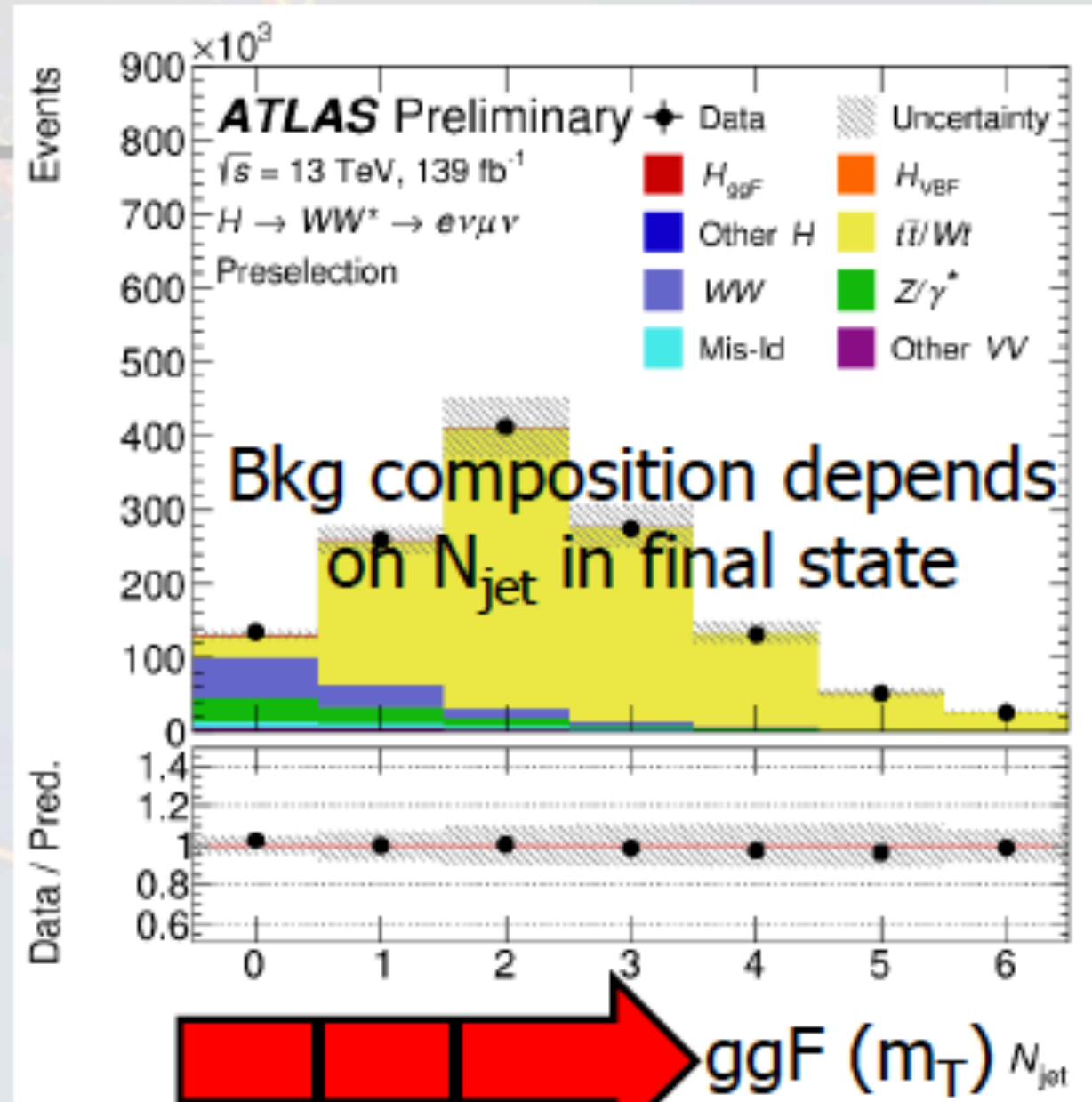
H → WW* production

13 TeV, 139 fb⁻¹
H → W[±]W^{∓*} → e[±]νμ[∓]ν

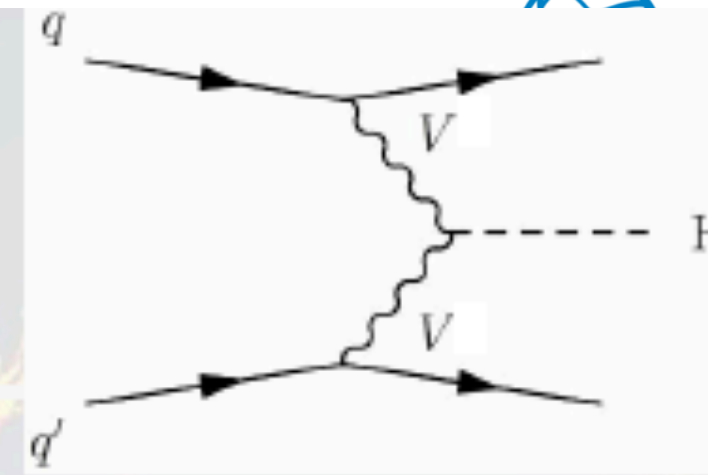


Gluon fusion ggF
 $\sigma \cdot B(H \rightarrow WW^*) \sim 10 \text{ pb}$

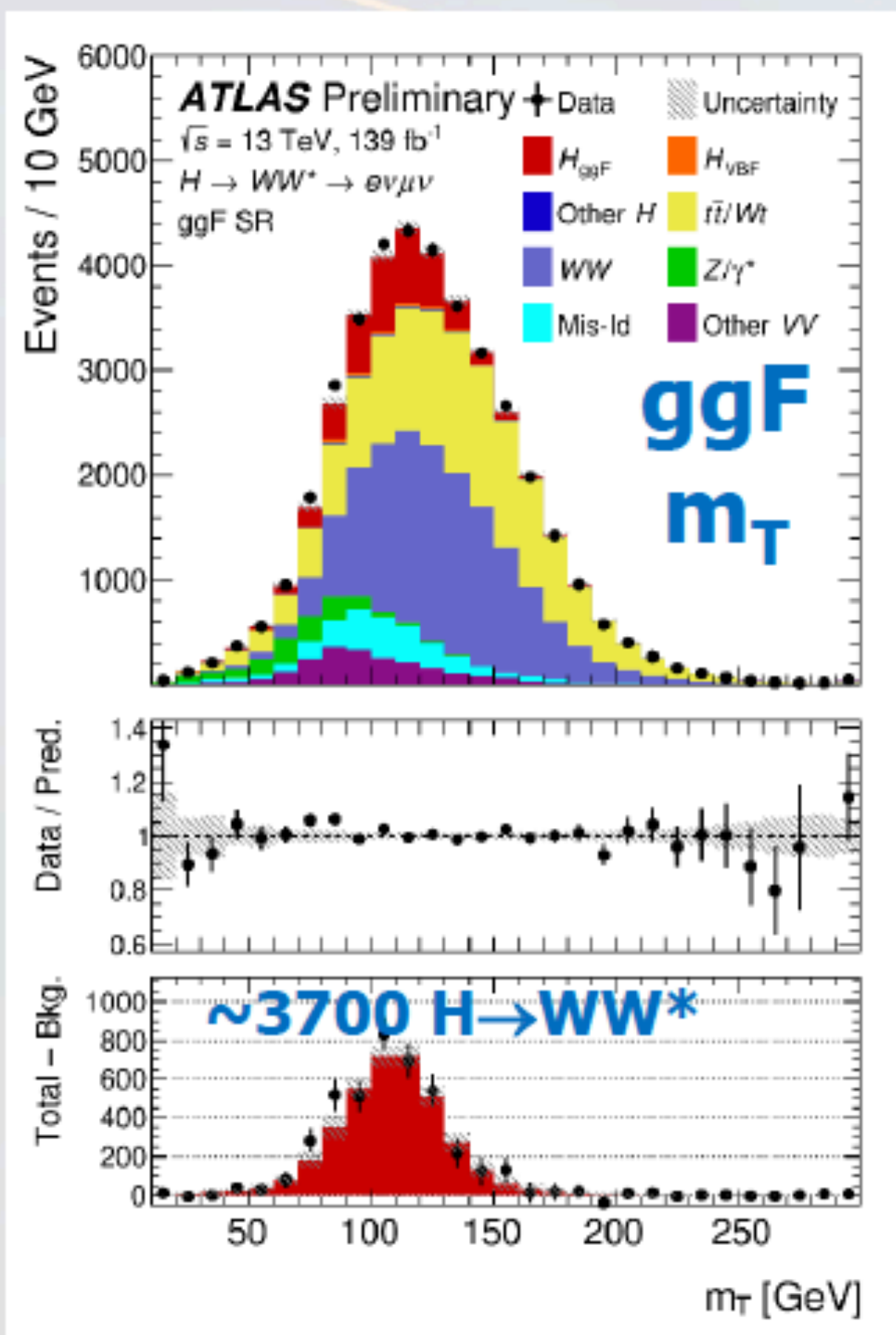
ATLAS-CONF-2021-014
Physics Briefing



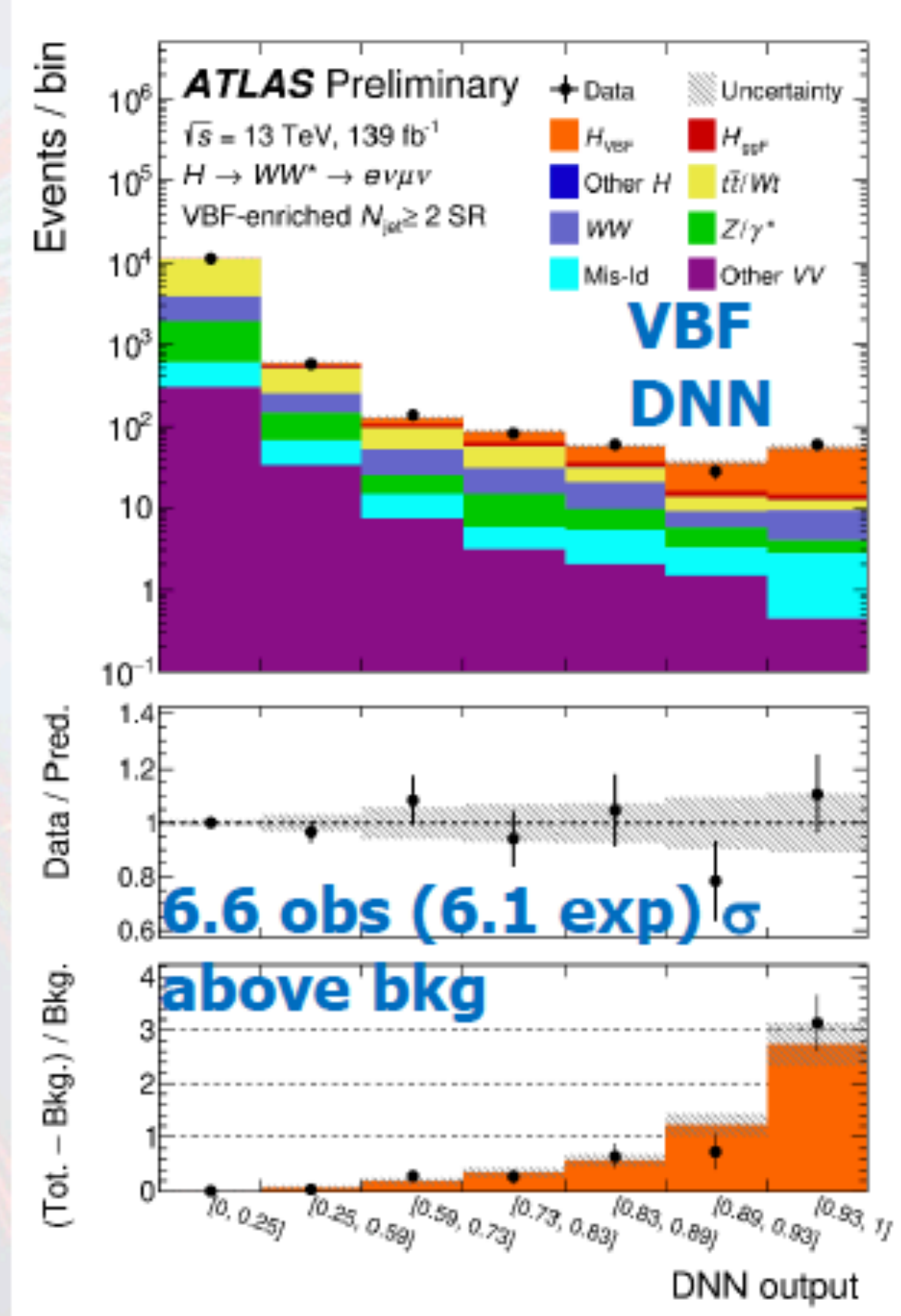
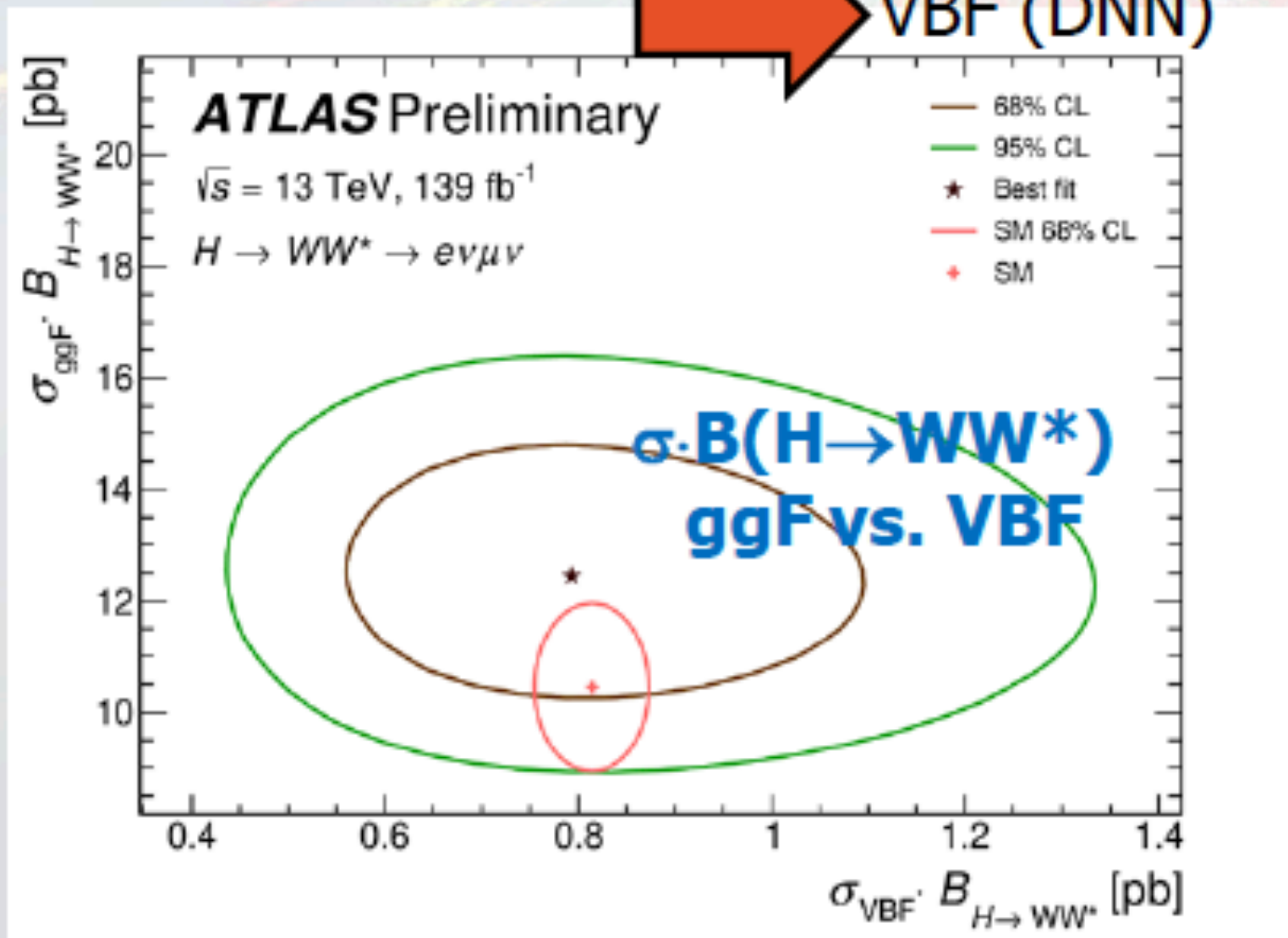
Vector-boson fusion VBF
 $\sigma \cdot B(H \rightarrow WW^*) \sim 1 \text{ pb}$



To probe Higgs-boson production and decay mechanisms...

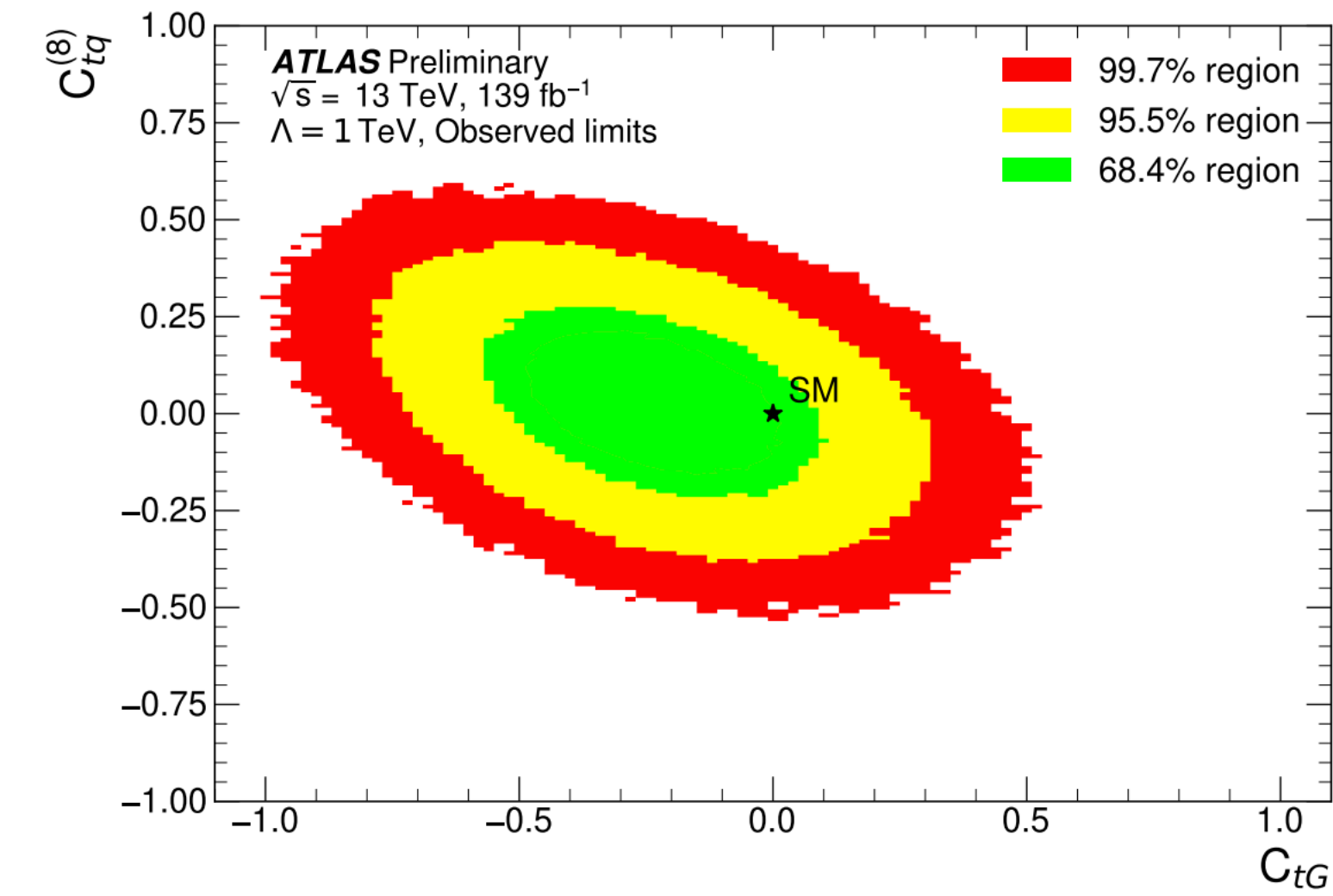
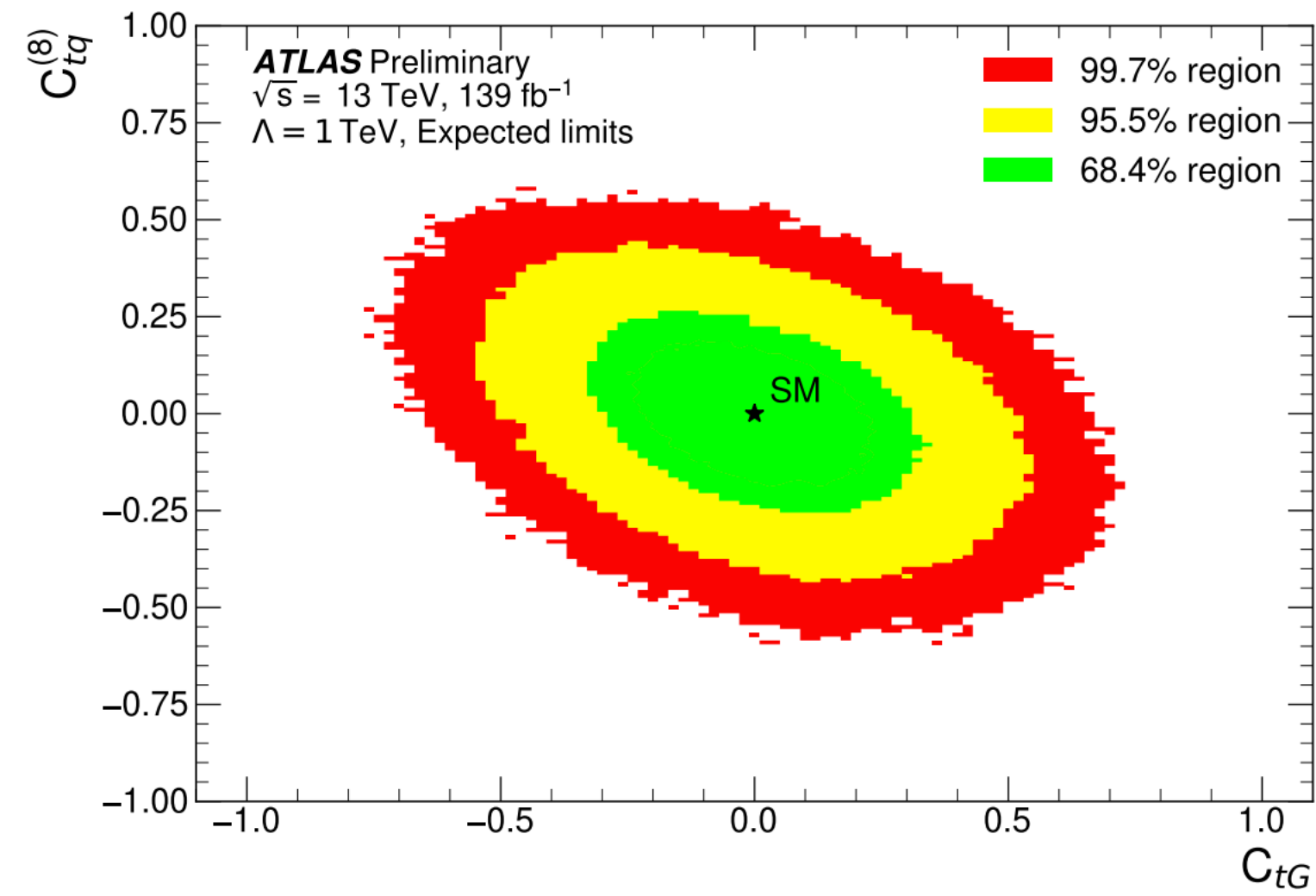
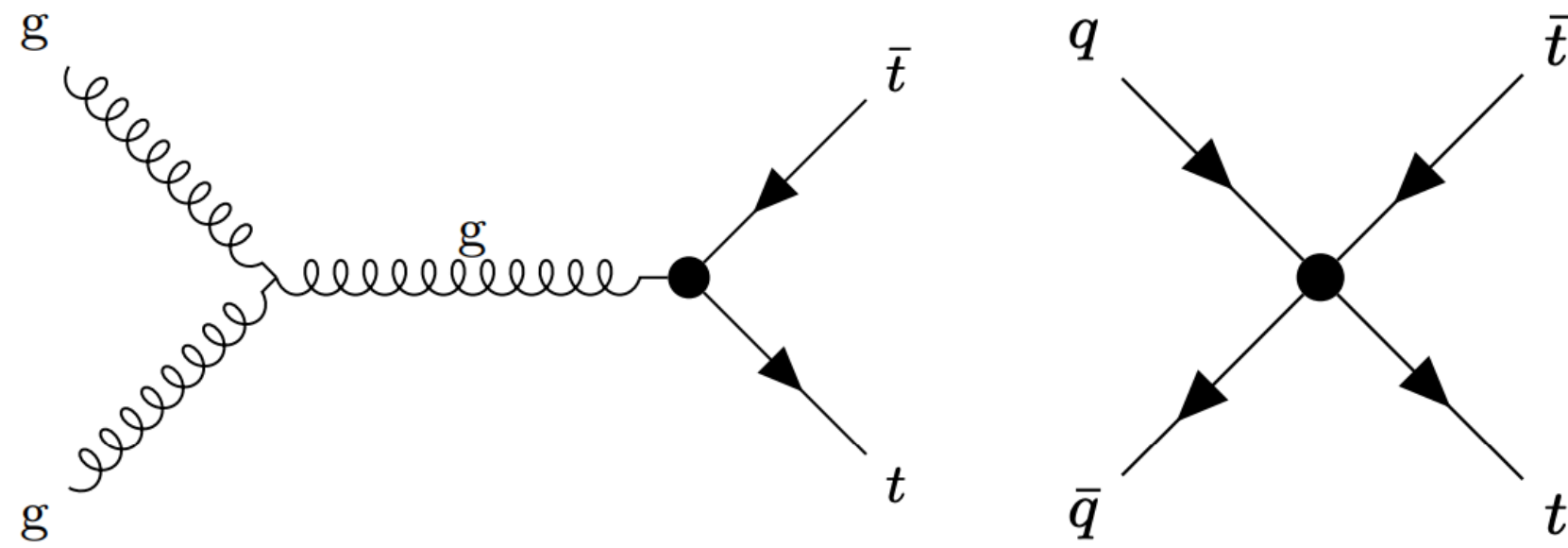


11 fiducial [Stage 1.2 STXS] cross sections
(6 ggH, 5 EW qqH)
[see backup]



Top-quark EFT constraints

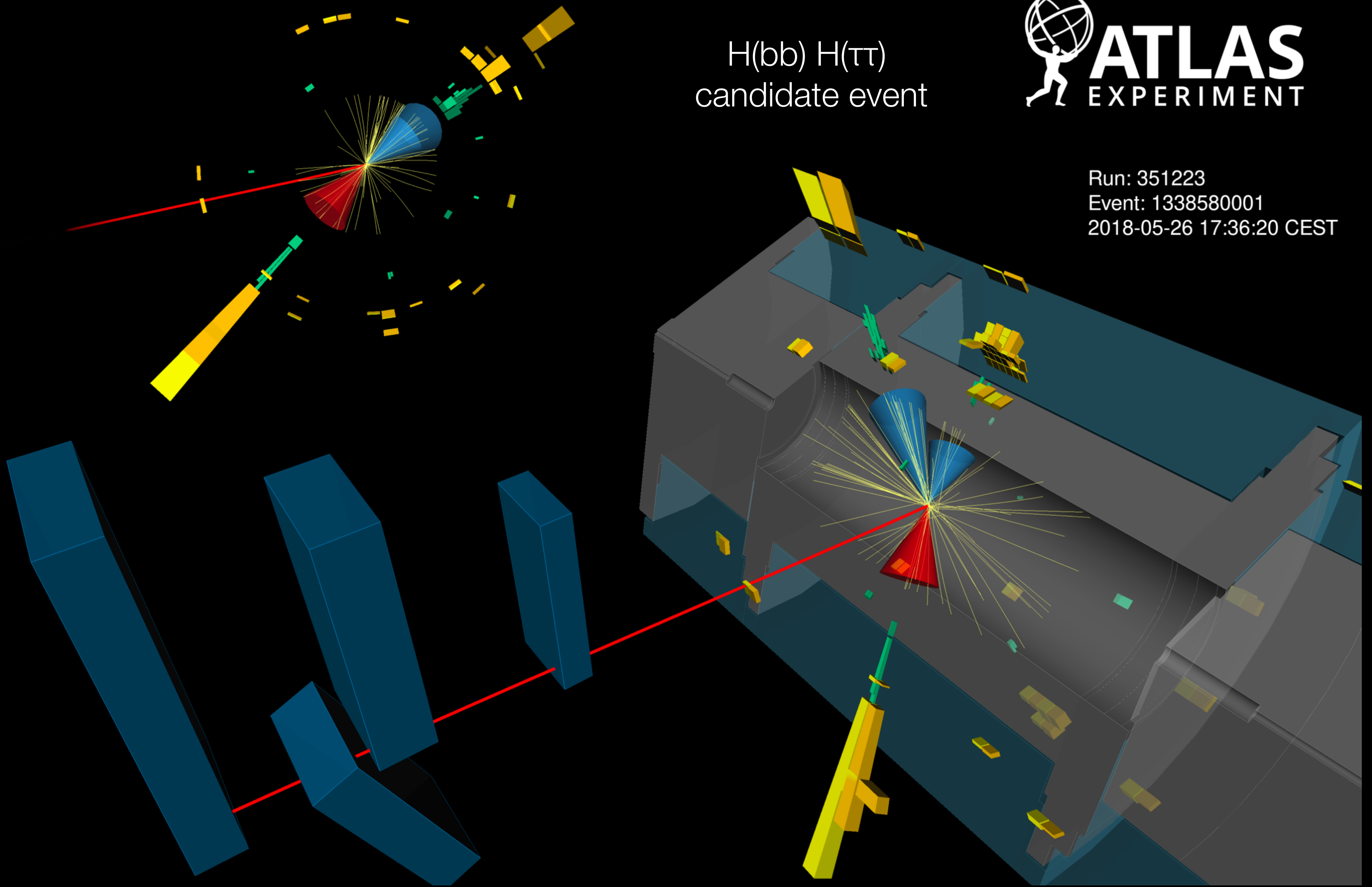
- EFT constraints from $t\bar{t}$ production



H(bb) H($\tau\tau$)
candidate event

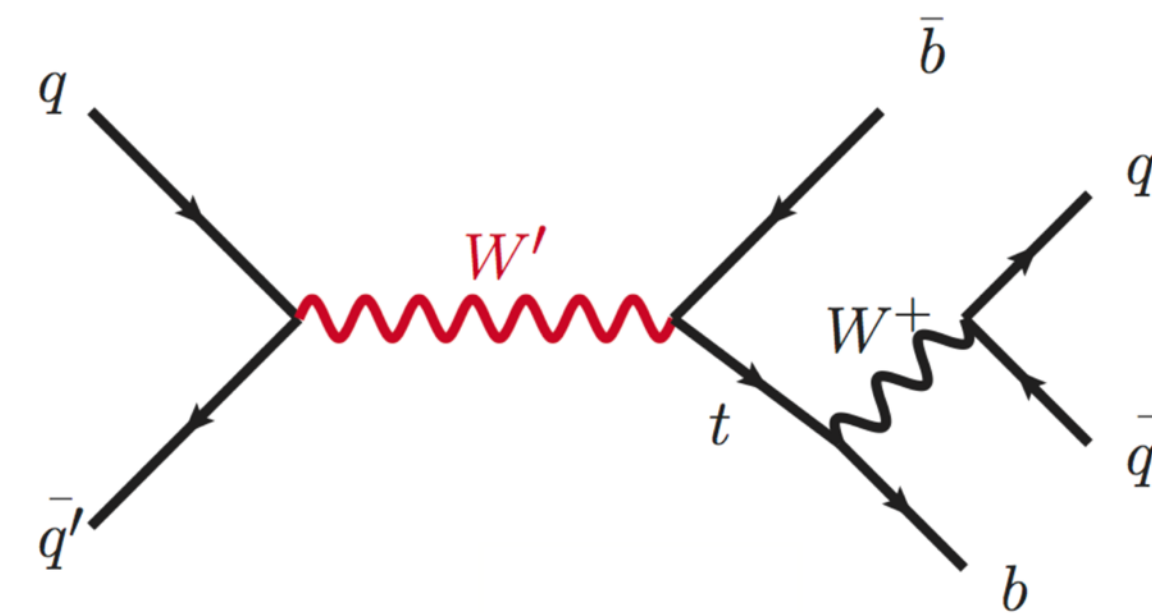


Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST



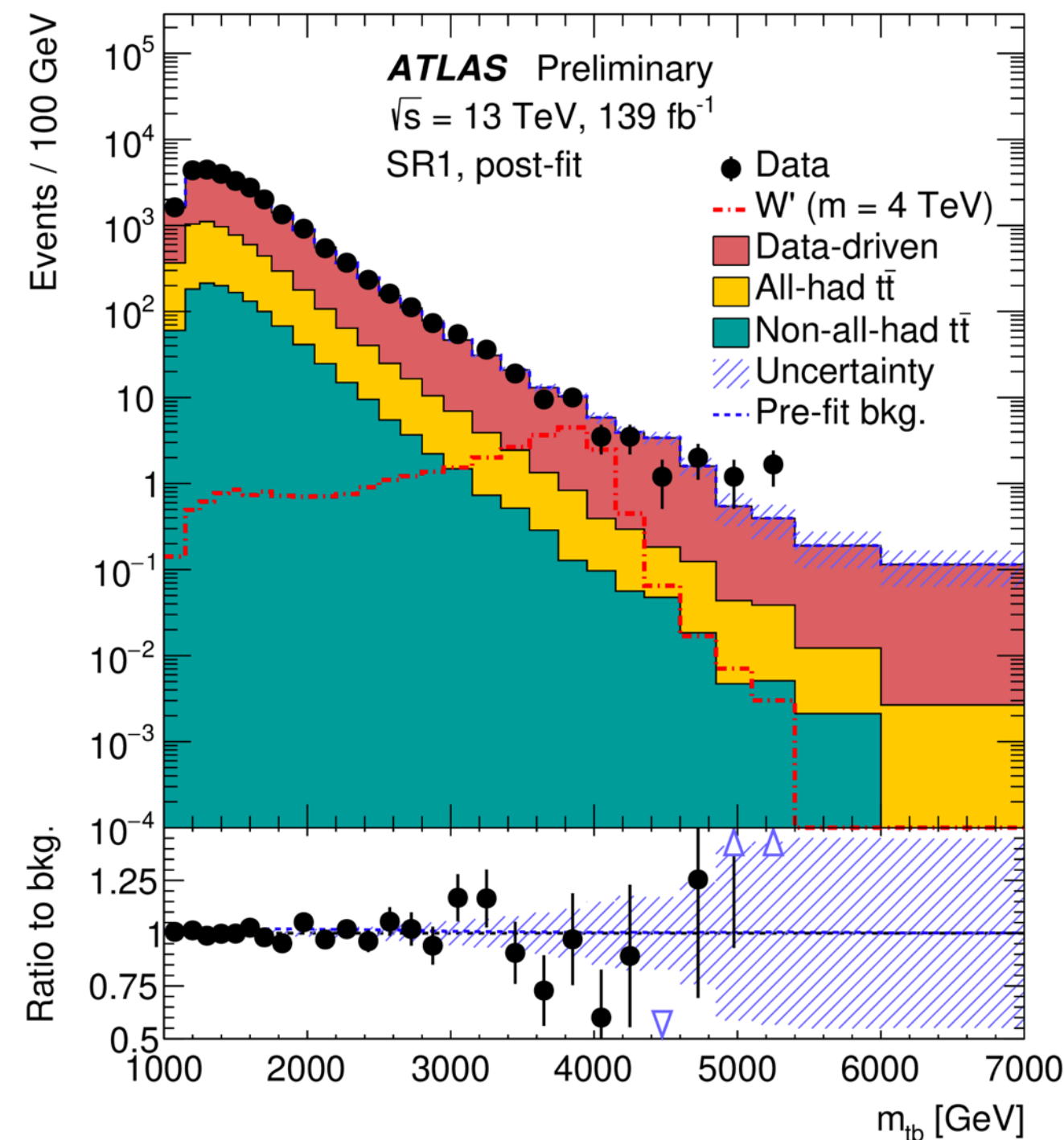
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{BSM}}$$

- Motivated by hierarchy problem \rightarrow new physics at TeV scale
- Heavy gauge boson** with right-handed couplings
 - Top-tagged large-R jet + b-tagged small-R jet
 - Deep NN top tagger using jet substructure
 - Discriminant: m_{tb}

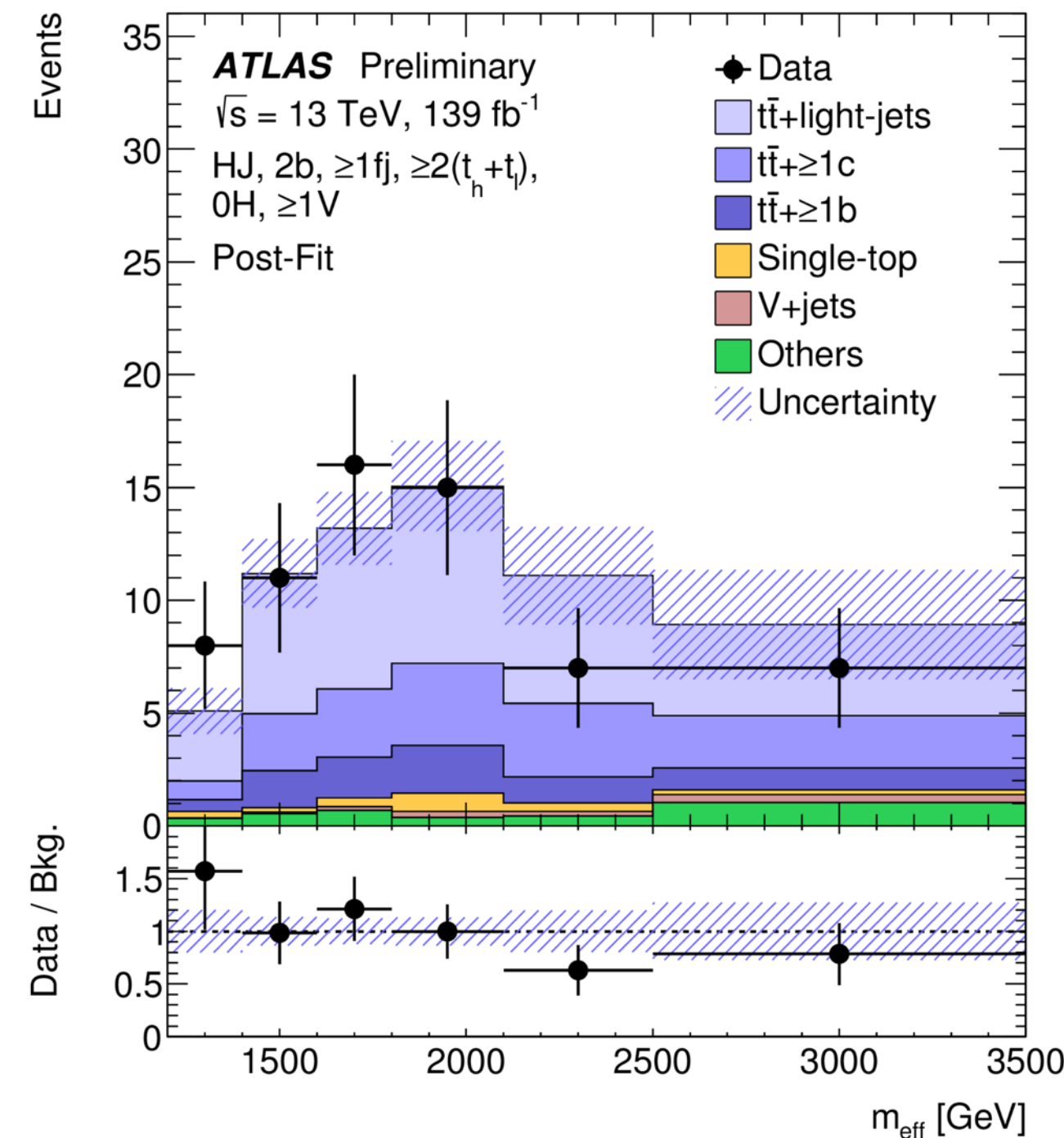
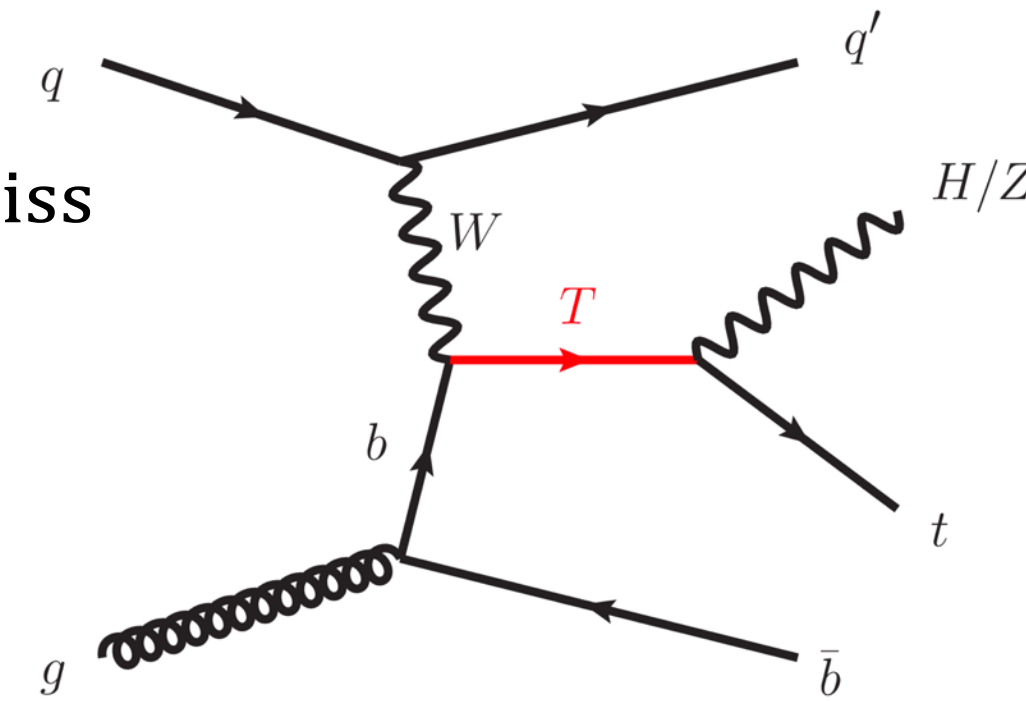


$m(W'_R) > 4.4\text{TeV}(4.1\text{TeV})$
obs(exp)

lower limit improves upon
best previous limit by 1 TeV



- Vector-like top quark** (single production)
 - e/ μ + Z/H-tagged large-R jet + small-R jets (some b-tagged)
 - Discr.: $m_{\text{eff}} = \sum_i p_{T_i} + E_T^{\text{miss}}$

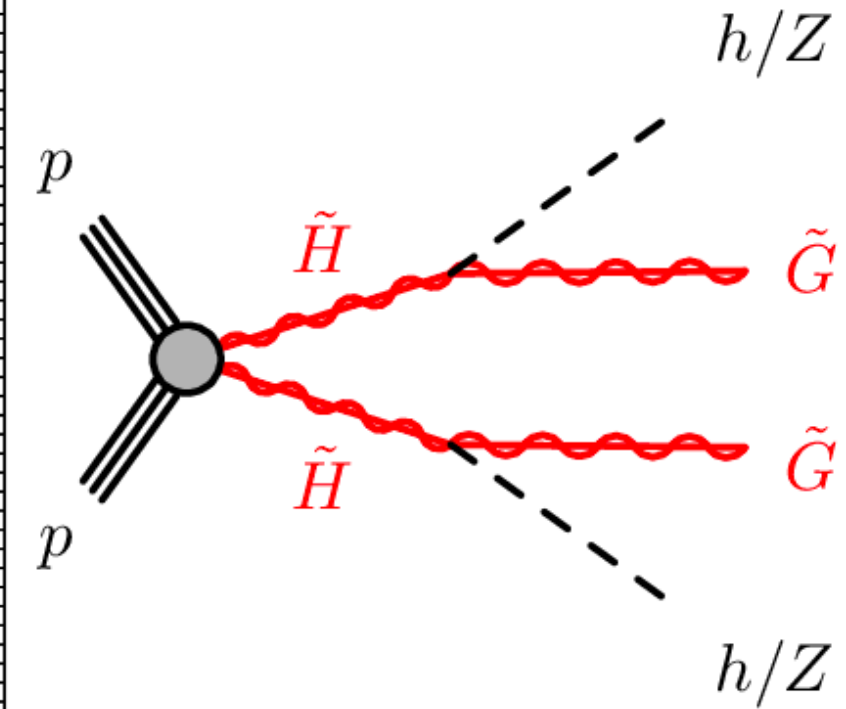
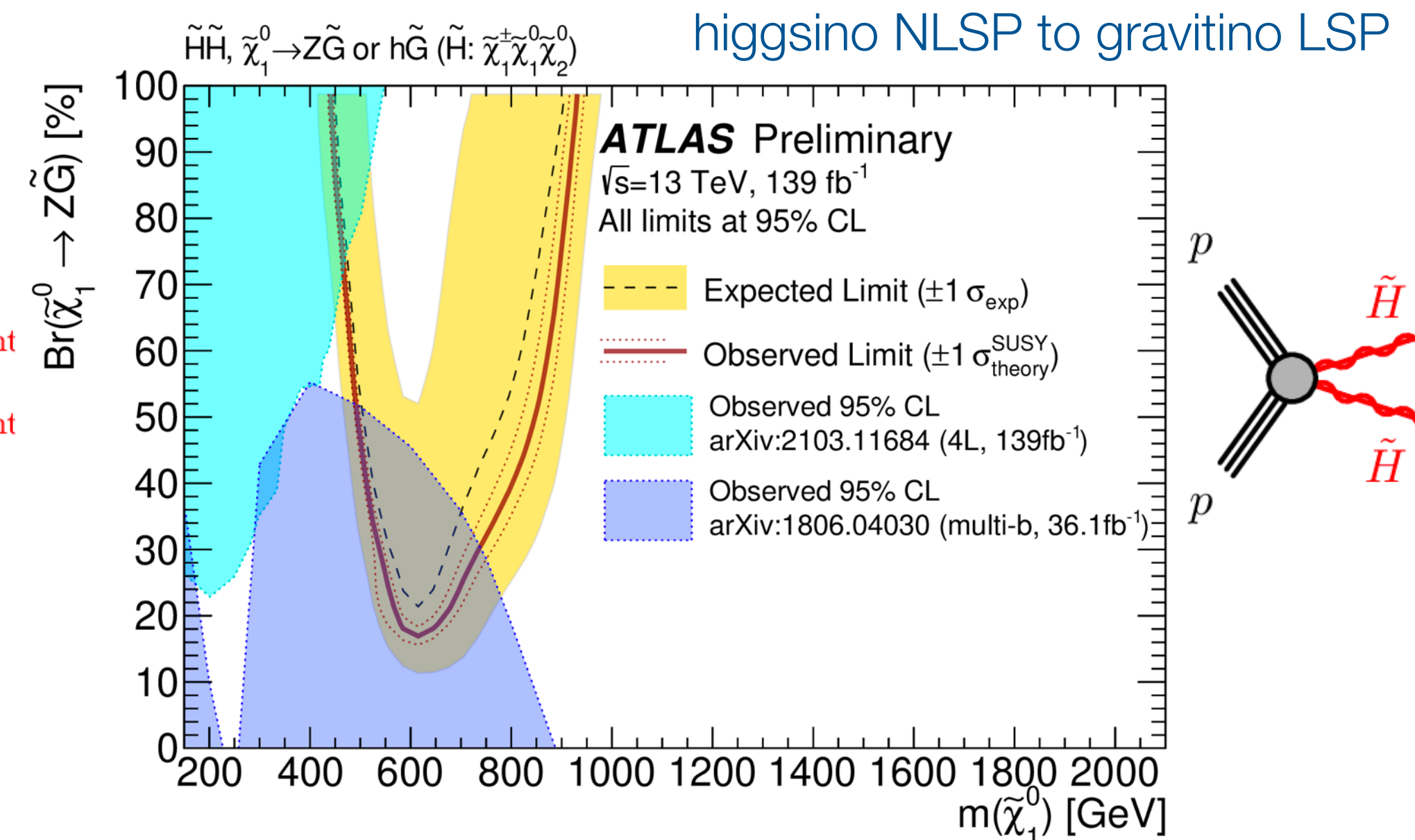
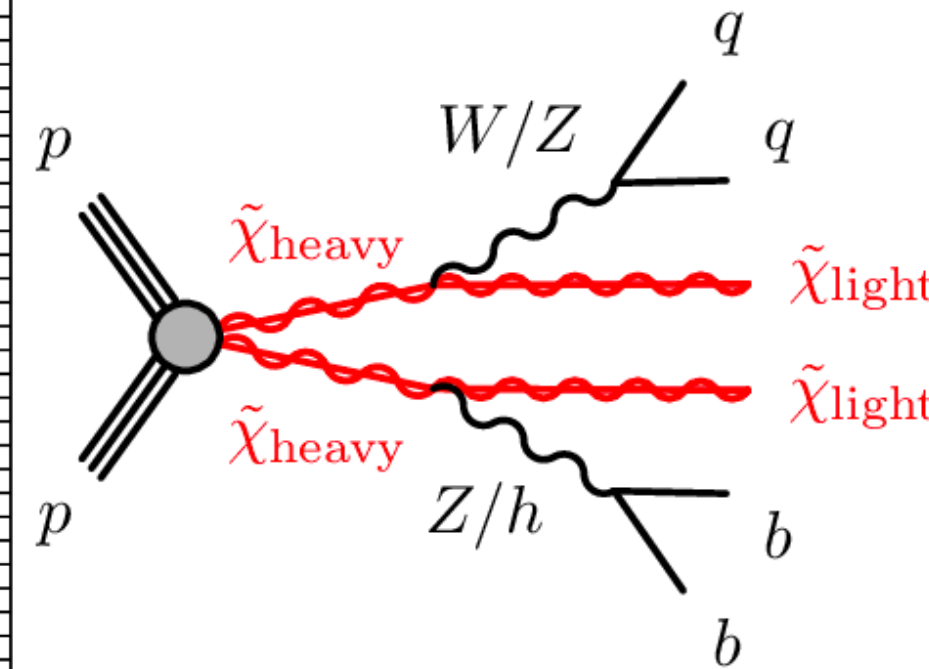
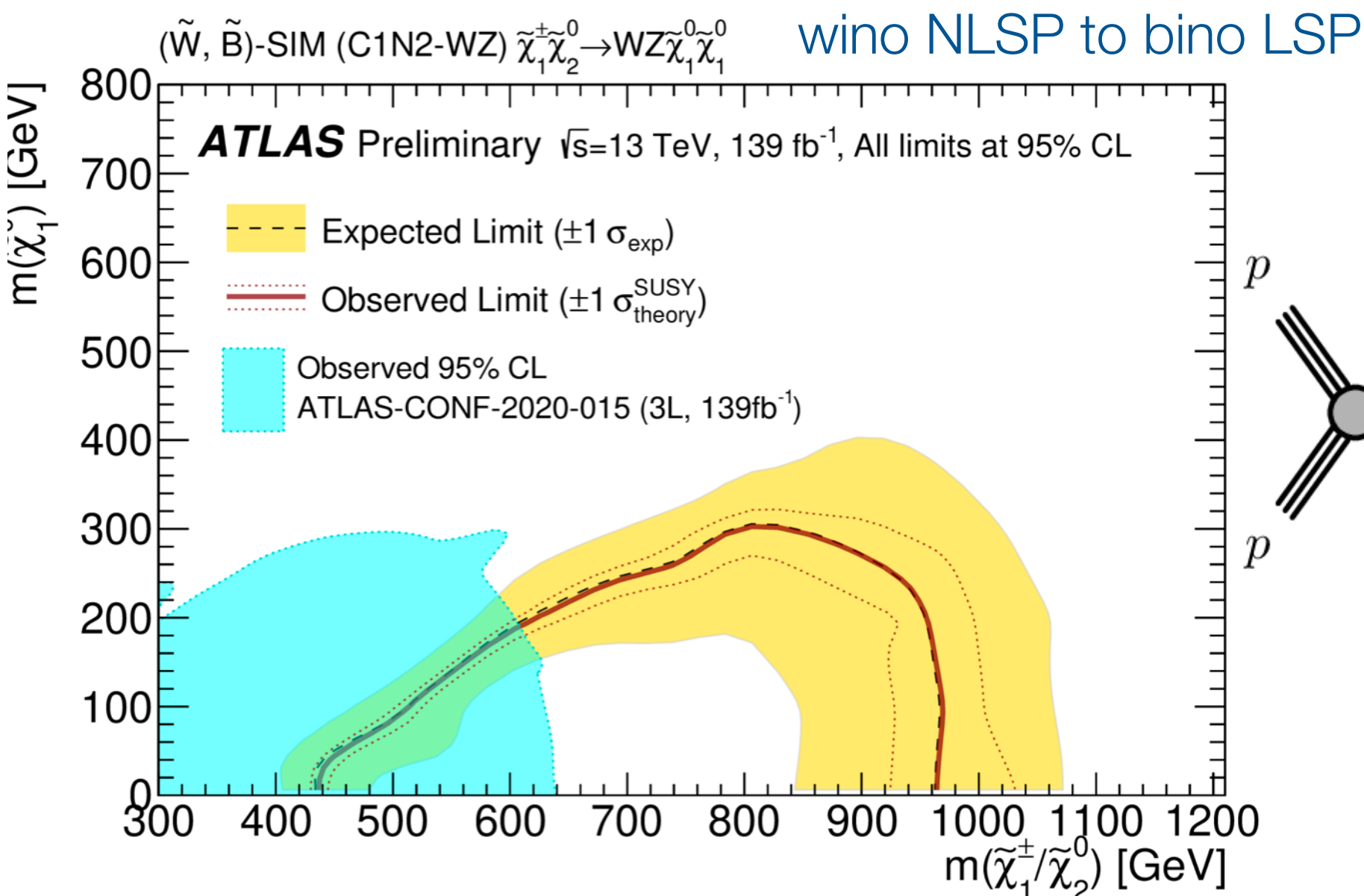
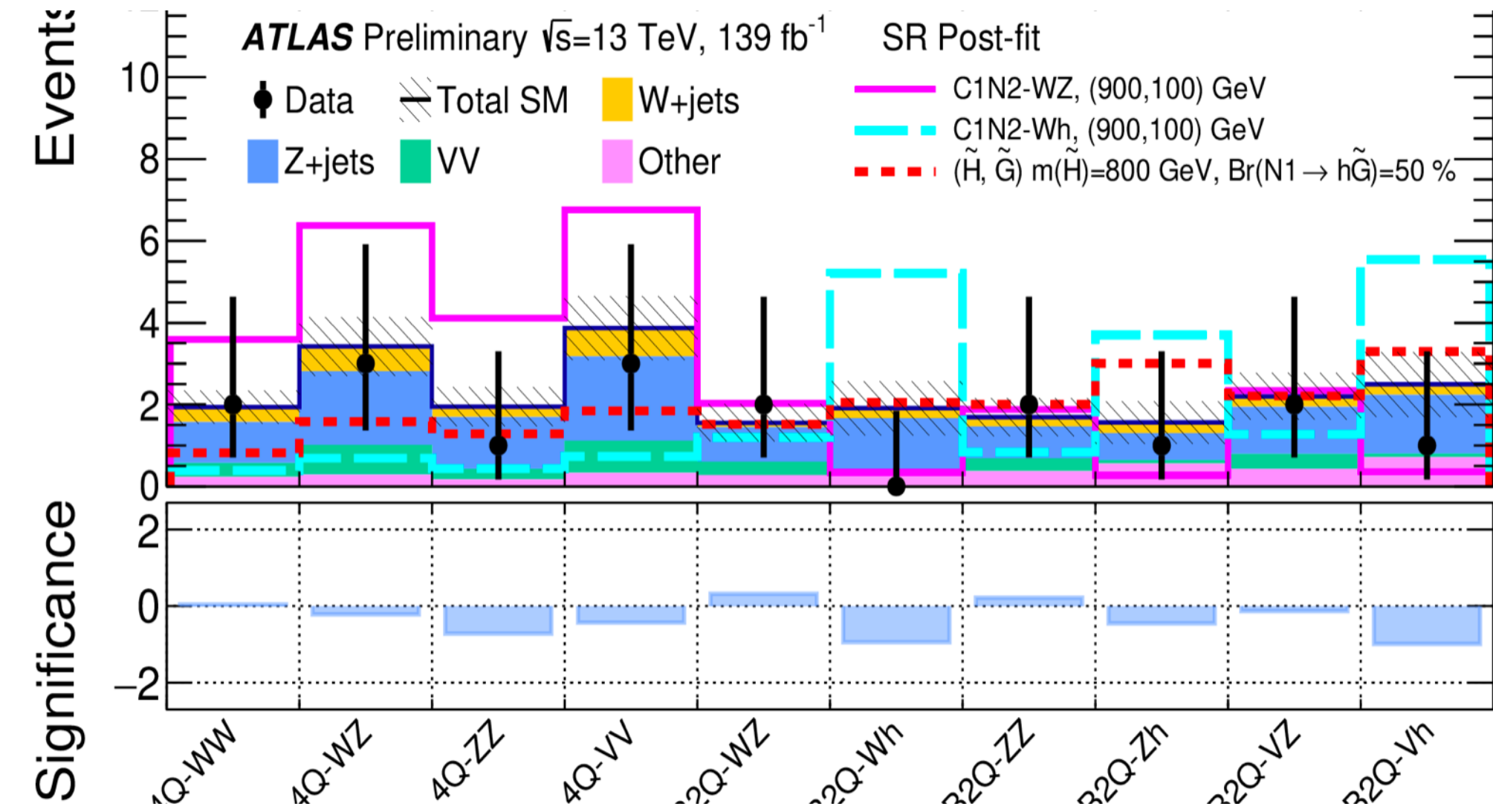


$m(T) > 1.8\text{TeV}(1.5\text{TeV})$
obs(exp)
for coupling $\kappa \geq 0.5$

SUSY: Electroweak production

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{SUSY}}$$

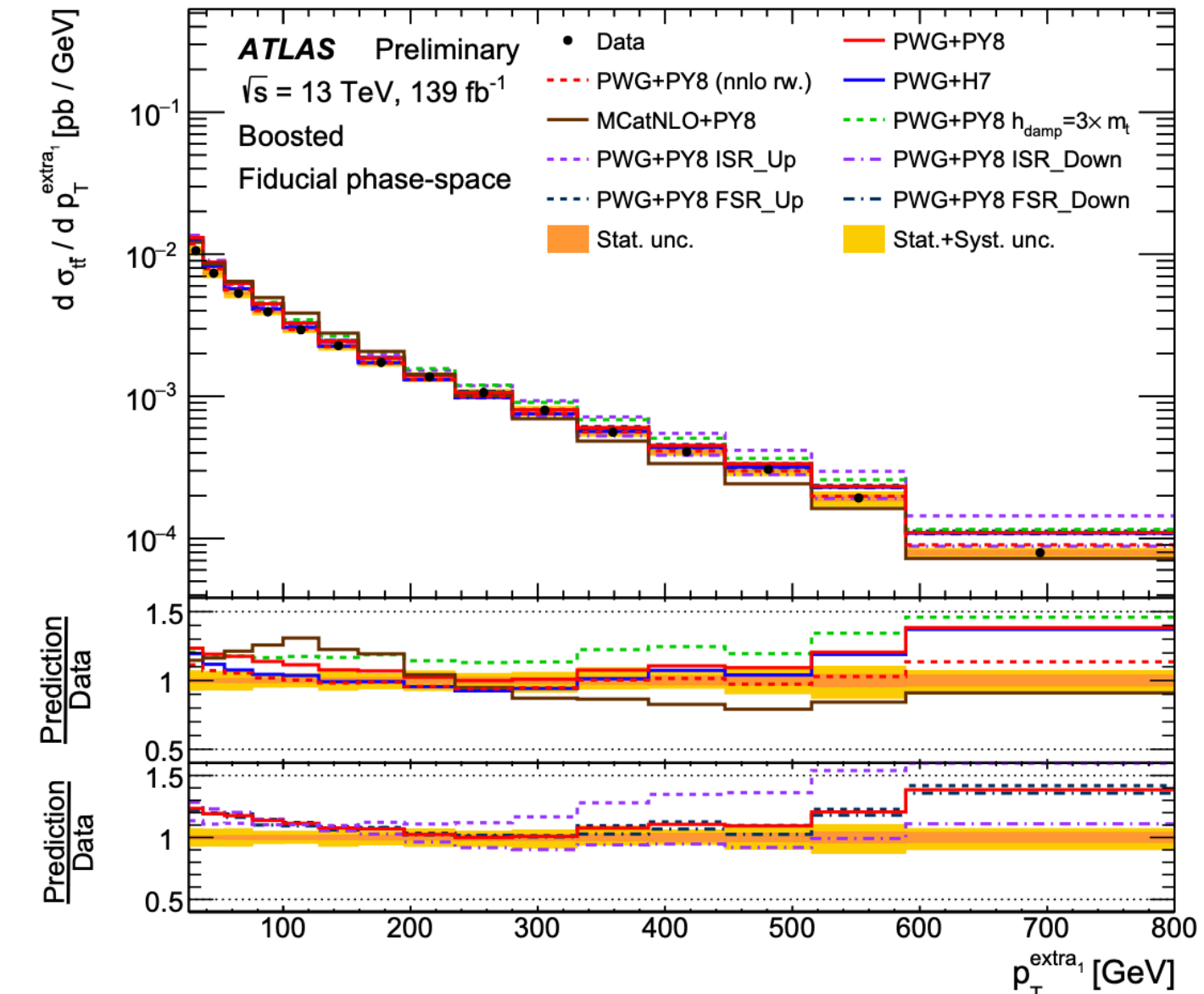
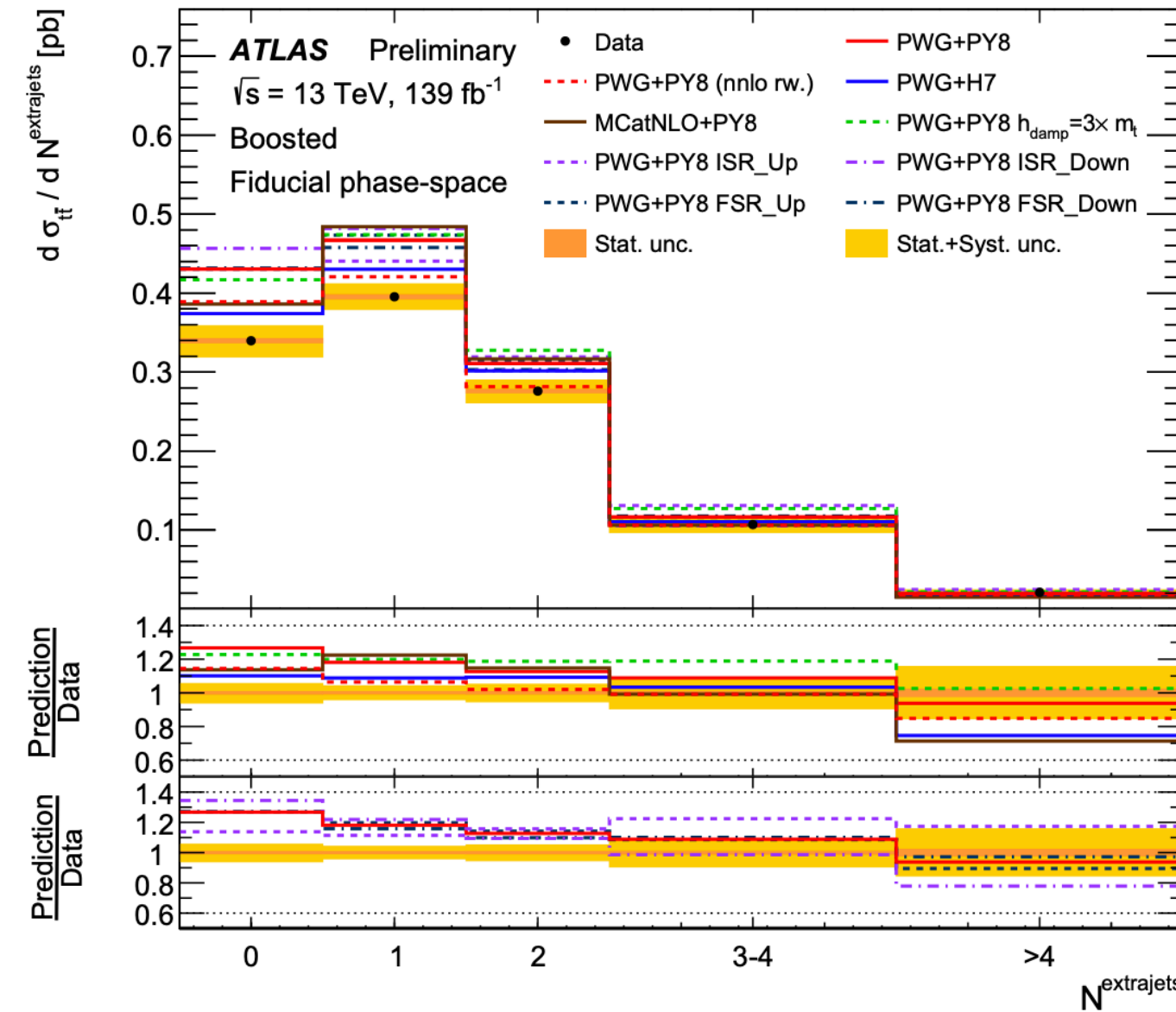
- **Electroweakinos** with mass $\sim 0.1 - 1$ TeV well motivated:
 - Neutralino LSP as dark matter, naturalness problem, muon $g-2$ anomaly
- Target mass splitting between NLSP and LSP > 400 GeV
- **First SUSY EW search** with fully hadronic final state using large-R jets tagged as W/Z or H jets
- Strongest limits at high electroweakino mass



Top-quark production

- Measurements of $t\bar{t}$ system + additional jets

- Difficulties in modeling of additional radiation in events with high- p_T top quarks \rightarrow test of parton shower

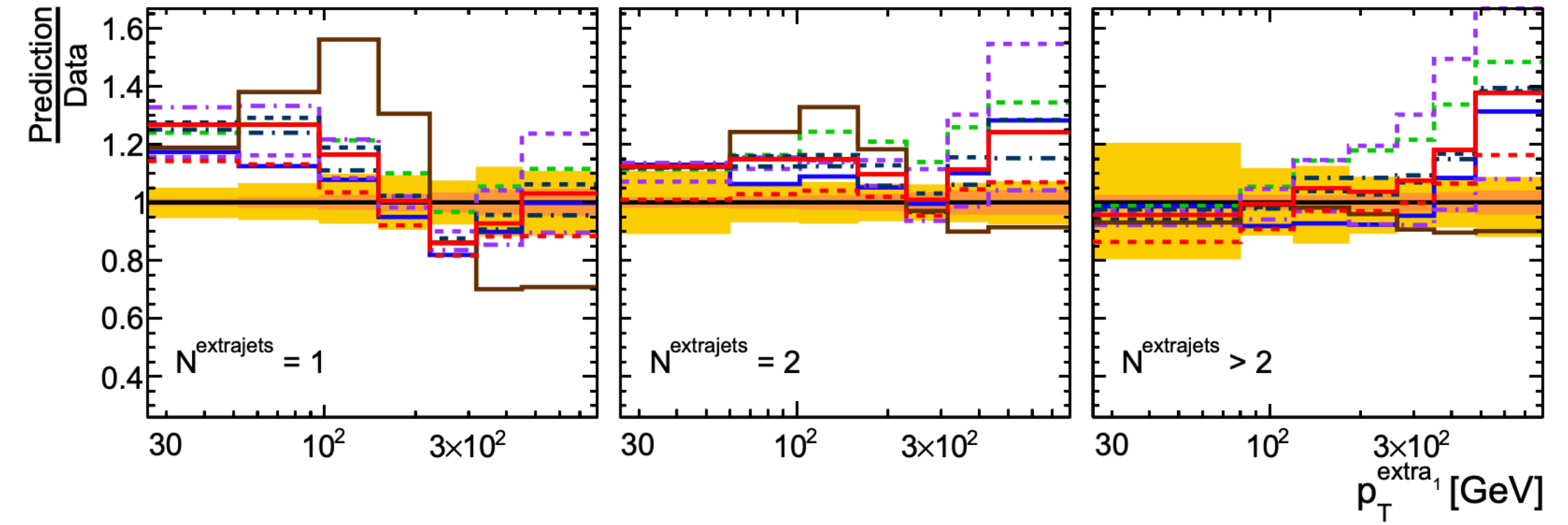
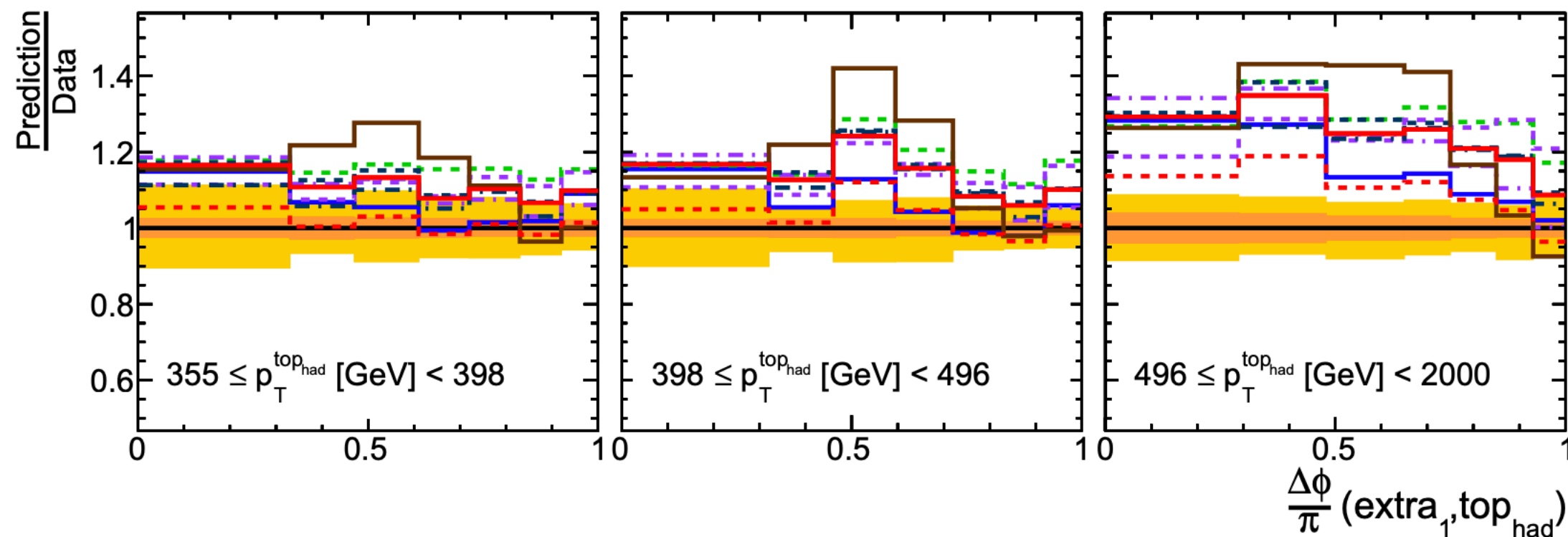


ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$
 Boosted
 Fiducial phase-space
 Absolute cross-section

Stat+Syst	Stat Only
Data	PW+PY8 $h_{\text{damp}}=1.5 m_t$
PWG+PY8 (nnlo rw.)	PWG+H7
MC@NLO+PY8	PWG+PY8 $h_{\text{damp}}=3 m_t$
PWG+PY8 ISR Up	PWG+PY8 FSR Up
PWG+PY8 ISR Down	PWG+PY8 FSR Down

ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$
 Boosted
 Fiducial phase-space
 Absolute cross-section

Stat+Syst	Stat Only
Data	PW+PY8 $h_{\text{damp}}=1.5 m_t$
PWG+PY8 (nnlo rw.)	PWG+H7
MC@NLO+PY8	PWG+PY8 $h_{\text{damp}}=3 m_t$
PWG+PY8 ISR Up	PWG+PY8 FSR Up
PWG+PY8 ISR Down	PWG+PY8 FSR Down

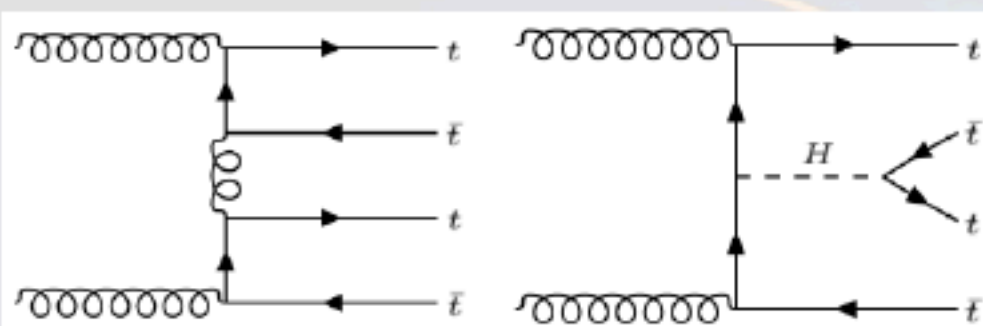


$t\bar{t}\bar{t}\bar{t}$ production

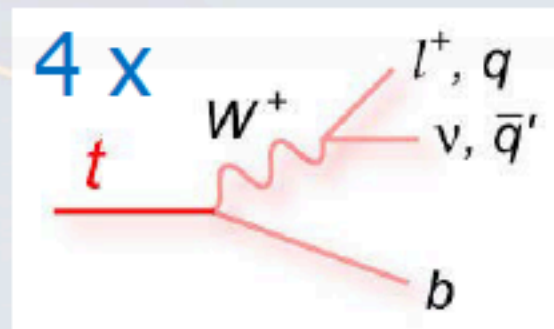
To probe t - H Yukawa coupling, sensitivity to BSM processes...

13 TeV, 139 fb⁻¹
 $t\bar{t}\bar{t}\bar{t}$ 1 l / 2 l OS ($l = e, \mu$)
[57% of $t\bar{t}\bar{t}\bar{t}$ events]

Enhancements from pair production gluino & scalar gluons, 2HDM



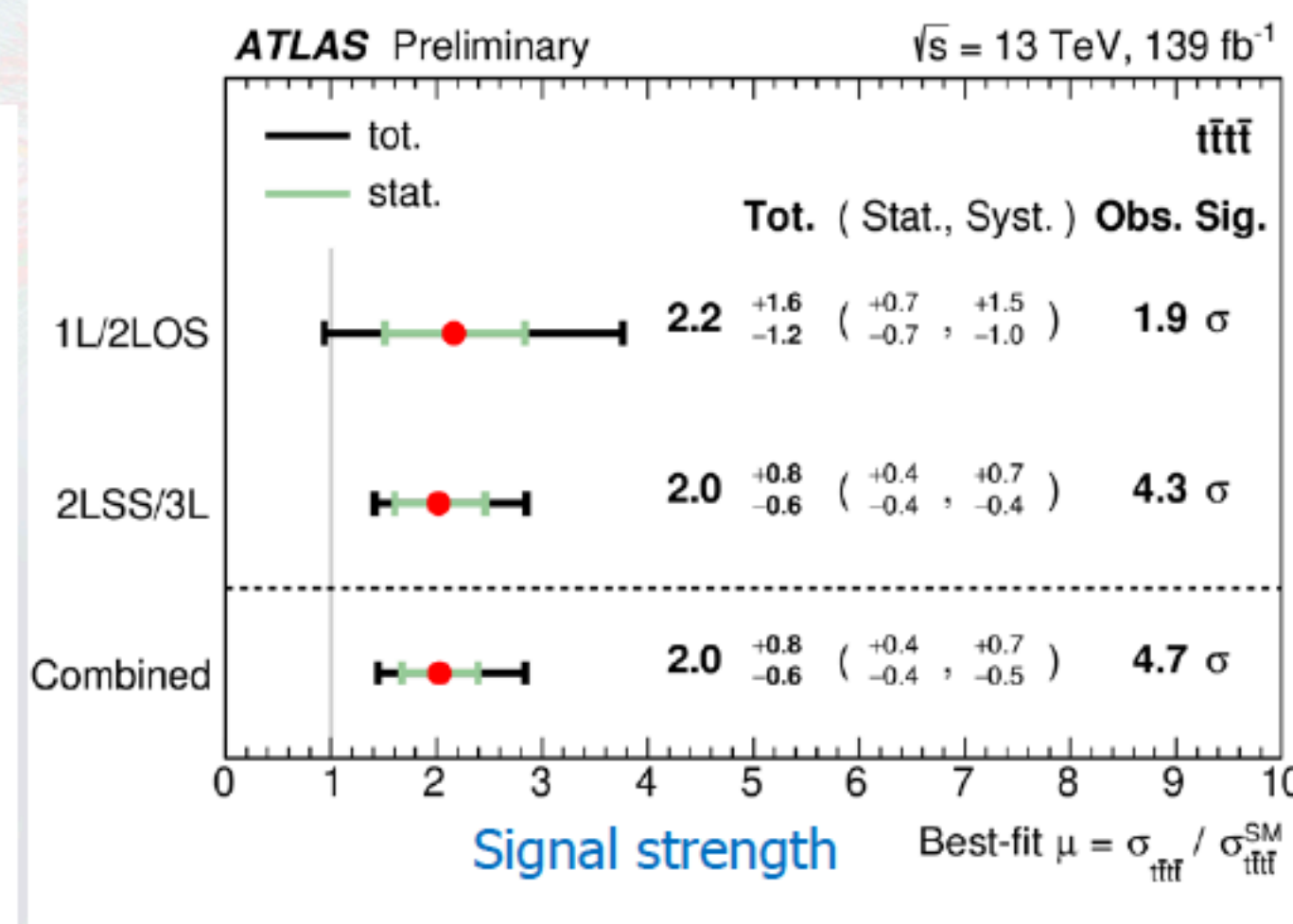
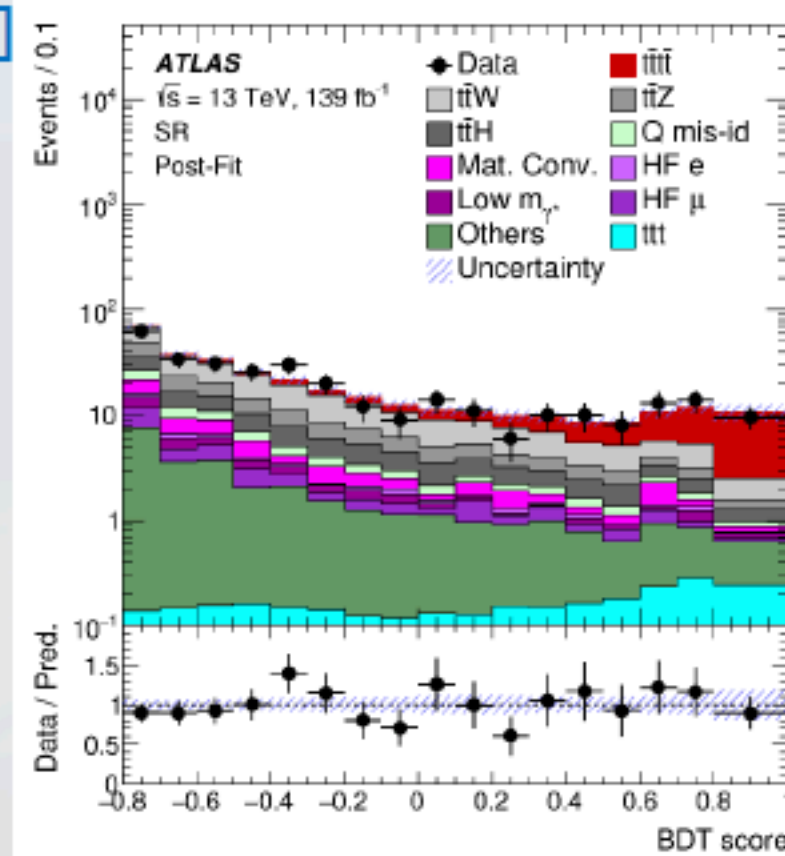
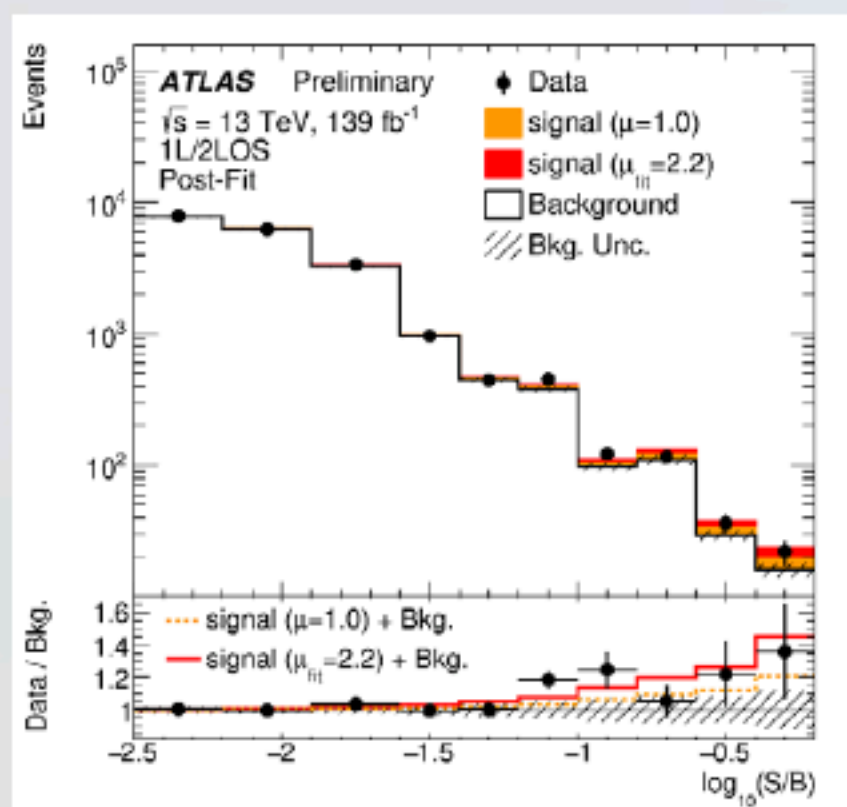
Challenge: $t\bar{t}$ bkg



+ combined fit [with Eur. Phys. J. C 80 \(2020\) 1085](#)

13 TeV, 139 fb⁻¹
 $t\bar{t}\bar{t}\bar{t}$ 2 l SS / 3 l ($l = e, \mu$)
[13% of $t\bar{t}\bar{t}\bar{t}$ events]

Binned profile likelihood [BDT in signal regions]

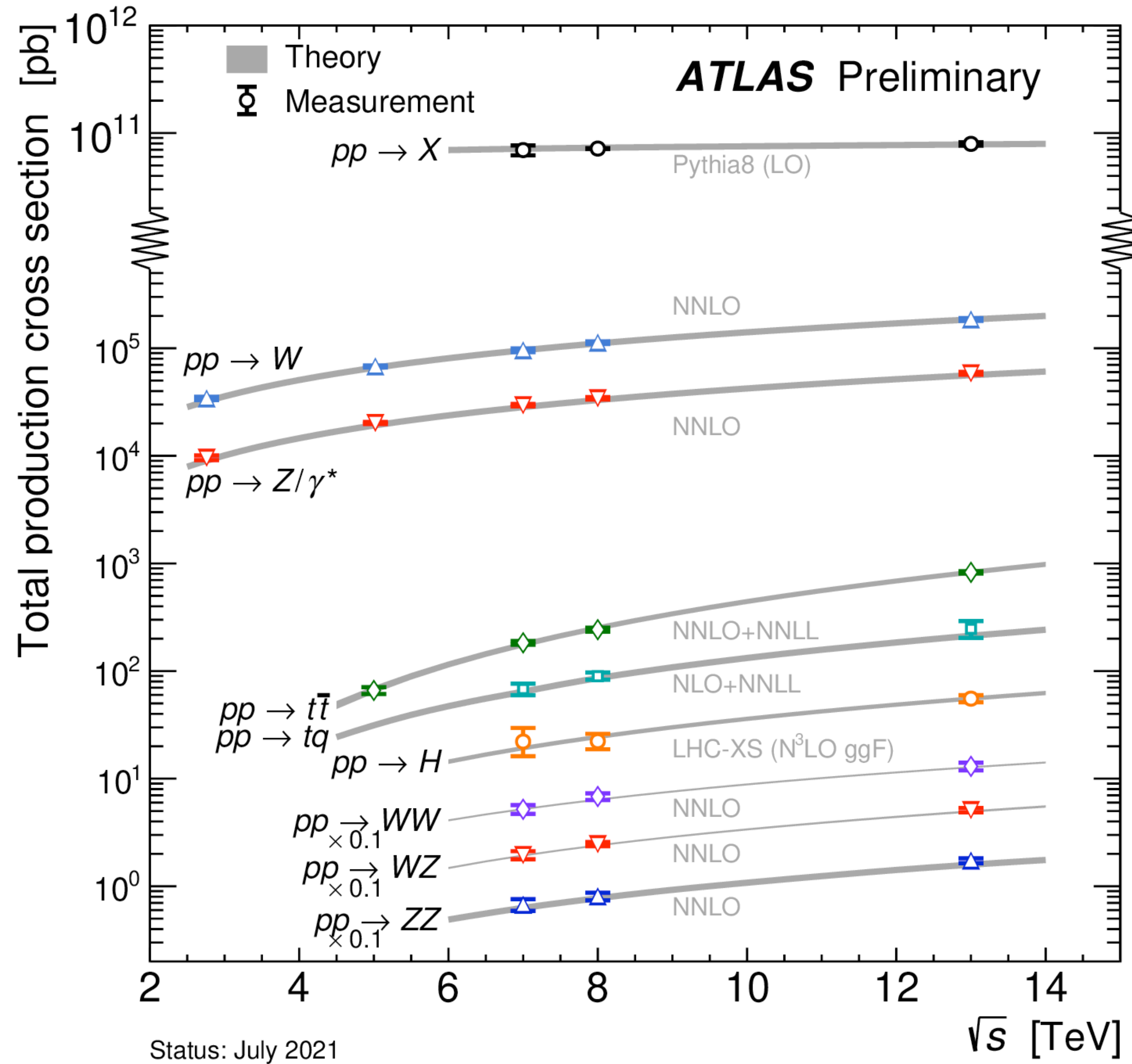


Prediction: $\sigma_{t\bar{t}\bar{t}\bar{t}} = 12.0 \pm 2.4$ fb (NLO, incl EW corr.)

4.7 σ obs. (2.6 σ exp.) above bkg-only hypothesis

Result: $\sigma_{t\bar{t}\bar{t}\bar{t}} = 26 \pm 8$ (stat.) ± 15 (syst.) fb, 1.9 obs. (1.0 exp.) σ

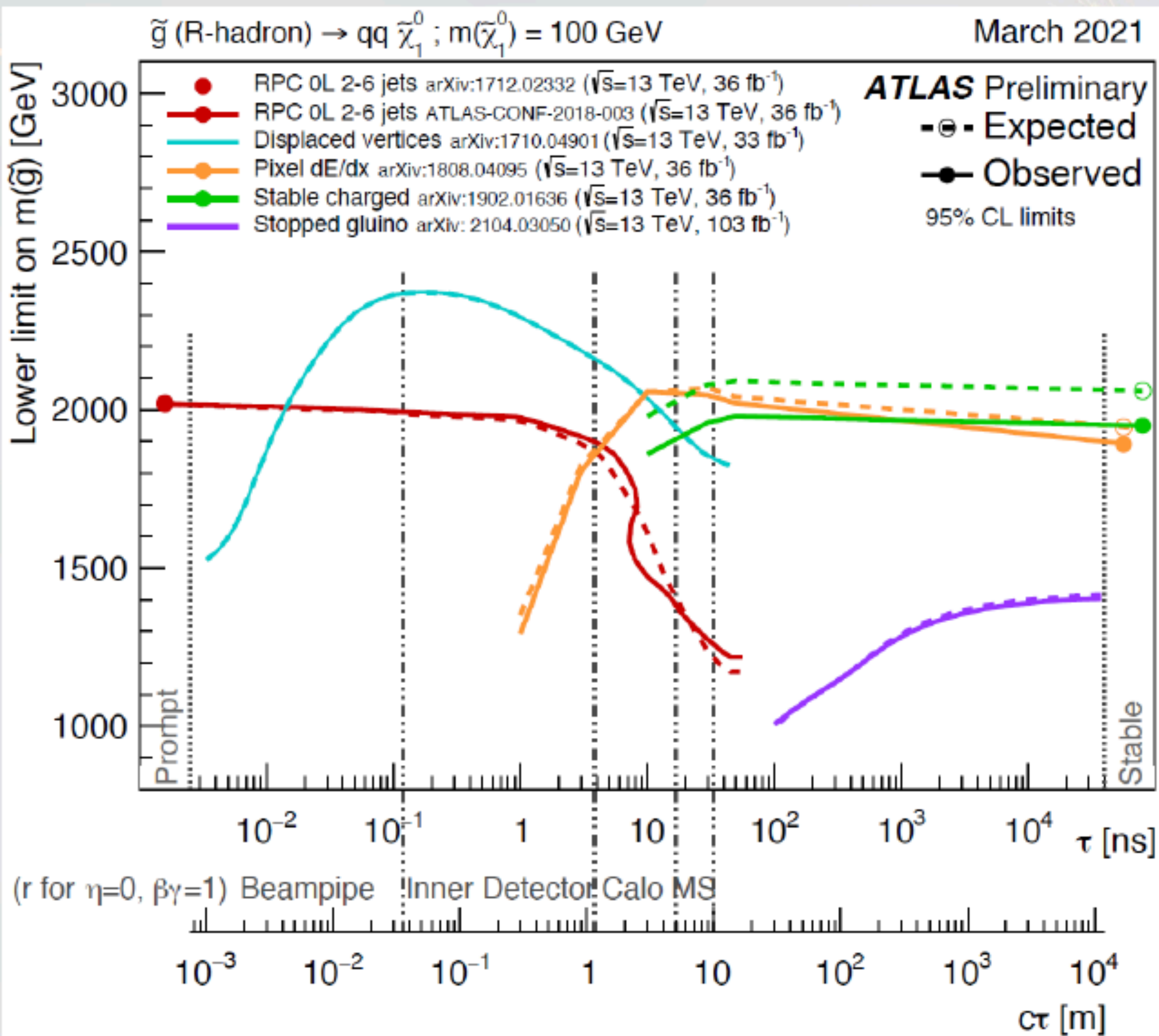
Standard Model:



- \square $pp \rightarrow X$
 7 TeV, $20 \mu\text{b}^{-1}$, Nat. Commun. 2 (2011) 463
 8 TeV, $500 \mu\text{b}^{-1}$, PLB 761 (2016) 158
 13 TeV, $60 \mu\text{b}^{-1}$, PRL 117 182002 (2016)
- \triangle $pp \rightarrow W$ ∇ $pp \rightarrow Z/\gamma^*$
 2.76 TeV, 4pb^{-1} , EPJC 79 (2019) 901
 5 TeV, 25pb^{-1} , EPJC 79 (2019) 128
 7 TeV, 4.6fb^{-1} , EPJC 77 (2017) 367
 8 TeV, 20.2fb^{-1} , JHEP 02, 117 (2017) (for Z)
 8 TeV, 20.2fb^{-1} , EPJC 79 (2019) 760 (for W)
 13 TeV, 81pb^{-1} , PLB 759 (2016) 601 (for W)
 13 TeV, 3.2fb^{-1} , JHEP 02, 117 (2017) (for Z)
- \diamond $pp \rightarrow t\bar{t}$
 5 TeV, 257pb^{-1} , ATLAS-CONF-2021-003
 7 TeV, 4.6fb^{-1} , EPJC 74 (2014) 3109
 8 TeV, 20.3fb^{-1} , EPJC 74 (2014) 3109
 13 TeV, 3.2fb^{-1} , EPJC 80 (2020) 528
- \square $pp \rightarrow tq$
 7 TeV, 4.6fb^{-1} , PRD 90, 112006 (2014)
 8 TeV, 20.3fb^{-1} , EPJC 77 (2017) 531
 13 TeV, 3.2fb^{-1} , JHEP 1704 (2017) 086
- \square $pp \rightarrow H$
 7 TeV, 4.5fb^{-1} , EPJC 76 (2016) 6
 8 TeV, 20.3fb^{-1} , EPJC 76 (2016) 6
 13 TeV, 139.0fb^{-1} , ATLAS-CONF-2019-032
- \diamond $pp \rightarrow WW$
 7 TeV, 4.6fb^{-1} , PRD 87, 112001 (2013)
 8 TeV, 20.3fb^{-1} , JHEP 09 029 (2016)
 13 TeV, 36.1fb^{-1} , EPJC 79 (2019) 884
- ∇ $pp \rightarrow WZ$
 7 TeV, 4.6fb^{-1} , EPJC 72 (2012) 2173
 8 TeV, 20.3fb^{-1} , PRD 93, 092004 (2016)
 13 TeV, 36.1fb^{-1} , EPJC 79 (2019) 535
- \triangle $pp \rightarrow ZZ$
 7 TeV, 4.6fb^{-1} , JHEP 03, 128 (2013)
 8 TeV, 20.3fb^{-1} , JHEP 01, 099 (2017)
 13 TeV, 36.1fb^{-1} , PRD 97, 032005 (2018)

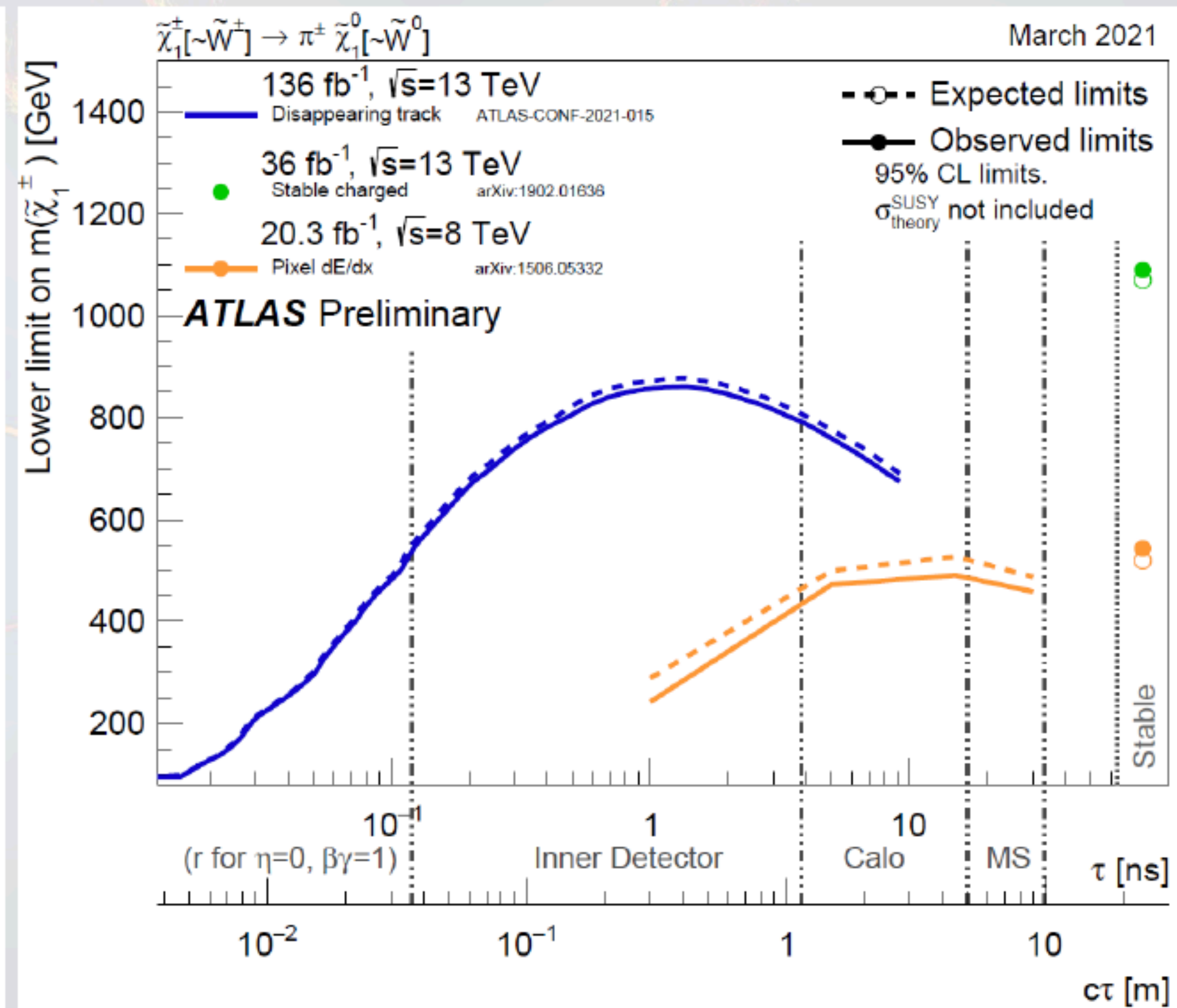
Full LLP programme covers extensive range...

Constraints on gluino mass vs. lifetime



Gluino mass vs. lifetime for split-SUSY model with gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV.

Constraints on chargino mass vs. lifetime

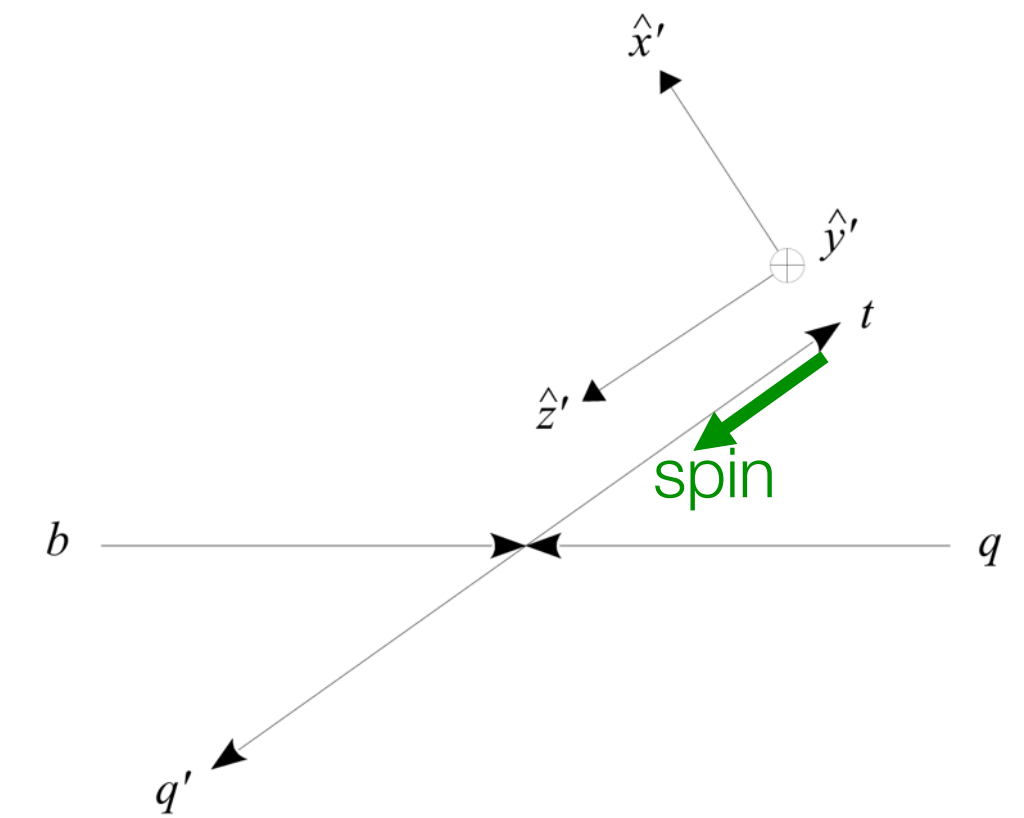
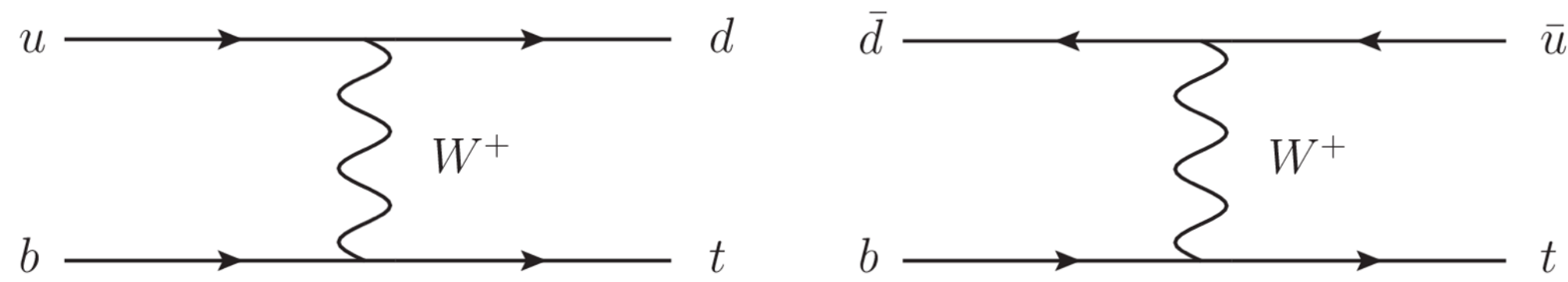


Chargino mass vs. lifetime for AMSB model with $\tan(\beta)=5, \mu>0$. Wino-like chargino is pair-produced and decays to wino-like neutralino and a very soft charged pion.

EFT from top measurements

- Single top polarization

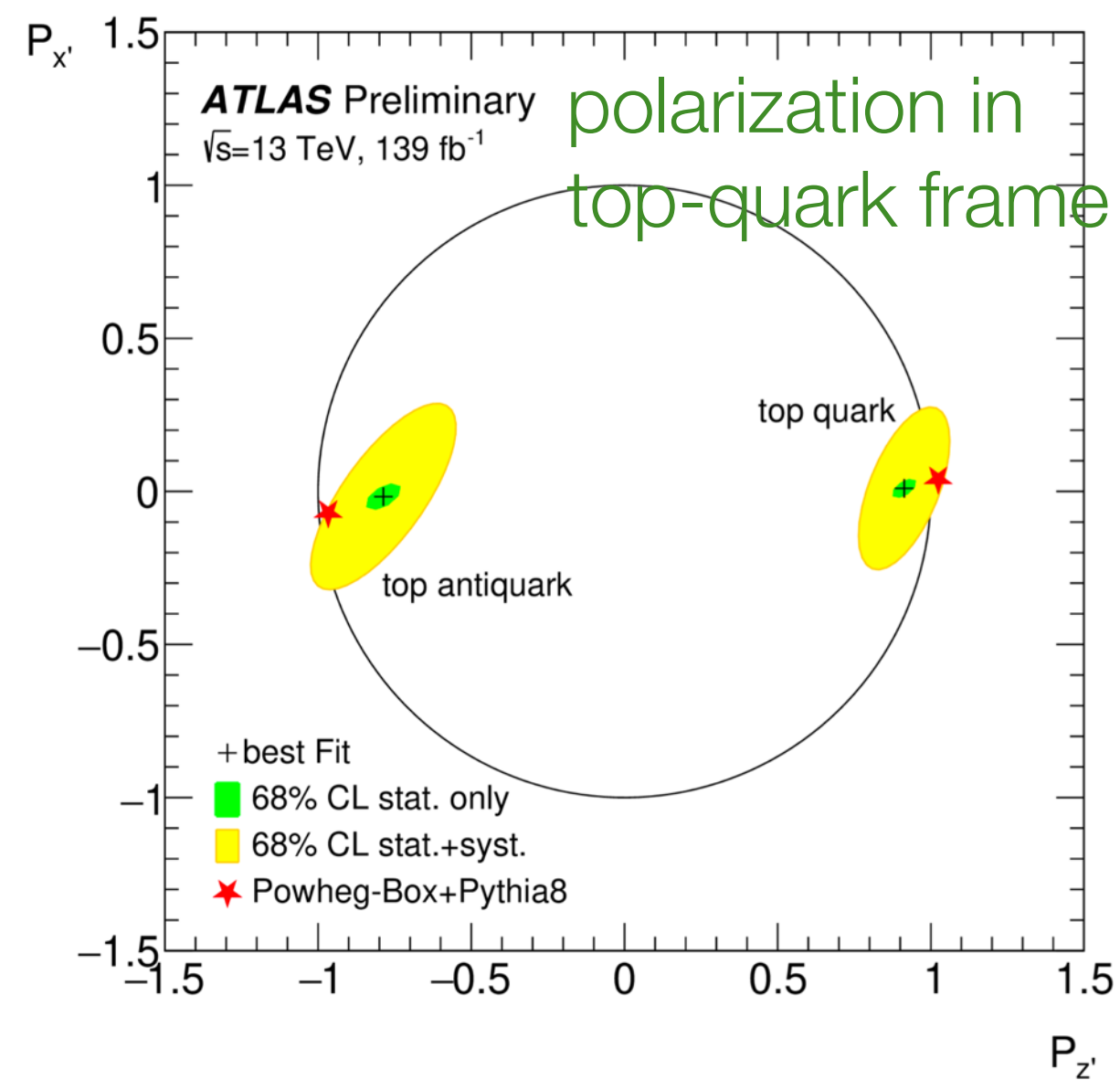
- t -channel dominates single top-quark production, large polarization from V-A



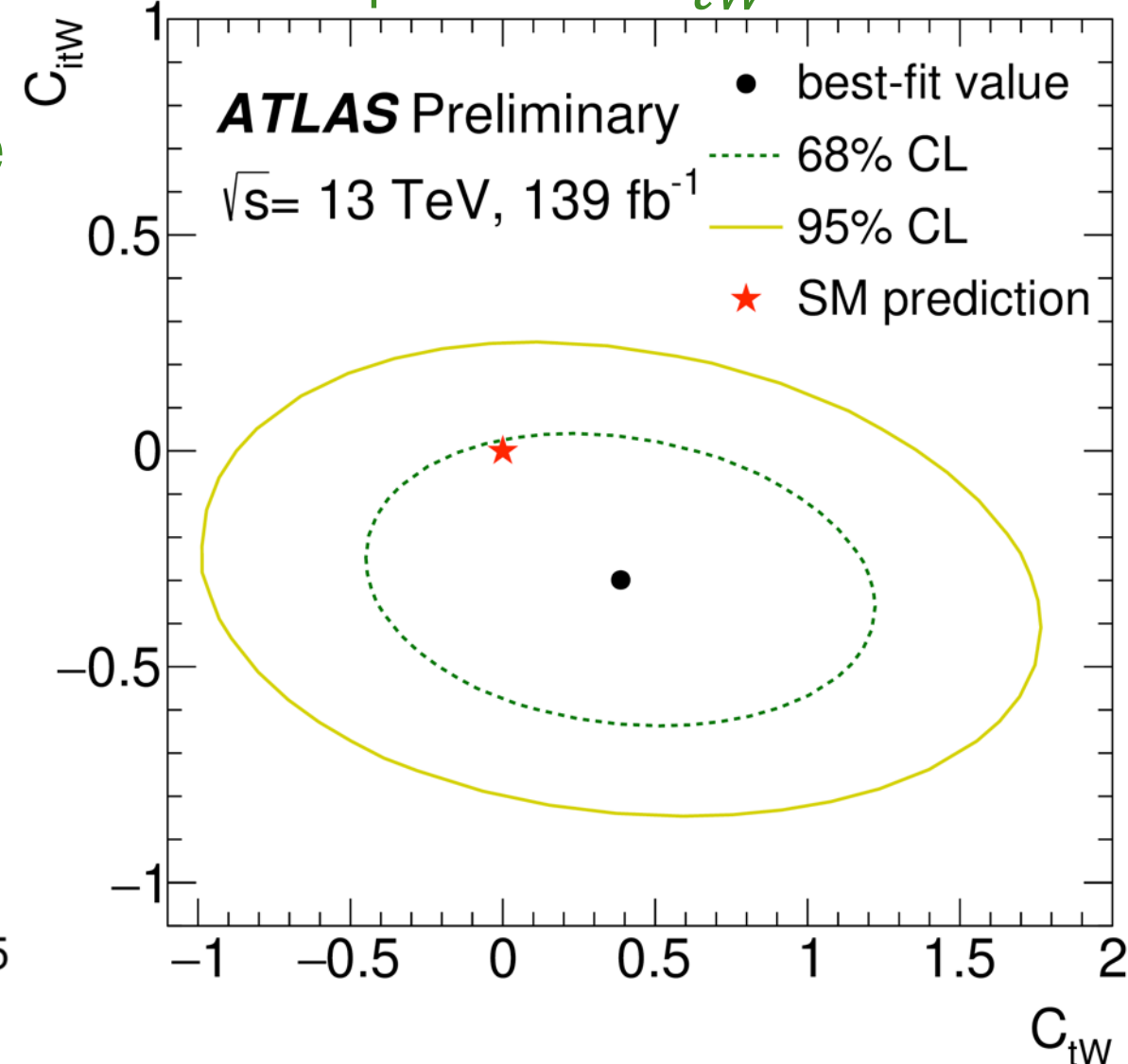
- Measurement of polarization in 3-D via angular distributions from $t \rightarrow b\ell\nu$ decay ($\ell = e, \mu$)

- Measurement of energy asymmetry in $tt+j$: $A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$ $\Delta E = E_t - E_{\bar{t}}$

[ATLAS-CONF-2021-027](#)

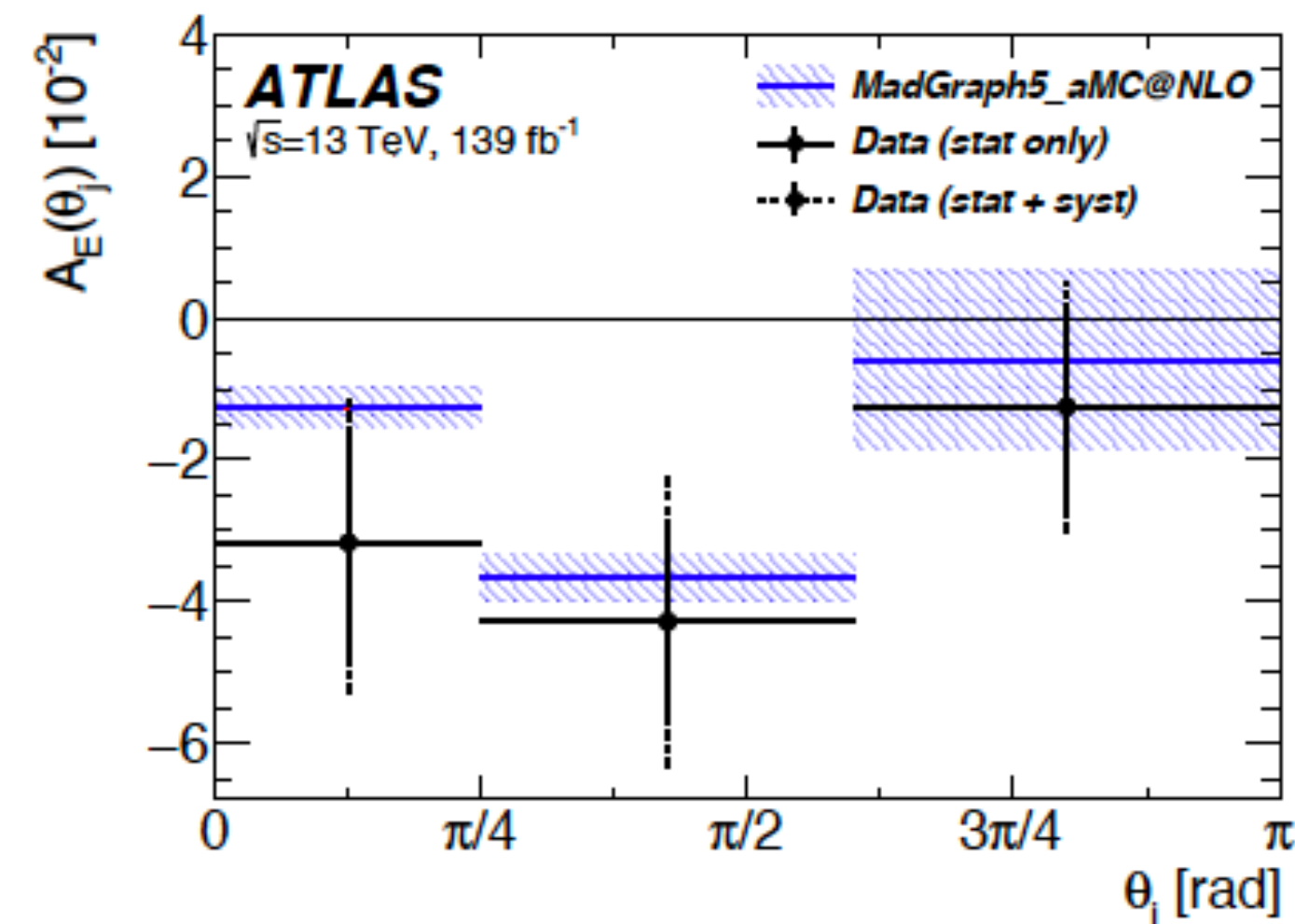


Re and Im part of EFT operator \mathcal{O}_{tW}



[ArXiv:2110.05453](#)

Energy asymmetry in ttj



Constraints on t-q EFT operators

