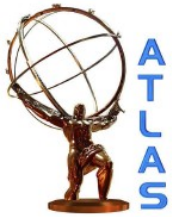
Recent Highlights on QCD, Electroweak and Top Quark Physics from LHC



Alexander Grohsjean

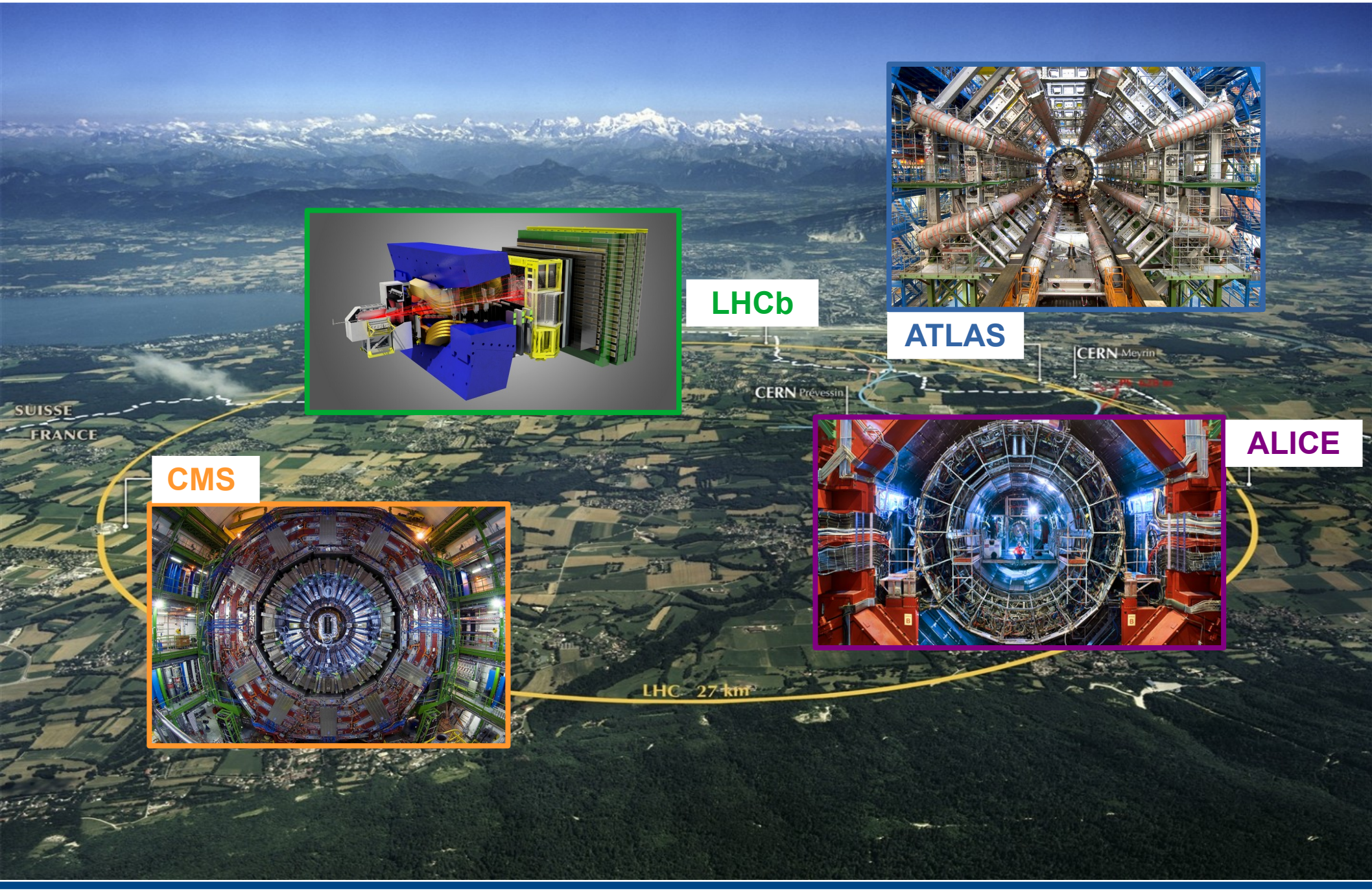
29th International Workshop on
DIS and Related Subjects

02.05.2022

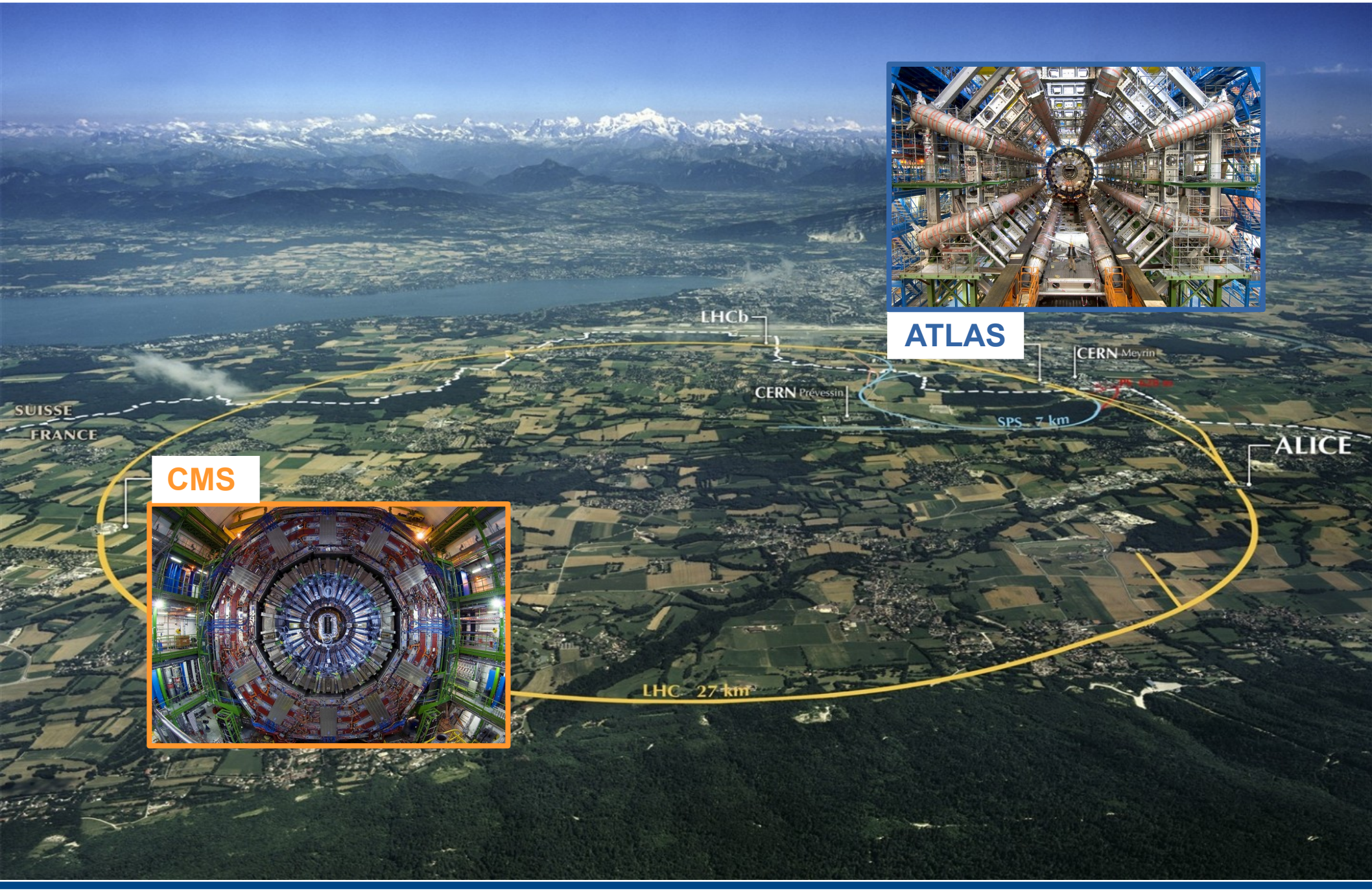
Santiago de Compostela

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Abundance of Beautiful Physics at LHC



Focus on ATLAS and CMS



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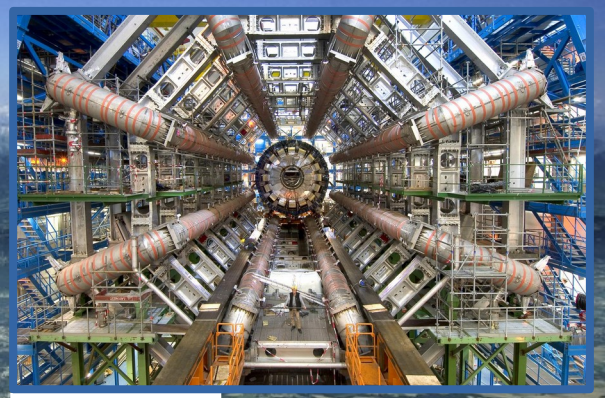
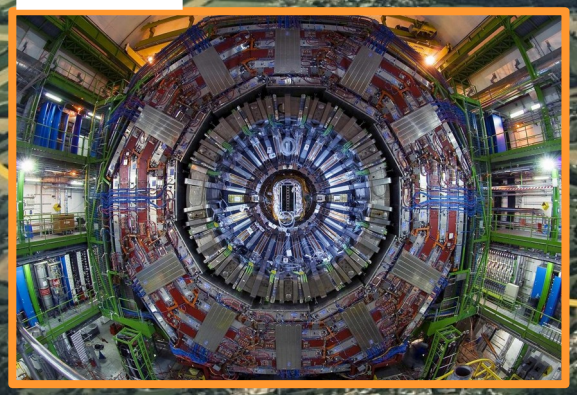
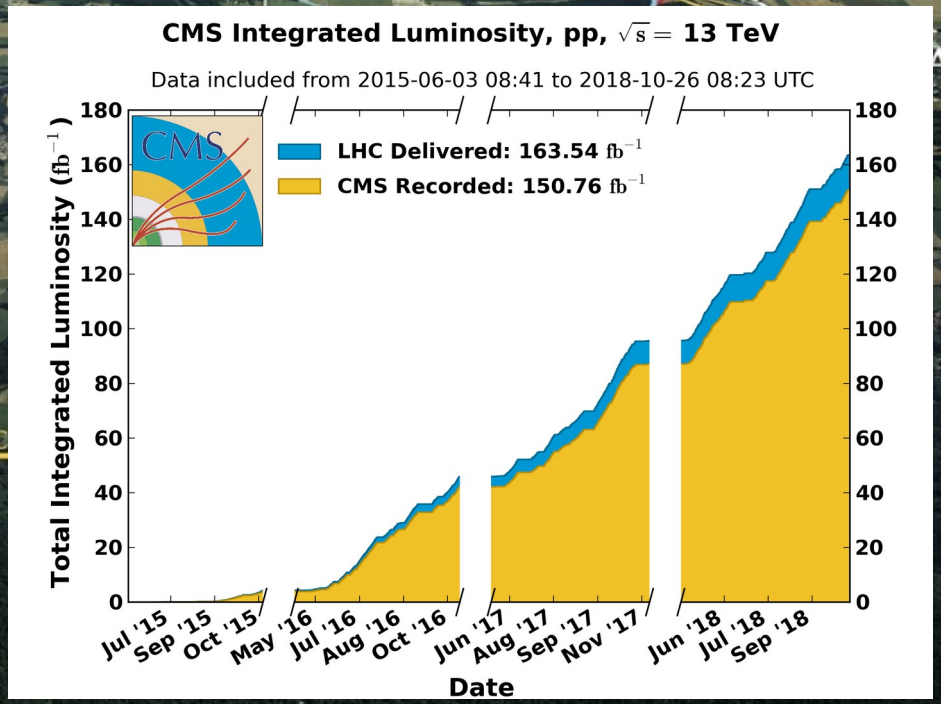


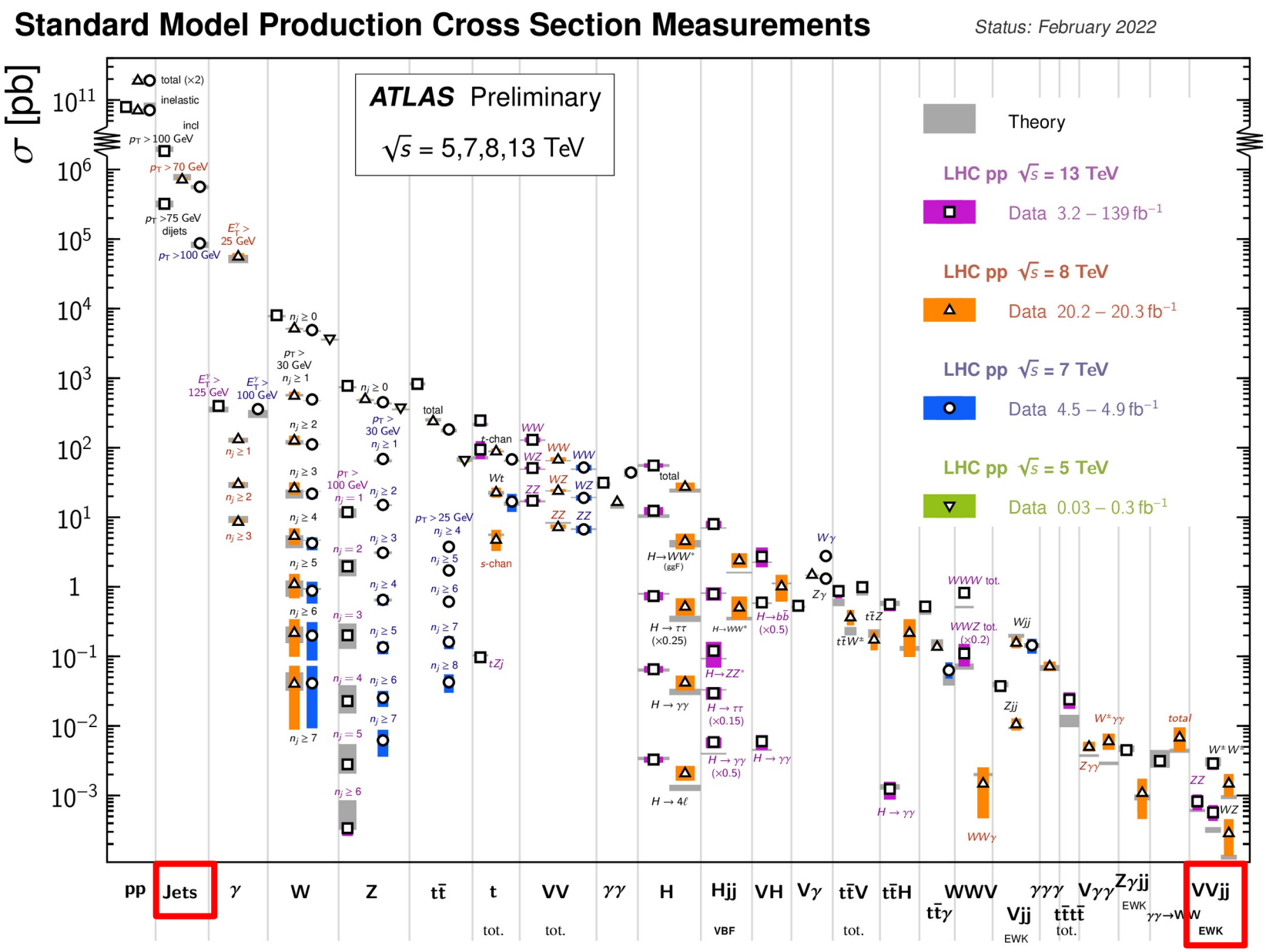
ATLAS

CMS





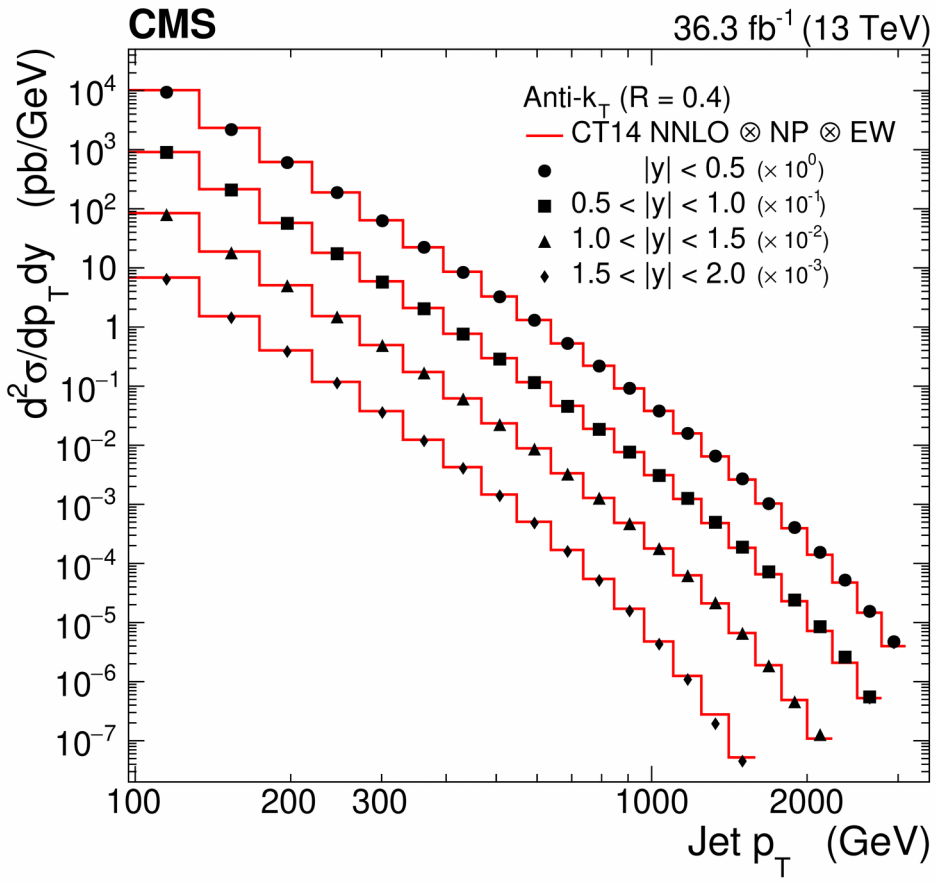
Exploring 9 Orders of Magnitude in Cross Section

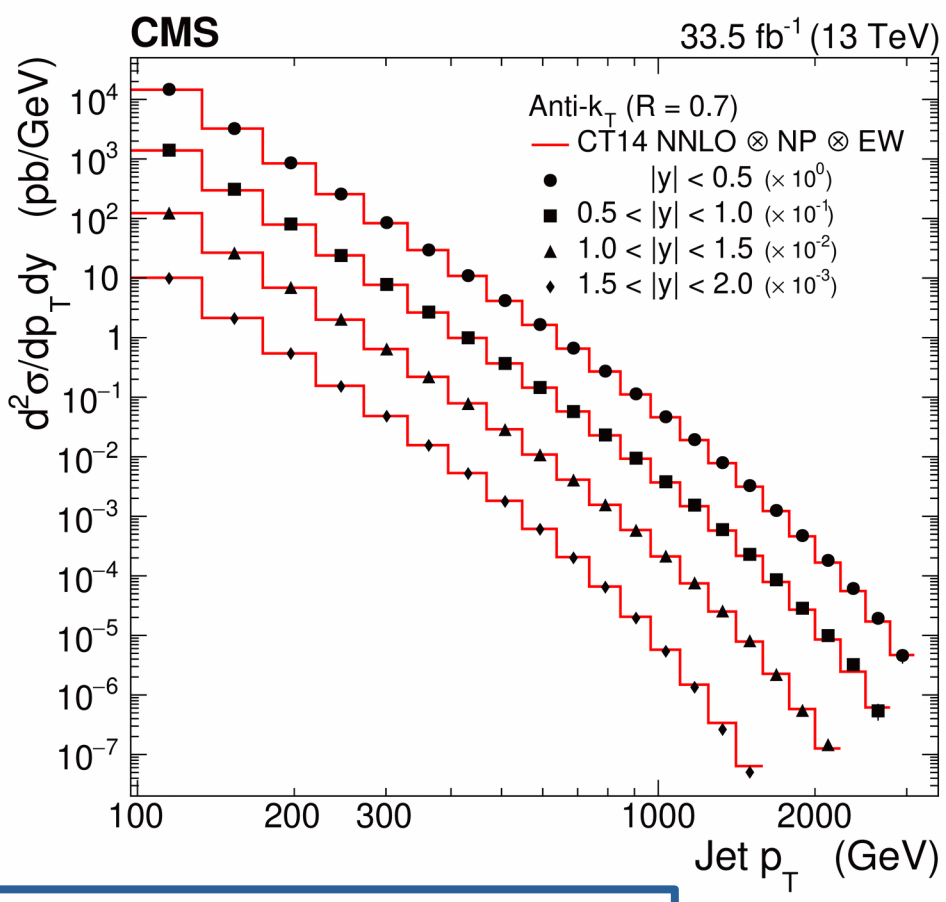


Inclusive Jet Cross Section

JHEP 02 (2022) 142

- key to test QCD at the highest achievable energy scales
  - double-differential measurements of R=0.4/0.7 anti-k_T jet production





high p_T: predictions slightly too low/high in central/forward region

generally very good agreement

Inclusive Jet Cross Section

JHEP 02 (2022) 142

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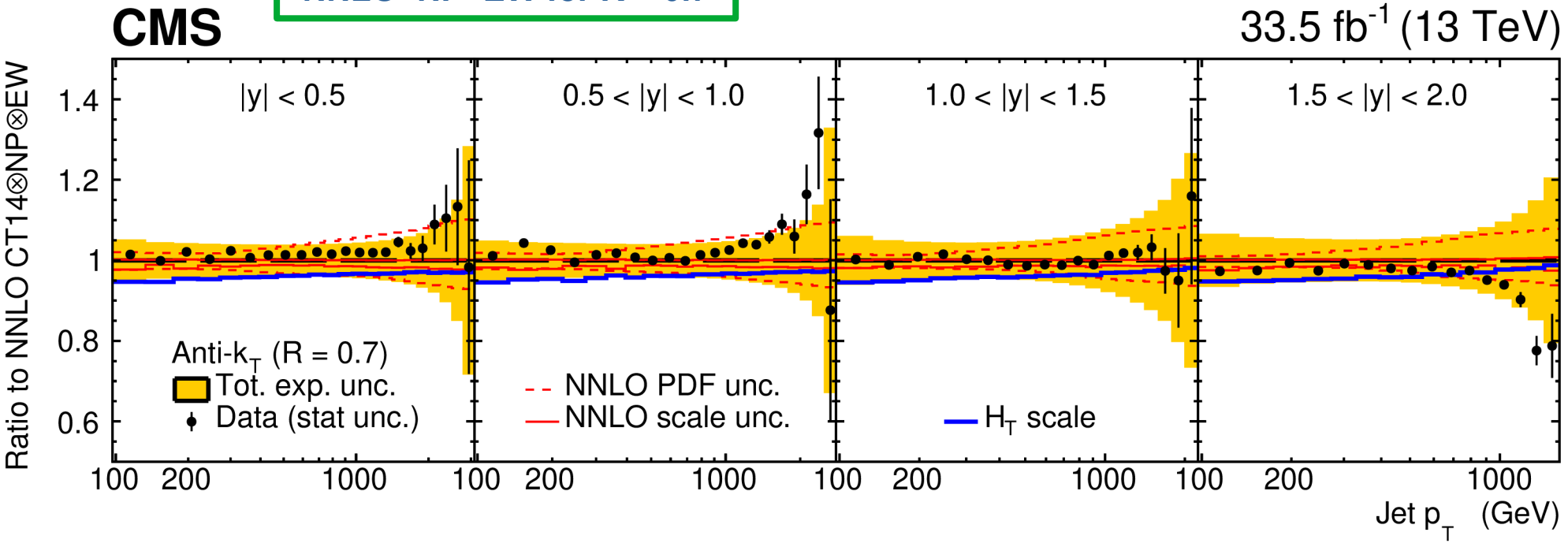
zooming in:
NNLO+NP+EW for R = 0.7



- agreement worsen using H_T as scale instead of jet p_T
- large PDF uncertainties indicate sensitivity to high-x gluon PDF

Inclusive Jet Cross Section

JHEP 02 (2022) 142

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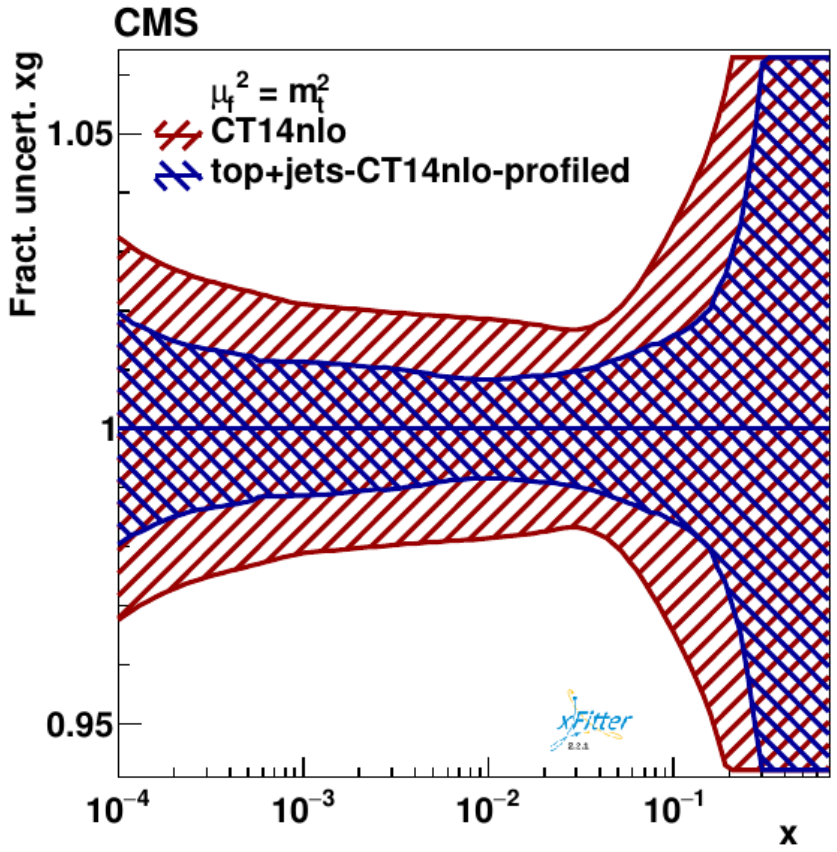
- QCD analysis at NLO of
  - R=0.7 jet cross sections
  - 3-dimensional $t\bar{t}$ cross section from CMS
  - charged- and neutral-current DIS cross sections of HERA

$\alpha_s(m_Z) = 0.1188 \pm 0.0031$

$m_{top}^{pole} = 170.4 \pm 0.6$ GeV



significantly improved top mass and gluon PDF

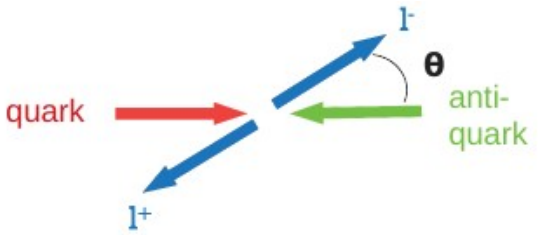
Forward-Backward Asymmetry in Drell-Yan

arXiv:2202.12327 [hep-ex]

- stringent test of V-A of electroweak sector

$$A_{FB} = (N(\cos\theta_{l^-} > 0) - N(\cos\theta_{l^-} < 0)) / (N(\cos\theta_{l^-} > 0) + N(\cos\theta_{l^-} < 0))$$

forward configuration:



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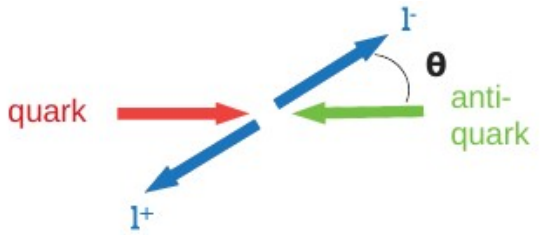
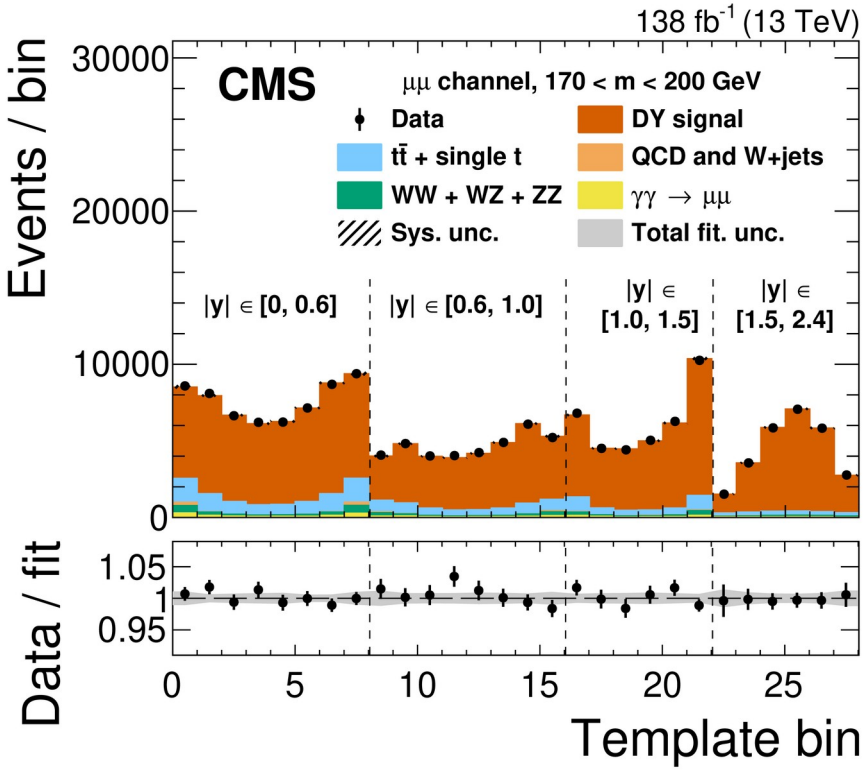


- extract A_{FB} from a template fit in bins of lepton pair rapidity |y| and cos θ

$$\frac{d\sigma}{d\cos\theta} \propto \frac{3}{8}\left[1 + \cos^2\theta + \frac{A_0}{2}(1 - 3\cos^2\theta) + A_4\cos\theta\right]$$



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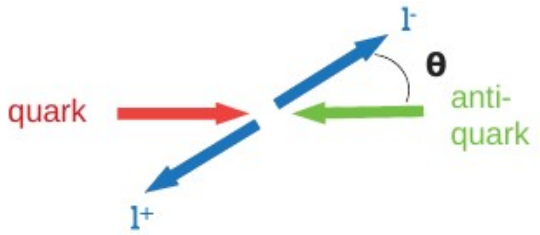

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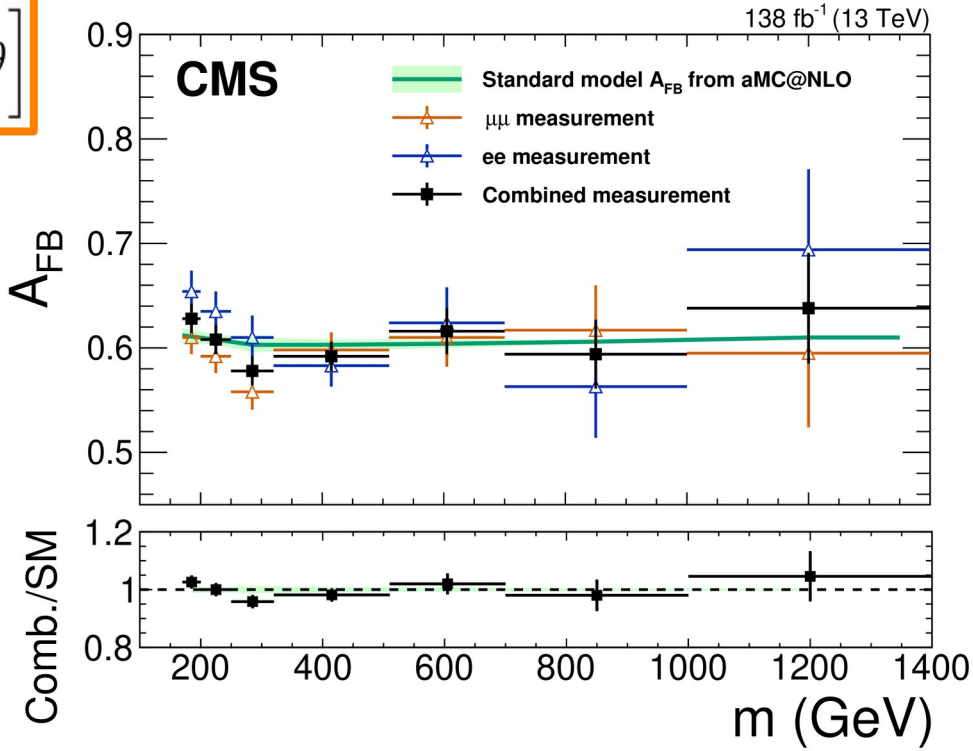

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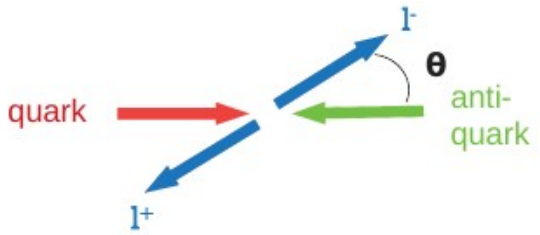

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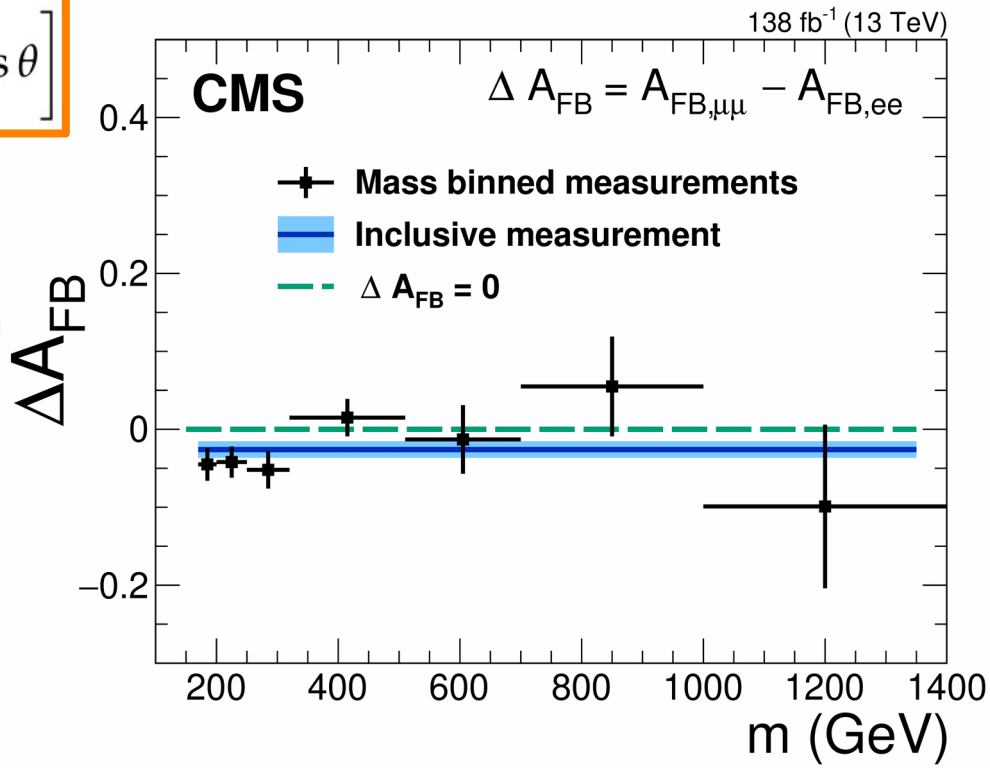
- split between electron and muon to test lepton flavor universality:
  - 2.4 SD different from 0



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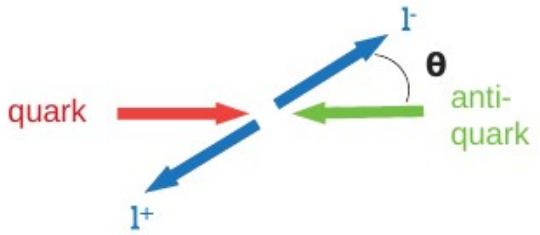

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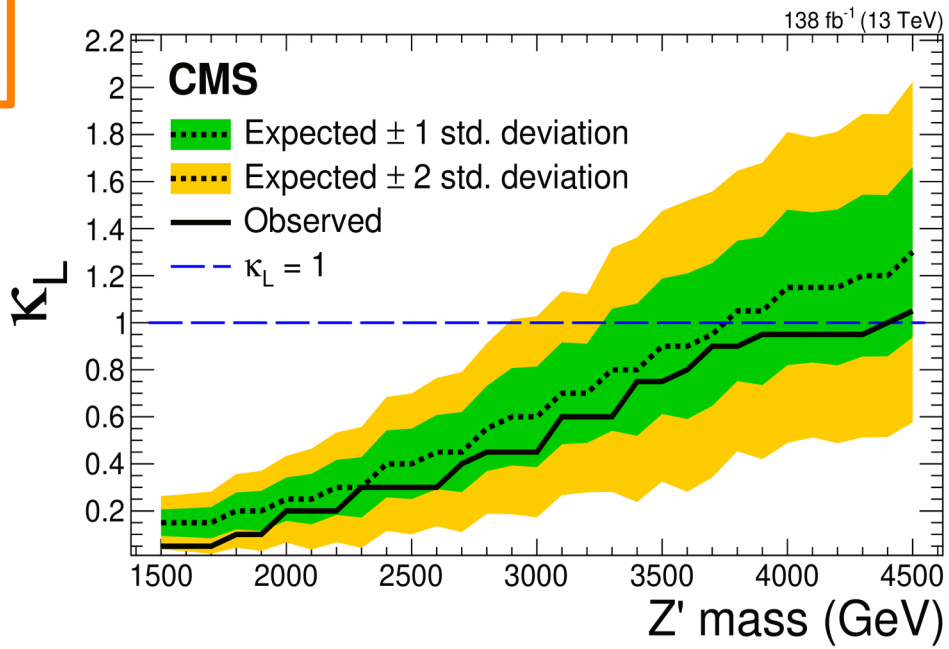
- combined A_{FB} in sync with SM expectation
- split between electron and muon to test lepton flavor universality:
  - 2.4 SD different from 0
- complementary sensitivity to new Z':
  - lower mass limit of 4.4 TeV

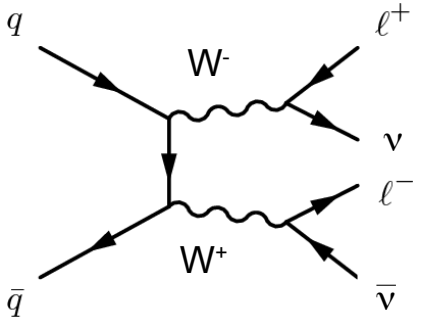


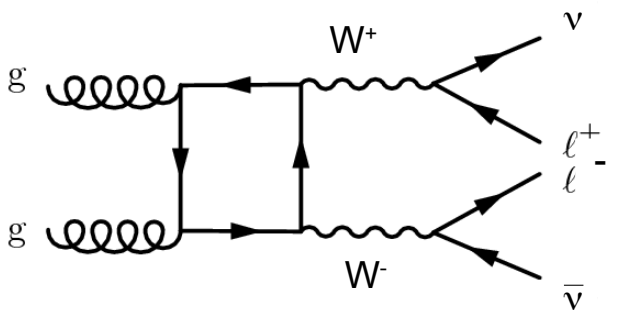
powerful probe of BSM physics

Diboson Production in BSM Phase Space

ATLAS-CONF-2022-011

- no direct link between searches and SMP measurements: control regions used to derive adhoc scale factors from data
- novel approach by ATLAS: unfolded particle-level measurements in BSM (here SUSY) associated topologies





$m_{eu} > 100$ GeV
$60 < E_t^{miss}/\text{GeV} < 100$
$60 < m_{T2}/\text{GeV} < 100$

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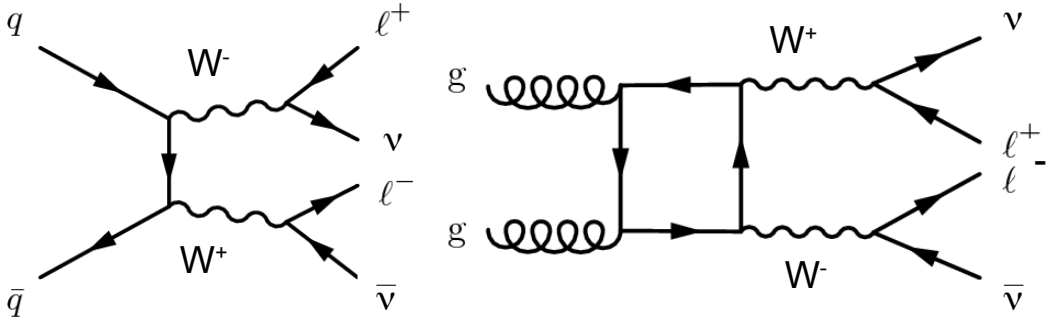

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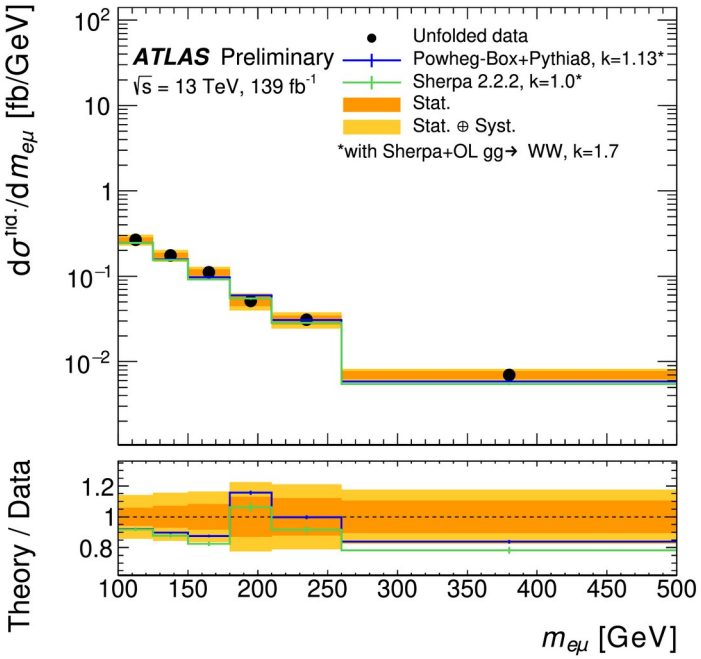
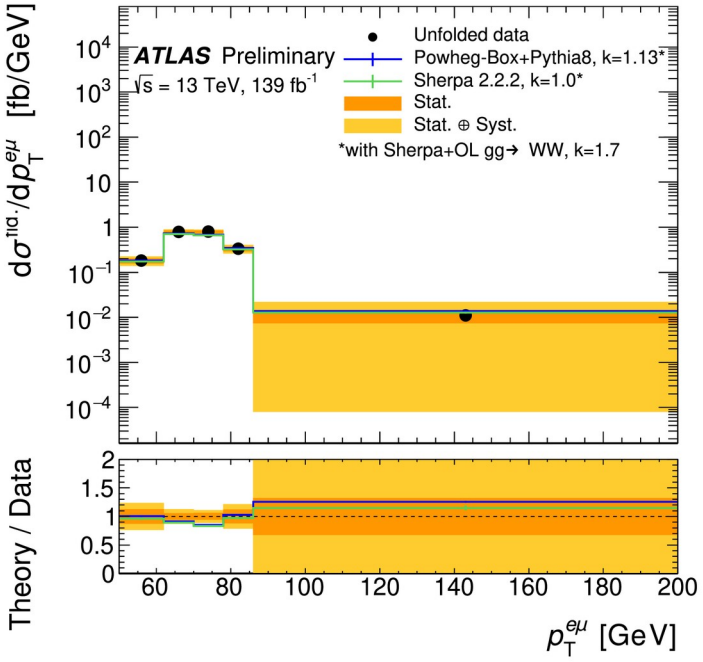
energy related observables generally well described





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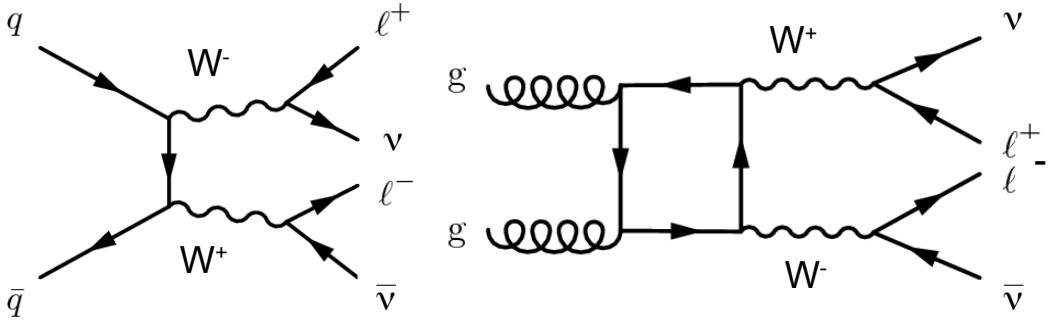

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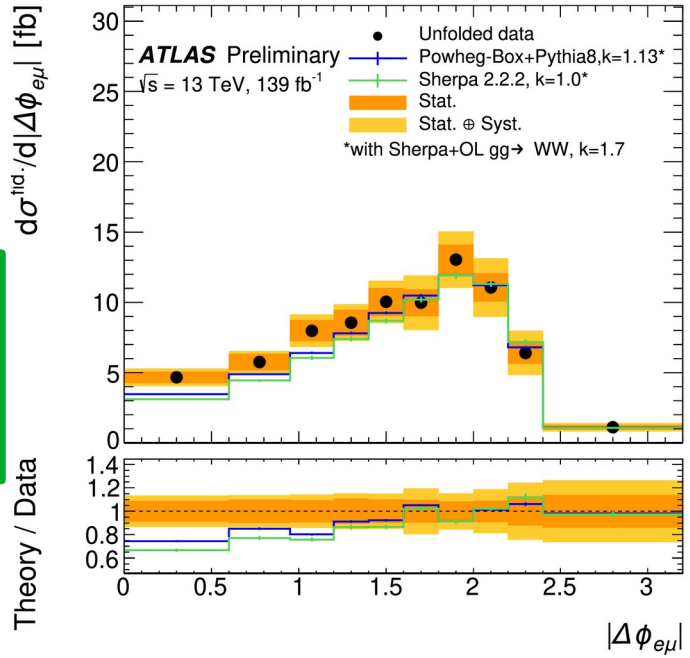
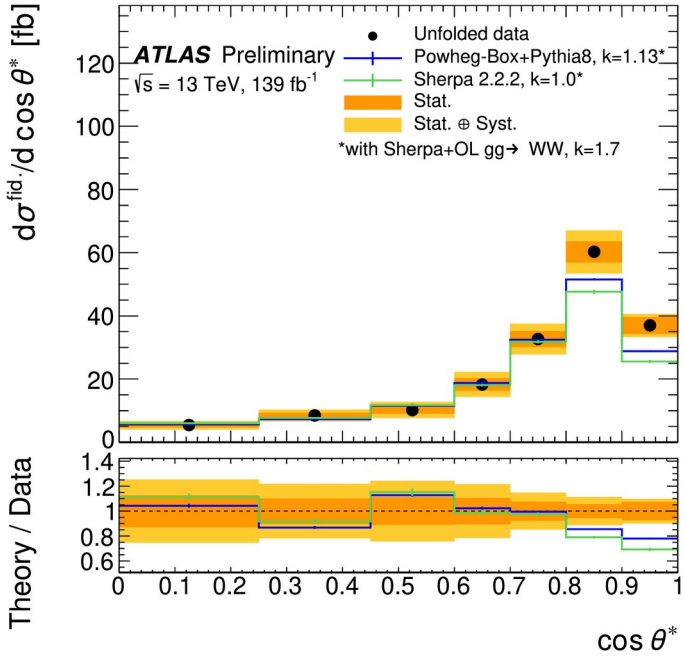
region of small azimuthal angles and large rapidity differences underestimated





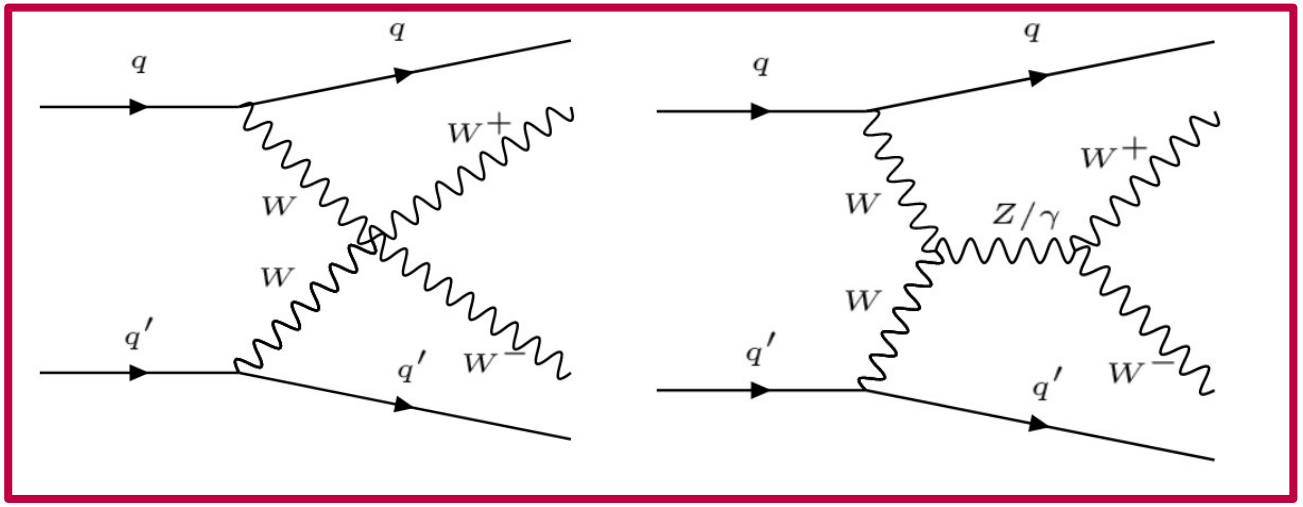
Observation of Electroweak W^+W^- Boson Production

CMS-PAS-SMP-21-001

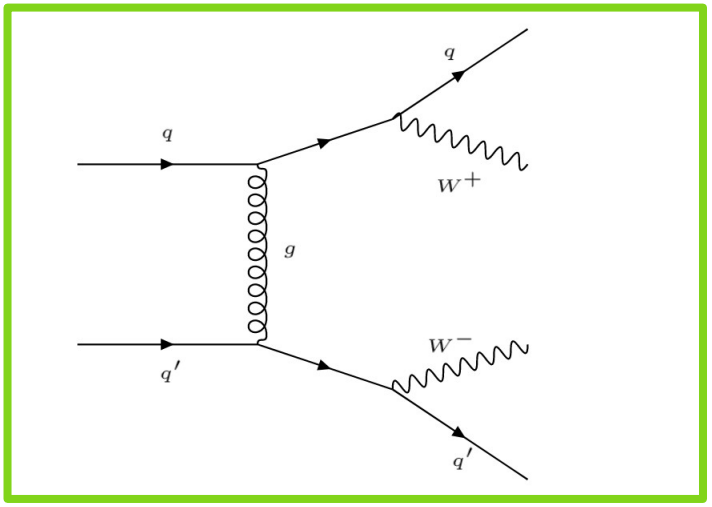
- first observation of $W^\pm W^\pm$ using 2016 data only
  - W^+W^- more challenging due to large top background
- electroweak production characterized by large

  separation in jet pseudorapidity and high invariant jet mass

electroweak production



strong production



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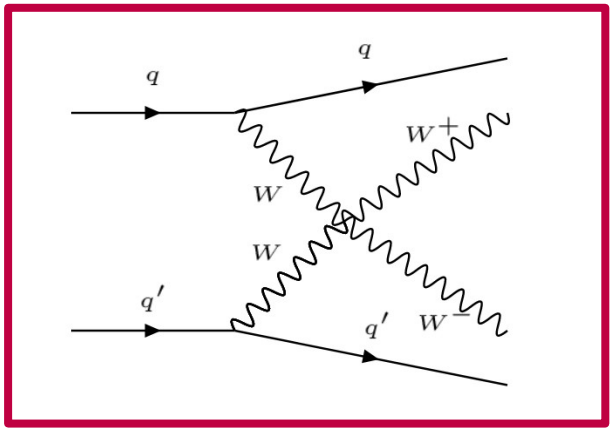

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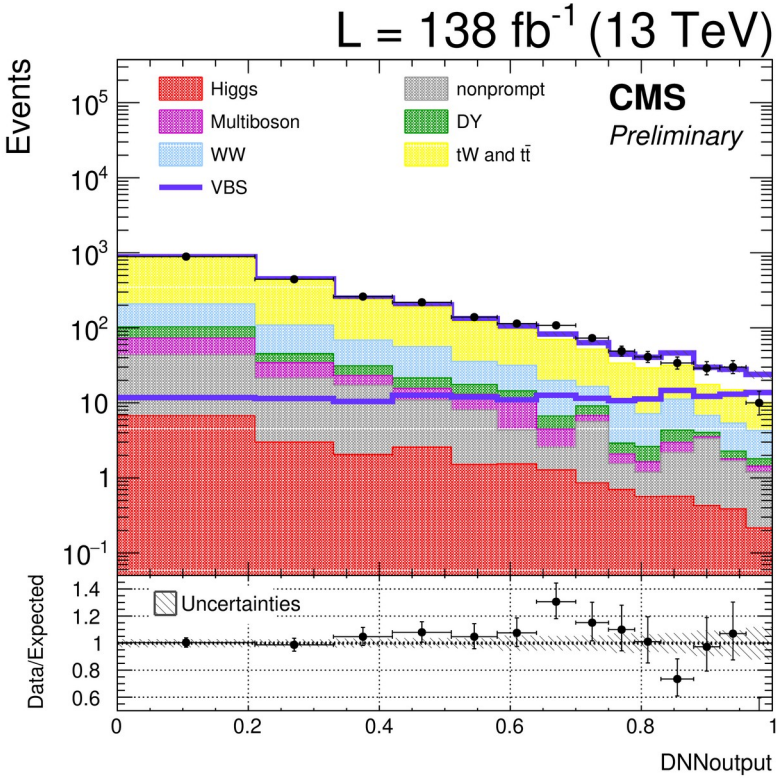
  - W^+W^- more challenging due to large top background
- electroweak production characterized by large separation in jet pseudorapidity and high invariant jet mass

- $m_{jj}/\Delta\eta_{jj}$ bins for ee/μμ, DNN discriminant for eμ

$$\sigma_{fid}^{obs} = 10.2 \pm 2.0 \text{ fb}$$
$$\sigma_{fid}^{theo} = 9.1 \pm 0.6 \text{ fb}$$

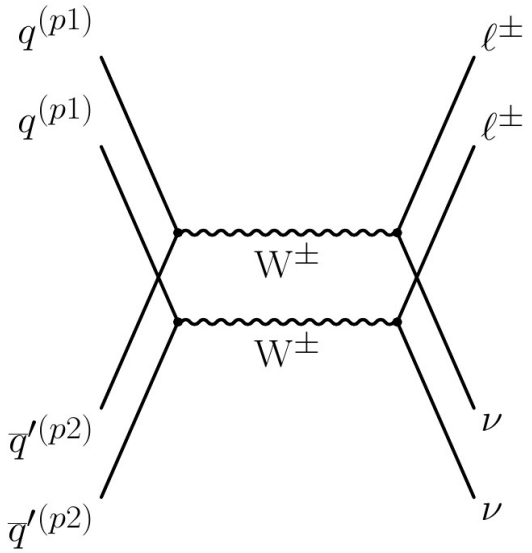
- first observation with 5.6 (5.2) SD obs. (exp.)
  - dominated by statistical uncertainty
  - sizable systematic uncertainty from QCD scale choice for background

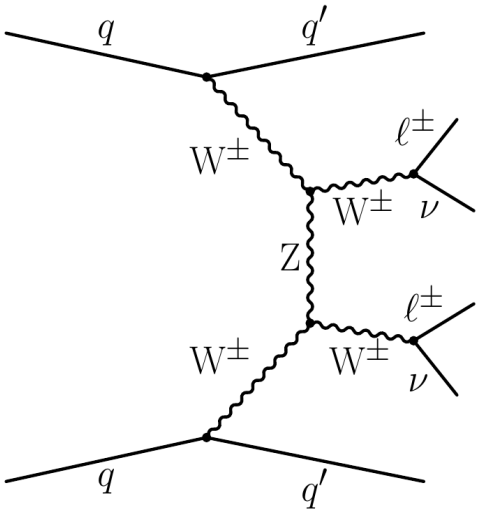


Observation of $W^{\pm}W^{\pm}$ from Double-Parton Scattering

CMS-PAS-SMP-21-013

- DPS allows studying correlation of partons inside same proton





DPS vs SPS

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CMS-PAS-SMP-21-013

DPS vs SPS

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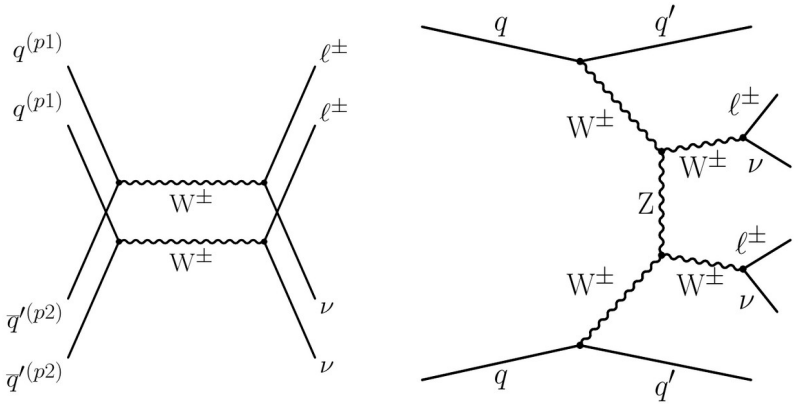
- approximately described by

$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}, \quad (n(A=b)=1:2)$$

  - σ_{eff} ~ (transverse inter-parton distance)^2



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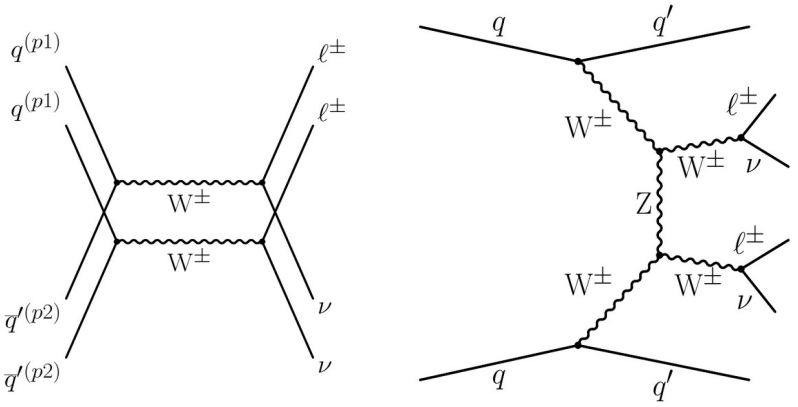
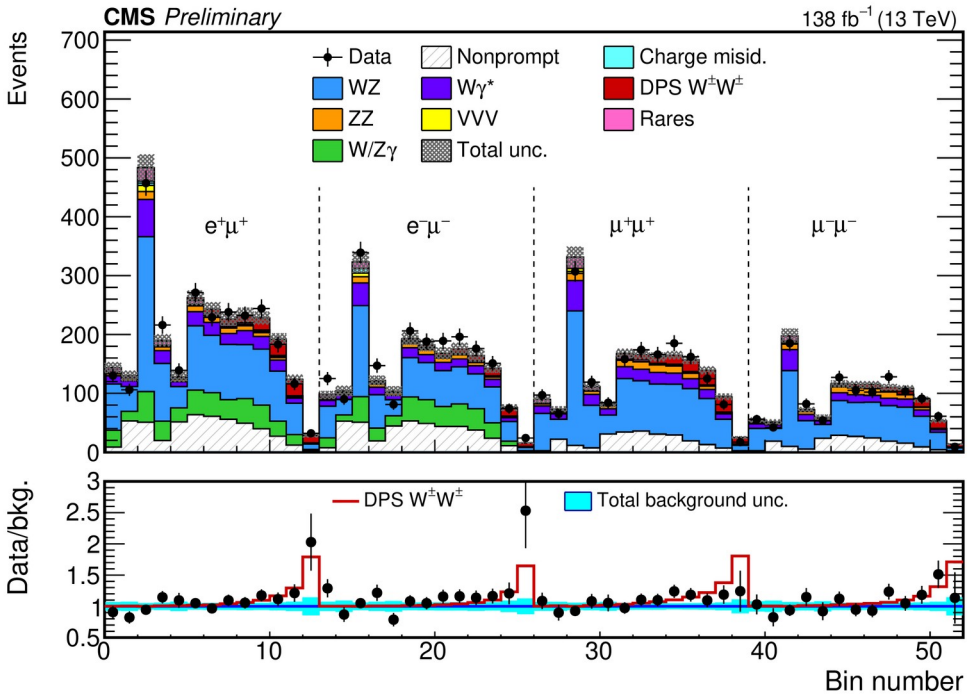


- two BDTs to discriminate against WZ and non-prompt lepton background



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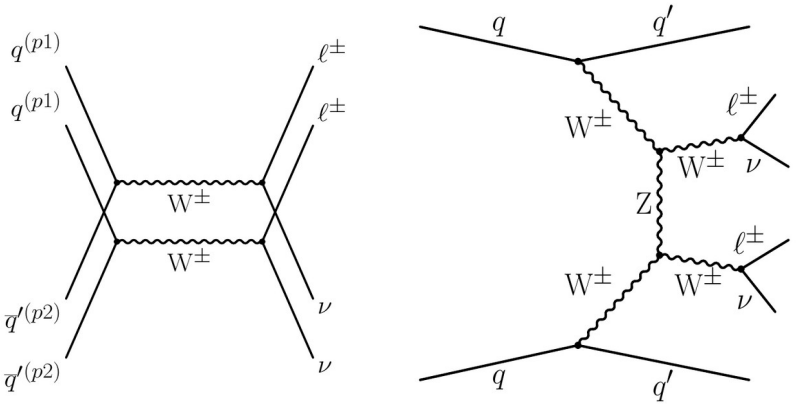


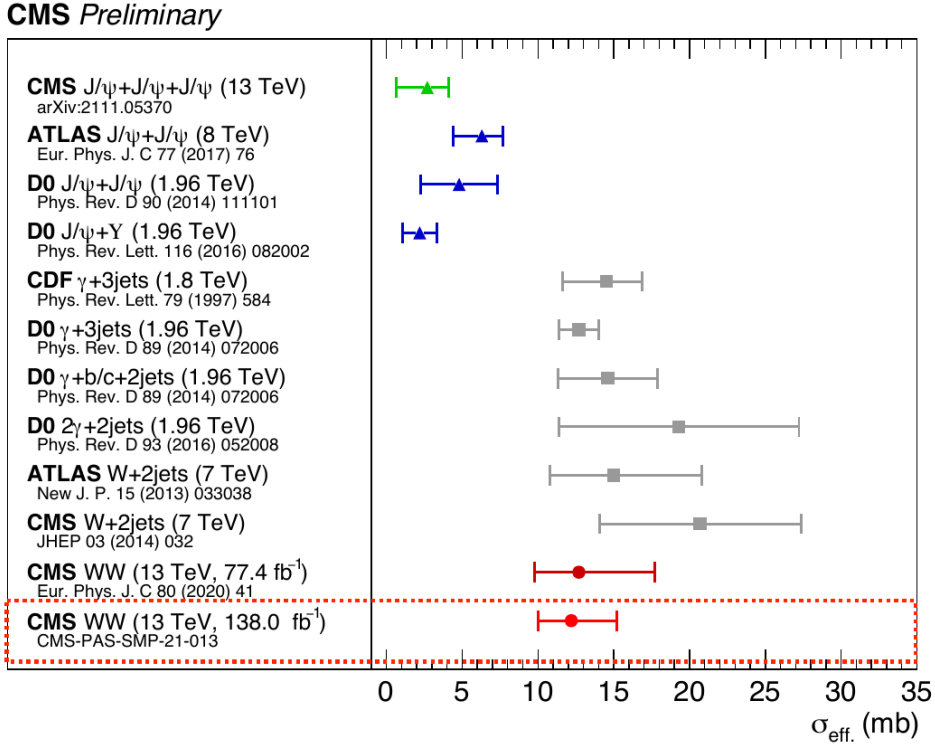
- two BDTs to discriminate against WZ and non-prompt lepton background

- DPS with 6.2 SD observed

$$\sigma_{incl}^{DPS\ WW} = 0.16 \pm 0.02\ (stat) \pm 0.02\ (syst) \pm 0.02\ (model)\ pb$$

- effective cross section of 12.2 $^{+2.9}_{-2.2}$ mb in sync with vector boson results:

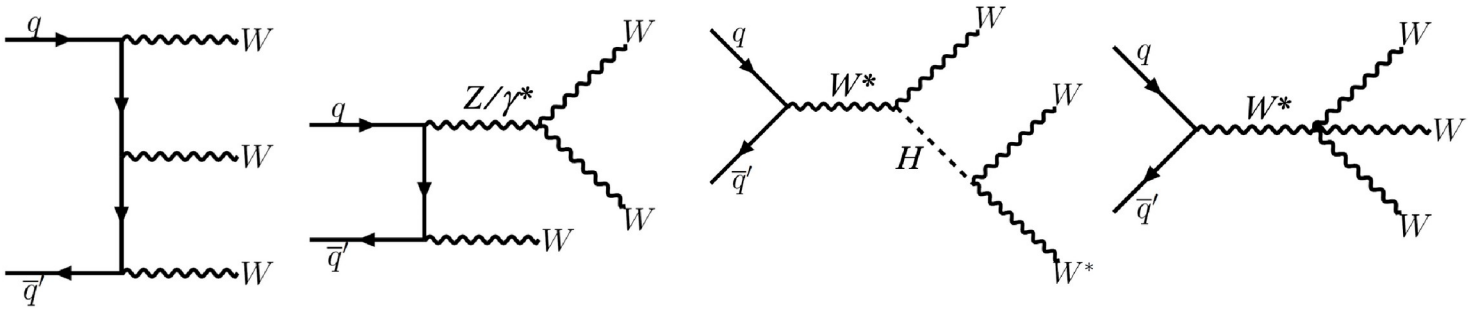
difference between $q\bar{q}$ and gg dominated processes



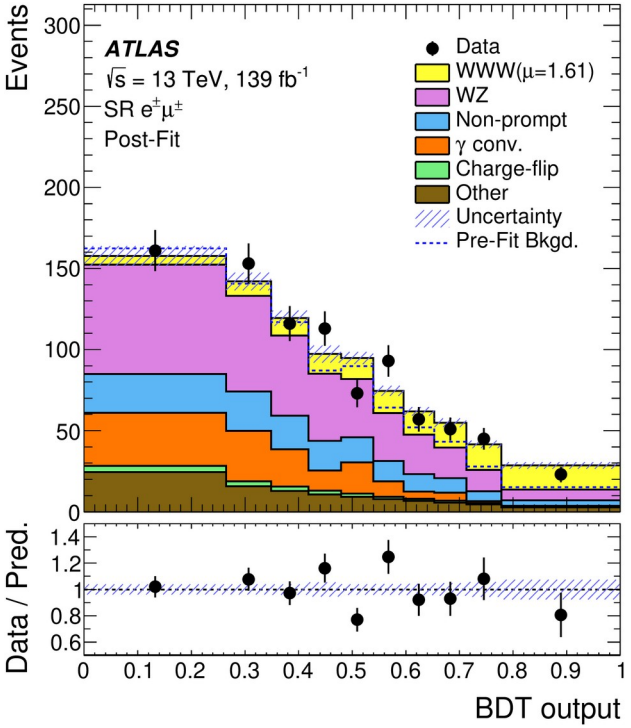
Observation of Tri-Boson Production

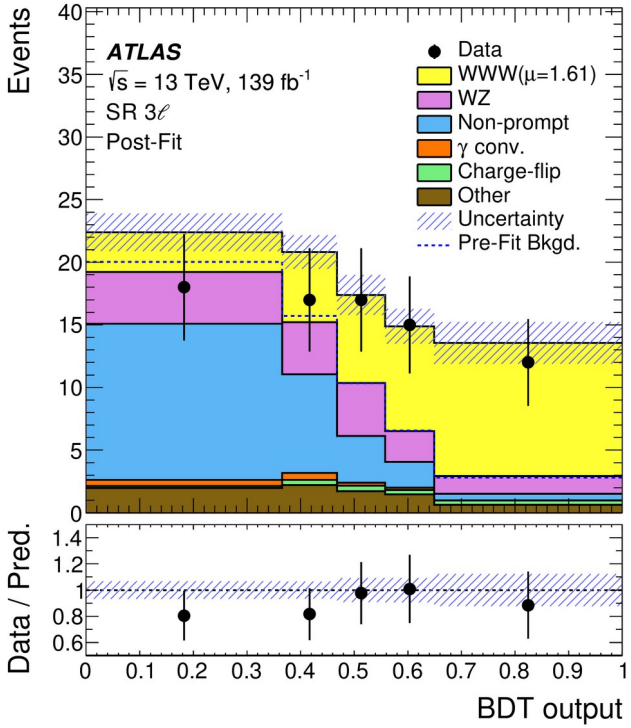
arXiv:2201.13045 [hep-ex]

- direct test of gauge boson self-interactions



- use BDT to enhance signal in 2l ($e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$) and 3l categories separately





μ(WWW) = 1.61 ± 0.25

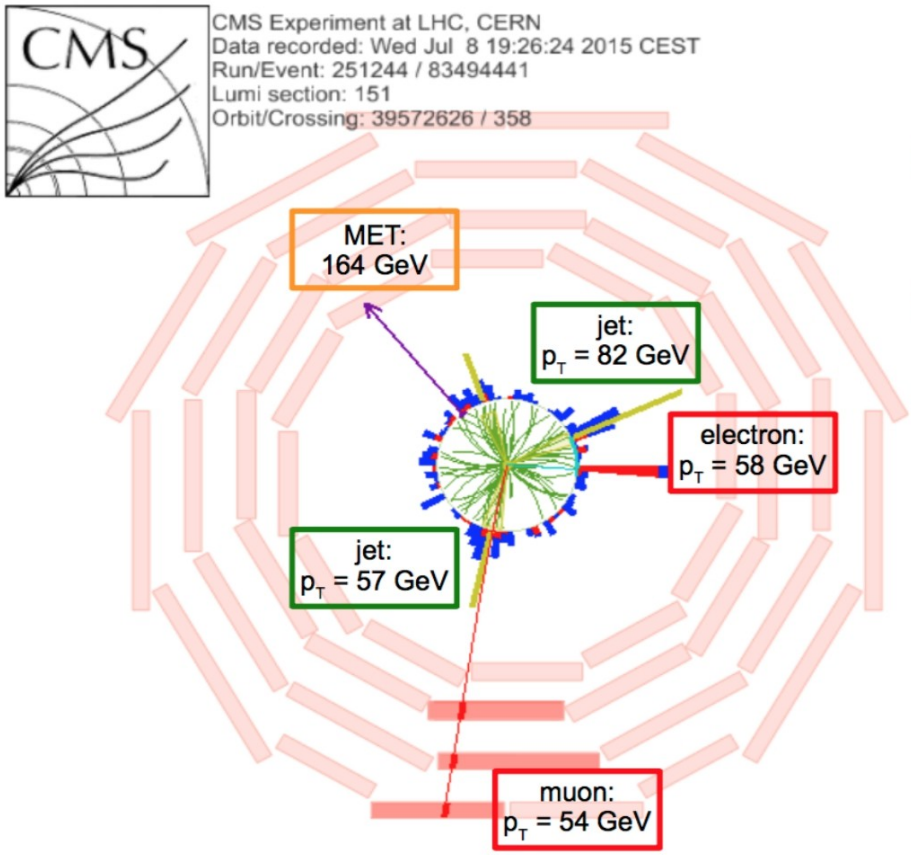
2.6 SD different from NLO prediction of 511 ± 18 fb

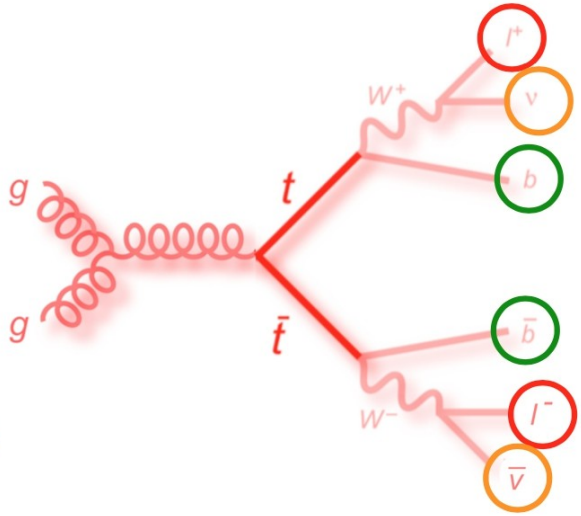
first observation of WWW

Differential Probe of $t\bar{t}$ Production

CMS-PAS-TOP-20-006

- variety of up to tripple-differential cross section measurements in dilepton final states
  - e.g. $p_{T\text{top}}$, $y_{t\bar{t}}$, $m_{t\bar{t}}$, $p_{T,t\bar{t}}$,...
- uncertainties halved compared to previous results





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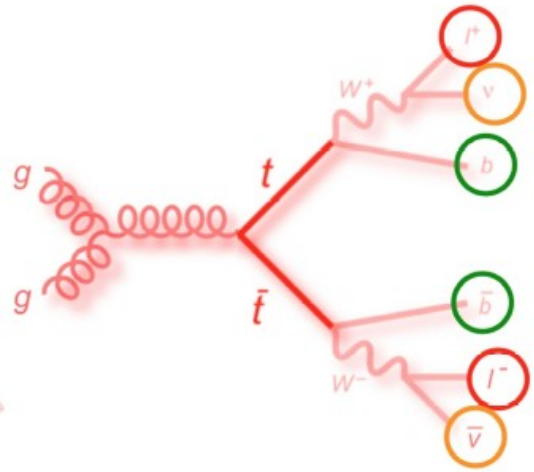
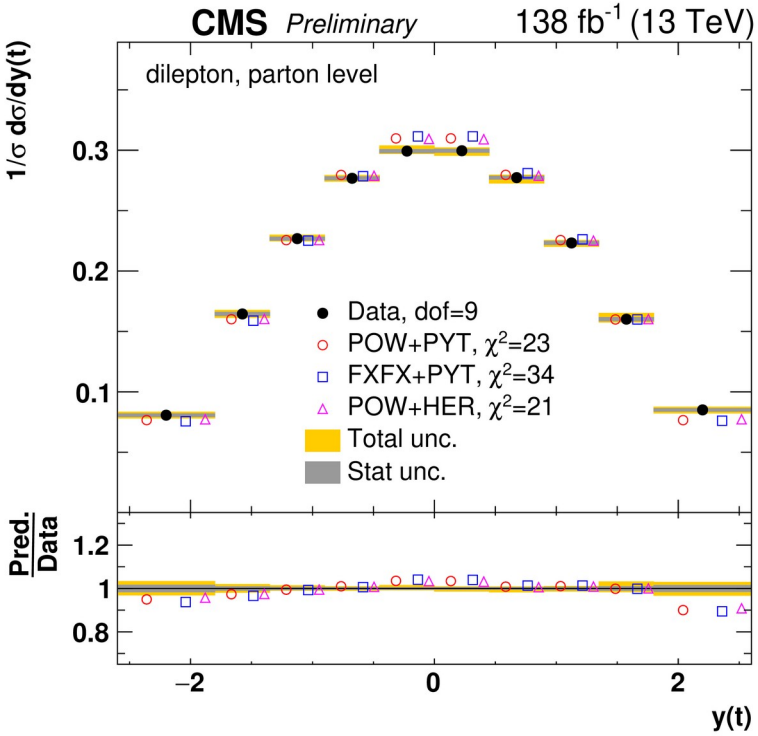


NLO predictions slightly too central



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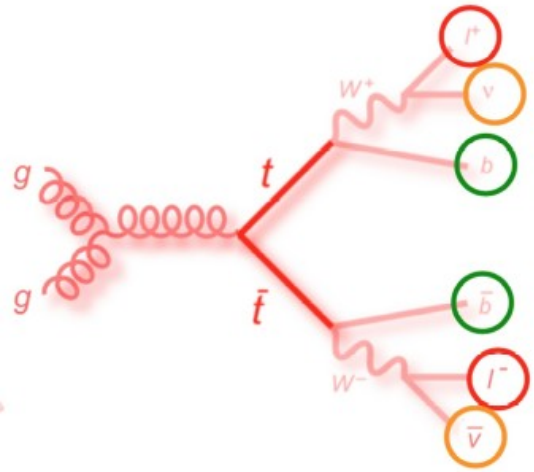
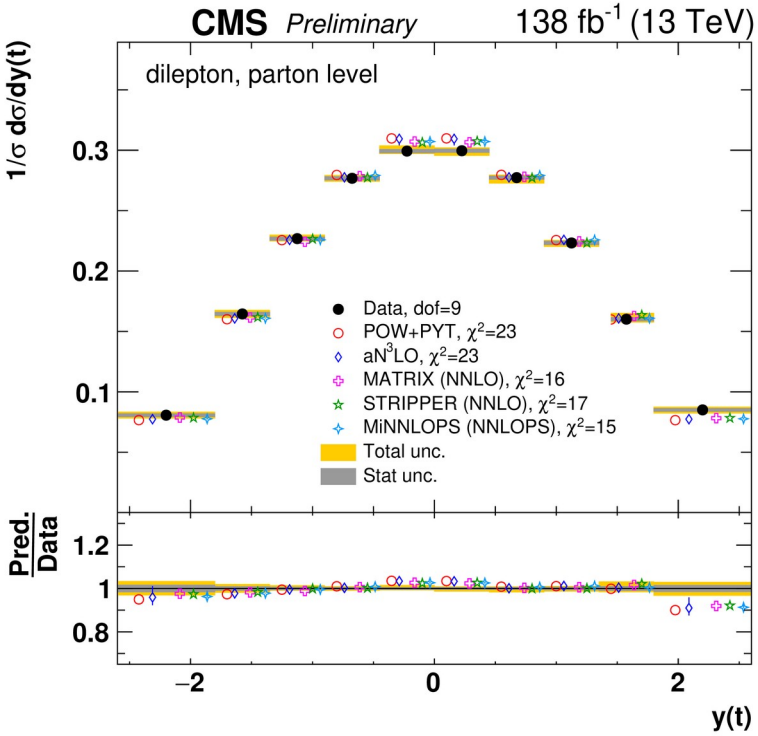


best described by MiNNLOPS



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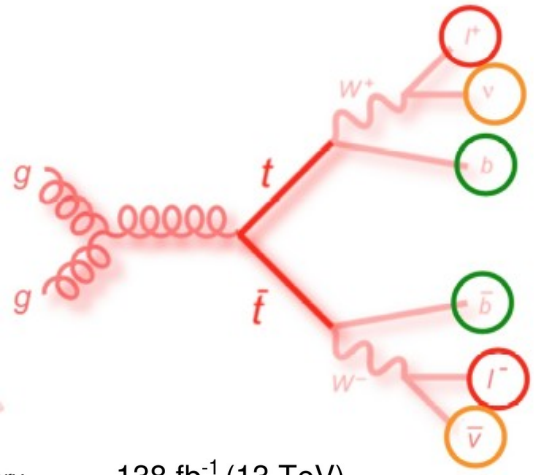

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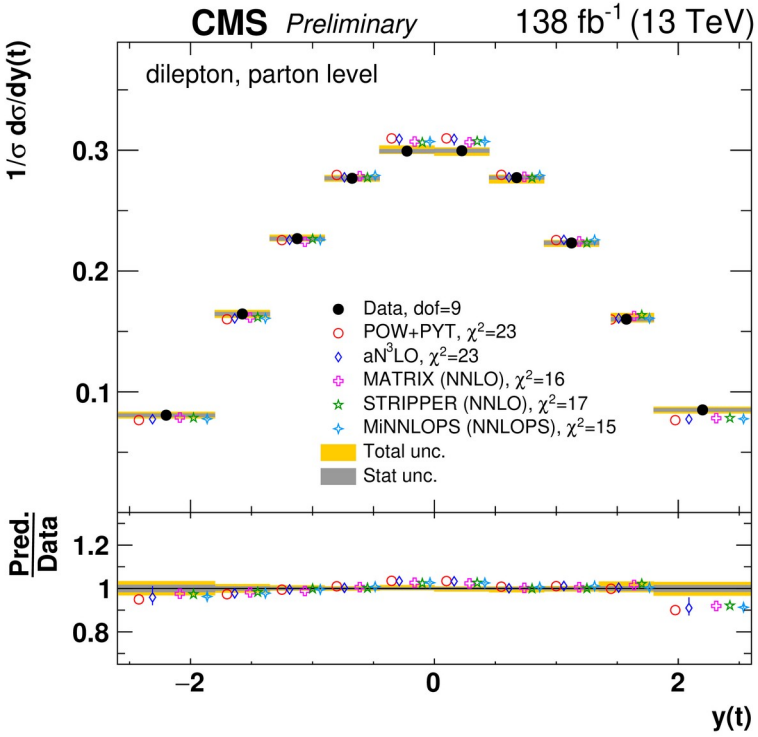

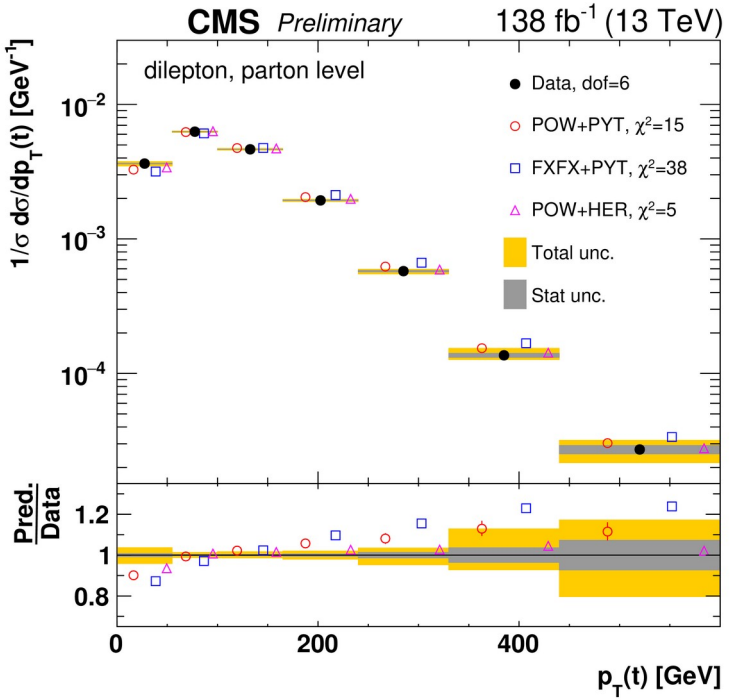

best description of top pT by Powheg+H7

MG5_aMCatNLO with add. jets at NLO worst

Differential Probe of $t\bar{t}$ Production

CMS-PAS-TOP-20-006

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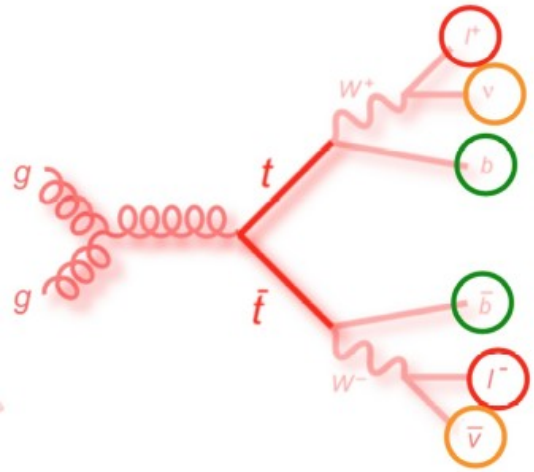

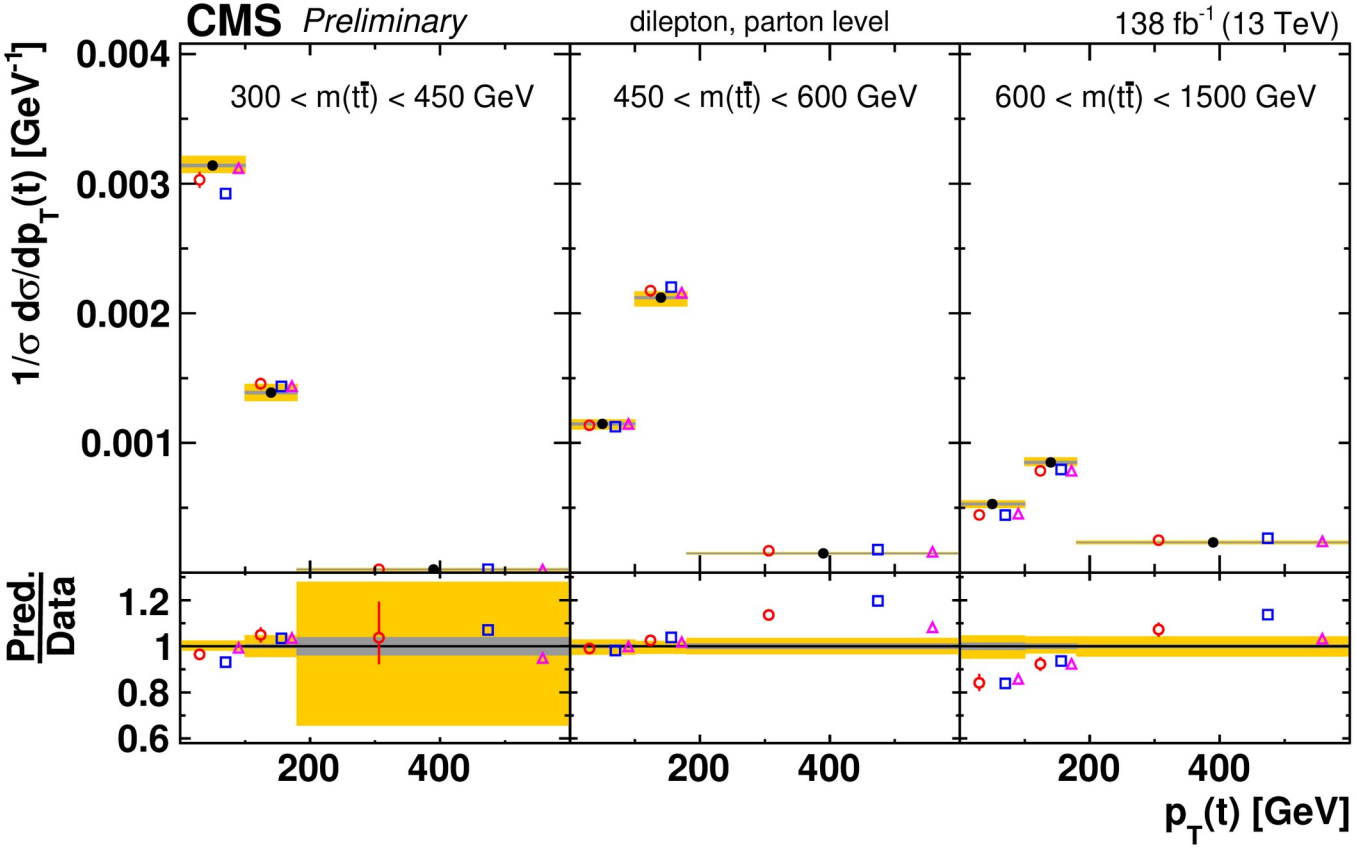

problem of top p_T modeling most pronounced at high $m_{t\bar{t}}$

Differential Probe of $t\bar{t}$ Production

CMS-PAS-TOP-20-006

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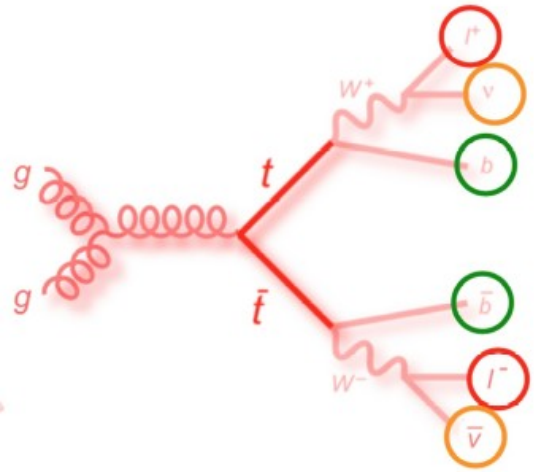
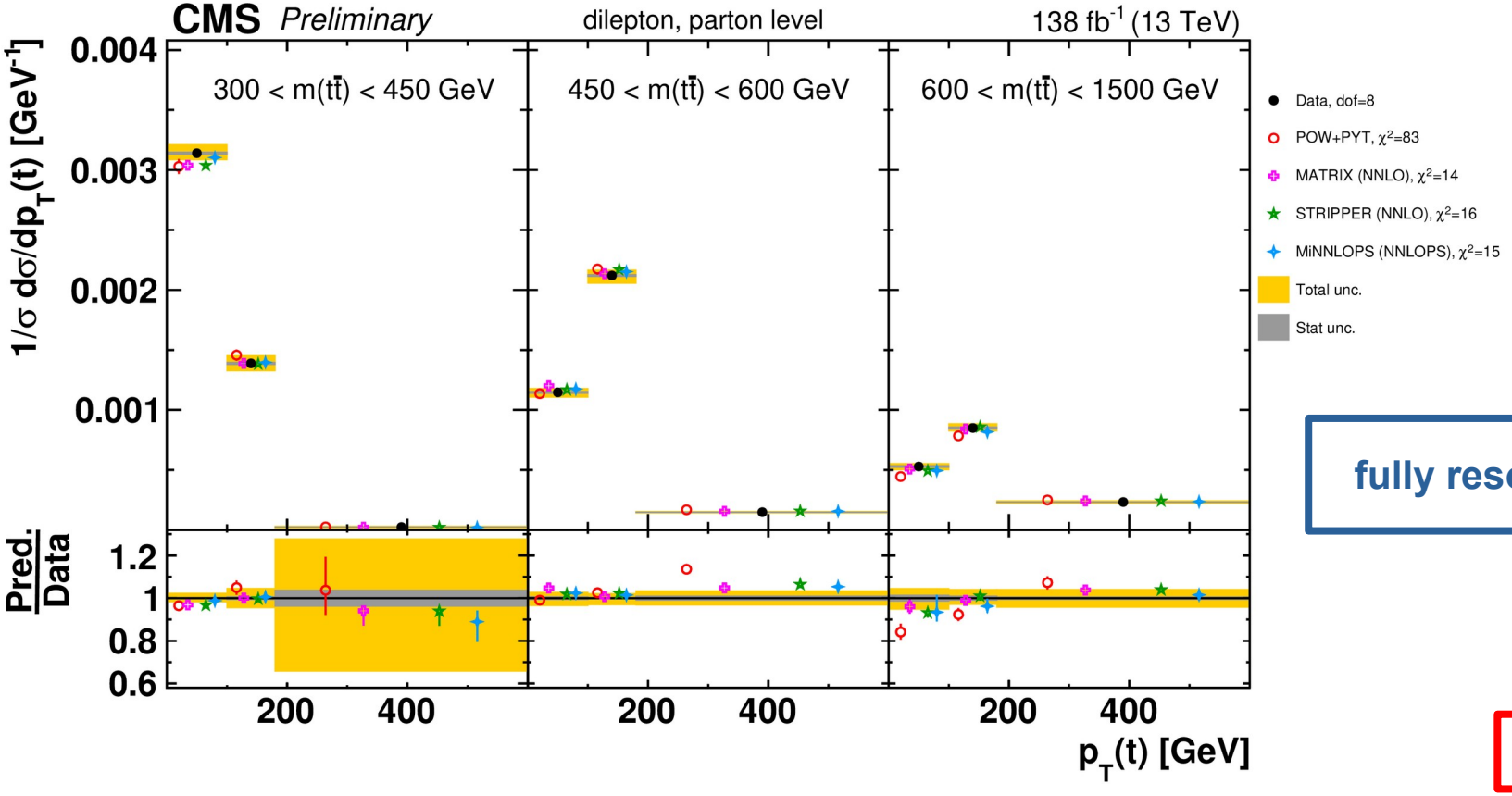




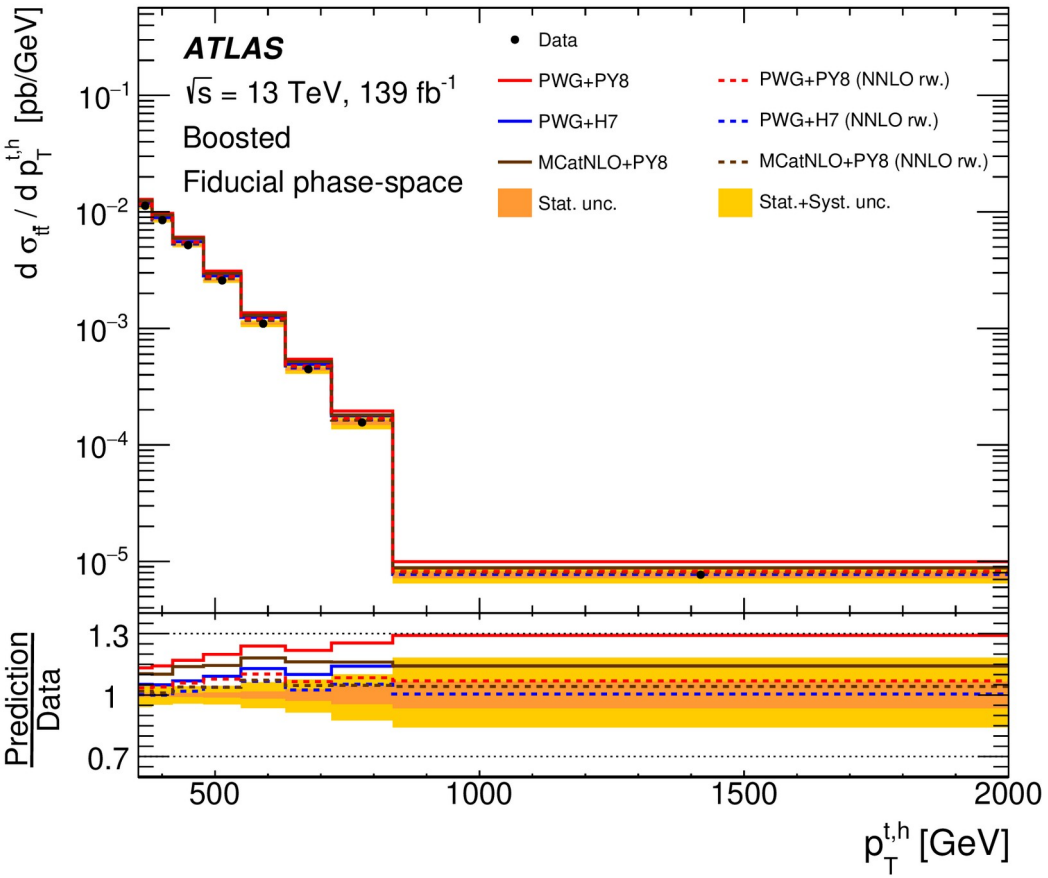
fully resolved at NNLO

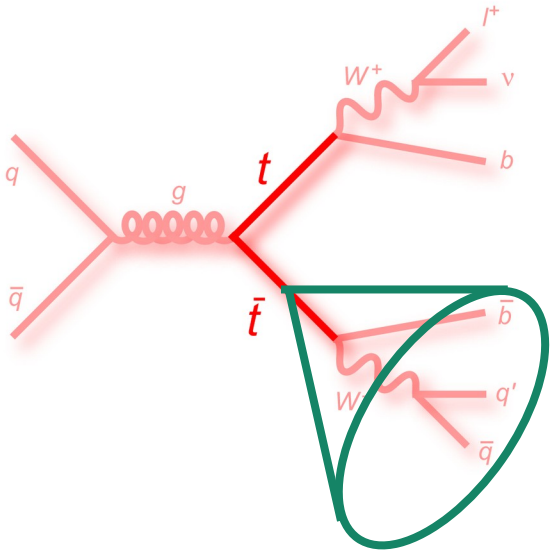
NNLO essential !

$t\bar{t}$ Production at Highest Energies

arXiv:2202.12134 [hep-ex]

- differential measurements probing boosted top quarks
  - reaching transverse momenta up to 2 TeV





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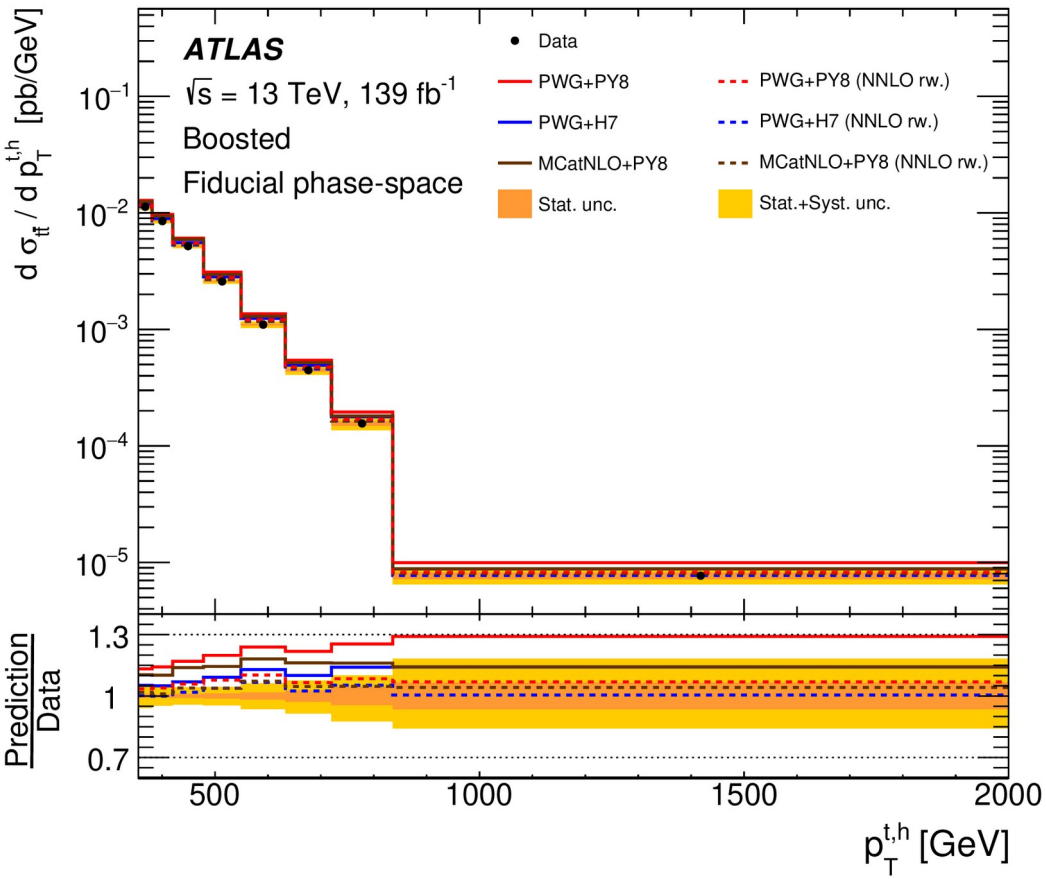

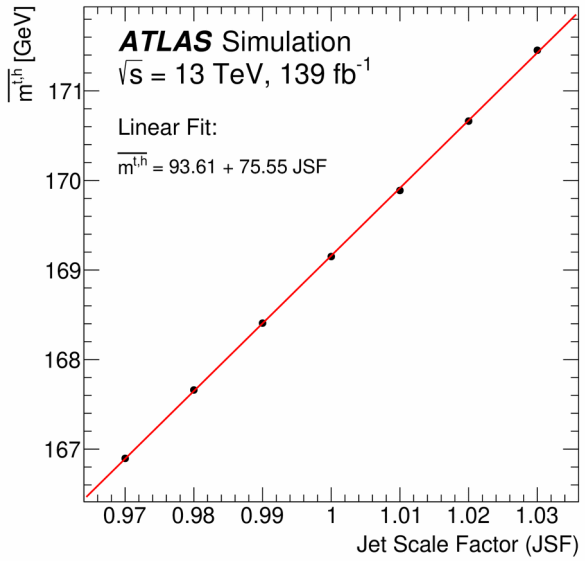

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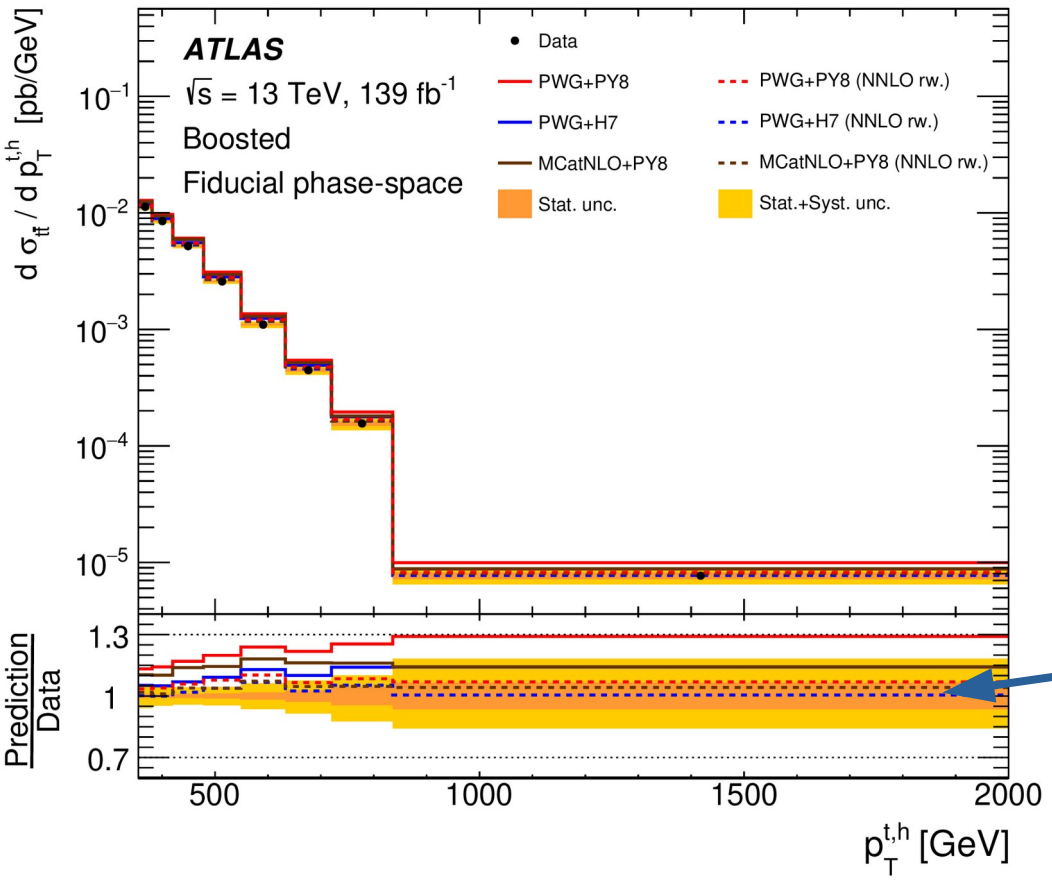
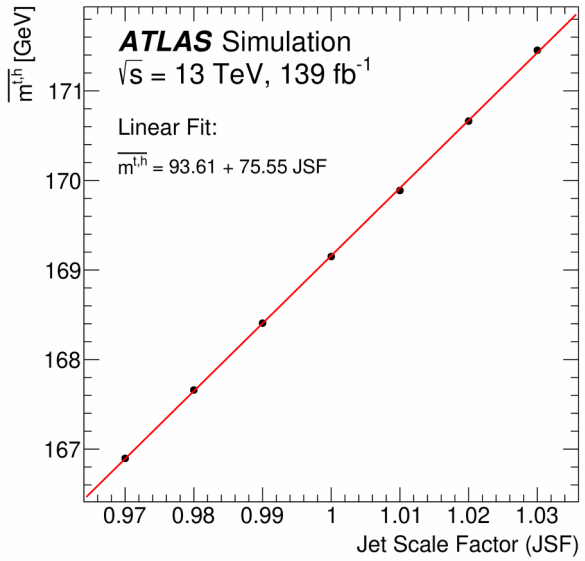


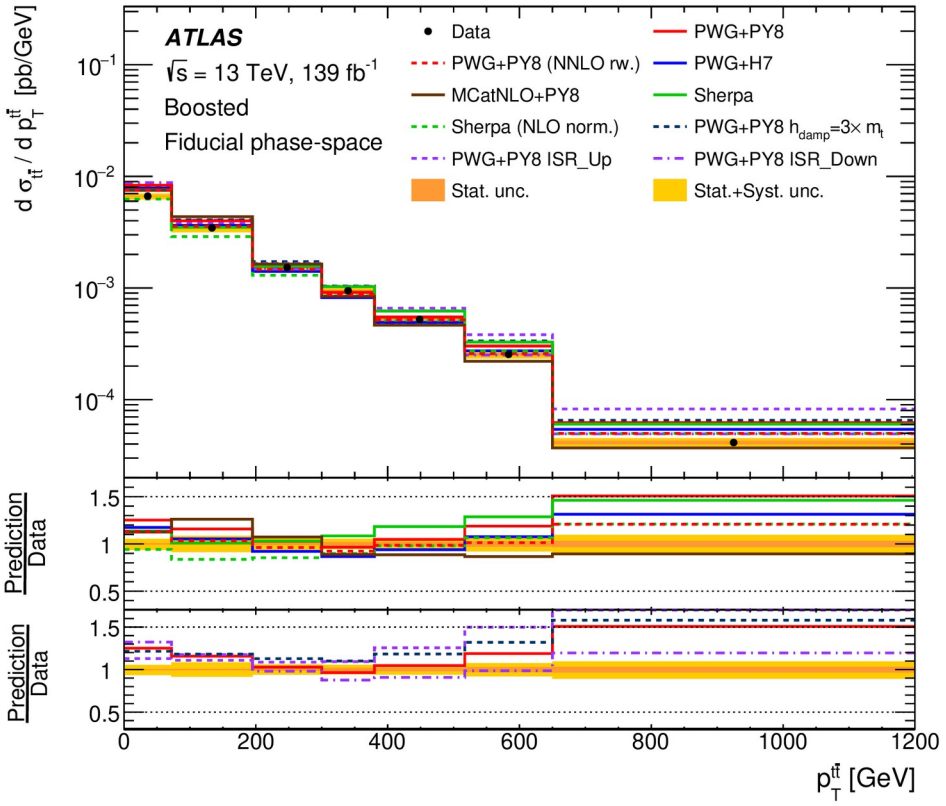


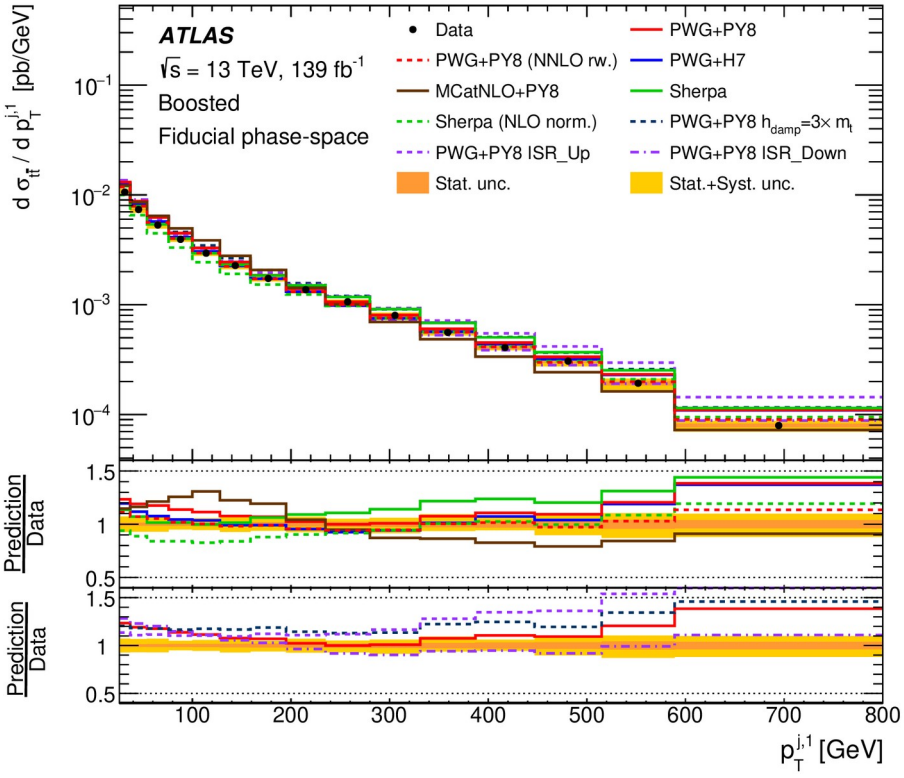
significantly improved performance through NNLO-based reweighting

$t\bar{t}$ Production at Highest Energies

arXiv:2202.12134 [hep-ex]

- differential measurements probing boosted top quarks
  - reaching transverse momenta up to 2 TeV
  - studying QCD radiation in boosted regime





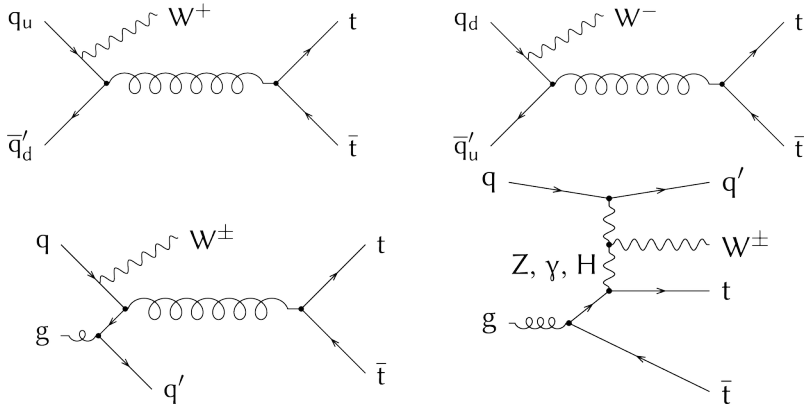
several predictions with significant discrepancies

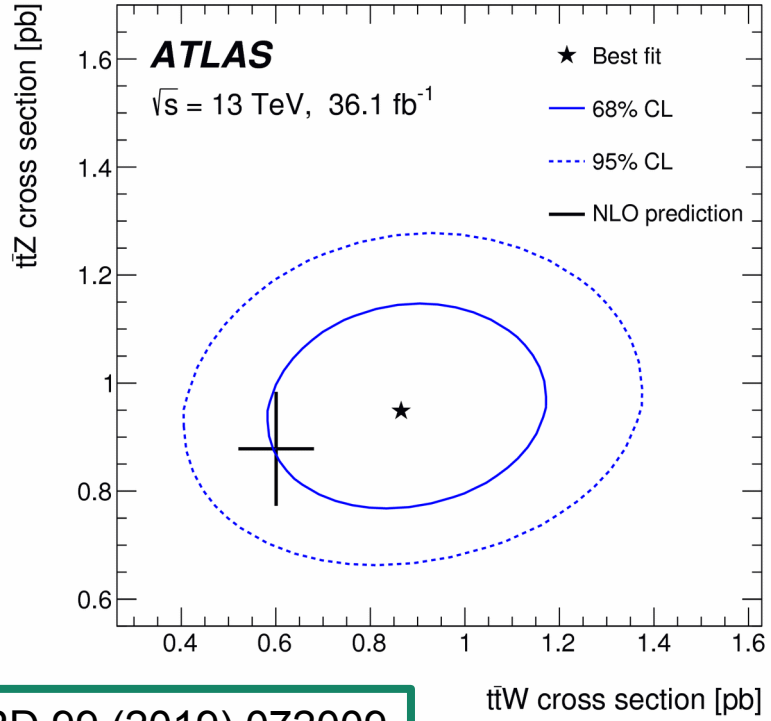
best results from Powheg+Pythia8 with reduced ISR

Understanding $t\bar{t}W$

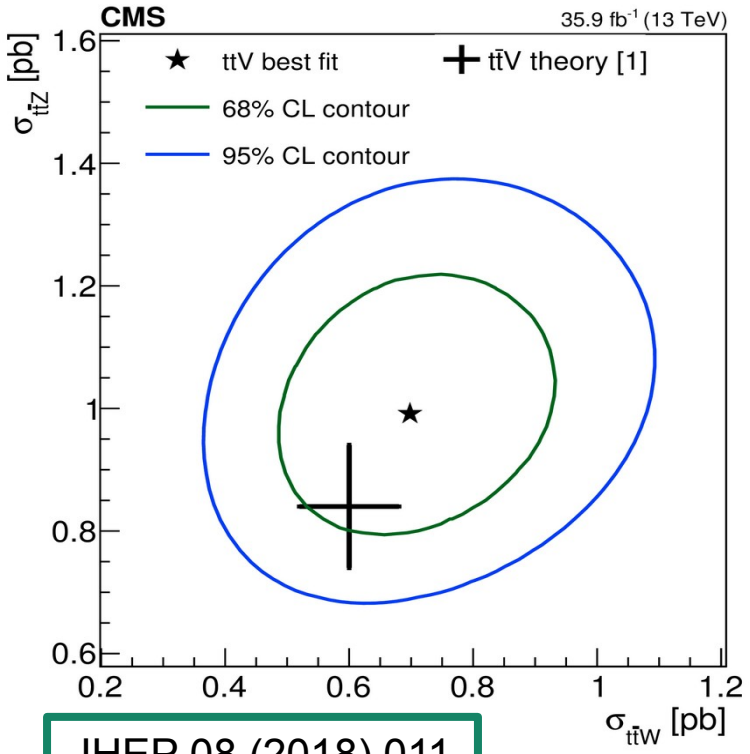
CMS-PAS-TOP-21-011

- $t\bar{t}W$ production dominated by $q\bar{q}$
- previous results above SM (but compatible)





PRD 99 (2019) 072009

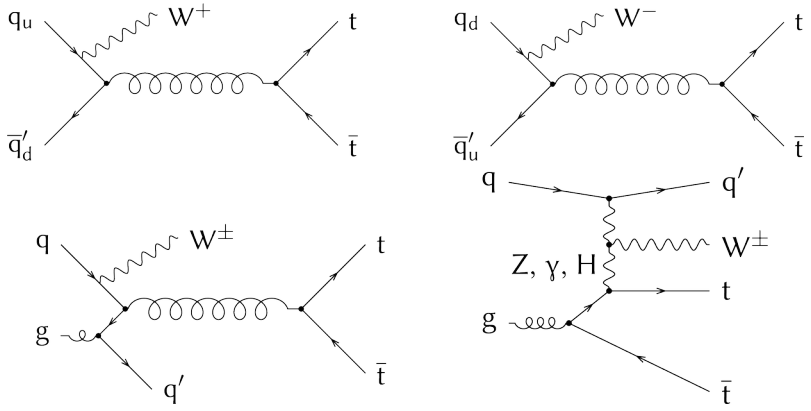


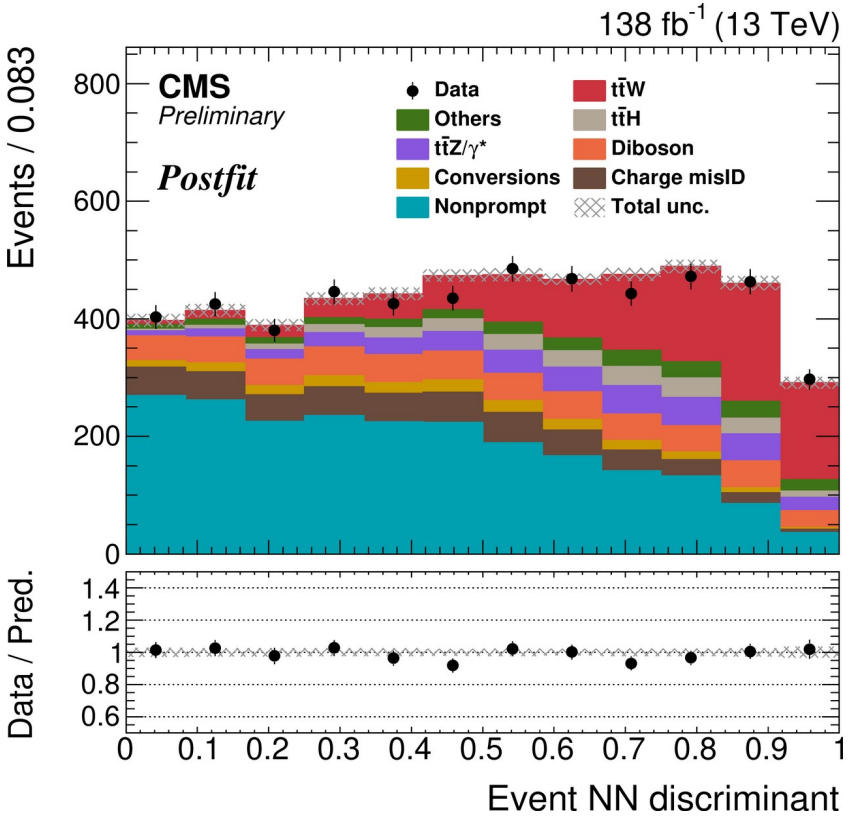
JHEP 08 (2018) 011

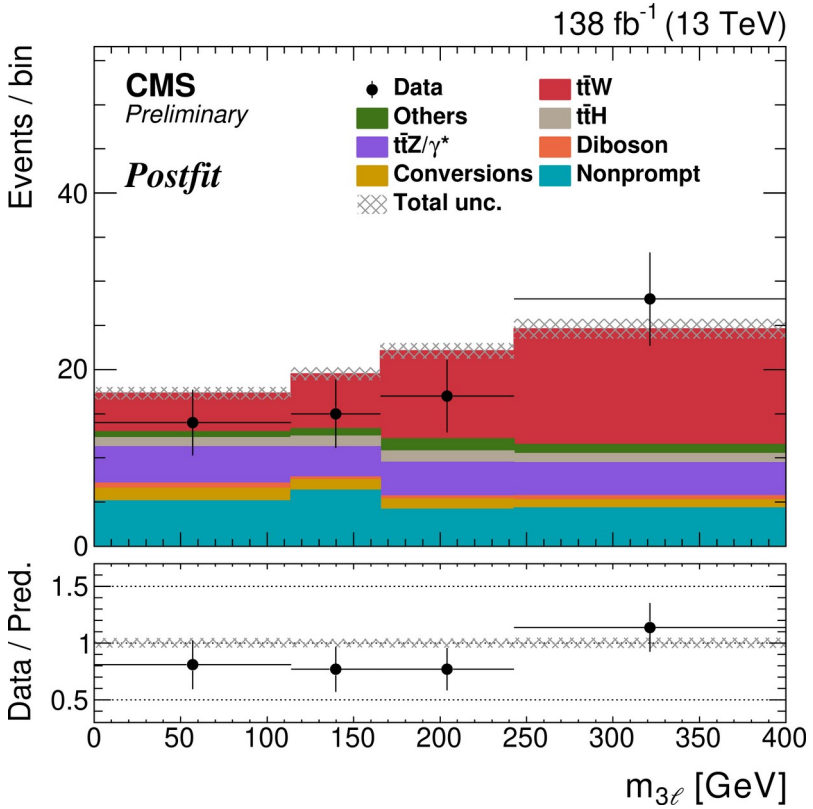
Understanding $t\bar{t}W$

CMS-PAS-TOP-21-011

- $t\bar{t}W$ production dominated by $q\bar{q}$
- previous results above SM (but compatible)
- explore NN discriminant in dilepton channel (left) and m_{3l} for final states with three leptons (right)







Understanding ttW

CMS-PAS-TOP-21-011

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- previous results above SM (but compatible)
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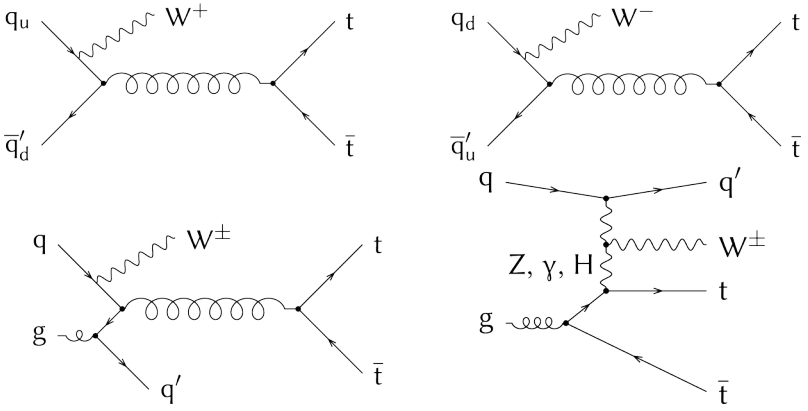
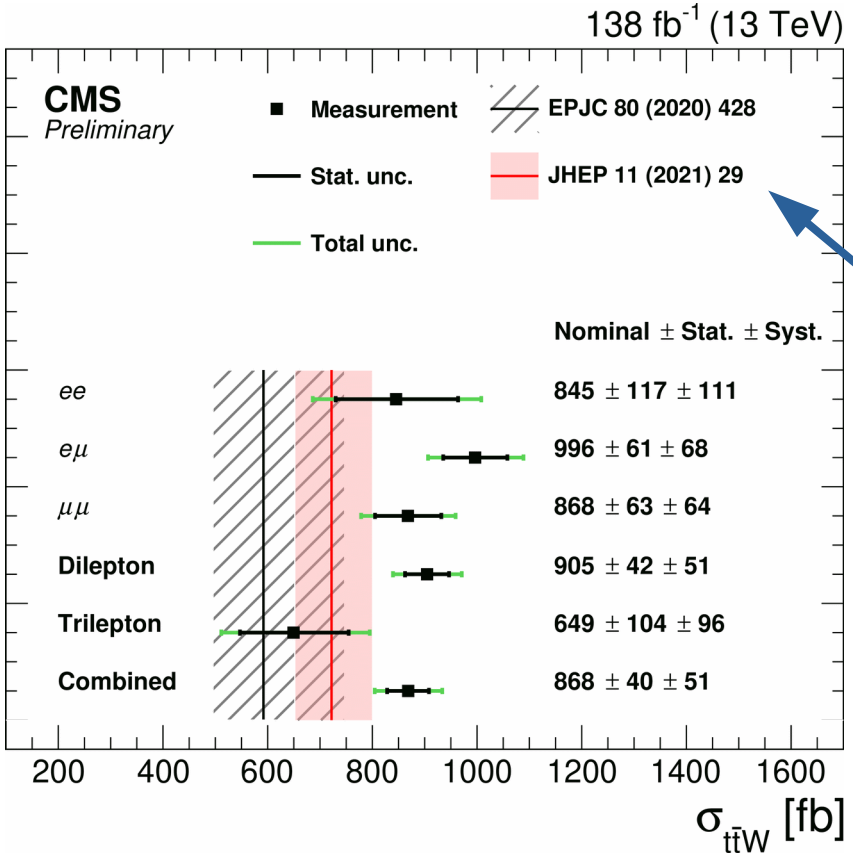


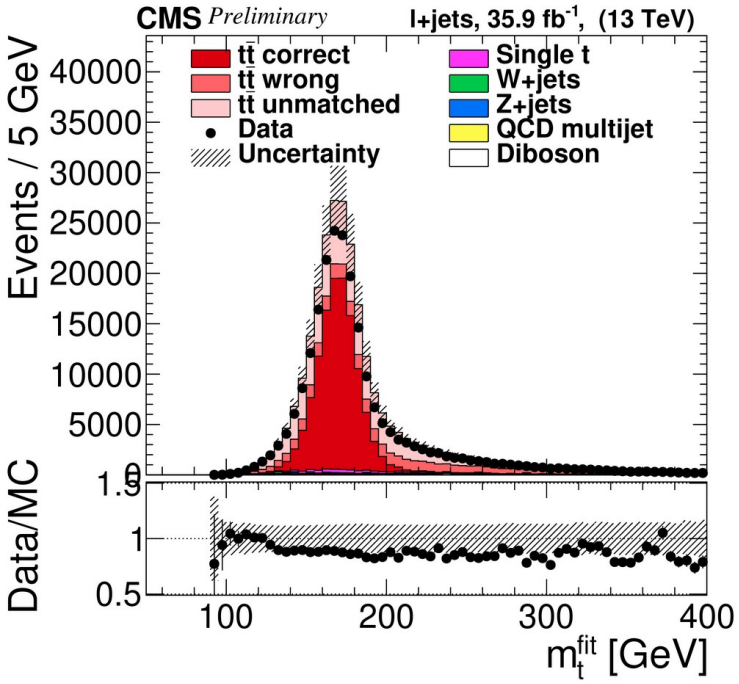


NLO with improved FxFx merging in better agreement
small tension remains

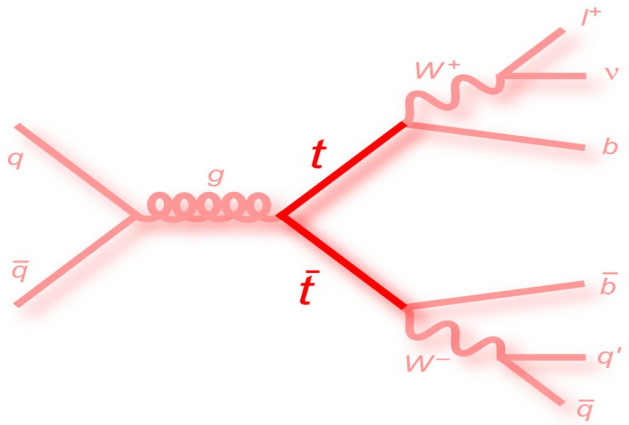
close collaboration with theory crucial

Pinning down the top quark mass

CMS-PAS-TOP-20-008



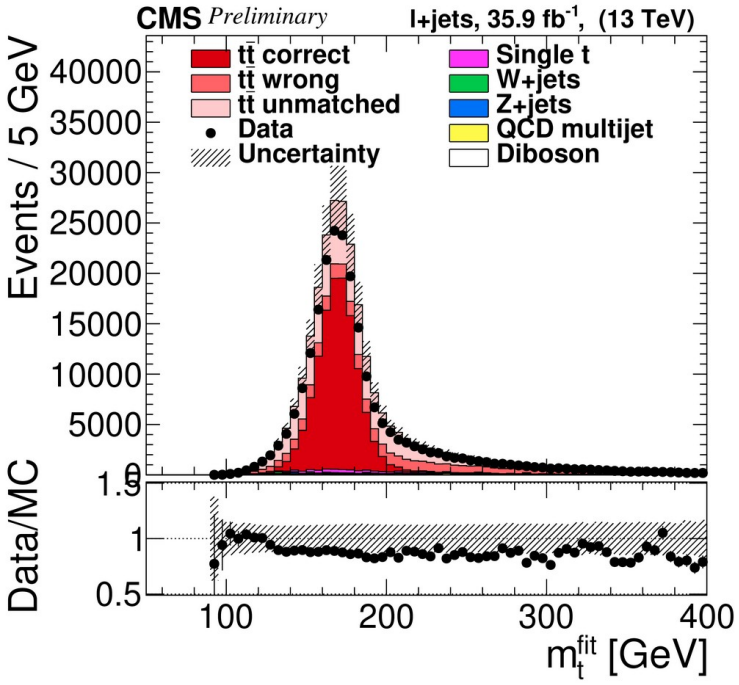
- baseline observable: m_t from kinematic fit
  - ~ 50% events with correct object matching
  - less than 5% background



- m_{top}: key parameter to check consistency of SM

Pinning down the top quark mass

CMS-PAS-TOP-20-008



- baseline observable: m_t from kinematic fit
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- adding 4 complementary observables to constrain systematics → total reduction by 40%

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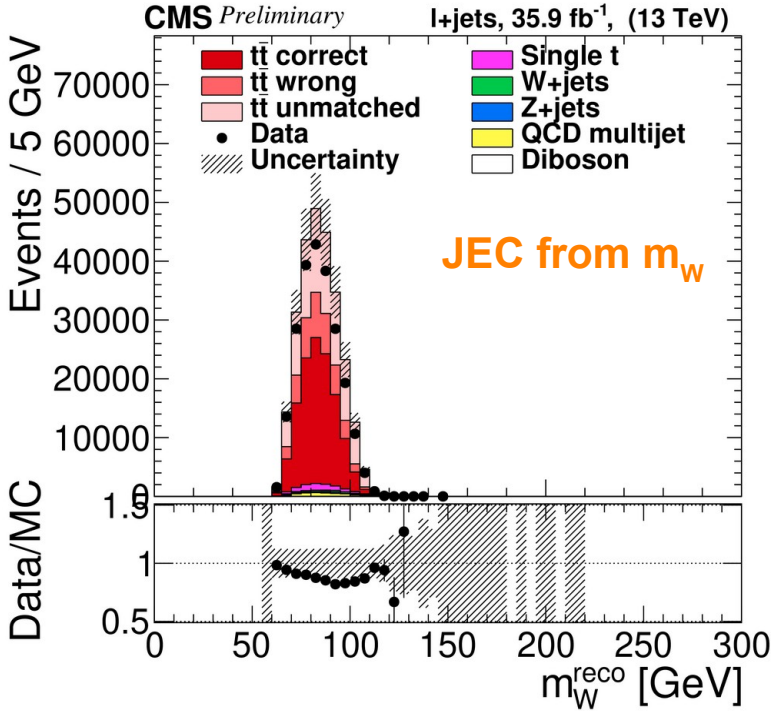
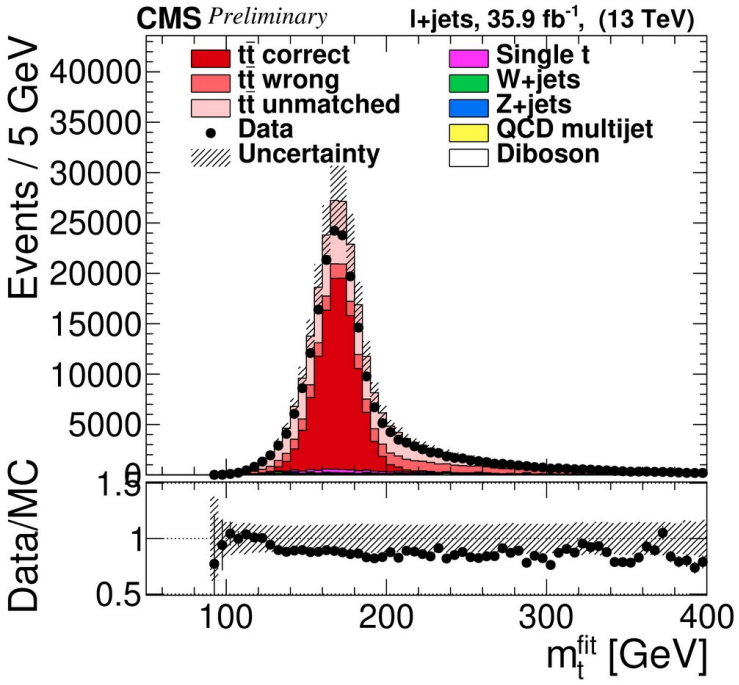


Pinning down the top quark mass

CMS-PAS-TOP-20-008



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  - ~ 50% events with correct object matching
  - less than 5% background
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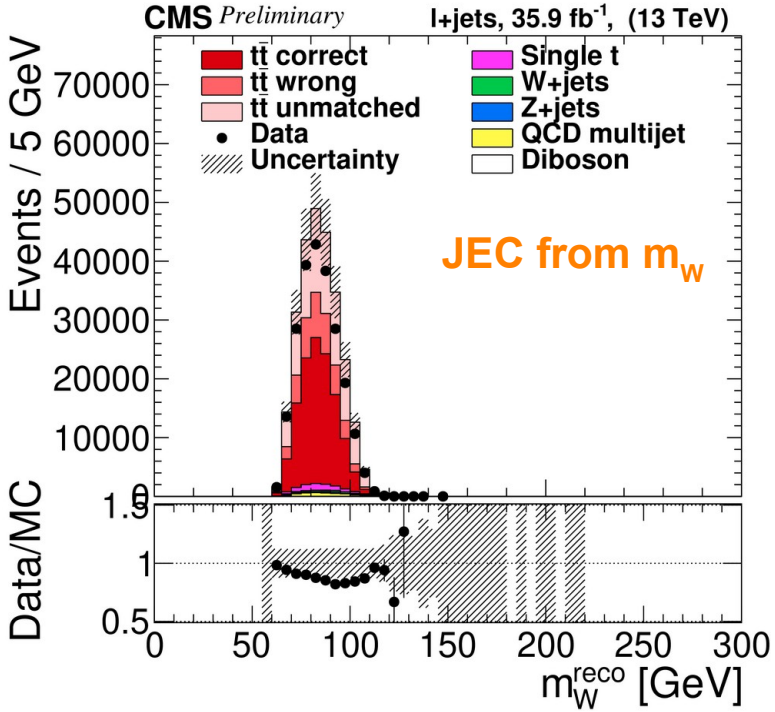
- m_{top}: key parameter to check consistency of SM

$m_t = 171.77 \pm 0.38$ GeV

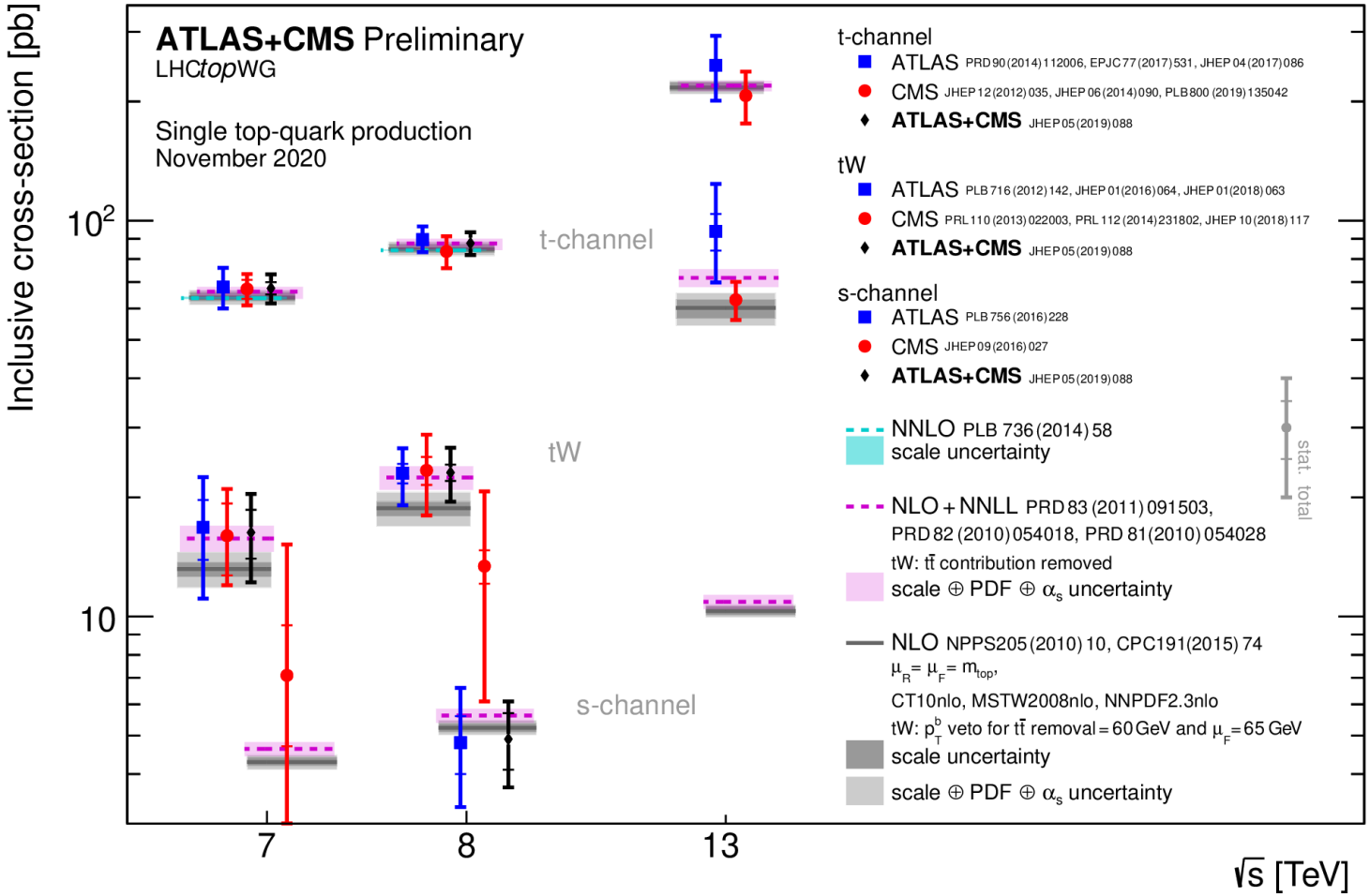
- largest uncertainty from b JEC, parton shower and color reconnection

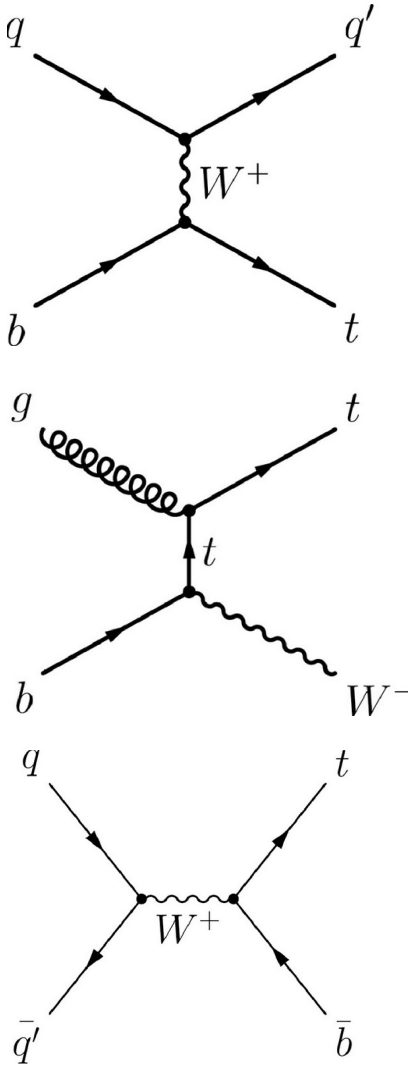
most precise top quark mass



Electroweak Top Quark Production

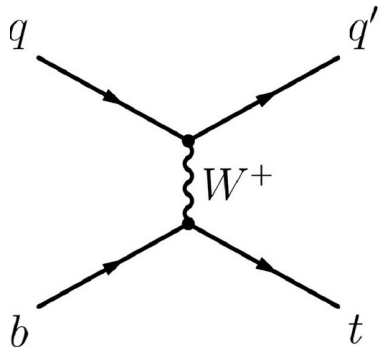
- t and tW channels of single top production very well established at LHC
  - good agreement with SM predictions at 7, 8 and 13 TeV



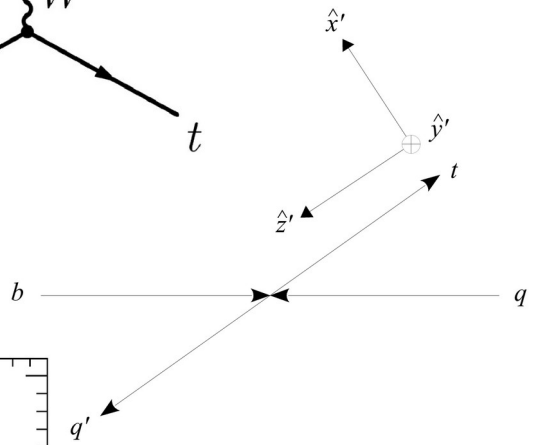


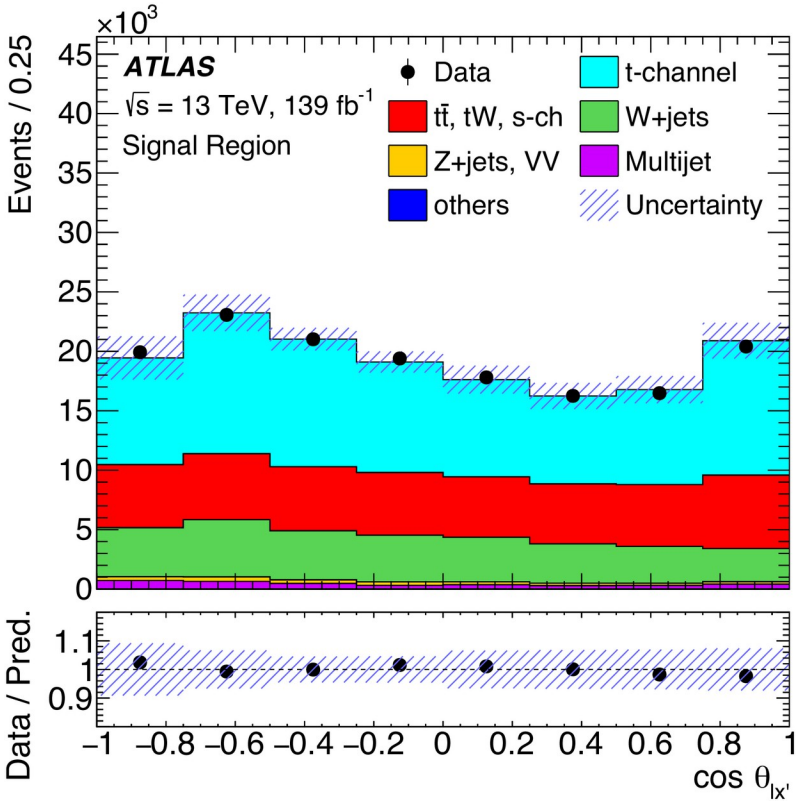
Studying Polarized Top Quarks

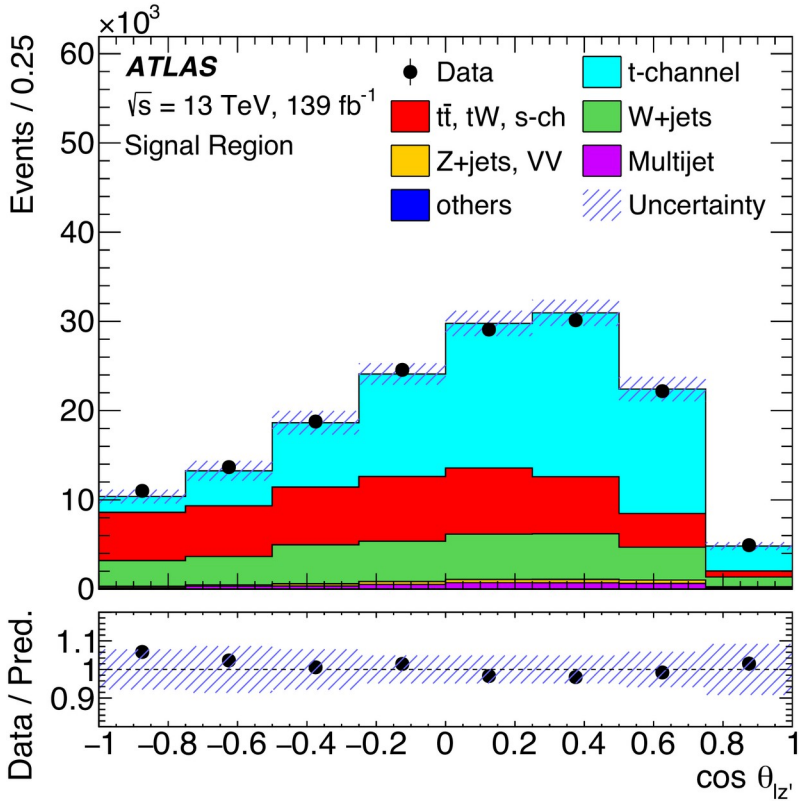
arXiv:2202.11382 [hep-ex]



- single top quarks produced via V-A:
  maximally polarized along direction of spectator quark
- polarization inferred from template fit to three
  orthogonal angular distributions of lepton from top decay







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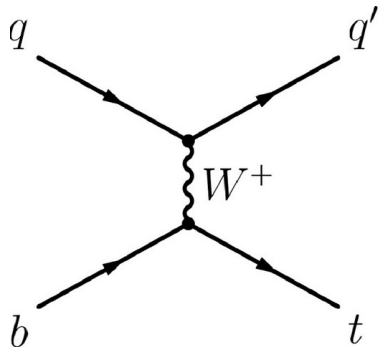

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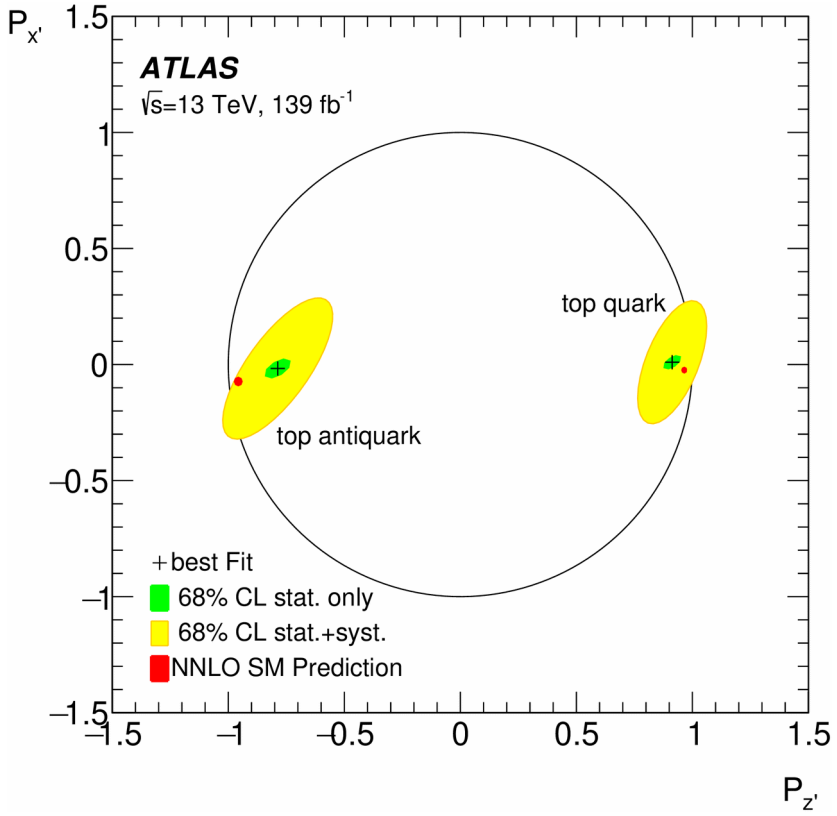
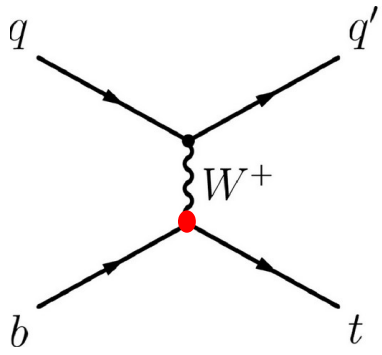


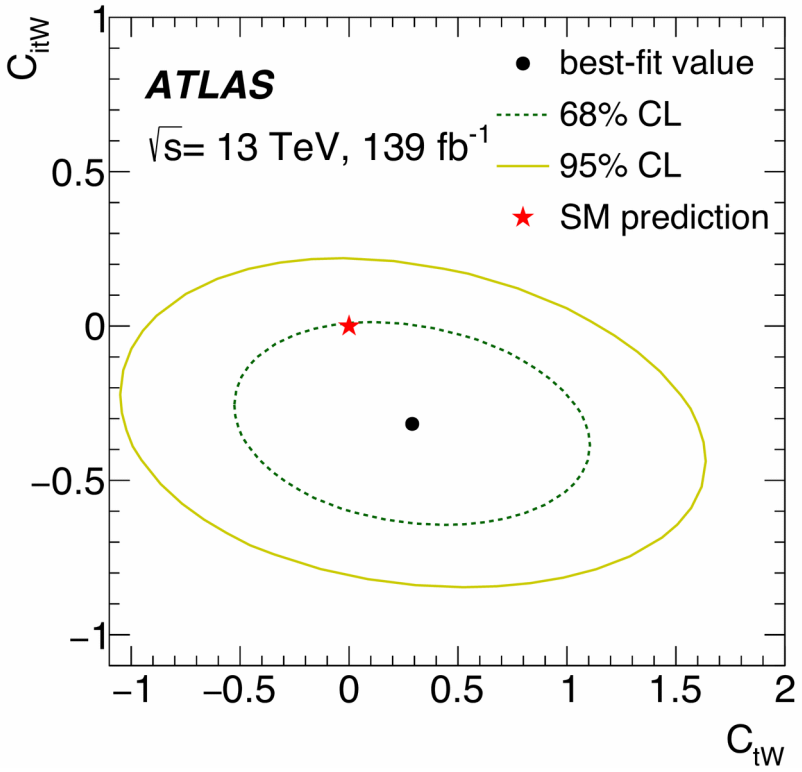
excellent agreement with NNLO predictions
for top quark and antiquark

Studying Polarized Top Quarks

arXiv:2202.11382 [hep-ex]



- single top quarks produced via V-A:
  maximally polarized along direction of spectator quark
- polarization inferred from template fit to three
  orthogonal angular distributions of lepton from top decay
- use unfolded distributions of cos θ_{lx} and cos θ_{ly} to constraint C_{tW} and C_{itW}



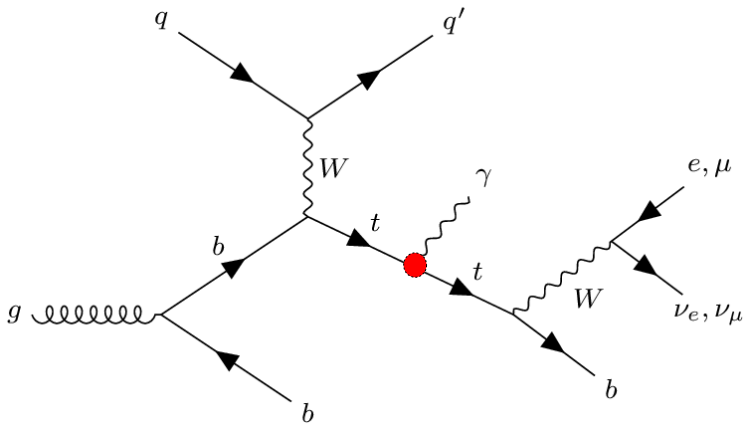
limits on C_{itW} improved by factor of 3
compared to previous simultaneous fits

spin: powerful and complementary probe of BSM

Observing Photon Associated Single Top Production

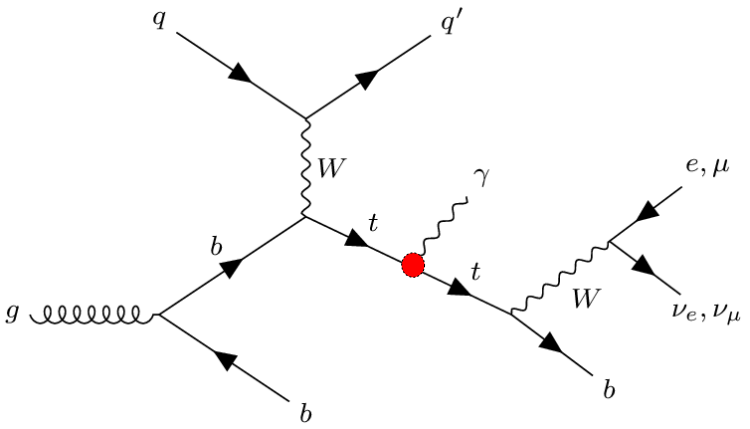
ATLAS-CONF-2022-013

- fundamental probe of top-electroweak couplings

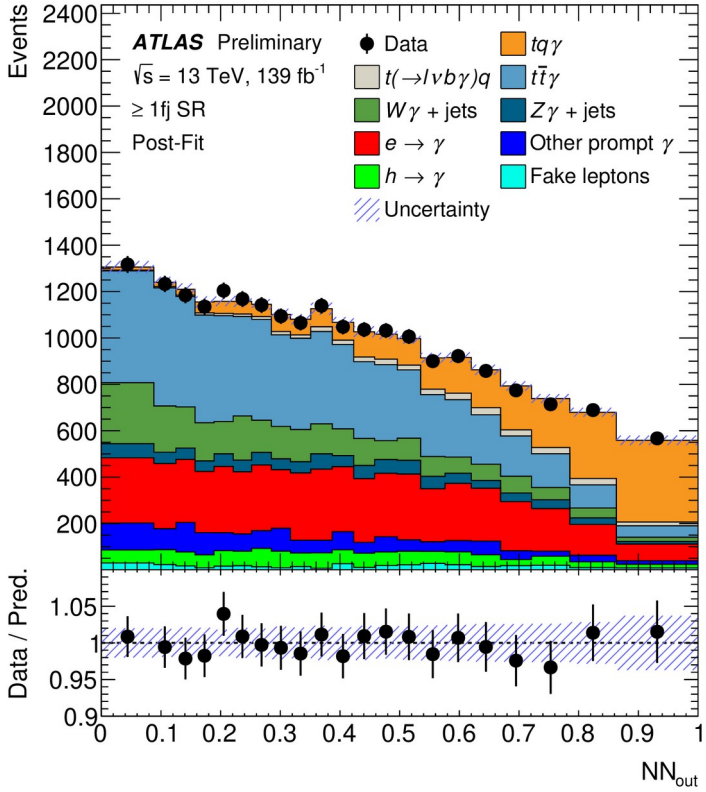


Observing Photon Associated Single Top Production

ATLAS-CONF-2022-013



- fundamental probe of top-electroweak couplings
- dedicated DNN provides clear separation between signal and background in region with tagged forward jet



fiducial cross section : $\sigma_{fid} = \sigma_{tq\gamma} \times BR(t \rightarrow l\nu b) + \sigma_{t(\rightarrow l\nu b\gamma)q}$

$\sigma_{fid}^{meas} = 287 \pm 8\ (stat.) \pm 31(syst.)$ fb

$\sigma_{fid}^{theo} = 207^{+26}_{-11}$ fb (4FS, NLO)

- compatible with SM within 1.9 SD
- 40% increased result consistent with CMS

Summary

- ATLAS and CMS started a new era of particle physics
  - several new, rare processes with full Run 2 data set observed
  - boosted final states allow to probing new regions of phase space

- key to success
  - excellent performance and calibration of leptons, photons and jets
  - novel machine learning techniques (S/B separation, object identification, regression, ...)
  - simultaneous fits of several parameters including systematic uncertainties

- framework of effective field theory provides a universal language to preserve our results and might reveal first hints of BSM physics in high precision measurements