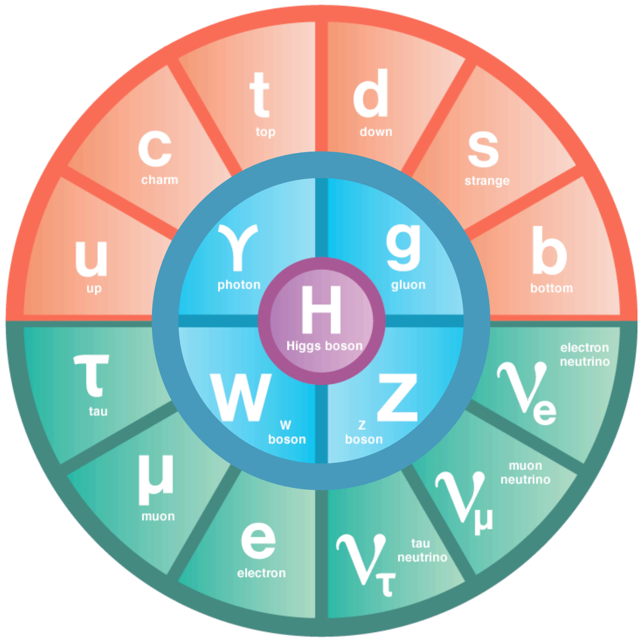
Top Measurements at ATLAS & CMS

Louise Skinnari (Northeastern University)

presenting results from the ATLAS & CMS Collaborations

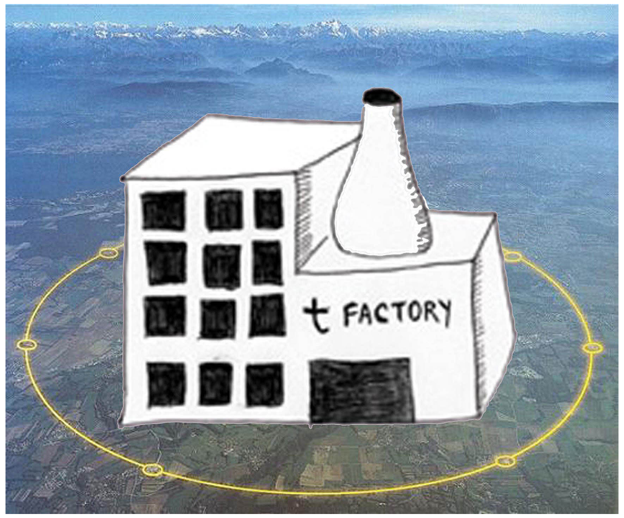
La Thuile: Les Rencontres de Physique de la Vallée d’Aoste, 07/03/2024

Why top quark physics?



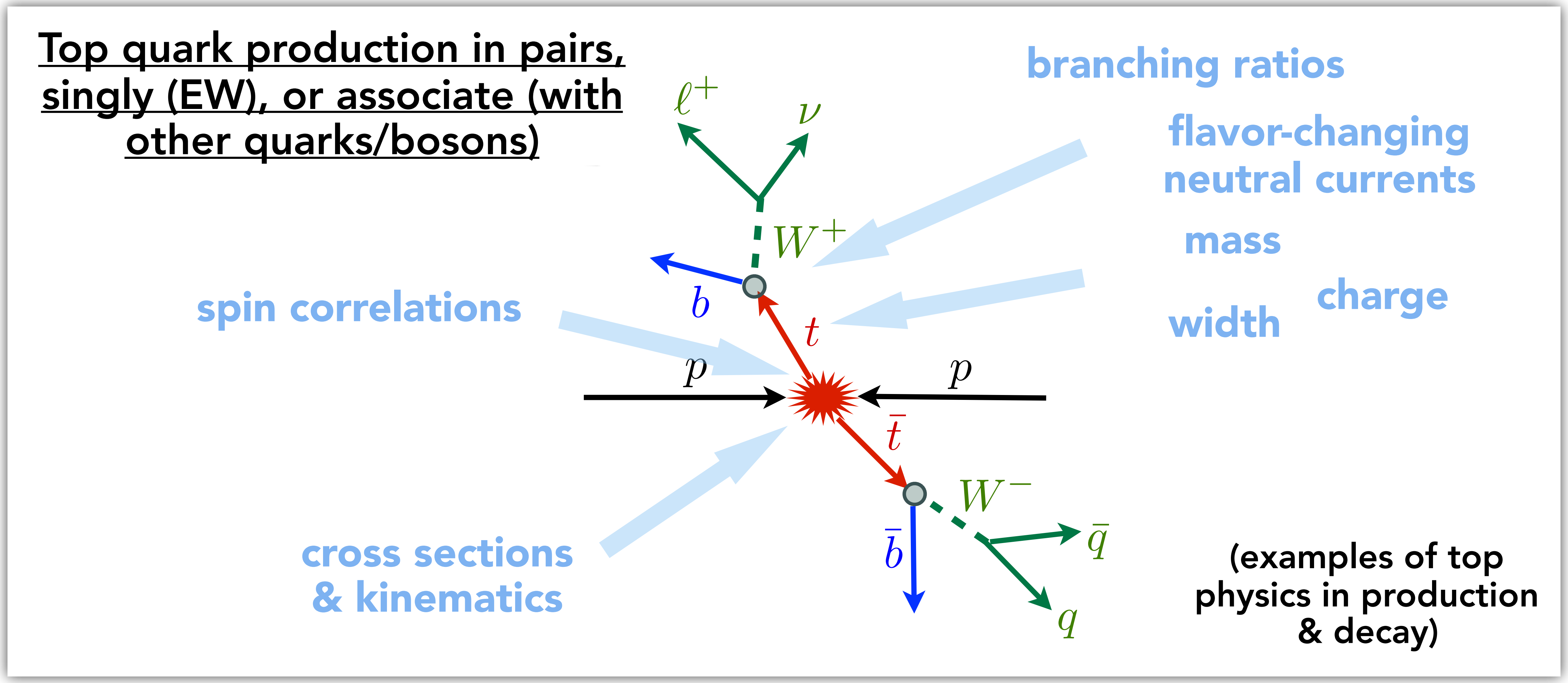
- **<u>Mass:</u>** Heaviest known elementary particle, Yukawa coupling (y_t) ≈ 1
- **<u>Lifetime:</u>** Extremely short-lived → decays before hadronizing → observe properties of bare quark
- A unique candidate for studying QCD processes, and provides a window to new physics through <u>*direct*</u> & <u>*indirect*</u> searches

- Many new results over the past year! Focusing here on select recent results, see also:
  - **ATLAS:** https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
  - **CMS:** https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP



Top quark measurements

Top quark measurements play an essential role in testing the Standard Model (SM)

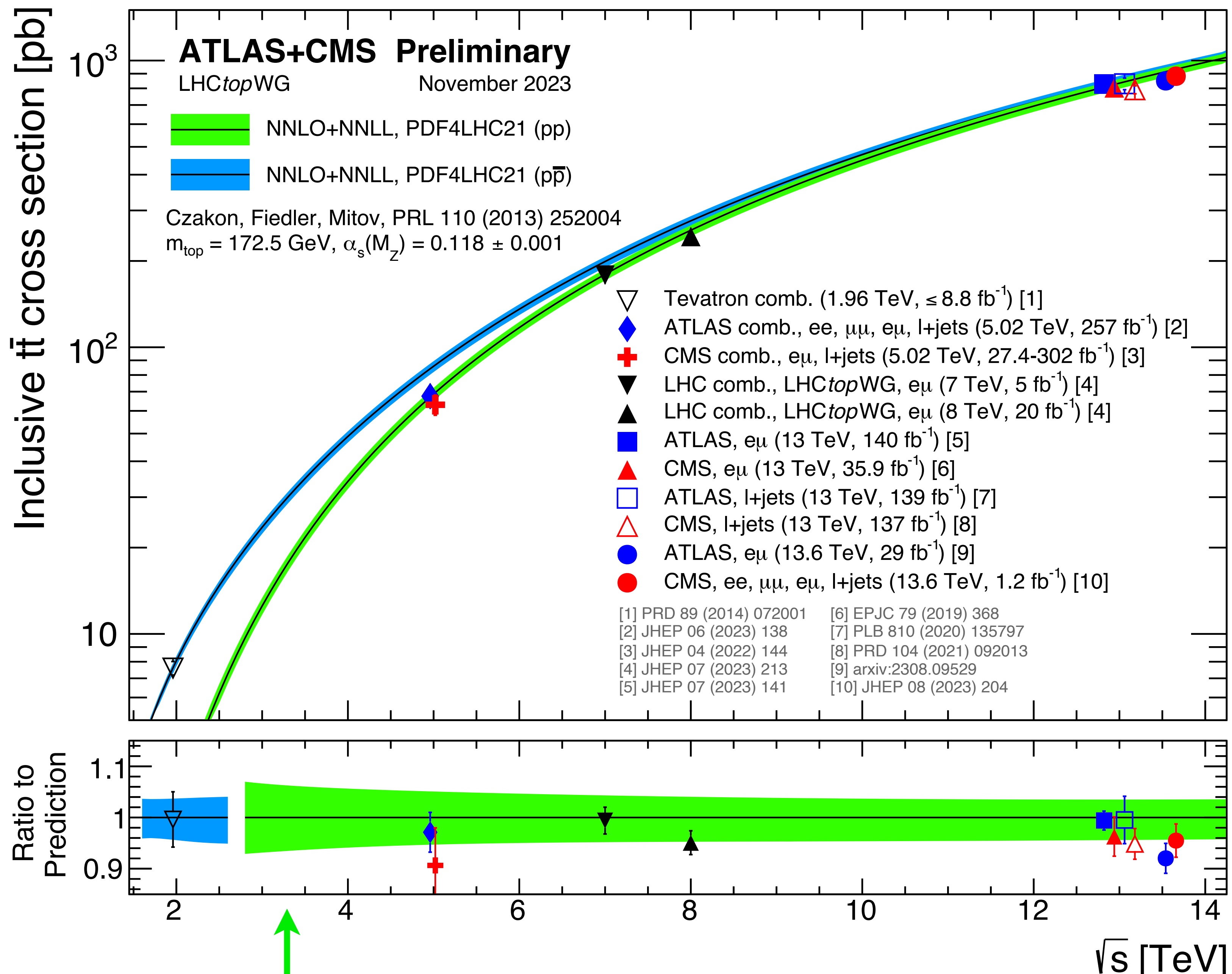


tX+ttX processes discussed in Peter Berta's talk!

Top quark pair production

- *Test QCD predictions & extract SM parameters*
- *Constrain top quarks as background process*

LHCTopWGSummaryPlots



Compatibility with theory predictions at high order in perturbation theory

Top quark pair production

- *Test QCD predictions & extract SM parameters*
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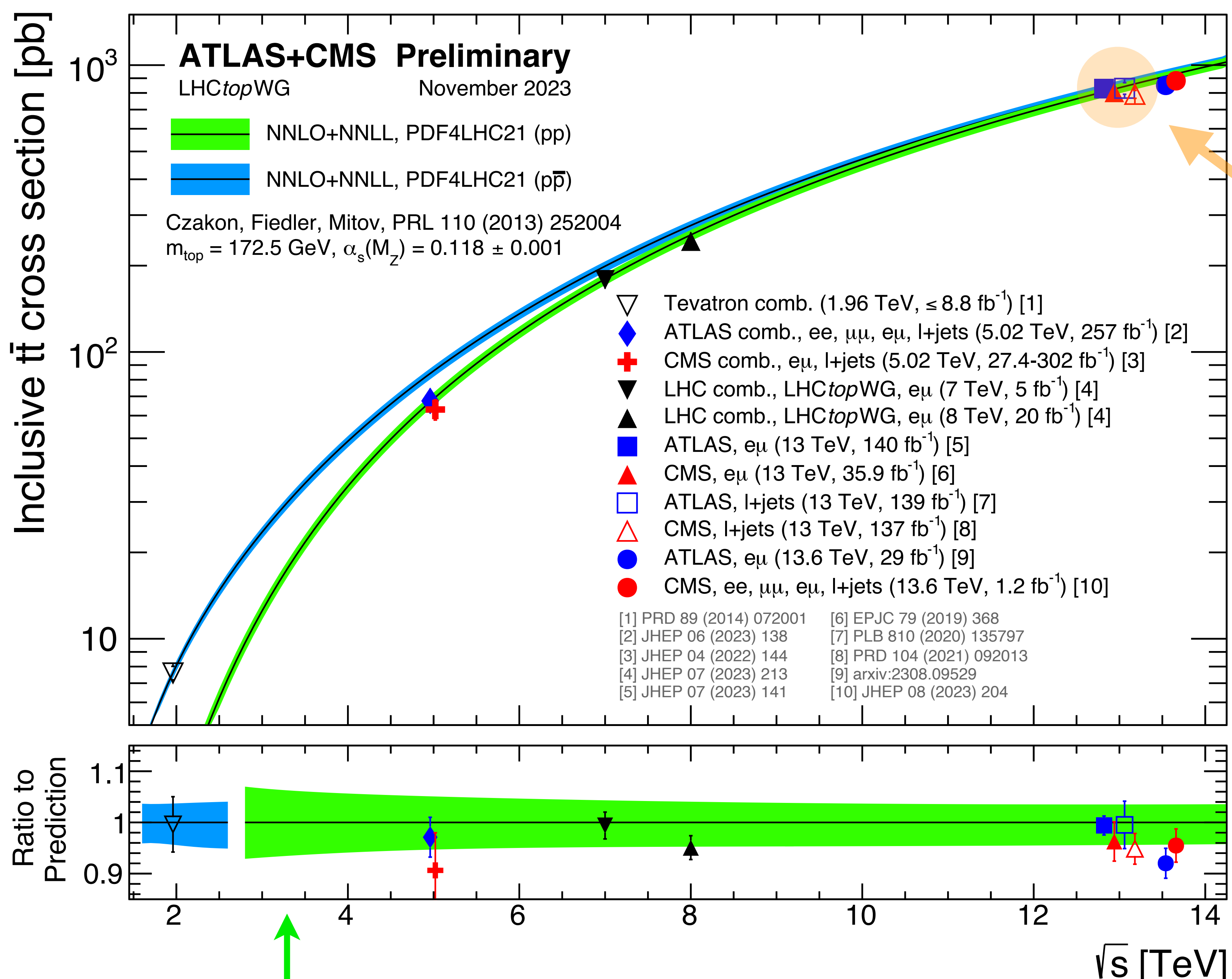
LHCTopWGSummaryPlots



13 TeV

New ATLAS result now reaches a precision of 1.8%!

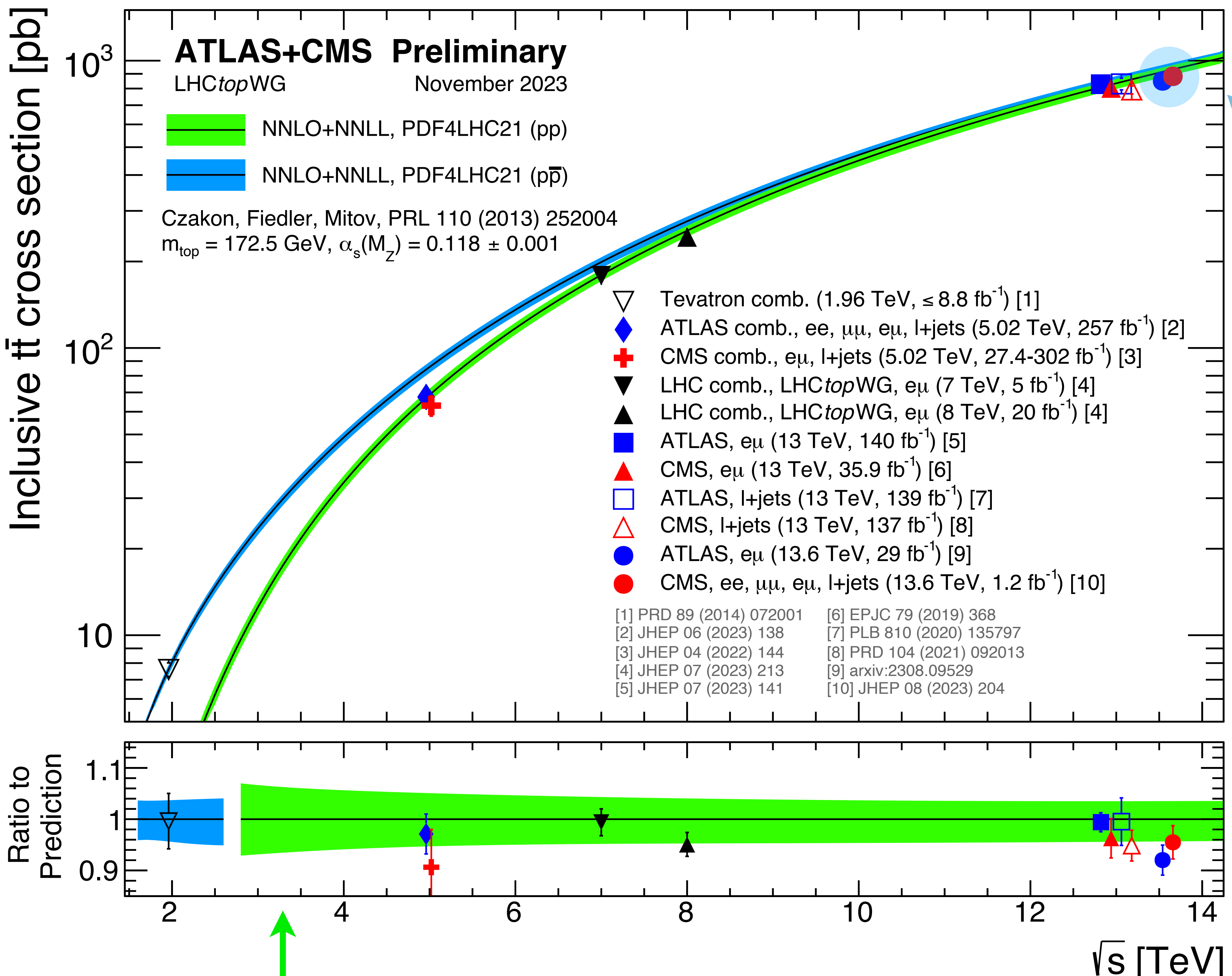
JHEP 07 (2023) 141

Compatibility with theory predictions at high order in perturbation theory

Top quark pair production

- *Test QCD predictions & extract SM parameters*
- *Constrain top quarks as background process*

LHCTopWGSummaryPlots



13.6 TeV

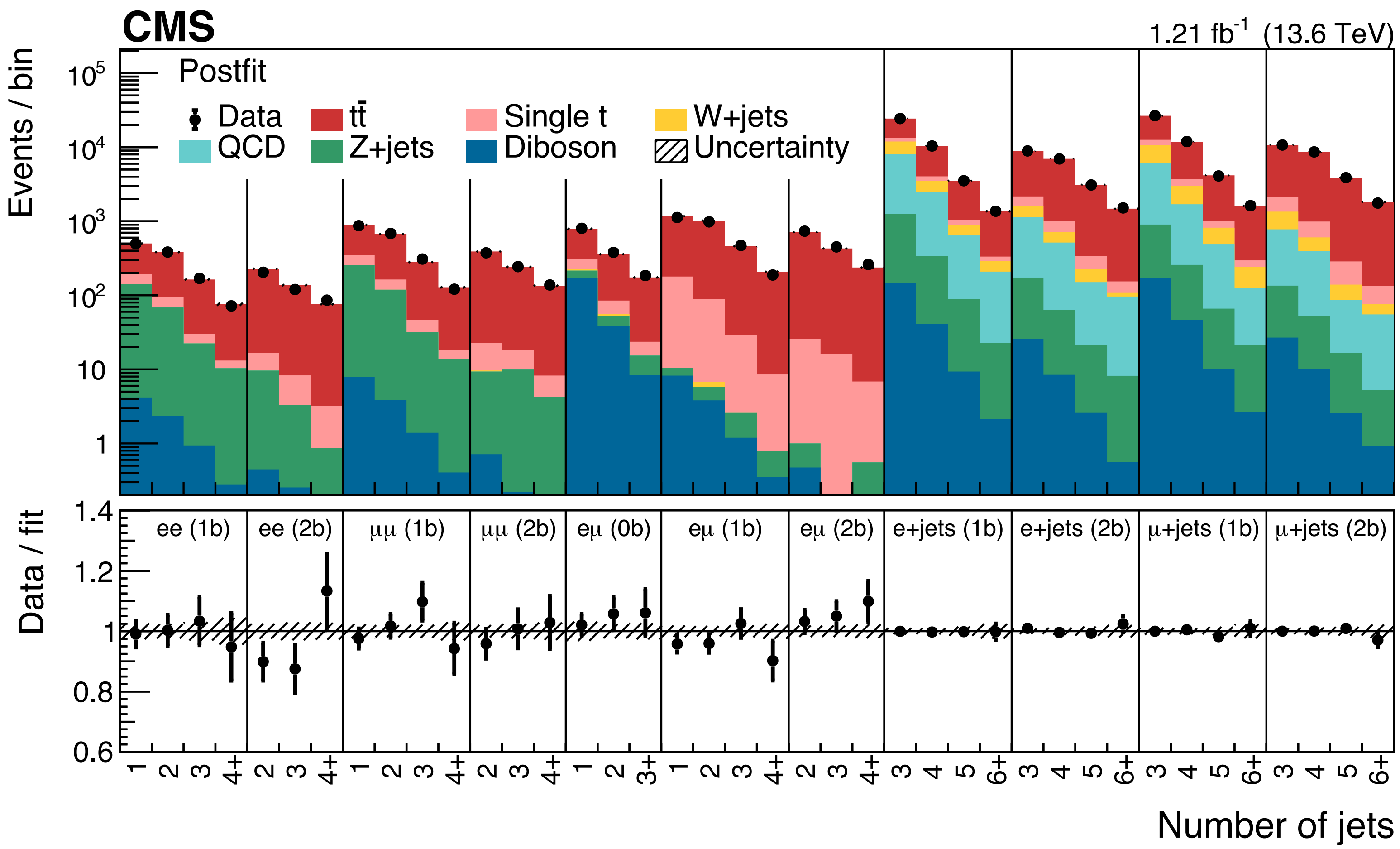
Test scaling with sqrt(s) and upgraded detectors/SW

Compatibility with theory predictions at high order in perturbation theory

$t\bar{t}$ @ 13.6 TeV (CMS)

JHEP 08 (2023) 204

- Combination of dilepton (ee, eμ, μμ) and e/μ+jets channels
  - ✦ Using 1.21 fb^{-1} of data collected during summer 2022
- Likelihood fit in bins of:
  - ✦ Number/flavor of leptons
  - ✦ Number of b-jets
  - ✦ Number of jets
    - b-tagging and lepton ID efficiency calibrated in-situ



- Dominant uncertainties:
  - ✦ Integrated luminosity, lepton identification, b-tagging efficiency
- **Inclusive cross section:** $\sigma_{t\bar{t}} = 881 \pm 23(\mathrm{stat+syst}) \pm 20(\mathrm{lumi})\ \mathrm{pb}$

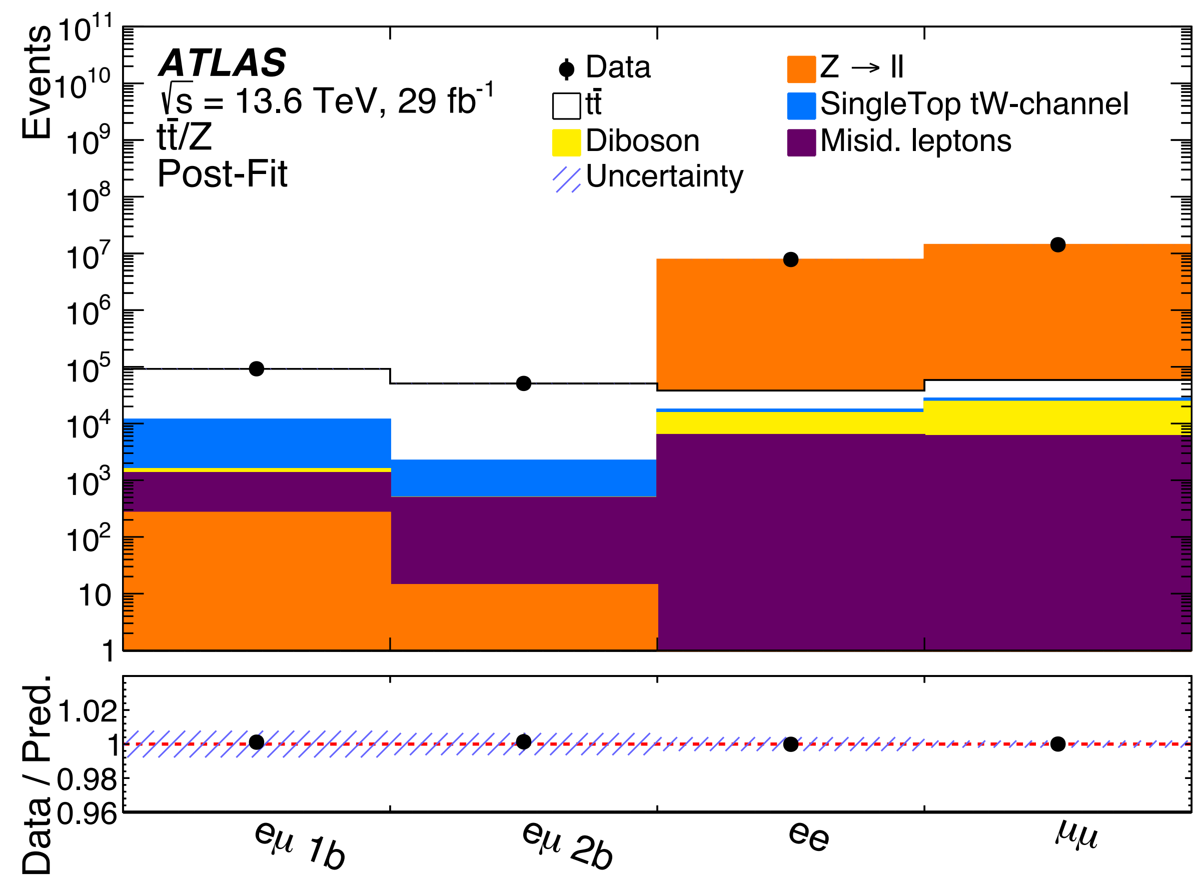
$\sigma_{t\bar{t}}^{\mathrm{theory}} = 924^{+32}_{-40}\ \mathrm{pb}$

~3.5% total uncertainty

$t\bar{t}$ @ 13.6 TeV (ATLAS)

PLB 848 (2024) 138376

- Measurement targets most pure final state (dilepton eμ)
  - Using full 2022 data of 29 fb^{-1}
- Simultaneously extracting σ_Z in ee/μμ channels and σ_Z/σ_{tt} ratio
  - Cross section extracted together with efficiency to reconstruct & tag a bottom jet
- Dominant uncertainties:
  - Integrated luminosity, lepton reconstruction, ttbar modelling



- **Inclusive cross section:**

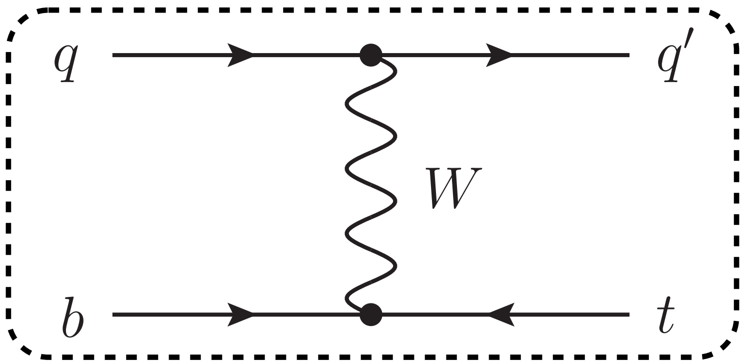
$$\sigma_{t\bar{t}} = 850 \pm 3(\text{stat}) \pm 18(\text{syst}) \pm 20(\text{lumi})\ \text{pb}$$

$$\sigma_{t\bar{t}}^{\text{theory}} = 924^{+32}_{-40}\ \text{pb}$$

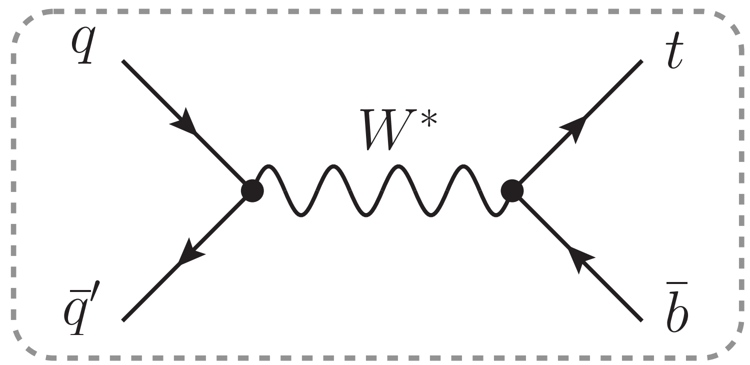
~3.2% total uncertainty

Single top quark production

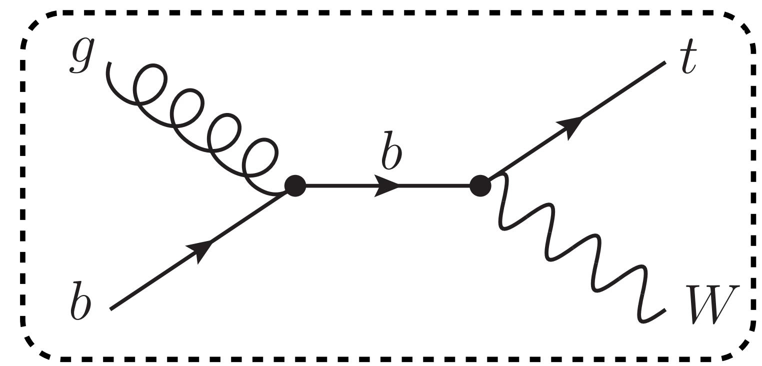
t-channel **~220 pb**



s-channel **~10 pb**

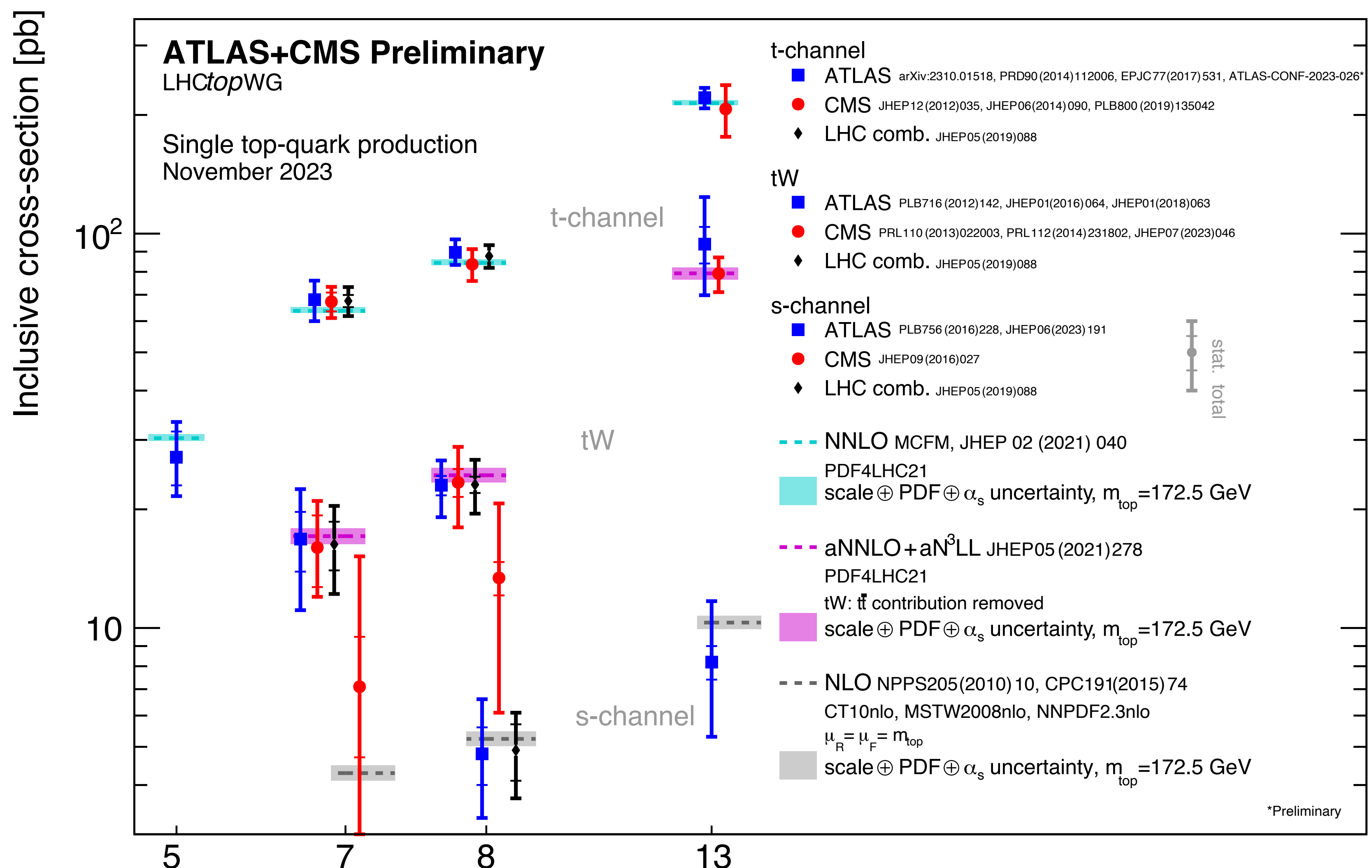


tW **~70 pb**



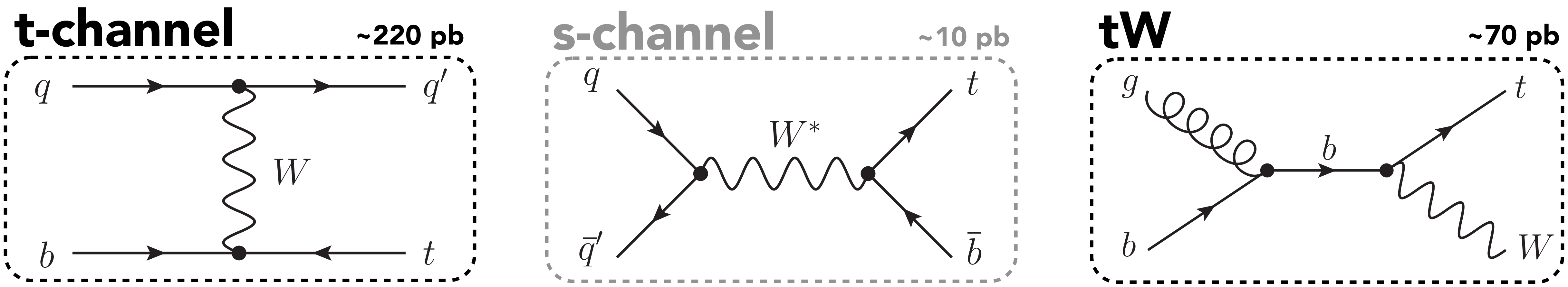
Observation @ Tevatron only!

- *Electroweak production of tops*
- *Cross section extractions rely on multivariate techniques to distinguish signal from backgrounds*



LHCTopWGSummaryPlots

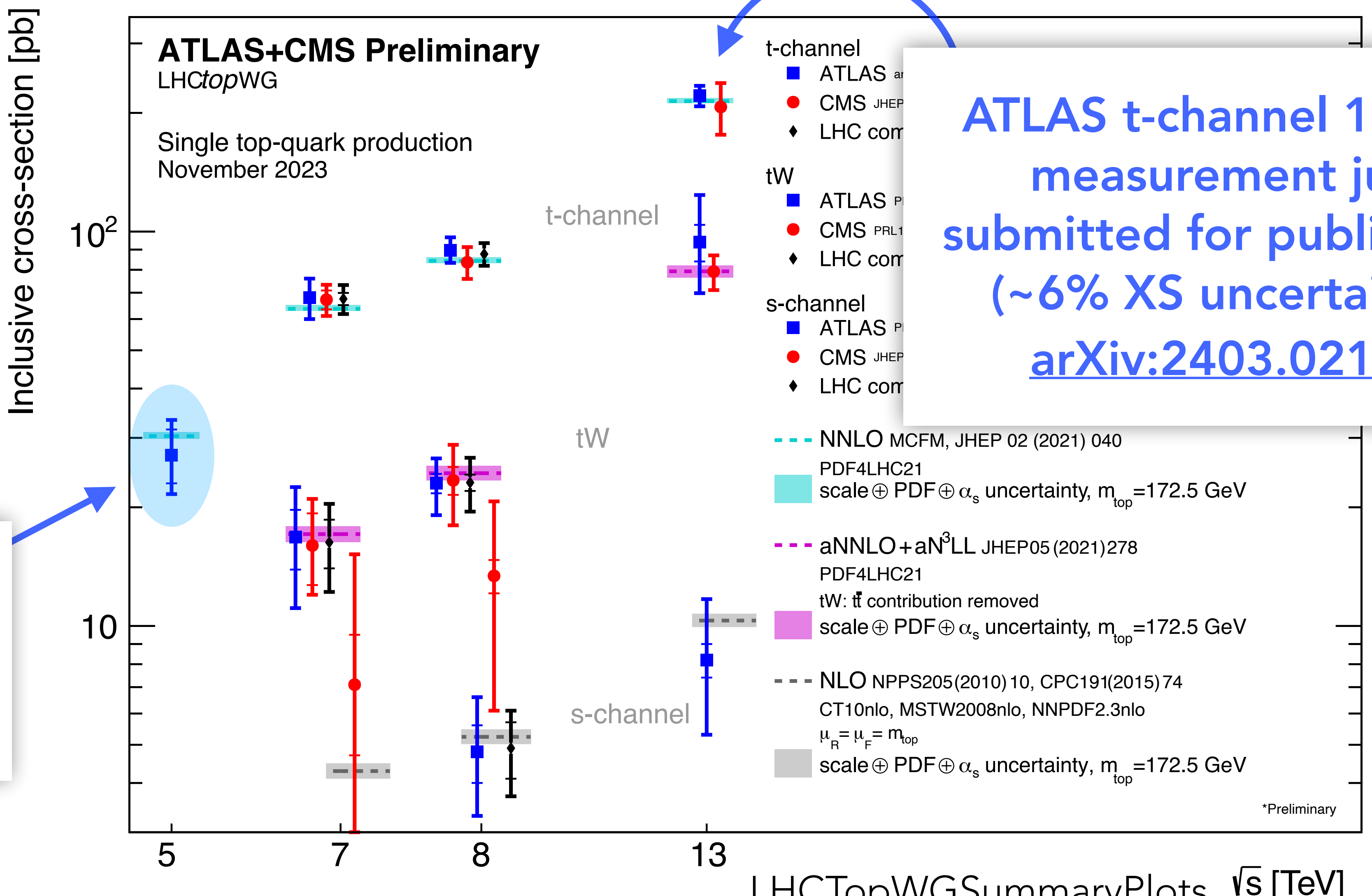
Single top quark production



Observation @ Tevatron only!

- *Electroweak production of tops*
- *Cross section extractions rely on multivariate*

now includes t-channel measurement at 5 TeV [arXiv:2310.01518]



ATLAS t-channel 13 TeV measurement just submitted for publication (~6% XS uncertainty) [arXiv:2403.02126]

LHCTopWGSummaryPlots

Top quarks everywhere

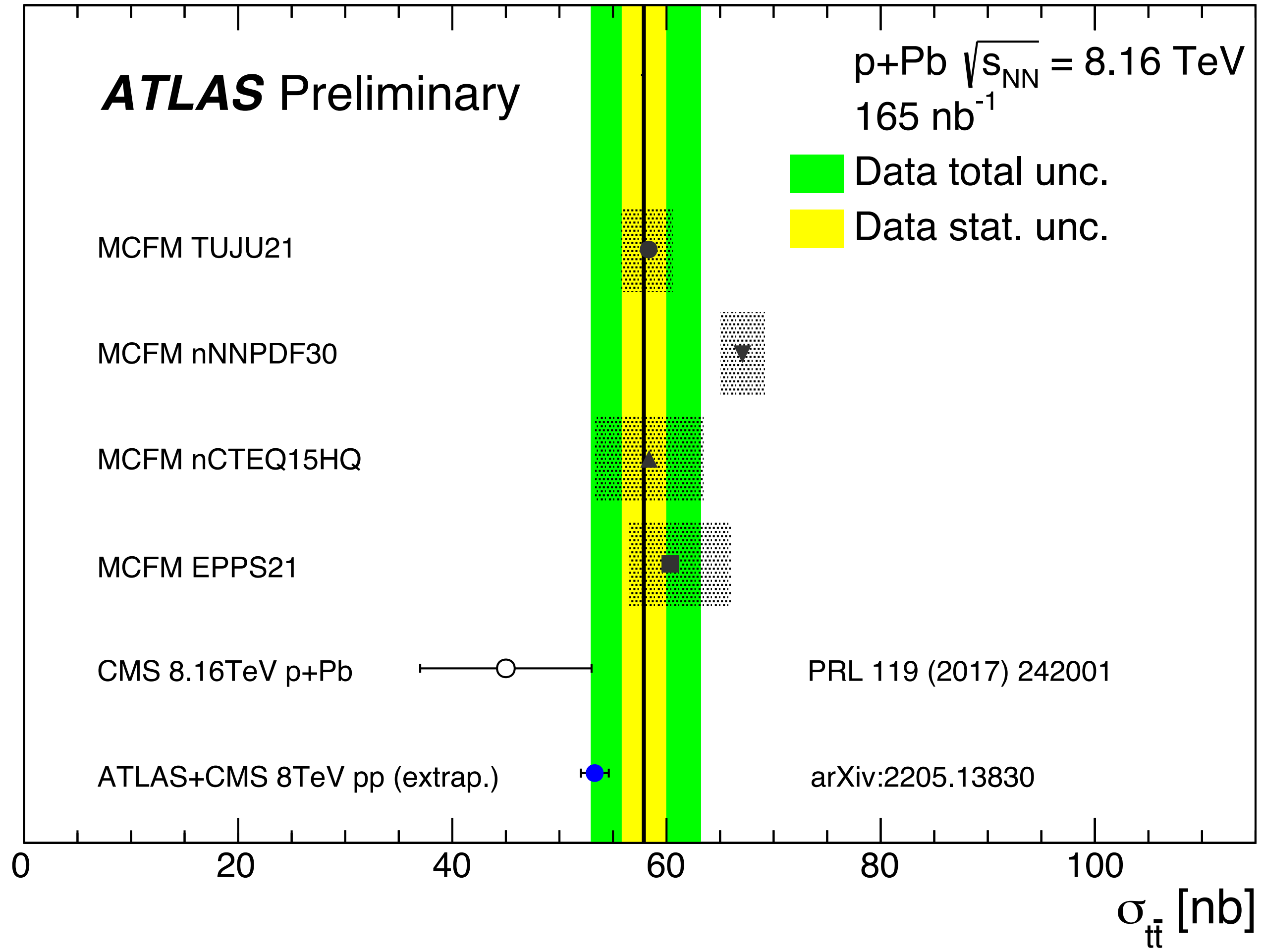
- Top quarks also studied in lead (pPb, PbPb) collisions
  - ✦ First observation of top quarks in pPb collisions (CMS) [PRL 119 (2017) 242001](#)
  - ✦ Evidence for ttbar production in PbPb collisions (CMS) [PRL 125 (2020) 222001](#)
    - Precise probe of nuclear gluon density

ATLAS-CONF-2023-063

- New result from ATLAS:
  - ✦ Observation of ttbar production in pPb collisions at 8.16 TeV in lepton+jets & dilepton channels
  - ✦ **Measurement:**

$$\sigma_{t\bar{t}} = 57.9 \pm 2.0(\text{stat})^{+4.9}_{-4.5}(\text{syst})\ \text{nb}$$

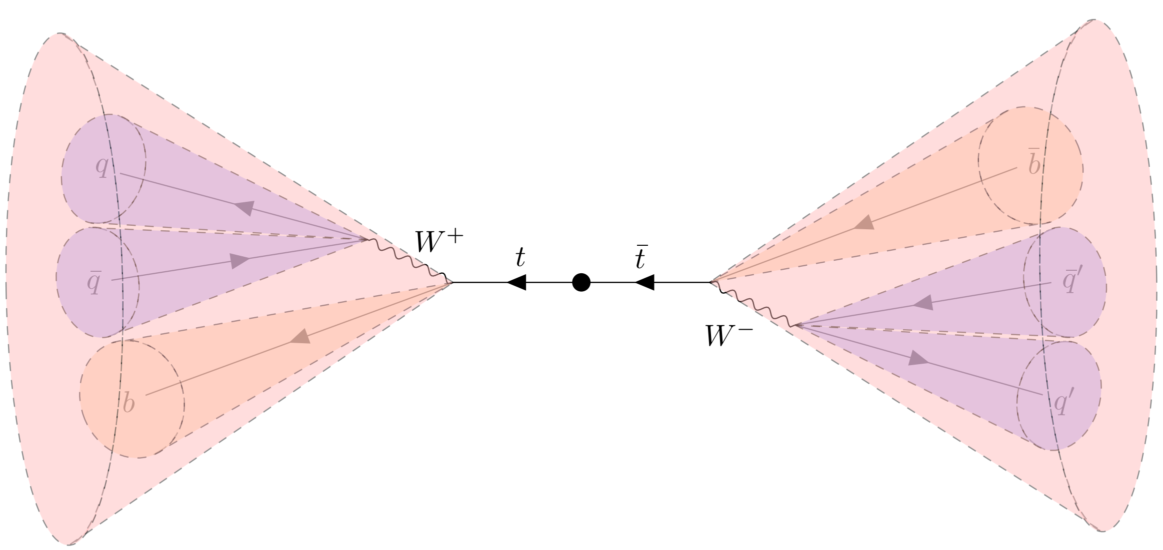
  - ✦ Total integrated cross section uncertainty of ~9%

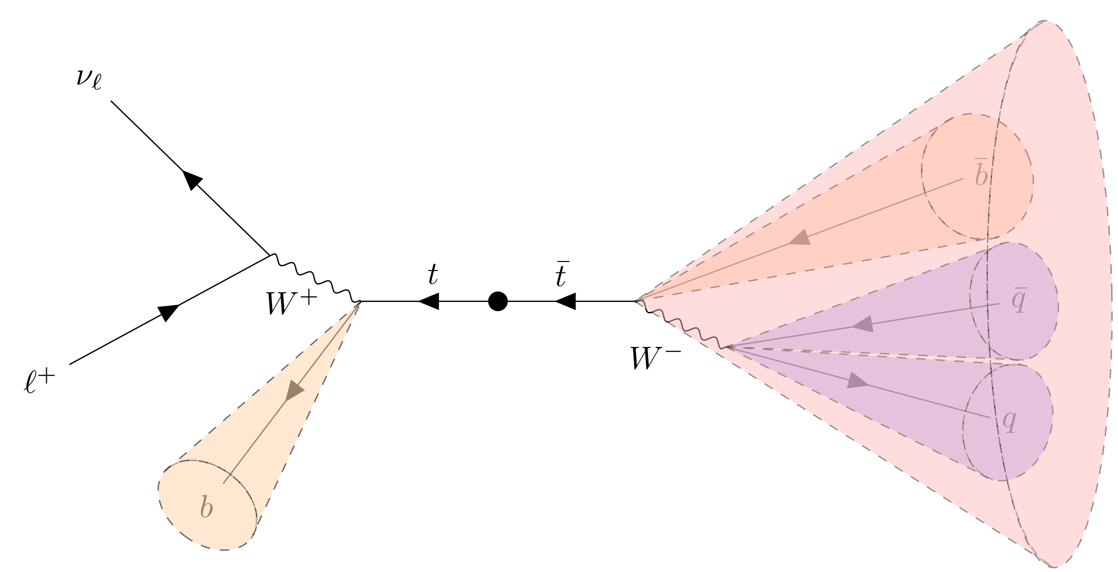


Jet substructure (ATLAS)

arXiv:2312.03797

- Measurement of jet substructure inside merged "top jets"
  - ✦ Utilize high-p_T (boosted) top quarks decaying hadronically, with decay products collimated into single large-R jet
    - R=1.0 top jets
    - Fully hadronic and semi-leptonic final states considered
  - ✦ Test modeling of substructure variables for top taggers, important tests of QCD, sensitivity to BSM physics



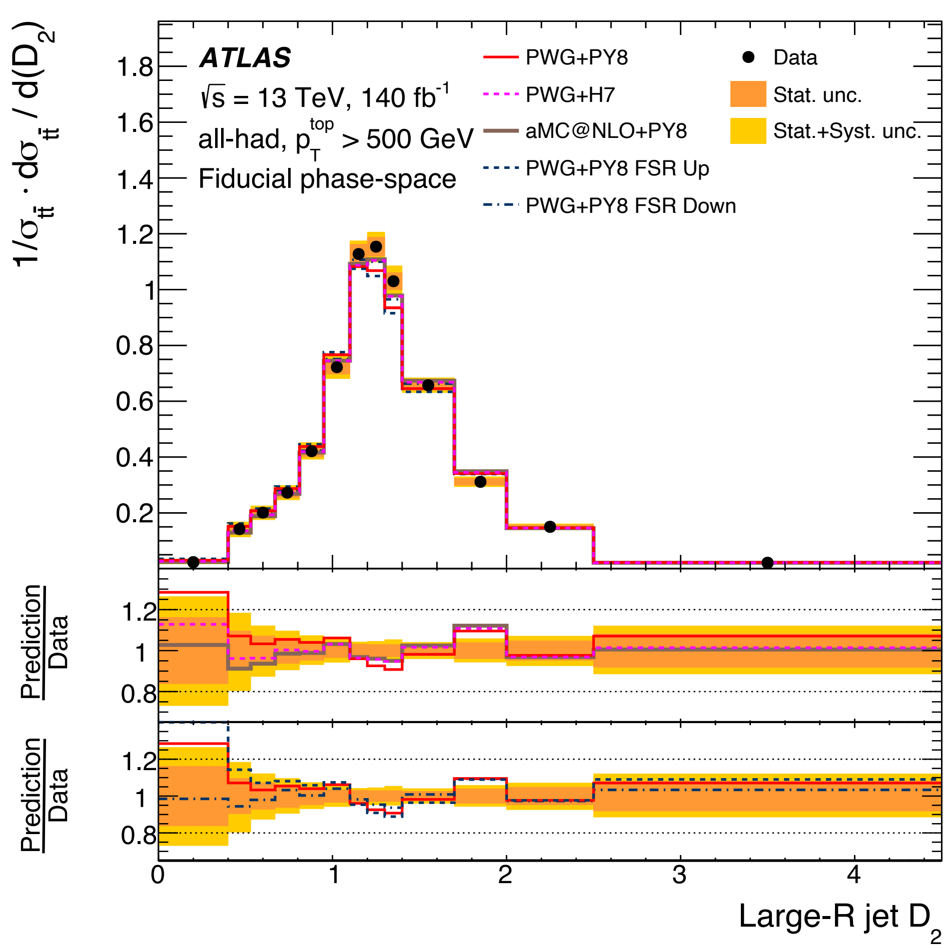


Jet substructure (ATLAS)

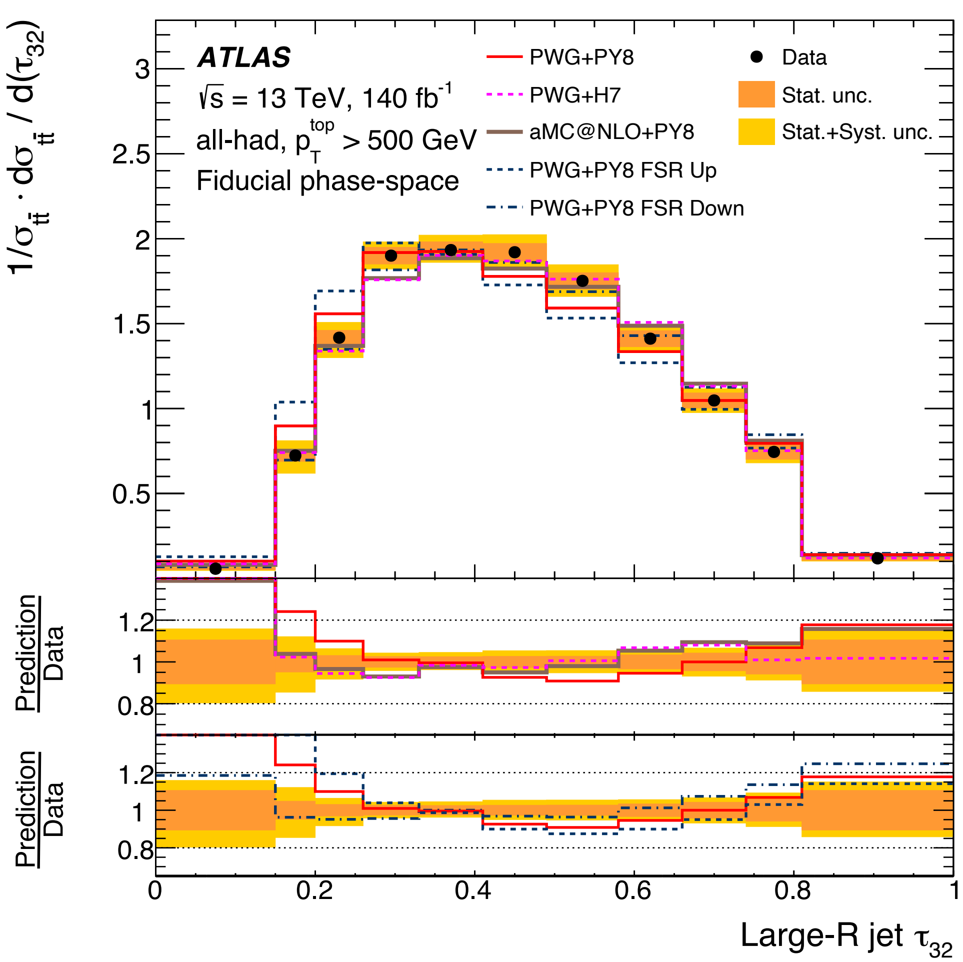
arXiv:2312.03797

- Measure single- and double-differential cross sections
  - ✦ Two-body substructure variables generally rather well-described
  - ✦ Three-body substructure variables less well described => data favor lower scale / higher α_S than in nominal final-state radiation (FSR)
    - *Important information for MC development*

Ratio of energy correlation functions



Ratio of n-subjettiness variables



Quantum entanglement (ATLAS)

- *Study quantum entanglement in quarks!*

- Short top quark lifetime → spin information is transferred to its decay products → **spin correlations** are observable
  - Spin correlations well-established in top physics, see e.g.:

    CMS: *PRD 100, 072002 (2019)*, ATLAS: *EPJC 80 (2020) 754*

- Use spin correlations to probe effects of quantum entanglement

- New ATLAS analysis utilizes very clean dilepton (eμ) final state

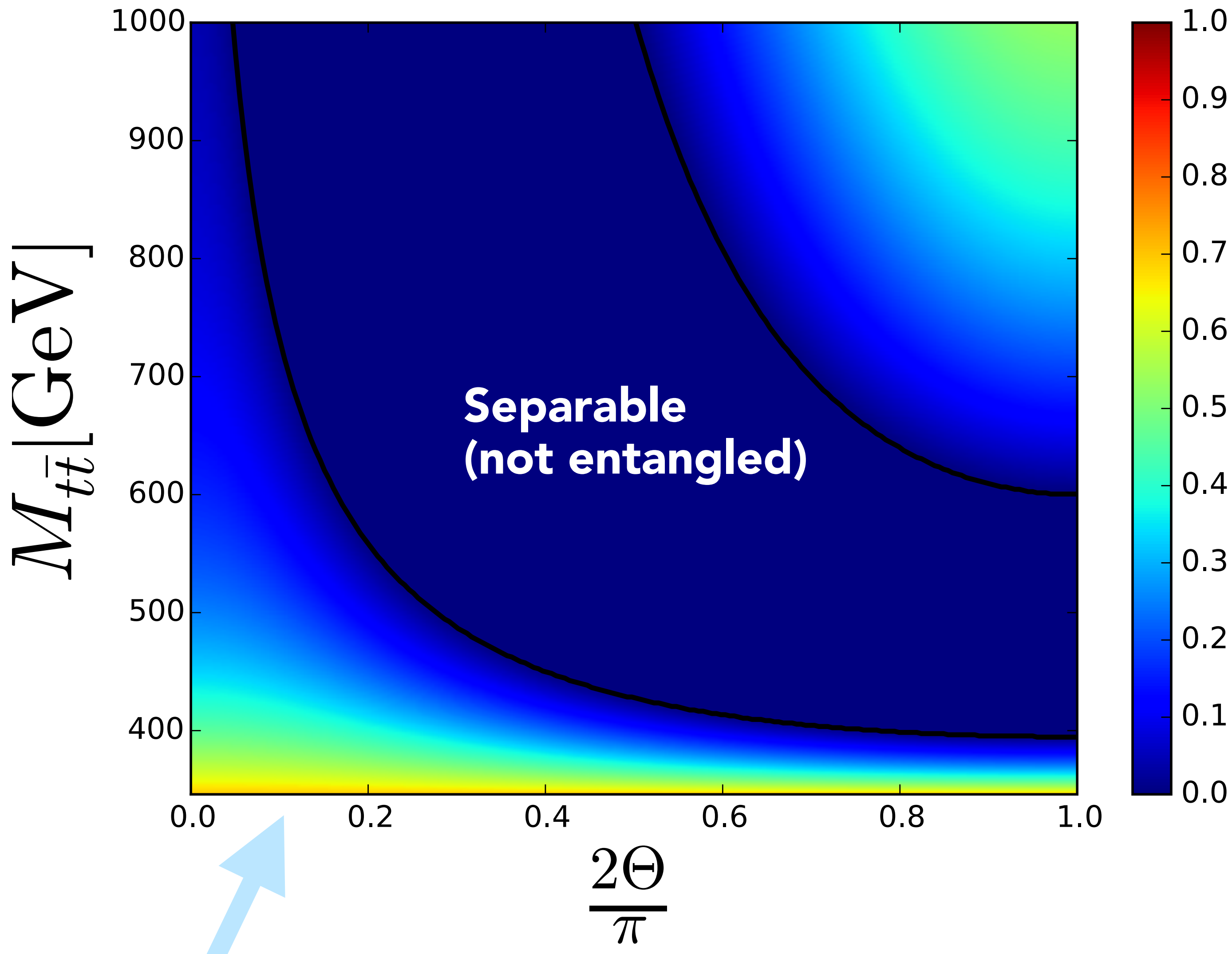
Quantum entanglement

arXiv:2311.07288

- Observable D (degree of entanglement) strongly dependent on ttbar kinematics

- Events separated by m(tt)
  - **340 < m(tt) < 380 GeV** *entanglement signal region*
  - 380 < m(tt) < 500 GeV *validation region (dilution from mis-reconstruction)*
  - m(tt) > 500 GeV *no-entanglement validation region*
    - *Highly-boosted region also has sensitivity, analysis choice to use low m(tt) region*

Entanglement vs m(tt) & top angle w.r.t beam



Entangled (gg→tt in maximally entangled spin singlet)

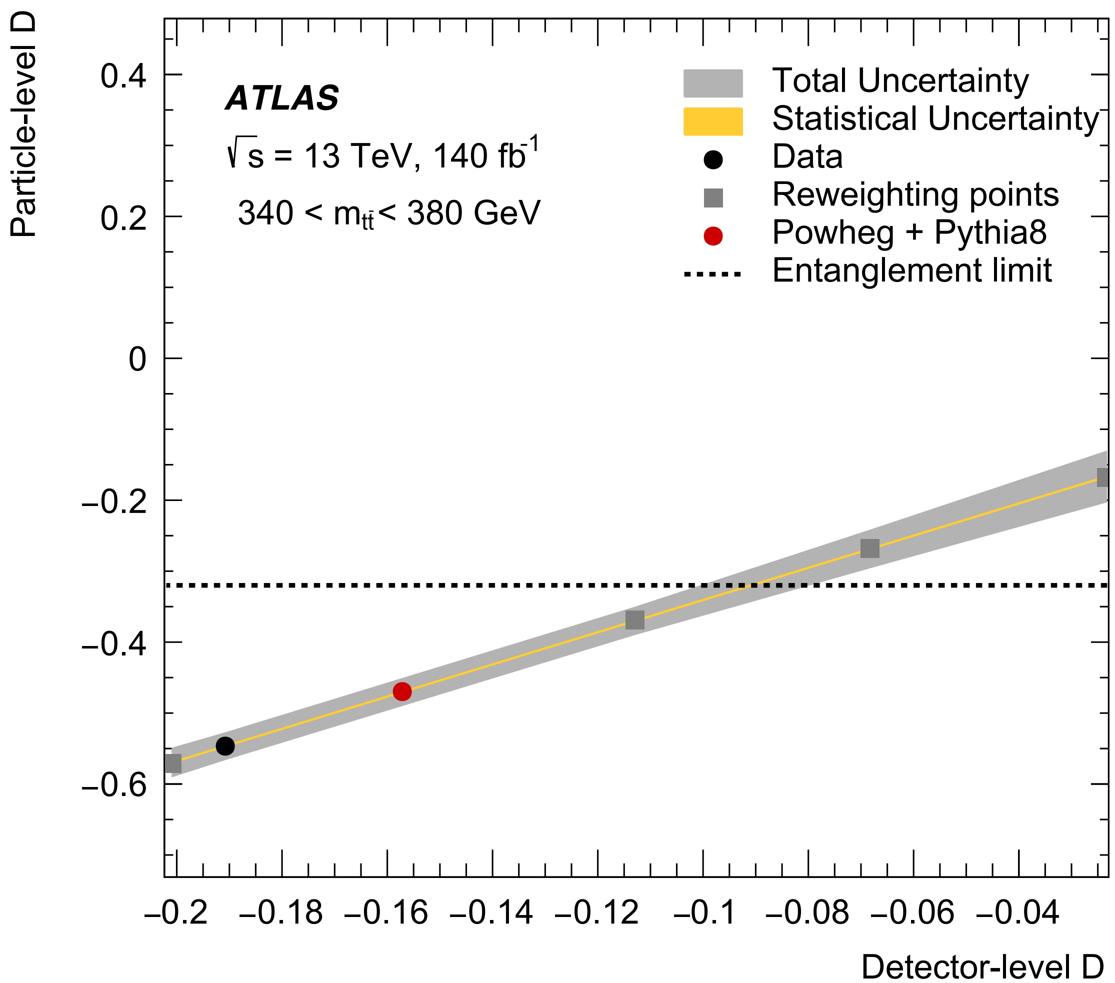
Eur. Phys. J. Plus (2021) 136:907

Quantum entanglement

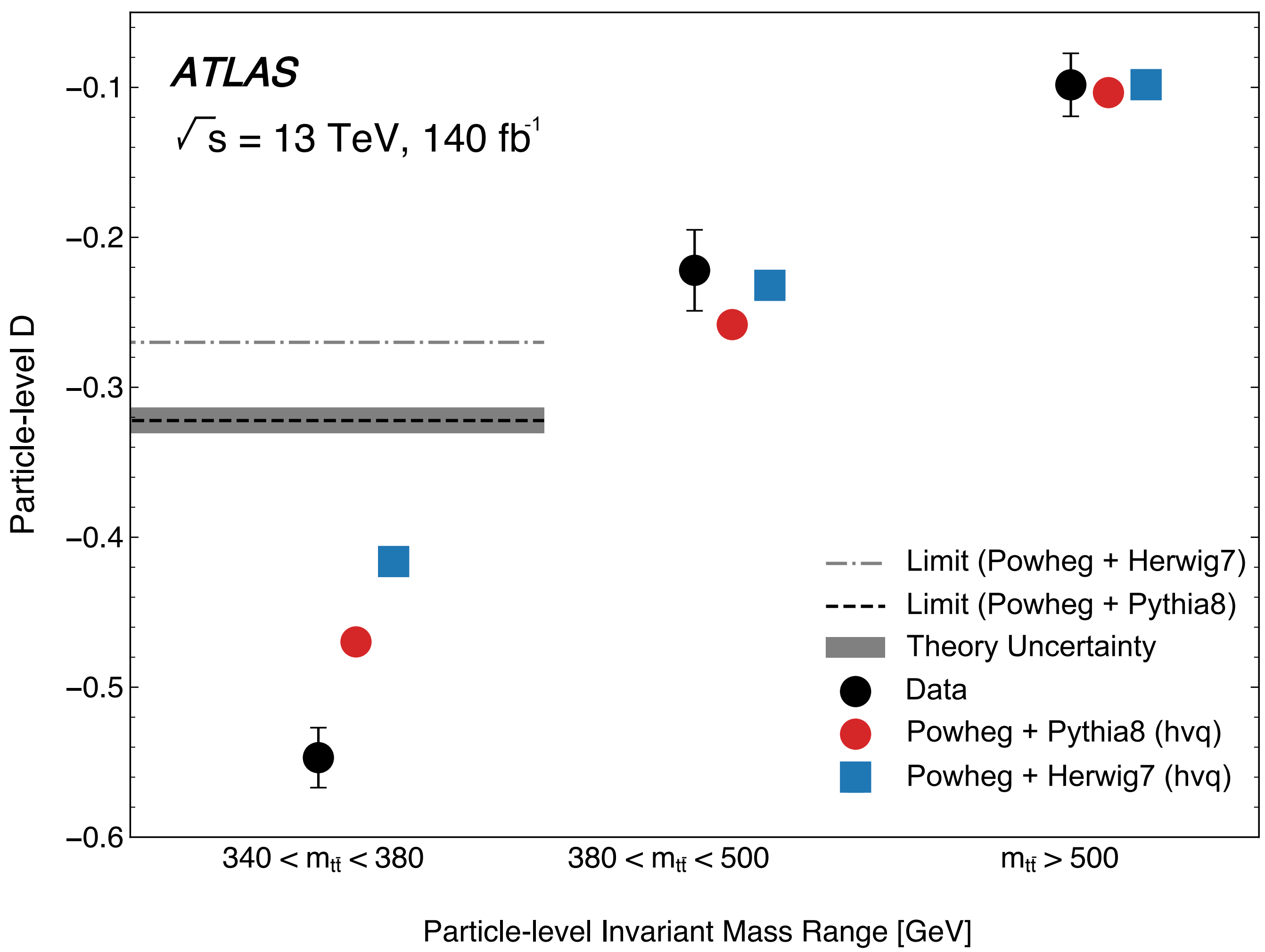
arXiv:2311.07288

- Measurement: $D = -0.547 \pm 0.002(\mathrm{stat}) \pm 0.020(\mathrm{syst})$
- **>5σ observation** of entanglement in a pair of quarks and highest-energy observation of entanglement to date

Calibration for dependence between particle-level vs detector-level D



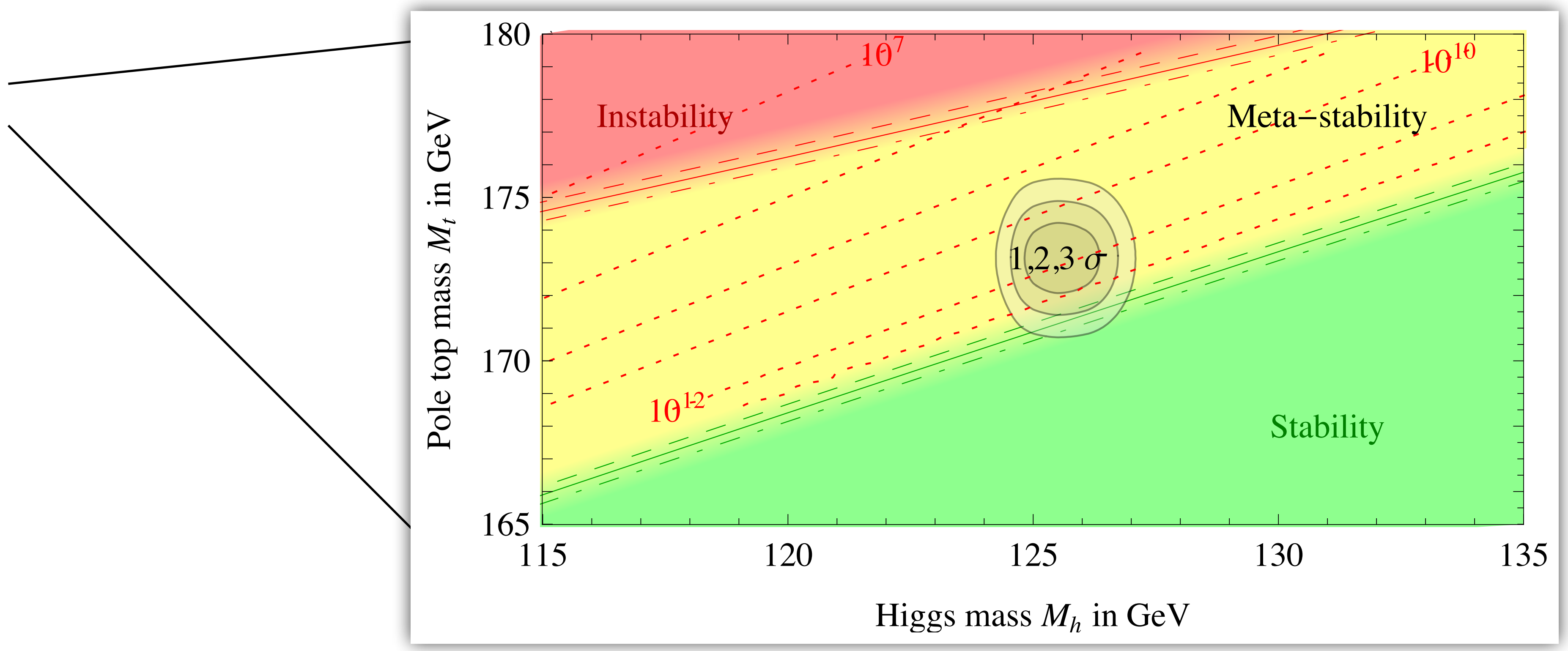
Observed and expected D at particle level for different m(tt) regions



Top quark mass (ATLAS+CMS)

- *New Run-1 ATLAS+CMS top quark mass combination!*

- **<u>Why</u>** measure top quark mass?
  - ✦ A fundamental SM parameter, must be measured experimentally
  - ✦ Stability of effective SM Higgs potential sensitive to m_{top}/m_H
    - If not, new physics needed to stabilize it



JHEP 08 (2012) 098

Top quark mass

arXiv:2404.08713

- Combination of **15** ATLAS+CMS top quark mass measurements
  - ✦ Performed using 7/8 TeV data
  - ✦ Different final states: dilepton, l+jets, all-jets
  - ✦ Other topologies (fits to invariant masses that are sensitive to m_{top}): single top (t-channel), secondary vertex, J/Psi

- **<u>Method:</u>** **B**est **L**inear **U**nbiased **E**stimated – **BLUE**

SoftwareX 11 (2020) 100468
EPJC 74 (2014) 3004

$$m_t = \sum_i w_i m_t^i \quad \text{where} \quad \sum_i w_i = 1$$

- To estimate correlations:
  - ✦ Split systematics into sources
  - ✦ Assign / assess correlations
  - ✦ Sum covariance matrices

ATLAS+CMS $\sqrt{s}$ = 7,8 TeV

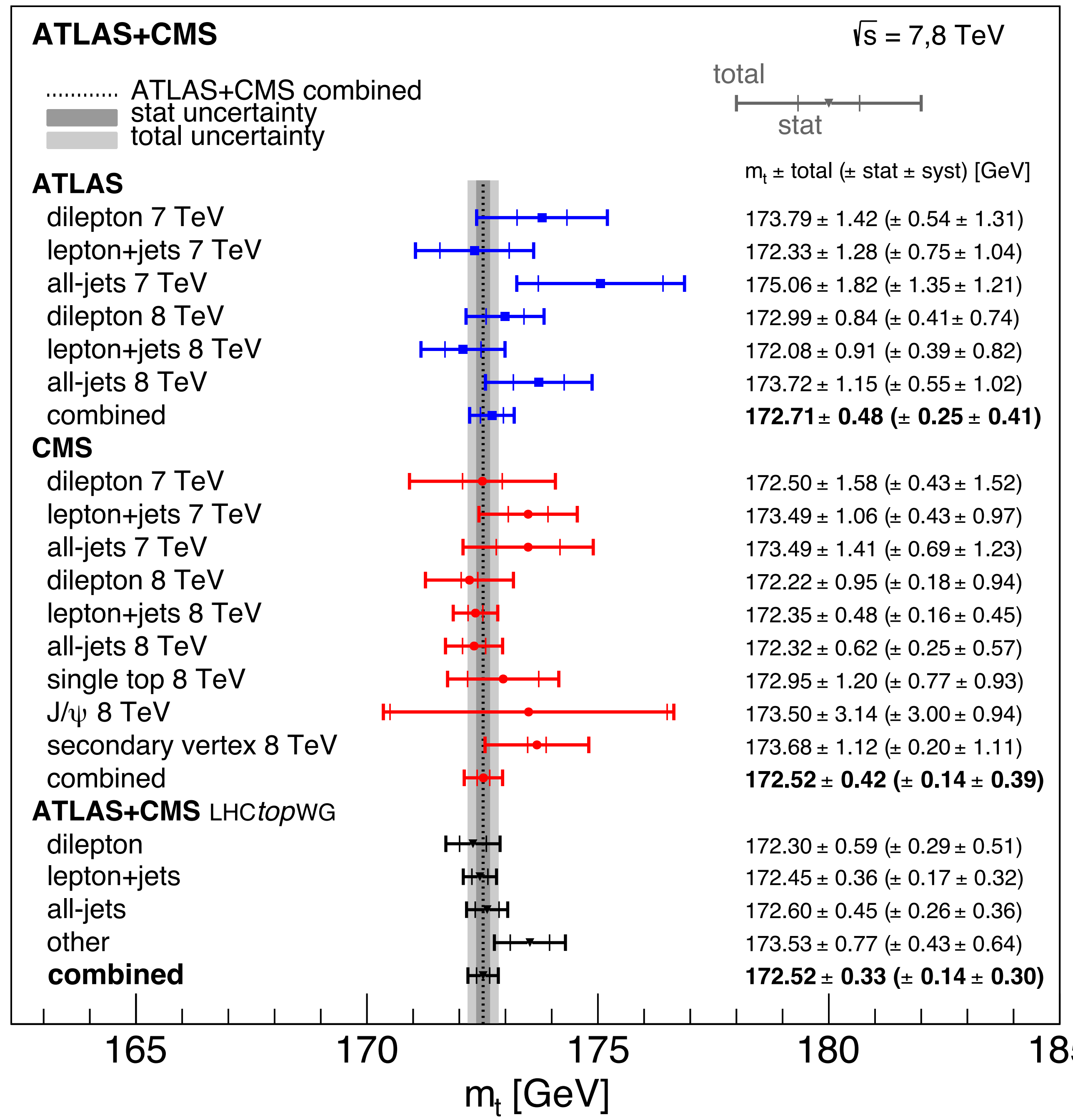
	ATLAS dil 7 TeV	ATLAS lj 7 TeV	ATLAS aj 7 TeV	ATLAS dil 8 TeV	ATLAS lj 8 TeV	ATLAS aj 8 TeV	CMS dil 7 TeV	CMS lj 7 TeV	CMS aj 7 TeV	CMS dil 8 TeV	CMS lj 8 TeV	CMS aj 8 TeV	CMS t 8 TeV	CMS J/Ψ 8 TeV	CMS vtx 8 TeV
ATLAS dil 7 TeV	1.00	-0.07	0.42	0.51	0.06	0.07	0.13	0.22	0.11	0.18	0.23	0.13	0.10	-0.06	-0.15
ATLAS lj 7 TeV	-0.07	1.00	-0.01	0.00	-0.07	-0.02	0.09	0.08	0.03	0.08	0.04	0.01	0.10	0.02	-0.04
ATLAS aj 7 TeV	0.42	-0.01	1.00	0.29	-0.06	0.00	0.11	0.19	0.11	0.13	0.21	0.16	0.09	-0.01	-0.04
ATLAS dil 8 TeV	0.51	0.00	0.29	1.00	-0.18	0.31	0.09	0.16	0.08	0.12	0.16	0.10	0.07	-0.04	-0.10
ATLAS lj 8 TeV	0.06	-0.07	-0.06	-0.18	1.00	-0.03	0.02	-0.00	-0.00	-0.04	0.05	-0.03	0.03	-0.01	0.00
ATLAS aj 8 TeV	0.07	-0.02	0.00	0.31	-0.03	1.00	0.10	0.11	0.06	-0.01	0.14	0.08	0.07	0.01	0.10
CMS dil 7 TeV	0.13	0.09	0.11	0.09	0.02	0.10	1.00	0.31	0.57	0.31	0.46	0.36	0.26	0.08	0.13
CMS lj 7 TeV	0.22	0.08	0.19	0.16	-0.00	0.11	0.31	1.00	0.53	0.10	0.41	0.45	0.29	-0.03	0.03
CMS aj 7 TeV	0.11	0.03	0.11	0.08	-0.00	0.06	0.57	0.53	1.00	0.12	0.34	0.35	0.21	-0.03	0.07
CMS dil 8 TeV	0.18	0.08	0.13	0.12	-0.04	-0.01	0.31	0.10	0.12	1.00	0.23	0.07	0.09	-0.04	-0.16
CMS lj 8 TeV	0.23	0.04	0.21	0.16	0.05	0.14	0.46	0.41	0.34	0.23	1.00	0.70	0.48	0.06	0.15
CMS aj 8 TeV	0.13	0.01	0.16	0.10	-0.03	0.08	0.36	0.45	0.35	0.07	0.70	1.00	0.47	0.05	0.22
CMS t 8 TeV	0.10	0.10	0.09	0.07	0.03	0.07	0.26	0.29	0.21	0.09	0.48	0.47	1.00	-0.01	0.08
CMS J/Ψ 8 TeV	-0.06	0.02	-0.01	-0.04	-0.01	0.01	0.08	-0.03	-0.03	-0.04	0.06	0.05	-0.01	1.00	0.12
CMS vtx 8 TeV	-0.15	-0.04	-0.04	-0.10	0.00	0.10	0.13	0.03	0.07	-0.16	0.15	0.22	0.08	0.12	1.00

Top quark mass

arXiv:2404.08713

- **Result:** $$m_t = 172.52 \pm 0.14(\text{stat}) \pm 0.30(\text{syst})\ \text{GeV}$$
  - ✦ Total uncertainty of 0.33 GeV (0.2%) !!
  - ✦ Most precise measurement of top quark mass to date
  - ✦ Uncertainty dominated by systematic sources (JES, b-tagging, $t\bar{t}$ modeling)

Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
...	...	...	...
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42



Lepton flavor violation (CMS)

arXiv:2312.03199

- Charged-lepton flavor violation (CLFV) extremely rare in the SM
- New analysis using Run-2 data in three-lepton (e/μ) final states
  - Separate regions to target top production and decay signals
  - Parametrize signals with dim-6 effective field theory (EFT) operators

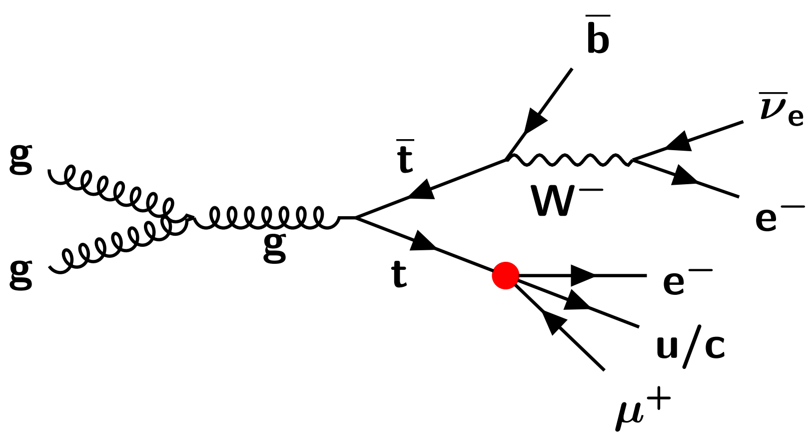


Figure 2: **Top decay**

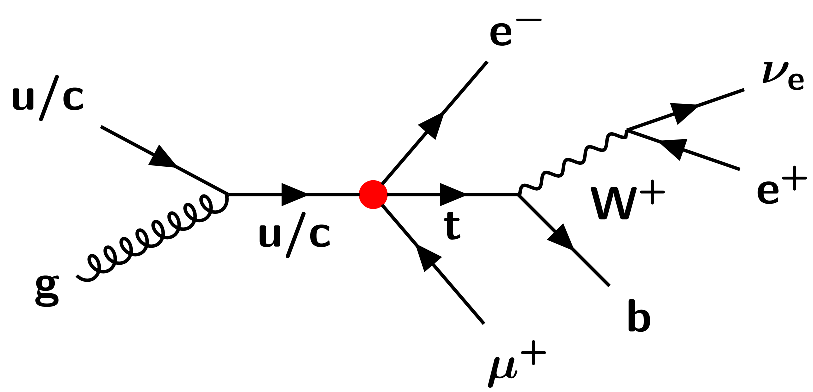


Figure 3: **Top production**

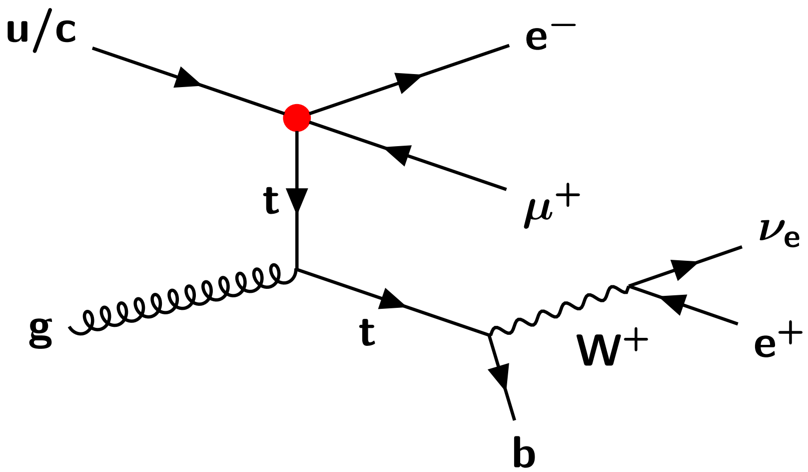


Figure 4: **Top production**

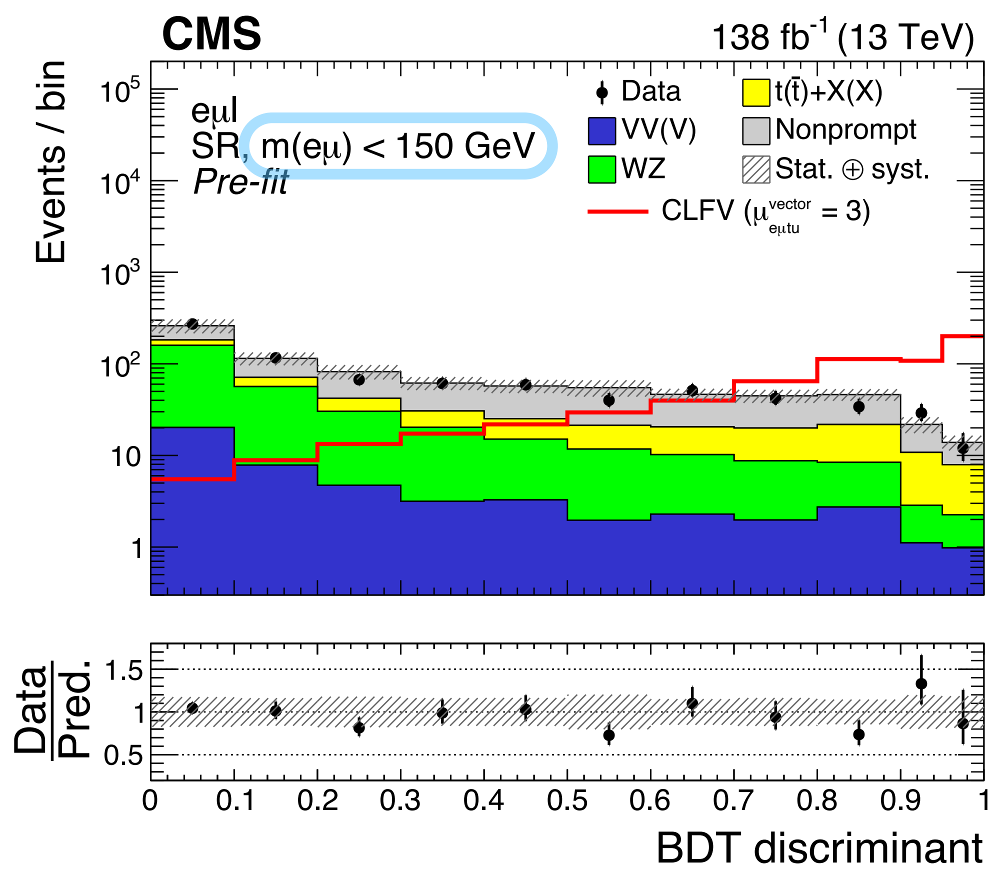
- *Previous searches involving eμtq interaction (ATLAS-CONF-2018-044, CMS: JHEP 06 (2022) 082) compatible with the SM*
- *Recent result on μτtq interaction also consistent with the SM (ATLAS-CONF-2023-001)*

Lepton flavor violation (CMS)

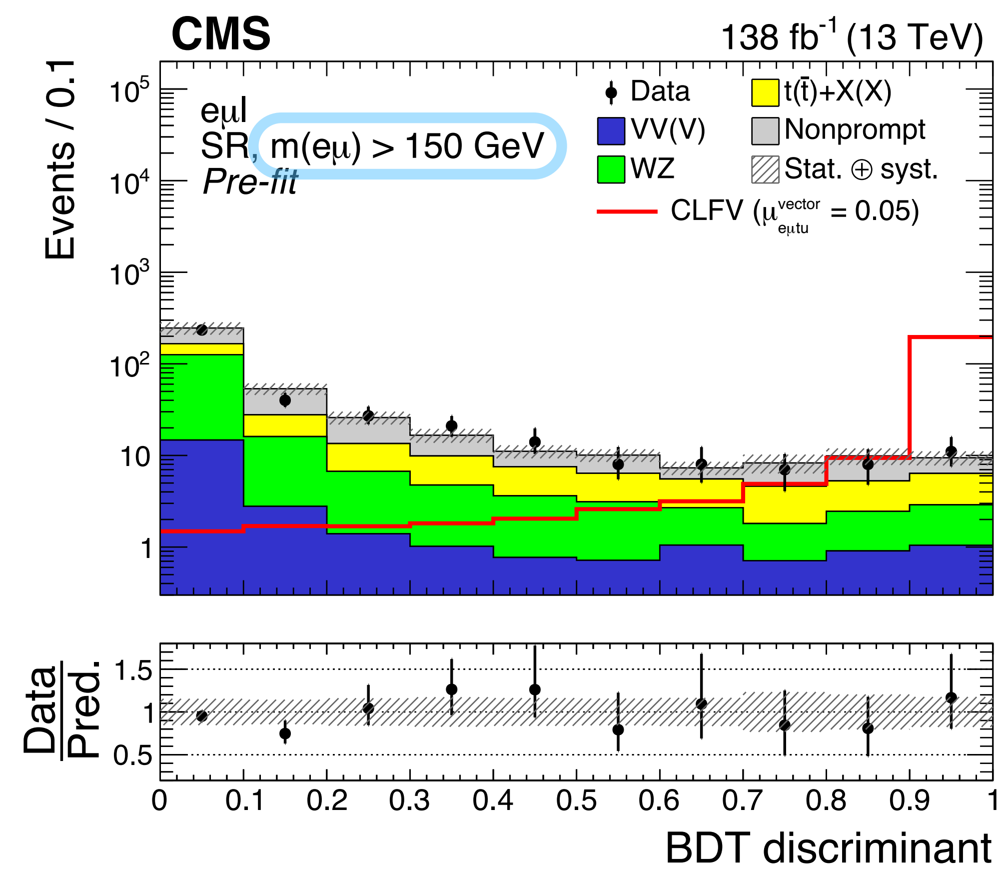
arXiv:2312.03199

- BDT trained for each signal region (production vs decay signals)

Top decay signal enriched



Top production signal enriched



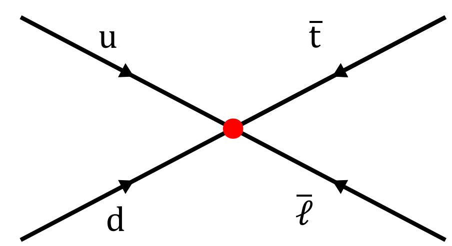
- No significant excess over SM expectation → most stringent limits to date on BR(t => eμq)
  - ✦ Improving upon previous limits by an order of magnitude

Int. type	$\mathcal{B}(t\to e\mu u)\times10^{-7}$	$\mathcal{B}(t\to e\mu c)\times10^{-7}$
Tensor	0.32	4.98
Vector	0.22	3.69
Scalar	0.12	2.16

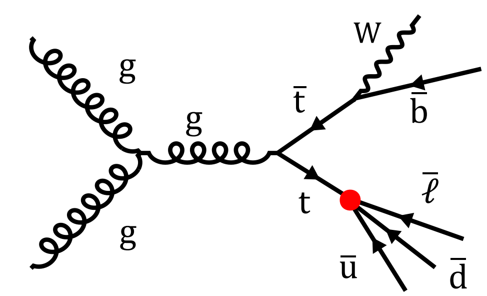
Baryon number violation (CMS)

arXiv:2402.18461

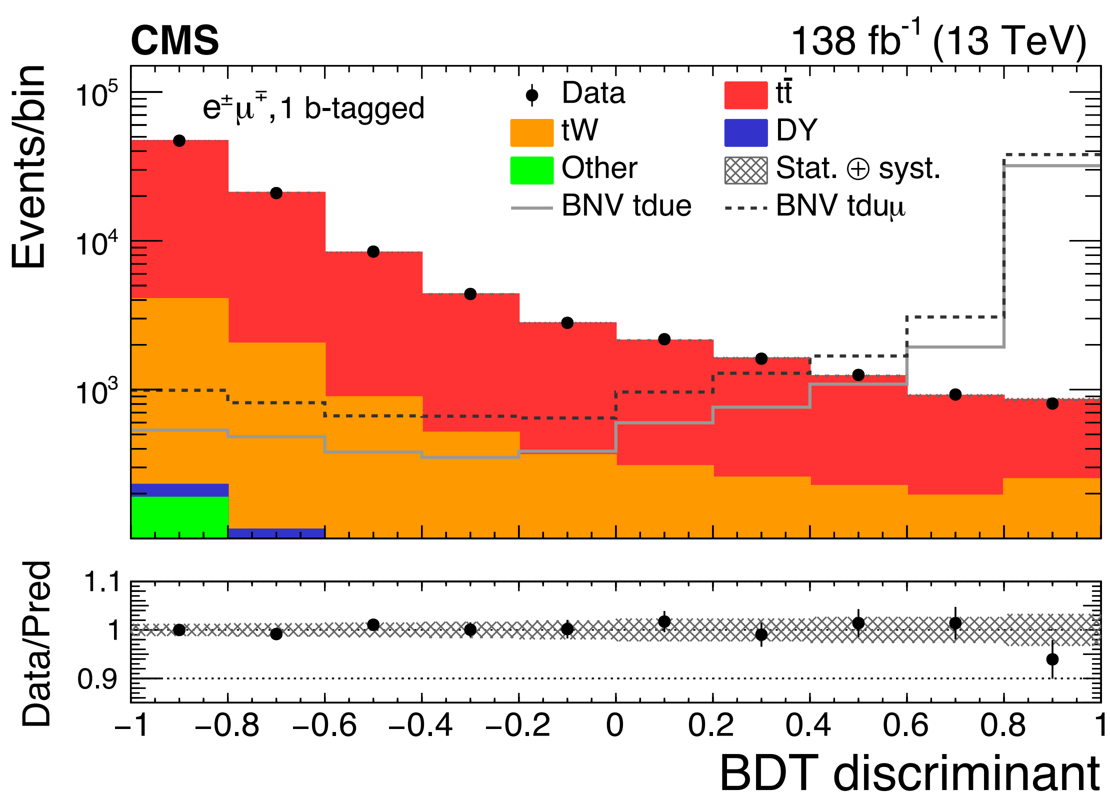
- ***New*** search for baryon number violating (BNV) processes in production/decay of top quarks
  - ✦ Consider dilepton final states (ee, μμ) + one b-jet, L=138 fb^{-1}
  - ✦ Use BDT to distinguish signal from background processes; trained using kinematics for leptons & top quark system
  - ✦ Limits improved by **3-6 orders of magnitude**

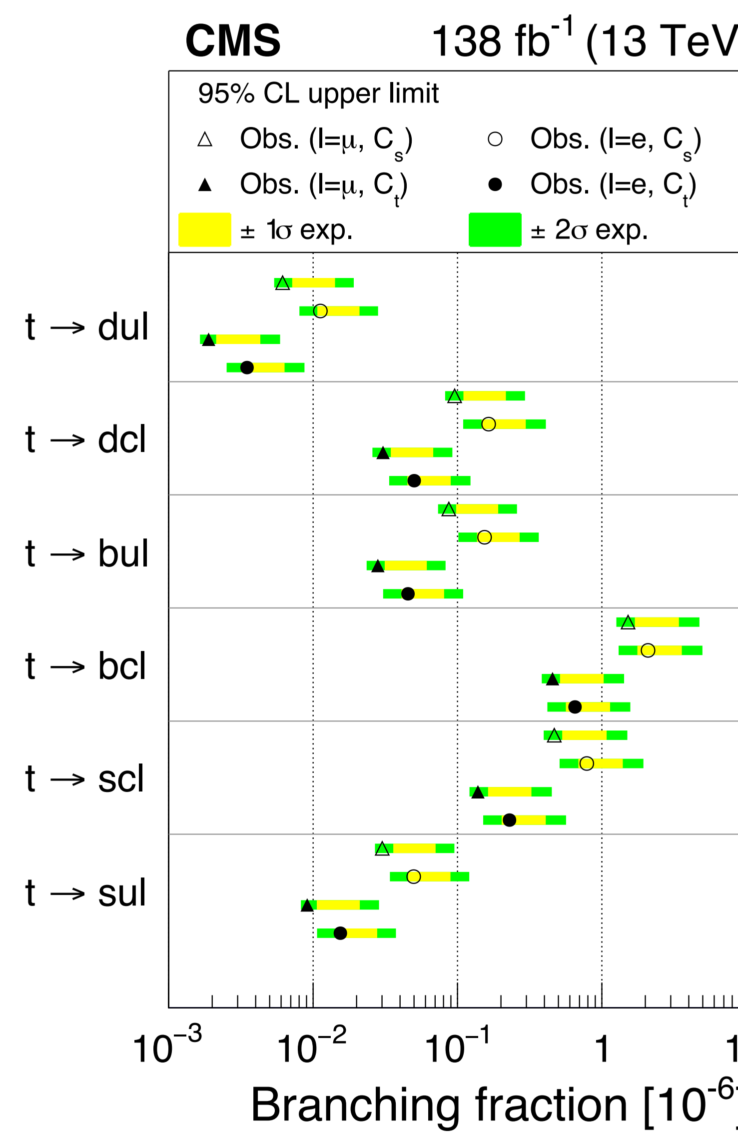


BNV top production



BNV top decay

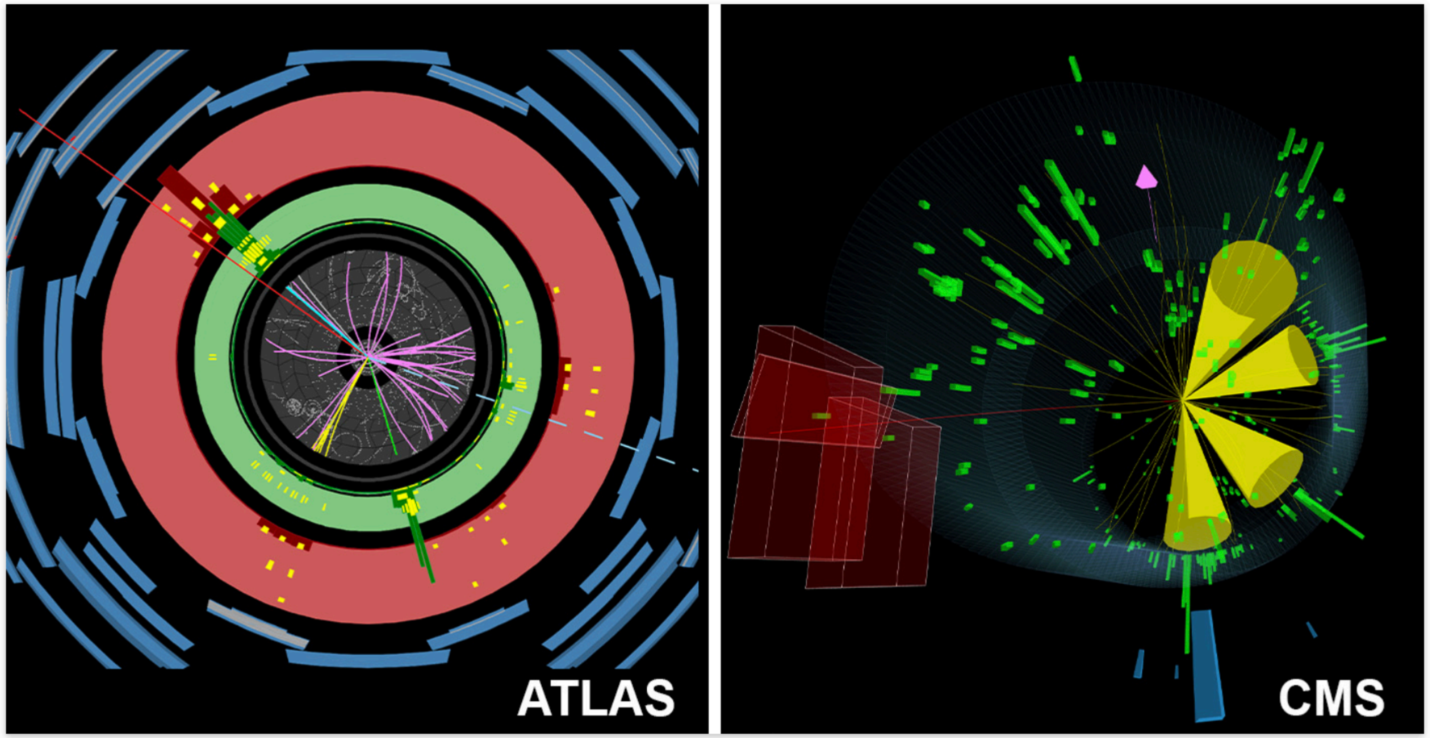




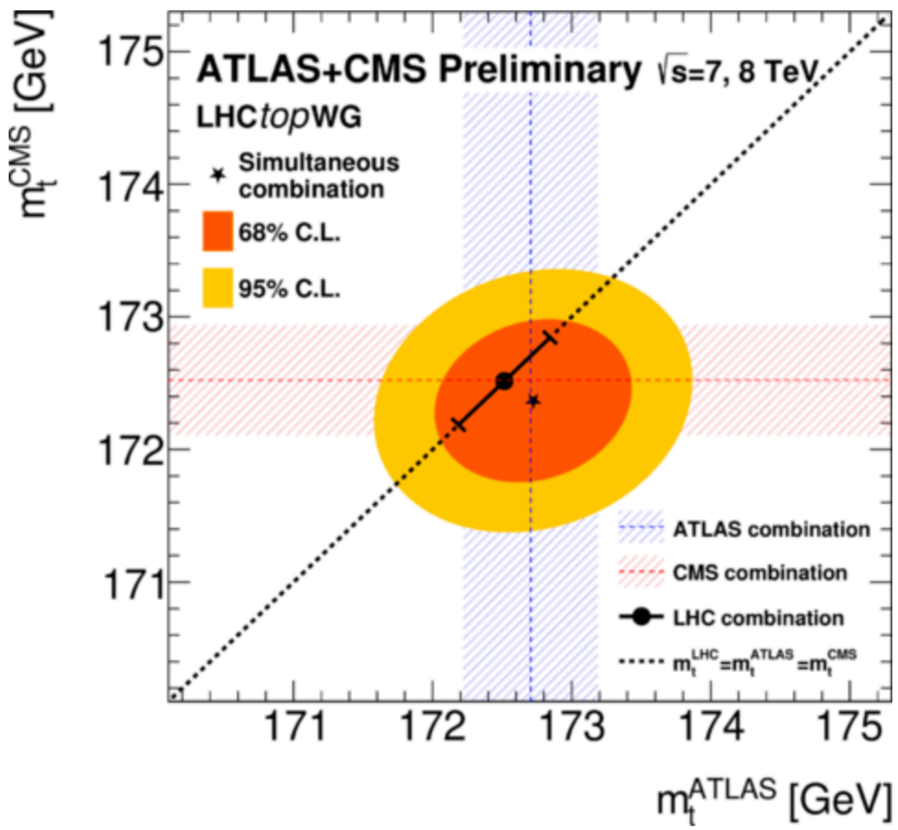
Outlook

- Measurements in top quark sector are key in continuing testing the SM & searching for physics beyond it
  - On one hand, pushing the precision limit in e.g. cross section and mass measurements: Top mass measured to the 0.2% level !
  - On the other hand, novel analyses carried out: Quantum entanglement, substructure measurements, hunts for deviations from the SM

- **Top quark physics forms an exciting and very active research program at the LHC!**



Collision event displays of top-quark production from ATLAS (left) and CMS (right). (Image: ATLAS/CMS/CERN)



CMS AND ATLAS UNITE TO WEIGH IN ON THE TOP QUARK

02 OCT 2023

The ATLAS and CMS Experiments at CERN have just released a new measurement of the mass of the top quark. The new result combines 15 previous measurements to give the most precise determination of the top-quark mass to date. Among the known...

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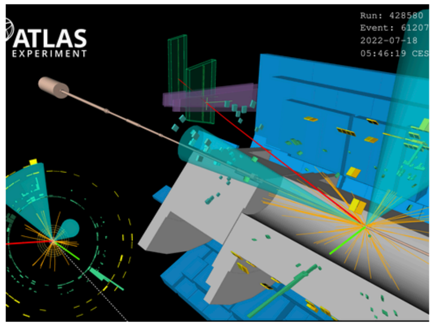


ATLAS moves into top gear for Run 3

The ATLAS Collaboration has just released its first Run 3 measurements, studying data collected in the first half of August 2022. Researchers have measured the interaction strength (or cross-section) of two well-known processes: the production of a pair of top quarks and the production of a Z boson.

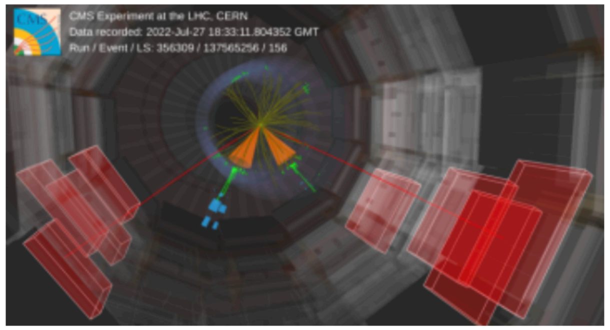
Physics Briefing | 30 November 2022

Physics Briefings:

Top quark mass ATLAS+CMS

Top entanglement from ATLAS

13.6 TeV measurements at ATLAS and at CMS



TOP QUARKS FAST TO ARRIVE AT NEW ENERGY FRONTIER

24 OCT 2022

On 5 July 2022, the LHC surpassed the previous energy limits of experimental particle physics, breaking its own record by achieving stable proton-proton collisions at a center-of-mass energy of $\sqrt{s}$ = 13.6 TeV. This marked the start of Run 3, the...

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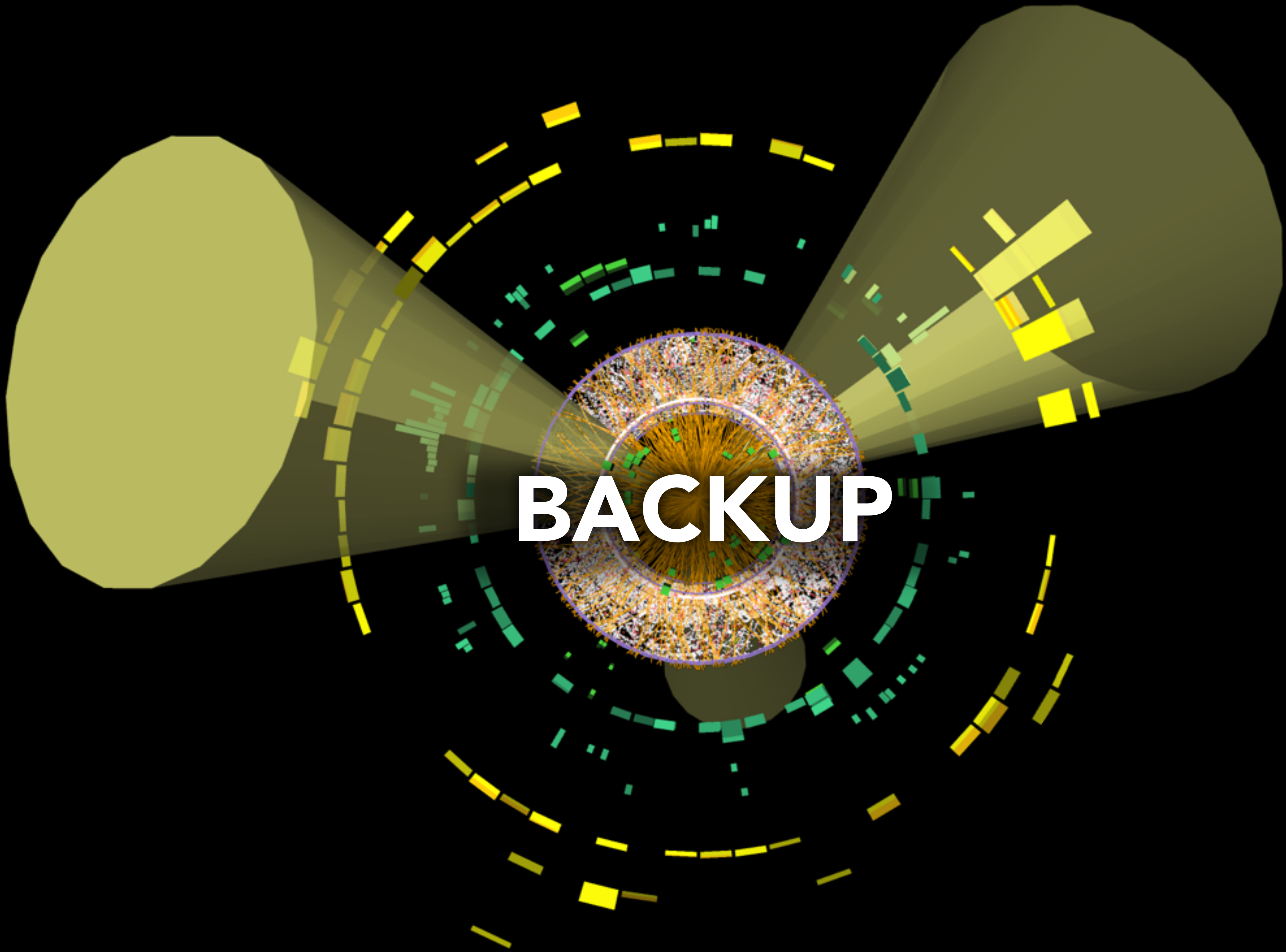
ATLAS achieves highest-energy detection of quantum entanglement

In a new result from the ATLAS Collaboration, physicists observed – for the first time – quantum entanglement between a pair of quarks. This is the highest-energy measurement of entanglement to date.

Physics Briefing | 28 September 2023

BACKUP



References

Discussed here:

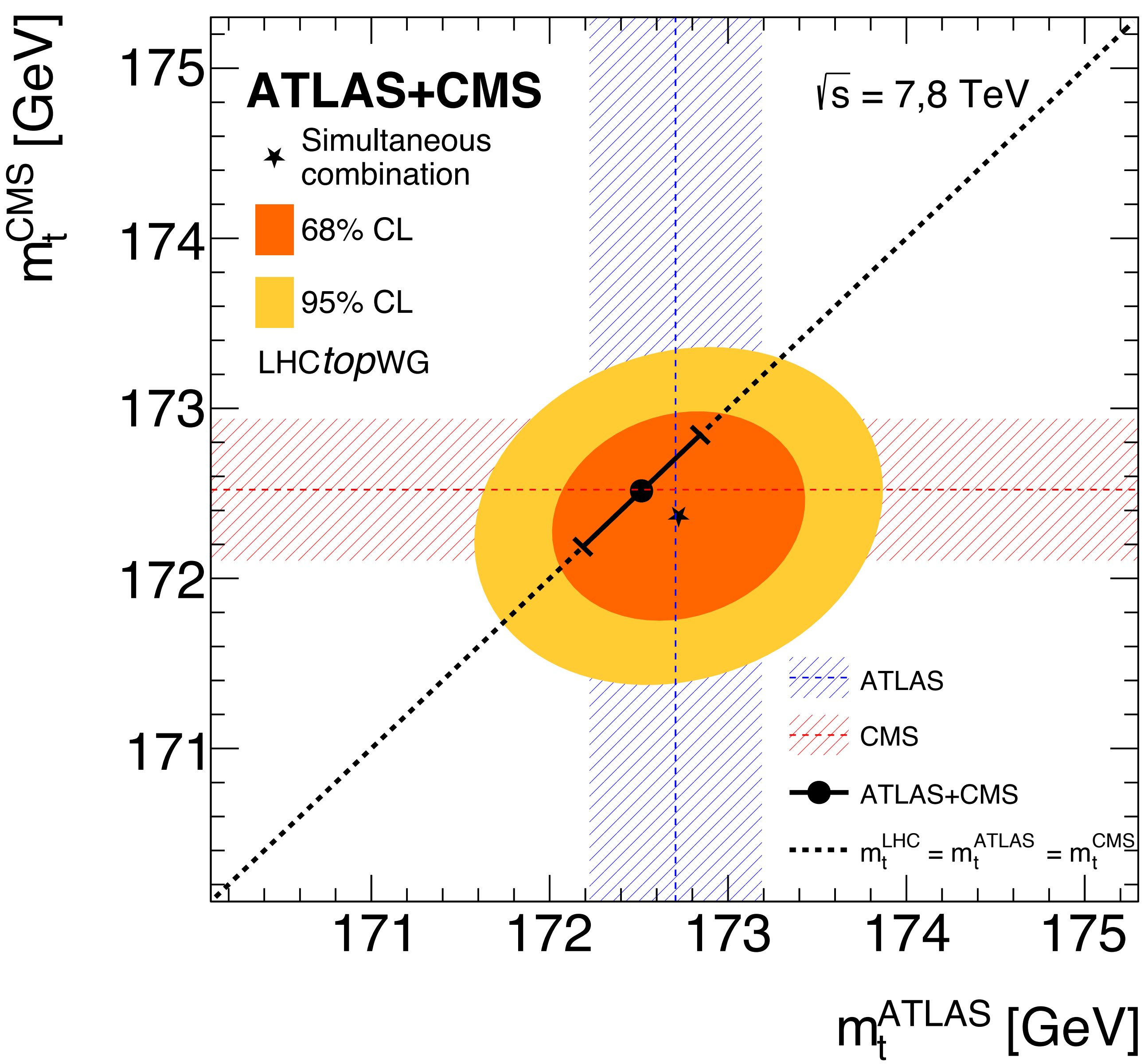
- Measurement of ttbar cross section at 13.6 TeV (CMS): JHEP 08 (2023) 204
- Measurement of ttbar cross section at 13.6 TeV (ATLAS): PLB 848 (2024) 138376
- ttbar production in pPb collisions at 8.16 TeV (ATLAS): ATLAS-CONF-2023-063
- Jet substructure (ATLAS): arXiv:2312.03797
- Quantum entanglement (ATLAS): arXiv:2311.07288
- Run-1 top mass combination (ATLAS+CMS): arXiv:2404.08713
- Search for charged-lepton flavor violation (CMS): arXiv:2312.03199
- Search for baryon number violation (CMS): arXiv:2402.18461

Other recent top quark measurements:

- Differential tt+jets cross section at 13 TeV (CMS): arXiv:2402.08486
- Differential tt+jets cross section at 13 TeV (ATLAS): ATLAS-CONF-2023-068
- Inclusive and differential tt+bb measurement at 13 TeV (CMS): arXiv:2309.14442
- Inclusive and differential ttbar cross section at 13 TeV (ATLAS): JHEP 07 (2023) 141
- Search for Lorentz invariance in ttbar events (CMS): CMS-PAS-TOP-22-007
- Single top t-channel production at 13 TeV (ATLAS): arXiv:2403.02126
- Single top t-channel production at 5 TeV (ATLAS): arXiv:2310.01518

Top quark mass

arXiv:2404.08713



Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

Jet substructure (ATLAS)

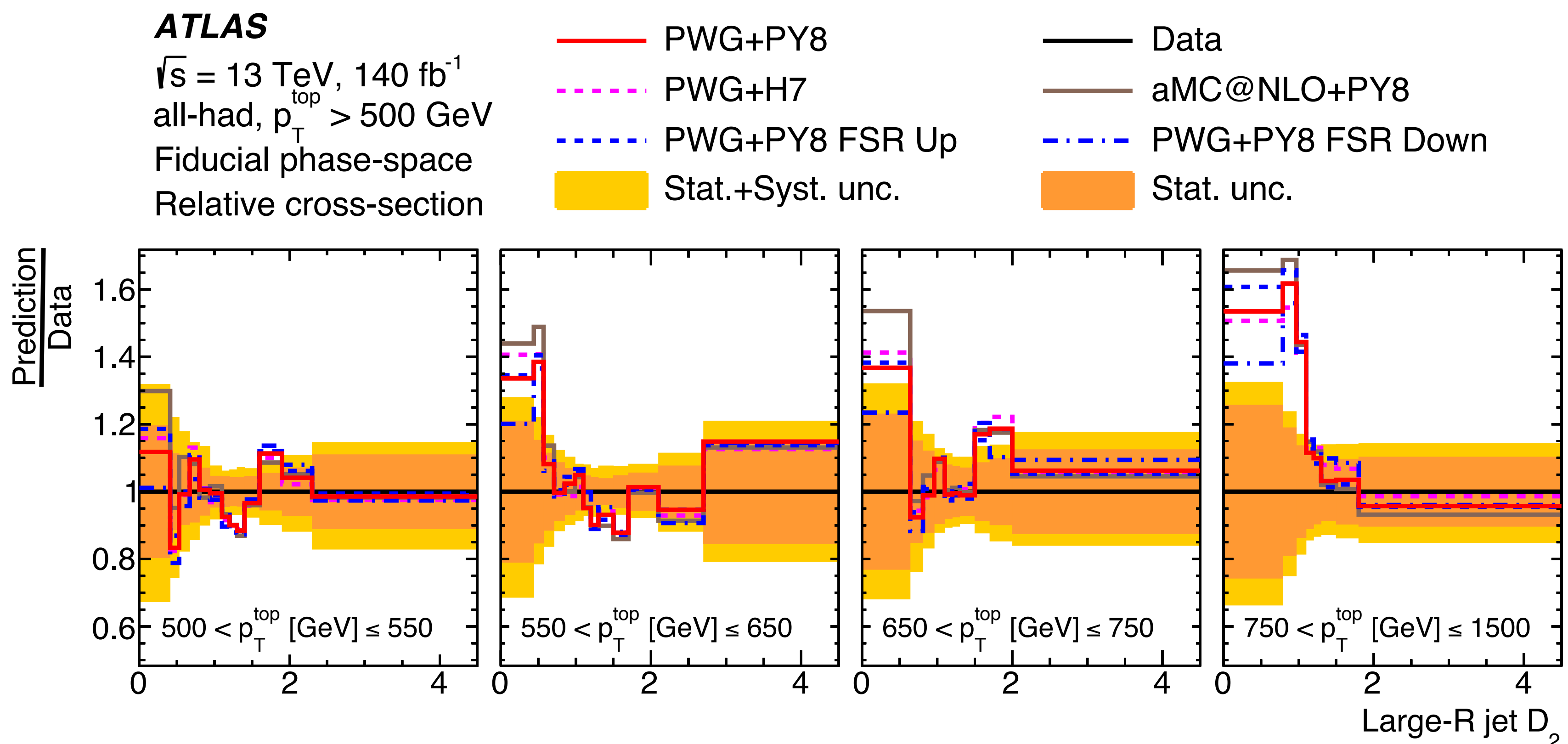
arXiv:2312.03797

Ratio of energy correlation functions, D_2 targets jets with two-body structure:

$$D_2 = \frac{\mathrm{ECF}(3)\,\mathrm{ECF}(1)^3}{\mathrm{ECF}(2)^3}$$

$$\mathrm{ECF}(N) = \sum_{i_1<i_2<\ldots<i_N\in J}\left(\prod_{a=1}^{N} p_{\mathrm{T},i_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N}\Delta R(i_b,i_c)\right)$$

arXiv:1305.0007



N-subjettiness measures degree to which jet is compatible with comprising N or fewer subjets:

$$\tau_{32} \equiv \tau_3/\tau_2$$

$$\tau_N = \frac{1}{d_0}\sum_k p_{\mathrm{T},k}\min\left\{\Delta R_{1,k},\Delta R_{2,k},\cdots,\Delta R_{N,k}\right\},$$

$$\text{with } d_0 = \sum_k p_{\mathrm{T},k} R_0.$$

JHEP 1103:015 (2011)